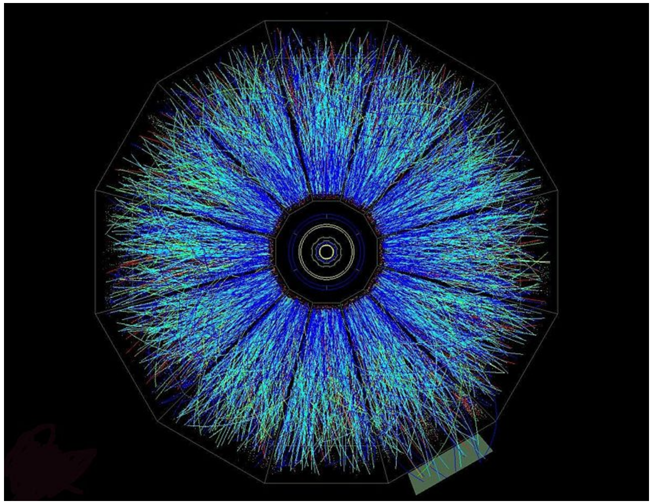
Implications of topological charge fluctuations on heavy ion collisions



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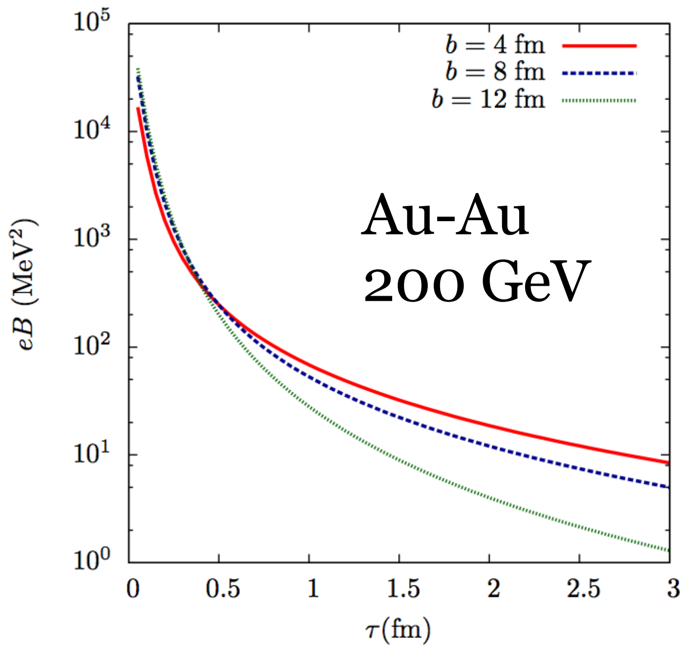
Collaborators: Kenji Fukushima, Dmitri Kharzeev and Larry McLerran.

Alexander von Humboldt Stiftung/Foundation

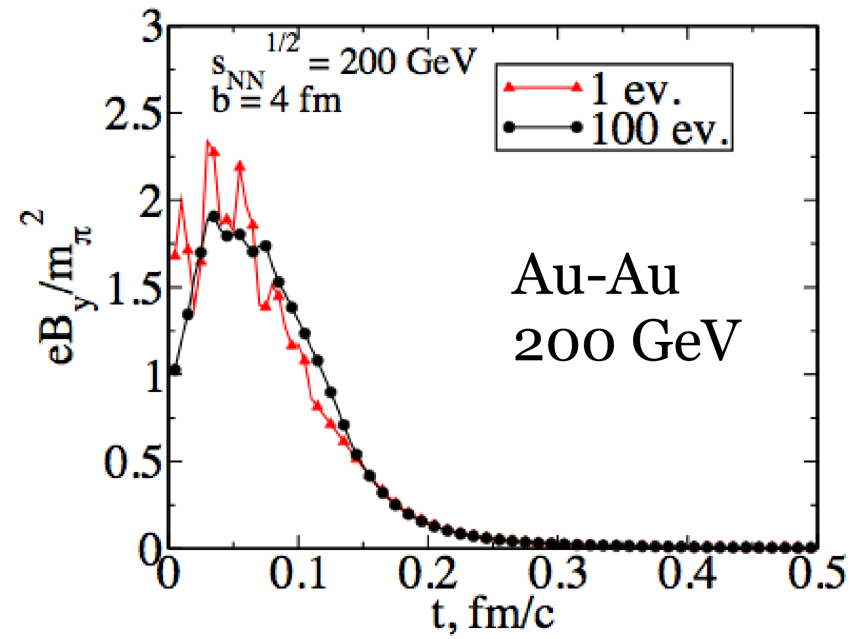
Kharzeev, McLerran & HJW, Nucl. Phys. A **803**, 227 (2008)
HJW, J.Phys.G **35**, 104012 (2008)
Fukushima, Kharzeev & HJW, Phys. Rev. D **78**, 074033 (2008)
HJW, arXiv:0906.2803
Kharzeev & HJW, Phys. Rev. D **80**, 034028 (2009)

Observation I:

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



Pancake approximation
Kharzeev, McLerran & HJW ('08)

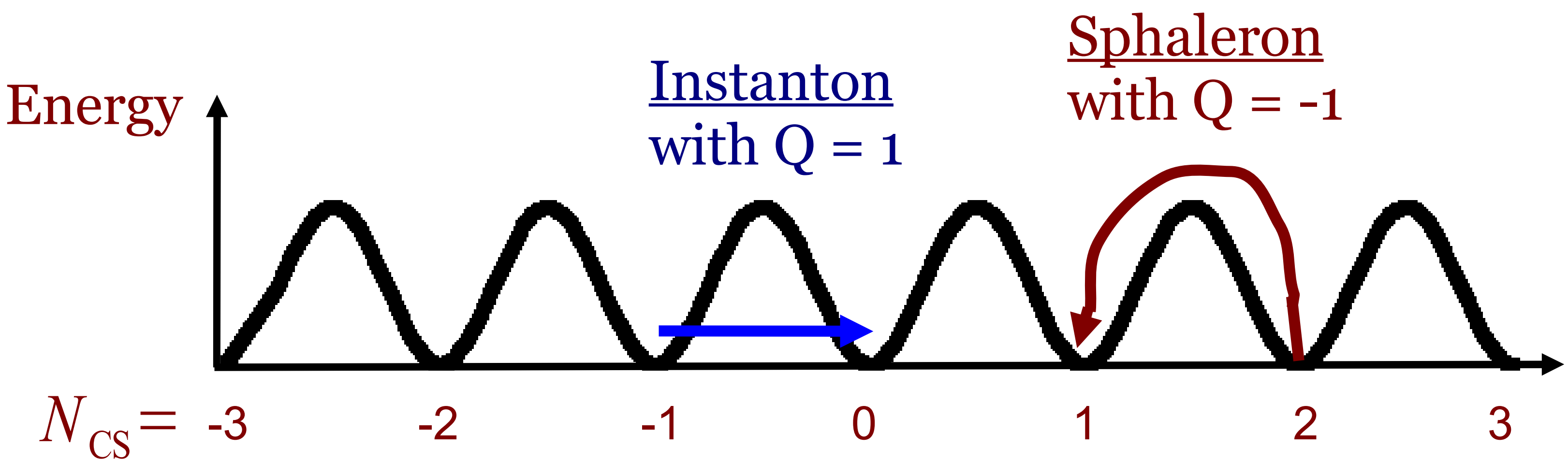


URQMD calculation
Skokov, Illarionov, Toneev ('09)

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

Observation II:

Topological charge fluctuations present in QCD and hence in produced matter



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

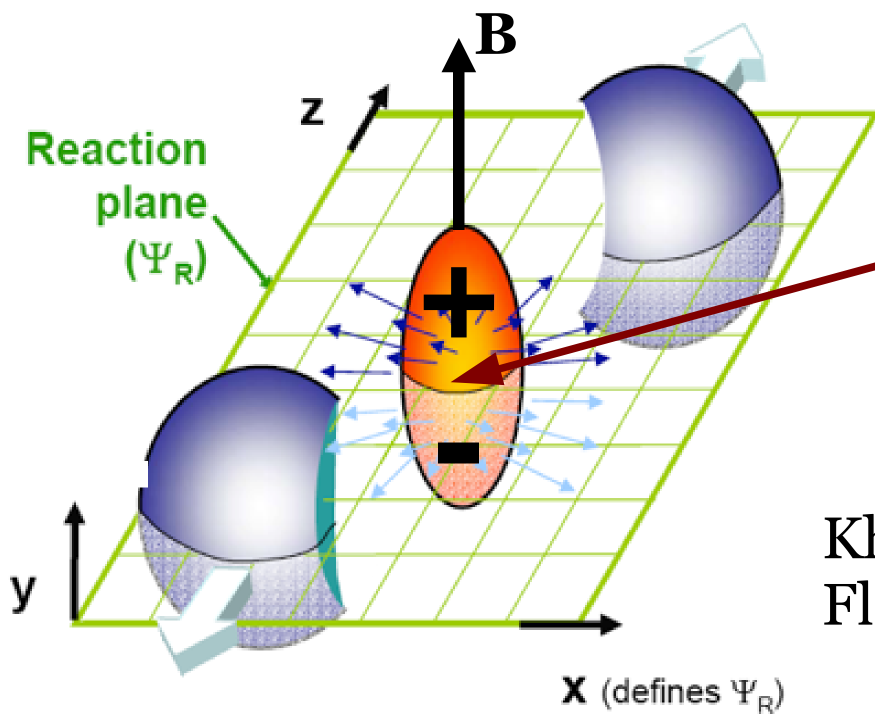
$$\text{Rate} = \frac{1}{Vt}\langle Q^2 \rangle_{\text{Minkowski}} \sim 385\,\alpha_S^5 T^4$$

Bödeker, Moore and Rummukainen ('00)
several transitions per fm^{-3} per fm/c

Outline

To explain you that

Magnetic Field + Topological charge =



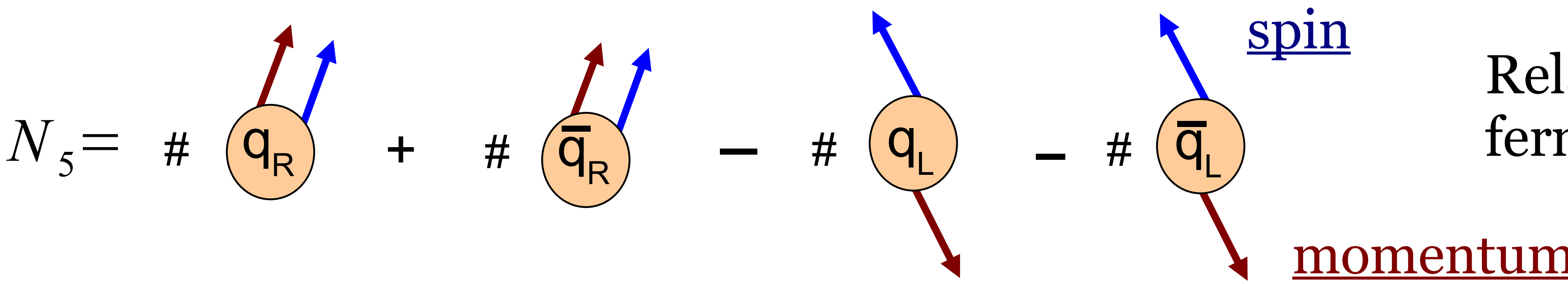
Q < 0

Kharzeev ('06)
Fluctuating EDM of QGP

Charge separation

Topological charge induces chirality

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



Relativistic fermions

Axial anomaly: topological charge induces chirality

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

$$\Delta N_5 = -2Q$$

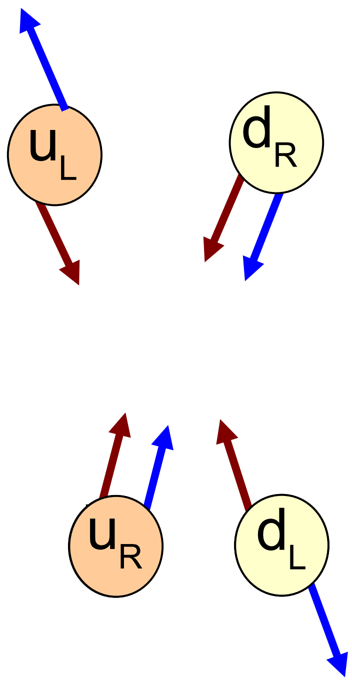
Generation of chirality is a P- and CP-odd effect

See also Kharzeev, Pisarski and Tytgat ('98)

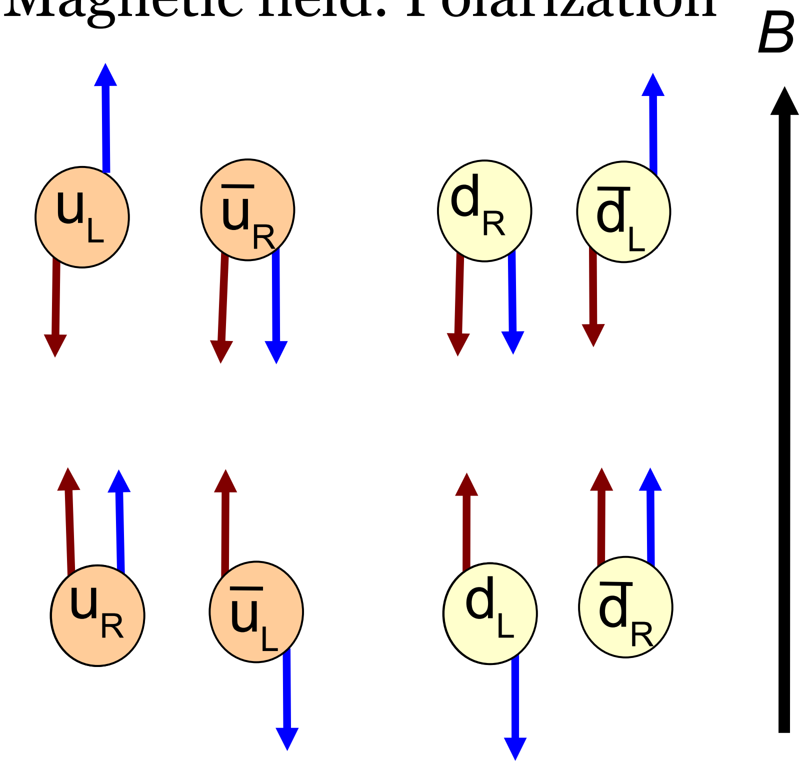
Magnetic field induces polarization

Magnetic field aligns spins, depending on electric charge

No Magnetic Field: No polarization



Magnetic field: Polarization

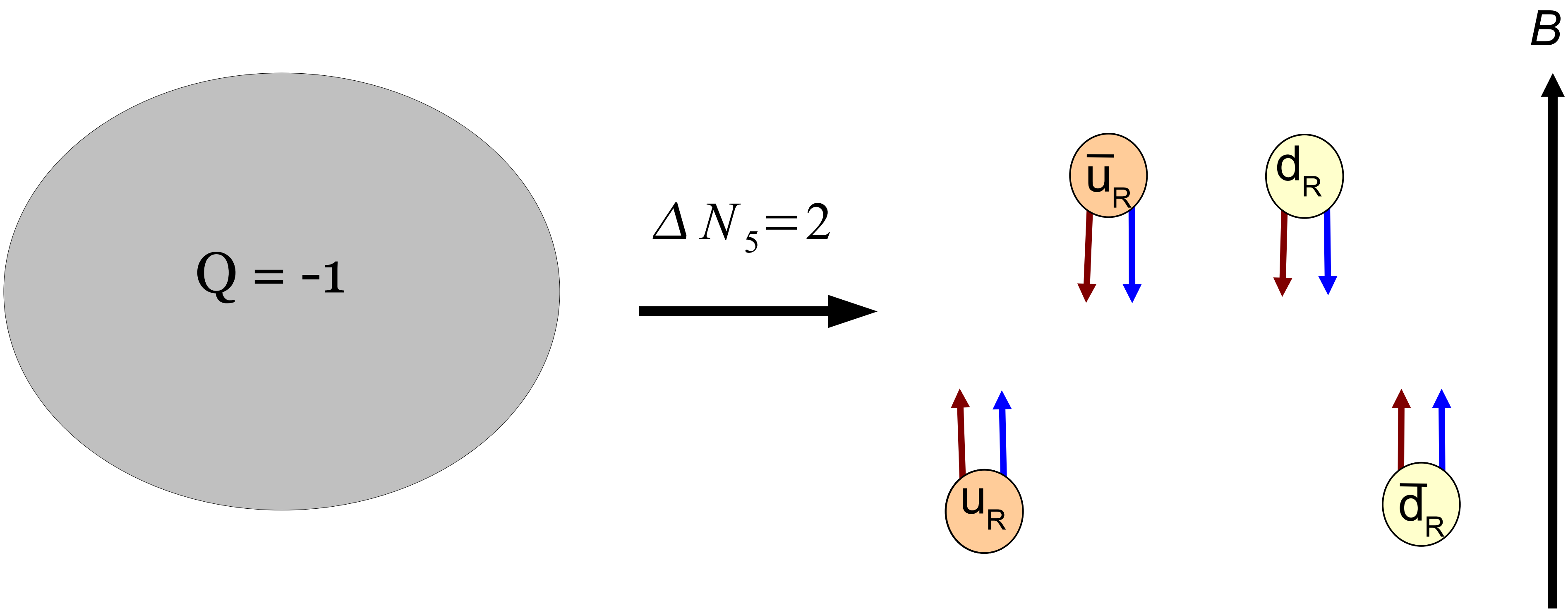


The momenta of the quarks align along the magnetic field

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 =

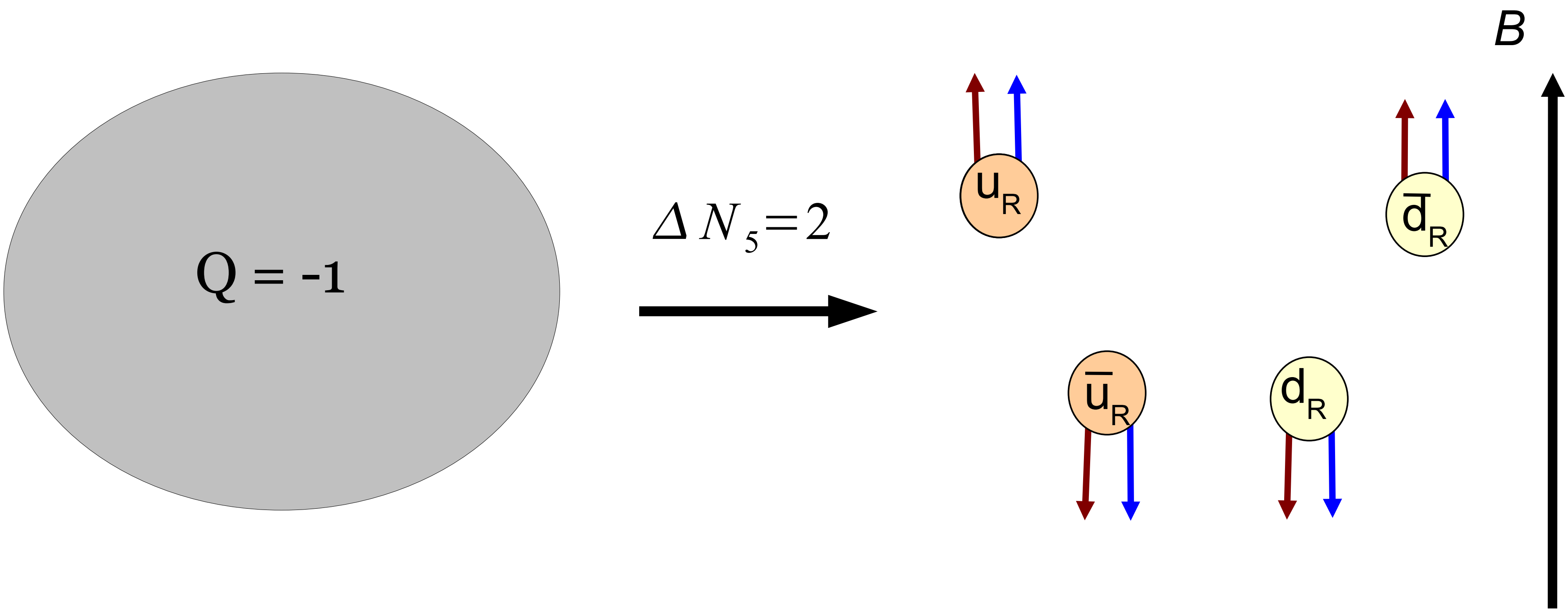


Q < -1: Positively charged particles move parallel to magnetic field, negatively charged antiparallel

… = Electromagnetic Current

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

Topological Charge + Magnetic field = Chirality + Polarization =

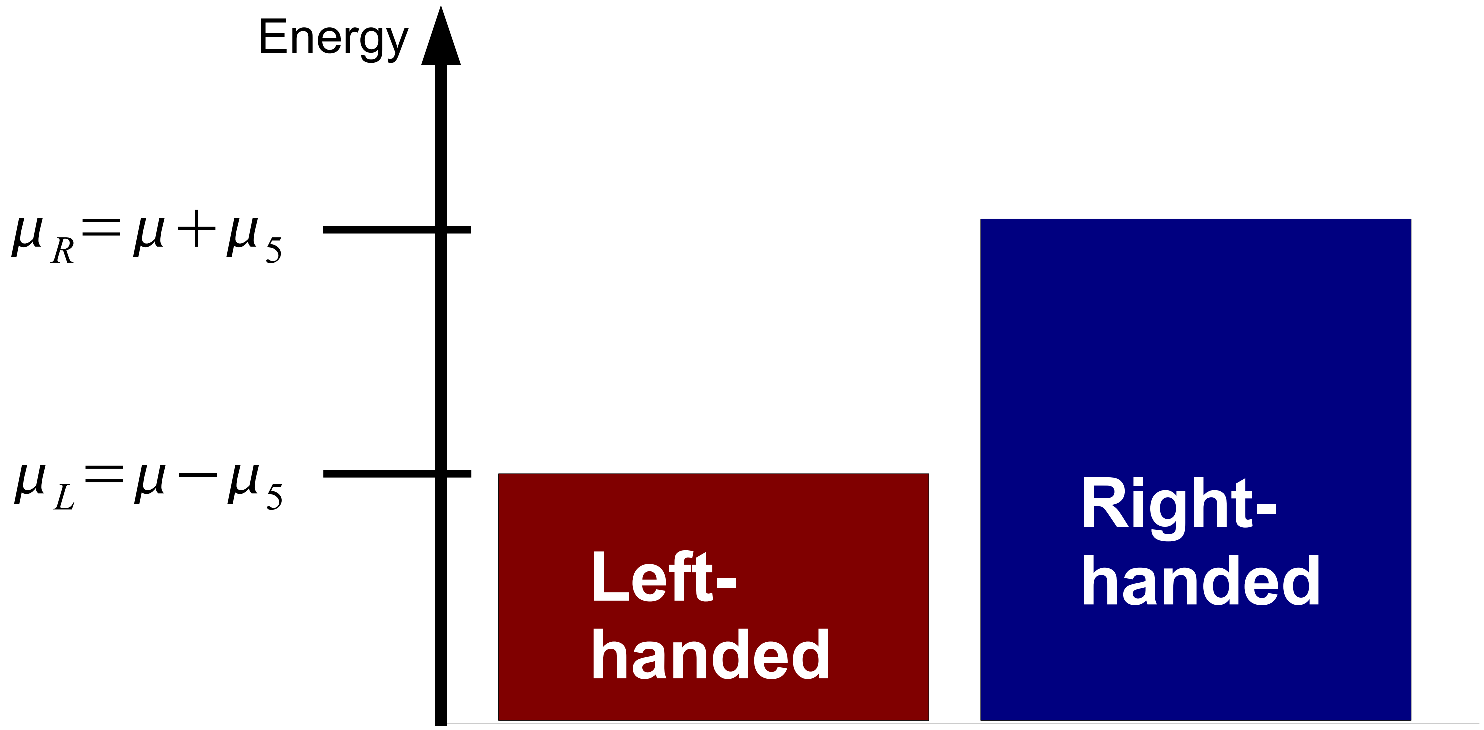


Size of Current: $J = \int d^3x \langle \bar{\psi} \gamma^3 \psi \rangle = -2Q \sum_f |q_f|$

Valid for full polarization, what about smaller fields?

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

How chirality reacts to magnetic field



Nonzero Chirality: Nonzero chiral chemical potential μ_5

Compute induced current in magnetic field

Magnitude of the induced current

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

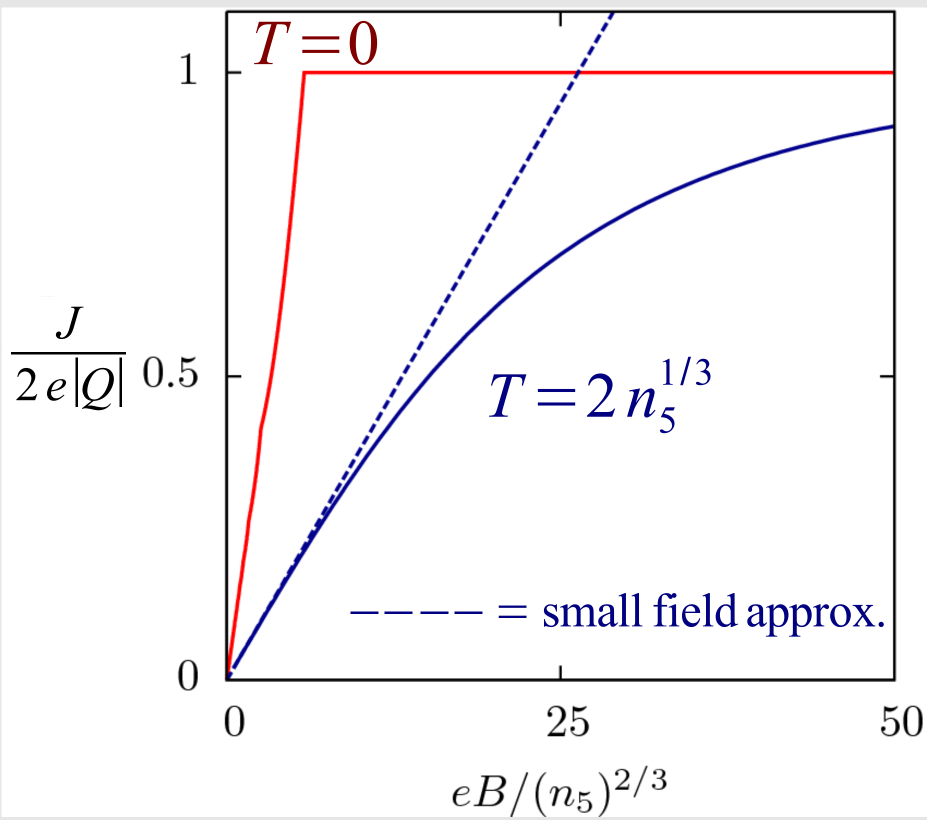
6. AVV triangle diagram $j = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5 B$

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 mu5?

Induced current by top. charge



$$N_5 = -2Q$$

$$n_5 = \frac{\partial \Omega}{\partial \mu_5}$$ In QCD computable at high T

---- = small field approx.:

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

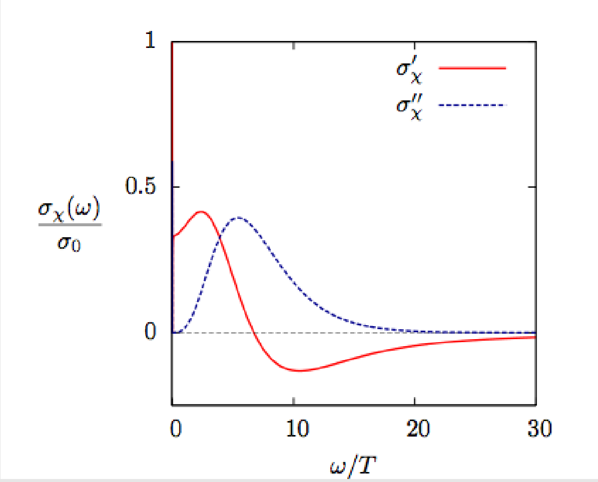
Chiral Magnetic Effect in lattice QCD: Buividovich, Chernodub, Luschevskaya and Polikarpov. (arXiv:0907.0494)

Chiral Magnetic Effect in time-dep. field

Kharzeev and HJW ('09)

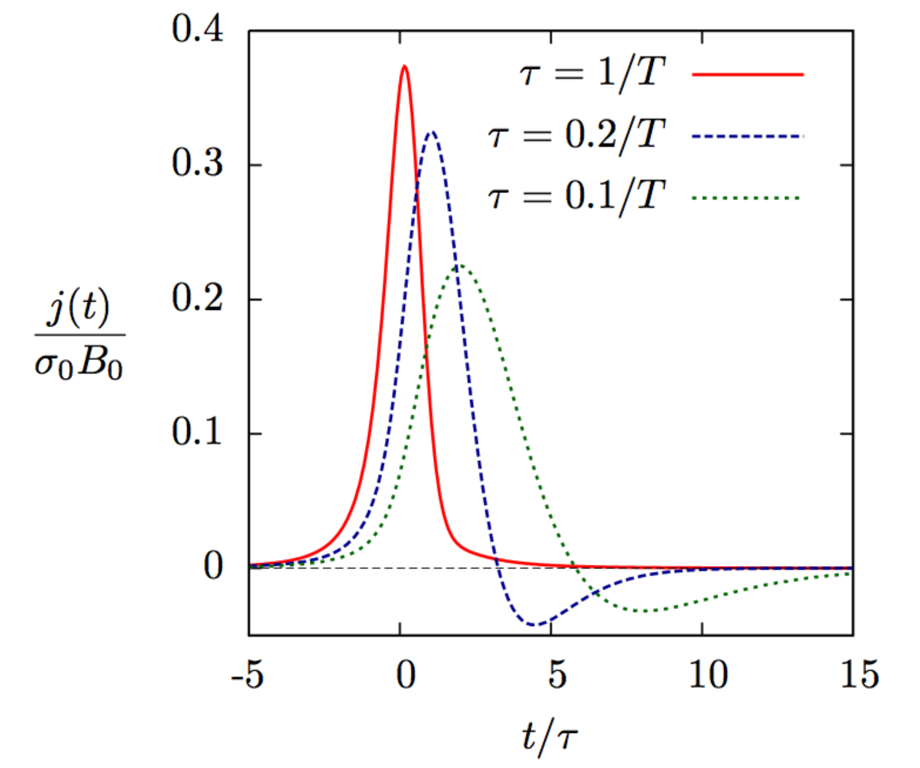
CM conductivity: $\sigma(\omega) = \lim_{p^i \to 0} \frac{1}{2 i p^i} \epsilon^{ijk} \tilde{\Pi}_R^{jk}(\omega, p)$

CM Conductivity



$$\sigma(\omega=0) = \frac{N_c \sum_f q_f^2}{2\pi^2} \mu_5$$

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

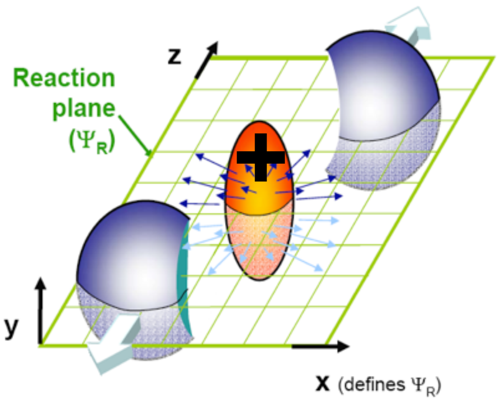


Results for one-loop pert. QCD valid at high temperature

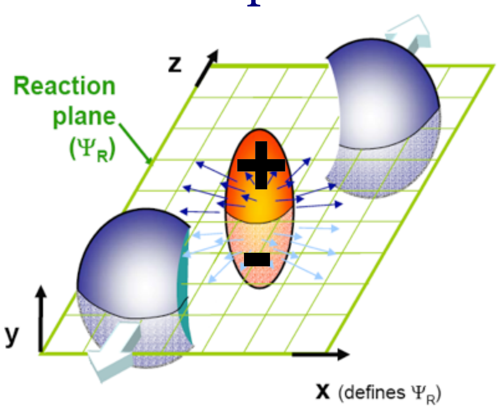
Charge correlations at RHIC

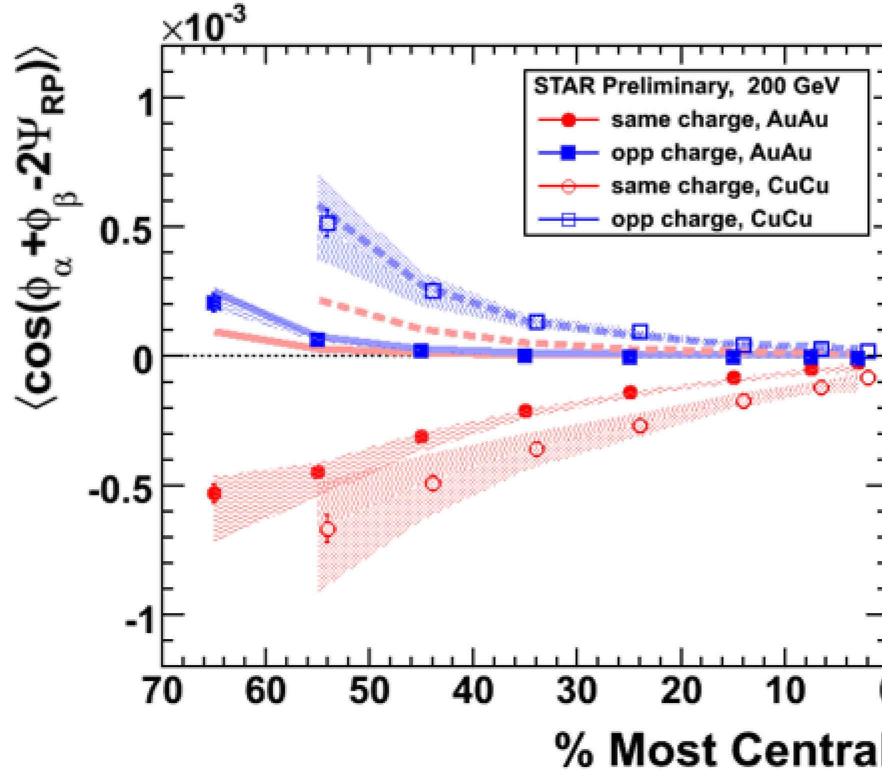
Au-Au and Cu-Cu @ 200 GeV

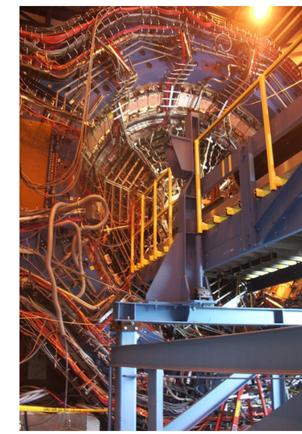
Red points:



Blue points:







STAR detector

S. Voloshin (STAR Collaboration)
Quark Matter 2009, Knoxville TN

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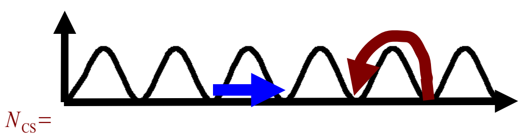
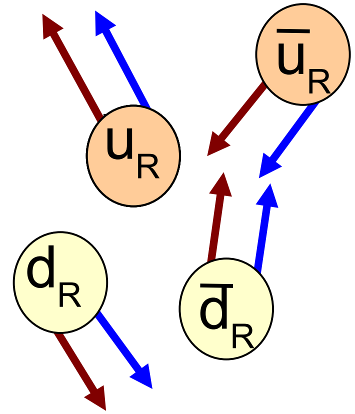
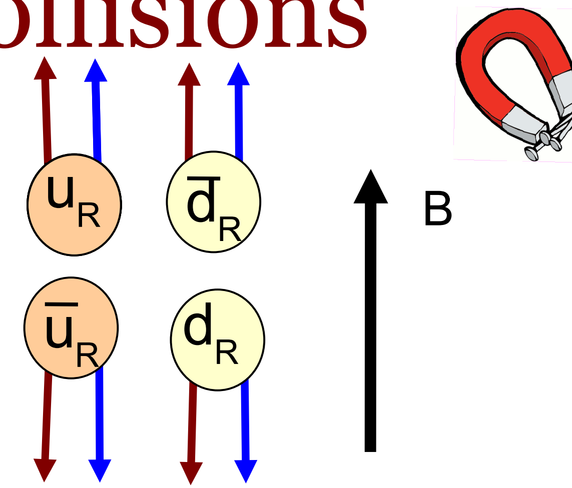


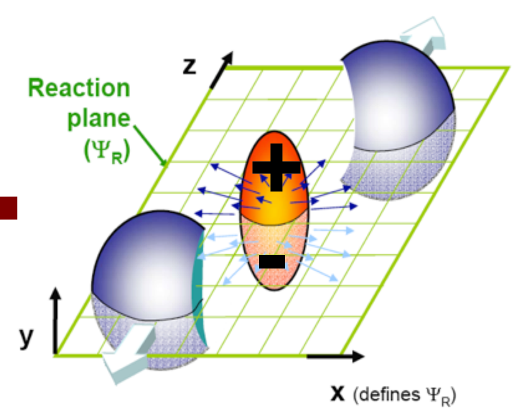
$$\langle Q^2 \rangle \neq 0$$



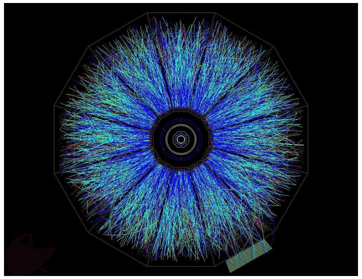
$$\langle N_5^2 \rangle \neq 0$$

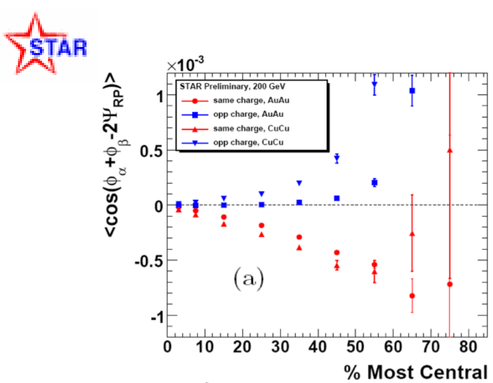


$$\langle J_z^2 \rangle > \langle J_{x,y}^2 \rangle$$



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





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

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