Chiral Magnetic Effect and the Isobar run

Dmitri Kharzeev

U.S. DEPARTMENT OF **ENERGY**

Office of Science

Center for Nuclear Theory
Stony Brook University

C²QA
Co-design Center for Quantum Advantage

Brookhaven National Laboratory

Chirality: the definition

Greek word: χειρ (cheir) - hand
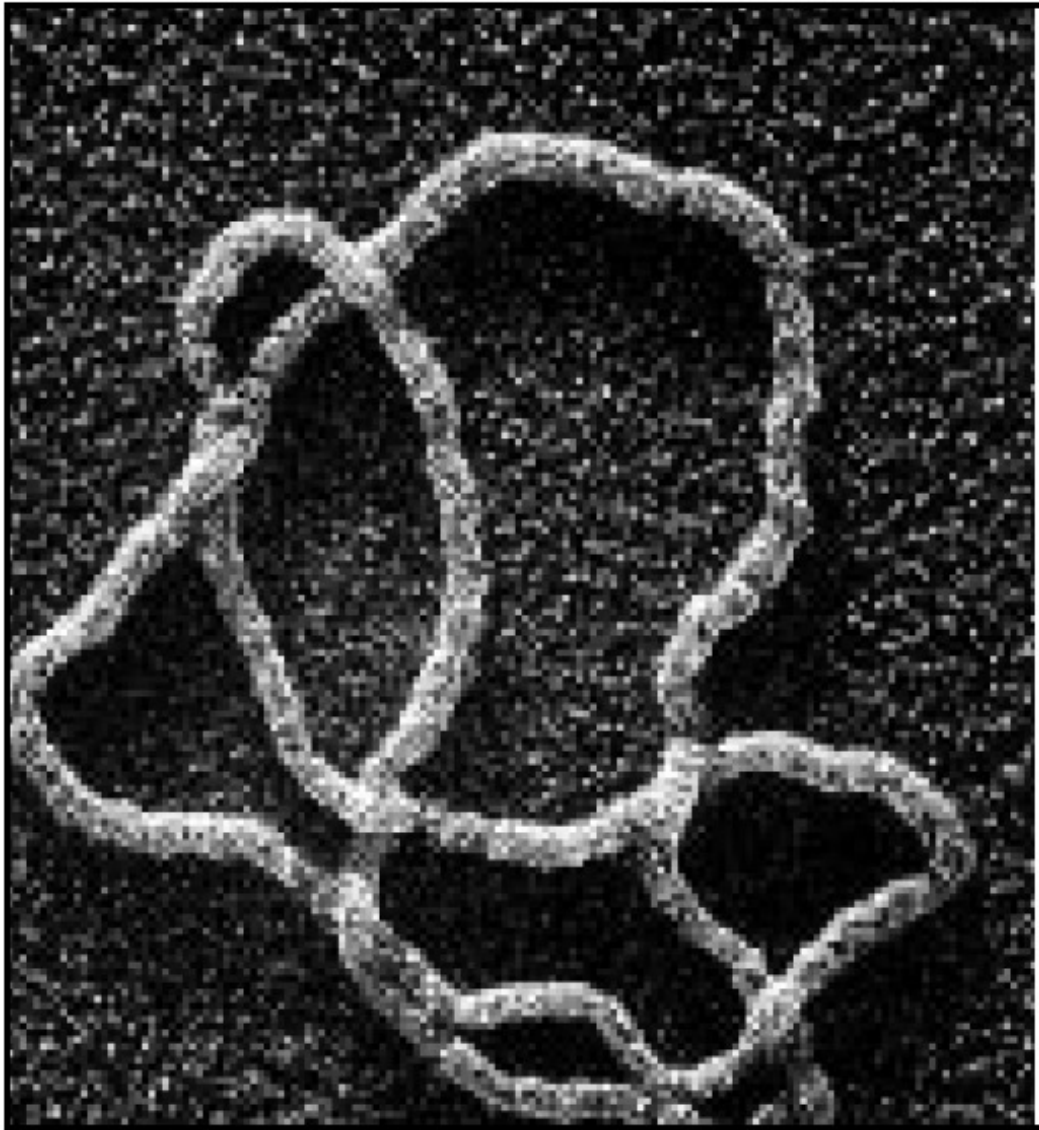
Lord Kelvin (1893):

"I call any geometrical figure, or groups of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself."

Chirality: DNA

Chirality: DNA

De Witt Sumners, Notices of the AMS, 1995

Chirality in subatomic world: chiral fermions
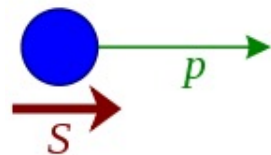
Fermions:
E. Fermi, 1925

Dirac equation:
P. Dirac, 1928

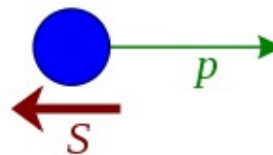Weyl fermions:
H. Weyl, 1929

Majorana fermions:
1937

$$(i\not{\partial} - m)\psi = 0$$

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

$$-i\not{\partial}\psi + m\psi_c = 0$$

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

Right-handed:

Left-handed:
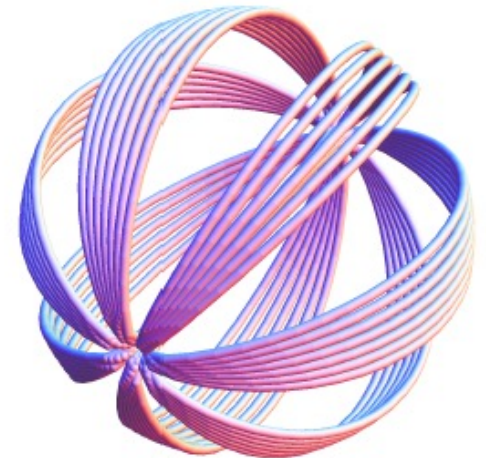
5

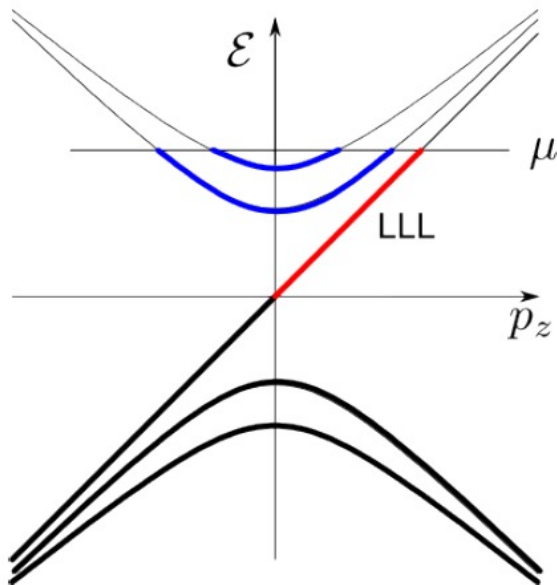# Chirality of gauge fields

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:

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

QCD (Quantum ChromoDynamics) vacuum:

Energy of gluon field

$N_{CS} =$ -2

-1

0

1

2

instanton

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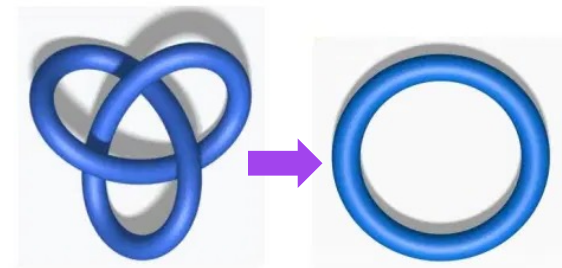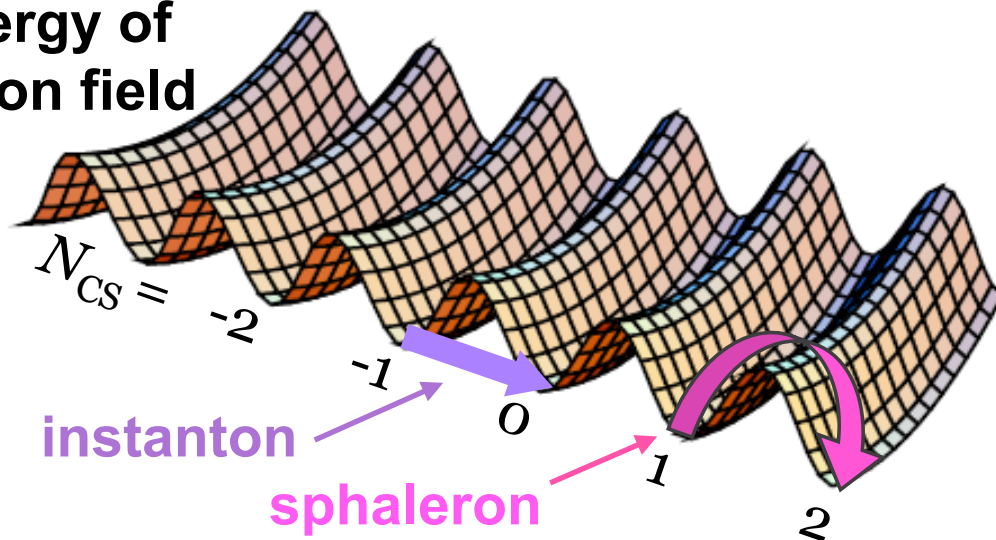
Chirality and the origin of Matter-Antimatter asymmetry in the Universe

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

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!
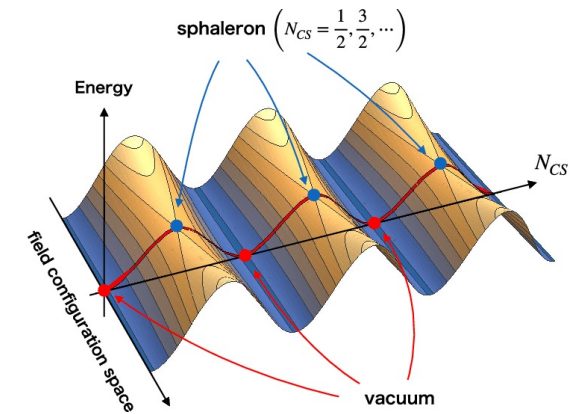
Generation of chirality in the QCD plasma

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 plasm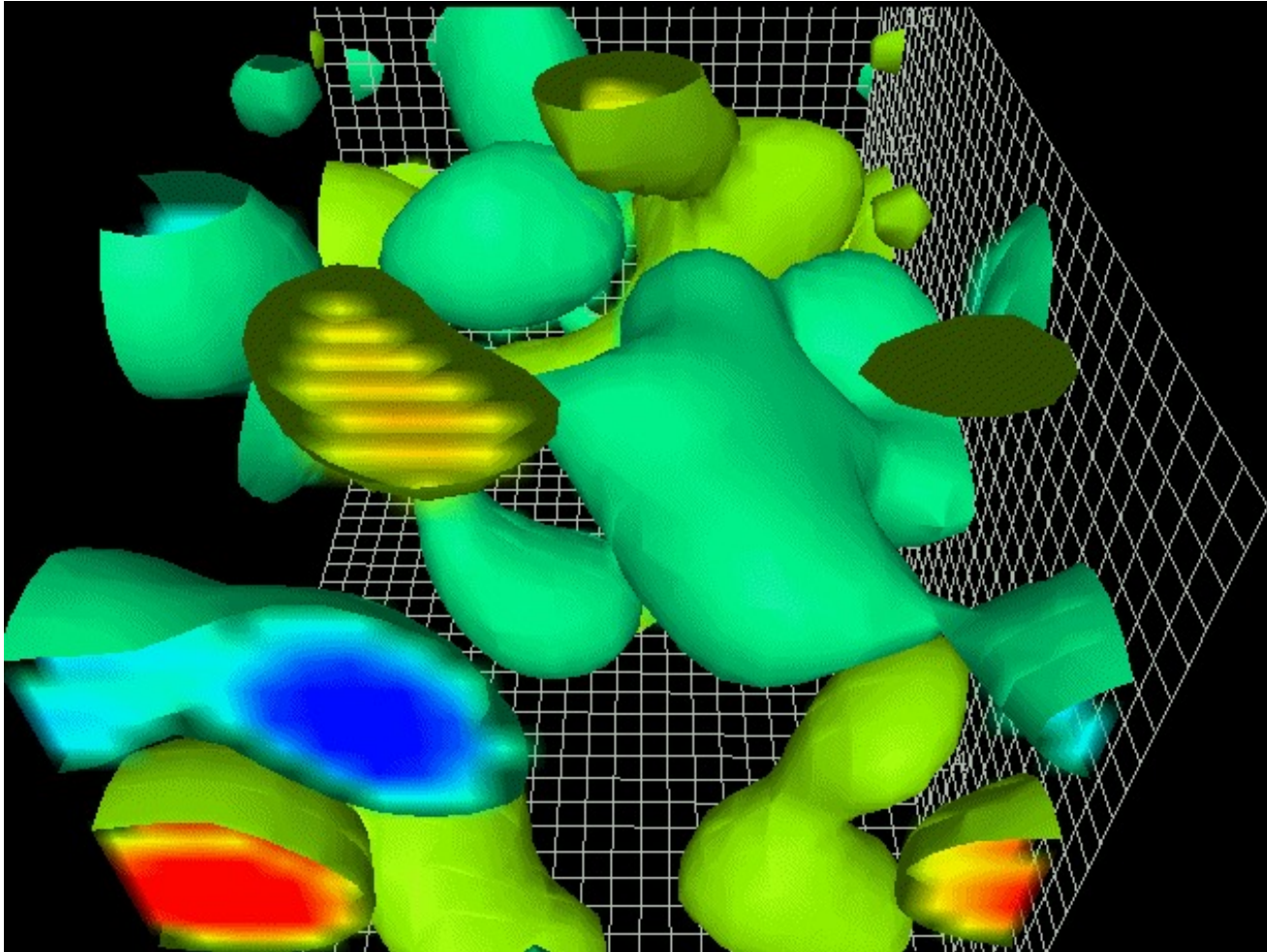a drives it out of thermal equilibrium – thus we expect to see a substantial **generation of net chirality**, <u>of fluctuating sign</u>, **in heavy ion collisions**!
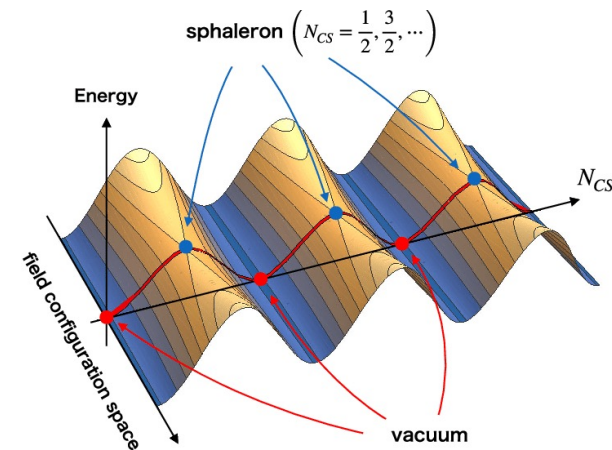
Graphics: Hamada, Kikuchi,'20
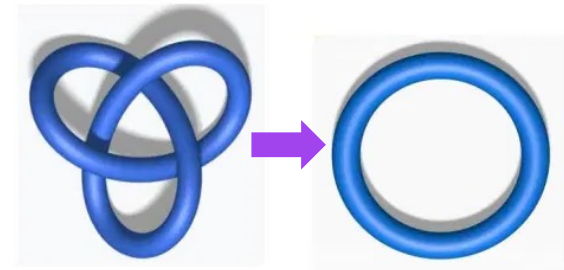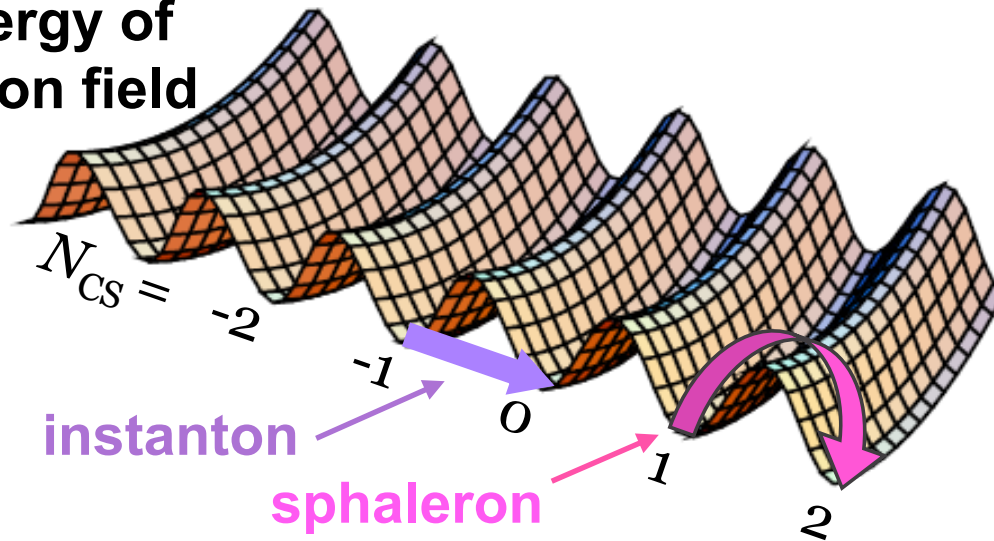
Topological transitions in QCD vacuum

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.

Energy of gluon field

$N_{CS} =$ -2 -1 0 1 2

instanton

sphaleron

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

hep-ph/0406125 (June 2004)

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:

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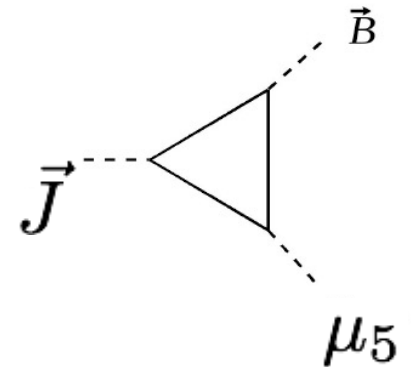
Compute the current through

$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$
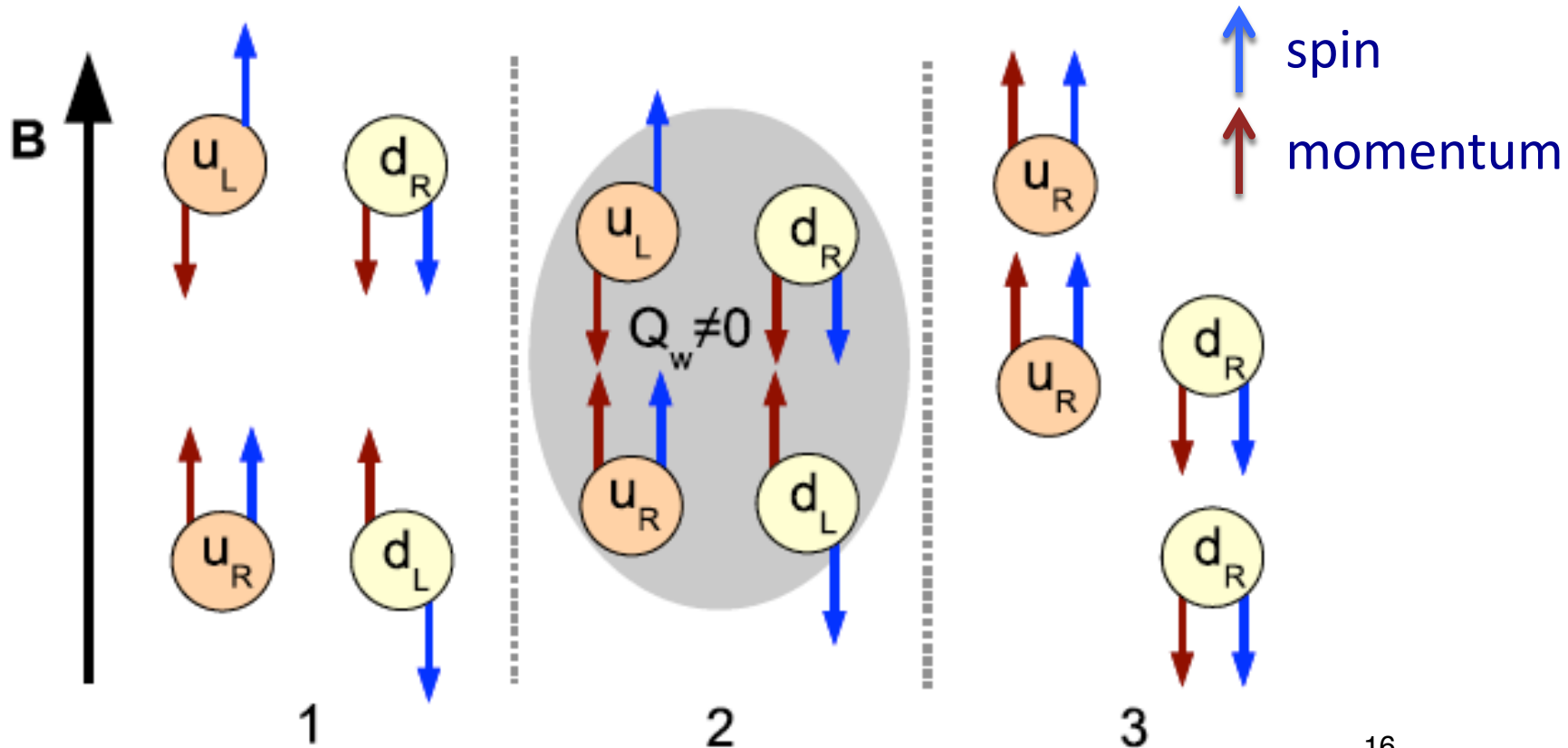
Absent in Maxwell theory!

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

Coefficient is fixed by the chiral anomaly, no corrections

15

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

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.
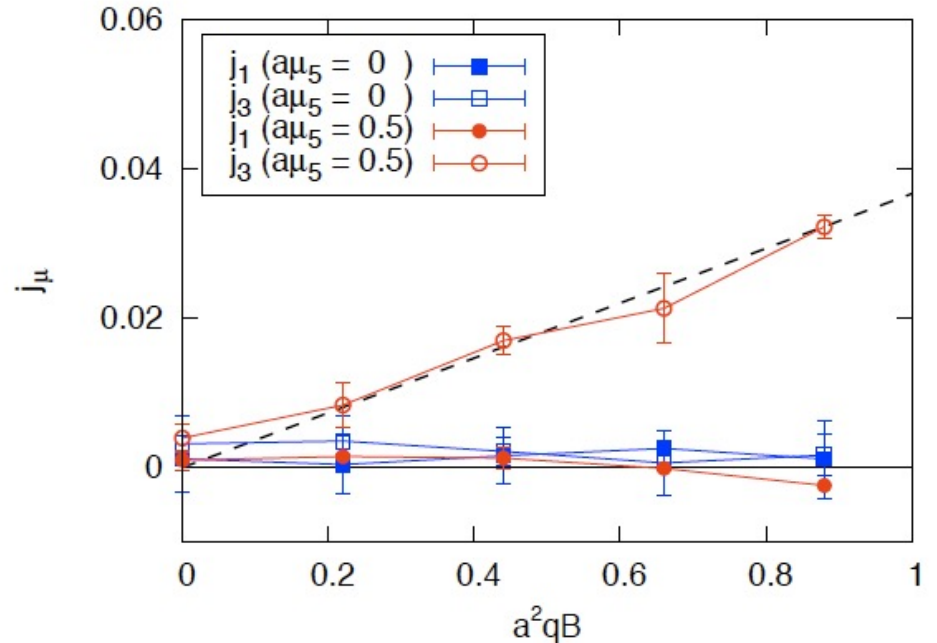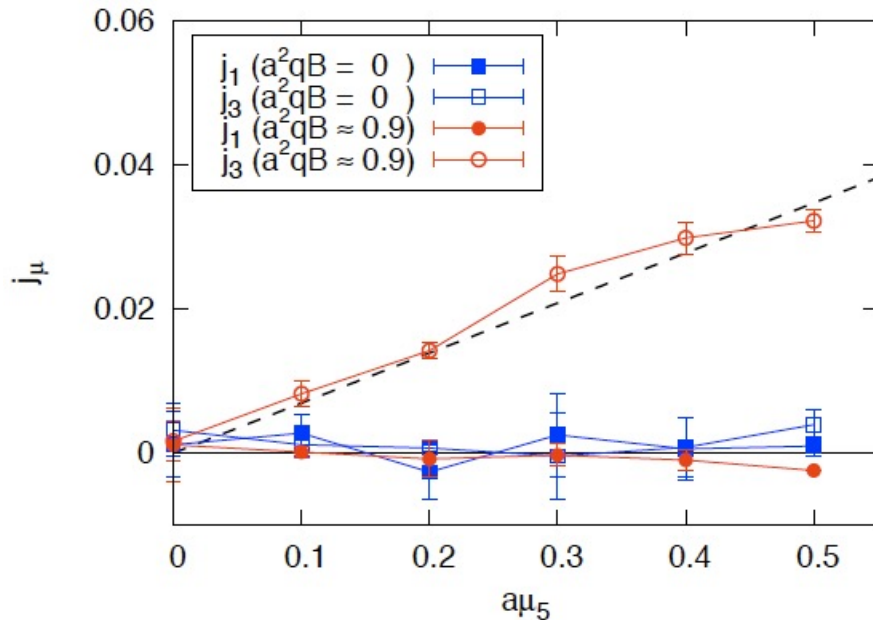
Chiral magnetic effect as a signature of chiral symmetry restoration
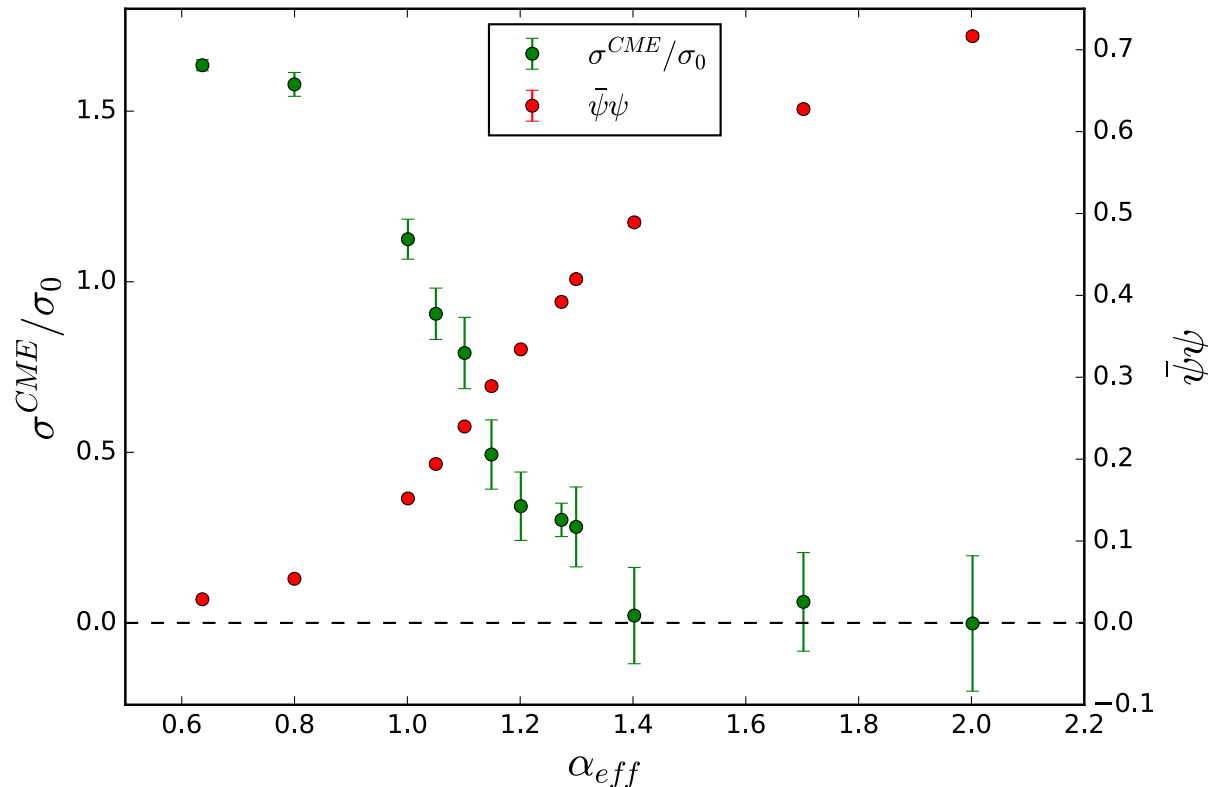
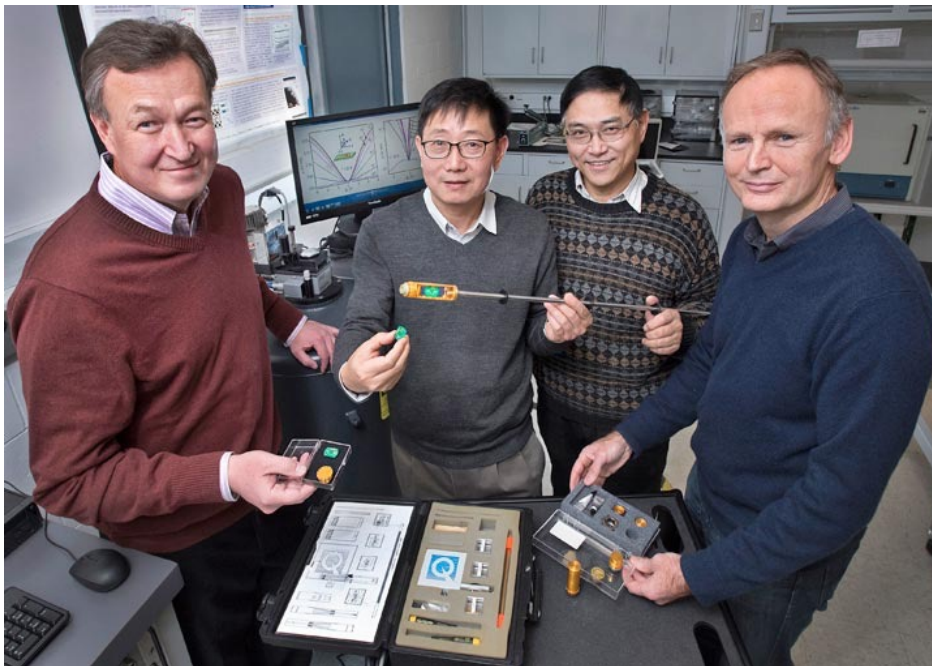V.Braguta et al,
arxiv:1704.07132,
[PRD]

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

nature
physics

JUNE 2016 VOL 12 NO 6
www.nature.com/naturephysics

Rogue and dusty

DIRAC SEMIMETALS
Chiral magnetic effect observed

BRAIN MORPHOGENESIS
Folds under pressure

ULTRACOLD FERMI GASES
Spin-orbit coupling in 2D

DIRAC SEMIMETALS
Chiral magnetic effect observed

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
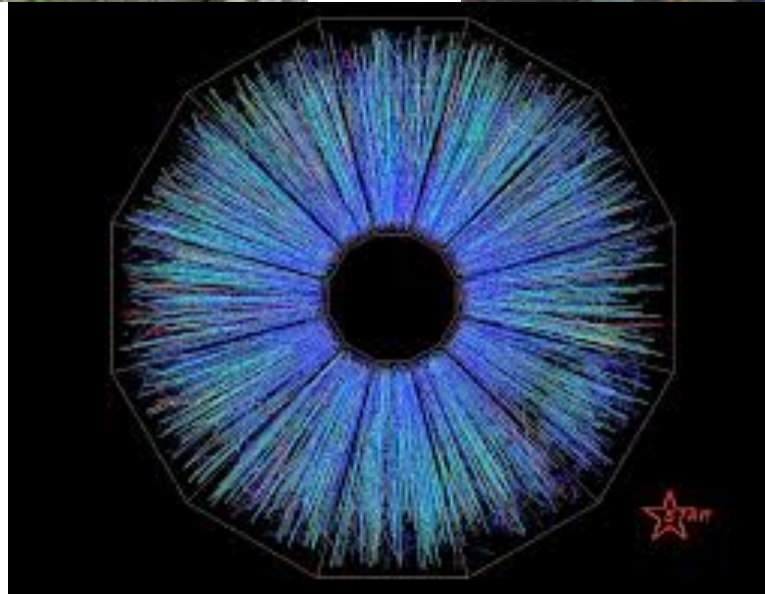
February 8, 2016
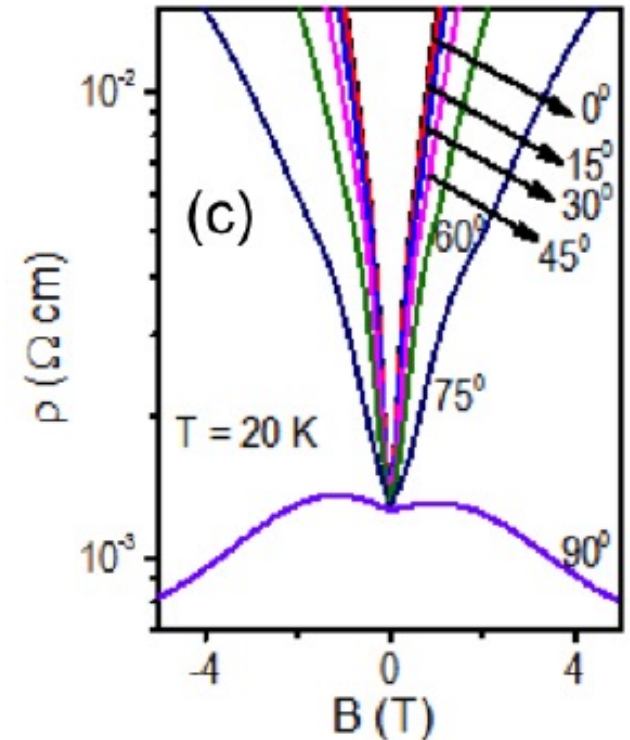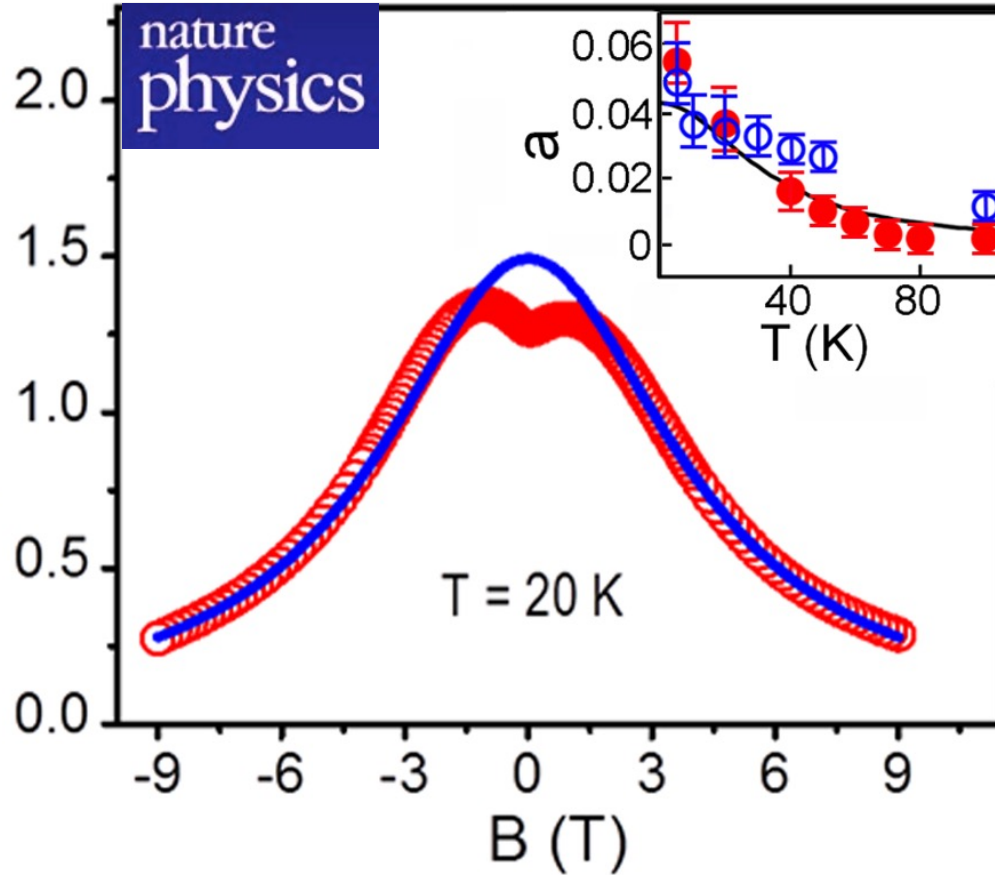
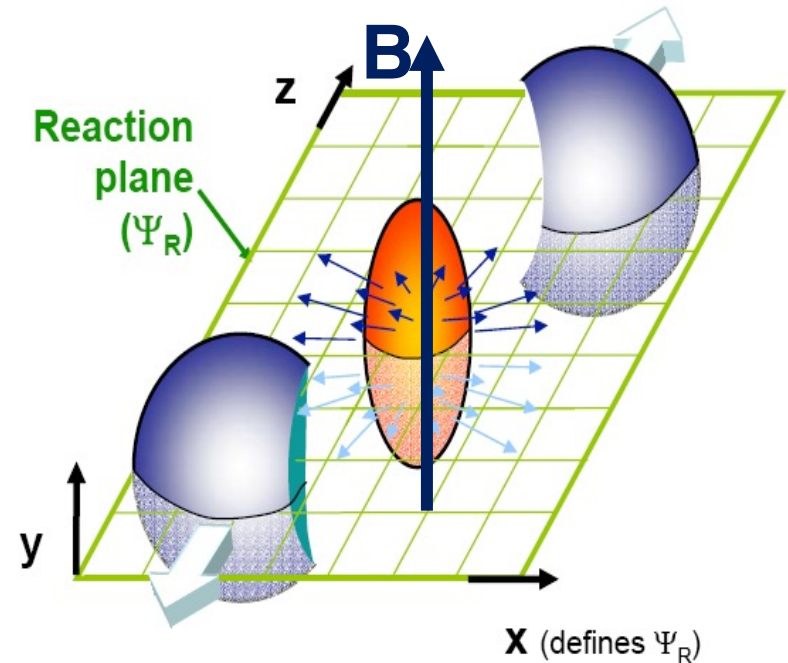# Can one detect QCD topological transitions in heavy ion collisions?
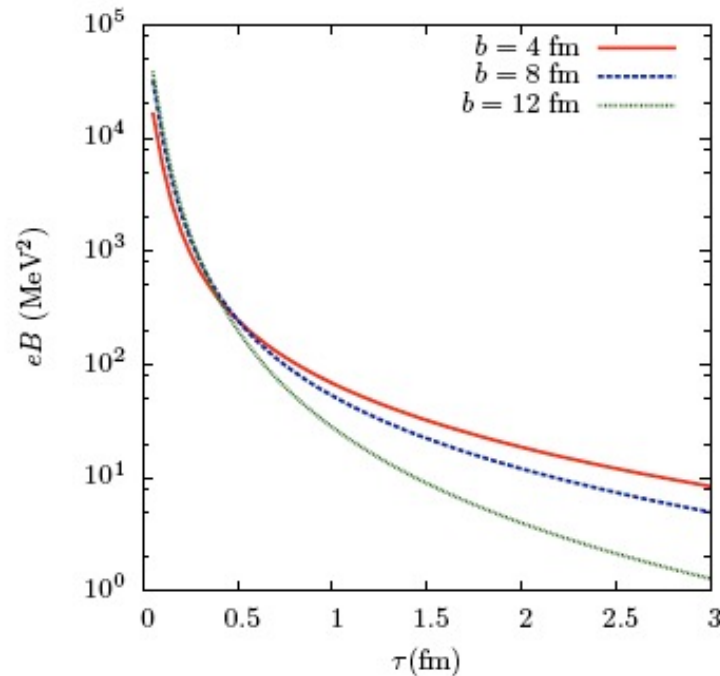

Relativistic Heavy Ion Collider (RHIC) at BNL

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
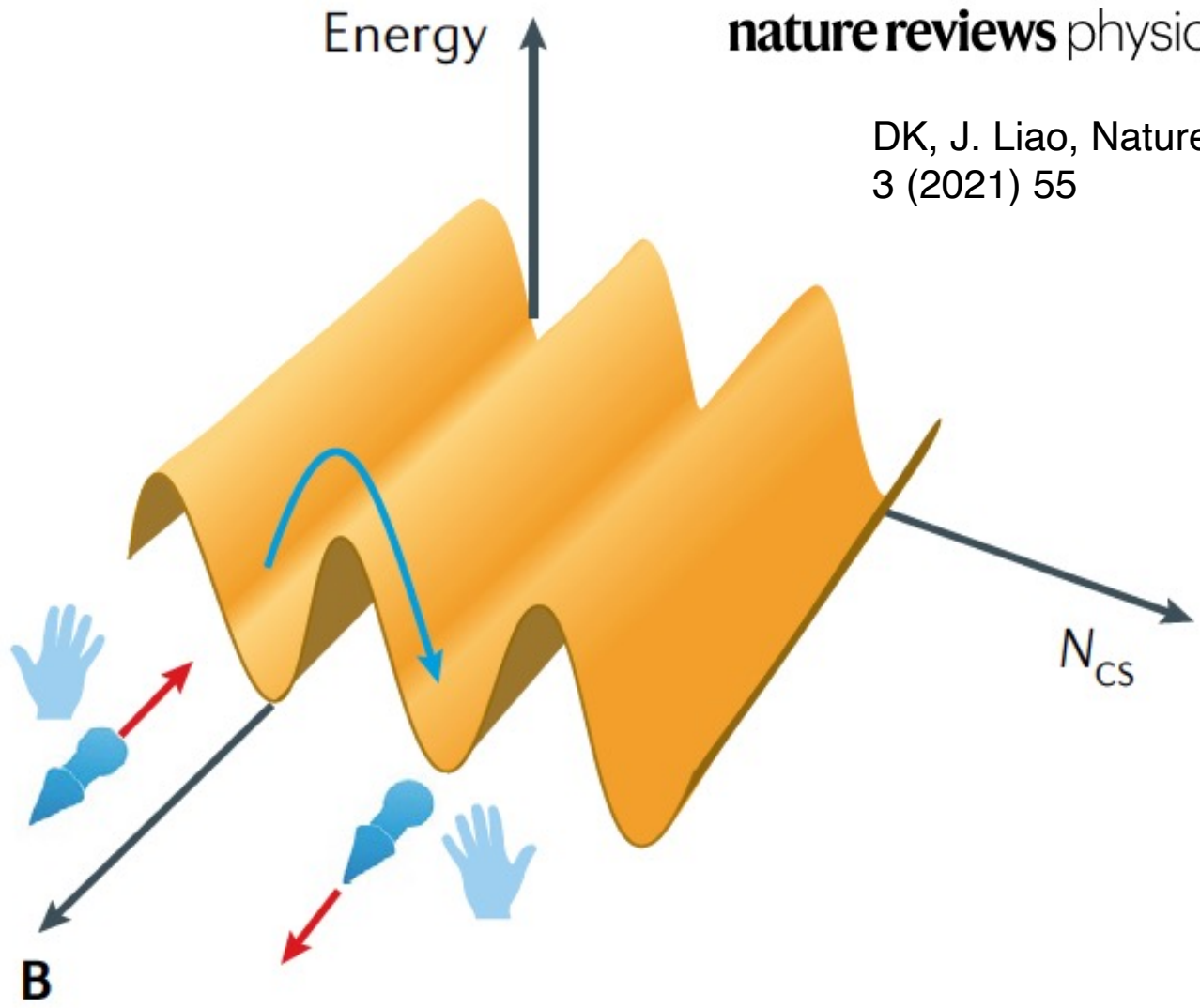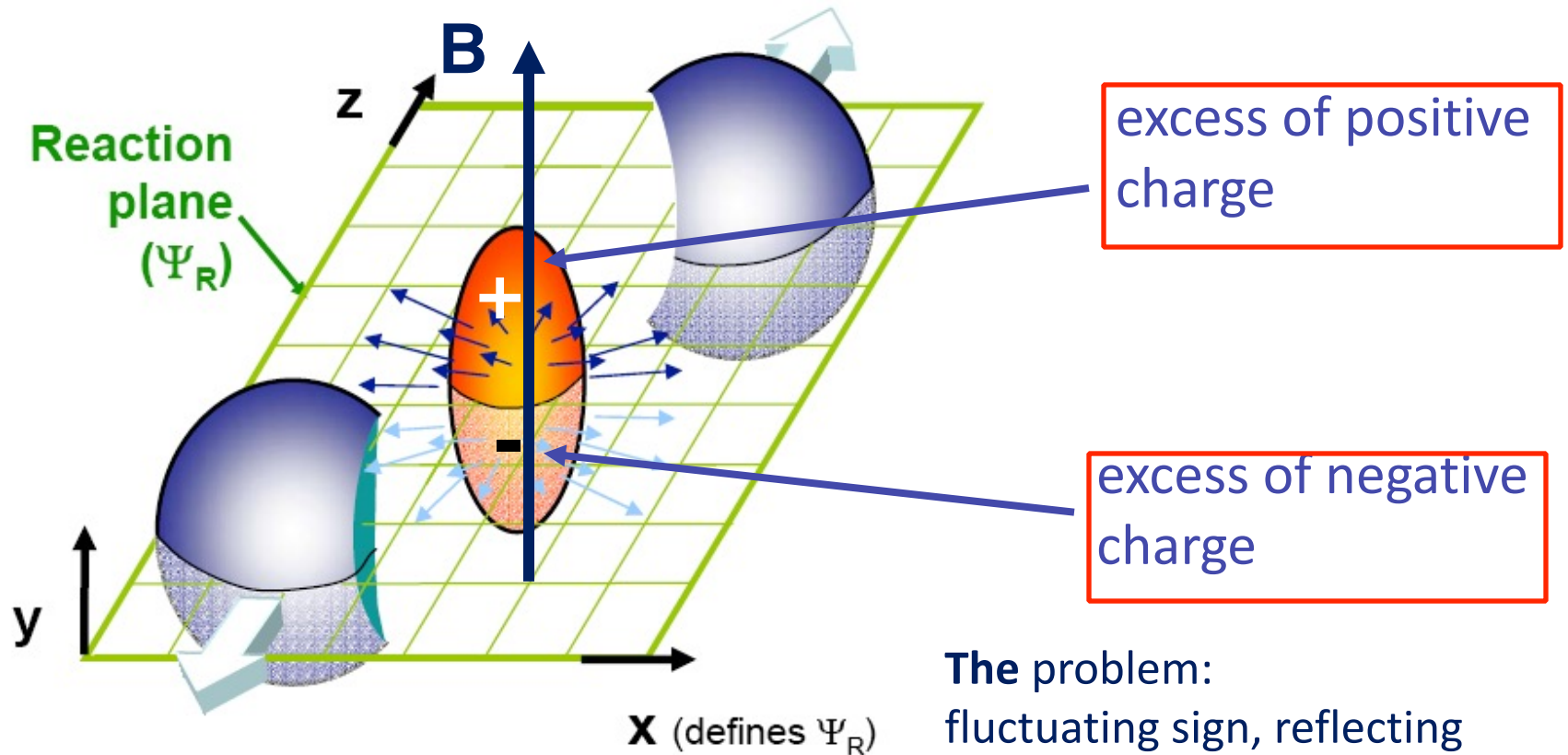
22

Energy

N_{cs}

B

Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quan-** tum chromodynamics matter. The QCD vac-
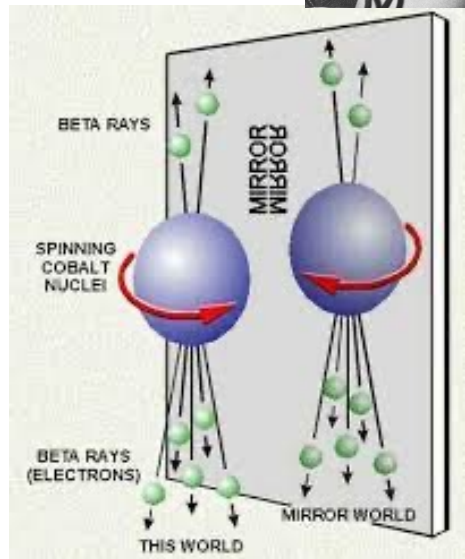
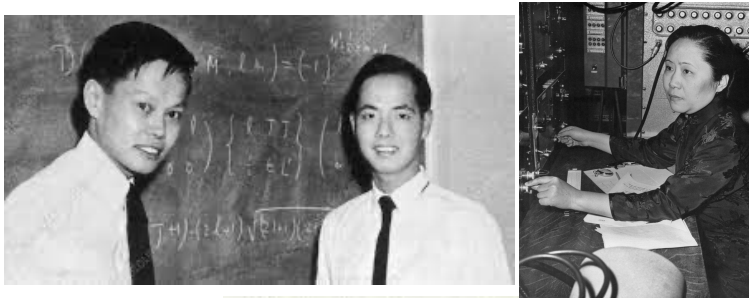# CME as a probe of topological transitions and chiral symmetry restoration in QCD plasma

Electric dipole moment due to chiral imbalance

B

z

Reaction plane (Ψ_R)

+

−

y

X (defines Ψ_R)

excess of positive charge

excess of negative charge

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

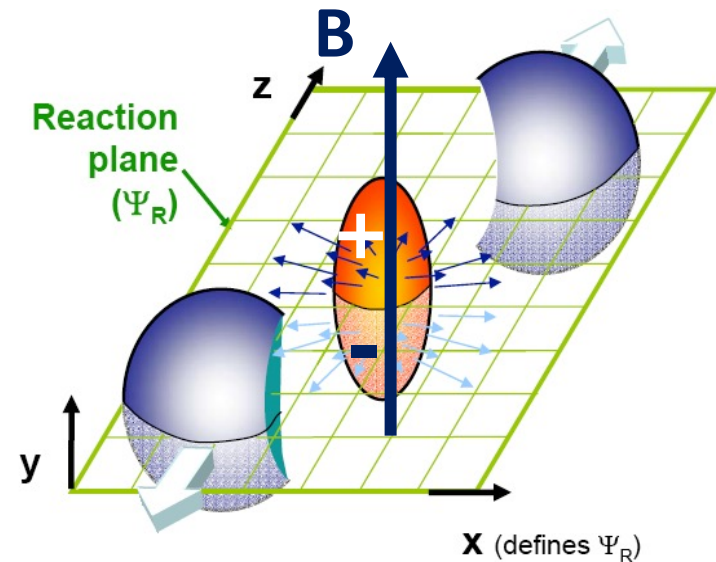DK, hep-ph/0406125; Phys.Lett.B633(2006)260

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 ?

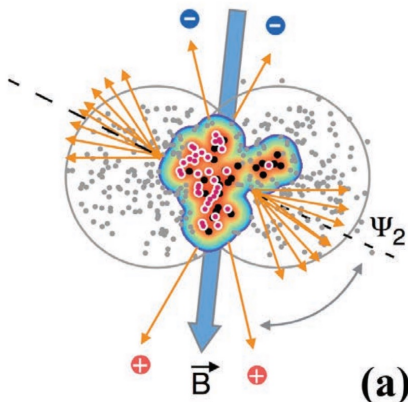# Separating the signal from background: the beginning

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.
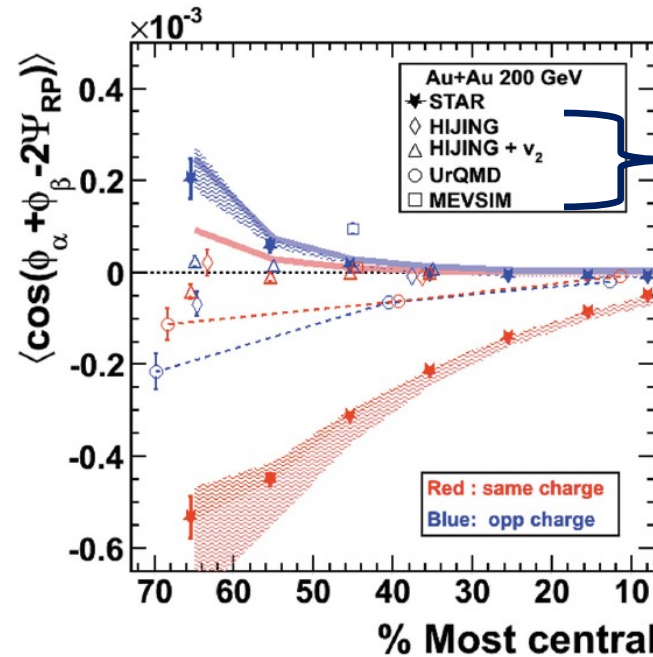

(a)

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

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

26

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)
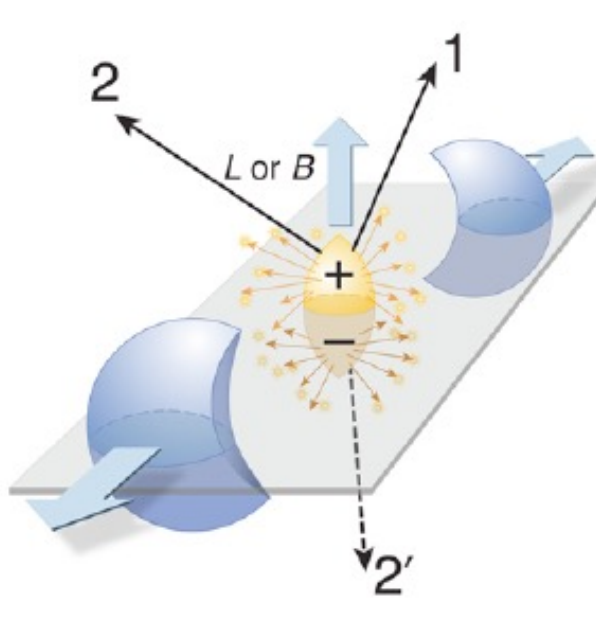
Monte Carlo generators
do not describe the data

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

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

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

27

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

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

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

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

28

Baseline: scaling with 1/N (inverse multiplicity)

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.

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

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:

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

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

Review:
DK, J.Liao, S.Voloshin, G.Wang,
Prog. Part. Nucl. Phys. 88 (2016) 1
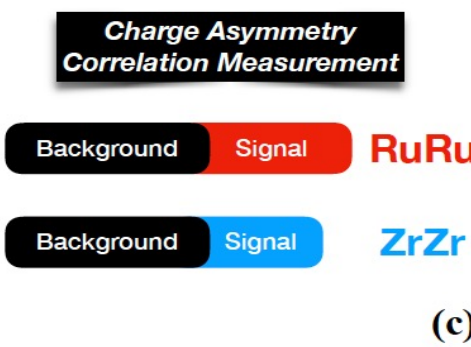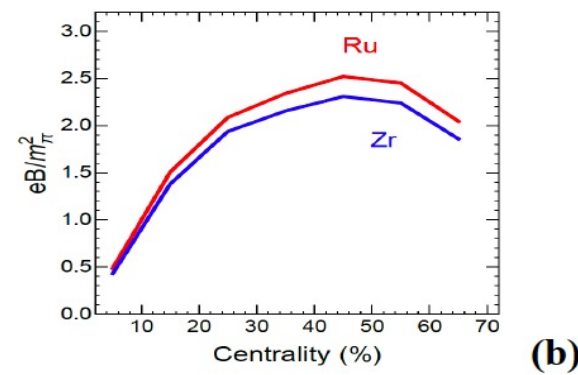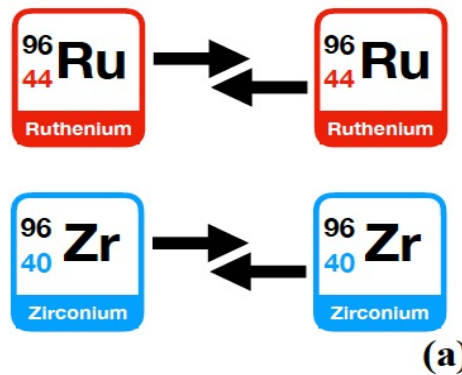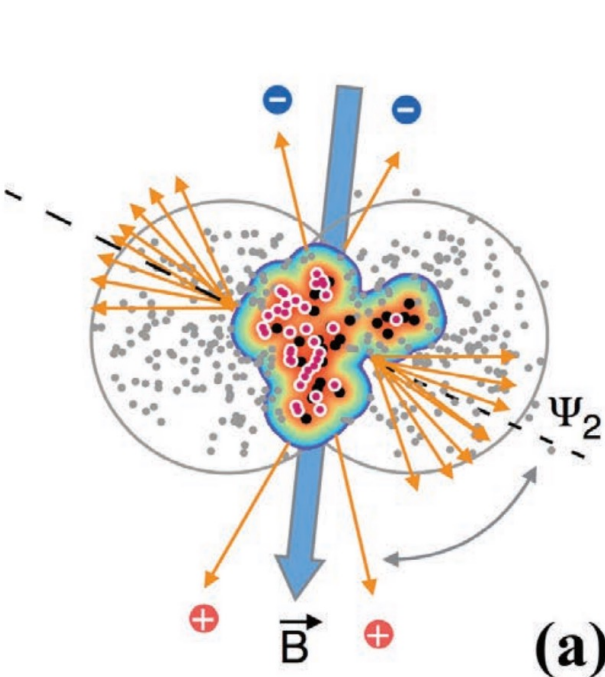
29

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
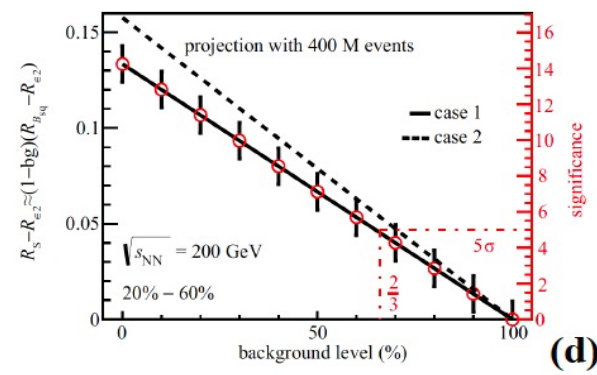
STAR Collaboration

Detection of QCD topological transitions using the isobar collisions at RHIC

The results have just been released! (Aug 31, 2021)

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

< 1 !

CME excluded?

not predicted by any theory, CME or not
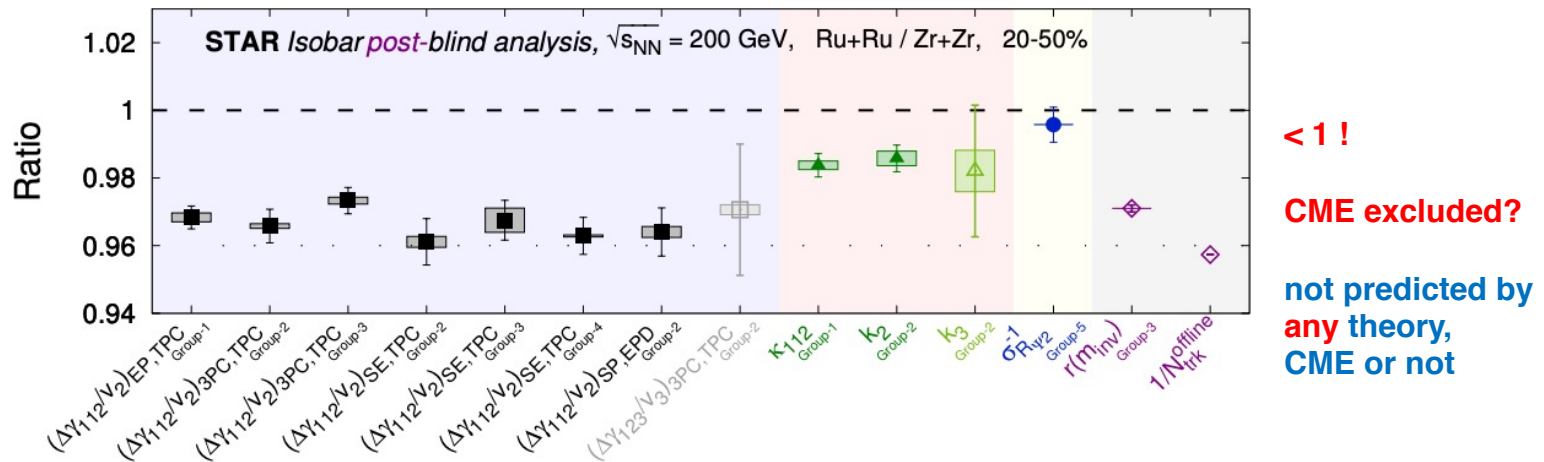
Detection of QCD topological transitions using the isobar collisions at RHIC

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

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.

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:
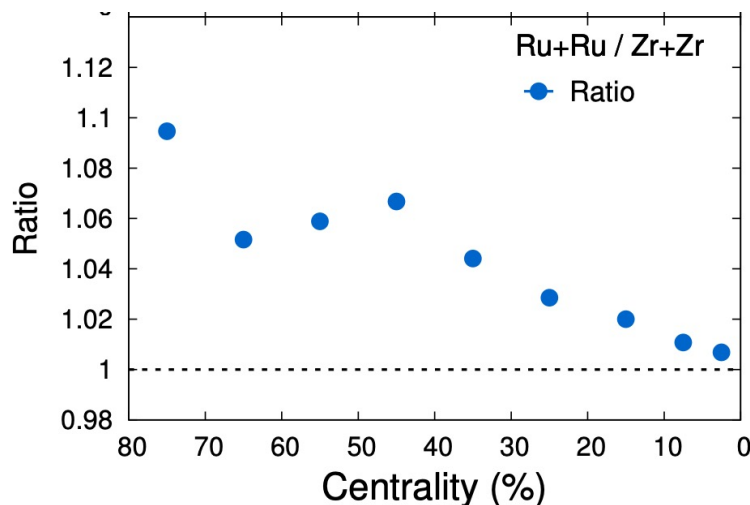

Since both signal and background scale as 1/N, the baseline has to be changed. This is not part of the "predefined criteria".

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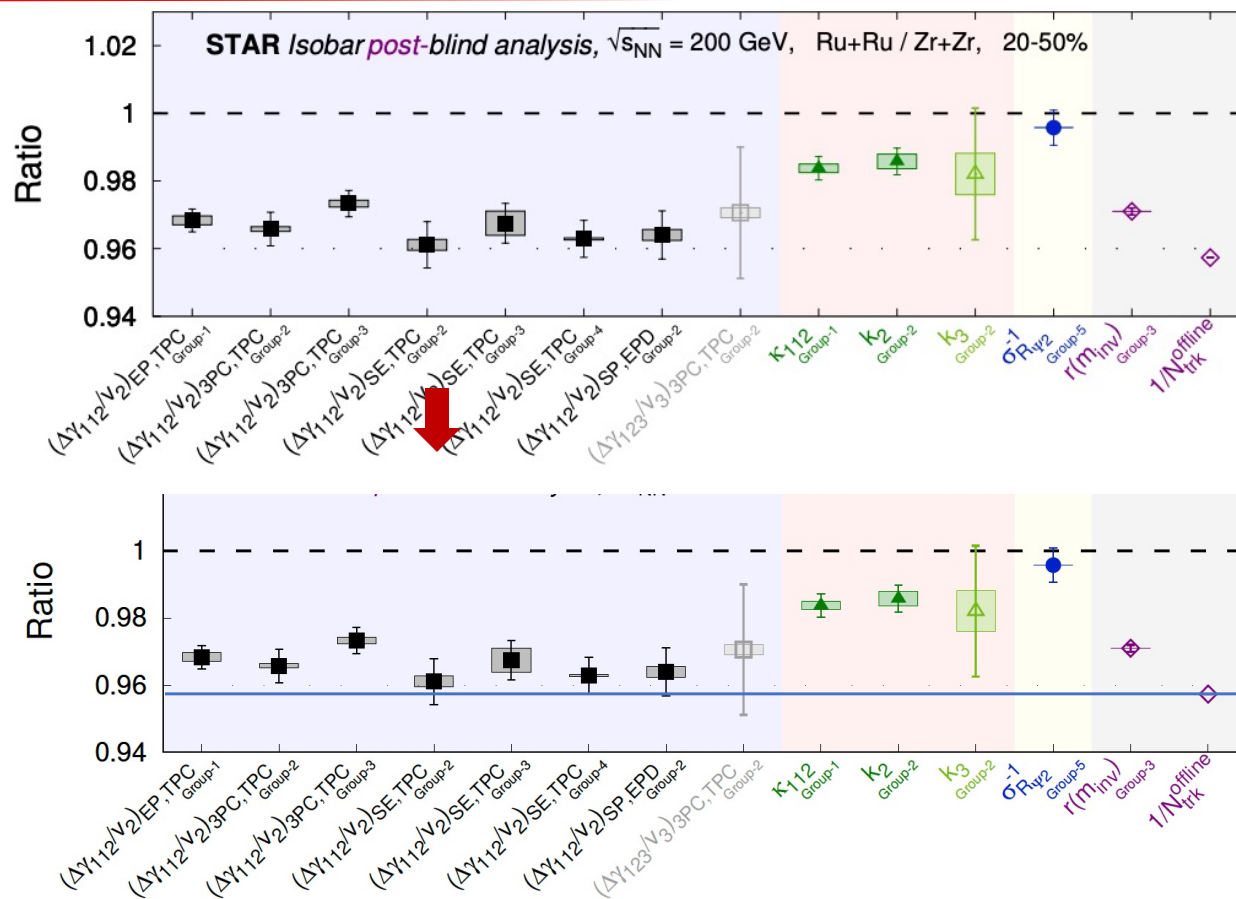
Depending on the observable, CME is present at 1-4 σ level

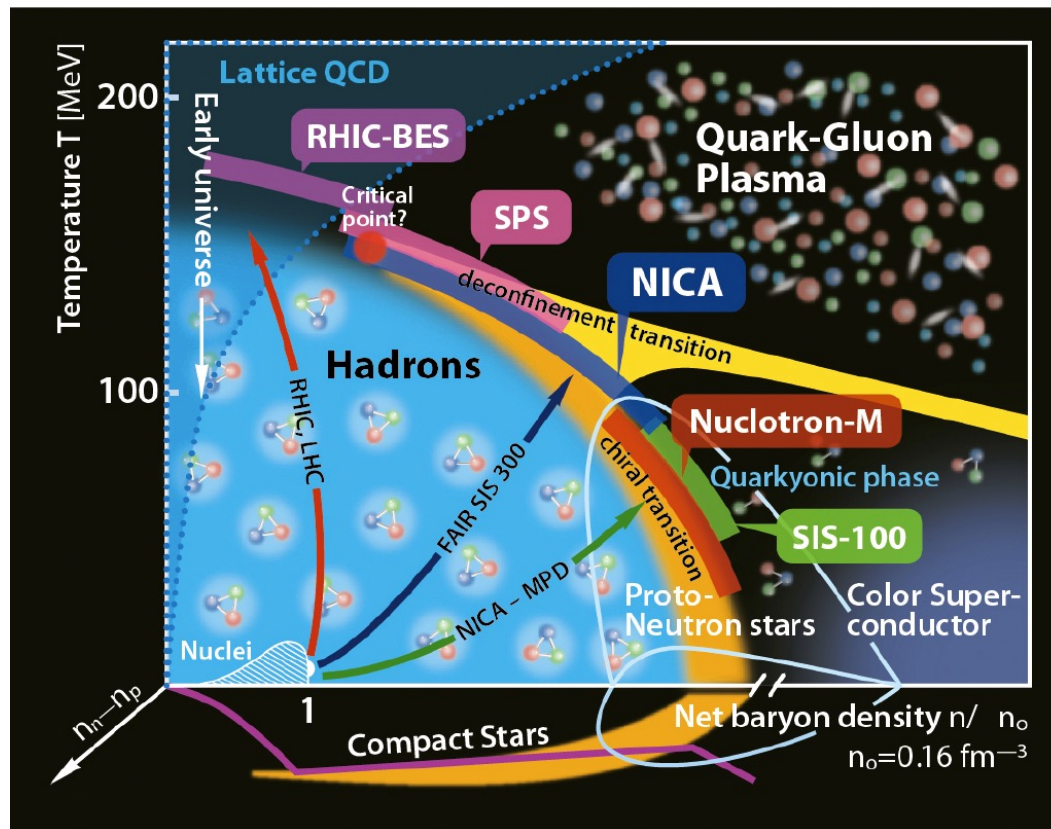**Detailed analysis is needed, and is ongoing**

Stay tuned!

Conference on "Chirality, vorticity and magnetic field in heavy ion collisions"

Stony Brook University, November 1-5, 2021

Chern-Simons fluctuations near a critical point

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

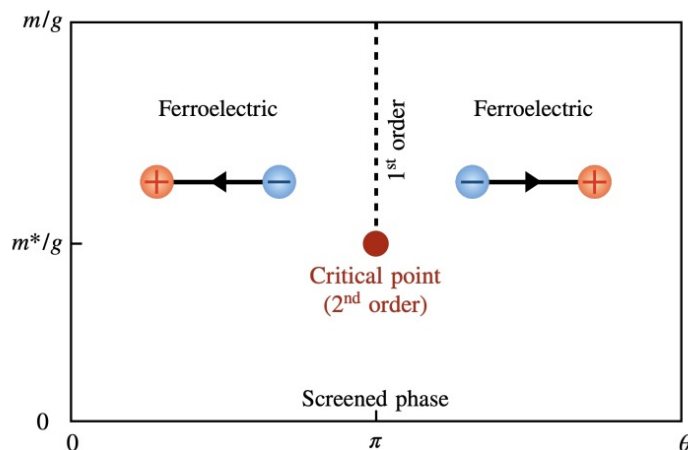## Simple system that exhibits a critical point: massive Schwinger model near θ = π

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

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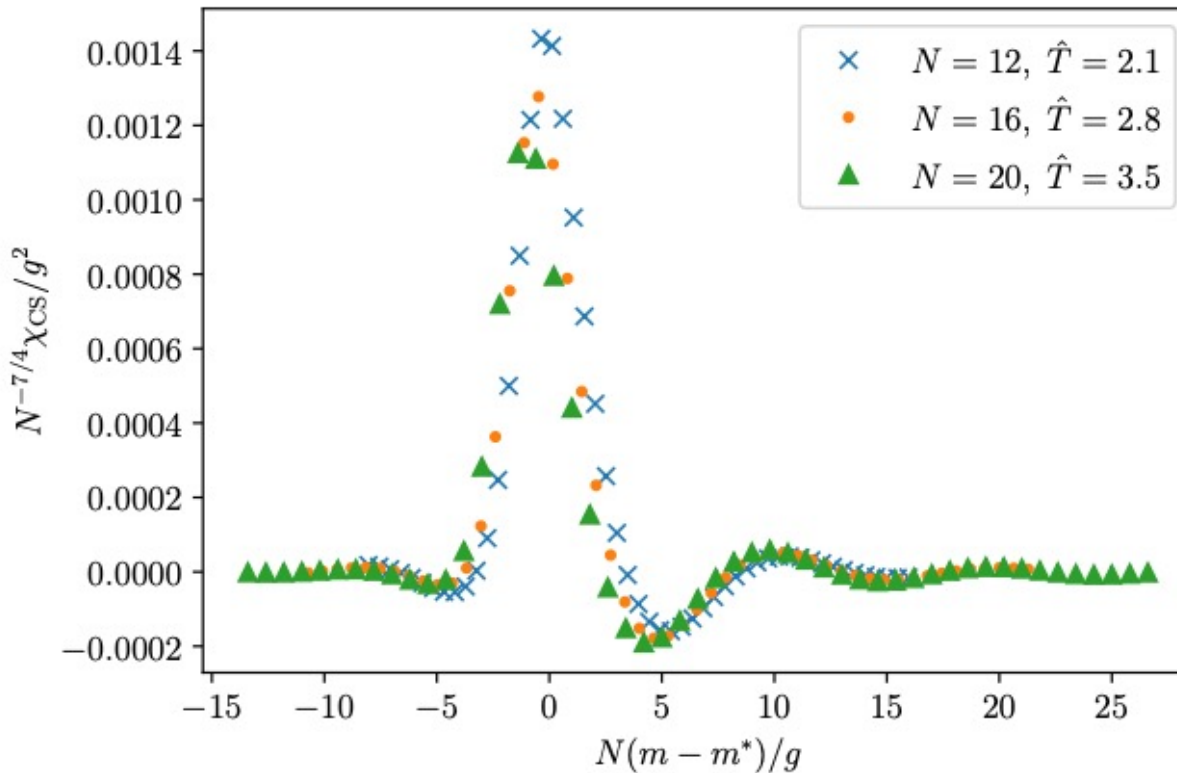
bosonization

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

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

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

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

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

Sharp peak in topological fluctuations near the critical point!

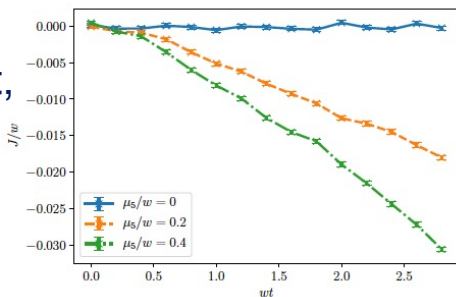Search for CME in low-energy heavy ion collisions?

Real-time dynamics of CME

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

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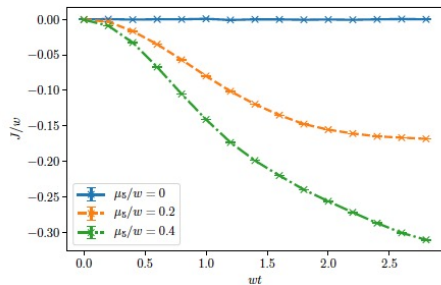
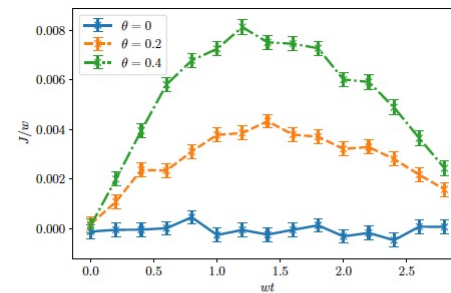Jordan-Wigner transformation – spin chain

CME current,

μ_5 quench:

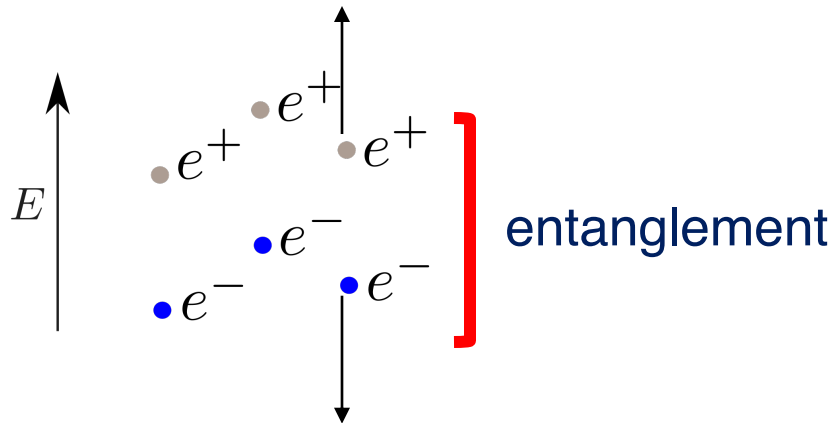CME current,

θ quench:

(a) $M/w = 0.1$

(b) $M/w = 0.5$

(a) $M/w = 0.1$
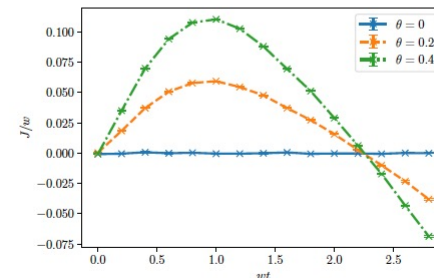
(b) $M/w = 0.5$

Real-time dynamics of CME and "chiral entanglement"

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

entanglement

$$S_G = \int dk_1 \left[\left(1 - |\beta_{k_1,t^*}|^2\right) \log \left(1 - |\beta_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log \left(|\beta_{k_1,t^*}|^2\right) \right],$$

Gibbs entropy

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

Entanglement entropy

$$S_E = - \int dk_1 \left[|\alpha_{k_1,t^*}|^2 \log \left(|\alpha_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log \left(|\beta_{k_1,t^*}|^2\right) \right]$$

Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK,
to appear on June 3

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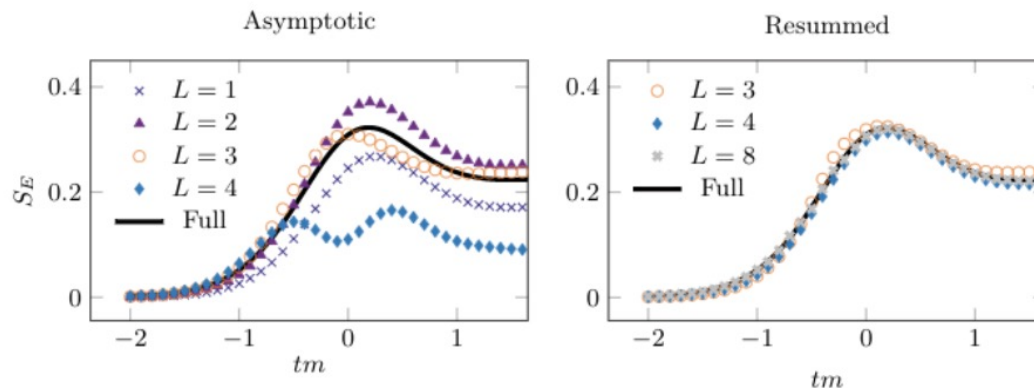the moments of multiplicity distribution:

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

Derived first for shot noise in Quantum Point Contacts:

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

Bernoulli numbers

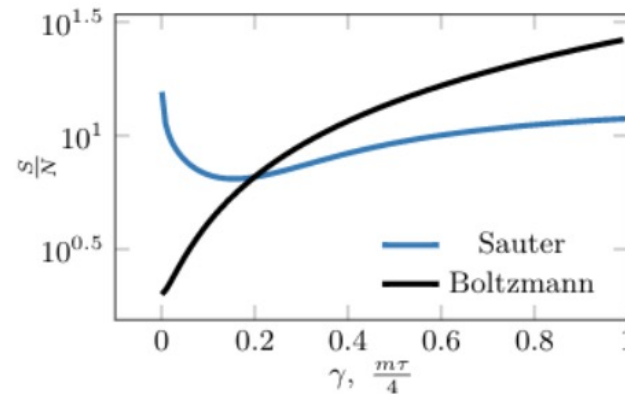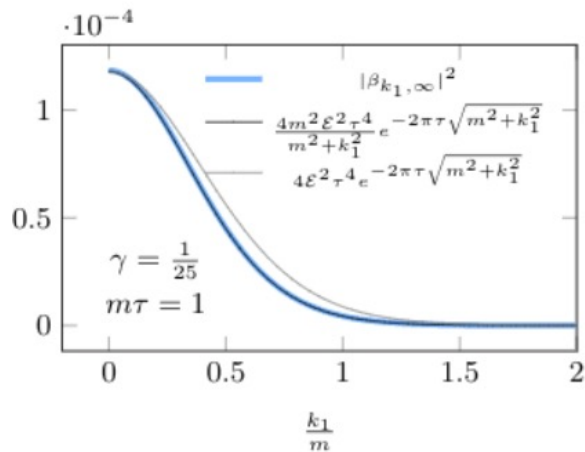An efficient way to resum this series is found, using Pade-Borel methods:

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?

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 (<u>including the baseline differences between the isobars</u>) is imperative, and requires a concerted effort of experimentalists and theorists].

   [Early estimates suggest the presence of CME at 1-4 σ level]