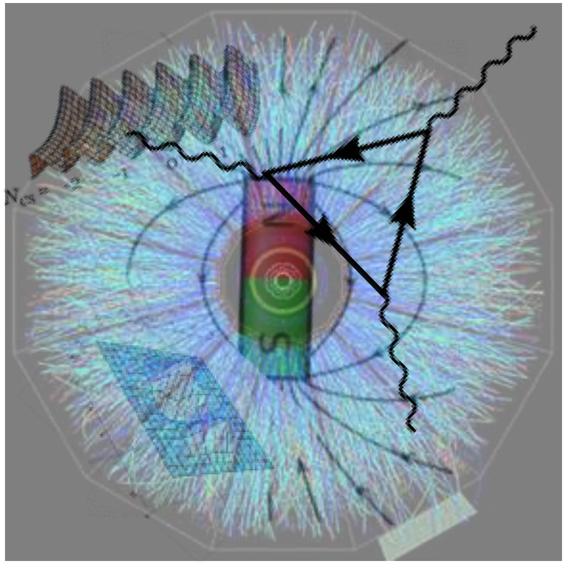
SQM @ UCLA *Mar. 2026*

Chiral Transport and Its Dependence on Collision Beam Energy



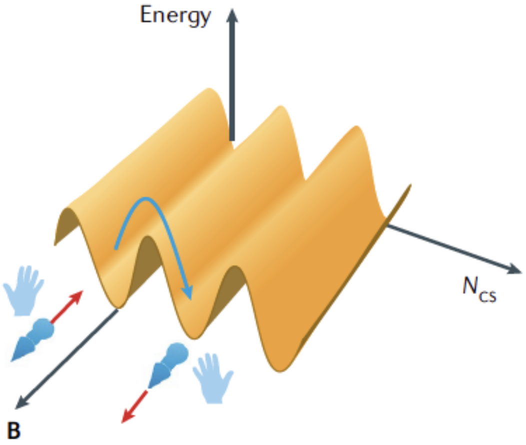
Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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



Electric Current

Q.M. Transport

Magnetic Field

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

Anomalous Transport from Quarks to the Cosmos

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

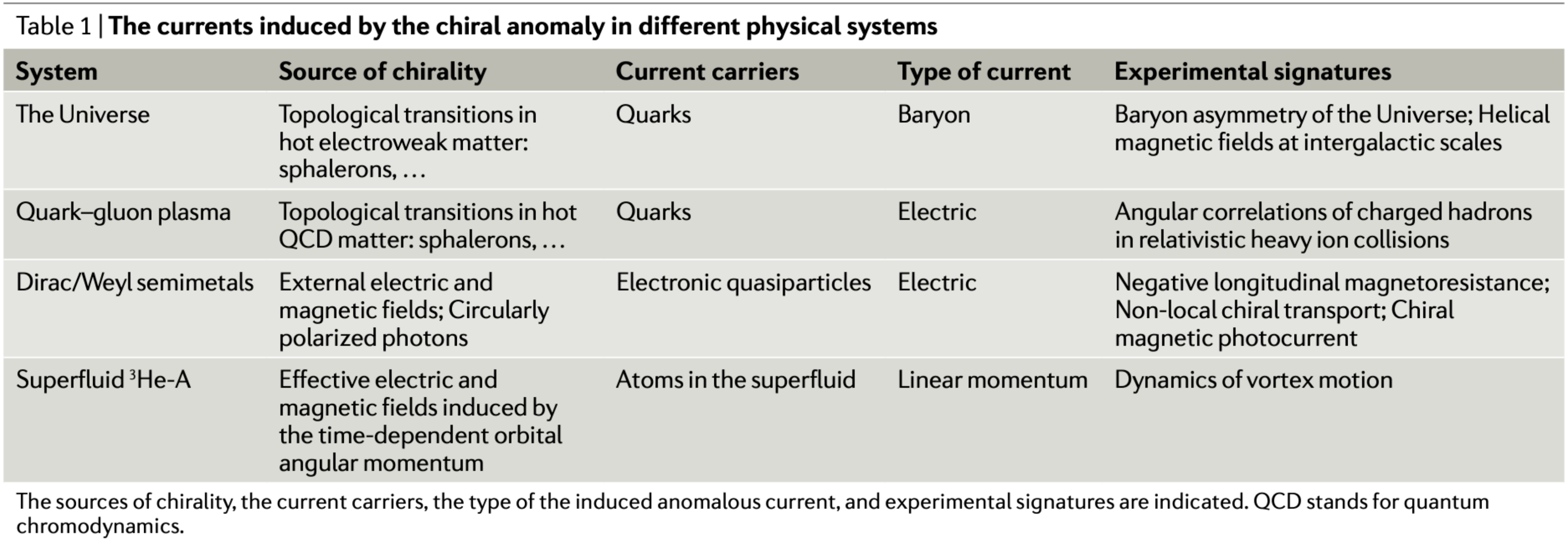


Table 1 | **The currents induced by the chiral anomaly in different physical systems**

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.

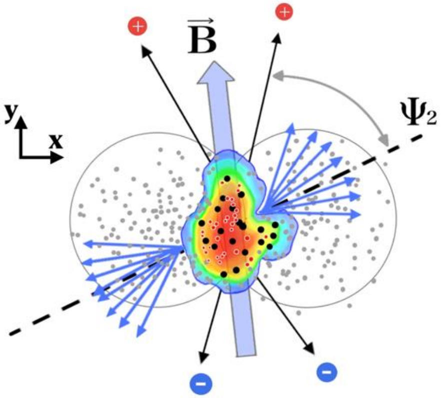
2023 US Long Range Plan for Nuclear Science:

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"?

Charge Dependent Azimuthal Correlators

CME sensitive correlator as observables:

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



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

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

Another useful correlator:

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

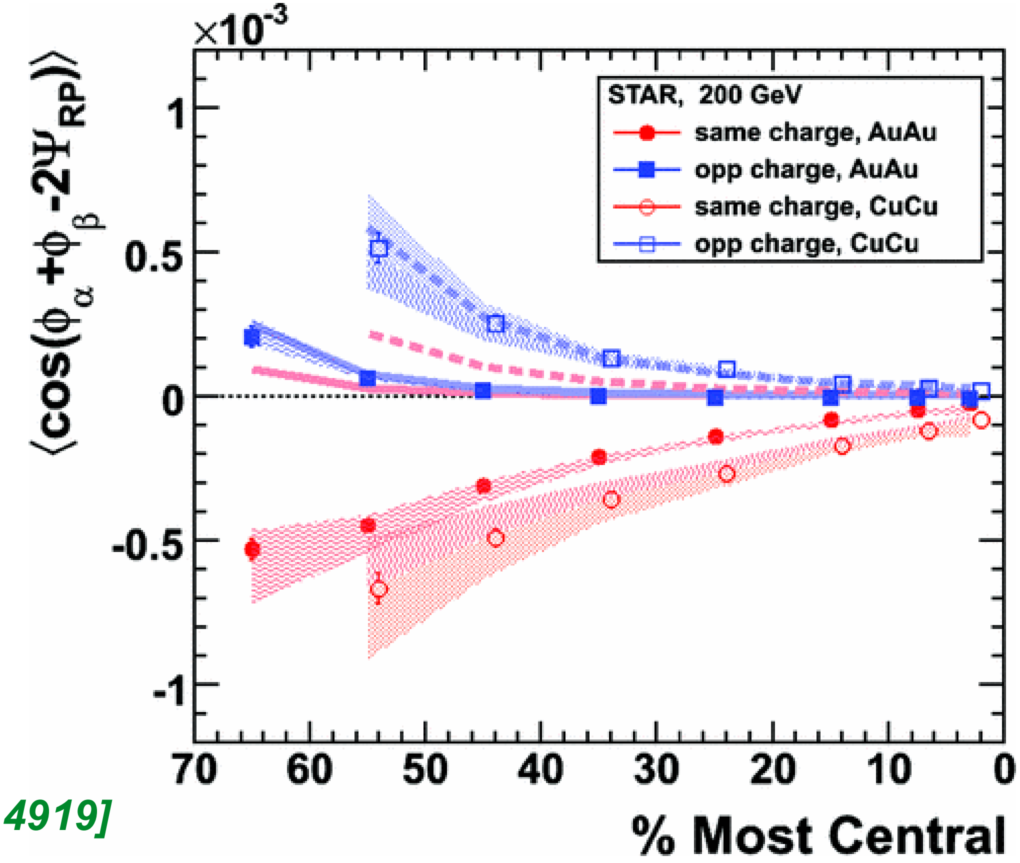
The First CME Measurement: STAR2009

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.

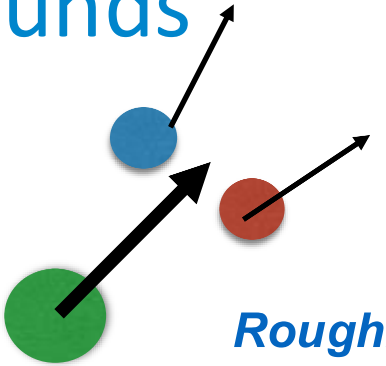


[F. Wang, arXiv:0911.1482]

[S. Pratt, arXiv:1002.1758]

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

Battling the 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

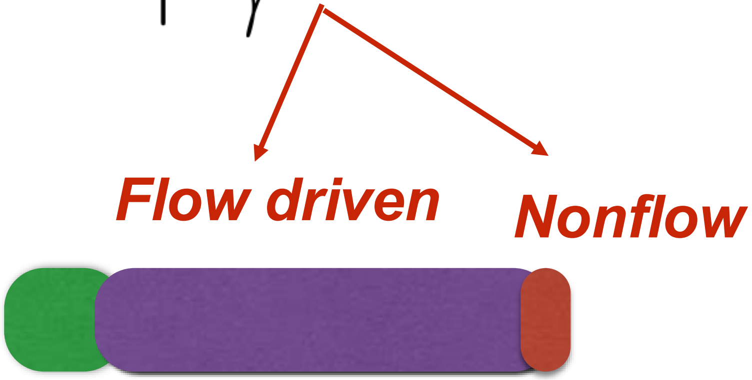
We are not alone!
Think about many other difficult searches, e.g. for Higgs, gravitational wave, temperature fluctuations of CMB, EDM, WIMP, 2-beta decay, …

Battling the Backgrounds

- *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!

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



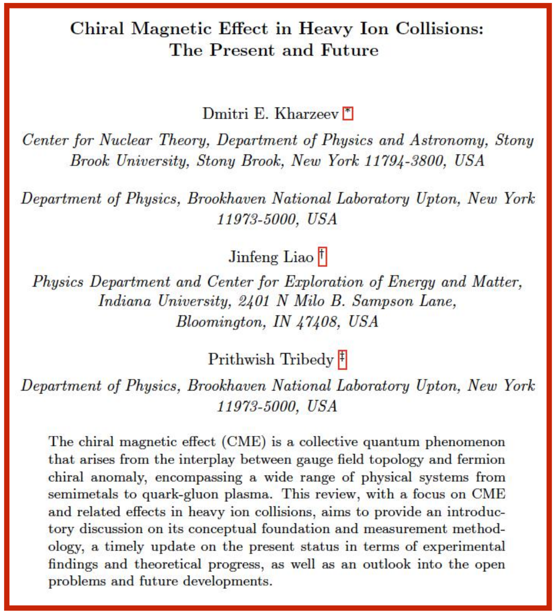
Flow driven

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 (~2024)?



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

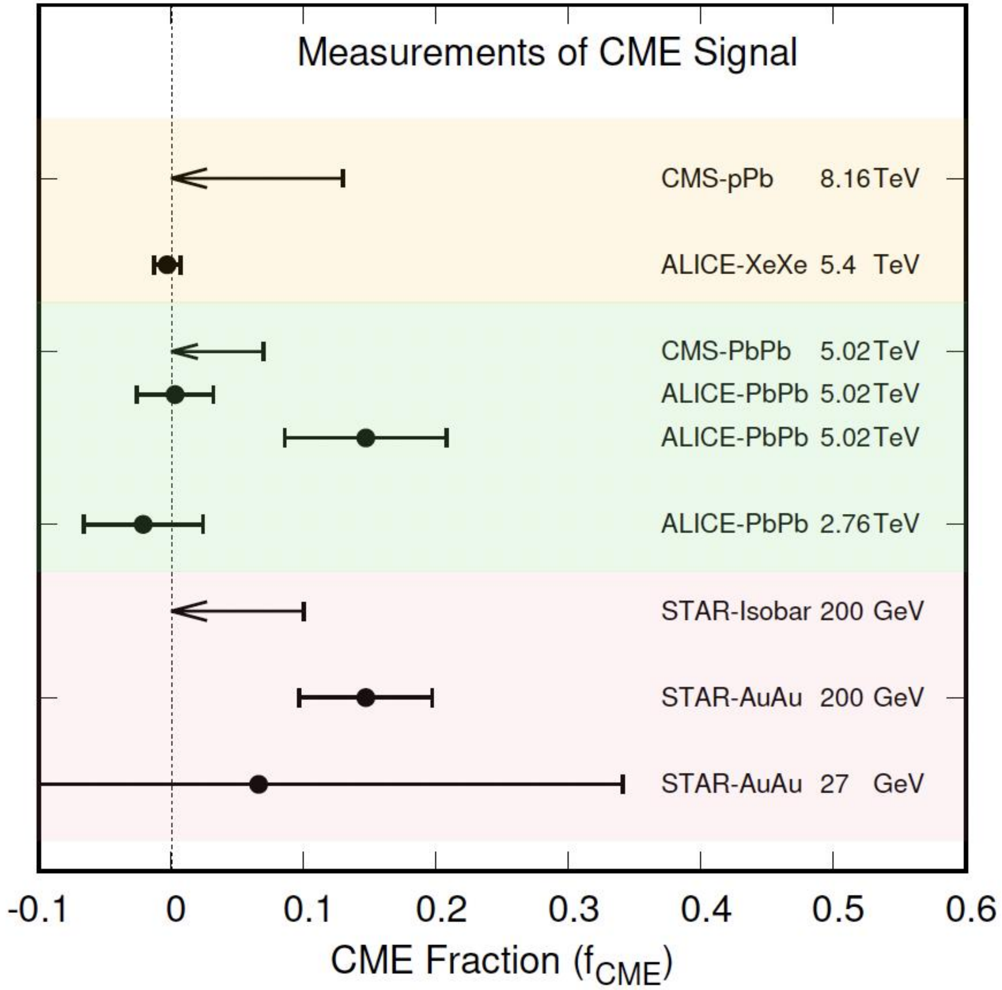
Jinfeng Liao[†]

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.



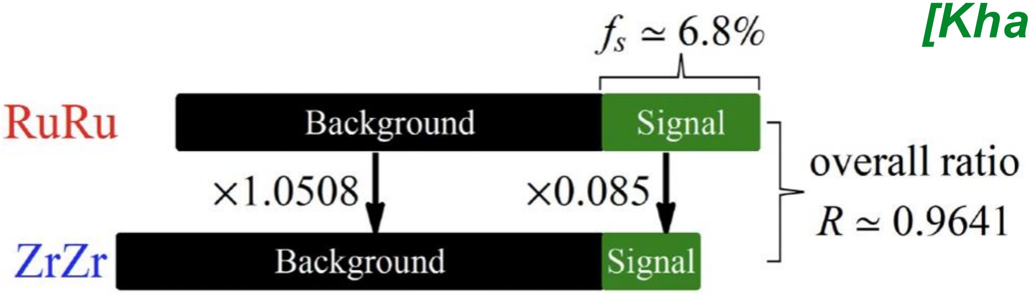
[~130pages; arXiv:2405.05427 (Int.J.Mod.Phys.E 33 (2024) 09, 2430007) (QGP6)]

20 years of hunting CME, hundreds of experimental publications —> encouraging hints at RHIC energies, especially lower energies.

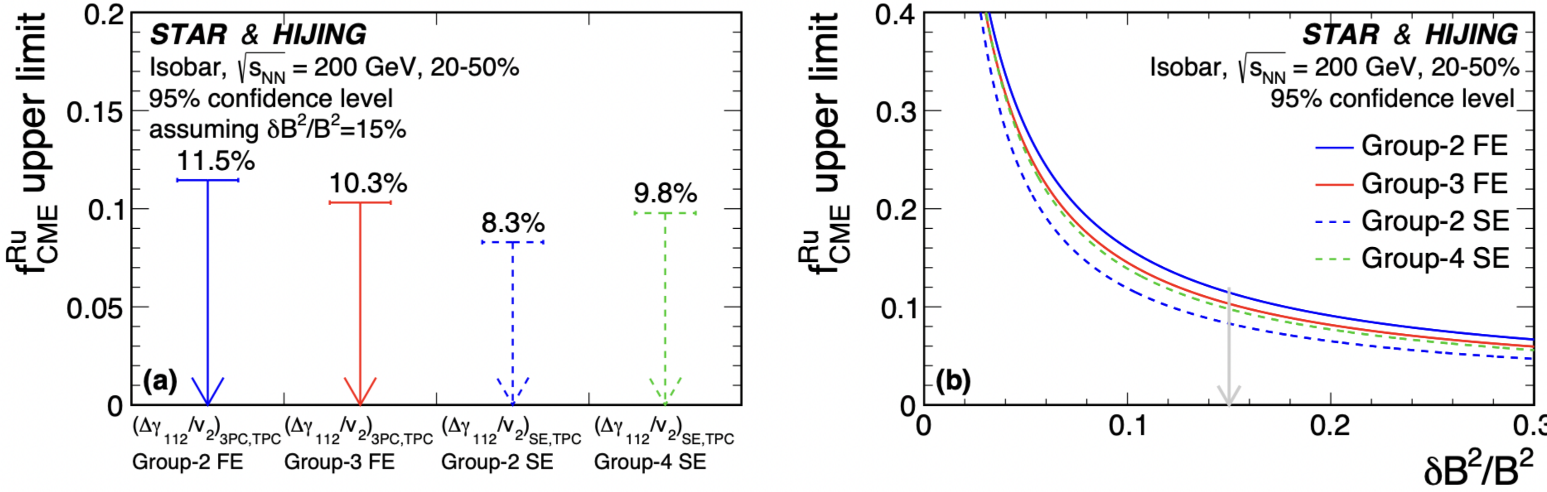
Isobar Collisions

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

[Khazeev, JL, Shi, arXiv:2205.00120]

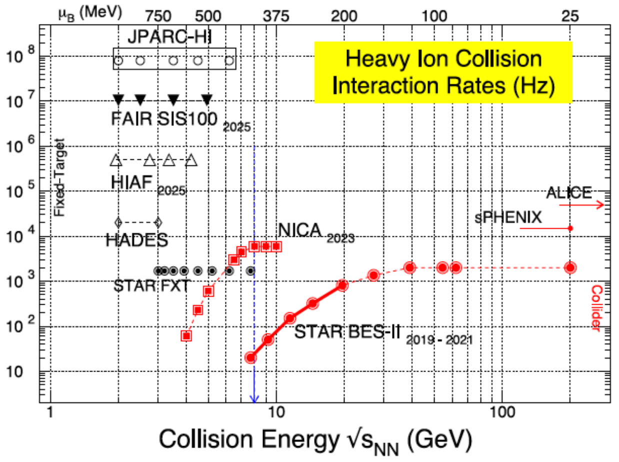


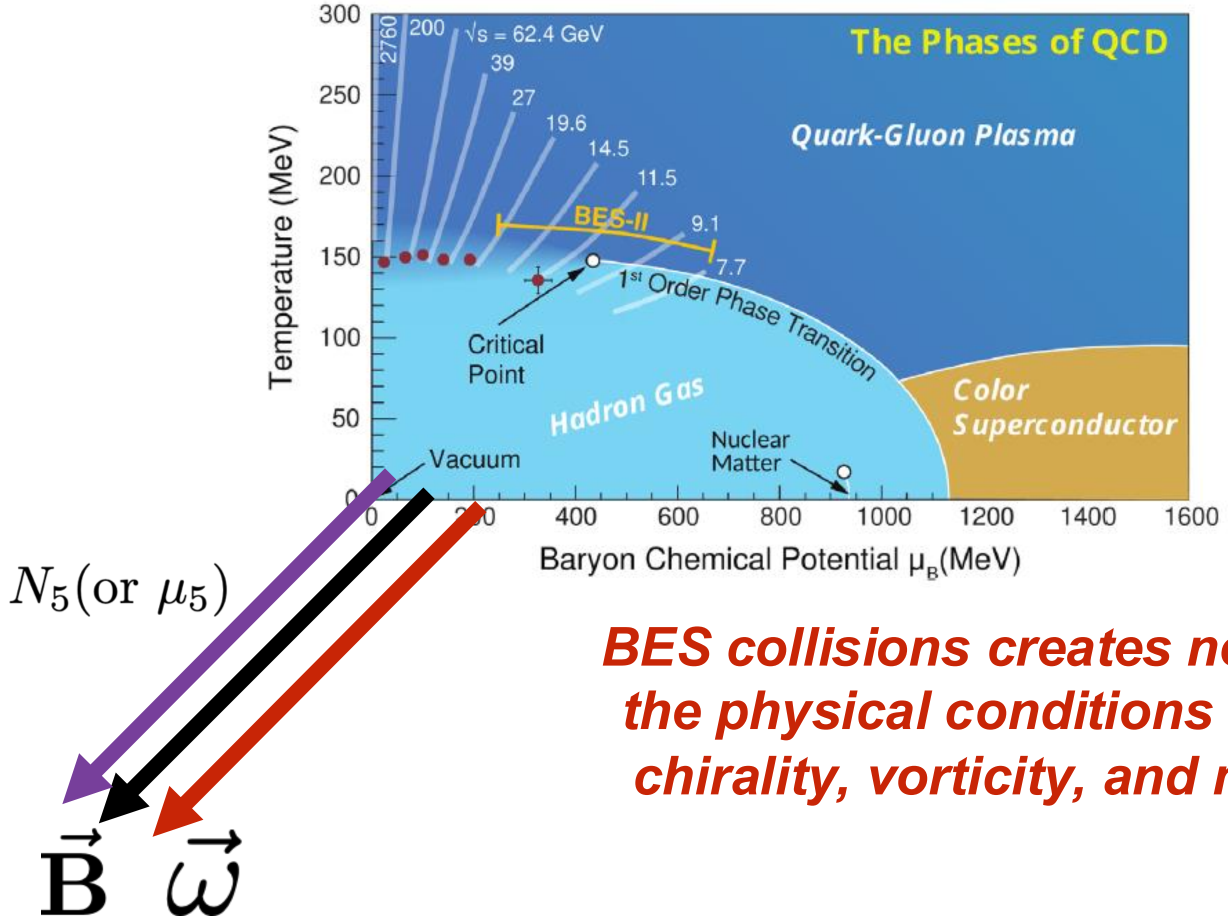
[STAR, arXiv:2310.13096;2308.16846]



- *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 (BES) Programs





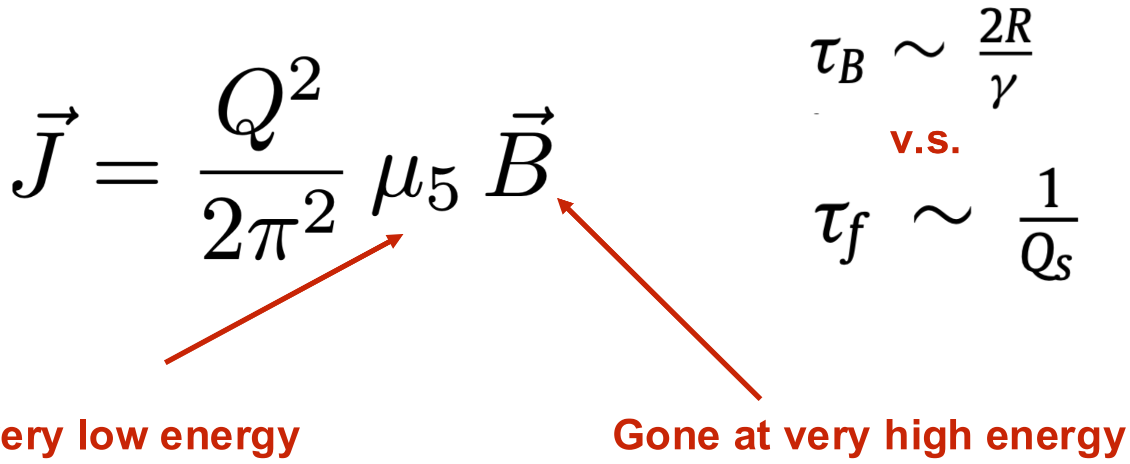
BES collisions creates nontrivial shifts in the physical conditions associated with chirality, vorticity, and magnetic fields.

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

Beam Energy Dependence of Chiral Transport

5.4. The beam energy dependence of anomalous chiral transport

In this last subsection, we discuss how the anomalous chiral transport may vary with the collision energy, which is an important question for the BES experimental program. The answer relies upon a number of key ingredients, to be discussed below.



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

$$\tau_B \sim \frac{2R}{\gamma}$$

v.s.

$$\tau_f \sim \frac{1}{Q_s}$$

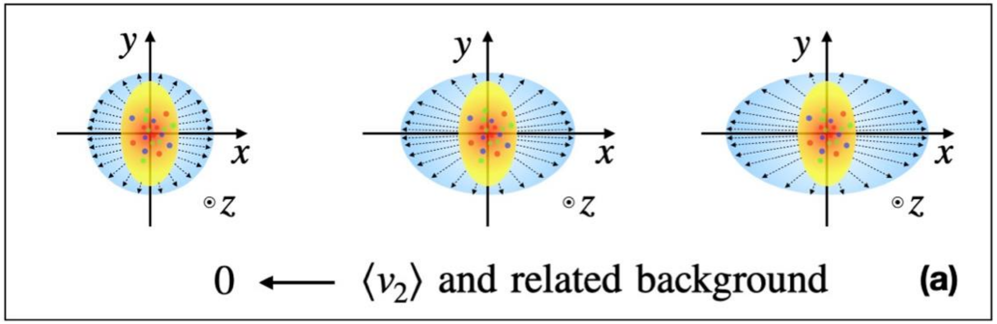
Gone at very low energy

Gone at very high energy

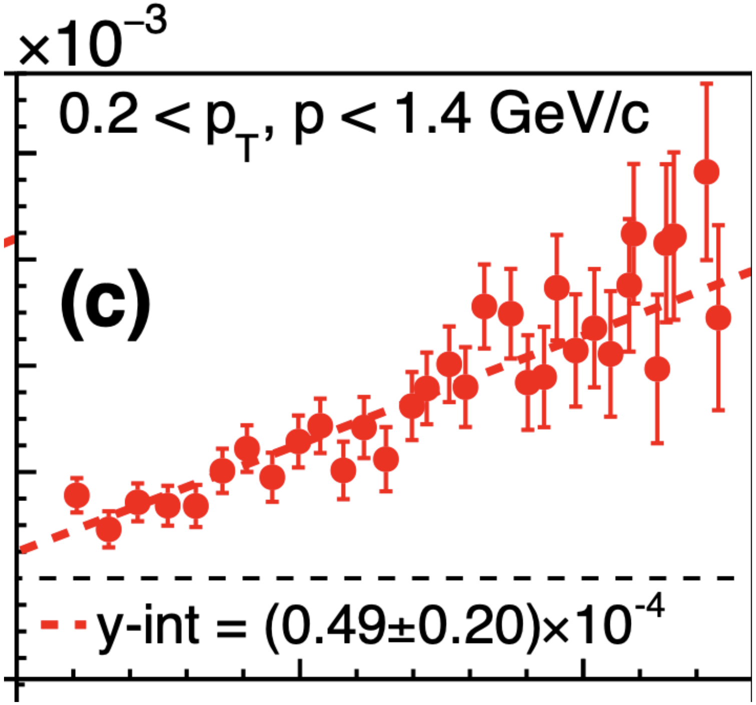
To conclude this brief discussion, it is quite plausible that potential signals from anomalous chiral transport effects would have nontrivial dependence on the collision beam energy, possibly disappearing in collisions both at very low energy end (e.g. below $\sim \hat{O}(10)\,\mathrm{GeV}$) and at very high energy end (e.g. beyond $\sim \hat{O}(1)\,\mathrm{TeV}$). From the estimate above, it appears quite likely that the optimal beam energy window may be in the range of $\hat{O}(10 \sim 100)\,\mathrm{GeV}$. Due to this non-monotonic trend, the beam energy scan program at RHIC provides the unique opportunity to look for the signals from anomalous chiral transport. In fact, such a pattern of beam energy dependence could in itself be considered as a characteristic signature for the search of such effects.

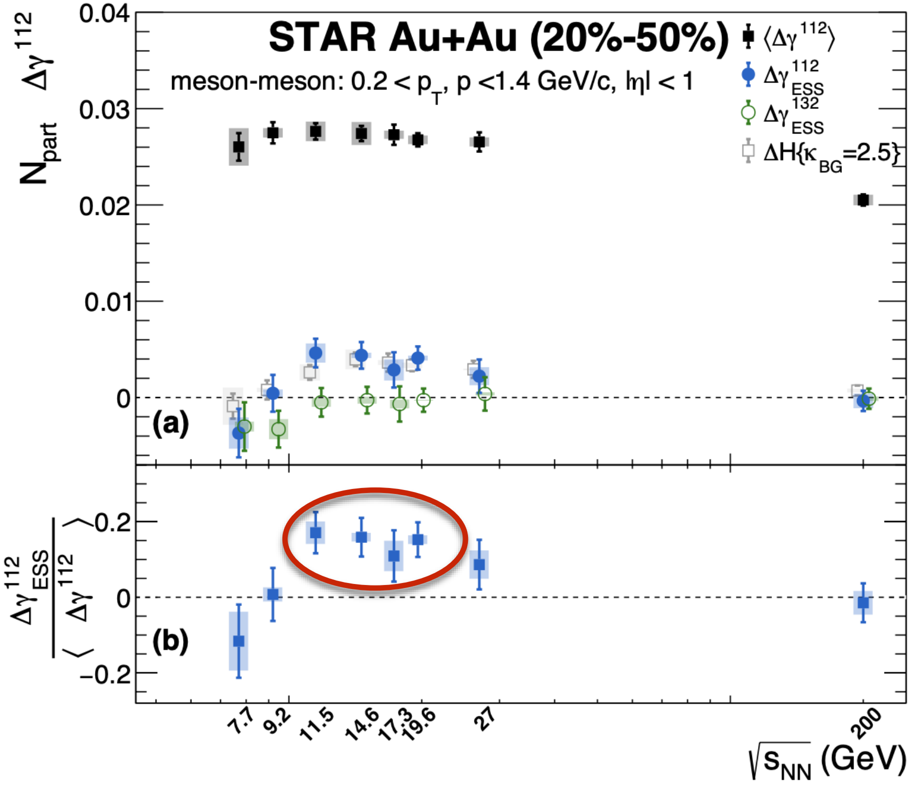
"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87.

Beam-Energy-Scan-II: STAR2025

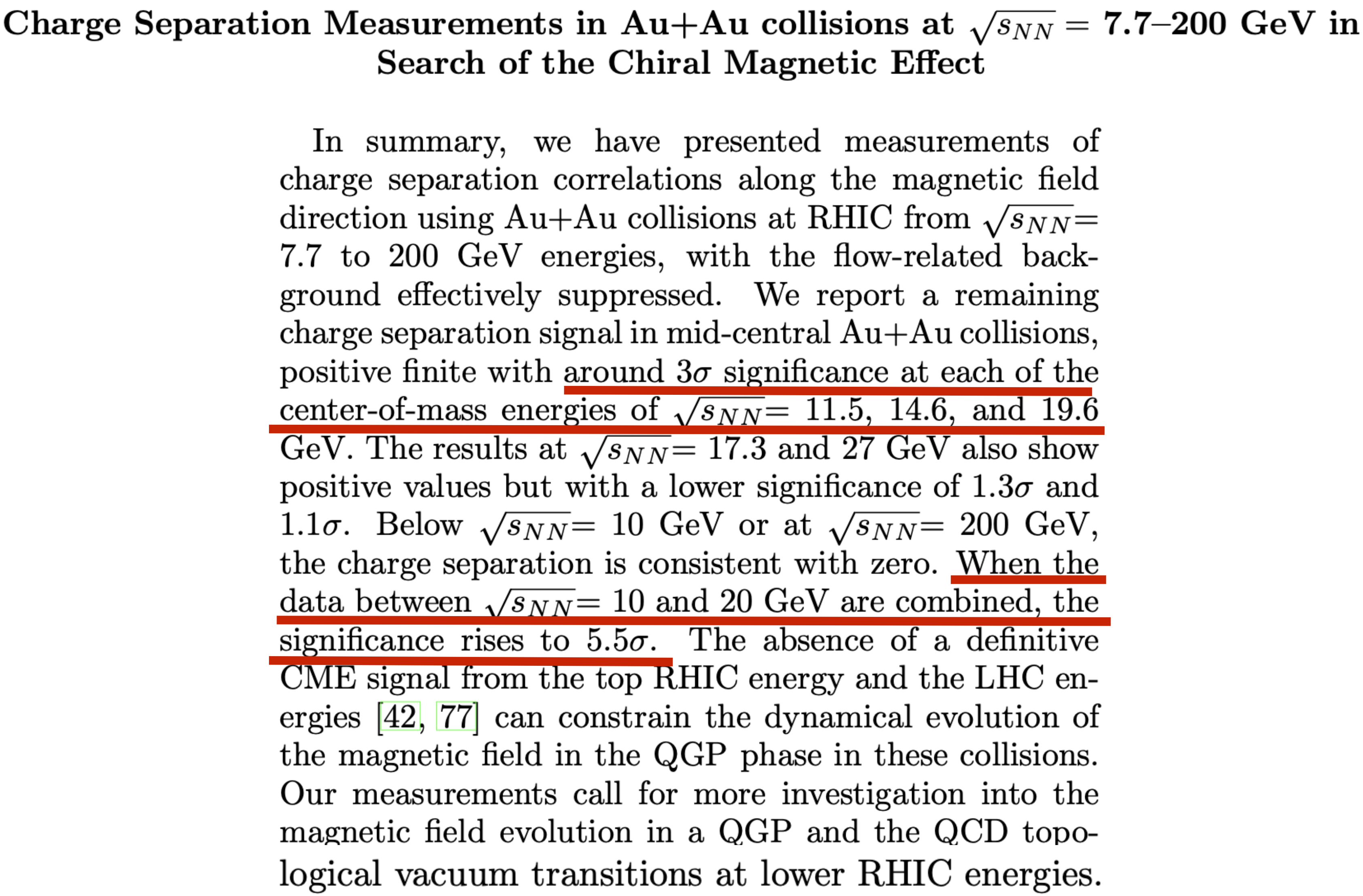


STAR Collaboration:
2506.00275;
2506.00278





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 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.***

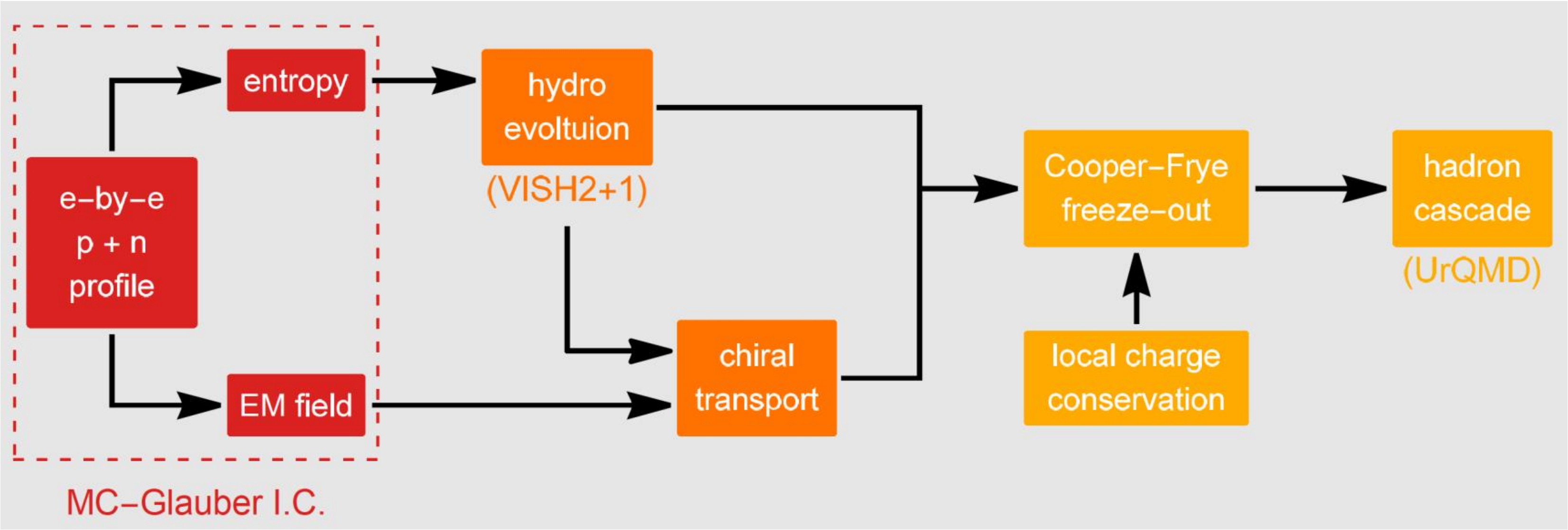
- ***Can we "bypass" this problem and take an "unbiased" look at the exp data?***

- ***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!

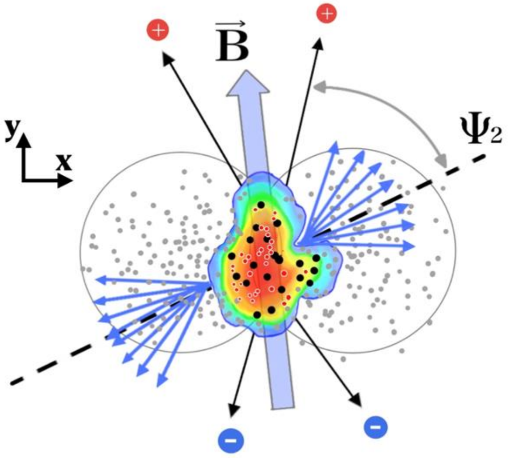
EBE-AVFD:
event-by-event anomalous-viscous fluid dynamics

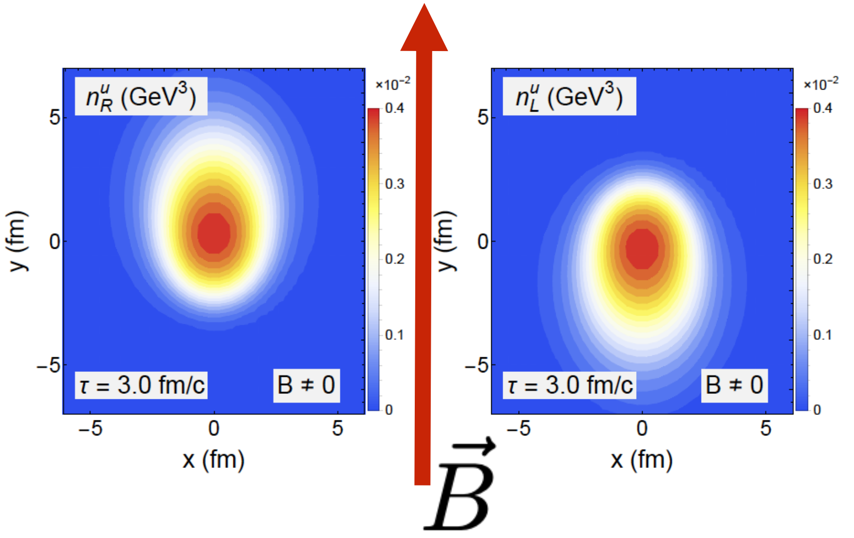


[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

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

Hydrodynamic Realization of CME in HIC





From cartoon to quantitative physics

Chirality transport

—>

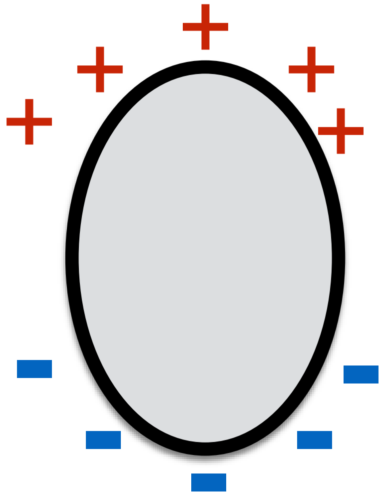
R/L asymmetry

—>

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, v2, net proton, …)

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

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

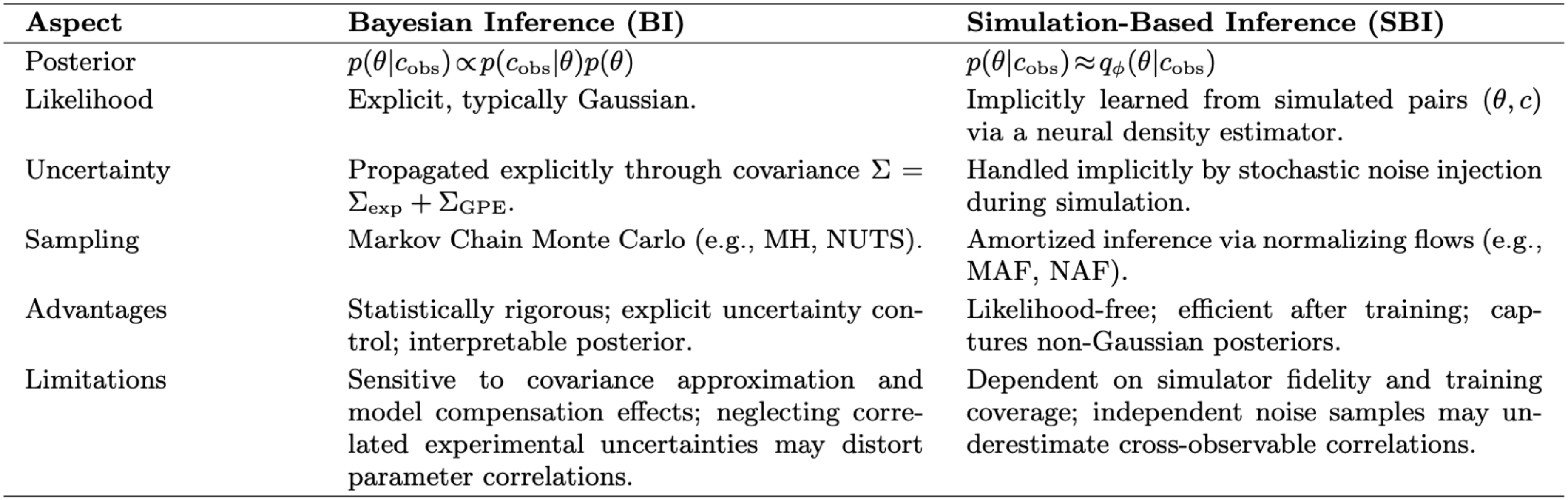
— Gaussian Process Emulator (GPE)

— 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

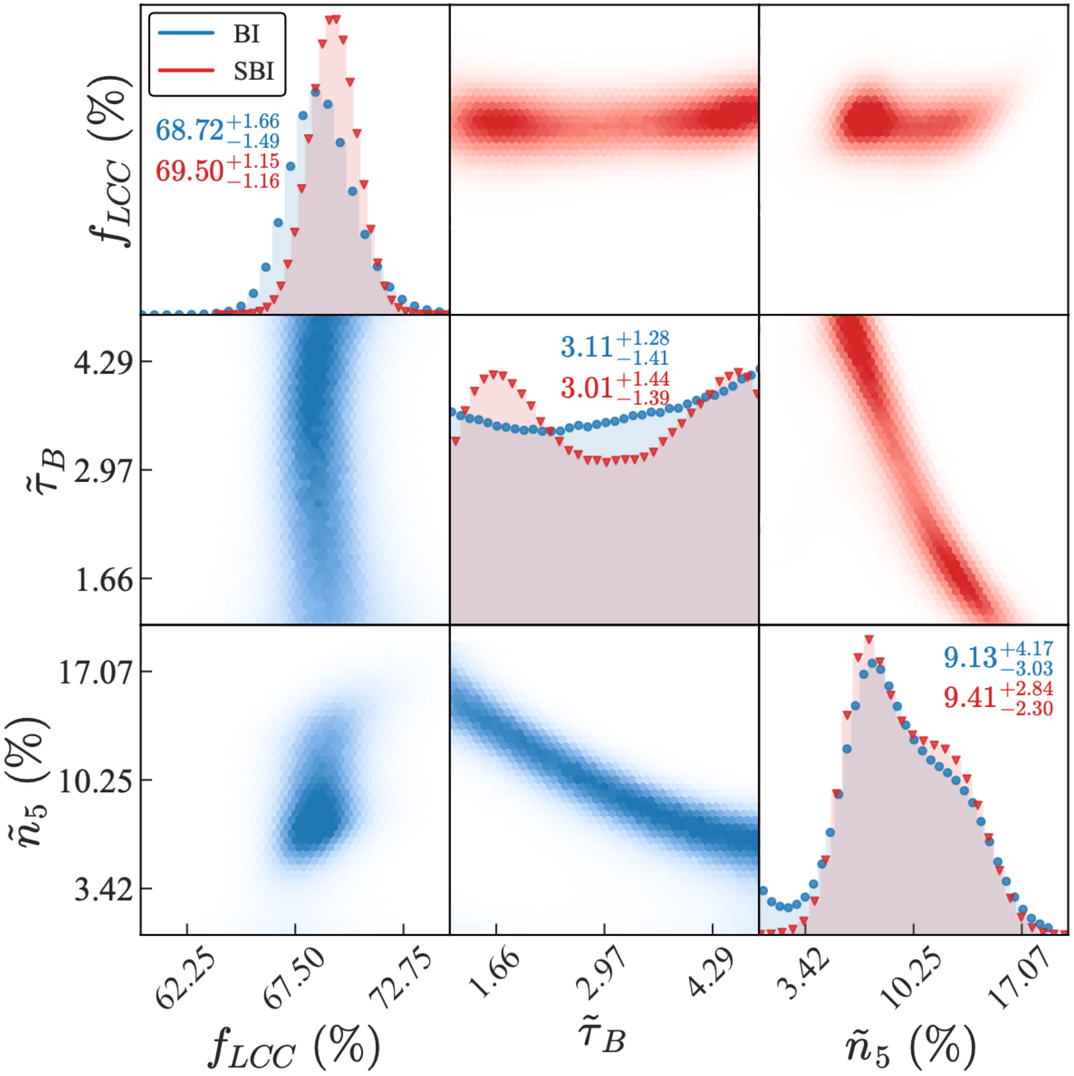


Aspect	Bayesian Inference (BI)	Simulation-Based Inference (SBI)
Posterior	$p(\theta\|c_{\mathrm{obs}}) \propto p(c_{\mathrm{obs}}\|\theta)p(\theta)$	$p(\theta\|c_{\mathrm{obs}}) \approx q_{\phi}(\theta\|c_{\mathrm{obs}})$
Likelihood	Explicit, typically Gaussian.	Implicitly learned from simulated pairs (θ, c) via a neural density estimator.
Uncertainty	Propagated explicitly through covariance $\Sigma = \Sigma_{\mathrm{exp}} + \Sigma_{\mathrm{GPE}}$.	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.

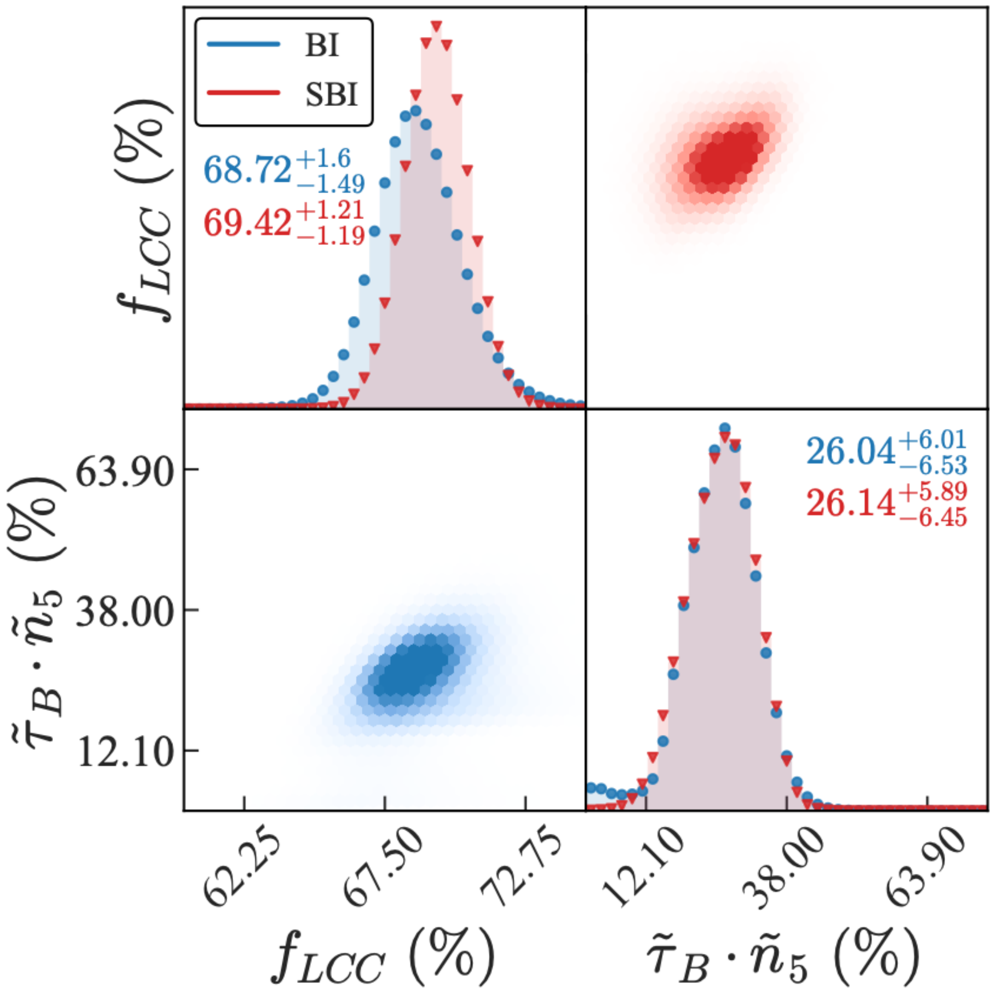
A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

Posterior Distributions



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

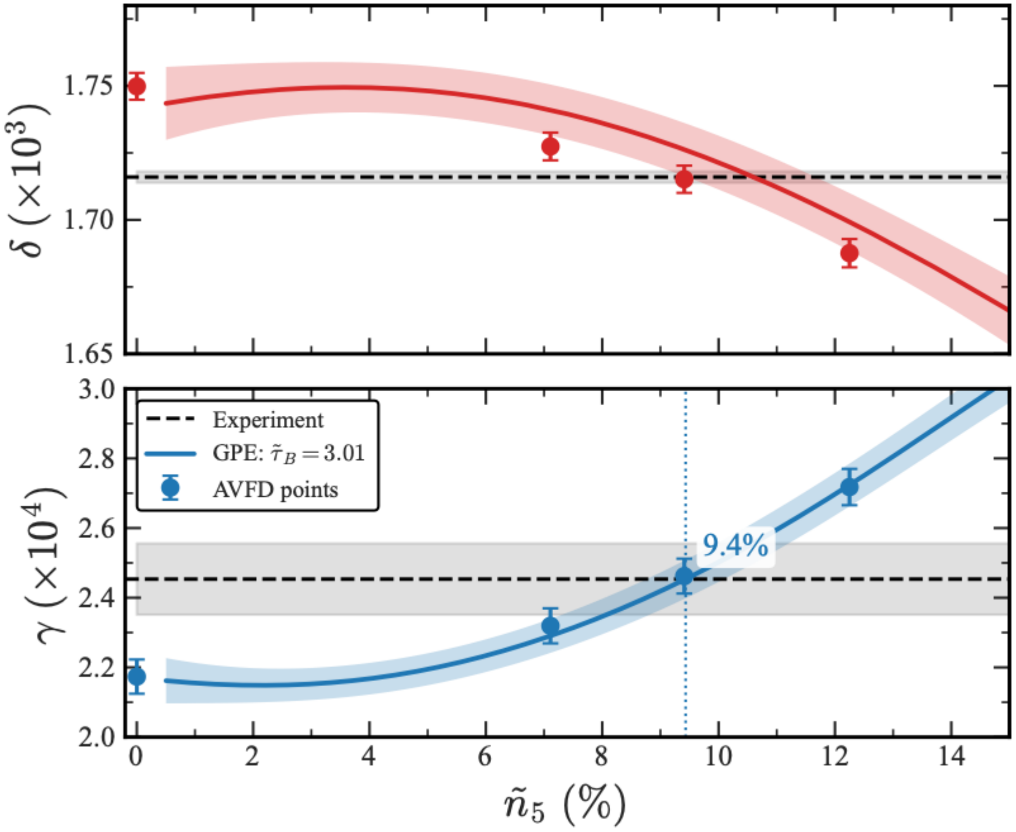
Posterior Distributions



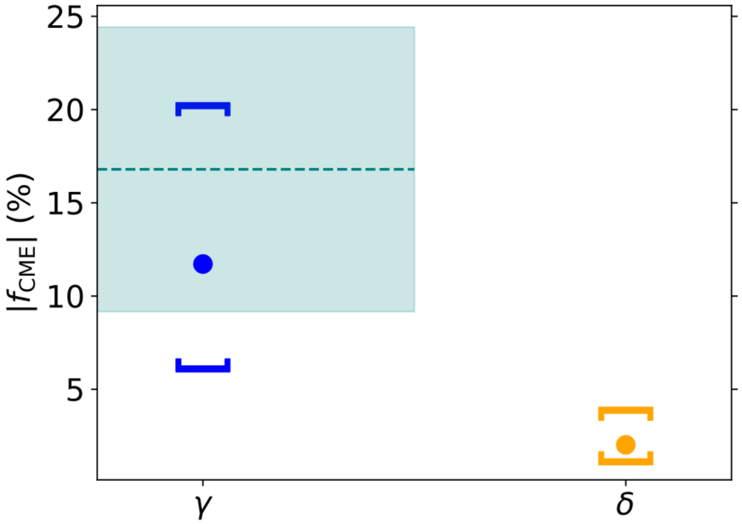
robust and unambiguous evidence for CME transport

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

Posterior Validations

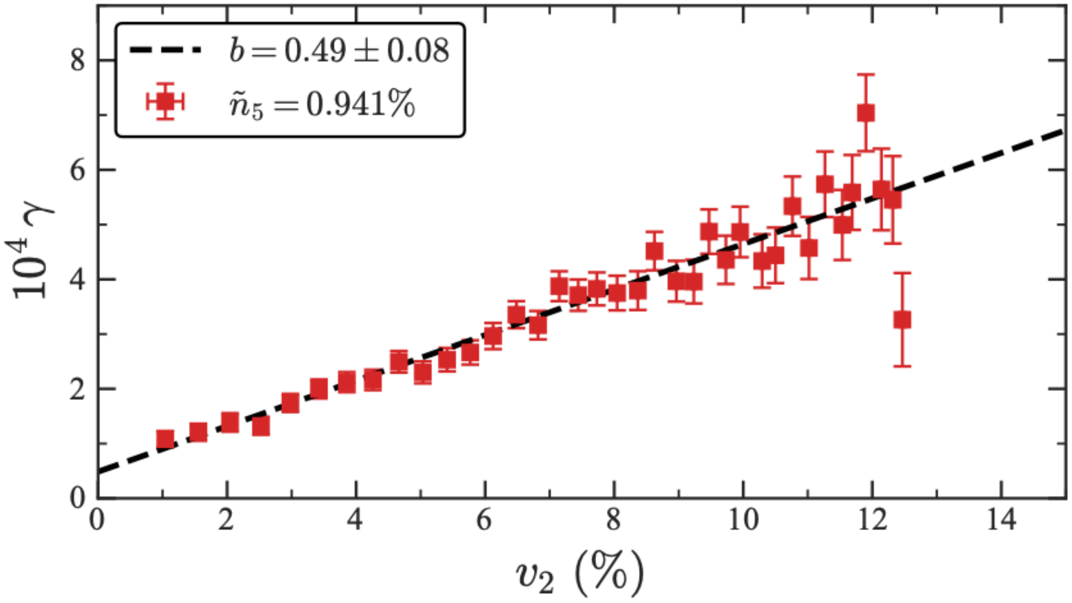


Excellent description of experimental data!



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

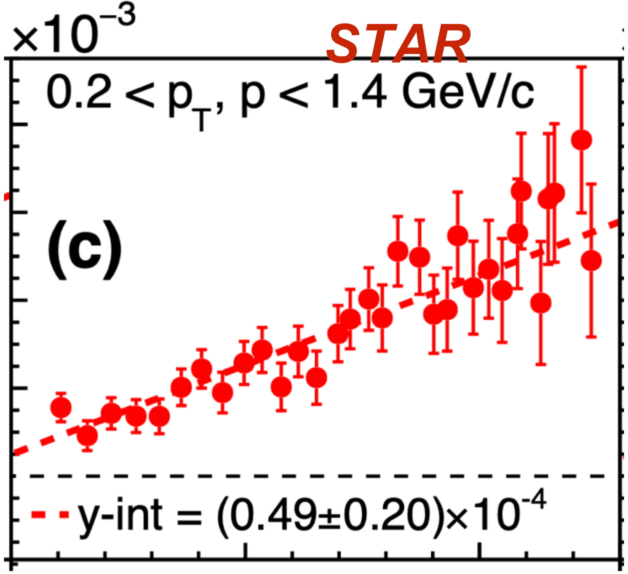
Posterior Validations



From our analysis

Excellent description of experimental data!

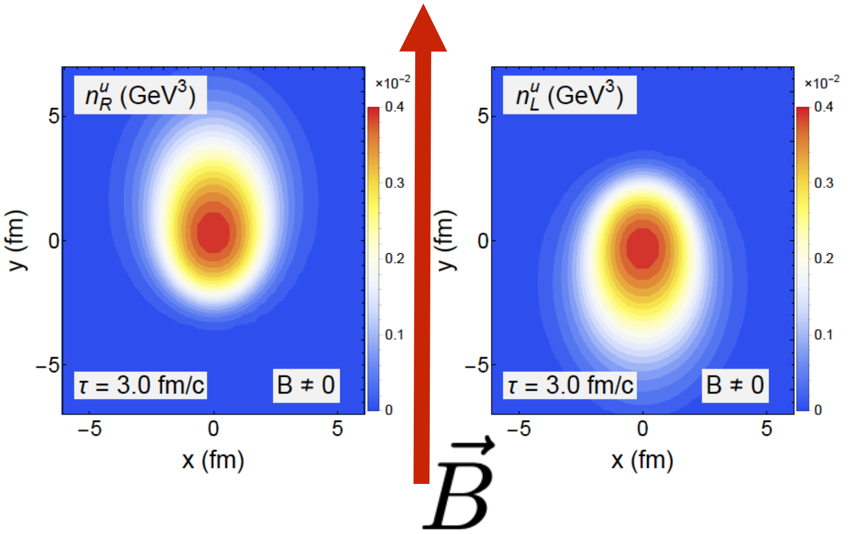
From STAR

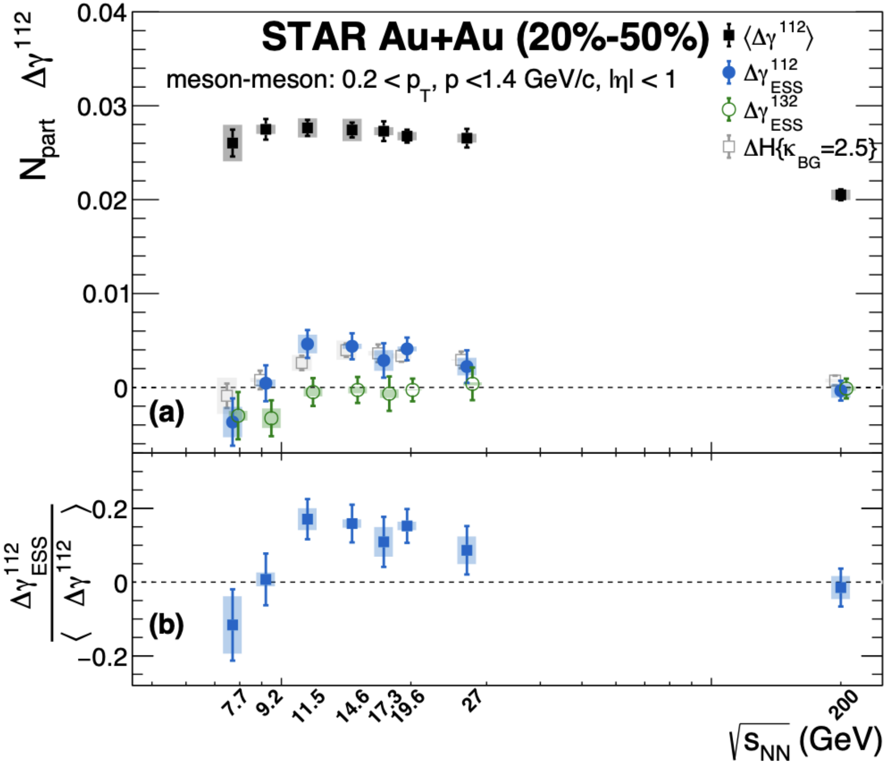


A. Akridge, Y. Guo, JL, S. Shi, H. Xing, H. Zhang: in preparation.

The Beam Energy Dependence

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





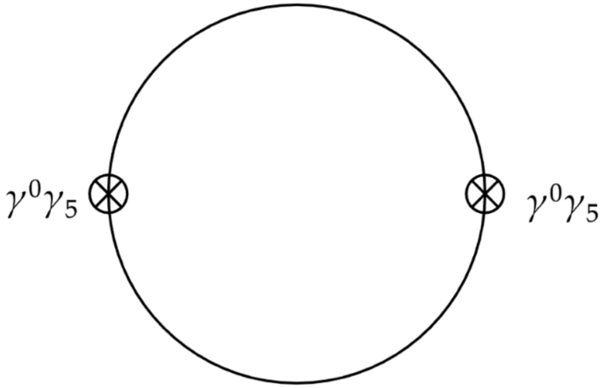
Longer magnetic field lifetime

Enhanced fluctuations of axial charges near phase boundary

Shorter fireball evolution

Axial Charge Dynamics

On the theoretical side, it is important to understand the "turnoff" at very low beam energy
—> analyze the axial charge dynamics across phase boundary



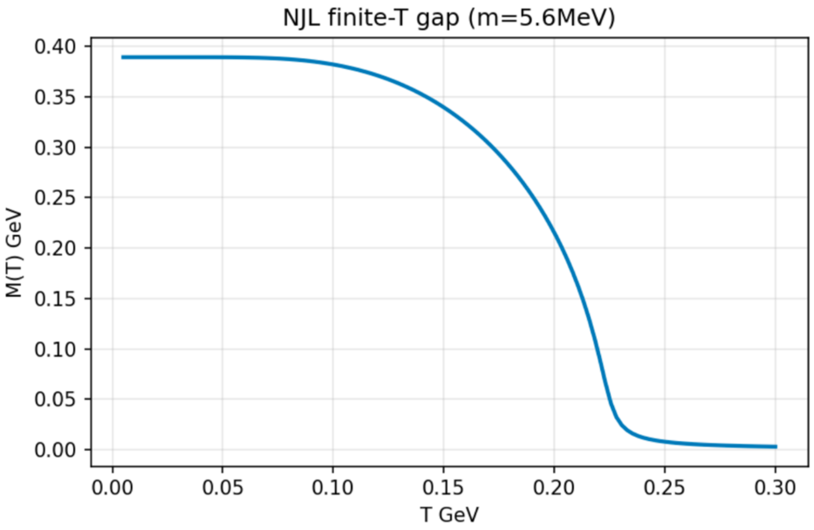
$$\langle N_5(t_2)N_5(t_1)\rangle = \int d^3\vec{x}\,\langle\left[\bar{\psi}\gamma^0\gamma_5\psi\right](t_2,x)\left[\bar{\psi}\gamma^0\gamma_5\psi\right](t_1,0)\rangle = \int dq_0 e^{iq_0(t_2-t_1)}\Pi^{>,00}(q_0)$$

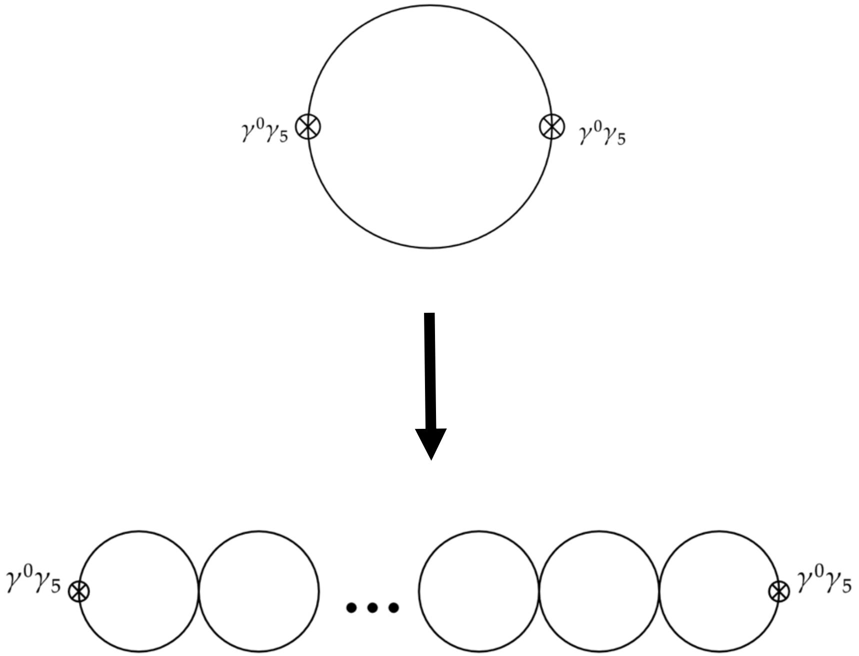
$$\langle\Delta N_5^2\rangle = \langle N_5(t)N_5(t)\rangle - \langle N_5(t)N_5(0)\rangle - \langle N_5(0)N_5(t)\rangle + \langle N_5(0)N_5(0)\rangle$$

D. Hou and S. Lin, Phys.Rev.D 98 (2018) 5, 054014

Axial Charge Dynamics near Chiral Transition

We use a chiral effective model, NJL model, to do this computation.



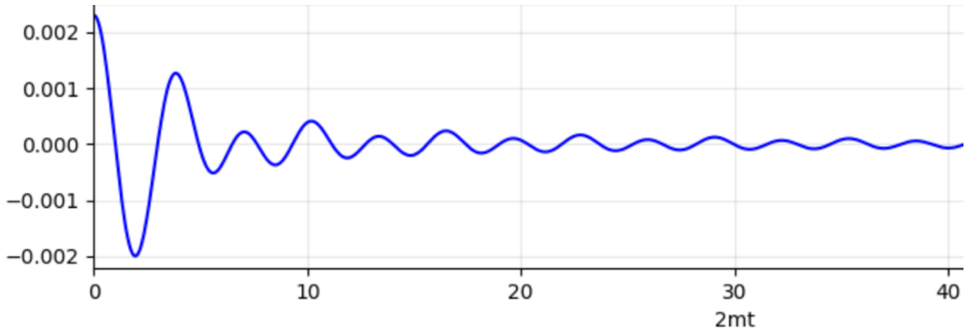


Scan temperatures across the chiral transition

RPA summations to go beyond mean field approx.

D. Hou, JL, S. Lin, J. Tian: in preparation.

Axial Charge Dynamics near Chiral Transition

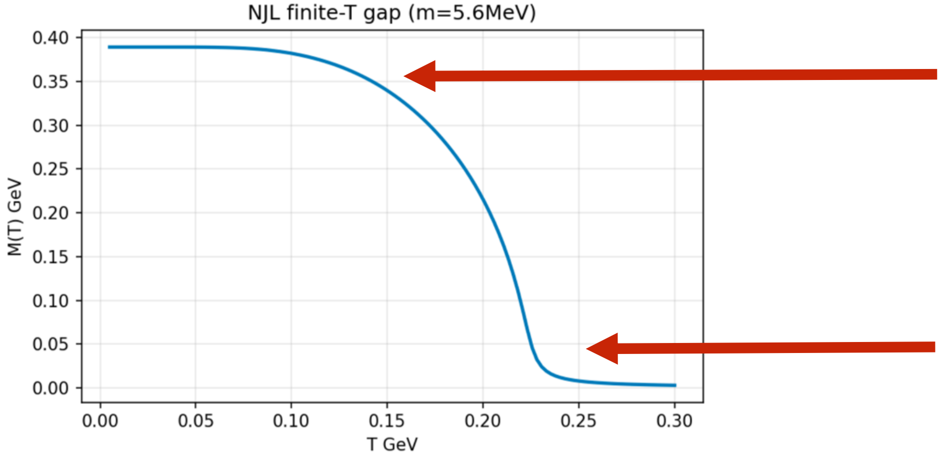


The oscillatory behavior could be analytically understood with some approximations

$$\simeq \frac{\#\cdot e^{i2mt}}{(mt)^{3/2}} + \frac{\#\cdot e^{iQ_\Lambda t}}{(Q_\Lambda t)}$$

Time scale controlled by 1/m

Decay ~ 1 / t^(3/2)



Low energy: large mass; quick decay of axial charge

High energy: small mass; slow decay of axial charge

D. Hou, JL, S. Lin, J. Tian: in preparation.

Summary

- *Chiral Magnetic Effect offers a unique pathway to access fundamental aspects of QCD: chirality, anomaly, topology, and chiral symmetry restoration.*

- *The search for CME in heavy ion collisions is ongoing, with potentially significant signals in the 10~20GeV collisions.*

- *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.*

- *Theoretical calculations of axial charge dynamics suggest the fast decay of axial charge due to large mass after chiral symmetry breaking, and thus the turnoff of anomalous transport at very low energies.*