Chirality, magnetic field, and local parity violation in hot QCD matter

D. Kharzeev

Quark Matter Annecy 2011

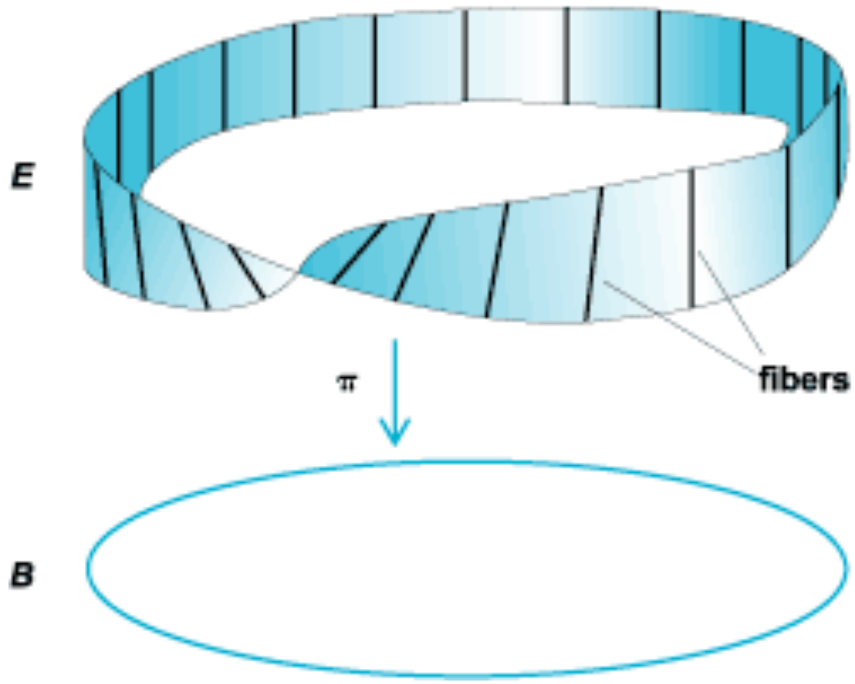
Stony Brook State University of New York

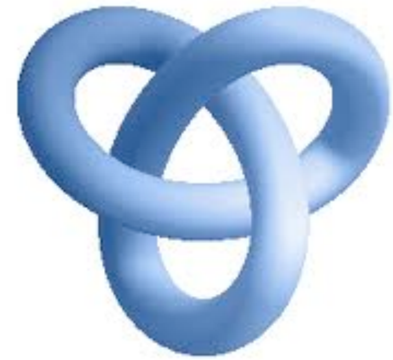
Brookhaven National Laboratory

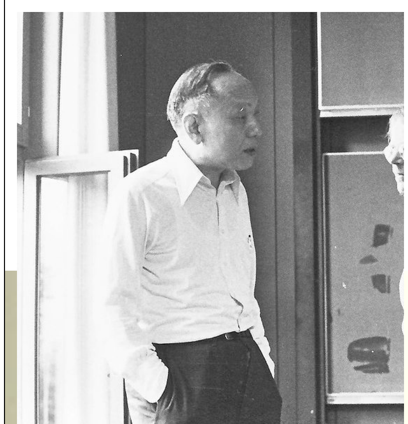
Collaborators

- Gokce Basar (UConn -> Stony Brook)
- Yannis Burnier (Stony Brook)
- Gerald Dunne (UConn)
- Kenji Fukushima (RIKEN-BNL -> Keio U.)
- Larry McLerran (BNL)
- Jinfeng Liao (BNL -> Indiana U.)
- Dam Son (U. Washington)
- Raju Venugopalan (BNL)
- Harmen Warringa (BNL -> Frankfurt U.)
- Ho-Ung Yee (Stony Brook)
- Eric Zhitnitsky (British Columbia)

Gauge fields possess non-trivial topology



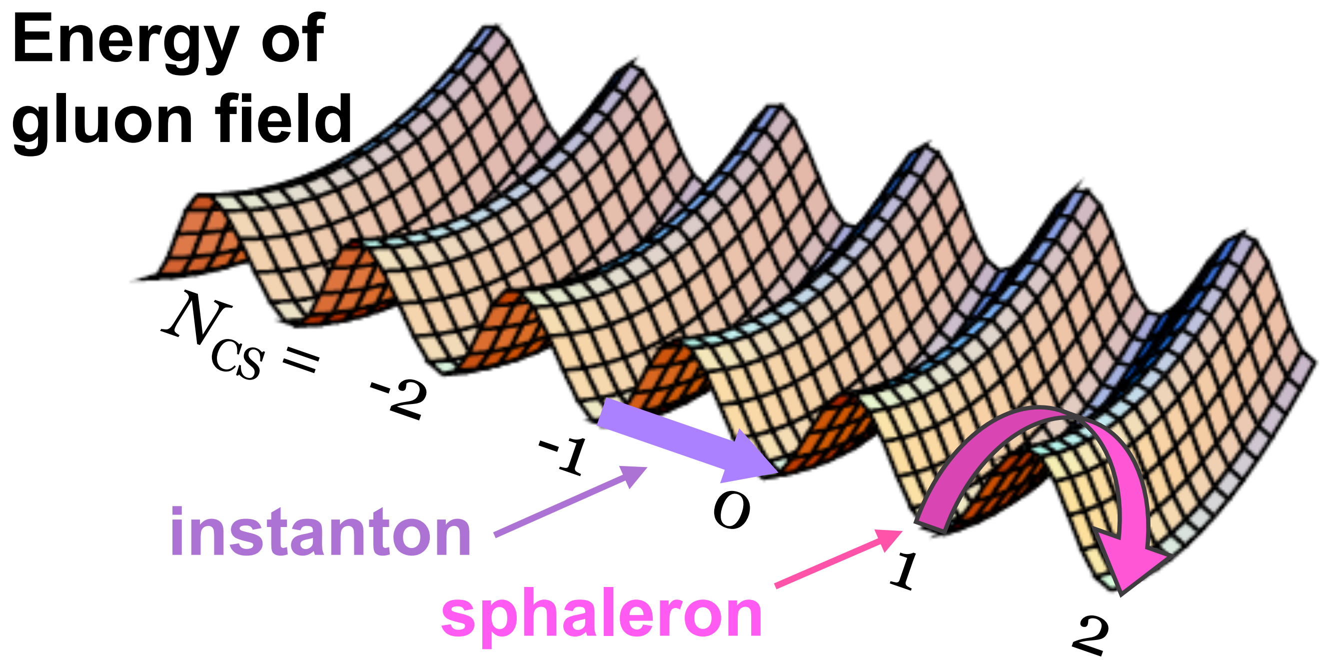




CHARACTERISTIC FORMS

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

QCD vacuum is a superposition of states with different topology



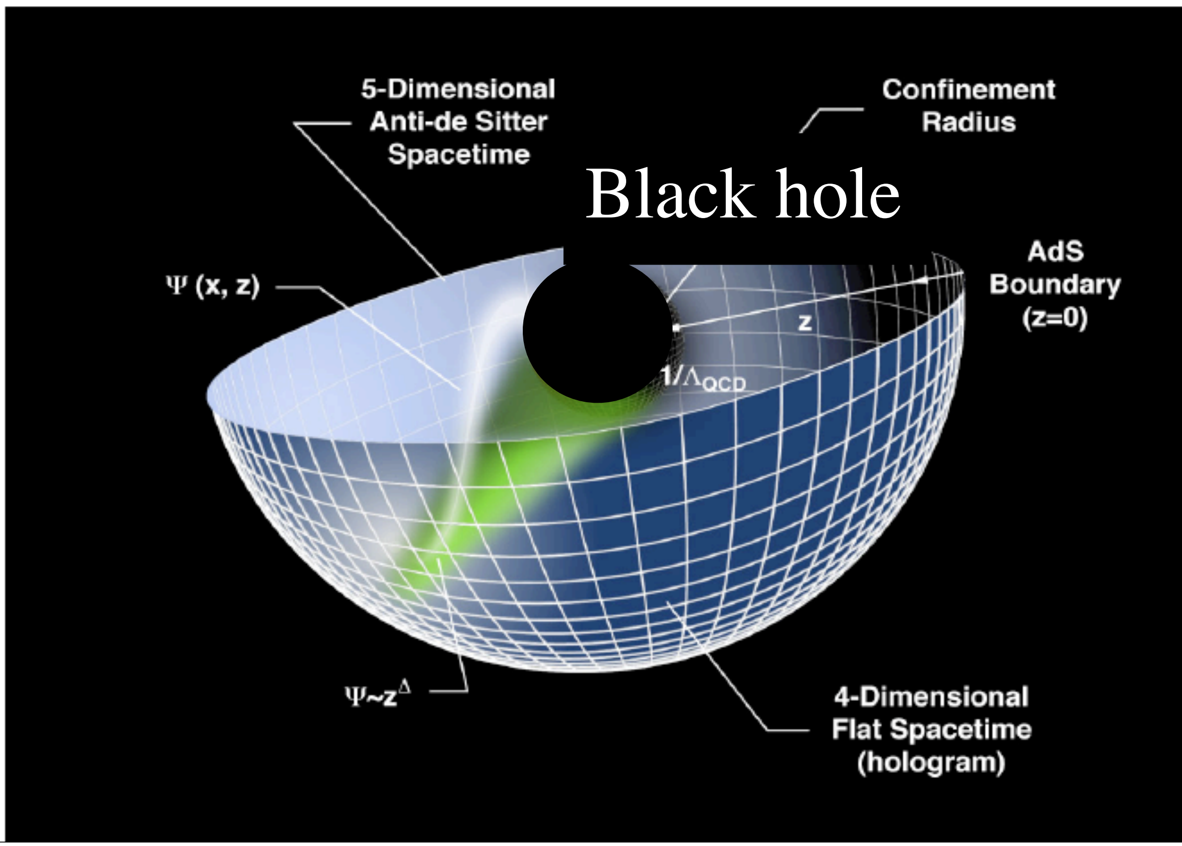
Transitions between such states create the local imbalance of chirality

Topological transitions are frequent in sQGP

Chern-Simons number
diffusion rate
at strong coupling

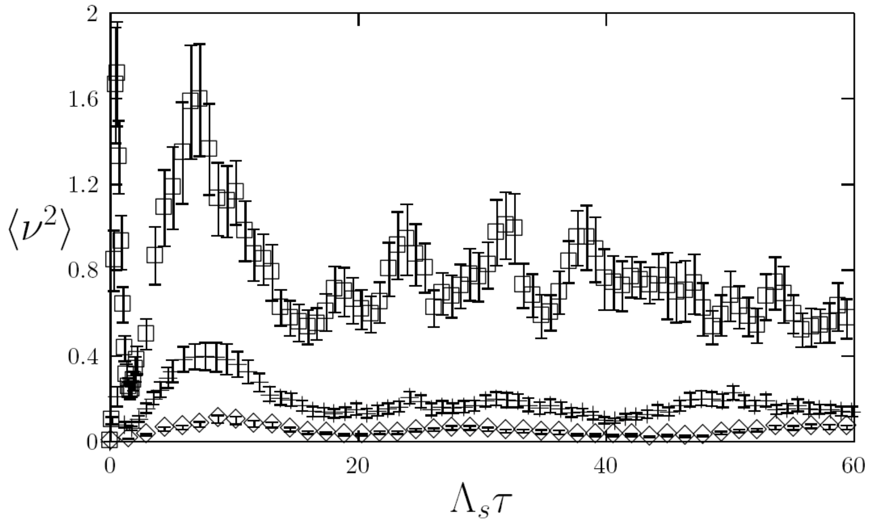
$$\Gamma = \frac{(g_{\rm YM}^2 N)^2}{256\pi^3} T^4$$

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

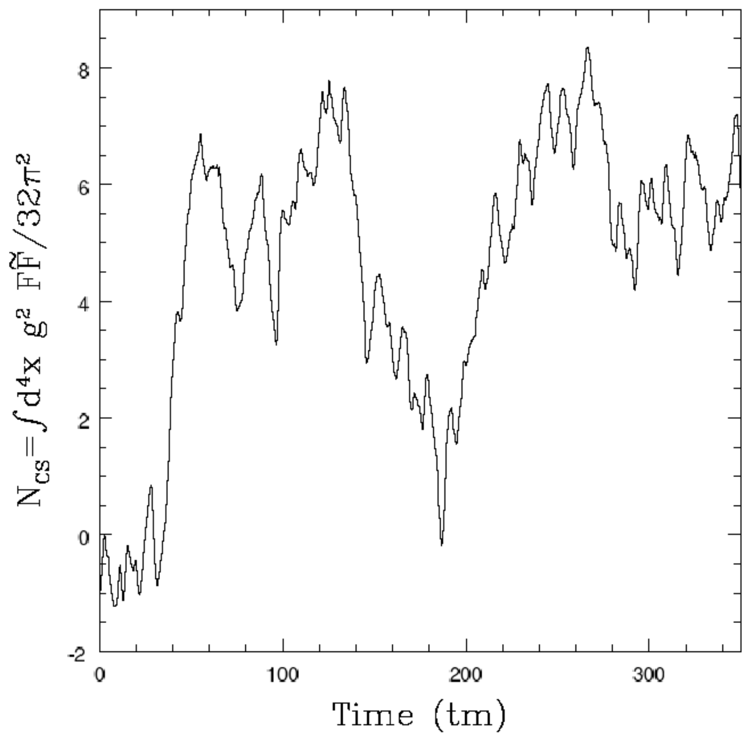


NB: This calculation is completely analogous to the calculation of shear viscosity that led to the "perfect liquid"

Topological transitions in QCD are seen in real-time lattice simulations



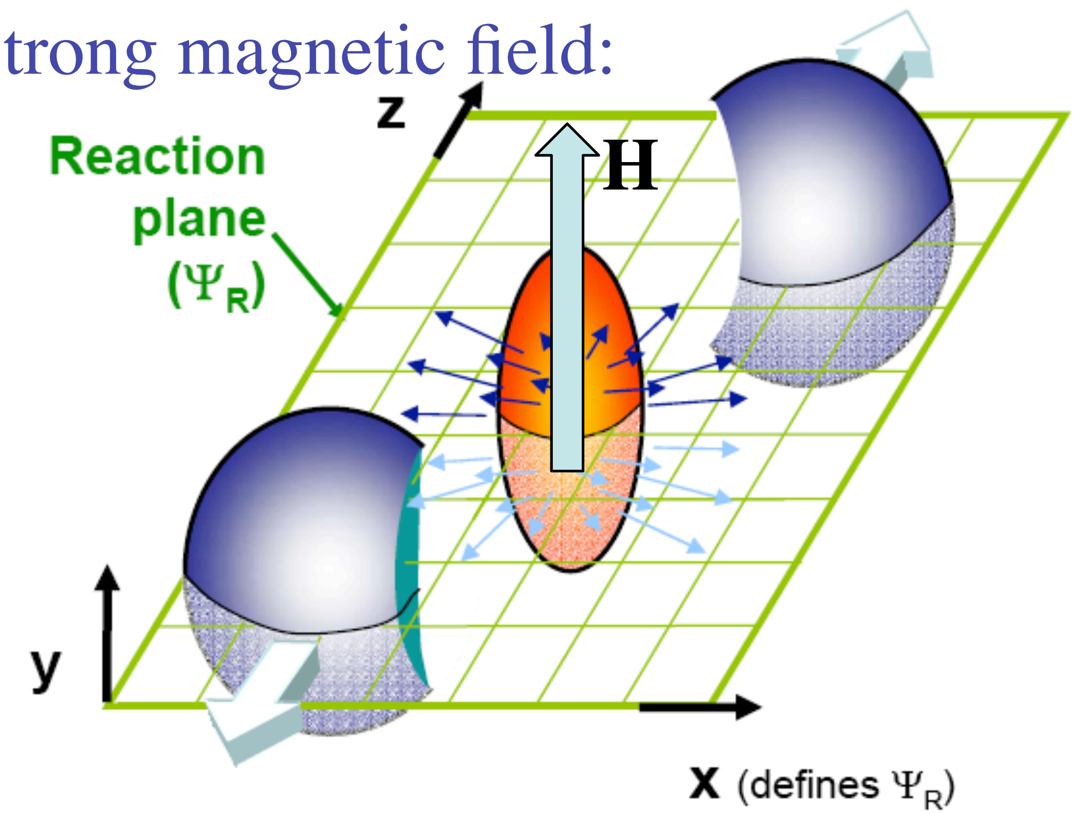
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002

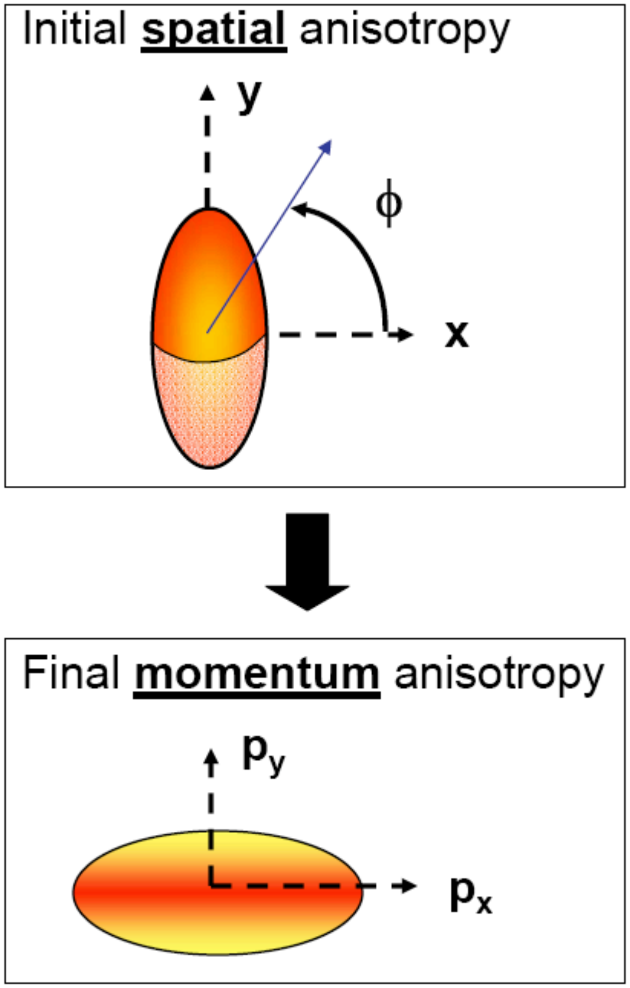


P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

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

Also:
V. Skokov,
V. Toneev,
A. Illarionov...

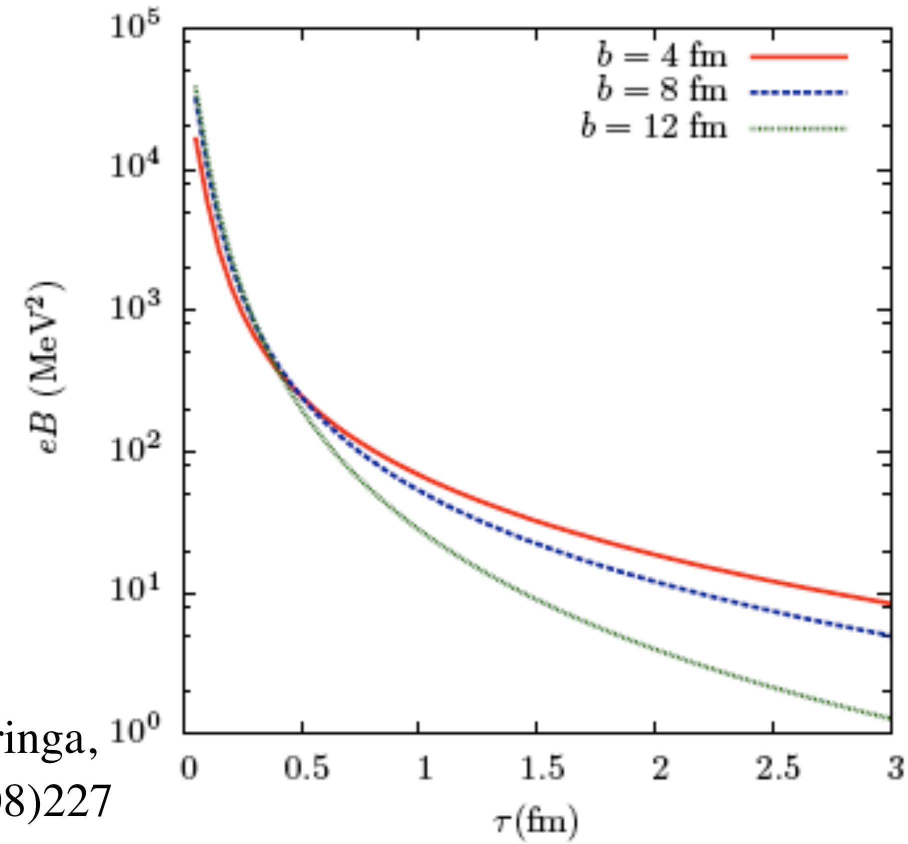


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

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

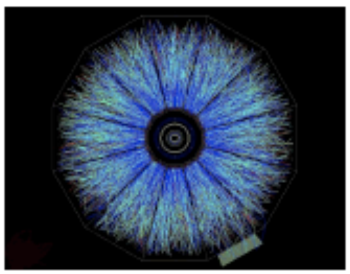
In a conducting plasma, Faraday induction can make the field long-lived:
K.Tuchin, arXiv:1006.3051

NB: magnetic flux is conserved in MHD! - expect the effect at LHC

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

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

Chiral Magnetic Effect in a chirally imbalanced plasma

Fukushima, DK, Warringa, PRD'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

Chiral magnetic conductivity: discrete symmetries

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

P-odd
T-odd

P-even
T-odd

P-odd

<u>P-odd effect!</u>

T-even

<u>Non-dissipative current!</u>

(quantum computing etc)

cf Ohmic conductivity:

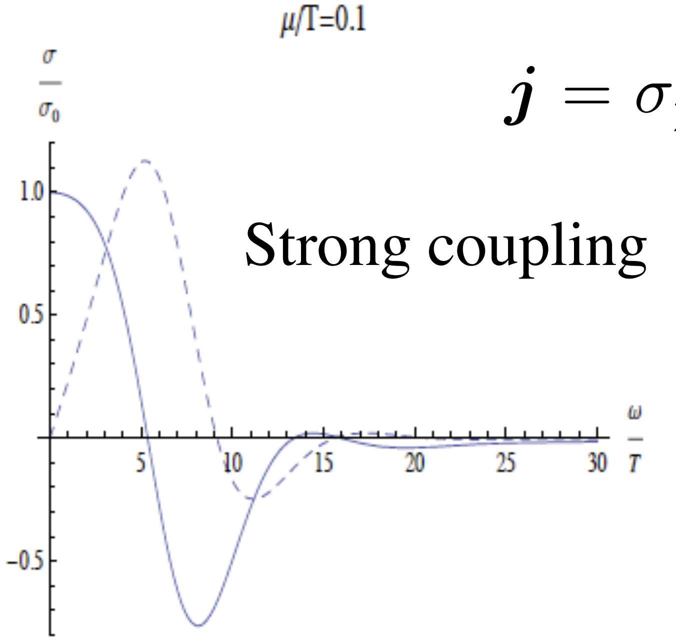
$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

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

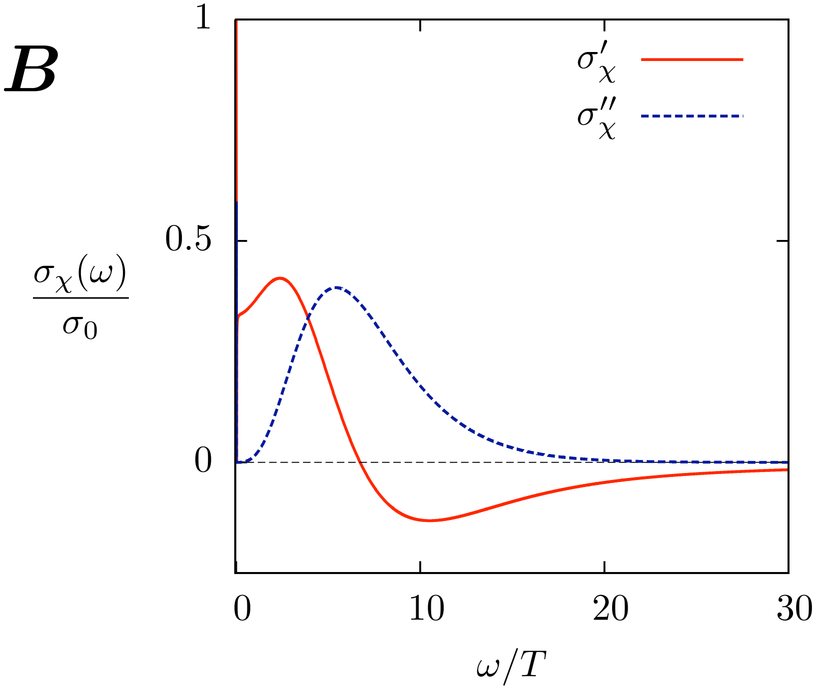
$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$

Strong coupling



H.-U. Yee, arXiv:0908.4189,
JHEP 0911:085, 2009;
V. Rubakov, arXiv:1005.1888, ...

Weak coupling



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

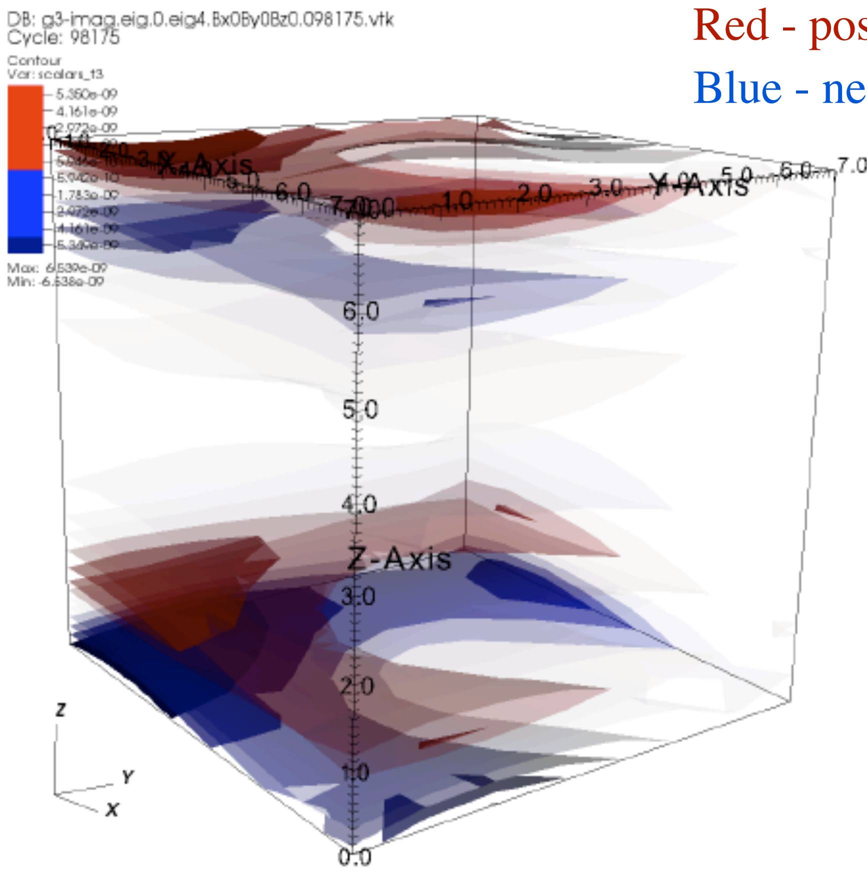
A. Rebhan et al, JHEP 0905, 084 (2009), G.Lifshytz, M.Lippert, arXiv:0904.4772;...
E. D' Hoker and P. Krauss, arXiv:0911.4518; A. Gorsky, P. Kopnin, A. Zayakin, arXiv:1003.2293,
also: Chiral separation, D. Son and P. Surowka, '09

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

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

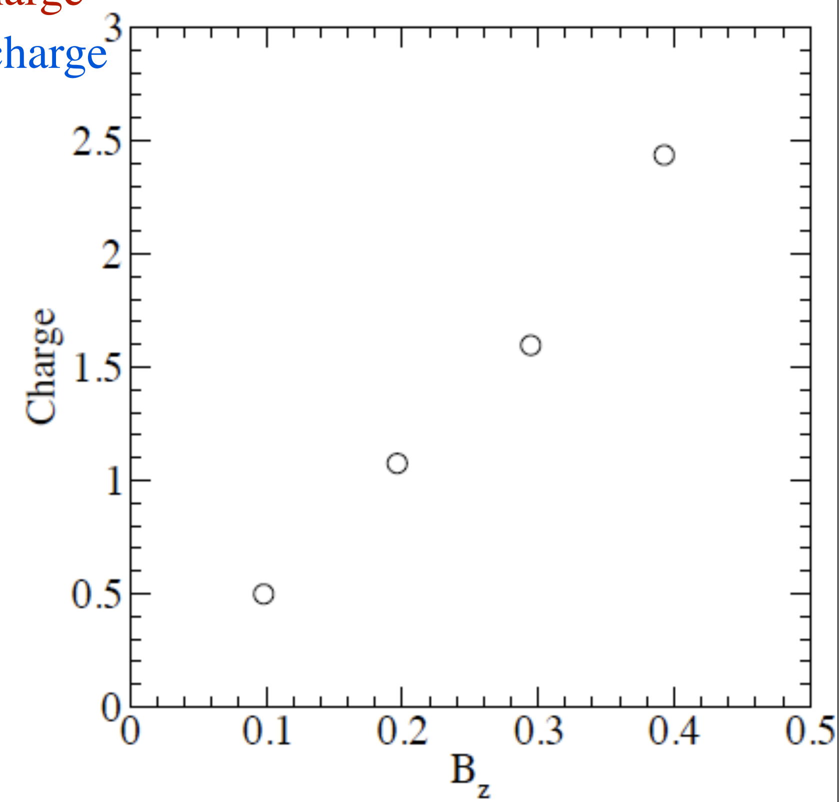
“Chiral magnetic effect in 2+1 flavor QCD+QED”,

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



Red - positive charge

Blue - negative charge



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

No sign problem for the chiral chemical potential - direct lattice studies are possible

Let us finally point out that the chiral chemical potential has no sign problem, i.e. the fermionic determinant with μ_5 is real and positive. In the presence of a chiral chemical potential the fermionic determinant reads in Euclidean space-time,

$$\det\mathcal{M}(\mu_5) \equiv \det\left(\not{D} + \mu_5\gamma_E^0\gamma^5 + m\right), \tag{7}$$

where $\not{D} = \gamma_E^\mu D_\mu$. Here we have chosen a representation in which all γ_E matrices are Hermitian, $\gamma_E^0 = \gamma^0, \gamma_E^i = i\gamma^i$. Since $\not{D}$ and $\gamma_E^0\gamma^5$ are anti-Hermitian the eigenvalues of $\mathcal{M}(\mu_5)$ are of the form $i\lambda_n + m$, where $\lambda_n \in \mathbb{R}$. Because γ_5 anticommutes with $\not{D} + \mu_5\gamma_E^0\gamma^5$, all eigenvalues come in pairs, which means that if $i\lambda_n + m$ is an eigenvalue, also $-i\lambda_n + m$ is an eigenvalue. Since the determinant is the product of all eigenvalues we see that the determinant is the product over all n of $\lambda_n^2 + m^2$. Hence the determinant is real and also positive semi-definite. This is very interesting because it allows for a lattice QCD simulation of chirally asymmetric systems. The lattice

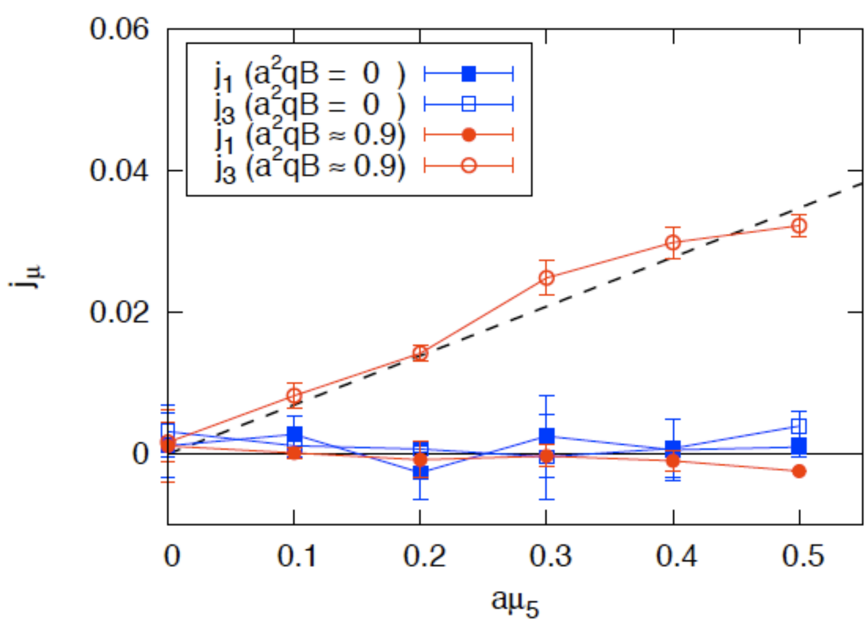
Fukushima, DK, Warringa, PRD'08

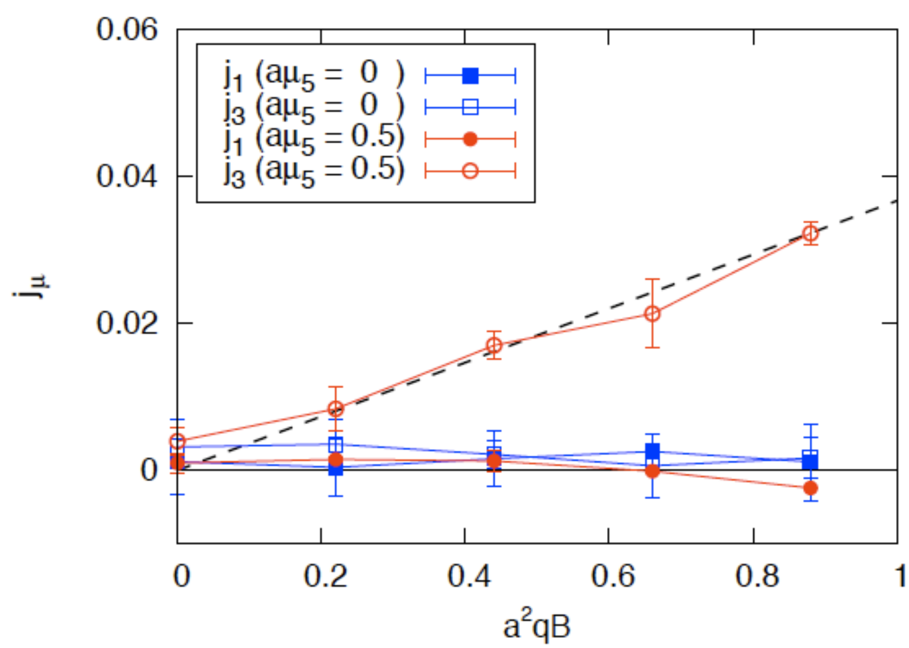
arXiv:1105.0385, May 3, 2011

Chiral magnetic effect in lattice QCD with chiral chemical potential

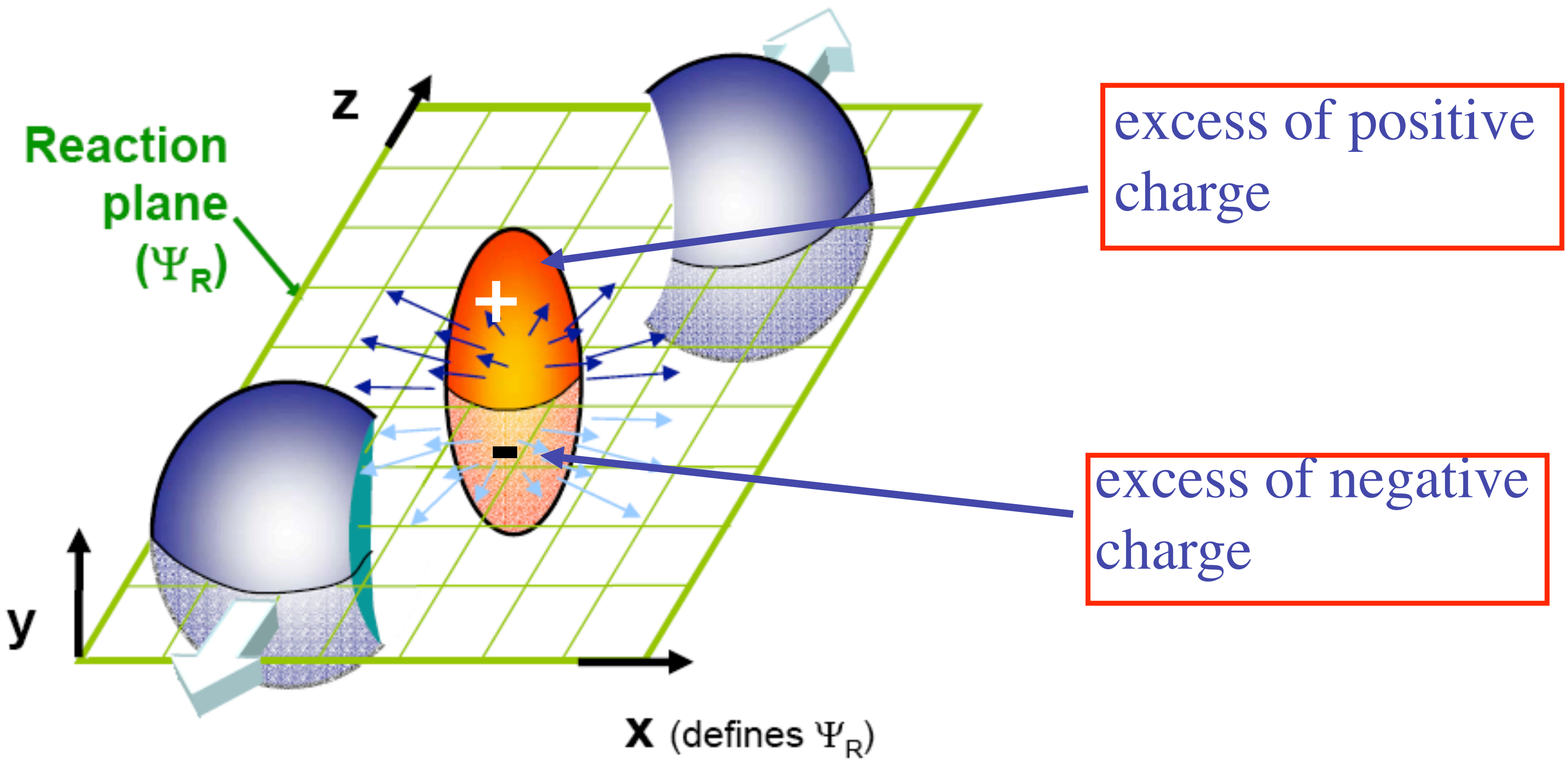
Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
(Dated: May 3, 2011)

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.





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

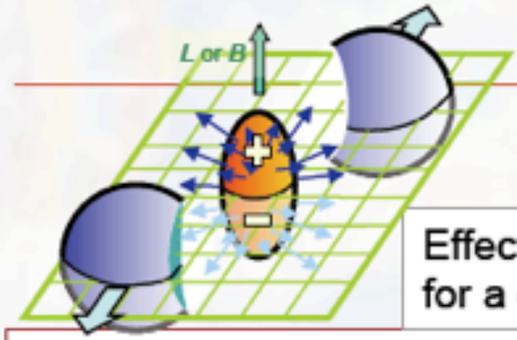


Electric dipole moment of QCD matter!

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

Observable

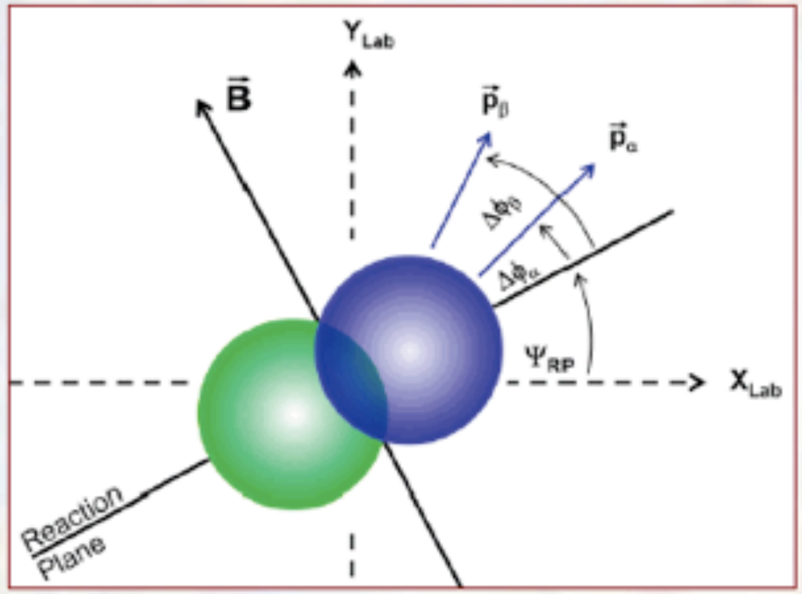
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

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

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



- 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

Slide from S. Voloshin

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

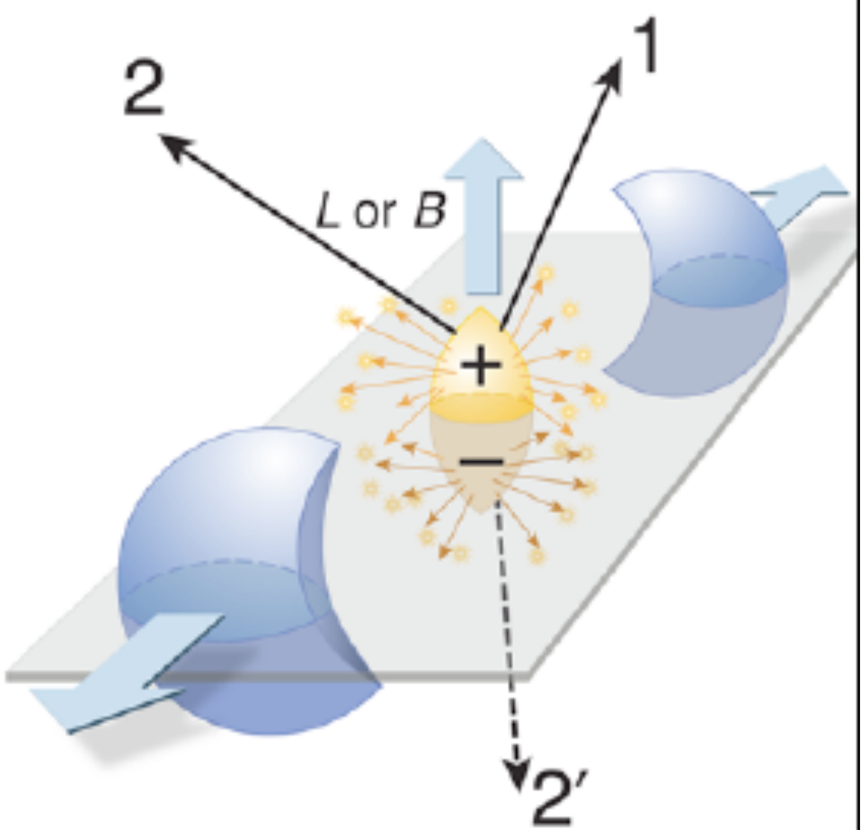
$$B^{in} \approx B^{out}, \quad v_1 = 0$$

A practical approach: three particle correlations:

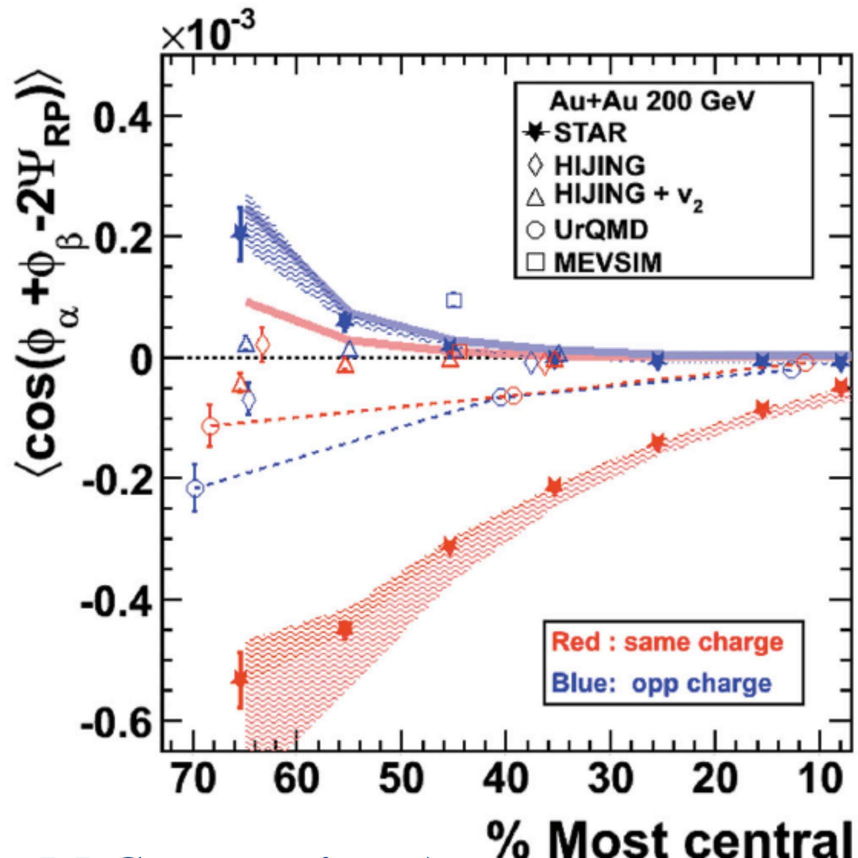
$$\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$$

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)



NB: P-even quantity (strength of P-odd fluctuations)

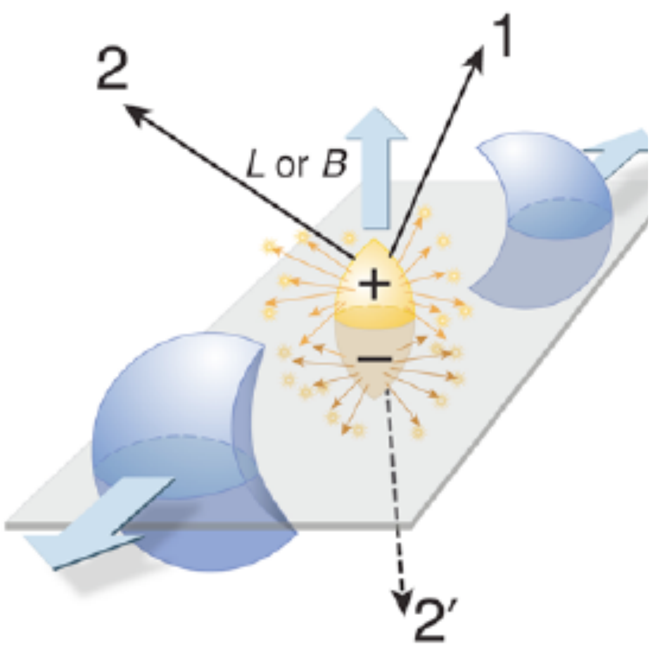
PRL **103,** 251601 (2009)

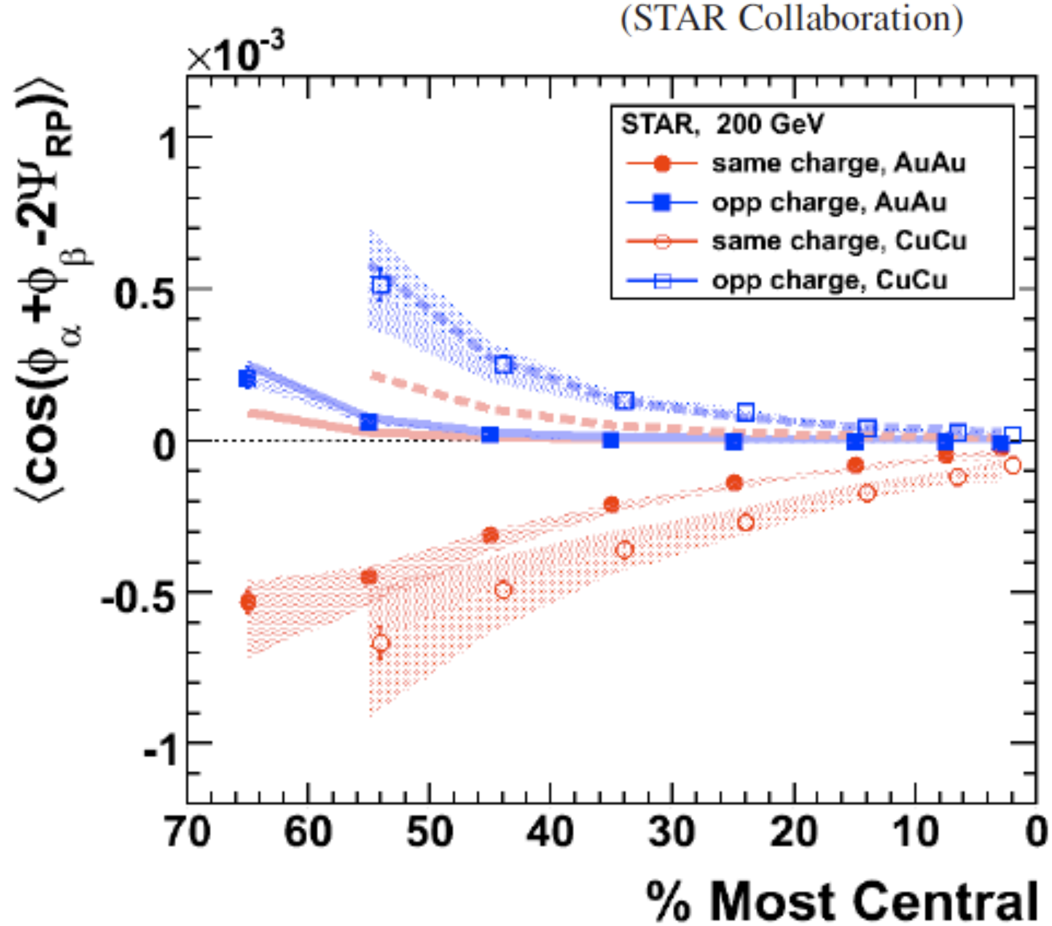
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2009

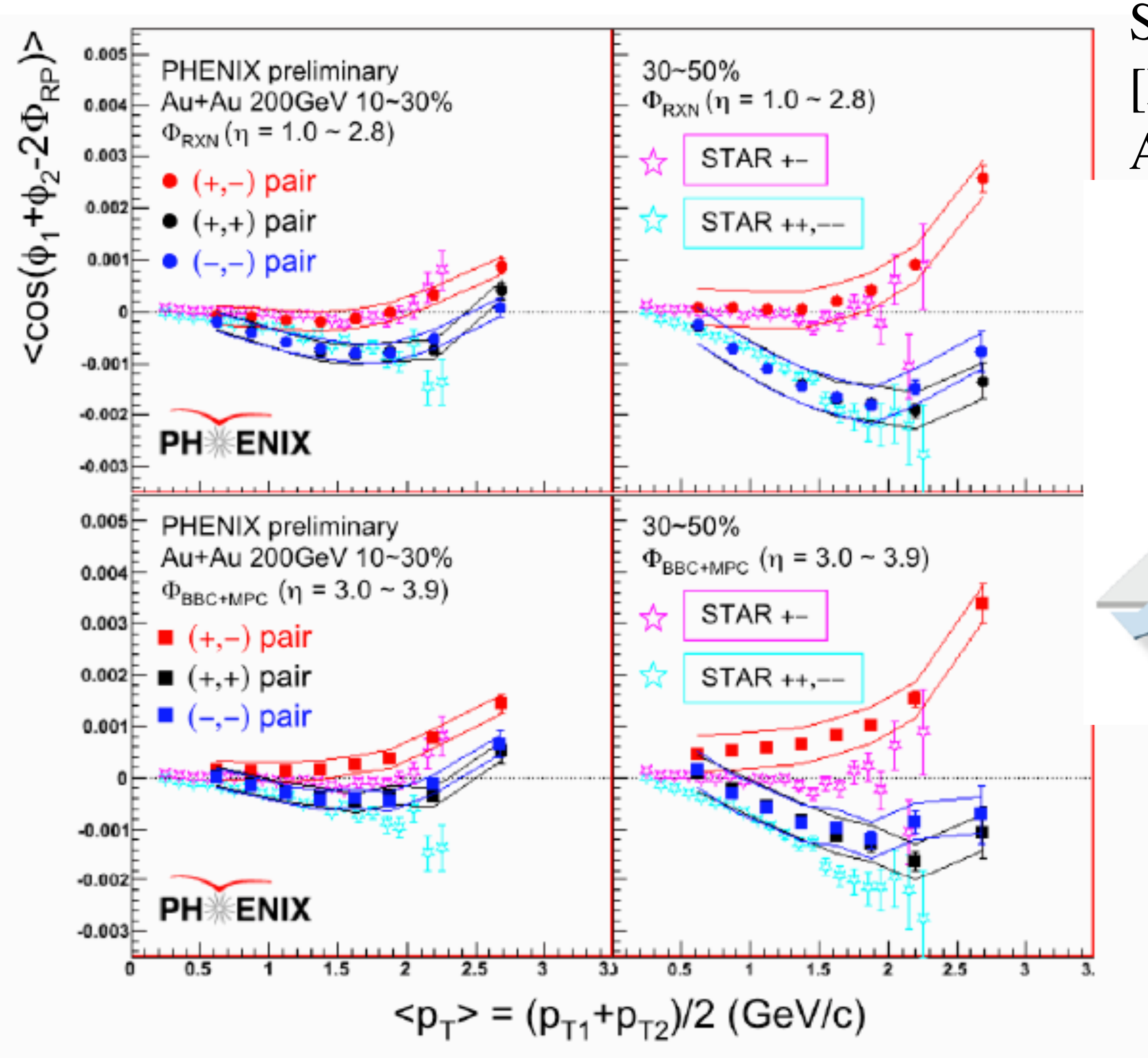
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)

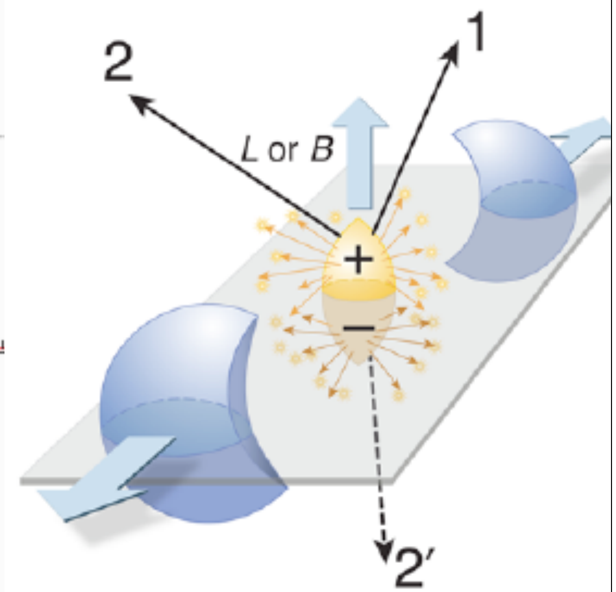




NB: P-even quantity (strength of P-odd fluctuations)



S.Esumi et al
[PHENIX Coll]
April 2010



Talk by
N.Ajitanand
(PHENIX)

Relatively good agreement between PHENIX & STAR

Are the observed fluctuations of charge asymmetries a convincing evidence for the CME?

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

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

physics “backgrounds” — e.g. 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!**

A new test: baryon asymmetry

DK, D.T.Son
arXiv:1010.0038; PRL

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

CME

Vorticity-induced
"Chiral Vortical Effect"

$$J_E^{CME} \sim \frac{2}{3} \;\; (N_f = 3) \;\; \text{or} \;\; \frac{5}{9} \;\; (N_f = 2)$$

$$J_B^{CME} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{9} \;\; (N_f = 2).$$

CME:
(almost) only
electric charge

$$J_E^{CVE} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{3} \;\; (N_f = 2);$$

$$J_B^{CVE} \sim 1 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{2}{3} \;\; (N_f = 2).$$

CVE:
(almost) only
baryon charge

The CME in relativistic hydrodynamics:
The Chiral Magnetic Wave

DK, H.-U. Yee, arXiv:1012.6026 [hep-th]; PRD

$$\vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B}; \quad \vec{j}_A = \frac{N_c\, e}{2\pi^2}\mu_V \vec{B},$$

CME　　　　Chiral separation

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\, e\vec{B}}{2\pi^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix}$$

Propagating chiral wave: (if chiral symmetry is restored)

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

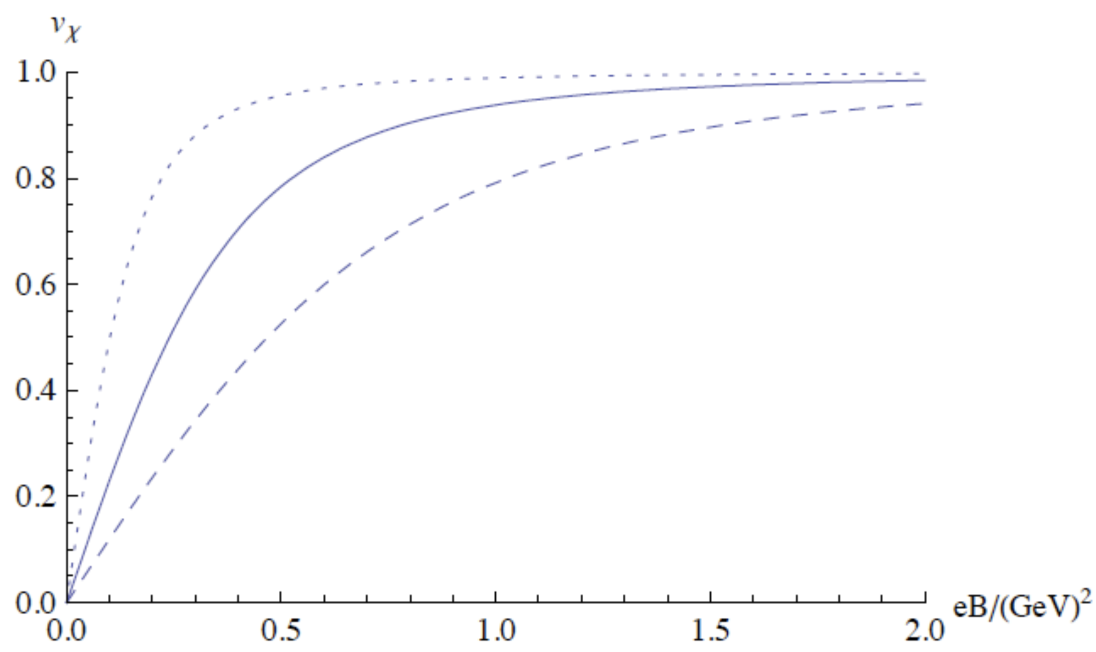
Gapless collective mode is the carrier of CME current in MHD:

$$\omega = \mp v_\chi k - i D_L k^2 + \cdots$$

The Chiral Magnetic Wave

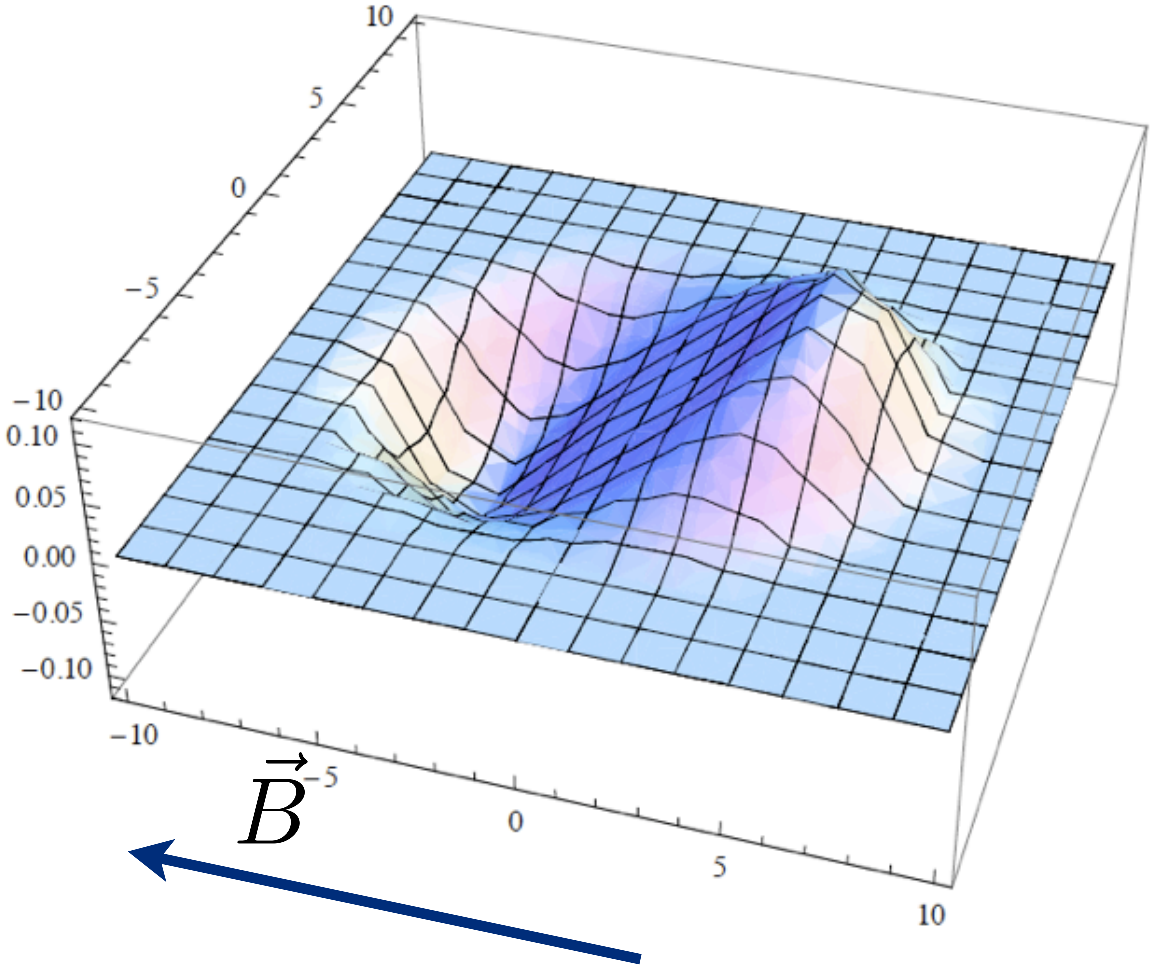
The velocity of CMW computed in Sakai-Sugimoto model (holographic QCD)

In strong magnetic field, CMW propagates with the speed of light!



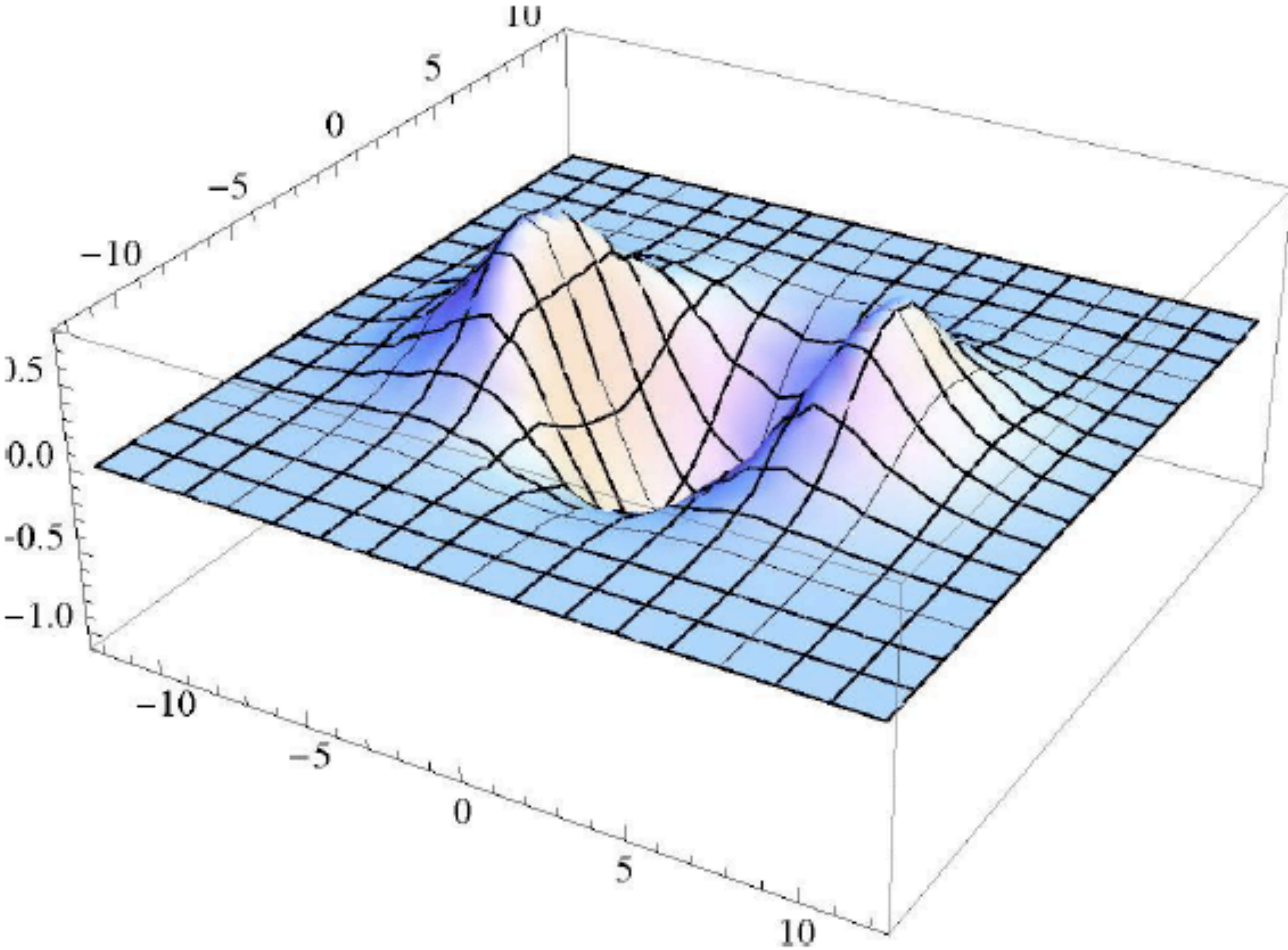
DK, H.-U. Yee, arXiv:1012.6026 [hep-th]

CMW in QGP fluid at finite baryon density:
the chiral dipole moment



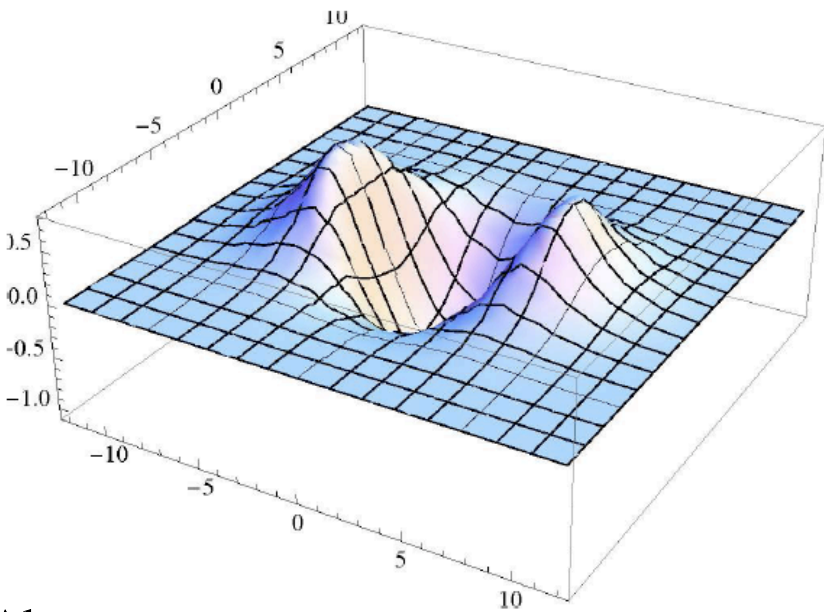
Y.Burnier, DK, J. Liao, H.-U.Yee, arXiv:1103.1307

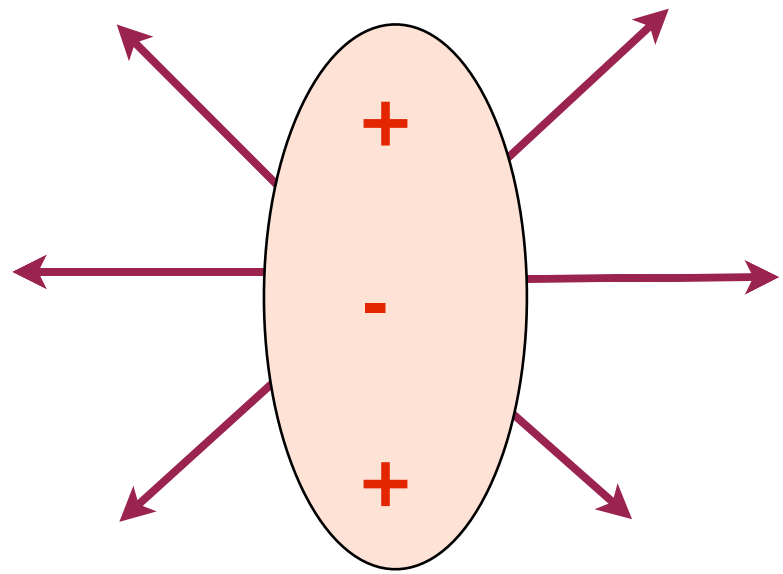
Electric quadrupole moment of QGP at finite baryon density



Y.Burnier, DK, J. Liao, H.-U.Yee, arXiv:1103.1307

Electric quadrupole moment of QGP: the signature





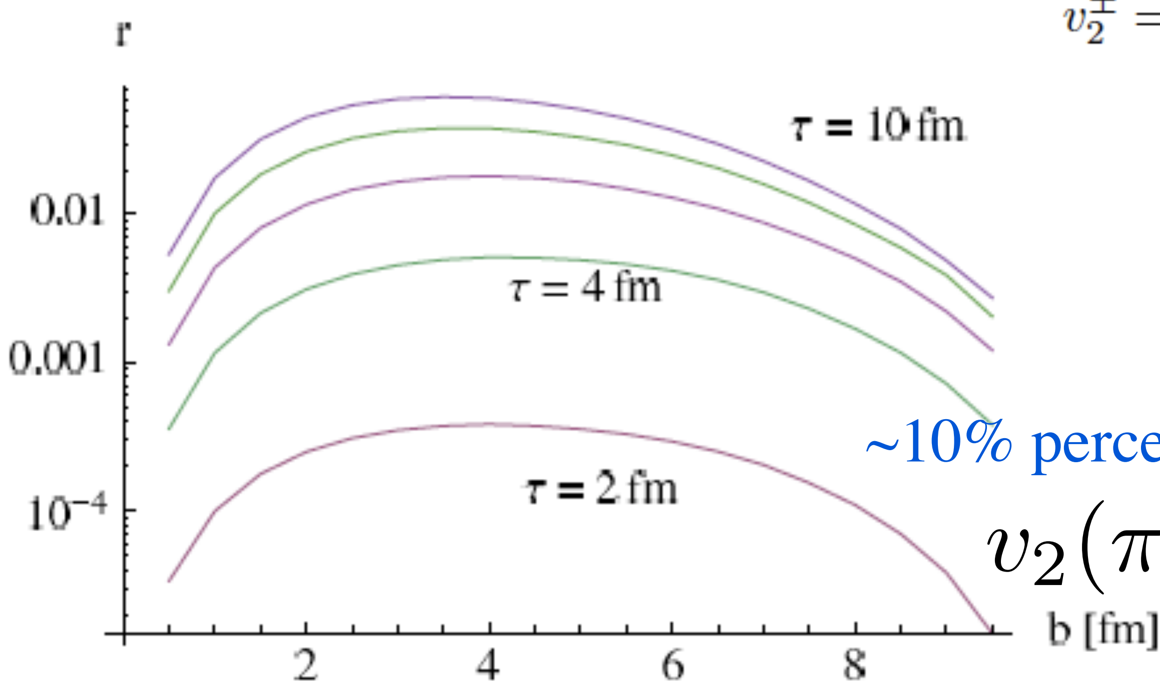
Also:

relevant for charge correlations! (RHIC vs LHC)

Elliptic flow of positive pions should be smaller than that of negative ones (always, not a fluctuation!)

Y.Burnier, DK, J. Liao, H.-U.Yee, arXiv:1103.1307 - submitted to PRL

The difference of elliptic flows: quantitative <u>estimates</u>



$$v_2^{\pm} = v_2 \mp \left(\frac{q_e}{\bar{\mu}_e}\right)\left(\frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}\right)$$

$$r = \left(\frac{q_e}{\bar{\mu}_e}\right)$$

~10% percent difference in v_2?

$$v_2(\pi^+) < v_2(\pi^-)$$

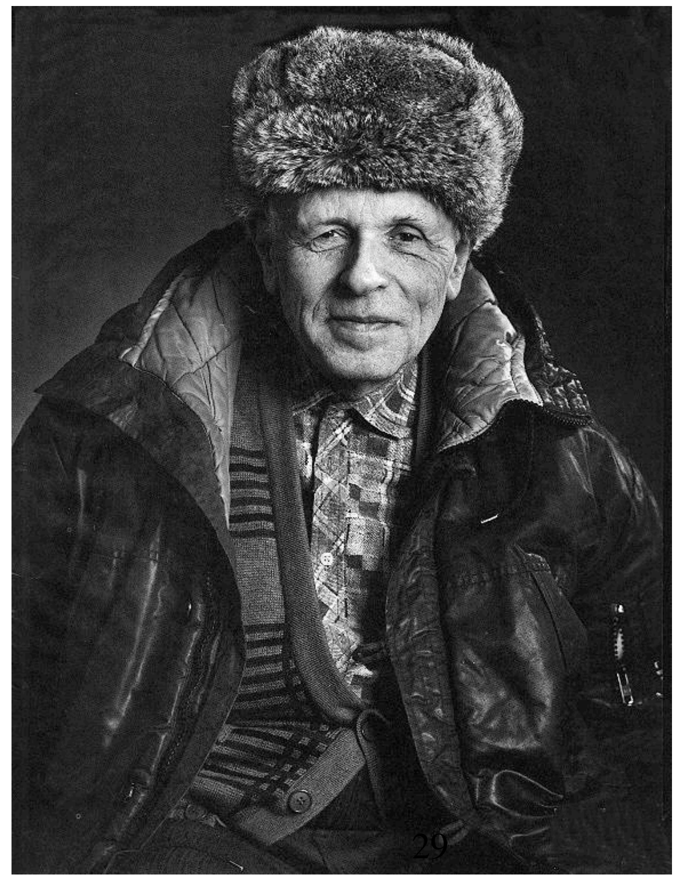
FIG. 3: The normalized electric quadrupole moment r, $eB|_{max} = m_\pi^2$, $T = 165$ MeV.

Y.Burnier, DK, J. Liao, H.-U.Yee, arXiv:1103.1307

Chirality generation in QGP vs. Baryogenesis in the Early Universe

1. B violation
2. CP violation
3. Non-equilibrium dynamics

A.D. Sakharov,
JETP Lett. 5 (1967) 24



Baryon number		Chirality
EW sphalerons	⟷	QCD sphalerons
Big Bang		“Little bang”

Summary

Chiral symmetry and parity invariance are fundamental

Interplay of topology, chirality and
magnetic field leads to
the Chiral Magnetic Effect:
confirmed by lattice QCD x QED,
signature of chiral symmetry restoration

Experimental evidence at RHIC?
need for more studies at RHIC and LHC;
they are underway (PID, low and high energies)