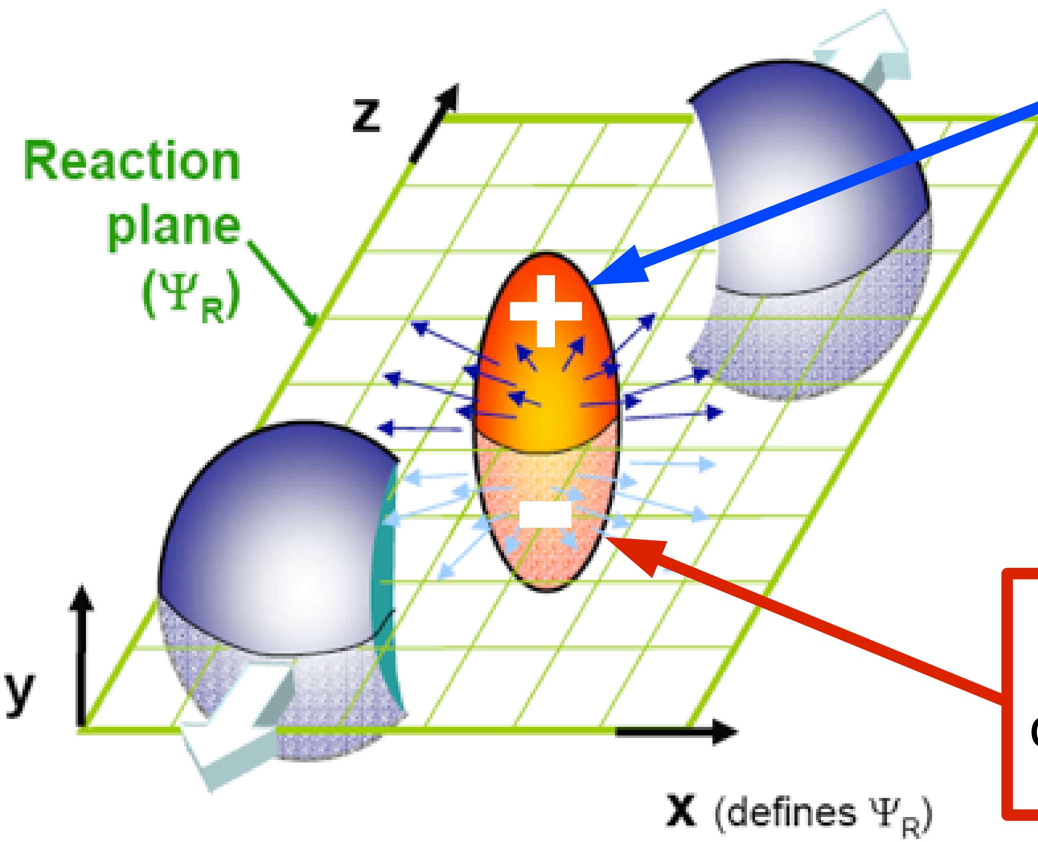
# Implications of CP-violating transitions in hot quark matter on heavy ion collisions




Excess of Positive Charge on one side of Reaction Plane

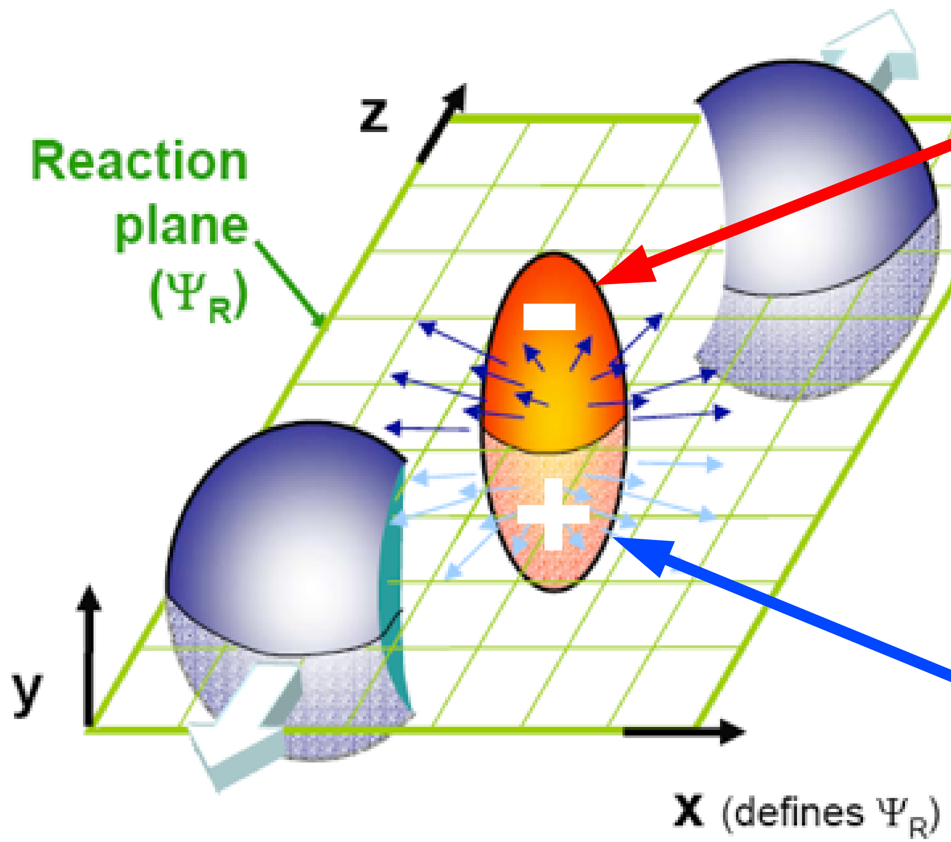
D. Kharzeev: hep-ph/0406125

Excess of Negative Charge on other side of Reaction Plane

Harmen Warringa, BNL

Based on work with Dima Kharzeev and Larry McLerran arXiv:0711.0950

# Implications of CP-violating transitions in hot quark matter on heavy ion collisions




Excess of Negative Charge on one side of Reaction Plane

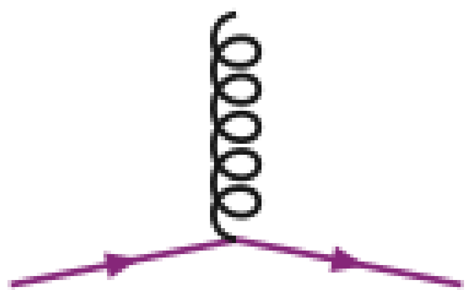
D. Kharzeev: hep-ph/0406125

Excess of Positive Charge on other side of Reaction Plane

- Why P- and CP-violating transitions
- What does it lead to
- How to detect it

# P- and CP-violating transitions

Perturbative gluonic interactions do not break P and CP




Perturbative gluonic interactions do not induce difference

between number of left- and right-handed fermions

# P- and CP-violating transitions

Color fields with winding number

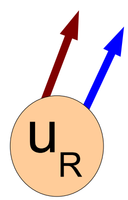
$$Q_w = \frac{g^2}{8\pi^2}\int \mathrm{d}^4x\, \vec{E}_a \cdot \vec{B}_a = 0, \pm 1, \pm 2, ....$$

induce difference between number of left- and right-handed fermions.

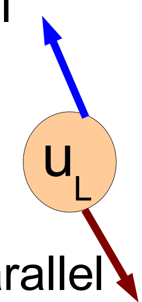
Nonperturbative P- and CP-violating transition

In chiral limit:

Right-handed fermions

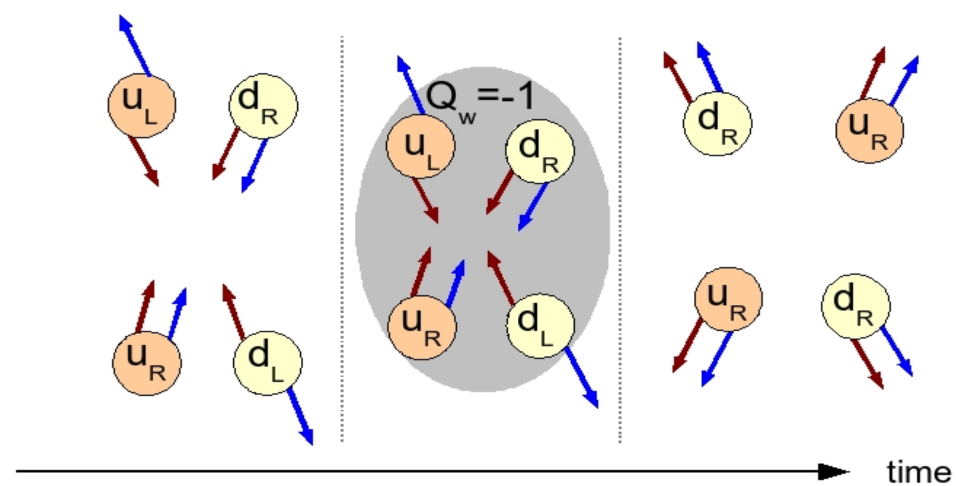



have spin and momentum parallel




Left-handed fermions

have spin and momentum anti-parallel

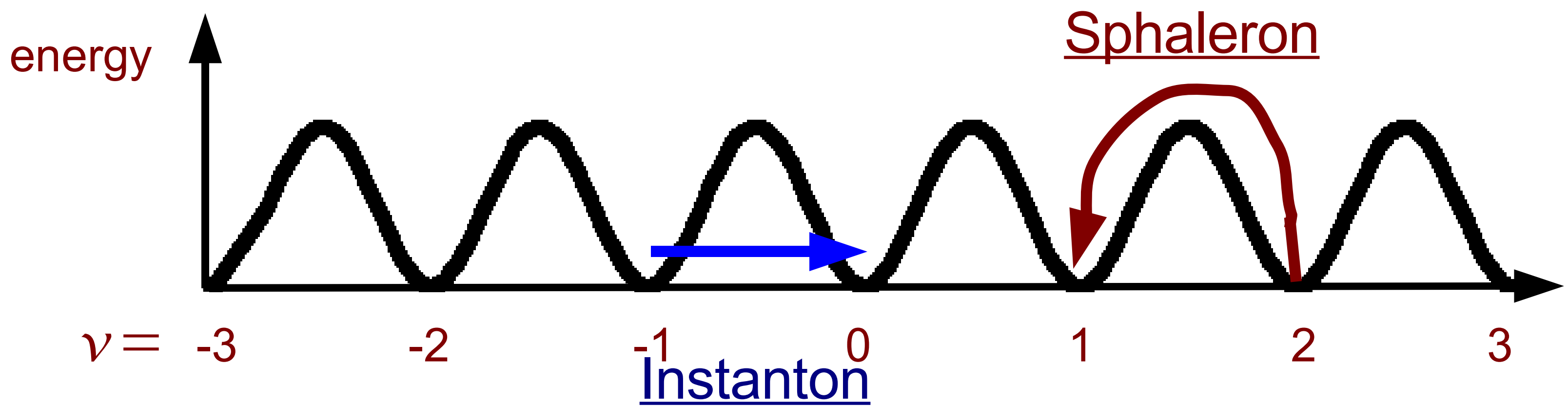



$$[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2N_f Q_w$$

Axial Ward Identity at work

# Color fields with a winding number

Change topological charge vacuum




Instantons: Configuration with finite action. Tunneling through barrier

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

Sphaleron: Configuration with finite energy. Go over barrier.

Only possible at finite temperature, rate not suppressed.

$$\frac{d\,N_t^{\pm}}{d^3 x\, d\, t} \sim 385\, \alpha_S^5\, T^4$$

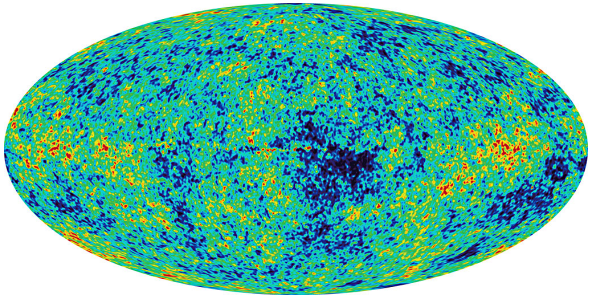
Bödeker, Moore and Rummukainen ('00)

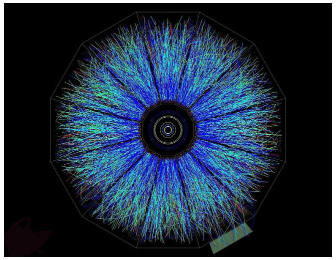
# Similarities between

Electroweak Baryogenesis
in the early universe

&

CP-violating transitions
in hot quark matter





Topological charge changing transitions

induce nonzero baryon + lepton number

Topological charge changing transitions

induce difference between number of left- and right-handed fermions

At high temperatures these transitions are unsuppressed (sphalerons)

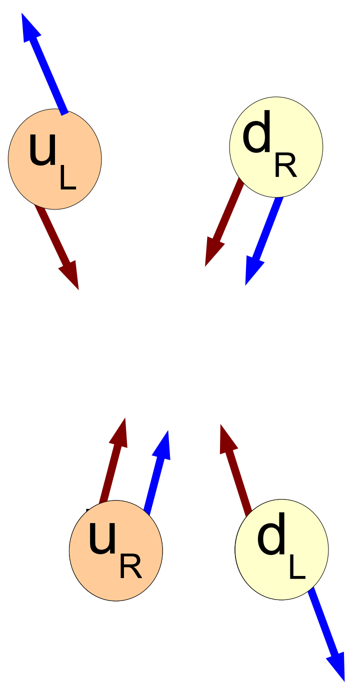
We observe an asymmetry between matter and antimatter

How to observe topological charge changing transitions in hot quark matter?

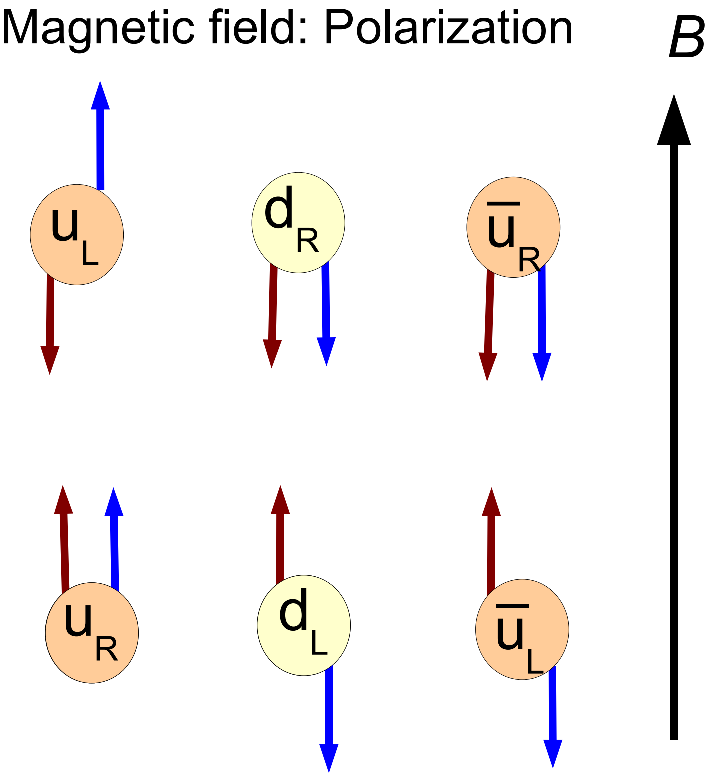
# Adding a Magnetic Field

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

No Magnetic Field: No polarization




Magnetic field: Polarization

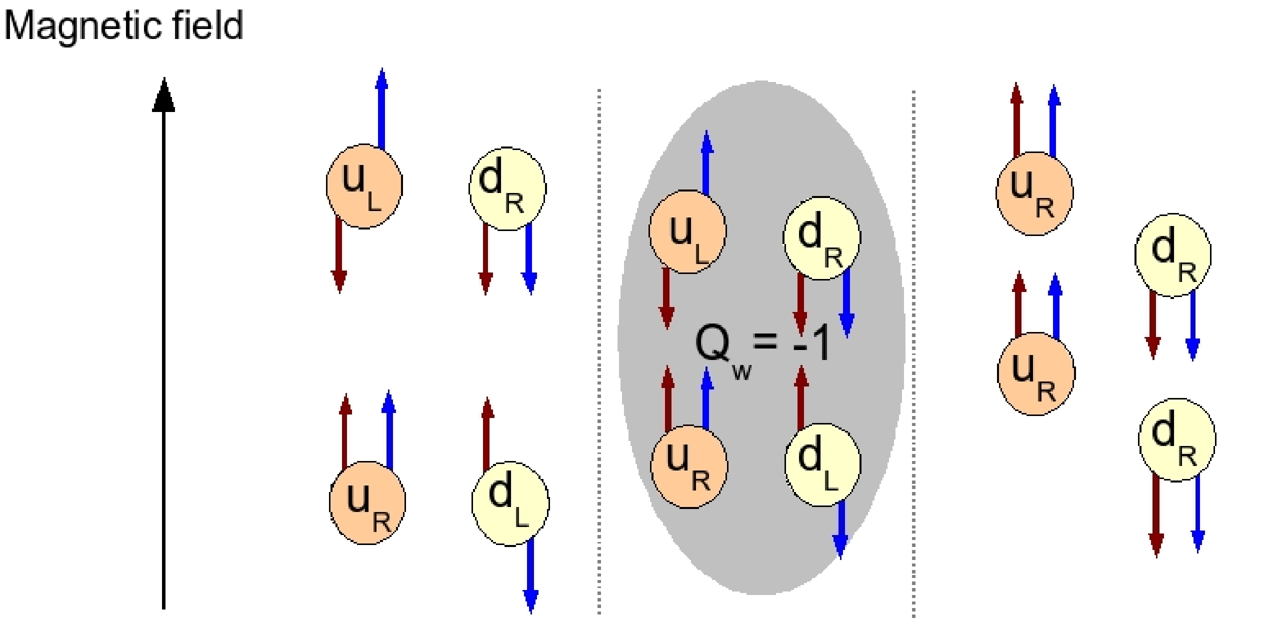



In the chiral limit the momenta align along the magnetic field

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

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

# The Chiral Magnetic Effect




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

Charge difference:

$$Q = 2 Q_w \sum_f |q_f|$$

Same sign for antiparticles!

Topological charge charging transition induces Chirality

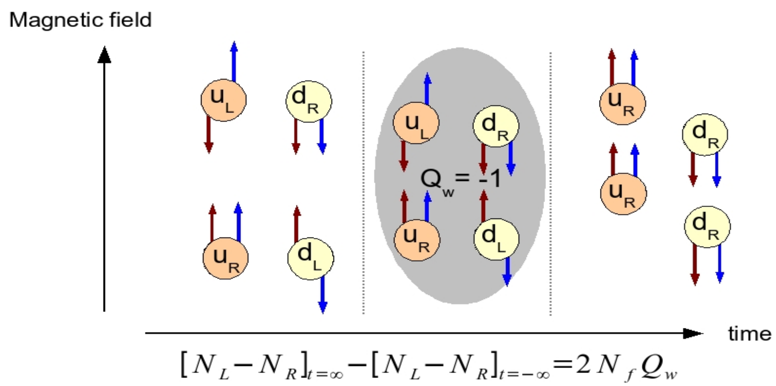
In presence of Magnetic field this induces Electromagnetic Current

In finite volume this causes separation of positive from negative charge

Kharzeev ('04), Kharzeev & Zhitnitsky ('07), Kharzeev, McLerran & HJW ('07)

# The Chiral Magnetic Effect

*In a moderate magnetic field (some polarization)*




Charge difference:

$$Q = 2 Q_w \sum_f |q_f| \, \text{polarization}(q_f)$$

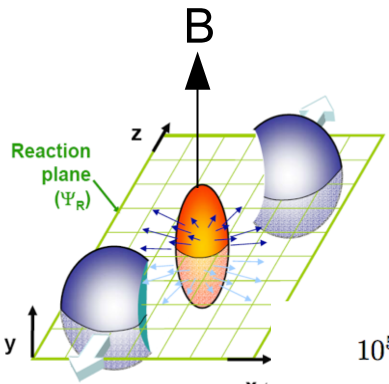
Quarks with energy smaller than inverse size of sphaleron are changing chirality

$$\text{polarization}(q_f) = \frac{|N_\uparrow - N_\downarrow|}{N_\uparrow + N_\downarrow} \approx 2 |q_f e B| \rho^2$$

Size of sphalerons is of order $\rho \sim \frac{1}{\alpha_s T}$

To get reasonable polarization we need $e B \sim \frac{1}{\rho^2} \sim \alpha_s^2 T^2 \sim 10^3 - 10^4 \text{ MeV}^2$

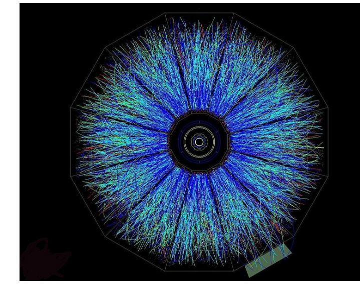
# Magnetic Field in Heavy Ion Collisions

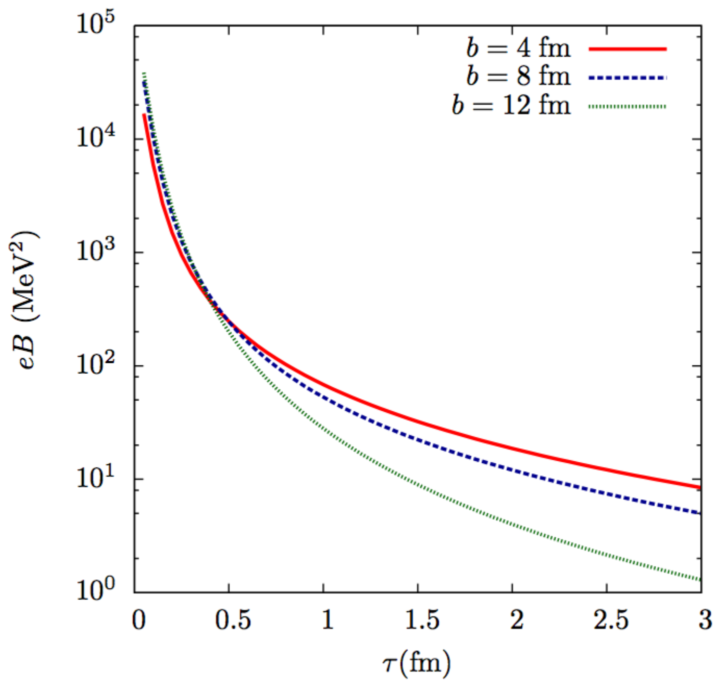



*Computed numerically at origin in pancake approximation*

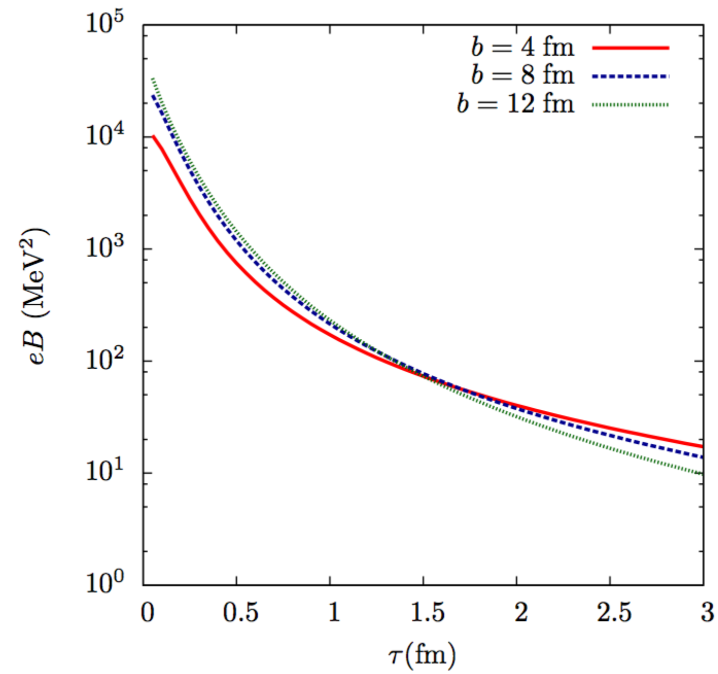
RHIC@BNL

$$eB(\tau=0.2\,\mathrm{fm})=10^3\sim10^4\ \mathrm{MeV}^2\sim10^{17}\,\mathrm{G}$$






100 GeV per Nucleon



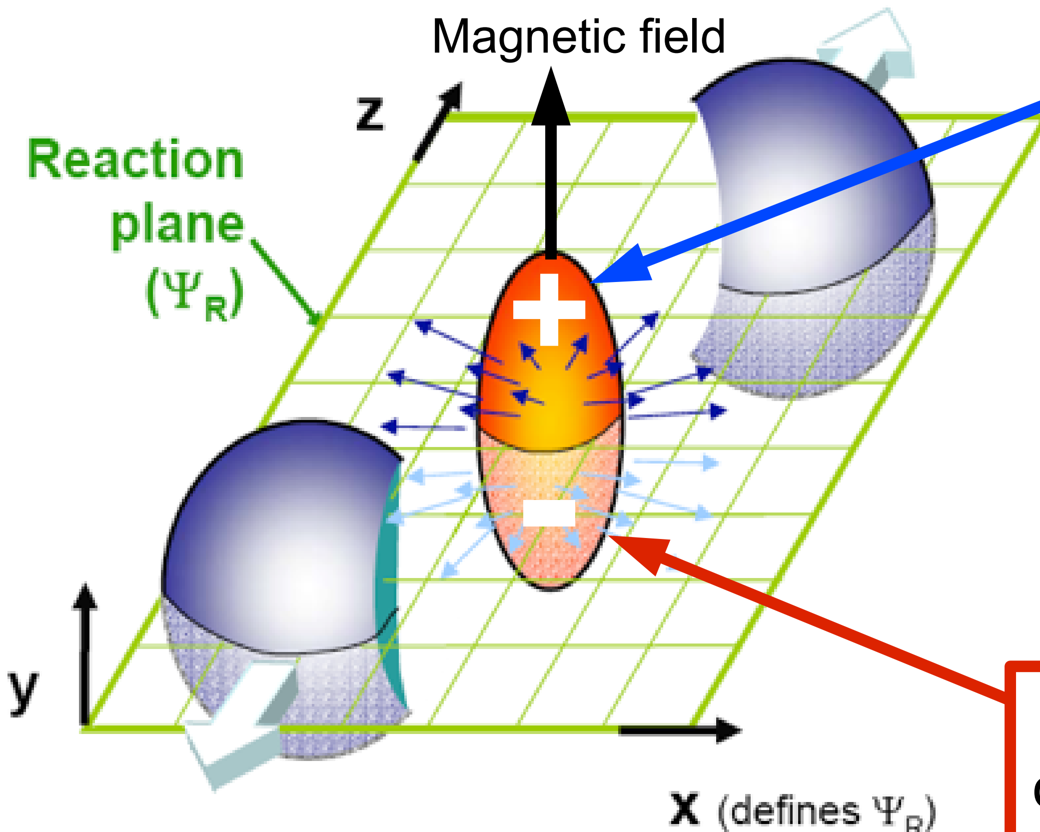

31 GeV per Nucleon

Low energy quarks which are produced in early stages will be polarized in the direction perpendicular to reaction plane to some degree.

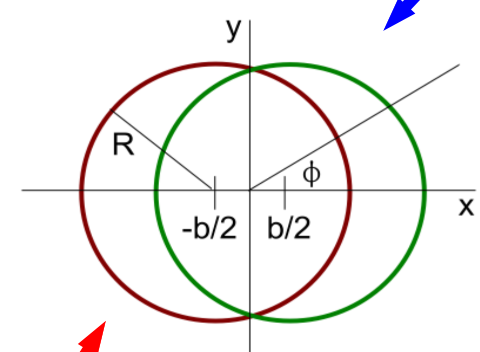
*Magnetic field falls off rapidly: Chiral Magnetic Effect is early time dynamics*

# The Chiral Magnetic Effect in Heavy Ion Collisions

*Event by event P- and CP-violation*




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

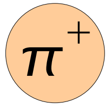


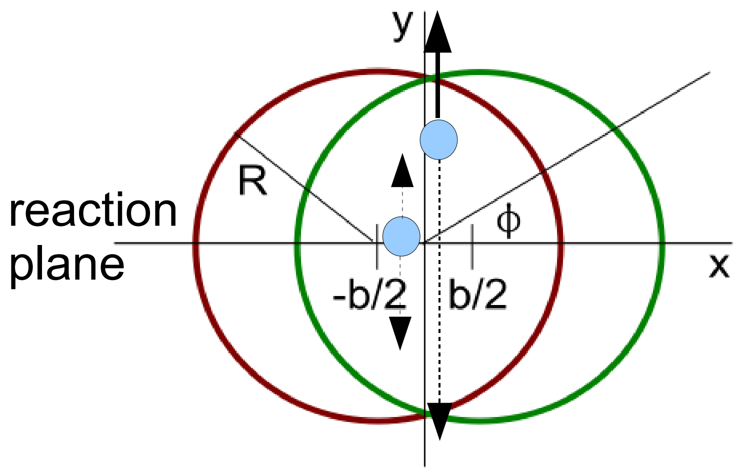

Excess of Negative Charge on other side of Reaction Plane around $\phi=3\pi/2$

Charge conserved in hadronization:

More positively charged quarks implies more positively charged hadrons

# Computing observables

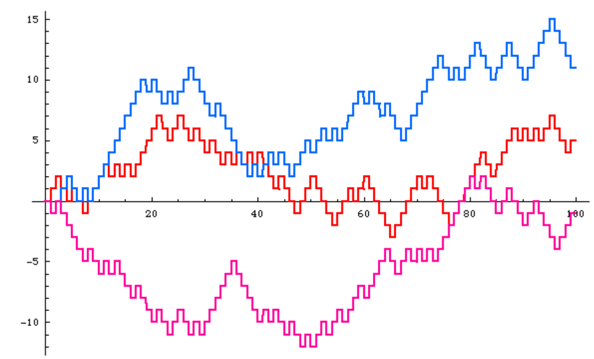



The Chiral Magnetic Effect is a near the surface effect

Medium causes screening

1-d random walk



The variances are the observables

Variance topological charge change equal to total number of transitions

Variance of charge difference between both sides reaction plane:

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

Time & Volume integral
Overlap region

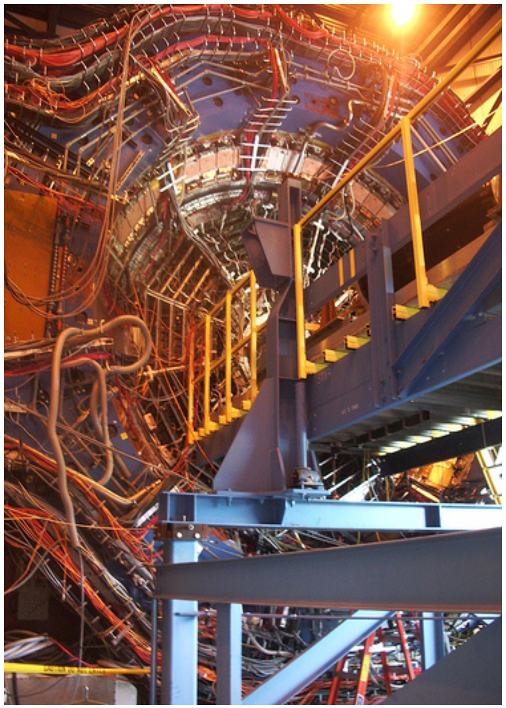
Rate of
Transitions

Screening
Functions

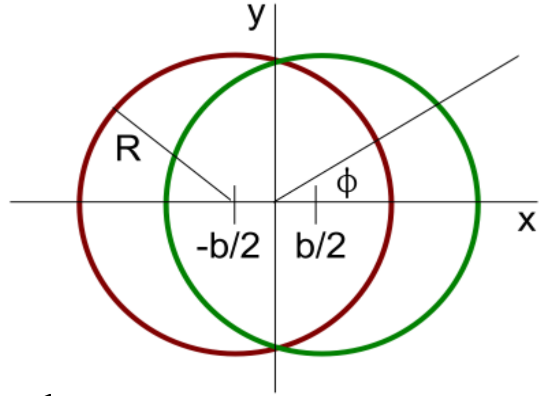
Square of Change
Charge difference

# Observables

Voloshin ('04), See Poster 205



STAR detector
Full azimuthal coverage




$\phi$ : angle between particle and reaction plane

$$\frac{dN_\pm}{d\phi} = \frac{N_\pm}{2\pi} + a_\pm \sin\phi + v_2 \cos 2\phi + ....$$

Average over many equivalent events (to cancel statistical fluctuations) can give us

$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$ Pref. emission positive on one side

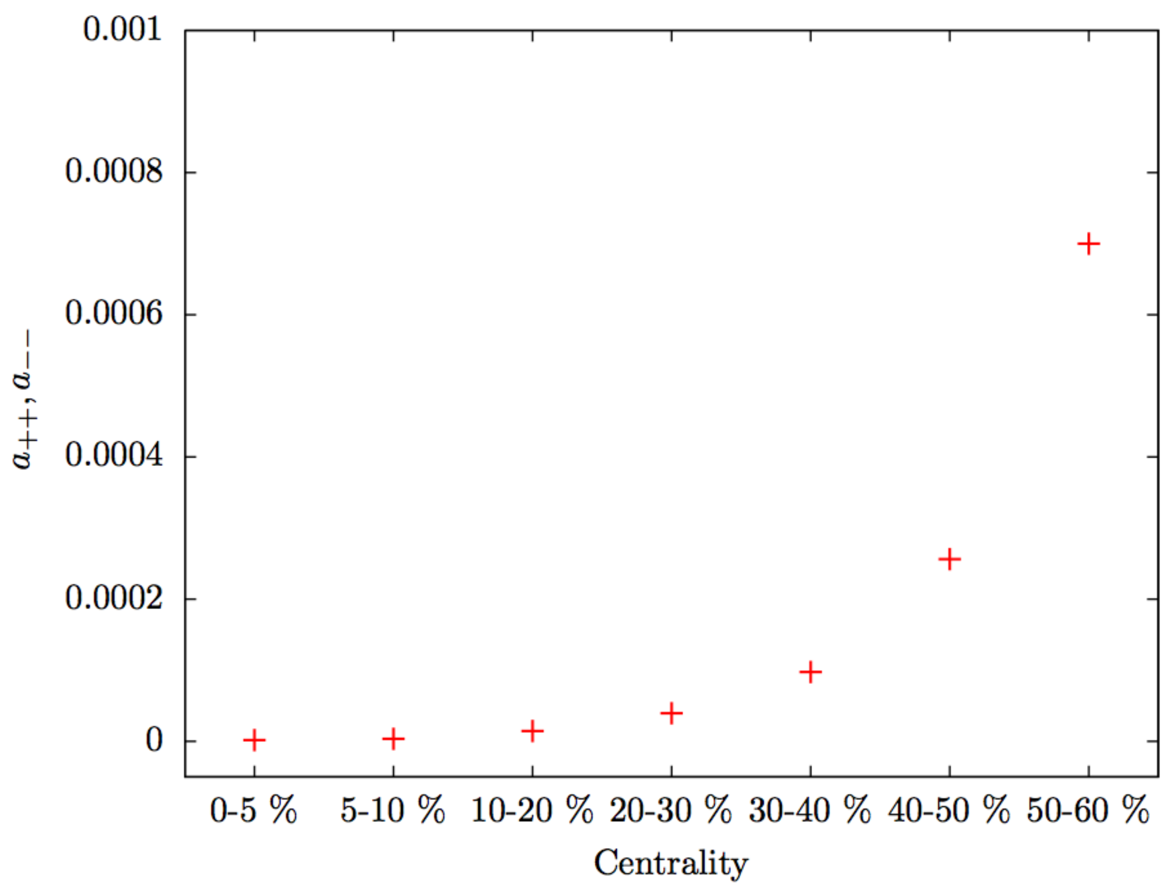
$\langle a_-^2 \rangle \sim \langle \Delta_-^2 \rangle$ Pref. emission negative on one side

$\langle a_+ a_- \rangle \sim \langle \Delta_+ \Delta_- \rangle$ Correlations between positive on one and negative on other side

Preliminary analysis performed by STAR collaboration (Poster 205)

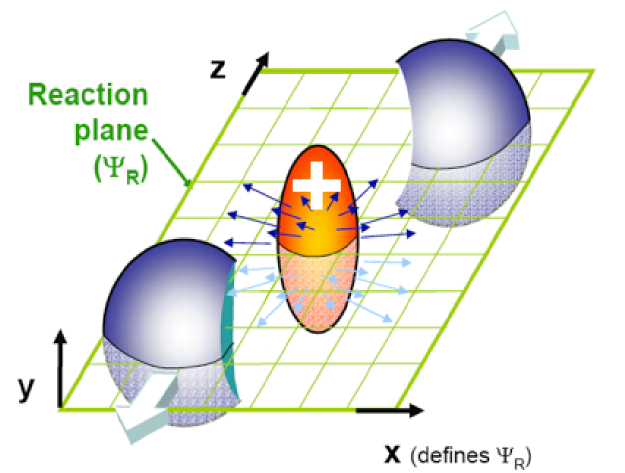
Observables are not P and CP-odd, understand possible backgrounds

# Correlators vs. Centrality



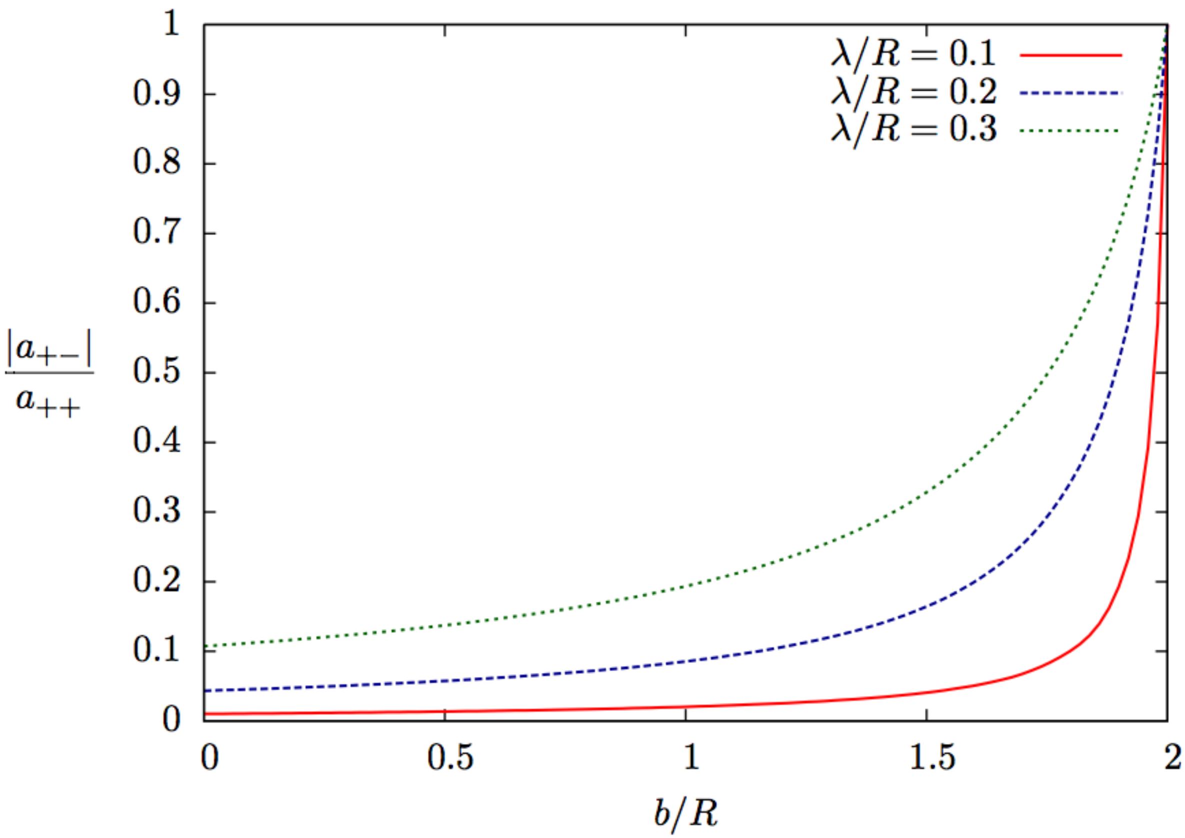

$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$

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




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

# Suppression of +/- correlations



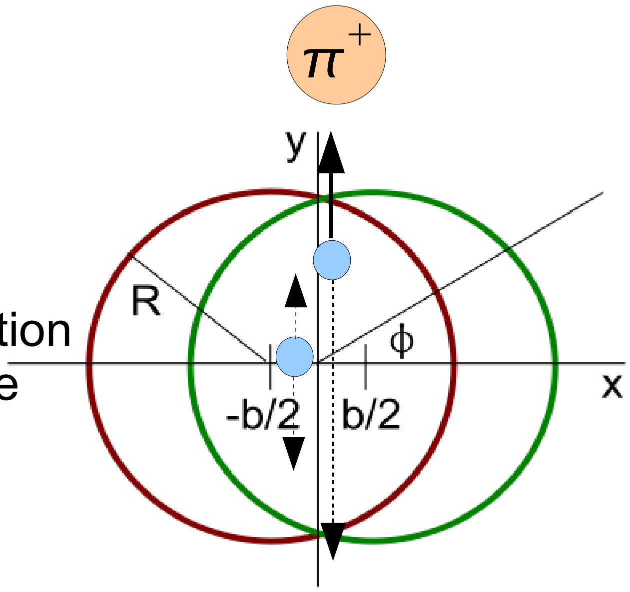

A possible result of the Chiral Magnetic Effect

Suppression of correlations

between positively charged particles on one side and

negatively charged particles on other side of reaction plane

due to screening.



# Features of the Chiral Magnetic Effect

- For gold-gold at 130 GeV per nucleon we estimate with order of magnitude uncertainty $a_{++} \sim 10^{-4}$ at large impact parameter

- The correlators are proportional to $Z^2$

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

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

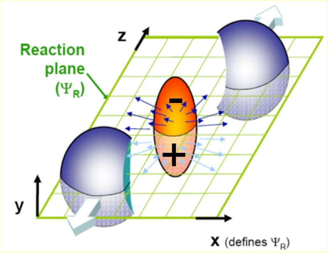
- Order parameter for chiral symmetry restoration / deconfinement?

- Probably a typical transverse momentum dependence

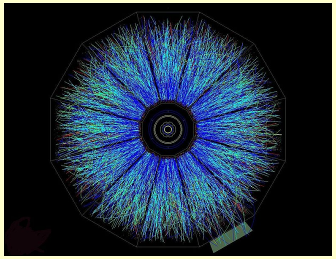
- Particle species dependence not known yet

# Conclusions and outlook

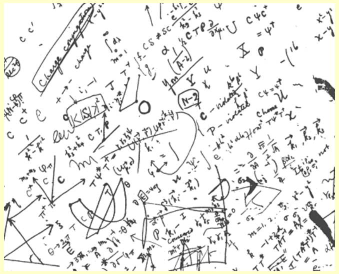
-The Chiral Magnetic Effect can be used to detect
P and CP-violation transitions in QCD.




- This can be done using Heavy Ion Collisions.
Preliminary STAR analysis, see Poster 205 Voloshin

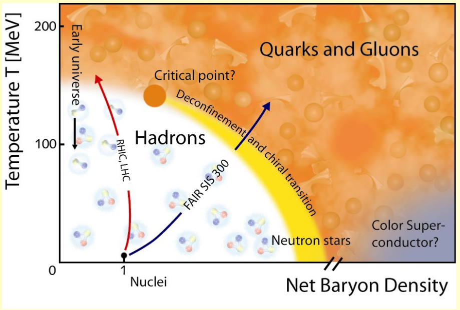


- We can make a number of predictions,
more precise possible.



- Establishing the observation of the Chiral Magnetic
Effect requires detailed experimental and theoretical study

- Maybe the Chiral Magnetic Effect can be used as an
order parameter for chiral symmetry breaking.



# Thanks for your attention

And thanks to:

- The organizers of this conference

- Dmitri Kharzeev
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- Ilya Selyuzhenkov
- Yannis Semertzidis
- Sergei Voloshin