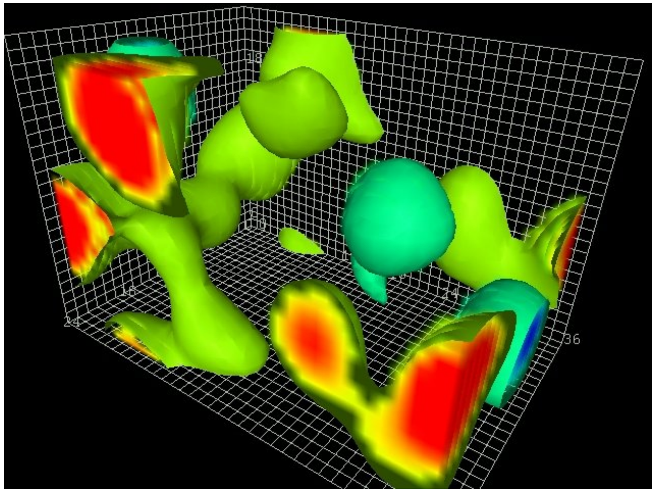
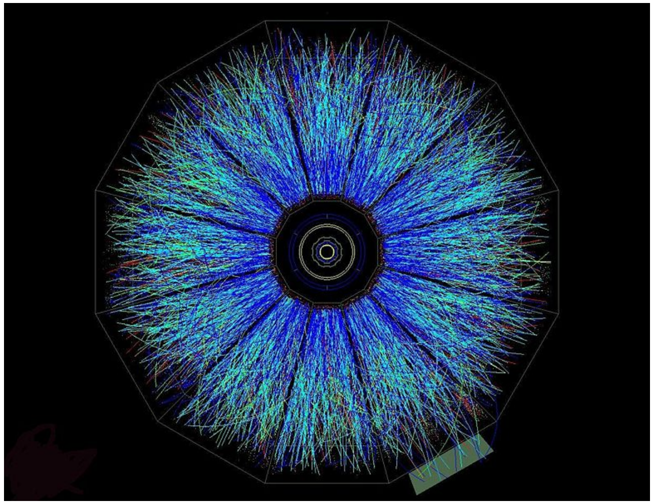
How to find Topological Charge in the Quark-Gluon Plasma

Or from



Topological charge flucutations,
D. Leinweber

To



Tracks in TPC of STAR

And back!

Kharzeev, McLerran & HJW, Nucl. Phys. A803, 227 (2008)
HJW, J.Phys.G35, 104012 (2008)
Fukushima, Kharzeev & HJW, Phys.Rev.D78, 074033 (2008)
Kharzeev & HJW, arXiv:0907.5007

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Harmen Warringa,
Institut für Theoretische Physik,
Goethe Universität, Frankfurt

EMMI
ExtreMe Matter Institute EMMI

Alexander von Humboldt Stiftung/Foundation

Three (out of many) Intriguing Properties of QCD

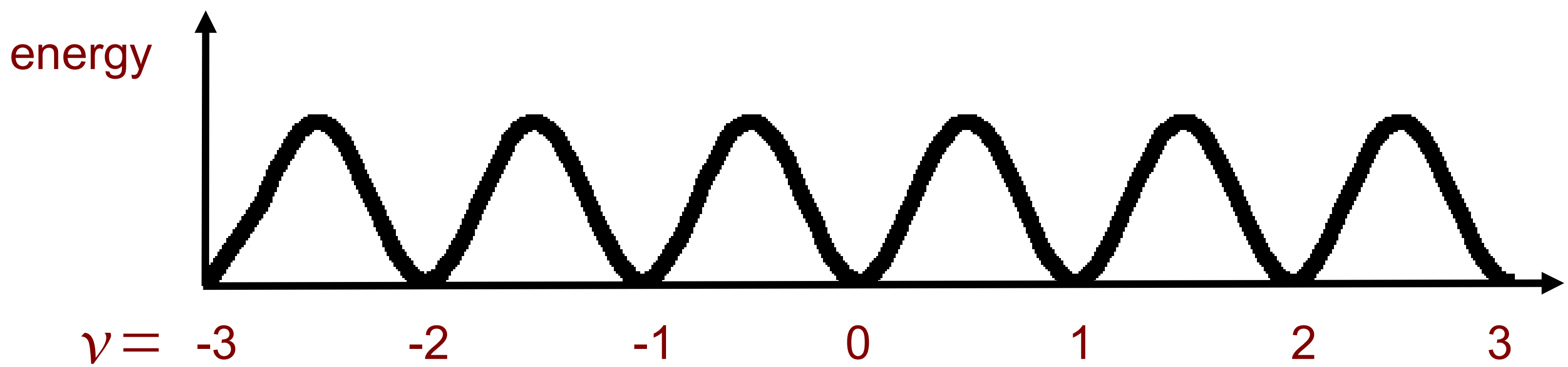
Topological Charge

Axial anomaly

P- and CP-odd effects

Can we see their effects in heavy ion collisions?

The vacuum of the gluon sector of QCD has non trivial structure



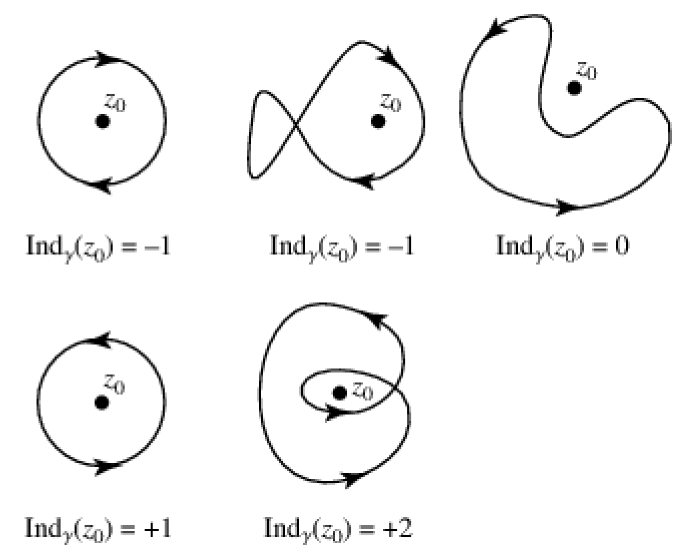
Callan, Dashen, Gross ('76)

$$\nu = \text{complicated formula}\,(A_i) = 0,\ \pm 1,\ \pm 2\ldots$$

Winding number = Topological invariant.

Smooth deformations cannot change winding number.

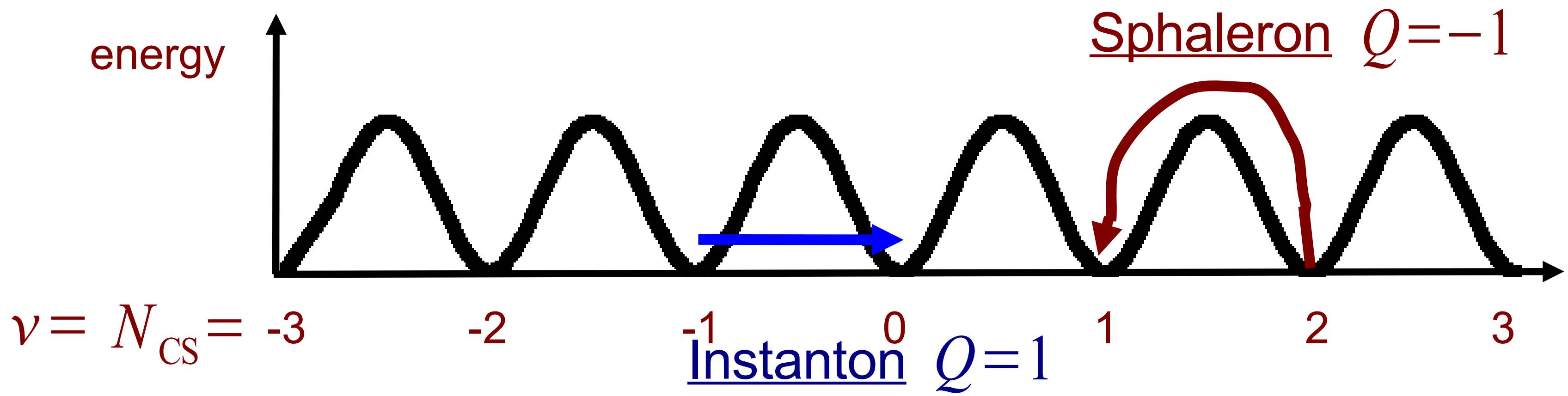
Need to go out of pure gauge=energy to change winding number.



mathworld.org

Transitions between vacua: topological charge

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



Instantons: Configuration with finite action. Tunneling through barrier

Suppression of rate at large temperature 't Hooft ('76), Pisarski and Yaffe ('80)

$$\Gamma = \lim_{V,t\to\infty}\frac{1}{Vt}\langle Q^2\rangle \sim \exp\left(-\frac{8\pi}{g^2}\right) \qquad \Gamma(T=0) \approx (180\,\text{MeV})^4$$

Euclidean topological susceptibility

Sphaleron: Configuration with finite energy. Real time. Go over barrier.
Only possible at finite temperature, rate not suppressed!

Manton ('83), Manton and Klinkhamer ('84), McLerran, Mottola and Shaposhnikov ('88)

$$\Gamma \sim 385\,\alpha_S^5 T^4$$

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

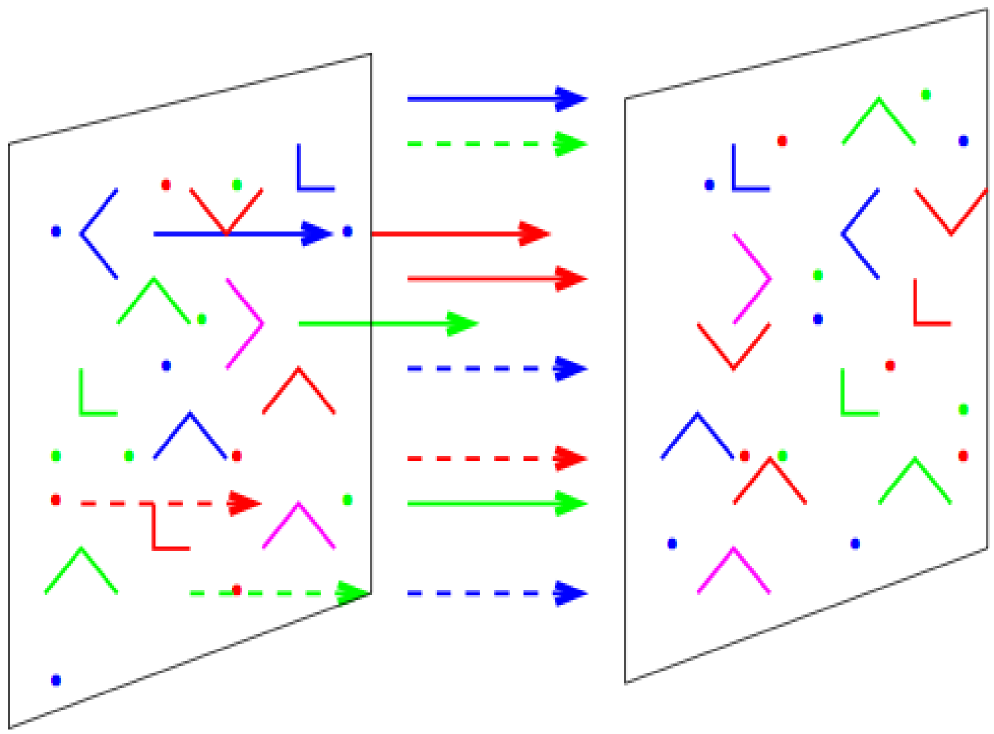
Minkowski topological susceptibility

Also AdS/CFT sphaleron
Son & Starinets ('02)

Also topological charge from Glasma

HIC = Colliding sheets of color

Taking into account collision geometry + out of thermal equilibrium effects.



$$\langle \vec{E}_a \cdot \vec{B}^a \rangle \neq 0$$

Krasnitz, Kharzeev, Venugopalan ('02)

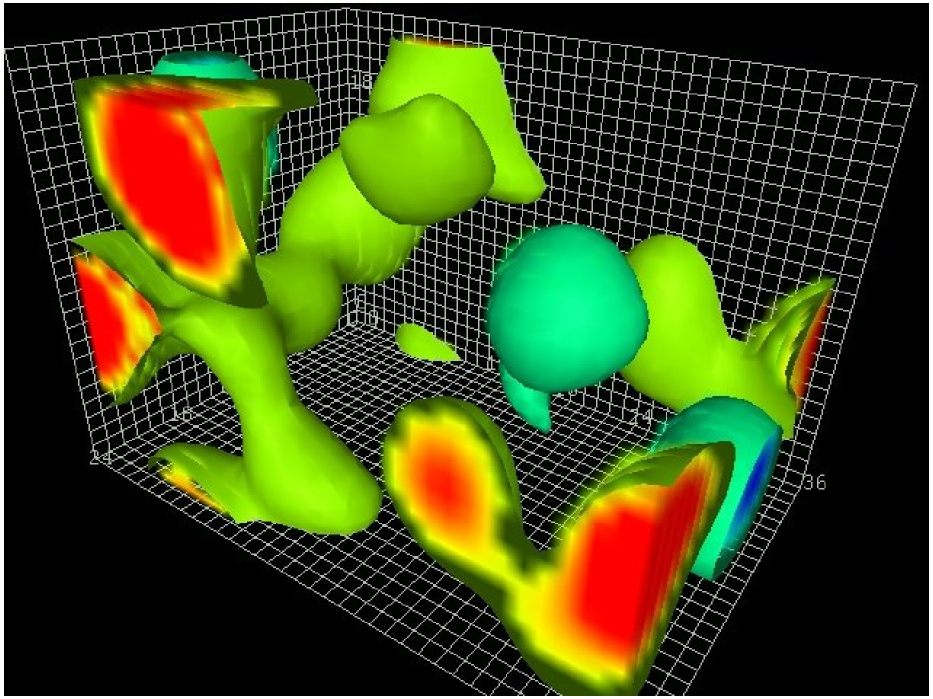
Lappi, McLerran ('06)

Longitudinal Chromo-Electric and Chromo-Magnetic fields just after collision

QCD: Gluon fields can have topological charge

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

Belavin, Polyakov, Schwartz and Tyupkin ('75)



D. Leinweber, Topological charge flucutations

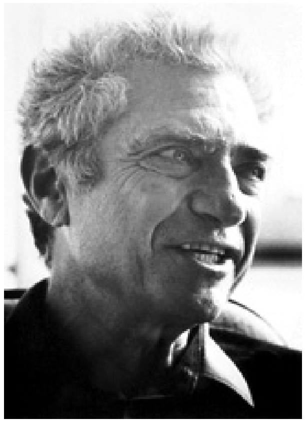
Non-perturbative physics

Average over time and space vanishes $\langle Q \rangle = 0$

But fluctuations not $\langle Q^2 \rangle \neq 0$

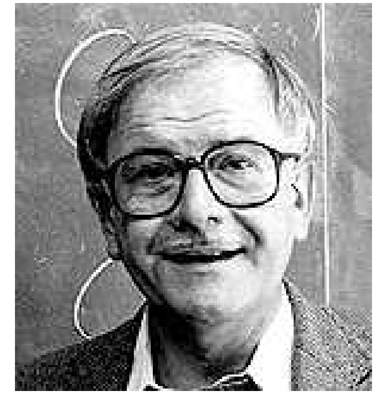
How does topological charge deal with quarks?

The Axial Anomaly (= quantum mech. sym. breaking)

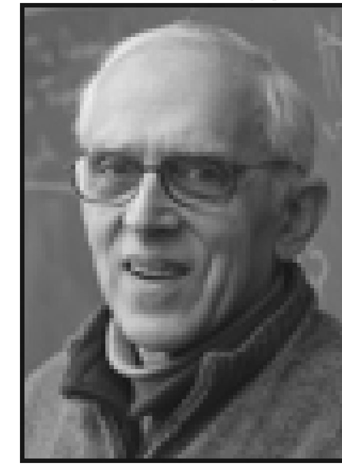


Steinberger ('49)

Schwinger ('51)



Bell, Jackiw ('69)



Adler ('69)

$$j_5^{\mu}(x) = \langle \bar{\psi}(x) \gamma^{\mu} \gamma^{5} \psi(x) \rangle$$

Axial current in the chiral limit is not conserved

QED $\quad \partial_{\mu} j_5^{\mu} = -\frac{e^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$

Pion decay to two photons

$$\pi^0 \rightarrow \gamma\gamma$$

QCD $\quad \partial_{\mu} j_5^{\mu} = -\frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}_a^{\mu\nu}$

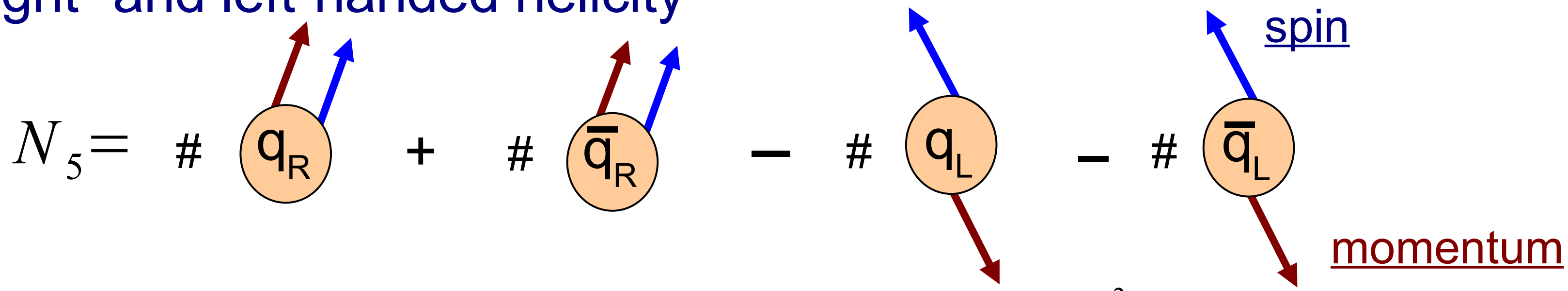
Axial U(1) symmetry breaking

$$m_{\eta}' \gg m_{\pi}, m_K$$

Note: these relations are exact in chiral limit

Topological charge induces chirality

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



Relativistic fermions

Integrating Axial Ward Identity $\partial_\mu \langle \bar{\Psi} \gamma^\mu \gamma^5 \psi \rangle = -\frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$ over volume and time gives

$$\Delta N_5 \equiv [N_R - N_L]_{t=\infty} - [N_R - N_L]_{t=-\infty} = -2Q$$

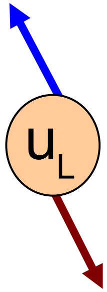
Axial Anomaly: Topological charge induces chirality

Total number right- and left-handed fermions can differ in each event **globally**.

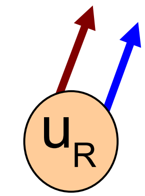
$N_R \neq N_L$

Imbalance

Event-by-event parity- (P) and charge-parity (CP) violation.



Chirality and Helicity



Left-handed chirality: $\psi_L = \frac{1}{2}(1-\gamma_5)\psi$

Right-handed chirality: $\psi_R = \frac{1}{2}(1+\gamma_5)\psi$

Left-handed helicity: $\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = -1$

Right-handed helicity: $\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = 1$

In the chiral limit

Particle (P) with Left/Right-handed chirality has Left/Right-handed helicity

Antiparticle (AP) with Left/Right-handed chirality has Right/Left-handed helicity

$$N_5 = \int d^3x \langle \bar{\psi}\gamma^0\gamma^5\psi \rangle = \int d^3x [\langle \psi_R^+ \psi_R \rangle - \langle \psi_L^+ \psi_L \rangle]$$

$N_5 = N_R - N_L =$

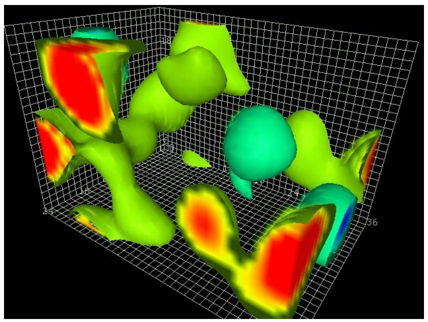
(P - AP) with RH chirality - # (P - AP) with LH chirality

(P + AP) with RH helicity - # (P + AP) with LH helicity

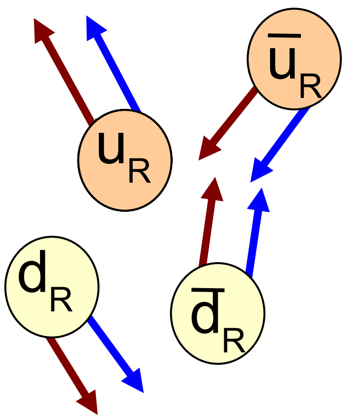
$$[N_R - N_L]_{t=\infty} - [N_R - N_L]_{t=-\infty} = -2N_f Q$$

How to find topological in Heavy Ion Collisions

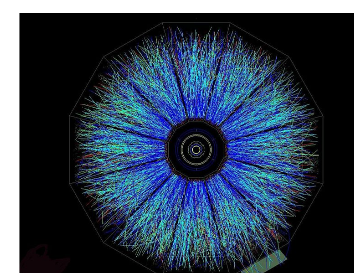
Or from



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

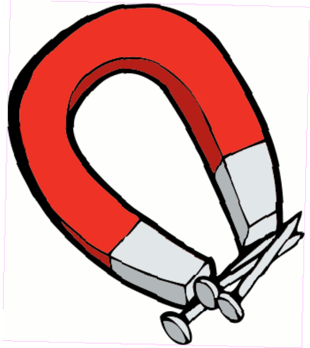


$\langle N_5^2 \rangle \neq 0$



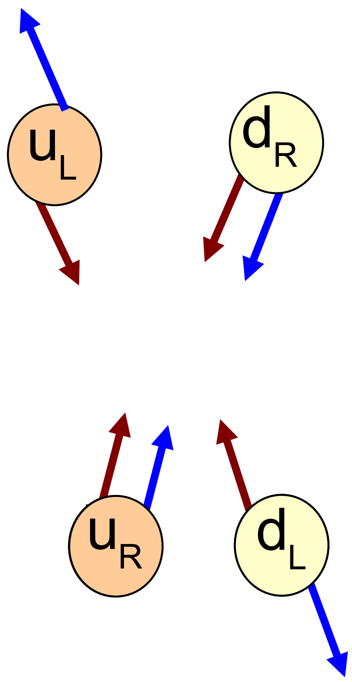
And back!

What does a magnetic field do to quarks

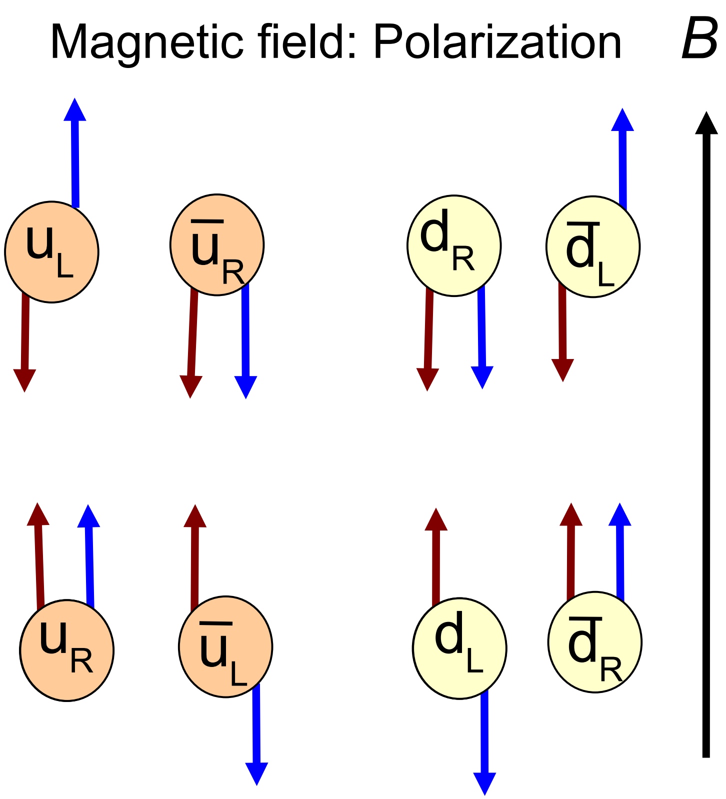


A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization



Magnetic field: Polarization

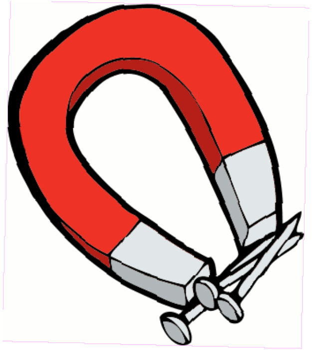


The momenta of the quarks align along the magnetic field

A quark with right-handed helicity will have momentum opposite to a left-handed one

In this way the magnetic field can distinguish between right and left

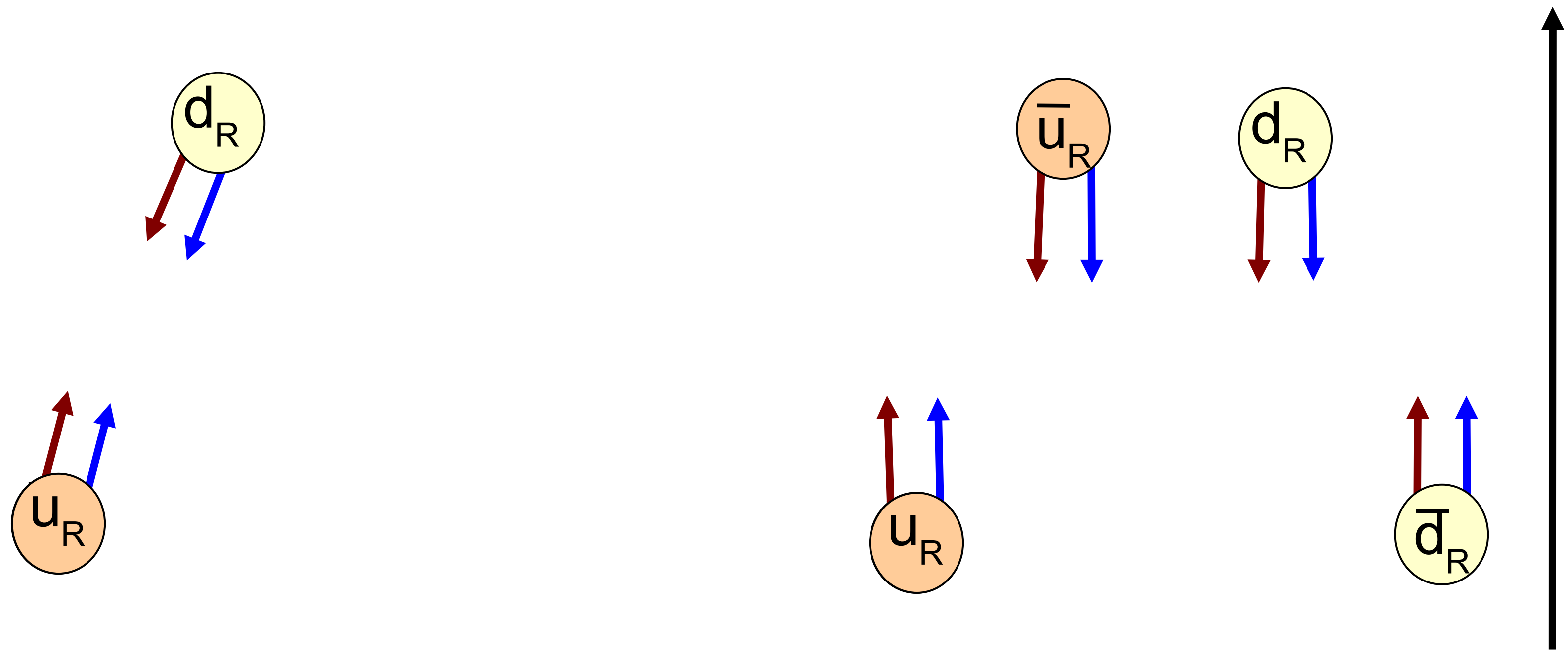
What does a magnetic field do with chirality (generated by topological charge)



A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization

Magnetic field: Polarization B



Positively charged particles move parallel the magnetic field

Negatively charged particles move to antiparallel to magnetic field

An electromagnetic current is created along the magnetic field

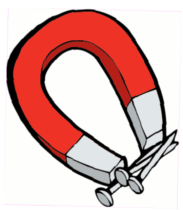
The Chiral Magnetic Effect

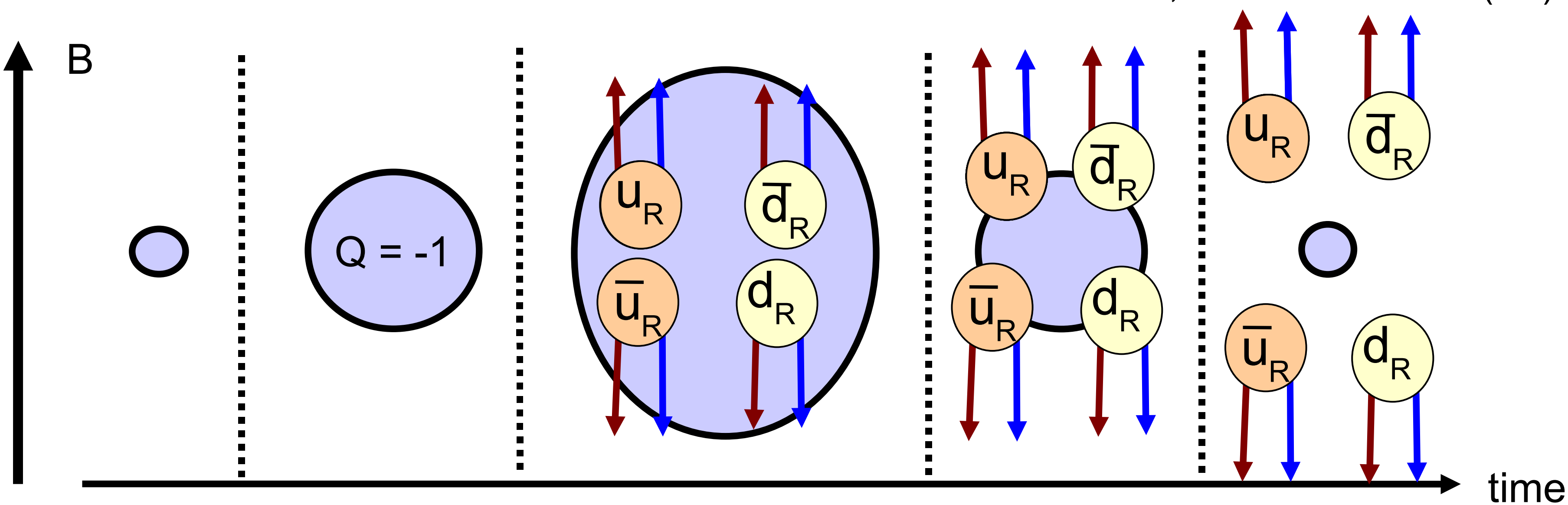
1. Topological charge induces Chirality

2. In presence of Magnetic field this induces an Electromagnetic Current along Magnetic Field.

3. In finite volume this causes separation of positive from negative charge

Kharzeev, McLerran & HJW ('07)



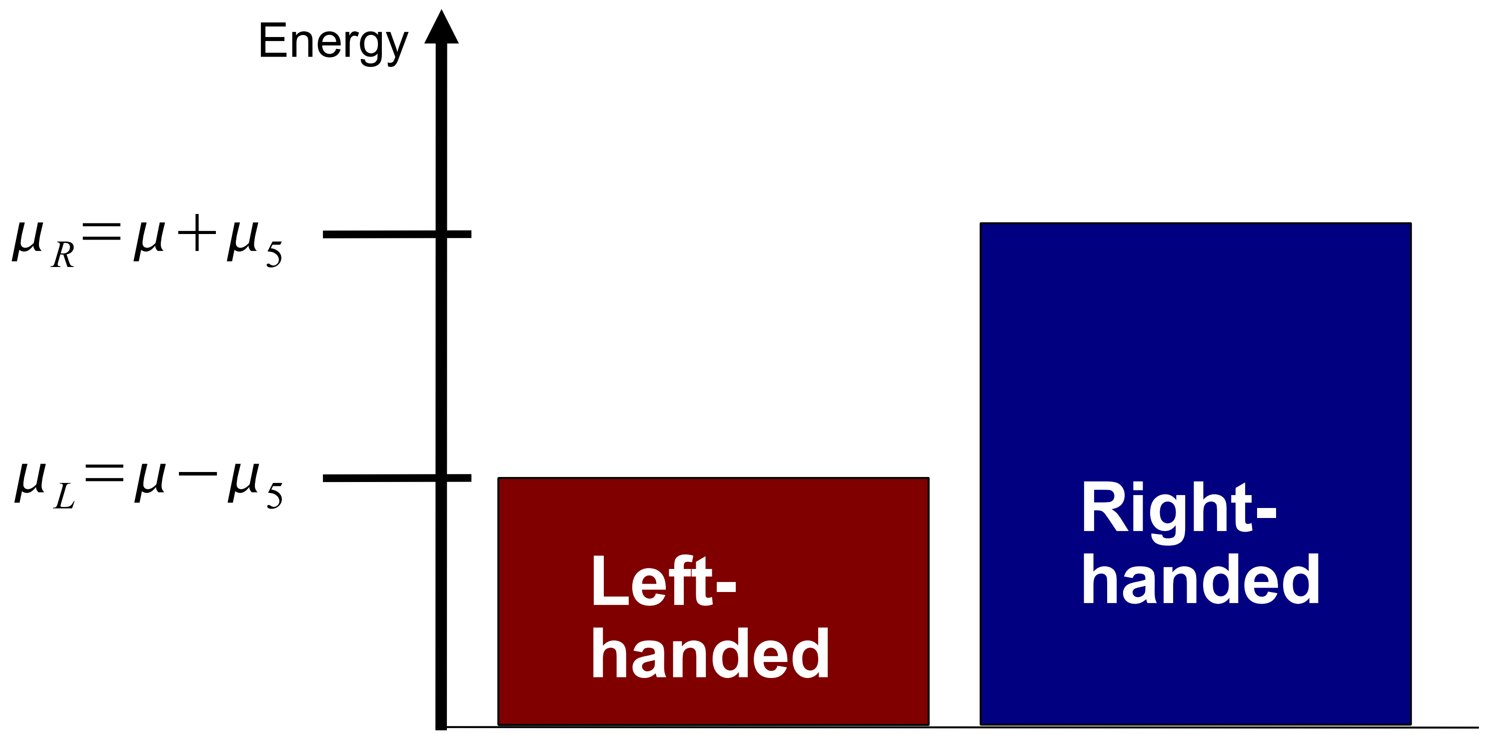


Size of current: $$J = N_5 \sum_f |q_f| = -2Q \sum_f |q_f|$$

Valid for full polarization, what about smaller fields? $$J^\mu = e\int d^3x \langle \bar{\psi} \gamma^\mu \psi \rangle$$

The chiral chemical potential

$$\mu \bar{\Psi} \gamma^0 \psi$$
$$\mu_5 \bar{\Psi} \gamma^0 \gamma^5 \psi$$



If a system has Chirality, Fermi-surfaces Right- and Left-handed fermions differ, imbalance.

This can be described by a chiral chemical potential μ_5
Study equilibrium response to Magnetic Field

Computing the induced current (1)

Introduce Chiral Chemical Potential μ_5 to obtain nonzero Chirality
Study equilibrium response to Magnetic Field $\vec{B}=B(x,y)\hat{z}$

$$J^{\mu}=e\int d^3x\langle\bar{\psi}\gamma^{\mu}\psi\rangle \qquad j^3=e\langle\bar{\psi}\gamma^3\psi\rangle=e\langle\phi_R^{+}\sigma^3\phi_R\rangle-e\langle\phi_L^{+}\sigma_3\phi_L\rangle$$

Current is number density of right-handed particles in Lowest Landau level minus density of left-handed particles in lowest Landau Level

$$\text{density of states}\sim\text{floor}\left[\frac{e\Phi}{2\pi}\right]\approx\frac{eBL^2}{2\pi} \qquad \Phi=\int \mathrm{d}x\,\mathrm{d}y\,B(x,y)$$

$$J_3=\frac{e^2BL^3}{2\pi^2}\mu_5$$

Independent of mass, temperature and baryon chemical potential

4 alternative ways to compute current: Chern-Simons term
Thermodynamic potential, Energy Conservation,
Linear respons (time dep mag field)

Kharzeev, Fukushima & HJW ('08)
See also: Metlitsky and Zhitnitsky ('05)

Computing the induced current (2)

Introduce Chiral Chemical Potential μ_5 to obtain nonzero Chirality
Study equilibrium response to Magnetic Field $J^\mu = \int d^3x \langle \bar{\psi} \gamma^\mu \psi \rangle$

1. Consider Parallel Electric and Magnetic Fields
2. Chirality is generated by the EM anomaly with rate $$\frac{d(N_R - N_L)}{dt} = \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$
3. Moving particles from one to other Fermi Surface costs energy per unit time $$\mu_5 \frac{d(N_R - N_L)}{dt} = \mu_5 \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$
4. Energy has to be delivered by current, energy conservation gives $$\int d^3x \, \vec{j} \cdot \vec{E} = \mu_5 \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$

Nielsen and Ninomiya ('83)

5. Take limit Electric field -> 0 $$J_3 = \frac{eBL^3}{2\pi^2} \mu_5$$

The Chiral Magnetic Effect:

Kharzeev, Fukushima & HJW ('08)

QCD anomaly provides chirality
EM anomaly provides current

See paper this and 4 other methods to arrive at this result

Result for the induced current

$$J_3 = \frac{e^2 B L^3}{2\pi^2} \mu_5$$

What is the value of the chiral chemical potential? $\mu_5 = ?$

Chirality conserved by changing temperature etc..,
not the chiral chemical potential $\mu_5 = f(Q, T, \mu, B)$

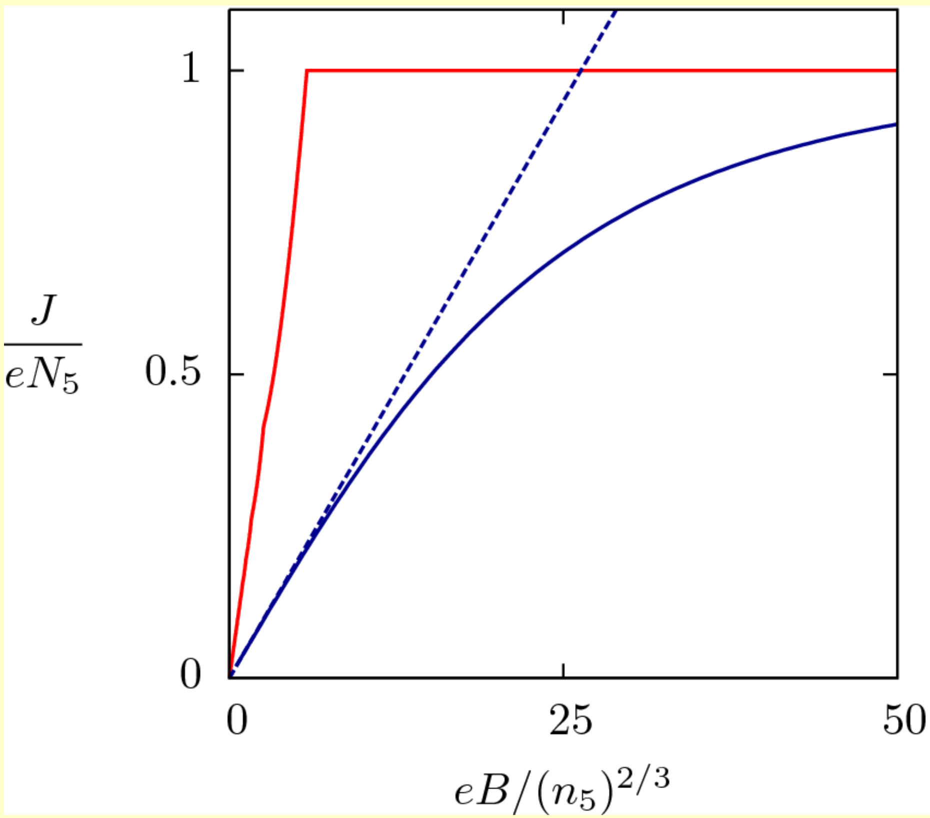
Chirality is directly related to topological charge $N_5 = -2 N_f Q$

Express chiral chemical potential in terms of chirality
in QCD we can get only exact results at high T $n_5 = \frac{\partial \Omega}{\partial \mu_5}$

Kharzeev, Fukushima & HJW ('08)

Current as a function of Chirality

$J=\frac{e^2 B L^3}{2\pi^2}\mu_5$ Express μ_5 in terms of N_5 (neglecting gluonic corrections)



Current as a function of magnetic field
zero temp (red) and $T/n_5^{1/3}=2$ (blue)

High temperature and small magnetic field approx. (dashed line) valid for QCD

$$\mu_5=\frac{3n_5}{T^2+\mu^2/\pi^2}$$

$$N_5=-2N_f Q$$

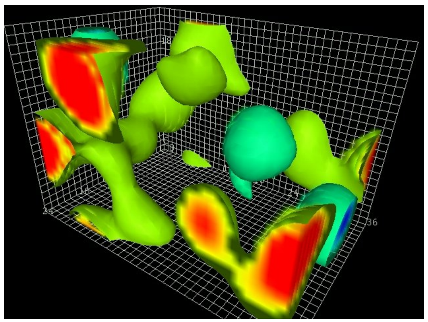
$$J=-\frac{3e^2}{\pi^2}\frac{Q}{T^2+\mu^2/\pi^2}B\sum_f q_f^2$$

Kharzeev, Fukushima & HJW ('08)

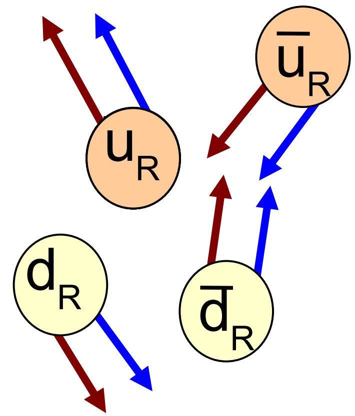
See also lattice QCD work by P.V. Buividovich et al. (arXiv:0907.0494)

How to find topological charge in the quark-gluon plasma

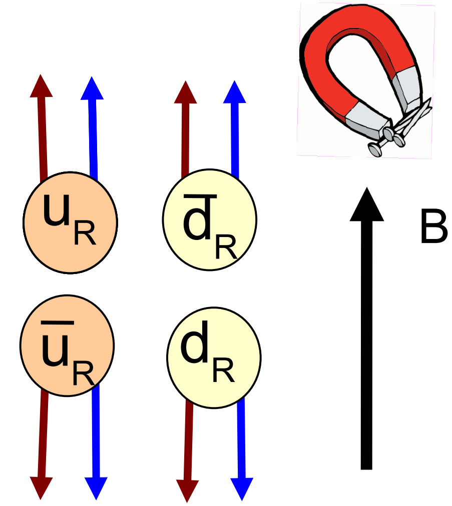
Or from



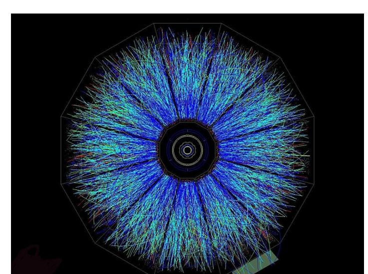
$$\langle Q^2 \rangle \neq 0$$



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



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

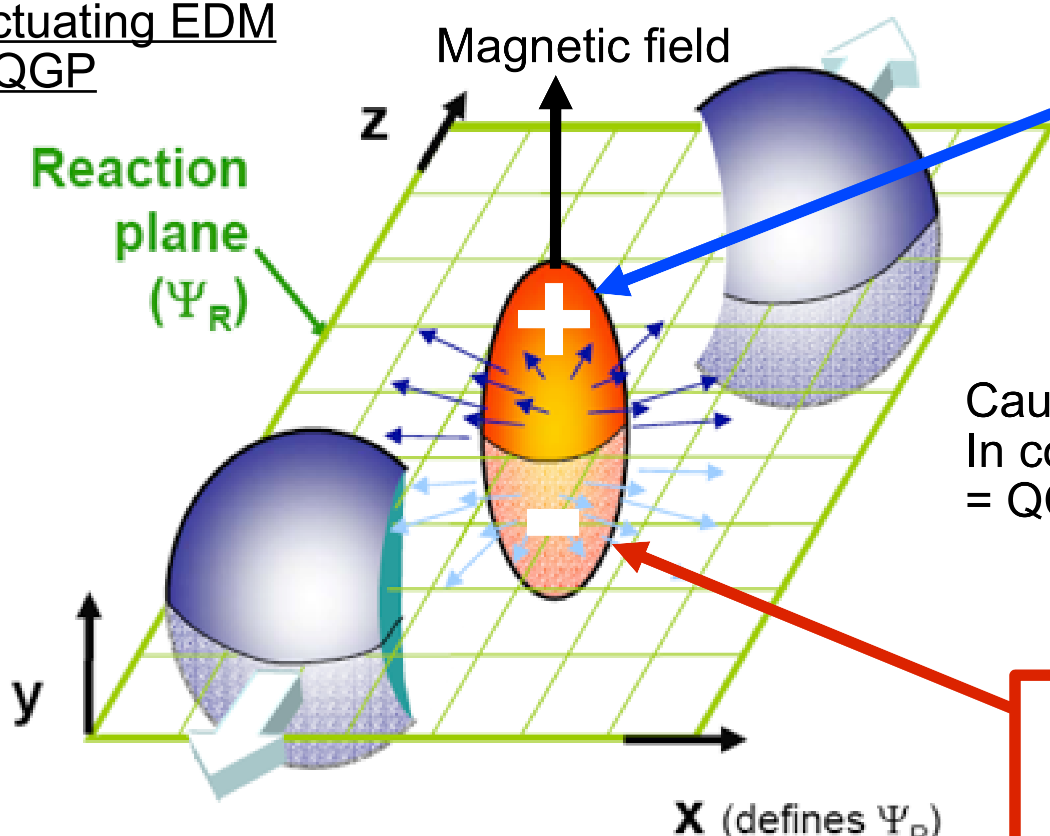


And back!

The Chiral Magnetic Effect in Heavy Ion Collisions

Event by event P- and CP-violation

Kharzeev ('06)
fluctuating EDM of QGP



Excess of Positive Charge on one side of Reaction Plane around $\phi = \pi/2$

Caused by top. charge in quark-gluon plasma
In combination with Magnetic Field heavy ions
= QCD + EM

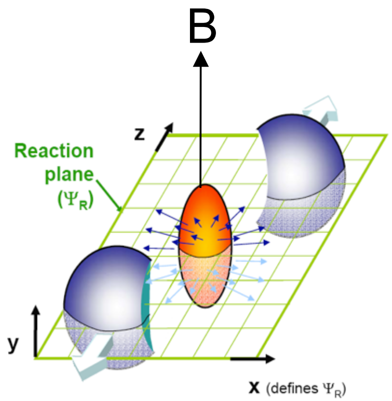
Excess of Negative Charge on other side of Reaction Plane around $\phi = 3\pi/2$

Charge conserved in hadronization:

More positively charged quarks implies more positively charged hadrons

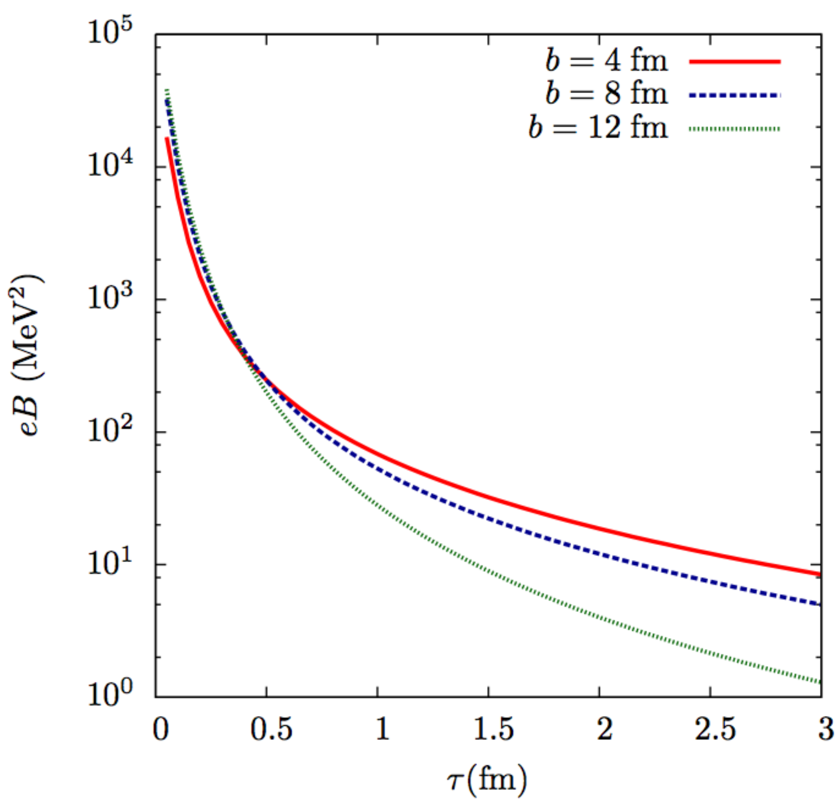
Kharzeev ('06), Kharzeev & Zhitnitsky ('07), Kharzeev, McLerran & HJW ('07)

Magnetic Field in Heavy Ion Collisions



Computed numerically at origin in pancake approximation

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



Yocto second pulses

(1 ys = 1E-24 s =0.3 fm/c)

Quarks which are produced in early stages polarized in the direction perpendicular to reaction plane to some degree.

See also: Asakawa, Minakata and Muller ('98)

Sokov, Illarionov & Toneev, arXiv:0907.1396

100 GeV per Nucleon Kharzeev, McLerran & HJW ('07)

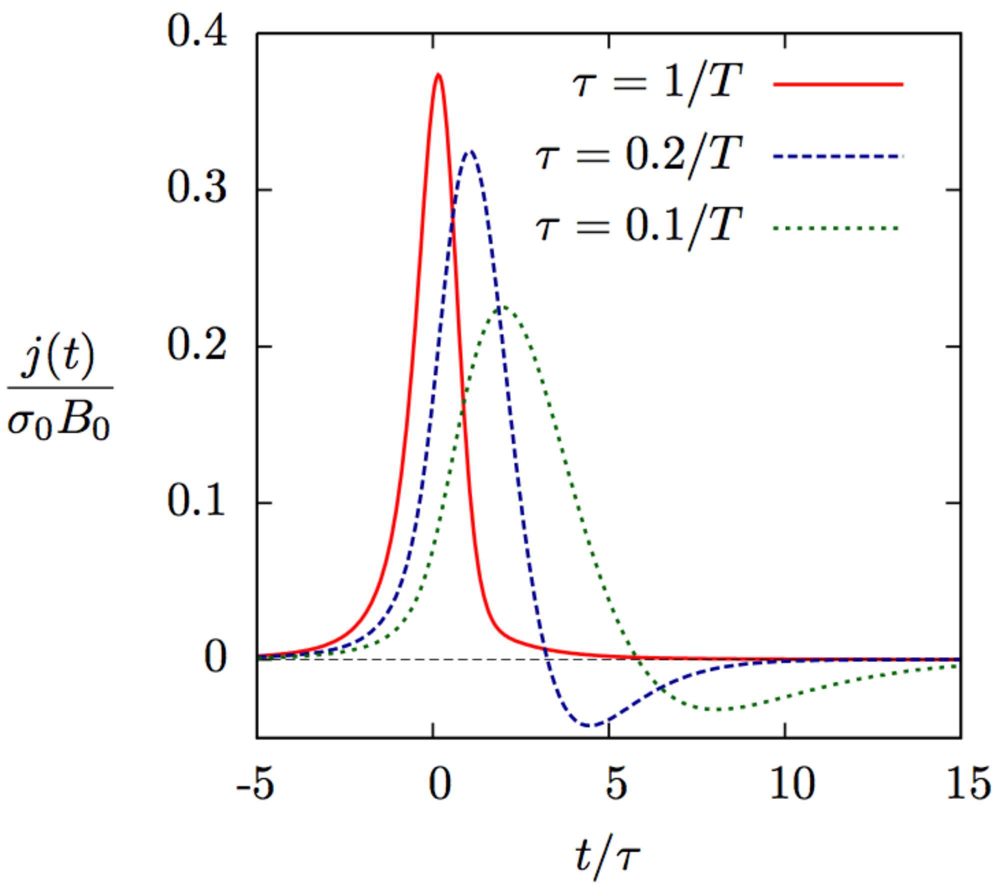
Magnetic field falls off rapidly: early time dynamics

Current in time-dep. magnetic field

Chiral Magnetic Conductivity σ for nonzero frequencies. $j=\sigma B$

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

Anti-symmetric part of off-diagonal photon polarization tensor (nonzero in presence of μ_5)



$$\sigma(\omega=0) \equiv \sigma_0 = \frac{e^2}{2\pi^2}\mu_5$$

Constant chirality in time-dep mag. field

1 loop result, valid at high T.

Result can be systematically improved by taking into 2 loop corrections.

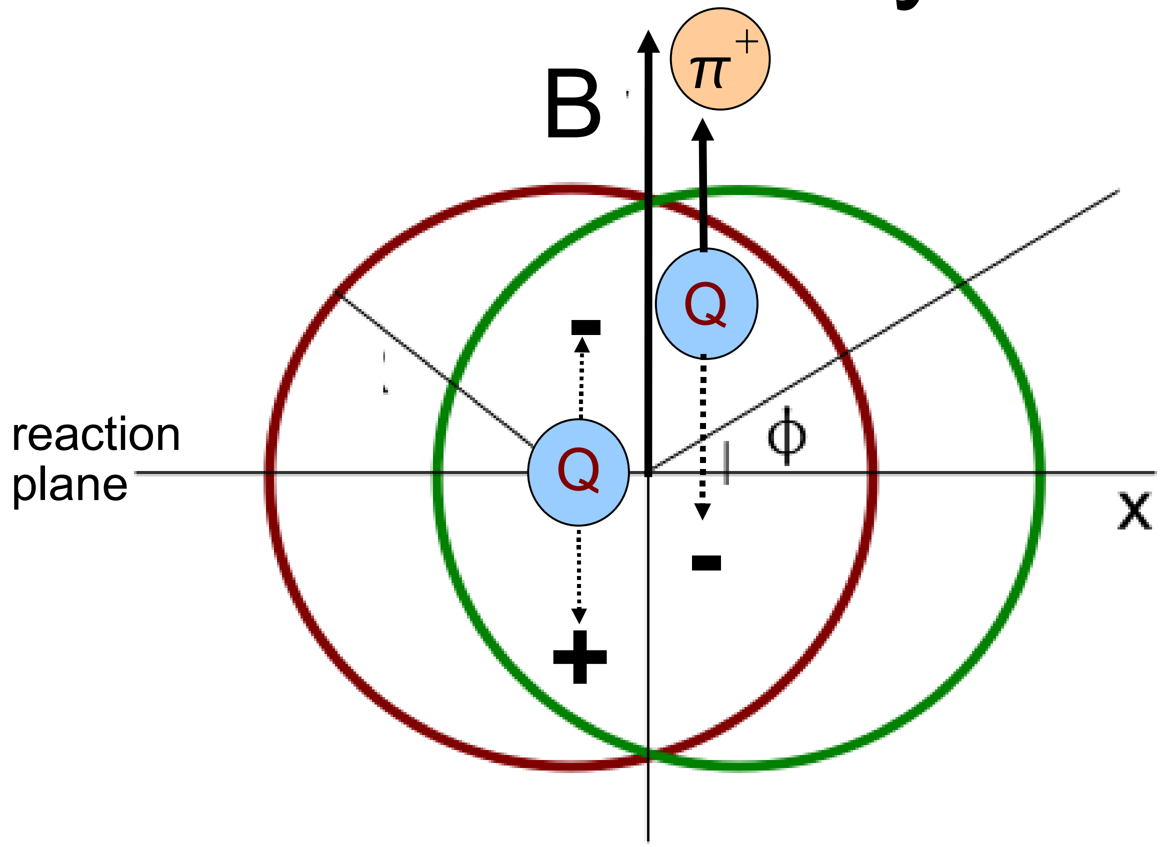
Strong interactions: fast response.

Even very quickly changing magnetic field gives rise to sizable current.

$$B(t) = \frac{B_0}{[1+(t/\tau)^2]^{3/2}}$$

Kharzeev & HJW, arXiv:0907.5007

The Chiral Magnetic Effect in Heavy Ion Collisions



Topological charge Q fluctuates anywhere in the QGP

Measure: variances -> nonzero Event-by-Event P- & CP-violation

The Chiral Magnetic Effect is a near the surface effect

Medium causes screening

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

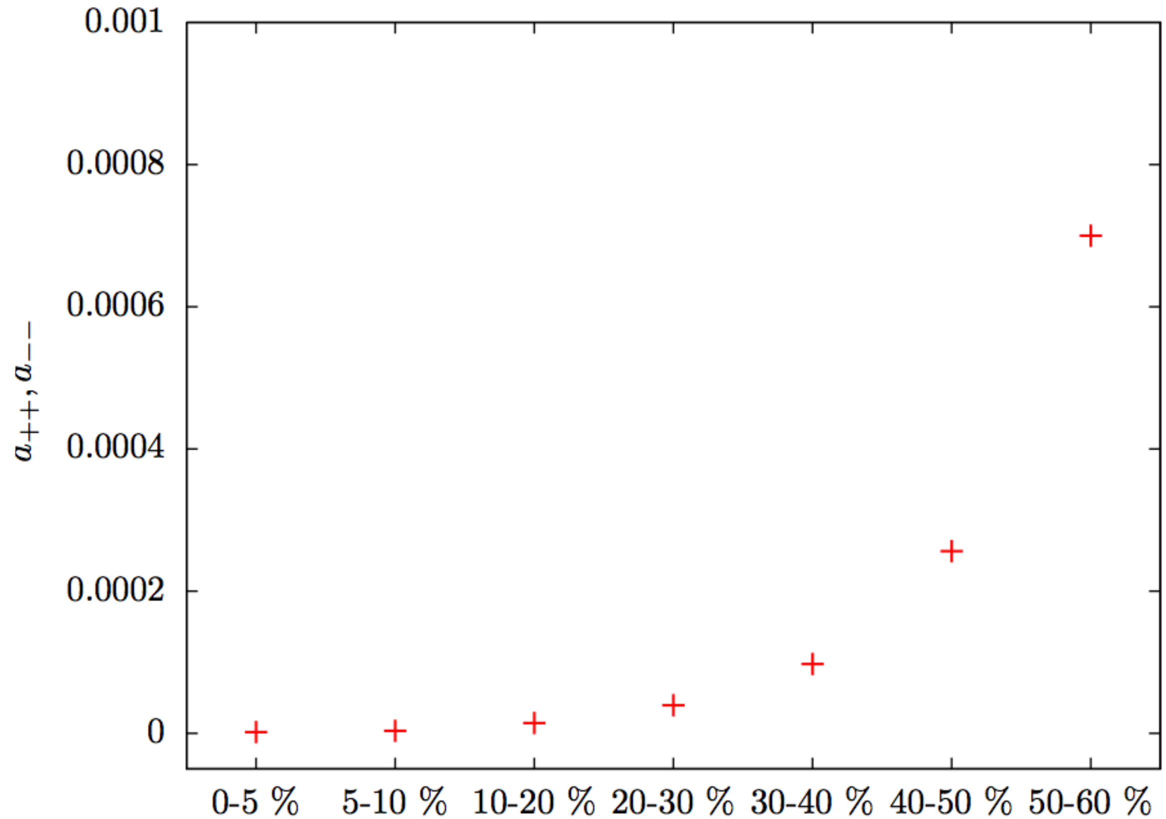
$$\langle \Delta_{\pm}^2 \rangle = 2\int_{t_i}^{t_f} \mathrm{d}t \int_V \mathrm{d}^3x \;\; \Gamma \;\; [\xi_+^2(x_\perp)+\xi_-^2(x_\perp)] \;\; \left(\sum_f q_f^2 e B \rho\right)^2$$

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.

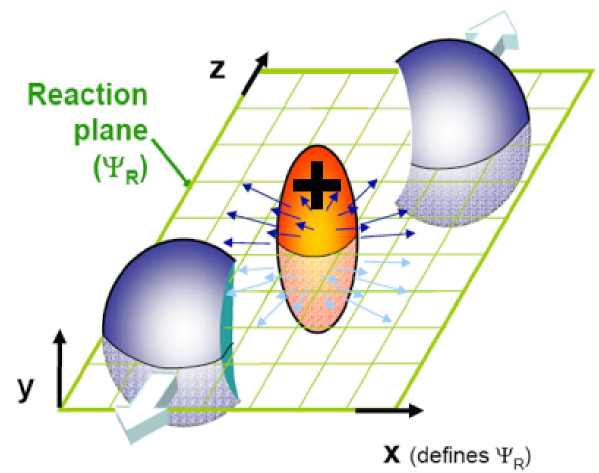
Chiral Magnetic Effect prediction: Correlators vs. Centrality

$\langle \Delta_{\pm}^{2} \rangle / N_{\pm}^{2}$



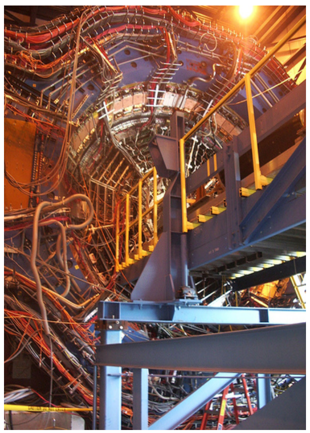
Most Central % Centrality Most peripheral

Preferential emission of positively charged particles around $\phi = 3\pi/2$ or $\phi = 3\pi/2$



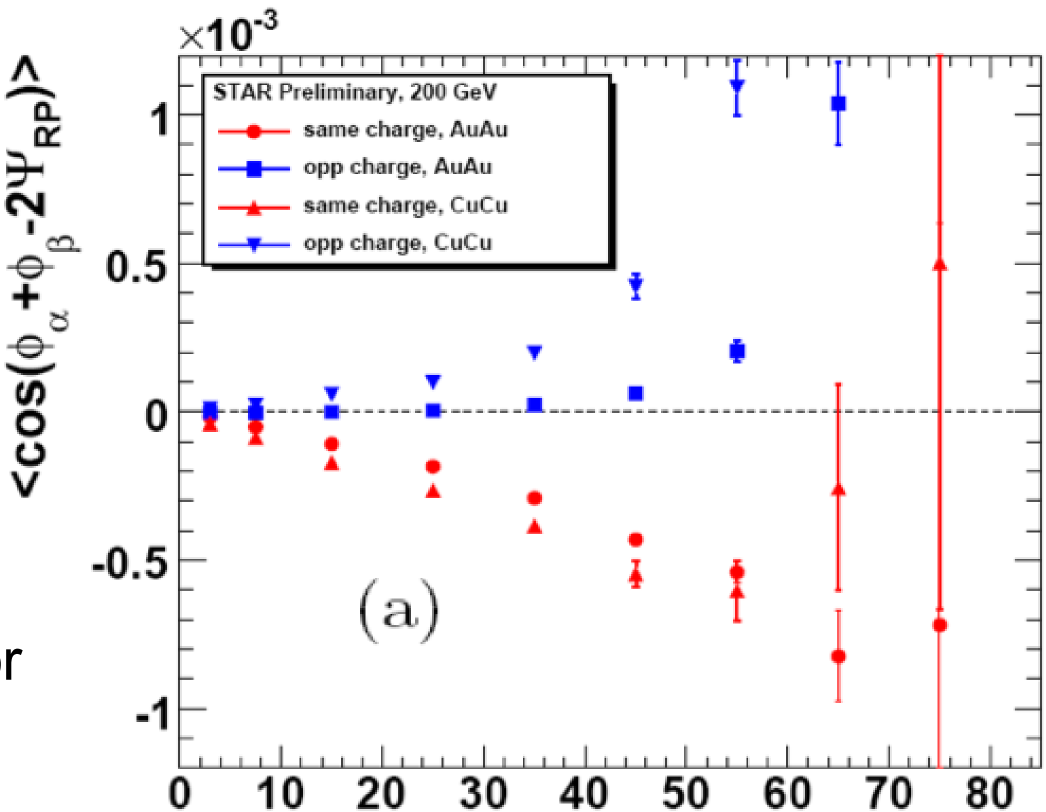
A possible result of the Chiral Magnetic Effect in Gold-Gold collisions at 130 GeV per nucleon

Preliminary data Au & Cu 200 GeV



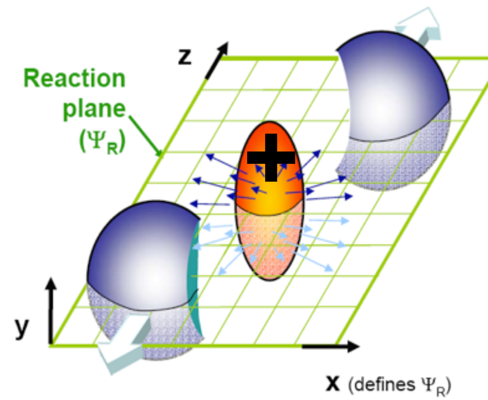
STAR detector

minimum bias

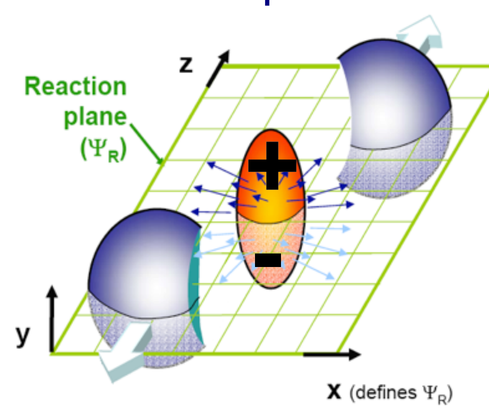


Most Central % Centrality Most peripheral

Red points:



Blue points:



Sergei Voloshin (STAR Collaboration)
Quark Matter 2008 and Quark Matter 2009.

also data for 62 GeV

$$\frac{1}{N_\pm}\frac{dN_\pm}{d\phi} = \frac{1}{2\pi} + a_\pm \sin(\phi - \Psi_{RP}) + v_2 \cos[2(\phi - \Psi_{RP})] + \ldots.$$

Possible BACKGROUNDS?

Features of the Chiral Magnetic Effect

Order parameter for Confinement / Deconfinement
Confined quarks cannot be separated.

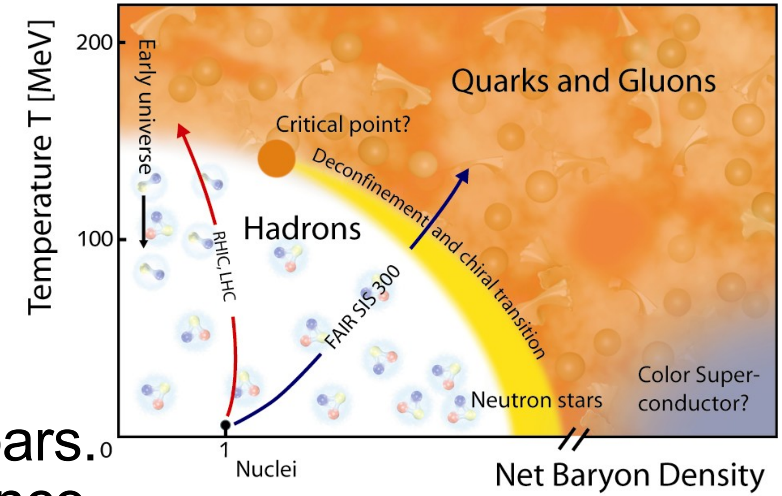
Order parameter for Chiral Symmetry Breaking / Restoration
Chirality will be removed by the chiral condensate (L-R pairing).
Mass term in anomaly.

Hence no QGP implies: no Chiral Magnetic Effect

Test: Energy scan

The correlators are proportional to Z^2
Chiral magnetic effect: QCD + EM

Test: use nuclei with same A and different Z, isobars.
Need to be stable + almost 100% natural abundance.
Calcium-40 (Z=20) compared to Argon-40 (Z=18).
Expected: 24.5% increase



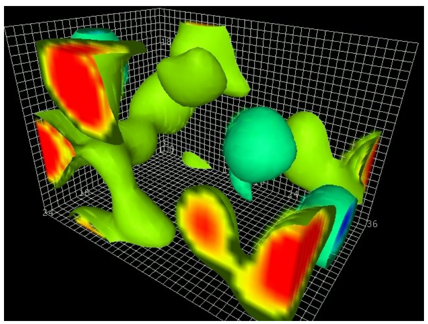
Work to do. More accurate beam energy dependence (what happens at LHC?), A dependence, correlations between different charged particles, ...

Kharzeev, McLerran & HJW ('07)

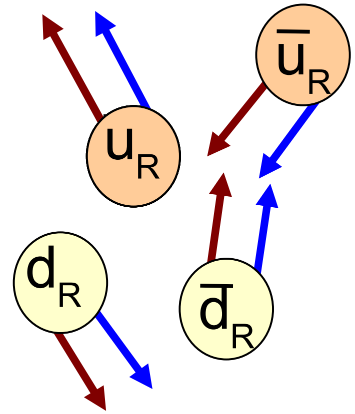
Conclusions

how to find topological charge in the quark-gluon plasma

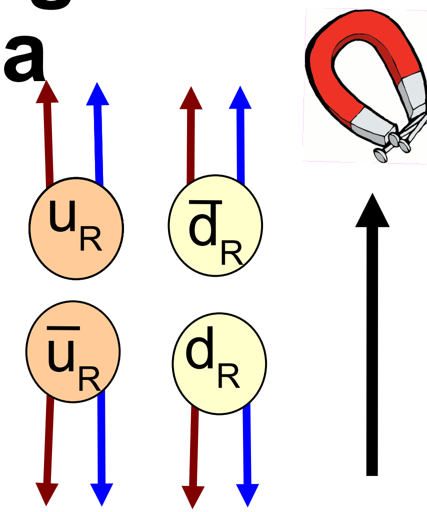
Or from



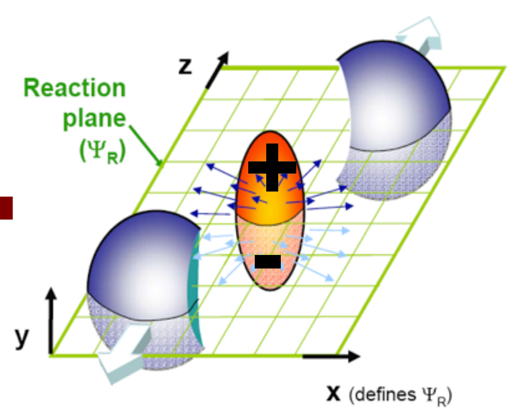
$\langle Q^2 \rangle \neq 0$



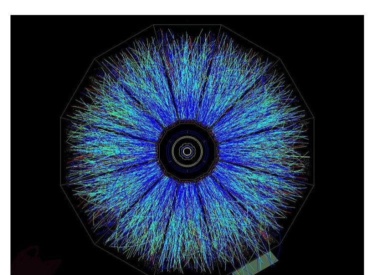
If QGP $\langle N_5^2 \rangle \neq 0$



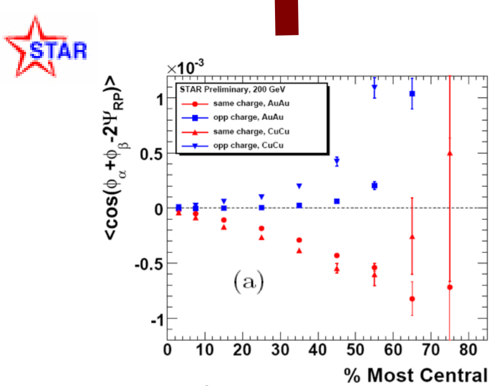
$\langle J_z^2 \rangle > \langle J_{x,y}^2 \rangle$



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



And back!



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

?

Backup slides

Computing the induced current

Introduce Chiral Chemical Potential μ_5 to obtain nonzero Chirality
Study equilibrium response to Magnetic Field $J^\mu = \int d^3x \langle \bar{\psi} \gamma^\mu \psi \rangle$

1. Consider Parallel Electric and Magnetic Fields
2. Chirality is generated by the EM anomaly with rate $$\frac{d(N_R - N_L)}{dt} = \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$
3. Moving particles from one to other Fermi Surface costs energy per unit time $$\mu_5 \frac{d(N_R - N_L)}{dt} = \mu_5 \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$
4. Energy has to be delivered by current, energy conservation gives $$\int d^3x \, \vec{j} \cdot \vec{E} = \mu_5 \frac{e^2}{2\pi^2} \int \mathrm{d}^3x \, \vec{E} \cdot \vec{B}$$

   Nielsen and Ninomiya ('83)

5. Take limit Electric field -> 0 $$J_3 = \frac{e B L^3}{2\pi^2} \mu_5$$

The Chiral Magnetic Effect:

Kharzeev, Fukushima & HJW ('08)

QCD anomaly provides chirality
EM anomaly provides current

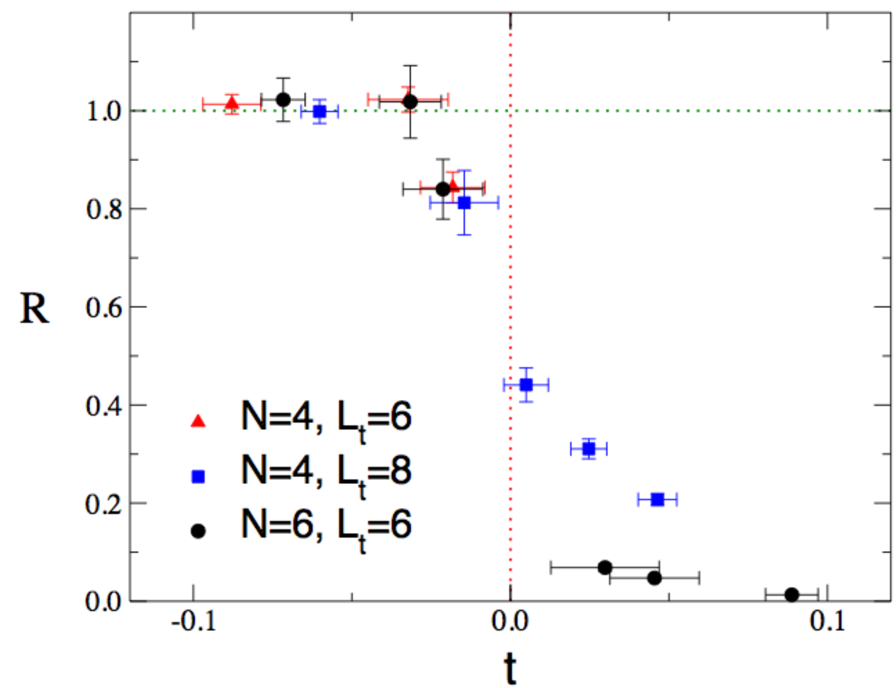
See paper this and 4 other methods to arrive at this result

Topological Susceptibility in Euclidean space-time

$$\Gamma = \lim_{V,t\to\infty} \frac{1}{V\,t}\langle [N_{CS}(t) - N_{CS}(t=0)]^2\rangle = \frac{1}{V_4}\langle Q^2\rangle$$

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

$$\chi = \frac{1}{V_4}\langle Q^2\rangle = \int d^4x \langle q(x)\,q(0)\rangle$$



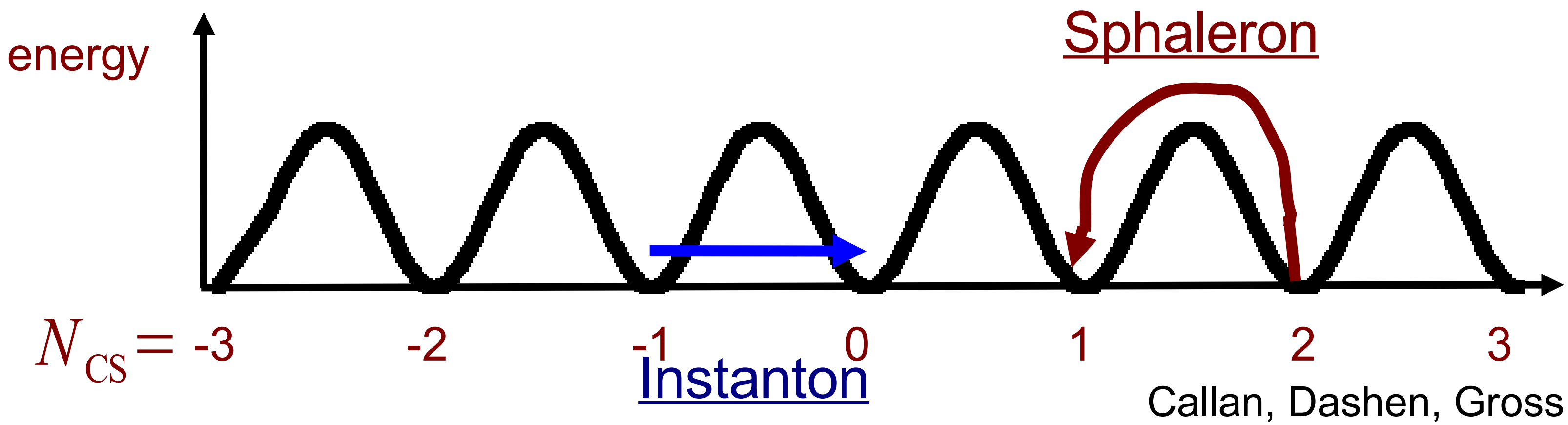
Del Debbio, Panagopolous & Vicari ('02)

$$\Gamma \sim \exp[-S] \sim \exp[-\frac{8\pi^2}{g^2}|Q|]$$

Large suppression at large temperatures..

$$\frac{2N_f}{f_\pi^2}\chi = m_{\eta'}^2 + m_\eta^2 - 2m_K^2 \qquad \chi(T=0) \approx (180\,\mathrm{MeV})^4$$

Topological susceptibiliy in Minkowski space-time



Callan, Dashen, Gross ('76)

Sphaleron: Configuration with finite energy. Go over barrier.

Only possible at finite temperature, rate not suppressed, look for it in QGP!

Manton ('83), Manton and Klinkhamer ('84), McLerran, Mottola and Shaposhnikov ('88)

$$\Gamma \sim 385\, \alpha_S^5\, T^4$$

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

Winding in real-time is very different from winding in Euclidean space-time. See Arnold and McLerran ('88). “The sphaleron strikes back” for a nice discussion.

Relation between current and topological charge

$$J_3 = \frac{e B L^3}{2\pi^2} \mu_5 \qquad \mu_5 = ? \qquad N_5 = -2Q$$

$$n_5 = \frac{\partial \Omega}{\partial \mu_5} \qquad \Omega = \frac{1}{\beta V} \log Z$$

At large temperatures and small magnetic fields,

We can take a free noninteracting gas of fermions. This can be improved.

$$\mu_5 = \frac{3 n_5}{T^2 + \mu^2/\pi^2} \qquad J_3 \approx \frac{3 e^2}{\pi^2} \frac{Q}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$$

Fluctuations in topological charge lead to fluctuations in the current

$$\langle J_3^2 \rangle \approx \left[\frac{3 e^2}{\pi^2} \frac{1}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2 \right]^2 \langle Q^2 \rangle$$

Kharzeev, Fukushima & HJW ('08)

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Nielsen and Ninomiya ('83)

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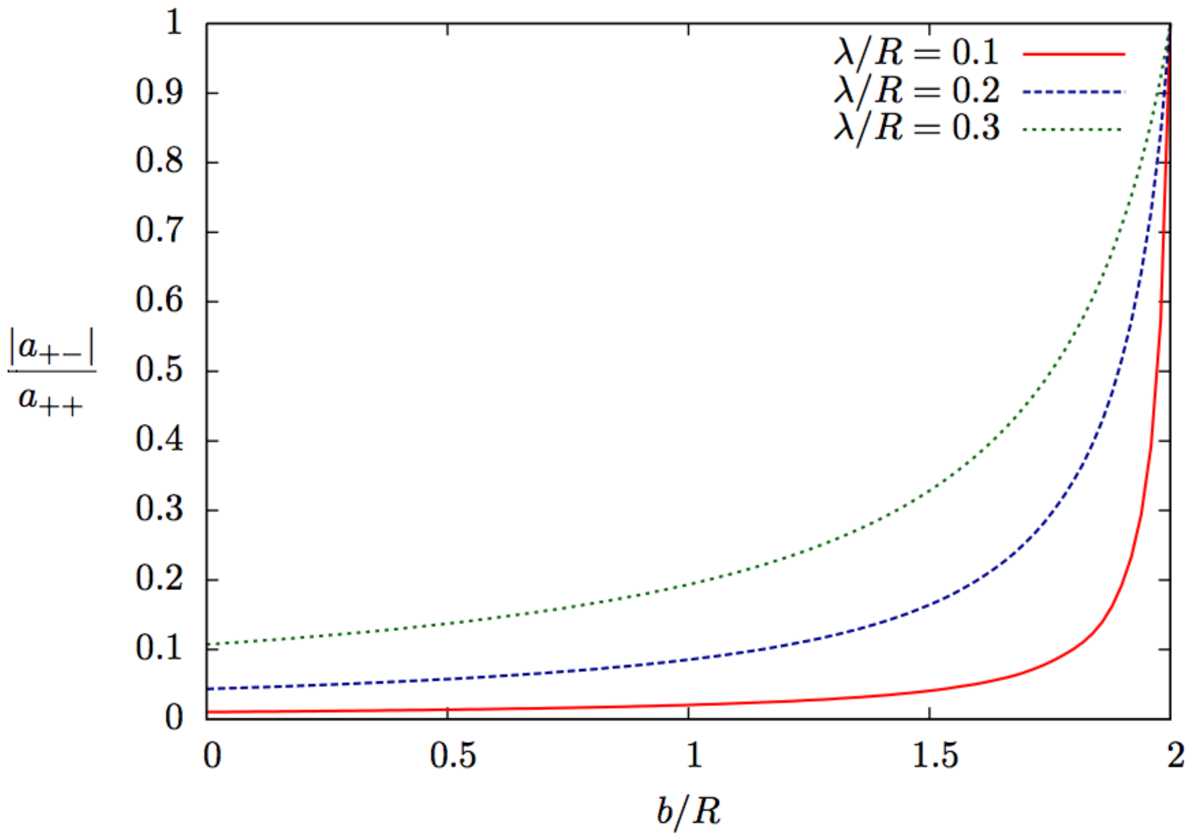
QCD anomaly provides chirality
EM anomaly provides current

See paper this and 4 other methods to arrive at this result

Suppression of +/- correlations

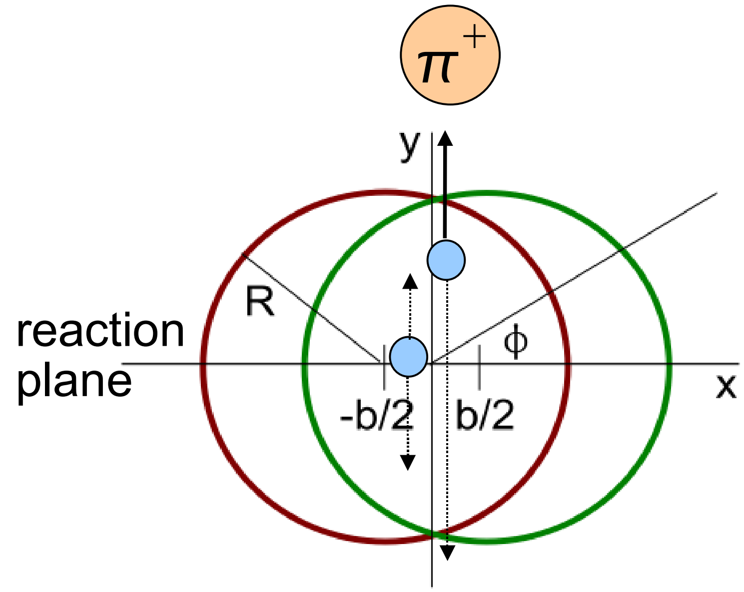


Suppression of correlations

between positively charged particles on one side and

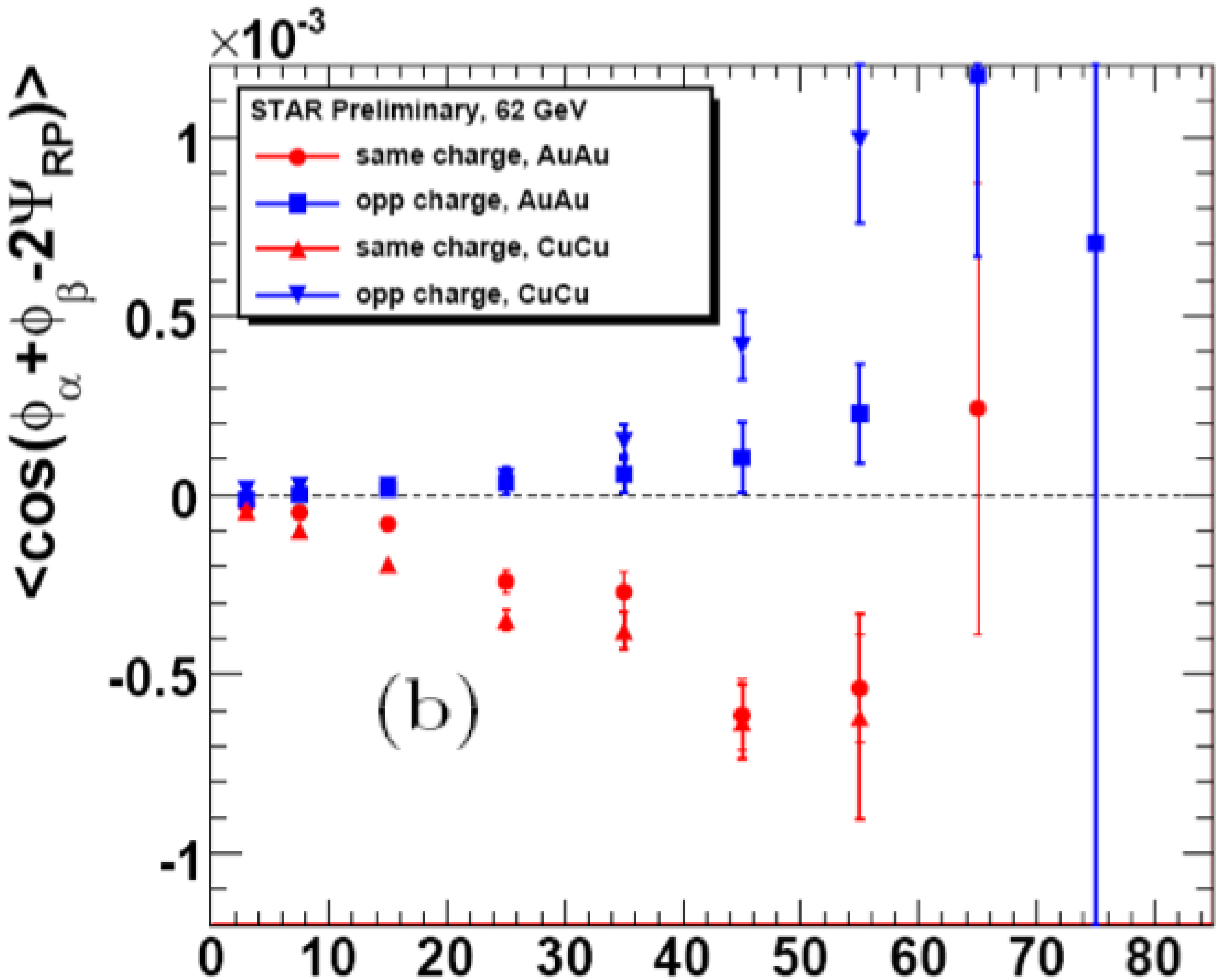
negatively charged particles on other side of reaction plane

due to screening.



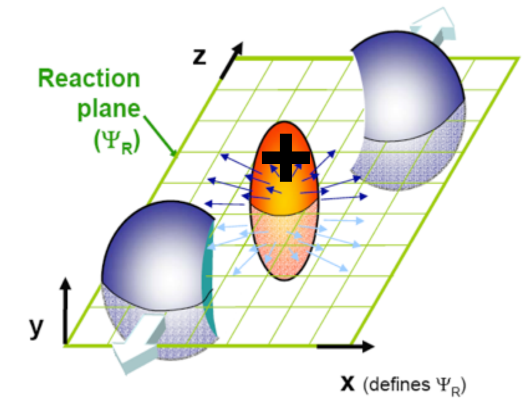
A possible result of the Chiral Magnetic Effect

Preliminary data Au & Cu 62 GeV

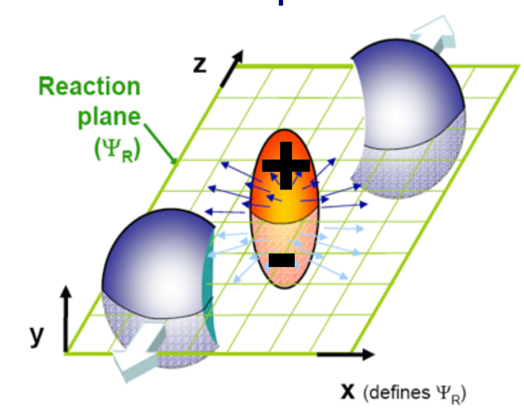


Most Central % Centrality Most peripheral

Red points:



Blue points:



Voloshin (STAR Collaboration) Quark Matter 2008

The Chiral Battery

EM Current created with constant magnetic field? ->
No violation of energy conservation

Chirality means storage of energy

Imagine hypothetical material exactly described by massless Dirac equation.

This might be pure Science Fiction, but anyway.. at least useful analogy

We can store chirality=energy in this material by placing it in parallel electric and magnetic fields,

The Chiral Battery

Graphene comes close,

But is not the right material.
Pseudospin instead of real spin
Also need something 3-d.

Kharzeev, Fukushima & HJW ('08)

The Chiral Battery

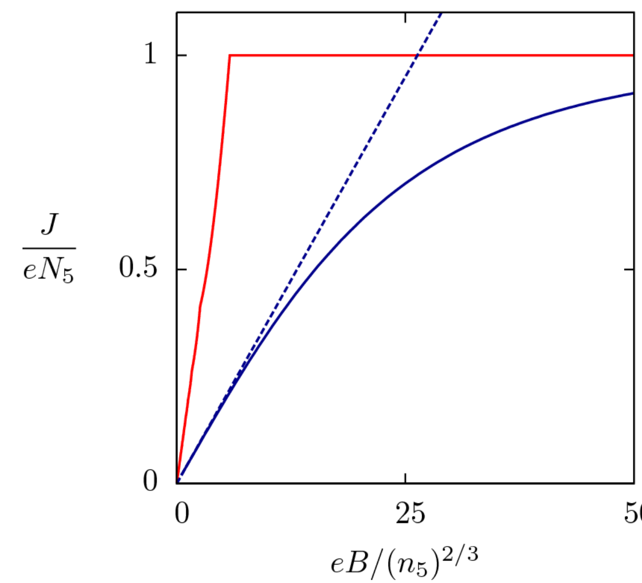
Charging: use axial anomaly,
place battery in parallel electric and magnetic fields.

Utilize: apply (constant) magnetic field in the direction one wants the current to flow. The behavior of the current follows from our analysis.

Discharge: Voltage difference is created over the terminals, hence electric field, but now antiparallel to magnetic field.

The battery will also discharge by the axial anomaly.

Capacity: same order of magnitude as ordinary batteries.



Note the chiral battery is environmentally friendly, rechargeable

Kharzeev, Fukushima & HJW ('08)

Measurements suggest

Preferential emission of charged particles in one direction perpendicular to reaction plane.

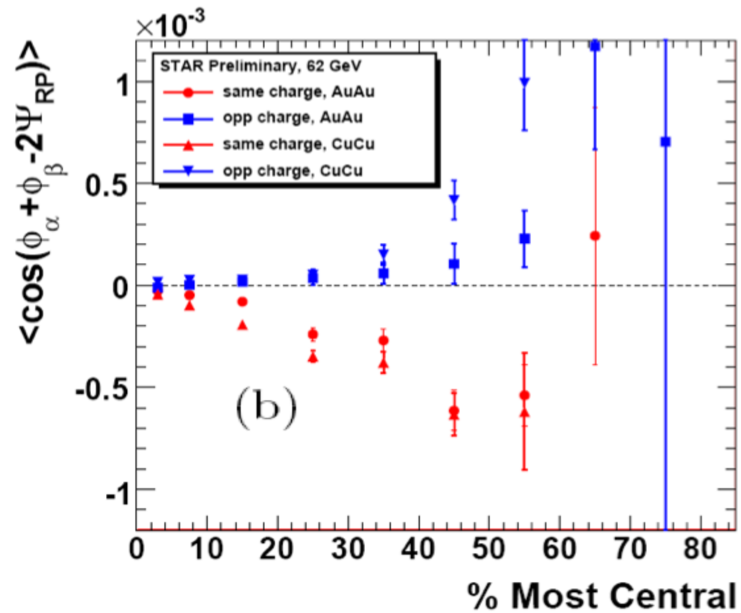
Correlations between positively charged particles and negatively charged particles on opposite sides.

Existence of screening effect.

About 1-3 % asymmetry

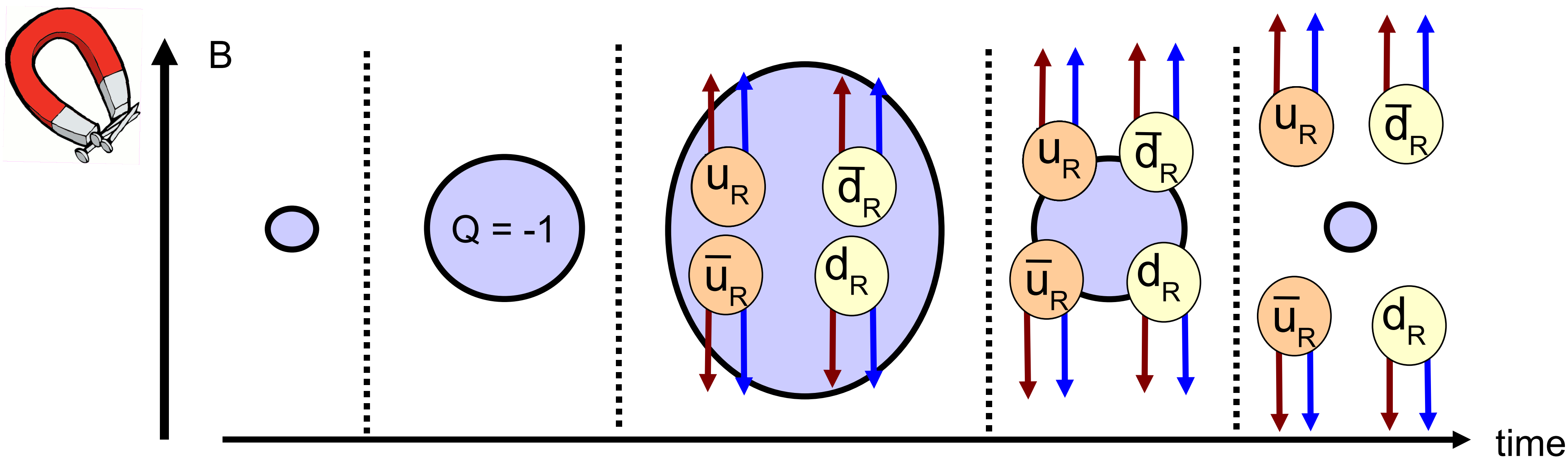
Relative asymmetry increases for more peripheral collisions

Magnitude asymmetry Cu-Cu and Au-Au very similar both at 62 GeV and 200 GeV for all centralities.



Sergei Voloshin (STAR Collaboration)
Quark Matter 2008

Is it due to the Chiral Magnetic Effect or due to something else, and how to find out?



B
Q = -1
u_R
$\bar{d}_R$
$\bar{u}_R$
d_R
u_R
$\bar{d}_R$
$\bar{u}_R$
d_R
u_R
$\bar{d}_R$
$\bar{u}_R$
d_R
time

Features of the Chiral Magnetic Effect

- Magnitude of asymmetry estimate: gold-gold at 130 GeV at large impact parameter $a_{++} \sim 10^{-4}$ with large uncertainty

- Atomic Number (A) dependence is determined by initial time. A better computation (no pancake approximation) could give us this more accurately.

For now it seems that for intermediate energies we have $(Z/A)^2$ dependence, not completely certain: depends on dynamics

- The correlators are proportional to Z^2
  Test: use nuclei with same A and different Z, isobars

- Particle species dependence

- Beam energy dependence is determined by initial time. A better computation (no pancake approximation) could give us this.

At LHC smaller asymmetries. Magnetic field decays faster.