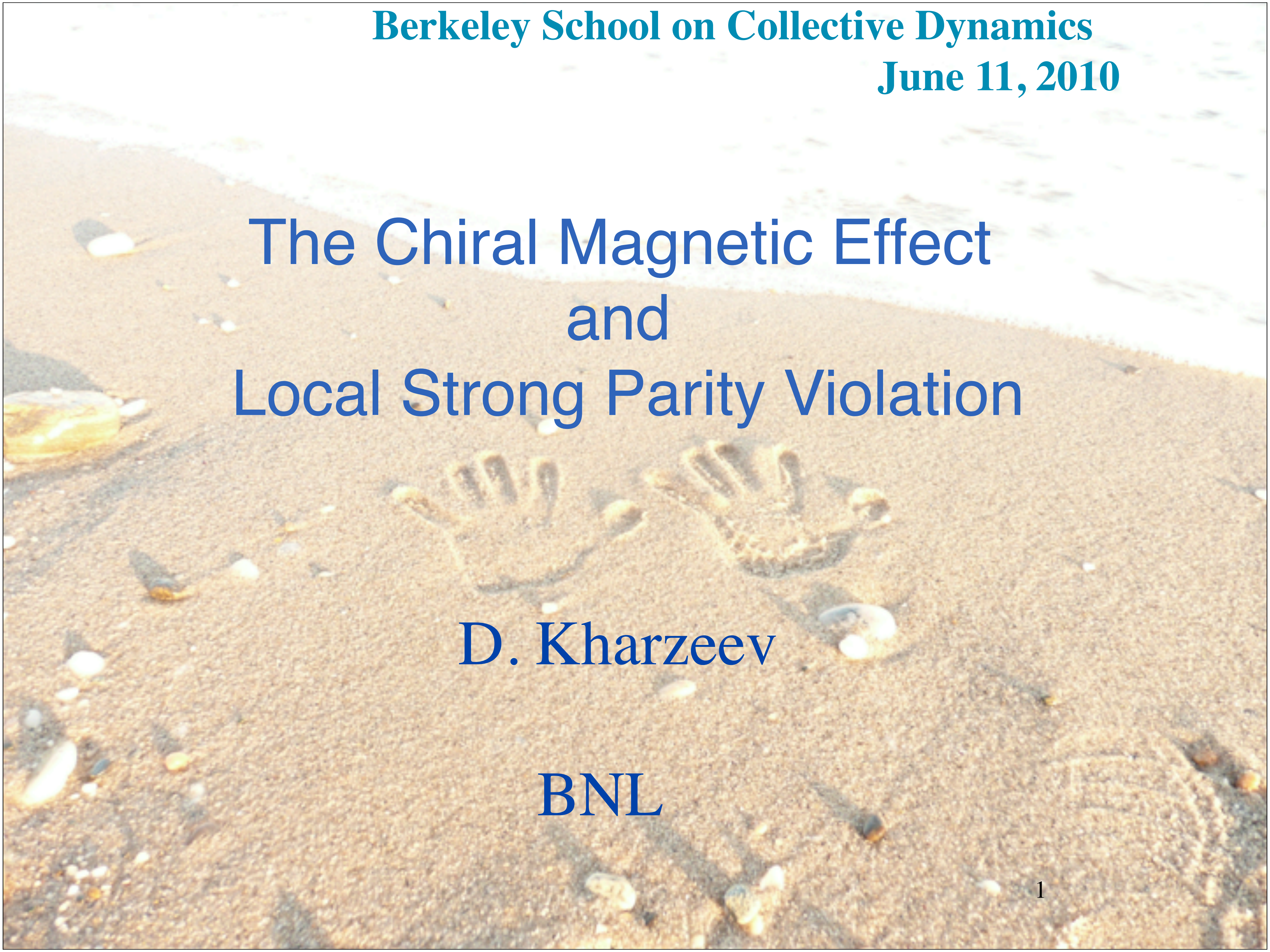
Berkeley School on Collective Dynamics
June 11, 2010



The Chiral Magnetic Effect and Local Strong Parity Violation

D. Kharzeev

BNL

Outline

- QCD topology and the “strong CP problem”
- Chiral Magnetic Effect (CME)
  and local P and CP violation (LPV)
  in hot QCD
- CME in the chirally broken phase:
  the Chiral Magnetic Spiral
- A new spin-off: P-odd effects in
  polarized quark fragmentation

Based on:

DK, hep-ph/0406125 (PLB)

DK, A. Zhitnitsky, arXiv: 0706.1026 (NPA)

DK, L. McLerran, H. Warringa, arXiv:0711.0950 (NPA)

K. Fukushima, DK, H. Warringa, arXiv: 0808.3382 (PRD); 0912.2961 (NPA); 1002.2495 (PRL)

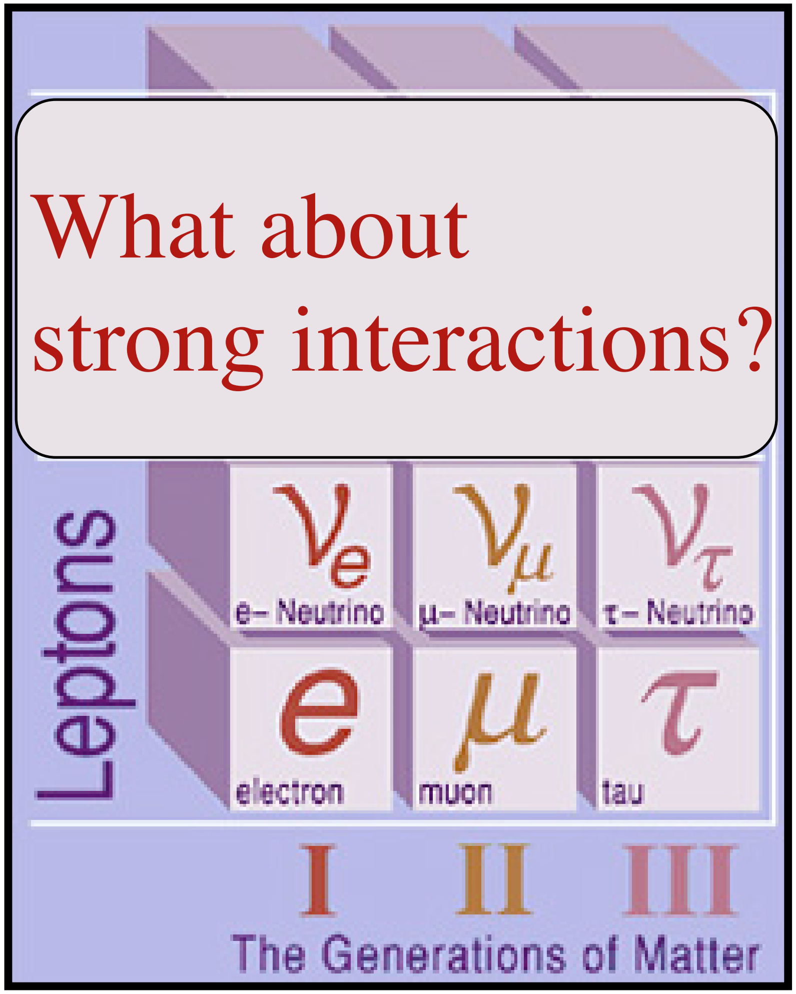
DK, H. Warringa, arXiv: 0907.5007 (PRD)

DK, arXiv: 0911.3715 (Ann. Phys.)

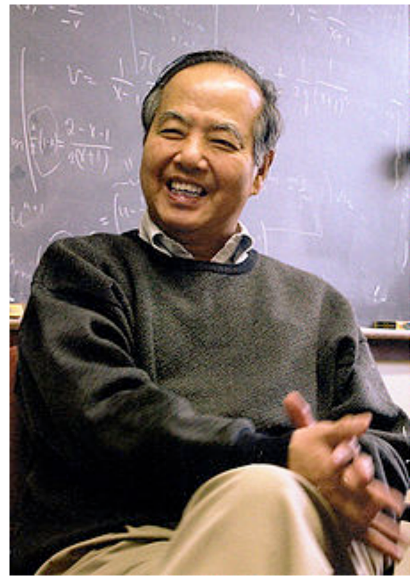
G. Basar, G. Dunne, DK, arXiv: 1003.3464 (PRL)

Z. Kang, DK, arXiv:1006.2132 (today)

P and CP invariances are violated by weak interactions



What about strong interactions?



T.D.Lee

C.N.Yang

1957

CP violation J.W.Cronin, V.L.Fitch

1980

Complex CKM mass matrix

Y. Nambu, M. Kobayashi, T. Maskawa

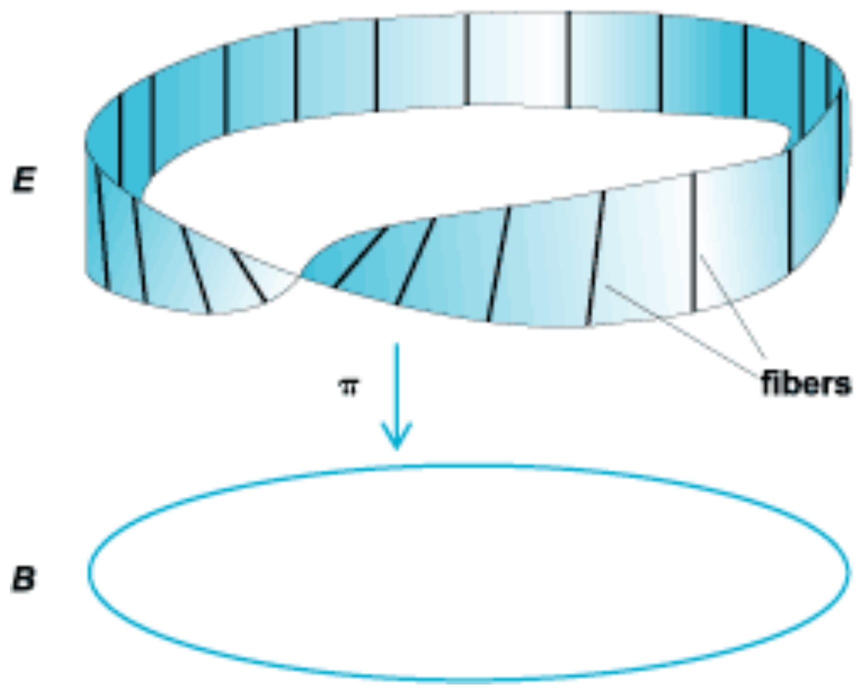
2008

Very strict experimental limits exist on the amount of global violation of P and CP invariances in strong interactions (mostly from electric dipole moments)

But: P and CP conservation in QCD is by no means a trivial issue...

Can a local P and CP violation occur in QCD matter?

Gauge fields and topology



Möbius strip, the simplest nontrivial example of a fiber bundle

Gauge theories "live" in a fiber bundle space that possesses non-trivial topology (knots, links, twists,...)

Characteristic forms and geometric invariants

Annals of Mathematics, 1974

By SHIING-SHEN CHERN AND JAMES SIMONS*

1. Introduction

This work, originally announced in [4], grew out of an attempt to derive a purely combinatorial formula for the first Pontrjagin number of a 4-manifold. The hope was that by integrating the characteristic curvature form (with respect to some Riemannian metric) simplex by simplex, and replacing the integral over each interior by another on the boundary, one could evaluate these boundary integrals, add up over the triangulation, and have the geometry wash out, leaving the sought after combinatorial formula. This process got stuck by the emergence of a boundary term which did not yield to a simple combinatorial analysis. The boundary term seemed interesting in its own right and it and its generalization are the subject of this paper.

Topology and Chern-Simons forms

6. Applications to 3-manifolds

In this section M will denote a compact, oriented, Riemannian 3-manifold, and $F(M) \xrightarrow{\pi} M$ will denote its $SO(3)$ oriented frame bundle equipped with the Riemannian connection θ and curvature tensor Ω. For A, B skew symmetric matrices, the specific formula for P_1 shows $P_1(A \otimes B) = -(1/8\pi^2)\operatorname{tr} AB$. Calculating from (3.5) shows

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\}\,. \quad (6.1)$$

What does it mean for a gauge theory?

Chern-Simons theory

CHARACTERISTIC FORMS

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\} . \qquad (6.1)$$

What does it mean for a gauge theory?

Geometry ⟷ Physics

Riemannian connection ⟷ Gauge field

Curvature tensor ⟷ Field strength tensor

$$S_{CS} = \frac{k}{8\pi}\int_M d^3x\ \epsilon^{ijk}\left(A_i F_{jk} + \frac{2}{3}A_i[A_j, A_k]\right)$$

Abelian non-Abelian

Chern-Simons theory

$$S_{CS} = \frac{k}{8\pi}\int_M d^3x\ \epsilon^{ijk}\left(A_i F_{jk} + \frac{2}{3}A_i[A_j, A_k]\right)$$

Remarkable novel properties:

- gauge invariant, up to a boundary term
- topological - does not depend on the metric, knows only about the topology of space-time **M**
- when added to Maxwell action, induces a mass for the gauge boson - different from the Higgs mechanism!
- **breaks Parity invariance**

Chern-Simons theory and the vacuum of Quantum Chromodynamics

Equation:

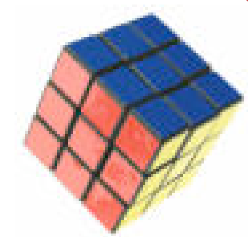
$$D^{\mu} F^{a}_{\mu\nu} = 0$$

Belavin, Polyakov, Tyupkin, Schwartz;
tunneling events:
't Hooft; Gribov;....

Solution:

$$A^a_\mu(x) = \frac{2\eta_{a\mu\nu}x_\nu}{x^2+\rho^2}.$$

Coupling of space-time and color:

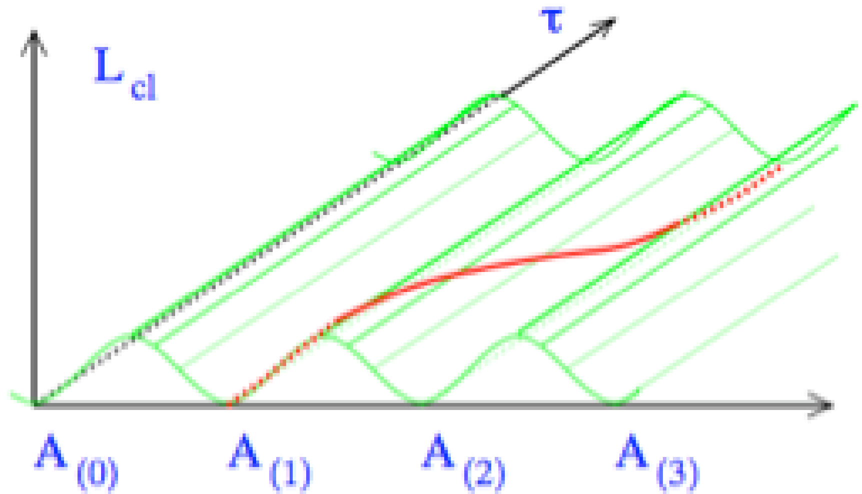


Integer $\quad Q = \int d\sigma_\mu K_\mu$

$$\eta_{a\mu\nu} = \begin{cases} \epsilon_{a\mu\nu} & \mu,\nu = 1,2,3, \\ \delta_{a\mu} & \nu = 4, \\ -\delta_{a\nu} & \mu = 4. \end{cases}$$

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

QCD vacuum as a Bloch crystal



"θ - vacuum"

$$|\theta\rangle = \sum_q e^{i\theta q}|q\rangle$$

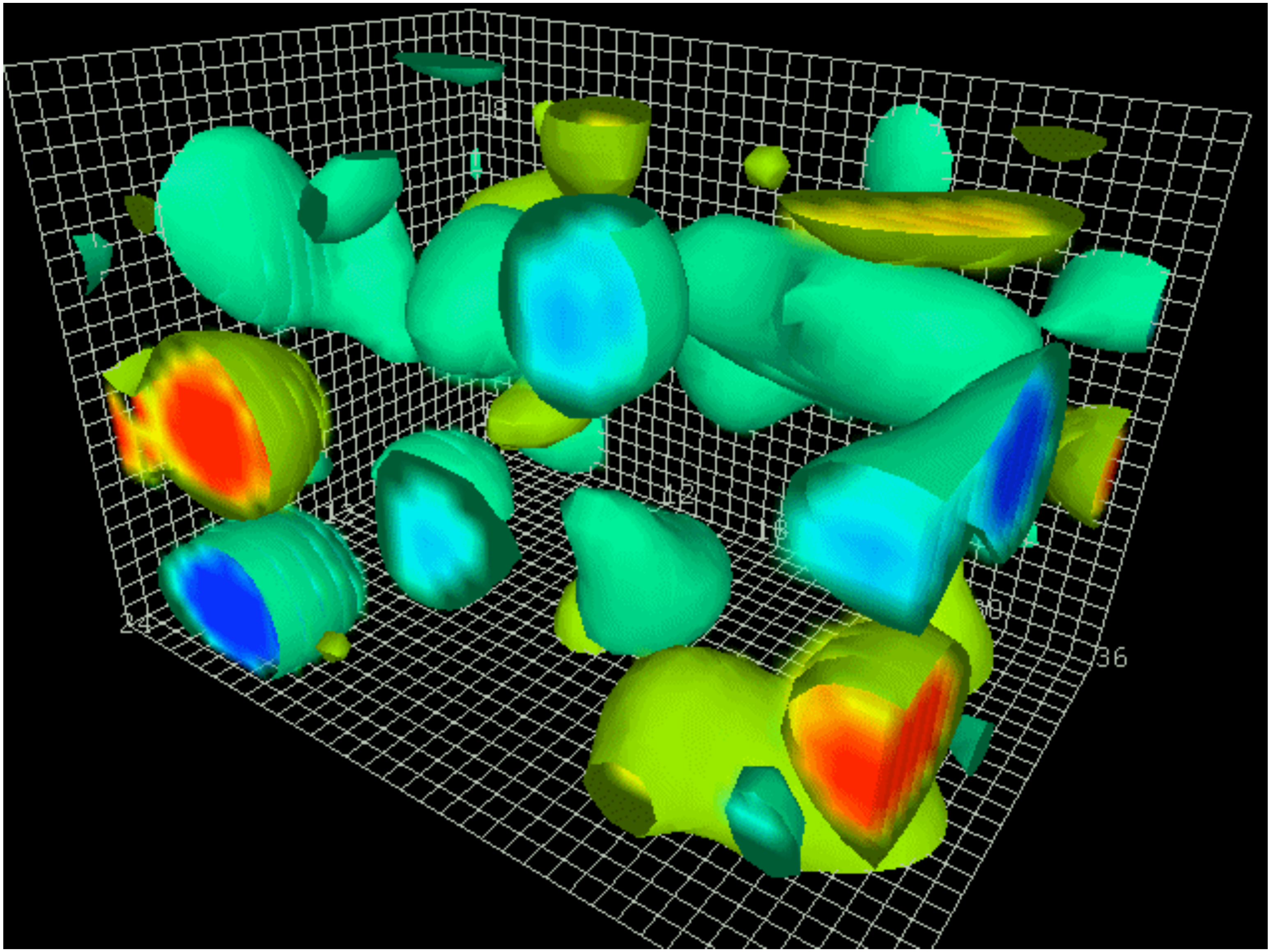
$$\langle\mathcal{O}\rangle = \sum_q f(q)\int_q D[\psi]D[\bar{\psi}]D[A]\exp(iS_{QCD})\mathcal{O}(\psi,\bar{\psi},A)$$

$$f(q_1+q_2) = f(q_1)f(q_2) \longrightarrow f(q) = \exp(i\theta q)$$

85

"quasi-momentum" "coordinate"

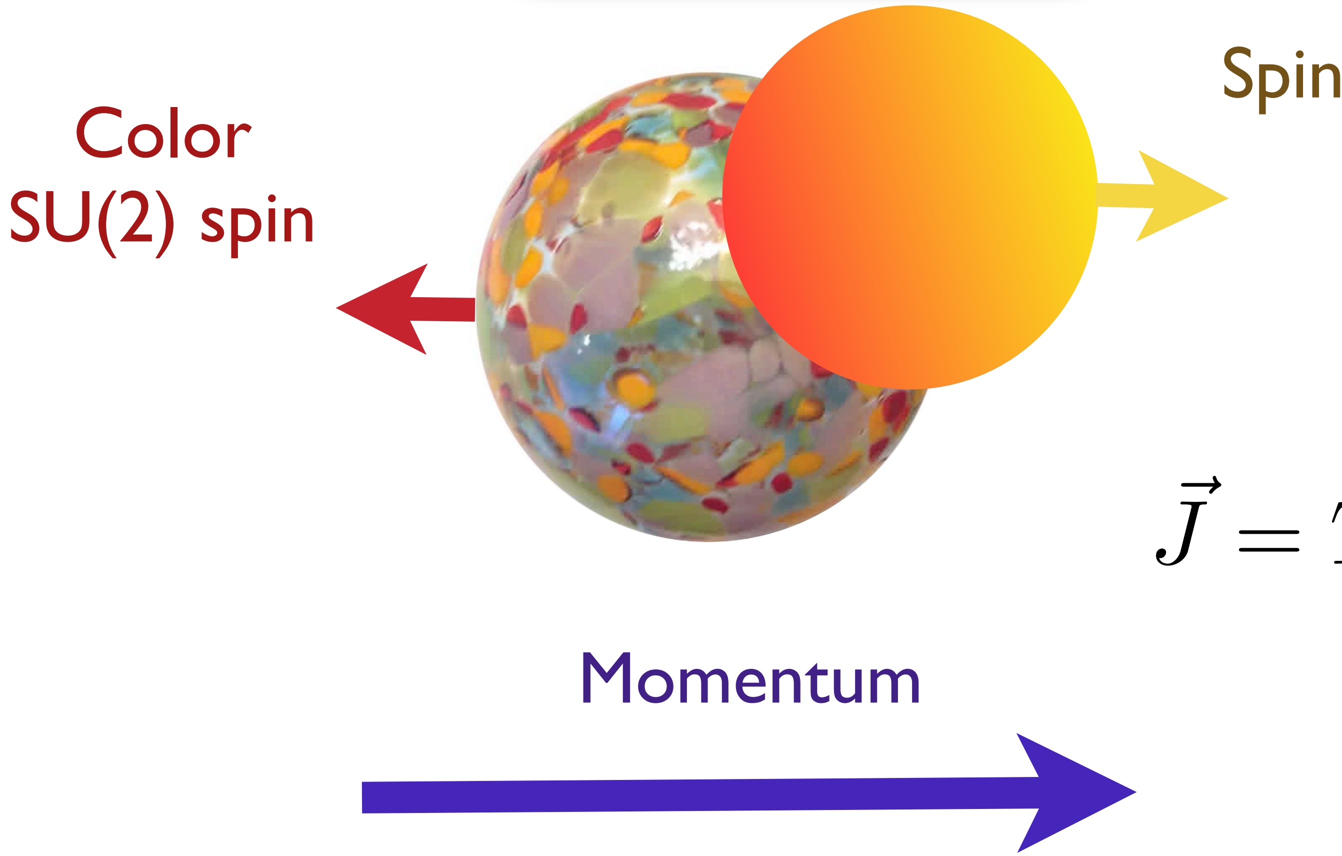
Topological number fluctuations in QCD vacuum



D. Leinweber

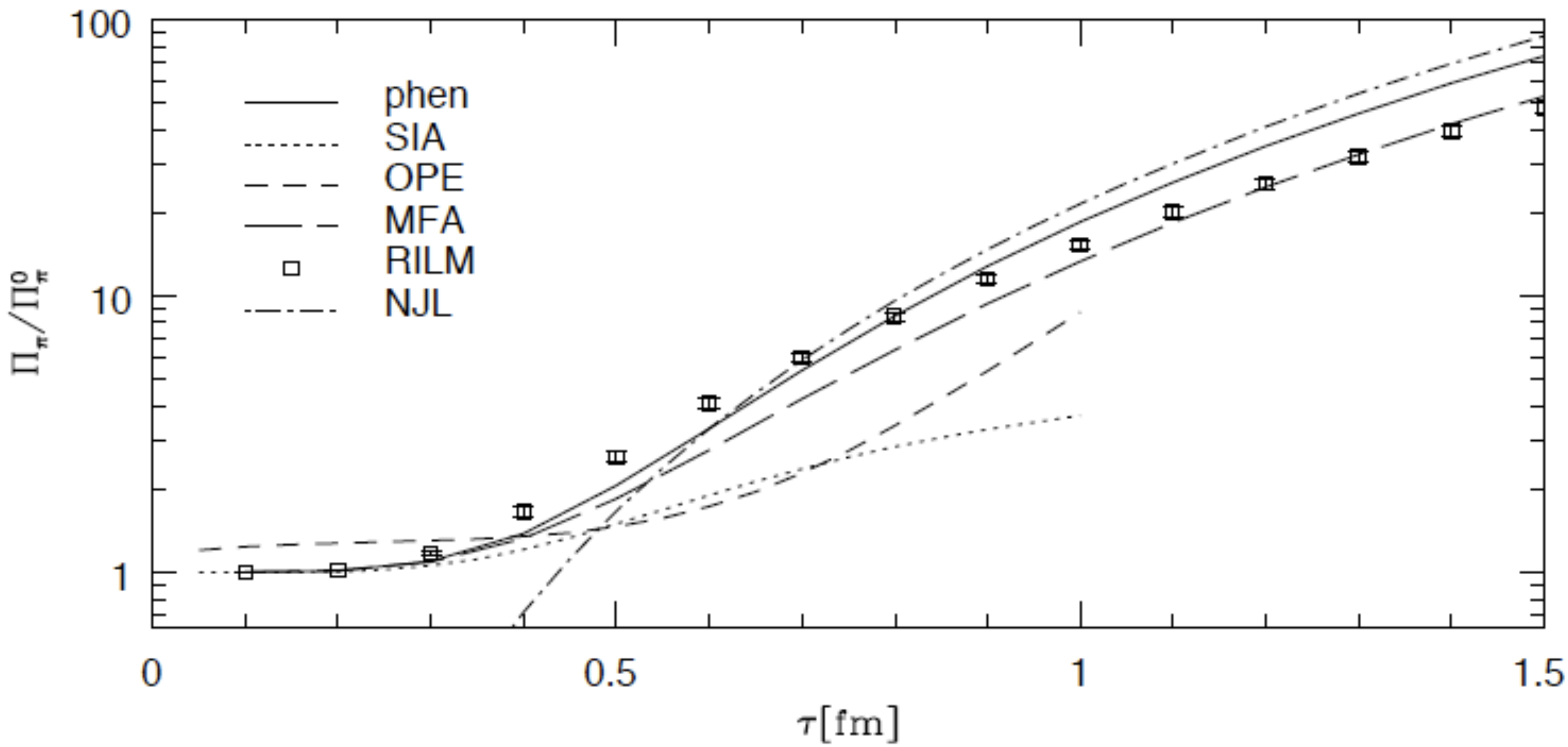
Topology-induced change of chirality

Right ↔ Left



$$\vec{J} = \vec{T} + \vec{S}$$

Extensive role of topological effects in the properties of hadrons

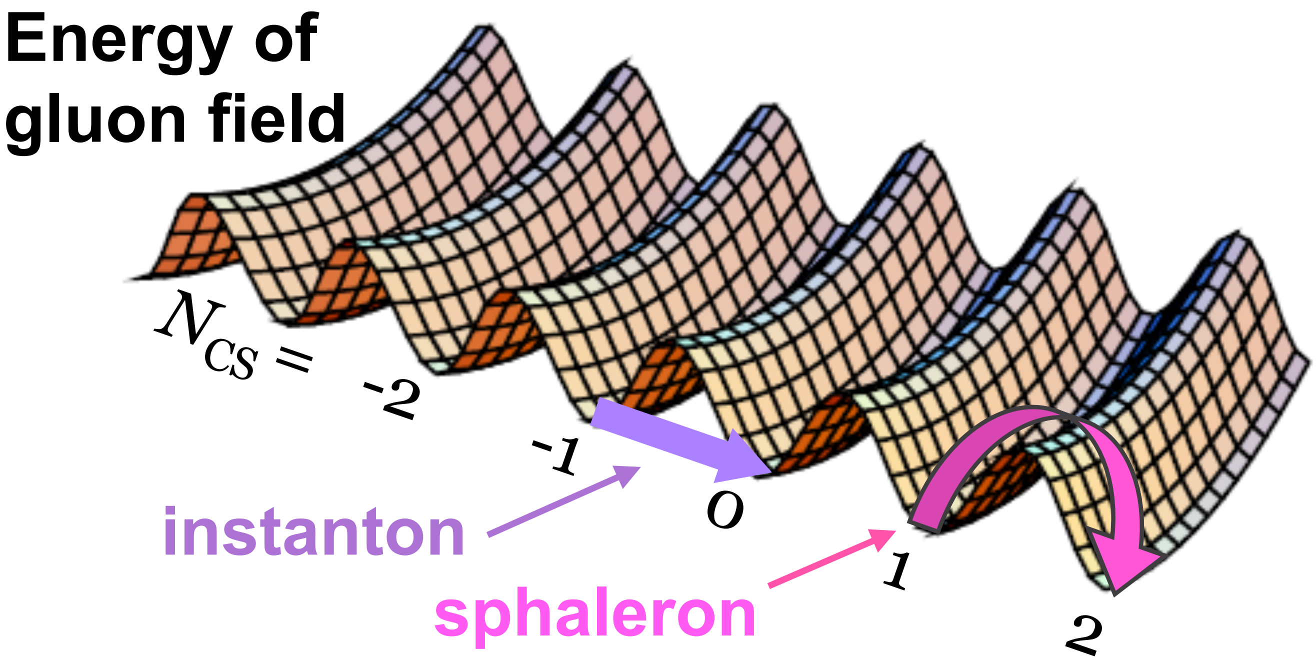


Instantons solve the η' puzzle, explain why the pion is so light, etc

T. Schafer and E.Shuryak, Rev. Mod. Phys. 70 (1998) 323

Sphaleron transitions at finite energy or temperature

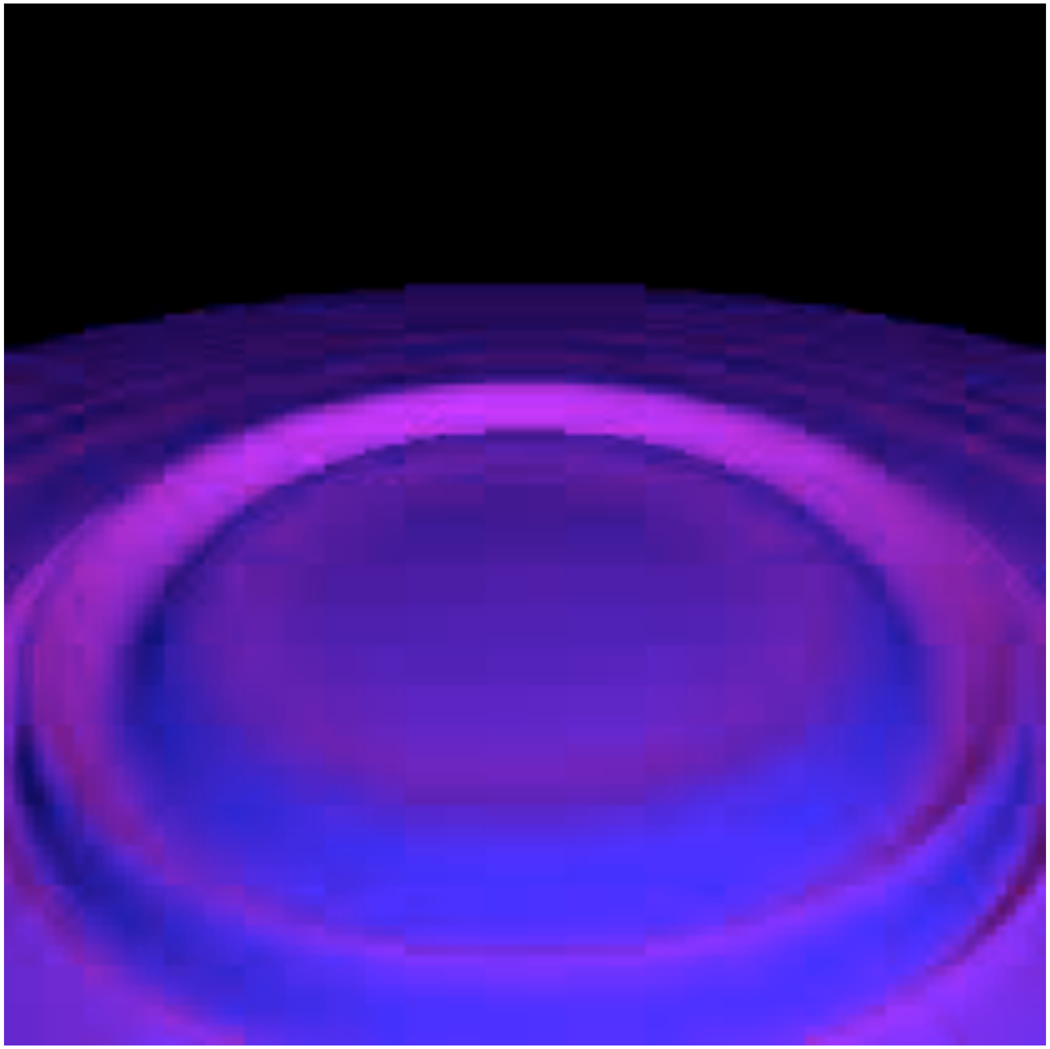
$$\Gamma = \frac{1}{2} \lim_{t\to\infty} \lim_{V\to\infty} \int_0^t \langle (q(x)q(0) + q(0)q(x)) \rangle d^4x$$



Sphalerons:
random walk of
topological charge at finite T:

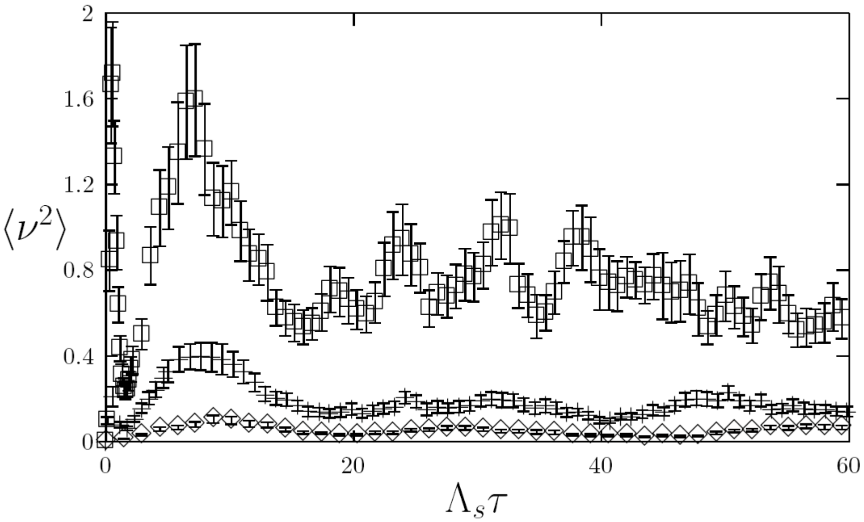
$$\langle Q^2 \rangle = 2\Gamma V t, \quad t \to \infty$$

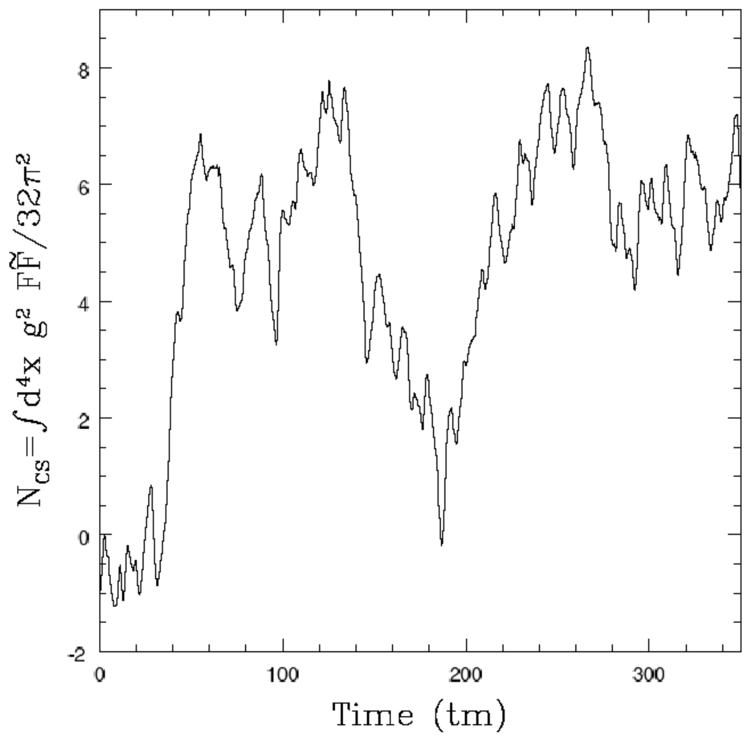
Sphaleron transitions at finite energy or temperature



C. Rebbi, http://scv.bu.edu/visualization/gallery

Diffusion of Chern-Simons number in QCD: real time lattice simulations

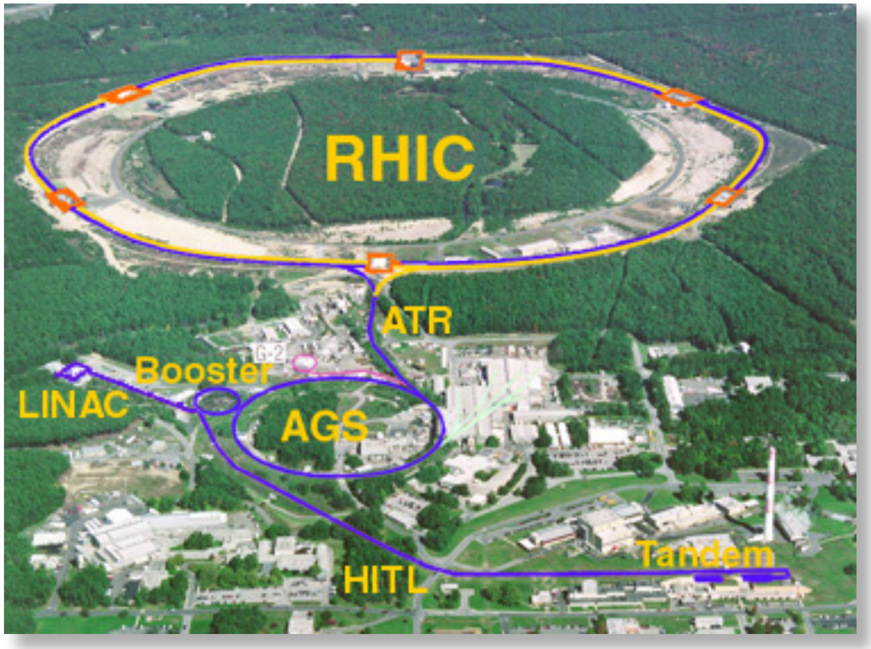


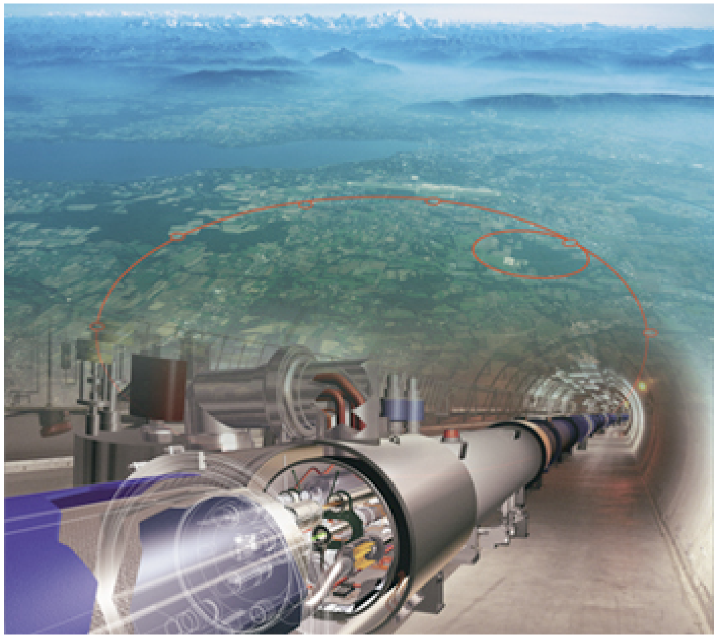


DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002

P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

Experimental test of Chern-Simons dynamics in hot QCD: Heavy ion collisions



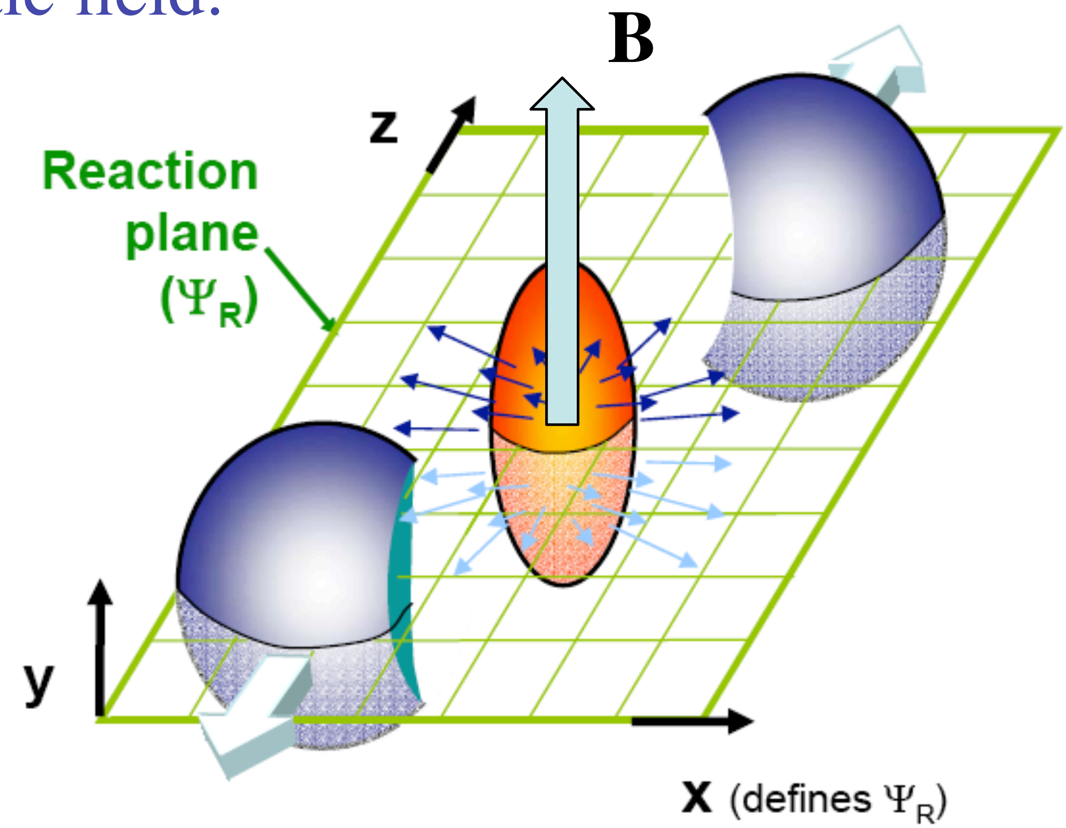


LHC

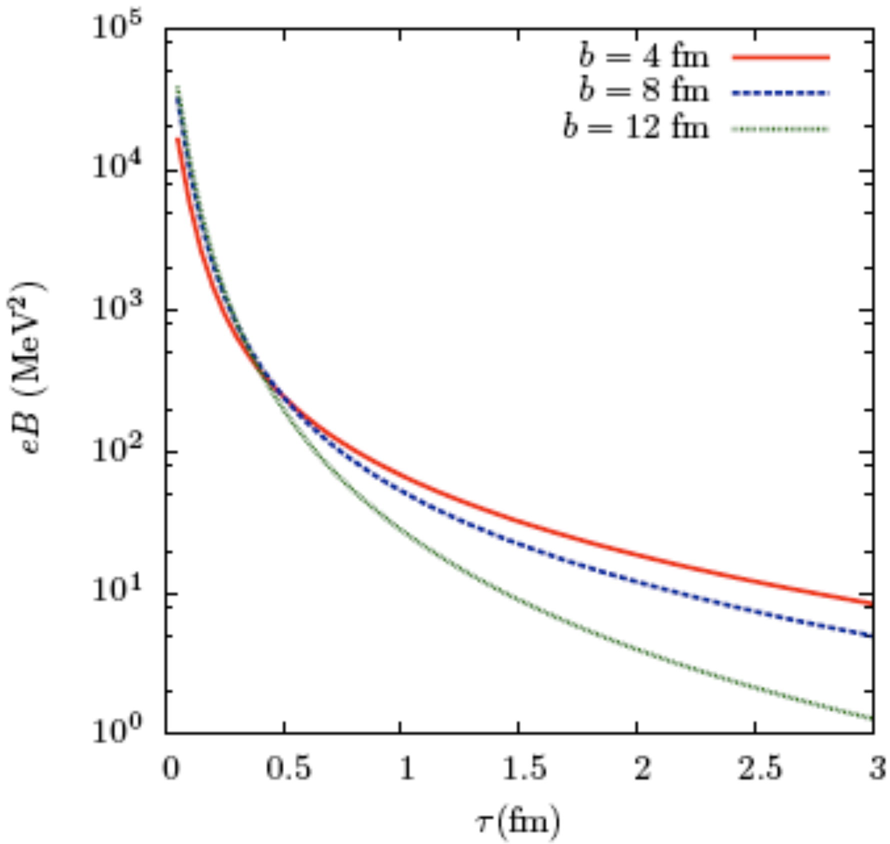
NICA,
JINR

Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create
a strong magnetic field:



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



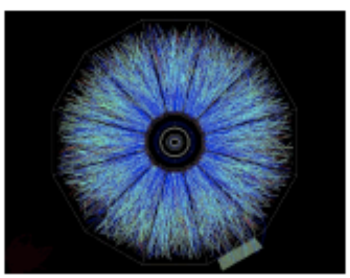
DK, McLerran, Warringa,
Nucl Phys A803(2008)227

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 ($Y_0 = 5.4$).

Comparison of magnetic fields

The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$eB(\tau=0.2\,\text{fm}) = 10^3 \sim 10^4\ \text{MeV}^2 \sim 10^{17}\ \text{Gauss}$$

From QCD back to electrodynamics: Maxwell-Chern-Simons (axion) theory

$$\mathcal{L}_{\mathrm{MCS}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu J^\mu + \frac{c}{4}\, P_\mu J^\mu_{CS}$$

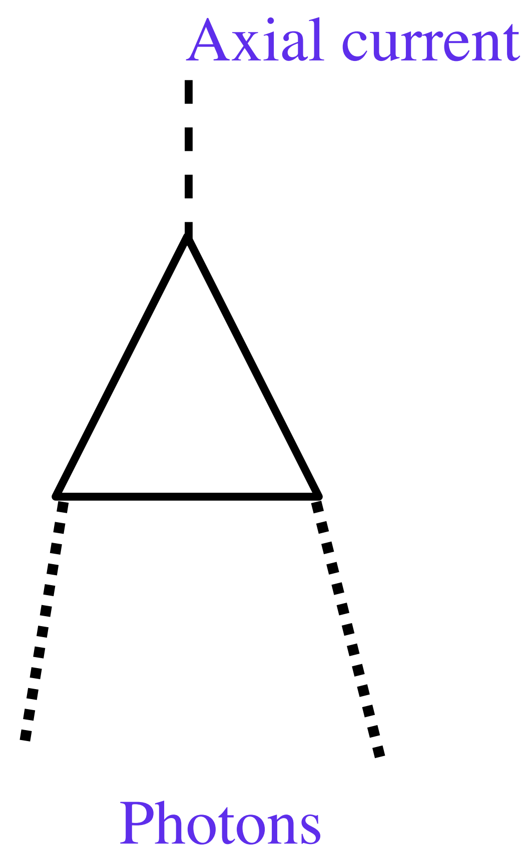
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu \theta = (\dot{\theta}, \vec{P})$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + \underline{c\left(\dot{\theta}\vec{B} - \vec{P} \times \vec{E}\right)},$$

$$\vec{\nabla} \cdot \vec{E} = \rho + \underline{c\vec{P} \cdot \vec{B}},$$

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0,$$

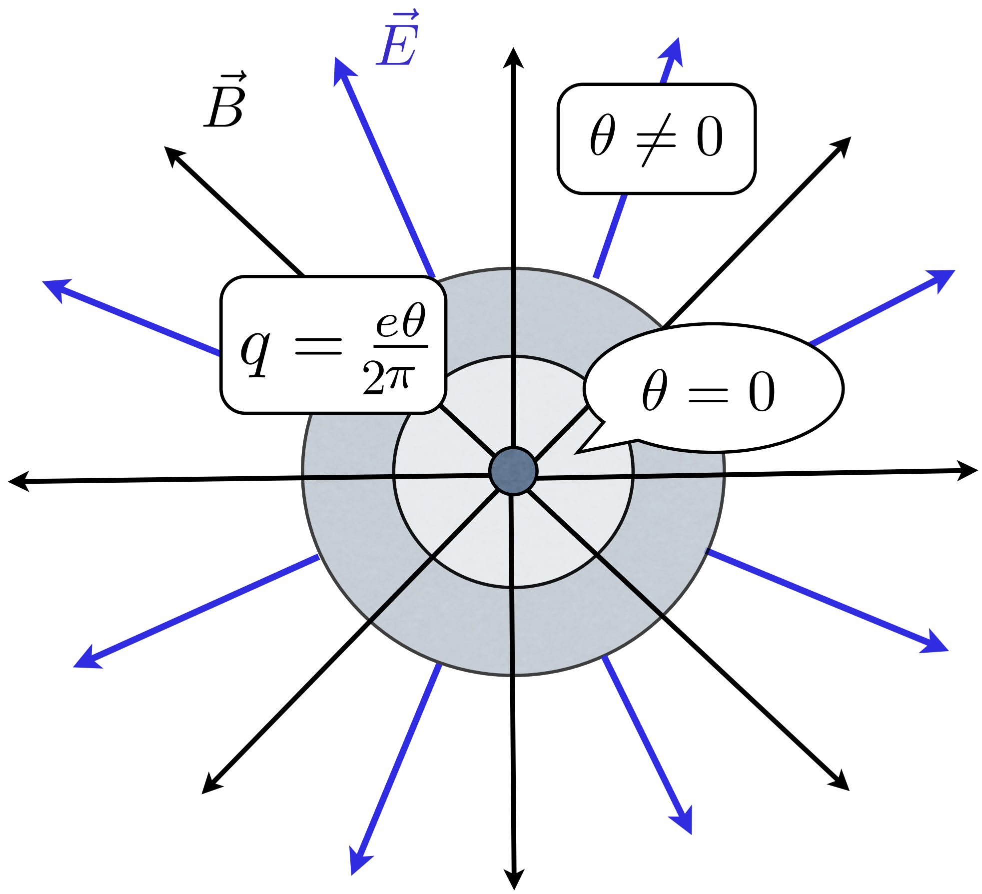
$$\vec{\nabla} \cdot \vec{B} = 0,$$



Magnetic monopole at finite θ : the Witten effect

$$\vec{\nabla}\cdot\vec{E} = \rho + c\vec{P}\cdot\vec{B}$$

$$\vec{P} \equiv \vec{\nabla}\theta$$



E. Witten;

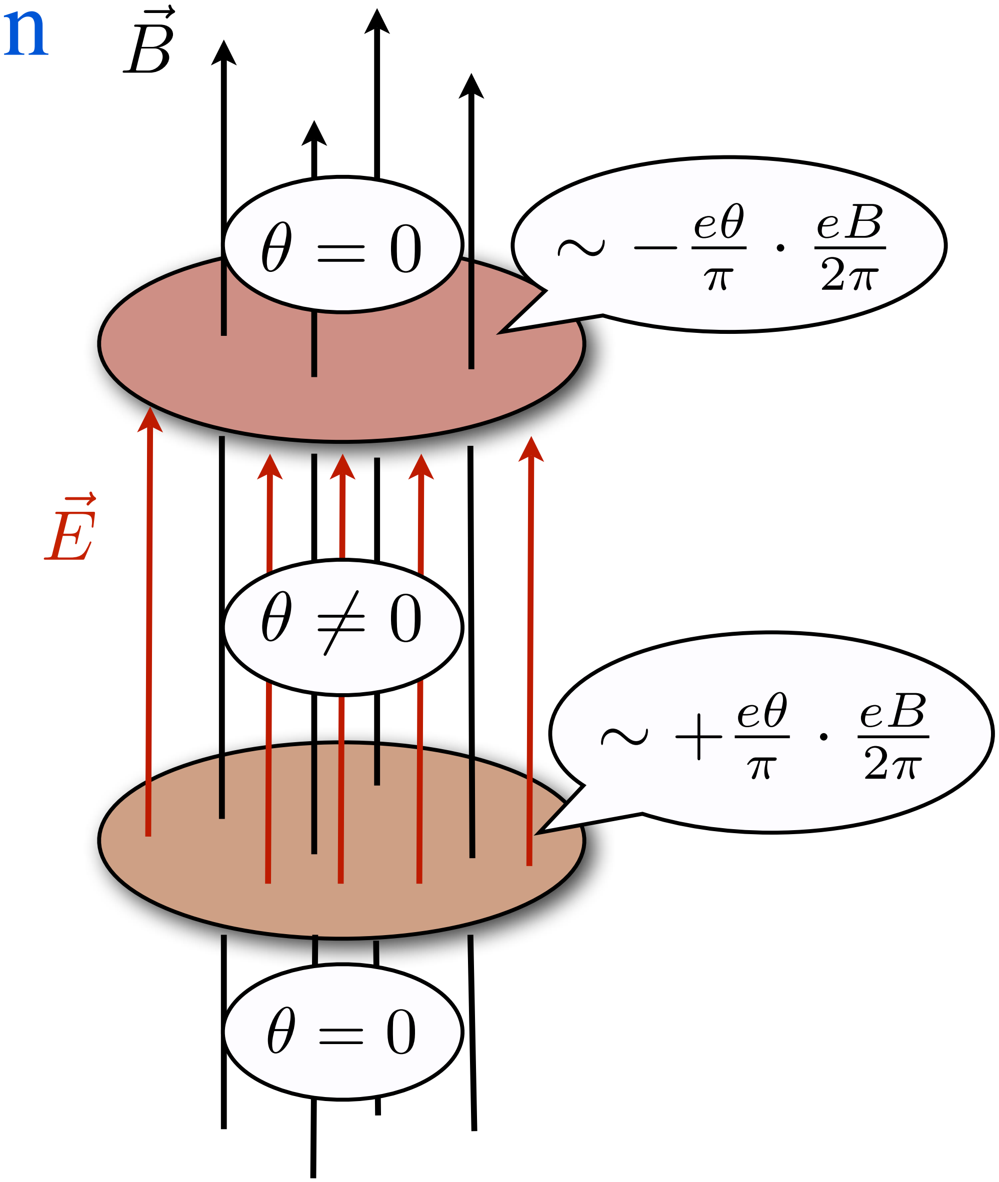
F. Wilczek

Induced electric charge: $q = c\,\theta\,g = \frac{e^2}{2\pi^2}\,\theta\,g = \frac{e}{2\pi^2}\,\theta\,(eg) = e\,\frac{\theta}{2\pi}$

The Chiral Magnetic Effect I: Charge separation

$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B}$$

$$\vec{P} \equiv \vec{\nabla}\theta$$

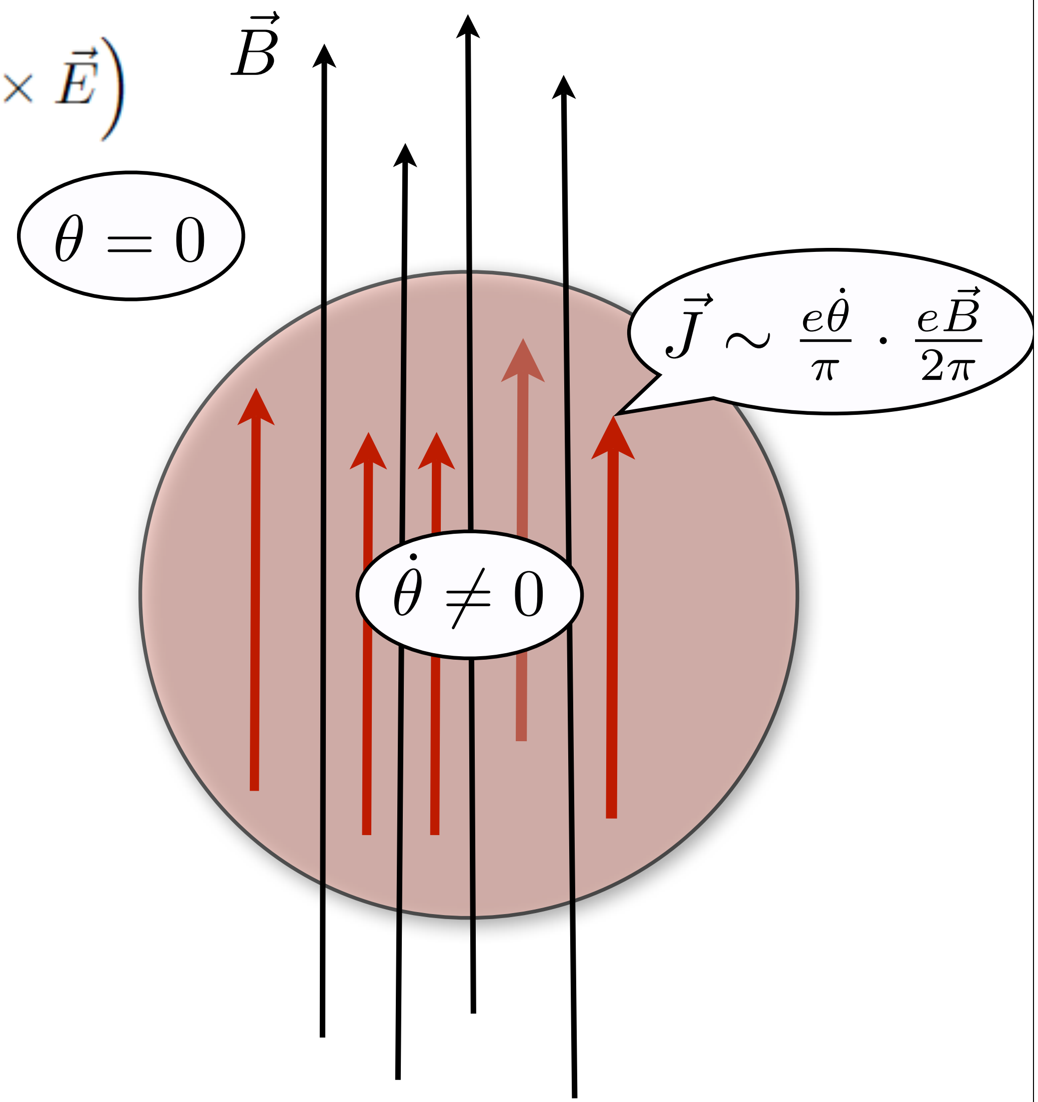


$$d_e = \sum_f q_f^2 \left(e \, \frac{\theta}{\pi}\right) \left(\frac{eB \cdot S}{2\pi}\right) L$$

DK '04;
DK, A. Zhitnitsky '06;
DK arXiv:0911.3715; Annals of Physics (2010)

The chiral magnetic effect II: chiral induction

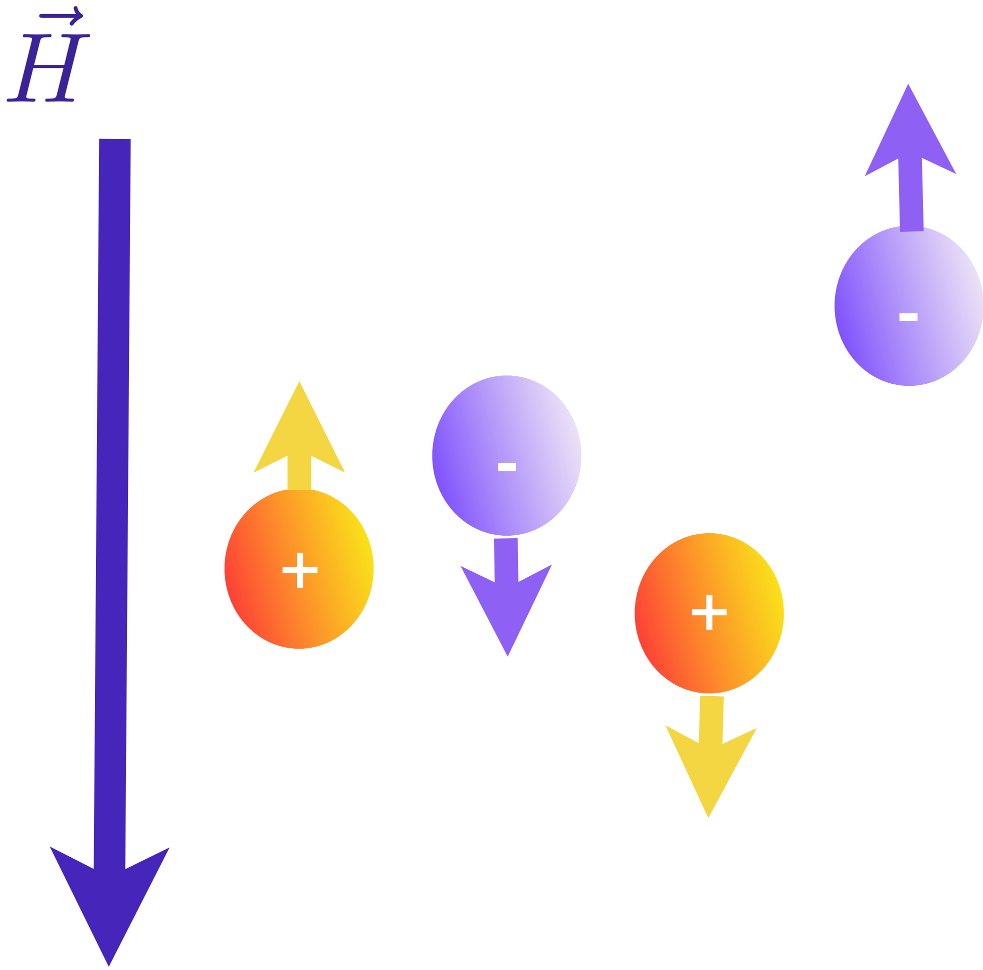
$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(\dot{\theta}\vec{B} - \vec{P} \times \vec{E}\right)$$



$$\vec{J} = -\frac{e^2}{2\pi^2}\dot{\theta}\vec{B}$$

DK, L. McLerran, H. Warringa '07;
K. Fukushima, DK, H. Warringa '08;
DK, H.Warringa arXiv:0907.5007

The Chiral Magnetic Effect



Let all fermions
be right-handed,
$Q = N_R - N_L > 0$

this means the spin
is parallel to momentum.

Magnetic field pins down
the directions of spins
and thus induces
an electric current

Computing the induced current

Fukushima, DK, Warringa, '08

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

In this background, vector e.m. current is not conserved:

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

Compute the current through

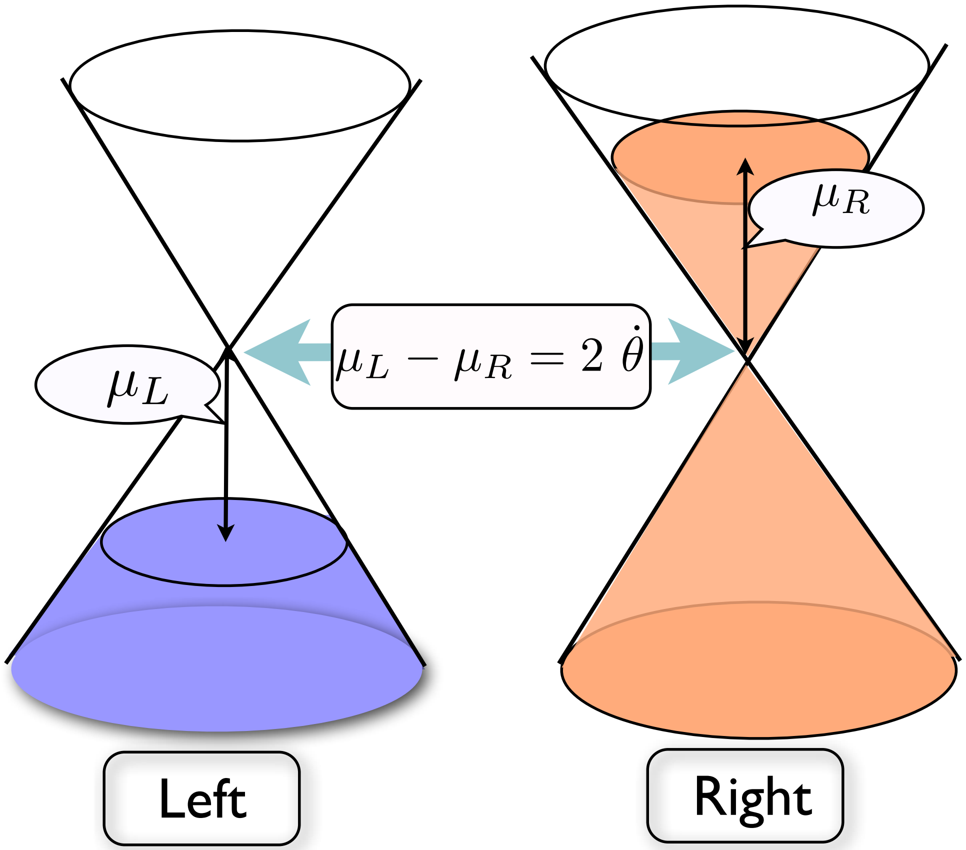
$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

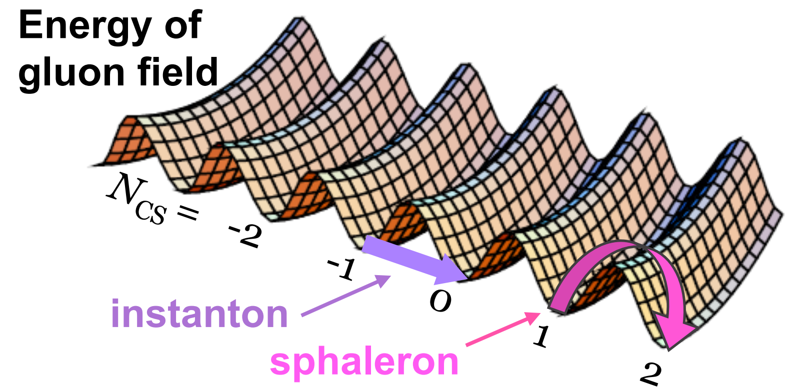
The result:

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

Coefficient is fixed by the axial anomaly, no corrections

What powers the CME current?



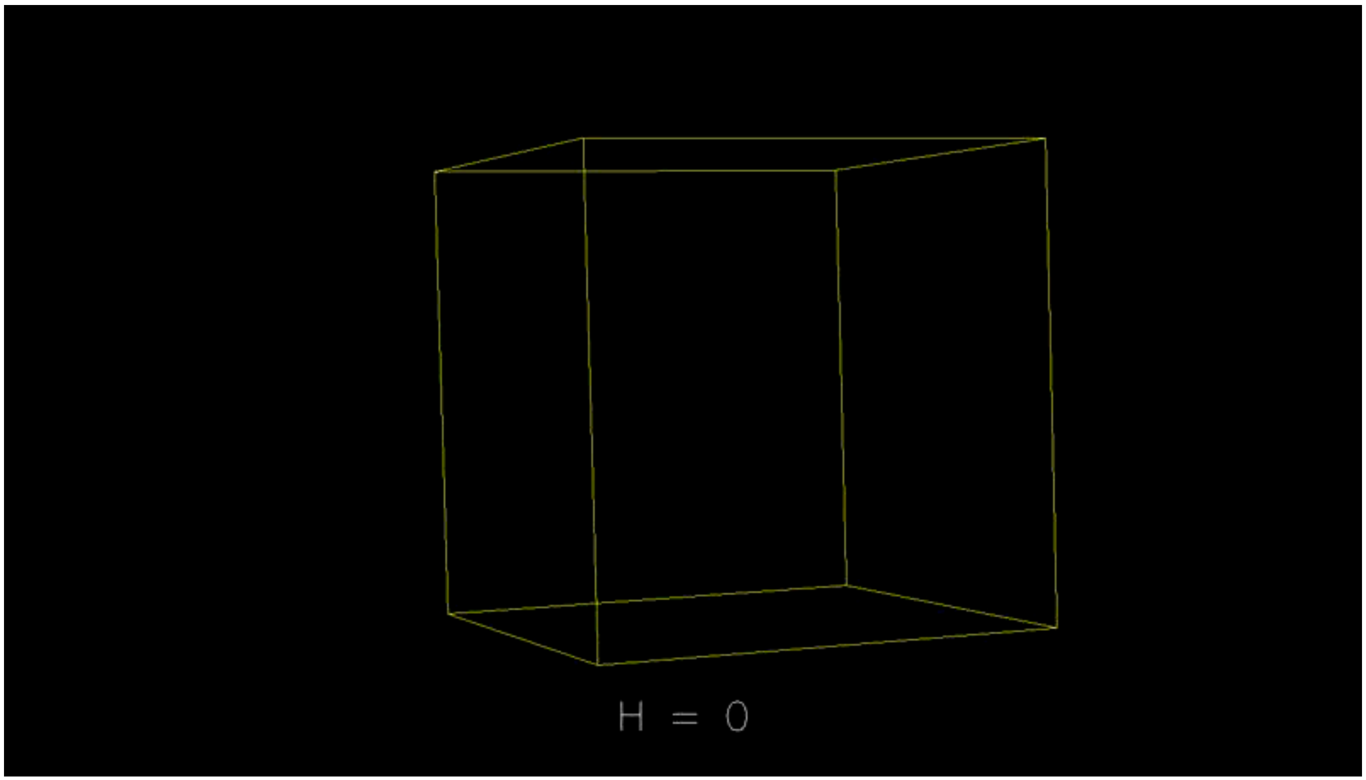


$$\text{Power} = \text{Force} \times \text{Velocity}$$

$$P = \int d^3x\ \vec{J} \cdot \vec{E} = -\dot{\theta}\ \frac{e^2}{2\pi^2} \int d^3x\ \vec{E} \cdot \vec{B} = -\dot{\theta}\ \dot{Q}_5$$

“Numerical evidence for chiral magnetic effect in lattice gauge theory”,

P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov, ArXiv 0907.0494; PRD’09



Red - positive charge
Blue - negative charge

SU(2) quenched, Q = 3; Electric charge density (H) - Electric charge density (H=0)

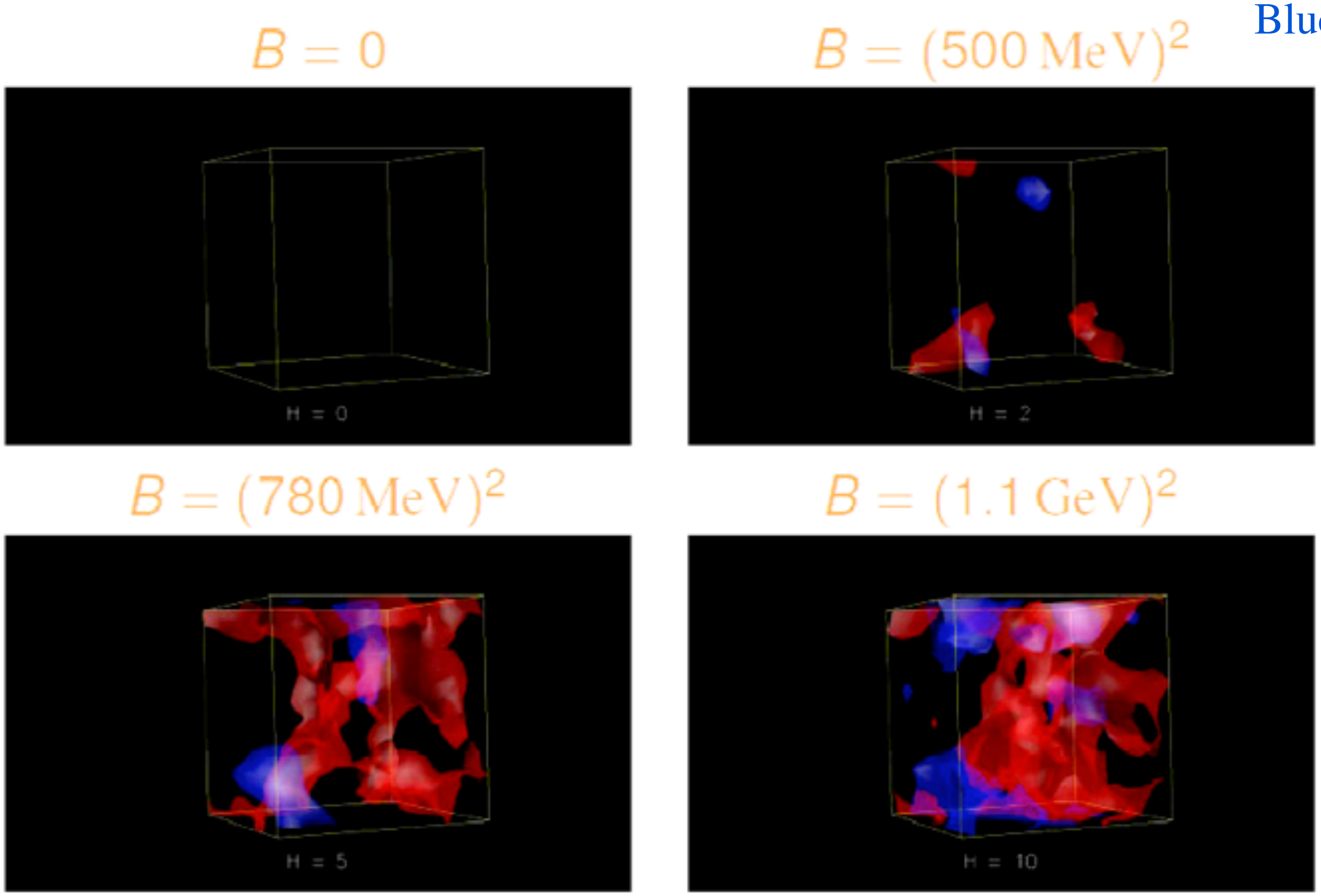
“Numerical evidence for chiral magnetic effect in lattice gauge theory”,

P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov, ArXiv 0907.0494; PRD’09

Density of the electric charge vs. magnetic field, 3D time slices

Red - positive charge

Blue - negative charge

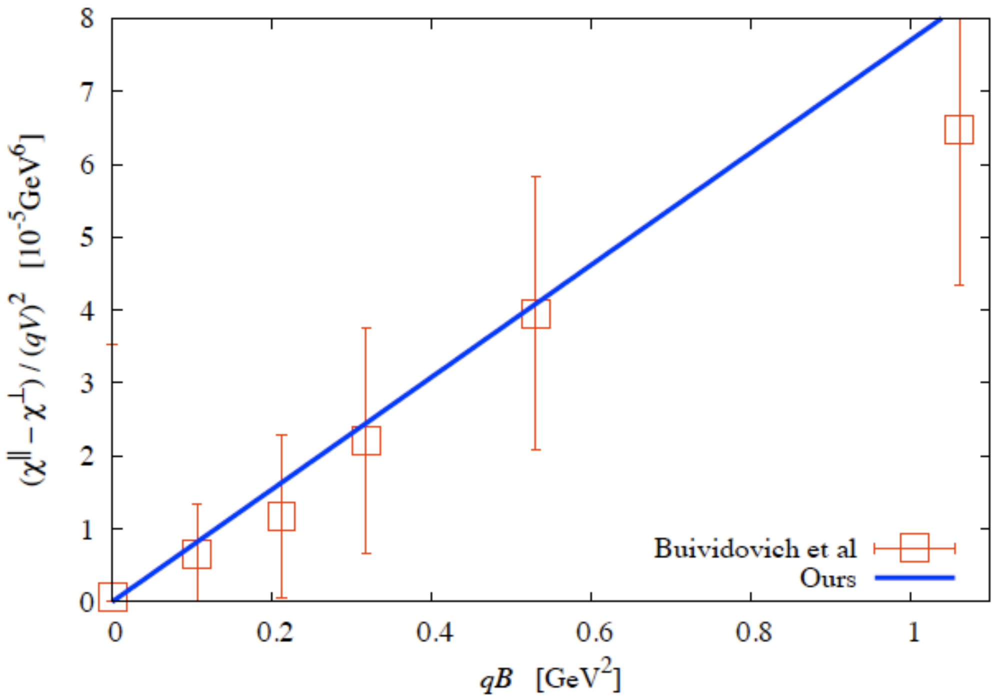


note:
B has to be measured in units of the pion mass^2 !

Electric current susceptibility

$$\cos(\Delta\phi_\alpha + \Delta\phi_\beta) \propto \frac{\alpha\beta}{N_\alpha N_\beta}\left(J_\perp^2 - J_\parallel^2\right)$$

K.Fukushima, DK,
H. Warringa, arXiv:0912.2961



The fluctuations of electric current in magnetic background are anisotropic, the difference of susceptibilities is UV finite.

Lattice data are well reproduced theoretically.

$$\chi_{\mu_5}^\parallel - \chi_{\mu_5}^\perp = VTN_c \sum_{f,s} \frac{q_f^2|q_f B|}{4\pi^2} \frac{\Lambda}{\omega_{\Lambda\lambda}} \left(1 + \frac{s\mu_5}{\Lambda}\right)\left[1 - n_F(\omega_{\Lambda\lambda}) - \bar{n}_F(\omega_{\Lambda\lambda})\right]$$

$$\xrightarrow[\Lambda\to\infty]{} VTN_c \sum_f \frac{q_f^2|q_f B|}{2\pi^2}.$$

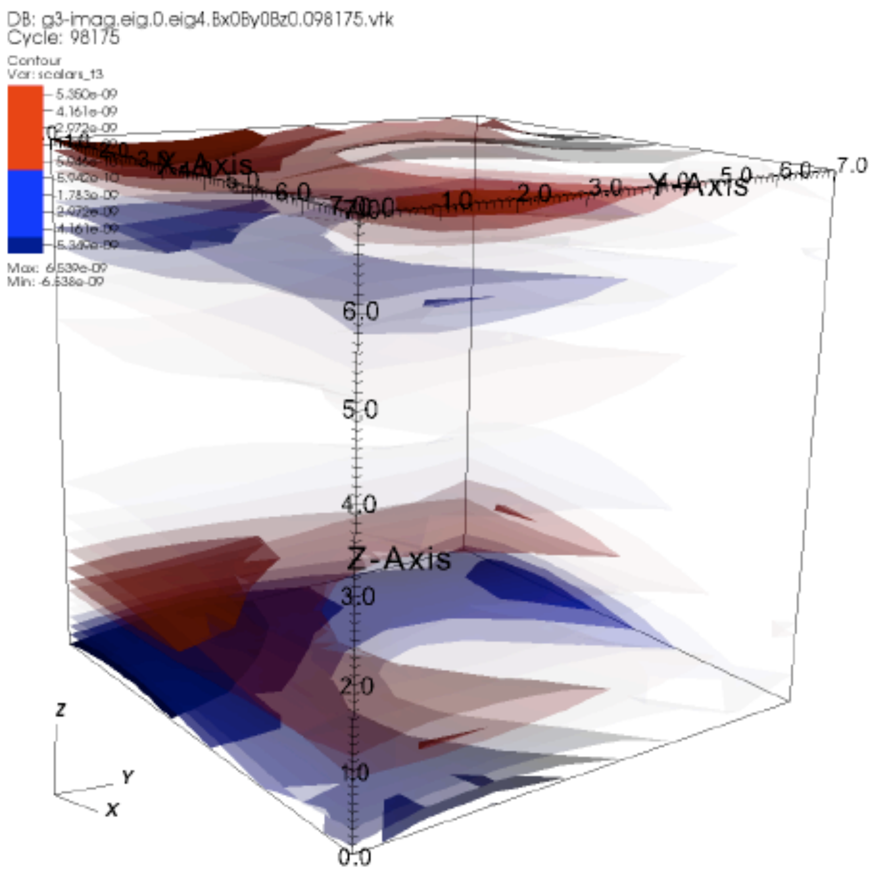
AdS/CFT calculation of susceptibility:
A.Krikun, arXiv:1003.1041

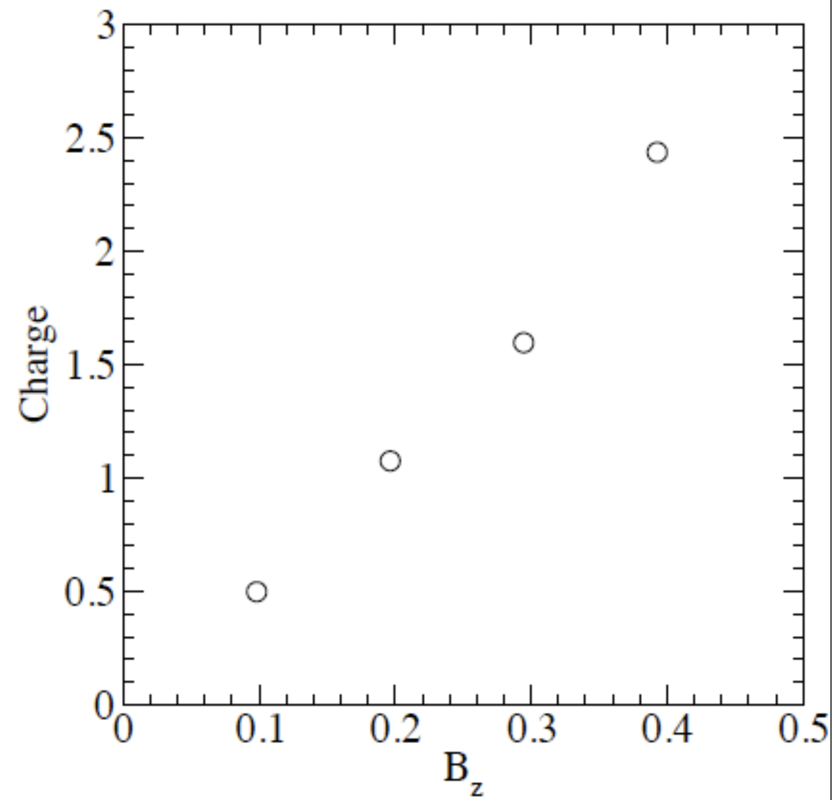
“Chiral magnetic effect in 2+1 flavor QCD+QED”,

M. Abramczyk, T. Blum, G. Petropoulos, R. Zhou, ArXiv 0911.1348;
Columbia-Bielefeld-RIKEN-BNL

Red - positive charge

Blue - negative charge



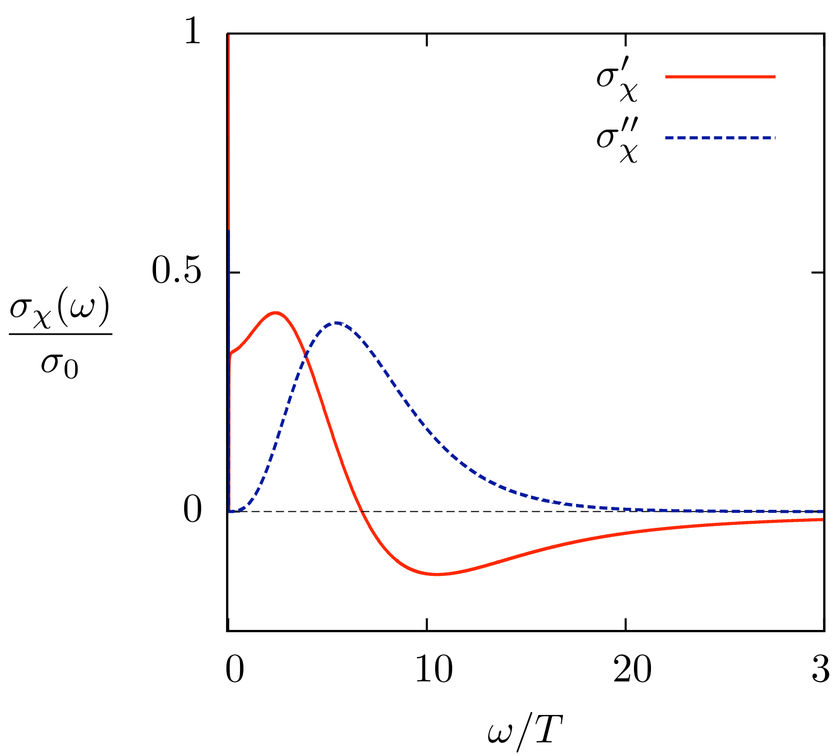


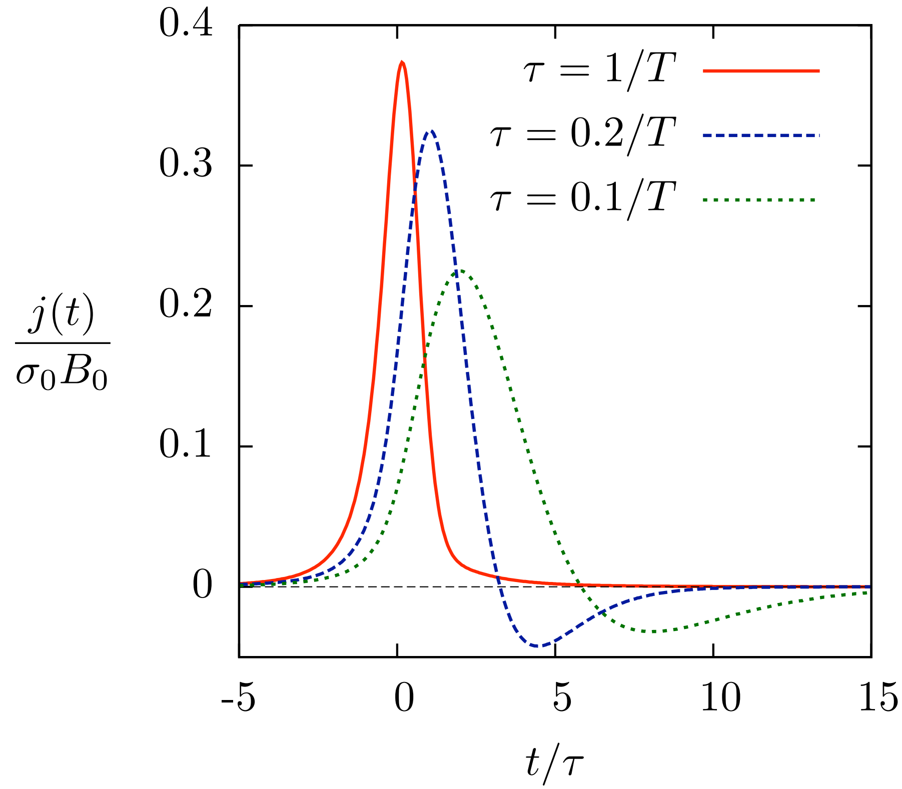
2+1 flavor Domain Wall Fermions, fixed topological sectors, 16^3 x 8 lattice

Chiral magnetic conductivity

$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$

$$\sigma_\chi(\omega = 0, \boldsymbol{p} = 0) \equiv \sigma_0 = \frac{e^2}{2\pi^2}\mu_5$$





D.K., H. Warringa, Phys Rev D80 (2009) 034028

Topological number diffusion at strong coupling

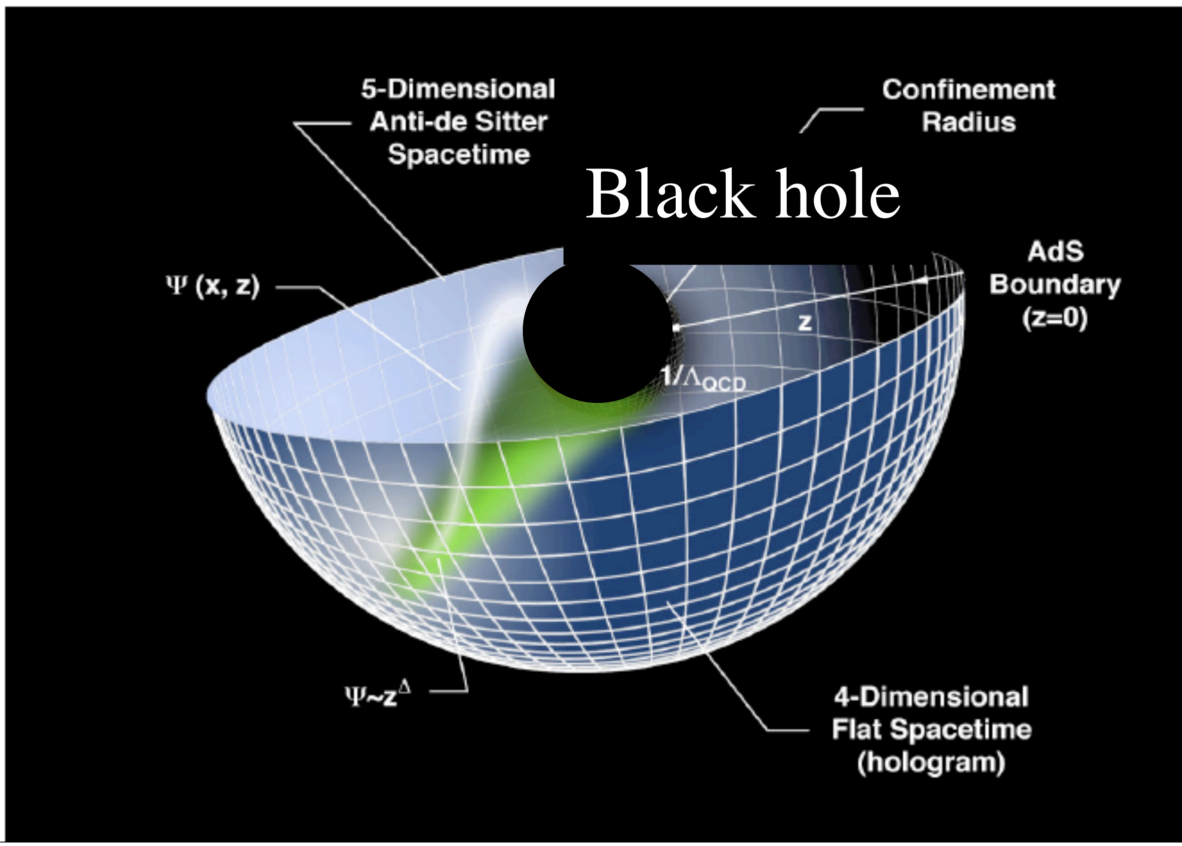
Chern-Simons number diffusion rate at strong coupling

$$\Gamma = \frac{(g_{\rm YM}^2 N)^2}{256\pi^3} T^4$$

D.Son, A.Starinets hep-th/ 020505

NB: In strongly coupled N=4 SUSY:

- small shear viscosity "perfect liquid"
- large rate of topological fluctuations

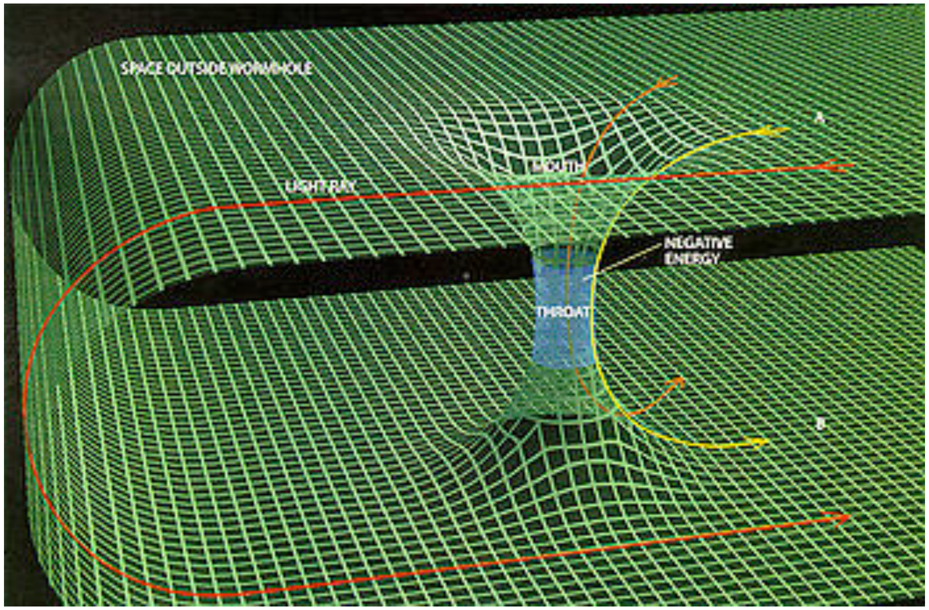


Axial anomaly in hydrodynamics:

D.Son and P.Surowka, arXiv:0906.5044

Classical topological solutions at strong coupling?

yes: D-instantons in (dual) weakly coupled supergravity



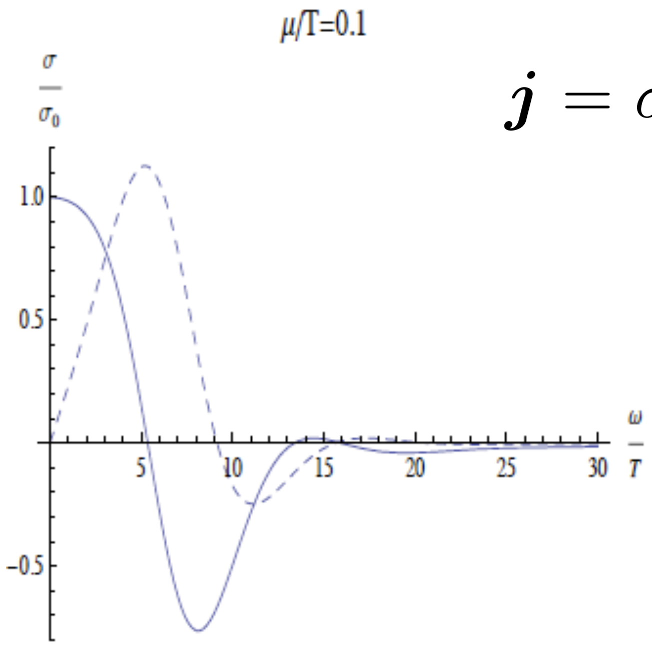
D-instanton as
an Einstein-Rosen
wormhole;
the flow of RR charge
down the throat of
the wormhole describes
change of chirality

G. W. Gibbons, M. B. Green and M. J. Perry, Phys. Lett. B **370**, 37 (1996) [arXiv:hep-th/9511080].

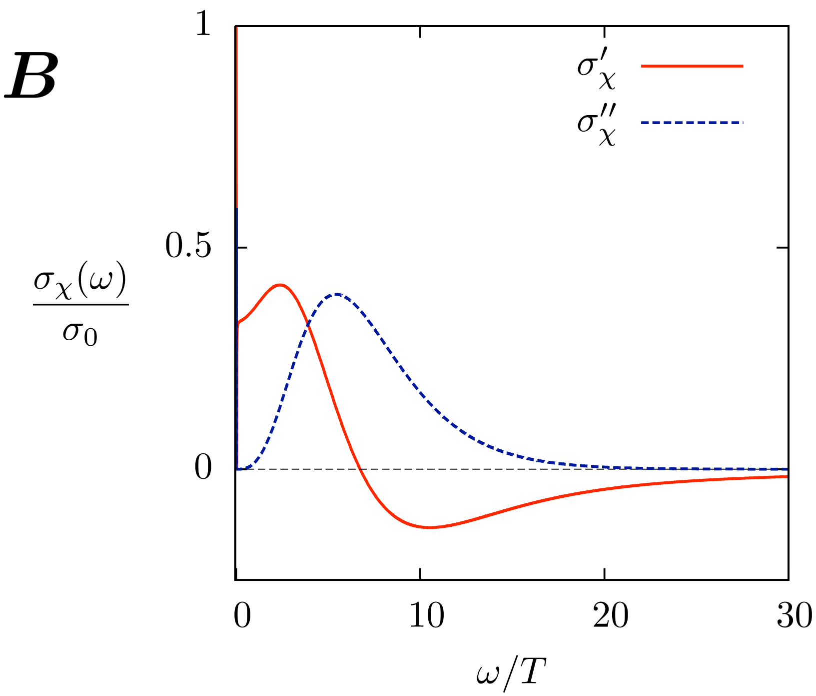
D-instantons as a source of multiparticle production in N=4 SYM?

DK, E.Levin, arXiv:0910.3355; JHEP (2010)

Holographic chiral magnetic effect: the strong coupling regime (AdS/CFT)



$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$



H.-U. Yee, arXiv:0908.4189,
JHEP 0911:085, 2009

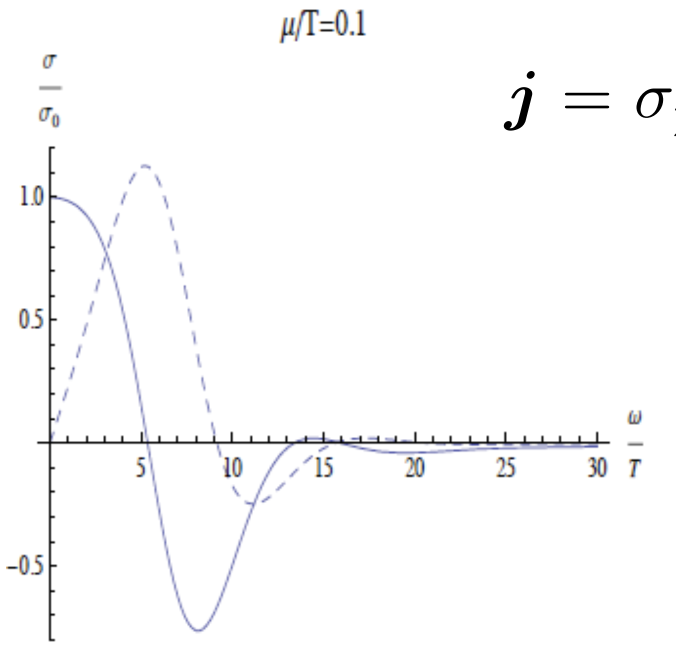
Strong coupling
(still controversial)

D.K., H. Warringa
Phys Rev D80 (2009) 034028

Weak coupling

A. Rebhan et al, JHEP 0905, 084 (2009), G.Lifshytz, M.Lippert, arXiv:0904.4772;
E. D' Hoker and P. Krauss, arXiv:0911.4518; ...

Holographic CME:
is the current renormalized at strong coupling?



$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$

H.-U. Yee, arXiv:0908.4189, JHEP 0911:085, 2009

H.-U.Yee: No

A. Rebhan et al: Yes (to zero)

Resolved very recently:
V.Rubakov, arXiv:1005.1888;
A. Gynther, K. Landsteiner, F. Pena-Benitez, A. Rebhan, arXiv:1005.2587

CME current is the same at strong and weak coupling

What carries the current at strong coupling?

CME in the chirally broken phase

G. Basar, G. Dunne, DK, arXiv: 1003.3464;
Phys.Rev.Lett., in press

"Chiral spiral" in (1+1) theories:

V. Schoen, M. Thies, hep-th/0008175

Gross-Neveu:

$$\mathcal{L} = \bar{q}\, \mathrm{i}\gamma^\mu \partial_\mu q + \frac{1}{2} g^2 \left[(\bar{q}q)^2 - \lambda \left(\bar{q}\gamma^5 q\right)^2 \right] - m_0 \bar{q} q$$

't Hooft:

$$\mathcal{L} = \bar{q}\, \mathrm{i} \not{D} q - \frac{1}{2} \mathrm{tr} F_{\mu\nu} F^{\mu\nu} , \qquad \not{D} = \gamma^\mu (\partial_\mu + \mathrm{i} g A_\mu)$$

because of constraints on Dirac matrices in 1+1, explicit form e.g.

$$\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} , \qquad \gamma^1 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

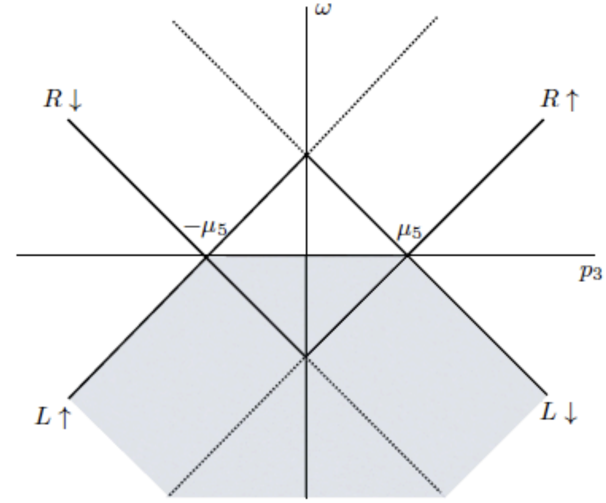
there is an intricate connection between the vector (baryon) and chiral currents

$$j_V^0 = j_A^1 , \quad j_V^1 = j_A^0$$

Baryon density - chiral current;
chiral density - vector current

Chiral magnetic spiral

G. Basar, G. Dunne, DK, arXiv: 1003.3464



Plane waves describing the pairing fermions acquire a phase difference due to the chemical potential - the spiral nature of condensates.

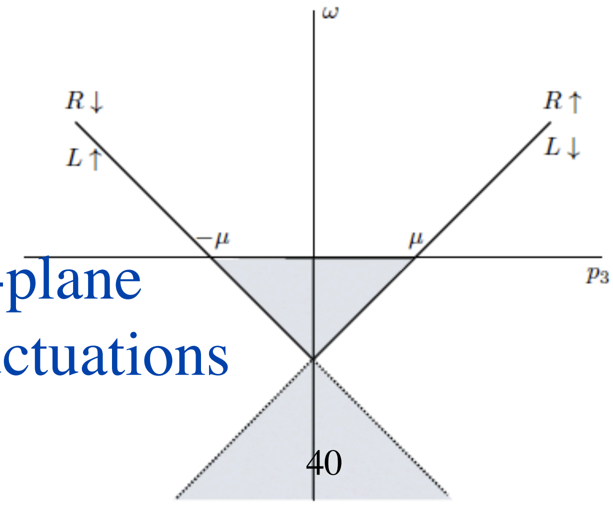
Gapless collective spiral excitation that carries a vector current (at finite chirality) or a chiral current (at finite baryon density).

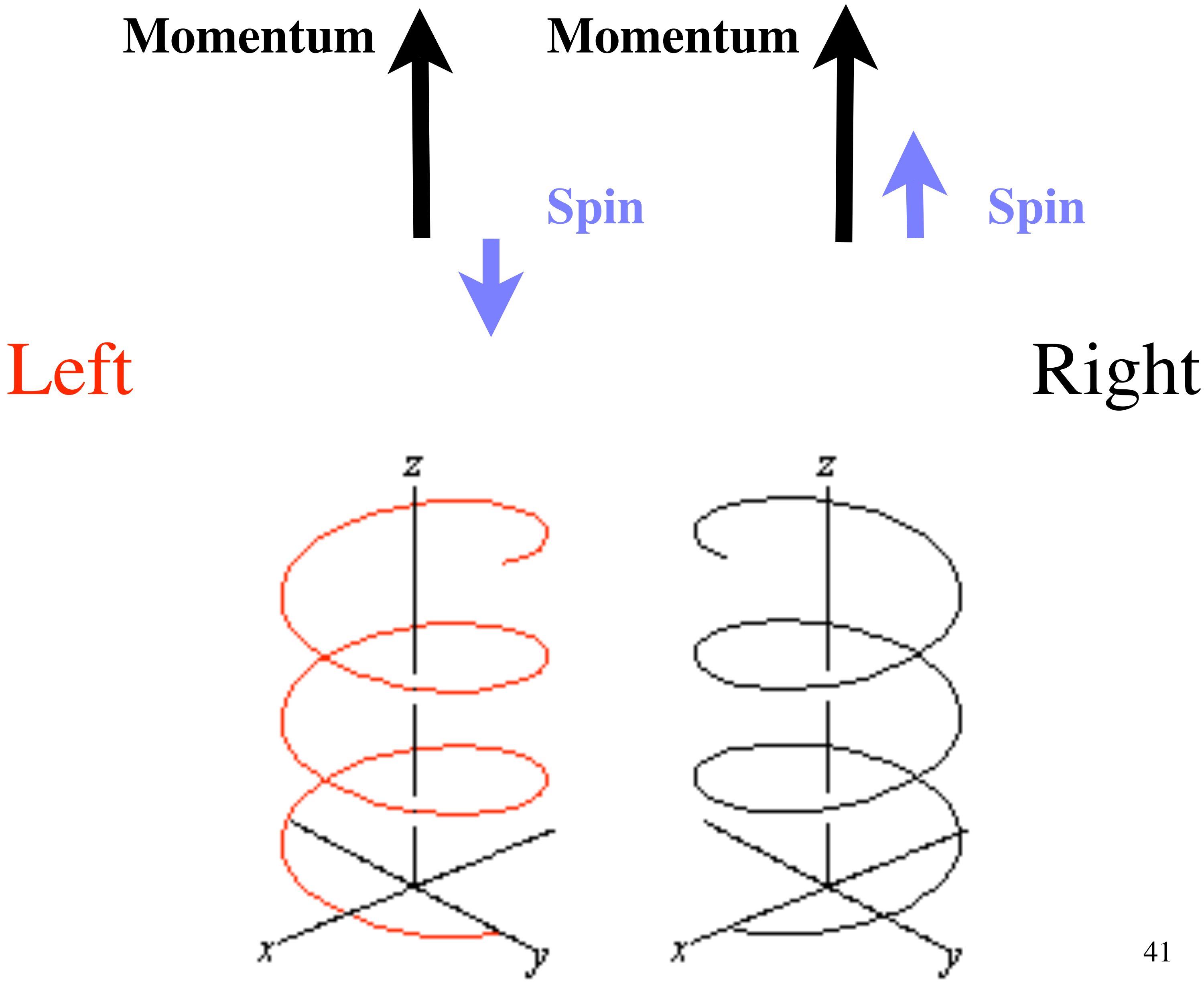
$$\langle J^3 \rangle = \frac{eB}{2\pi}\frac{e\mu_5}{\pi} \qquad \langle J^3_5 \rangle = \frac{eB}{2\pi}\frac{e\mu}{\pi}$$

4 =2x(1+1)

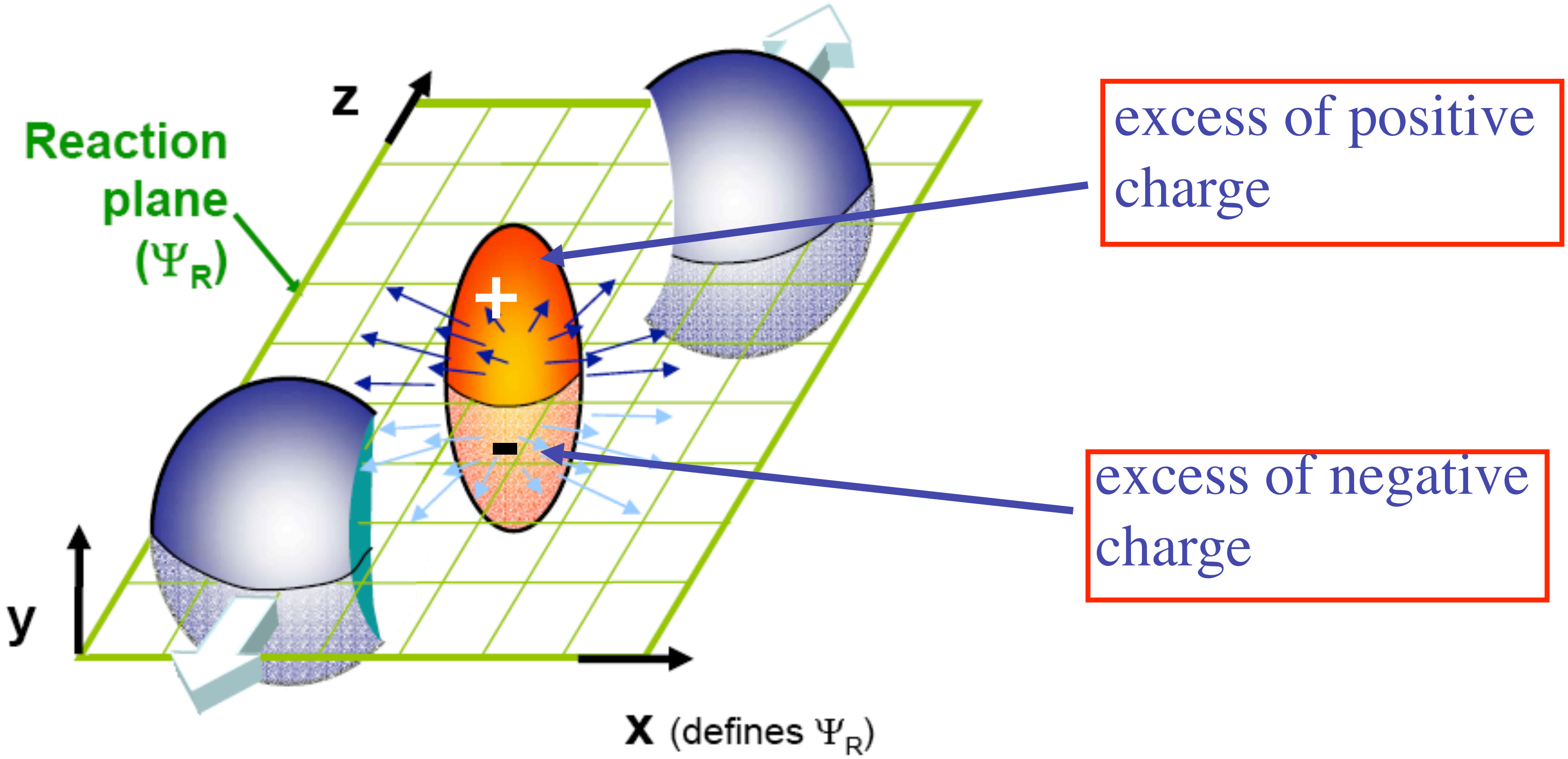
$$\begin{aligned}
\langle J^1 \rangle &= C^2 \cos(2\mu_5 z - \phi_R) - D^2 \cos(2\mu_5 z + \phi_L) \\
\langle J^2 \rangle &= -C^2 \sin(2\mu_5 z - \phi_R) + D^2 \sin(2\mu_5 z + \phi_L) \\
\langle J^1_5 \rangle &= C^2 \cos(2\mu_5 z - \phi_R) + D^2 \cos(2\mu_5 z + \phi_L) \\
\langle J^2_5 \rangle &= -C^2 \sin(2\mu_5 z - \phi_R) - D^2 \sin(2\mu_5 z + \phi_L)
\end{aligned}$$

in-plane fluctuations




Momentum
Momentum
Spin
Spin
Left
Right
z
z
x
y
x
y

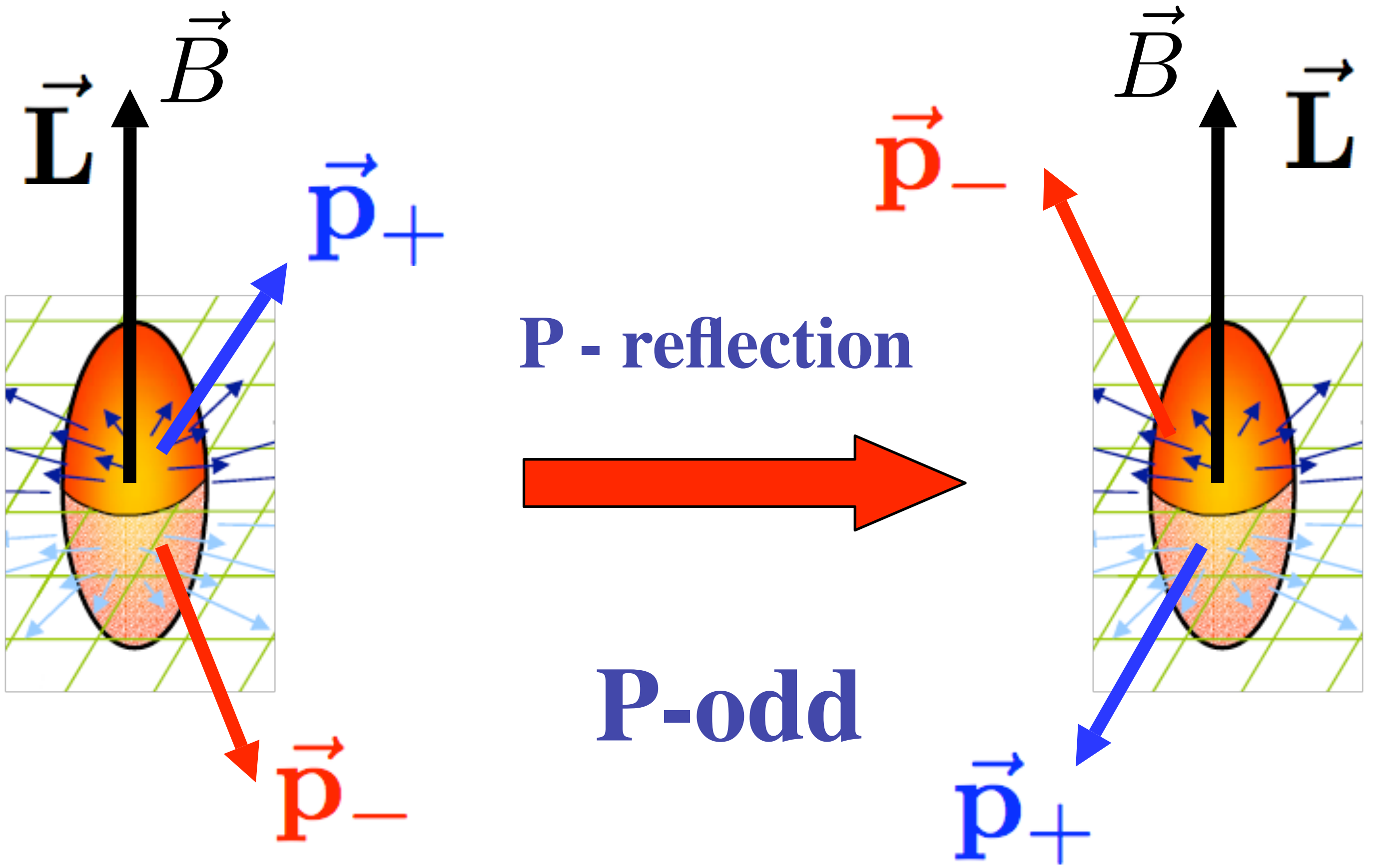
Charge asymmetry w.r.t. reaction plane as a signature of strong P violation



Electric dipole moment of QCD matter!

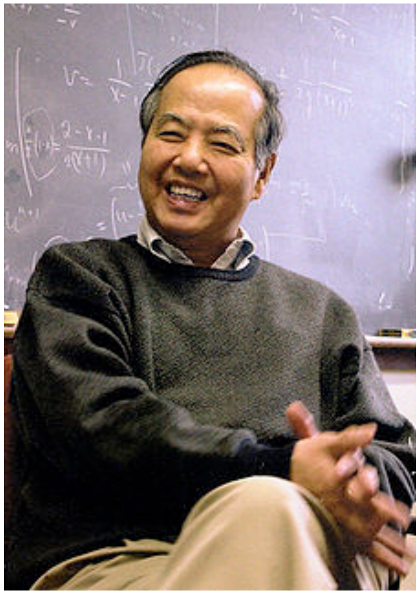
DK, Phys.Lett.B633(2006)260 [hep-ph/0406125]

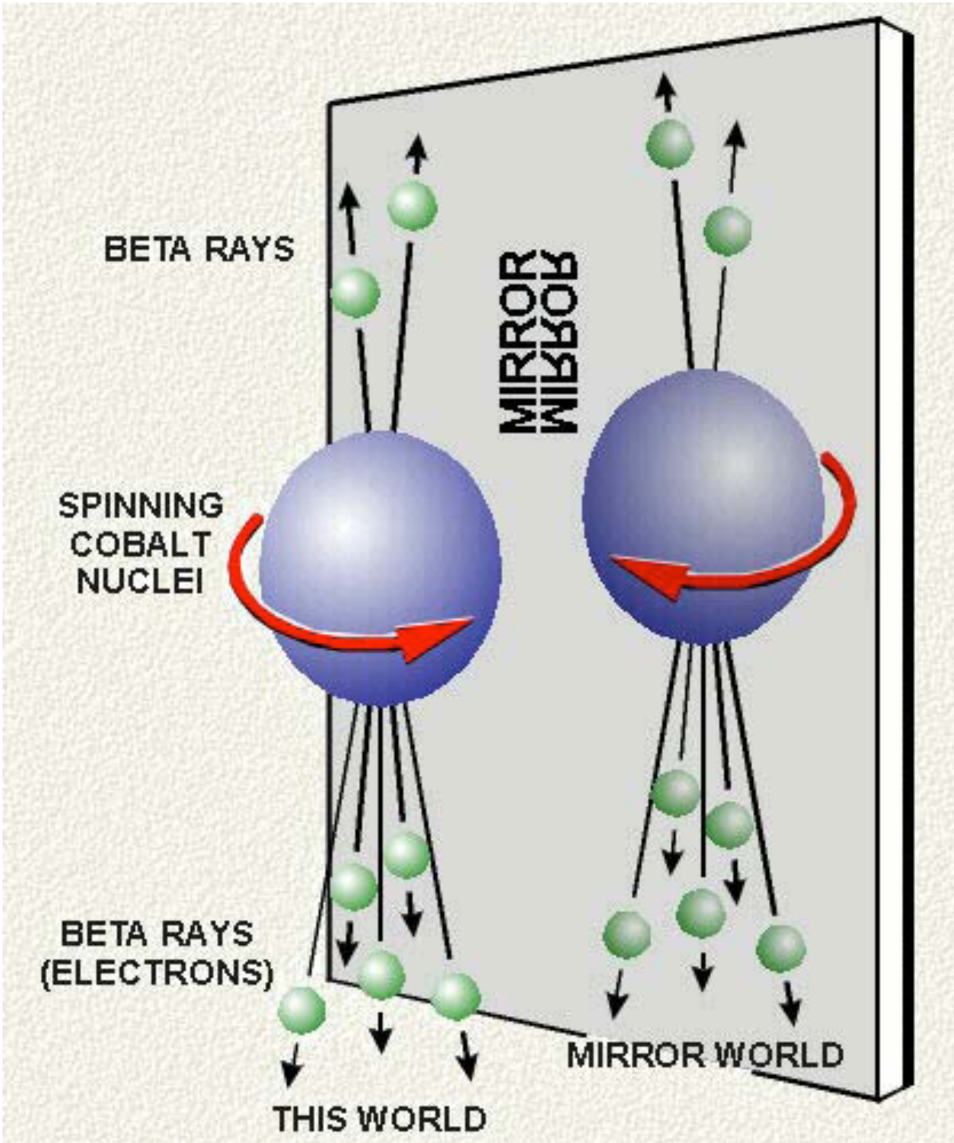
Charge separation = parity violation:



$$\mathcal{P}: \quad \vec{p} \longrightarrow -\vec{p}; \quad \vec{B} \longrightarrow \vec{B}; \quad \vec{L} \longrightarrow \vec{L}$$

Analogy to P violation in weak interactions



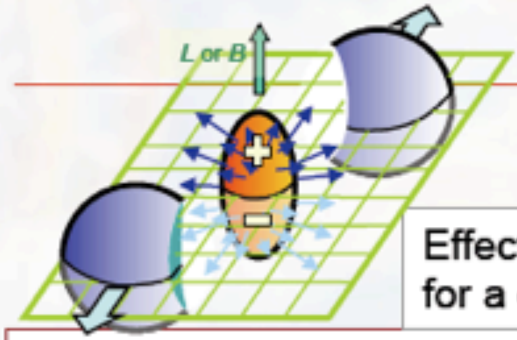


C.S. Wu, 1912-1997

BUT:
the sign of the asymmetry fluctuates event by event

Observable

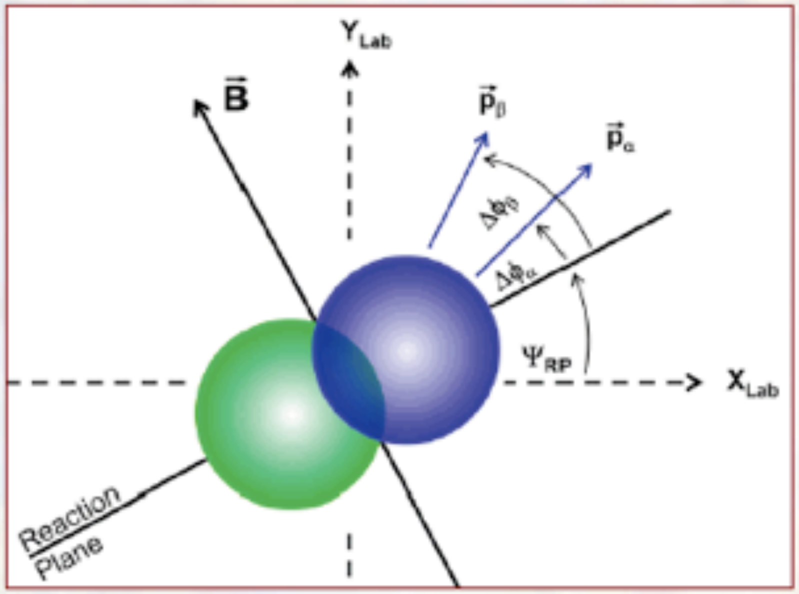
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \dots + 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \dots,$$

$$\Delta\phi = (\phi - \Psi_{RP})$$



- The effect is too small to observe in a single event
- The sign of Q varies and $\langle a \rangle = 0$ (we consider only the leading, first harmonic) ➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)
- $\langle a_\alpha a_\beta \rangle$ is expected to be ~ 10^{-4}
- $\langle a_\alpha a_\beta \rangle$ can not be measured as $\langle \sin\varphi_\alpha \sin\varphi_\beta \rangle$ due to large contribution from effects not related to the orientation of the reaction plane

➔ study the difference in corr's in- and out-of-plane

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle = $$
$$= \langle\cos\Delta\phi_\alpha\,\cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha\,\sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\langle a_\alpha a_\beta\rangle + B^{out}].$$

$$B^{in} \approx B^{out}, \quad v_1 = 0$$

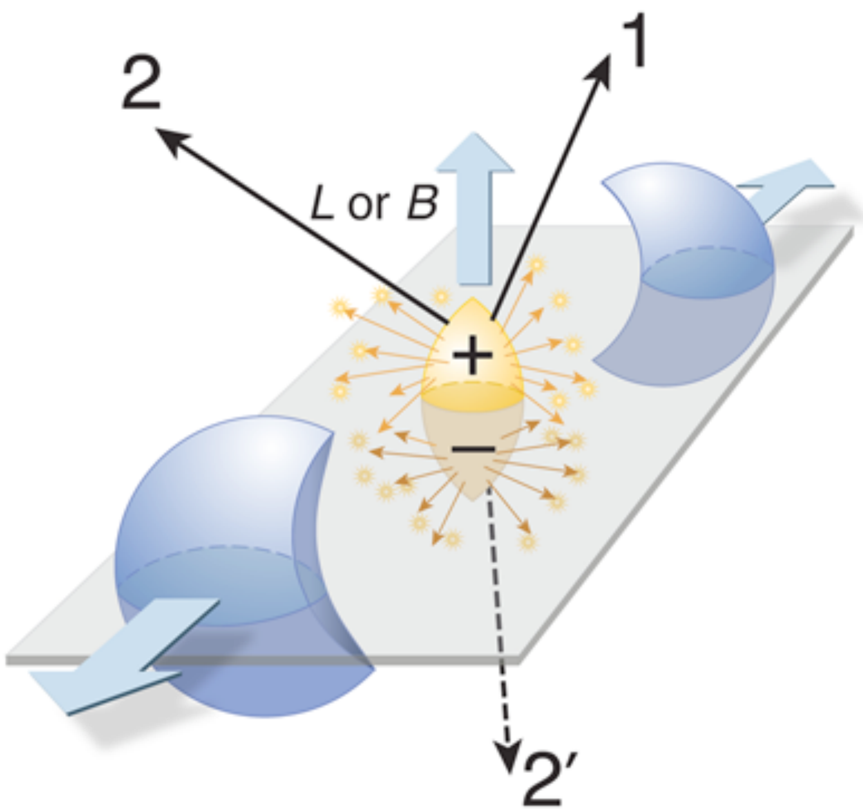
A practical approach: three particle correlations:

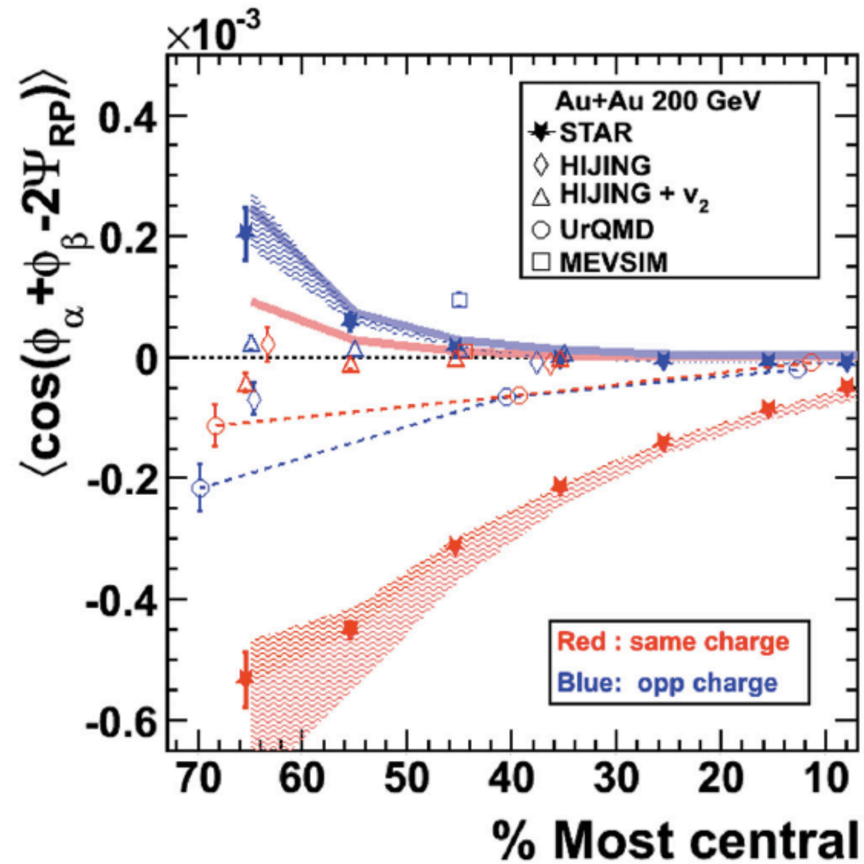
$$\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$$

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

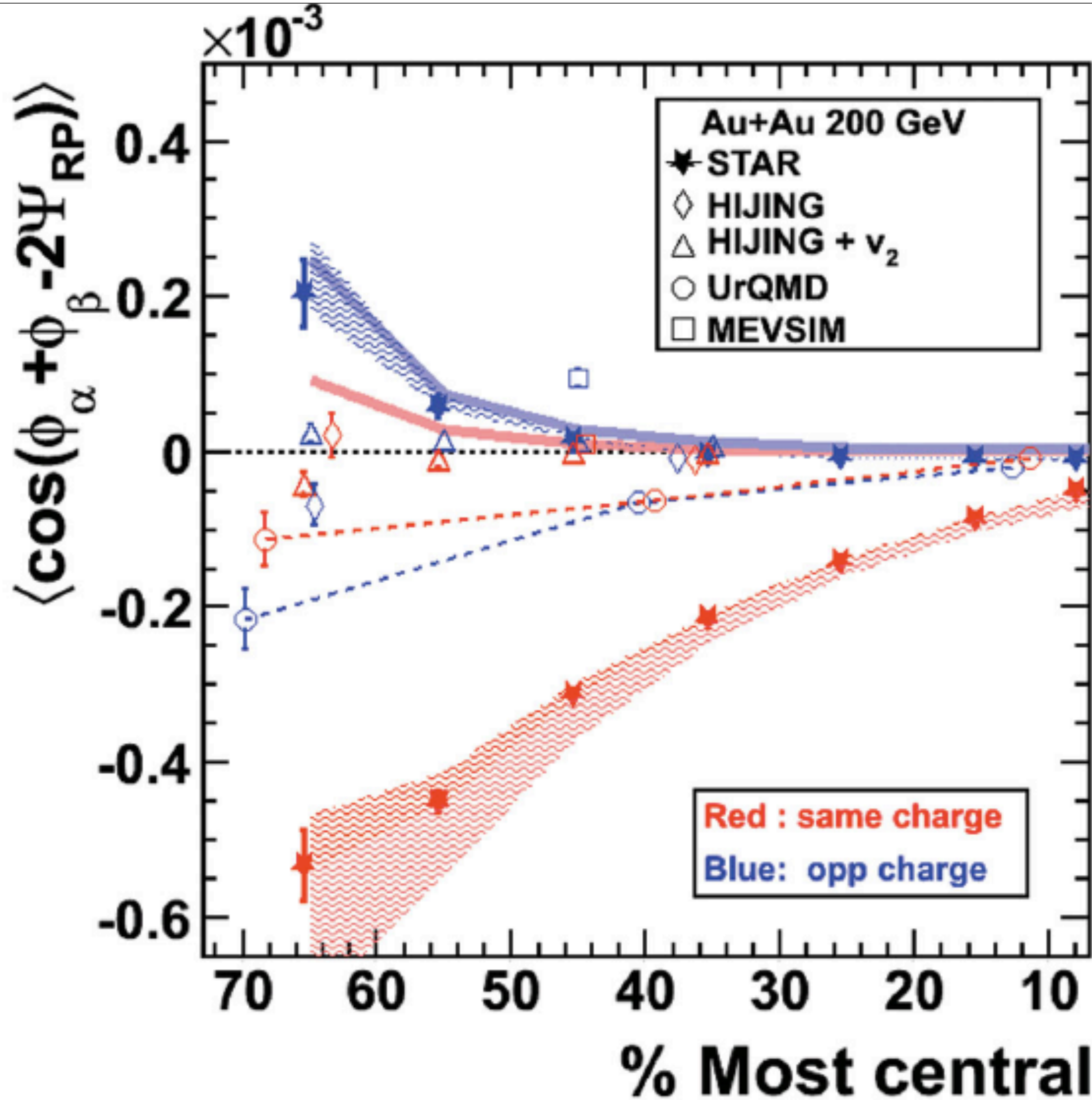
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)



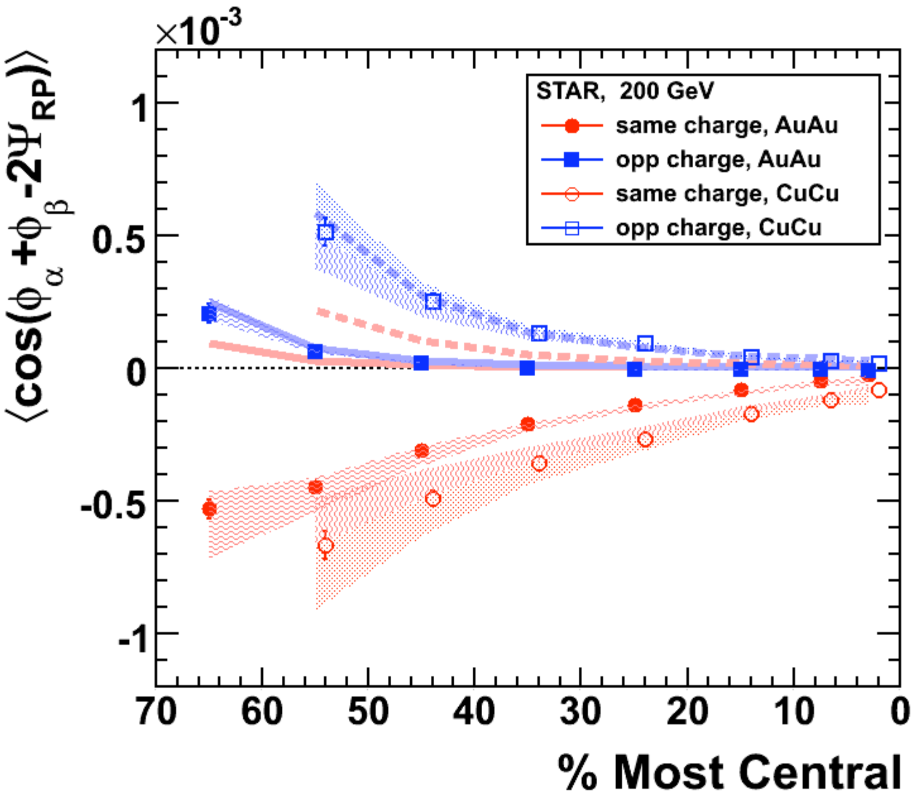


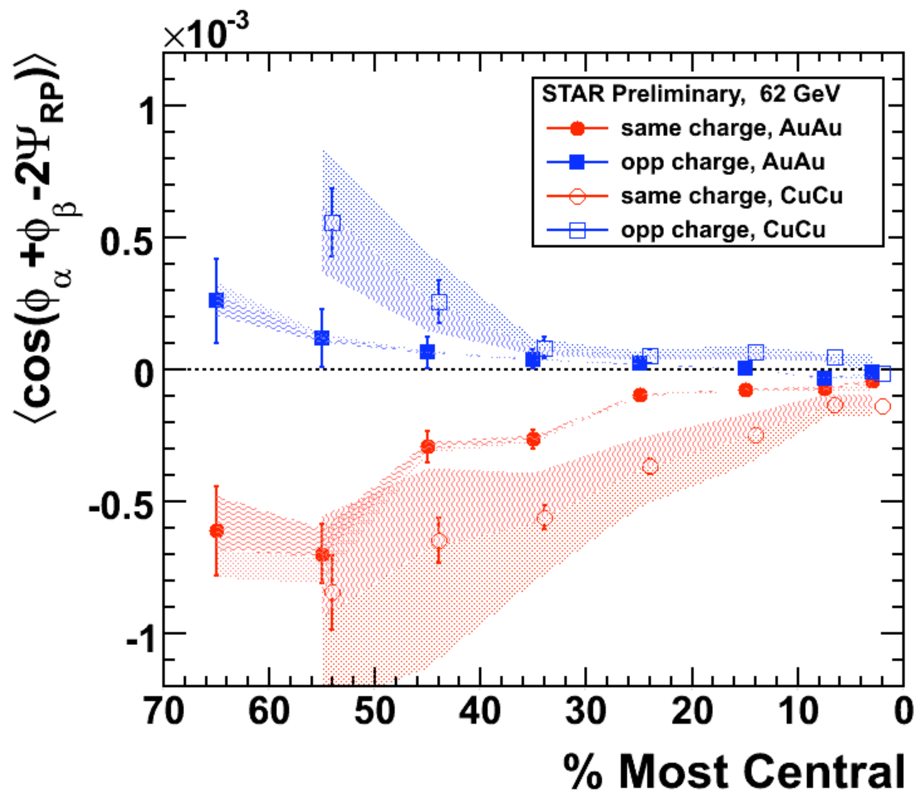
Lecture by S. Voloshin



P-even observable; but: sensitive to P-odd fluctuations

Mass number and energy dependences



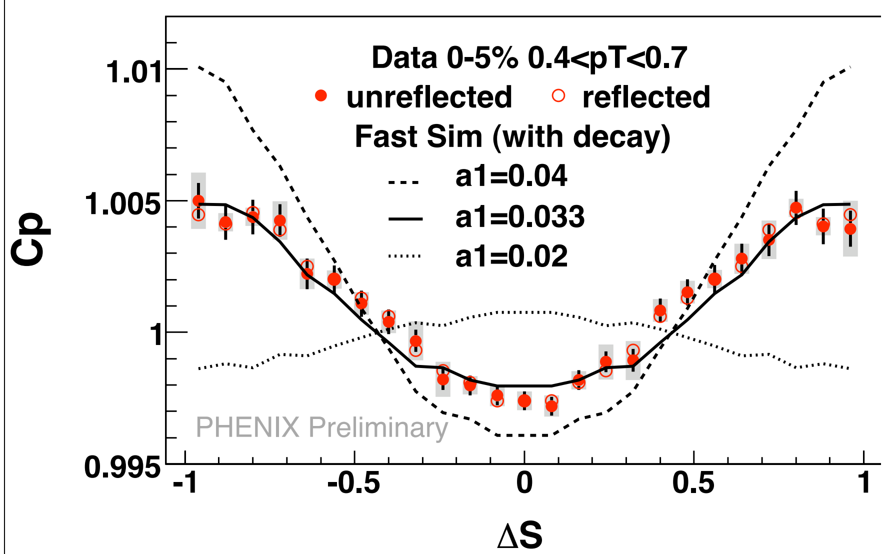


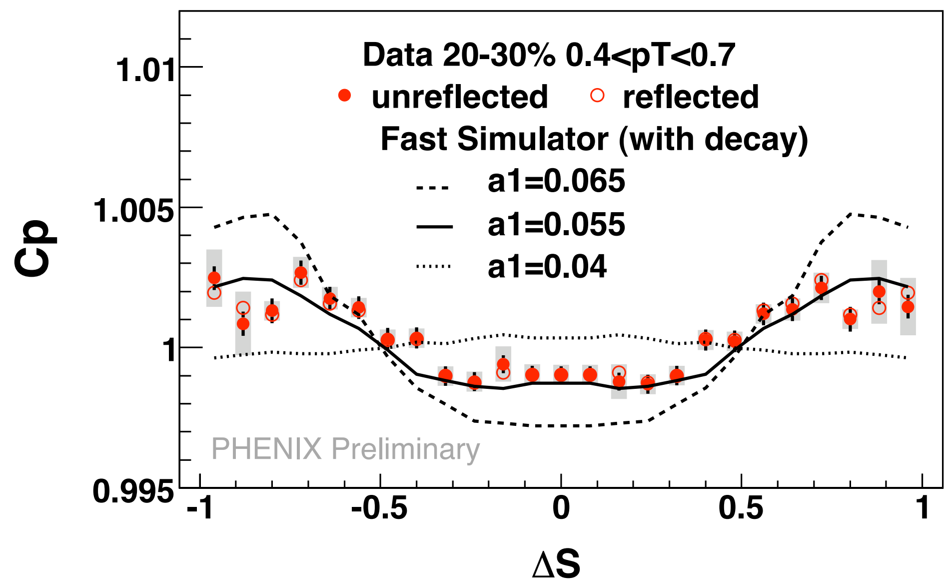
STAR Coll., arXiv:0909.1717
(Phys Rev C)

Expectations for the energy dependence: slow growth towards low energies reflecting longer-lived magnetic field, then gradual disappearance (no QGP): there has to be a maximum somewhere

The PHENIX result

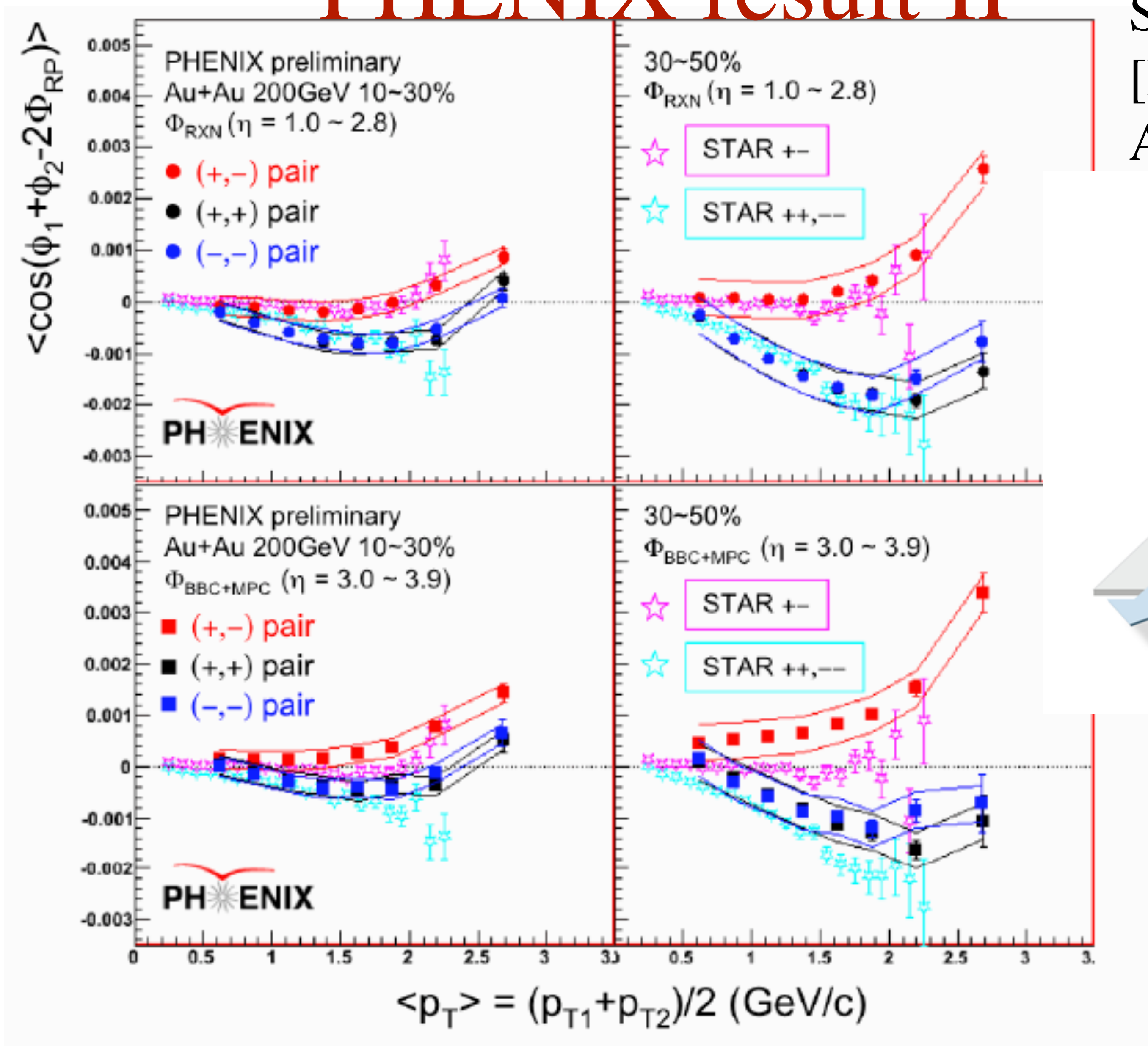
talk by N. Ajitanand, Dec 17

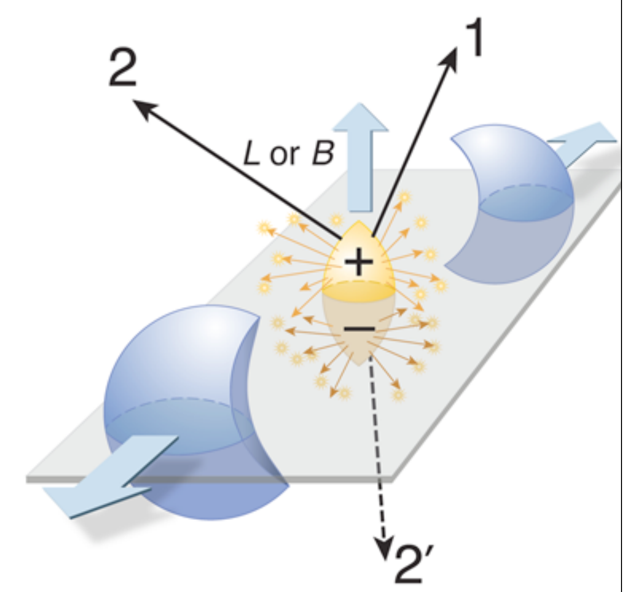




PHENIX result II

S.Esumi et al
[PHENIX Coll]
April 2010





Relatively good agreement between PHENIX & STAR

Are the observed fluctuations of charge asymmetries a convincing evidence for the local parity violation?

A number of open questions that still have to be clarified:

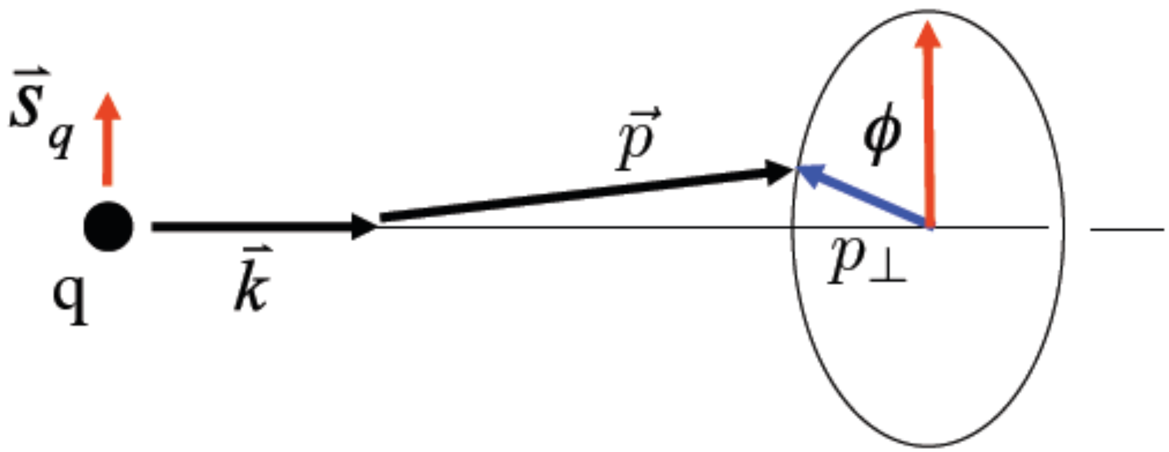
in-plane vs out-of-plane, new observables? — A. Bzdak, V. Koch, J. Liao, arXiv:0912.5050; 1005.5380

physics "backgrounds" — M. Asakawa, A. Majumder, B. Muller, arXiv:1003.2436
S. Pratt and S. Schlichting, arXiv:1005.5341
F. Wang, arXiv: 0911.1482

Fortunately, a number of analytical and numerical (lattice) tools are available to theorists, and the new data (low energy, PID asymmetries, U-U) will hopefully come - this question can be answered!

Local P violation in the fragmentation of polarized quarks

Z. Kang, DK, arXiv:1006.2132 (today)



P-odd:

$$D_{\pi/q^\uparrow}(z,p_\perp) = D(z,p_\perp^2) + H_1^\perp(z,p_\perp^2)\frac{(\hat{k}\times p_\perp)\cdot s_q}{M} + \widetilde{H}_1^\perp(z,p_\perp^2)\frac{p_\perp\cdot s_q}{M}$$

Z. Kang, DK, arXiv:1006.2132

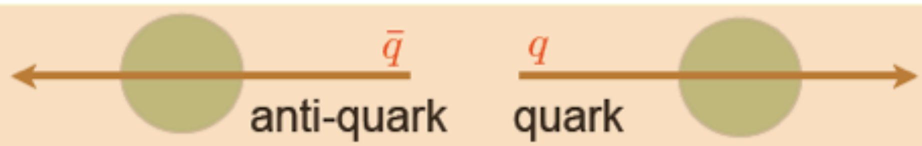
Cross section in e+e- annihilation:

$$\frac{d\sigma}{dz_1 dz_2 d\cos\theta d(\phi_1+\phi_2)} = \sigma_0 \sum_q e_q^2 \Big\{ (1+\cos^2\theta)\Big[D_q(z_1)D_{\bar q}(z_2) - \widetilde{D}_q(z_1)\widetilde{D}_{\bar q}(z_2)\Big]$$
$$+\sin^2\theta\cos(\phi_1+\phi_2)\Big[H_q^\perp(z_1)H_{\bar q}^\perp(z_2) + \widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)\Big]$$
$$+\sin^2\theta\sin(\phi_1+\phi_2)\Big[H_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2) - \widetilde{H}_q^\perp(z_1)H_{\bar q}^\perp(z_2)\Big]\Big\}$$

"Collins effect"

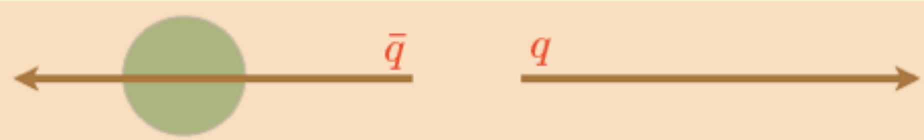
P-odd, only EbyE

- Physical pictures:
  - P-odd times P-odd terms:

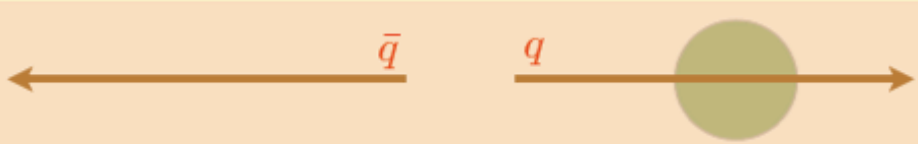


$\widetilde{D}_q(z_1)\widetilde{D}_{\bar q}(z_2)$ OR $\widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)$

  - P-odd term alone:



$H_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)$



$-\widetilde{H}_q^\perp(z_1)H_{\bar q}^\perp(z_2)$

RIKEN-BNL-CATHIE Workshop on

P- and CP-odd Effects in Hot and Dense Matter

April 26-30, 2010

Brookhaven National Laboratory
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http://www.bnl.gov/riken/hdm/

Registration deadline: March 1, 2010

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Summary

- The existence of topological solutions is an indispensable property of non-Abelian gauge theories that form the Standard Model

- Electric charge separation in the background magnetic field (CME) allows a **direct** observation of a topological effect in QCD

- The existence of the Chiral Magnetic Effect (CME) has been confirmed by several calculations done by different methods, both at weak and strong coupling

- CME has been observed in first-principle lattice QCD calculations

- There is a recent observation of dynamical fluctuations in charge asymmetry at RHIC - an evidence for the CME?