RBRC 25th Anniversary Celebration

Brookhaven National Laboratory, June 22, 2023

25 years with RBRC: a personal story

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Center for Nuclear Theory

C2QA Co-design Center for Quantum Advantage

U.S. Department of Energy Office of Science

Stony Brook University

Center for Frontiers in Nuclear Science

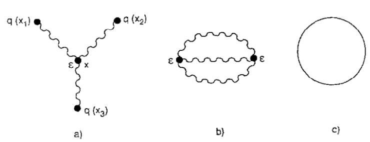
Brookhaven National Laboratory

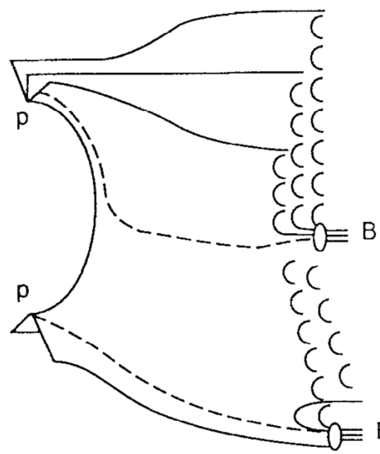
Throughout its 25+ years history, RBRC has been a place where scientific creativity is nurtured, and young scientists are given a chance to pursue their ideas.

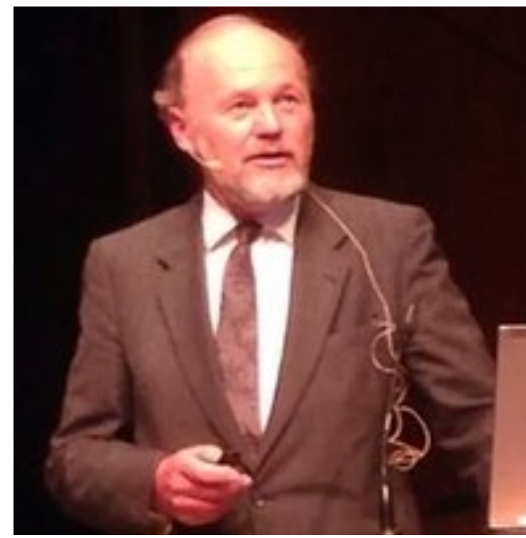
The RBRC was established in 1997.

I joined it on August 11, 1997, becoming one of the two first Fellows of RBRC (together with Dirk Rischke), and the first member of scientific staff to arrive. This talk is an attempt to describe the impact of RBRC on young physicists using my personal story as a typical example.

I first heard about the creation of RBRC from M. Gyulassy (Columbia U) during the 1996 INT (Seattle) program on "Ultra-relativistic nuclei: from structure functions to the quark-gluon plasma". Miklos and I had an intense debate about my (then) recent paper on baryon junctions (inspired by conversations with G. Veneziano at CERN).







From:
D.K., Phys.Lett.B378(1996)238

Miklos then told me about RBRC and described the plan of Prof. T.D.Lee and Prof. A.Arima - it was really exciting.
My postdoc stay at Theory Division of CERN (1993-1996) was approaching its end, and I was looking for a job.

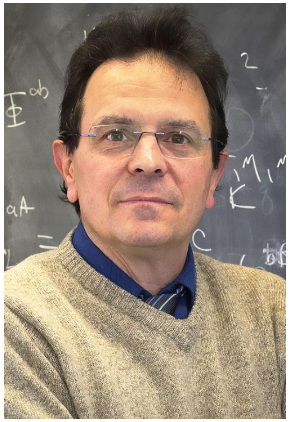
Soon after, a RBRC ad appeared, and I immediately applied and started to wait for a response. But no response came. I got invitations to interview at other places. I was then at Bielefeld University, working with Prof. Helmut Satz.

1980 conference in Bielefeld:
Left to right: A.B. Migdal, T.D. Lee, H. Satz

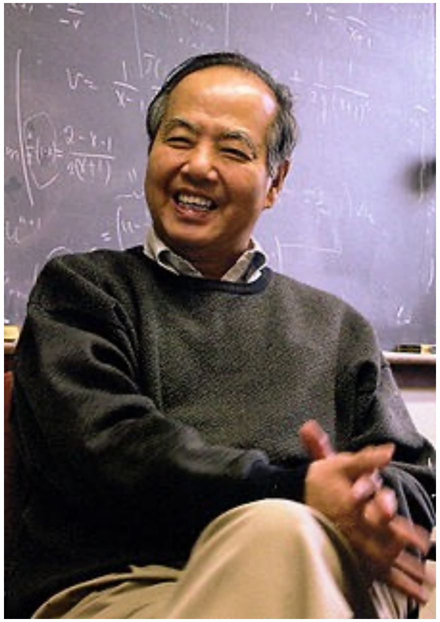
Thar desert, India, 1997:
Left to right: D. Kharzeev, H. Satz, J. Schukraft

In January of 1997, I went to a workshop on "QCD phase transitions" in Hirschegg (Austria), where, fortunately for me, I met Rob Pisarski from BNL.

Rob asked me why I never responded to the invitation to interview at RBRC…



Shortly afterwards, I came to interview at BNL, and then met with Prof. T.D. Lee at Columbia University



Prof. T.D. Lee in his RBRC office at BNL

Pupin Hall at Columbia U.

At the end of the meeting, he told me that the decision was made, and I should get ready to come to RBRC.

This was exciting!

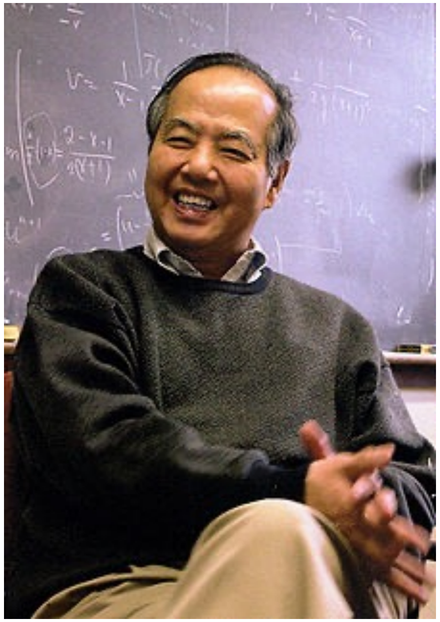
When the offer letter arrived, it contained the starting date of September 1, 1997. But my wife Irina was expecting our daughter in late September, so I asked to start later or earlier.

Prof. T.D. Lee suggested us to come earlier, at the beginning of August. As a result, I was the first member of RBRC scientific staff to arrive.

JFK airport, New York, August 11, 1997

In the fall of 1997, there was a RBRC conference on “Non-equilibrium many body dynamics” followed by the Inauguration ceremony. There I met many people who later became my collaborators and colleagues.

Upon arriving to BNL, I had a meeting with Prof. T.D. Lee, and asked him an advice on the topics I should work on.



Prof. T.D. Lee in his RBRC office at BNL

I still remember exactly what he said:

"*Find a problem in physics that you consider the most important and interesting. Focus fully on trying to solve it. Whatever this problem is, if you work hard, I will support you.*"

I followed his advice, and decided to focus on the topic that interested me (and still does!) the most:

the effects of the quantum vacuum on physical observables.

The vacuum is believed to be responsible for the entire mass of the visible Universe (through spontaneous breaking of chiral symmetry in QCD and Higgs condensation), for baryon asymmetry in the Universe (through electroweak sphalerons), and for the structure of matter inside and around us (through confinement of quarks in QCD).

Yet, we know very little about quantum vacuum from experiment! Is there a way to directly detect vacuum effects?

Two ways, enabled by **scale** and **chiral anomalies**.

I learned about scale anomaly from John Ellis, with whom I was fortunate to collaborate at CERN. He discovered scale anomaly in pre-QCD era.

John Ellis in his office at CERN

Photo by J.Ellis, Mendoza, Argentina, 2005

Back then, he referred to it as Partially Zero (O) Trace, or POT…

J. Ellis at SLAC

SLAC-PUB-1028
(TH)
March 1972

CANONICAL ANOMALIES AND BROKEN SCALE INVARIANCE*

Michael S. Chanowitz and John Ellis**
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

7.A.2 Nuclear Physics B22 (1970) 478-492. North-Holland Publishing Company

ASPECTS OF CONFORMAL SYMMETRY AND CHIRALITY

John ELLIS
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, England

Both scale and chiral anomalies provide a bridge between quantum phenomena that occur at short and large distances.

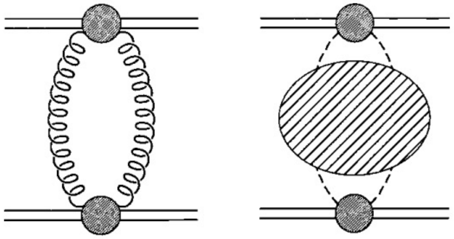
Therefore, scale anomaly matching can be used to establish the effects of QCD vacuum on the long-distance interactions of small objects, heavy quarkonia.

This was our project with one of the first RBRC postdocs, Hirotsugu Fujii (now professor at Tokyo University, Komaba)

PHYSICAL REVIEW D, VOLUME 60, 114039

Long-range forces of QCD

H. Fujii* and D. Kharzeev
RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973
(Received 26 March 1999; published 12 November 1999)



$$V^{\pi\pi}(R) \rightarrow -\left(\bar{d}_2 \frac{a_0^2}{\epsilon_0}\right)^2 \left(\frac{4\pi^2}{b}\right)^2 \frac{3}{2}(2m_\pi)^4 \frac{m_\pi^{1/2}}{(4\pi R)^{5/2}} e^{-2m_\pi R}.$$

I was surprised and delighted when this paper was noticed by one of my physics heroes, James Bjorken:

What's New in Hadron Physics

James D. Bjorken

Stanford Linear Accelerator Center
Stanford University, Stanford, California 95409

hep-ph/0008048

1. Perturbing the Chiral Vacuum

A classic way of trying to understand the properties of a macroscopic system is to perturb it with a small, localized impurity and study its response. In the case of the chiral vacuum of long-distance QCD, a nice way of doing this is by putting a small color dipole, such as heavy onium, into the vacuum and examining its response. This implies creation at large distances of a very weak pion cloud around the onium. The importance of this cloud can be assessed by putting in another small dipole, and determining the long range force between them, due to essentially two-pion meson exchange. This has been done elegantly and cleanly by Fujii and Kharzeev [3], who find that this force dominates at separations greater than about 0.6 fermi. To be sure the potential energy associated with this effect is

The role of scale anomaly in low energy interactions of heavy quarkonia with nucleons is currently under study at JLab, and will be studied in much more detail at the EIC

Determining the Proton's Gluonic Gravitational Form Factors

Nature 615 (2023) 7954, 813-816

B. Duran[3,1], Z.-E. Meziani[1,3**], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[7], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], M. Paolone[3], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[7], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]

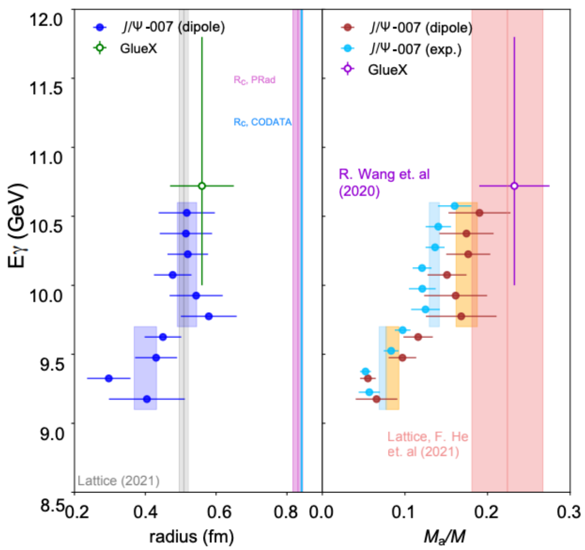


Figure 5. Left panel:The extracted radius as a function of the photon energy according to Ref. 9 together with the GlueX result. Both our and the Gluex extractions used a

Indication that a mass radius of the proton is much smaller than its charge radius

(consequence of scale anomaly?)

New NREC (Nuclear Radius Extraction Coll.) led by Jan Bernauer, Haiyan Gao, Douglas Higinbotham, Vlad Khachatryan

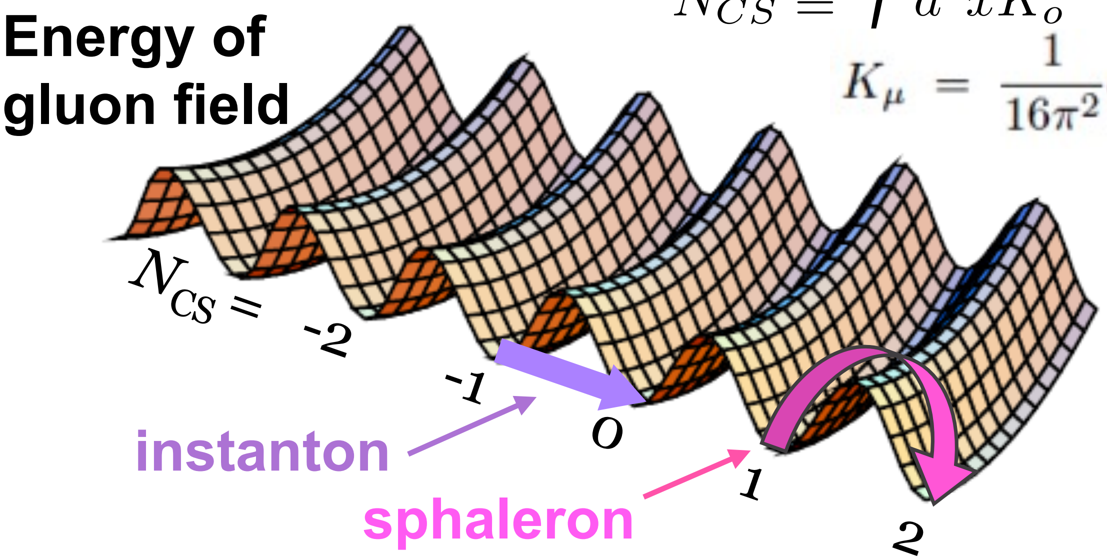
9. Kharzeev, D. E. Mass radius of the proton. *Phys. Rev. D* **104**, 054015, DOI: 10.1103/PhysRevD.104.054015 (2021). 2102.00110.

Another way to detect the quantum vacuum effects?

The vacuum of non-Abelian gauge theories (QCD, electroweak theory) has a periodic crystal-like structure with an infinite number of degenerate sectors that have different topology (different Chern-Simons numbers)

$$N_{CS} \equiv \int d^3x K_o$$

$$K_\mu = \frac{1}{16\pi^2}\epsilon_{\mu\alpha\beta\gamma}\left(A^a_\alpha \partial_\beta A^a_\gamma + \frac{1}{3} f^{abc} A^a_\alpha A^b_\beta A^c_\gamma\right)$$



Quantum transitions between these sectors change topology of the gauge field, and the chirality of fermions coupled to it (chiral anomaly, Atiyah-Singer index theorem), creating domains with local chirality imbalance. **Can one detect them?**

We addressed this problem in the 1998 paper with Rob Pisarski and Michel Tytgat:

VOLUME 81, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1998

Possibility of Spontaneous Parity Violation in Hot QCD

Dmitri Kharzeev,[1] Robert D. Pisarski,[2] and Michel H. G. Tytgat[2,3]
[1]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000*
[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000*
[3]*Service de Physique Théorique, CP 225, Université Libre de Bruxelles, Boulevard du Triomphe, 1050 Bruxelles, Belgi*
(Received 3 April 1998)

We argue that for QCD in the limit of a large number of colors, the axial U(1) symmetry of massless quarks is effectively restored at the deconfining phase transition. If this transition is of second order, metastable states in which parity is spontaneously broken can appear in the hadronic phase. These metastable states have dramatic signatures, including enhanced production of η and η' mesons, which can decay through parity violating decay processes such as $\eta \to \pi^0\pi^0$, and global parity odd asymmetries for charged pions. [S0031-9007(98)06613-7]

A working group with STAR experimentalists was formed to find a way to detect this local parity violation (chirality imbalance):

J. Sandweiss, S. Voloshin, J. Thomas, E. Finch, A. Chikanian, R. Longacre, …

But after a few years of hard work it has become clear that the proposed pion correlations are very difficult to detect.

In 2004, another way to detect chirality imbalance was found:

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

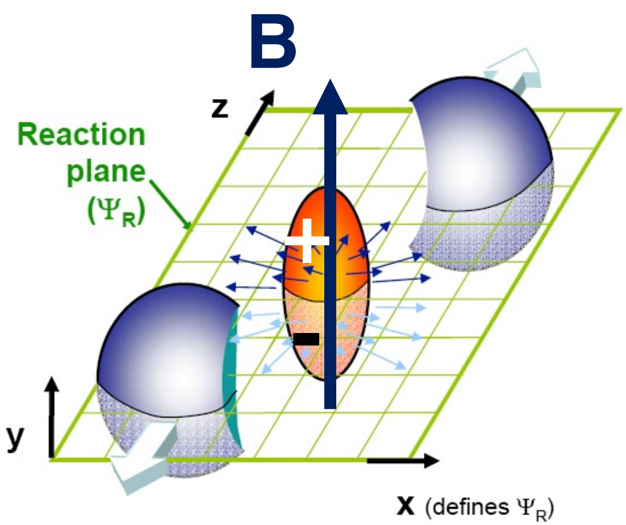
Dmitri Kharzeev

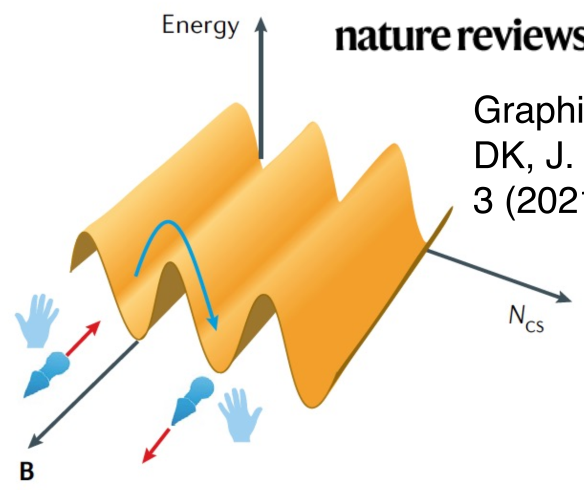
Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005

hep-ph/0406125 (June 4, 2004)

In the presence of a background magnetic field **B**, or angular momentum **L**, chirality imbalance induces an electric current (directed along **B** or **L**).





nature reviews physics

Graphics from:
DK, J. Liao, Nature Rev. (Phys) 3 (2021) 55

Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quantum chromodynamics matter.** The QCD vac-

This idea was developed further with my colleagues and friends:

Charge separation induced by $\mathcal{P}$-odd bubbles in QCD matter

Dmitri Kharzeev [a,*], Ariel Zhitnitsky [b]

[a] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[b] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada*

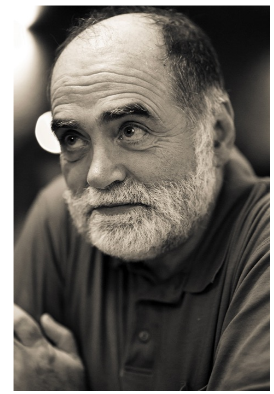
Received 19 June 2007; received in revised form 17 September 2007; accepted 1 October 2007

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], 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*

Received 15 November 2007; received in revised form 28 January 2008; accepted 3 February 2008



PHYSICAL REVIEW D **78,** 074033 (2008)

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 New York 11973, USA*
(Received 2 September 2008; published 31 October 2008)

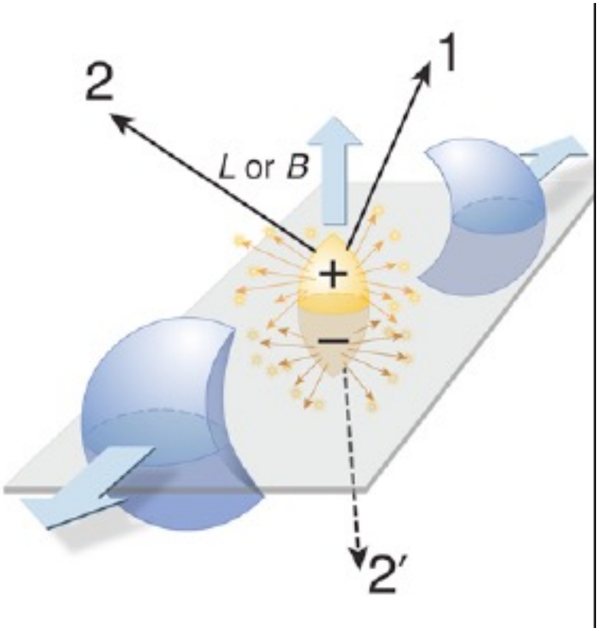
We called it the Chiral Magnetic Effect (CME)

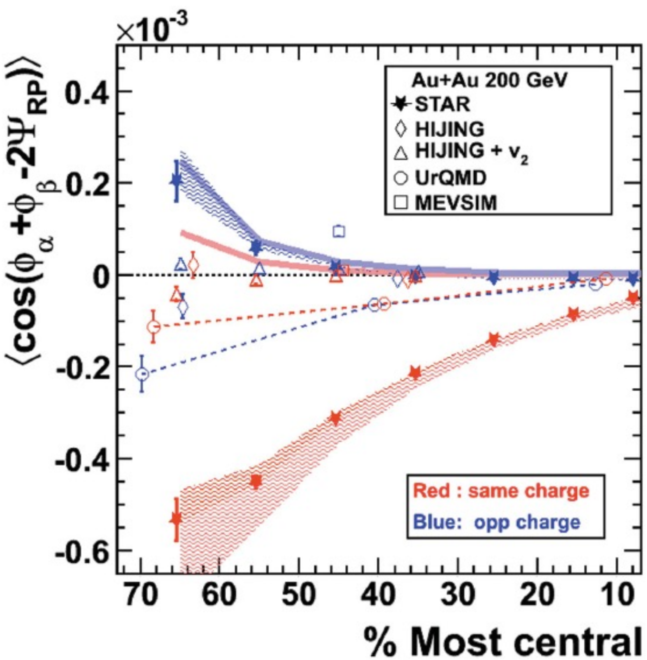
There is an ongoing active CME search program at RHIC that began in 2009:

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

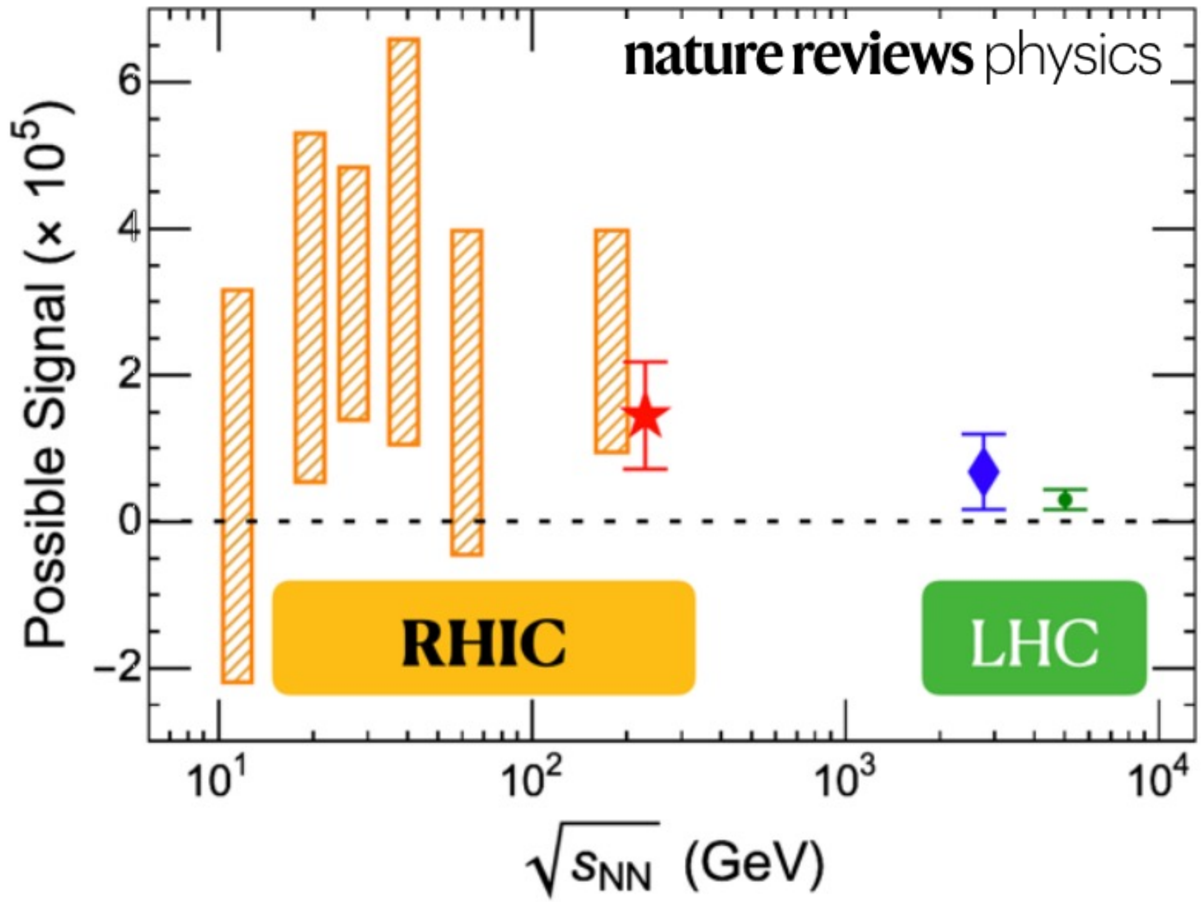
(STAR Collaboration)





Review of CME with heavy ions: DK, J. Liao, S. Voloshin, G. Wang, Rep. Prog. Phys.'16

Review + Compilation of the current data: DK, J. Liao, Nature Reviews (Phys.) 3 (2021) 55

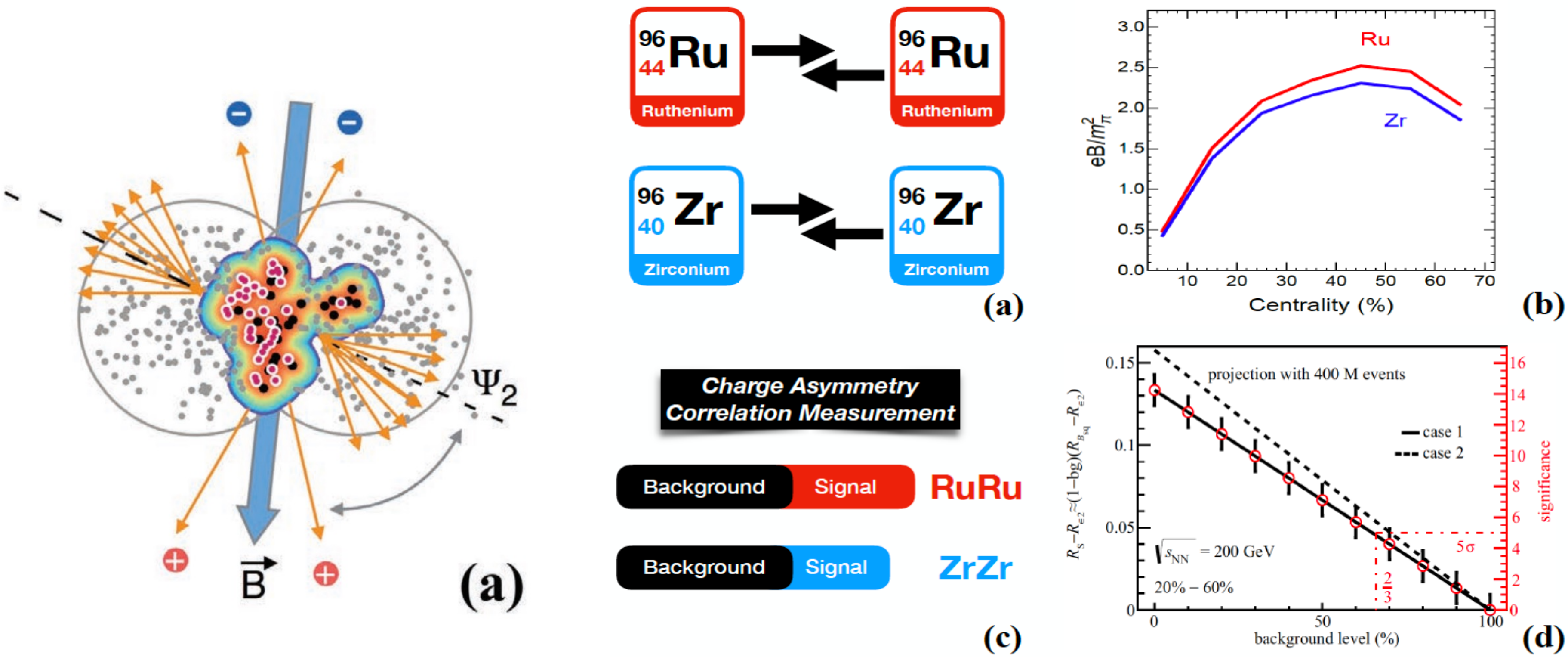


Separating the signal from background is the main subject of the ongoing work –

Big new development: the isobar run!

Successful collaboration of BNL, RIKEN, Oak Ridge, and other institutes

Isobars: same shape = same background(**?**),
different Z = different magnetic field – change in signal



STAR Collaboration

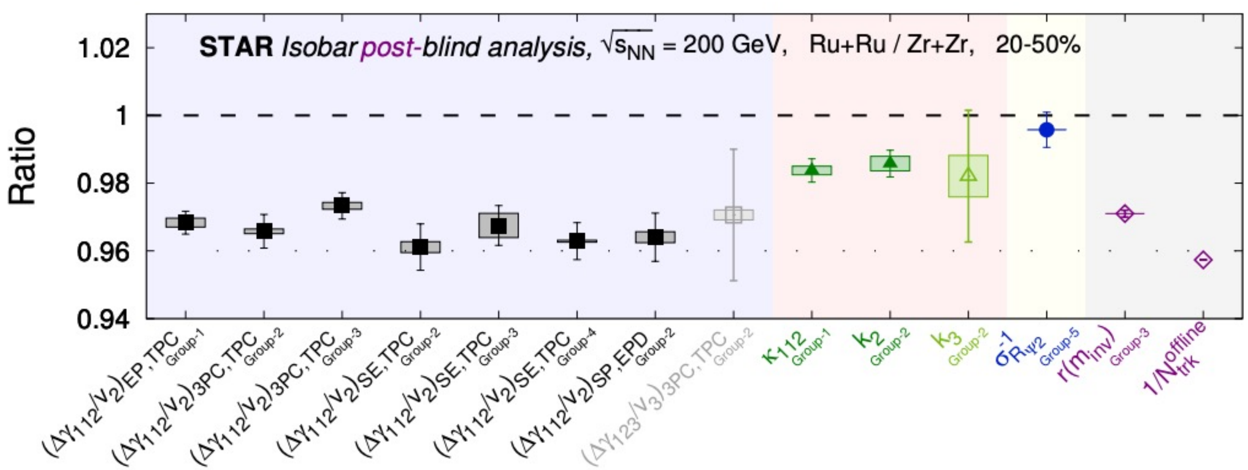
Search for CME using the isobar collisions at RHIC

The results have been released on Aug 31, 2021

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

STAR, nucl-ex 2109.00131, PRC (2022)

between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.



< 1 !

CME excluded?

not predicted by any theory, CME or not

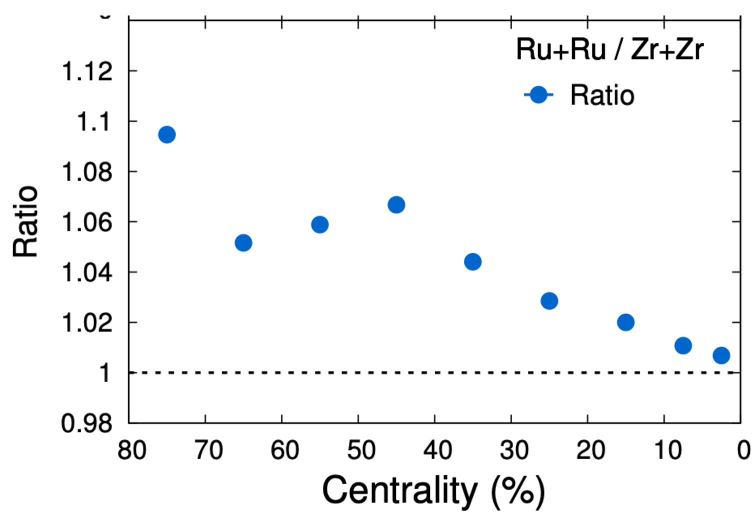
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

STAR, nucl-ex 2109.00131, PRC (2022)

The predefined criteria assume that the multiplicities in RuRu and ZrZr collisions (in the same cross section cuts) are the same.
Is this criterion supported by the data?

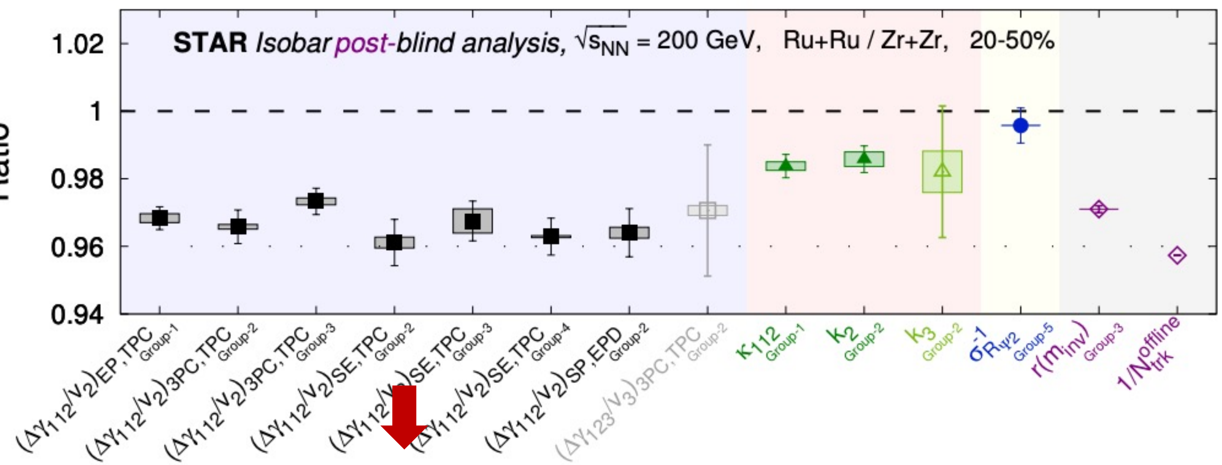
No. The **measured** multiplicities are **significantly** different:

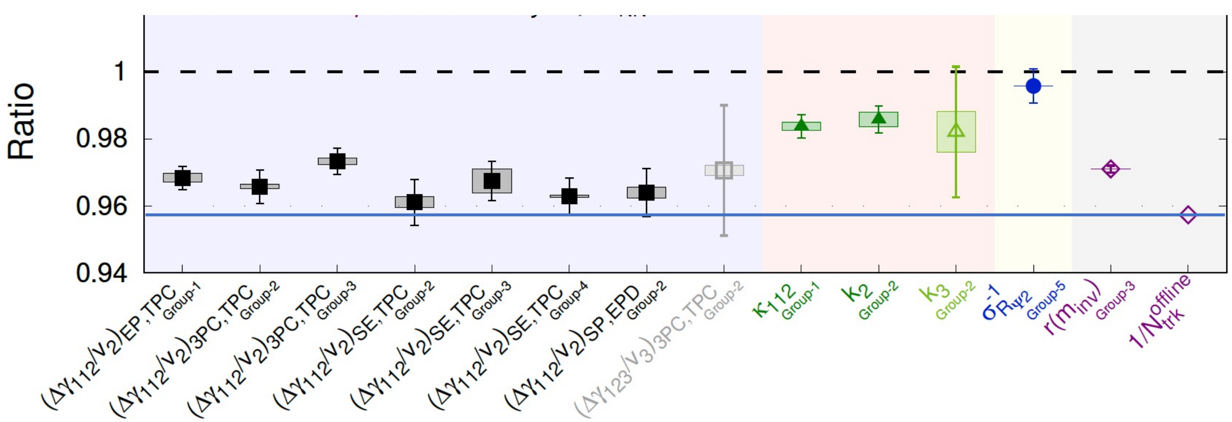


Since both signal and background scale as 1/N, the baseline has to be changed. This is not part of the "predefined criteria".
Also: different v_2, p_T spectra?

CME search with isobar collisions at RHIC

of clusters scaling with multiplicity, the value of $\Delta\gamma$ scales with the inverse of multiplicity [20], i.e. $N\Delta\gamma \propto v_2$ with the proportionality presumably equal between the two isobars. Because of this, it may be considered that the proper baseline for the ratio of $\Delta\gamma/v_2$ between the two isobars is the ratio of the inverse multiplicities of the two systems. Analysis with respect to this baseline is not documented in the pre-blinding procedures of this blind analysis, so is not reported as part of the blind analysis. We include this inverse multiplicity ratio as the right-most point in Fig. 27.





Depending on the observable, CME is present at 1-4 σ level

Recent theoretical analysis:

CME fraction is 6.8+-2.6 %

DK, J.Liao, S. Shi, arXiv:2205.00120, Phys. Rev. C106(2022)

AuAu@200 GeV: STAR results

PHYSICAL REVIEW LETTERS **128,** 092301 (2022)

Search for the Chiral Magnetic Effect via Charge-Dependent Azimuthal Correlations Relative to Spectator and Participant Planes in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

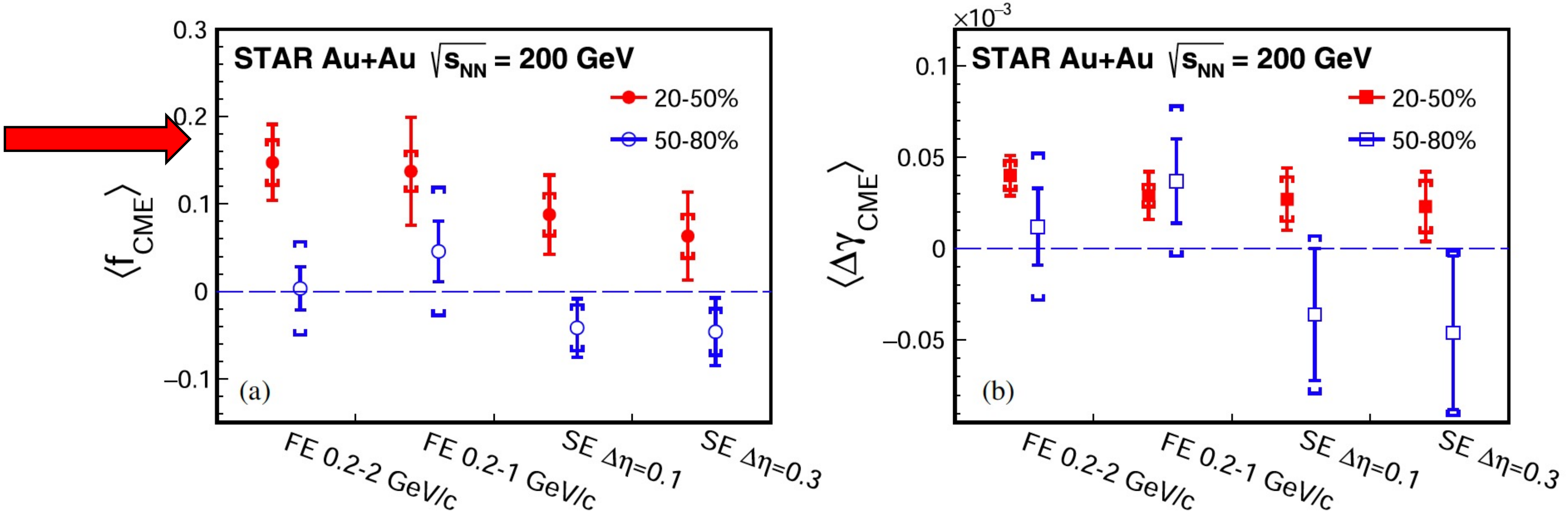


FIG. 3. The flow-background removed $\langle f_{\mathrm{CME}} \rangle$ (a) and $\langle \Delta\gamma_{\mathrm{CME}} \rangle$ (b) signal in 50%–80% (open markers) and 20%–50% (solid markers) centrality Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, extracted by various analysis methods [full-event (FE), subevent (SE)] and kinematic cuts. Error bars show statistical uncertainties; the caps indicate the systematic uncertainties.

AuAu@200 GeV STAR results

PHYSICAL REVIEW LETTERS **128,** 092301 (2022)

PHYSICAL REVIEW LETTERS **128,** 092301 (2022)

TABLE I. The inclusive $\langle \Delta\gamma\{\psi_{\mathrm{TPC}}\} \rangle$ and the extracted $\langle f_{\mathrm{CME}} \rangle$ and $\langle \Delta\gamma_{\mathrm{CME}} \rangle$, averaged over 20%–50% and 50%–80% centrality ranges in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the full-event method (with two POI p_{T} ranges) and the subevent method (with two η gaps). The first quoted uncertainty is statistical and the second systematic.

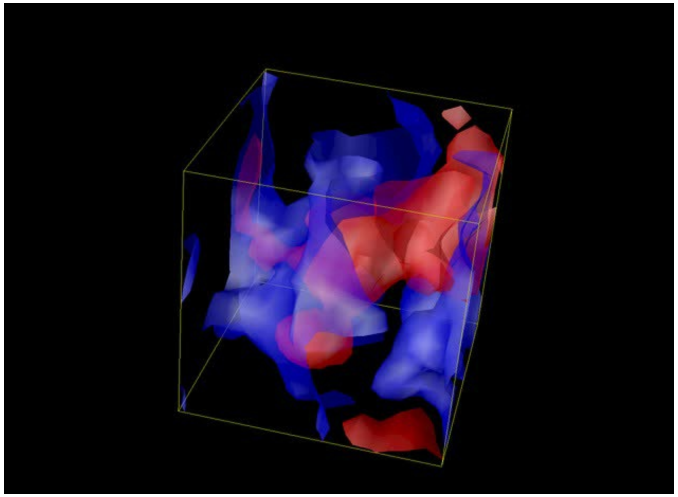
Centrality	Method	$\langle \Delta\gamma_{\mathrm{inc}} \rangle$ ($\times 10^{-4}$)	$\langle f_{\mathrm{CME}} \rangle$ (%)	$\langle \Delta\gamma_{\mathrm{CME}} \rangle$ ($\times 10^{-4}$)
20%–50%	Full-event, $p_T = 0.2$–2 GeV/c	$1.89 \pm 0.01 \pm 0.10$	$14.7 \pm 4.3 \pm 2.6$	$0.40 \pm 0.11 \pm 0.08$
	Full-event, $p_T = 0.2$–1 GeV/c	$1.48 \pm 0.01 \pm 0.07$	$13.7 \pm 6.2 \pm 2.3$	$0.29 \pm 0.13 \pm 0.06$
	Subevent, $\Delta\eta_{\mathrm{sub}} = 0.1$, $p_T = 0.2$–2 GeV/c	$2.84 \pm 0.01 \pm 0.15$	$8.8 \pm 4.5 \pm 2.4$	$0.27 \pm 0.17 \pm 0.12$
	Subevent, $\Delta\eta_{\mathrm{sub}} = 0.3$, $p_T = 0.2$–2 GeV/c	$2.94 \pm 0.01 \pm 0.15$	$6.3 \pm 5.0 \pm 2.5$	$0.23 \pm 0.19 \pm 0.14$

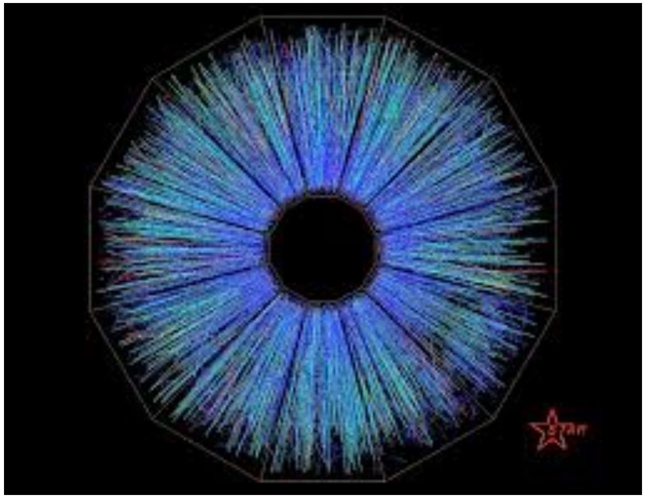
the spectator protons. Under these assumptions, the possible CME signals are extracted using the new method in this Letter. Some indication of finite signals is seen in 20%–50% Au + Au collisions. However, nonflow effects (especially for the full-event method without η gap) may still be present that warrant further investigation.

The future of CME at RHIC

With ~ 10 billion more AuAu events, **if** the central value of the CME fraction stays the same, the statistical significance of STAR data is expected to reach 5σ

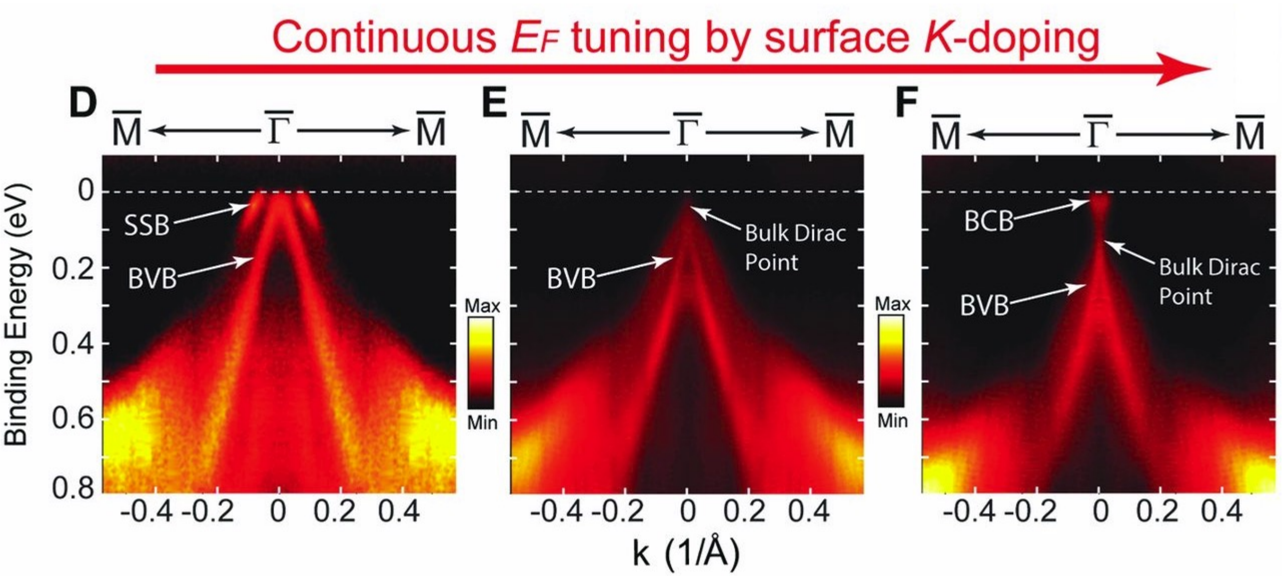
A lot of ongoing work by experimentalists and theorists worldwide

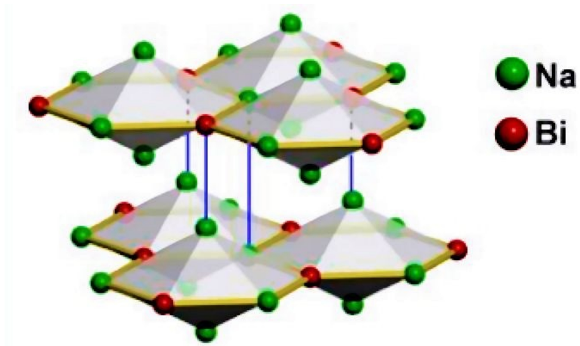




Theoretical research in nuclear and high energy physics often finds important applications beyond these fields.

CME is an example of that. Chiral fermions analogous to quarks exist also in recently discovered materials,
Dirac and Weyl semimetals. Can they exhibit CME?





Z.K.Liu et al., Science 343 p.864

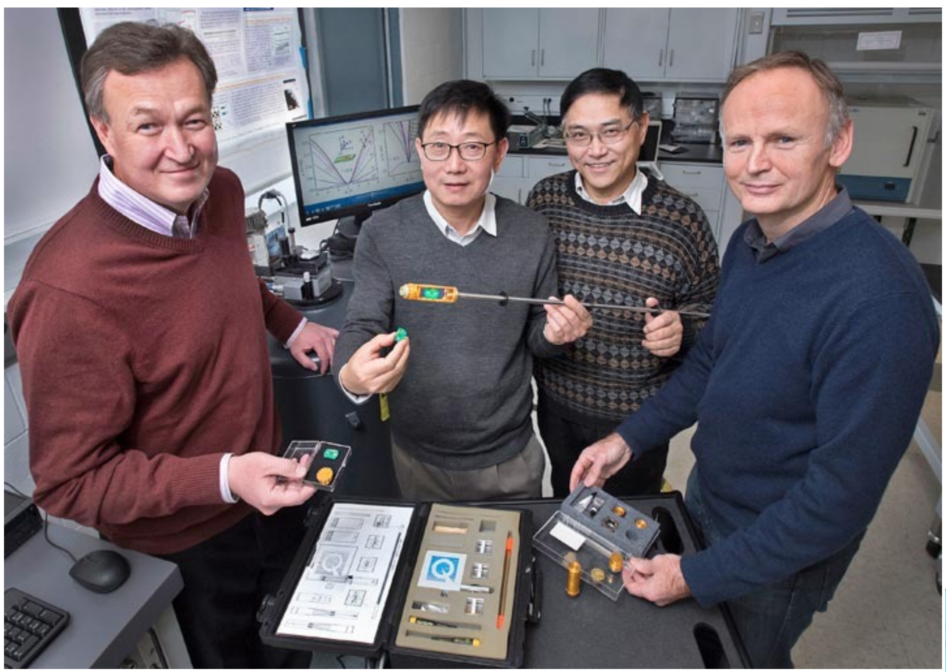
A review:
N.P.Armitage,E.Mele,A.Vishwanath,
Rev.Mod.Phys.90, 015001 (2018)

CME in chiral materials

Observation of the chiral magnetic effect in $ZrTe_5$

Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5] A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

BNL - Stony Brook - Princeton - Berkeley



Nature Phys. 12 (2016) 550

arXiv:1412.6543 [cond-mat.str-el]

The Importance of Pure Theory

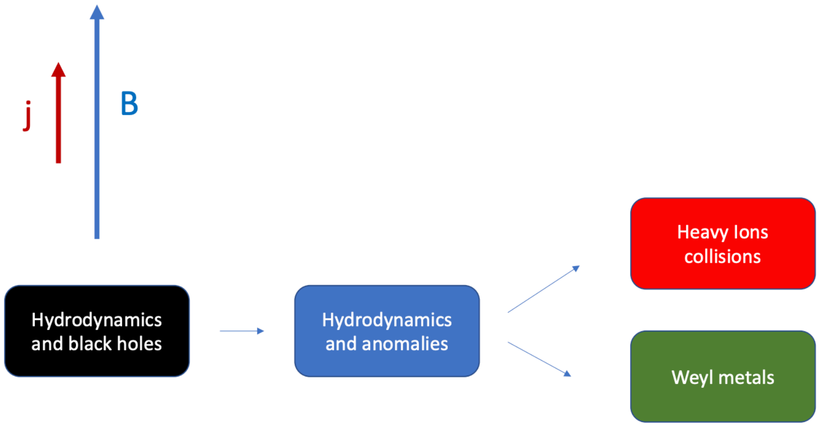
Juan Maldacena

P5 Town Hall

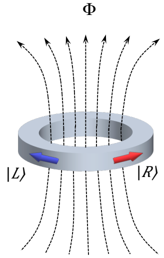
SLAC 2023

Case study

Anomalies and the chiral magnetic effect



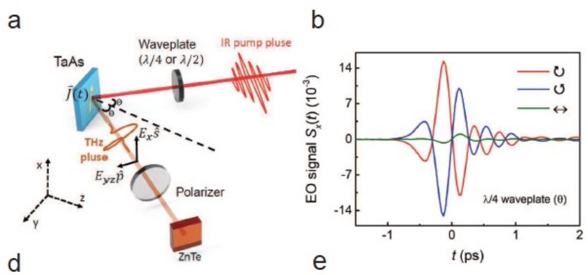
CME in chiral materials: practical applications

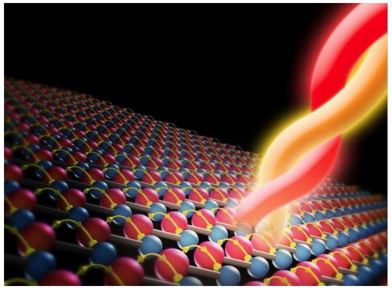


Currently, CME has been established in dozens of different chiral materials. Active ongoing work on applications beyond the academic domain, including quantum sensors, quantum memories, quantum transducers, and quantum qubits

Chiral terahertz wave emission from the Weyl semimetal TaAs

Y. Gao[1], S. Kaushik[2], E.J. Philip[2], Z. Li[3,4], Y. Qin[1,5], Y.P. Liu[6], W.L. Zhang[1], Y.L. Su[1], X. Chen[2], H. Weng[4,7], D.E. Kharzeev[2,8,9*], M.K. Liu[2*] & J. Qi[1*]

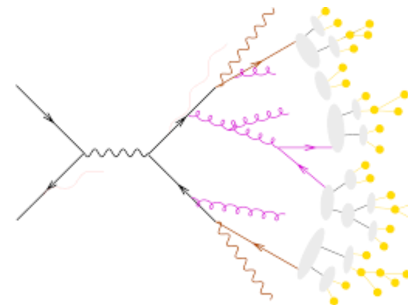


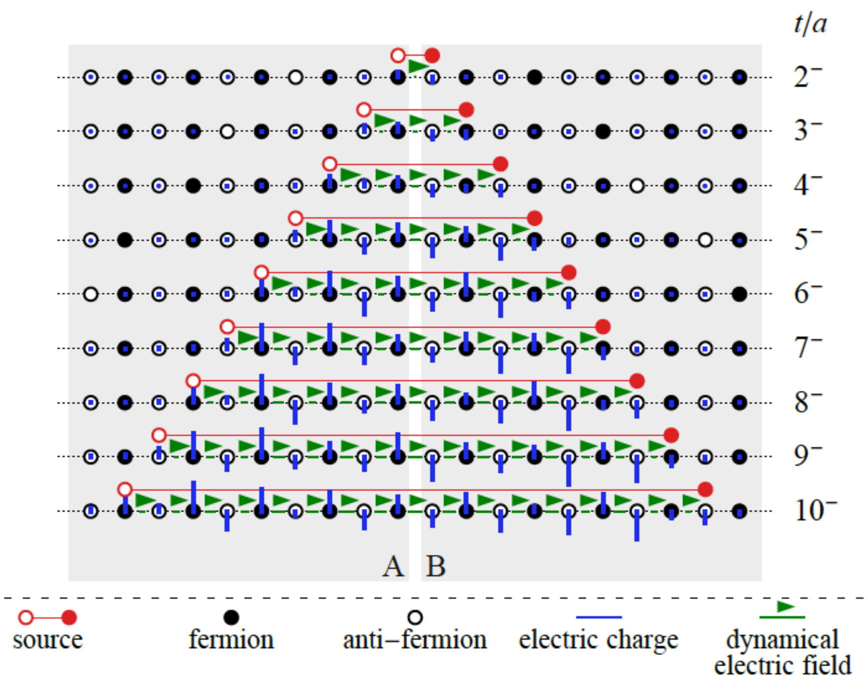


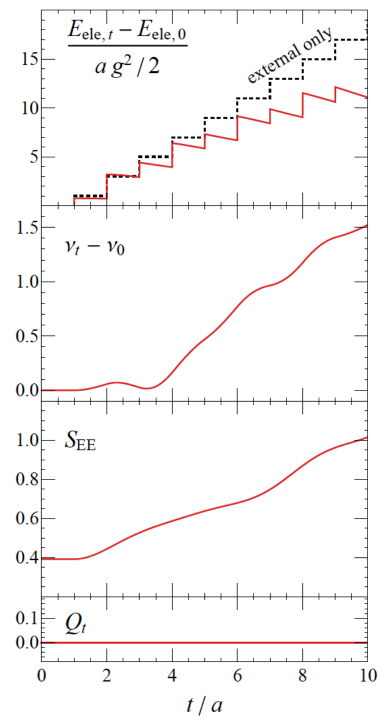
nature COMMUNICATIONS

Fascinating new intersections between chirality and quantum information

Quantum entanglement between the jets!







A.Florio, D. Frenklakh, K. Ikeda, DK, V. Korepin, S. Shi, K. Yu, arXiv:2301.11991; to appear in PRL

C²QA Co-design Center for Quantum Advantage

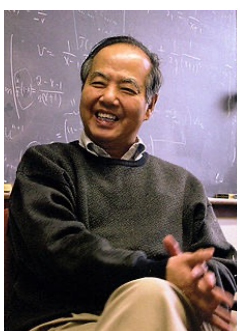
Study this at RHIC and EIC!

Summary

It all started for me, and for dozens of other graduates, here at RBRC. We stay connected to RBRC (and I even returned as a head of RBRC Theory group for several years) and are very grateful to our scientific Alma Mater.

Over the past quarter century, RBRC has been an intellectual center and a launchpad for many successful careers in science.

I am deeply indebted to RBRC founders and directors.






I also hope that RBRC will remain at the forefront of science for years to come!