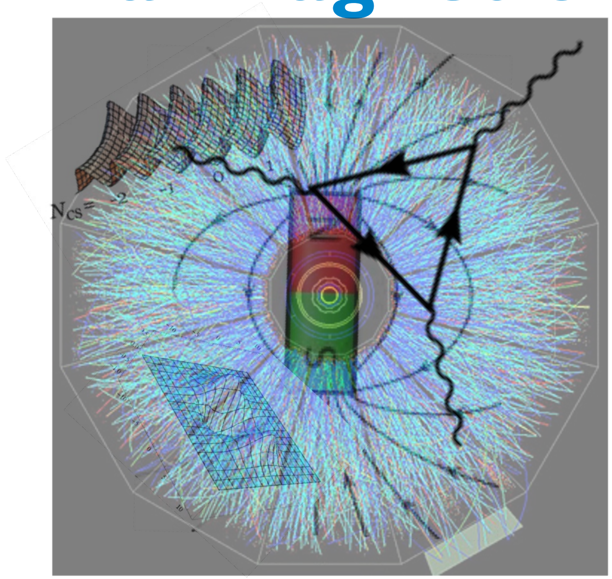
Nov 2025, Guangzhou

Machine Learning Extraction of Chiral Magnetic Transport

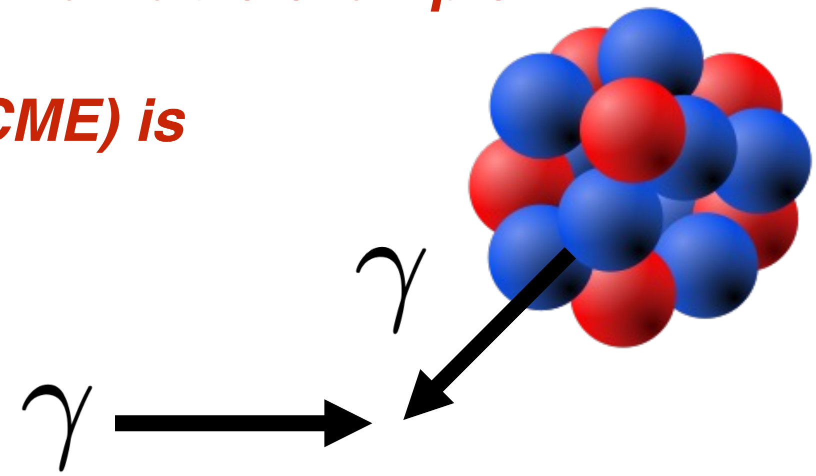


Jinfeng Liao

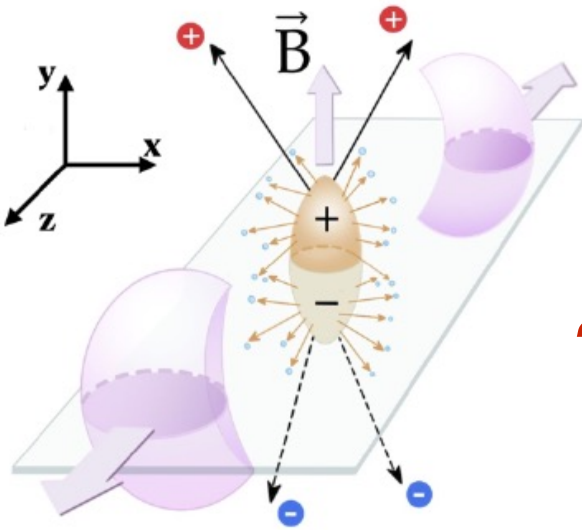
Indiana University, Physics Dept. & CEEM

EM Fields of Atomic Nucleus

- *The EM fields of atomic nucleus was historically important for discovery of antimatter.*
- *Zhao Zhongyao: gamma + Pb (~1930)*
- *Perhaps the earliest "UPC": Chadwick, Blackett & Occhialini, alpha + beryllium (~1933)*
- *High energy nuclear collisions provide a unique venue of exploring EM fields of atomic nucleus, with modern UPC as a remarkable example*
- *Chiral Magnetic Effect (CME) is another novel example*



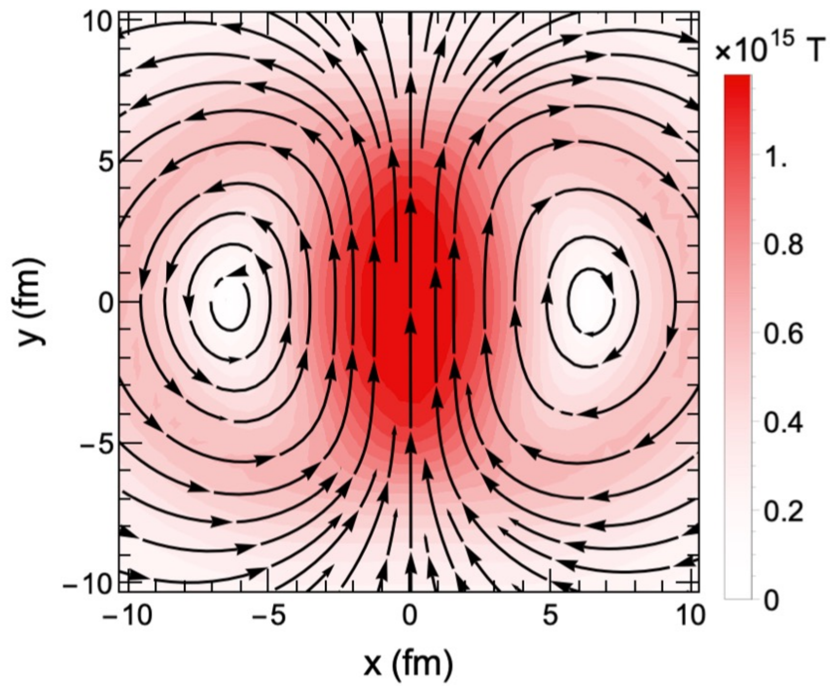
The Strongest Magnetic Fields



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

The strongest B field ~ 10^15 Tesla or larger

Subatomic "lightning"!



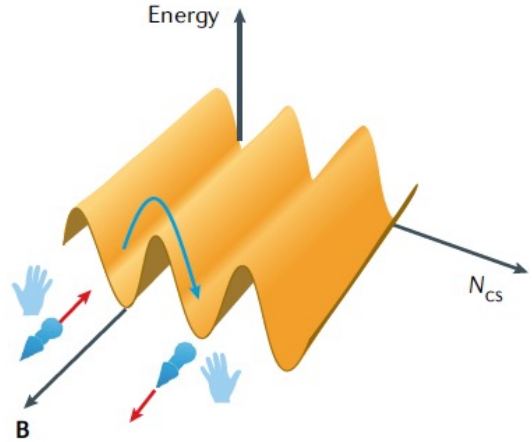
However: maybe short-lived

Interesting new ways to probe the extreme magnetic fields: Conserved charge fluctuations; Directed flow; Spin polarization splitting; UPC; …

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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



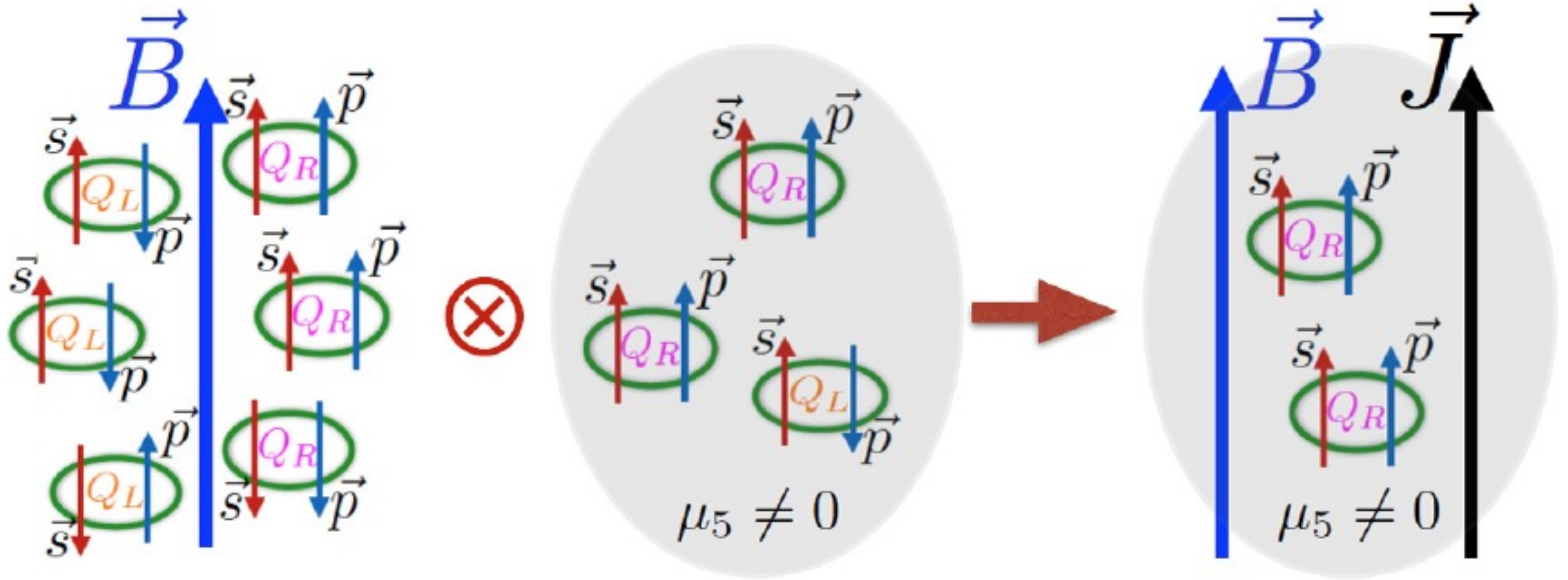
Electric Current

Magnetic Field

Q.M. Transport

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

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

Intuitive understanding of CME:

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

$\otimes$

Chirality Polarization —>
correlation between directions of
SPIN & MOMENTUM

→ ***Transport current along magnetic field***

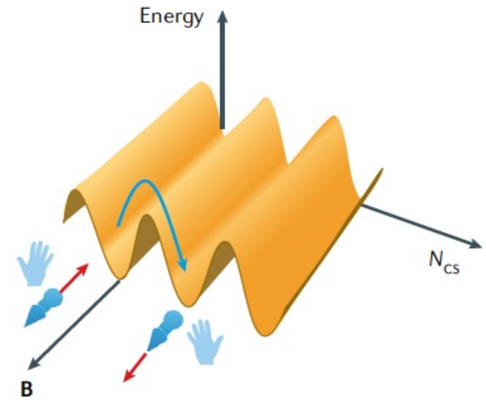
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Why CME?

- *Chirality plays a fundamental role in the construction of the Standard Model. CME allows access to quark chirality.*
- *The CME can be an indicator of chiral symmetry restoration at high temperature.*
- *The CME provides a unique way for revealing the nontrivial topological structures of QCD vacuum.*
- *CME could help understand the generation of baryon asymmetry in the early universe.*
- *CME has become a phenomenon of multi-disciplinary interests.*

Why CME?

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



[Kharzeev, JL, Nature Reviews Physics 3, 55-63 (2021)]

Table 1 | **The currents induced by the chiral anomaly in different physical systems**

System	Source of chirality	Current carriers	Type of current	Experimental signatures
The Universe	Topological transitions in hot electroweak matter: sphalerons, …	Quarks	Baryon	Baryon asymmetry of the Universe; Helical magnetic fields at intergalactic scales
Quark–gluon plasma	Topological transitions in hot QCD matter: sphalerons, …	Quarks	Electric	Angular correlations of charged hadrons in relativistic heavy ion collisions
Dirac/Weyl semimetals	External electric and magnetic fields; Circularly polarized photons	Electronic quasiparticles	Electric	Negative longitudinal magnetoresistance; Non-local chiral transport; Chiral magnetic photocurrent
Superfluid ^{3}He-A	Effective electric and magnetic fields induced by the time-dependent orbital angular momentum	Atoms in the superfluid	Linear momentum	Dynamics of vortex motion

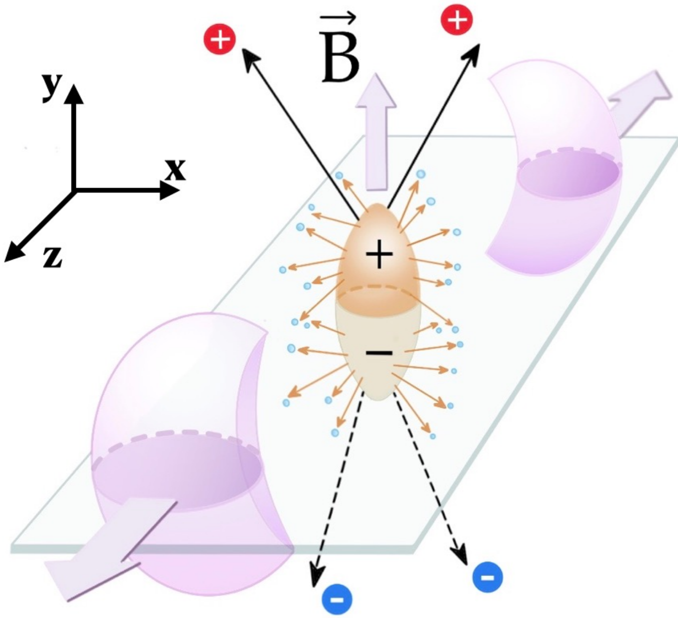
The sources of chirality, the current carriers, the type of the induced anomalous current, and experimental signatures are indicated. QCD stands for quantum chromodynamics.

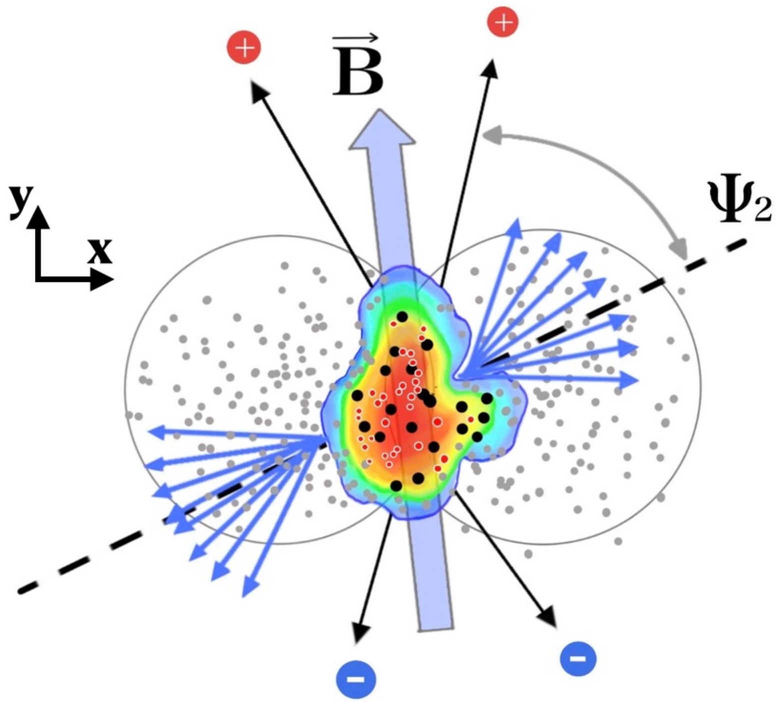
2023 US Long Range Plan for Nuclear Science:

The study of CME helps provide insights into the solution of "one of the biggest questions in physics", namely: "Why does the universe contain more matter than antimatter"?

Looking for CME Signals in Nuclear Collisions

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



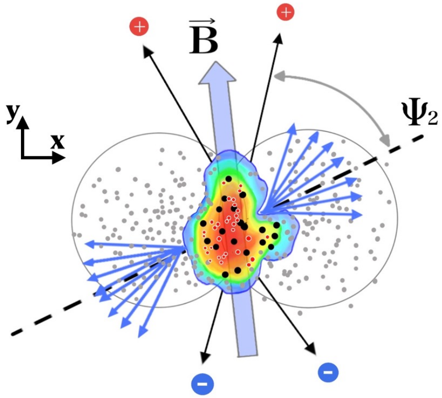


A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

Charge Dependent Azimuthal Correlators

CME sensitive correlator as observables:

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



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

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

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

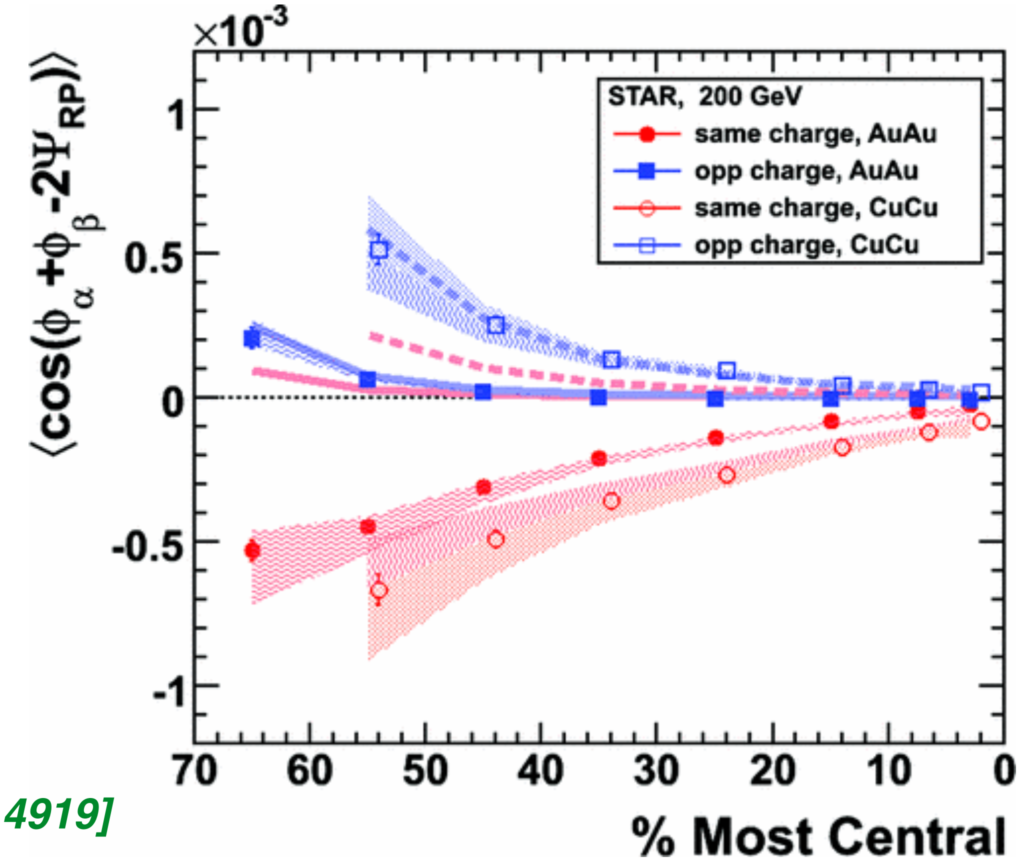
Data could be in line with CME expectations.

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

[F. Wang, arXiv:0911.1482]

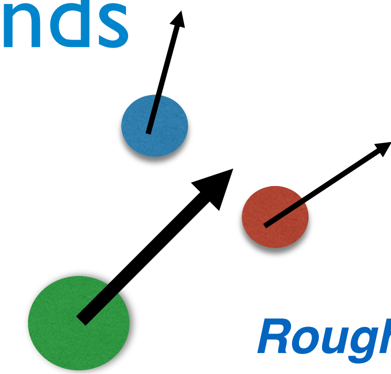
[S. Pratt, arXiv:1002.1758]

[Bzdak, Koch, JL: arXiv:0912.5050;1005.5308;1008.4919]



Battling Backgrounds

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



Roughly scaling ~ v2 / N

New strategy: two-component decomposition

$\gamma = \kappa v_2 F - H$

$\delta = F + H$

F: Bulk Background

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 v2; Vary v2 with fixed B; Vary v2 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

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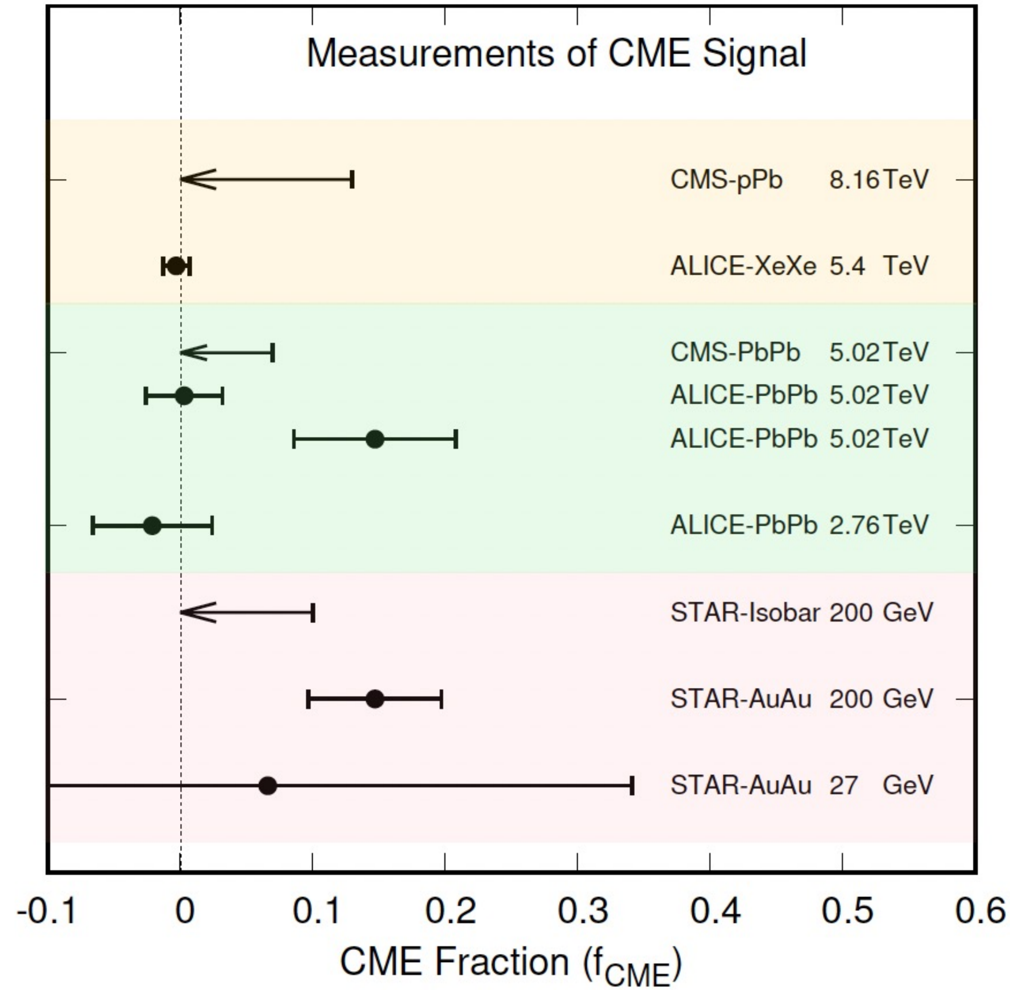
The chiral magnetic effect (CME) is a collective quantum phenomenon that arises from the interplay between gauge field topology and fermion chiral anomaly, encompassing a wide range of physical systems from semimetals to quark-gluon plasma. This review, with a focus on CME and related effects in heavy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

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

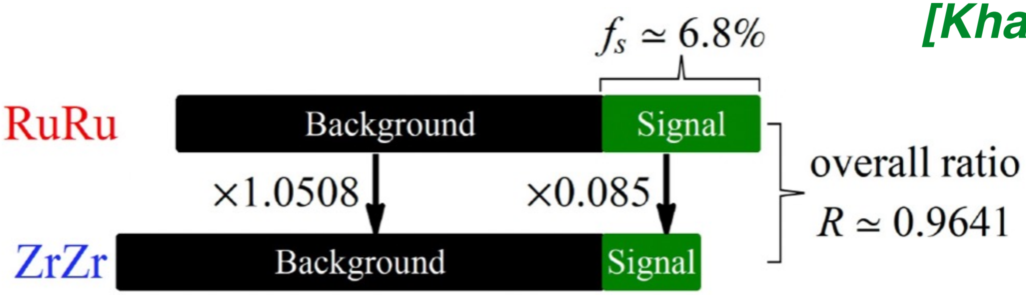


20 years of hunting CME, hundreds of experimental publications

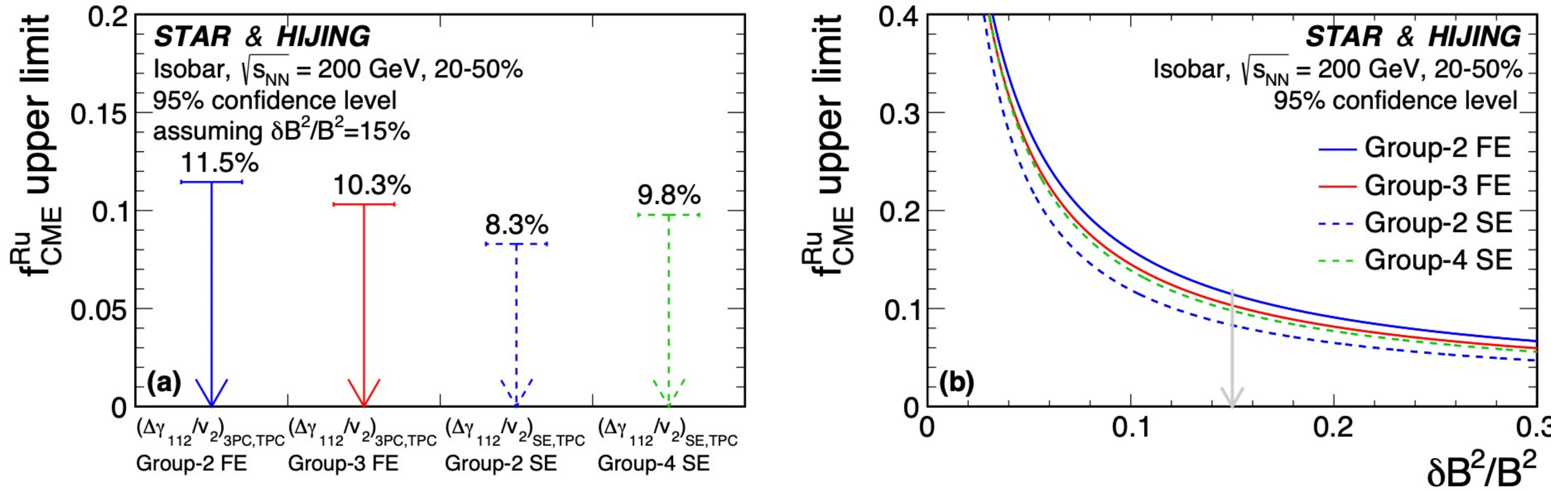
Isobar Collisions

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

[Khazeev, JL, Shi, arXiv:2205.00120]

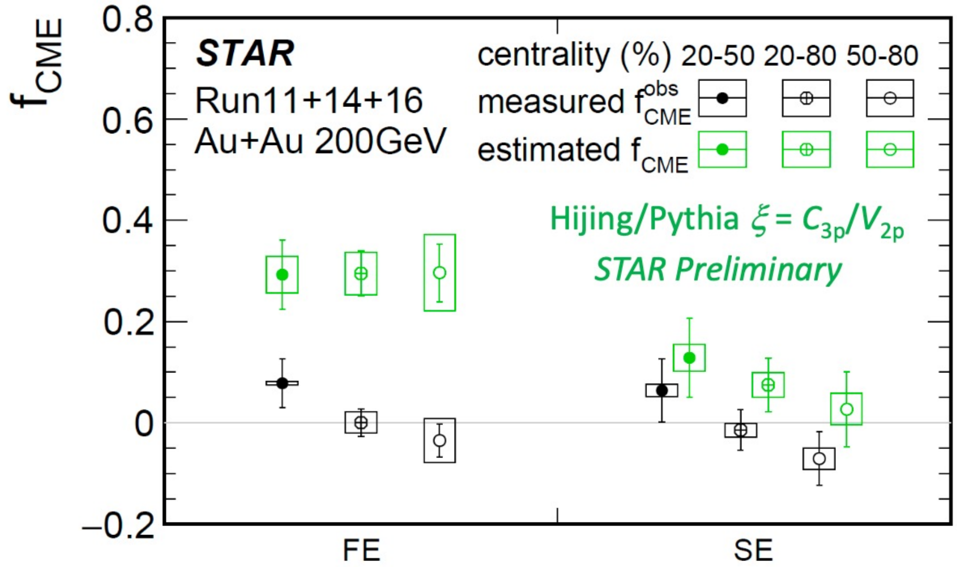


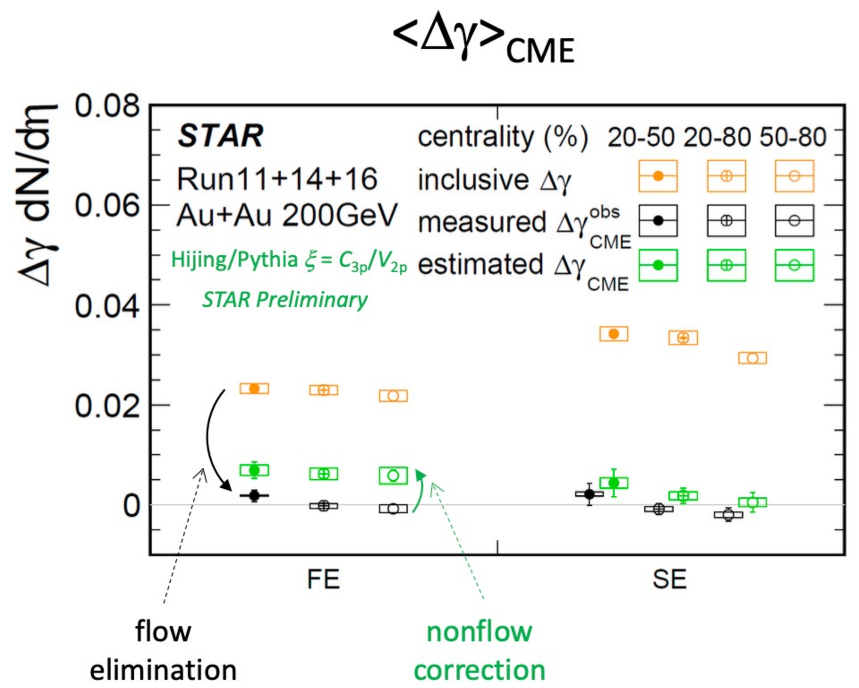
[STAR, arXiv:2310.13096;2308.16846]



– *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*

Nonflow Correction

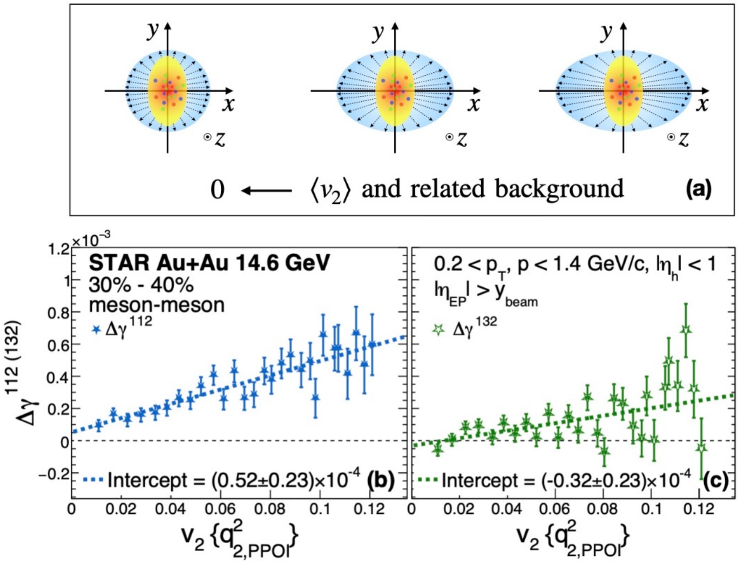




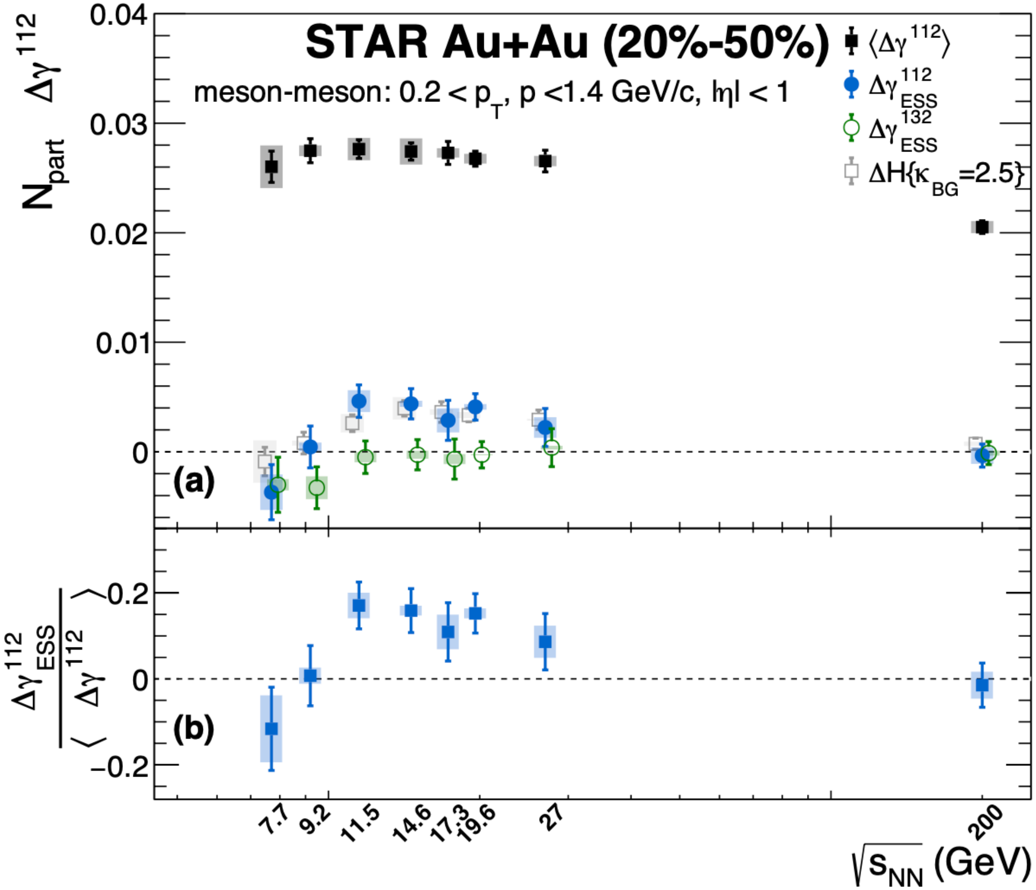
- Significant f_{CME} in full-event
- Weak centrality dependence
- f_{CME} full-event > sub-event; $\Delta\gamma_{CME}$ compatible in 20-50% centrality.

[from Fuqiang Wang]

Beam-Energy-Scan-II: STAR2025



STAR Collaboration:
2506.00275;
2506.00278



Beam-Energy-Scan-II: STAR2025

Charge Separation Measurements in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$–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, 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

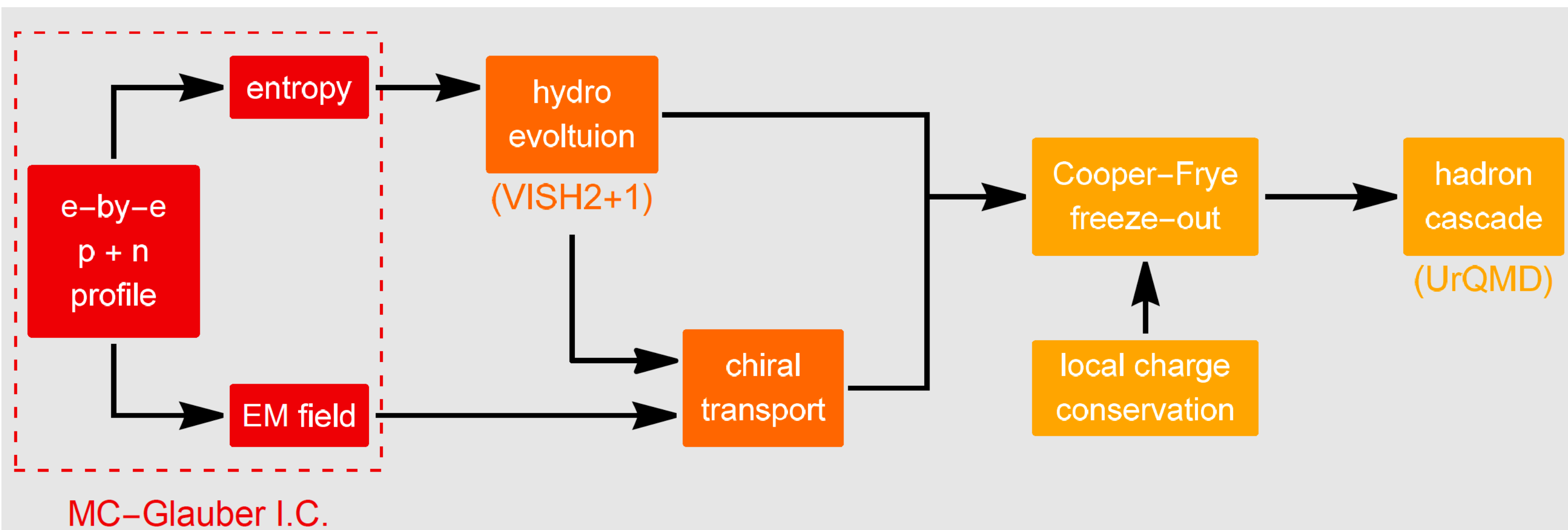
A New “holistic” Approach

- *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 a holistic 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!

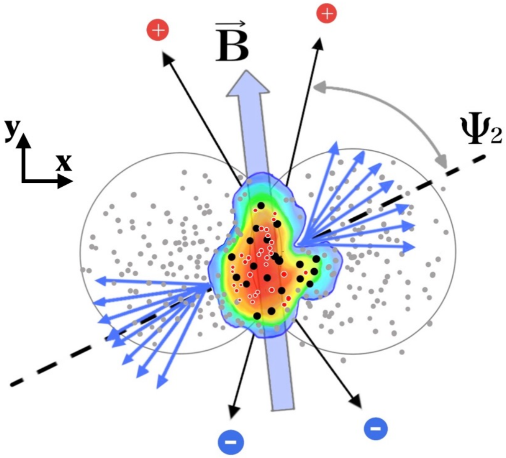
EBE-AVFD:
event-by-event anomalous-viscous fluid dynamics

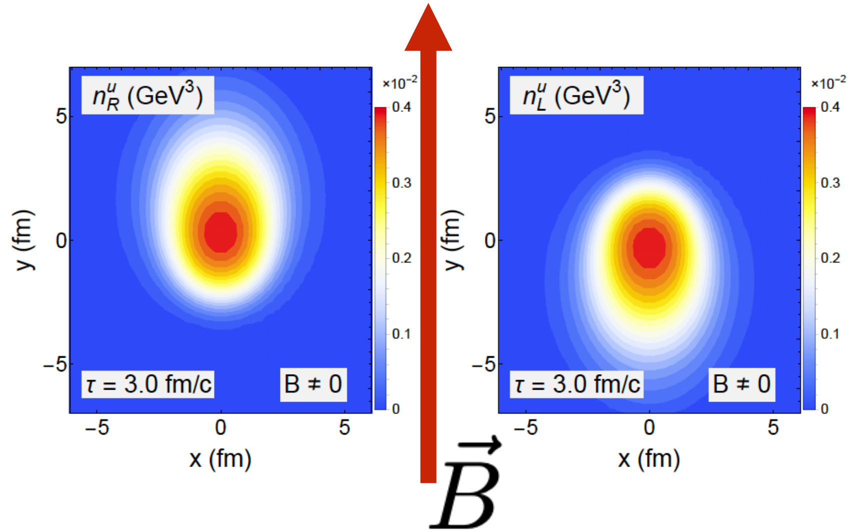


[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

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

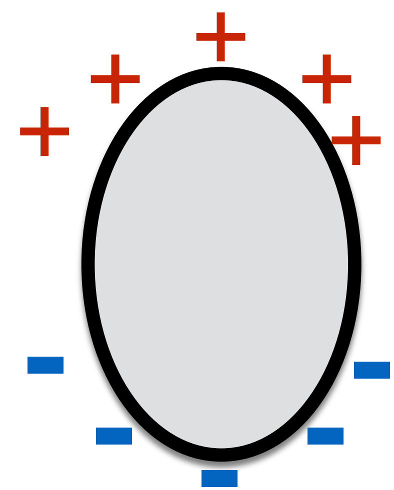
Hydrodynamic Realization of CME in HIC





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, v2, net proton, …)*

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

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

— *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.

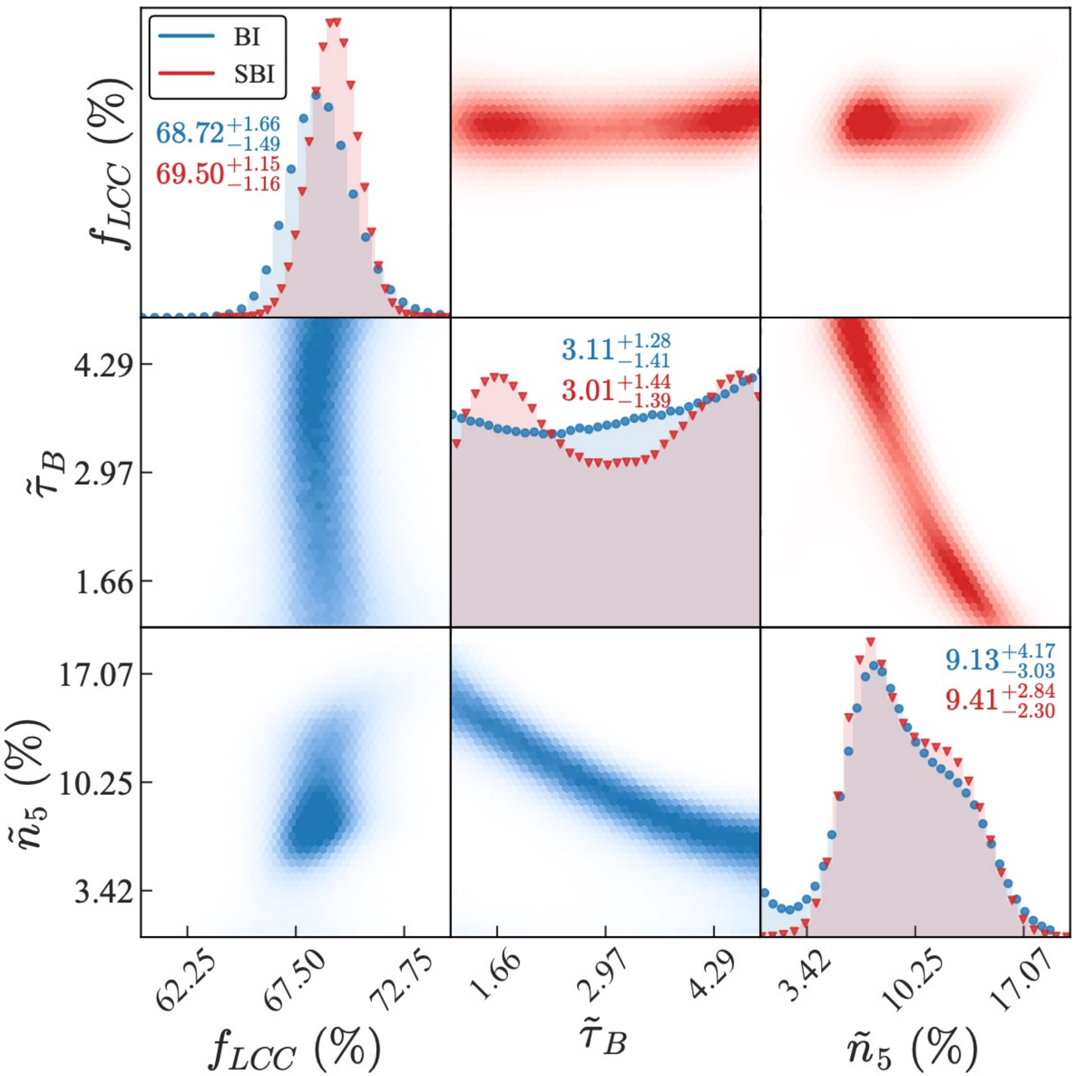
Two Analysis Methods

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.

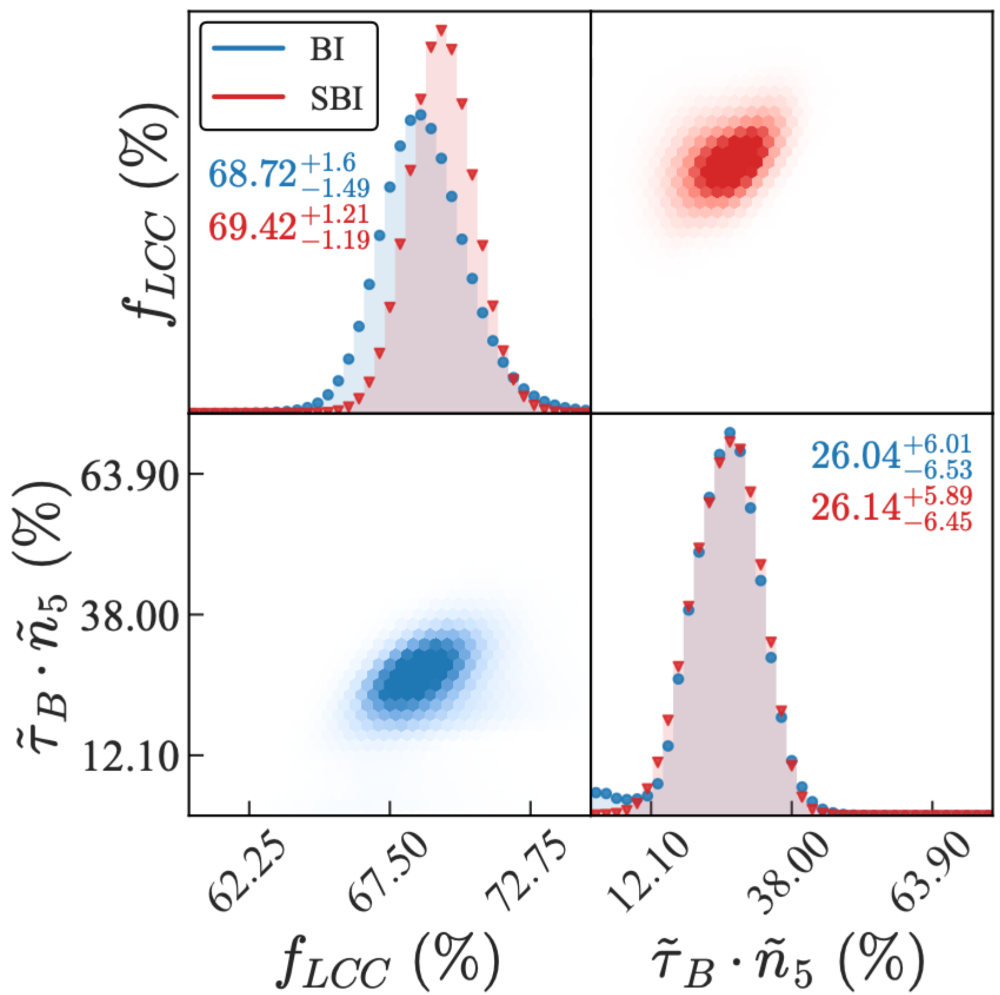
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Distributions



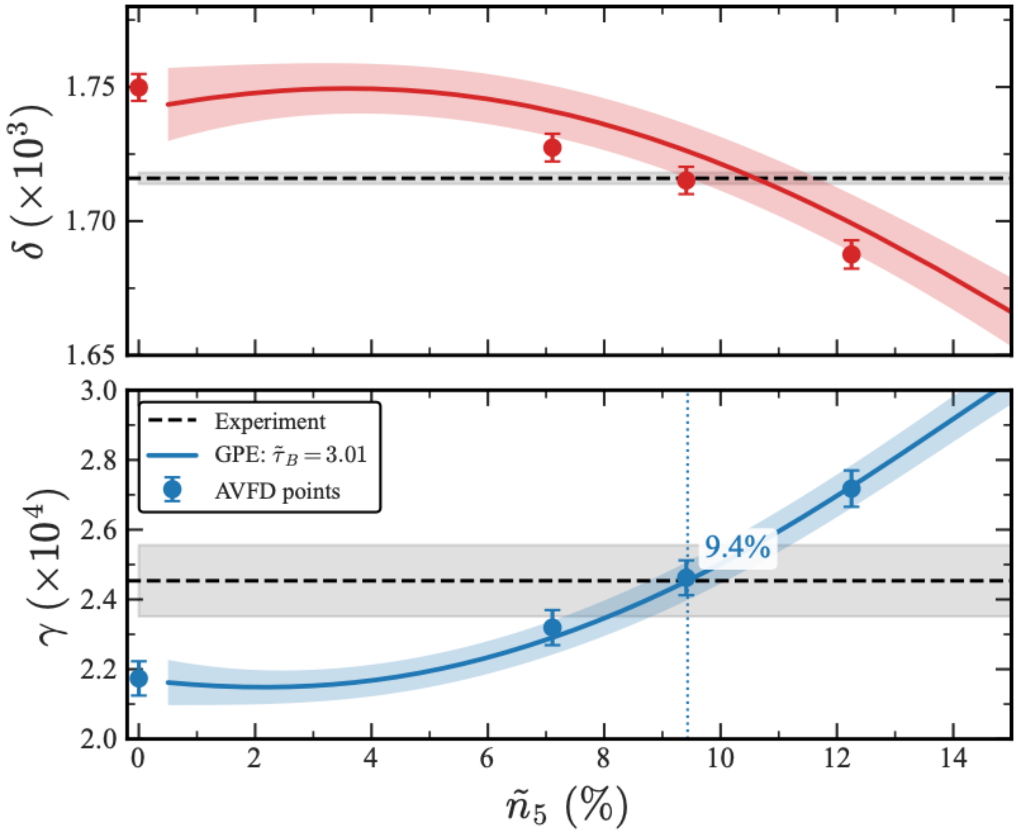
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

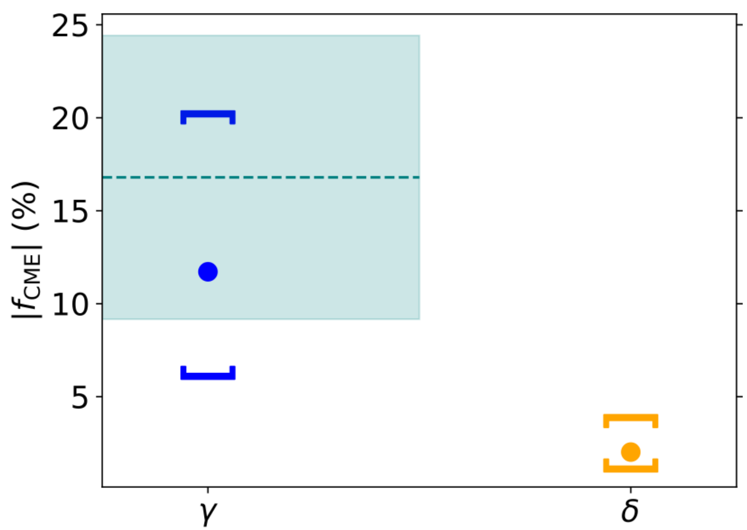
Posterior Distributions



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

Posterior Validations





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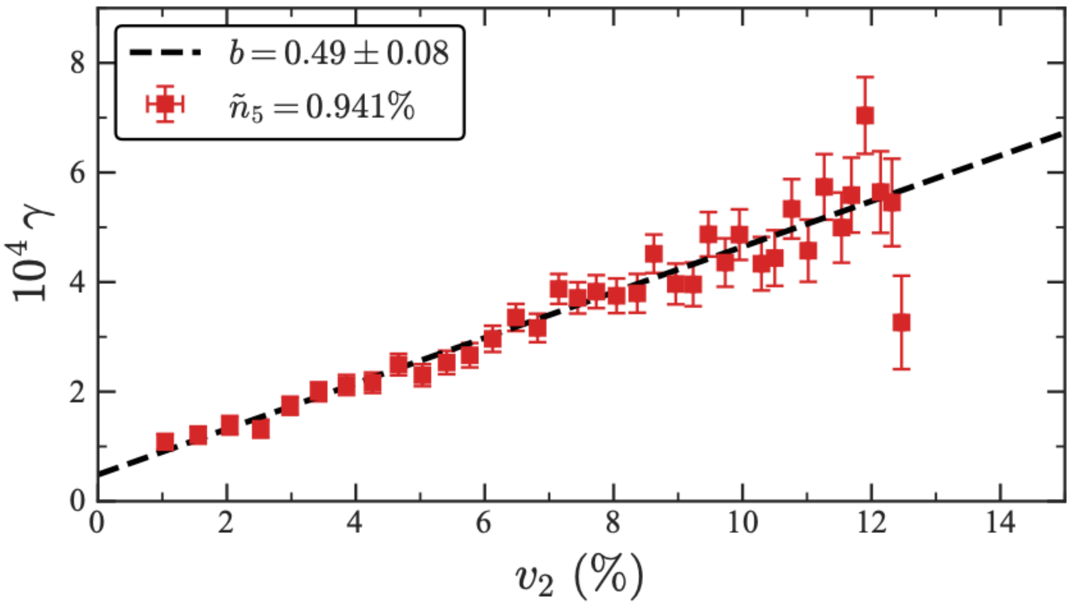
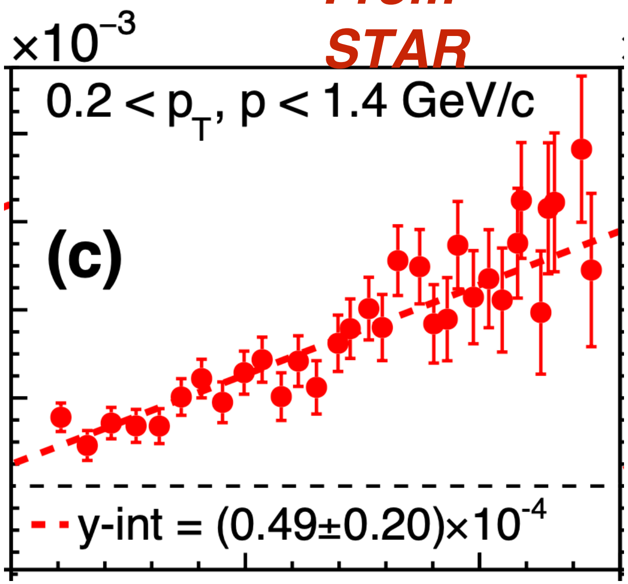
Posterior Validations



From our analysis

From STAR



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

Summary

– ***Chiral Magnetic Effect provides a unique way to access chirality. It allows us to explore topological vacuum structures of non-Abelian gauge fields and to study chiral symmetries in QCD.***

– ***The search for CME in heavy ion collisions is ongoing, with significant achievements in recent years.***

– ***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.***