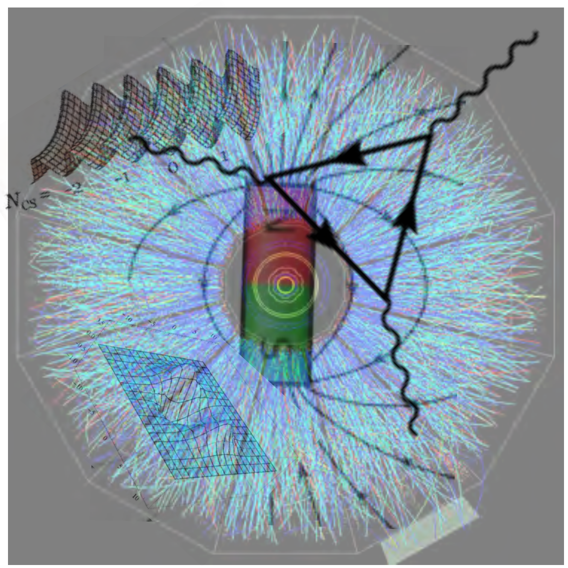
ATHIC2021@ Incheon Nov. 6, 2021

CME: What is the next step after the isobar result?



Jinfeng Liao

INDIANA UNIVERSITY

BEST COLLABORATION

Chirality 2021 @ Stony Brook

[***https://indico.bnl.gov/event/7012/***]

Outline

- *Introduction on Chiral Magnetic Effect (CME)*
- *Search for CME in heavy ion collisions*
- *The isobar collision experiment*
- *What's next?*

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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

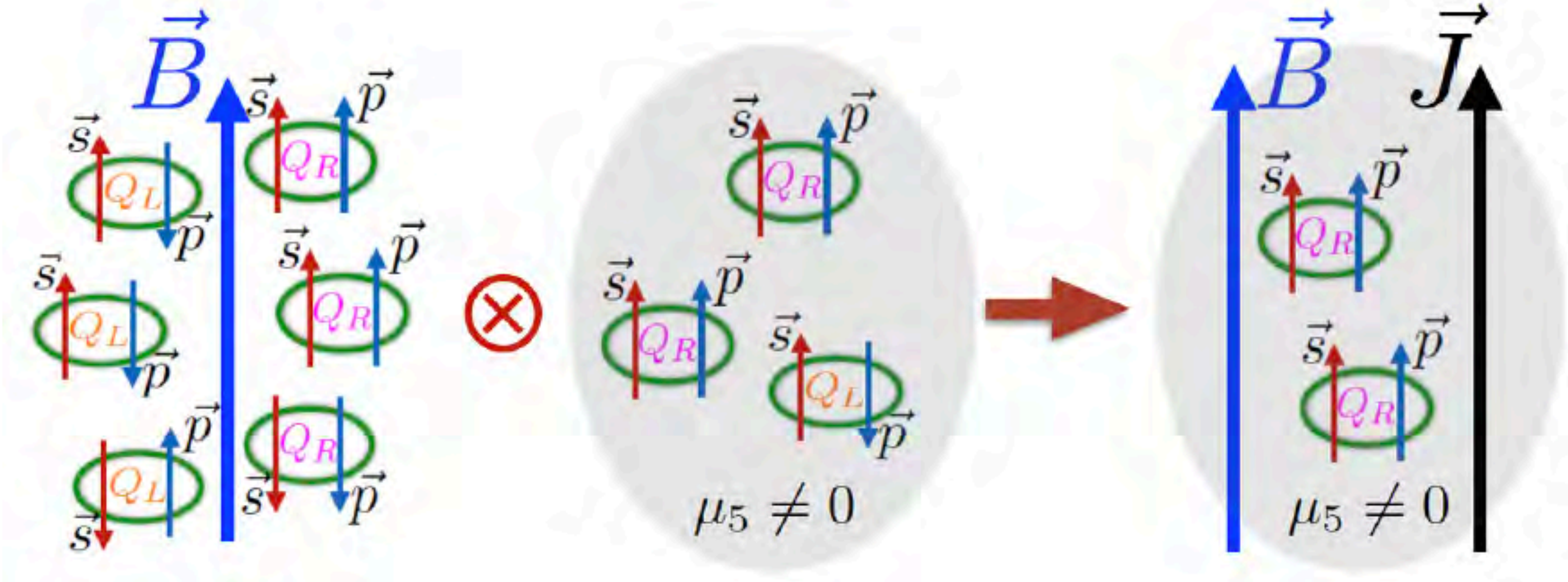
Electric Current

Magnetic Field

Q.M. Transport

[Kharzeev, Fukushima, Warringa, McLerran, …]

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

Intuitive understanding of CME:

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

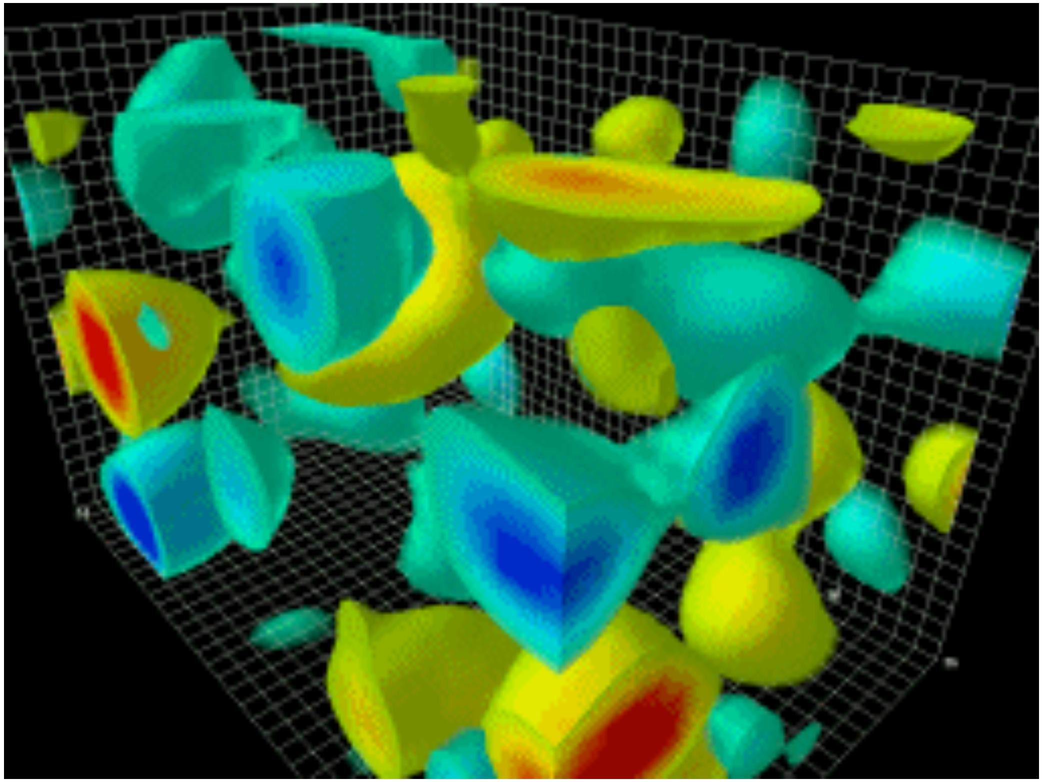
$\otimes$

Chirality Polarization —> correlation between directions of SPIN & MOMENTUM

Transport current along magnetic field

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

From Gluon Topology to Quark Chirality



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

Quarks

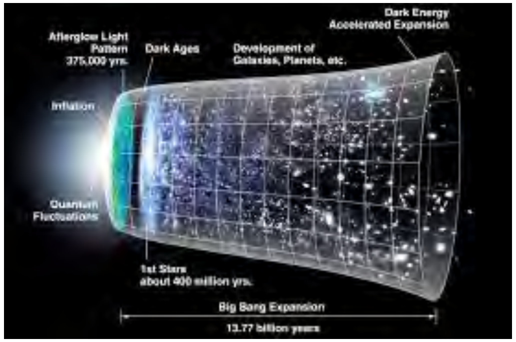
$$N_5(t \to +\infty) - N_5(t \to -\infty) = \frac{g^2}{16\pi^2} \int dt d^3\mathbf{r} \, G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

QCD anomaly: gluon topology —> chirality imbalance

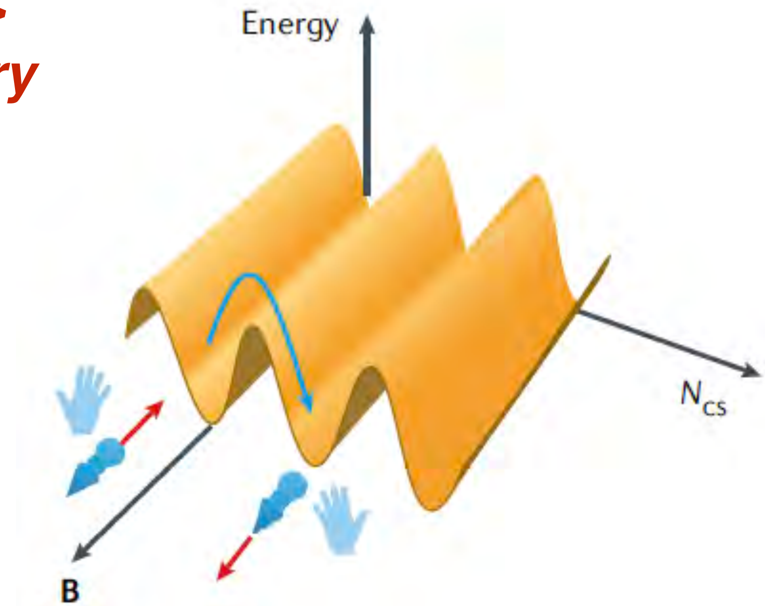
$$N_R - N_L = N_5 = 2Q_w$$

Net chirality <—> topo fluctuations & chiral restoration

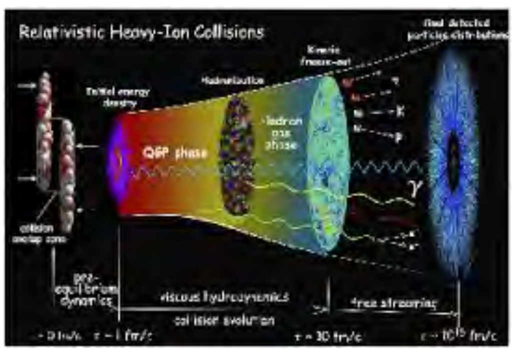
CME: A Cosmic Connection



Cosmic topo.—> Baryon Asymmetry



Rapidly expansion + Topological transitions in non-Abelian gauge plasma



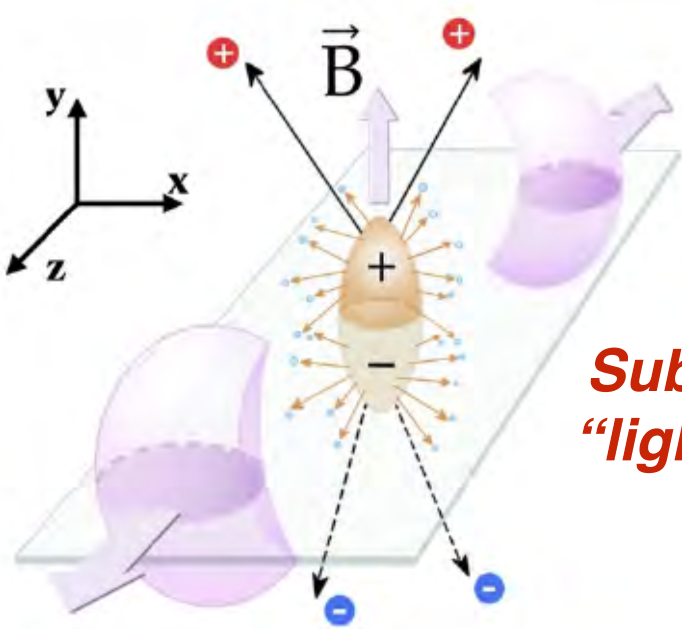
Heavy ion topo.—> Chiral Asymmetry

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

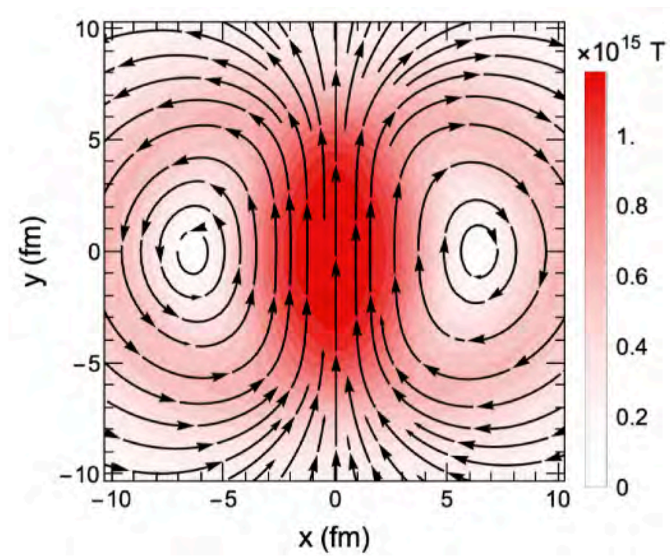
CME: Strong Interdisciplinary Interests

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

Heavy Ion Collision: the Most Magnetized Fluid



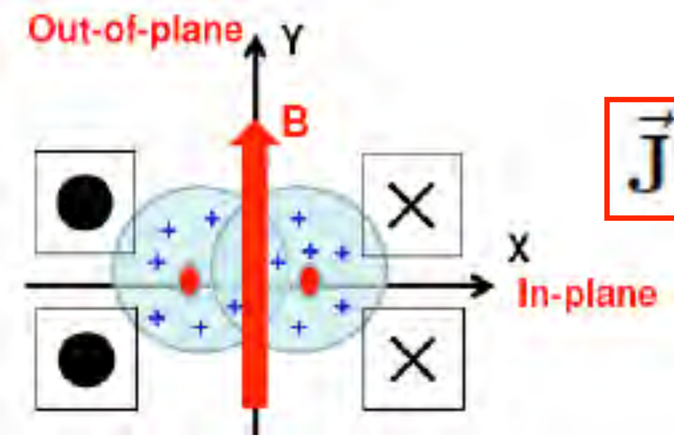
Subatomic "lightning"!



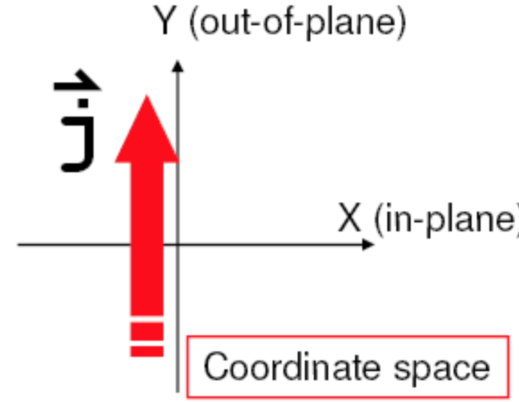
The strongest B field ~ 10^15 Tesla

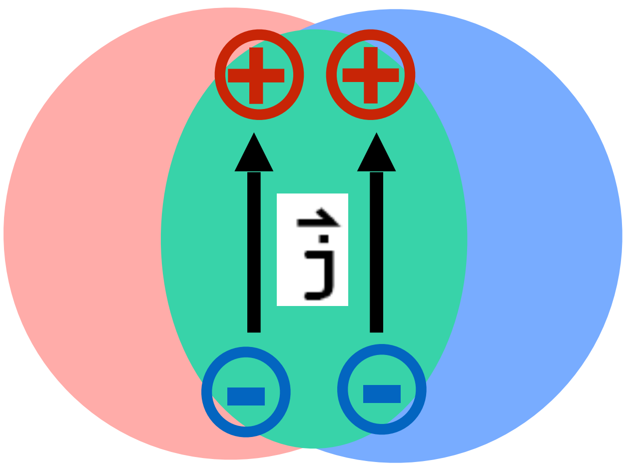
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

From CME to Charge Separation

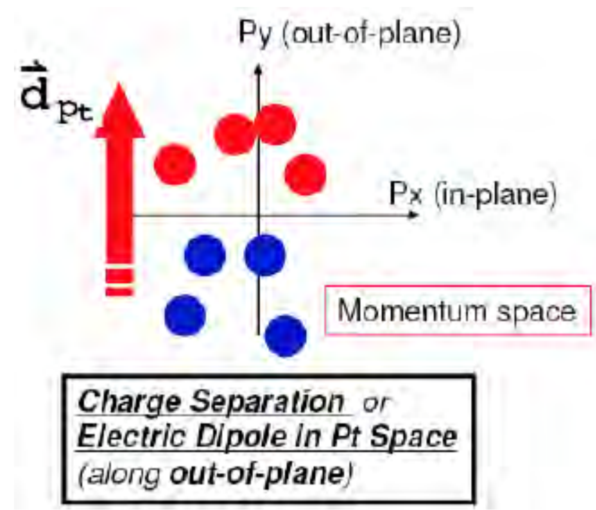


$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$





strong radial blast:
position —> momentum



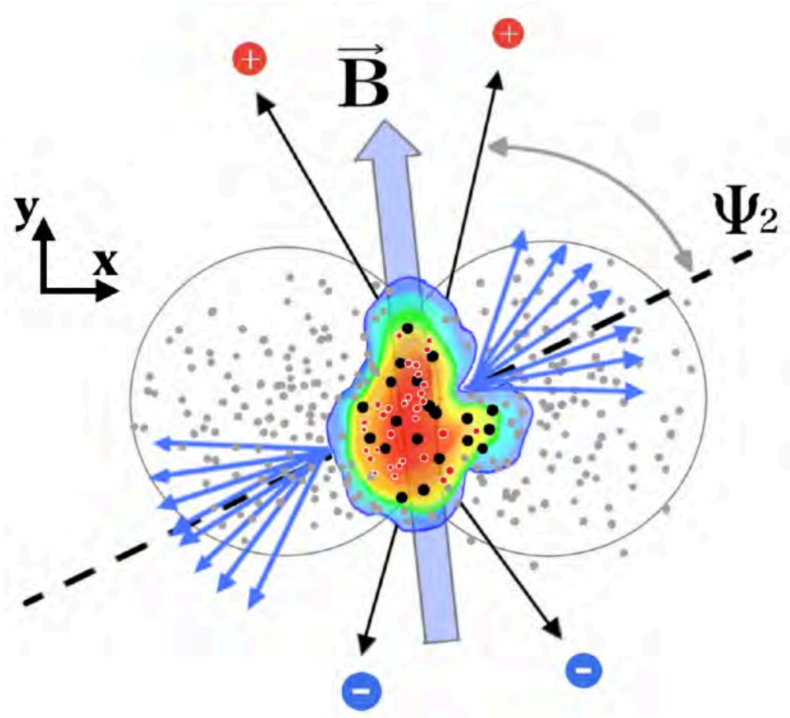
$$\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})$$

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

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

Looking for CME Signals in Nuclear Collisions

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



Gamma-correlator;
Gamma + v2 subtraction;
Gamma + event shape;
Gamma RP versus EP;
Gamma + invariant mass;
Signed balance function;
R-correlator

[arXiv:2105.06044]

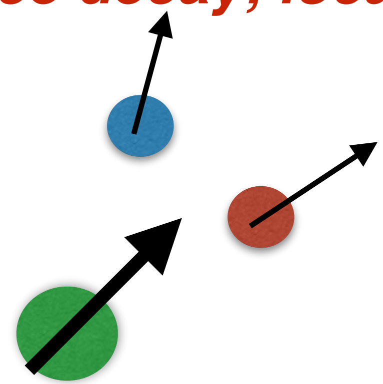
A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

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)

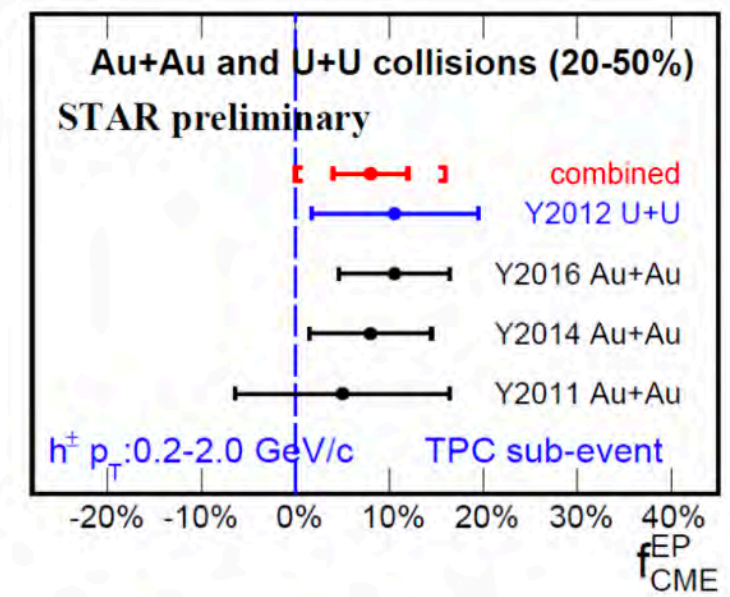


Roughly scaling ~ v2 / N

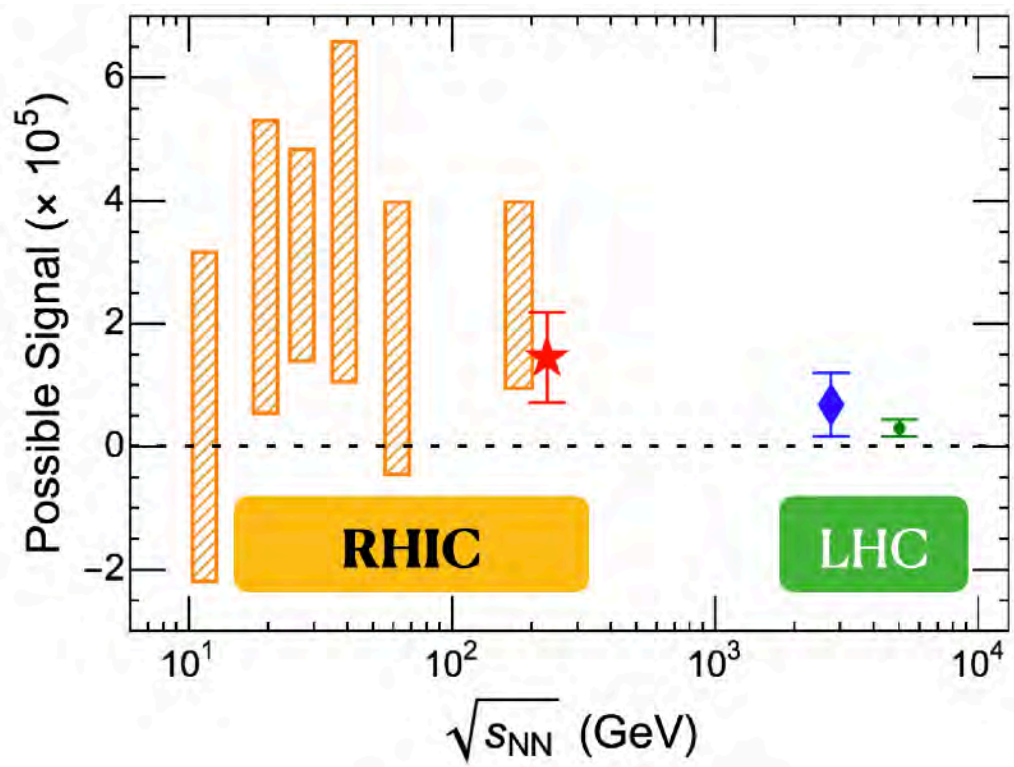
Redefining the question: extracting / constraining the fraction of CME signal within the measured correlations

Where Do We Stand?

[STAR compilation @QM19]



A very positive hint, yet inconclusive.



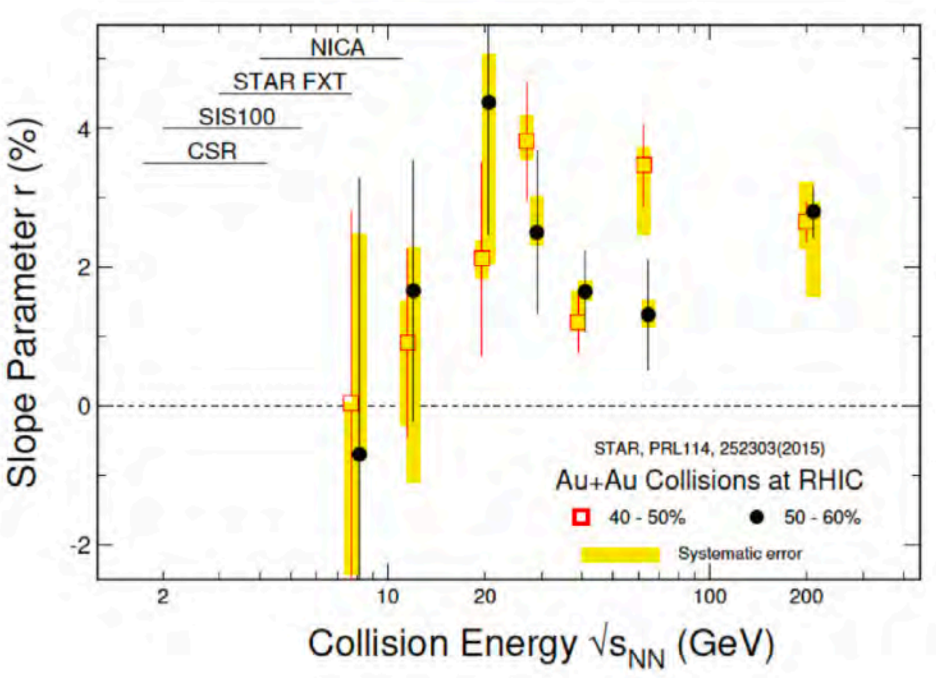
[Kharzeev, JL, arXiv:2102.06623; Nature Rev Phys 3, 55-63 (2021)]

Chiral Magnetic Wave

A related search: chiral magnetic wave (CMW)

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

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



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

Experimental data: very positive hints, need quantitative modeling.

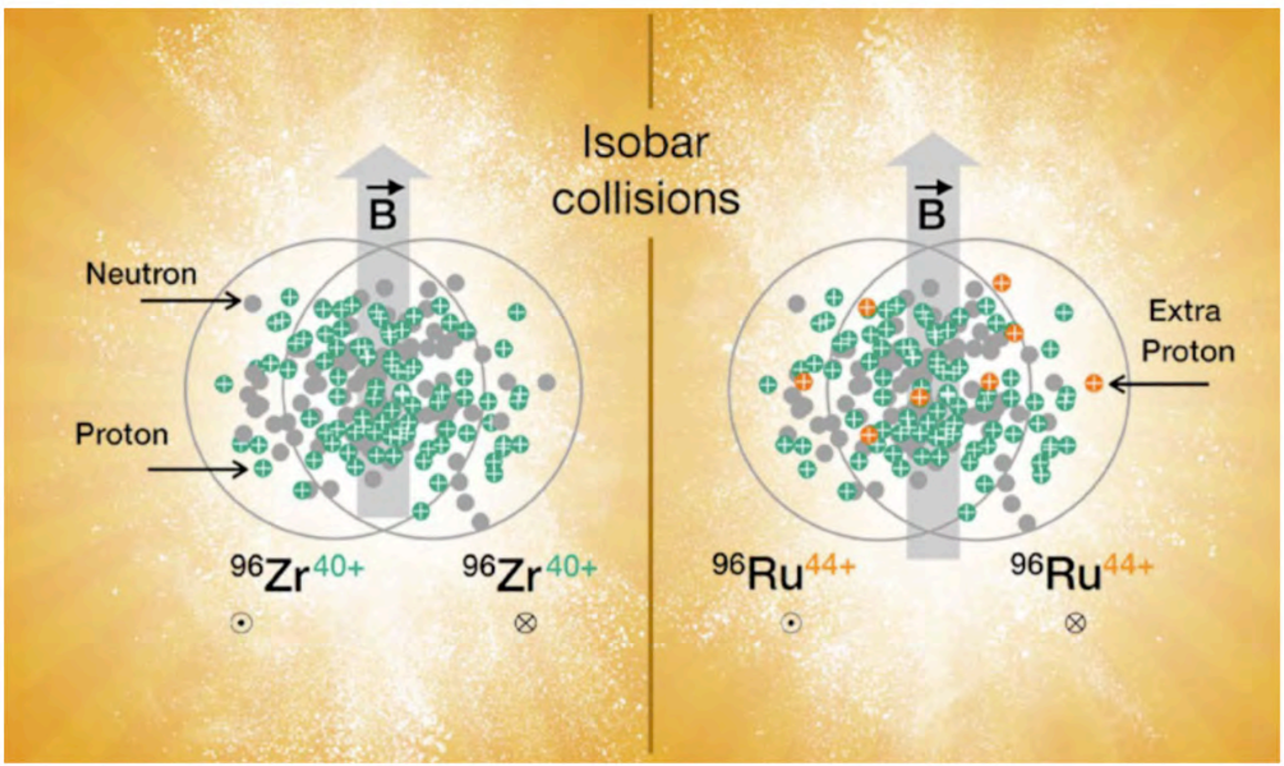
From:Phys. Rep. 853(2020)1-87.

The Isobar Collision Experiment

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

Chiral Magnetic Effect Task Force Report

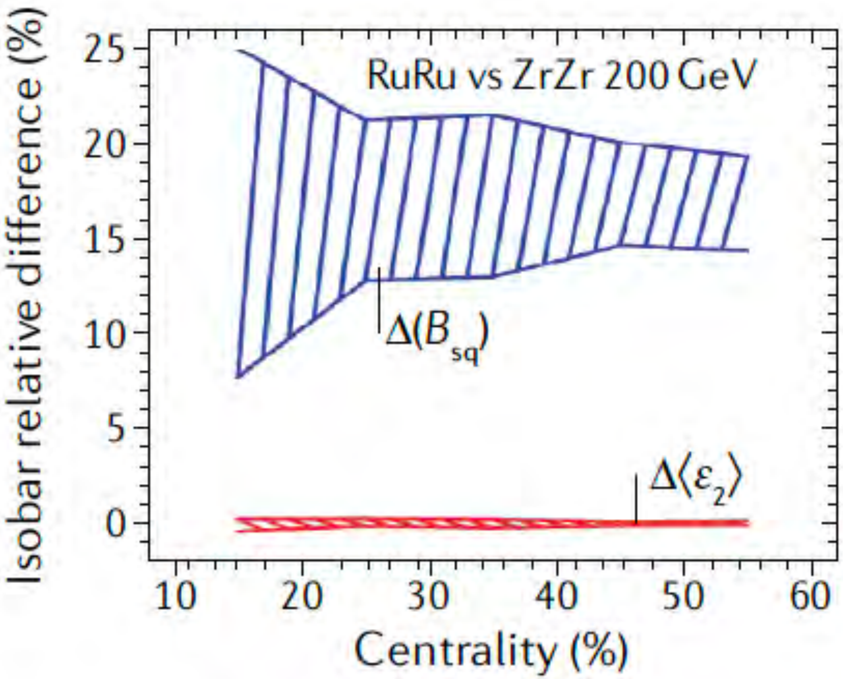
Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

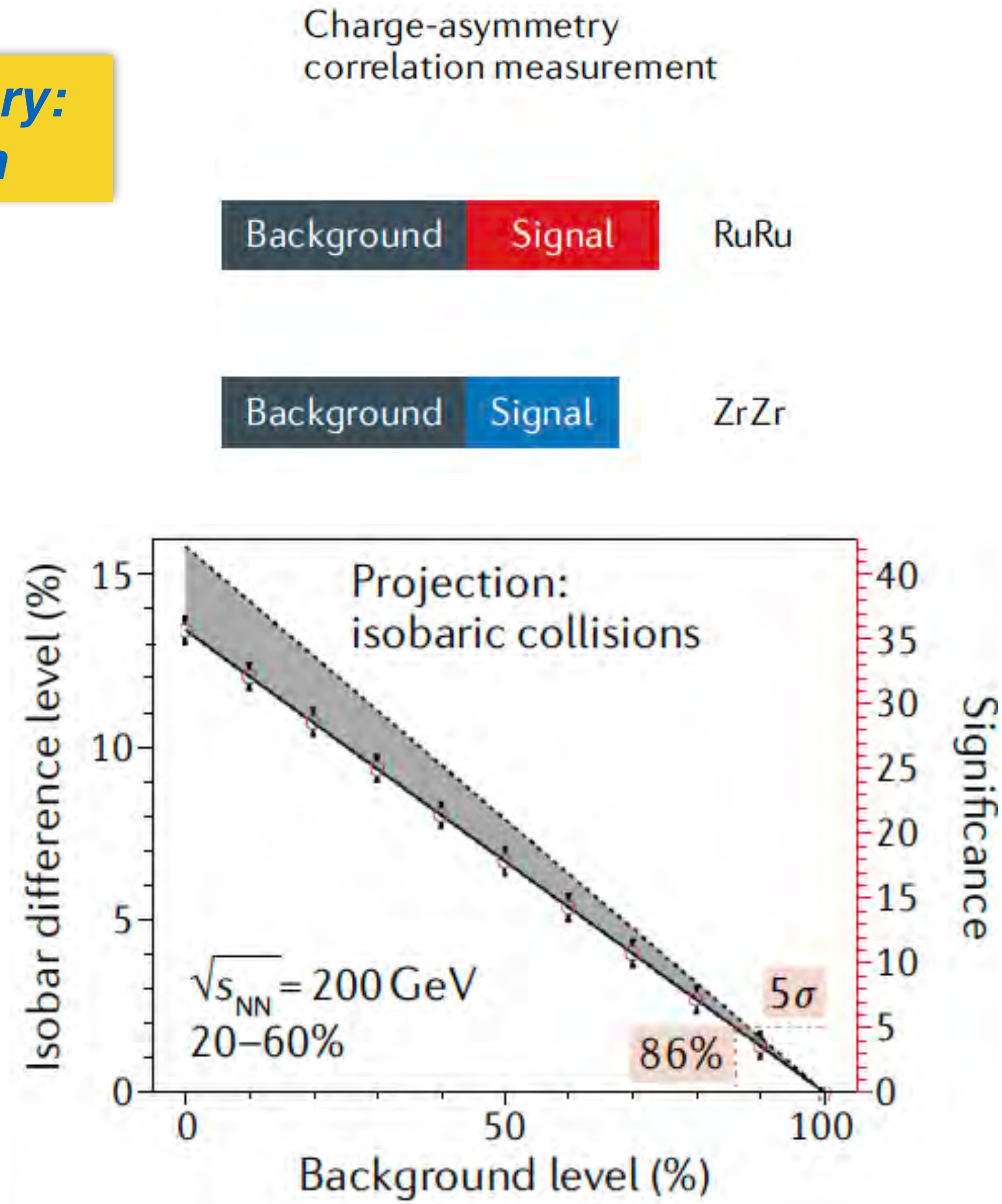


[image from Helen Caines talk @ Chirality 2021]

The Isobar Collision Experiment

Exciting opportunity of discovery: 2 billion events for each system



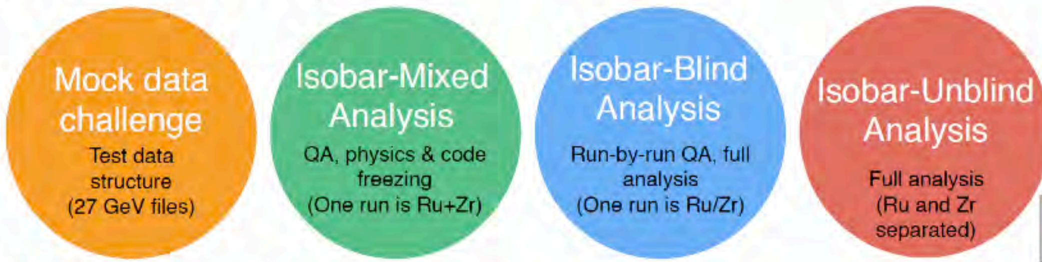


The Isobar Collision Experiment

Decision to blind the analyses

2017 PAC recommended ***blind analyses*** of ***CME*** using Run-18 isobar data

Methods developed and accepted by collaboration in January 2018, well before 2018 data-taking



STAR, arXiv:1911.00596
Cartoon: arXiv:2009.01230

Step-1, "The Reference"

Provide output files composed of collision data from a ***mix*** of the two isobar species

As much as possible, order of collision "events" ***respects time-dependent changes in detector conditions***

Analysis code and **time-dependent QA** tuned and frozen

Step-2, "The run by run QA sample"

Provide files that blind the isobar species but do not "mix" data from different data acquisition runs

Only allow "run-by-run" corrections and code alteration directly resulting from these correctior

Step-3, Full un-blinding

Analysis completed and published as is

Combined effort of many many people in STAR

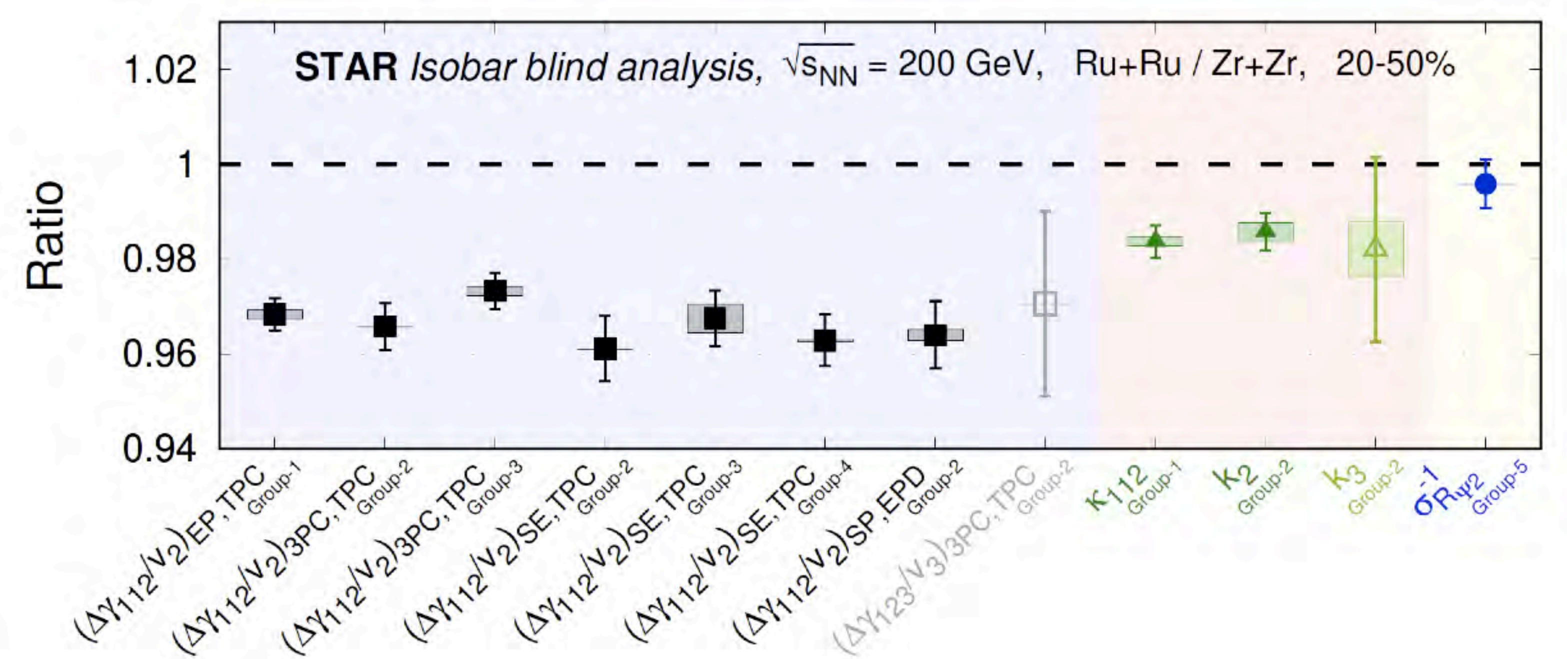
[image from Helen Caines talk @ Chirality 2021]

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

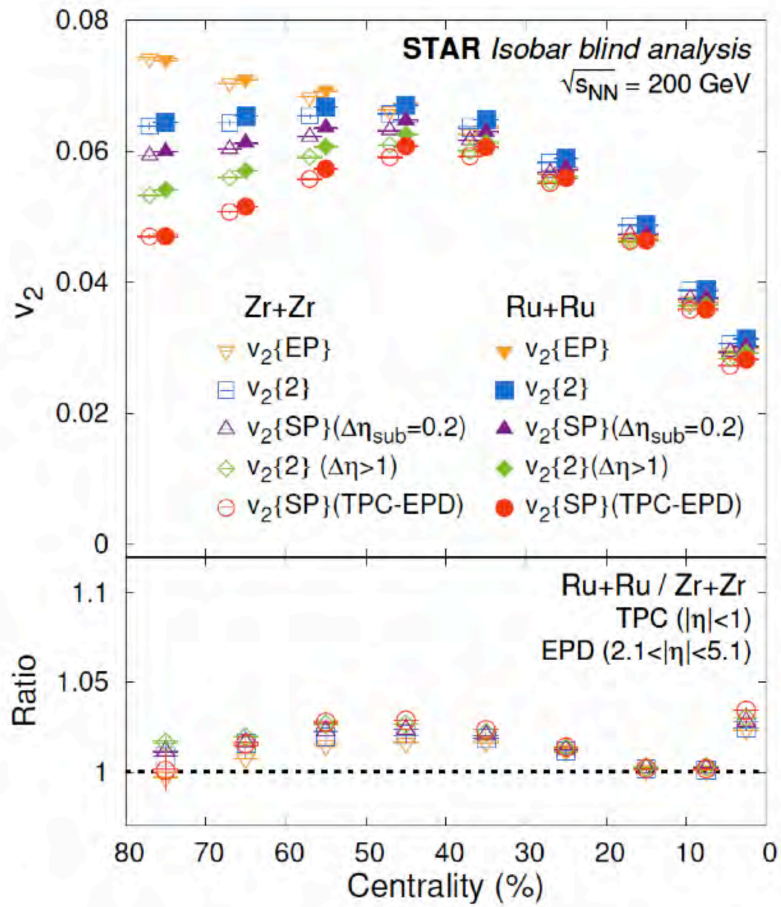
Predefined criteria: Signal(Ru)/Signal(Zr) > 1

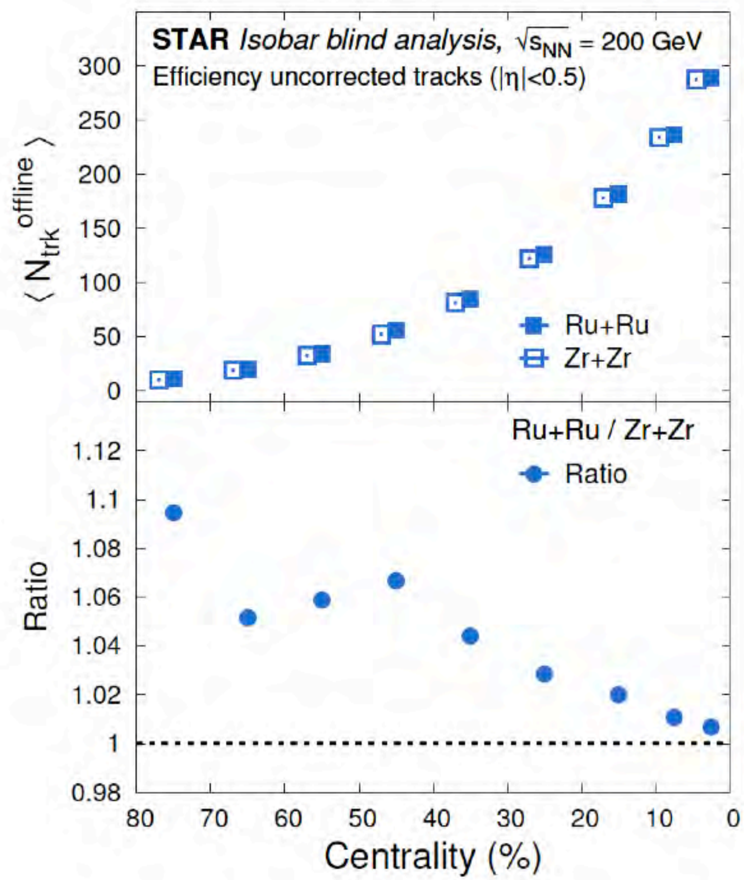
[STAR paper: 2109.00131]



No CME signal per the predefined criteria;
However — not in line with pure background either ?!

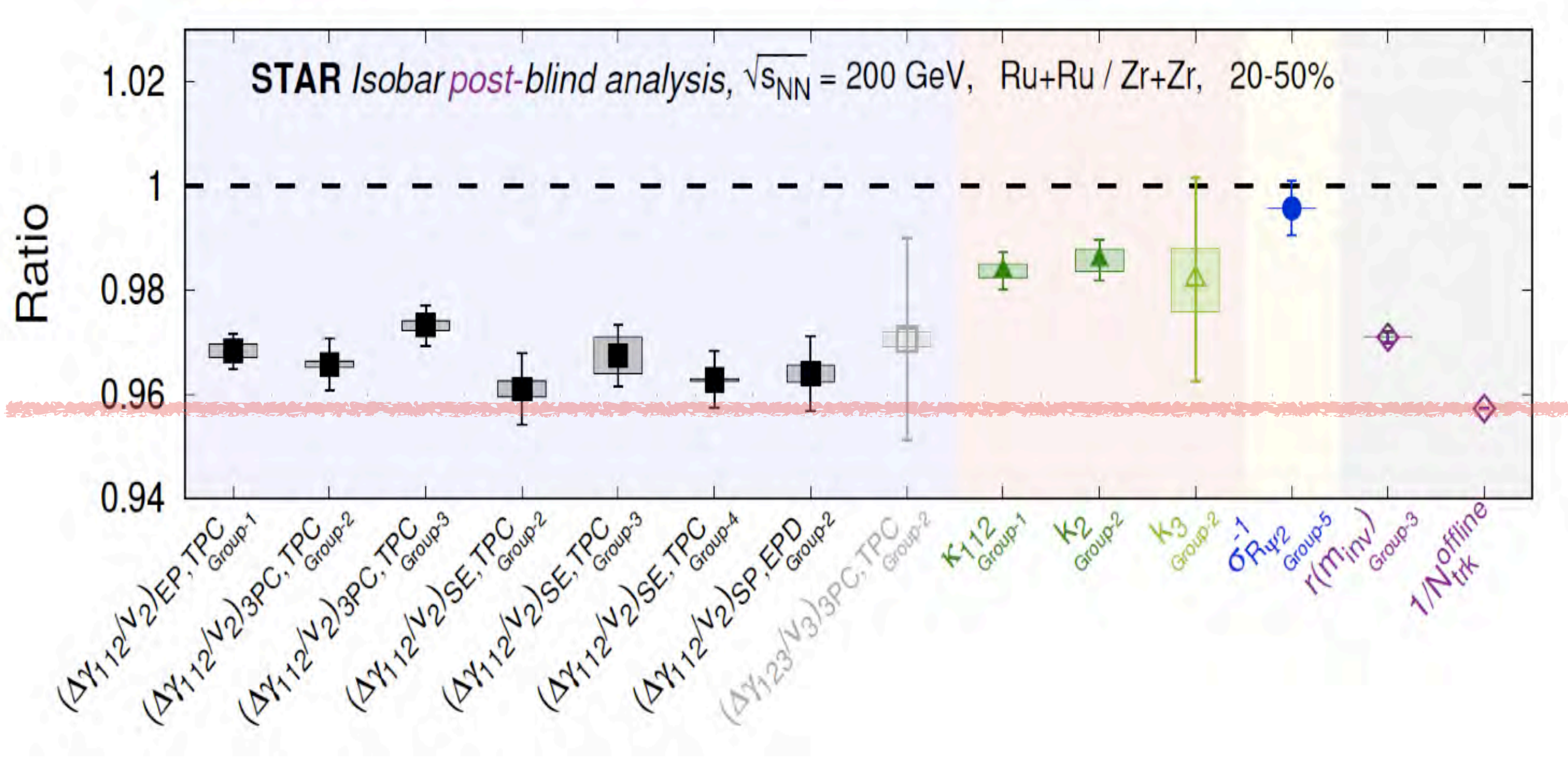
The Trouble: A Failed Assumption





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

Where is the Baseline ?!

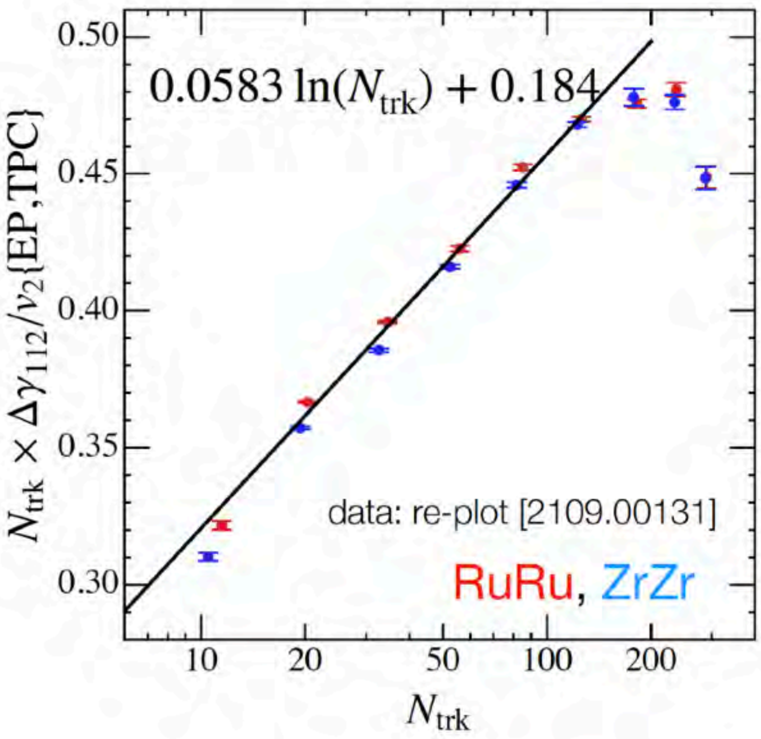


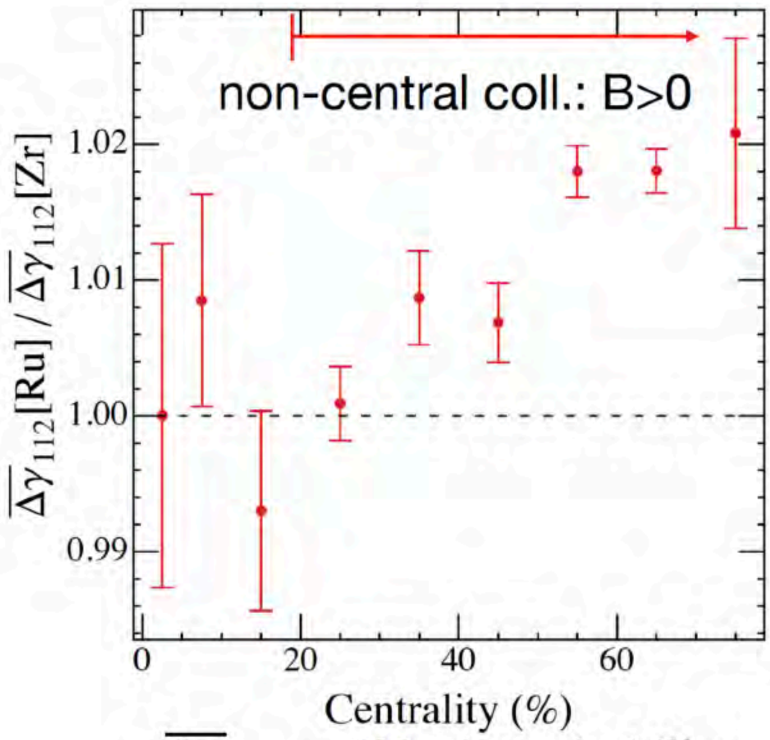
There appears to be room for potential CME signal above the 1/N baseline!!

Digesting the Isobar Results

[from Shuzhe Shi talk @ Chirality 2021]

CME expectation: $\Delta\gamma_{112}[\mathrm{Ru}] > \Delta\gamma_{112}[\mathrm{Zr}]$

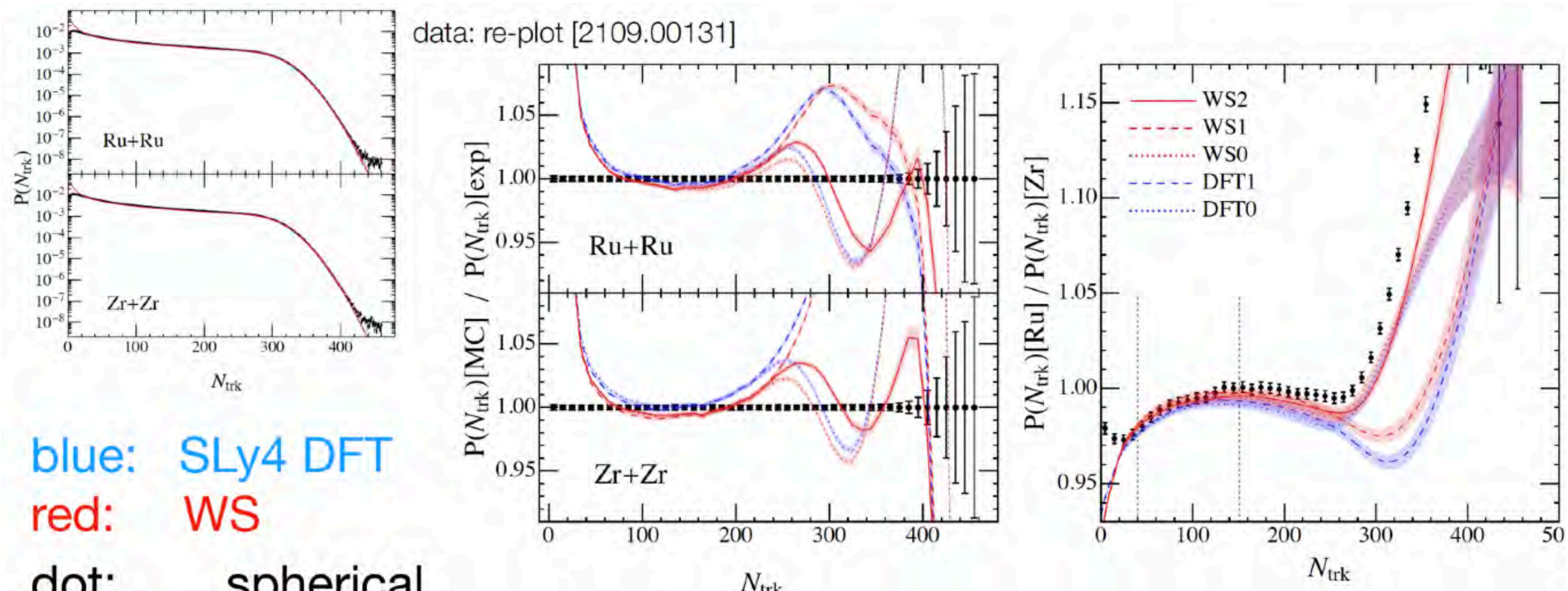




$\overline{\Delta\gamma}_{112} \equiv (N_{trk}\Delta\gamma_{112}/v_2)/\mathrm{line}$

Digesting the Isobar Results

[from Shuzhe Shi talk @ Chirality 2021]



blue: SLy4 DFT

red: WS

dot: spherical

dash: deformed, same R and a as dotted lines

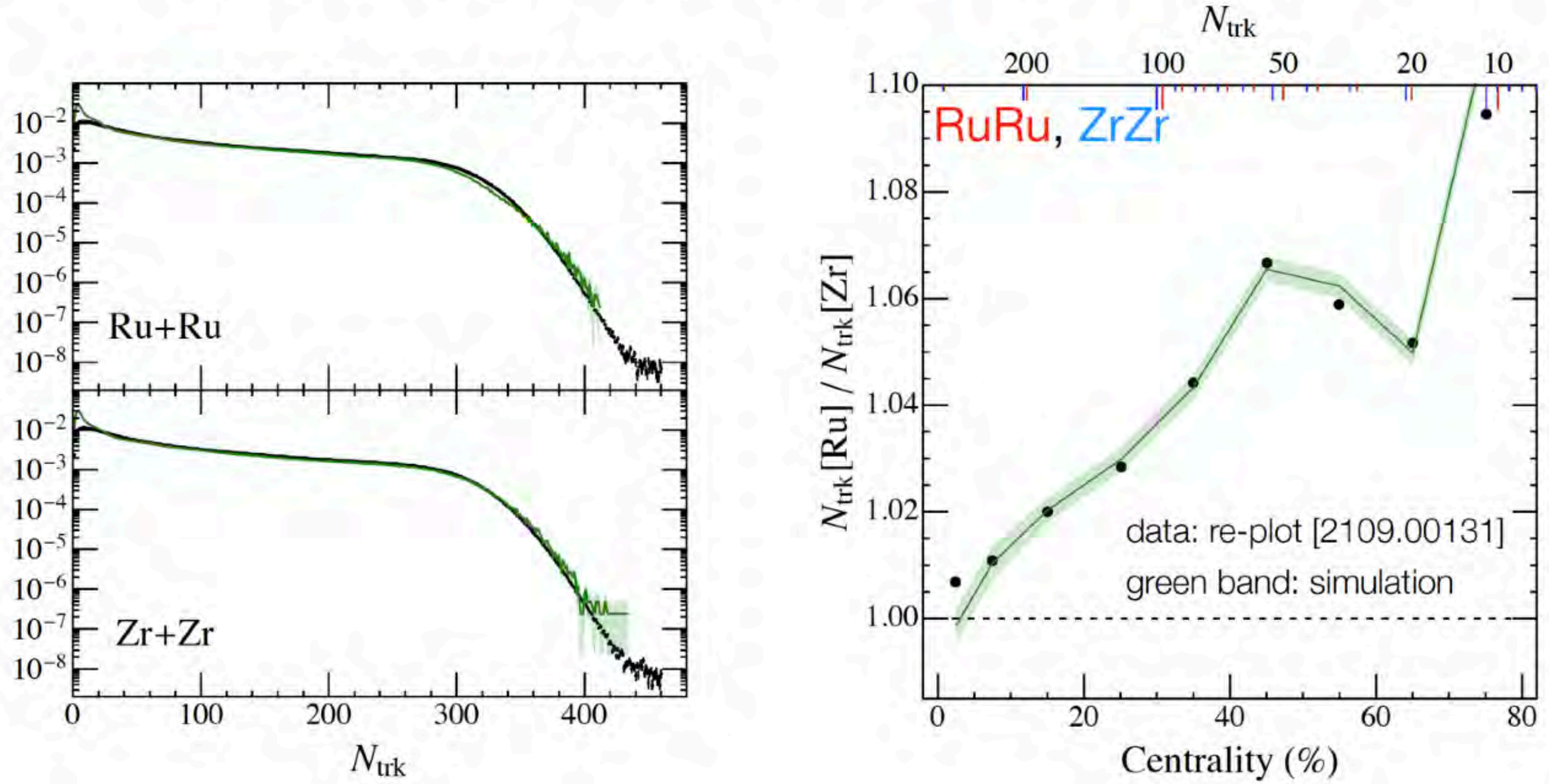
solid: deformed, new R and a to fit $\langle r \rangle, \langle r^2 \rangle$

Sensitivity to nuclear structure inputs

Digesting the Isobar Results

[from Shuzhe Shi talk @ Chirality 2021]

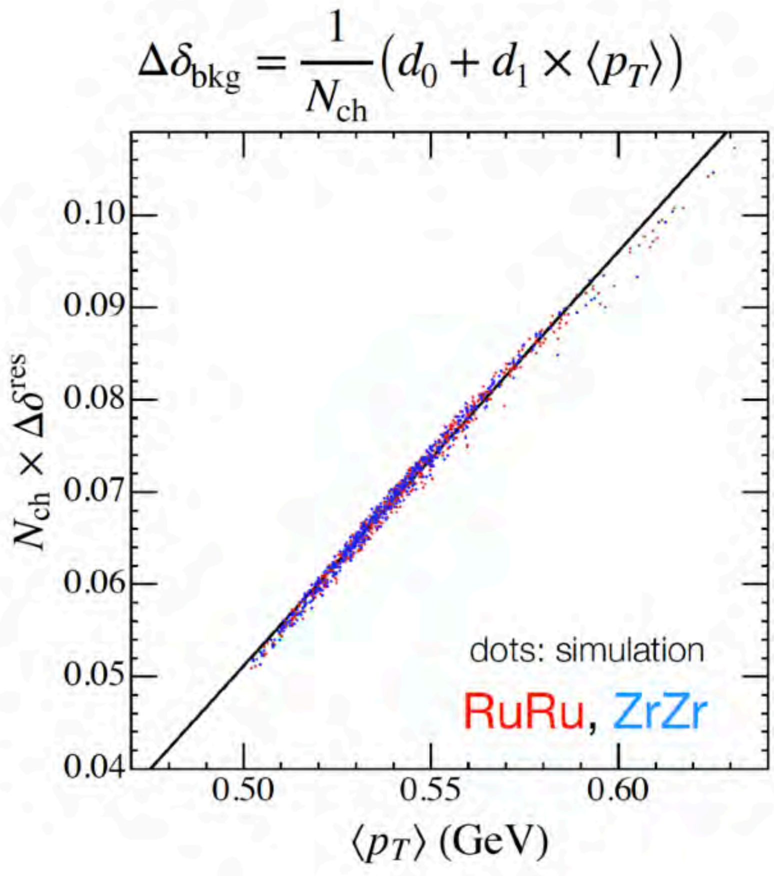
multiplicity ratio [MC Glauber + hydro + hadron scattering]

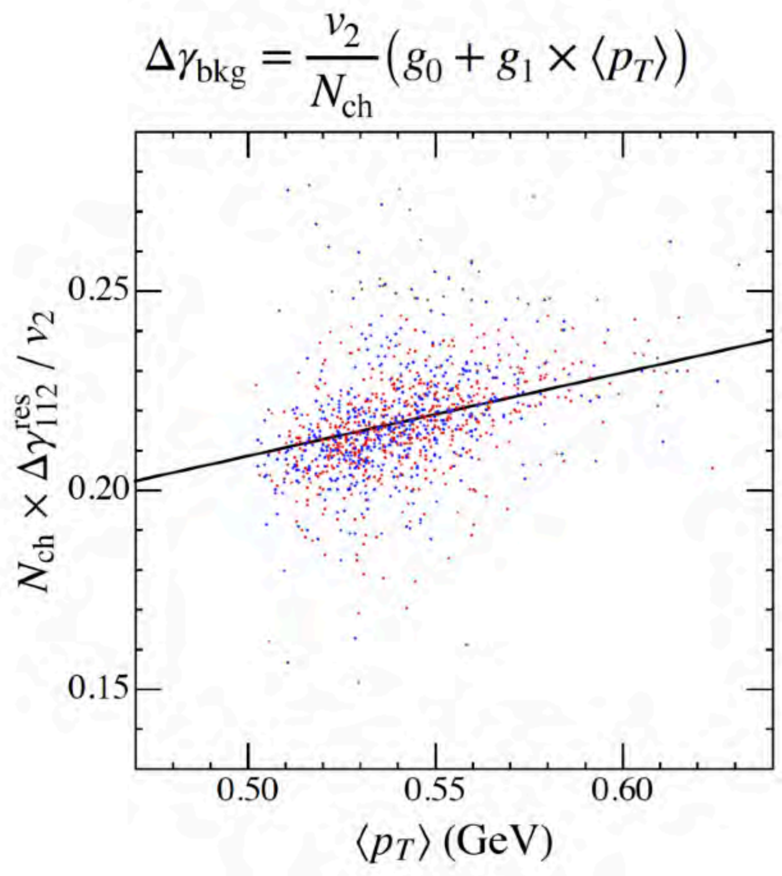


The multiplicity difference is mainly a consequence of the multiplicity cuts applied for defining centrality classes.

Digesting the Isobar Results

[from Shuzhe Shi talk @ Chirality 2021]



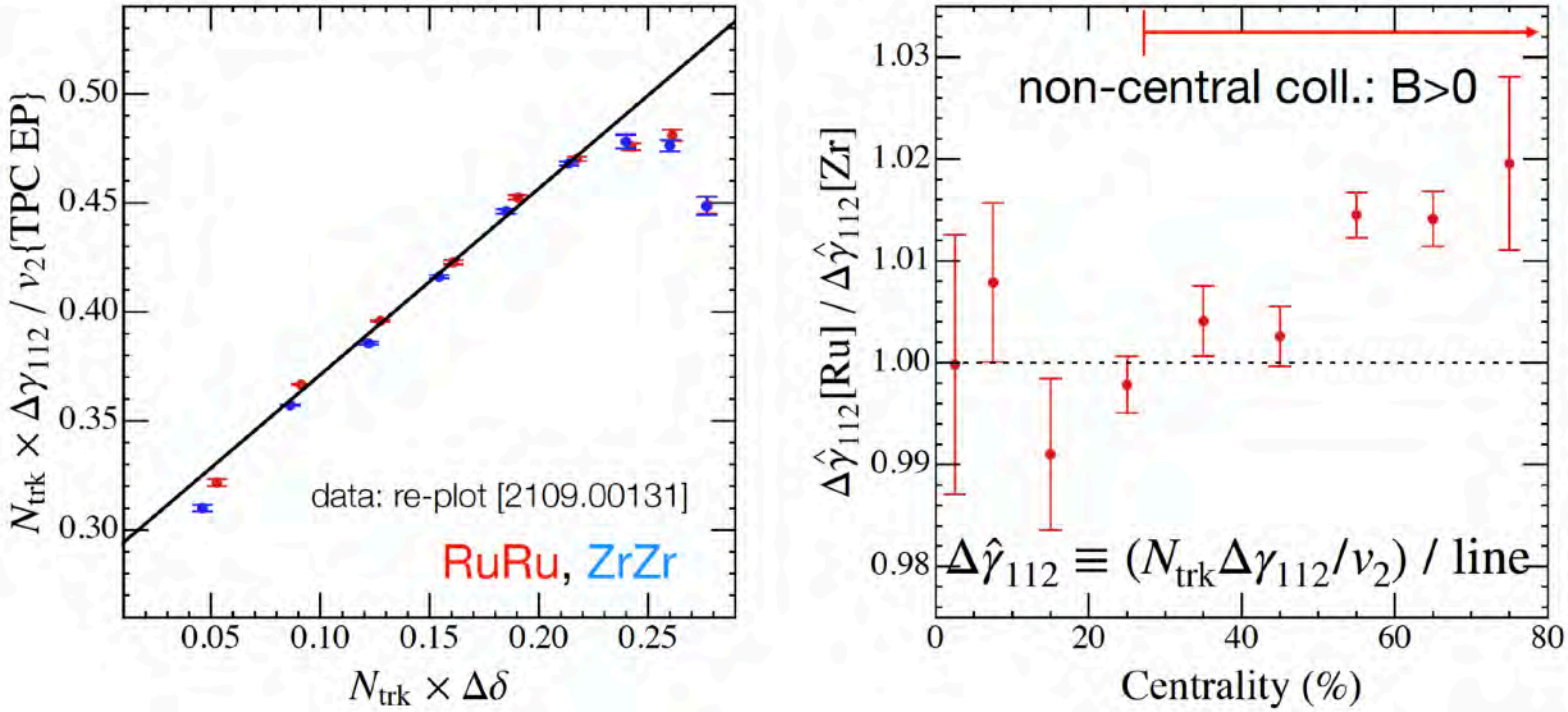


The background issue is more than just multiplicity.
Minor difference in radial flow "push" has a visible imprint on background correlations.

Digesting the Isobar Results

[from Shuzhe Shi talk @ Chirality 2021]

experiment: inconsistent with pure background expectation in non-central collisions ---> CME?

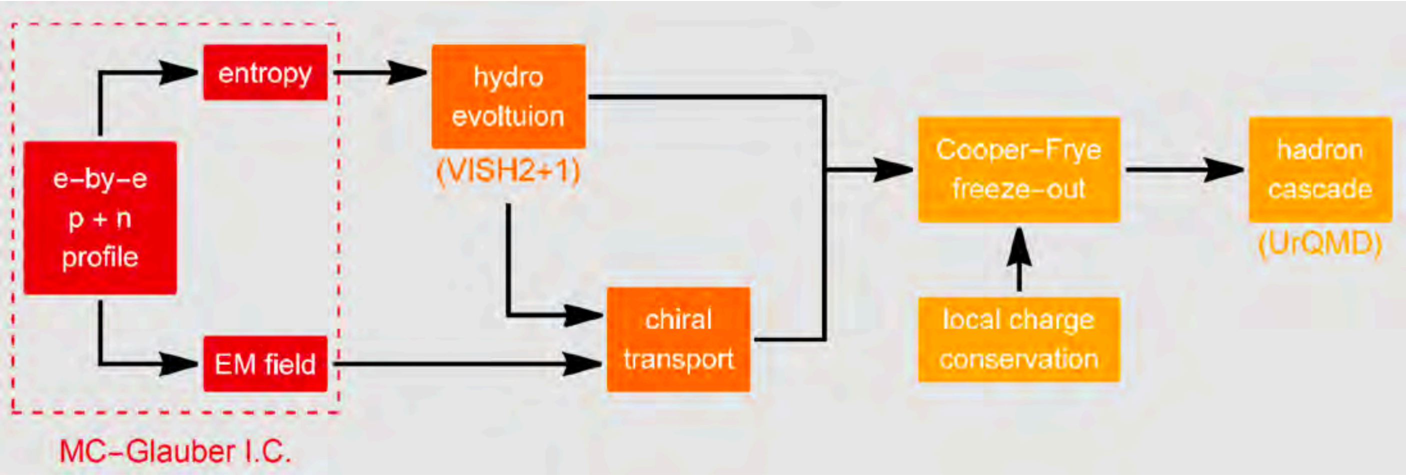


It would be very difficult to interpret exp data with pure backgrounds. CME signal is perhaps rather weak, albeit still possibly detectable. Lots more TH/EXP works are needed to reach a conclusion.

The Next Steps

Near term focus of theoretical efforts:
nailing down the correct baseline for the isobar contrast;
requiring a precision understanding of isobar bulks

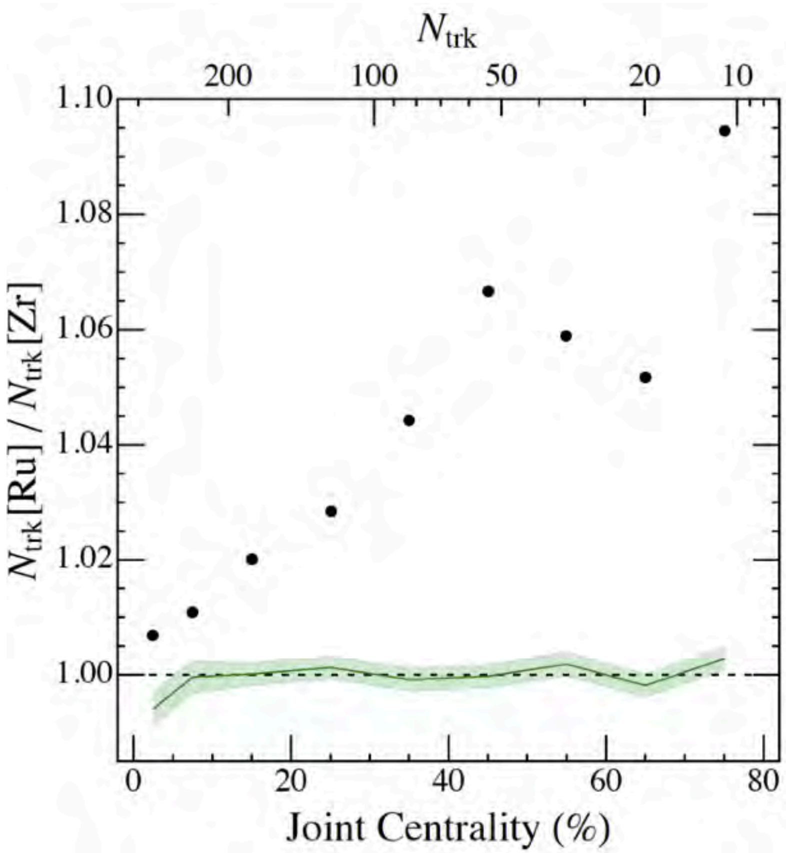
Anomalous-Viscous Fluid Dynamics (AVFD)
+ well informed nuclear structure inputs
+ data calibration for bulk properties
—> establish baseline for various observables
—> further examine responses to CME signals
—> quantify signal level in statistically meaningful way

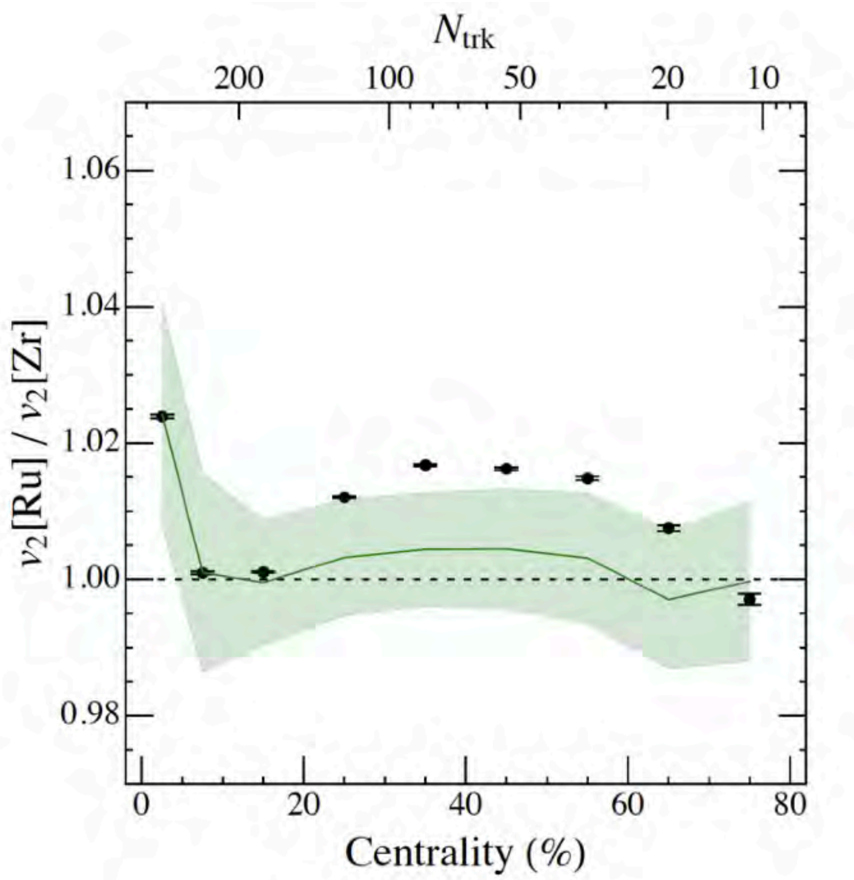


[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

The Next Steps

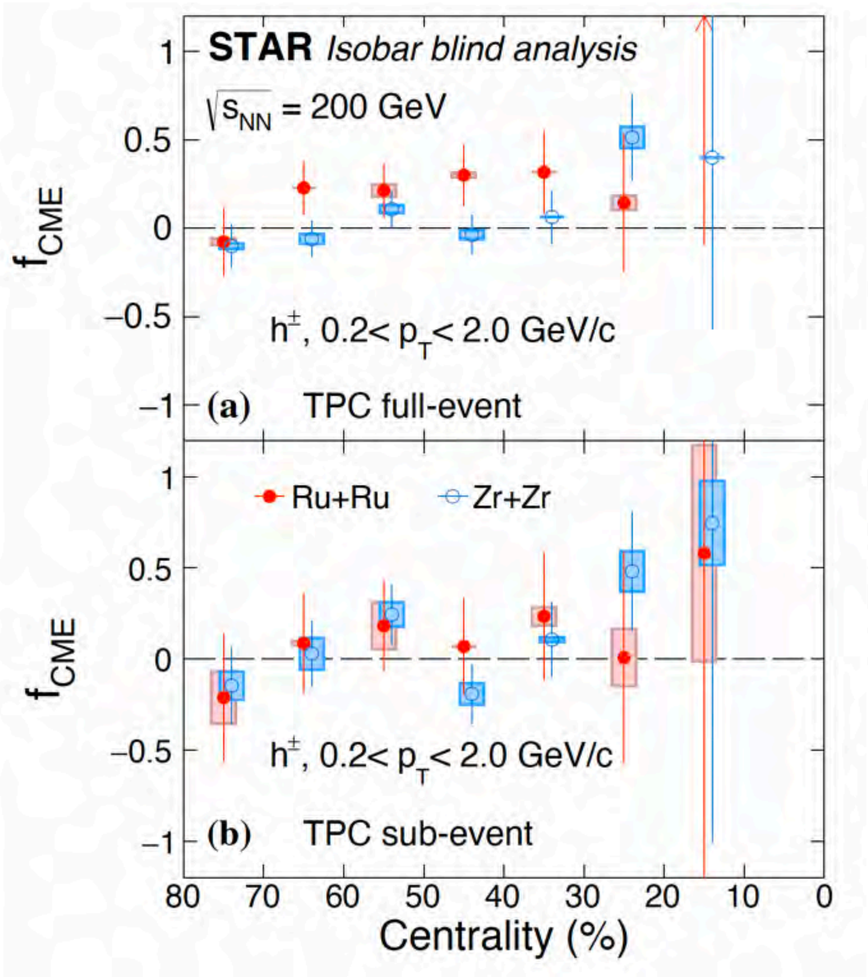
EXP analysis: e.g. using identical multiplicity cuts

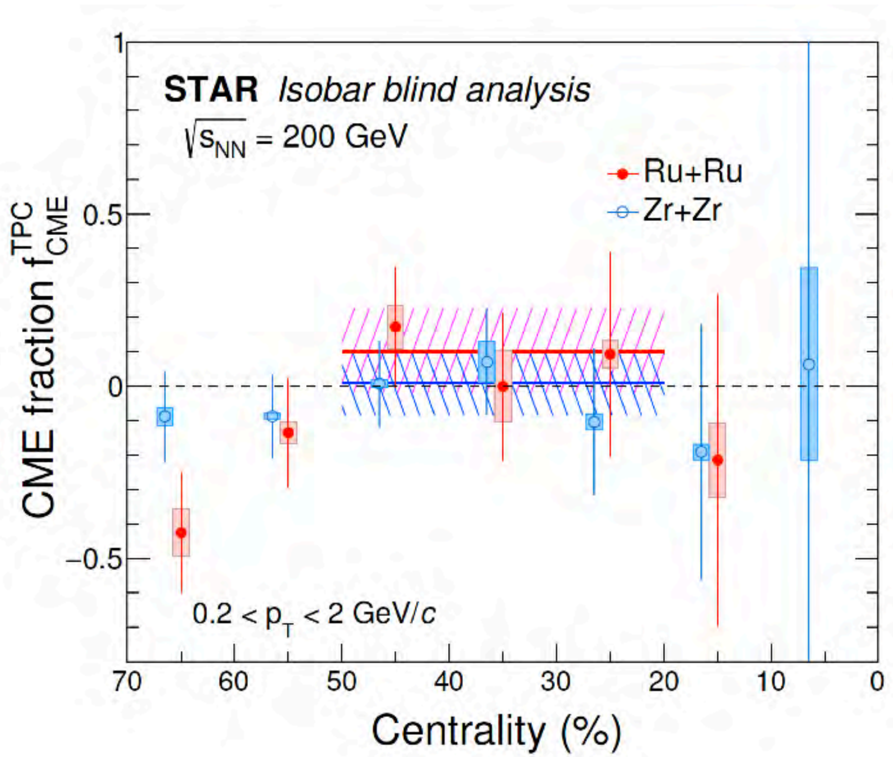




The Next Steps

Contrast v.s. Individual systems: e.g. SP/EP signals



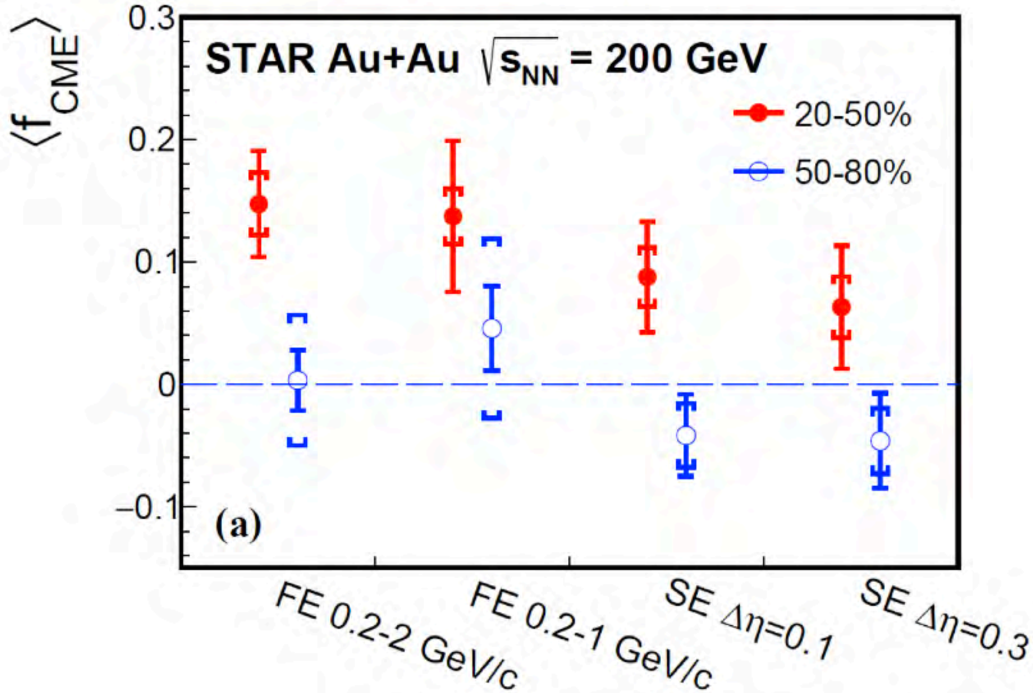


The Next Steps

A coherent understanding of AuAu + isobars is important.

Beam energy dependence of AuAu measurements e.g. via BES-II data would be very valuable too!

STAR, arXiv:2106.09243



[from Fuqiang Wang talk @ Chirality 2021]

Summary

- *Physics of CME is rich and fundamental.*
- *Search for CME in heavy ion collisions proves difficult but possible.*
- *Initial blind analysis results from isobar collision experiment does not reveal a signal based on predefined criteria. However, such criteria itself is invalidated by the same data.*
- *There is room for potential signal in isobar systems, and possibly even more room in AuAu provided a similar data precision.*
- *TH/EXP efforts are closely collaborating to carry forward the in-depth search. Stay tuned!*