Chirality retreat, UCLA, December 2-4, 2022

Chiral Magnetic Effect in heavy ion collisions:

where do we stand, and what needs to be done?

Dmitri Kharzeev

C²QA Co-design Center for Quantum Advantage

U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University | Center for Nuclear Theory

Brookhaven National Laboratory

We are not very pleased when we are forced to accept a mathematical truth by virtue of a complicated chain of formal conclusions and computations, which we traverse blindly, link by link, feeling our way by touch.

We want first an overview of the aim and of the road; we want to understand the idea of the proof, the deeper context.

Hermann Weyl,
"Levels of infinity"

$$\sigma^\mu \partial_\mu \psi = 0$$

What is the "deeper context" of CME search in heavy ion collisions?

Detecting quantum vacuum transitions!

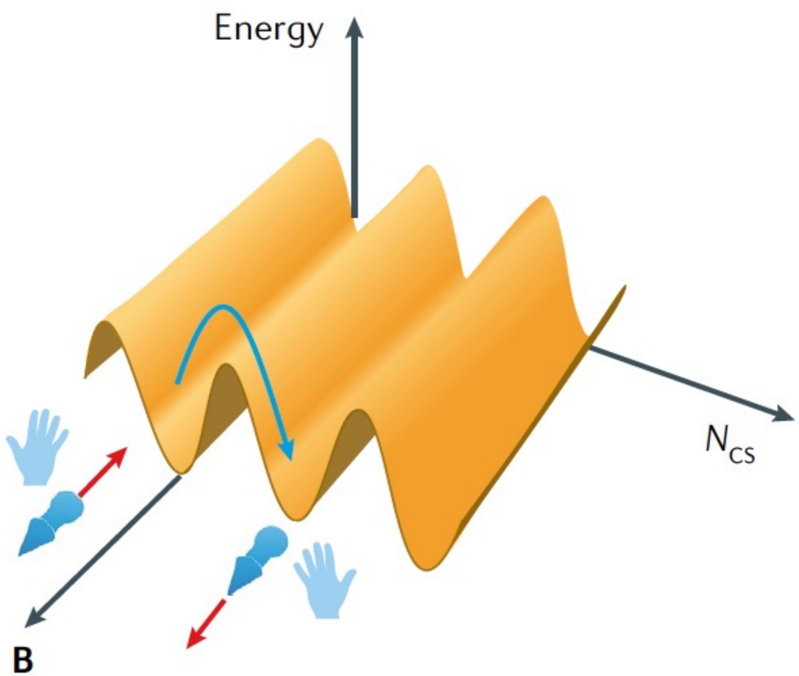


Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quantum chromodynamics matter.** The QCD vac-

θ vacuum:

a beautiful amalgam of **geometry** and **quantum theory**

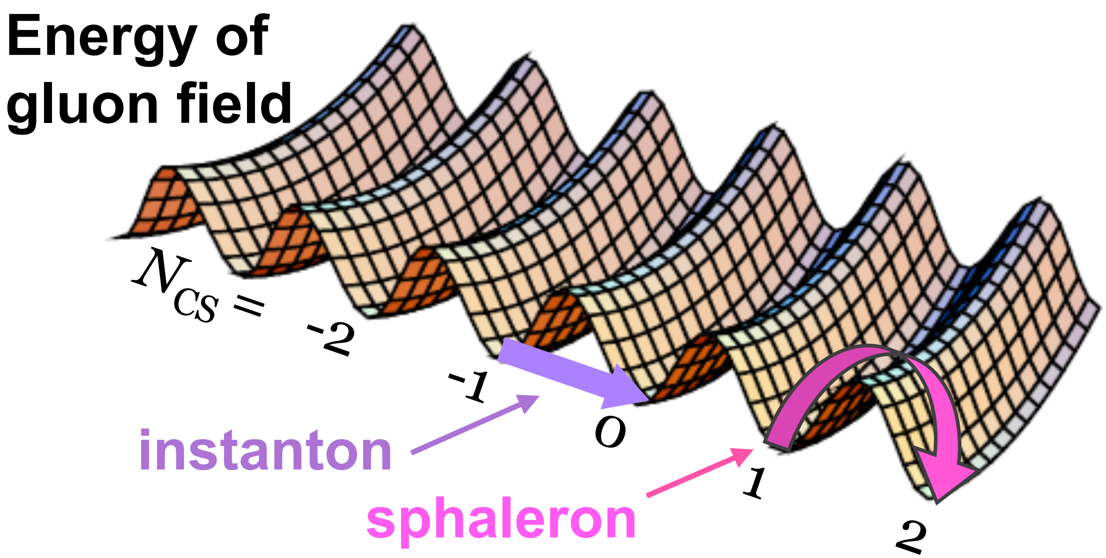
Graphics:
DK, J. Liao, Nature Rev. (Phys) 3 (2021) 55
nature reviews physics

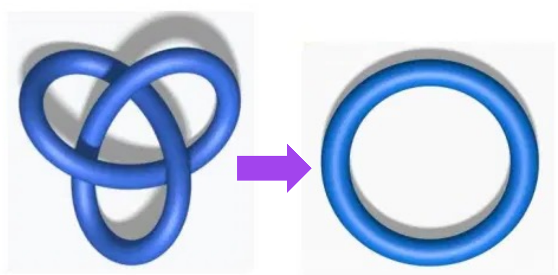
Chirality in the vacuum of the Standard Model

The instanton and sphaleron solutions in non-Abelian gauge theories describe transitions between topological sectors of the vacuum marked by different integer values of the Chern-Simons number:

$$N_{CS} \equiv \int d^3x K_o \qquad K_\mu = \frac{1}{16\pi^2}\epsilon_{\mu\alpha\beta\gamma}\left(A^a_\alpha \partial_\beta A^a_\gamma + \frac{1}{3} f^{abc} A^a_\alpha A^b_\beta A^c_\gamma\right)$$

QCD (Quantum ChromoDynamics) vacuum:





Vacuum transitions and the origin of Matter-Antimatter asymmetry in the Universe

Sakharov conditions for baryogenesis:

1. Baryon number violation
2. C and CP symmetries violation
3. Interactions out of thermal equilibrium

A.D. Sakharov, 1967

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles

Vacuum transitions and the origin of Matter-Antimatter asymmetry in the Universe

Within the Standard Model, baryon number violating sphaleron transitions in hot electroweak plasma operate in the expanding Early Universe.

ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

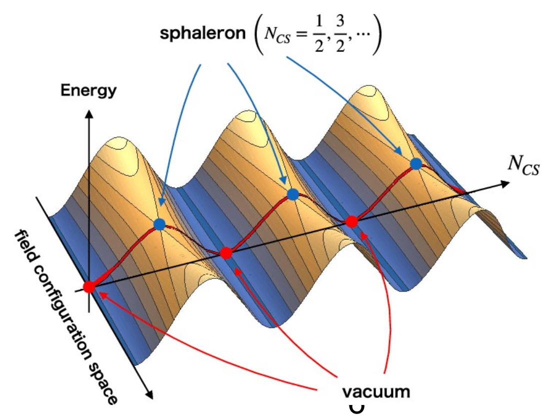
V.A. KUZMIN, V.A. RUBAKOV
Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow, USSR

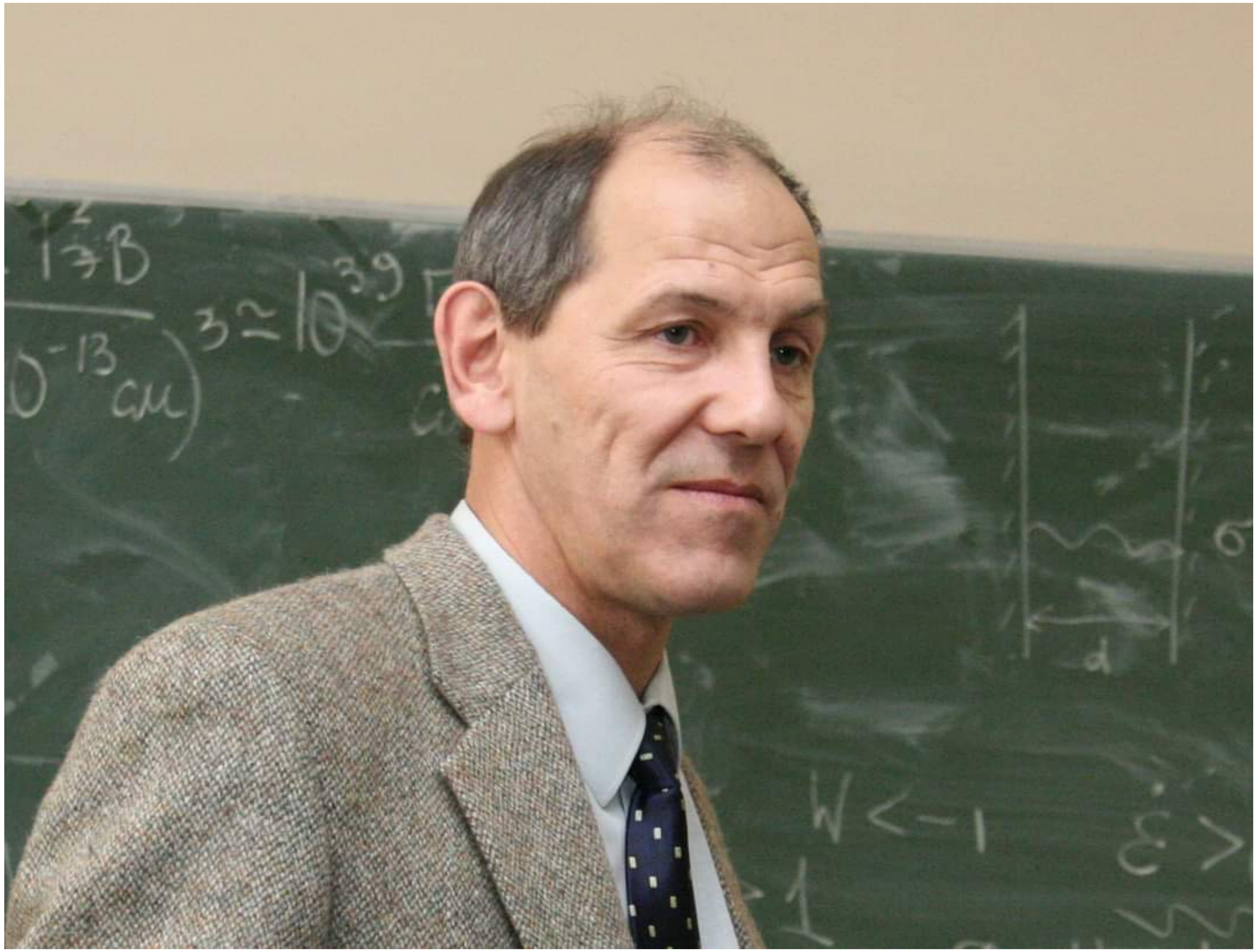
and

M.E. SHAPOSHNIKOV [1]
International Centre for Theoretical Physics, Trieste, Italy

Received 8 February 1985

Graphics: Hamada, Kikuchi,'20





V.A. Rubakov

1955-2022

Elephants in hot non-Abelian plasma

Boltzmann factor [21]. This contradicts a widely held view that processes such as monopole–antimonopole production are highly suppressed (in homogeneous systems) at very high temperatures. After all, at temperatures of the order of the mass of an elephant, one is not likely to find many elephants.

BARYON NUMBER VIOLATION AT HIGH TEMPERATURE IN THE STANDARD MODEL

Michael DINE, Olaf LECHTENFELD and Bunji SAKITA

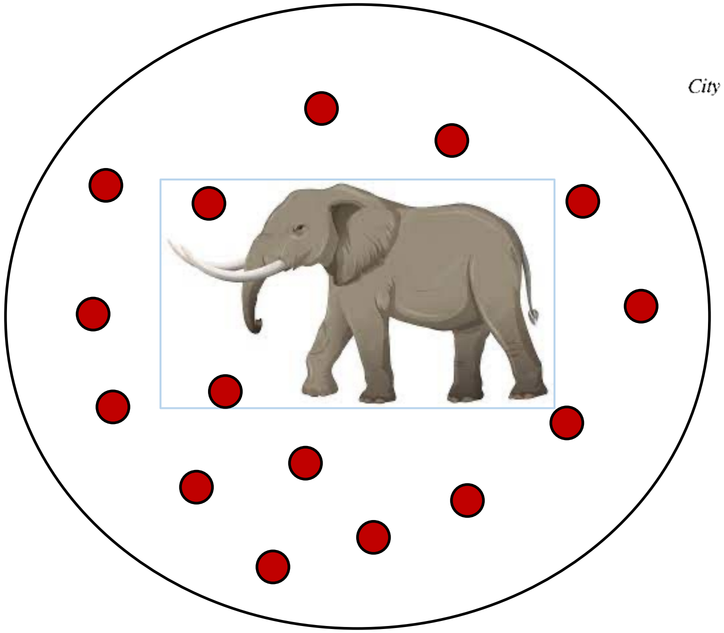
City College of the City University of New York, New York, NY 10031, USA

Willy FISCHLER and Joseph POLCHINSKI

University of Texas at Austin, Austin, TX 78712, USA

Received 20 December 1989

How many elephants are there in the plasma at $T \sim M_{elephant}$?



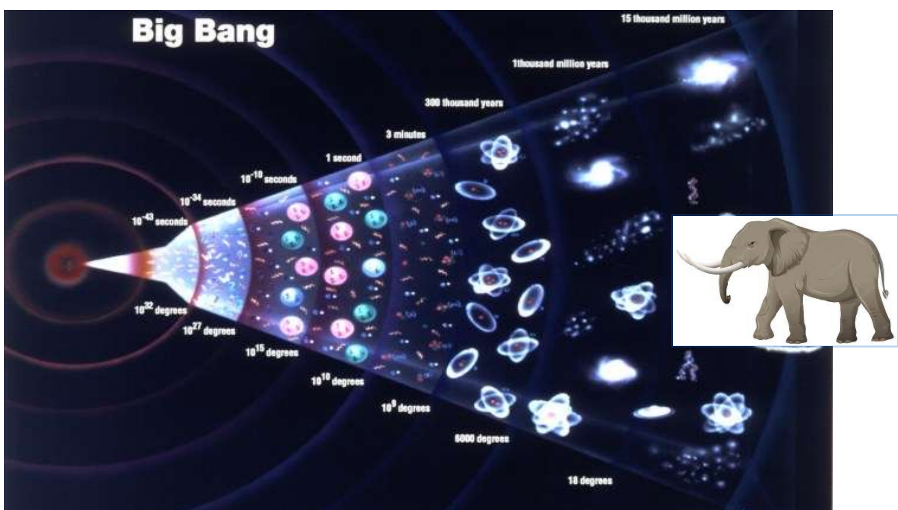
Multi-particle field configurations **can** be excited thermally

Is the Universe a Vacuum Fluctuation?

EDWARD P. TRYON

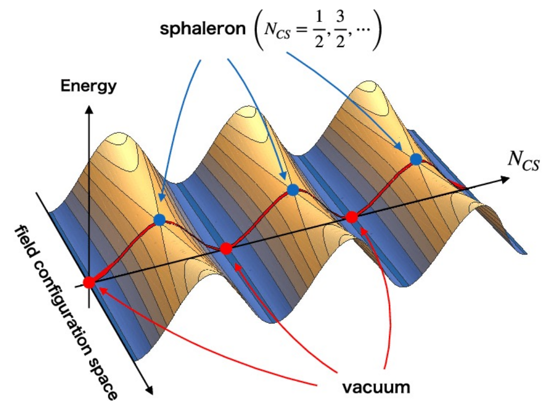
Department of Physics and Astronomy, Hunter College of the City University of New York, New York, New York 10021

If it is true that our Universe has a zero net value for all conserved quantities, then it may simply be a fluctuation of the vacuum, the vacuum of some larger space in which our Universe is imbedded. In answer to the question of why it happened, I offer the modest proposal that our Universe is simply one of those things which happen from time to time.



Chirality and the origin of Matter-Antimatter asymmetry in the Universe

Within the Standard Model, baryon number violating sphaleron transitions in hot electroweak plasma operate in the expanding Early Universe.



Graphics: Hamada, Kikuchi,'20

Can we study these processes in the lab?

No – the temperature of electroweak phase transition is too high, $T_{EW} \approx 160\ GeV \sim\ 10^{15}$ K

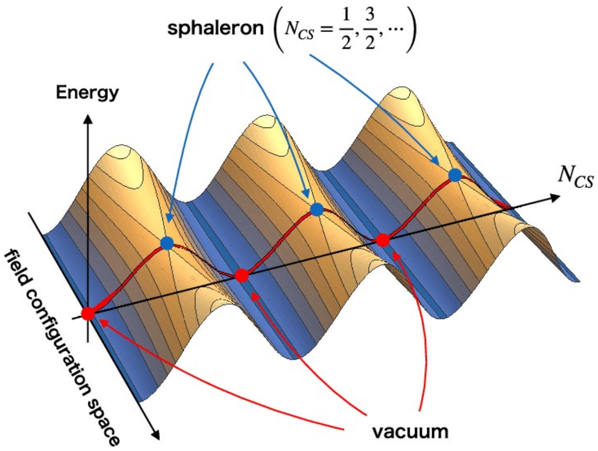
But: we can study analogous processes in another non-Abelian gauge theory of the Standard Model – QCD!

Generation of chirality in the QCD plasma

The temperature of QCD phase transition is 1,000 times lower:
$T_{QCD} \approx 160\ MeV \sim\ 10^{12}$ K

QCD plasma can be produced and studied in the ongoing heavy ion experiments at RHIC (BNL) and LHC (CERN).

QCD sphalerons induce chirality violation (instead of baryon number violation), and rapid expansion of the produced plasma drives it out of thermal equilibrium –



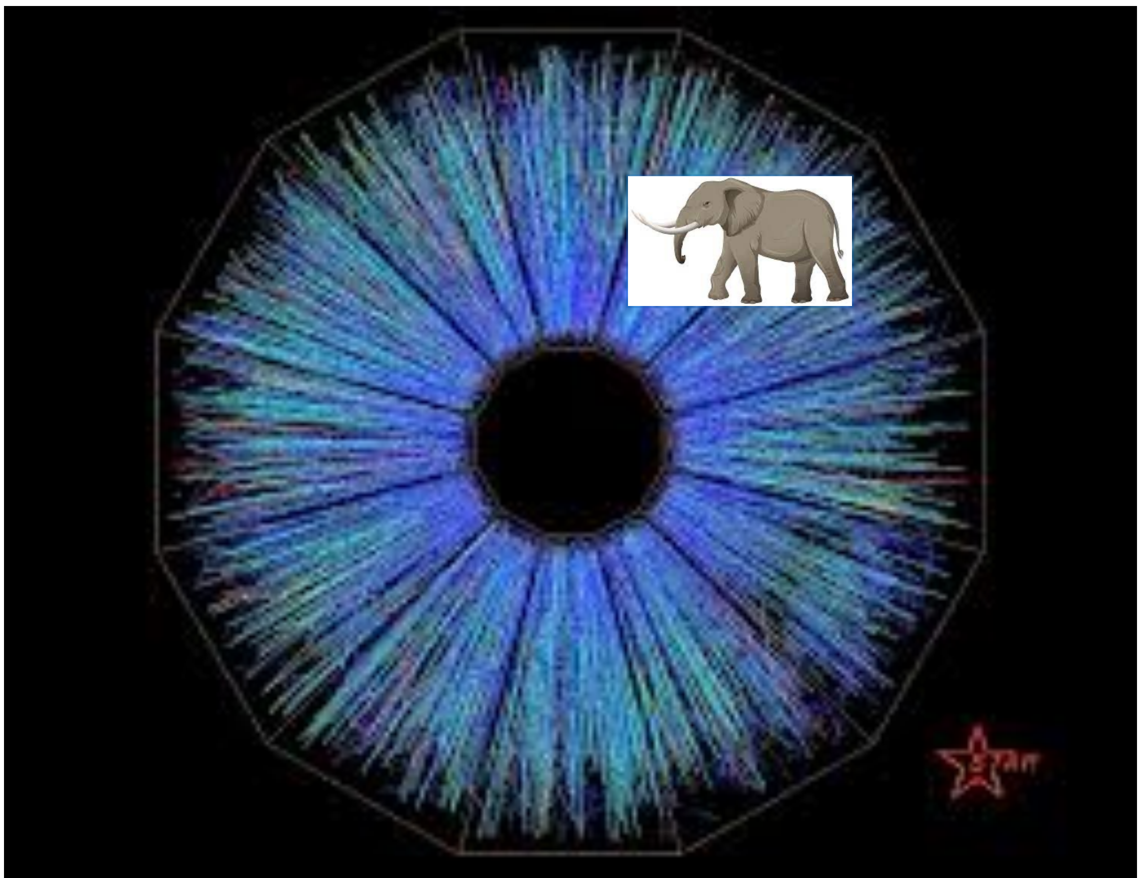
Graphics: Hamada, Kikuchi,'20

thus we expect to see a substantial **generation of net chirality**, <u>of fluctuating sign</u>, **in heavy ion collisions**!

The challenge:

How to separate the fluctuations induced by vacuum transitions from mundane background?

Searching for elephants in heavy ion collisions:



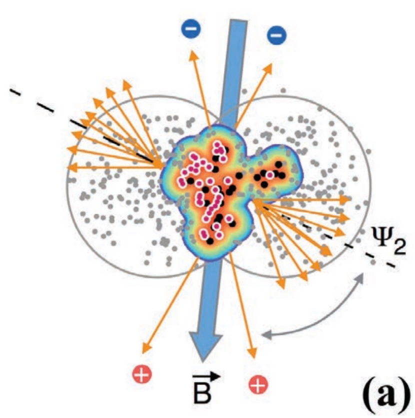
Separating the signal from background: the beginning

PHYSICAL REVIEW C **70**, 057901 (2004)

Parity violation in hot QCD: How to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA
(Received 5 August 2004; published 11 November 2004)

In a recent paper (hep-ph/0406125) Kharzeev argues for the possibility of *P*- and/or *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.

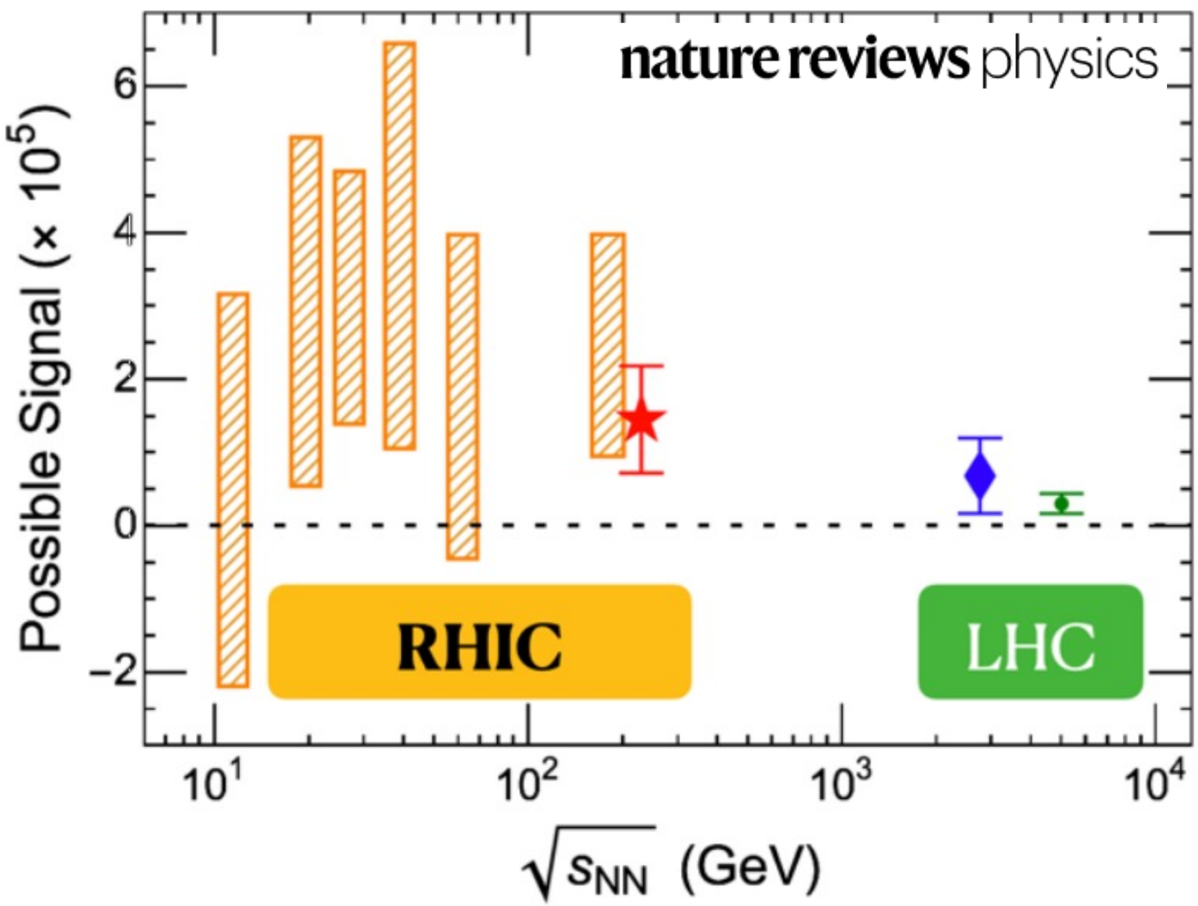


$$\langle \cos(\phi_a - \Psi_2)\cos(\phi_b - \Psi_2) - \sin(\phi_a - \Psi_2)\sin(\phi_b - \Psi_2)\rangle = \langle \cos(\phi_a + \phi_b - 2\Psi_2)\rangle = (v_{1,a}v_{1,b} - a_a a_b)\,\langle \cos(2\Psi_2)\rangle \quad (1)$$

Measure the difference of charged hadron fluctuations along and perpendicular to magnetic field (direction of $\vec{B}$ is defined by the reaction plane)

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

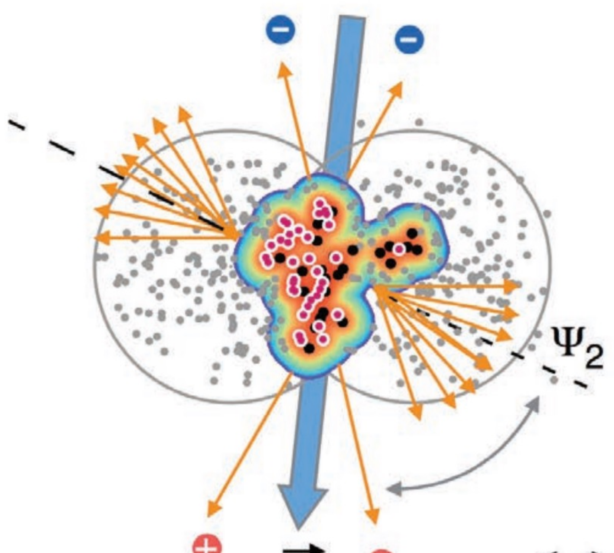
Review + Compilation of the recent data: DK, J. Liao, Nature Reviews (Phys.) 3 (2021) 55



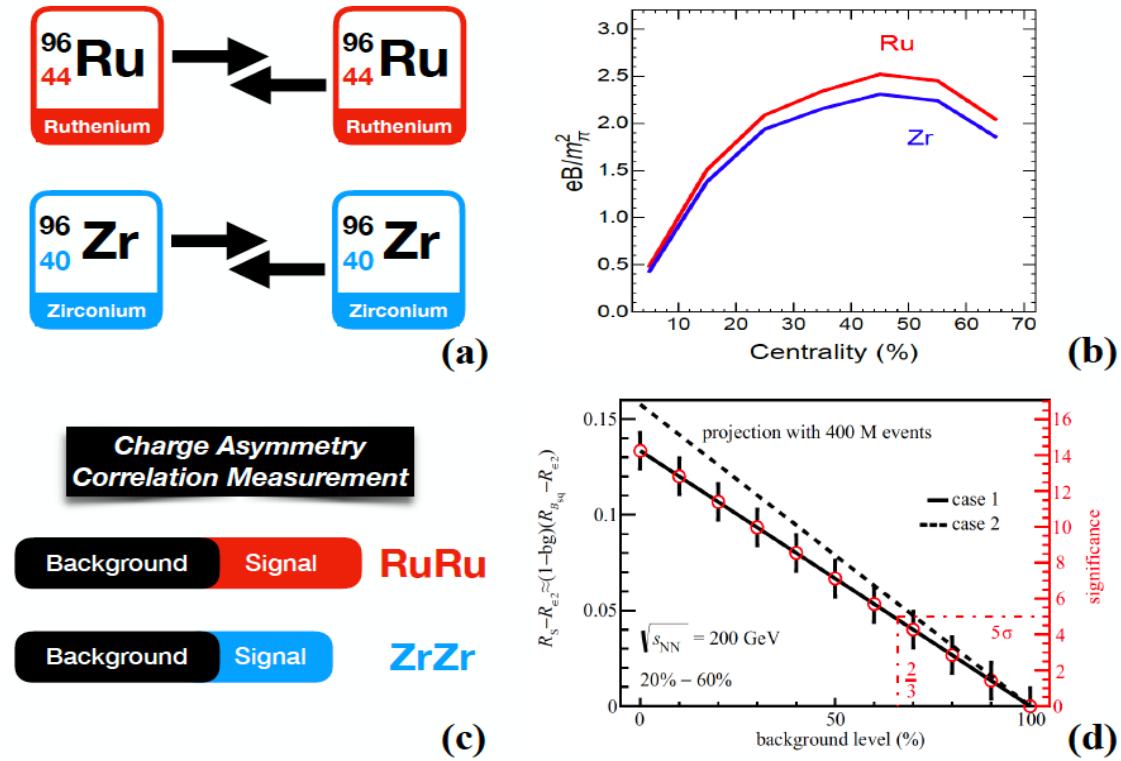
Separating the signal from background is the main subject of the ongoing work –

Big new development: the isobar run!

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



(a)



STAR Collaboration

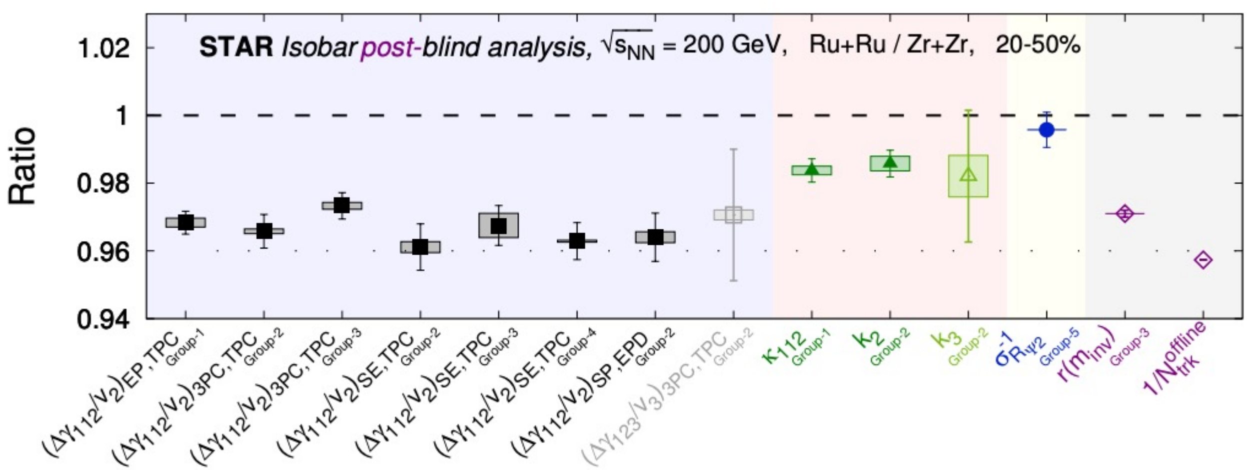
CME search in isobar collisions at RHIC

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

CME search in isobar collisions at RHIC

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

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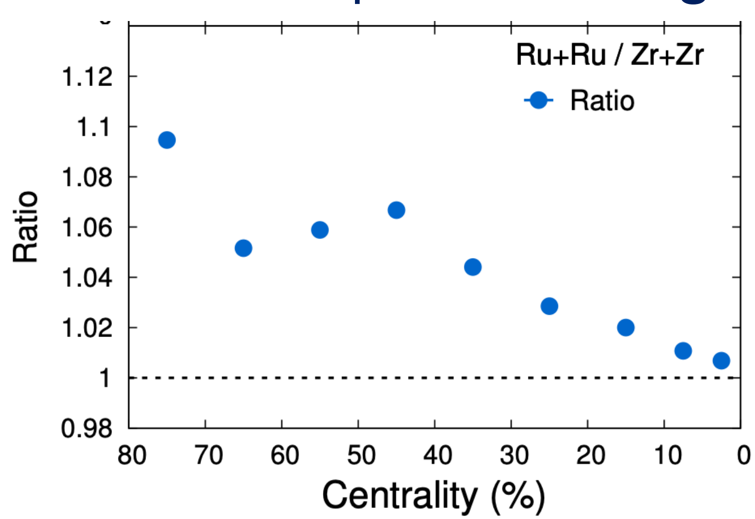
STAR, nucl-ex 2109.00131, PRC (2022)

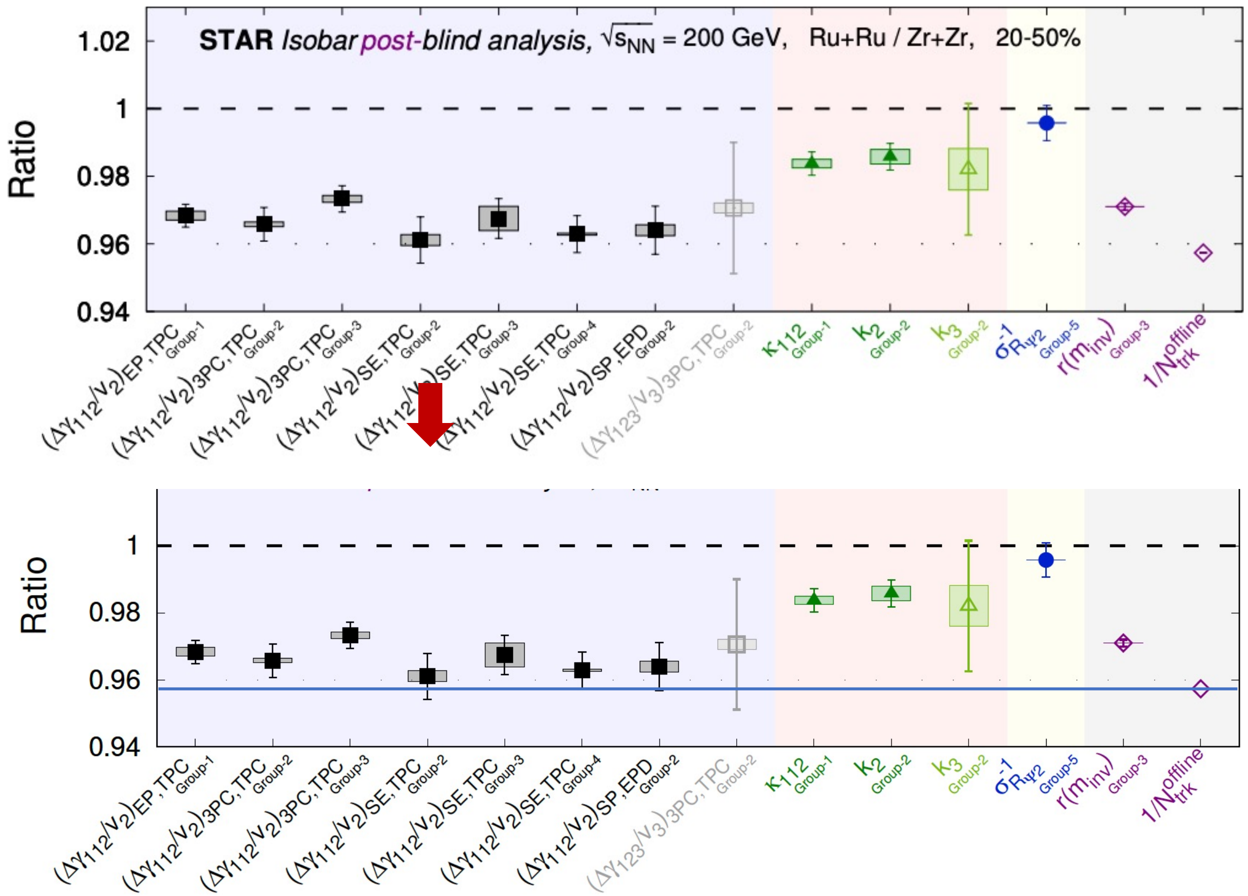
The predefined criteria assume that the multiplicities in RuRu and ZrZr collisions (in the same cross section cuts) are the same.
Is this criterion supported by the data?
No. The **measured** multiplicities are **significantly** different:



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 in isobar collisions at RHIC

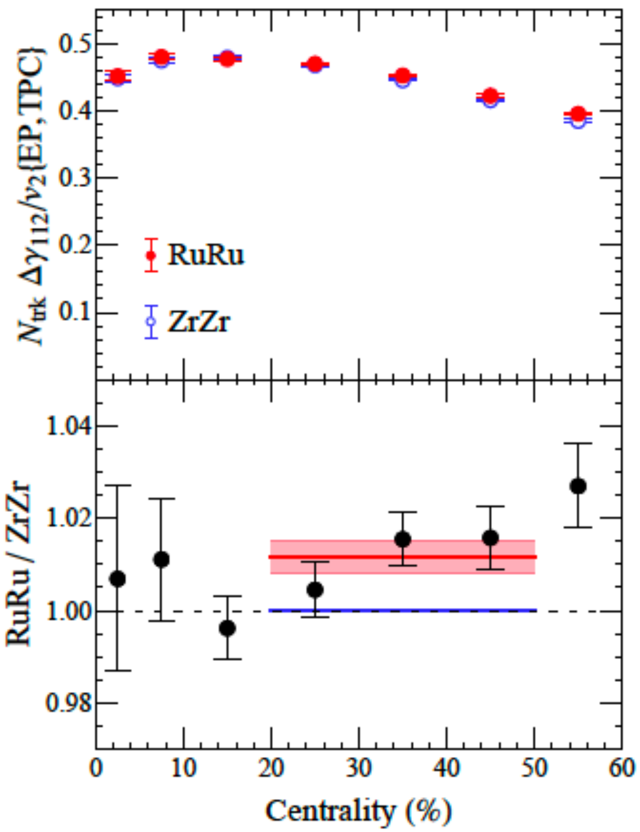
of clusters scaling with multiplicity, the value of $\Delta\gamma$ scales with the inverse of multiplicity [20], i.e. $N\Delta\gamma \propto v_2$ with the proportionality presumably equal between the two isobars. Because of this, it may be considered that the proper baseline for the ratio of $\Delta\gamma/v_2$ 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.

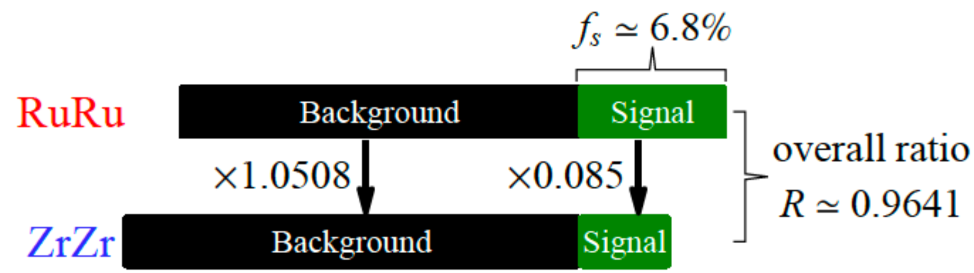


CME search in isobar collisions at RHIC: a theory analysis

DK, J. Liao, S. Shi, Phys Rev C 106 L051903 (2022)

Talks by S. Shi and J. Liao





Isobar results are consistent with the CME fraction of

$$f_s \simeq +(0.068 \pm 0.026) = (6.8 \pm 2.6)\%.$$

Post-blinding STAR analysis is urgently needed!

New AuAu@200 GeV STAR

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

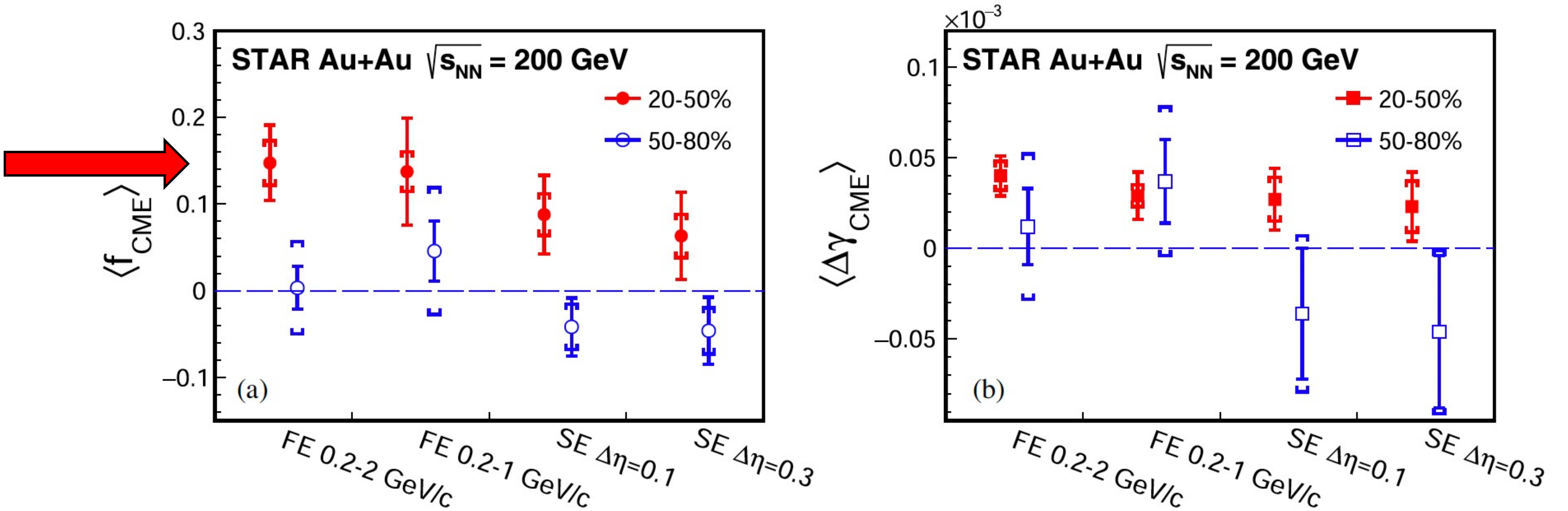


FIG. 3. The flow-background removed $\langle f_{\mathrm{CME}} \rangle$ (a) and $\langle \Delta\gamma_{\mathrm{CME}} \rangle$ (b) signal in 50%–80% (open markers) and 20%–50% (solid markers) centrality Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, extracted by various analysis methods [full-event (FE),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

New AuAu@200 GeV STAR

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.

New idea: shear-induced CME

M. Buzzegoli, DK, Y.-C. Liu, S. Shi, S. Voloshin, H.-U. Yee,
Phys Rev C 106 L051902 (2022)

Talk by S. Shi

Shear-induced polarization is likely to contribute to the observed Λ:

talk by F. Becattini

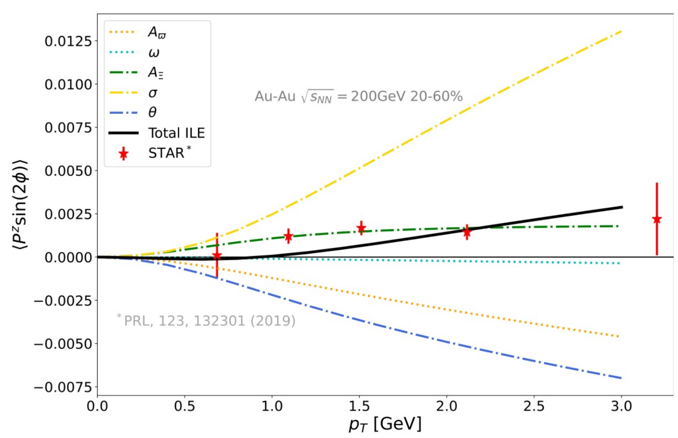


Fig. 2. Contributions to the quadrupole longitudinal components of Λ polarization at ILE stemming from kinematic vorticity ω, shear tensor σ, acceleration (from vorticity A_ϖ and shear A_Ξ) and expansion rate θ, see Eqs. (10) and (11) .

M.Buzzegoli, F.Becattini, G.Inghirami, Y. Karpenko, A.Palermo, QM 2022

What about shear-induced CME (siCME)?

Shear-induced CME

Talk by S. Shi

M. Buzzegoli, DK, Y.-C. Liu, S. Shi, S. Voloshin, H.-U. Yee,
Phys Rev C 106 L051902 (2022)

In fact, it appears in second-order chiral MHD:

$$j^{\mu}_{(2)} = \xi_1 \sigma^{\mu\nu} \omega_\nu + \xi_2 Q \sigma^{\mu\nu} B_\nu$$

$$\sigma^{\mu\nu} = \tfrac{1}{2}(\partial_\perp^\mu u^\nu + \partial_\perp^\nu u^\mu)$$

DK, H.-U.Yee,
Phys Rev D84, 045025 (2011)

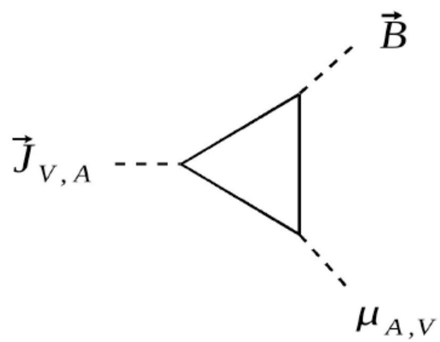
$$\xi_1 = -\frac{N_F N_c}{\sqrt{3}\pi^3}\frac{\mu_A \mu}{T} \qquad \xi_2 = -\frac{N_F N_c}{\sqrt{3}\pi^3}\frac{\mu_A}{T}$$

Talk by S. Shi

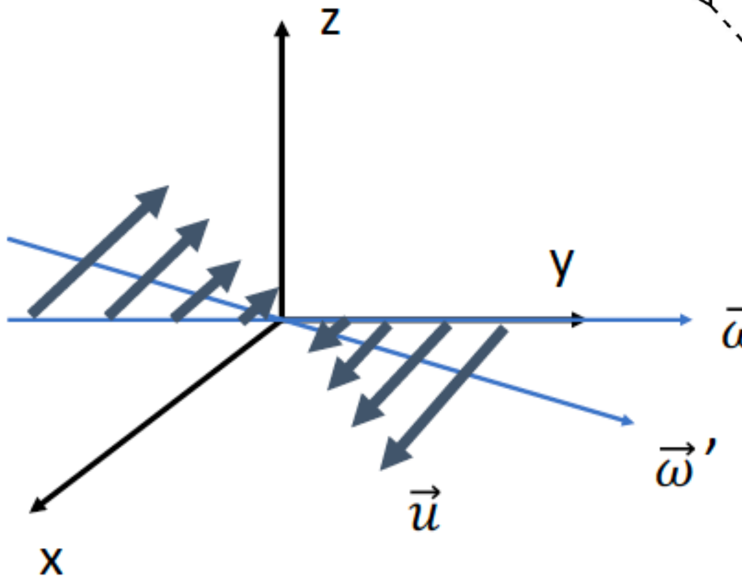
Shear-induced CME

M. Buzzegoli, DK, Y.-C. Liu, S. Shi, S. Voloshin, H.-U. Yee,
Phys Rev C 106 L051902 (2022)

How can a current perpendicular to **ω** arise from the anomaly?



Anomalous Ward identities are exact at operator level, but matrix elements can be modified by the medium.

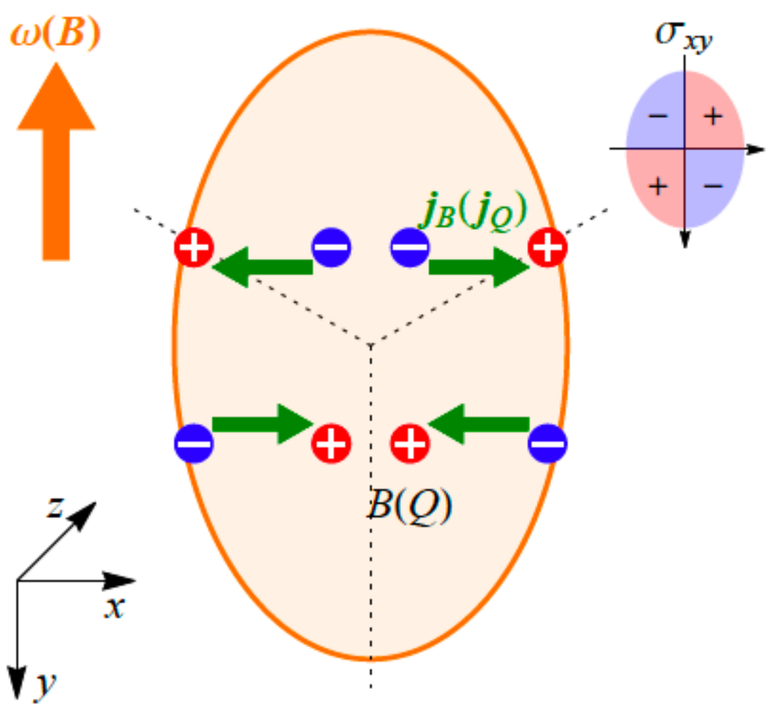


Rotation of vorticity by the shear flow (tornado formation,…)

Shear-induced CME

Talk by S. Shi

M. Buzzegoli, DK, Y.-C. Liu, S. Shi, S. Voloshin, H.-U. Yee,
Phys Rev C 106 L051902 (2022)



Signature:

charge asymmetry of the triangular flow!

Summary

1. CME in heavy ion collisions is a unique opportunity to observe in the lab topological vacuum transitions

2. CME is not excluded by isobar results (?) STAR post-blinding analysis of the isobar data is urgently needed!

3. With an expected order-of-magnitude increase in statistics, AuAu data analysis should allow to draw a definite conclusion about CME in heavy ion collisions