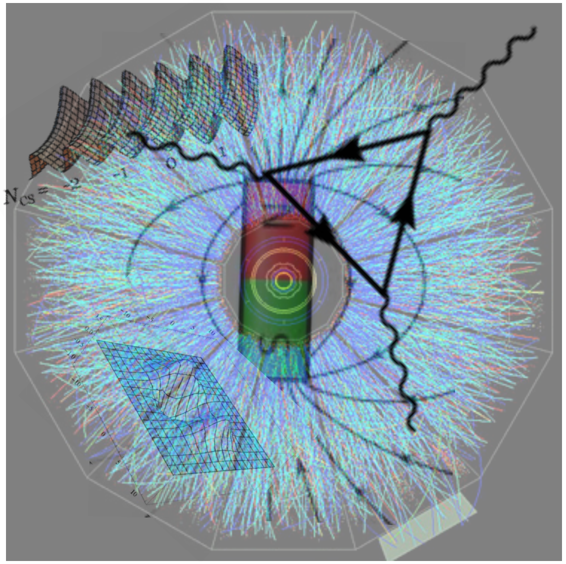
INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

Feb. 08, 2023

Impact of Nuclear Structure on the CME Search



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

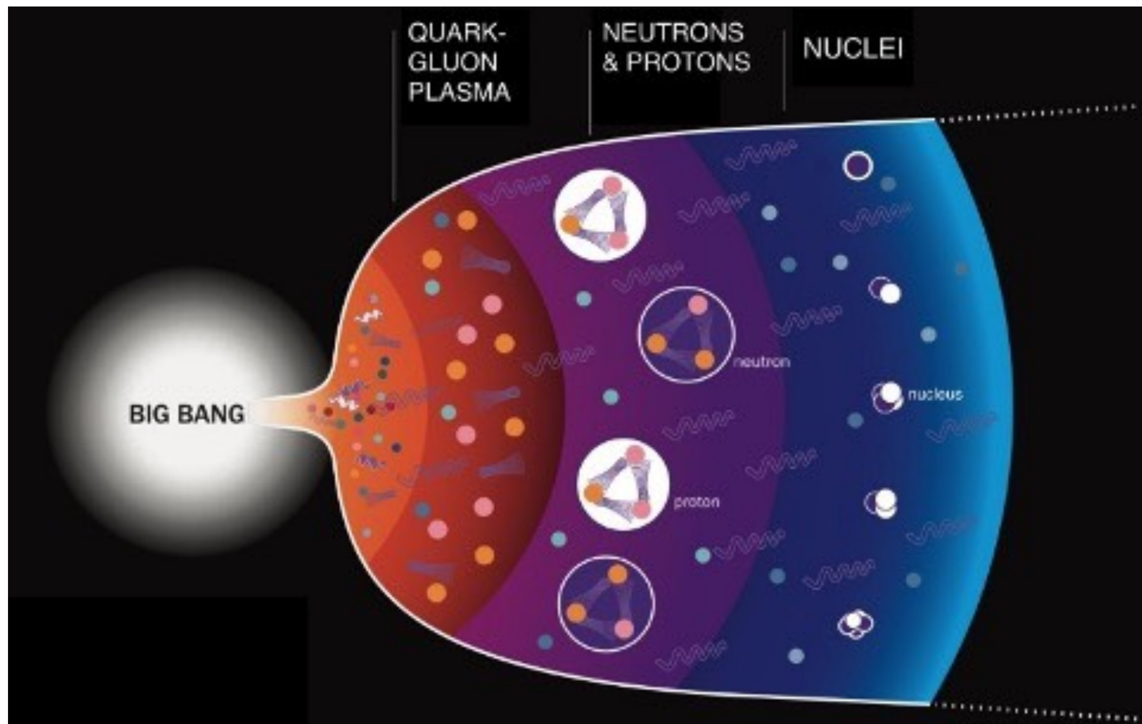
Plan of the Talk

- *Why are we so interested in the Chiral Magnetic Effect (CME)?*
- *Why is the CME search so difficult?*
- *What have we learned from the 1st set of isobar collision results?*
- *Where do we stand and what's next?*

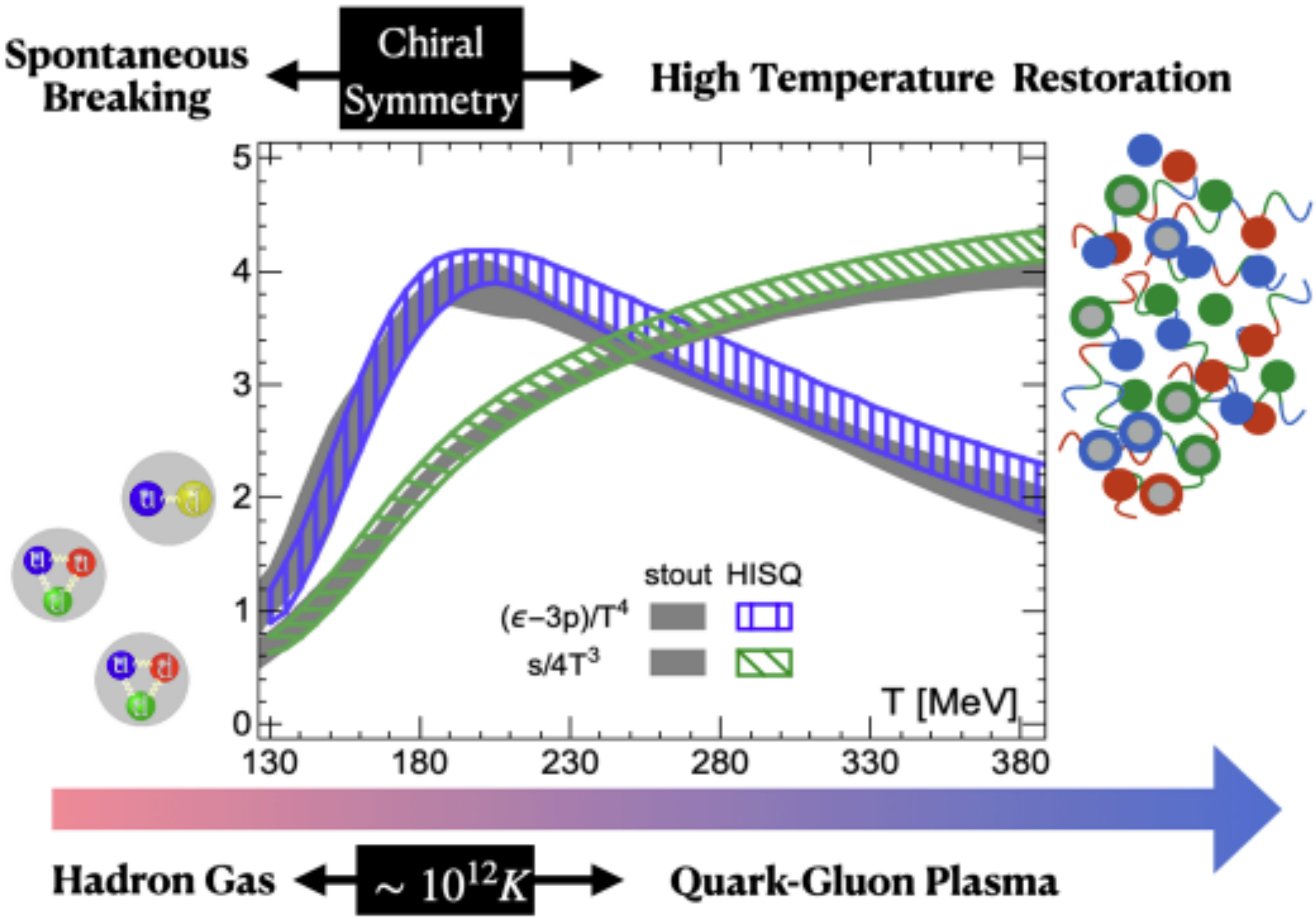
Introduction

Quarks to Cosmos

Back Then:
Cosmos = Hot Quark (& Gluon) Soup



Quark-Gluon Plasma (QGP): A New Phase of Matter



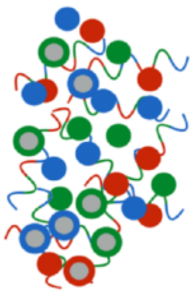
"Condensed matter physics of QCD"

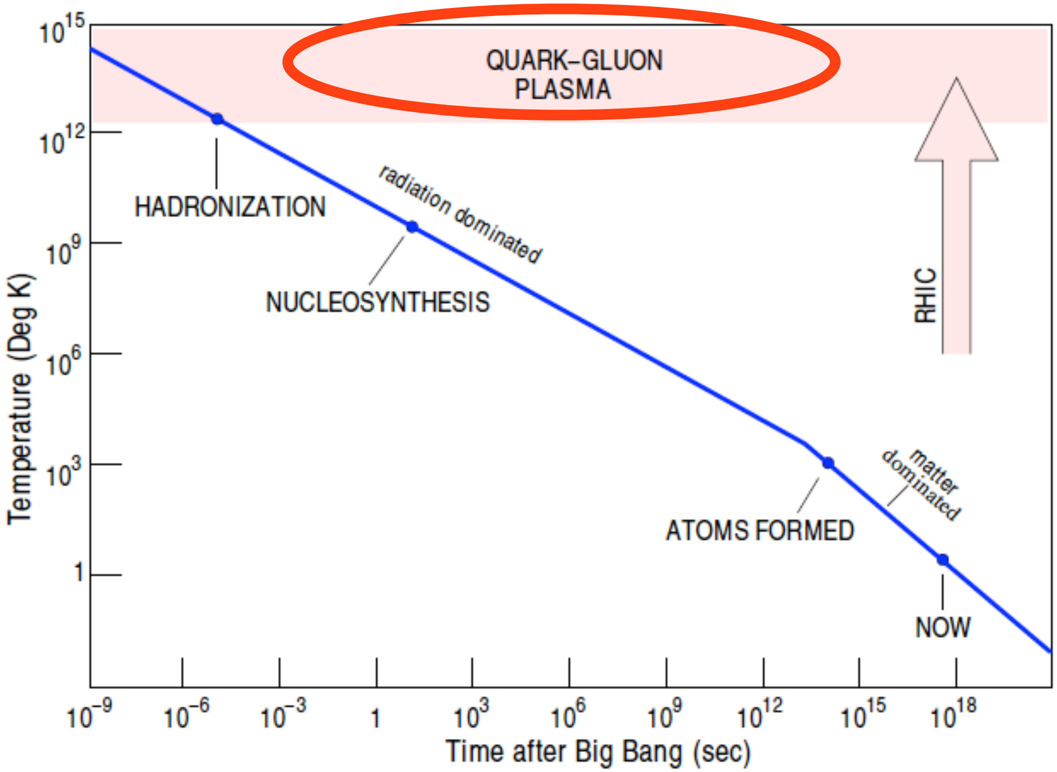
Images from: Nature Reviews Physics 3, 55-63 (2021 [arXiv:2102.06623]

QGP: An Old Phase of Matter

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

THEN





NOW

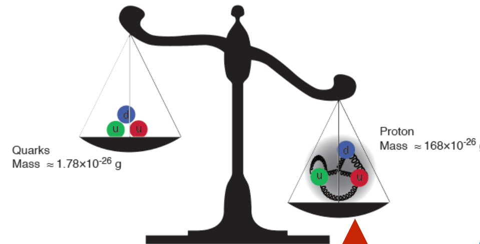
The quark-gluon plasm is an old phase of matter!

“Little Bangs”: Yesterday Once More

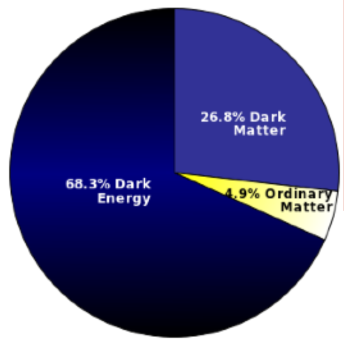
Quark Gluon Plasma (QGP) is created and measured in heavy ion collisions.

Heavy ion collision is the only venue for replicating and studying the early universe environment.

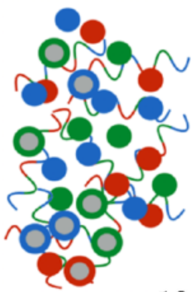
Between NOW and THEN

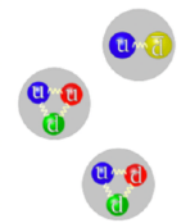


Missing QCD chiral symmetry

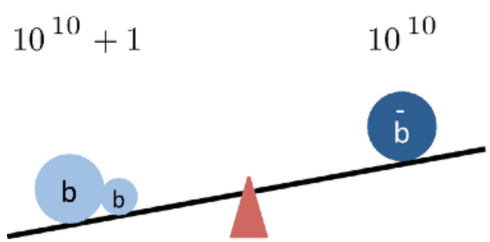


THEN





NOW



Matter-anti-matter asymmetry

The study of Chiral Magnetic Effect (CME) helps understand these fundamental issues about "why we are here"!

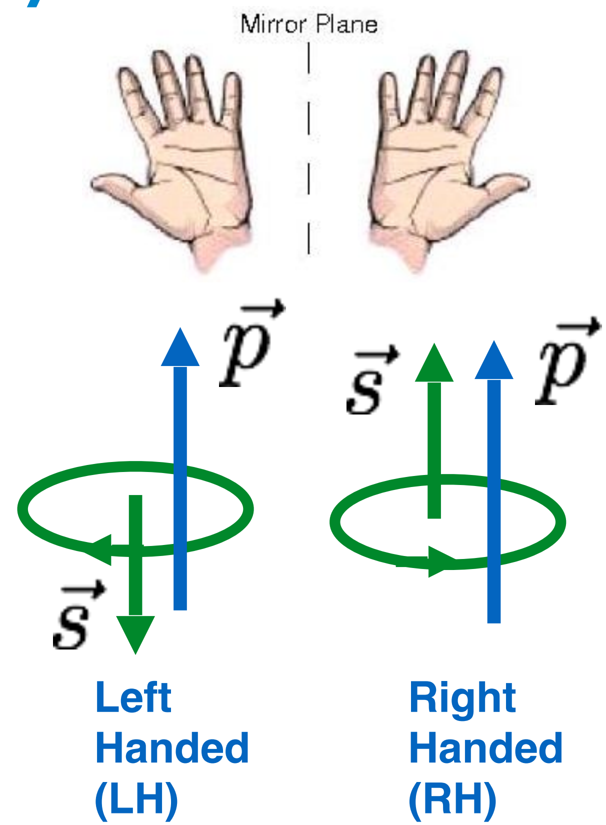
Spin & Chirality

Dirac fermion in massless limit:
chirality well defined

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

Axial symmetry
—> classical conserved axial current

Specific correlation
between spin and momentum!!



A (large) mass term spoils all that:

$$m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right)$$

$$\partial_\mu J_5^\mu = 2im\bar{\Psi}\gamma^5\Psi$$

In QCD:

$$M = m - 2G\langle\bar{\psi}\psi\rangle$$

Constituent ***SM*** ***Chiral condensate***

(Nearly) chiral quarks only upon chiral restoration

Chiral Anomaly

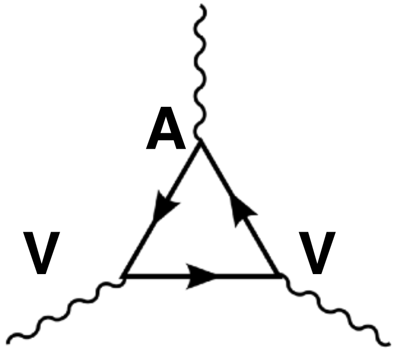
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

Classical axial symmetry broken at QM level:

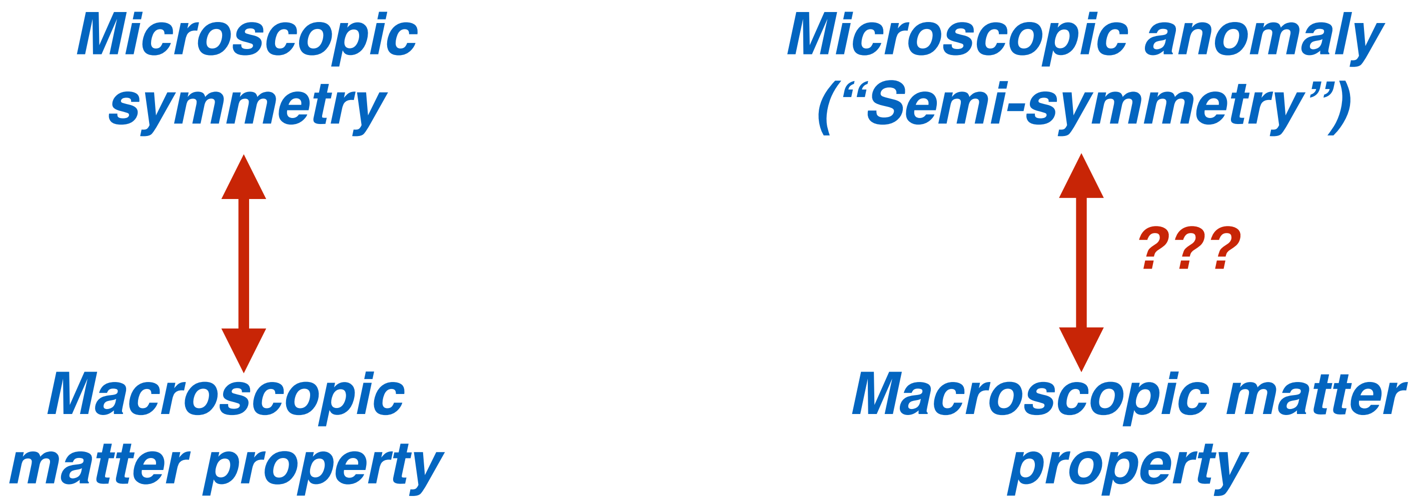
$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

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

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



[e.g. pi0—> 2 gamma]



Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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

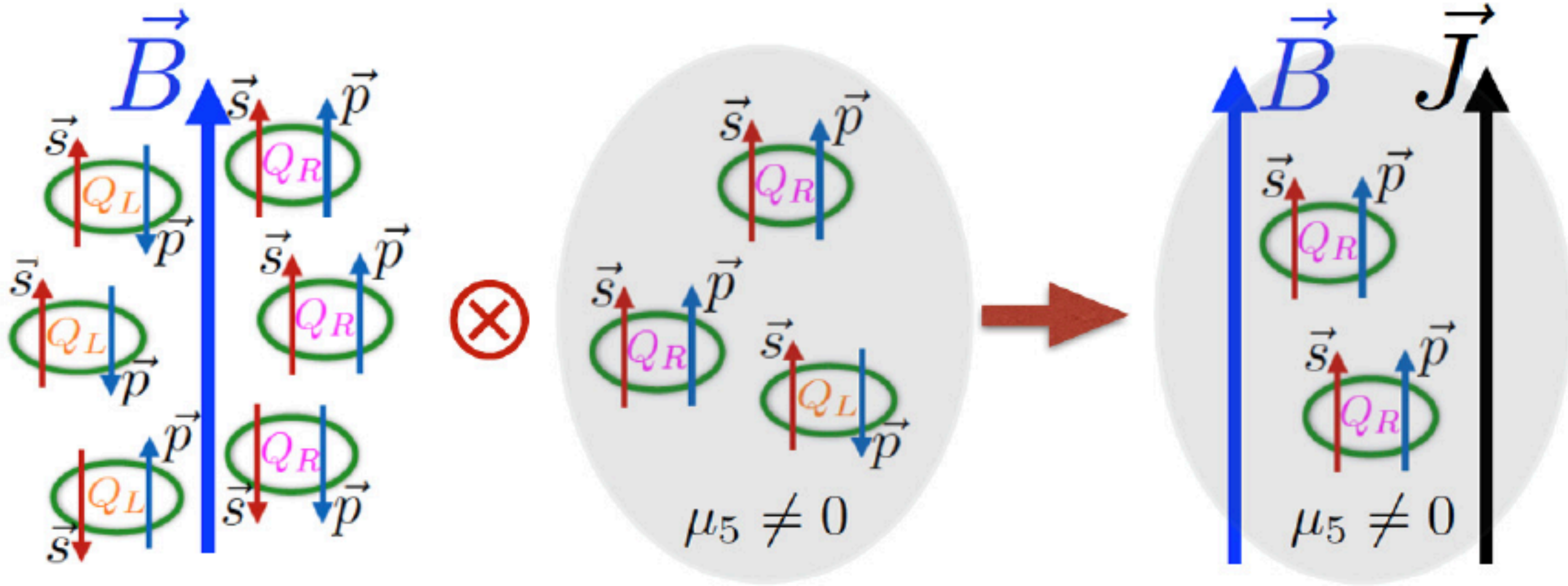
Electric Current

Magnetic Field

Q.M. Transport

It requires macroscopic chirality, i.e. imbalance between RH and LH fermions.

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

Intuitive understanding of CME:

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

$\otimes$

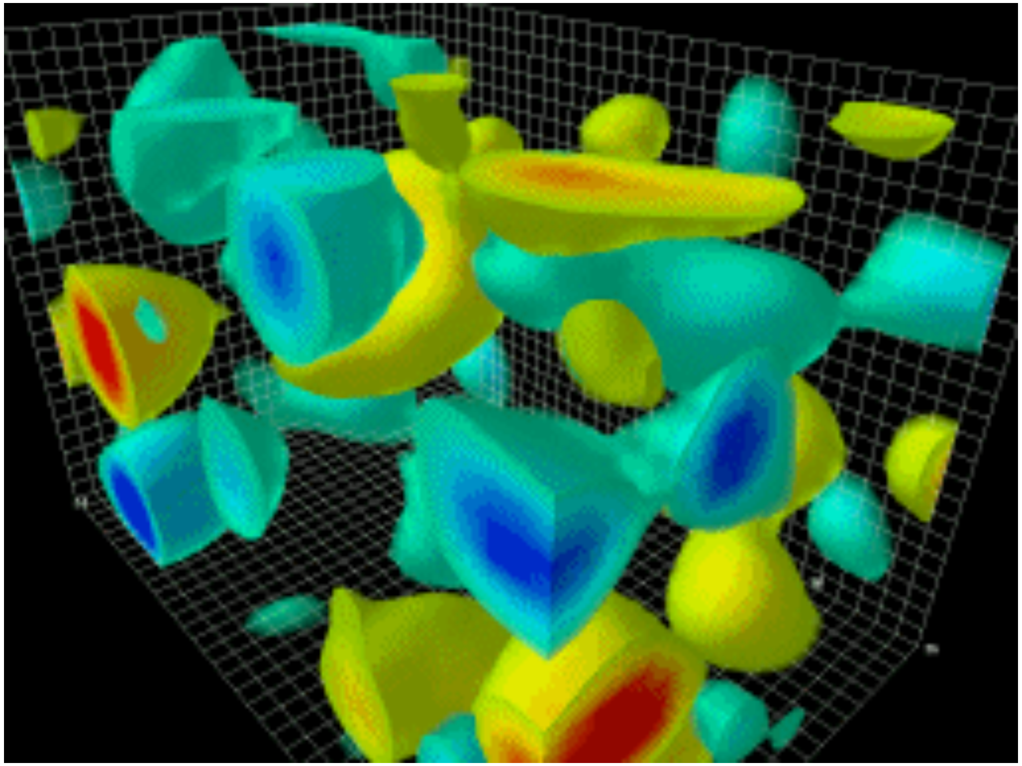
Chirality Polarization —>
correlation between directions of
SPIN & MOMENTUM

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

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

Topologically Nontrivial Gluon Fields

Instantons/sphelarons:
twisting color orientation of gluon fields around spacetime boundary



$$Q_w = \frac{1}{32\pi^2}\int d^4x\,(gG_a^{\mu\nu})\cdot(g\tilde{G}^a_{\mu\nu}) \quad \sim \vec{E}^a \cdot \vec{B}^a$$

P & CP ODD

From Gluon Topology to Quark Chirality

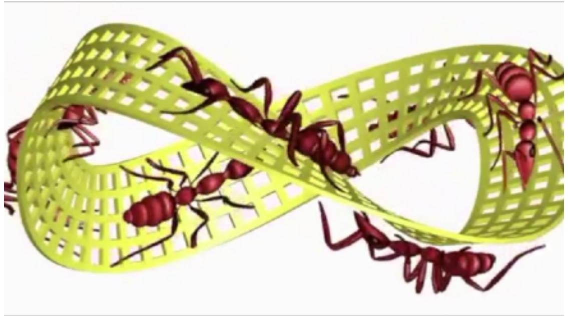
Atiyah-Singer Index Theorem

Abel Prize 2004

Theorem (M.F. Atiyah and I.M. Singer): *Let $P(f) = 0$ be a system of differential equations. Then*

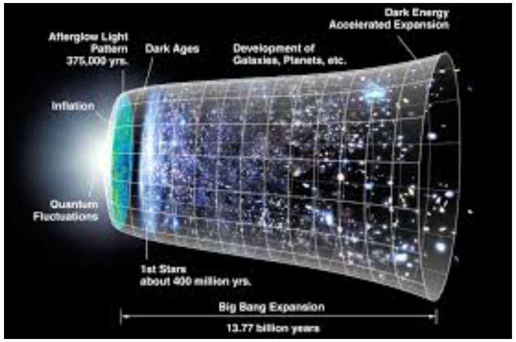
$$\textit{analytical index}(\mathrm{P}) = \textit{topological index}(\mathrm{P}) .$$

$$N_R - N_L = N_5 = 2Q_w$$

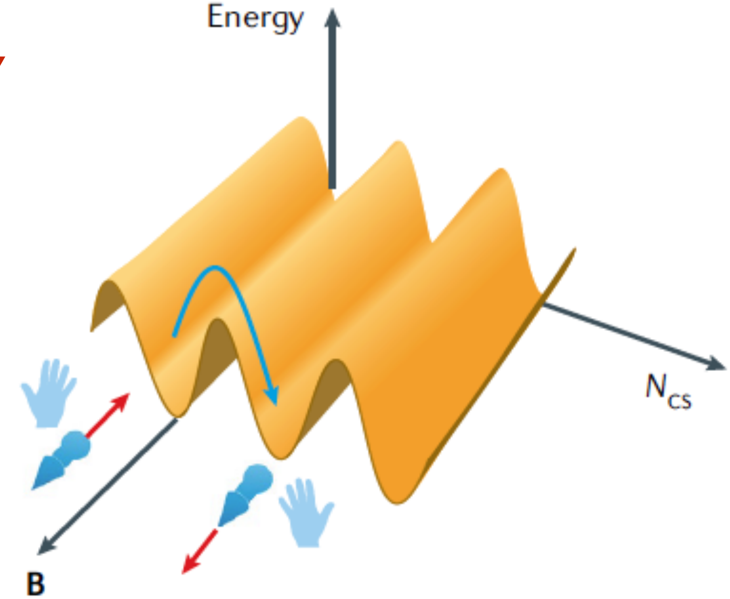


Net chirality <—> topo fluctuations

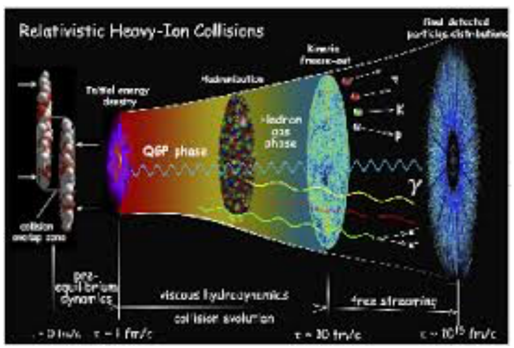
CME: A Cosmic Connection



Cosmic topo.—>
Baryon Asymmetry



Rapid expansion +
Topological transitions in
non-Abelian gauge plasma



Heavy ion topo.—>
Chiral Asymmetry

CME allows probing this mechanism via laboratory experiments and helps understand “why we are here”.

More Anomalous Transport Phenomena

- *Chiral separation effect (CSE)*
- *Chiral electric separation effect (CESE)*
- *Chiral vortical effect (CVE)*
- *Chiral magnetic wave (CMW)*
- *Chiral plasma instabilities*
- *……*

Strong Interdisciplinary Interests

- *Condensed matter: CME in semimetals*
- *Astrophysics: leptons in supernova / compact star*
- *Cosmology: analogy beween Baryo-genesis and Chiro-genesis; primordial B fields*
- *Plasma physics: MHD with CME & magnetic helicity*
- *Quantum information: devices based on CME*
- *QFT & many-body theory: new "playground" (chiral transport theory; chiral hydrodynamics; …)*

Exciting Progress: See Recent Reviews

Kharzeev & JL, Nature Reviews Physics 3(2021)1, 55-63

Kharzeev, JL, Voloshin, Wang,
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050].

Li, Wang, arXiv: 2002.10397, ARNPS2020

Miransky & Shovkovy, Phys. Rept. 576(2015)1.

Gao, Ma, Pu, Wang, Nucl. Sci. Tech., 31 (2020) no.9, 90.

Wang, Zhao, Nucl. Sci. Tech., 29 (2018) no.12, 179.

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

Huang, Rep.Prog.Phys 79(2016)076302.

Fukushima, arXiv:1812.08886, PPNP2019.

Zhao, Wang, arXiv:1906.11413, PPNP2019.

Search for CME in Heavy Ion Collisions

Laying the Theoretical Foundation

BNL–NT–04/21; June 9, 2004

Parity violation in hot QCD: why it can happen, and how to look for it

Dmitri Kharzeev[1]
[1] *Physics Department, Brookhaven National Laboratory Upton, NY 11973-5000*

(Dated: October 22, 2018)

The arguments for the possibility of violation of $\mathcal{P}$ and $\mathcal{CP}$ symmetries of strong interactions at finite temperature are presented. A new way of observing these effects in heavy ion collisions is proposed – it is shown that parity violation should manifest itself in the asymmetry between positive and negative pions with respect to the reaction plane. Basing on topological considerations, we derive a *lower* bound on the magnitude of the expected asymmetry, which may appear within the reach of the current and/or future heavy ion experiments.

[arXiv:hep-ph/0406125]

The effects of topological charge change in heavy ion collisions: "Event by event $\mathcal{P}$ and $\mathcal{CP}$ violation"

Dmitri E. Kharzeev, [a] Larry D. McLerran [a,b] and Harmen J. Warringa [a]

[a] *Department of Physics, Brookhaven National Laboratory, Upton NY 11973, USA*

[b] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*

Abstract

Quantum chromodynamics (QCD) contains field configurations which can be characterized by a topological invariant, the winding number Q_w. Configurations with nonzero Q_w break the charge-parity ($\mathcal{CP}$) symmetry of QCD. We consider a novel mechanism by which these configurations can separate charge in the presence of a background magnetic field – the "Chiral Magnetic Effect". We argue that sufficiently large magnetic fields are created in heavy ion collisions so that the Chiral Magnetic Effect causes preferential emission of charged particles along the direction of angular momentum. Since separation of charge is $\mathcal{CP}$-odd, any observation of the Chiral Magnetic Effect could provide a clear demonstration of the topological nature of the QCD vacuum. We give an estimate of the effect and conclude that it might be observed experimentally.

[arXiv:0711.0950]

[arXiv:0808.3382]

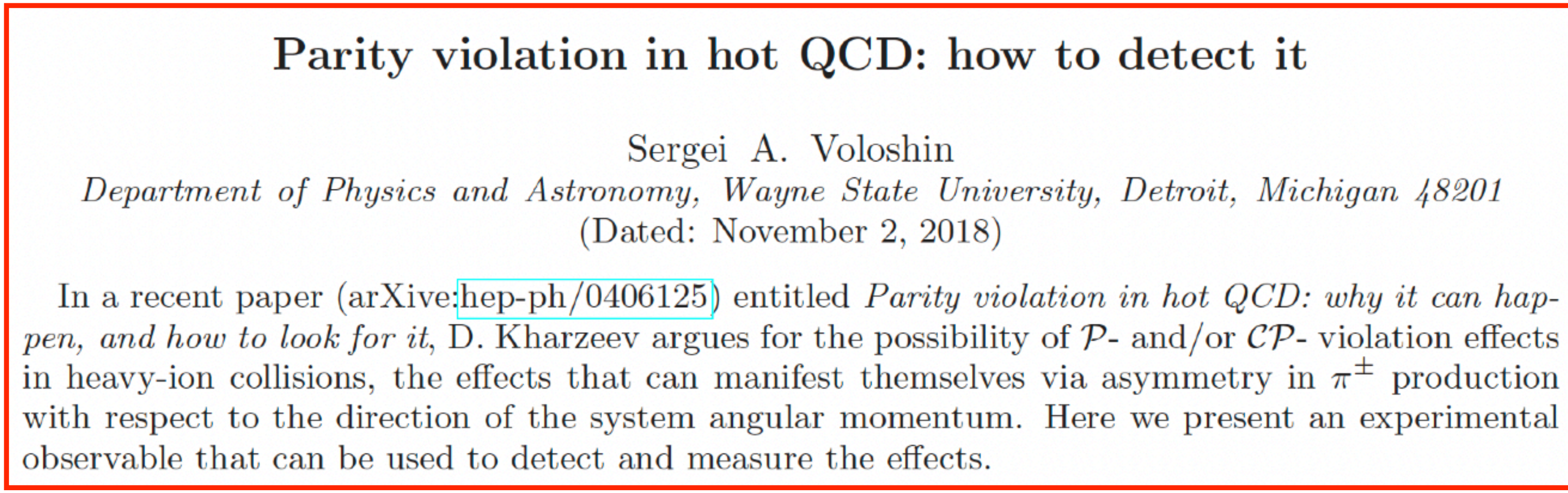
The Chiral Magnetic Effect

Kenji Fukushima,[1,*] Dmitri E. Kharzeev,[2,†] and Harmen J. Warringa[2,‡]
[1] *Yukawa Institute, Kyoto University, Kyoto, Japan*
[2] *Department of Physics, Brookhaven National Laboratory, Upton NY 11973, USA*

(Dated: August 25, 2008)

Topological charge changing transitions can induce chirality in the quark-gluon plasma by the axial anomaly. We study the equilibrium response of the quark-gluon plasma in such a situation to an external magnetic field. To mimic the effect of the topological charge changing transitions we will introduce a chiral chemical potential. We will show that an electromagnetic current is generated along the magnetic field. This is the Chiral Magnetic Effect. We compute the magnitude of this current as a function of magnetic field, chirality, temperature, and baryon chemical potential.

Developing Experimental Observable



Parity violation in hot QCD: how to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201
(Dated: November 2, 2018)

In a recent paper (arXive:hep-ph/0406125) entitled *Parity violation in hot QCD: why it can happen, and how to look for it*, D. Kharzeev argues for the possibility of $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in $\pi^{\pm}$ production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

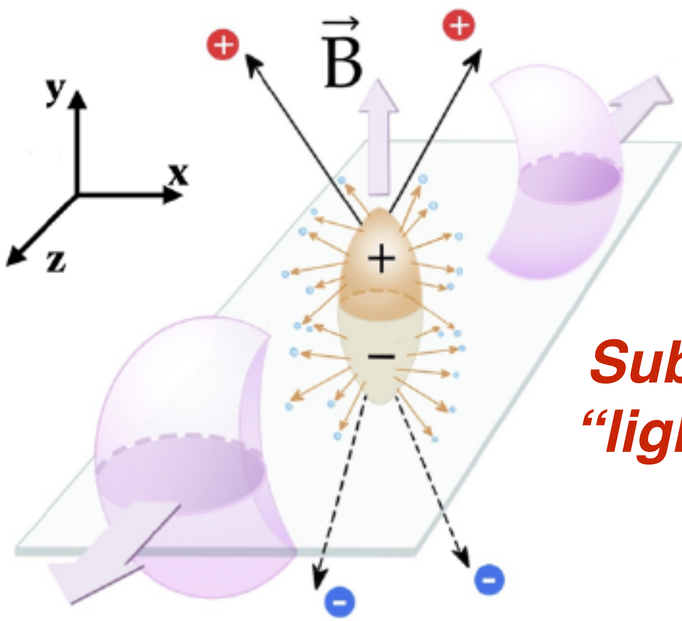
[arXiv:hep-ph/0406311]

Gamma-correlator

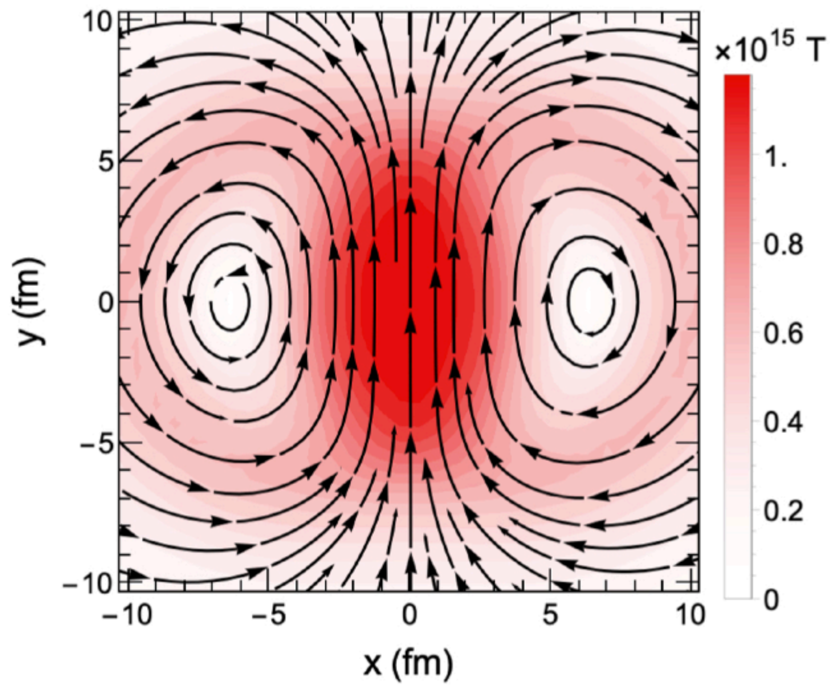
$$\gamma_{\alpha,\beta} = \left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle = \left\langle \cos(\phi_\alpha)\cos(\phi_\beta) \right\rangle - \left\langle \sin(\phi_\alpha)\sin(\phi_\beta) \right\rangle$$

Many more new observables were developed subsequently, e.g. differential gamma correlator, RP/EP ratio, signed balance function, R-correlator, …

Heavy Ion Collision: the Most Magnetized Fluid



Subatomic "lightning"!



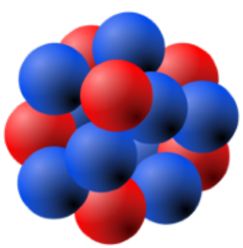
The strongest B field ~ 10^15 Tesla

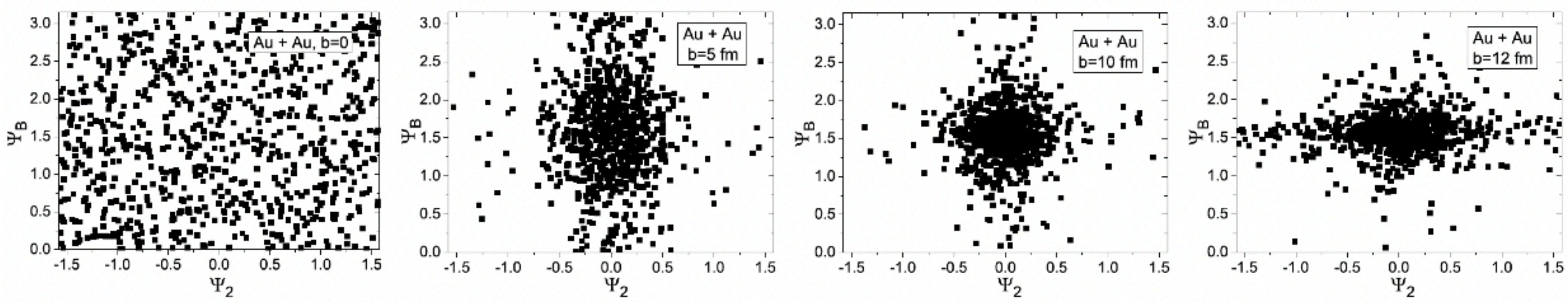
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

Azimuthally Fluctuating Magnetic Fields

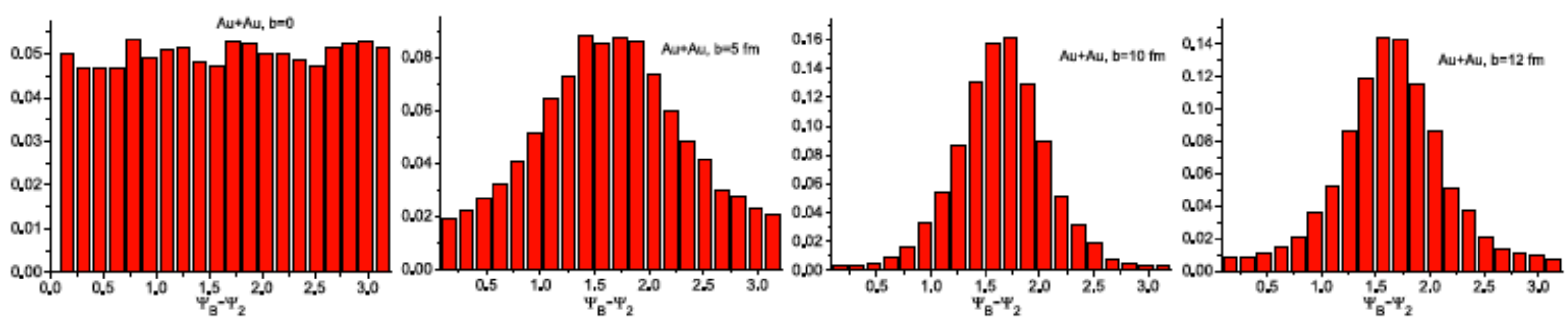
Bloczynski, et al, arXiv:1209.6594[PLB]

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





Eccentricity fluctuations: dominated by participants;
B field azimuthal fluctuations: dominated by spectators.



Azimuthally Fluctuating Magnetic Fields

Bloczynski, et al, arXiv:1209.6594[PLB]

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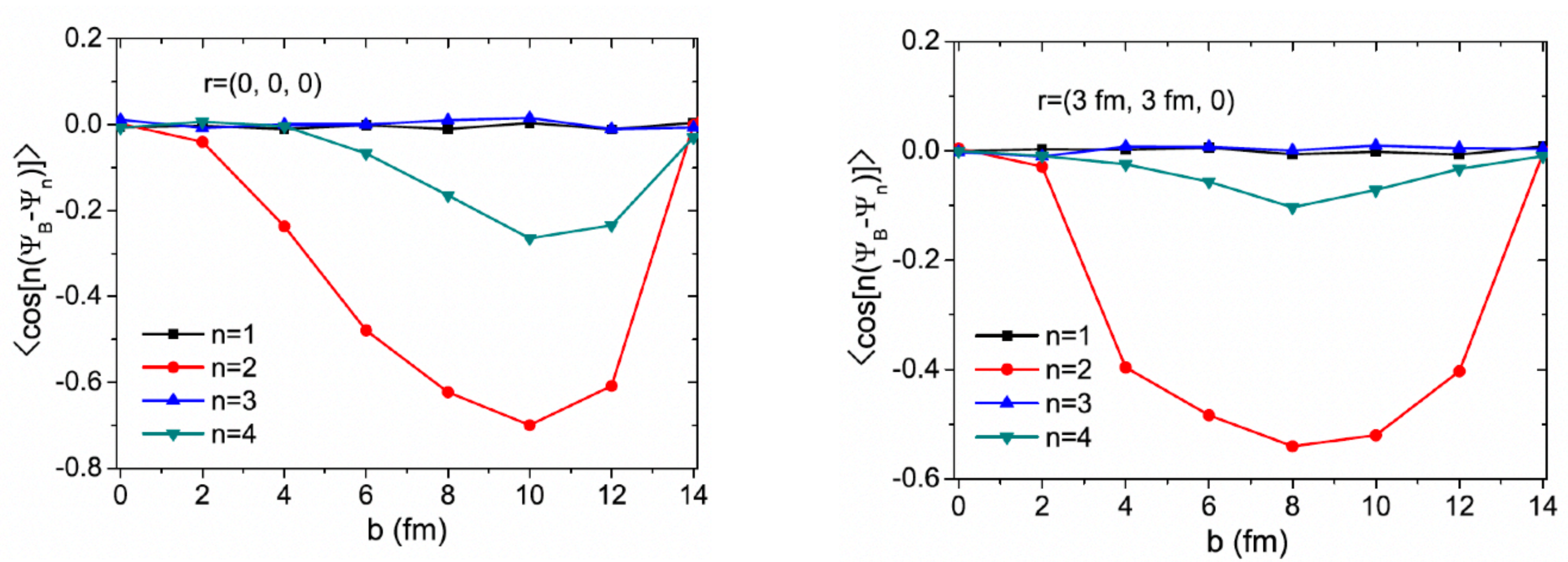
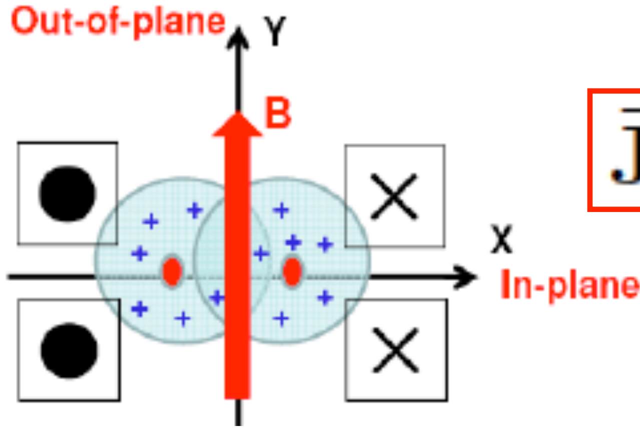
correlations $\langle\cos[n(\Psi_{\mathbf{B}} - \Psi_n)]\rangle$ as functions of impact parameter

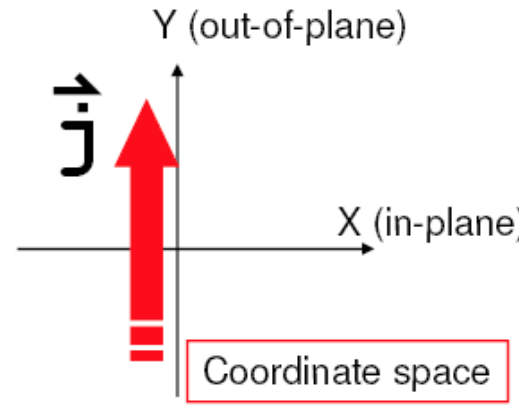


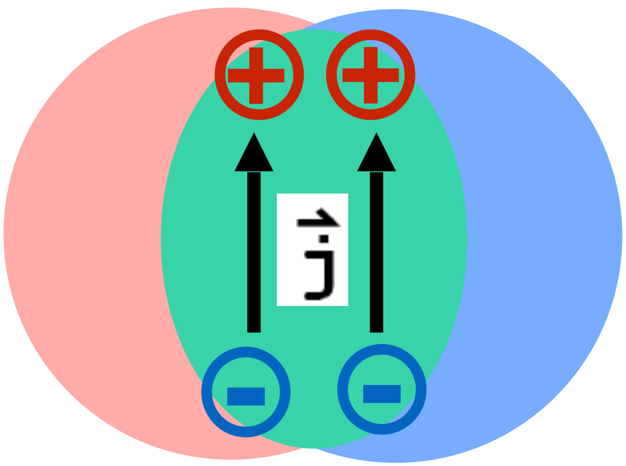
B field has different angular (de-)correlation with RP and with EP, and is NOT correlated with triangular-EP
—— a valuable feature for validating B-field induced signal !!

From CME to Charge Separation

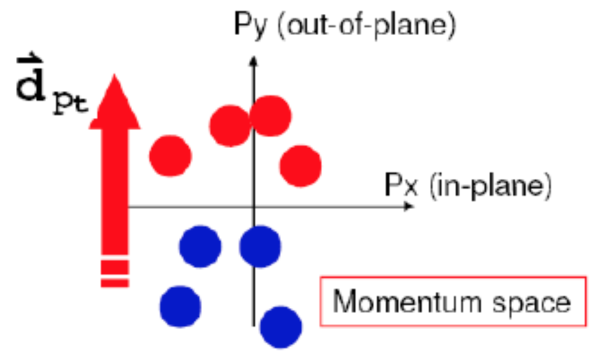


$$\boxed{\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}}$$





strong radial blast:
position —> momentum



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

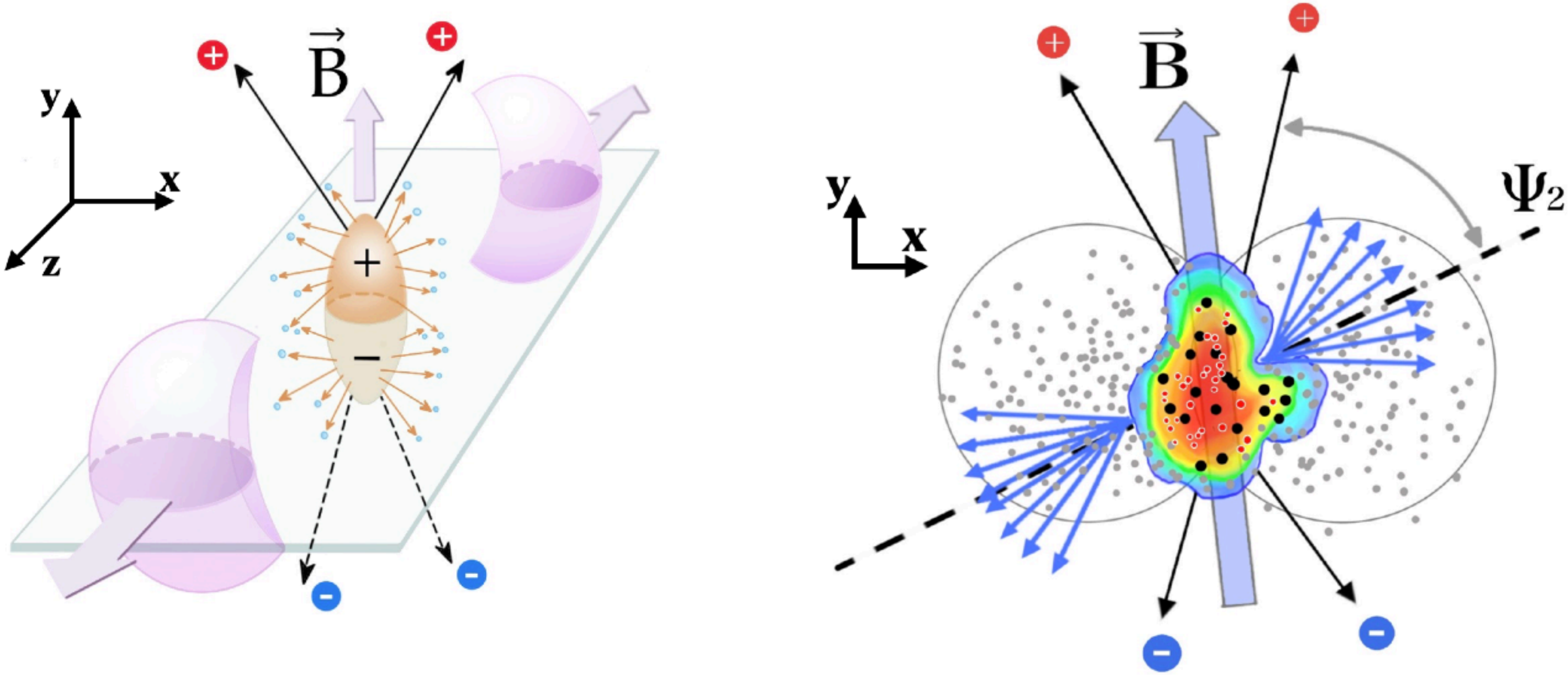
$$\boxed{\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})}$$

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

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

Looking for CME Signals in Nuclear Collisions

CME transport induces a charge dipole distribution along magnetic field direction in the QGP fluid.



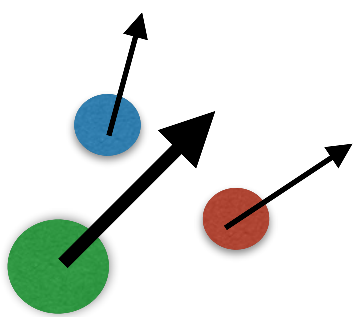
A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

Have We Seen the CME?

- *First measurement ~ 2009 by STAR;*
- *Efforts in past decades by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, PbPb*

It proves to be a very difficult search:
Very small signal contaminated by very strong background correlations!

Major charge-dependent backgrounds have been identified:
Resonance decay; local charge conservation (LCC)



Roughly scaling ~ v2 / N

Redefining the question: extracting / constraining the fraction of CME signal within the measured correlations

$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

Fighting with Backgrounds

We are not alone!
Think about many other famous searches, e.g. for Higgs, gravitational wave, temperature fluctuations of CMB, EDM, WIMP, 2-beta decay, …

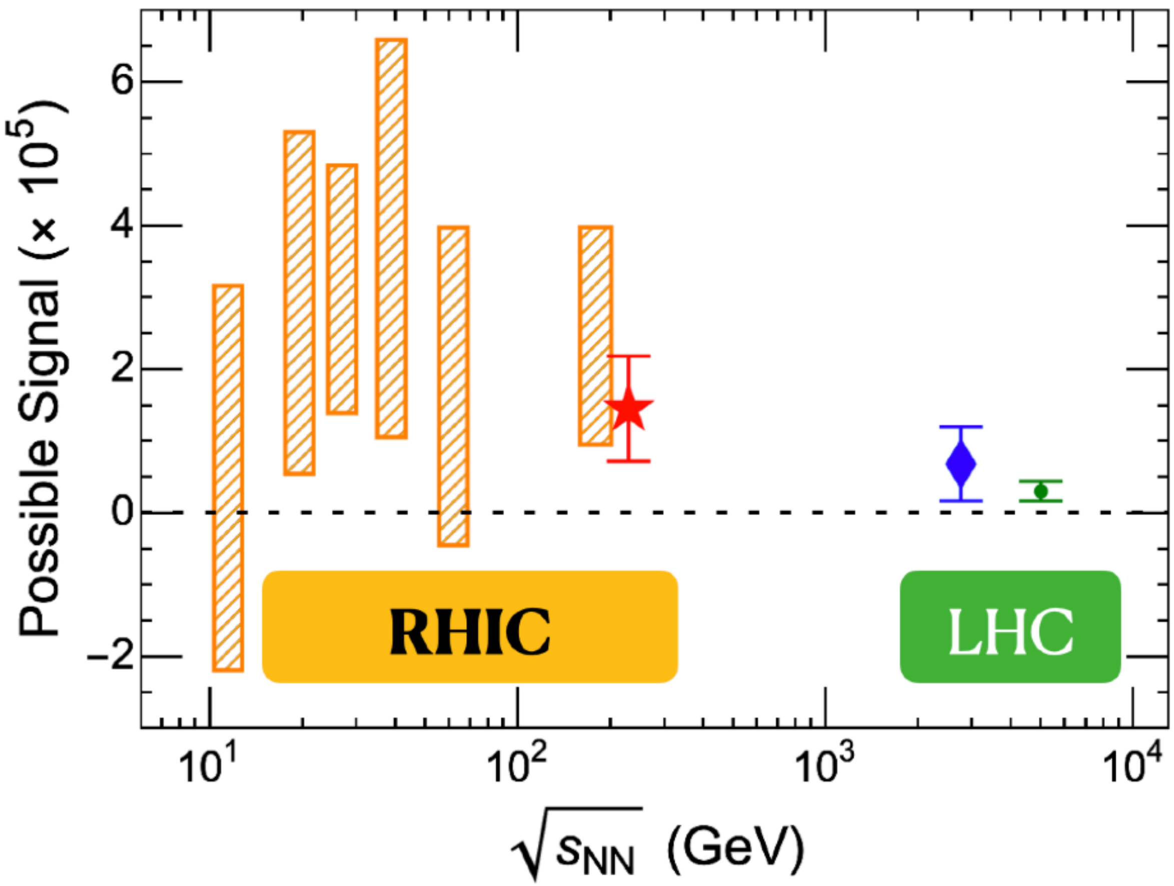
Two-component decomposition/competition:
CME signal driven by B field; *[Bzdak, Koch, JL: arXiv:1207.7327]*
Backgrounds driven by bulk elliptic flow.

Various new approaches, especially contrast methods:
— vary bulk flow for fixed B, e.g. event shape analysis
— vary B for fixed bulk flow, e.g. isobar collisions
— vary B and bulk flow in opposite way, e.g. EP versus SP
— using small colliding systems to constrain backgrounds

Need theoretical tool for quantitatively and realistically understanding both signals and backgrounds!

Status before the Isobar Results

A positive hint, yet inconclusive.



[Kharzeev, JL, arXiv:2102.06623; Nature Rev Phys 3, 55-63 (2021)]

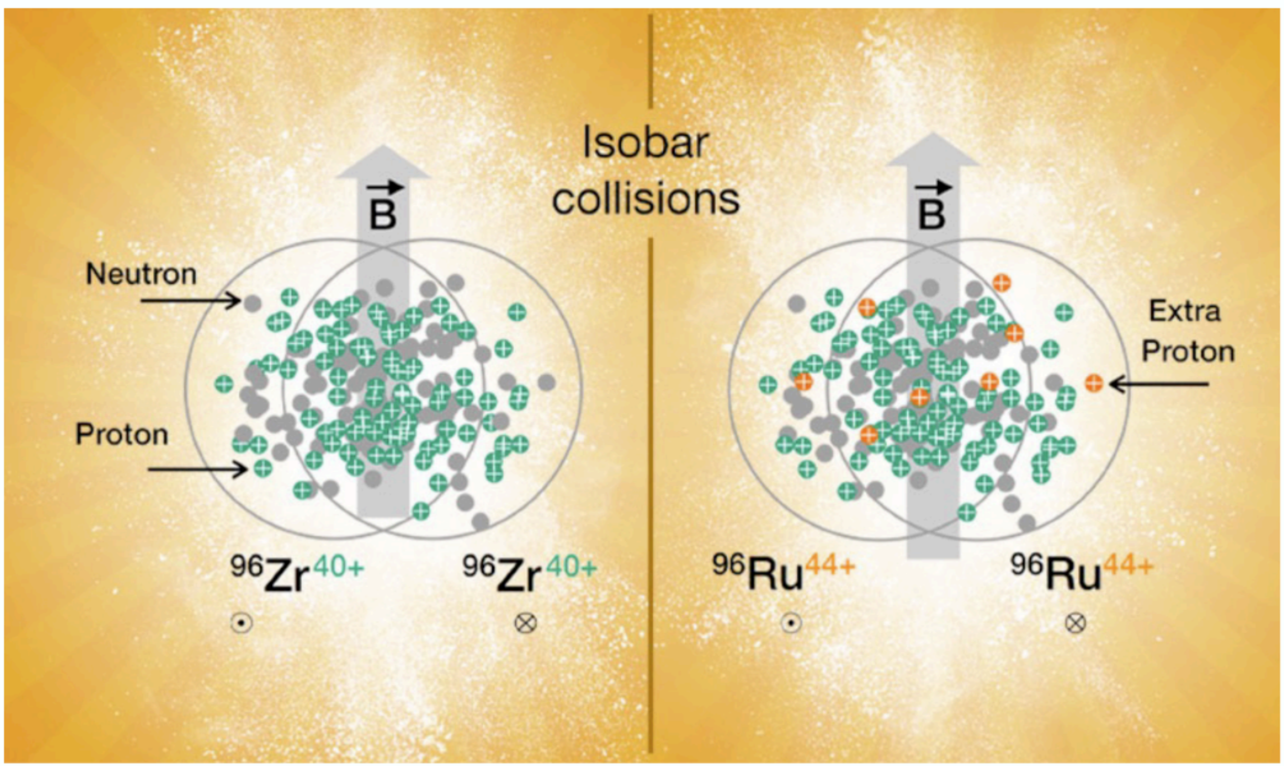
Isobar Collisions

Isobar Collision Experiment

[Voloshin, PRL105,172301(2011)] *[arXiv:1608.00982]*

Chiral Magnetic Effect Task Force Report

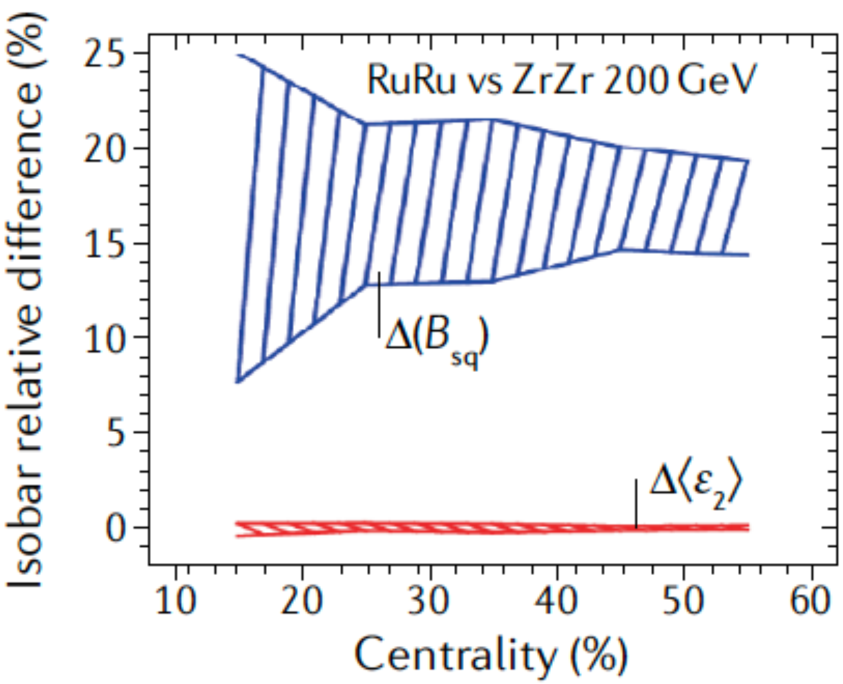
Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

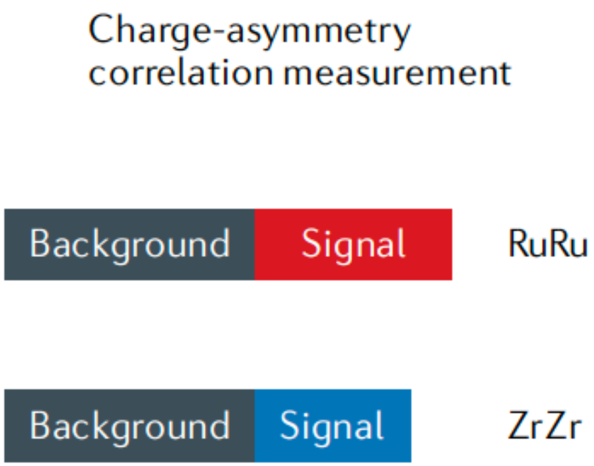


[image from STAR]

Isobar Collision Experiment

Exciting opportunity of discovery: ~2 billion events collected for each system





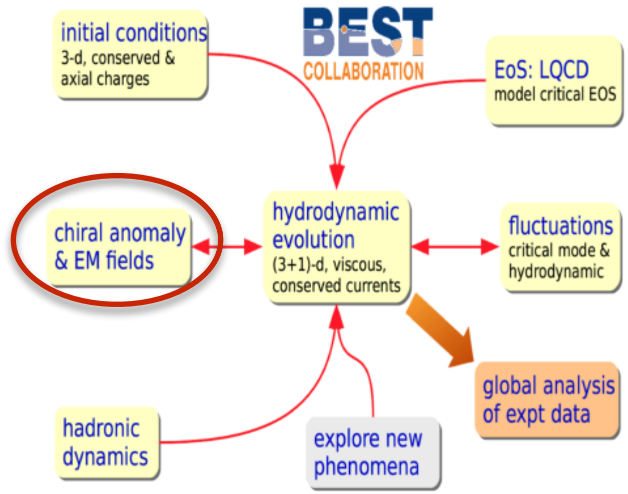
Expectation: Identical background; Different signal

$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

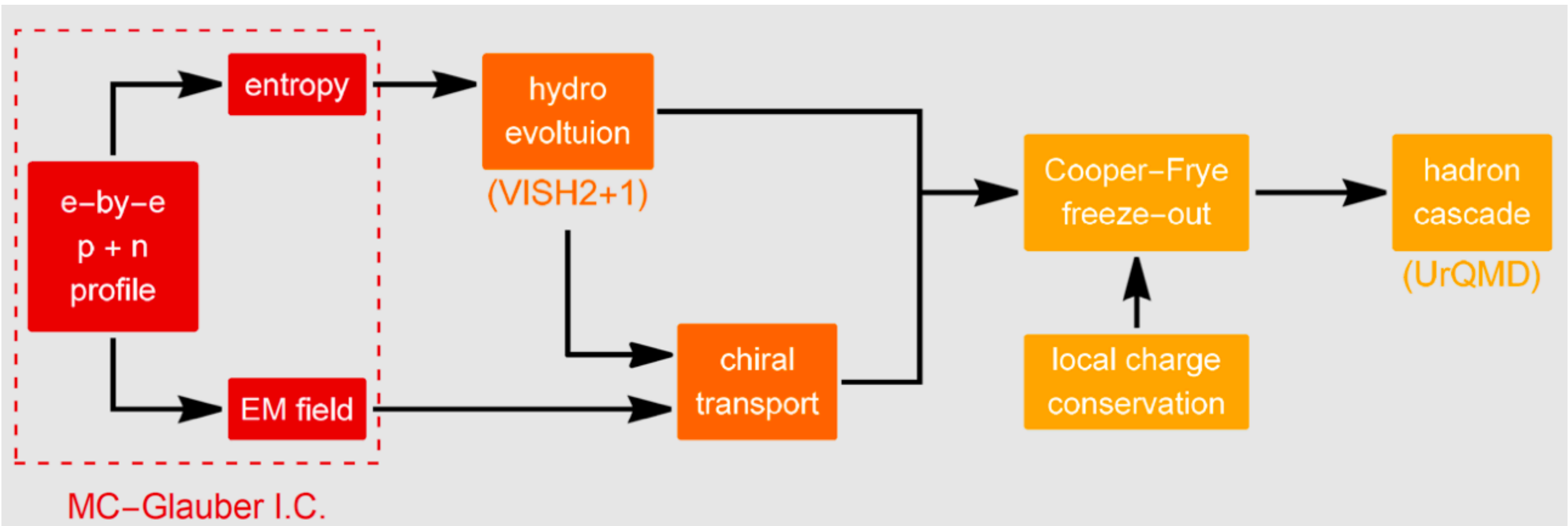
Images from Nature Reviews Physics 3, 55-63 (2021) [arXiv:2102.06623]

CME Working Group @ BEST Collaboration

Theoretical tool for quantitative predictions of CME and related backgrounds is crucial!



EBE-AVFD:
event-by-event anomalous-viscous fluid dynamics



[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

[BEST Collaboration publication: Nucl. Phys. A 1017(2022)122343]

A Deep Dive into Observables

EBE-AVFD has now become a widely used tool for developing CME observables, calibrating sensitivity to signals and backgrounds, as well as obtaining quantitative understanding of data.

Chinese Physics C Vol. 46, No. 1 (2022) 014101

Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment*

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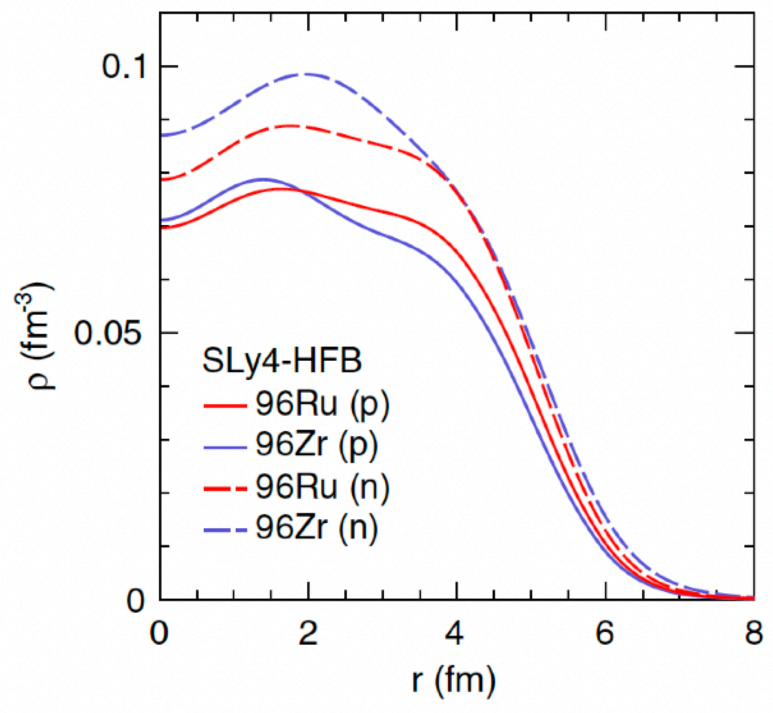
[STAR CME & Shuzhe Shi & JL, CPC46(2022)4,014101, arXiv:2105.06044]

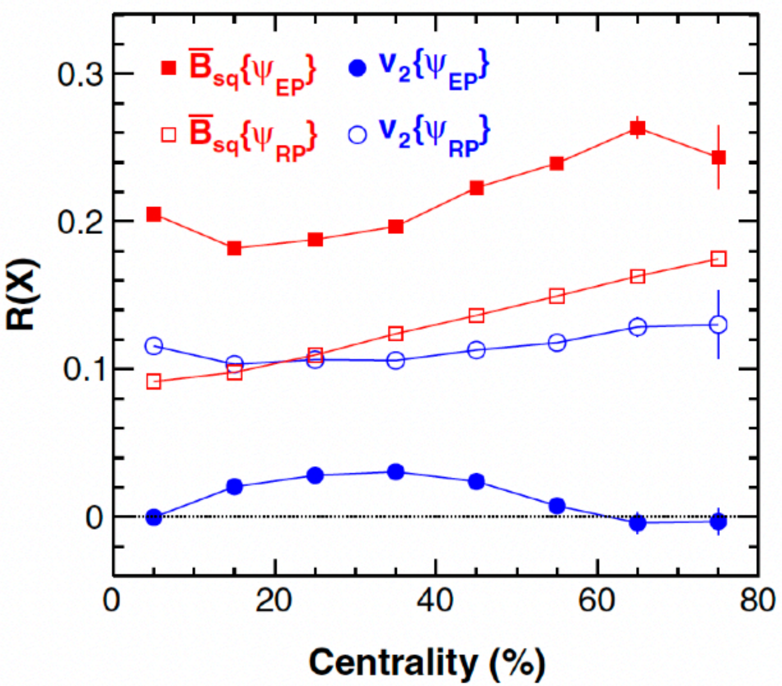
The preparation for isobar analysis has helped significantly advance the understanding of measurement observables and the ability to separate backgrounds and signal.

Uncertainty about Nuclear Structure Inputs

There were worries owing to uncertainty in nuclear structure inputs which influence initial conditions.

H.J. Xu, et al, PRL2018;
S. Shi, H. Zhang, D. Hou, JL, arXiv:1807.05604 [QM2018 proceedings];
H. Elfner & collaborators, arXiv: 1908.10231





Could this mess up the isobar contrast?

Isobar Comparison Strategy

Key for success: identical bulk between RuRu & ZrZr .
There may be worries owing to uncertainty in nuclear geometry.

S. Shi, H. Zhang, D. Hou, JL, arXiv:1807.05604 [QM2018 proceedings]

Strategies to overcome the issue:
— apply joint multiplicity & ellipticity cut for event samples
— stay at the relatively peripheral region

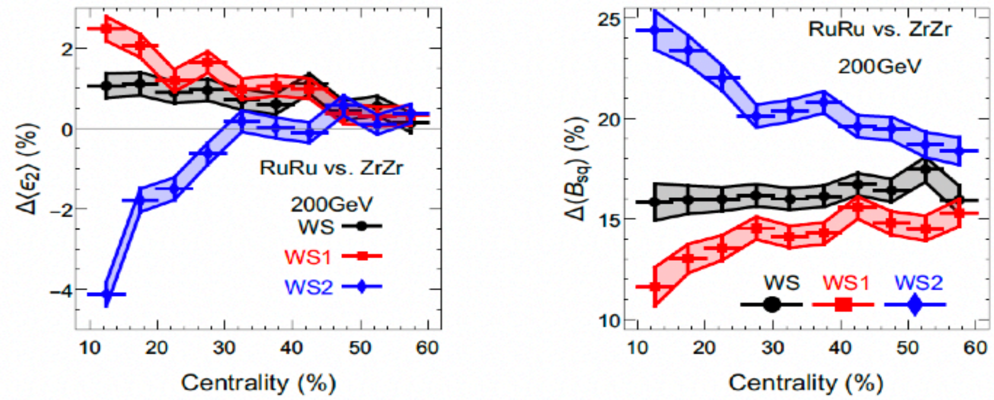


Fig. 1. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta\langle B_{sq}\rangle$ (right) between RuRu and ZrZr, with conventional centrality event selection.

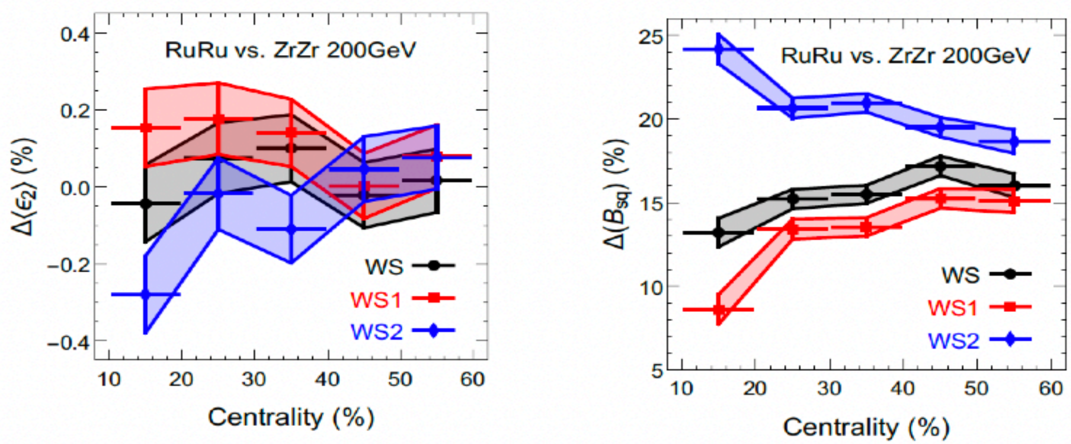


Fig. 2. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta\langle B_{sq}\rangle$ (right) between RuRu and ZrZr, with the proposed joint (multiplicity + elliptic-flow) event selection.

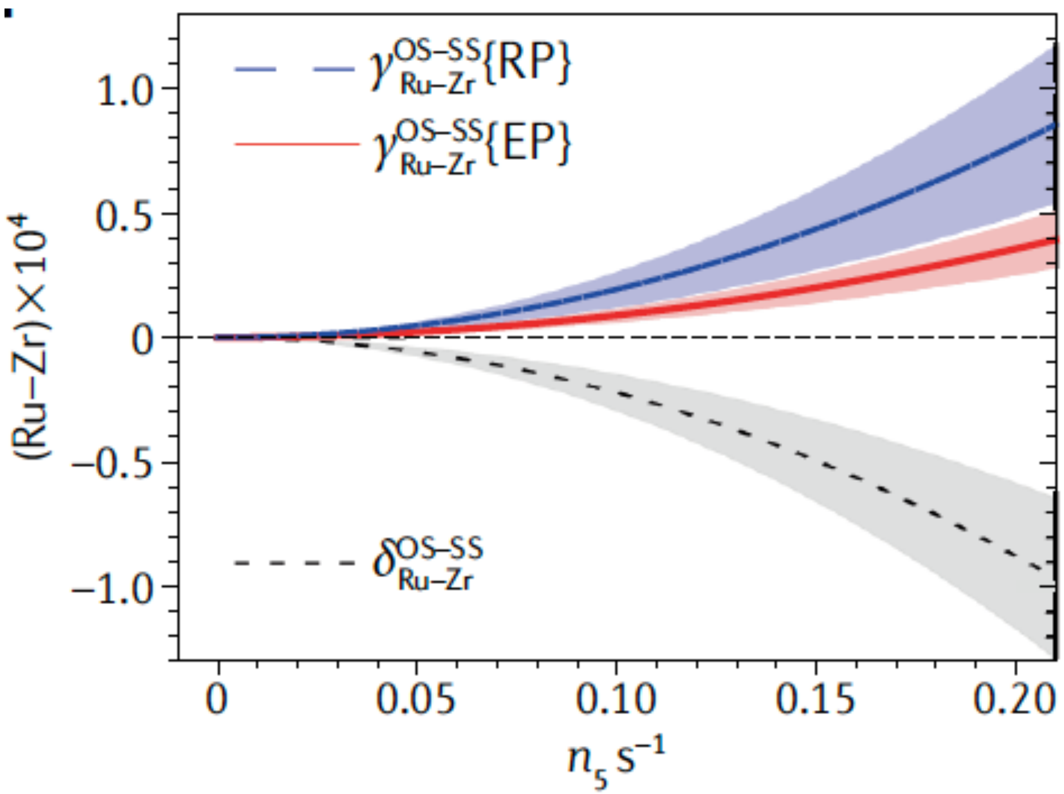
Theoretical Predictions from EBE-AVFD

Quantitative predictions of CME signal with proper multiplicity-v2 joint selections that suppress background difference.

PHYSICAL REVIEW LETTERS **125**, 242301 (2020)

Signatures of Chiral Magnetic Effect in the Collisions of Isobars

Shuzhe Shi,[1] Hui Zhang,[2,3,4] Defu Hou,[2,*] and Jinfeng Liao[5,†]



$$\zeta^{RP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{RP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{RP}} \simeq -(0.90 \pm 0.45)$$

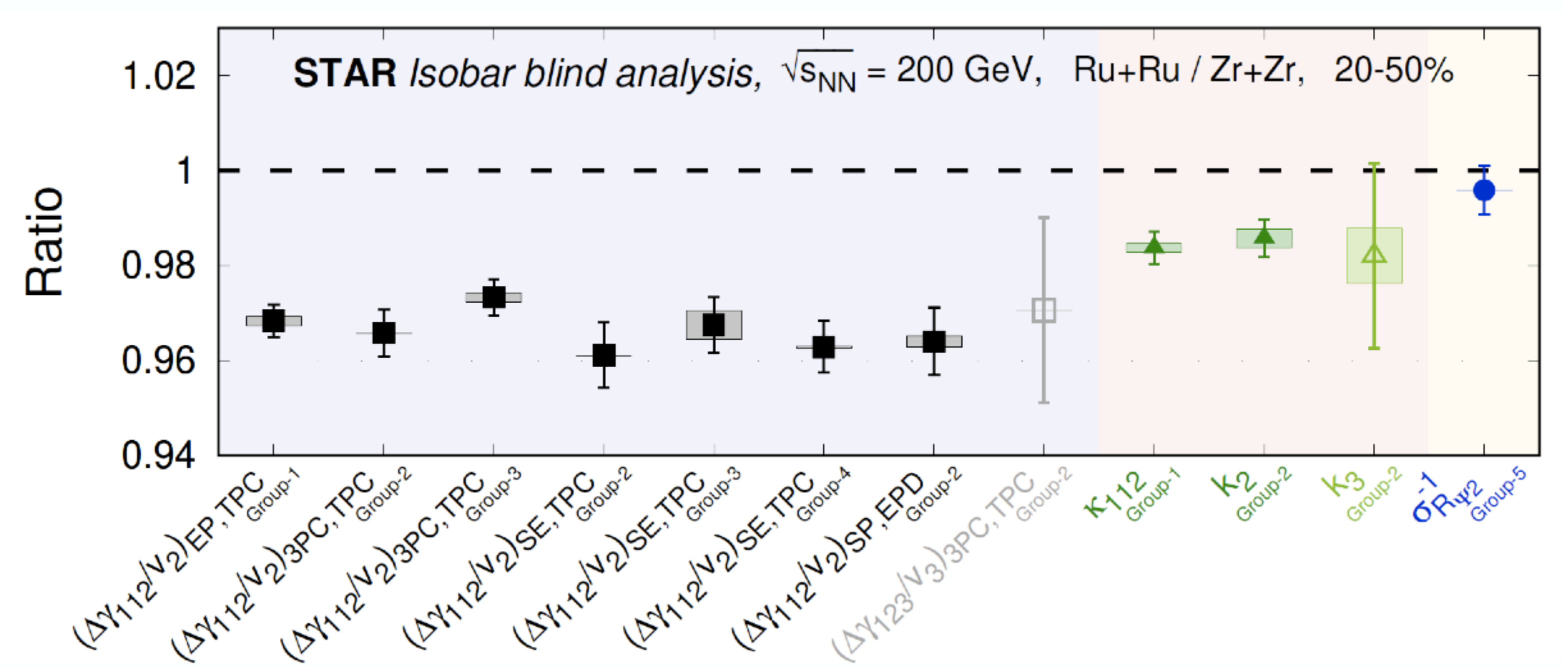
$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$

The STAR Blind Analysis Results

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

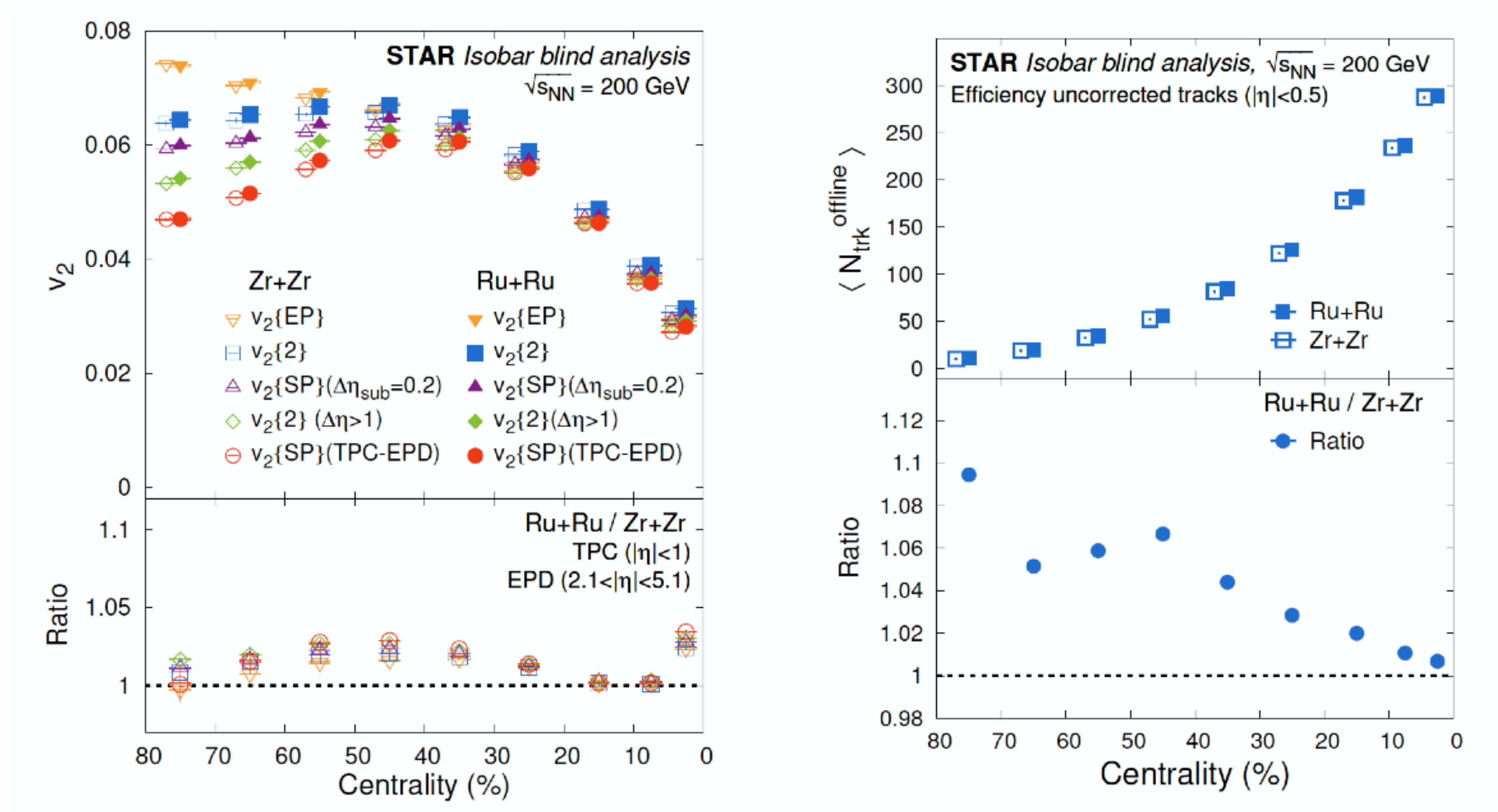
Predefined criteria: Gamma(Ru) / Gamma(Zr) > 1

[STAR paper: 2109.00131 Phys.Rev.C 105 (2022) 1, 014901]



Predefined baseline (background only): Gamma(Ru) / Gamma(Zr) =1

The Trouble: A Failed Assumption



A few percent level of difference in the bulk properties between the isobar pairs: non-identical background correlations!

Key for success: identical bulk between RuRu & ZrZr .
The nuclear structure does have an important impact here!!

The Isobar Collision Experiment

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

[STAR paper: 2109.00131. Phys.Rev.C 105 (2022) 1, 014901]

VII. CONCLUSION

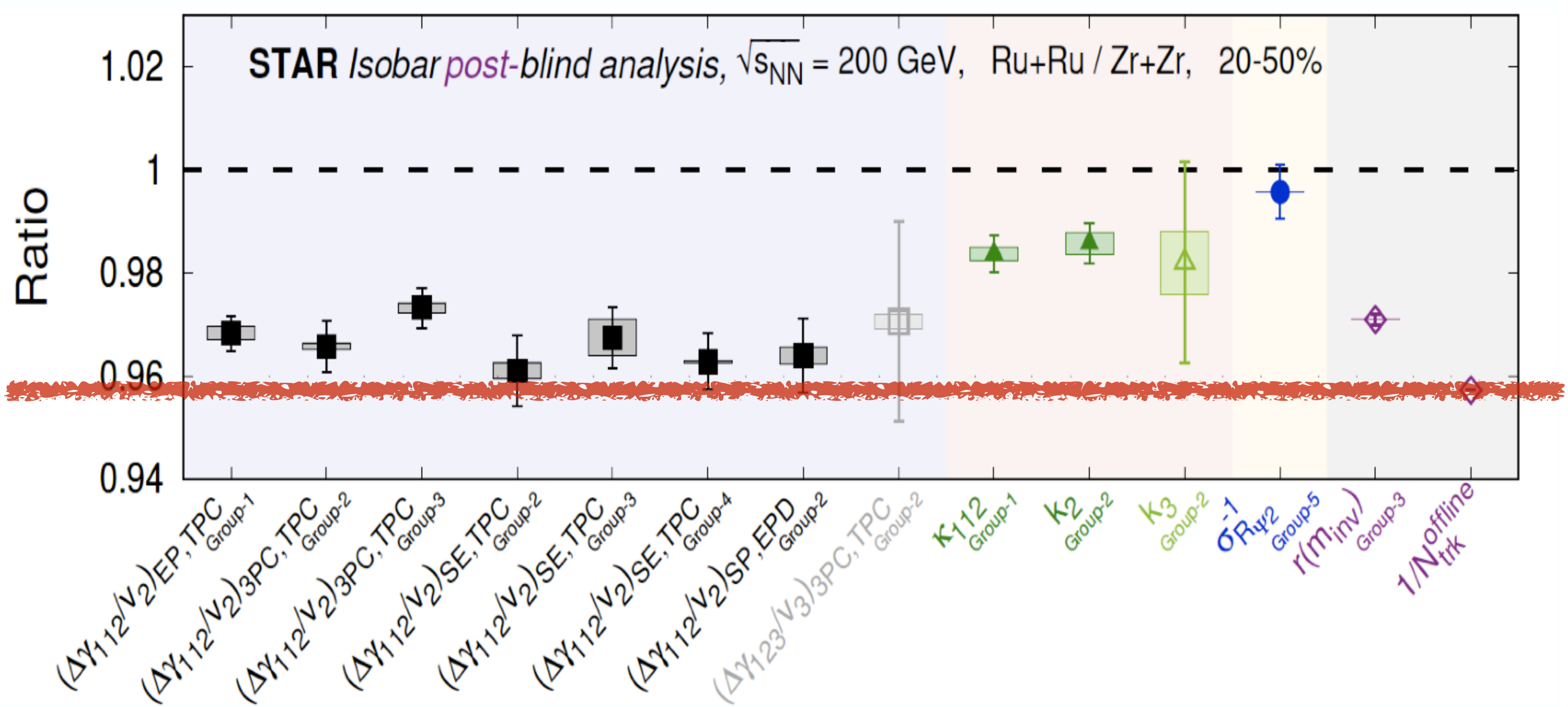
We report an experimental test of the Chiral Magnetic Effect by a blind analysis of a large statistics data set of isobar $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr collisions at nucleon-nucleon center-of-mass energy of 200 GeV, taken in 2018 by the STAR Collaboration at RHIC. The backgrounds are reduced using the difference in observables between the two isobar collision systems. The criteria for a positive CME observation are predefined, prior to the blind analysis, as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions. Consistent results are obtained by the five independent groups in this blind analysis. Significant differences in the multiplicity and flow harmonics are observed between the two systems in a given centrality, indicating that the magnitude of the CME background is different between the two species. A precision down to 0.4% is achieved in the relative magnitudes of pertinent observables between the two isobar systems. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

A more transparent "translation":

The predefined criteria is not applicable as its assumption is invalided by the same dataset.

No real conclusion could be reached yet.

Where is the Baseline ?!

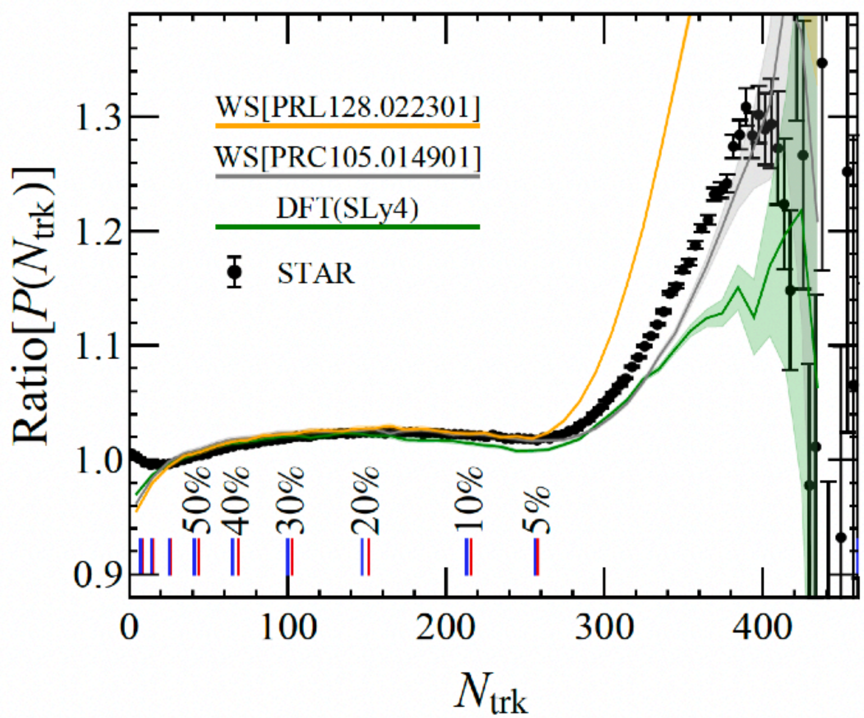


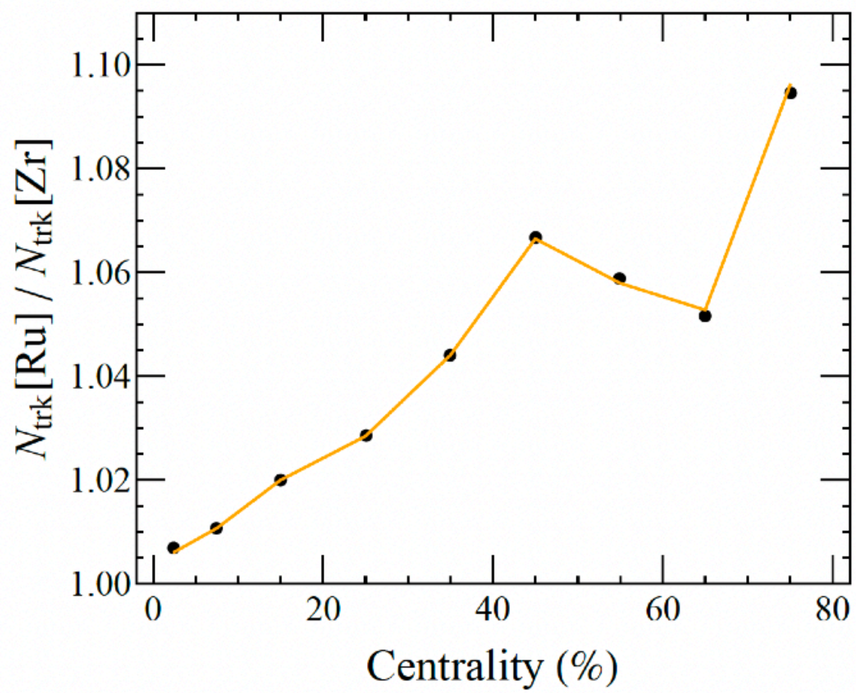
There appears room for potential CME signal above the 1/N line!
Need accurate calibration of the true baseline!

$$\gamma_{bkg} \propto \frac{1}{N_{ch}} \qquad N_{ch}^{Ru} > N_{ch}^{Zr} \qquad \frac{\gamma_{bkg}^{Ru}}{\gamma_{bkg}^{Zr}} < 1$$

A Possible Signal in Isobar Systems

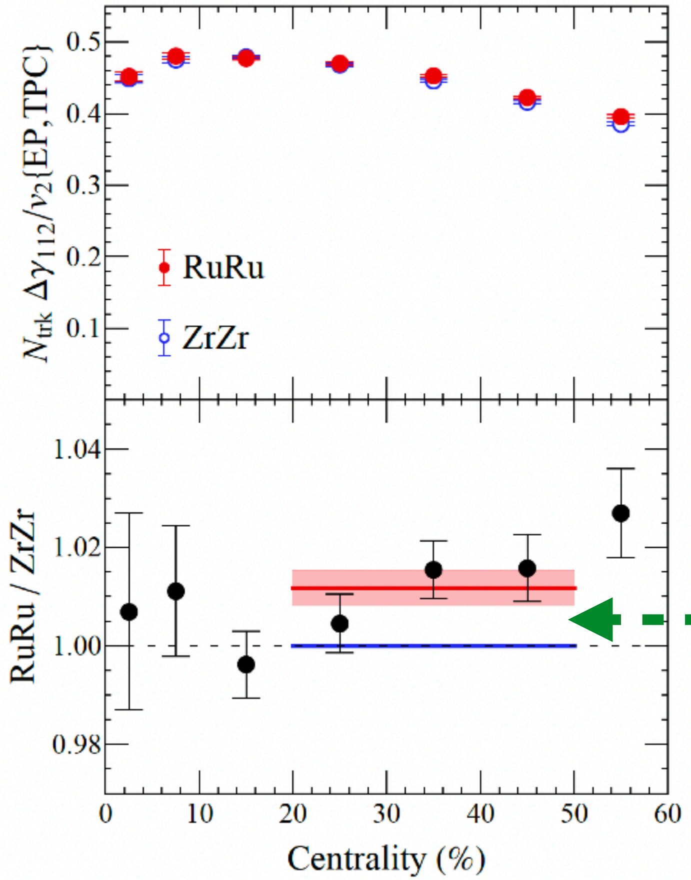
Simulations quantitatively reproduce multiplicity difference by using more informed nuclear structure inputs (from C. Zhang & J. Jia)



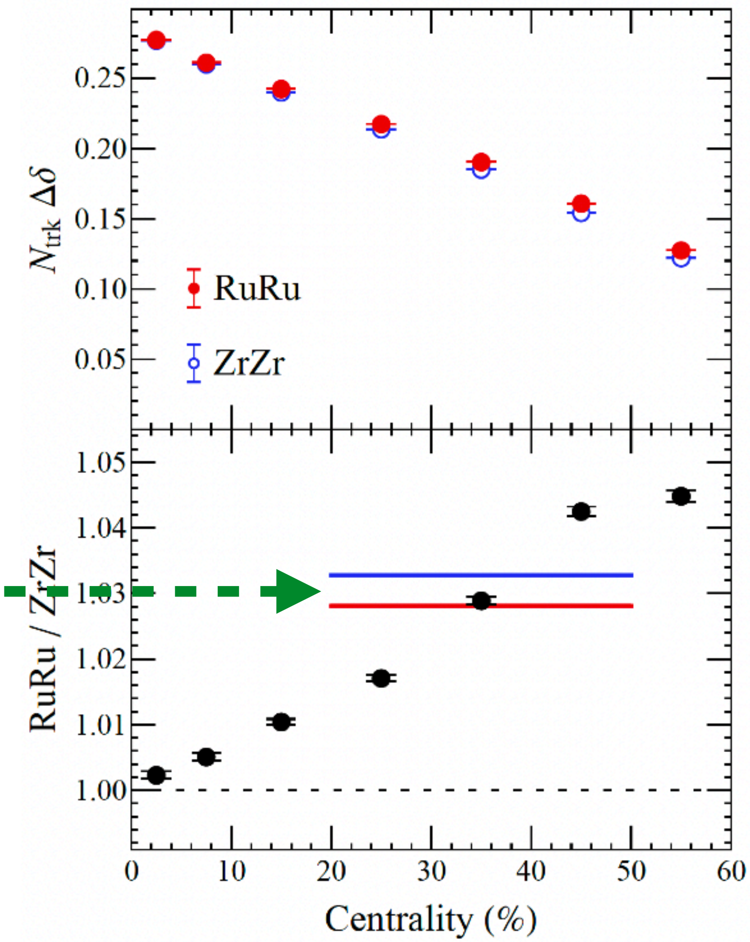


[Khazeev, JL, Shi, arXiv:2205.00120]

A Possible Signal in Isobar Systems



CME Signal



After taking into account Nch difference: data versus baseline —> CME signal contribution

[Khazeev, JL, Shi, arXiv:2205.00120]

Extracting CME Fraction

$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

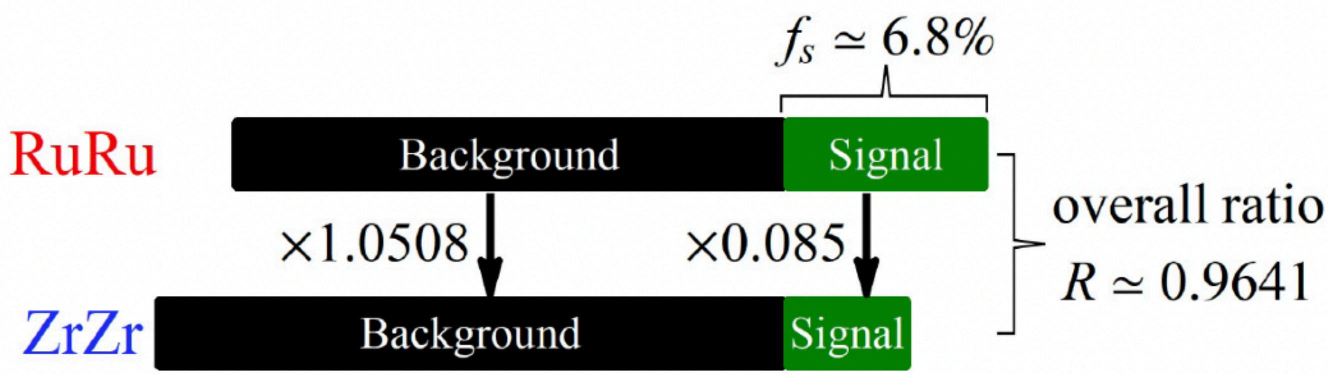
$$f_s = \frac{\lambda_b - \lambda_R}{\lambda_s + \lambda_b}$$

f_s: signal fraction in gamma

labdam_s: relative isobar sig difference

labdam_b: relative isobar bkg difference

labdam_R:
relative isobar gamma difference from data



$$\boxed{f_s \simeq +(0.068 \pm 0.026) = (6.8 \pm 2.6)\%.}$$

[Khazeev, JL, Shi, arXiv:2205.00120]

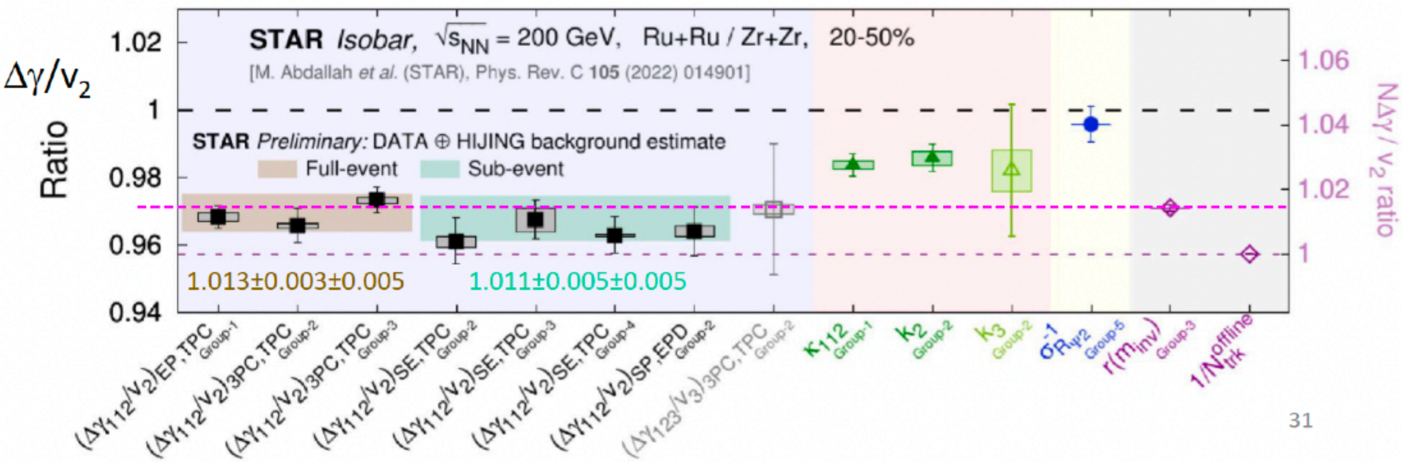
Similar Message from Experimentalists

From Fuqiang Wang

Current total uncertainty:
0.4%⊕0.3%⊕0.5% = 0.7%

Assuming 15% B^2 diff:
δf_{CME} = 0.7%/15% = 5%

My conservative estimate:
f_{CME} < 10% at 98% CL

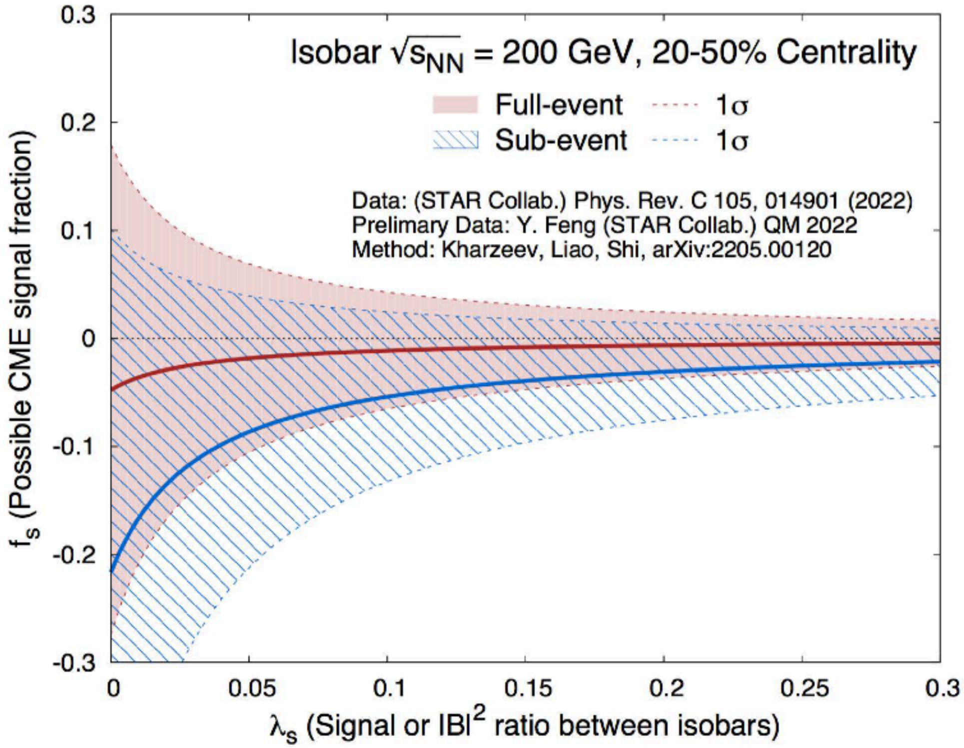


Quantifying the remaining non flow uncertainty is crucial.

More post-blind analysis results are expected from STAR.

Similar Message from Experimentalists

From Prithwish Tribedy



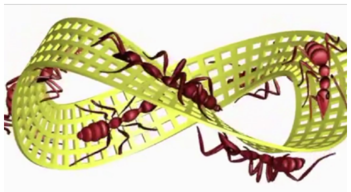
Quantifying the remaining non flow uncertainty is crucial.

More post-blind analysis results are expected from STAR.

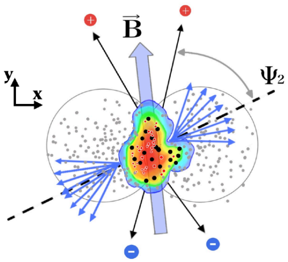
Summary & Outlook

Summary

$$N_R - N_L = N_5 = 2Q_w$$



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



EXP correlations In heavy ion collisions

— The physics of CME is rich and fundamental.

— The search for CME in heavy ion collisions is of great importance yet challenging.

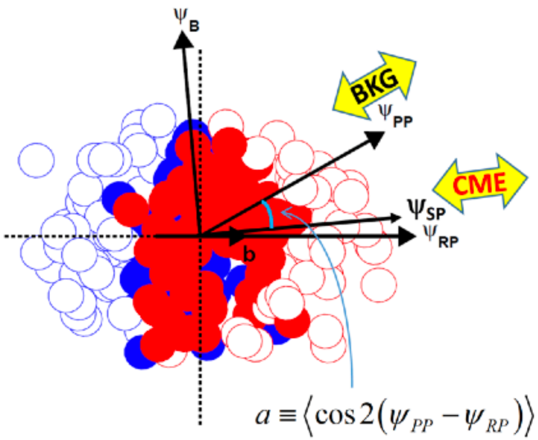
— Isobar collisions collect a high precision data set with a potential signal for CME.

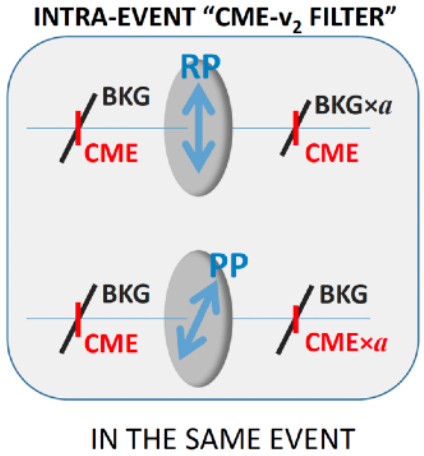
— Nuclear structure inputs play a crucial role, the understanding of which can benefit both heavy ion and nuclear structure physics

What's next?

Event-Plane/Spectator-Plane Contrast

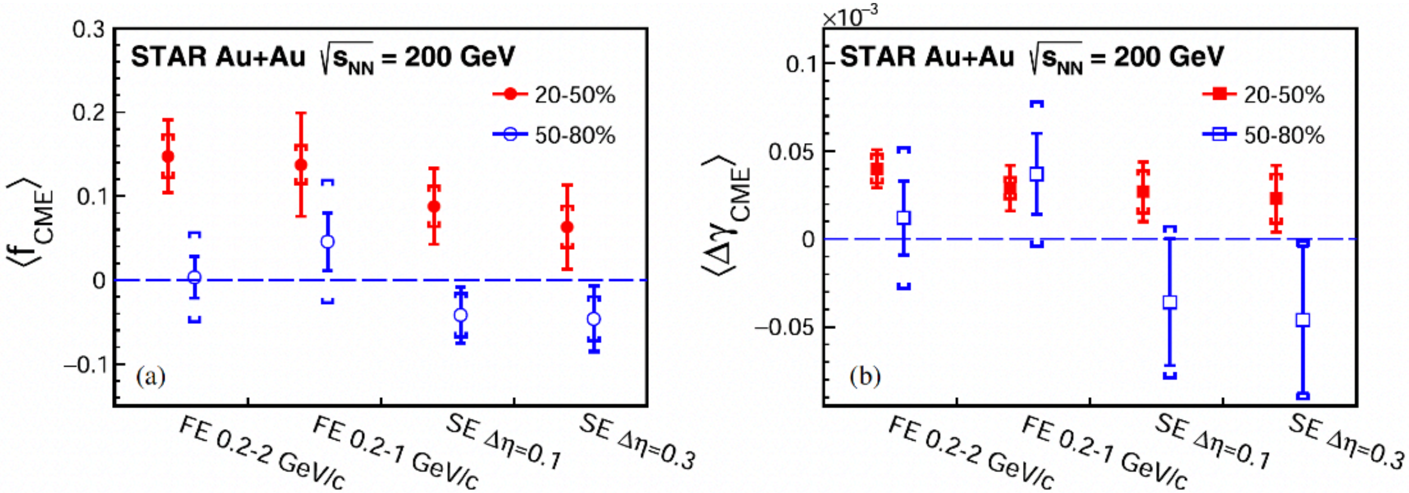
H.-j. Xu, FW, et al., CPC 42 (2018) 084103, arXiv:1710.07265
S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300





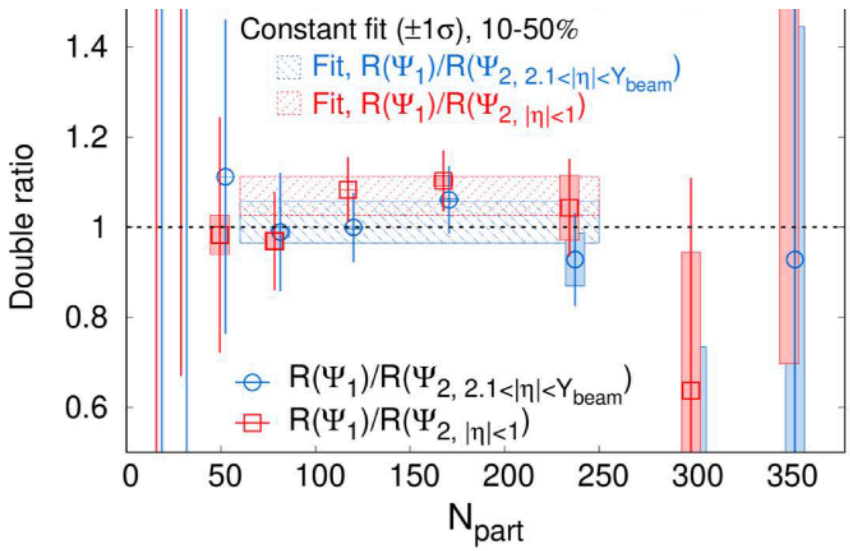
CME signal in 20~50% AuAu at RHIC 200GeV at 1~3 sigma level

[From: F. Wang talk]

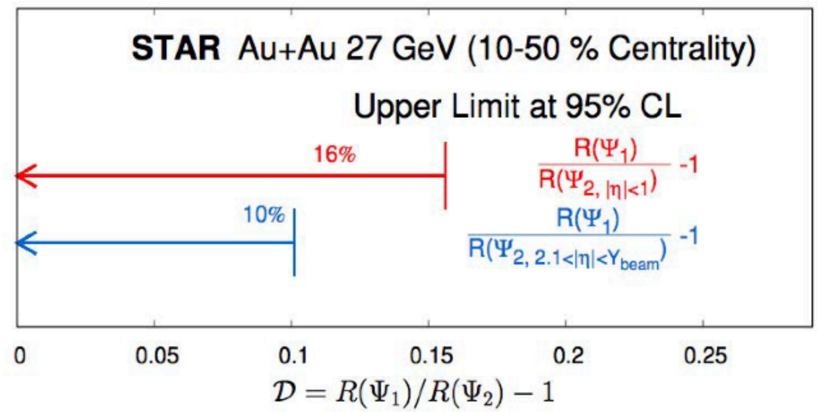


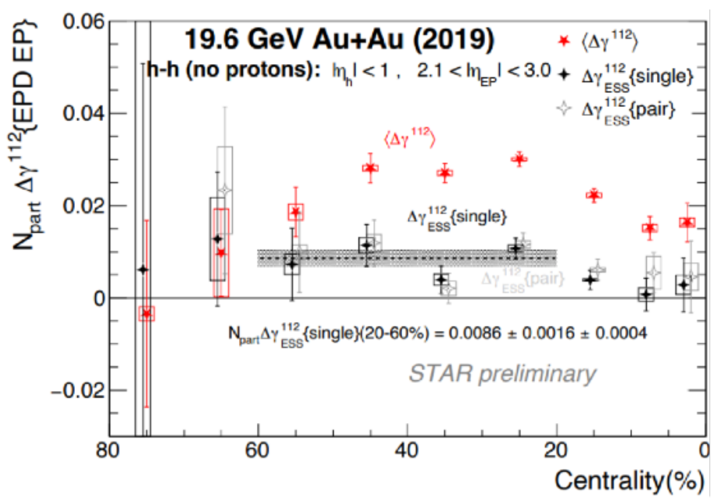
[STAR PRL128,092301(2022)]

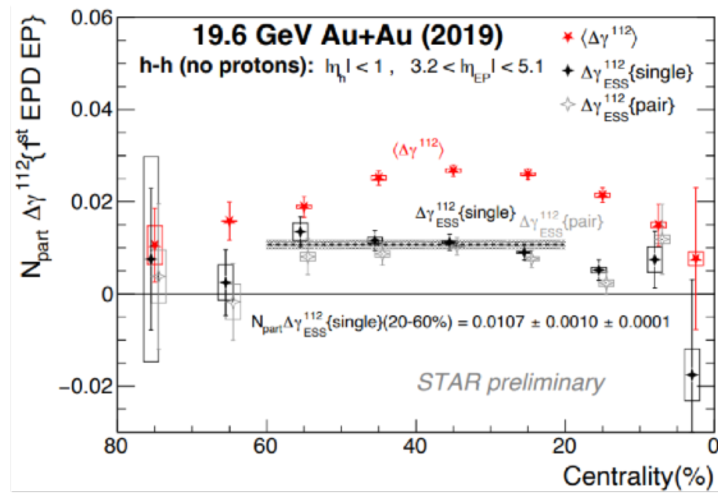
CME Search at Lower Beam Energy



[From P. Tribedy]







[From Huang et al]

CME Search: What's Next

- *Isobar: a significant step forward in CME search*
  - *major backgrounds under control; residue non flow effect is the next issue to take care of*
  - *post-blind analysis, informed baseline, alternative approach (e.g. multiplicity selection), extracting signal fraction or at least a reliable upper limit*

- *RHIC AuAu: upcoming large data set 2023~2025, pushing measurements toward high sigma level for a decisive conclusion*

- *Beam energy scan: mapping the full range beam energy dependence of CME phenomenon from BES energies to LHC energies*

CME @ 2027? Stay tuned!

Backup Slides

Hydrodynamic Realization of CME in HIC

Anomalous-Viscous Fluid Dynamics

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

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

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

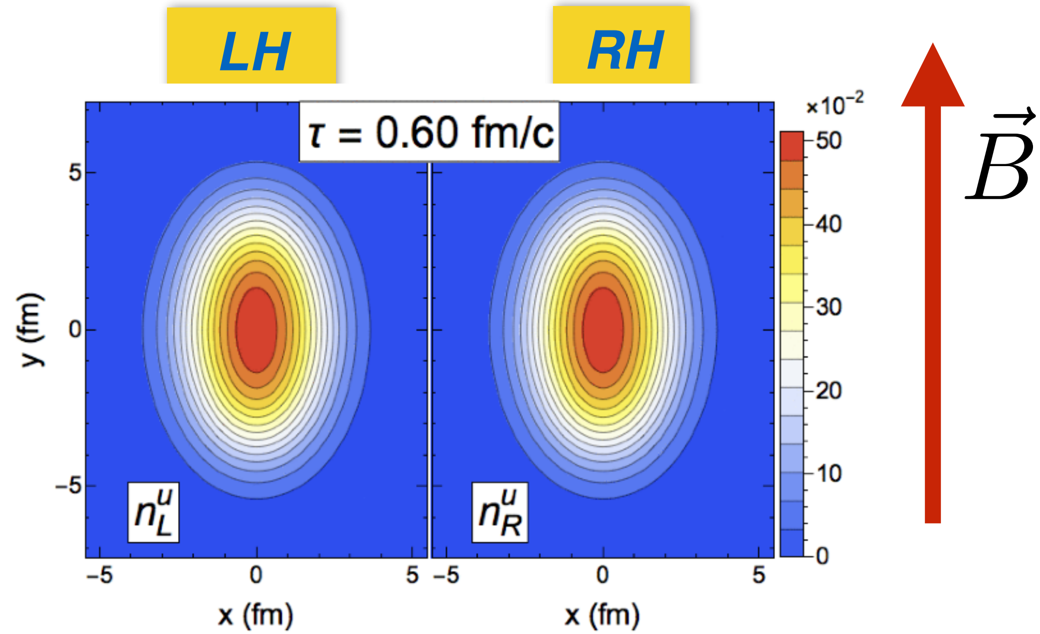
CME

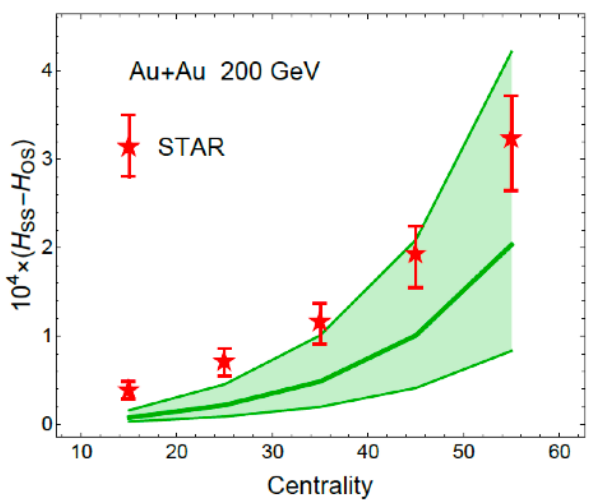
Viscous Effect

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

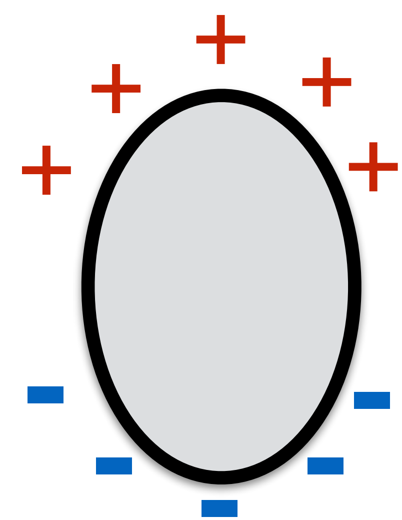
$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

on top of VISH2+1D -- OSU Group





Chirality imbalance
—>
R/L asymmetry
—>
charge asymmetry



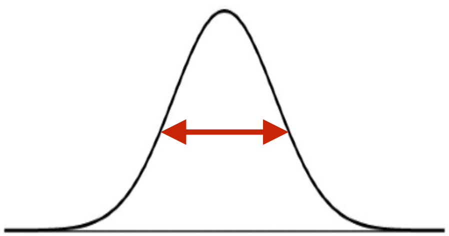
[Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

The Gamma Correlator

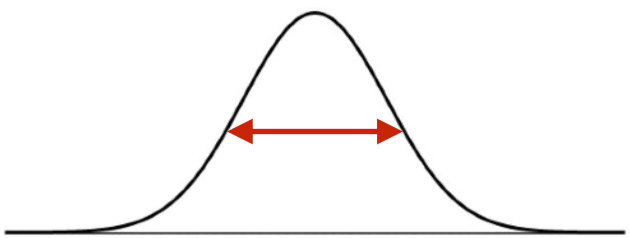
$$\boxed{\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})} \qquad < a_\pm > \sim \pm < \mu_5 > B$$

Average gives zero; can only look for fluctuations/variance!

$$\gamma_{\alpha,\beta} = \left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle = \left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle - \left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle$$



Looking for a dipole fluctuation DIFFERENCE between In-plane and out-of-plane



Looking for DIFFERENCE between same-sign pairs and opposite-sign pairs

$$\gamma^{SS}_{CME} \rightarrow -\langle a_1^2 \rangle$$

$$\gamma^{OS}_{CME} \rightarrow +\langle a_1^2 \rangle$$

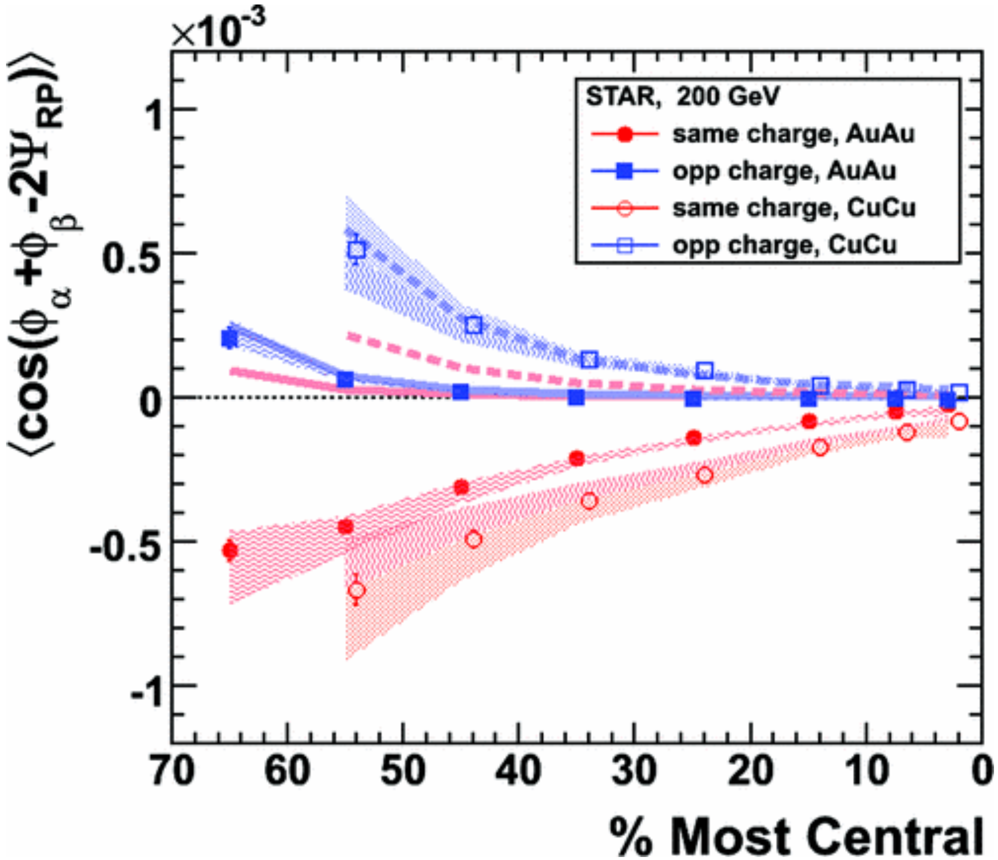
It is sensitive to CME. But it also picks up the elliptic-flow driven difference in background correlations.

The 2009 STAR Results

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

B. I. Abelev *et al.* (STAR Collaboration)
Phys. Rev. Lett. **103**, 251601 – Published 14 December 2009

Data could be in line with CME expectations.



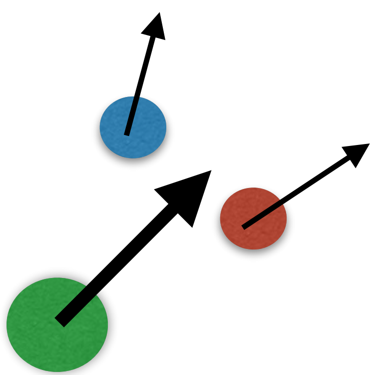
(Almost Immediate) Skepticism

[F. Wang, arXiv:0911.1482] **Resonance decay**

Effects of Cluster Particle Correlations on Local Parity Violation Observables

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.



Roughly scaling ~ v2 / N

Alternative Contributions to the Angular Correlations Observed at RHIC Associated with Parity Fluctuations

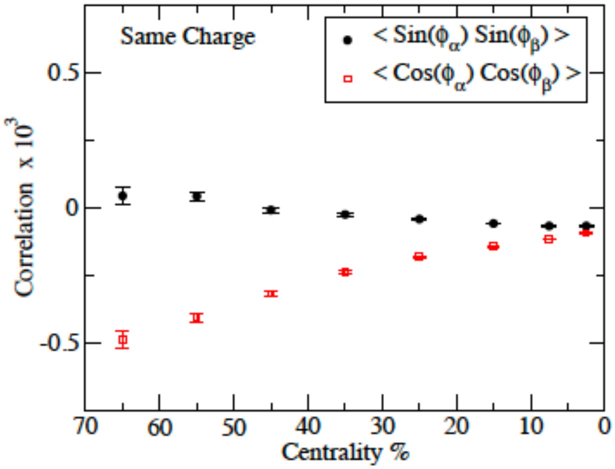
Scott Pratt
Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory,
Michigan State University
East Lansing, Michigan 48824
(Dated: April 13, 2019)

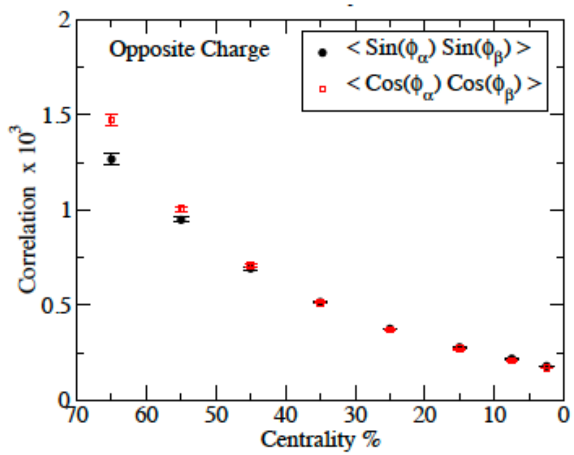
Recent measurements at RHIC of angular correlations of same-sign vs. opposite sign pairs have been interpreted as evidence for large-scale fluctuations of parity-odd fields. In this paper, we provide alternative explanations of the same phenomena based on correlations from charge and momentum conservation overlaid with elliptic flow. These effects are shown to produce correlations with similar magnitudes as those measured. Other correlations are also considered, but estimates of their size suggest they are inconsequential.

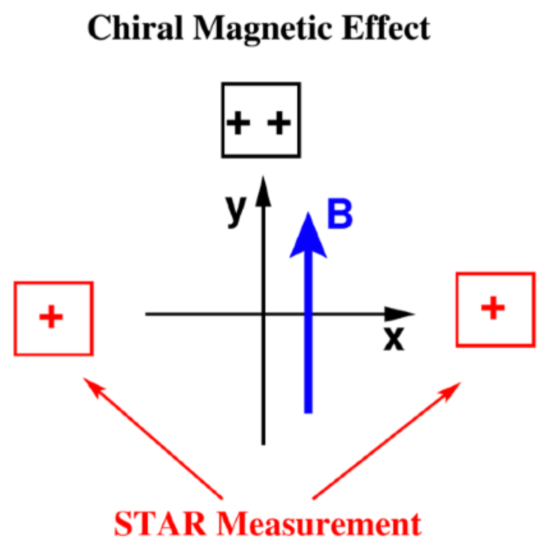
Local charge conservation (LCC) [S. Pratt, arXiv:1002.1758]

(Almost Immediate) Skepticism

$$\delta_{\alpha,\beta} = \langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle \cos(\phi_\alpha)\cos(\phi_\beta) \rangle + \langle \sin(\phi_\alpha)\sin(\phi_\beta) \rangle$$







Transverse momentum conservation (TMC)

[Bzdak, Koch, JL: arXiv:0912.5050;1005.5308;1008.4919]

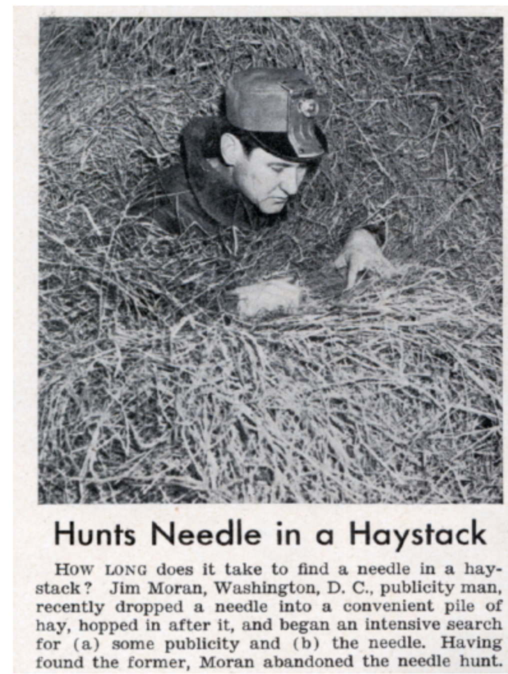
Facing the Setback

$\hat{O} \times 10^3$	$\langle \cos(\phi_1 + \phi_2) \rangle_{++}$	$\langle \cos(\phi_1 + \phi_2) \rangle_{+-}$	$\langle \cos(\phi_1 - \phi_2) \rangle_{++}$	$\langle \cos(\phi_1 - \phi_2) \rangle_{+-}$
CME	$-(0.1 - 1)$	$+(0.01 - 0.1)$	$+(0.1 - 1)$	$-(0.01 - 0.1)$
LCC	~ 0	$+(0.1 - 1)$	~ 0	$+(1 - 10)$
TMC	~ -0.1	~ -0.1	~ -1	~ -1
DATA	-0.45	$+0.06$	-0.38	$+1.97$

[Bzdak, Koch, JL: arXiv:1008.4919]

Redefining the question:
Is there anything remaining?
What fraction of gamma could still be from CME?

Not the time to give up yet!
— think about the search for e.g. EDM, WIMP, 2-beta decay, magnetic monopoles, …



Hunts Needle in a Haystack

HOW LONG does it take to find a needle in a haystack? Jim Moran, Washington, D. C., publicity man, recently dropped a needle into a convenient pile of hay, hopped in after it, and began an intensive search for (a) some publicity and (b) the needle. Having found the former, Moran abandoned the needle hunt.

Image source: http://blog.modernmechanix.com/hunts-needle-in-a-haystack/

Fighting with Backgrounds

Two-component decomposition:

$\gamma = \kappa\, v_2\, F - H$

$\delta = F + H$

F: Bulk Background

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

[Bzdak, Koch, JL: arXiv:1207.7327]

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

Various new approaches:

Vary v2 for fixed B:

AuAu v.s. UU;

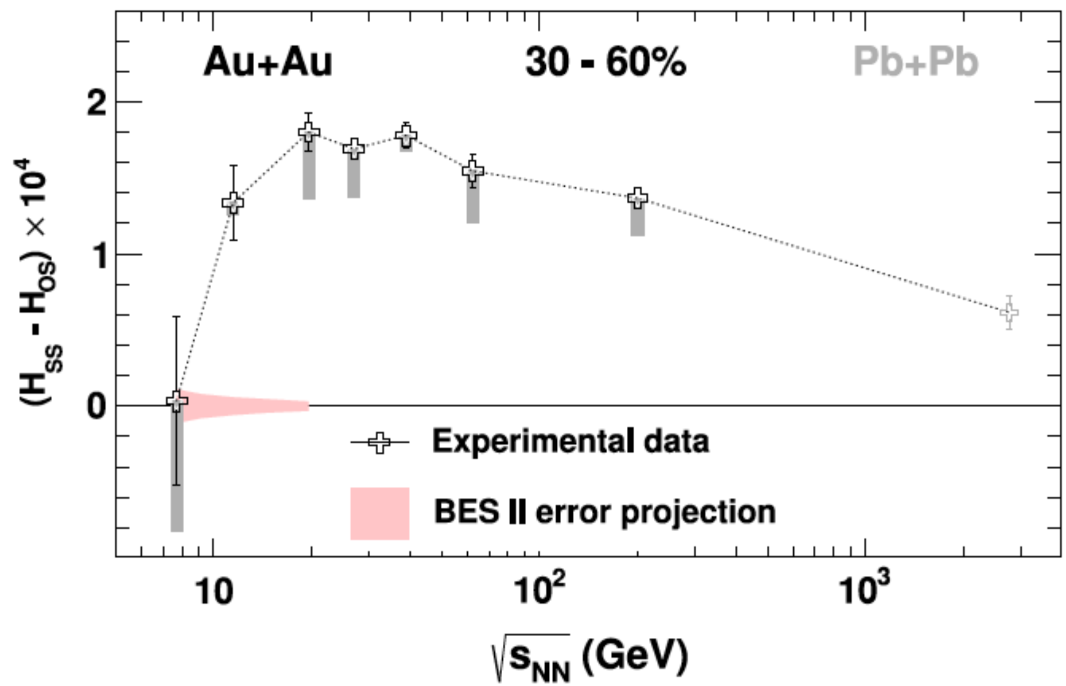
Varying event-shape;

2-component subtraction.

Vary B for fixed v2:

Isobaric collisions with

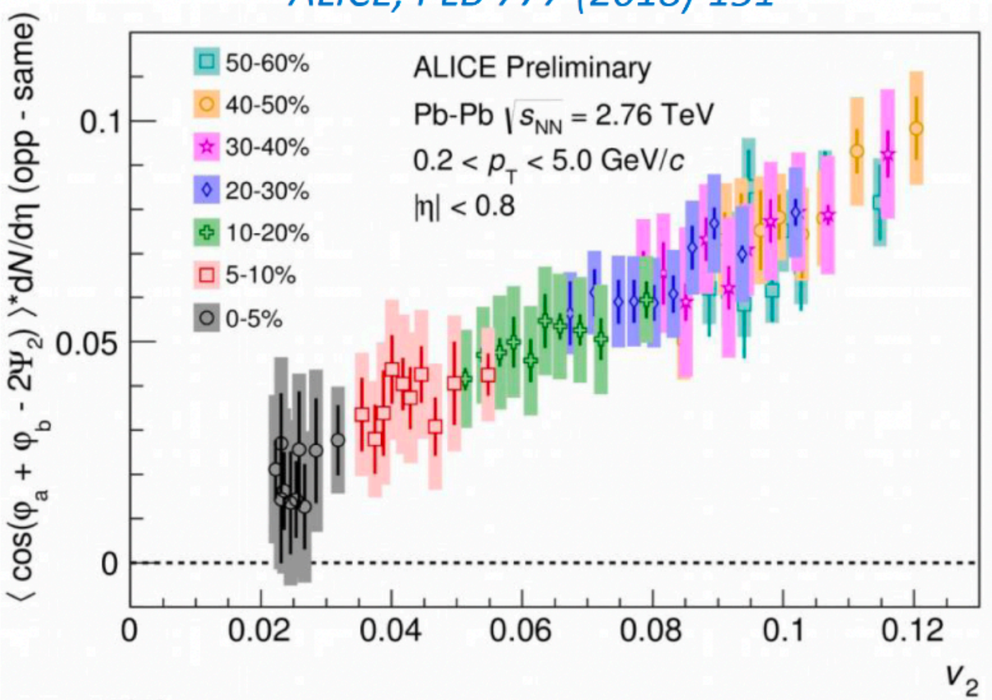
RuRu v.s. ZrZr



STAR PRL2014

Event Shape Measurements at LHC

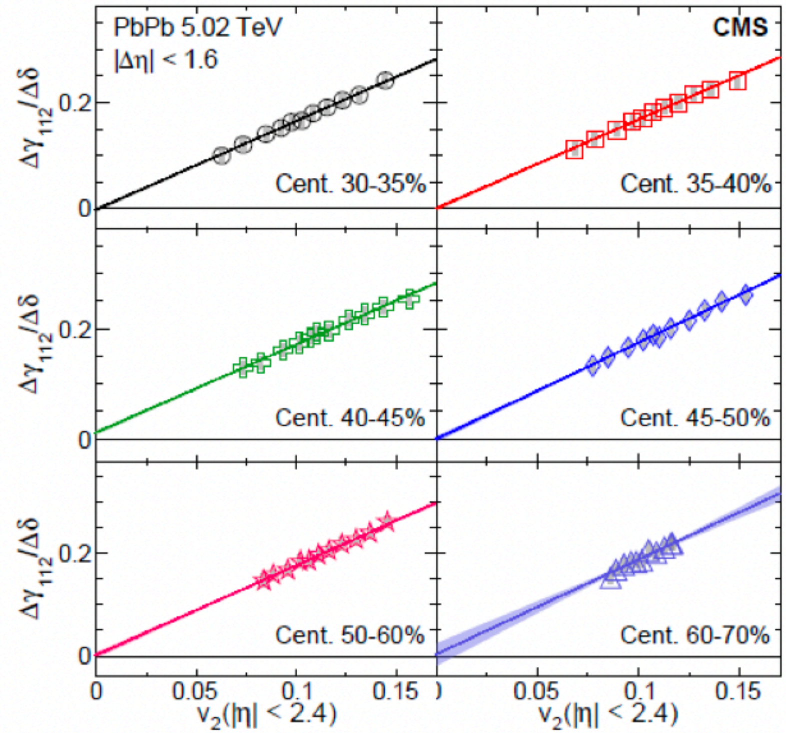
ALICE, PLB 777 (2018) 151



More sophisticated (model-dep.) assumption of B dependence on v2 within a given centrality

Upper limit 26%

CMS, PRC 97 (2018) 044912



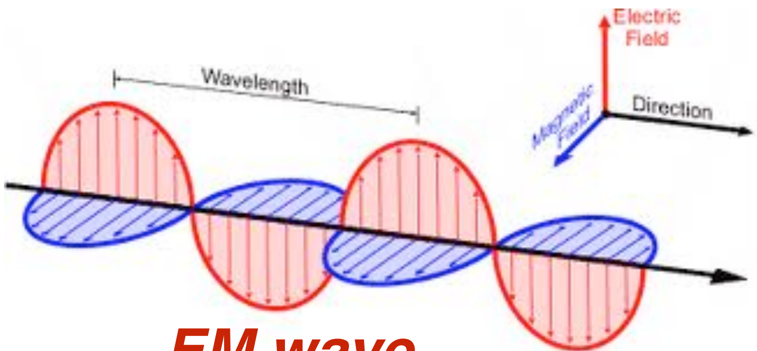
Assume CME does not depend on v_2 within a given centrality

Upper limit 7%

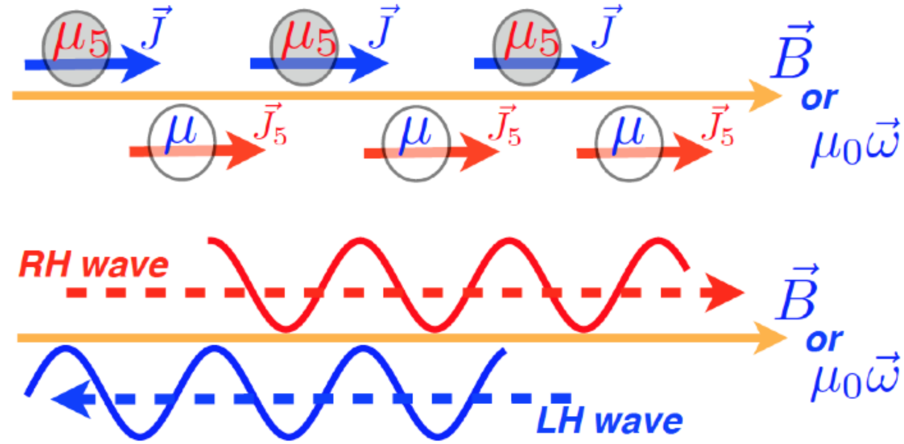
[From: F. Wang talk @QM22]

Chiral Magnetic Wave (CMW)

Wave: propagating "oscillations" of two coupled quantities e.g. sound wave (pressure & density); EM wave (E & B fields)



EM wave



Chiral Magnetic Wave

CME + CSE —> gapless collective excitations, the CMW

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

$$\vec{\mathrm{J}}_5 = \sigma_5 \mu \vec{\mathrm{B}}$$

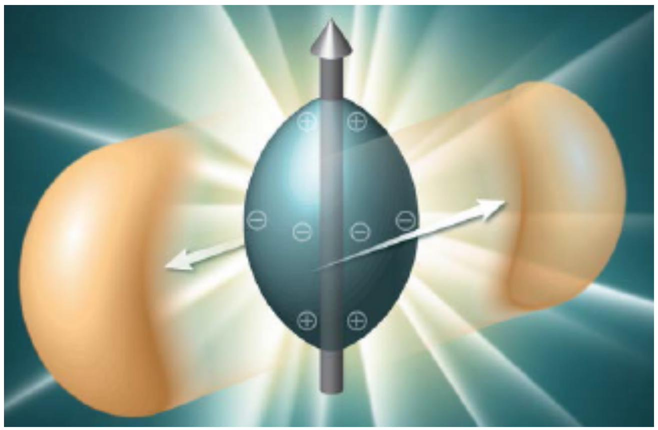
$$\left(\partial_0 \pm \frac{(Qe)}{(4\pi^2)\chi}\vec{\mathrm{B}}\cdot\nabla\right)\delta J^0_{R/L} = \left(\partial_0 \pm v_B \partial_{\hat{\mathrm{B}}}\right)\delta J^0_{R/L} = 0.$$

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, 2011]

CMW Induced Flow Splitting

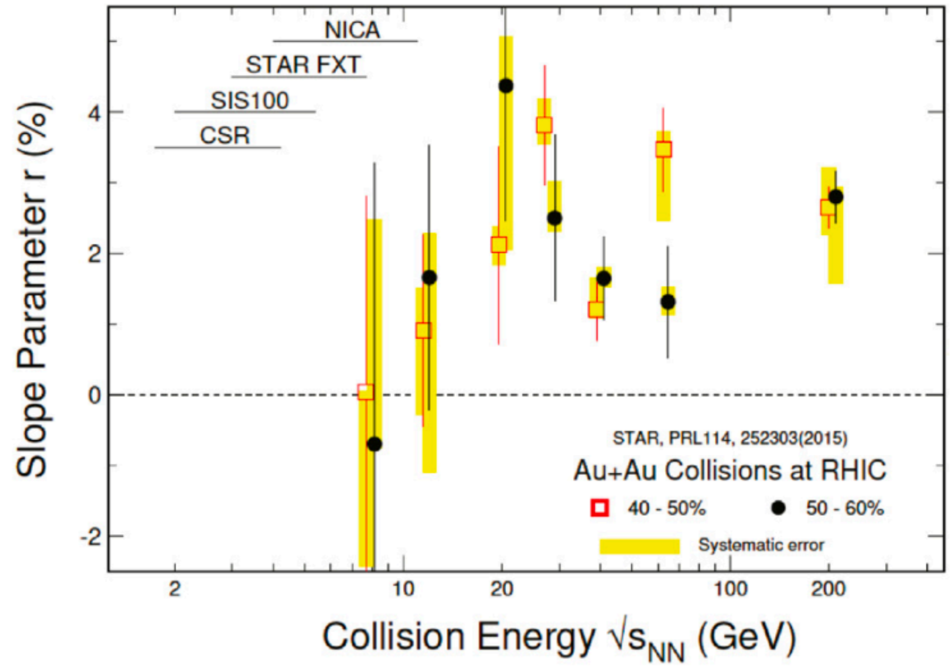
CMW —> charge quadrupole of QGP —> elliptic flow splitting

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



$$\boxed{v_2^- - v_2^+ = r_e A}$$

charge quadrupole due to CMW transport



Positive exp. hints

[STAR, PRL2015]

[Also seen by ALICE@LHC]

Experimental Observable

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

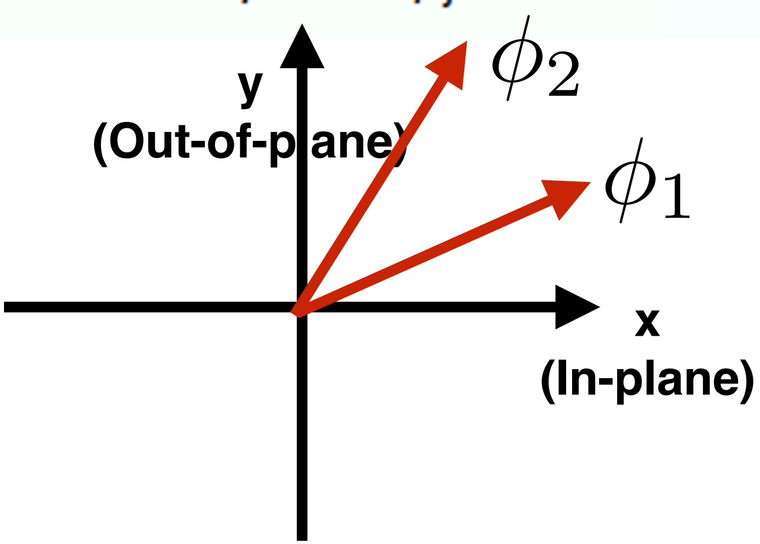
charge separation $\Rightarrow$ charge dept. two-particle correlation

Voloshin, 2004

$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

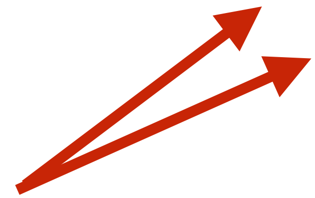
$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

These correlations are sensitive to CME contributions, however they are also sensitive to many non-CME backgrounds!



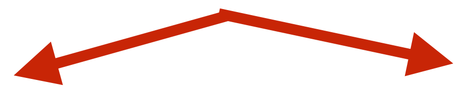
Understand the Correlation Observables

$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle$$



$\delta > 0$

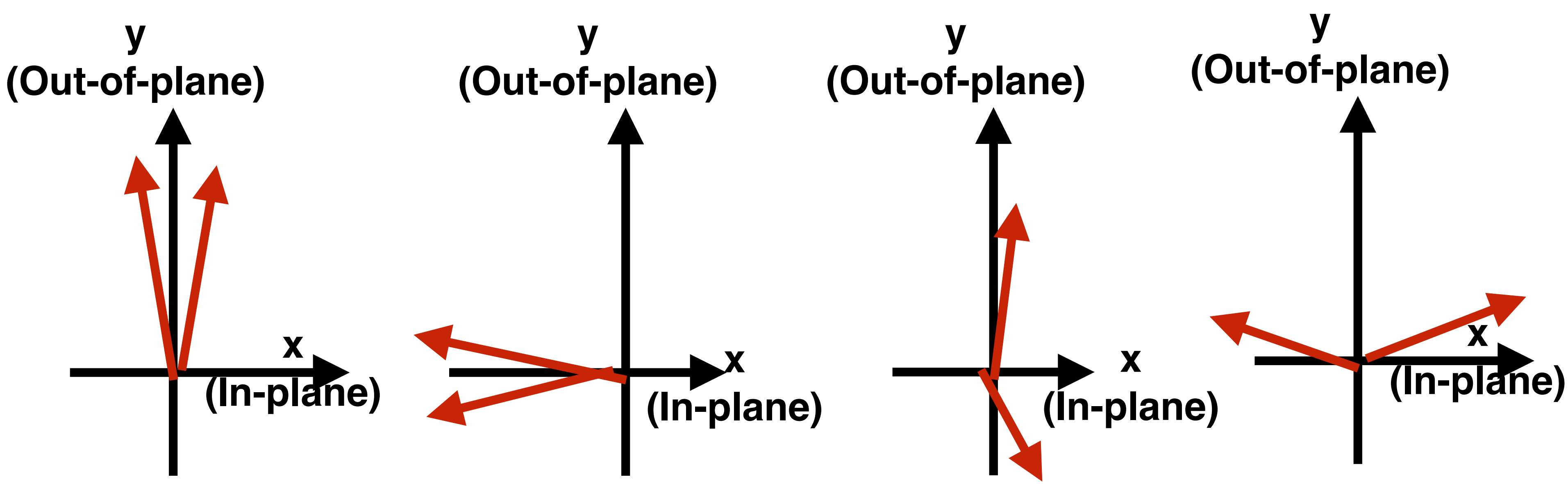
Near-side versus back-to-back



$\delta < 0$

$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle$$

It is R.P.-dependent!



$\gamma < 0$ $\gamma > 0$ $\gamma > 0$ $\gamma < 0$

CME & Backgrounds

CME expectation:

$$\gamma_{SS} < 0 \,, \delta_{SS} > 0$$

$$\gamma_{OS} > 0 \,, \delta_{OS} < 0$$

Transverse Momentum Conservation (TMC)

$$\gamma < 0 \,, \delta < 0$$

Local Charge Conservation (LCC)

$$\gamma_{OS} > 0 \,, \delta_{OS} > 0$$

Resonance decay: similar to LCC

Background contribution to gamma is due to nonzero v2!!