AdS4CME@HIC, IFT UAM, Madrid, March 14-17, 2022

Chiral Magnetic Effect in Heavy Ion Collisions: where do we stand?

Dmitri Kharzeev

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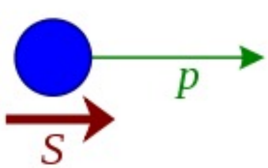
Chirality in subatomic world: chiral fermions

Fermions:
E. Fermi,1925

Dirac equation:
P. Dirac, 1928

$$(i\partial\!\!\!/ - m)\psi = 0$$

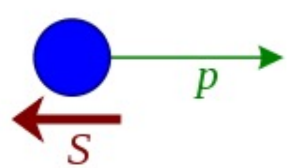
Right-handed:



Weyl fermions:
H. Weyl, 1929

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

Left-handed:



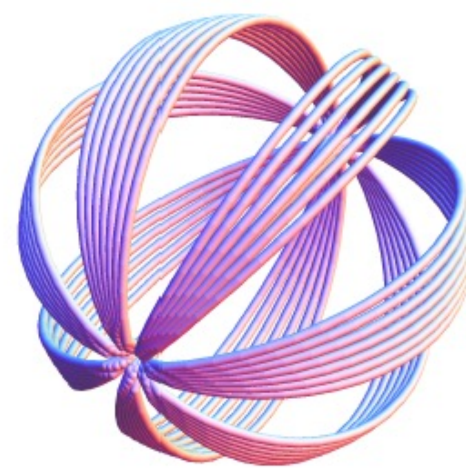
Majorana fermions:
1937

$$-i\partial\!\!\!/\psi + m\psi_c = 0$$

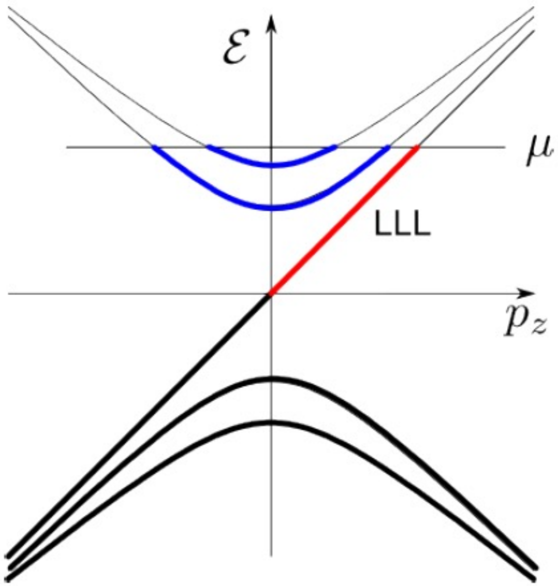
$$\psi_c := i\psi^*$$

Chirality of gauge fields

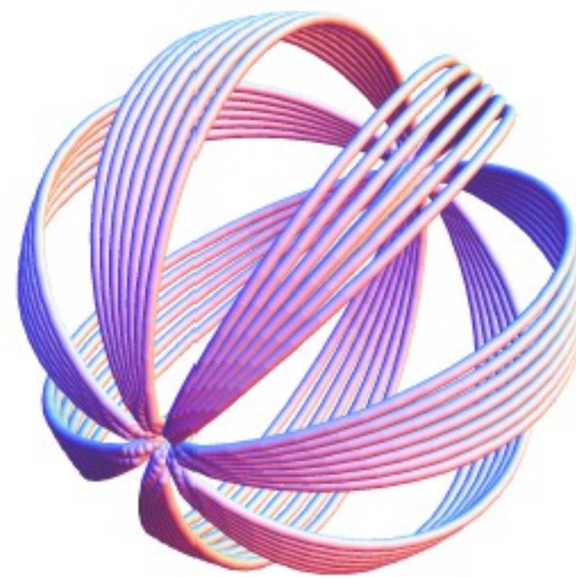
Gauge fields can form **chiral knots** – for example, knots of magnetic flux in magnetohydrodynamics (magnetic helicity), characterized by Chern-Simons number



Chiral anomaly: chirality transfer from fermions to gauge fields (or vice versa)



Right-handed fermion on the lowest Landau level in a magnetic field



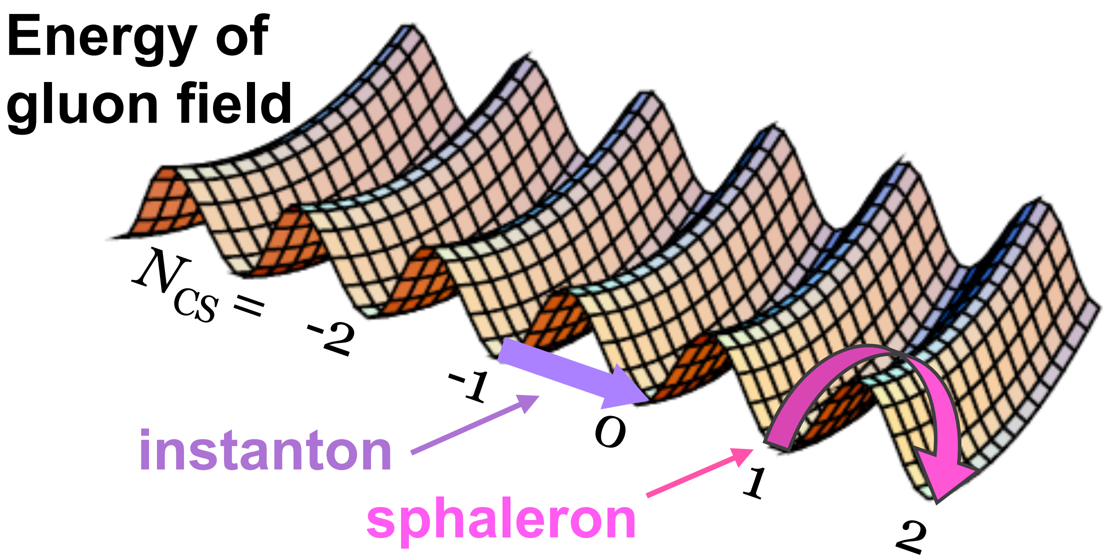
Right-handed chiral knot of magnetic flux

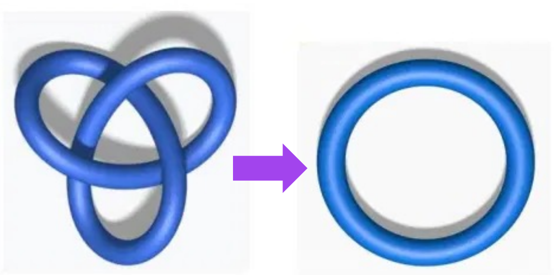
Chirality in the vacuum of the Standard Model

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:



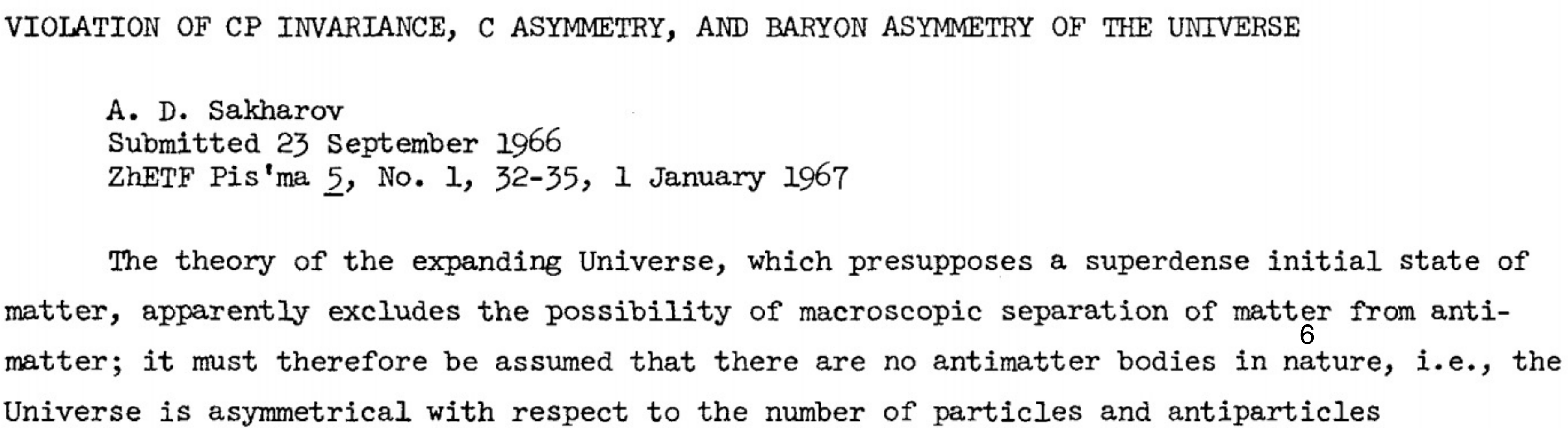


Chirality and the origin of Matter-Antimatter asymmetry in the Universe

A.D. Sakharov, 1967

Sakharov conditions for baryogenesis:

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



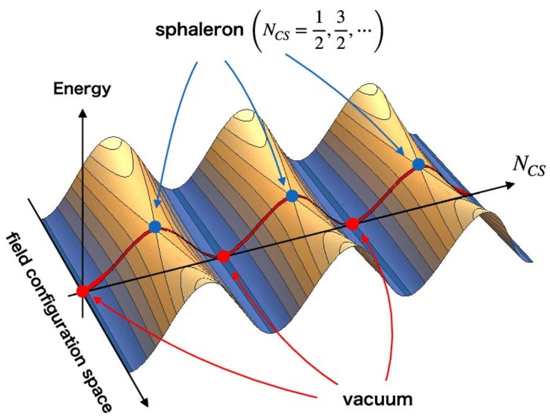
VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

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

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?

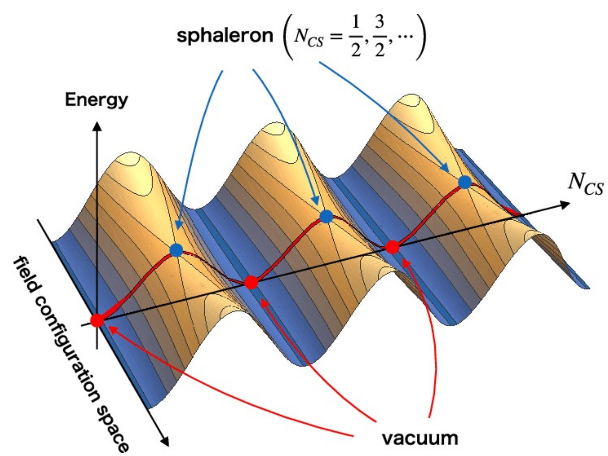
No – the temperature of electroweak phase transition is too high, $T_{EW} \approx 160\ GeV \sim\ 10^{15}$ K

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).

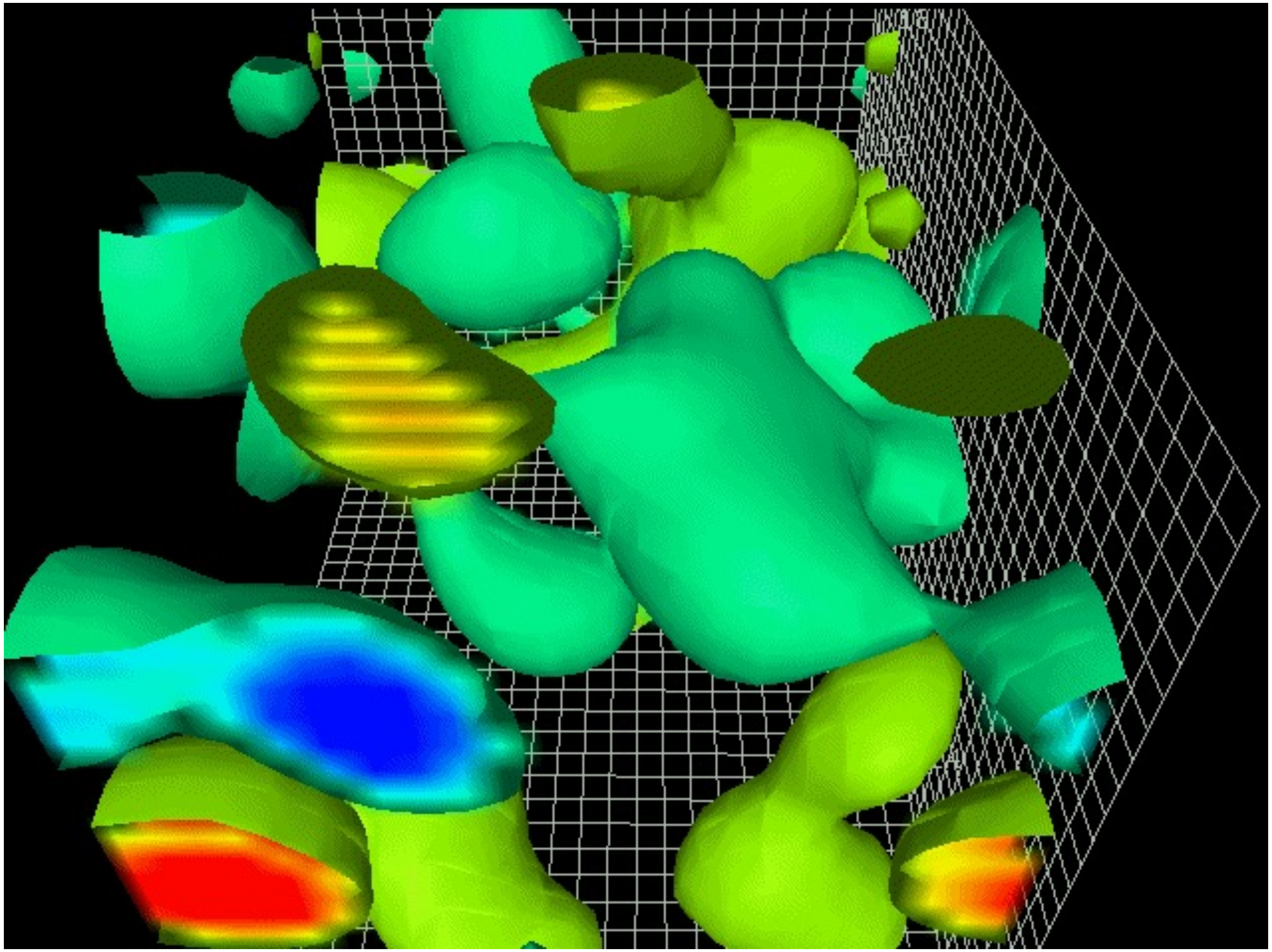


Graphics: Hamada, Kikuchi,'20

QCD sphalerons induce chirality violation (instead of baryon number violation), and rapid expansion of the produced plasma drives it out of thermal equilibrium –
thus we expect to see a substantial **generation of net chirality**, <u>of fluctuating sign</u>, **in heavy ion collisions**!

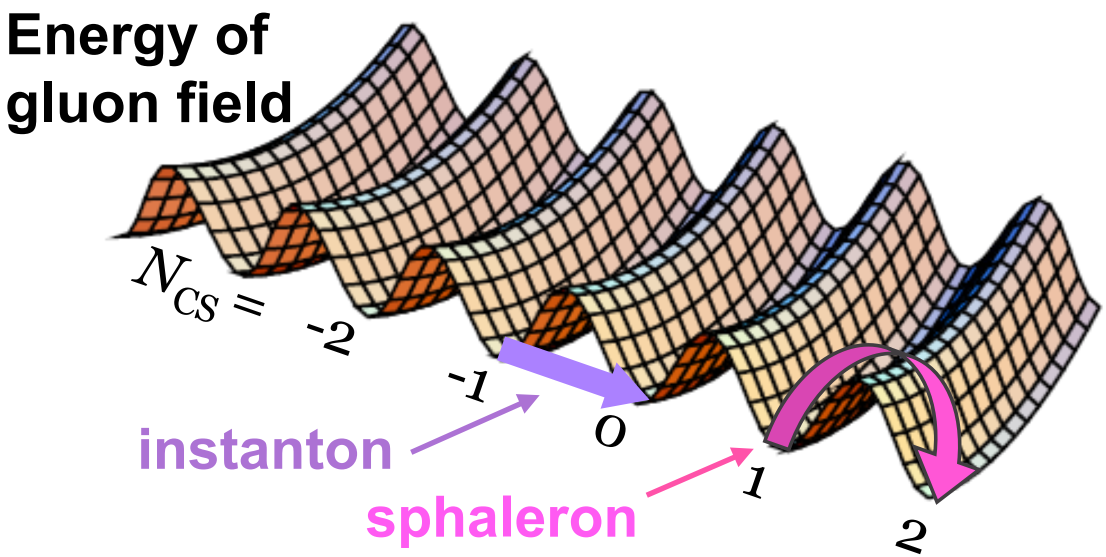
Topological transitions in QCD vacuum

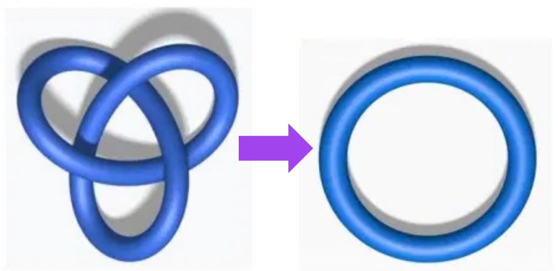
D. Leinweber



Chirality in the vacuum of the Standard Model

Topological chirality-changing transitions between the vacuum sectors of QCD are responsible for the spontaneous chiral symmetry breaking and thus most of the mass of visible Universe.





Is it possible to directly observe these chirality-changing transitions in experiment?

Detecting the topological structure of QCD vacuum

Topological transitions in the QCD plasma change chirality of quarks. However, quarks are confined into hadrons, and their chirality cannot be detected in heavy ion experiments.

Therefore , to observe these chirality-changing transitions we have to find a way to convert chirality of quarks into something observable – perhaps, a (fluctuating) **electric dipole moment of the QCD plasma**? This would require an external magnetic field or an angular momentum.

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

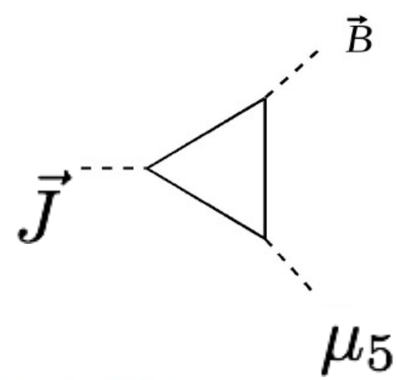
hep-ph/0406125 (June 2004) Physics Letters B 633 (2006) 260–264

Chiral Magnetic Effect

DK'04; DK, A. Zhitnitsky '07; DK, L.McLerran, H.Warringa '07; K.Fukushima, DK, H.Warringa, "Chiral magnetic effect" PRD'08; Review and list of refs: DK, arXiv:1312.3348 [Prog.Part.Nucl.Phys]

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, and in the presence of B, vector e.m. current is generated:



$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2} \left(F_L^{\mu\nu} \tilde{F}_{L,\mu\nu} - F_R^{\mu\nu} \tilde{F}_{R,\mu\nu} \right)$$

Compute the current through $$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

Absent in Maxwell theory!

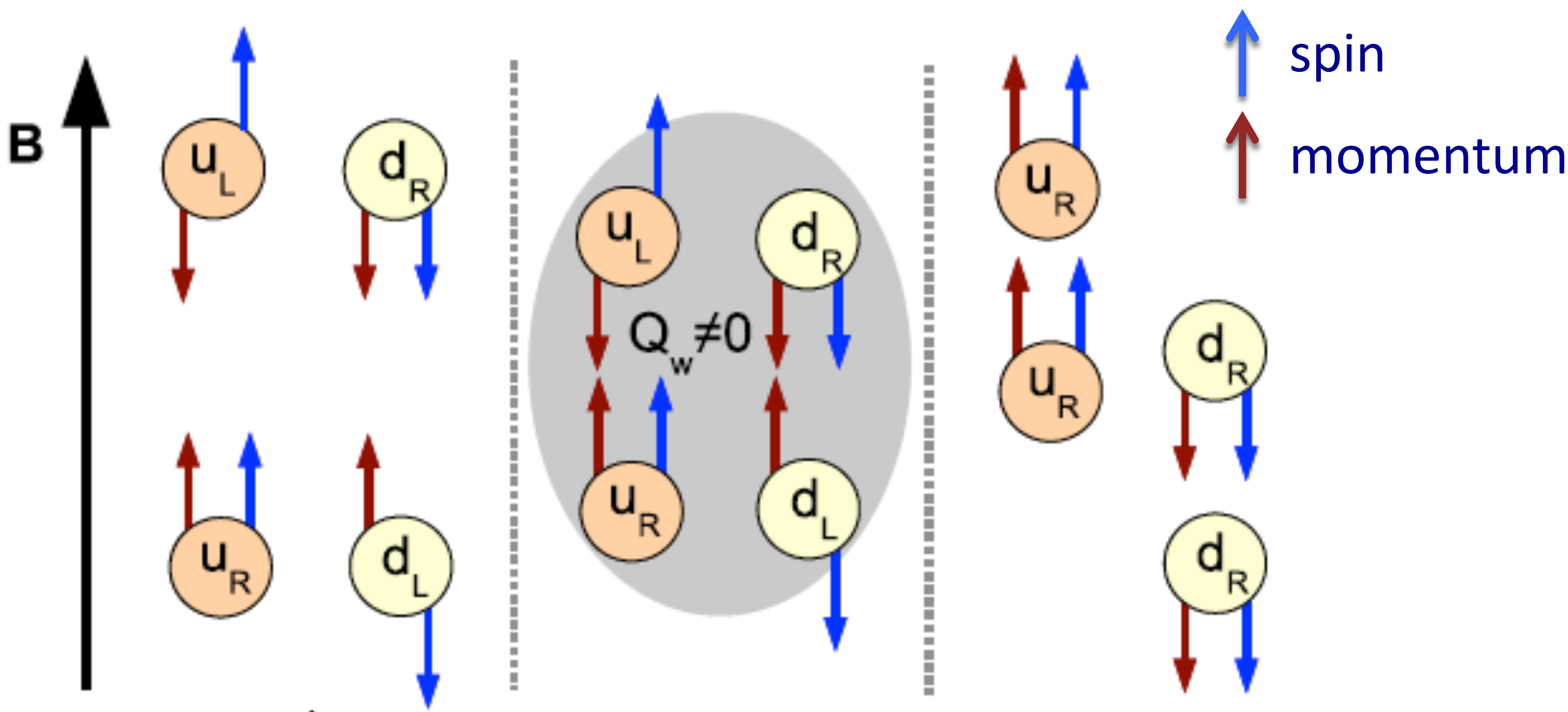
$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}}$$

Coefficient is fixed by the chiral anomaly, no corrections

Chirally imbalanced system is a non-equilibrium, steady state

Chirality in 3D: the Chiral Magnetic Effect

chirality + magnetic field = current



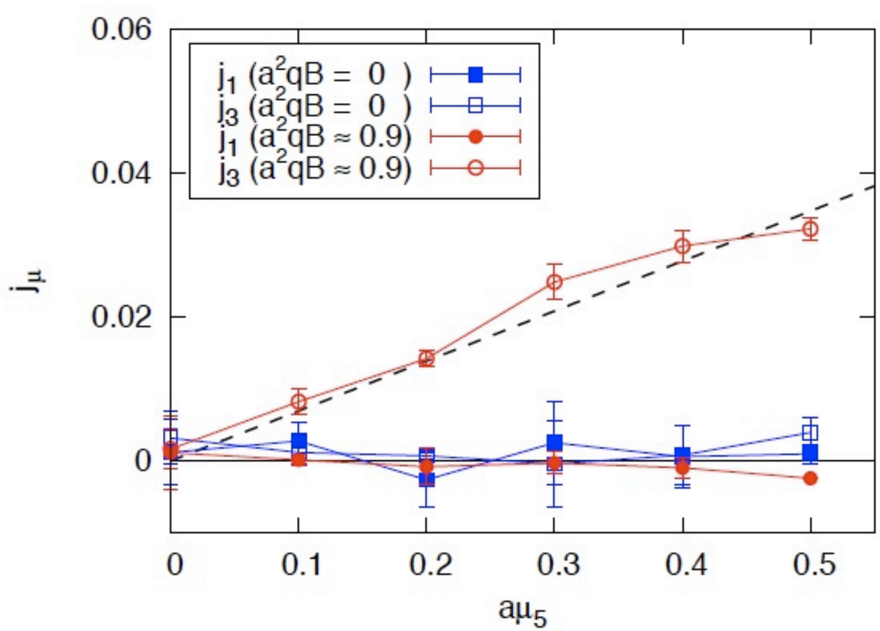
DK'04; DK, L.McLerran, H. Warringa '07; K. Fukushima, DK, H. Warringa '08 arXiv:1105.0385, PRL

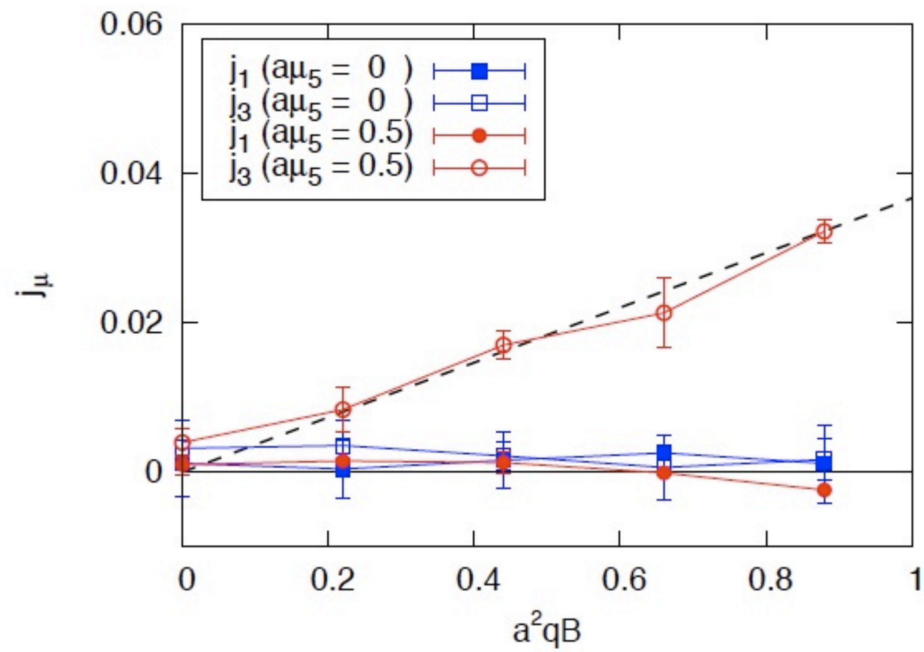
Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan

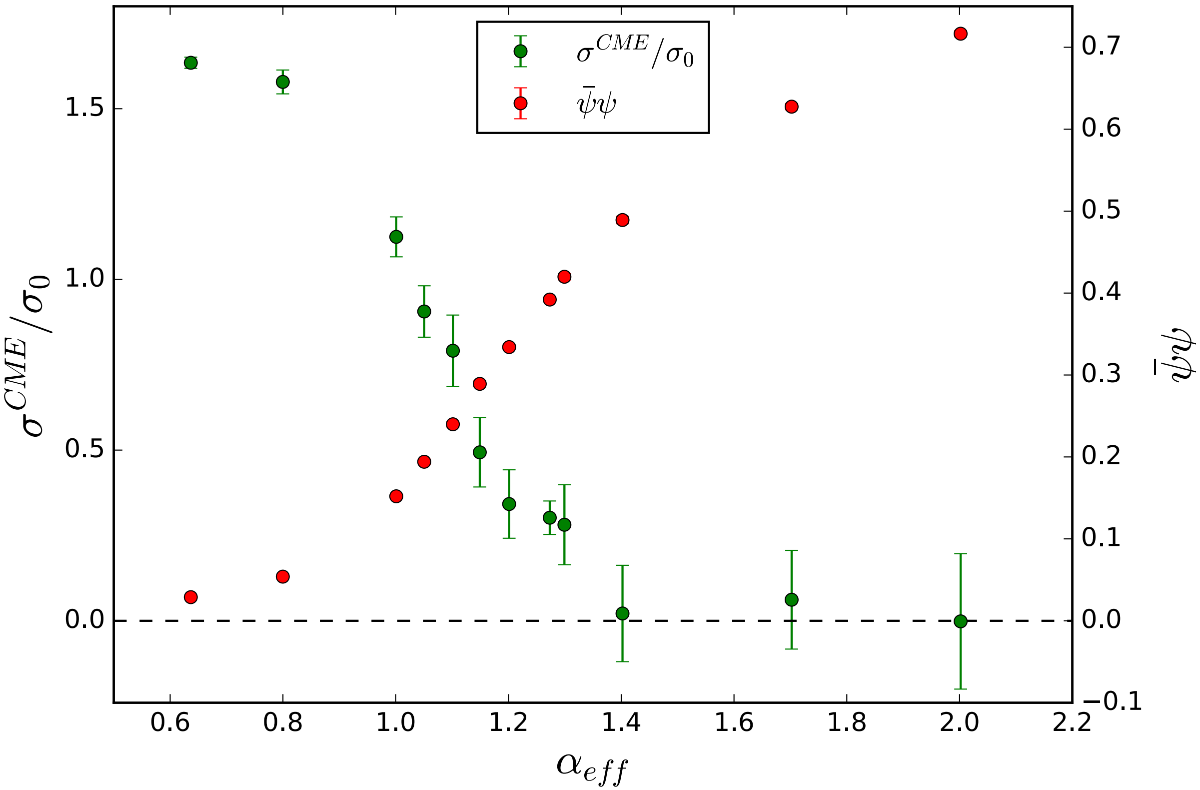
(Dated: May 3, 2011)

We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.





Chiral magnetic effect as a signature of chiral symmetry restoration



V.Braguta et al, arxiv:1704.07132, [PRD]

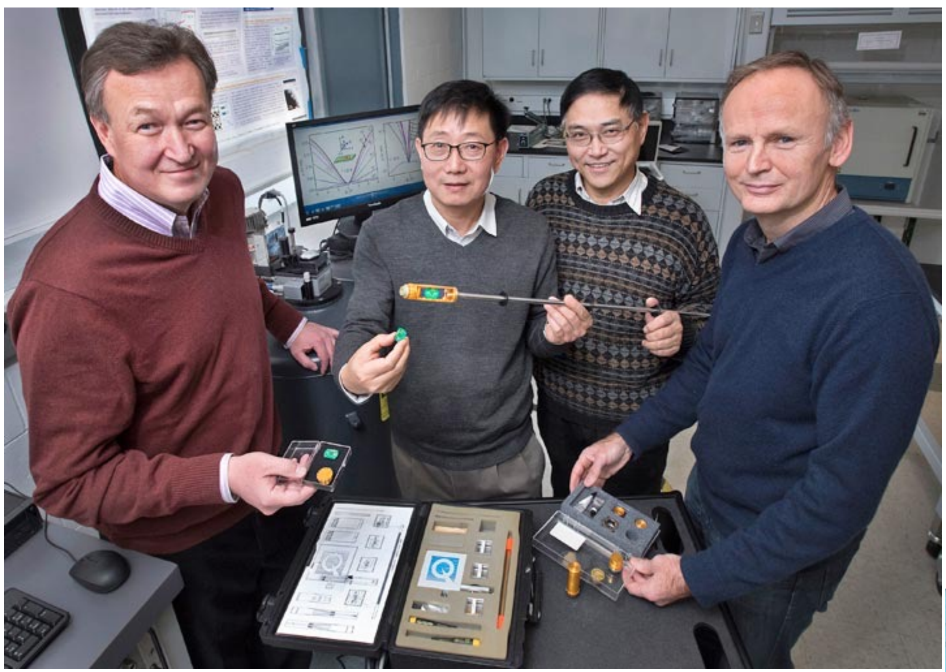
The spontaneous breaking of chiral symmetry does not allow the chiral magnetic current to propagate

CME in condensed matter:

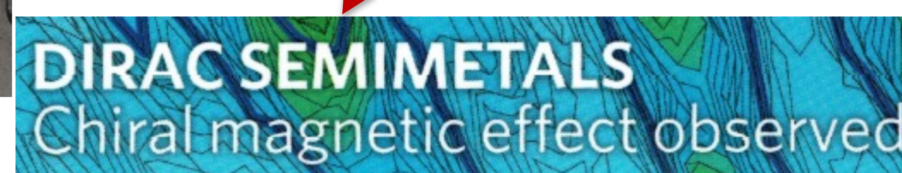
Observation of the chiral magnetic effect in $ZrTe_5$

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



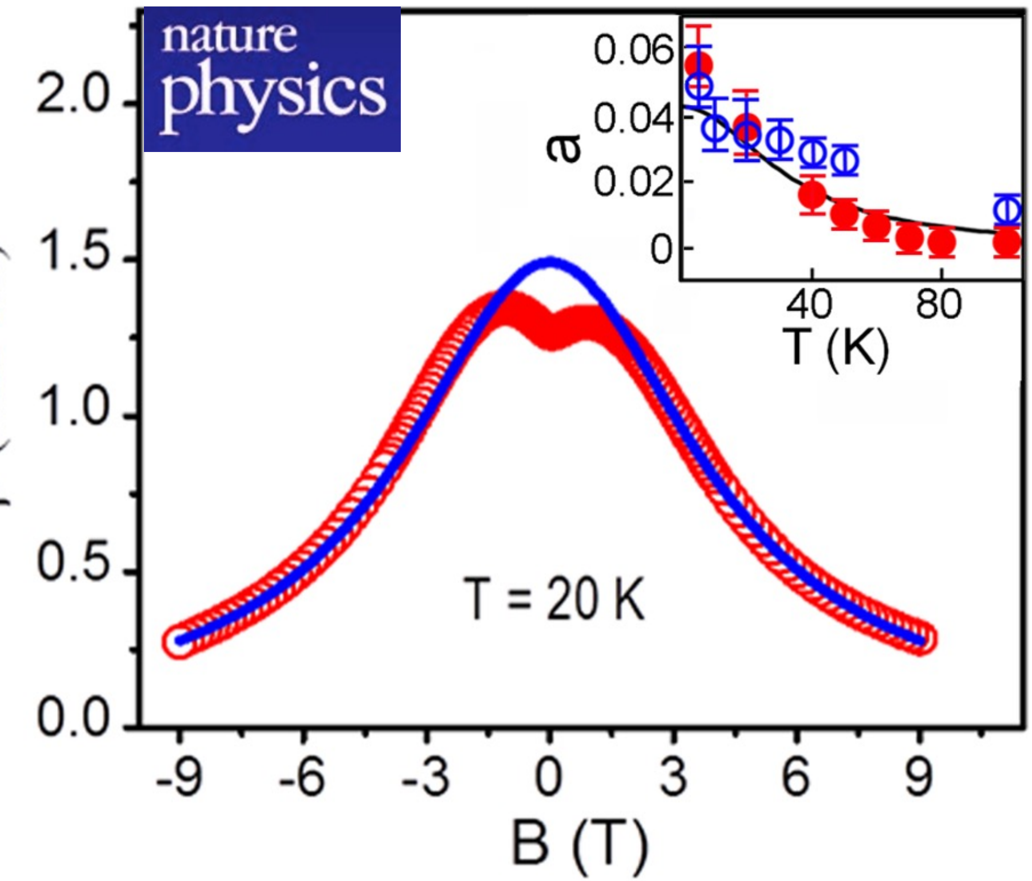
arXiv:1412.6543 [cond-mat.str-el]

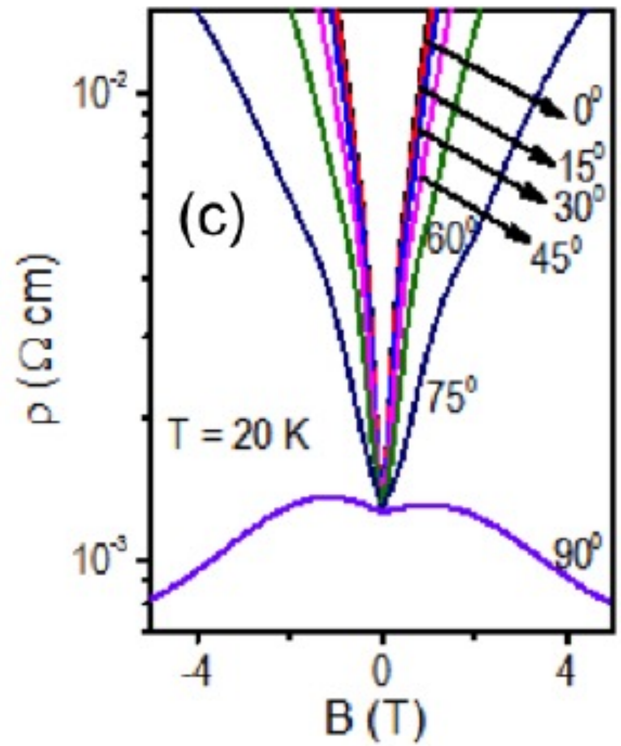
Chiral Magnetic Effect Generates Quantum Current

Separating left- and right-handed particles in a semi-metallic material produces anomalously high conductivity

February 8, 2016

Nature Physics **12**, 550 (2016)

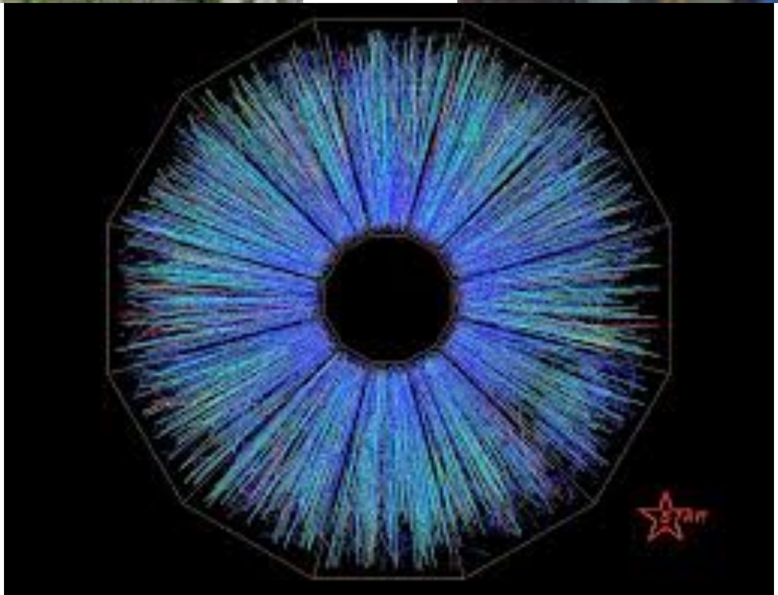




Can one detect QCD topological transitions in heavy ion collisions?

Relativistic Heavy Ion Collider (RHIC) at BNL

The STAR Collaboration at RHIC



Charged hadron tracks in a Au-Au collision at RHIC [STAR experiment]

Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

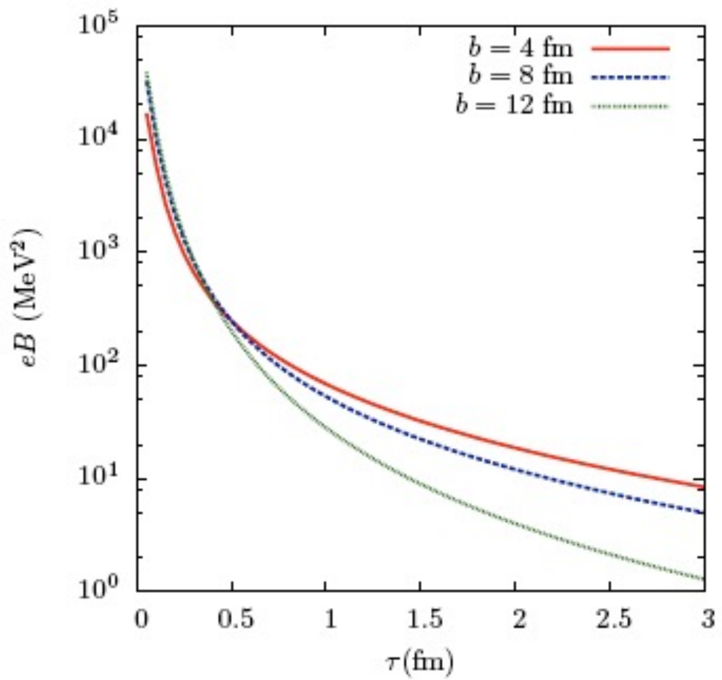
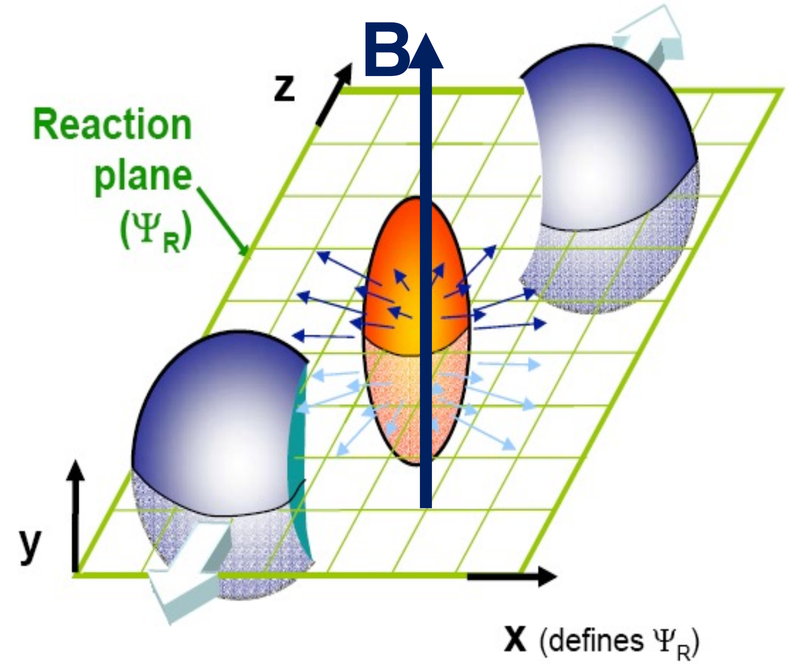
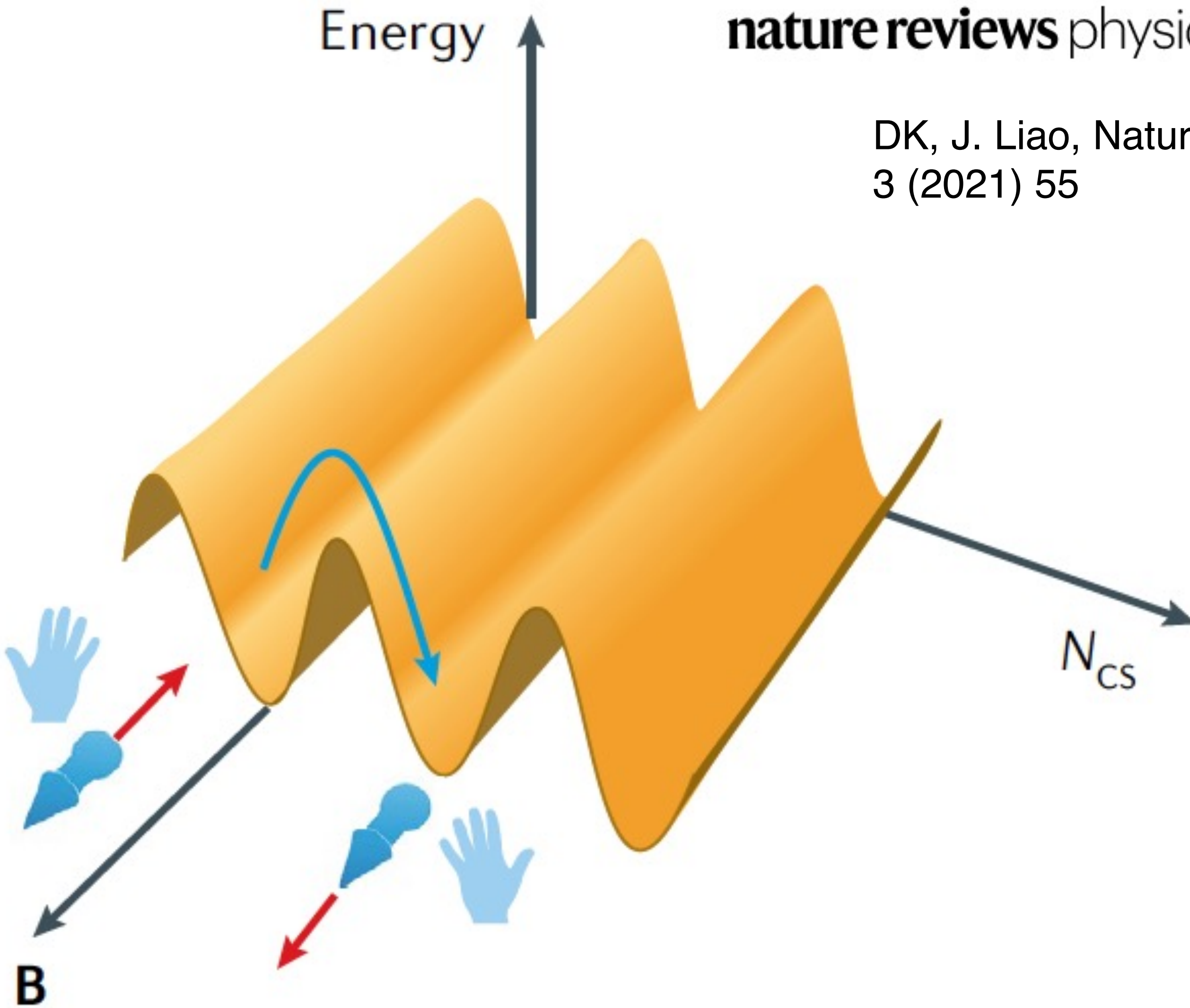


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).



DK, McLerran, Warringa, Nucl Phys A803(2008)227

At higher energies, the produced magnetic field rapidly decays – RHIC has more favorable conditions for CME than LHC



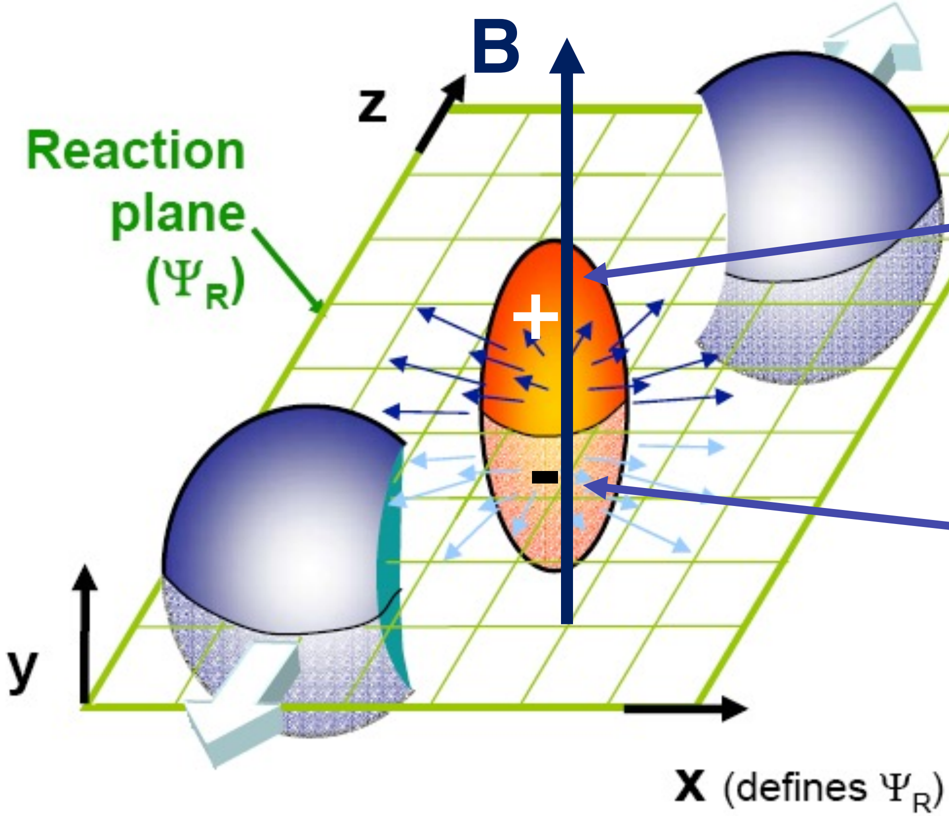
nature reviews physics

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-

CME as a probe of topological transitions and chiral symmetry restoration in QCD plasma

Electric dipole moment due to chiral imbalance



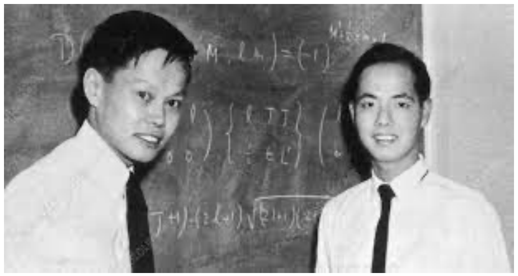
excess of positive charge

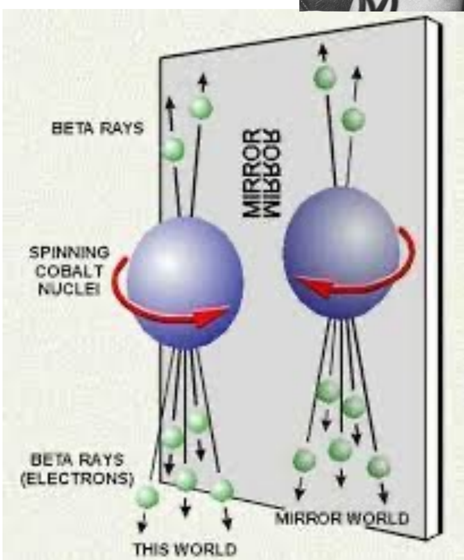
excess of negative charge

The problem:
fluctuating sign, reflecting topological fluctuations in QCD
- backgrounds!

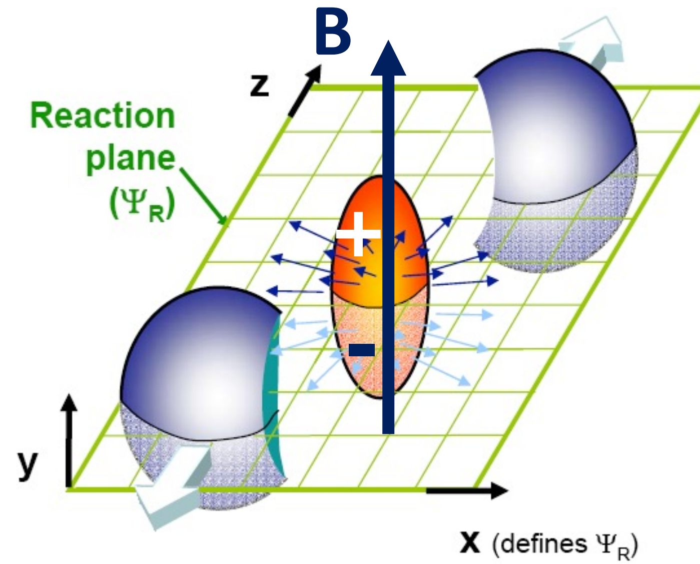
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

CME as a probe of topological transitions and Event-by-event parity violation in QCD plasma





Global Parity violation
in Weak interactions



Local, Event-by-event Parity violation
in Strong Interactions ?

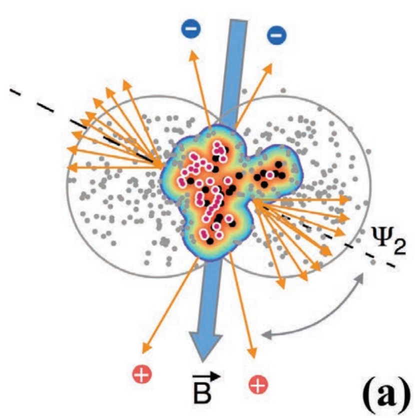
Separating the signal from background: the beginning

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.



(a)

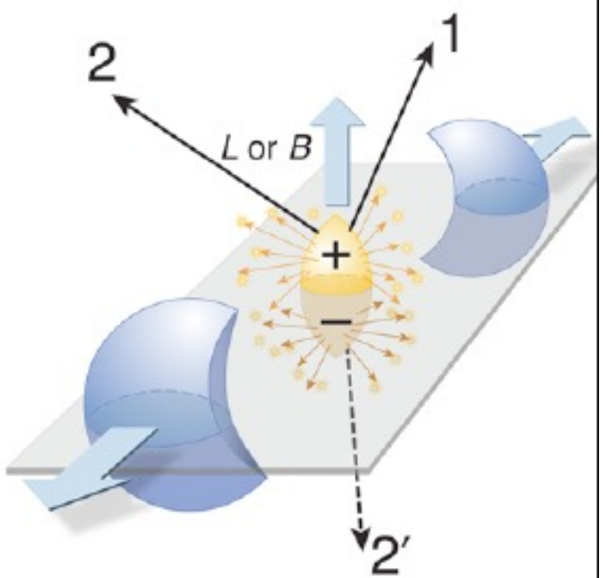
$$\begin{aligned}\langle \cos(\phi_a - \Psi_2)\cos(\phi_b - \Psi_2) \\ - \sin(\phi_a - \Psi_2)\sin(\phi_b - \Psi_2)\rangle \quad (1) \\ = \langle \cos(\phi_a + \phi_b - 2\Psi_2)\rangle = (v_{1,a}v_{1,b} - a_a a_b)\,\langle \cos(2\Psi_2)\rangle\end{aligned}$$

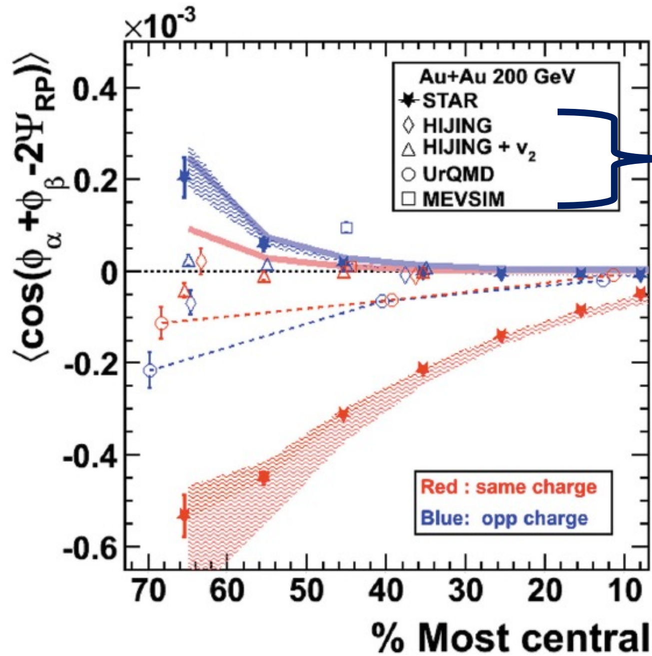
Measure the difference of charged hadron fluctuations along and perpendicular to magnetic field
(direction of $\vec{B}$ is defined by the reaction plane)

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)





Monte Carlo generators do not describe the data

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\rm IN}] - [\langle a_\alpha a_\beta \rangle + B_{\rm OUT}] \approx -\langle a_\alpha a_\beta \rangle + [B_{\rm IN} - B_{\rm OUT}],$$

NB: P-even quantity (strength of P-odd fluctuations) – subject to large background contributions

Review: DK, J. Liao, S. Voloshin, G. Wang, Prog.Part.Nucl.Phys.(2016)

Baseline: scaling with 1/N (inverse multiplicity)

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

Dmitri Kharzeev

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

Available online 7 December 2005

Editor: J.-P. Blaizot

Both signal and background scale as 1/N
(N is hadron multiplicity):

Let us consider a $\mathcal{P}$-odd domain with a topological charge $Q \geqslant 1$. Then $N_R - N_L = Q$ in (10); if the total multiplicity of positive pions is $N_R + N_L = N_{\pi^+}$ we get for the asymmetry an estimate

$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}}, \tag{11}$$

Baseline: scaling with 1/N (inverse multiplicity)

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

Parity violation in hot QCD: How to detect it

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Both signal and background scale as 1/N
(N is hadron multiplicity):

Review:
DK, J.Liao, S.Voloshin, G.Wang,
Prog. Part. Nucl. Phys. 88 (2016) 1

The main systematic uncertainty in three particle correlation measurements is due to processes when particles a and b are products of a resonance decay, and the resonance itself exhibits elliptic flow [6, 7]. Keeping only this contribution one can write:

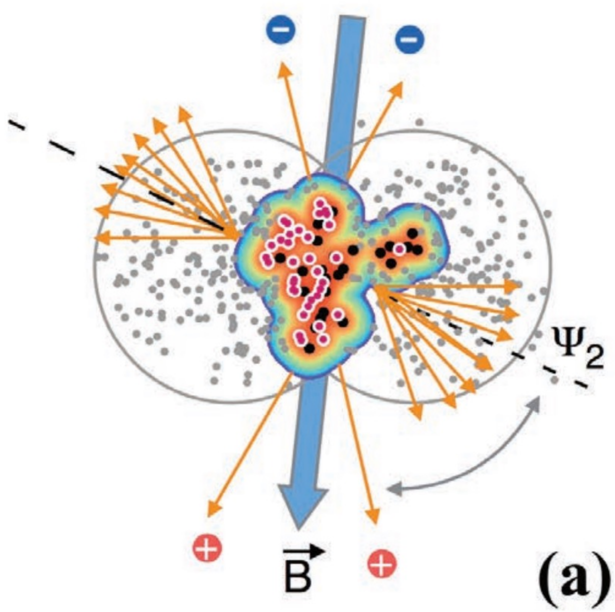
$$\begin{aligned} &\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \\ &\quad = \langle \cos((\phi_a + \phi_b - 2\phi_{res}) + 2(\phi_{res} - \phi_c)) \rangle \\ &\quad \approx \frac{f_{res} \langle \cos(\phi_a + \phi_b - 2\phi_{res}) \rangle \, v_{2,res}}{N_\pi} v_{2,c}, \qquad (3) \end{aligned}$$

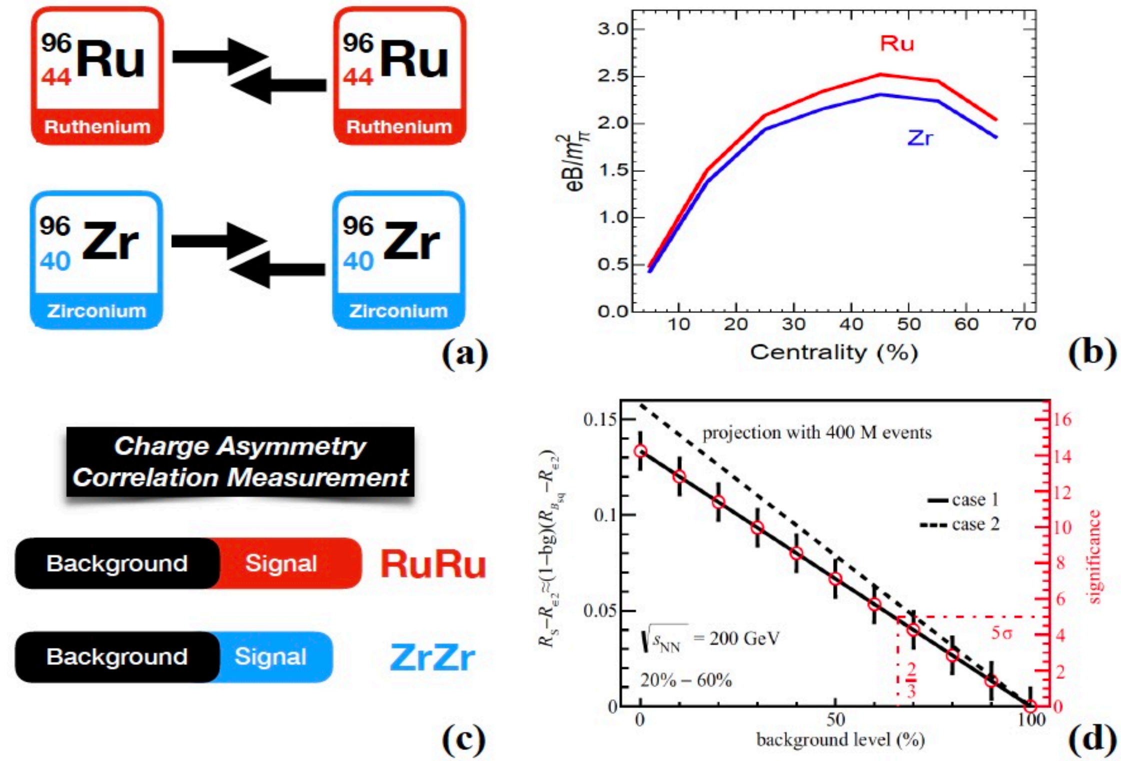
where f_{res} is the fraction of pion pairs originating from resonance decays (should be relatively small for the same charge combinations), $\langle \cos(\phi_a + \phi_b - 2\phi_{res}) \rangle$ can be considered as a measure of the azimuthal correlations of

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





STAR Collaboration

Detection of QCD topological transitions using the isobar collisions at RHIC

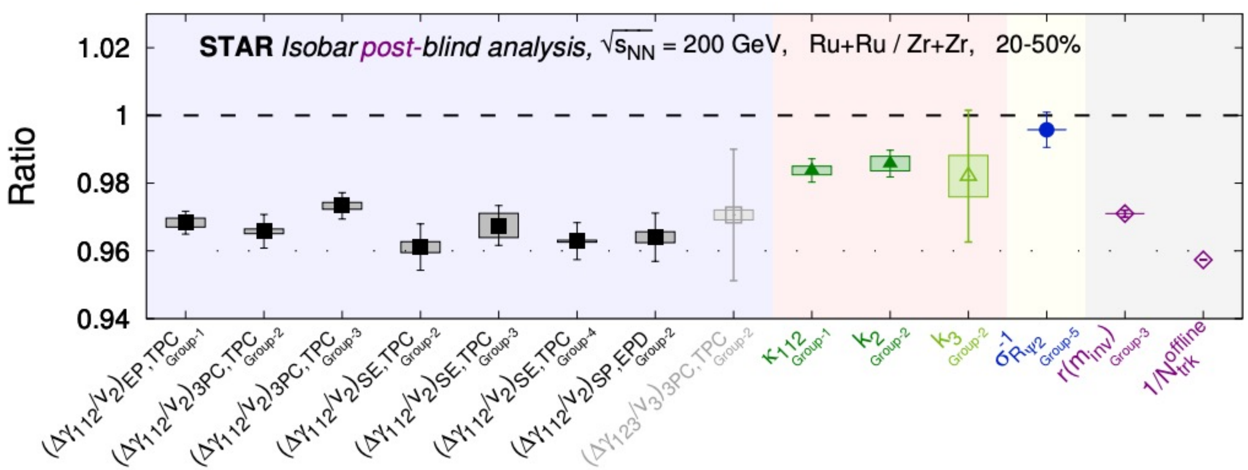
Talk by R. Lacey

The results have been released on Aug 31, 2021

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{\rm NN}} = 200$ 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

Detection of QCD topological transitions using the isobar collisions at RHIC

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

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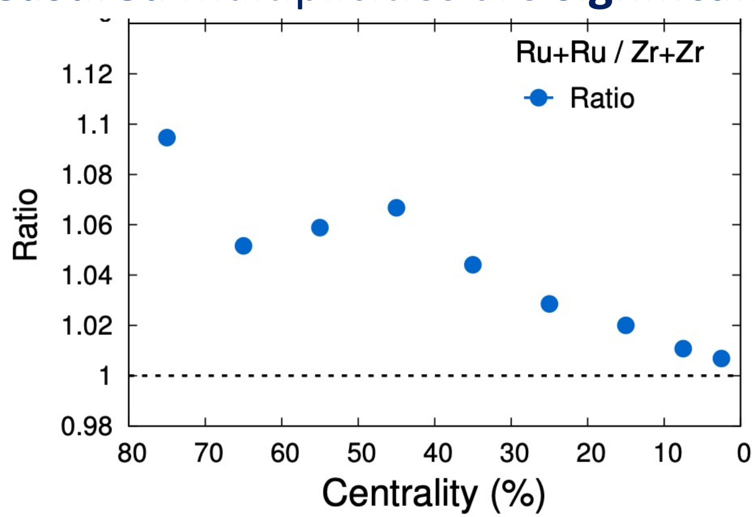
STAR, nucl-ex 2109.00131, PRC (2022)

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?

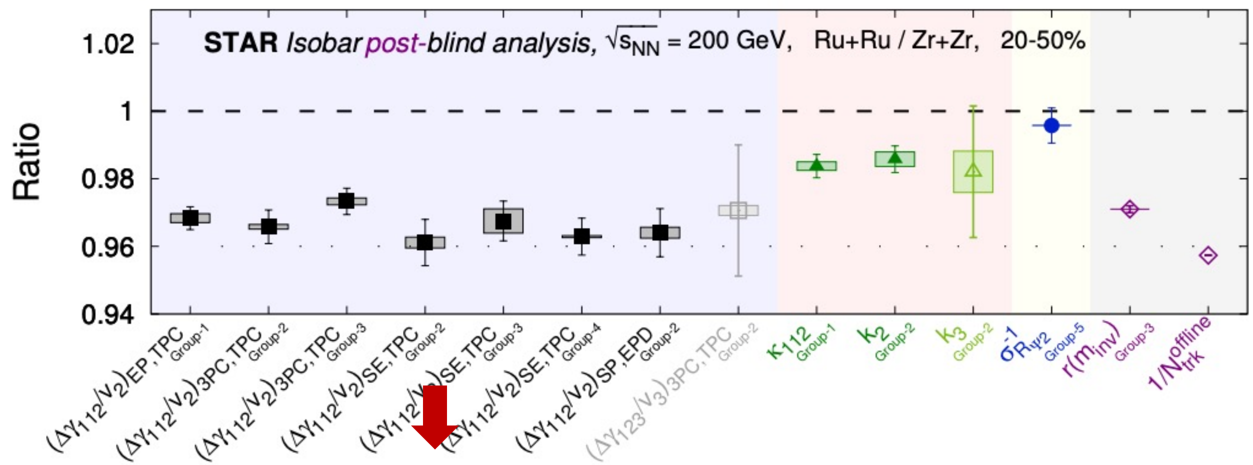
No. The **measured** multiplicities are **significantly** different:

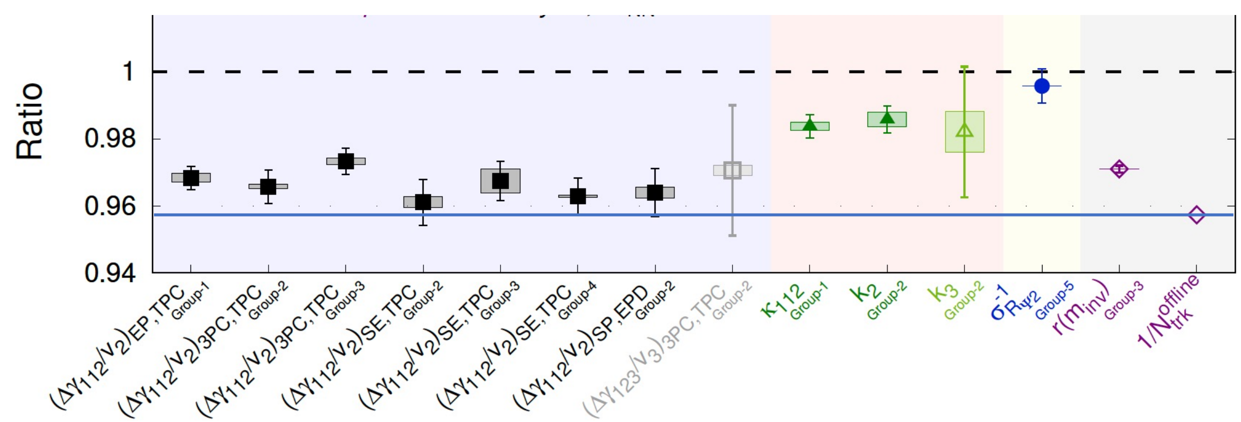


Since both signal and background scale as 1/N, the baseline has to be changed. This is not part of the "predefined criteria".

Direct detection of QCD topological transitions using the 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.



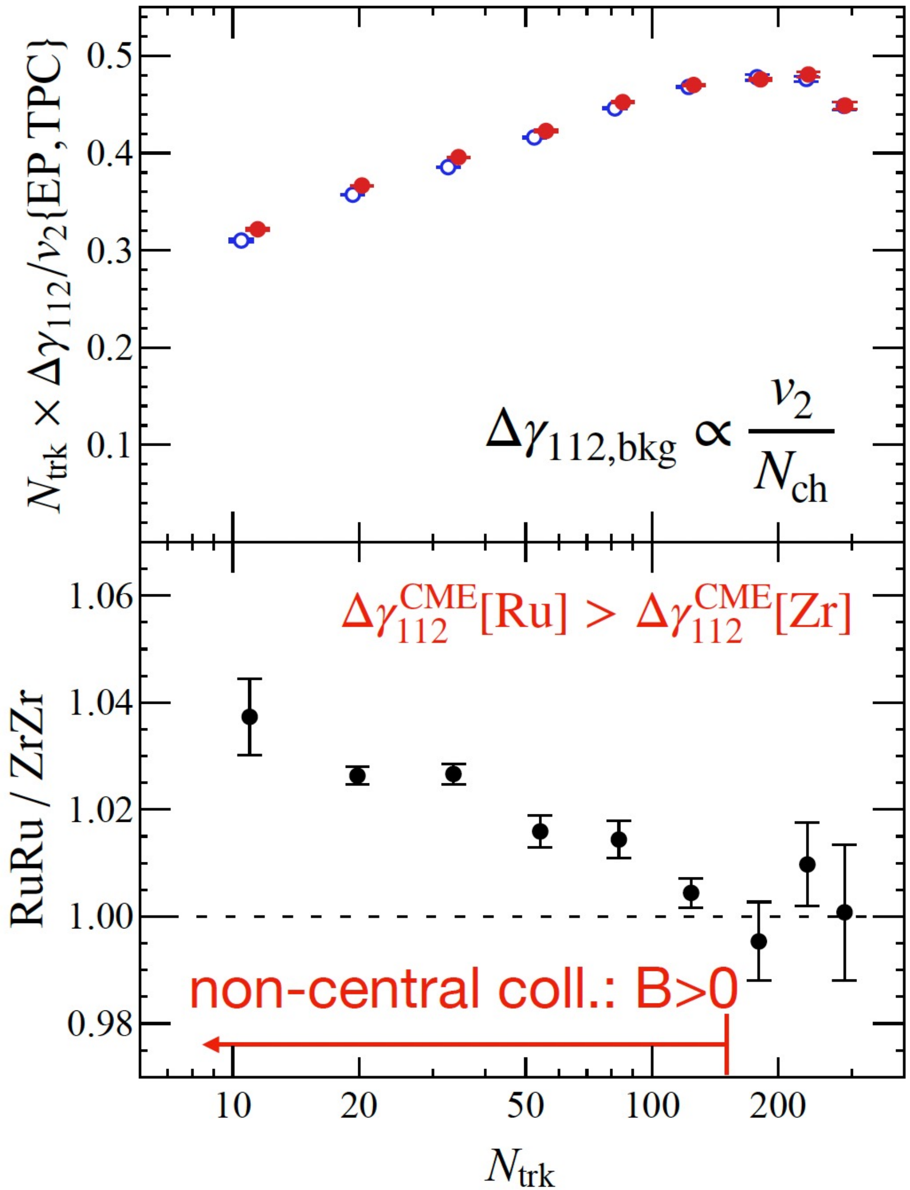


Depending on the observable, CME is present at 1-4 σ level

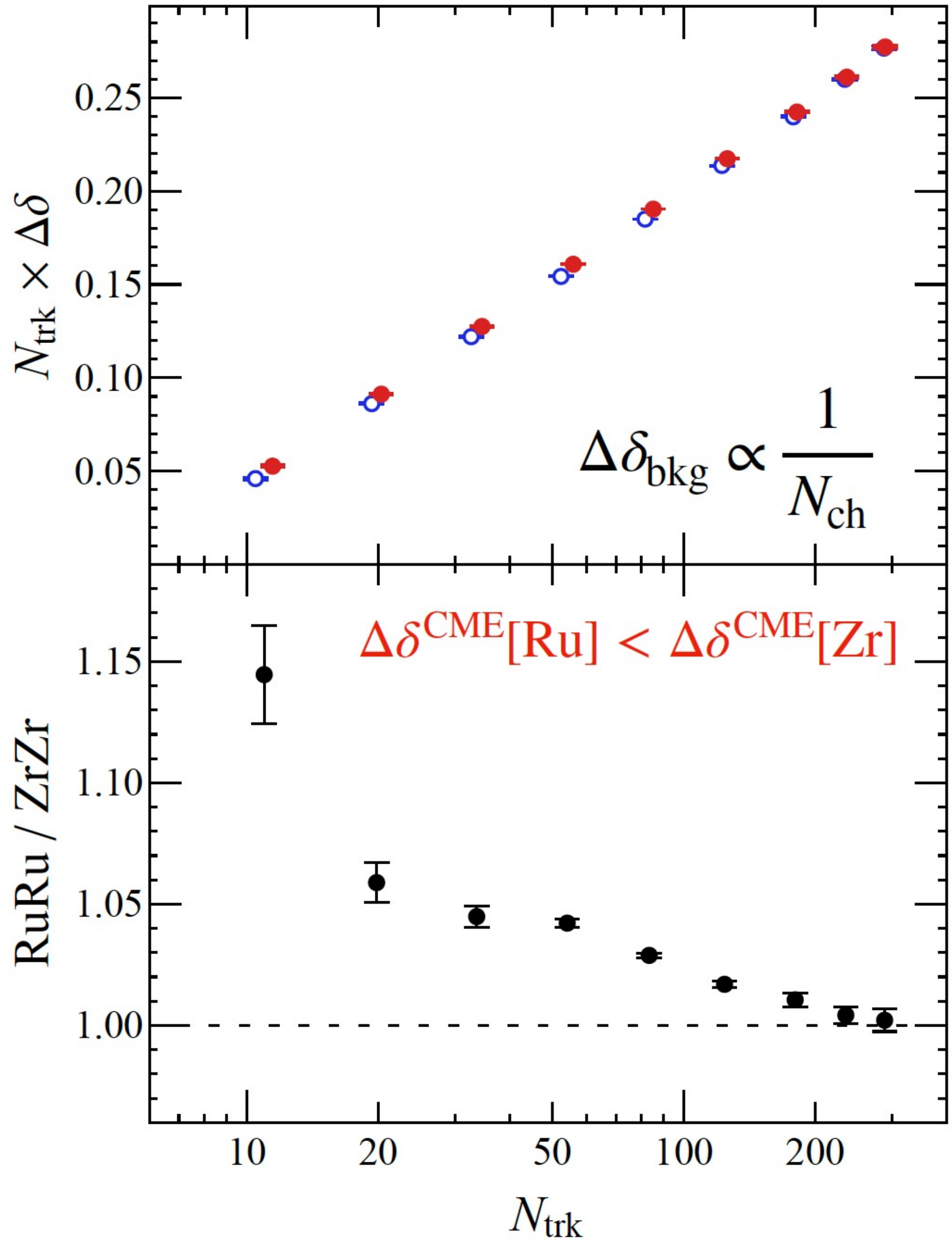
Detailed analysis is needed

$$< \cos(\phi_i + \phi_j - 2\phi_k) >= v_2 < \cos(\phi_i + \phi_j - 2\Psi_{RP}) >$$

S. Shi, DK, J. Liao, to appear



When properly rescaled to account for the background, Ru/Zr ratio is above 1, in accord with CME data: re-plot [STAR,PhysRevC.105.014901]



S. Shi, DK, J. Liao, to appear

But $\Delta\delta$ is still puzzling

A.Bzdak, V.Koch,
J. Liao, 2012

$$f_\chi(\phi, q) \propto 1 + 2\,v_2 \cos[2(\phi - \Psi_{RP})] + 2\,q\,\chi\,d_1 \cos(\phi - \Psi_{CS})$$

If CME is the only effect that contributes (no background exists – definitely unrealistic assumption), then

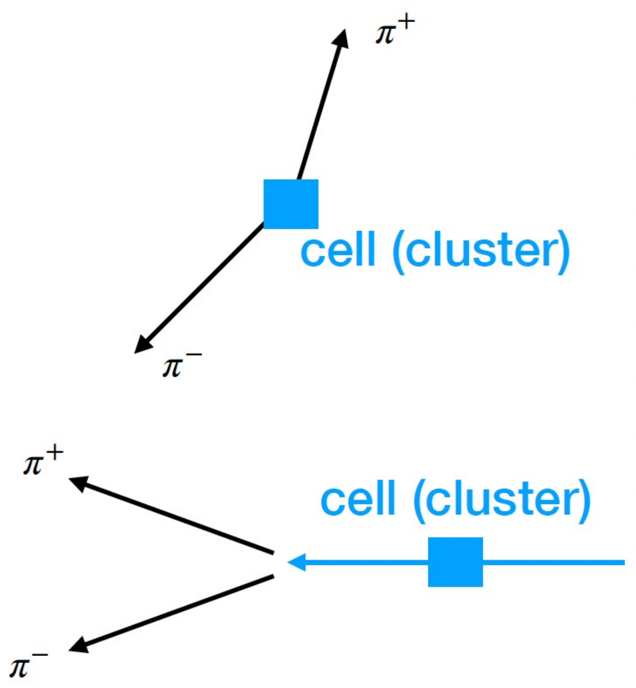
$$\begin{aligned}\gamma_{++/--} &=< \cos(\phi_i + \phi_j - 2\Psi_{RP}) >_{++/--} = -\,d_1^2 < 0,\\ \delta_{++/--} &=< \cos(\phi_i - \phi_j) >_{++/--} = +\,d_1^2 > 0.\end{aligned}$$

$$\begin{aligned}\gamma_{+-} &=< \cos(\phi_i + \phi_j - 2\Psi_{RP}) >_{+-} = +\,d_1^2 > 0,\\ \delta_{+-} &=< \cos(\phi_i - \phi_j) >_{+-} = -\,d_1^2 < 0.\end{aligned}$$

So $\Delta\delta$ should behave differently from $\Delta\gamma$ – it does not… Why? The simplest “explanation”: it is completely dominated by backgrounds that we do not understand. But one may try -

δ_{+-} measures correlations between positive and negative particles and contains strong contributions from resonance decays and local charge conservation.

Both of these effects depend on p_T , i.e. the transverse flow



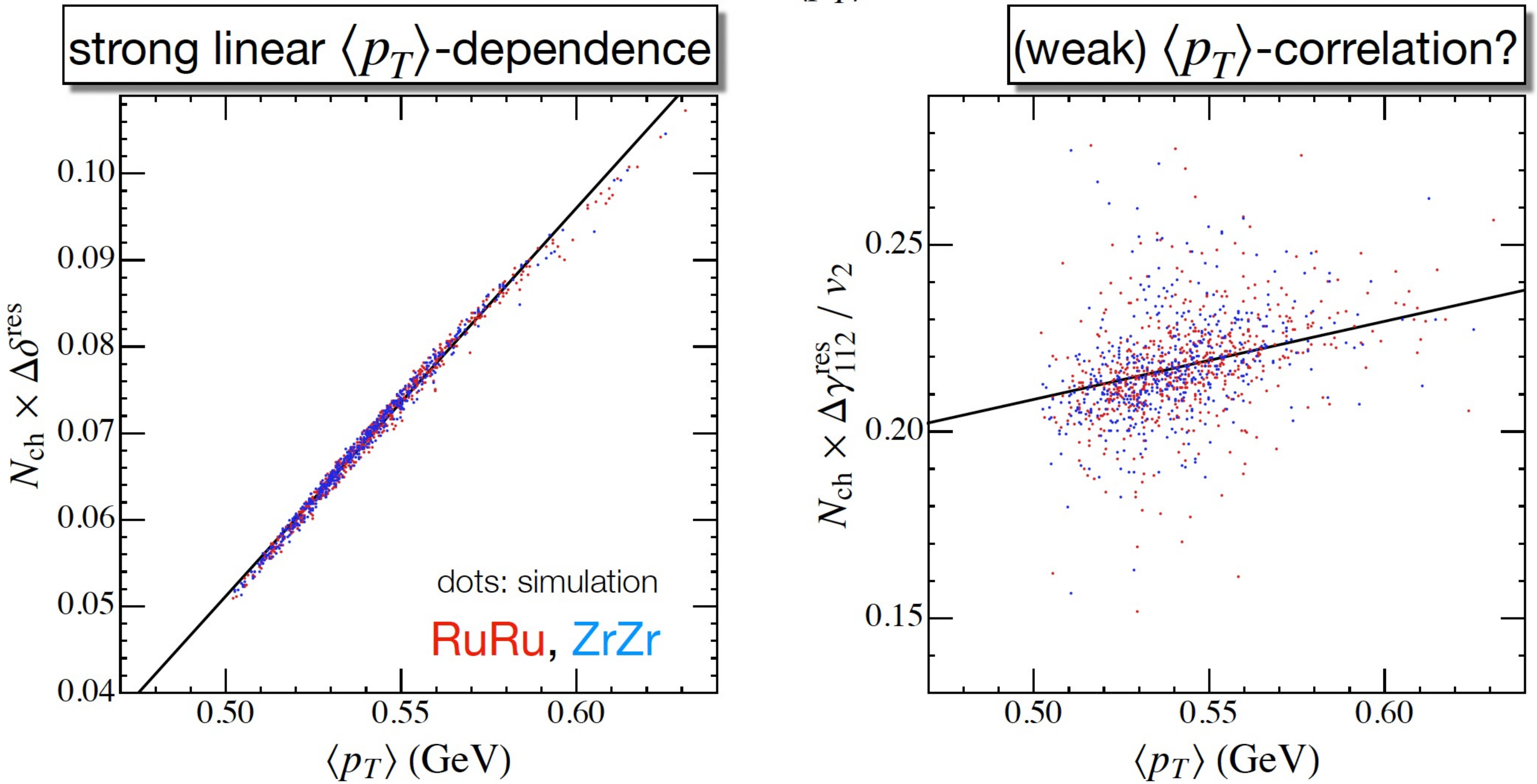
S. Shi, DK, J. Liao, to appear

This is confirmed by hydro simulations:

S. Shi, DK, J. Liao, to appear

$\langle p_T \rangle$-dependence of background [hydro+CooperFrye+resonance]

CME turned-off in simulations; plot $\langle p_T \rangle$ and correlator of each hydro-event



Is mean p_T larger in RuRu than in ZrZr?

(due to the difference in shape) Possibly, yes hydro results: Govert Nijs, Wilke van der Schee, 2112.13771 [nucl-th]

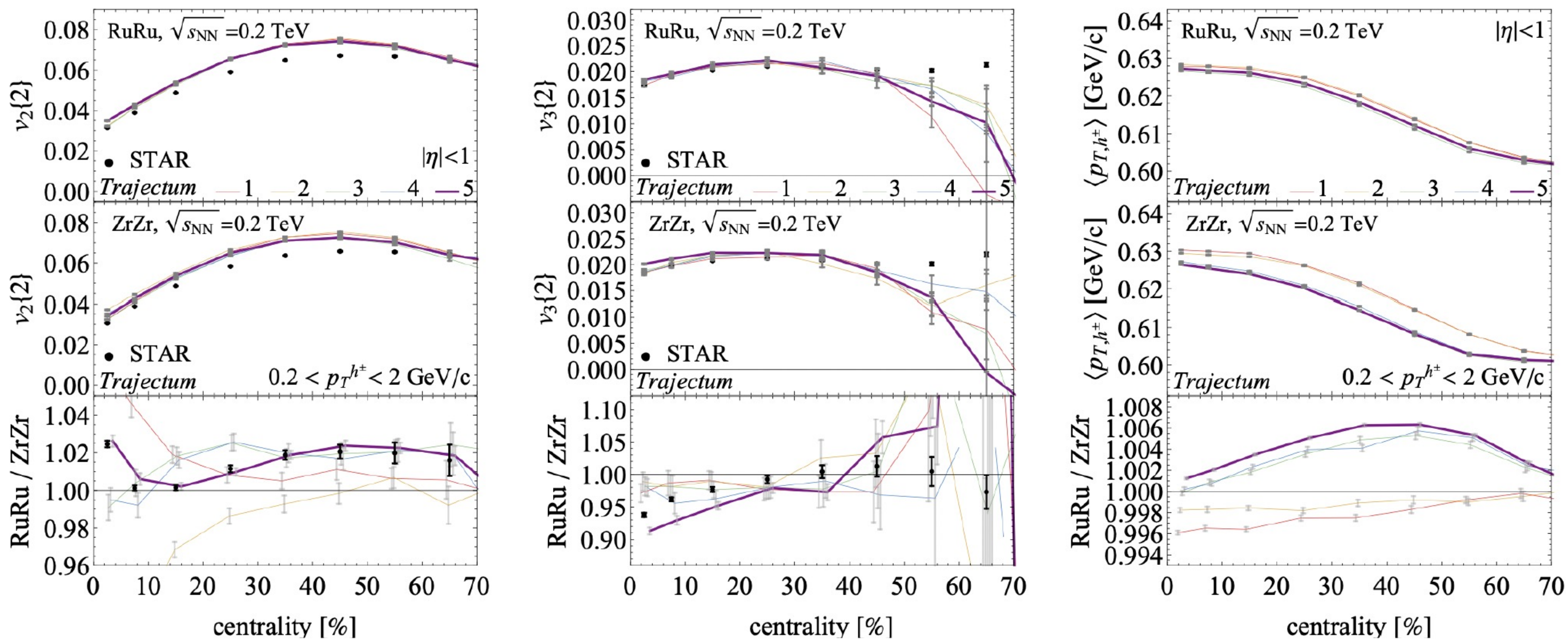


FIG. 2. We show $v_2\{2\}$ (left), $v_3\{2\}$ (middle) and $\langle p_T \rangle$ (right) for $^{96}_{44}$Ru (top), $^{96}_{40}$Zr (middle) and their ratio (bottom) for all five cases of Tab. I together with STAR data [1]. Note that *Trajectum* is only tuned to LHC energies and hence an absolute agreement is not expected. Case 5 is the only case with an octupole deformation β_3, which leads to a qualitative agreement for the $v_3\{2\}$ ratios and full consistency for the $v_2\{2\}$ ratios. All theoretical uncertainties are statistical only (gray).

Need to verify this directly, in experimental data – how big is the difference?

Maybe the isobar data do tell us a consistent story (~ 3 σ CME effect?)

Probing nuclear structure with mean transverse momentum in relativistic isobar collisions

Hao-jie Xu,[1] Wenbin Zhao,[2] Hanlin Li,[3] Ying Zhou,[4] Lie-Wen Chen,[4] and Fuqiang Wang[1,5]

nucl-th 2111.14812

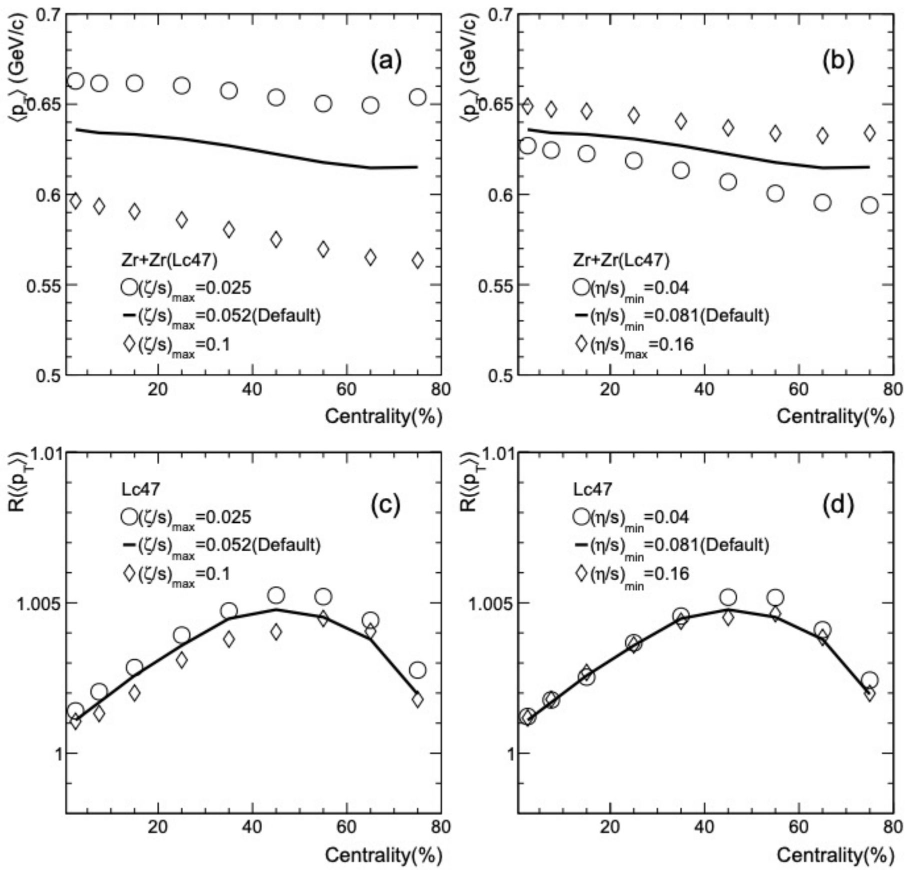


FIG. 1: (a,b) The mean transverse momentum $\langle p_\perp \rangle$ as functions of centrality in Zr+Zr collisions, calculated by the iEBE-VISHNU model with different $(\eta/s)_{\rm min} = 0.04, 0.08, 0.12$ and $(\zeta/s)_{\rm max} = 0.025, 0.052, 0.1$ with the Lc47 densities. (c,d) The corresponding Ru+Ru/Zr+Zr ratio $R_{\langle p_\perp \rangle}$.

Talk by R. Lacey

New 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

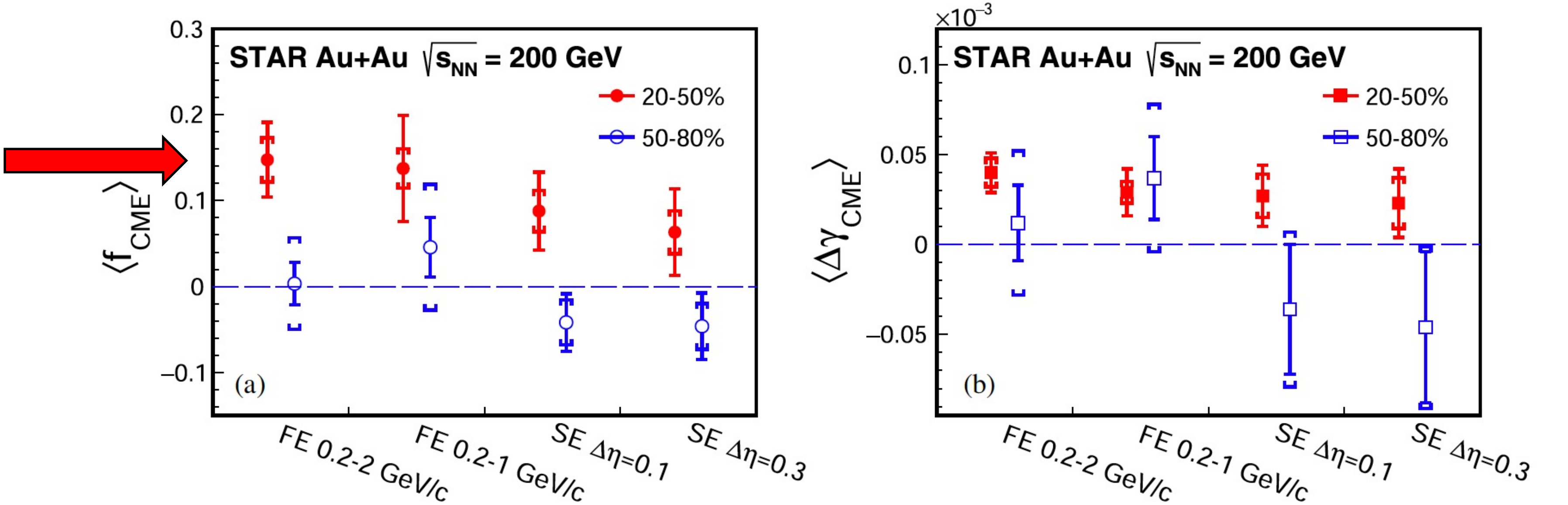


FIG. 3. The flow-background removed $\langle f_{\mathrm{CME}} \rangle$ (a) and $\langle \Delta\gamma_{\mathrm{CME}} \rangle$ (b) signal in 50%–80% (open markers) and 20%–50% (solid markers) centrality Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, extracted by various analysis methods [full-event (FE),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

Talk by R. Lacey

New 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	$2.94 \pm 0.01 \pm 0.15$	$6.3 \pm 5.0 \pm 2.5$	$0.23 \pm 0.19 \pm 0.14$

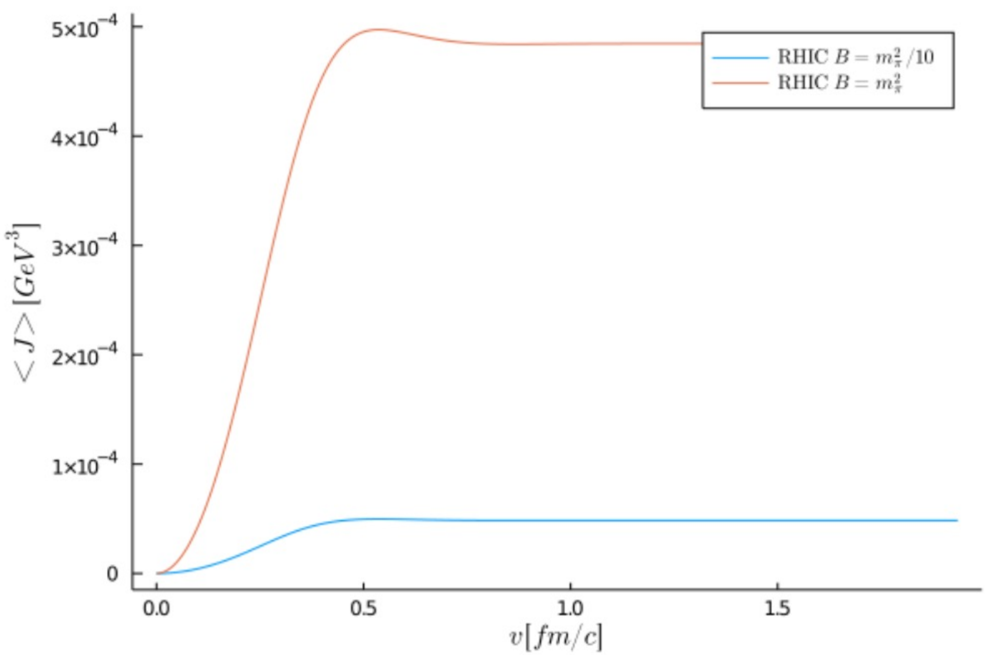
the spectator protons. Under these assumptions, the possible CME signals are extracted using the new method in this Letter. Some indication of finite signals is seen in 20%–50% Au + Au collisions. However, nonflow effects (especially for the full-event method without η gap) may still be present that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

The case for CME in Beam Energy Scan

Is the Chiral Magnetic Effect fast enough?

Jewel K. Ghosh[1,2,*] Sebastian Grieninger[3,4,†] Karl Landsteiner[3,‡] and Sergio Morales-Tejera[3,4§]

arXiv 2105.05855; PRD (2022)



Lower energies – longer lived magnetic field – stronger CME

Energy dependence of the chiral magnetic effect in expanding holographic plasma

Casey Cartwright,* and Matthias Kaminski,†
Department of Physics and Astronomy, University of Alabama, 514 University Boulevard, Tuscaloosa, AL 35487, USA

Björn Schenke‡
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
(Dated: December 30, 2021)

arXiv 2112.13857; PRD (2022)

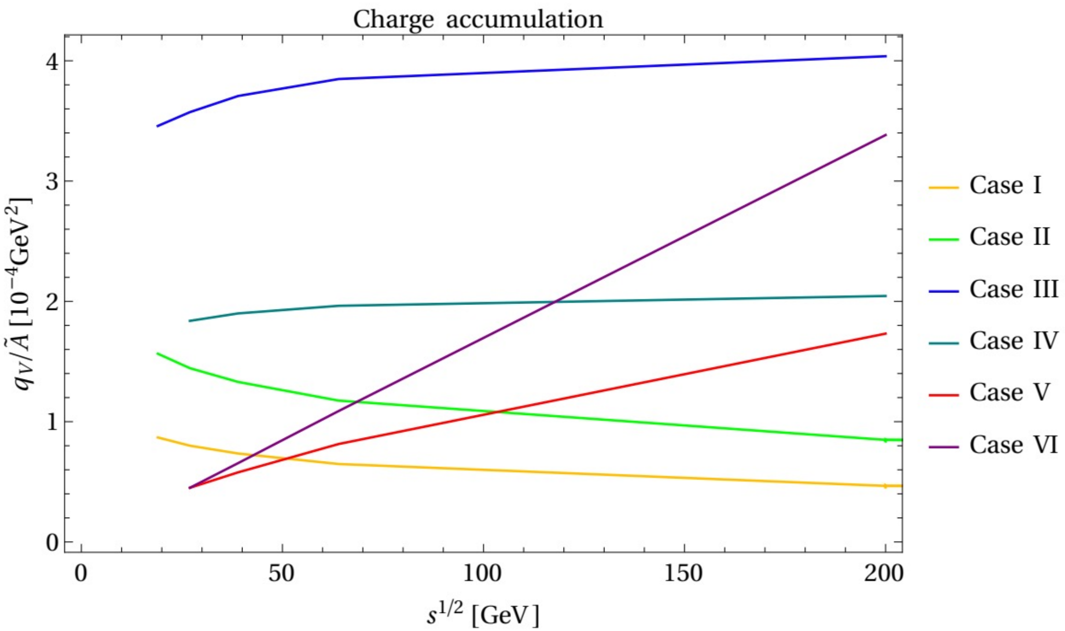
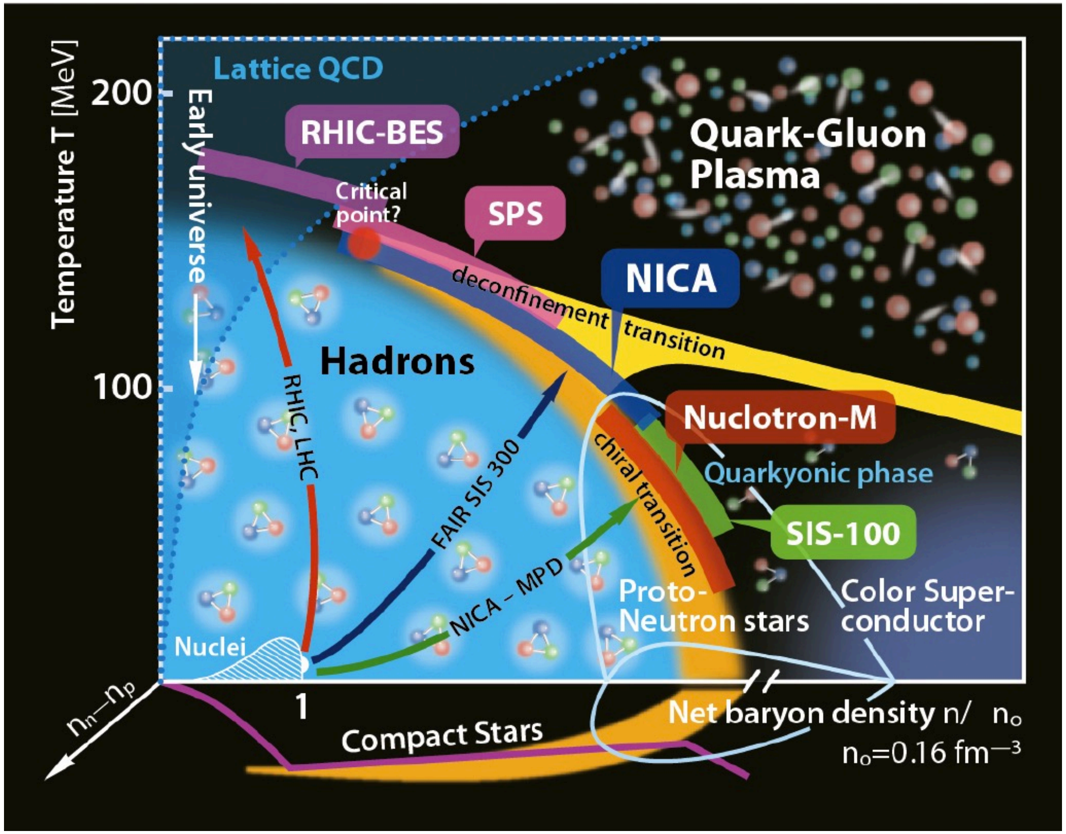


FIG. 6. *Charge accumulation from time-integrated CME current:* The total amount of charge per area which has flowed during the simulations considered throughout this work (see eq. (43)). The plot legend labels the case in which the total charge was computed corresponding to the titled paragraphs in section III. The cases differ by either holding fixed, or varying, the initial value of the magnetic field and the axial charge density, $(B_1(\tau_0), \langle J^0_{(5)}(\tau_0)\rangle)$, as a function of the initial energy density at the initial time, τ_0. Case I: both $\langle J^0_{(5)}(\tau_0)\rangle$ and $B_1(\tau_0)$ are constant as a function of initial energy. Case II: both $\langle J^0_{(5)}(\tau_0)\rangle$ and $B_1(\tau_0)$ are constant as a function of initial energy while the Chern-Simons coupling α is taken at the supersymmetric value. Case III: $B_1(\tau_0)$ is held fixed while $\langle J^0_{(5)}(\tau_0)\rangle$ varies as a function of initial energy density. Case IV: case III is repeated with $B_1(\tau_0)$ taking half the value of case III. Case V: $\langle J^0_{(5)}(\tau_0)\rangle$ is held fixed while $B_1(\tau_0)$ varies as a function of initial energy density. Case VI: both $\langle J^0_{(5)}(\tau_0)\rangle$ and $B_1(\tau_0)$ vary as a function of the initial energy density.

Chern-Simons fluctuations near a critical point

K. Ikeda, DK, Y. Kikuchi,
arXiv: 2012.02926 PRD'21

Motivation: what happens to topological fluctuations near the critical point? Could there be an enhancement due to criticality?



Chern-Simons fluctuations near a critical point

Simple system that exhibits a critical point: massive Schwinger model near θ = π

S. Coleman, Annals Phys. 101(1976) 239

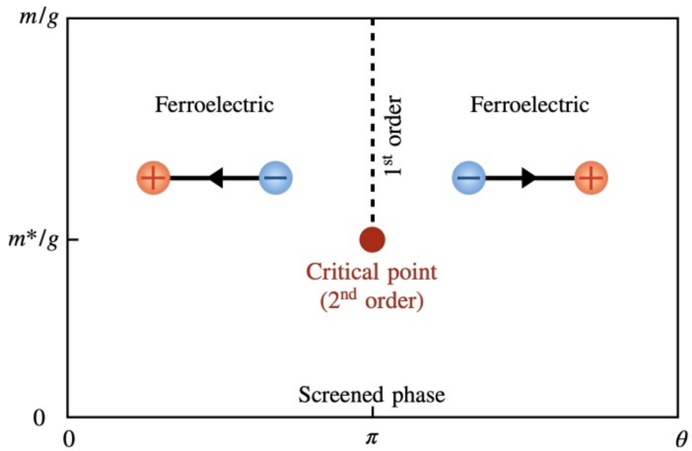


FIG. 1: Phase diagram of the massive Schwinger model in the $(\theta, m/g)$ plane. At $\theta = \pi$ and large masses $m > m^*$, the ferroelectric phases with opposite orientations of electric field are separated by the line of the first order phase transition. This line terminates at $m^* \approx 0.33g$ at the critical point, where the phase transition is second order. For small masses $m \ll m^*$, the electric field is screened by the production of light fermion-antifermion pairs.

K. Ikeda, DK, Y. Kikuchi, arXiv: 2012.02926

$$S = \int d^2x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\gamma_5 \theta})\psi \right]$$

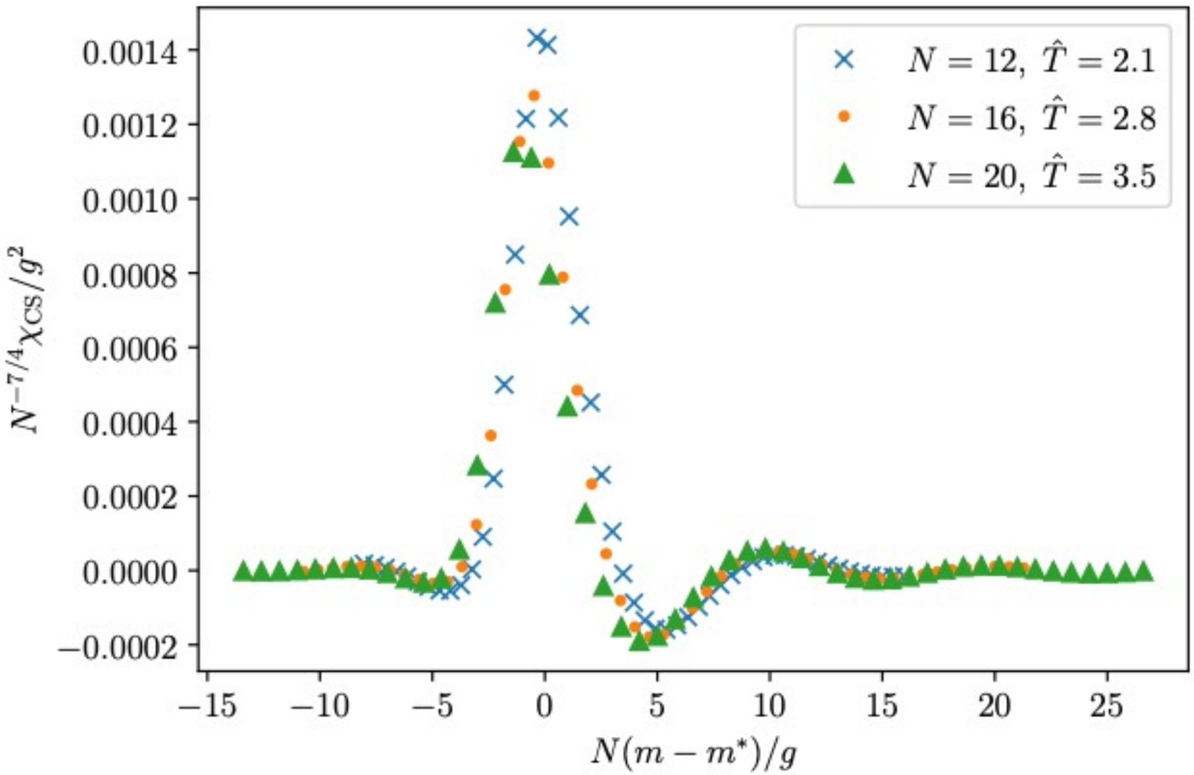
$\Downarrow$ bosonization

$$H = \int dx \left[\frac{1}{2}\dot{\varphi}^2 + \frac{1}{2}(\partial_1 \varphi)^2 + \frac{\mu^2}{2}\left(\varphi + \frac{\theta}{2\sqrt{\pi}}\right)^2 - c m \mu \cos(2\sqrt{\pi}\varphi) \right].$$

$$\mu = \frac{g}{\sqrt{\pi}}$$

$$U(\varphi) = \frac{\mu^2}{2}\left(\varphi + \frac{\theta}{2\sqrt{\pi}}\right)^2 - c m \mu \cos\left(2\sqrt{\pi}\varphi\right)$$

Chern-Simons fluctuations near a critical point: a digital quantum simulation

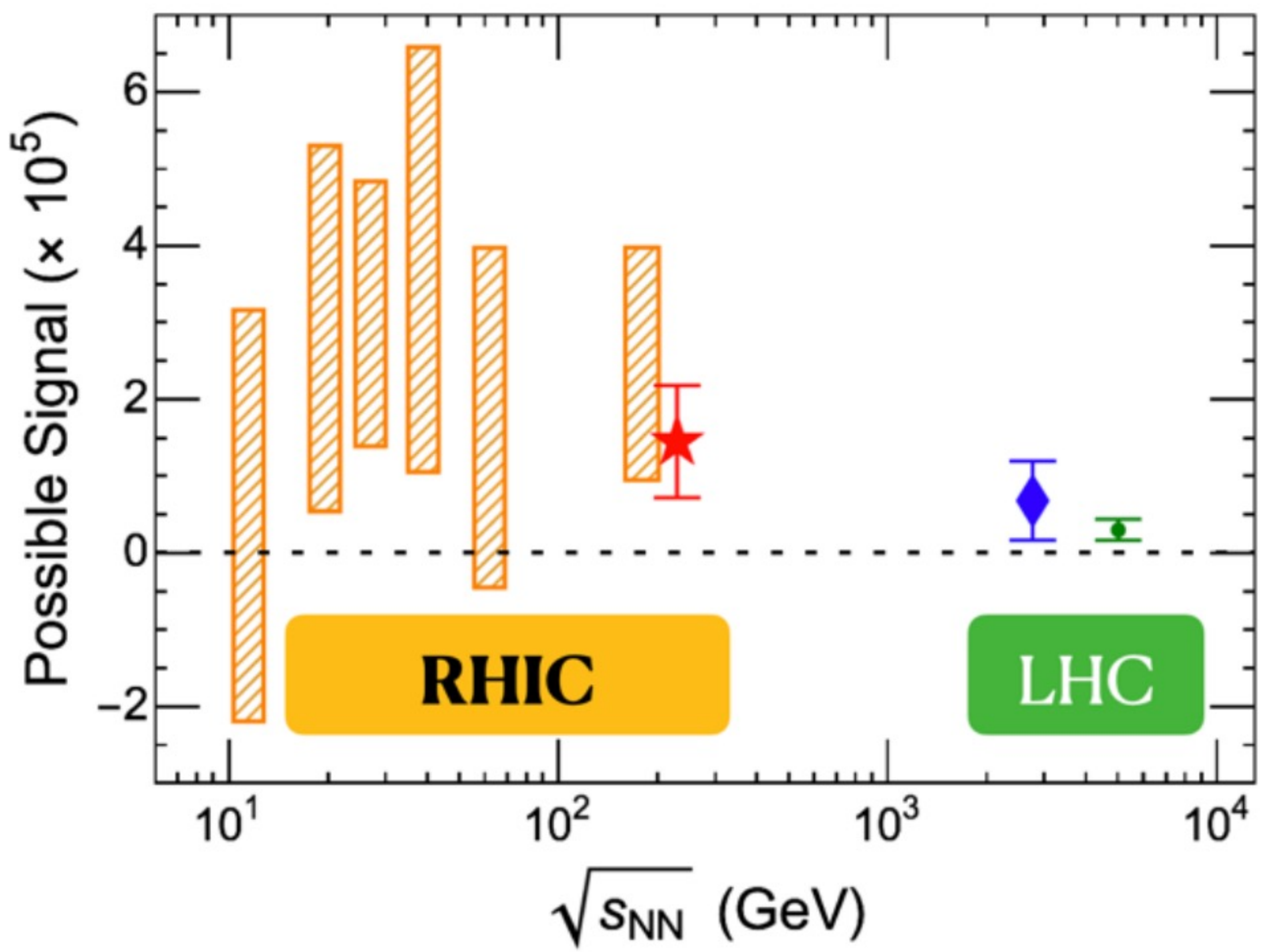


K. Ikeda, DK, Y. Kikuchi, arXiv: 2012.02926, PRD

Sharp peak in topological fluctuations near the critical point!

Search for CME in low-energy heavy ion collisions?

A hint from the data?



Data compilation:

DK, J. Liao, Nature Reviews (2021)

CME and QIS

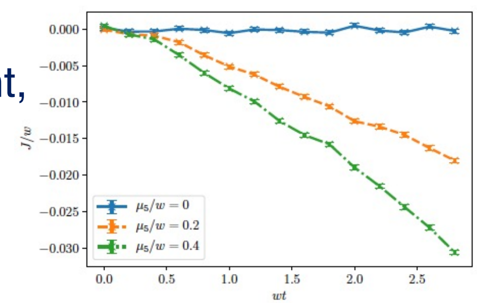
Study of real-time CME dynamics in (1+1) QED using a digital quantum simulation (IBM-Q)

DK, Y. Kikuchi, arXiv:2001.00698, Phys.Rev.Res. 2 (2020)

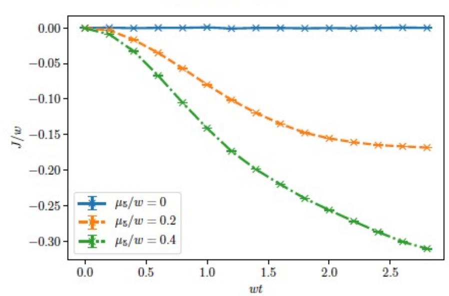
$$S = \int \mathrm{d}^2x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{g\theta}{4\pi} \epsilon^{\mu\nu} F_{\mu\nu} + \bar{\psi}(\mathrm{i}\gamma^\mu D_\mu - m)\psi \right]$$

Jordan-Wigner transformation – spin chain

CME current, μ_5 quench:

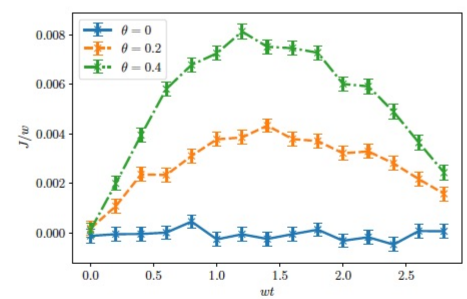


(a) $M/w = 0.1$

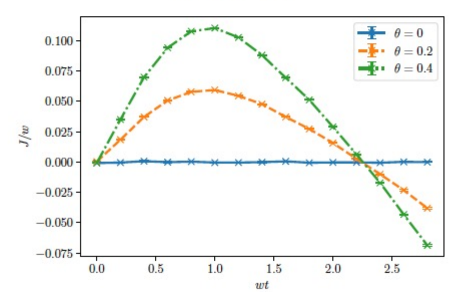


(b) $M/w = 0.5$

CME current, θ quench:



(a) $M/w = 0.1$

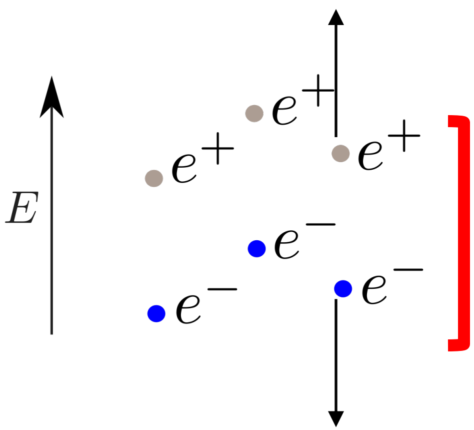


(b) $M/w = 0.5$

Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK, PRD '21

Study of real-time evolution of entanglement between the left- and right-movers in Schwinger pair production by electric pulses



entanglement

$$S_G = \int \mathrm{d}k_1 \left[\left(1 - |\beta_{k_1,t^*}|^2\right) \log\left(1 - |\beta_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \right] ,$$

Gibbs entropy

$$|\alpha_{k_1,t^*}|^2 = 1 - |\beta_{k_1,t^*}|^2$$

Entanglement entropy

$$S_E = -\int \mathrm{d}k_1 \left[|\alpha_{k_1,t^*}|^2 \log\left(|\alpha_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \right]$$

Real-time dynamics of CME and “chiral entanglement”

A. Florio, DK, PRD’21

Entanglement entropy can be reconstructed from the moments of multiplicity distribution:

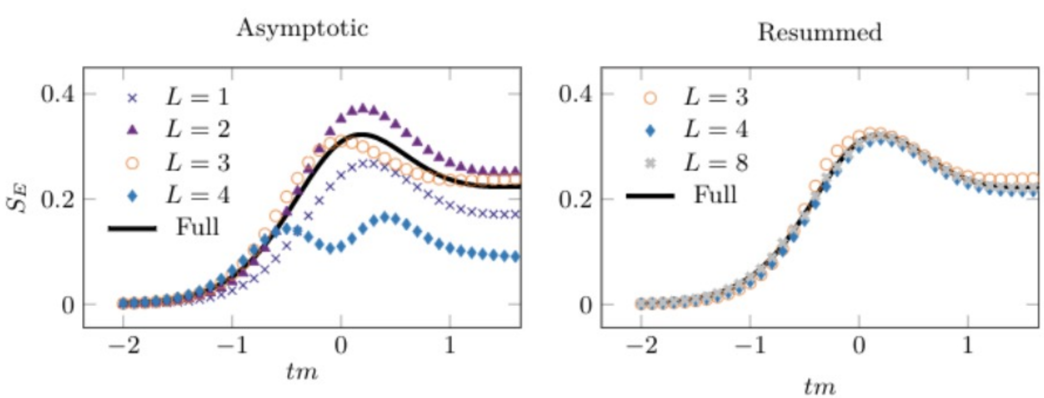
$$S_E = \sum_{l=1}^{\infty} \frac{C_{2l}}{(2l)!} (2\pi)^{2l} |B_{2l}|$$

Bernoulli numbers

Derived first for shot noise in Quantum Point Contacts:

I. Klich, L. Levitov, PRL (2009)

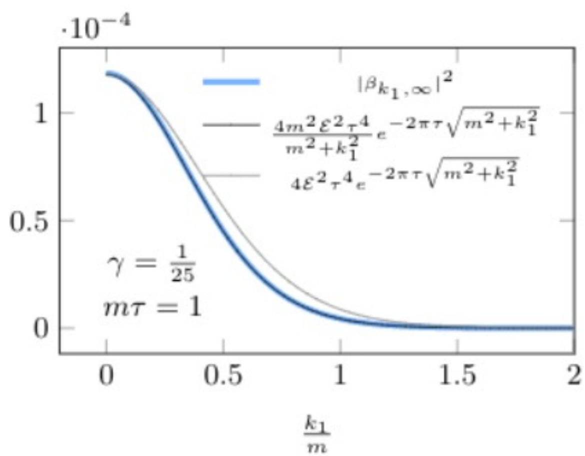
An efficient way to resum this series is found, using Pade-Borel methods:

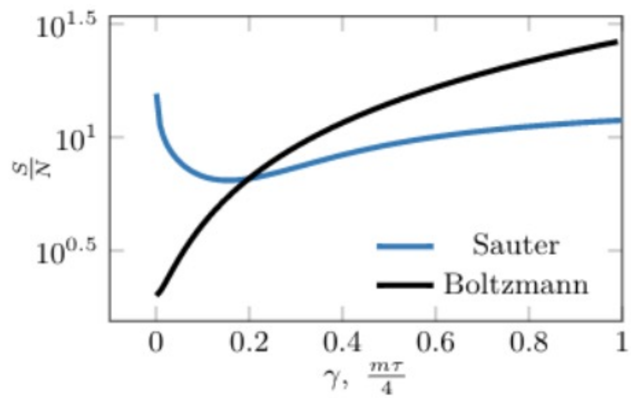


Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK, PRD '21

Short pulses lead to an approximately thermal entropy and momentum spectrum:





Semiclassical derivation:

DK, K. Tuchin, NPA (2005)

Could entanglement be at the origin of "fast equilibration" in high-energy hadron and heavy ion collisions?

Where do we stand with CME in heavy ion collisions?

Experimental status:

Talk by R. Lacey

1. There seems to be an indication for CME at 3 σ level both from AuAu at 200 GeV and the isobar run

2. Increase of AuAu@200 GeV statistics by factor of 3-4 is feasible and could allow a definitive result (5 σ ?)

3. There may be an enhancement of CME signal in BES, but statistics may be insufficient for a definite claim (?)

4. Time horizon is limited (~5 years), so need to focus

What needs to be done in theory?

1. Dynamical description of the axial charge generation, including back-reaction to CME current

2. Dynamical description of magnetic field coupled to CME current; perturbative treatment is probably OK

3. Given all theoretical uncertainties, try to produce quantitative predictions, estimate theory error bars

4. Collaborate with experimentalists on post-blinding isobar run analysis

Summary

1. Chiral Magnetic Effect and related quantum transport phenomena are direct probes of topology of gauge fields

2. CME in heavy ion collisions is a unique opportunity to observe in the lab topological fluctuations in QCD

3. Isobar run has been extremely successful – unprecedented amount of precise data has become available. Careful analysis of this data (including the baseline differences between the isobars) is imperative, and requires a concerted effort of experimentalists and theorists].

4. New AuAu data and post-blinding analysis of isobar data indicate the presence of CME (at 3 σ level in mid-central colln's)