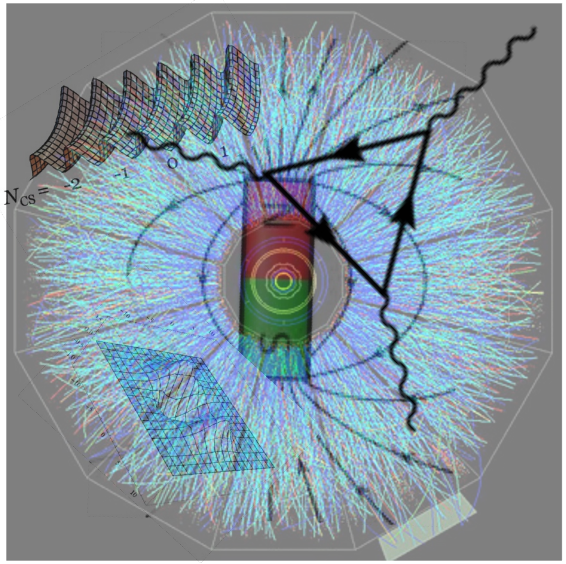
Perspectives & Discussions on the CME Search



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

INDIANA UNIVERSITY

Plan of the Talk

- ***Some recent progress***
- ***Discussions on current status***
- ***Discussions on what’s next***

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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

Electric Current

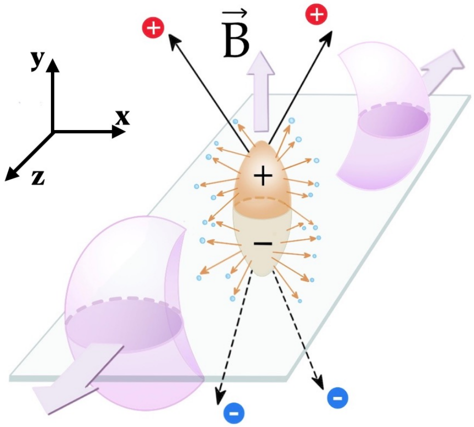
Q.M. Transport

Magnetic Field

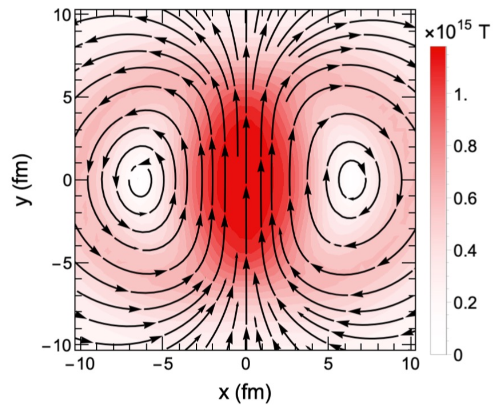
Two key ingredients:
Macroscopic chirality, i.e. RH/LH imbalance;
Strong magnetic field.

Looking for CME Signals in Nuclear Collisions

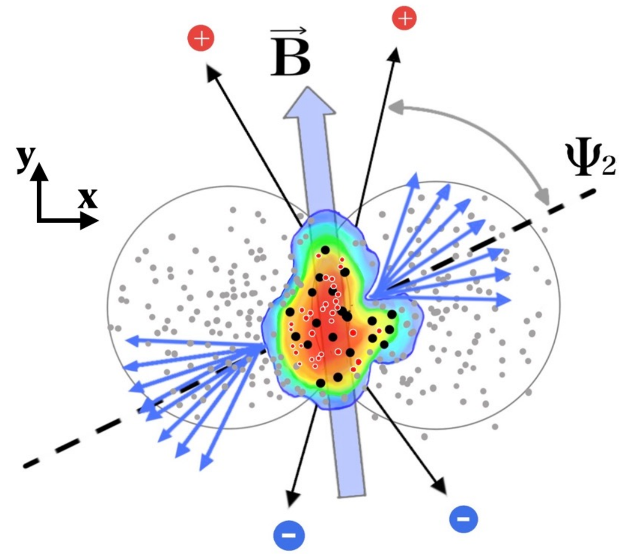
CME transport induces a charge dipole distribution along magnetic field direction in the QGP fluid.



The strongest B field ~ 10^15 Tesla



Subatomic "lightning"!



A specific emission pattern of charged particles along B field:

Same-sign hadrons emitted preferably side-by-side;

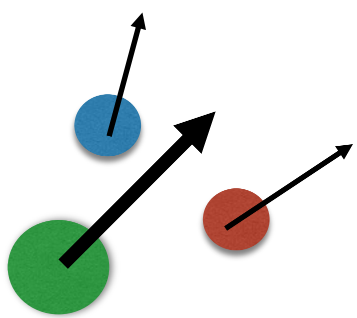
Opposite-sign hadrons emitted preferably back-to-back.

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;
Backgrounds driven by bulk elliptic flow.

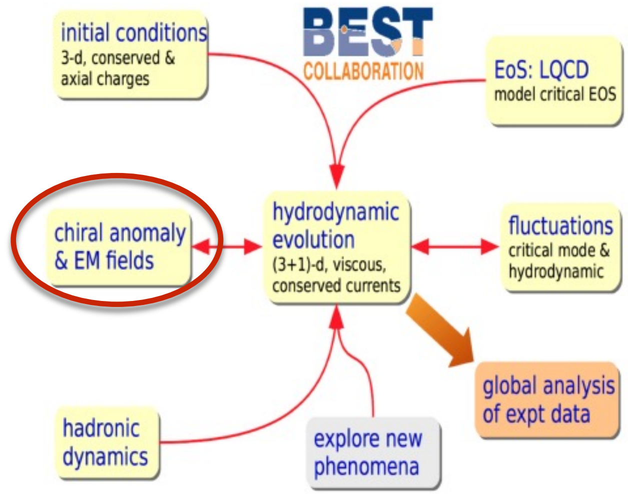
[Bzdak, Koch, JL: arXiv:1207.7327]

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

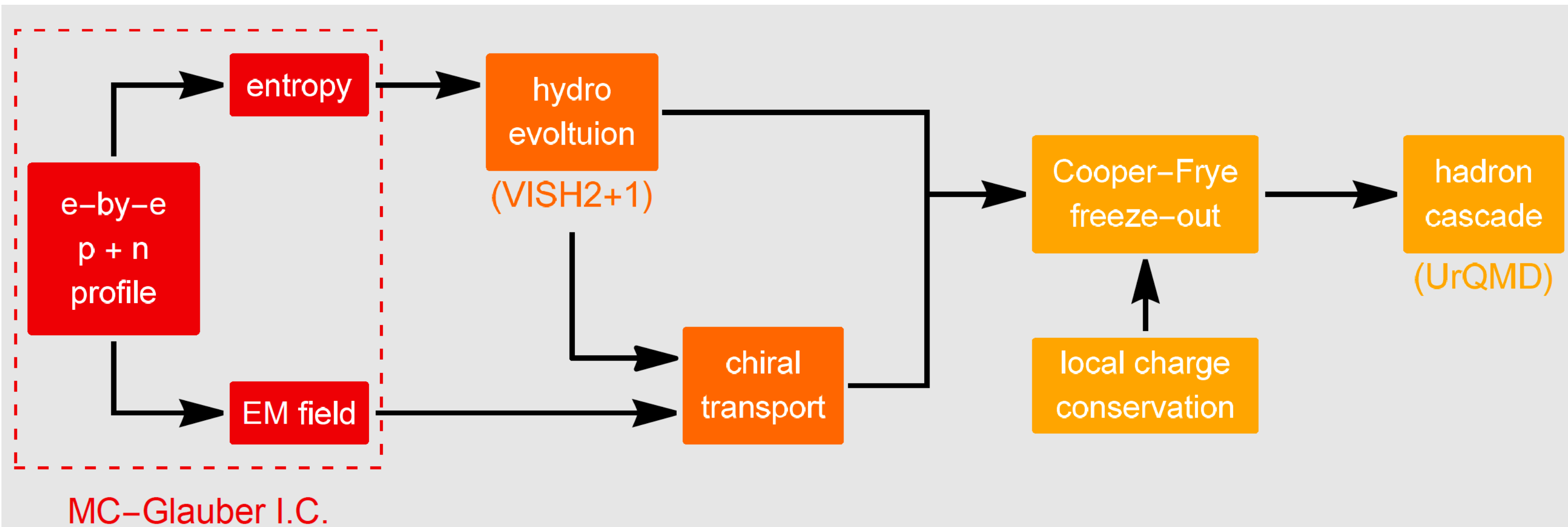
Need theoretical tool for quantitatively and realistically understanding both signals and backgrounds!

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]

Hydrodynamic Realization of CME in HIC

Anomalous-Viscous Fluid Dynamics

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

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

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

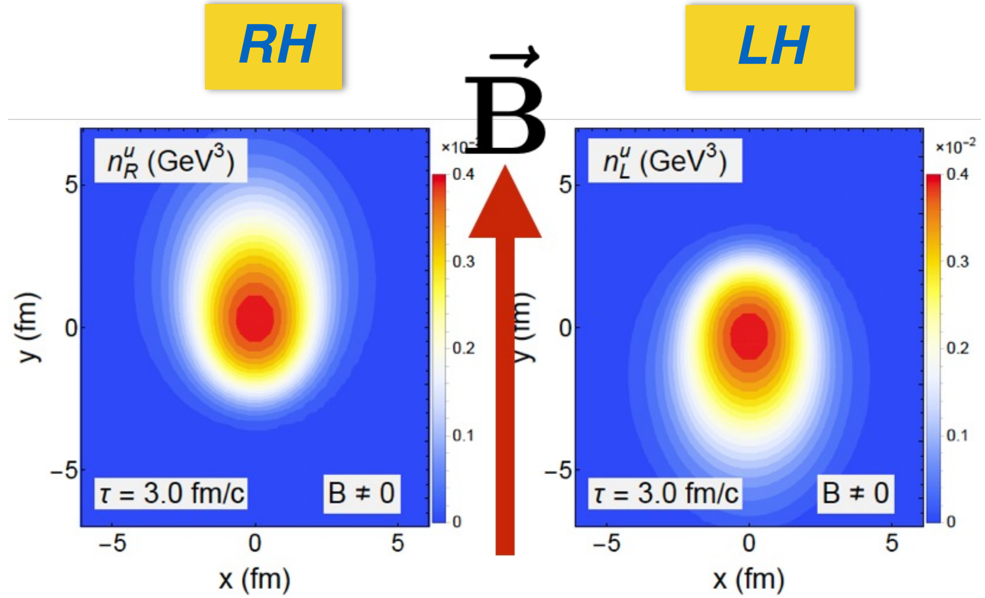
CME

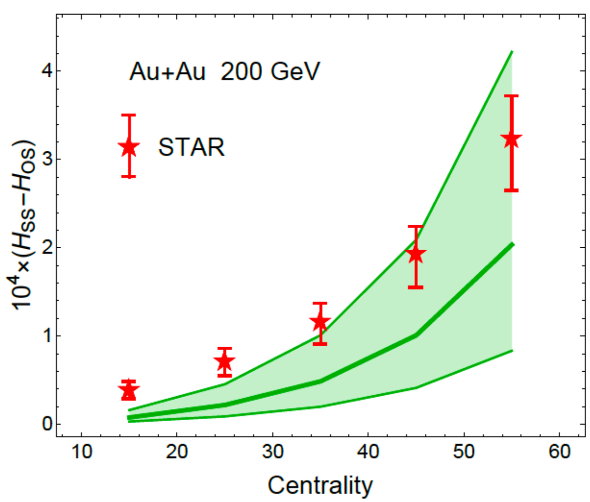
Viscous Effect

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

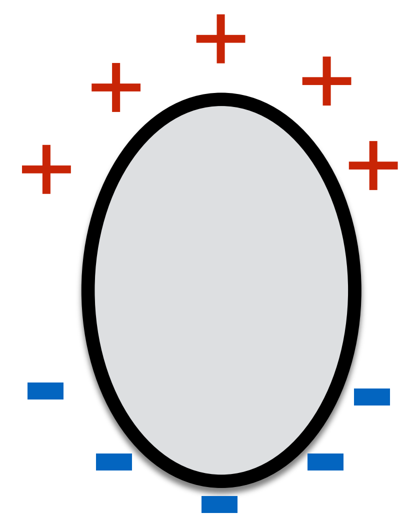
$$\nu_{NS}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

on top of `VISH2+1D` —— OSU Group





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



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

EBE-AVFD as a Key Theoretical Tool

EBE-AVFD has now become a very useful tool for developing CME observables, calibrating sensitivity to signals and backgrounds, as well as interpreting data.

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

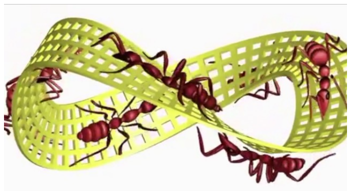
Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment*

Subikash Choudhury[1] Xin Dong[2] Jim Drachenberg[3] James Dunlop[4] ShinIchi Esumi[5] Yicheng Feng(冯毅程)[6]
Evan Finch[7] Yu Hu(胡昱)[1,4] Jiangyong Jia[4,8] Jerome Lauret[4] Wei Li[9] Jinfeng Liao(廖劲峰)[10]
Yufu Lin(林裕富)[11,12†] Mike Lisa[13] Takafumi Niida[5] Robert Lanny Ray[14] Masha Sergeeva[15]
Diyu Shen(申迪宇)[1‡] Shuzhe Shi(施舒哲)[16] Paul Sorensen[4] Aihong Tang(唐爱洪)[4] Prithwish Tribedy[4]
Gene Van Buren[4] Sergei Voloshin[17] Fuqiang Wang(王福强)[6] Gang Wang(王钢)[15] Haojie Xu(徐浩洁)[18]
Zhiwan Xu(徐之湾)[15] Nanxi Yao[15§] Jie Zhao(赵杰)[6]

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

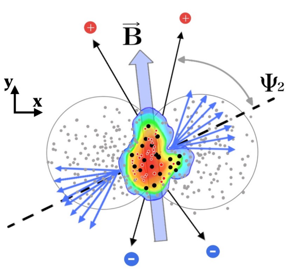
Axial Charge Dynamics

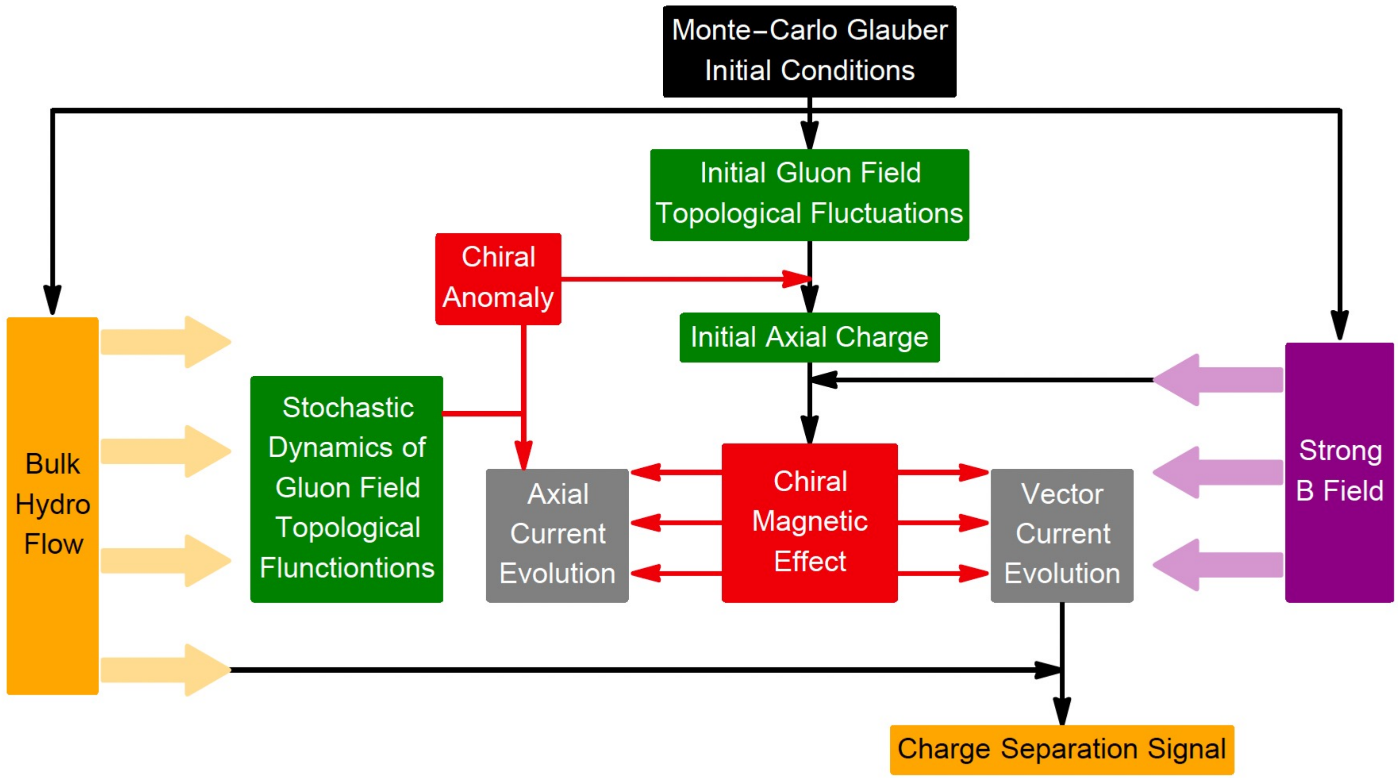
Axial charge from initial gluon topological fluctuations; Stochastic dynamics during dynamical evolution



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

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

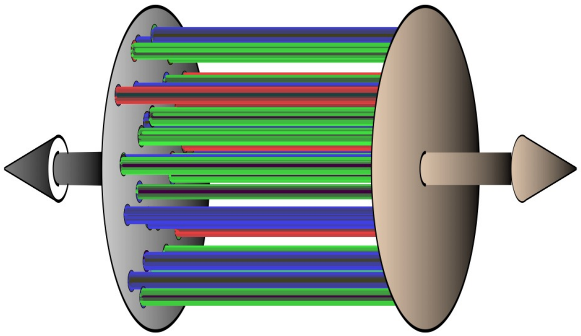




[A. Huang, S. Shi, S. Lin, X. Guo, JL, arXiv:2106.10847]

Axial Charge Dynamics

Initial axial charge profile:



$$n_{5,i}(\tau_0, x, y) = (\pm) \cdot \lambda \frac{Q_s^2}{8\pi^2} \tau_0 \left[\frac{1}{2\sigma^2} e^{-\frac{(\mathbf{x}-\mathbf{x}_i)^2}{2\sigma^2}} \right]$$

[Hirono, Hirano, Kharzeev, arXiv:1412.0311]

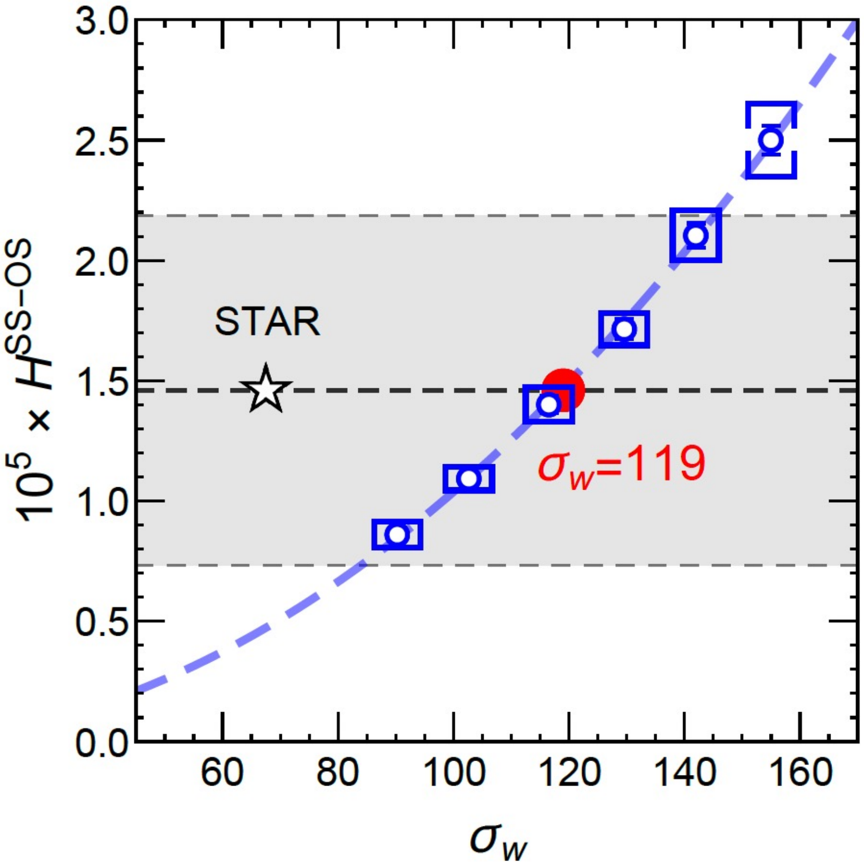
Stochastic evolution:

$$\partial_\mu J^\mu_{f,5} = -\frac{N_c Q_f^2}{2\pi^2} E \cdot B - \frac{n_{f,5}}{\tau_{cs}}$$

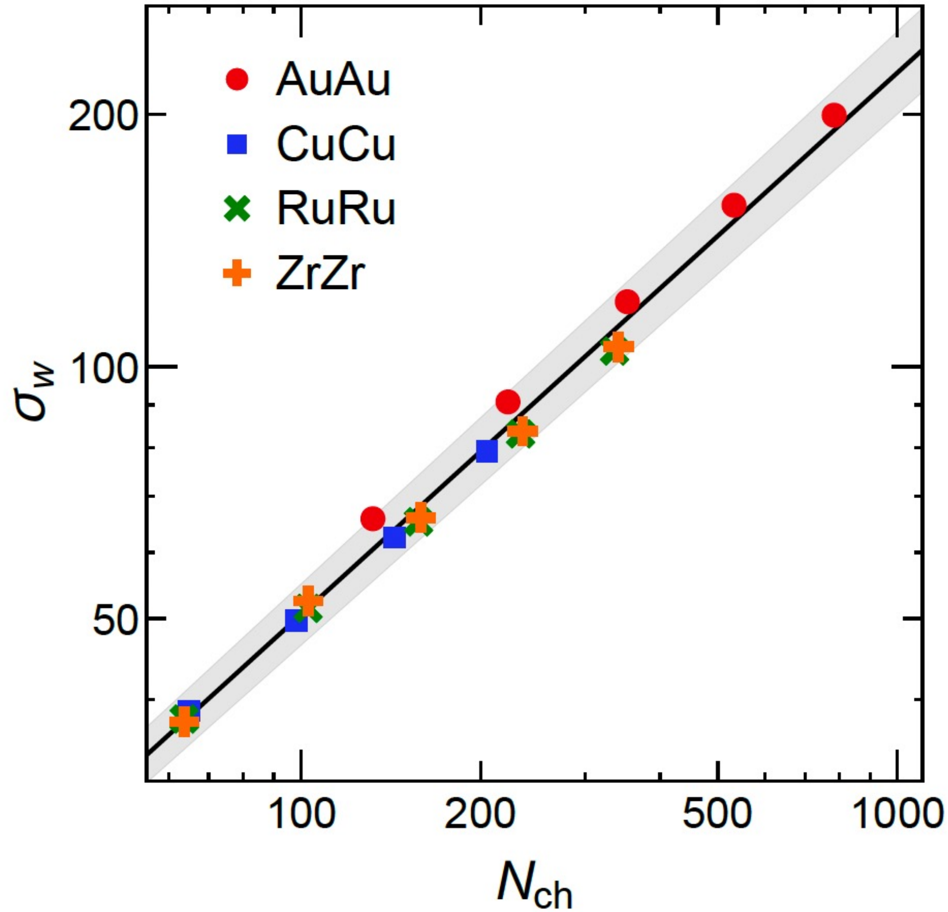
$$\tau_{cs} = \frac{\chi T}{2 N_f^2 \Gamma_{cs}} \qquad \Gamma_{cs} \approx 30(\alpha_s T)^4$$

[Iatrakis, Lin, Yin, arXiv:1411.2863;1506.01384]

Axial Charge Dynamics



$$\sigma_w \equiv \sqrt{\langle Q_w^2 \rangle_{event}}$$



$$\sigma_w = (2.56 \pm 0.17) \times \; N_{ch}^{(0.648 \pm 0.013)}$$

[A. Huang, S. Shi, S. Lin, X. Guo, JL, arXiv:2106.10847]

Dynamical Magnetic Fields

Need a framework for describing dynamical evolution of magnetic fields that is as realistic as possible

Dynamical magnetic fields in heavy-ion collisions

Anping Huang[a,b], Duan She[c], Shuzhe Shi[d], Mei Huang[a],* and Jinfeng Liao[b]†

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[b] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*

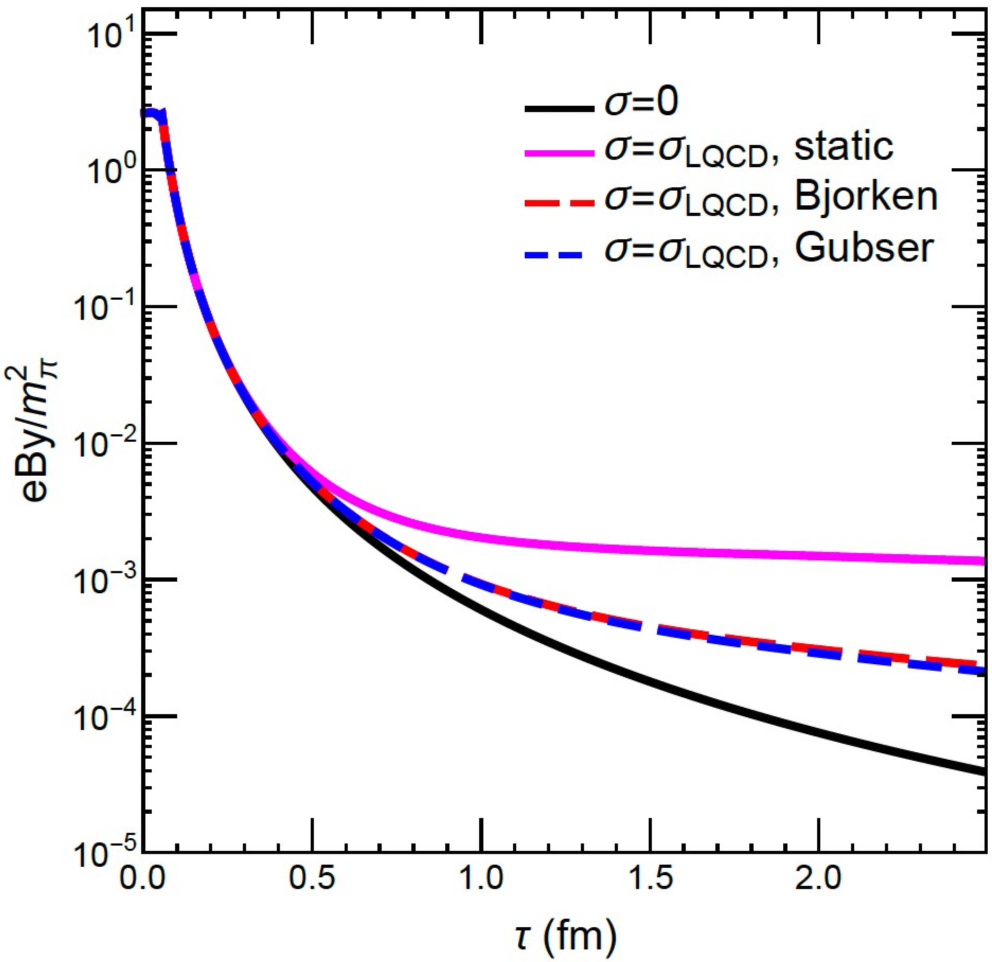
[c] *Institute of Particle Physics, central China Normal University, Wuhan 430079, China*

[d] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*

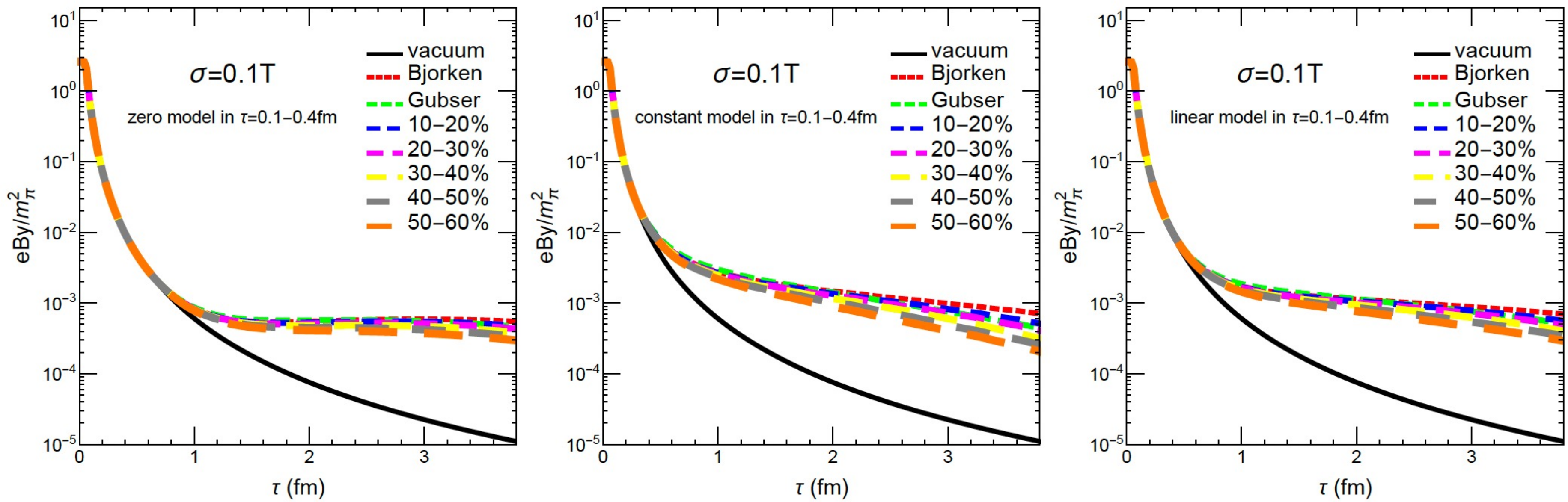
[A. Huang, et al, to appear soon]

Dynamical Magnetic Fields

Numerically solving Maxwell's equations on top of bulk hydro evolution; weak field method; Medium response via spacetime dependent conductivity



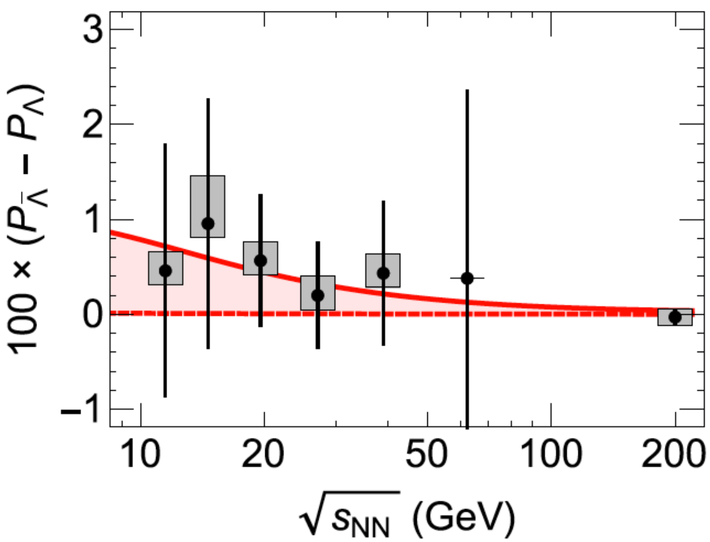
Dynamical Magnetic Fields

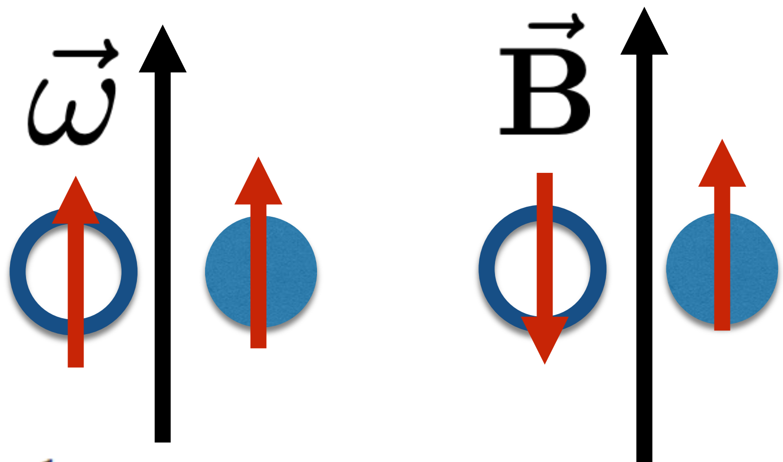


Main takeaways:
Medium effect at hydro stage too late;
Effective medium response at early stage crucial;
Longitudinal expansion important while transverse expansion details not so important.

Constraining B Field Lifetime

A possible solution to a puzzle in STAR data at low energy:
polarization difference between particle/anti-particle





$$\tilde{S}^{\mu} = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\nu}\left[\varpi_{\rho\sigma} \mp 2(eF_{\rho\sigma})\mu_{\Lambda}/T_f\right]$$

Late-time magnetic field could explain the polarization difference;

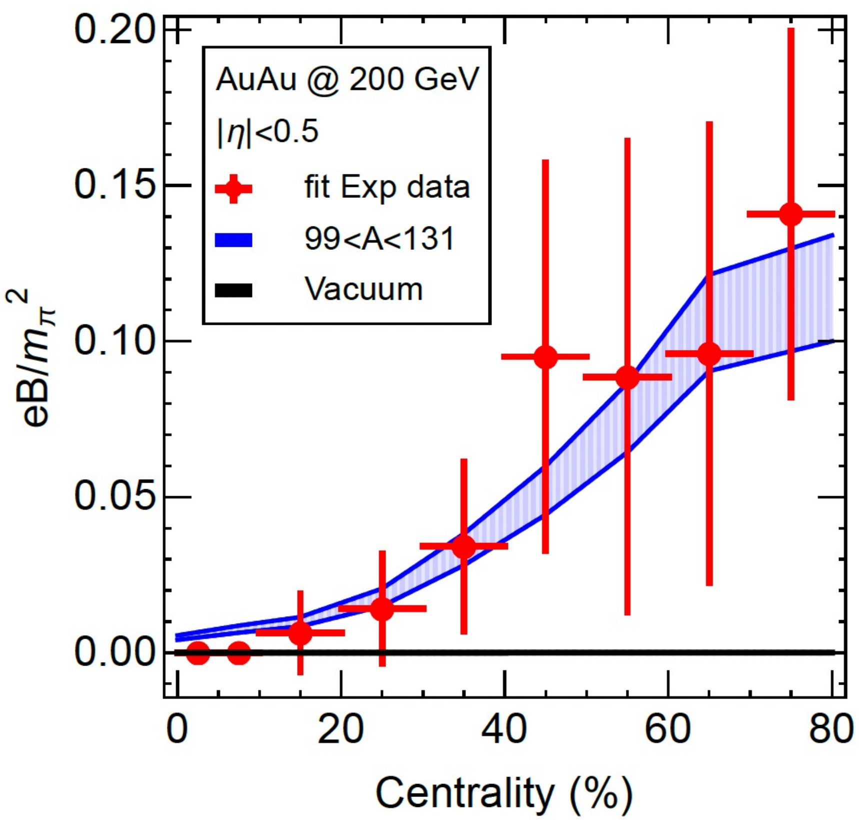
$$\tau_B \simeq \frac{115\mathrm{GeV}\cdot\mathrm{fm/c}}{\sqrt{s_{NN}}}$$

[Guo, Shi, Feng, JL, arXiv:1905.12613, PLB2019; Mueller, Schaefer, 1806.10907]

Charged rotating fluid contributes to late-time B field via Barnett-like mechanism.

[Guo, JL, Wang, arXiv:1904.04704, Scientific Reports 2020]

Constraining B Field Lifetime



Net proton fluctuations (cumulants) could be sensitive to late magnetic field effect

[Y. Guo, et al, to appear soon]

Discussions on CME Search: Current Status

The Isobar Blind Analysis

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 translation that does not create confusion:

"The predefined criteria is not applicable as its assumption is invalided by the same dataset. No real conclusion could be reached yet."

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;

H.J. Xu, et al, PRL2018; H. Elfner & collaborators, arXiv: 1908.10231

Strategies to overcome the issue:

— apply joint multiplicity— ellipticity cut for event samples

— stay at the relatively peripheral region

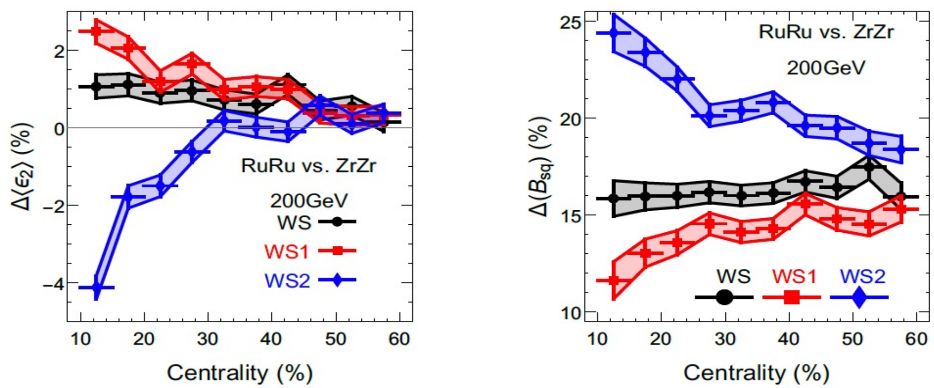


Fig. 1. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with conventional centrality event selection.

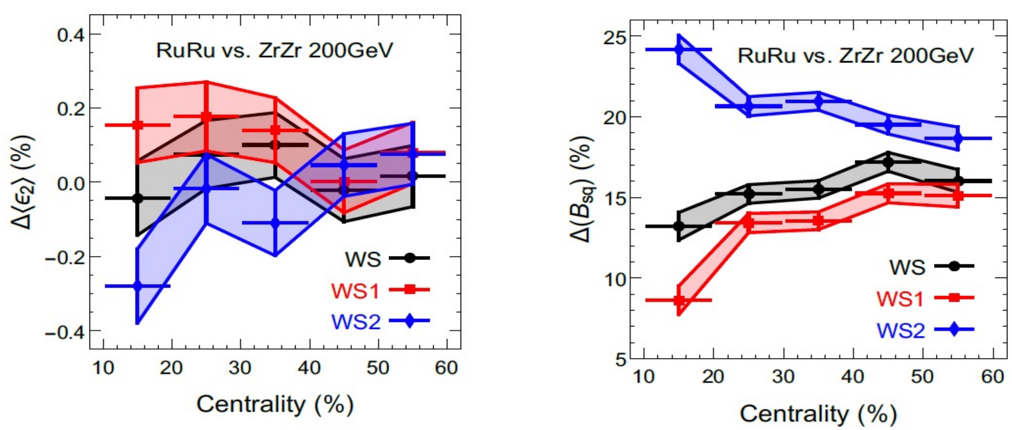


Fig. 2. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with the proposed joint (multiplicity + elliptic-flow) event selection.

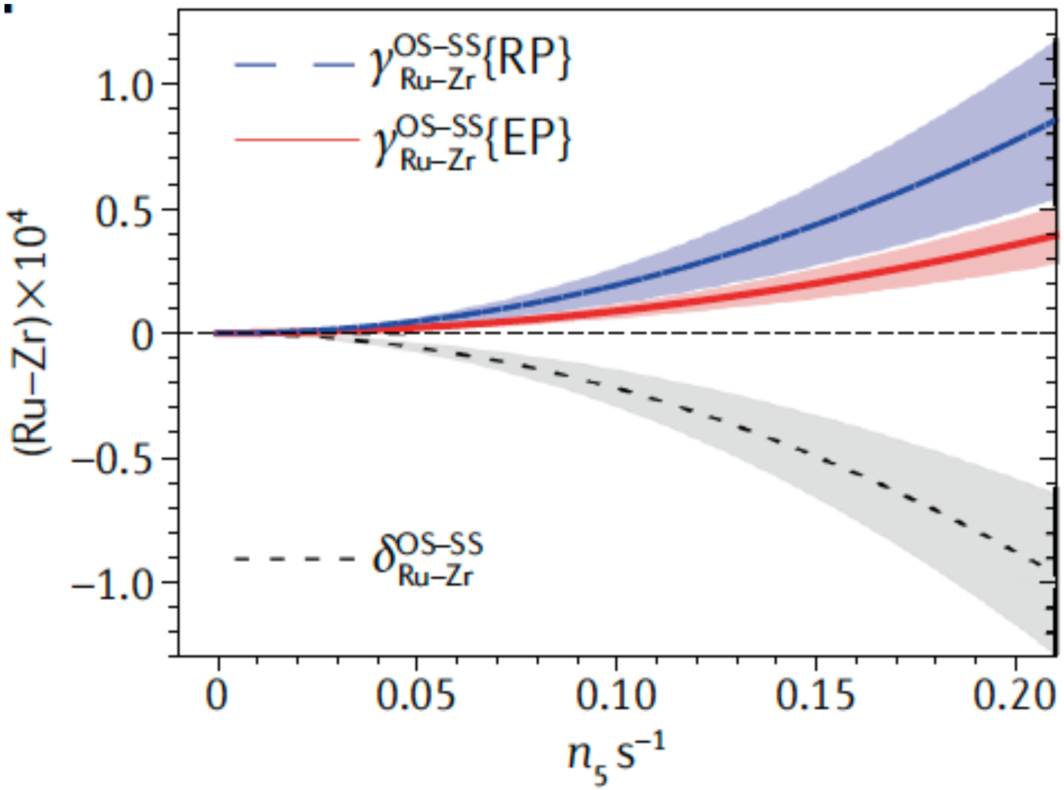
Theoretical Predictions from EBE-AVFD

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

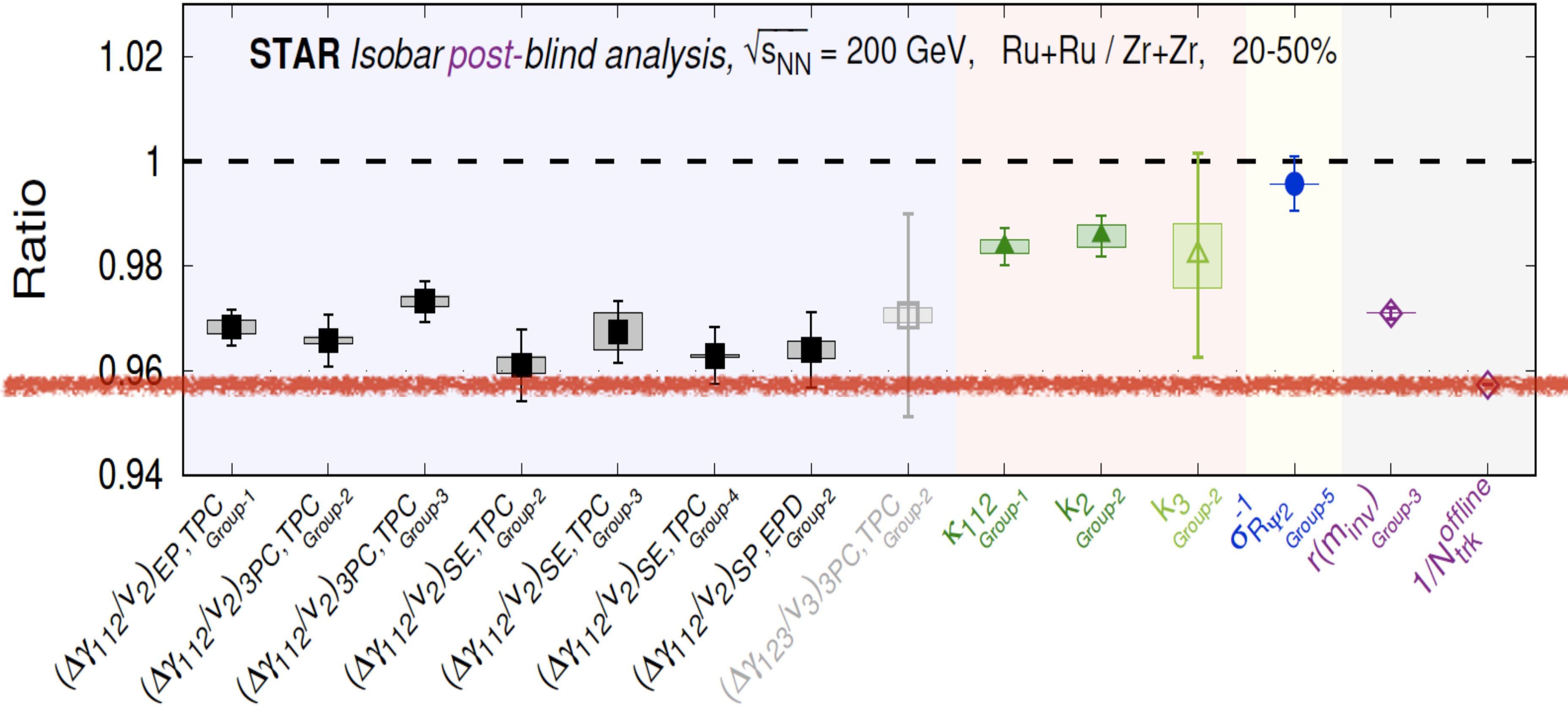
Shuzhe Shi,[1] Hui Zhang,[2,3,4] Defu Hou,[2,*] and Jinfeng Liao[5,†]



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

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

Where is the Baseline ?!



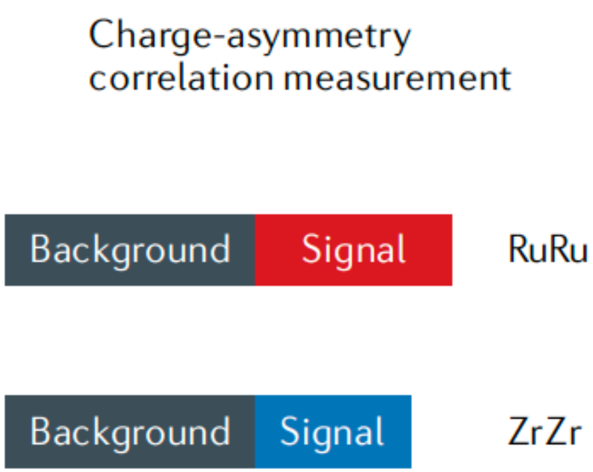
There appears room for potential CME signal above the 1/N line!
Need accurate calibration of the true baseline!

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

Implications of the Isobar Results

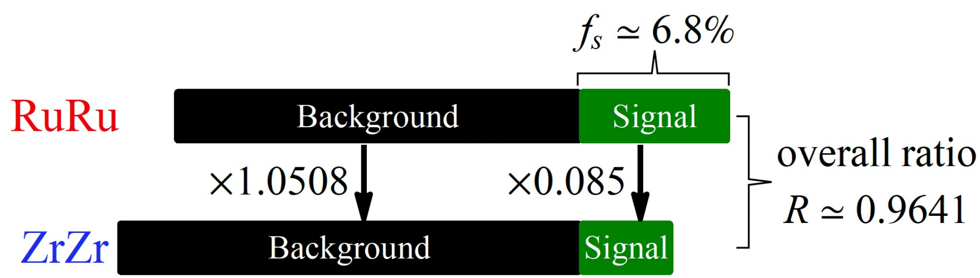
$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

Original (naive) expectation:
Identical background;
Different signal



The real world situation:

[Khazeev, JL, Shi, arXiv:2205.00120]

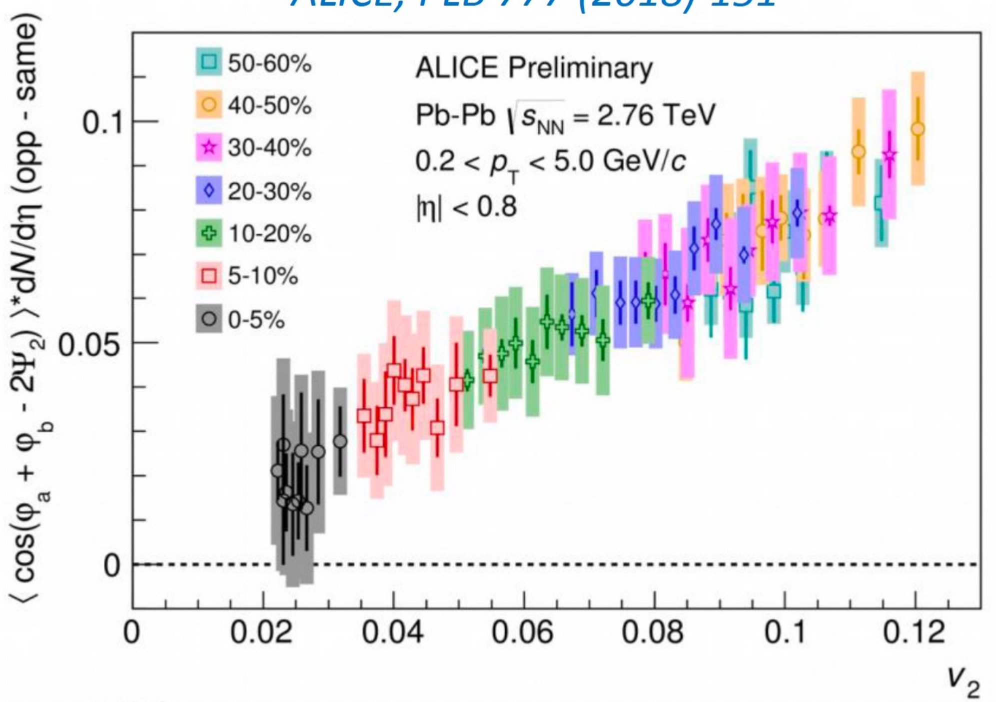


$$\boxed{f_s \simeq +(0.068 \pm 0.026) = (6.8 \pm 2.6)\%.}$$

See more in-depth discussions in talks by F. Wang and by S. Shi

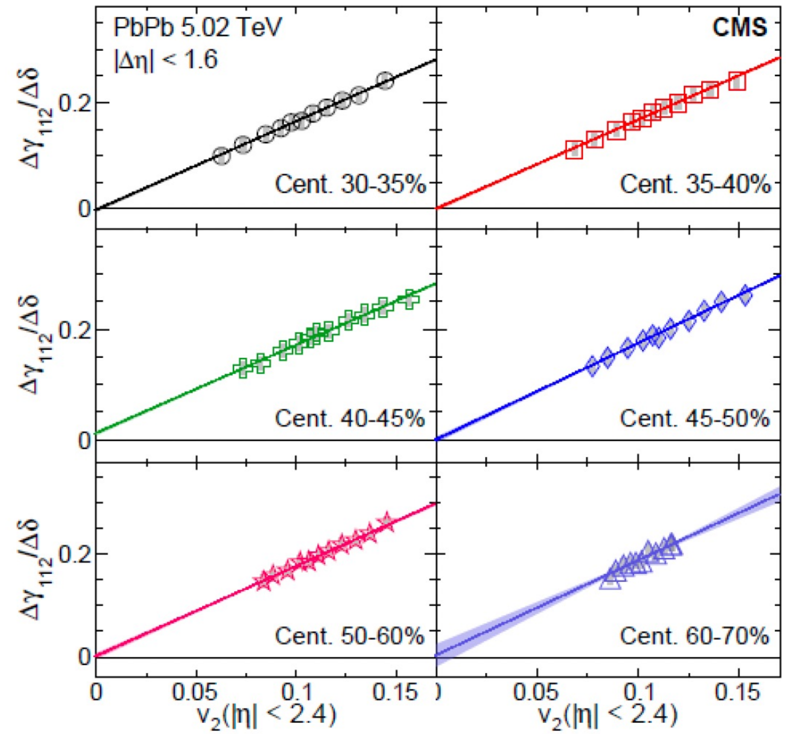
CME Search at LHC Energies

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



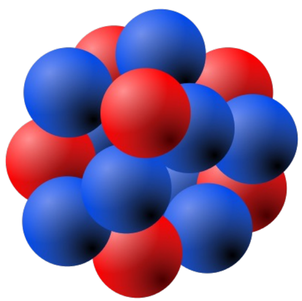
Assume CME does not depend on v_2 within a given centrality
Upper limit 7%

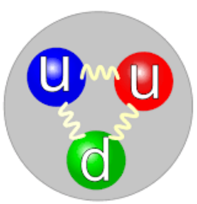
[From: F. Wang talk @QM22]

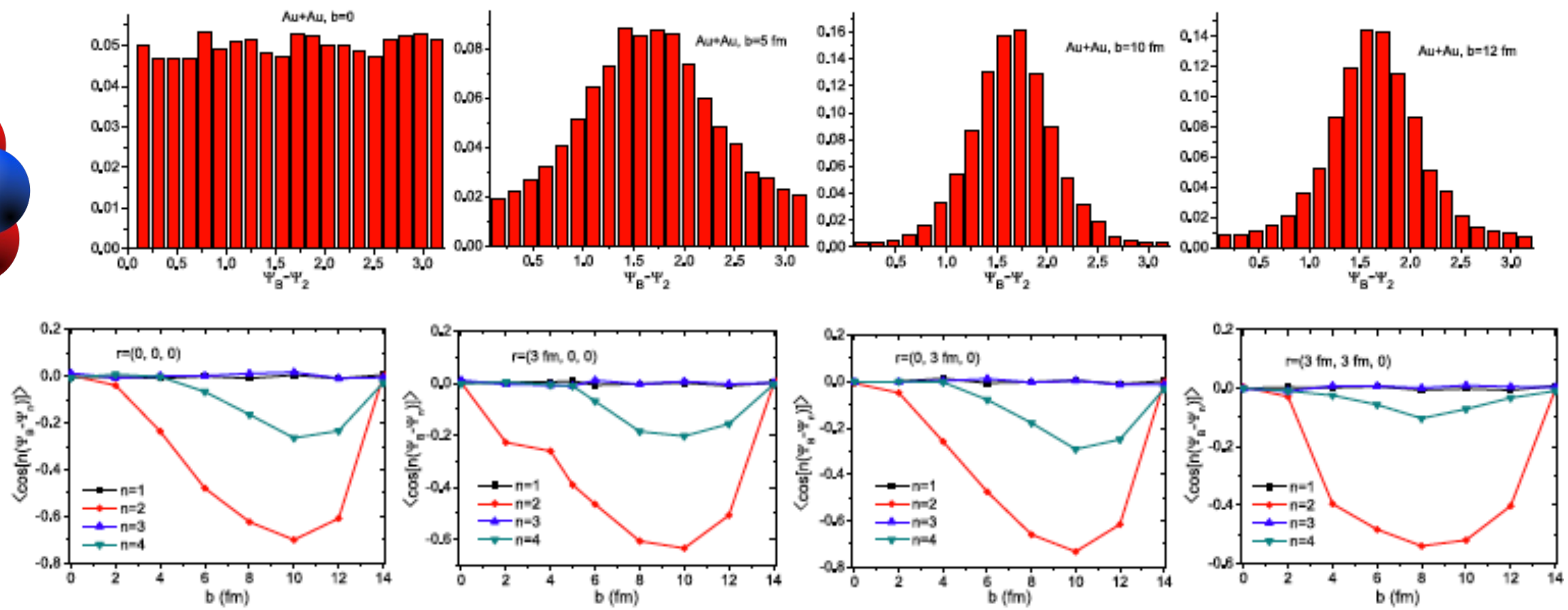
Azimuthally Fluctuating Magnetic Fields

Bloczynski, et al, arXiv:1209.6594[PLB]

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***



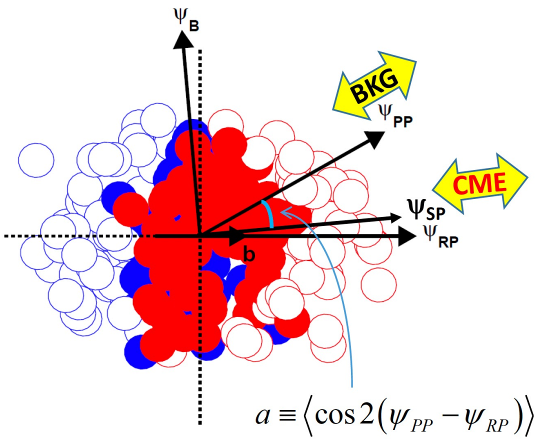


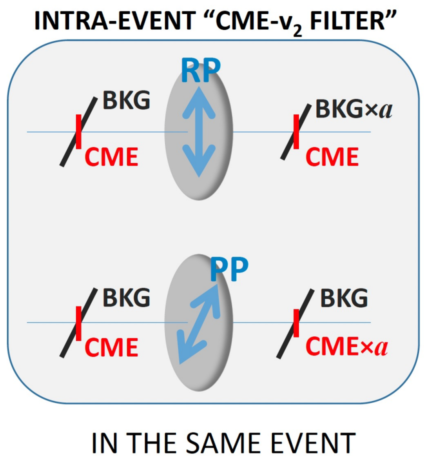


B field has different angular (de-)correlation with RP and with EP,
and is NOT correlated with triangular-EP
—— a valuable feature for validating B-field induced signal !!

Event-Plane/Spectator-Plane Contrast

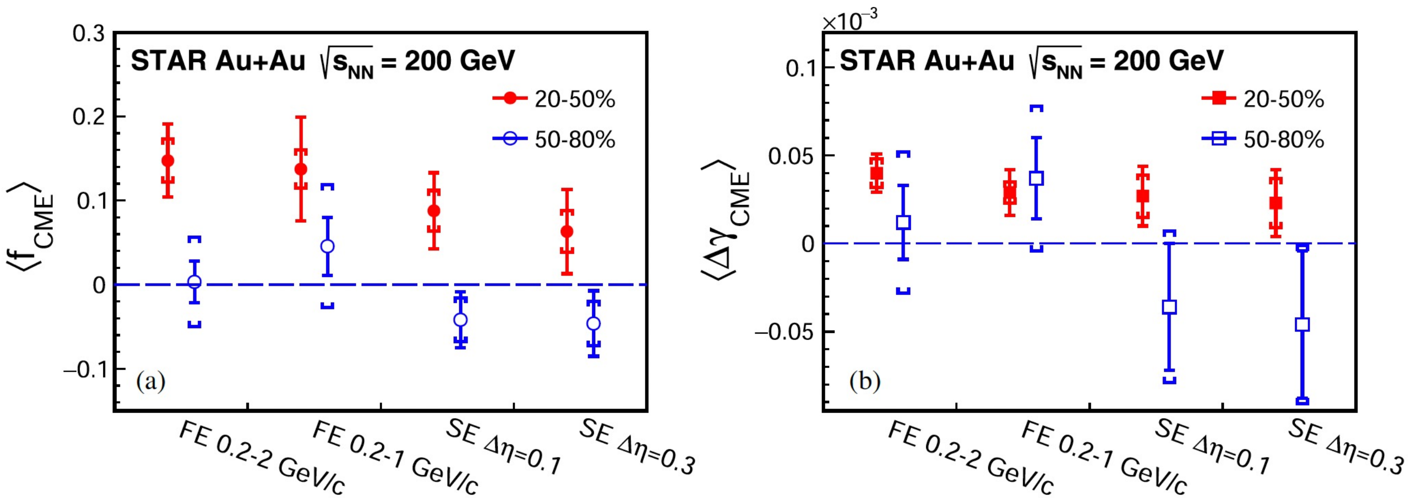
H.-j. Xu, FW, et al., CPC 42 (2018) 084103, arXiv:1710.07265
S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300





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

[From: F. Wang talk @QM22]



[STAR PRL128,092301(2022)]

Discussions on CME Search: Current Status

- ***LHC: stringent limits; likely not detectable***
- ***RHIC AuAu: Nonzero signal @ 200GeV, 1~3 sigma level***
- ***Isobar: high precision data revealing bulk property (and thus background) variation; baseline in need of calibration; room for a signal fraction at few percent***

Discussions on CME Search: What's Next

- ***Isobar: 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***