Joint CATHIE / TECHQM Workshop

December 14-18, 2009

# The future of Local Parity Violation

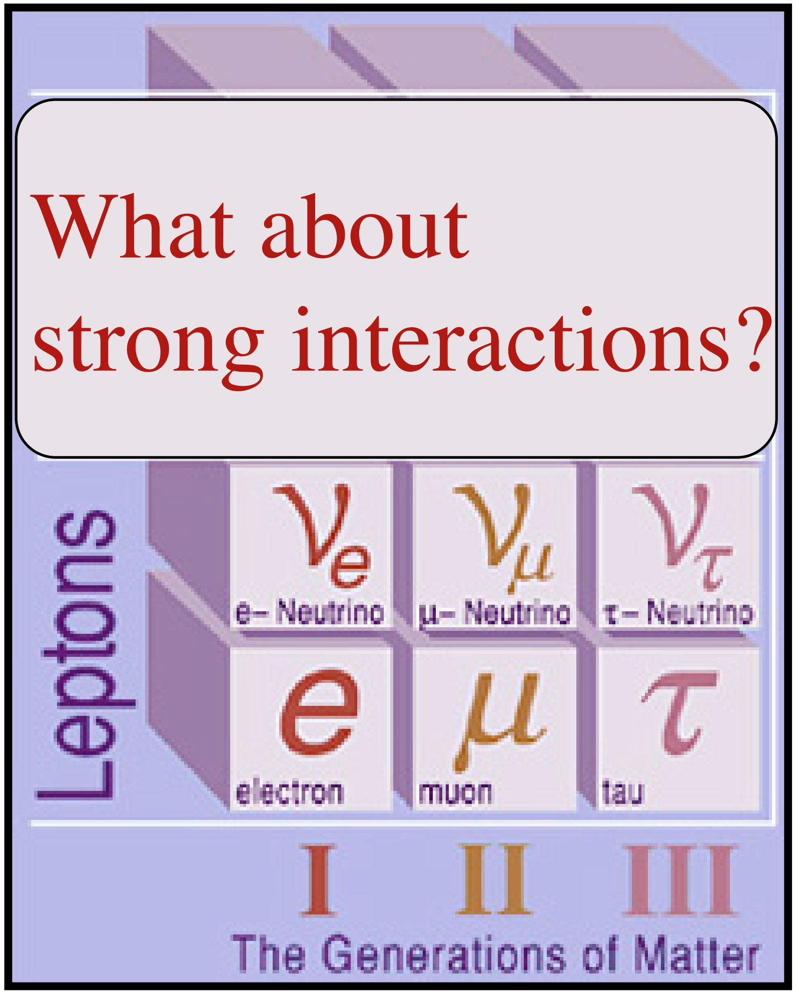
D. Kharzeev

BNL

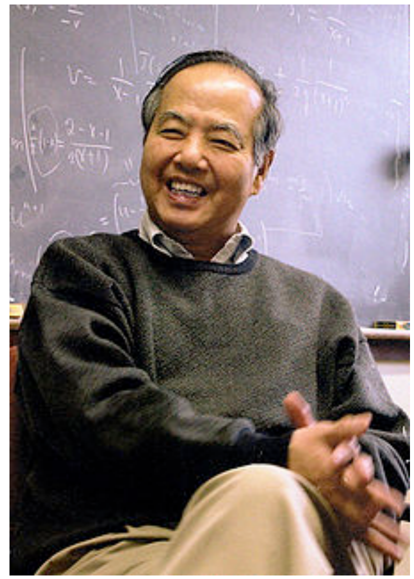
Since the beginning of physics, symmetry considerations have provided us with an extremely powerful and useful tool in our effort to understand nature. Gradually they have become the backbone of our theoretical formulation of physical laws.

T.D. Lee

# 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

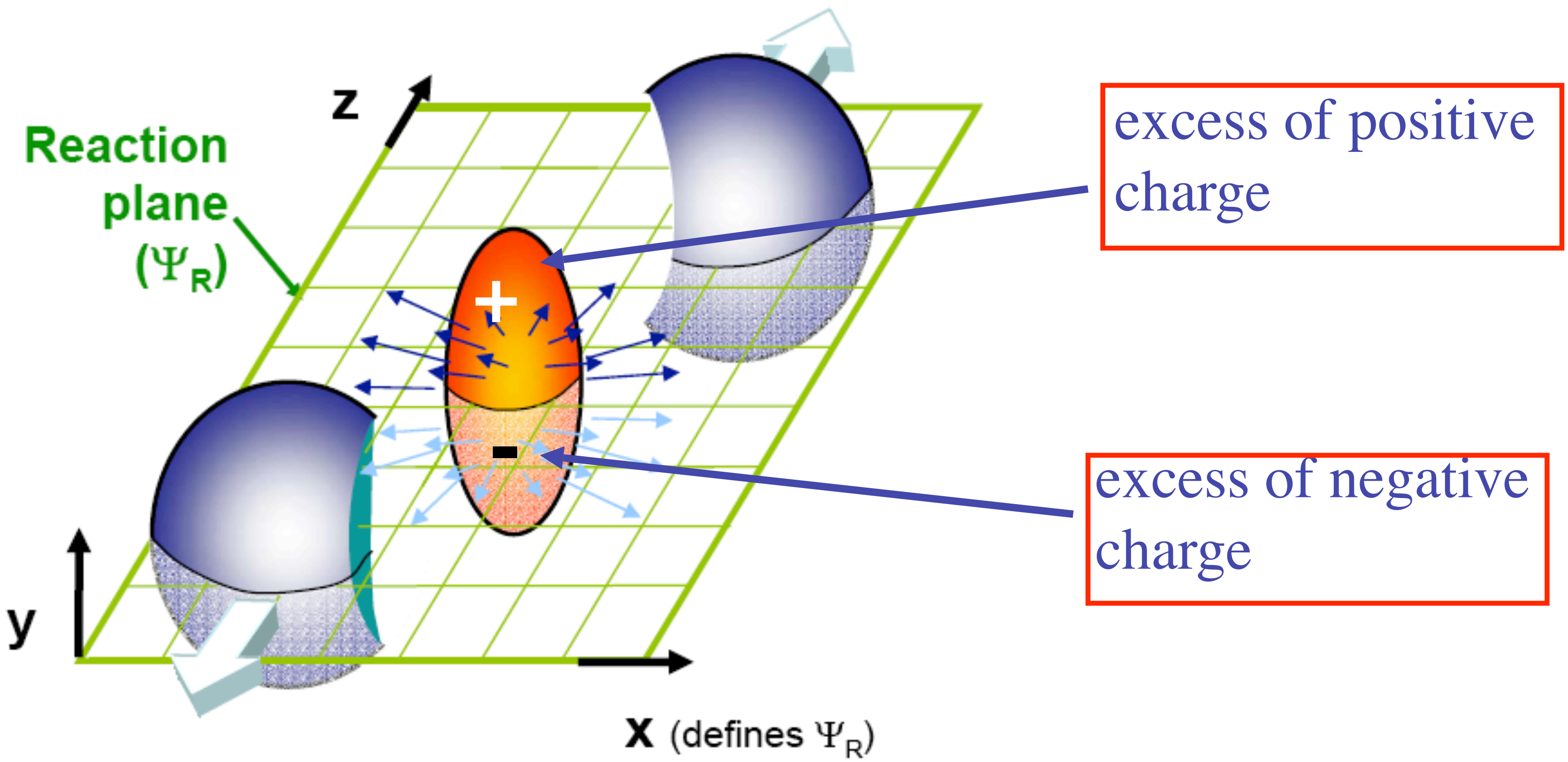
2008

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?

# 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]

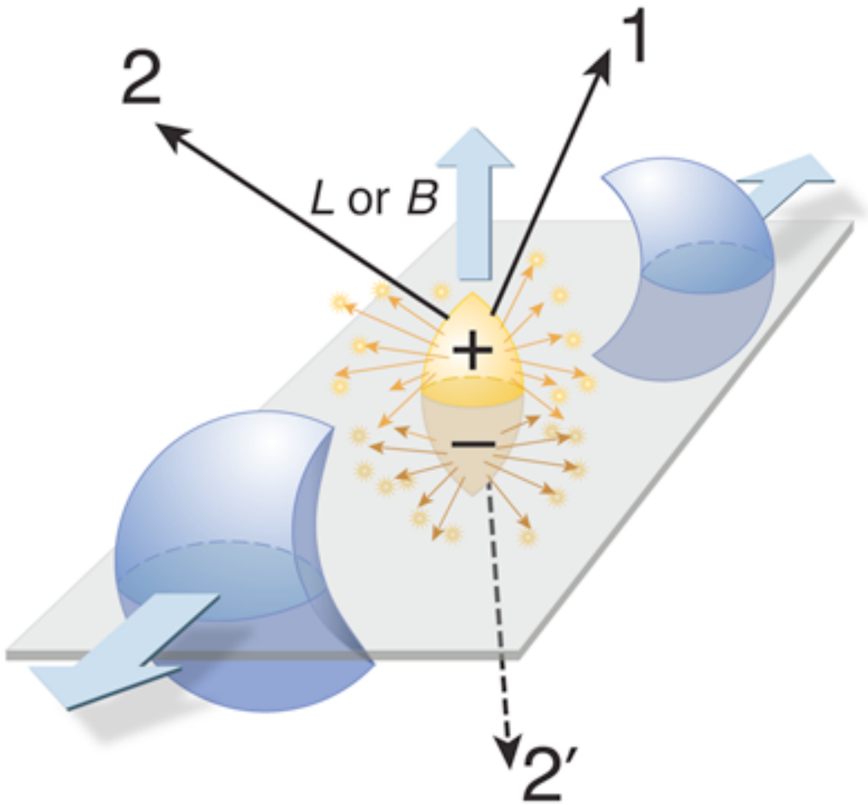
PRL 103, 251601 (2009)

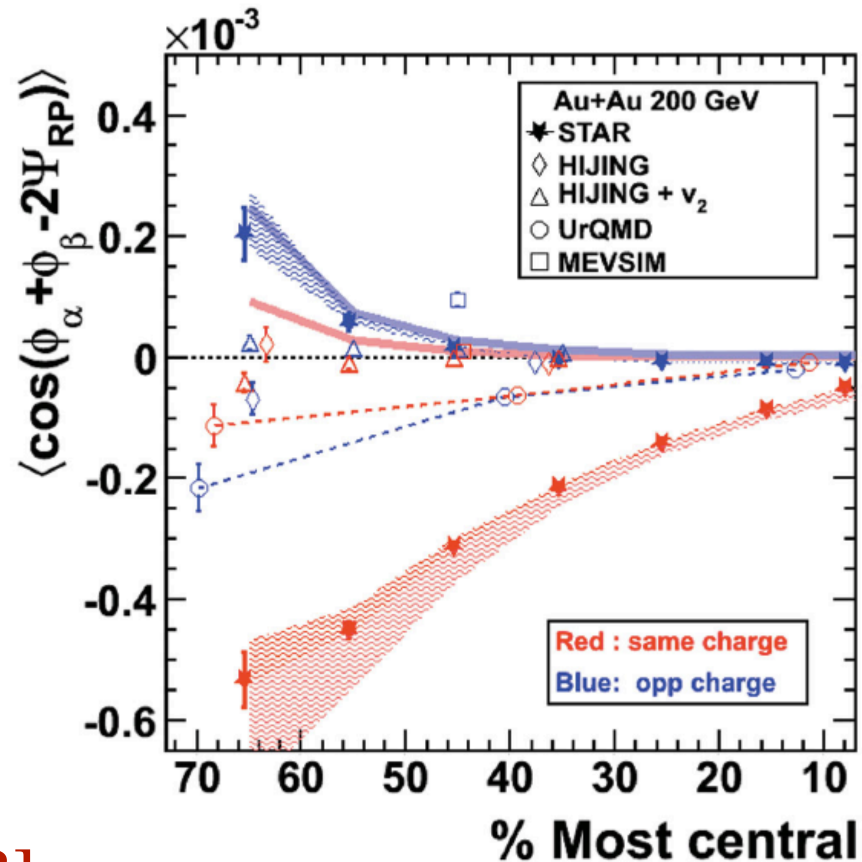
Selected for a Viewpoint
PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2009

**Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation**

(STAR Collaboration)



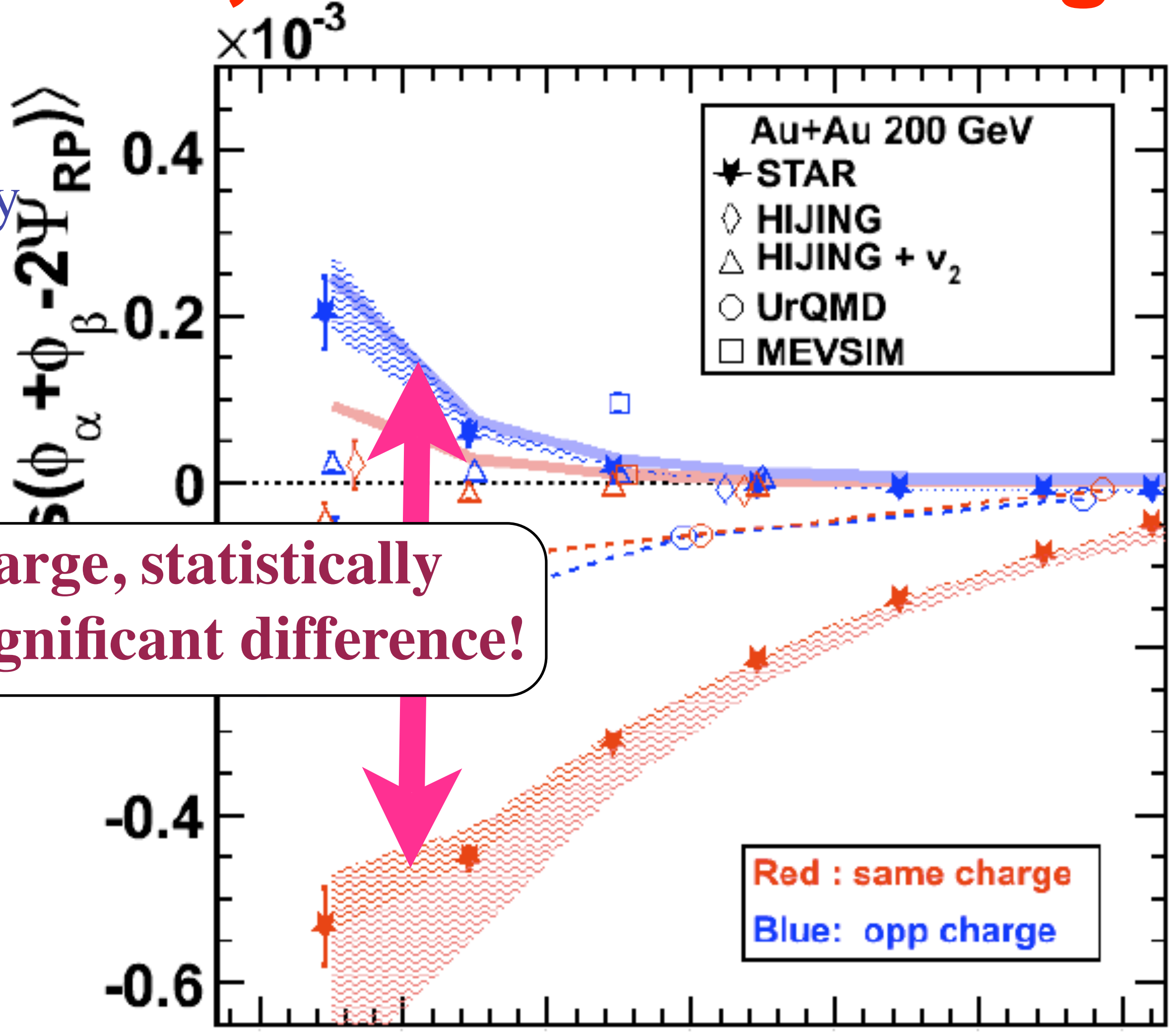




**Talk by I. Selyuzhenkov [STAR]**

# Local P, CP violation at high T ?

Charge asymmetry w.r.t. reaction plane,

~ - $a^k a^m$




Talk by
I. Selyuzhenkov

[STAR Coll.]


PRL **103,** 251601 (2009)

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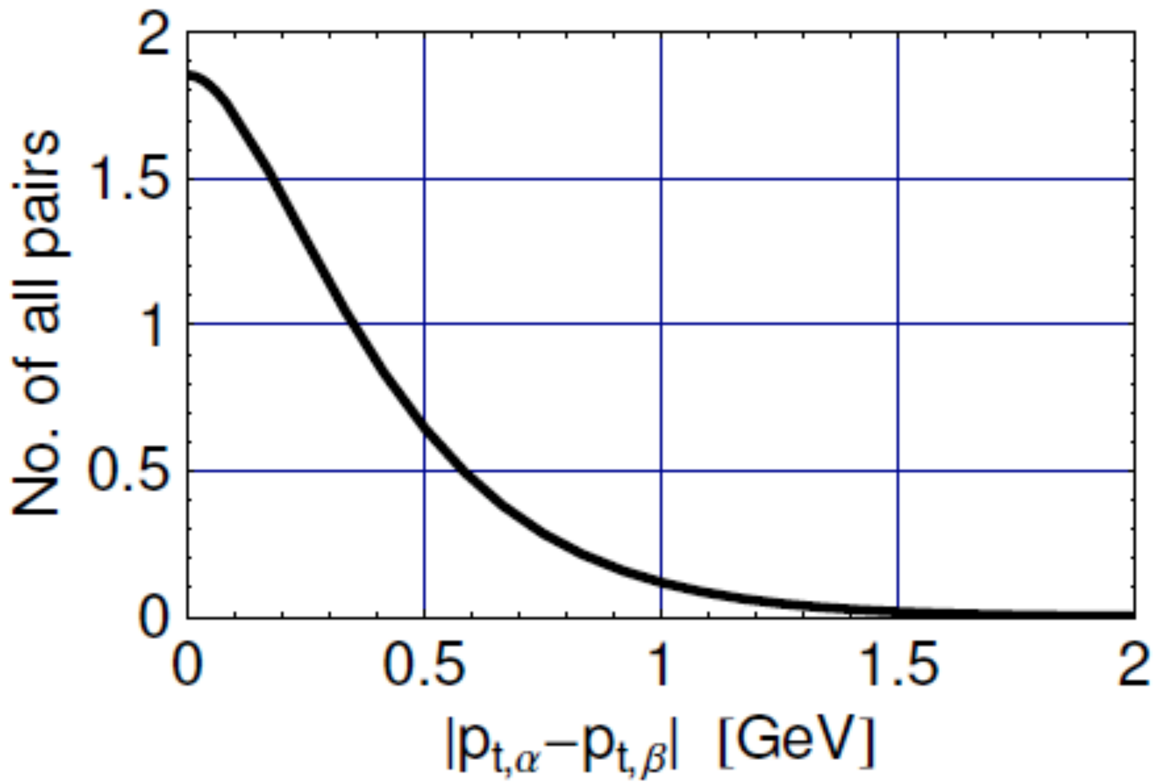
18 DECEMBER 2009


**Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation**



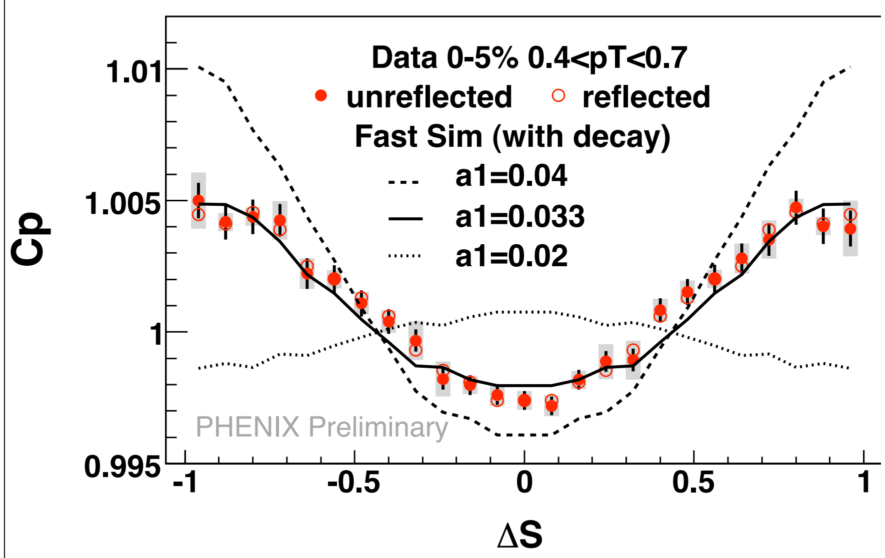

Disentangle
azimuthal,
p_t dependence
from the data:

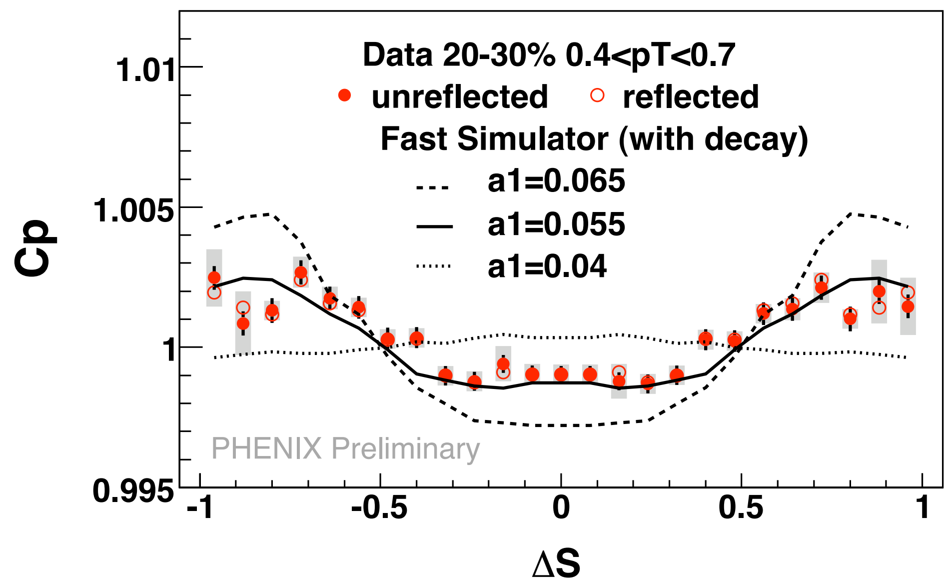
talk by A.Bzdak

P-odd-correlated pairs are produced at small p_t!?

# The PHENIX result

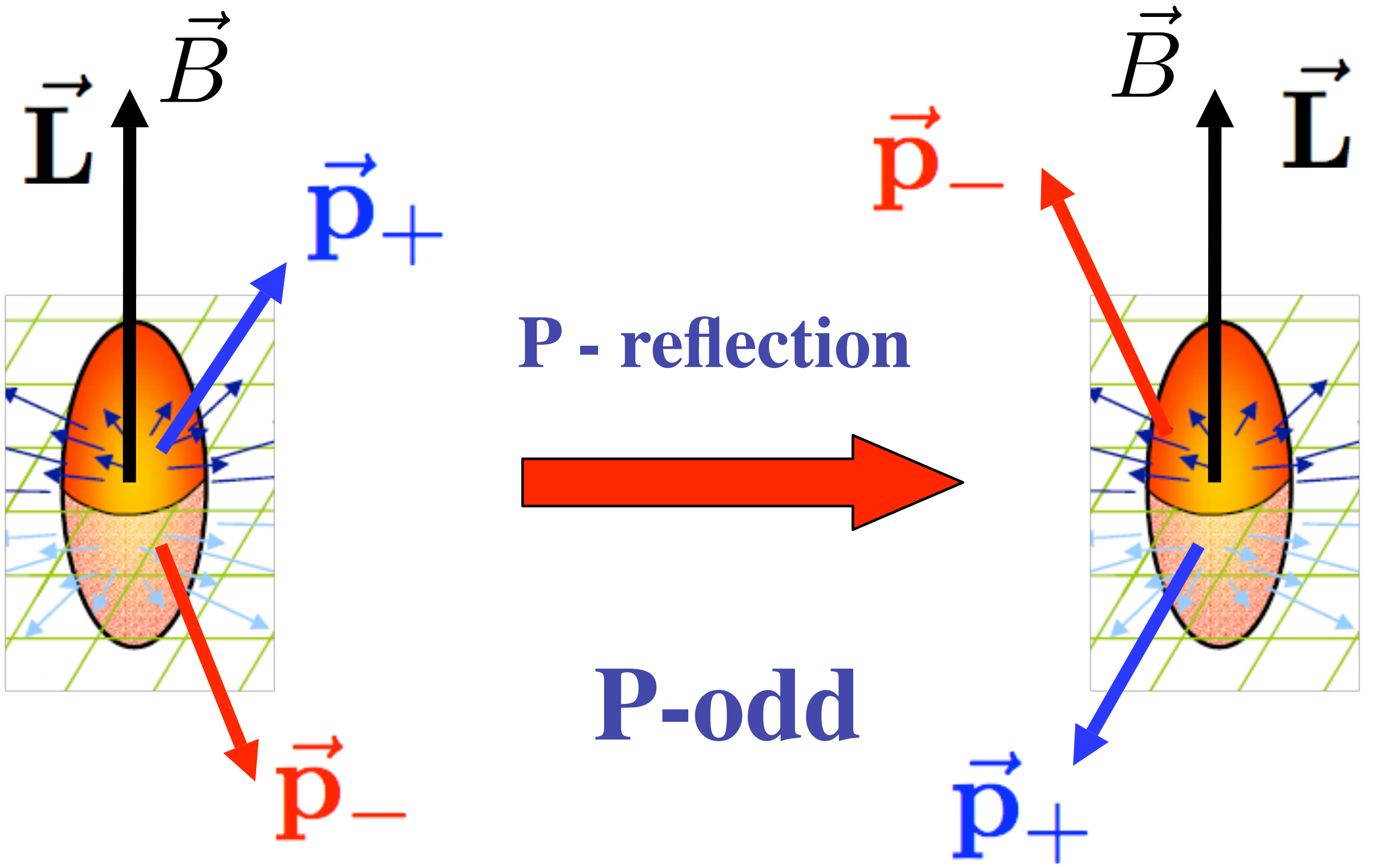
talk by N. Ajitanand, Dec 17




A P-odd observable?!?!

# Charge separation = parity violation:




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

# 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.

# 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 $\theta$ and curvature tensor $\Omega$. 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

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

What does it mean for a gauge theory?

# Chern-Simons theory

CHARACTERISTIC FORMS

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

## 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

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

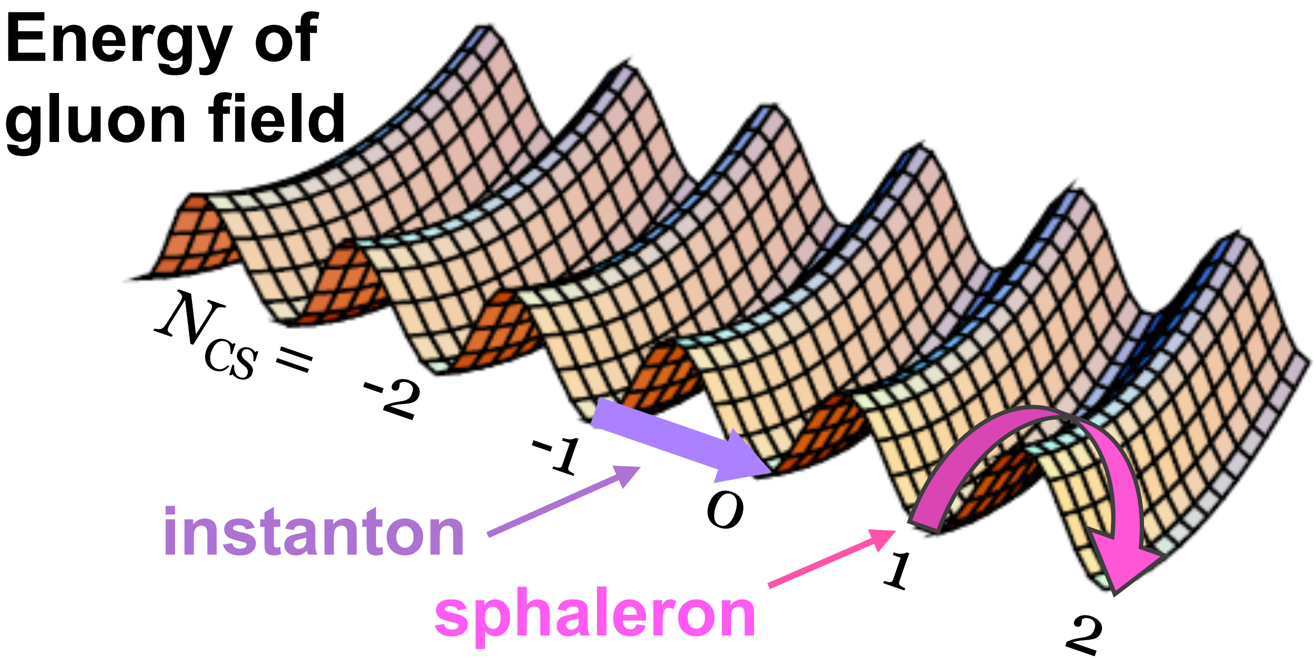
## Remarkable novel properties:

- 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**

# Topology in QCD

talk by E. Shuryak

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

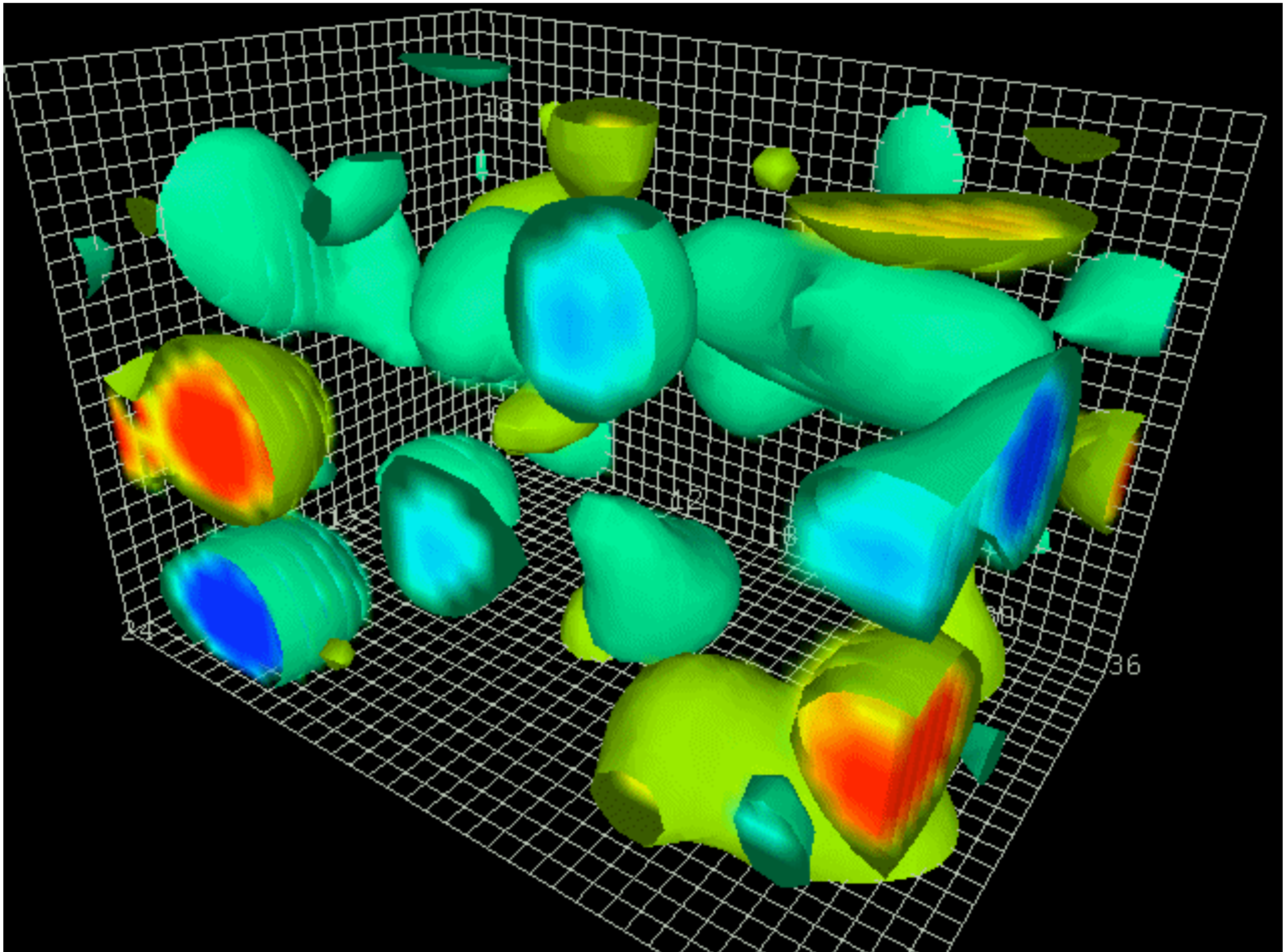



Sphalerons:
random walk of
topological charge at finite T:

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

# Topological number fluctuations in QCD vacuum

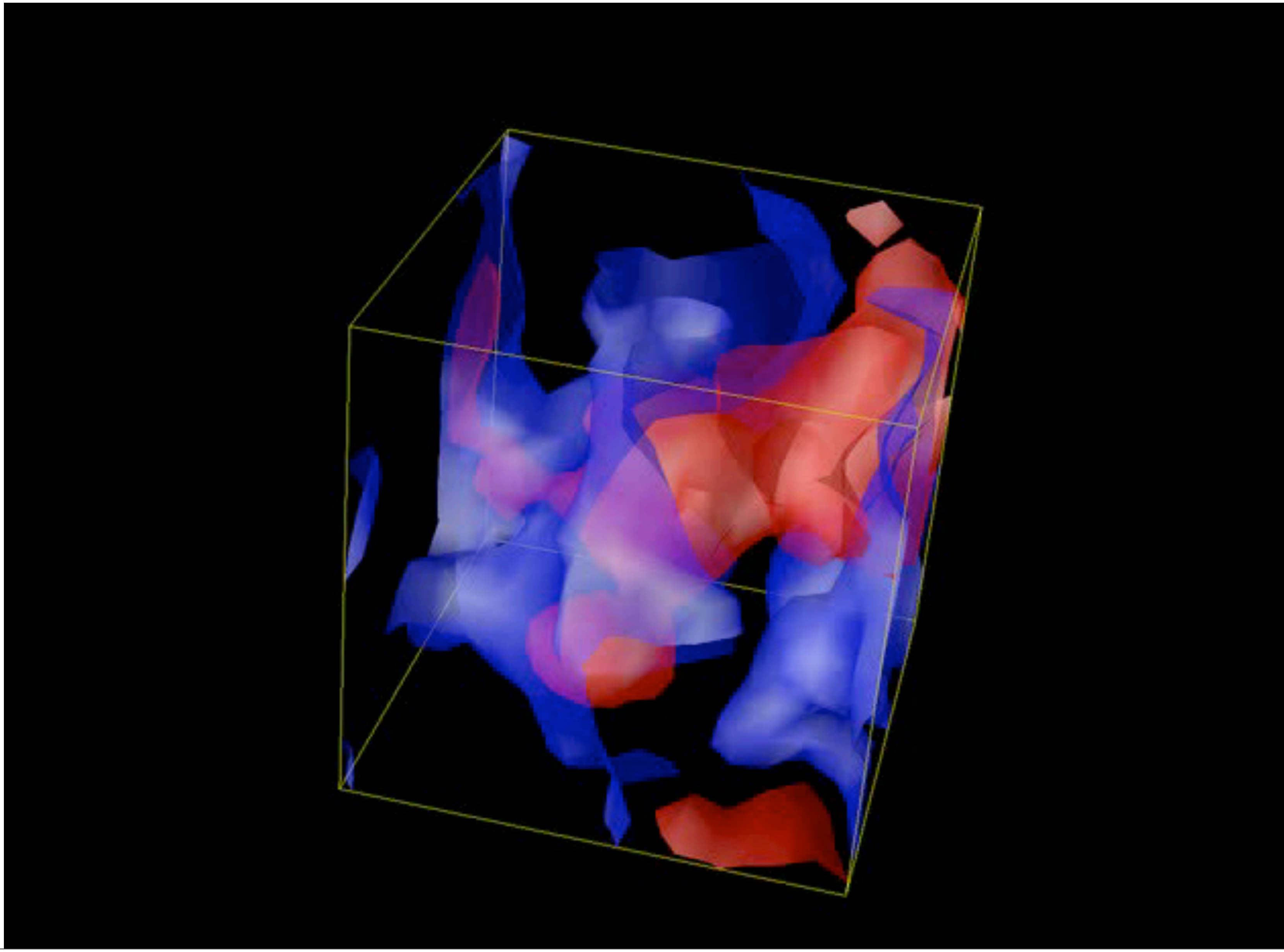
(“cooled” configurations)



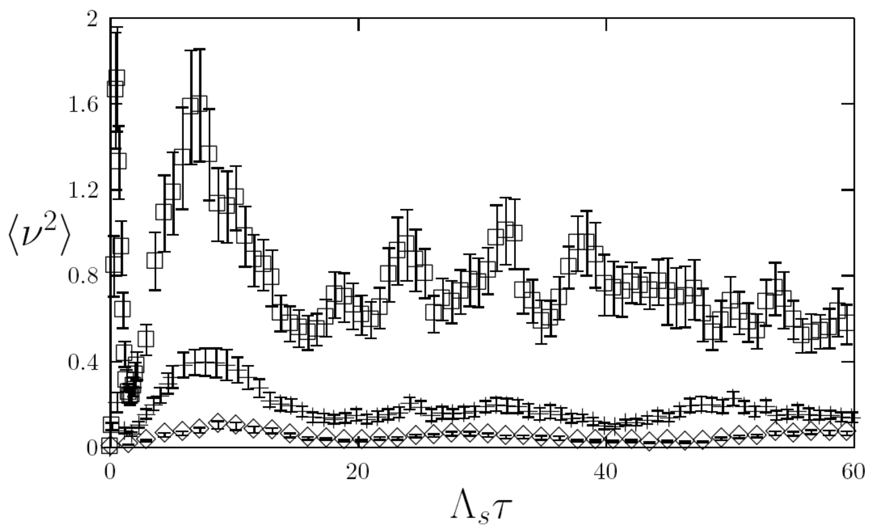

D. Leinweber

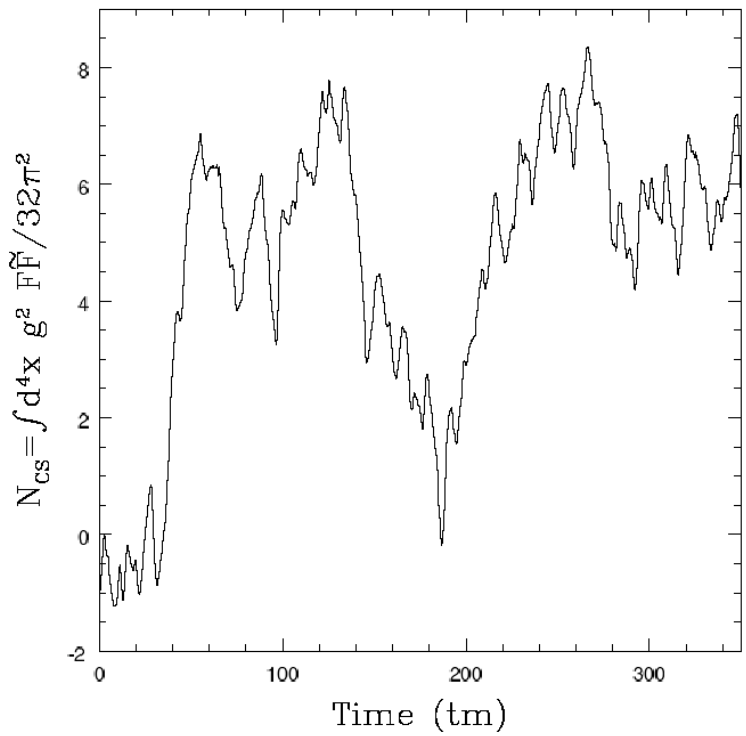
# Topological number fluctuations in QCD vacuum

ITEP Lattice Group



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




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

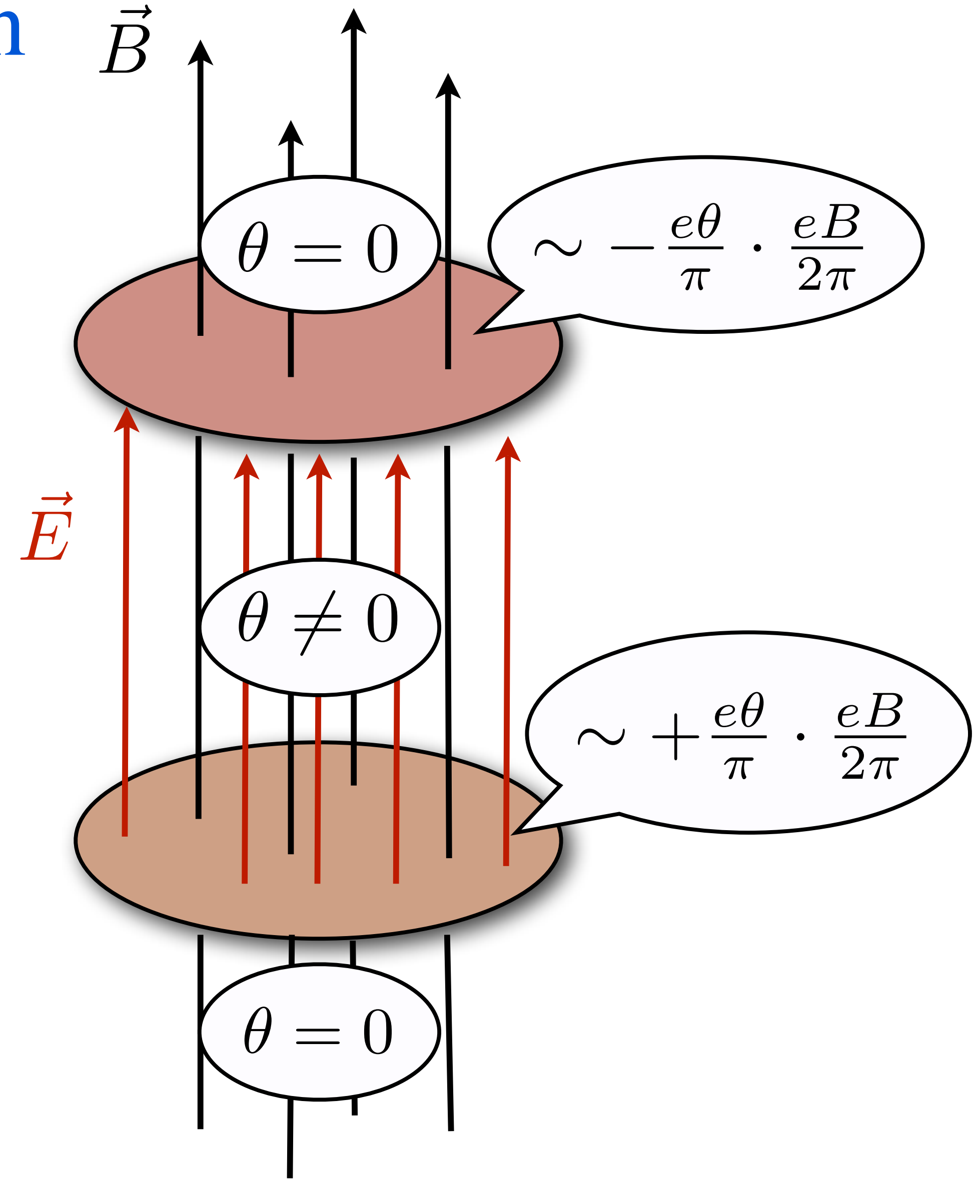
P.Arnold and G.Moore, Phys.Rev.D73:025006,2006

# The Chiral Magnetic Effect I: Charge separation

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

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

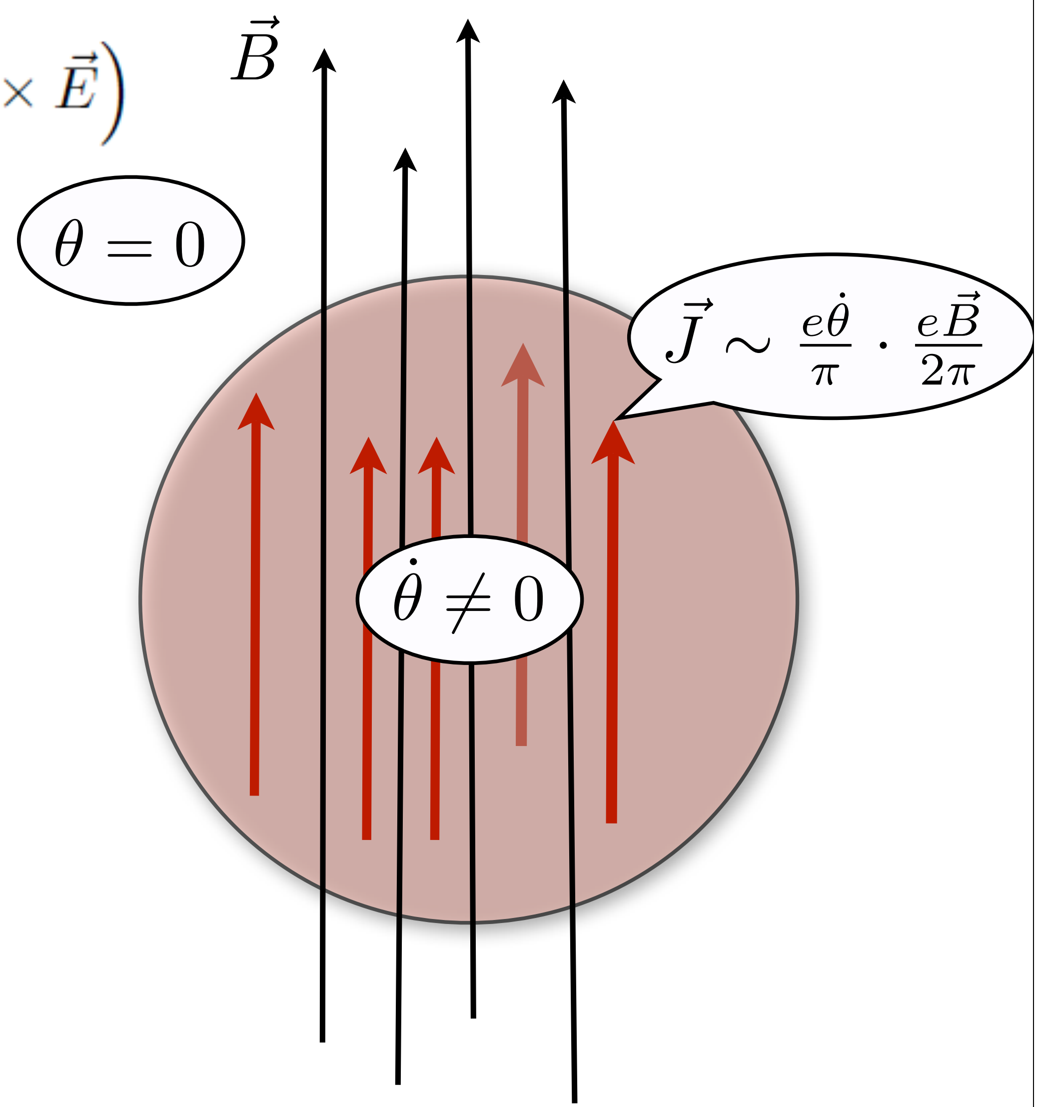
$$d_e = \sum_f q_f^2 \left( e\,\frac{\theta}{\pi} \right) \left( \frac{eB \cdot S}{2\pi} \right) L$$




DK ’04;
DK, A. Zhitnitsky ’06;
DK arXiv:0911.3715

# The chiral magnetic effect II: chiral induction

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

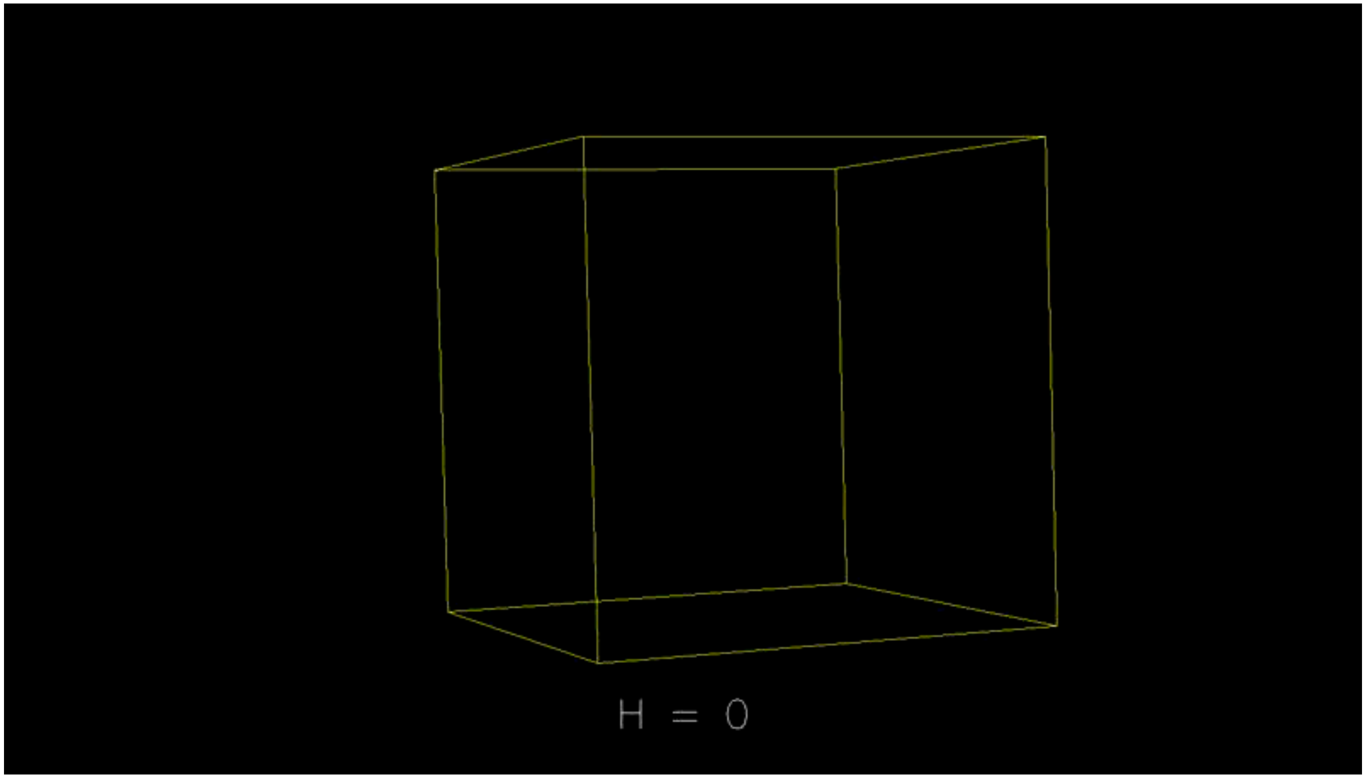



$$\vec{J} = -\frac{e^2}{2\pi^2}\dot{\theta}\vec{B}$$

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

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

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




Red - positive charge

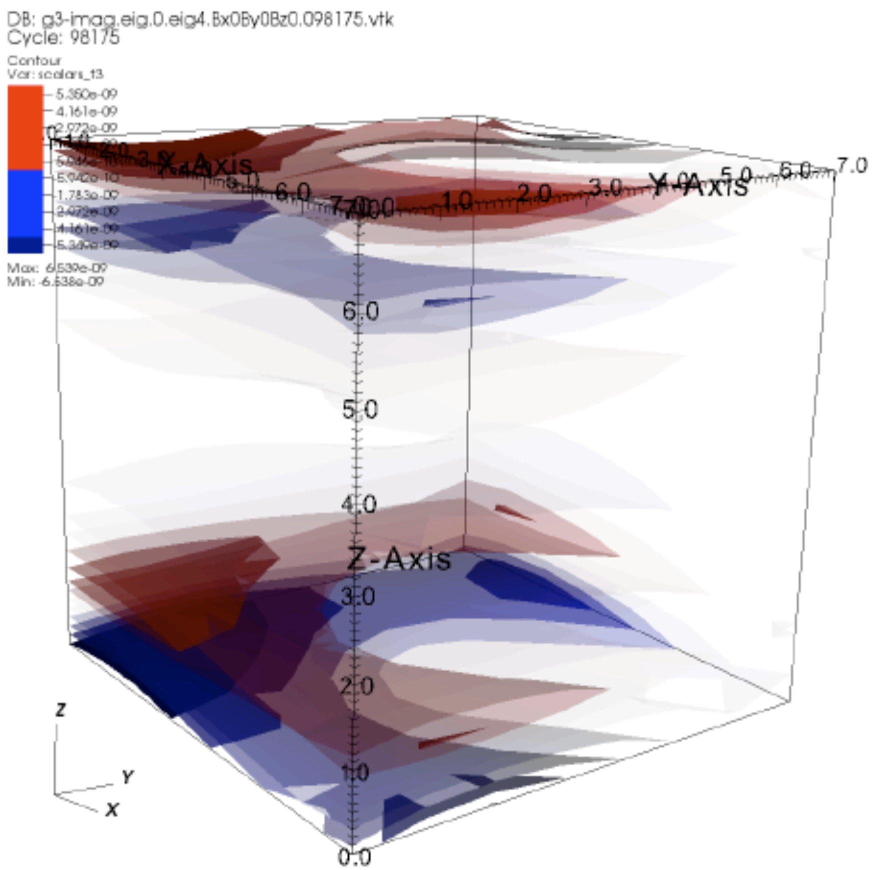
Blue - negative charge

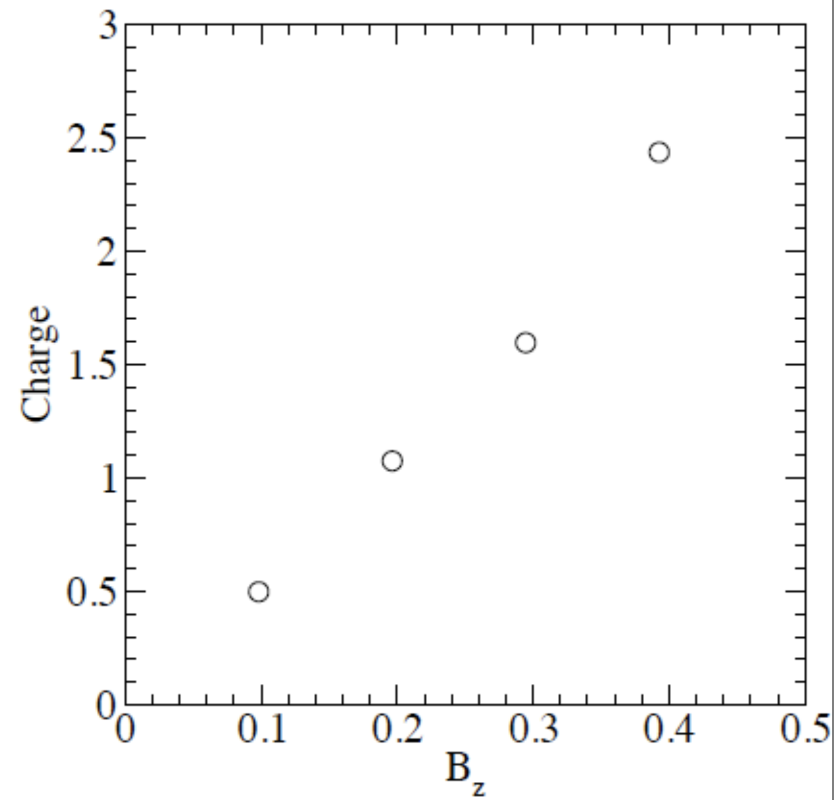
SU(2) quenched, Q = 3; Electric charge density (H) - Electric charge density (H=0)

## “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



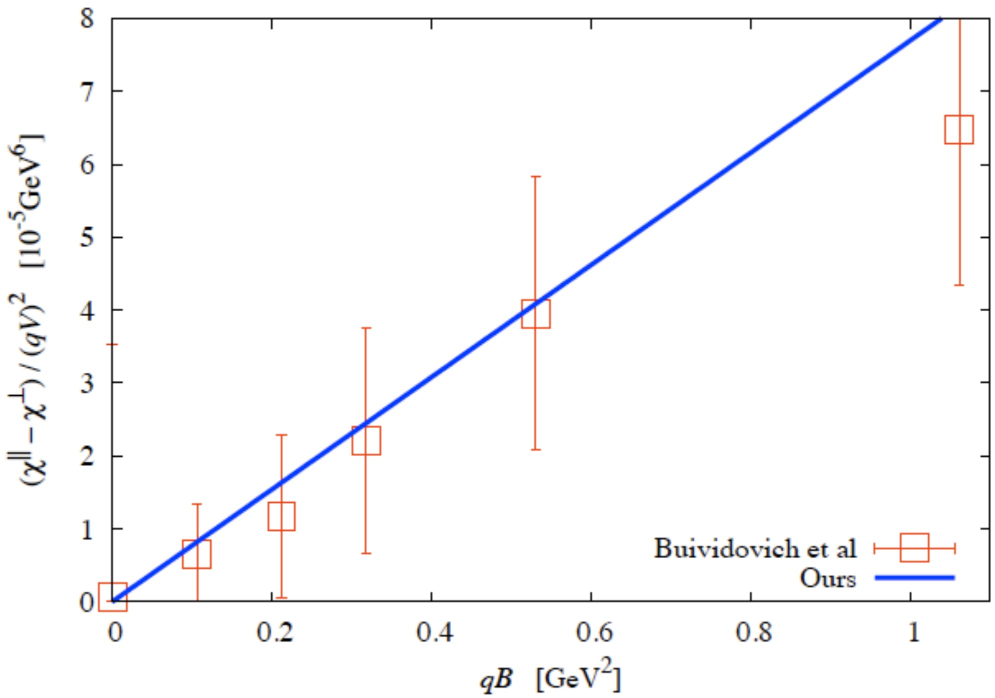




2+1 flavor Domain Wall Fermions, fixed topological sectors, 16^3 x 8 lattice

# 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.

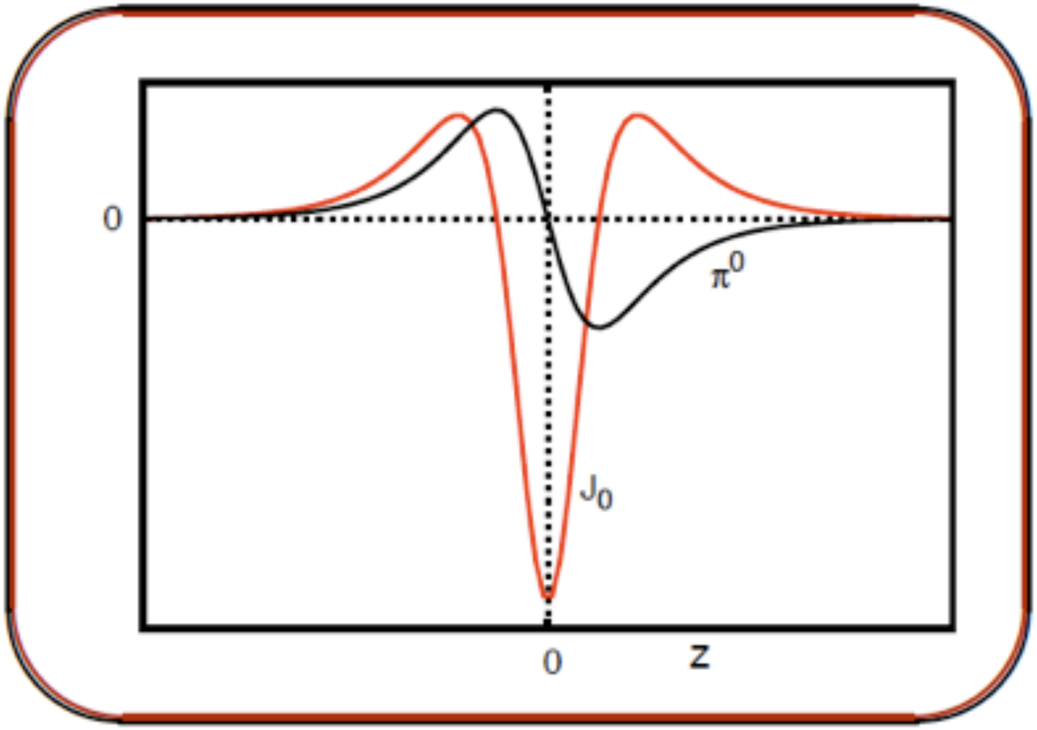
Lattice data are well reproduced theoretically.

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

$$\underset{\Lambda\to\infty}{\longrightarrow} VTN_c \sum_f \frac{q_f^2|q_f B|}{2\pi^2}\,.$$

# Charge separation at low $T$

$$J_0 = \frac{3e^2 m_\pi}{2\pi^2}\left(q_u^2 - q_d^2\right)\frac{B\cos\theta\, e^{m_\pi z}}{1 + e^{2m_\pi z}}$$




- $J_0 \to 0$ as $m_\pi \to 0$

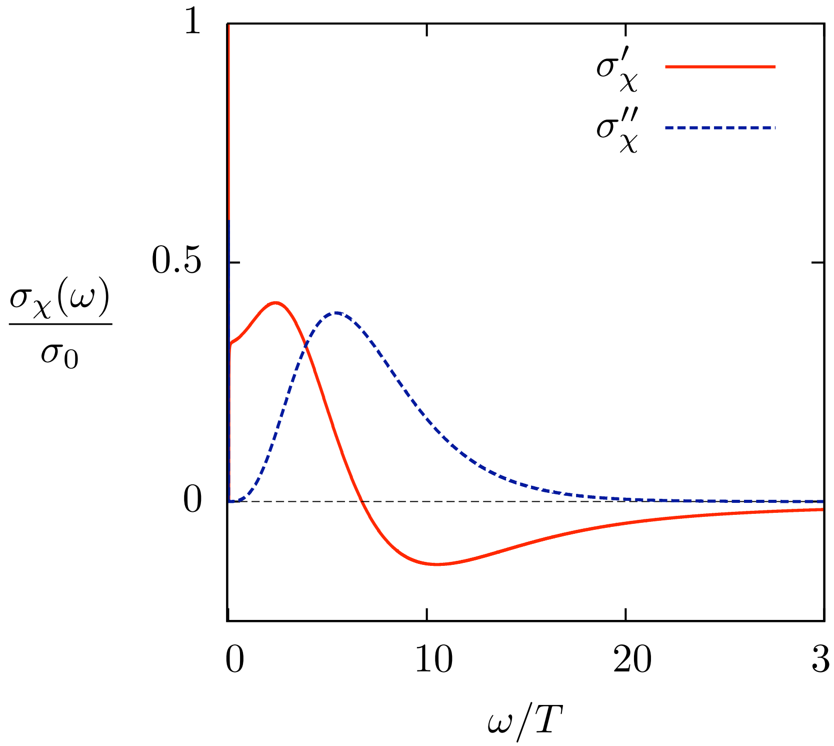
**Induced charge in the confined chirally broken phase is suppressed**

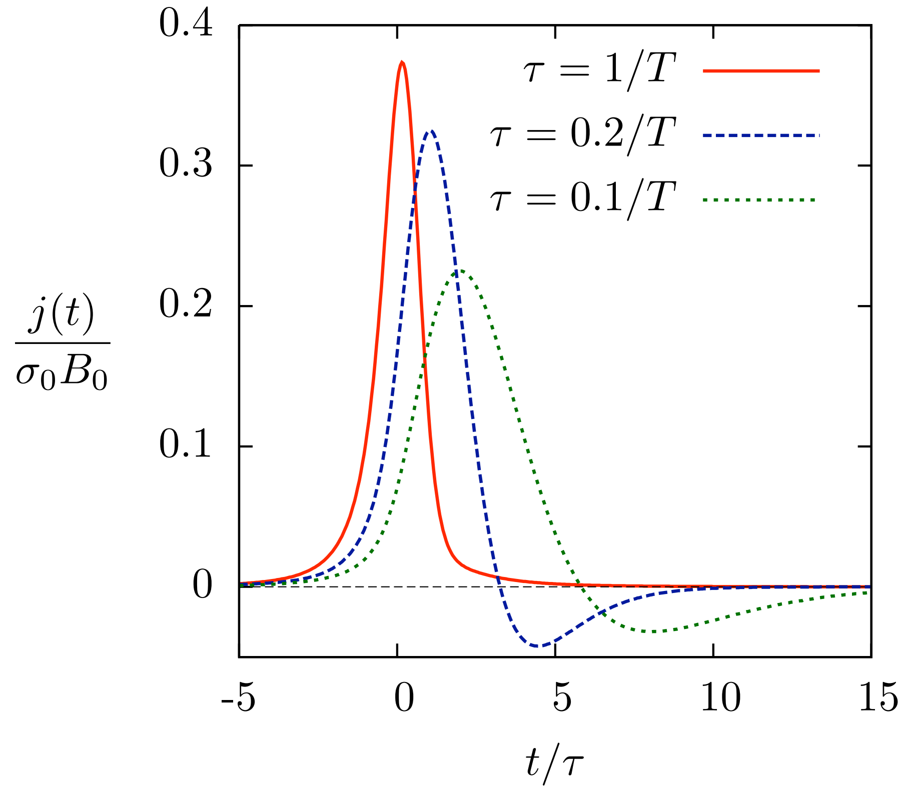
**Talk by S. Mukherjee**

# Chiral magnetic conductivity

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

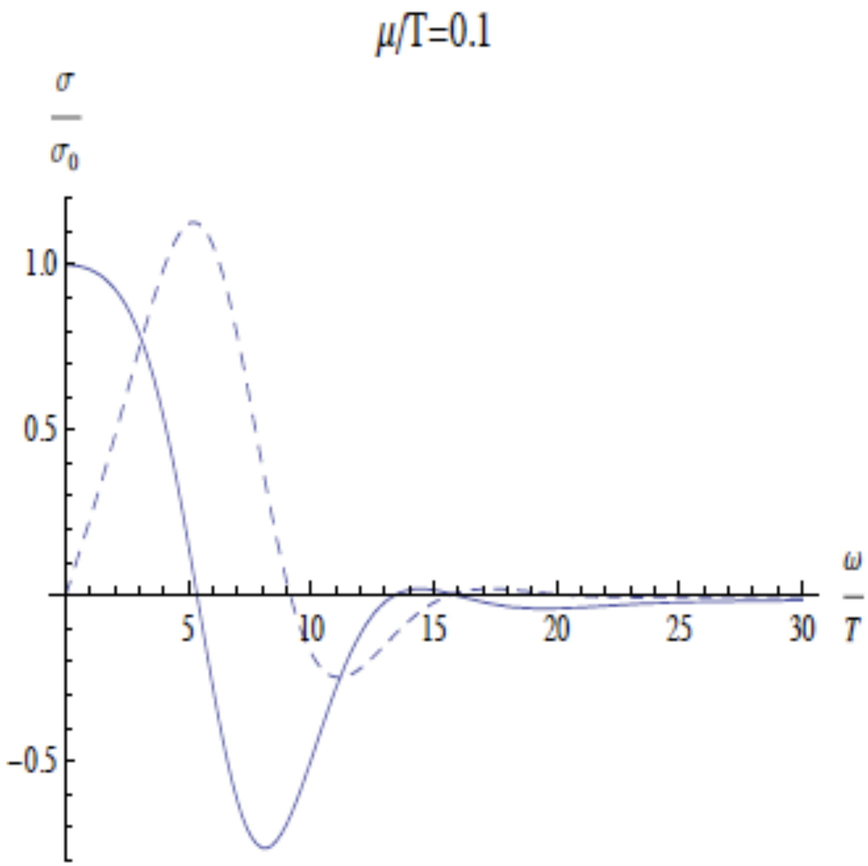
$$\sigma_\chi(\omega = 0, \boldsymbol{p} = 0) \equiv \sigma_0 = \frac{e^2}{2\pi^2}\mu_5$$




D.K., H. Warringa PRD'09

# Holographic chiral magnetic conductivity: the strong coupling regime




H.-U. Yee, arXiv:0908.4189

A. Rebhan et al, JHEP 0905, 084 (2009), and to appear;
G.Lifshytz, M.Lippert, arXiv:0904.4772

Sakai-Sugimoto model;

D.Son and P.Surowka, arXiv:0906.5044

CME in relativistic hydrodynamics;

E. D' Hoker and P. Krauss, arXiv:0911.4518

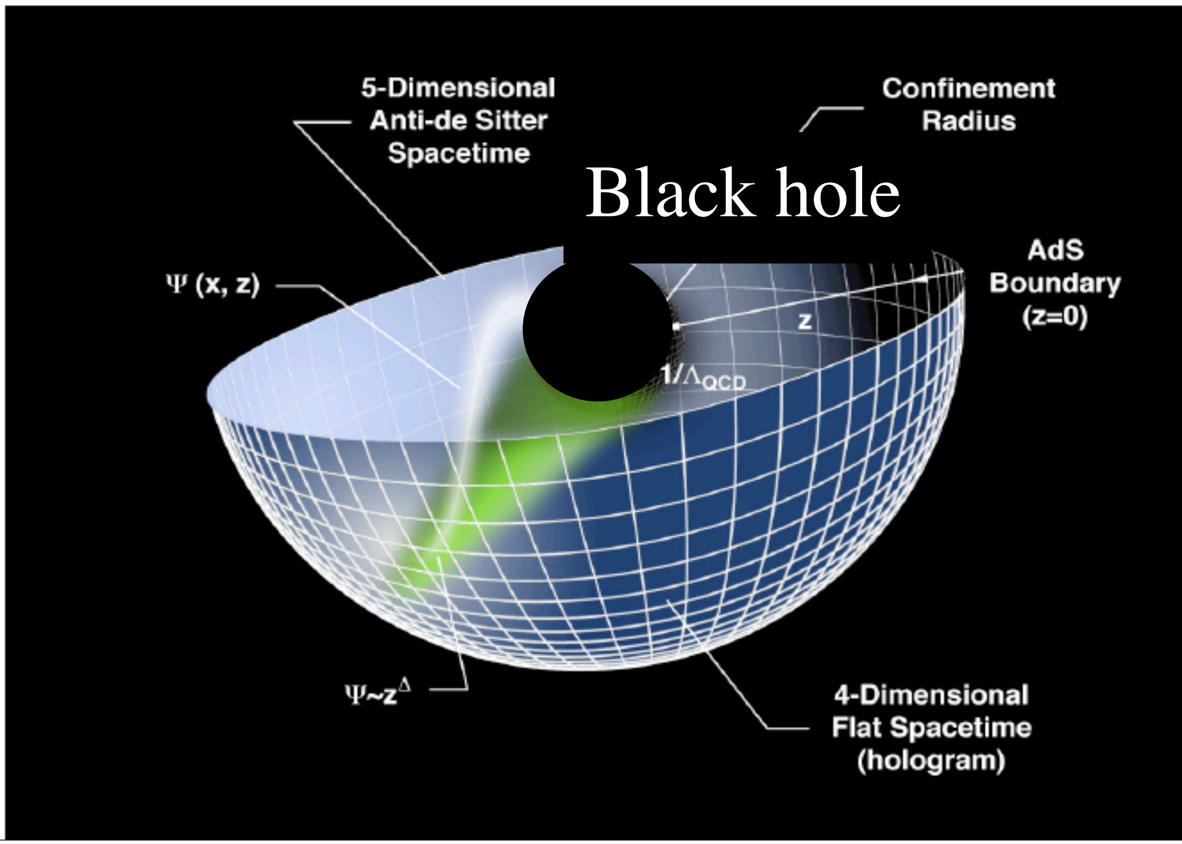
5D Einstein gravity with Reissner-Nordstrom black hole coupled to $U(1)_L \times U(1)_R$

# Topological number diffusion at strong coupling

Chern-Simons number diffusion rate at strong coupling

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

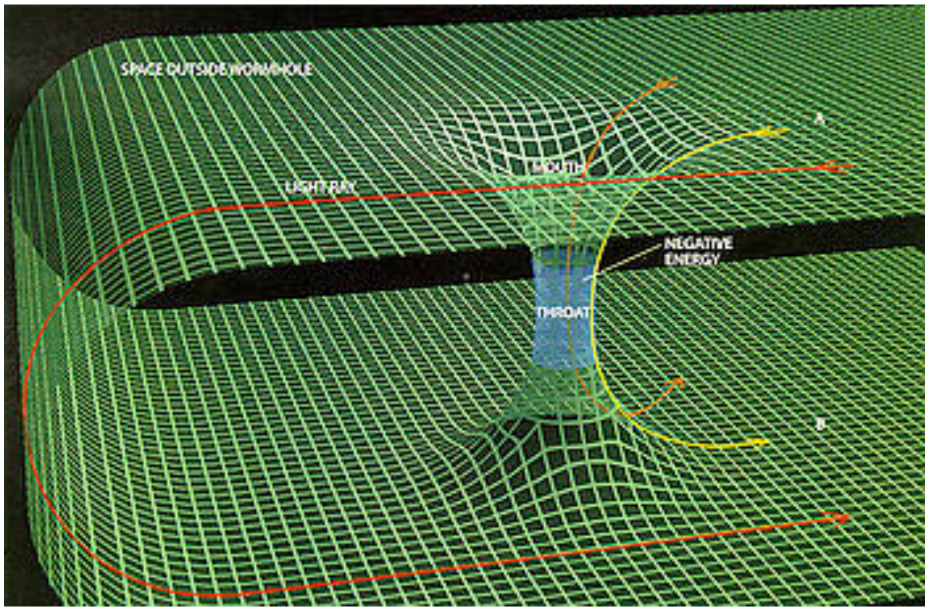
D.Son, A.Starinets hep-th/ 020505




NB: This calculation is completely analogous to the calculation of shear viscosity that led to the "perfect liquid"

# Classical topological solutions at strong coupling?

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



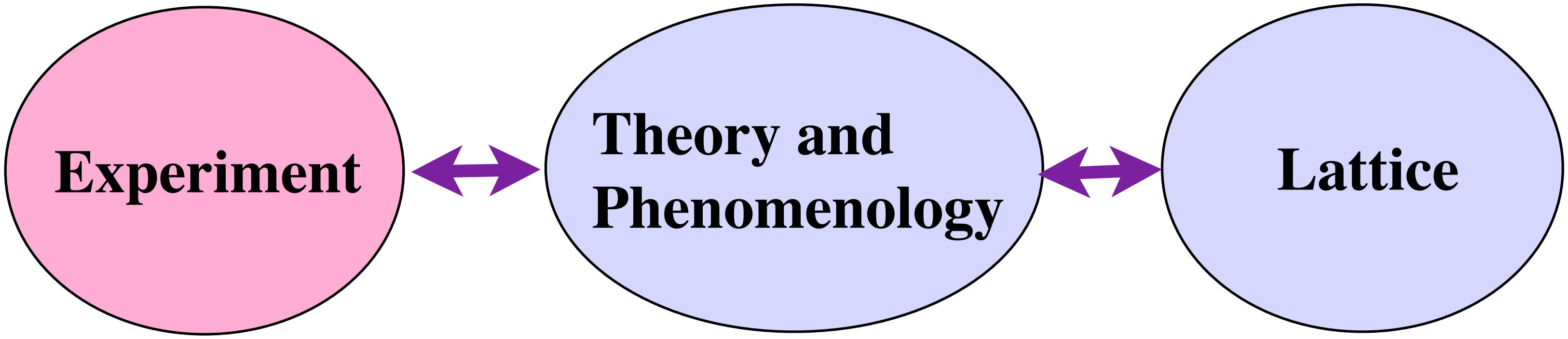

D-instanton as
an Einstein-Rosen
wormhole;
the flow of RR charge
down the throat of
the wormhole describes
change of chirality

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

# What next?



# Further tests at RHIC

- Parity-odd observable?
- Correlations for identified hadrons? K^0?
- Low-energy run: the effect is expected to weaken below the deconfinement/chiral symmetry transition
- P-odd decays? talk by E.Shuryak
- Double diffractive production in pp collisions: sphaleron decay in magnetic field?

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

RIKEN BNL Research Center Workshop
April 26-30, 2010 at Brookhaven National Laboratory

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Save the date: April 26-30, 2010

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Supported by RIKEN-BNL, BNL, and Stony Brook University