Seminar by the STAR Collaboration, August 31, 2021

Chiral Magnetic Effect:

from heavy ion collisions to the Early Universe

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 in subatomic world: chiral fermions

Fermions:
E. Fermi,1925

Dirac equation:
P. Dirac, 1928

Weyl fermions:
H. Weyl, 1929

Majorana fermions:
1937

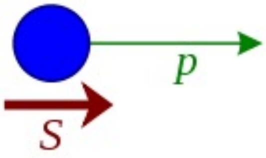
$$(i\partial\!\!\!/ - m)\psi = 0$$

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

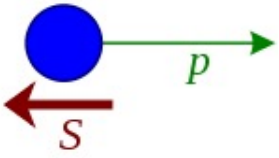
$$-i\partial\!\!\!/\psi + m\psi_c = 0$$

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

Right-handed:

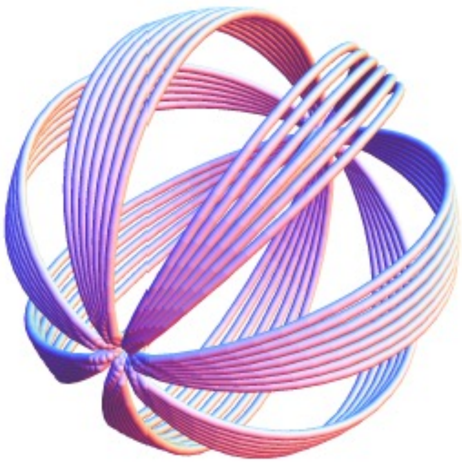


Left-handed:

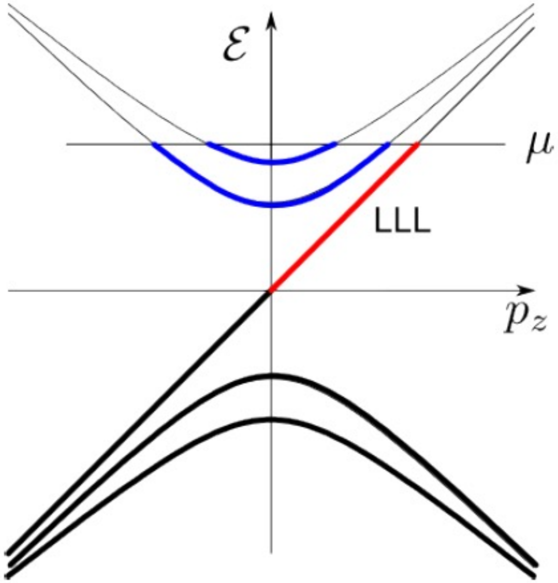


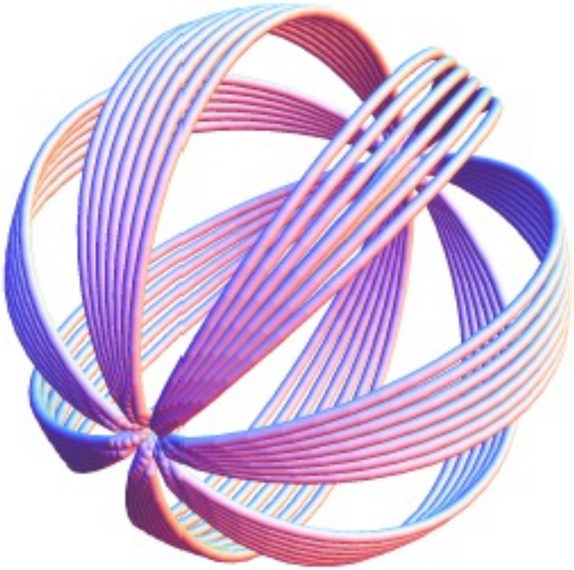
Chirality of gauge fields

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

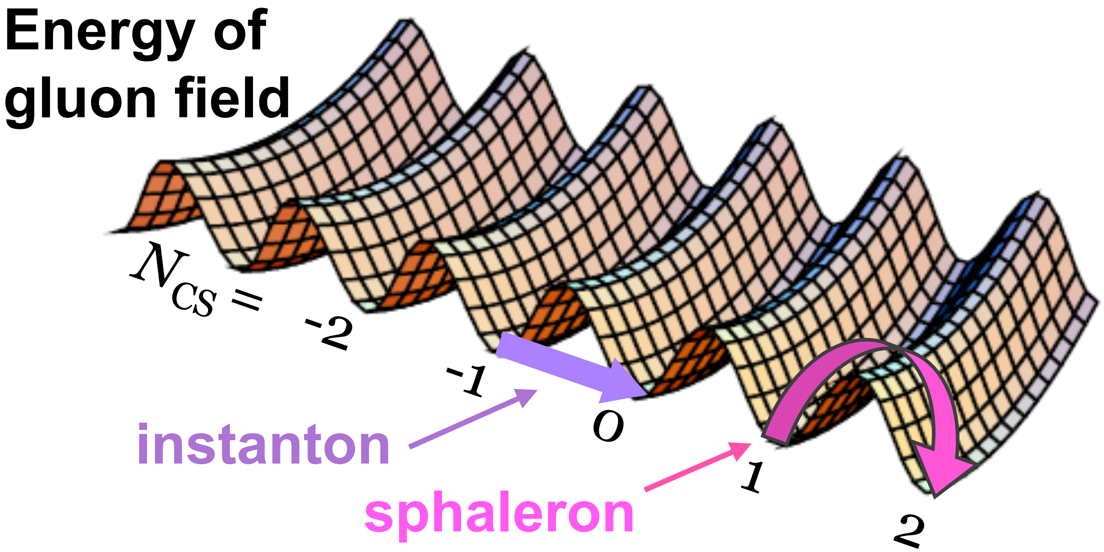
Chirality in the vacuum of the Standard Model

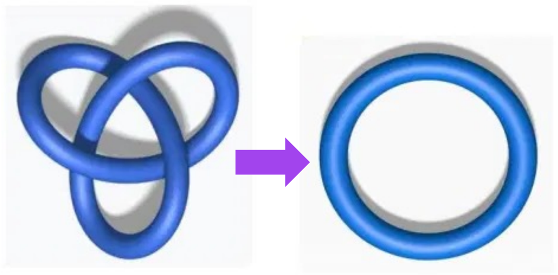
The instanton and sphaleron solutions in non-Abelian gauge theories describe transitions between topological sectors of the vacuum marked by different integer values of the Chern-Simons number:

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

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

QCD (Quantum ChromoDynamics) vacuum:



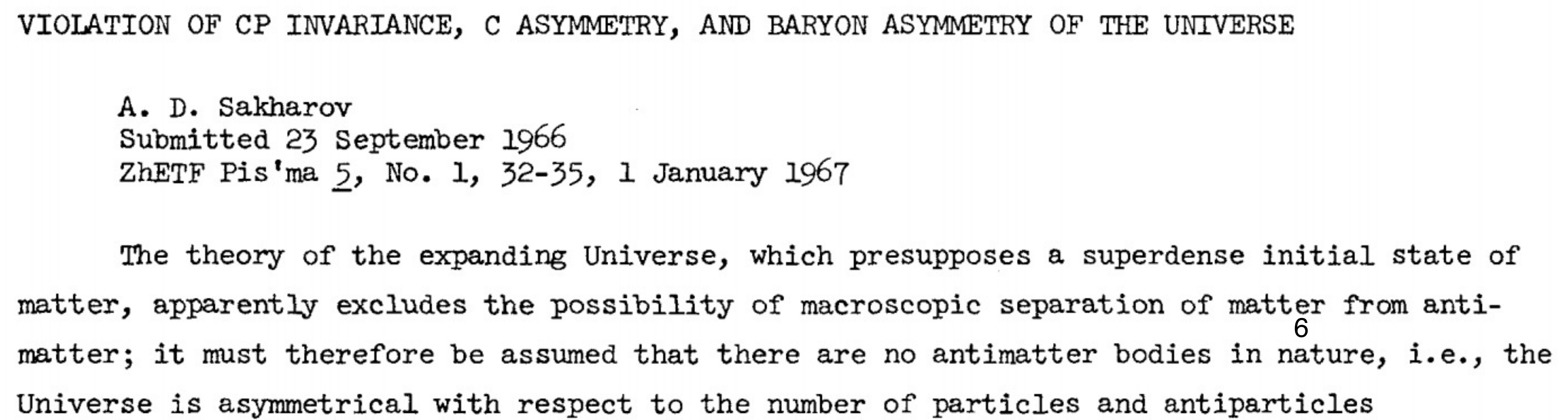


Chirality and the origin of Matter-Antimatter asymmetry in the Universe

Sakharov conditions for baryogenesis:

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

A.D. Sakharov, 1967



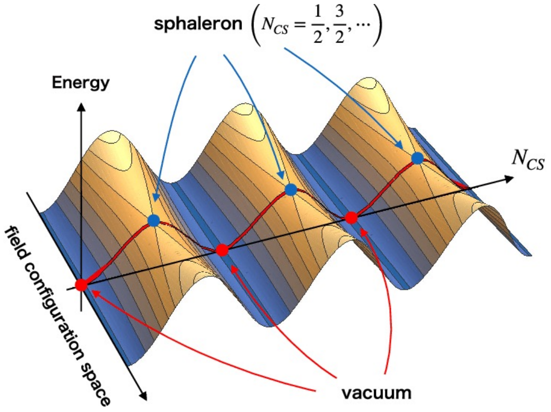
VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

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 antimatter; 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

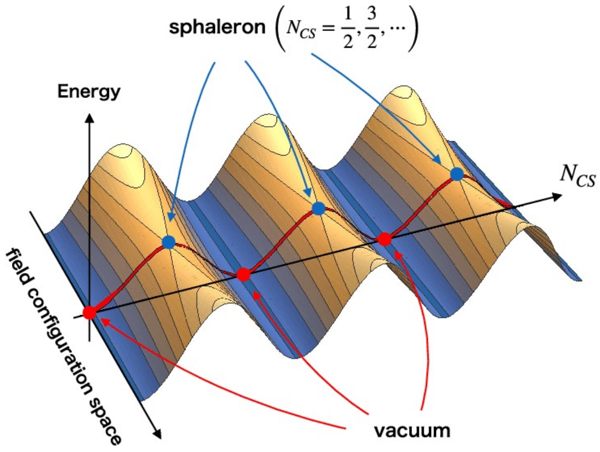
But: we can study analogous processes in another non-Abelian gauge theory of the Standard Model – QCD!

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).

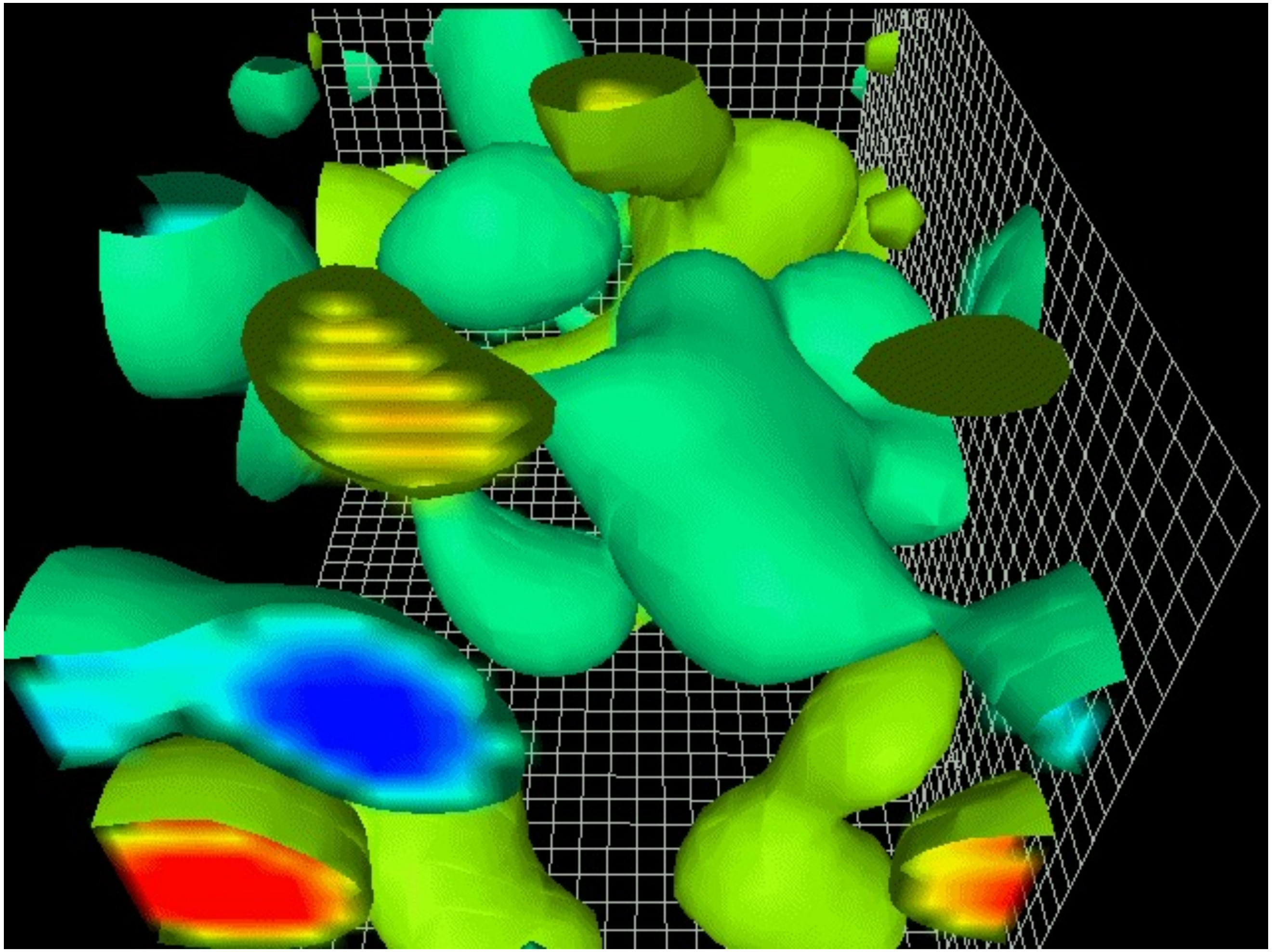
QCD sphalerons induce chirality violation (instead of baryon number violation), and rapid expansion of the produced plasma drives it out of thermal equilibrium – thus we expect to see a substantial **generation of net chirality**, <u>of fluctuating sign</u>, **in heavy ion collisions**!



Graphics: Hamada, Kikuchi,'20

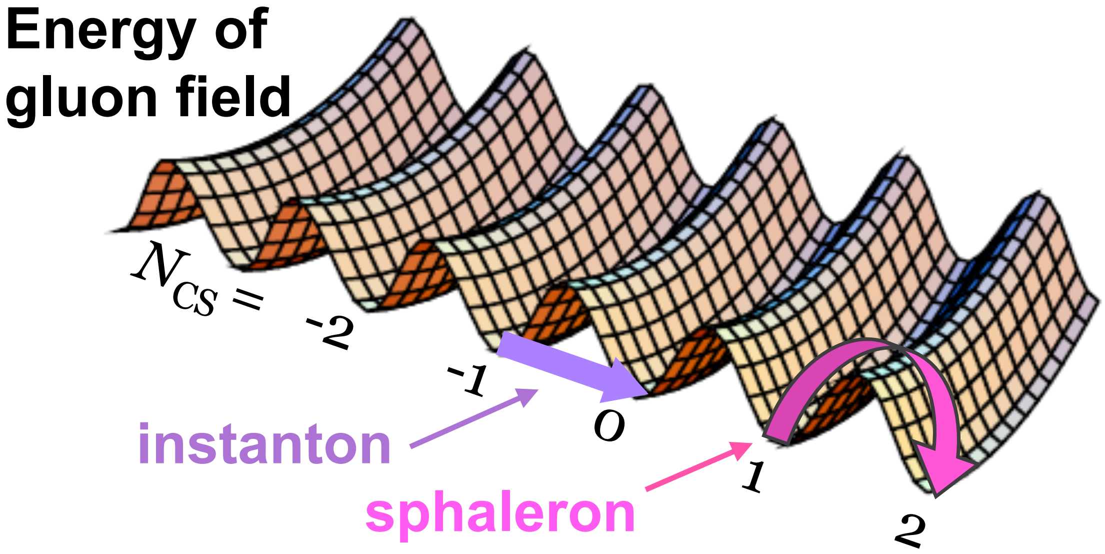
Topological transitions in QCD vacuum

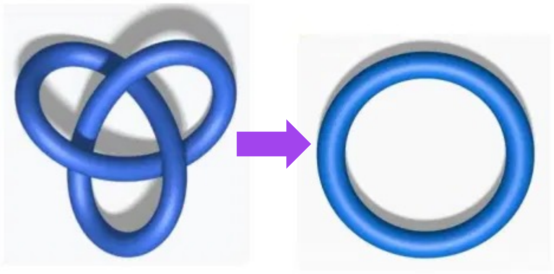
D. Leinweber



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.



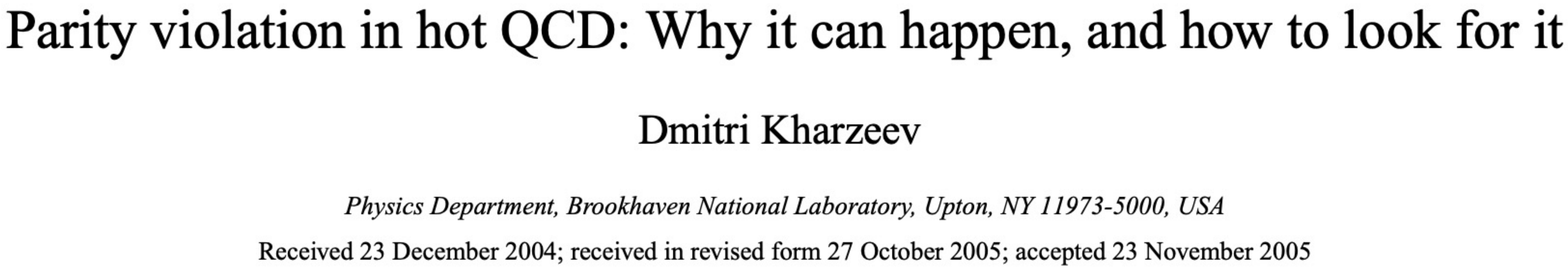


Is it possible to directly observe these chirality-changing transitions in experiment?

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

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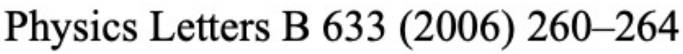
Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005

hep-ph/0406125 (June 2004)



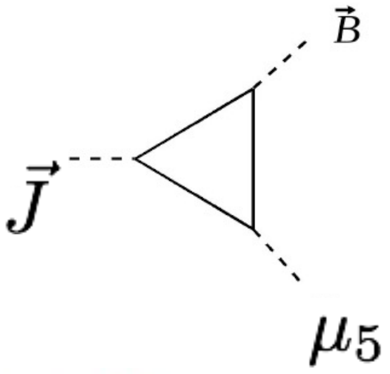
Physics Letters B 633 (2006) 260–264

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!

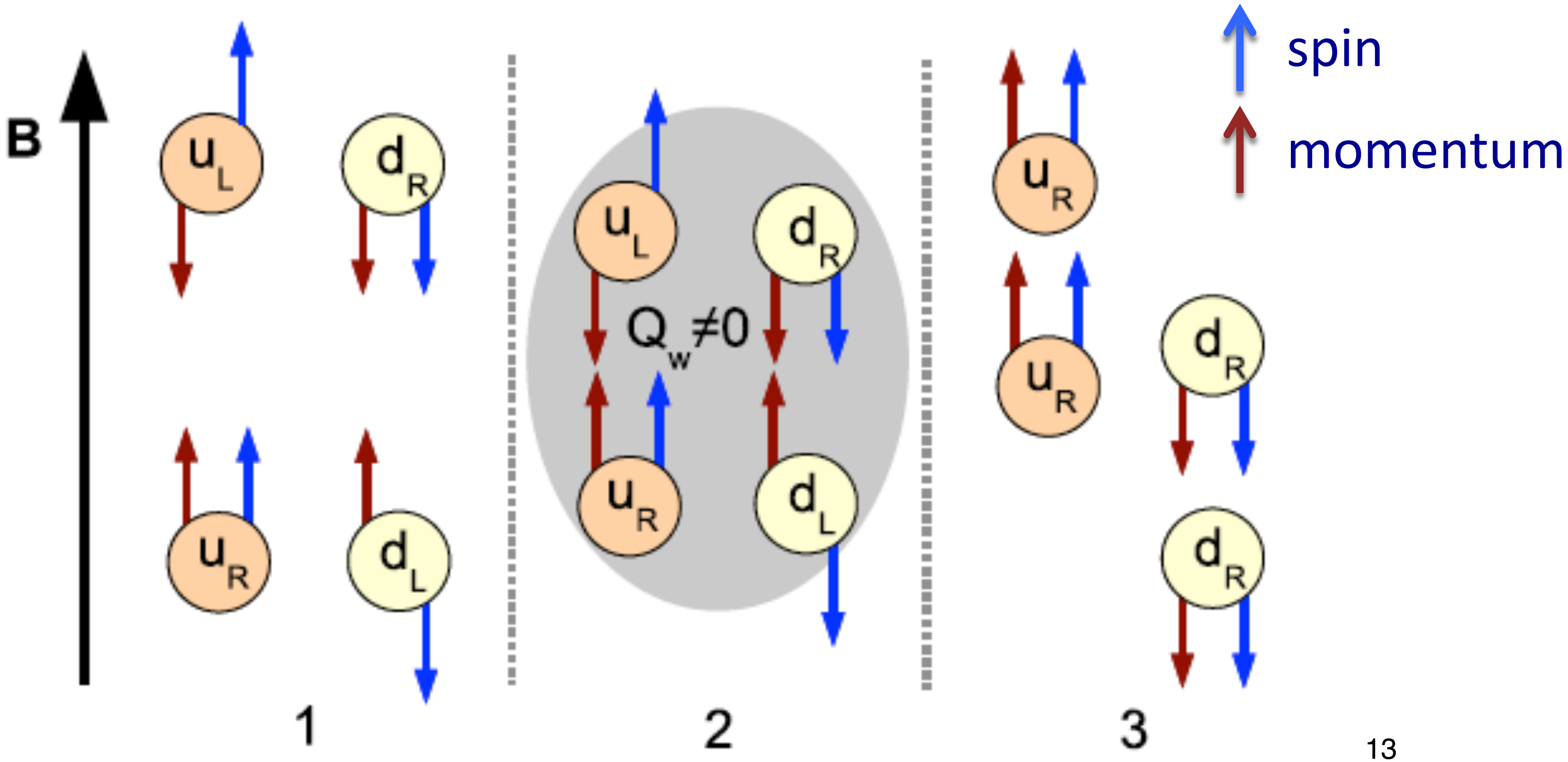
$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}}$$

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

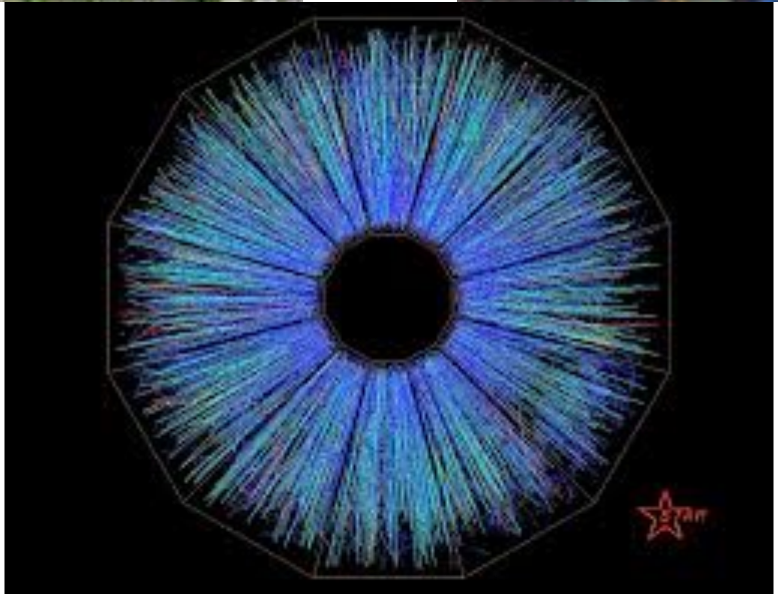


DK'04; DK, L.McLerran, H. Warringa '07; K. Fukushima, DK, H. Warringa '08

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

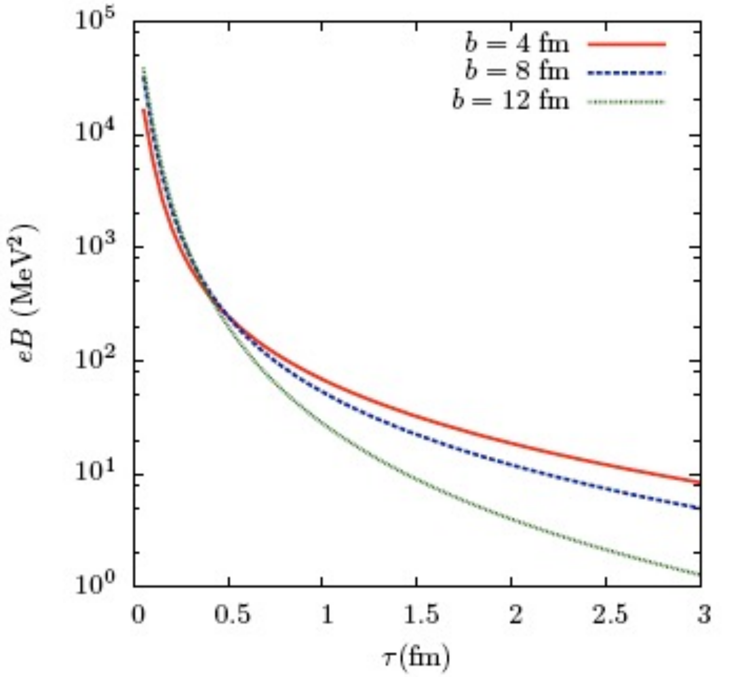
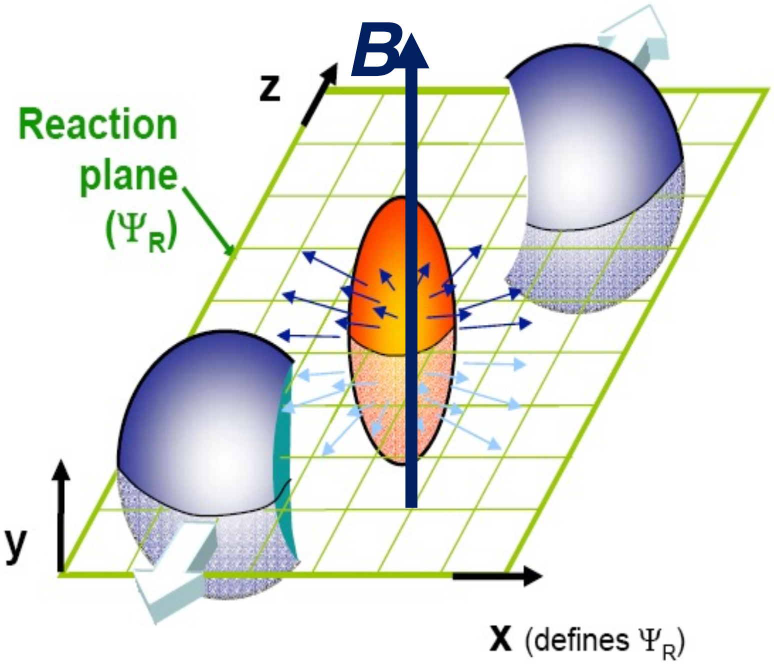


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).



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

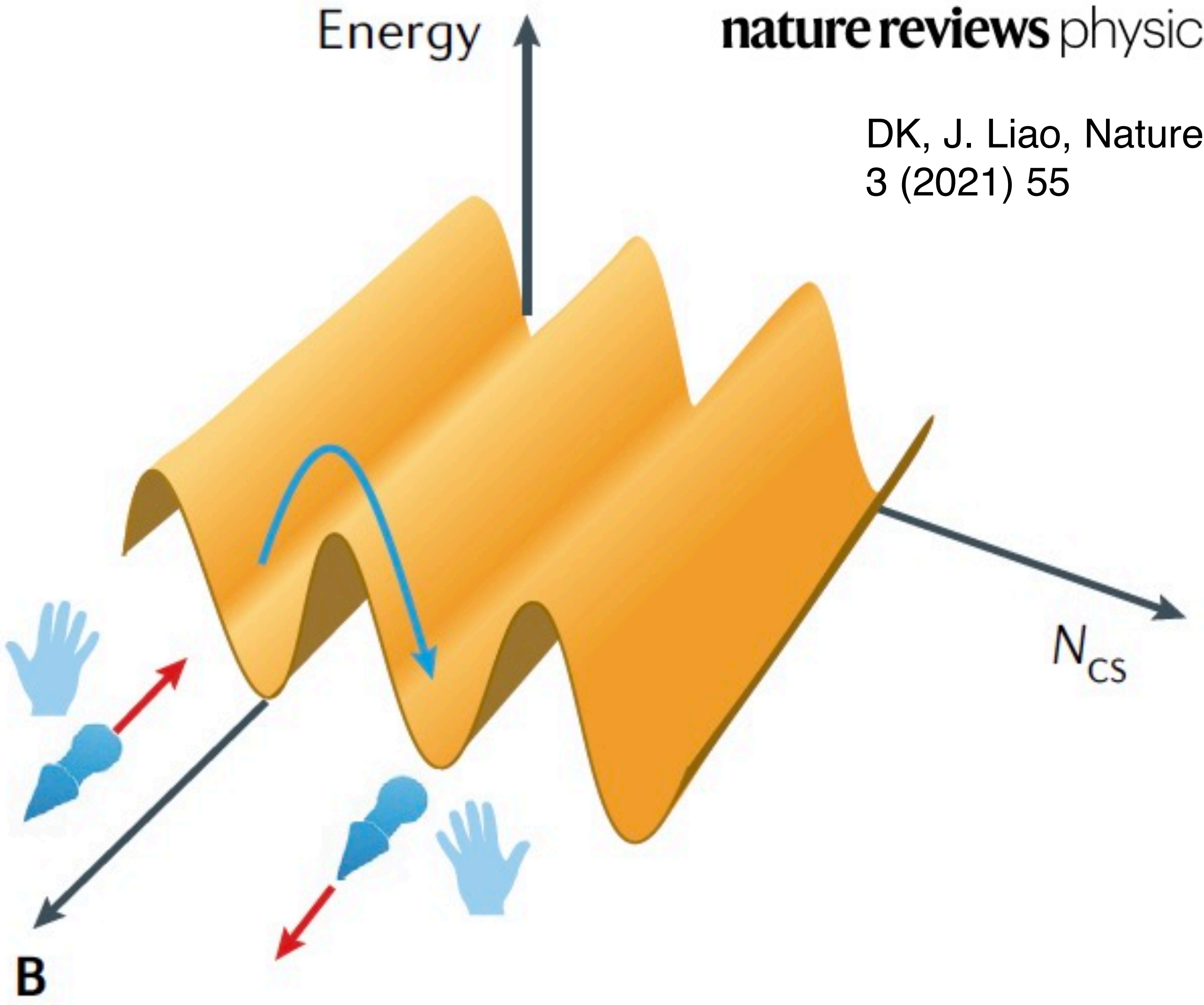
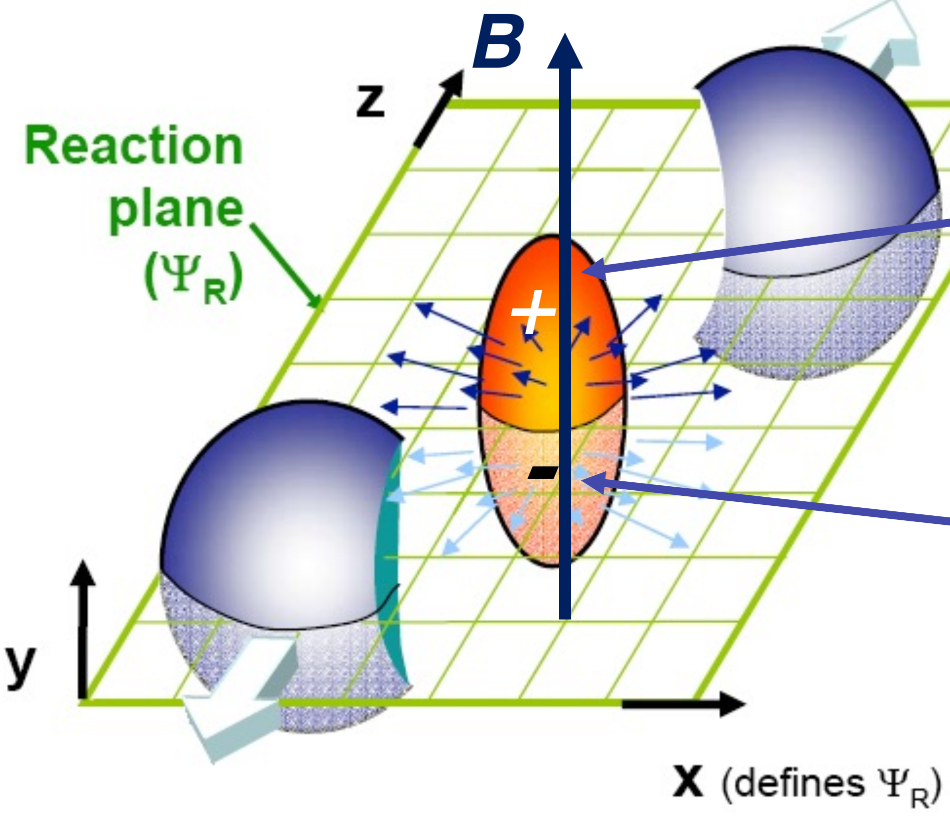


Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quantum chromodynamics matter.** The QCD vac-

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

Electric dipole moment due to chiral imbalance



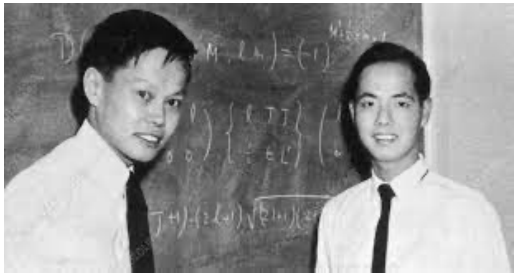
excess of positive charge

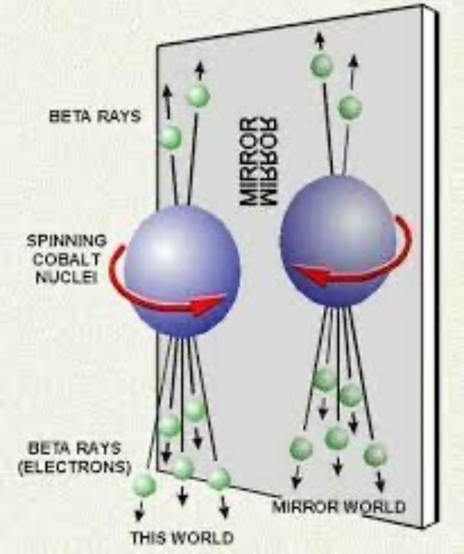
excess of negative charge

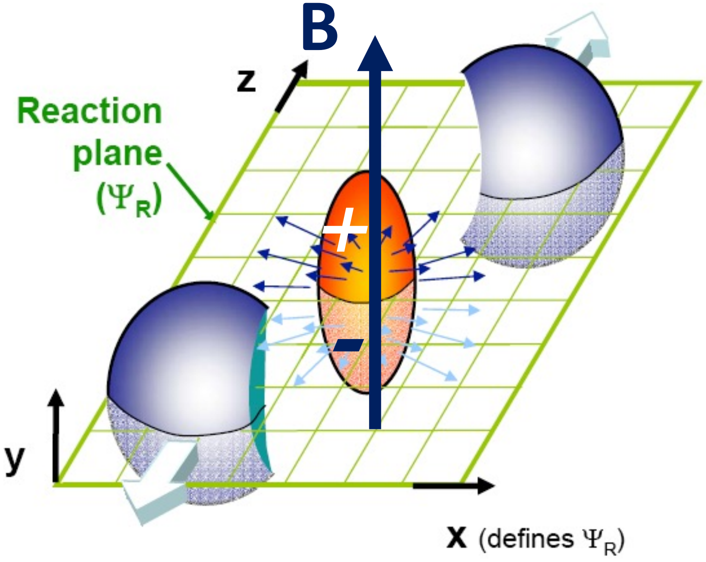
The problem:
fluctuating sign, reflecting topological fluctuations in QCD
- backgrounds!

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



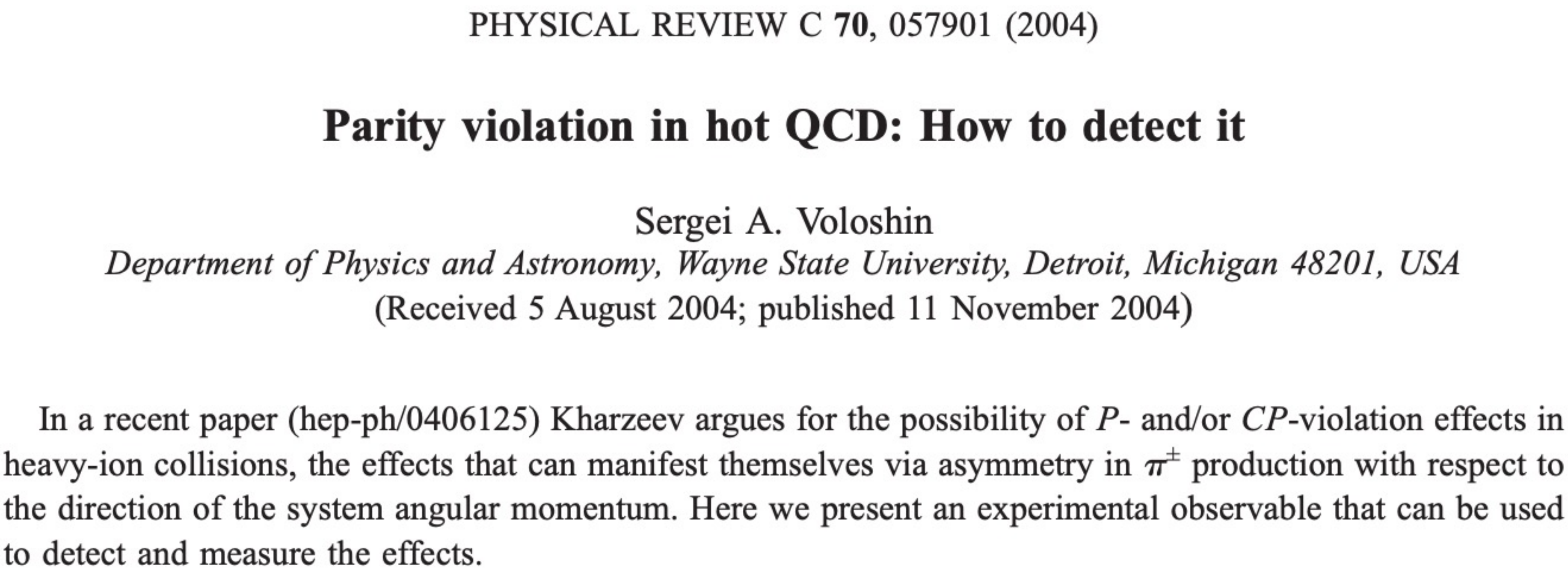




Global Parity violation in Weak interactions

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

Separating the signal from background: the beginning

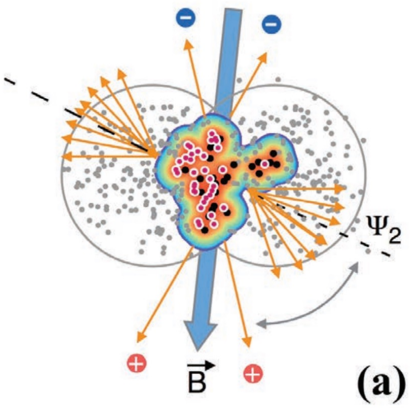


PHYSICAL REVIEW C **70**, 057901 (2004)

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.



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

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

PRL **103,** 251601 (2009)

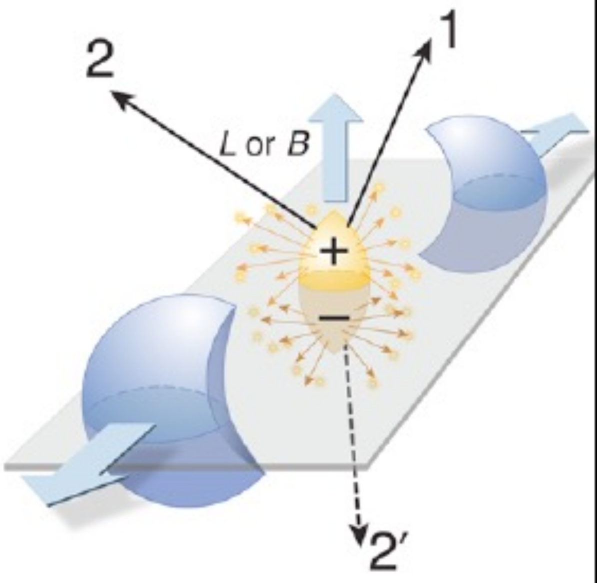
Selected for a Viewpoint in *Physics*

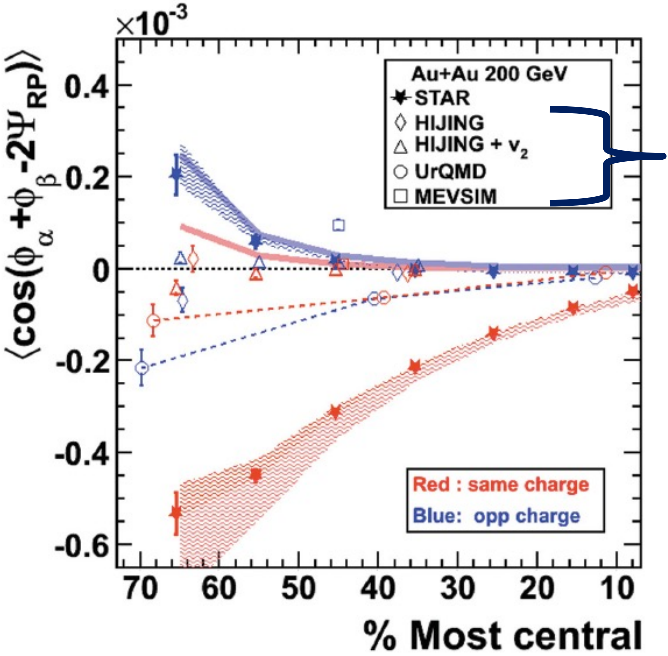
PHYSICAL REVIEW LETTERS

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

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

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

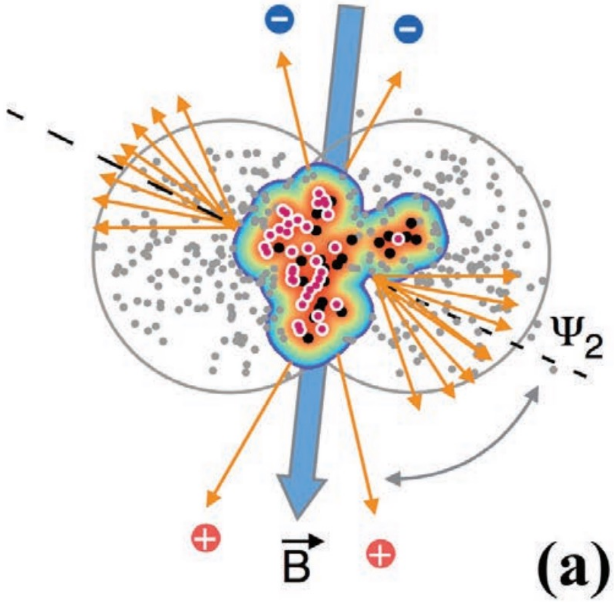
NB: P-even quantity (strength of P-odd fluctuations) – subject to large background contributions

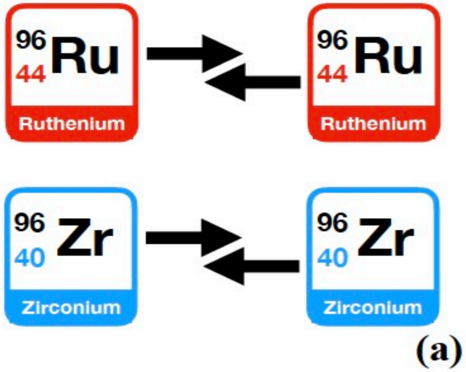
Review: DK, J. Liao, S. Voloshin, G. Wang, Prog.Part.Nucl.Phys.(2016)

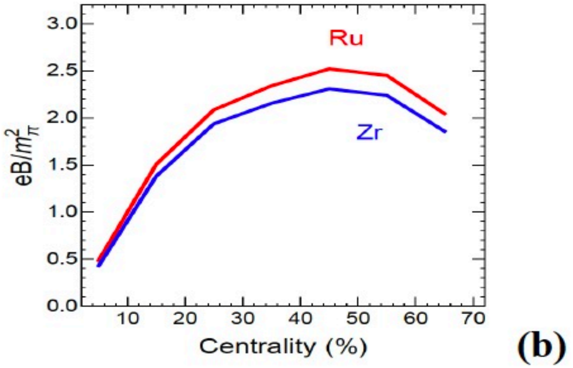
Separating the signal from background is the main subject of the ongoing work –

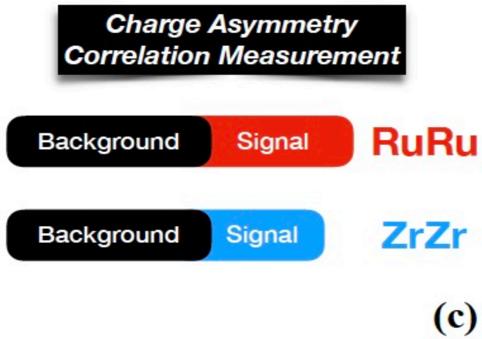
Big new development: the isobar run, results to follow!

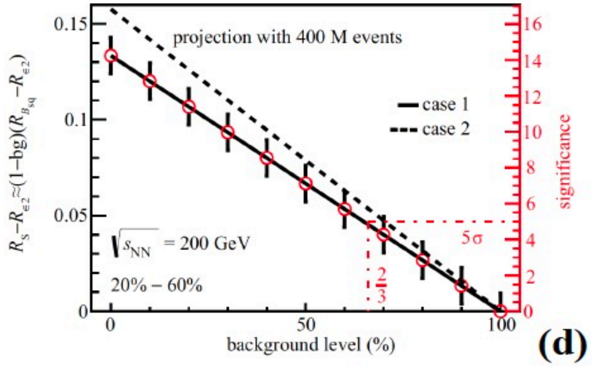
Isobars: same shape = same background, different Z = different magnetic field – change in signal?











STAR Collaboration