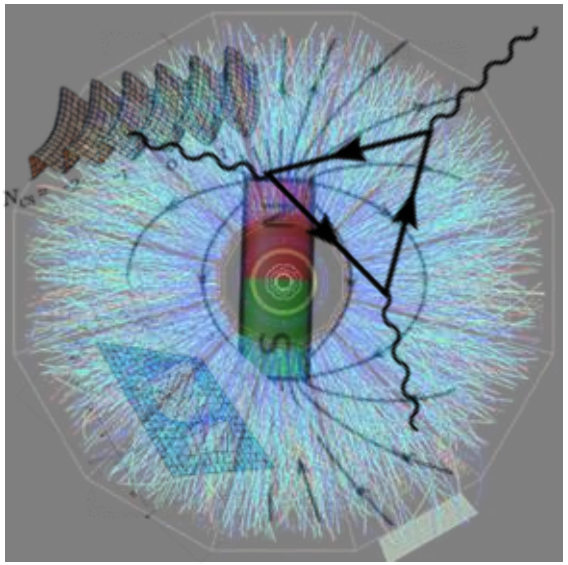


Nov. 16, 2026

Spin as a Unifying Theme in QCD



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Plan of the Talk

- ***Introduction***
- ***Spin Transport in Heavy-Ion Collisions***
- ***Chirality Transport in Heavy-Ion Collisions***
- ***Summary***

A Recent Review

SCIENCE ADVANCES | REVIEW

SPIN

Spin in quantum chromodynamics

Abhay Deshpande[1,2]*†, Dmitri E. Kharzeev[3,4]*†, Jinfeng Liao[5]*†

This article surveys the role of spin in quantum chromodynamics (QCD), tracing its manifestations from the internal structure of the nucleon to the collective dynamics of strongly interacting matter. We review the decomposition of the proton spin into the spin and orbital angular momentum of quarks and gluons and discuss the theoretical and experimental progress that has shaped our modern understanding of polarized parton structure. We then examine spin transport phenomena in hot and dense QCD matter, highlighting theoretical developments of phase structures under rotation and spin hydrodynamics theory as well as the experimental discovery of global polarization and other related phenomena. Last, we present anomalous transport and the chiral magnetic effect as paradigmatic examples of how quantum anomalies convert chirality and topology into macroscopic, nondissipative currents whose signal can be measured in experiments. Together, these topics illustrate how spin provides a unifying framework linking hadronic structure, gauge field topology, quark field chirality, and relativistic many-body dynamics in QCD.

Sci.Adv. 12 (2026) 38, eaeh1991
https://doi.org/10.1126/sciadv.aeh1991
(open access)

Introduction

From Microscopic Symmetries to Conserved Quantum Numbers

Spacetime translational symmetries	→ *Energy momentum conservation* →	*Energy & momentum (Mass)*	P^μ
Phase symmetry	→ *Charge conservation* →	*Charge*	N
Lorentz symmetry	→ *Angular momentum conservation* →	*Angular momentum (AM)*	J

These quantum numbers are essential for characterizing properties of matter.

QCD

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu a} + \sum_f \bar{\psi}_f (i \not{D} - m_f) \psi_f$$

$$\mathbf{J}_{\mathrm{QCD}} = \int \mathrm{d}^3\mathbf{x} \left[\psi_f^\dagger \frac{\boldsymbol{\Sigma}}{2} \psi_f + \psi_f^\dagger \mathbf{x} \times (-i\nabla) \psi_f + \mathbf{E}_a \times \mathbf{A}_a + E_a^i (\mathbf{x} \times \nabla) A_a^i \right],$$

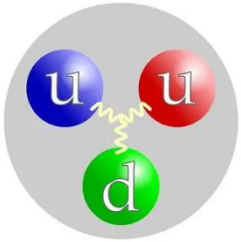
Or

$$\mathbf{J}_{\mathrm{QCD}} = \int \mathrm{d}^3 x \left[\psi_f^\dagger \frac{\boldsymbol{\Sigma}}{2} \psi_f + \psi_f^\dagger \mathbf{x} \times (-i\nabla - g_s \mathbf{A}) \psi_f + \mathbf{x} \times (\mathbf{E} \times \mathbf{B}) \right],$$

?

The famous issue of pseudo-gauge

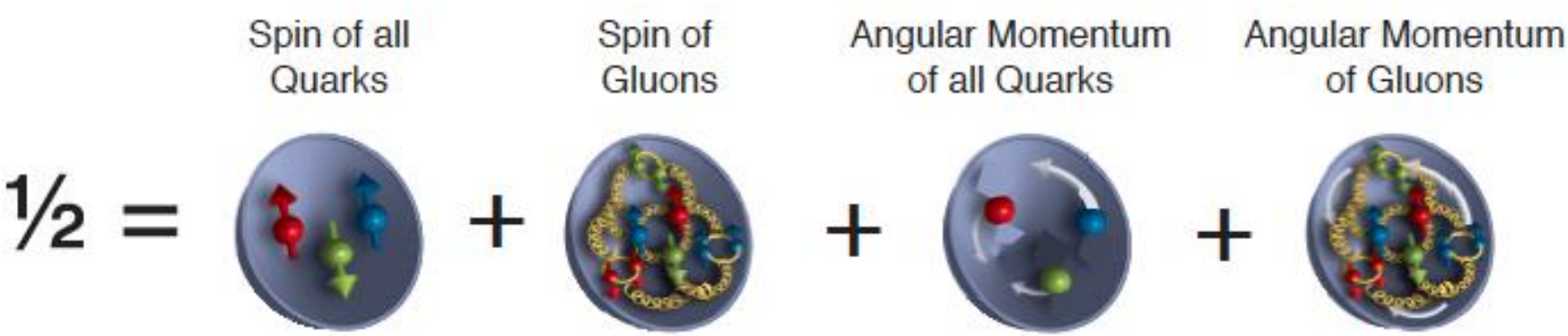
Proton as a QCD Laboratory



A QCD quantum state with M=0.94GeV, Q=+1, and J =1/2

Proton is essentially a many-body quark-gluon system.

Putting quarks/gluons back together into a proton is a lot harder then one would naively expect…



Proton as a QCD Laboratory for Spin

Ambiguities in the decomposition into quarks/gluons

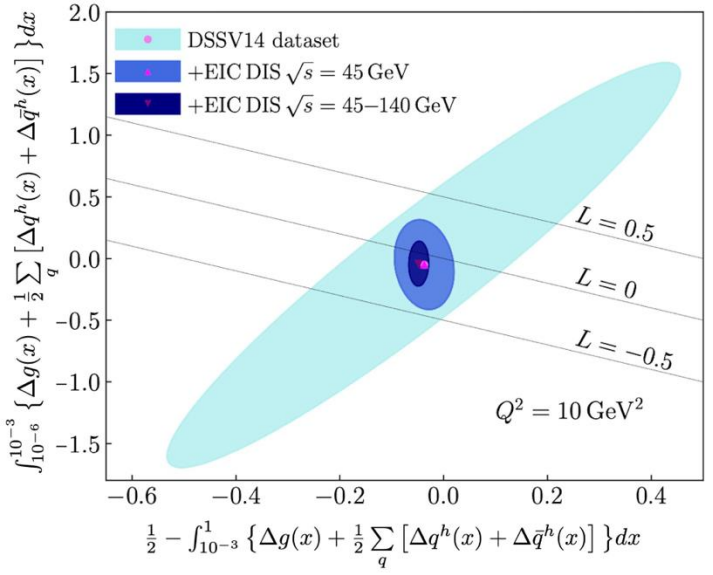
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$ ***Jaffe-Manohar***

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q^{kin} + J_g$$ ***Ji***

$$\frac{1}{2}\Delta\Sigma \approx 0.13$$

$$\Delta G(x > 0.01) \approx 0.20$$

$$L_q + L_g + \Delta G(x \leq 0.01) \approx 0.17$$



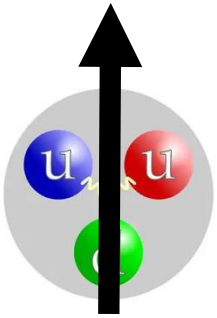
Need the future EIC to further solve the "spin crisis", and to extract the OAM.

HIC as a QCD Laboratory for Spin

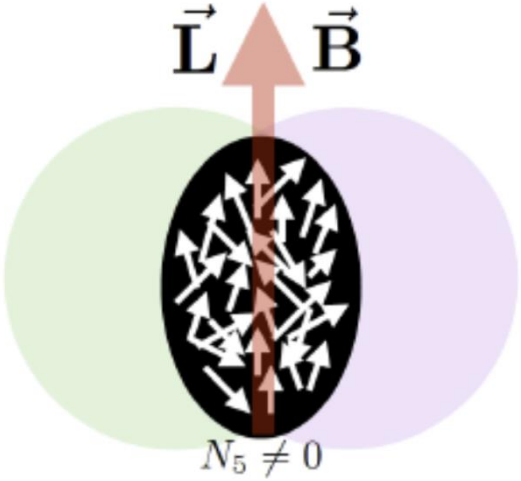
The interplay of spin & AM with QCD is highly nontrivial.

The decomposition of angular momentum into spin and orbital components could be subtle.

Proton serves a QCD laboratory for studying these.



Heavy ion collision systems provide a new, different, and more dynamical QCD laboratory for understanding spin & AM.



Spin Transport

From Microscopic Symmetries to Macroscopic Matter

Spacetime translational symmetries → ***Energy momentum conservation*** → ***Energy momentum transport***

$$P^\mu \rightarrow \beta_\mu \rightarrow \partial_\mu T^{\mu\nu} = 0$$

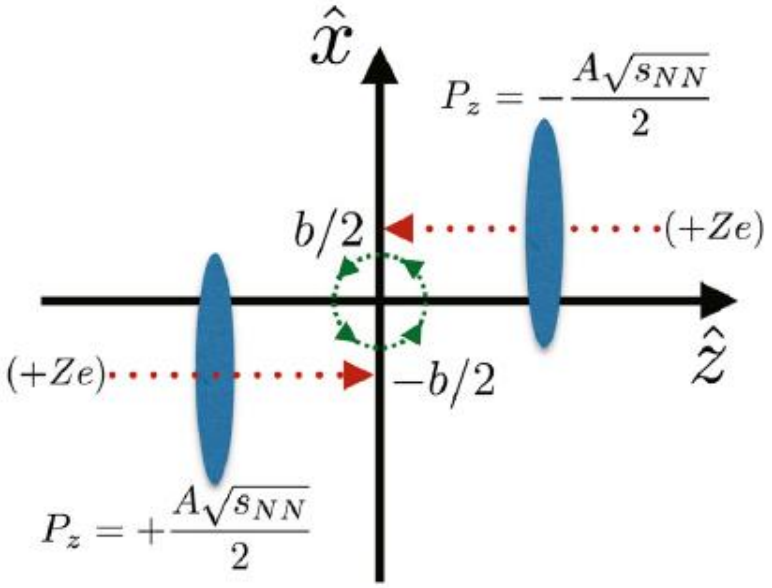
Phase symmetry → ***Charge conservation*** → ***Charge transport***

$$N \rightarrow \mu_N \rightarrow \partial_\mu J^\mu = 0$$

Lorentz symmetry → ***Angular momentum conservation*** → ***Angular momentum transport***

$$J^{\nu\rho} \rightarrow \omega^{\nu\rho} \rightarrow \partial_\mu \Sigma^{\mu\nu\rho} = 0$$

Angular Momentum in Heavy Ion Collisions

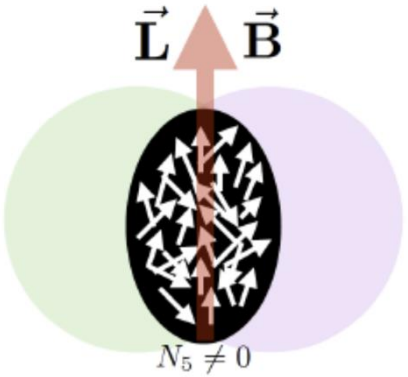


Huge angular momentum for the system in non-central collisions

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

Liang & Wang ~ 2004:
Large orbital angular momentum carried by colliding ions
—> spin-orbital coupling —> spin polarization and alignment

[nucl-th/0410079, PRL2005; nucl-th/0411101, PLB2005]



The injection of a new DoF (Spin/AM) for studying heavy-ion physics!

Thermodynamics with Global AM

Global AM —> Rotational polarization (in a simplified picture):

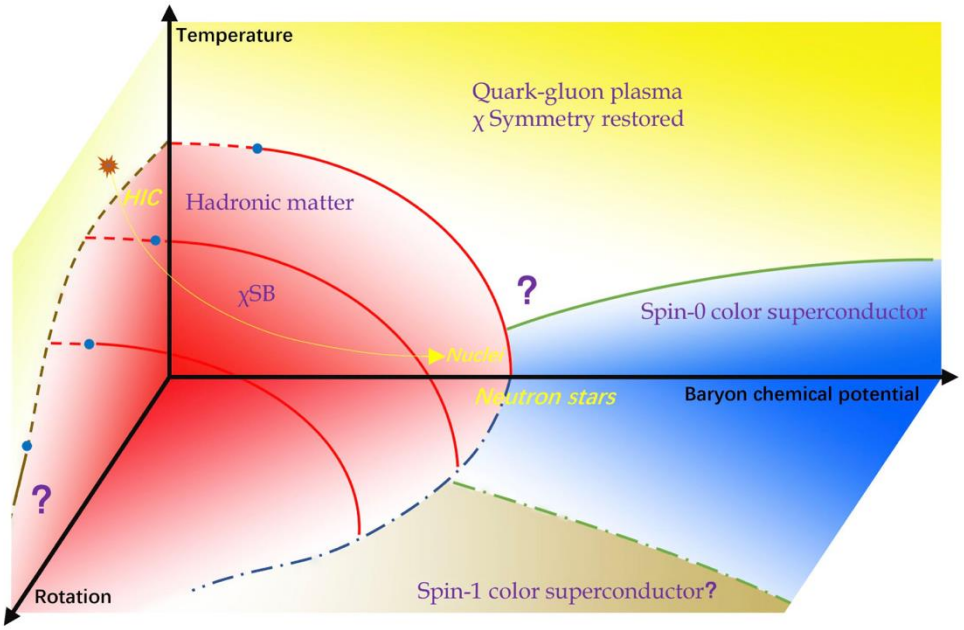
$$H_R = -\omega \cdot \mathbf{j} = -\omega \cdot (\mathbf{l}+\mathbf{s}) \quad \rightarrow \quad \rho(\mathbf{l},\mathbf{s}) \propto e^{\omega\cdot(\mathbf{l}+\mathbf{s})/T}$$

Global equilibrium?

Equation of state?

Phase structures?

……



From: H.L. Chen, X.G. Huang, JL,

Lect.Notes Phys. 987 (2021) 349-379
e-Print: 2108.00586 [hep-ph]

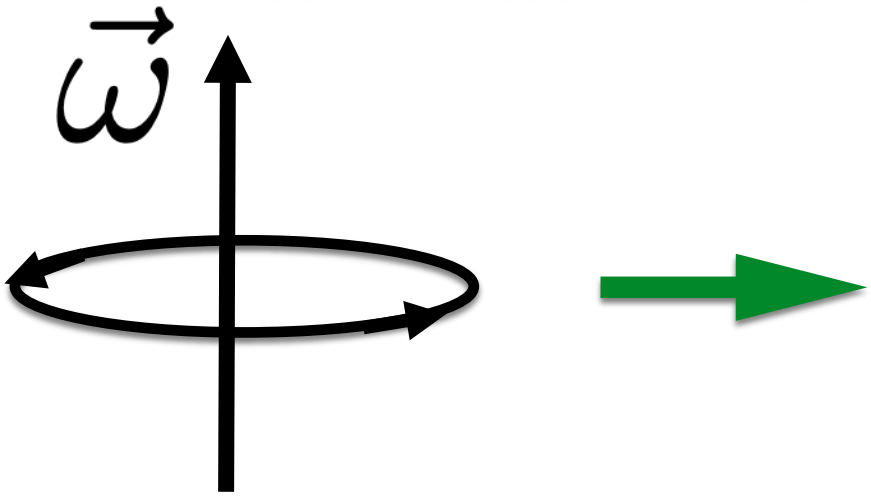
Vorticity and Spin Polarization

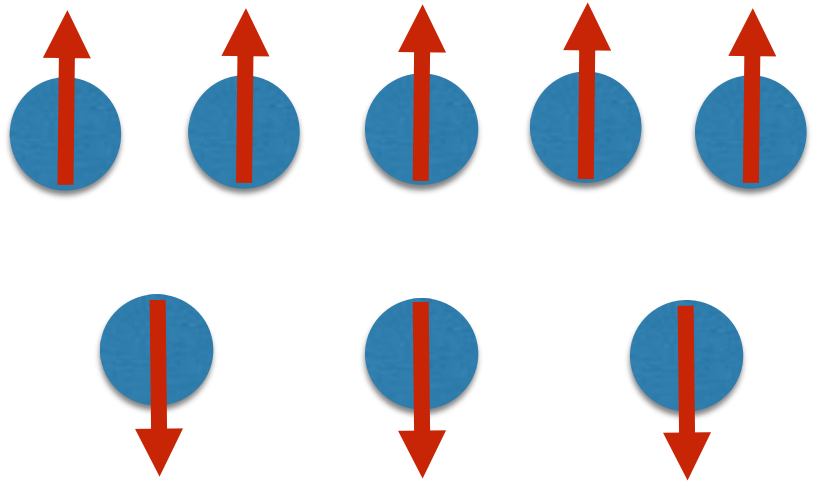
Angular momentum —> fluid vorticity —> spin polarization

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

[0711.1253 [nucl-th], PRC2008;1303.3431 [nucl-th], Annals Phys 2013]

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





Macroscopic rotation; Global angular momentum

Microscopic spin polarization

“Rotating” Quark-Gluon Plasma

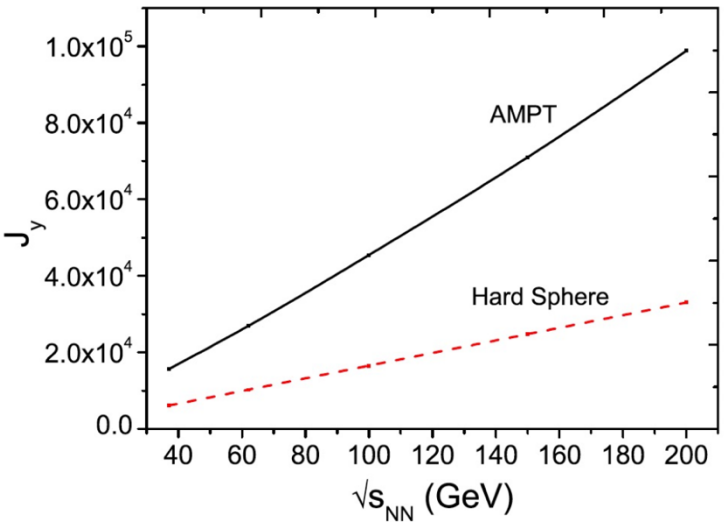
$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

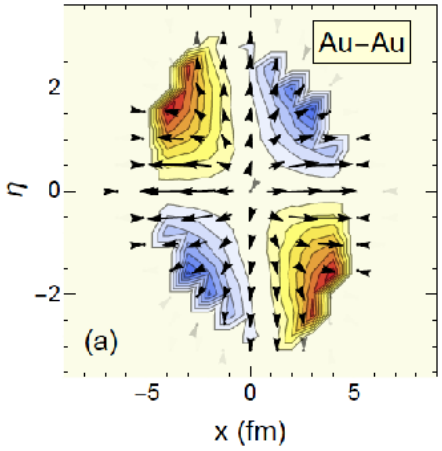
PHYSICAL REVIEW C 94, 044910 (2016)

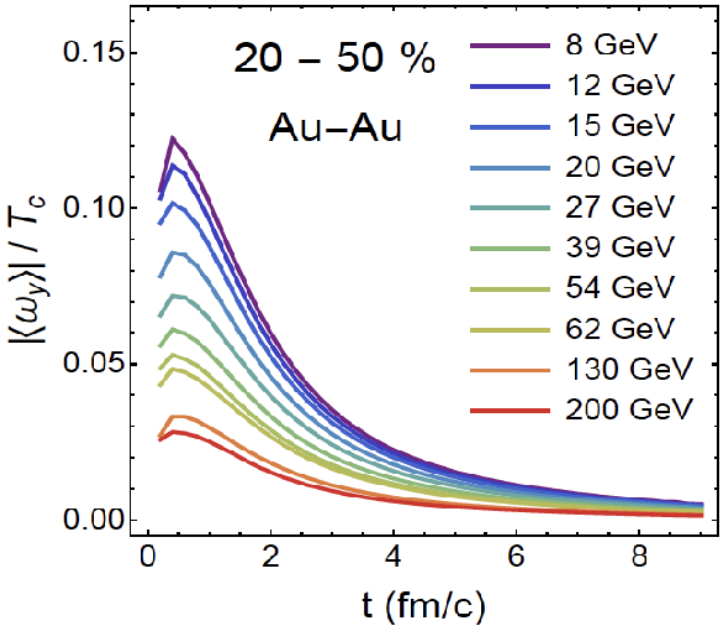
Rotating quark-gluon plasma in relativistic heavy-ion collisions

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*

[Jiang, Lin, JL, Phys.Rev.C 94 (2016) 4, 044910]



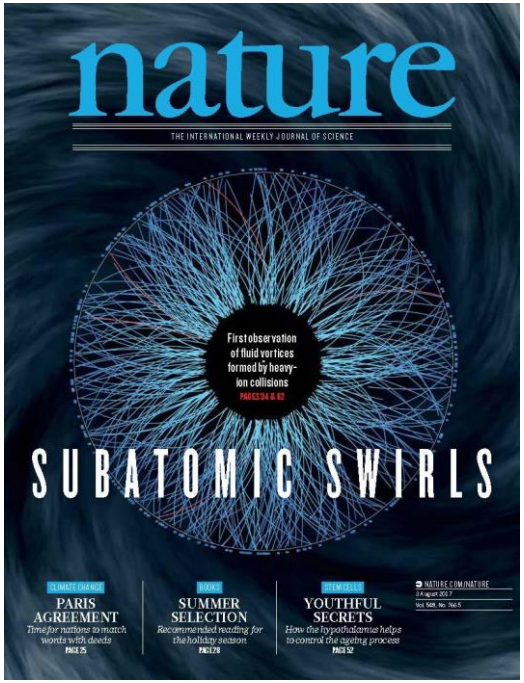




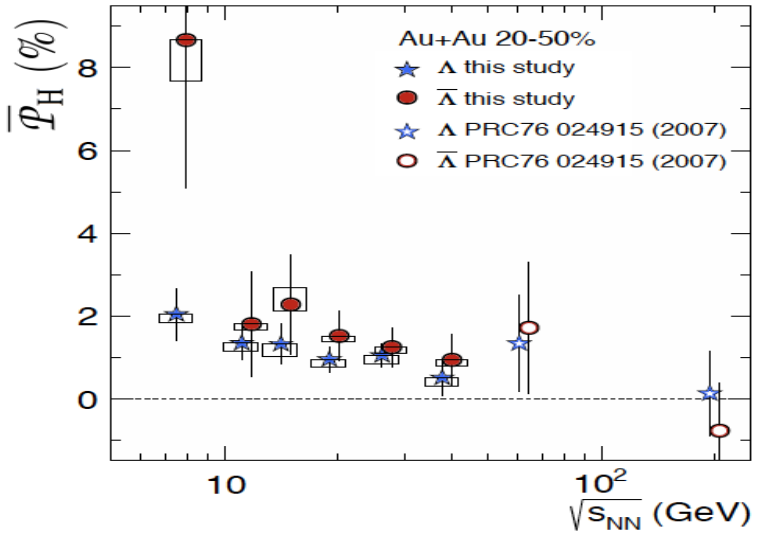
Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

[See also e.g. Deng & Huang, Phys.Rev.C 93 (2016) 6, 064907]

The Most Vortical Fluid



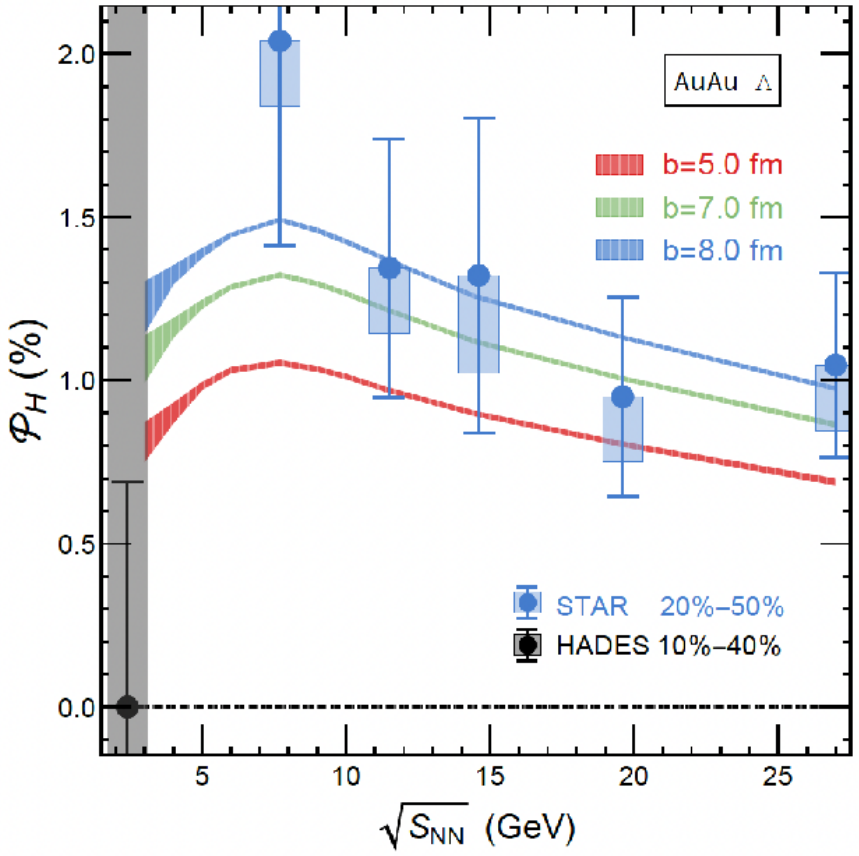
An exciting discovery from STAR Collaboration at RHIC (~2017): The most vortical fluid!



Global & local spin polarization;
Global & local spin alignment;
Spin-spin correlations;
…

Trend of Global Polarization toward O(1) GeV

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



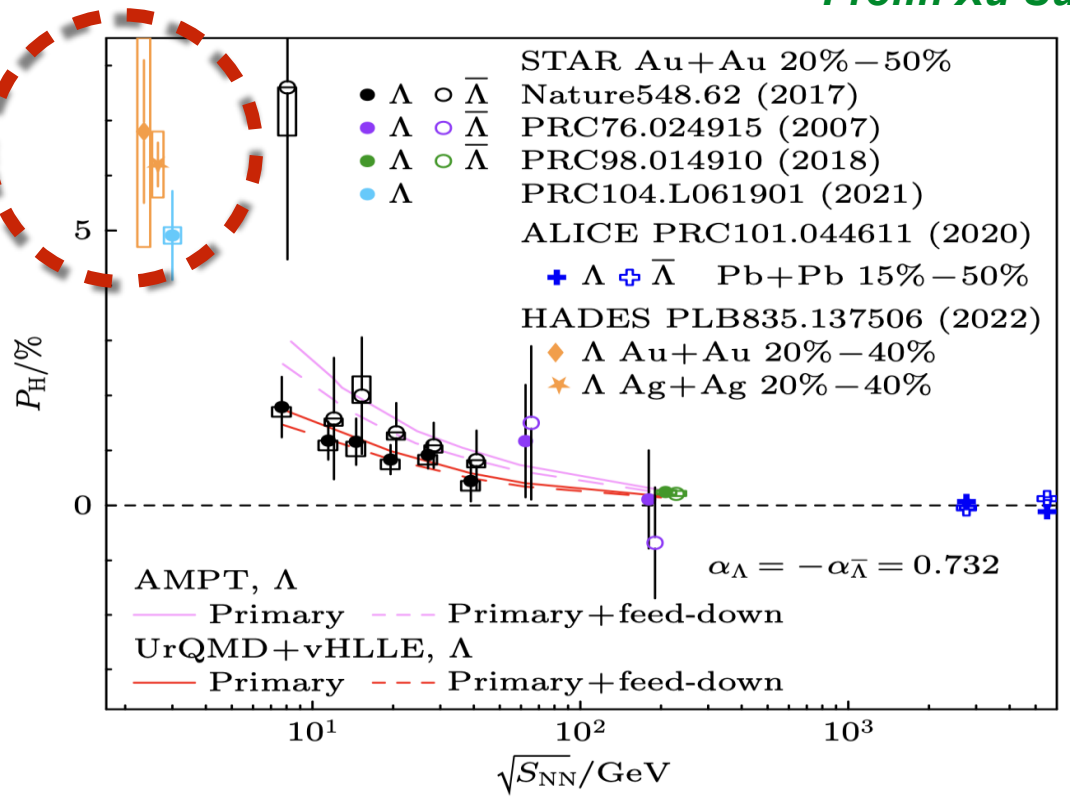
Yu Guo, et al, PRC2021
arXiv:2105.13481

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

[See also e.g. Deng, Huang, Ma, Zhang, Phys.Rev.C 101 (2020) 6, 064908]

Dependence on Beam Energy

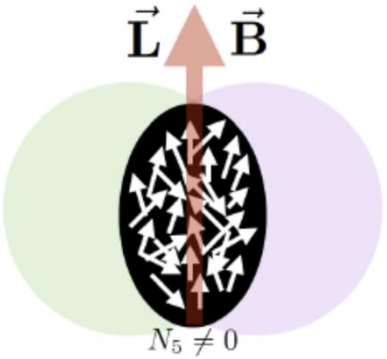
From: Xu Sun, et al, Acta Phys. Sin. (2023)072401



Surprisingly large signal even very close to threshold?!

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

AM/Spin Transport



AM/Spin transport in heavy-ion collisions:

Initial conditions → **(Hydro)dynamical evolution** → **Freeze-out/Final state observables**

Need quantitative understanding of the amount of angular momentum being stopped in mid rapidity.

Need spin hydrodynamics

Need "spin-thermal" production

$$Tr\{\hat{O}\ \hat{\rho}_E\}$$

Pseudo-gauge issue?

Hydrodynamics with Angular Momentum

$$\partial_\mu \mathcal{J}^{\mu\nu\rho}(x) = 0, \quad \mathcal{J}^{\mu\nu\rho}(x) = (x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu}) + \Sigma^{\mu\nu\rho}$$

$$\Sigma^{\mu\nu\rho} = u^\mu \sigma^{\nu\rho} + \tilde{\Sigma}\left[u^\kappa, \partial^\lambda\left(\omega^{\sigma\xi}/T\right)\right]^{\mu\nu\rho} + \hat{O}(\partial\,\partial)$$

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;
……

Relativistic Viscous Hydro with Ang. Mom.

Science Bulletin 67 (2022) 2265–2268

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Science Bulletin
www.scibull.com

Perspective

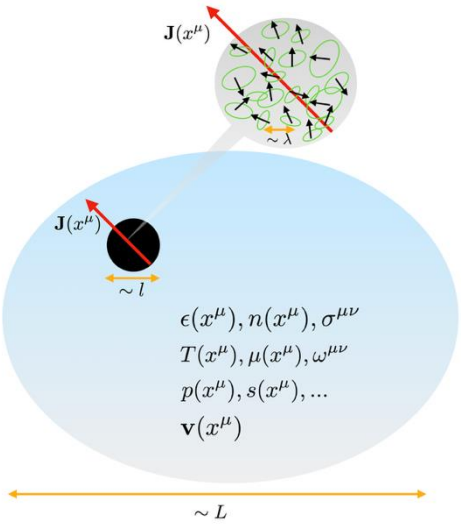
Relativistic viscous hydrodynamics with angular momentum

Duan She [a,b,c,1], Anping Huang [b,d,1], Defu Hou [a,*], Jinfeng Liao [b,*]

[a] Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
[b] Physics Department and Center for Exploration of Energy and Matter, Indiana University, Bloomington IN 47408, USA
[c] Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China
[d] School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

[arXiv:2105.04060]

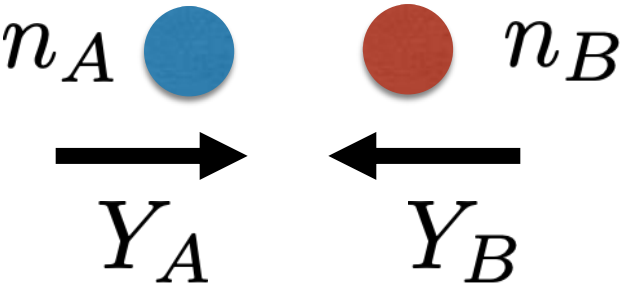
A nontrivial issue (pseudo-gauge): decomposition of AM into orbital and spin components, akin to the decomposition issue of proton case.



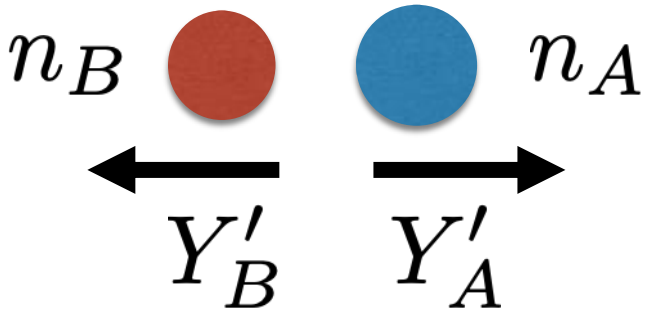
We suggest to work directly with angular momentum tensor as the hydrodynamic variable.

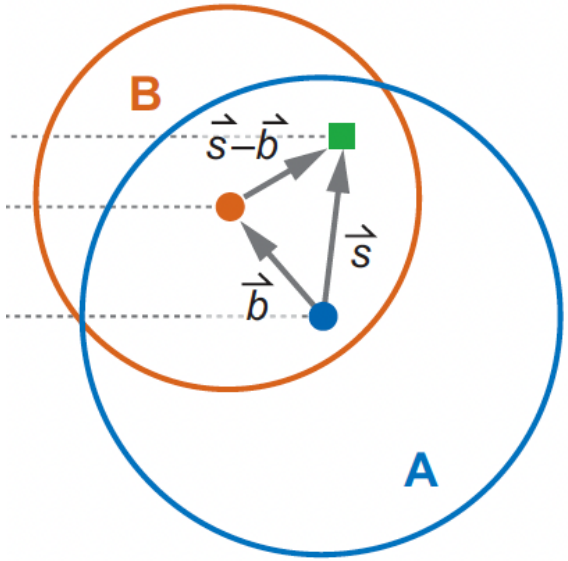
Nucleon Stopping & Angular Momentum

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



$$e = \frac{Y'_B - Y'_A}{Y_B - Y_A}$$



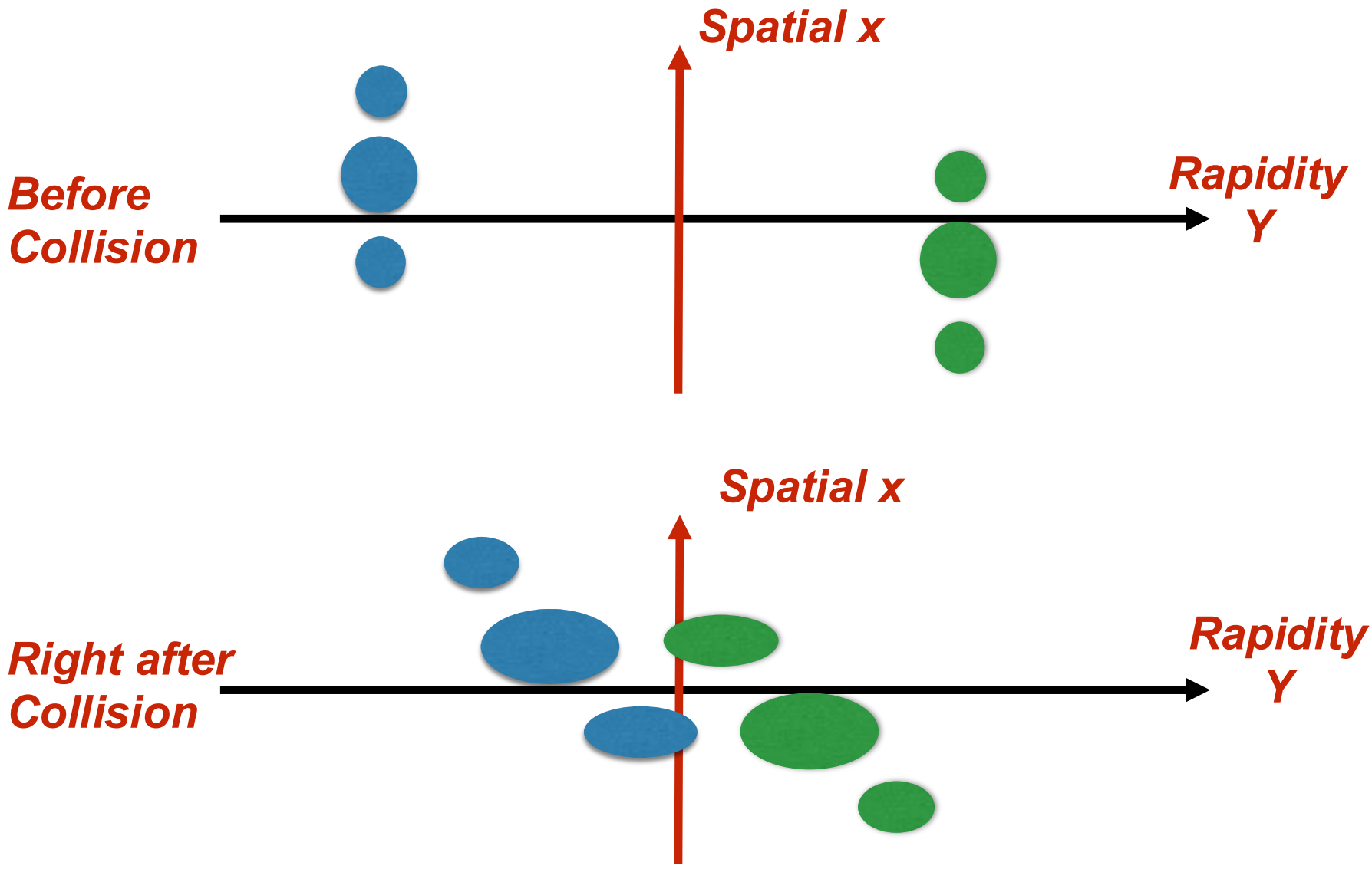


Various spots on the overlapping zone —> "spread-out" (i.e. distribution) along rapidity

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 (PRC 2025)

Rapidity Loss

"Wounded nucleon"

$$(\lambda m_{\mathrm{N}})^2 \equiv m'^2 + p_\perp^2$$

$$e = \frac{Y'_B - Y'_A}{Y_B - Y_A} \qquad Y_A = -Y_B \qquad Y'_B = Y'_A - 2eY_A$$

Energy momentum conservation

$$(n_A - n_B)\sinh(Y_A) =$$
$$\lambda[(n_A + n_B\cosh(2eY_A))\sinh(Y'_A) - n_B\sinh(2eY_A)\cosh(Y'_A)]$$
$$(n_A + n_B)\cosh(Y_A) =$$
$$\lambda[(n_A + n_B\cosh(2eY_A))\cosh(Y'_A) - n_B\sinh(2eY_A)\sinh(Y'_A)]$$



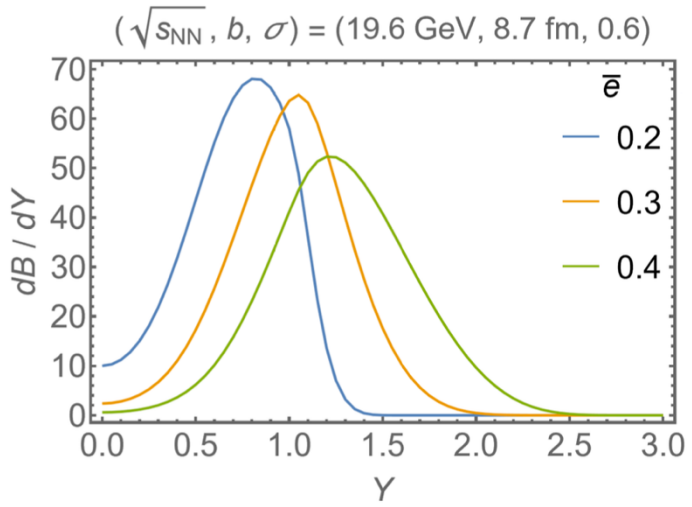
$$Y'_A = \tanh^{-1}\left(\frac{n_A - n_B}{n_A + n_B}\tanh(Y_A)\right) + u$$
$$= \tanh^{-1}\left(\frac{(n_A/n_B) - 1}{(n_A/n_B) + 1}\tanh(Y_A)\right) + \tanh^{-1}\left(\frac{\sinh(2eY_A)}{(n_A/n_B) + \cosh(2eY_A)}\right)$$

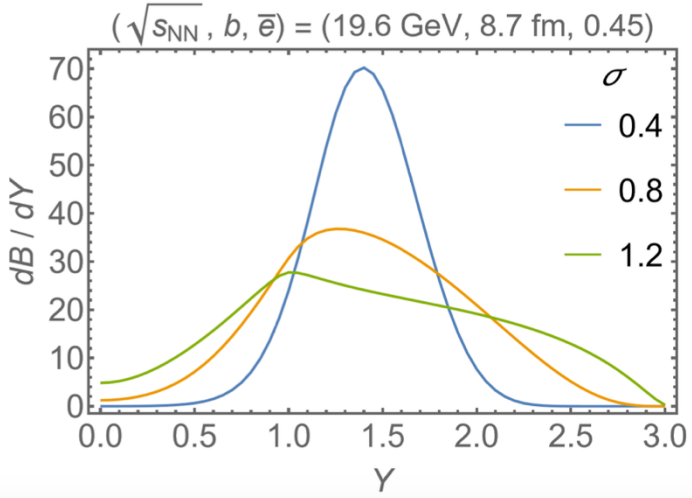
$$\lambda^2 = \frac{\cosh(Y_A - w)\cosh(Y_A + w)}{\cosh(eY_A - w)\cosh(eY_A + w)} \qquad w = \tanh^{-1}\left(\frac{n_A - n_B}{n_A + n_B}\right) = \frac{1}{2}\ln\left(\frac{n_A}{n_B}\right)$$

Results depend on three quantities: n_A/n_B, e, and Y_{beam}

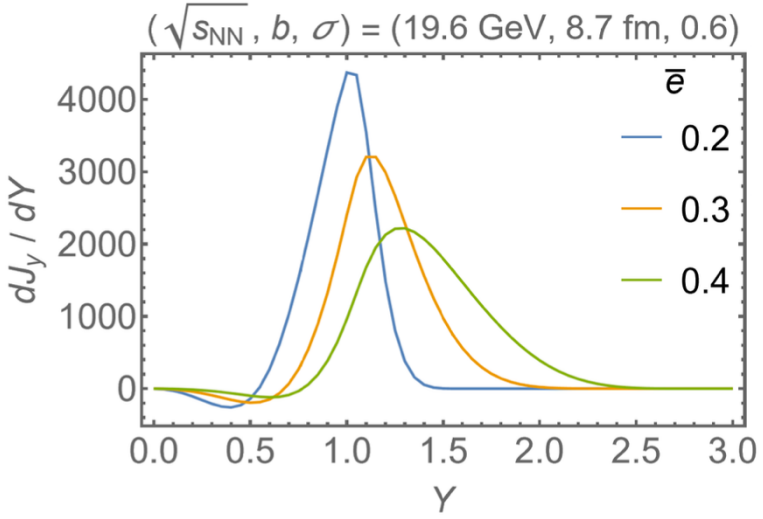
Rapidity Distributions

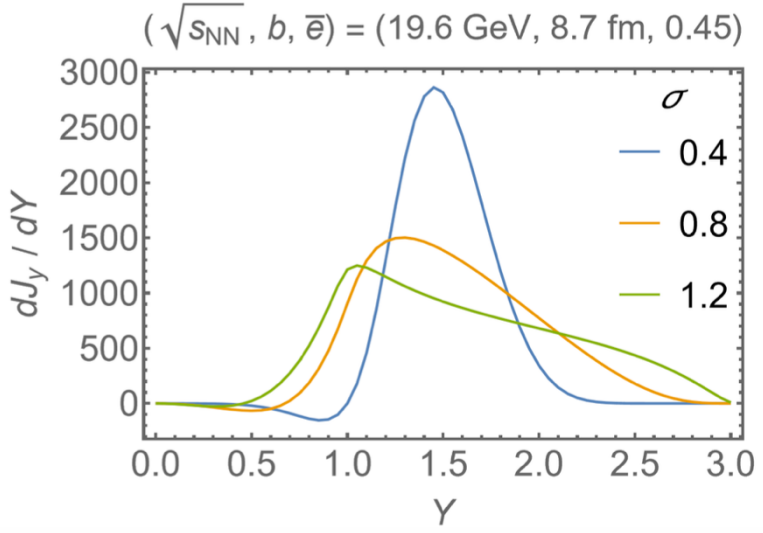
Net baryon





Angular momentum





A. Akridge, D. Gallimore, H. Morales, JL, arXiv:2504.02192 (PRC 2025)

Rapidity Loss

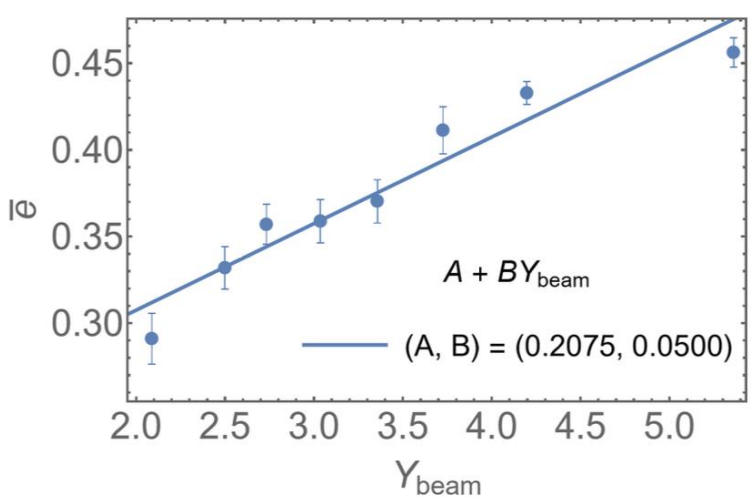
Rapidity distributions of B and J:

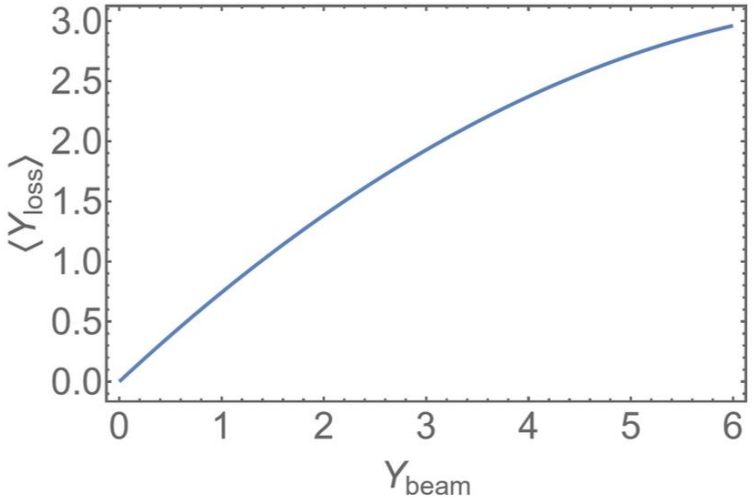
$$\frac{dB}{dY} = \int dxdy\,[n_A\delta(Y - Y'_A) + n_B\delta(Y - Y'_B)]$$

$$\frac{dJ_y}{dY} = -\int dxdy\; x\lambda m_{\mathrm{N}}\,[n_A \sinh(Y'_A)\delta(Y - Y'_A) + n_B \sinh(Y'_B)\delta(Y - Y'_B)]$$

Fluctuations in e is also implemented.

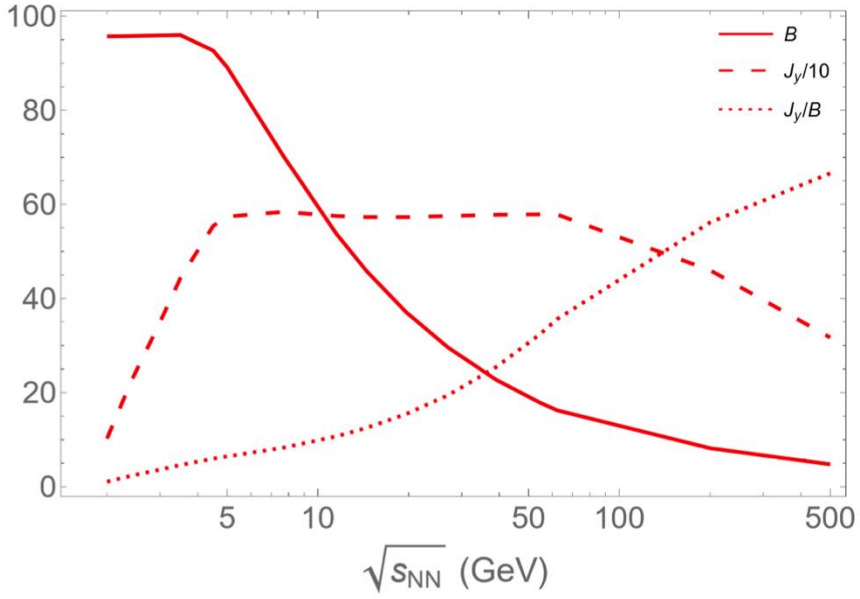
Data for mid-rapidity net baryon is used to calibrate the parameter e at each energy.

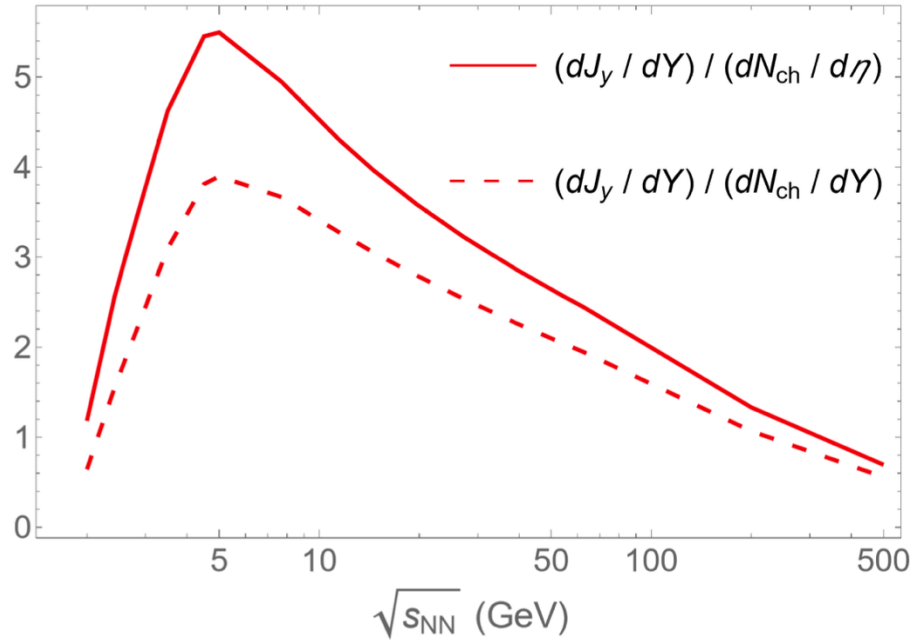




Normalized Initial Angular Momentum

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

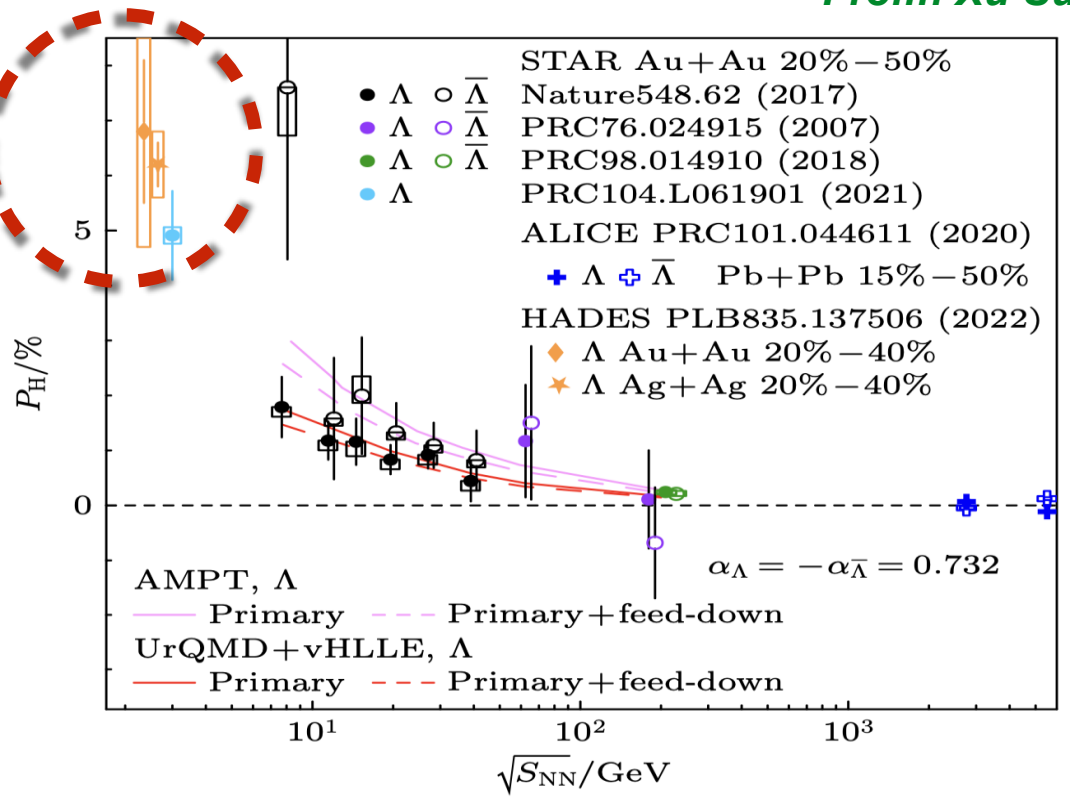




Key message: angular momentum driven phenomena unlikely keep increasing toward extremely low energy.

Dependence on Beam Energy

From: Xu Sun, et al, Acta Phys. Sin. (2023)072401



Alternative mechanism of polarization at near-threshold energies?

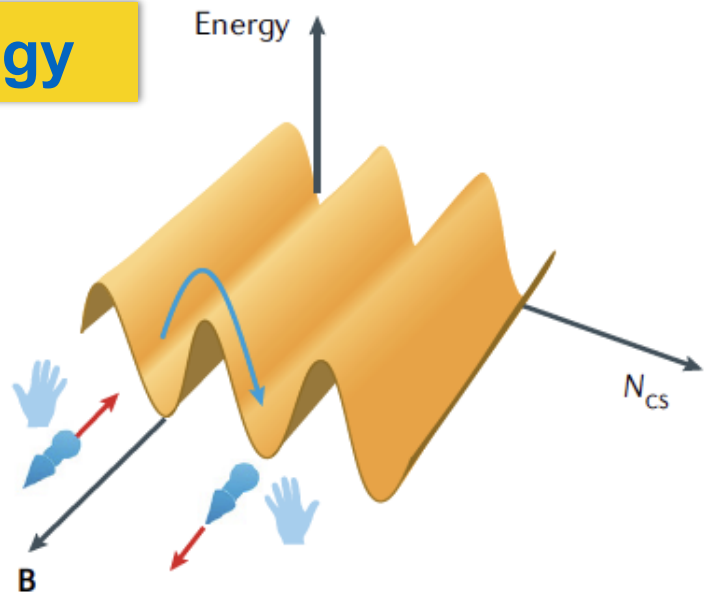
Connection with intrinsic spin structures of nucleon/hyperon?

Chirality Transport

Chiral Magnetic Effect (CME)

Chirality & Anomaly & Topology

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

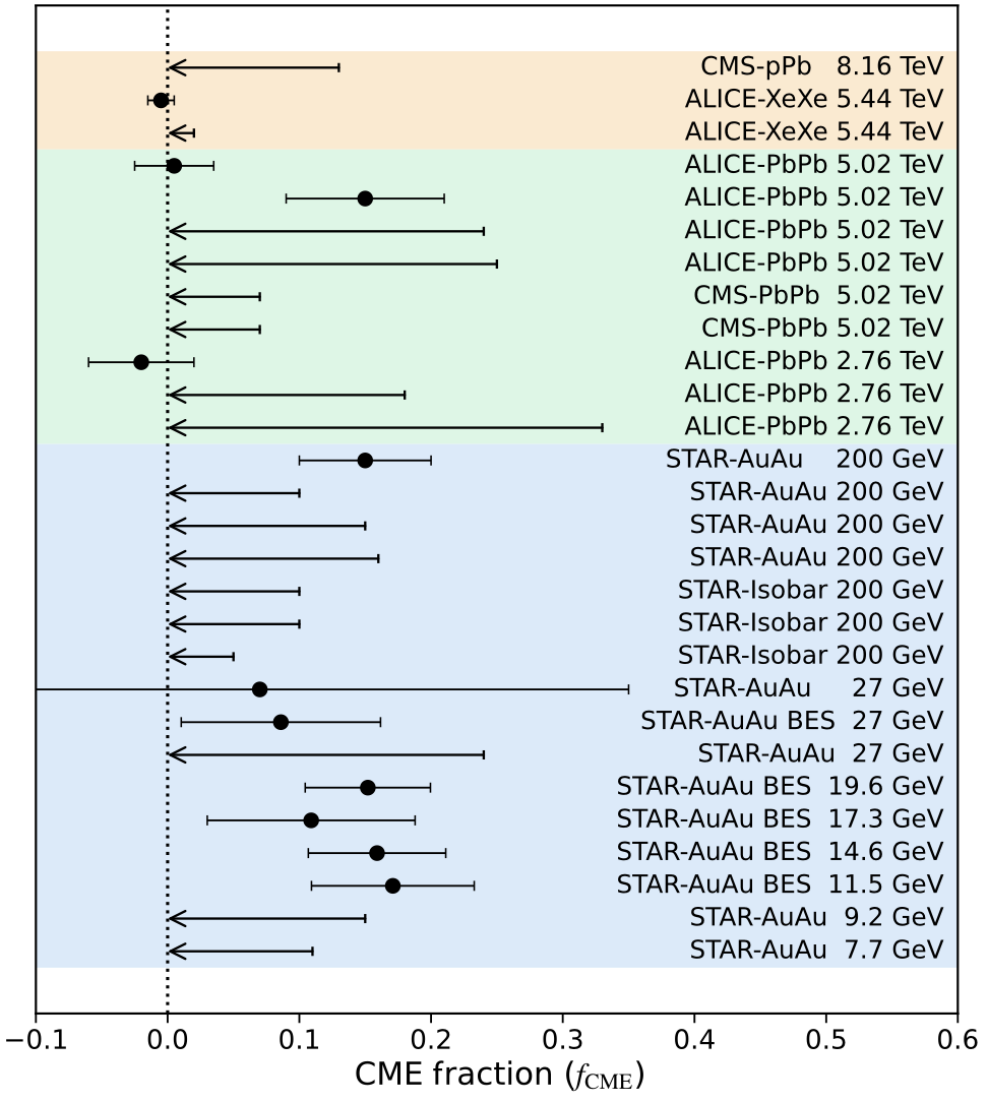


Electric Current ← **Magnetic Field**

Q.M. Transport

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

Have We Seen the CME?



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

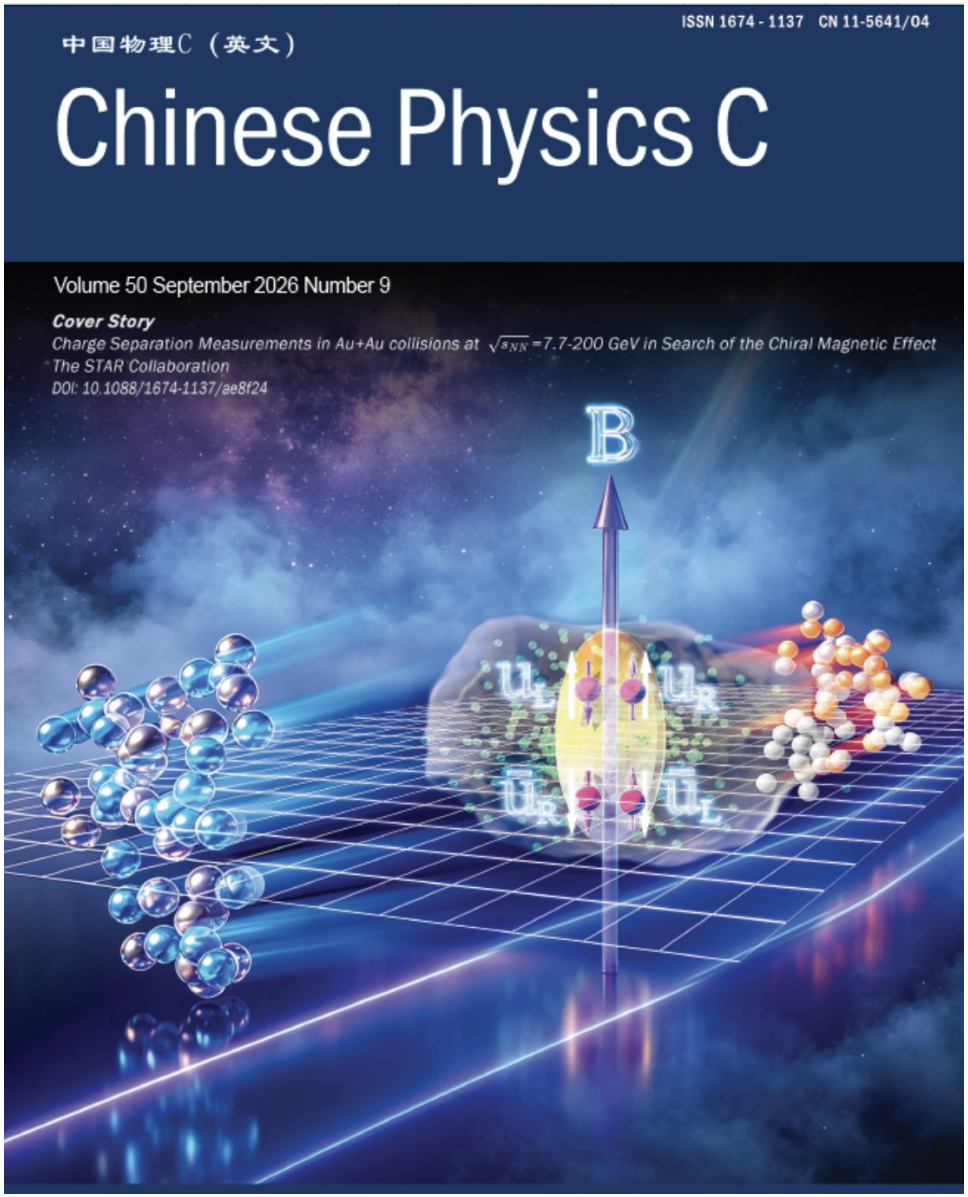
$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

Flow driven ***Nonflow***



[Deshpande, Kharzeev, JL, Sci. Adv. 12, no.38, eaeh1991 (2026)]

Latest Results from Beam-Energy-Scan-II

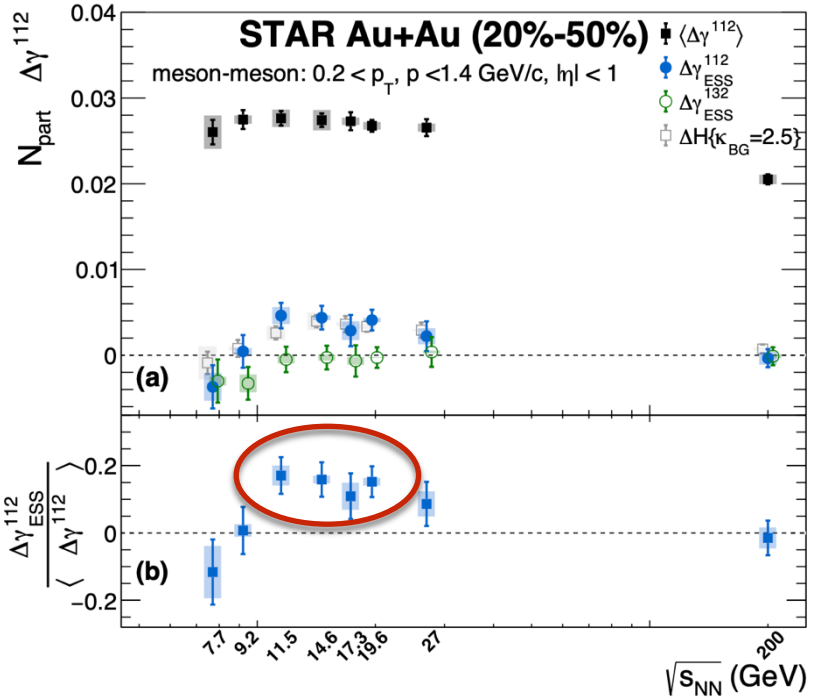


Latest Results from Beam-Energy-Scan-II

Charge Separation Measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7–200 GeV in Search of the Chiral Magnetic Effect

The STAR Collaboration

In summary, we have presented measurements of charge separation correlations along the magnetic field direction using Au+Au collisions at RHIC from $\sqrt{s_{NN}}$= 7.7 to 200 GeV energies, with the flow-related background effectively suppressed. We report a remaining charge separation signal in mid-central Au+Au collisions, positive finite with around 3σ significance at each of the center-of-mass energies of $\sqrt{s_{NN}}$= 11.5, 14.6, and 19.6 GeV. The results at $\sqrt{s_{NN}}$= 17.3 and 27 GeV also show positive values but with a lower significance of 1.3σ and 1.1σ. Below $\sqrt{s_{NN}}$= 10 GeV or at $\sqrt{s_{NN}}$= 200 GeV, the charge separation is consistent with zero. When the data between $\sqrt{s_{NN}}$= 10 and 20 GeV are combined, the significance rises to 5.5σ. The absence of a definitive CME signal from the top RHIC energy and the LHC energies [42, 77] can constrain the dynamical evolution of the magnetic field in the QGP phase in these collisions. Our measurements call for more investigation into the magnetic field evolution in a QGP and the QCD topo-



STAR Collaboration: 2506.00275; 2506.00278

A New Data-Driven Extraction

- ***The key challenge is the separation of signal and background in the inclusive gamma measurements.***
- ***Analysis methods still suffer from various issues.***
- ***Can we "bypass" this problem and take an "unbiased" look at the exp data?***
- ***Is it possible to extract CME transport from exp data without the need of such separation?***

Machine Learning Extraction of CME Transport

— *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)*

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

— *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. Xing, H. Zhang: in preparation.
See talk by Yu Goo (Nov. 19 morning, Thu, Parallel 1)

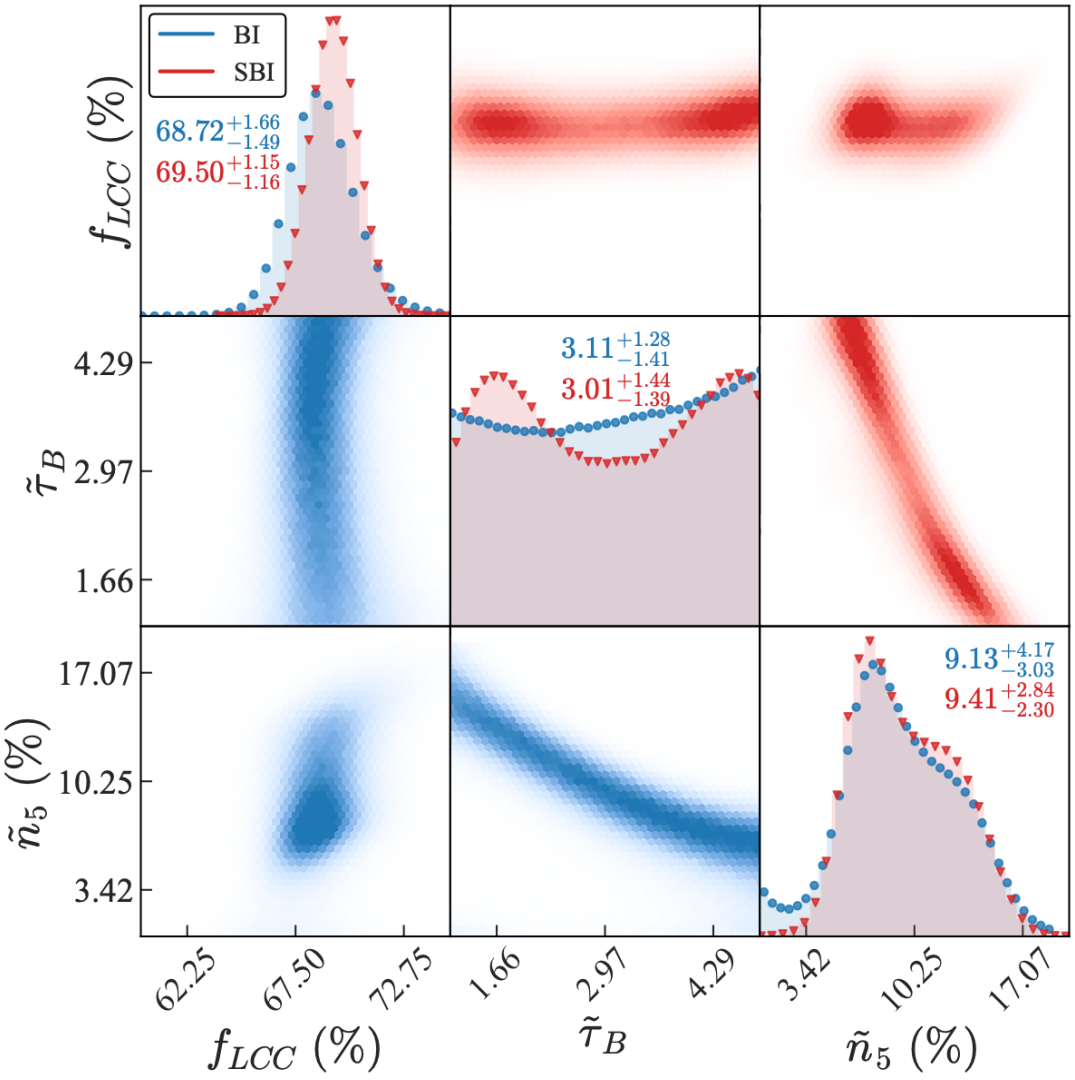
Two Analysis Methods

Aspect	Bayesian Inference (BI)	Simulation-Based Inference (SBI)
Posterior	$p(\theta\|c_{\text{obs}}) \propto p(c_{\text{obs}}\|\theta)p(\theta)$	$p(\theta\|c_{\text{obs}}) \approx q_\phi(\theta\|c_{\text{obs}})$
Likelihood	Explicit, typically Gaussian.	Implicitly learned from simulated pairs (θ, c) via a neural density estimator.
Uncertainty	Propagated explicitly through covariance $\Sigma = \Sigma_{\text{exp}} + \Sigma_{\text{GPE}}$.	Handled implicitly by stochastic noise injection during simulation.
Sampling	Markov Chain Monte Carlo (e.g., MH, NUTS).	Amortized inference via normalizing flows (e.g., MAF, NAF).
Advantages	Statistically rigorous; explicit uncertainty control; interpretable posterior.	Likelihood-free; efficient after training; captures non-Gaussian posteriors.
Limitations	Sensitive to covariance approximation and model compensation effects; neglecting correlated experimental uncertainties may distort parameter correlations.	Dependent on simulator fidelity and training coverage; independent noise samples may underestimate cross-observable correlations.

We use two different inference methods to ensure the robustness of the results.

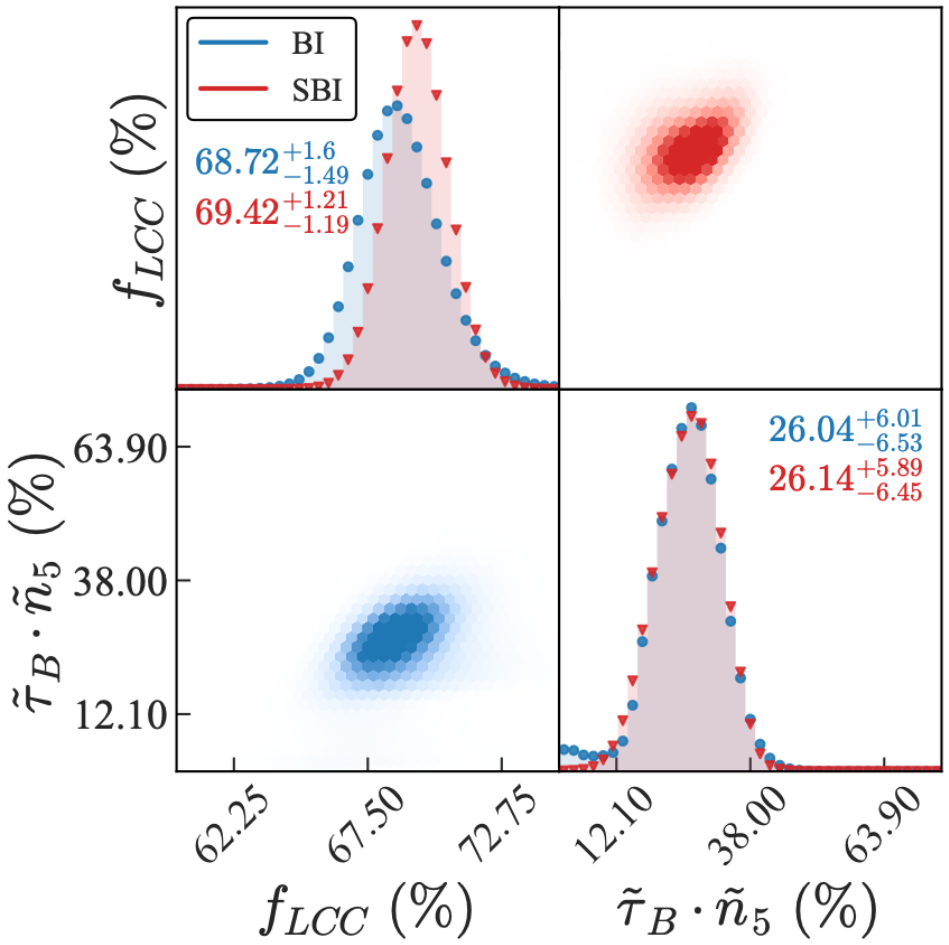
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Posterior Distributions



A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.
See talk by Yu Goo (Nov. 19 morning, Thu, Parallel 1)

Posterior Distributions

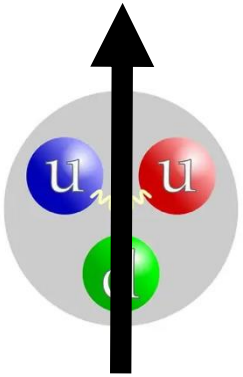


robust and unambiguous evidence for CME transport !

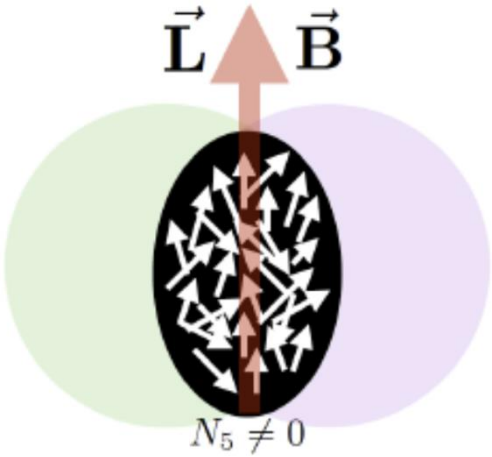
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Summary

Summary



Nontrivial interplay between spin/AM and QCD: A unifying theme from nucleon structures to heavy-ion collisions



- ***Nontrivial theoretical issues related to the pseudo-gauge need to be understood coherently.***
- ***AM initial conditions are crucial for understanding spin transport and its beam energy dependence.***
- ***Advanced inference tools could help extract CME from experimental measurements***
- ***We have a wealth of experimental data, offering more questions than answers!***