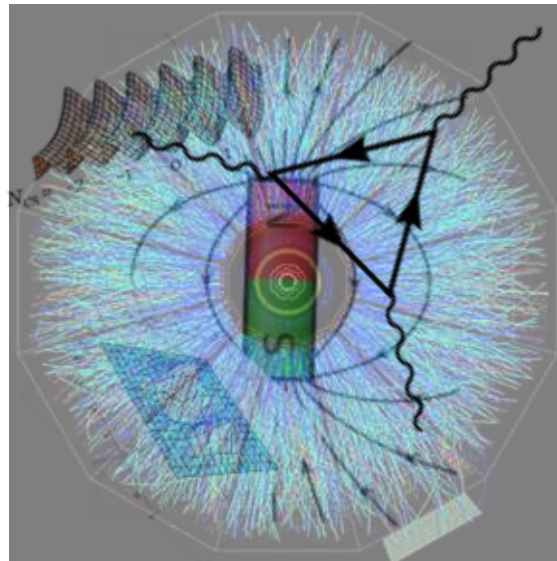


Chirality Transport at BES Energies

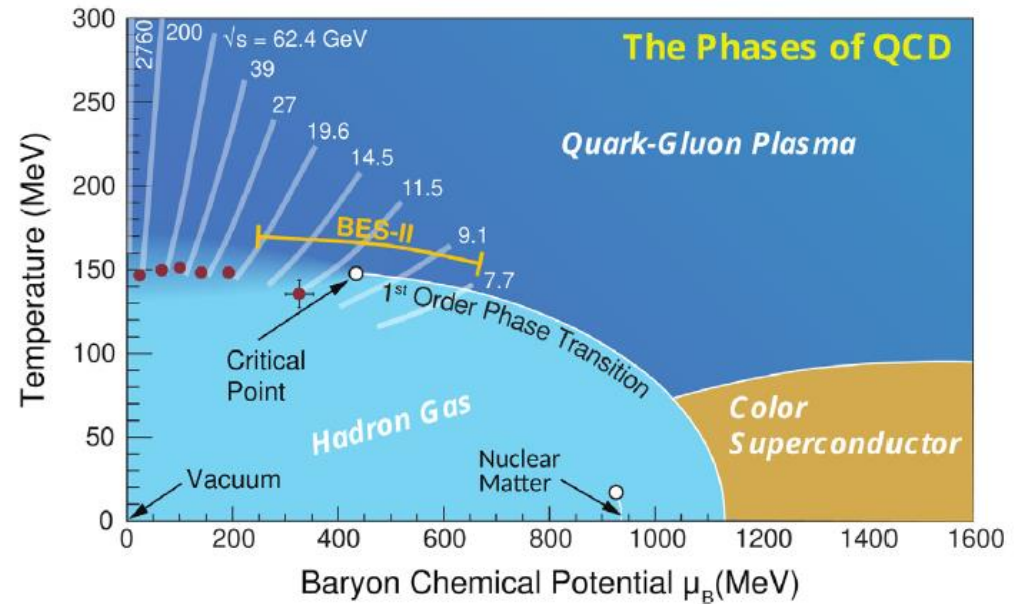
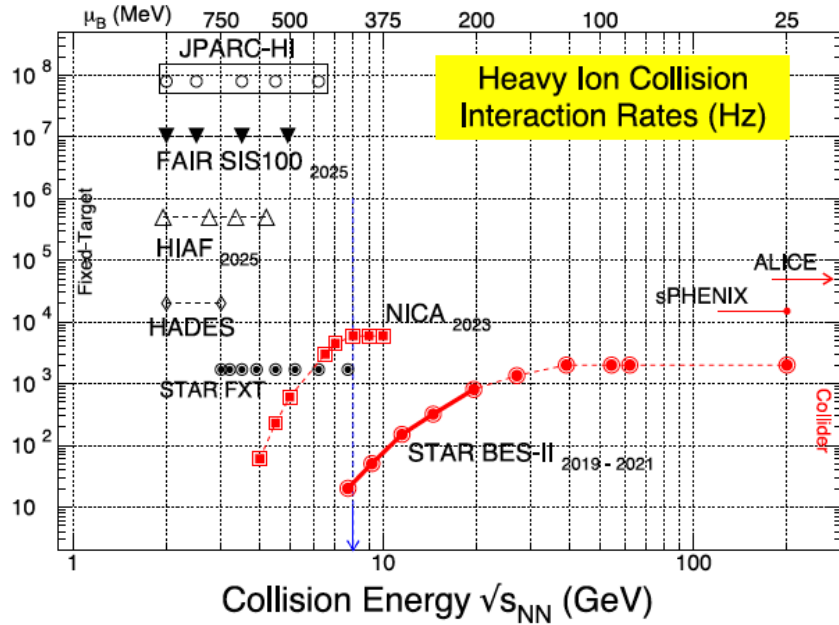


Jinfeng Liao

Indiana University, Physics Dept. & CEEM

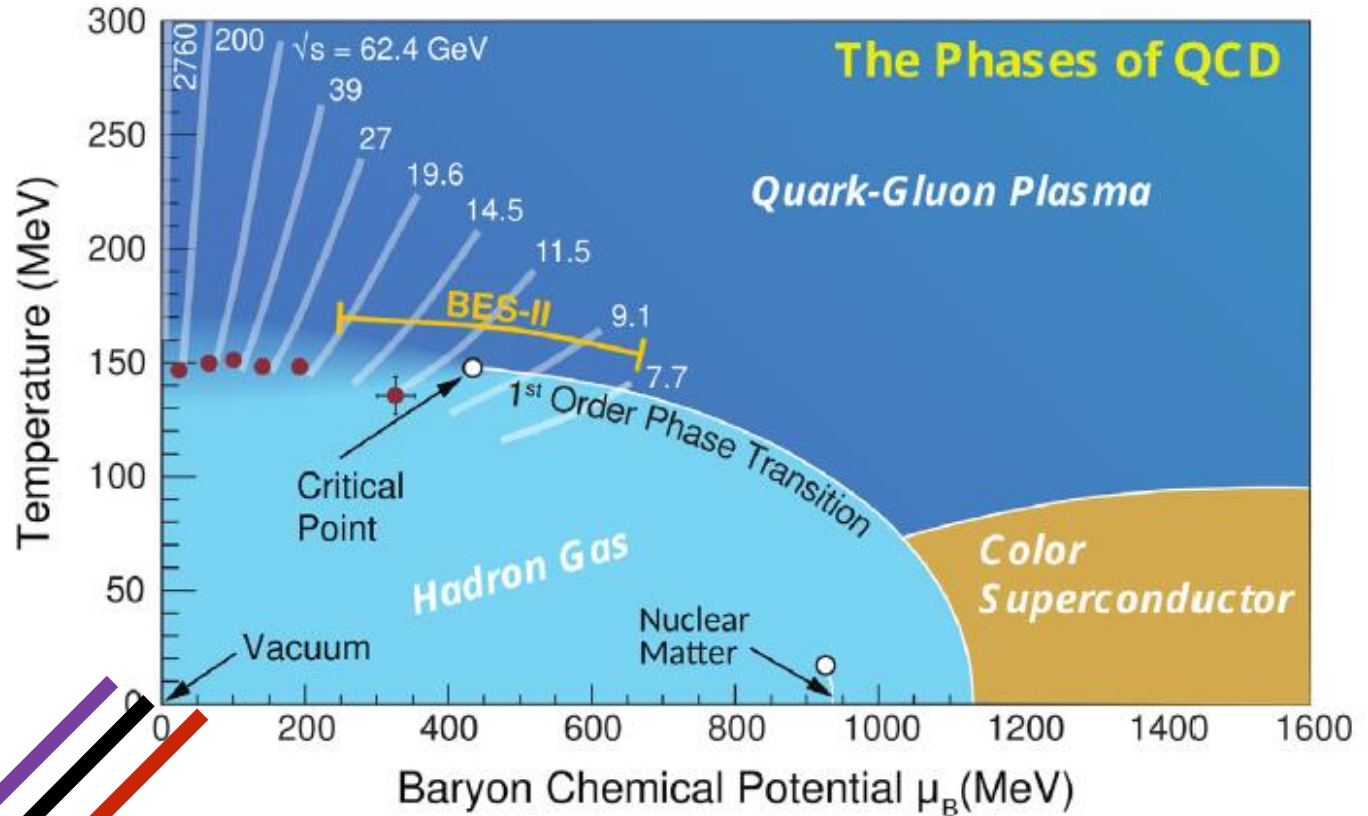


Beam Energy Scan (BES) Programs



“Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan”,
 Bzdak, Esumi, Koch, JL, Stephanov, Xu, *Phys. Rep.* 853(2020)1-87.

Chirality, Vorticity, and Magnetic Fields



N_5 (or μ_5)

\vec{B} $\vec{\omega}$

BES scan also creates nontrivial shifts in the conditions associated with chirality, vorticity, and magnetic fields.

A Remarkable Example: Global Spin Polarization

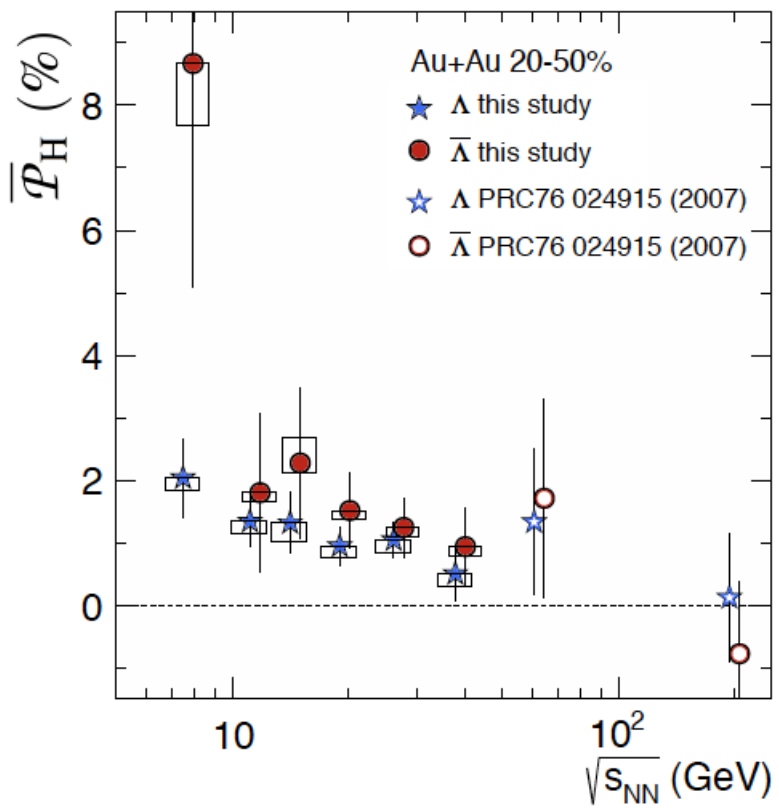
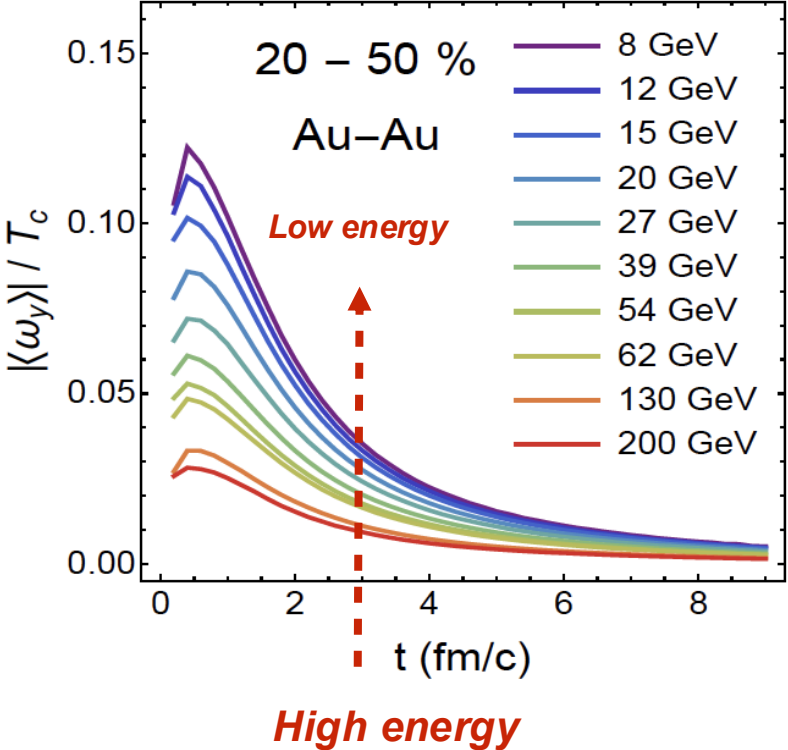
$$L_y = \frac{1}{2} Ab\sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

**STAR Collaboration,
Nature 2017**

**Vorticity @ O(10) GeV >> @ O(100) GeV
Baryon stopping is the KEY!**

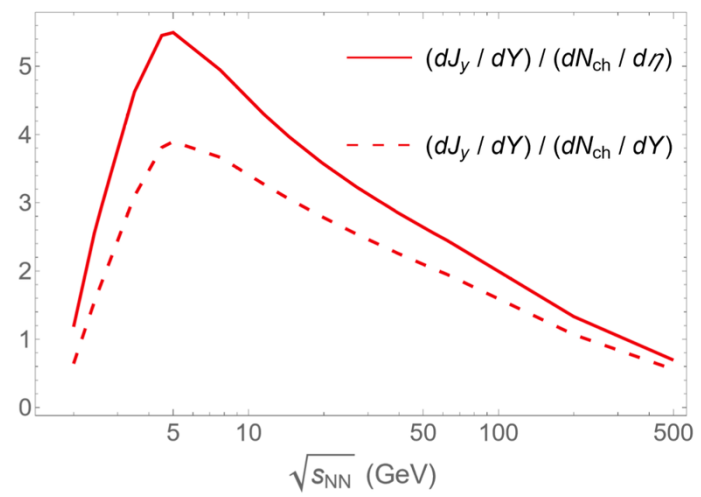
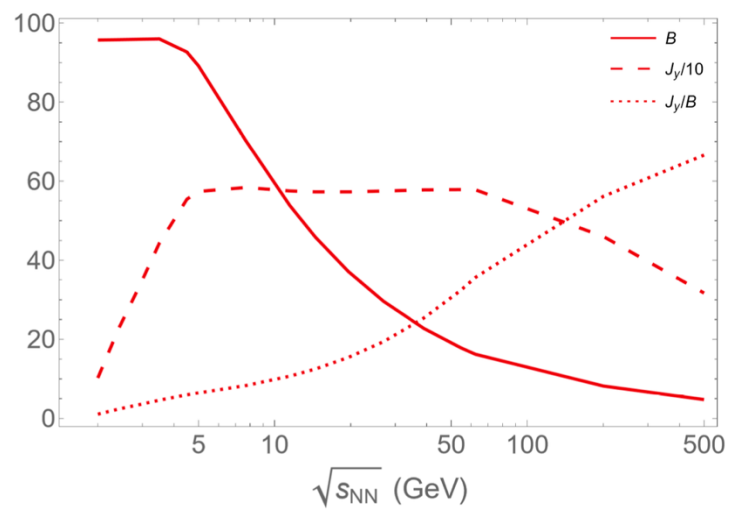
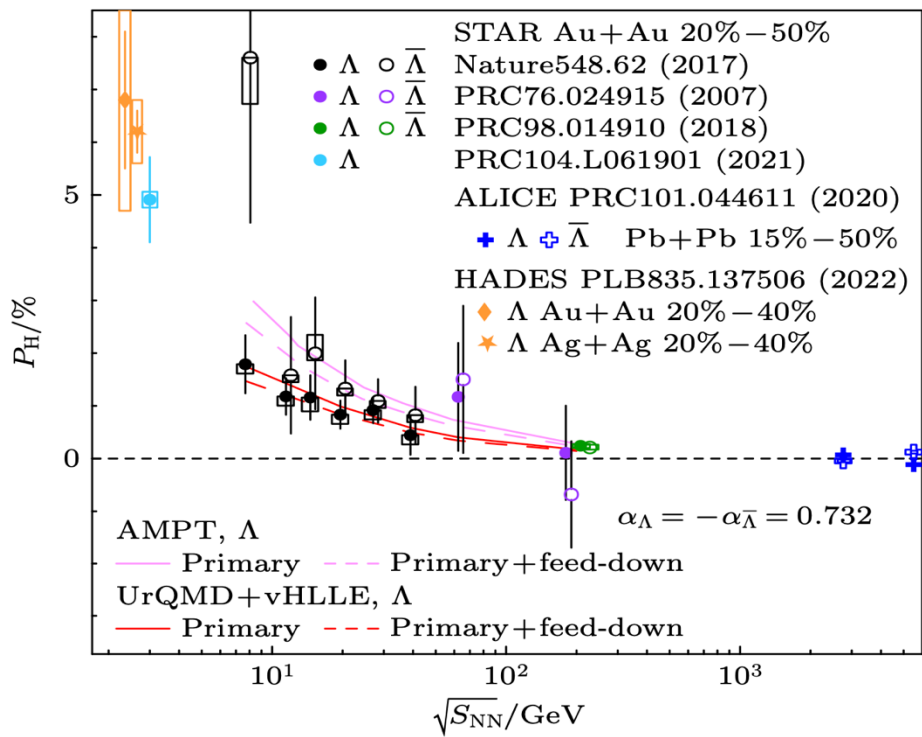
$$\omega \approx (9 \pm 1) \times 10^{21} \text{ s}^{-1}$$

The most vortical fluid!



A Remarkable Example: Global Spin Polarization

From: Xu Sun, et al,
Acta Phys. Sin. 72 (2023)072401

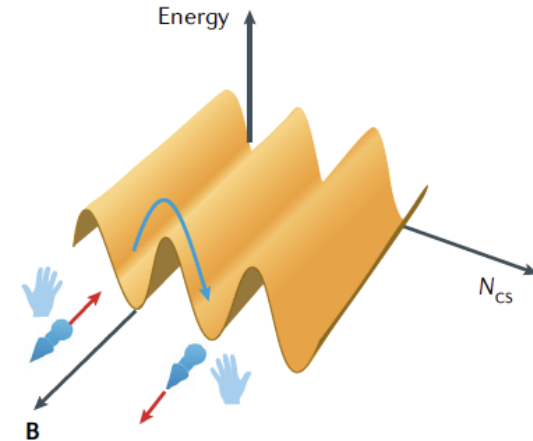


Angular momentum driven phenomena unlikely keep increasing toward extremely low energy...

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

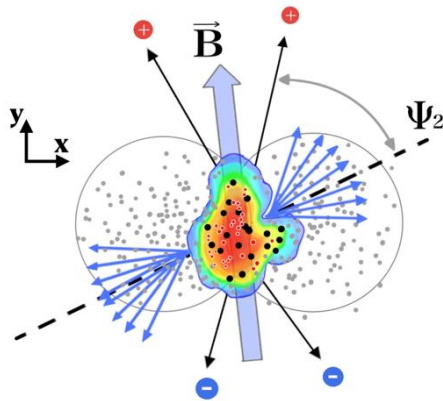
Q.M. Transport

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

Charge Dependent Azimuthal Correlators

CME sensitive correlator as observables:

$$\gamma_{\alpha,\beta} = \langle \cos(\phi_\alpha + \phi_\beta) \rangle = \langle \cos(\phi_\alpha) \cos(\phi_\beta) \rangle - \langle \sin(\phi_\alpha) \sin(\phi_\beta) \rangle$$



$$\gamma_{CME}^{SS} \rightarrow -\langle a_1^2 \rangle$$

$$\gamma_{CME}^{OS} \rightarrow +\langle a_1^2 \rangle$$

Another useful correlator:

$$\delta_{\alpha,\beta} = \langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle \cos(\phi_\alpha) \cos(\phi_\beta) \rangle + \langle \sin(\phi_\alpha) \sin(\phi_\beta) \rangle$$

The First CME Measurement: STAR2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

B. I. Abelev *et al.* (STAR Collaboration)

Phys. Rev. Lett. **103**, 251601 – Published 14 December 2009

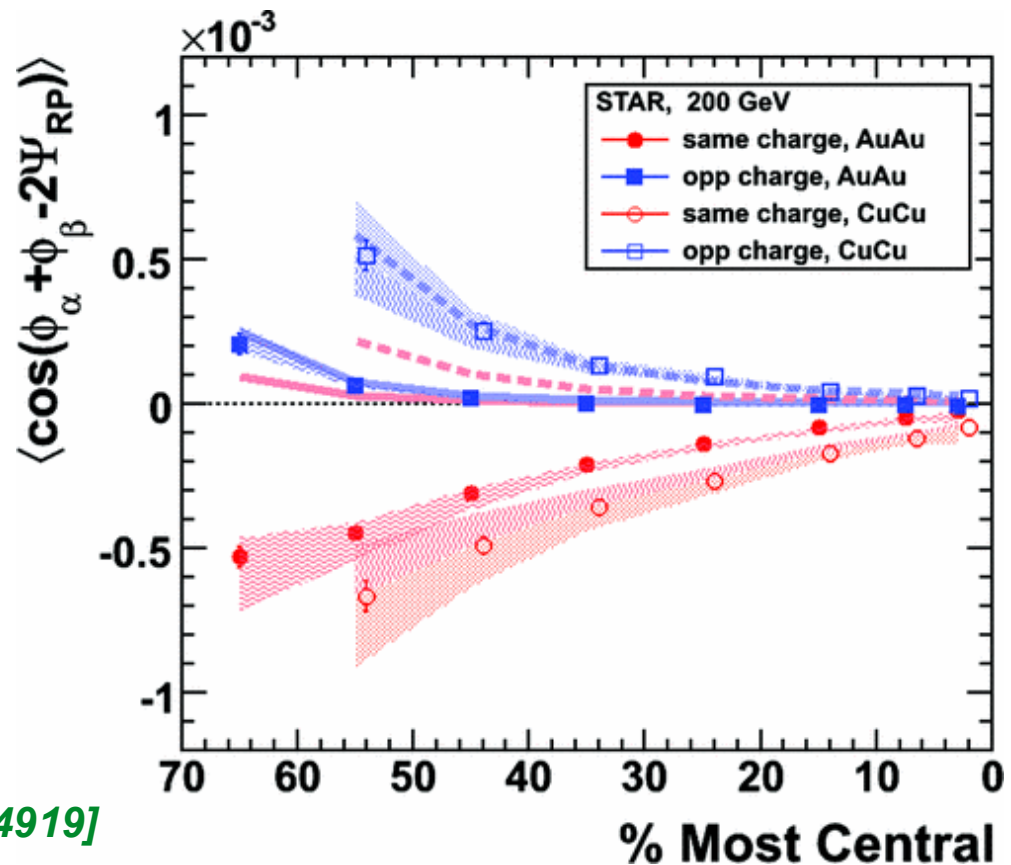
Data could be in line with CME expectations.

It was however quickly realized that data are dominated by backgrounds.

[F. Wang, [arXiv:0911.1482](https://arxiv.org/abs/0911.1482)]

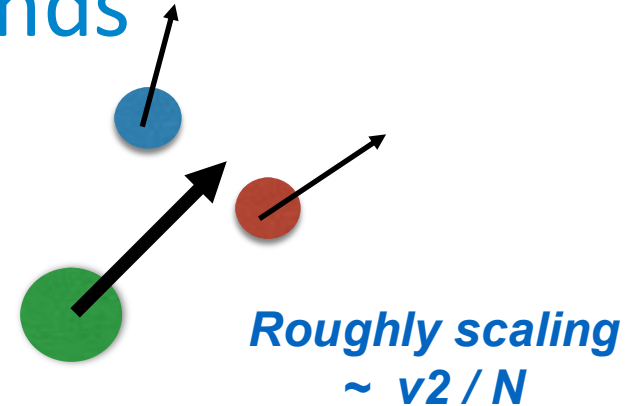
[S. Pratt, [arXiv:1002.1758](https://arxiv.org/abs/1002.1758)]

[Bzdak, Koch, JL:
[arXiv:0912.5050](https://arxiv.org/abs/0912.5050); [1005.5308](https://arxiv.org/abs/1005.5308); [1008.4919](https://arxiv.org/abs/1008.4919)]



Battling Backgrounds

Two major sources of backgrounds: resonance decay; local charge conservation (LCC).



New strategy: two-component decomposition

$$\gamma = \kappa v_2 F - H$$

F: Bulk Background

$$\delta = F + H$$

H: Possible Pure CME Signal = $(a_{1,CME})^2$

[Bzdak, Koch, JL: arXiv:1207.7327]

Redefining the mission: extract CME signal out of the correlators

A number of smart approaches:

Vary B with fixed v_2 ; Vary v_2 with fixed B; Vary v_2 and B in opposite ways

We are not alone!

Think about many other difficult searches, e.g. for Higgs, gravitational wave, temperature fluctuations of CMB, EDM, WIMP, 2-beta decay, ...

Have We Seen the CME?

- *Efforts in the past ~20 yrs by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5440GeV beam energies*
- *Various colliding systems: pp, pA, dAu, CuCu, RuRu, ArAr, AuAu, PbPb, XeXe*

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



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?

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

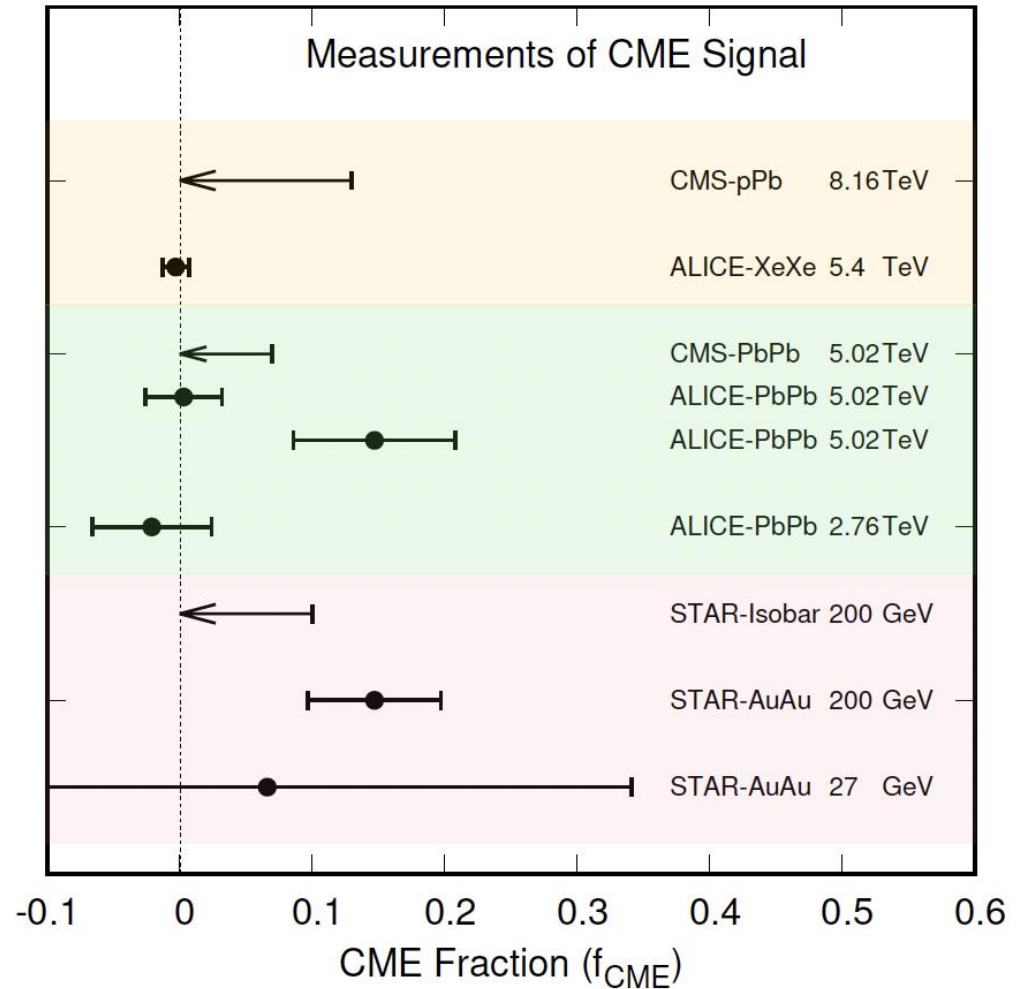
Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA

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.

[~130pages;
arXiv:2405.05427
(Int.J.Mod.Phys.E 33 (2024)
09, 2430007) (QGP6)]

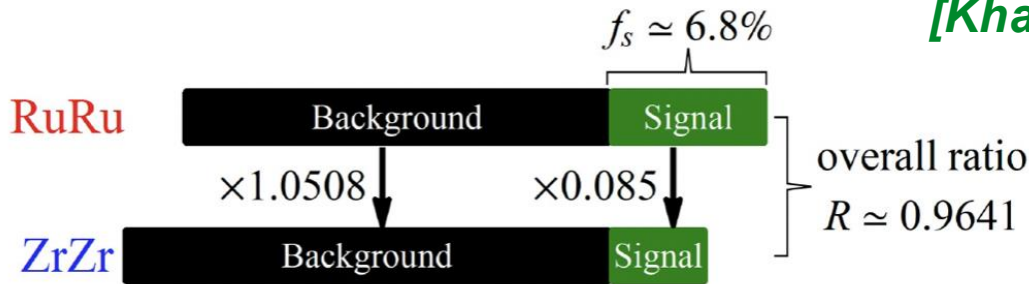


20 years of hunting CME, hundreds of experimental publications

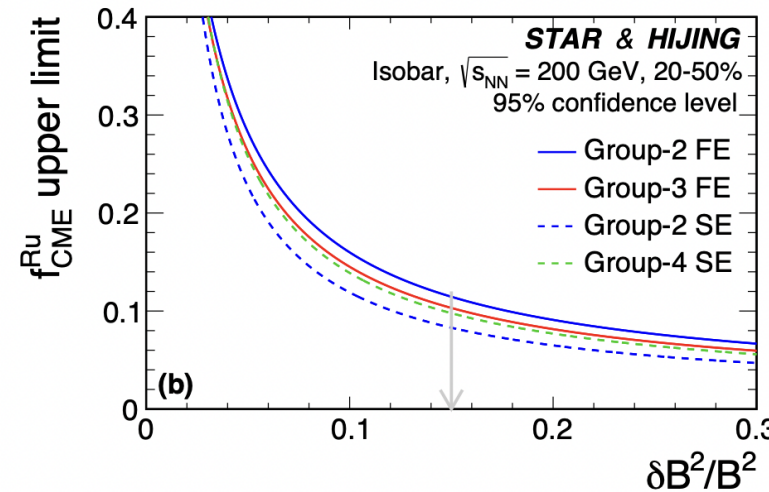
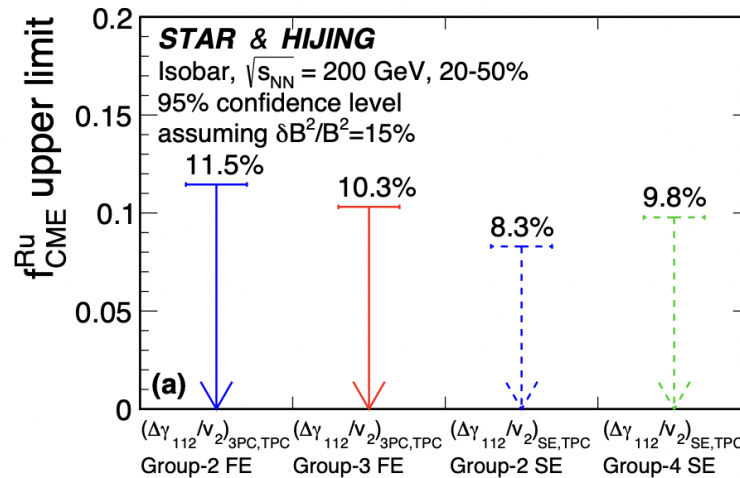
Isobar Collisions

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

[Khazeev, JL, Shi, arXiv:2205.00120]

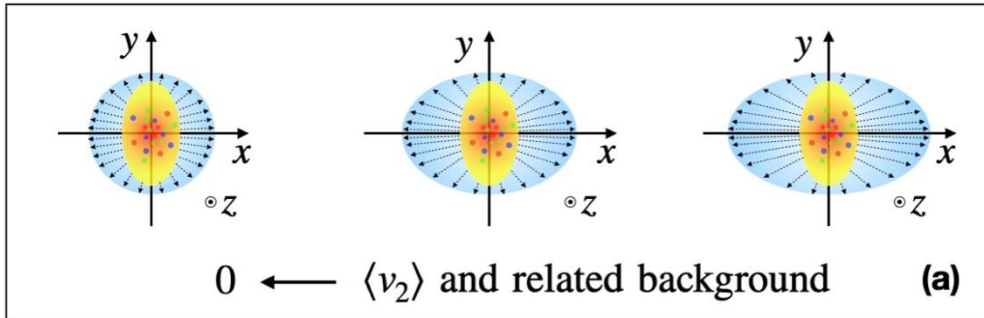


[STAR, arXiv:2310.13096;2308.16846]

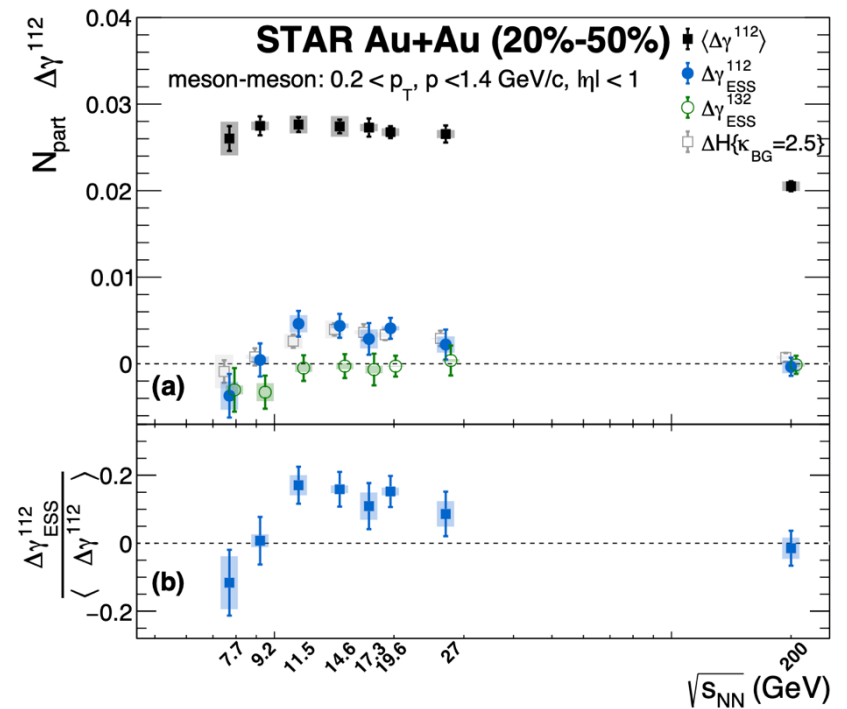
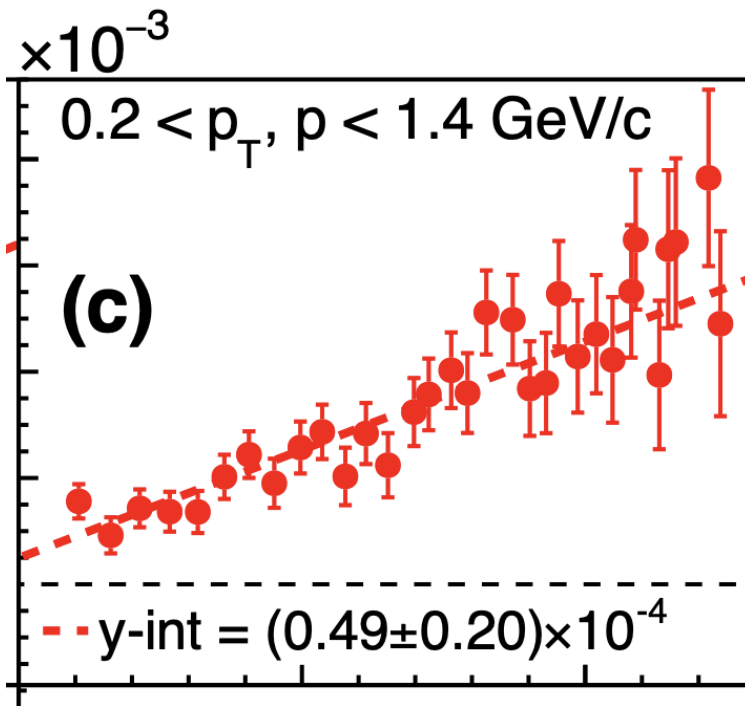


- **Upper limits have been set by STAR for isobar collisions.**
- **Consistent with theoretical expectations**
- **Indicating a still better chance for the search in AuAu collisions**

Beam-Energy-Scan-II: STAR2025



STAR Collaboration:
2506.00275;
2506.00278



Beam-Energy-Scan-II: STAR2025

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

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 $\sqrt{s_{NN}} = 11.5, 14.6, \text{ and } 19.6$ 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 topological vacuum transitions at lower RHIC energies.

STAR Collaboration: 2506.00275; 2506.00278

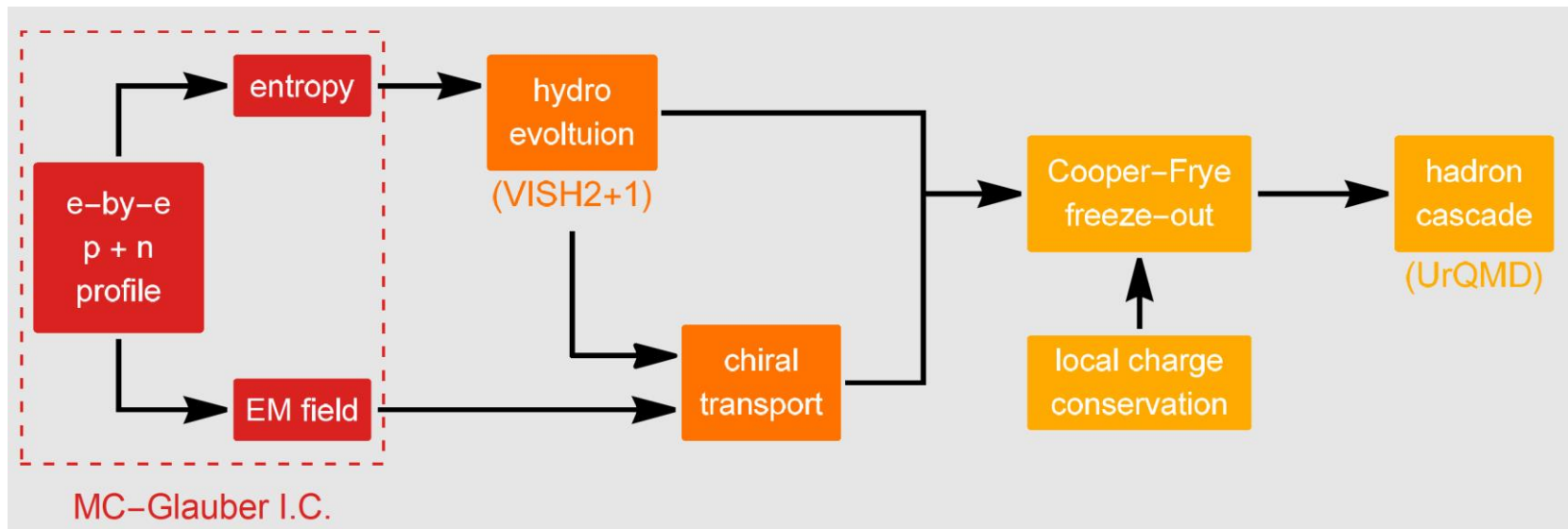
A New Data-Driven Approach

- *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?*

The EBE-AVFD

Theoretical tool for quantitative predictions of CME and related backgrounds is crucial!

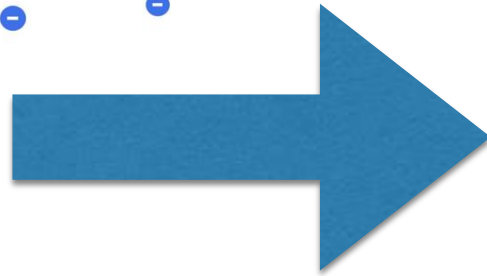
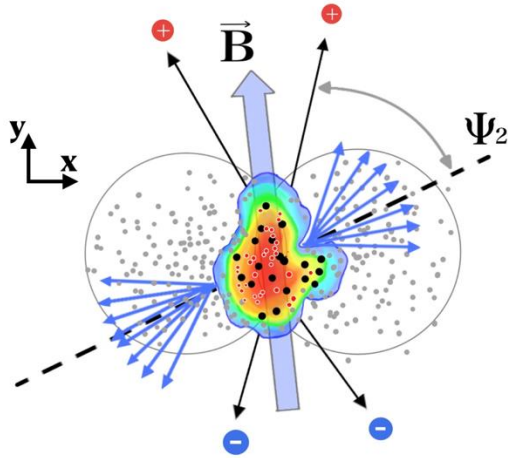
*EBE-AVFD:
event-by-event anomalous-
viscous fluid dynamics*



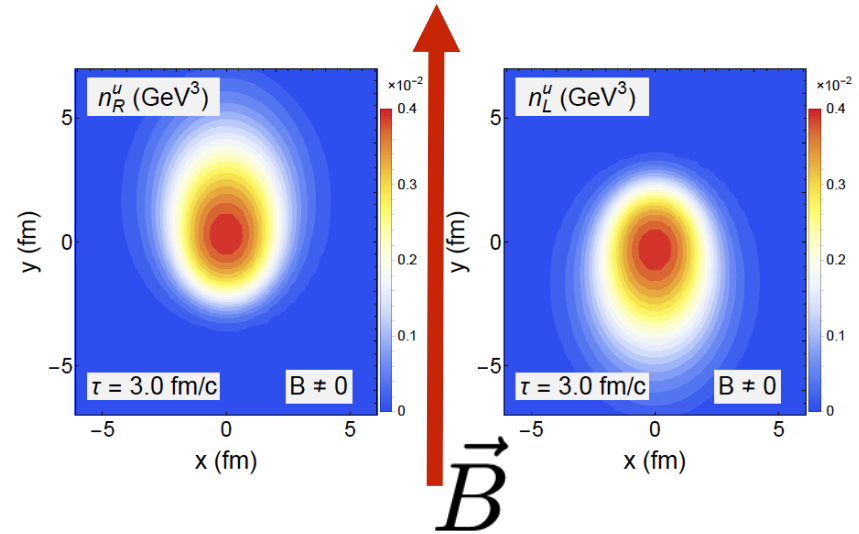
[Shuzhe Shi, JL, ..., arXiv:1611.04586; 1711.02496; 1910.14010]

[BEST Collaboration publication: Nucl. Phys. A 1017(2022)122343]

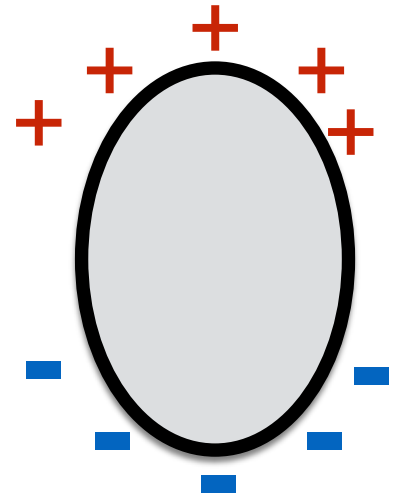
Hydrodynamic Realization of CME in HIC



From cartoon to quantitative physics



Chirality transport
 →
R/L asymmetry
 →
charge asymmetry
 →
exp. data



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

Machine Learning Extraction of CME Transport

- Upgrade the EBE-AVFD for BES energies (focusing on 19.6GeV for now)
- Calibration with bulk data (multiplicity, v_2 , 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. Xing, H. Zhang: in preparation.

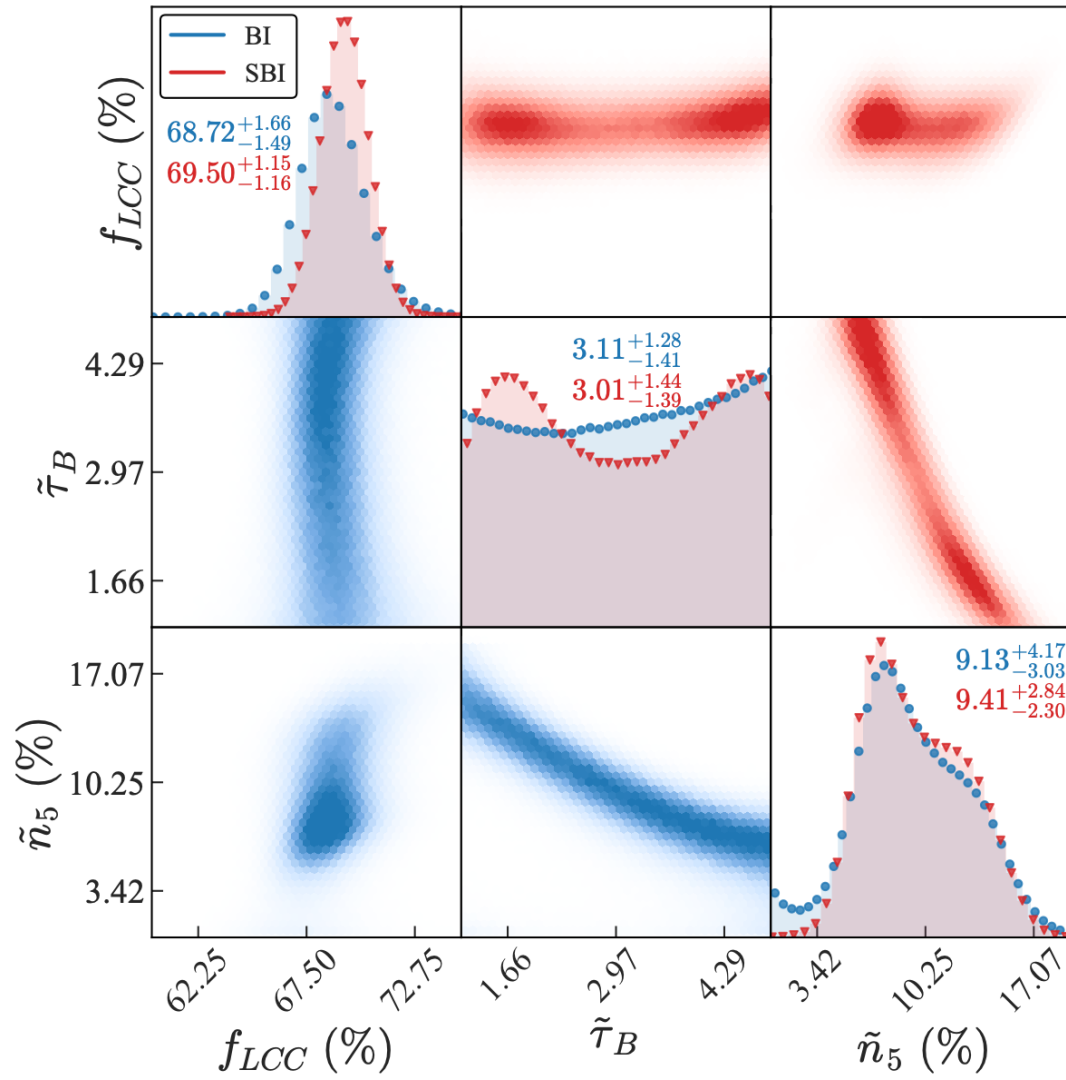
Two Analysis Methods

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 methods to ensure the robustness of the results.

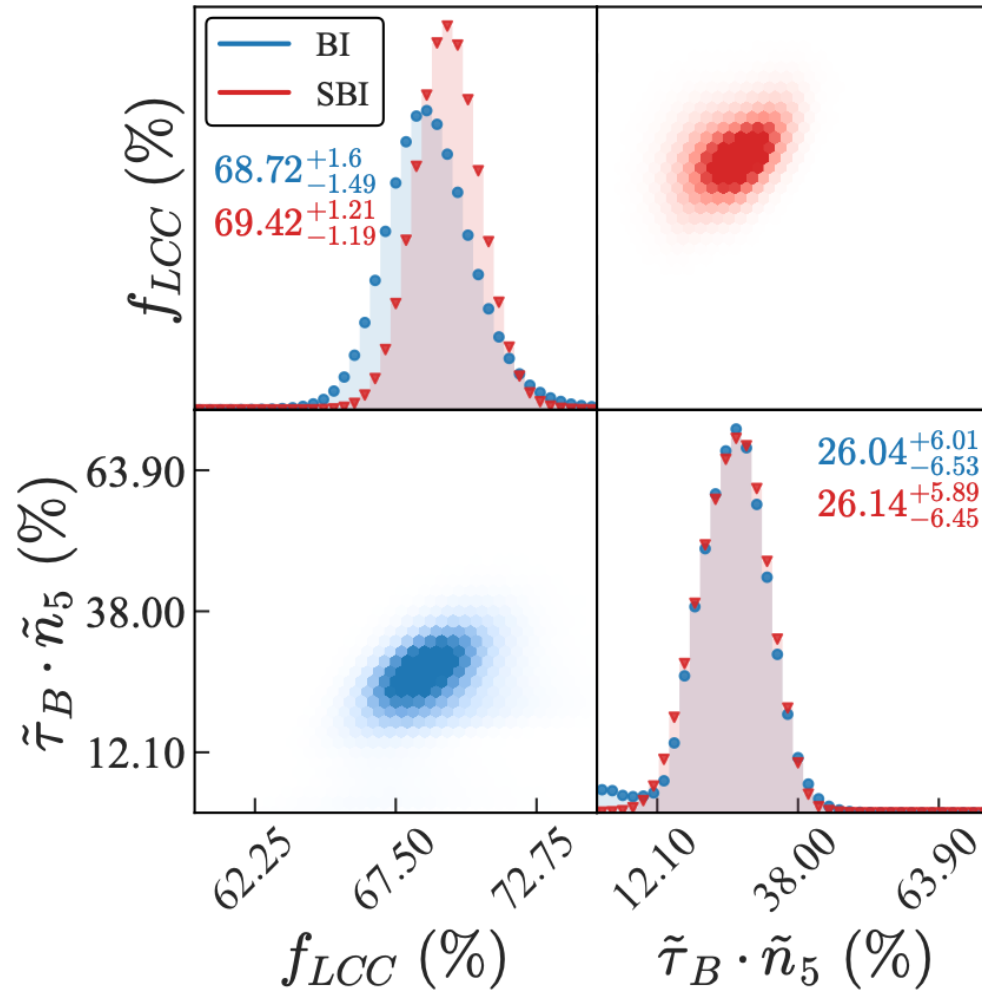
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Distributions



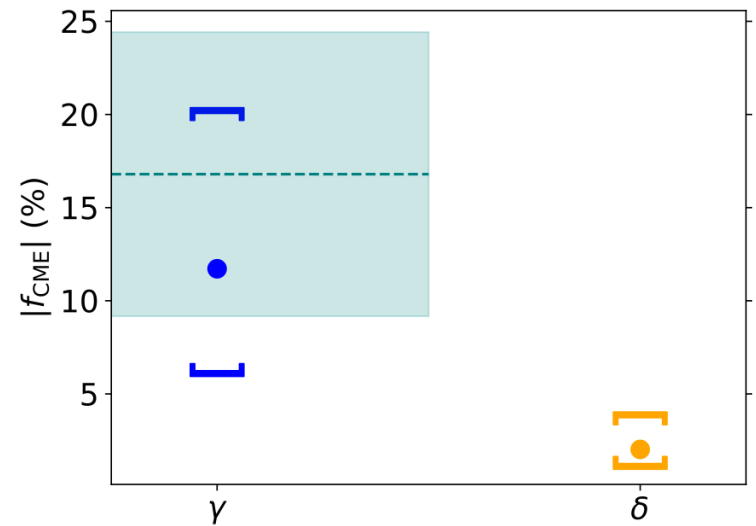
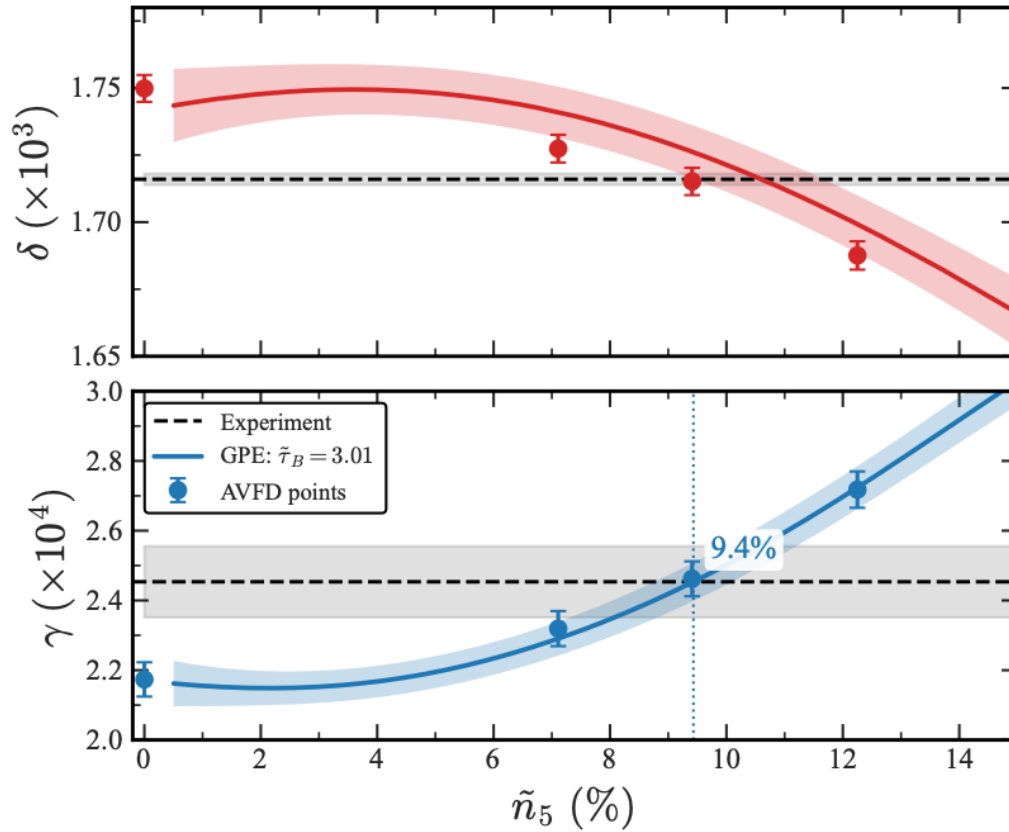
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Distributions



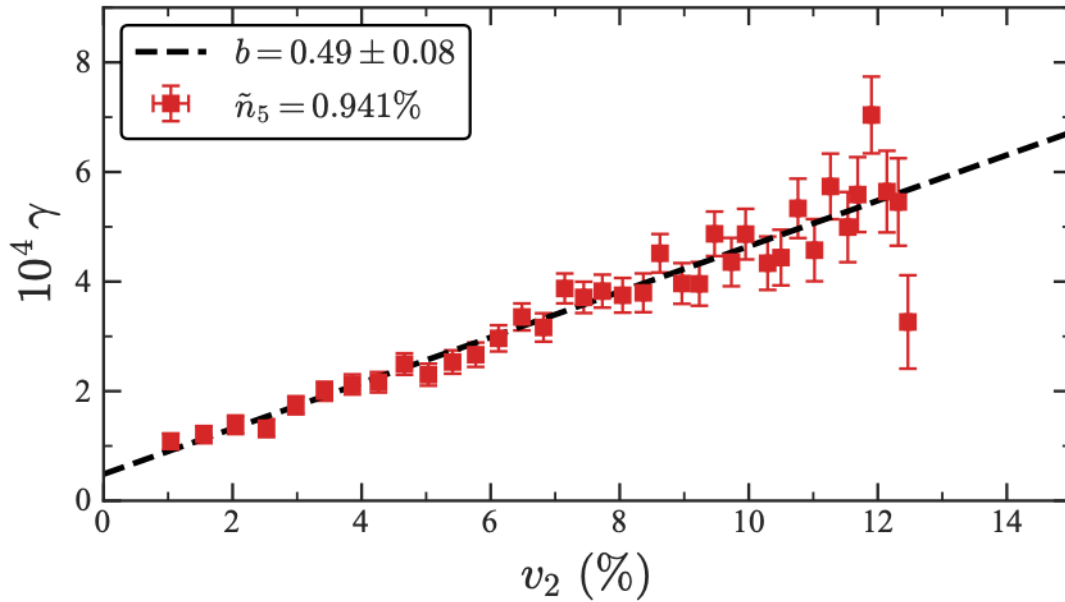
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Validations

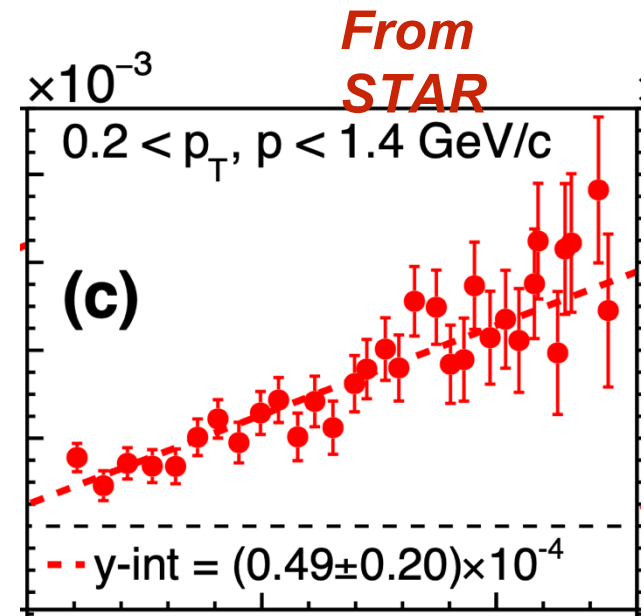


A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Validations



From our analysis



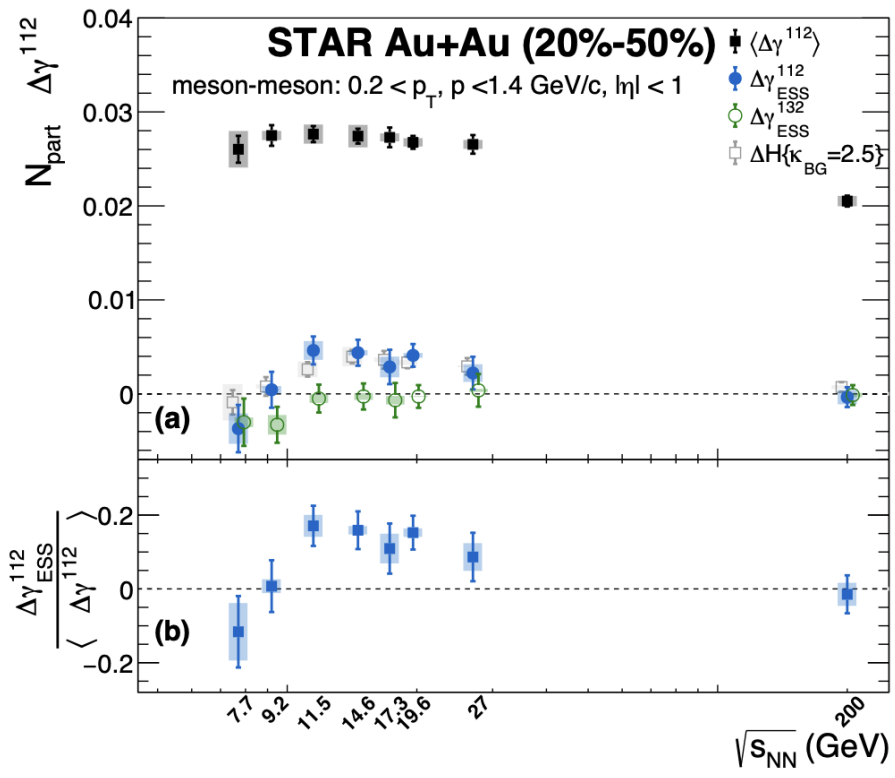
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Summary

- *The search for CME in heavy ion collisions is ongoing, with current data indicating a positive signal, especially around BES energy range.*
- *We develop a novel approach for extracting CME transport from inclusive measurements with machine learning tools.*
- *Our analysis finds robust and unambiguous evidence for CME transport and provides quantitative interpretation of the experimental data.*

Discussion: Why the Beam Energy Dependence?

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



Longer magnetic field lifetime

Enhanced fluctuations of axial charges near CEP

Shorter fireball evolution