26th Winter Workshop on Nuclear Dynamics, Ocho Rios, Jamaica, January 2-9, 2010

The Chiral Magnetic Effect and Local Parity Violation

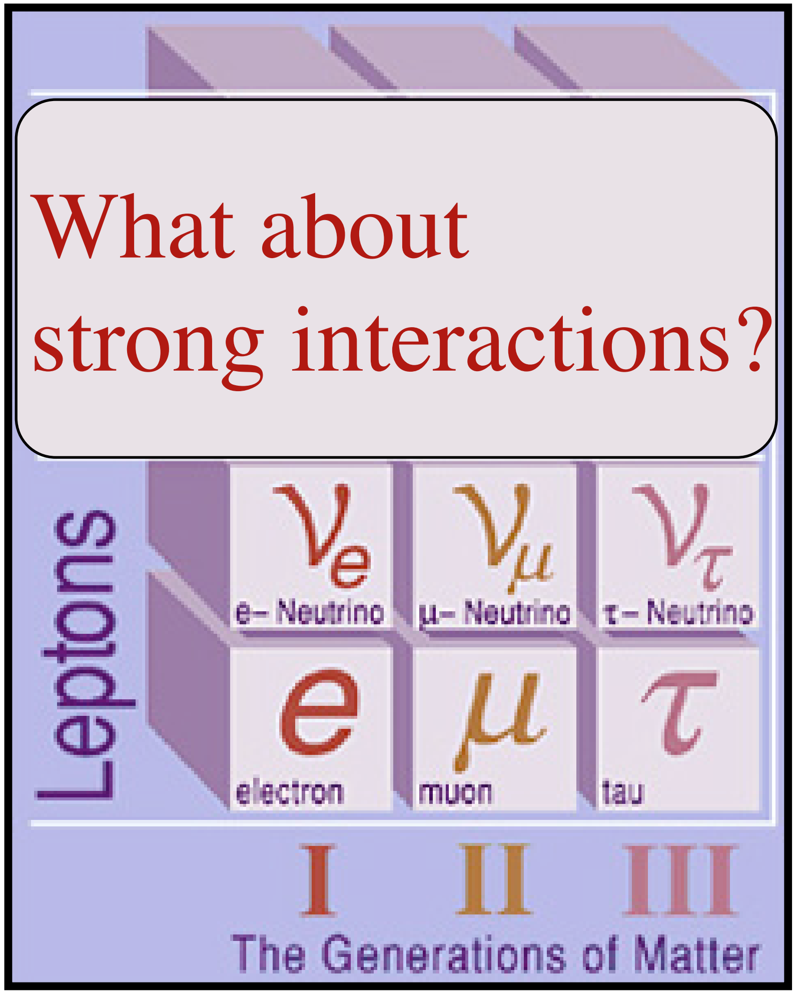
D. Kharzeev

BNL & Yale

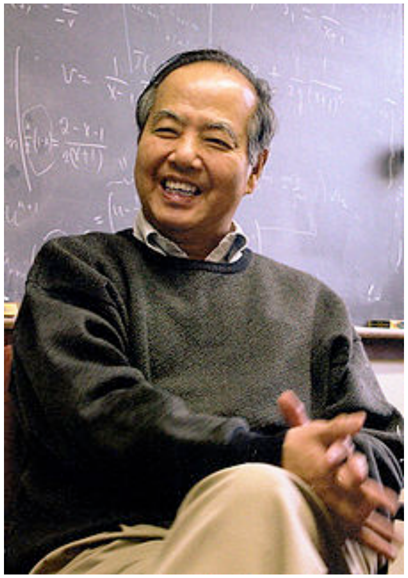
Since the beginning of physics, symmetry considerations have provided us with an extremely powerful and useful tool in our effort to understand nature. Gradually they have become the backbone of our theoretical formulation of physical laws.

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

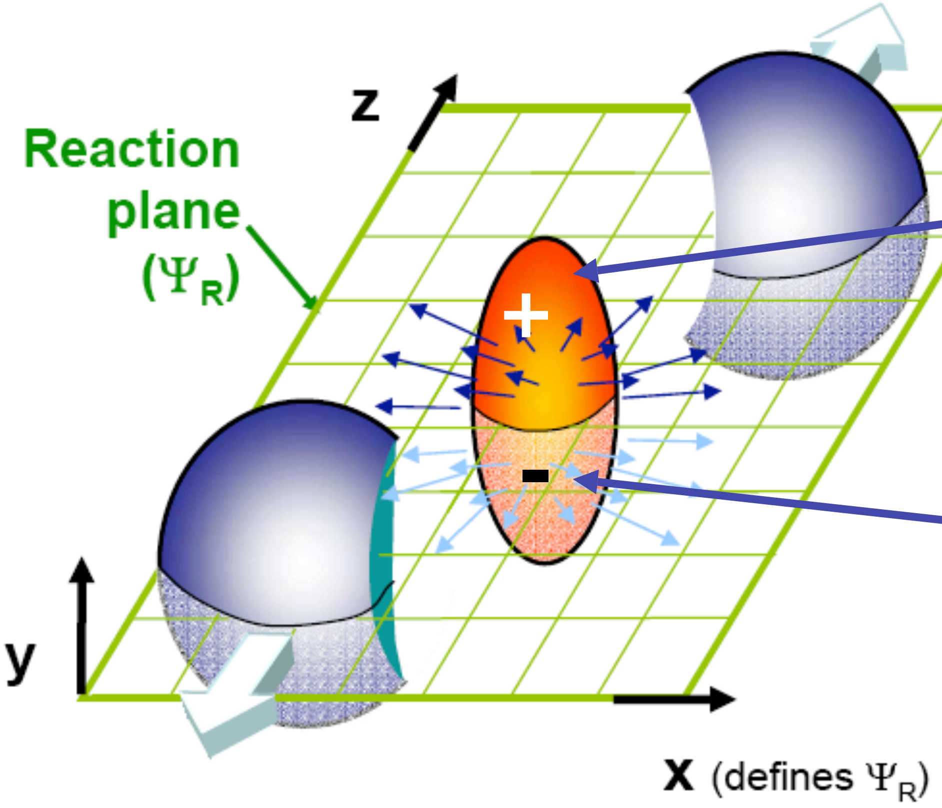
2008

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



excess of positive charge

excess of negative charge

Electric dipole moment of QCD matter!

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

PRL **103,** 251601 (2009)

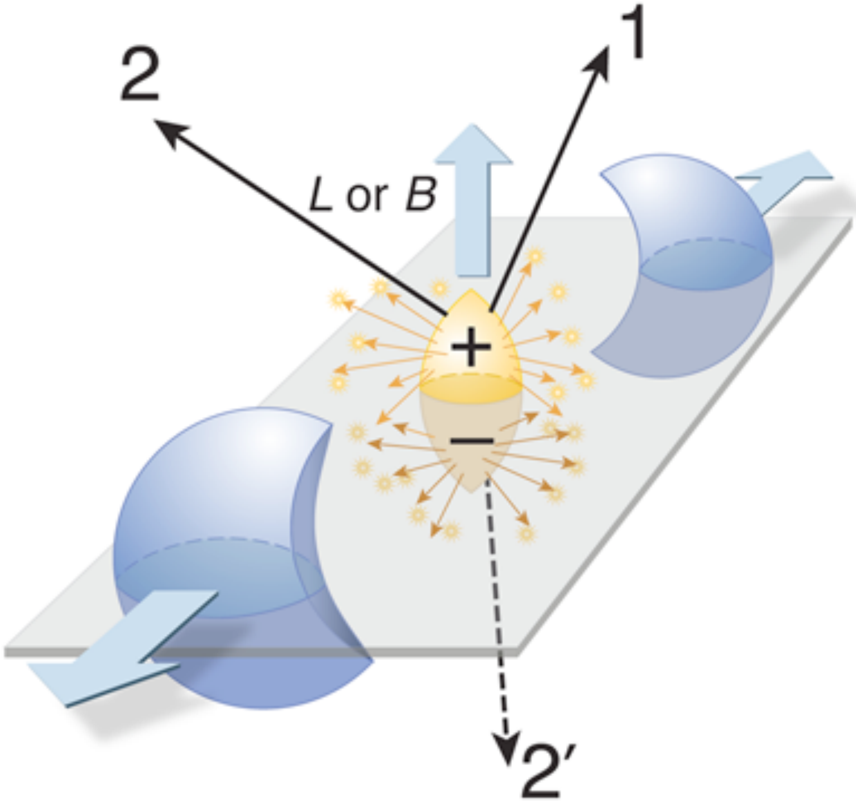
Selected for a Viewpoin

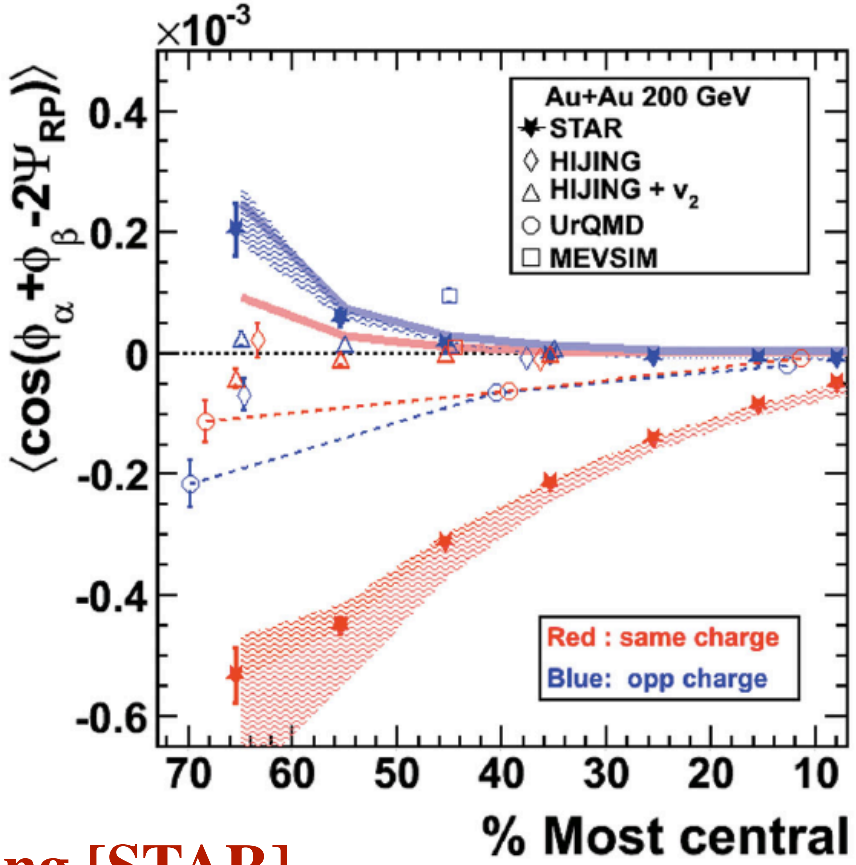
PHYSICAL REVIEW

week ending
18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

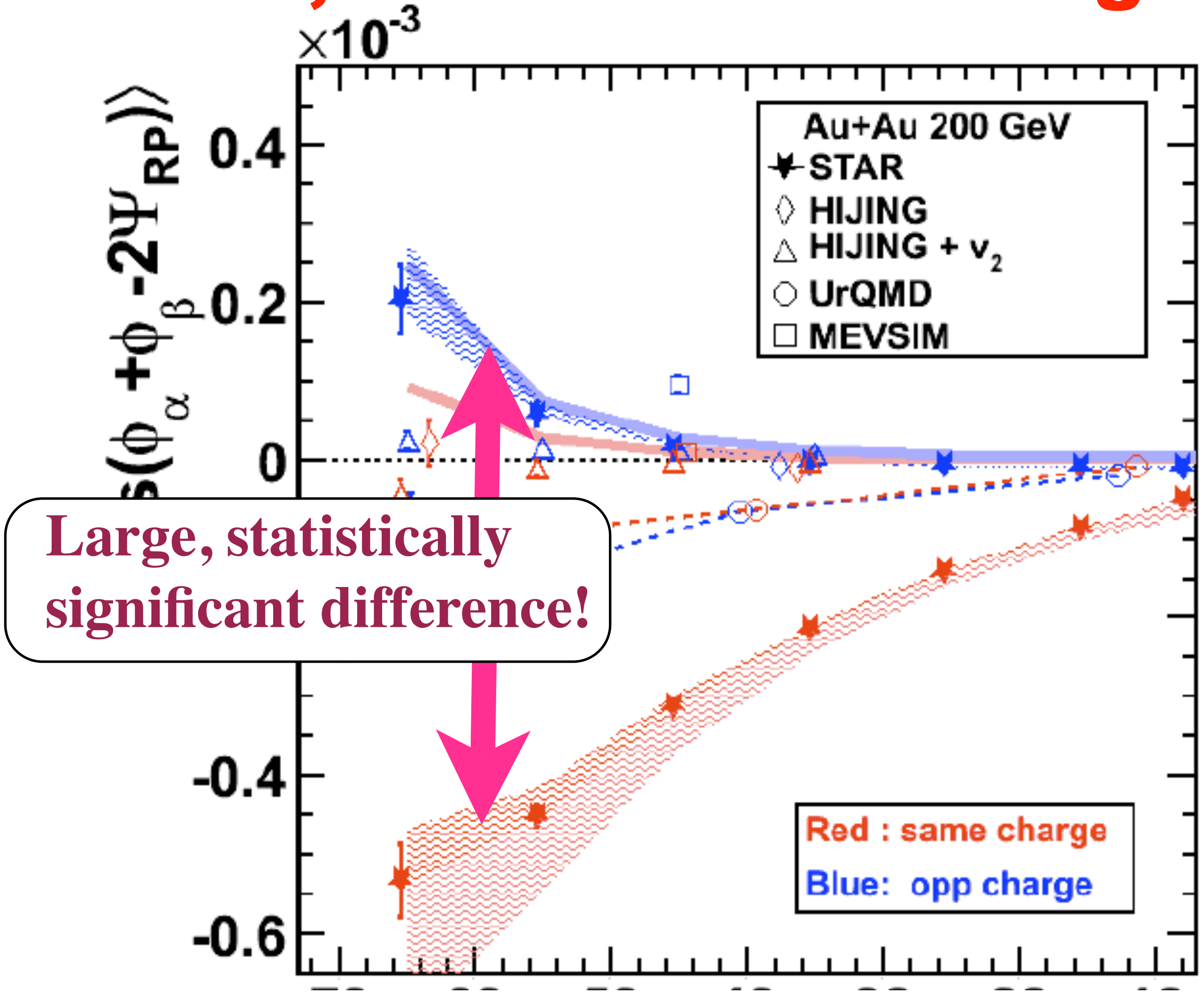
(STAR Collaboration)





Talks by S. Voloshin and G. Wang [STAR]

Local P, CP violation at high T ?



Large, statistically significant difference!

Talks by
S. Voloshin,
G. Wang

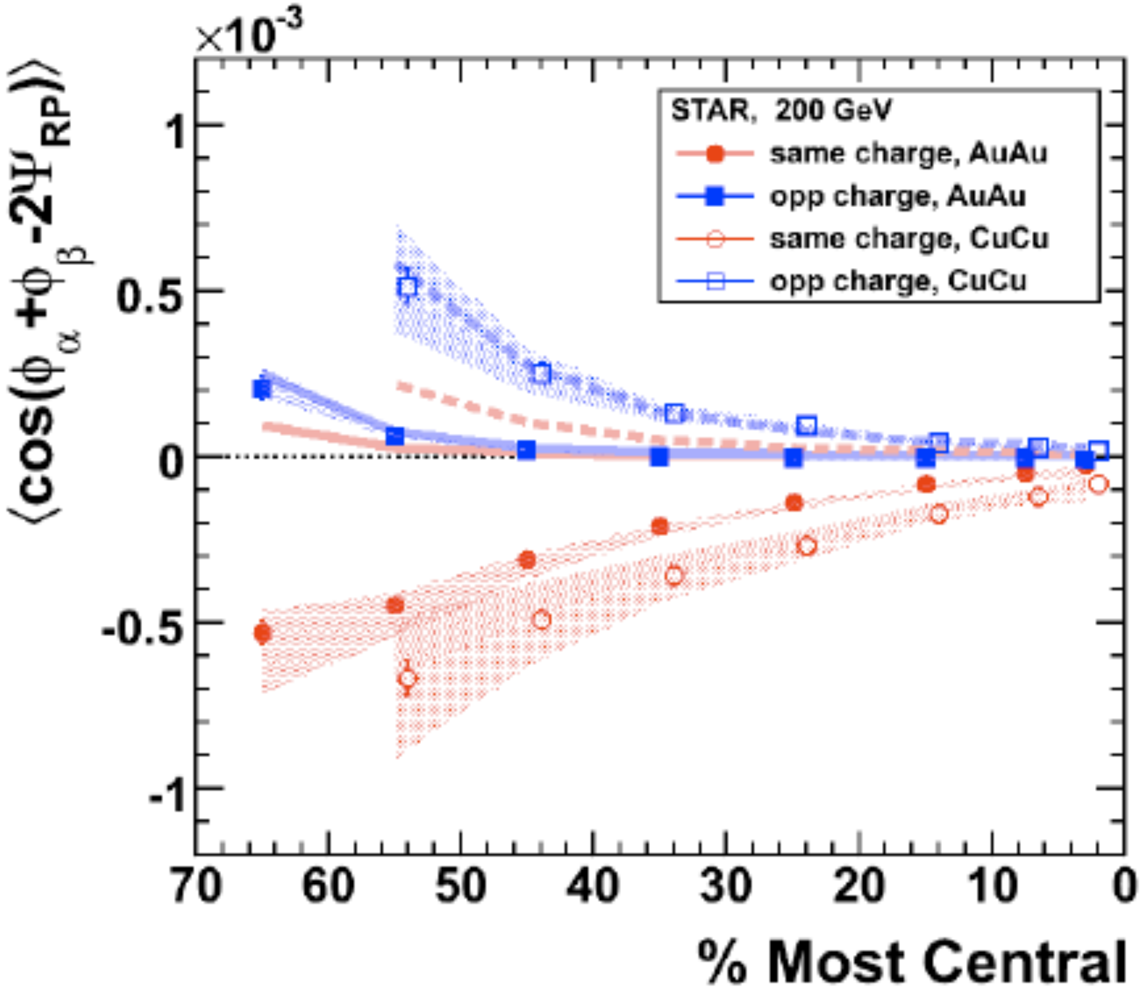
[STAR Coll.]

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

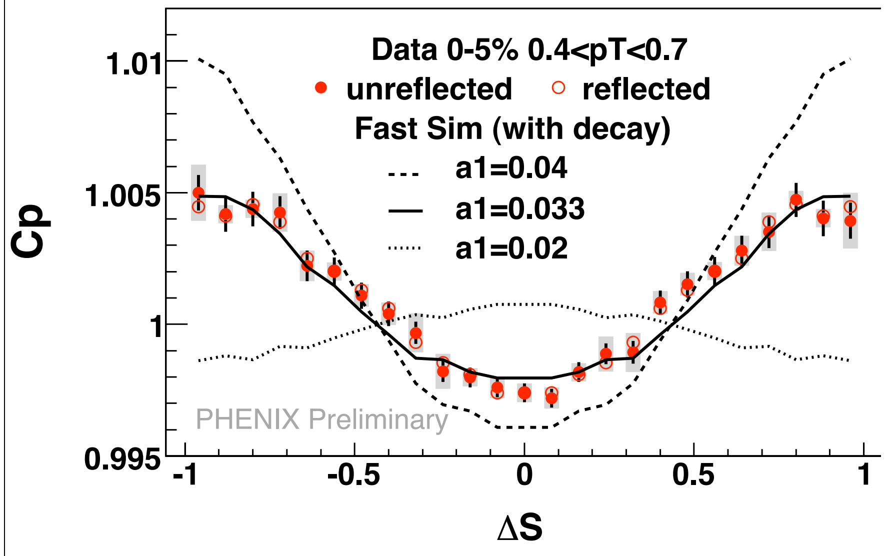
Stronger opposite-charge correlations in CuCu (less absorption?)

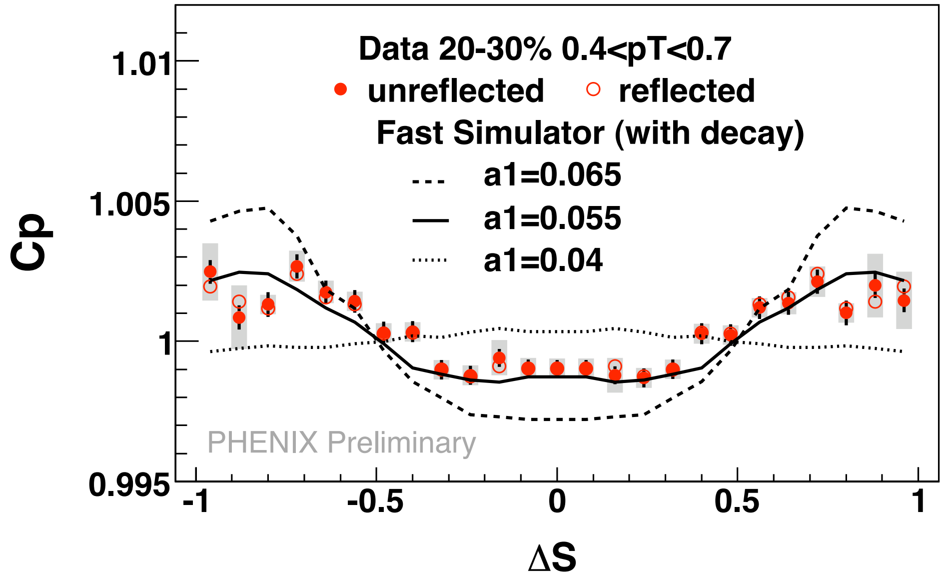


STAR Coll.,
arXiv:0909.1717

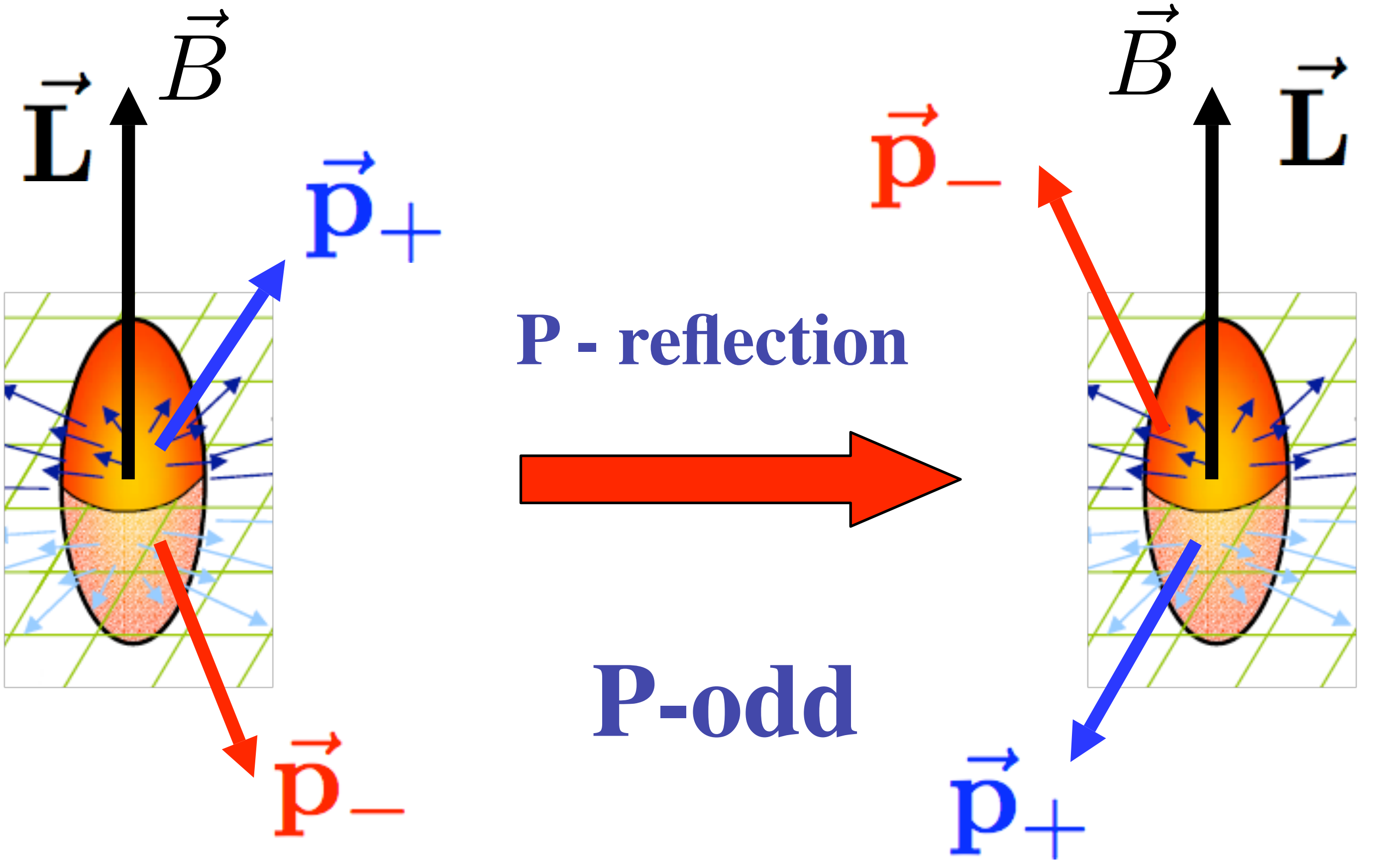
The PHENIX result

talk by N. Ajitanand, Dec 17





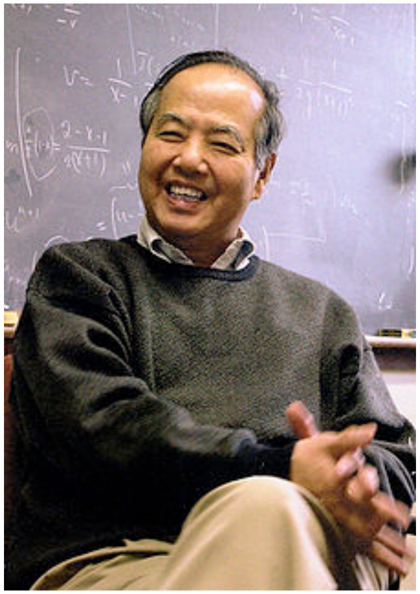
Charge separation = parity violation:

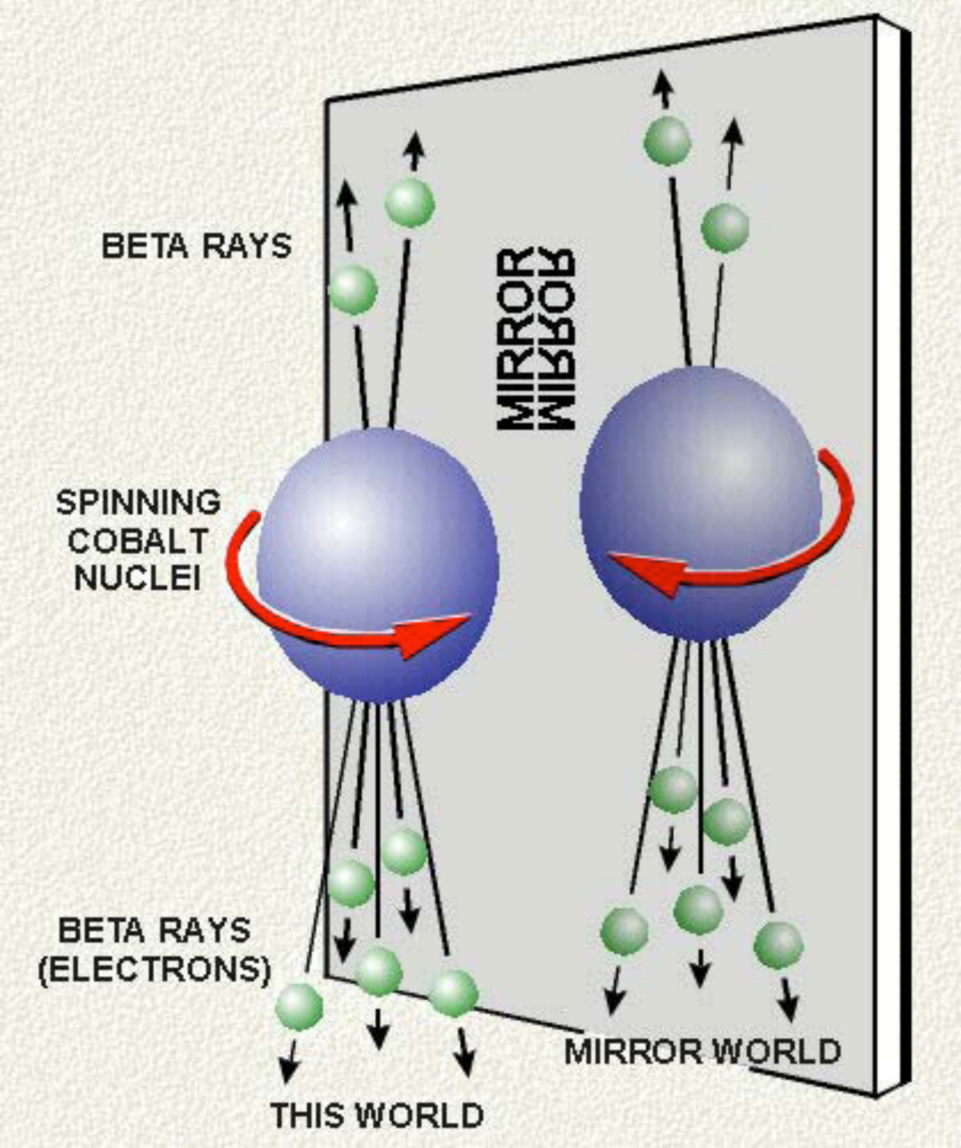


P-odd

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

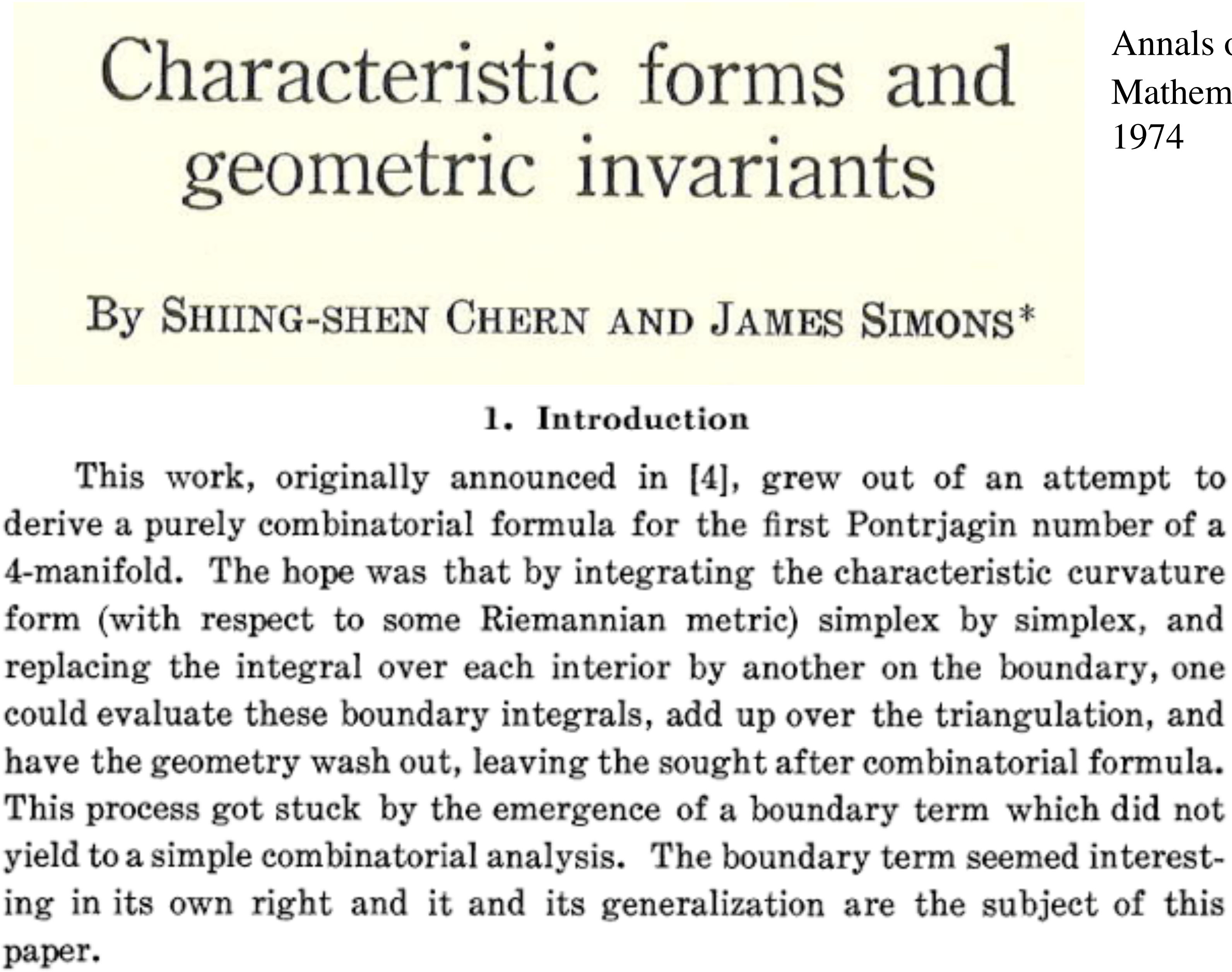
Analogy to P violation in weak interactions





C.S. Wu, 1912-1997

BUT:
the sign of
the asymmetry
fluctuates
event by event



Characteristic forms and geometric invariants

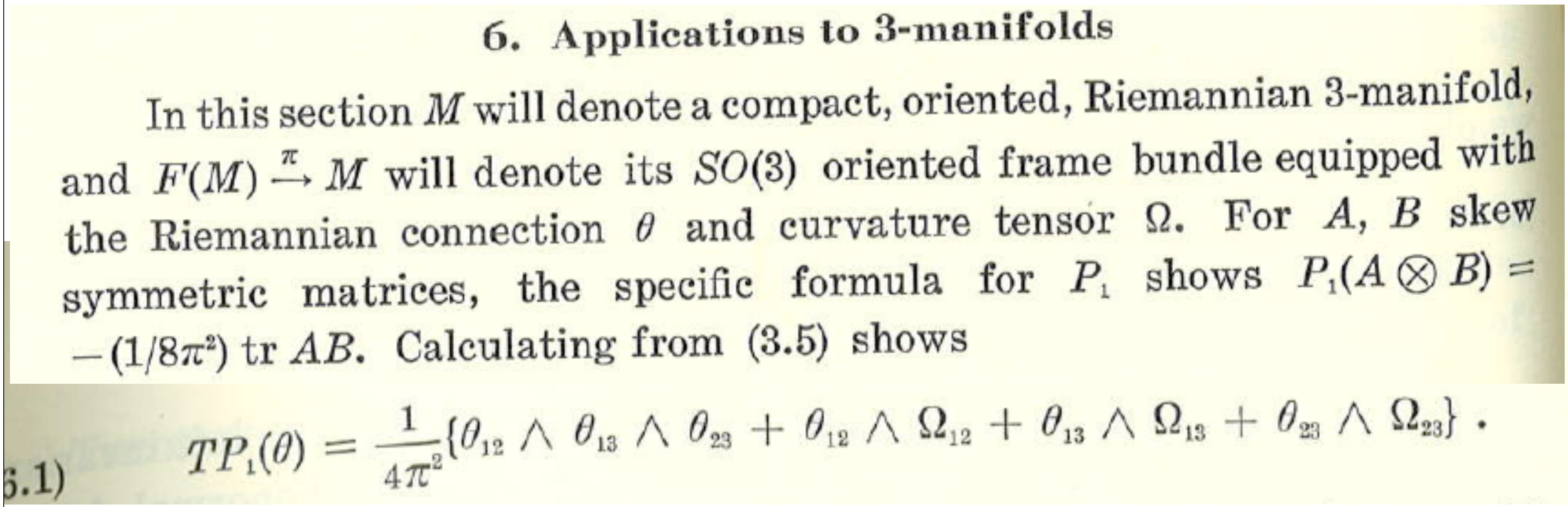
By Shiing-shen Chern and James Simons[*]

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.

Annals of
Mathematics,
1974

Chern-Simons forms



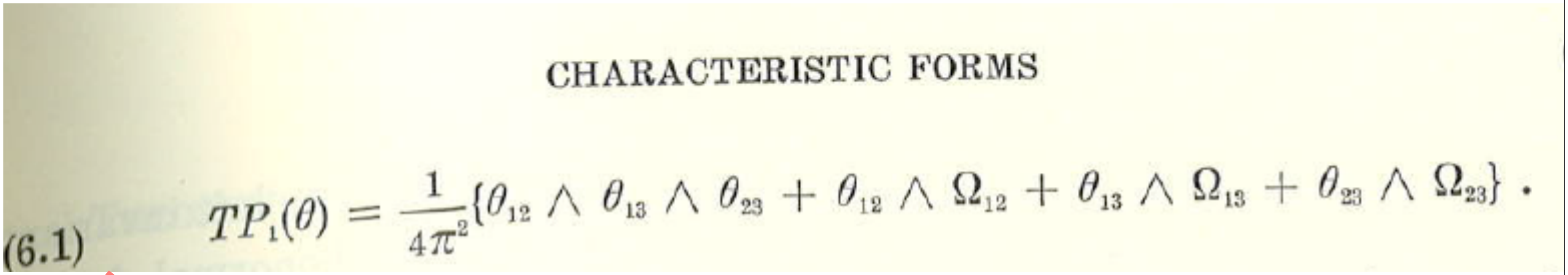
6. Applications to 3-manifolds

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 $P_1(A \otimes B) = -(1/8\pi^2)\,\mathrm{tr}\,AB$. Calculating from (3.5) shows

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

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

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

Abelian non-Abelian

Chern-Simons theory

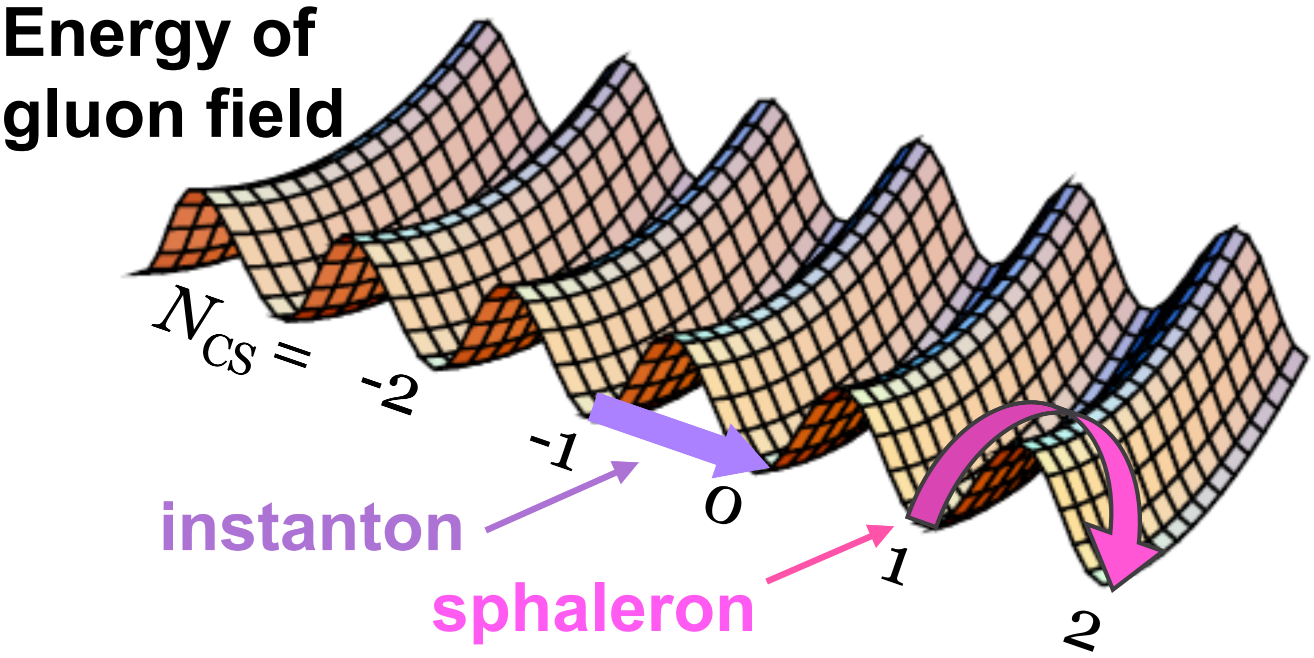
$$\boxed{S_{CS} = \frac{k}{8\pi} \int_M d^3x \; \epsilon^{ijk} \left(A_i F_{jk} + \frac{2}{3} A_i [A_j, A_k] \right)}$$

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

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

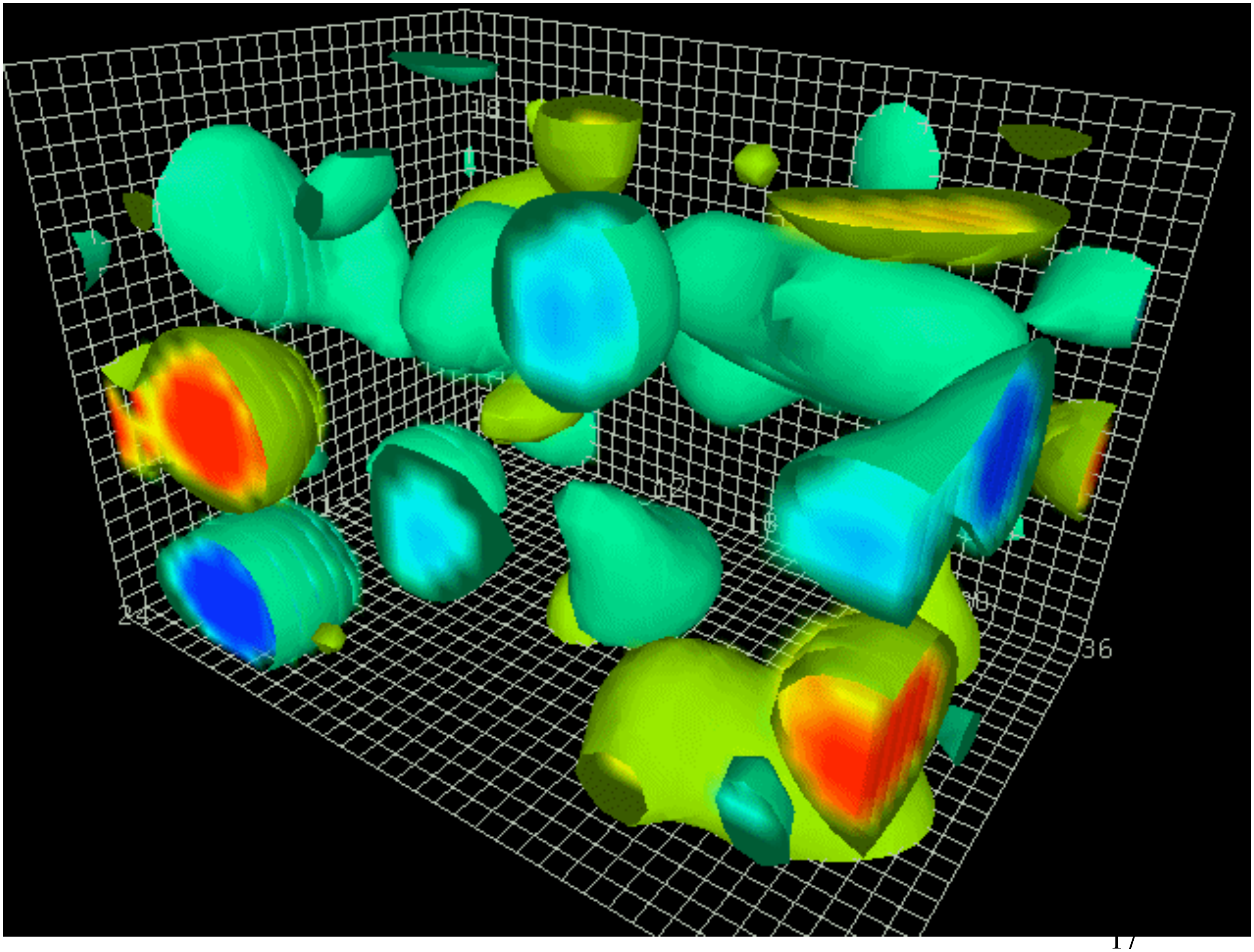


Sphalerons:
random walk of
topological charge at finite T:

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

Topological number fluctuations in QCD vacuum

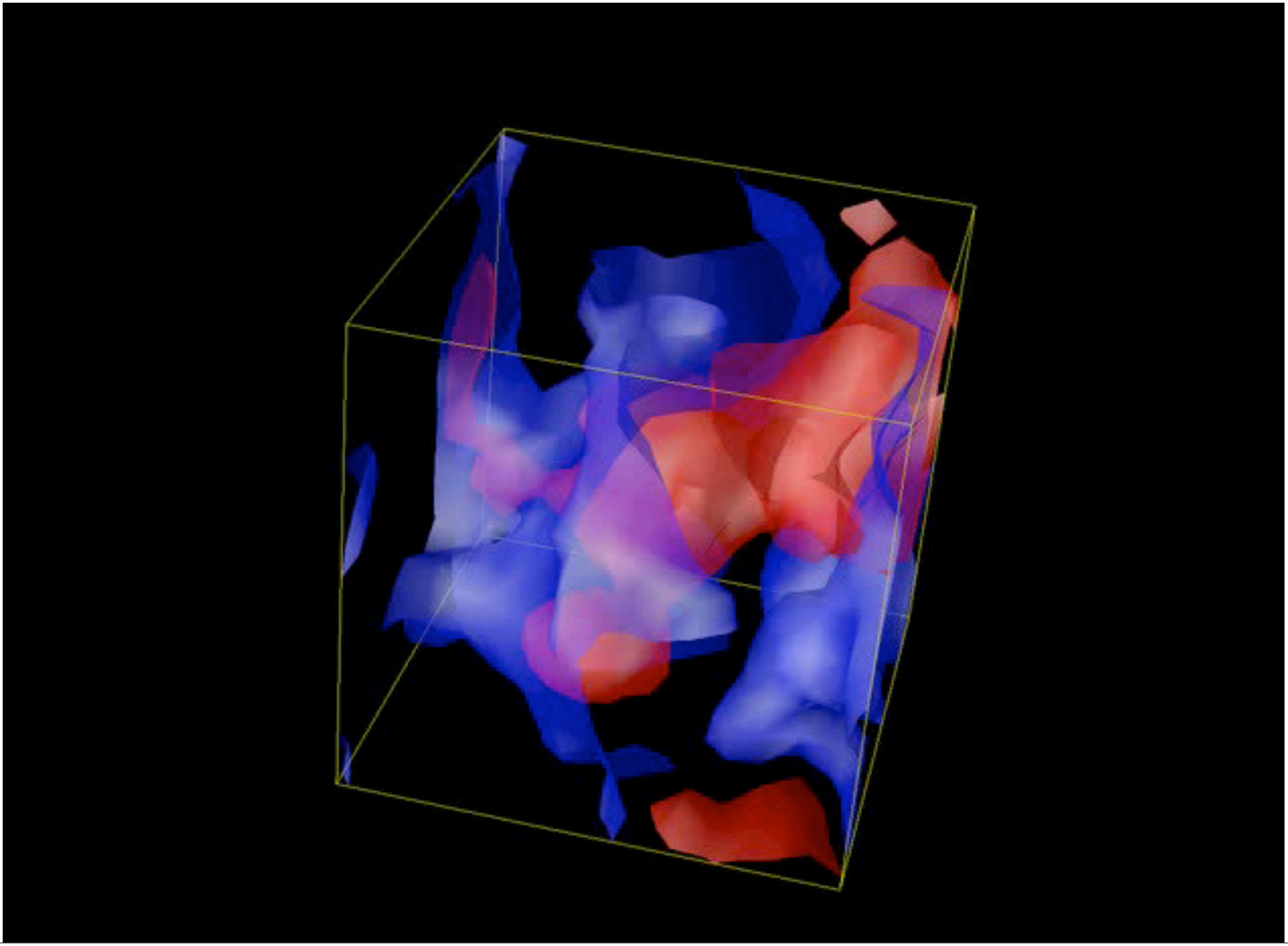
(“cooled” configurations)



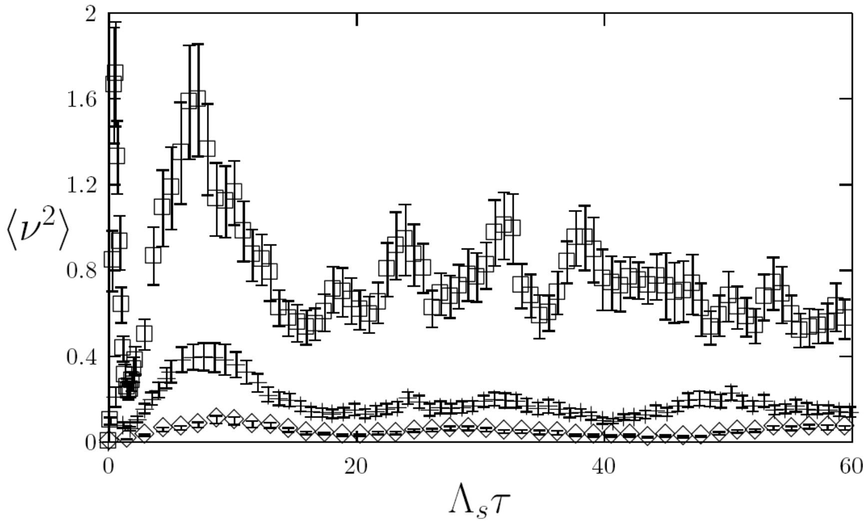
D. Leinweber

Topological number fluctuations in QCD vacuum

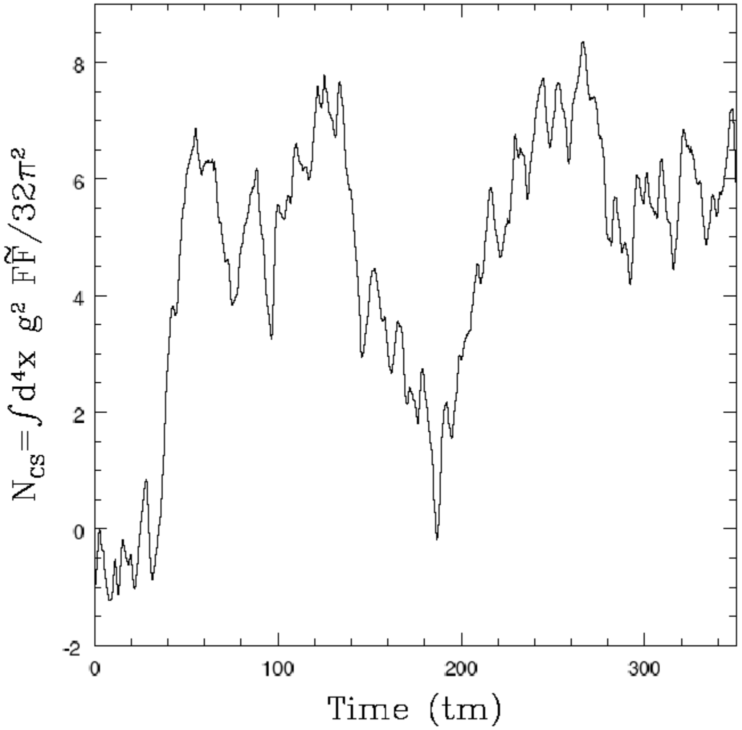
ITEP Lattice Group



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



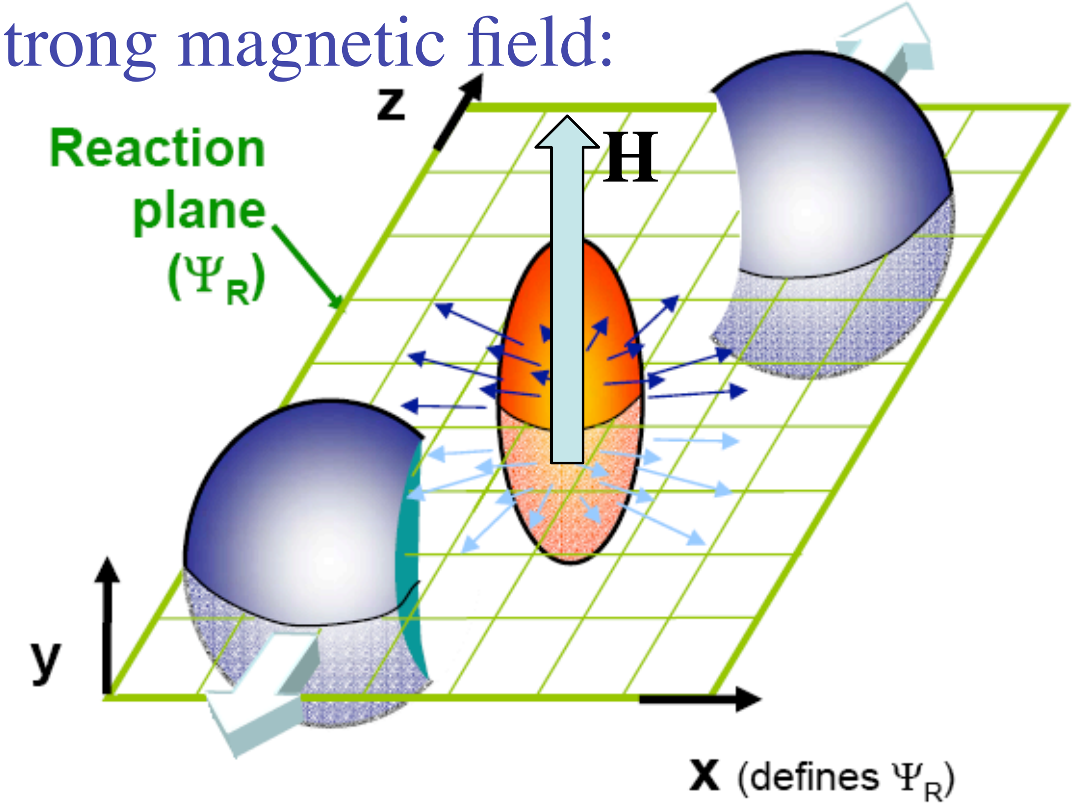
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002

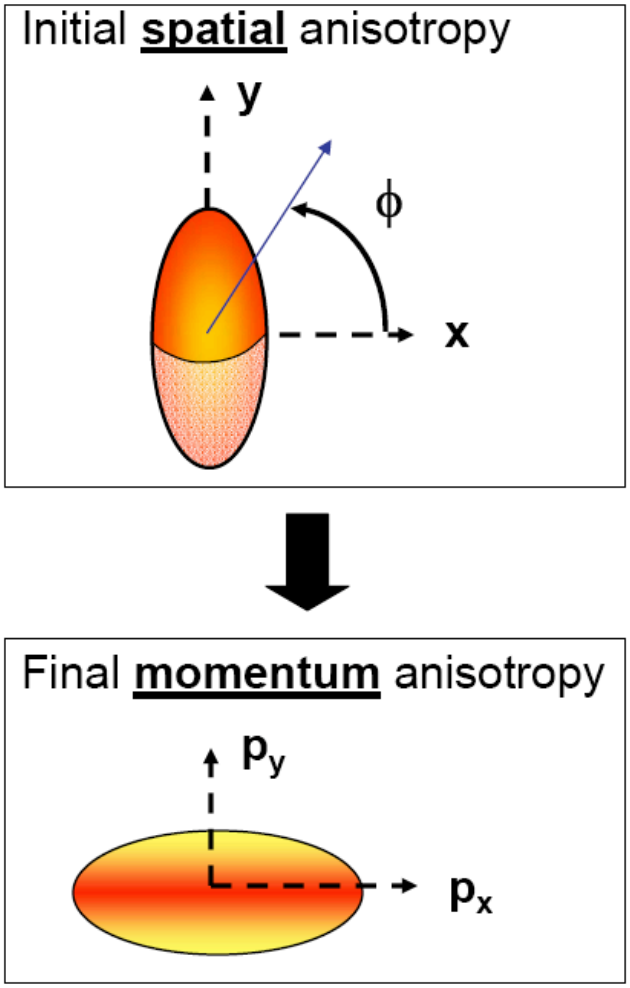


P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

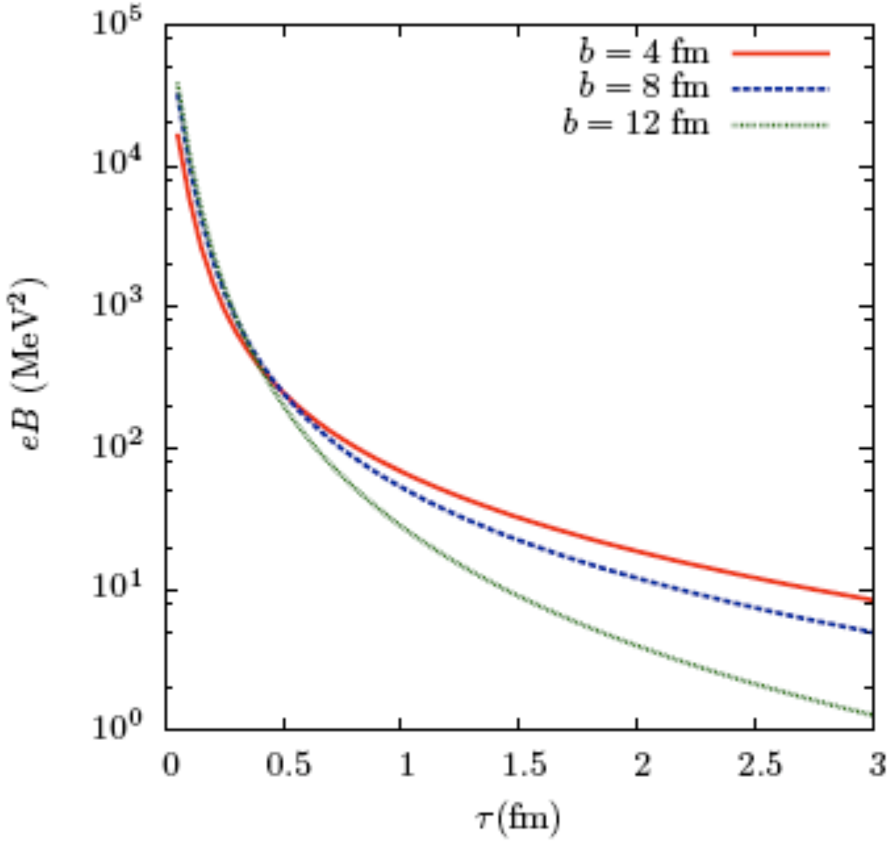
Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create a strong magnetic field:





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



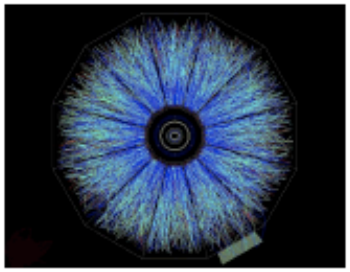
DK, McLerran, Warringa

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 x 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

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

From QCD back to electrodynamics: Maxwell-Chern-Simons theory

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

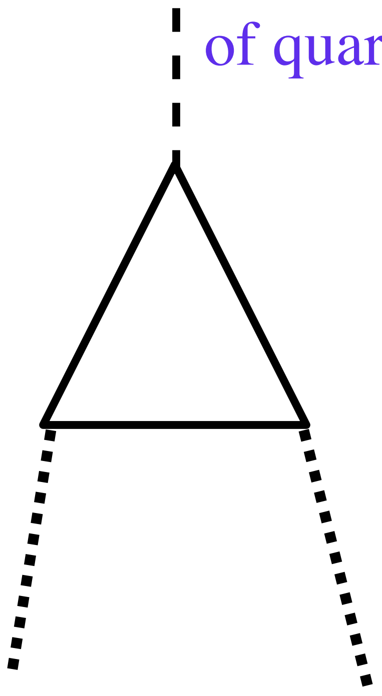
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu\theta = (M, \vec{P})$$

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

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

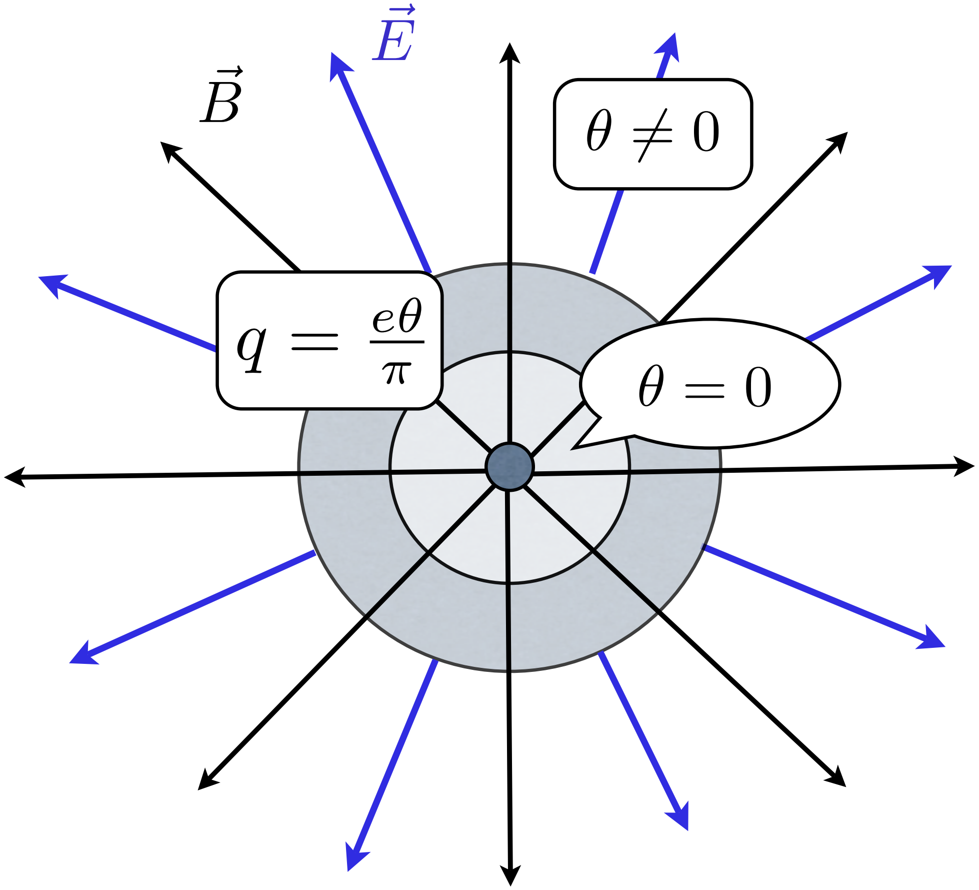
$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = 0,$$

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



Magnetic monopole at finite θ : the Witten effect

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



E. Witten;

F. Wilczek

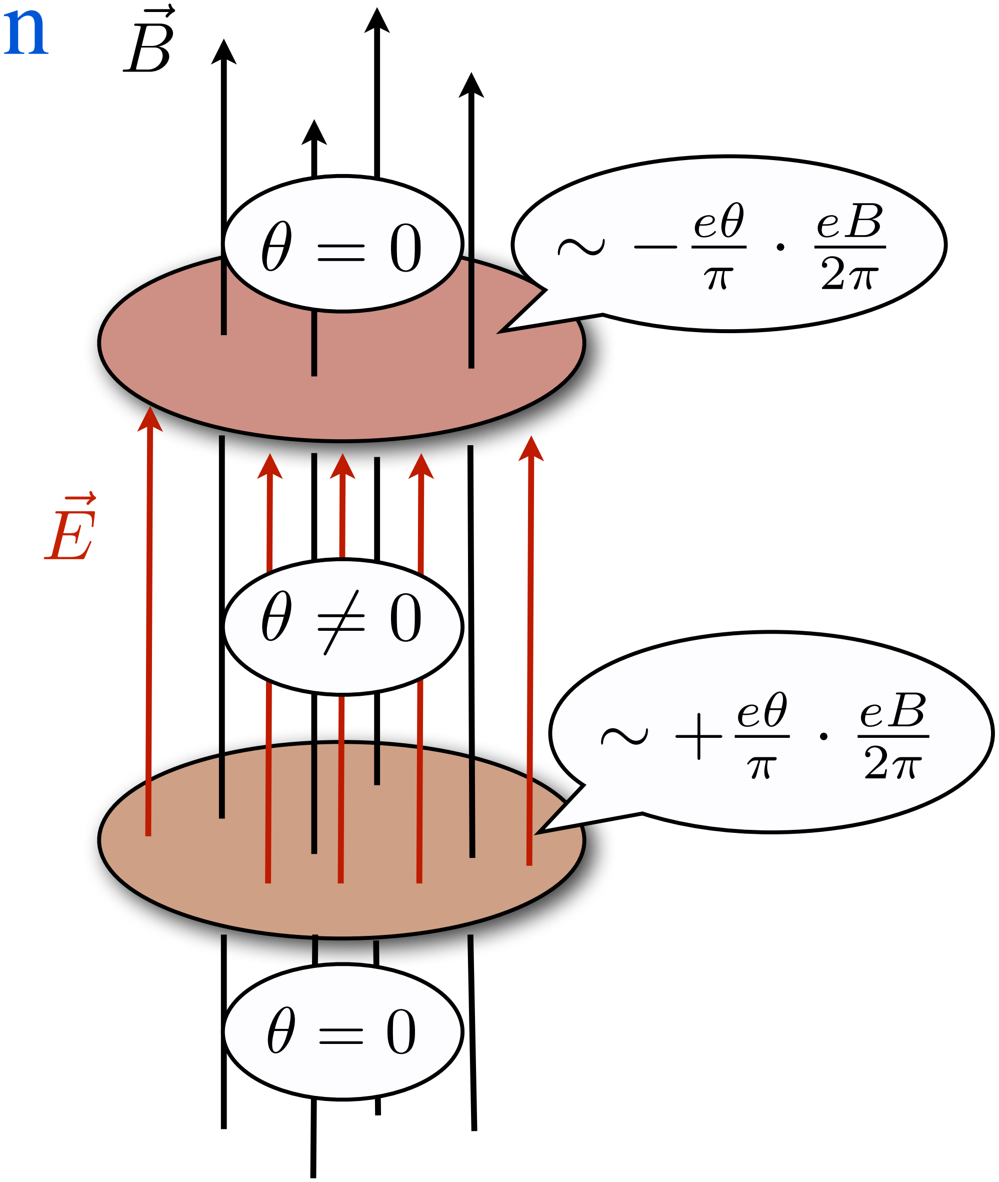
$$q = c\ \theta\ g = \frac{e^2}{2\pi^2}\ \theta\ g = \frac{e}{2\pi^2}\ \theta\ (eg) = e\ \frac{\theta}{\pi}$$

The Chiral Magnetic Effect I:
Charge separation

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

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

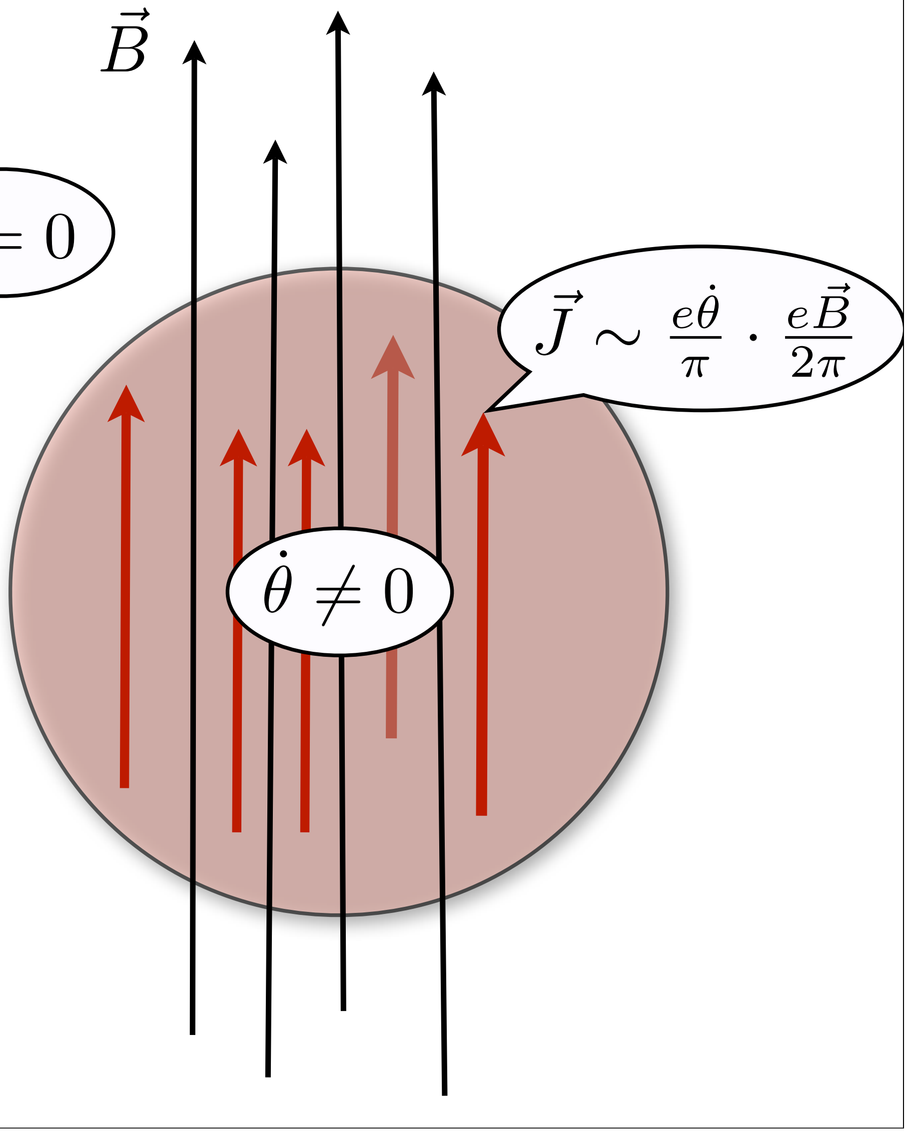
$$\boxed{d_e = \sum_f q_f^2 \left(e\,\frac{\theta}{\pi}\right)\left(\frac{eB\cdot S}{2\pi}\right) L}$$



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

The chiral magnetic effect II: chiral induction

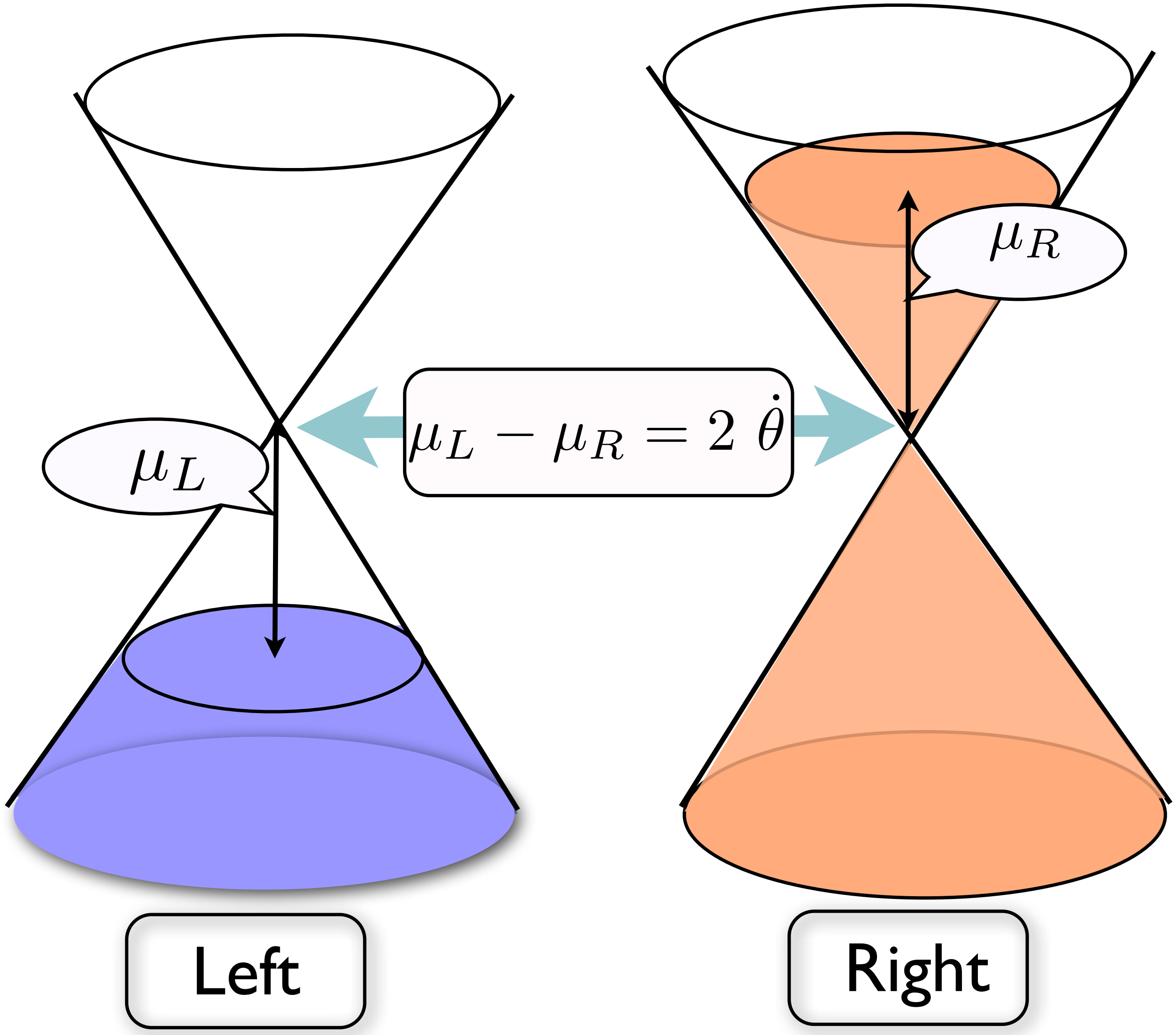
$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(\dot{\theta}\vec{B} - \vec{P} \times \vec{E}\right)$$



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

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

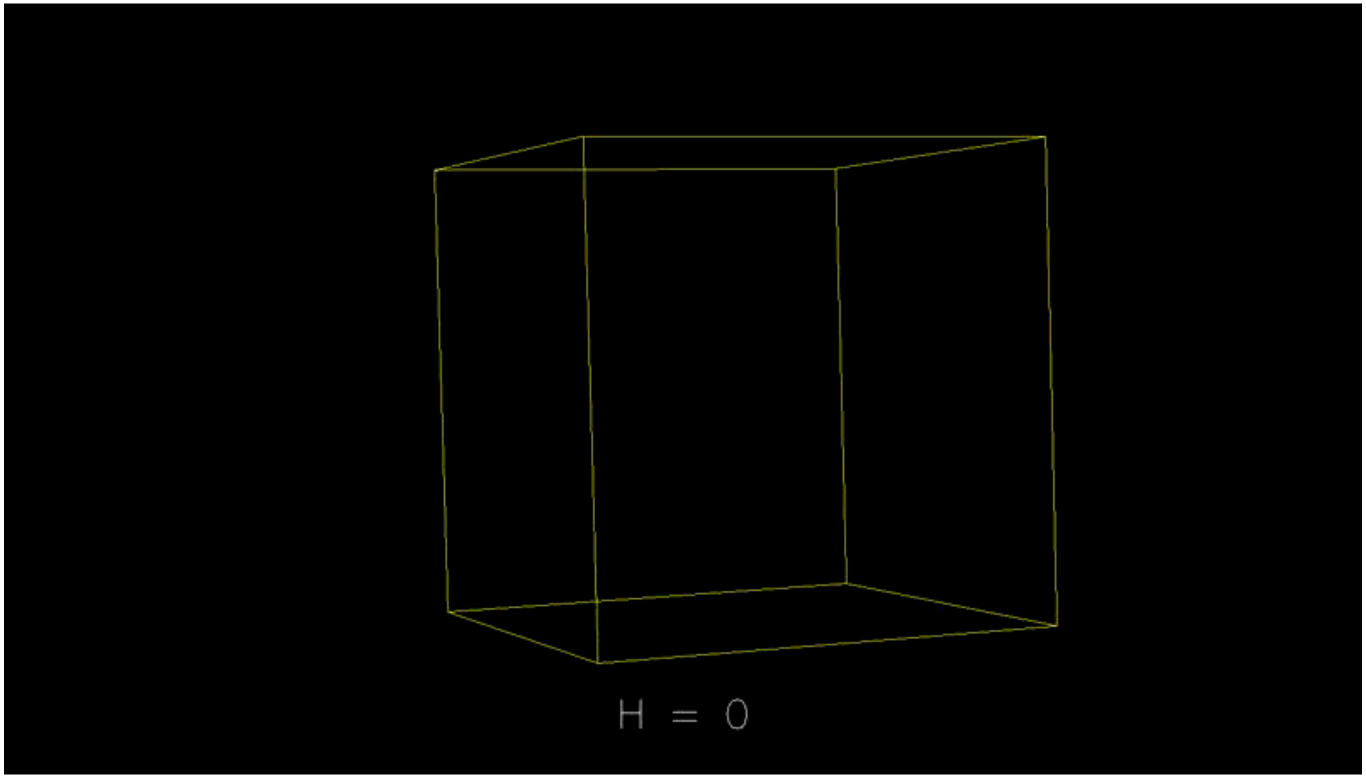
What powers the CME current?



$$\mu_L - \mu_R = 2\,\dot{\theta}$$

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

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



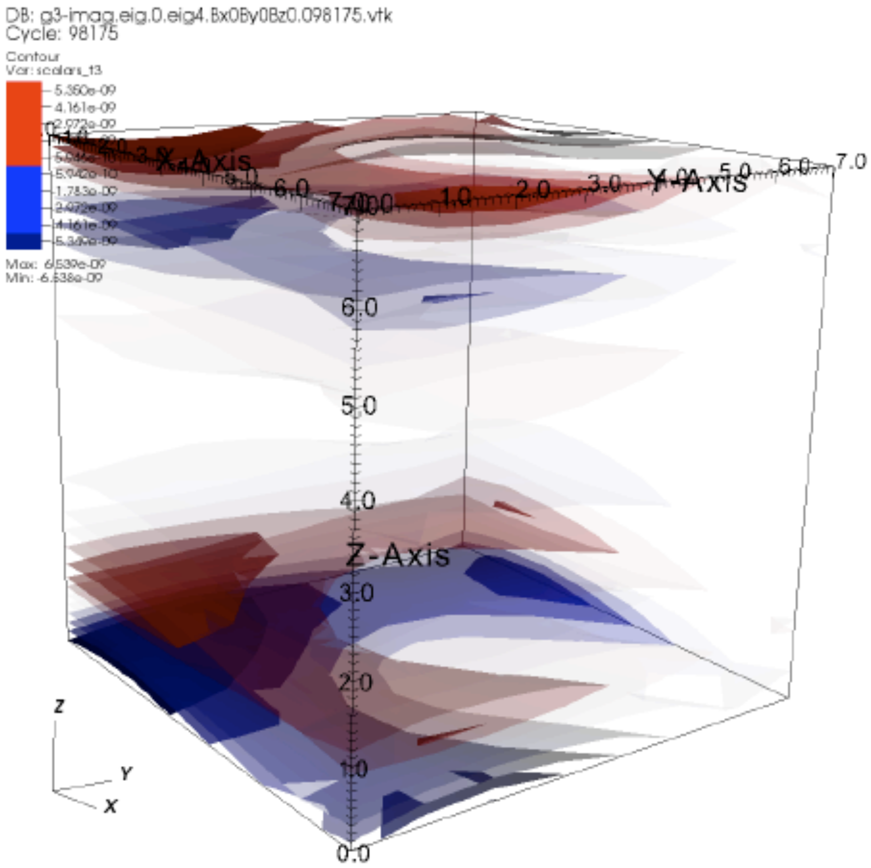
Red - positive charge
Blue - negative charge

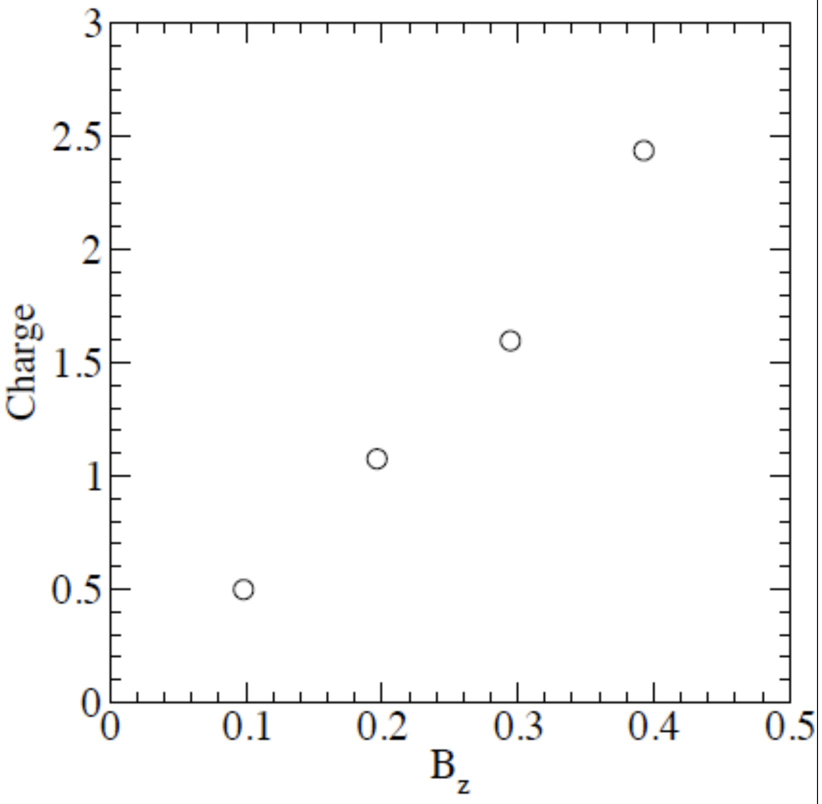
SU(2) quenched, Q = 3; Electric charge density (H) - Electric charge density (H=0)

“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



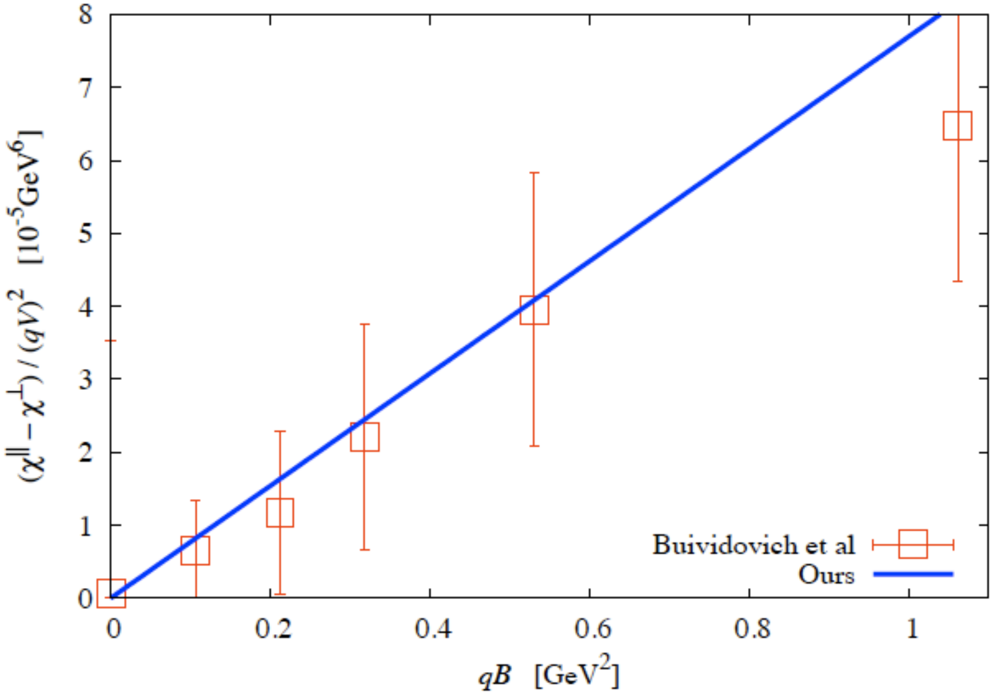


2+1 flavor Domain Wall Fermions, fixed topological sectors, 16^3 x 8 lattice

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.

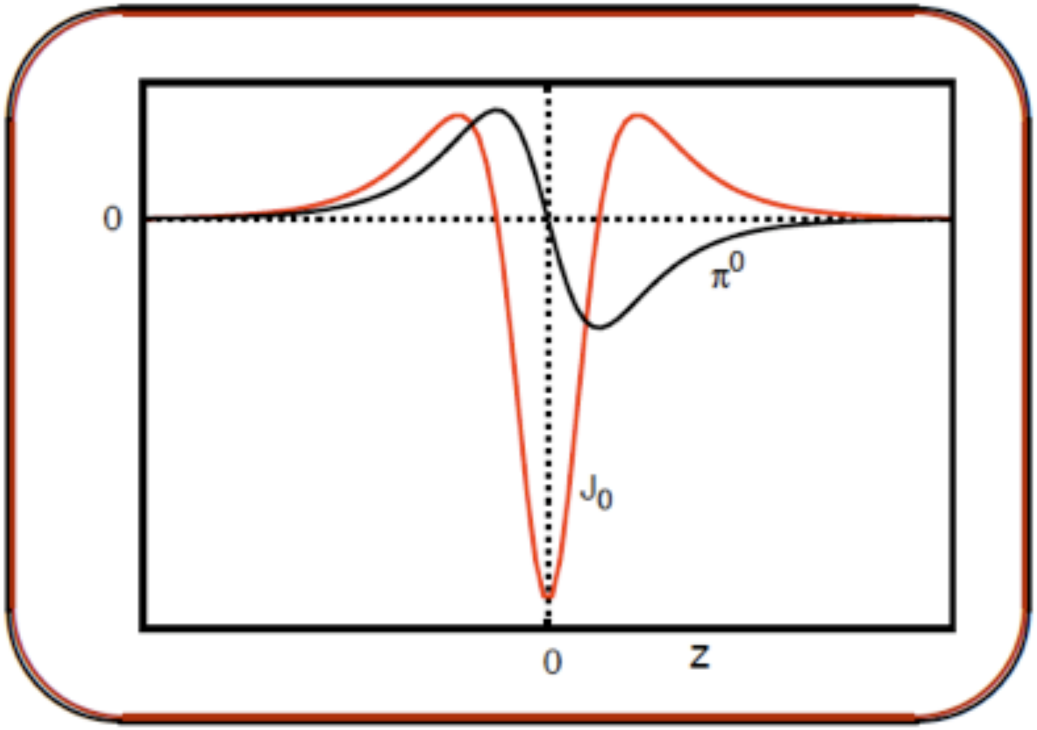
Lattice data are well reproduced theoretically.

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

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

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 $m_\pi \to 0$

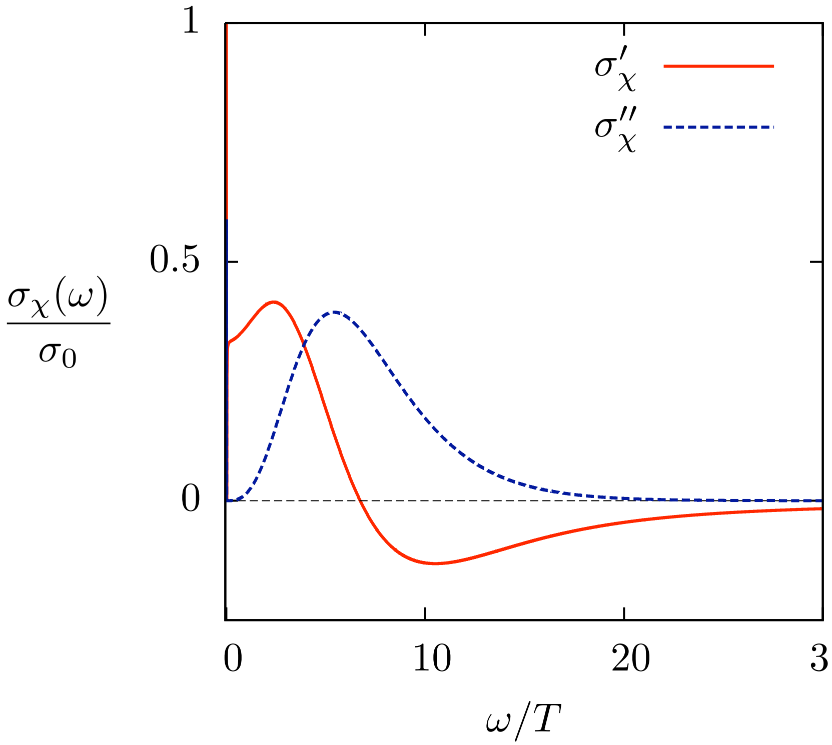
Induced charge in the confined chirally broken phase is suppressed

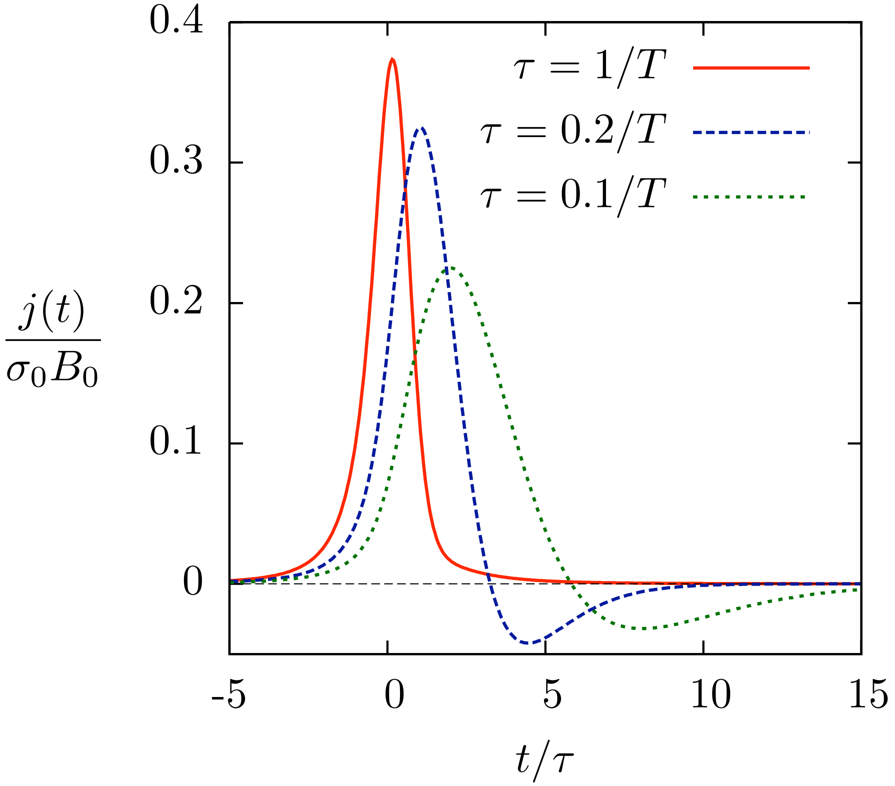
DK, S. Mukherjee,
to appear

Chiral magnetic conductivity

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

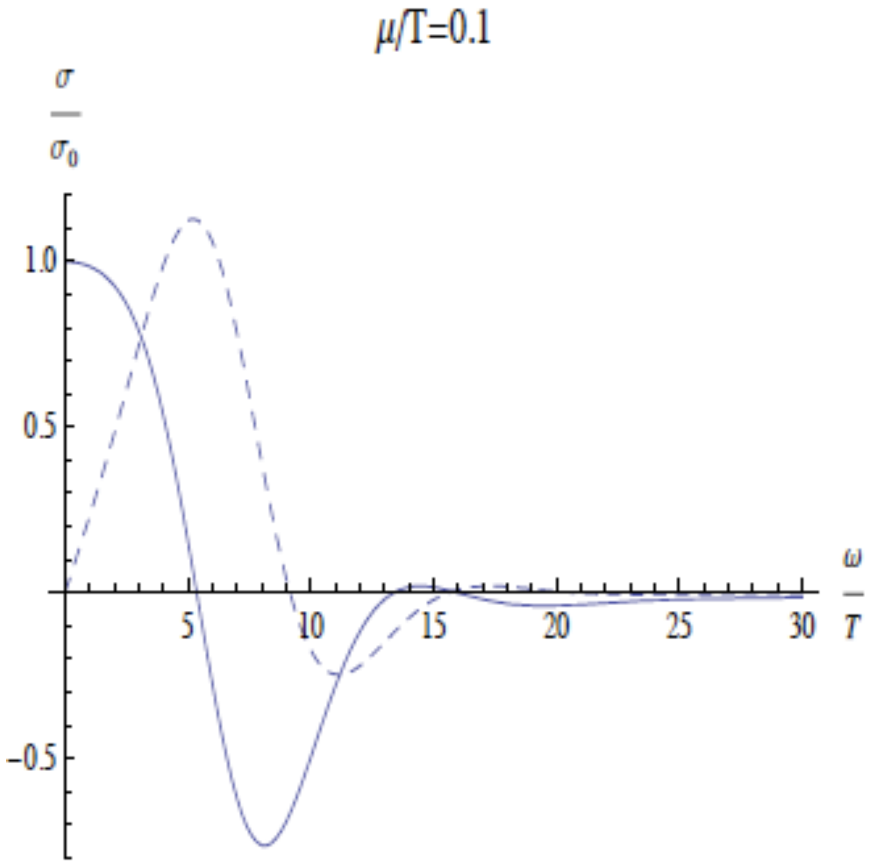
$$\sigma_\chi(\omega = 0, \boldsymbol{p} = 0) \equiv \sigma_0 = \frac{e^2}{2\pi^2}\mu_5$$





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

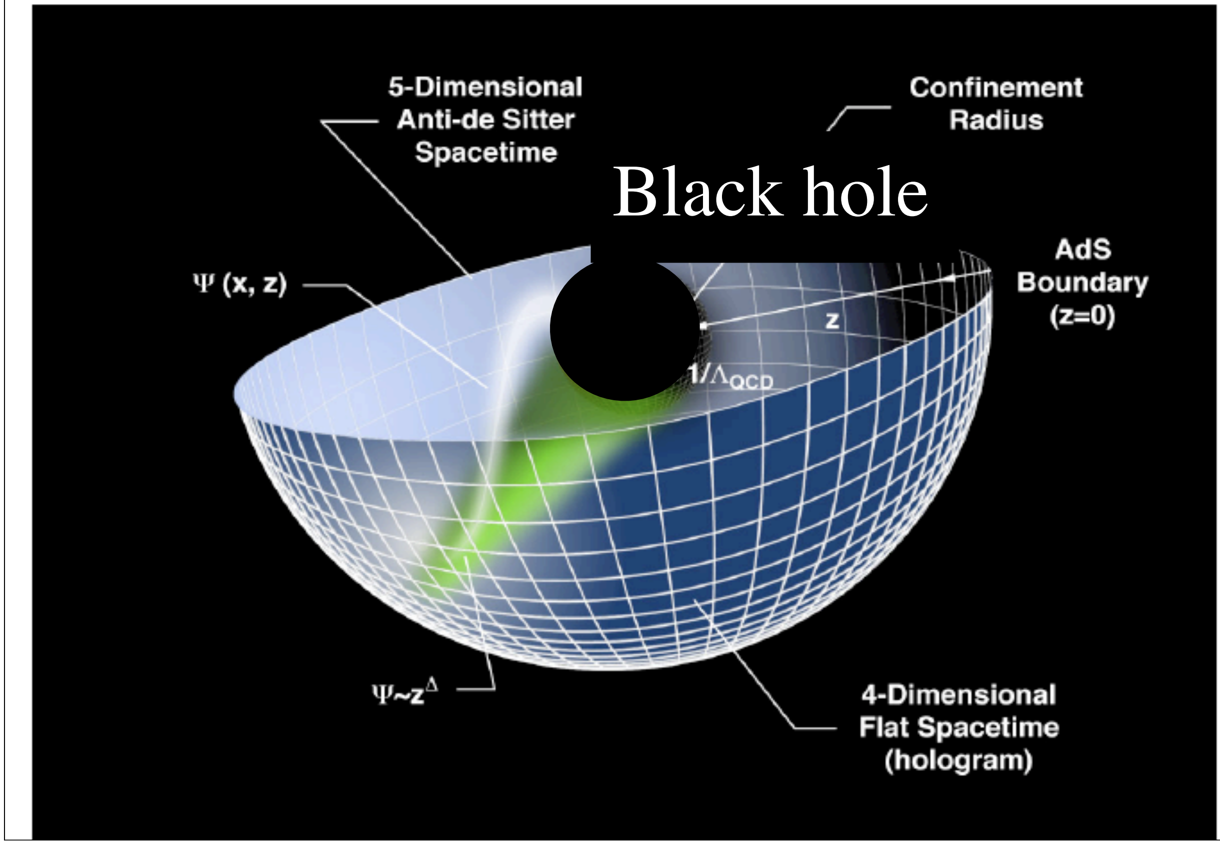
5D Einstein gravity with
Reissner-Nordstrom black hole
coupled to $U(1)_L \times U(1)_R$

Topological number diffusion at strong coupling

Chern-Simons number
diffusion rate
at strong coupling

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

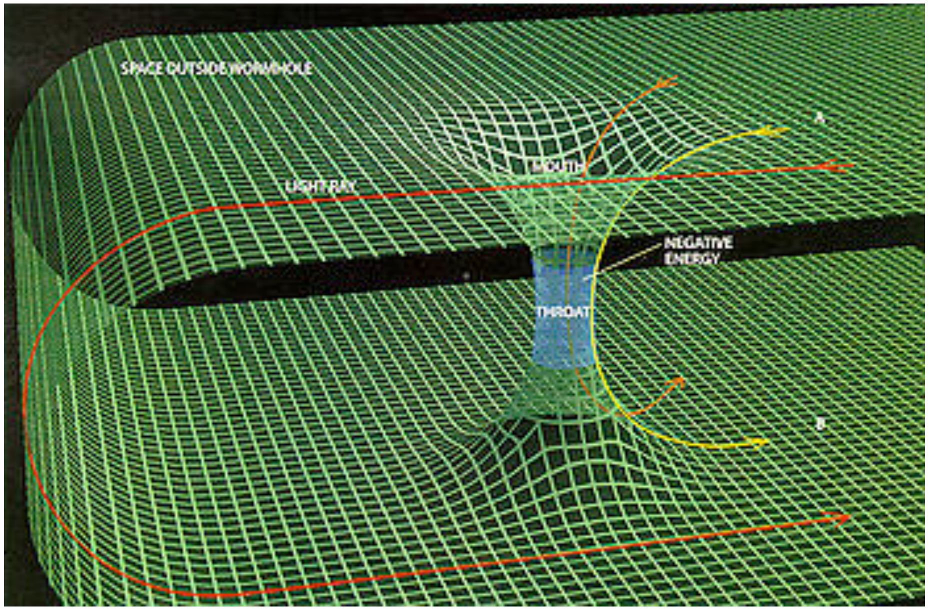
D.Son,
A.Starinets
hep-th/
020505



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



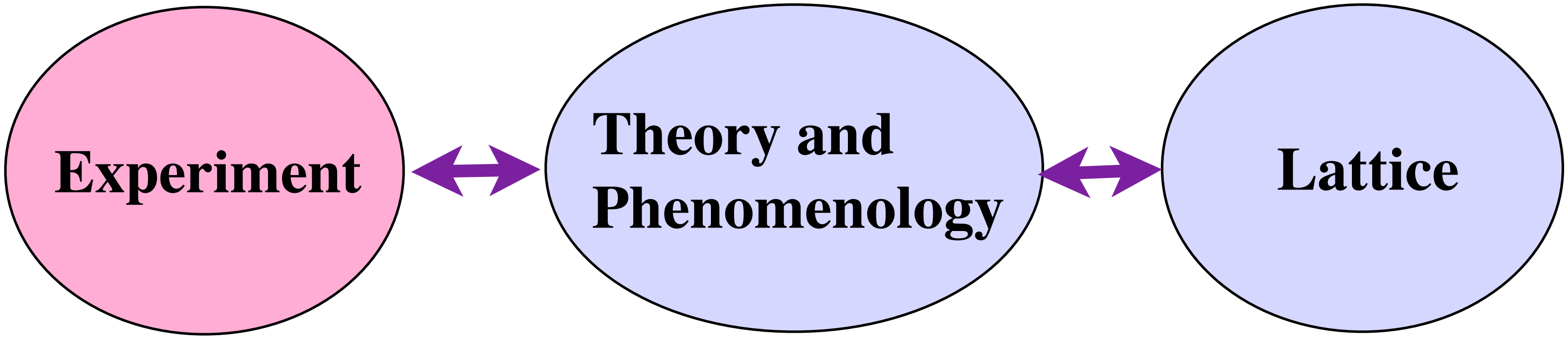
D-instanton as
an Einstein-Rosen
wormhole;
the flow of RR charge
down the throat of
the wormhole describes
change of chirality

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?



Experiment

Theory and Phenomenology

Lattice

Dynamical real-time modeling, quantitative description of the data and detailed predictions are urgently needed, and are on the way

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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- H. En'yo (RIKEN)
- M. Gyulassy (Columbia Univ.)
- F. Karsch (BNL & Bielefeld)
- T.D. Lee (Columbia Univ.)
- A. Nakamura (Hiroshima Univ.)
- M. Polikarpov (ITEP)
- K. Rajagopal (MIT)
- V. Rubakov (INR)
- J. Sandweiss (Yale Univ.)
- E. Shuryak (Stony Brook Univ.)
- A. Tsvelik (BNL)
- N. Xu (LBNL)
- V. Zakharov (ITEP)

Save the date: April 26-30, 2010

http://www.bnl.gov/riken/hdm/

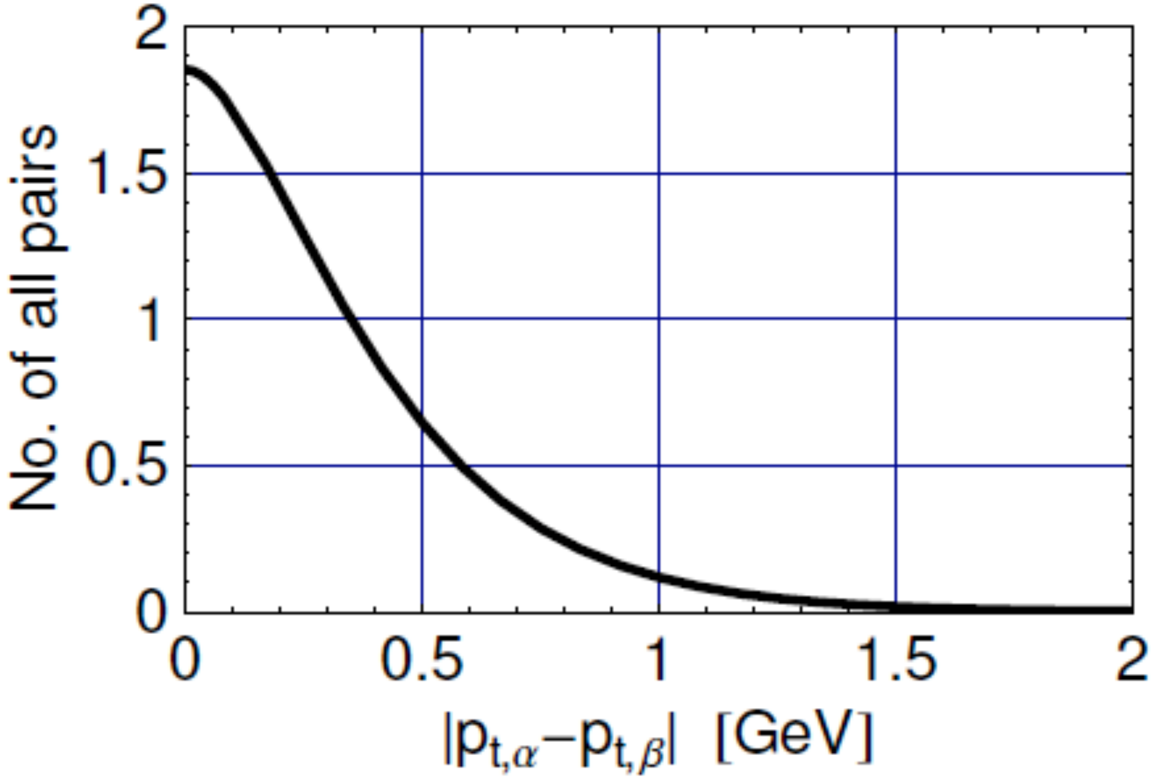
P- and CP-odd effects in: nuclear, particle, condensed matter physics and cosmology

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

Back-up slides

Further tests at RHIC

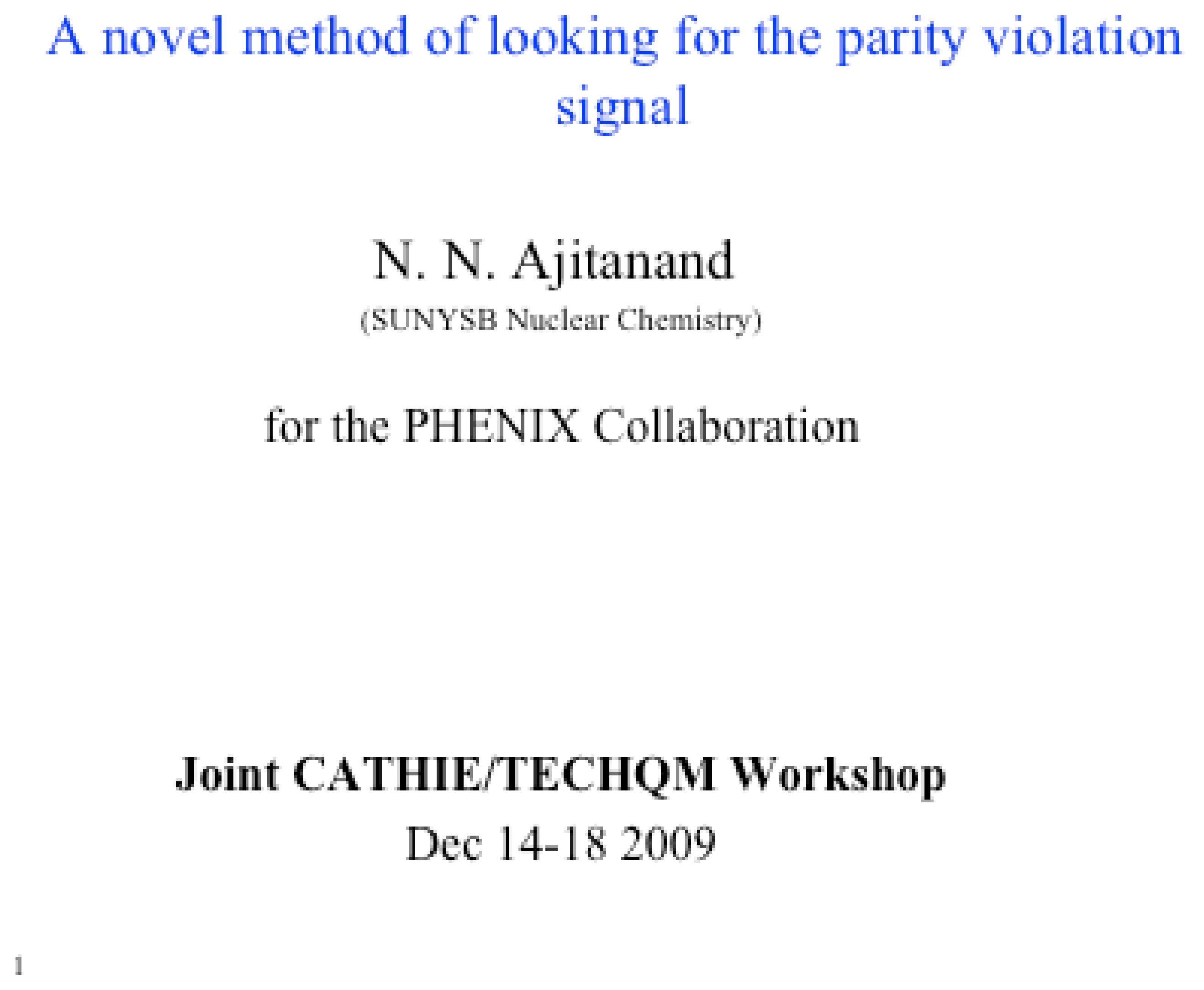
- Parity-odd observable?
- Correlations for identified hadrons? K_0^S ?
- Low-energy run: the effect is expected to weaken below the deconfinement/chiral symmetry transition
- P-odd decays? R. Millo & E.Shuryak, '09
- Double diffractive production in pp collisions: sphaleron decay in magnetic field?



Disentangle
azimuthal,
p_t dependence
from the data:

A.Bzdak, V.Koch,
J.Liao,
arXiv:0912.5050

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



A novel method of looking for the parity violation signal

N. N. Ajitanand

(SUNYSB Nuclear Chemistry)

for the PHENIX Collaboration

Joint CATHIE/TECHQM Workshop

Dec 14-18 2009

Presented here for the first time a new method involving a novel correlation C_p
The new correlation C_p is constructed as follows :

$S = \sin(\varphi\text{lab} - \Psi_{RP})$

where Ψ_{RP} is the reconstructed reaction plane
Consider an event of multiplicity M having p positively charged hadrons and n negatively charged hadrons i.e. $M = p + n$

Define

$\langle S_p^{h+} \rangle$ = average of S over the p positively charged hadrons in the event

$\langle S_n^{h-} \rangle$ = average of S over the n negatively charged hadrons in the event

$\langle S_p^{h} \rangle$ = average over p randomly chosen hadrons irrespective of charge in the same event

$\langle S_n^{h} \rangle$ = average over the remaining n hadrons in same event