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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 96

P- and CP-odd Effects in Hot and Dense Matter

April 26-30, 2010

Organizing Committee:

A. Deshpande, K. Fukushima, D. Kharzeev, H. Warringa, and S. Voloshin

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~50 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are ninety seven proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998.

N. P. Samios, Director
March 2010

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Introduction

RBRC/CATHIE Workshop on P- and CP-odd Effects in Hot and Dense Matter

This volume contains the proceedings of the RBRC/CATHIE workshop on "P- and CP-odd Effects in Hot and Dense Matter" held at the RIKEN-BNL Research Center on April 26–30, 2010. The workshop was triggered by the experimental observation of charge correlations in heavy ion collisions at RHIC, which were predicted to occur due to local parity violation (P- and CP-odd fluctuations) in hot and dense QCD matter. This experimental result excited a significant interest in the broad physics community, inspired a few alternative interpretations, and emphasized the need for a deeper understanding of the role of topology in QCD vacuum and in hot and dense quark-gluon matter. Topological effects in QCD are also closely related to a number of intriguing problems in condensed matter physics, cosmology and astrophysics. We therefore felt that a broad cross-disciplinary discussion of topological P- and CP-odd effects in various kinds of matter was urgently needed. Such a discussion became the subject of the workshop.

Specific topics discussed at the workshop include the following:

- The current experimental results on charge asymmetries at RHIC and the physical interpretations of the data;
- Quantitative characterization of topological effects in QCD matter including both analytical (perturbative and non-perturbative using gauge/gravity duality) and numerical (lattice-QCD) calculations;
- Topological effects in cosmology of the Early Universe (including baryogenesis and dark energy);
- Topological effects in condensed matter physics (including graphene and superfluids);
- Directions for the future experimental studies of P- and CP-odd effects at RHIC and elsewhere.

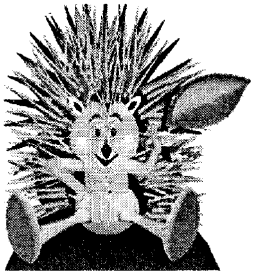
In five days, there were 39 talks and several contributed talks in the discussion sessions; the highlights of these presentations are included in this volume. For the complete set of presentation slides please visit the workshop website;
`http://quark.phy.bnl.gov/~kharzeev/cpodd/`

We feel that the talks and intense discussions during the workshop were extremely useful, and resulted in new ideas in both theory and experiment. We hope that the workshop has contributed to the progress in understanding the role of topology in QCD and related fields. We thank all the speakers and participants, and express our gratitude to the event coordinator Pam Esposito for her hard work.

Abhay Deshpande, Kenji Fukushima, Dmitri Kharzeev,
Sergei Voloshin, and Harmen Warringa

Topology of QCD and magnetic plasma at RHIC

Edward Shuryak
Department of Physics and Astronomy
Stony Brook



1. Chiral symmetry breaking, fermionic quasizero modes =>instanton liquid => dyon plasma?
2. Instantons/dyons and their role in confinement => effective potential for <P> (Diakonov)? Composite monopoles (Unsal)?
3. sphalerons and their explosion => diffractive clusters in pp at RHIC
4. Confinement as monopole BEC, magnetic plasma at RHIC => ridges, flux tubes, dual MHD
5. Qualitative calculation of the CP-odd charge asymmetry and RHIC data <= (most of other talks)

QCD sphalerons and their explosion => diffractive clusters at RHIC

Semiclassical Theory of High Energy Collisions based on Instantons and Sphalerons

- ''pomeron from instantons'':

ES, Zahed PRD62:085014,2000 hep-ph/0005152

D. E. Kharzeev, Y. V. Kovchegov and E. Levin Nucl. Phys. A **690**, 621 (2001) [hep-ph/0007182].

M. A. Nowak, ES and Zahed, PRD 64, 034008 (2001) [hep-ph/0012232].

G.W.Carter,D.Ostrovsky and ES, Phys. Rev. D **65**, 074034 (2002) [hep-ph

- the turning states and their explosion

D.Ostrovsky, G.W.Carter and ES, hep-ph/0204224,PRD

- Landau method for cross section - rescaled YM sphalerons are produced

D. Diakonov and V. Petrov, Phys. Rev. D **50**, 266 (1994) R. A. Janik, ES and Zahed, hep-ph/0206005.

- Explicit solution of the Dirac eqn in the exploding field background: an end of ''the fermion puzzle''?

ES and Zahed, hep-ph/0206022.

- Gluonic cluster production in double-Pomeron processes (e.g. $pp->pp\eta'; pp f_0(1600), pp+$cluster) compared to data; ES and Zahed,2002
- Instanton-induced Double DIS $\gamma^*\gamma^*$)ES and Zahed,2003

Semiclassical Double-Pomeron Production of Glueballs, η' and clusters

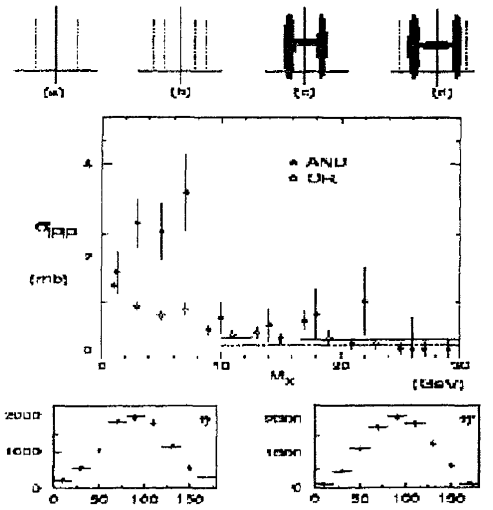
ES and I.Zahed,Phys.Rev. D68 (2003) 034001

Pomeron-Pomeron into cluster, cross section from UA8 collaboration: heavy gluonic clusters with isotropic decay. What are they?

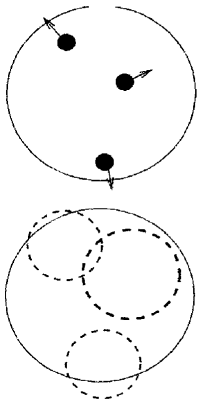
Note: a cross section that is an order of magnitude larger than the one predicted by Pomeron factorization

WA102 collaboration at CERN, pp Double-Pomeron into identified central hadron: strong dependence of the cross section on the azimuthal angle ϕ (between two kicks to two protons), not expected from standard Pomeron phenomenology.

we get $\cos^2(\phi)$ for P=+ and $\sin^2(\phi)$ for P=-1.



"magnetic scenario": (color) magnetic monopoles are important excitations near Tc

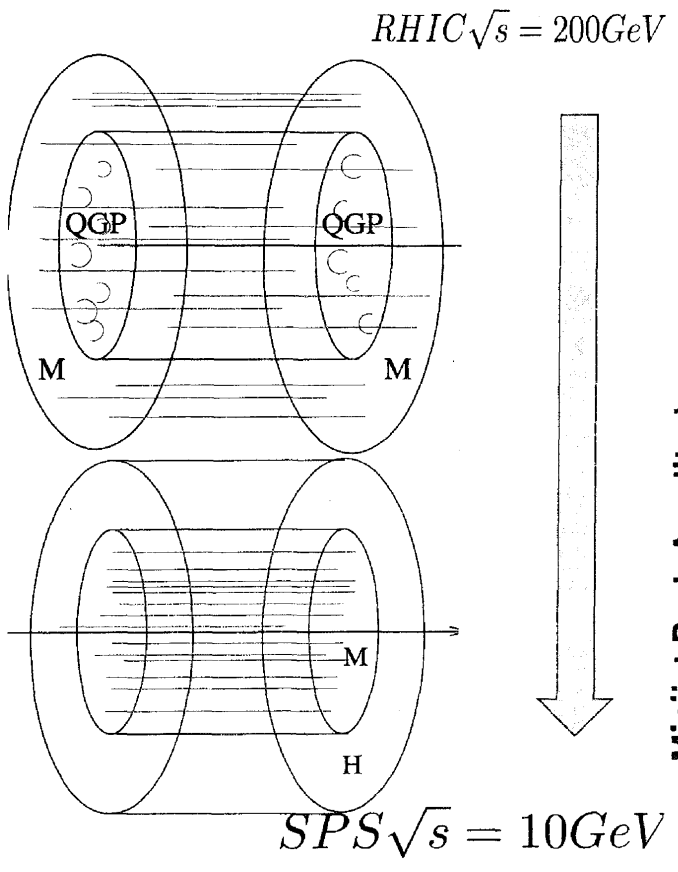


- **Strongly coupled plasma with electric and magnetic charges.**
  Liao,ES,_ Phys.Rev.C75:054907,2007.
  hep-ph/0611131
- **Magnetic component of Yang-Mills plasma**,M.N.Chernodub and V.I.Zakharov, 98, 082002 (2007) [arXiv:hep-ph/0611228].
- **Electric Flux Tube in Magnetic Plasma.**
  Liao,ES, Phys.Rev.C77:064905,2008.
  arXiv:0706.4465
- Magnetic monopoles in the high temperature phase of Yang-Mills theories, A.D'Alessandro and M.D'Elia, Nucl.Phys.B 799, 241 (2008) [arXiv:0711.1266
- **Magnetic Component of Quark-Gluon Plasma is also a Liquid!** Liao,ES,_
  Phys.Rev.Lett.101:162302,2008.
  e-Print: arXiv:0804.0255
- **Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition.**
  Jinfeng Liao,, Edward Shuryak Phys.Rev.Lett. 102:202302,2009.
  e-Print: arXiv:0810.4116
- **Thermal Monopole Condensation and Confinement in finite temperature Yang-Mills Theories.**
  Alessio D'Alessandro, Massimo D'Elia, Edward Shuryak, . Feb 2010. 17pp.

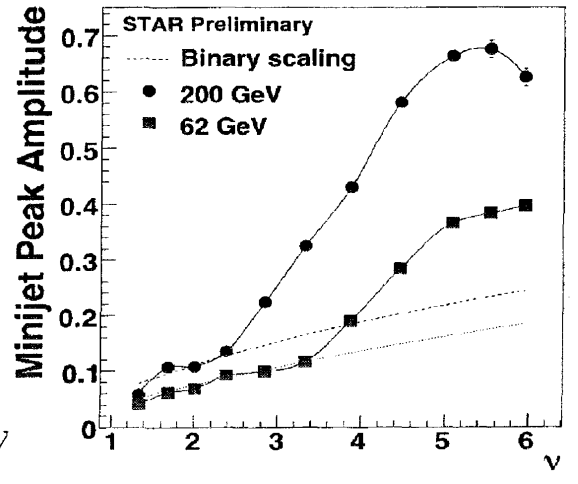
⇑

See Massimo's talk

Predictions for energy dependence: ridges



As energy decreases, M phase Goes inside the fireball => Much smaller radial flow => Disappearance of the ridge happens at fixed density of matter!



L.Ray, Also in CuCu

summary

Instantons provide quantiative description of chiral symmetry breaking, solve the U(1) problem and produce good correlators: but do not explain confinement. => would dyon plasma do it?

Prompt excitation instanton=>sphaleron in diffractive pp collisions should be studied at RHIC

CP effects at RHIC must come from exploding sphalerons at early time <= magnetic field strongly decreases with (subject of the workshop)

Color magnetic monopoles found in MAG behave as physical objects: Coulomb plasma, BEC at Tc

"RHIC ridges" are the "QGP corona"

flux tubes are more stable in magnetic plasma than in vacuum!

The Chiral Magnetic Effect

Harmen Warringa, Goethe Universität, Frankfurt

Collaborators: Kenji Fukushima, Dmitri Kharzeev and Larry McLerran.

Abstract:

Gluon field configurations with nonzero topological charge generate chirality, which in the presence of an external magnetic field induces an electromagnetic current along this field. This mechanism is called the chiral magnetic effect. First I will give a qualitative explanation of the chiral magnetic effect, then I will discuss a quantitative static calculation and finally I present a fully dynamic calculation.

In heavy ion collisions enormously strong magnetic fields are created, moreover it is likely that topological charge fluctuations take place in the produced hot matter. Therefore it might be possible that the chiral magnetic effect is realized in heavy ion collisions, where it is predicted to lead to charge separation along the direction of angular momentum of the collision.

I will explain you that the Chiral Magnetic Effect is

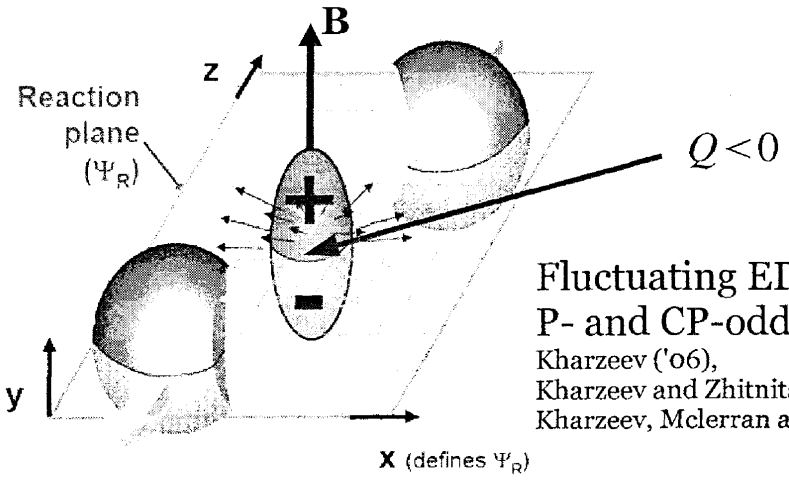
Topological charge + Magnetic Field =

Induces chirality: P- and CP-odd effect

Pointing perpendicular to reaction plane

$\langle Q \rangle = 0$

$\langle Q^2 \rangle \neq 0$



$Q < 0$

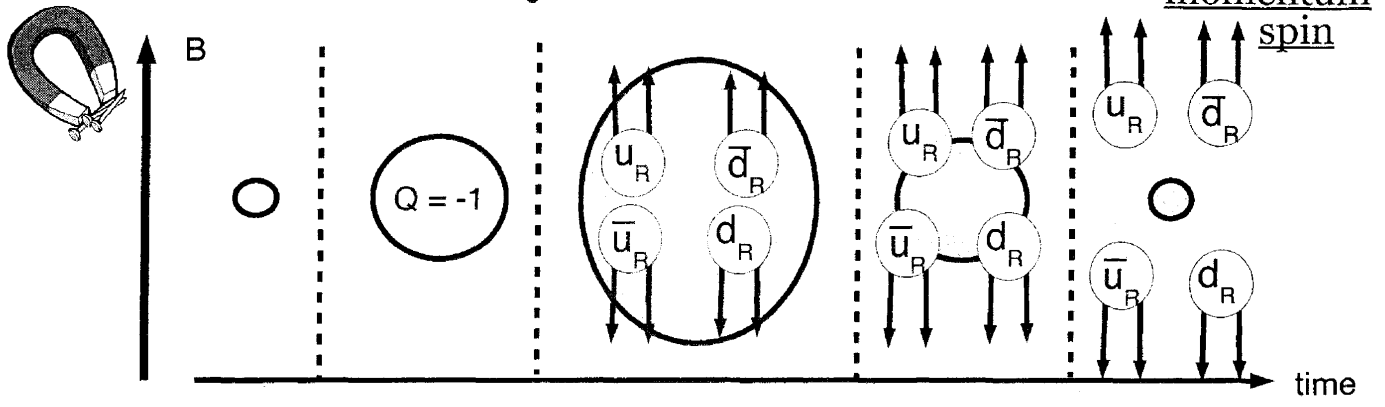
Fluctuating EDM of QGP
P- and CP-odd effect
Kharzeev ('06),
Kharzeev and Zhitnitsky ('07)
Kharzeev, Mclerran and Warringa ('08)

Charge separation

Investigate experimentally by charge correlation study Voloshin ('04) *Talks by Sergei Voloshin, Roy Lacey & Jack Sandweiss*

Alternative mechanisms for charge separation *Talk by Berndt Mueller*

Topological Charge + Magnetic field = Chirality + Polarization =



Q < -1: Positively charged particles move parallel to magnetic field, negatively charged antiparallel

... = Electromagnetic Current

P- and CP-odd effect --> Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('08)

$$J = \int d^3x \langle \bar{\psi} \gamma^3 \psi \rangle = -2Q \sum_f |q_f|$$

Valid for full polarization, what about smaller fields?

Magnitude of the induced current

Fukushima, Kharzeev and HJW ('08)

Static calculation: induce difference between #right- and #left-handed by chiral chemical potential μ_5

Current density becomes:

$$j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$$

Express μ_5 in terms of chirality density cf. baryon chem. potential and density

$$n_5 = \frac{\partial \Omega}{\partial \mu_5}$$

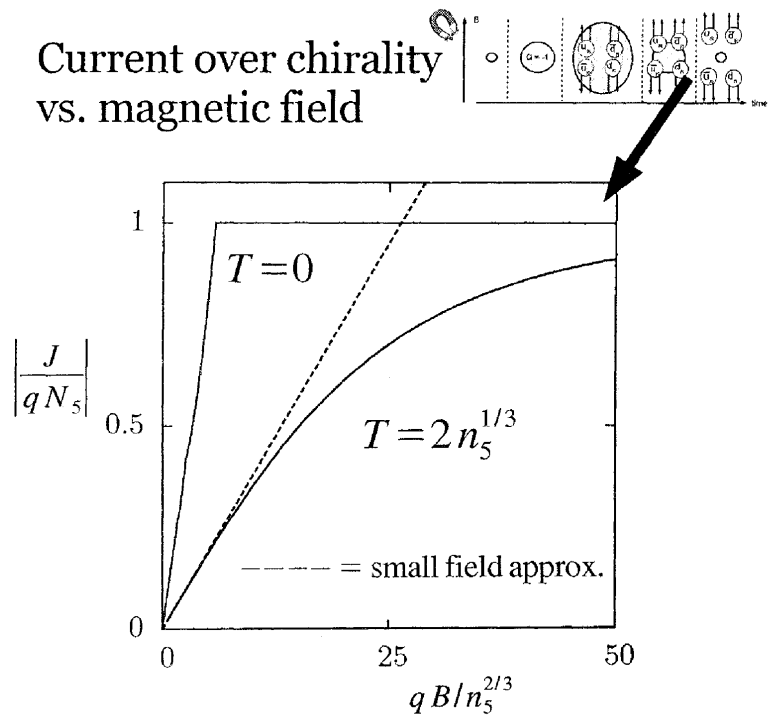
Obtain thermodynamic potential Ω with B at high T using LO. pert. QCD.

$$\mu_5 = f(T, B, \mu, n_5)$$

Relate total chirality to top. charge

$$N_5 = -2Q$$

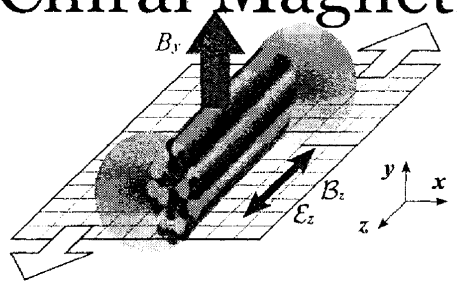
Current over chirality vs. magnetic field



Obtained: estimate induced current in small mag. field: $J \approx -\frac{3}{\pi^2} \frac{Q}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$

Fukushima, Kharzeev and HJW, arXiv:1002.2495

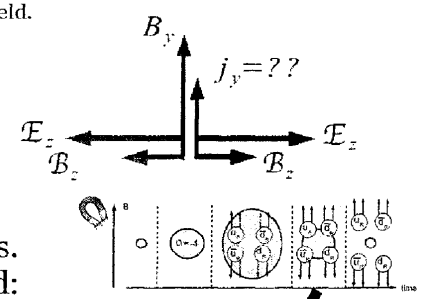
Chiral Magnetic Effect in Color Flux Tube



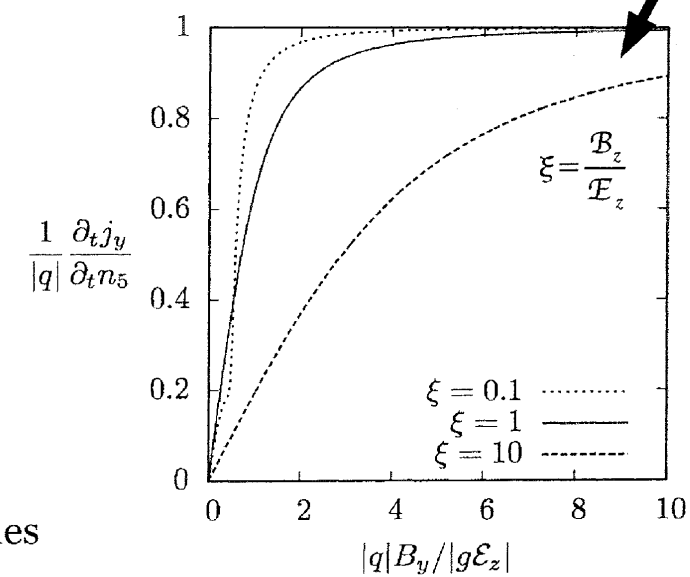
Setup: Homogeneous flux tube + mag field.
Flux tube: infinite topological charge, generates chirality dynamically

$$\partial_\alpha J^\alpha_5 = -\frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a = \frac{g^2}{4\pi^2} \vec{\mathcal{E}} \cdot \vec{\mathcal{B}}$$

Goal: Current in y-direction
Verify Chiral Magnetic effect



Current over chirality rate vs. perpendicular magnetic field:



Dynamical calculation of Chiral Magnetic Effect:

- Completely analytic result for jy
- Only EM current in y direction
- No By, or no chirality: jy = 0
- Large By: current=chirality
- Quark mass: reduction in current
- No anomaly: fictional scalar particles completely different behavior.

Conclusions

Topological charge + magnetic field naturally leads to charge separation, which is a P- and CP-odd effect.

It could be an explanation for the charge correlations observed by STAR.

We need more phenomenology and rule out alternative explanations.

What (little) we Know about The SU(3) Sphaleron Rate

Guy Moore

McGill University

- Reminder: physics of Sphaleron Rate
- Correlation function defining Sphaleron Rate
- Difficulty with Analytic Continuation
- Evaluation at weak coupling
- Gaps in our knowledge, and Which Gaps we can Fill

CP odd workshop, Brookhaven, 26 April 2010:

Diffusion and Relaxation

Mean-square change per 4-volume:

$$\Gamma_{\rm Sphal} \equiv \frac{\langle (\Delta N_{\rm cs})^2 \rangle}{Vt} = \int d^4x \left\langle \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}(x) \frac{g^2}{32\pi^2} F_{\alpha\beta}\tilde{F}^{\alpha\beta}(0) \right\rangle$$

Diffusion rate of topological number.

Fluctuation–Dissipation: Relaxation rate for $Q_5 \equiv \langle J_5^0 \rangle$:

(Giudice-Shaposhnikov hep-ph/9311367, Moore hep-ph/9705248)

$$\frac{dQ_5}{dt} = -(Q_5 - Q_{5,\rm equil}) \frac{(2N_{\rm f})^2}{\chi_Q} \frac{\Gamma_{\rm Sphal}}{2T} \simeq -Q_5 \frac{6N_{\rm f}}{N_{\rm c}} \frac{\Gamma_{\rm Sphal}}{T^3}$$

(Using free-theory Q_5 susceptibility $\chi_Q = \frac{1}{3} N_{\rm f} N_{\rm c} T^2$)

nonperturbative relationship (so far)

Euclidean methods???

I can calculate Euclidean version on the lattice. Not the same:

$$\int_0^\beta d\tau \int d^3x \langle F\tilde{F}(x,\tau) F\tilde{F}(0,0)\rangle \neq \int dt_{\rm mink} \int d^3x \langle F\tilde{F}(x,t) F\tilde{F}(0,0)\rangle$$

The Sphaleron Strikes Back, Peter Arnold and Larry McLerran, Phys.Rev.**D37**:1020,1988. 316 references

Consider rigid rotor or pendulum, coupled to thermal bath of SHO's or anharmonic oscillators. High temperature: $\left\langle (\int_0^\beta d\tau (d\theta/dt))^2 \right\rangle$ exponentially small but really rotor should spin like crazy.

But they do have something to do with each other.
Minkowski quantity is $\lim_{\omega\to 0} T \frac{d}{d\omega} \sigma_{F\tilde{F},F\tilde{F}}(\omega, k=0)$ (spectral func)

$$\int d^3x \left\langle \langle F\tilde{F}(x,\tau) F\tilde{F}(0,0)\right\rangle_{\rm eucl} = \int_0^\infty \frac{d\omega}{\pi} \frac{\sigma_{F\tilde{F},F\tilde{F}}(\omega)}{\omega} \frac{\omega \cosh \omega(\tau - \beta/2)}{\sinh \omega\beta/2}$$

Can I invert this relation?

CP odd workshop, Brookhaven, 26 April 2010:

Large Coupling

D. Son and A. Starinets hep-th/0205051 calculated $\Gamma_{\rm sphal}$ in $\mathcal{N}$=4 SYM theory in the $N_{\rm c} \to \infty$, $(g^2 N_{\rm c}) \gg 1$ limit and found

$$\Gamma_{\rm sphal}(\mathcal{N}{=}4{\rm SYM}) = \frac{(g^2 N_{\rm c})^2}{256\pi^3} T^4 \,.$$

Note, $\chi_Q \sim N_{\rm c} N_{\rm f} T^2$, $\Gamma_{\rm sphal}/(\chi_Q T^2) \ll 1$.

Guess: behavior at reasonable $N_{\rm c}$, $g^2 N_{\rm c}$ similar.

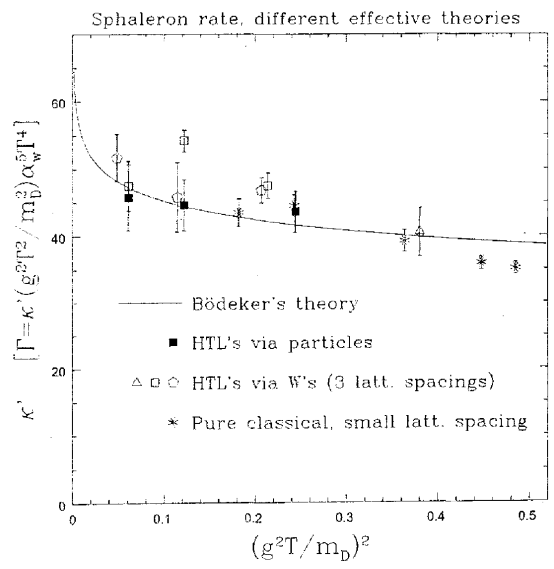
Plausible that at $N_{\rm c} \sim 3$, $g^2 N_{\rm c} \sim 1$, $\Gamma_{\rm sphal}/(\chi_Q T^2) \sim 1$.
(May not be well defined in that case ...)

Case of SU(2)

Bödeker's Effective Theory:

$$\Gamma_{\rm sphal}[{\rm SU}(2)] = 10.0 \left(\frac{g^2}{4\pi}\right)^5 T^4 \left(3.041 + \ln \frac{2\pi\sqrt{\frac{4+N_{\rm f}}{6}}\ln\, x}{g}\right)$$

Comparison with particle simulations: good agreement.
Can do same for SU(3) but we haven't



CP odd workshop, Brookhaven, 26 April 2010:

Larger N_c: speculations

I once speculated (hep-ph/0009161) that:

$$\Gamma \sim .24 N_c^3 (N_c^2 - 1) \left(\frac{N_c g^2 T^2}{m_D^2} \right) \alpha^5 T^4 \left[\ln \frac{m_D}{\frac{g^2 N_c}{4\pi} \ln x} + 3.041 \right] .$$

Argument was that N_{cs} fluctuates randomly inside regions of correlation length $2\pi / g^2 N_c T$.

Problem: region too small to hold a sphaleron.
Get further and further from $\Delta N_{cs} = 1$ as N_c grows.
Picture right? Or is there large N_c suppression?

Need to go back and do other N_c values!

Magnetic Field Induced Conductivity of the Vacuum of Gluodynamics

M.I. Polikarpov

ITEP, 117218 Russia, Moscow, B. Cheremushkinskaya str. 25

Abstract

We use the chirally invariant lattice Dirac operator to study the correlator of two vector currents in quenched SU(2) lattice gauge theory with constant external magnetic field. In the confinement phase the correlator of the components of the current parallel to the magnetic field decays much slower than in the absence of magnetic field, for other components the correlation length slightly decreases. We find that in the confinement phase the external magnetic field induces nonzero electric conductivity along the direction of the field, the vacuum becomes an anisotropic conductor. In the deconfinement phase the conductivity does not depend on the magnetic field. The other effects which are due to the interference of strong and electromagnetic interactions are: chiral magnetic effect, magnetization of the vacuum, local quark dipole moment, enhancement of the chiral condensate, local generation of the anomalous quark electric dipole moment along the axis of magnetic field. The results are published in arXiv:1003.2180, arXiv:0910.4682, arXiv:0909.2350, arXiv:0909.1808, arXiv:0907.0494, arXiv:0906.0488, arXiv:0812.1740

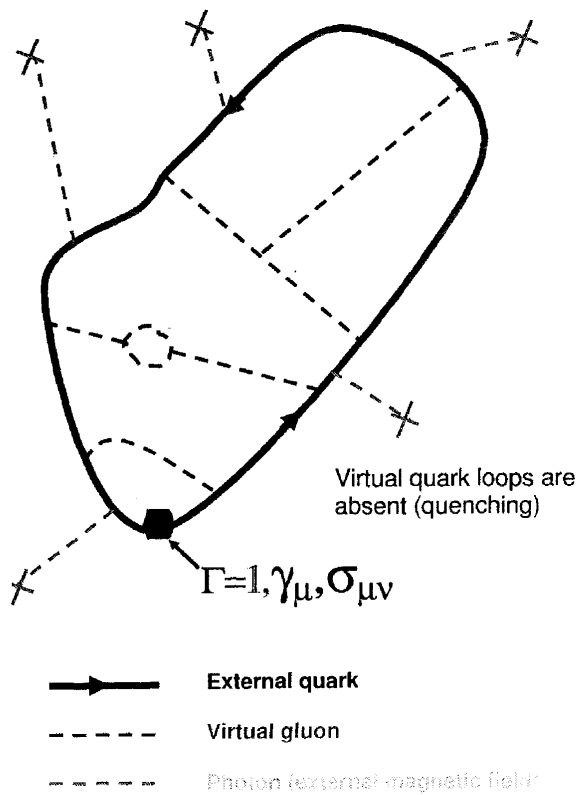
Magnetic forces are of the order of strong interaction forces

$$eB \approx \Lambda^2_{QCD}$$

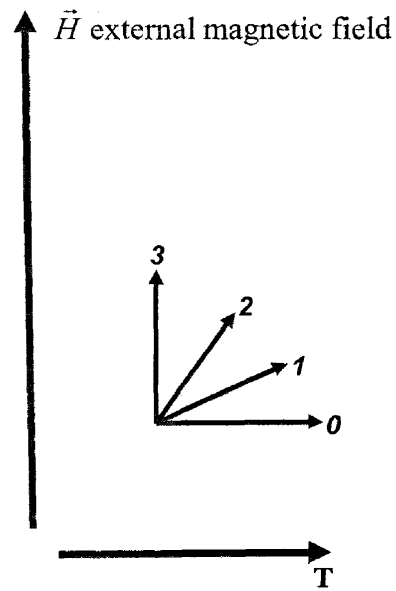
We expect the influence of magnetic field on strong interaction physics
The effects are nonperturbative,
and we use

Lattice Calculations

$$eB = \frac{2\pi qk}{L^2}; \; eB \geq 250 \; Mev$$

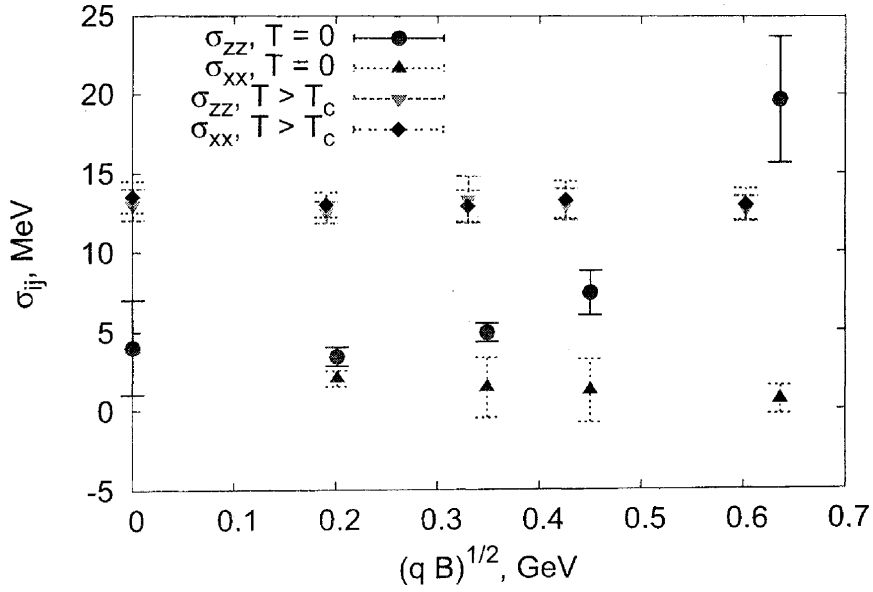


We calculate $<\overline{\psi}\,\Gamma\psi>;\ \Gamma=1,\gamma_\mu,\sigma_{\mu\nu}$ **in the external magnetic field and in the presence of the vacuum gluon fields. We consider SU(2) gauge fields in quenching approximation and overlap Dirac operator**

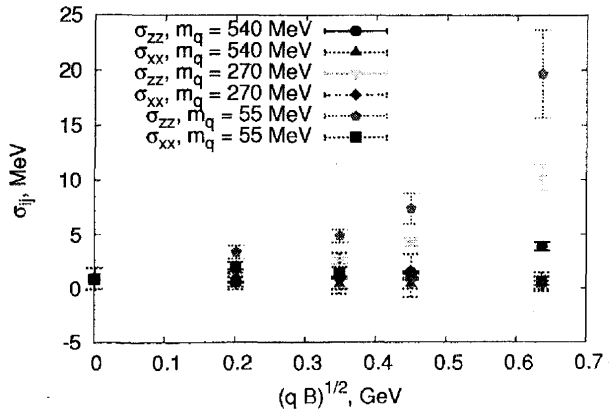


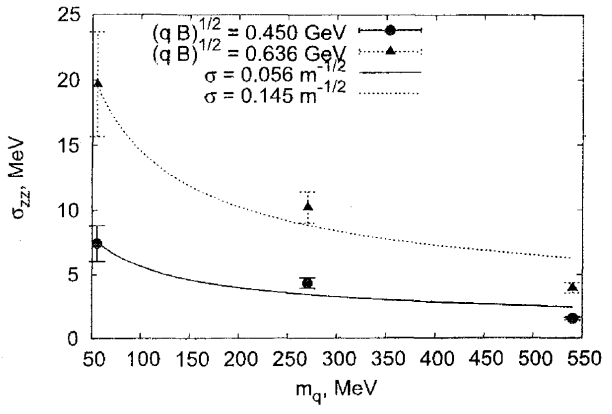
Calculations in SU(2) gluodynamics, conductivity vs. magnetic field at *T=0 and T>0*

$$\sigma_{ij} = \frac{\rho_{ij}(0)}{4T}$$

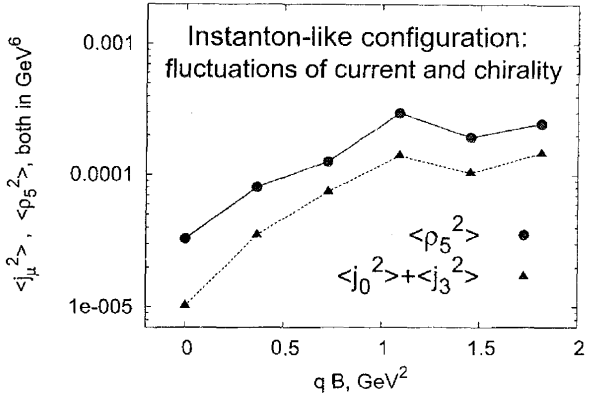


Calculations in SU(2) gluodynamics, conductivity vs. magnetic field at *T=0,* for various quark masses

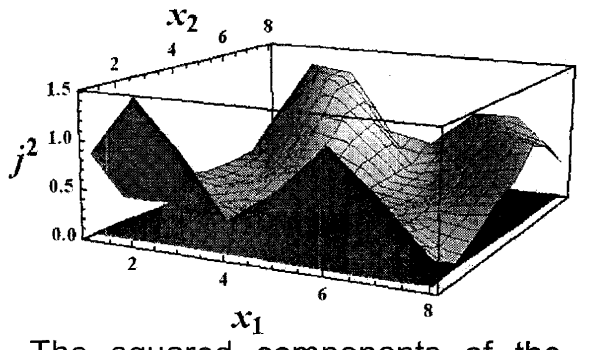




5. Electric currents in instanton field+magnetic field (CME)



The fluctuations of the chirality $\rho_5 = \overline{\psi}\gamma_5\psi$ and the fluctuations of the longitudinal electric current as a function of the magnetic field.



The squared components of the electric current in a 12-plane. The upper sheet represents the spatial distribution of the longitudinal current, the lower sheet corresponds to the transverse current.

$$< j_i^2 >_{IR} = < j_i^2(H,T) > - < j_i^2(0,0) >, \quad j_i = \overline{\psi}\gamma_i\psi$$

Axial anomalies in hydrodynamics

Dam T. Son

Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550

Abstract

We discuss the effects of chiral anomalies in hydrodynamics.

Parity-odd effects?

- QFT: may have *chiral fermions*
  - example: QCD with massless quarks
- Parity invariance does not forbid

$$j^{5\mu} = n^5 u^\mu + \xi(T,\mu)\omega^\mu$$

$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} u_\nu \partial_\alpha u_\beta$$ vorticity

- The same order in derivatives as dissipative terms (viscosity, diffusion)

in 2+1D: $\tau_{\mu\nu} = \cdots + \epsilon_{\mu\alpha\beta} u_\alpha u_{\nu\beta} + (\mu \leftrightarrow \nu)$ Hall viscosity

Relativistic theories are different

- There can be current ~ vorticity
- It is related to triangle anomalies

$$\partial_\mu j^{5\mu} = \# E \cdot B$$

  but the effect is there even in the absence of external field

- The kinetic coefficient ξ is determined completely by anomalies and equation of state

Anomalous hydrodynamics

- These equations have to be supplemented by the constitutive relations:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + P g^{\mu\nu}$$ +viscosities

$$j^\mu = n u^\mu + \xi \omega^\mu + \xi_B B^\mu \qquad B^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} u_\nu F_{\alpha\beta}$$

+diffusion+Ohmic current

- Demand that there exist an entropy current with positive derivative: $\partial_\mu s_\mu \geq 0$

Entropy production

- Positivity of entropy production completely fixes ξ and ξ_B

$$\xi = C\left(\mu^2 - \frac{2}{3}\frac{n\mu^3}{\epsilon + P}\right)$$

anomaly coefficient

$$\xi_B = C\left(\mu - \frac{1}{2}\frac{n\mu^2}{\epsilon + P}\right)$$

$$j^\mu = \cdots + \xi\omega^\mu + \xi_B B^\mu$$

These expressions have been checked for N=4 SYM

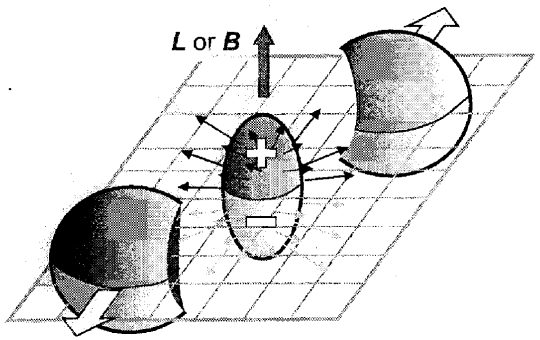
Chiral magnetic effect

- Large axial chemical potential μ_5 for some reason
- Leads to a vector current: charge separation
- π^+ and π^- would have anticorrelation in momenta
- Some experimental signal?
- Can be explained by $j \sim \mu_5 B$ Kharzeev, Fukushima, Warringa, McLerran...
- Chiral rotation effect: $j \sim \mu_5 \omega$

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

Sergei A. Voloshin WAYNE STATE UNIVERSITY

for the STAR *Collaboration*



Outline:

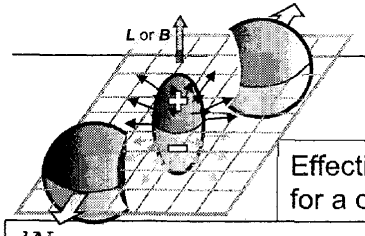
- Chiral Magnetic Effect and observables
- STAR results (PRL , long paper – arXiv: 0909.1717, submitted to PRC)
- Future directions
- Summary

PRL 103, 251601 (2009) | Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

Observable

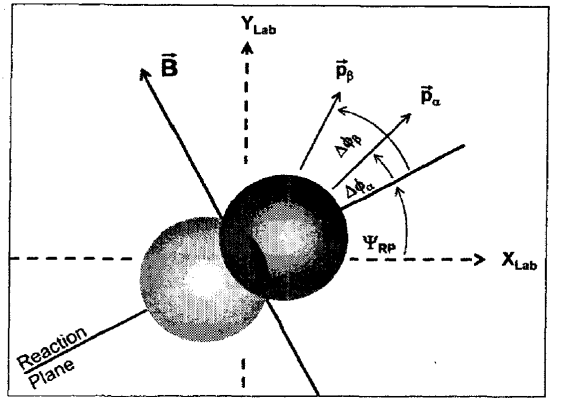
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \ldots$$
$$+\ 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \ldots,$$

$$\Delta\phi = (\phi - \Psi_{RP})$$



- The effect is too small to observe in a single event
- The sign of Q varies and $\langle a \rangle = 0$ (we consider only the leading, first harmonic) ➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)
- $\langle a_\alpha a_\beta \rangle$ is expected to be ~ 10^{-4}
- $\langle a_\alpha a_\beta \rangle$ can not be measured as $\langle \sin\varphi_\alpha \sin\varphi_\beta \rangle$ due to large contribution from effects not related to the orientation of the reaction plane

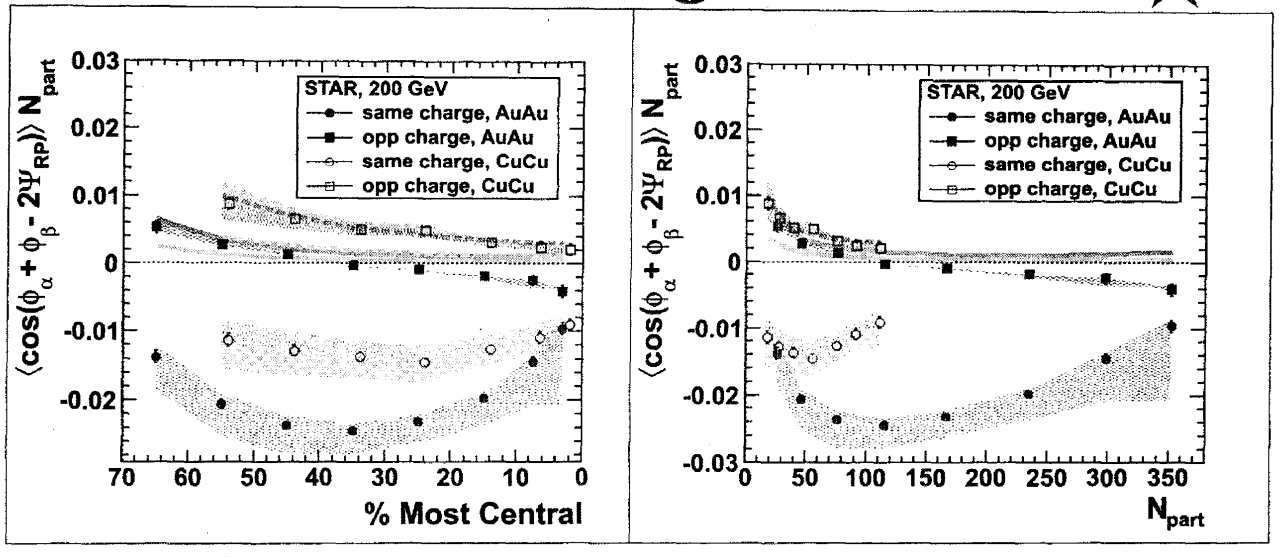
➔ study the difference in corr's in- and out-of-plane

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle =$$
$$= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B^{in}] - [\langle a_\alpha a_\beta \rangle + B^{out}].$$

$B^{in} \approx B^{out}$, $v_1 = 0$

A practical approach: three particle correlations: $\langle \cos(\phi_a + \phi_\beta - 2\phi_c) \rangle = \langle \cos(\phi_a + \phi_\beta - 2\Psi_{RP}) \rangle\, v_{2,c}$

Au+Au and Cu+Cu @ 200 GeV



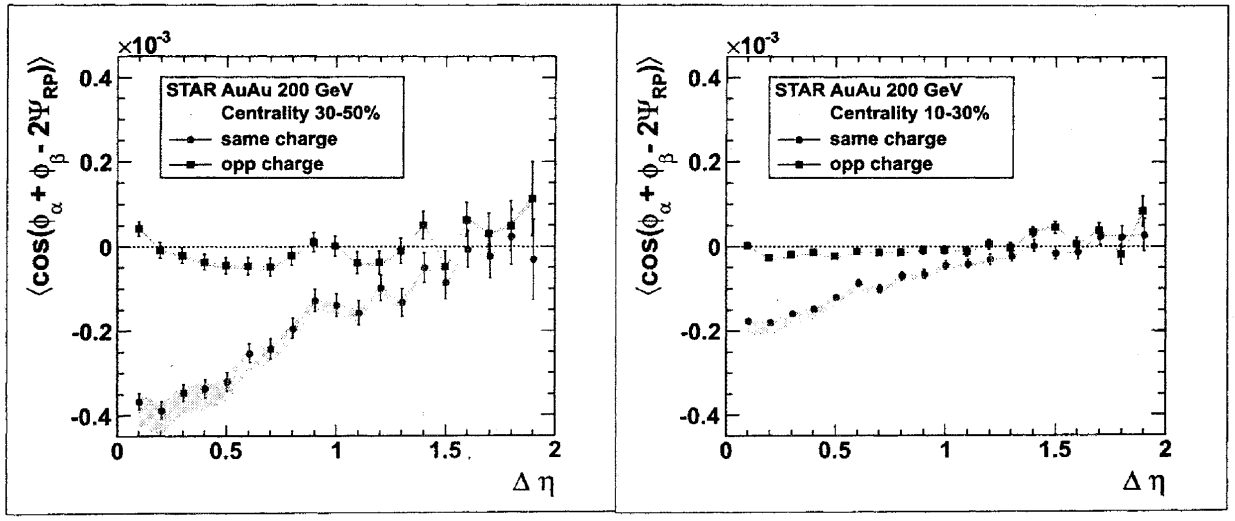
The signal is multiplied by N_{part} to remove "trivial" dilution due to multiplicity increase in more central collisions and/or lighter system.

Opposite charge correlations scale with N_{part}, (suppression of the back-to-back correlations ?)

Same charge signal is suggestive of correlations with the reaction plane

Opposite charge corr's are somewhat stronger in CuCu compared to AuAu at the same N_{part}

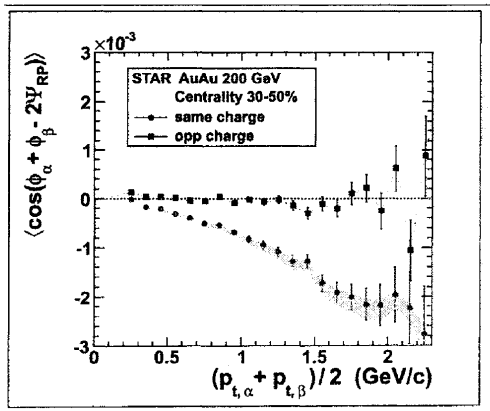
$\Delta\eta$ dependences (AuAu200).

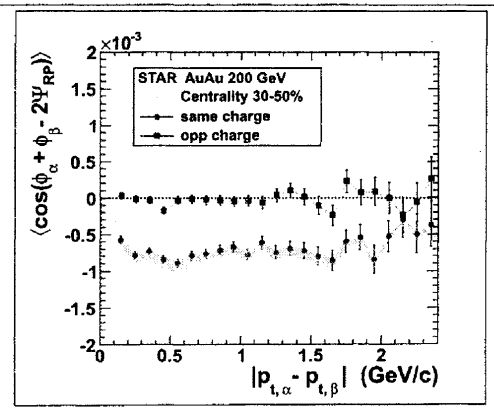


Typical "hadronic" width, consistent with "theory".

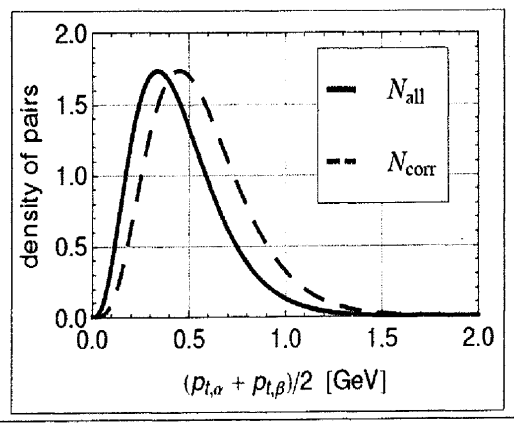
What about color flux tubes?

Transverse momentum dependences (AuAu200).





Signal persists to too high p_t ?



Adam Bzdak[a,b], Volker Koch[a], and Jinfeng Liao[a]
[arXiv:0912.5050v1 [nucl-th] 27 Dec 2009]

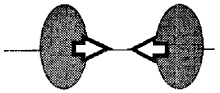
The transverse momentum dependence of the signal shown in the previous slide is fully consistent with a picture in which particles from a LPV cluster decay has p_t distribution only slightly "harder" than the bulk.

$$\langle\cos(\phi_\alpha + \phi_\beta)\rangle = \frac{N_{corr}}{N_{all}}$$

Developing a program

Dedicated experimental and theoretical program focused on the local parity violation, and more generally on non-perturbative QCD: structure of the vacuum, hadronization, etc.

Experiment:



- U+U central body-body collisions

  Such collisions ("easy" to trigger on) will have low magnetic field and large elliptic flow – clean test of the $\mathcal{LPV}$ effect.

- Beam energy scan / Critical point search

  Look for a critical behavior, as $\mathcal{LPV}$ predicted to depend strongly on deconfinement and chiral symmetry restoration

- Isobaric beams

  Colliding isobaric nuclei (the same mass number and different charge) and by that controlling the magnetic field

  $^{96}_{44}\mathrm{Ru}+^{96}_{40}\mathrm{Zr}$

  Note that such studies will be also very valuable for understanding the initial conditions, baryon stopping, origin of the directed flow, etc.

- **High statistics PID studies / properties of the clusters** in particular with neutral particles; see also next slides

Azimuthal Charge-asymmetry Measurements @ RHIC "a la PHENIX"

Roy A. Lacey
Chemistry Dept.
Stony Brook University

STONY BROOK
STATE UNIVERSITY OF NEW YORK

✓3:10 S. Voloshin — Results from STAR

4:00 S. Esumi, N. Ajitanand — Results from PHENIX

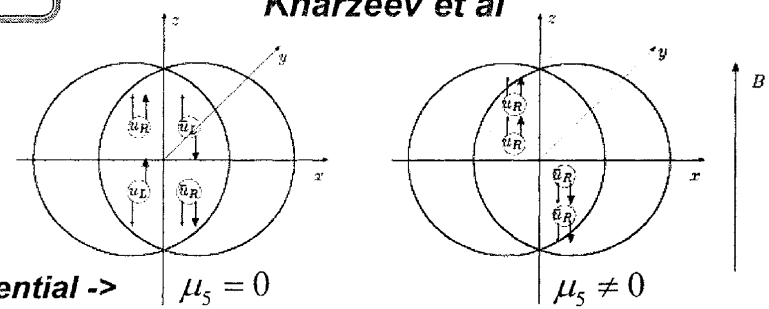
Task

1. *Outline the methodology employed by PHENIX for azimuthal charge asymmetry studies*
2. *Give a survey of current PHENIX results from two very different analysis techniques*
   - *the two particle correlation technique*
   - *the multi-particle correlation technique (New)*
3. *Compare to STAR results where possible*

The Central Question

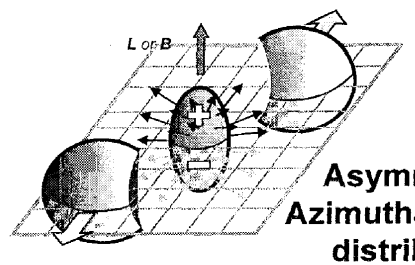
Axial anomaly ->
parity odd metastable domains
in which $u_L(\overline{u}_L) \neq u_R(\overline{u}_R)$

Chiral magnetic effect
Kharzeev et al



Chiral chemical potential ->

Does the new phase of QCD matter created in RHIC collisions provide new insights on P/CP invariance of the strong interaction ? If it does, how do we tell ?



Asymmetric Azimuthal charge distribution

Axial anomaly ->
anomalous global symmetry current in hydrodynamics
D. Son et al

Why study *Azimuthal Charge-asymmetry*?

Unambiguous experimental observations of the chiral magnetic effect would be a clear demonstration of the non-trivial topological structure of the QCD vacuum

A prerequisite for local P-violation in strongly interacting matter is deconfinement [with restored chiral symmetry]

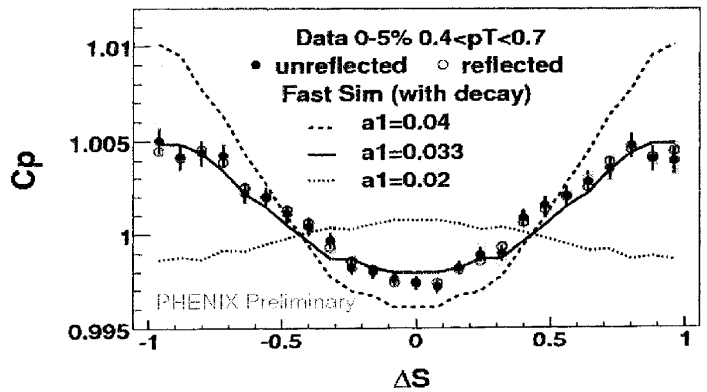
Azimuthal charge-asymmetry studies could also be an indispensible tool for further insights on deconfinement [and chiral symmetry restoration]

Summary

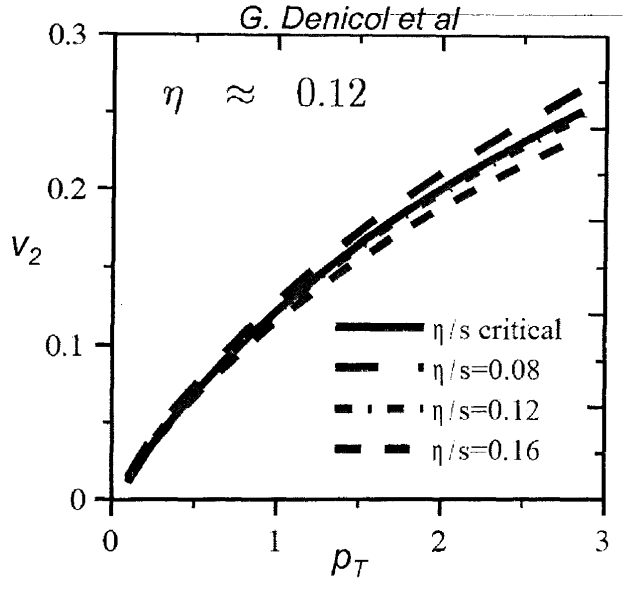
- PHENIX measurements of azimuthal charge-asymmetry presented for two separate methods

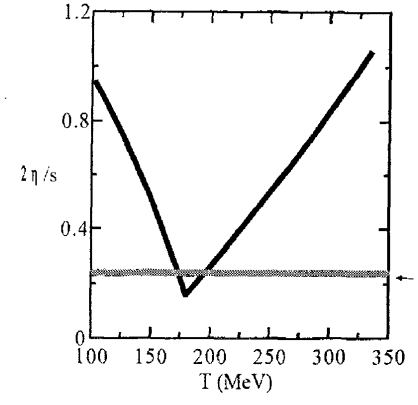
➢ Azimuthal charge-asymmetry observed..

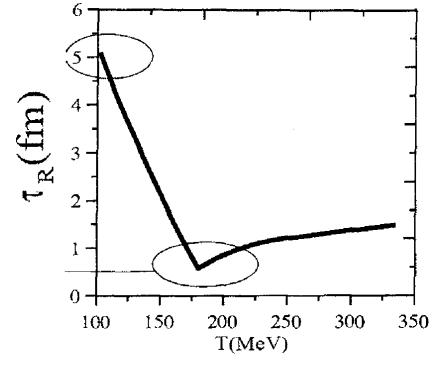
➢PHENIX measurements are robust, pervasive and rife with opportunity for detailed model comparisons.



Estimates for η/s







Relaxation time limits η/s to small values

Chiral Magnetic Effect in the Sakai-Sugimoto model

Anton Rebhan
Institute for Theoretical Physics
Vienna University of Technology, Vienna, Austria

Abstract

In the chiral magnetic effect an imbalance in the number of left- and right-handed quarks gives rise to an electromagnetic current parallel to the magnetic field produced in noncentral heavy-ion collisions. The chiral imbalance may be induced by topologically nontrivial gluon configurations via the QCD axial anomaly, while the resulting electromagnetic current itself is a consequence of the QED anomaly. In the Sakai-Sugimoto model, which in a certain limit is dual to large-N_c QCD, we discuss the proper implementation of the QED axial anomaly, the (ambiguous) definition of chiral currents, and the calculation of the chiral magnetic effect. We show that this model correctly contains the so-called consistent anomaly, but requires the introduction of a (holographic) finite counterterm to yield the correct covariant anomaly. Introducing net chirality through an axial chemical potential, we find a nonvanishing vector current only before including this counterterm. This seems to imply the absence of the chiral magnetic effect in this model. On the other hand, for a conventional quark chemical potential and large magnetic field, which is of interest in the physics of compact stars, we obtain a nontrivial result for the axial current that is in agreement with previous calculations and known exact results for QCD.

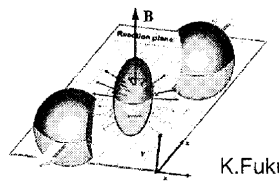
Anomaly-induced currents in dense matter with strong $\vec{B}$-fields

[M.A. Metlitski, A.R. Zhitnitsky, PRD 72, 045011 (2005)]: axial current

$$\vec{J}_5 = \frac{e^2 N_c}{2\pi^2}\mu\vec{B}$$

... exact when χ symmetry unbroken [G.M. Newman, D.T. Son, PRD73, 045006 (2006)]

Similarly (?) the **Chiral Magnetic Effect** (cf. yesterday's talks):



$$\vec{J}_{\rm e.m.} = \frac{e^2 N_c}{2\pi^2}\mu_5\vec{B}$$

$\mu_5 \leftrightarrow$ net chiral density

K.Fukushima, D.E.Kharzeev, H.J.Warringa, PRD 78, 074033 (2008)

Q: corrections from strong interactions possible?

NO, exact: A.Y. Alekseev, V.V. Cheianov, J. Fröhlich, PRL 81, 3503 (1998); FKW

YES, reduced: K. Fukushima, M. Ruggieri, arXiv:1004.2769

Holographic QCD

Top-down:

Holographic N=4 Super-Yang-Mills: AdS/CFT with $N_c \to \infty$ $D3$ branes from type-IIB string theory (Maldacena 1998)

E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998):

Holographic *nonsupersymmetric* QCD from type-IIA string theory

with $N_c \to \infty$ $D4$ branes compactified on circle $x_4 \equiv x_4 + 2\pi/M_{\rm KK}$

- antisymmetric b.c. for adjoint fermions: masses $\sim M_{\rm KK}$
- adjoint scalars not protected by gauge symmetry: also masses $\sim M_{\rm KK}$

$\to$ dual to pure-glue YM theory

3+1-dimensional after $M_{\rm KK} \to \infty$, $\lambda = \frac{g_5^2 N_c}{2\pi/M_{\rm KK}} \ll 1$

but supergravity approximation needs $\lambda \gg 1$

D8 brane action

$$S_{\rm D8} = S_{\rm YM} + S_{\rm CS}$$

$N_f = 1$ for simplicity; $A_z = 0$ gauge

$$\begin{aligned} S_{\rm YM} &= \kappa M_{\rm KK}^2 \int d^4x \int_{-\infty}^{\infty} dz \left[k(z) F_{z\mu} F^{z\mu} + \frac{h(z)}{2M_{\rm KK}^2} F_{\mu\nu} F^{\mu\nu} \right] , \\ S_{\rm CS} &= \frac{N_c}{24\pi^2} \int d^4x \int_{-\infty}^{\infty} dz\, A_\mu F_{z\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} , \end{aligned}$$

$$\kappa \equiv \frac{\lambda N_c}{216\pi^3} , \qquad k(z) \equiv 1 + z^2 , \qquad h(z) \equiv (1+z^2)^{-1/3}$$

- chemical potentials $\mu = (\mu_R + \mu_L)/2$, $\mu_5 = (\mu_R - \mu_L)/2$
  as boundary conditions $A_0(z = \pm\infty) = \mu_{L/R}$
- *external* U(1) gauge field (nondynamical) $A_1(x_2, z = \pm\infty) = -x_2 B$

following Sakai-Sugimoto: $M_{KK} \simeq 949$ MeV, $N_c = 3$, $\lambda \simeq 16.6$, $\kappa \simeq 0.007$

Chiral currents

Field equations

$$\begin{aligned} \kappa M_{\rm KK}^2\, \partial_z [k(z) F^{z\mu}] + \kappa h(z) \partial_\nu F^{\nu\mu} &= \frac{N_c}{16\pi^2} F_{z\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} , \\ \kappa M_{\rm KK}^2\, \partial_\mu [k(z) F^{z\mu}] &= \frac{N_c}{64\pi^2} F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} , \end{aligned}$$

From gospel according to Witten:

$$\mathcal{J}^\mu_{L/R} \equiv -\frac{\delta S}{\delta A_\mu(x, z = \pm\infty)} = \Big(\underbrace{\mp 2\kappa M_{\rm KK}^2 k(z) F^{z\mu}}_{\mathcal{J}_{\rm YM}} \underbrace{\pm \frac{N_c}{24\pi^2} \epsilon^{\mu\nu\rho\sigma} A_\nu F_{\rho\sigma}}_{\mathcal{J}_{\rm CS}} \Big)_{z=\pm\infty}$$

NB: when $\mathcal{J}_{\rm CS} \neq 0$ different than factor in normalizable mode!!

$$A_\mu(x,z) = \underbrace{A_\mu(x, z = \pm\infty)}_{\text{enters } \mathcal{J}_{\rm CS}} \pm \frac{\mathcal{J}^{L/R}_{\mu,\rm YM}}{2\kappa M_{\rm KK}^2} \frac{1}{z} + \mathcal{O}\left(\frac{1}{z^2}\right)$$

Consistent and covariant anomalies

$$\partial_\mu \mathcal{J}^\mu_{L/R} = \partial_\mu (\mathcal{J}_{\rm YM} + \mathcal{J}_{\rm CS})^\mu_{L/R} = \mp \frac{N_c}{16\pi^2}\left(1 - \frac{2}{3}\right) F^{L/R}_{\mu\nu} \widetilde{F}^{\mu\nu}_{L/R}\,,$$

consistent anomaly (left and right separate; symmetric in V and A) [Bardeen 1969]

$$\begin{aligned}
\partial_\mu \mathcal{J}^\mu_5 &= \frac{N_c}{\boxed{24}\pi^2}\left(F^V_{\mu\nu}\widetilde{F}^{\mu\nu}_V + F^A_{\mu\nu}\widetilde{F}^{\mu\nu}_A\right) \\
\partial_\mu \mathcal{J}^\mu &= \frac{N_c}{12\pi^2} F^V_{\mu\nu}\widetilde{F}^{\mu\nu}_A \not\equiv 0\,,
\end{aligned}$$

Bardeen's counterterm

$$\Delta S = c \int d^4x (A^L_\mu A^R_\nu F^L_{\rho\sigma} + A^L_\mu A^R_\nu F^R_{\rho\sigma})\epsilon^{\mu\nu\rho\sigma}\,,$$

ΔS is metric independent, can be written as holographic (surface) counter term

$\longrightarrow$ renormalized left- and right-handed currents

$$\bar{\mathcal{J}}^\mu_{L/R} \equiv \mathcal{J}^\mu_{L/R} + \Delta\mathcal{J}^\mu_{L/R}, \text{ similarly } \bar{\mathcal{J}}_\mu,\ \bar{\mathcal{J}}^5_\mu$$

Choosing $c = \frac{N_c}{48\pi^2}$ leads to the *covariant* anomaly

$$\begin{aligned}
\partial_\mu \bar{\mathcal{J}}^\mu &= \boxed{0}\,, \\
\partial_\mu \bar{\mathcal{J}}^\mu_5 &= \frac{N_c}{\boxed{8}\pi^2} F^V_{\mu\nu}\widetilde{F}^{\mu\nu}_V + \frac{N_c}{24\pi^2} F^A_{\mu\nu}\widetilde{F}^{\mu\nu}_A\,.
\end{aligned}$$

[Adler, Bell, Jackiw, 1969]

Only YM current

If only YM part of current taken (occasionally done without justification), find:

$$\partial_\mu \mathcal{J}^\mu_{\mathrm{YM},L/R} = 3 \times \partial_\mu (\mathcal{J}_{\mathrm{YM}} + \mathcal{J}_{\mathrm{CS}})^\mu_{L/R}$$

thus same equations as with consistent anomaly but times 3:

$$\begin{aligned} \partial_\mu \mathcal{J}^\mu_{\mathrm{YM}} &= \frac{N_c}{4\pi^2} F^V_{\mu\nu} \widetilde{F}^{\mu\nu}_A \,, \\ \partial_\mu \mathcal{J}^\mu_{\mathrm{YM},5} &= \frac{N_c}{\boxed{8}\pi^2} \left(F^V_{\mu\nu} \widetilde{F}^{\mu\nu}_V + F^A_{\mu\nu} \widetilde{F}^{\mu\nu}_A \right) \,, \end{aligned}$$

Coincides with covariant anomaly for $F_A = 0$, but $\partial_\mu \mathcal{J}^\mu \not\equiv 0$!

OK as long as $F_A = 0$?

But need $\vec{\nabla}\mu_5 \sim \vec{E}_A$ for charge separation at RHIC!?

$$\partial_t \rho = -\nabla \mathcal{J} \propto B \nabla \mu_5$$

Ansatz and results for bulk gauge fields

boundary conditions $A_0(z = \pm\infty) = \pm\mu_5$ (when $\mu = 0$),

$$A_1(z = \pm\infty, x_2) = -x_2 B$$

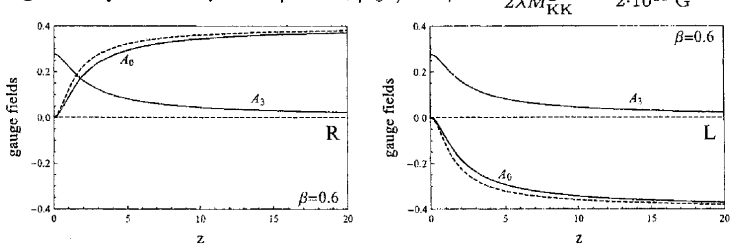
Ansatz: nonzero (brane) gauge fields with dependence on z: $A_0(z), \quad A_3(z)$

$\longrightarrow$ magnetic field constant in bulk: $A_1(x_2) = -x_2 B$

$\longrightarrow$ closed-form solutions with YM approximation to DBI action

(good for small and also very large B)

e.g. chirally restored phase, $\mu = 0$, $\mu_5 \neq 0$, $\beta \equiv \frac{27\pi B}{2\lambda M^2_{\mathrm{KK}}} \simeq \frac{B}{2 \cdot 10^{19}\,\mathrm{G}}$



(dashed is $\beta = 0$; full is $\beta = 0.6$, where $A_3 \not\equiv 0 \leftrightarrow \mathcal{J}_3$)

Results for currents

[A. Rebhan, A. Schmitt, S.A. Stricker, JHEP 1001, 026 (2010)]

	$\mathcal{J}_{\rm YM}$	$\mathcal{J}_{\rm YM+CS}$	$\mathcal{J}_{\rm YM+CS}+\Delta\mathcal{J}$	$\mathcal{J}'_{\rm YM+CS}$
anomaly	"semi-covariant":	consistent:	covariant:	absent:
$\partial_\mu \mathcal{J}_5^\mu / \frac{N_c}{24\pi^2}$	$3F_V\widetilde{F}_V + 3F_A\widetilde{F}_A$	$F_V\widetilde{F}_V + F_A\widetilde{F}_A$	$3F_V\widetilde{F}_V + F_A\widetilde{F}_A$	0
$\partial_\mu \mathcal{J}^\mu / \frac{N_c}{24\pi^2}$	$6F_V\widetilde{F}_A$	$2F_V\widetilde{F}_A$	$\underline{0}$	0
$(\mathcal{J}_\parallel^5 / \frac{\mu B N_c}{2\pi^2})\Big\vert_{T>T_c}$	1	$\frac{2}{3}$	$\mathbf{1} = 1 - \frac{1}{3} + \frac{1}{3}$	$\frac{1}{2}$
CME: $\mathcal{J}_\parallel / \frac{\mu_5 B N_c}{2\pi^2}$	1	$\frac{2}{3}$	$\mathbf{0} = 1 - \frac{1}{3} - \frac{2}{3}$	$\frac{1}{2}$

$\mathcal{J}'_{\rm YM+CS}$ corresponds to ad-hoc modified CS action enforcing thermodynamic consistency Bergman, Lifshytz, Lippert 08
however, eliminates anomaly! RSS 2010

Questions

- Time dependence of B!
  Need frequency-dependent chiral magnetic conductivity?
  Only static DC component should play a role in charge separation!
- Is $\mathcal{J}_{\rm YM}$ (normalizable mode in gauge field) the more appropriate quantity?
  But with $\nabla\mu_5 \neq 0$ as needed for actual charge seperation
  ($\partial_t\rho = -\nabla\mathcal{J} \propto B\nabla\mu_5$ when B homogeneous)
  $\partial_\mu \mathcal{J}^\mu_{\rm YM} \neq 0$
- Does $\mathcal{J}$ in contrast to $\mathcal{J}_5$ receive (strong) corrections?
  Fukushima & Ruggieri: $\mathcal{J} = (top.result)/(1+g^2\ldots) \to 0$ for $g \to \infty$?
- Could SS result for renormalized current $\bar{\mathcal{J}}$ be even right?
  E.g., through absence of quasiparticles at infinite coupling?
- ...

Holographic chiral magnetic conductivity, chiral shear wave, and chiral magnetic spiral

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In QCD, some global symmetries suffer triangle anomalies. The most important example is axial symmetry $U(1)_A$ under which positive helicity states have opposite charge to the states of negative helicity. There are many interesting phenomena in QCD and its finite temperature plasma which have their roots in triangle anomaly. In this talk, we study three examples which are potentially relevant in relativistic heavy-ion experiments; chiral magnetic conductivity, chiral shear waves, and chiral magnetic conductivity, using a framework of AdS/QCD or gauge/gravity correspondence, commonly called holographic QCD. In holographic QCD, triangle anomalies are encoded in 5D Chern-Simons terms. Chiral magnetic effect is a phenomenon of electric current generated by applied magnetic field in the presence of non-zero axial charge density. We compute frequency dependent chiral magnetic conductivity in holographic QCD, and also discuss an issue involving zero-frequency limit. Chiral shear wave refers to a chiral nature of dispersion relations of two helicity-modes of shear waves, again in the presence of axial charge density. This may imply some spiral imprints in the plasma due to triangle anomaly. We compute chiral dispersion relations of the shear waves in holographic set-up to observe this phenomenon. Our final subject of chiral magnetic spiral is based on a recent proposal that in a chiral symmetry-broken phase, an applied magnetic field in the presence of axial/baryonic chemical potential may induce a non-zero expectation value of transverse currents whose shape along the magnetic field looks like a spiral. As the holographic QCD can provide a corroboration of this proposal in strong-coupling regime, it is very interesting to study it in the framework. By studying linearized instability from the homogeneous phase towards chiral magnetic spiral phase, we have a preliminary result that a sufficiently large axial chemical potential indeed causes chiral magnetic spirals, but pure baryonic phase seems not to support them.

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Three phenomena we will discuss

All these relations have their roots in triangle anomaly

We will discuss three phenomena involving triangle anomaly potentially/possibly relevant in **RHIC plasma** using

AdS/CFT or Gauge/Gravity correspondence

- Chiral magnetic conductivity (Fukushima-Kharzeev-Warringa)
- Chiral shear waves
  (Matsuo-Sin-Takeuchi-Tsukioka,Sahoo-Yee,Nakamura-Ooguri-Park)
- Chiral magnetic spirals (Basar-Dunne-Khazeev)

Note : the last example is for the χSB phase at a late stage of RHIC

Holographic chiral magnetic conductivity

Chiral magnetic effect:

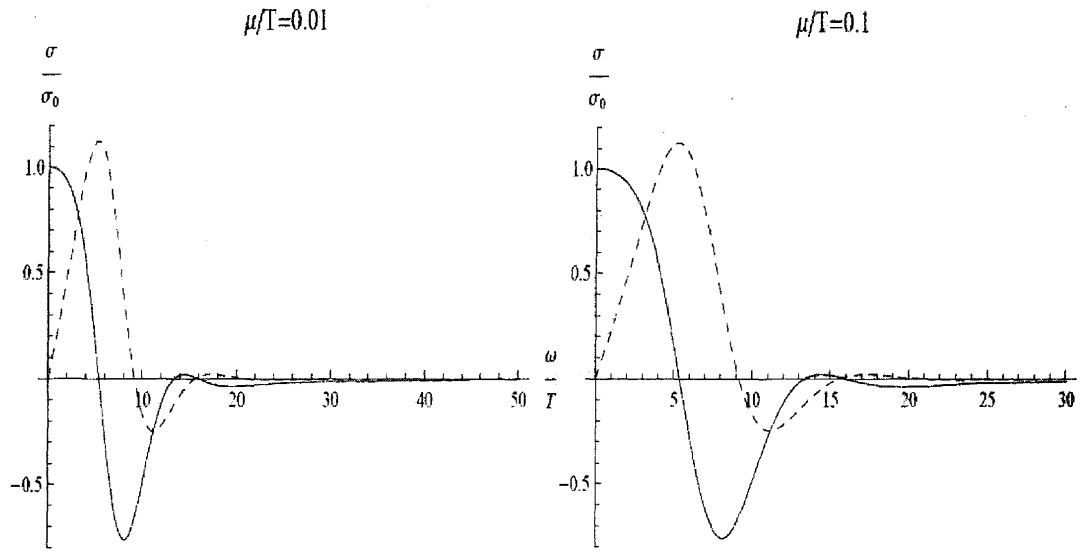
In the presence of axial charge density, an applied EM magnetic field induces a net electromagnetic current along the same direction

- In linear response framework,

$$j(\omega) = \sigma(\omega) B(\omega) \qquad \omega = \text{frequency} \tag{3}$$

  and $\sigma(\omega)$ is called chiral magnetic conductivity
- It has been estimated that the relevant scales in RHIC experiments justify linear response approximation
- As the RHIC plasma is time-dependent, chiral magnetic conductivity of general ω seems interesting
- In the field theory side, only 1-loop perturbative computation by Kharzeev-Warringa is available
- Let's provide a strong-coupling prediction using AdS/CFT technique !!! (Rebhan-Schmitt-Stricker, Yee)

Numerical results



Solid line: $\mathrm{Re}\sigma(\omega)$, Dashed line : $\mathrm{Im}\sigma(\omega)$

AdS/CFT computation of chiral shear waves

- As a model theory, we take

$$(16\pi G_5)\mathcal{L} = R + 12 - \frac{1}{4}F_{MN}F^{MN} - \frac{\kappa}{4\sqrt{-g_5}}\epsilon^{MNPQR}A_M F_{NP}F_{QR} \quad , \quad (13)$$

  and consider a charged black-hole plasma background
- Study linear fluctuations, especially helicity ± 1 transverse shear modes. One finds that Chern-Simons effect (anomaly effect) appears only on these modes
- From analyzing these modes in AdS/CFT, one can obtain their dispersion relations. The result depends on the sign of helicity, which maybe called chiral shear waves
- Our result is

$$\omega \approx -i\frac{\eta}{\epsilon + p}\, k^2 \pm i\frac{\kappa Q^3}{8m^2 r_H^3}\, k^3 + \mathcal{O}\left(k^4\right) \quad : \quad \text{helicity} \pm 1 \quad , \quad (14)$$

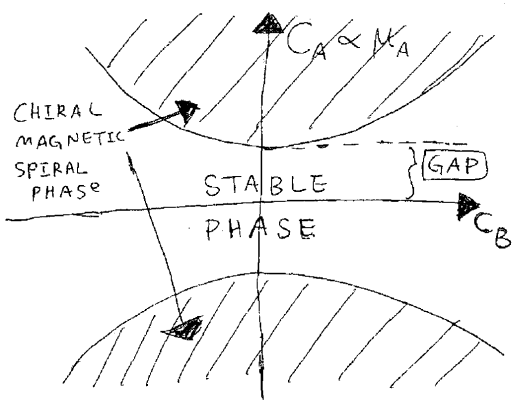
  where $\mathcal{O}(k^3)$ is the chiral term from anomaly. In fact, any term with odd powers of k comes from anomaly
- Nakamura-Ooguri-Park observed that for a sufficiently large κ, the anomaly-induced term can be big enough to overcome the leading piece, to induce an instability toward forming chiral shear waves

Rough phase diagram for chiral magnetic spirals

Chiral magnetic spirals would exist in the region

$$C_A^2 - C_B^2 > \left(\frac{16\pi^2\kappa}{N_c}\right)^2 \lambda_{eff}^2$$

with some finite number λ_{eff}^2



- Pure baryonic branch seems stable against chiral magnetic spirals
- Pure axionic branch seems to develop chiral magnetic spirals above a finite critical gap

Hadronic and Partonic Mechanisms of Charge Asymmetry Fluctuations

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We discuss various mechanisms for the creation of an asymmetric charge fluctuation with respect to the reaction plane among hadrons emitted in relativistic heavy-ion collisions. We show that such mechanisms exist in both, the hadronic gas and the partonic phases of QCD.

Kharzeev, McLerran, and Warringa [1] showed that the coherent magnetic field generated by two heavy nuclei colliding off-centrally at high energy can convert topological charge fluctuations in the QCD gauge field into electric charge fluctuations with respect to the reaction plane and called this mechanism the *chiral magnetic effect.* This effect was further analyzed by Fukushima, Kharzeev, and Warringa [2]. The STAR collaboration has analyzed the final states of heavy-ion collisions at RHIC (Au+Au and Cu+Cu) for the presence of non-vanishing fluctuations in appropriate observables and has reported the existence of such an asymmetry in a recent publication [3].

In order to induce a current *parallel* to the external magnetic field $\mathbf{B}$, the combined QED-QCD effective action must contain a contribution of the pseudoscalar form $\mathcal{L}_{\rm eff} = \mathcal{P}\,\mathbf{E}\cdot\mathbf{B}$, where $\mathcal{P}$ is a pseudoscalar operator constructed from strongly interacting fields. Using this form of the effective Lagrangian, one obtains the general form for the anomalous electromagnetic current:

$$\mathbf{j}_{\rm an}(x) = -(\partial\mathcal{P}/\partial t)\,\mathbf{B}.$$

The pseudoscalar $\mathcal{P}$ can either be represented by the gluon topological charge density $\rho_{\rm CS} = (g^2/8\pi^2)\mathbf{E}^a\cdot\mathbf{B}^a$ or by the neutral pseudoscalar meson fields π^0, η, η'. The interactions $\mathcal{L}_{\rm eff}$ are well known in all these cases from both, basic theoretical considerations related to the axial anomaly or from hadron phenomenology.

In a recent manuscript [4] we have pointed out that the mechanism producing an asymmetric charge fluctuation of the kind induced by the chiral magnetic effect is not constrained to an environment in which quarks are deconfined. We showed that an analogous mechanism, *magnetic $\pi-\rho$ conversion* ($\pi^0+\gamma\to\rho^0\to\pi^++\pi^-$), exists in a confined hadronic environment. We also analyzed how a local electric charge asymmetry can be converted into a global asymmetry of charged hadron emission by transverse collective flow or geometric effects during freeze-out. We found that approximate treatments of the charge transport can lead to a large uncertainty in the size of the expected effect.

The creation of an event-by-event reaction plane charge asymmetry in heavy ion collisions due to the interaction of the magnetic field with the pseudoscalar sector of the QCD matter may occur in five distinct scenarios, which we call the Color Glass Condensate (CGC) scenario, the Glasma scenario, Quark-Gluon Plasma (QGP) scenario, the Corona scenario, and the Hadron Gas scenario. Quantitative predictions were presented for the CGC and Corona scenarios, which both occur during the peak phase of the magnetic field. It is worth noting that at top RHIC energy the duration of the magnetic field peak, of order $R/\gamma \approx 0.1$ fm is too short to be resolved by soft hadronic processes. The anomalous current is mainly sensitive to the time integrated magnetic field strength, which is independent of beam energy at high energies.

Our analysis shows that reaction plane charge asymmetry fluctuations do not require "local" or global parity violation for their formation, as the constituent processes of most mechanisms are well known from ordinary hadronic physics. We found that the estimated magnitude of the expected effect in the considered scenarios is much smaller than the effect observed by the STAR experiment. This suggests that the observations may be due to some other process. Rigorous predictions of the reaction plane charge asymmetry fluctuations will need to include in-medium effects on the interactions involved in the various mechanisms, such as modifications of the meson masses and effective couplings, and quantitatively track the charge density transport from the creation by the anomalous current through the expanding matter up to the freeze-out hypersurface.

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[3] B. I. Abelev [The STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009).
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The anomalous current

$\mathcal{L}_{\rm eff} = \mathcal{P}\,(\mathbf{E}\cdot\mathbf{B}) = \frac{1}{4}\mathcal{P}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$ implies a conserved, "anomalous" current

$$j^{\mu} = \frac{\partial \mathcal{L}_{\rm eff}}{\partial A_{\mu}} = \frac{\partial \mathcal{P}}{\partial x^{\nu}}\,\tilde{F}^{\mu\nu}$$

Vector components: $\mathbf{j} = (\partial\mathcal{P}/\partial t)\,\mathbf{B}$ (Compare with $\mathbf{j} = \sigma\,\mathbf{E}$)

$\partial\mathcal{P}/\partial t$ can be thought of as parity-odd electric conductivity ("chiral conductivity")

A nonzero expectation value $\langle\mathcal{P}\rangle \neq 0$ would imply parity violation in the QCD sector, but nonzero transition matrix elements $\langle f|\mathcal{P}|i\rangle \neq 0$ are easily allowed. They give rise to anomalous current fluctuations:

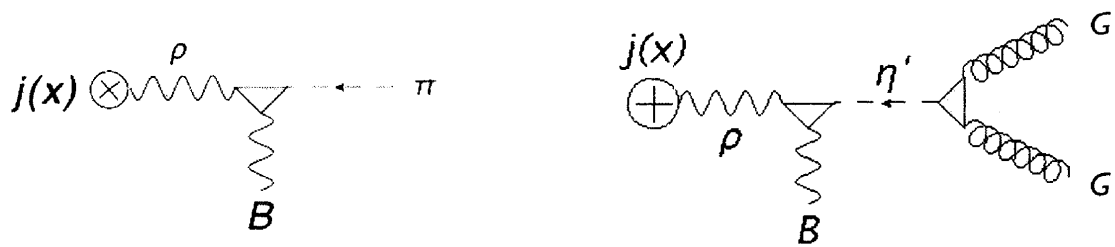
$$\langle\, j_i(x) j_k(x')\,\rangle = \langle\, \partial_t\mathcal{P}(x)\,\partial_t'\mathcal{P}(x')\,\rangle\, B_i(x) B_k(x')$$

"Anomalous" current

Vector meson dominance (VMD) relates the electromagnetic hadronic current to the neutral rho-meson field:

$$j^\mu = -\frac{e\, m_\rho^2}{g_{\rho\pi\pi}}\, \rho^\mu$$

Thus, the B-field generates an "anomalous" current by converting a pseudoscalar meson (π, η, η') into a rho-meson:



The relevant interactions are experimentally known from radiative decays:

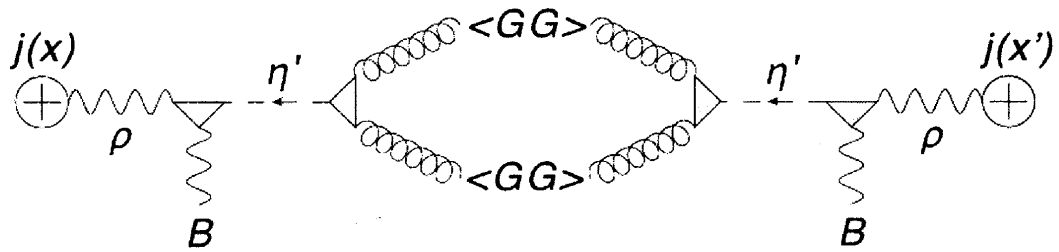
$$\Gamma_{\rho^0\to\pi^0\gamma} = 3\alpha\, g^2_{\rho\pi\gamma}\, \frac{p^3_{\rm cm}}{m^2_\rho} \approx 90 \pm 12 \text{ keV}$$

$$g_{\rho\pi\gamma} = 0.58$$

$$\Gamma_{\eta'\to\rho\gamma} = \alpha\, g^2_{\rho\eta'\gamma}\, \frac{p^3_{\rm cm}}{m^2_{\eta'}} \approx 60 \pm 5 \text{ keV}$$

$$g_{\rho\eta'\gamma} = 1.31$$

CGC mechanism



$$\langle j^3(x) j^3(x') \rangle \approx e^2\, C \langle (\mathbf{E}^a \cdot \mathbf{B}^a)(x) (\mathbf{E}^b \cdot \mathbf{B}^b)(x') \rangle$$

with $C = \frac{g^2_{\rho\eta'\gamma}}{g^2_{\rho\pi\pi}} \frac{3(Z\alpha)^2 \alpha_s^2 \cos^2\theta}{(2\pi f_\eta)^2 m^2_{\eta'} m^2_\rho} \frac{b^2\gamma^2}{R^6}$

Because CGC color fields are nearly transverse, the fields in $\mathbf{E}^a \cdot \mathbf{B}^a$ must come from different nuclei. The gluon matrix element can be expressed in terms of the nuclear gluon distribution:

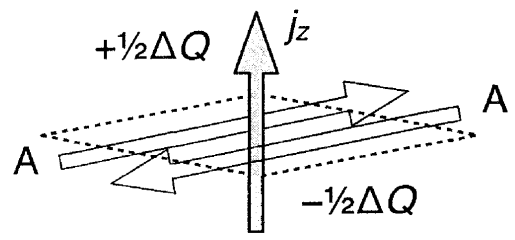
$$\langle (\mathbf{E}^a \cdot \mathbf{B}^a)(\mathbf{E}^b \cdot \mathbf{B}^b) \rangle \propto [x_0 G(x_0)]^2\, T_{AA}(\bar{\mathbf{x}}_\perp; \mathbf{b})$$

This mechanism can be enhanced if the η′ mass is lowered by medium interactions.

CGC mechanism (II)

The nuclear gluon density can be related to the CGC saturation scale Q_s by:

$$A\left[\xi_0 G(\xi_0)\right] = \frac{(N_c^2-1)\,R^2 Q_s^2}{8\pi^2\alpha_s}$$



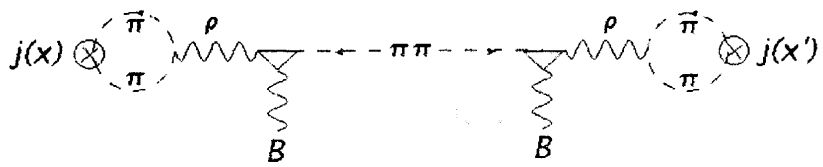
To calculate the up-down charge asymmetry fluctuations, we calculate the current through the reaction plane and assume that all charges above are emitted upwards and all charges below are emitted downwards (an overestimate!). After a lengthy calculation involving various additional "reasonable" approximations one finds:

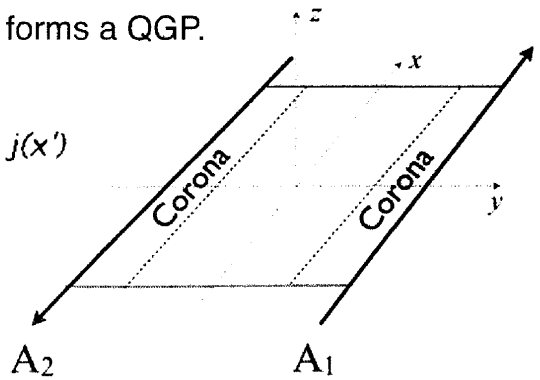
$$\left\langle(\Delta N_{\rm ch})^2\right\rangle = \begin{cases} C\,\frac{9(N_c^2-1)v_f^2}{(8\pi)^3\alpha_s^2}\,Q_s^2\,f(b) \approx 5\times10^{-5}\,v_f^2\,\frac{b^2}{R^2}\,f(b) & \text{(weak flow)} \\ C\,\frac{3(N_c^2-1)}{32\pi^4\alpha_s^2}\,Q_s^3 R\,f(b) \approx 1.7\times10^{-3}\,\frac{b^2}{R^2}\,f(b) & \text{(geometric)} \end{cases}$$

with $f(b) \approx 1-(b^2/R^2)(1-b/4R)^2$

Corona mechanism

We now consider the hadronic corona which never forms a QGP.





Assuming a thermal pion gas with $T = 150$ MeV and integrating over the entire B-field history, one finds in the geometric approximation:

$$\langle(\Delta N_{\rm ch})^2\rangle \approx \frac{(\pi Z\alpha g_{\rho\pi\gamma} g_{\rho\pi\pi})^2}{768\, e^2}\left(\frac{T}{m_\rho}\right)^6 \frac{b^2}{R^2} f(b) \approx 3\times 10^{-5}\,\frac{b^2}{R^2} f(b)$$

Both results are far too small to explain the STAR data, because this would require:

$$\frac{\langle(\Delta N_{\rm ch})^2\rangle}{(N_{\rm ch})^2} \approx 10^{-3}\,\frac{b^2}{R^2}$$

Chiral Magnetic Spiral

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This talk is based on the recent paper [1] with Gokce Basar and Dima Kharzeev. We argue that the presence of a very strong magnetic field induces inhomogeneous expectation values, of a spiral nature along the magnetic field axis, for the currents of charge and chirality, when there is finite baryon density or an imbalance between left and right chiralities. This "chiral magnetic spiral" is a gapless excitation transporting the currents of (i) charge (at finite chirality), and (ii) chirality (at finite baryon density) along the direction of the magnetic field in the chirally broken phase. In both cases it also induces in the transverse directions oscillating currents of charge and chirality. In heavy ion collisions, the chiral magnetic spiral possibly provides contributions both to the out-of-plane and the in-plane dynamical charge fluctuations recently observed at RHIC.

Recently, the STAR Collaboration at the Relativistic Heavy Ion Collider reported [2, 3] observation of charge-dependent azimuthal correlations, representing evidence for the Chiral Magnetic Effect (CME) [4–8] in QCD coupled to electromagnetism. The essence of the effect is the generation of electric current along the direction of an external magnetic field in the presence of topologically nontrivial gauge field configurations creating a local imbalance between left and right chiralities. The colliding positively charged ions generate, at early times, a very strong magnetic field, $eB \sim m_\pi^2$ [6], that inside the produced quark-gluon matter is directed perpendicular to the reaction plane of the collision. Topological fluctuations in the produced matter then induce the experimentally measured charge asymmetry with respect to the reaction plane that fluctuates on an event-by-event basis.

A natural question arises about the nature of the low frequency mode capable of transporting the charge current in the vacuum. In this talk I discuss the mechanism of the CME in the chirally broken phase using the method of dimensional reduction appropriate in the presence of a strong magnetic field. The two important physical effects are the lowest Landau level (LLL) projection induced by the strong magnetic field, which leads to an effective reduction of the system to $1+1$ dimensions, as in the physics of magnetic catalysis of symmetry breaking [9, 10], and the topological charge fluctuations of the QCD vacuum, which induce local regions of chirality of zero modes. The dimensionally reduced system generically supports chiral spiral condensates [11–14]

In heavy ion collisions, the chiral magnetic spiral can induce both out- and in-plane fluctuating charge asymmetries (the separation of out- and in-plane fluctuations has been performed recently [15] on the basis of STAR data [2, 3]). In the absence of topological fluctuations ($\mu_5 = 0$), at finite baryon density ($\mu \neq 0$), and in the chirally broken phase, the current of charge has only transverse components, and the charge asymmetry will fluctuate only in-plane. It should be kept in mind that the presence of magnetic field increases the chiral transition temperature [9]. If topological fluctuations are present in the chirally broken phase, the CME current can be carried by the chiral magnetic spiral.

The work reported in this talk was supported by US DOE under grants DE-FG02-92ER40716 (GB and GD) and DE-AC02-98CH10886 (DK).

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currents and condensates

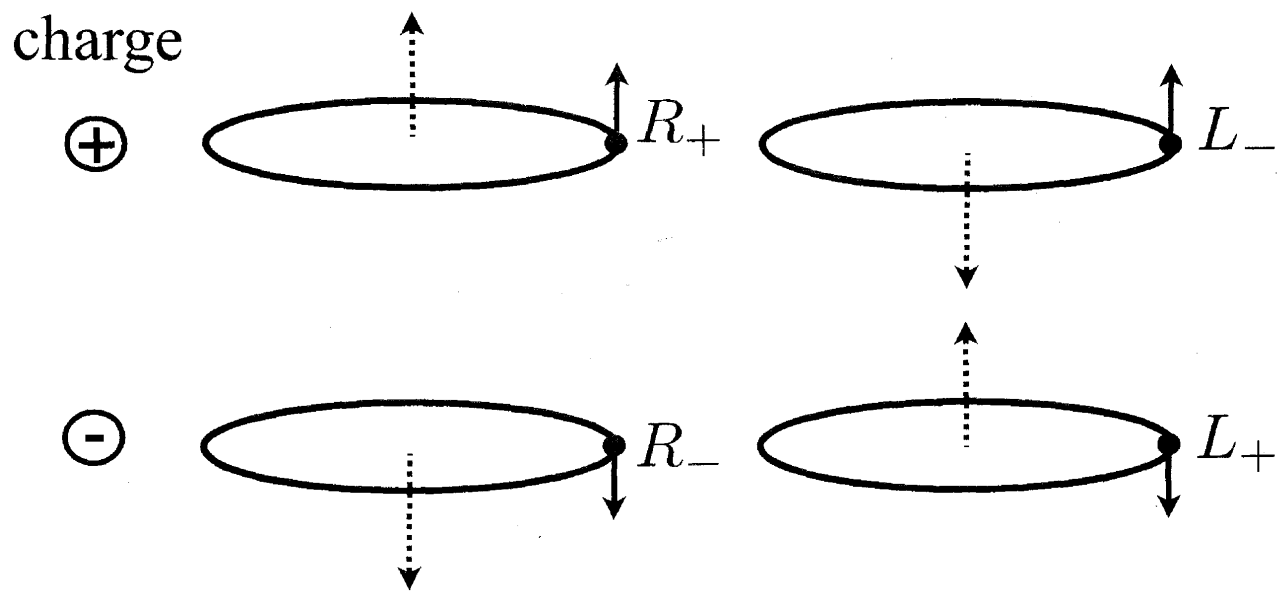
uniform charge density:

$$\langle j^0 \rangle = \langle \psi^\dagger \psi \rangle = \frac{\mu}{\pi}$$

$$\partial_\mu \langle j_5^\mu \rangle = 0$$

chiral spiral condensate:

$$\langle \bar{\psi}\psi \rangle - i \langle \bar{\psi} i \gamma^5 \psi \rangle = A\, e^{2i\mu x}$$


charge
⊕
⊖
R_+
L_-
R_-
L_+

$$J_5^0 = \mathcal{R}^\dagger\mathcal{R} - \mathcal{L}^\dagger\mathcal{L} \to \frac{1}{2}\frac{eB}{2\pi}\frac{e\,(\mu_R - \mu_L)}{\pi}$$

$$J^0 = \mathcal{R}^\dagger\mathcal{R} + \mathcal{L}^\dagger\mathcal{L} \to \frac{1}{2}\frac{eB}{2\pi}\frac{e\,(\mu_R + \mu_L)}{\pi}$$

L/R imbalance $\mu_R = \mu_5 = -\mu_L$

$$\langle J_5^0 \rangle = \frac{eB}{2\pi}\frac{e\,\mu_5}{\pi} \qquad \langle J^0 \rangle = 0$$

$$\langle J_5^3 \rangle = 0 \qquad \langle J^3 \rangle = \frac{eB}{2\pi}\frac{e\,\mu_5}{\pi}$$

"CME"

$$\langle J_5^\mu \rangle = \epsilon^{\mu\nu}\langle J^\nu \rangle$$

baryon chemical potential $\mu_R = \mu = \mu_L$

$$\langle J_5^0 \rangle = 0 \qquad \langle J^0 \rangle = \frac{eB}{2\pi}\frac{e\mu}{\pi}$$

$$\langle J_5^3 \rangle = \frac{eB}{2\pi}\frac{e\mu}{\pi} \qquad \langle J^3 \rangle = 0$$

Son, Zhitnitsky, 2004

the chiral magnetic spiral

transverse currents : chiral condensate

$$
\begin{aligned}
J_5^1 &= \bar{\mathcal{R}}\,\mathcal{R} + \bar{\mathcal{L}}\,\mathcal{L} \\
J_5^2 &= \bar{\mathcal{R}}\,i\Gamma^5\mathcal{R} - \bar{\mathcal{L}}\,i\Gamma^5\mathcal{L}
\end{aligned}
$$

$$
\begin{aligned}
J^1 &= \bar{\mathcal{R}}\,\mathcal{R} - \bar{\mathcal{L}}\,\mathcal{L} \\
J^2 &= \bar{\mathcal{R}}\,i\Gamma^5\mathcal{R} + \bar{\mathcal{L}}\,i\Gamma^5\mathcal{L}
\end{aligned}
$$

L/R imbalance : $\mu_5 \neq 0$ $\mu_R = \mu_5 = -\mu_L$

$$\langle J^{\perp} \rangle \sim \cos(2\mu_5\, z - \phi)$$

$$\langle J_5^{\perp} \rangle \sim \cos(2\mu_5\, z - \phi_5)$$

finite density : $\mu \neq 0$ $\mu_R = \mu = \mu_L$

$$\langle J^{\perp} \rangle \sim \cos(2\mu\, z - \chi)$$

$$\langle J_5^{\perp} \rangle \sim \cos(2\mu\, z - \chi_5)$$

Quarkyonic Chiral Spirals

Toru Kojo (RBRC)

based on the works

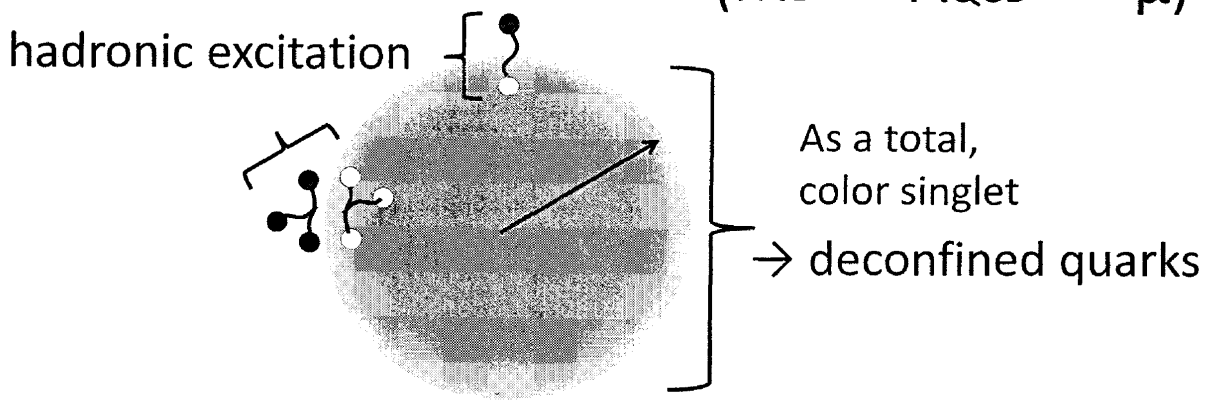
T.K., Y. Hidaka, L. McLerran, R. Pisarski ; arXiv:0912.3800 [hep-ph]
(to be published in NPA)

T.K., R. Pisarski, A.M. Tsvelik ; in preparation

Abstract: Local violation of Chiral symmetry is discussed in the context of confined, cold, dense quark matter. Its implication to local P, CP violation is briefly mentioned.

Quarkyonic Matter

McLerran & Pisarski (2007) $(M_D << \Lambda_{QCD} << \mu)$



Quark Fermi sea + baryonic Fermi surface → Quarkyonic

- Large Nc: $M_D \sim N_c^{-1/2} \to 0$

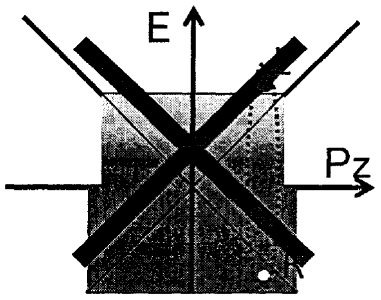
  Quarkyonic regime always holds.

  (so we can use vacuum gluon propagator)

Chiral Pairing Phenomena

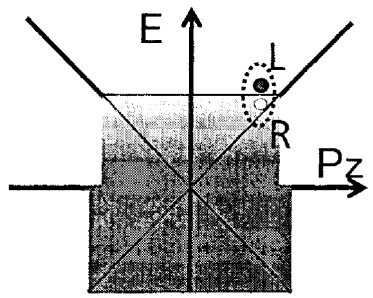
- Candidates which spontaneously break Chiral Symmetry

Dirac Type



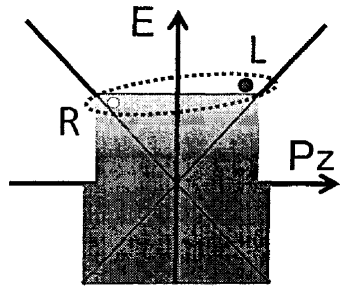
$P_{Tot}=0$ (uniform)

Exciton Type

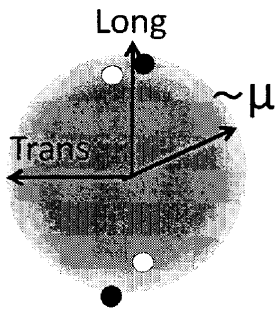


$P_{Tot}=0$ (uniform)

Density wave

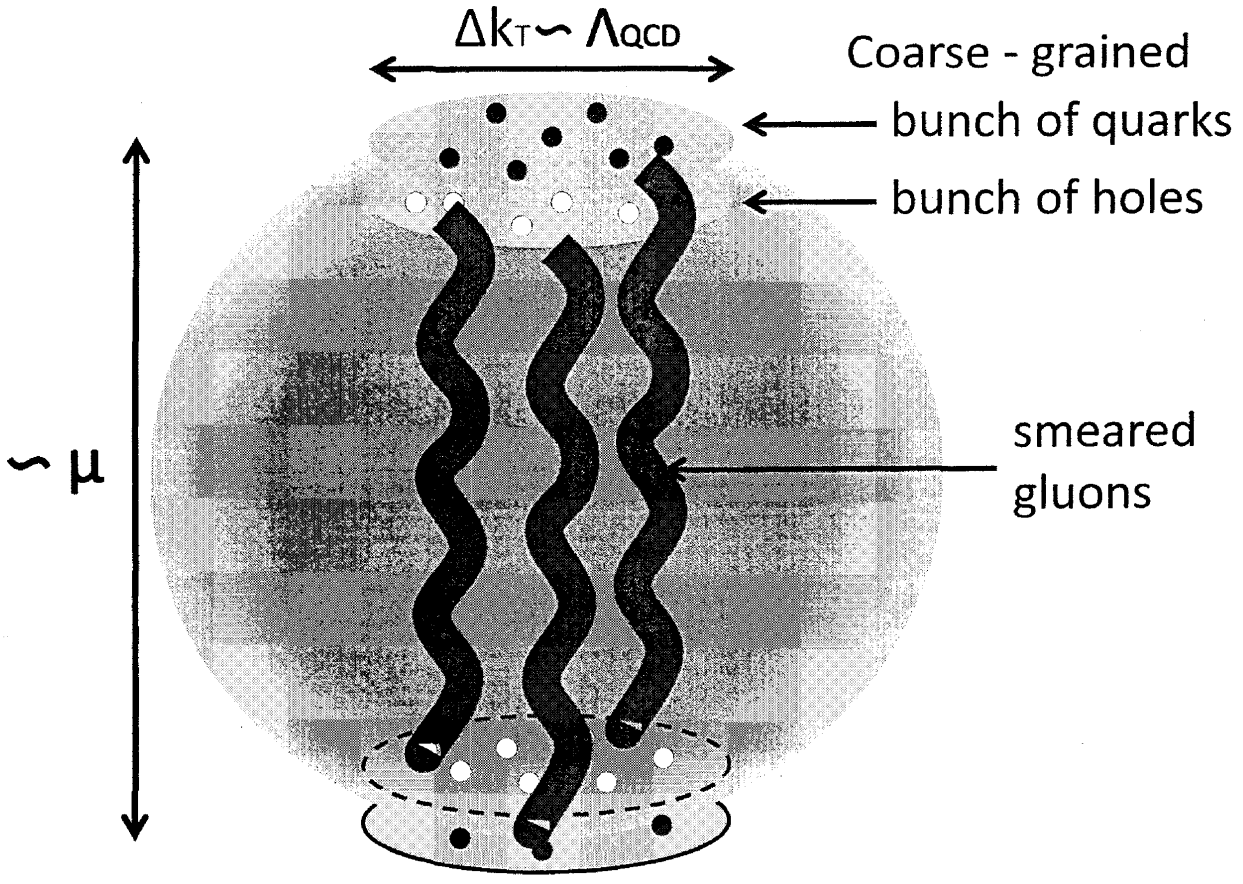


$P_{Tot}=2\mu$ (nonuniform)



We will identify the most relevant pairing:
Exciton & Density wave solutions
will be treated and compared simultaneously.

1+1 D dynamics of patches after reduction

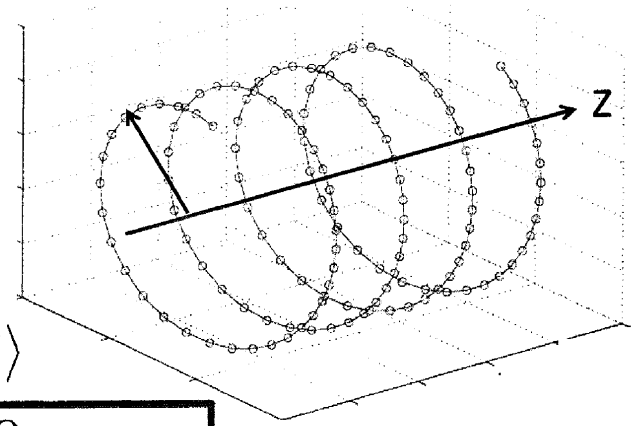


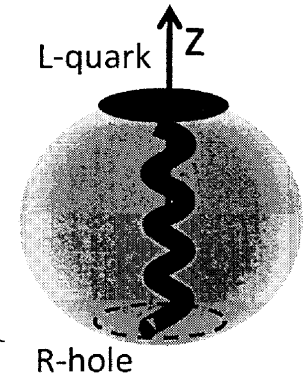
Quarkyonic Chiral Spirals in (3+1)D

- Chiral rotation evolves in the longitudinal direction:

$\langle \bar{\Psi}\Psi \rangle$

$\rightarrow \boxed{\langle \bar{\psi}\psi \rangle}$





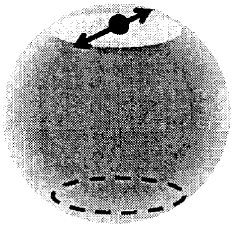
$\langle \bar{\Psi} i\Gamma_5 \Psi \rangle$

$\rightarrow \boxed{\langle \bar{\psi}\gamma^0\gamma^z\psi \rangle}$ (not conventional pion condensate in nuclear matter)

- Quarkyonic limit:
  - Baryon number is spatially constant.
  - No other condensates.

Summary

- 1; Quarkyonic regime: $\Lambda_{QCD}/\mu << 1$, but confining int.
  - Self-consistent eqs. for 1-patch are saturated within small momentum region.



$\longrightarrow$ (3+1) D → (1+1) D confining model for 1-patch

- 2; Nonzero V.E.V. of amp. field $\longrightarrow$ Local violation of sym.

$$\langle \bar{\varphi}_- \varphi_+ \rangle = \Delta e^{2i\mu z}$$

nonzero due to conf. int.

- 3; CDW accompanies Spiral structures: $\langle \bar{\Psi} i \Gamma_5 \Psi \rangle \neq 0$ (1+1)D
  - Due to mismatch of phases between Right and Left moving pairs.
- 4; Spirals accompany P & CP odd condensate: $\langle \bar{\psi} \gamma^0 \gamma^z \psi \rangle$ (3+1)D

Extra dimensions of space: are they going to be found any time soon?

Valery Rubakov

Institute for Nuclear Research
of the Russian Academy of Sciences, Moscow

Extra dimensions of space: old idea

T. Kaluza (1921) and O. Klein (1926):

attempt to unify the only known forces at the time, gravity and electromagnetism

Since then, unification aspect is still at the heart of constructions with extra dimensions

1980's: strongest motivation.
Theories that pretend to be most fundamental (superstring theory, M-theory) are consistent in (9+1)- or (10+1)-dimensional space-time. They either cannot be defined at all, or have pathologies in other dimensions.

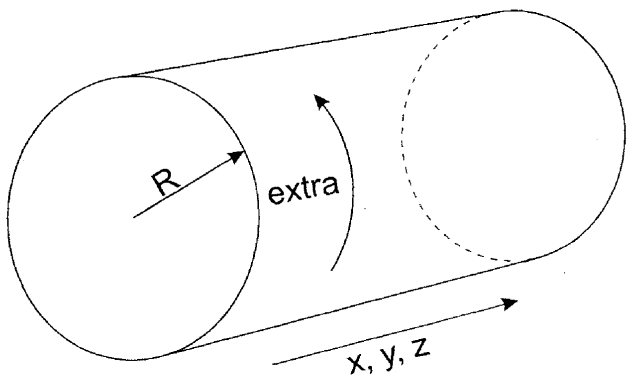
Despite long history, theories with extra dimensions is still a very lively area

No consensus on how extra dimensions look like.
This talk: several popular scenarios

Why don't we see extra dimensions?

Two proposals (or combination thereof)

- Original Kaluza–Klein: extra dimenions are compact



Quantum mechanics: angular momentum of rotation along extra dimension(s) is quantized,

$$L = 0, \ \pm\hbar, \ \pm 2\hbar, \ldots$$

$\Longrightarrow$ Energy of this rotation

$$E = 0, \ \frac{\hbar c}{R}, \ 2 \cdot \frac{\hbar c}{R}, \ldots$$

$\hbar = c = 1$ in what follows

Small $R \Longleftrightarrow$ large E.

Except for $L = 0 \Longleftrightarrow$ no motion along extra dimensions, no feel of them.

We have not yet reached energy threshold
of motion along extra dimensions

Extra dimensions will open up at $E > 1/R$

Signature: Kaluza–Klein partners of known particles

We do not see the motion along extra dimensions. For us, states of different angular momenta l look like different particles.

KK particle at rest w.r.t. us: no motion along our 3 dimensions, rotation along extra dimensions
$\Longrightarrow$ energy at rest in 3d sense $= l/R \Longrightarrow$

$$M_l = \frac{l}{R}$$

Heavy electrons, photons, quarks, ...

Regular pattern of their masses

Kaluza–Klein partners are characteristic of most of theories with extra dimensions. Their properties vary from model to model.

To summarize:

- There is a chance that energy scale of extra dimensions is TeV.

If so, extra dimensions will start to open up at LHC.

Quantum Gravity will become experimentally accessible.

- With even more luck, effects of extra dimensions may show up in table top or low energy particle physics experiments.

- There is fascinating connection between some theories in 4 and higher dimensions.

New way to approach complex dynamics
of strongly coupled theories.

It may well be that electroweak symmetry breaking
is best understood in terms of extra dimensions.

- There is a lot of room for crazy ideas. If any of them is true, revolution guaranteed.

Thermal Abelian Monopoles in the Deconfined Phase of Yang-Mills Theories

Massimo D'Elia
Genoa University & INFN

SUMMARY

We discuss the properties of thermal Abelian monopoles which are found in the deconfined phase of Yang-Mills theories. The temperature dependence of their density and their space distribution show the presence of non-trivial interactions among them. The statistical distribution of monopoles trajectories is compatible with a condensation of such objects happening right at the deconfining transition. The correlation of monopoles with the non-Abelian action density shows that these objects may be also source of chromo-electric fields, and thus linked to topological charge fluctuations. Issues regarding the dependence on the choice of the Abelian projection are discussed.

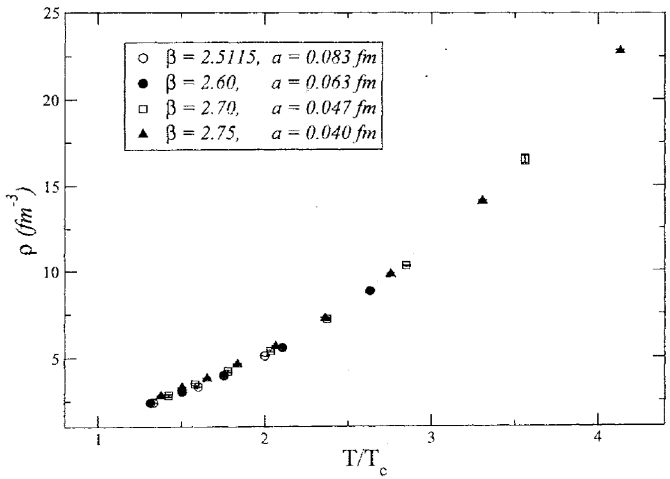
1 – Thermal monopole density and interactions

A. D'Alessandro, M. D., Nucl. Phys. B 799 241 (2008)

The thermal monopole density is then defined as

$$\rho = \langle \sum_{\vec{x}} |N_{wrap}(m_0(\vec{x},t))| \rangle / V_s$$

$N_{wrap}(m_0(\vec{x},t))$ **is the winding number of the current** $m_0(\vec{x},t)$, $V_s = (L_s a)^3$ **is the spatial volume**

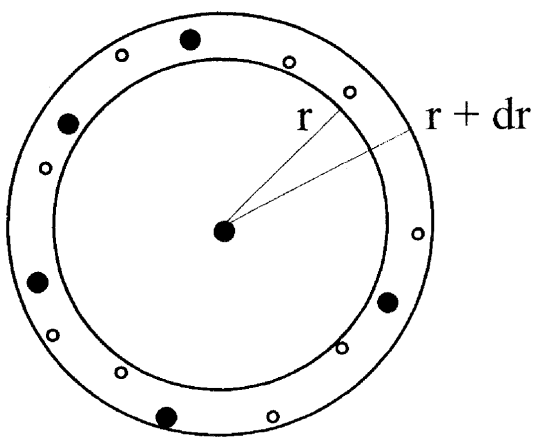


the density of wrapped trajectories scales well to the continuum limit

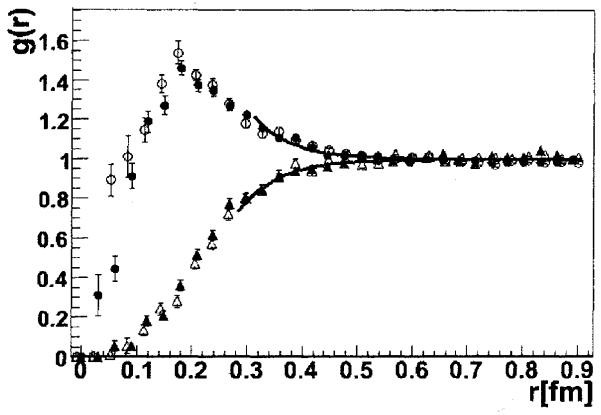
Monopole Interactions

Are wrapped trajectories (thermal monopole) randomly distributed in space? Or do they interact?

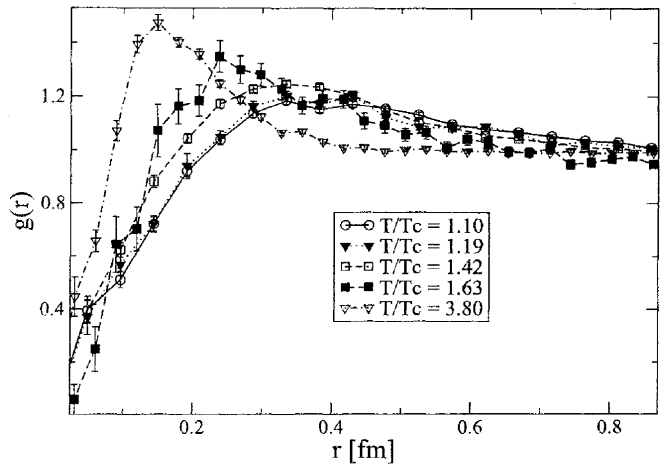
$\Longrightarrow$ **fix a reference monopole, count monopoles (antimonopoles) at distance** $\in [r, r + dr]$ **and normalize by the same number expected from random distribution: that gives the correlation function** $g(r)$



- $g(r) = 1 \Longrightarrow$ **no interaction**
- $g(r) \neq 1 \Longrightarrow$ **non-trivial interaction**



data for $T \simeq 2.85\, T_c$, $\beta = 2.7$ and 2.86



data for mono-antimono $g(r)$, various temperatures

- nice scaling
- monopole-monopole repulsion
- monopole-antimonopole attraction + hard core repulsion
- single peak in $g(r)$: typical of liquid/gas behaviour
- At large distances $g(r) \simeq e^{-V(r)/T}$, where $V(r) = \alpha_M e^{-r/\lambda}/r$ is a screened Coulomb potential, $\lambda \sim$ 0.1 fm.

2 – Thermal Monopoles and Confinement

A. D'Alessandro, M.D., E. Shuryak, arXiv:1002.4161

If thermal monopoles above T_c are really the objects condensing below T_c, can we follow their way back to condensation as we approach T_c from above?

Such an approach complements standard studies about the validity of the dual superconductor model for color confinement which look at the spontaneous breaking of a magnetic symmetry below T_c (Pisa, Bari, Moscow groups).

Condensation is a phenomenon related to the identity of quantum particles. Quantum statistics properties are encoded in monopole trajectories wrapping two or more times in the Euclidean time direction.

Assuming that MAG projection identifies the correct objects, what non-Abelian gauge configurations are associated with Abelian monopoles and what is their exact physical nature? What other quantum numbers do they carry?

Some steps in this direction have been done

(M. Chernodub, A. D'Alessandro, M.D. and V. Zakharov, arXiv:0909.5441)

It has been shown that a clear correlation exists between the non-Abelian gauge action density and the locations of thermal monopole trajectories; moreover the excess of magnetic action found around monopoles is comparable to that of the electric one:

MAG thermal monopoles, or at least part of them, may be source of both electric and magnetic fields. Can they be source of topological charge fluctuations? May thermal monopoles be similar to dyons?

Progress on Calorons

The progress on calorons (finite temperature instantons) is sketched. In particular there is some interest for confining temperatures (unfortunately not hot and dense matter), where the holonomy (the asymptotic value of the Polyakov loop) is non-trivial.
In the last section I give more recent results by others.

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in: P- and PC-odd Effects in Hot and Dense Matter
RIKEN BNL, USA

April 28, 2010

1. Introduction

There has been a revised interest in studying instantons at finite temperature T, so-called calorons [1, 2], because new explicit solutions could be obtained where the Polyakov loop at spatial infinity (the so-called holonomy) is non-trivial. They reveal more clearly the monopole constituent nature of these calorons [3]. Non-trivial holonomy is therefore expected to play a role in the confined phase (i.e. for $T < T_c$) where the trace of the Polyakov loop fluctuates around small values. The properties of instantons are therefore directly coupled to the order parameter for the deconfining phase transition.

At finite temperature A_0 plays in some sense the role of a Higgs field in the adjoint representation, which explains why magnetic monopoles occur as constituents of calorons. Since A_0 is not necessarily static it is better to consider the Polyakov loop as the analog of the Higgs field, $P(t,\vec{x}) = \mathrm{Pexp}\left(\int_0^\beta A_0(t+s,\vec{x})ds\right)$, which transforms under a periodic gauge transformation $g(x)$ to $g(x)P(x)g^{-1}(x)$, like an adjoint Higgs field. Here $\beta = 1/kT$ is the period in the imaginary time direction, under which the gauge field is assumed to be periodic. Finite action requires the Polyakov loop at spatial infinity to be constant. For SU(n) gauge theory this gives $\mathscr{P}_\infty = \lim_{|\vec{x}|\to\infty} P(0,\vec{x}) = g^\dagger \exp(2\pi i \mathrm{diag}(\mu_1,\mu_2,\ldots,\mu_n))g$, where g brings $\mathscr{P}_\infty$ to its diagonal form, with n eigenvalues being ordered according to $\sum_{i=1}^n \mu_i = 0$ and $\mu_1 \le \mu_2 \le \ldots \le \mu_n \le \mu_{n+1} \equiv 1+\mu_1$. In the algebraic gauge, where $A_0(x)$ is transformed to zero at spatial infinity, the gauge fields satisfy the boundary condition $A_\mu(t+\beta,\vec{x}) = \mathscr{P}_\infty A_\mu(t,\vec{x})\mathscr{P}_\infty^{-1}$.

Caloron solutions are such that the total magnetic charge vanishes. A single caloron with topological charge one contains $n-1$ monopoles with a unit magnetic charge in the i-th U(1) subgroup, which are compensated by the n-th monopole of so-called type $(1,1,\ldots,1)$, having a magnetic charge in each of these subgroups [4]. At topological charge k there are kn constituents, k monopoles of each of the n types. Monopoles of type j have a mass $8\pi^2 \nu_j/\beta$, with $\nu_j \equiv \mu_{j+1} - \mu_j$. The sum rule $\sum_{j=1}^n \nu_j \doteq 1$ guarantees the correct action, $8\pi^2 k$.

Prior to their explicit construction, calorons with non-trivial holonomy were considered irrelevant [2], because the one-loop correction gives rise to an infinite action barrier. However, the infinity simply arises due to the integration over the finite energy density induced by the perturbative fluctuations in the background of a non-trivial Polyakov loop [5]. The calculation of the non-perturbative contribution was performed in [14]. When added to this perturbative contribution, with minima at center elements, these minima turn unstable for decreasing temperature right around the expected value of T_c. This lends some support to monopole constituents being the relevant degrees of freedom which drive the transition from a phase in which the center symmetry is broken at high temperatures to one in which the center symmetry is restored at low temperatures. Lattice studies, both using cooling [7] and chiral fermion zero-modes [8] as filters, have also conclusively confirmed that monopole constituents do dynamically occur in the confined phase.

2. Some Properties of Caloron Solutions

Using the classical scale invariance we can always arrange $\beta = 1$, as will be assumed throughout. A remarkably simple formula for the $SU(n)$ action density exists [4],

$$\mathrm{Tr}F_{\alpha\beta}^2(x) = \partial_\alpha^2\partial_\beta^2 \log\psi(x), \quad \psi(x) = \tfrac{1}{2}\mathrm{tr}(\mathscr{A}_n\cdots\mathscr{A}_1) - \cos(2\pi t),$$

$$\mathscr{A}_m \equiv \frac{1}{r_m}\begin{pmatrix} r_m & |\vec{\rho}_{m+1}| \\ 0 & r_{m+1} \end{pmatrix}\begin{pmatrix} \cosh(2\pi\nu_m r_m) & \sinh(2\pi\nu_m r_m) \\ \sinh(2\pi\nu_m r_m) & \cosh(2\pi\nu_m r_m) \end{pmatrix},$$

with $r_m \equiv |\vec{x} - \vec{y}_m|$ and $\vec{\rho}_m \equiv \vec{y}_m - \vec{y}_{m-1}$, where $\vec{y}_m$ is the location of the mth constituent monopole with a mass $8\pi^2\nu_m$. Note that the index m should be considered mod n, such that e.g. $r_{n+1} = r_1$ and $\vec{y}_{n+1} = \vec{y}_1$ (there is one exception, $\mu_{n+1} = 1 + \mu_1$). It is sufficient that only one constituent location is far separated from the others, to show that one can neglect the $\cos(2\pi t)$ term in $\psi(x)$, giving rise to a static action density in this limit [4].

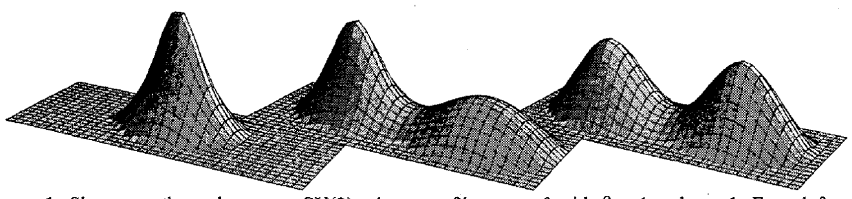

Figure 1: Shown are three charge one SU(2) caloron profiles at $t = 0$ with $\beta = 1$ and $\rho = 1$. From left to right for $\mu_2 = -\mu_1 = 0$ ($\nu_1 = 0, \nu_2 = 1$), $\mu_2 = -\mu_1 = 0.125$ ($\nu_1 = 1/4, \nu_2 = 3/4$) and $\mu_2 = -\mu_1 = 0.25$ ($\nu_1 = \nu_2 = 1/2$) on equal logarithmic scales, cutoff below an action density of $1/(2e)$.

In Fig. 1 we show how for SU(2) there are two lumps, except that the second lump is absent for trivial holonomy. Fig. 2 demonstrates for SU(2) and SU(3) that there are indeed n lumps (for SU(n)) which can be put anywhere. These lumps are constituent monopoles, where one of them has a winding in the temporal direction (which cannot be seen from the action density).

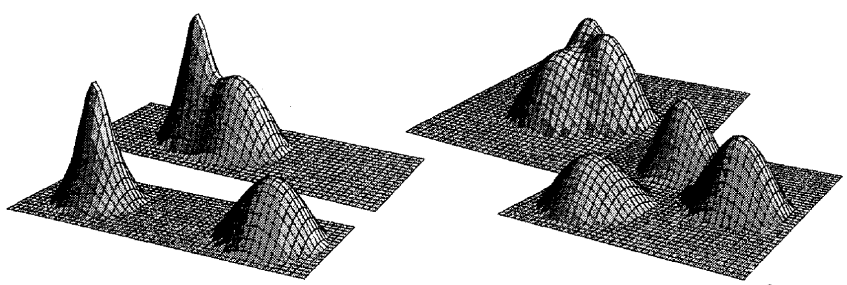

Figure 2: On the left are shown two charge one SU(2) caloron profiles at $t = 0$ with $\beta = 1$ and $\mu_2 = -\mu_1 = 0.125$, for $\rho = 1.6$ (bottom) and 0.8 (top) on equal logarithmic scales, cutoff below an action density of $1/(2e^2)$. On the right are shown two charge one SU(3) caloron profiles at $t = 0$ and $(\nu_1, \nu_2, \nu_3) = (1/4, 7/20, 2/5)$, implemented by $(\mu_1, \mu_2, \mu_3) = (-17/60, -1/30, 19/60)$. The bottom configuration has the location of the lumps scaled by 8/3. They are cutoff at $1/(2e)$.

2.1 Fermion Zero-Modes

An essential property of calorons is that the chiral fermion zero-modes are localized to constituents of a certain charge only. The latter depends on the choice of boundary condition for the fermions in the imaginary time direction (allowing for an arbitrary U(1) phase $\exp(2\pi i z)$) [9]. This provides an important signature for the dynamical lattice studies, using chiral fermion zero-modes as a filter [8]. To be precise, the zero-modes are localized to the monopoles of type

m provided $\mu_m < z < \mu_{m+1}$. Denoting the zero-modes by $\hat{\Psi}_z(x)$, we can write $\hat{\Psi}_z^\dagger(x)\hat{\Psi}_z(x) = -(2\pi)^{-2}\partial_\mu^2 \hat{f}_x(z,z)$, where $\hat{f}_x(z,z')$ is a Green's function which for $z \in [\mu_m, \mu_{m+1}]$ satisfies $\hat{f}_z(z,z) = \pi < v_m(z)|\mathscr{A}_{m-1}\cdots\mathscr{A}_1\mathscr{A}_n\cdots\mathscr{A}_m|w_m(z) > /(r_m\psi)$, where the spinors v_m and w_m are defined by $v_m^1(z) = -w_m^2(z) = \sinh(2\pi(z-\mu_m)r_m)$, and $v_m^2(z) = w_m^1(z) = \cosh(2\pi(z-\mu_m)r_m)$.

To obtain the finite temperature fermion zero-mode one puts $z = \frac{1}{2}$, whereas for the fermion zero-mode with periodic boundary conditions one takes $z = 0$. From this it is easily seen that in case of well separated constituents the zero-mode is localized only at $\vec{y}_m$ for which $z \in [\mu_m, \mu_{m+1}]$. To be specific, in this limit $\hat{f}_x(z,z) = \pi\tanh(\pi r_m v_m)/r_m$ for $SU(2)$, and more generally $\hat{f}_x(z,z) = 2\pi\sinh[2\pi(z-\mu_m)r_m]\sinh[2\pi(\mu_{m+1}-z)r_m]/(r_m\sinh[2\pi v_m r_m])^{-1}$. We illustrate in Fig. 3 the localization of the fermion zero-modes for the case of $SU(3)$.

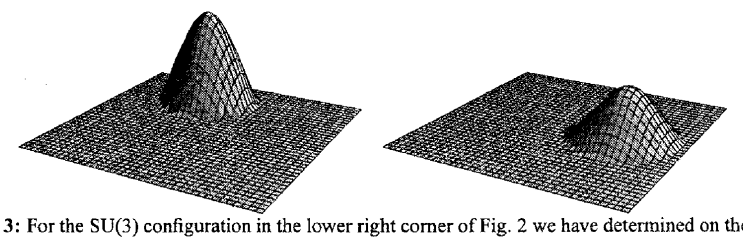

Figure 3: For the SU(3) configuration in the lower right corner of Fig. 2 we have determined on the left the zero-mode density for fermions with anti-periodic boundary conditions in time and on the right for periodic boundary conditions. They are plotted at equal logarithmic scales, cut off below $1/e^5$.

2.2 Calorons of Higher Charge

We have been able to use a "mix" of the ADHM and Nahm formalism [10], both in making powerful approximations, like in the far field limit (based on our ability to identify the exponentially rising and falling terms), and for finding exact solutions through solving the homogeneous Green's function [11]. We found axially symmetric solutions for arbitrary k, as well as for $k = 2$ two sets

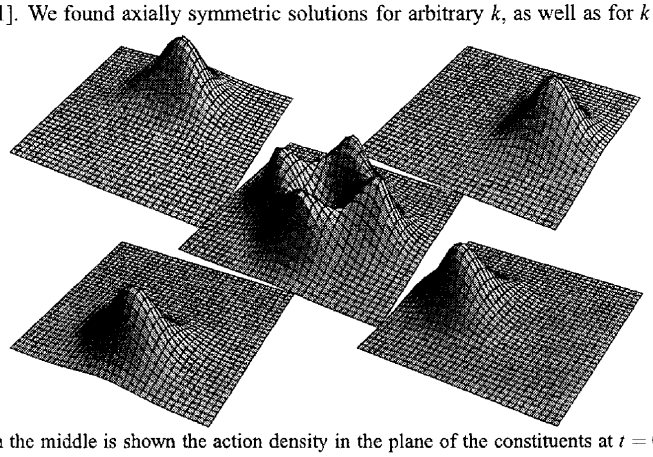

Figure 4: In the middle is shown the action density in the plane of the constituents at $t = 0$ for an SU(2) charge 2 caloron with $\mathrm{tr}\,\mathscr{P}_\infty = 0$, where all constituents strongly overlap. On a scale enhanced by a factor $10\pi^2$ are shown the densities for the two zero-modes, using either periodic (left) or anti-periodic (right) boundary conditions in the time direction.

of non-trivial solutions for the matching conditions that interpolate between overlapping and well-separated constituents. For this task we could make use of an existing analytic result for charge-2 monopoles [12], adapting it to the case of carolons. An example is shown in Fig. 4.

3. More recent results

There are more recent lectures by Bruckmann [13] and Diakonov [14]. Also, Diakonov and Petrov made some progress on constructing the hyperKähler metric which approximates the metric for an arbitrary number of calorons. They claim that this already gives confinement [14, 15]. But some cautionary remarks can be made [16]. Also multi-calorons were revisited [17], and the authors claim to have the full moduli space for $k = 2$.

The calorons have also adjoint fermionic zero-modes, and they are now known in analytical form [18]. Finally, Ünsal has published a paper concerning the mechanism of confinement in QCD-like theories [19], for example SU(2) with $1 \leq n_f \leq 4$ adjoint Majorana fermions. He argues that there are BPS and KK monopoles (precisely the constituents of the caloron), which have zero-modes under the adjoint fermions. They then make BPS-$\overline{\text{KK}}$ bound states (instead of BPS-KK).

Acknowledgments

I want to thank Dmitri Kharzeev who, despite my shortcomings, invited me to contribute.

References

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Axial anomaly and magnetism of nuclear and quark matter

M. Stephanov

(*U. of Illinois at Chicago*)

D. Son *(INT)*

Phys. Rev. D **77**, 014021 (2008) [arXiv:0710.1084 [hep-ph]]

QCD vacuum in the magnetic field

- Typically, critical B which modifies QCD vacuum $eB \sim m_\rho^2,\ f_\pi^2$.
  (Shushpanov-Smilga, Kabat et al, Miransky et al, Cohen et al)
- In (or near) the chiral limit, the response is governed by chiral Lagrangian.

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger + 2m_\pi^2 \Sigma\right]; \qquad \Sigma = \exp\left(\frac{i\tau_a\varphi_a}{f_\pi}\right);$$

- We shall look at a nontrivial solution — π^0 domain wall:

$$\pi^0 \equiv \varphi_3 = 4f_\pi \arctan e^{m_\pi z}; \quad \varphi_1 = \varphi_2 = 0;$$

which is unstable ("unwinding"). The spectrum of excitations has tachyonic branch:

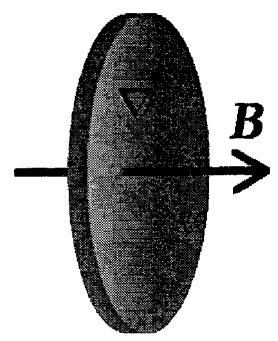
$$E^2 = k_x^2 + k_y^2 - 3m_\pi^2\,.$$

- This solution becomes *metastable* in the magnetic field $B > B_0$

$$E^2 = (2n+1)eB - 3m_\pi^2, \quad n = 0, 1, \ldots$$

$$B_0 = \frac{3m_\pi^2}{e} \approx 1.0 \times 10^{19}\ \mathrm{G},$$

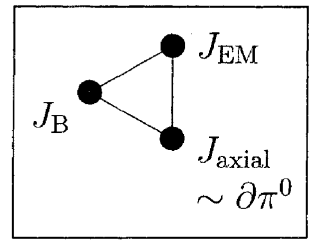
- Can it become *globally* stable?



Global stability at finite μ_B

- The wall carries energy per unit area: $\dfrac{\mathcal{E}}{S} = 8 f_\pi^2 m_\pi .$
- But, for $\boldsymbol{B} \neq 0$, it also carries baryon number!
- The *gauge invariant* baryon current is given by (Goldstone-Wilczek, Witten)

$$J_B^\mu = -\frac{\epsilon^{\mu\nu\alpha\beta}}{24\pi^2}\,\mathrm{tr}\left\{(L_\nu L_\alpha L_\beta) - 3ie\partial_\nu\left[A_\alpha Q(L_\beta + R_\beta)\right]\right\},$$



$\pi^0 \to \gamma\gamma$

where $L_\mu = \Sigma\partial_\mu\Sigma^\dagger$, $R_\mu = \partial_\mu\Sigma^\dagger\Sigma$ and $Q = \tau_3/2 + 1/6$.

- For the wall, $\boldsymbol{\nabla}\pi^0 \neq 0$, in the magnetic field $\boldsymbol{B}$:

$$J_B^0 = \frac{e}{4\pi^2 f_\pi}\boldsymbol{B}\cdot\boldsymbol{\nabla}\pi^0; \quad \Rightarrow \qquad \frac{N_B}{S} = \frac{eB}{2\pi}.$$

- I.e., the wall is stable towards decay into vacuum when $\mu_B > \dfrac{\mathcal{E}}{N_B} = \dfrac{16\pi f_\pi^2 m_\pi}{eB}$.

And if

$$B > B_1 = \frac{16\pi f_\pi^2 m_\pi}{e m_N} \approx 1.1 \times 10^{19}\ \mathrm{G}$$

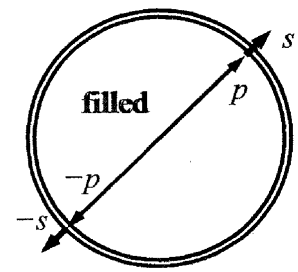
the wall wins over nuclear matter ($\mu_B \approx m_N$) in terms of $\mathcal{E}/N_B$.

- $B_1 \sim m_\pi \gg B_0 \sim m_\pi^2$ and both vanish in the chiral limit.

Large μ and color superconductivity

- Asymptotic freedom $\Rightarrow \alpha_s(\mu) \to 0$.

- Quarks of "different color" (color antisymmetric state) attract. Fermi sphere is unstable towards condensation of quark pairs (Cooper).



- For 2 flavors – 2SC: (Rapp et al, Alford et al, '97)

$$\langle u_R d_R \rangle = \langle u_L d_L \rangle \neq 0$$

— flavor singlet $\Rightarrow$ breaks U(1)$_A$ (not SU(2)$_A$).

- For 3 flavors — CFL: (Alford, Rajagopal, Wilczek)

$$\langle u_R d_R \rangle = \langle d_R s_R \rangle = \langle s_R u_R \rangle = (R \to L) \neq 0$$

— flavor triplet and color triplet

$$\left.\begin{array}{l} \mathrm{SU}(3)_R \times \mathrm{SU}(3)_{\mathrm{color}} \to \mathrm{SU}(3)_{R+\mathrm{color}} \\ \mathrm{SU}(3)_L \times \mathrm{SU}(3)_{\mathrm{color}} \to \mathrm{SU}(3)_{L+\mathrm{color}} \end{array}\right\} \quad \Rightarrow \quad \mathrm{SU}(3)_R \times \mathrm{SU}(3)_L \to \mathrm{SU}(3)_{L+R}$$

Breaks both U(1)$_A$ and SU(3)$_A$.

Domain walls in 2SC and CFL

- Spontaneously broken $U(1)_A$ and SU(3)$_A$ $\Rightarrow$ Goldstone bosons.
  - Note: U(1)$_A$ violation by QCD anomaly is suppressed at large μ.
- In 2SC and CFL: there are neutral axial Goldstone bosons.

The lightest is η in 2SC and $\eta - \eta'$ mixture ($s\bar{s}$) in CFL.

- Domain wall is energetically favorable state when $\mathcal{E}/N_B < \mu$.

$$\mathcal{E} \sim f_\eta^2 m_\eta \sim \mu^2 m_\eta, \quad N_B \sim eB;$$

$$B_c \sim \frac{\mu m_\eta}{e} \sim \underbrace{10^{17}}_{\text{CFL}} - \underbrace{10^{18}}_{\text{2SC}} \text{G}$$

Summary

- At $B_0 = 3m_\pi^2/e$ the π^0 domain wall becomes metastable.

- The wall carries baryon number $N_B/S = eB/(2\pi)$ and competes with the nuclear matter.

The wall wins at $B > B_1 \approx \dfrac{16\pi f_\pi^2 m_\pi}{e m_N} \sim 10^{19}$ G.

- Both B_1 and B_0 vanish in the chiral limit.

- In color superconducting quark matter η/η' domain wall wins for $B \sim 10^{17} - 10^{18}$ G.

- The "meson supercurrent" state in CFL is ferromagnetic and capable of producing $B \sim 10^{14} - 10^{15}$ G in a typical compact star.

Superhorizon Fluctuations, CMBR and Heavy Ion Collisions.

Saumia Pandiat
Collaborators: A. P. Mishra, R. K. Mohapatra and A. M. Srivastava
Institute of Physics, Bhubaneswar-751005, India

References: Phys. Rev. C **77**, 064902 (2008)
Phys. Rev. C **81**, 034903 (2010)

We show that there are crucial similarities in the physics of cosmic microwave background radiation (CMBR) anisotropies and the flow anisotropies in relativistic heavy-ion collision experiments (RHICE). We also argue that, following CMBR anisotropy analysis, a plot of root-mean square values of the flow coefficients, calculated in a lab fixed frame for RHICE, can yield important information about the nature of initial state anisotropies and their evolution. We also demonstrate the strength of this technique by showing that elliptic flow for non-central collisions can be directly determined from such a plot without any need for the determination of event-plane.

Similarities in the nature of density fluctuations in early universe and the plasma in relativistic heavy ion collisions:

Superhorizon fluctuations

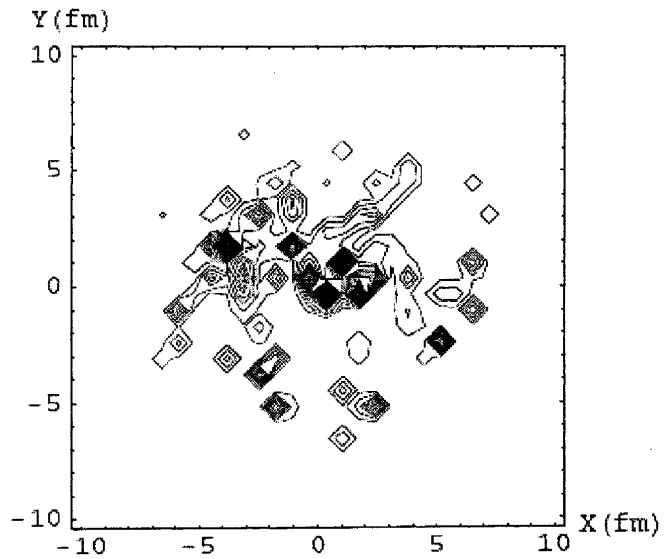
In universe: Inflation

In RHICE?

Consider central collision

Initial transverse energy density fluctuations at 1fm From HIJING

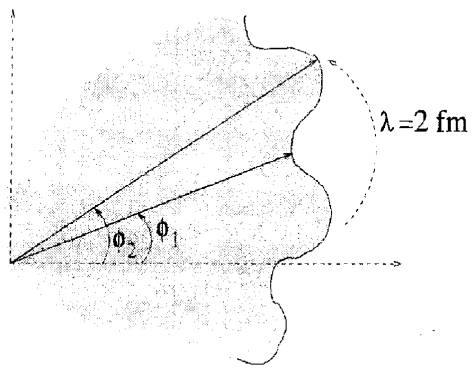
Nucleon size ~ 1.6 fm
horizon at thermalization ~ 1fm



Central Au – Au Collision

C M Energy 200 GeV

Elliptic mode oscillation: not seen in hydrodynamic simulations: Development of strong radial flow. Consider a short wavelenghth fluctuation



Due to short time scale of evolution here, radial expansion may still not be most dominant.

Oscillations

The anisotropies of larger wavelength compared to sound horizon should be suppressed by a factor, $\frac{H^{s}_{fr}}{\lambda/2}$

The Analysis:

Calculate the momentum anisotropies in different azimuthal bins in a fixed co-ordinate system.

Calculate the Fourier coefficients of the momentum anisotropies.

Find the root mean square values which will give different flow coefficients.

$$V_n^{rms} = \sqrt{< V_n^2 >}$$

$$\rho(\phi') = \sum_{n=-\infty}^{\infty} v_n e^{in\phi'}$$

Conventional flow coefficients

$$\rho_\psi(\phi) = \sum_{n=-\infty}^{\infty} v_n e^{in(\phi-\psi)}$$

re-written in lab fixed frames

$$\tilde{v}_n(\psi) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \rho_\psi(\phi) e^{-in\phi} d\phi$$

Flow co-efficients in lab fixed frame

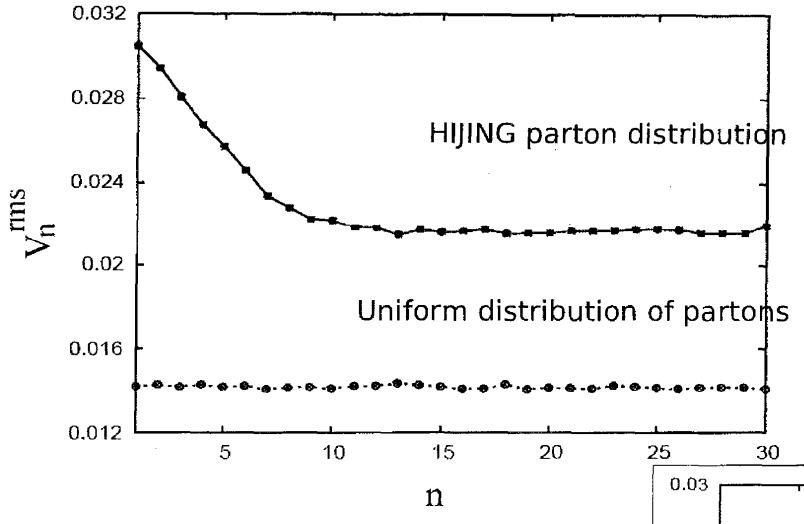
$$(\tilde{v}_n^{rms})^2 = \overline{\tilde{v}_n^2} = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\psi \tilde{v}_n(\psi)\tilde{v}_n^*(\psi)$$

$$\tilde{v}_n^{rms} = |v_n|$$

True for elliptic flow, but not for other fluctuations as the r.h.s. is the average value of flow coefficient.

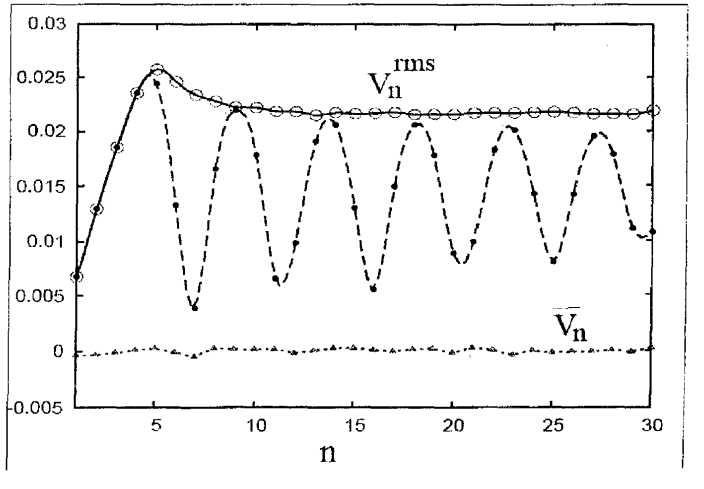
Results:

1

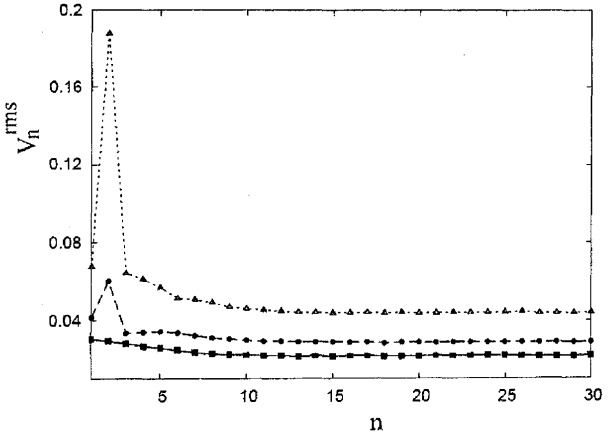


Plots for central collisions.
2.From HIJING parton distribution (spatial anisotropies converted to momentum anisotropies)
3.suppression and oscillations included.

2

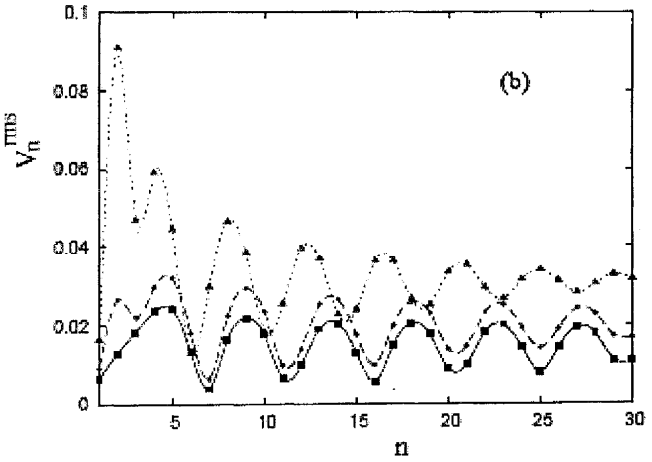


Plot for non-central collision from Hijing parton distribution



b = 8fm, 5fm and 0

Suppression and acoustic oscillations incorporated



Study of Magnetic Field's Effect on Events in HI Collisions

Alexei Chikanian
Yale University

It is expected that a very strong Magnetic Field (MF) is induced in Heavy Ion (HI) collisions. This field should deflect quarks created at the early stage of the collisions. After fragmentation, final state particles may still carry information on the parent quarks' deflection.

In this work, the results on the effect of MF on HI collision events are presented for STAR data in comparison with a simulation.

Motivation

- In HI Collision (HIC), an extremely strong ($\sim 10^{15}$Tesla) Magnetic Field (MF) is induced.
- Could we observe the effect of this MF on the events in HIC by looking for opposite deflection of + & - particles?

  (NOT a direct measurement of chiral magnetic effect but a test of an important ingredient)
- We are trying to answer this question based on:

  a) the data analysis

  Au+Au 200 GeV 2007 $\sim 50 \cdot 10^6$ events

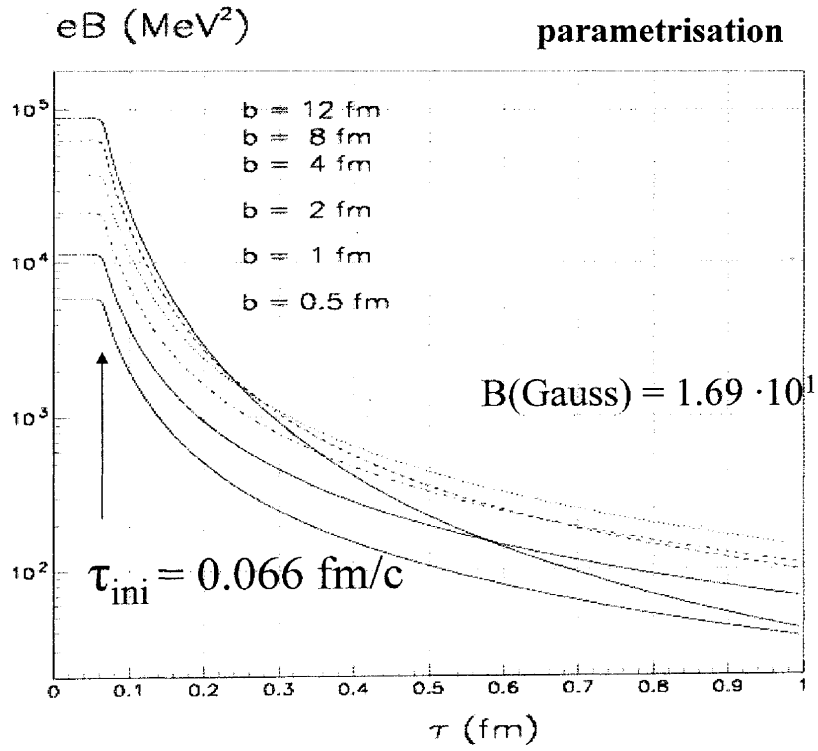
  b) simulation (with different assumptions)

  $10 \cdot 10^6$ or $50 \cdot 10^6$ events

Magnetic Field

D.Kharzeev et al./N.P. A803 (2008) 227-253

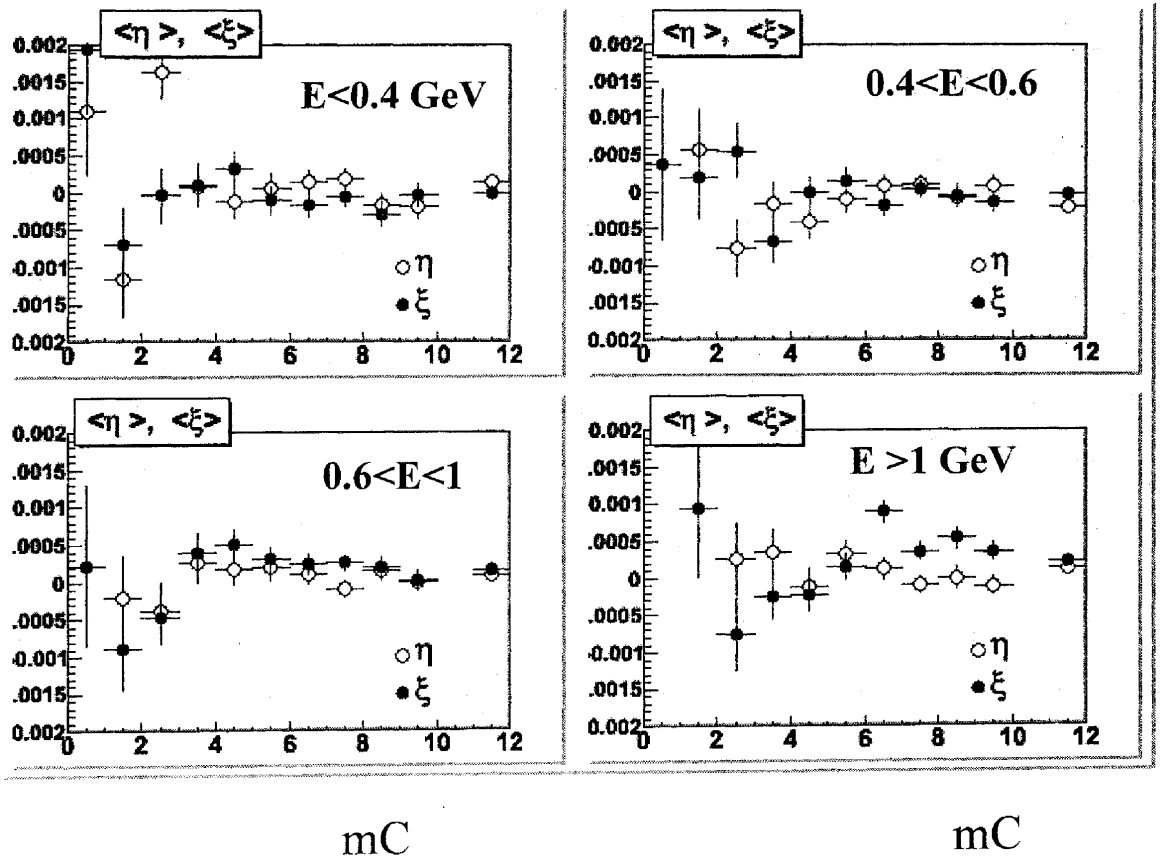
parametrisation



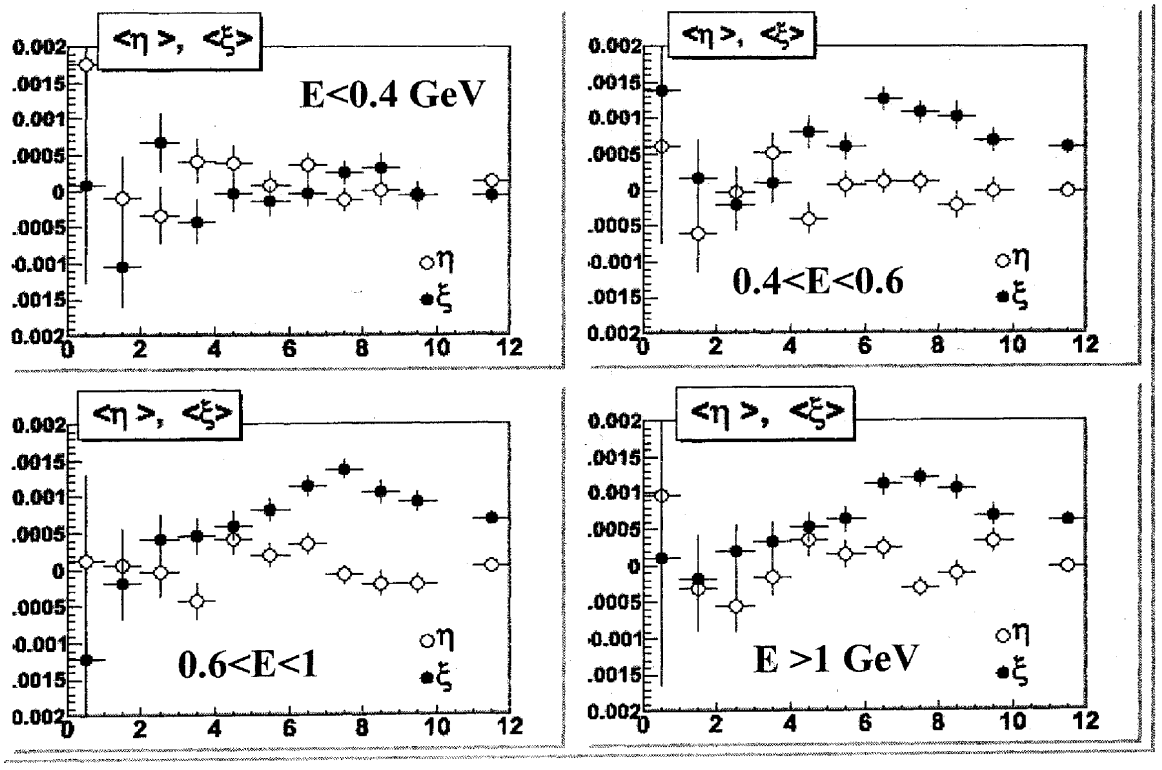
$B(\text{Gauss}) = 1.69 \cdot 10^{14}\ eB\ (\text{MeV}^2)$

$\tau_{ini} = 0.066$ fm/c

<η>, <ξ> data (STAR preliminary)



$\langle\eta\rangle$, $\langle\xi\rangle$ with 200 MeV/c dilution but deflection with τ_0=0.5 fm/c (simulation,50M ev.)



mC mC

Conclusion

- MF deflection signal observed in the real data is of the order of 10^{-4} or lower
- Significant signal ($\sim 10^{-2}$) was observed in the simulation with MF starting at $\tau_0 = 0$.

  Dilution (fragmentation, etc.) affects the signal for low energy particles only.
- Simulation results for $\tau_0 = 0.5$ fm/c are much lower ($\sim 10^{-3}$) than for $\tau_0 = 0$ but still ~ 10 times bigger than the data points.

Medium-modified Jets and Initial State Fluctuations as Sources of Charge Correlations Measured at RHIC

Hannah Petersen, Duke University

(in collaboration with Thorsten Renk and Steffen Bass)

The contribution of medium-modified jets to the asymmetry in charged particle production with respect to the reaction plane is investigated. The different pathlength combinations of jets through the medium in non-central heavy ion collisions result in finite correlations of like and different charged particles emitted in the different hemispheres. Our calculation is based on combining jet events from YaJEM (Yet another Jet Energy Loss Model) and a bulk medium evolution. It is found that the jet production probabilities are too small to observe this effect in a realistic heavy ion reaction.

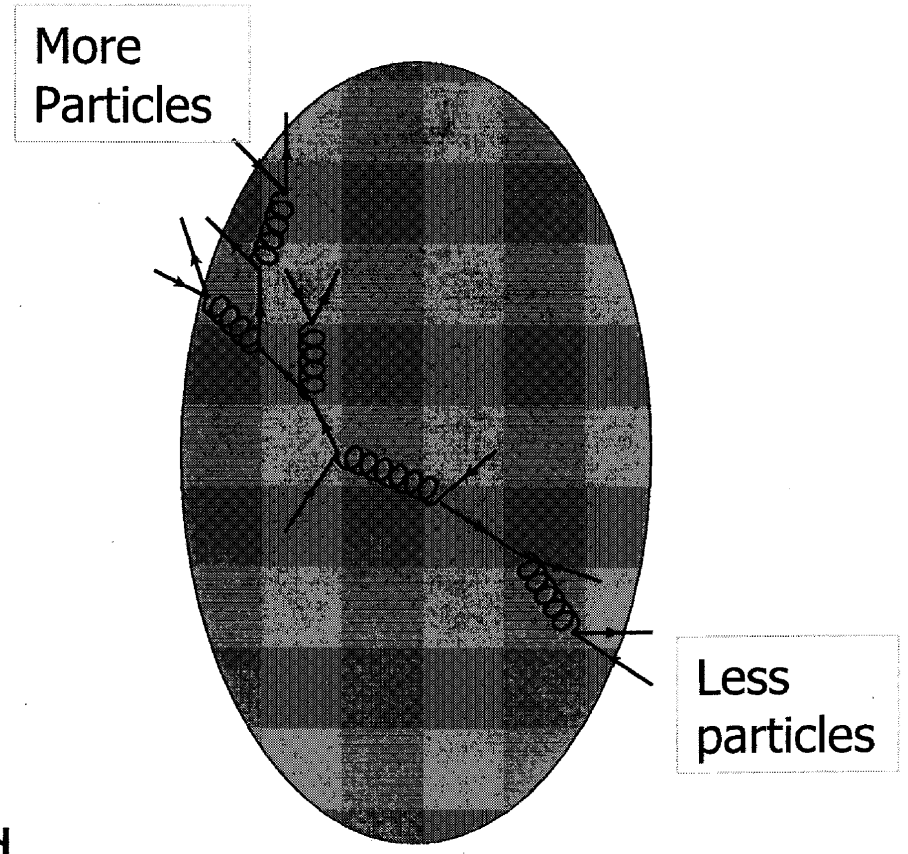
In addition, the influence of initial state fluctuations on this observable is explored using an event-by-event (3+1)d hybrid approach that is based on UrQMD (Ultra-relativistic Quantum Molecular Dynamics) with an ideal hydrodynamic evolution. In this calculation momentum conservation and elliptic flow are explicitly taken into account. The asymmetries in the initial state are translated to a final state momentum asymmetry by the hydrodynamic flow profile. Dependent on the size of the initial state fluctuations the resulting charged particle asymmetries are in qualitative agreement with the preliminary STAR results.

Medium-Modified Jets

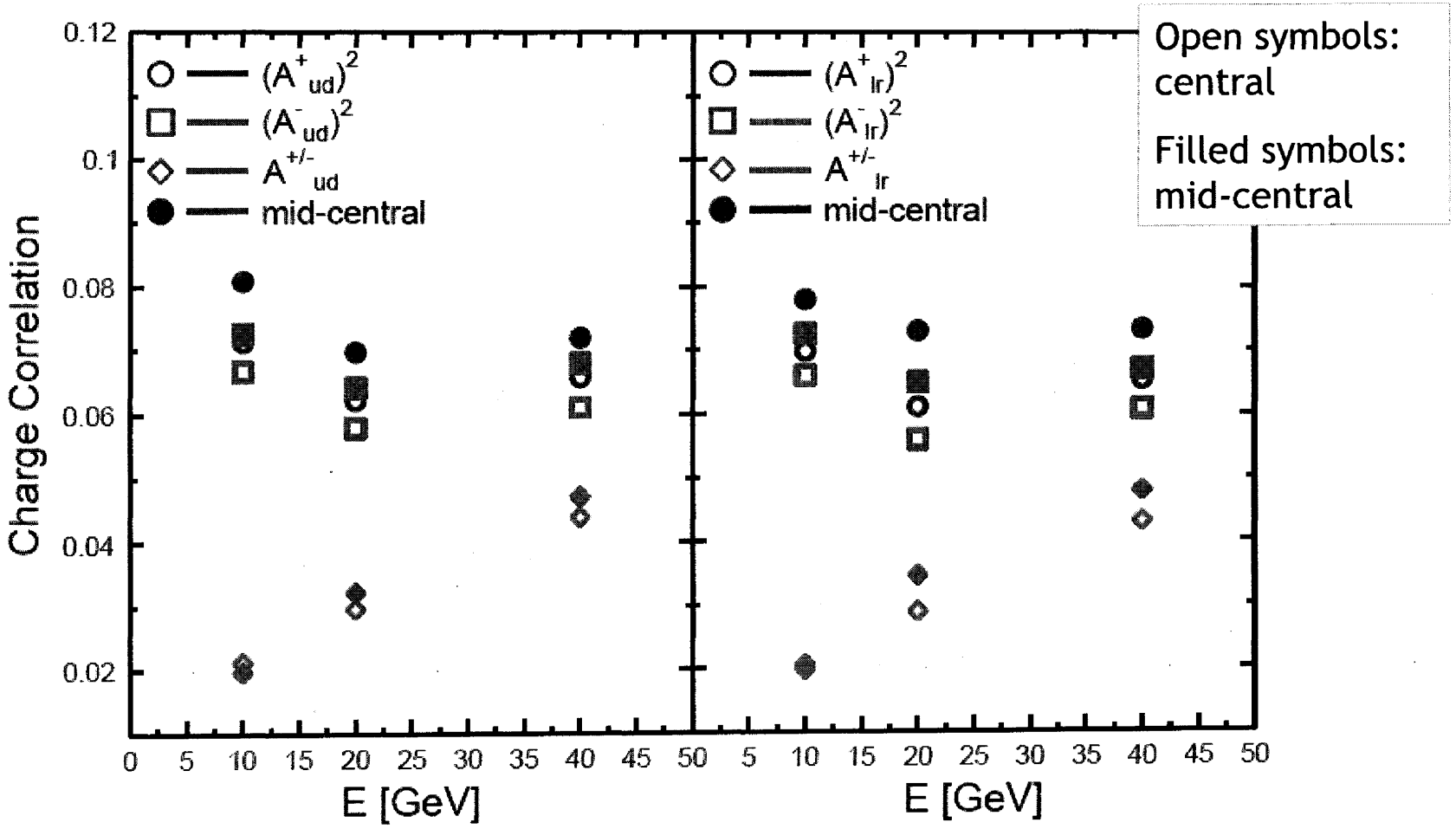
- Energy loss of a high energetic parton might lead to an asymmetry in the particle production
- The out-of-plane direction should be more modified because of longer average pathlength

→ leads to the correct up-down/left-right asymmetry

- Idea: Add jet events from YaJEM to UrQMD background



Coefficients for Jets only

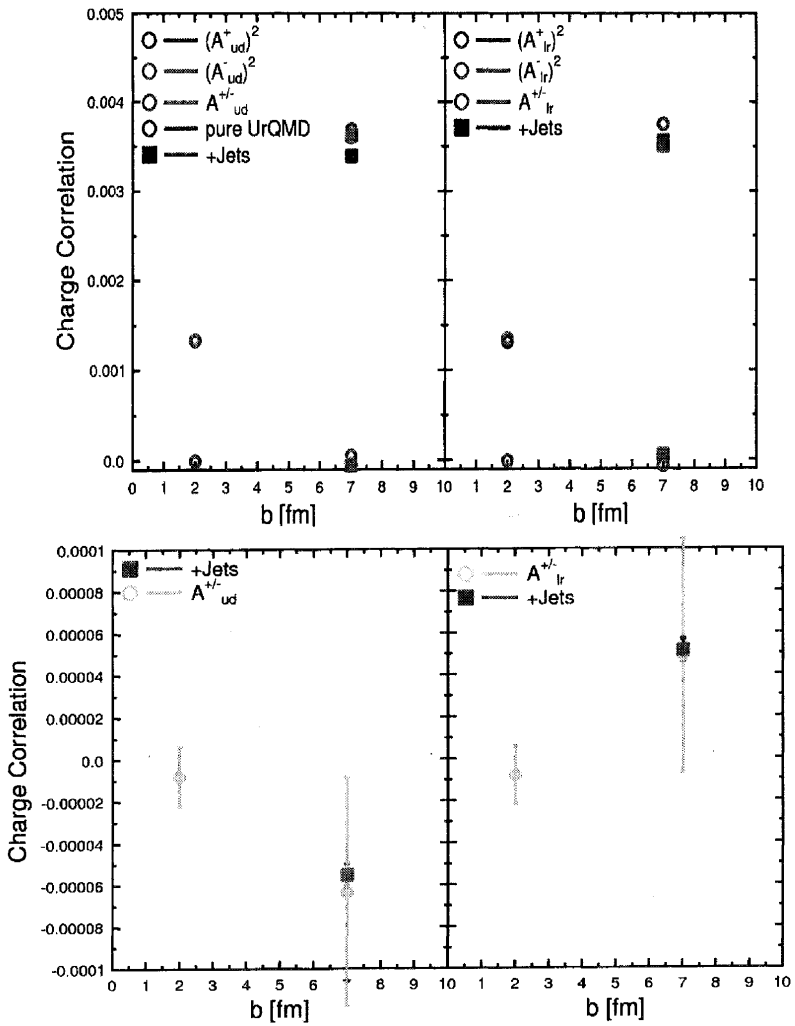


Open symbols: central

Filled symbols: mid-central

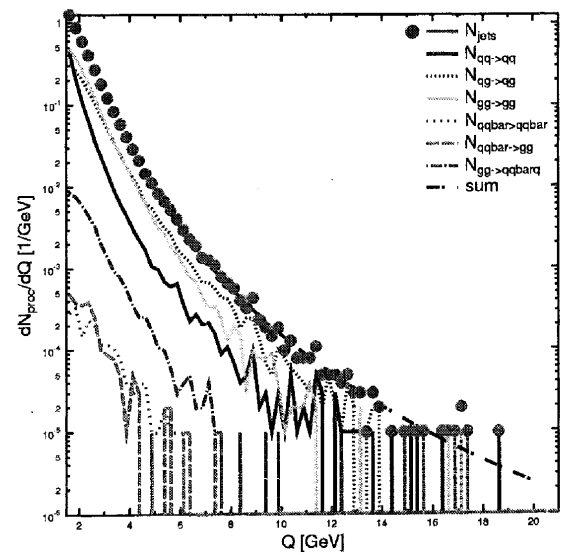
→ Finite resulting asymmetry is visible

Full Result



- UrQMD background shows no asymmetries

→ Lack of coordinate-momentum-space correlation



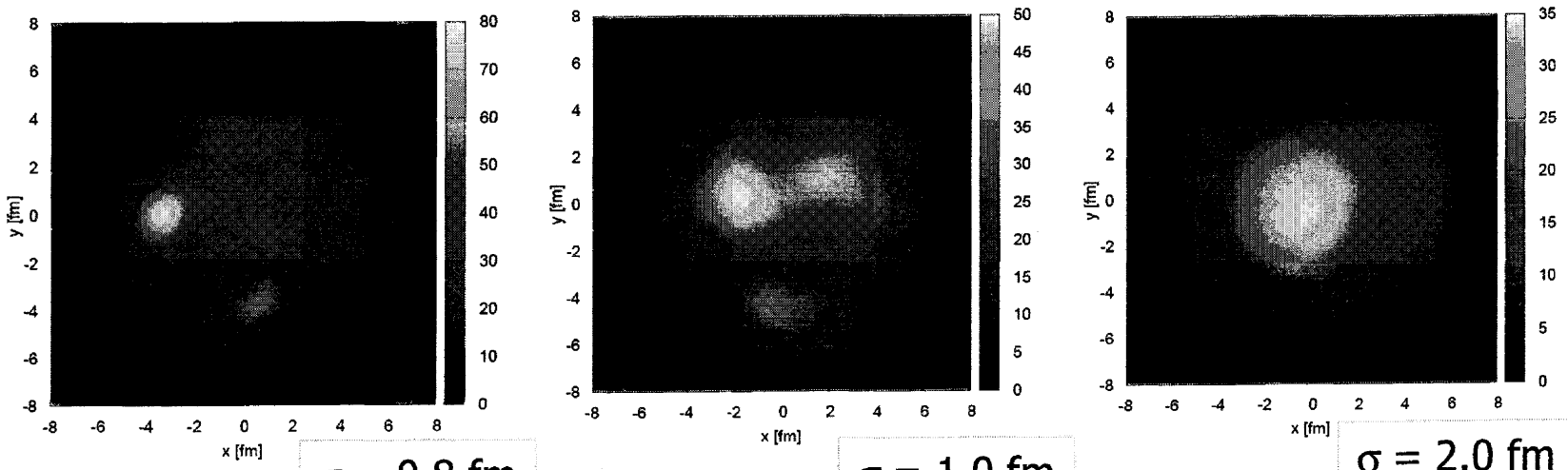
→ Jet production probabilities are too small to observe an effect

Initial State

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

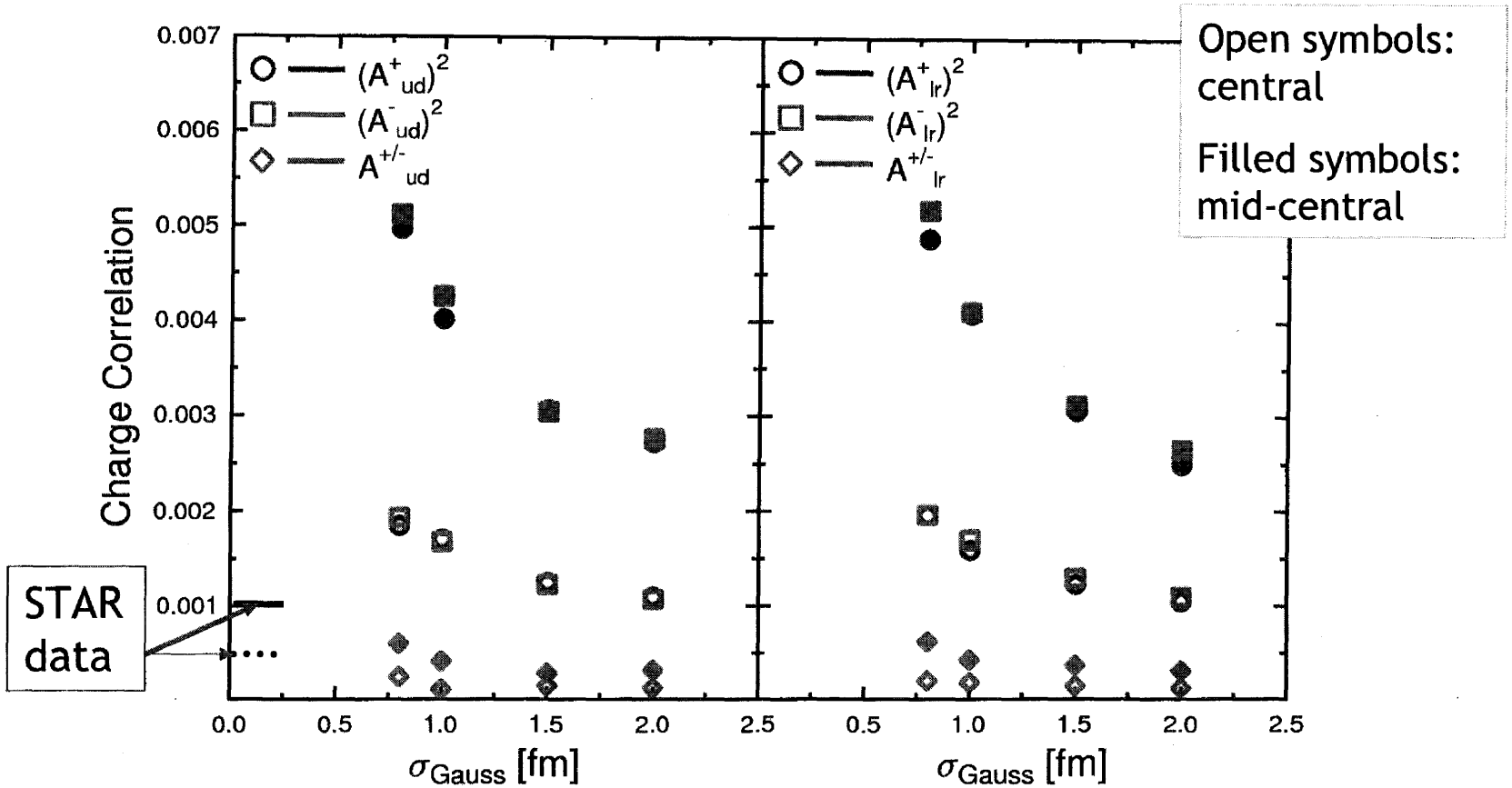
$$\epsilon_{\rm cf}(x,y,z) = N \exp -\frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma_z(z-z_p))^2}{2\sigma^2}$$

- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade



(J.Steinheimer et al., PRC 77,034901,2008)

Charged Particle Asymmetry



- Asymmetries are larger for mid-central collisions
- More granularity of initial state leads to higher correlation

Quantum criticality, the AdS/CFT correspondence, and the cuprate superconductors

Subir Sachdev
Harvard University

Talk online: sachdev.physics.harvard.edu

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Wednesday, April 28, 2010

Max Metlitski, Harvard

Eun Gook Moon, Harvard

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Sean Hartnoll, Harvard
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Outline

1. The superfluid-insulator transition

   Quantum criticality and the AdS/CFT correspondence

2. Graphene

   'Topological' Fermi surface transition

3. The cuprate superconductors

   Fluctuating spin density waves, and pairing by "topological" gauge fluctuations

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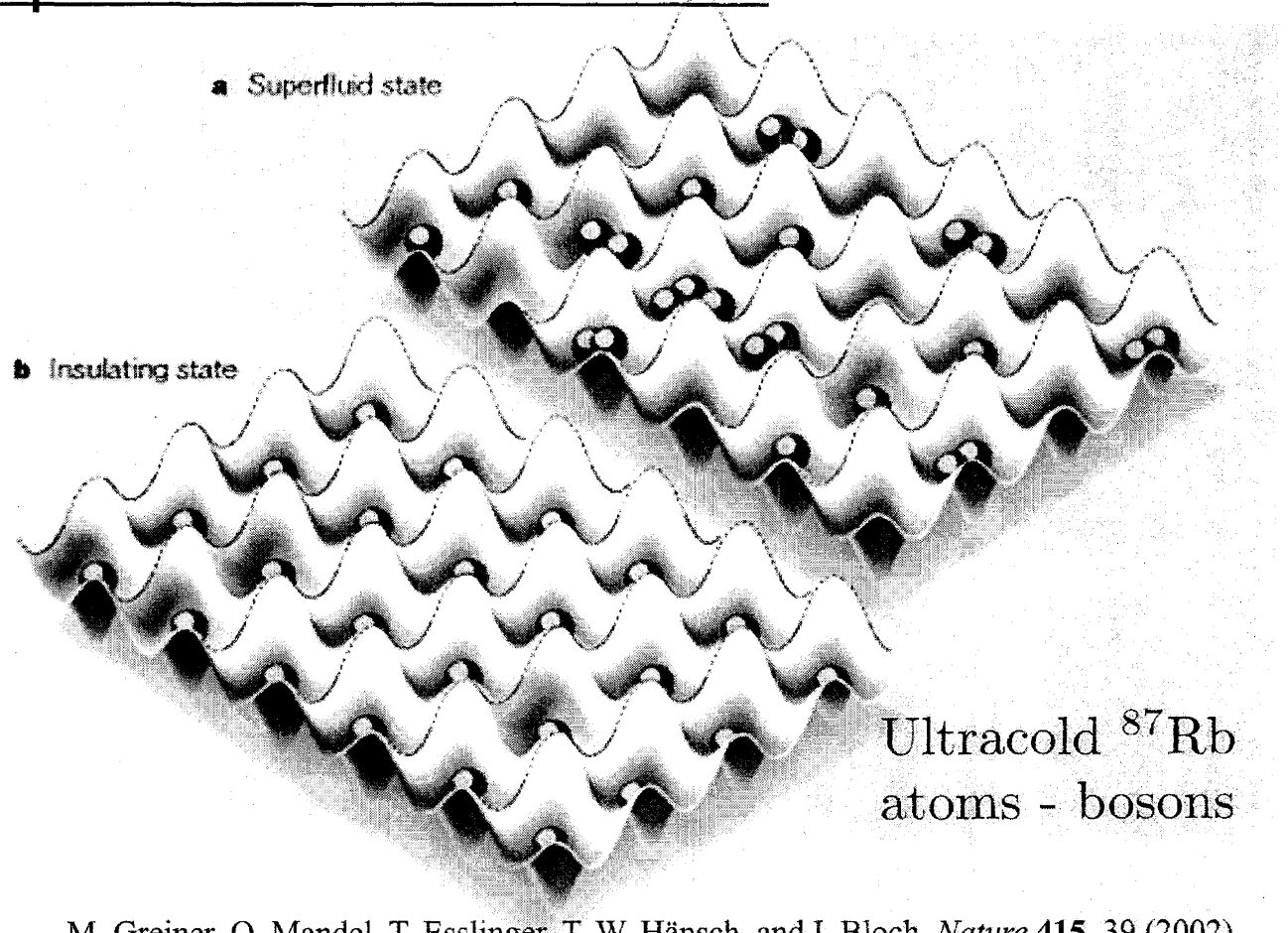
Superfluid-insulator transition



Ultracold ^{87}Rb atoms - bosons

M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

Wednesday, April 28, 2010

Conclusions

Gauge theory for pairing of Fermi pockets in a metal with fluctuating spin density wave order: Many qualitative similarities to holographic strange metals and superconductors

Is a color superconductor topological ?

Phys. Rev. D 81, 074004 (2010) [arXiv:1001.2555]

Yusuke Nishida (MIT)

1. What is topological superconductor?
2. Is a color superconductor topological?
3. Possible physical implications

Topological charge

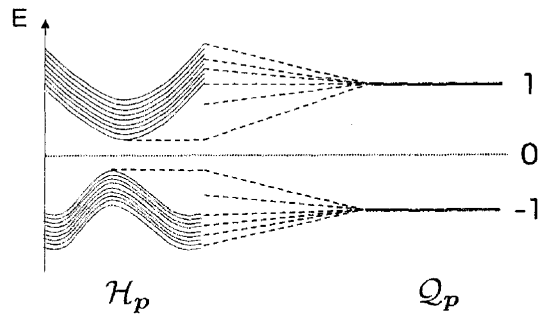
Topological charge for "class DIII" Hamiltonians in 3D

$(\mathcal{C}^{-1}\mathcal{H}\mathcal{C} = -\mathcal{H}^* \quad \mathcal{T}^{-1}\mathcal{H}\mathcal{T} = \mathcal{H}^* \quad \text{with} \quad \mathcal{C}^2 = 1 \quad \mathcal{T}^2 = -1)$

Hamiltonian in momentum space

$$\mathcal{H}_{\boldsymbol{p}} = U_{\boldsymbol{p}} \begin{pmatrix} \mathcal{E}_{\boldsymbol{p}} & 0 \\ 0 & -\mathcal{E}_{\boldsymbol{p}} \end{pmatrix} U_{\boldsymbol{p}}^\dagger$$

$$\mathcal{Q}_{\boldsymbol{p}} \equiv U_{\boldsymbol{p}} \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix} U_{\boldsymbol{p}}^\dagger \rightarrow \begin{pmatrix} 0 & q_{\boldsymbol{p}} \\ q_{\boldsymbol{p}}^\dagger & 0 \end{pmatrix}$$



$q_{\boldsymbol{p}} \in \mathrm{U}(n)$ is a map from p^3-space to unitary matrix

➡ winding number : $\pi_3[\mathrm{U}(n)] = \mathbb{Z} \quad (n \geq 2)$

$$N = \frac{1}{24\pi^2} \int d\boldsymbol{p}\, \epsilon^{ijk}\, \mathrm{Tr}\big[(q_{\boldsymbol{p}}^{-1}\partial_i q_{\boldsymbol{p}})(q_{\boldsymbol{p}}^{-1}\partial_j q_{\boldsymbol{p}})(q_{\boldsymbol{p}}^{-1}\partial_k q_{\boldsymbol{p}})\big]$$

A. P. Schnyder et al., Phys. Rev. B (2008)

Color superconductor

free-space Hamiltonian with $\Delta(x) = \Delta_0$: constant

In the chiral limit (m=0) : $\mathcal{H} = \mathcal{H}_R + \mathcal{H}_L \quad \Rightarrow \quad N = N_R + N_L$

even parity paring

$$N_R = \frac{\Delta_0}{2|\Delta_0|} \qquad N_L = -\frac{\Delta_0}{2|\Delta_0|}$$

topologically nontrivial

$\Downarrow$ $m \neq 0$

$$N = 0$$

topologically trivial

odd parity paring

$$N_R = \frac{\Delta_0}{2|\Delta_0|} \qquad N_L = \frac{\Delta_0}{2|\Delta_0|}$$

$\Downarrow$ $m \neq 0$

$$N = \frac{\Delta_0}{|\Delta_0|} \quad \text{for} \quad m^2 < \mu^2 + \Delta_0^2$$

$\Downarrow$ topological phase transition

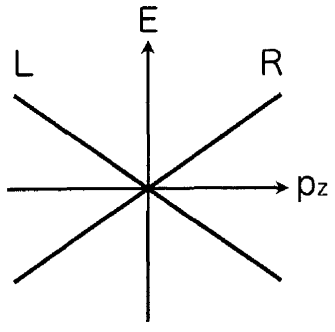
$$N = 0 \quad \text{for} \quad m^2 > \mu^2 + \Delta_0^2$$

Is a color superconductor topological ?

Yes, in the chiral limit ($N_R, N_L \neq 0$)

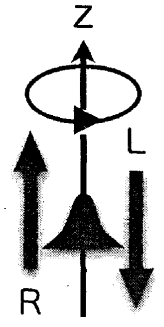
➡ $U_B(1)$ vortex in rotating CFL quark matter supports 9 sets of gapless right- and left-handed quarks

5 on a non-Abelian vortex [Yasui, Itakura, Nitta (arXiv:1001.3730)]



$$E = \pm v p_z$$

$\otimes$ 9



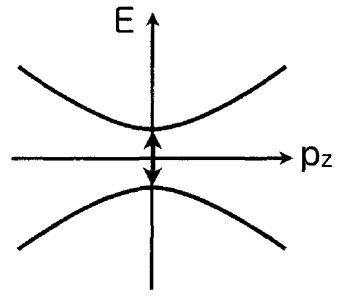
➡ Microscopic origin of axial current flowing on a vortex derived using anomalies

$$J_z^5 = \frac{\mu}{2\pi} \times (\text{vorticity})$$

D. T. Son & A. R. Zhitnisky, Phys. Rev. D (2004)

Is a color superconductor topological ?

No, with nonzero quark mass (N=0)



➡ localized quarks become gapped

$$E = \pm v\sqrt{m^2 + p_z^2}$$

- much lighter than bulk quarks

$$vm/\Delta \sim 5 \times 10^{-3} \quad \text{for} \quad \mu \sim 500\,\text{MeV} \quad \Delta \sim 50\,\text{MeV} \quad m \sim 10\,\text{MeV}$$

- parametrically lighter than pseudo-NG bosons

$$vm \to m\,(\Delta/\mu)^2 \ln(\mu/\Delta) \ll m_{\text{NG}} \to m\,(\Delta/\mu)$$

D. T. Son & M. A. Stephanov
Phys. Rev. D (2000)

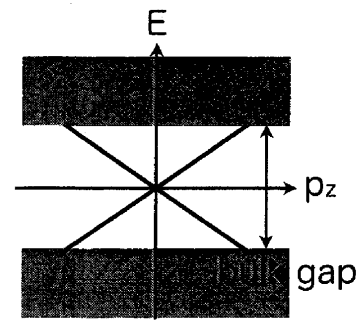
➡ could be important low-energy degrees of freedom

- impact on the physics of rotating neutron/quark stars?
  (transport property, neutrino emissivity, pulser kick, ...)

- topology of Hamiltonian ⇔ existence of gapless fermions
- effect of interaction

Effective 1D theory @ vortex

Bulk fermions are gapped by $\Delta(r \to \infty)$



Low-energy effective theory should involve (nearly) gapless fermions on a vortex line

$$H_{1\mathrm{D}} = \frac{v}{2} \int \frac{dp_z}{2\pi} \left(p_z \, \psi^{\mathrm{R}\dagger}_{p_z} \psi^{\mathrm{R}}_{p_z} - p_z \, \psi^{\mathrm{L}\dagger}_{p_z} \psi^{\mathrm{L}}_{p_z} + im \, \psi^{\mathrm{R}\dagger}_{p_z} \psi^{\mathrm{L}}_{p_z} - im \, \psi^{\mathrm{L}\dagger}_{p_z} \psi^{\mathrm{R}}_{p_z} \right)$$

mass term for even parity pairing

velocity

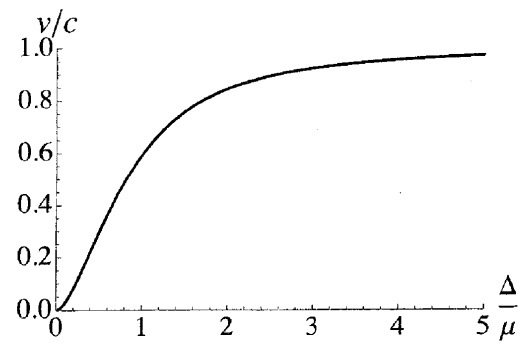
Majorana fermions

$$\psi^{\mathrm{R(L)}\dagger}_{p_z} = \psi^{\mathrm{R(L)}}_{-p_z}$$

$$v = \frac{\int_0^\infty dr \, r \left[J_0^2(\mu r) - J_1^2(\mu r) \right] e^{-2 \int_0^r |\Delta(r')| dr'}}{\int_0^\infty dr \, r \left[J_0^2(\mu r) + J_1^2(\mu r) \right] e^{-2 \int_0^r |\Delta(r')| dr'}}$$

simple case

$\Delta(r) = \Delta$



Magnetic catalysis in a holographic approach.

Elena Gubankova
Goethe University, Frankfurt

BNL, April 26-30, 2010

Calculation set up. Black hole

$$
\begin{aligned}
f &= 1 + \frac{Q^2 + H^2}{r^4} - \frac{M}{r^3} \\
A_t &= \mu\left(1 - \frac{r_h}{r}\right), \quad A_x = -\mathcal{H}y \\
\mu &= \frac{g_F Q}{R^2 r_h}, \quad \mathcal{H} = \frac{g_F H}{R^4}, \quad T \sim |f'(r_h)|/4\pi
\end{aligned}
$$

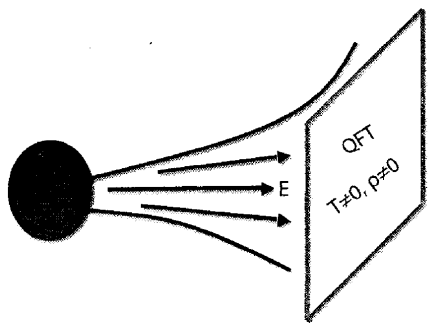


Figure: T. Faulkner et al, 2010

Quasinormal modes of black holes. Fermionic response

$$
\begin{aligned}
G_R(\omega, k) &= \frac{h_1}{k - k_F - \frac{\omega}{v_F} - \Sigma(\omega, k_F)} \\
\Sigma(\omega, k_F) &= hG^{IR}(\omega, k_F) = hc(k_F)\omega^{2\nu_{k_F}} \\
\omega_c(k) &= \omega_*(k) - i\Gamma(k)
\end{aligned}
$$

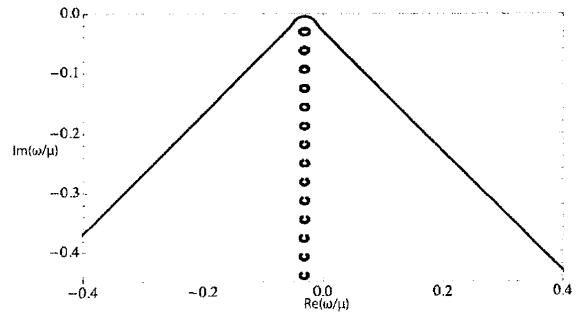


Figure: S. Hartnoll, 2009

Fermi momentum k_F

$$\frac{{}_2F_1(1+\nu_{k_F}+\frac{iq\mu}{6}),\frac{1}{2}+\nu_{k_F}-\frac{\sqrt{2}q\mu}{3},1+2\nu_{k_F},\frac{2}{3}(1-i\sqrt{2})}{{}_2F_1(\nu_{k_F}+\frac{iq\mu}{6},\frac{1}{2}+\nu_{k_F}-\frac{\sqrt{2}q\mu}{3},1+2\nu_{k_F},\frac{2}{3}(1-i\sqrt{2}))}=\frac{6\nu_{k_F}-iq\mu}{k_F(-2i+\sqrt{2})}$$

$$\nu_{k_F}=\frac{1}{6}\sqrt{6k_F^2-(q\mu)^2}$$

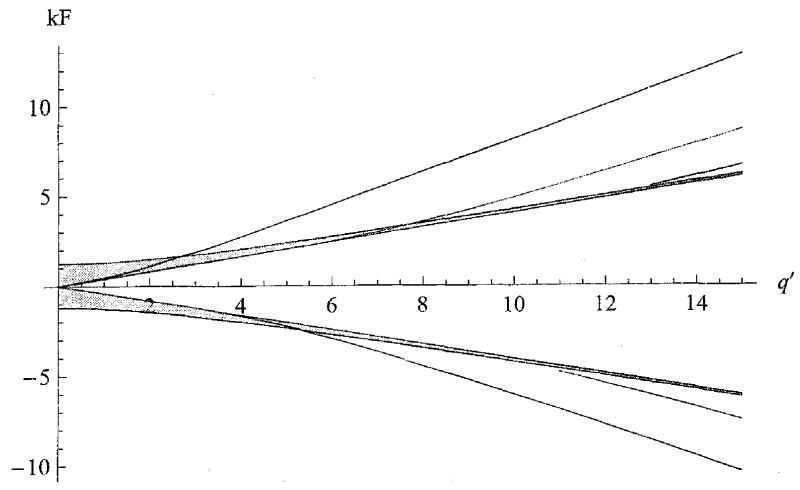


Figure: Fermi momentum k_F vs. charge of the fermion field $q'=\sqrt{3}q$. We set $r_*=1$, $g_F=1$, $\mu=\sqrt{3}$.

Fermi velocity

$$v_F = \frac{1}{h_1}\left(\int_0^1 dz\sqrt{g/g_{tt}}\psi^{0\dagger}\psi^0\right)^{-1} \lim_{z\to 1}\frac{|\tilde{y}_1^0 + i\tilde{y}_2^0|^2}{(1-z)^3}$$

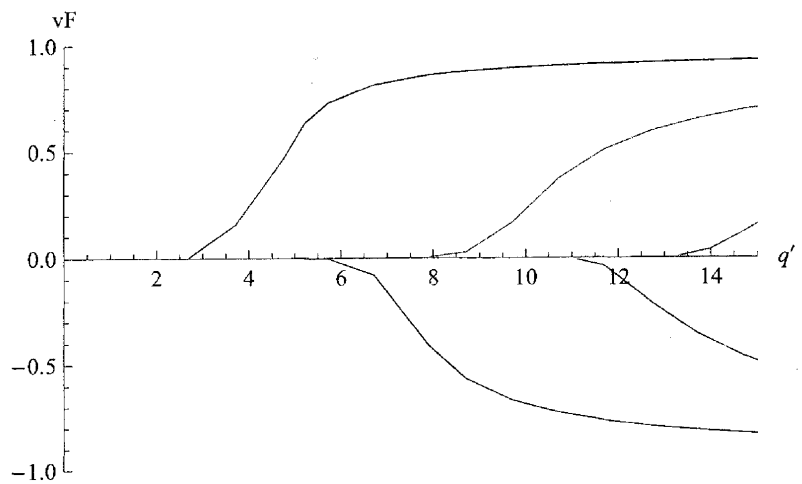


Figure: Constant v_F, reflecting the UV physics of the AdS_4 bulk, vs. charge $q' = \sqrt{3}q$. It vanishes at $\nu_{k_F} = \frac{1}{2}$. For the first Fermi surface it happens ($\nu_{k_F} = \frac{1}{2}$) at $q' = 2.71$

Critical temperature T_c

$$T_c = \frac{G_{int}|q\mathcal{H}|h_1^2 v_F^2}{\pi^2} \int dz \sqrt{-g} (\psi^0(z)^\dagger \sigma^1 \psi^0(z))^2$$

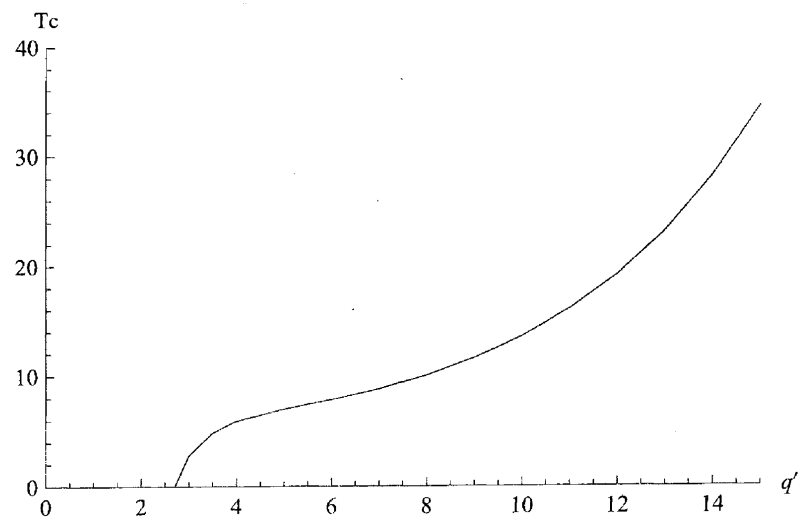


Figure: Critical temperature T_c vs. the charge $q' = \sqrt{3}q$ for the first Fermi surface.

Parity breaking in dense nucler matter

Domènec Espriu

Universitat de Barcelona and CERN

We argue that parity violation in QCD can take place spontaneously under extreme conditions due to condensation of neutral pseudoscalar matter. Its detection by heavy-ion (HI) experiments may be feasible. It would lead to rather remarkable experimental signals such as the same in-medium resonance being able to decay into even and odd number of pions, the occurrence of additional (light and massless) Goldstone bosons (six right at the phase transition, and five throughout the broken parity phase).
It may provide an alternative method of generating a CME and may be key to understand some results concerning dilepton excess in HI experiments.

UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

P and CP-odd effects in hot and dense matter - BNL April 2010

Spontaneous parity breaking in dense nuclear matter

A.Andrianov[1], V.Andrianov[1] and D. Espriu[2]
[1]*University of Sant Petersburg*
[2]*University of Barcelona and CERN*

arXiv: 0709.0049 [hep-ph]
arXiv:0710.0362 [hep-ph]
Phys.Lett.B663:450,2008.
arXiv: 0904.0413 [hep-ph]
Phys.Lett.B678:416, 2009.

We conjecture it to occur at low temperature but large baryon number density due to condensation of parity-odd mesons (pions, kaons,... and their radial excitations)

$$\rho_B \sim (3-10)\,\rho_N \qquad \rho_N \sim 0.17\ \mathrm{fm}^{-3} = (0.18\ \mathrm{fm})^{-3}$$

<u>Beyond the range of validity</u> of pion-nucleon effective Lagrangian but <u>not large enough</u> for quark percolation, *i.e.* in the hadronic phase with heavy meson excitations playing an essential role

Extended linear sigma model

with two multiplets of scalar and pseudoscalar mesons (as close to QCD as possible)

$$H_j = \sigma_j \mathbf{I} + i\hat{\pi}_j, \quad j = 1,2; \quad H_j H_j^\dagger = (\sigma_j^2 + (\pi_j^a)^2)\mathbf{I}, \qquad \hat{\pi}_j \equiv \pi_j^a \tau^a$$

Chiral limit $\longrightarrow$ $SU_L(2) \times SU_R(2)$ **symmetry**

$$\begin{aligned} V_{\text{eff}} = \frac{1}{2}\text{tr}\Big\{ & -\sum_{j,k=1}^{2} H_j^\dagger \Delta_{jk} H_k \\ & + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 \\ & + \frac{1}{2}\lambda_4 (H_1^\dagger H_2 H_1^\dagger H_2 + H_2^\dagger H_1 H_2^\dagger H_1) + \frac{1}{2}\lambda_5 (H_1^\dagger H_2 + H_2^\dagger H_1) H_1^\dagger H_1 \\ & + \frac{1}{2}\lambda_6 (H_1^\dagger H_2 + H_2^\dagger H_1) H_2^\dagger H_2 \Big\} + \mathcal{O}(\frac{|H|^6}{\Lambda^2}), \end{aligned}$$

9 real constants

$\Delta_{jk} \sim \lambda_A \sim N_c$

Chiral expansion in $1/\Lambda$ **in hadron phase of QCD**

$$\Lambda \simeq 4\pi F_\pi \sim 4 M_{dyn}$$

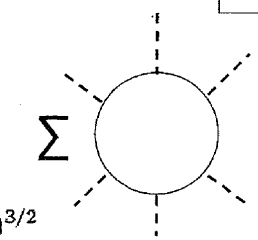
Embedding a chemical potential $\int dx\, \mu \left(\bar{q}\gamma_0 q(x) - \rho_B \right)$

Local coupling to quarks $\mathcal{L}_{int} = -(\bar{q}_R H_1 q_L + \bar{q}_L H_1^\dagger q_R)$

Superposition of physical meson states
(quark matter=nuclear matter)

$$\Delta V_{\text{eff}}(\mu) = \frac{\mathcal{N}}{2}\Theta(\mu - |H_1|)\left[\mu|H_1|^2\sqrt{\mu^2 - |H_1|^2} - \frac{2\mu}{3}(\mu^2 - |H_1|^2)^{3/2} - |H_1|^4 \ln\frac{\mu + \sqrt{\mu^2 - |H_1|^2}}{|H_1|}\right]\left(1 + O\left(\frac{\mu^2}{\Lambda^2}\right)\right)$$

$$\mathcal{N} \equiv \frac{N_c N_f}{4\pi^2}$$



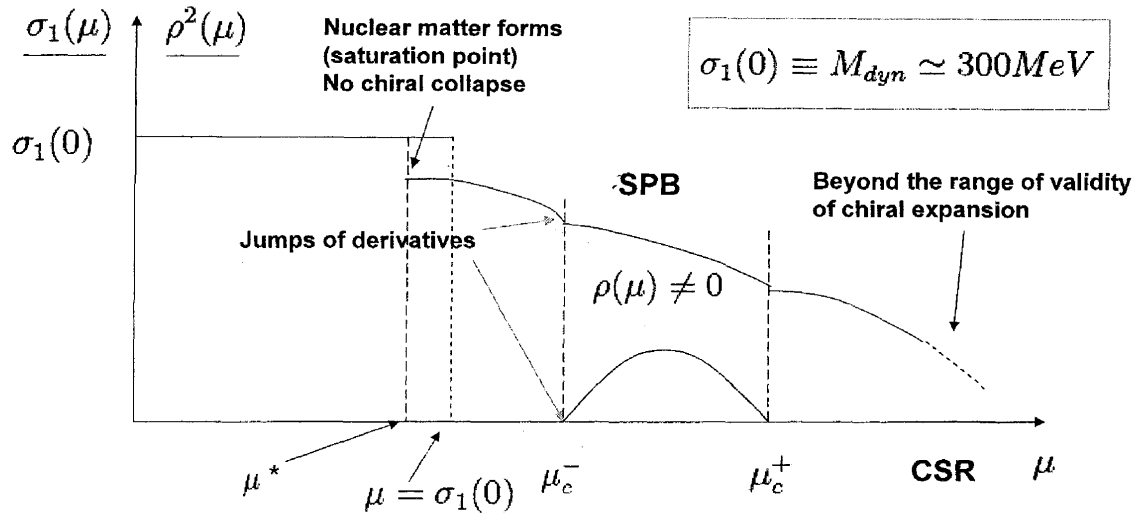
Density and Fermi momentum

$$\varrho_B = -\frac{1}{3}\partial_\mu \Delta V_{\text{eff}}(\mu) = \frac{N_c N_f}{9\pi^2} p_F^3 = \frac{N_c N_f}{9\pi^2}(\mu^2 - |\langle H_1 \rangle|^2)^{3/2}$$

The calculation can be easily extended to finite T
no thermal loops for mesons
(OK in large N-limit)

$$\Delta V_{\text{eff}}(\mu) \longrightarrow \Delta V_{\text{eff}}(T, \mu)$$

Spontaneous P-parity breaking (2nd order phase transition)



$$\sigma_1(0) \equiv M_{dyn} \simeq 300 MeV$$

With increasing μ one enters SPB phase and leaves it before (?) encountering any new phase (CSR, CFL ...)

Order of the phase transition?

P-breaking phase

Mixing with massless pions is different for neutral and charged ones because vector isospin symmetry is broken

$$\tilde{\pi}^{\pm} = \pi^{\pm} + \zeta \Pi^{\pm}, \qquad \tilde{\pi}^{0} = \pi^{0} + \frac{F_0^2}{F_0^2 + A_{22}\rho^2}\Big(\zeta \Pi^0 - \frac{\rho}{F_0}\sum_{j=1}^{2} A_{j2}\partial_\mu \Sigma_j\Big).$$

Partially diagonalized kinetic term

$$\begin{aligned}\mathcal{L}^{(2)}_{kin} = {} & \partial_\mu \tilde{\pi}^{\pm}\partial^\mu \tilde{\pi}^{\mp} + (A_{22} - \zeta^2)\partial_\mu \Pi^{\pm}\partial^\mu \Pi^{\mp} + \frac{1}{2}\Big(1 + \frac{A_{22}\rho^2}{F_0^2}\Big)\partial_\mu \tilde{\pi}^0 \partial^\mu \tilde{\pi}^0 \\ & + \frac{1}{2}\Big(A_{22} - \frac{F_0^2}{F_0^2 + A_{22}\rho^2}\zeta^2\Big)\partial_\mu \Pi^0 \partial^\mu \Pi^0 + \frac{1}{2}\sum_{j,k=1}^{2} \frac{A_{jk}F_0^2 + \rho^2 \det A \delta_{1j}\delta_{1k}}{F_0^2 + A_{22}\rho^2}\partial_\mu \Sigma_j \partial^\mu \Sigma_k \\ & - \frac{F_0 \rho}{F_0^2 + A_{22}\rho^2}\zeta \partial_\mu \Pi^0 \sum_{j=1}^{2} A_{j2}\partial^\mu \Sigma_j\end{aligned}$$

Isospin breaking $\quad SU_V(2) \to U(1)$

Possible experimental/observational signatures of P-parity breaking

Resonances do not have a definite parity and the same heavy resonance can decay both in two and three pions . It will look like doubling of states.

At the very point of the phase transition leading to parity breaking one has six massless pion-like states. Throughout the P-breaking phase charged massless pions exist and their production is enhanced.

Substantial modifications in the equation of state (neutron stars)

PCAC relations for massless charged pions are modified giving enhancement of electroweak decays (more leptons)

Additional strong isospin breaking: $f_{\pi_0} \neq f_{\pi_\pm}$

However some of these signals may be quite subtle to interpret or to have a good theoretical control over them.

Ideally we would like a signal that involves `easy' particles such as photons, electrons or muons.

See A. Andrianov's talk.....

CP-ODD Workshop @ BNL , Apr, 2010

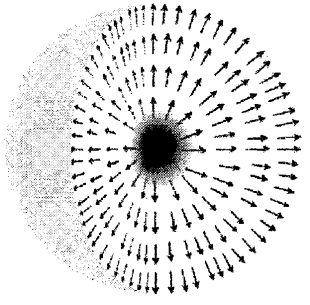
Probing the Topological Components of sQGP

Jinfeng Liao

Lawrence Berkeley National Laboratory

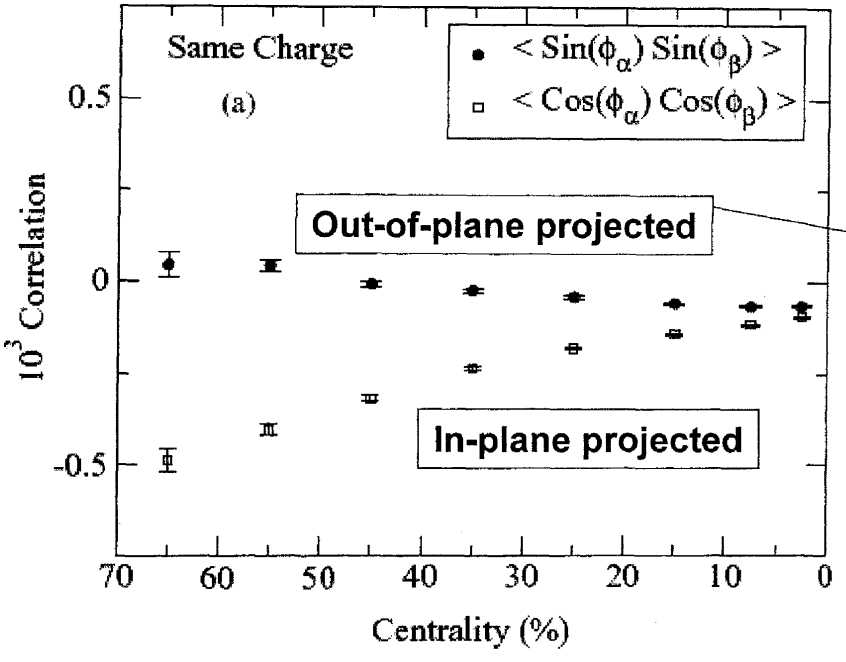
SUMMARY:

- The recent STAR measurements motivated by the Chiral Magnetic Effect show certain puzzling in-plane back-to-back "background" correlations.
- New measurements based on joint quadruple & electric dipole E-by-E determination are proposed, which will hopefully be less sensitive to background and able to distinguish CME related signal.
- Possible chrome- Electric-Magnetic See-Saw(Duality) in QCD is conjectured and various evidences discussed
- It is proposed that an effective theory for magnetic component near Tc and confinement shall be developed a la dimensional reduction with fixed nontrivial holonomy.



BERKELEY LAB

Same-Charge Projected Correlations



<sin*sin> ~ 0
A very strong constraint we have to live with !

In-plane-dominant, back-to-back

Bzdak, Koch, JL (09)
PRC81,031901(R),2010

Pinpoint the Dipole

In each event : N particles, (η_i, p_{ti}, ϕ_i, q_i)

Recall Q2 analysis for elliptic flow:
looking for the maximal quadruple

$$Q_2 \cos 2\Psi_2 \equiv \sum_i \cos 2\phi_i$$

$$Q_2 \sin 2\Psi_2 \equiv \sum_i \sin 2\phi_i$$

In analogy, Q^c_1 analysis:
looking for the maximal dipole

$$Q_1^c \cos \Psi_1^c \equiv \sum_i q_i \cos \phi_i$$

$$Q_1^c \sin \Psi_1^c \equiv \sum_i q_i \sin \phi_i$$

In each event ⇒ (Q_2, Ψ_2) & ($Q^c{}_1$, $\Psi^c{}_1$)

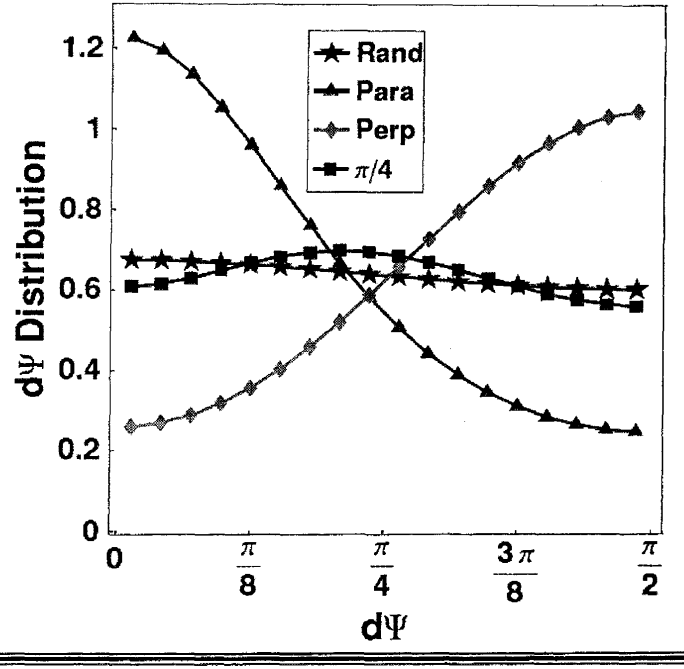
Relative orientation !

Discriminating the Angular Pattern

Azimuthal distribution: *JL, Koch, Bzdak (to appear)*

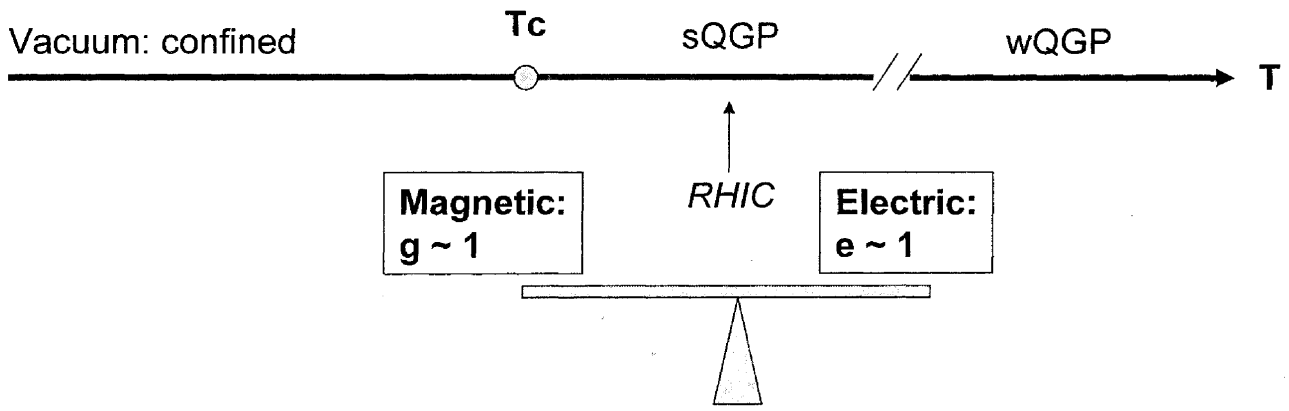
$$f_\chi(\phi, q) \propto 1 + 2\,v_2 \cos(2\phi - 2\Psi_{R.P.}) + 2\,q\,\chi\,d_1 \cos(\phi - \Psi_{C.S.})$$

Monte Carlo sampling of events according the above with different relative orientation:
(a) Random (b) parallel
(c) perpendicular (d) 45deg.
Then applying the
joint Q2 & Q^c_1 analysis !
[details: 200 +, 200 -, v2 =0.1 , d1=0.05]

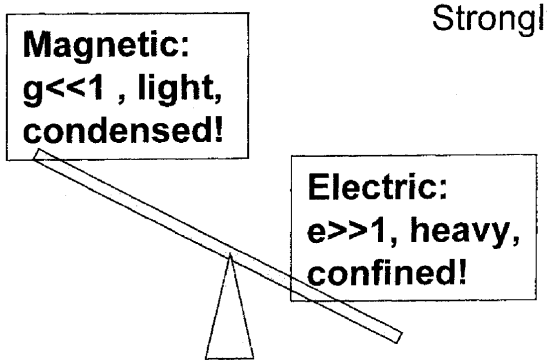


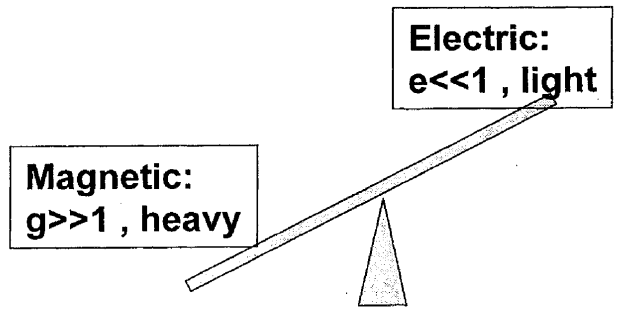
* Great discriminating power, may clarify the situation;
* Robust: surviving tests with built-in cluster type correlations.

QCD See-Saw ? !

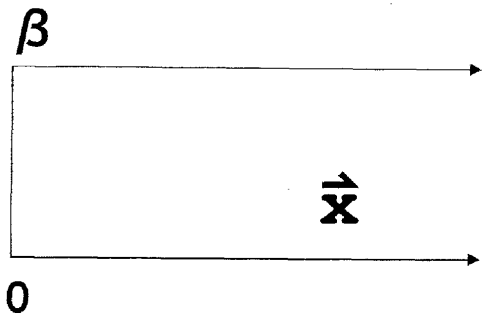


Strongly coupled plasma with **E & M** charges





How/what monopoles arise in QCD



$$L(\mathbf{x}) = \mathcal{P}\,\exp\left(i\int_0^{\frac{1}{T}} dt\, A_4(t,\mathbf{x})\right)$$

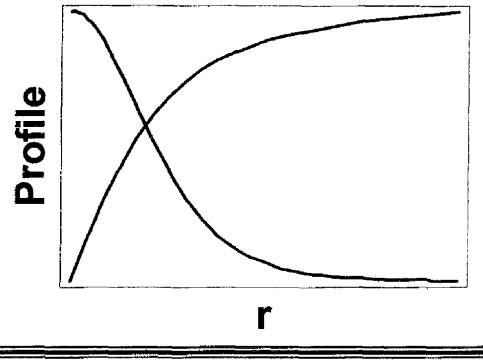
$$L = \mathrm{diag}\left(e^{2\pi i\mu_1}, e^{2\pi i\mu_2}, \ldots, e^{2\pi i\mu_N}\right)$$

Consider static configurations:

$$\mathbf{L}\ (\,|\,\vec{\mathbf{x}}\,|\ \longrightarrow\infty)$$

$$\mathbf{A_4}\ \mathbf{as\ adj-scalar}$$

$$\mathcal{L} \sim -\frac{1}{4}\,\mathbf{Tr F_{ij}\,F^{ij}} + \mathbf{Tr}\,[\mathbf{D_i\,A_0}]\,[\mathbf{D^i\,A_0}]$$



However:
BPS ; long range E charge, i.e. dyon

$\mathbf{V[A_0]}$ From dimensional reduction with fixed (nontrivial) holonomy;

Essential for an effective theory

The chiral magnetic effect from the lattice

Tom Blum with

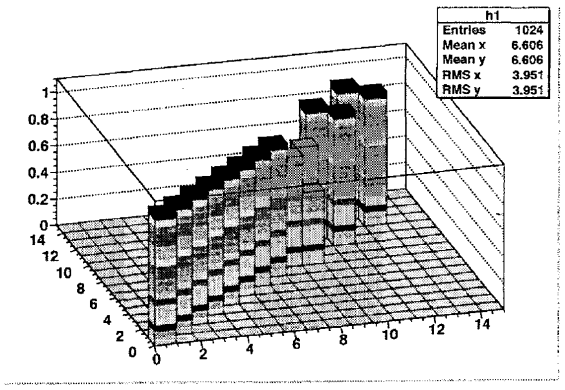
Michael Abramczyk, Gregory Petropoulos, and Tomomi Ishikawa
(University of Connecticut)

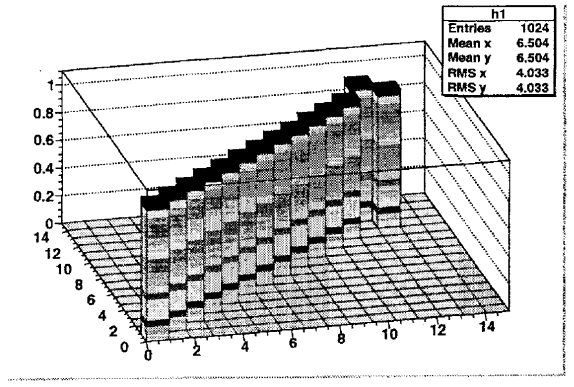
We investigate the chiral magnetic effect on the lattice, on a single continuum(-like) instanton configuration and on real 2+1 flavor QCD+QED configurations generated with domain wall fermions (DWF). In the presence of a strong magnetic field, we find electric charge separation associated with the would-be-zero modes corresponding to $\vec{B} = 0$. If the field is strong enough, the would-be zero-modes have chirality significantly less than one, signaling strong charge separation. Charge separation associated with would-be zero modes supported by instantons is observed in QCD when $eB_z \sim 1.5 - 2$ GeV^2. Paired near zero-modes which are presumably associated with instanton/anti-instanton pairs show charge separation for smaller values of $\vec{B}$. Investigations of the effects of T, $\vec{B}$, and quark mass are underway.

Classical instanton (-like solution)

Degeneracy of Landau levels goes like n_Φ:

$B_z = 0.19635$ $(n_\Phi = 2)$ $\qquad$ $B_z = 0.294524$ $(n_\Phi = 3)$

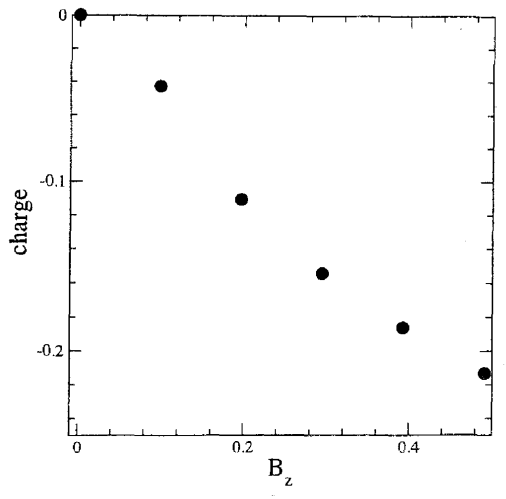




8 Zero modes (4 plane waves) $\qquad$ 12 Zero modes (6 plane waves)

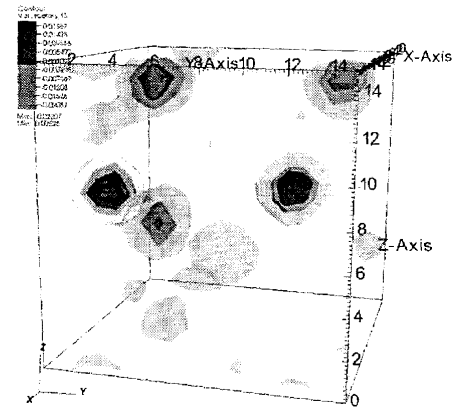
and so on...

Classical instanton (-like solution) Put it all together.
It works...

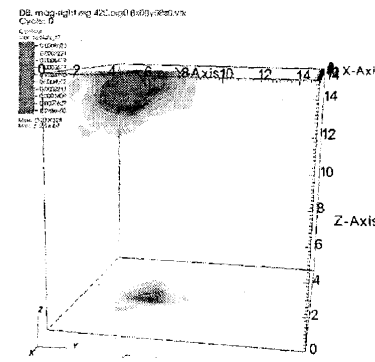


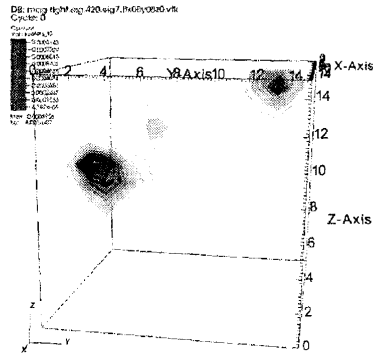
Charge in top (z-)half of lattice from near-zero-modes.
Dividing in x, y, or t gives zero, effect flips sign under $B_z \to -B_z$

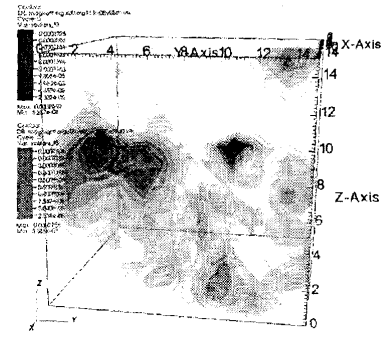
DB: top.vtk



Top. charge and low eigen-modes





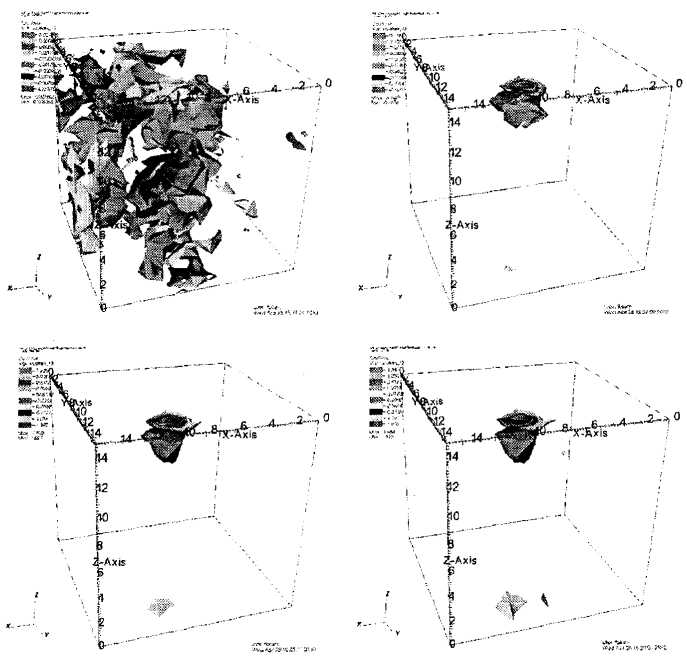


Low eigen-modes correlated with instantons

APE smeared, "5LI" definition of Q. $Q = 9 - 10$ (5li) for config. 420, or 10 from zero-modes (index)

2 "zero-modes", 1 "near-zero mode" shown

Charge density (from zero modes)

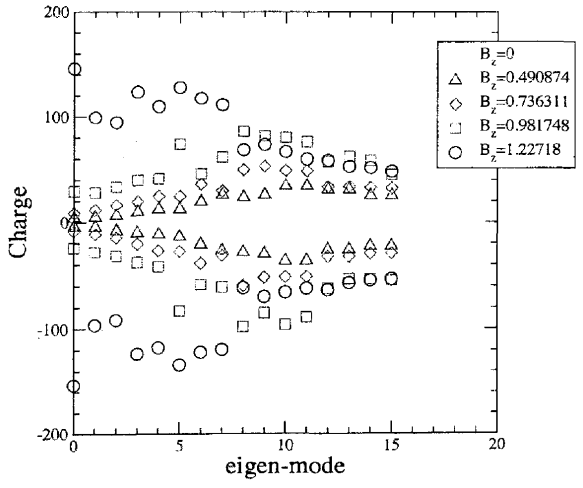


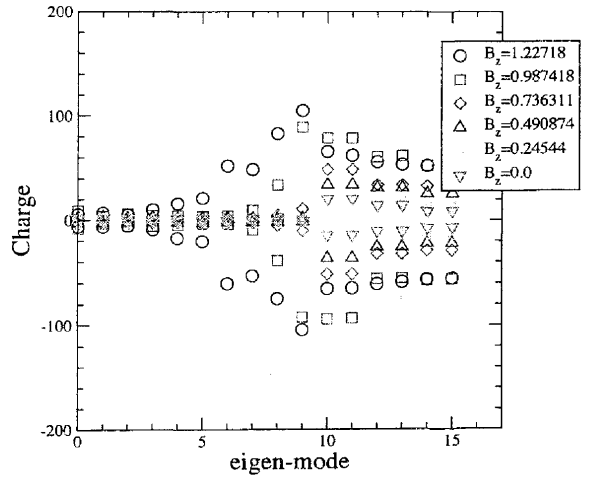
$B_z = 0.490874$, 0.736311

$B_z = 0.981748$, 1.22178

$|\rho\text{max}| = 0.002$, 0.167, 1.627, 1.825

Charge separation (from zero modes)





Charge separation for large B_z, $n_\Phi = 30$ to 50

Depends on L_s (lattice artifact χ SB – expensive)

P-odd correlation in quark fragmentation

Zhong-Bo Kang
RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

Quantum Chromodynamics (QCD) with quarks and gluons as fundamental constituents is firmly established as the dynamical theory of the strong interaction. As a non-abelian gauge theory, QCD contains gauge field configurations carrying a topological charge. These configurations could lead to local $\mathcal{P}$-odd domains in the space-time. When quark penetrates the non-trivial gauge field configurations, the way it fragments to the final-state hadron will change correspondingly. We study the quark fragmentation in such situations, and identify the $\mathcal{P}$-odd modes in the quark fragmentation functions.

Particularly we have found there could be two $\mathcal{P}$-odd fragmentation functions appear along with the usual $\mathcal{P}$-even fragmentation functions,

$$\begin{aligned}\Delta(z,p_\perp) &= \frac{1}{2z}\int\frac{dy^-d^2y_\perp}{(2\pi)^3}e^{ik^+y^--i\vec{k}_\perp\cdot\vec{y}_\perp}\langle 0|\psi(y)|PX\rangle\langle PX|\bar{\psi}(0)|0\rangle \\ &= \frac{1}{2}\left[D(z,p_\perp^2)\not{n}+H_1^\perp(z,p_\perp^2)\sigma^{\mu\nu}\frac{p_{\perp\mu}n_\nu}{M}\right]+\frac{1}{2}\left[\widetilde{D}(z,p_\perp^2)\not{n}\gamma^5+\widetilde{H}_1^\perp(z,p_\perp^2)\sigma^{\mu\nu}i\gamma^5\frac{p_{\perp\mu}n_\nu}{M}\right],\end{aligned}$$

where $D(z,p_\perp^2)$ is the unpolarized fragmentation function, $H_1^\perp(z,p_\perp^2)$ is the Collins fragmentation function, both of them are $\mathcal{P}$-even. On the other hand, $\widetilde{D}(z,p_\perp^2)$ and $\widetilde{H}_1^\perp(z,p_\perp^2)$ are the new $\mathcal{P}$-odd fragmentation functions.

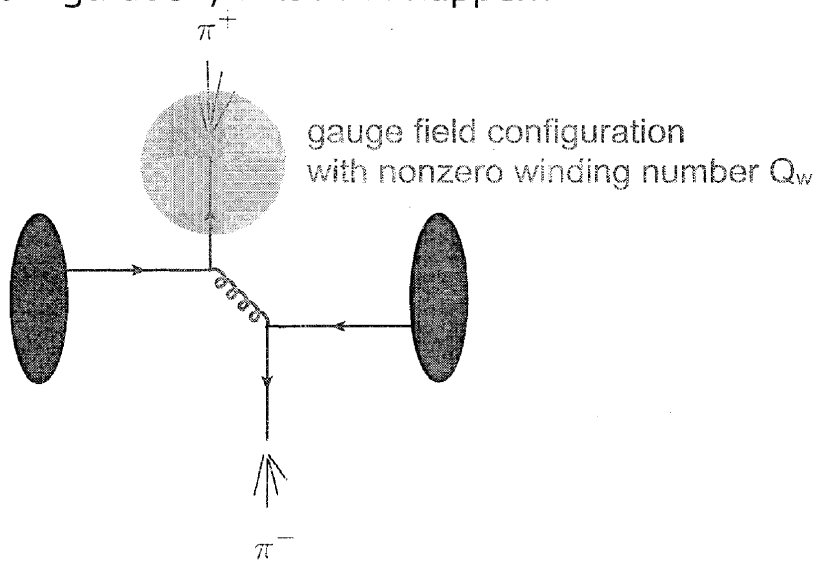
To estimate the relative size of these new $\mathcal{P}$-odd fragmentation functions, we use the effective chiral quark model established by Manohar and Georgi, which has been widely accepted as an effective theory of QCD at low energies. However, since the chiral quark model Lagarangian density conserves parity, it won't be able to generate nonvanishing results for $\mathcal{P}$-odd fragmentation functions $\widetilde{D}(z,p_\perp^2)$ and $\widetilde{H}_1^\perp(z,p_\perp^2)$ without modifications. The effect of non-trivial gauge field configuration could be mimicked by an effective θ angle, which could depend on space-time, $\frac{g^2}{32\pi^2}\theta(x,t)F_a^{\mu\nu}\tilde{F}_{\mu\nu}^a$. By performing an axial $U(1)$ rotation, this term could be transformed into the fermionic contribution:

$$\frac{1}{2N_f}\partial_\mu\theta\bar{\psi}_q\gamma^\mu\gamma^5\psi_q \equiv \bar{\theta}_\mu\bar{\psi}_q\gamma^\mu\gamma^5\psi_q \tag{1}$$

which leads to a change in the quark propagator. With the modification of quark propagation in the $\mathcal{P}$-odd bubble, we are able to generate the non-vanishing results for both the $\mathcal{P}$-odd fragmentation functions. We have derived the formalism to relate the size of these functions with the space-time fluctuation of $\theta(x)$ parameter within the chiral quark model. We further study the experimental effect of the $\mathcal{P}$-odd fragmentation functions in back-to-back dihadron production in e^+e^- collisions, and found that there is a new azimuthal correlation $\propto \sin(\phi_1+\phi_2)$ appears. Since the new azimuthal correlation is explicitly $\mathcal{P}$-odd, it could be observed only in an event-by-event basis. We encourage the relevant experiments to be carried out to constrain the $\mathcal{P}$-odd fragmentation function, which could also be used to study the charge separation observed in the heavy ion collisions.

Fragmentation inside P-odd bubble

- During the process while the outgoing parton penetrates non-trivial gauge field configuration, what will happen?

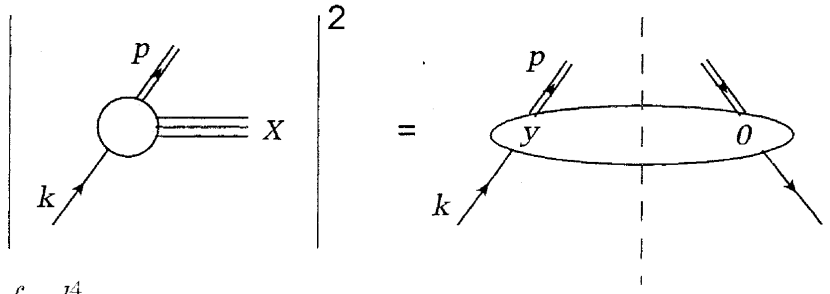


- P-odd modes in quark fragmentation could be populated

How is fragmentation function defined?

- Fragmentation function usually has a probability interpretation

$\Delta(p,k) =$



$$\Delta(p,k) \sim \int \frac{d^4y}{(2\pi)^4} e^{ik\cdot y} \langle 0|\psi(y)|PX\rangle\langle PX|\bar{\psi}(0)|0\rangle$$

- What are the usual parametrizations for fragmentation function?
  - Expand Δ(p, k) in spinor space
  - Impose certain constraints
  - Pick the leading projection or contribution

Fragmentation functions: parametrization (II)

- How constraints affect the parametrization

$$\Delta(p,k) = \left[MA_1 1 + A_2 \not{p} + A_3 \not{k} + A_4 \sigma^{\mu\nu}\frac{k_\mu p_\nu}{M}\right] + \left[A_5 \not{p}\gamma^5 + A_6 \not{k}\gamma^5 + MA_7 i\gamma^5 + A_8 \sigma^{\mu\nu} i\gamma^5 \frac{k_\mu p_\nu}{M}\right]$$

  - Hermiticity: all A_i are real

$$A_i^* = A_i$$

  - Parity: $A_5=A_6=A_7=A_8=0$

  - Time-reversal doesn't give any further constraint since it changes out-state to in-state

Quark fragmentation in P-odd bubble

- If the fragmentation happens or is initiated in the P-odd bubble, then P-odd modes (or P-odd fragmentation functions) could be populated
  - Without parity constraint, A_5, A_6, A_7, and A_8 do not vanish any more

$$\begin{aligned}\Delta(p,k) &= \left[MA_1 1 + A_2 \not{p} + A_3 \not{k} + A_4 \sigma^{\mu\nu}\frac{k_\mu p_\nu}{M}\right] \\ &+ \left[A_5 \not{p}\gamma^5 + A_6 \not{k}\gamma^5 + MA_7 i\gamma^5 + A_8 \sigma^{\mu\nu} i\gamma^5 \frac{k_\mu p_\nu}{M}\right]\end{aligned}$$

  - Twist-expansion again:

$$\begin{aligned}\Delta(z,p_\perp) &= \frac{1}{2}\left[D(z,p_\perp^2)\not{n} + H_1^\perp(z,p_\perp^2)\sigma^{\mu\nu}\frac{p_{\perp\mu}n_\nu}{M}\right] \\ &+ \frac{1}{2}\left[\widetilde{D}(z,p_\perp^2)\not{n}\gamma^5 + \widetilde{H}_1^\perp(z,p_\perp^2)\sigma^{\mu\nu} i\gamma^5 \frac{p_{\perp\mu}n_\nu}{M}\right]\end{aligned}$$

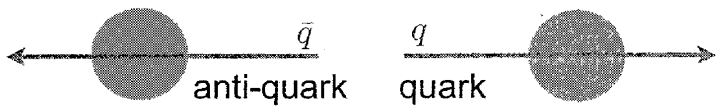
    - $D(z,p_\perp^2)$ and $H_1^\perp(z,p_\perp^2)$ are parity-even
    - $\widetilde{D}(z,p_\perp^2)$ and $\widetilde{H}_1^\perp(z,p_\perp^2)$ are parity-odd

The effect in $e^+e^- \to h_1 h_2 + X$ process

- The final azimuthal correlations

$$\frac{d\sigma}{dz_1 dz_2 d\cos\theta d(\phi_1+\phi_2)} = \sigma_0 \sum_q e_q^2 \Big\{ (1+\cos^2\theta)\left[D_q(z_1)D_{\bar{q}}(z_2) - \widetilde{D}_q(z_1)\widetilde{D}_{\bar{q}}(z_2)\right] + \sin^2\theta\cos(\phi_1+\phi_2)\left[H_q^\perp(z_1)H_{\bar{q}}^\perp(z_2) + \widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar{q}}^\perp(z_2)\right] + \sin^2\theta\sin(\phi_1+\phi_2)\left[H_q^\perp(z_1)\widetilde{H}_{\bar{q}}^\perp(z_2) - \widetilde{H}_q^\perp(z_1)H_{\bar{q}}^\perp(z_2)\right]\Big\}$$

- Physical pictures:
  - P-odd times P-odd terms:



$\widetilde{D}_q(z_1)\widetilde{D}_{\bar{q}}(z_2)$ OR $\widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar{q}}^\perp(z_2)$

  - P-odd term alone:

$H_q^\perp(z_1)\widetilde{H}_{\bar{q}}^\perp(z_2)$

$-\widetilde{H}_q^\perp(z_1)H_{\bar{q}}^\perp(z_2)$

Results on Charged Pion Correlations and Prospects for Detecting P-odd Effects

Anselm Vossen (University of Illinois)
Ralf Seidl (RBRC)
Matthias Grosse Perdekamp
(University of Illinois)
Martin Leitgab (University of Illinois)
Akio Ogawa (BNL/RBRC)

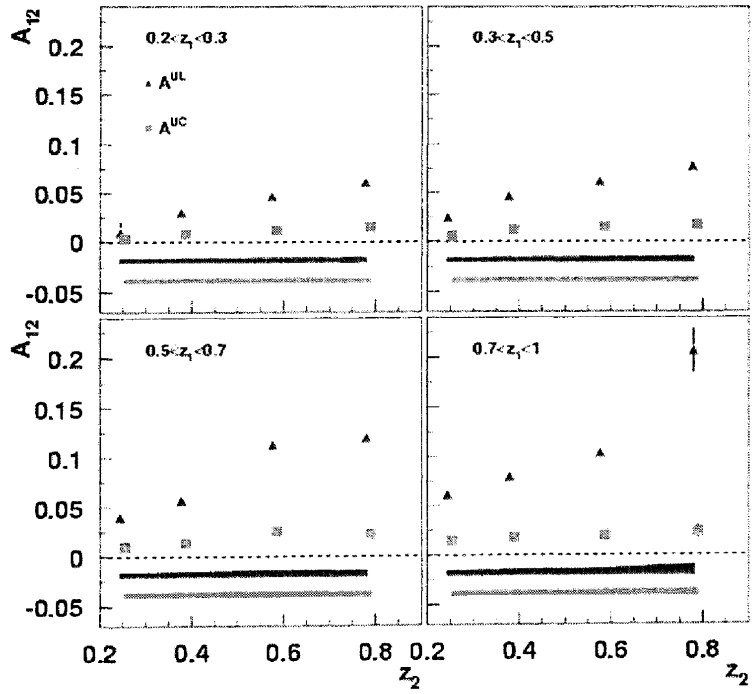
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

P- and CP-odd Effects in Hot and Dense Matter, BNL, 4/29/2010

Motivation

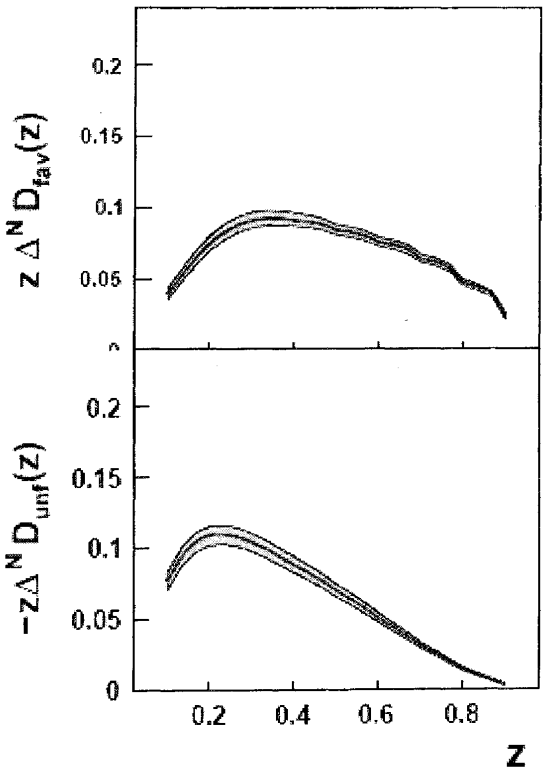
- Local Parity Violating Effects can lead to azimuthal Asymmetries in Quark Fragmentation (see Talk by Z. Kang)
- Can be measured in e^+e^- into light mesons
- At Belle we plan to extract local P-odd signals
- Similar Asymmetries for Single and Di-Hadrons have already been measured with high precision

Collins Fragmentation at Belle



Belle 547 fb^{-1} data set
(Phys.Rev.D78:032011,2008.)

Extraction of the Collins FF

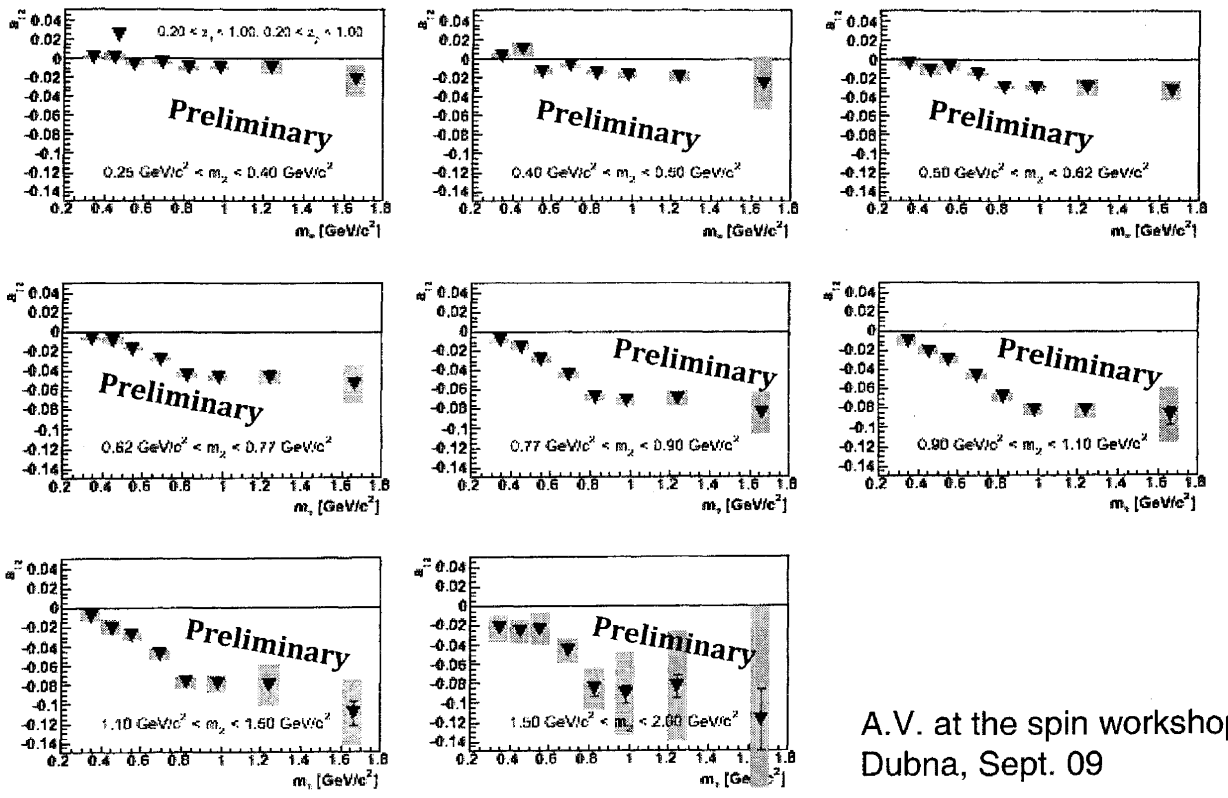


M. Anselmino, M. Boglione, (Turin U. & INFN, Turin) , U. D'Alesio, (Cagliari U. & INFN, Cagliari) , E. Leader, (Imperial Coll., London) , S. Melis, (INFN, Turin & Piemonte Orientale U., Alessandria) , F. Murgia, (INFN, Cagliari) , A. Prokudin, (Turin U. & INFN, Turin)

Talk given at 17th International Workshop on Deep-Inelastic Scattering and Related Subjects .
e-Print: **arXiv:0907.3999** [hep-ph]

Unfavored FF: different sign, similar magnitude

Belle: Asymmetries in $e^+ e^-$



8x8 m_1 m_2 binning

A.V. at the spin workshop in Dubna, Sept. 09

Summary

- The Belle Experiment is uniquely suited to measure Spin dependent Fragmentation Functions
- High Precision
- Experience with Extraction of CollinsFF and Interference FF Functions
- Extraction of parity violating Fragmentation Functions is work in progress

The Combined Influence of Instantons and Strong Magnetic Fields on Quark Matter

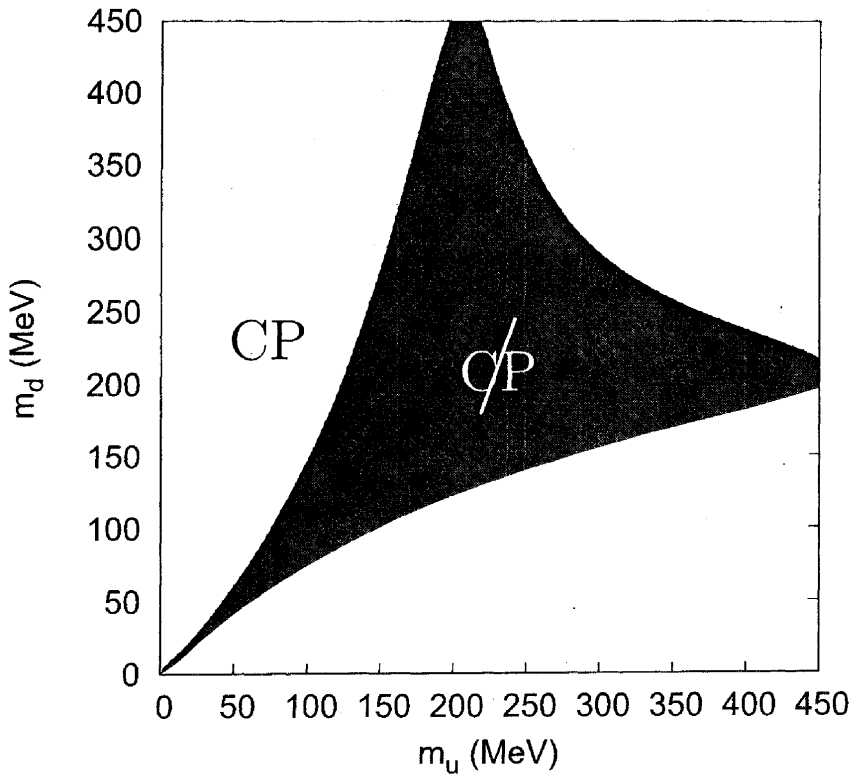
Jorn K. Boomsma
Vrije Universiteit Amsterdam

An interesting feature of the strong interaction is that topologically nontrivial field configurations known as instantons can have physical effects. An example is the phenomenon of spontaneous CP violation (SCPV) at $\theta = \pi$, which we discuss in this talk. Inspired by the Chiral Magnetic Effect we also discuss the combined effects of instantons and strong magnetic fields on quark matter. The investigations discussed in this talk are done using the Nambu–Jona-Lasinio (NJL) model. In this model the effects of instantons are included through the 't Hooft determinant interaction.

Firstly, we investigate SCPV at $\theta = \pi$. The occurrence of this spontaneous breaking depends, among others, on the strength of the determinant interaction. If this strength reaches a critical value, which depends on the values of the current quark masses, spontaneous breaking of CP invariance occurs. When the phase diagram is considered as a function of the up and down current quark mass at $\theta = \pi$ and a large enough value for the determinant interaction strength, a region in the diagram exists where CP invariance is spontaneously broken. In the NJL model both a lower and an upper boundary are found, in contrast to Tytgat (2000), who studied two-flavor chiral perturbation theory and only found a lower boundary. If the temperature is increased, the region becomes smaller and eventually disappears, which implies that SCPV is a low-energy phenomenon. Moreover, this disappearance may indicate that the suggestions for metastable states with an effective nonzero θ may not hold in QCD. It remains to be seen if these conclusions persist beyond the mean-field approximation and for the three-flavor case.

Secondly, we investigate the combined influence of instantons and strong magnetic fields on quark matter. This is of interest, as both in heavy-ion collisions and in magnetars very strong magnetic fields are generated. These fields influence the form of matter. In this talk we investigate the combined effect of instantons and strong magnetic fields on the dependence of the quark constituent masses on chemical potential. We study two regimes in the QCD phase diagram, high chemical potential and zero temperture and the other way around. This is relevant for respectively neutron stars and heavy ion collisions. At very high magnetic fields, around $B = 5m_\pi^2/e$ and zero temperature, the phase structure becomes rather complex due to Landau quantization, more phases appear and also metastable phases develop. In the case of high temperture, zero chemical potential, a remarkable difference is found with the linear sigma model coupled to quarks with respect to the order of the phase transition.

The (m_u, m_d)-phase-diagram for $\theta = \pi$ at $c = .4$, $T = 120$

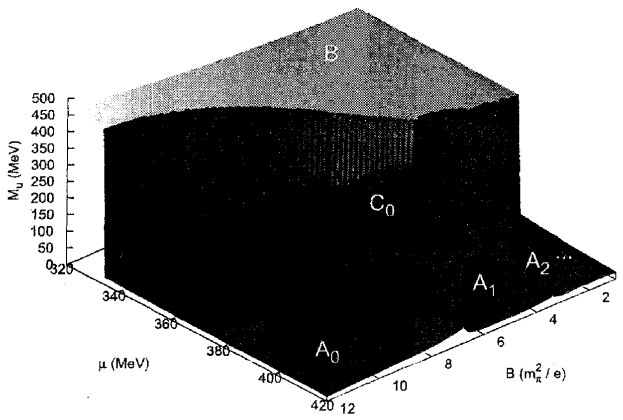


The CP-violating region becomes smaller with increasing temperature

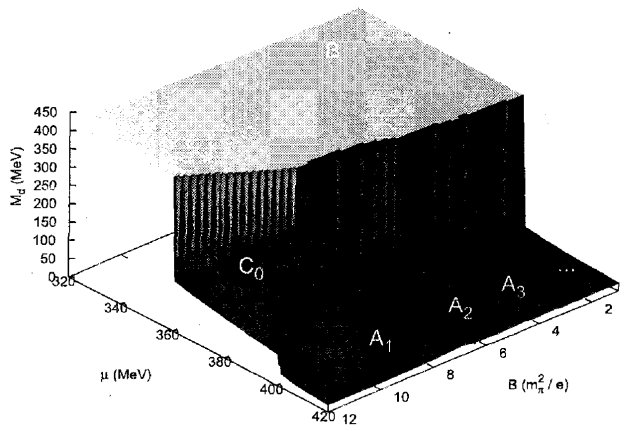
SCPV is a low-energy phenomenon

Nonzero chemical potential at $G_2 = 0$

Up quark



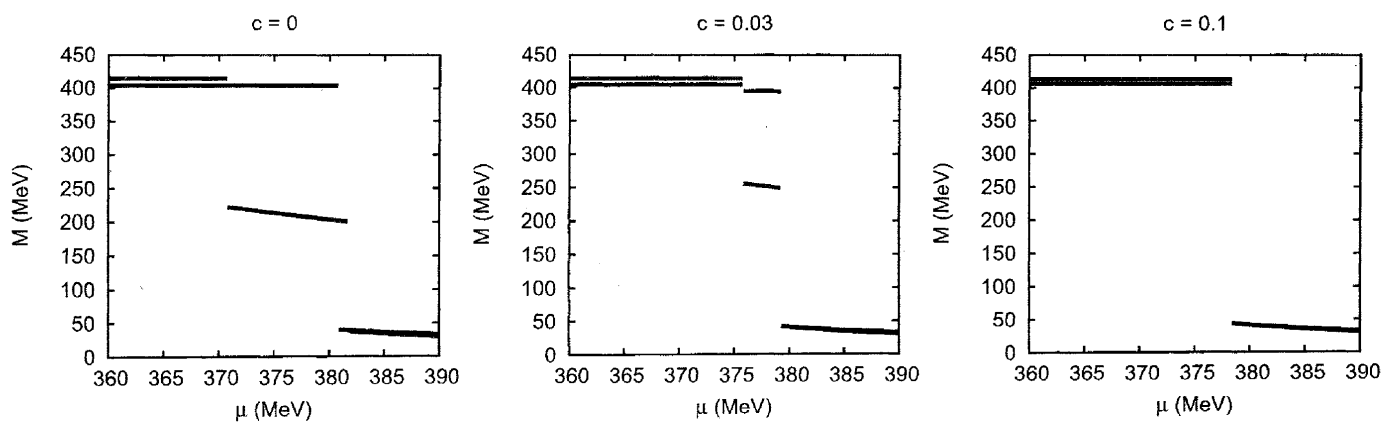
Down quark



- Similar phase structure found by Ebert et al. 2000; Ebert and Klimenko (2003) with $G_2 = G_1$
- Discontinuous de Haas-van Alphen effect
- A region exists with a considerable mass difference $\longrightarrow$ large spontaneous breaking of isospin ($\langle\bar{\psi}\tau_3\psi\rangle \neq 0$)

Effect of the instanton interaction II

$$B = 5m_\pi^2/e$$

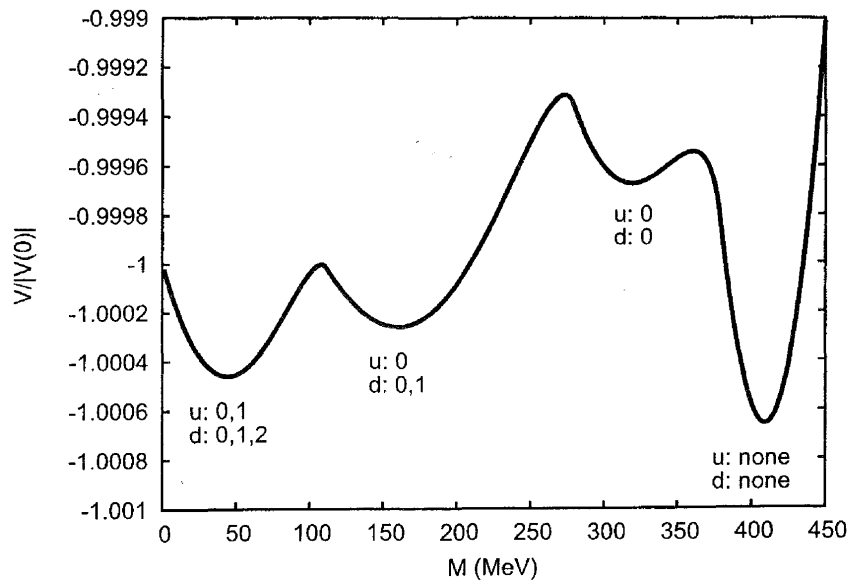


- C_0 phase disappears with increasing c $(= G_2/(G_1 + G2))$
- Regions with large mass differences disappear
- Behavior similar to Frank, Buballa & Oertel (2003) $(\mu_I \neq 0, B = 0)$

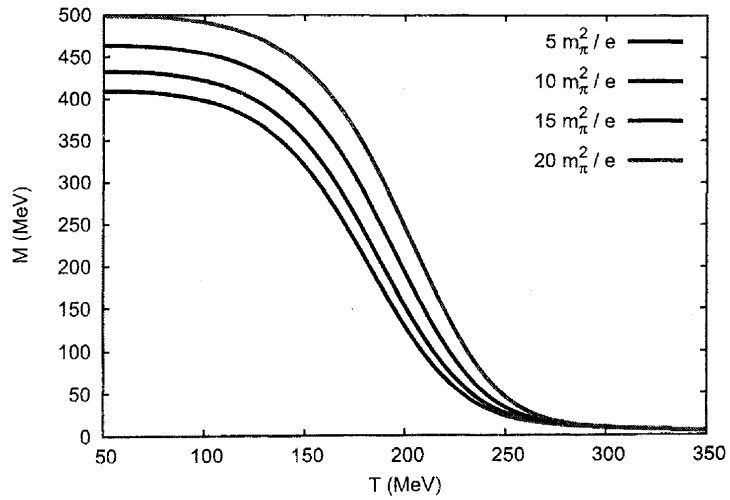
Nearly degenerate metastable states

Normalized effective potential as function of $M = M_u = M_d$ at

$B = 5m_\pi^2/e$, $c = 1/2$ $(G_1 = G_2)$, $\mu = 378\,\mathrm{MeV}$



T-dependence of masses at $c = 1/2$



- High T χ symmetry restoring transition remains crossover ($m_q \neq 0$) at nonzero B
- First order transition in linear sigma model coupled to quarks Stronger at larger B

  Mizher & Fraga (2009)

CP Violation and the Nature of the Chiral Transition

Ana Julia Mizher
Univ Federal do Rio de Janeiro

Motivated by the phenomenological scenario of the chiral magnetic effect that can be possibly found in high-energy heavy ion collisions, we study the role of very intense magnetic fields and strong CP violation in the phase structure of strong interactions and, more specifically, their influence on the nature of the chiral transition. We find that the CP violation is intrinsically related to an eta condensate and that high temperature restores this symmetry. Since the critical temperature for the CP transition is different from the critical temperature for the chiral transition, three phases occur. The presence of a strong magnetic background turns the chiral transition from a crossover to first-order. It also enhances the CP broken phase. Such influence on the nature of the phase transition can reflect itself on the relevant time scales for dynamical process. This result is also relevant in the case of the early universe.

Including CP violation (AJM and E.S.Fraga (2009))

We calculate the LSM potential for a $SU(2_f) \times SU(2_f)$ field

$$\phi = \frac{1}{\sqrt{2}}(\sigma + i\eta) + \frac{1}{\sqrt{2}}(\vec{\alpha} + i\vec{\pi}) \cdot \vec{\tau}$$

With:

$$\langle \sigma \rangle = \langle \bar{\psi} \lambda_0 \psi \rangle \qquad \langle \eta \rangle = \langle \bar{\psi} \lambda_0 i \gamma_5 \psi \rangle$$

$$\langle a_0 \rangle = \langle \bar{\psi} \lambda \psi \rangle \qquad \langle \pi \rangle = \langle \bar{\psi} \lambda i \gamma_5 \psi \rangle$$

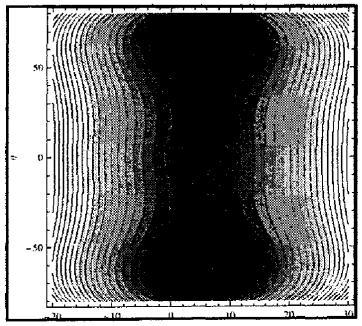
Mean field approx. where σ and η are classical fields plus fluctuations

$$V_{cl} = \frac{\lambda}{4}(\langle\sigma\rangle^2 - v_\theta^2)^2 - H\langle\sigma\rangle + \frac{\lambda}{4}(\langle\eta\rangle^2 - u_\theta^2)^2 - c sen(\theta)\langle\sigma\rangle\langle\eta\rangle + \frac{\lambda}{2}\langle\sigma\rangle^2\langle\eta\rangle^2 - \frac{\lambda}{4}(v_\theta^4 + u_\theta^4)$$

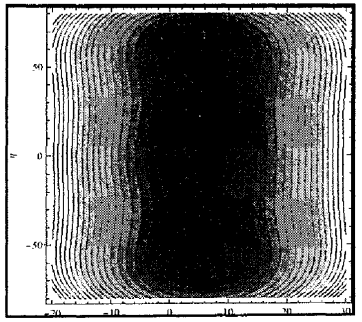
$$v_\theta^2 \equiv \frac{a + c\ \cos\theta}{\lambda} \quad ; \quad u_\theta^2 \equiv v_\theta^2 - \frac{2c}{\lambda}\cos\theta$$

$T > 0$, $\theta=\pi$:

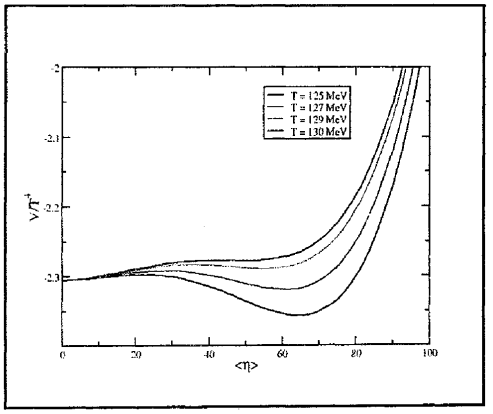
For $\theta=\pi$ the minima are almost in the η direction. As the temperature raises a new minimum appears at $\eta=0$, separated by a barrier, signaling a first-order transition. The critical temperatures for melting the two condensates are different, so that three phases are allowed.



T=125 MeV



T=128 MeV



V *vs.* η for several temperatures around the transition.

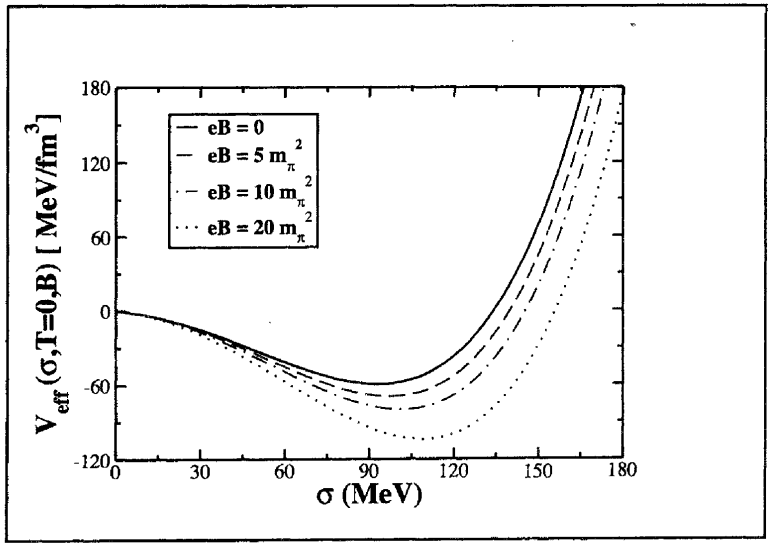
Incorporating a strong magnetic field background

AJM and E.S. Fraga (2008)

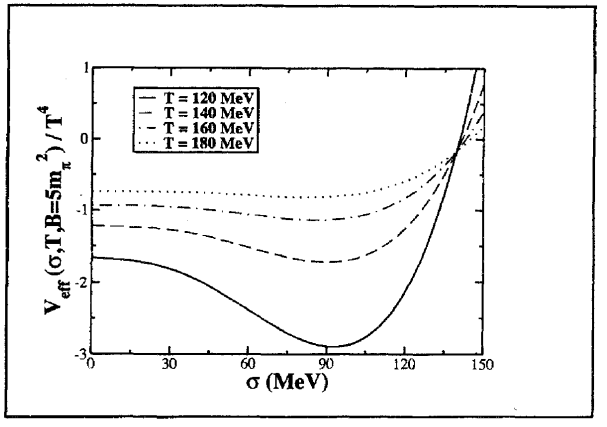
New dispersion relations

Scalar field → $p_{0n}^2 = p_z^2 + m^2 + (2n+1)|q|B$

Spinorial field → $p_{0n}^2 = p_z^2 + m^2 + (2n+1-\sigma)|q|B$



- Condensate grows with increasing magnetic field
- Minimum deepens with increasing magnetic field
- Relevant effects for equilibrium thermodynamics and nonequilibrium process of phase conversion ?

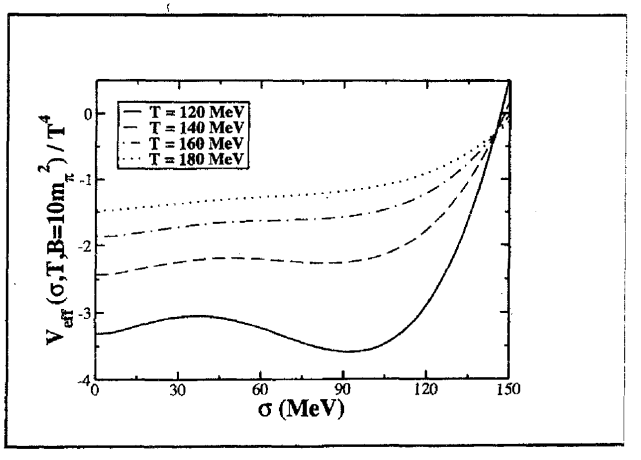


eB = 5 m_π^2:

- Higher critical temperature: T_c > 200 MeV
- A small barrier appears indicating a weak first order transition

- Critical temperature goes down again due to the larger hot fermionic contribution (T_c < 140 MeV)
- Larger barrier: clear 1st order chiral transition!
- Non-trivial balance between T and B

•Work on NJL model indicates a different phase transition (Boomsma & Boer (2009))



eB = 10 m_π^2:

Conclusions and perspectives

- The proposal for observation of CP violation in heavy ion collisions requires a strong magnetic field to make the effect observable.
- In this work we model the effects of the magnetic field, and see that its presence in our model changes the order of the phase transition, and consequently, the dynamics of the system.
- We include the possibility of CP violation, depending on the value of the coefficient.
- We saw that CP violation is related to an η condensate. The critical temperature to the η parameter is different to the one for the σ, yielding three different phases.
- The effect of the magnetic field in our model is to drive both transitions at first order, with the height of the barrier depending on the magnitude of the field.

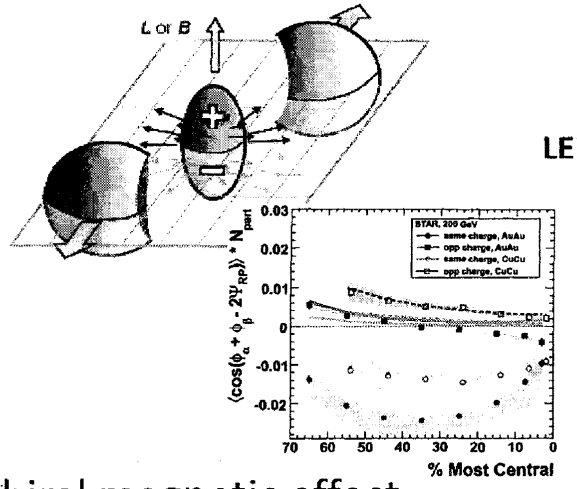
Measurements of Charge Asymmetry Correlations in High Energy Nuclear Collisions

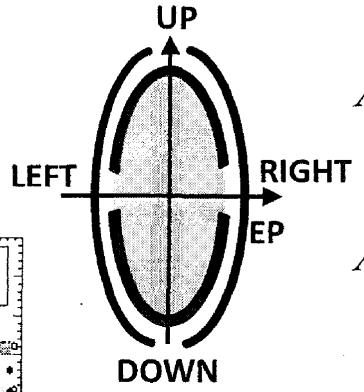
Quan Wang, Fuqiang Wang, Purdue University

For the STAR Collaboration

- Motivation: Local Parity Violation (LPV)
- Charge asymmetry observables
- Analysis details
- Results
- Summary

Motivation and Observables





$$A_{\pm,UD} = \frac{N_{\pm,up} - N_{\pm,down}}{N_{\pm,up} + N_{\pm,down}}$$

$$A_{\pm,LR} = \frac{N_{\pm,left} - N_{\pm,right}}{N_{\pm,left} + N_{\pm,right}}$$

Chiral magnetic effect:

- LPV + large magnetic field

→**charge separation** along the system angular momentum.

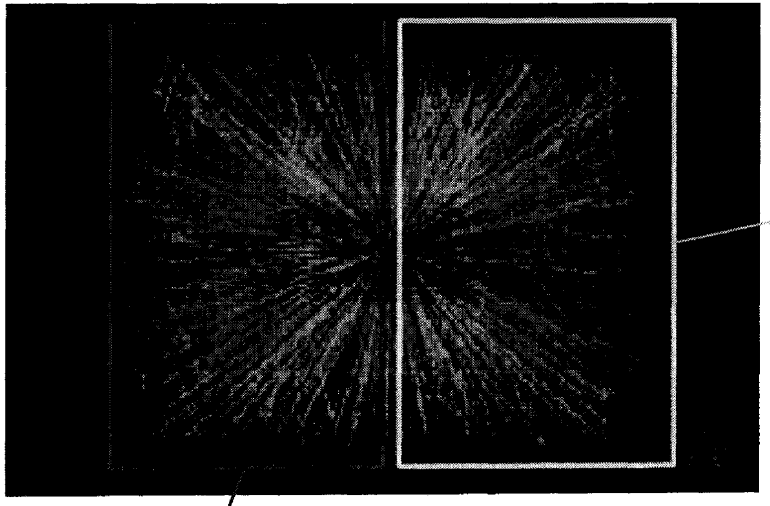
Kharzeev et al. NPA 803 (2008) 227

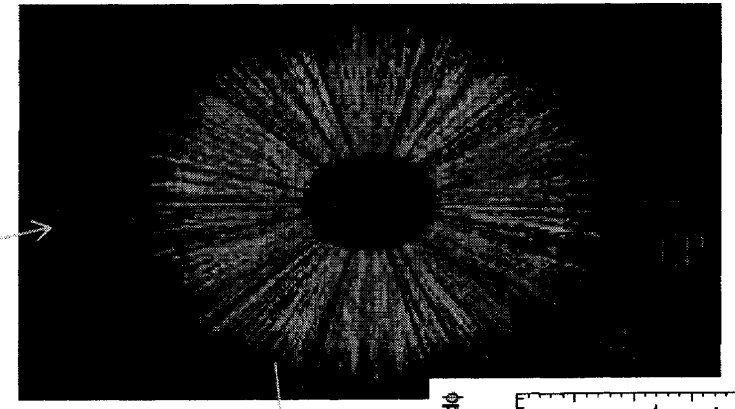
LPV effects in UD. LR is null-reference.

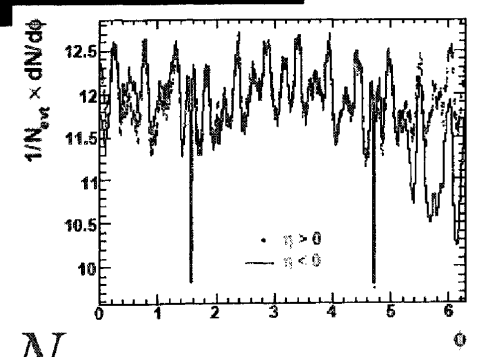
LPV expectations:

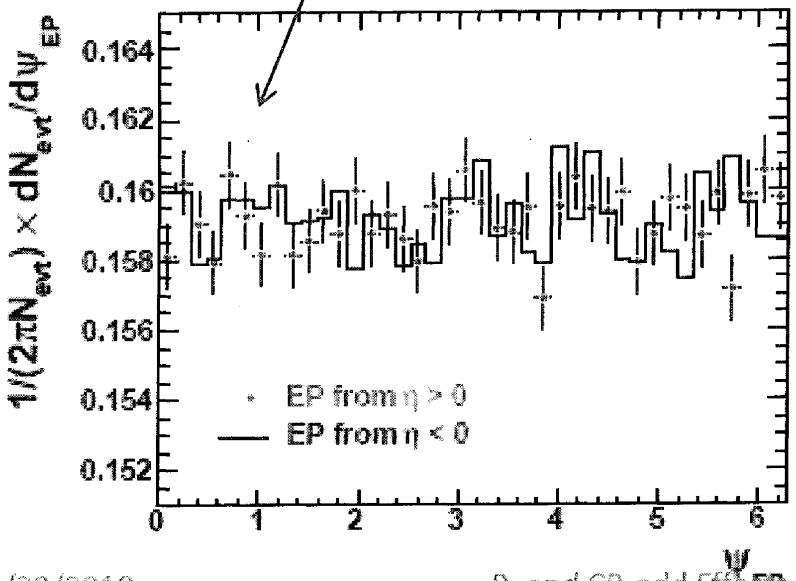
- $\mathbf{A_{+UD}}$ and $\mathbf{A_{-UD}}$ are anti-correlated
  → $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$
- Additional dynamical fluctuation broadens $A_{\pm UD}$ distributions
  → $\langle A_\pm^2\rangle_{UD} > \langle A_\pm^2\rangle_{LR}$

Analysis: to avoid self-correlation





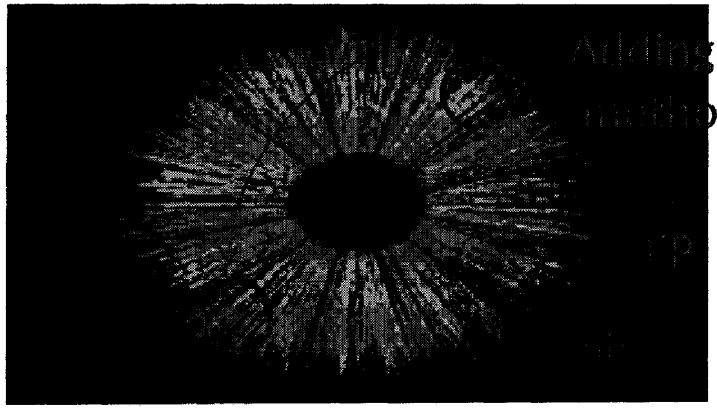




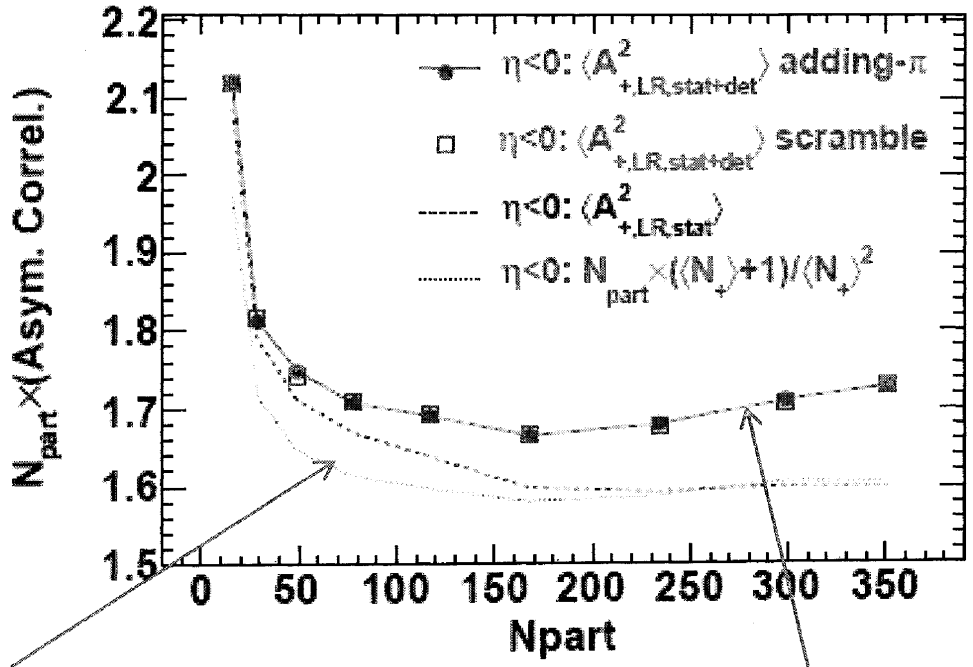
$$A_{\pm,UD} = \frac{N_{\pm,up} - N_{\pm,down}}{N_{\pm,up} + N_{\pm,down}}$$

$$A_{\pm,LR} = \frac{N_{\pm,left} - N_{\pm,right}}{N_{\pm,left} + N_{\pm,right}}$$

Stat. fluc. + detector effects in ‹A²›



STAR preliminary

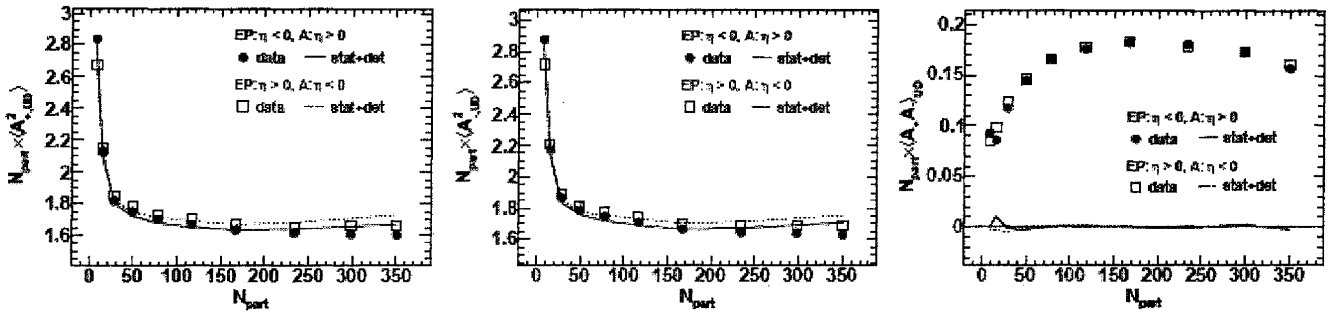


$$\frac{1}{\langle N\rangle}+\frac{1}{\langle N\rangle^2}$$

Stat. fluct. + Detector effects

Subtracting stat+det effects

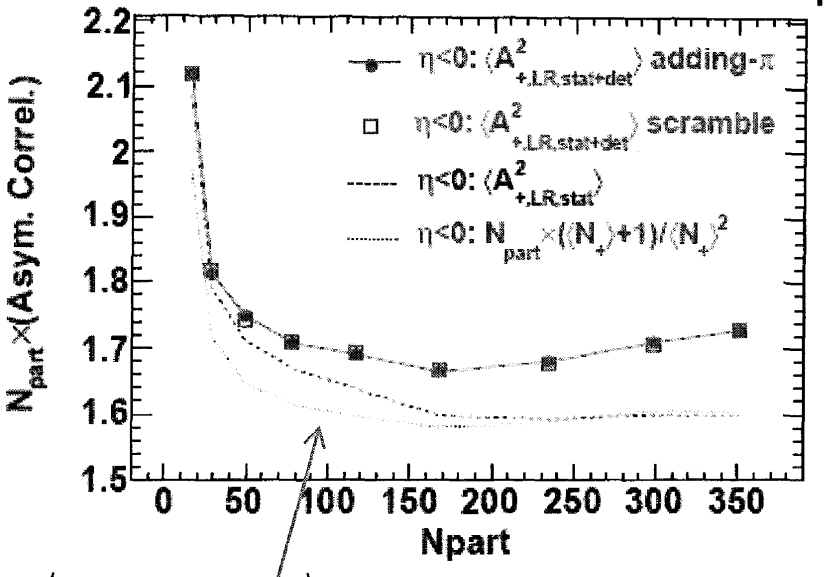
STAR preliminary

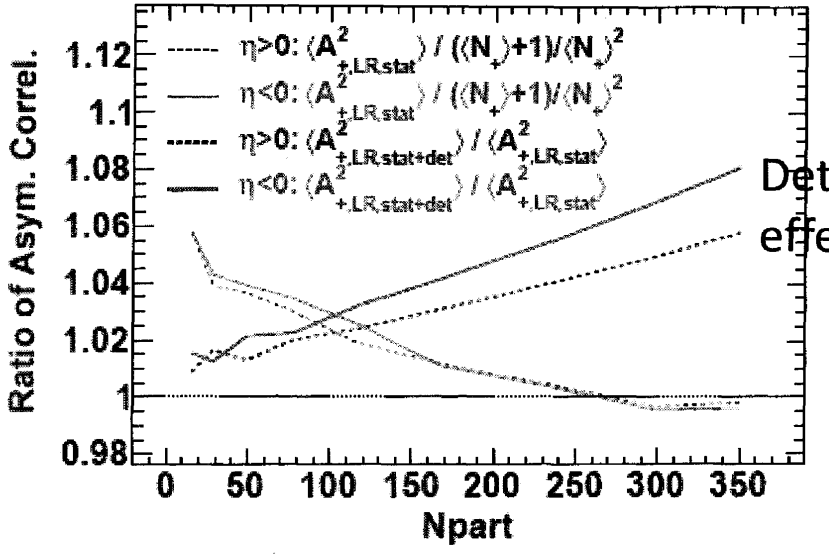


- Symbols are data (TPC left/right, positive/negative charges).
- Curves: net effect of statistical fluct. and detector non-uniformity.
- Stat+det effects are actually wider than data in $\langle A_{\pm}^2 \rangle$.
- Physical processes narrow charge asymmetry distributions → same-sign back-to-back pairs.

Stat. fluc. + detector effects in ‹A²›

STAR preliminary



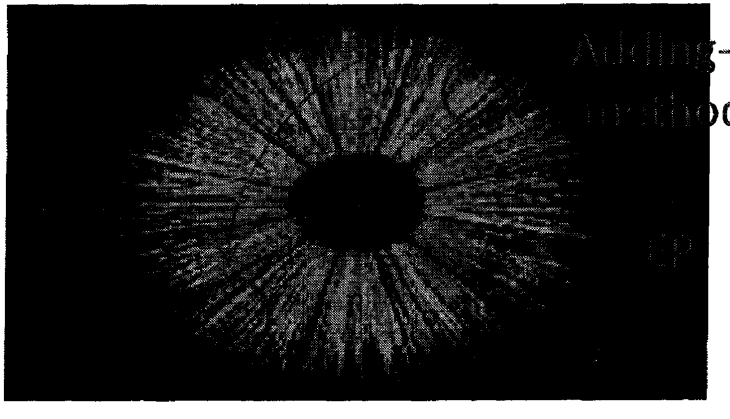


Detector effects

$$\langle A^2\rangle = \left\langle \left(\frac{N_{up}-N_{down}}{N_{up}+N_{down}} \right)^2 \right\rangle$$

$$= \frac{1}{\langle N\rangle^2} \left\langle \left(\frac{\delta N_{up}-\delta N_{down}}{1+(\delta N_{up}+\delta N_{down})/\langle N\rangle} \right)^2 \right\rangle$$

$$\approx \frac{\langle N\rangle+1}{\langle N\rangle^2}$$



Adding-π method

The Topological Glasma

Larry McLerran
RIKEN-BNL Center and Physics Department, Brookhaven National Lab.,
Upton, NY, 11973 USA

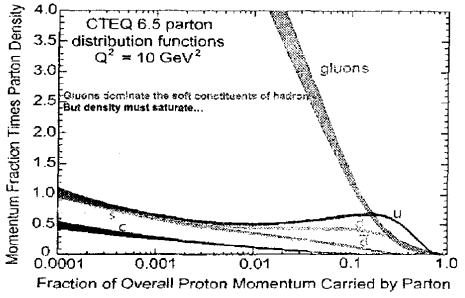
May 3, 2010

Abstract

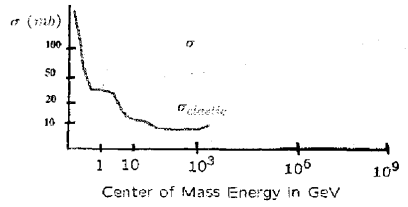
I provide a brief introduction to the theoretical ideas and phenomenological motivation for the Color Glass Condensate and the Glasma. The Glasma generates a maximal topological charge density, and through its evolution by turbulent modes, can generate net topological charge.

The Topological Glasma

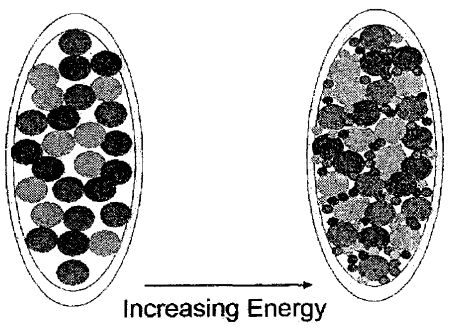
As one evolves the gluon density, the density of gluons becomes large:



The total hadronic cross section:



Gluons are described by a stochastic ensemble of classical fields, and JKMMW argue there is a renormalization group description



In target rest frame: Fast moving particle sees classical fields from various longitudinal positions as coherently summed

In infinite momentum frame, these fields are Lorentz contracted to sit atop one another and act coherently

Density per unit rapidity is large

Leads to name for the saturated gluon media of Color Glass Condensate:

Color: Gluon Color

Glass: V. Gribov's space time picture of hadron collisions

Condensate: Coherence due to phase space density

$$\frac{dN}{dy d^2 p_T d^2 r_T} \sim \frac{1}{\alpha_S(Q_{sat})}$$

Derivation JIMWLK evolution equations that for correlators is BK equation

The theoretical description overlaps:

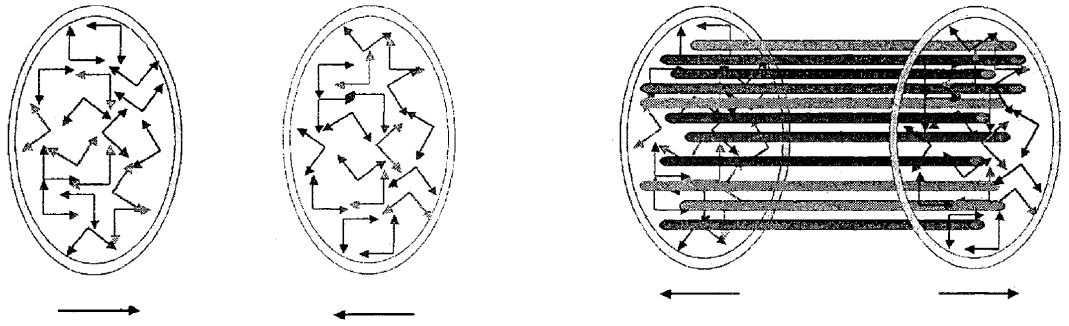
Perturbative QCD at large momenta (low density)

Includes the Pomeron and Multi-Reggeon configurations of Lipatov

In various approximations, "Pomeron loop" effects can be included.

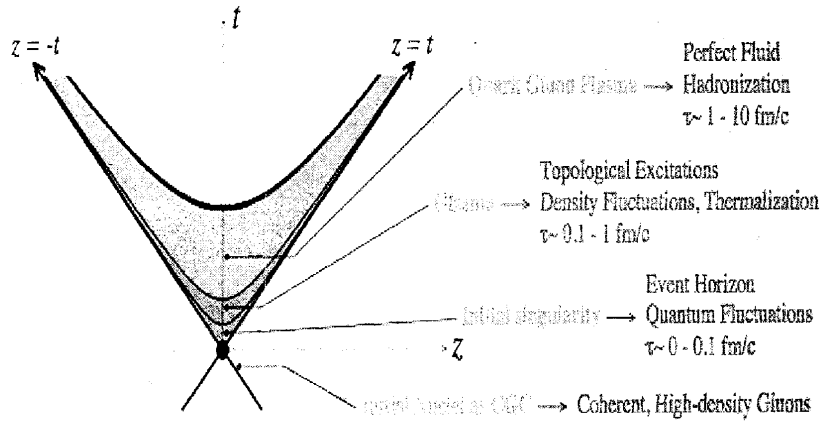
Theoretical issue is more when the approximations used are valid, not whether framework is valid

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

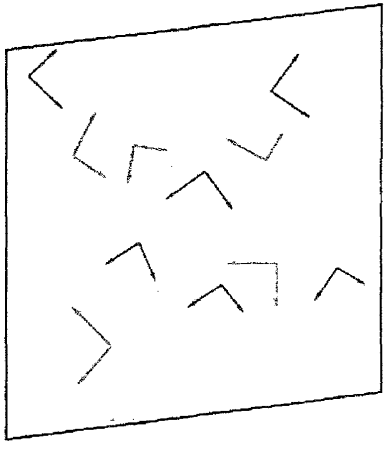


Longitudinal electric and magnetic fields are set up in a very short time

$$t \sim \frac{1}{Q_{sat}} e^{-\kappa/\alpha_S} << \frac{1}{Q_{sat}}$$



What does a sheet of Colored Glass look like?



$\vec{E} \perp \vec{B} \perp \vec{z}$

On the sheet $x^- = t - z$ is small

Independent of $x^+ = t + z$

$F^{i-} = E - B$ small

$F^{i+} = E + B$ big

F^{ij} 0(1)

Lienard-Wiechart potentials

Random Color

Density of gluons per unit area

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} Q^2_{sat}$$

The CGC Path Integral:

$$Z = \int_{\Lambda} [dA][d\rho] exp\{iS[A,\rho] - F[\rho]\}$$

The current source:

$$J^{\mu} = \delta^{\mu +} \rho(x_T, y)$$

Rapidity:

$$y = ln(x_0^- / x^-) \sim ln(1/x) \sim \frac{1}{2} ln(p^+ / p^-)$$

The separation scale is in rapidity or longitudinal momentum Λ

Phase Diagram of Hot QCD in an External Magnetic Field

Eduardo Souza Fraga

Instituto de Física
Universidade Federal do Rio de Janeiro

Abstract

The structure of the phase diagram for strong interactions becomes richer in the presence of a magnetic background, which enters as a new control parameter for the thermodynamics. Motivated by the relevance of this physical setting for current and future high-energy heavy ion collision experiments and for the cosmological QCD transitions, we use the linear sigma model coupled to quarks and to Polyakov loops as an effective theory to investigate how the chiral and the deconfining transitions are affected, and present a general picture for the temperature-magnetic field phase diagram. We compute and discuss each contribution to the effective potential for the approximate order parameters, and uncover new phenomena such as the paramagnetically-induced breaking of global Z_3 symmetry, and possible splitting of deconfinement and chiral transitions in a strong magnetic field.

*Based on work done in collaboration with A.J. Mizher and M.N. Chernodub.

Effective theory

[A.J. Mizher, M. Chernodub & ESF (2010)]

A. Degrees of freedom and approximate order parameters

O(4) chiral field: $\phi = (\sigma, \vec{\pi})\,, \qquad \vec{\pi} = (\pi^+, \pi^0, \pi^-)$

quark spinors: $\psi = \begin{pmatrix} u \\ d \end{pmatrix}$

Polyakov loop: $L(x) = \frac{1}{3}\mathrm{Tr}\,\Phi(x)\,, \quad \Phi = \mathcal{P}\exp\Big[i\int_0^{1/T} \mathrm{d}\tau A_4(\vec{x},\tau)\Big]$

$$\text{Chiral symmetry}: \quad \begin{cases} \langle\sigma\rangle \neq 0\,, & \text{low } T \\ \langle\sigma\rangle = 0\,, & \text{high } T \end{cases}$$

$$\text{Confinement}: \quad \begin{cases} \langle L\rangle = 0\,, & \text{low } T \\ \langle L\rangle \neq 0\,, & \text{high } T \end{cases}$$

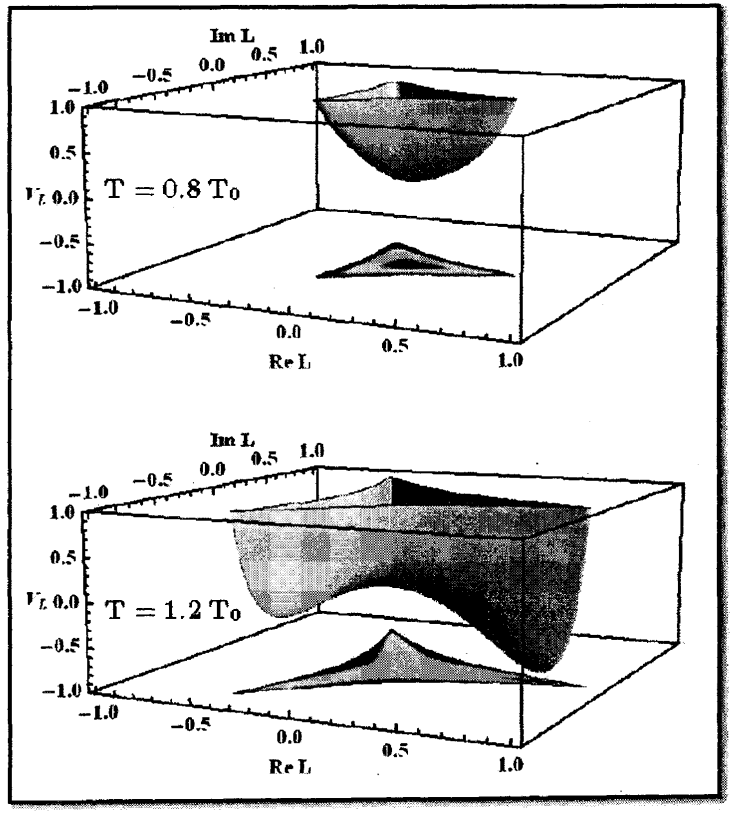
C. Paramagnetically-induced breaking of Z(3) [A.J. Mizher, M. Chernodub & ESF (2010)]

The magnetic field drastically affects the potential for the Polyakov loop. For <u>very large</u> fields $|q|B \gg m_q^2$:

$$\Omega_q^{\rm para} = -3\frac{g\sigma|q|BT}{\pi^2}K_1\left(\frac{g\sigma}{T}\right)\mathrm{Re}\,L$$

(not Z(3) invariant)

<u>New phenomenon</u>: the magnetic field tends to break Z(3) and induce deconfinement, forcing <L> to be real-valued!



$$\sqrt{eB} = 3T$$

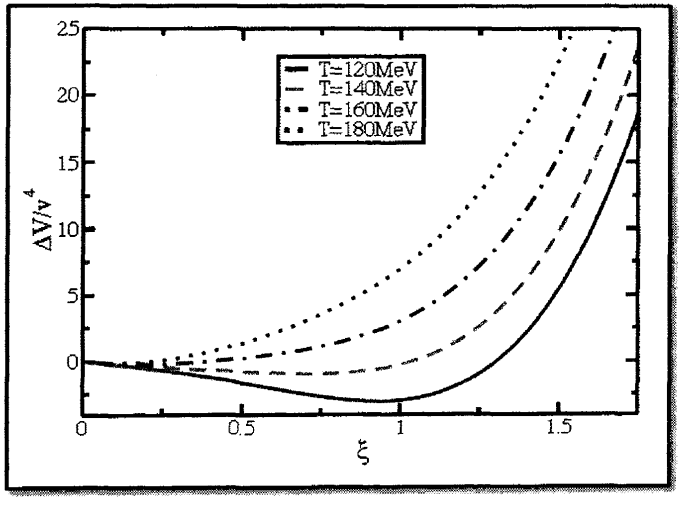
Phase structure

[A.J. Mizher, M. Chernodub & ESF (2010)]

Case 1: B = 0 , T ≠ 0

(i) $\phi = 0$ (chiral):

effective potential

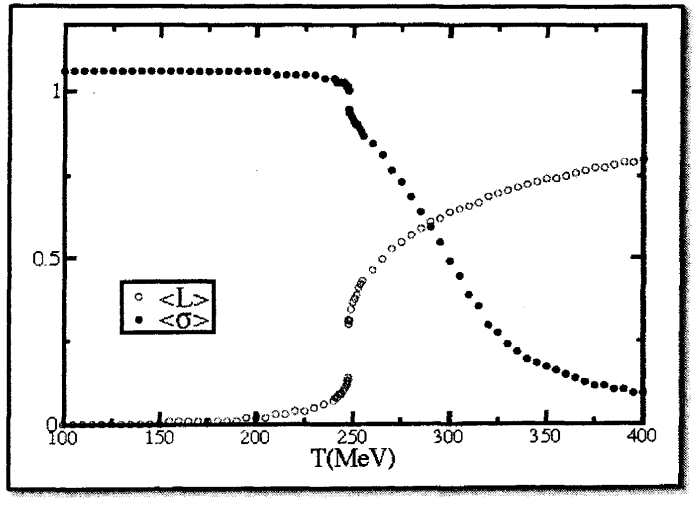


$\xi = \sigma/v$ (v used as mass scale)

crossover

(ii) $\phi \neq 0$ (chiral + deconf):

condensates



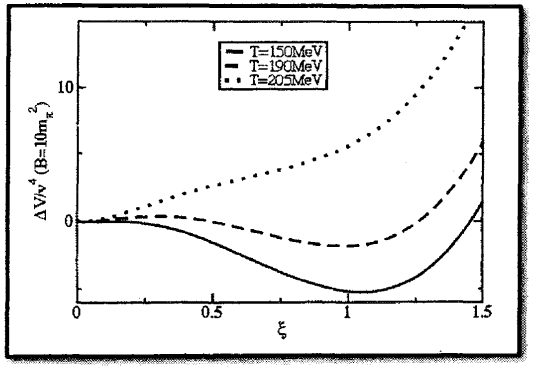
weak 1st order

Case 2. $B \neq 0$, $T \neq 0$, $\phi \neq 0$:

Effective potential

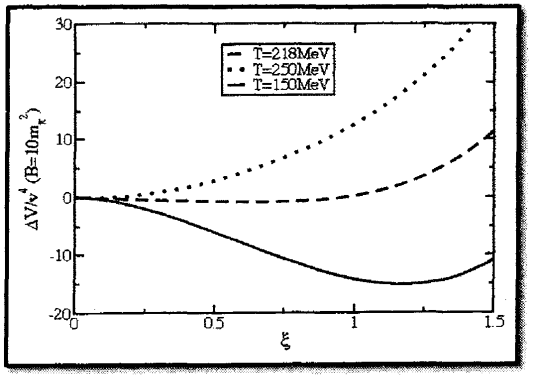
(i) Chiral condensate direction:

Without vacuum corrections



- **Clear barrier: 1st order chiral transition.**
- **Part of the system kept in the false vacuum: some bubbles and spinodal instability, depending on the intensity of supercooling.**

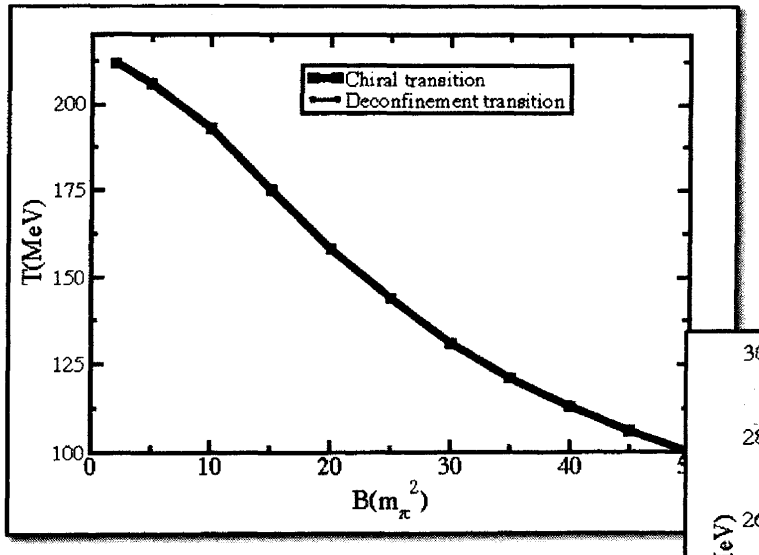
With vacuum corrections



- **No barrier: crossover for the chiral transition.**
- **System smoothly drained to the true vacuum: no bubbles or spinodal instability.**

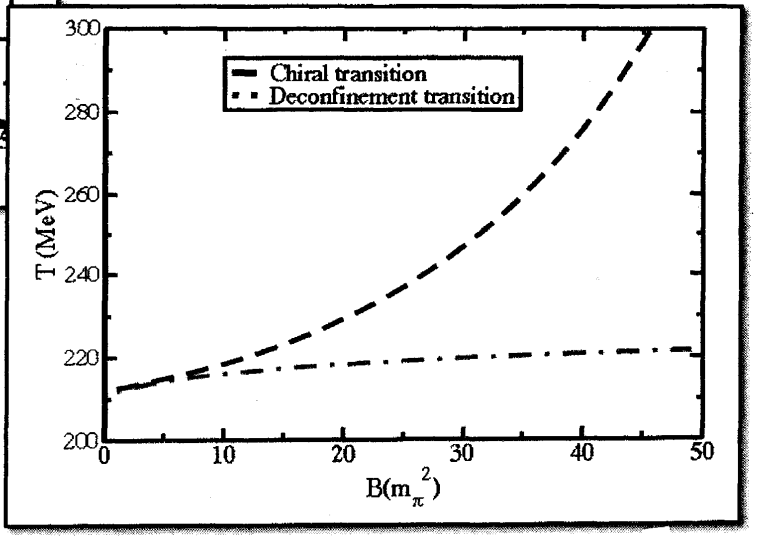
Phase diagrams

Without vacuum corrections



- Chiral and deconfinement lines coincide.
- The transitions are 1st order down to very low B, where they turn to a crossover.
- Magnetic catalysis reproduced in the vacuum. [ESF & A.J. Mizher (2008)]

With vacuum corrections



- Chiral and deconfinement (crossover) lines initially coincide, then split (3 phases).
- The deconfinement line goes down again for high enough B (but not to zero).
- Chiral restoration becomes more and more difficult for high B.

Workshop on P- and CP-odd effects in hot and dense matter, BNL, 26-30.April 2010

Photon Instability in Variable Pion/Axion Condensate : A Possible Hint to PHENIX anomaly

A.A. Andrianov

Sankt-Petersburg State University

Санкт-Петербургский государственный университет

(in collaboration with D. Espriu)

Abstract

Photon Instability in Variable Pion/Axion Condensate is elucidated and a possible explanation of the abnormally large excess of e+e- pairs recently detected PHENIX is presented as an evidence for local parity violation. Different signatures of this effect are discussed such as a hierarchy of thresholds for different type of leptons, circular polarization of event-by-event date, resonant enhancement of dilepton yield, induced additional mixing with vector mesons.

A. Andrianov, D. Espriu, P. Giacconi and R. Soldati, JHEP 09 (2009) 057
A. Andrianov, D. Espriu, F. Mescia and A. Renau, Phys.Lett. B684 (2010) 101

Photon instability in pseudoscalar background

For slowly growing/decreasing neutral pion condensate

$$\eta_\alpha \simeq \partial_\alpha \langle \Pi \rangle \simeq \delta_{\alpha 0} \langle \dot{\Pi}(t) \rangle$$

or isoscalar theta field $\mu_5 = \partial_0 \theta / (2N_f)$ ← axial chemical potential

(in central heavy ion collisions)

Induced C-S term $\boxed{\Delta \mathcal{L} = \frac{1}{4} \eta \epsilon^{ijk} A_i F_{jk}}$ $\eta_\alpha = (\eta, 0, 0, 0)$

Adiabatic approximation: $\dot{\eta}/f_\pi \ll \eta \ll \omega_\gamma$

in units $1/fm \sim f_\pi$ time derivative of CS vector << photon frequency

Photons of different circular polarizations have different dispersion relation between their frequencies and wave vectors

$$k^{\mu}_{\pm} = (\omega_{\mathbf{k}\pm}, \mathbf{k}) \qquad \omega_{\mathbf{k}\pm} = \sqrt{\mathbf{k}^2 + m_\gamma^2 \pm \eta|\mathbf{k}|}$$

Effective photon masses $k^2_{\pm} = m_\gamma^2 \pm \eta\,|\mathbf{k}| \simeq \pm\eta\,|\mathbf{k}|$

Photon "-" is a tachyon

Photon "+"decays $\gamma \to l^+ l^-$

for $m_\gamma \ll m_e$

$$\boxed{|\mathbf{k}| \geq \frac{4m_l^2}{\eta} \equiv k_{\rm th}}$$

Threshold hierarchy!
If for electrons/positrons the threshold is of order 100 MeV then for muons it is four orders of magnitude higher , i.e. 1 TeV !
<u>No muon pairs excess in the PHENIX data!</u>? Maybe in NA60?

Polarizations $A = T, L, +, -$

$$\varepsilon_T^\mu(k) \equiv \frac{\mathrm{i}k^\mu}{\sqrt{k^2}} \qquad (k^2 > 0),$$

$$\varepsilon_L^\mu(k) \equiv (k^2 \mathrm{D})^{-1/2}\left(k^2 \eta^\mu - k^\mu \eta \cdot k\right) \qquad (k^2 > 0)$$

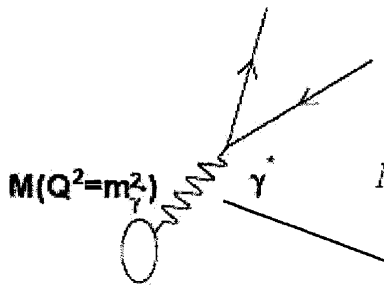
(Almost) circular polarizations of distorted photons

$$\varepsilon_\pm^\mu(k) \equiv \left[\frac{\mathbf{k}^2 - (\epsilon \cdot k)^2}{2\mathbf{k}^2}\right]^{-1/2} P_\pm^{\mu\nu}\, \epsilon_\nu$$

$$P_\pm^{\mu\nu} \equiv \frac{S^{\mu\nu}}{S} \pm \frac{\mathrm{i}}{\sqrt{S/2}} \varepsilon^{\mu\nu\alpha\beta} \eta_\alpha k_\beta \qquad S_\lambda^\nu \equiv \varepsilon^{\mu\nu\alpha\beta} \eta_\alpha k_\beta \varepsilon_{\mu\lambda\rho\sigma} \eta^\rho k^\sigma$$

Polarized decay !! $\gamma \to l^+ l^-$

Dilepton pair creation



$$M \equiv m_{ee} \equiv m_{\gamma^*}$$

$$\frac{d^2N_{ee}}{dM^2} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}dN_{\gamma^*},$$

$$L(M) = \sqrt{1-\frac{4m_e^2}{M^2}}\left(1+\frac{2m_e^2}{M^2}\right)$$

"Giant" resonance with variable position

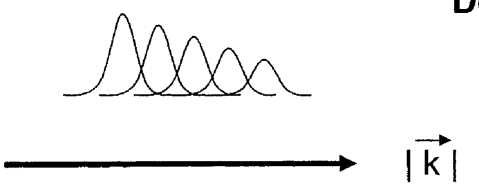
$$\frac{1}{\pi}\Theta\left(|\vec{k}| - \frac{4m_e^2}{\eta}\right)\frac{2\Gamma_+\omega_+(|\vec{k}|)}{(M^2-\eta|\vec{k}|)^2+4\Gamma_+^2\omega_+^2(|\vec{k}|)}$$

Decay width

$$\Gamma_+ = \tau_+^{-1} \simeq \frac{\alpha\eta}{3}$$

Photon frequency

$$\omega_+(|\vec{k}|) = \sqrt{\vec{k}^2+\eta|\vec{k}|}$$



$\sim 1/\Gamma_+\omega_+(|\vec{k}|) \sim 1/\alpha M^2$ $\quad k \gg \eta$ **"On-shell" enhancement in a range of $|\vec{k}|$!**

In order to derive the value of η one has to resolve

Mixing with vector mesons $\quad (V_{\mu,a}) \equiv (A_\mu,\, \omega_\mu,\, \rho_\mu)$

In the lagrangian $\quad \mathcal{L}_{mixing}(k) \;=\; \eta\, \epsilon_{jkl}\, V_{j,a}\, N_{ab}\, \partial_k V_{j,b}$

coupling constants N_{ab} are known from the anomaly or, independently, can be derived from radiative decays $\quad \pi_0 \to \gamma\gamma \qquad \omega \to \pi_0\gamma \qquad \rho_0 \to \pi_0\gamma$

One can, in principle, disentangle the isospin of pseudoscalar condensate:

for isoscalar $\quad \eta \sim \langle \dot{\theta} \rangle \qquad (N_{ab}) \simeq c_m \begin{pmatrix} \frac{5}{9}e^2 & \frac{1}{6}eg & \frac{1}{2}eg \\ \frac{1}{6} & g^2 & 0 \\ \frac{1}{2}eg & 0 & g^2 \end{pmatrix}$

for pion condensate $\quad \eta \sim \langle \dot{\pi}_0 \rangle \qquad (N_{ab}) \simeq c_m \begin{pmatrix} \frac{1}{3}e^2 & \frac{1}{2}eg & \frac{1}{6}eg \\ \frac{1}{2} & 0 & g^2 \\ \frac{1}{6}eg & g^2 & 0 \end{pmatrix}$

where coupling constants

γ	ω	ρ
e	$g_\omega \simeq$	$g_\rho \equiv g$

Mass-shell for transversal polarizations

$$\left[P_\perp^{\mu\nu}(k)\left(k^2\delta_{ab} - (\hat{m}^2)_{ab}\right) + i\, c_m\, \epsilon^{\mu\nu\sigma\rho}\eta_\sigma k_\rho N_{ab}\right] V_{\nu,b}(k) \;=\; 0 \qquad \hat{m}^2 \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_\omega^2 & 0 \\ & 0 & m_\rho^2 \end{pmatrix}$$

CP-violation and baryogenesis

Valery Rubakov

Institute for Nuclear Research
of the Russian Academy of Sciences, Moscow

Outline

- Introduction
- Electroweak sphalerons
- Leptogenesis: *CP*-violation via interference
- Electroweak baryogenesis: *CP*-violation in bubble wall
- Affleck–Dine baryogenesis: *CP*-violation by initial conditions
- Conclusions

Baryon asymmetry of the Universe

- There is matter and no antimatter in the present Universe.
- Baryon-to-photon ratio, almost constant in time:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

Baryon-to-entropy, constant in time: $n_B/s = 0.9 \cdot 10^{-10}$

What's the problem?

Early Universe ($T > 10^{12}$ K $= 100$ MeV):
creation and annihilation of quark-antiquark pairs $\Rightarrow$

$$n_q, n_{\bar{q}} \approx n_\gamma$$

Hence

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9}$$

How was this excess generated in the course of the cosmological evolution?

Sakharov conditions

To generate baryon asymmetry, three necessary conditions should be met at the same cosmological epoch:

- B-violation
- Honest C- and CP-violation
- Thermal inequilibrium

NB. Reservation: L-violation with B-conservation at $T \gg 100$ GeV would do as well $\Longrightarrow$ Leptogenesis.

Electroweak sphalerons

One of ingredients: Baryon number violation in electroweak interactions.
Triangle anomaly in baryonic current B^μ:

$$\partial_\mu B^\mu = \left(\frac{1}{3}\right)_{B_q} \cdot 3_{colors} \cdot 3_{generations} \cdot \frac{g_W^2}{16\pi^2} F\tilde{F}$$

$F^a_{\mu\nu}$: $SU(2)_W$ field strength; g_W: $SU(2)_W$ coupling

Likewise, each leptonic current $(n = e, \mu, \tau)$

$$\partial_\mu L_n^\mu = \frac{g_W^2}{16\pi^2} \cdot F\tilde{F}$$

Hence, selection rules $\Delta B = 3\Delta L_e = 3\Delta L_\mu = 3\Delta L_\tau$ or

$$B - L = \text{conserved}$$

where $L = L_e + L_\mu + L_\tau$.

To conclude

- *CP*-violation, together with baryon and lepton number non-conservation, is crucial for generating baryon asymmetry, and hence for our existence.
- Kobayashi–Maskawa *CP*-violation in the Standard Model insufficient
- Relevant mechanism of *CP*-violation may be quite non-trivial
- Electroweak sphalerons are important in many (but not all) scenarios of baryogenesis.

Cosmological implications of P and CP-odd phenomena in QCD

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- Observational Cosmological Puzzles and *Charge Separation Effect (Big Bang)*
- Witten-Veneziano resolution of the U(1) problem and the Veneziano Ghost
- Observations. P- violation on very large scales in the Universe. CMB and magnetic fields.
- The dark Energy from (P-ODD) Veneziano Ghost in the expanding universe
- Unruh effect in the accelerating universe and nonzero temperature

ANOTHER θ -RELATED CONNECTION...

- THE θ DEPENDENCE IN QCD DETERMINES THE η' MASS (WITTEN,VENEZIANO, 1979)

$$L = \frac{1}{2}\partial_\mu\eta'\partial^\mu\eta' - \frac{1}{\chi}Q^2 - \left(\theta - \frac{\eta'}{f_{\eta'}}\right)Q + N_f m_q| < \bar{q}q > |\cos\left[\frac{\eta'}{f_{\eta'}}\right]$$

$$Q \equiv \frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}, \quad \chi = -\frac{\partial^2\epsilon_{vac}(\theta)}{\partial\theta^2} = i\int d^4x < T\{Q(x), Q(0)\} >$$

- THE TOPOLOGICAL SUSCEPTIBILITY $\chi \neq 0$ DOES NOT VANISH IN SPITE OF THE FACT THAT OPERATOR Q IS TOTAL DERIVATIVE

- SIGN OF $\chi < 0$ IS NEGATIVE (IT IS OPPOSITE TO WHAT ONE SHOULD EXPECT FROM A PHYSICAL DEGREE OF FREEDOM)-- SO THE TERM "<u>THE VENEZIANO GHOST</u>"

- INTEGRATING OUT Q FIELD PRODUCES η' MASS WITH NO ANY TRACES OF MASSLESS (UNPHYSICAL) GHOSTS.

θ-RELATED VACUUM ENERGY

- WHAT WOULD HAPPEN TO THE TOTAL (DELOCALIZED) ENERGY IF THE SYSTEM IS DEFINED ON A FINITE MANIFOLD SIZE L ~ 1/H ~ 10 G YEARS, OR/AND IF THE UNIVERSE IS SLOWLY EXPANDING WITH RATE H (FRLW UNIVERSE)?

- ``NAIVE ANSWER": THE CORRECTIONS DUE TO A FINITE SIZE OR EXPANSION (~H) SHOULD BE EXTREMELY SMALL AS ALL PHYSICAL DEGREES OF FREEDOM ARE MASSIVE

$$\exp(-L\Lambda_{QCD}) \sim \exp(-\frac{\Lambda_{QCD}}{H}) \sim \exp(-10^{41})$$

- IN REALITY, THE PHYSICS COULD BE MUCH MORE INTERESTING/COMPLICATED DUE TO THE TOPOLOGICAL NATURE OF THE θ VACUA (SENSITIVITY TO BOUNDARIES)

- No cancellation between the Veneziano ghost and its partner could occur in expanding system as a result of opposite sign (-) in commutation relations and negative sign (-) in Hamiltonian.

- if we had started with a conventional scalar field we would derive a well-known formula for Plank spectrum for radiation at $T = a/(2\pi)$ observed by a Rindler observer in Minkowski vacuum which is conventional Unruh effect

- The cancellation fail to hold for the accelerating Rindler observer because the properties of the operator which selects the positive frequency modes with respect to Minkowski time t and observer's proper time η are not equivalent.

Technical reason for non-cancellation:

- THE GROUND STATE FOR MINKOWSKI OBSERVER IS DEFINED AS USUAL

$$a_k|0>=0\,, \quad b_k|0>=0\,, \quad \forall k\,.$$

- THE VACUUM FOR R-RINDLER OBSERVER IS DEFINED AS

$$a_k^L|0_R>=0\,, \quad a_k^R|0_R>=0\,, \quad b_k^L|0_R>=0\,, \quad b_k^R|0_R>=0\,, \quad \forall k\,.$$

- THE BOGOLUBOV'S COEFFICIENTS ARE KNOWN TO MIX POSITIVE AND NEGATIVE FREQUENCY MODES:

$$a_k^L = \frac{e^{-\pi\omega/2a}a_{-k}^{1\dagger} + e^{\pi\omega/2a}a_k^2}{\sqrt{e^{\pi\omega/a} - e^{-\pi\omega/a}}} \qquad a_k^R = \frac{e^{-\pi\omega/2a}a_{-k}^{2\dagger} + e^{\pi\omega/2a}a_k^1}{\sqrt{e^{\pi\omega/a} - e^{-\pi\omega/a}}}$$

$$b_k^L = \frac{e^{-\pi\omega/2a}b_{-k}^{1\dagger} + e^{\pi\omega/2a}b_k^2}{\sqrt{e^{\pi\omega/a} - e^{-\pi\omega/a}}} \qquad b_k^R = \frac{e^{-\pi\omega/2a}b_{-k}^{2\dagger} + e^{\pi\omega/2a}b_k^1}{\sqrt{e^{\pi\omega/a} - e^{-\pi\omega/a}}}\,.$$

- WE INTERPRET THE EXTRA CONTRIBUTION TO THE ENERGY OBSERVED BY AN ACCELERATING OBSERVER AS A RESULT OF FORMATION OF THE SQUEEZED STATE WHICH CAN BE COINED AS THE "GHOST CONDENSATE" RATHER THAN A PRESENCE OF "FREE PARTICLES" AT $T = a/2\pi$ PREPARED IN A SPECIFIC MIXED STATE.

$$|0>=\prod_k \frac{1}{\sqrt{(1-e^{-2\pi\omega/a})}} \exp\left[e^{-\pi\omega/a}\left(b_k^{R\dagger} b_{-k}^{L\dagger} - a_{-k}^{R\dagger} a_k^{L\dagger}\right)\right] |0^R> \otimes |0^L>$$

- WE INTERPRET THE GHOST CONTRIBUTION TO THE ENERGY AS A CONVENIENT WAY TO ACCOUNT FOR A NONTRIVIAL INFRARED PHYSICS AT THE HORIZON AND/OR THE BOUNDARY. IT IS POSSIBLE THAT THE SAME PHYSICS, IN PRINCIPLE, IS DESCRIBABLE WITHOUT THE GHOSTS (SUCH A DESCRIPTION WOULD BE MUCH MORE TECHNICALLY COMPLICATED).

- IS IT OBSERVABLE AT RHIC AT $T = a/2\pi$?

Response of dense relativistic matter to a magnetic field

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At zero density and temperature, the structure of the ground state in relativistic chiral invariant theories in a magnetic field is dictated by the magnetic catalysis phenomenon: the magnetic field is a strong catalyst of spontaneous chiral symmetry breaking [1]. The situation becomes much more complicated in the case of dense relativistic matter in a magnetic field. It has been recently revealed [2] that in the normal phase of dense relativistic matter in a magnetic field, there exists a contribution to the axial current associated with a relative shift Δ of the longitudinal momenta in the dispersion relations of opposite chirality fermions. Unlike the topological contribution in the axial current at the lowest Landau level, recently discussed in the literature [3], the dynamical one appears only in interacting matter and affects the fermions in *all* Landau levels, including those around the Fermi surface.

The properties of such a Δ solution were described in detail in the Nambu-Jona-Lasinio (NJL) model [2]. In accordance with the magnetic catalysis scenario, the vacuum state of relativistic matter in a magnetic field is characterized by a non-zero dynamical Dirac mass m_{dyn}. However, when the chemical potential exceeds a certain critical value, $\mu_c \simeq m_{dyn}/\sqrt{2}$, such a state is replaced by the normal ground state that is characterized by the following two properties: (i) the presence of an induced axial current along the magnetic field and (ii) the presence of the dynamically generated chiral shift parameter Δ, which is a $3+1$ dimensional analog of the parity odd mass term in $2+1$ dimensions leading to the Chern-Simons term. We find that, in addition to the previously known topological term in the induced current, there are also interaction-driven contributions from the lowest as well as from the higher Landau levels. In fact, the newly found contributions are directly related to a dynamically generated value of the chiral shift parameter Δ. This parameter quantifies the relative shift of the longitudinal momenta in the dispersion relations of opposite chirality quasiparticles. It is important that most of the results are not modified much when the chiral symmetry is approximate, i.e., when the fermions have non-zero bare Dirac masses, but such masses are small compared to the value of the chemical potential μ. Interestingly, the temperature dependence of Δ is very weak when $T \ll \mu$. Moreover, this chiral shift parameter does not vanish even in the non-degenerate limit ($T \gg \mu$). Therefore, the generation of a non-zero Δ can also affect the chiral magnetic effect in heavy ion collisions [4].

One of the consequences of this phenomenon is the possibility of a qualitatively new mechanism for the pulsar kicks [5]. In the presence of a magnetic field, almost any type of relativistic matter inside a protoneutron star should develop axial currents. The main carriers of such currents are the electrons in the nuclear matter, and the quarks together with the electrons in the deconfined quark matter. Since the induced currents and the chiral shift parameter have only a weak temperature dependence (assuming $T \ll \mu$), this phenomenon may provide a robust anisotropic medium even at the earliest stages of the protoneutron star. This is important because moderately hot matter with 10 MeV $\lesssim T \lesssim$ 50 MeV, present during the first few tens of seconds of the protoneutron star evolution, may have a large enough amount of the thermal energy to power the strongest (with $v \gtrsim 1000$ km/s) pulsar kicks observed [5]. In contrast, the constraints of the energy conservation make it hard, if not impossible, to explain such kicks if the interior matter is cold ($T \lesssim 1$ MeV). The common difficulty of using a hot matter, however, is the very efficient thermal isotropization that washes out a non-isotropic distribution of neutrinos produced by almost any mechanism [6, 7]. In the mechanism proposed in Ref. [2], however, the asymmetric distribution of the neutrinos *develops* as a result of their multiple elastic scattering on the left-handed electrons or quarks, flowing in the whole bulk of the stellar matter in one direction along the magnetic field.

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[6] A. Kusenko, G. Segre, and A. Vilenkin, Phys. Lett. B **437**, 359 (1998).
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Model

- Lagrangian density:

$$\mathcal{L} = \bar{\psi}\left(iD_\nu + \mu_0\delta_\nu^0\right)\gamma^\nu\psi + \frac{G_{\rm int}}{2}\left[\left(\bar{\psi}\psi\right)^2 + \left(\bar{\psi}i\gamma^5\psi\right)^2\right]$$

- The dimensionless coupling is

$$g \equiv G_{\rm int}\Lambda^2/(4\pi^2) \ll 1$$

- Magnetic field is inside $D_\nu = \partial_\nu - ieA_\nu$

  where $A_\nu = xB\delta_\nu^2$ (Landau gauge)

Vacuum state

- Magnetic catalysis (spontaneous generation of a nonzero Dirac mass even at $g \ll 1$):

$$m_{\rm dyn}^2 = \frac{1}{\pi l^2} \exp\left(-\frac{\Lambda^2 l^2}{g}\right) \text{ where } l = 1/\sqrt{|eB|}$$

(along with $\mu = \mu_0$)

[Gusynin, V.M., Shovkovy, PRL **73**, 3499 (1994); PLB **349**, 477 (1995)]

- The solution exists for $\mu_0 < m_{dyn}$, although it will be less stable than the normal state ($m = 0$) already for $\mu_0 \gtrsim m_{\rm dyn}/\sqrt{2}$ [Clogston, PRL **9**, 266 (1962)]

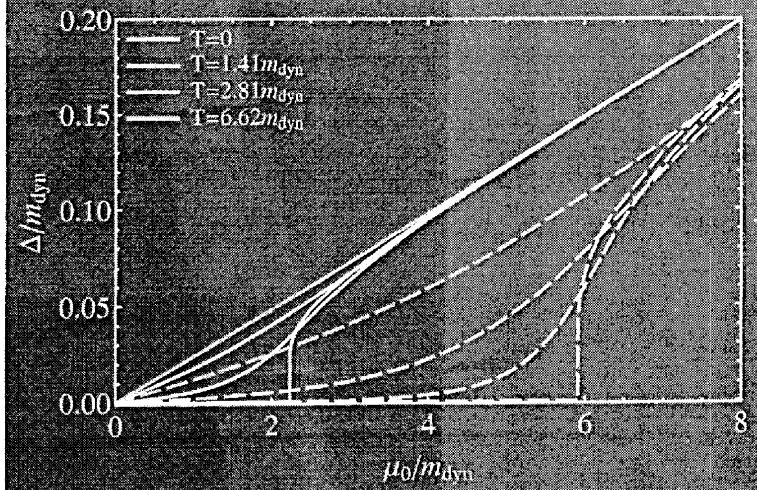
"Abnormal" normal ground state

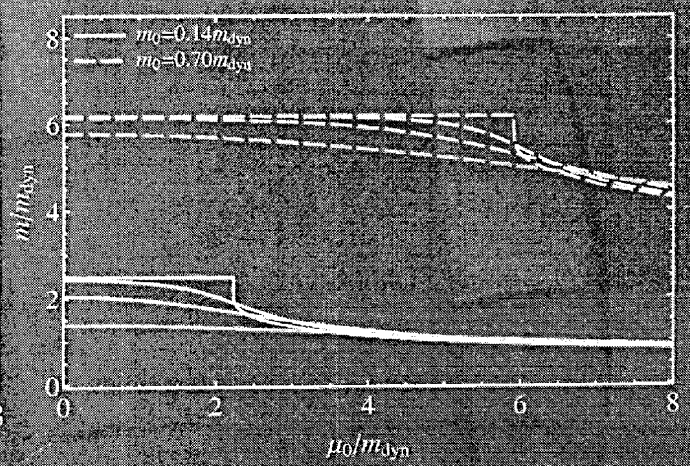
- The gap equation allows another solution,

$$\mu \simeq \mu_0 \text{ and } \Delta \simeq g\mu_0 eB/\Lambda^2$$

- This solution is almost independent of temperature when $T \ll \mu$
- This is the normal ground state since its symmetry is same as in the Lagrangian
- Besides, there is no trivial solution $\Delta=0$

T≠0 results





- These are smoothed versions of the T=0 results
- The dependence μ-μ_0 versus μ_0 (not shown) at T≠0 is similar to Δ versus μ_0 (shown)

Induced axial current

- The axial current in the ground state is

$$\langle \bar{\psi}\gamma^3\gamma^5\psi \rangle = \boxed{\frac{eB}{2\pi^2}\mu} - \frac{|eB|}{2\pi^2}\Delta - \frac{|eB|}{\pi^2}\Delta \sum_{n=1}^{\infty} \kappa(\sqrt{2n|eB|}, \Lambda)$$

- In addition to the topological contribution, $\frac{eB}{2\pi^2}\mu$ there are dynamical ones $\propto \Delta$
- An equivalent result is also obtained in the Pauli-Villars regularization
- Note: on the solution to the gap equation:

$$\langle j_5^3(u) \rangle = \frac{2\Delta}{G_{\rm int}} = \frac{\Delta}{2\pi^2}\frac{\Lambda^2}{g}$$

Fluctuation of Electric Dipole Moment in the Chirally Broken Phase

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Abstract: We study the anomaly-induced fluctuation of electric dipole moment in the presence of magnetic field in the confined and chirally-broken phase of QCD. By using the chiral Lagrangian with the Wess-Zumino-Witten-Novikov term, we find that the domain walls in the neutral pion field in the background magnetic field acquire locally non-vanishing density of electric charge and a configuration of such domain-wall and anti-domain-wall will give rise to fluctuation of electric dipole moment. The electric charge density is proportional to the pion mass and thus vanishes in the chiral limit.

April 2010, BNL

QCD inequality in presence of EM

$$\mathcal{D} = \gamma_\mu \left(\partial_\mu + \imath g A_{\alpha\mu} t_\alpha + \imath e \mathcal{Q} A_\mu\right) + \mathcal{M}$$

- $\mathcal{Q} = \mathrm{diag}\,(2/3, -1/3)$
- $\mathcal{M} = \mathrm{diag}\,(m, m)$
- $\mathcal{Q} = \mathcal{I}_3 + \mathcal{B}/2,\ \mathcal{I}_3 = \tau_3/2,\ \mathcal{B} = \mathbb{1}/3$
- $(\gamma_5\tau_{1,2})\,\mathcal{D}\,(\gamma_5\tau_{1,2})^\dagger \neq \mathcal{D}^\dagger$

$$(\gamma_5\tau_3)\,\mathcal{D}\,(\gamma_5\tau_3)^\dagger = \mathcal{D}^\dagger$$

- $\underline{I = 1}$: $\qquad M(\boldsymbol{x}) = \bar{\Psi}(\boldsymbol{x})\Gamma\Psi(\boldsymbol{x})$

$$\langle M(\boldsymbol{x})M^\dagger(\boldsymbol{0})\rangle = \langle \mathrm{Tr}\ S(\boldsymbol{x},\boldsymbol{0})\Gamma\,(\gamma_5\tau_3)\,S^\dagger(\boldsymbol{x},\boldsymbol{0})\,(\gamma_5\tau_3)\,\bar{\Gamma}\rangle \leq \langle \mathrm{Tr}\ S(\boldsymbol{x},\boldsymbol{0})S^\dagger(\boldsymbol{x},\boldsymbol{0})\rangle$$

- $S(\boldsymbol{x},\boldsymbol{0}) = \mathcal{D}^{-1}_{\boldsymbol{x},\boldsymbol{0}}, \qquad \bar{\Gamma} = \gamma_0\Gamma\gamma_0$

$$\Gamma = \gamma_5\tau_3$$

Low T & π^0

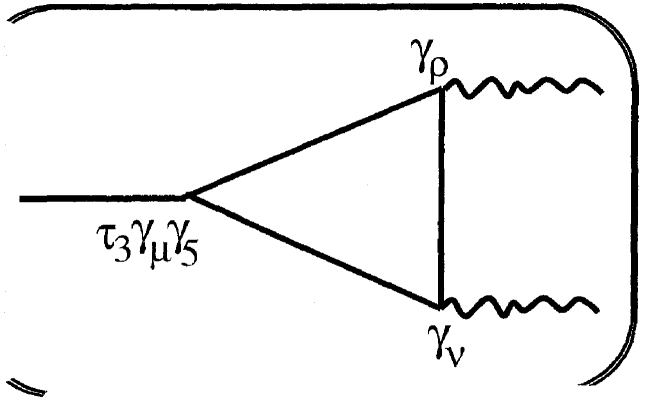
$$\partial_\mu J^{\mu 5,3} = -\frac{3e^2}{16\pi^2}\left(q_u^2 - q_d^2\right) F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$\mathcal{L}_{eff} = \frac{3e^2}{16\pi^2 f_\pi}\left(q_u^2 - q_d^2\right) \pi^0 F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$\mathcal{L}_{eff} = \frac{3e^2}{16\pi^2 f_\pi}\left(q_u^2 - q_d^2\right) \pi^0 \partial^\mu J_\mu^{CS}$$

$$J_\mu^{CS} = \epsilon_{\mu\nu\delta\gamma} A^\nu F^{\delta\gamma}$$

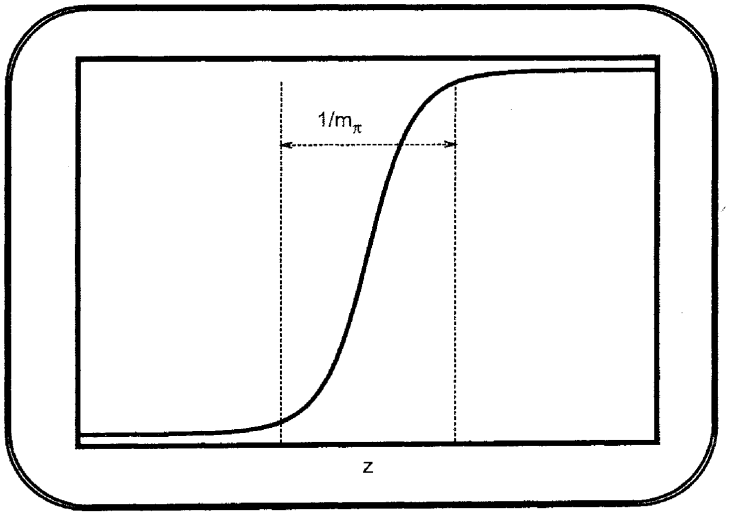
$$\mathcal{L}_{eff} = \frac{3e^2}{16\pi^2 f_\pi}\left(q_u^2 - q_d^2\right) J_\mu^{CS}\left(\partial_\mu \pi^0\right)$$



$$J_0 = \frac{3e^2}{8\pi^2 f_\pi}\left(q_u^2 - q_d^2\right) B\left(\partial_z \pi^0\right)$$

π^0 domain-wall

$$\pi^0 = 4\tan^{-1}\exp\left[m_\pi z\right]$$

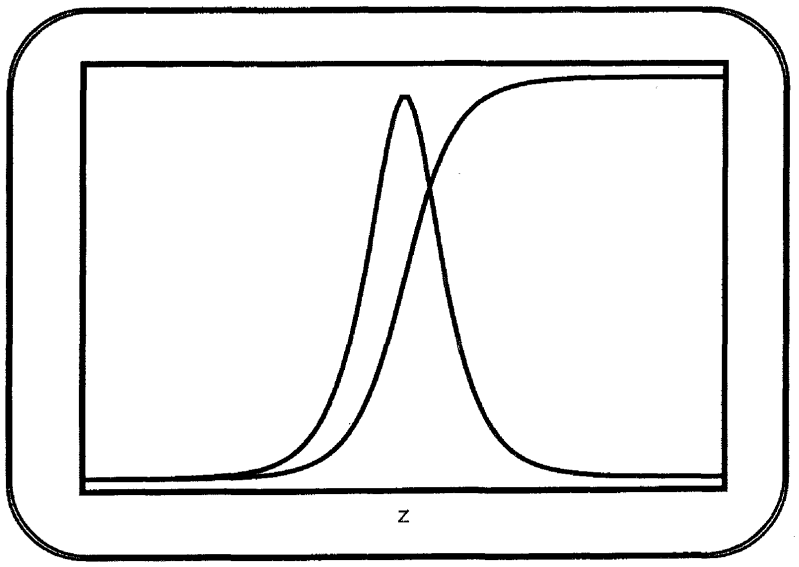


- Metastable: $eB \gtrsim 3m_\pi^2$
- $E \sim f_\pi^2 m_\pi$

Son & Stephanov, PRD 77, 014021

π^0 domain-wall

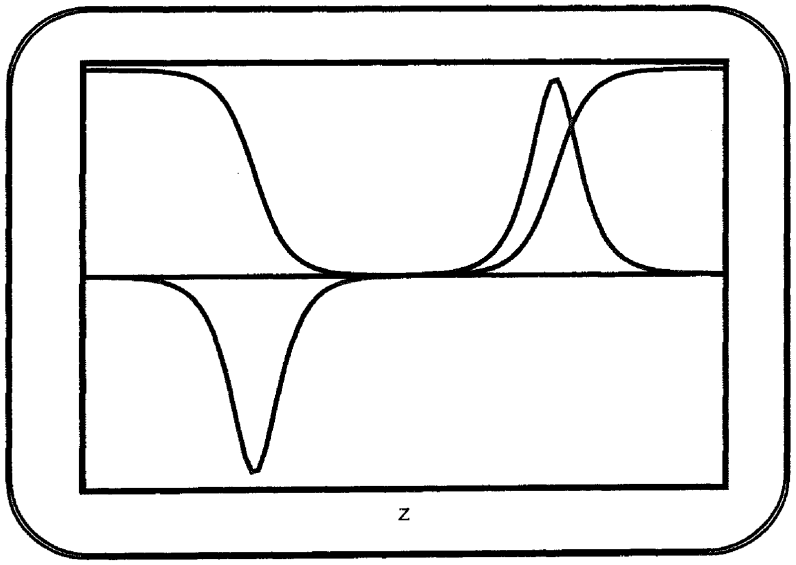
$$J_0 = \frac{3e^2 B}{2\pi^2}\left(q_u^2 - q_d^2\right)\frac{\boldsymbol{m}_\pi\, e^{m_\pi z}}{1 + e^{2m_\pi z}}$$



- $J_0 \to 0$ as $m_\pi \to 0$

Fluctuation of edm at low T

domain-wall — anti-domain-wall configuration



- $edm = d\ J_0$
- $\left\langle (edm)^2 \right\rangle \neq 0$
- vanishes in the chiral limit

Musings on Present and Future Azimuthal Charge-asymmetry Measurements

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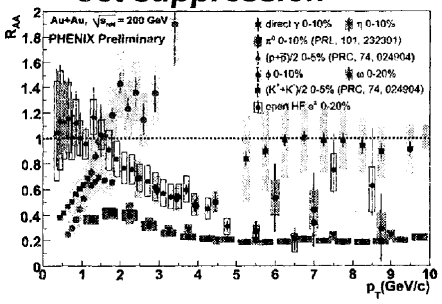
Chemistry Dept.
Stony Brook University

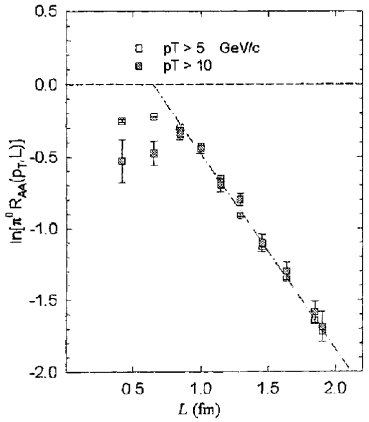
STONY BROOK
STATE UNIVERSITY OF NEW YORK

Charge

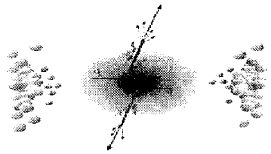
1. *Reiterate why charge-asymmetry measurements are important*
2. *Review the methodologies exploited in PHENIX and give a summary of current results from:*
   - *the two particle correlation technique*
   - *the multi-particle correlation technique (New)*
3. *Give a quick survey of measurements which could be insightful*

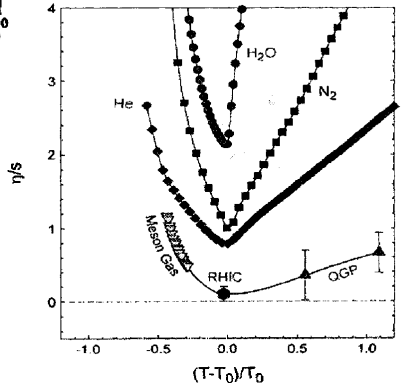
Jet suppression





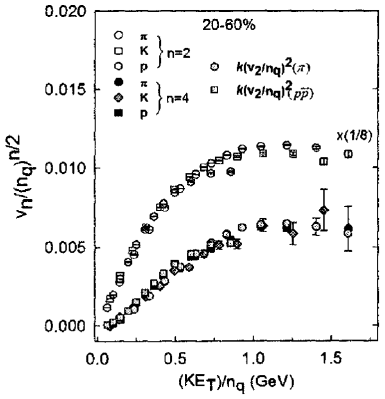
Jet suppression scales

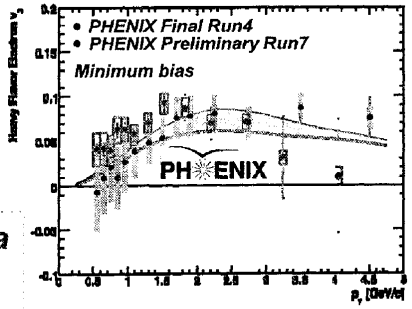




A strongly coupled plasma is produced in heavy ion Collisions at RHIC

Flow scales with q_n





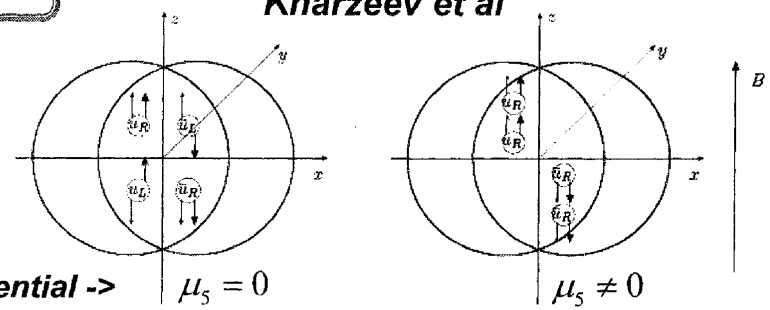
Charm Flows

Roy A. Lacey, Stony Brook University;
P- and CP-odd Workshop, BNL USA, April 26-30th, 2010

The Central Question

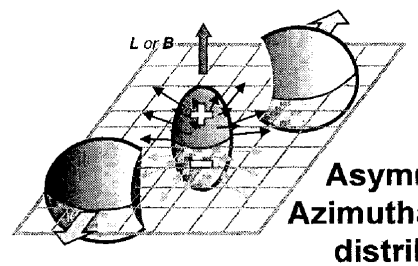
Axial anomaly ->
parity odd metastable domains
in which $u_L(\overline{u}_L) \neq u_R(\overline{u}_R)$

Chiral magnetic effect
Kharzeev et al



Chiral chemical potential ->

Does the new phase of QCD matter created in RHIC collisions provide new insights on P/CP invariance of the strong interaction ? If it does, how do we tell ?



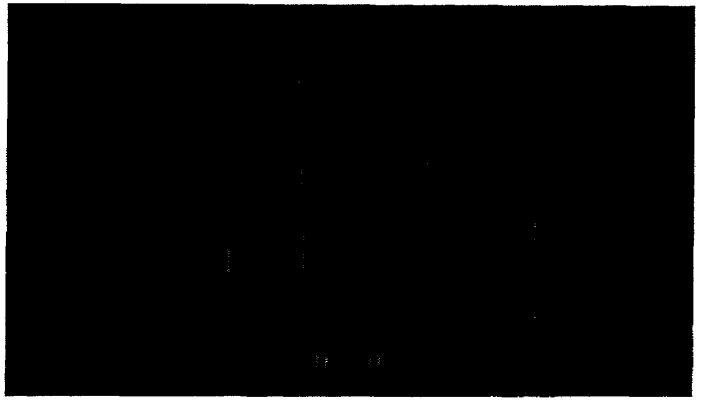
Asymmetric Azimuthal charge distribution

Axial anomaly ->
anomalous global symmetry current in hydrodynamics
D. Son et al

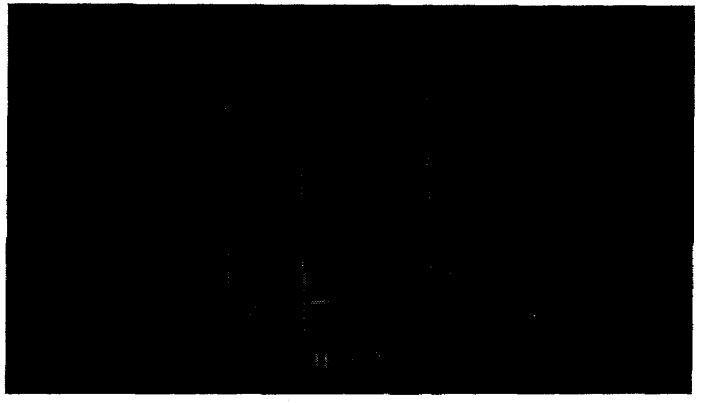
Chiral Magnetic Effect on the Lattice

Polikarpov et. al

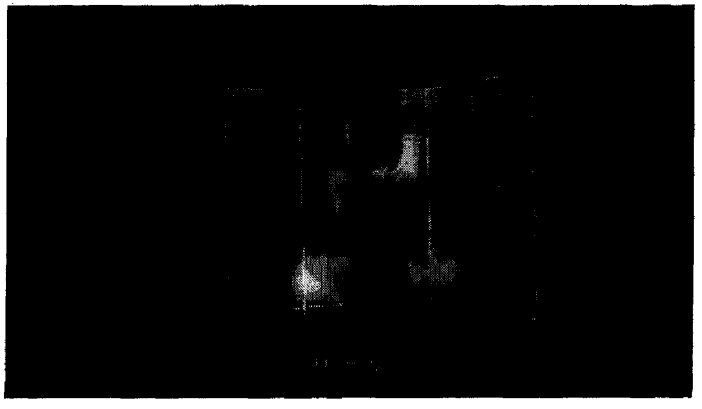
$B = 0$



$B = (500\,\mathrm{MeV})^2$



$B = (780\,\mathrm{MeV})^2$



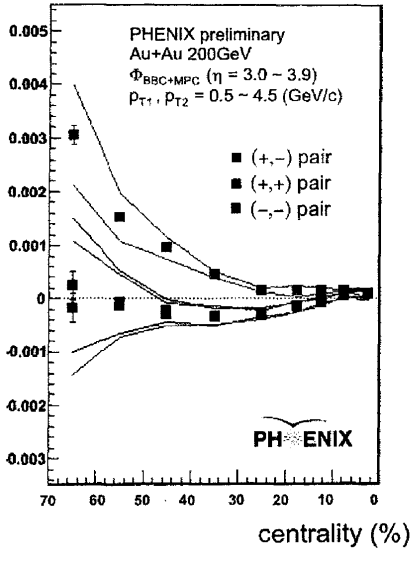
$B = (1.1\,\mathrm{GeV})^2$

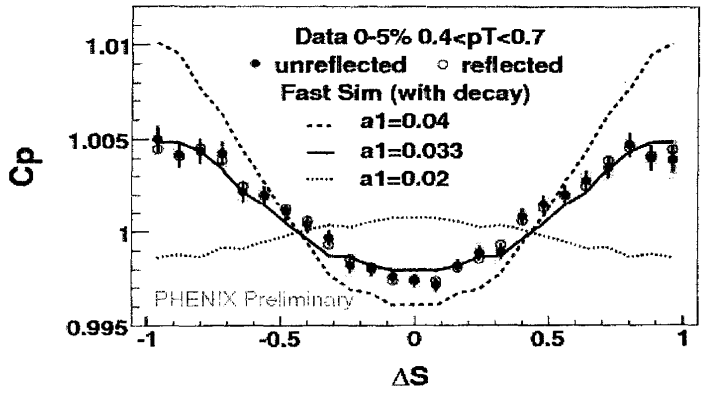
Lattice calculations now confirm the chiral magnetic effect

Summary

Azimuthal charge-asymmetry measurements are very well launched.

- **Charge-asymmetry observed..**





- **Much work remains**
  – but the stakes are high

P and CP odd effects in hot and dense matter
Future Studies

April 30, 2010

J. Sandweiss

P-CP workshop

As Yogi Berra noted “predictions are hard, especially for the future”

Nevertheless, I will offer some thoughts

About the topic, including some general observations which you probably already know, but which are relevant to “future Studies”.

P-CP workshop

- Perhaps the central issue derives from the fact that what we can observe is a correlation predicted by the LPV (local parity violation) theory but is not in itself a parity odd operator. Observation of this correlation thus does not definitively prove LPV.
- Indeed, there have been several attempts to show that this correlation could arise from what we could loosely call “known physics”.

P-CP workshop

- Therefore, the elucidation of the source of the observed effect requires considerable additional experimental and theoretical work, some of which I will try to describe.

- Many of the ideas have been given by others and I do not pretend to originality.

P-CP workshop

- One class of experiments are those where the LPV theory would not predict an effect, but which it is reasonable to expect that the non LPV "background" effects should be present.
- Another class of experiments studies the behaviour of the LPV effect as the experimental parameters are varied. Clearly this study requires the theory to predict what the behaviour should be. To do this adequately in most cases is a considerable challenge to theorists.

P-CP workshop

- To summarize:
- A long program of experiment and comparison with theoretical models of the LPV effect and of other non LPV theories needs to be done if we are to understand

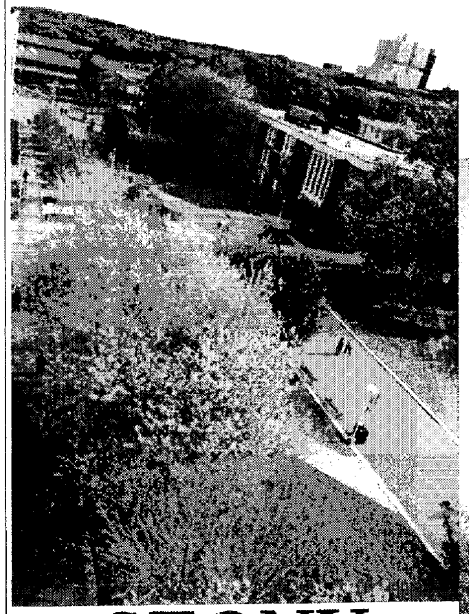
origin and physics of the correlations we have observed.

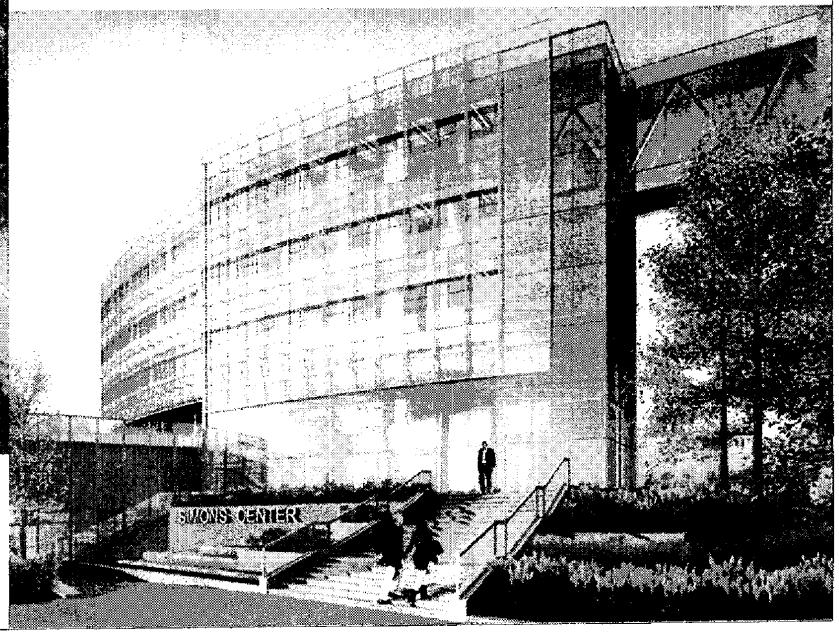
But the goal is a much more profound understanding of the nature of the new state(s) of hadronic matter discovered at RHIC

2nd Workshop on P- and CP-odd Effects in Hot and Dense Matter ("CP-Odd 2012")

Stony Brook University, Spring 2012

Simons Center for Geometry and Physics





STONY BROOK
STATE UNIVERSITY OF NEW YORK

P- and CP-odd Effects in Hot and Dense Matter

April 26–30, 2010

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P- and CP-odd Effects in Hot and Dense Matter

April 26–30, 2010

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P- and CP-odd Effects in Hot and Dense Matter

BNL, Physics Department Large Seminar Room
April 26-30, 2010

Agenda

Monday, April 26

8:30 - 9:15 ***Registration*** *(coffee and pastries served)*

Chair: D. Kharzeev

9:15	N. Samios	Welcome from RBRC (10')
9:25	E. Shuryak	Confinement and Magnetic Plasma Near Tc (40+10')

10:15 - 10:35 ***Coffee Break***

10:35	H. Warringa	The Chiral Magnetic Effect (30+10')
11:15	G. Moore	What We Do and Don't Know about the SU(3) Sphaleron Rate (30+10')

11:55 – 1:30 ***Lunch***

Chair: A. Deshpande

1:30	M. Polikarpov	Magnetic Field Induced Conductivity of the Vacuum of Gluodynamics (30+10')
2:10	D. Son	Axial Anomalies and Hydrodynamics (30+10')

2:50 - 3:10 ***Coffee Break***

3:10	S. Voloshin	Results from STAR (40+10')
4:00	R. Lacey	Results from PHENIX (40+10')

Tuesday, April 27

Chair: D. Son

9:00	A. Rebhan	CME in the Sakai-Sugimoto Model (30+10')
9:40	H.U. Yee	Holographic CME (30+10')

10:20 - 10:40 ***Coffee Break***

10:40	B. Mueller	Some Mechanisms for Charge Asymmetry Fluctuations with Respect to the Reaction Plane (30+10')
11:20	G. Dunne	Chiral Magnetic Spiral (30+10')
12:00	T. Kojo	Quarkyonic Chiral Spirals (30+10')

12:40 – 2:00 ***Lunch***

2:00 Physics Department Colloquium: N. Wingreen, Intracellular Networks
4:00 BSA Lecture (Berkner Hall): V. Rubakov, Extra Dimensions of Space

Wednesday, April 28

Chair: L. McLerran

9:00	M. D'Elia	Thermal Abelian Monopoles in the Deconfined Phase of Yang-Mills Theories (30+10')
9:40	P. van Baal	Progress on Calorons (30+10')

10:20 - 10:40 ***Coffee Break***

10:40	M. Stephanov	Axial Anomaly and Magnetism of Nuclear and Quark Matter (30+10')
11:20	S. Pandiat	Superhorizon Fluctuations, CMBR and Relativistic Heavy Ion Collisions (TBC) (15+5')
11:40	A. Chikanian	Effects of Magnetic Field in Heavy Ion Collisions (15+5')
12:00	H. Petersen	Medium-modified Jets and Initial State Fluctuations as Sources of Charge Correlations Measured at RHIC (15+5')

12:20 – 2:00 ***Lunch***

2:00	S. Sachdev	Quantum Criticality and the Cuprate Superconductors (50+10')

3:00 – 3:30 ***Coffee Break***

Chair: A. Tsvelik

3:30	Y. Nishida	Is a Color Superconductor Topological? (30+10')
4:10	E. Gubankova	Quantum Hall Effect in Holographic Graphene (30+10')

Thursday, April 29

Chair: S. Voloshin

9:00	D. Espriu	Parity Breaking in Dense Nuclear Matter (30+10')
9:40	J. Liao	Probing the Topological Environment in Heavy Ion Collisions (30+10')
10:20	T. Blum	CME on the Lattice (30+10')

11:00 - 11:20 ***Coffee Break***

11:20	Z. Kang	P-odd Correlations in Quark Fragmentation (30+10')
12:00	A. Vossen	Belle Results on Charged Pion Correlations and Prospects for Detecting P-odd Effects (30+10')

12:40 – 2:00 ***Lunch***

Chair: H. Warringa

2:00	J. Boomsma	The Combined Influence of Instantons and Strong Magnetic Fields on Quark Matter (30+10')
2:40	A. Mizher	CP Violation and the Nature of the Chiral Transition (30+10')

3:20-3:40 ***Coffee Break***

3:40 Discussion on New Theory Ideas (everyone is encouraged to submit a short talk) **Leader**: K. Fukushima
4:40 F. Wang Measurements of Charge Asymmetry Correlations in High Energy Nuclear Collisions
5:10 Discussion on the Experimental Results

6:00 ***Workshop Banquet,*** *Brookhaven Center South Room (for registered participants)*

Friday, April 30

Chair: M. Polikarpov

9:00	L. McLerran	The Glasma and Topological Charge (30+10')
9:40	E. Fraga	Phase Diagram of Hot QCD in an External Magnetic Field (30+10')

10:20 - 10:40 ***Coffee Break***

10:40	A. Andrianov	Photon Instability in Variable Pion/axion Condensate: A Possible Hint to PHENIX Anomaly (30+10')
11:20	V. Rubakov	CP Violation and Baryogenesis (30+10')
12:00	A. Zhitnitsky	Cosmological and Astrophysical Implications of P- and CP-odd Phenomena in QCD (30+10')

12:40 – 2:00 ***Lunch***

Chair: E. Shuryak

2:00	V. Miransky	Response of Dense Relativistic Matter to a Magnetic Field (30+10')
2:40	S. Mukherjee	Charge Separation in the Chirally Broken Phase (30+10')

3:20 - 3:40 ***Coffee Break***

3:40	R. Lacey	Local Parity Violation Studies with PHENIX (30+10')
4:20	J. Sandweiss	Future Studies of Local Parity Violation with STAR (30+10')
5:00	E. Shuryak	Announcement CP 2010

6:00 ***Workshop Ends***

Additional RIKEN BNL Research Center Proceedings:

Volume 95 – Progress in High-pT Physics at RHIC, March 17-19, 2010 – BNL-94214-2010
Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009 – BNL
Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1-31, 2009 – BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30-July 4, 2008, Beijing, China, BNL-81685-2008
Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 – BNL-81478-2008
Volume 89 – Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 – BNL-81318-2008
Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, Dec 12-14, 2005 – BNL-76915-2006
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – RBRC Scientific Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003

Additional RIKEN BNL Research Center Proceedings:

Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics –BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

RIKEN BNL RESEARCH CENTER

P- and CP-odd Effects in Hot and Dense Matter

April 26-30, 2010

Li Keran

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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

A. Andrianov	T. Blum	J. Boomsma	A. Chikanian	M. D'Elia
G. Dunne	D. Espriu	E. Fraga	E. Gubankova	Z. Kang
T. Kojo	R. Lacey	J. Liao	L. McLerran	G. Moore
V. Miransky	A. Mizher	B. Mueller	S. Mukherjee	Y. Nishida
S. Pandiat	H. Petersen	M. Polikarpov	A. Rebhan	V. Rubakov
S. Sachdev	J. Sandweiss	D. Son	E. Shuryak	M. Stephanov
P. van Baal	S. Voloshin	A. Vossen	F. Wang	H. Warringa
H.U. Yee	A. Zhitnitsky			

Organizers: K. Fukushima, D. Kharzeev, H. Warringa, A. Deshpande and S. Voloshin