P- and CP-odd effects in heavy ion collisions

Harmen Warringa, Goethe Universität, Frankfurt

Collaborators: Kenji Fukushima, Dmitri Kharzeev and Larry McLerran.

Kharzeev, McLerran & HJW, Nucl. Phys. A **803**, 227 (2008)
Fukushima, Kharzeev & HJW, Phys. Rev. D **78**, 074033 (2008)
Kharzeev & HJW, Phys. Rev. D **80**, 034028 (2009)
Fukushima, Kharzeev & HJW, arXiv:0912.961
Fukushima, Kharzeev & HJW, to appear.

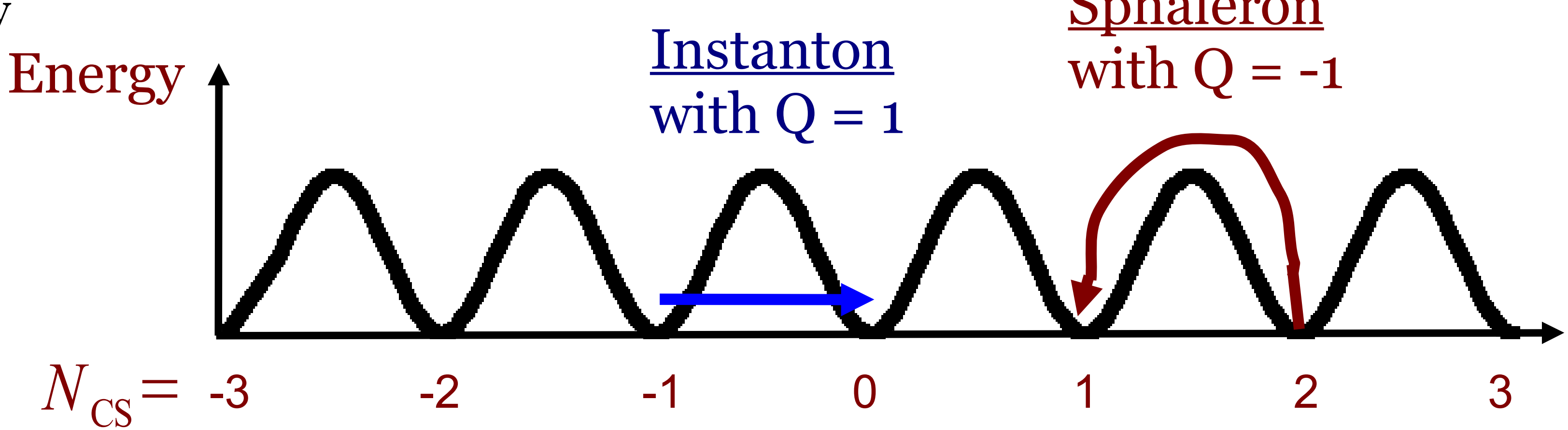
Observation I:

Topological charge fluctuations present in QCD and hence in heavy ion collisions

Topological charge of gauge field: $Q = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a = \Delta N_{CS}$

Nonzero Q contributes to path-integral, and hence to physical quantities.

The nontrivial vacuum structure of a SU(N) gauge theory



Belavin et. al. ('75), Jackiw & Rebbi ('76), Callan et al. ('76), 't Hooft ('76), Klinkhamer & Manton ('84), ...

Observation I:

Topological charge fluctuations present in QCD and hence in heavy ion collisions

Topological charge of gauge field: $Q = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a = \Delta N_{CS}$

Nonzero Q contributes to path-integral, and hence to physical quantities.

$\langle Q^2 \rangle \neq 0$ Mass of eta-prime meson. ('t Hooft, Witten, Veneziano)

$$\frac{2N_f}{f_\pi^2 V_4} \langle Q^2 \rangle = m_{\eta'}^2 + m_\eta^2 - 2m_K^2$$

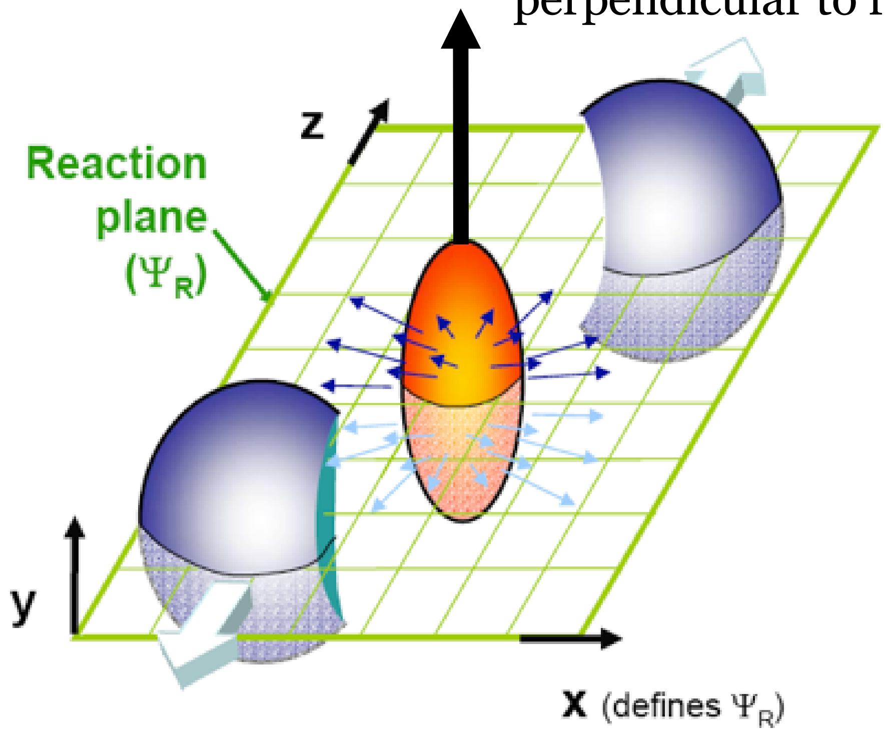
$\langle Q \rangle = 0$ Neutron electric dipole moment (Baker et.al. ('06))

$|\theta| < 10^{-10}$ No P- and CP-violation in QCD!
But Q can induce P- and CP-odd effects.

Observation II:

Ultra high-energy heavy ion collisions = Ultra strong (EM) magnetic fields

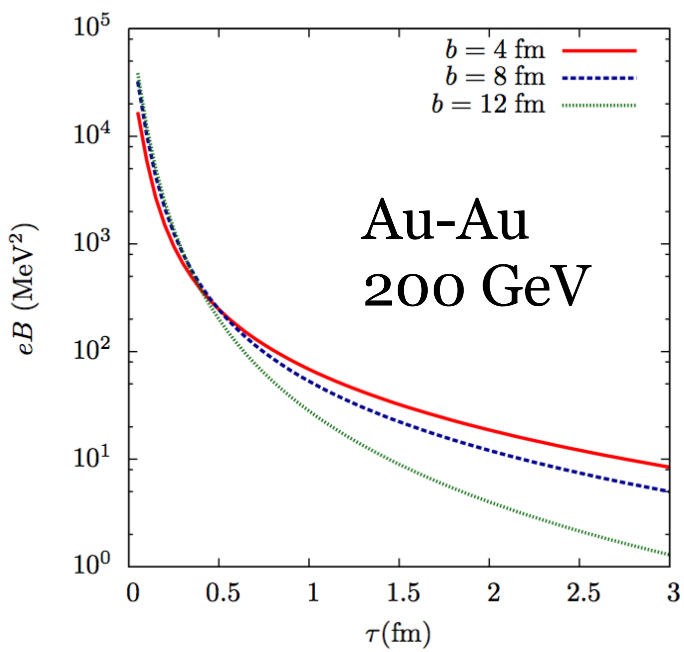
B, direction of mag. field.
perpendicular to reaction plane



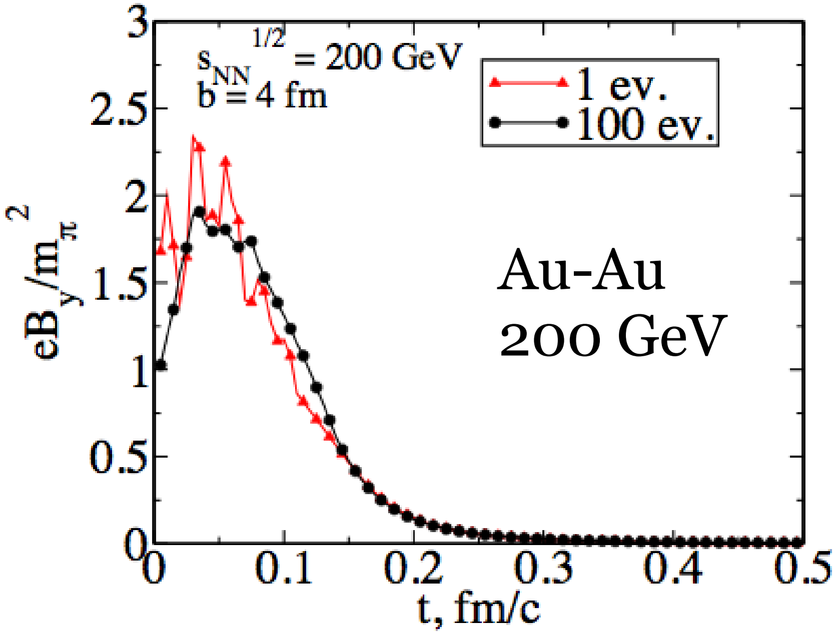
Gold – Gold collision: two currents which carry 79 charges each

Observation II:

Ultra high-energy heavy ion collisions = Ultra strong (EM) magnetic fields



Pancake approximation
Kharzeev, McLerran & HJW ('08)



URQMD calculation
Skokov, Illarionov, Toneev ('09)

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

See also Minakata and Müller ('96)

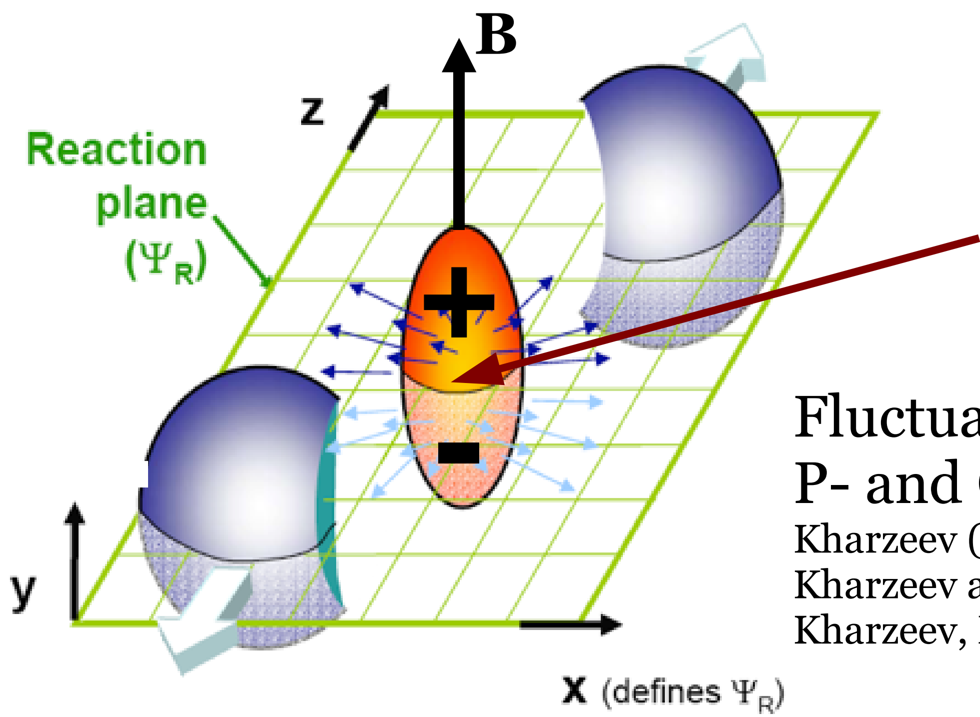
Outline

To explain you that

Topological charge + Magnetic Field =

$\langle Q \rangle = 0$

$\langle Q^2 \rangle \neq 0$



$Q < 0$

Fluctuating EDM of QGP
P- and CP-odd effect
Kharzeev ('06),
Kharzeev and Zhitnitsky ('07)
Kharzeev, Mclerran and Warringa ('08)

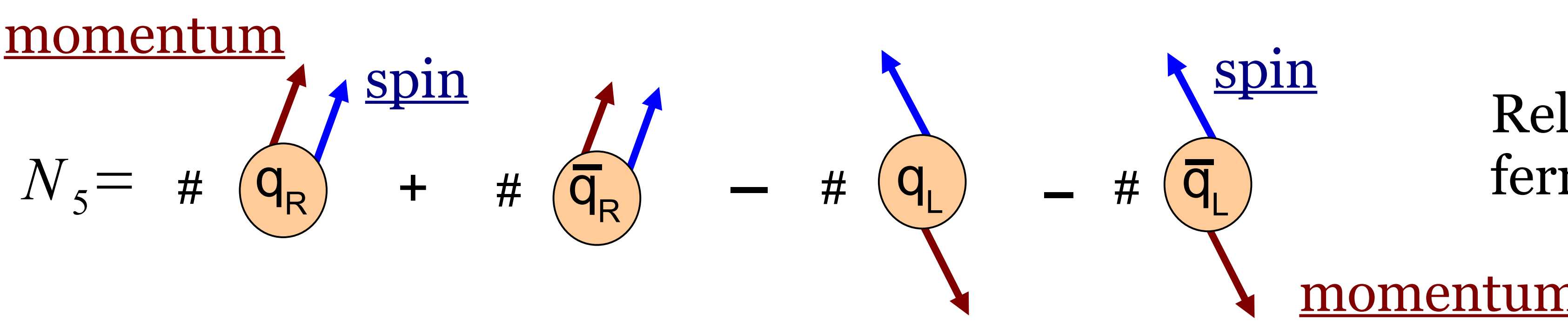
Charge separation

This can potentially be observed in experiment by charge correlation study [Voloshin ('04)]

Topological charge induces chirality

This is the P- and CP-odd effect

Chirality: difference between number of quarks + antiquarks with right- and left-handed helicity



Relativistic fermions

Axial anomaly: topological charge induces chirality

Steinberger ('49), Schwinger ('51), Alder ('69), Bell and Jackiw ('69)

$$\partial_\mu \langle \bar{\Psi} \gamma^\mu \gamma^5 \psi \rangle_A = 2m \langle \bar{\Psi} i \gamma^5 \psi \rangle_A - 2 \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

Exact equation

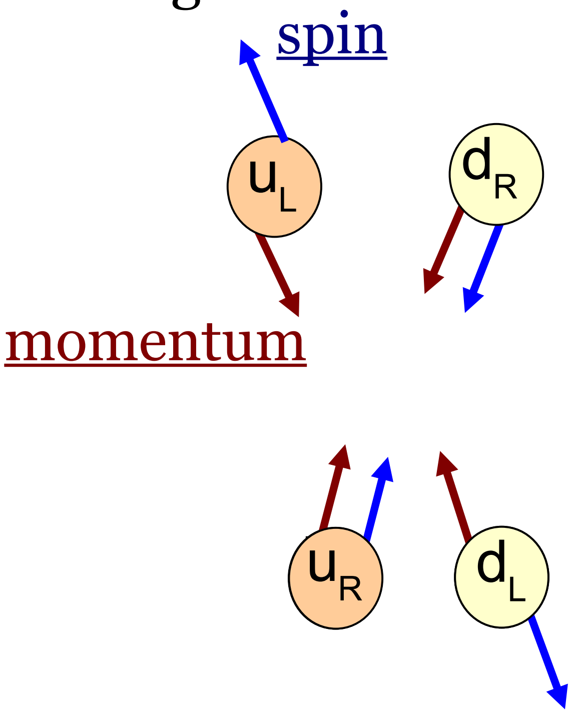
Change in chirality over time for each flavor = - 2 x Topological charge

$$\Delta N_5 = -2Q$$

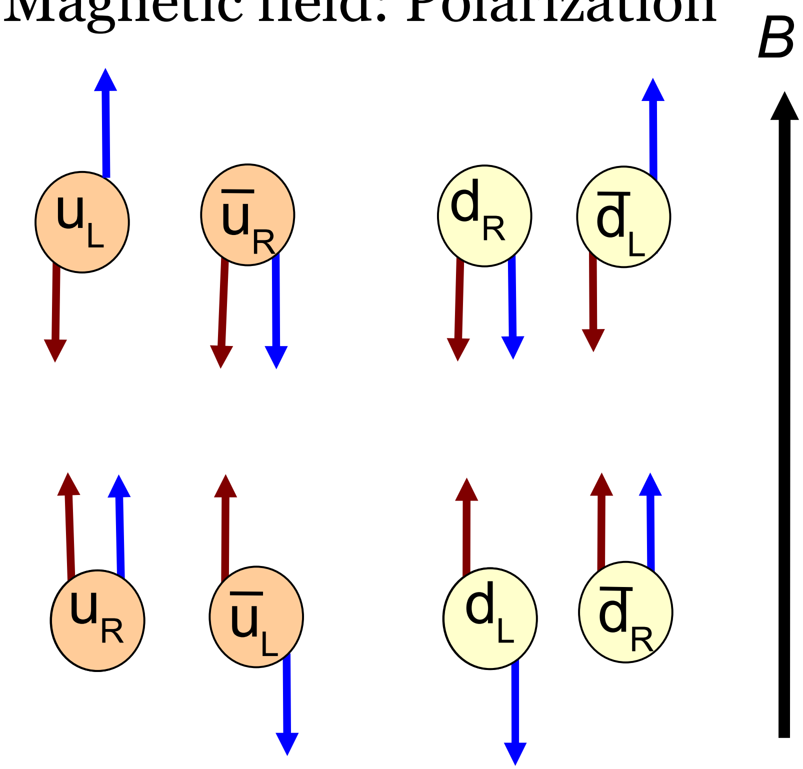
Magnetic field induces polarization

Magnetic field aligns spins, depending on electric charge

No Magnetic Field: No polarization



Magnetic field: Polarization

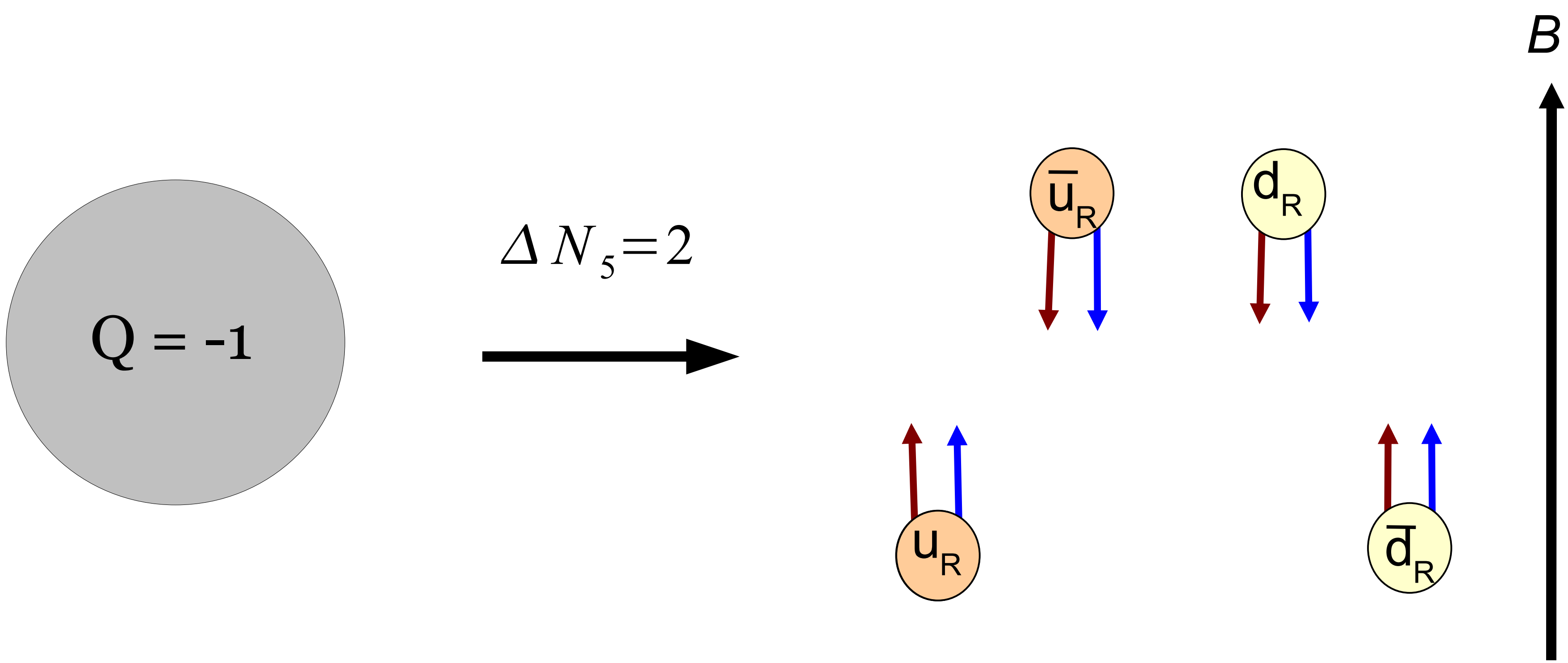


The momenta of the quarks align along the magnetic field

Quark with R-helicity obtains momentum opposite to one with L-helicity

Hence magnetic field distinguishes between right and left

Topological Charge + Magnetic field = Chirality + Polarization =

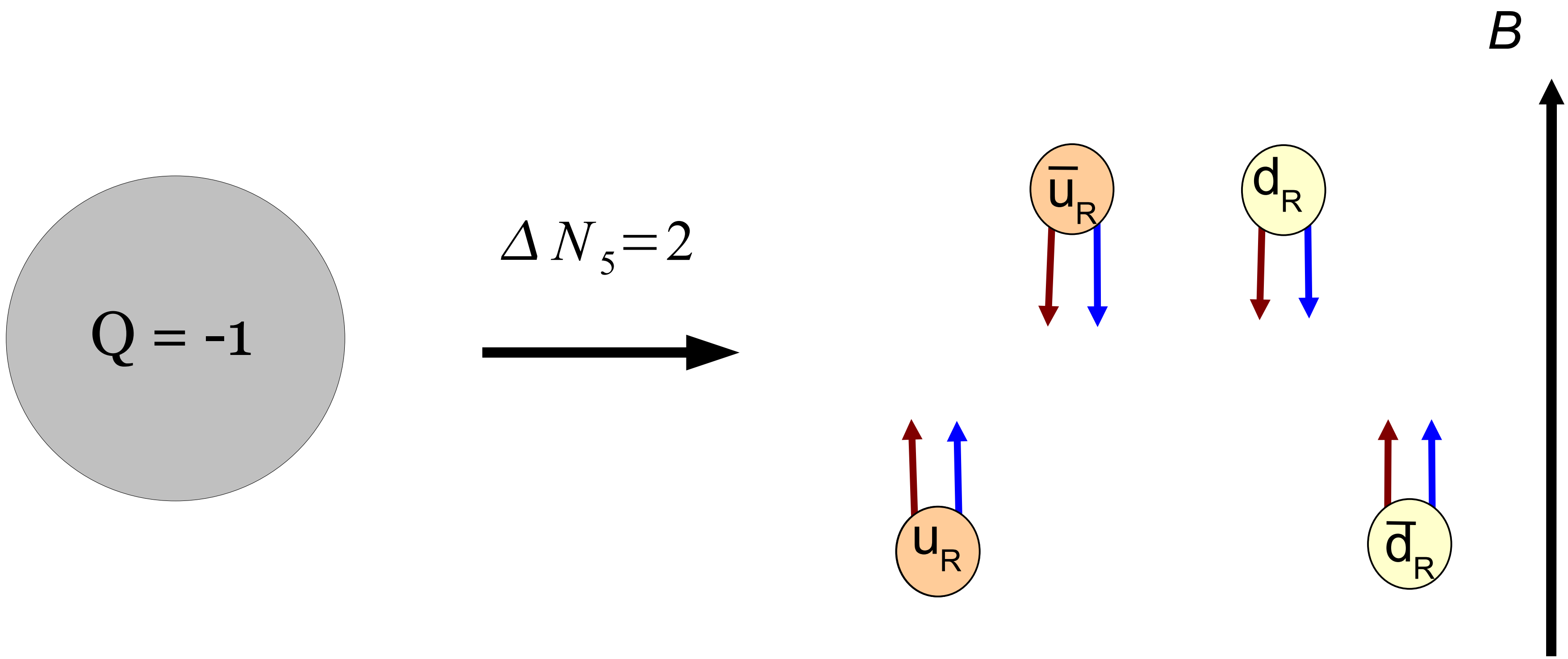


Q < -1: Positively charged particles move parallel to magnetic field, negatively charged antiparallel

… = Electromagnetic Current

Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('07)

Topological Charge + Magnetic field = Chirality + Polarization =

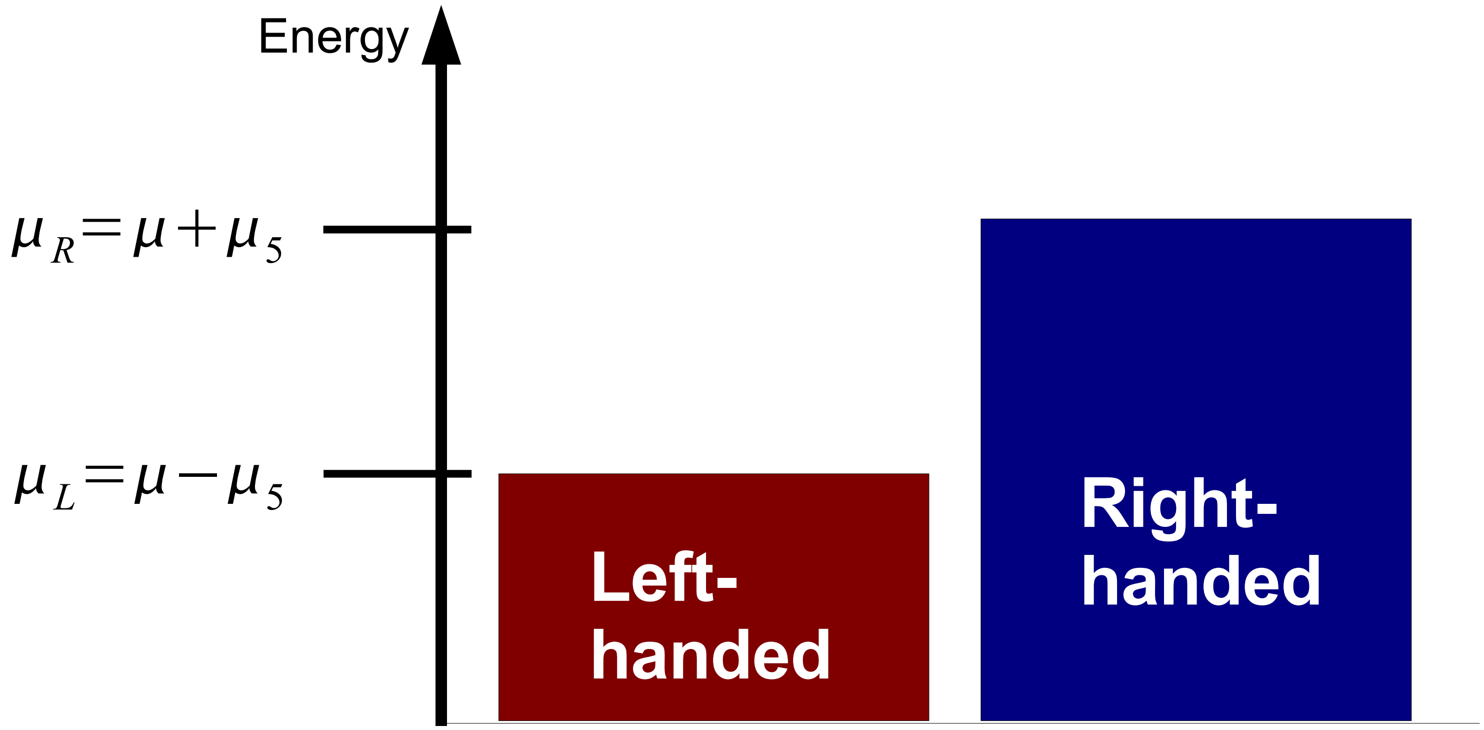


Size of Current: $J = \int d^3x \langle \bar{\psi} \gamma^3 \psi \rangle = -2Q \sum_f |q_f|$

Valid for full polarization, what about smaller fields?

Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('08)

How chirality reacts to magnetic field



Nonzero Chirality: Nonzero chiral chemical potential μ_5

$$H \to H - \mu_5 \int \mathrm{d}^3 x \, \bar{\psi} \gamma^0 \gamma^5 \psi$$

Compute induced current in magnetic field

Magnitude of the induced current

Alekseev, Cheianov, Fröhlich ('98), Fukushima, Kharzeev and HJW ('08)

1. Energy conservation $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

Nielsen and Ninomiya ('83)

2. Density in Lowest Landau Level $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

See also Metlitsky and Zhitnitsky ('06)

3. Chern-Simons term $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

4. Thermodynamic potential $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

5. Linear response $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

6. Propagator in magnetic field $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

Result follows from EM axial anomaly. Therefore exact and independent of coupling strength.

Anomaly induced currents: c.f. Goldstone and Wilczek ('81)

Magnitude of the induced current

Fukushima, Kharzeev and HJW ('08)

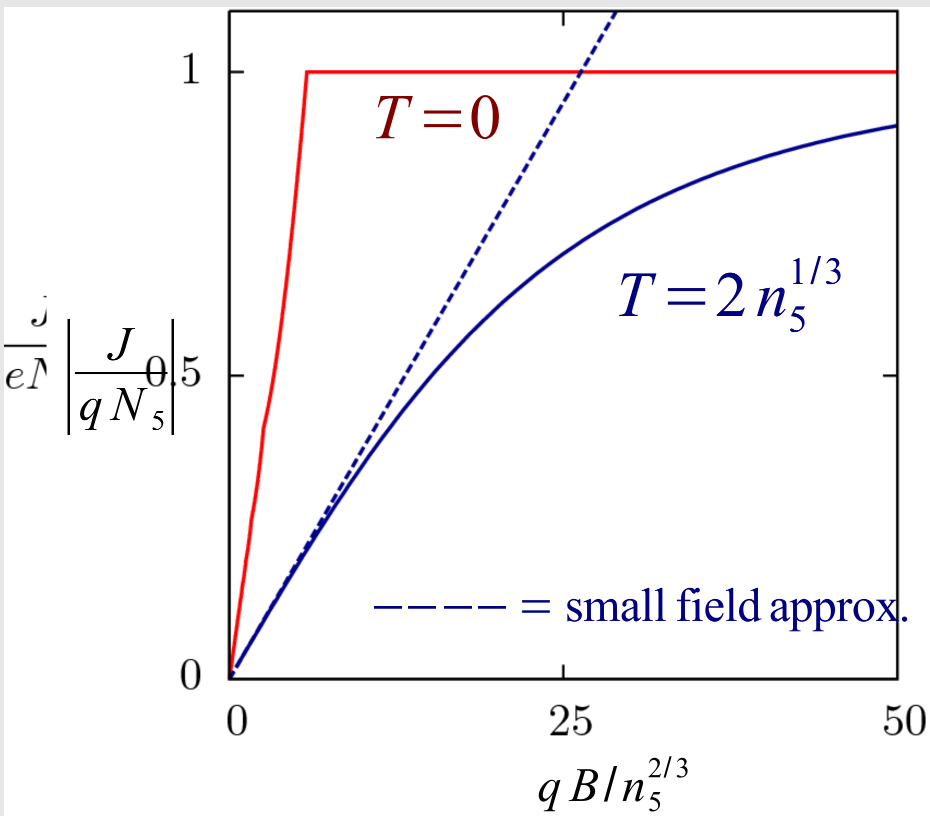
$$j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$$

But what is μ_5 ?

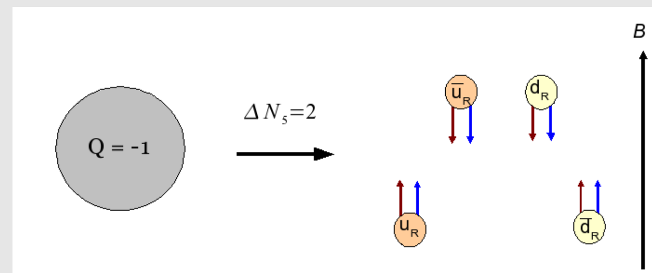
$$n_5 = \frac{\partial \Omega}{\partial \mu_5} \qquad N_5 = -2Q$$

Computed at high T (lo. pert. QCD)

Current as a function of magnetic field



Strong fields:



$$J = -2Q \sum_f |q_f|$$

---- = small field approx. :

$$J = -\frac{3}{\pi^2} \frac{Q}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$$

Chiral Magnetic Effect in time-dep. field

Kharzeev and HJW ('09)

$\vec{j} = \sigma_E \vec{E}$ $\sigma_E =$ electrical conductivity

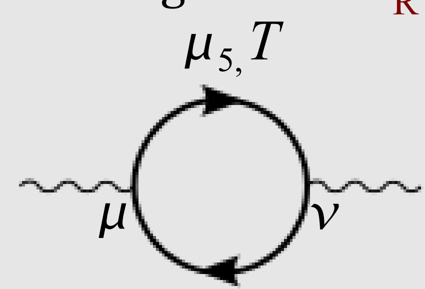
$\vec{j} = \sigma_\chi \vec{B}$ $\sigma_\chi =$ chiral magnetic conductivity

Compute induced current using linear response

$$\langle j^\mu(x) \rangle = \int \mathrm{d}^4 x' \, \Pi_R^{\mu\nu}(x - x') A_\mu(x') + o(A_\mu^2)$$

$$\sigma_\chi(\omega) = \lim_{p^i \to 0} \frac{1}{2 i p^i} \epsilon^{ijk} \tilde{\Pi}_{\mathrm{R}}^{jk}(\omega, p)$$

Leading order $\tilde{\Pi}_{\mathrm{R}}^{jk}$



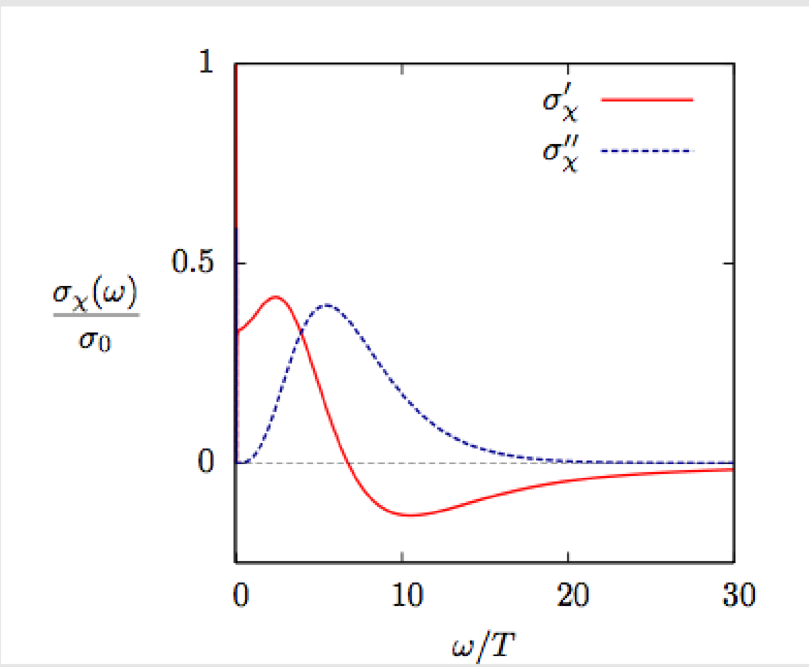
Off diagonal, antisymmetric part of
photon polarization tensor. Nonzero with μ_5

CM conductivity: weak vs. strong coupling

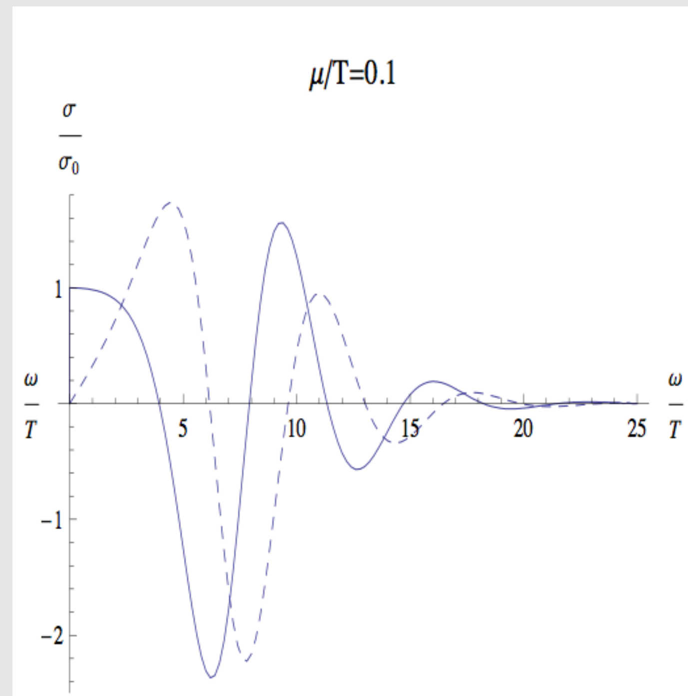
Displayed: normalized conductivity as a function of frequency. $\sigma_0 = \frac{N_c \sum_f q_f^2}{2\pi^2}\mu_5$

Weak coupling
(1 loop pert. QCD)

Strong coupling
(holographic model of QCD)



Kharzeev and HJW ('09)



Ho-Ung Yee ('09)

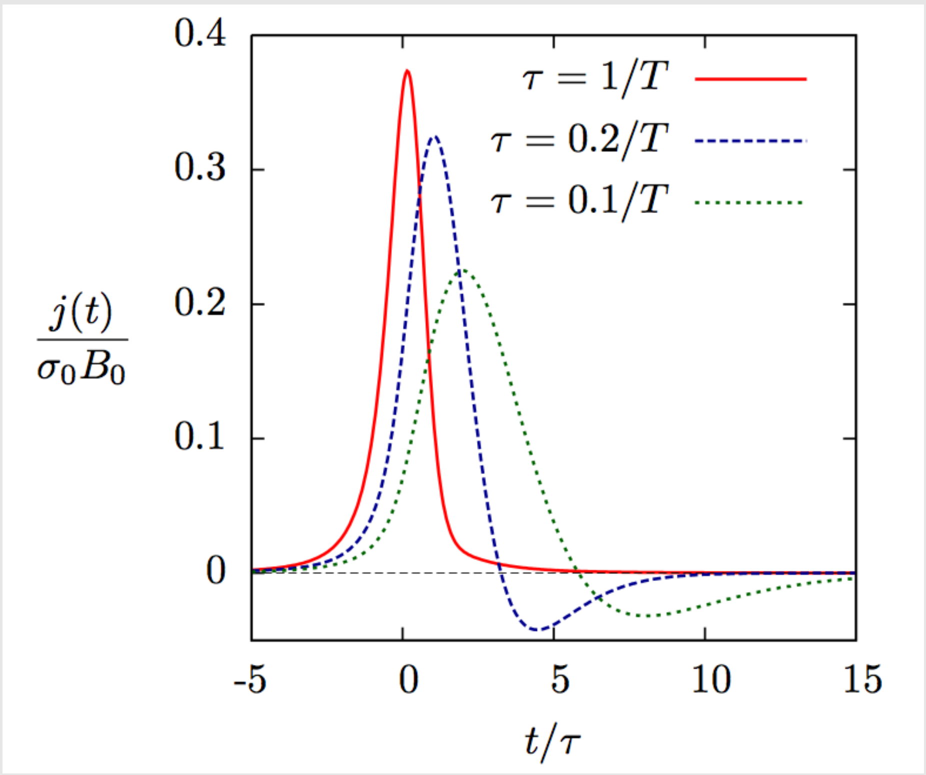
Real part: in-phase response, imaginary part: 90 degrees out of phase response

Chiral Magnetic Effect in time-dep. field

Kharzeev and HJW ('09)

$$j(t) = \int_0^\infty \frac{d\omega}{\pi}[\sigma'_\chi(\omega)\cos(\omega t)+\sigma''_\chi(\omega)\sin(\omega t)]\tilde{B}(\omega)$$

Current: const. chirality + time dep. mag. field $B(t)=\frac{B_0}{[1+(t/\tau)^2]^{3/2}}$



Red: current in slowly changing fields, adiabatic appr. = ok

Blue and green curves, faster changing mag field, but still induced current.

Even stronger response in strongly coupled regime.

Conclusion: also sizable current in fast changing magnetic field

Chiral Magnetic Effect: other methods

Lattice QCD:

Buividovich, Chernodub, Luschevskaya and Polikarpov ('09)
Abramczyk, Blum, Petropoulos and Zhou ('09)

AdS/CFT:

H.U. Yee ('09)
Rebhan, Schmitt and Stricker ('09)

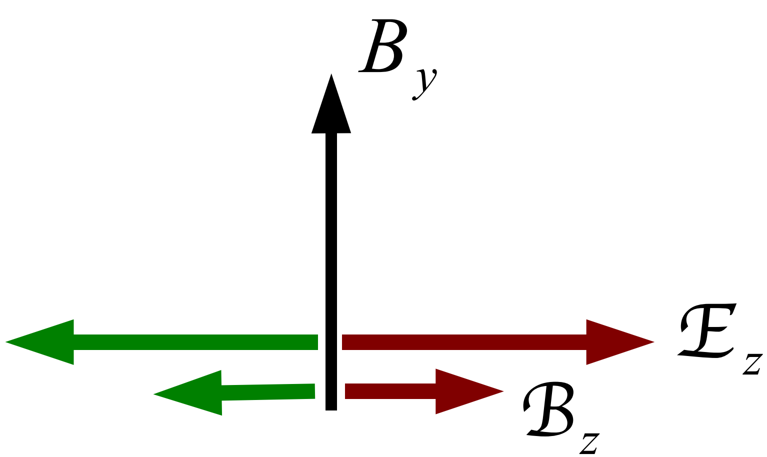
Instanton:

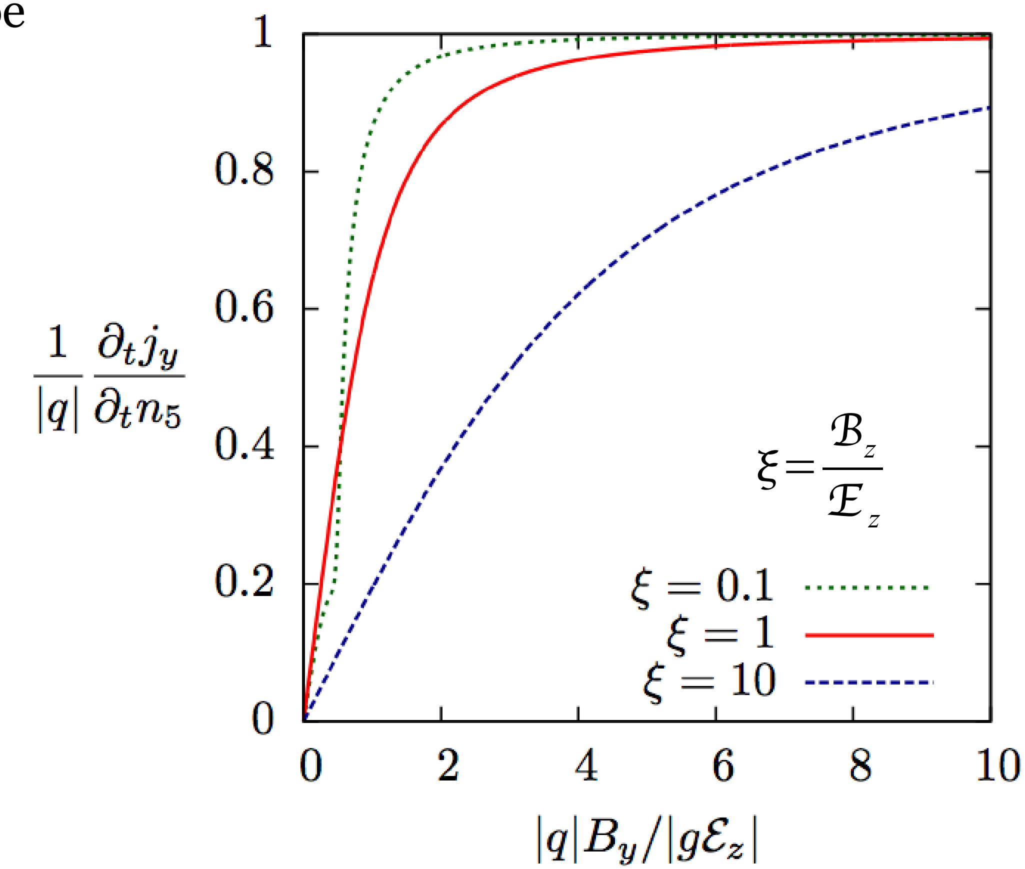
S. Nam ('09)

Induced current in color-flux tube

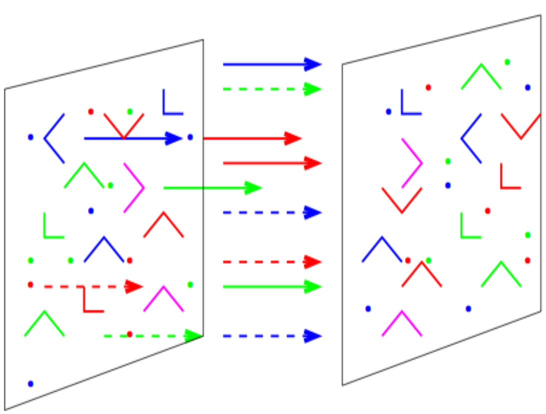
Fukushima, Kharzeev and HJW (to appear)

Perpendicular magnetic field to color flux tube





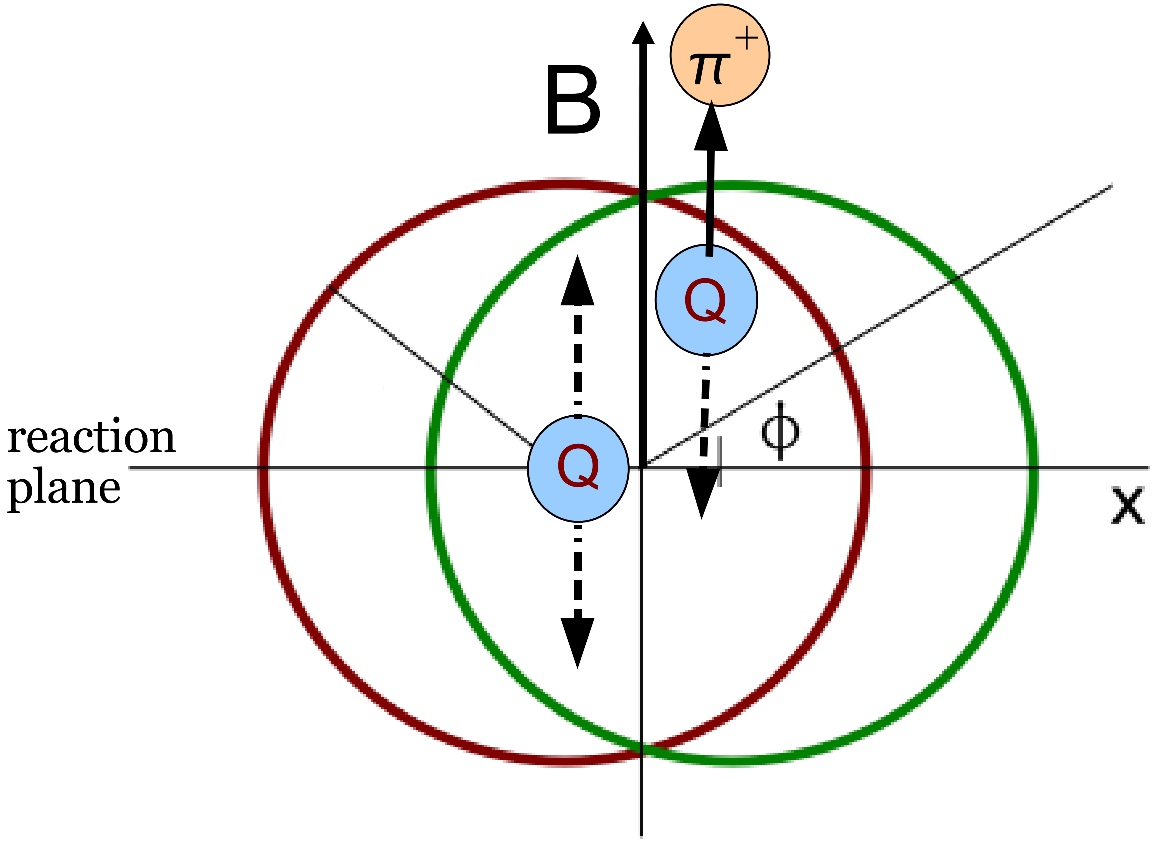
Flux tube generates chirality dynamically



Flux tubes naturally arise in glasma

Krasnitz et al. ('02), Lappi & McLerran, ('06)

P- and CP-odd effects in Heavy Ion Collisions



Topological charge Q fluctuates anywhere in the QGP

Measure: variances = nonzero

Medium causes screening

Variance of charge difference between upper and lower side reaction plane:

$$\langle \Delta_{\pm}^2 \rangle = 2\int_{t_i}^{t_f} \mathrm{d}t \int_V \mathrm{d}^3x \;\Gamma\; [\xi_+^2(x_\perp)+\xi_-^2(x_\perp)] \left(\sum_f \frac{3 q_f^2 e B}{\pi^2 T^2}\right)^2$$

Time & Volume integral Overlap region

Rate of creation Topological charge

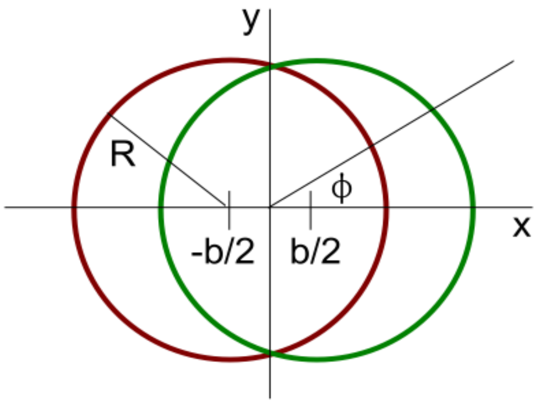
Screening Functions

Square of Change Charge difference

Estimate magnitude relative asymmetry for large impact parameter 10^{-4} with 1-2 orders of magnitude uncertainty.

Experimental observables

Voloshin ('04)



Correlations in azimuthal angle of charged particles

$$a_{++} = \langle \frac{1}{N_+ N_+} \sum_{i,j=1}^{N_+, N_+} \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle$$

$$= \langle \frac{1}{N_+^2} [\sum_{i=1}^{N_+} \cos(\phi_i - \Psi_{RP})]^2 \rangle$$

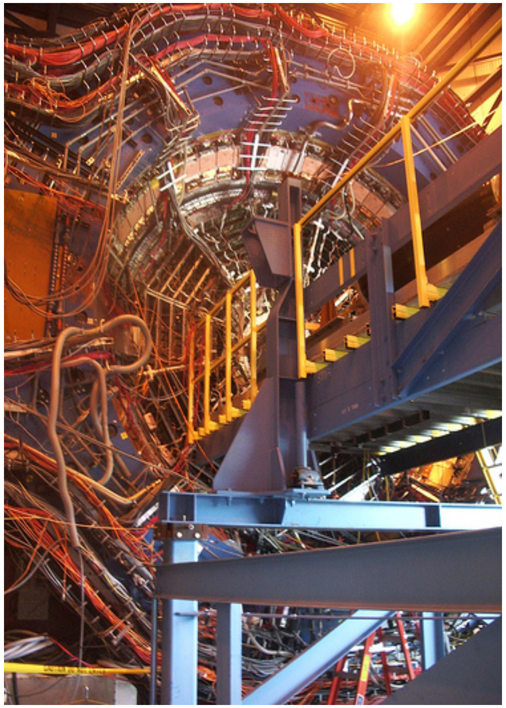
Charge fluctations in x-direction

$$- \langle \frac{1}{N_+^2} [\sum_{i=1}^{N_+} \sin(\phi_i - \Psi_{RP})]^2 \rangle$$

Minus fluctuations in y direction

Average is over many similar minimum bias events

Take symmetric interval around zero rapidity



STAR detector
Full azimuthal coverage

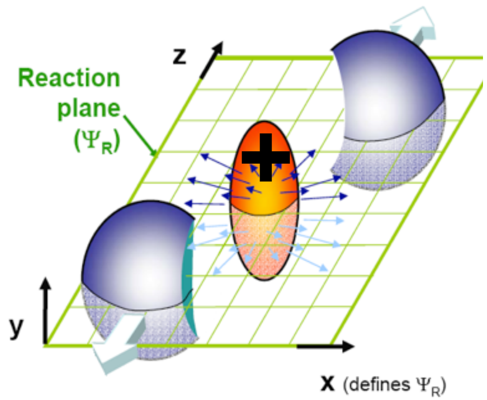
Analysis (and problems) similar to elliptic flow.
See also talks by Jean-Yves Ollitrault and Raimond Snellings

Charge correlations at RHIC

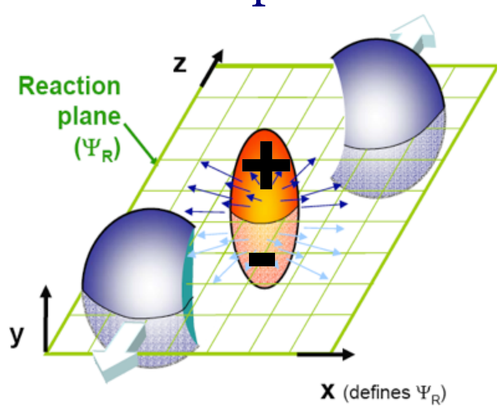
Au-Au and Cu-Cu @ 200 GeV

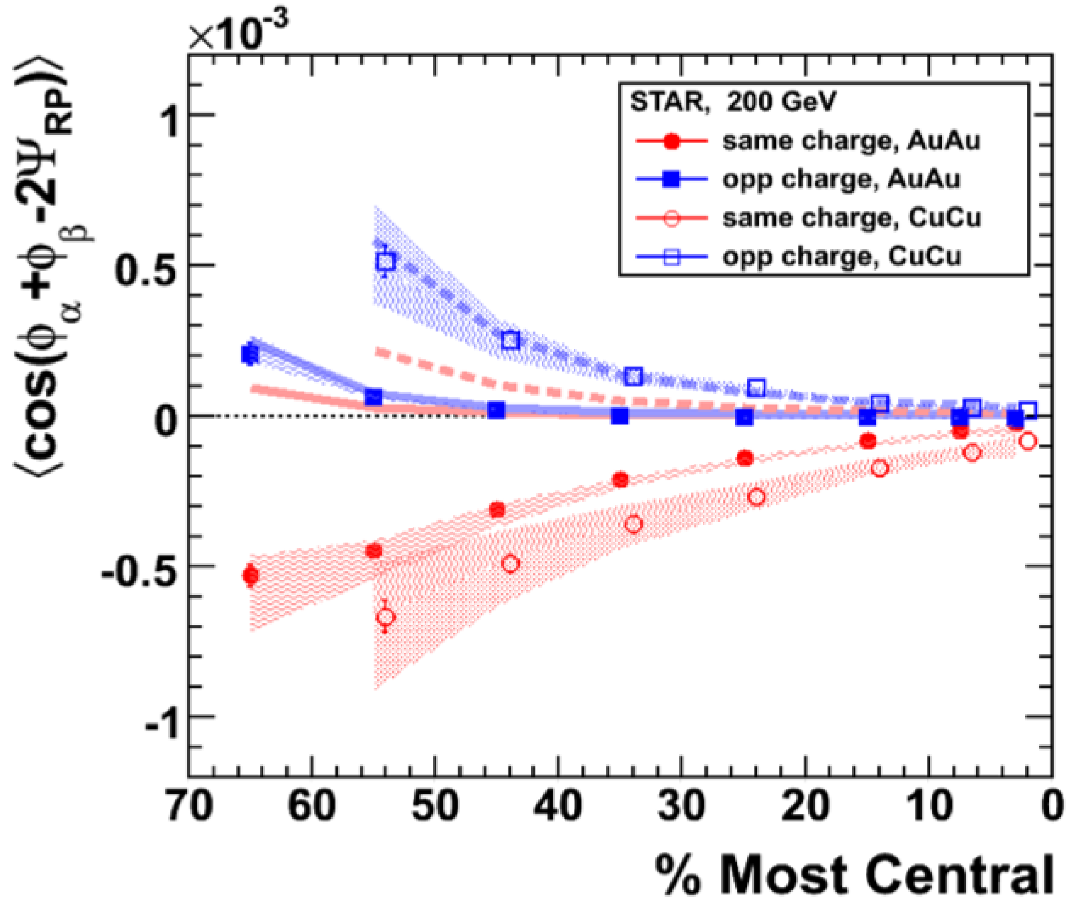
min. bias, $|\eta|<1.0$, $0.15<p_t<2\,\text{GeV}/c$

Red points:



Blue points:





Data cannot be explained by

HIJING
HIJING+v2,
MeVSIM,
UrQMD

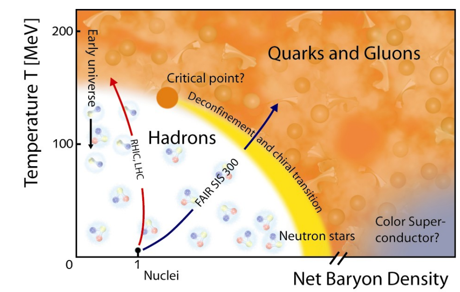
STAR, Phys.Rev.Lett. **103**, 251601 (2009) and arXiv:0909.1717

See also B. Müller, Physics 2, 104 (2009)

Strong charge correlations observed at RHIC
is it due to P- and CP-odd effects or something else?

STAR data due to P- and CP-odd effects?

Deconfinement necessary to separate quarks
Chiral Symmetry restoration necessary to induce chirality



Hence no Chiral Magnetic Effect at low energies.
Test energy scan. Also test at LHC

Magnetic field the correlators proportional to Z^2.

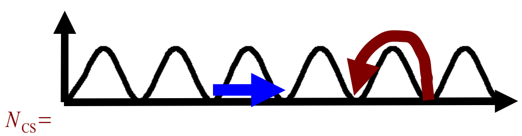
Test: compare collisions with same A and different Z, isobars
Argon-40 (Z=18), vs. Calcium-40 (Z=20), 23% increase in signal

More quantitative phenomenology really necessary
More data also possible: individual charged particle correlations

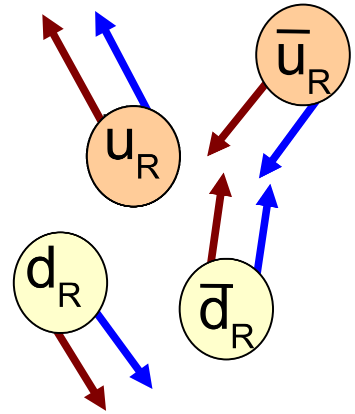
Think of other explanations

Cluster model of F. Wang ('09), ... ???

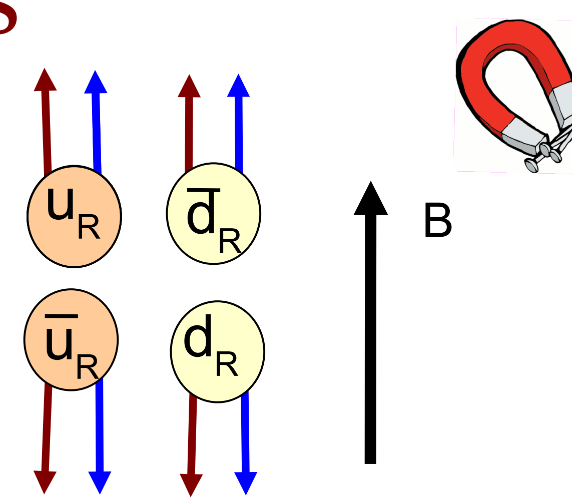
Conclusions: P- and CP-odd effects in heavy ion collisions



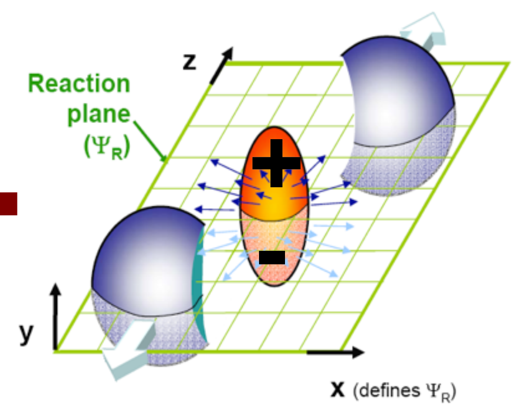
$$\langle Q^2 \rangle \neq 0$$



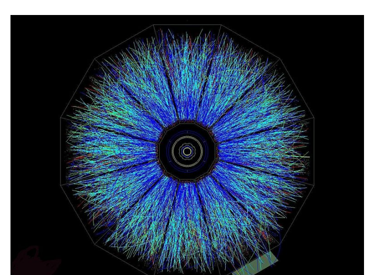
$$\langle N_5^2 \rangle \neq 0$$

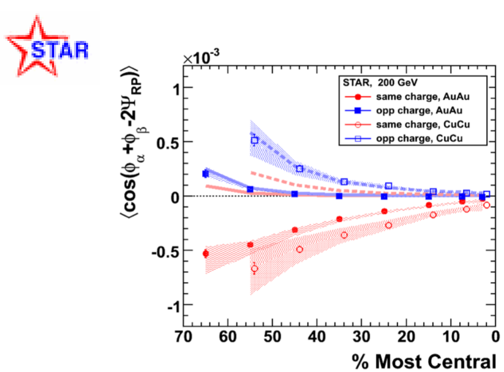


$$\langle J_z^2 \rangle > \langle J_{x,y}^2 \rangle$$



$$\langle \Delta_\pm^2 \rangle > 0, \quad \langle \Delta_+ \Delta_- \rangle < 0$$





$$\langle \cos(\phi_i^\pm + \phi_j^{\pm,\mp} - 2\Psi_{RP}) \rangle \neq 0$$

?

RIKEN-BNL-CATHIE Workshop on

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

Brookhaven National Laboratory,
Long Island, New York, USA
April 26-30, 2010

Organizing Committee

- Kenji Fukushima (Kyoto Univ)
- Dmitri Kharzeev (BNL)
- Harmen Warringa (Johann Wolfgang Goethe-Univ)
- Abhay Deshpande (Stony Brook Univ. / RBRC)
- Sergei Voloshin (Wayne State Univ.)

International Advisory Committee

- J. Bjorken (SLAC)
- 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)

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

Additional information and registration at
http://www.bnl.gov/riken/hdm/

Registration deadline:
March 1, 2010

Supported by RIKEN-BNL Center, Brookhaven National Laboratory and Stony Brook University (Office of Vice-President for BNL Affairs)