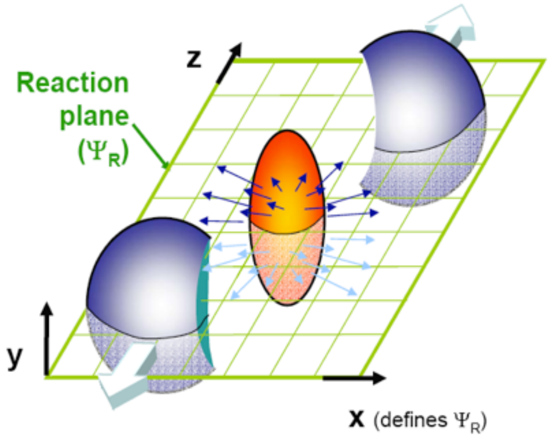
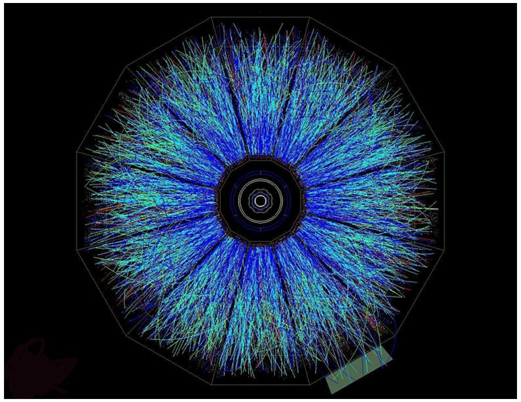
The Chiral Magnetic Effect

Harmen Warringa, Goethe Universität, Frankfurt

Collaborators: Kenji Fukushima, Dmitri Kharzeev and Larry McLerran.

P- and CP-odd effects in heavy ion collisions





P- and CP-odd effects might occur in hot matter

T.D. Lee ('73), T.D. Lee & Wick ('74), Morley and Schmidt ('85), Kharzeev, Pisarski, Tytgat ('98), Halperin & Zhitnitsky ('98) , ...

How to observe these effects in data?

I will explain you that the Chiral Magnetic Effect is

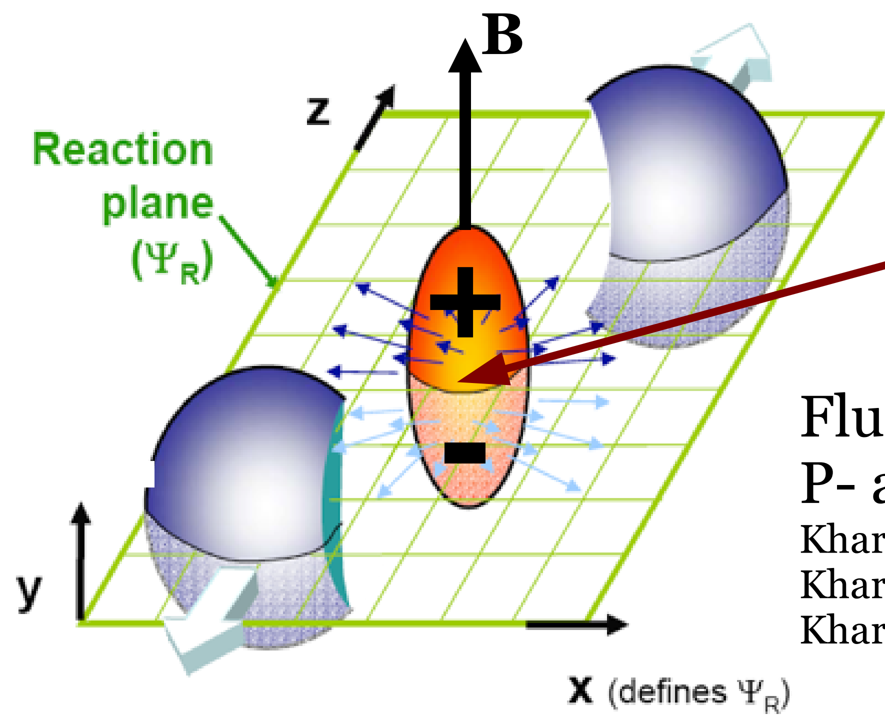
Topological charge + Magnetic Field =

Induces chirality: P- and CP-odd effect

Pointing perpendicular to reaction plane

$\langle Q \rangle = 0$

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



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

Charge separation

Investigate experimentally by charge correlation study Voloshin ('04) *Talks by Sergei Voloshin, Roy Lacey & Jack Sandweiss*

Alternative mechanisms for charge separation *Talk by Berndt Mueller*

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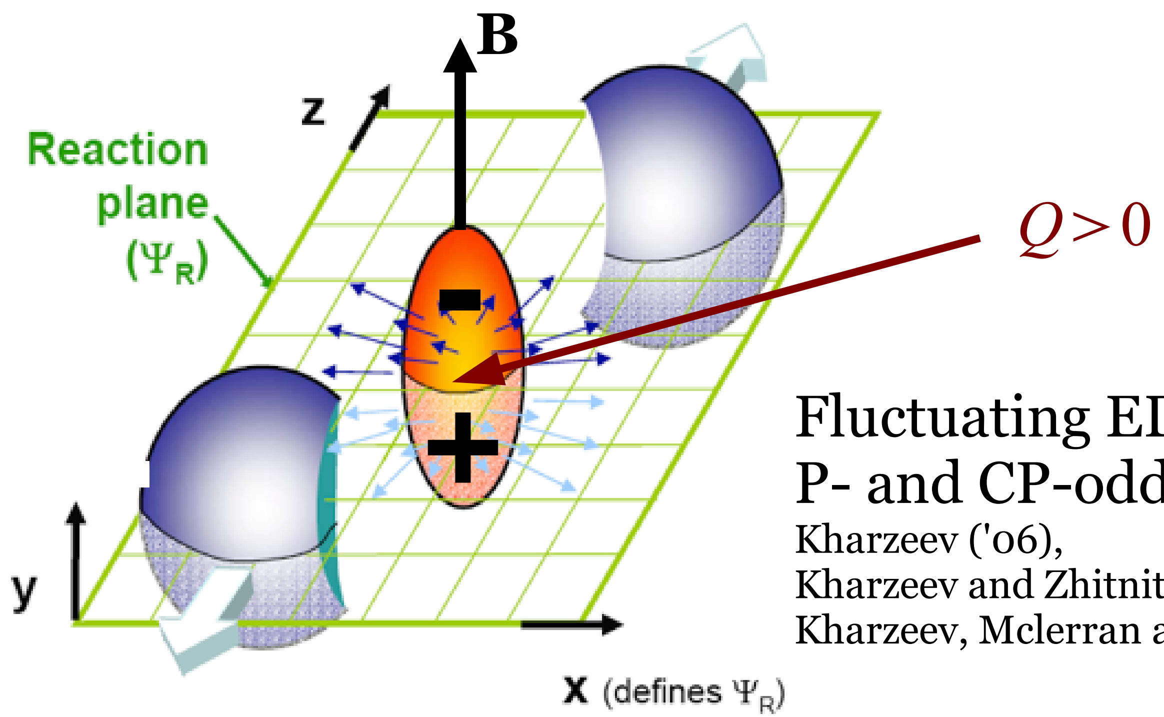

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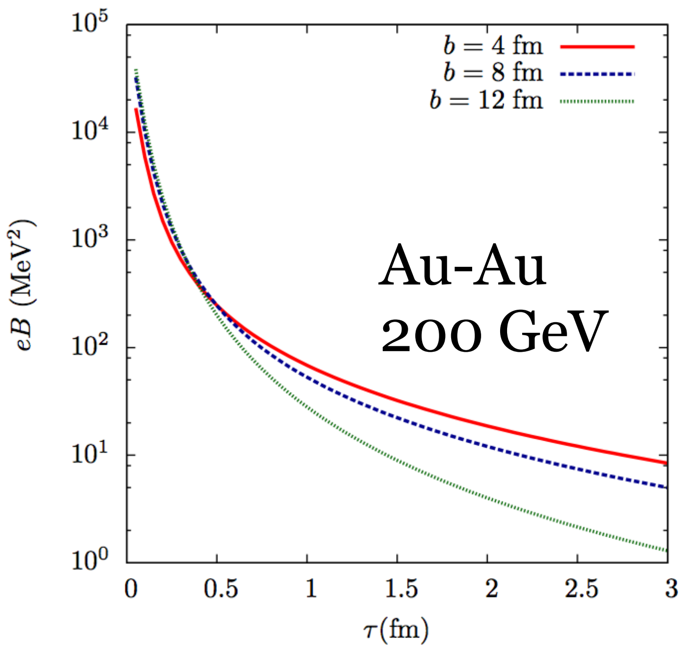
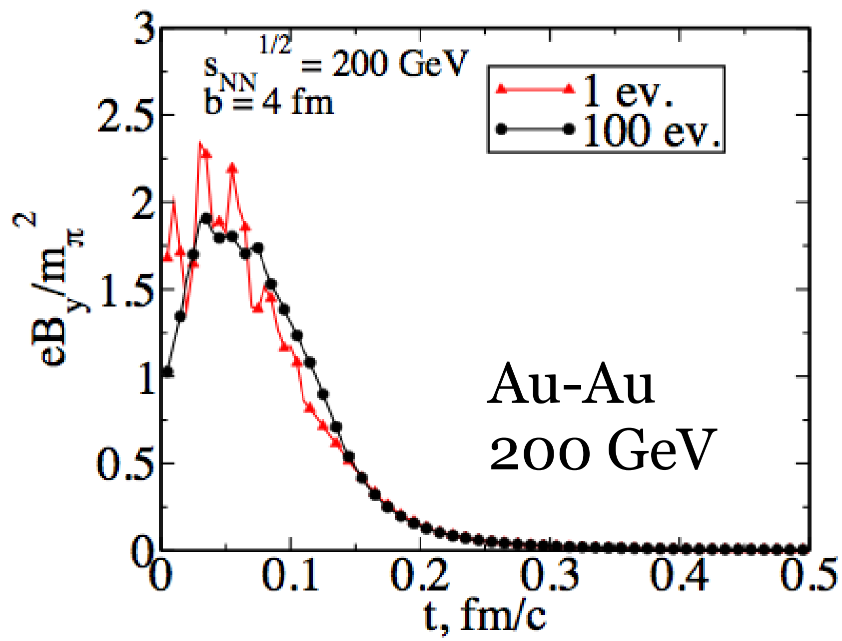
Ultra high-energy heavy ion collisions = Ultra strong (EM) magnetic fields



Pancake approximation
Kharzeev, McLerran & HJW ('08)
See also Minakata and Müller ('96)



URQMD calculation
Skokov, Illarionov, Toneev ('09)

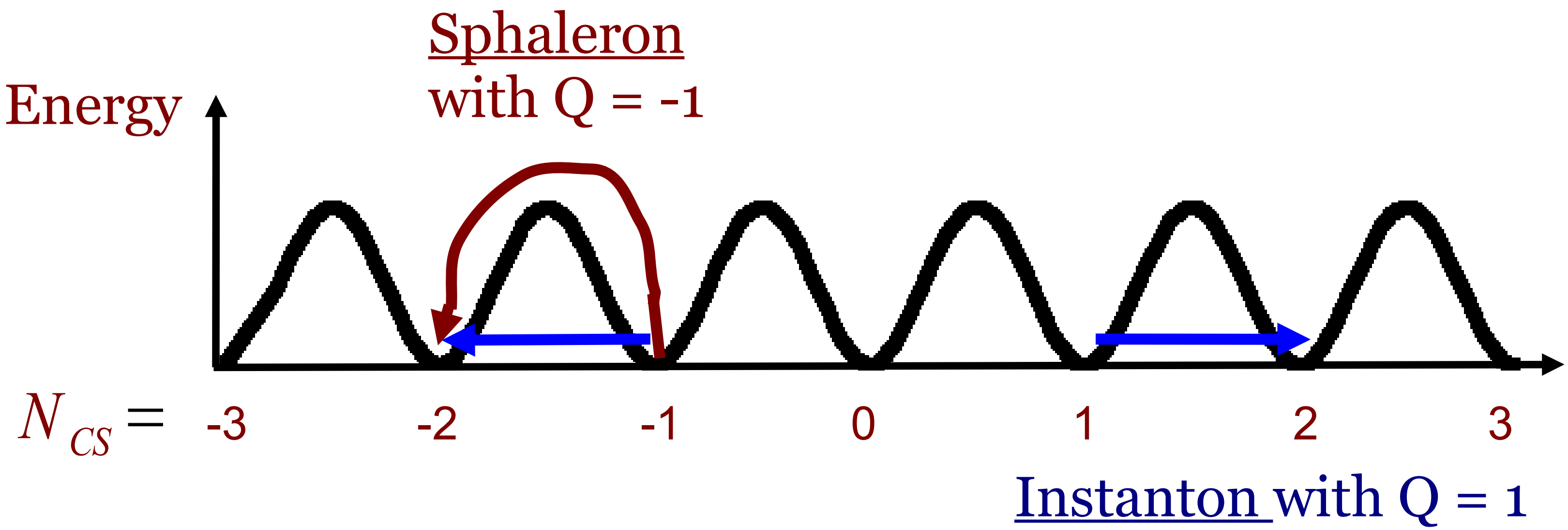
$$eB(\tau = 0.2\ \text{fm/c}) \approx 10^3 \sim 10^4\,\text{MeV}^2 \approx 10^{18}\,\text{G}$$

Talks by A. Chikanian, Jorn Boomsma, Eduardo Fraga, ...

Topological charge fluctations

Q = topological charge
= change in winding number

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



- Quantum tunneling: Instanton, (Belavin et al. ' t Hooft, ...)

Caloron, (finite T. instanton) (Gross, Pisarski, & Yaffe, Kraan & Van Baal, ..)

Talk by Pierre van Baal

- Thermal activation: Sphaleron, (Klinkhamer & Manton, Kuzmin, Rubakov & Shaposnikov, ...)

Talks by Guy Moore, Valery Rubakov

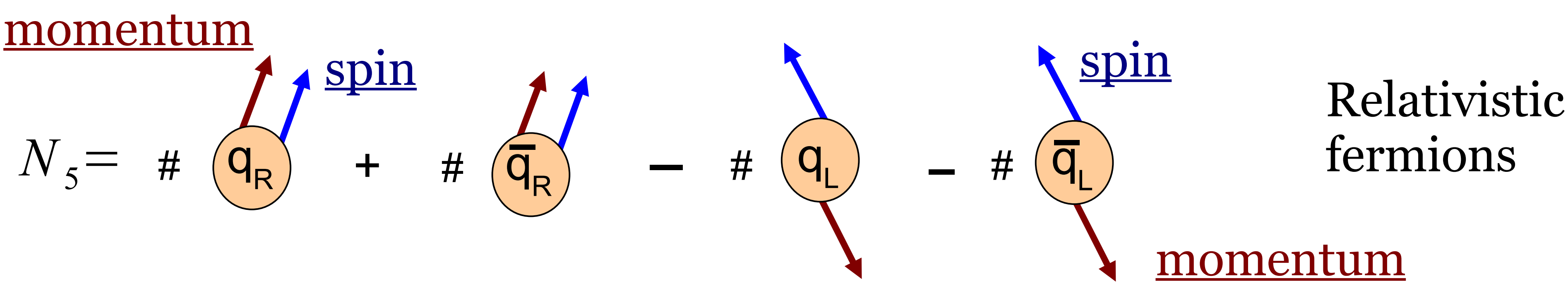
- In Glasma: (Kharzeev, Krasnitz & Venugopalan, McLerran & Lappi, ...)

Talk by Larry McLerran

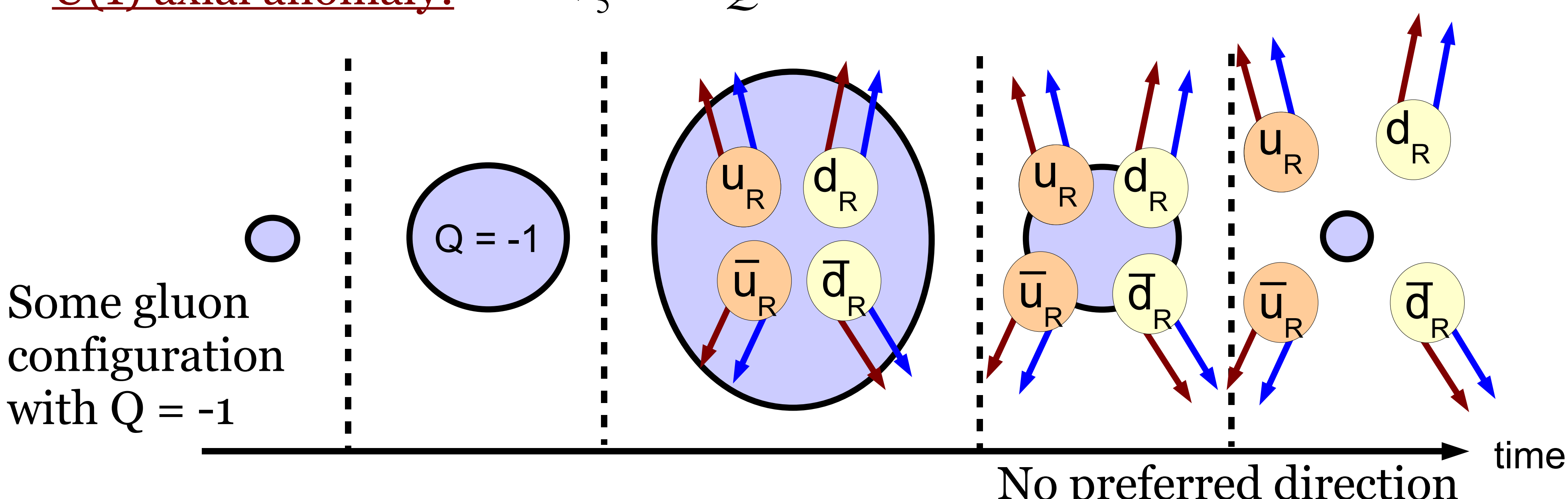
Topological charge: P- and CP-odd effects

This is the P- and CP-odd effect

Chirality: N5= difference # quarks + antiquarks with R & L-handed helicity



U(1) axial anomaly: $\Delta N_5 = -2Q$



Outline

I. Qualitative explanation

II. Static calculation

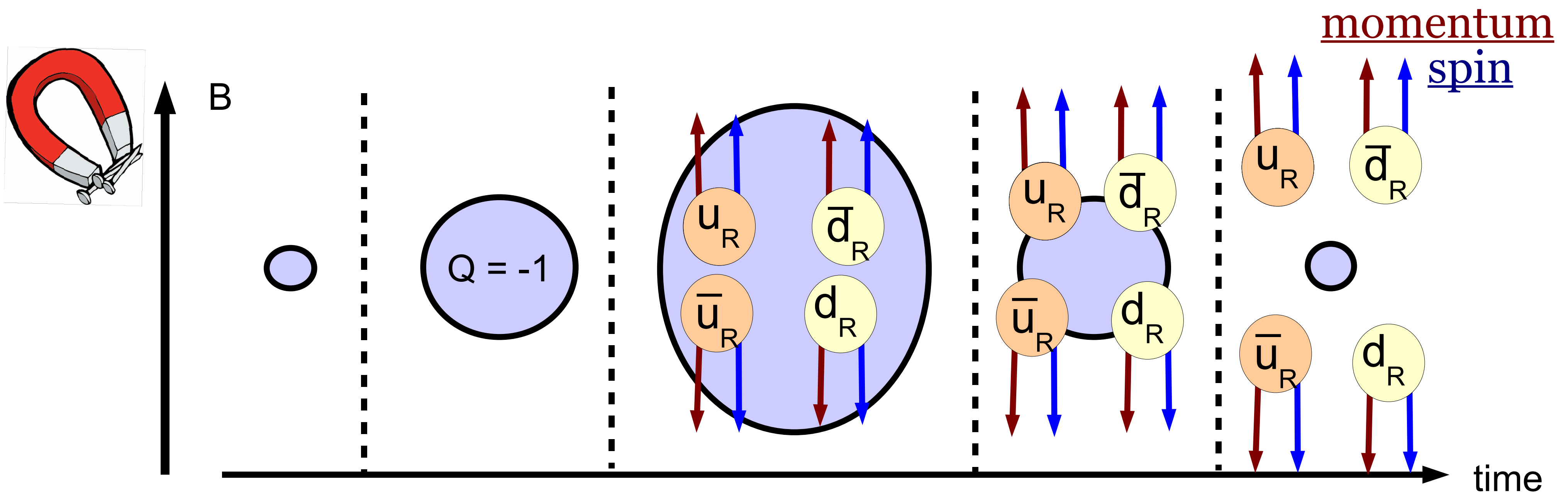
III. Semi-static calculation

IV. Dynamic calculation

V. Investigating with heavy ion collisions

I. A qualitative explanation of the Chiral Magnetic Effect

Topological Charge + Magnetic field = Chirality + Polarization =

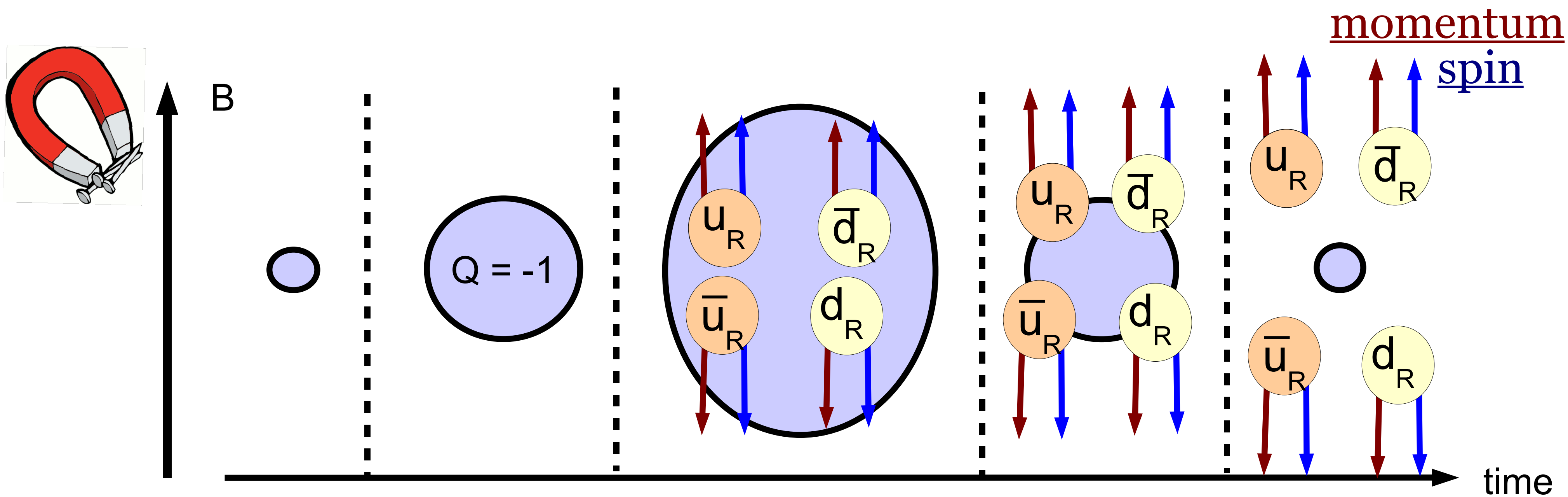


Q < -1: Positively charged particles move parallel to magnetic field, negatively charged antiparallel

... = Electromagnetic Current

P- and CP-odd effect --> Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('08)

Topological Charge + Magnetic field = Chirality + Polarization =



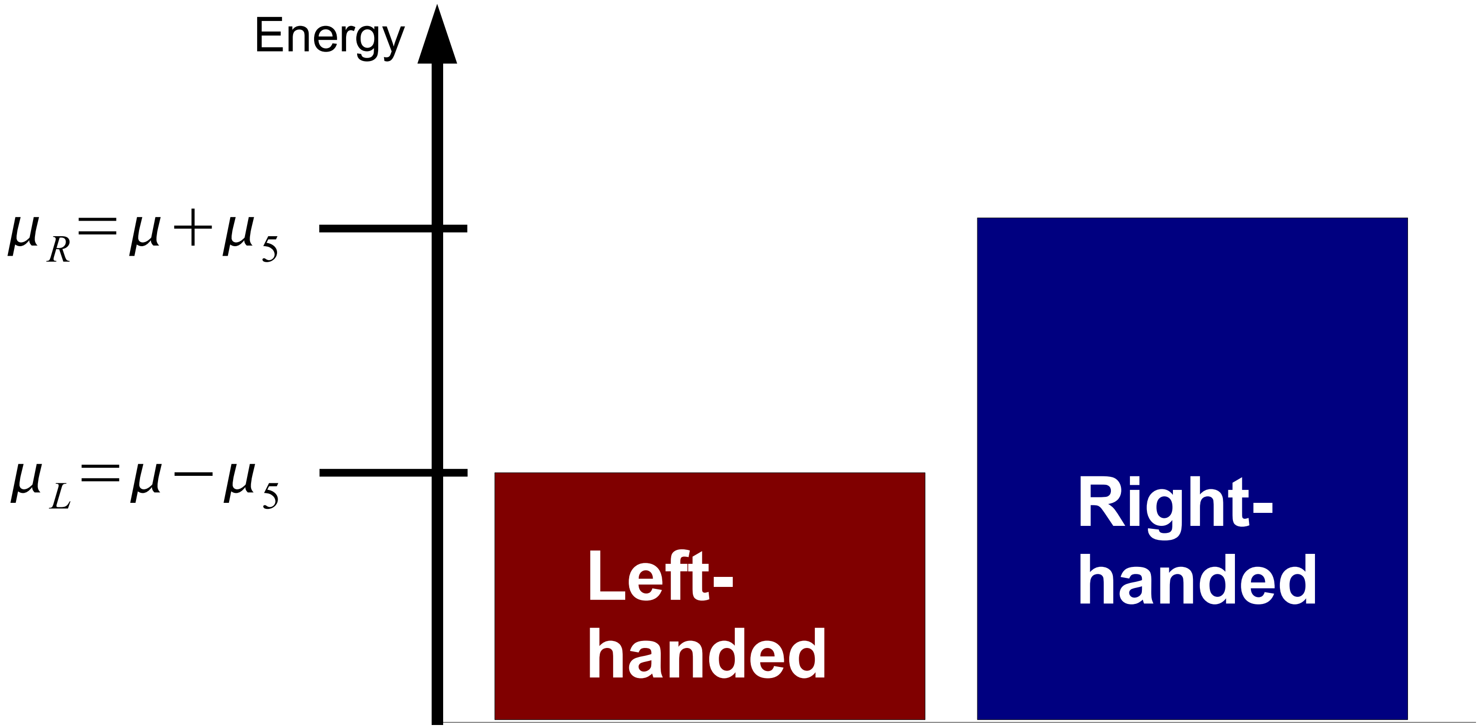
Size of Current: $J = \int d^3x \langle \bar{\psi} \gamma^3 \psi \rangle = -2Q \sum_f |q_f|$

Valid for full polarization, what about smaller fields?

P- and CP-odd effect --> Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('08)

II. A static calculation of the Chiral Magnetic Effect

Static calculation: Introduce chirality by hand



Nonzero Chirality: Nonzero chiral chemical potential μ_5

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

Obtain induced EM current in magnetic field

Magnitude of the induced current

Nielsen and Ninomiya ('83), Alekseev, Cheianov, Fröhlich ('98), Fukushima, Kharzeev and HJW ('08)

See also Metlitsky and Zhitnitsky ('06), Newman and Son ('06), Charbonneau and Zhitnitsky ('09) Gorbar, Miransky and Shovkovy ('09)

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

Many different ways to derive:

1. Energy conservation
2. Density in Lowest Landau Level
3. Chern-Simons term
4. Thermodynamic potential
5. Linear response
6. Propagator in magnetic field

Result follows from EM axial anomaly. Exact and independent of coupling strength??

AdS/CFT strong coupling: *Talk by Ho-Ung Yee*
Boundary terms can make this vanish: *Talk by Anton Rebhan*
Modification due to vector interaction: Fukushima and Ruggieri ('10)
Spatial modulation: chiral magnetic spiral: *Talk by Gerald Dunne*
Anomaly induced currents in Hydrodynamics: *Talk by Dam Son*
Anomaly and magnetism: *Talk by Misha Stephanov*

Magnitude of the induced current

Fukushima, Kharzeev and HJW ('08)

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

Express μ_5 in terms of chirality density
cf. baryon chem. potential and density

$$n_5 = \frac{\partial \Omega}{\partial \mu_5}$$

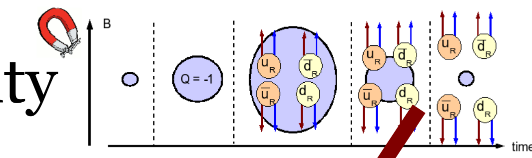
Obtain thermodynamic potential Ω with B at high T using LO. pert. QCD.

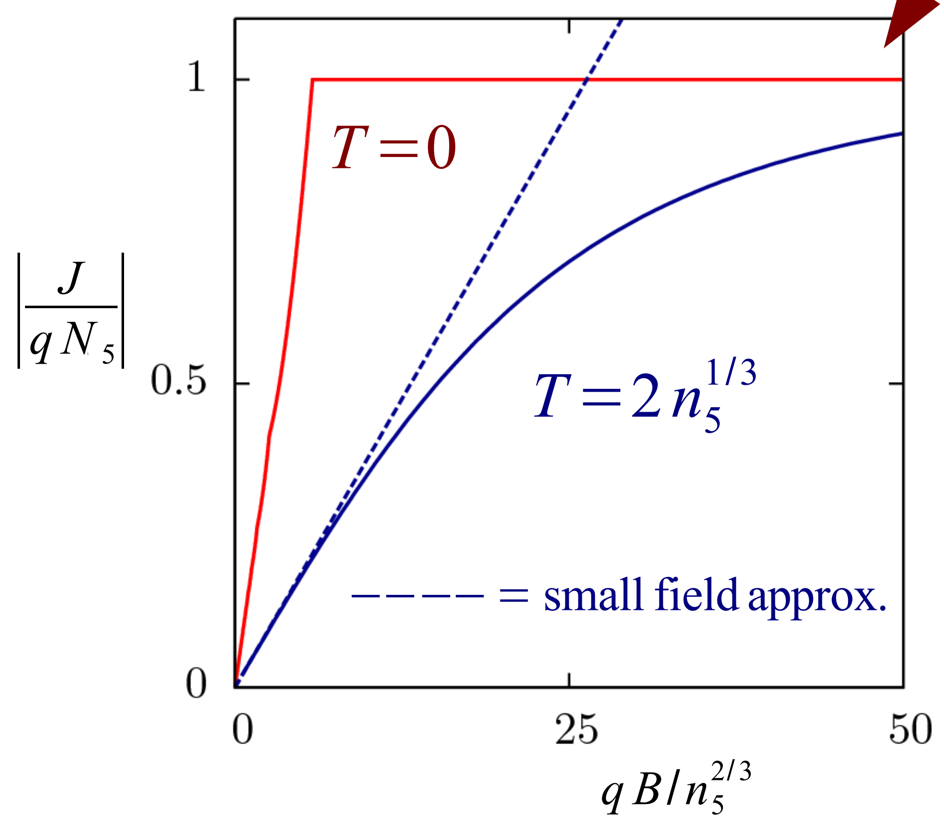
$$\mu_5 = f(T, B, \mu, n_5)$$

Relate total chirality to top. charge

$$N_5 = -2Q$$

Current over chirality vs. magnetic field



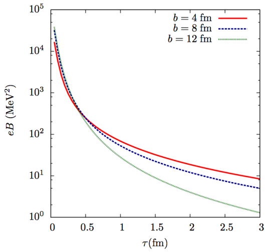


Obtained: estimate induced current in small mag. field: $J \approx -\frac{3}{\pi^2} \frac{Q}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$

III. A semi-static calculation of the Chiral Magnetic Effect

Static chirality + time-dep. field

Kharzeev and HJW ('09)



Can we have chiral magnetic effect
even in the fast changing mag. field of collisions?

$\vec{j} = \sigma_E \vec{E}$ $\quad \sigma_E(\omega) =$ electrical conductivity

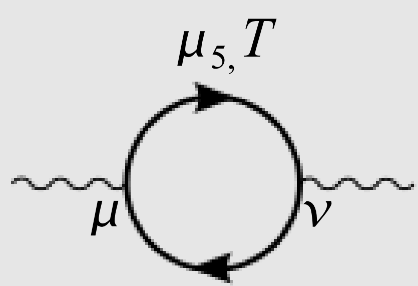
$\vec{j} = \sigma_\chi \vec{B}$ $\quad \sigma_\chi(\omega) =$ chiral magnetic conductivity

Compute chiral magnetic conducitivity as
a function of frequency using linear response

Leading order
pert. QCD

Kharzeev and HJW ('09)

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



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

AdS/CFT
strong coupling:
Ho-Ung Yee ('09)

Talk by Ho-Ung Yee

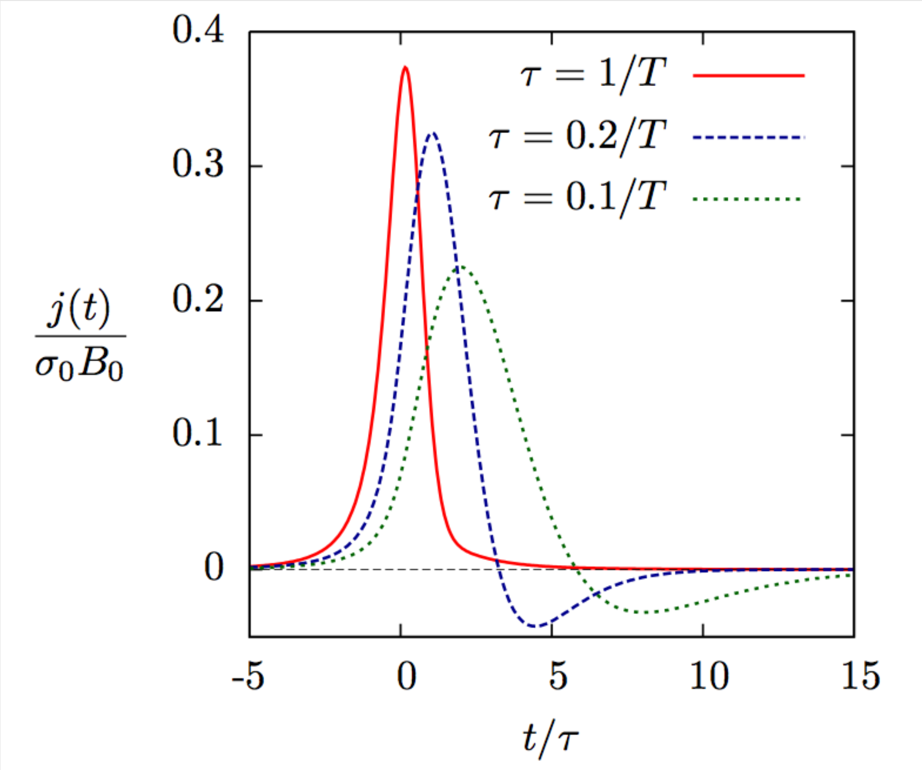
Static chirality + time-dep. field

Kharzeev and HJW ('09)

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

Normalized current as a function of time

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



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. AdS/CFT: Ho-Ung Yee ('09)

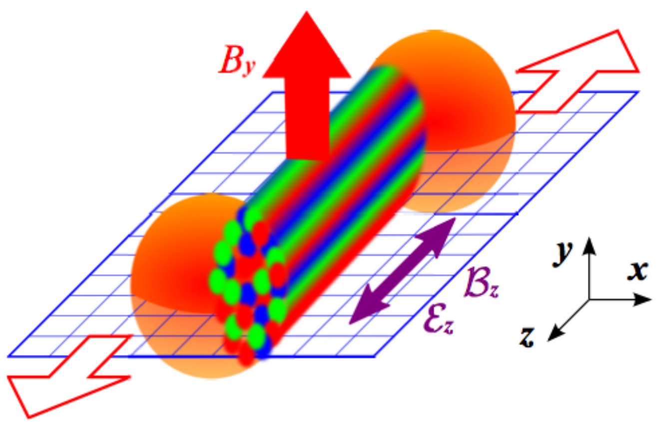
Conclusion: also sizable current in fast changing magnetic field

IV. A dynamic calculation of the Chiral Magnetic Effect

Fukushima, Kharzeev and HJW, arXiv:1002.2495

Chiral Magnetic Effect in Color Flux Tube

Heavy ion collison: Perpendicular magnetic field to color flux tube



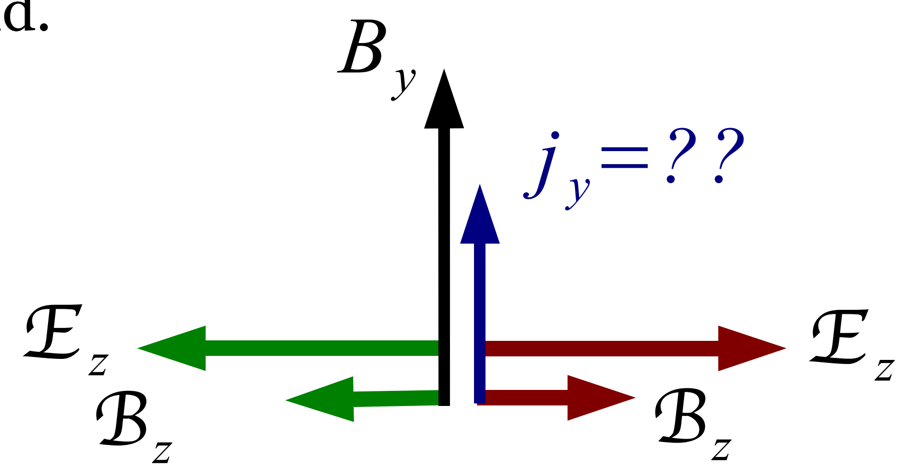
Flux tubes naturally arise in initial state collision
Talk by Shuryak, Glasma

Kharzeev, Krasnitz, Venugopalan ('02),
Rebhan, Romatschke, Strickland ('05)
Lappi & McLerran, ('06), ...

Setup: Homogeneous flux tube + mag field.
Flux tube: infinite topological charge, generates chirality dynamically

$$\partial_\mu J_5^\mu = -\frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a = \frac{g^2}{4\pi^2} \vec{\mathcal{E}} \cdot \vec{\mathcal{B}}$$

Goal: Current in y-direction
Verify Chiral Magnetic effect



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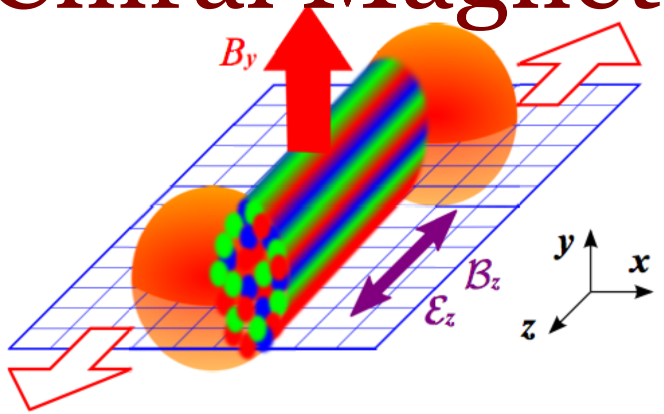
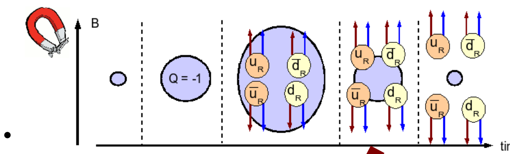
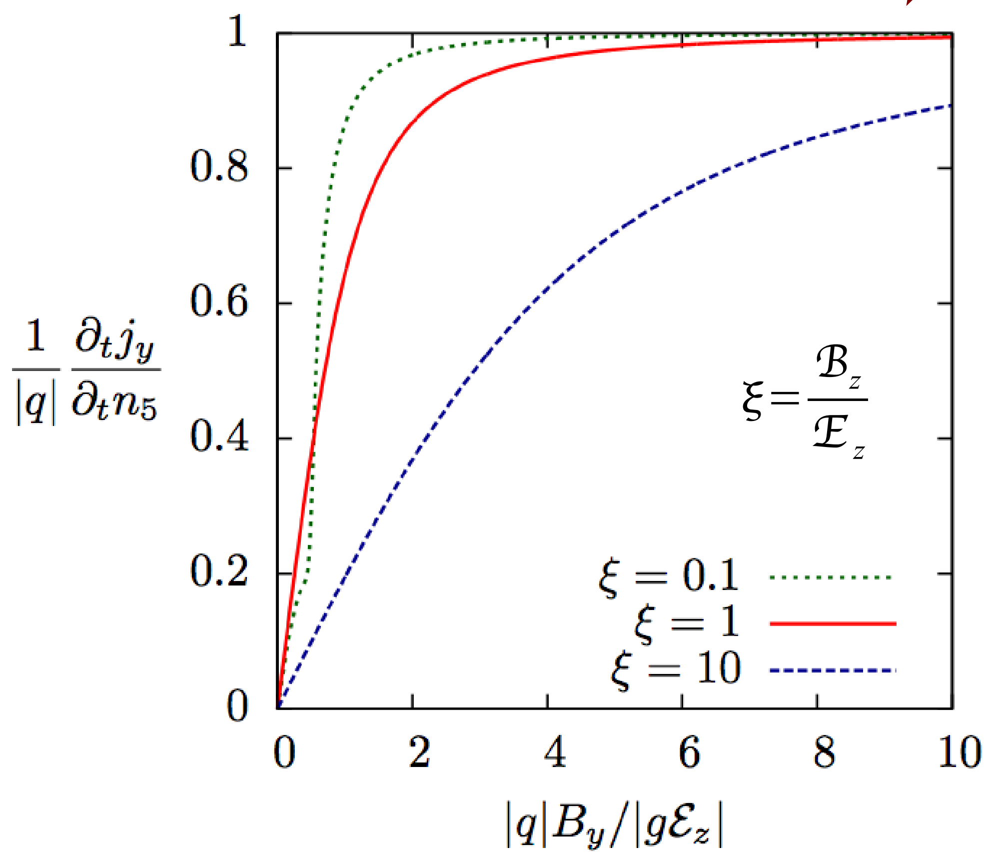


Current over chirality rate vs. perpendicular magnetic field:





Dynamical calculation of Chiral Magnetic Effect:

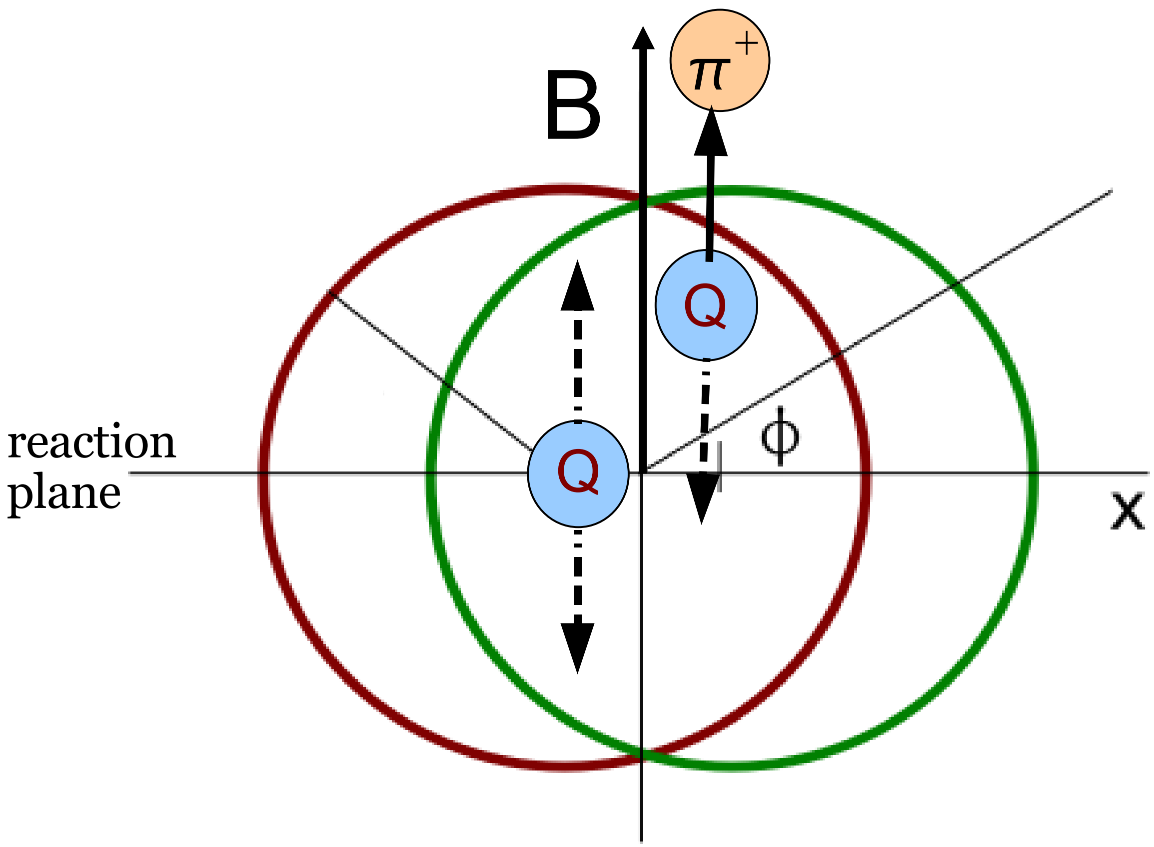
- Completely analytic result for jy
- Only EM current in y direction
- No By, or no chirality: jy = 0
- Large By: current=chirality
- Quark mass: reduction in current
- No anomaly: fictional scalar particles completely different behavior.

IVb. Chiral Magnetic Effect on the Lattice

Talks by M. Polikarpov and T. Blum

V. Investigating Chiral Magnetic Effect with heavy ion collisions

Rough phenomenology



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:

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

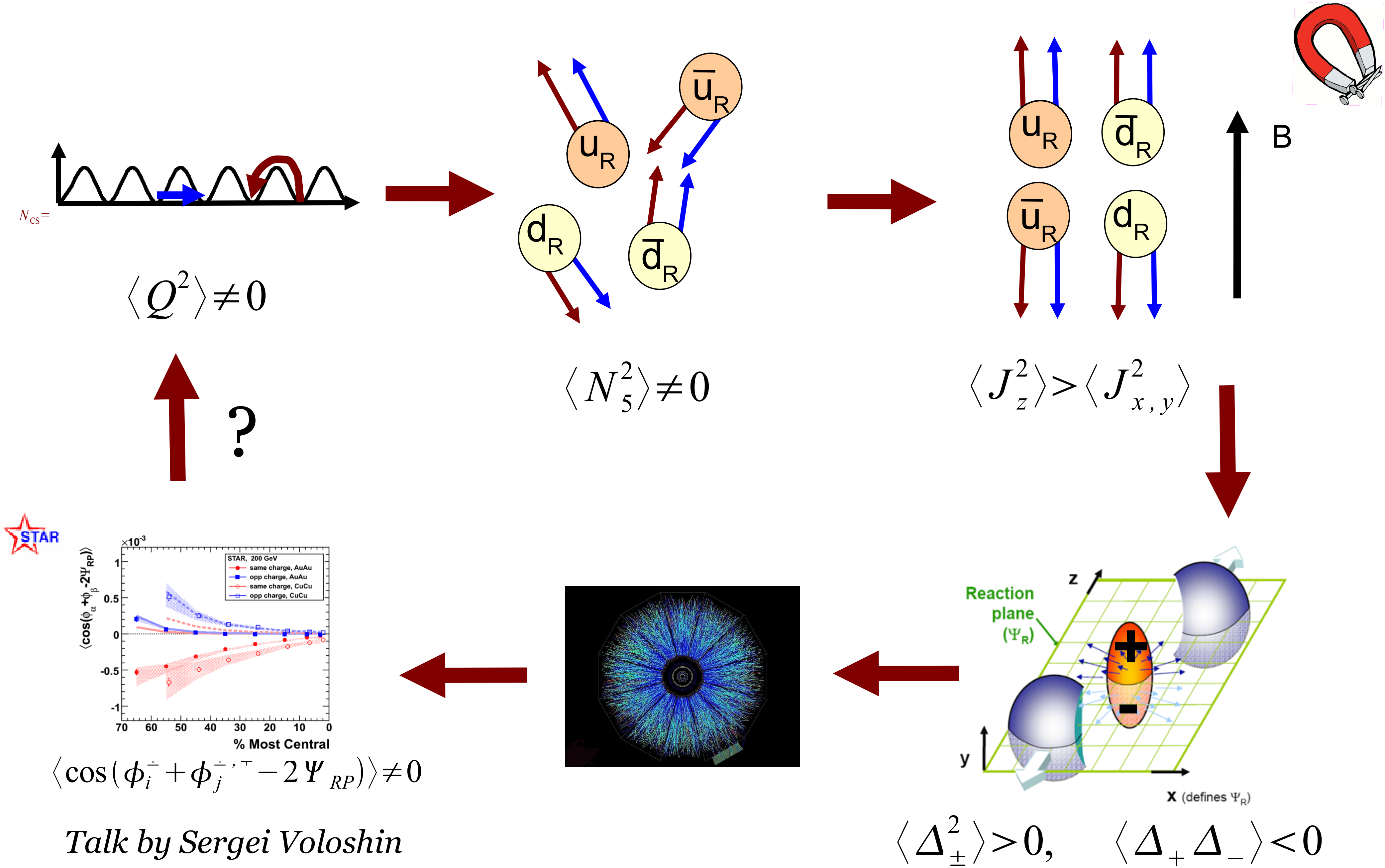
Integral over overlap region

Rate of topological charge generation

Screening functions

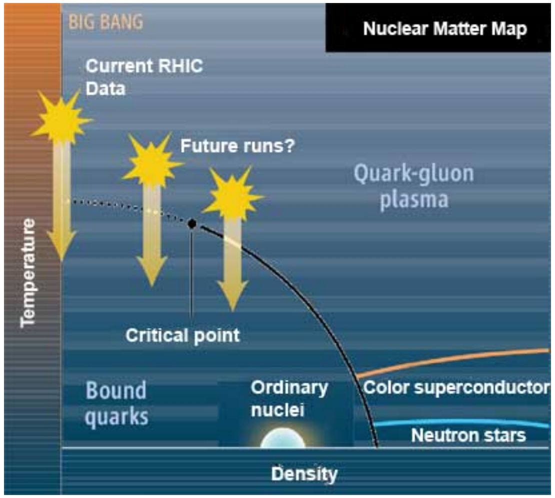
Amount charge separated by unit top. charge

Conclusions: The Chiral Magnetic Effect



STAR data due to Chiral Magnetic Effect?

Required:
Deconfinement: to separate quarks
Chiral Symmetry restoration: 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), ... ???

Topological charge + magnetic field naturally leads to charge separation, which is a P- and CP-odd effect.

It could be an explanation for the charge correlations observed by STAR.

We need more phenomenology and rule out alternative explanations.

Backup slides

Test 1. Magnetic field

Charge separation proportional to polarization quarks.

For small fields polarization is proportional to magnetic field.

Magnetic field is proportional to Z (charge nuclei).

Observables are a correlation between two particles,
Should scale with Z^2.

Compare Nuclei with same A but different Z (isobars)
(change only magnetic field)

Most suitable (high natural abundance, stable, large Z difference, QGP):

Argon-40 Z=18 natural abundance 99.6%
Calcium-40 Z=20 natural abundance 96.9%

Expected increase in signal: (20/18)^2 -1 = 23%

Test 2. Magnetic field

Since up quarks have charge 2/3 and down quarks 1/3,
Degree of polarization up quarks should be twice as high.

More separation of up anti-up than down anti-down pairs.

Absolute $\Delta^{++}(\mathrm{u\,u\,u})$ correlations at least 4 times larger than $\Delta^{-}(\mathrm{d\,d\,d})$ correlations.

Possible critism:
- Probability that delta's get charge correlations is negligible.
- Maybe difficult to measure
- Other possible correlations more suitable

Test 3. Baryon separation

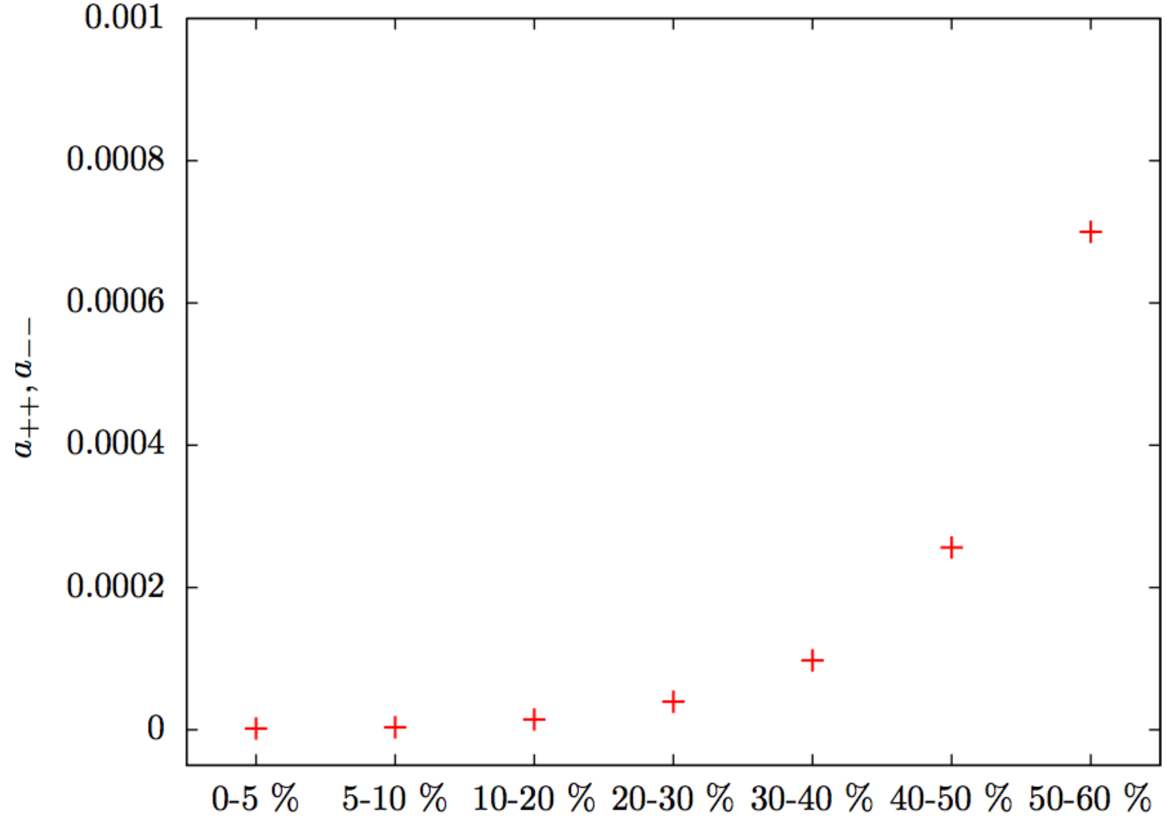
Next to charge separation: separation of baryon number and strangeness.

$$\frac{J_B}{J_Q} = \frac{\sum_f \frac{1}{3} q_f}{\sum_f q_f^2} = \begin{cases} 0 & \text{if } m_s = 0 \\ \frac{1}{5} & \text{if } m_s = \infty \end{cases}$$

Expected: at least 25 times stronger signal in <u>absolute</u> total charge correlations than in absolute total baryon number correlations.

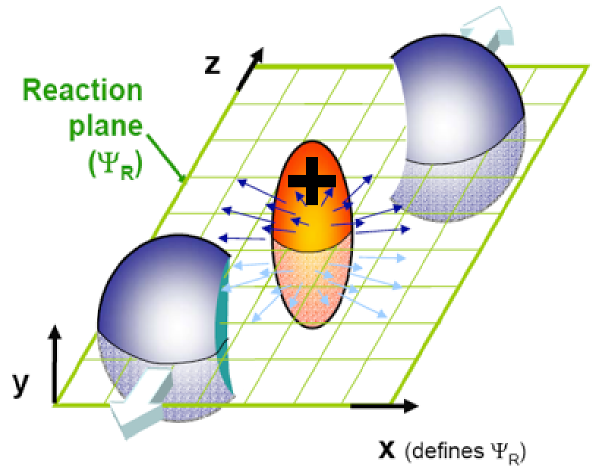
Test 4. Centrality dependence

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



Most Central % Centrality Most peripheral

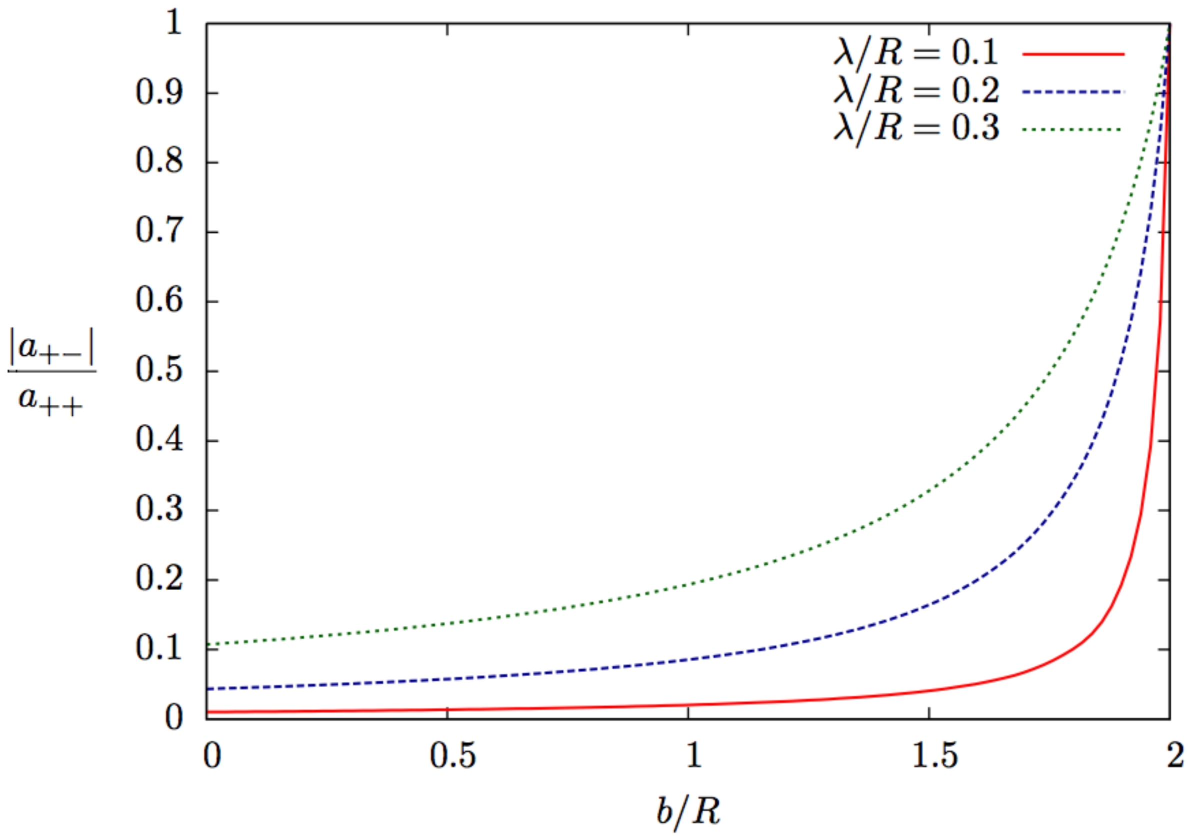
Preferential emission of positively charged particles around $\phi = 3\pi/2$ or $\phi = 3\pi/2$



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

Better predictions would be nice.

Test 5. Suppression of +/- correlations



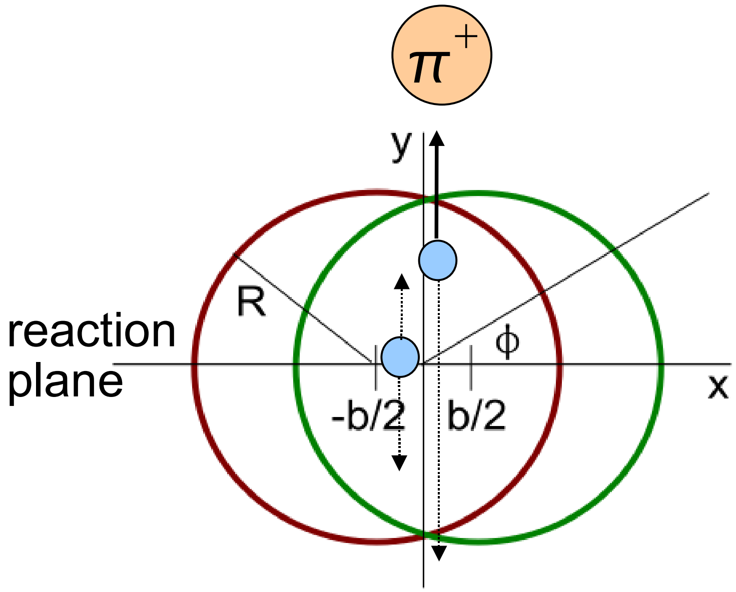
Suppression of correlations

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



Other possible tests

- Beam energy dependence.

- Nuclear mass (A) dependence.

- Rapidity and Pt dependence.

- K+/pi- and other combinations

We have to more calculations. Beam and nuclear mass dependence determined hugely by magnetic field and screening.

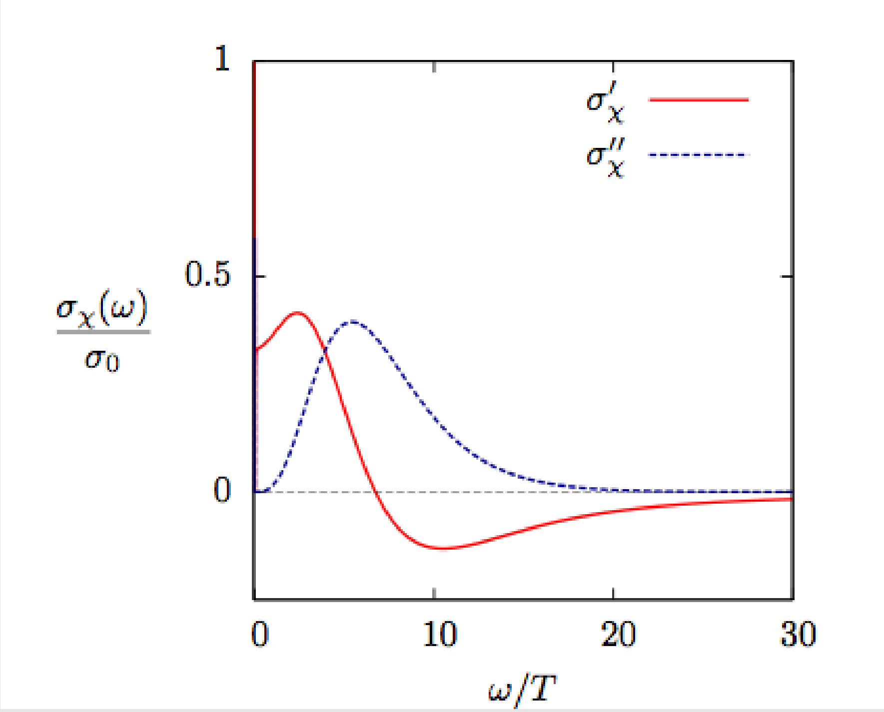
Would expect lower relative asymmetry at LHC but important to quantify this.

At low energies no QGP we expect no asymmetry. QGP is necessary.

CM conductivity: weak vs. strong coupling

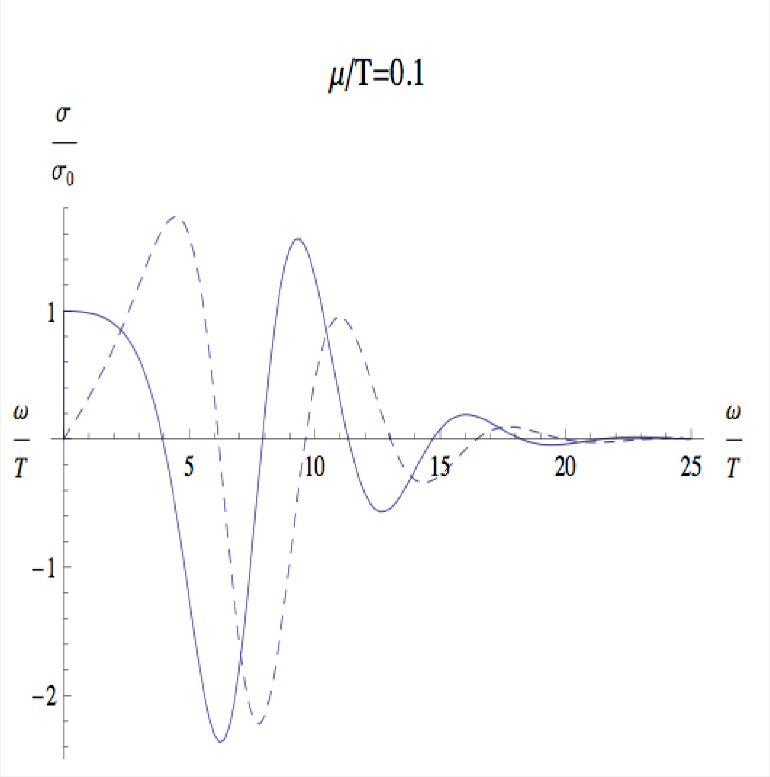
CM conductivity: $\sigma_\chi(\omega) = \lim_{p^i \to 0} \frac{1}{2i\,p^i} \epsilon^{ijk} \tilde{\Pi}_R^{jk}(\omega, p)$

Weak coupling
(1 loop pert. QCD)



Kharzeev and HJW ('09)

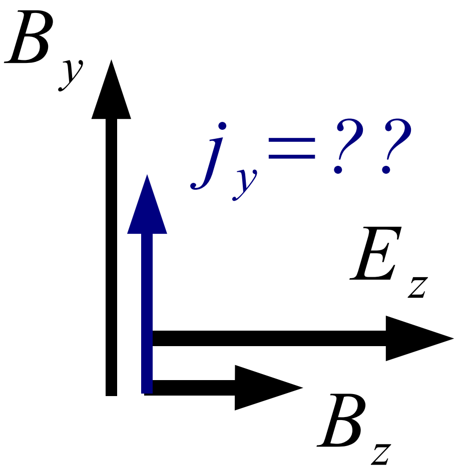
Strong coupling
(holographic model of QCD)



Ho-Ung Yee ('09)

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

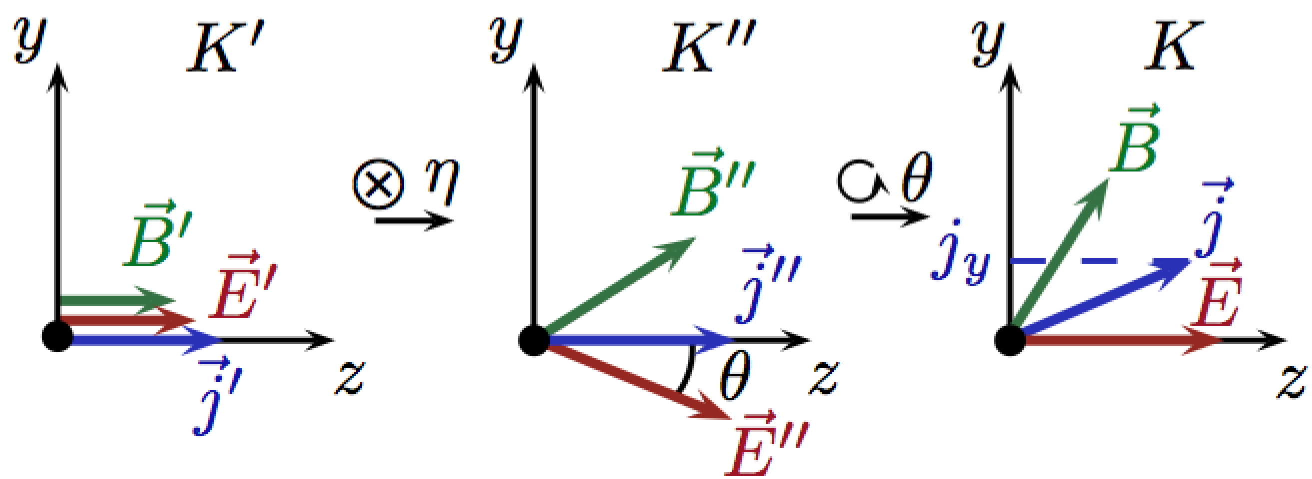
Chiral Magnetic Effect in Color Flux Tube



$$q\,E_z = \pm\tfrac{1}{2}\,g\,\mathcal{E}_z$$

$$q\,B_z = \pm\tfrac{1}{2}\,g\,\mathcal{B}_z$$

Solve Dirac equation.



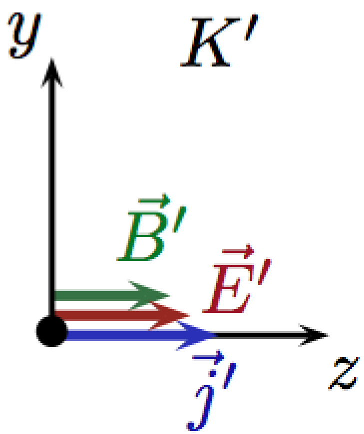
1. Start from frame K', E and B parallel

2. Lorentz boost with rapidity eta in x-dir.

3. Rotation angle theta around x-axis.

Fukushima, Kharzeev and HJW, arXiv:1002.2495

Chiral Magnetic Effect in Color Flux Tube



In K' particle-anti particle pairs are produced by Schwinger process (Schwinger '51)

Rate per unit volume = (n=1 term in imaginary part effective Lagrangian)

$$\Gamma = \frac{q^2 E_z' B_z'}{4\pi^2} \coth\left(\pi \frac{B_z'}{E_z'}\right) \exp\left(-\frac{m^2 \pi}{|q E_z'|}\right)$$

Nikhishov ('69)
Bunkin and Tugov ('70)

Induced current density: each pair contributes two units

$$\partial_{t'} \vec{j}\,' = 2 q \,\mathrm{sgn}(q E_z') \,\Gamma\, \boldsymbol{e}_z$$

Numerically: Tanji ('09)
Also possible to show analytically
(hard work, Gavrilov and Gitman ('08))

Chirality: Large B', small E' limit of rate

$$\partial_t n_5 = \frac{q^2 E_z' B_z'}{2\pi^2} \exp\left(-\frac{m^2 \pi}{|q E_z'|}\right)$$

$$m = 0 \quad \partial_\mu J_5^\mu = -\frac{e^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Fukushima, Kharzeev and HJW, arXiv:1002.2495

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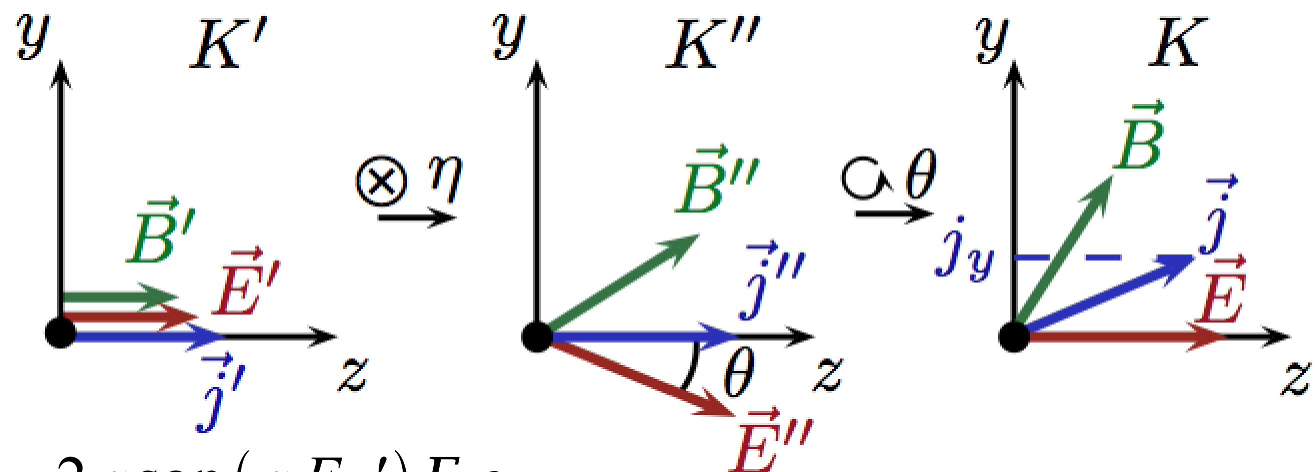
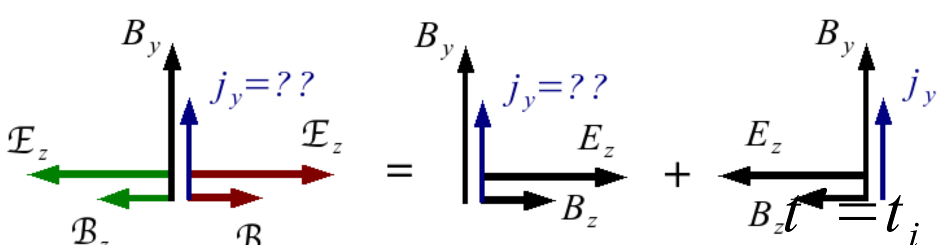


In K' $\partial_{t'} \vec{j}\,' = 2q\,\mathrm{sgn}(qE_z')\,\Gamma\,\boldsymbol{e}_z$

In K $\partial_t j_y = 2q\,\mathrm{sgn}(qE_z')\,\Gamma\cosh(\eta)\sin(\theta)$

Compute boost and rotation angle in terms of Ez, Bz and By

Express in terms of color fields.



$$qE_z = \pm\frac{1}{2}g\,\mathcal{E}_z$$

$$qB_z = \pm\frac{1}{2}g\,\mathcal{B}_z$$

$t = t_i$

Note: homogeneous switch-on in frame K'
becomes inhomogeneous in K

$$t' = t'_i$$

$$t = t'_i/\cosh(\eta) - x\tanh(\eta)$$