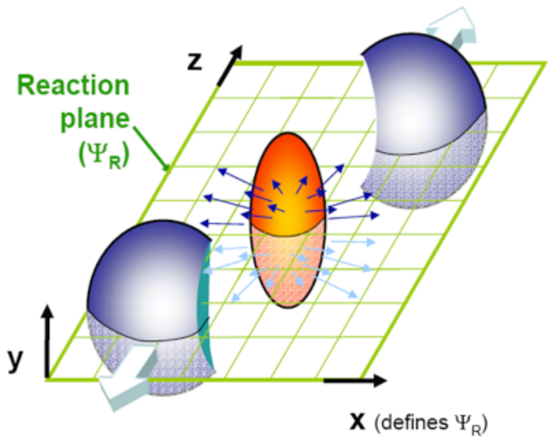
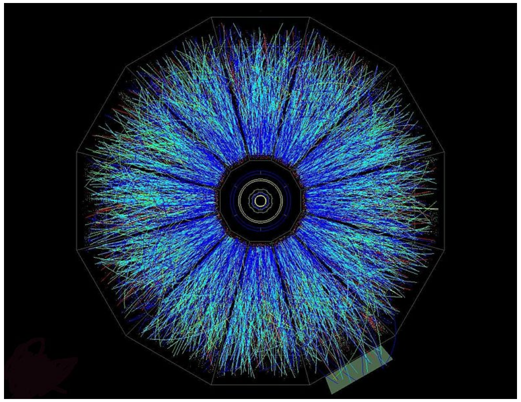
P- and CP-odd effects in hot matter

Harmen Warringa, Goethe Universität, Frankfurt

Collaborators: Kenji Fukushima, Dmitri Kharzeev and Larry McLerran.

Motivation





P- and CP-odd effects
induced by QCD topological charge
might occur in hot matter
produced in heavy ion collisions

How to find evidence
for these effects in data?

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

Outline

I. Magnetic field, topological charge and heavy ion collisions

II. Charge asymmetry

qualitative explanation

III. Quantitative calculation

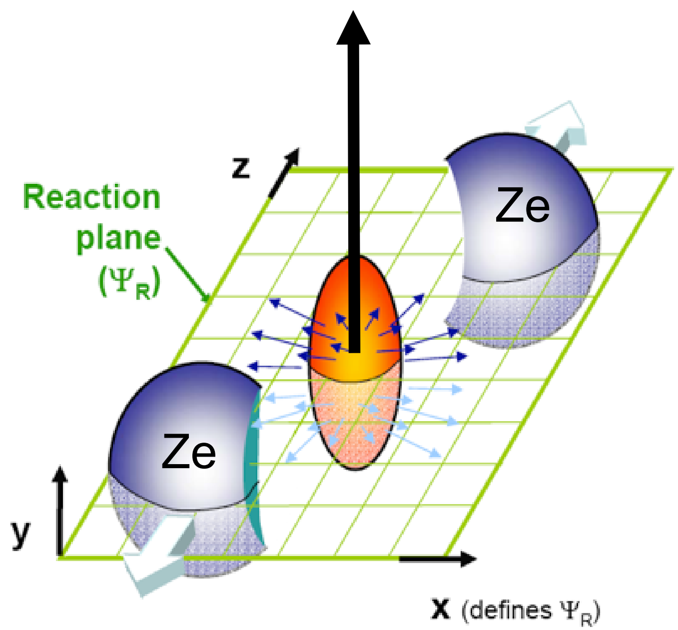
static, dynamic

IV. Investigating with heavy ion collisions

I. Magnetic field, topological charge and heavy ion collisions

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

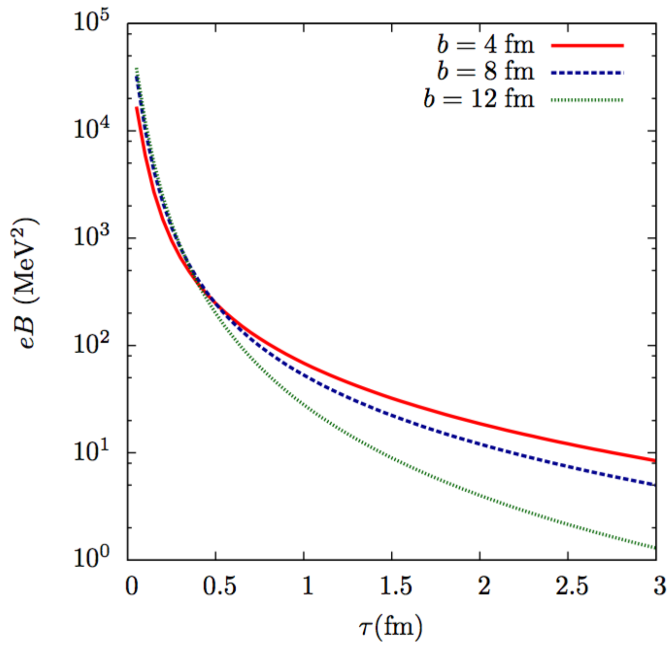
Magnetic field B



$$eB(\tau = 0.2\ \text{fm/c}) \approx$$

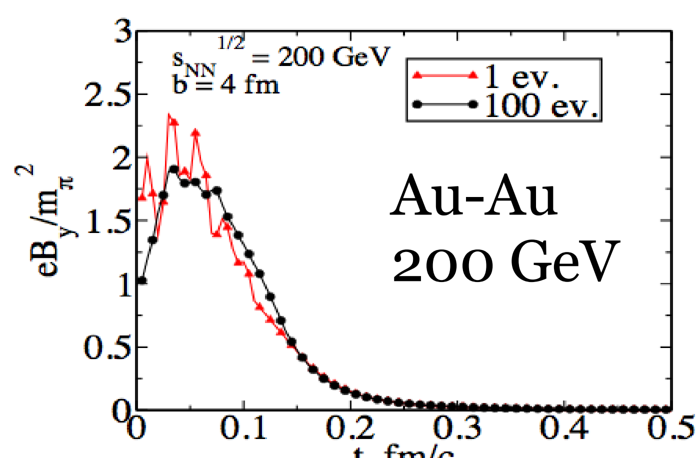
$$10^3 \sim 10^4\, \text{MeV}^2 \approx 10^{18}\, \text{G}$$

Extremely strong, but rapid decay



Pancake approximation Kharzeev, McLerran & HJW ('08)

See also Minakata and Müller ('96)

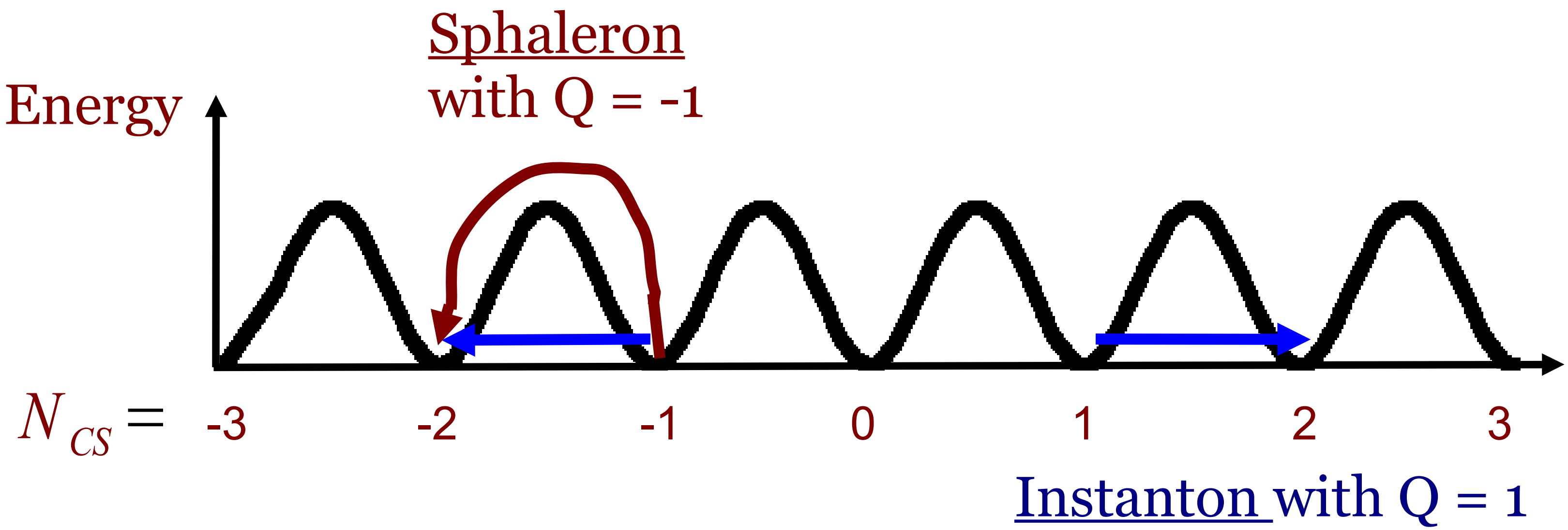


URQMD Skokov, Illarionov, Toneev ('09)

QCD contains topological charge fluctations

Q = topological charge
= change in Chern-Simons number

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



Processes that can have nonzero topological charge:

- Quantum tunneling: Instanton, (Belavin et al. ' t Hooft, ...)
  Caloron, (finite T. instanton) (Gross, Pisarski, & Yaffe, Kraan & Van Baal, ..)
- Thermal activation: Sphaleron, (Klinkhamer & Manton, Kuzmin, Rubakov & Shaposnikov, ...)
- In Glasma: (Kharzeev, Krasnitz & Venugopalan, McLerran & Lappi, ...)

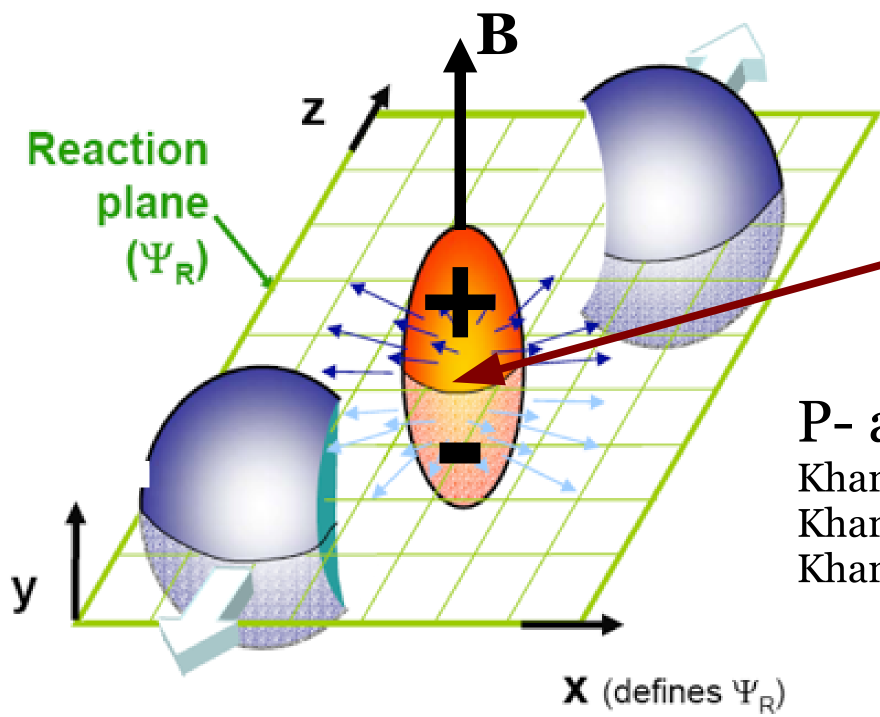
Quantum average vanishes, $\langle Q \rangle = 0$ but fluctuations do not $\langle Q^2 \rangle \neq 0$

I will explain you that the Chiral Magnetic Effect is

Topological charge + Magnetic Field =

$\langle Q \rangle = 0$

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



$Q < 0$

P- and CP-odd effect

Kharzeev ('06),

Kharzeev and Zhitnitsky ('07)

Kharzeev, Mclerran and Warringa ('08)

Charge separation

↓

Fluctuating EDM of QGP

Investigate experimentally by charge correlation study Voloshin ('04)

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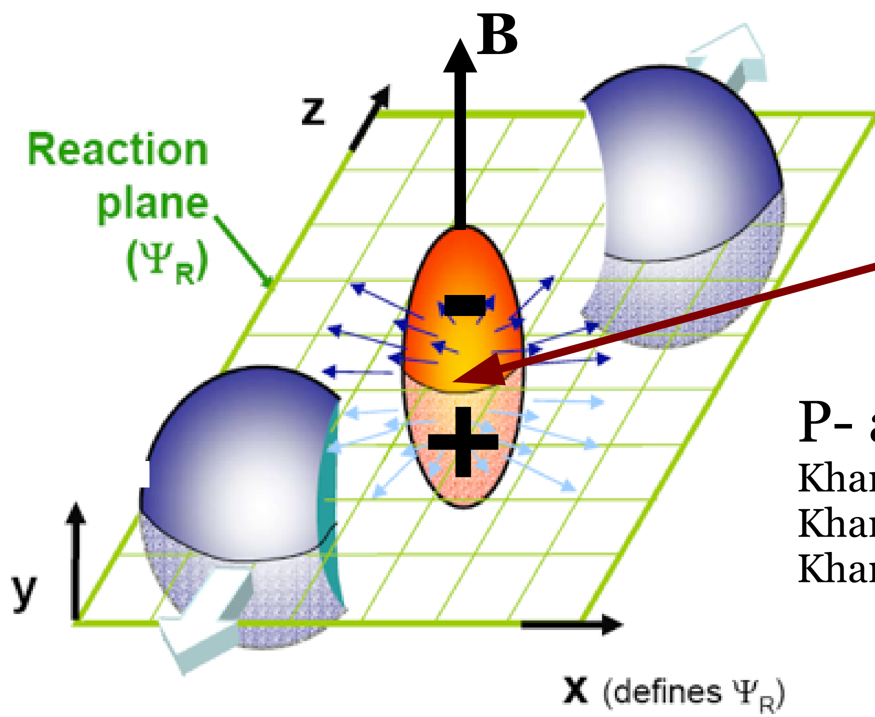

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↓

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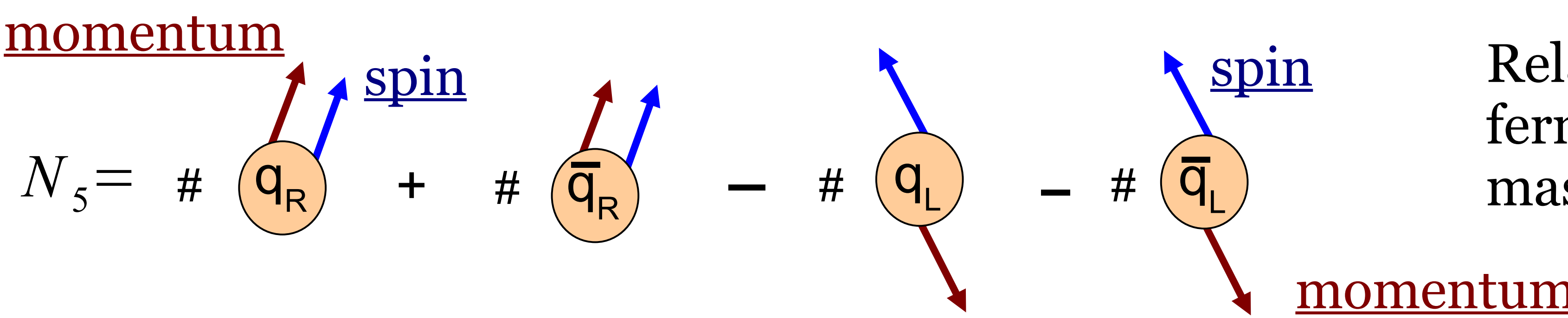
II. A qualitative explanation of charge asymmetries

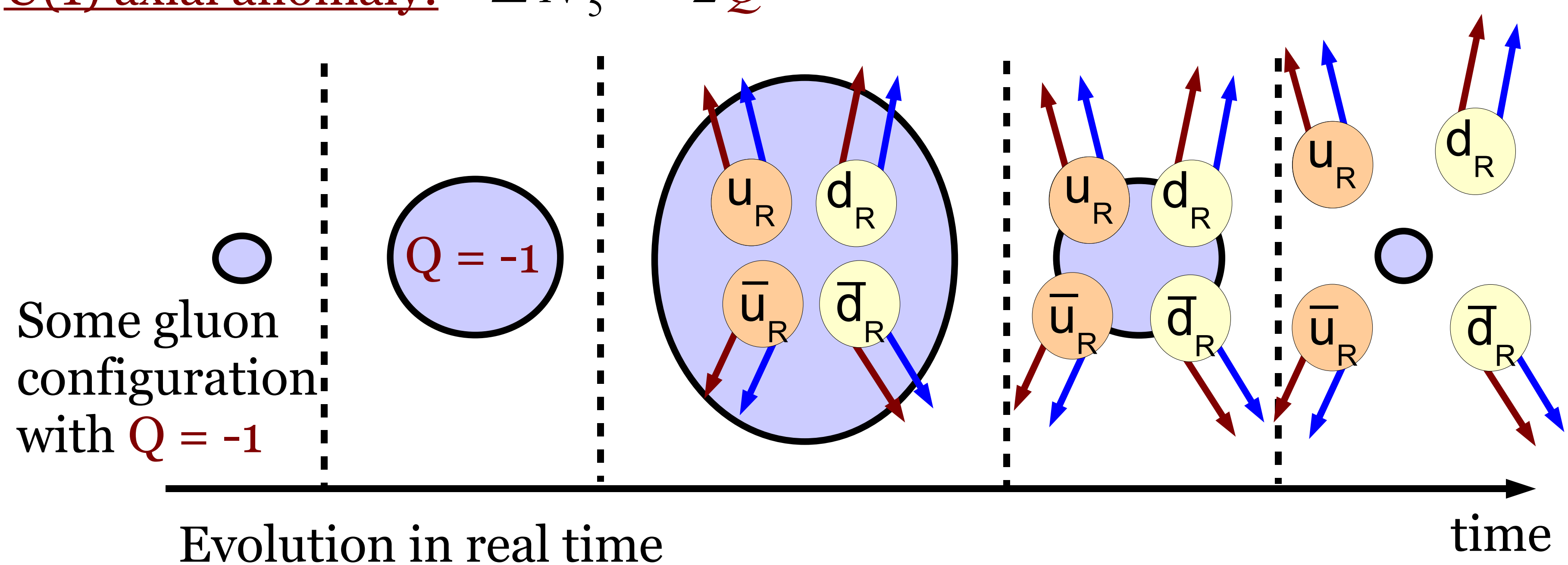
Topological charge Q ➛ P- & CP-odd effects

Chirality: N_5= difference # quarks + antiquarks with R & L-handed helicity



Relativistic fermions mass = 0

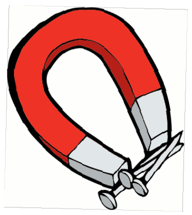
U(1) axial anomaly: $\Delta N_5 = -2Q$

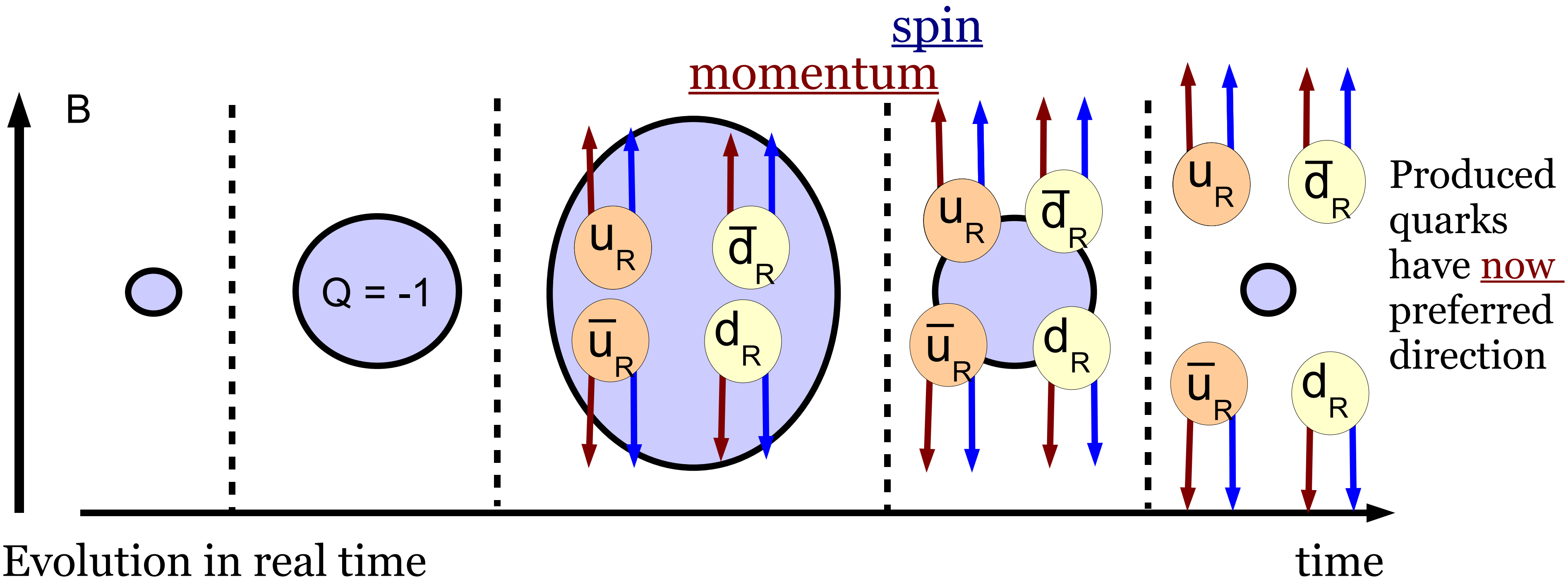


Produced quarks have no preferred direction

Topological Charge + Magnetic field = Chirality + Polarization =

Polarization -> spin aligns along field, direction dep. on el. charge





... = Electromagnetic Current

Kharzeev, McLerran & HJW ('08)

Topological Charge + Magnetic field = Chirality + Polarization =

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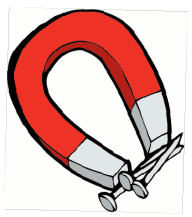
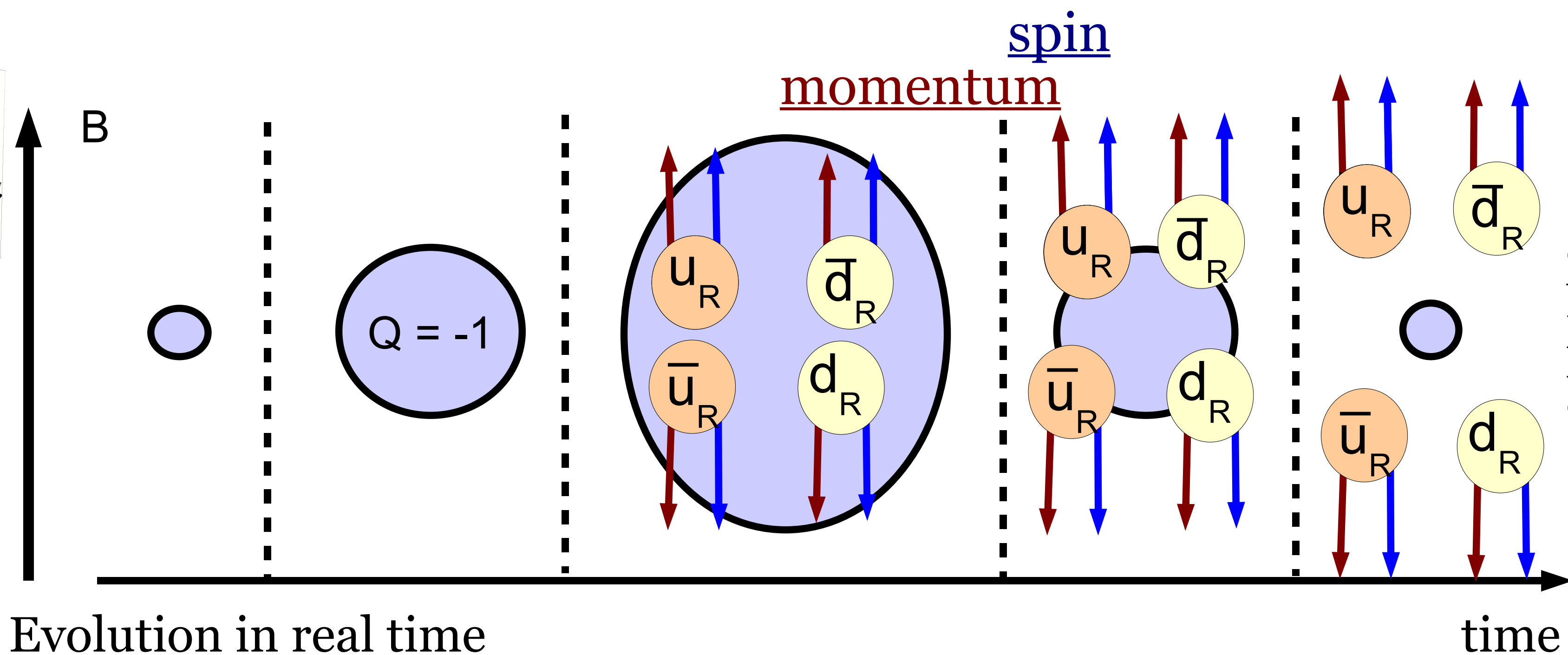




Produced quarks have now preferred direction

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

Valid for full polarization, implies infinitely strong magnetic fields, quantitative calculations required for smaller fields

Kharzeev, McLerran & HJW ('08)

III. Quantative calculations of the Chiral Magnetic Effect

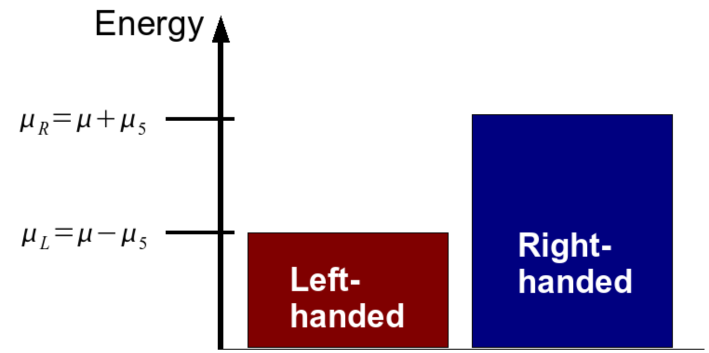
Fukushima, Kharzeev and HJW ('08)

IIIa. Static calculation:

1. Introduce chirality by hand

Using chiral chemical potential μ_5

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



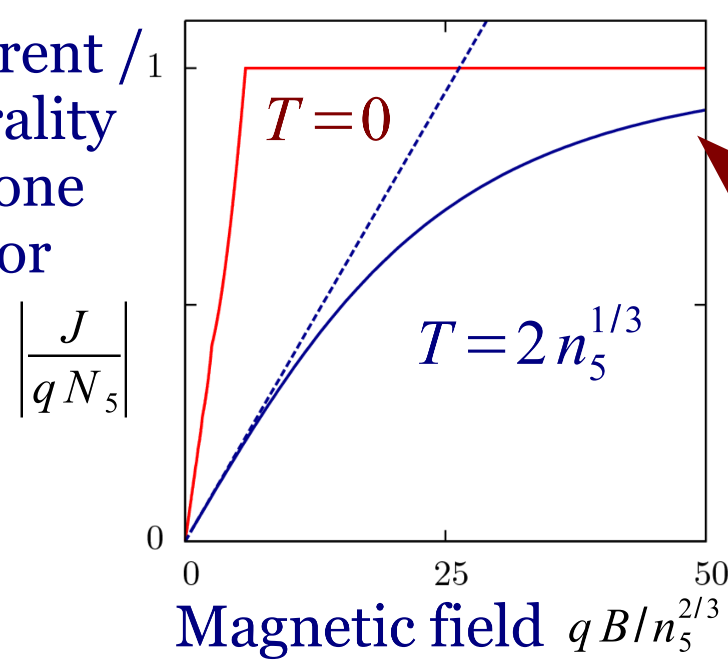
2. Obtain induced EM current in magnetic field

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

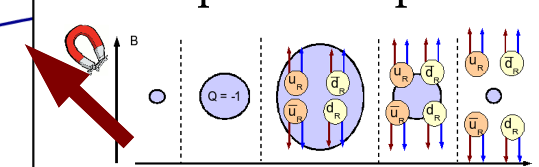
$$\mu_5 = f(T, B, \mu, n_5)$$

(from therm. potential)

Current / chirality for one flavor



Perfect agreement with qualitative picture



Large mag. fields

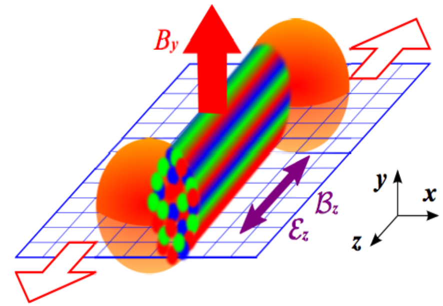
$$J \approx -2Q \sum_f |q_f|$$

Obtained: estimate for small fields $J \approx -\frac{3}{\pi^2} \frac{Q}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$

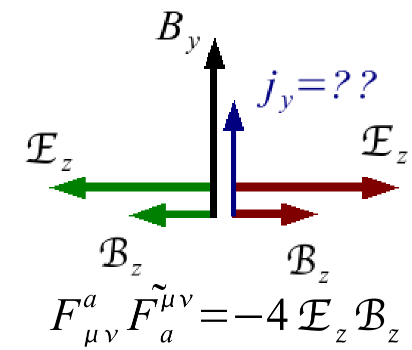
IIIb. Dynamic calculation

Heavy ion collison: Perpendicular EM magnetic field to color flux tubes

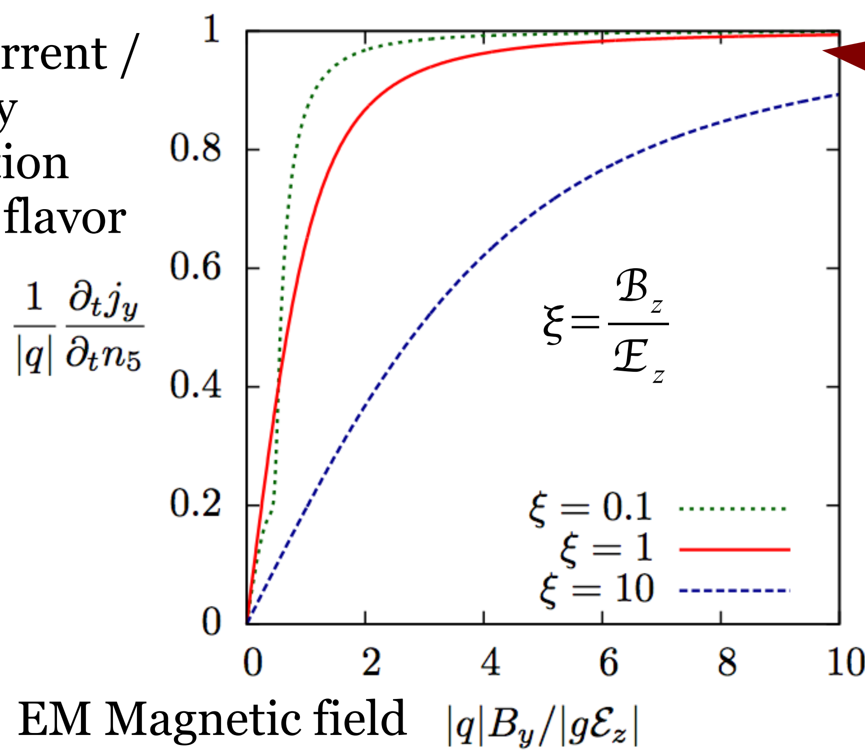
Glasma: Kharzeev, Krasnitz, Venugopalan ('02), Rebhan, Romatschke, Strickland ('05), Lappi & McLerran, ('06), ...



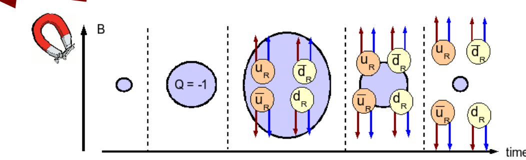
Setup: single tube



Rate current / chirality generation for one flavor



- Completely analytic result for jy



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

Confirmation of CME with dynamic generation of chirality

Charge asymmetry from topology + magnetic field happens in QCD

Confirmation from several theoretical studies

- Static using chiral chemical potential

  with *time-dep. mag field:* Kharzeev & Warringa ('09)

- Dynamic for single flux tube

- Ads/CFT: effect also at strong coupling

Ho-Ung Yee ('09), Rebhan, Schmitt & Stricker ('09), Rubakov ('10),
Gynther, Landsteiner, Pena-Benitez & Rebhan ('10)

- Lattice QCD

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

To compare with experiment need to compute charge fluctuations

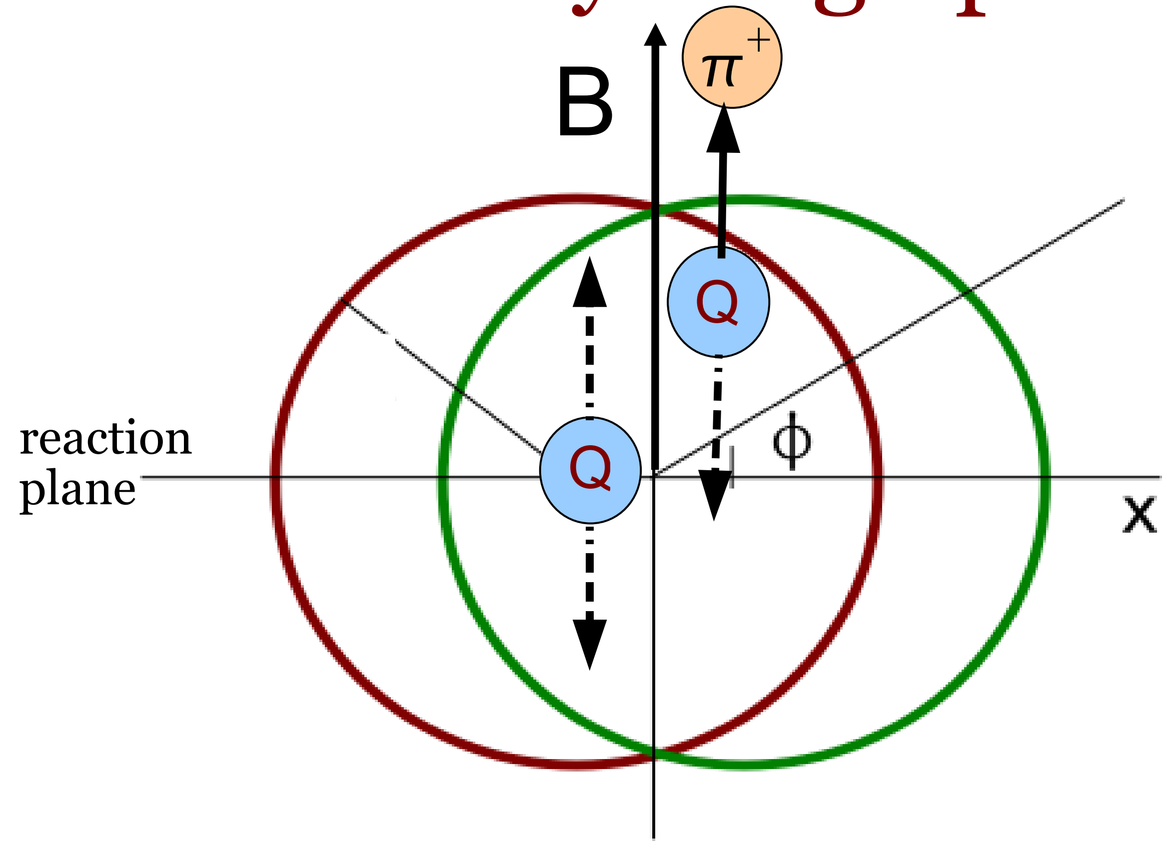
Fukushima, Kharzeev, Warringa ('10), Orlovsky, Shevchenko ('10)

$$J \sim Q\,B \longrightarrow \langle J^2 \rangle \sim \langle Q^2 \rangle B^2 + \text{non topological backgrounds}$$

IV. Investigating Chiral Magnetic Effect with heavy ion collisions

Very rough phenomenology

Kharzeev, McLerran & HJW ('08)



Topological charge Q fluctuates anywhere in the QGP

Measure: variances = nonzero

Medium causes screening

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

$$\langle \Delta_{\pm}^2 \rangle = \frac{2}{N_{\pm}^2} \int_{t_i}^{t_f} \mathrm{d}t \int_V \mathrm{d}^3 x \ \frac{\langle Q^2 \rangle}{V_4} \ [\xi_+^2(x_\perp) + \xi_-^2(x_\perp)] \ \left(\sum_f \frac{3 q_f^2 e B}{\pi^2 T^2} \right)^2$$

Integral over overlap region	Topological charge fluctuations	Screening functions	Amount charge separated by unit top. charge

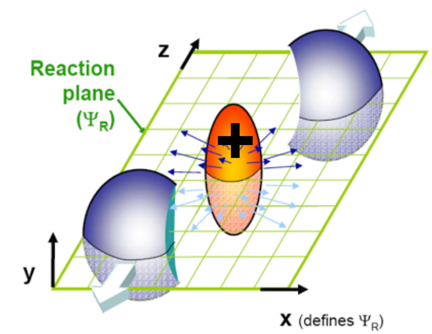
Very rough estimate at large impact parameters with order of mag. uncertanties

$$\langle \Delta_{\pm}^2 \rangle \sim 10^{-4}$$

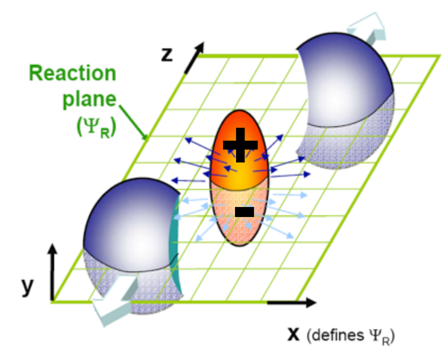
Charge correlations at RHIC

Interpretation:

Red points:

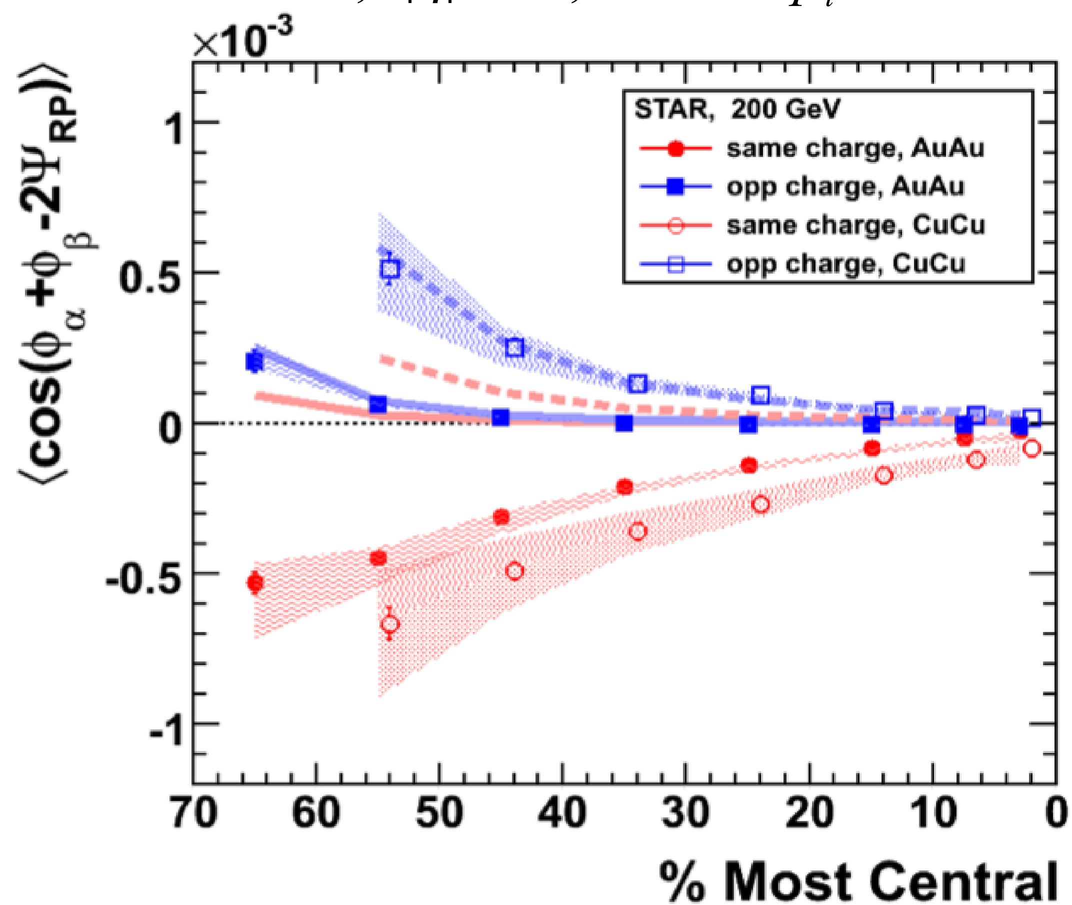


Blue points:



Au-Au and Cu-Cu @ 200 GeV

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



Data cannot be explained by

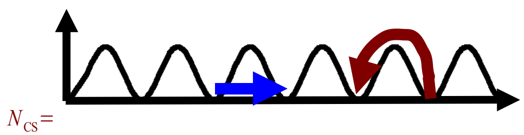
HIJING
HIJING+v2,
MeVSIM,
UrQMD

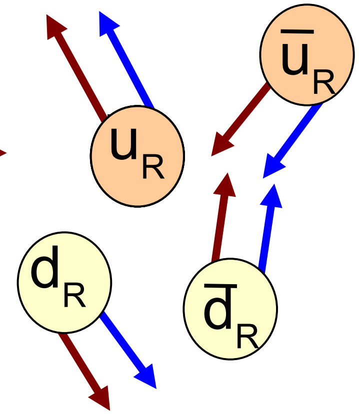
STAR, Phys.Rev.Lett. **103**, 251601 (2009) and arXiv:0909.1717

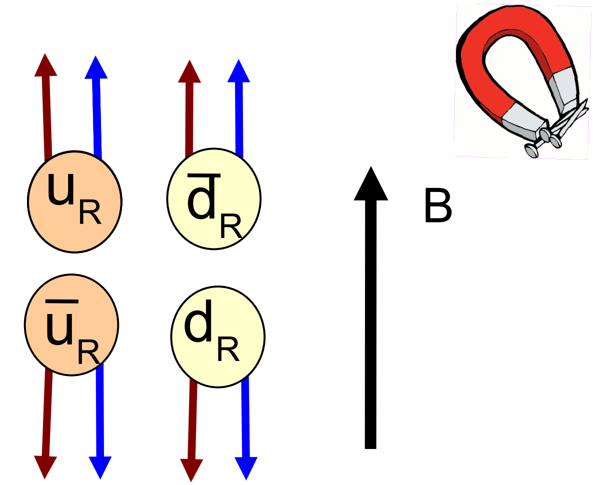
Puzzles:

- Backgrounds, Voloshin ('04), Asakawa, Majumdar & Mueller ('10)
- Interpretation of data, F. Wang ('09), Bzdak, Koch & Liao ('10)

Conclusions:





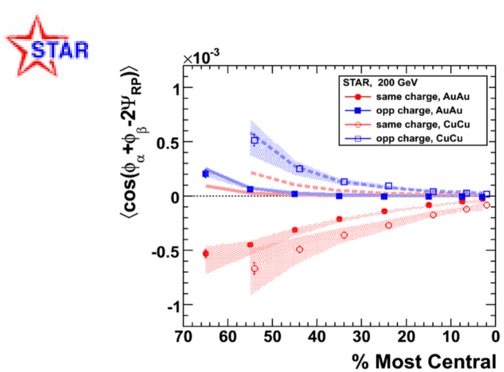


$\langle Q^2 \rangle \neq 0$

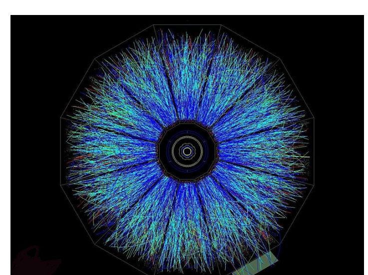
$\langle N_5^2 \rangle \neq 0$

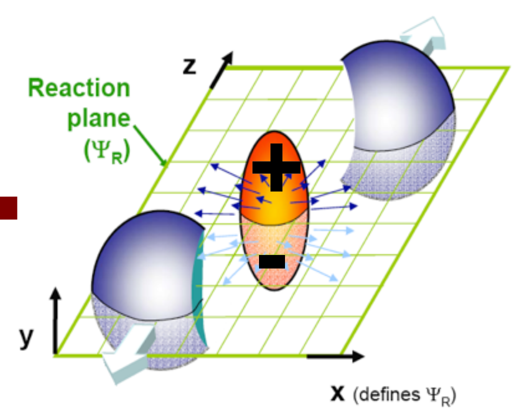
$\langle J_z^2 \rangle > \langle J_{x,y}^2 \rangle$

?



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





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

Topological charge + magnetic field naturally leads to charge asymmetry,

Chiral Magnetic Effect: Lot's of theoretical evidence

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

Data clean, but puzzles with interpretation

We need to make predictions for energy, nucleus, etc. dependence

Understand backgrounds and confront with data

Established obervation learns us about topology, chiral symmetry and confinement

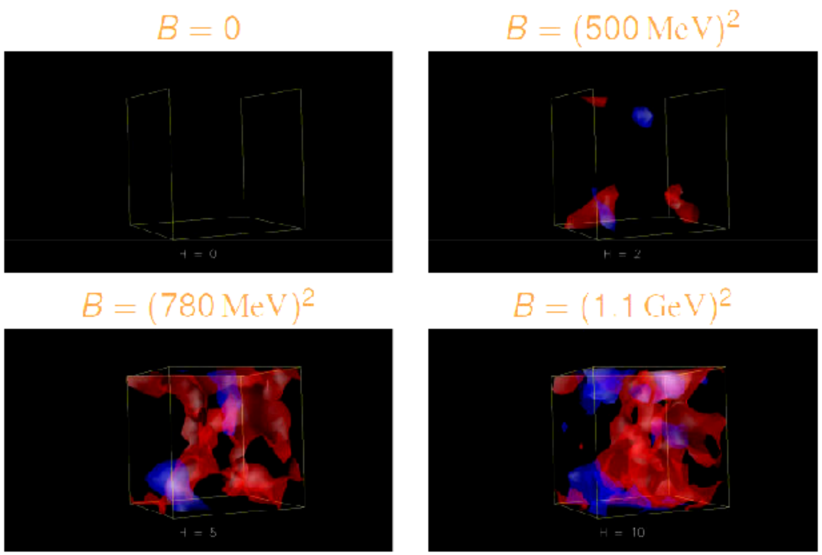
Talks CP-odd workshop: http://quark.phy.bnl.gov/~kharzeev/cpodd

Backup slides

Charge asymmetry from topology + magnetic field happens in QCD

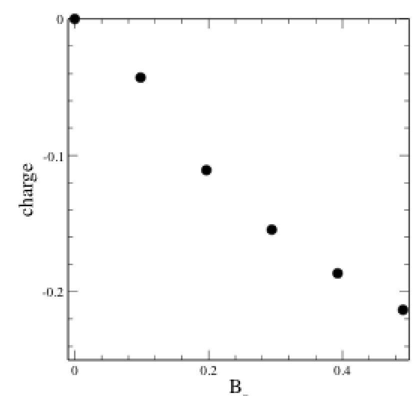
Confirmation from Lattice QCD

Density of the electric charge vs. magnetic field,
3D time slices



Buividovich, Chernodub,
Luschevskaya & Polikarpov ('09)

Classical instanton (-like solution) Put it all together.
It works...



Charge in top (z-)half of lattice from near-zero-modes.
Dividing in x, y, or t gives zero, effect flips sign under $B_z \to -B_z$

Abramczyk, Blum, Petropoulos, Zhou ('09)

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

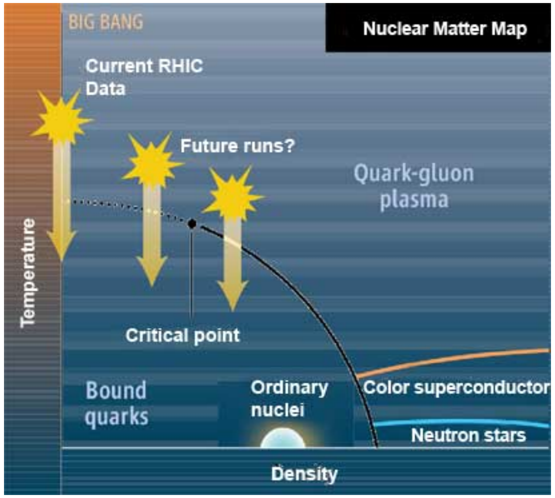
Result follows from EM axial anomaly. Exact and independent of coupling strength.

Confirmation from AdS/CFT (strong coupling):

Ho-Ung Yee ('09), Rebhan, Schmitt & Stricker ('09),
Rubakov ('10), Gynther, Landsteiner, Pena-Benitez & Rebhan ('10)

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

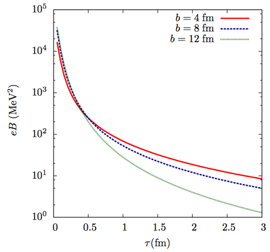
More quantitative phenomenology really necessary
More data also possible: individual charged particle correlations

Think of other explanations

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

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

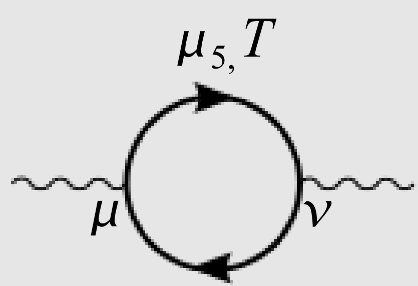
$\vec{j} = \sigma_\chi \vec{B}$ $\quad \sigma_\chi(\omega) =$ chiral magnetic conductivity

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

Leading order
pert. QCD

Kharzeev and HJW ('09)

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



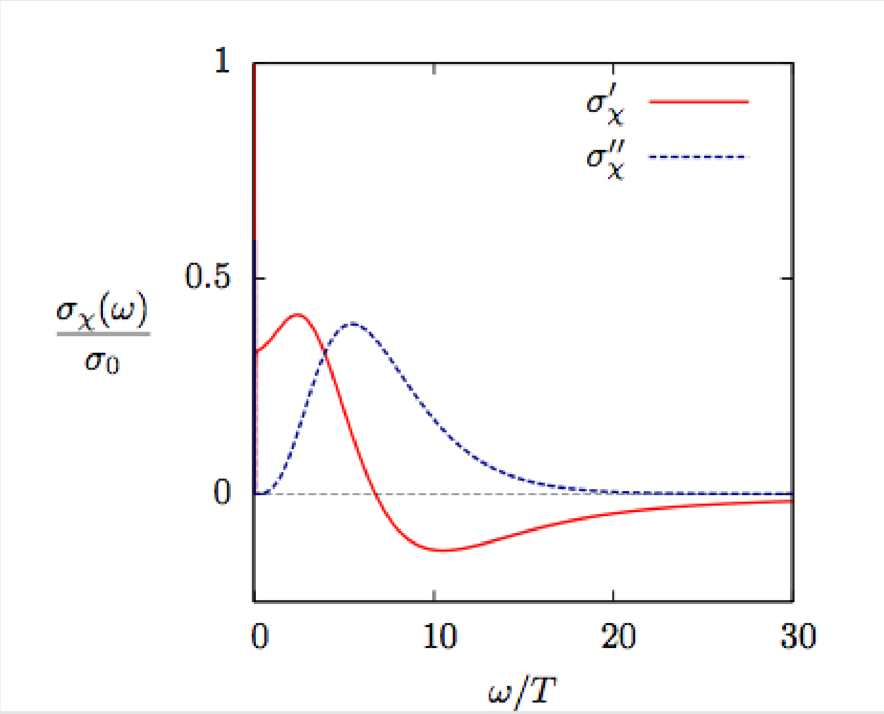
$\tilde{\Pi}_R^{jk}$

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

CM conductivity: weak vs. strong coupling

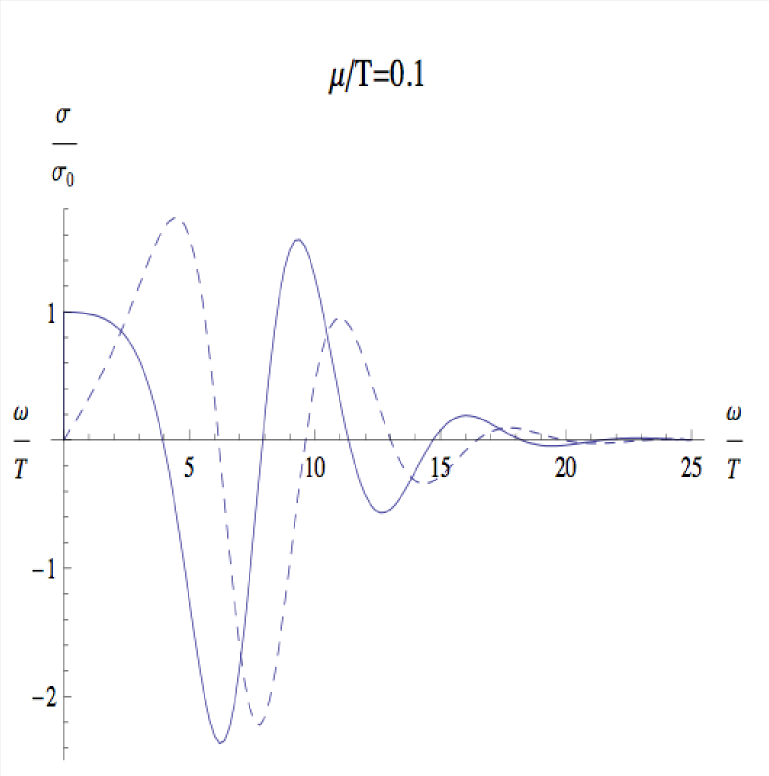
CM conductivity: $\sigma_\chi(\omega) = \lim_{p^i \to 0} \frac{1}{2i\, p^i} \epsilon^{ijk} \tilde{\Pi}_R^{jk}(\omega, p)$

Weak coupling
(1 loop pert. QCD)



Kharzeev and HJW ('09)

Strong coupling
(holographic model of QCD)



Ho-Ung Yee ('09)

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

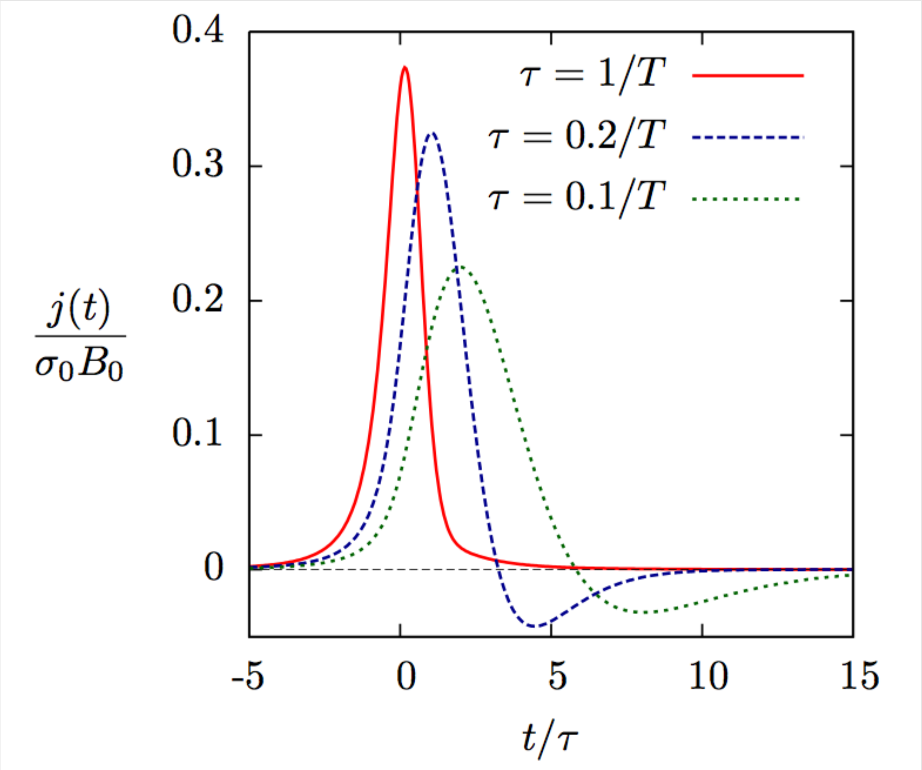
Static chirality + time-dep. field

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

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

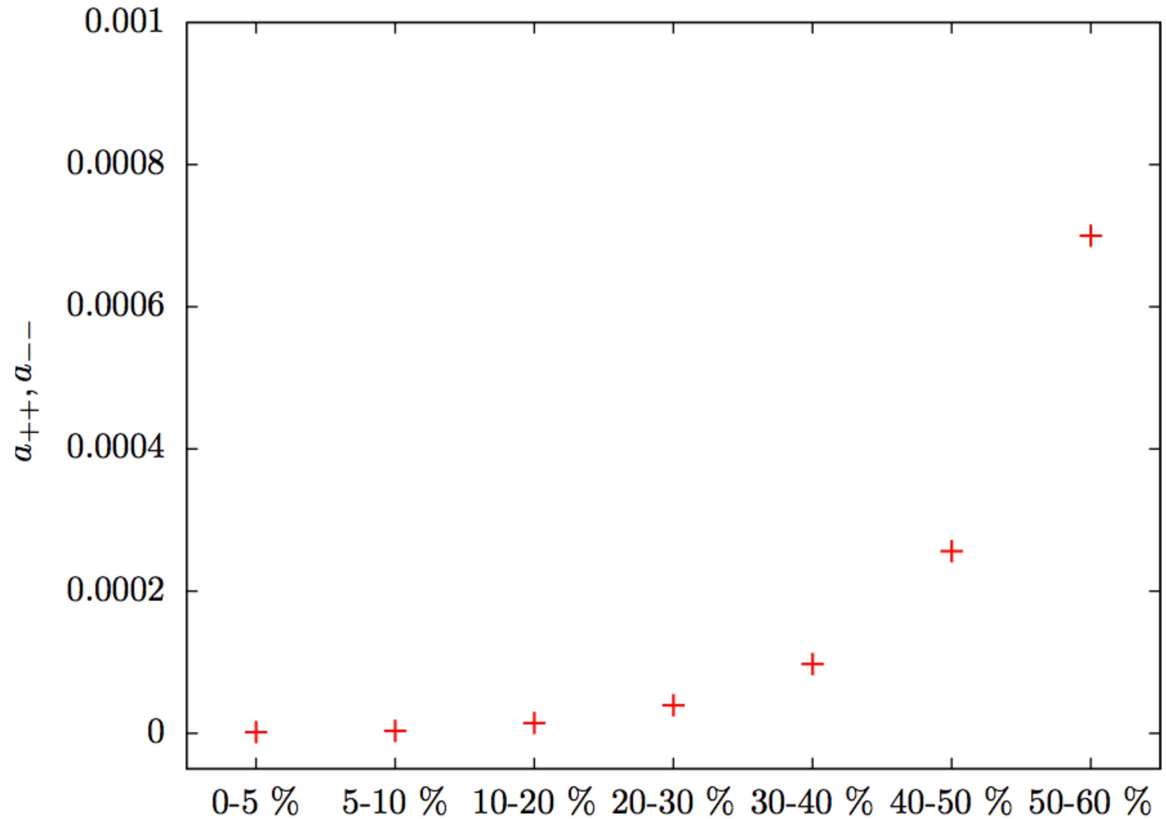
Next to charge separation: separation of baryon number
and strangeness.

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

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

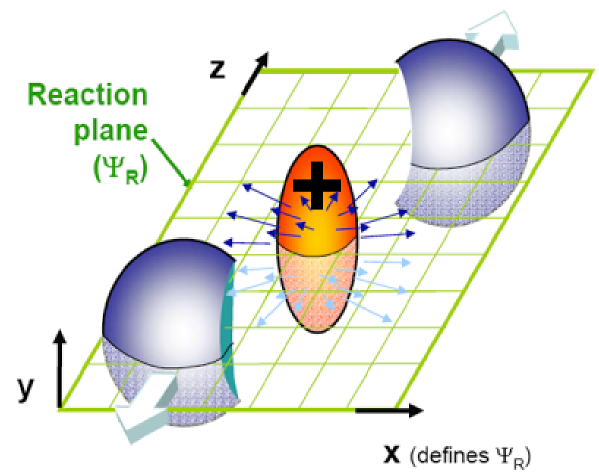
Test 4. Centrality dependence

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



Most Central % Centrality Most peripheral

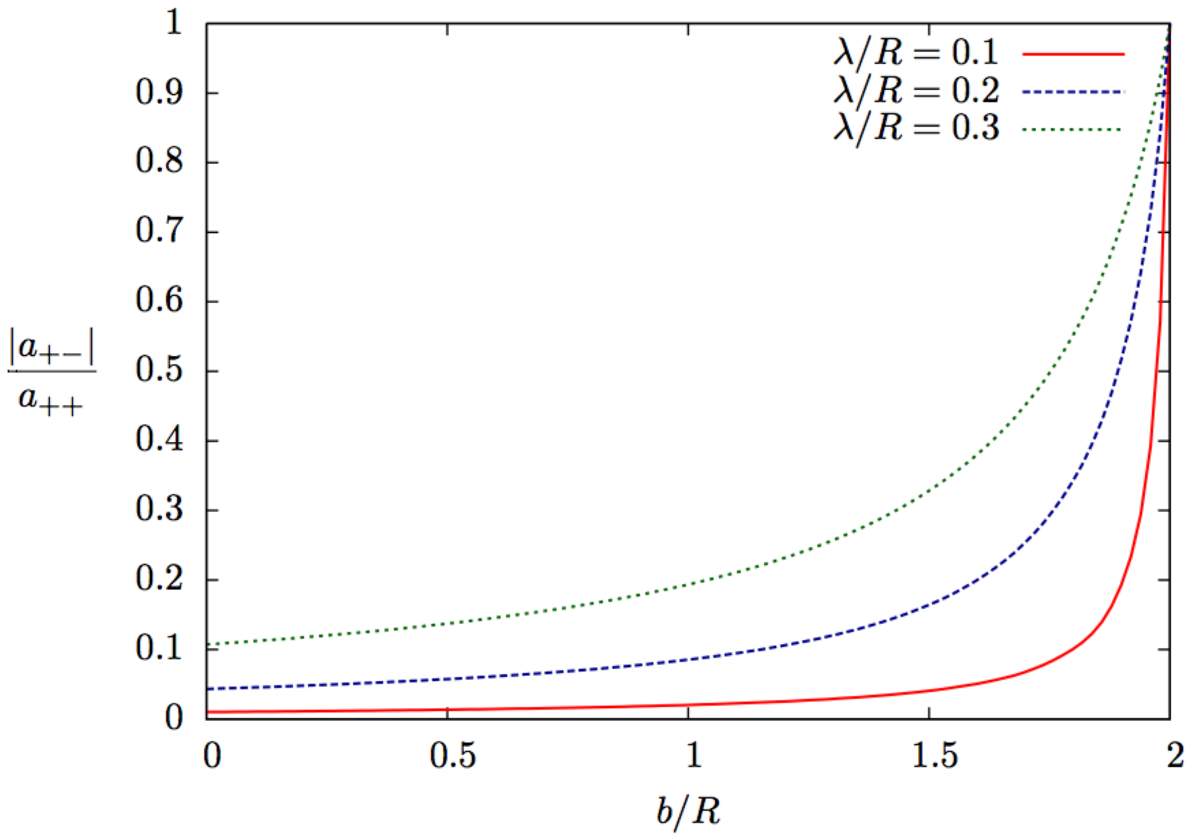
Preferential emission of positively charged particles around $\phi = 3\pi/2$ or $\phi = 3\pi/2$



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



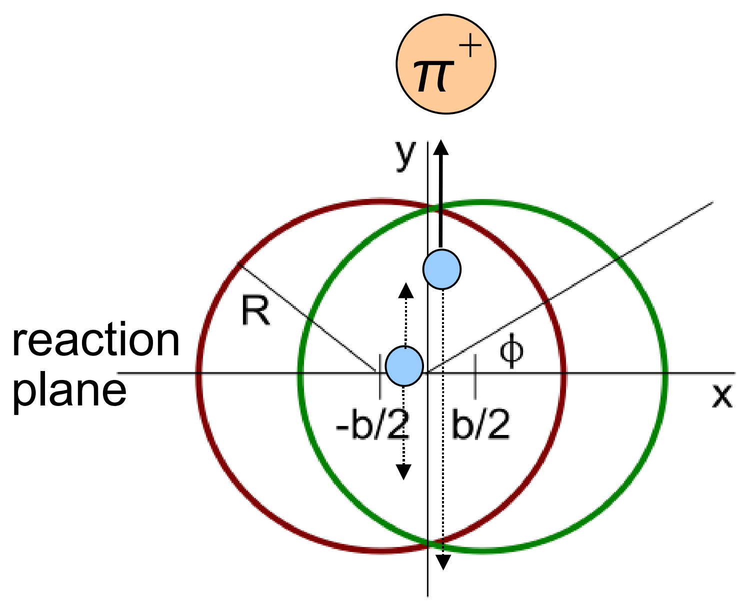
Suppression of correlations

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

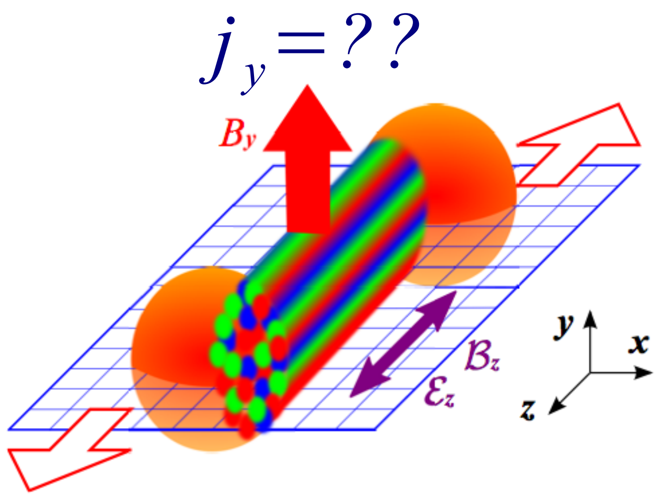
We have to more calculations. Beam and nuclear mass dependence determined hugely by magnetic field and screening.

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

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

Setup: Color Flux Tube

Heavy ion collison: Perpendicular magnetic field to color flux tube



Setup: Homogeneous color flux tube + EM mag field.

Goal: Current in y-direction
Verify Chiral Magnetic effect

- We choose Abelianized flux-tube:

$$A_a^\mu = \mathcal{A}_a^\mu n_a \qquad n_{a=3} = 1,\ n_{a\neq 3} = 0$$

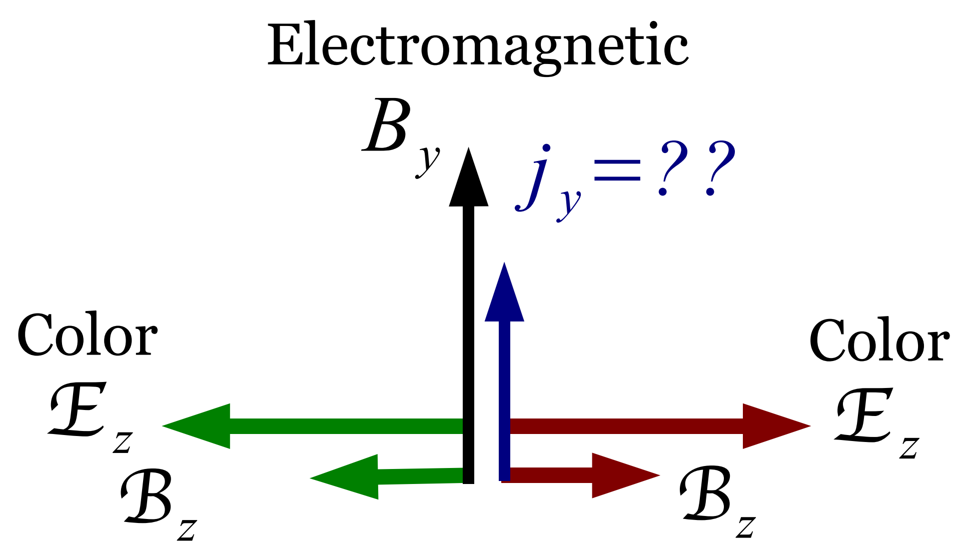
$$F_a^{\mu\nu} = \mathcal{F}^{\mu\nu} n_a$$

- Covariant derivative contains:

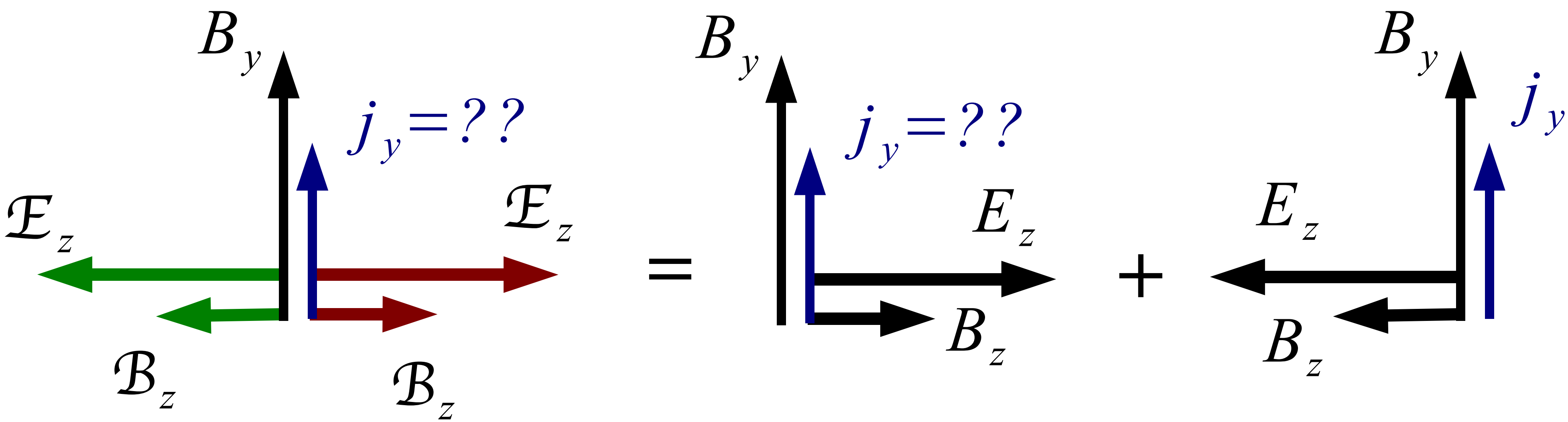
$$g\, A_\mu^a t^a - q\, A_\mu =$$

$$\mathrm{diag}\left(\tfrac{1}{2} g\, A_\mu^{a=3} - q\, A_\mu,\ -\tfrac{1}{2} g\, A_\mu^{a=3} - q\, A_\mu,\ -q\, A_\mu\right)$$

Red Green Blue quarks



Chiral Magnetic Effect in Color Flux Tube

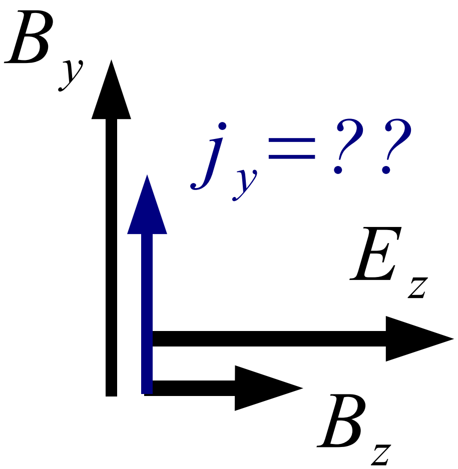


QCD problem = 2 x QED problem with

$q\,E_z = \pm\frac{1}{2}\,g\,\mathcal{E}_z \qquad q\,B_z = \pm\frac{1}{2}\,g\,\mathcal{B}_z$

$q\,B_y = q\,B_y$

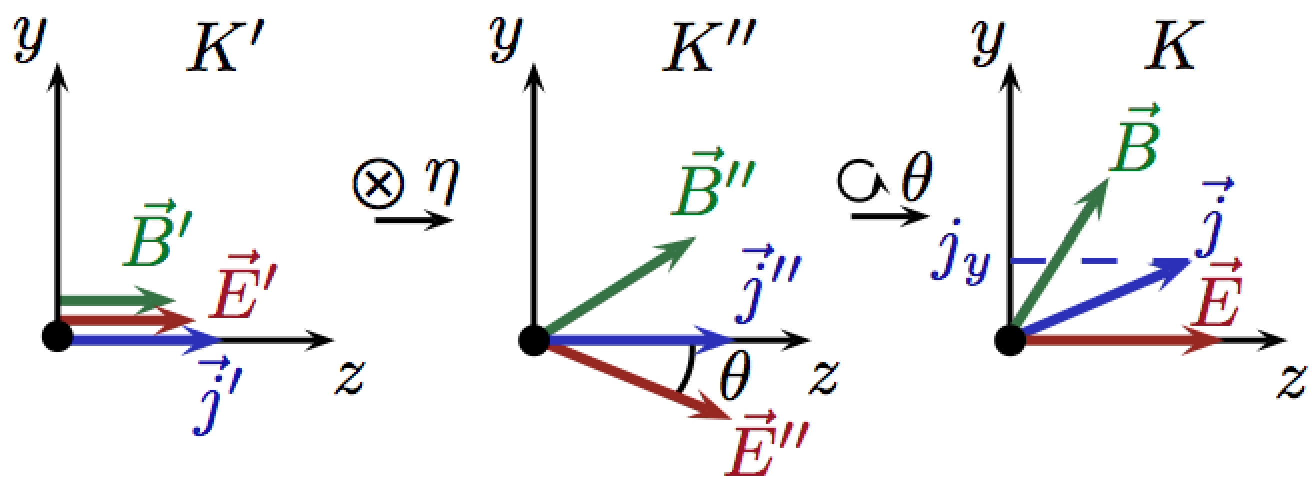
Chiral Magnetic Effect in Color Flux Tube



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

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

Solve Dirac equation.

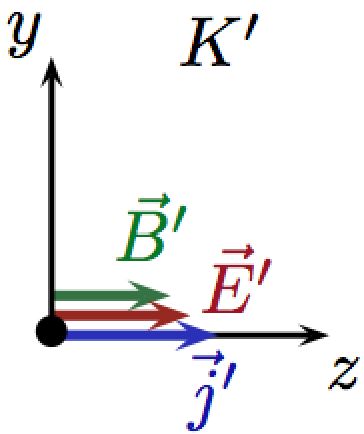


1. Start from frame K', E and B parallel

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

3. Rotation angle theta around x-axis.

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)

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

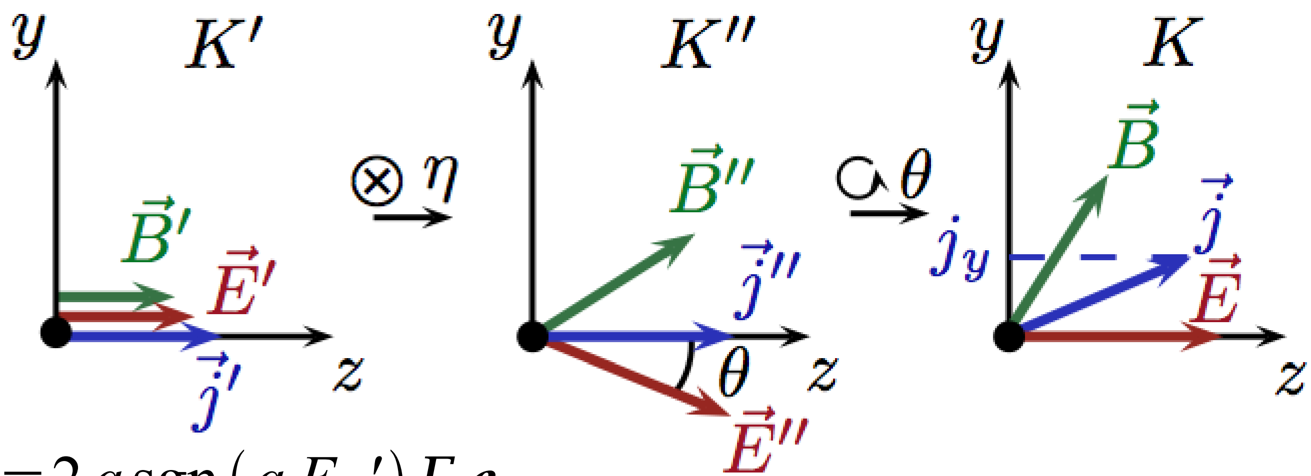
Nikhishov ('69)
Bunkin and Tugov ('70)

- 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
Gavrilov and Gitman ('08)

Chiral Magnetic Effect in Color Flux Tube

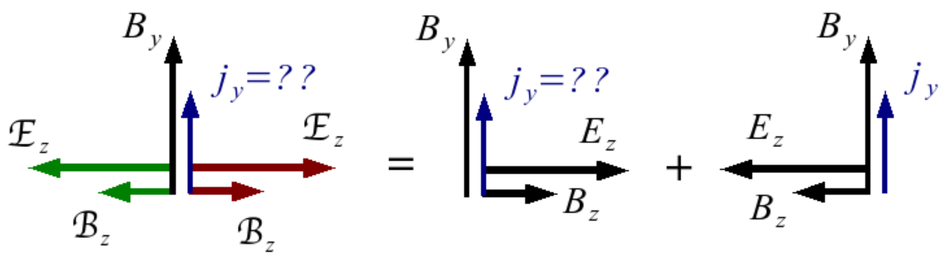


In K' $\partial_{t'} \vec{j}\,' = 2q\,\mathrm{sgn}(q E_z')\,\Gamma\, \boldsymbol{e}_z$

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

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

- Express in terms of color fields.



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

Dynamics of the Chiral Magnetic Effect

Completely analytic and exact result.

Induced current for each individual flavor

$$\partial_t j_y = \frac{q^2|q|B_y}{\pi^2}\frac{ab^2\mathrm{sgn}(\mathcal{E}_z\mathcal{B}_z)}{a^2+b^2}\coth\left(\frac{\pi b}{a}\right)\exp\left(-\frac{m^2\pi}{|qa|}\right)$$

$$a = a(\mathcal{E}_z, \mathcal{B}_z, B_y) \qquad b = b(\mathcal{E}_z, \mathcal{B}_z, B_y)$$

Small By limit:

$$\partial_t j_y \simeq \frac{q^2 B_y}{2\pi^2}\frac{g\mathcal{E}_z\mathcal{B}_z^2}{\mathcal{B}_z^2+\mathcal{E}_z^2}\coth\left(\frac{\mathcal{B}_z}{\mathcal{E}_z}\pi\right)\exp\left(-\frac{2m^2\pi}{|g\mathcal{E}_z|}\right)$$