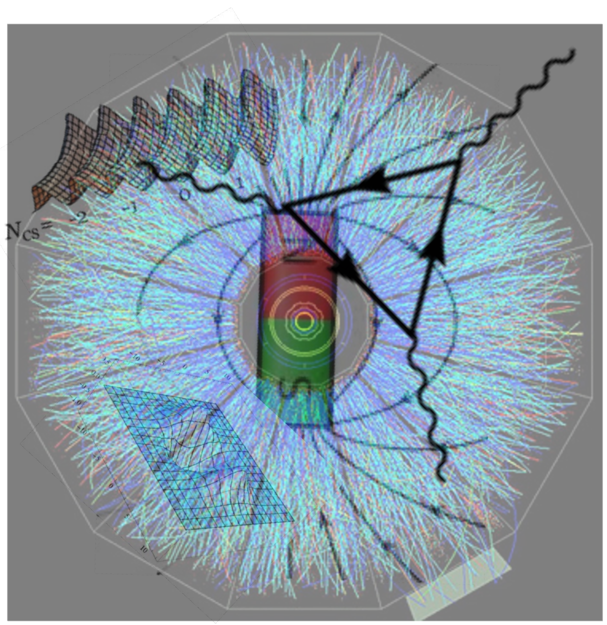
26th International Symposium on Spin Physics
A Century of Spin

Sep 2025, Qingdao

Chiral Magnetic Effect



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

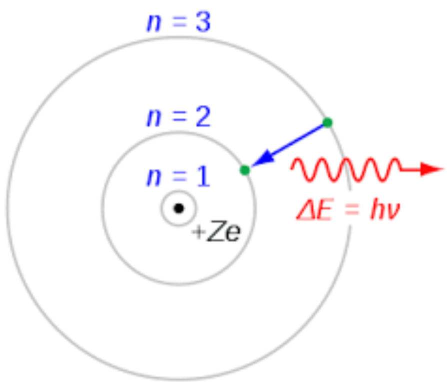
Plan of the Talk

- ***Spin and Chirality***
- ***Chiral Magnetic Effect: What and Why***
- ***The Search for Chiral Magnetic Effect***
- ***Summary & Outlook***

SPIN and Chirality

Spin: “Classically Indescribable Two-valued-ness”

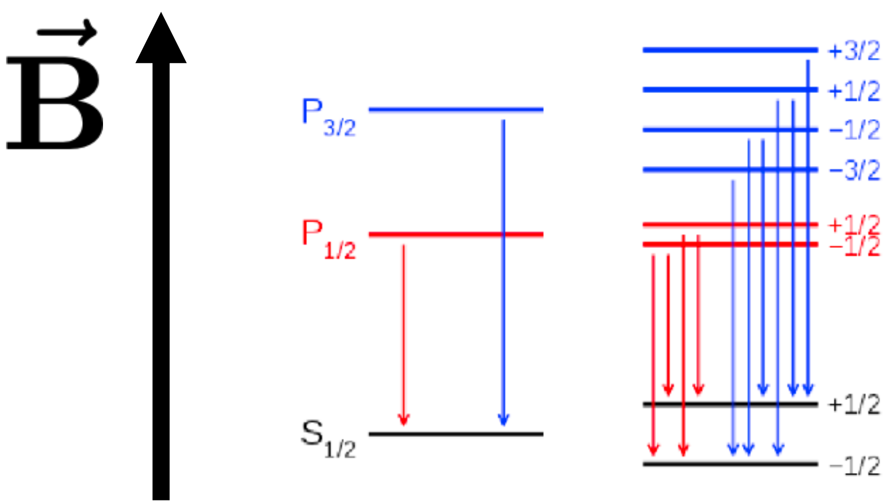
Hydrogen (& alkali atoms)
[Bohr; Sommerfeld, Lande,Pauli,…]



(n, l, m)

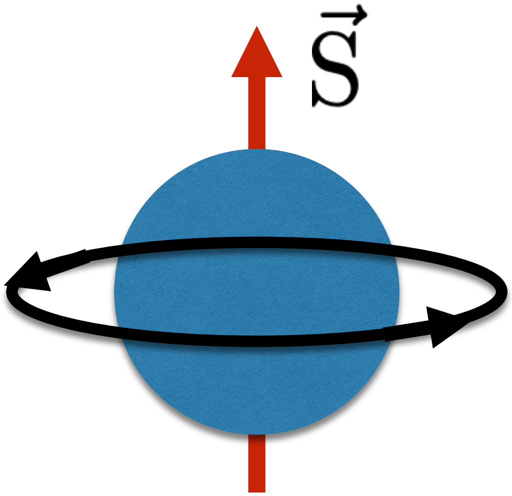
Pauli, 1923~1924:
(n, l, m, <u>s</u>)
Exclusion principle
—> <u>2</u> * (2*l +1)

Electron orbits in magnetic field:
Zeeman effect & Paschen-Back effect



Spin as Self-Rotation?

The two-valued-ness has features related to angular momentum and magnetic moment



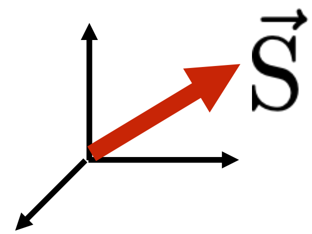
Kronig; Uhlenbeck-Goudsmit (~1925): Self-rotation?

$$S = \frac{\hbar}{2} = \frac{2}{5} M_e R (R\omega) = \frac{2}{5} M_e R \, v_R$$

However, it would not work classically… (Lorentz; Pauli; …)

Pauli's quantum description: "rotation" in internal/intrinsic space

$$\psi(x) \to \psi(x) \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

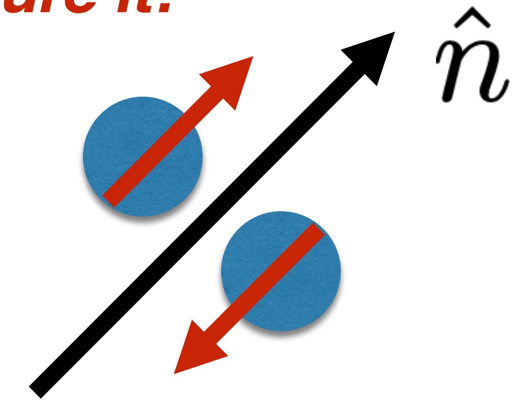


$$\hat{\mathbf{S}} = \frac{\hbar}{2} \boldsymbol{\sigma} = \frac{\hbar}{2} \left(\sigma_1 \, \mathbf{i} + \sigma_2 \, \mathbf{j} + \sigma_3 \, \mathbf{k} \right)$$

Spin Polarization

Spin is in any direction, until you measure it!

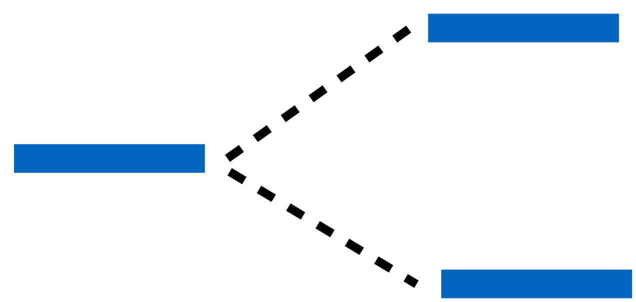
$$\hat{\mathbf{S}} \cdot \hat{\mathbf{n}} = \frac{\hbar}{2} \begin{pmatrix} \cos\theta & \sin\theta\, e^{-i\phi} \\ \sin\theta\, e^{+i\phi} & -\cos\theta \end{pmatrix}$$



An example: electron in an external magnetic field

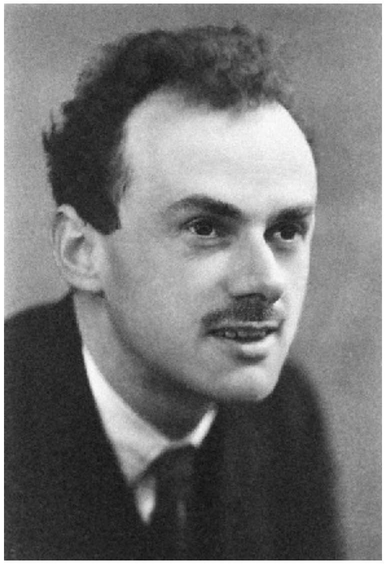
$$\boldsymbol{\mu}_s = \frac{g_s q \hbar}{2m} \frac{\mathbf{S}}{\hbar}$$ ***Magnetic moment***

$$\hat{H}_I = -\mathrm{B} \cdot \boldsymbol{\mu}_s = \left(-\frac{g_s q \hbar}{4m} \right) \mathrm{B} \cdot \boldsymbol{\sigma}$$



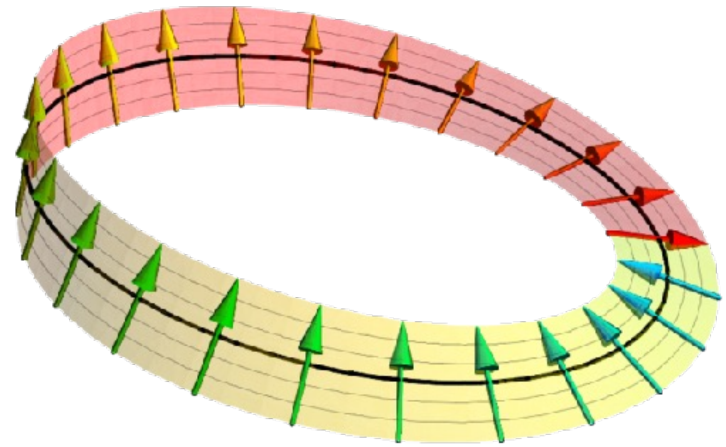
Magnetization energy—> atomic level splitting; Pauli paramagnetism; Landau levels; ……

Dirac Theory: from Spin to Spinor



Dirac theory for a spin-1/2 fermion, or a spinor

$$\psi \Rightarrow \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$



$$\mathcal{L} = \bar{\Psi}\left[i\gamma^\mu \partial_\mu - m\right]\Psi$$

$$\left[i\gamma^\mu \partial_\mu - m\right]\Psi = 0$$

Only (orbital + spin) is conserved.

Their separation becomes subtle.

$$\mathbf{J} = \mathbf{L} + \tfrac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\Sigma}$$

Adding EM coupling & taking NR limit

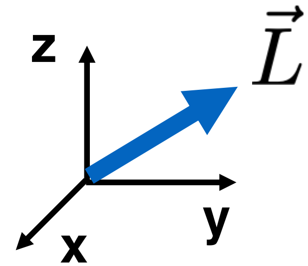
$$\partial_\mu \rightarrow \partial_\mu - ieA_\mu$$

$$\hat{H}_I = -\mathrm{B}\cdot\boldsymbol{\mu}_s = \left(-\frac{g_s q\hbar}{4m}\right)\mathrm{B}\cdot\boldsymbol{\sigma}$$

$$g_s = 2 \quad !$$

Nature of Spinor: Lorentz Symmetry

Orbital angular momentum:
SO(3) rotational symmetry of space



Special relativity: Lorentz symmetry of space & time

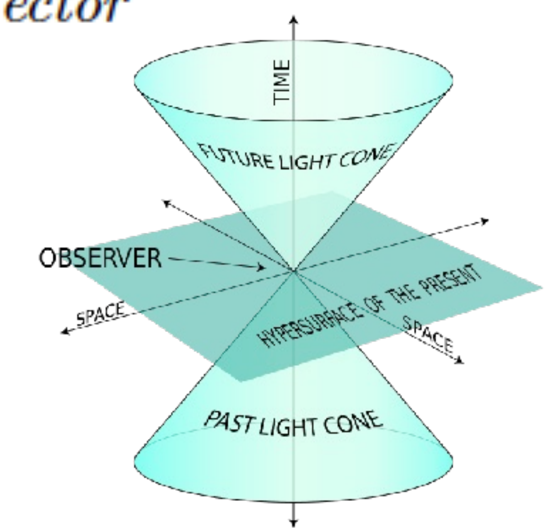
$$[J_i, J_j] = +i\varepsilon_{ijk}J_k \ ,$$
$$[J_i, K_j] = +i\varepsilon_{ijk}K_k \ ,$$
$$[K_i, K_j] = -i\varepsilon_{ijk}J_k \ .$$

$(1,1) = Scalar \text{ or } singlet$

$(2,1) = Left\text{-}handed \ spinor$

$(1,2) = Right\text{-}handed \ spinor$

$(2,2) = Vector$



One can no longer single out the spatial rotation or spin.

A Dirac spinor (4 dofs)
= A left-handed Weyl spinor (2 dofs)
+ A right-handed Weyl spinor (2 dofs)

Chirality / Handedness

Massless fermions: chiral symmetry

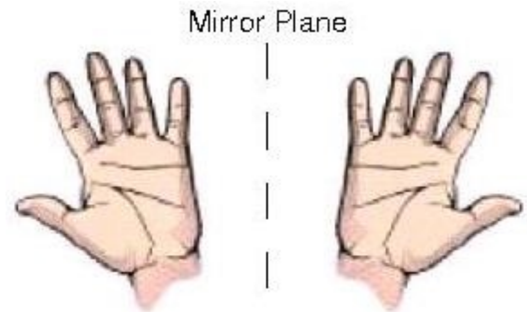
$$\mathcal{L} = i\bar{\Psi}\gamma^{\mu}\partial_{\mu}\Psi$$

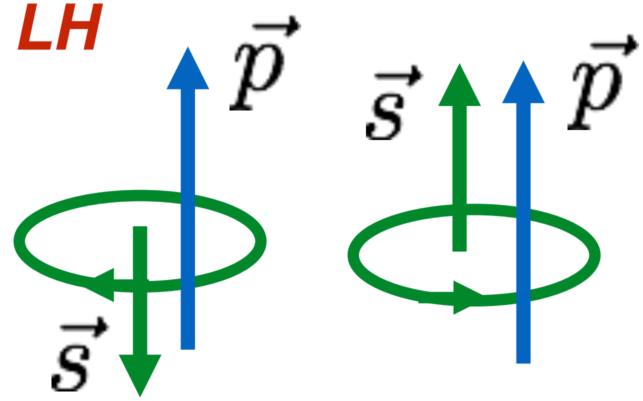
$$\Lambda_A : \Psi \rightarrow e^{i\gamma_5\theta}\Psi$$

$$\partial_{\mu}J_5^{\mu} = 0$$

$$\mathcal{L} \rightarrow i\bar{\Psi}_L\gamma^{\mu}\partial_{\mu}\Psi_L + i\bar{\Psi}_R\gamma^{\mu}\partial_{\mu}\Psi_R$$

—> LH & RH sectors

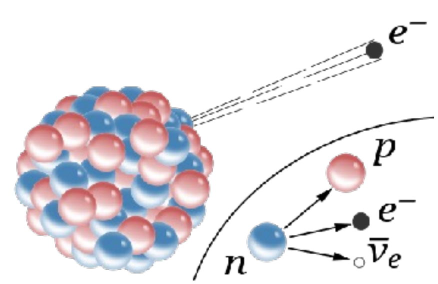




Chirality Polarization

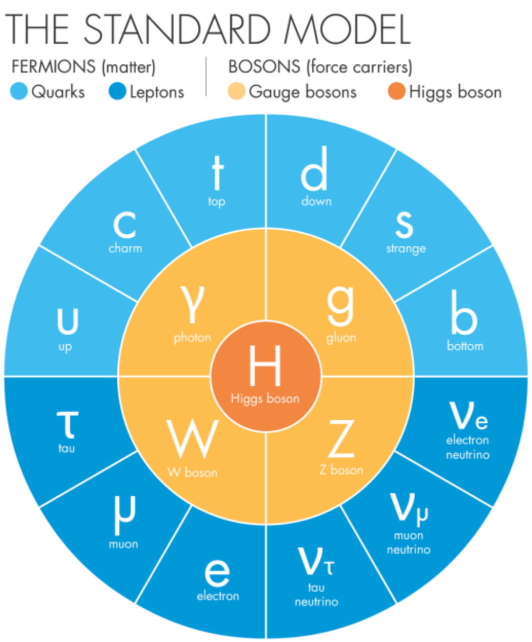
For massless fermions: chirality <—> helicity

A prime example: neutrinos & parity violation in weak interaction



Chirality as a Fundamental Feature

Chirality plays a fundamental role in the construction of the Standard Model.



All matter particles start as massless chiral fermions before symmetry breaking via Higgs mechanism.

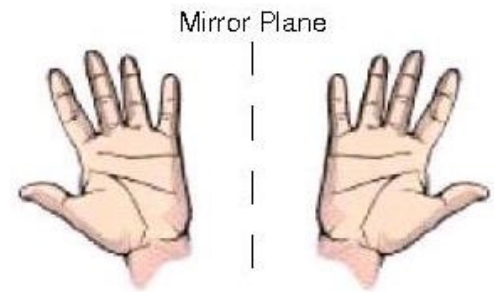
Electroweak interactions are chiral.

Strong interactions preserve chirality.

Chirality is conceptually very important. However, it is not directly measurable. Access to chirality often relies on spin.

Chiral Magnetic Effect (CME)

Chirality in QCD



Dirac fermion in massless limit:

$$\mathcal{L} \to \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R$$

Vector and axial/chiral symmetries

A (large) mass term spoils all of that:

$$m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L\right) \qquad \partial_\mu J_5^\mu = 2im\bar{\Psi}\gamma^5\Psi$$

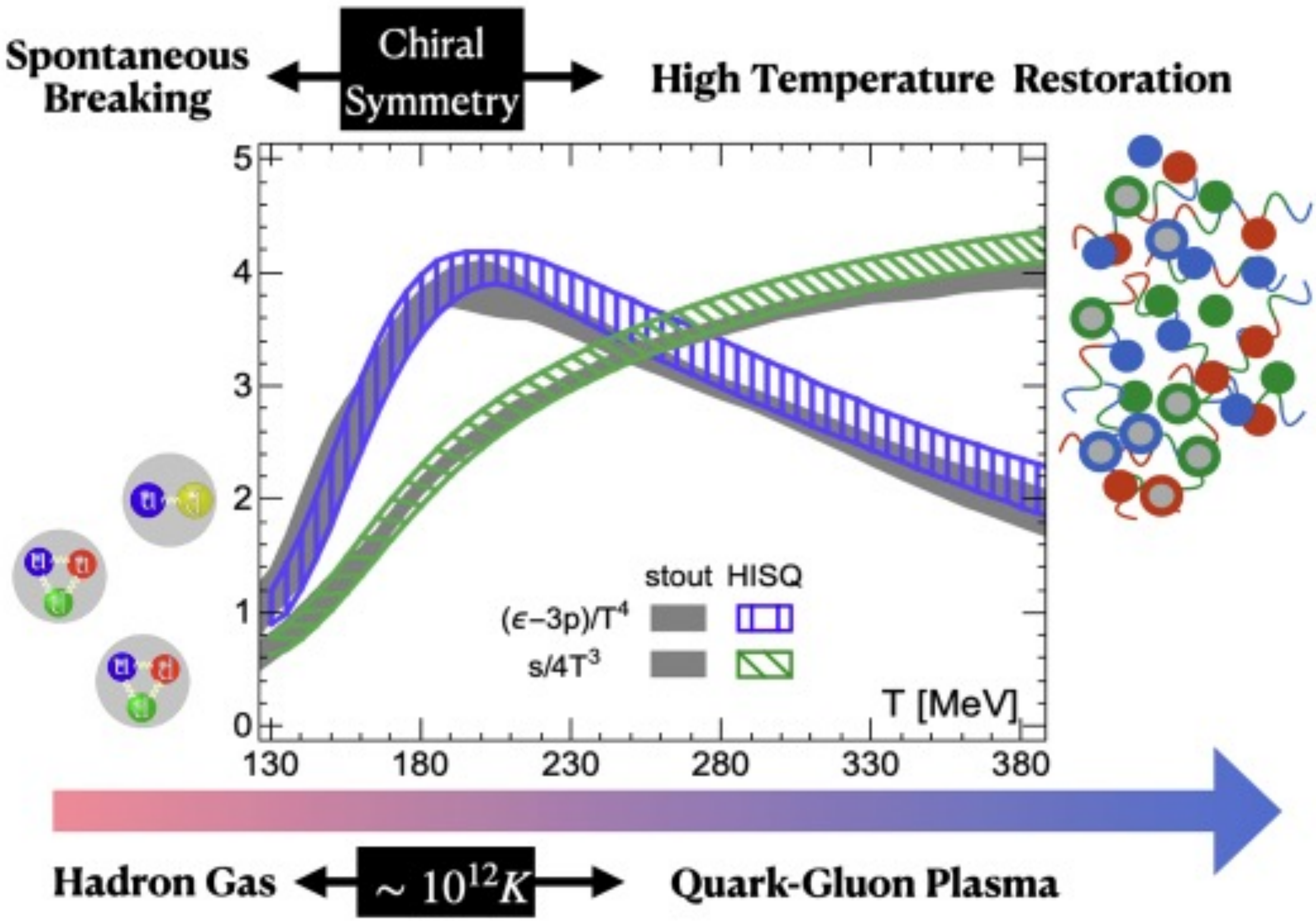
In QCD: $M = m - 2G\langle\bar{\psi}\psi\rangle$

Constituent *SM* *Spontaneous chiral symmetry breaking*

Chirality becomes hidden in QCD vacuum.

(Nearly) chiral quarks only upon chiral symmetry restoration at finite temperature.

Quark-Gluon Plasma (QGP): A New Phase of Matter

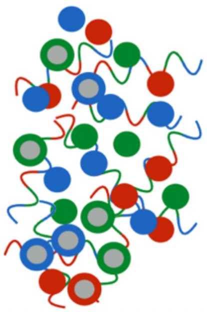


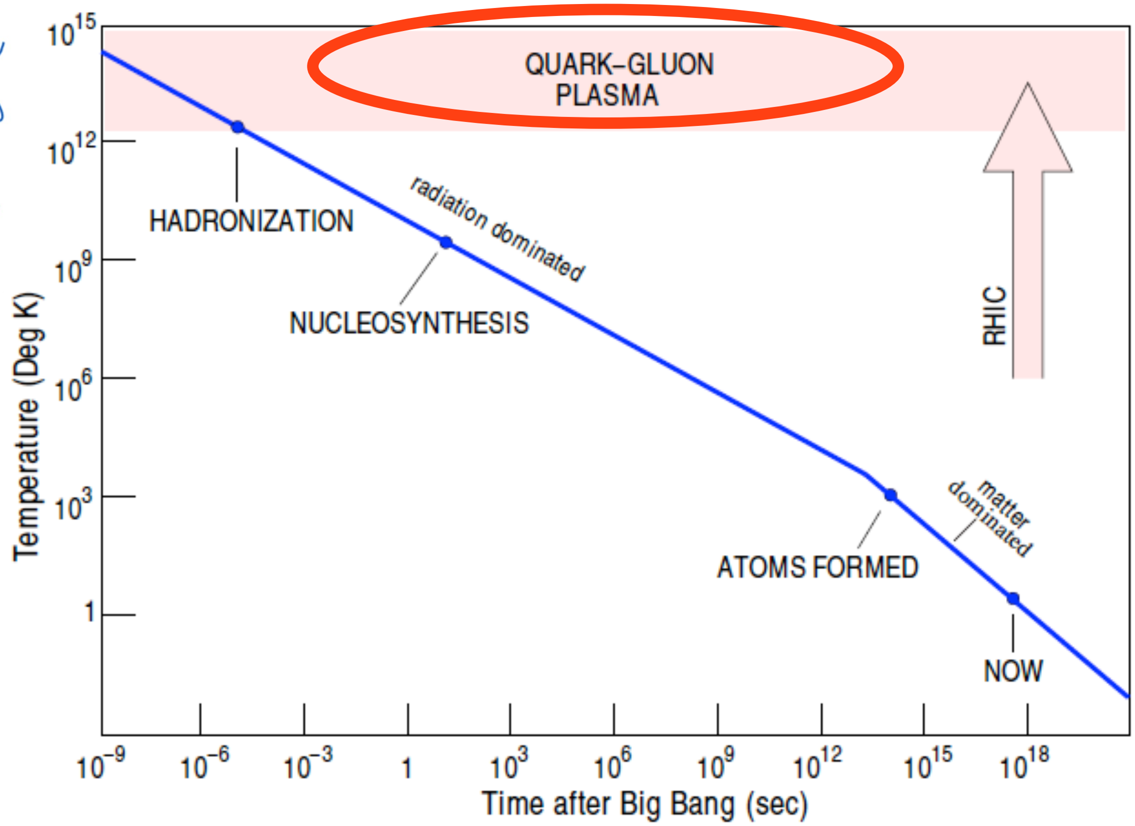
"Curie transition" of QCD

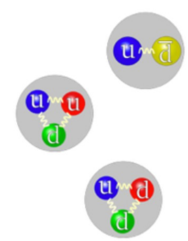
QGP: An Old Phase of Matter

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

THEN







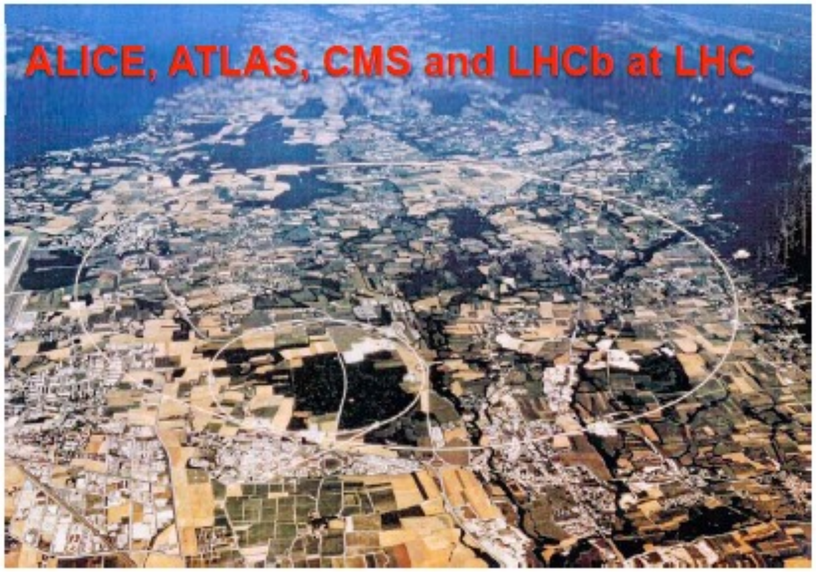
NOW

The quark-gluon plasm is an old phase of matter!

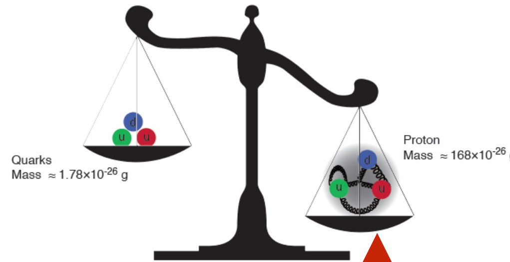
"Little Bangs": Yesterday Once More

Quark Gluon Plasma (QGP) is created and measured in heavy ion collisions.

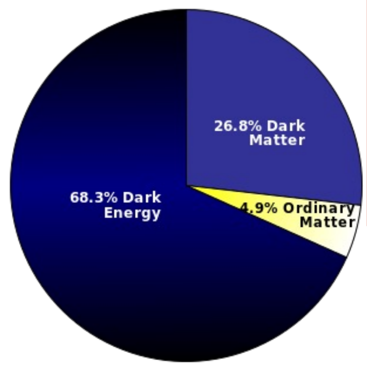
Heavy ion collision is the only venue for recreating the early universe environment.



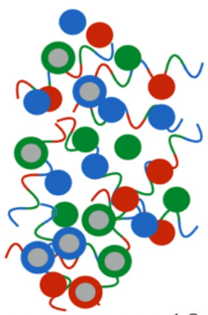
Between NOW and THEN

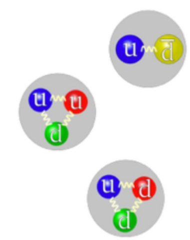


Missing QCD chiral symmetry

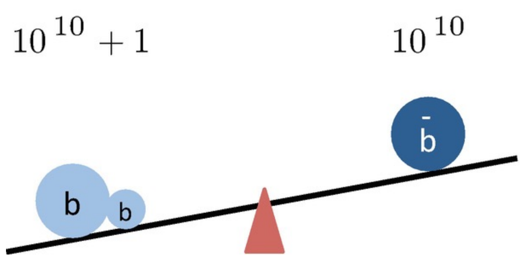


THEN





NOW



Matter-anti-matter asymmetry

The study of Chiral Magnetic Effect (CME) helps understand these fundamental issues about "why we are here"!

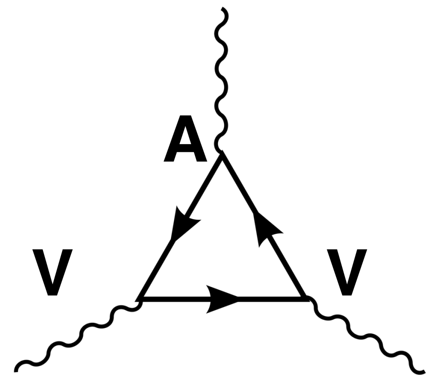
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

Classical axial symmetry broken at QM level:

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathrm{x}}} C_A \vec{\mathrm{E}} \cdot \vec{\mathrm{B}}$$



[e.g. pi0—> 2 gamma]

* C_A is universal anomaly coefficient

* Anomaly is intrinsically QUANTUM effect

Microscopic symmetries	Microscopic anomaly ("Semi-symmetry")
↕	↕ ???
Macroscopic properties	Macroscopic properties

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

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

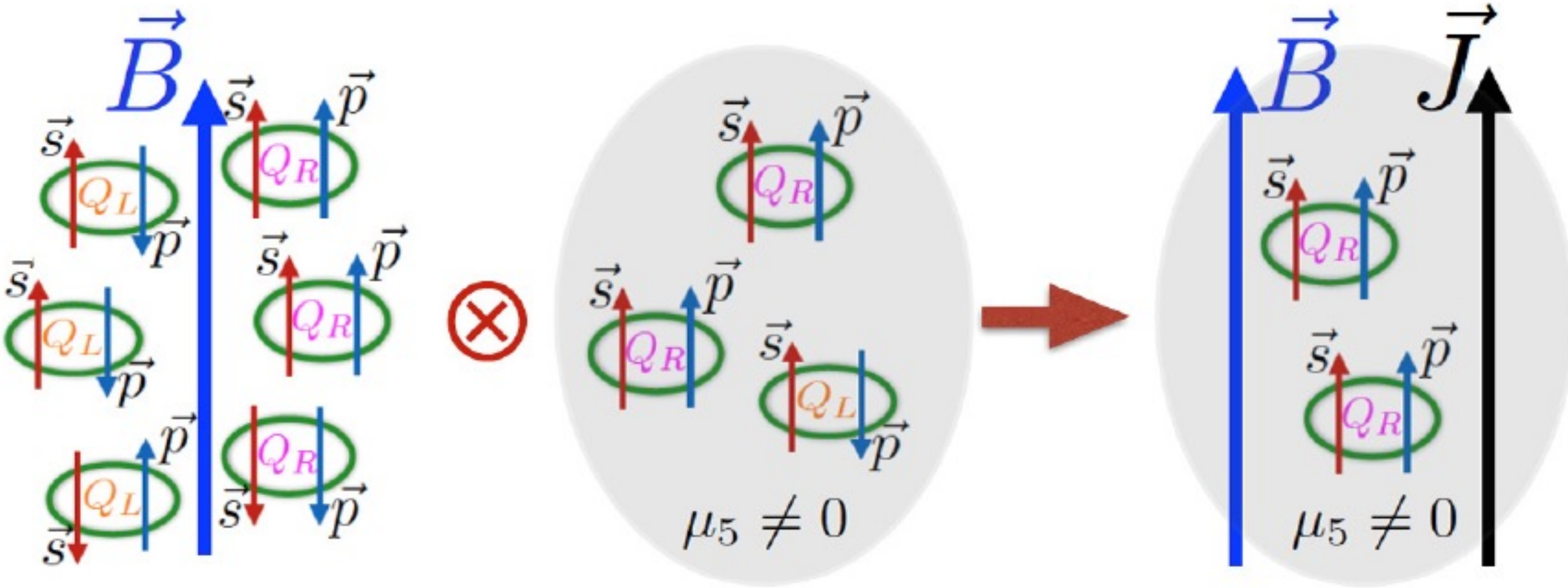
Electric Current

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

⊗

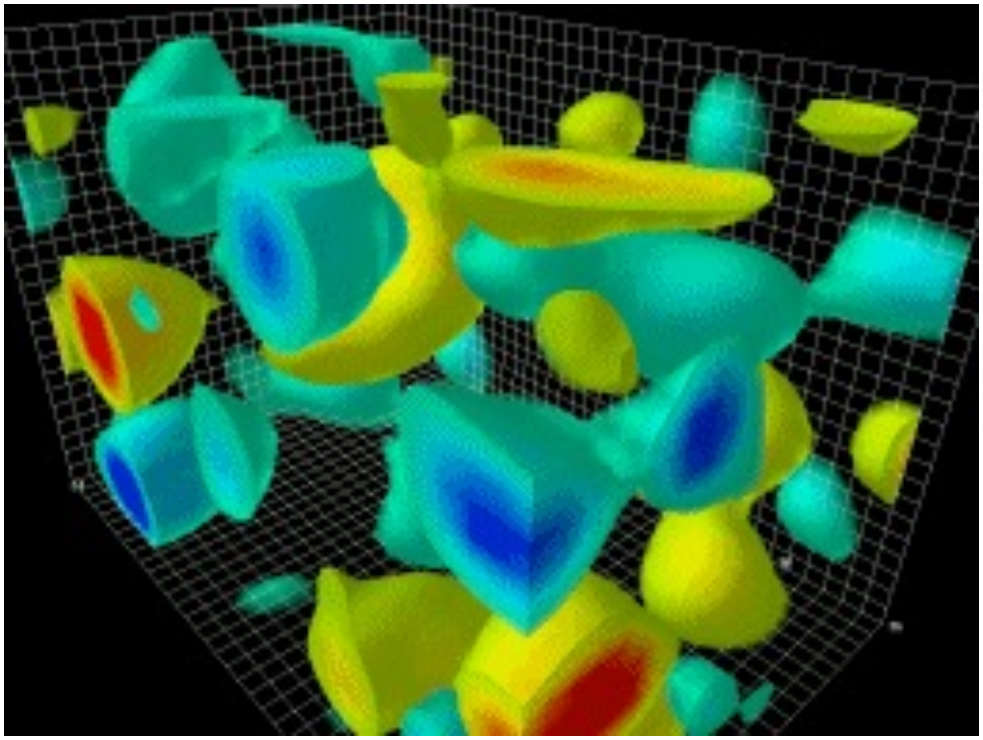
Chirality Polarization —>
correlation between directions of
SPIN & MOMENTUM

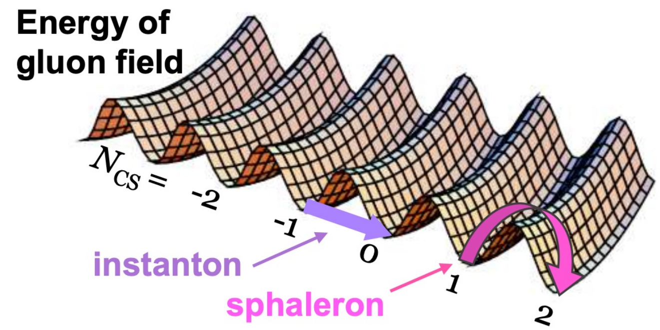
→ ***Transport current along magnetic field***

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

Topologically Nontrivial Gauge Fields

Instantons/sphelarons:
twisting gauge space orientation of non-Abelian gauge fields around spacetime boundary





In the context of QCD, they are crucial for understanding vacuum and hadron properties

[Rev. Mod. Phys. 70:323-426,1998]

$$Q_w = \frac{1}{32\pi^2}\int d^4x\,(gG_a^{\mu\nu})\cdot(g\tilde{G}^a_{\mu\nu}) \sim \vec{E}^a \cdot \vec{B}^a$$

P & CP ODD

From Gauge Field Topology to Quark Chirality

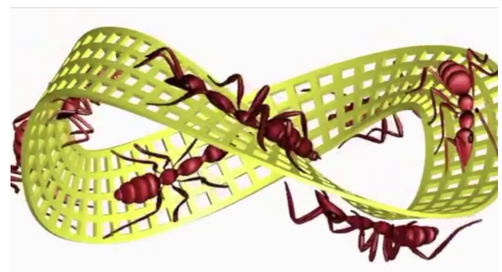
Atiyah-Singer Index Theorem

Abel Prize 2004

Theorem (M.F. Atiyah and I.M. Singer): *Let $P(f) = 0$ be a system of differential equations. Then*

$$\textit{analytical index}(\mathrm{P}) \; = \; \textit{topological index}(\mathrm{P}) \; .$$

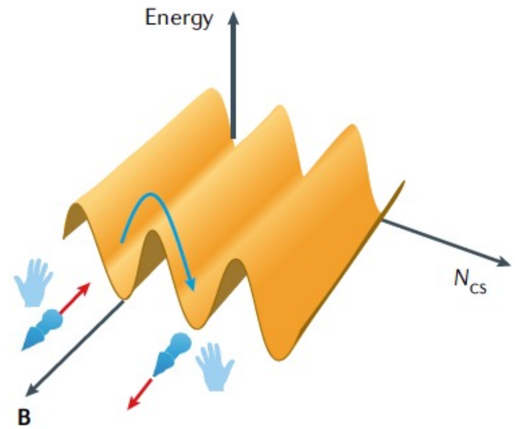
$$N_R - N_L = N_5 = 2Q_w$$



Topologically distinct vacuum sectors are a generic feature of non-Abelian gauge fields.
Tunneling between them constitutes the crucial ingredients of the baryogenesis and thus of our world.

Chiral Magnetic Effect: What & Why

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



[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:

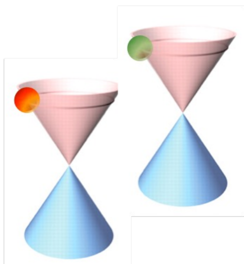
The study of CME helps provide insights into the solution of "one of the biggest questions in physics", namely: "Why does the universe contain more matter than antimatter"?

The Search for CME

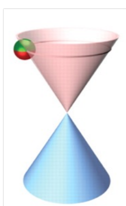
CME in Laboratory Experiments

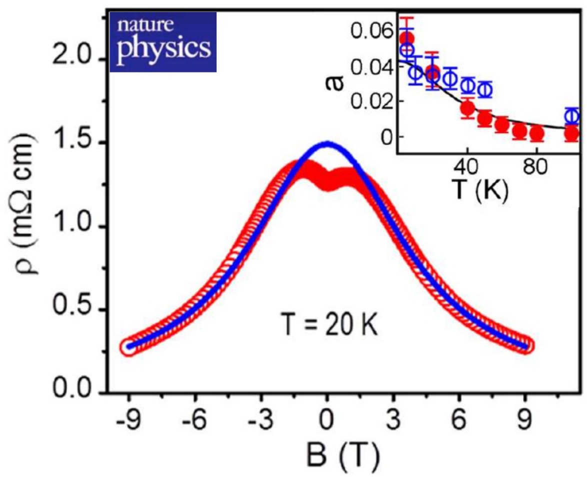
CME transport has been observed by condensed matter experiments with Dirac and Weyl semimetals

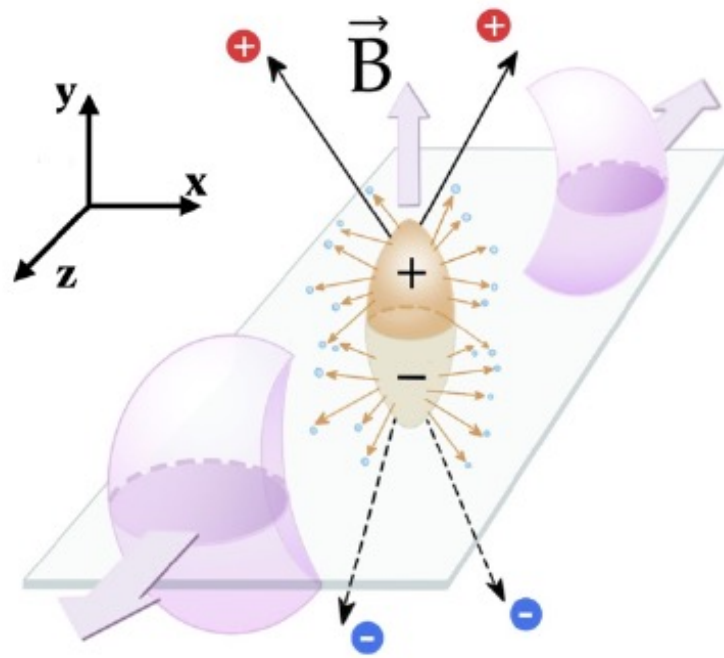
Weyl semimetal
(non-degenerated bands)



Dirac semimetal
(doubly degenerated bands)

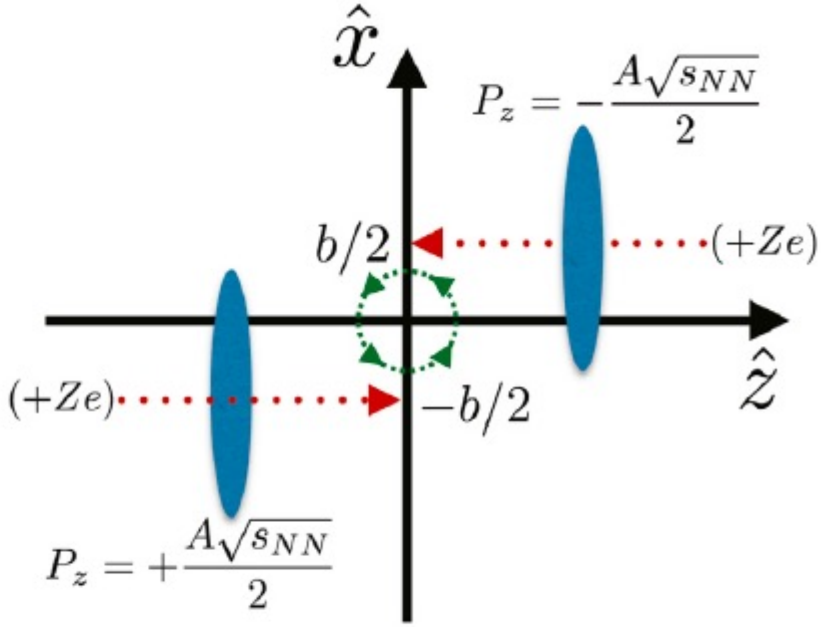






Key question here: can we observe it in heavy ion collisions?
For that, we need chirality and magnetic field.
—— Both are available in heavy ion collisions!

Angular Momentum in Heavy Ion Collisions



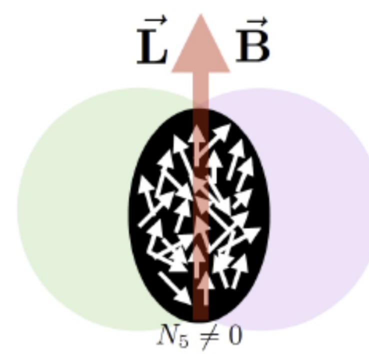
Huge angular momentum for the system in non-central collisions

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

Liang & Wang ~ 2004: ***[nucl-th/0410079, PRL2005]***
Large orbital angular momentum carried by colliding ions
—> spin-orbital coupling —> spin polarization and alignment

The beginning of a new direction:
spin transport in heavy ion collisions

[See talks by: F. Becattini & T. Niida]



Laying the Foundation of CME

[arXiv:hep-ph/0406125]

BNL–NT–04/21; June 9, 2004

Parity violation in hot QCD: why it can happen, and how to look for it

Dmitri Kharzeev[1]
[1] *Physics Department, Brookhaven National Laboratory Upton, NY 11973-5000*
(Dated: October 22, 2018)

The arguments for the possibility of violation of $\mathcal{P}$ and $\mathcal{CP}$ symmetries of strong interactions at finite temperature are presented. A new way of observing these effects in heavy ion collisions is proposed – it is shown that parity violation should manifest itself in the asymmetry between positive and negative pions with respect to the reaction plane. Basing on topological considerations, we derive a *lower* bound on the magnitude of the expected asymmetry, which may appear within the reach of the current and/or future heavy ion experiments.

[arXiv:0711.0950]

The effects of topological charge change in heavy ion collisions: "Event by event $\mathcal{P}$ and $\mathcal{CP}$ violation"

Dmitri E. Kharzeev, [a] Larry D. McLerran[a,b] and Harmen J. Warringa[a]
[a] *Department of Physics, Brookhaven National Laboratory, Upton NY 11973, USA*
[b] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*

Abstract
Quantum chromodynamics (QCD) contains field configurations which can be characterized by a topological invariant, the winding number Q_w. Configurations with nonzero Q_w break the charge-parity ($\mathcal{CP}$) symmetry of QCD. We consider a novel mechanism by which these configurations can separate charge in the presence of a background magnetic field – the "Chiral Magnetic Effect". We argue that sufficiently large magnetic fields are created in heavy ion collisions so that the Chiral Magnetic Effect causes preferential emission of charged particles along the direction of angular momentum. Since separation of charge is $\mathcal{CP}$-odd, any observation of the Chiral Magnetic Effect could provide a clear demonstration of the topological nature of the QCD vacuum. We give an estimate of the effect and conclude that it might be observed experimentally.

The beginning of a new direction: chirality transport in heavy ion collisions

The Chiral Magnetic Effect

Kenji Fukushima,[1,*] Dmitri E. Kharzeev,[2,†] and Harmen J. Warringa[2,‡]
[1] *Yukawa Institute, Kyoto University, Kyoto, Japan*
[2] *Department of Physics, Brookhaven National Laboratory, Upton NY 11973, USA*
(Dated: August 25, 2008)

Topological charge changing transitions can induce chirality in the quark-gluon plas
axial anomaly. We study the equilibrium response of the quark-gluon plasma in such a s
an external magnetic field. To mimic the effect of the topological charge changing transit
introduce a chiral chemical potential. We will show that an electromagnetic current is
along the magnetic field. This is the Chiral Magnetic Effect. We compute the magnit
current as a function of magnetic field, chirality, temperature, and baryon chemical pote

[arXiv:0808.3382]

[arXiv:hep-ph/0406311]

Parity violation in hot QCD: how to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201
(Dated: November 2, 2018)

In a recent paper (arXive:hep-ph/0406125) entitled *Parity violation in hot QCD: why it can happen, and how to look for it*, D. Kharzeev argues for the possibility of $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in $\pi^{\pm}$ production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

20 Years of Exciting Progress: See Reviews

Kharzeev,JL, Tribedy, 2405.05427

Kharzeev & JL, Nature Reviews Physics 3(2021)1, 55-63

Bzdak, Esumi, Koch, JL, Stephanov, Xu,
arXiv:1906.00936 [Phys. Rep. 853 (2020) 1-87].

Kharzeev, JL, Voloshin, Wang,
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050].

Gao, Ma, Pu, Wang, Nucl. Sci. Tech., 31 (2020) no.9, 90.

Wang, Zhao, Nucl. Sci. Tech., 29 (2018) no.12, 179.

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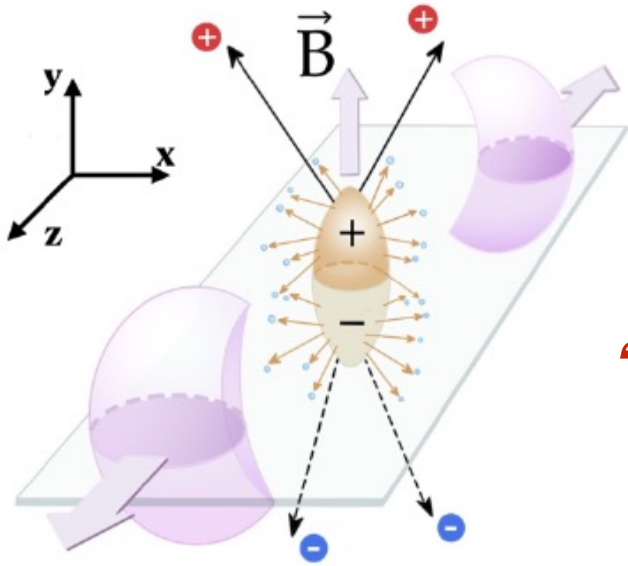
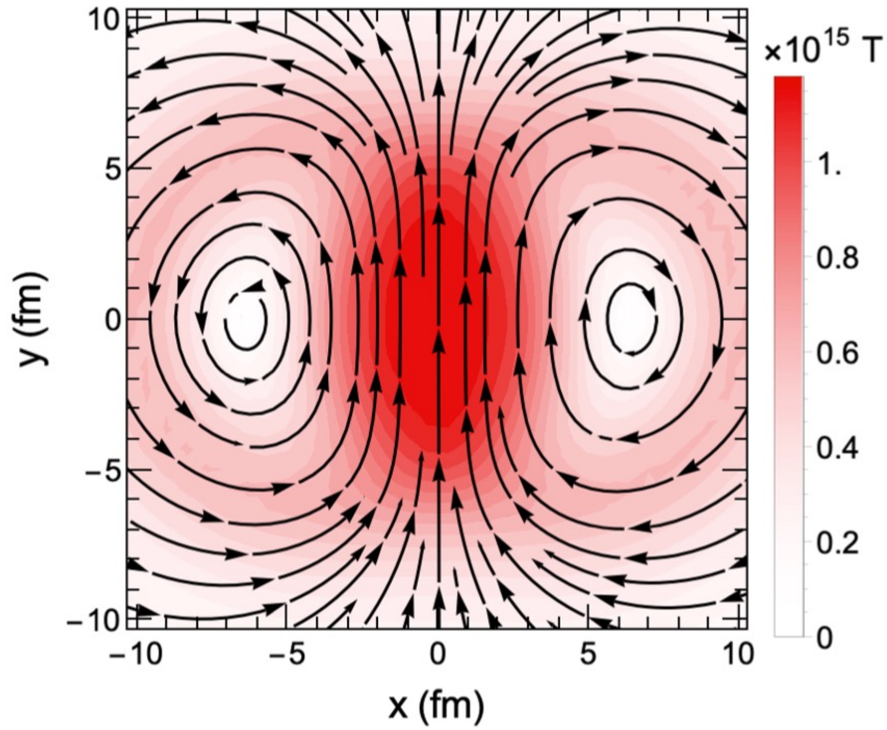
Strongest Magnetic Fields in Heavy Ion Collisions



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

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; …

Manifesting Extreme Magnetic Fields

PHYSICAL REVIEW X **14**, 011028 (2024)

Featured in Physics

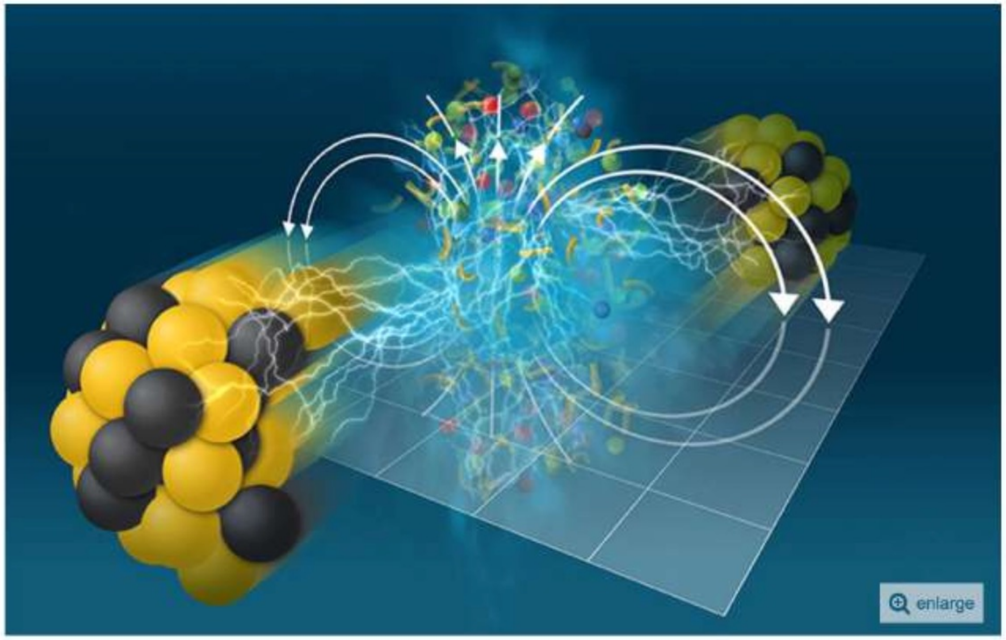
STAR Collaboration

Observation of the Electromagnetic Field Effect via Charge-Dependent Directed Flow in Heavy-Ion Collisions at the Relativistic Heavy Ion Collider

Super Strong Magnetic Fields Leave Imprint on Nuclear Matter

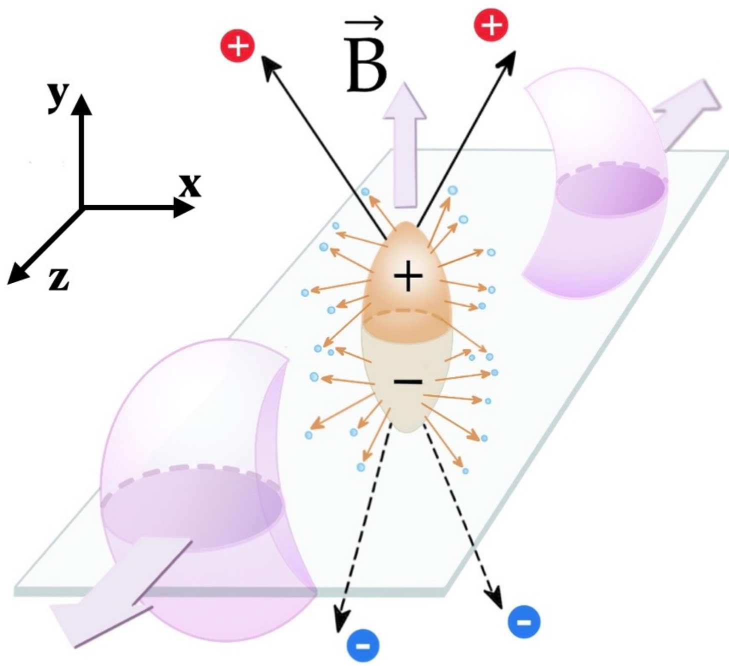
Data from heavy ion collisions give new insight into electromagnetic properties of quark-gluon plasma

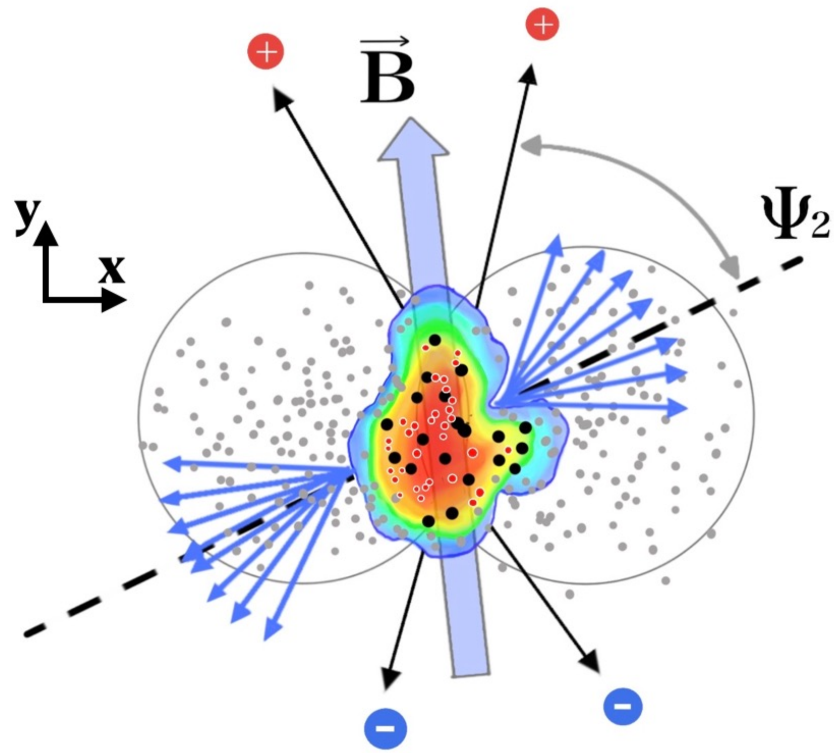
February 23, 2024



Looking for CME Signals in Nuclear Collisions

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



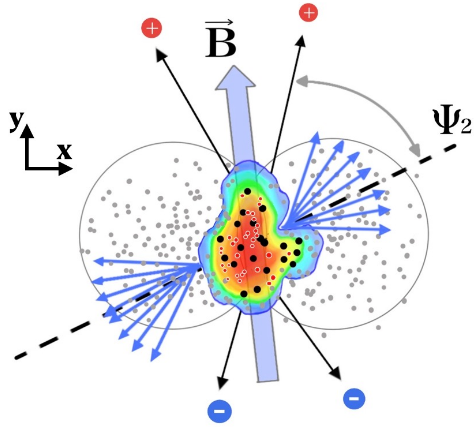


A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

Charge Dependent Azimuthal Correlators

CME sensitive correlator as observables:

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



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

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

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

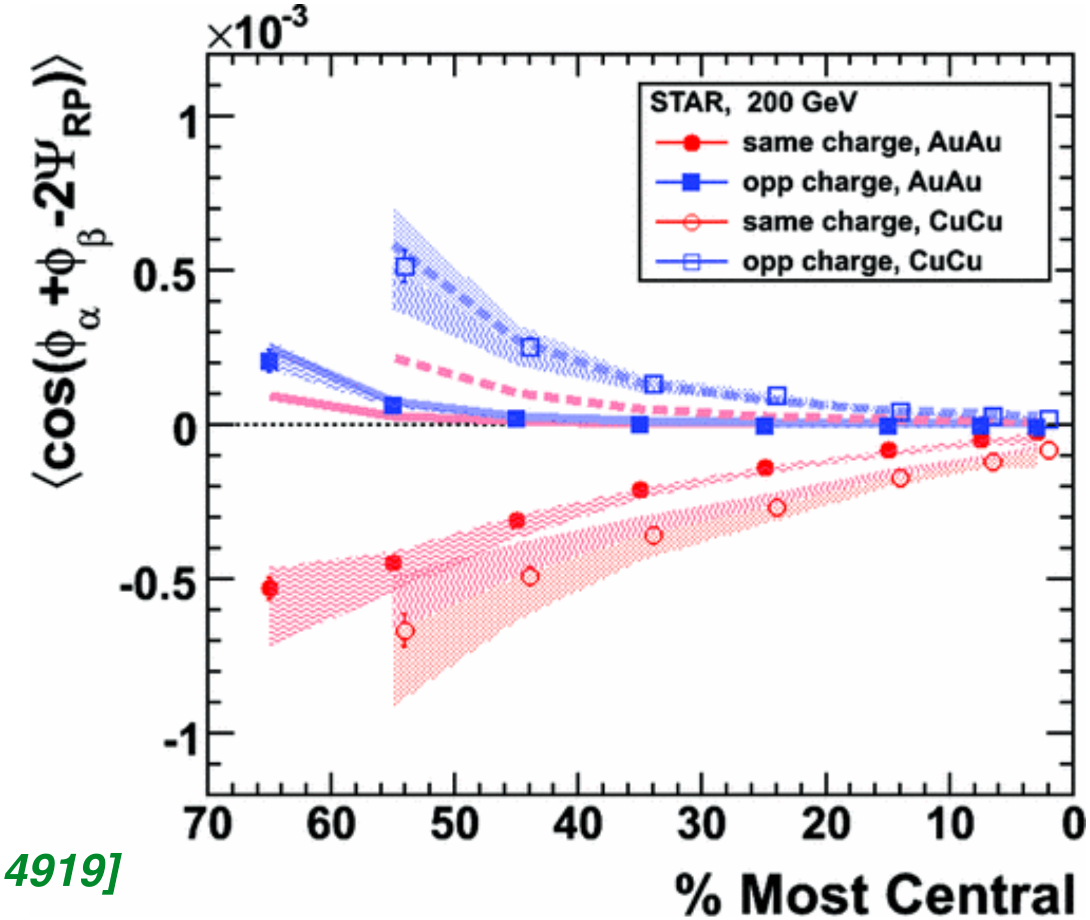
Data could be in line with CME expectations.

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

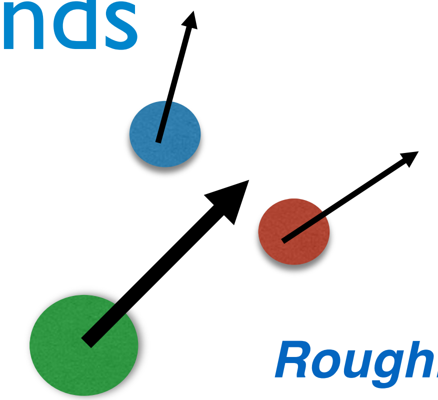
[F. Wang, arXiv:0911.1482]

[S. Pratt, arXiv:1002.1758]

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



Battling 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

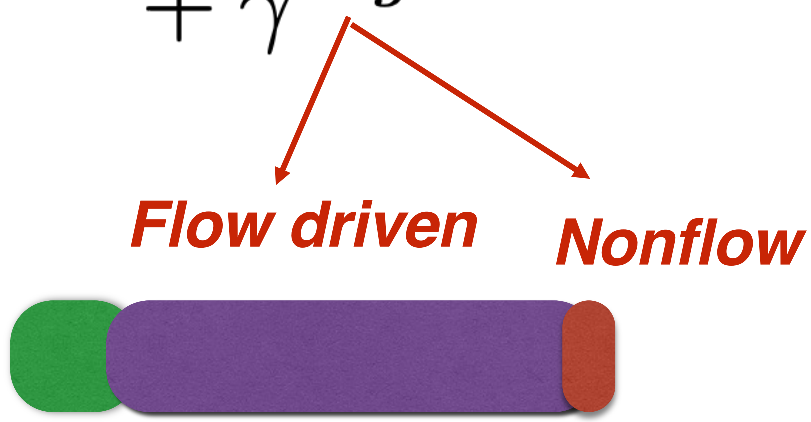
We are not alone!
Think about many other difficult searches, e.g. for Higgs, gravitational wave, temperature fluctuations of CMB, EDM, WIMP, 2-beta decay, …

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!

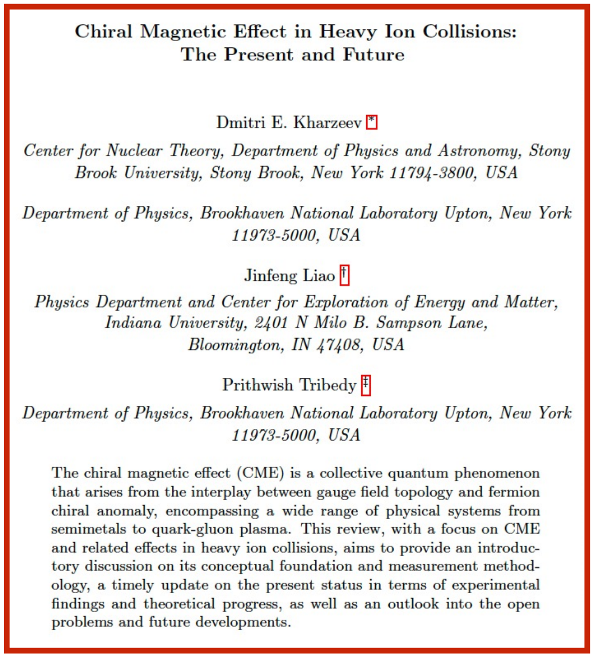
$$\gamma = \gamma^{CME} + \gamma^{bkg}$$



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

Jinfeng Liao [†]

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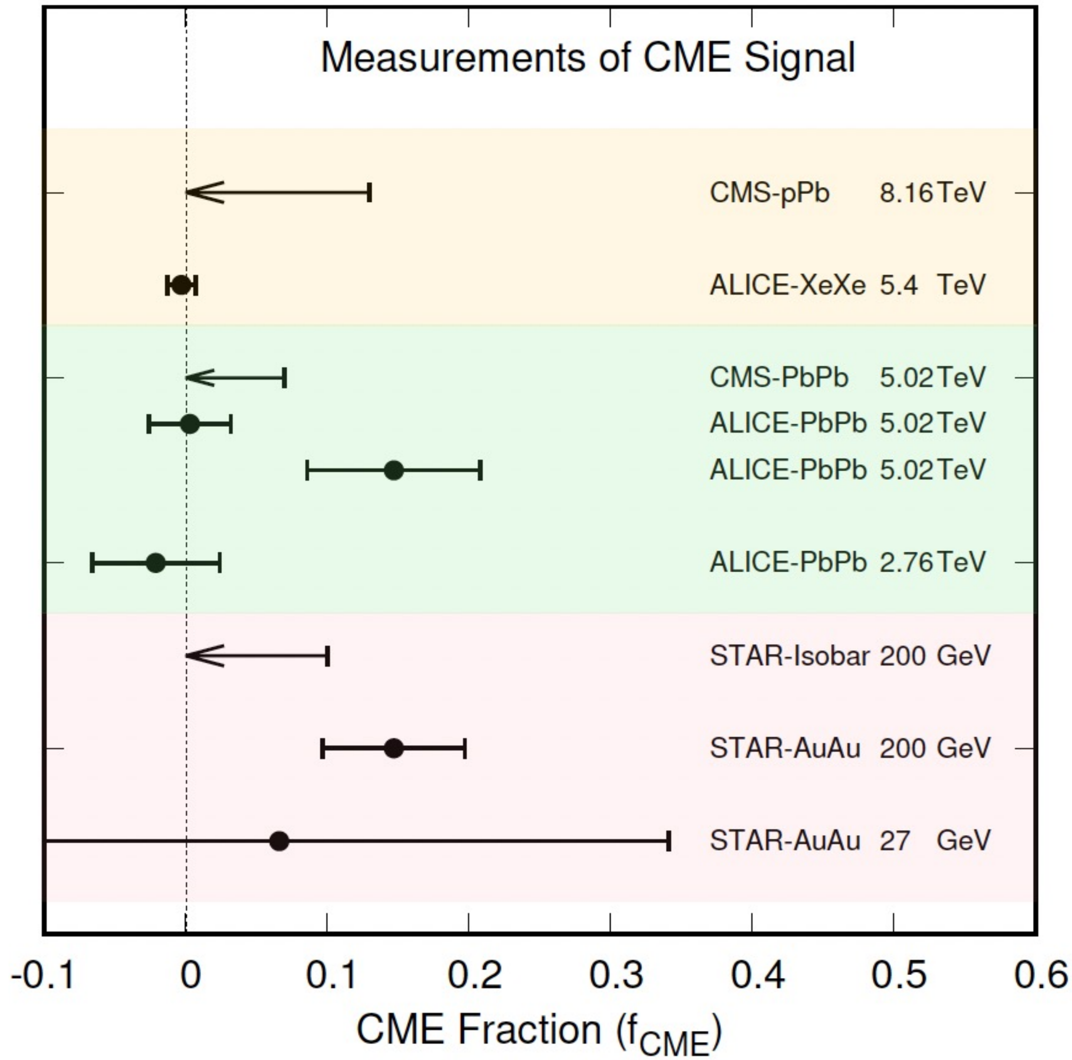
The chiral magnetic effect (CME) is a collective quantum phenomenon that arises from the interplay between gauge field topology and fermion chiral anomaly, encompassing a wide range of physical systems from semimetals to quark-gluon plasma. This review, with a focus on CME and related effects in heavy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



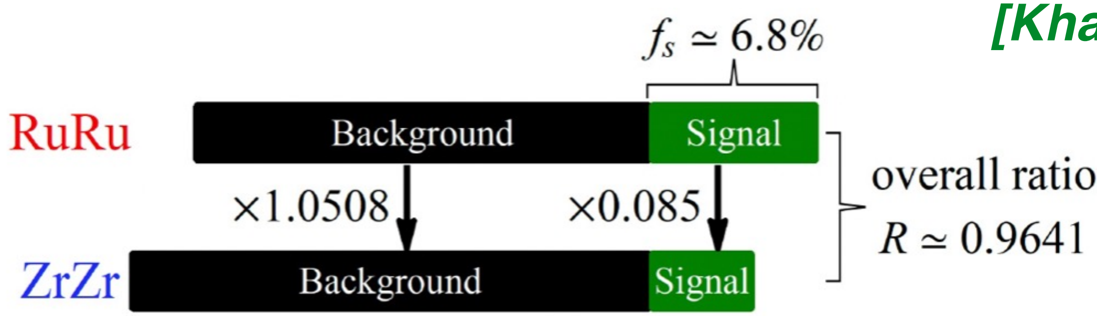
20 years of hunting CME, hundreds of experimental publications

Many contributions from Chinese groups in STAR & ALICE: CCNU, Fudan, Huzhou U, IMP, Shandong U, Tsinghua U, USTC, …

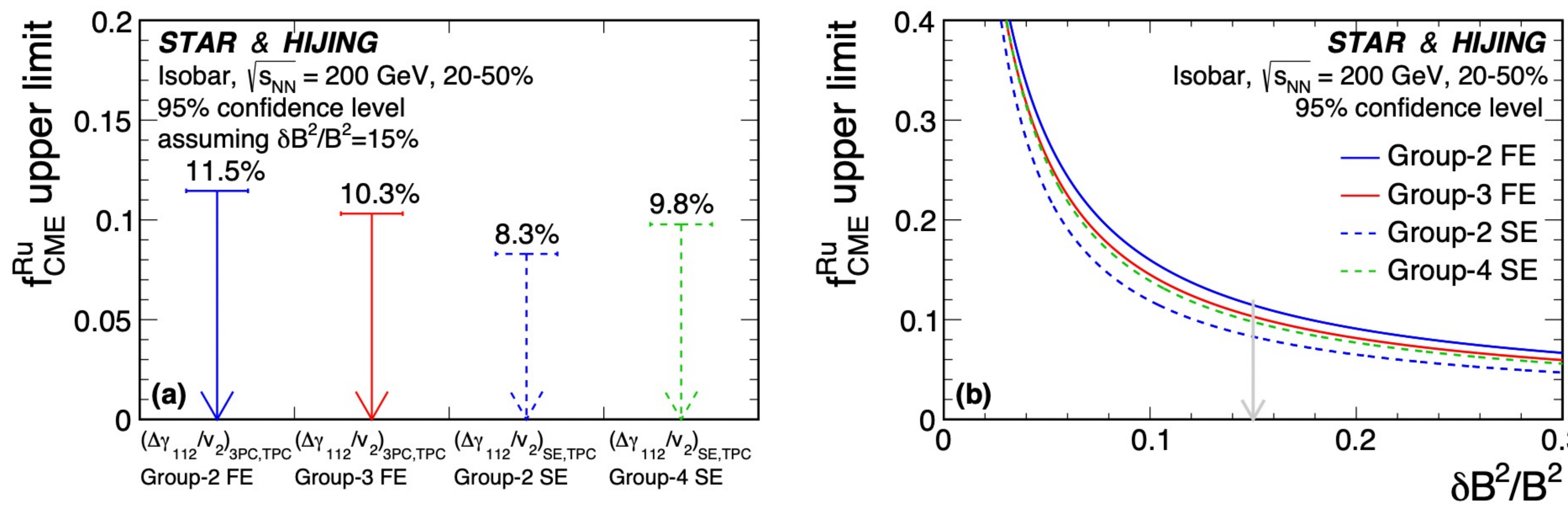
Isobar Collisions

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

[Khazeev, JL, Shi, arXiv:2205.00120]

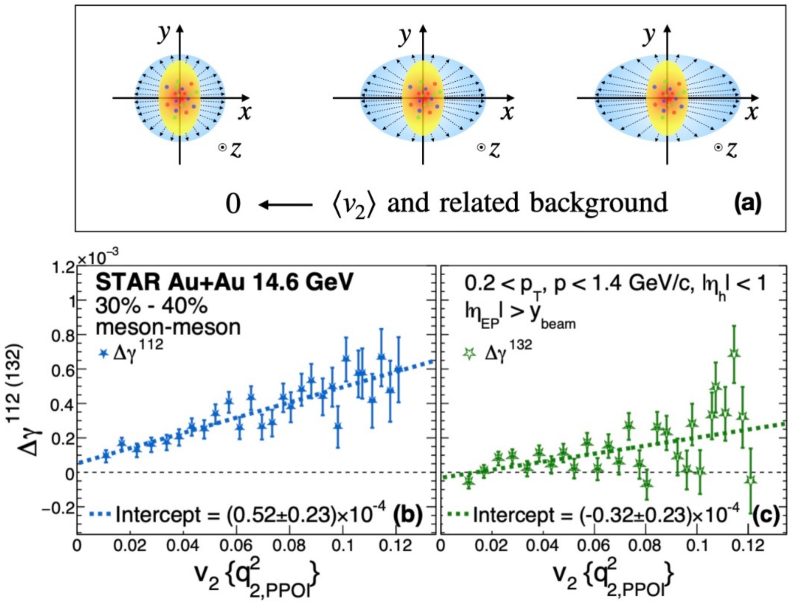


[STAR, arXiv:2310.13096;2308.16846]

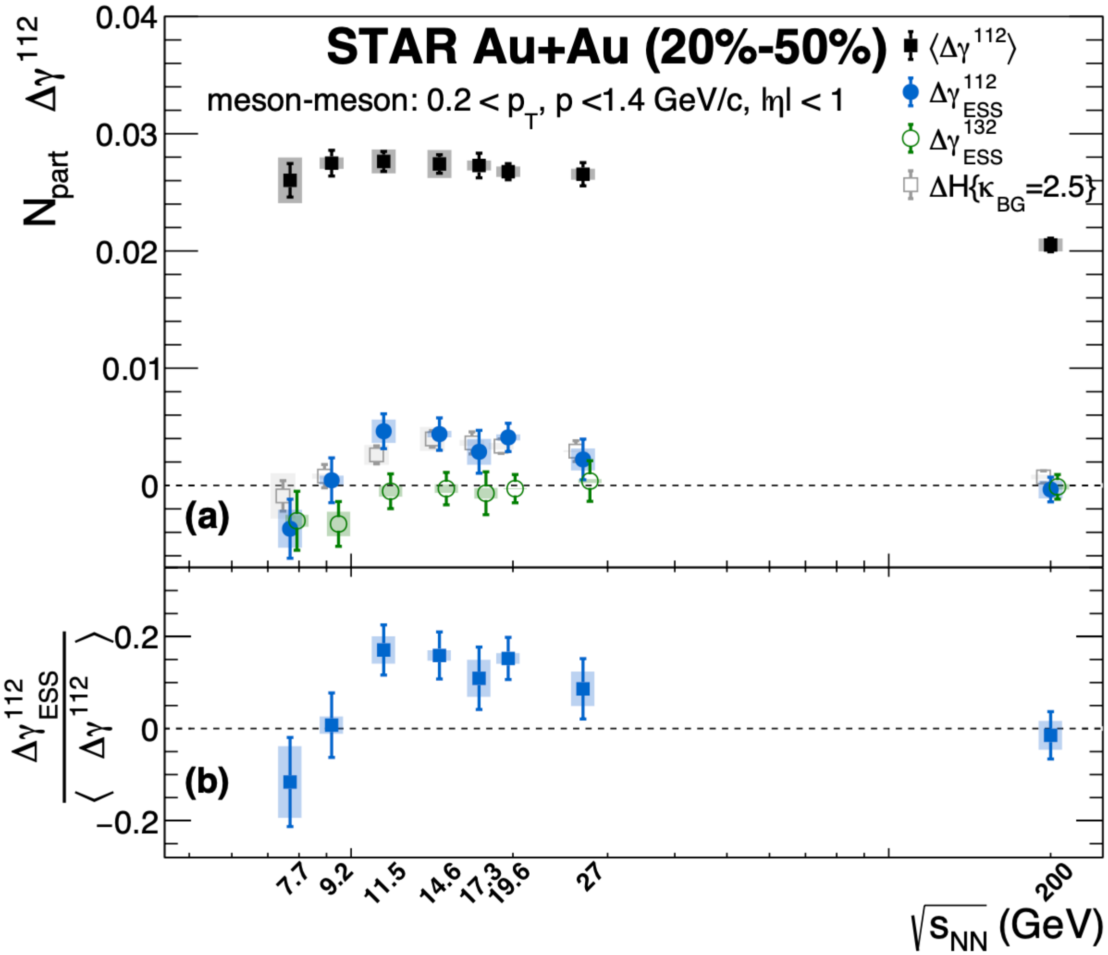


– ***Upper limits have been set by STAR for isobar collisions.***
– ***Consistent with theoretical expectations***
– ***Indicating a still better chance for the search in AuAu collisions***

Beam-Energy-Scan-II: STAR2025



STAR Collaboration:
2506.00275;
2506.00278



Beam-Energy-Scan-II: STAR2025

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

Theoretical Progress

Many thousands of theoretical papers in a short 20 years!

A whole family of chiral effects
(CVE,CESE,CMW,Chiral Instabilities,…)

Theoretical developments
(Chiral kinetic theory; anomalous hydrodynamics; magnetohydrodynamics; holography; lattice; quantum computing; …)

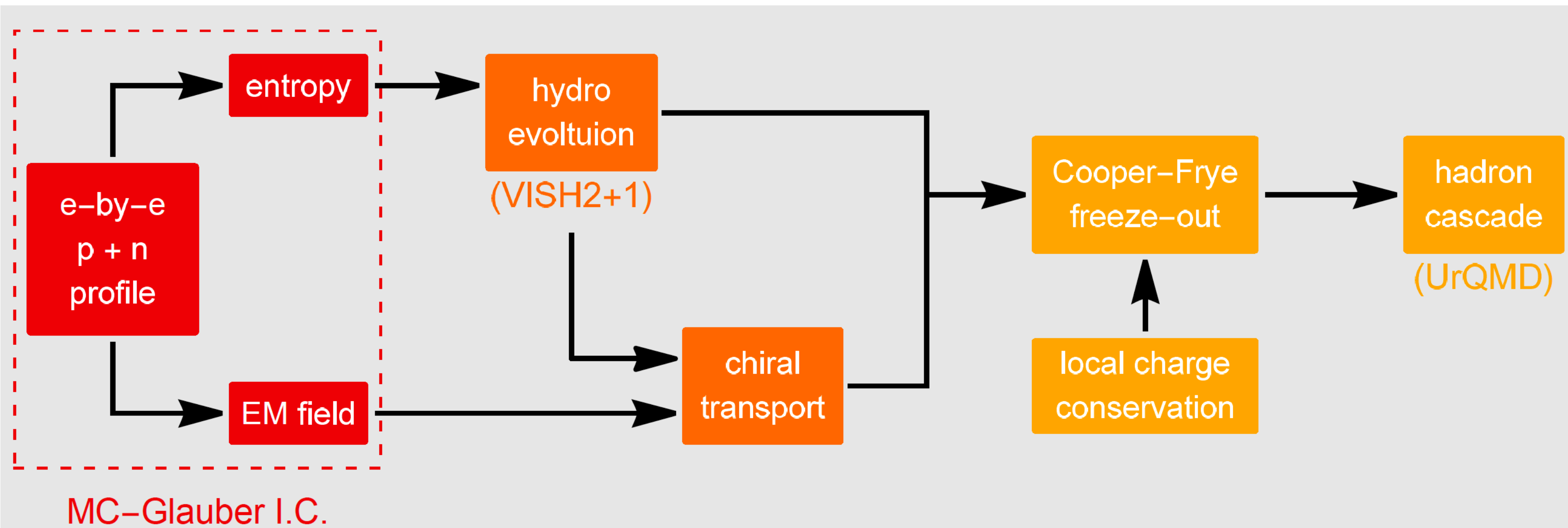
Phenomenology
(Transport models; hydro models; applications to other systems e.g. astrophysics; …)

Sorry for not being able to discuss everything…

CME Working Group @ BEST Collaboration

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

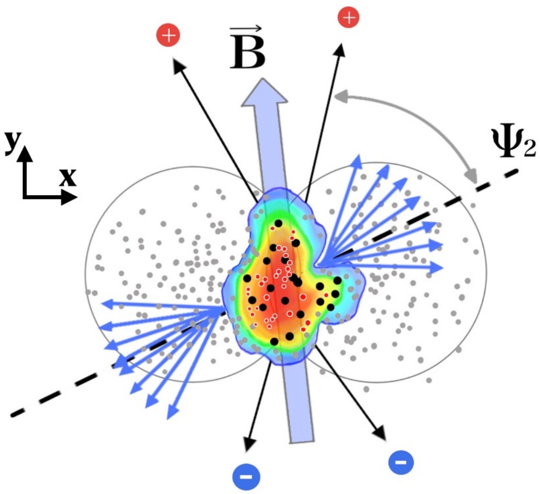
EBE-AVFD:
event-by-event anomalous-viscous fluid dynamics

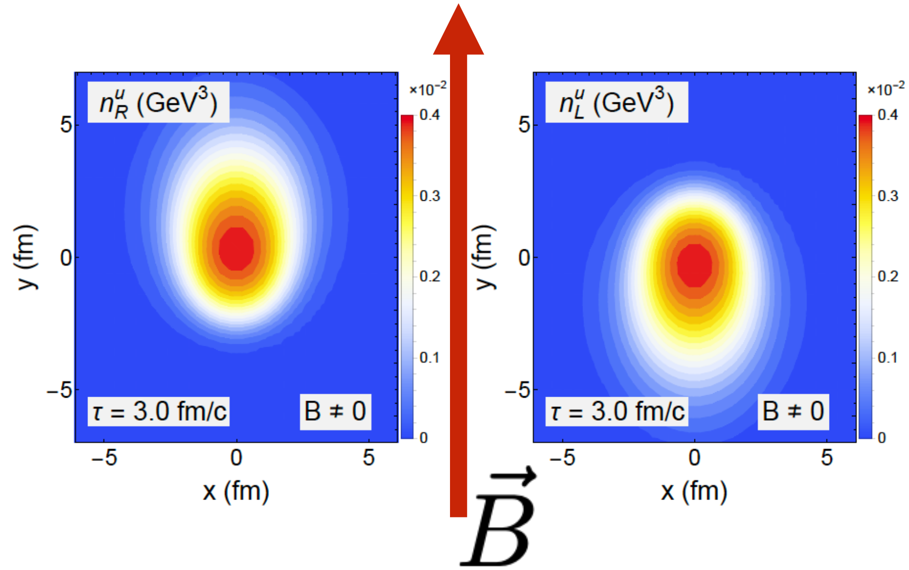


[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

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

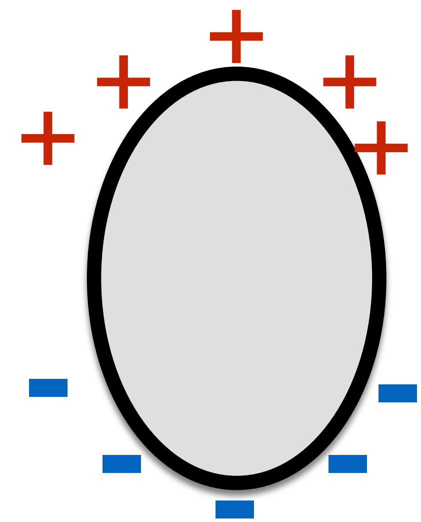
Hydrodynamic Realization of CME in HIC





From cartoon to quantitative physics

Chirality transport
—>
R/L asymmetry
—>
charge asymmetry
—>
exp. data



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

Data Driven 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)*

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

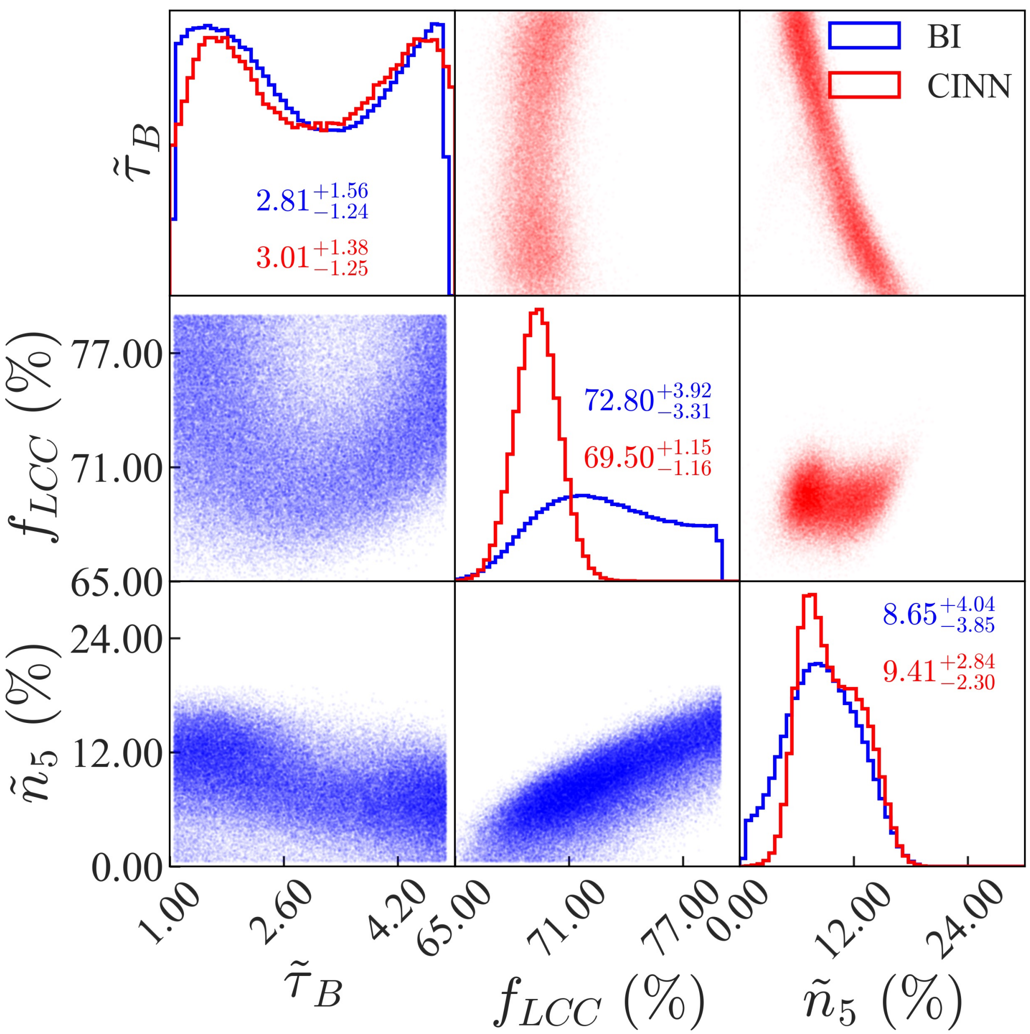
— *Gaussian Process Emulator (GPE)*

— *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.

Machine-Learning Extraction



EBE-AVFD calculations for 19.6GeV AuAu collisions

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

We conclude that data clearly demands CME contributions and offers 1st determination of n5!

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

Summary & Outlook

Summary & Outlook

– ***Chirality is a fundamental concept in relativistic quantum field theory and instrumental in the Standard Model.***

– ***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 over the past 20 years.***

– ***It is an exciting time and we are on the verge of reaching a final conclusion, given the currently available experimental information and anticipated future dataset.***