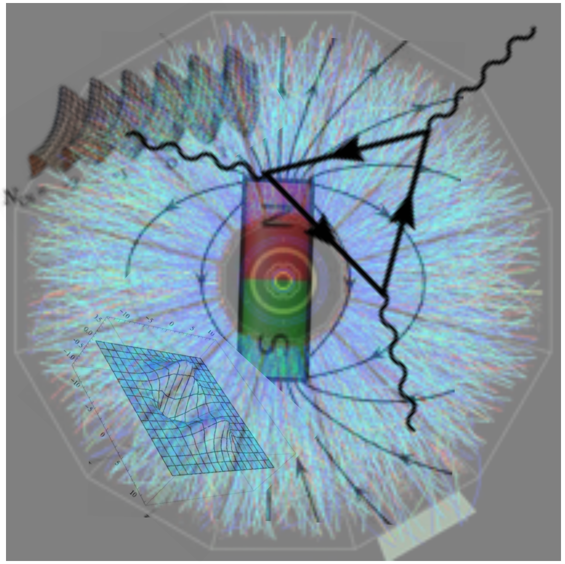
Talk @ INT Program   Sep 27, 2016

Quantitative Modeling of Anomalous Chiral Transport



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by NSF & DOE

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Outline

- *A brief introduction*
- *Status of CME measurements*
- *Quantitative CME:*

  Anomalous Viscous Fluid Dynamics
- *Summary & Outlook*

Exciting Progress: See Recent Reviews

Progress in Particle and Nuclear Physics 88 (2016) 1–28

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

D.E. Kharzeev [a,b], J. Liao [c,d,*], S.A. Voloshin [e], G. Wang [f]

[a] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
[b] Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[c] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 727 E Third Street, Bloomington, IN 47405, USA
[d] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48201, USA
[f] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

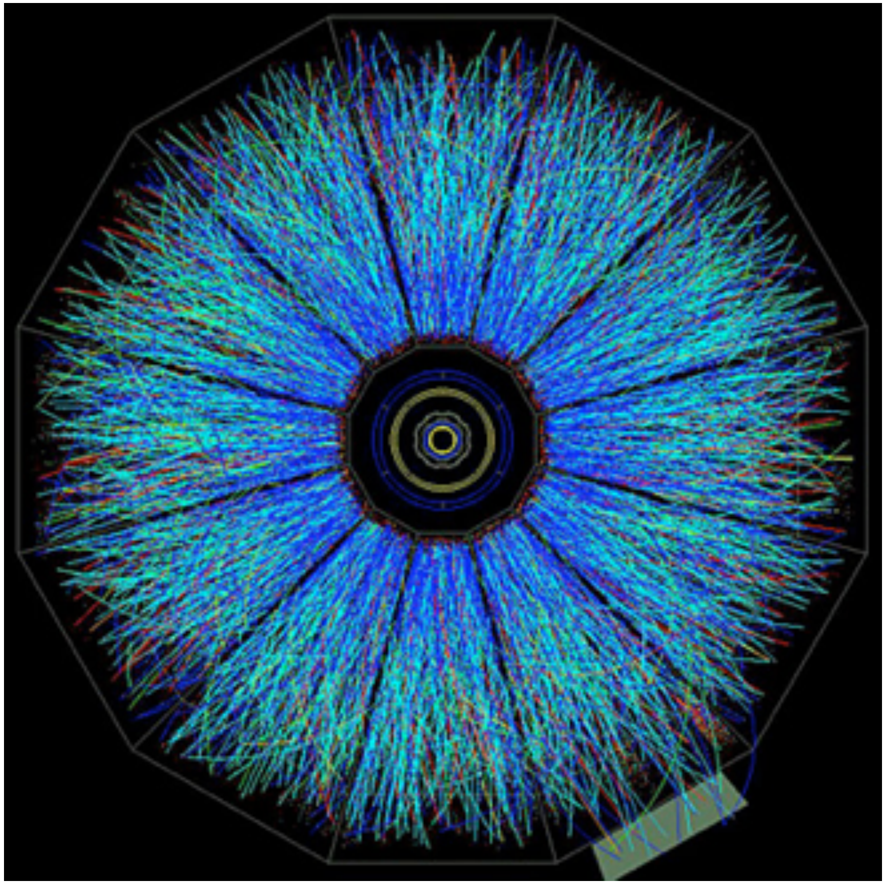
Prog. Part. Nucl. Phys. 88, 1 (2016) [arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

Bzdak, Koch, Liao, Lect. Notes. Phys 871(2013)503.

Quark-Gluon Plasma: A Chiral Fluid

It is a nearly perfect liquid: around the quantum limit.



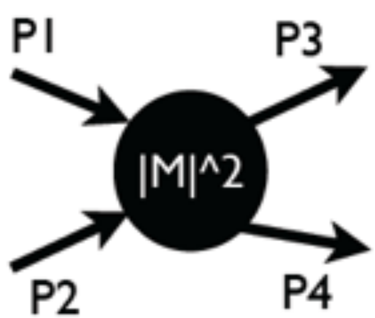
It is a hot plasma with approximately chiral quarks.

Would chiral anomaly, usually considered at microscopic level, manifest itself MACROSCOPICALLY in a fluid system of many chiral fermions? If so, how?

Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^\mu = 0$

$$\mathcal{L} \to \mathcal{L}$$



Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^\mu = 0$

WHAT ABOU "HALF"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

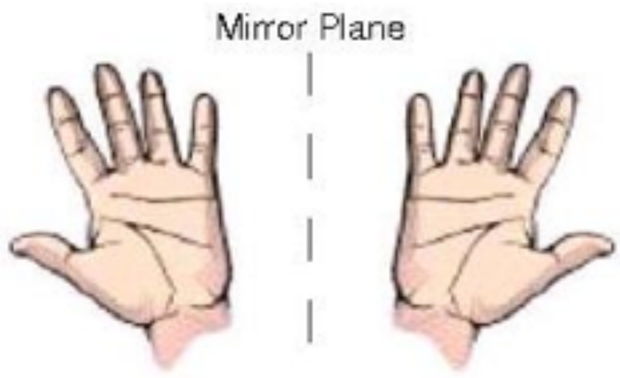
Classical symmetry:

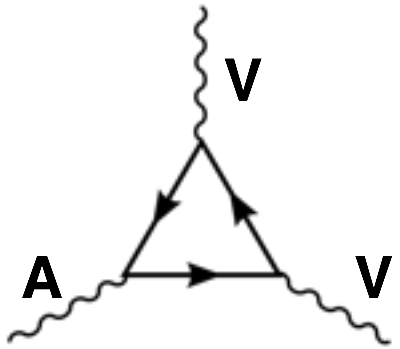
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

$$\mathcal{L} \to i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_\mu J_5^\mu = 0$$





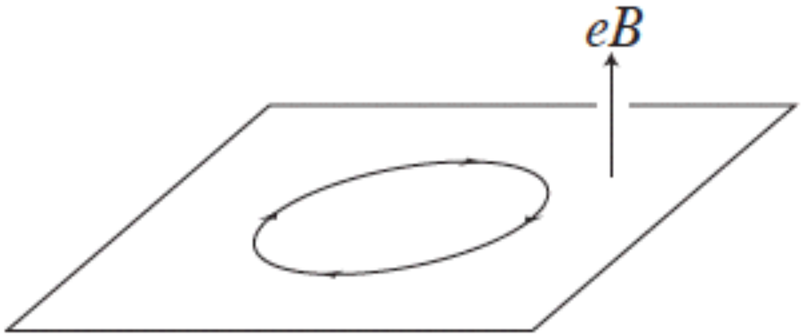
Broken at QM level:

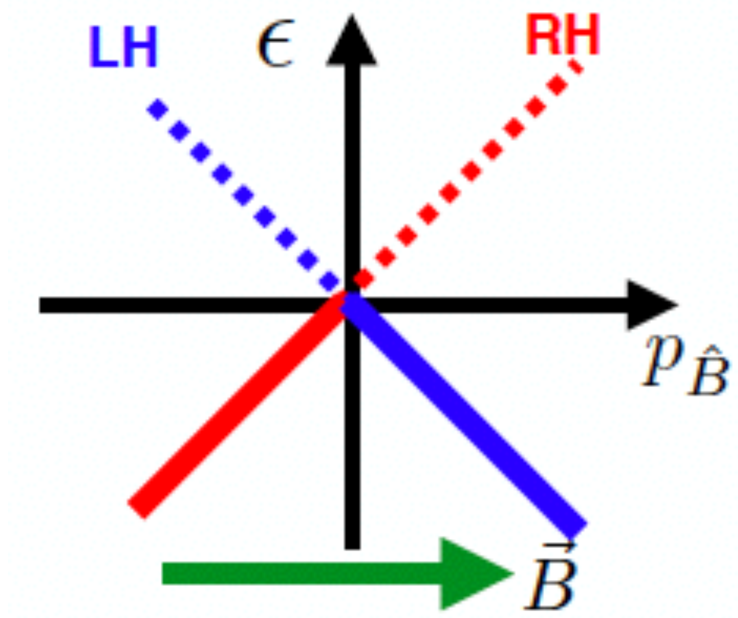
$$\partial_\mu J_5^\mu = C_A\vec{E}\cdot\vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Landau Levels in Magnetic Field





$$E_n^2 = p_z^2 + 2nB$$

Lowest-Landau-Level (LLL):
LLL is chiral!

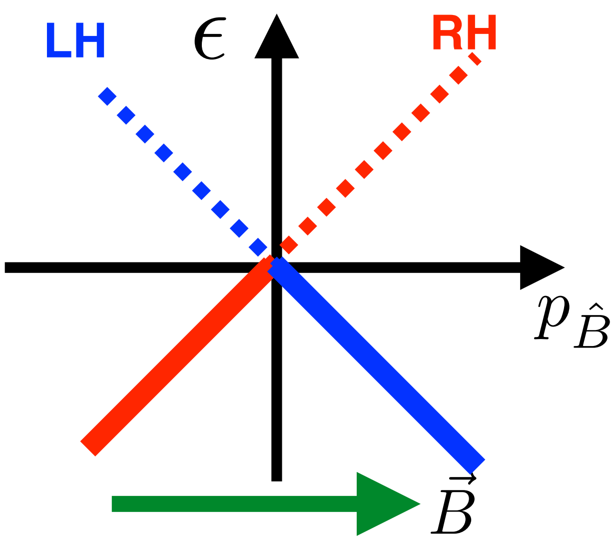
Chiral Anomaly

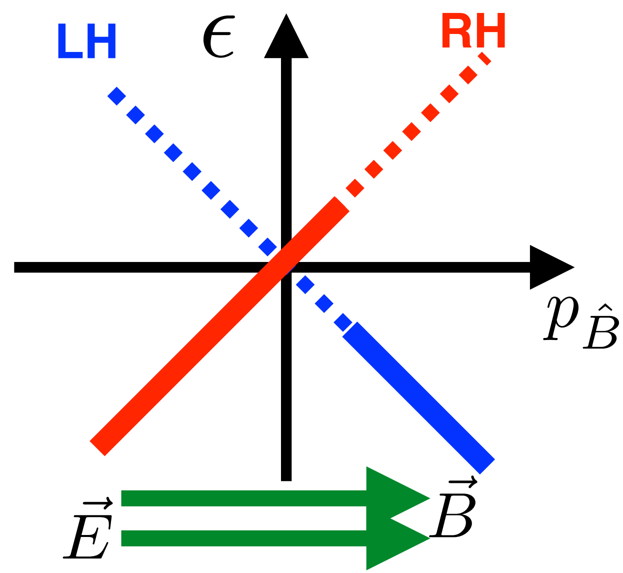
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

$$J_5^\mu = J_R^\mu - J_L^\mu$$





Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!

Anomalous Transport: Chiral Magnetic Effect

*** The Chiral Magnetic (CME) is an anomalous transport**

$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$

P odd
CP even

P even
CP odd

In NORMAL environment, this will NOT happen.

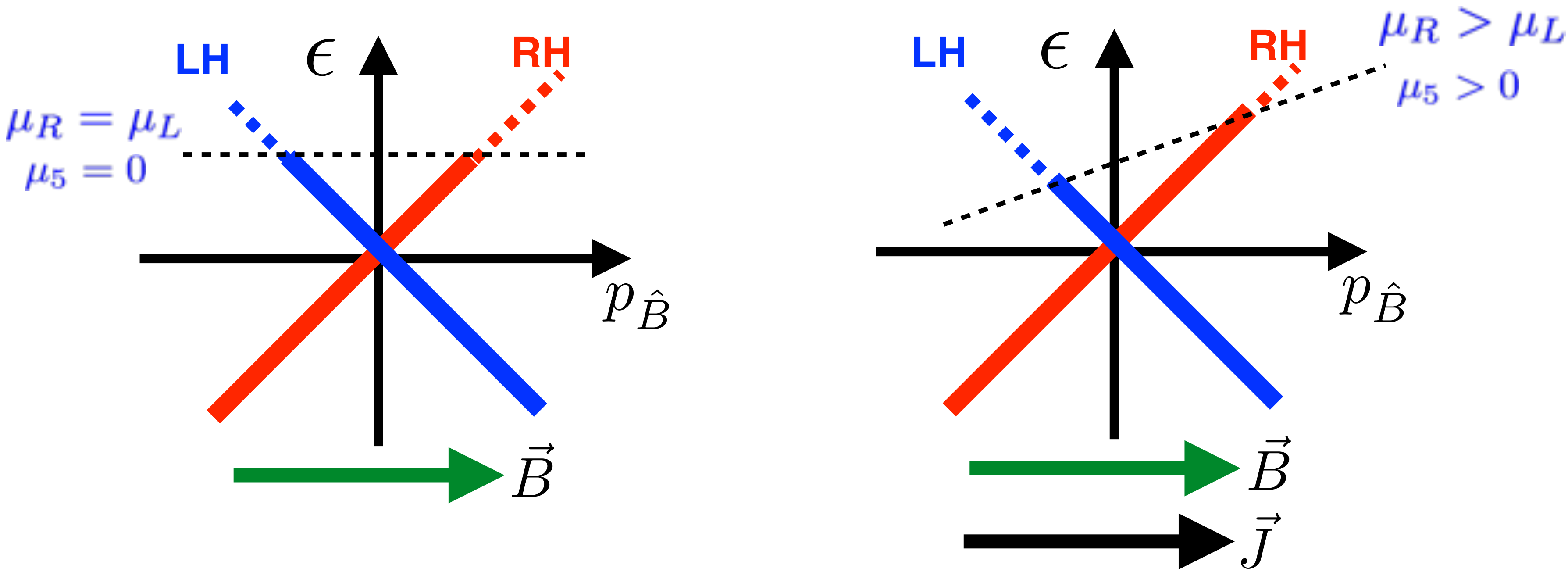
For this to occur: need a P- and CP-Odd environment!

$$\mu_5$$

A (convenient) way to quantify
IMBALANCE
in the numbers of
LH vs RH chiral fermions
—>
CHIRAL MATTER!

Such imbalance can be generated through chiral anomaly coupled with E-dot-B (e.g. topological fluctuations of QCD).

So How Does CME Work?



One may recognize deep connection between CME & anomaly.

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$\updownarrow$$

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

The CME conductivity is

**** fixed entirely by quantum anomaly***

**** T-even, non-dissipative***

**** universal from weak to strong coupling***

We need to modify hydrodynamics!

Hydrodynamics That Knows Left & Right

conservation law: $\partial_\mu J^\mu = 0 \rightarrow \partial_\mu J^\mu = C E^\mu B_\mu$

constituent relation: $J^\mu = n u^\mu + \nu^\mu$

$\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu$$

[Son, Surowka, 2009;…]

CVE CME

In Chiral Fluid: Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

It is the "21st century hydrodynamics": the 1st new terms added since Navier-Stocks!

[In passing: fluid rotation induces similar effects as magnetic field]

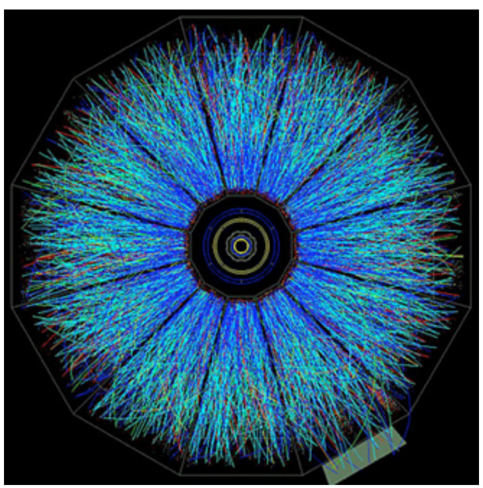
Wrap-up: Emergence in Chiral Matter

Chiral anomaly:
Basic QM dynamics
of chiral fermions

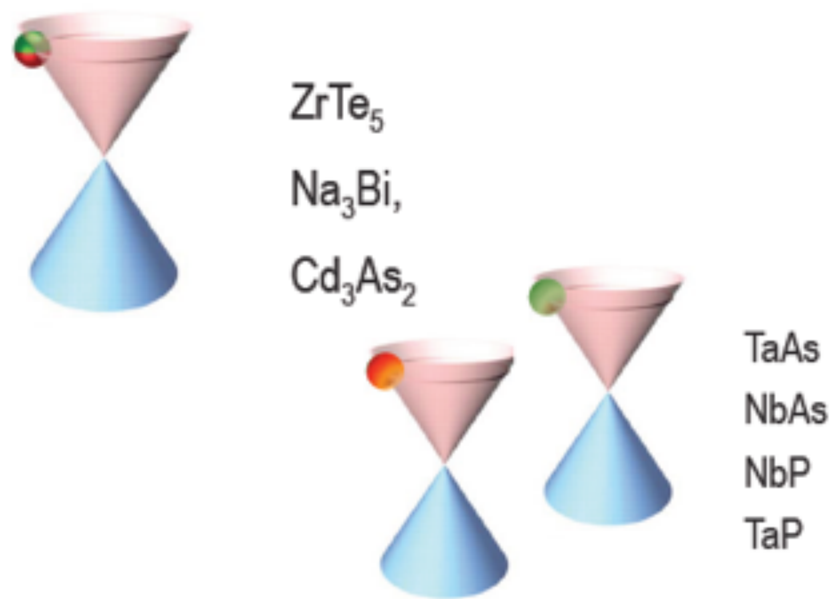
→

Anomalous chiral transport
(Chiral magnetic effect):
Emergent phenomenon
in <u>Chiral Matter</u>:

Quark-gluon plasma
[This talk focuses on QGP.]

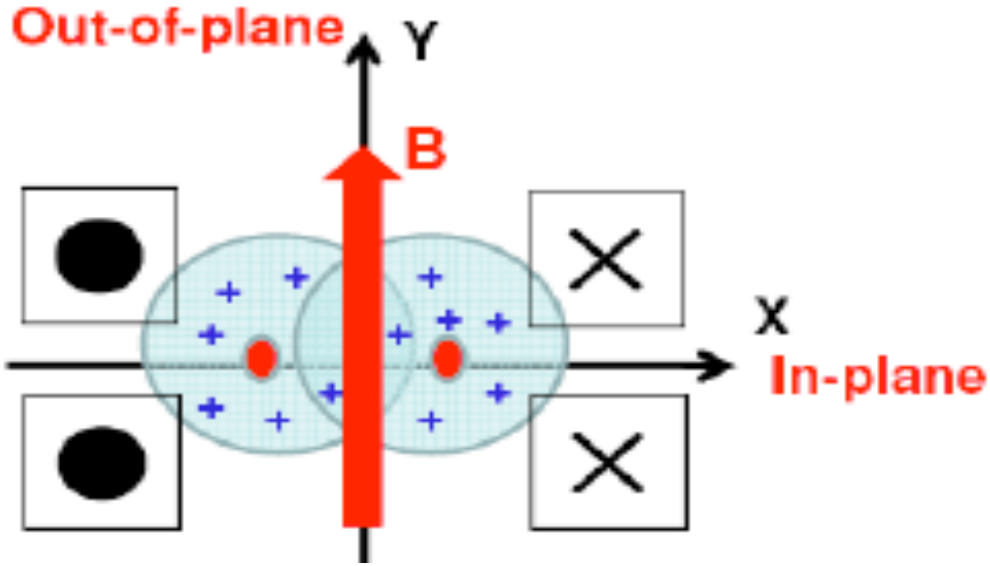


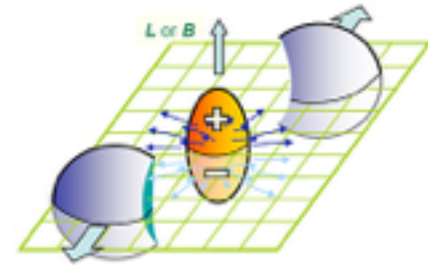
Dirac & Weyl Semimetals



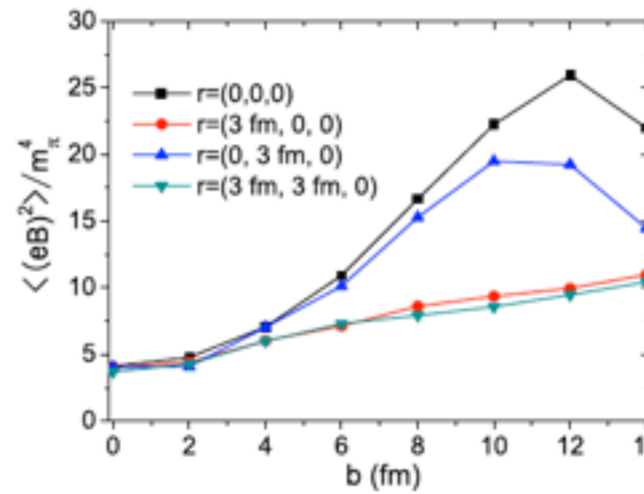
Status of CME Measurements

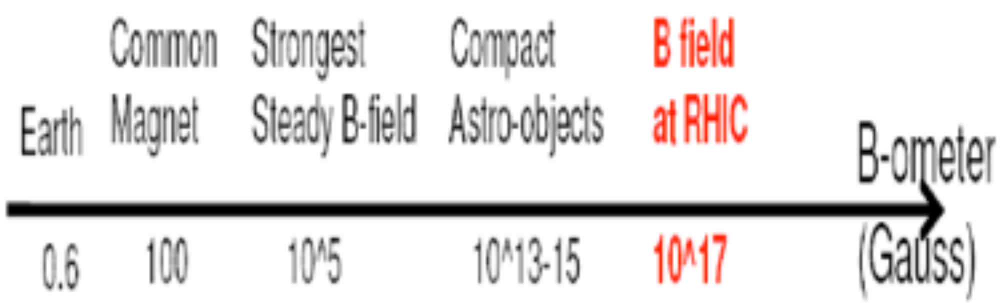
Strong EM Fields in Heavy Ion Collisions





$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$





- Strongest B field (and strong E field as well) naturally arises!

[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran;Tuchin; ...]

- “Out-of-plane” orientation (approximately)

Event-By-Event Magnetic Fields

PLB 718 (2013) 1529 [arXiv:1209.6594]

Physics Letters B 718 (2013) 1529–1535

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

John Bloczynski [a], Xu-Guang Huang [a,*], Xilin Zhang [a], Jinfeng Liao [a,b]

[a] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[b] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA

A R T I C L E I N F O

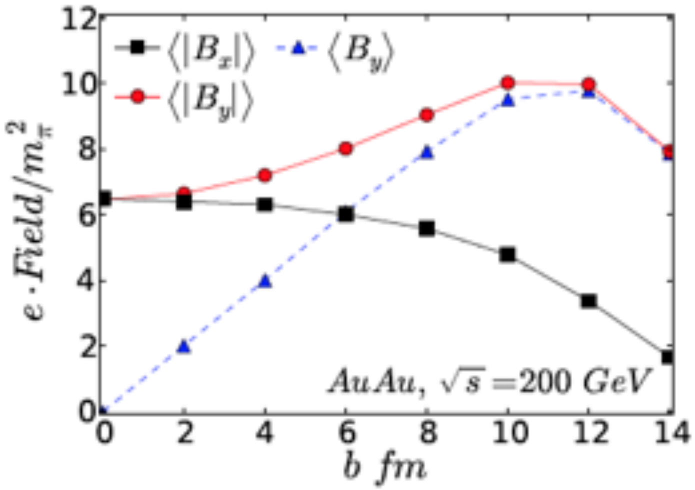
Article history:
Received 9 October 2012
Received in revised form 11 December 2012
Accepted 12 December 2012
Available online 14 December 2012
Editor: J.-P. Blaizot

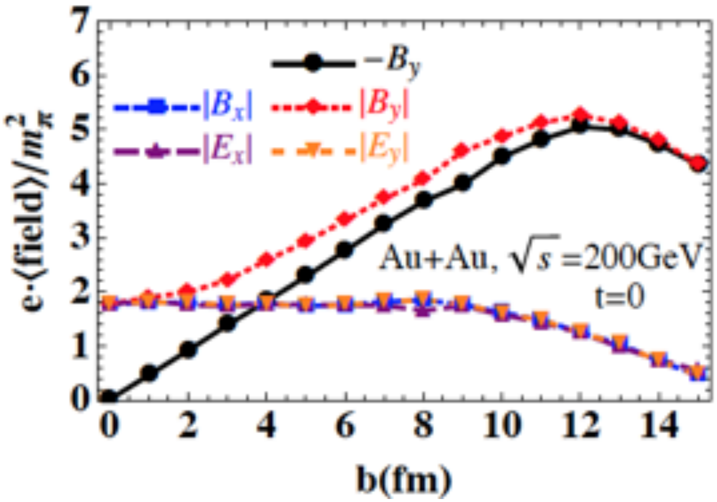
A B S T R A C T

The heavy-ion collisions can produce extremely strong transient magnetic and electric fields. We study the azimuthal fluctuation of these fields and their correlations with the also fluctuating matter geometry (characterized by the participant plane harmonics) using event-by-event simulations. A sizable suppression of the angular correlations between the magnetic field and the 2nd and 4th harmonic participant planes is found in very central and very peripheral collisions, while the magnitudes of these correlations peak around impact parameter $b \sim 8$–10 fm for RHIC collisions. This can lead to notable impacts on a number of observables related to various magnetic field induced effects, and our finding suggests that the optimal event class for measuring them should be that corresponding to $b \sim 8$–10 fm.

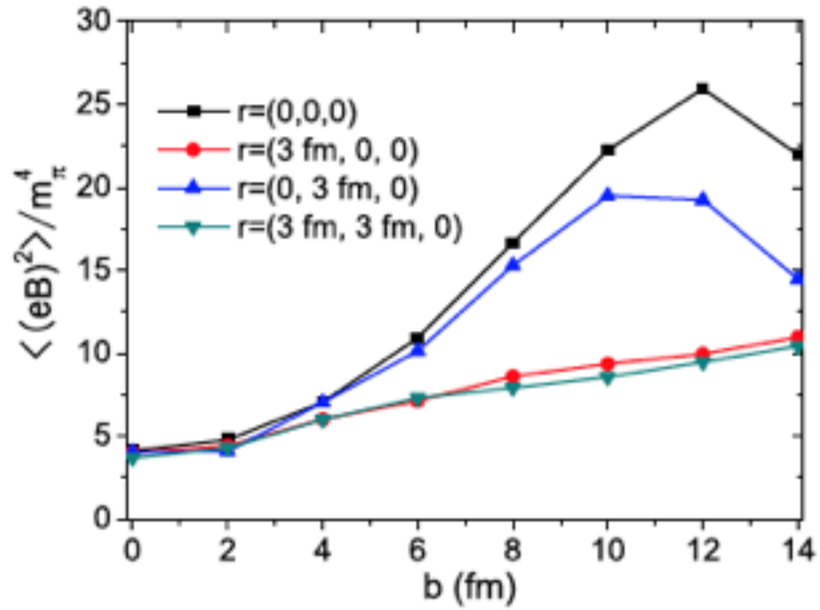
Event-By-Event Magnetic Fields

Bzdak & Skokov, arXiv:1111.1949





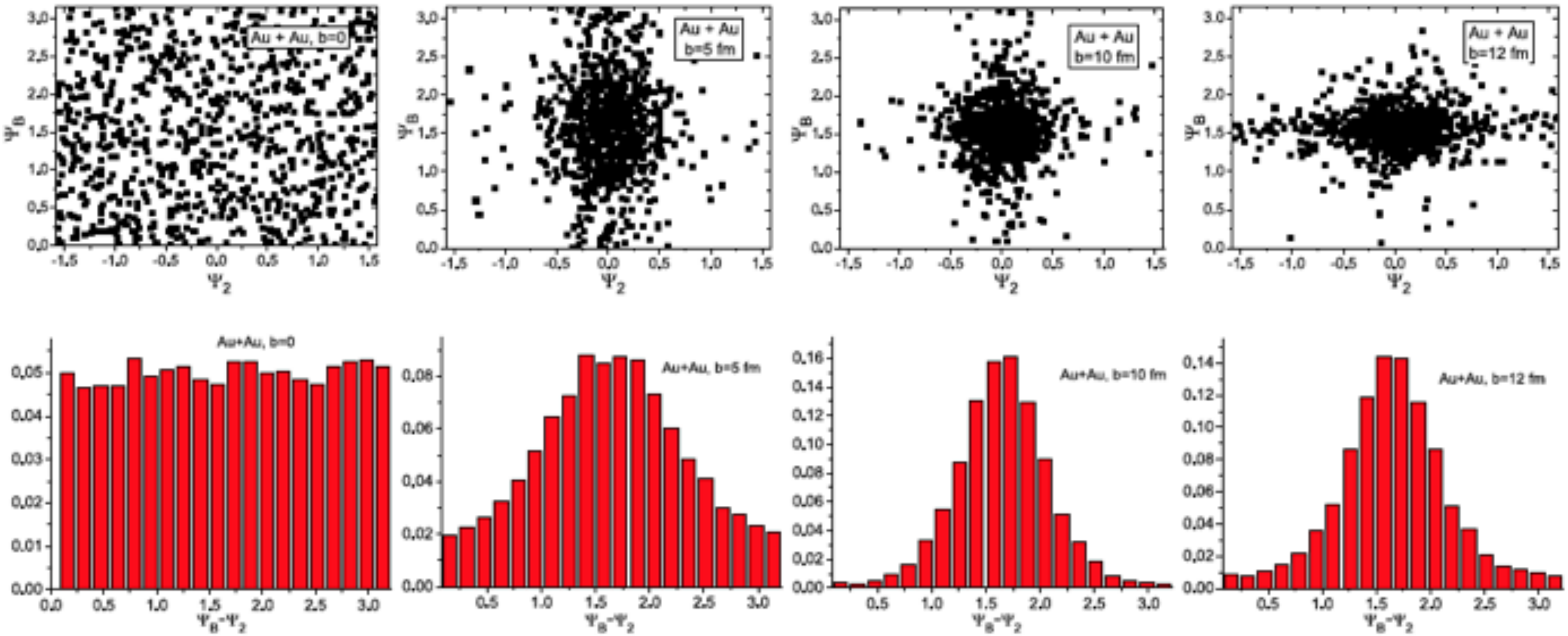
Deng & Huang, arXiv:1201.5108

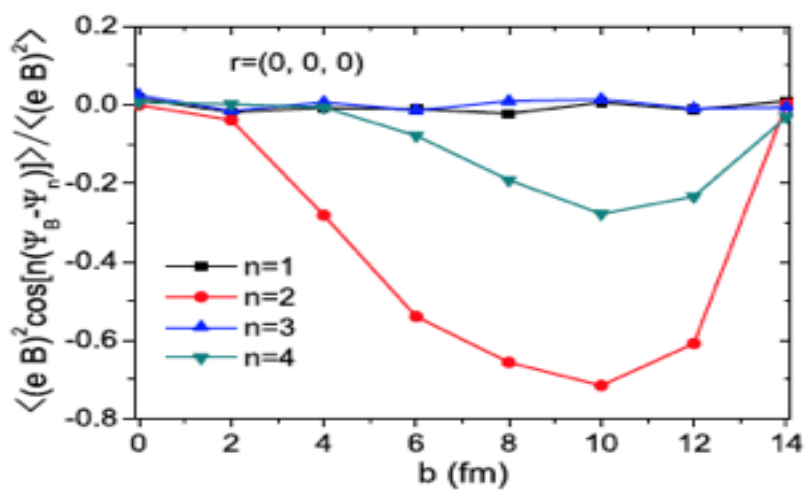


PLB 718 (2013) 1529 [arXiv:1209.6594]

Proton is a finite size object!

Event-By-Event Magnetic Fields



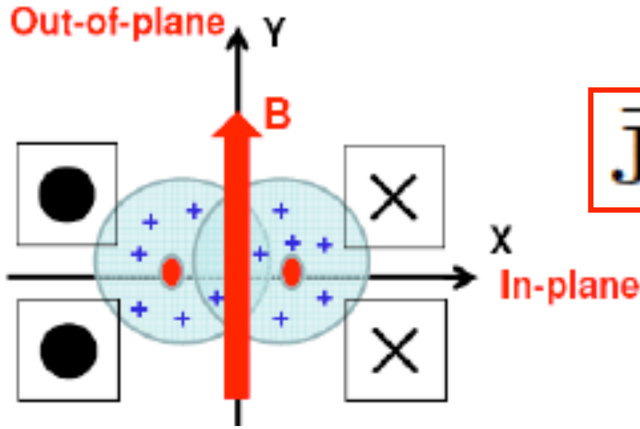


Measurable effects (CME, CMW, photon v2,…) are controlled by:

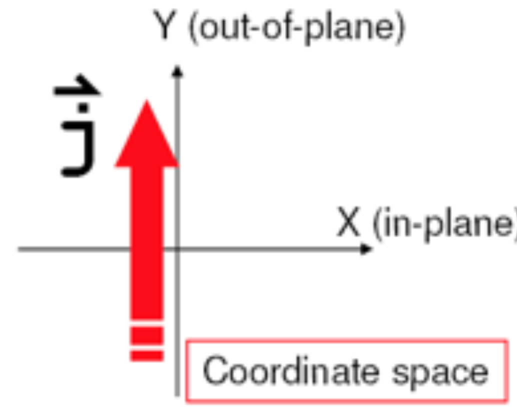
$$\langle (e\mathbf{B})^2 \cos(2\bar{\Psi}_{\mathbf{B}}) \rangle$$

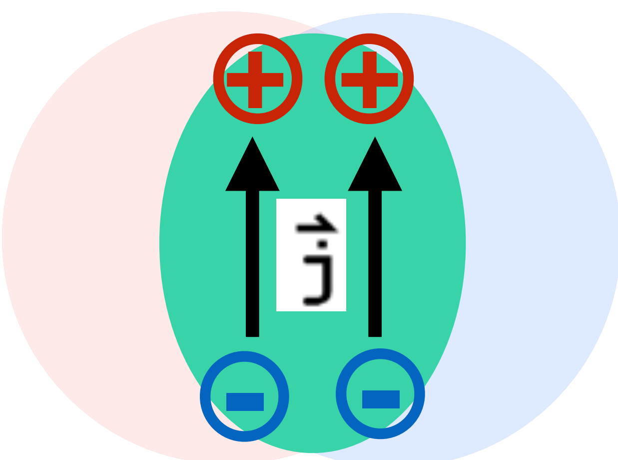
PLB 718 (2013) 1529 [arXiv:1209.6594]

From CME Current to Charge Separation

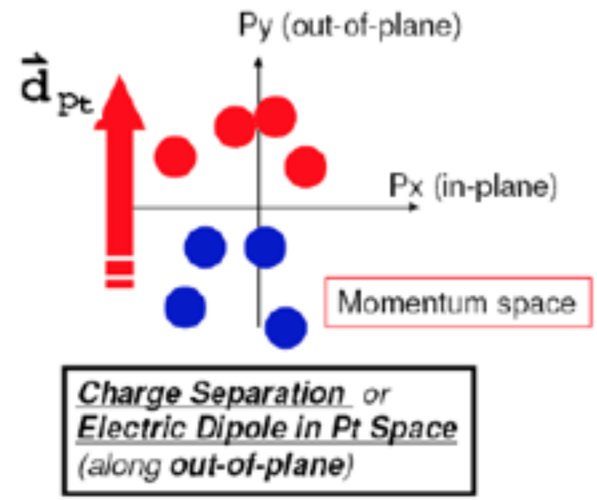


$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$





strong radial blast:
position —> momentum



$$\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})$$

$$< a_\pm > \sim \pm < \mu_5 > B$$

[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

Charge Separation Observable

$$\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})$$

$$< a_\pm > \sim \pm < \mu_5 > B \to 0$$

The dipole flips e-by-e and averages to zero (no global P-violation)

[Voloshin, 2004]

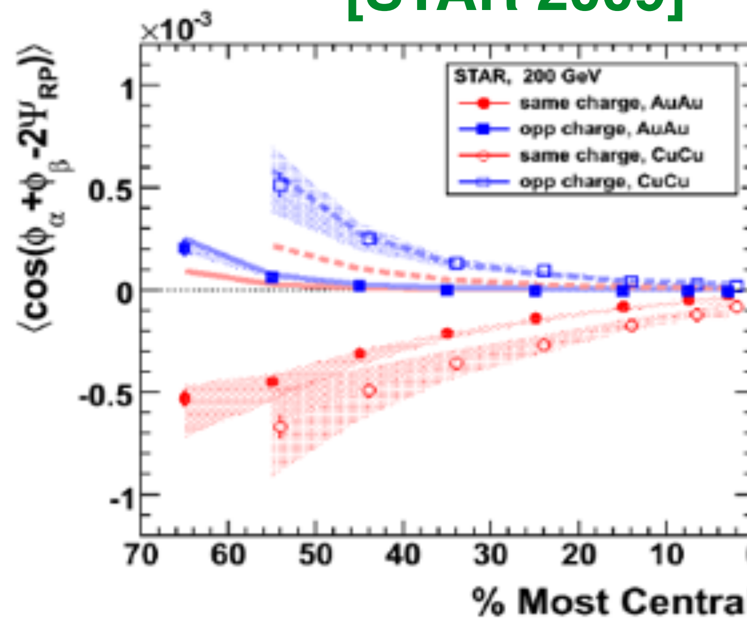
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

known to be very small

The hope was: these two cancel out to be negligible…

what we are looking for

[STAR 2009]



As it was pointed out later, the backgrounds turn out to be NOT negligible…

[2009~2010: Wang; Bzdak, Koch, JL; Pratt, Schlichting; …]

Flow-Driven Background

$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

$$[B_{in} - B_{out}] \sim v_2 \sim \gamma$$

Effects of Cluster Particle Correlations on Local Parity Violation Observables

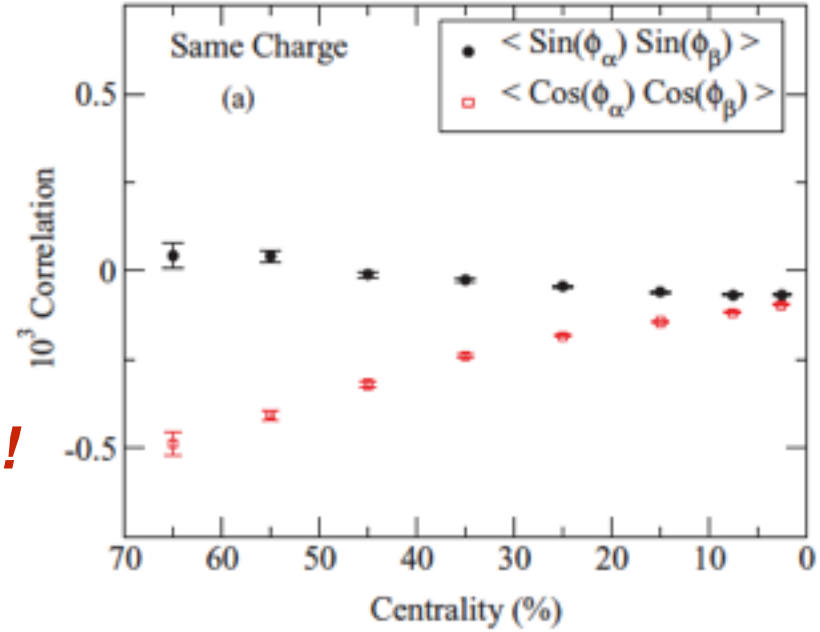
[Wang, 2009]

Fuqiang Wang[1]

[1] *Department of Physics, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907*

We investigate effects of cluster particle correlations on two- and three-particle azimuth correlator observables sensitive to local strong parity violation. We use two-particle angular correlation measurements as input and estimate the magnitudes of the effects with straightforward assumptions. We found that the measurements of the azimuth correlator observables by the STAR experiment can be entirely accounted for by cluster particle correlations together with a reasonable range of cluster anisotropy in non-peripheral collisions. Our result suggests that new physics, such as local strong parity violation, may not be required to explain the correlator data.

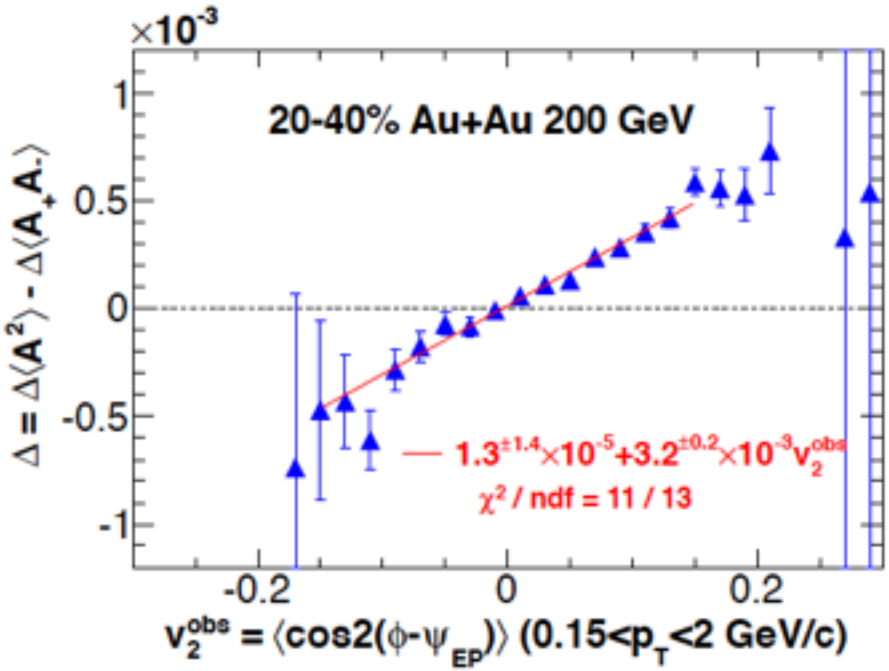
Clearly there are flow driven background contributions: need to develop ways of suppressing such correlations!

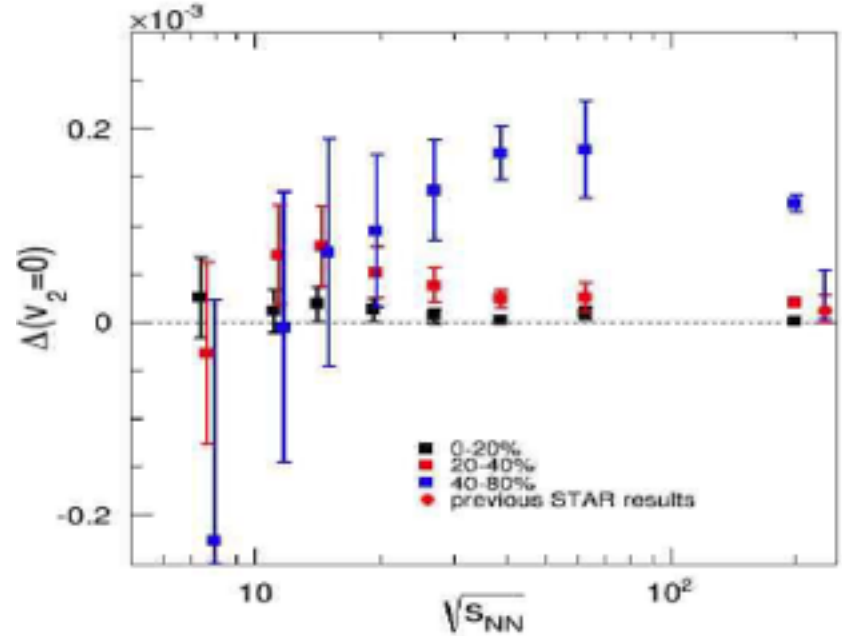


[Bzdak, Koch, JL, 2009]

Separation of CME & Flow-Driven Background

Event shape selection method **[Bzdak, Skokov; Wang]**





[STAR2013, by Purdue group]

[STAR2015@QM15]

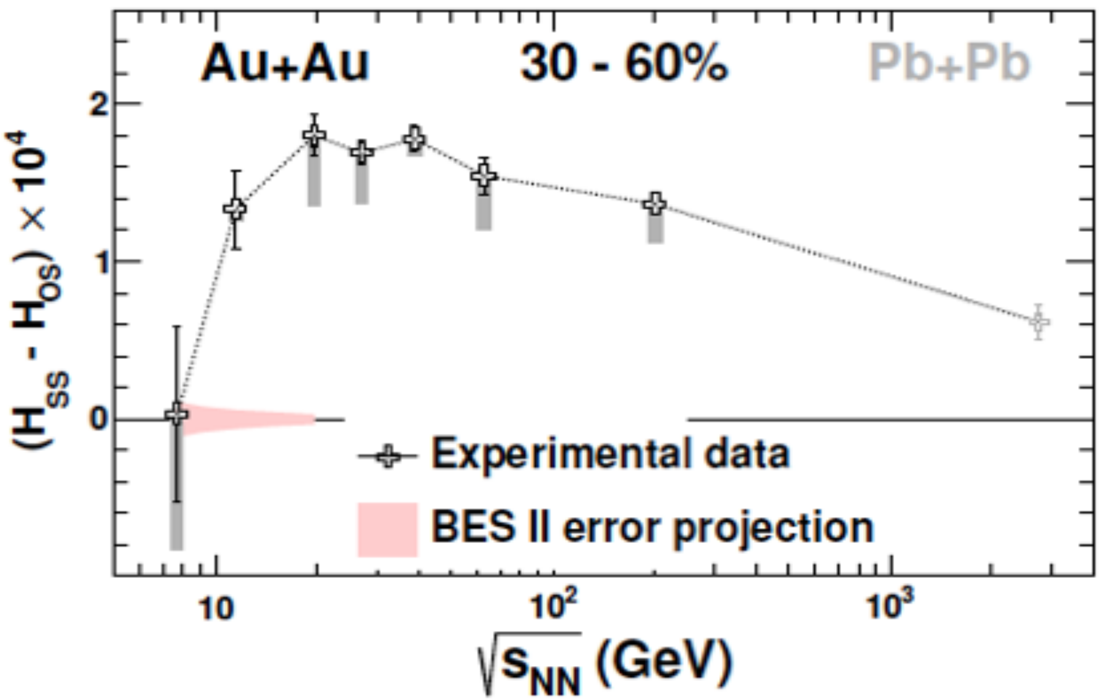
Separation of CME & Flow-Driven Background

Making sense of data in a two-component picture

[Bzdak, Koch, JL, 2012;
Blocynski, Huang, Zhang, JL, 2013]

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

H: "CME Signal"
F: "Flow Driven Background"



[STAR PRL 2014]

[also measured by ALICE@LHC]

$$H_{CME} \rightarrow 2a_1^2$$

Encouraging experimental evidence for CME in QGP — can we quantitatively compute CME signal?

Summarizing Exp. Status

Main challenge: flow-driven background v.s. CME signal

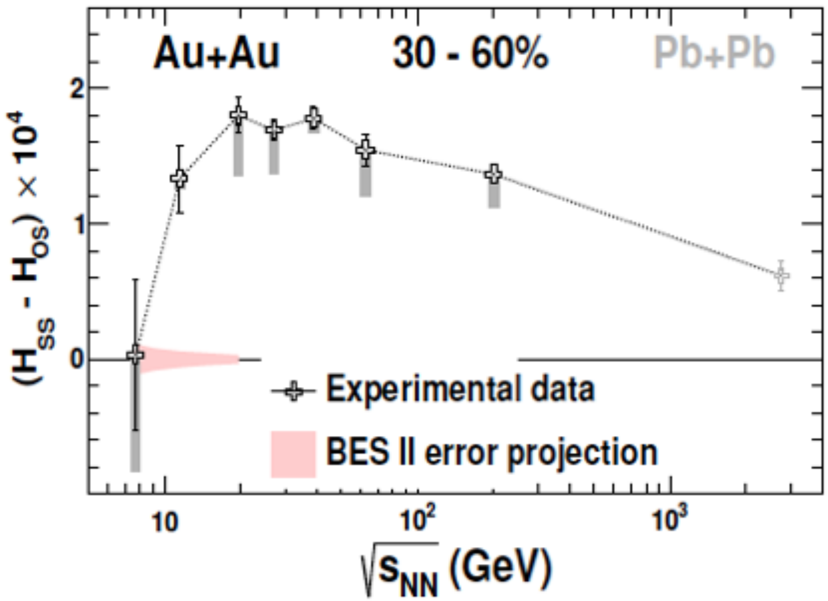
Vary v2 for fixed B:

AuAu v.s. UU;
Varying event-shape;
2-component subtraction.

Vary B for fixed v2:

Isobaric collisions with
RuRu v.s. ZrZr

Our best guess for now:



Caveat: Additional backgrounds from resonance decay in subtracting v2 backgrounds

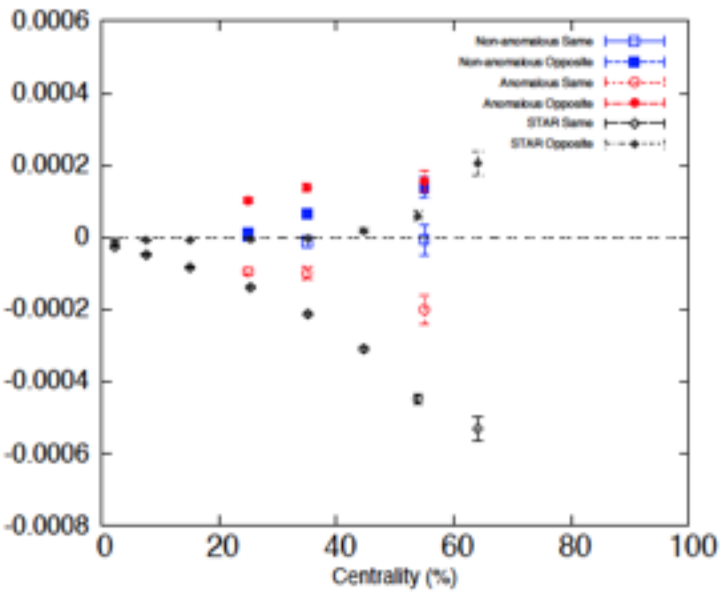
[Wang, Zhao, 1608.06610]

Quantitative CME from Anomalous Viscous Fluid Dynamics

Early Attempts at CME Modeling

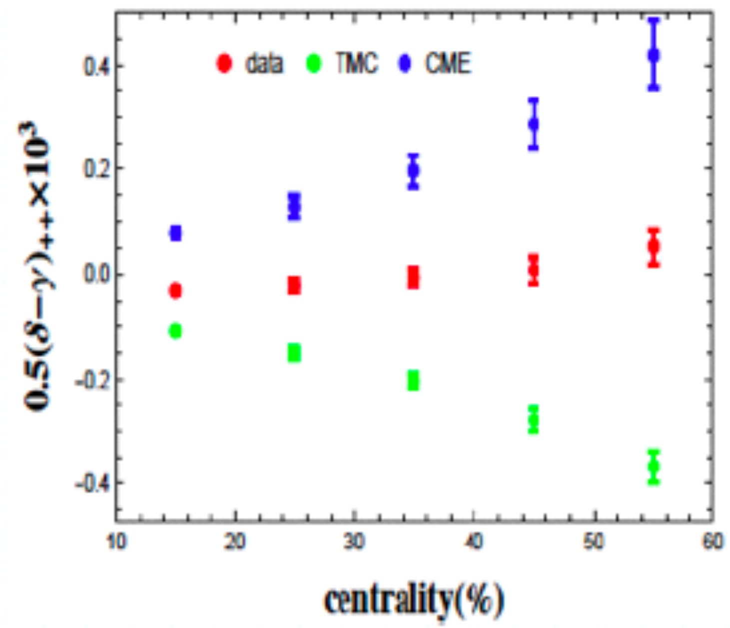
[Hirono, Hirano, Kharzeev, arXiv:1412.0311]

**** 3+1D ideal hydro***
**** event-by-event simulations***
**** full current evolution***
**** glasma initial condition***



[Yi Yin, JL, arXiv:1504.06906; PLB2016]

**** OSU hydro: data validated***
**** linearized current evolution***
**** quantifying background in same hydro***



[Early applications to CMW: Hirano, Hirono, … 2012; Yee,Yin, 2012]

Anomalous-Viscous Fluid Dynamics (AVFD)

[Jiang, Shi, Yin, JL, 2016.]

$$D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{\sigma}{2} E^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu + \frac{\sigma}{2} E^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu$$

CME

$$d\, \nu_{R,L}^\mu = (\nu_{NS}^\mu - \nu_{R,L}^\mu) / \tau_{rlx}$$

on top of 2+1D VISHNew— OSU Group

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

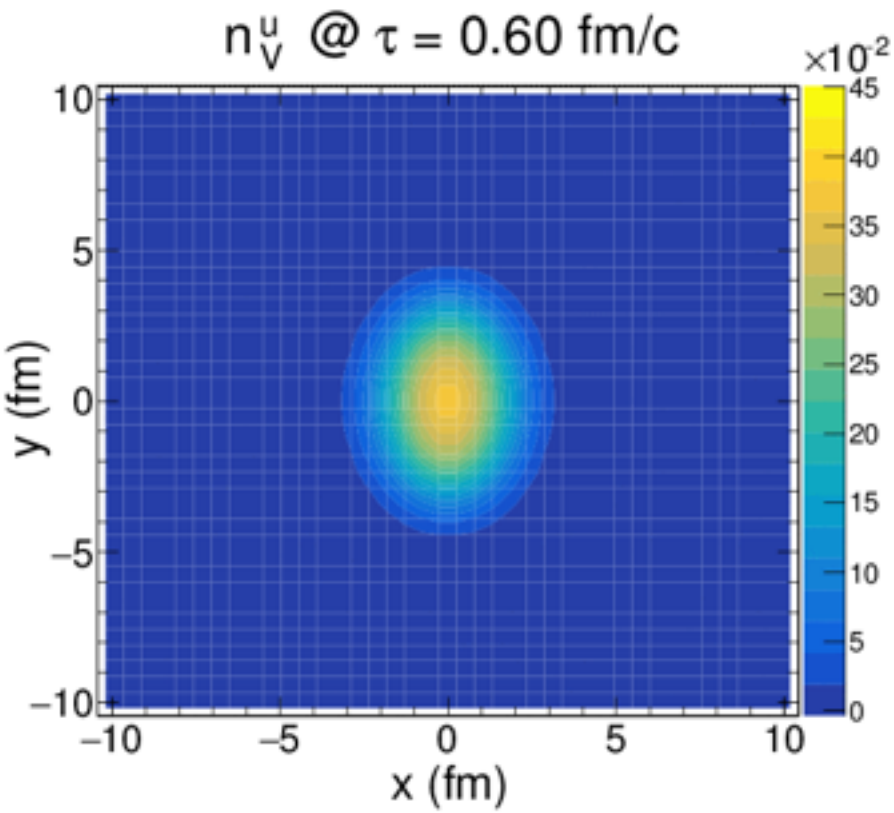
B field + μ_A ⇒ charge separation

$$dN_\pm/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$

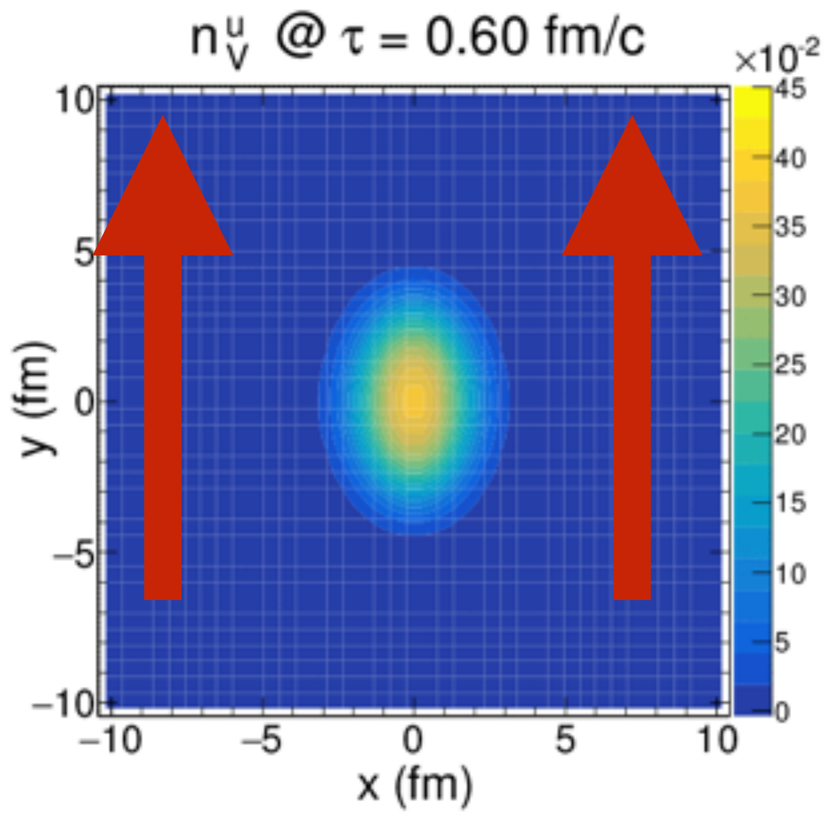
Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]

No B Field



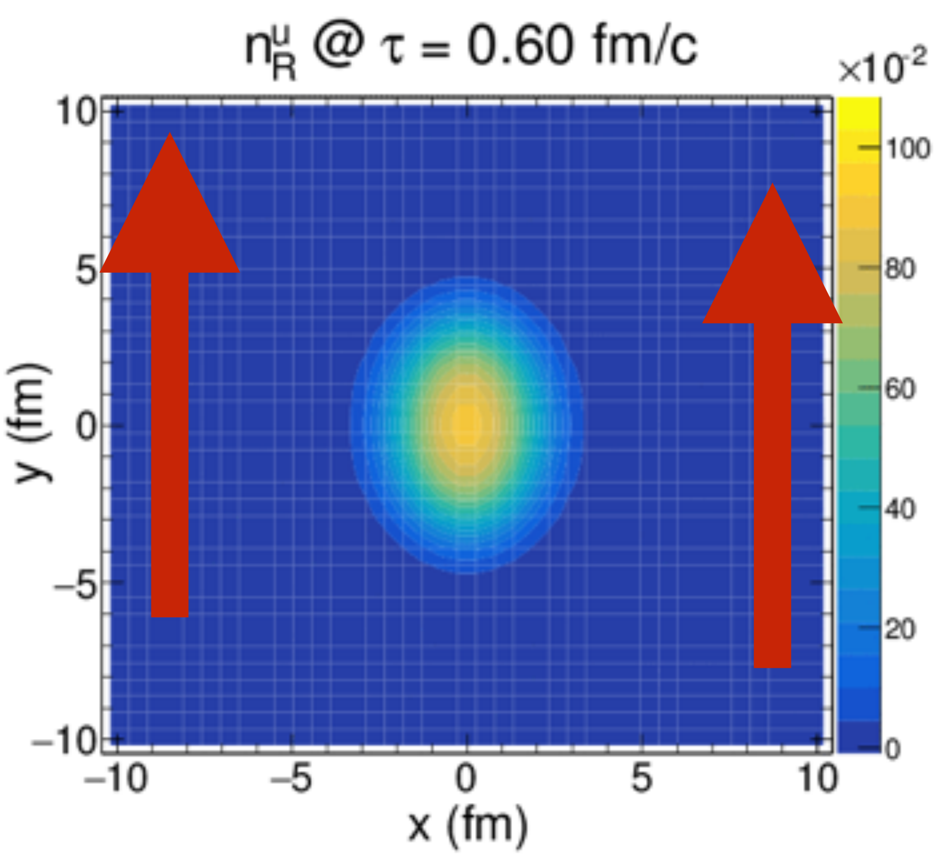
With B Field



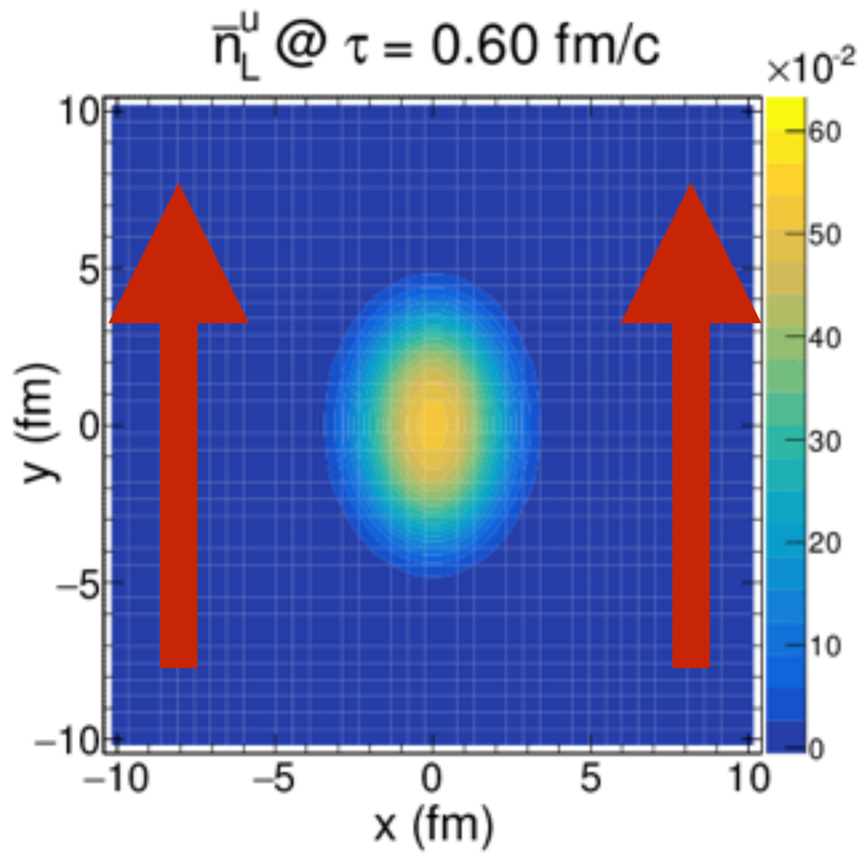
Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]

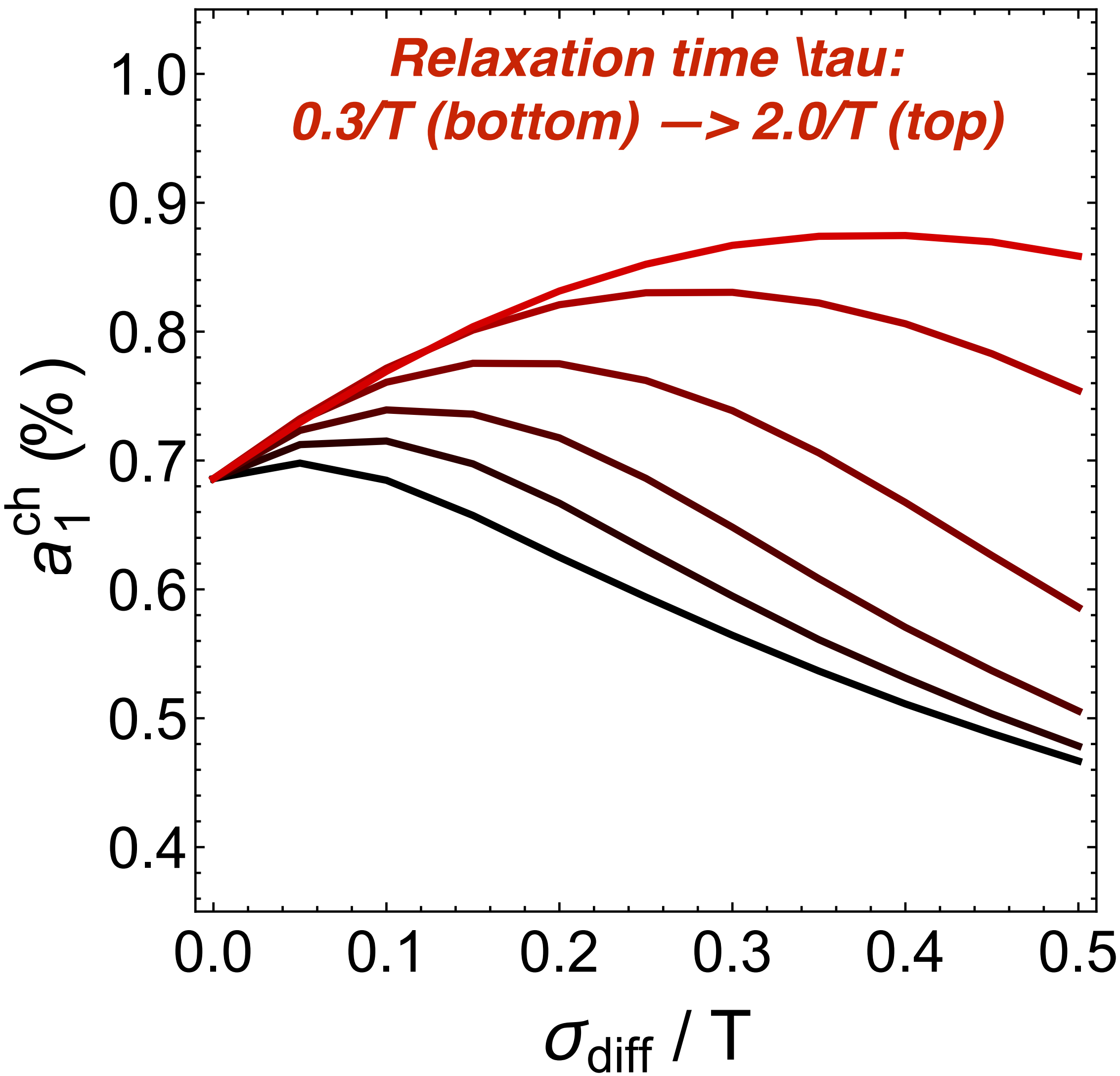
Right-Handed Density



Left-Handed Density



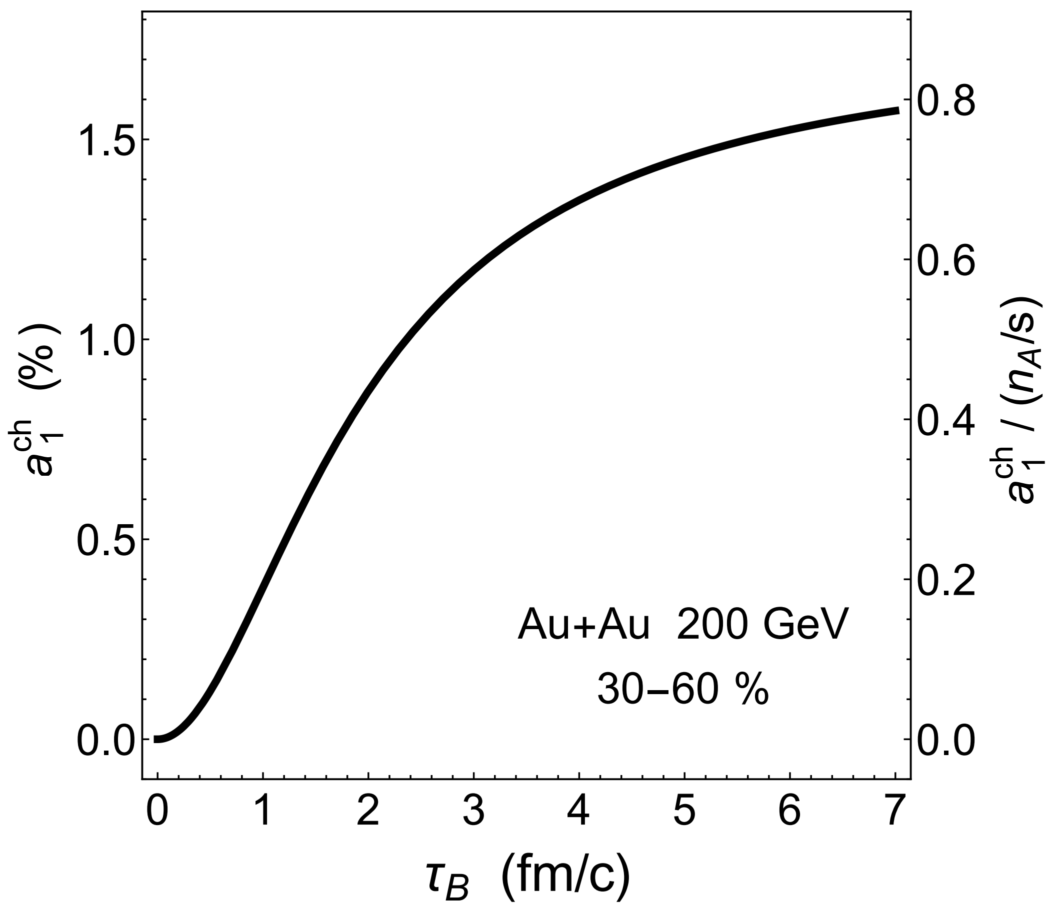
Dependence on Viscous Parameters



Charge separation could vary within a factor of 2 for a reasonable and broad range of values.

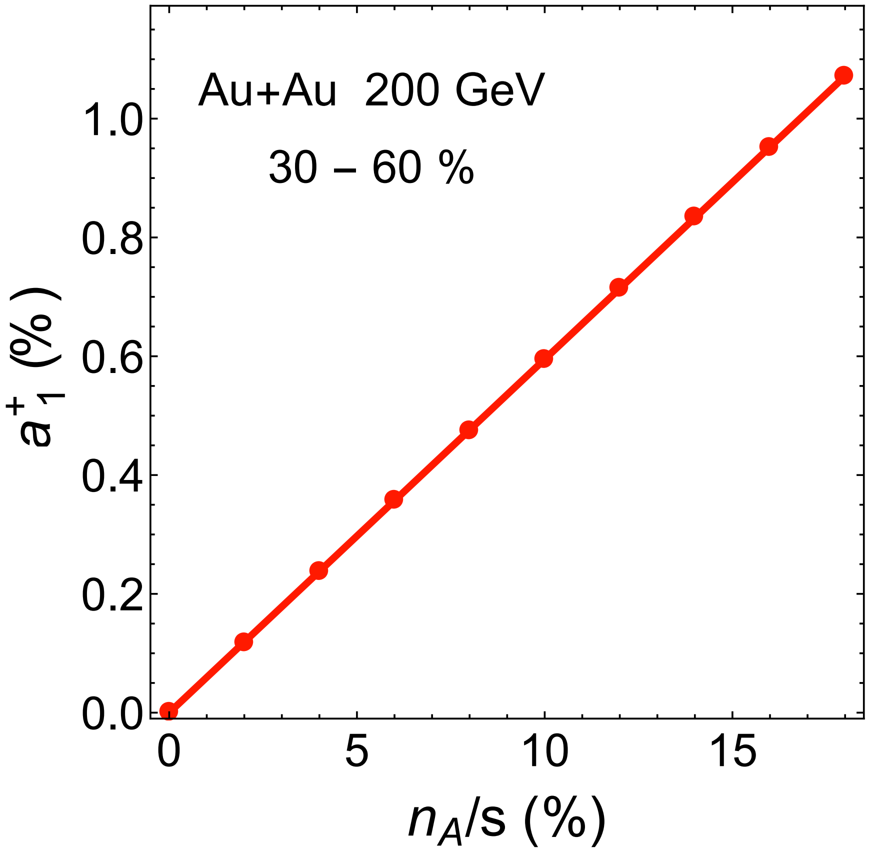
A "standard" choice:
\sigma = 0.3*T
\tau = 0.5 / T

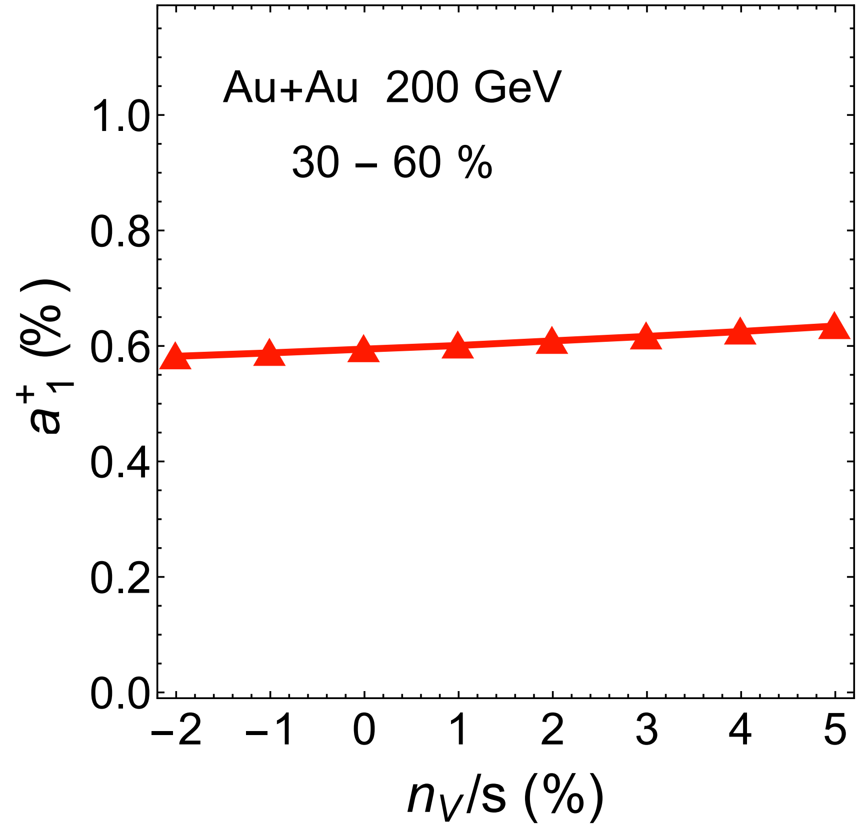
Dependence on B Field Lifetime



Charge separation has a strong dependence on B field lifetime.

Dependence on Initial Conditions





- ***Charge separation is VERY sensitive to initial axial charge density.***
- ***Charge separation is NOT sensitive to initial vector charge density.***

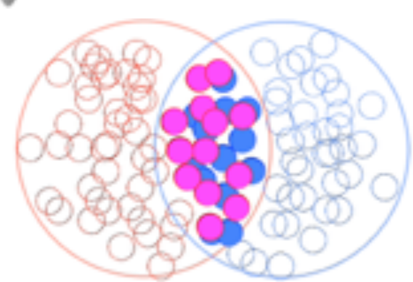
Discussions on Choice of B and N5

About B field Lifetime — Logically three possibilities:

1. \tau_B >> \tau_hydro —— It appears unlikely.
2. \tau_B ~ \tau_hydro —— We will use this.
3. \tau_B << \tau_hydro —— CME has to occur pre-hydro.

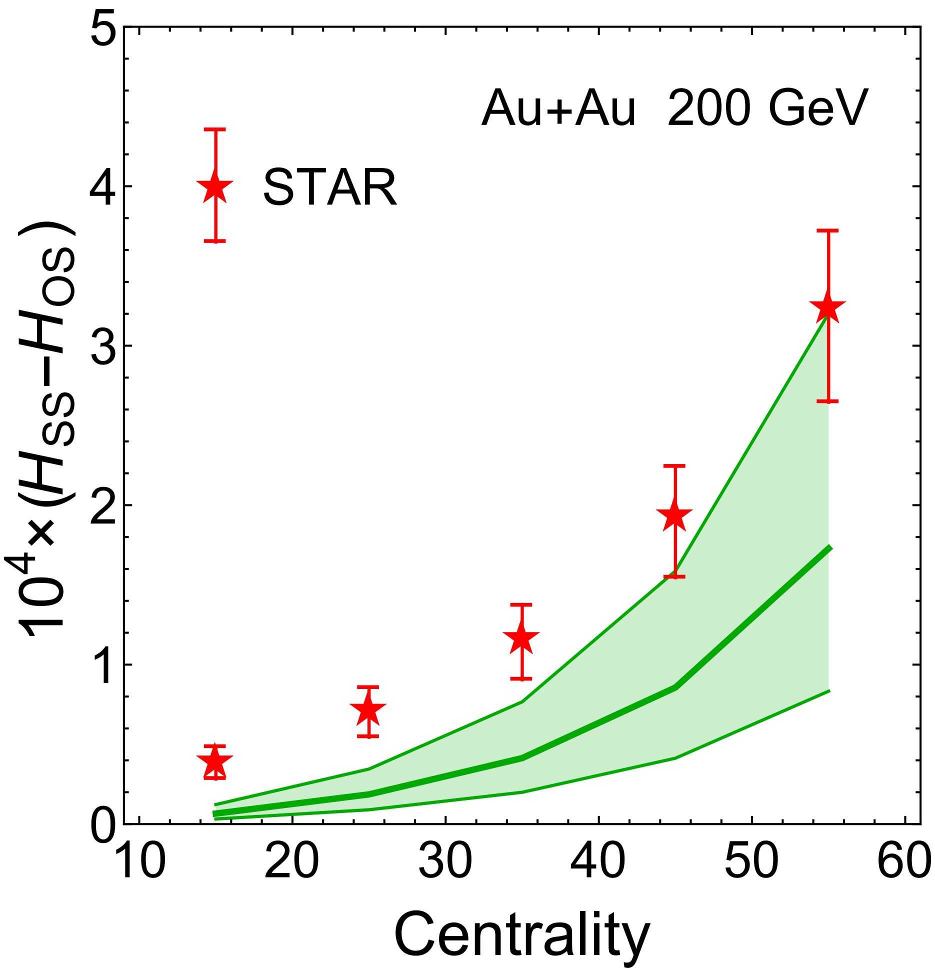
About initial axial charge density:

[c.f. Hirono,Hirano,Kharzeev,2014; Mueller, Schaefer, 2010; Kharzeev, Krasnitz,Venugopalan]



$$< n_5 > \simeq \tau_{in} \frac{Q_s^4}{16\pi^2} \frac{\sqrt{N_{co.}}\,(\pi\rho^2)}{A}$$

Anomalous-Viscous Fluid Dynamics (AVFD)



$$B = \frac{B_0}{1 + \left(\frac{\tau}{\tau_B}\right)}$$

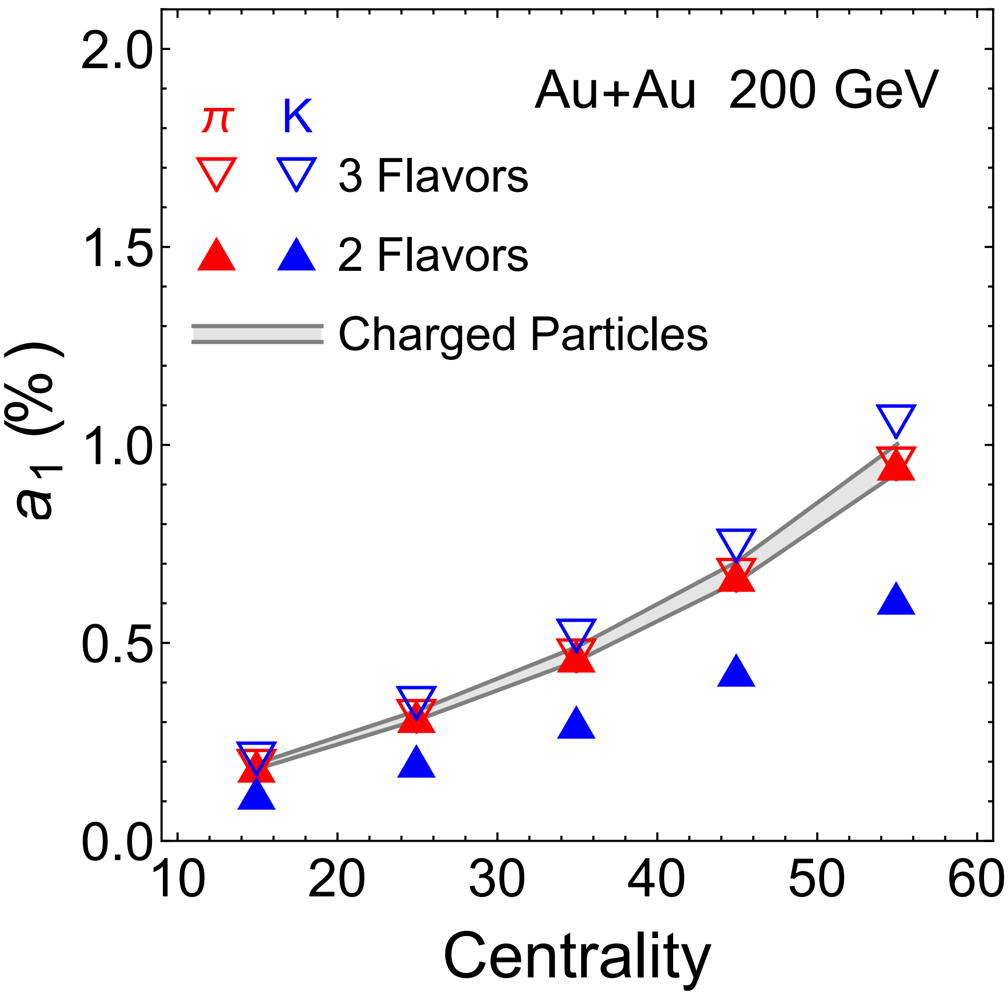
$$\tau_B = 0.6\mathrm{fm/c}$$

$$< n_5 > \simeq \tau_{in} \frac{Q_s^4}{16\pi^2} \frac{\sqrt{N_{co.}}\,(\pi\rho^2)}{A}$$

With realistic initial axial charge density and short magnetic lifetime, data could be described.

[Jiang, Shi, Yin, JL, 2016.]

Is Strangeness Chiral ?



Kaon charge separation is very sensitive to potential contributions from anomalous transport in strangeness sector.

Pre-Hydro CME ?

\tau_B << \tau_hydro —— CME has to occur pre-hydro.

The CME can certainly occur in non-equilibrium setting in the pre-hydro stage:

(1) direct production in EdotB glasma fields [Fukushima; Mace, Schlichting,…]

(2) Chiral kinetic transport [see afternoon discussions]

How to incorporate pre-hydro CME contribution?
—> As initial conditions for hydro !

No-pre-hydro CME: $J^\mu(\tau_{hydro}) \to J^0 \propto s \ , \ \vec{J} = 0$

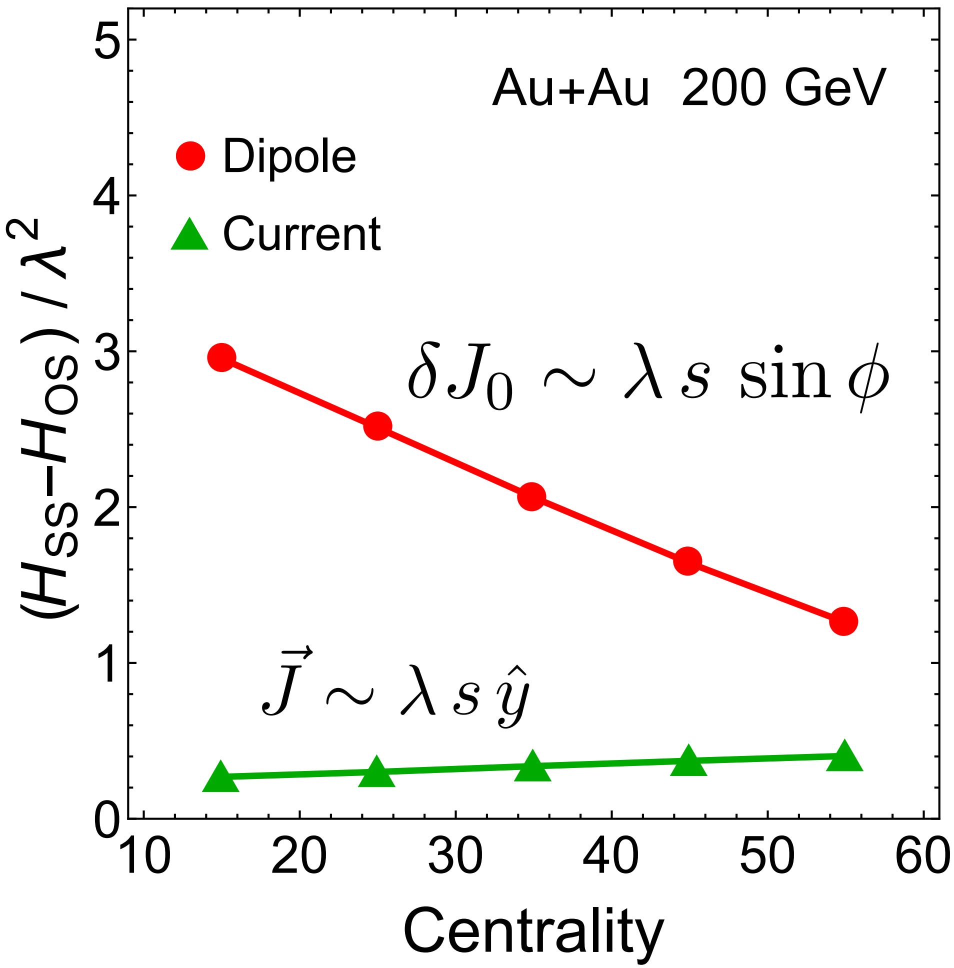
Pre-hydro CME could modify initial conditions in two ways:

dipole in density $\delta J_0 \sim \lambda\, s\, \sin\phi$

anomalous 3-current $\vec{J} \sim \lambda\, s\, \hat{y}$

Pre-Hydro CME ?

A "proof-of-principle" study in our hydro simulation tool:



Pre-hydro CME could propagate through the bulk evolution process and survive into final charge separation signal.

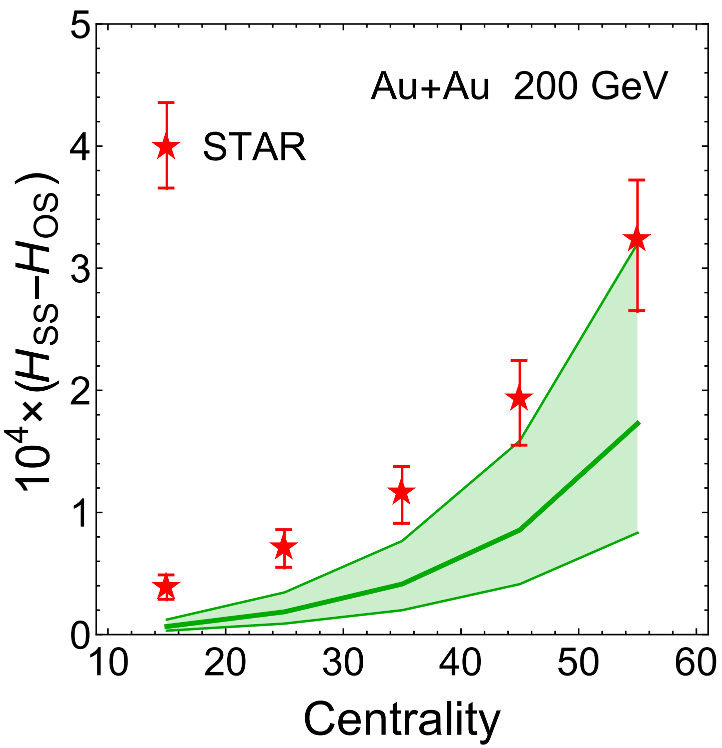
Hydro simulation could quantify such signal, given the initial conditions.

Summary & Outlook

Summary

Microscopic chiral anomaly emerges as anomalous chiral transport in chiral matter (e.g. QGP): Chiral Magnetic Effect, Chiral Magnetic Wave, Vortical Effects, …

There is experimental progress in suppressing flow background and extracting CME signal: need more work; need quantitative modeling.



We report an anomalous-viscous fluid dynamics framework which provides sophisticated modeling for CME in high energy collisions.

Detailed AVFD studies, with reasonable parameters and initial conditions, predict CME signals that could quantitatively explain data.

Outlook

Mainly a to-do-list within the BEST CME efforts:

* A detailed study of CMW (ongoing)
* Event-by-event simulations (first batch of events obtained)
* Sophisticated modeling for isobaric collisions (ongoing)
* Change background hydro to 3+1D viscous hydro
* To be coupled with sophisticated pre-hydro modeling
* Ideal test tool for future full-fledged modeling code
* ……