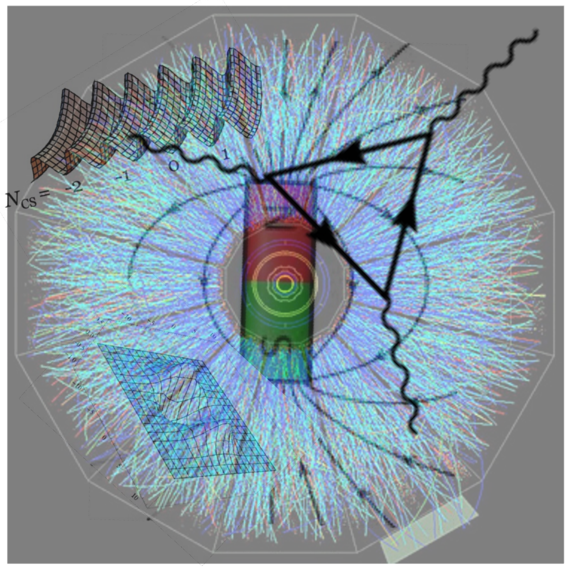
Jun. 16, 2024

Strong Interaction Matter Under Extreme Fields



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Plan of the Talk

– ***Brief Introduction***

– ***Chirality: the search for CME***

– ***Vorticity: angular momentum transport***

– ***Summary & Discussions***

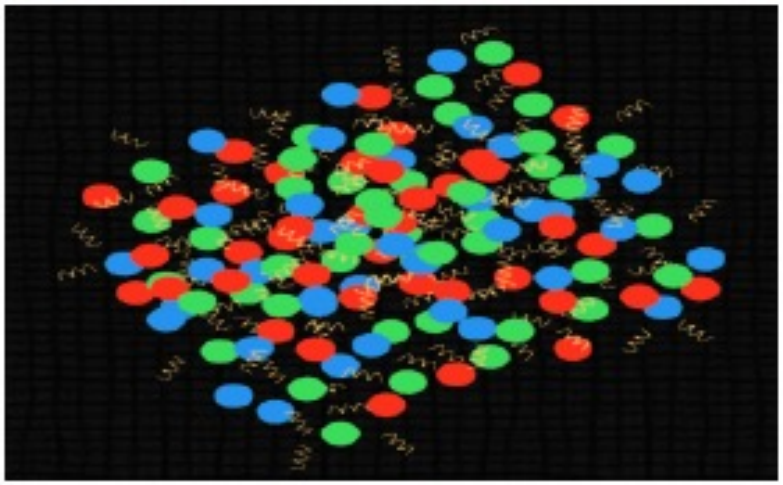
"Little Bangs": Yesterday Once More

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

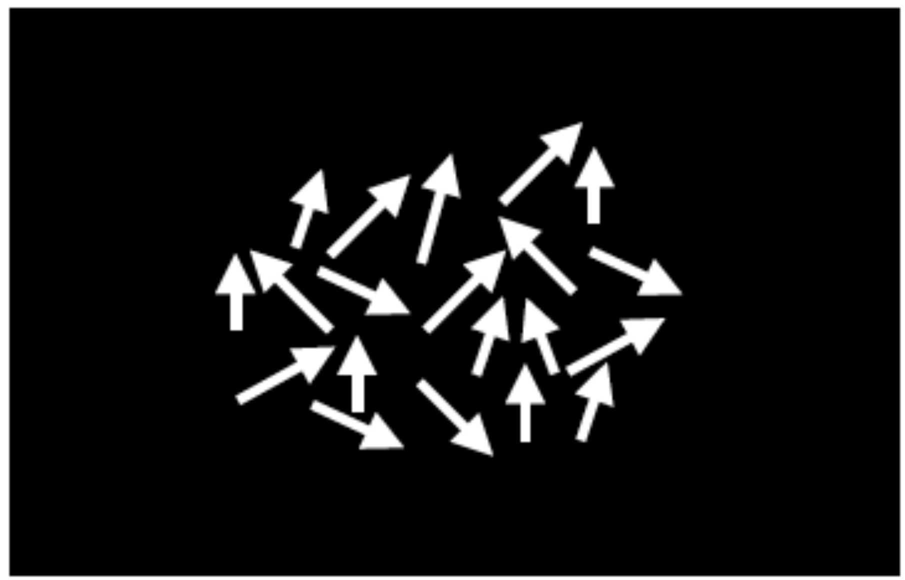
Heavy ion collision is the only venue for replicating and studying the early universe environment.

A Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)

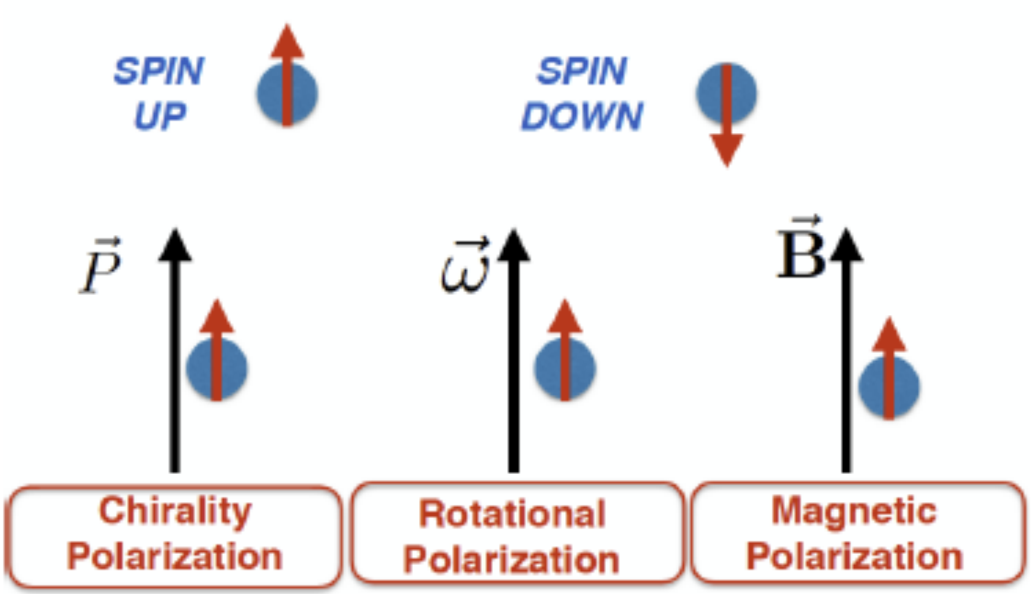


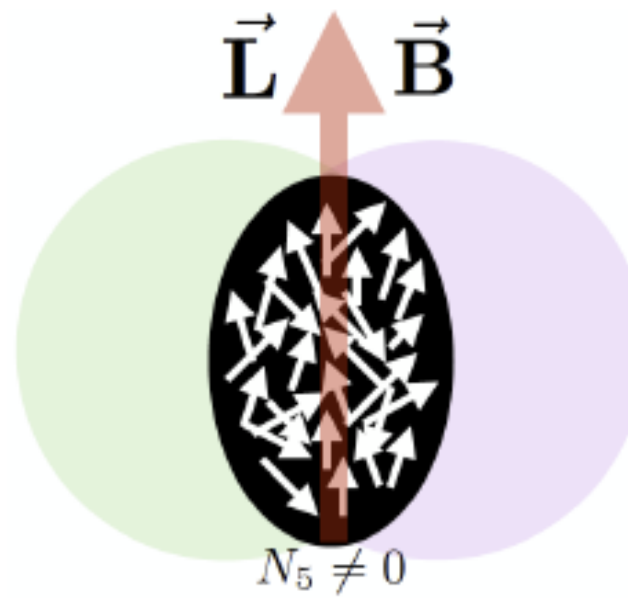
What happens to the spin DoF in the fluid???



Spin transport in a quantum fluid!

Spin @ Chirality, Vorticity and Magnetic Field





[arXiv:2004.00569]

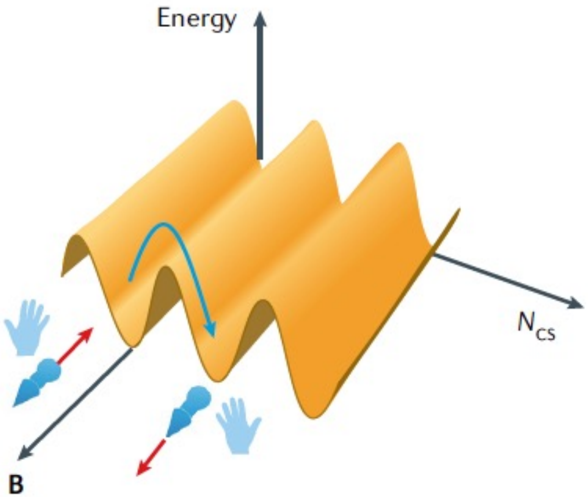
The interplay of spin with chirality/vorticity/magnetic field —> many novel phenomena

Chiral Magnetic Effect

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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



Electric Current

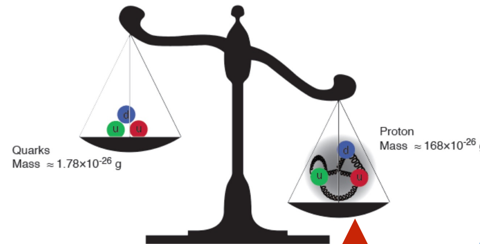
Magnetic Field

Q.M. Transport

The key issue at stake:

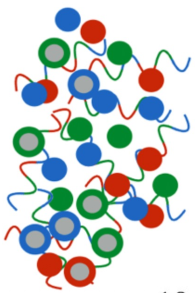
Can we observe it in heavy ion collisions?

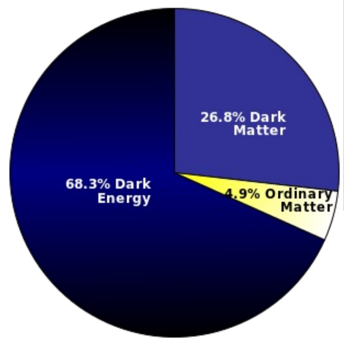
Between NOW and THEN

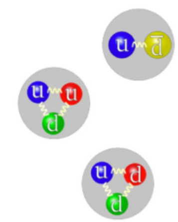


Missing QCD chiral symmetry

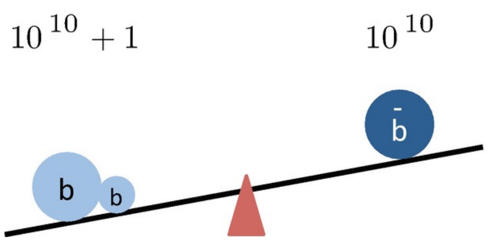
THEN







NOW

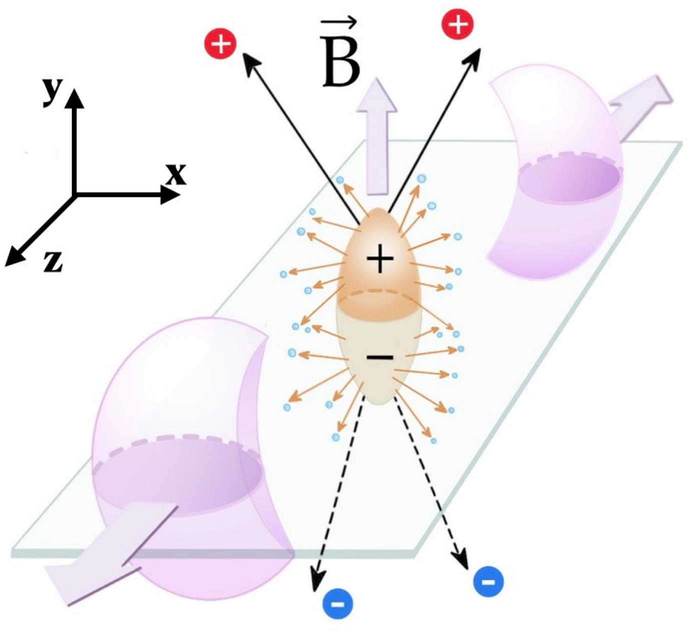


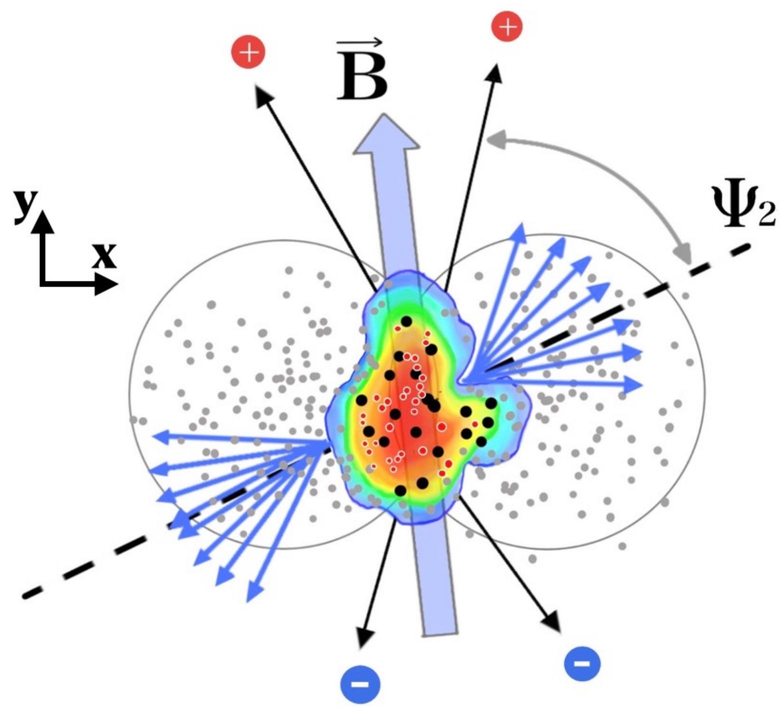
Matter-anti-matter asymmetry

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

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 the past ~14 yrs by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5440GeV beam energies*
- *Various colliding systems from small to large systems*

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

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

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, …

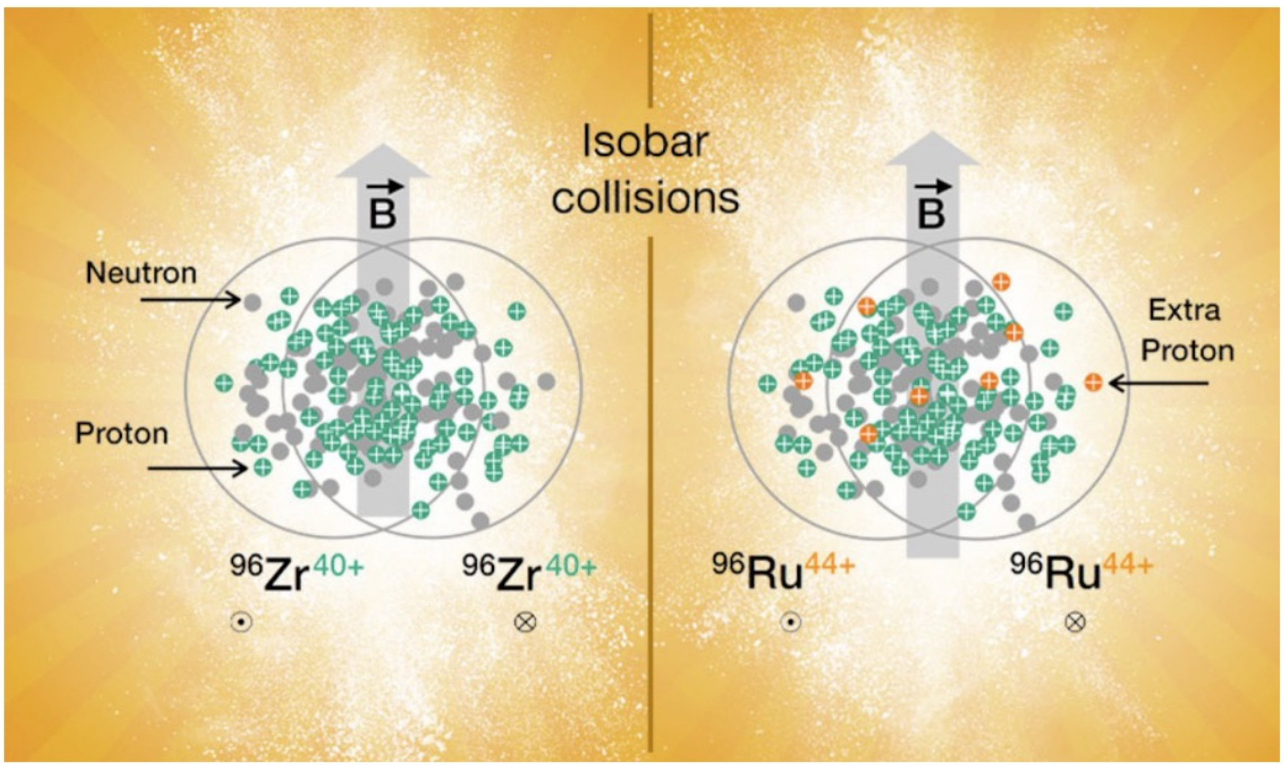
It took some 20+ years to finally discover quark-gluon plasma itself in heavy ion collisions!

Isobar Collision Experiment

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

Chiral Magnetic Effect Task Force Report

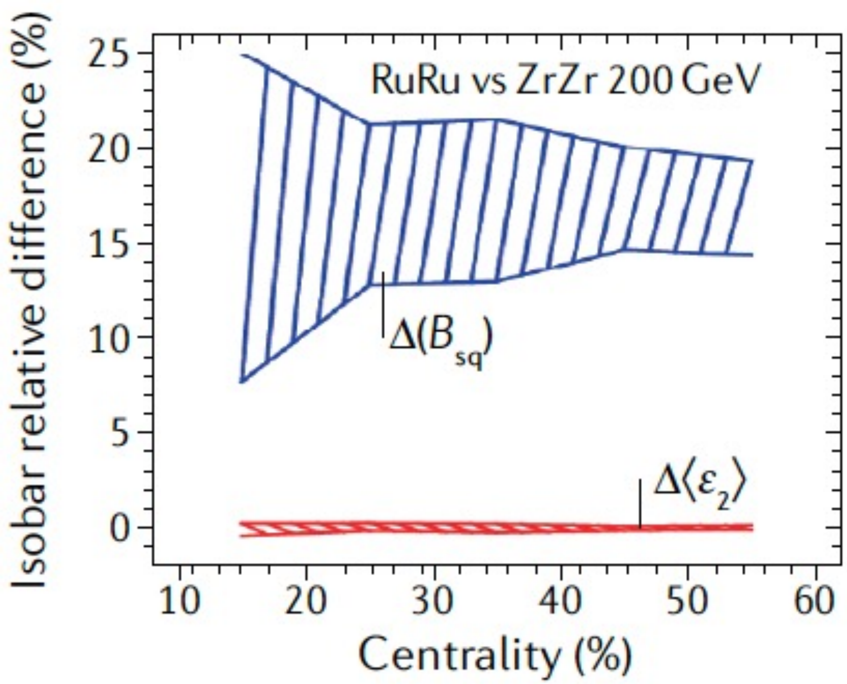
Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

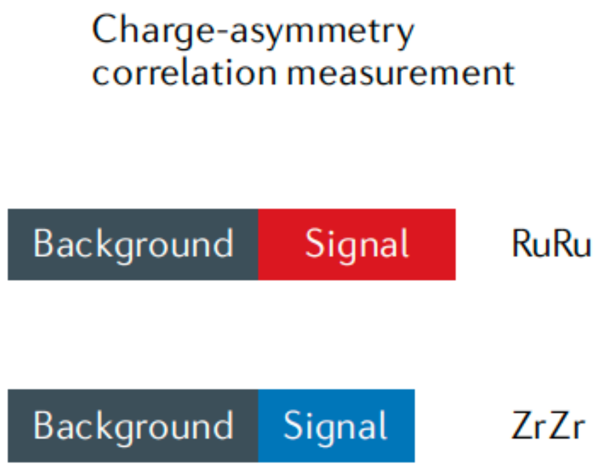


[image from STAR]

Isobar Collision Experiment

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





Expectation:
Identical background;
Different signal

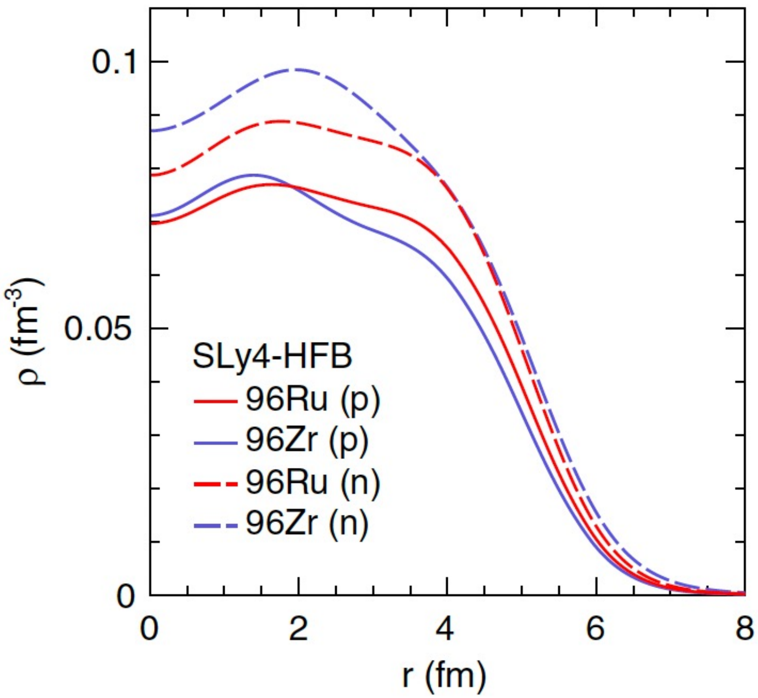
$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

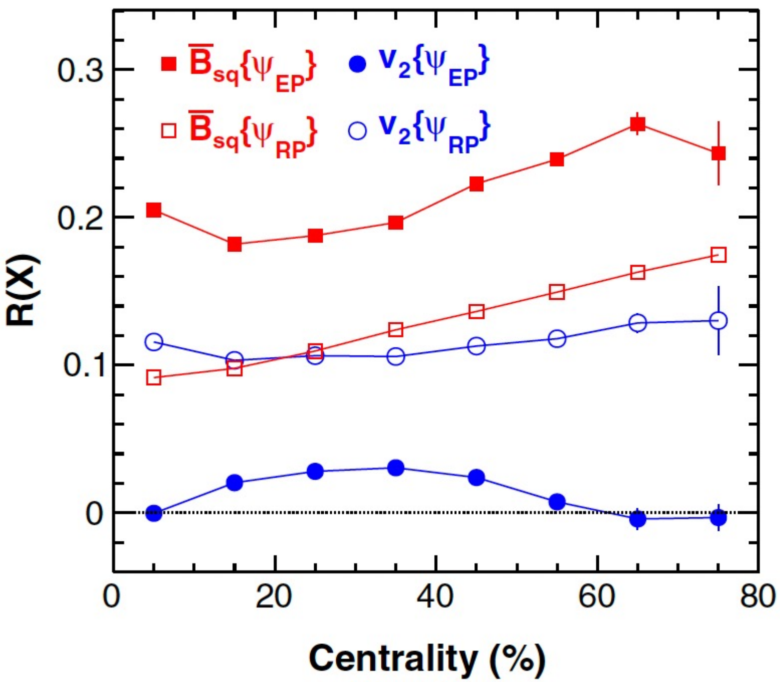
Images from
Nature Reviews Physics 3, 55-63 (2021)
[arXiv:2102.06623]

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?
There was a small pre-QM19 meeting with intensive discussions…

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

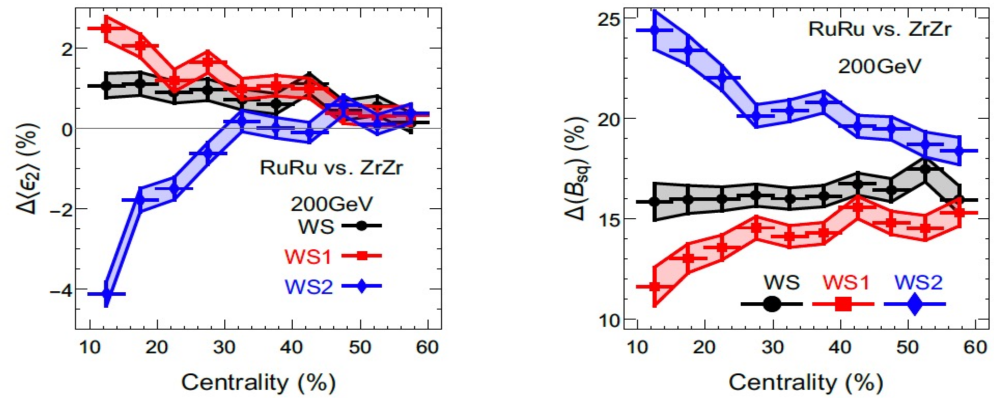


Fig. 1. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with conventional centrality event selection.

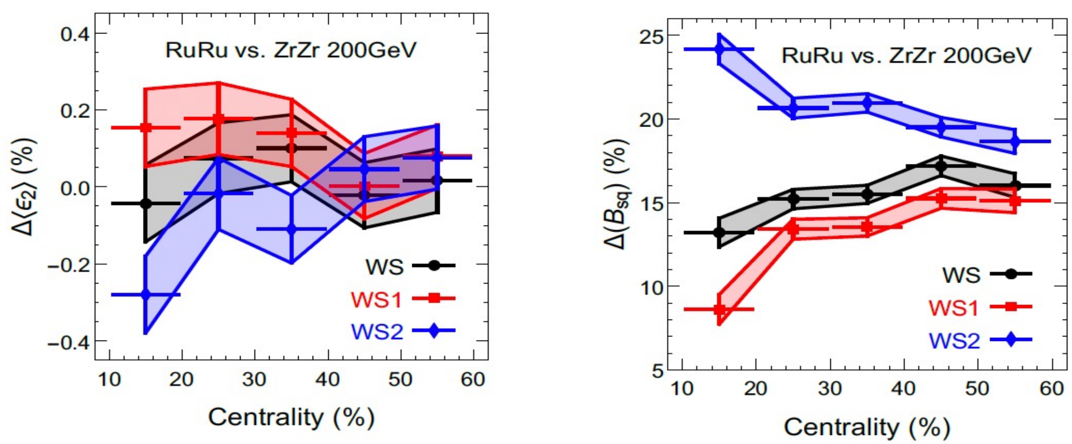
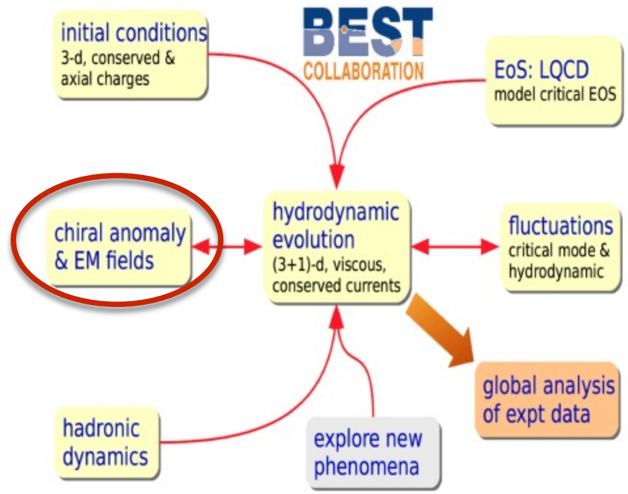


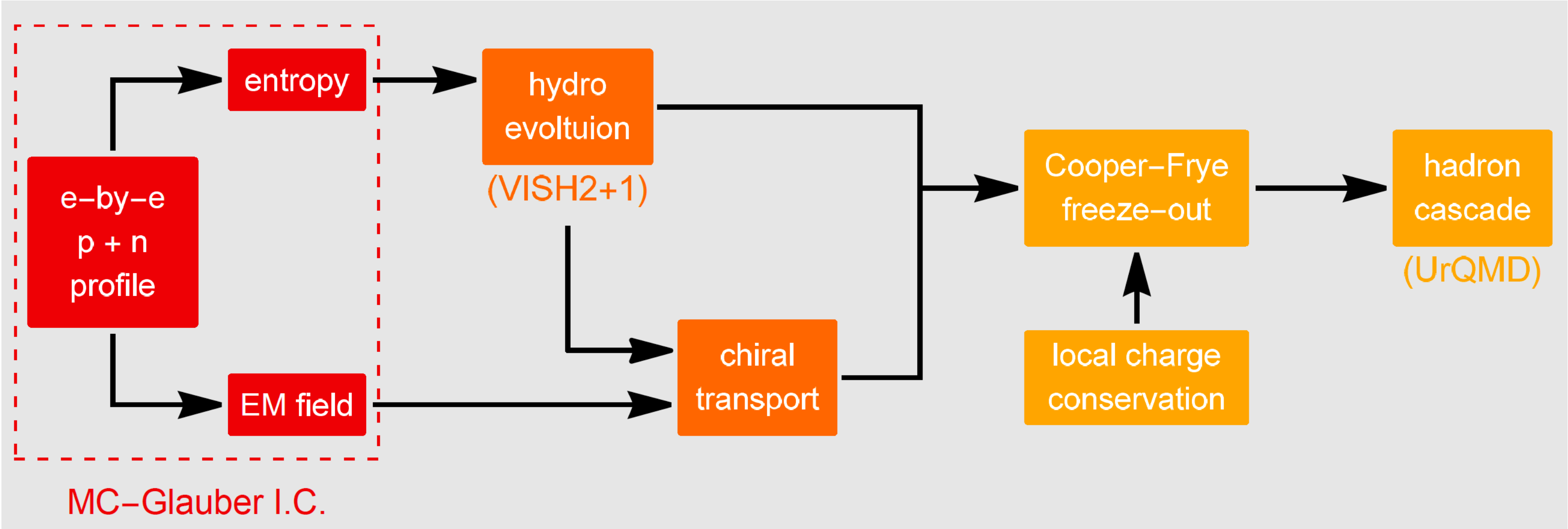
Fig. 2. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with the proposed joint (multiplicity + elliptic-flow) event selection.

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]

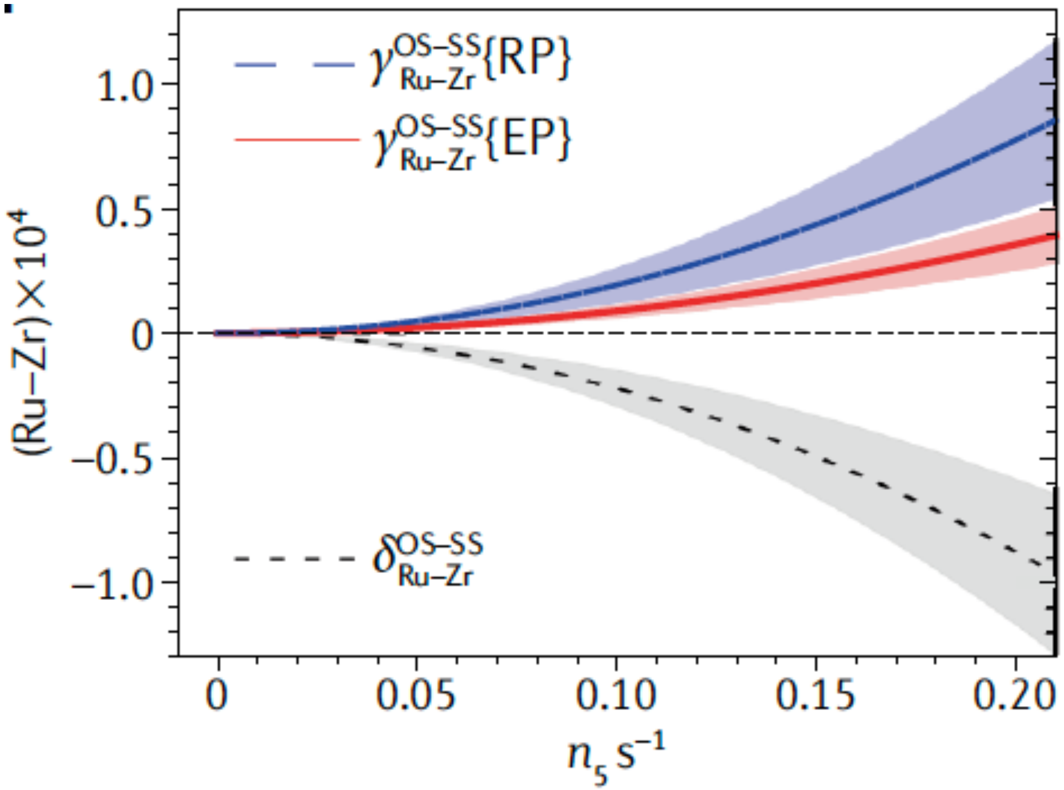
Theoretical Predictions from EBE-AVFD

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,†]



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

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

A Deep Dive into Observables

EBE-AVFD has 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*

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]

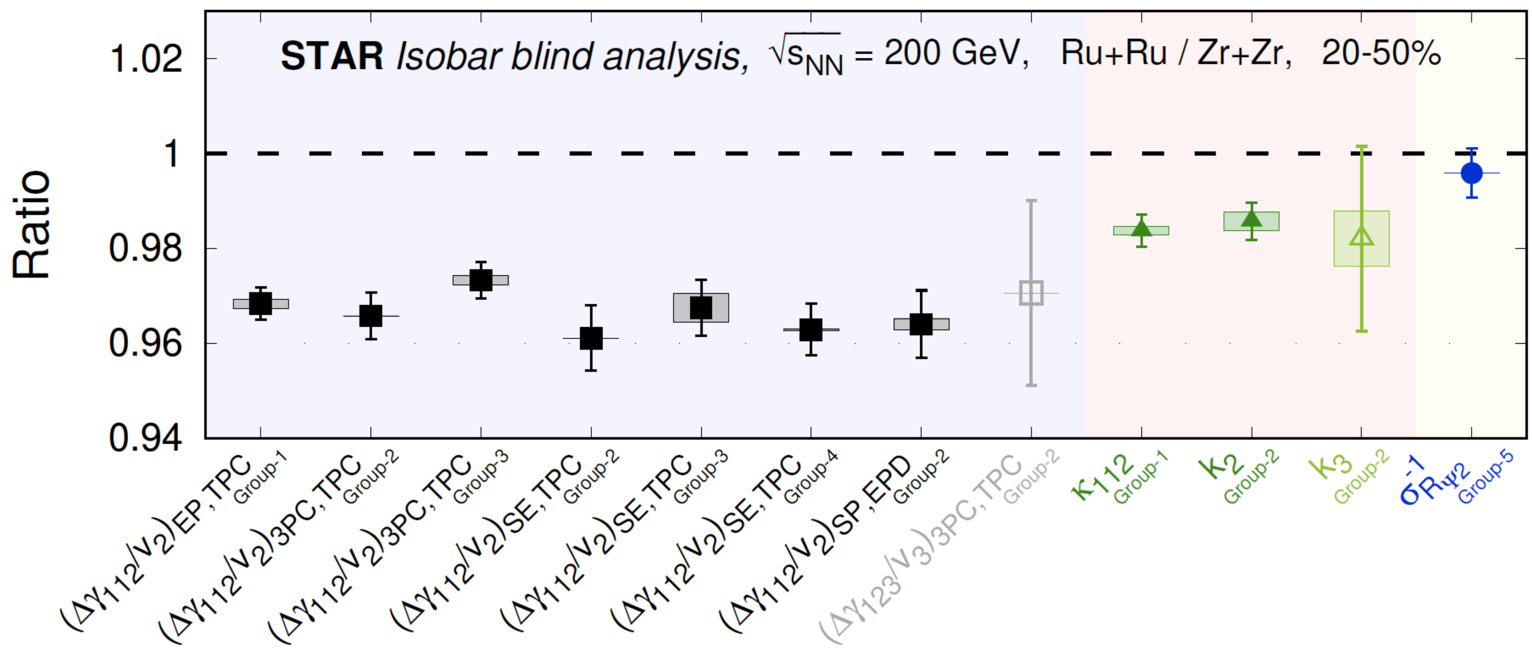
The preparation for isobar analysis has helped significantly advance the understanding of measurement observables and the ability to separate backgrounds and signal.

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

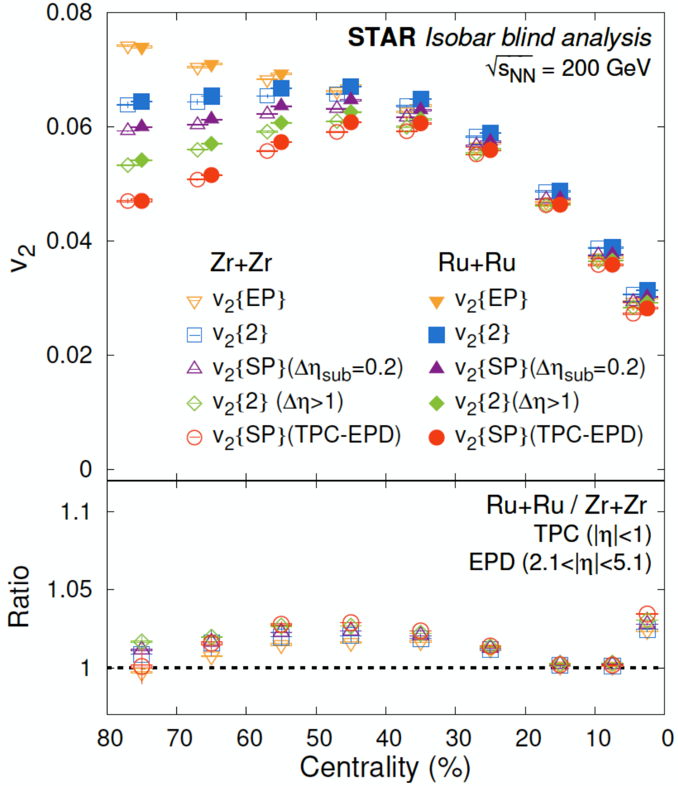
Predefined criteria:
Gamma(Ru) / Gamma(Zr) > 1

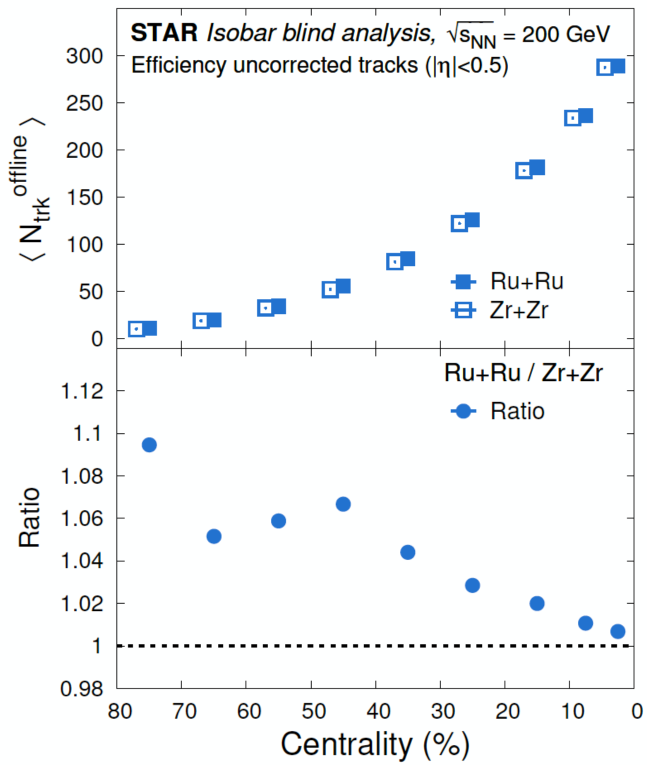
[STAR paper: 2109.00131
Phys.Rev.C 105 (2022) 1, 014901]



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 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]

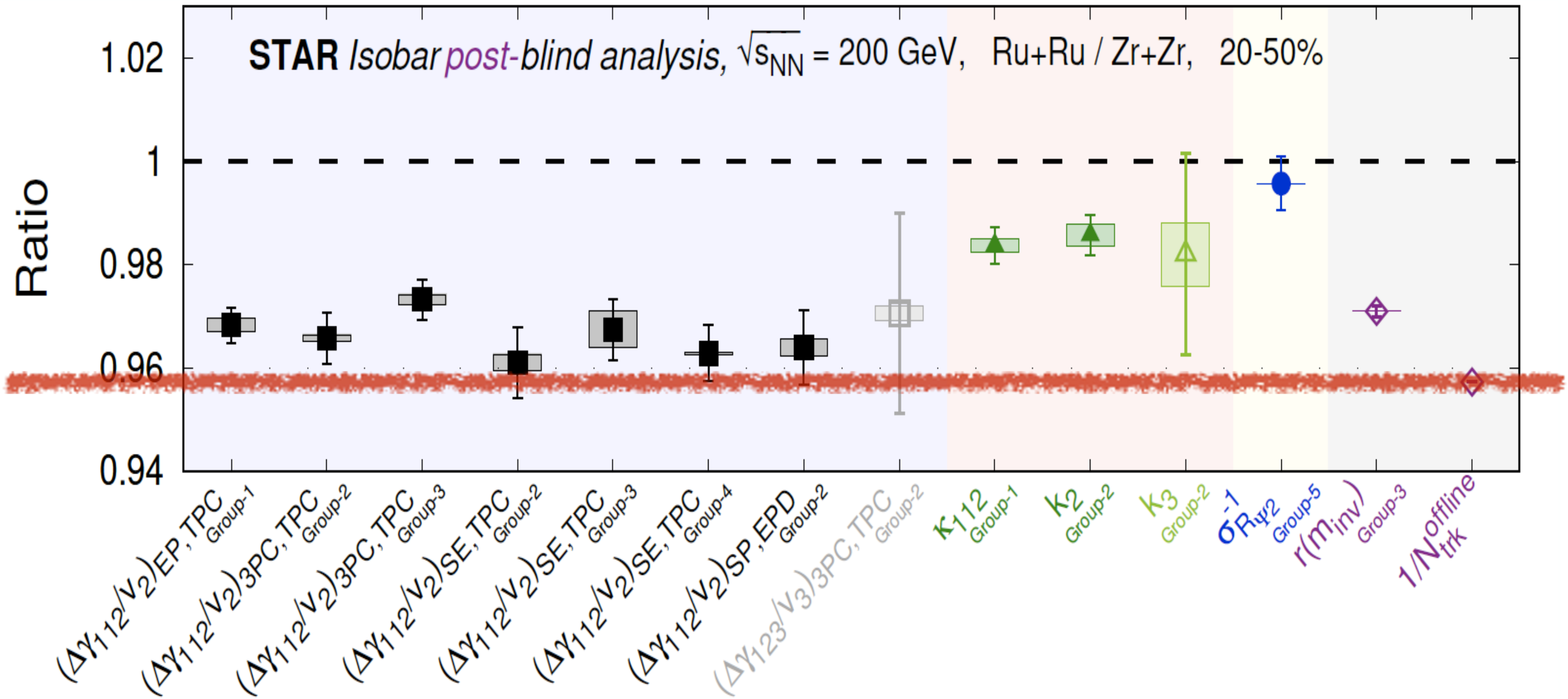
VII. CONCLUSION

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 is not misleading:

"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!

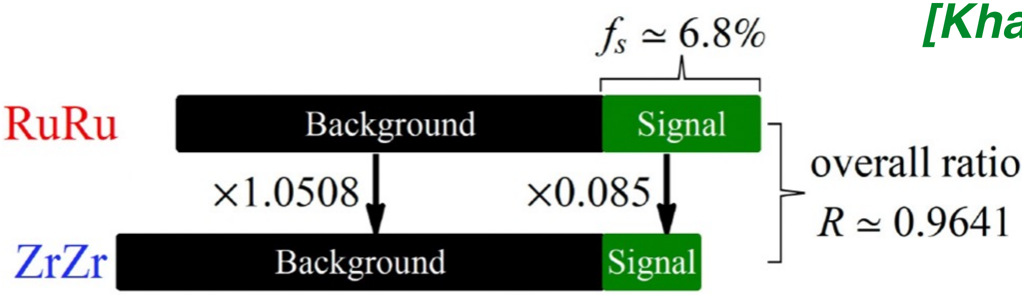
Need accurate calibration of the true baseline!

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

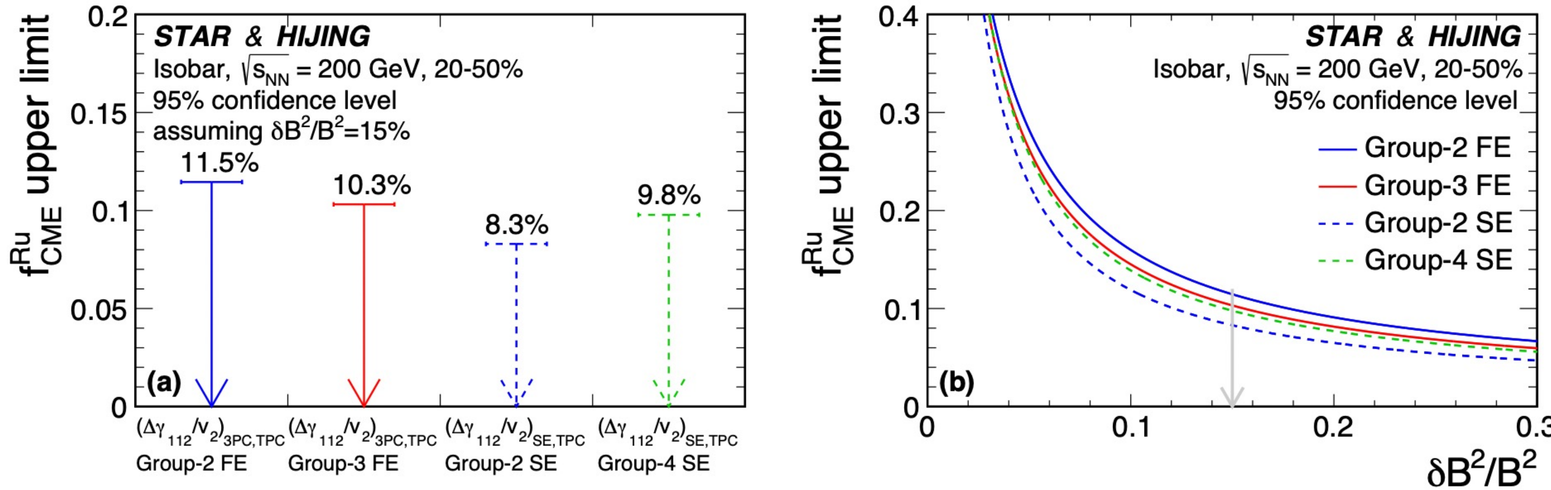
Where Do We Stand?

– ***Theoretical analysis suggests a nonzero signal in isobar collisions***

[Khazeev, JL, Shi, arXiv:2205.00120]



[STAR, arXiv:2310.13096;2308.16846]



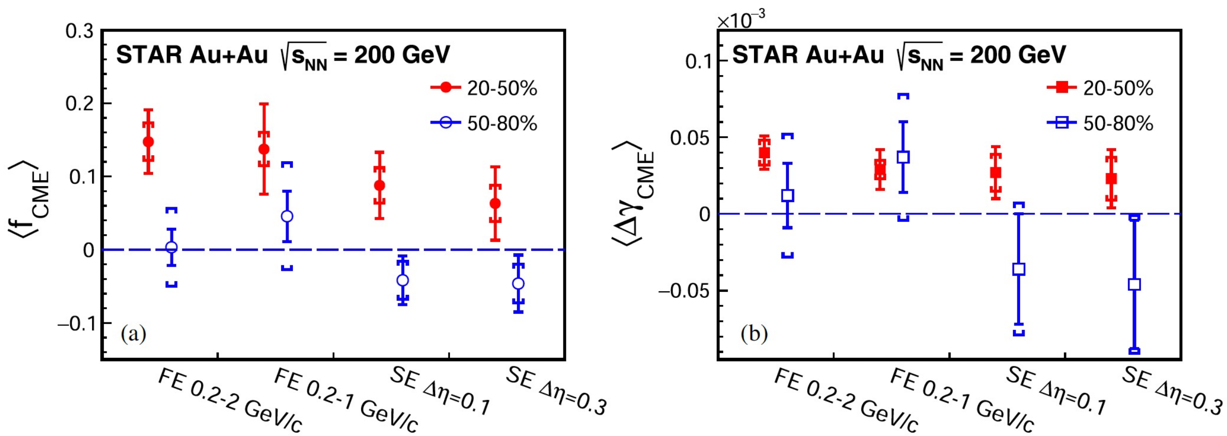
– ***Upper limits have been set by STAR for isobar collisions.***
– ***Consistent with theoretical expectations***
– ***Indicating a still better chance for the search in AuAu collisions***

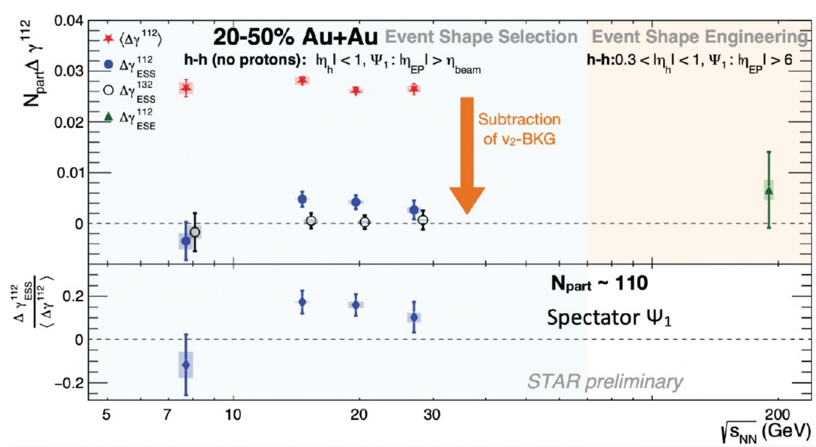
Where Do We Stand?

– ***Upper limits have been set by ALICE and CMS measurements for LHC energies***

– ***A potential signal from AuAu at RHIC 200 GeV***

– ***Exciting new results for signal from AuAu at RHIC BES energies***





Significant Progress in the Search

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

Flow driven ***Nonflow***

We've come a long way in fighting with the backgrounds
— recognizing the dominance of flow driven backgrounds (2009~2015)

— developing exp methods as well as theoretical calculations to quantify and remove the flow driven backgrounds (2015~2021)

— studying nonflow for final extraction of CME signal (2021~now)

Have We Seen the CME?

arXiv:2405.05427
(for QGP 6 ed. by XN Wang)

Chiral Magnetic Effect in Heavy Ion Collisions: The Present and Future

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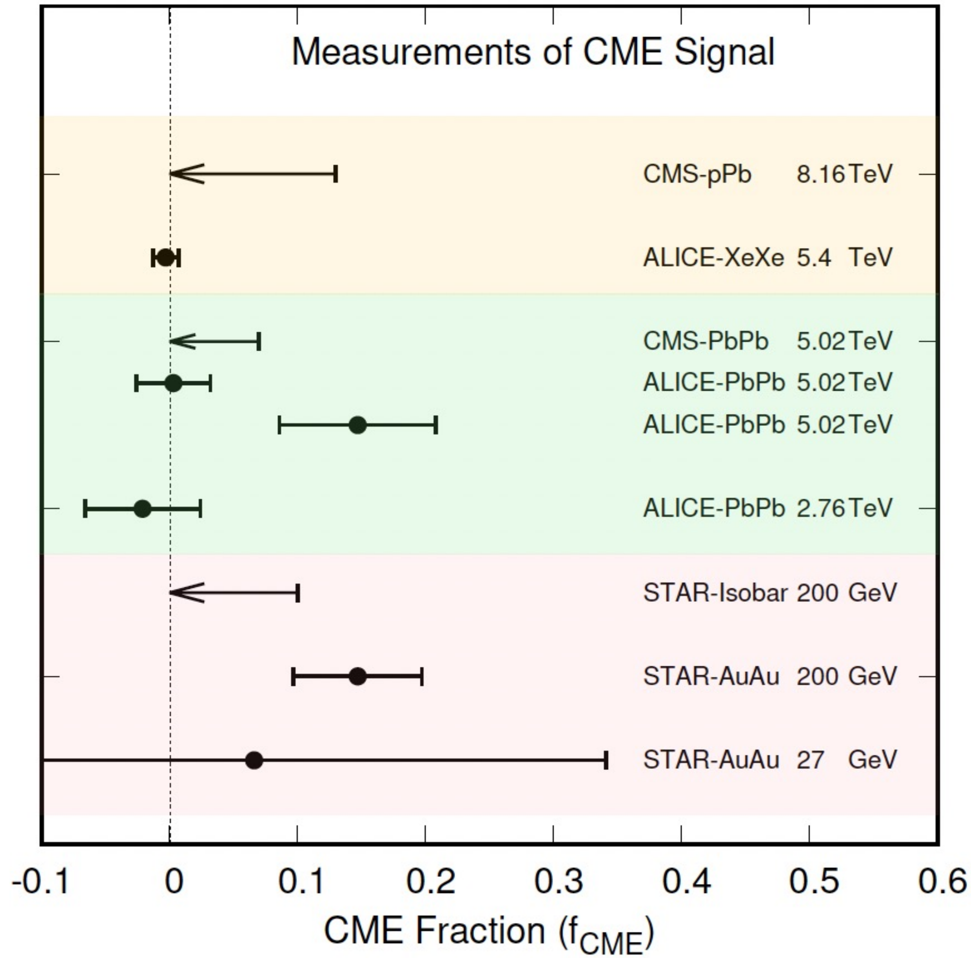
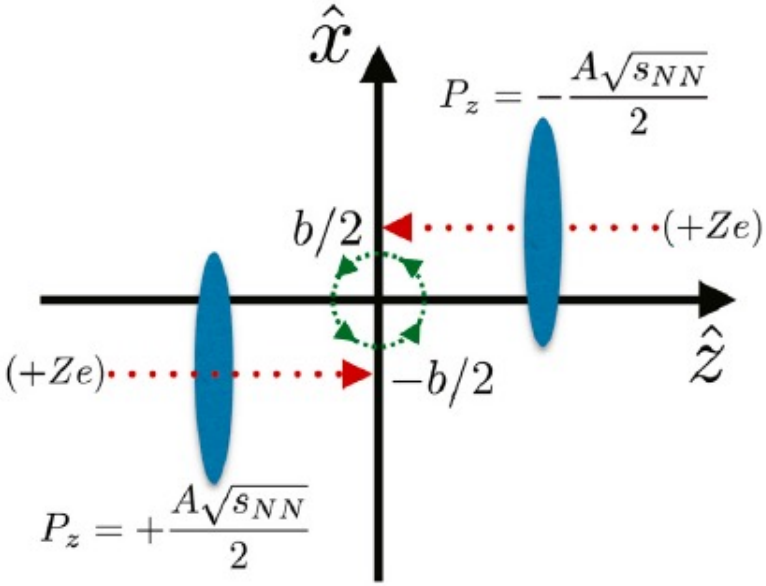
The chiral magnetic effect (CME) is a collective quantum phenomenon that arises from the interplay between gauge field topology and fermion chiral anomaly, encompassing a wide range of physical systems from semimetals to quark-gluon plasma. This review, with a focus on CME and related effects in heavy ion collisions, aims to provide an introductory discussion on its conceptual foundation and measurement methodology, a timely update on the present status in terms of experimental findings and theoretical progress, as well as an outlook into the open problems and future developments.



The key issue at stake:
Can we find it in heavy ion collisions?
— No conclusive answer yet, but very promising!

Vorticity & Rotational Polarization

Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions

$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

Liang & Wang ~ 2005:
orbital L —> spin polarization via partonic collision processes

Betz, Gyulassy, Torrieri ~ 2007: quantitative assessment of the effect

Becattini, et al ~ 2008, 2013: A fluid dynamical scenario

$$S^{\mu} = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\nu} \varpi_{\rho\sigma} \qquad \varpi_{\mu\nu} = \frac{1}{2}\left[\partial_\nu\left(\frac{1}{T}u_\mu\right) - \partial_\mu\left(\frac{1}{T}u_\nu\right)\right]$$

"Rotating" Quark-Gluon Plasma

$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

PHYSICAL REVIEW C **94**, 044910 (2016)

Rotating quark-gluon plasma in relativistic heavy-ion collisions

Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]

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

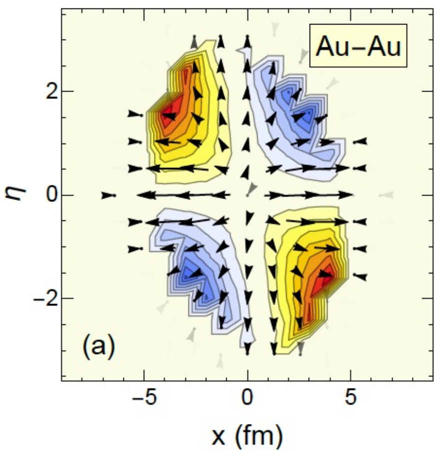
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

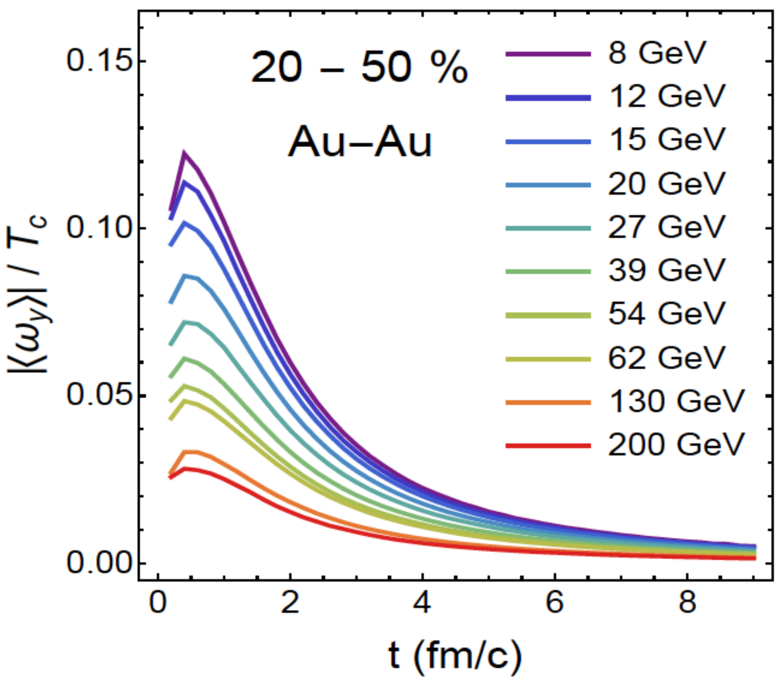
[3]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

What fraction stays in fireball?
— up to ~20%, strongly depending on collision energy.

Is this portion conserved?
—YES!

How QGP accommodates this angular momentum?
— Fluid vorticity!

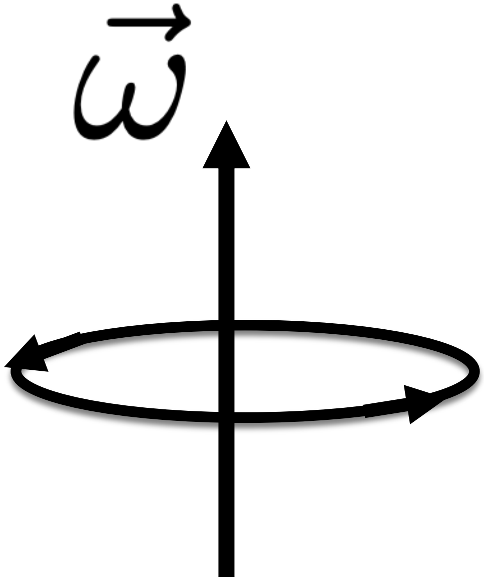




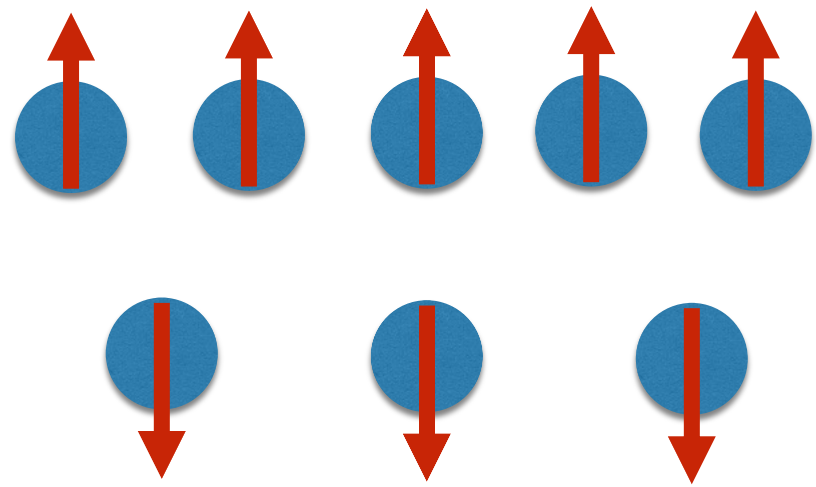
Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization



$$dN \propto e^{\frac{\vec{\omega}\cdot\vec{J}}{T}}$$

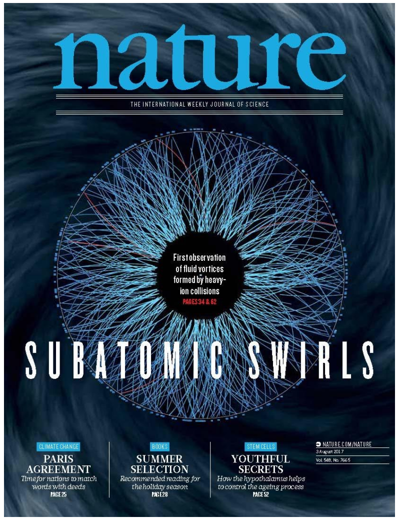


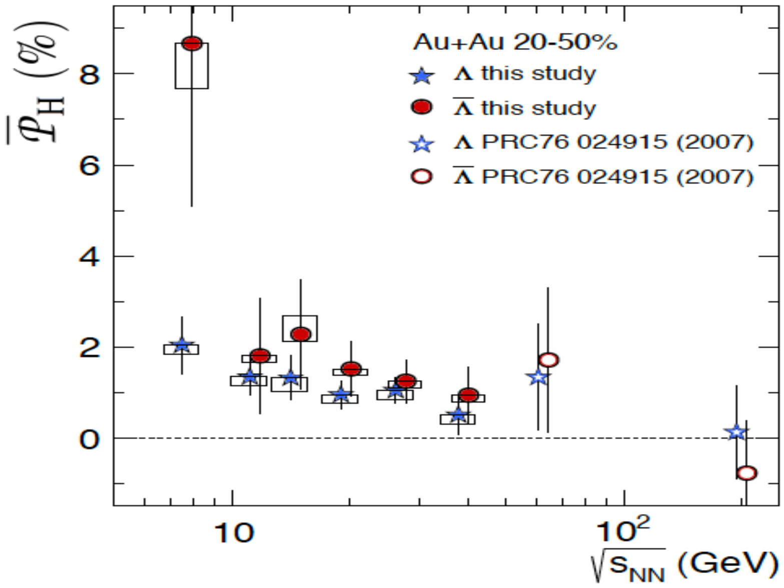
Macroscopic rotation; Global angular momentum

Microscopic spin alignment

"Fluid spintronics" in condensed matter systems

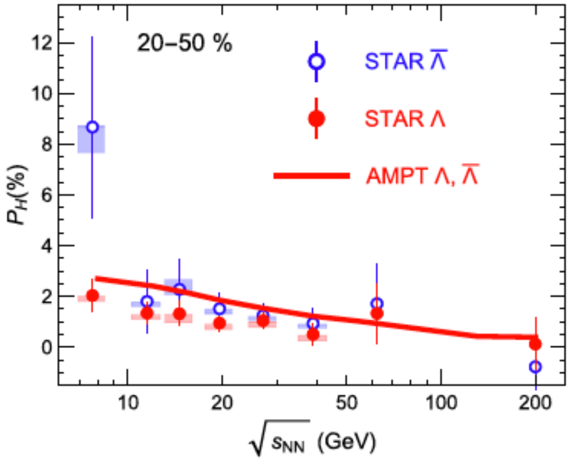
The Most Vortical Fluid





An exciting discovery from STAR Collaboration at RHIC: The most vortical fluid!

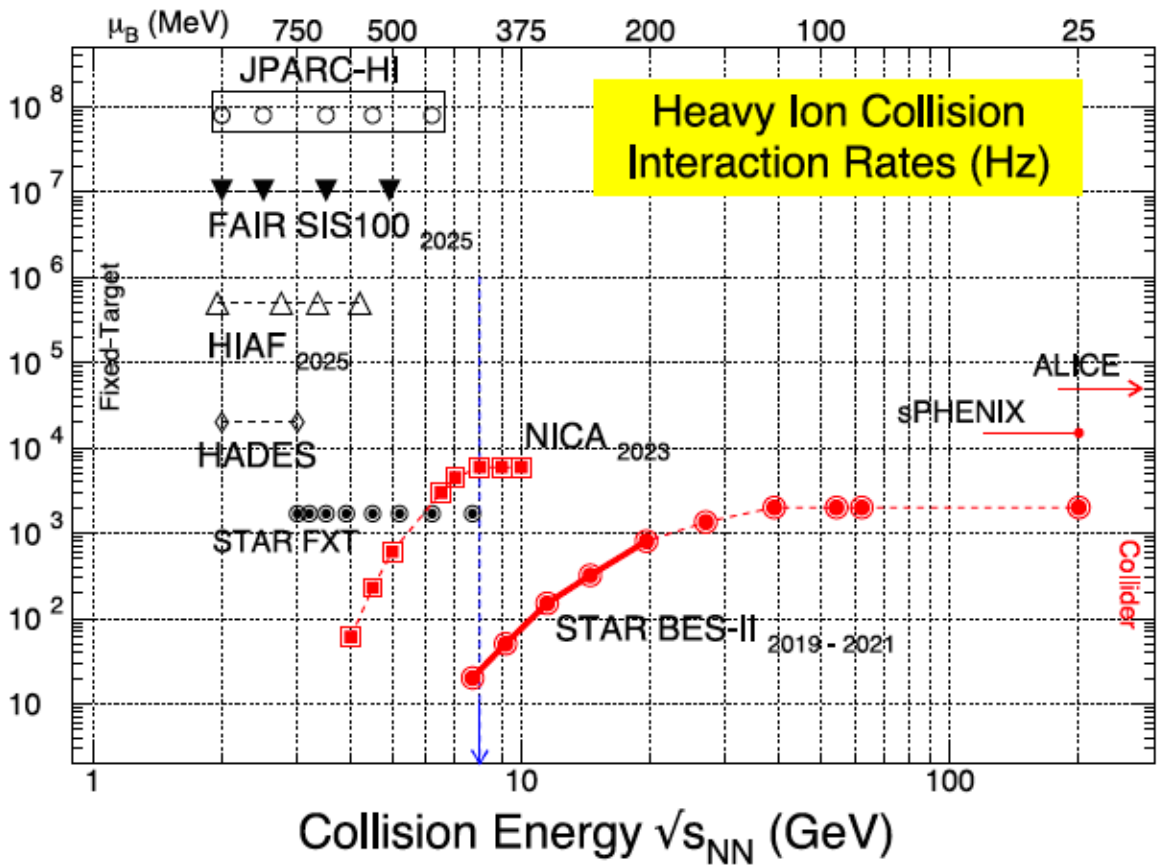
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$



Many calculations based on hydro or transport models

Relativistic Nuclear Collisions @ O(1-10) GeV

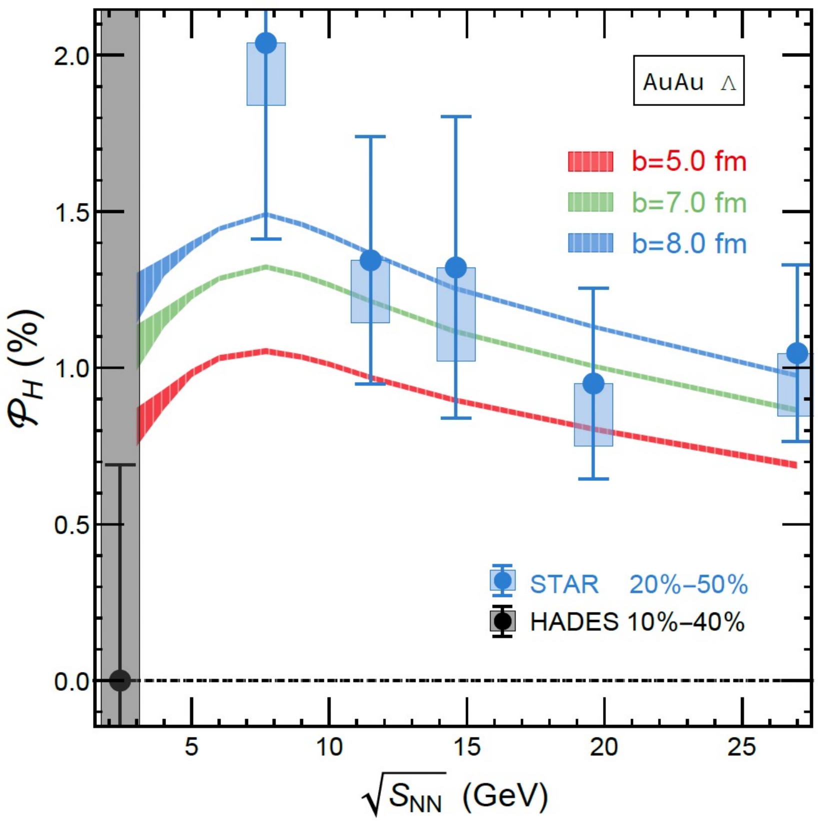
A number of current and planned experiments will explore the O(1) GeV regime of relativistic nuclear collisions



"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87. [arXiv:1906.00936]

Trend of Global Polarization toward O(1) GeV

The Question: Trend for global hyperon polarization @ O(1~10) GeV ???



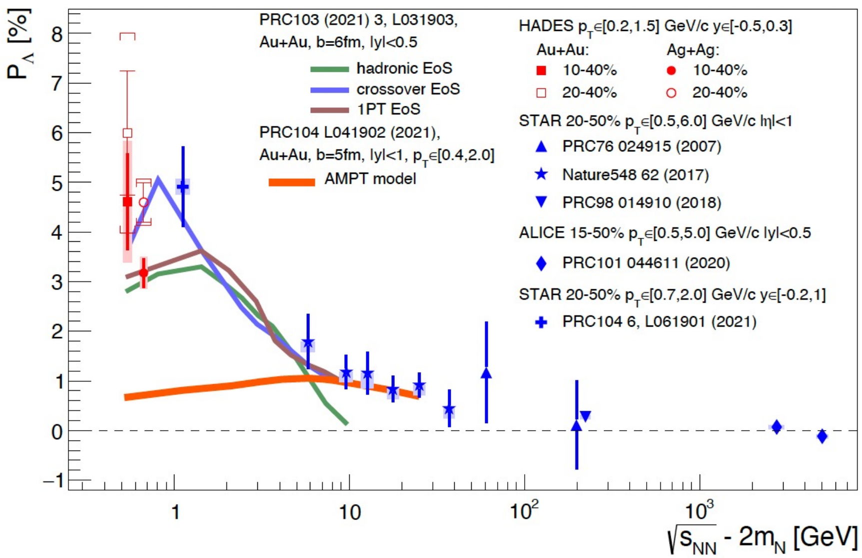
Yu Guo, et al, PRC2021 arXiv:2105.13481

AMPT calculations predict non-monotonic behavior in the dependence of global polarization on beam energy —> maximum around 7.7 GeV

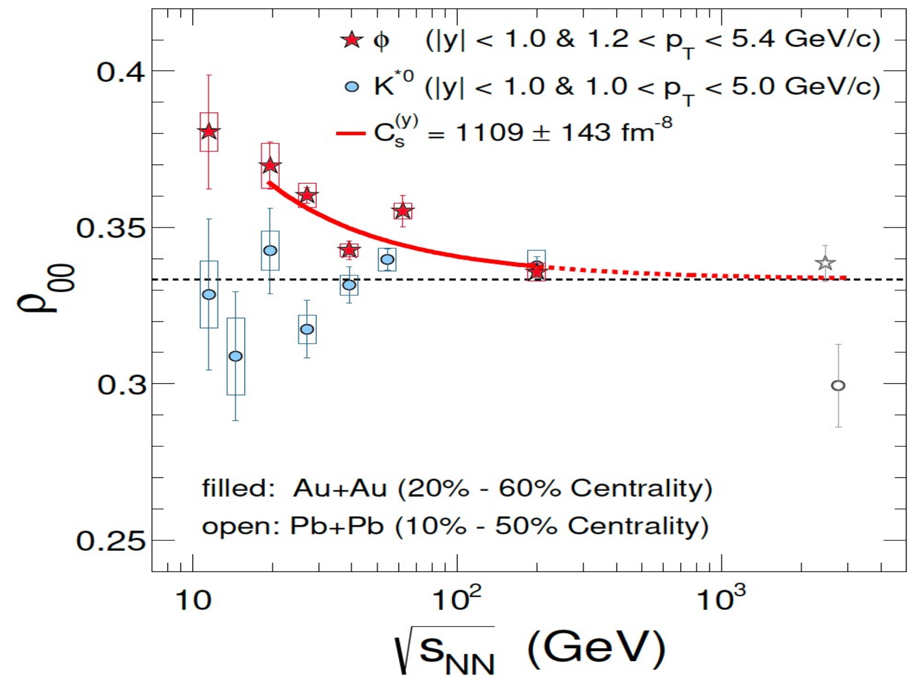
See also results for differential dependence and local polarization in the paper.

Highly Polarized Fluid at Low Beam Energy

HADES, arXiv: 2207.05160



STAR, Nature 2023, arXiv: 2204.02302



Surprisingly large signal even very close to threshold?!

$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

Many other measurements (e.g. local polarization, other vector mesons, LHC, etc)

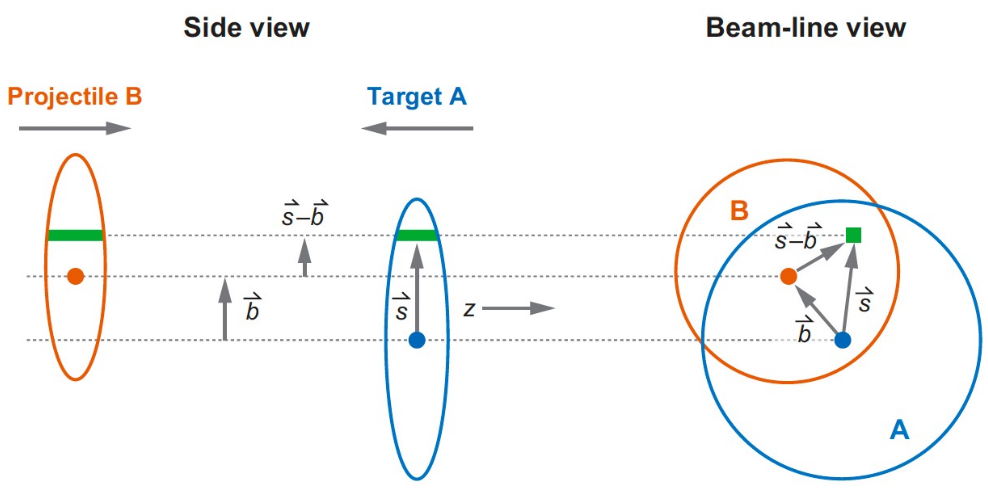
Nuclear Stopping & Angular Momentum

Total angular momentum monotonically increases with beam energy

$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

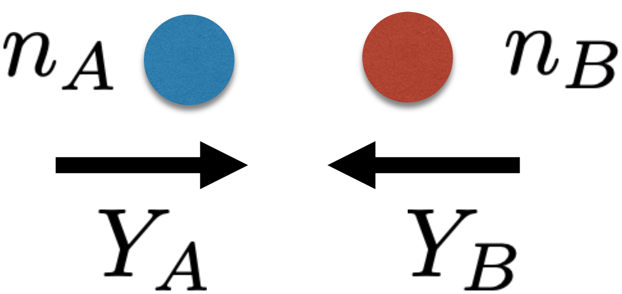
But what is relevant to measurements is the amount of angular momentum being stopped in mid rapidity.

This is quantitatively related to the baryon stoping and can be calibrated with baryon number measurements.

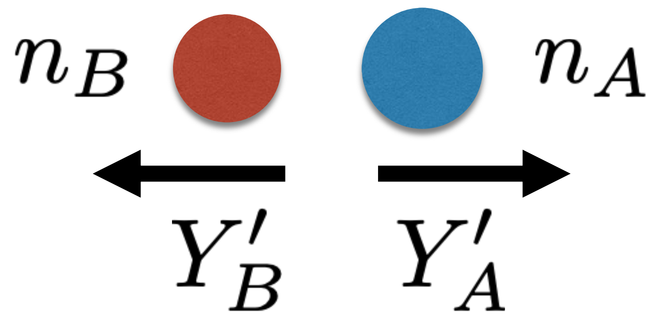


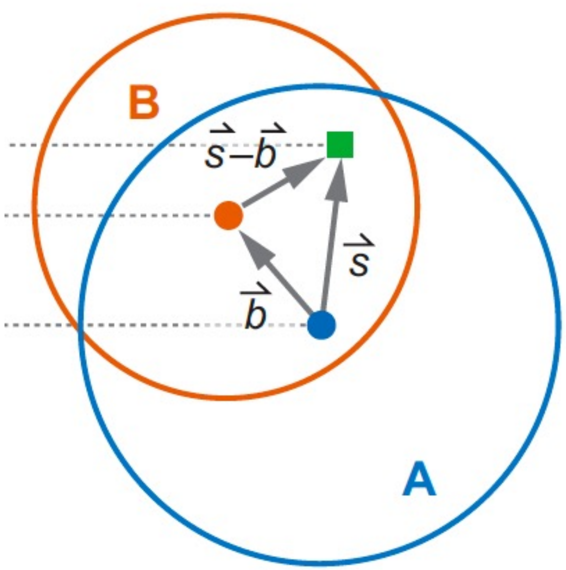
Nuclear Stopping & Angular Momentum

The key is to understand the rapidity loss in the initial collision.



$$e = \frac{Y_B' - Y_A'}{Y_B - Y_A}$$



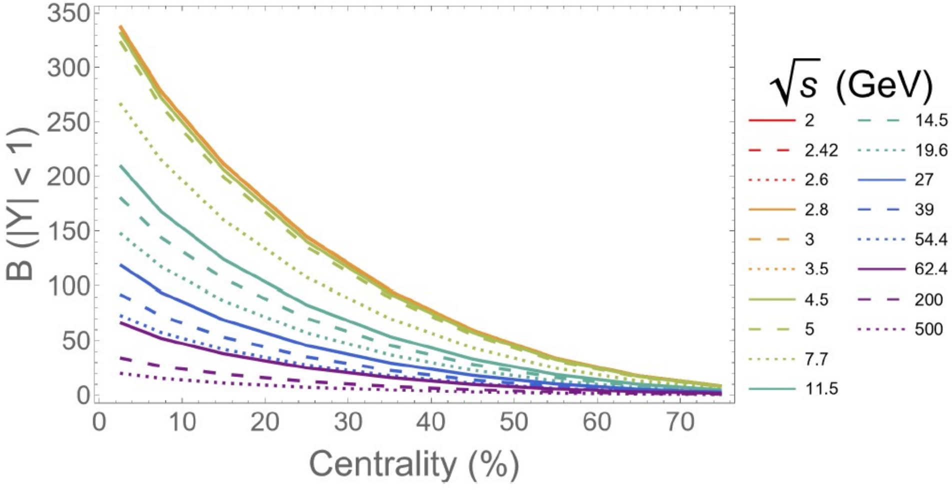


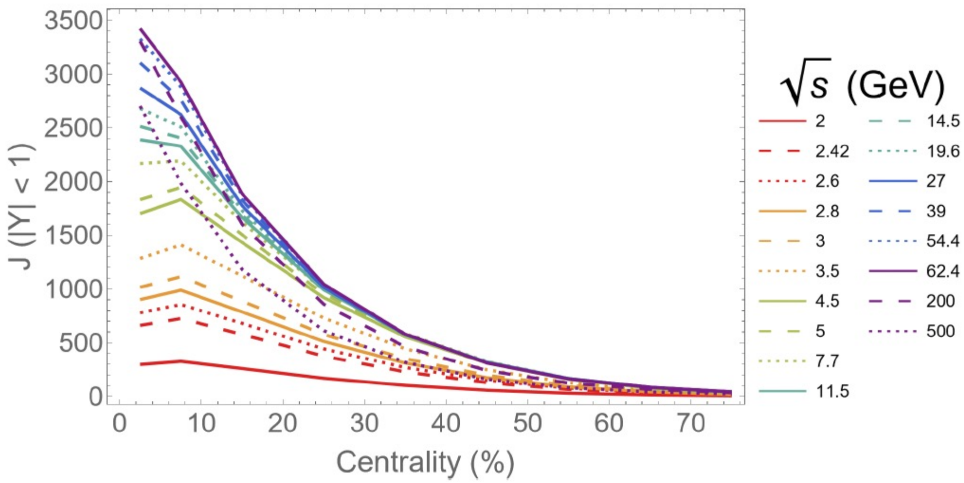
Various spots on the overlapping zone —> A "spread-out" (i.e. distribution) along rapidity

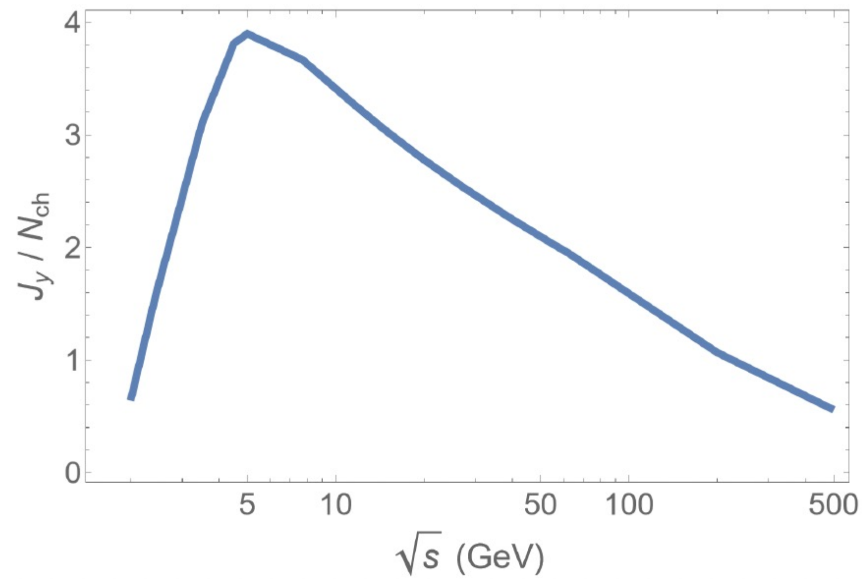
Fluctuations at each spot —> Additional "spread-out" along rapidity

Both net baryon and angular momentum come from this "spread-out"

Initial Angular Momentum

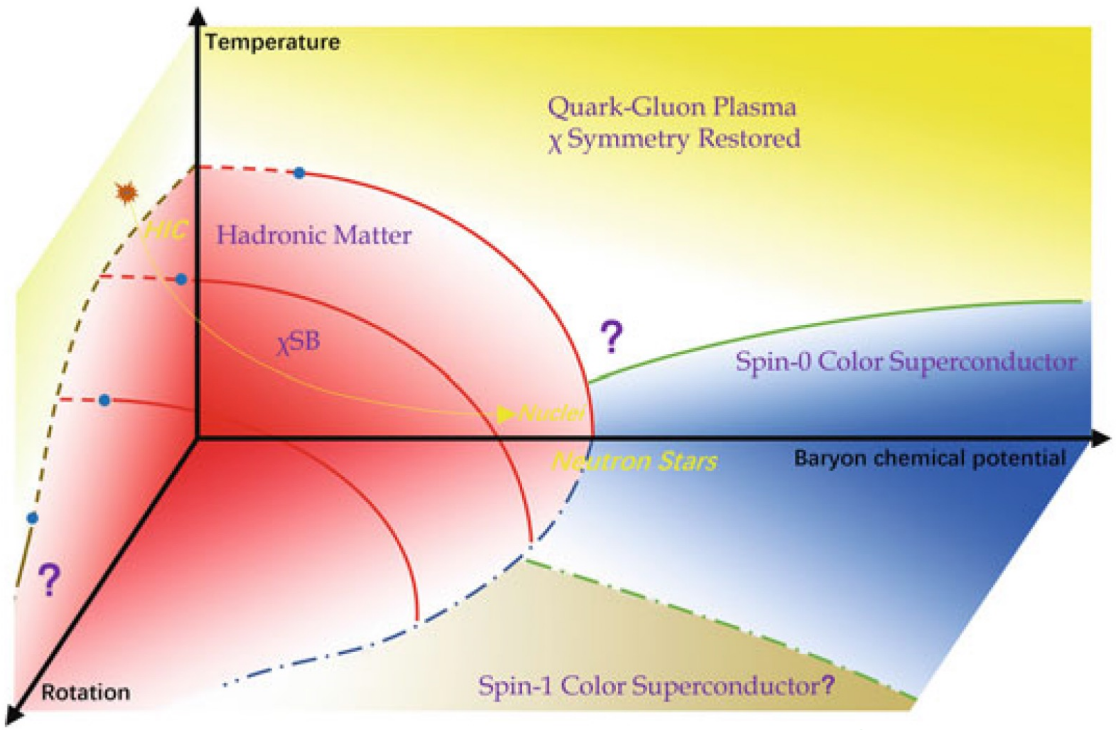






Key message: angular momentum driven phenomena unlikely keeps increasing toward extremely low energy.

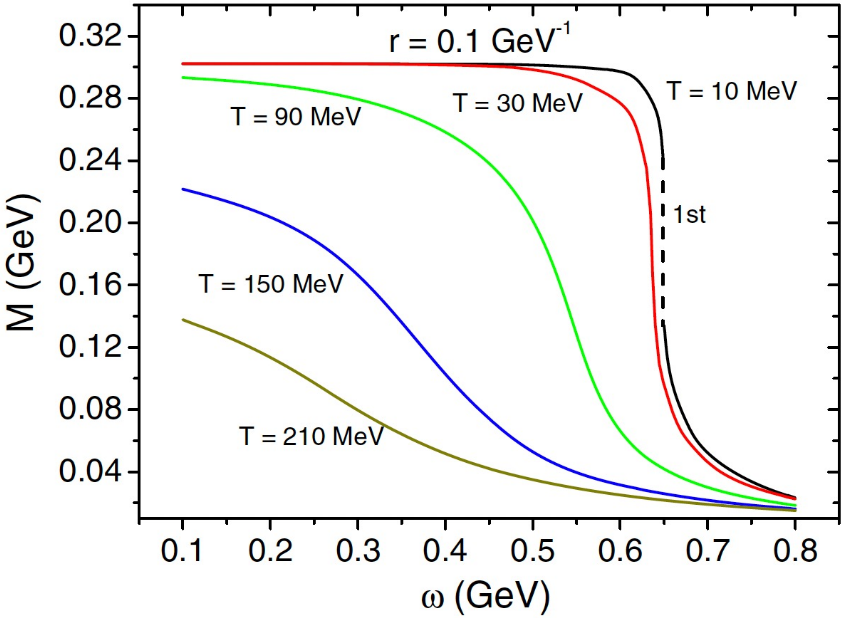
Phase Structures under Rotation

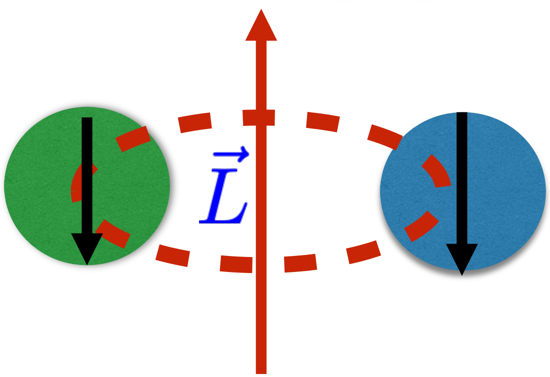


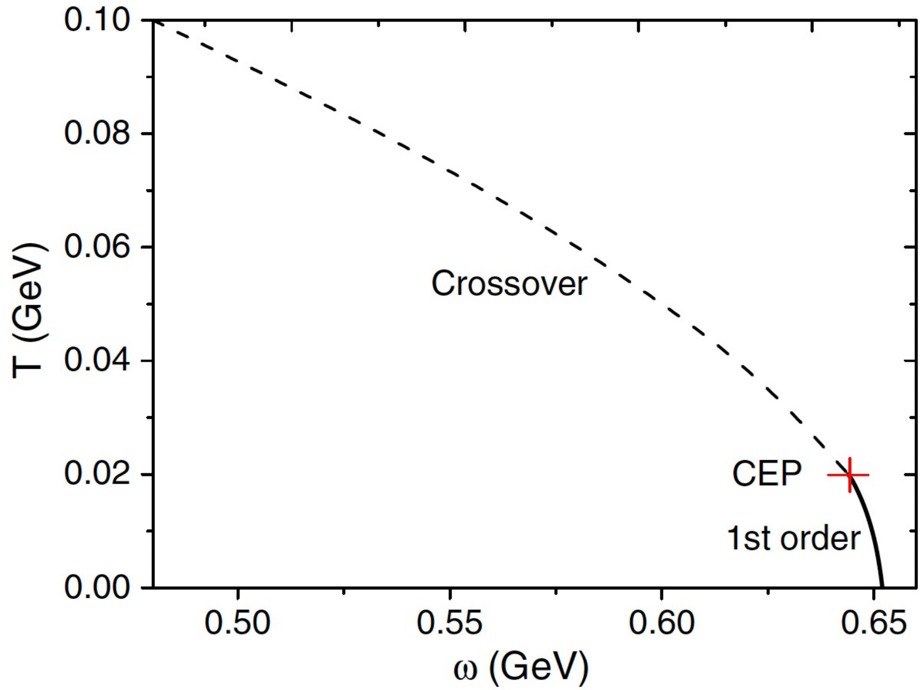
from arXiv: 2108.00586

Rotation tends to align both spin and orbital angular momentum to align with global angular momentum.

Chiral Condensate under Rotation

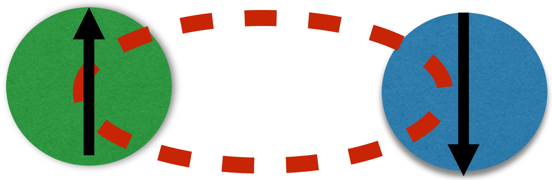


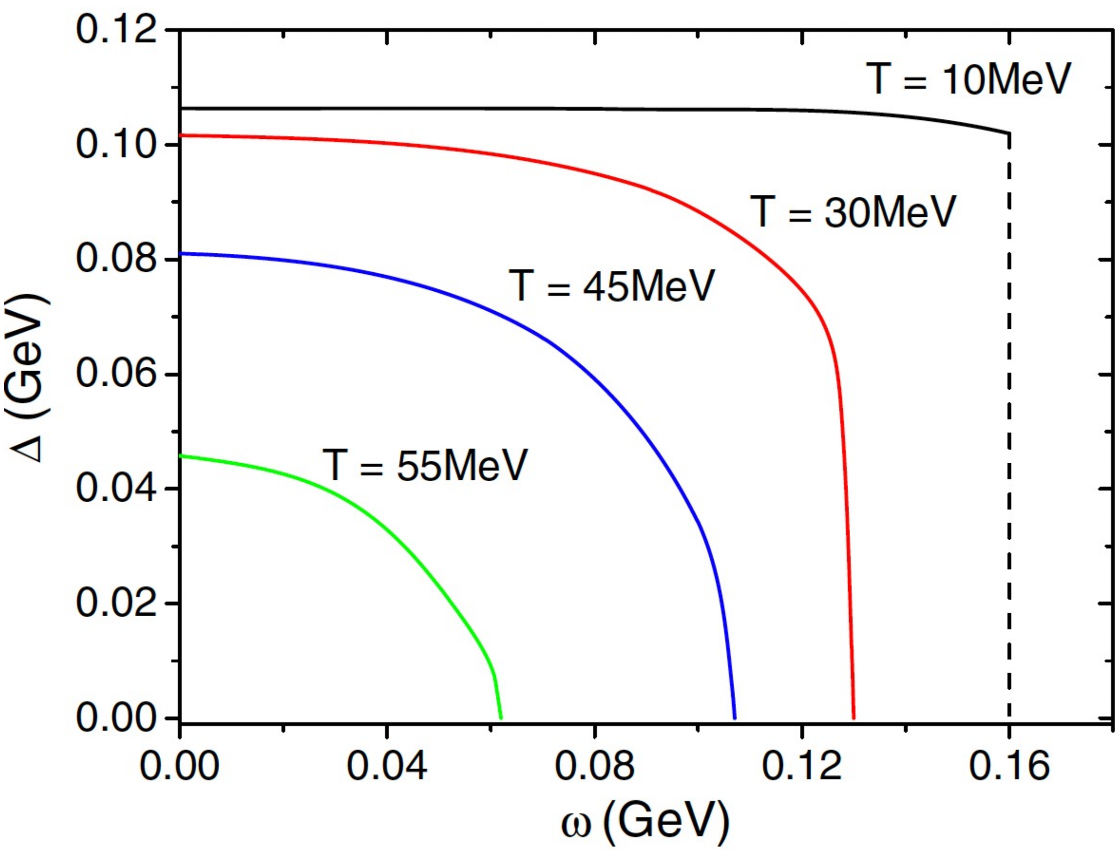




[Yin Jiang, JL, PRL2016]

Color Superconductor under Rotation

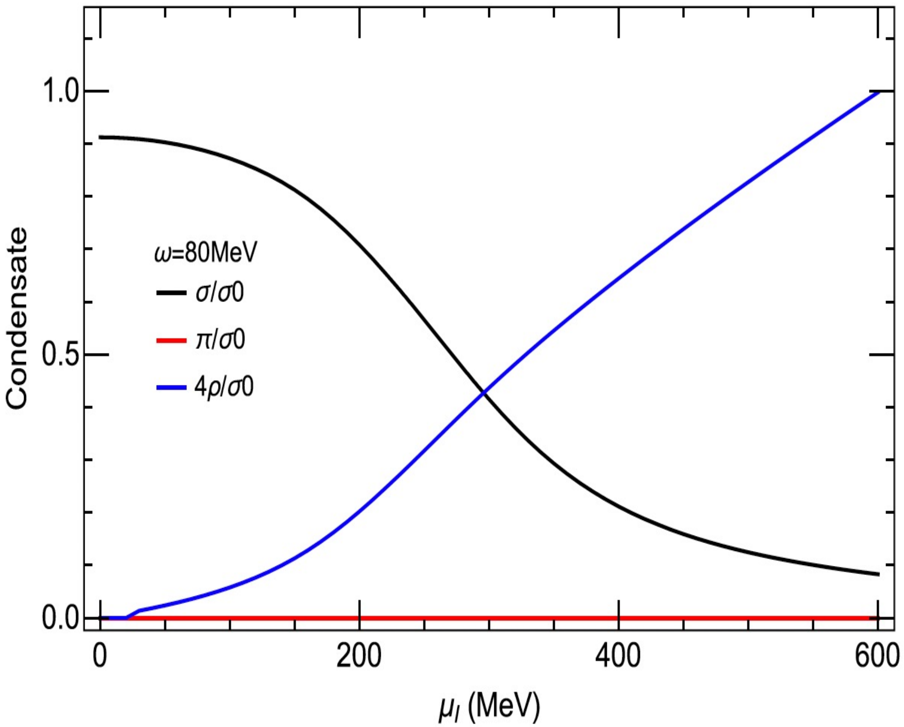


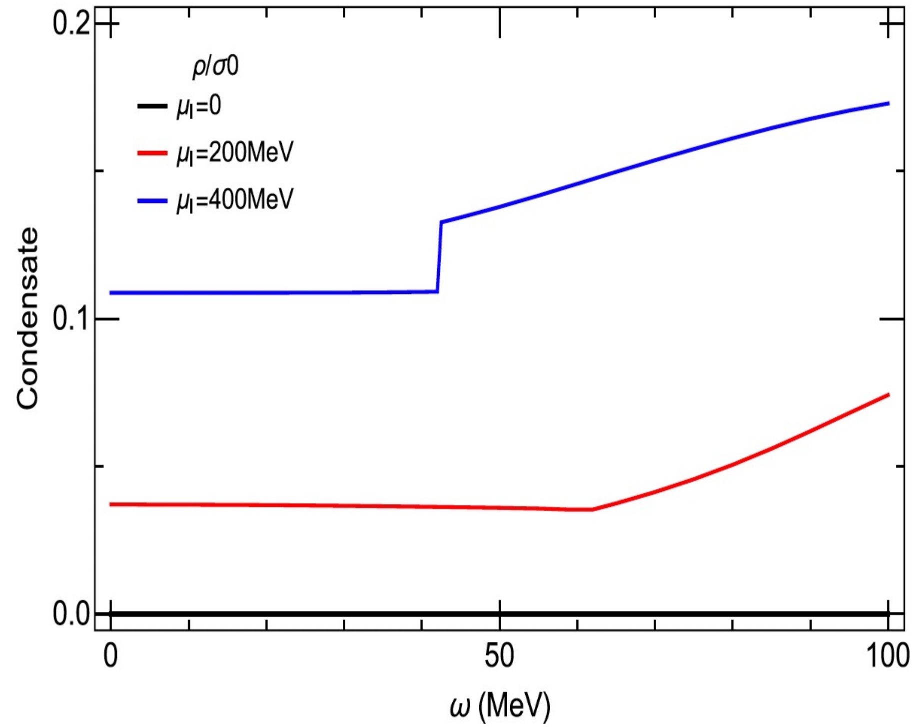


[Yin Jiang, JL, PRL2016]

Isospin Matter under Rotation

Vacuum: sigma condensate;
Static isospin matter: pion superfluidity;
Isospin matter under rotation: emergence of rho condensate!
This effect is more significant at high baryon density.





[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Isospin Matter under Rotation

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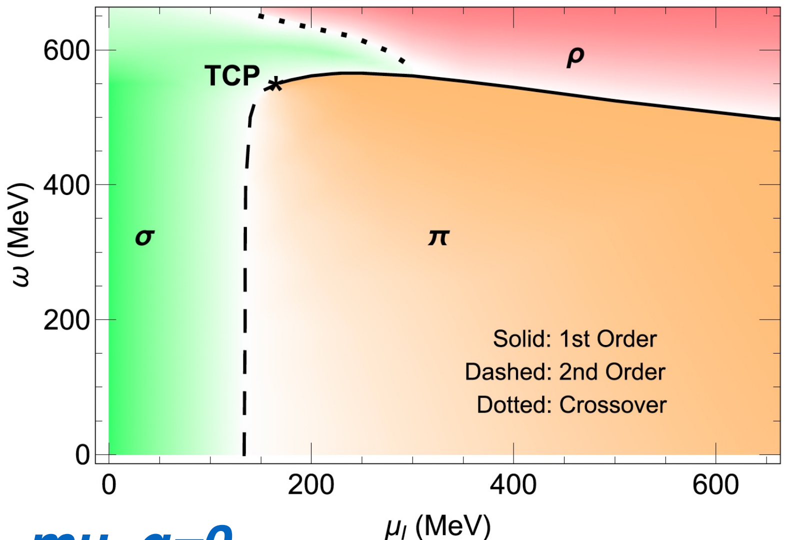
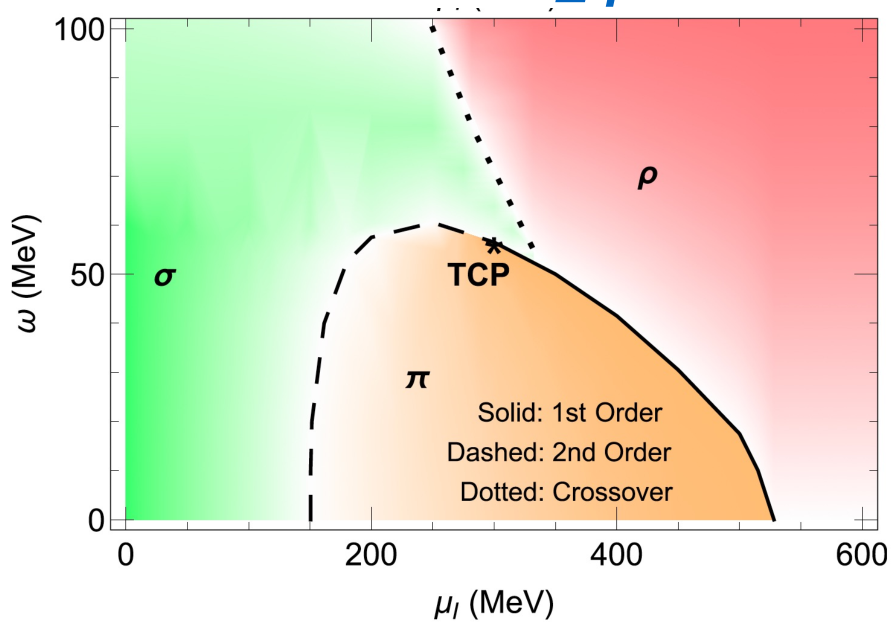


mu_q=0

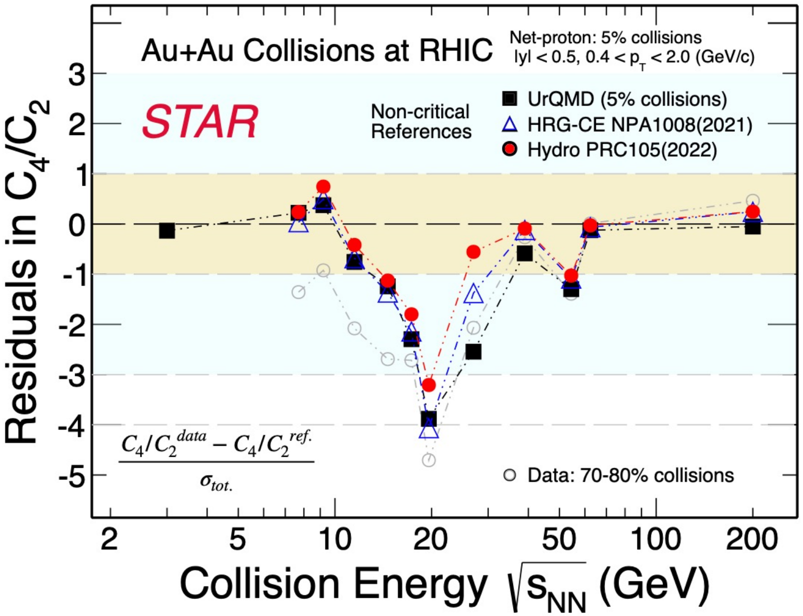
mu_q=250MeV



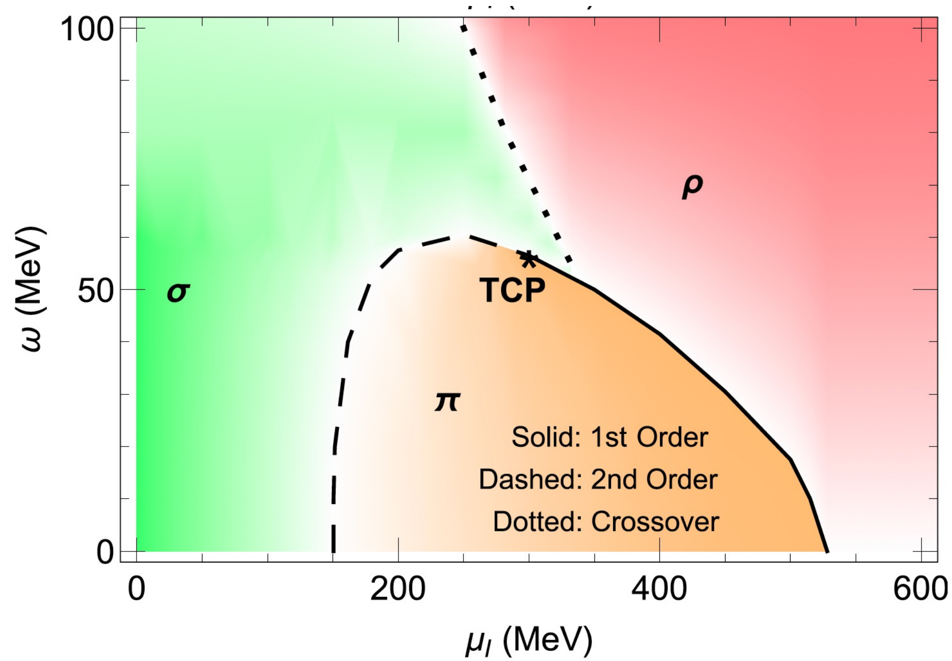
Rich phase structures of isospin matter under rotation;
Relevant to low energy HIC or neutron star matter;
Implications for particle polarization / dileptons?!

[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Isospin Matter under Rotation

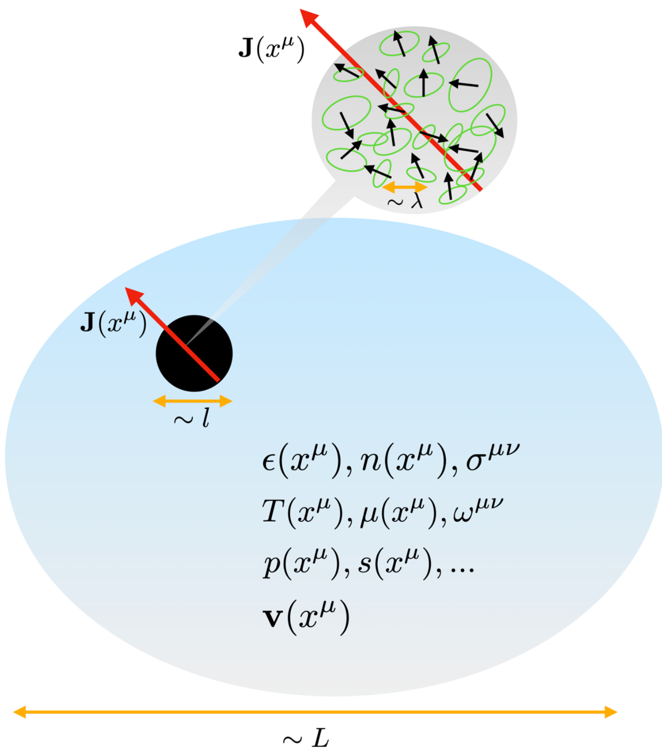


mu_q=250MeV



Enhanced rho condensation could play a role in generating a significant repulsive force and might be relevant to the "dip" in low energy collisions!

QCD Matter with Large Angular Momentum



"Spin physics" of a quantum fluid

$$\partial_\mu J^{\mu\alpha\beta} = 0,$$

$$J^{\mu\alpha\beta} = \left(x^\alpha T^{\mu\beta} - x^\beta T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta}.$$

Many interesting questions:
— EOS and phase structures
— decomposition of spin/orbital
— gradients and viscous terms
— phenomenological effects
— ……

[She, Huang, You, JL, Science Bulletin 67(2022)2265-2268 (arXiv:2105.04060)]

Hydrodynamics with Angular Momentum

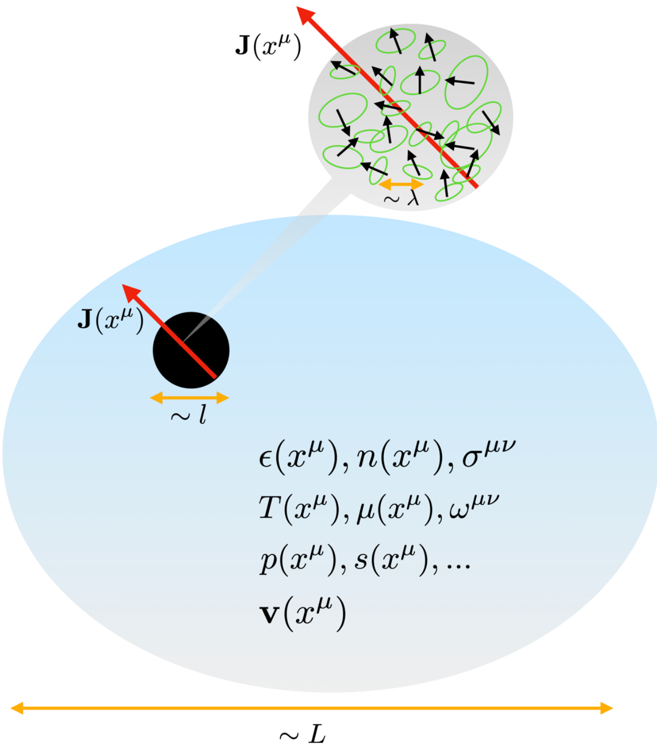
Phenomenological issues?

How to incorporate the angular momentum into the hydrodynamic framework?

In particular, how to include spin degrees of freedom?

Florkowski, Ryblewski, Kumar, …;
Becattini, Tinti, Buzzegoli, …;
Hattori, Hongo, Huang, …;
Fukushima, Pu;
Shi, Gale, Jeon;
Weickgenannt, Speranza, Sheng, Wang, Rischke;
Liu, Yin, …;
Gallegos, Gursoy, Yarom;
Li, Stephanov, Yee;
……

Goal: Navier-Stokes Hydro for Ang. Mom.



$\lambda \ll l \ll L$, a coarse-graining process

$$\partial_\mu T^{\mu\nu} = 0,$$
$$\partial_\mu N^\mu = 0,$$

$$\partial_\mu J^{\mu\alpha\beta} = 0,$$

$$J^{\mu\alpha\beta} = \left(x^\alpha T^{\mu\beta} - x^\beta T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta}.$$

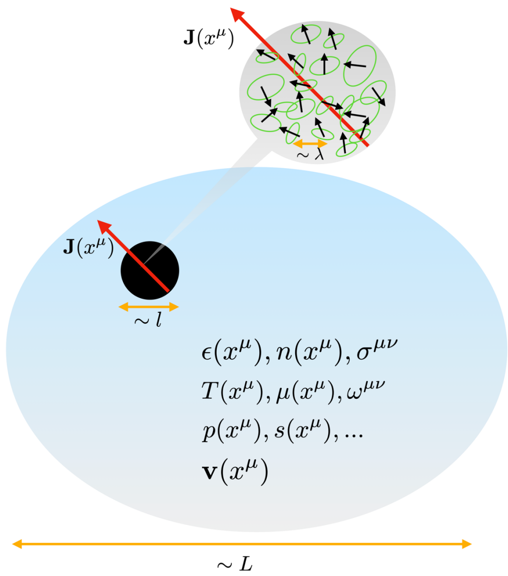
We choose to deal with only the conserved quantities, i.e. angular momentum.

Local angular momentum current $\Sigma^{\mu\alpha\beta}$

Local angular momentum density $\sigma^{\alpha\beta}(x^\mu)$

Local angular momentum chemical potential $\omega_{\alpha\beta}(x^\mu)$

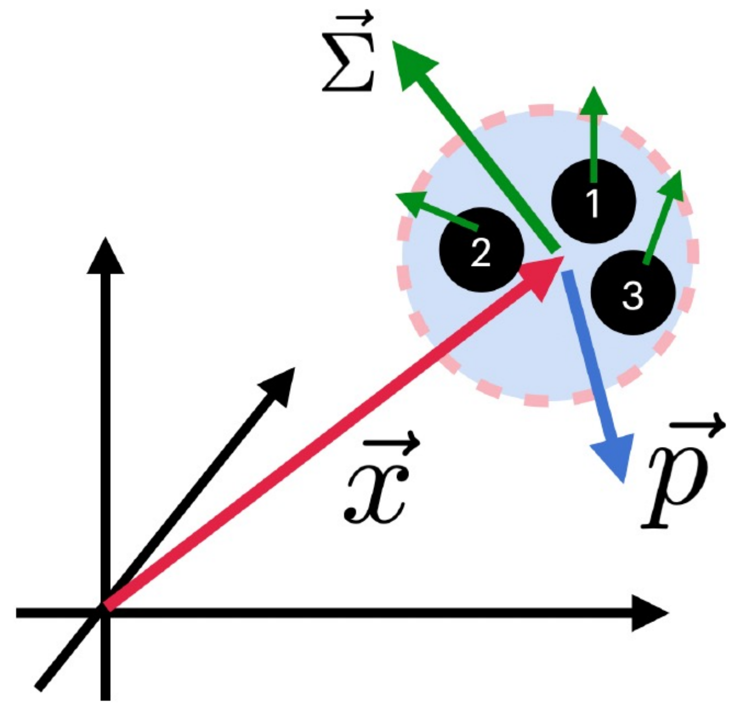
Decomposition of Fluid Cell Angular Momentum



$\lambda \ll l \ll L$, a coarse-graining process

Conceptually, it may NOT be feasible to further separate the spin part out of the local angular momentum of a coarse-grained fluid cell.

$$J^{\mu\alpha\beta} = \left(x^{\alpha}T^{\mu\beta} - x^{\beta}T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta}\,.$$



$$\vec{\mathbf{J}} = \vec{\mathbf{x}}\times\vec{\mathbf{p}} + \sum_{i=1,2,3}\left(\vec{\mathbf{x}'}_i \times \vec{\mathbf{p}'}_i + \vec{\mathbf{s}}_i\right).$$

$$\vec{\boldsymbol{\Sigma}} = \sum_{i=1,2,3}\left(\vec{\mathbf{x}'}_i \times \vec{\mathbf{p}'}_i + \vec{\mathbf{s}}_i\right)$$

Viscous Hydro with Ang. Mom.

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - p\Delta^{\mu\nu} + \widetilde{T}^{\mu\nu} \,,$$
$$N^\mu = n u^\mu + \widetilde{N}^\mu \,,$$
$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + \widetilde{\Sigma}^{\mu\alpha\beta} \,,$$
$$S^\mu = s u^\mu + \widetilde{S}^\mu .$$

Let us first focus on entropy current:

$$S^\mu = p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta}$$

Leading order:

$$\partial_\mu S^\mu_{(0)} = 2\beta\omega_{\alpha\beta}\widetilde{T}^{\alpha\beta}_{(a)} \,. \quad \Rightarrow \quad \widetilde{T}^{\alpha\beta}_{(a)} = 0.$$

Next order (2nd-gradient):

$$\begin{aligned} \partial_\mu S^\mu &= \partial_\mu \left(p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta} \right) \\ &= \widetilde{T}^{\mu\nu}\partial_\mu\beta_\nu - \widetilde{N}^\mu\partial_\mu\alpha - \widetilde{\Sigma}^{\mu\alpha\beta}\partial_\mu\left(\beta\omega_{\alpha\beta}\right) , \end{aligned}$$

$$\partial_\mu S^\mu \geq 0.$$

Viscous Hydro with Ang. Mom.: Eckart Frame

$$u_E^\mu = \frac{N^\mu}{\sqrt{N^\nu N_\nu}},$$

Write down all allowed Lorentz structures to the correct order of gradient expansion

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\,\Delta^{\mu\nu} + 2u^{(\mu} q^{\nu)} + \pi^{\mu\nu},$$

$$N^\mu = n u^\mu,$$

$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + 2u^{[\alpha}\Delta^{\mu\beta]}\Phi + 2u^{[\alpha}\tau_{(s)}^{\mu\beta]} + 2u^{[\alpha}\tau_{(a)}^{\mu\beta]} + \Theta^{\mu\alpha\beta}.$$

Plug these into the entropy current divergence and look for conditions of positivity:

$$\partial_\mu S^\mu = \partial_\mu \left(p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta}\right) = \widetilde{T}^{\mu\nu}\partial_\mu\beta_\nu - \widetilde{N}^\mu\partial_\mu\alpha - \widetilde{\Sigma}^{\mu\alpha\beta}\partial_\mu\left(\beta\omega_{\alpha\beta}\right),$$

$$\partial_\mu S^\mu \geq 0.$$

Viscous Hydro with Ang. Mom.: Eckart Frame

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$$\partial_\mu S^\mu \geq 0.$$

$$\Pi = -\zeta\theta,$$
$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle},$$
$$q^\mu = \lambda T\left(\frac{\nabla^\mu T}{T} - Du^\mu\right)$$
$$= -\frac{\lambda n T^2}{\epsilon+p}\left[\nabla^\mu\left(\frac{\mu}{T}\right) + \frac{\sigma^{\alpha\beta}}{n}\nabla^\mu\left(\frac{\omega_{\alpha\beta}}{T}\right)\right]$$

$$\Phi = -\chi_1 u^\alpha \nabla^\beta\left(\frac{\omega_{\alpha\beta}}{T}\right), \quad (25)$$

$$\tau_{(s)}^{\mu\beta} = -\chi_2 u^\alpha\left[\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} + \Delta^{\mu\rho}\Delta^{\beta\gamma}\right) - \frac{2}{3}\Delta^{\mu\beta}g^{\rho\gamma}\right]\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right) \quad (26)$$

$$\tau_{(a)}^{\mu\beta} = -\chi_3 u^\alpha\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} - \Delta^{\mu\rho}\Delta^{\beta\gamma}\right)\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right), \quad (27)$$

$$\Theta^{\mu\alpha\beta} = -\chi_4\left(u^\beta u^\rho\Delta^{\alpha\delta} - u^\alpha u^\rho\Delta^{\beta\delta}\right)\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right) + \chi_5\Delta^{\alpha\delta}\Delta^{\beta\rho}\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right). \quad (28)$$

Five new positive angular momentum transport coefficients:

$\chi_1, \chi_2, \chi_3, \chi_4$ and χ_5

Summary & Discussions

Summary

- *CME offers the unique opportunity to unravel topological structures of QCD, with fundamental importance and broad impact.*

- *Searching for CME is difficult, but imperative.*

- *We are at the verge of reaching a conclusion and the prospect is exciting.*

- *Strong interaction matter with large angular momentum offers a new "playground" for QCD and many-body physics.*

- *There are now an abundance of experimental results and open questions, crying for understanding.*

- *The "party" has just started!*

Discussions

Chirality — pressing issues:

What does it take to further push the experimental search toward a final conclusion? How to prepare for the upcoming >10B AuAu data analysis?

Can we achieve a consistent understanding of all these relevant measurements across a variety of beam energies and colliding systems?

A coherent interpretation of various B field driven phenomena?

Vorticity — pressing issues:

How to quantitatively understand the large signal at low energy?

A coherent picture of spin alignment for different vector mesons?

How can we differentiate effects driven by angular momentum from effects from something else?

Hydrodynamics and transport theories with angular momentum?