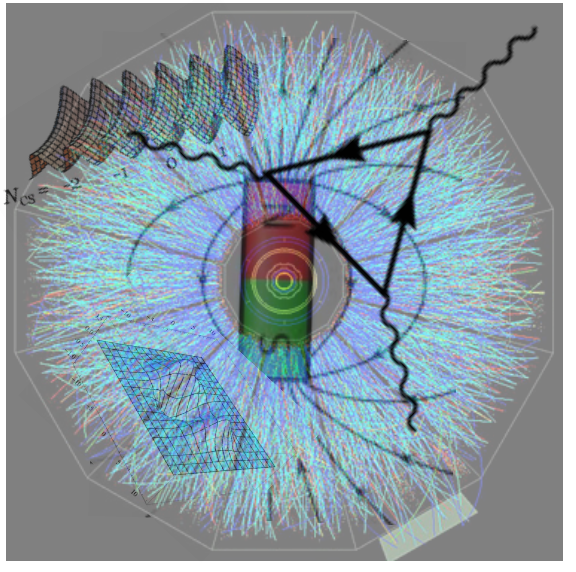
Novel Phenomena in Quantum Chromo Matter

I. Chiral Magnetic Effect and Isobar Collisions



Jinfeng Liao

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INDIANA UNIVERSITY

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BEST COLLABORATION

Research Supported by NSF & DOE

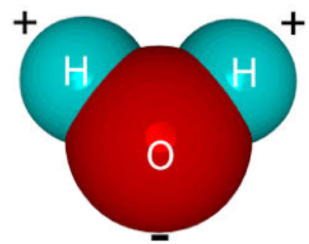
Introduction

Nuclear Physics: Exploring the Heart of Matter

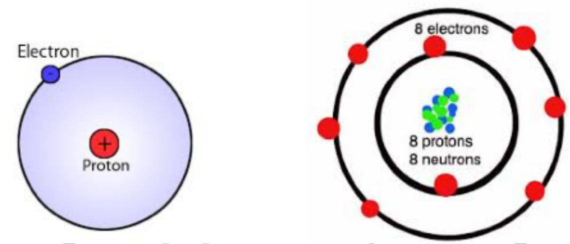
The physical world has a hierarchy of structures.

matter

molecule

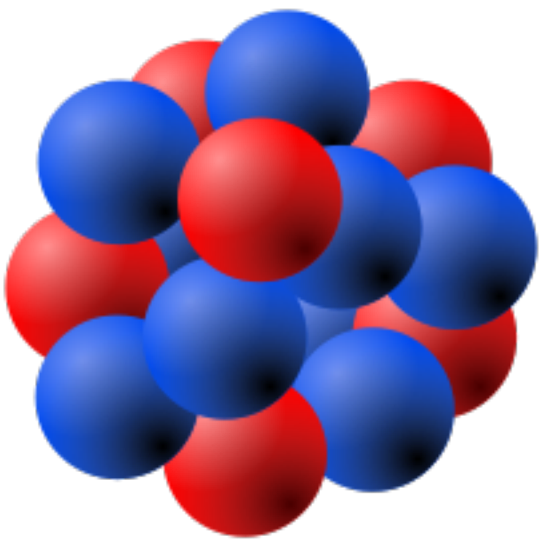


atoms



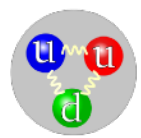
[a millionth of a mm]

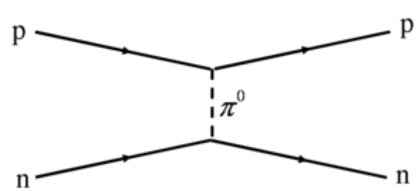
atomic nucleus



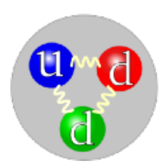
[a trillionth of a mm]

proton



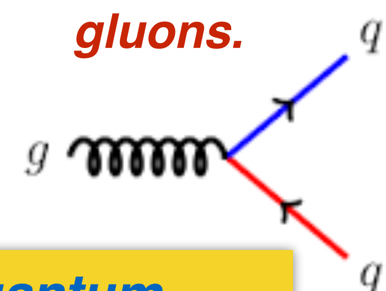


nuclear force



neutron

Most basic entities: quarks and gluons.



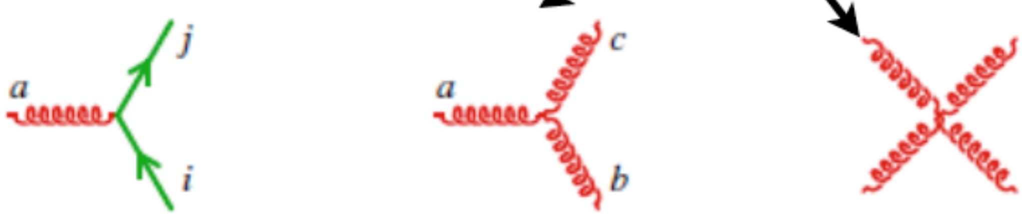
Quantum Chromodynamics (QCD)

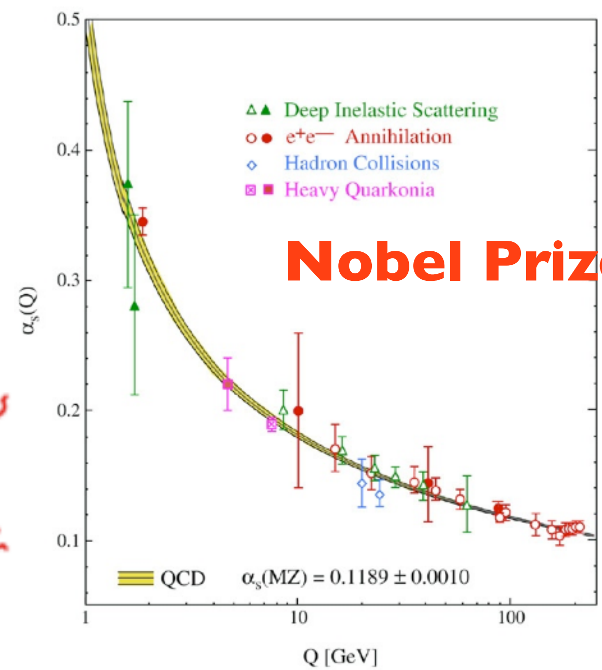
Quantum Chromodynamics (QCD)

The fundamental theory of strong nuclear force:
QCD, a non-Abelian gauge theory of quarks and gluons

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - M - g A\!\!\!/_a G^a)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$





Nobel Prize 2004

Asymptotic Freedom: coupling becomes large at low energy or long distance scale.

$$\Lambda_{QCD} \sim 200\text{MeV} \qquad R \sim 1\,\text{fm}$$

where "quark math" becomes very hard!

Emergent Phenomena in NP/QCD

F. Wilczek @ QM2014

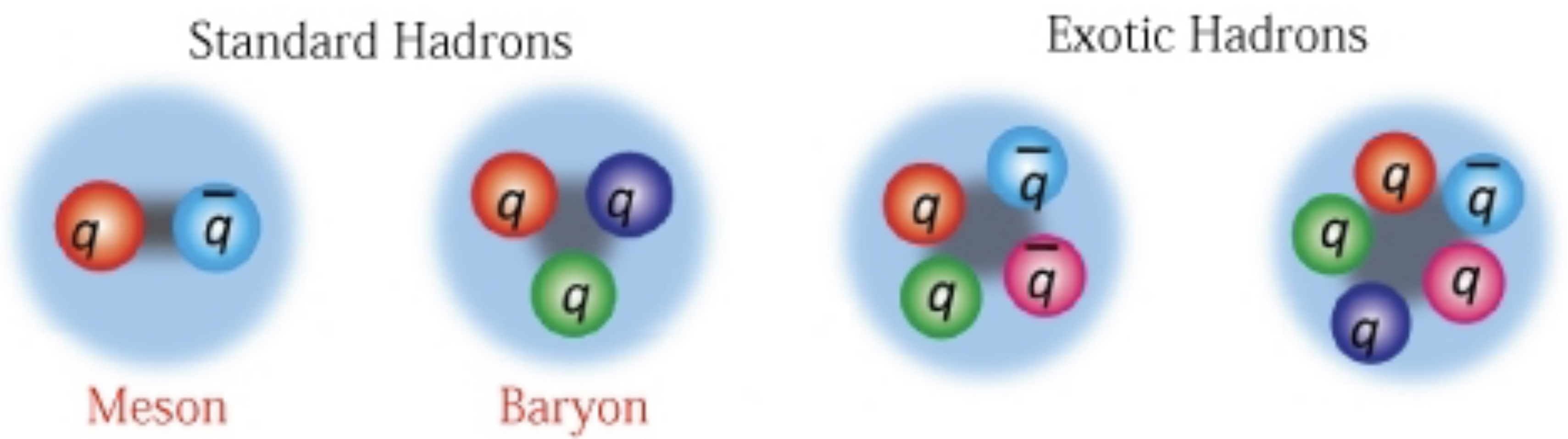
The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

It *embodies* many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)

The Quark Math/Mystery: Exotic Hadrons?!

Confinement: non-perturbative force binds quarks in hadrons.
What are possible? Why some are possible and some not?

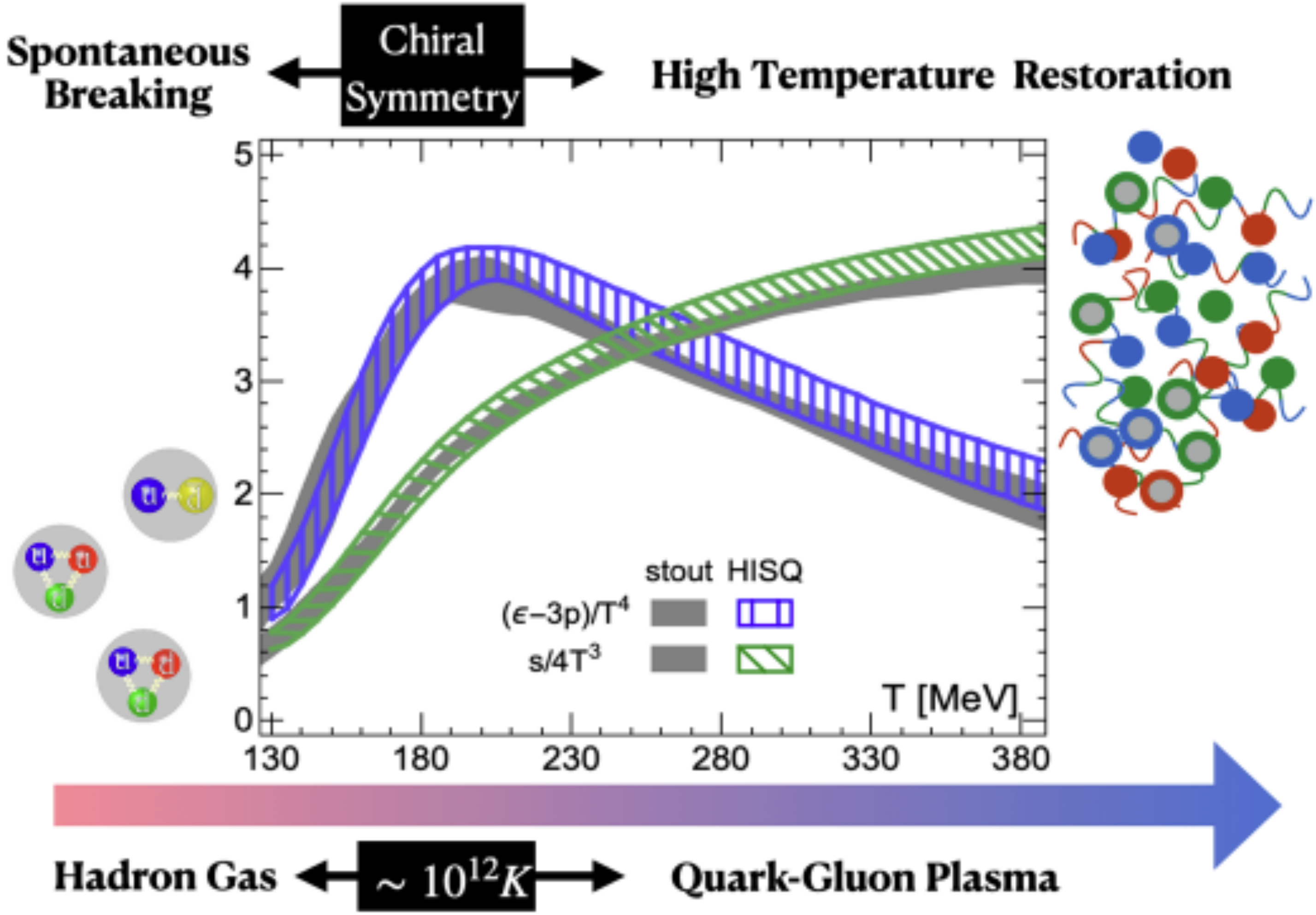


Understanding the "quark math" of hadrons:

Unravel the mysteries of nonperturbative QCD force between quarks/antiquarks;

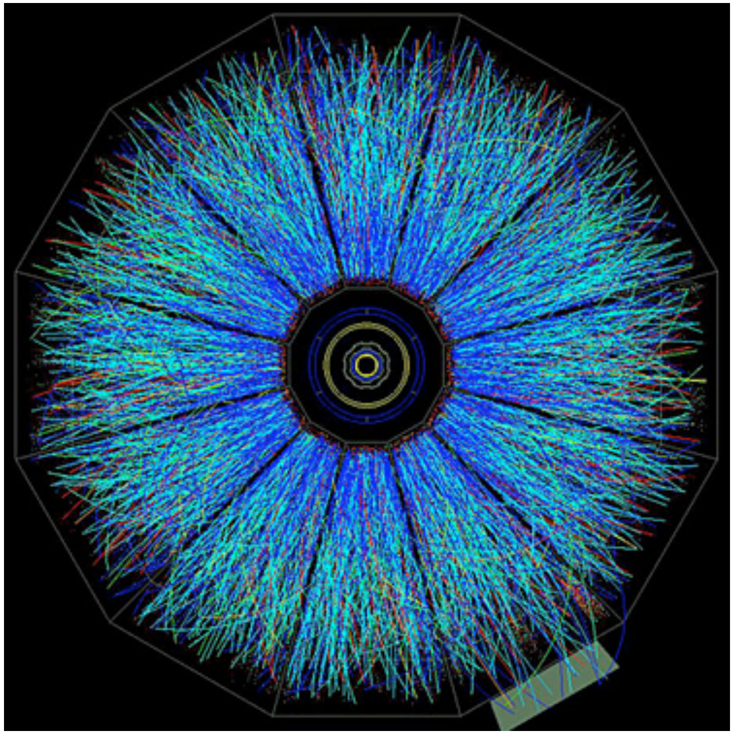
An exciting frontier of today's nuclear physics research

Cooking up a "Quark Soup"



"Condensed matter physics of QCD"

Little Bangs in Heavy Ion Collisions (HIC)

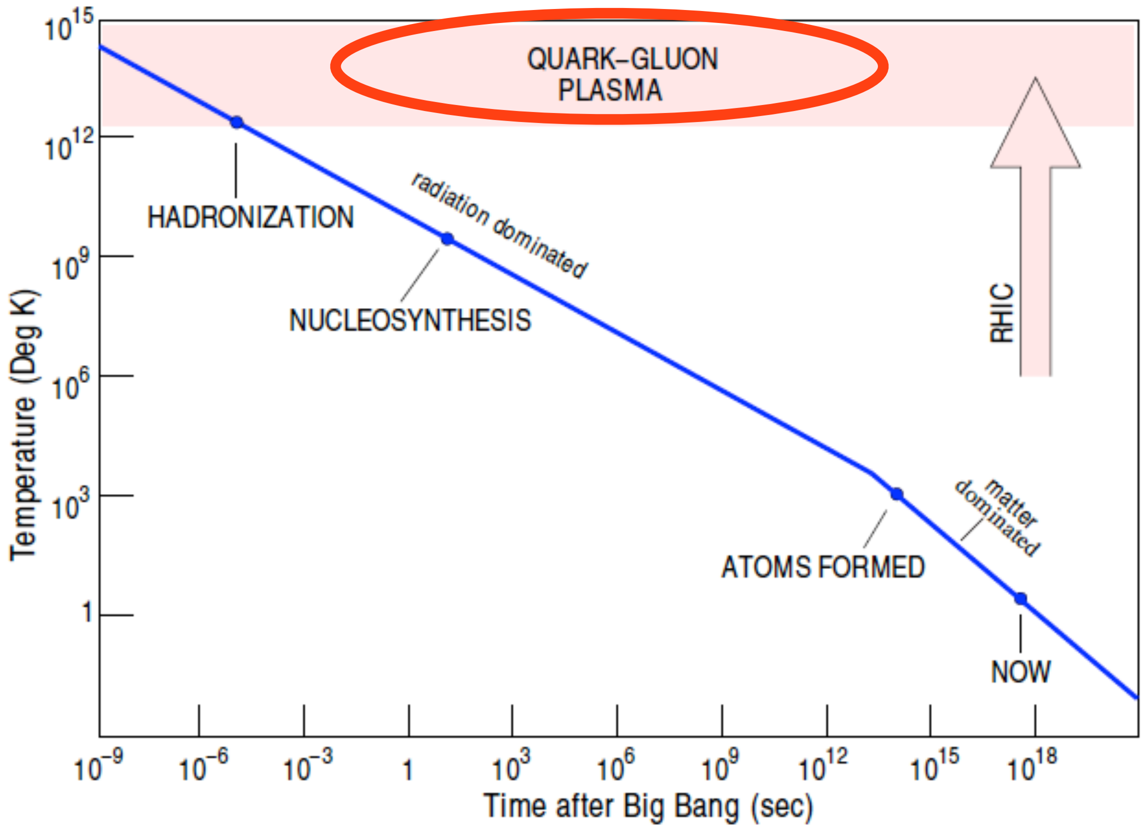


Quark Gluon Plasma (QGP): A New phase of matter

our most powerful heating machine ever

QGP: An Old Phase of Matter

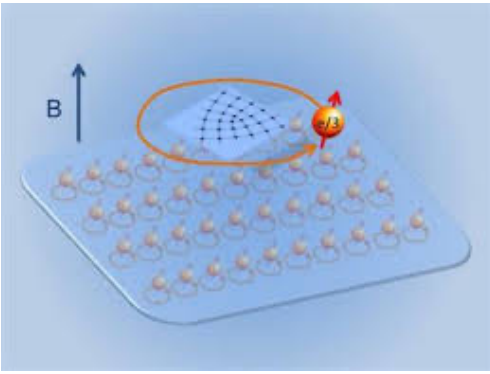
The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

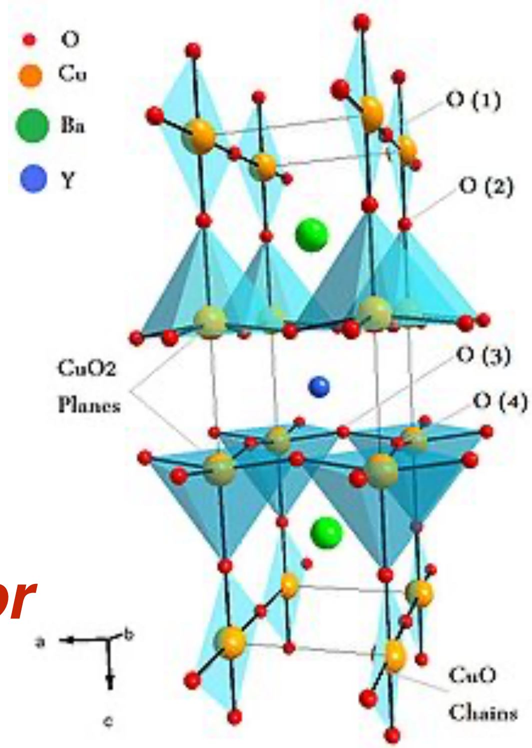


The quark-gluon plasm is an old phase of matter! Heavy ion collision is the only venue for replicating and studying the early universe environment.

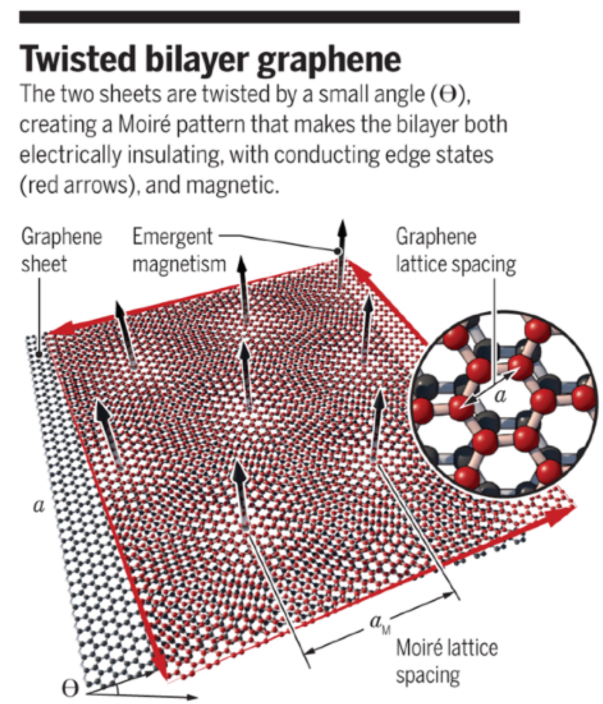
What's Next? Dialing All Knobs You've Got!

Quantum hall effect





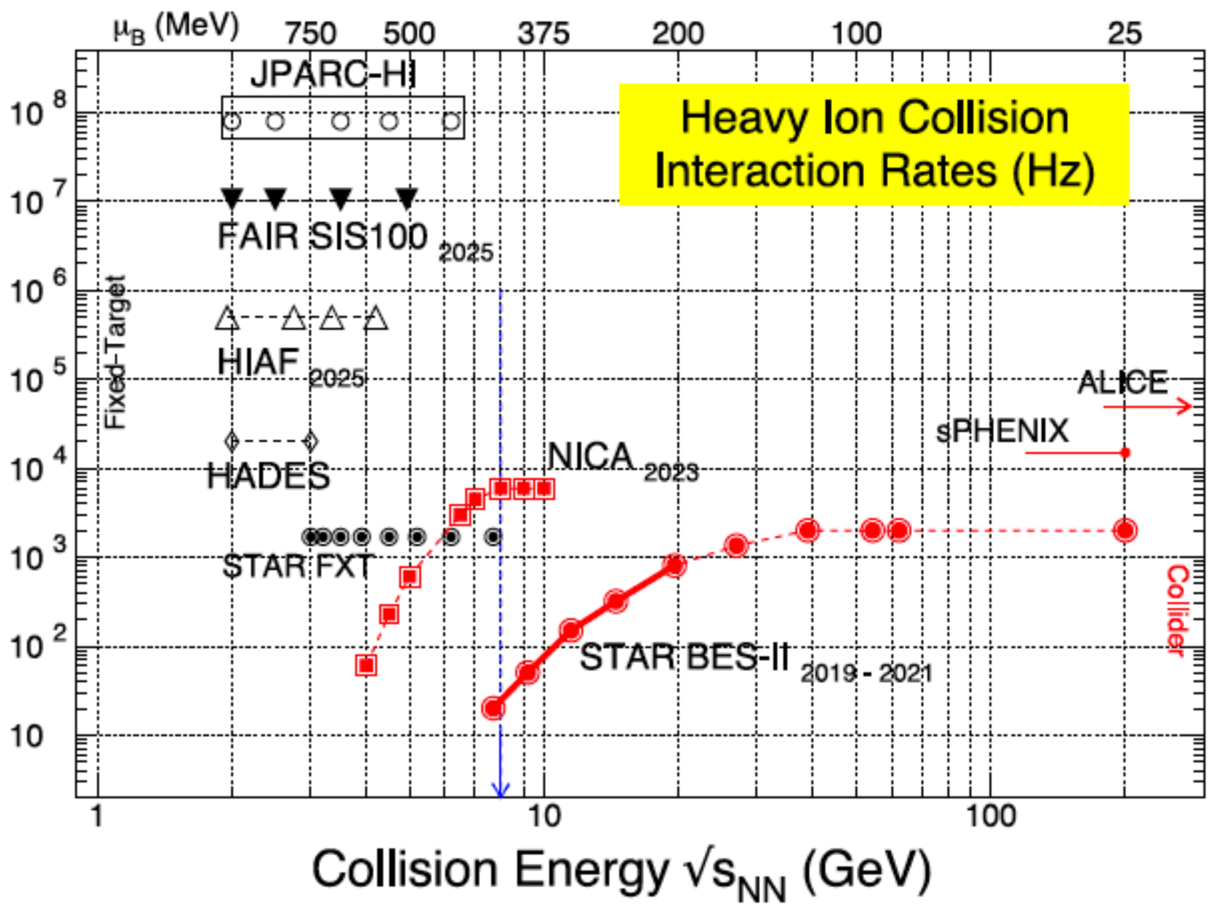
High-Tc superconductor



"Magic angle"

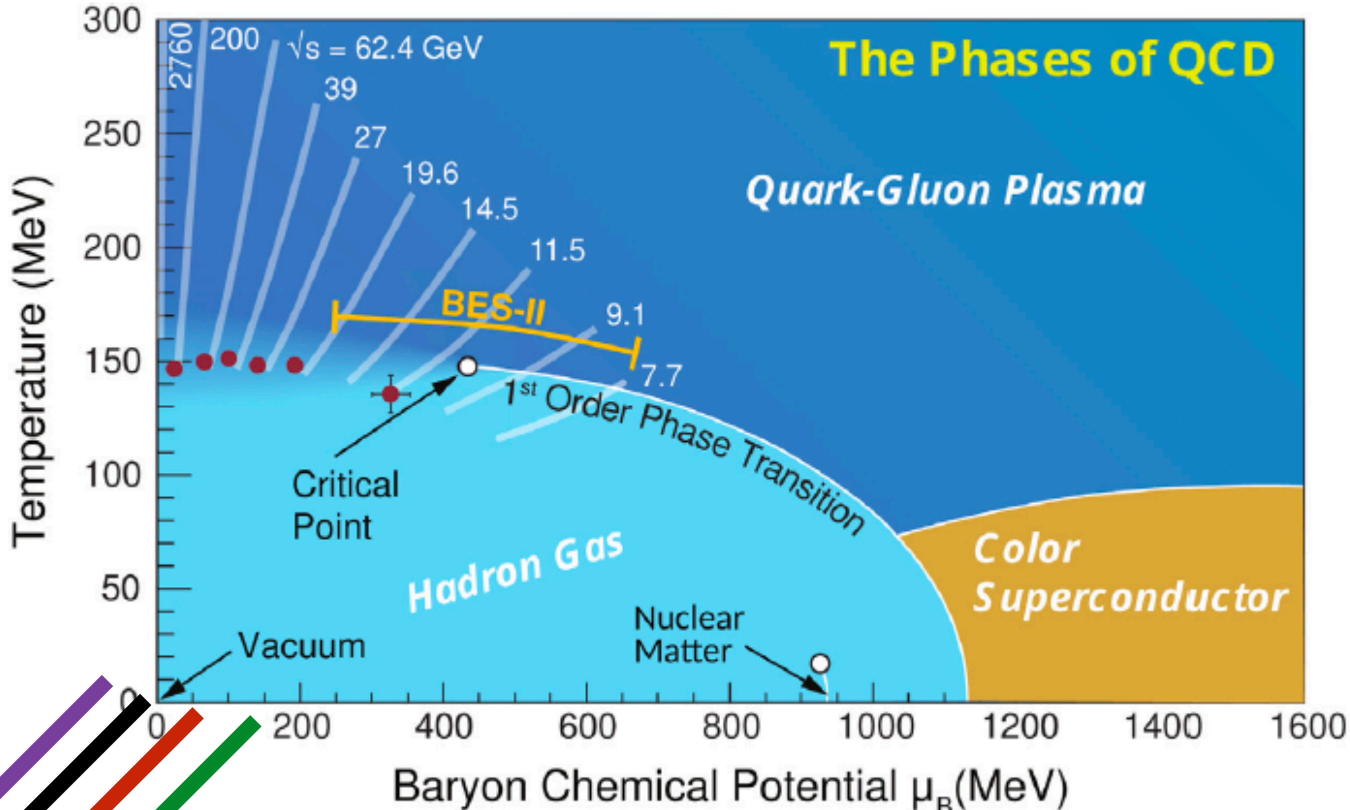
Collisions Across Wide Beam Energy Range

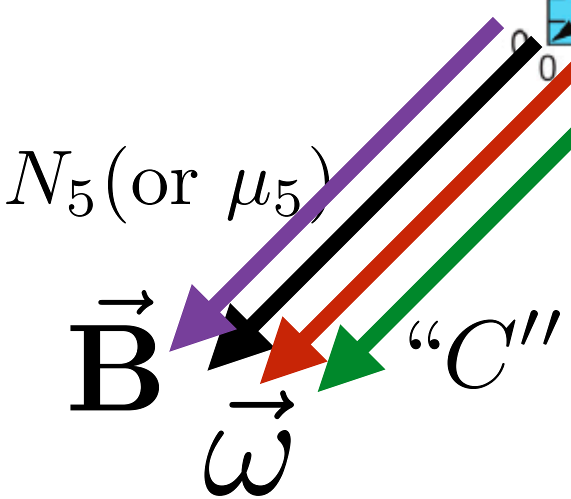
Relativistic nuclear collisions have been and will continue to be done from O(1) GeV to O(1000) GeV beam energy!



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

Charting the Quantum Chromo Matter





Opening many novel dimensions for exploring Quantum Chromo Matter!

Chiral Magnetic Effect

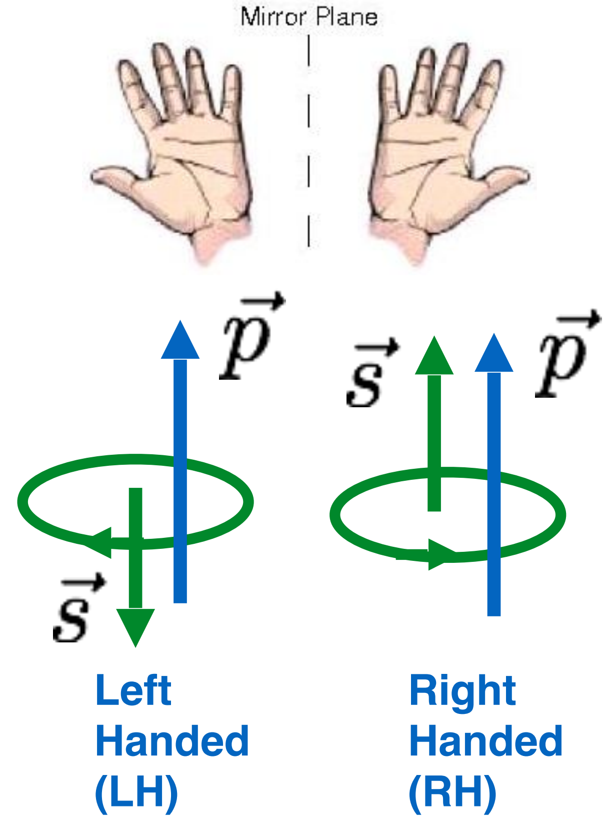
Spin & Chirality

Dirac fermion in massless limit: chirality well defined

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

Axial symmetry
—> classical conserved axial current

Specific correlation between spin and momentum!!



A (large) mass term spoils all that:

$$m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L\right)$$

$$\partial_\mu J_5^\mu = 2im\bar{\Psi}\gamma^5\Psi$$

In QCD:

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

Constituent ***SM*** ***Chiral condensate***

(Nearly) chiral quarks only upon chiral restoration

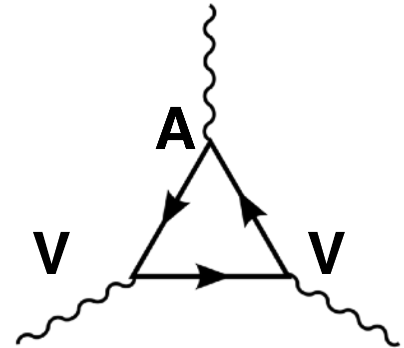
Chiral Anomaly

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

Classical axial symmetry broken at QM level:

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

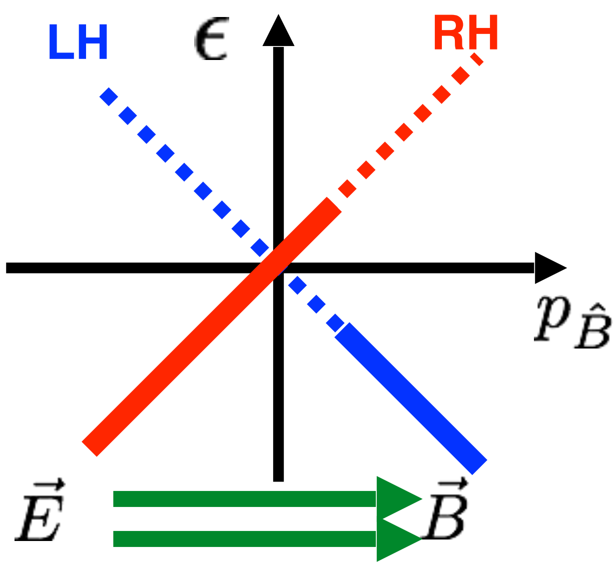
$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$



[e.g. pi0—> 2 gamma]

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Illustration based on LLL



Micro symmetry
<—>
macro properties

What does chiral anomaly imply for matter?

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

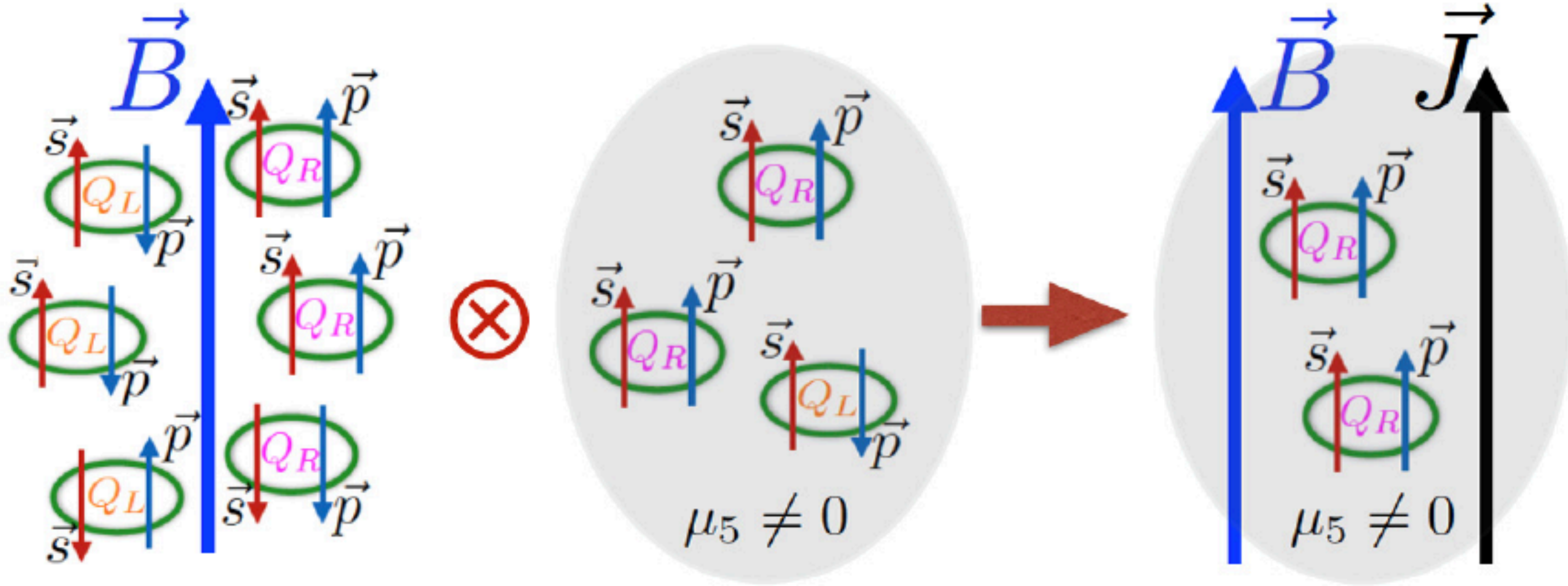
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current ← **Magnetic Field**

Q.M. Transport

[Kharzeev, Fukushima, Warringa, McLerran, …]

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

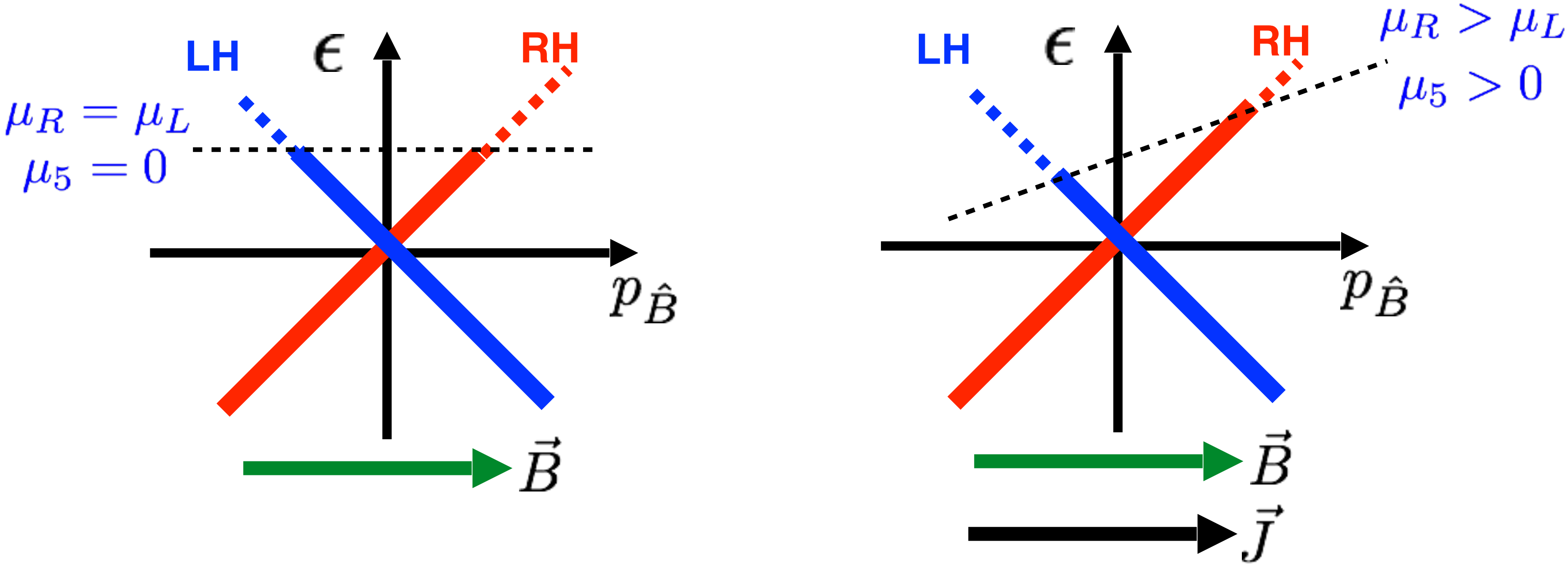
Intuitive understanding of CME:

Magnetic Polarization —> **correlation between micro. SPIN & EXTERNAL FORCE** $\otimes$ **Chirality Polarization —>** **correlation between directions of SPIN & MOMENTUM**

Transport current along magnetic field

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

Connecting CME with Anomaly



One may recognize deep connection between CME & anomaly.

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

$$\updownarrow$$

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

The CME conductivity is

**** fixed entirely by quantum anomaly***

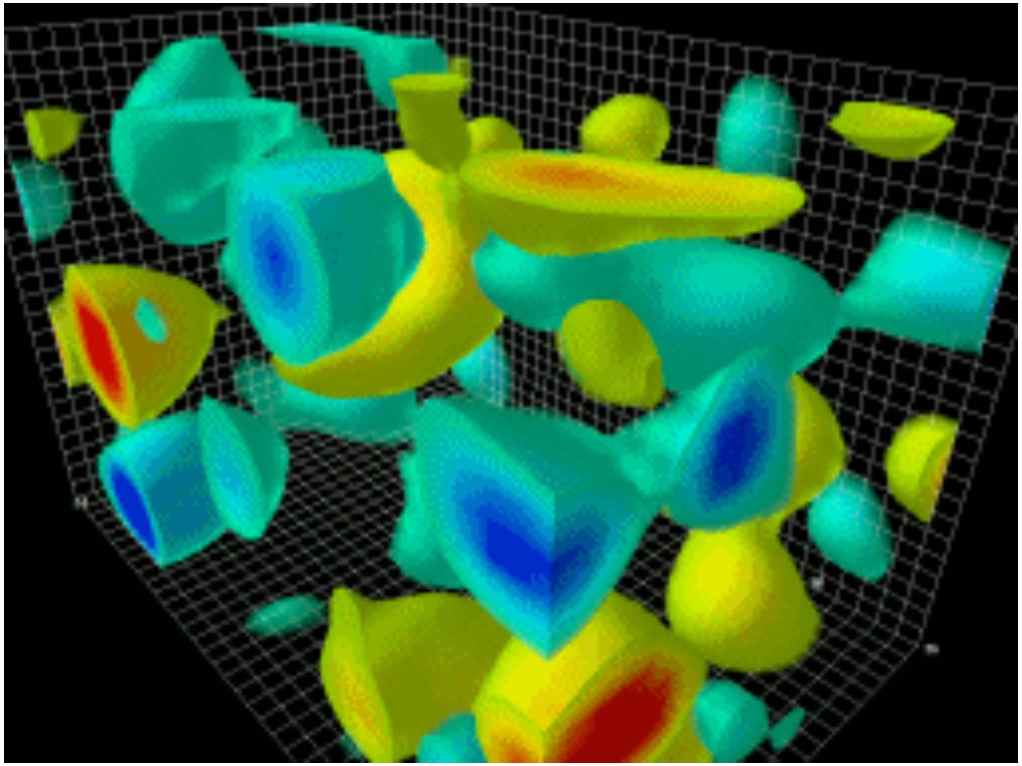
**** T-even, non-dissipative***

**** universal from weak to strong coupling***

Macroscopic effect of chiral anomaly!

Topologically Nontrivial Gluon Fields

Instantons/sphelarons:
twisting color orientation of gluon fields around spacetime boundary



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

P & CP ODD

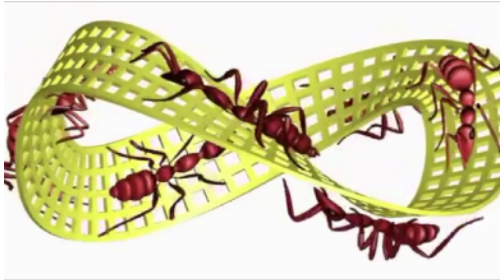
A Deep Mathematical Connection

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*

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

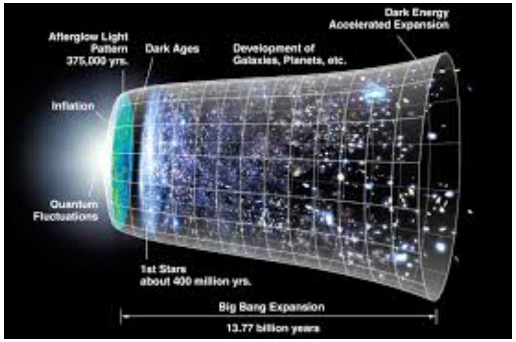


$$N_R - N_L = N_5 = 2Q_w$$

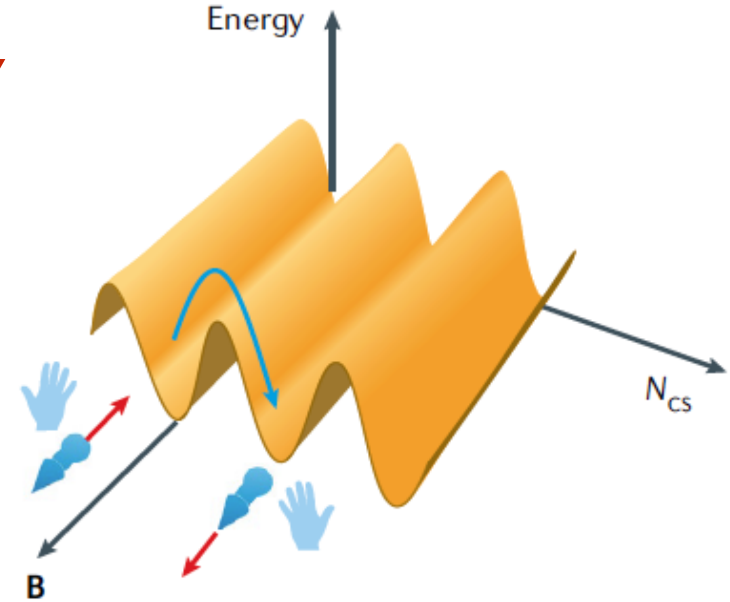
Net chirality <—> topo fluctuations & chiral restoration

Probing topology & chirality is of fundamental interest!

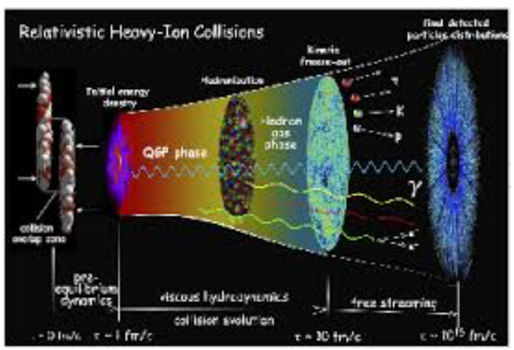
CME: A Cosmic Connection



Cosmic topo.—> Baryon Asymmetry



Rapidly expansion + Topological transitions in non-Abelian gauge plasma



Heavy ion topo.—> Chiral Asymmetry

CME allows probing this mechanism via laboratory experiments and helps understand "why we are here".

More Chiral Transport Phenomena

- *Chiral separation effect (CSE)*
- *Chiral electric separation effect (CESE)*
- *Chiral vortical effect (CVE)*
- *Chiral magnetic/vortical waves*
- *Chiral plasma instabilities*
- *……*

Strong Interdisciplinary Interests

- *Condensed matter: CME in semimetals*
- *Astrophysics: leptons in supernova / compact star*
- *Cosmology: analogy beween Baryo-genesis and Chiro-genesis*
- *Plasma physics: MHD with CME & magnetic helicity*
- *Quantum information: devices based on CME*
- *QFT & many-body theory: new "playground" (chiral transport theory; chiral hydrodynamics; …)*

Exciting Progress: See Recent Reviews

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.

Hattori, Huang, Nucl. Sci. Tech., 28 (2017) no.2, 26.

Huang, Rep.Prog.Phys 79(2016)076302.

Fukushima, arXiv:1812.08886, PPNP2019.

Zhao, Wang, arXiv:1906.11413, PPNP2019.

Li, Wang, arXiv: 2002.10397, ARNPS2020

Becattini, Lisa, arXiv: 2003.03640, ARNPS2020

Miransky & Shovkovy, Phys. Rept. 576(2015)1.

Search for CME in Heavy Ion Collisions

The Starting Point of (Modern) CME

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:hep-ph/0406125]

Laying Theoretical Foundation

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.

[arXiv:0711.0950]

[arXiv:0808.3382]

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 plasma by the axial anomaly. We study the equilibrium response of the quark-gluon plasma in such a situation to an external magnetic field. To mimic the effect of the topological charge changing transitions we will introduce a chiral chemical potential. We will show that an electromagnetic current is generated along the magnetic field. This is the Chiral Magnetic Effect. We compute the magnitude of this current as a function of magnetic field, chirality, temperature, and baryon chemical potential.

Starting Point of Exp Search

Parity violation in hot QCD: how to detect it

Sergei A. Voloshin

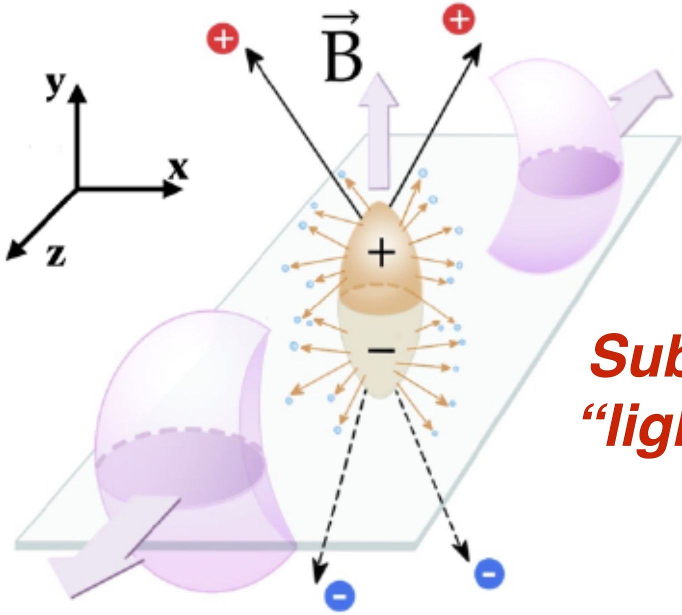
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201

(Dated: November 2, 2018)

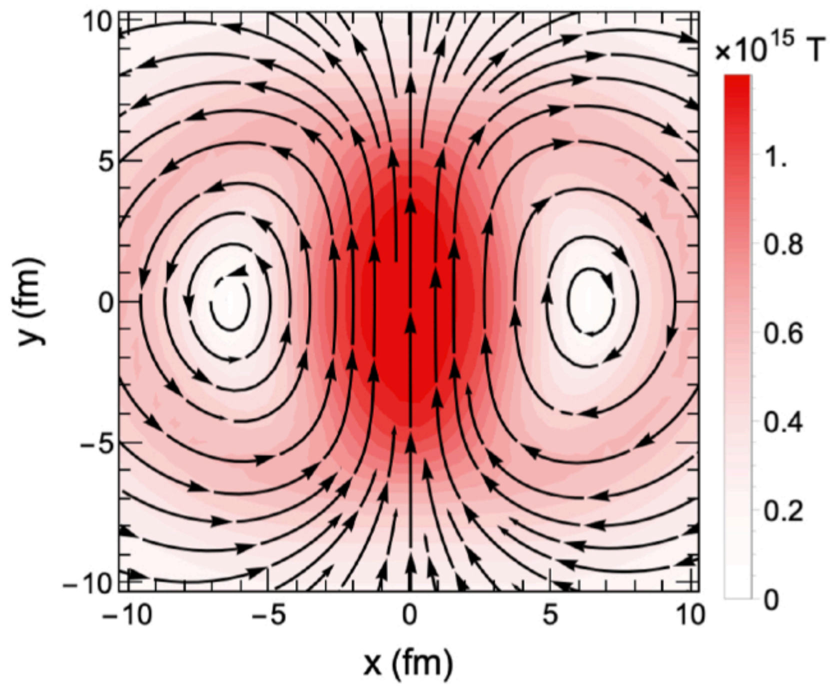
In a recent paper (arXive:hep-ph/0406125) entitled *Parity violation in hot QCD: why it can happen, and how to look for it*, D. Kharzeev argues for the possibility of $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry 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.

[arXiv:hep-ph/0406311]

Heavy Ion Collision: the Most Magnetized Fluid



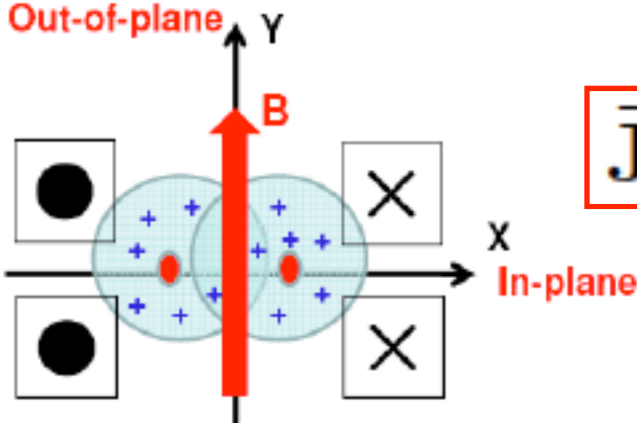
Subatomic "lightning"!



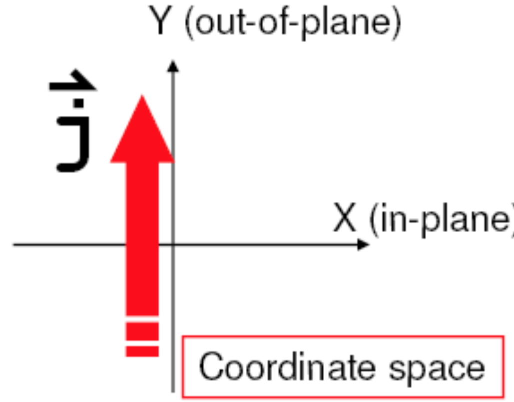
The strongest B field ~ 10^15 Tesla

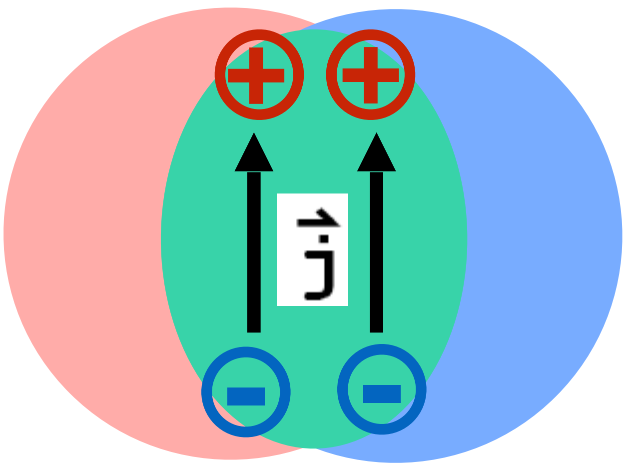
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

From CME to Charge Separation

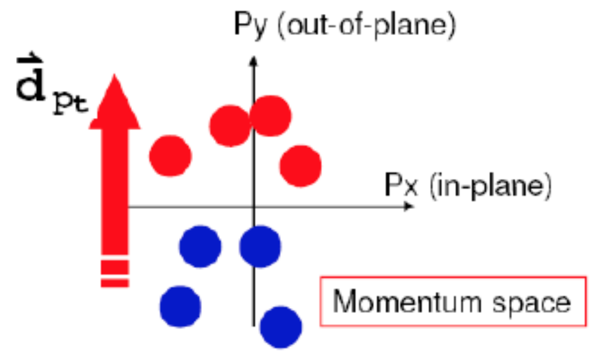


$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$





strong radial blast: position —> momentum



Charge Separation *or*
Electric Dipole in Pt Space
*(along **out-of-plane**)*

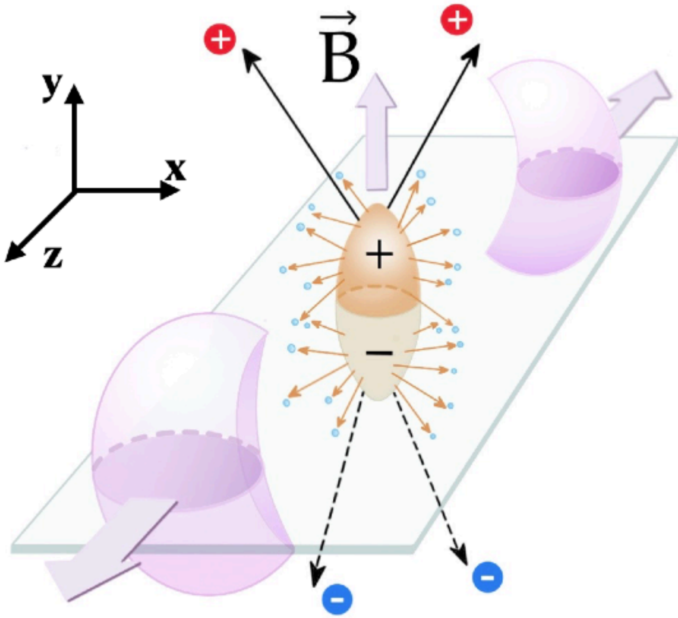
$$\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})$$

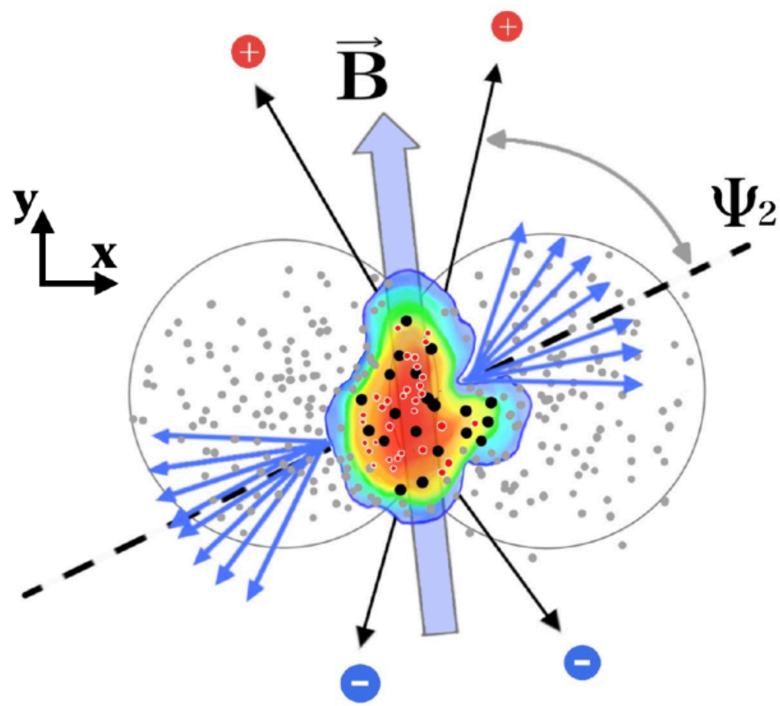
$$< a_\pm > \sim \pm < \mu_5 > B$$

[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

Looking for CME Signals in Nuclear Collisions

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





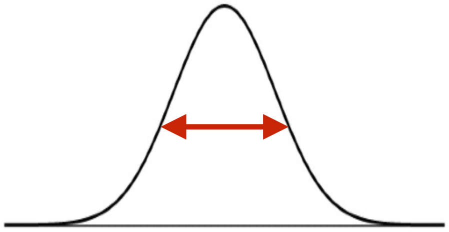
A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

The Gamma Correlator

$$\frac{dN_{\pm}}{d\phi} \propto \ldots + a_{\pm} \sin(\phi - \Psi_{RP}) \qquad < a_{\pm} > \sim \pm < \mu_5 > B$$

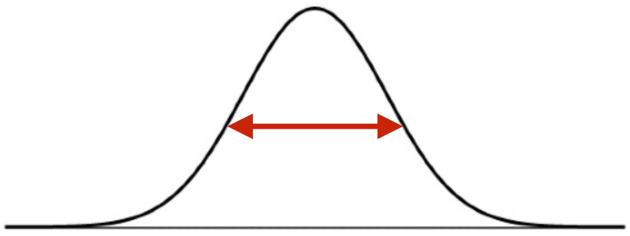
Average gives zero; can only look for fluctuations/variance!

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



Looking for a dipole fluctuation DIFFERENCE between In-plane and out-of-plane

Looking for DIFFERENCE between same-sign pairs and opposite-sign pairs



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

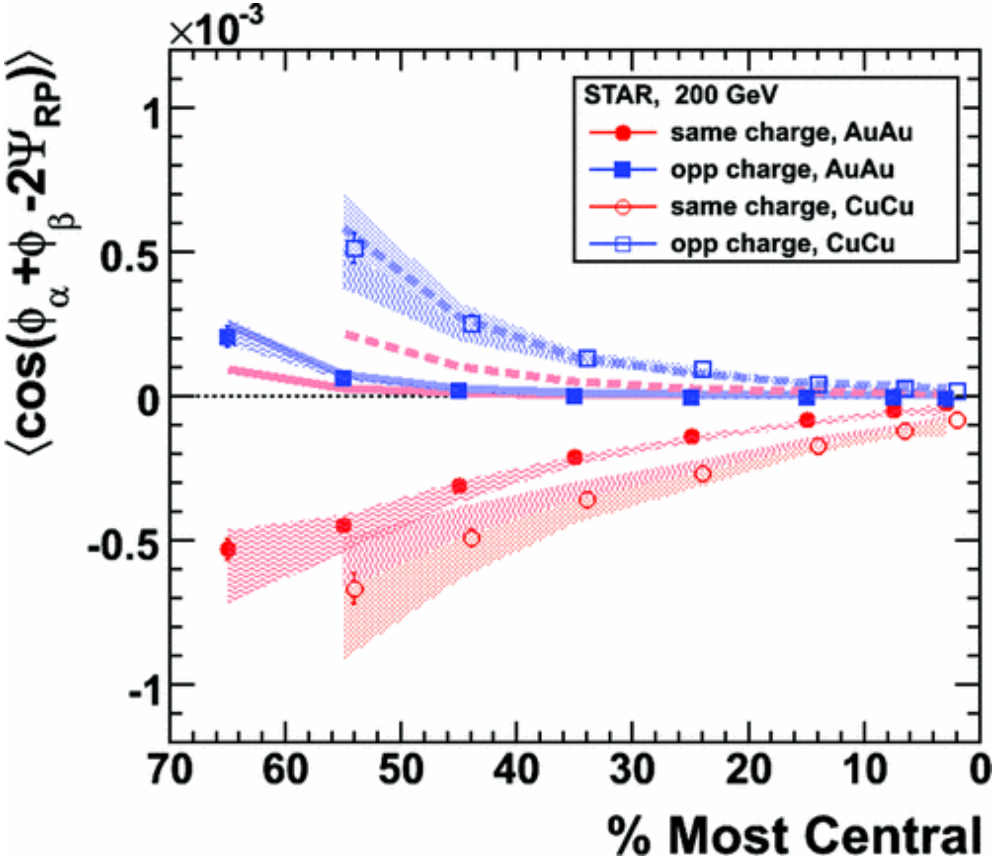
$$\gamma^{OS}_{CME} \rightarrow +\langle a_1^2 \rangle$$

The 2009 STAR Results

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 <u>could be</u> in line with CME expectations.



(Almost Immediate) Skepticism

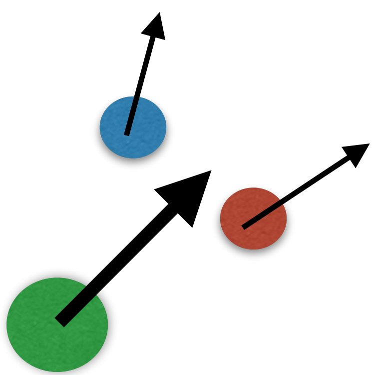
[F. Wang, arXiv:0911.1482] **Resonance decay**

Effects of Cluster Particle Correlations on Local Parity Violation Observables

Fuqiang Wang[1]

[1]*Department of Physics, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907*

We investigate effects of cluster particle correlations on two- and three-particle azimuth correlator observables sensitive to local strong parity violation. We use two-particle angular correlation measurements as input and estimate the magnitudes of the effects with straightforward assumptions. We found that the measurements of the azimuth correlator observables by the STAR experiment can be entirely accounted for by cluster particle correlations together with a reasonable range of cluster anisotropy in non-peripheral collisions. Our result suggests that new physics, such as local strong parity violation, may not be required to explain the correlator data.



Roughly scaling
~ v2 / N

Alternative Contributions to the Angular Correlations Observed at RHIC Associated with Parity Fluctuations

Scott Pratt

Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory,
Michigan State University
East Lansing, Michigan 48824

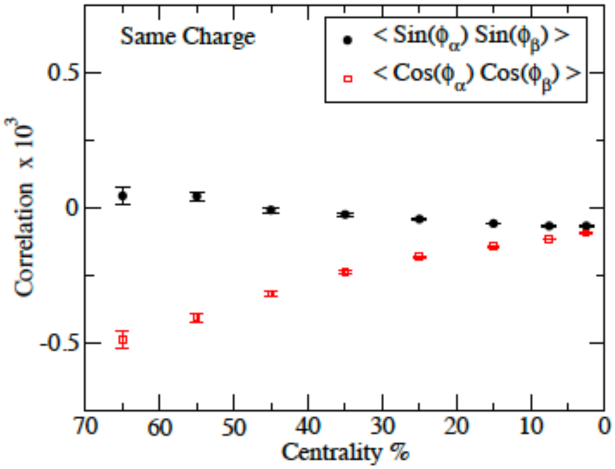
(Dated: April 13, 2019)

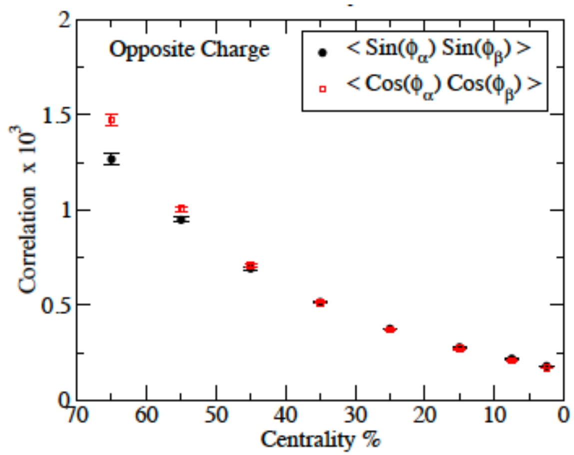
Recent measurements at RHIC of angular correlations of same-sign vs. opposite sign pairs have been interpreted as evidence for large-scale fluctuations of parity-odd fields. In this paper, we provide alternative explanations of the same phenomena based on correlations from charge and momentum conservation overlaid with elliptic flow. These effects are shown to produce correlations with similar magnitudes as those measured. Other correlations are also considered, but estimates of their size suggest they are inconsequential.

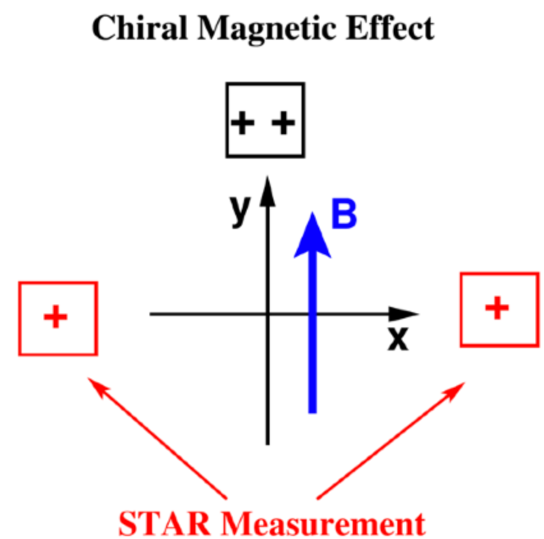
Local charge conservation (LCC) **[S. Pratt, arXiv:1002.1758]**

(Almost Immediate) Skepticism

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







Transverse momentum conservation (TMC)

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

Facing the Setback

$\hat{O} \times 10^3$	$\langle\cos(\phi_1+\phi_2)\rangle_{++}$	$\langle\cos(\phi_1+\phi_2)\rangle_{+-}$	$\langle\cos(\phi_1-\phi_2)\rangle_{++}$	$\langle\cos(\phi_1-\phi_2)\rangle_{+-}$
CME	$-(0.1-1)$	$+(0.01-0.1)$	$+(0.1-1)$	$-(0.01-0.1)$
LCC	~ 0	$+(0.1-1)$	~ 0	$+(1-10)$
TMC	~ -0.1	~ -0.1	~ -1	~ -1
DATA	-0.45	$+0.06$	-0.38	$+1.97$

[Bzdak, Koch, JL: arXiv:1008.4919]

Redefining the question:
Is there anything remaining?
What fraction of gamma could still be from CME?

Not the time to give up yet!
— think about the search for e.g. EDM, WIMP, 2-beta decay, magnetic monopoles, …

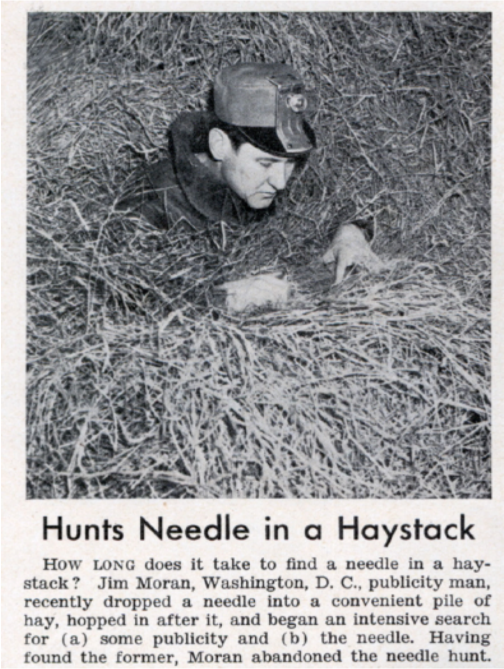


Image source: http://blog.modernmechanix.com/hunts-needle-in-a-haystack/

Fighting with Backgrounds

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]

$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

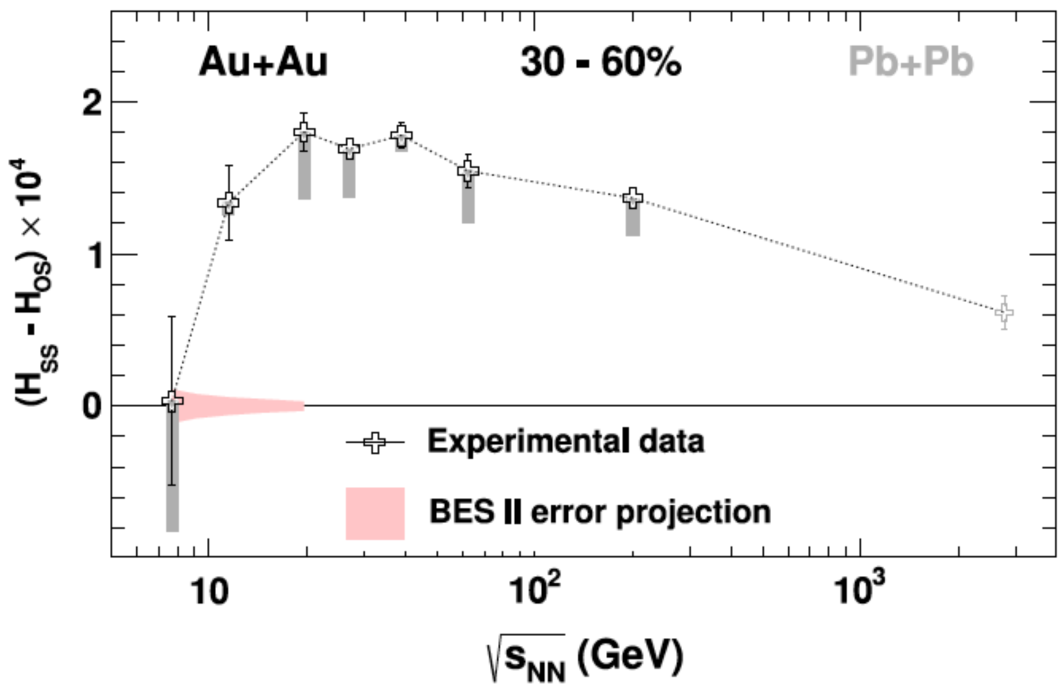
Various new approaches:

Vary v2 for fixed B:

AuAu v.s. UU;
Varying event-shape;
2-component subtraction.

Vary B for fixed v2:

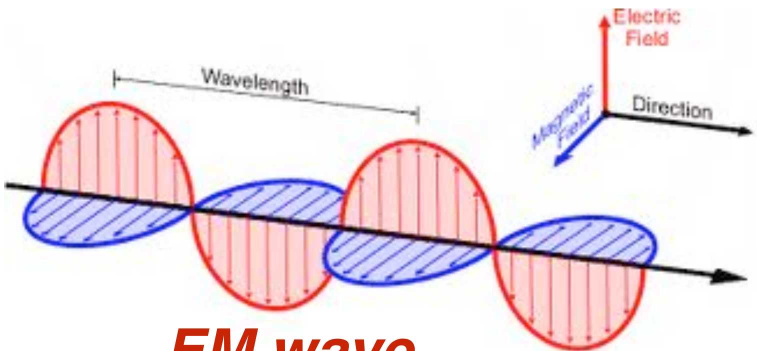
Isobaric collisions with
RuRu v.s. ZrZr



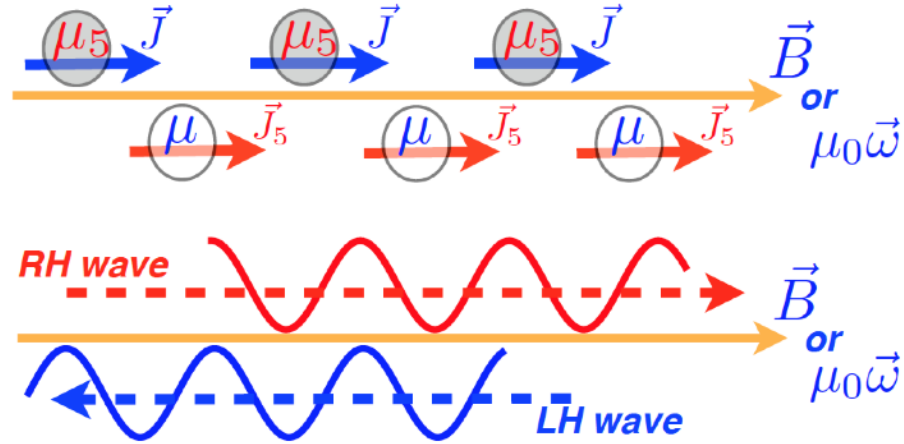
STAR PRL2014

Chiral Magnetic Wave (CMW)

Wave: propagating "oscillations" of two coupled quantities
e.g. sound wave (pressure & density); EM wave (E & B fields)



EM wave



Chiral Magnetic Wave

CME + CSE —> gapless collective excitations, the CMW

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

$$\vec{\mathrm{J}}_5 = \sigma_5 \mu \vec{\mathrm{B}}$$

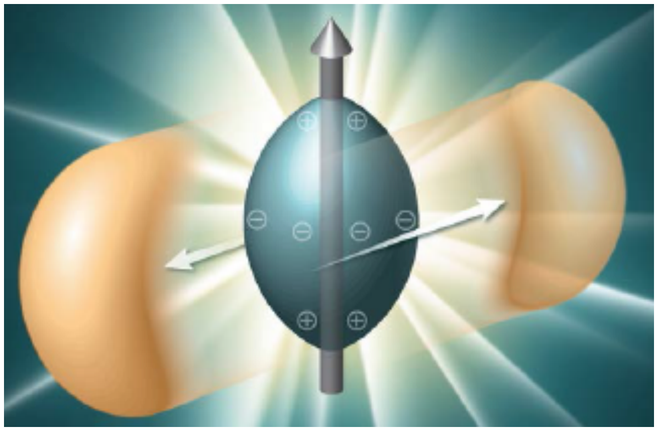
$$\Rightarrow \quad \left(\partial_0 \pm \frac{(Qe)}{(4\pi^2)\chi}\vec{\mathrm{B}}\cdot\nabla\right)\delta J^0_{R/L} = \left(\partial_0 \pm v_B \partial_{\hat{\mathrm{B}}}\right)\delta J^0_{R/L} = 0.$$

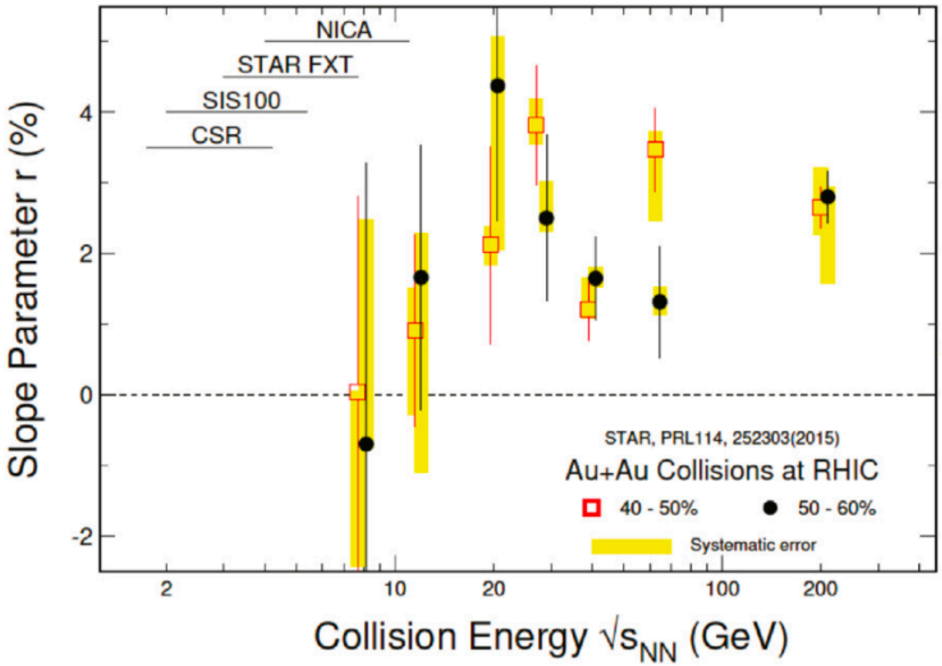
[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, 2011]

CMW Induced Flow Splitting

CMW —> charge quadrupole of QGP —> elliptic flow splitting

[Burnier, Kharzeev, JL, Yee, PRL2011; and arXiv: 1208.2537]





$$v_2^- - v_2^+ = r_e\, A$$

charge quadrupole due to CMW transport

Positive exp. hints

[STAR, PRL2015]

[Also seen by ALICE@LHC]

Toward the Next Stage (~2015)

– *A status report*

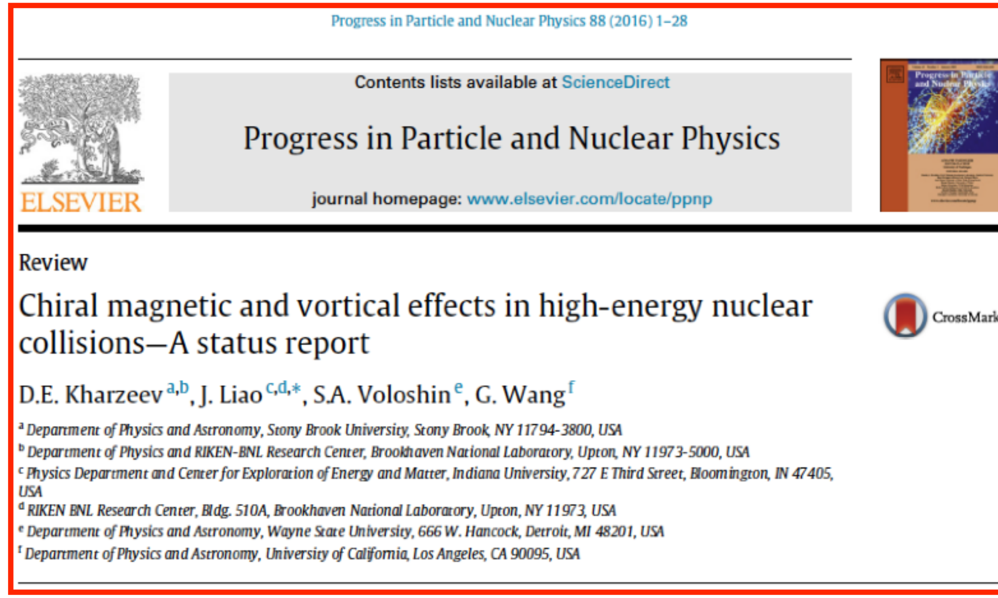
– *CME in semimetals*

– *Quark Matter 2015*

– *Chirality meeting series*

– *Beam Energy Scan Theory (BEST) Collaboration*

– *Isobar task force*


Progress in Particle and Nuclear Physics 88 (2016) 1–28

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

D.E. Kharzeev[a,b], J. Liao[c,d,*], S.A. Voloshin[e], G. Wang[f]

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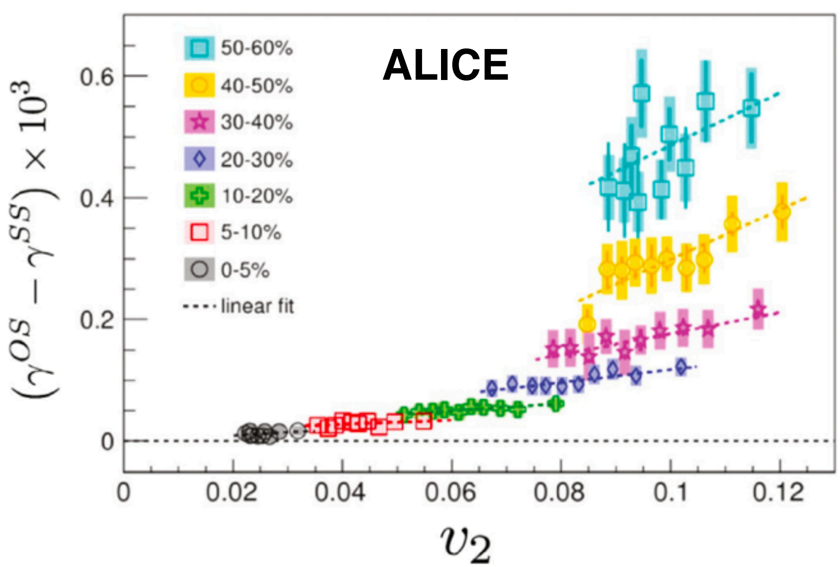
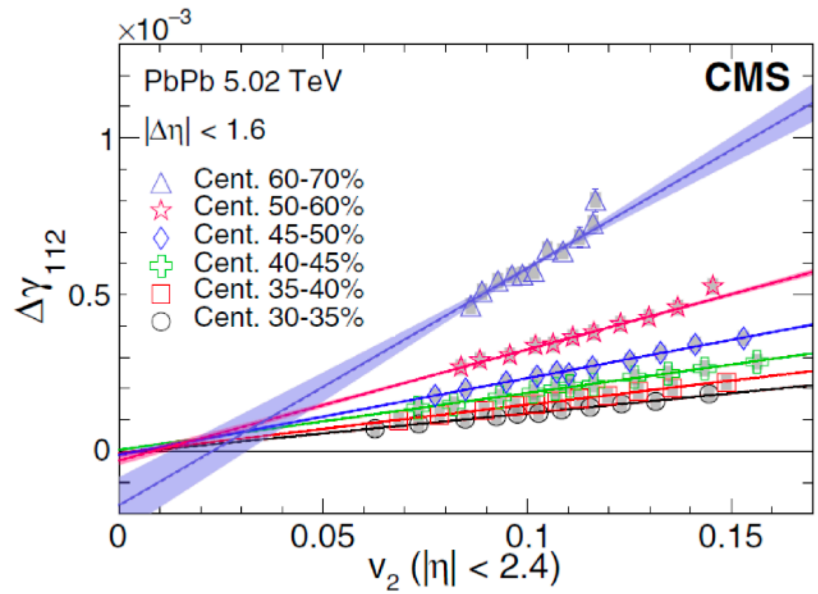
[b] Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[c] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 727 E Third Street, Bloomington, IN 47405, USA
[d] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48201, USA
[f] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

Prog. Part. Nucl. Phys. 88(2016)1-28 [arXiv: 1511.04050]

Strong Exp. Activities

- *New analysis strategies to extract signal out of backgrounds*
- *Efforts by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, PbPb*

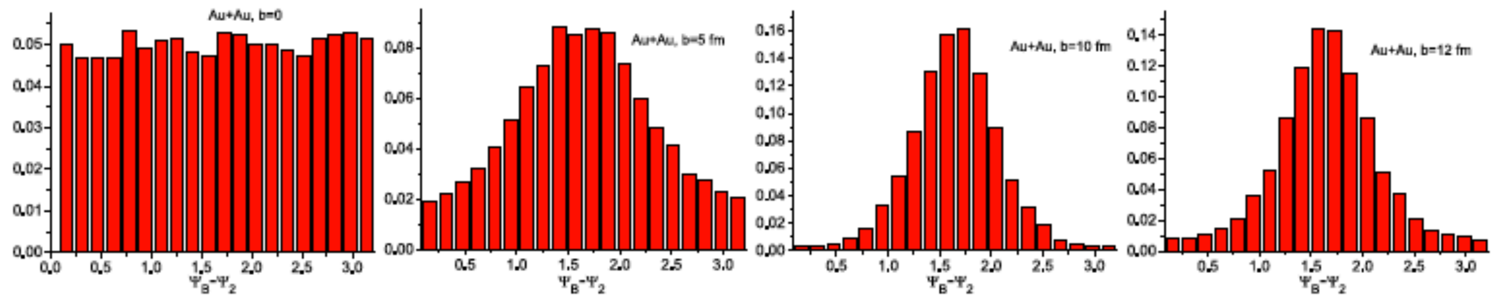




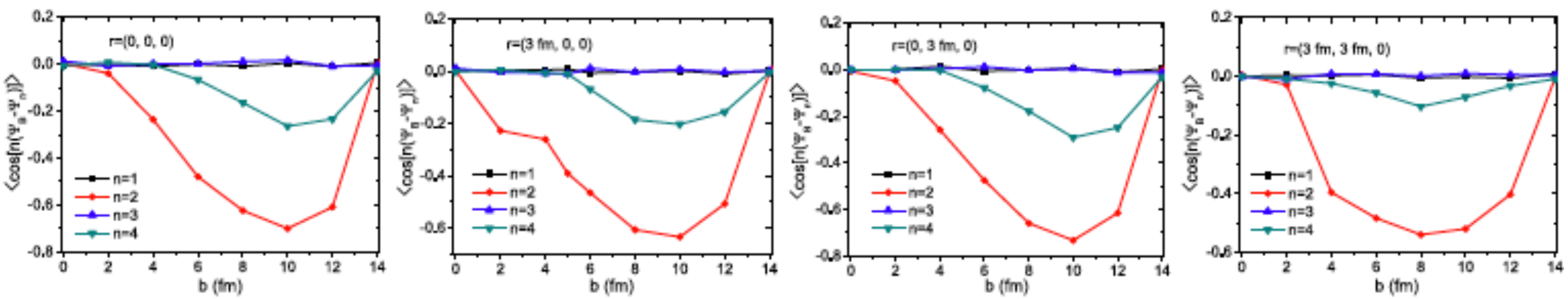
Event shape engineering

Strong Exp. Activities

- *New analysis strategies to extract signal out of backgrounds*
- *Efforts by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, PbPb*



Bloczynski, Huang, Zhang, JL arXiv:1209.6594[PLB]



Fuqiang. Wang, et al; also Voloshin: gamma-RP versus gamma-EP

Strong Exp. Activities

- *New analysis strategies to extract signal out of backgrounds*
- *Efforts by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
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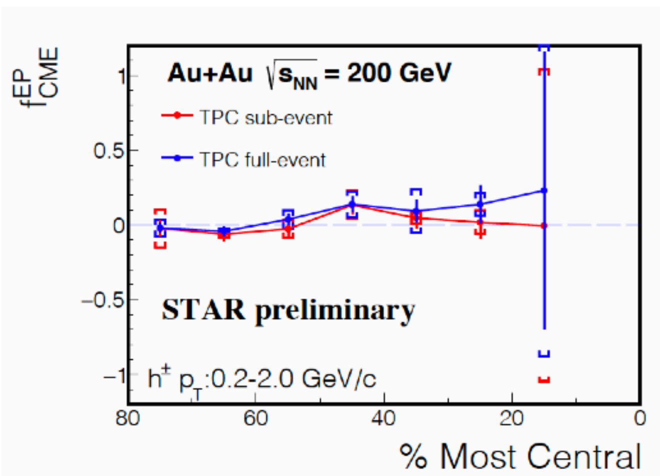
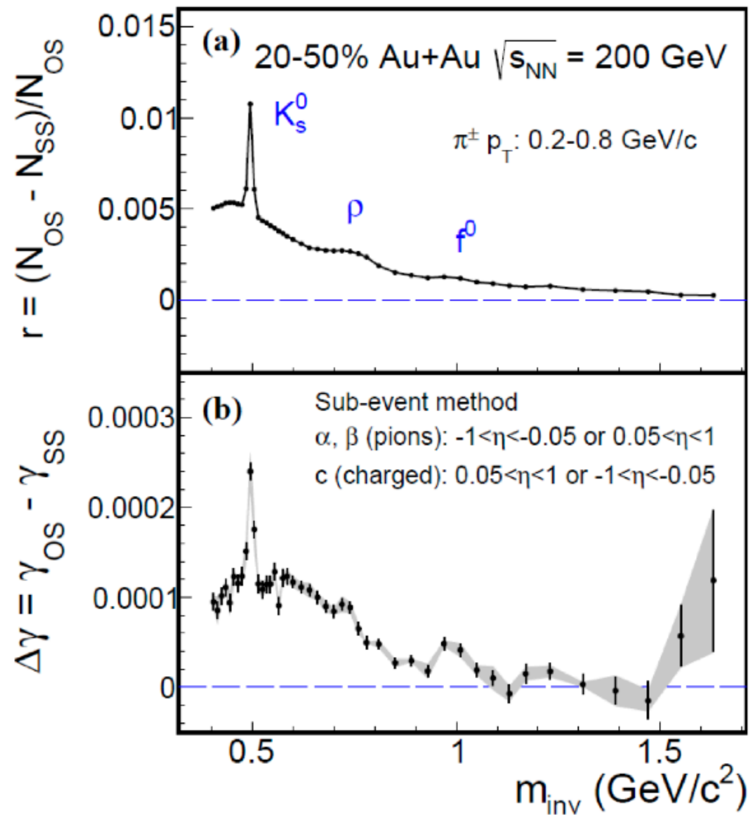


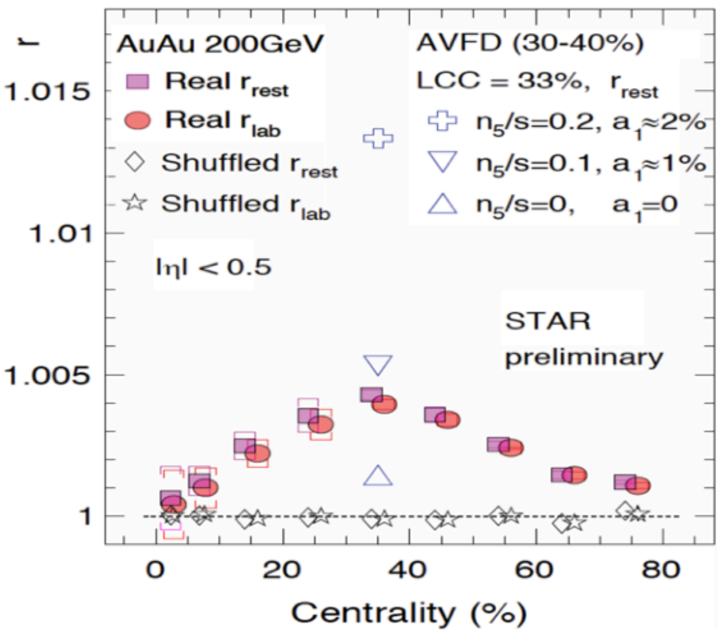
Extraction of signal ratio via EP/RP



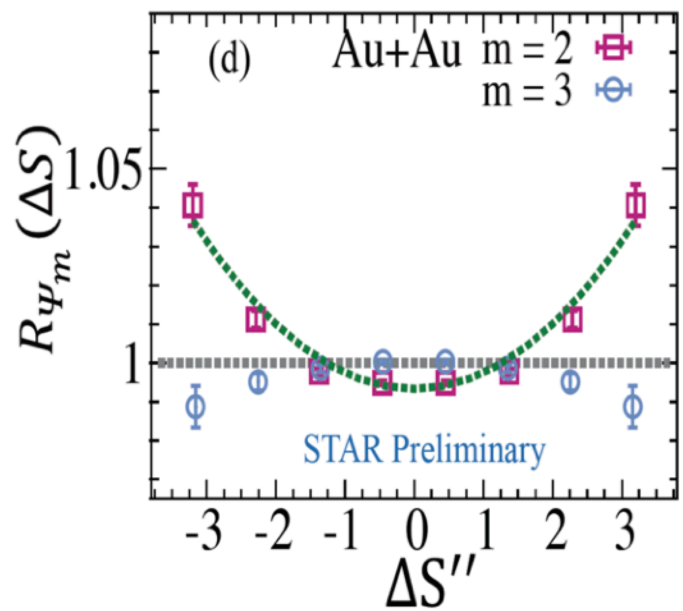
Invariant mass selection

Strong Exp. Activities

- *New analysis strategies to extract signal out of backgrounds*
- *Efforts by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, XeXe, PbPb*



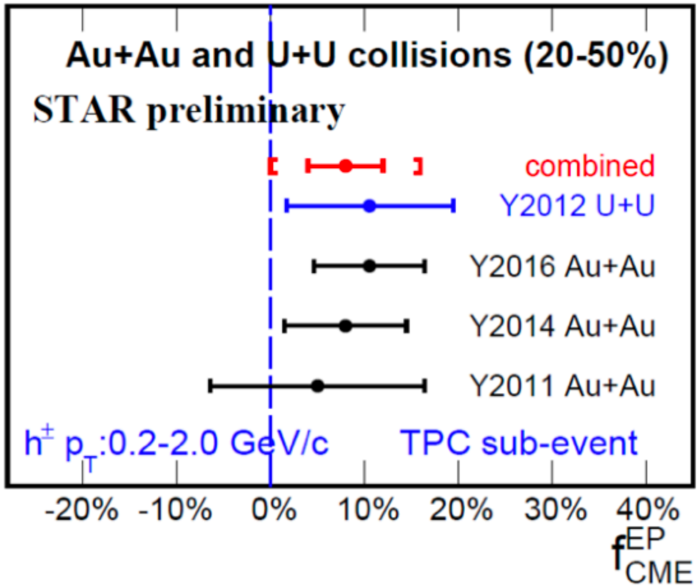
A. Tang:
Signed balance function

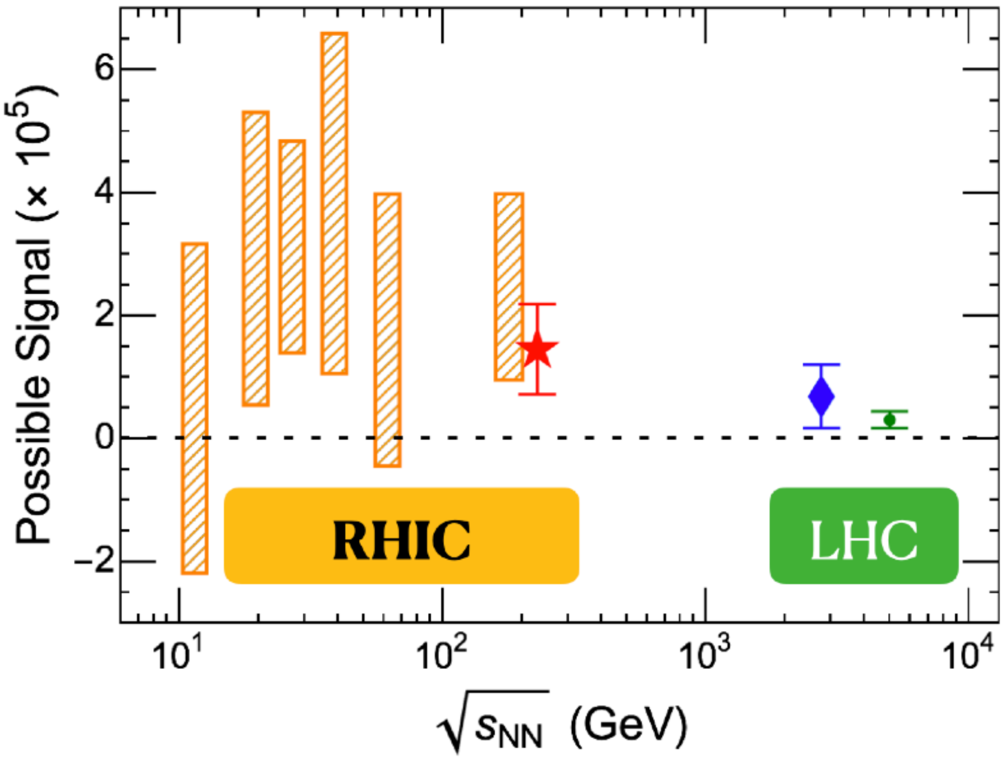


R. Lacey, et al:
R-correlator

Where Did We Stand (till ~2020)?

[STAR compilation @QM19]



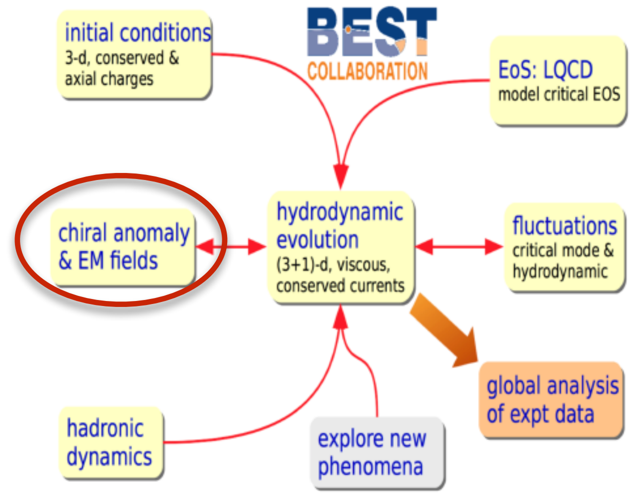


A very positive hint, yet inconclusive.

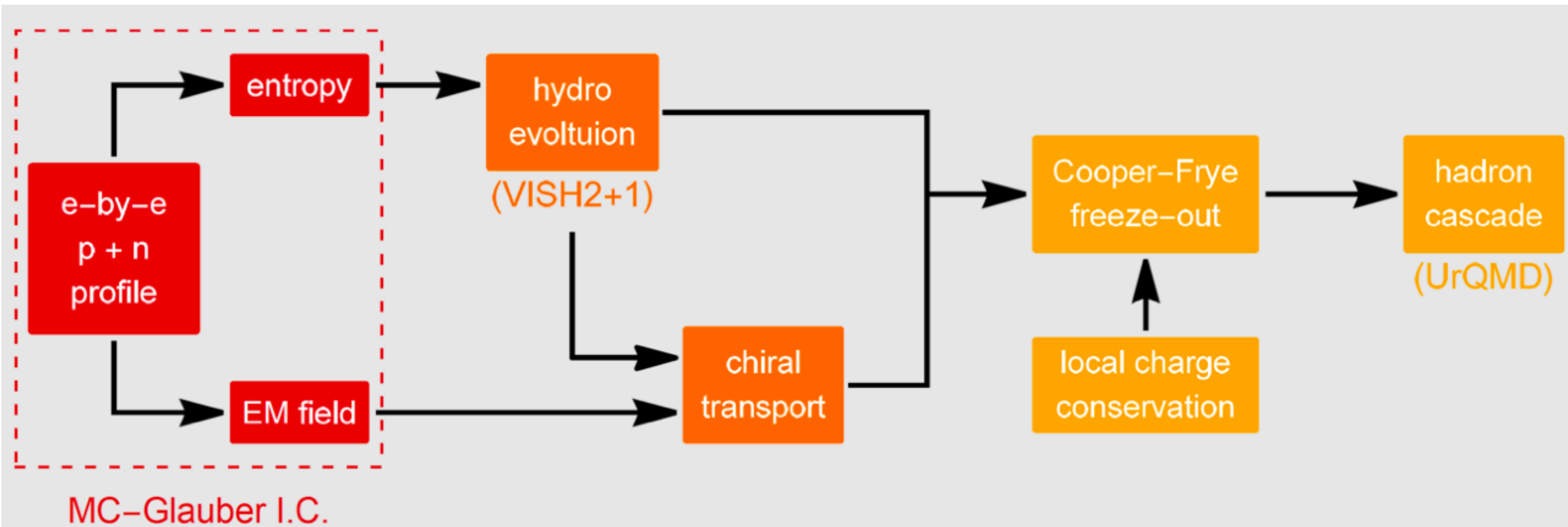
[Kharzeev, JL, arXiv:2102.06623; Nature Rev Phys 3, 55-63 (2021)]

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

Anomalous-Viscous Fluid Dynamics

$$D_\mu J_R^\mu = +\frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = -\frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2}\mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2}\mu_L B^\mu$$

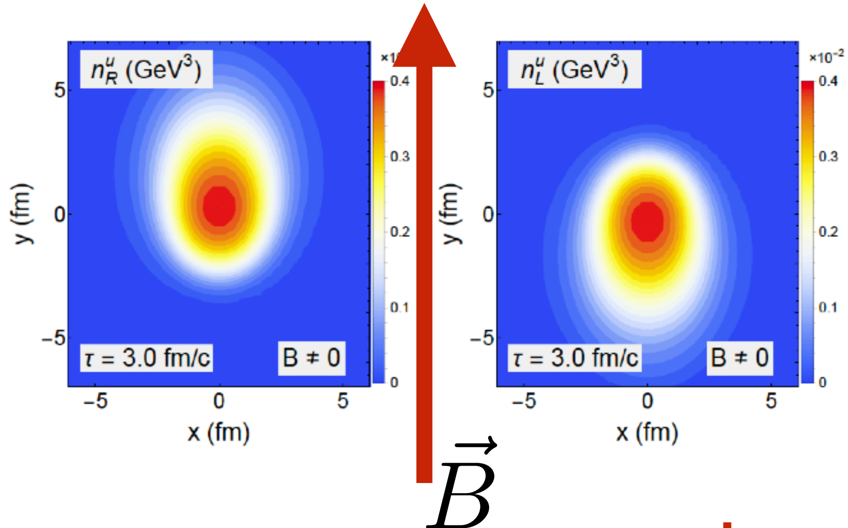
CME

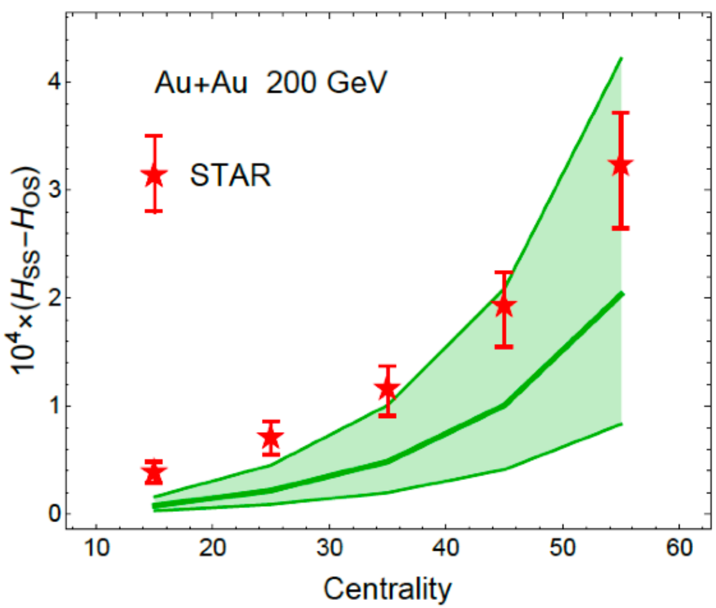
Viscous Effect

$$\Delta^\mu{}_\nu \, d\, \nu_{R,L}^\nu = -\frac{1}{\tau_{rlx}}(\nu_{R,L}^\mu - \nu_{NS}^\mu)$$

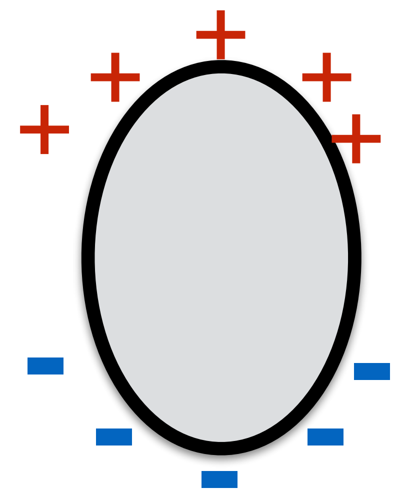
$$\nu_{NS}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

on top of VISH2+1D –– OSU Group





Chirality imbalance
–>
R/L asymmetry
–>
charge asymmetry



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

EBE-AVFD as a Key Theoretical Tool

EBE-AVFD has now become a widely used tool for developing CME observables, calibrating sensitivity to signals and backgrounds, as well as obtaining quantitative understanding of data.

Chinese Physics C Vol. 46, No. 1 (2022) 014101

Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment*

Subikash Choudhury[1] Xin Dong[2] Jim Drachenberg[3] James Dunlop[4] ShinIchi Esumi[5] Yicheng Feng(冯毅程)[6] Evan Finch[7] Yu Hu(胡昱)[1,4] Jiangyong Jia[4,8] Jerome Lauret[4] Wei Li[9] Jinfeng Liao(廖劲峰)[10] Yufu Lin(林裕富)[11,12†] Mike Lisa[13] Takafumi Niida[5] Robert Lanny Ray[14] Masha Sergeeva[15] Diyu Shen(申迪宇)[1‡] Shuzhe Shi(施舒哲)[16] Paul Sorensen[4] Aihong Tang(唐爱洪)[4] Prithwish Tribedy[4] Gene Van Buren[4] Sergei Voloshin[17] Fuqiang Wang(王福强)[6] Gang Wang(王钢)[15] Haojie Xu(徐浩洁)[18] Zhiwan Xu(徐之湾)[15] Nanxi Yao[15§] Jie Zhao(赵杰)[6]

[STAR CME & Shuzhe Shi & JL, CPC46(2022)4,014101, arXiv:2105.06044]

Transport Model Studies of CME

*** Approach based on transport models.**

– ***AMPT based***
(Guoliang Ma, Yugang Ma, X.G. Huang, ……)

Refs:
Phys.Rev. C94 (2016) 041901; Phys. Rev. C 97, 044901 (2018);
Phys. Rev. C 97, 024910 (2018);Phys. Rev. C 99, 034903 (2019);
Phys. Lett. B 792 (2019) 413; Phys. Rev. C 99, 054906 (2019);
Phys.Rev.C 101 (2020) 2, 024916.

– ***Chiral kinetic transport based***
(Che-ming Ko and collaborators)

Refs:
Phys.Rev.C 98 (2018) 1, 014911; Phys.Rev.C 95 (2017) 3, 034909;
Phys.Rev.C 94 (2016) 4, 045204; Phys.Lett.B 769 (2017) 219-222.

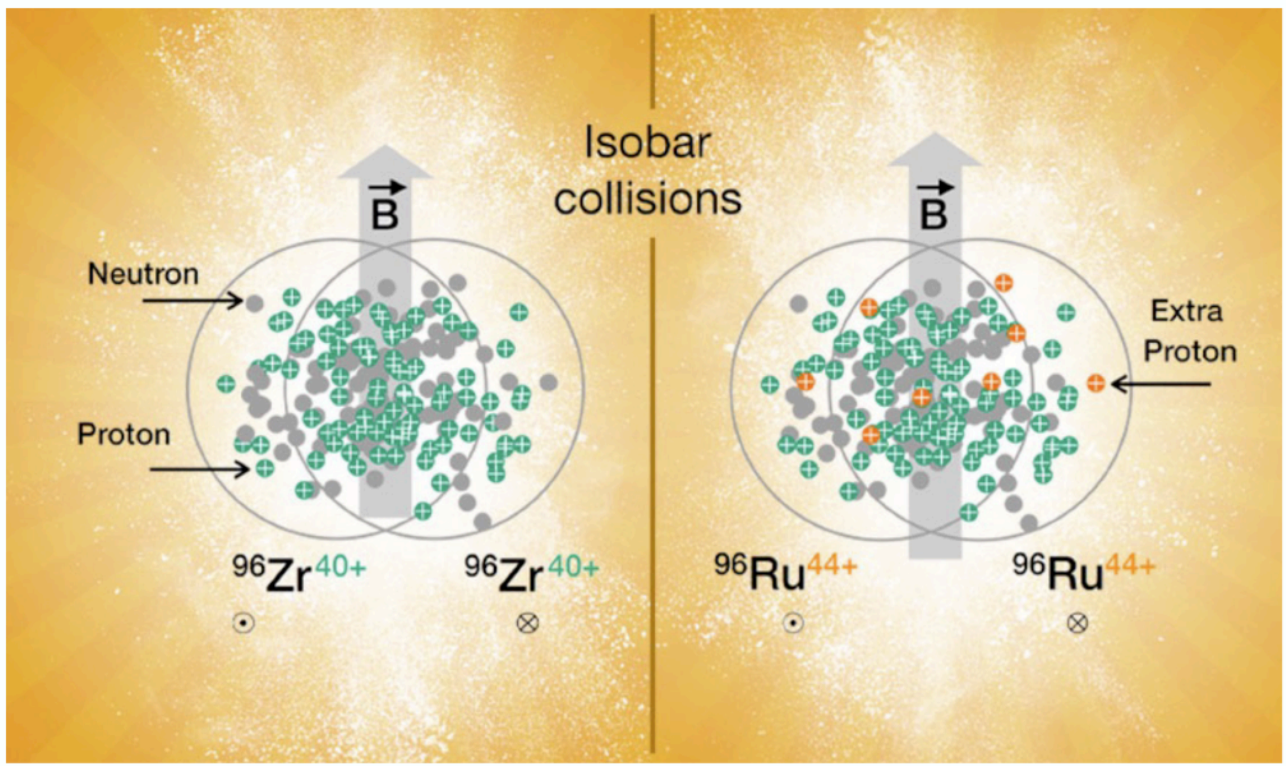
Isobar Collisions

A New Hope: Isobar Collisions

[Voloshin, PRL105,172301(2011)] *[arXiv:1608.00982]*

Chiral Magnetic Effect Task Force Report

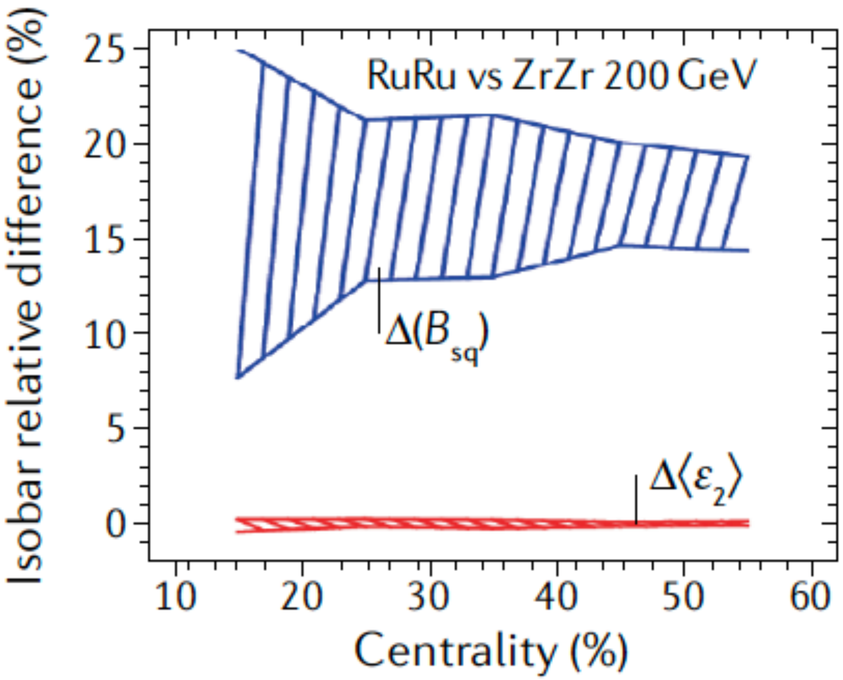
Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

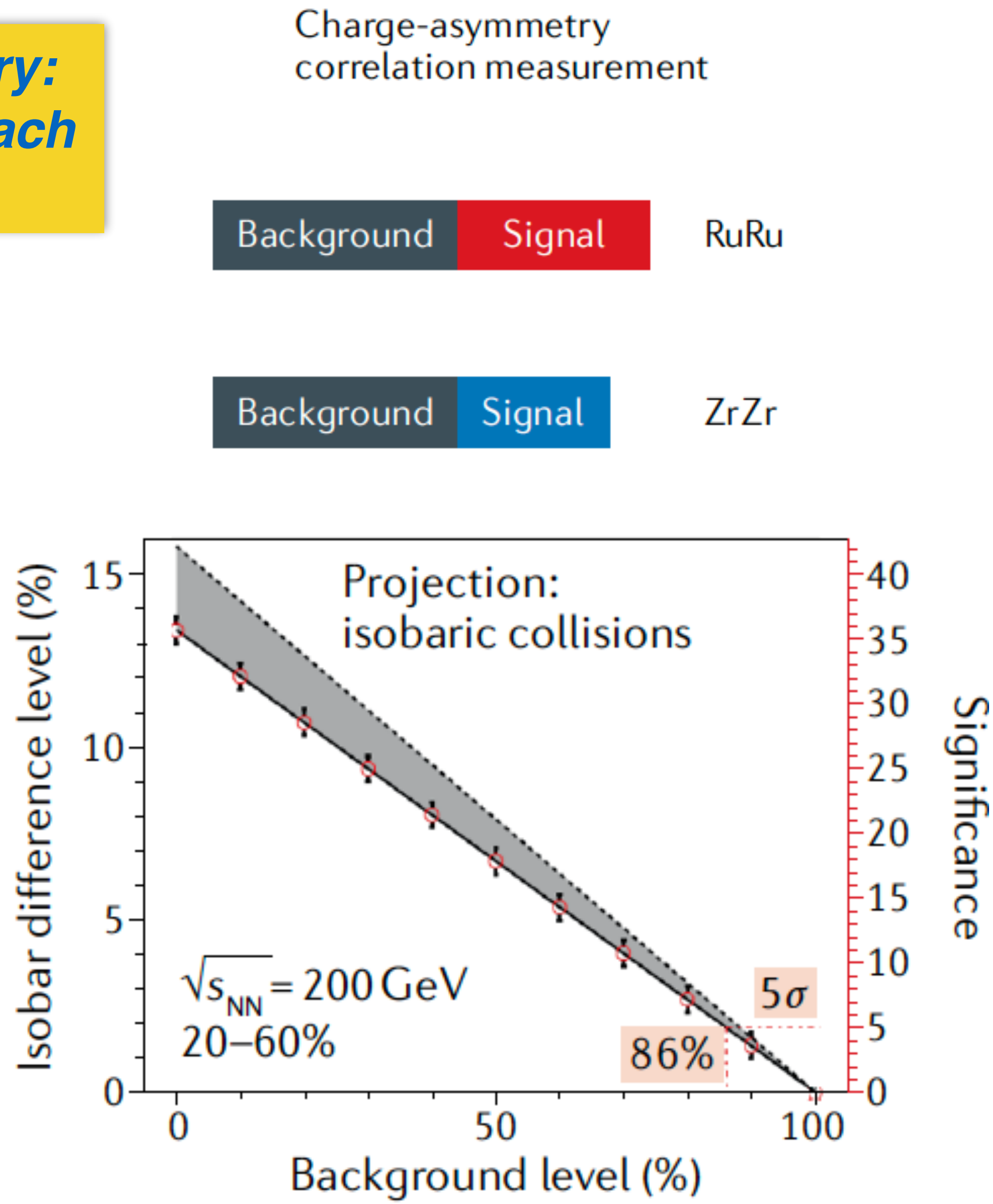


[image from Helen Caines talk @ Chirality 2021]

Isobar Collision Experiment

Exciting opportunity of discovery: ~2 billion events collected for each system; results in ~ months!!!





More discussions in Nature Reviews Physics 3, 55-63 (2021) [arXiv:2102.06623]

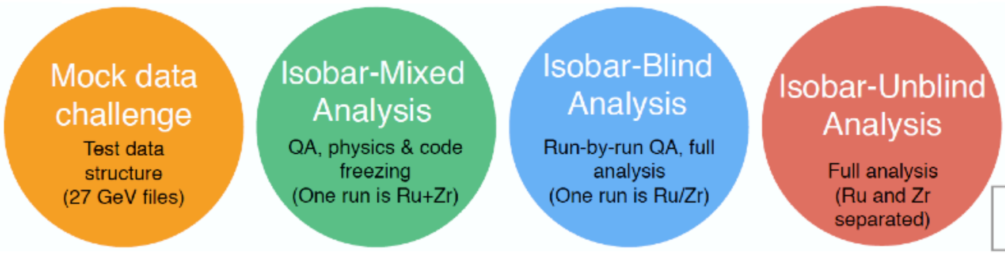
The Blind Analyses

Decision to blind the analyses

2017 PAC recommended ***blind analyses*** of ***CME*** using Run-18 isobar data

Methods developed and accepted by collaboration in January 2018, well before 2018 data-taking

[image from Helen Caines talk @ Chirality 2021]



STAR, arXiv:1911.00596
Cartoon: arXiv:2009.01230

Step-1, "The Reference"

Provide output files composed of collision data from a ***mix*** of the two isobar species

As much as possible, order of collision "events" ***respects time-dependent changes in detector conditions***

Analysis code and **time-dependent QA** tuned and frozen

Step-2, "The run by run QA sample"

Provide files that blind the isobar species but do not "mix" data from different data acquisition runs

Only allow "run-by-run" corrections and code alteration directly resulting from these correctior

Step-3, Full un-blinding

Analysis completed and published as is

Combined effort of many many people in STAR

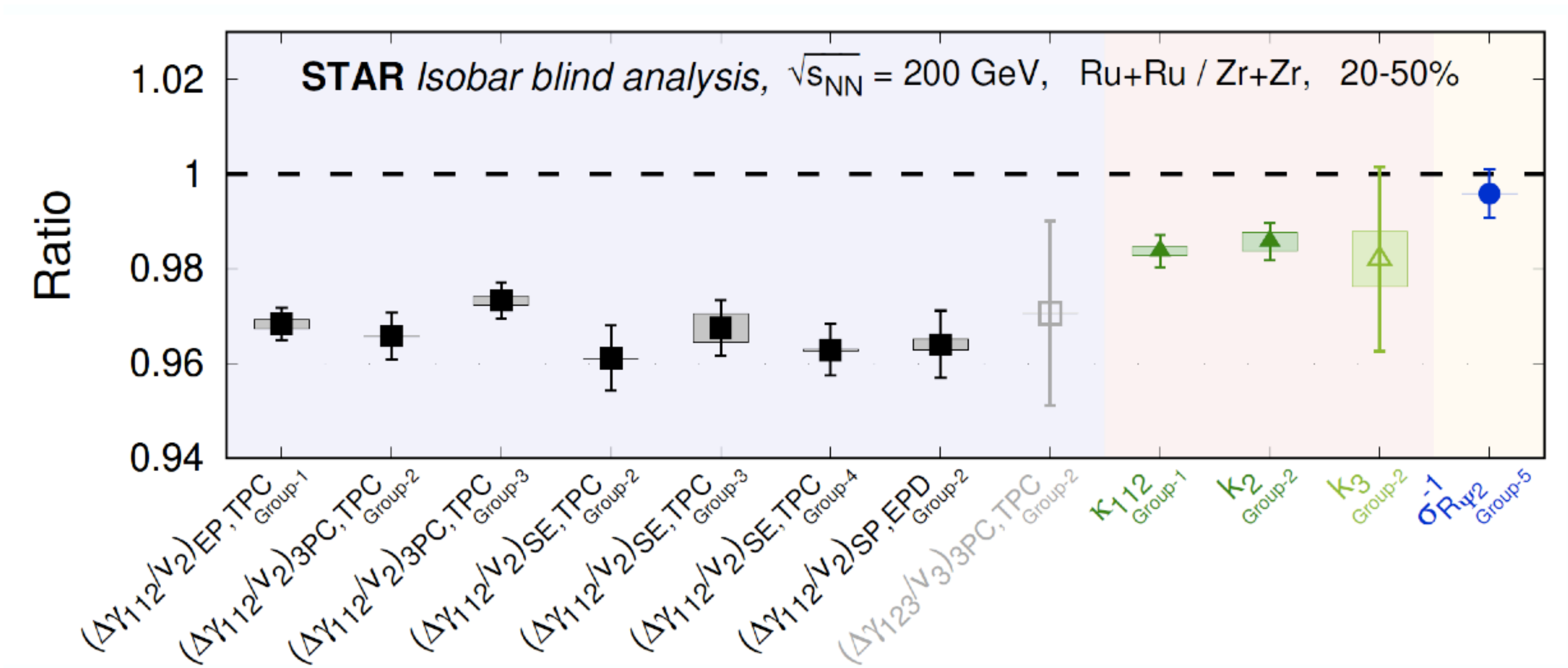
[STAR Collaboration, Nucl.Sci.Tech. 32 (2021) 5, 48]

The Isobar Collision Experiment

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

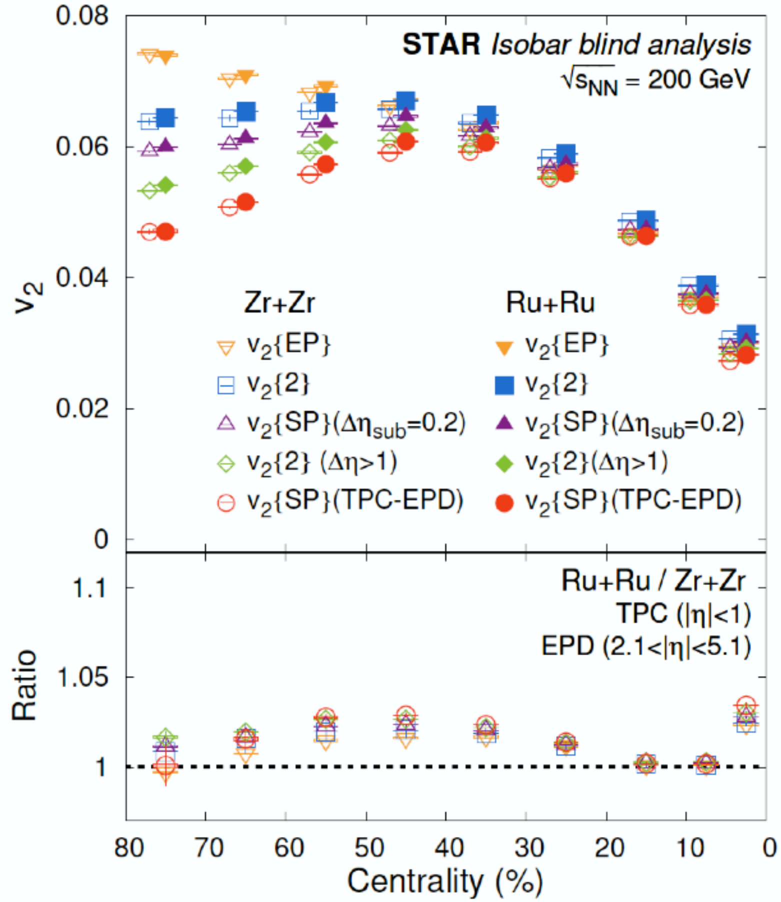
Predefined criteria:
Signal(Ru)/Signal(Zr) > 1

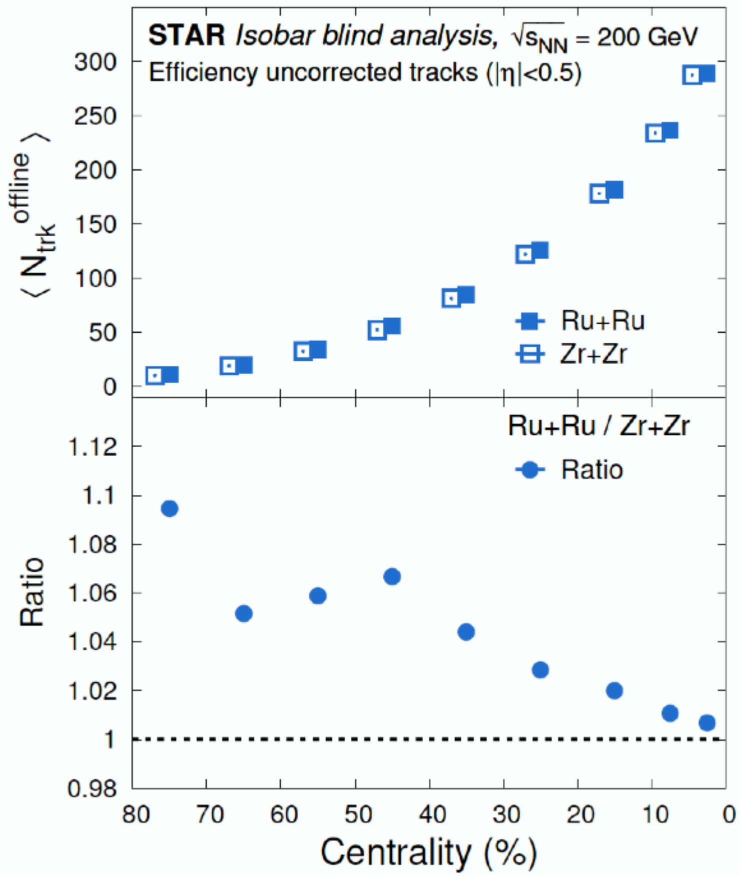
[STAR paper: 2109.00131
Phys.Rev.C 105 (2022) 1, 014901]



Predefined baseline (background only):
Signal(Ru)/Signal(Zr) =1

The Trouble: A Failed Assumption





A few percent level of difference in the bulk properties between the isobar pairs: non-identical background correlations!

The Isobar Collision Experiment

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

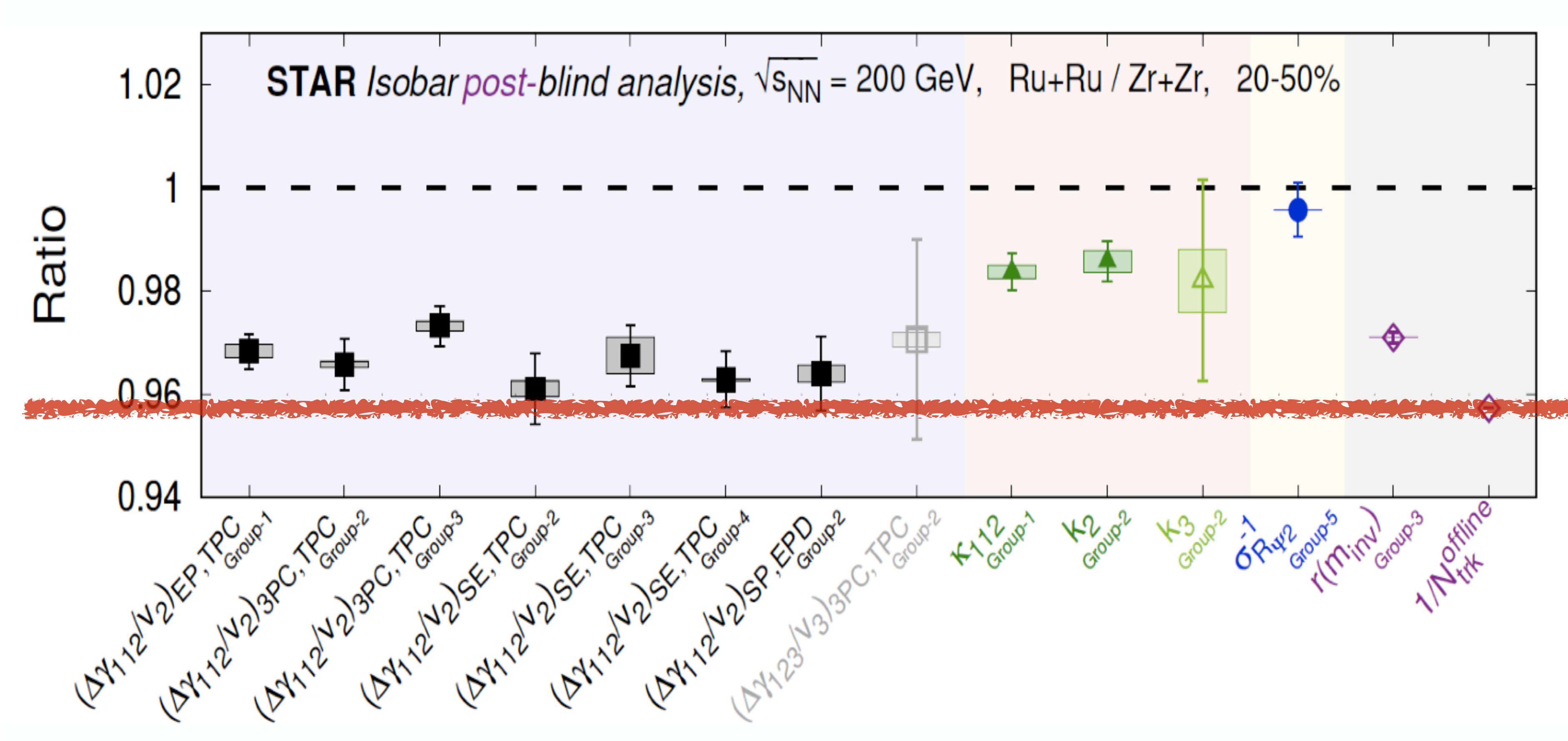
***[STAR paper: 2109.00131
Phys.Rev.C 105 (2022) 1, 014901]***

VII. CONCLUSION

We report an experimental test of the Chiral Magnetic Effect by a blind analysis of a large statistics data set of isobar $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr collisions at nucleon-nucleon center-of-mass energy of 200 GeV, taken in 2018 by the STAR Collaboration at RHIC. The backgrounds are reduced using the difference in observables between the two isobar collision systems. The criteria for a positive CME observation are predefined, prior to the blind analysis, as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions. Consistent results are obtained by the five independent groups in this blind analysis. Significant differences in the multiplicity and flow harmonics are observed between the two systems in a given centrality, indicating that the magnitude of the CME background is different between the two species. A precision down to 0.4% is achieved in the relative magnitudes of pertinent observables between the two isobar systems. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

***The predefined criteria is wrong.
No real conclusion could be made yet about signal.***

Where is the Baseline ?!

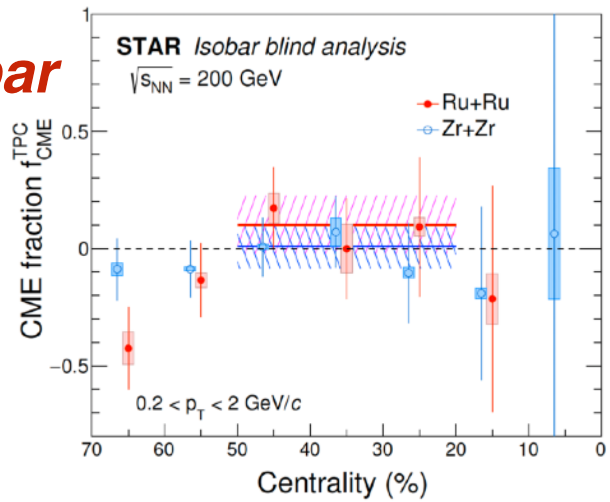


There appears room for potential CME signal above the 1/N line!
Need accurate calibration of the true baseline!

Direct Hints of Signal

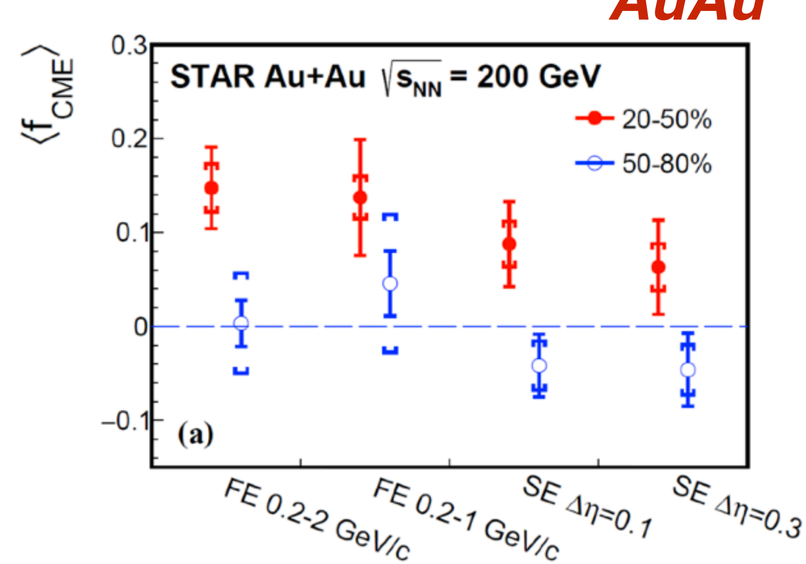
A method based on RP versus EP appears promising.
A coherent understanding of AuAu + isobars is important.

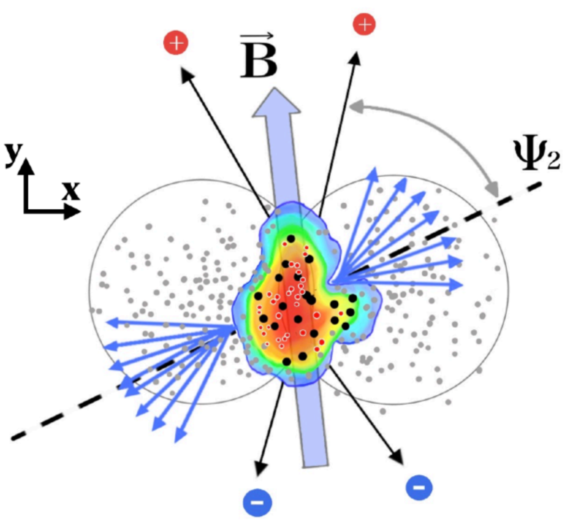
Isobar



STAR, arXiv:2106.09243

AuAu





Signal correlates better with y-axis;
Bkg correlates more with Psi_2 axis.

Bloczynski, Huang, Zhang, JL, arXiv:1209.6594[PLB]

EXP method: Voloshin; Fuqiang Wang, et al.

Isobar Backgrounds

Key for success: identical bulk between RuRu & ZrZr .
There may be worries owing to uncertainty in nuclear geometry.

S. Shi, H. Zhang, D. Hou, JL, arXiv:1807.05604;
H.J. Xu, et al, PRL2018; H. Elfner & collaborators, arXiv: 1908.10231

Strategies to overcome the issue:
— apply joint multiplicity— ellipticity cut for event samples
— stay at the relatively peripheral region

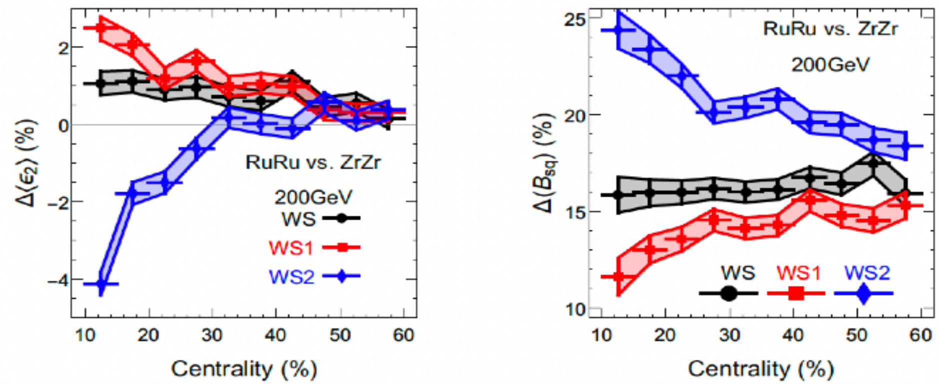


Fig. 1. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with conventional centrality event selection.

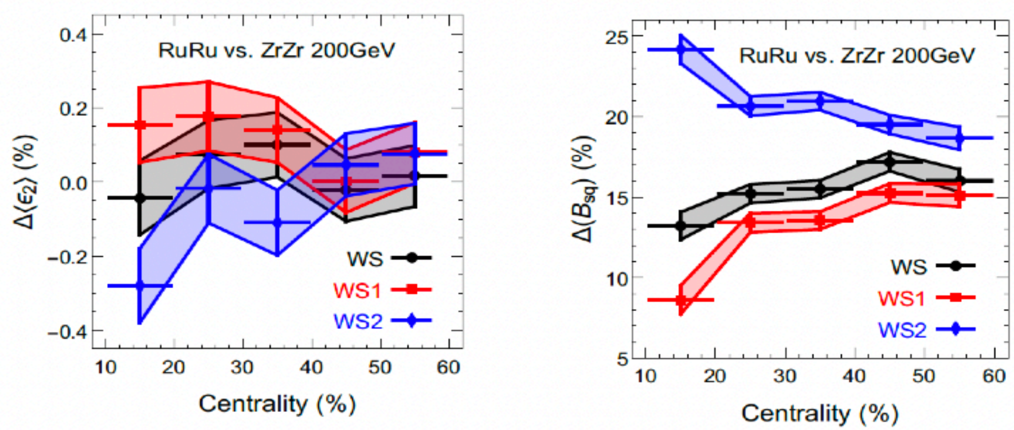


Fig. 2. (Color online) The relative difference in eccentricity $\Delta\langle\epsilon_2\rangle$ (left) and projected magnetic-field-strength-squared $\Delta(B_{sq})$ (right) between RuRu and ZrZr, with the proposed joint (multiplicity + elliptic-flow) event selection.

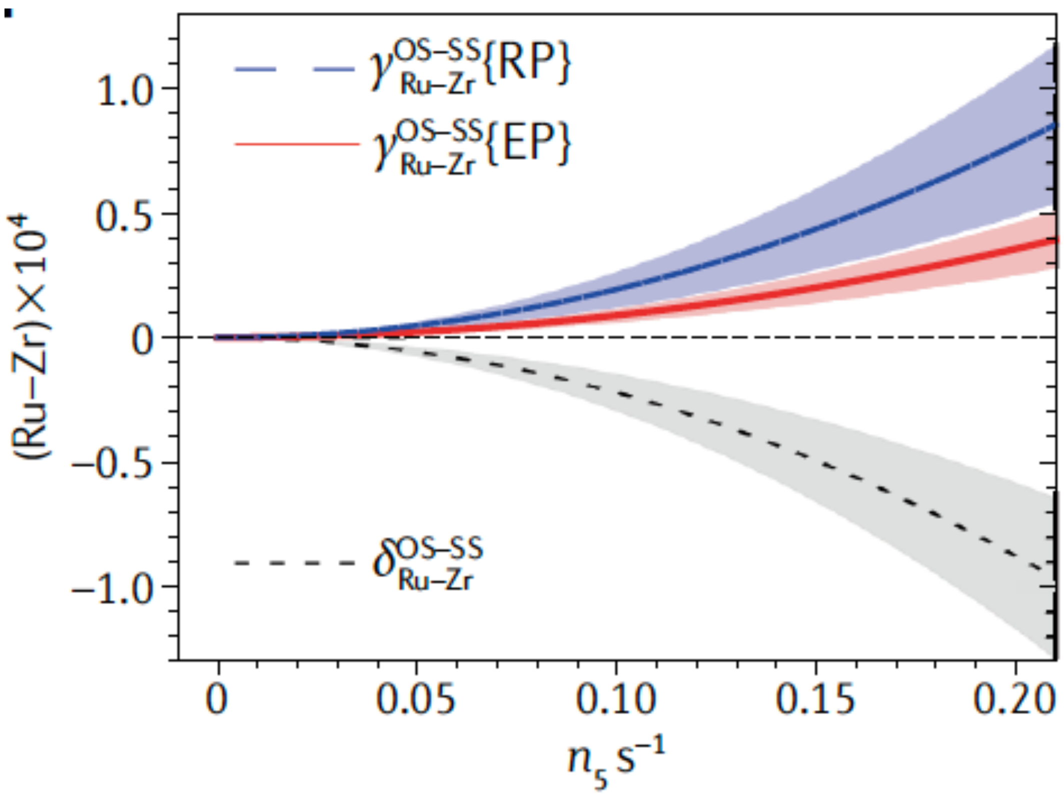
Theoretical Predictions from EBE-AVFD

Quantitative predictions of CME signal with proper multiplicity-v2 joint selections that suppress background difference.

PHYSICAL REVIEW LETTERS **125**, 242301 (2020)

Signatures of Chiral Magnetic Effect in the Collisions of Isobars

Shuzhe Shi,[1] Hui Zhang,[2,3,4] Defu Hou,[2,*] and Jinfeng Liao[5,†]



$$\zeta^{RP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{RP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{RP}} \simeq -(0.90 \pm 0.45)$$

$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$

Initial Conditions & Nuclear Geometry

One person's trouble may be another person's opportunities…

J. Jia, C. Zhang; Fuqiang Wang, et al; Guoliang Ma, et al; H. Song, et al; van der Schee; ……

RBRC Workshop: Physics Opportunities from the RHIC Isobar Run

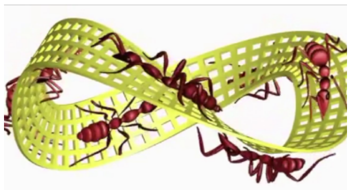
25 Jan 2022, 08:30 → 28 Jan 2022, 17:30 US/Eastern

Virtual Event

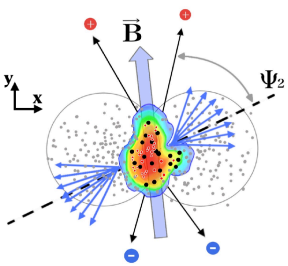
Summary

Summary

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



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



EXP correlations
In heavy ion collisions

[***arXiv: 2106.10847***]()

— The physics of CME is rich and fundamental.

— The search for CME in heavy ion collisions is of great importance yet challenging.

— Existing data show positive hints of signals but are inconclusive due to strong backgrounds.

— Isobar collisions collect a high precision data set with potential for finding CME.

What's Next?

Near term focus of theoretical efforts:
Nailing down the correct baseline for the isobar contrast;
Obtaining a precise understanding of isobar bulk properties;

> ***Using EBE-AVFD***
> ***+ well informed nuclear structure inputs***
> ***+ data calibration for bulk properties***
> ***—> establish baseline for various observables***
> ***—> further examine responses to CME signals***
> ***—> quantify signal level in statistically meaningful way***

Experimental efforts:
— isobar post-blind analyses ongoing
— new analysis strategies for isobars (e.g. multiplicity cut; event shape; etc)
— high precision AuAu analysis (2~3 sigma —> 5 sigma??)

Exciting time (over next couple years): stay tuned !!