Achieving RHIC science goals: theory perspective

D. Kharzeev

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Office of Science
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

BROOKHAVEN NATIONAL LABORATORY

Brookhaven Science Associates
U.S. Department of Energy

Our mission

- Excellence in scientific research aimed at reaching the goals set by BNL and DOE Office of Science
- Support and guidance for the experimental programs at RHIC and elsewhere
- Training the new generation of nuclear theorists
- Chart the course for the future developments in Nuclear Physics

Staff of the Nuclear Theory Group

Marcy Chaloupka - Secretary

Permanent Scientific Staff:

1. A. Baltz
2. D. Kharzeev (Group Leader)
3. L. McLerran
4. J. Millener
5. R. Pisarski
6. R. Venugopalan
7. W. Vogelsang

Research Scientists:

1. G. Soyez (LDRD)
2. H. Warringa

The physics program of BNL Nuclear Theory Group and the NSAC performance milestones

Physics of High Temperature and High Density Hadronic Matter:

a) perform realistic 3D numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC

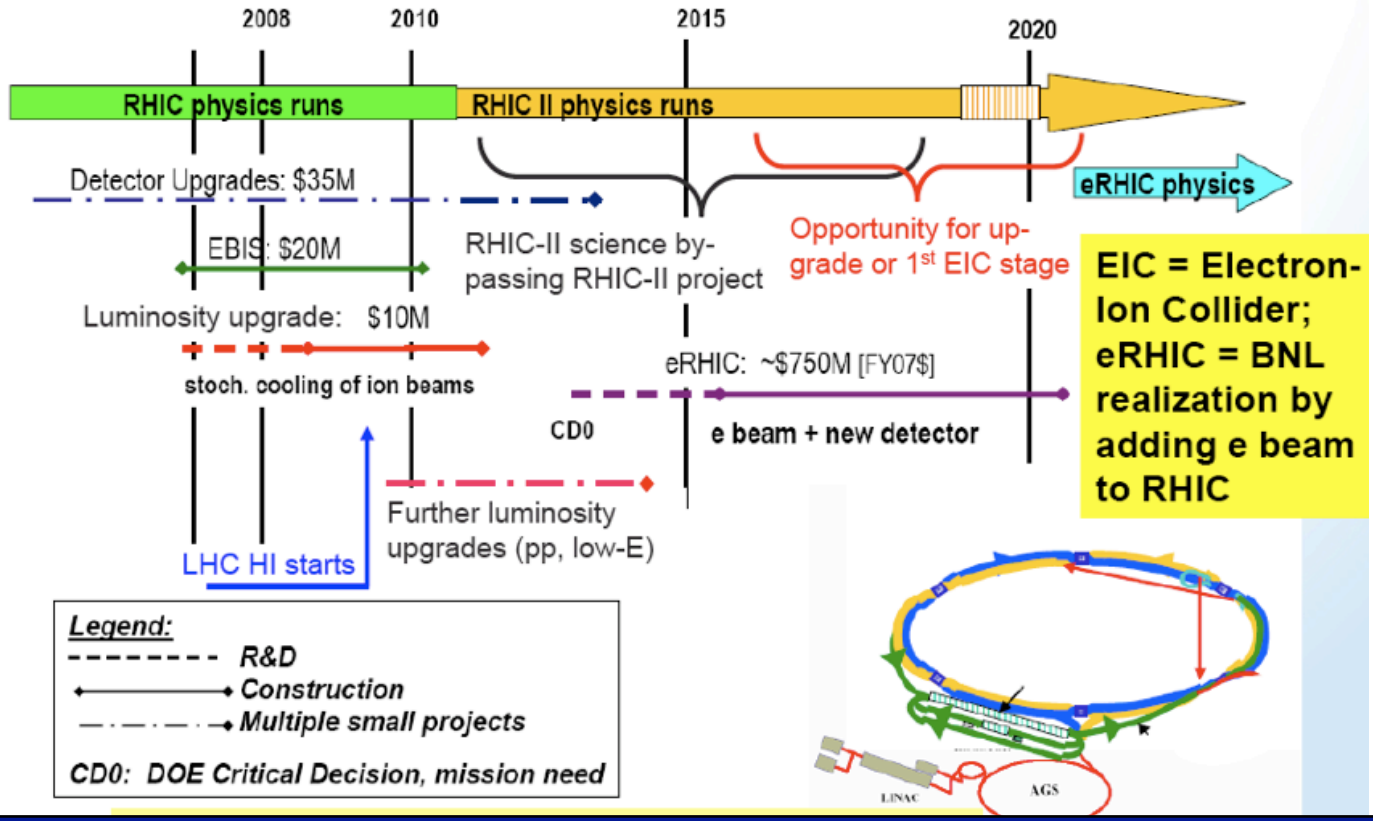
b) complete realistic calculations of jet production in a high density medium for comparison with experiment

c) Determine gluon densities at low x in cold nuclei

Hadronic physics: a) Make measurements of spin carried by the glue in the proton

b) Carry out ab-initio microscopic studies of the structure and dynamics of light nuclei + Nuclear Structure and Astrophysics

Nuclear Theory program in the context of BNL long-term plans



NT program is tightly connected to
the existing and planned experimental programs at BNL
and to the NSAC performance milestones for Nuclear Theory

The physics program of BNL Nuclear Theory Group

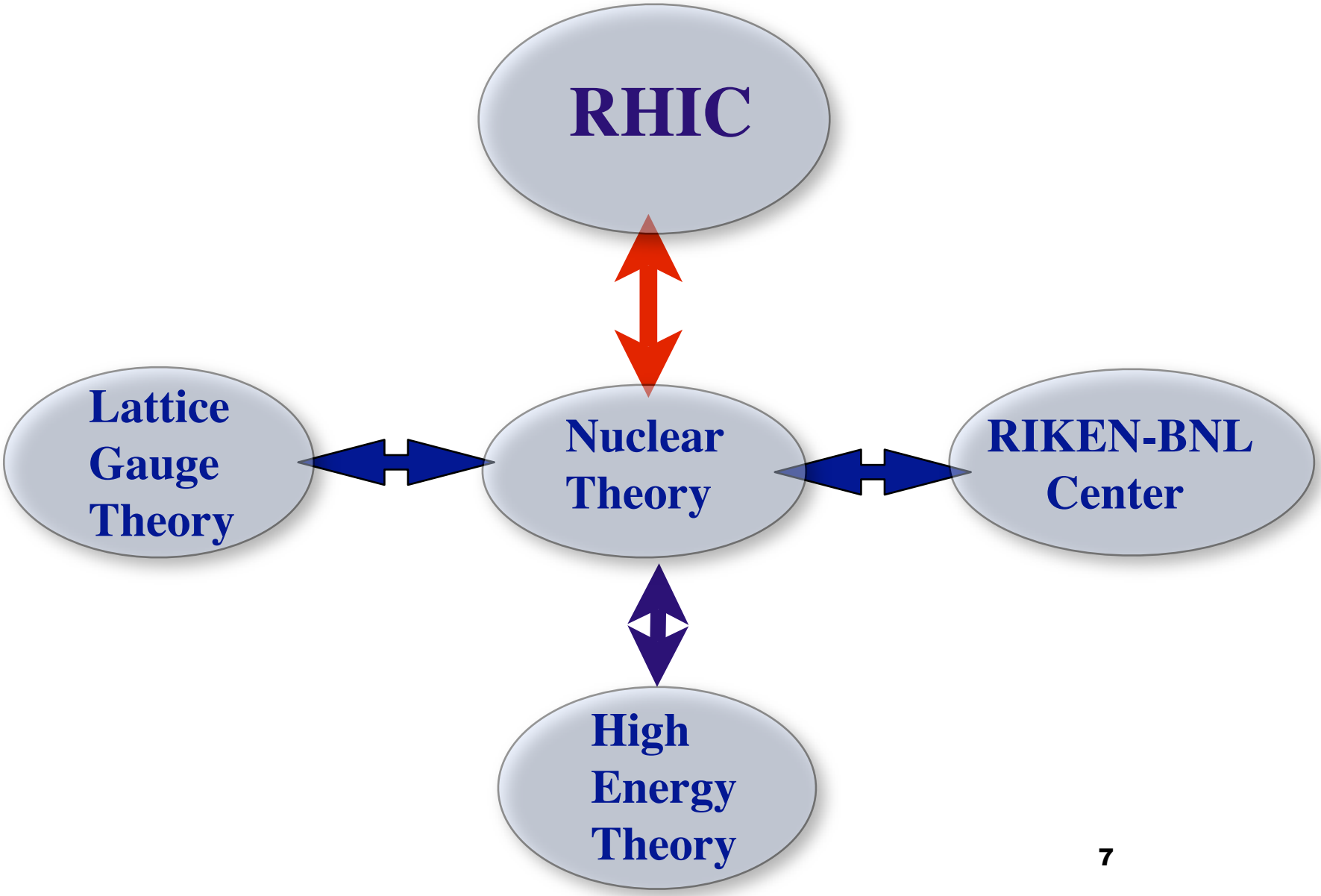
1. Quantum Chromo-Dynamics at finite temperature and density and the physics of Quark-Gluon Plasma

2. QCD at high energies and small x and the physics of the Color Glass Condensate

3. Perturbative QCD and the spin structure of the nucleon

4. Electromagnetic interactions of nuclei at high energies and nuclear structure

Nuclear Theory Group at BNL



RIKEN-BNL Center:

Founded by T. D. Lee

Director: N. Samios

Associate Director: H. Enyo

Theory Group Leader: L. McLerran

Experimental Group Leader: G. Bunce

Funded by RIKEN Institute in Japan

Physics Interests:

Experimental and Theoretical Aspects of Spin and Heavy Ion Collisions

Lattice Gauge Theory and QCDOC

Theory of Strong Interactions

Funds workshops, joint university fellows and postdocs

Renewed funding for

5 years

Slides from L.McLerran

Current Interests in RIKEN-BNL Center

Lattice Gauge Theory

Masses and matrix elements of hadrons
CKM matrix
Properties of QGP and hadronic matter

Structure of Hadrons

Origin of spin
Quark and gluon distribution functions
Perturbative QCD at RHIC and LHC

Color Glass Condensate, Glasma, Quark Gluon Plasma

High Energy Density Matter
RHIC Phenomenology
Everything for

$$x \leq 10^{-2}$$

RIKEN-BNL Theoretical Physics Fellows

Graduates

T. Blum, Tenured, U of Connecticut
D. Bodeker, Tenured C4, Bielefeld
D. Kharzeev , Tenured BNL
D. Rischke, Tenured C4 Frankfurt
D. Son, Tenured U of Washington
R. Venugopalan, Tenured BNL
T. Wettig, Tenured C-3 Regensburg
M. Stephanov Tenured U of Ill, Chicago
U. Van Kolck, Tenured U of Arizona
T. Schaefer, Tenured U of N. Carolina
A. Kusenko, Tenured UCLA
W. Vogelsang, Tenured at BNL
S. Bass, Tenured at Duke
T. K. Iida Tenured at Koichi U,
U. Wiedemann, Perm. Staff, CERN
S. Sasaki, Assoc. Prof. U of Tokyo
S. Jeon, Tenured at McGill
Chris Dawson*, Asst. Prof. Virginia

Current Fellows

S. Aoki, Tsukuba
R. Fries, Texas A&M
T. Izubuchi, Kanazawa U.
C. Lunardini, Arizona State
D. Molnar, Purdue
D. Teaney, Stony Brook
K. Tuchin, Iowa State
F. Yuan. LBL

Next Year:

A. Dumitru, Baruch College
T. Izubuchi, BNL
Anna Stasto, Penn State U

Current RBRC Fellows and Postdocs:

Spin and
Perturbative QCD:

C. Marquet,
(Columbia)

High Density Matter-
Phenomenology

K. Fukushima (-> Yukawa Inst.)

A. Mocsy (-> Pratt Institute) ,

Y. Hidaka, T. Kojo

M. Hamada (student)

Lattice:

S. Ohta

Y. Aoki, , T. Ishikawa, A. Lichtl, P. Petreczky

Success of Japanese RBRC

Young People

Kenji Fukushima Yukawa Inst. Asst. Professor (RBRC Postdoc)

K. Iida Tenured Koichi U. (RBRC Fellow)

Hiro Fuji Asst. Professor U of Tokyo (RBRC Postdoc)

S. Sasaki Assoc Prof. U of Tokyo (RBRC Fellow)

Tetsu Hirano Asst. Prof. U of Tokyo (RBRC Postdoc)

Masakiyo Kitazawa Asst. Prof. Osaka U. (RBRC Postdoc)

Yoshi Hatta Asst. Prof. Tsukuba U. (RBRC Student and Postdoc)

Y. Nara, Asst. Prof. Akita Intl. U. (RBRC Postdoc)

Taku Izubuchi, Kanazawa U -> BNL (RBRC Fellow)

Kazu Itukura, KEK (RBRC Postdoc)

Workshops:

Spin and Pert. QCD 39

Lattice and Computing 11

Quark Gluon Plasma 8

High Energy QCD 2

Jets and Hard Processes at RHIC 4

Flow, Hydrodynamics and Event Simulation 4

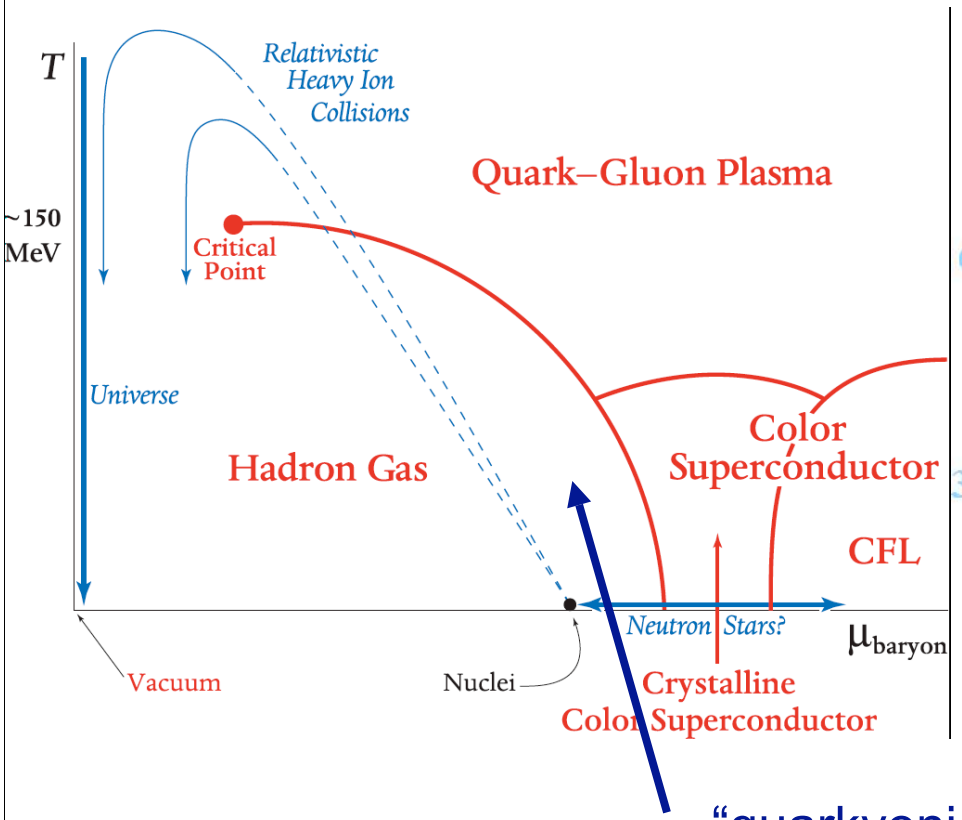
Hadron Physics and QCD 4

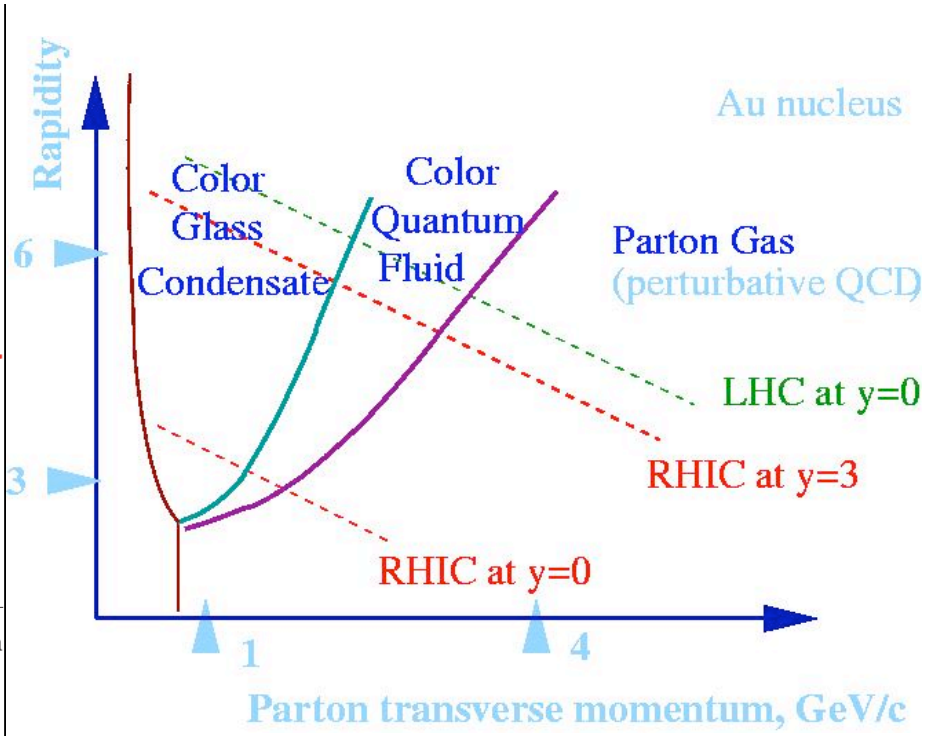
Color Glass Condensate 3

New Discoveries at RHIC 1

Research highlights:

QCD at high densities and energies

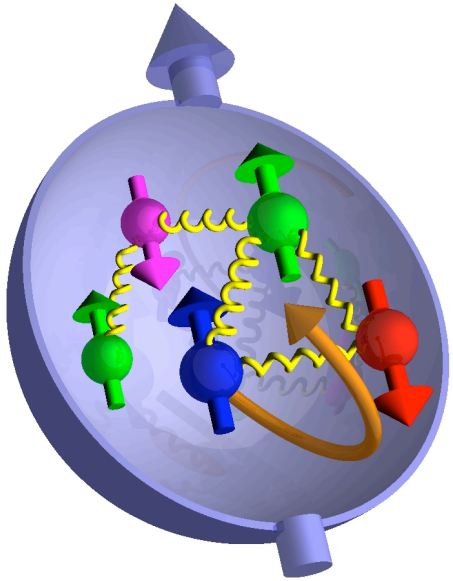




"quarkyonic" phase
(McLerran-Pisarski '07)

Exciting program with polarized protons underway at RHIC:

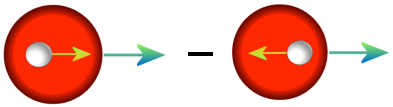
What carries the proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Quark spins

only ≈ 20 %



Gluon spins

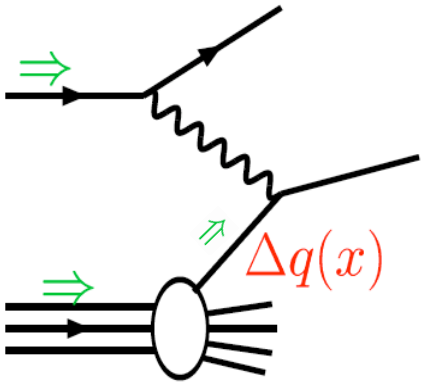
??

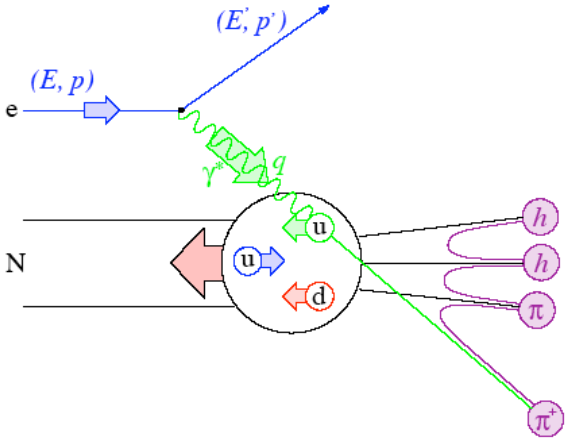
Quark and gluon orbital ang. mom.

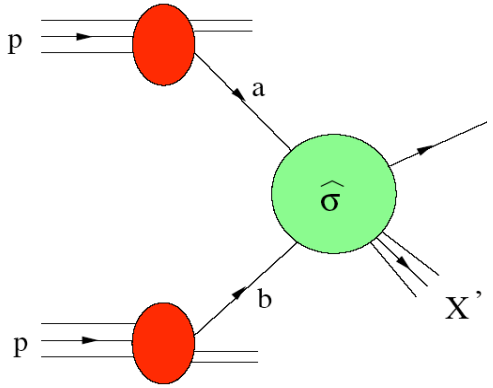
??

- **BNL Nuclear Theory devotes a major effort to QCD spin physics, in particular for RHIC**

Information on nucleon helicity structure :



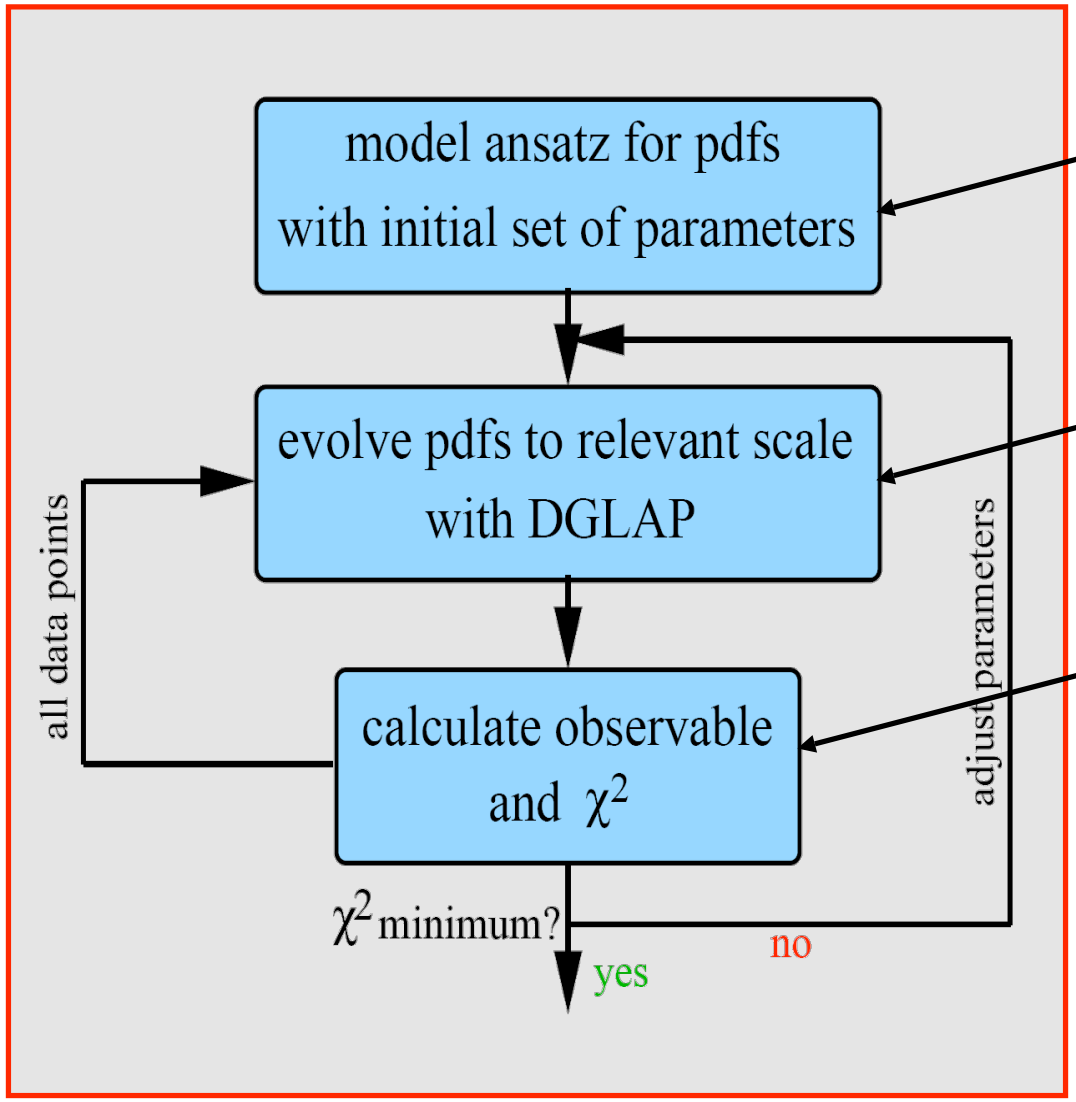




DIS **SIDIS** **RHIC**

- each reaction provides insights into certain aspects
- need to get best possible combined information:
  extract spin-dependent parton distribution functions

The solution: "global pdf analysis"



$$\Delta q(x,\mu_0)\,,\ \Delta g(x,\mu_0)$$
$$\propto\ N x^{\alpha}(1-x)^{\beta}\times\ldots$$

$$\Delta q(x,\mu)\,,\ \Delta g(x,\mu)$$

main bottleneck: complexity of NLO cr.sec. for pp need to compute ~10^5 times in fit!

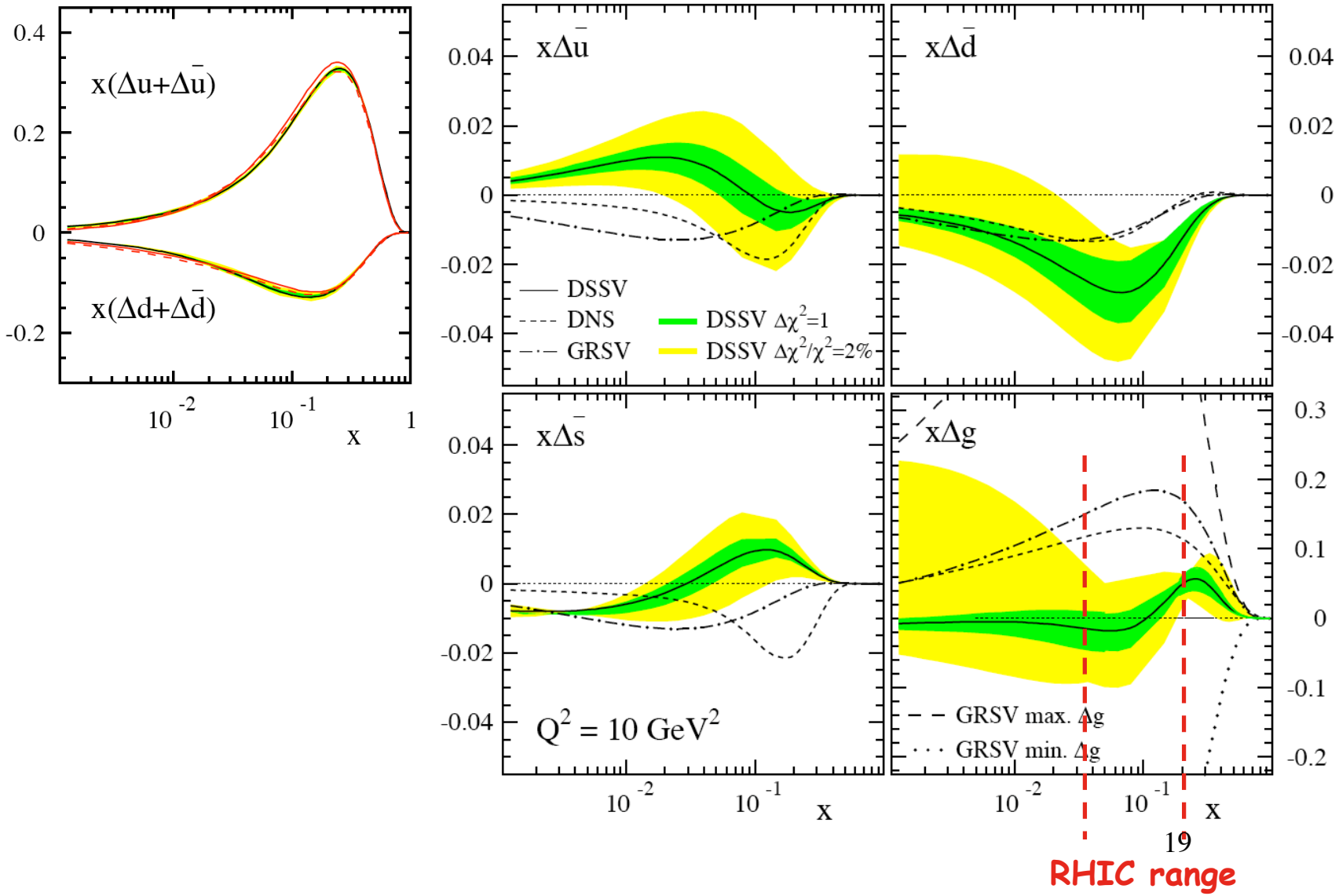
This problem has now been solved:

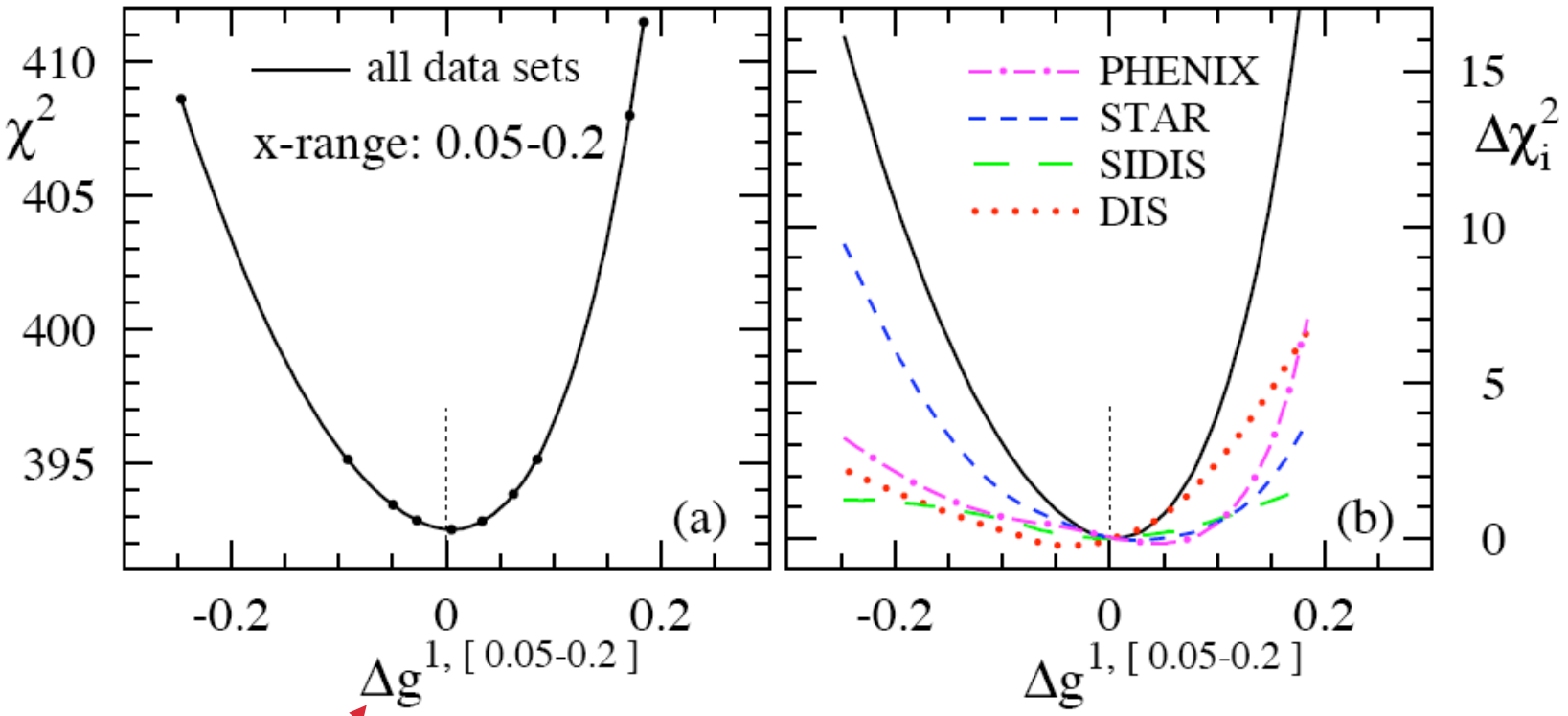
de Florian, Sassot, Stratmann, Vogelsang

- involves a number of tricks and techniques, such as
  - Mellin moments
  - Reorganization of the calculation
  - Monte-Carlo sampling
- this speeds up calculation by factor ~1,000
- will turn into collaborative effort between
  - theorists and experimentalists
- will be crucial tool for realizing RHIC's full potential

Resulting parton distributions:

de Florian, Sassot, Stratmann, Vogelsang



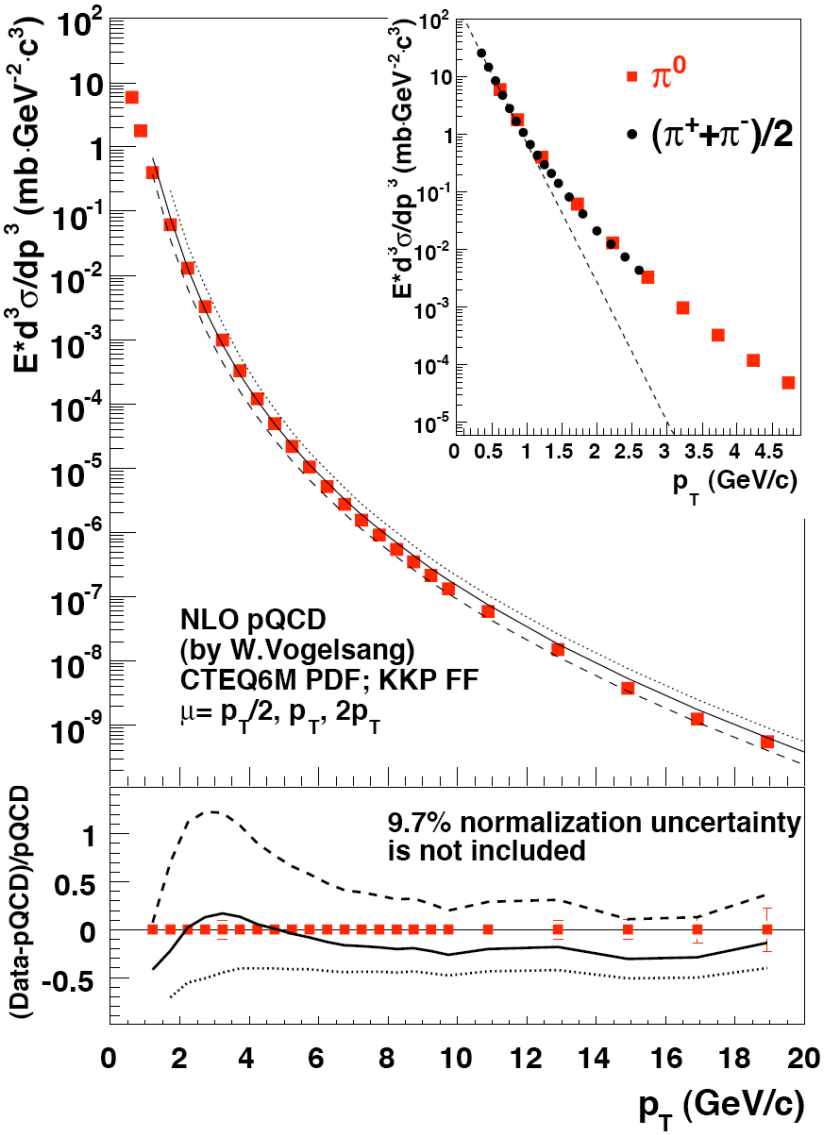


$$\int_{0.05}^{0.2} dx\, \Delta g(x)$$

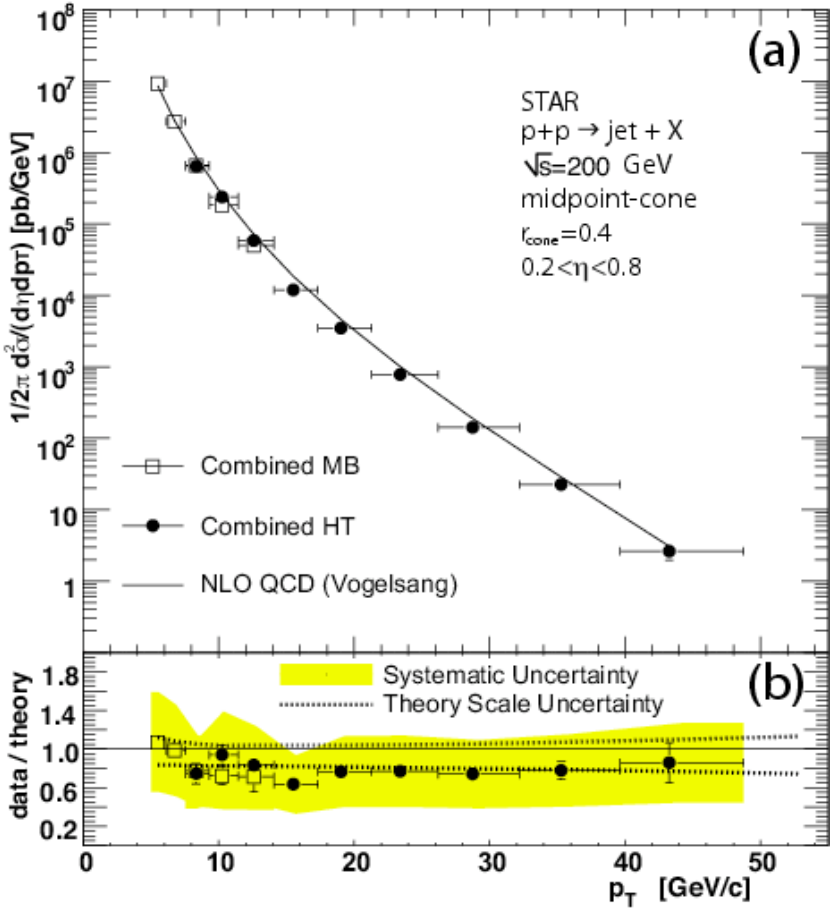
TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

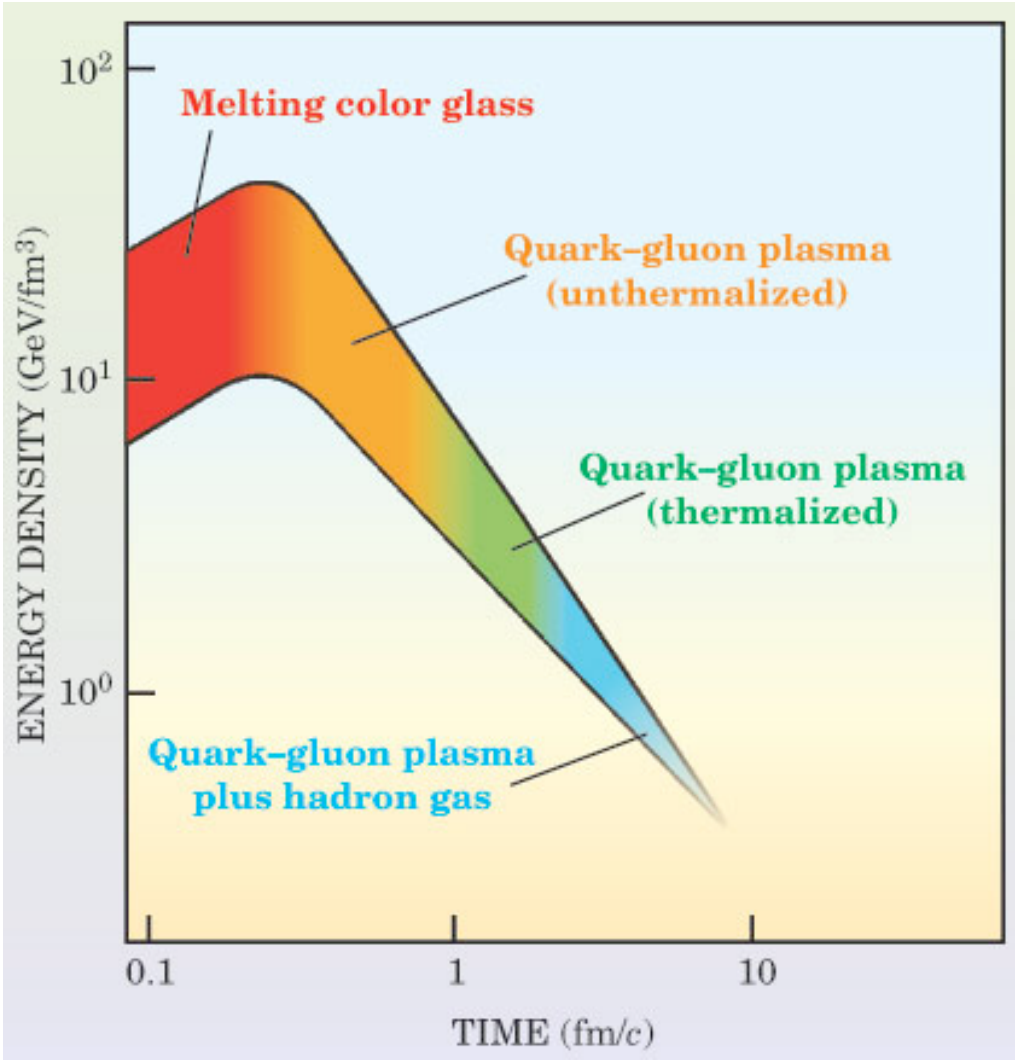
$pp \rightarrow \pi^0 X$ **PHENIX**



$pp \rightarrow \text{jet } X$ **STAR**



Time evolution in heavy ion collisions

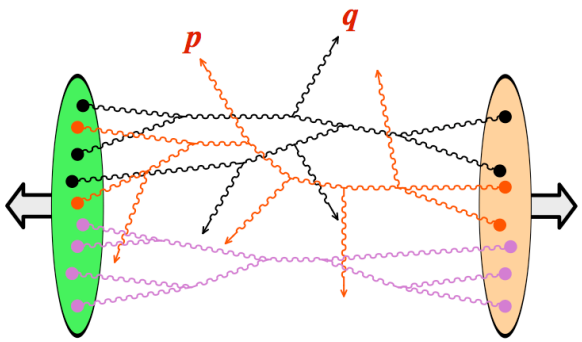


T. Ludlam,
L. McLerran,
Physics Today
October 2003

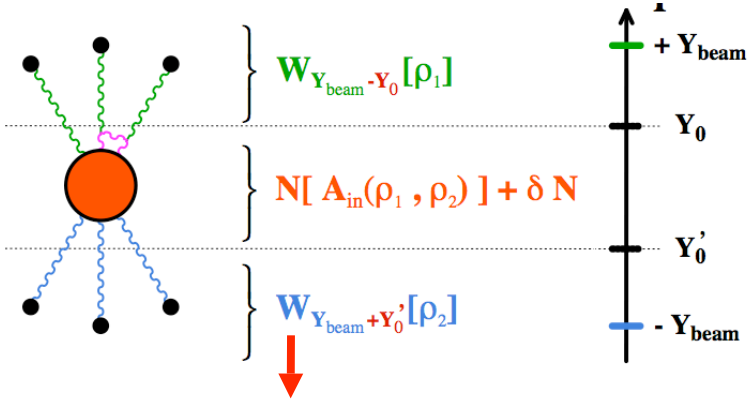
QCD Factorization, the Glasma & early thermalization

❑ ***Ab initio*** **quantitative framework for early (Glasma) stage of HI collisions**

Gelis, Lappi, Venugopalan, arXiv:0804.2630 [hep-ph]



Proof of high energy factorization in HI collisions at NLO: separate initial and final state effects



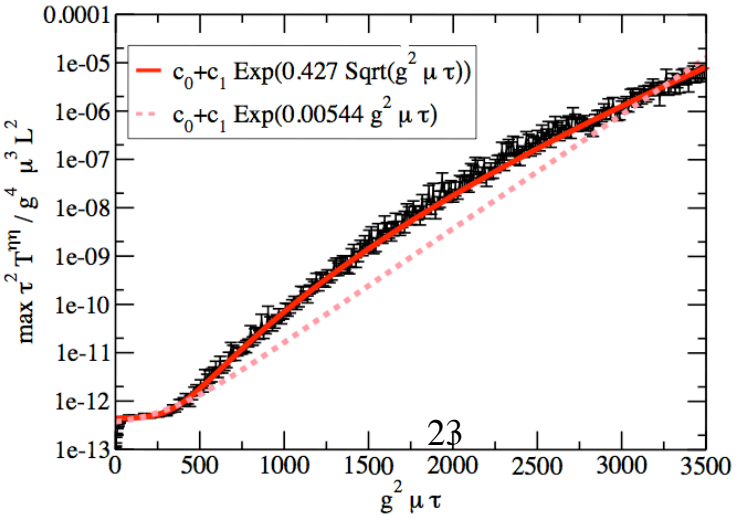
Universal dists. W -determined from p/D+A or e+A- obey JIMWLK evolution eqns

NLO quantum fluctuations cause instabilities in final state

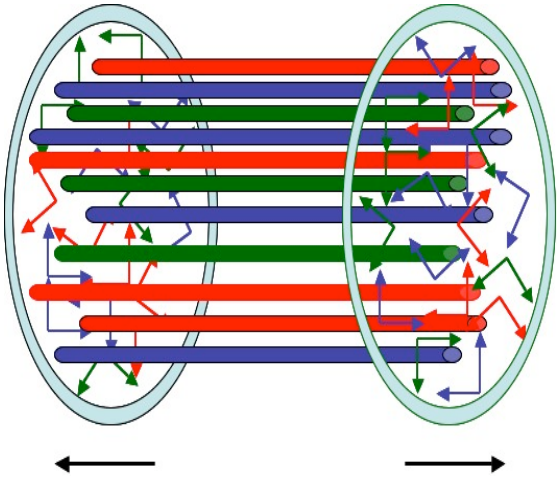
Romatschke, Venugopalan,
PRL 96, 062302 (2006), PRD 74:045011 (2006)

Systematic resummation of "secular divergences" gives more isotropic initial conditions - possible mechanism for early thermalization

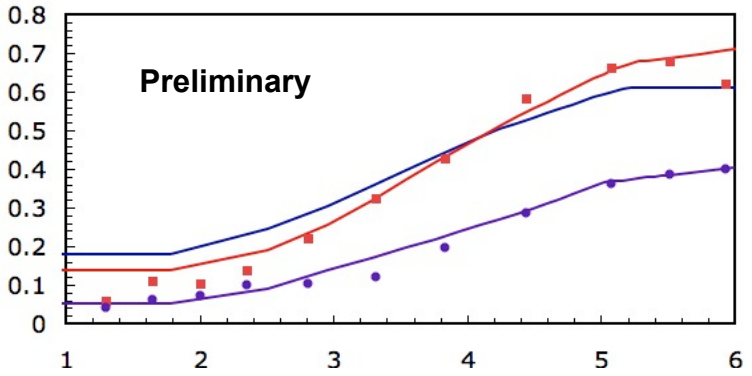
Gelis, Lappi, Venugopalan,
Int. J. Mod. Phys. E16:2595 (2007)



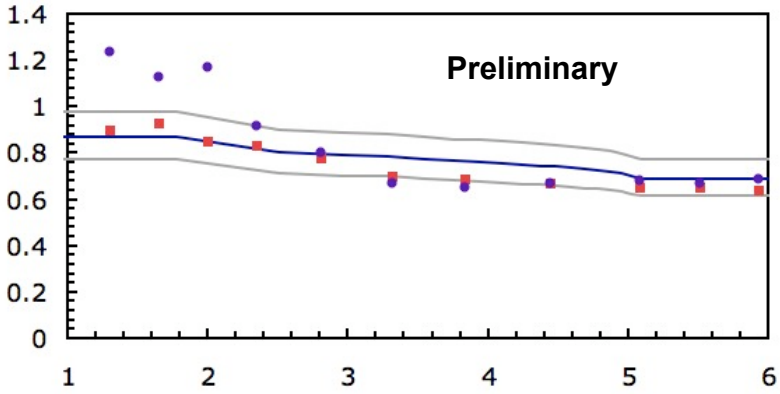
Seeing Glasma Flux Tubes at RHIC



Amplitude vs Centrality



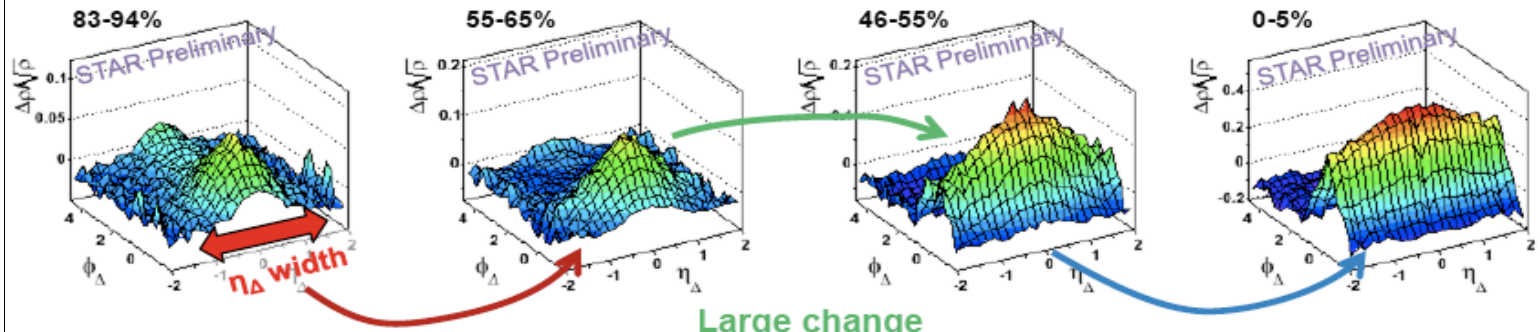
Angular width vs Centrality



Use only Blast Wave fits to Phenix,

Kharzeev-Nardi fit to multiplicity

No new parameters!



Shape changes little from peripheral to the transition

Large change within ~10% centrality

Smaller change from transition to most central

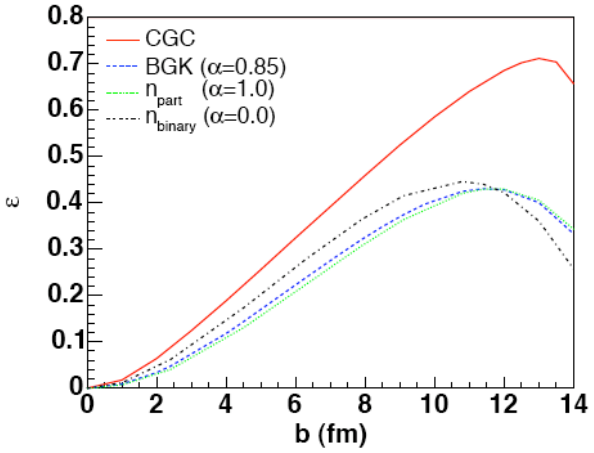
Low-p_T manifestation of the "ridge"

Dumitru, Gelis, McLerran and Venugopalan,

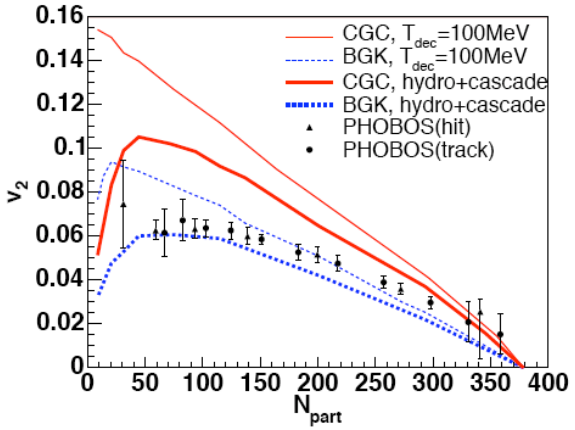
Gavin, McLerran and Moschelli

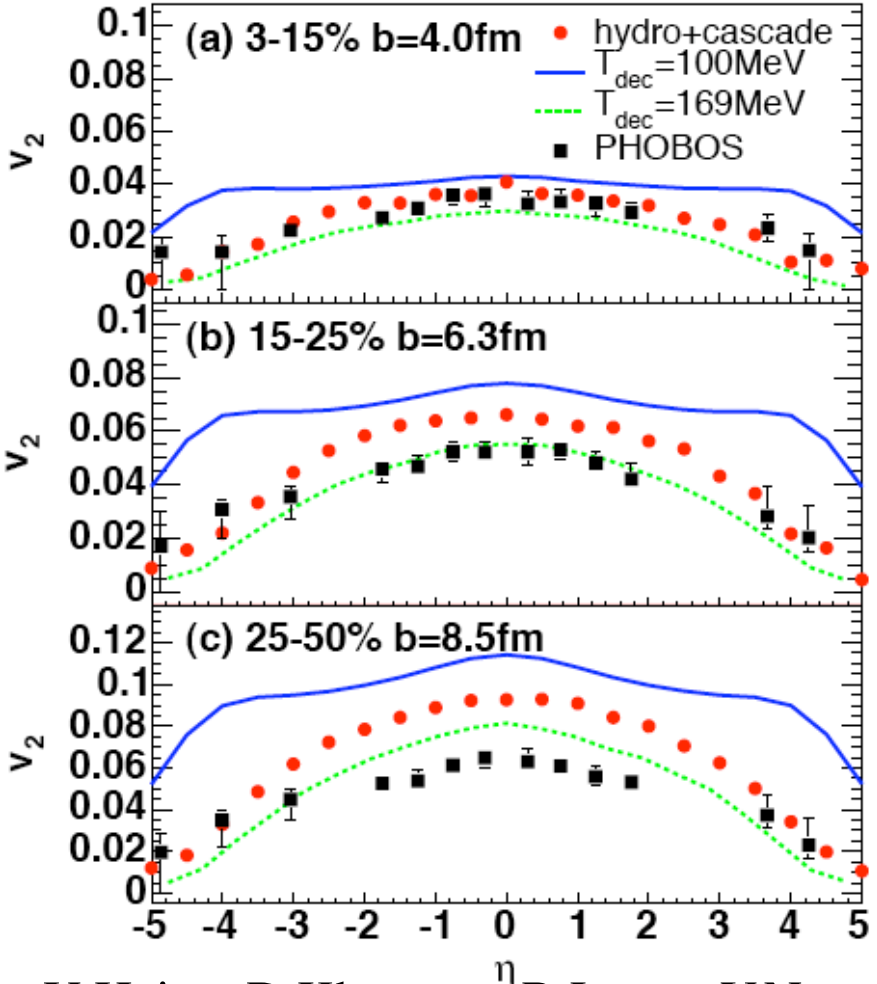
How small is the viscosity of sQGP?

CGC initial conditions lead to larger ellipticity,



require some viscous effects:

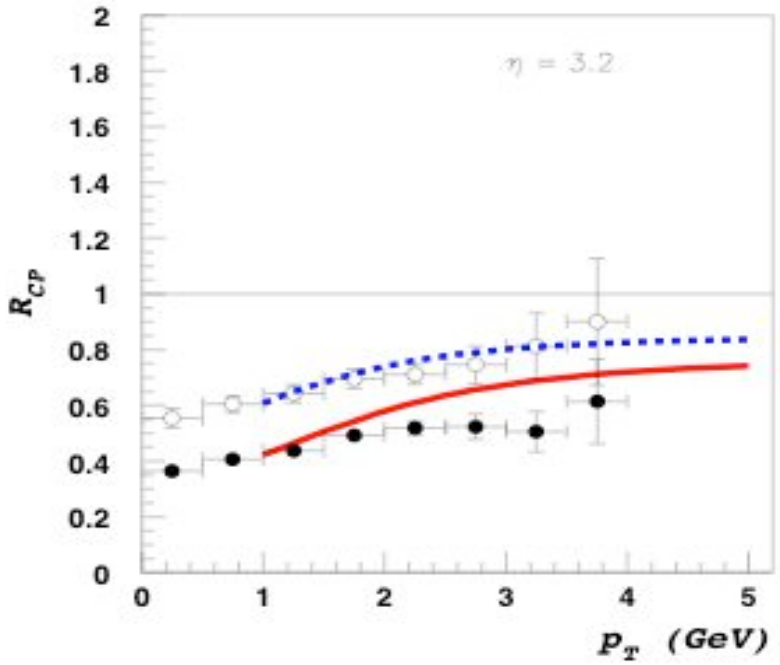




T.Hirano, U.Heinz, D.Kharzeev, R.Lacey, Y.Nara;
T. Lappi, R. Venugopalan

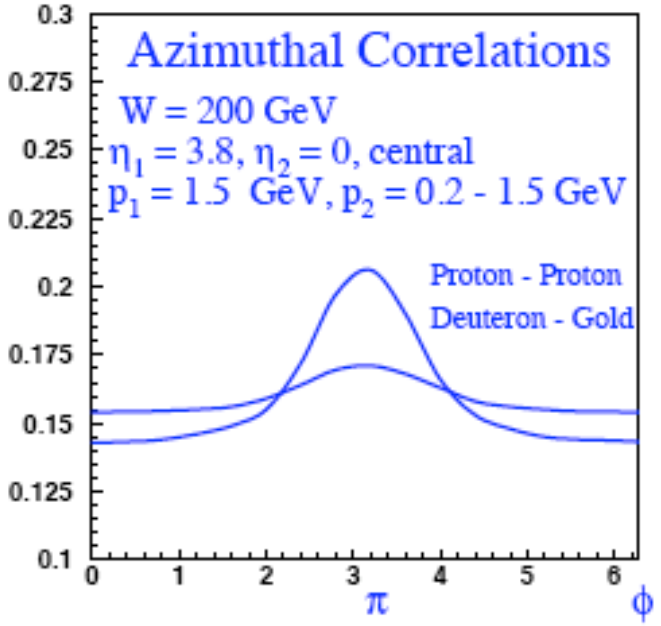
Color Glass Condensate at RHIC

Synergy between Nuclear Theory group and
RHIC experimentalists



Kharzeev-Kovchegov-Tuchin

"monojet" correlations:
ongoing test in dAu data!



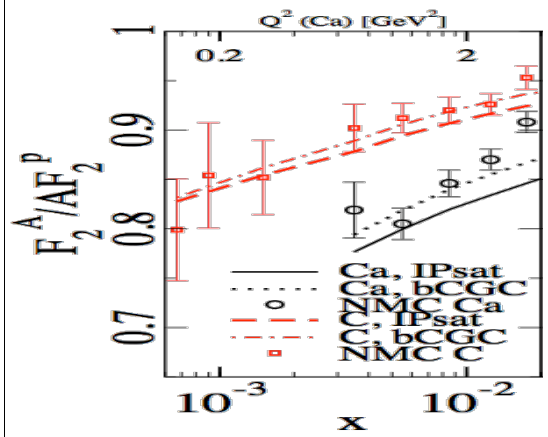
Kharzeev-Levin-McLerran

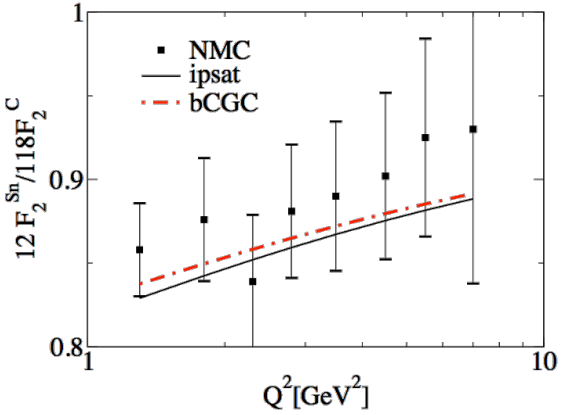
- **Saturation models (bCGC/IPsat) fit to HERA F_2 data give Chi-sq. ~ 1 agreement with HERA diffractive data.**

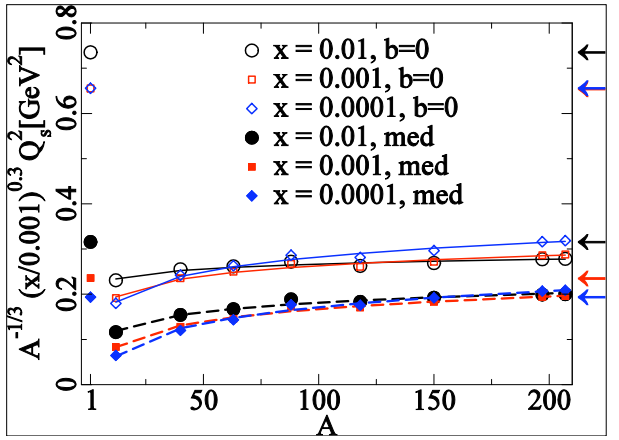
Kowalski,Lappi,Marquet,Venugopalan, arXiv:0805.4071[hep-ph]

- **Parameter free agreement with fixed target e+A data - predict $Q_s^2 \sim Q^2_{s,p} A^{1/3}$**

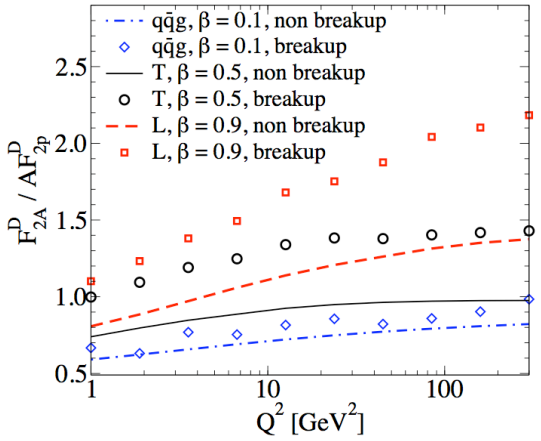
Kowalski,Lappi,Venugopalan, PRL 100:022303 (2008)

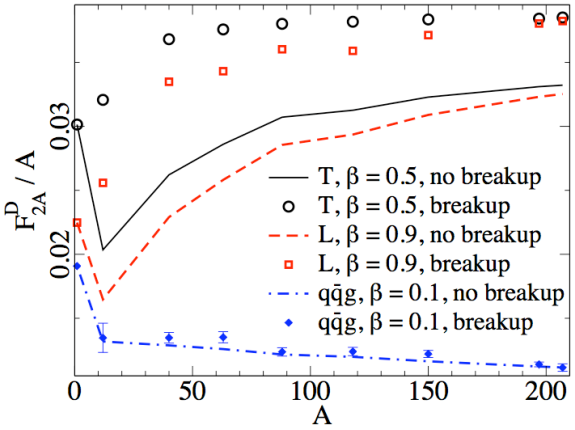


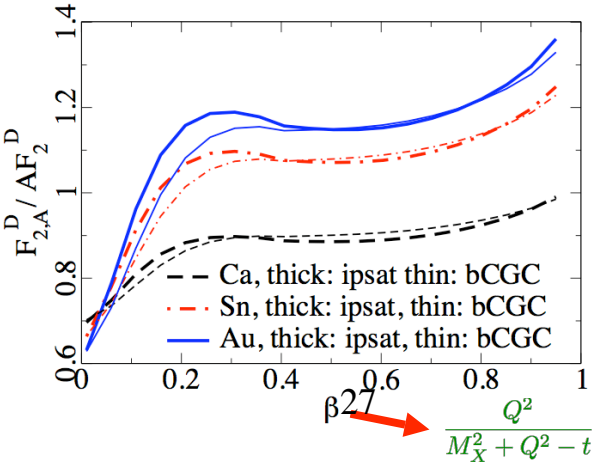




- **Striking pattern of enhancement & suppression of diffractive scattering at EIC**

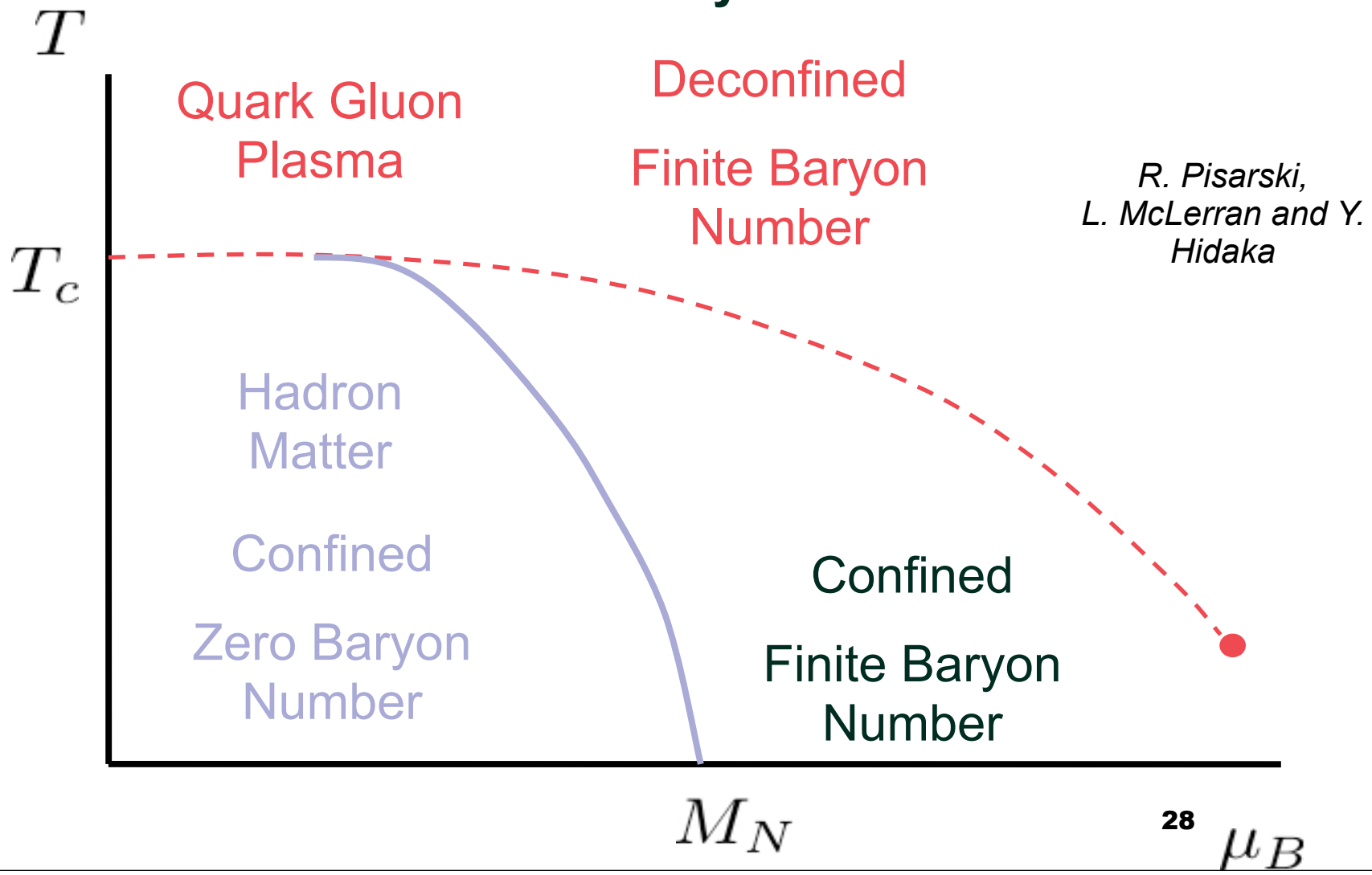






Large Number of Colors Argument:

May have missed a phase of matter at high baryon density

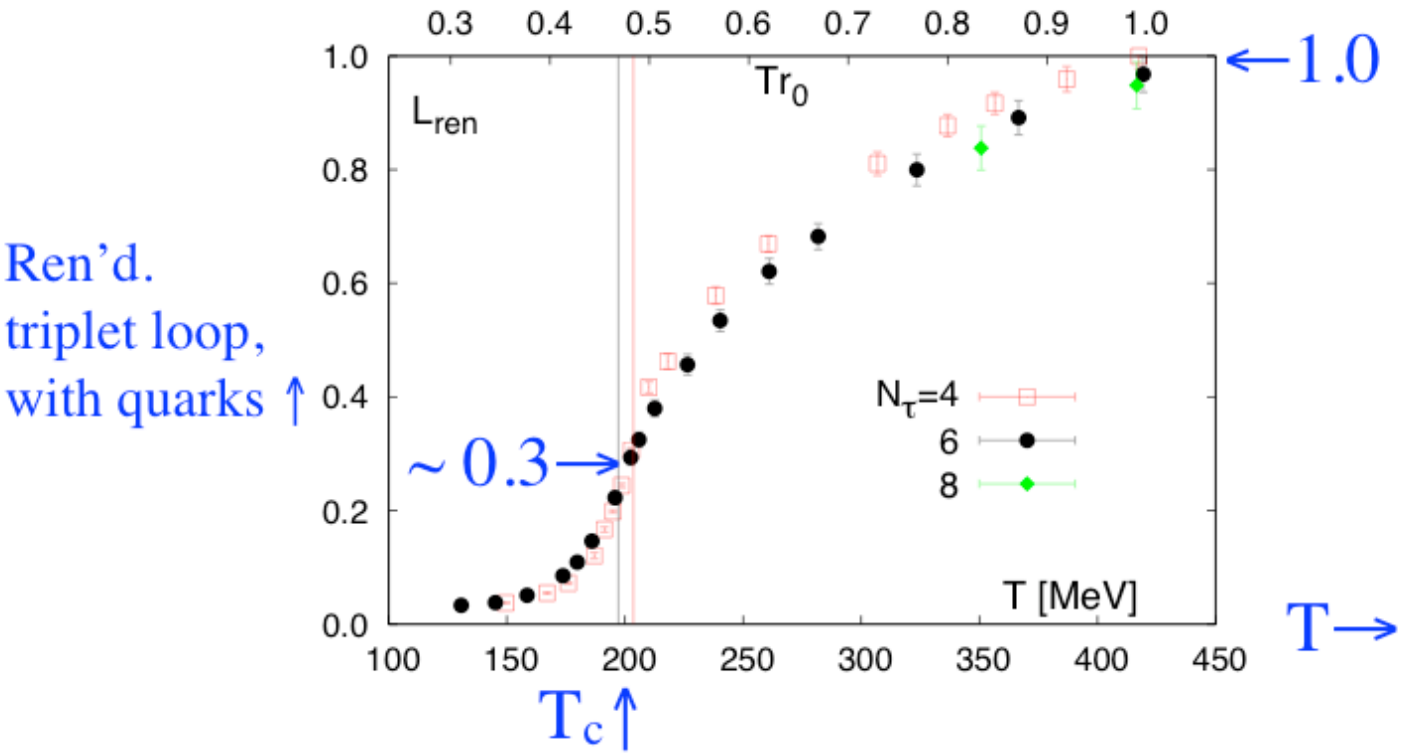


R. Pisarski, L. McLerran and Y. Hidaka

"Semi" QGP: partial deconfinement

Region between T_c, and ~ 2-3 T_c :"Semi-" QGP with *partial* deconfinment

Characterize by *renormalized* triplet Polyakov loop: Cheng +... 0710.0354:



Polyakov loops & shear viscosity

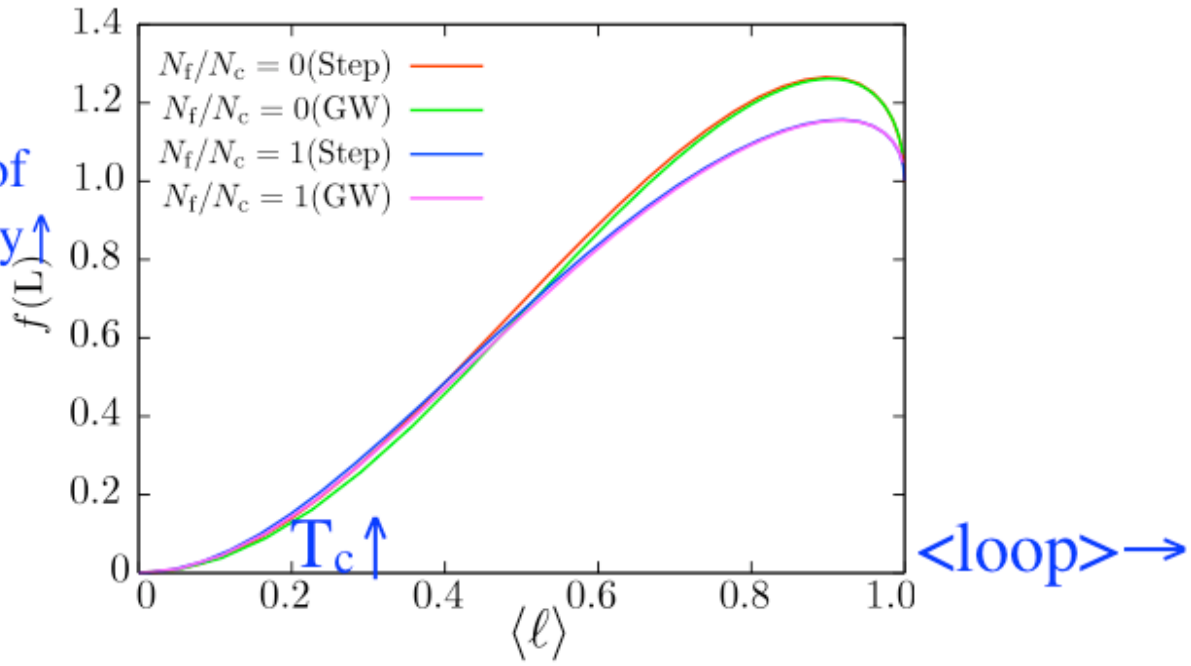
Y. Hidaka & R. Pisarski 0803.0453:
shear viscosity suppressed by ~ (loop)^2 for loop << 1: possibly factor 10!

Dynamical origin of minimum in viscosity near T_c.

Suggests: LHC ≠ RHIC! LHC *im*perfect fluid

Suppression of shear viscosity ↑

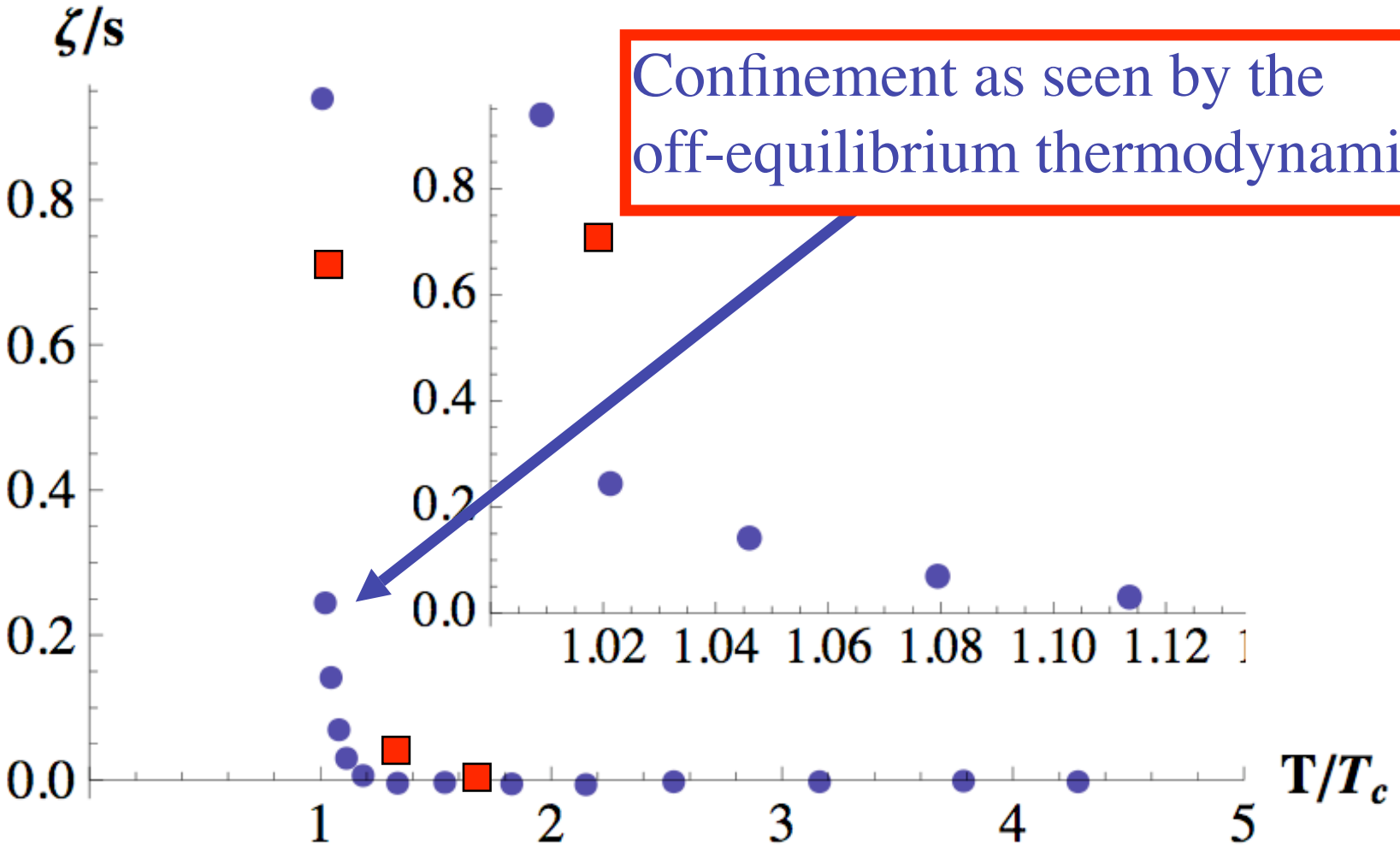
(vs perturbative result)



Bulk viscosity

Kharzeev-Tuchin
arXiv:0705.4280 [hep-ph]

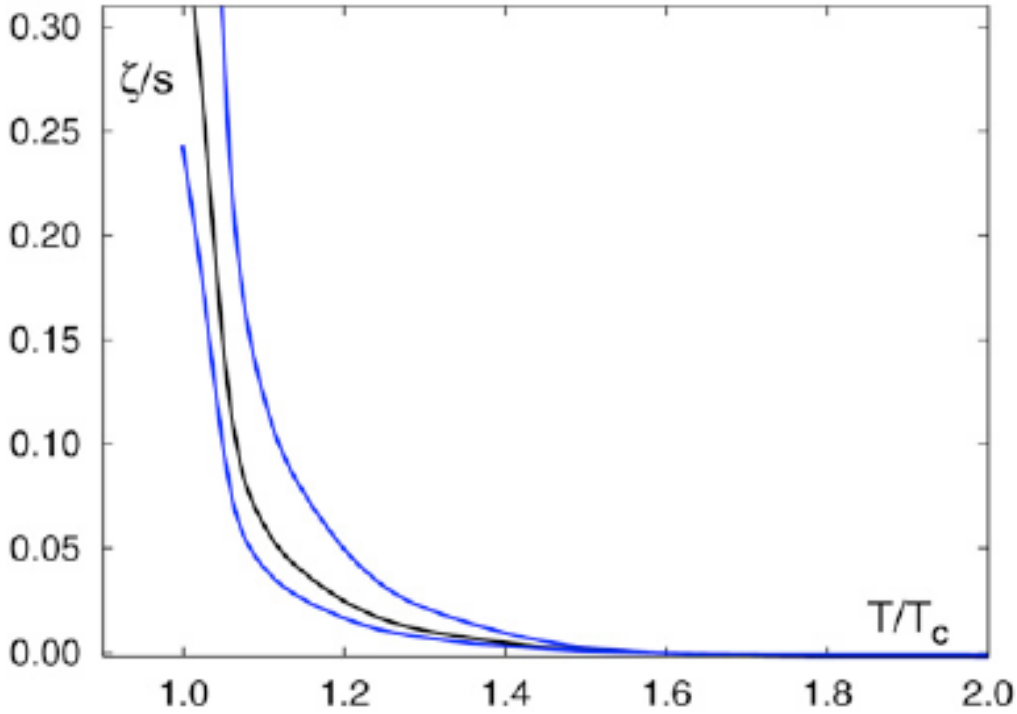
Meyer
arXiv:0710.3717[hep-lat]



Confinement as seen by the off-equilibrium thermodynamics

Full QCD with (almost) physical quark masses

F. Karsch, DK, K. Tuchin, arXiv:0711.0914

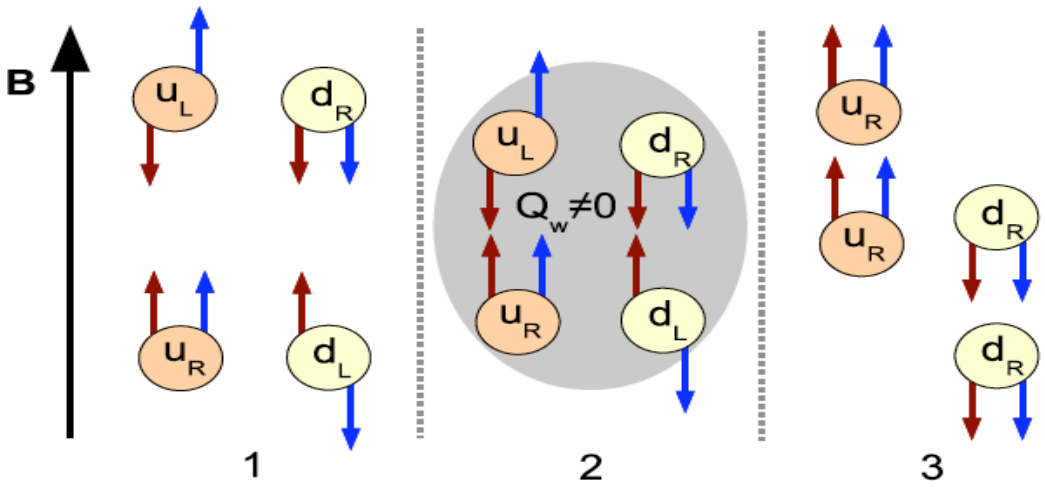


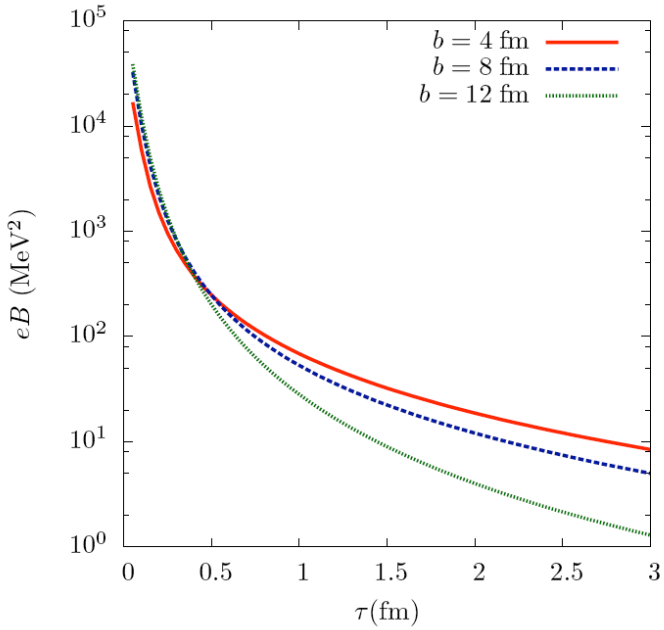
Synergy with The Lattice Gauge Theory Group!

$$2\int_0^\infty \frac{\rho(u,\vec{0})}{u}du = Ts\left(\frac{1}{c_s^2}-3\right)-4(\mathcal{E}-3P)+\left(T\frac{\partial}{\partial T}-2\right)\langle m\bar{q}q\rangle^* + 16|\epsilon_v| + 6\left(M_\pi^2 f_\pi^2 + M_K^2 f_K^2\right),$$

Parity violation in hot QCD matter and charge asymmetry:

DK hep-ph/0406125; DK and A. Zhitnitsky, 0706.1026;
DK, L.McLerran, H. Warringa, 0711.0950



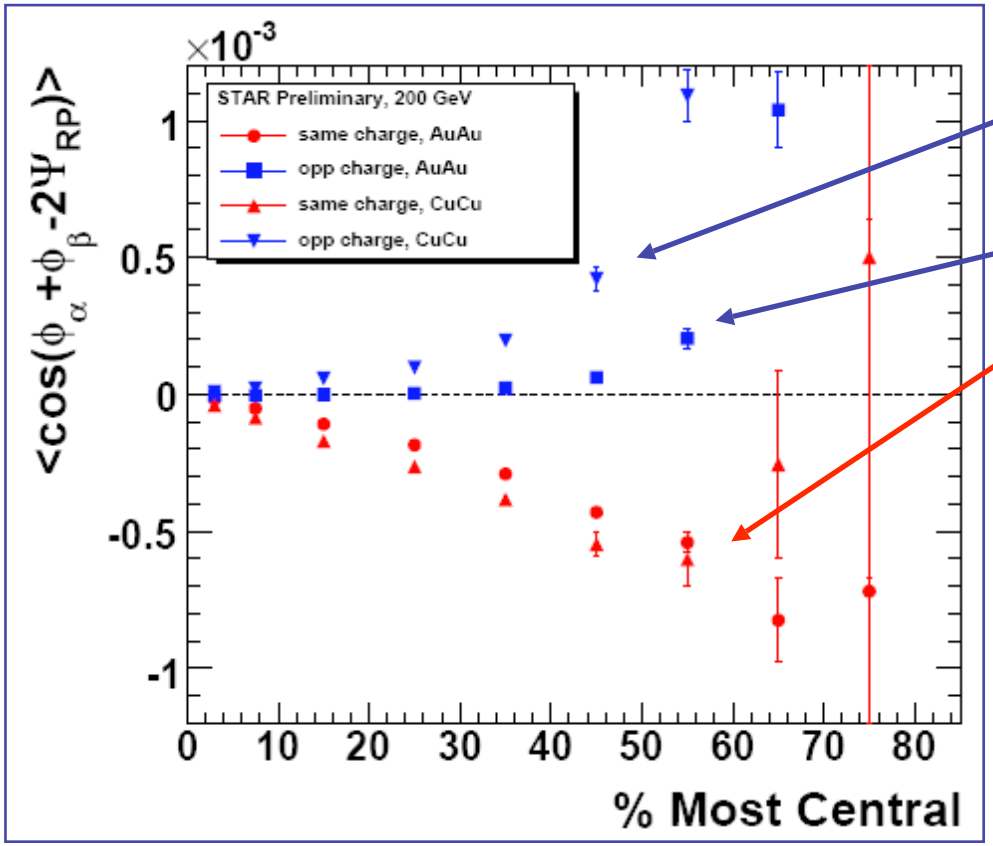


Red arrow - momentum; blue arrow - spin;
In the absence of topological charge no asymmetry between left and right (fig.1) ;the fluctuation of topological charge (fig.2) in the presence of magnetic field induces electric current (fig.3)

Strong P, CP violation at high T ?

Charge asymmetry w.r.t. reaction plane,

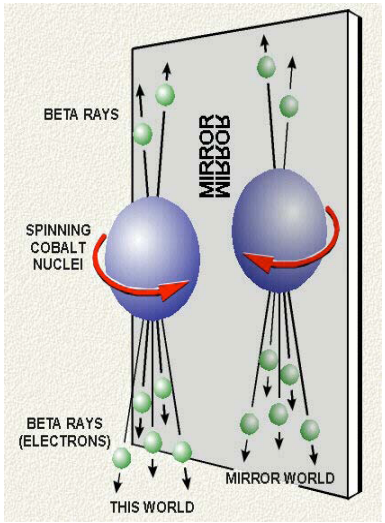
$\sim - a^k a^m$



CuCu

AuAu

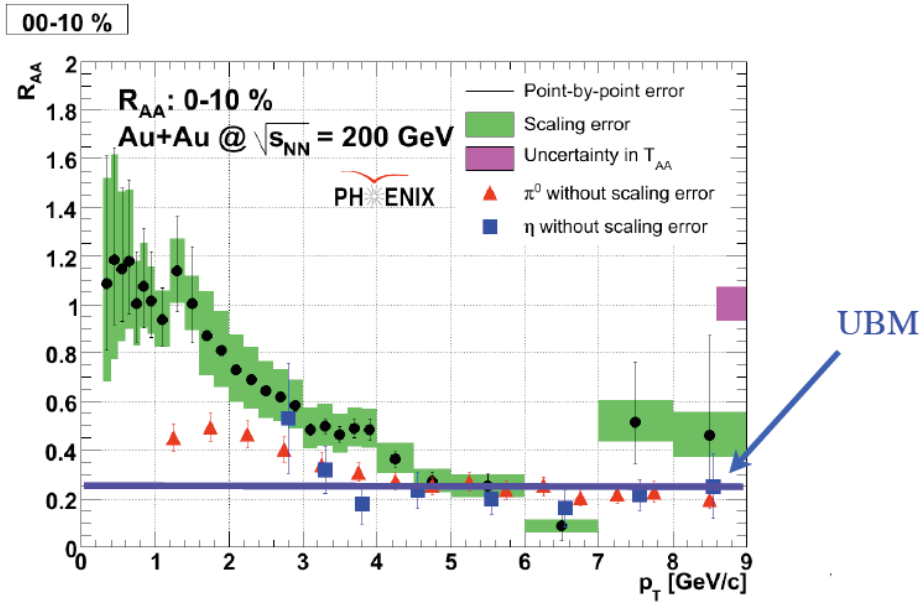
Analogous to P violation in weak interactions:



S. Voloshin et al [STAR Coll.], QM'08

This analysis is currently being finalized

The mechanism of jet energy loss



Universal upper bound on the energy of a parton escaping from a strongly coupled quark-gluon matter?

D.Kharzeev, 0806.0358

$$E_{bound} = \frac{2\pi}{\sqrt{\lambda}} \frac{m^4}{F^2} \frac{1}{L}$$

Heavy quark production in the medium - a crucial test of the energy loss mechanism ("dead cone" suppression of radiative energy loss) - Yu. Dokshitzer, DK '01

Vigorous work on the fast, efficient jet-finding algorithms -

G. Salam and G. Soyez, '07-'08

FastJet algorithm has been used by STAR in the recent jet reconstruction at RHIC

Electron-positron pair creation in heavy ion collisions

A.J. Baltz et al, Physics Reports 458 (2008) 1

Evidence for Higher Order QED Effects in e^+e^- Pair Production at RHIC

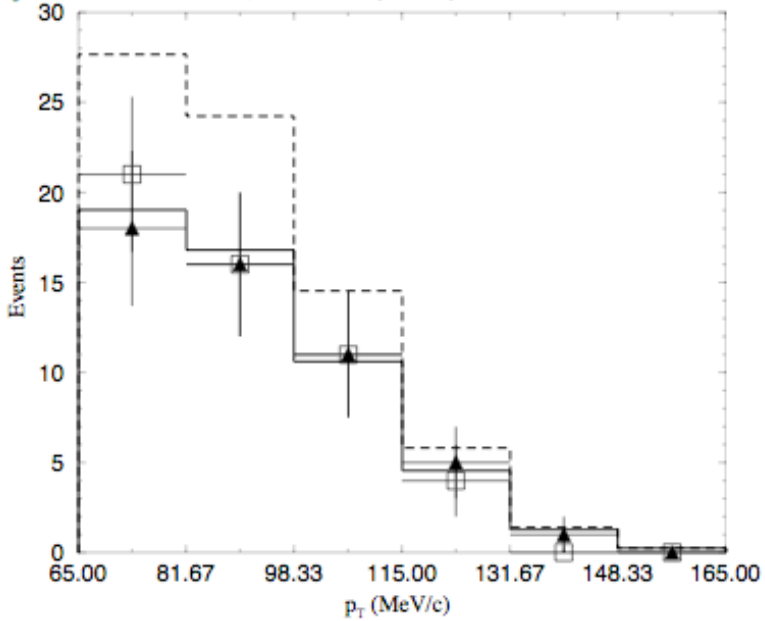
A. J. Baltz, Phys. Rev. Lett 100, 062302 (2008)

New lowest order QED with ZDC triggers – dashes: 2.34 mb.

STAR data: $1.65 \pm 0.23 \pm 0.30$ mb.

Higher order QED – solid: 1.67 mb.

Correct lowest order QED with STAR acceptance is as crucial as higher order QED.



- Comparison of QED calculations with STAR data provides the first evidence of higher-order QED in relativistic heavy ion reactions.

Conferences organized in ‘06-08

During 2006-08 the Group members have participated in organizing 26 International conferences and workshops, including Quark Matter ‘06 and ‘08, Hard Probes ‘08, International Conference on High Energy Physics (ICHEP), PANIC, and other high profile events.

Many workshops and programs at BNL;
recent example:

Workshop and program on
“Viscous hydrodynamics and transport models in heavy ion collisions”,
April 23- May 4, 2008
Organizers: D.Kharzeev, D. Molnar, P. Petreczky, D. Teaney;

real progress has been achieved: methods for viscous hydrodynamics developed, tested, and numerical results compared

New initiative aimed at promoting, along with TECHQM, interactions between theorists and experimentalists, supporting workshops and programs on RHIC physics, improving coordination between the US and international programs in heavy ion physics:

CATHIE
Center for Analysis and Theory of Heavy Ion Experiments

Advisory board:
(as of July 2008)

M. Gyulassy (Columbia)
J. Qiu (Iowa State)
F. Karsch (BNL LGT)
D. Kharzeev (BNL NT)
L. McLerran (BNL & RBRC)
D. Molnar (Purdue)
K. Rajagopal (MIT)
E. Shuryak (Stony Brook)
M. Stephanov (UIC)
X.-N. Wang (LBNL)

Coordinator: P. Petreczky (BNL)

CATHIE
Center for Analysis and Theory of Heavy Ion Experiments

http://quark.phy.bnl.gov/www/cathie.html

The following on-line forums (wiki pages) are available for interested researchers

Collective flow: Initial Conditions, Hydrodynamics and Transport Models

Hard and Electromagnetic Probes of QGP

TECHQM

Students supervised in the Group during 2001-08

J.Bjoraker, Y.Hatta, B. Jaeger, J.Lenaghan, R.Parwani, V.Peikert, J.Wirstam, H.Yokoya;
Starting in the summer '08: Steven Horvat (Yale)

Supervised by D.Kharzeev, R.Pisarski,
R.Venugopalan, W.Vogelsang

D. Kharzeev - Adjunct professor at Yale
W. Vogelsang - Adjunct professor at Stony Brook

Awards (2003-2008)

D. Kharzeev: APS Fellow, 2007
Emilio Segre Distinguished Scholar, 2005
Sackler Fellow, 2005

L. McLerran: BNL Science and Technology Award, 2007

R. Pisarski: Senior U.S. Scientist Award, Alexander von Humboldt foundation, 2003-04

R. Venugopalan: APS Fellow, 2008
Fellow, Andes Foundation, Chile, 2007
Fellow, Alexander von Humboldt foundation, 2003-4

W. Vogelsang: Friedrich-Wilhelm-Bessel Award, Humboldt Foundation , 2007

Publications in FY 07

71 papers, from which 50 in refereed journals

The Future

Detailed 4 year plan for the Group has been prepared in 2007;
it is aligned with NSAC performance measures and BNL plans and includes:

1. The physics of RHIC: 3D simulations of parton matter evolution, energy loss of heavy quarks

2. The physics of RHIC-II : heavy quarks, hard processes, forward rapidities

3. Spin physics : W production, transverse spin, …

4. The physics of the eRHIC : Deep Inelastic Scattering off nuclei and polarized protons

Significant progress in 2007-08 in all four directions

Summary

1. Nuclear Theory Group at BNL is among the World leaders in the field of High Energy Nuclear Physics

2. Vigorous research program, aimed at the understanding of fundamental structure of matter and achieving RHIC science goals

3. Synergy with the experimental program at RHIC, and with the research done by RIKEN-BNL Center, Lattice Gauge Theory Group, and High Energy Theory Group

4. A new effort to coordinate the theory-experiment interface on the national and international scale: CATHIE

Back-up slides

Nuclear Theory Budget

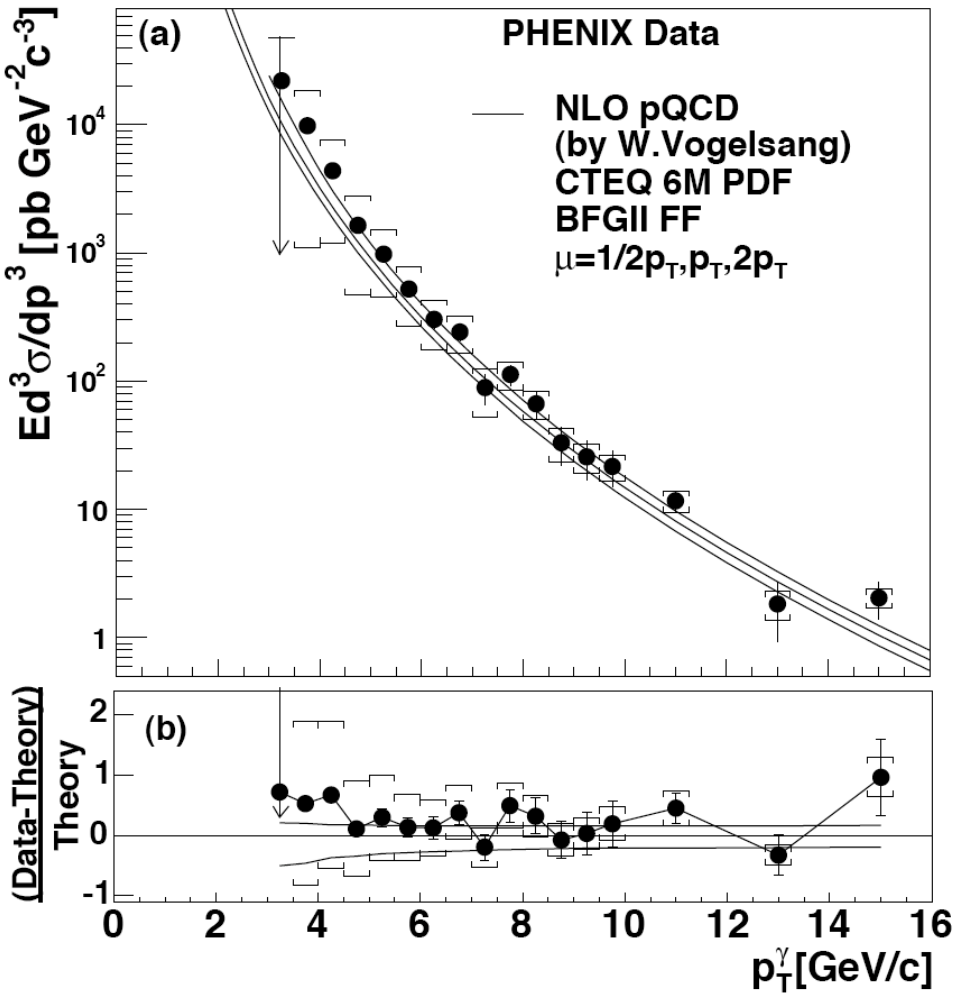
- Group size has been unchanged since FY05

  7 senior people, 2 post-docs (1 of which funded by LDRD)

- Budget pressure results from transition from a group partially supported by RIKEN and others, to a group entirely supported by DOE

Not sufficient funding for the Group;
Looking forward to the increment currently being discussed

$pp \rightarrow \gamma X$ PHENIX



Reliable
"baseline"
pQCD calculations