Chiral magnetic effect & early time dynamics

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Outline

1. Chiral magnetic effect in Heavy-Ion Collisions
   — Introduction
   — Current status & challenges

2. Chiral magnetic effect & early-time dynamics
   — New theoretical developments

3. Conclusions & Outlook
   — Isobar scan

Chiral Magnetic Effect (CME) & anomalous transport

Discovery of new kinds of conductivity for systems with (approx.) chiral fermions and chirality imbalanced

(Fukushima, Kharzeev, Warringa PRD 78 (2008) 074033)

Chiral Magnetic Effect: $\vec{j}_v \propto j_a^0 \vec{B}$

axial charge density (j_a^0) *magnetic field* ($\vec{B}$)

Several interesting effects due to interplay of axial and vector charges

Chiral Separation Effect (CSE), Chiral Magnetic Wave (CMW), …

Several manifestations of such effects beyond high-energy QCD

Discovery of CME in 3d Dirac/Weyl semi-metals

Li et al. Nature Physics (2016)

CME in Heavy-Ion Collisions

High-energy heavy-ion collisions provide an exciting environment to explore anomalous transport phenomena

Chiral Magnetic Effect: $\vec{j}_v \propto j_a^0 \vec{B}$

axial charge density (→ j_a^0) *magnetic field* (→ $\vec{B}$)

— *Strong magnetic field $eB \sim m_\pi^2$ present in off-central collisions*

— *Non-conservation of axial charge expected to lead to lead to significant fluctuations e.g. due to sphaleron transitions*

Good news: Chiral magnetic effect presents exciting opportunity to further explore dynamics of QGP, e.g. topological properties

CME in Heavy-Ion collisions

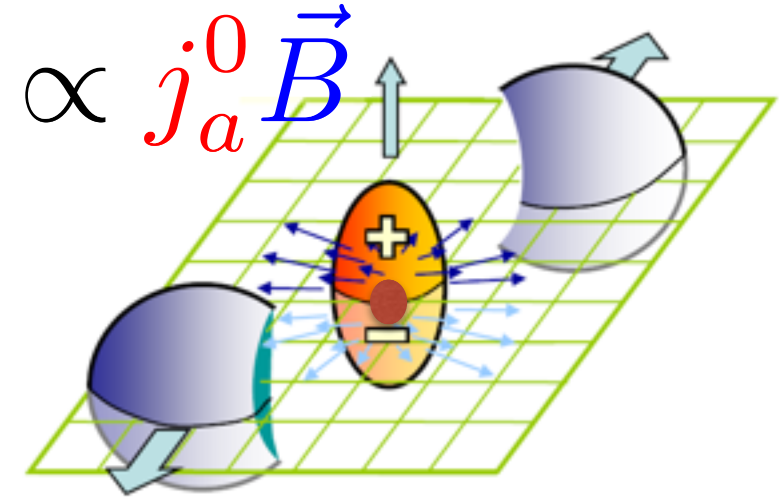
Since axial charge fluctuates from event to event on average <j_v>=0, so one can only measure fluctuations

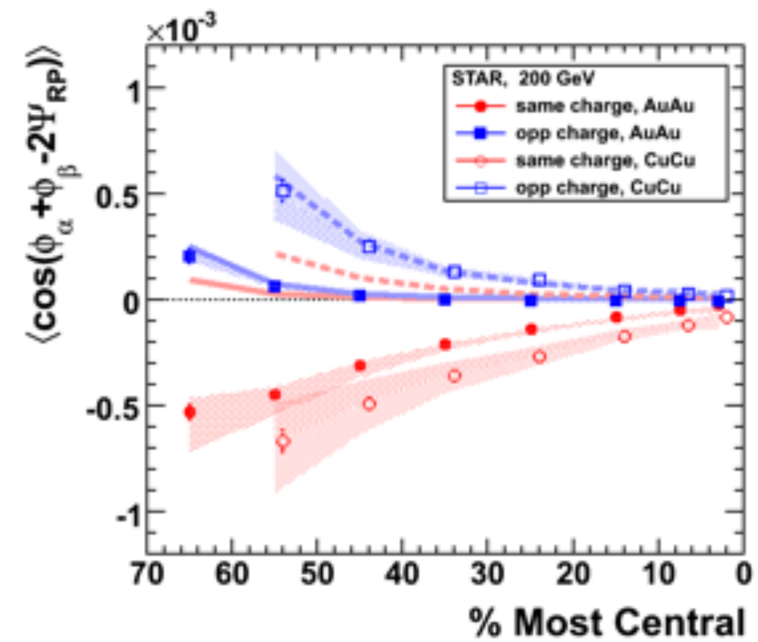
Basic idea is to look for back-to-back correlations of opposite charge particles with respect to the reaction plane

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle$$

Even though many qualitative features of the measurements at RHIC and LHC are in line with CME expectations (e.g. centrality dependence, event-shape engineering, …) , so far measurements are also subject to potentially large backgrounds

$$\vec{j}_v \propto j_a^0 \vec{B}$$





STAR PRC 81 (2010) 054908

-> Significant uncertainty interpretation due to unknown rel. contribution from CME & Co. and background

c.f. ``Chiral Magnetic Effect Task Force Report,'' arXiv:1608.00982 [nucl-th]

CME in Heavy-Ion Collisions

Quantitative theoretical understanding of anomaly induced transport phenomena (CME,CMW,…) in heavy-ion collisions desirable to guide experimental searches

Chiral Magnetic Effect: $\vec{j}_v \propto j_a^0 \vec{B}$

axial charge density (j_a^0) *magnetic field* ($\vec{B}$)

Quantitative description requires (at least) three ingredients

— space-time dependence of magnetic field

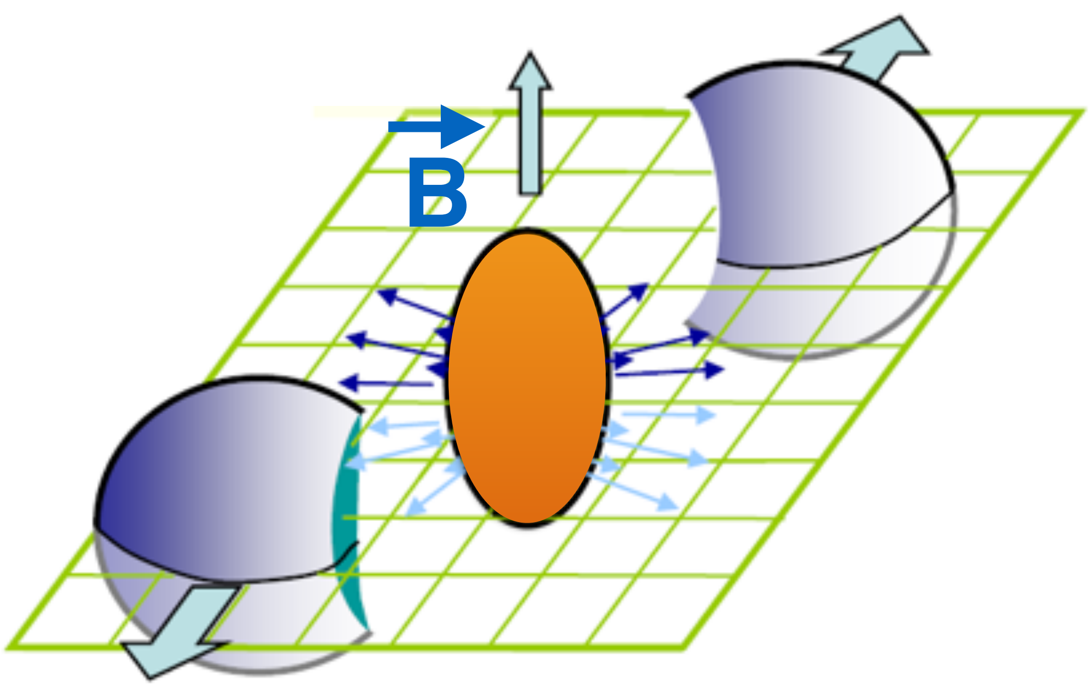
— information about the dynamics of axial charge changing processes in Quark-Gluon plasma

— microscopic/macroscopic description of anomalous transport

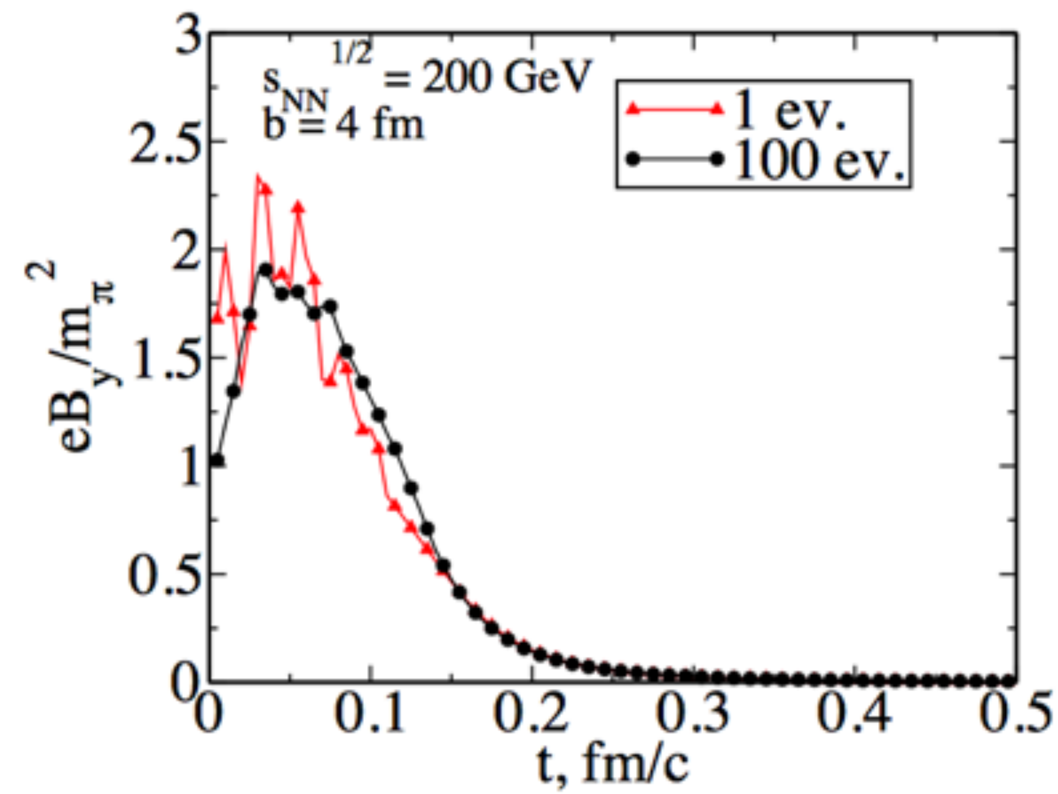
CME in Heavy-Ion collisions

Spectators in off-central collisions create a strong magnetic field eB ~ m_π^2 (unit conversion $m_\pi^2 \sim 10^{14}$ T)

(c.f. talk by V. Skokov)



STAR PRC 81 (2010) 054908



Skokov,Illarionov,Toneev
Int.J.Mod.Phys. A24 (2009) 5925-5932

Life-time of magnetic field in vacuum is very short < 1 fm/c

Expect significant fraction of the effect should take place during the pre-equilibrium stage

CME in Heavy-Ion collisions

Axial charge density: Not conserved in QCD due to axial anomaly

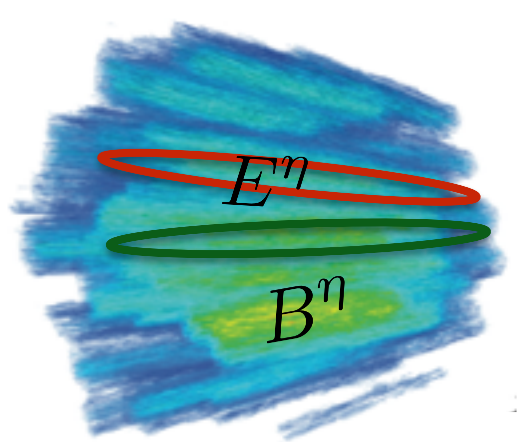
$$\partial_\mu j^\mu_{5,f} = 2m_f \bar{q}\gamma_5 q - \frac{g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

quark mass

field-strength fluctuations $\propto \vec{E}\cdot\vec{B}$

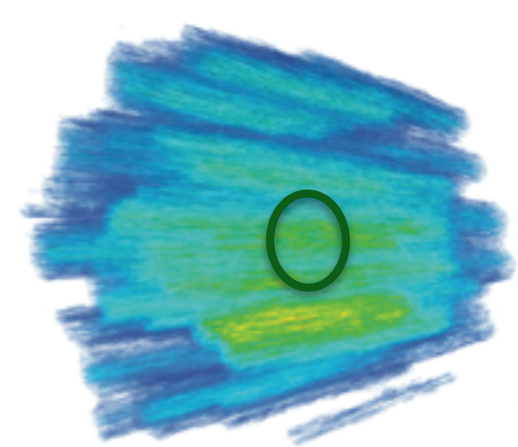
Even though on average $< j^0_a >=0$ the fact that the current is not conserved should lead to space-time dependent fluctuations

short distance



color flux tubes

long distance



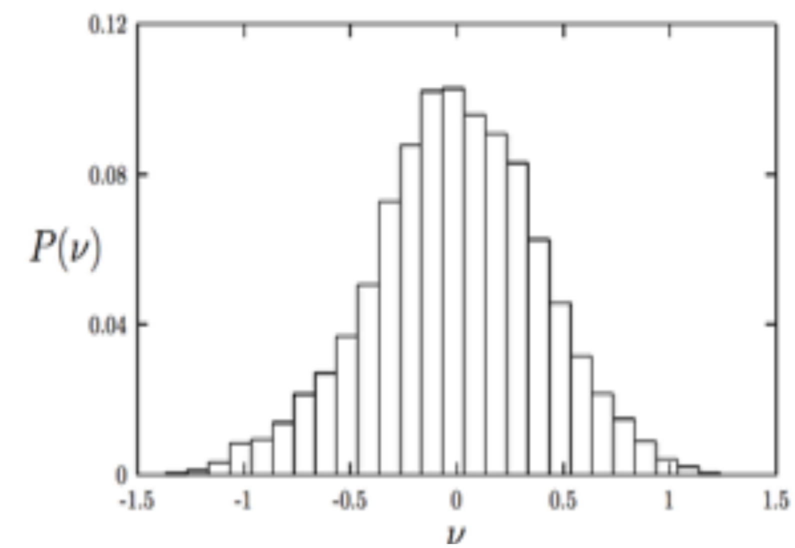
sphaleron transitions

Creation of axial charge imbalance

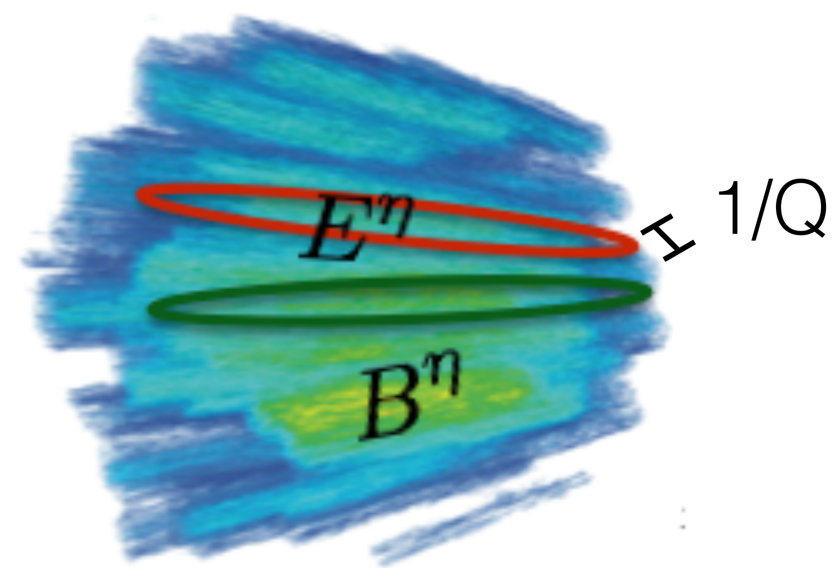
Early time dynamics of axial charge production can be addressed within classical Yang-Mills simulations

Global imbalance of axial charge is small at $\tau \sim 1/Q_s$

Kharzeev, Venugopalan, Krasnitz, PLB545 (2002) 298-306



Significant *local* imbalance of axial charge density created at $\tau \sim 1/Q$ Lappi, SS in preparation



Source term for axial charge production comparable to energy density

$$\langle tr[F_{\mu\nu}(x)\tilde{F}^{\mu\nu}(x)] tr[F_{\mu\nu}(y)\tilde{F}^{\mu\nu}(y)]\rangle \sim \frac{1}{N_c^2-1}\epsilon(x)\epsilon(y)$$

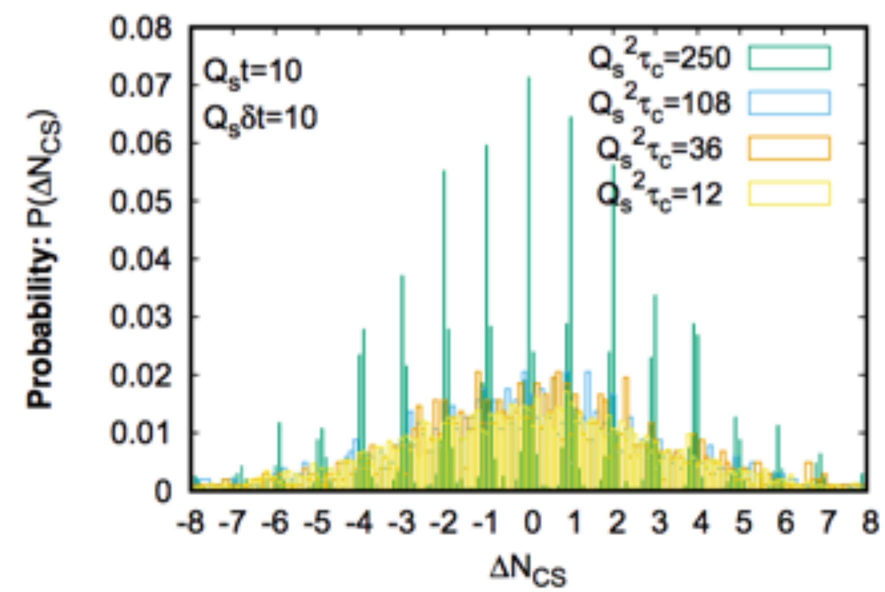
Correlation length of local domains is microscopically small $\sim 1/Q_s$

Creation of axial charge imbalance

Beyond very early times sphaleron transitions in and out-of equilibrium dominate axial charge production on long time/distance scales

Strong color-fields at early times can lead to an enhancement of sphaleron transition rate during the pre-equilibrium stage

Mace, SS, Venugopalan PRD93 (2016) no.7, 074036



Different mechanisms identified to create sizable fluctuations of axial charge density at early times, but further progress required to quantify effects

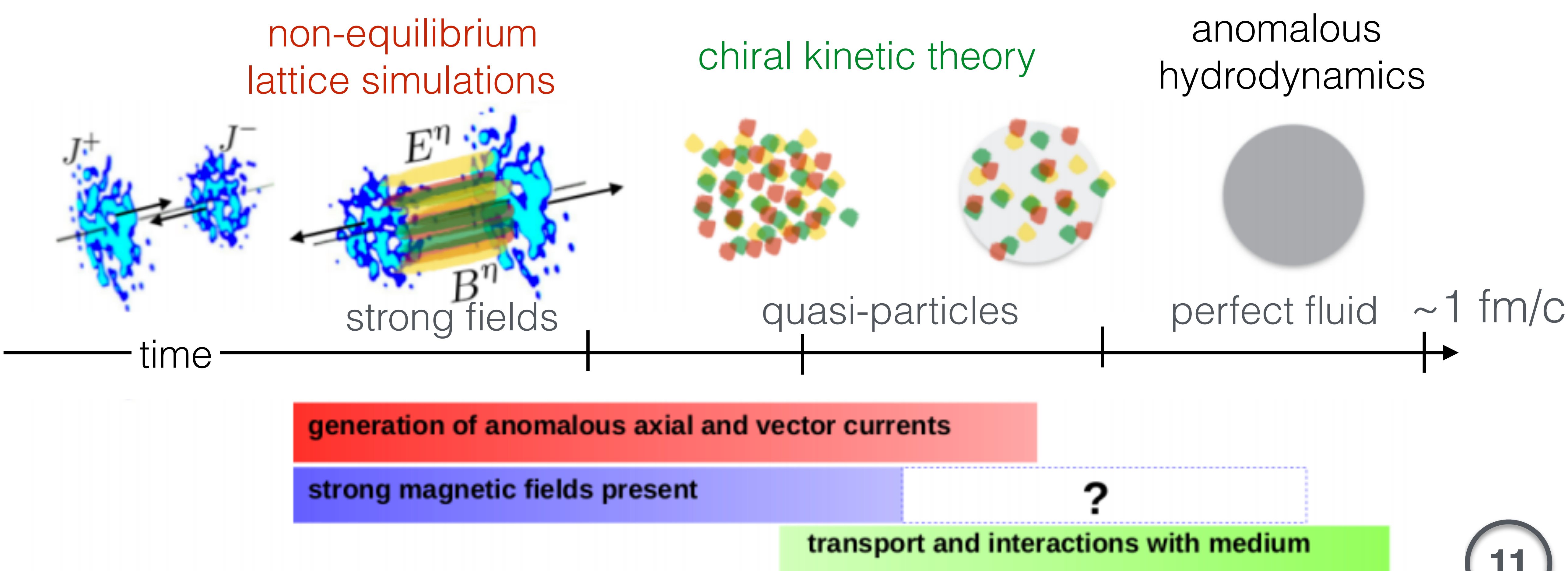
Since axial charge is *not* conserved, knowledge of "initial condition" for axial charge is in general *not sufficient* to describe subsequent space-time evolution

Still a major source of uncertainty in theoretical description of CME

CME & early-time dynamics

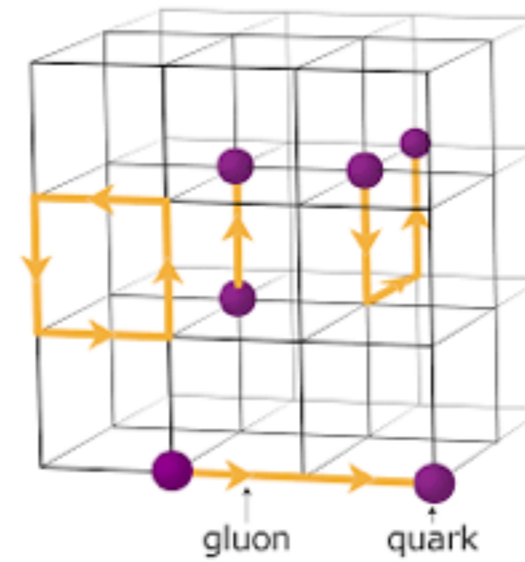
Different theoretical approaches have been developed to study anomalous transport (CME,CMW,…) in and out-of-equilibrium

Since early-time dynamics of heavy-ion collisions involves different degrees of freedom at different times, combination of different theoretical approaches required to describe pre-equilibrium dynamics of anomalous transport



Non-equilibrium lattice description

- Discretize theory on 3D spatial lattice using the Hamiltonian lattice formalism

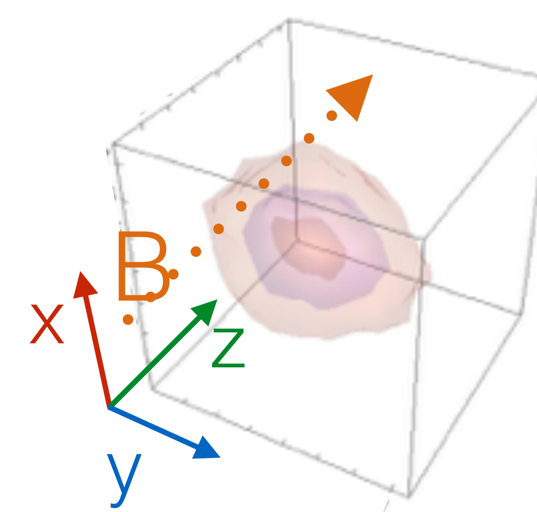


- Solve operator Dirac equation in the presence of classical SU(N) and U(1) gauge fields

$$i\gamma^0 \partial_t \hat{\psi} = (-i\not{D}^s_W + m)\hat{\psi}$$

- Compute expectation values of vector and axial currents to study anomalous transport processes

$$j^\mu_v(x) = \langle \hat{\bar{\psi}}(x)\gamma^\mu \hat{\psi}(x)\rangle \quad j^\mu_a(x) = \langle \hat{\bar{\psi}}(x)\gamma^\mu\gamma^5 \hat{\psi}(x)\rangle$$



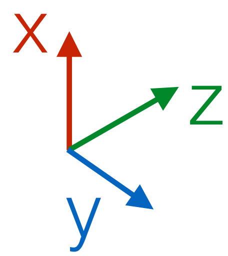
So far first results on small lattices (24 x 24 x 64) in a clean theoretical setup

SU(N): Isolated sphaleron transition U(1): constant magnetic field

Non-equilibrium CME dynamics

Axial charge j_5^0

Sphaleron transition induces local imbalance of axial charge density



Vector current j_V^z

Non-zero magnetic field B_z leads to vector current j_V^z in z-direction

Vector charge j_V^0

Vector current j_V^z leads to separation of electric charges j_V^0 along the z-direction

N.Mueller,SS, S. Sharma PRL 117 (2016) no.14, 142301

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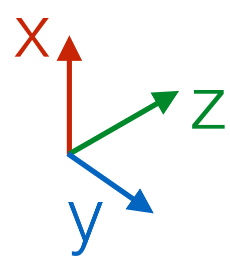

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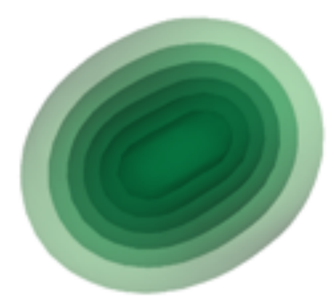

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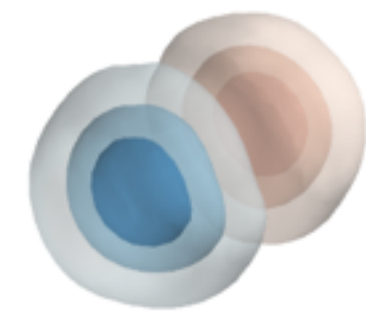


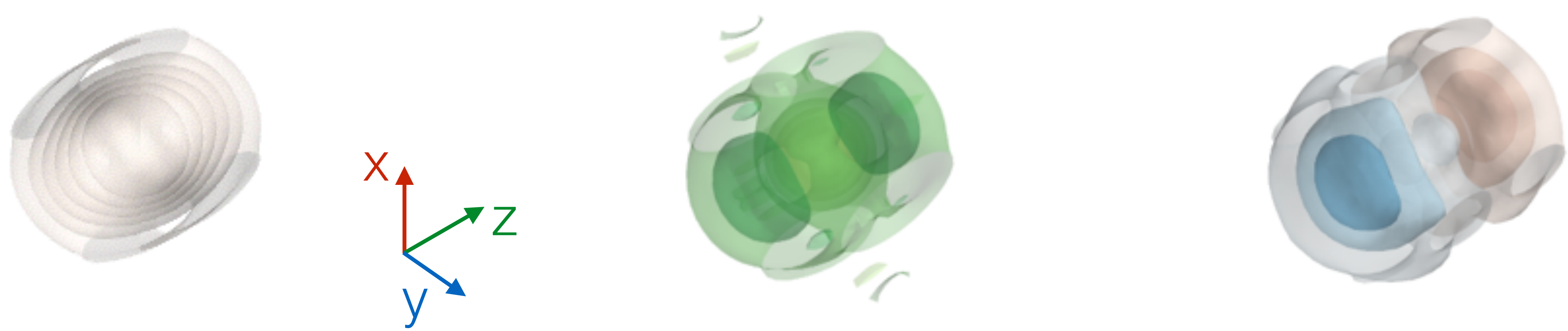
Vector current j_V^z leads to separation of electric charges j_V^0 along the z-direction

N.Mueller,SS, S. Sharma PRL 117 (2016) no.14, 142301

Non-equilibrium CME dynamics

Vector charge imbalance j_V^0 generates an axial current j_5^z so that axial charge also flows along the B-field direction

Axial charge j_5^0 | Vector current j_V^z | Vector charge j_V^0



Emergence of a Chiral Magnetic shock-wave of vector charge and axial charge propagating along B-field direction

N.Mueller,SS, S. Sharma PRL 117 (2016) no.14, 142301

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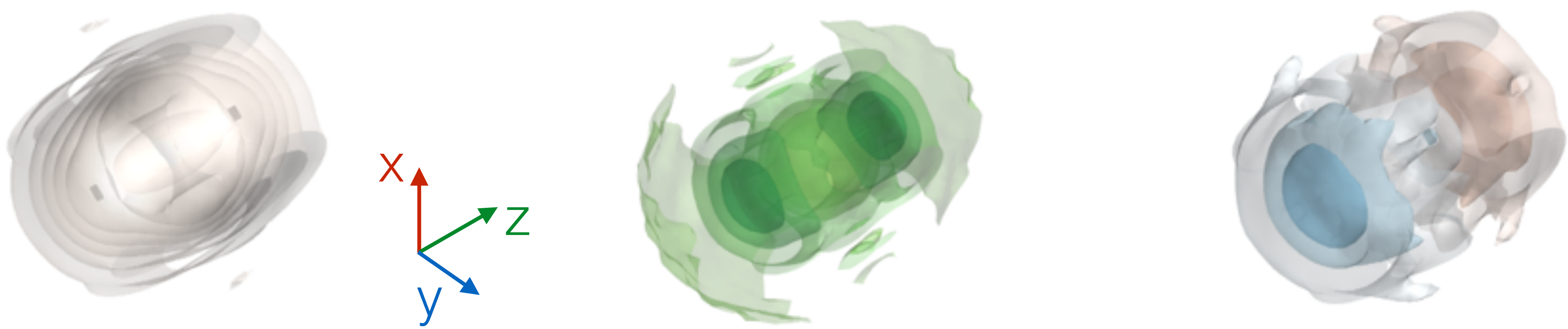

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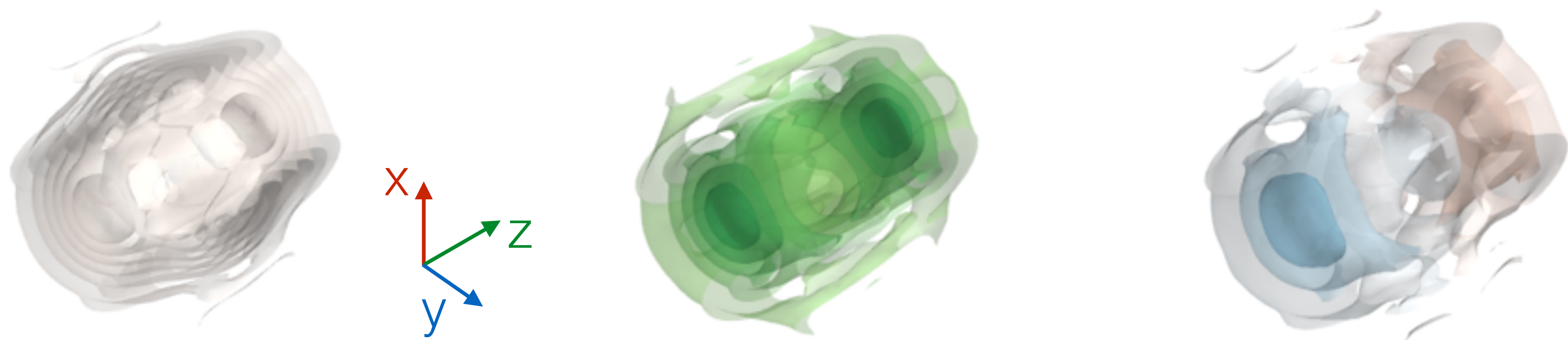

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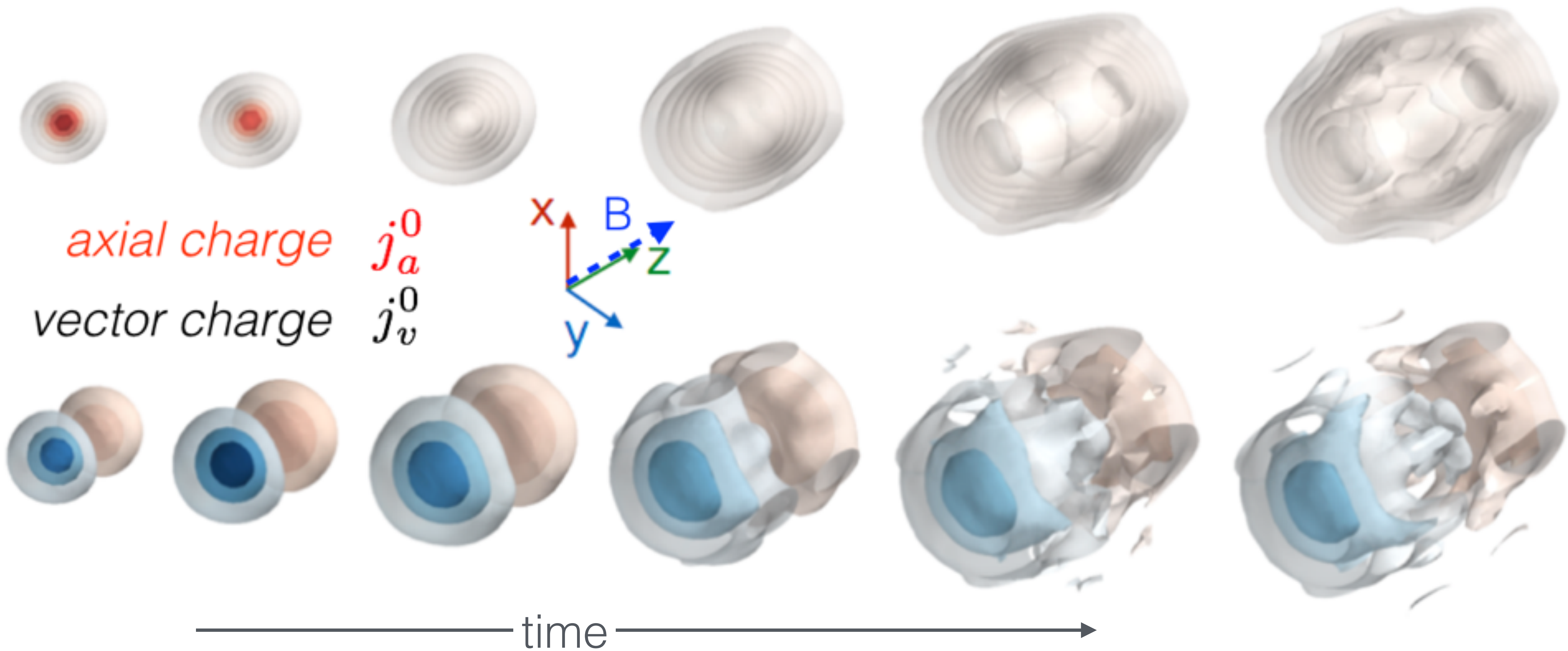
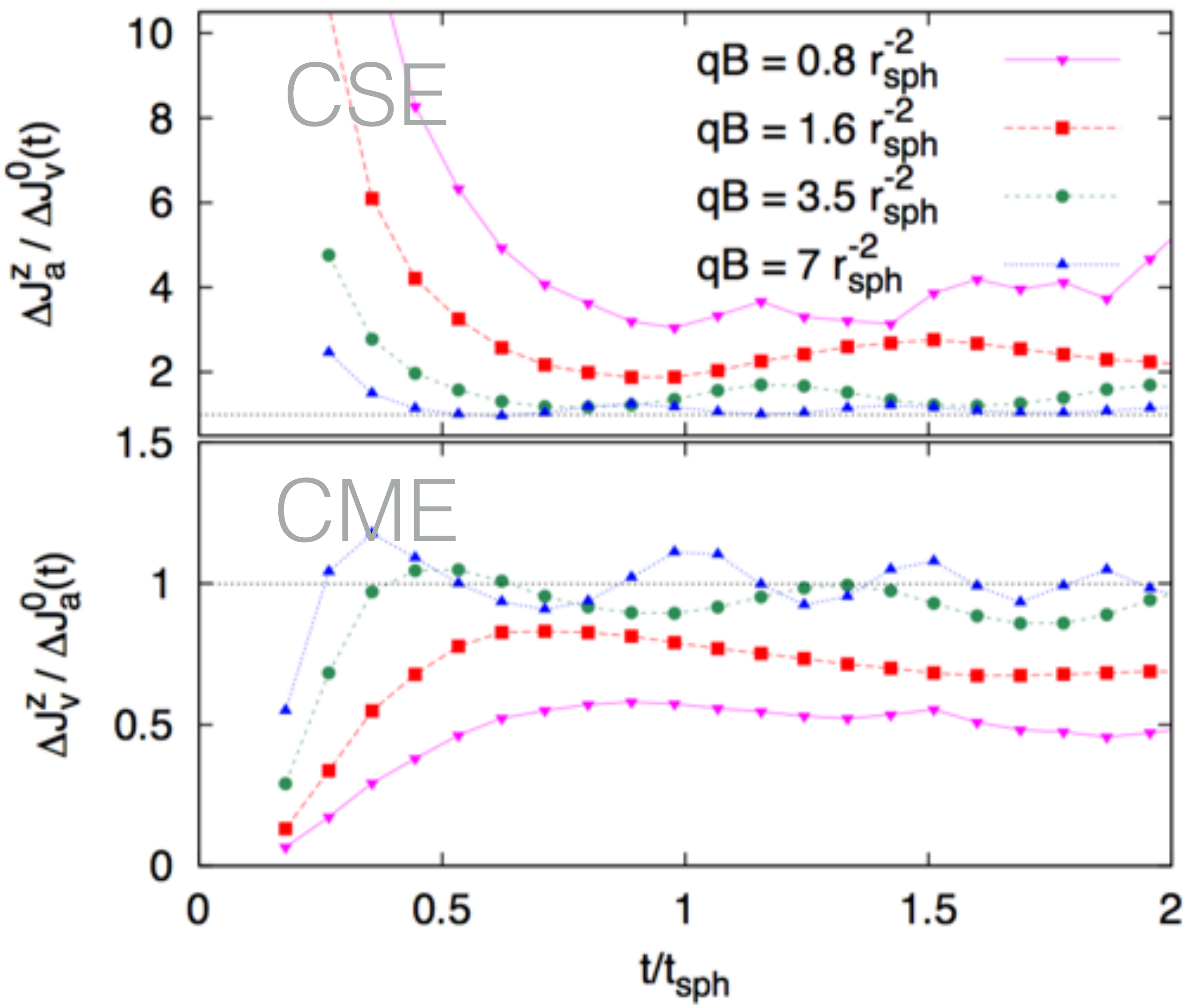


Clear separation of electric charge j_V^0 along the B-field direction

Validity of constitutive relations



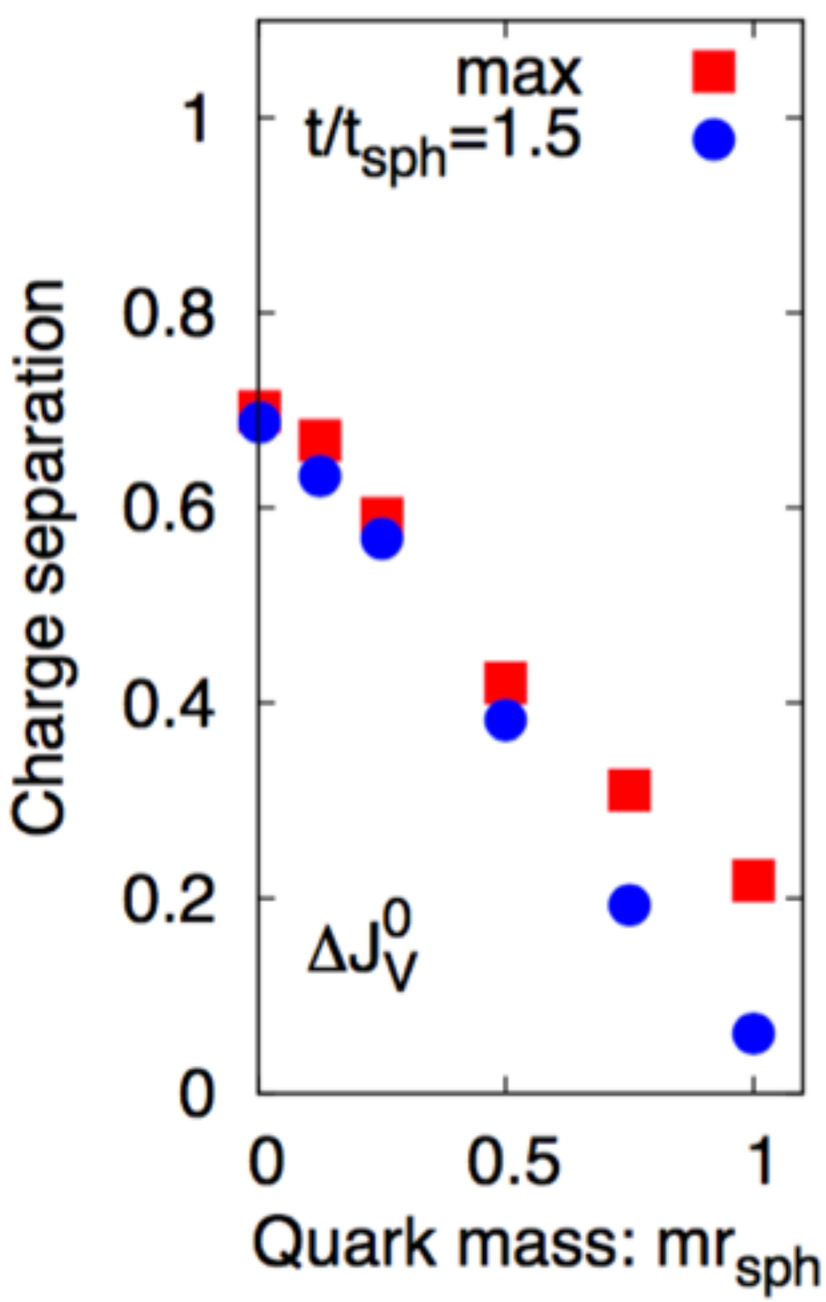
Besides providing a field theoretical description of early time dynamics, microscopic simulations can also be compared to macroscopic description e.g. in anomalous hydrodynamics

Simulation results indicate approach towards constant value with a finite relaxation time

Since lifetime of magnetic field is short this effect should also be incorporated in more phenomenological approaches

Mace,Mueller,SS, Sharma, PRD 95 (2017) no.3, 036023

Quark mass dependence



Explicit violation of axial charge conservation for finite quark mass

$$\partial_\mu j^\mu_a(x) = 2m\langle\hat{\bar{\psi}}(x) i\gamma_5 \hat{\psi}(x)\rangle - \frac{g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

leads to damping of axial charge

Since CME current is proportional to axial charge density it will also be reduced

$$\vec{j}_v \propto j^0_a \vec{B}$$

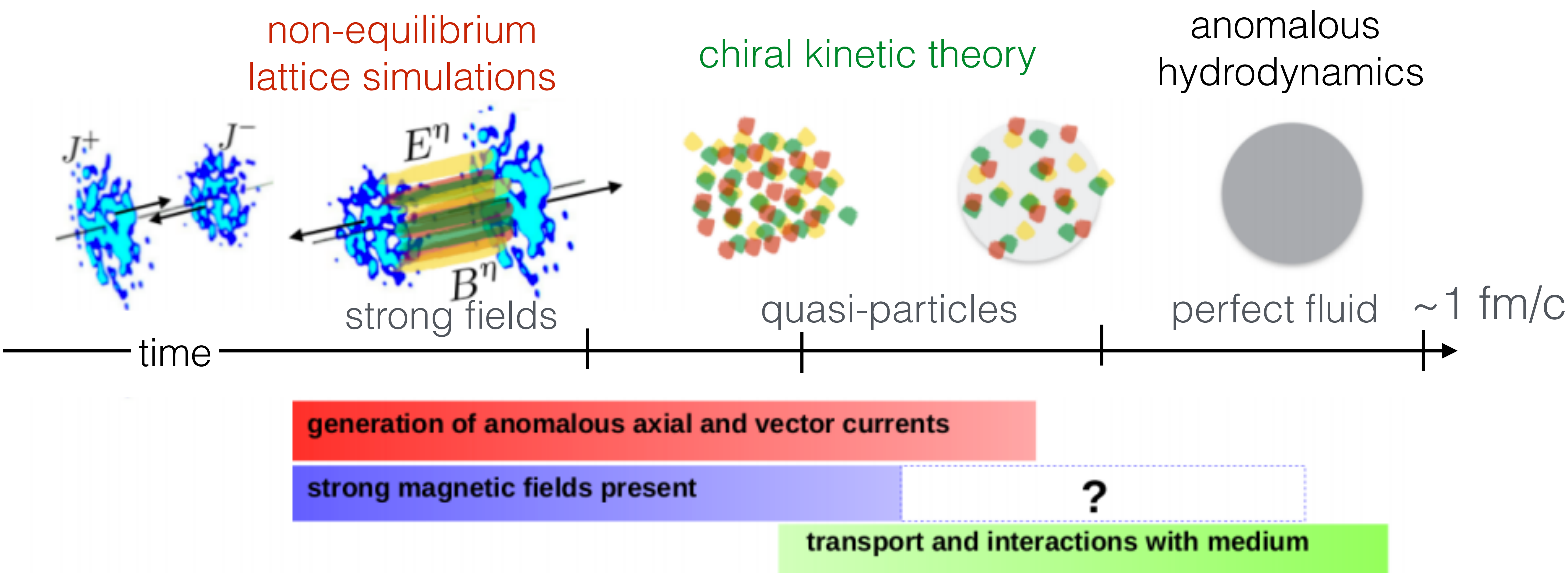
Significant reduction of the charge separation signal by factor ~5 already for moderate quark masses

-> unlikely that strange quarks contribute significantly

Mace,Mueller,SS, Sharma, PRD 95 (2017) no.3, 036023

CME & early-time dynamics

New theoretical tools to calculate early time dynamics of anomalous transport starting to become available



Challenge for the future will be to extend pre-equilibrium calculations to realistic heavy-ion environment

Anomalous hydrodynamics

Eventually the early time dynamics has to be matched to an extended version of usual hydrodynamic description of space-time evolution

$$D_\mu T^{\mu\nu} = 0$$

including the dynamics of axial (L/R) currents

$$D_\mu J_R{}^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad J_R{}^\mu = n_R\, u^\mu + \nu_R{}^\mu + \frac{N_c q}{4\pi^2} \mu_R\, B^\mu$$

$$D_\mu J_L{}^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad J_L{}^\mu = n_L\, u^\mu + \nu_L{}^\mu - \frac{N_c q}{4\pi^2} \mu_L\, B^\mu$$

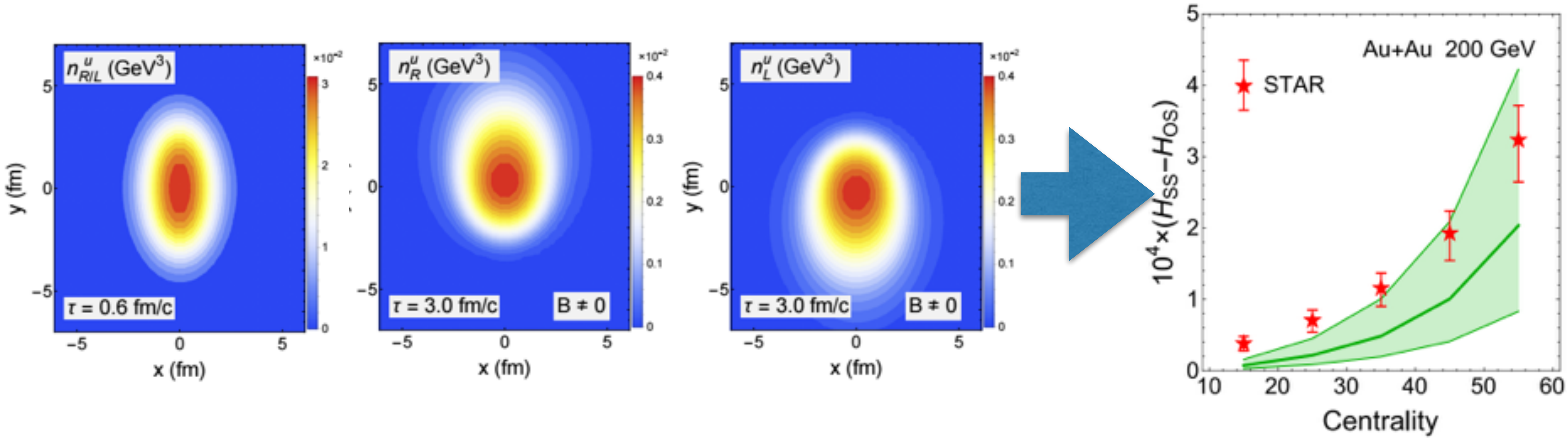
CME

Significant progress in recent years in development of anomalous hydrodynamic models

M.Hongo, Y.Hirono, T.Hirano (2013);H.-U.Yee, Y.Yin (2014); Y.Hirono, T.Hirano, D.Kharzeev (2014); S.Shi Y.Jiang, E.Lilleskov, Y.Yin, J.Liao (2016); …

Anomalous hydrodynamics

Based on flexible assumptions about axial charge distribution and magnetic field, models allow for a direct comparison with experiment (c.f. talk by S. Shi)



Effectively axial charge is treated as a conserved quantity in present phenomenological models

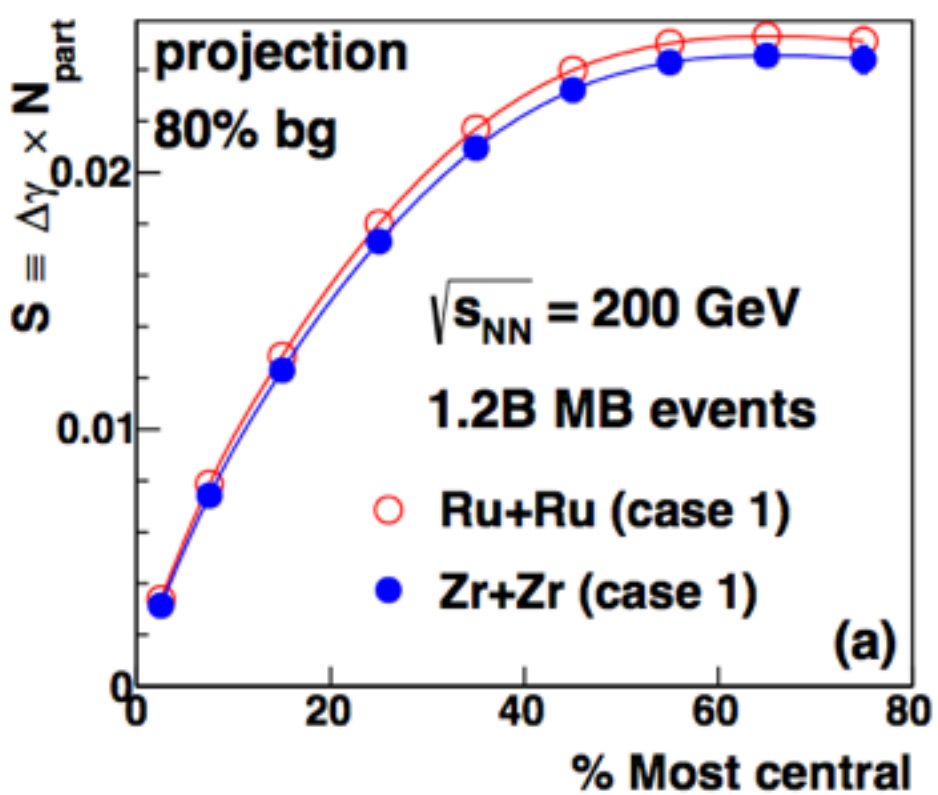
Choice of initial conditions for axial/vector charges/currents provides significant source of uncertainty

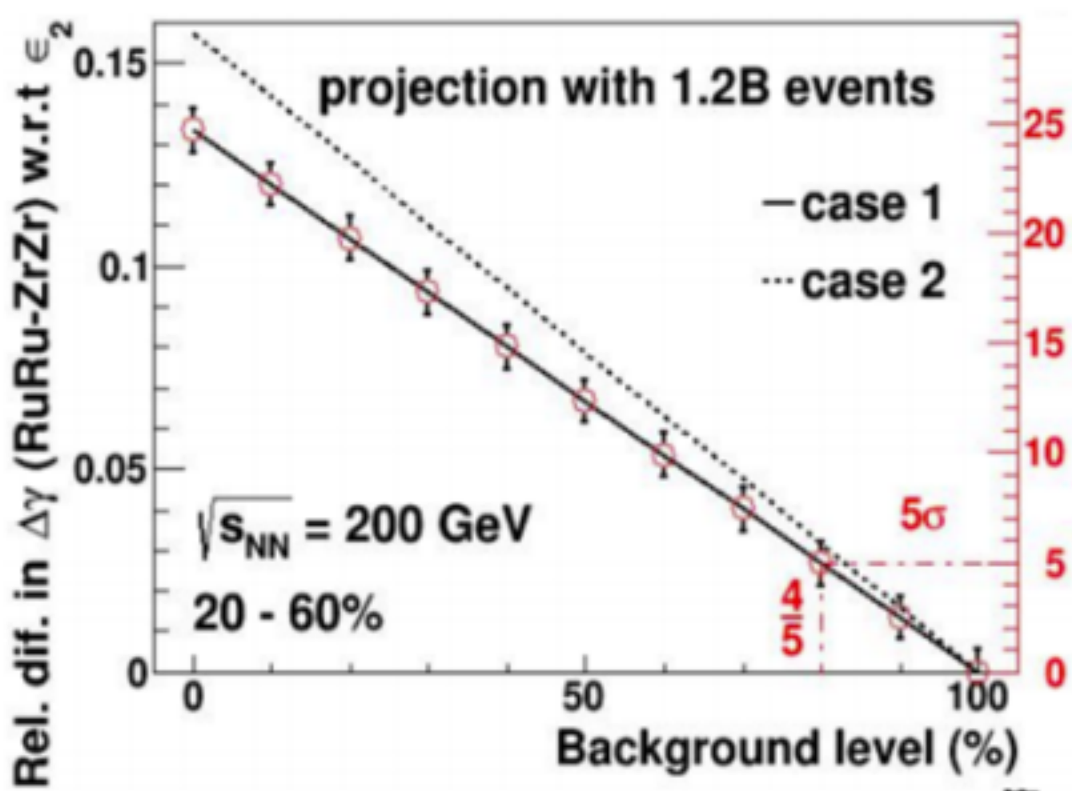
-> Despite significant advances quantitative predictions still require further theoretical progress

Experimental future — Isobars

Basic idea: By colliding different species of ions with same mass but different charge, one can vary the signal (~B) without changing the background

Projections based on 1.2 B events for each collision type (Zr+Zr,Ru+Ru)
(c.f. talk by L. Wen)





Deng,Huang,Ma,Wang, PRC 94 041901 (2016)

If background contributes less than 80% to $\Delta\gamma$ expect 5σ significance for unambiguous discovery

Conclusions

Chiral magnetic effect & anomalous transport phenomena provide an exciting opportunity to study new aspects of the QGP dynamics

Concepts developed in context of RHIC/LHC have already had a tremendous impact on the broader physics community

Despite significant progress on theory side, quantitative description of CME in heavy-ion collision remains a challenge

Combination of different theoretical methods required

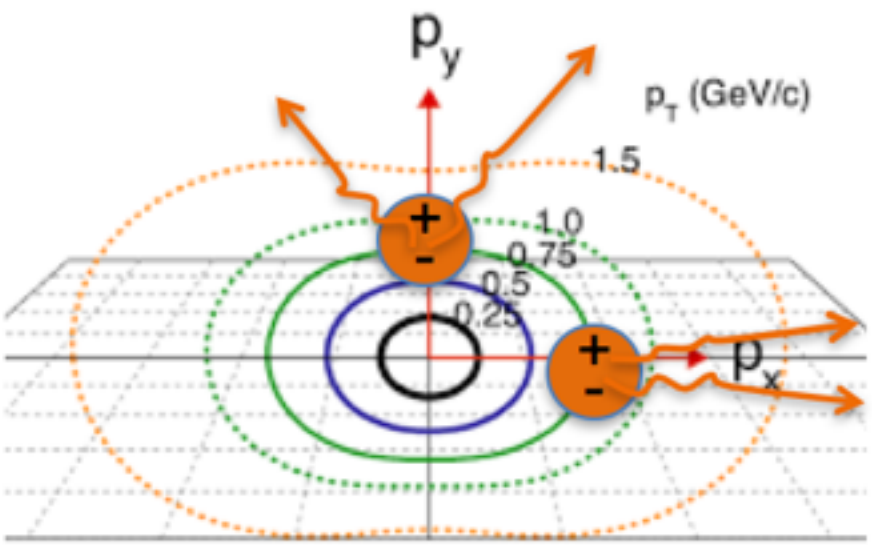
Even though has proven challenging to disentangle possible signatures of CME & backgrounds in heavy-ion experiments, upcoming decisive test in RHIC Isobar Scan

New insights into Chiral Magnetic Effect & underlying QCD dynamics

Backup

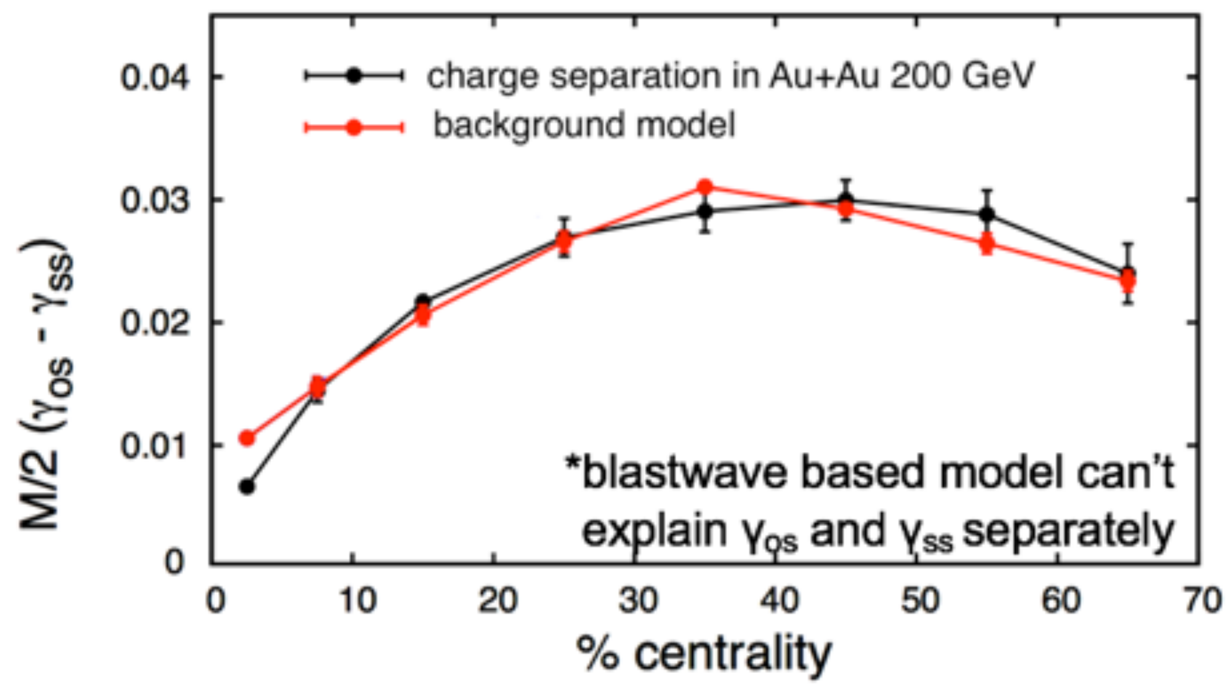
Potential Backgrounds

Backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation*



Flow boost collimates pairs more strongly in-plane than out of plane
known backgrounds are expected to go as v_2

S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)



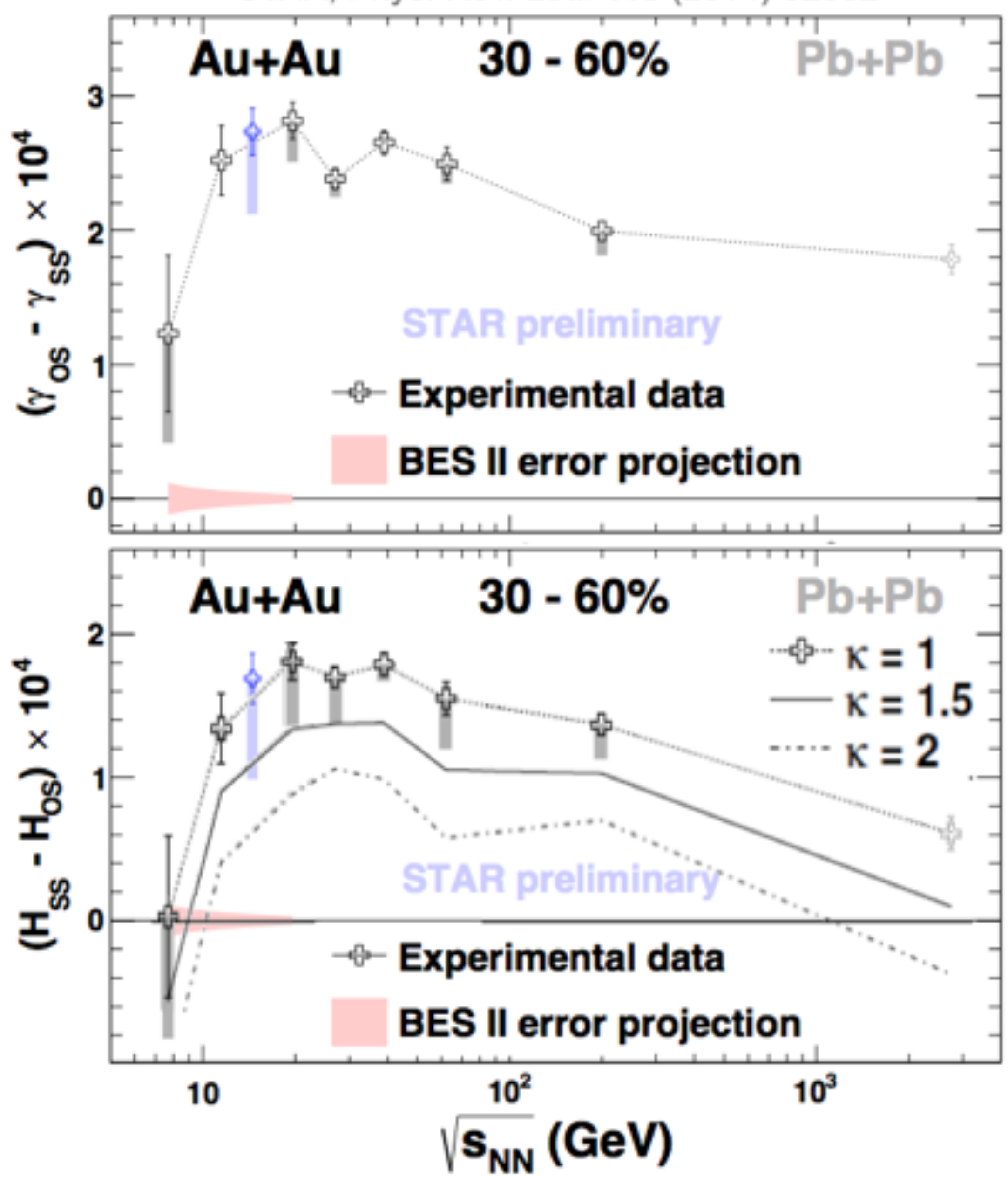
Difficult to draw definitive conclusions without better models, and an independent lever arm for magnetic field and v_2

slide by P. Sorenson

Beam Energy Dependence of Charge Separation

Initial attempts at subtracting the background

STAR, Phys. Rev. Lett. **113** (2014) 52302



Significant charge separation ($\Delta\gamma$) observed at all energies

Subtracting estimate of flow modulated background indicates residual signal is

- ♦ absent at 7.7 GeV
- ♦ maximum near 20 GeV
- ♦ falling with energy
- ♦ marginal at 2.76 TeV

background subtracted assuming factorization

$$H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$$

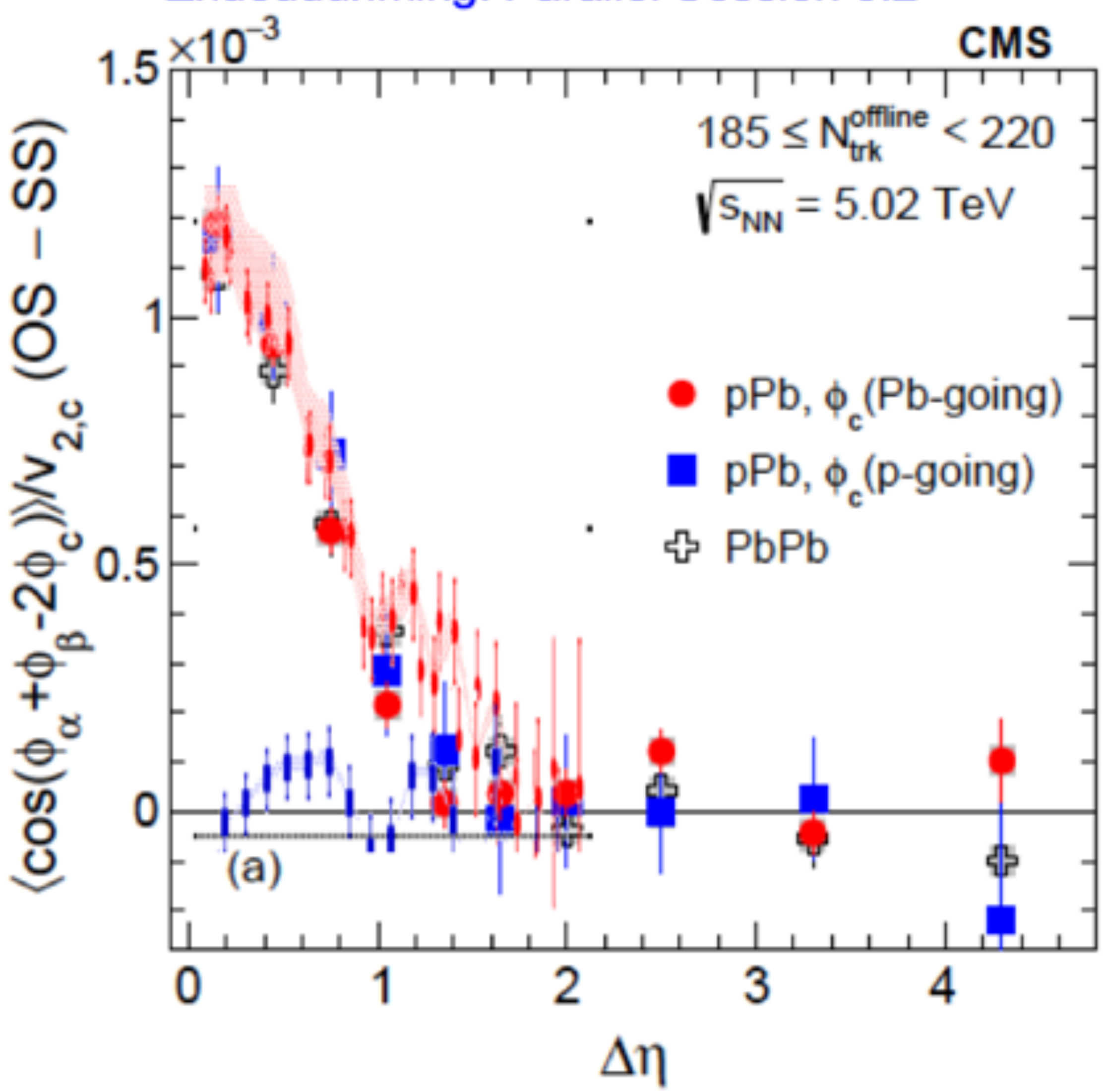
Bzdak, Koch and Liao, Lect. Notes Phys. 871, 503

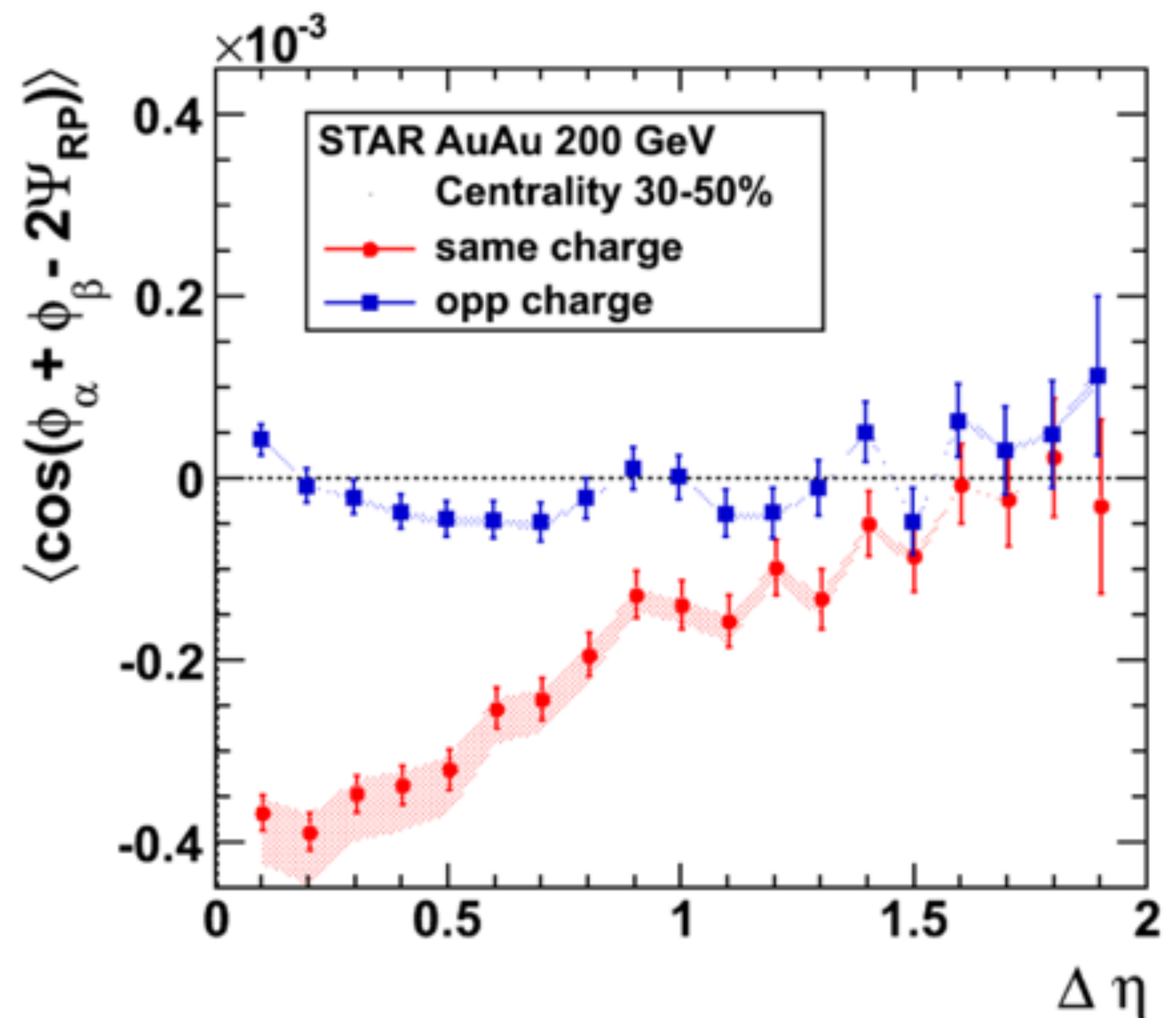
$$\delta = \langle \cos(\Delta\varphi) \rangle$$

slide by P. Sorenson

Testing CME with p+Pb and Pb+Pb

Zhuoudunming: Parallel Session 3.2





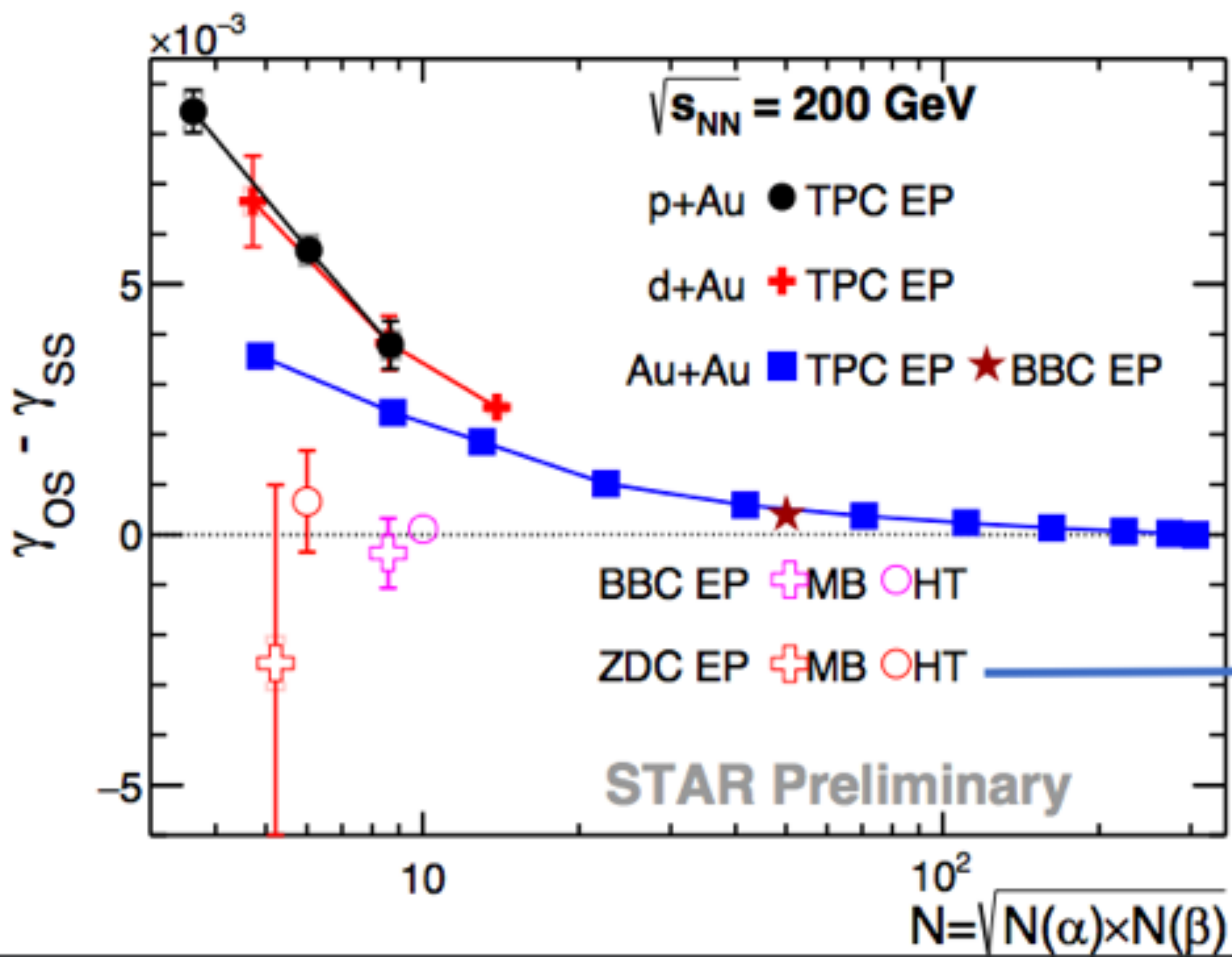
Widths in p+Pb, in peripheral Pb+Pb and in Au+Au are all similar

A surprising coincidence? a natural occurrence? or do all have the same origin in a non-CME background?

slide by P. Sorenson

γ correlation in p+Au and d+Au

- Sizable $\Delta\gamma$ in p+Au and d+Au w.r.t 2^{nd} –order event plane (EP) ψ_2 from TPC, the magnitude is similar to or higher than Au+Au
- $\Delta\gamma$ diappears in p+Au when η gap is introduced between EP and particles of interest: $\Delta\gamma$ in TPC EP results mostly from short range correlation.



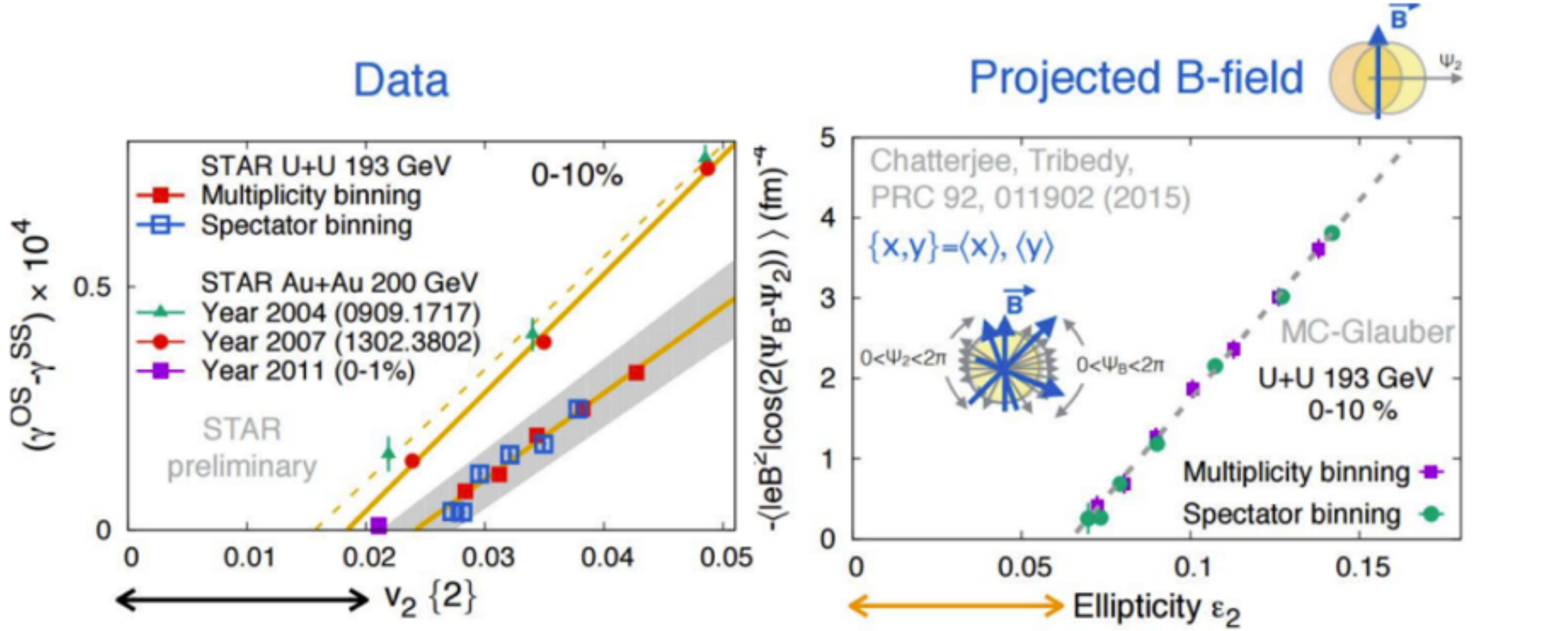
Time Projection Chamber: $|\eta| < 1$
Beam-Beam Counter: $3.8 < |\eta| < 5.2$
Zero Degree Calorimeter: $6 < |\eta|$

HT (High Tower): trigger on electromagnetic energy

slide by Liwen Wen

U+U?

- Why we need U+U collisions?
  - To disentangle the signal and the background by varying the background (trying to minimize flow background by selecting the most central collisions in UU)



Projected B-field vs ϵ_2 can provide a natural explanation to data.

slide by Liwen Wen