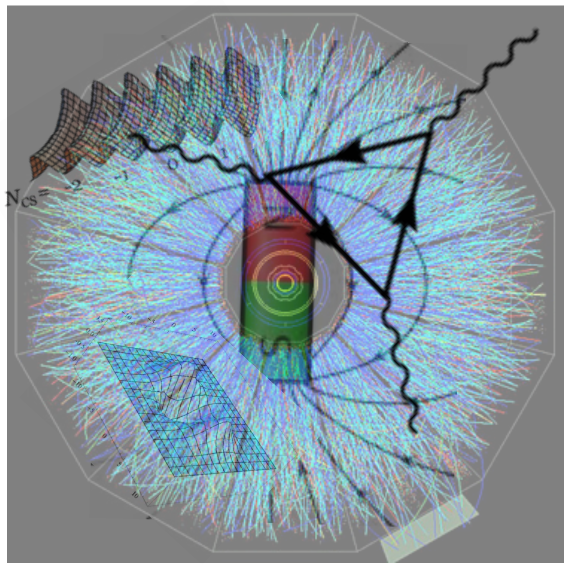
Chirality and Spin Transport in Heavy Ion Collisions

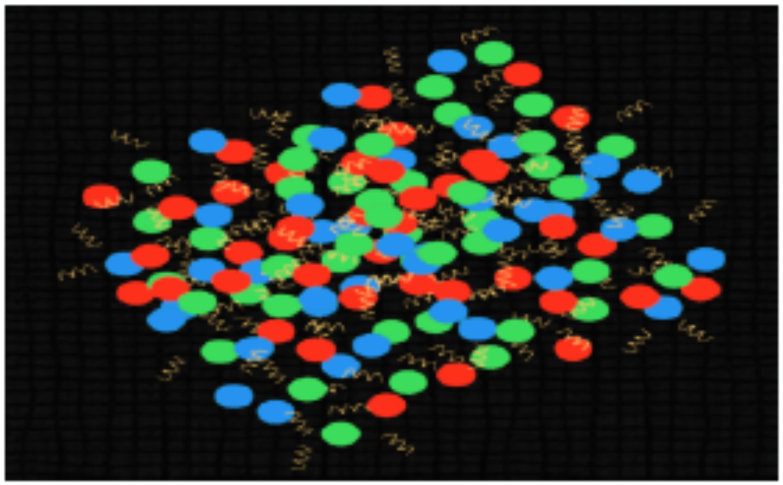


Jinfeng Liao

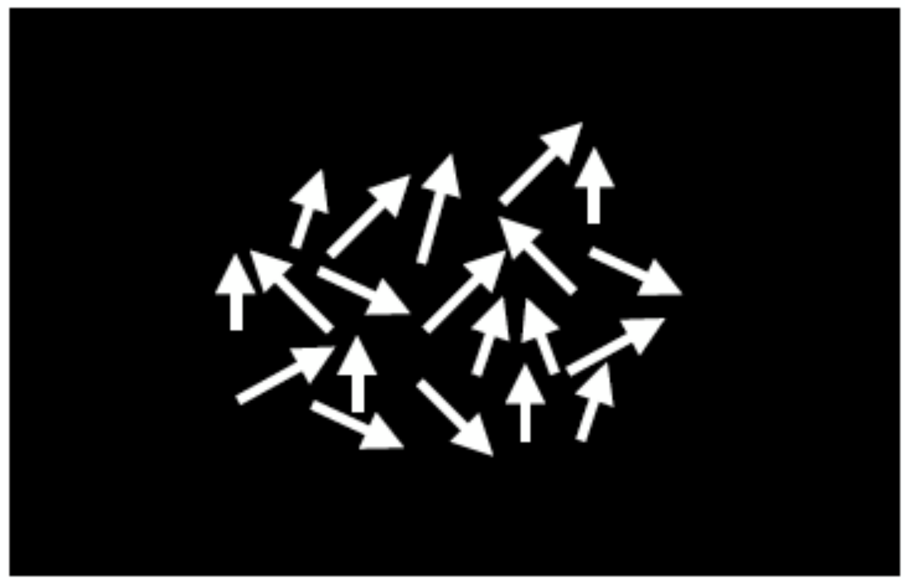
Indiana University, Physics Dept. & CEEM

A Quantum Fluid with Large Angular Momentum

A nearly perfect fluid (of energy-momentum)

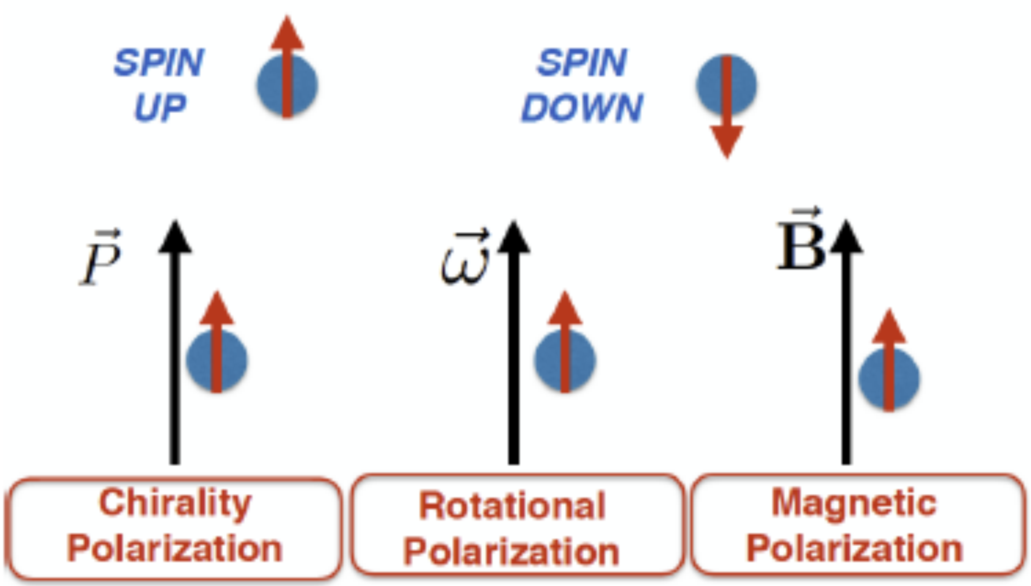


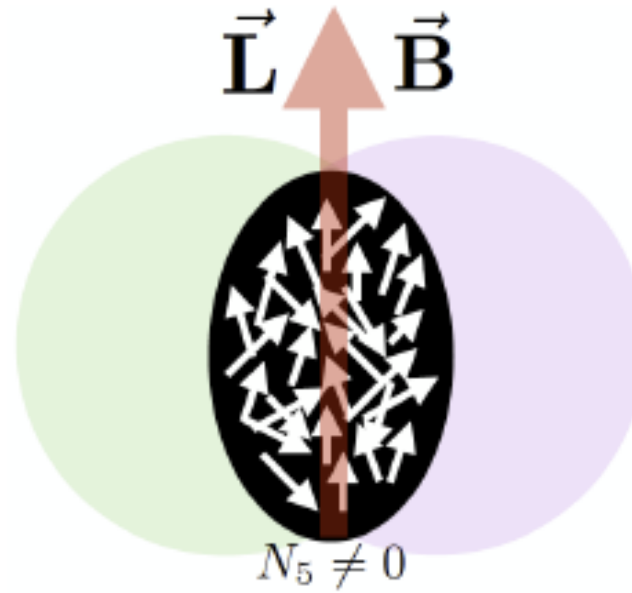
What happens to the spin DoF in the fluid???



Angular momentum transport in a quantum fluid!

Spin @ Chirality, Vorticity and Magnetic Field





[arXiv:2004.00569]

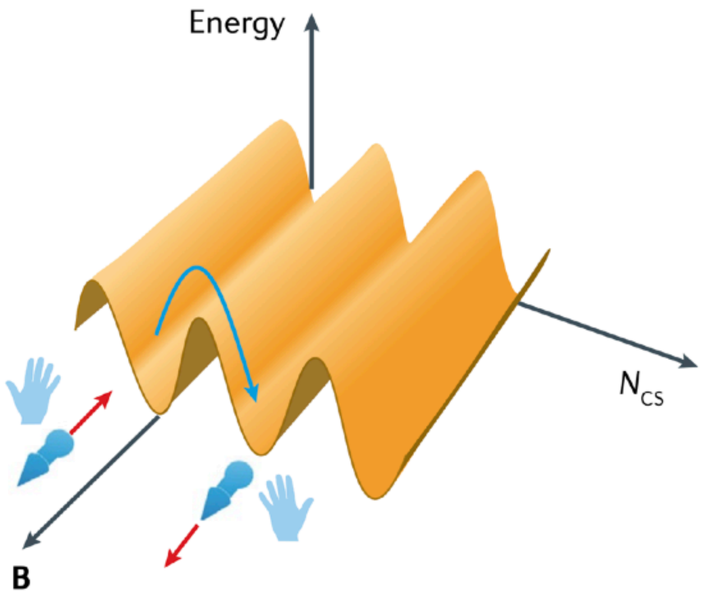
The interplay of spin with chirality/vorticity/magnetic field —> many novel phenomena

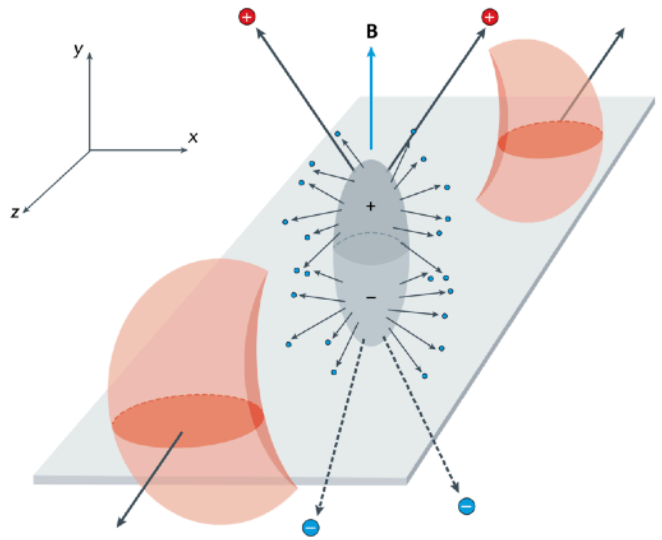
Chiral Magnetic Effect

Chiral Magnetic Effect (CME):

Macroscopic manifestation of chiral anomaly and gauge field topology

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





[From: Nature Reviews Physics 3 (2021) 1, 55-63 (arXiv:2102.06623)]

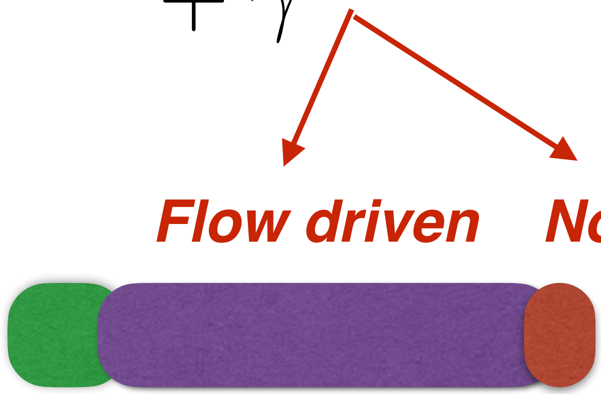
Key question at stake:
can we observe it in heavy ion collisions?

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've come a long way in fighting with the backgrounds.

[Chin.Phys.C 46 (2022) 1, 014101 (arXiv:2105.06044)]

Have We Seen the CME?

[arXiv:2405.05427 (Int.J.Mod.Phys.E 33 (2024) 09, 2430007) (QGP6)]

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

Dmitri E. Kharzeev [*]

Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

Department of Physics, Brookhaven National Laboratory Upton, New York 11973-5000, USA

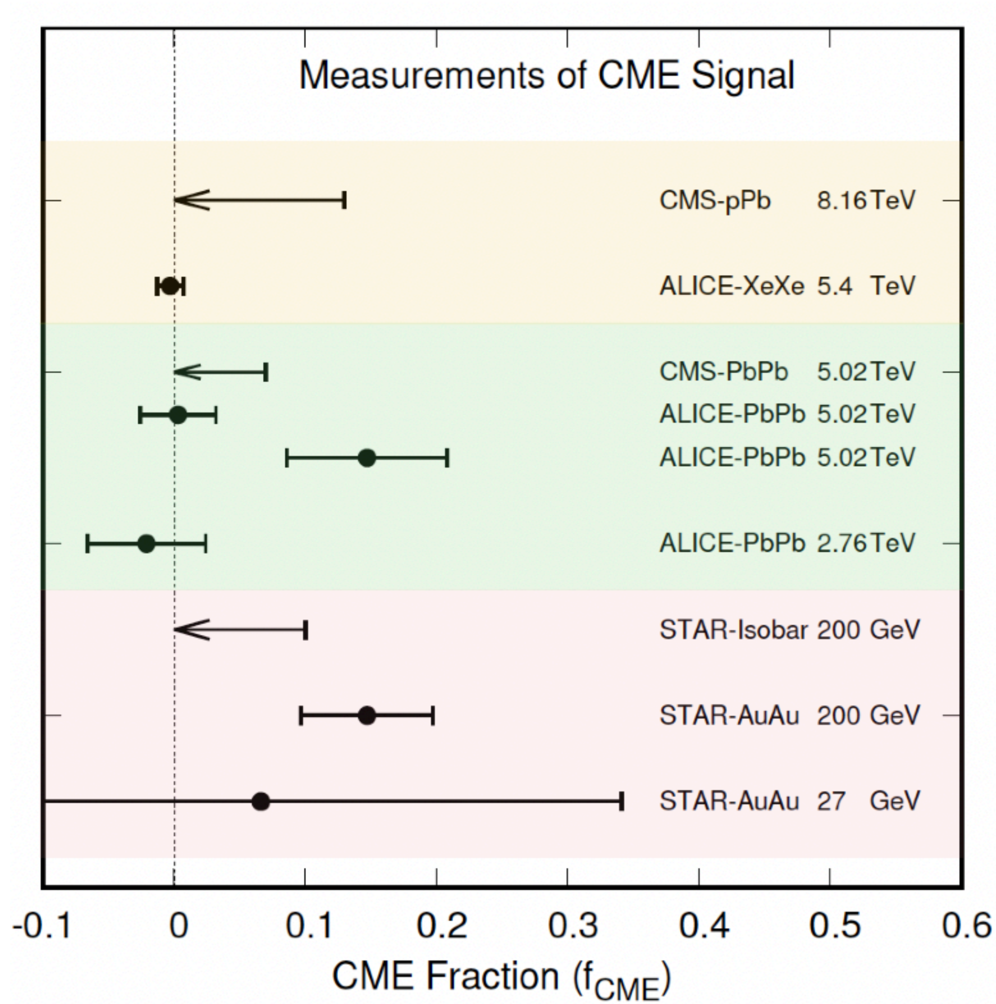
Jinfeng Liao [†]

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

Prithwish Tribedy [‡]

Department of Physics, Brookhaven National Laboratory Upton, New York 11973-5000, USA

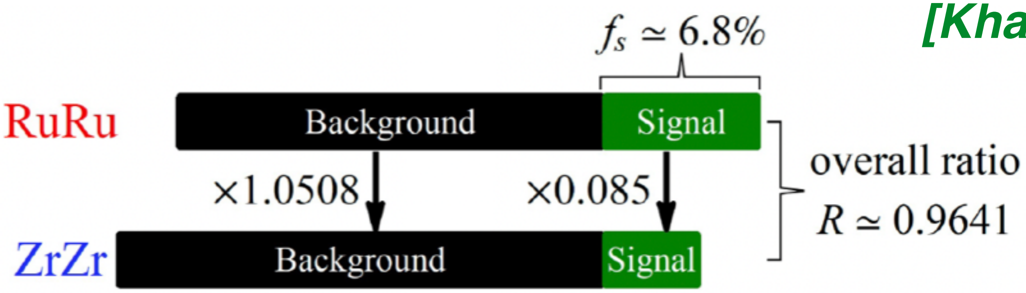
The chiral magnetic effect (CME) is a collective quantum phenomenon that arises from the interplay between gauge field topology and fermion chiral anomaly, encompassing a wide range of physical systems from semimetals to quark-gluon plasma. This review, with a focus on CME and related effects in heavy 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.



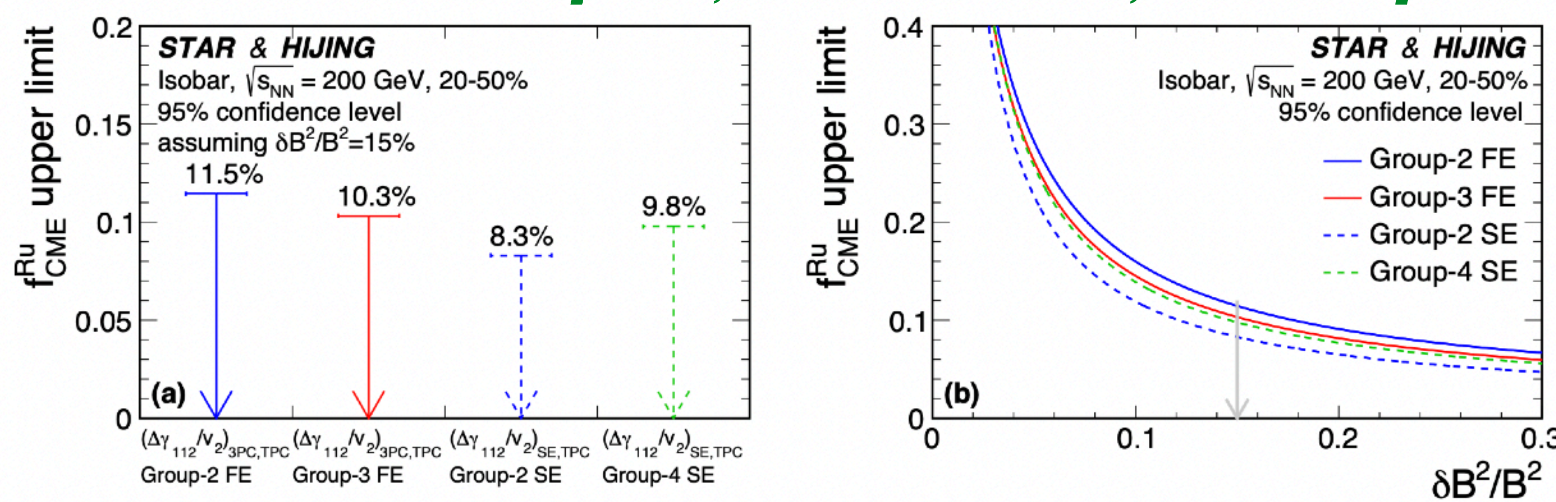
Where Do We Stand?

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

[Khazeev, JL, Shi, arXiv:2205.00120]

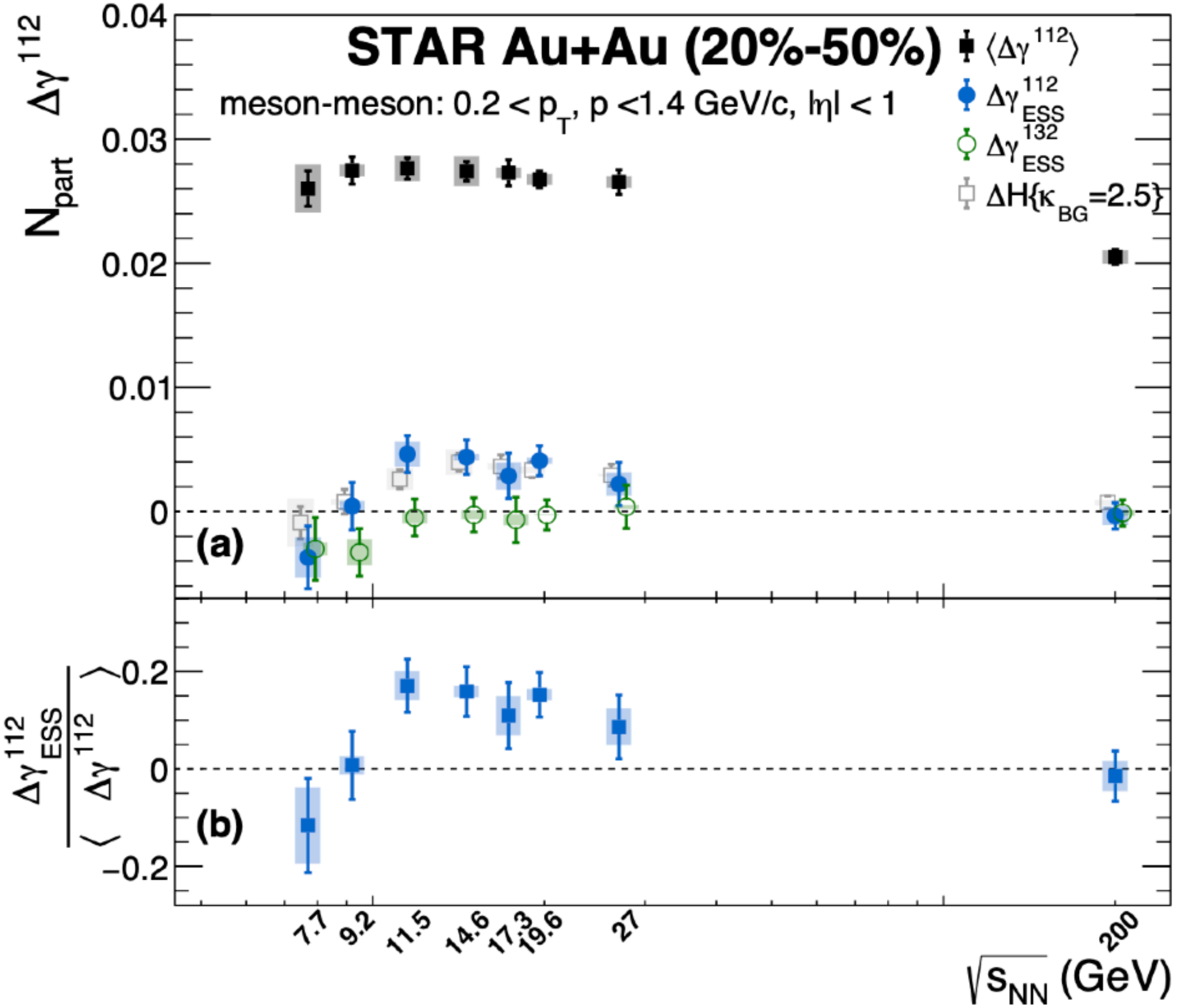


[STAR, arXiv:2310.13096;2308.16846]



– ***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***

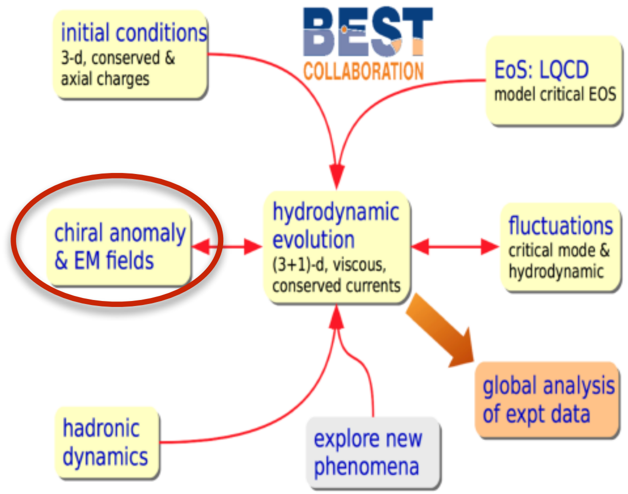
Latest Measurement from BES-II



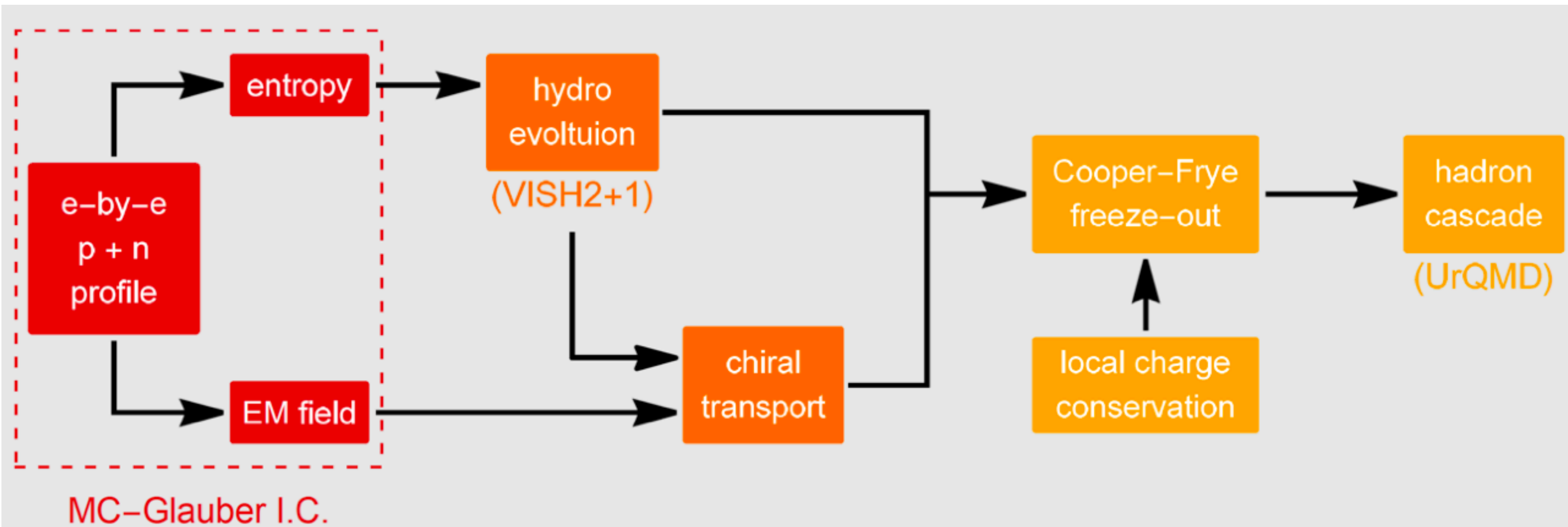
STAR: 2506.00275; 2506.00278

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]

Data Driven Extraction of Key Parameters

— *Upgrade the EBE-AVFD for BES energies (focusing on 19.6GeV for now)*

— *Calibration with bulk data (multiplicity, v2, net proton, …)*

— *Systematically scanning the key parameters for chiral magnetic transport (~1M events for each point)*

$$\tau_B \,, n_5/s, f_{LCC} \quad \longrightarrow \quad \gamma \,, \, \delta$$

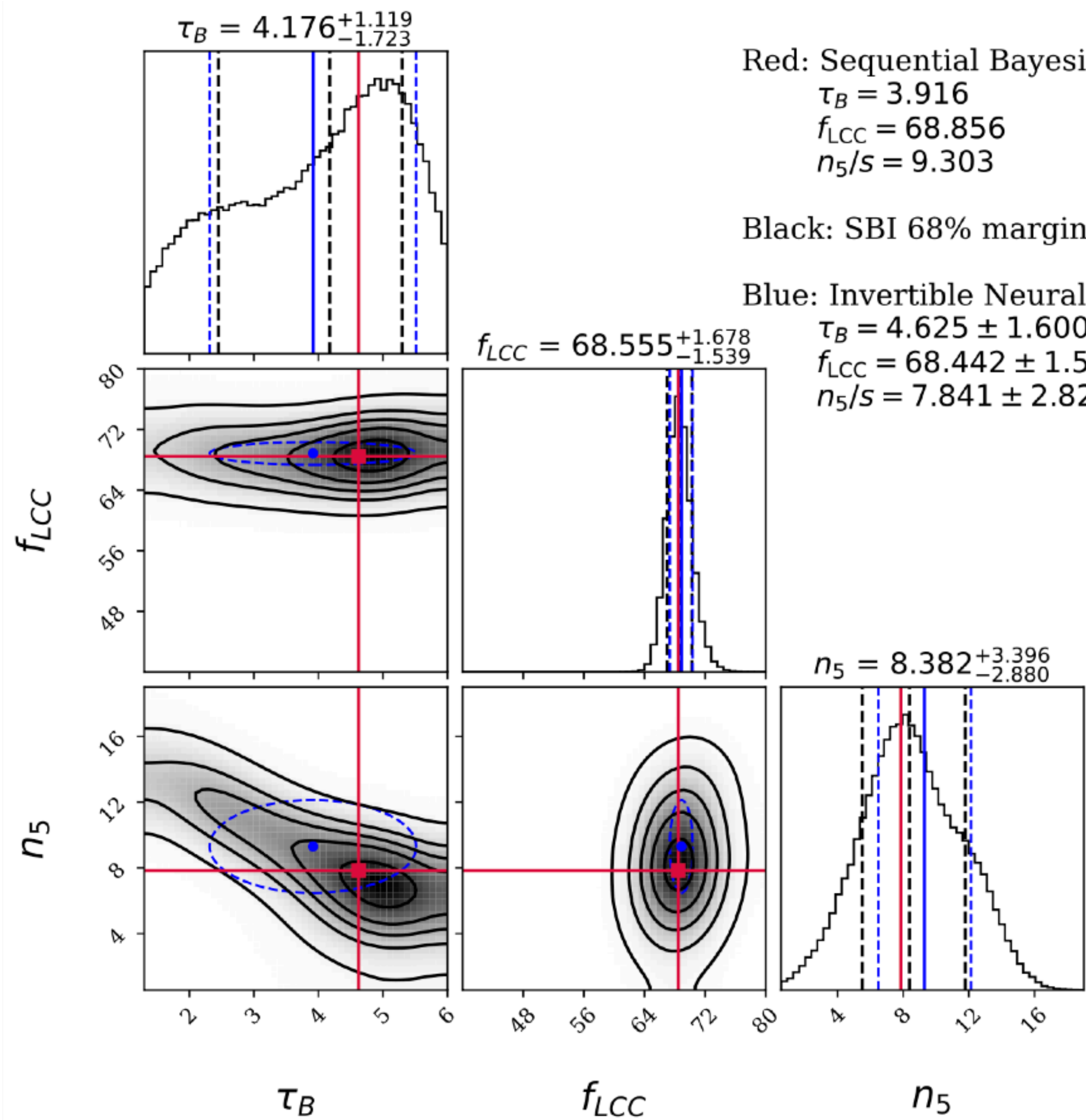
— *Gaussian Process Emulator (GPE)*

— *Exp data + Advanced statistics tools (Bayesian, neural networks)*

Major advantages:
No more assumption about B field lifetime;
No need of separating BKG/Signal in gamma & delta .

A. Akridge, Y. Guo, JL, S. Shi, H. Zhang: in preparation.

Exaction of Key Physics Parameters



Red: Sequential Bayesian Inference (SBI) MAP:
$\tau_B = 3.916$
$f_{LCC} = 68.856$
$n_5/s = 9.303$

Black: SBI 68% marginal CI

Blue: Invertible Neural Network (INN):
$\tau_B = 4.625 \pm 1.600$
$f_{LCC} = 68.442 \pm 1.506$
$n_5/s = 7.841 \pm 2.827$

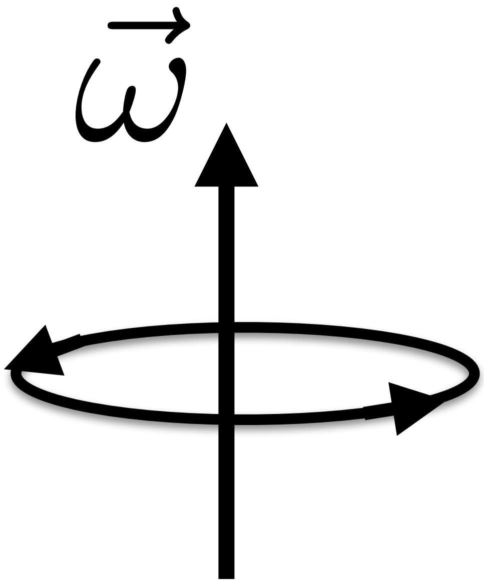
Powerful machine learning (ML) tool has enabled us to make robust extraction of key information for chiral magnetic transport!!!

A. Akridge, Y. Guo, JL, S. Shi, H. Zhang: in preparation.

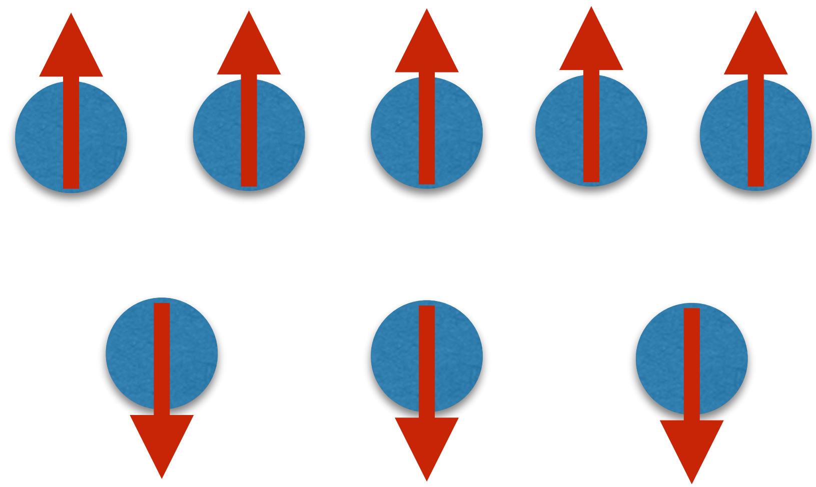
Initial Conditions for Angular Momentum

Rotational Polarization

Angular momentum —> global spin polarization



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

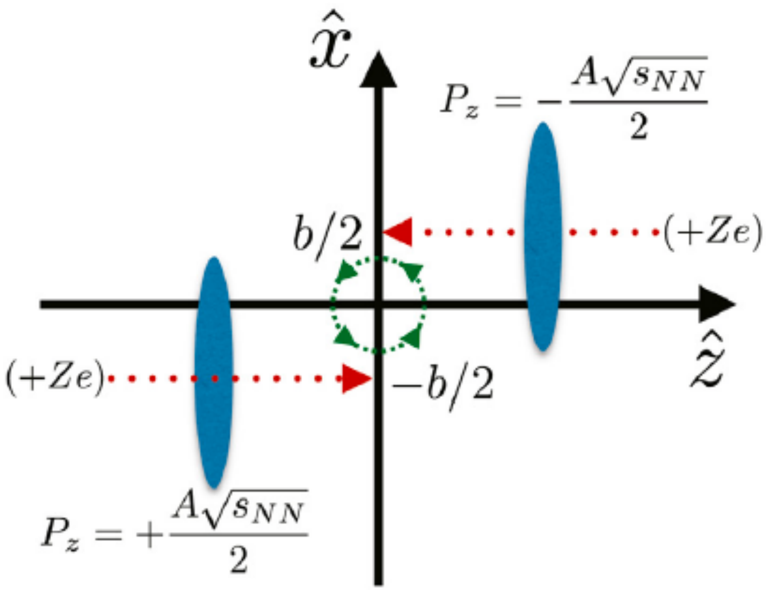


Macroscopic rotation; Global angular momentum

Microscopic spin alignment

"Fluid spintronics" in condensed matter systems

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)

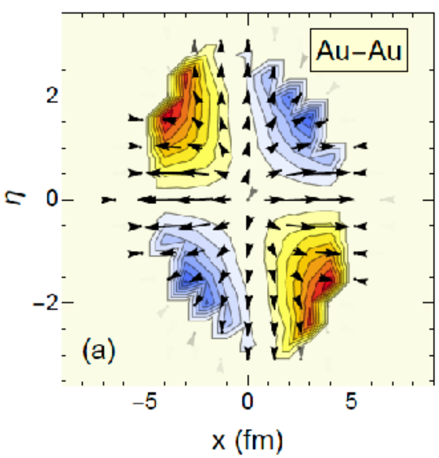
Rotating quark-gluon plasma in relativistic heavy-ion collisions

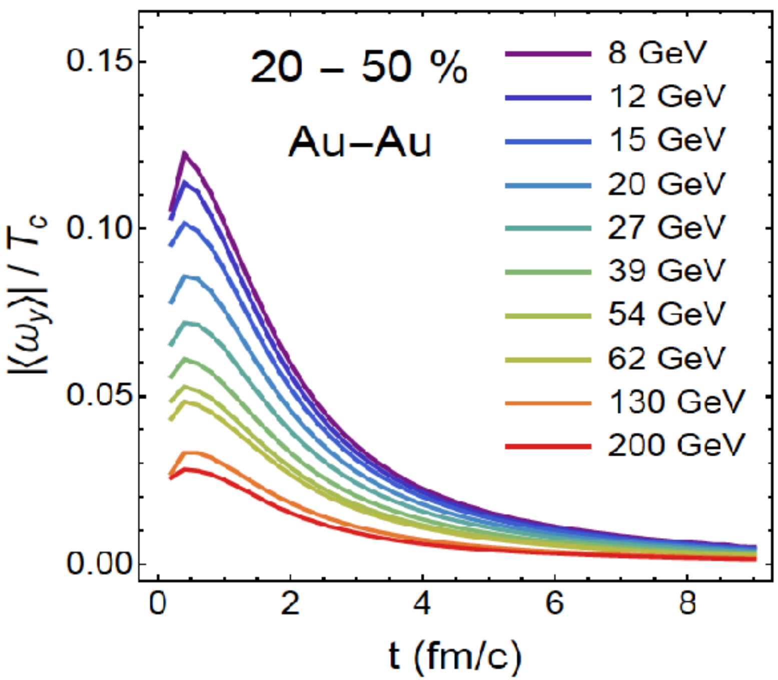
Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]
[1]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 North Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*
[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!

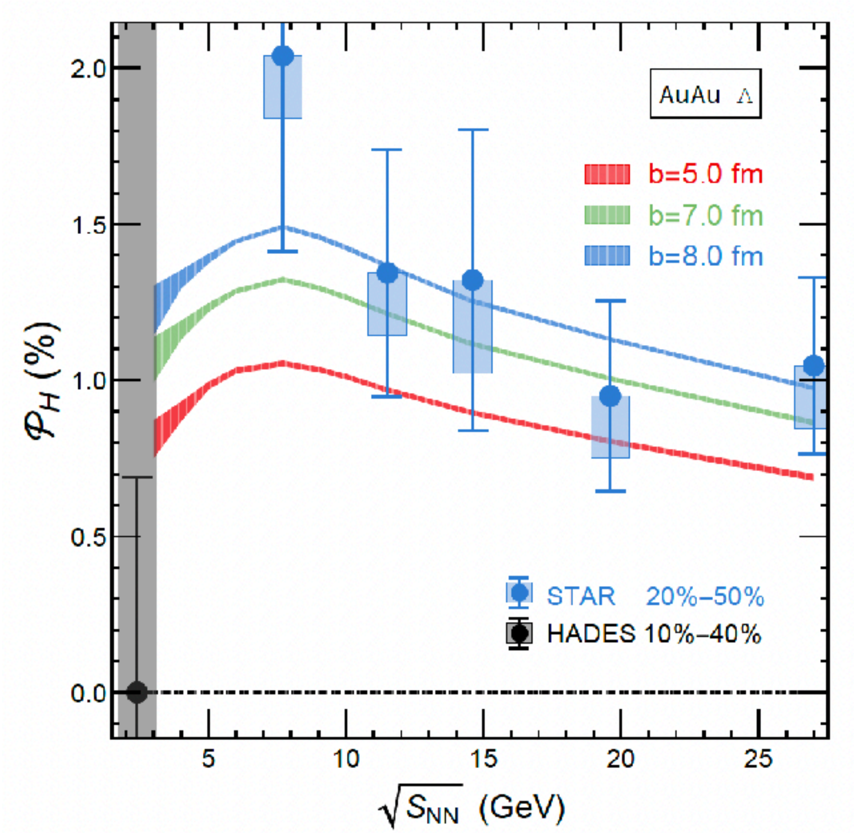




Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

Trend of Global Polarization toward O(1) GeV

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



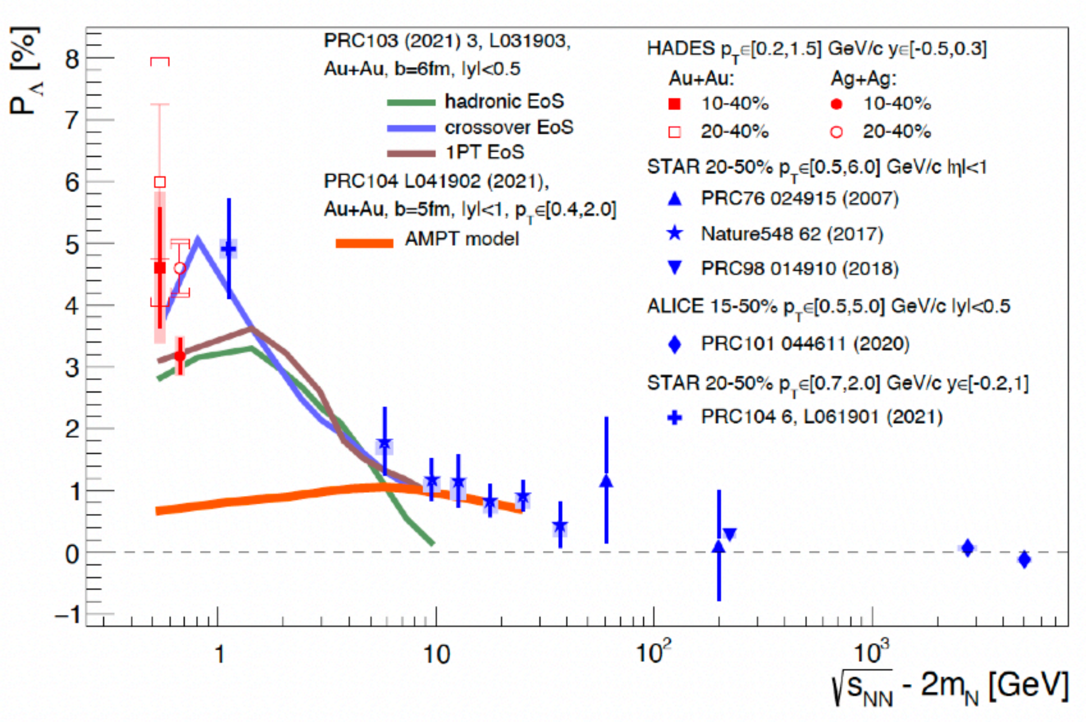
Yu Guo, et al, PRC2021
arXiv:2105.13481

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.

Dependence on Beam Energy

HADES, arXiv: 2207.05160



Surprisingly large signal even very close to threshold?!

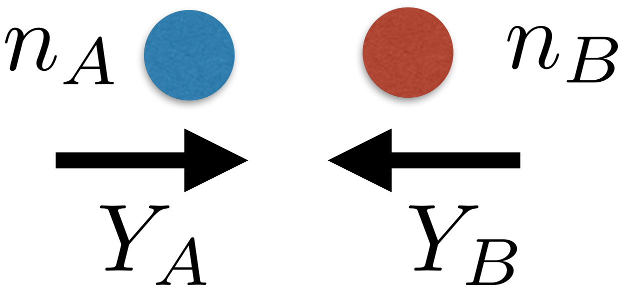
$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

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

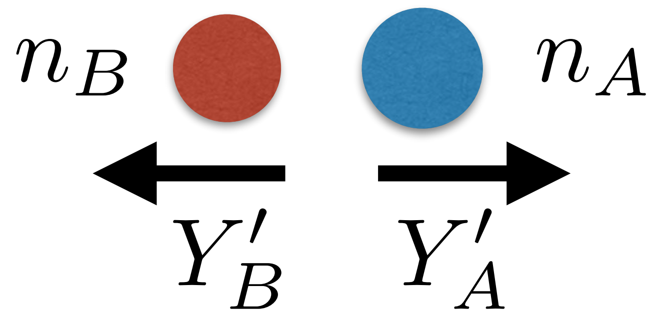
This is quantitatively related to the baryon stoping and can be calibrated with baryon number measurements.

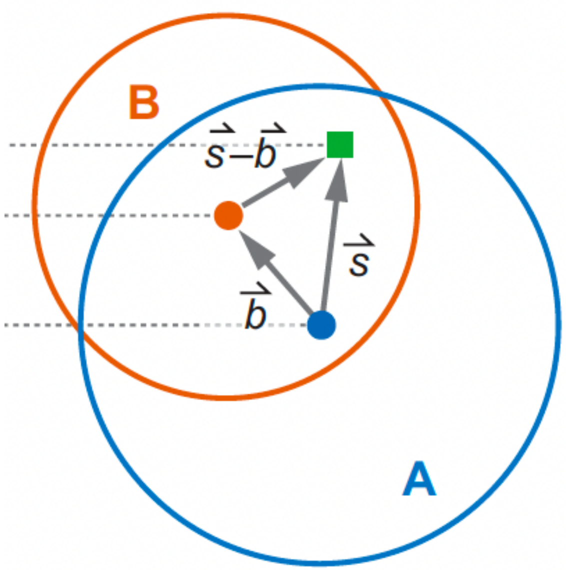
Nuclear Stopping & Angular Momentum

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



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



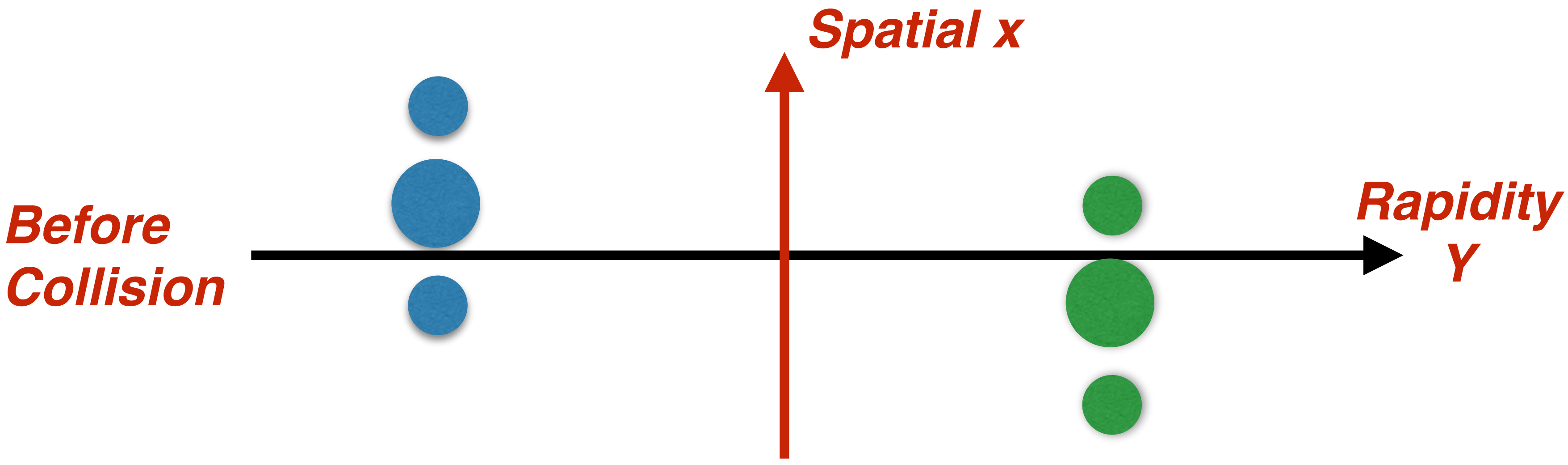


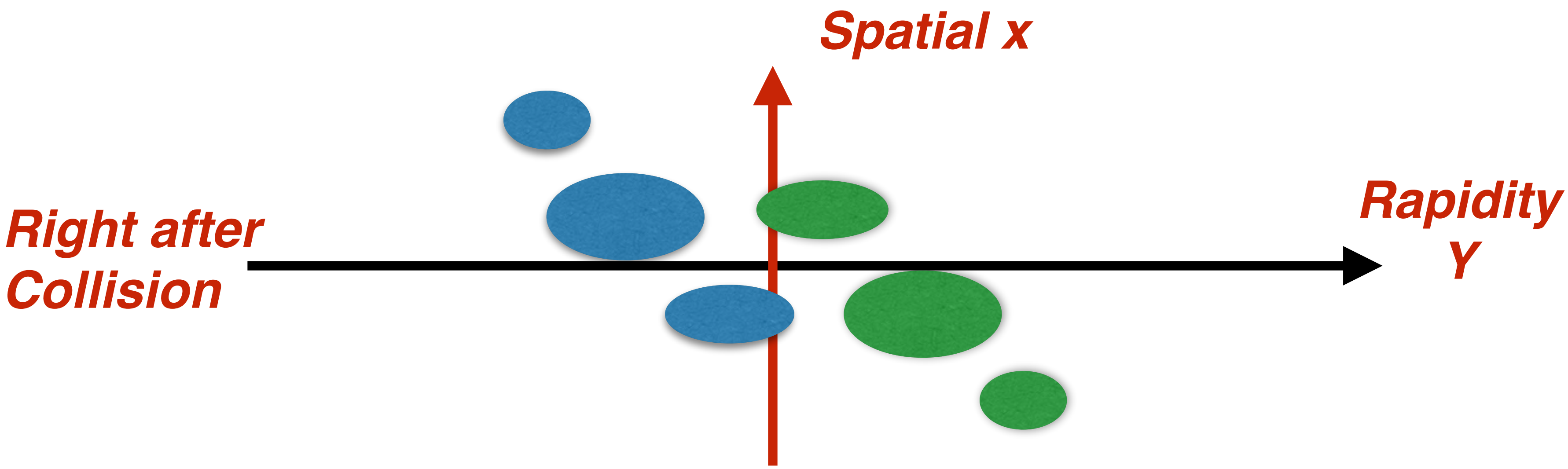
Various spots on the overlapping zone —> A "spread-out" (i.e. distribution) along rapidity

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

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

The "Glauber+" Picture

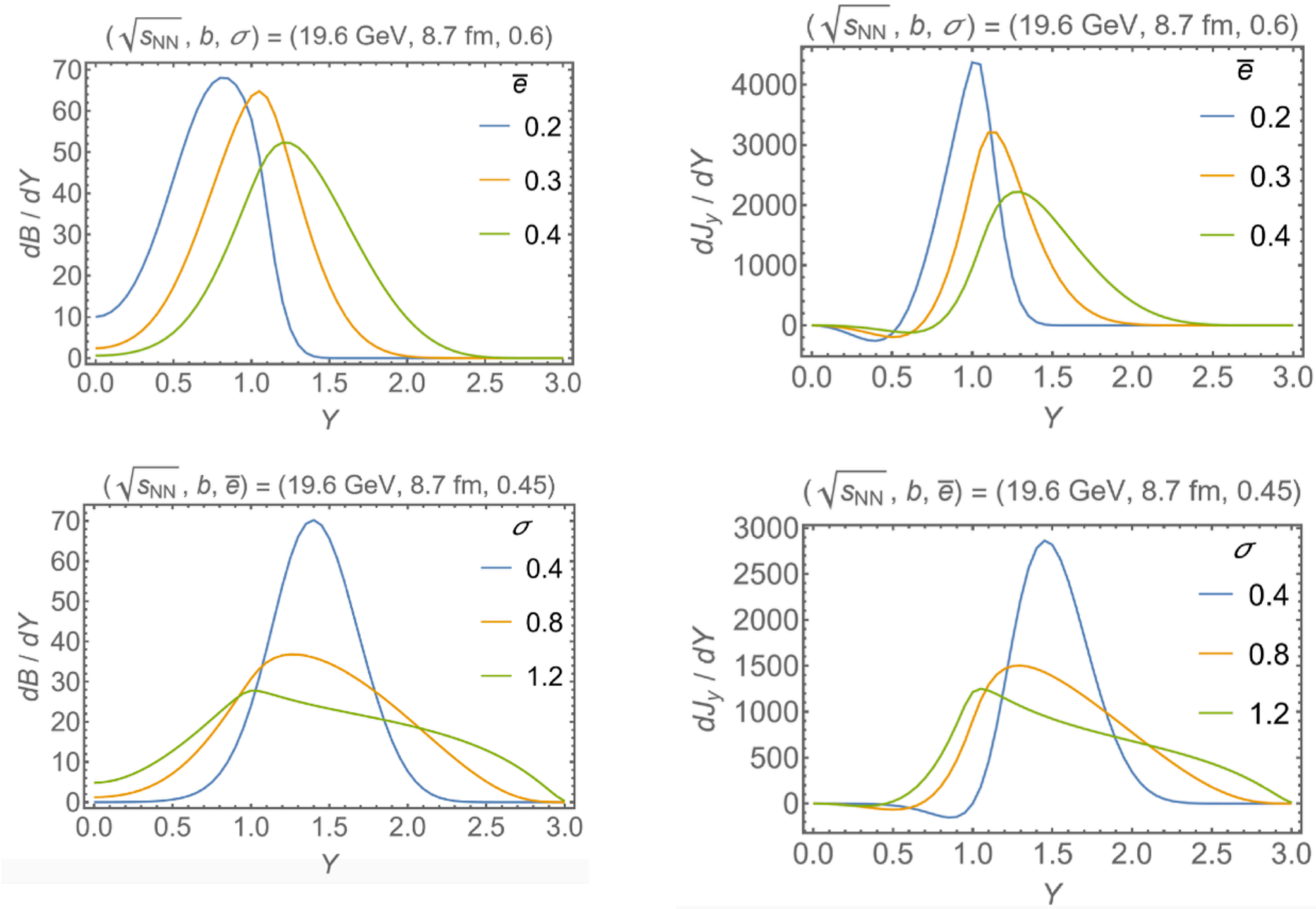




A. Akridge, D. Gallimore, H. Morales, JL, arXiv:2504.02192

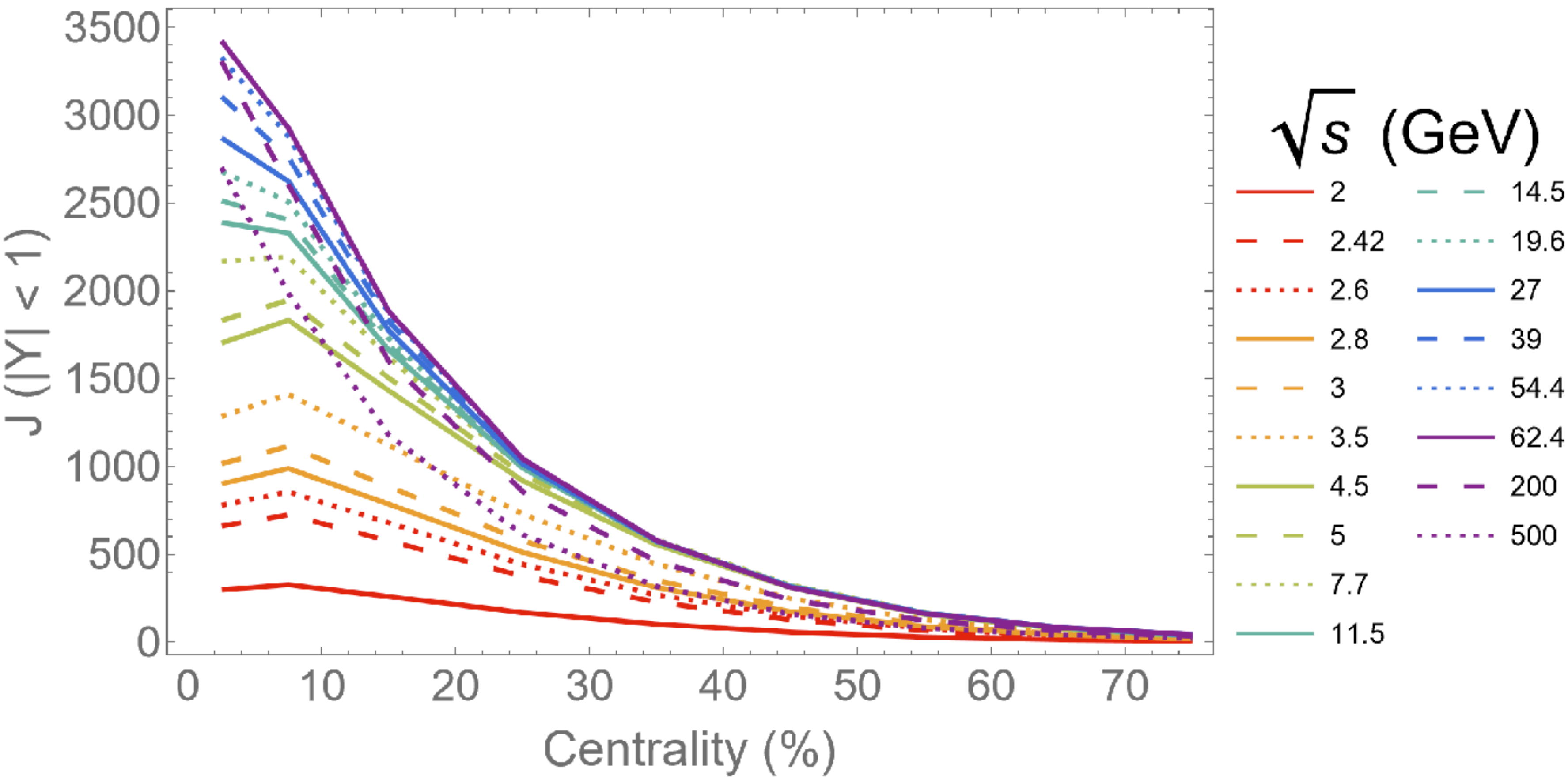
Rapidity Distributions

Net baryon | **Angular momentum**



A. Akridge, D. Gallimore, H. Morales, JL, arXiv:2504.02192

Initial Angular Momentum

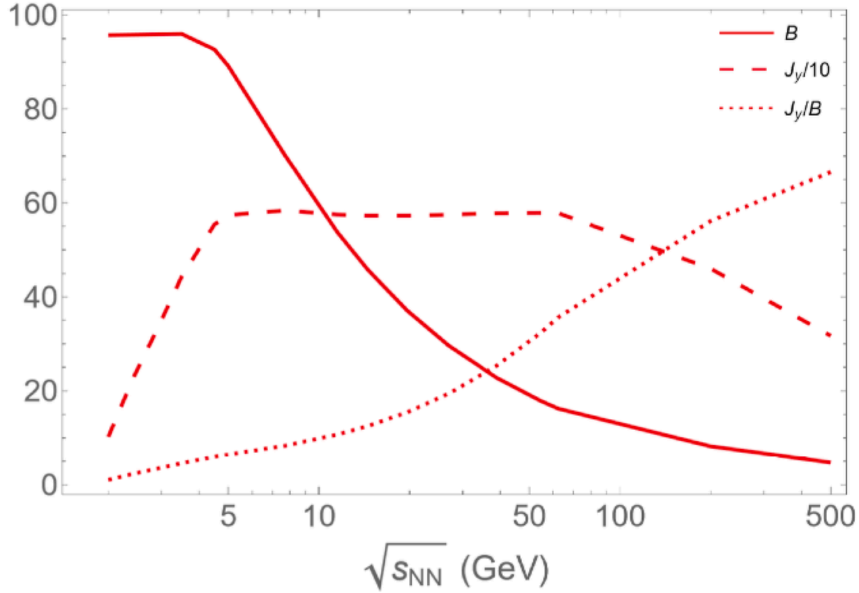


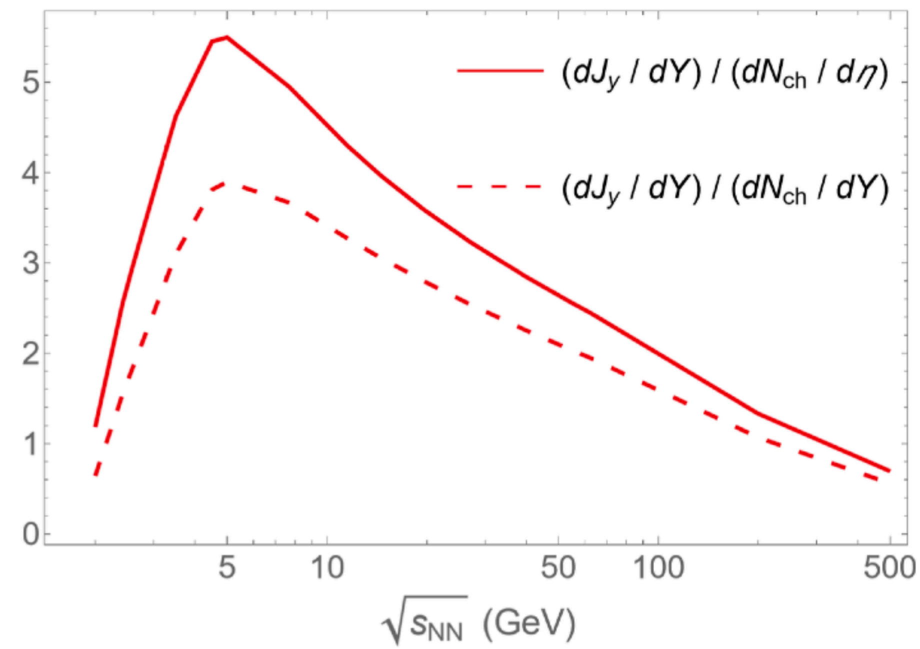
Mid-rapidity angular momentum

A. Akridge, D. Gallimore, H. Morales, JL, arXiv:2504.02192

Normalized Initial Angular Momentum

A. Akridge, D. Gallimore, H. Morales, JL, arXiv:2504.02192





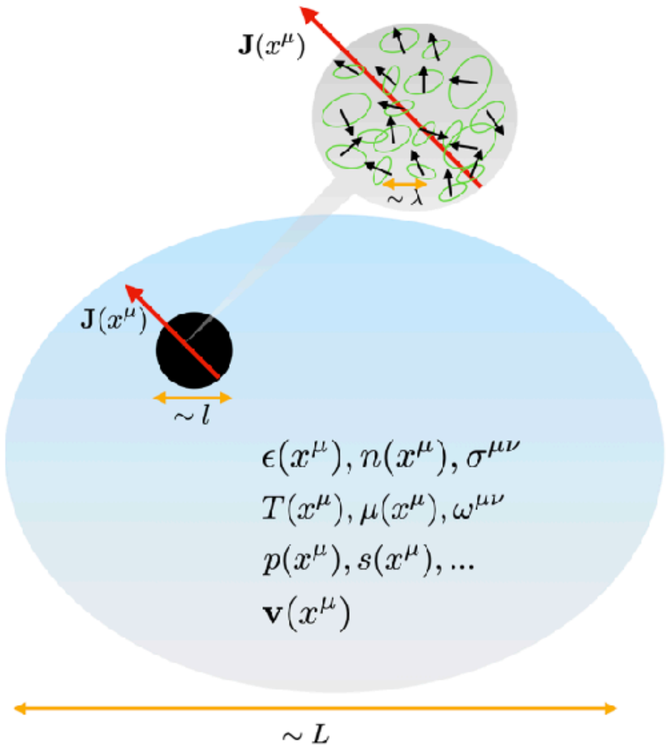
Key message: angular momentum driven phenomena unlikely keeps increasing toward extremely low energy.

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;
……

Hydrodynamics 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)]

Viscous Hydro with Ang. Mom.: Eckart Frame

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + 2u^{(\mu}q^{\nu)} + \pi^{\mu\nu},$$
$$N^\mu = nu^\mu,$$
$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + 2u^{[\alpha}\Delta^{\mu\beta]}\Phi + 2u^{[\alpha}\tau_{(s)}^{\mu\beta]} + 2u^{[\alpha}\tau_{(a)}^{\mu\beta]} + \Theta^{\mu\alpha\beta}.$$

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

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

$$\Phi = -\chi_1 u^\alpha \nabla^\beta\left(\frac{\omega_{\alpha\beta}}{T}\right), \quad (25)$$
$$\tau_{(s)}^{\mu\beta} = -\chi_2 u^\alpha\left[\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} + \Delta^{\mu\rho}\Delta^{\beta\gamma}\right) - \frac{2}{3}\Delta^{\mu\beta}g^{\rho\gamma}\right]\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right) \quad (26)$$
$$\tau_{(a)}^{\mu\beta} = -\chi_3 u^\alpha\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} - \Delta^{\mu\rho}\Delta^{\beta\gamma}\right)\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right), \quad (27)$$
$$\Theta^{\mu\alpha\beta} = -\chi_4\left(u^\beta u^\rho \Delta^{\alpha\delta} - u^\alpha u^\rho \Delta^{\beta\delta}\right)\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right) + \chi_5 \Delta^{\alpha\delta}\Delta^{\beta\rho}\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right). \quad (28)$$

Five new positive angular momentum transport coefficients:

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

[Science Bulletin 67(2022)2265-2268 (arXiv:2105.04060)]

Summary

- ***Theoretical analysis of the STAR BES-II data in search of CME suggests a strong evidence of chiral magnetic transport and provides a first data-driven determination of key parameters for both CME and background.***

- ***Initial angular momentum is directly correlated with the baryon stopping and can be quantified with a Glauber+ model, constrained with relevant data.***

- ***Initial angular momentum drops toward zero at very low energy and initial angular momentum per final hadron shows a peak around 5 GeV.***

- ***Exciting time, with an abundance of experimental measurements and theoretical challenges!***