STAR Parity Working Group, February 16, 2011

The News on Parity

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Outline

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

- Chiral Magnetic Wave at finite baryon density and the Electric Quadrupole Moment of quark-gluon plasma; the signature: $v_2(\pi^+) < v_2(\pi^-)$
  Y. Burnier, DK, J. Liao, H.-U. Yee, to appear (very soon!)

- Separating Chiral Magnetic and Chiral Vortical Effects using the Baryon Number asymmetries
  DK, D.T.Son, arXiv:1010.0038; Phys.Rev.Lett. '11

Other recent work on LPV and CME that I will not cover today:

Chiral Magnetic Spiral.
Gokce Basar, Gerald V. Dunne (Connecticut U.), Dmitri E. Kharzeev (Brookhaven). **Phys.Rev.Lett. 104 (2010) 232301**

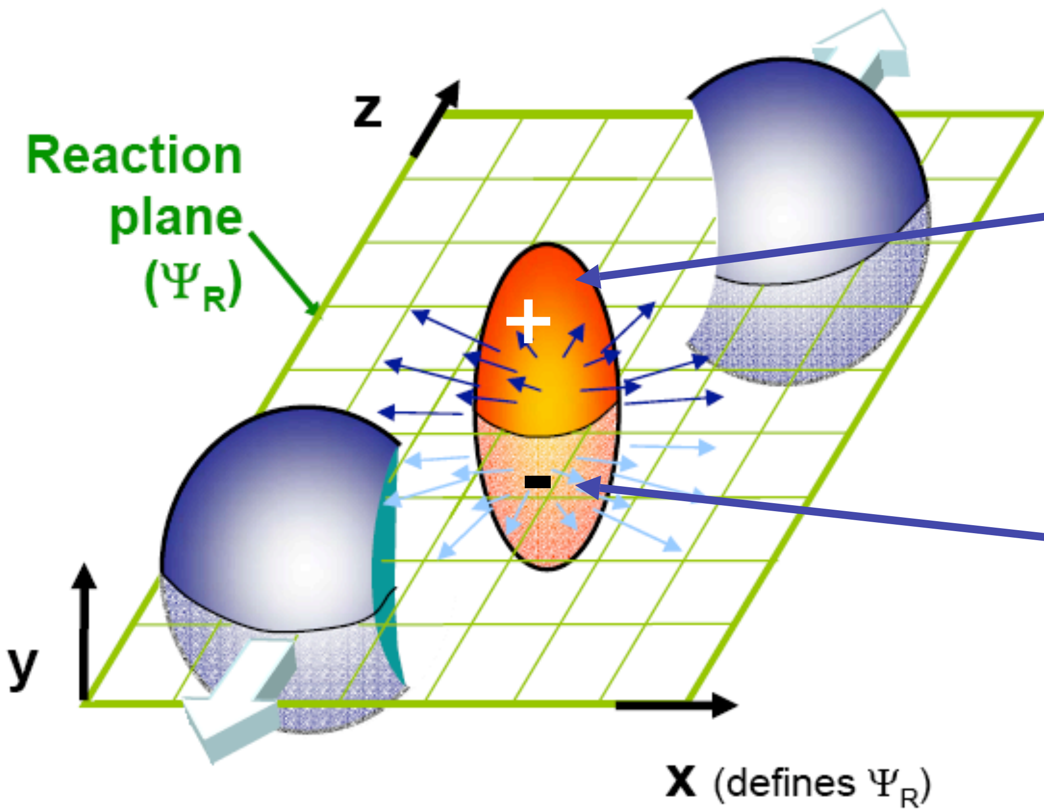
Real-time dynamics of the Chiral Magnetic Effect.
Kenji Fukushima (Kyoto U.), Dmitri E. Kharzeev (Brookhaven), Harmen J. Warringa (Frankfurt U.). **Phys.Rev.Lett. 104 (2010) 212001**

Quark fragmentation in the θ-vacuum.
Zhong-Bo Kang (RIKEN BNL), Dmitri E. Kharzeev (Brookhaven). **Phys.Rev.Lett. 106 (2011) 042001**

Electric-current Susceptibility and the Chiral Magnetic Effect.
Kenji Fukushima (Kyoto U., Yukawa Inst., Kyoto), Dmitri E. Kharzeev (Brookhaven), Harmen J. Warringa**Nucl.Phys. A836 (2010) 311-336**

Magnetic-Field-Induced insulator-conductor transition in SU(2) quenched lattice gauge theory.
P.V. Buividovich (Moscow, ITEP & Dubna, JINR), M.N. Chernodub (Tours U. & Gent U.), D.E. Kharzeev (Brookhaven & Yale U.), T. Kalaydzhyan (DESY & Moscow, ITEP), E.V. Luschevskaya (Moscow, ITEP & Dubna, JINR), M.I. Polikarpov (Moscow, ITEP). **Phys.Rev.Lett. 105 (2010) 132001**

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



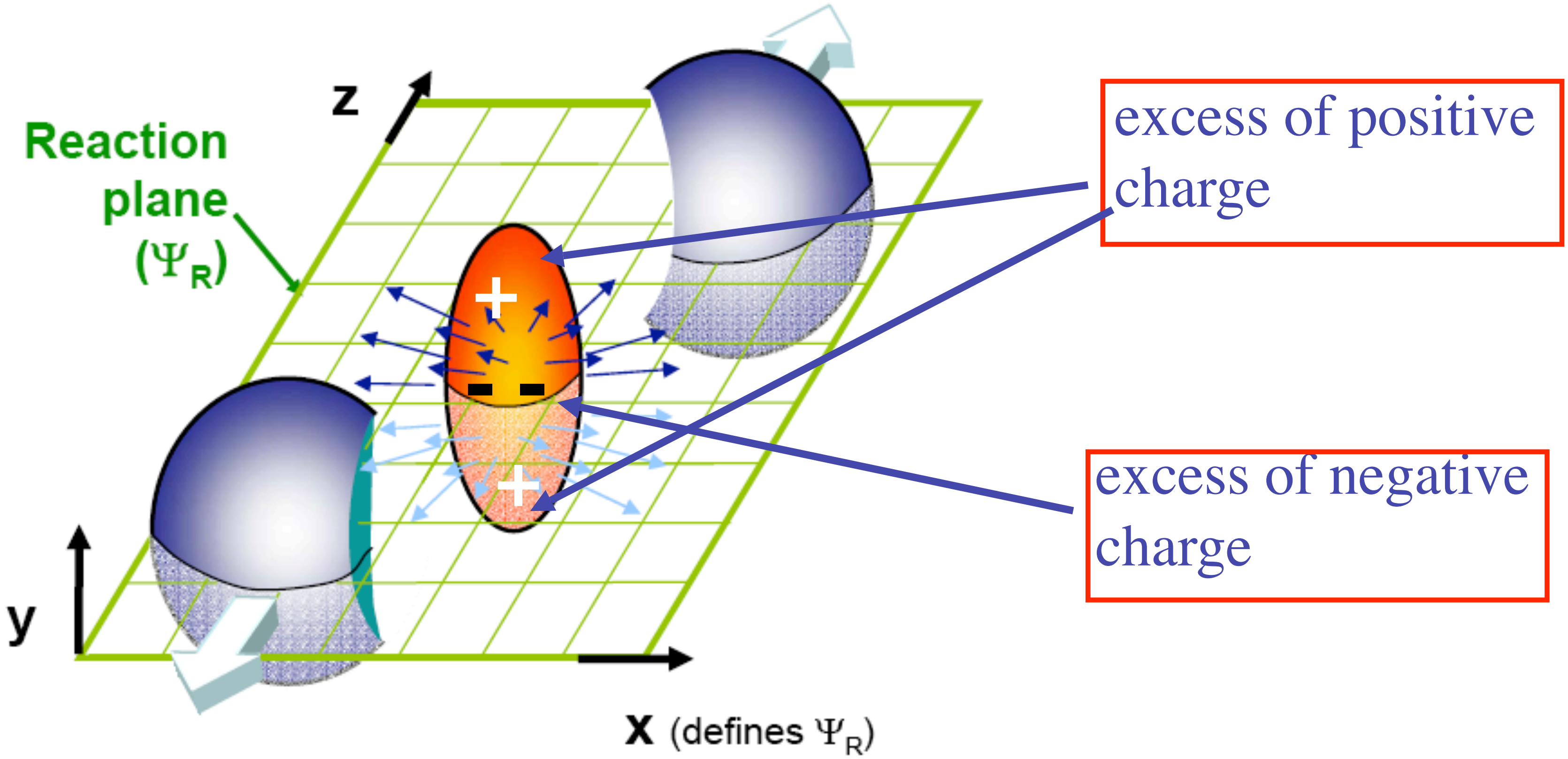
excess of positive charge

excess of negative charge

Electric dipole moment of QCD matter!

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

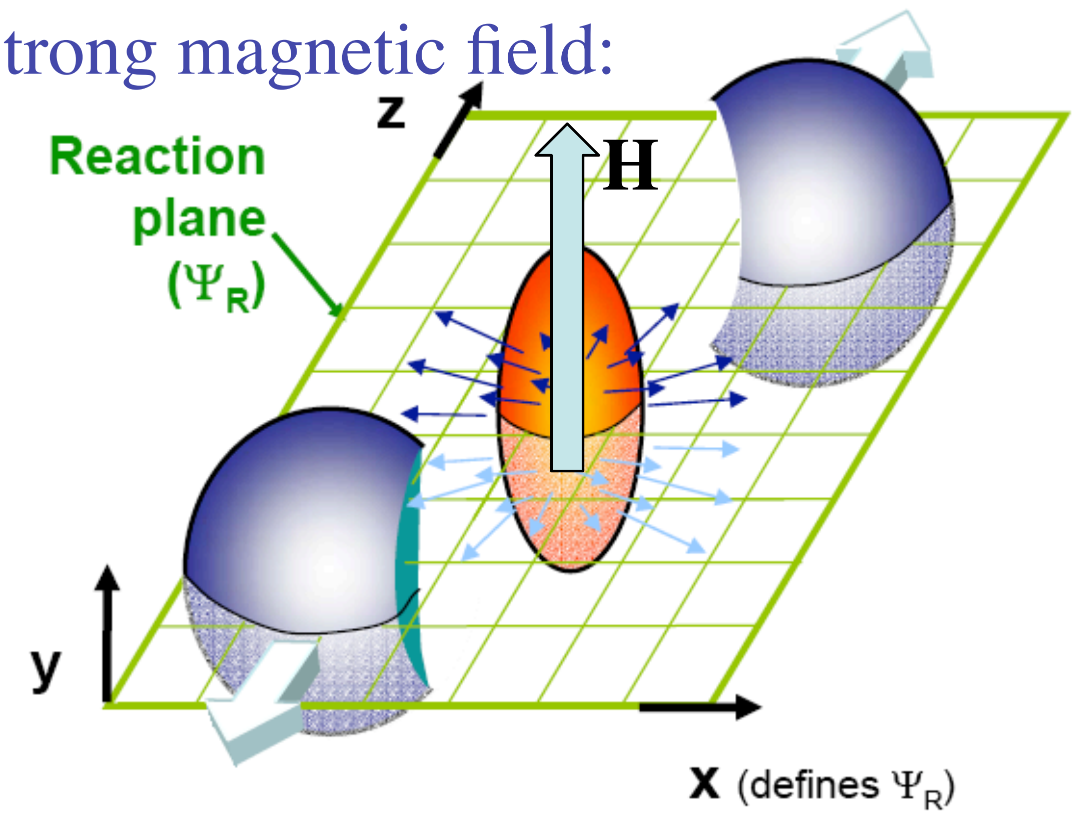
Finite baryon density (low energies):
electric quadrupole moment of QGP?

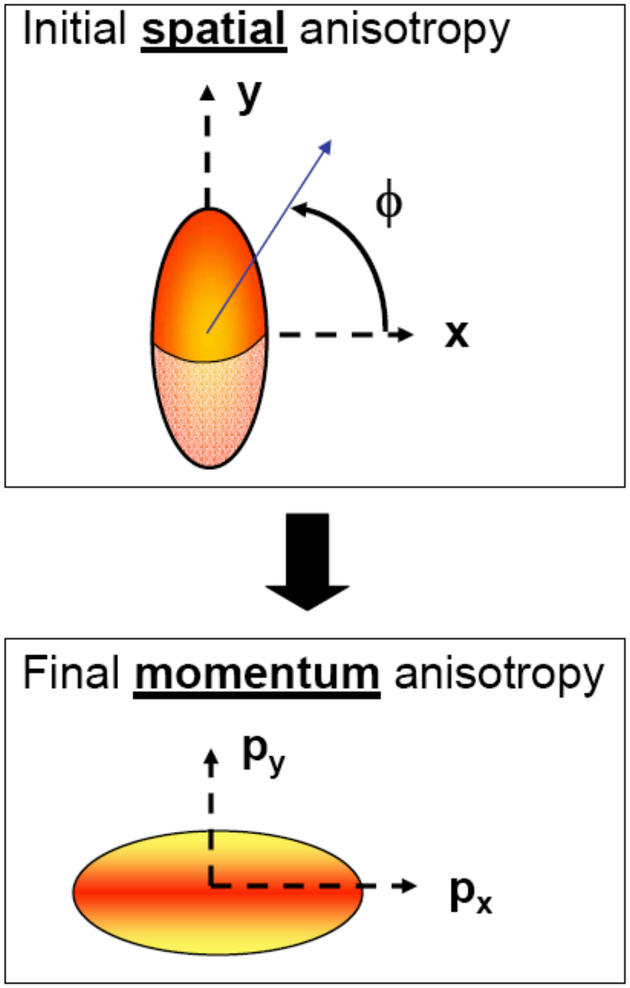


Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

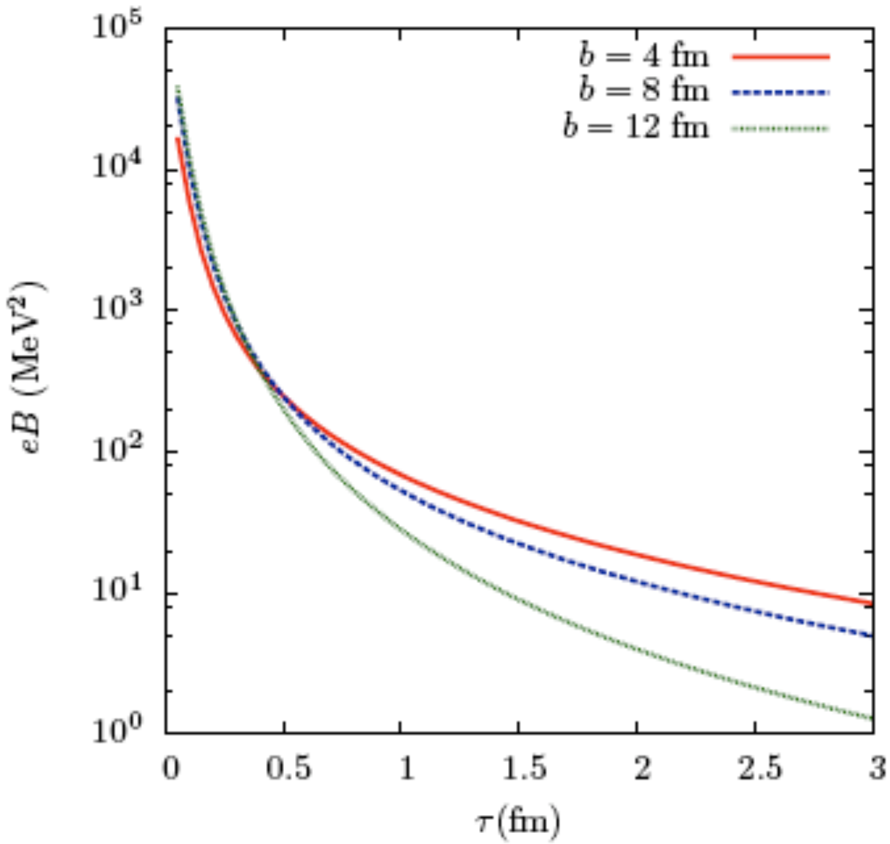
Chiral Magnetic Effect:
a brief summary

Relativistic ions create
a strong magnetic field:





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



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

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 ($Y_0 = 5.4$).

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

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

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

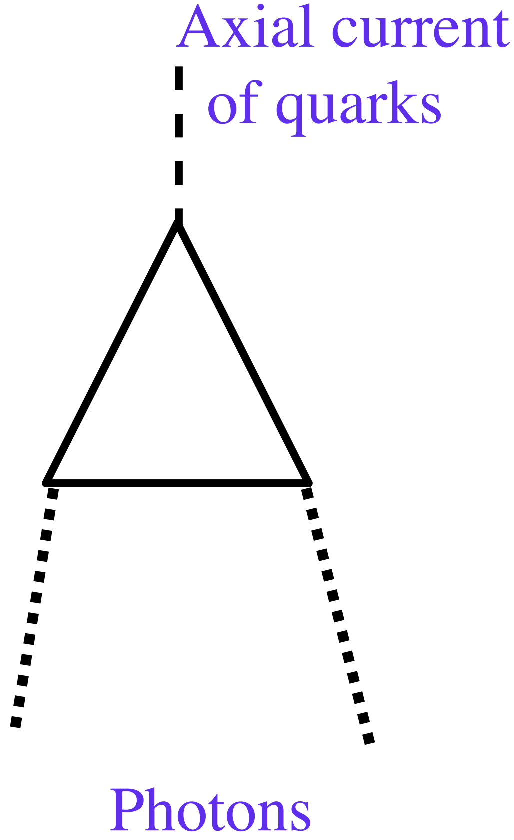
$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(\dot{\theta}\vec{B} - \vec{P} \times \vec{E}\right),$$

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

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

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

EM fields in QCD "aether"

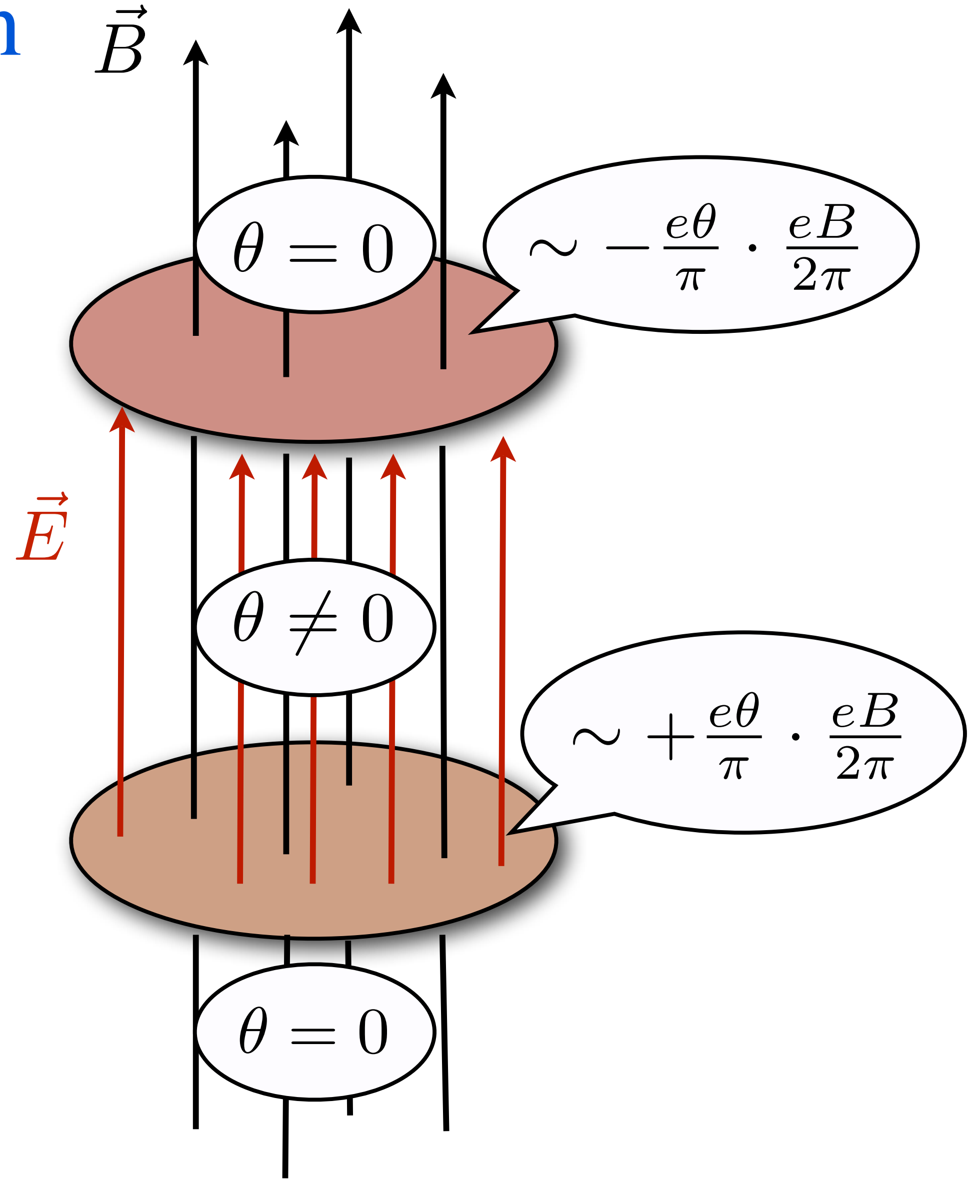


The Chiral Magnetic Effect I: Charge separation

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

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

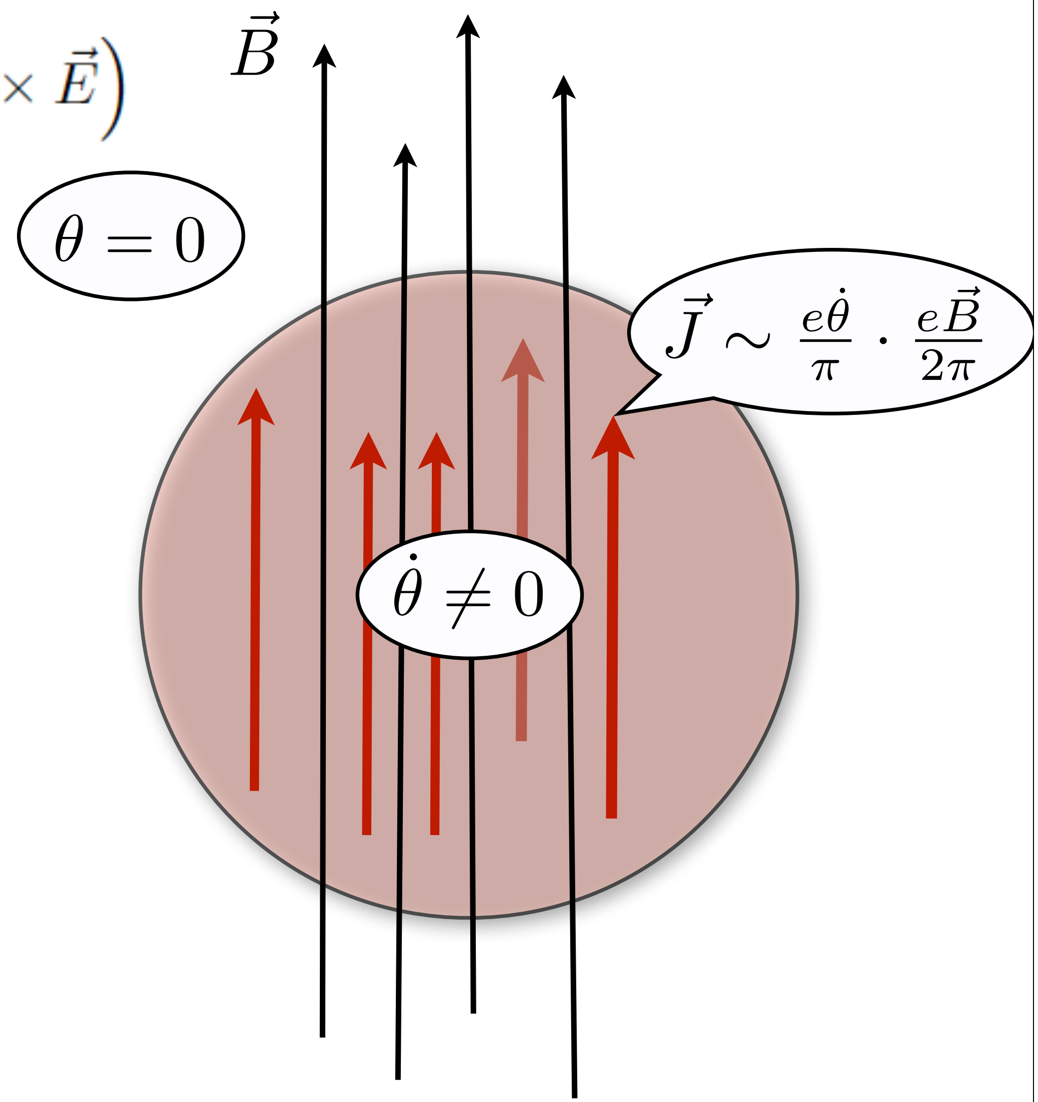
$$d_e = \sum_f q_f^2 \left(e\,\frac{\theta}{\pi} \right) \left(\frac{eB \cdot S}{2\pi} \right) L$$



DK '04;
DK, A. Zhitnitsky '06

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 Wave

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

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

CME Chiral separation

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

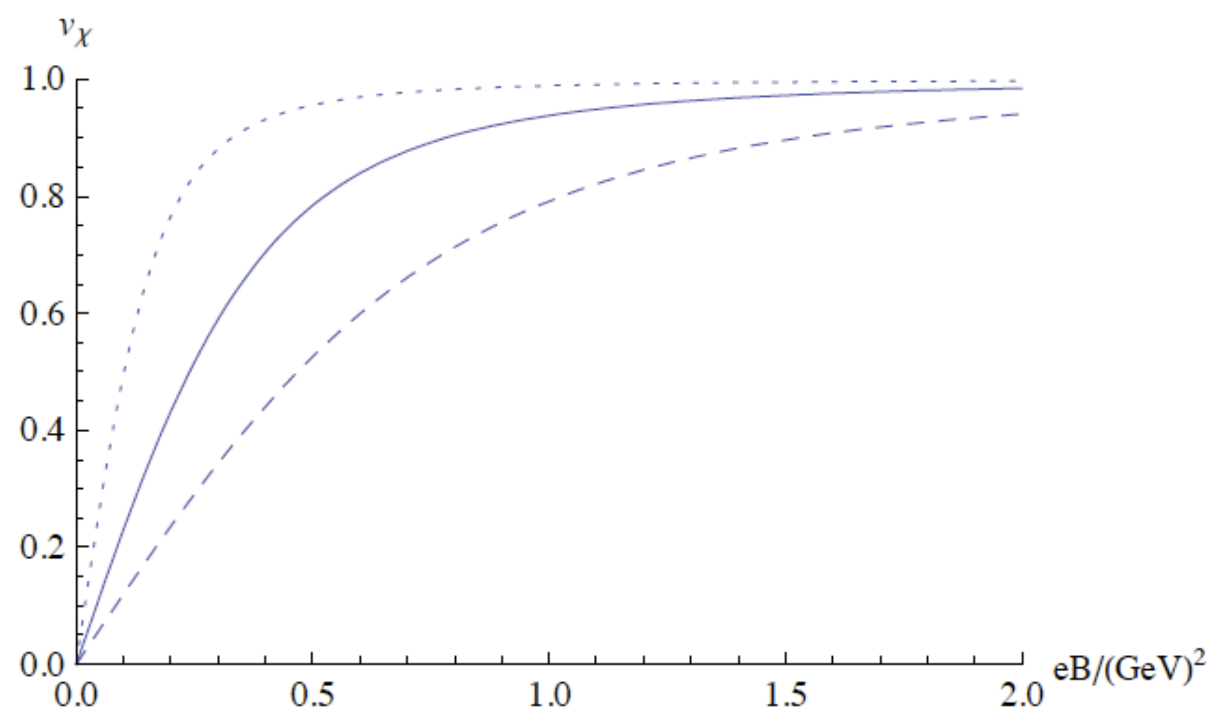
Propagating chiral wave:

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

Gapless collective mode

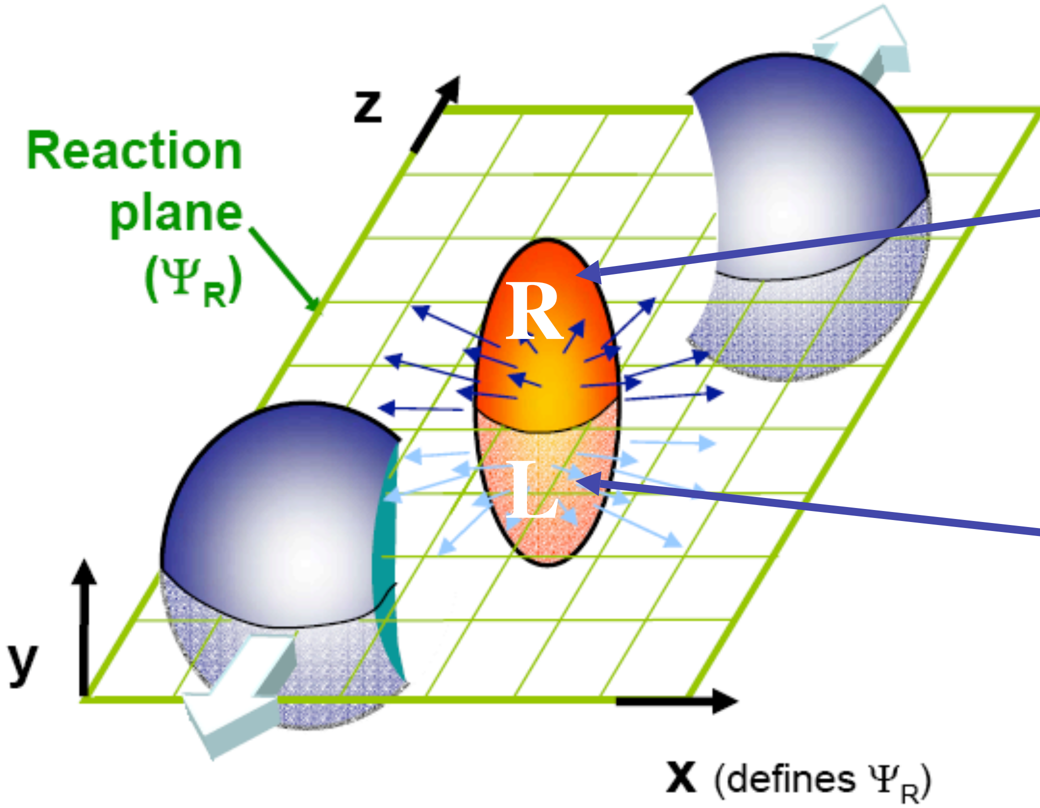
$$\omega = \mp v_\chi k - i D_L k^2 + \cdots$$

The Chiral Magnetic Wave



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

Quadrupole moment from CMW: step 1, chiral separation



excess of Right chiral charge

excess of Left chiral charge

Chiral dipole moment of QCD matter

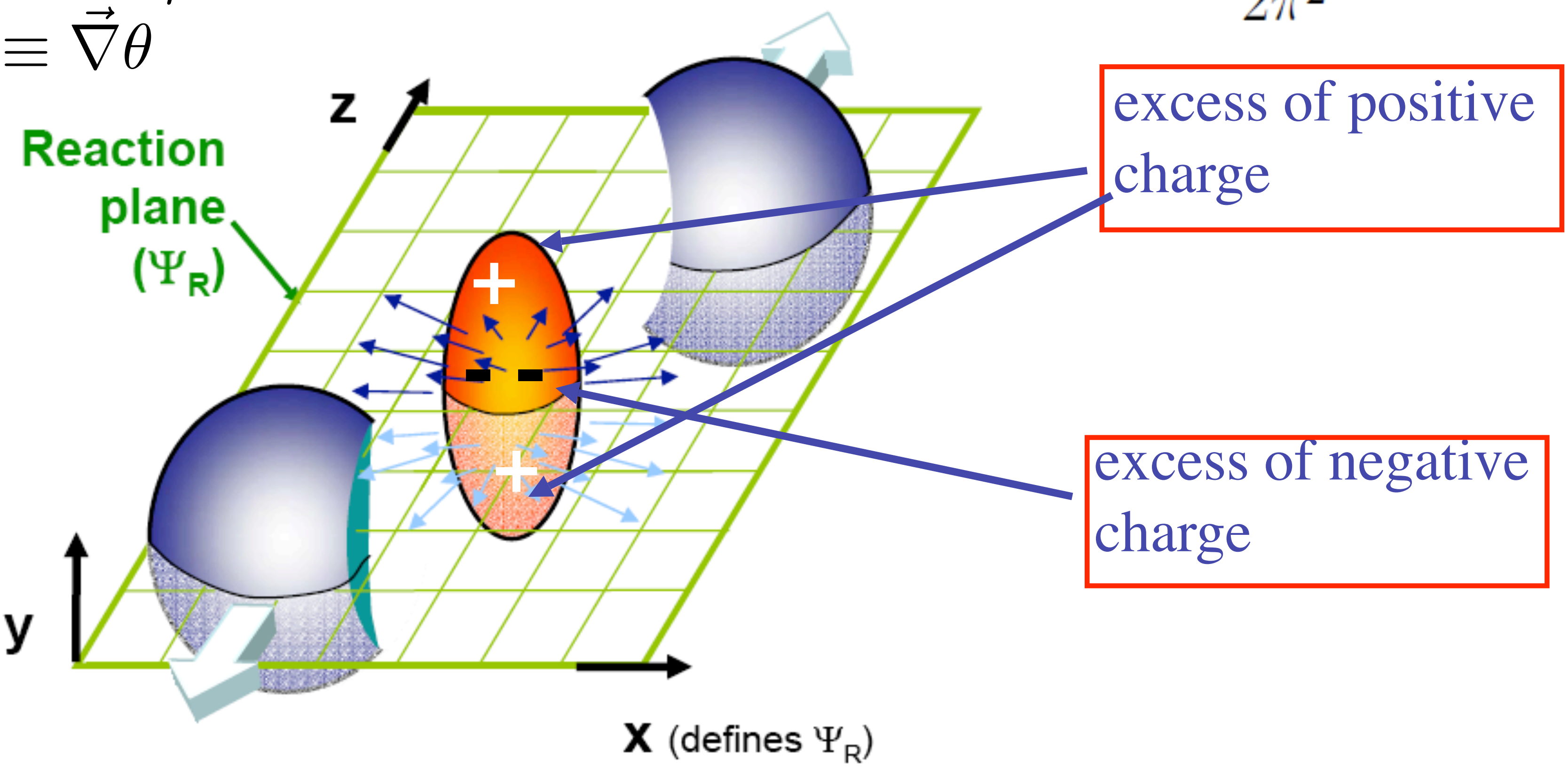
D. Son et al;

V. Miransky et al

Electric quadrupole moment of QGP at finite baryon density as a signature

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

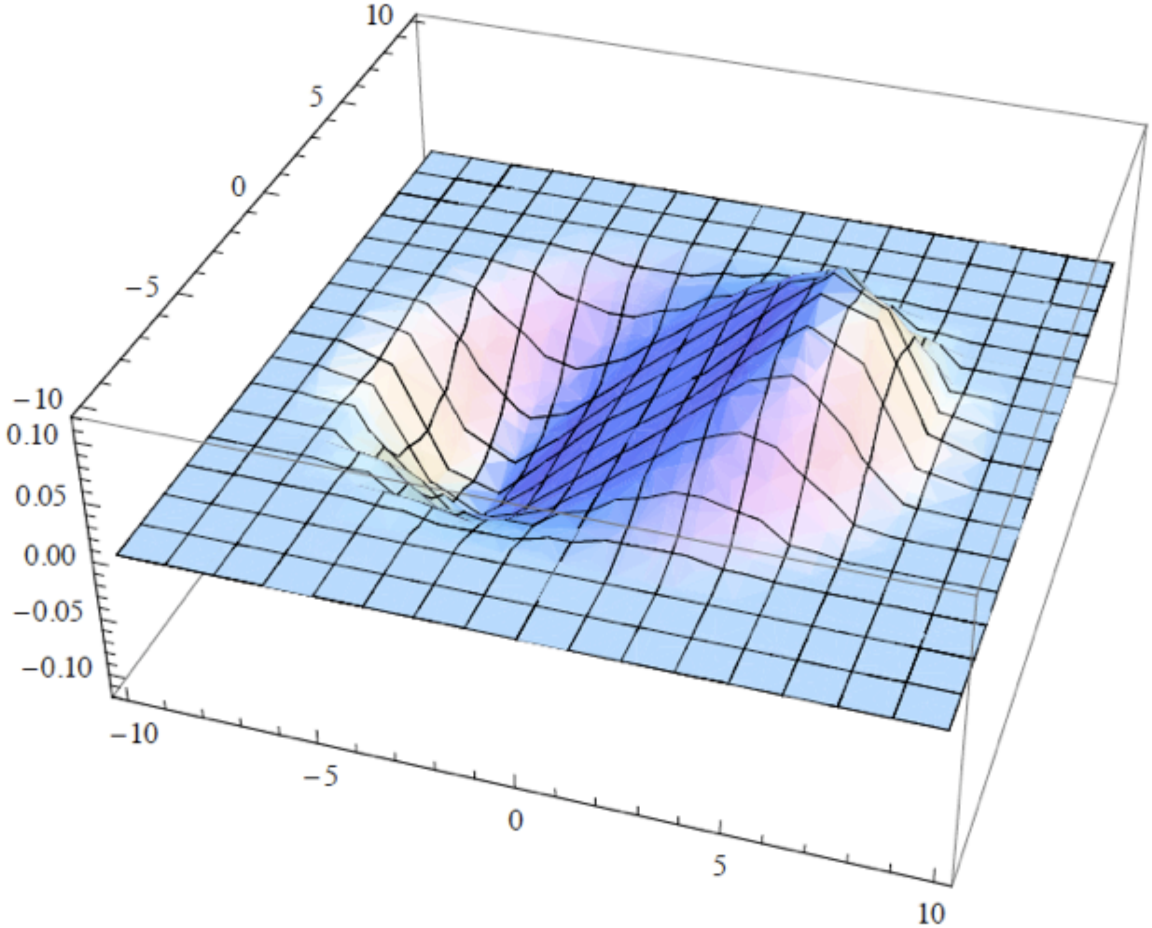
$$\vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B};$$



Electric quadrupole moment of QCD matter!

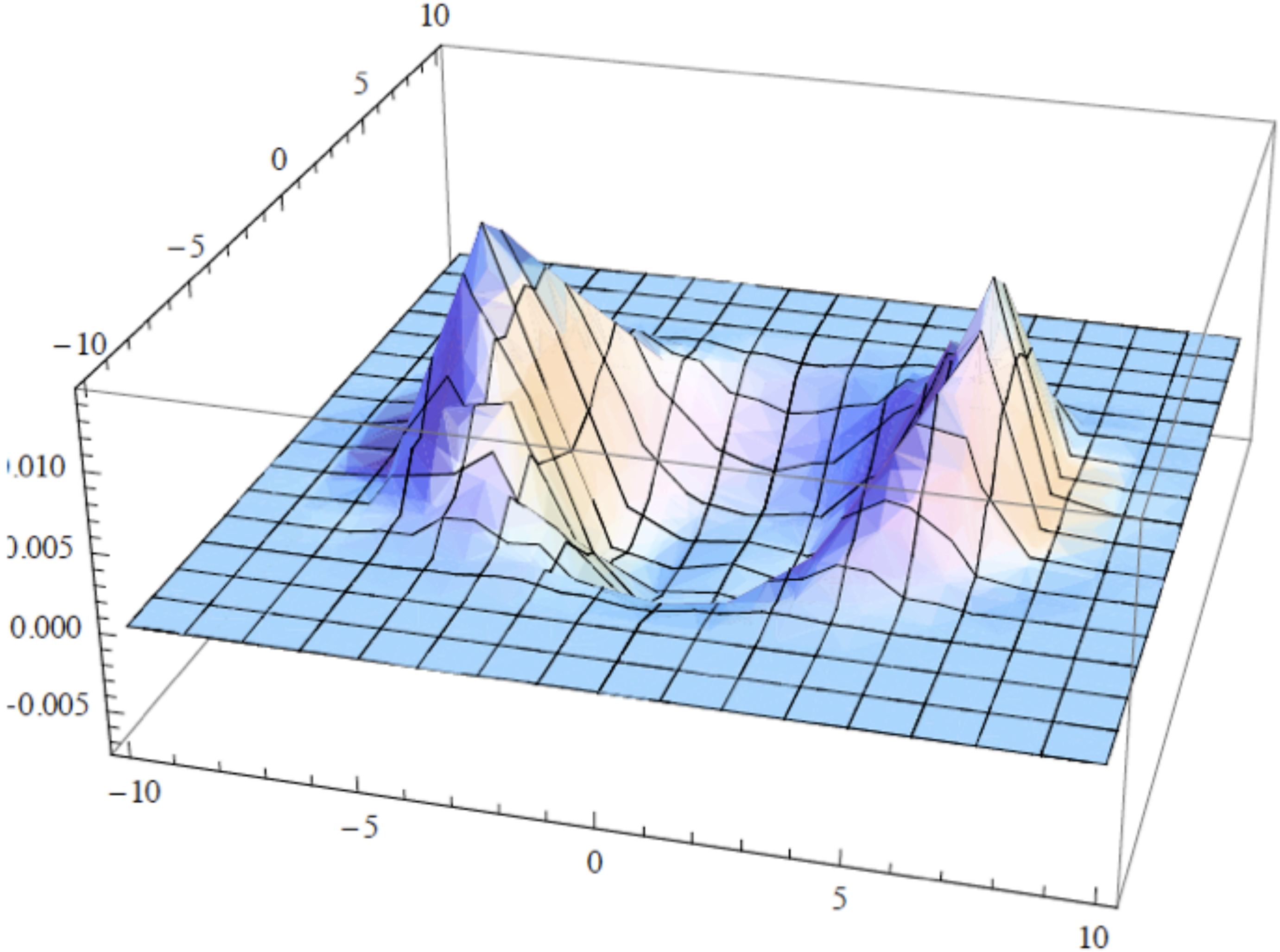
Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

Chiral dipole moment of QGP at finite baryon density



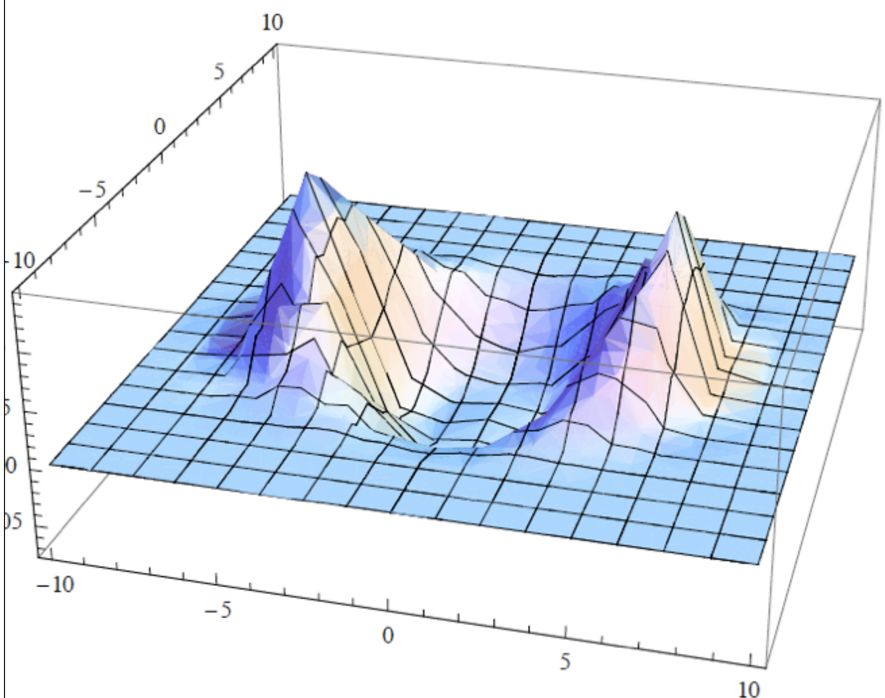
Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

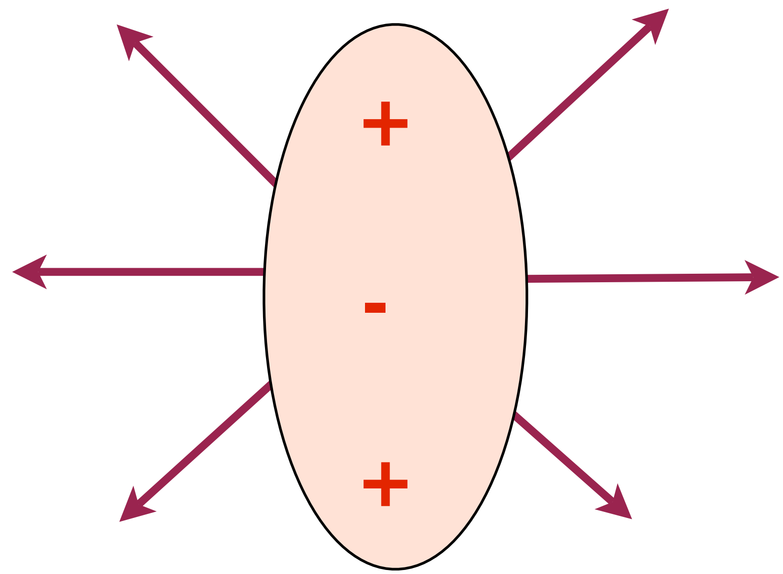
Electric quadrupole moment of QGP at finite baryon density



Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

Electric quadrupole moment of QGP: the signature

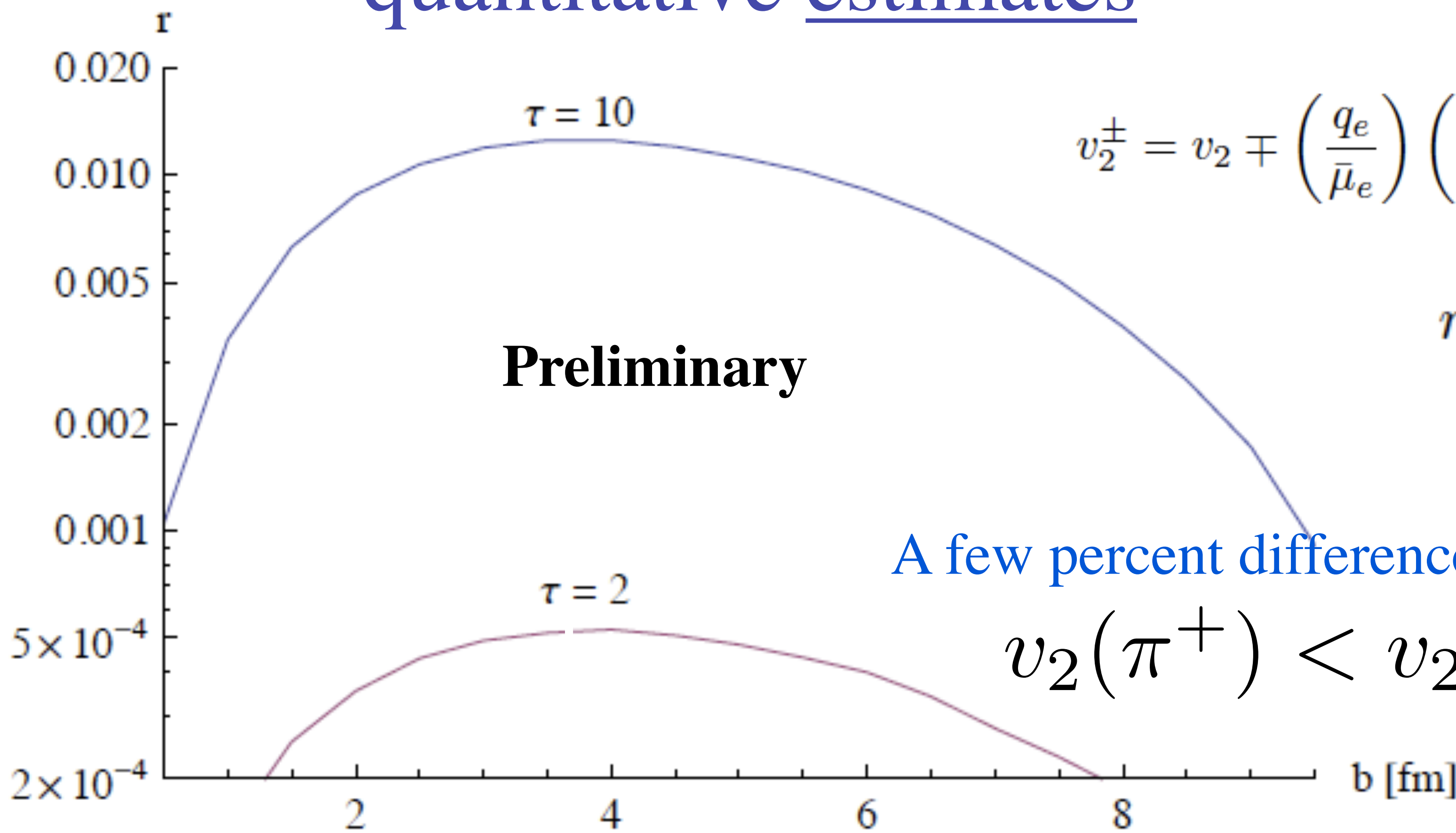




Elliptic flow of positive hadrons should be smaller than of negative ones (without absorption effects - e.g. antiproton annihilation)

Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

The difference of elliptic flows: quantitative estimates



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

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

A few percent difference in v_2?

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

FIG. 3: charge quadrupole r, $eB = m_\pi^2$, $\sqrt{s} = 11GeV$, $T = 164$

Y.Burnier, DK, J. Liao, H.-U.Yee, to appear

A new test of CME: baryon asymmetry

DK, D.T.Son
arXiv:1010.0038

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

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 separation

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

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

CVE: (almost) only baryon charge separation

Summary

- Anomalies lead to a number of subtle and beautiful phenomena in the chirally restored phase of QCD

- Chiral Magnetic Wave at finite baryon density and the Electric Quadrupole Moment of quark-gluon plasma; the signature: $v_2(\pi^+) < v_2(\pi^-)$

- Separating Chiral Magnetic and Chiral Vortical Effects using the Baryon Number asymmetries

Measurements would be extremely useful!