ICHEP2016 @ Chicago Oct 4, 2016

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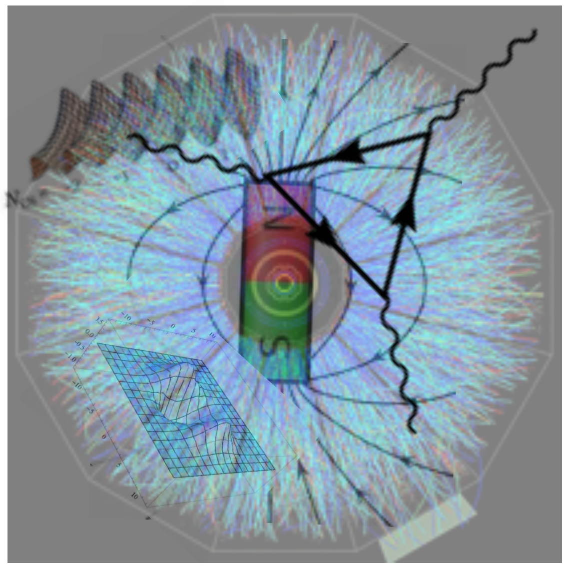
Anomalous Chiral Transport in Heavy Ion Collisions



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

RIKEN BNL Research Center

Research Supported by NSF & DOE

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BEST COLLABORATION

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

ELSEVIER

Review

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

CrossMark

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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]].

Chiral Anomaly

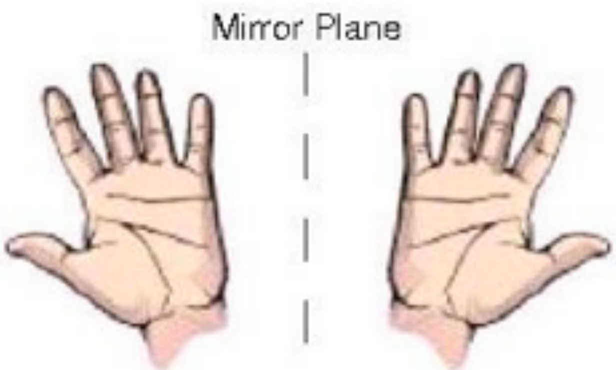
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

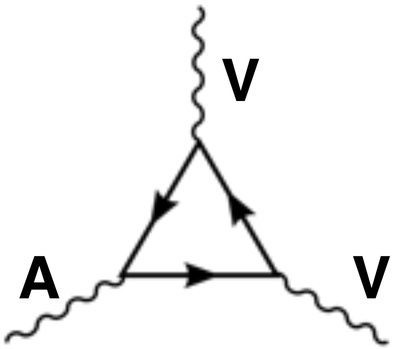
Classical symmetry:

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

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

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





Broken at QM level:

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

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

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

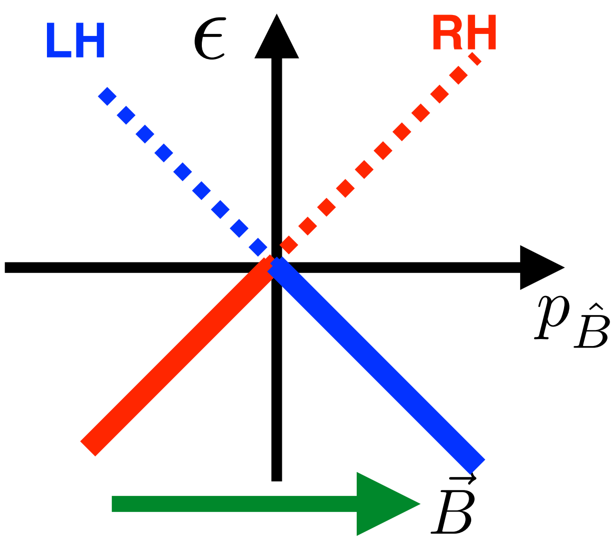
Chiral Anomaly

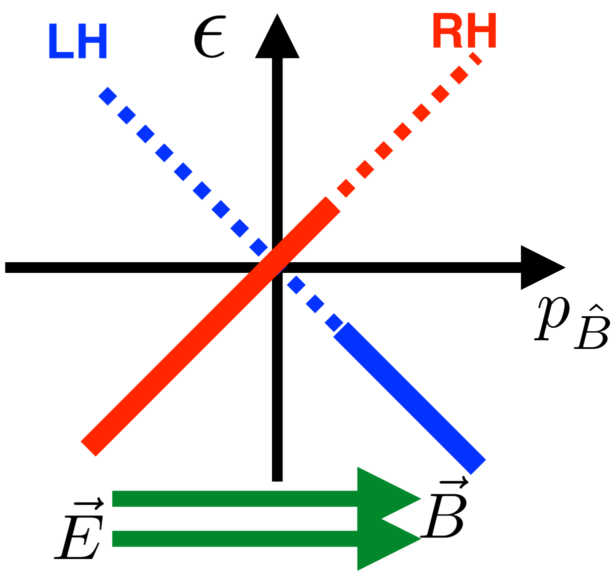
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

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

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

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



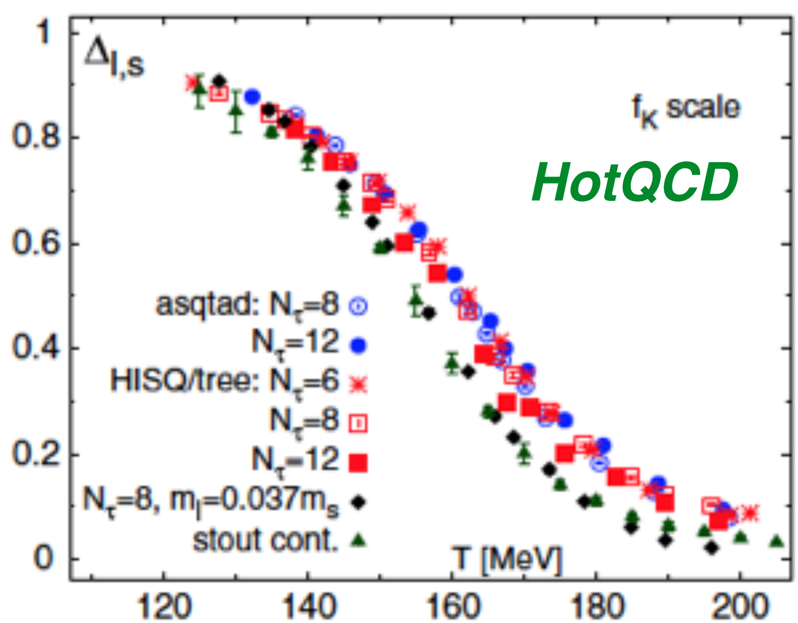


Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!

Chiral Anomaly in Many-Body System

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

This is a relevant question, for e.g. the quark-gluon plasma, where light quarks have approximate chiral symmetry at high T.



The restored chiral symmetry in quark-gluon plasma (QGP) phase

Anomalous Transport: Chiral Magnetic Effect

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

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

P odd
CP even

P even
CP odd

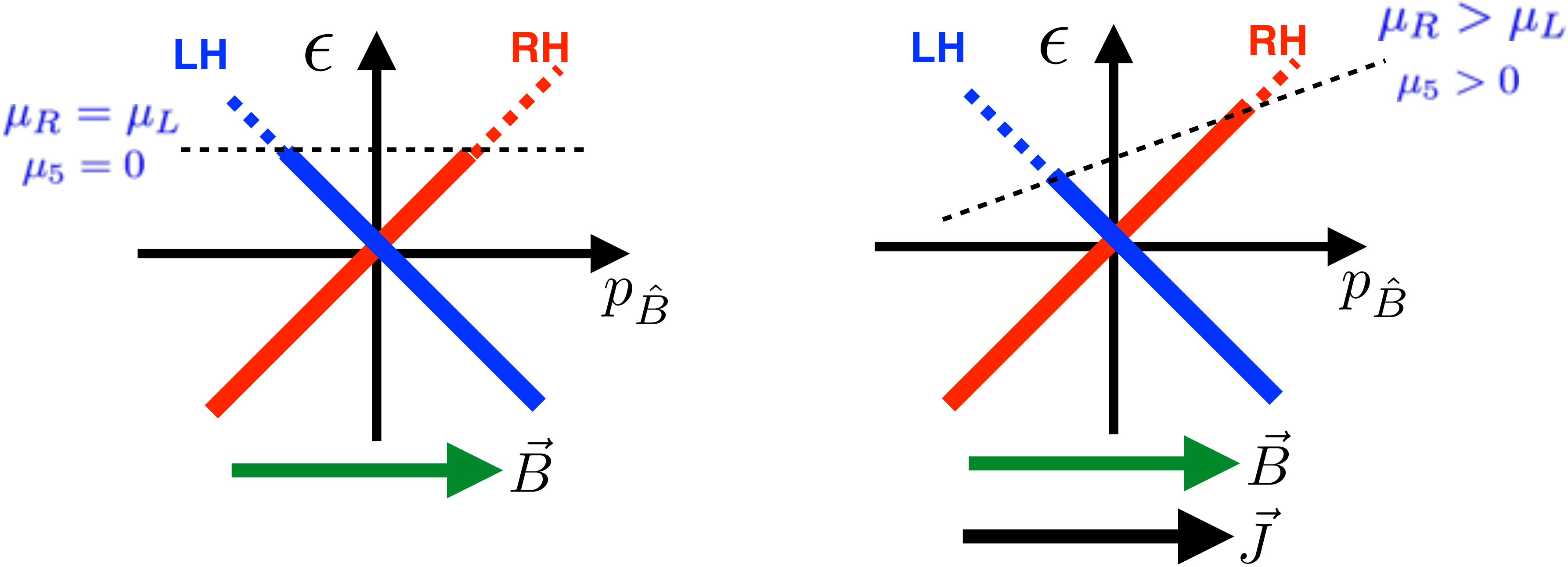
In NORMAL environment, this will NOT happen.
For this to occur: need a P- and CP-Odd environment!

μ_5

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

Such imbalance can be generated through chiral anomaly coupled with topological fluctuations (F-F-dual) of the gluonic sector.

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***

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

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

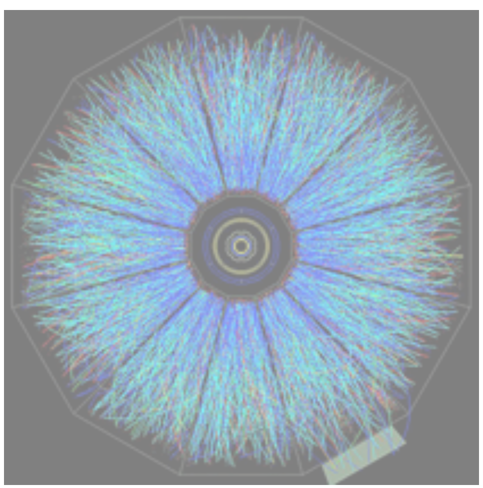
Wrap-up: Emergence in Chiral Matter

Chiral anomaly:
Basic dynamics of
QFT with chiral fermions

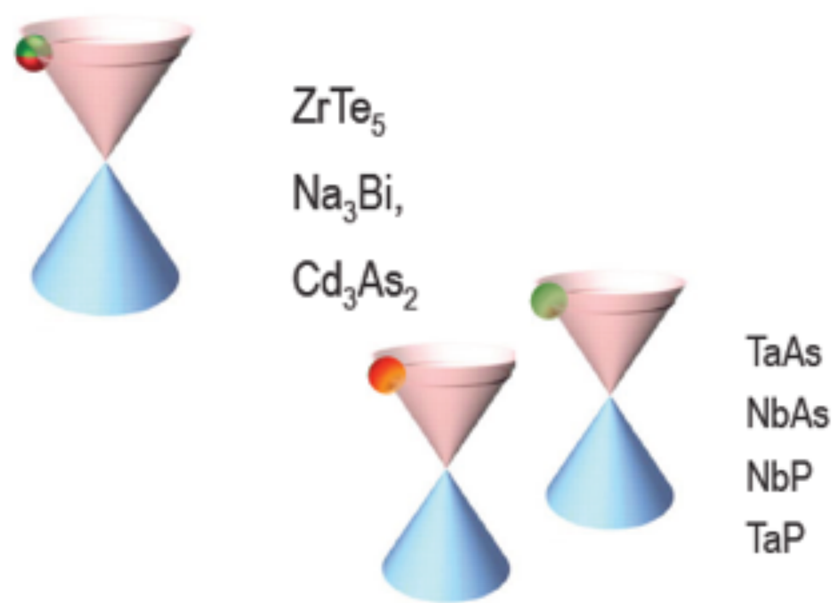
→

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

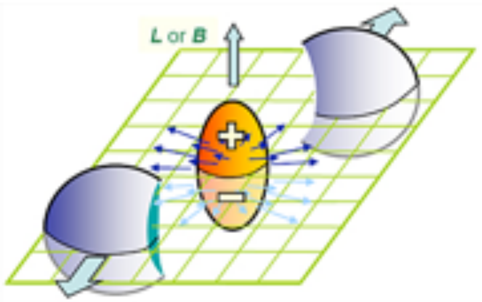
Quark-gluon plasma

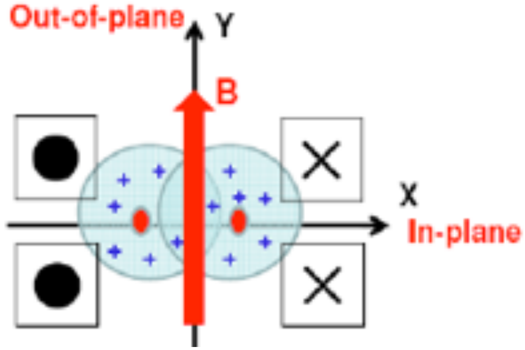


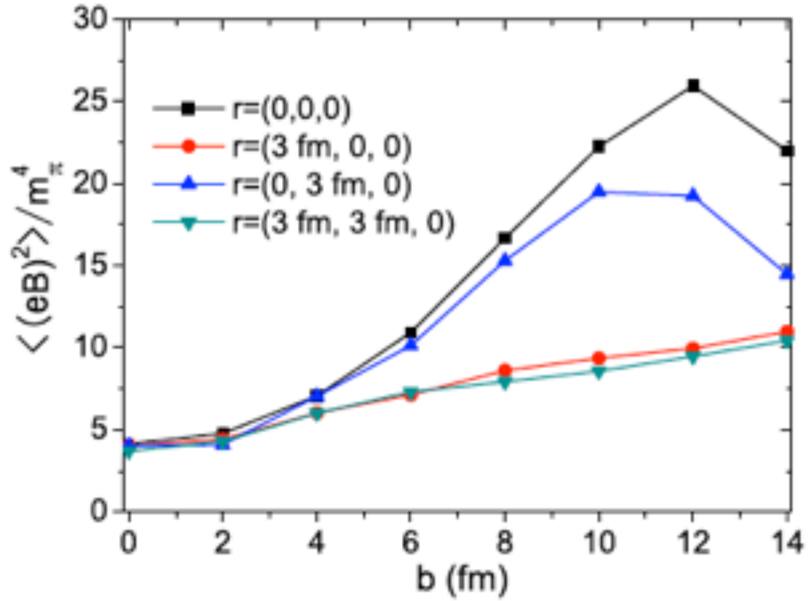
Dirac & Weyl Semimetals



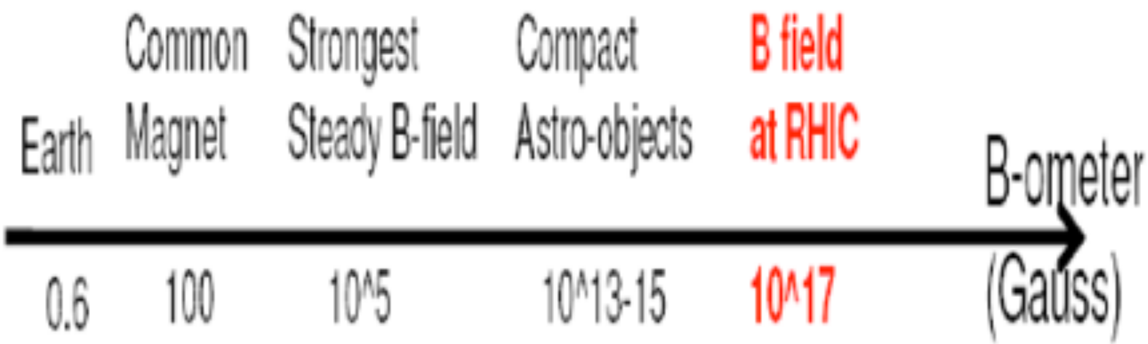
Strong EM Fields in Heavy Ion Collisions







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

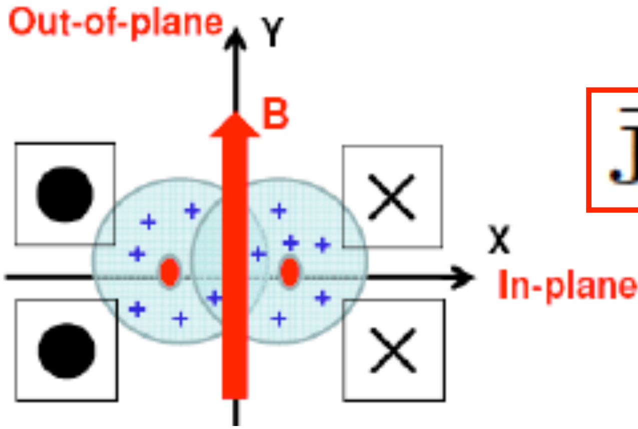


- Strongest B field (and strong E field as well) naturally arises!

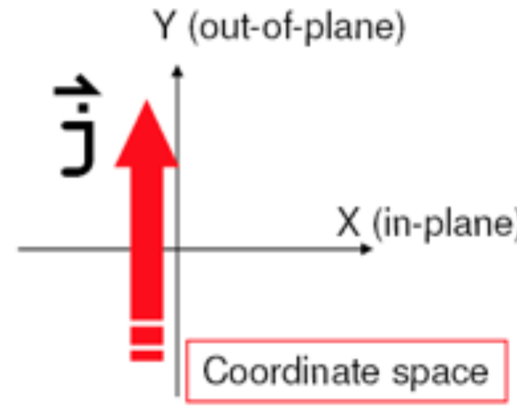
[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; Tuchin; ...]

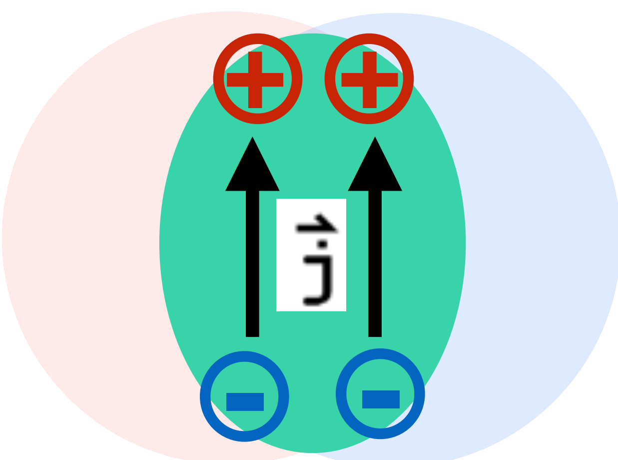
- “Out-of-plane” orientation (approximately)

From CME Current to Charge Separation

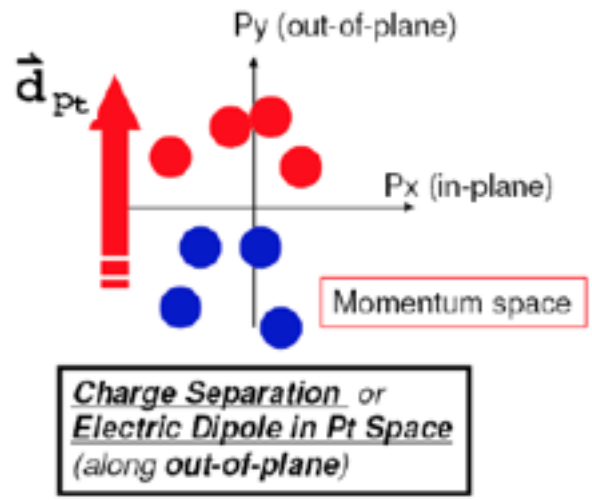


$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$





strong radial blast:
position —> momentum



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

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

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

Charge Separation Observable

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

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

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

[Voloshin, 2004]

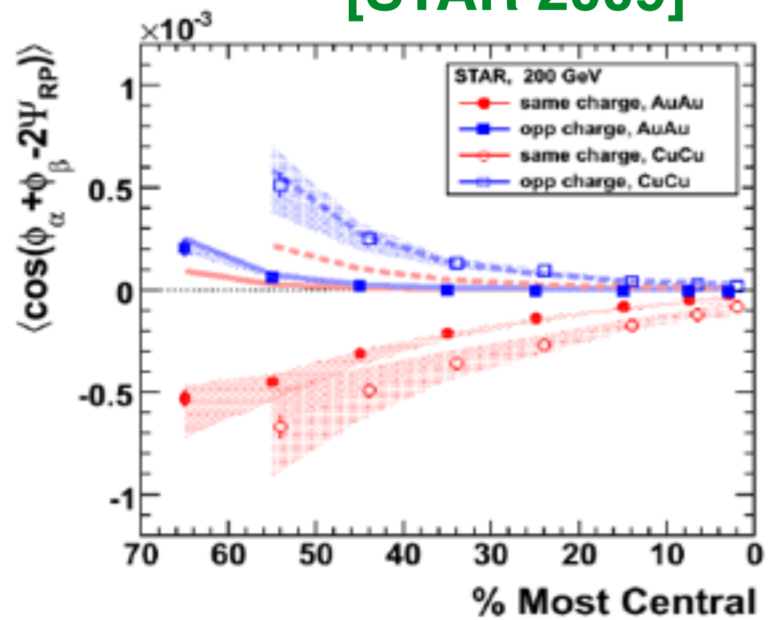
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

known to be very small

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

what we are looking for

[STAR 2009]



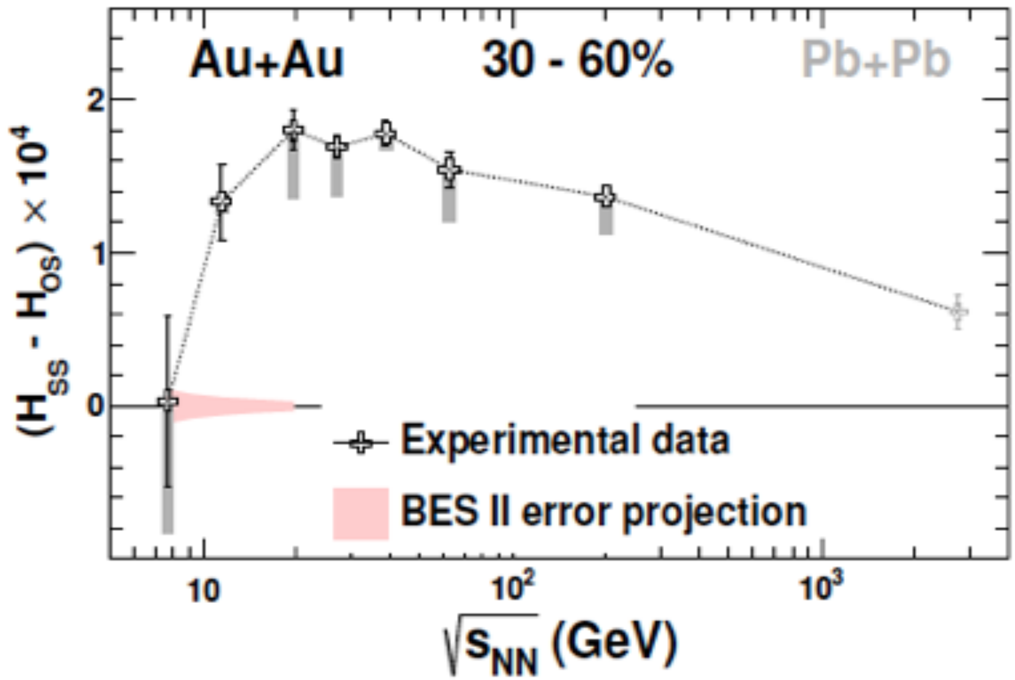
As it was pointed out later, the backgrounds turn out to be NOT negligible…

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

Separation of CME & Flow-Driven Background

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

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



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

A big step forward for the search of CME (in my view)

[STAR PRL 2014]

Making sense of data in a two-component picture

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

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

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

Fluid Dynamics That Knows Left & Right

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

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

$$\partial_\mu s^\mu \geq 0 \qquad \nu^\mu = -\sigma T P^{\mu\nu}\partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi\omega^\mu + \xi_B B^\mu$$

[Son, Surowka, 2009;…]   CVE   CME

Chiral Fluid: Microscopic Quantum Anomaly manifests itself as macroscopic hydrodynamic currents!

It provides a hydro framework for simulating anomaly effects. Initial attempts of applying Chiral-Hydro to heavy ion were made.

[Hirano, Hirono; Yin, Yee; Hirono, Hirano, Kharzeev; Yin, Liao;…]

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

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

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

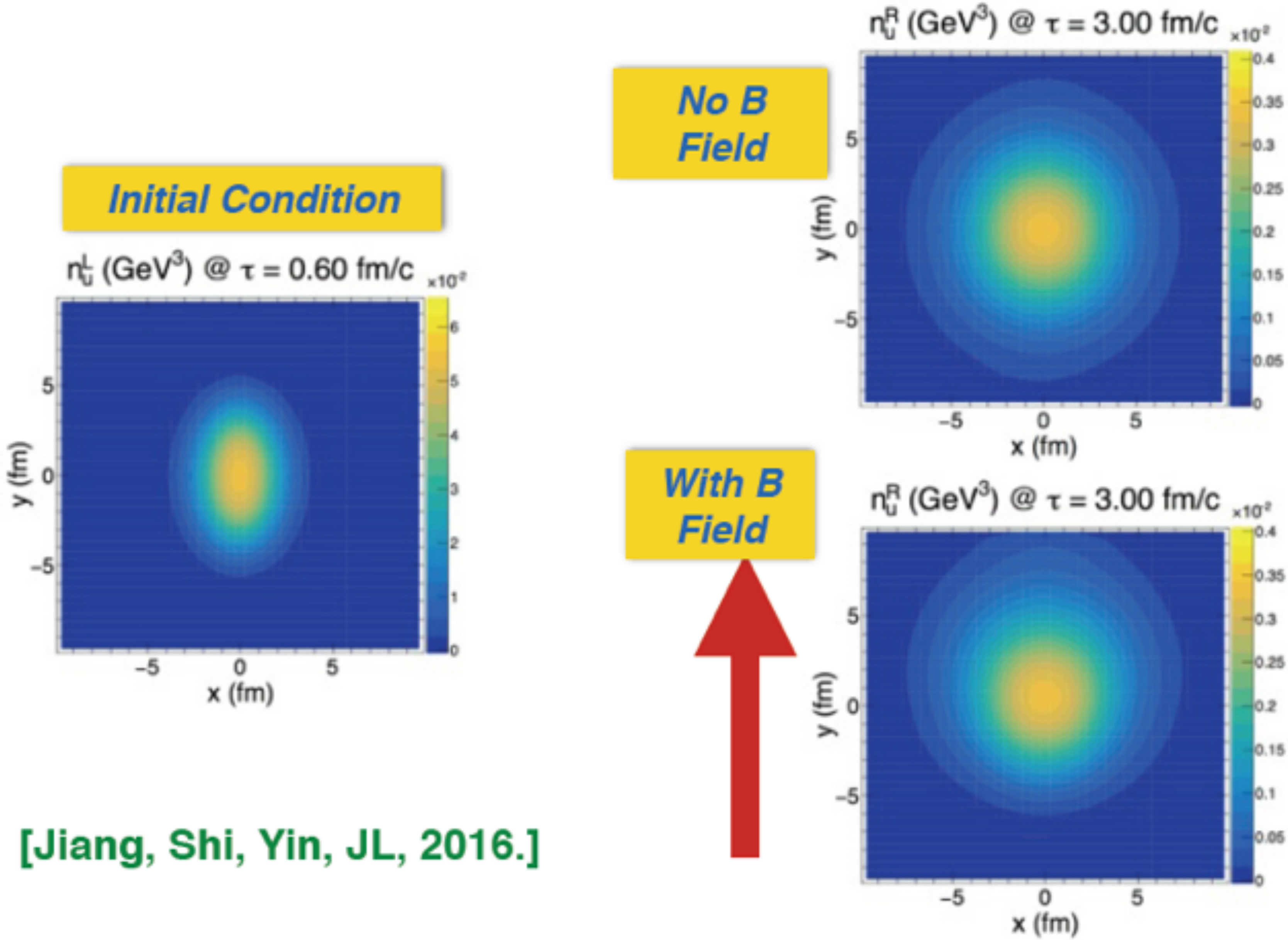
on top of 2+1D VISHNew— OSU Group

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

B field + μ_A ⇒ charge separation

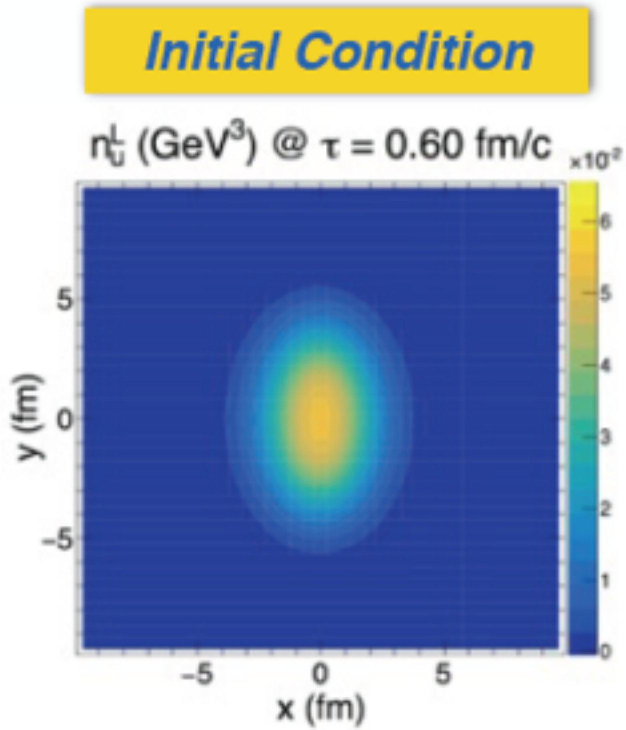
$$dN_\pm/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$

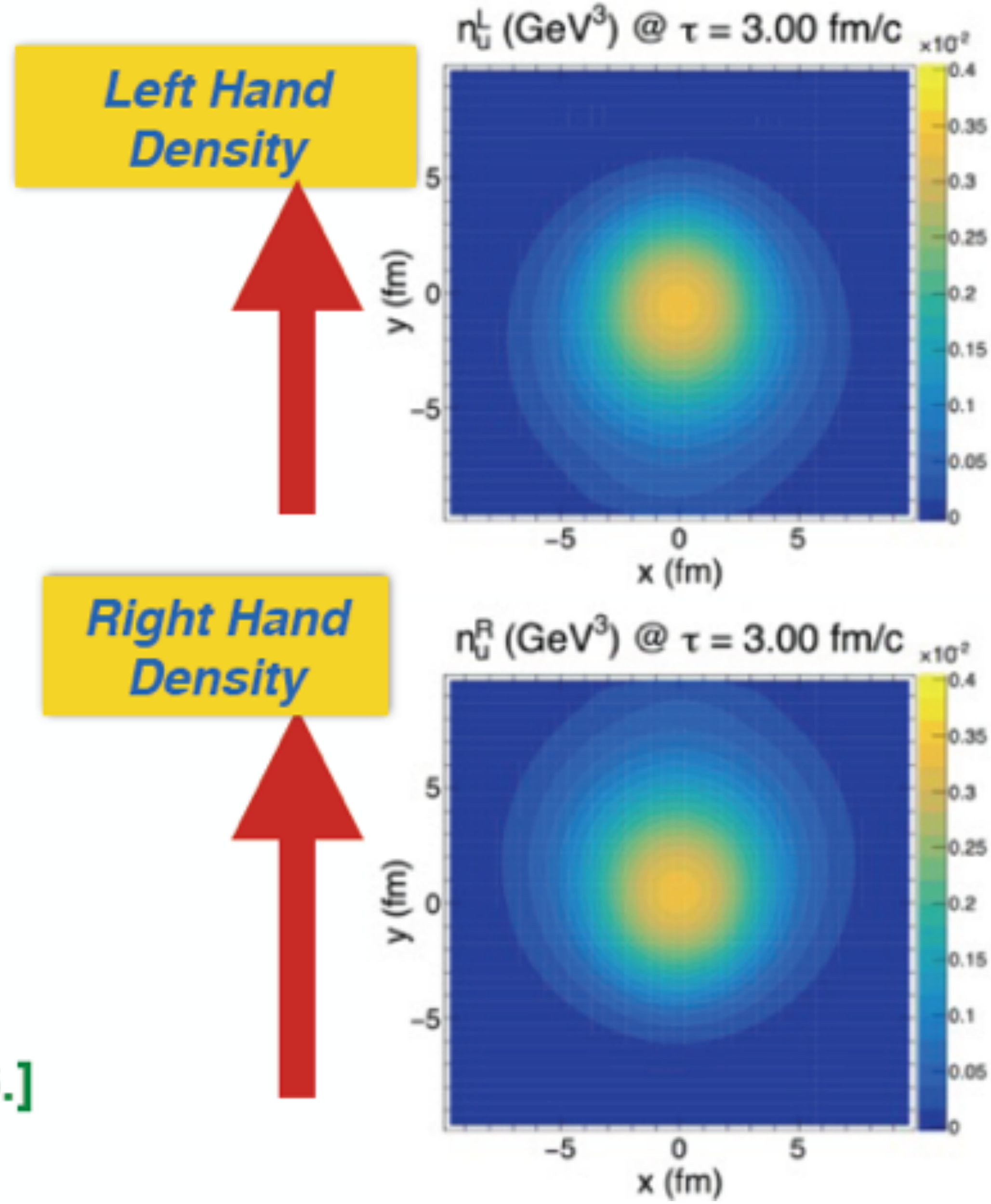
Anomalous-Viscous Fluid Dynamics (AVFD)



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

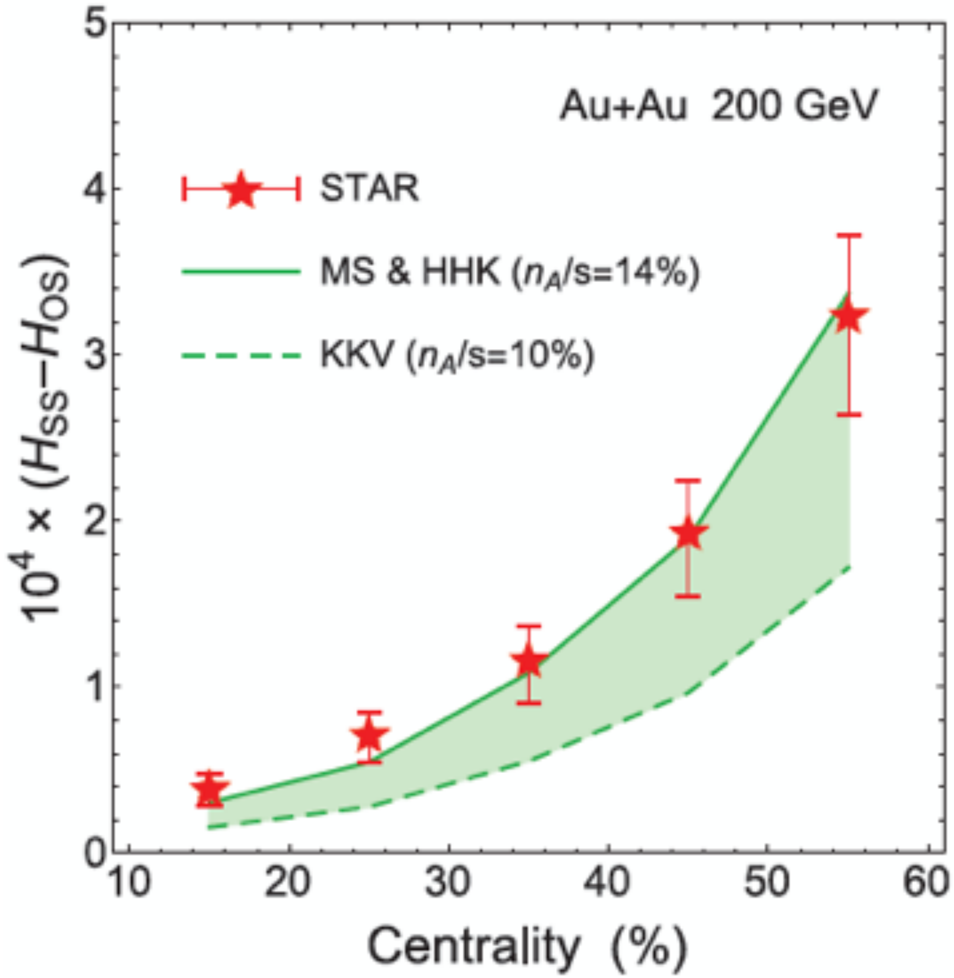
Anomalous-Viscous Fluid Dynamics (AVFD)





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

Anomalous-Viscous Fluid Dynamics (AVFD)



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

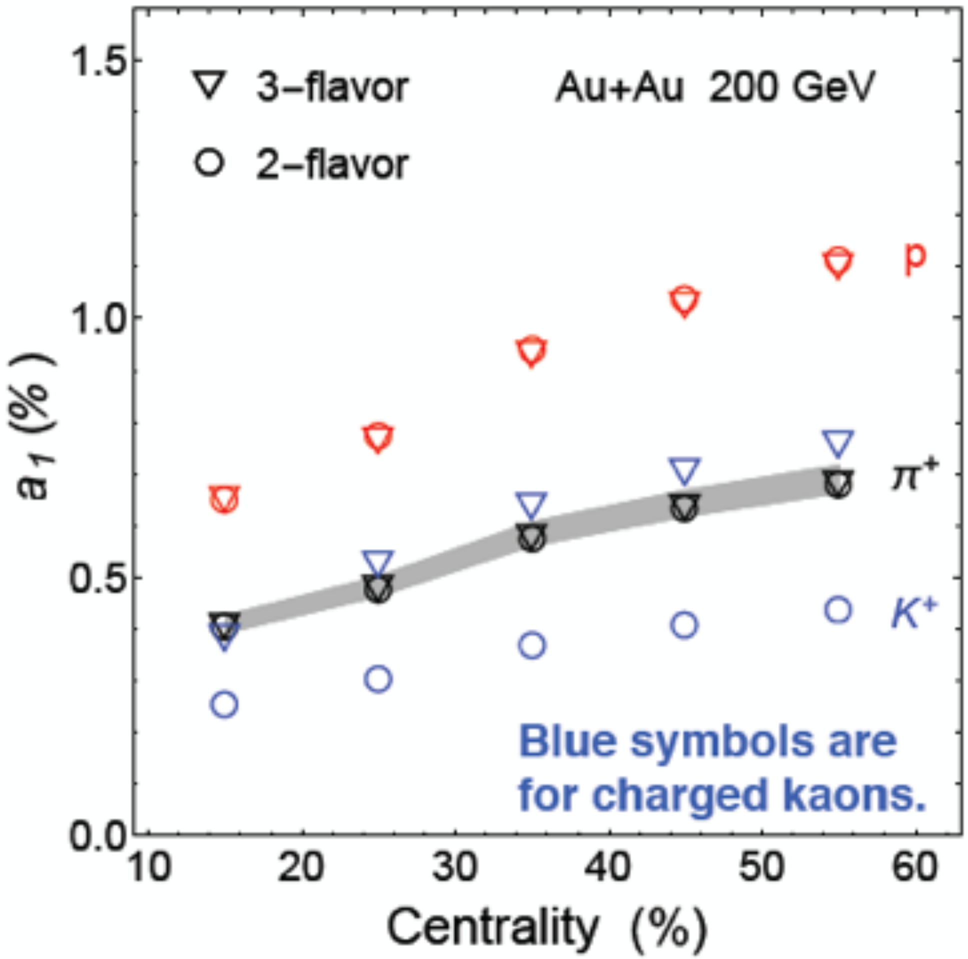
$$B = \frac{B_0}{1 + \left(\frac{\tau}{\tau_B}\right)}$$

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

$$\frac{n_A}{s} \propto \left(\frac{dN}{d\eta}\right)^{-1/3}$$

With realistic initial axial charge density and short magnetic lifetime, the data can be describe well.

Is Strangeness Chiral?



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

Measuring charge separation for Kaons: an exciting opportunity to tell to which extent the strange quarks are chiral!

Upcoming Isobaric Collisions (2018@RHIC)

New Proposal of Isobaric Collisions @ RHIC:
up to 10% variation in B field, thus ~20% shift of CME signal!

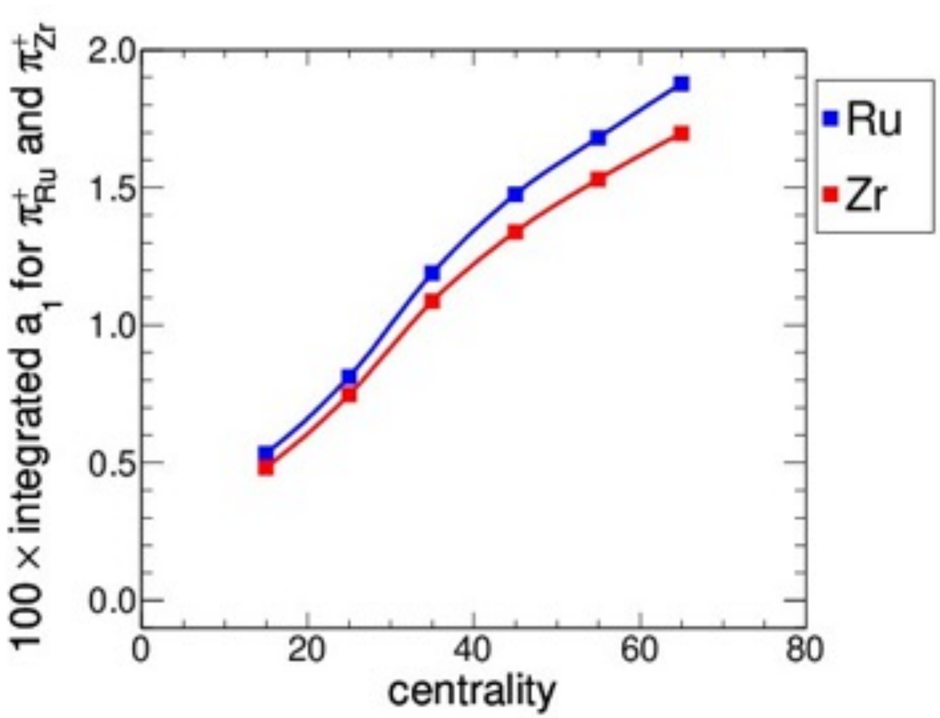
— $^{96}_{40}$Zirconium vs $^{96}_{44}$Ruthenium

	$^{96}_{44}$Ru+$^{96}_{44}$Ru vs $^{96}_{40}$Zr+$^{96}_{40}$Zr
Flow	≤
CMW	>
CME	>
CVE	=

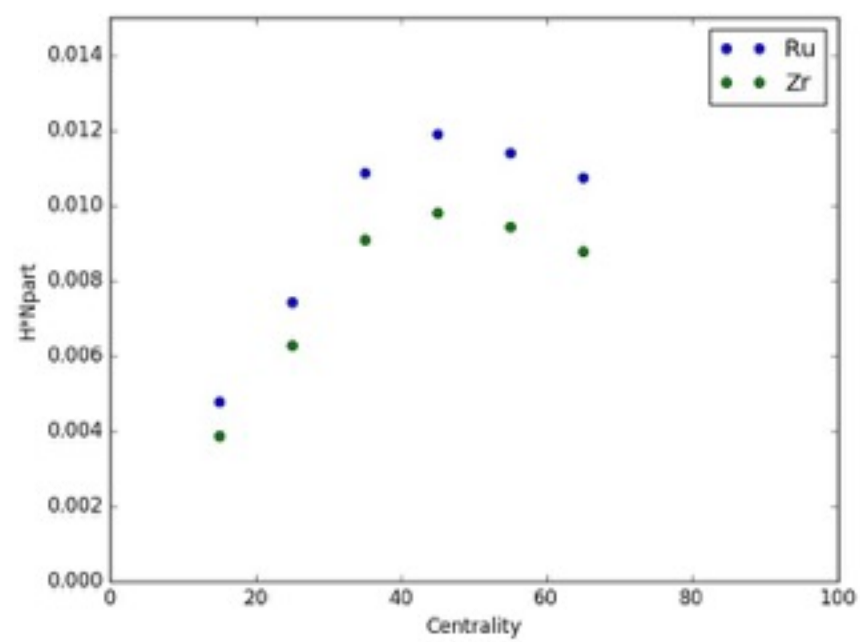
The isobaric collisions will be a crucial test!

[See e.g.: Deng, Huang, Ma, Wang, 1607.04697.]

AVFD Predictions for Isobaric Collisions



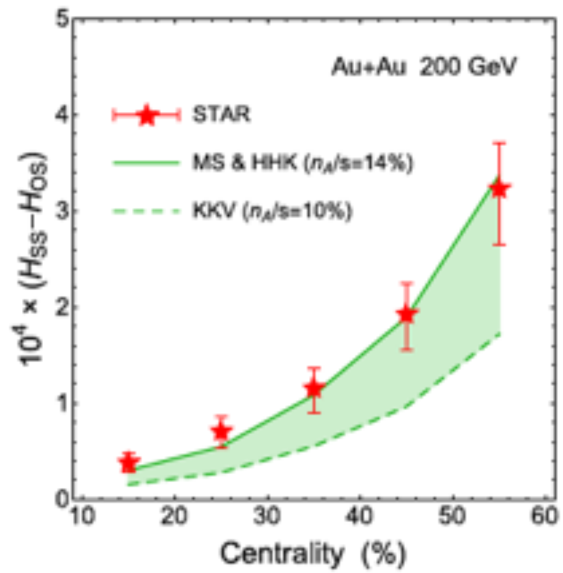
[Shi, Lilleskov, Jiang, Liao, in final preparation.]



Summary

* **Chiral anomaly emerges in chiral matter (e.g. QGP) as anomalous chiral transport: Chiral Magnetic Effect**

* **Quantitative CME from new Anomalous-Viscous Fluid Dynamics simulations: CME-induced charge separation signal could be explained.**



* **Future test: isobaric collisions**

* **Many other interesting anomalous transport phenomena:**

— ***Chiral Magnetic Wave [Burnier, Kharzeev, JL, Yee;…]***

— ***Chiral Vortical Effect [Kharzeev, Son;…]***

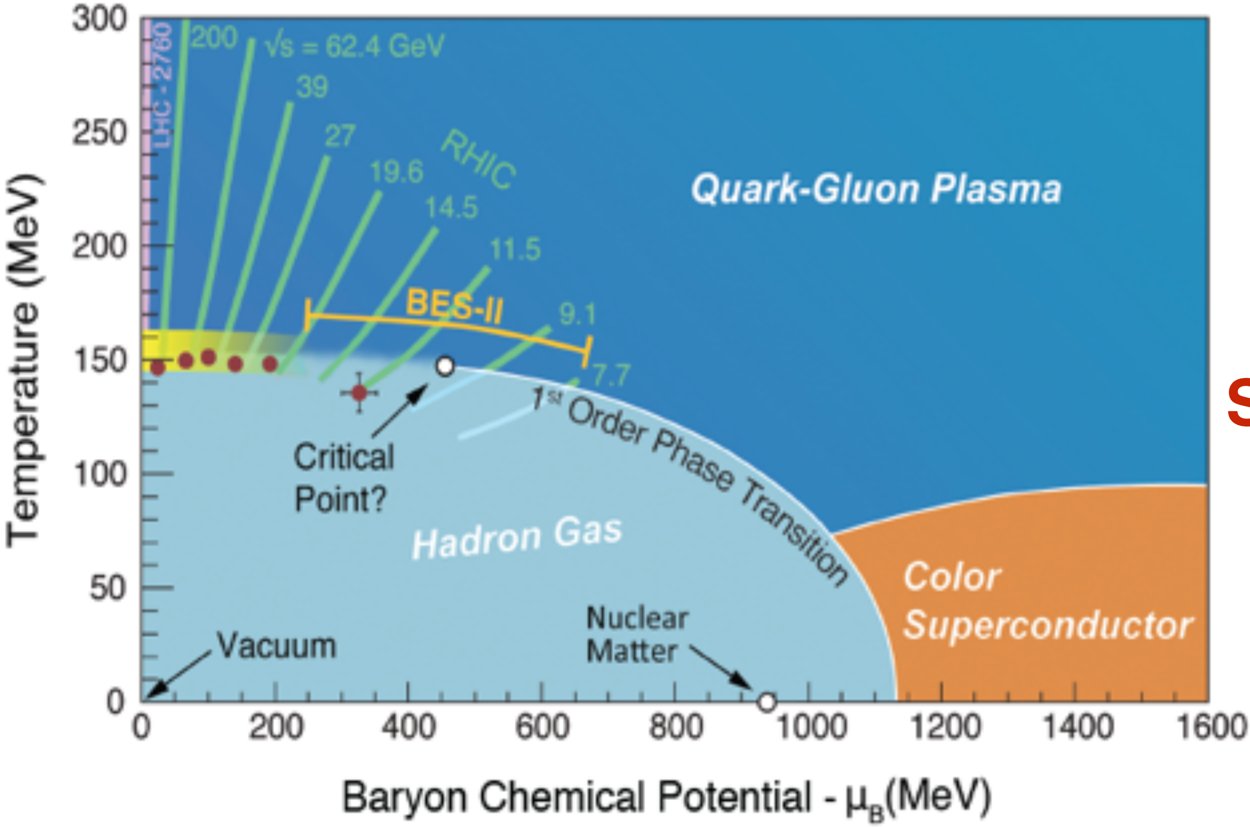
— ***Chiral Vortical Wave [Jiang, Huang, JL;…]***

— ***Chiral Kinetic Theory [Stephanov, Yin; Son, Yamamoto; …]***

— ***……***

Toward Physics of Beam Energy Scan

* *Establishing a chiral QGP at higher energy via anomalous chiral effects*
* *Searching for chiral critical point & 1st-order transition at lower energy*

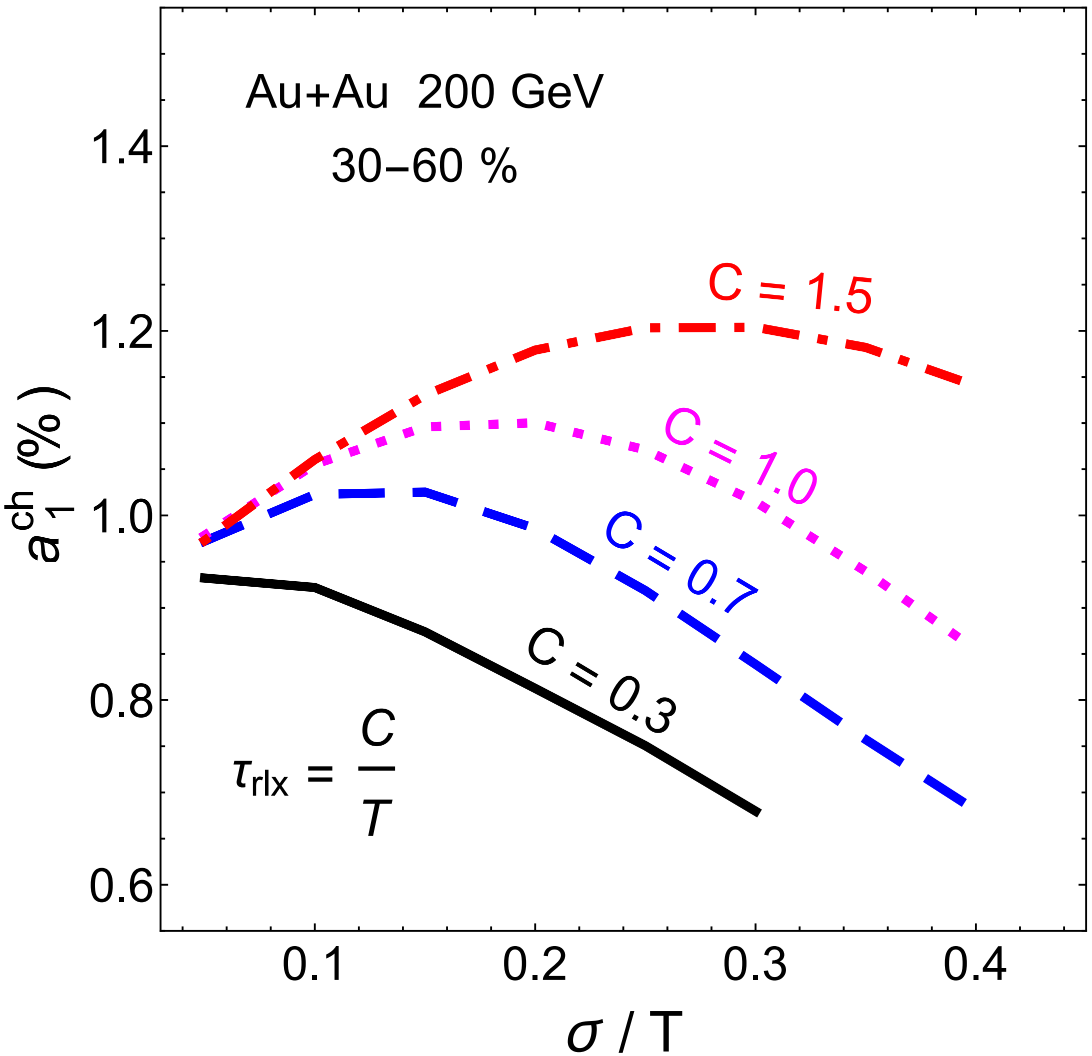


Stay tuned for news in the near future!

Beam Energy Scan Theory (BEST) Collaboration:
BNL, IU, LBNL, McGill U, Michigan State U, MIT, NCSU, OSU, Stony Brook U, U Chicago, U Conn, U Huston, UIC

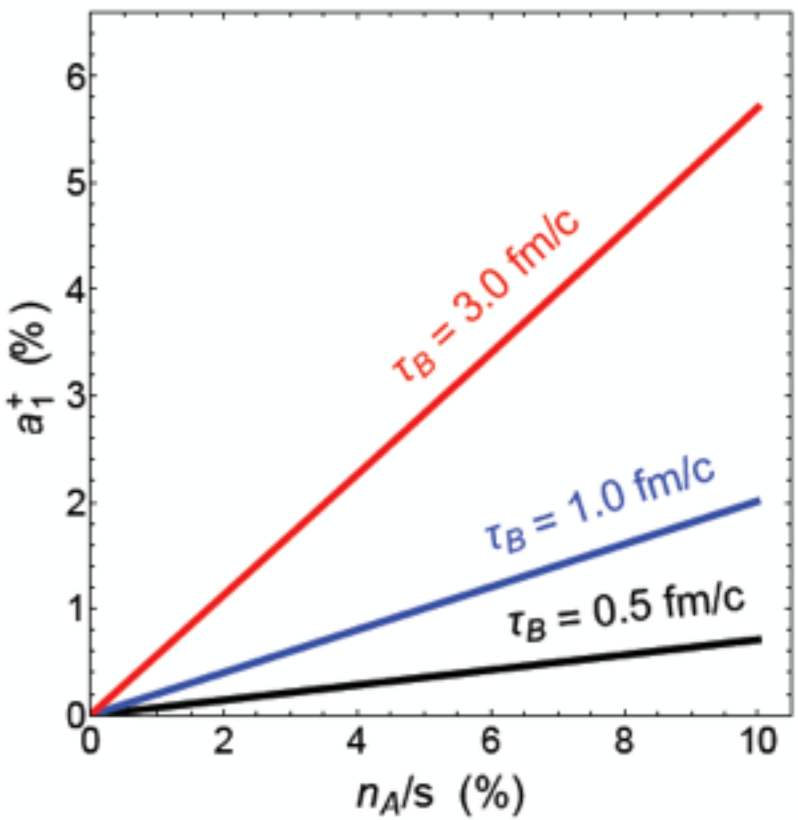
Backup Slides

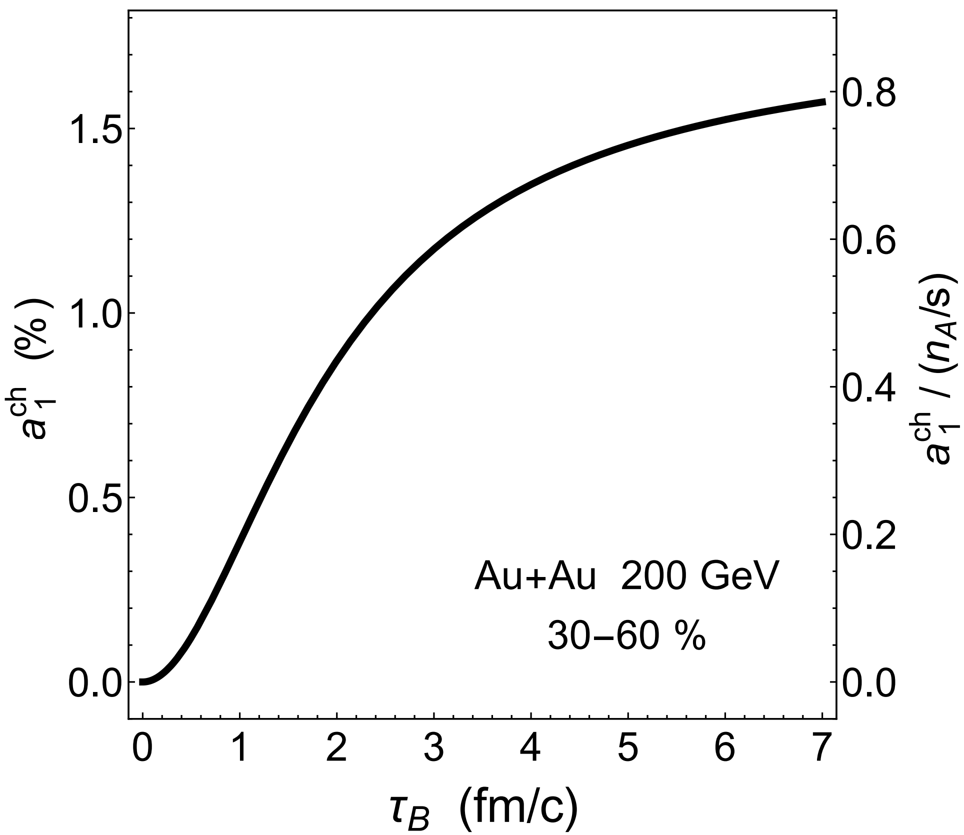
Anomalous-Viscous Fluid Dynamics (AVFD)



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

Anomalous-Viscous Fluid Dynamics (AVFD)





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

Quantitative Study of Anomalous Transport

Dynamical Evolution

Initial Conditions

Driving Forces

$$\vec{\mathbf{J}} = \sigma_5 \, \vec{\mathbf{B}},$$

CME

$$\vec{\mathbf{J}} = \frac{1}{\pi^2}\mu_5 \mu \vec{\omega}.$$

CVE

$$\left(\partial_0 \pm v_B \partial_{\hat{\mathbf{B}}}\right) \, \delta J^0_{R/L} = 0.$$

$$v_B \equiv \frac{(Qe)B}{(4\pi^2)\chi}$$

CMW

$$\left(\partial_0 \pm v_\omega \partial_{\hat{\omega}}\right) \, \delta J^0_{R/L} = 0$$

$$v_\omega \equiv \frac{\mu_0 \omega}{(2\pi^2)\chi_{\mu_0}}$$

CVW

Observable (“Chemistry”): partons —> hadrons

Possible backgrounds

Toward Quantitative CME

Physics Letters B 756 (2016) 42–46

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Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

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[c] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA

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

$$\partial_\mu J^\mu = \partial_\mu \left(n u^\mu + Q_f C_A \mu_A B^\mu \right) = 0$$

$$\partial_\mu J_A^\mu = \partial_\mu \left(n_A u^\mu + Q_f C_A \mu_V B^\mu \right) = -Q_f^2 e C_A E_\mu B^\mu$$

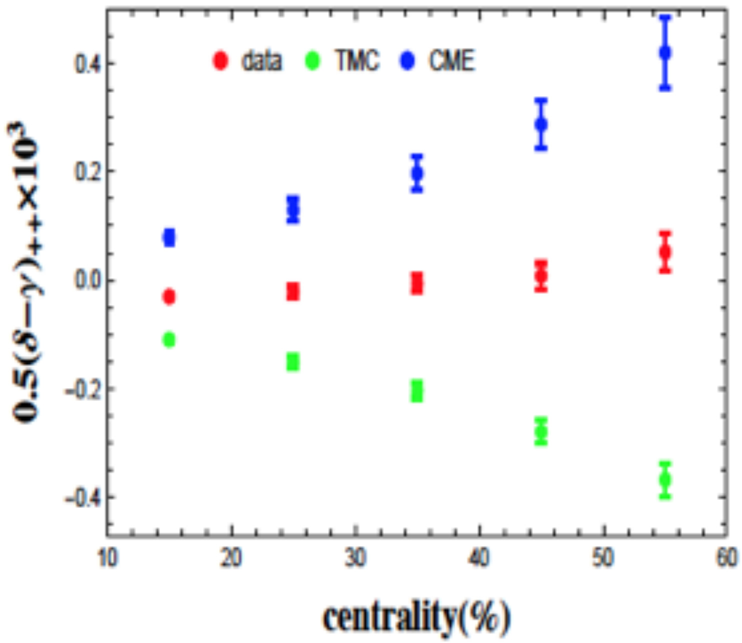
$$\left[\frac{dN^H}{d\phi}\right]_{\rm CME} \propto \left[1 + 2Q^H a_1^H \sin(\phi) + \ldots\right]$$

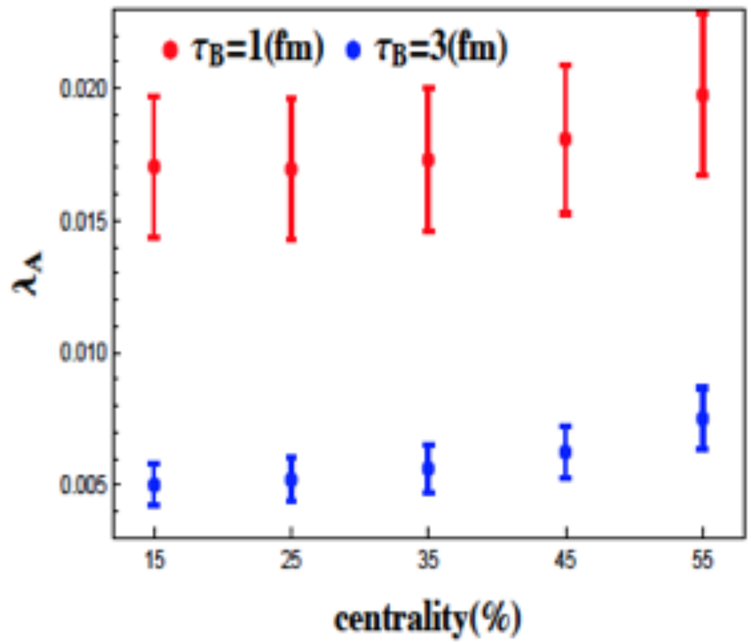
To quantitatively understand, in a viscous and anomalous hydrodynamic framework: how anomaly generates charge separation, and how much?

Quantitative Interpretation of Data

$$\gamma_{\alpha,\beta}^{\text{data}} \simeq \gamma_{\alpha,\beta}^{CME} + \gamma_{\alpha,\beta}^{TMC} \;,\; \delta_{\alpha,\beta}^{\text{data}} \simeq \delta_{\alpha,\beta}^{CME} + \delta_{\alpha,\beta}^{TMC}$$

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





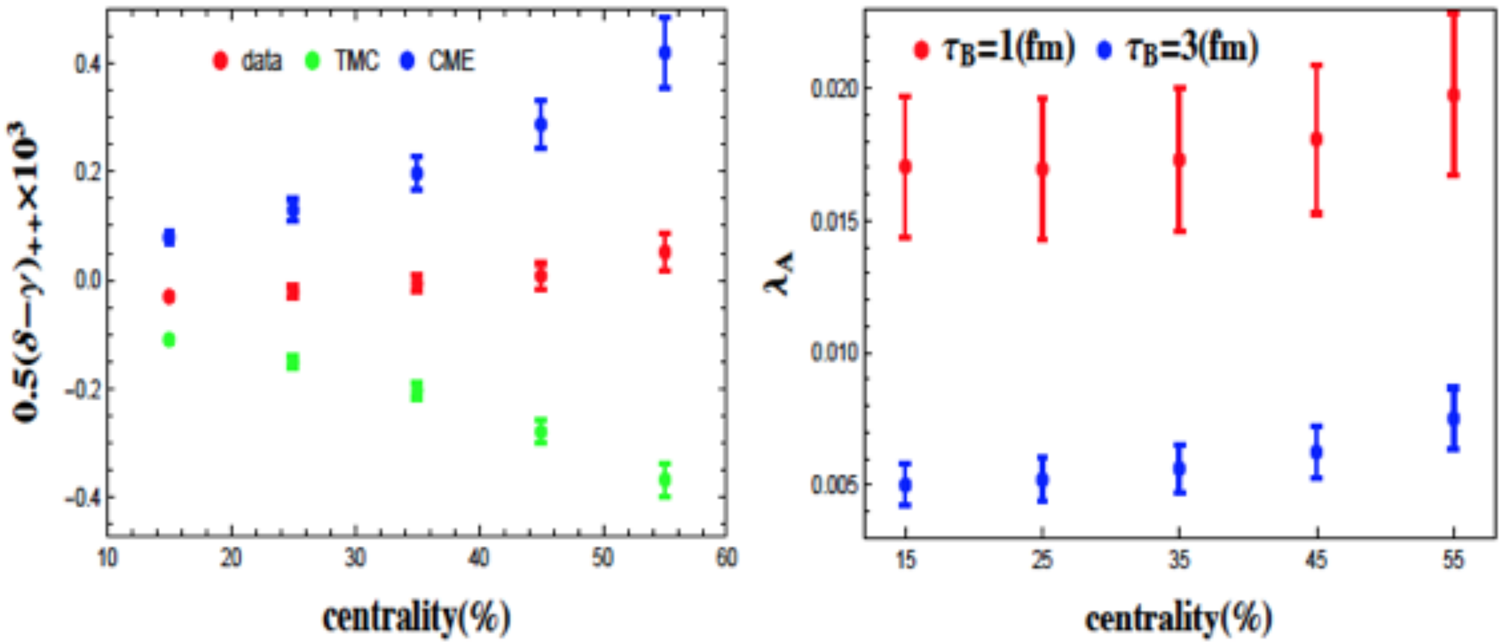
Using the particle spectra from the SAME VISH hydro, we evaluate quantitatively effect from transverse momentum conservation:

$$\delta_{\alpha\beta}^{\text{TMC}} \pm \gamma_{\alpha\beta}^{\text{TMC}} = \frac{[\langle p_\perp\rangle_\alpha(1 \pm \bar{v}_{2,\alpha})][\langle p_\perp\rangle_\beta(1 \pm \bar{v}_{2,\beta})]}{N_{TMC}\langle p_\perp^2\rangle(1 \pm \bar{\bar{v}}_2)}$$

Quantitative Interpretation of Data

$$\gamma_{\alpha,\beta}^{\rm data} \simeq \gamma_{\alpha,\beta}^{CME} + \gamma_{\alpha,\beta}^{TMC} \ , \ \delta_{\alpha,\beta}^{\rm data} \simeq \delta_{\alpha,\beta}^{CME} + \delta_{\alpha,\beta}^{TMC}$$

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



The messages:

*** B field *lifetime ~ 1fm/c (or less)* is OK!**

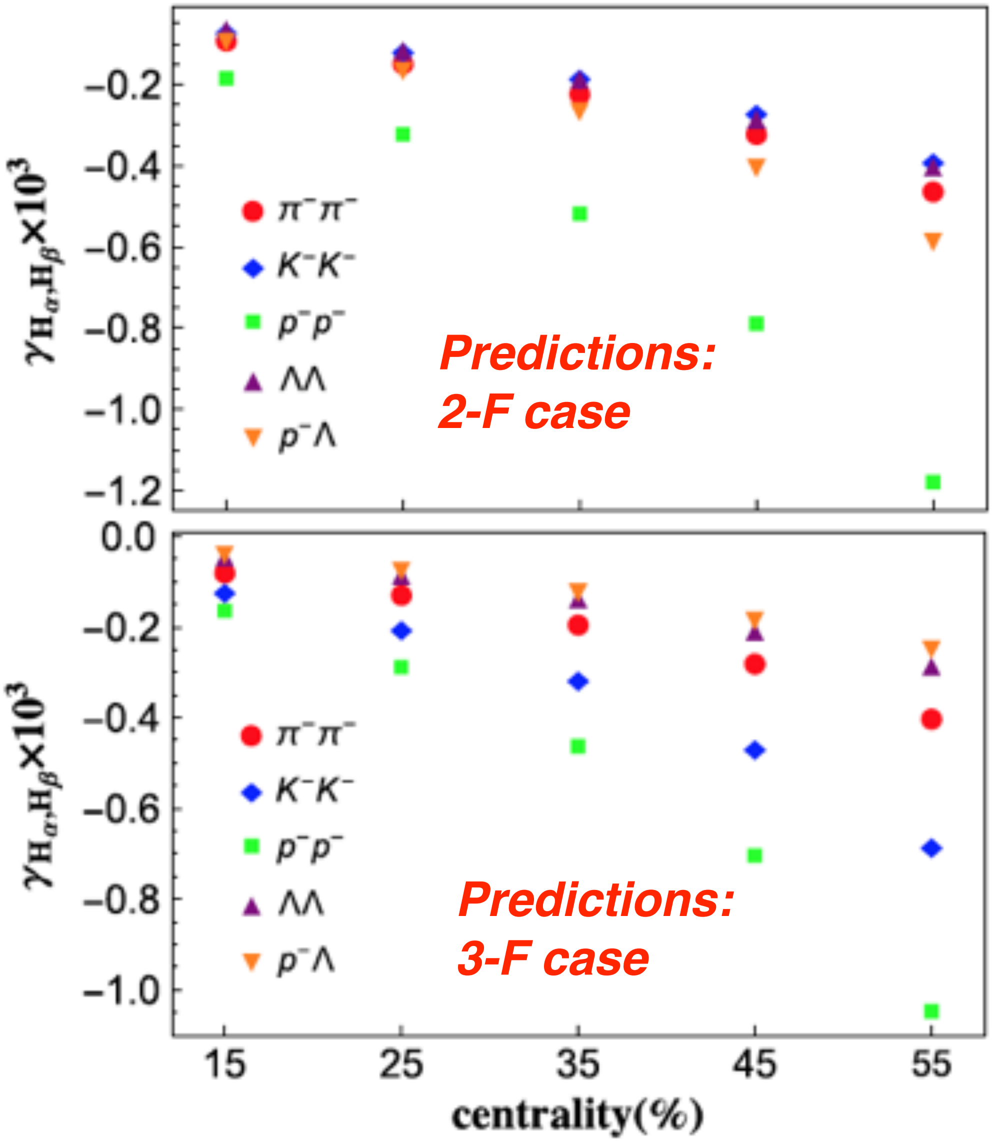
*** Needed axial charge realistic:**

~ percent of initial entropy density, or *n_5 ~ (0.2GeV)^3* !

*** Data could be quantitatively consistent with CME+backgrounds!**

Further Predictions for Future Test

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



Anomalous effects:
parton level transport —>
at freeze-out, combining into
identified hadron observables
in specific patterns:
"chemistry"

With parameters already fixed in our computations, we make predictions for identified hadron pair correlations: to be tested!

Cautionary remarks:
CME only,
for same charge pair only,
and including TMC only.