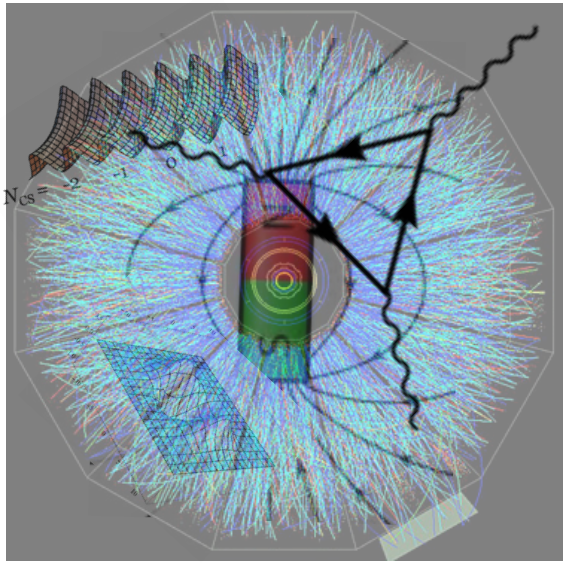
Signatures of Chiral Magnetic Effect in Heavy Ion Collisions



Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

A Recent Review: Collectivity, Criticality, Chirality

Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan

Adam Bzdak[a], ShinIchi Esumi[b], Volker Koch[c], Jinfeng Liao[d,e], Mikhail Stephanov[f], Nu Xu[c,e]

[a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Krakow, Poland
[b]Tomonaga Center for the History of the Universe, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
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[d]Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[e]Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China
[f]Physics Department, University of Illinois at Chicago, 845 W. Taylor St., Chicago IL 60607-7059, USA

Abstract

We review the present status of the search for a phase transition and critical point as well as anomalous transport phenomena in Quantum Chromodynamics (QCD), with an emphasis on the Beam Energy Scan program at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. We present the conceptual framework and discuss the observables deemed most sensitive to a phase transition, QCD critical point, and anomalous transport, focusing on fluctuation and correlation measurements. Selected experimental results for these observables together with those characterizing the global properties of the systems created in heavy ion collisions are presented. We then discuss what can be already learned from the currently available data about the QCD critical point and anomalous transport as well as what additional measurements and theoretical developments are needed in order to discover these phenomena.

Keywords: Heavy Ion Collision, Beam Energy Scan, QCD Phase Diagram, Critical Point, Chiral Magnetic Effect

arXiv:1906.00936

Recent Reviews on Chirality Related Topic

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]

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[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]].

Fukushima, arXiv:1812.08886, PPNP2019.

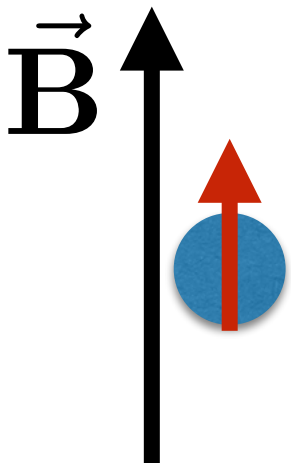
Zhao, Wang, arXiv:1906.11413, PPNP2019.

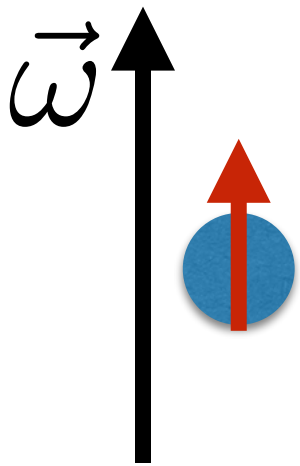
Hattori, Huang, Nucl. Sci. Tech., 28 (2017) no.2, 26.

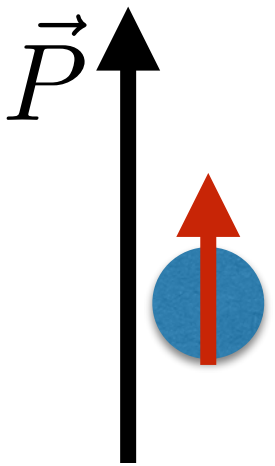
Spin: Chirality, Vorticity and Magnetic Field











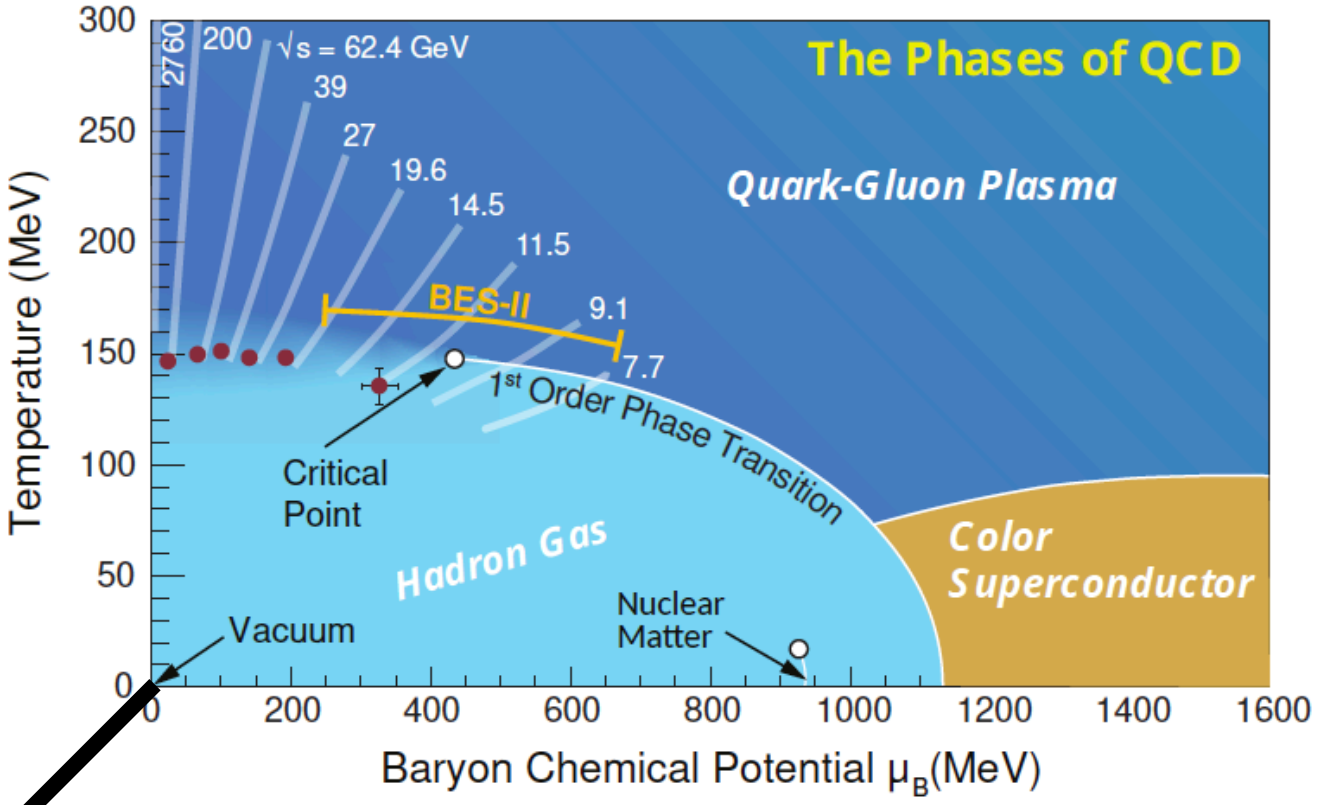
Magnetic Polarization

Rotational Polarization

Chirality Polarization

Interesting interplay —> highly nontrivial phenomena!

QCD Matter under New Extreme Conditions



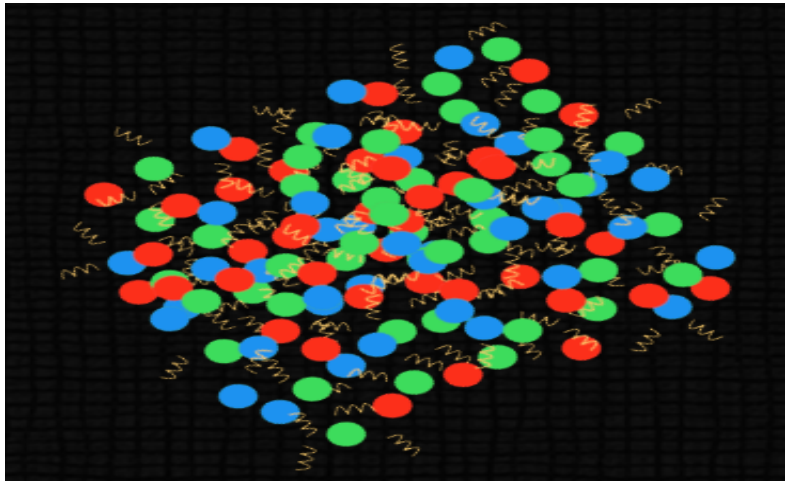
$\vec{\mathbf{B}}$ $\vec{\omega}$

$N_5(\text{or } \mu_5)$

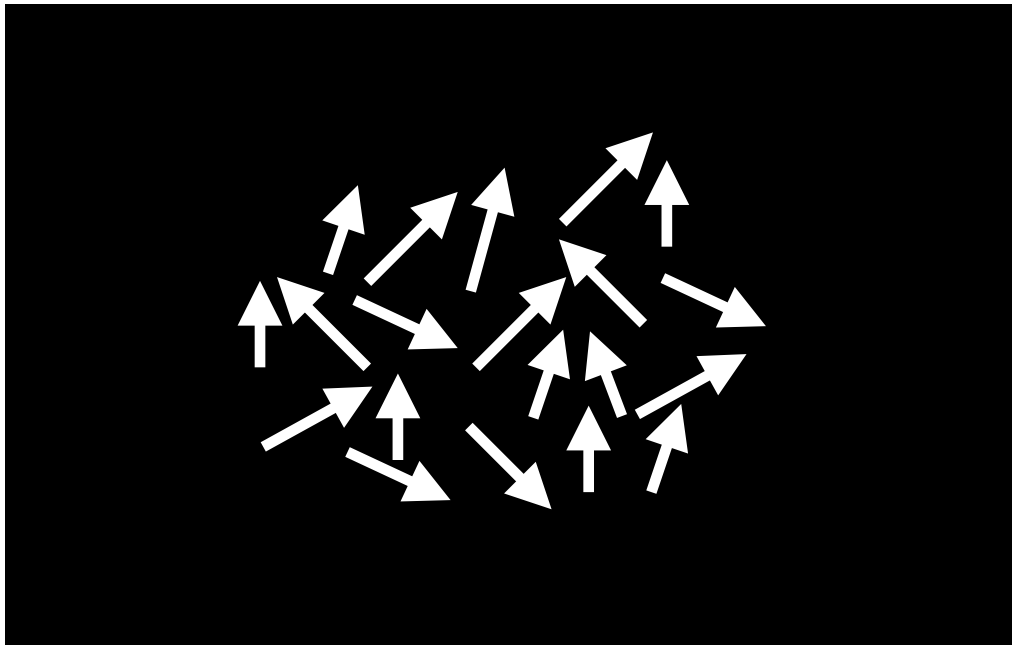
QCD phase structure under strong Chirality imbalance, vorticity and magnetic fields!

A New Paradigm: Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)

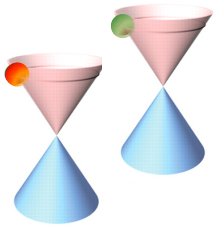


What happens to the spin DoF in the fluid???



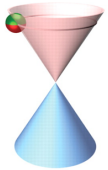
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

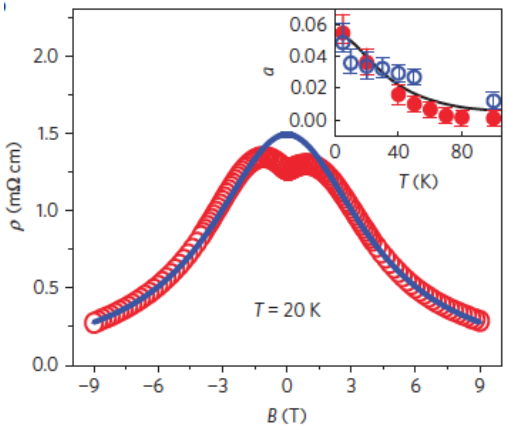


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2

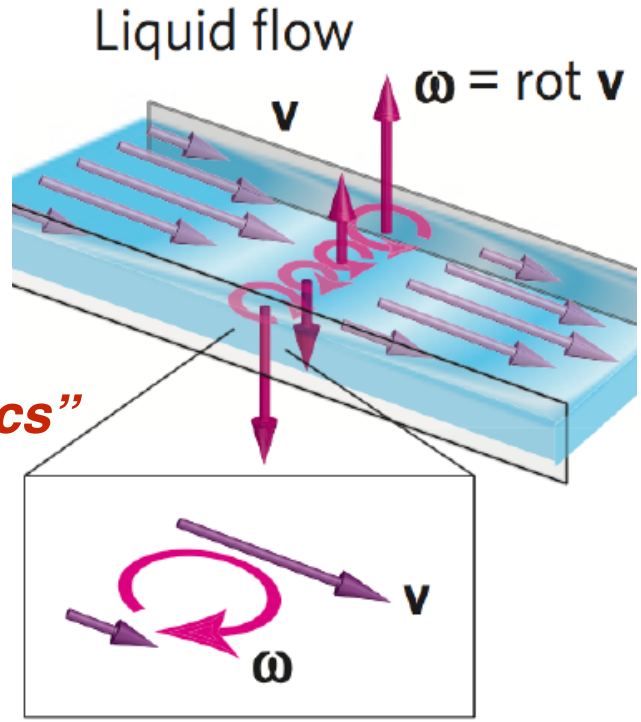


nature physics
LETTERS
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

Chiral magnetic effect in $ZrTe_5$

Qiang Li[1]*, Dmitri E. Kharzeev[2,3]*, Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1]*

"Spin hydrodynamic generation"
Takahashi, *et al*. Nat. Phys. (2016)

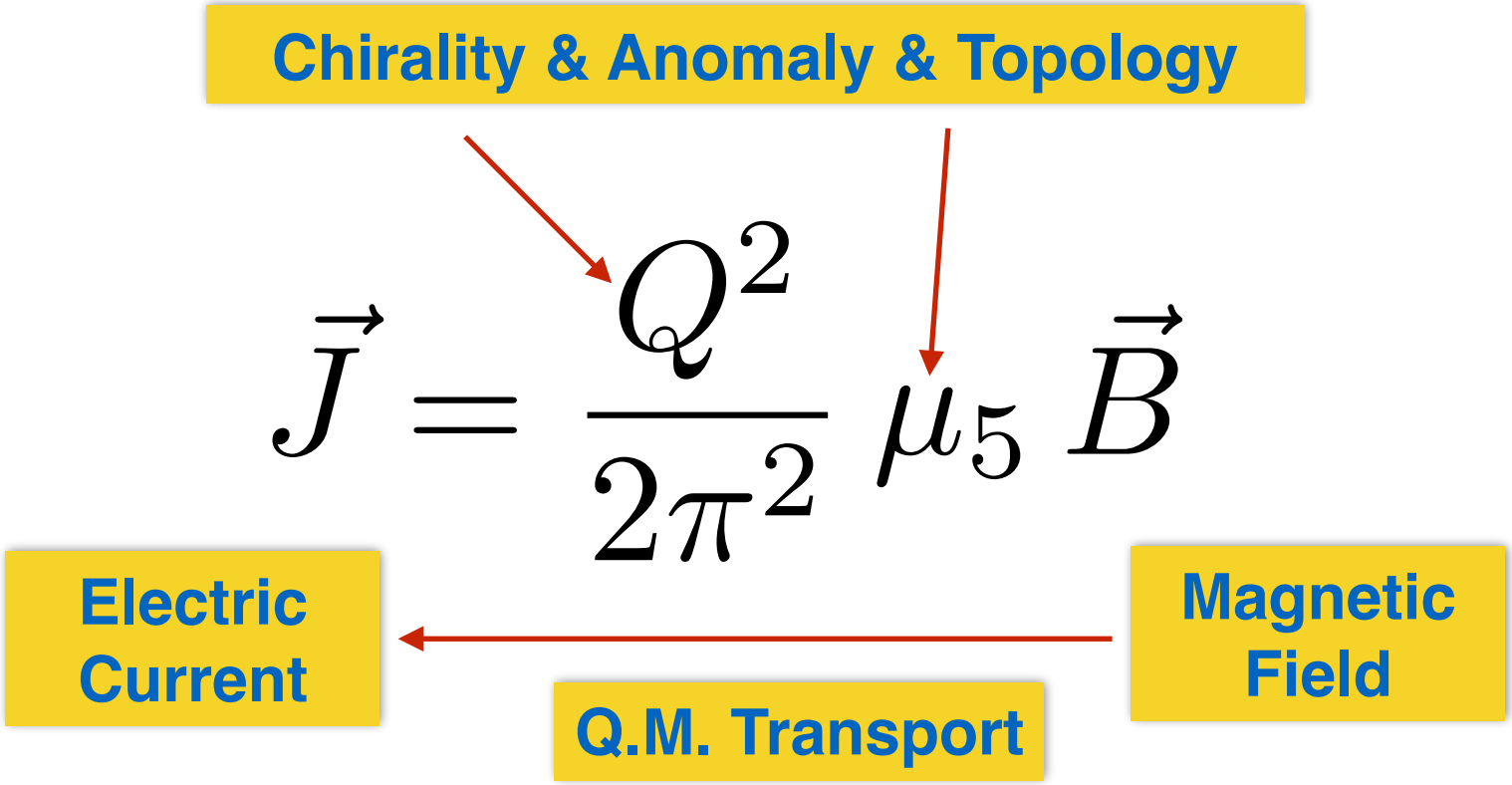


"Fluid Spintronics"

Condensed matter, cold atomic gases, neutron stars, cosmology, plasma physics, etc
[Chiral Matter workshops @ RIKEN, NTU]

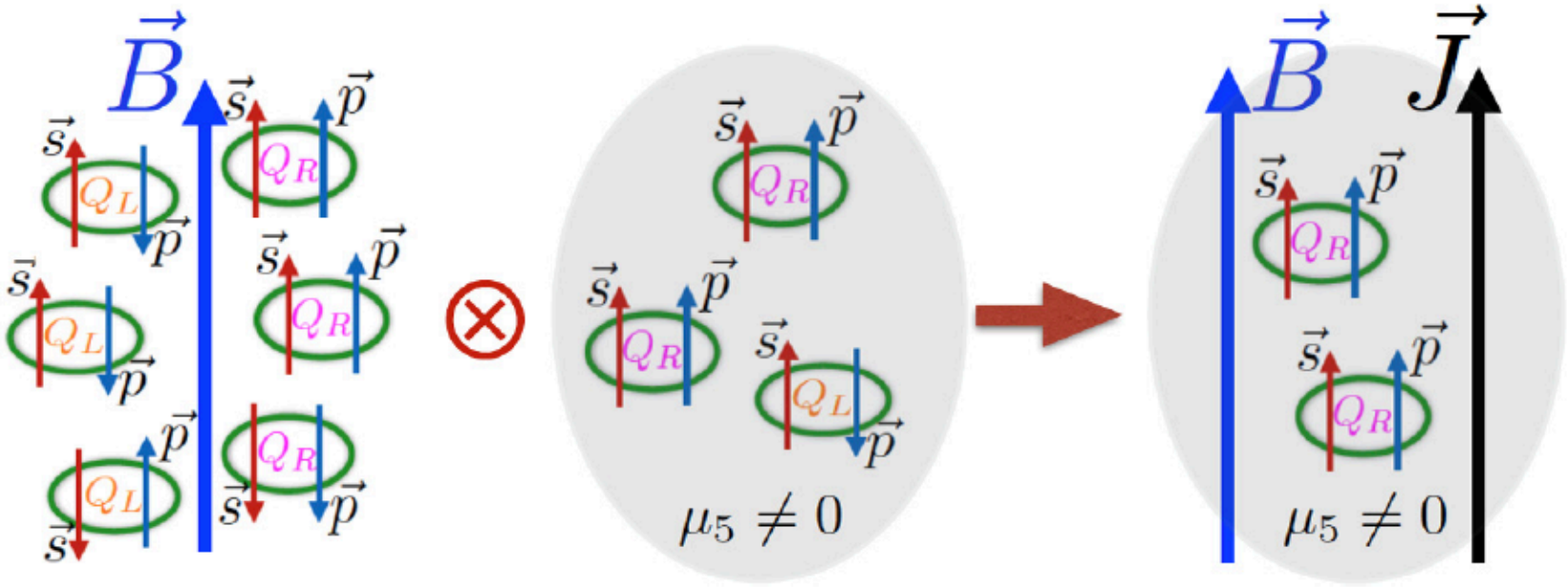
Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

This talk will focus on Chiral Magnetic Effect (CME)



[Kharzeev, Fukushima, Warringa, McLerran, …]

Intuitive Picture of CME



Intuitive understanding of CME:

Magnetic polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

⊗

Chiral imbalance —>
correlation between directions of
SPIN & MOMENTUM

→ ***Transport current along magnetic field***

$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

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

Many-Body Theory for CME

- ***New quantum transport equations (— see later talks).***
- ***New hydrodynamics with macro. quantum current!***

Normal Hydrodynamics

$$\partial_\mu J^\mu = 0$$

$$J^\mu = n u^\mu + \nu^\mu$$

Viscous Current

$$\nu^\mu = \frac{\sigma T}{2}\Delta^{\mu\nu}\partial_\nu\left(\frac{\mu}{T}\right) + \frac{\sigma}{2}E^\mu$$

Diffusion; Conduction



Anomalous Hydrodynamics

$$\partial_\mu J^\mu = C_A E^\mu B_\mu$$

Anomaly

$$J^\nu = n u^\mu + \nu^\mu + \nu_a^\mu$$

Viscous Current; Anomalous Current

$$\nu^\mu = \frac{\sigma T}{2}\Delta^{\mu\nu}\partial_\nu\left(\frac{\mu}{T}\right) + \frac{\sigma}{2}E^\mu$$

Diffusion; Conduction

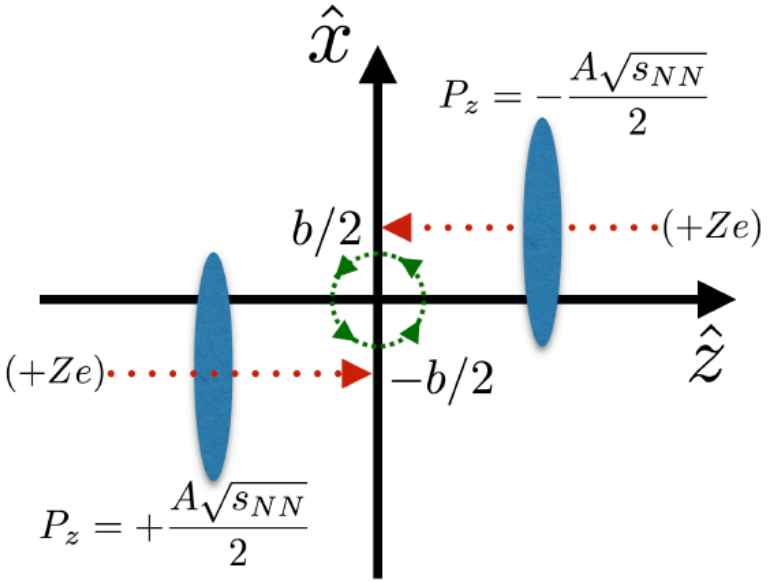
$$\nu_a^\mu = \xi_B B^\mu + \xi\,\omega^\mu$$

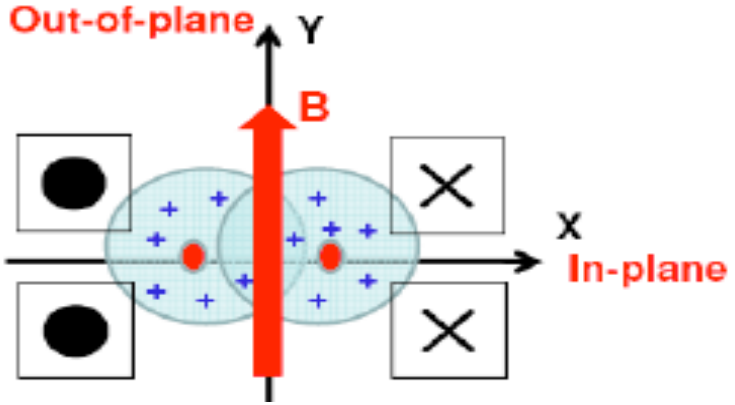
CME; CVE

[Son, Surowka; Kharzeev, Yee; Hidaka, Yang; Shi, JL, et al; …]

Strong Electromagnetic Fields

The angular momentum together with large (+Ze) nuclear charge —> strong magnetic field!





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

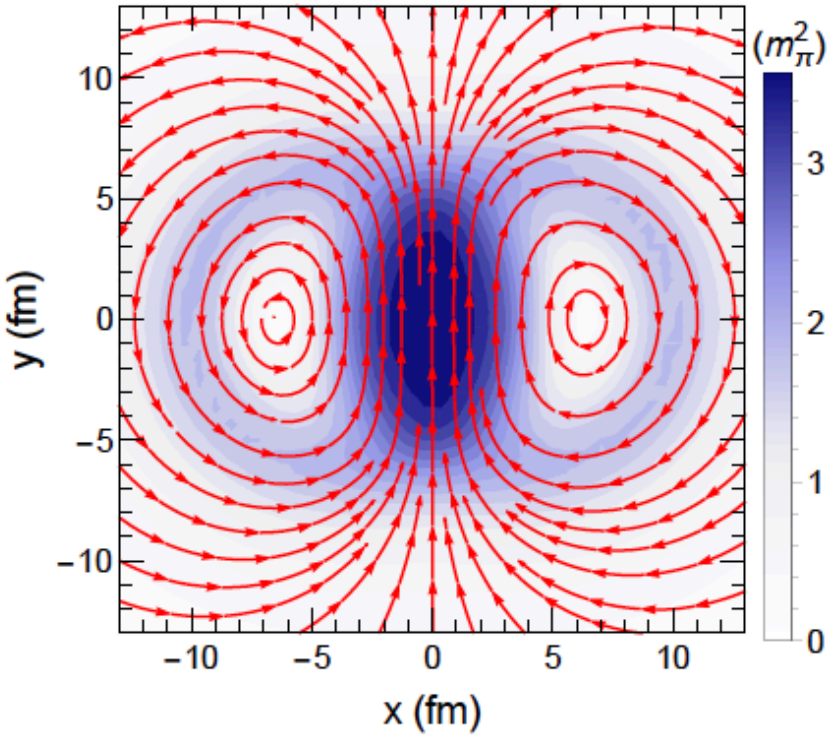
- Strongest B field (and strong E field as well) naturally arises!

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

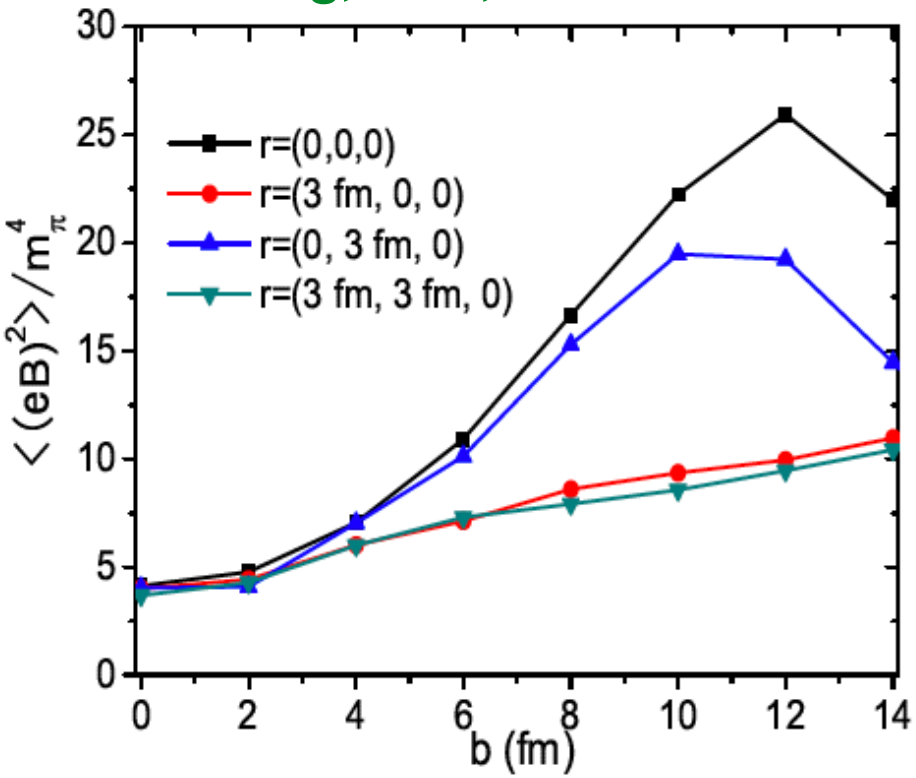
- "Out-of-plane" orientation (approximately)

[Bloczynski-Huang-Zhang-Liao]

Strong Electromagnetic Fields



Huang, Liao, et al PLB2012



Quantitative simulations confirm the existence of such extreme fields!

[Many interesting B-field induced effects: di-electron; polarization splitting; quarkonium v2; D meson v1; …]

Strong Electromagnetic Fields

Physics Letters B 718 (2013) 1529–1535

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Physics Letters B

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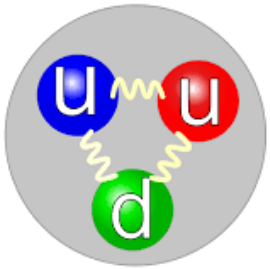
Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

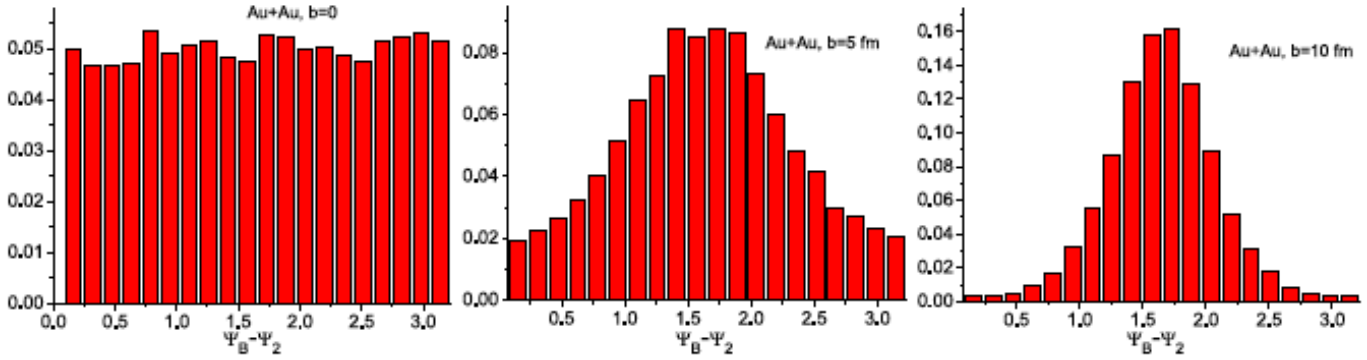
Huang, Liao, et al PLB2012

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

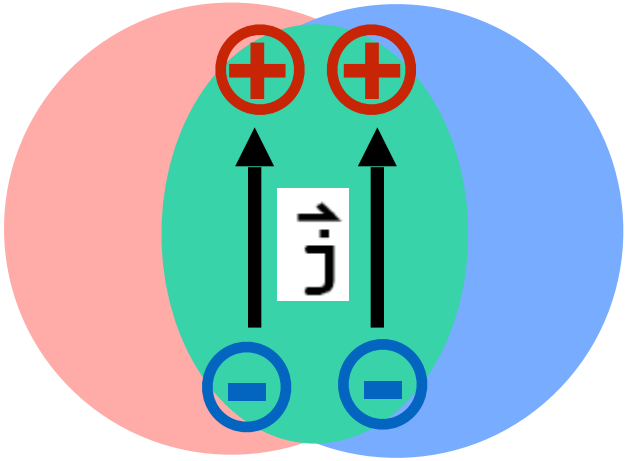
[a] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[b] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA

Two very important points in this paper:
**** azimuthal correlation/de-correlation between B fiend and geometry***
**** finite size of proton must be taken into account***



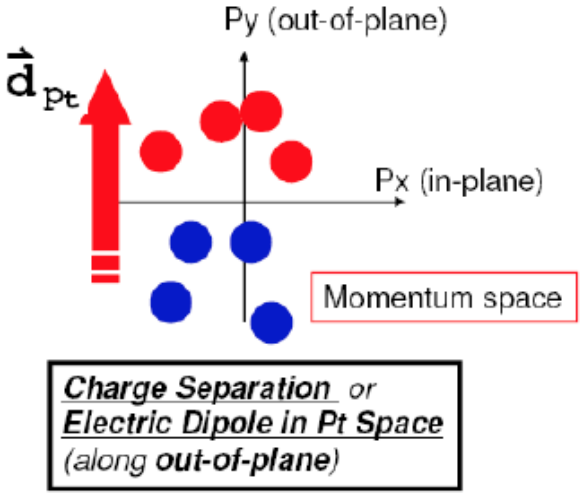


Signature of CME Current: Charge Separation



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

strong radial blast:
position —> momentum



Charge Separation *or*
Electric Dipole in Pt Space
(along ***out-of-plane****)*

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

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

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

Very difficult measurement:
- **** Zero average, only nonzero variance;***
- **** Correlation measurement with significant backgrounds;***
- **** Signal likely very small***

[See more discussions in Shou's talk]

Possible Signatures of CME in HIC

A two-component decomposition model:

$\gamma = \kappa\, v_2\, F - H$ F: Bulk Background

$\delta = F + H$ H: Possible Pure CME Signal = $(a_{1,CME})^2$

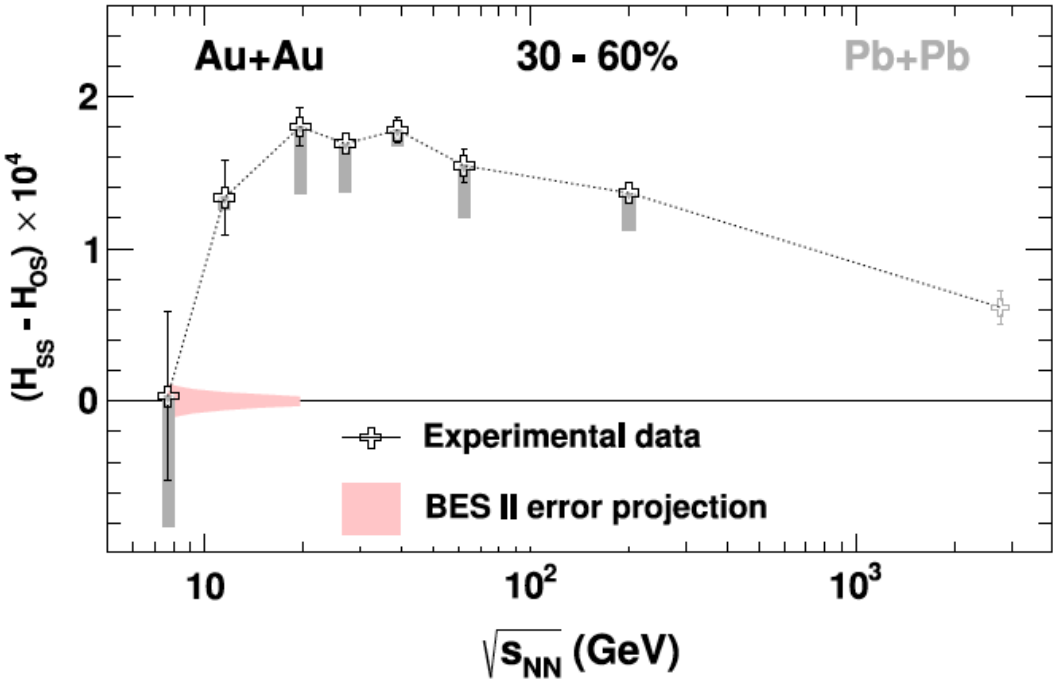
Bzdak, Koch, JL, 2012

$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

Many interesting proposals of new observables!

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

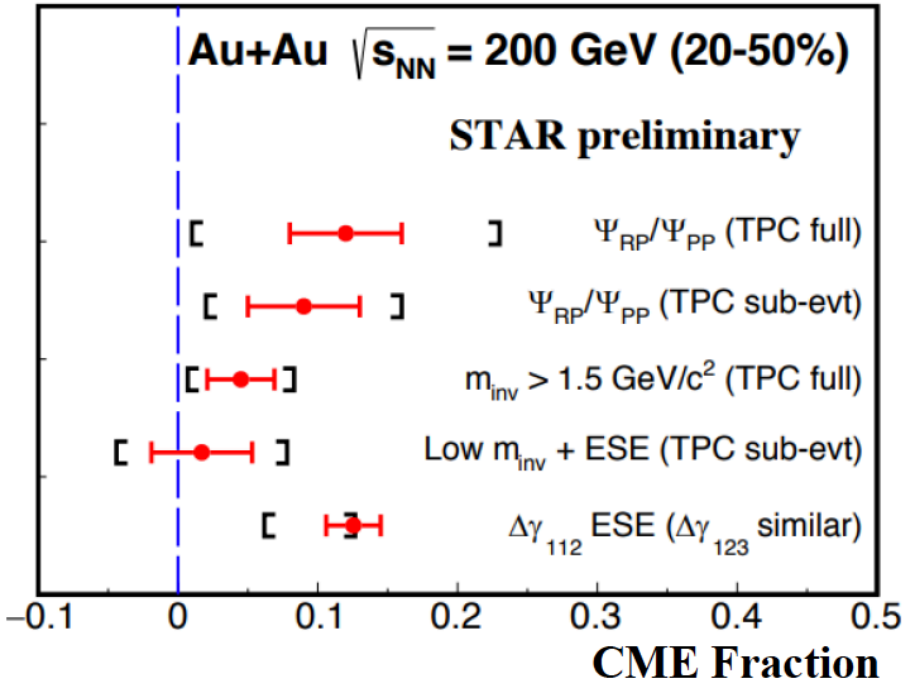


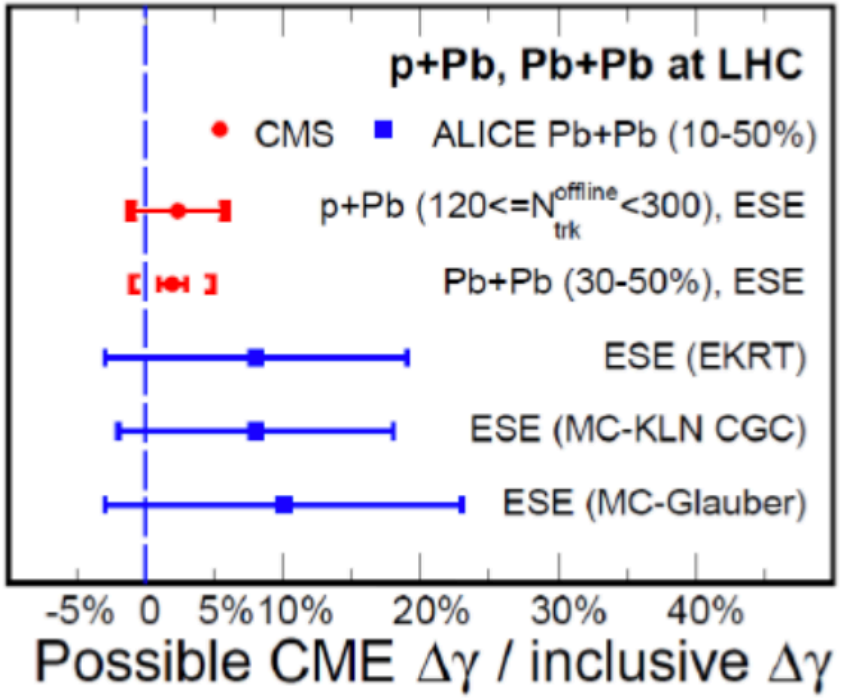
STAR PRL2014

Possible Signatures of CME in HIC

Key challenge: weak signal versus strong backgrounds.

Many new measurements at RHIC and LHC:
gamma correlator + certain procedure to constrain backgrounds





Lacey, Magdy, et al: R-correlator consistent with a1~1% at RHIC

Current data provide encouraging hints, esp. @ RHIC energy!

Need quantitative modeling of signal+bkg to help exp search!

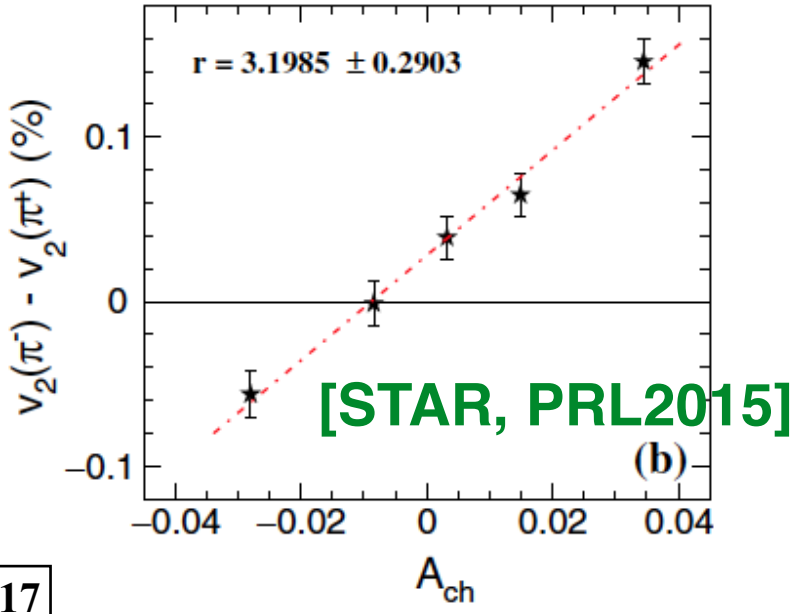
Chiral Magnetic Wave

CMW —> charge quadrupole of QGP —> elliptic flow splitting

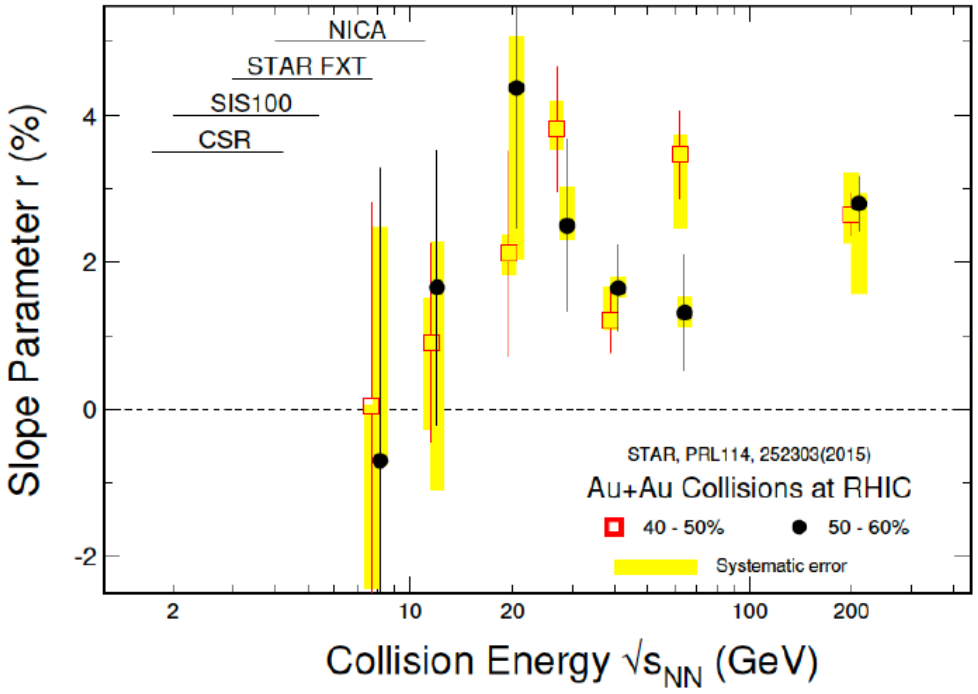
[Burnier, Kharzeev, JL, Yee, PRL2011; & arXiv: 1208.2537]

$$v_2^- - v_2^+ = r_e A$$

charge quadrupole due to CMW transport



[STAR, PRL2015]



A consistent trend as CME: Turning-off at low energy

[See more discussions in Shou's talk]

Quantifying CME in HIC

** Approach based on fluid dynamics (AVFD)*

- *our focus in this talk*

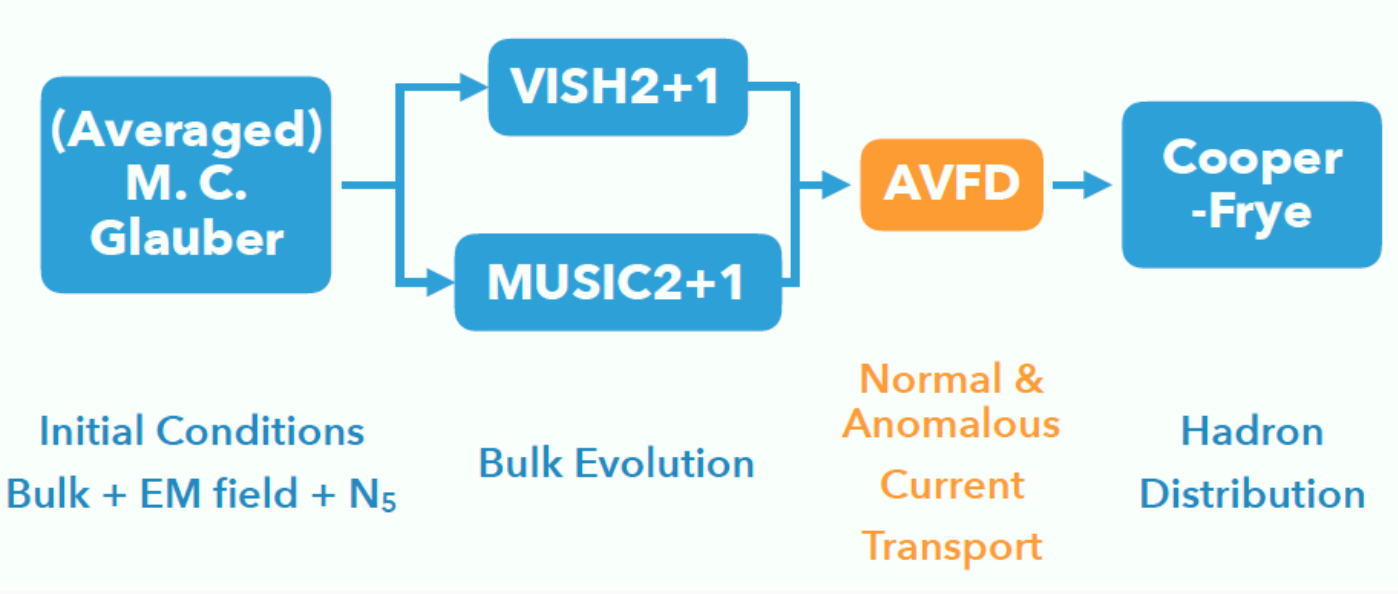
** Approach based on transport models.*

- *AMPT based*
  (Guoliang Ma, Yugang Ma, and collaborators)
- *Chiral kinetic transport based*
  (Che-ming Ko and collaborators)

AVFD Framework

Establishment of Anomalous-Viscous Fluid Dynamics (AVFD): Hydrodynamical realization of CME in HIC.

[newest developments: EBE-AVFD; AVFD+axial dynamics; AVFD+LCC]



We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

[S. Shi, JL, et al: arXiv:1611.04586; arXiv:1711.02496]

AVFD Framework



Note: bulk properties fully data-validated

[arXiv:1611.04586; arXiv:1711.02496]

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

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

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

CME

Viscous Effect

$$\Delta^\mu{}_\nu\, \mathrm{d}\, \nu_{R,L}{}^\nu = - \frac{1}{\tau_{rlx}} (\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu}\, \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q\, E^\mu$$

Chinese Physics C Vol. 42, No. 1 (2018) 011001

arXiv:1611.04586

Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics*

Yin Jiang(姜寅)[1] Shuzhe Shi(施舒哲)[2] Yi Yin(尹伊)[3] Jinfeng Liao(廖劲峰)[2,4;1)]

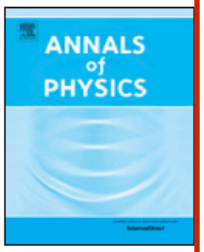
[1] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[2] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[3] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[4] Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan 430079, China

Annals of Physics 394 (2018) 50–72

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Anomalous chiral transport in heavy ion collisions from Anomalous-Viscous Fluid Dynamics

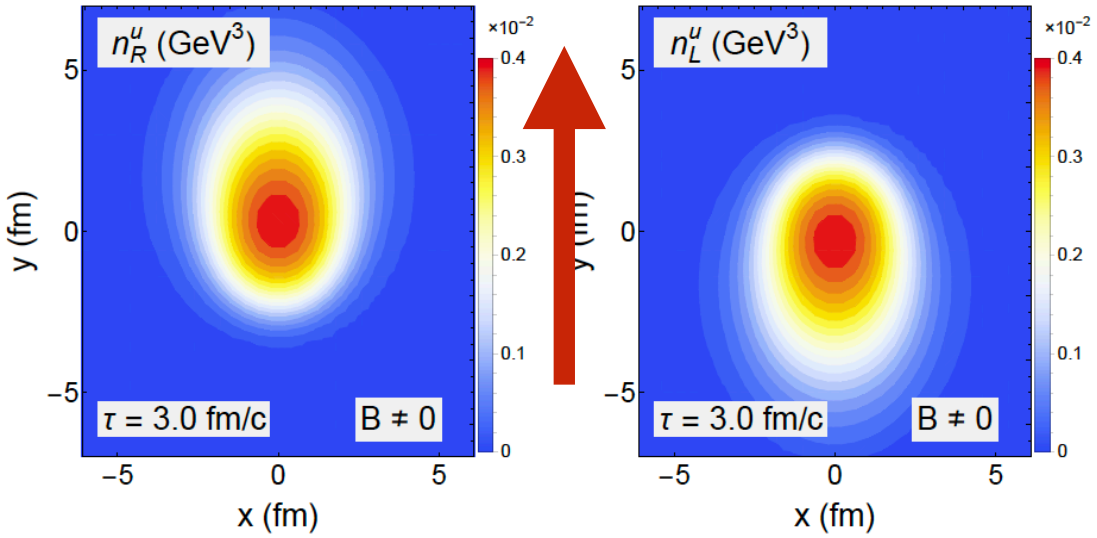
Shuzhe Shi [a,*], Yin Jiang [b,c], Elias Lilleskov [d,a], Jinfeng Liao [a,e,*]

arXiv:1711.02496

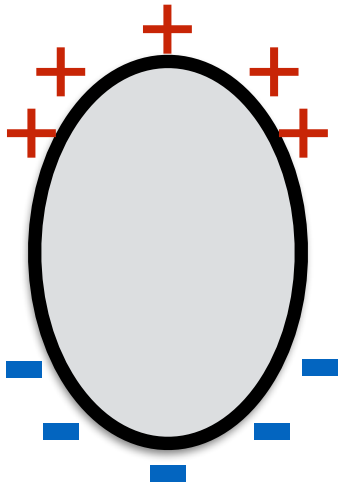
Shuzhe Shi (McGill; PhD @ IUB)

Yin Jiang (Beihang), Yi Yin (MIT), Elias Lilleskov (REU)

The Charge Separation from AVFD



$$E\frac{dN}{d^3p}(x^\mu, p^\mu) = \frac{g}{(2\pi)^3}\int_{\Sigma_{\rm fo}} p^\mu d^3\sigma_\mu f(x,p)$$



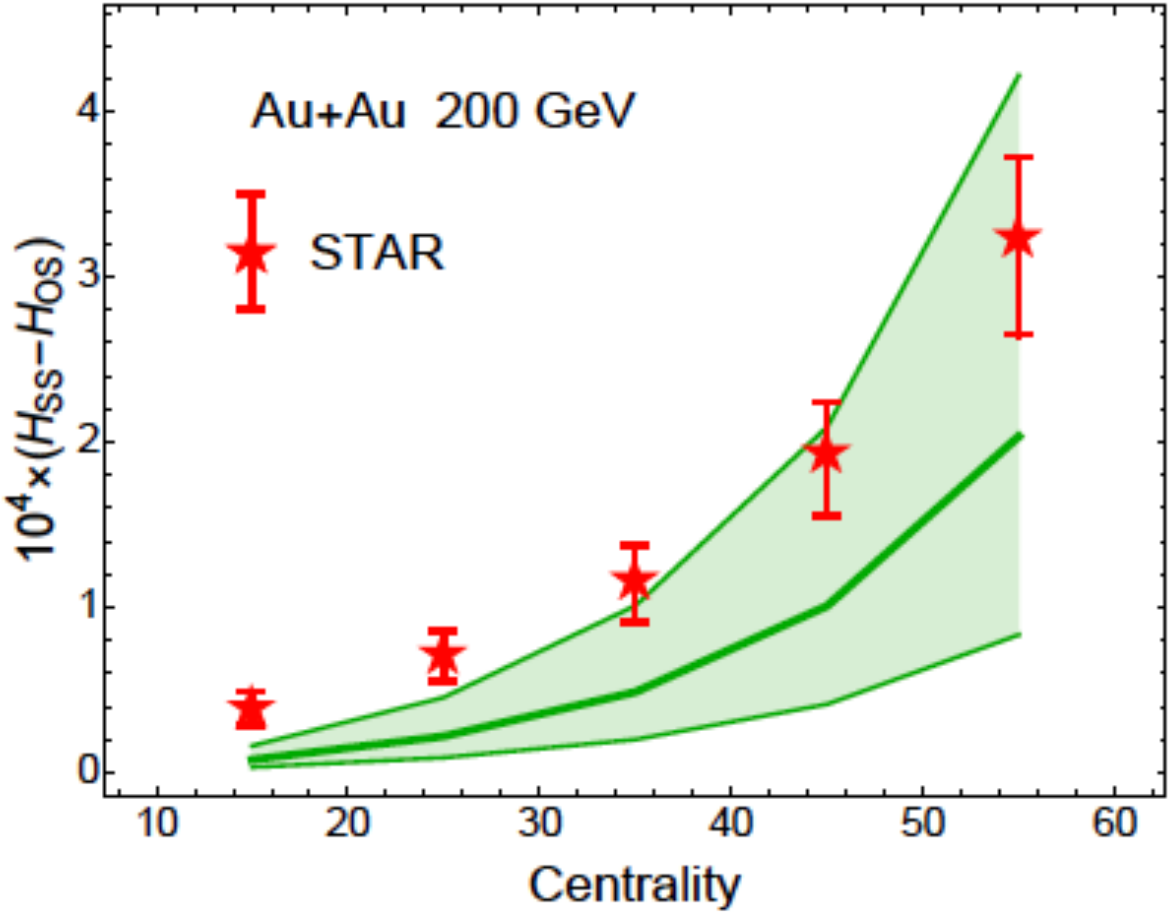
Hydrodynamic realization of CME in HIC: Chirality imbalance —> R/L asymmetry —> charge asymmetry

B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

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

$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

AVFD for AuAu Collisions

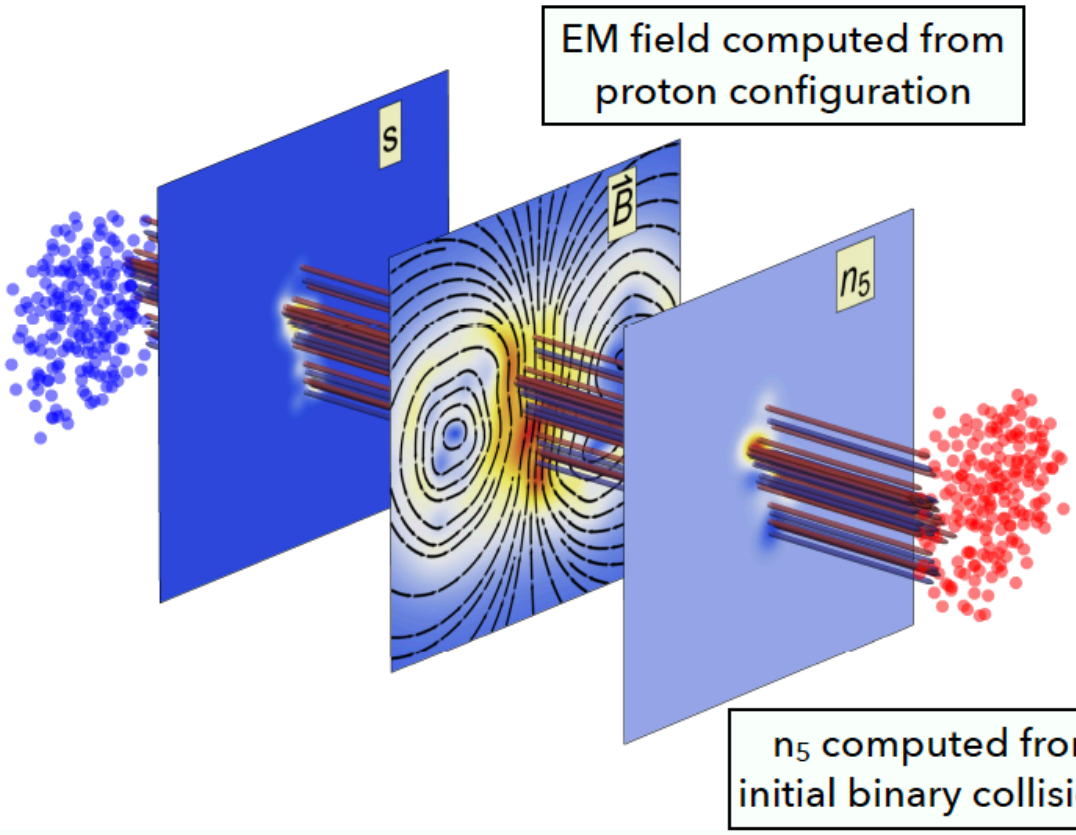


CME is quantitatively viable for describing relevant experimental observable!

AVFD provides the essential tool for quantitatively characterizing various features of CME in HIC!

[A lot of detailed results in:
Shi, Yin, JL, …, arXiv:1611.04586; arXiv:1711.02496]

Event-By-Event AVFD



Include EBE fluctuations:

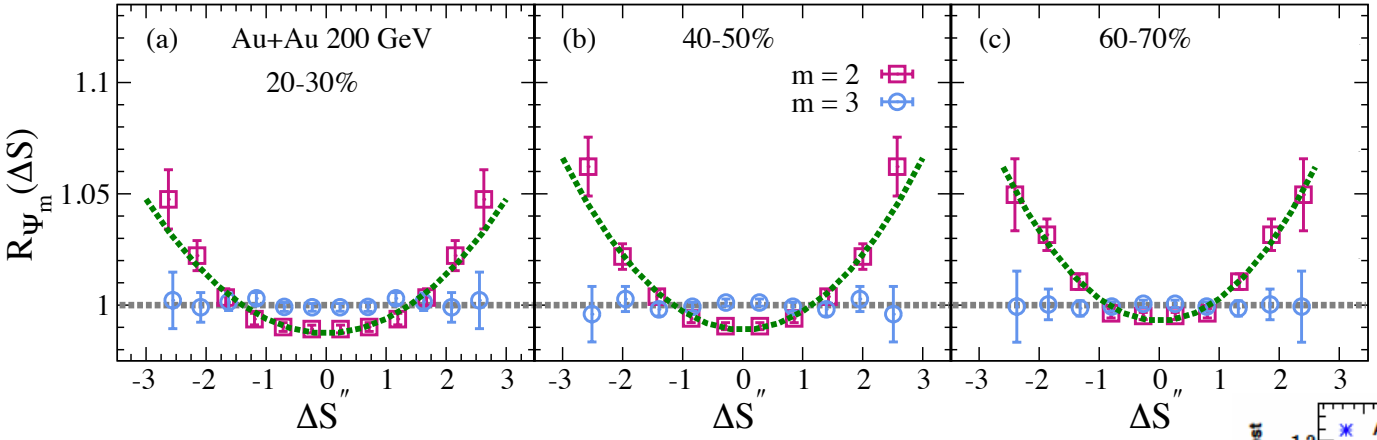
- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade

(~ half of all bkg.)

Important for better understanding:
**** Interplay between signal and BKG;***
**** Experimental analysis methods***

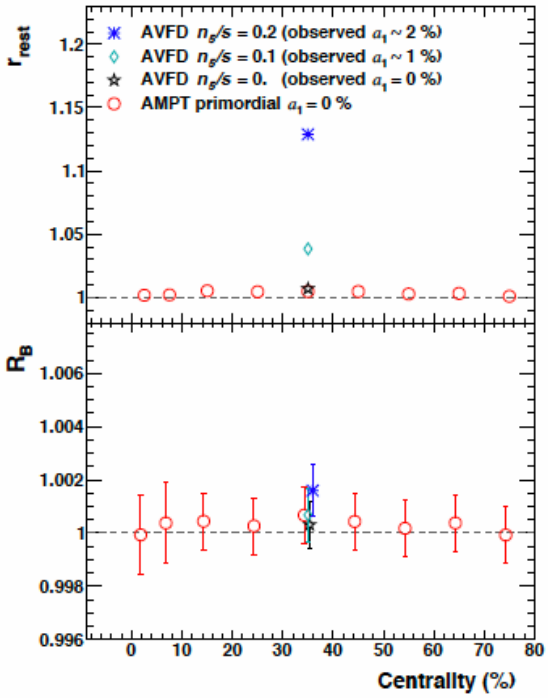
Shuzhe Shi, Hui Zhang, Defu Hou, JL, to appear soon; QM2018 proceedings.

EBE-AVFD for Testing Observables

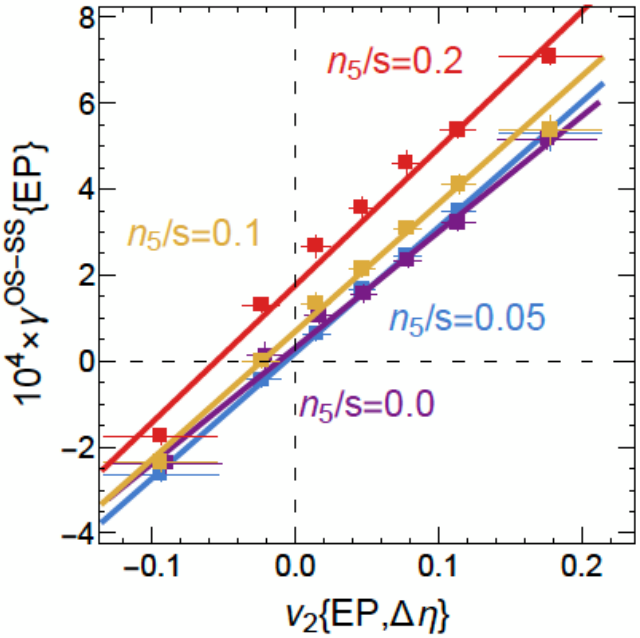


Lacey, Nagdy, et al

Tang



ESE



Now a key tool for understanding different observables' responses and sensitivity to signal and backgrounds

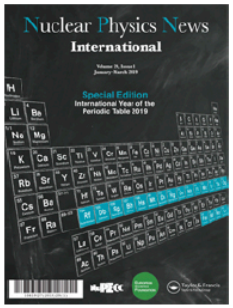
Isobaric Collision Experiment

Chinese Physics C Vol. 41, No. 7 (2017) 072001

Status of the chiral magnetic effect and collisions of isobars

Volker Koch[1] Soeren Schlichting[2] Vladimir Skokov[3;1)] Paul Sorensen[2;2)] Jim Thomas[1]
Sergei Voloshin[4] Gang Wang[5] Ho-Ung Yee[3,6]

[1] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA
[2] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
[3] RIKEN/BNL, Brookhaven National Laboratory, Upton, NY 11973, USA
[4] Wayne State University, 666 W. Hancock, Detroit, MI 48201, USA
[5] Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA
[6] Department of Physics, University of Illinois, Chicago, Illinois 60607, USA



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Nuclear Physics News

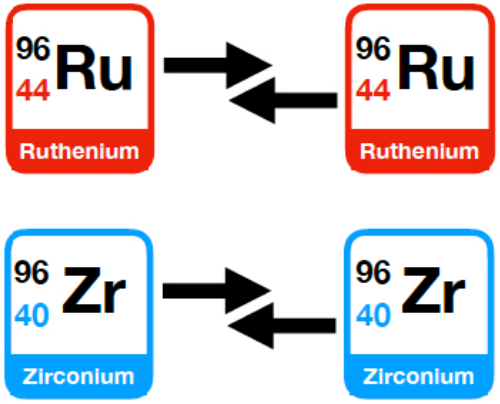
feature article

Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

D. E. Kharzeev[1,2] and J. Liao[3]

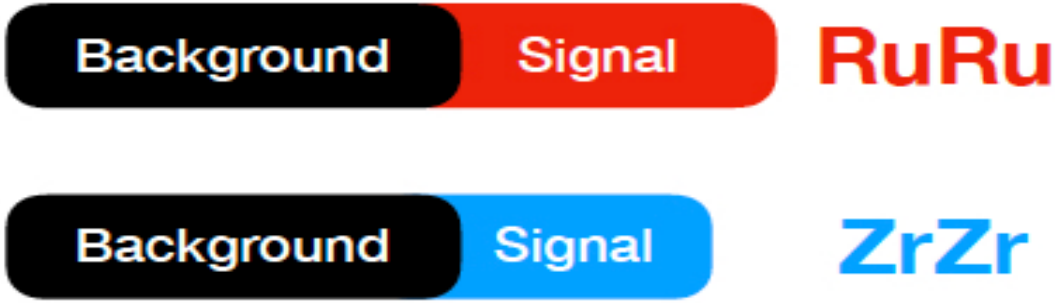
A Decisive Experiment: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC



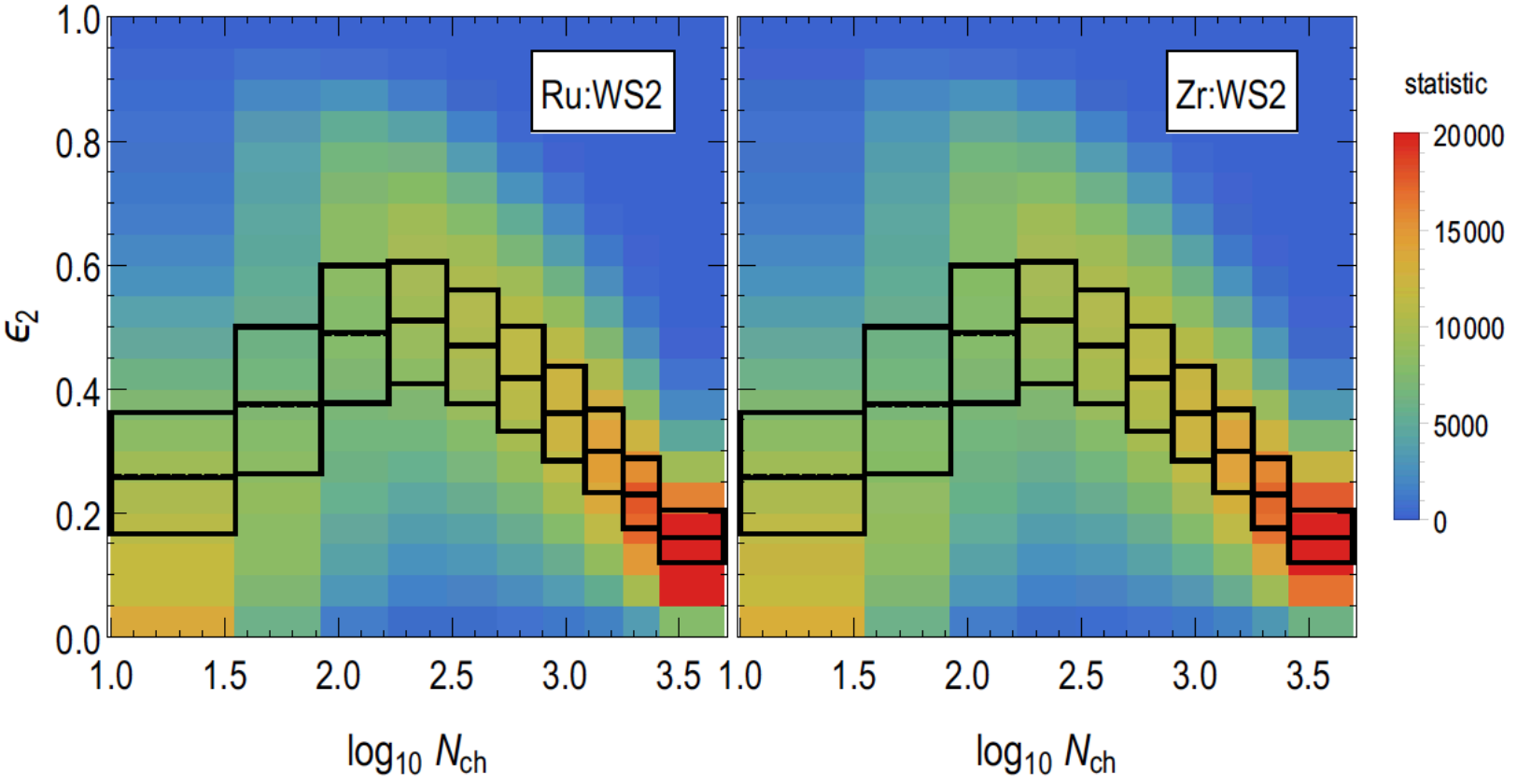
Key idea: contrasting two systems with identical bulk, varied magnetic fields.

Charge Asymmetry Correlation Measurement



~2 billion data collected successfully in RHIC 2018 run; processing and analysis underway!

Isobars: How to Choose Identical Systems?

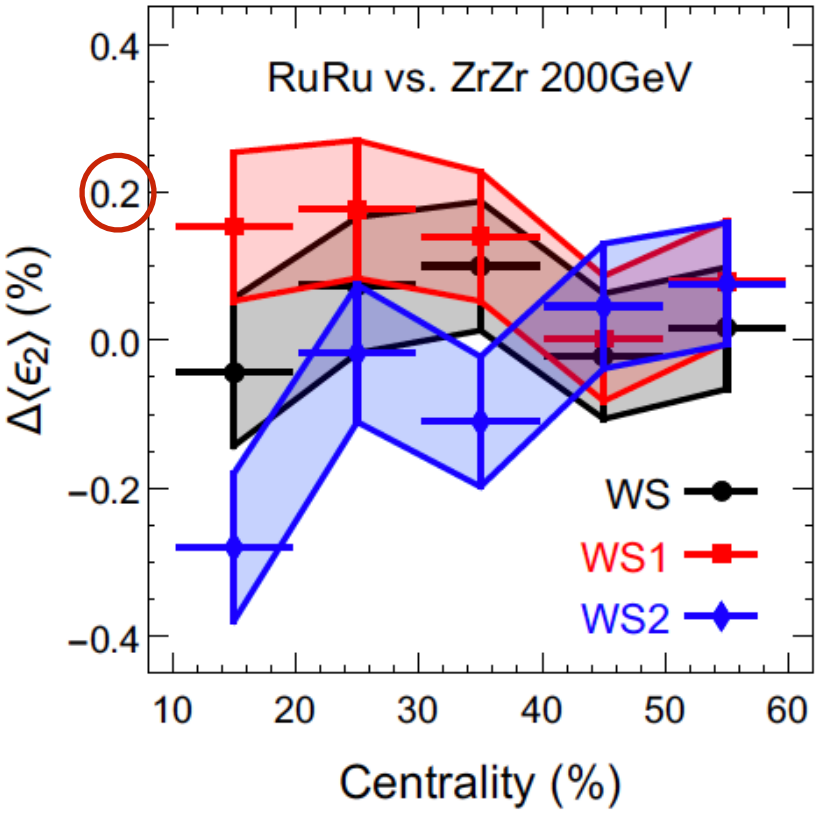


Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

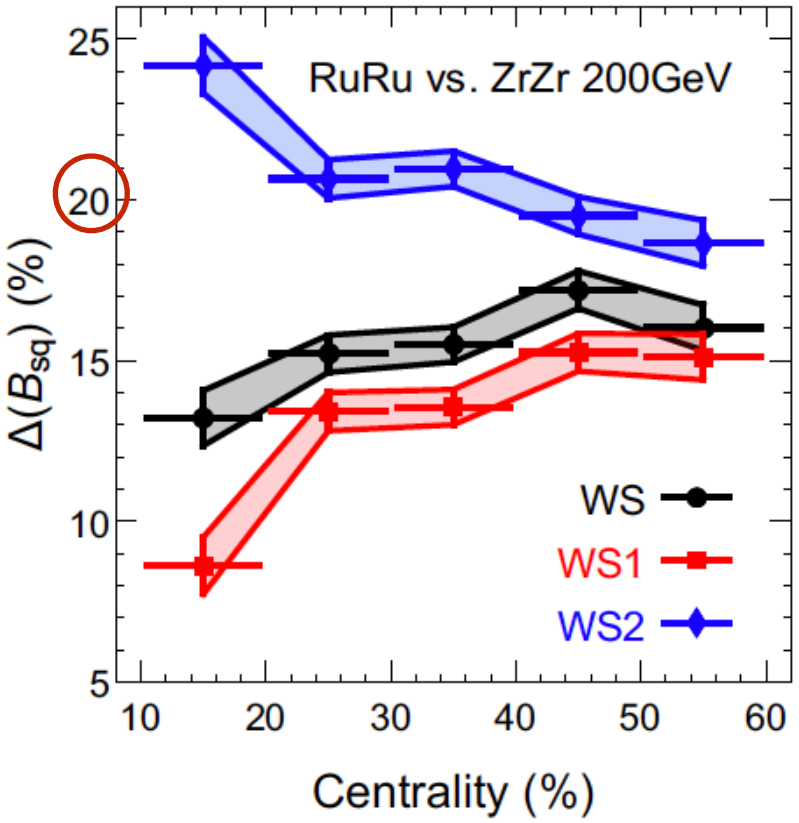
[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

Isobars: How to Choose Identical Systems?

Eccentricity is guaranteed the same!

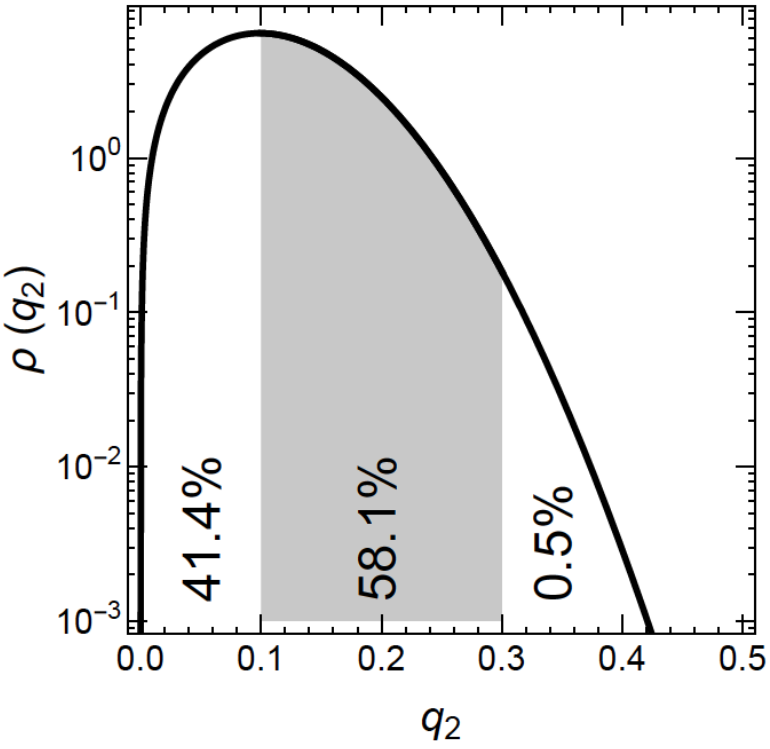


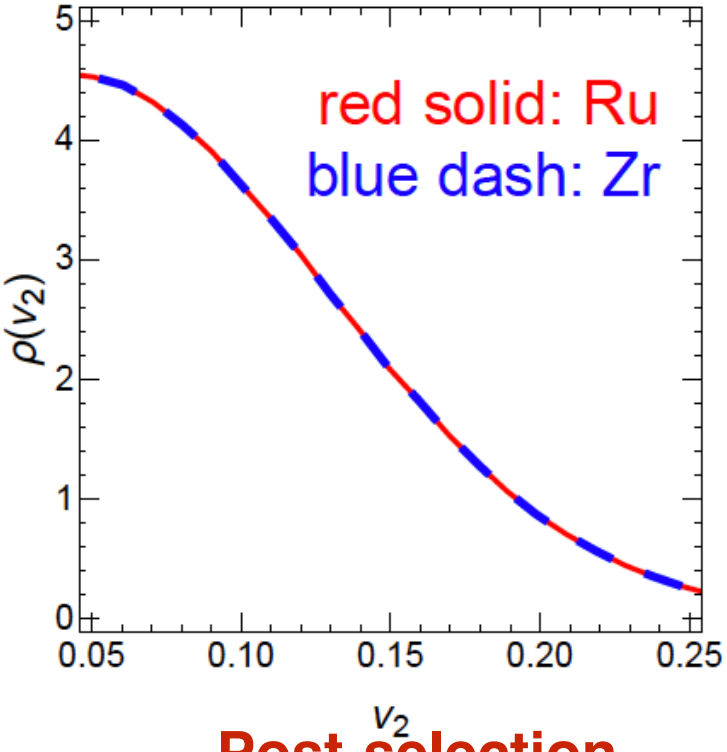
B field differs by 12~20% !



Joint multiplicity-geometry cut:
Vanishing difference in bulk properties,
Sizable difference in magnetic fields!!!

Analyzing Actual EBE-AVFD Events for Isobars





Millions of EBE-AVFD events: Subject to joint-cut

$$64 < N_{ch,\ |y|<1} < 96$$

$$0.1 < q_2 < 0.3$$

Post-selection double-check: Identical v2 !

Guaranteed to have two identical sample of isobar events for contrast!

AVFD Predictions for Isobars

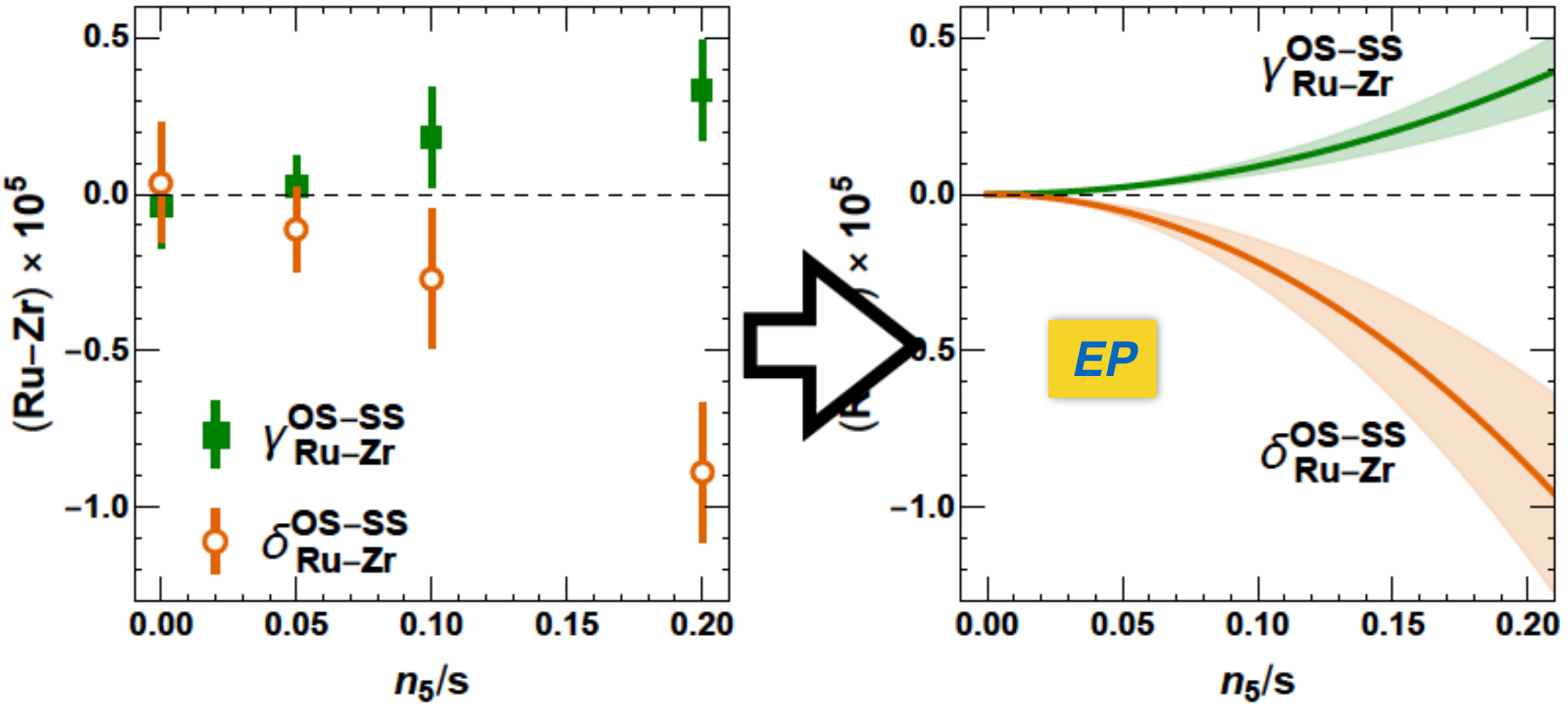
$-1 < \eta < 1$

$64 < N_{ch} < 96$

$0.05 < v_2^{ref} < 0.25$

Statistics: 10^7 events in AVFD simulation

~ 3×10^8 events in experiment

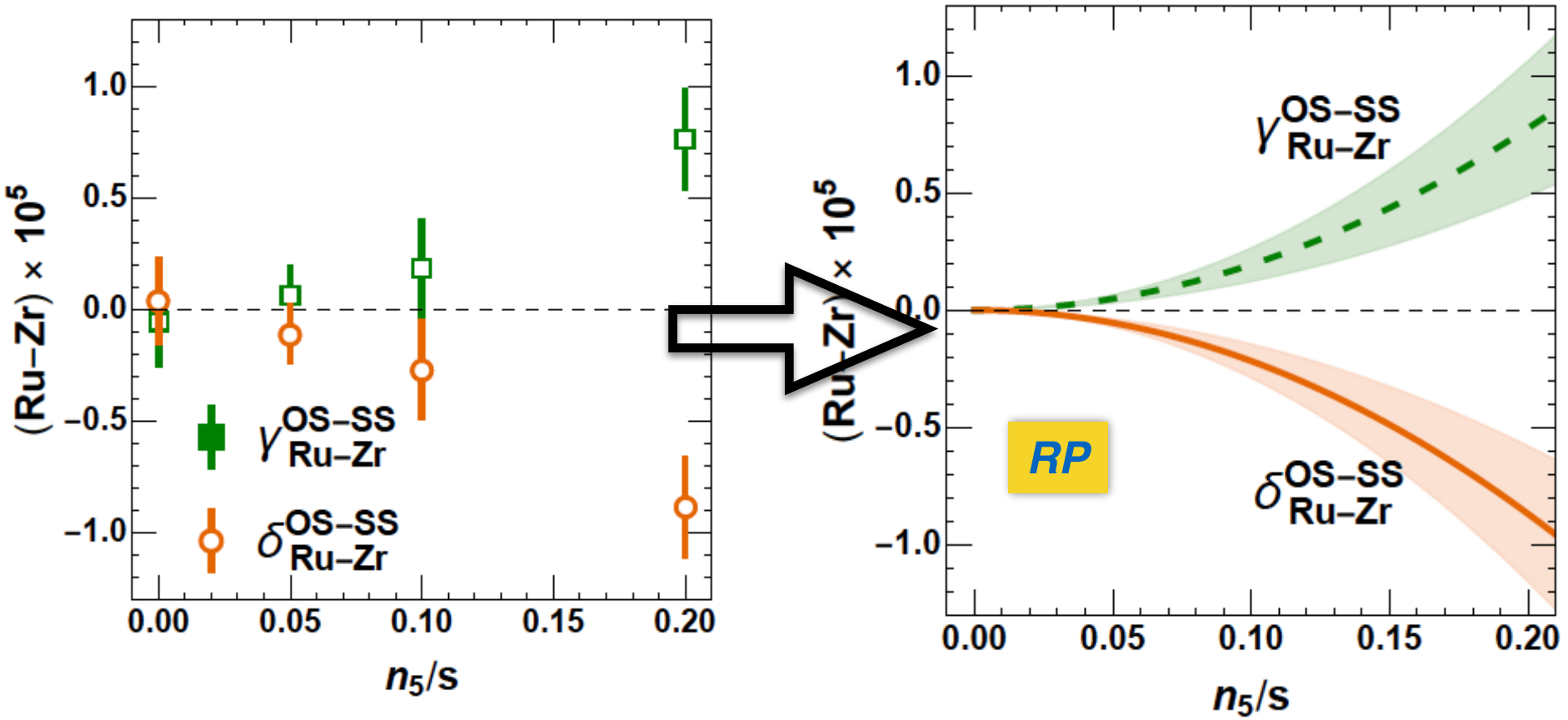


Look for absolute difference between isobars (after joint-cut)!

Look for consistency between delta- and gamma-correlators!

[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

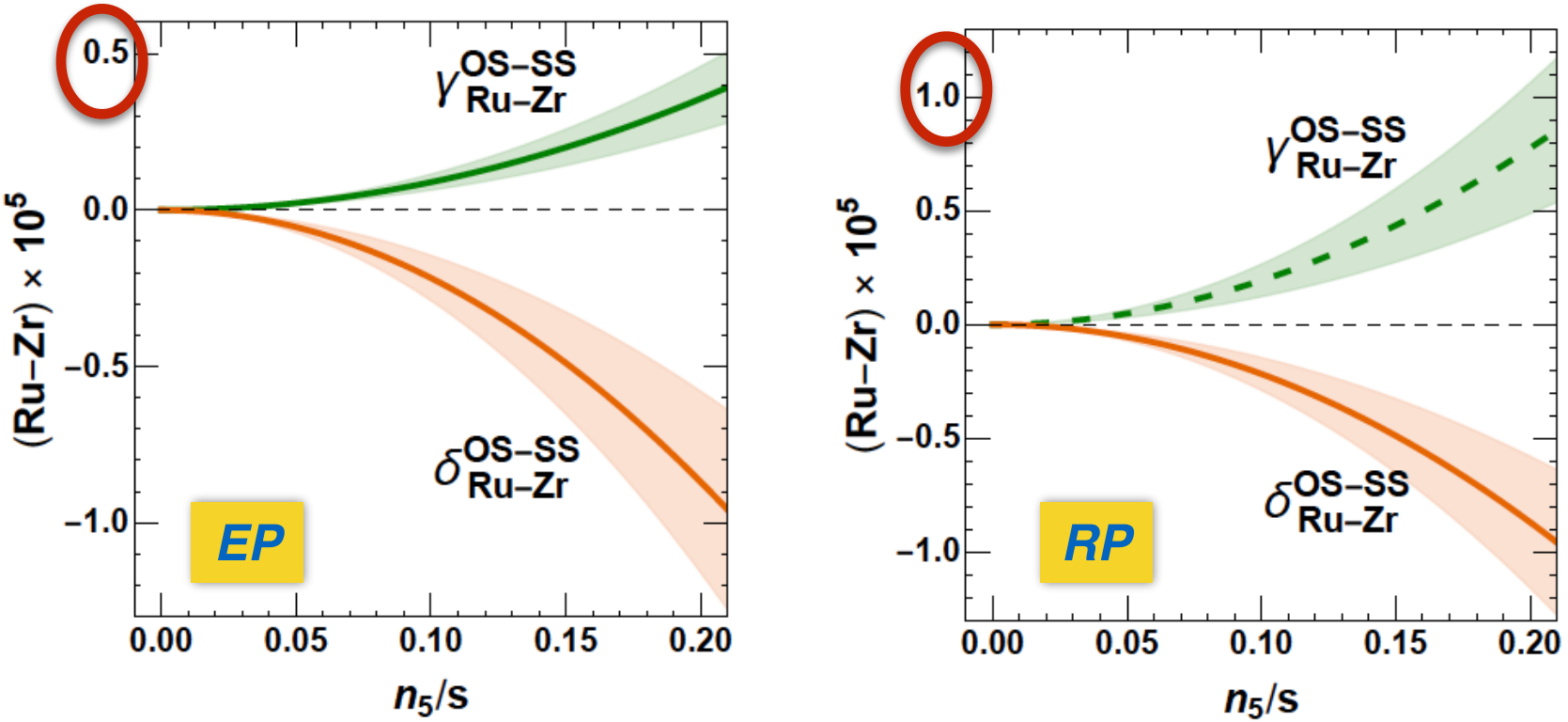
AVFD Predictions for Isobars



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AVFD Predictions for Isobars

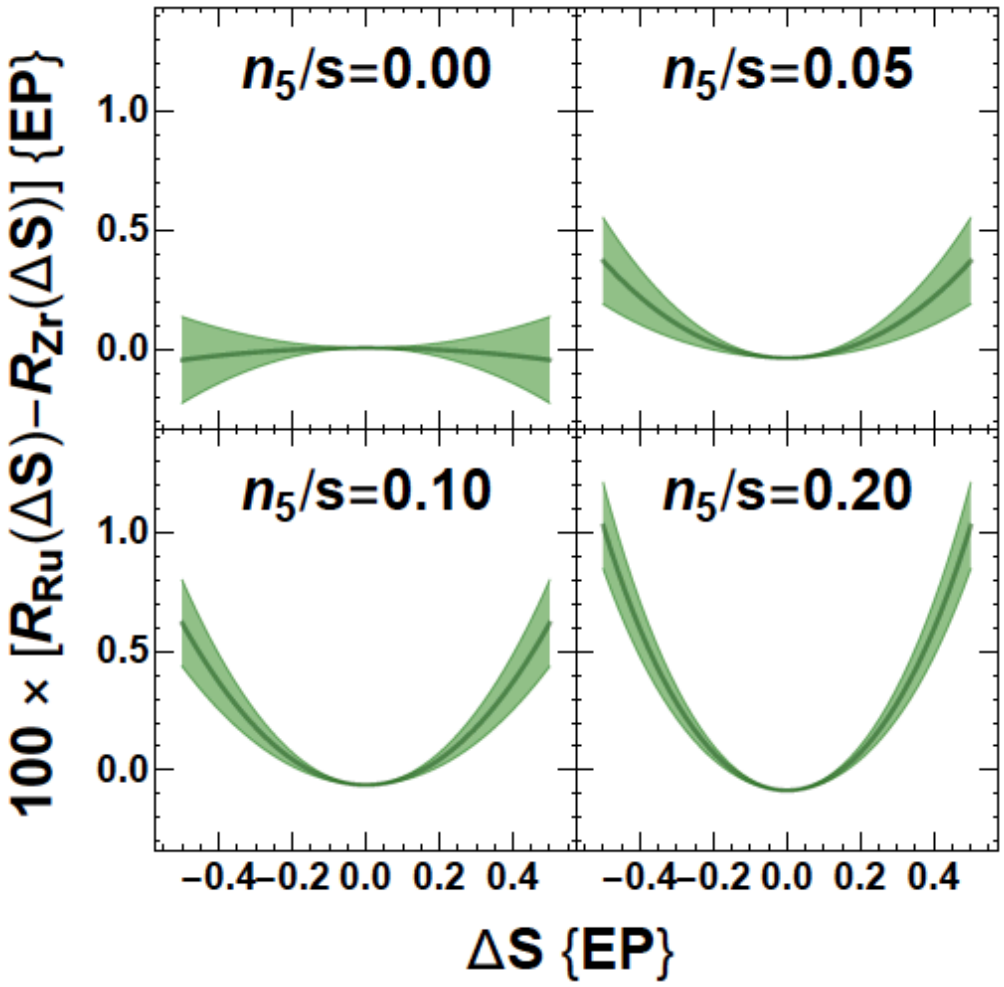


$$\gamma_{RP}^{[Ru-Zr]} : \gamma_{RP}^{[Ru-Zr]} : \delta^{[Ru-Zr]}$$

Potentially the most robust signature!
Reflecting the essential features of CME!

[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

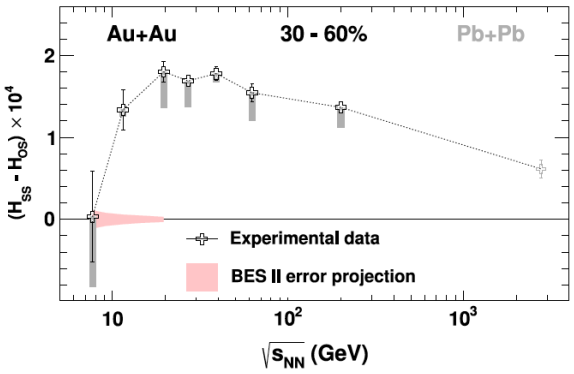
AVFD Predictions for Isobars

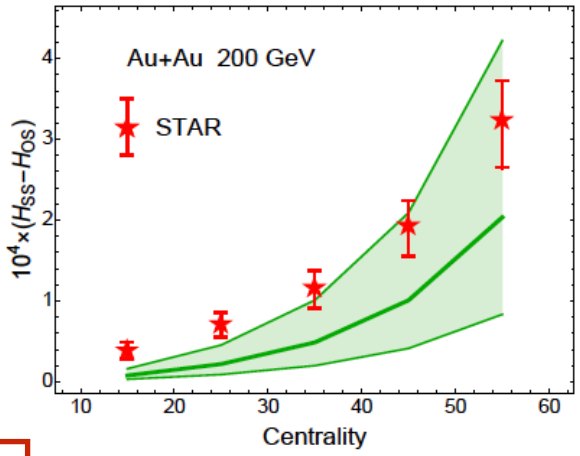


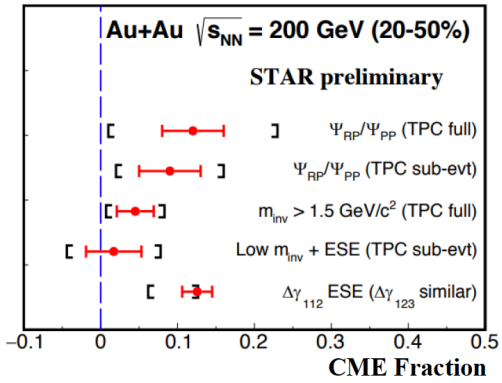
Look for absolute difference between isobars (after joint-cut)!
Look for R-correlator shape!

[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

Summary & Outlook

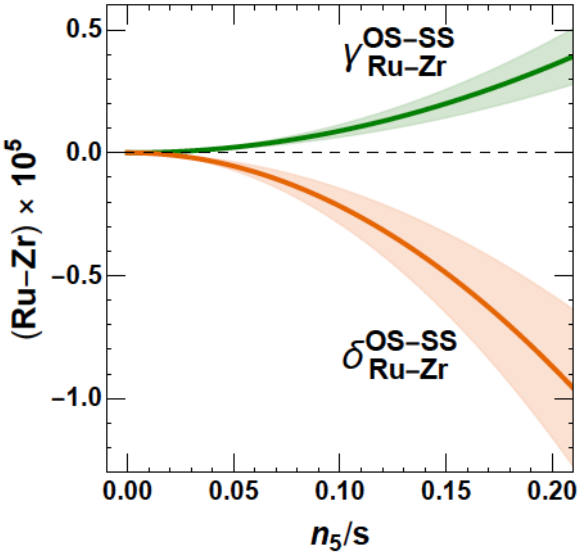






$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Exciting time(~2020): Stay tuned!



Charge Asymmetry Correlation Measurement

Background | Signal — RuRu

Background | Signal — ZrZr

$$\gamma_{RP}^{[Ru-Zr]} : \gamma_{RP}^{[Ru-Zr]} : \delta^{[Ru-Zr]}$$