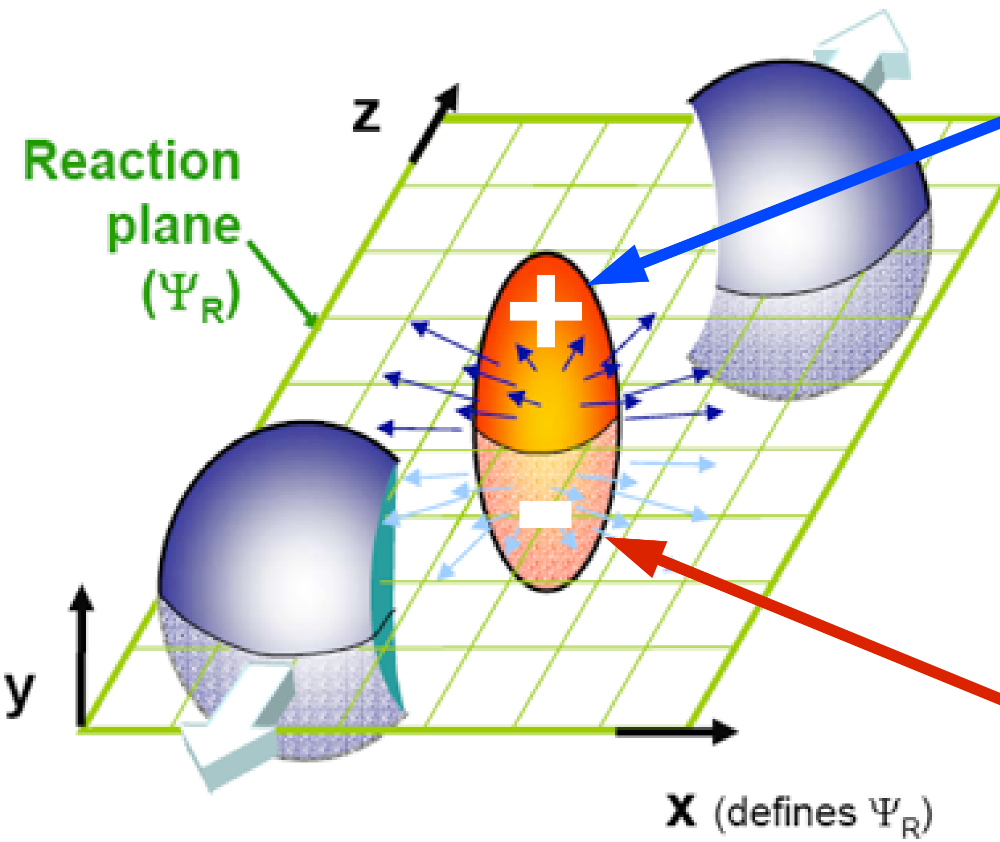
Implications of CP-violating transitions in hot quark matter on heavy ion collisions



Excess of Positive Charge on one side of Reaction Plane

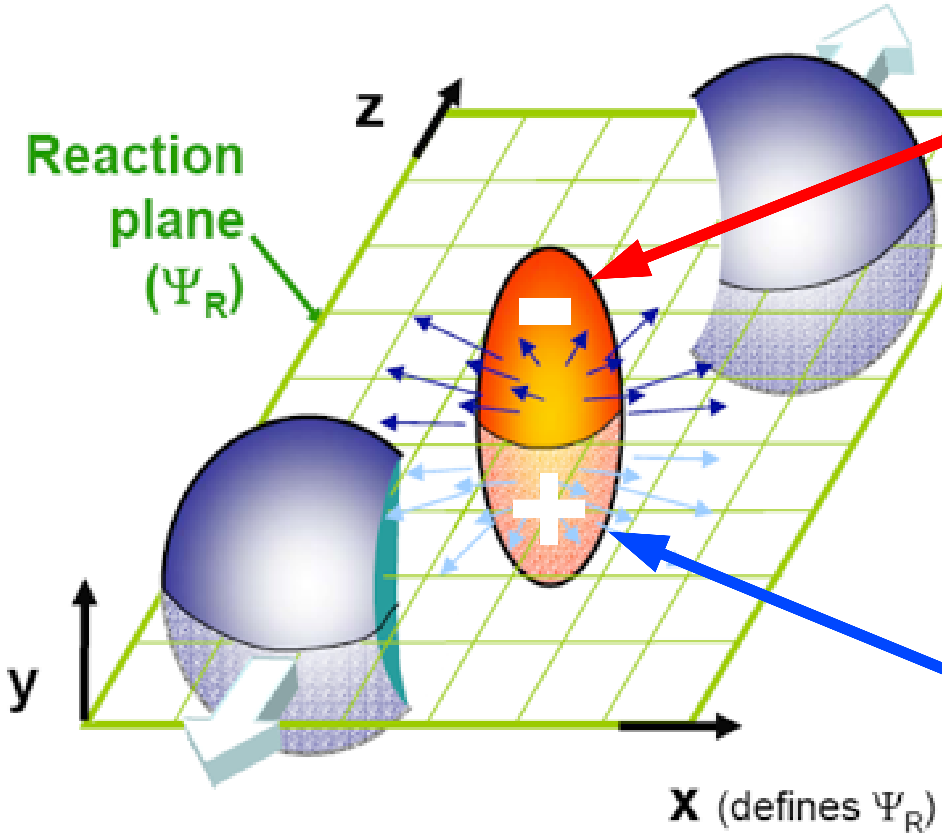
D. Kharzeev: hep-ph/0406125

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

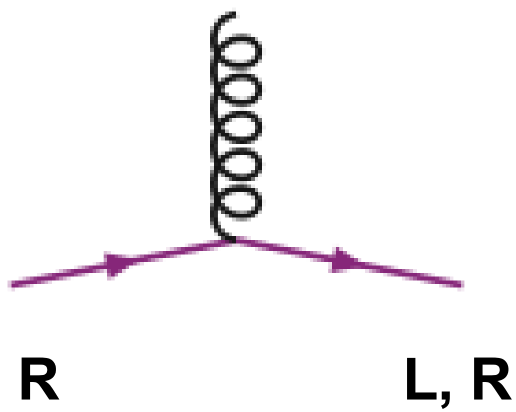
D. Kharzeev: hep-ph/0406125

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

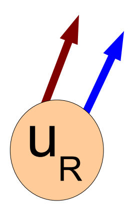
$$Q_w = \frac{g^2}{8\pi^2}\int \mathrm{d}^4x\, \vec{E}_a \cdot \vec{B}_a = 0, \pm 1, \pm 2, ...$$

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

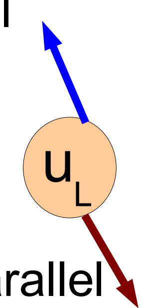
Nonperturbative P- and CP-violating transition

In chiral limit:

Right-handed fermions

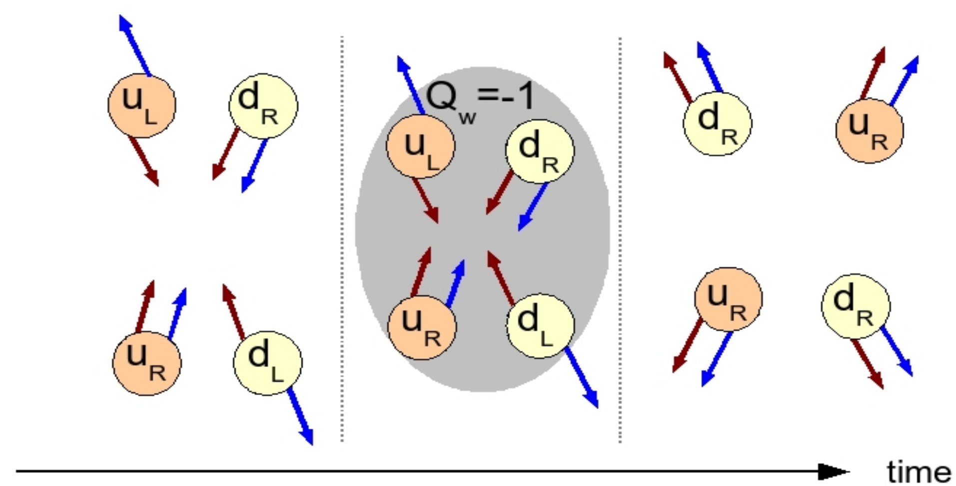


have spin and momentum parallel



Left-handed fermions

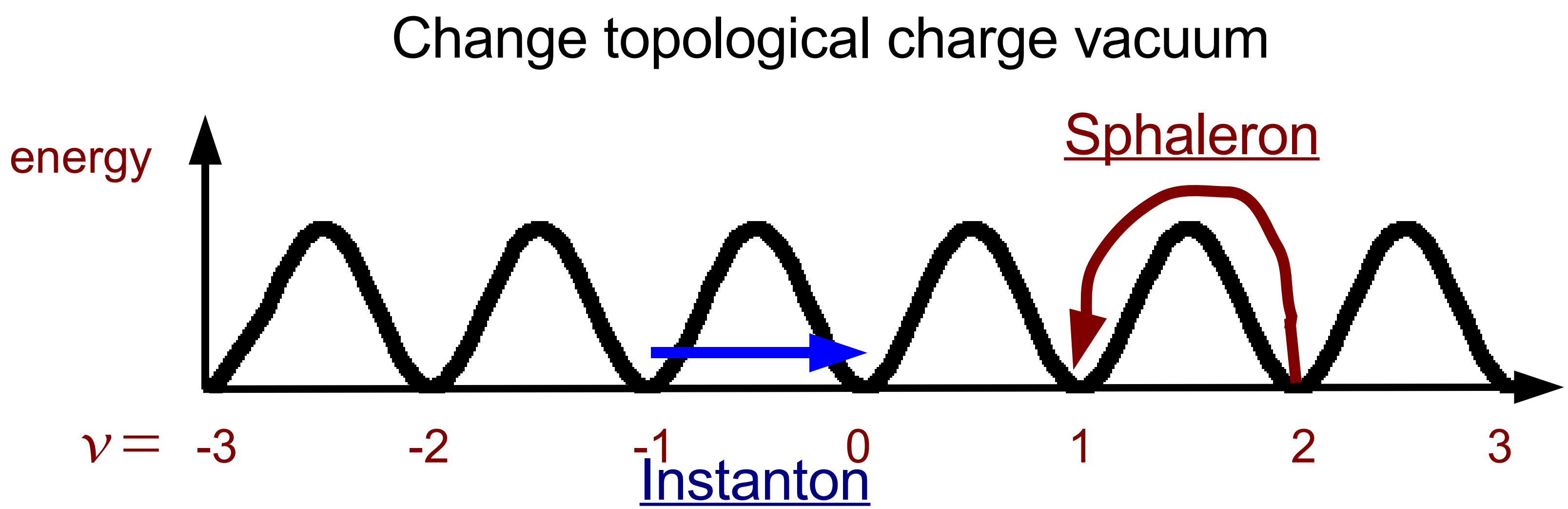
have spin and momentum anti-parallel



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

Axial Ward Identity at work

Color fields with a winding number



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.

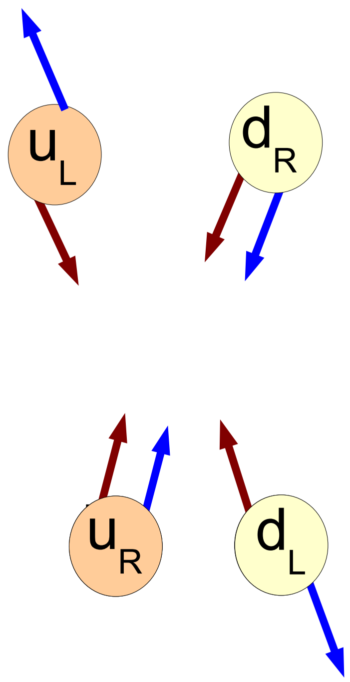
$$\frac{d\,N_t^{\pm}}{d^3x\,d\,t} \sim 385\,\alpha_S^5\,T^4$$

Bödeker, Moore and Rummukainen ('00)

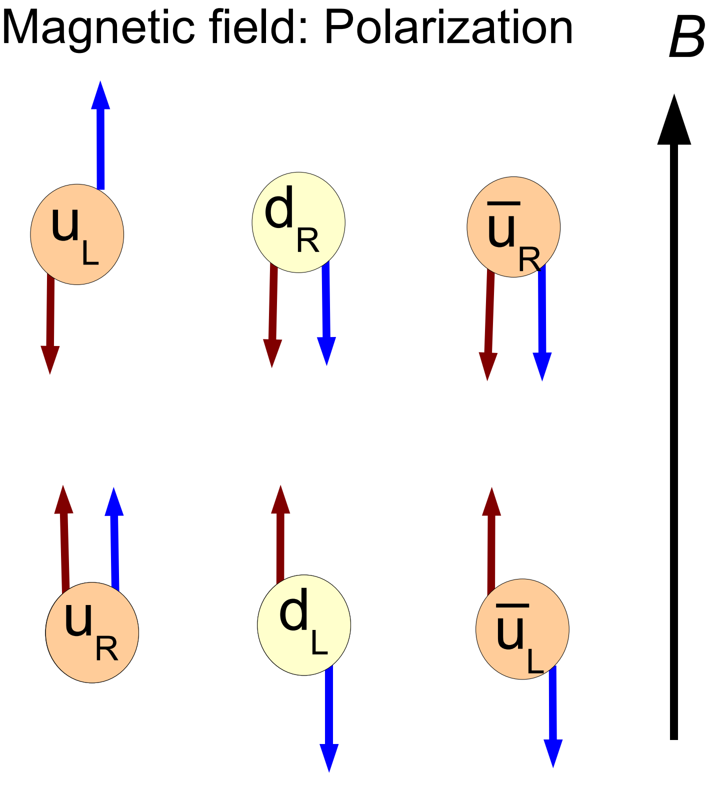
Adding a Magnetic Field

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

No Magnetic Field: No polarization



Magnetic field: Polarization

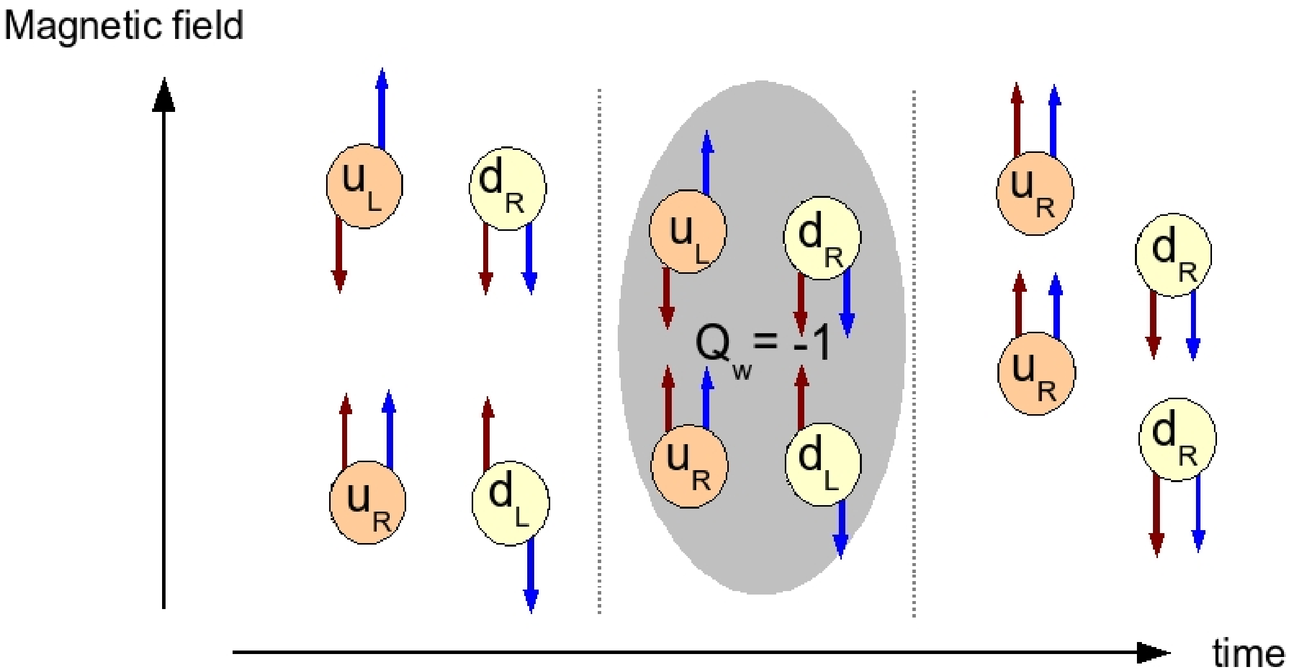


In the chiral limit the momenta align along the magnetic field

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

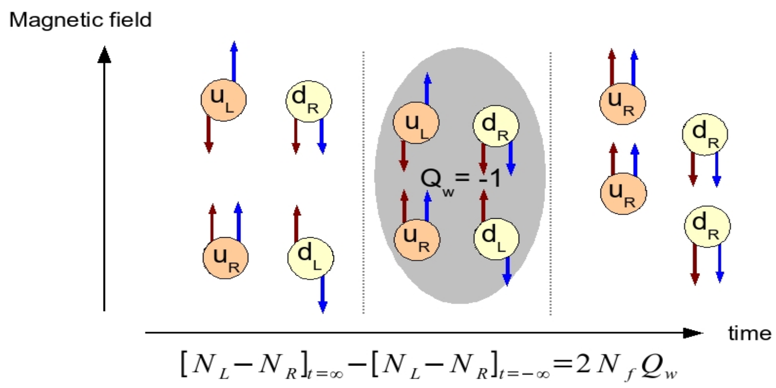
In presence of Magnetic field this induces Electromagnetic Current

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:

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

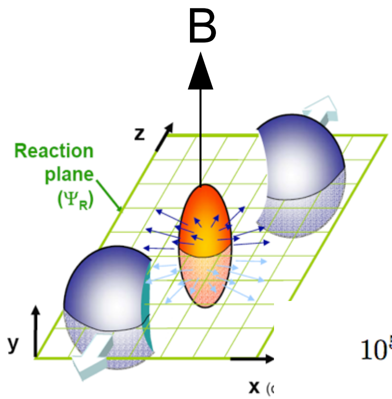
Quarks with energy smaller than inverse size of sphaleron are changing chirality

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

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

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

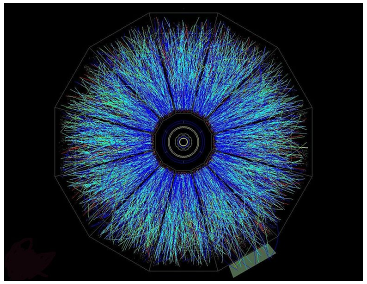
Magnetic Field in Heavy Ion Collisions

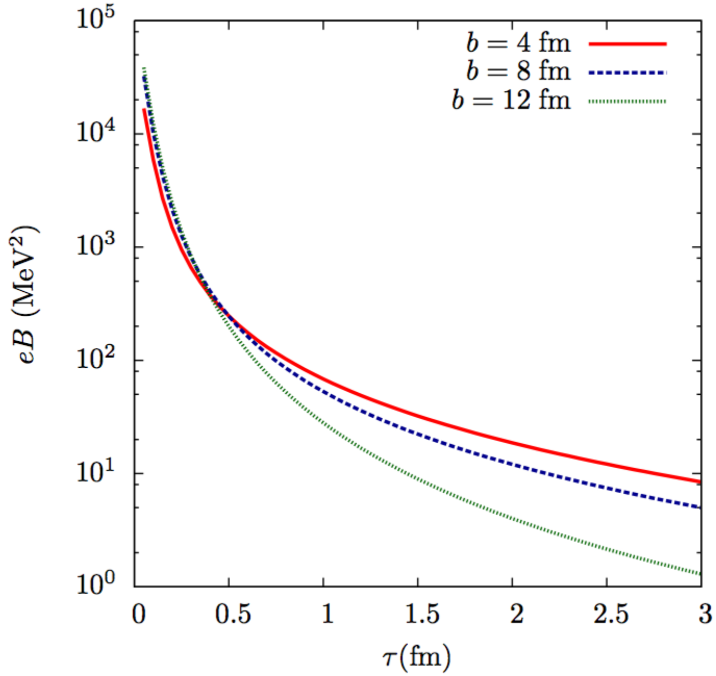


Computed numerically at origin in pancake approximation

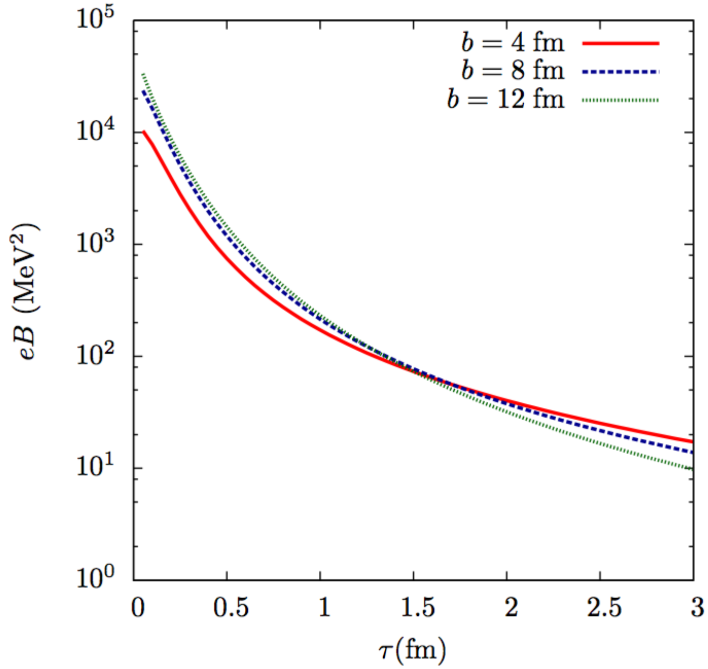
RHIC@BNL

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





100 GeV per Nucleon



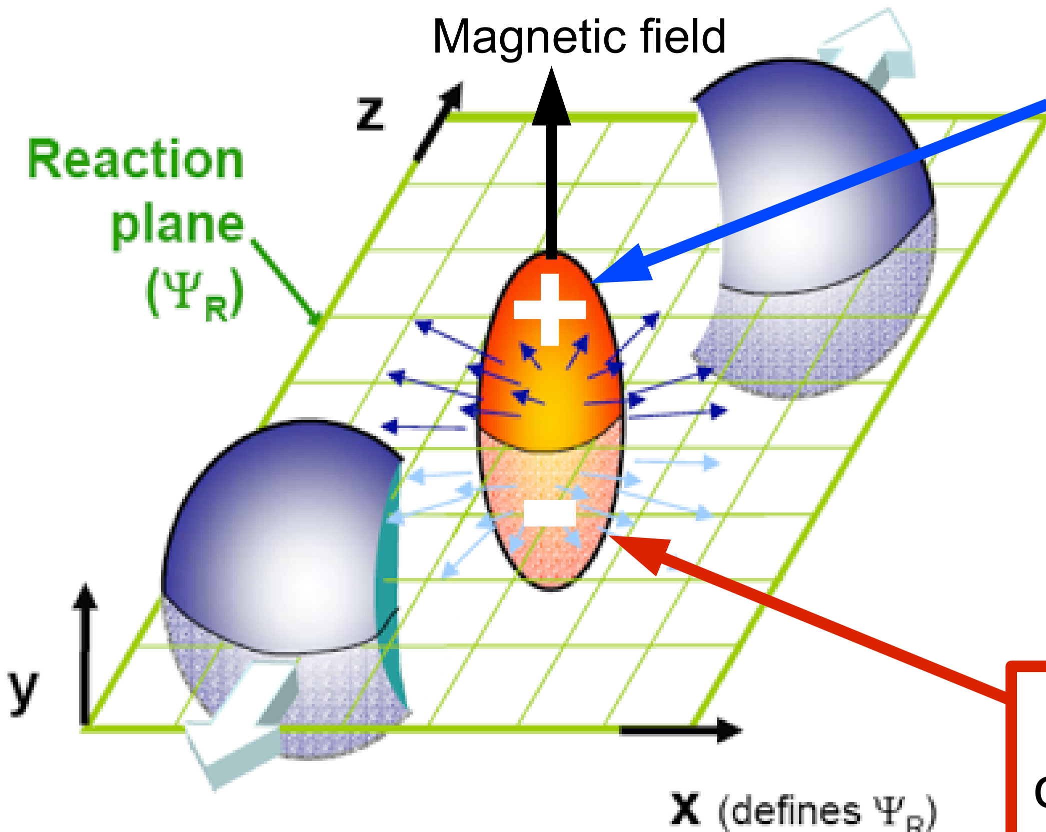
31 GeV per Nucleon

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

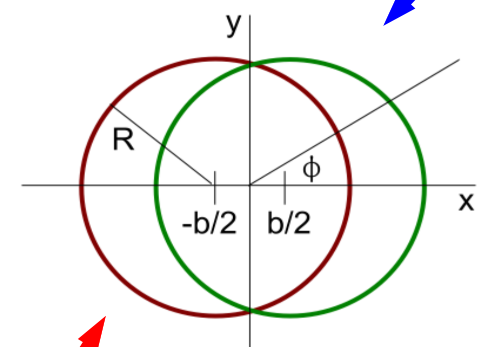
Magnetic field falls off rapidly: Chiral Magnetic Effect is early time dynamics

The Chiral Magnetic Effect in Heavy Ion Collisions

Event by event P- and CP-violation



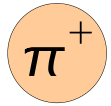
Excess of Positive Charge
on one side of Reaction Plane
around $\phi = \pi/2$



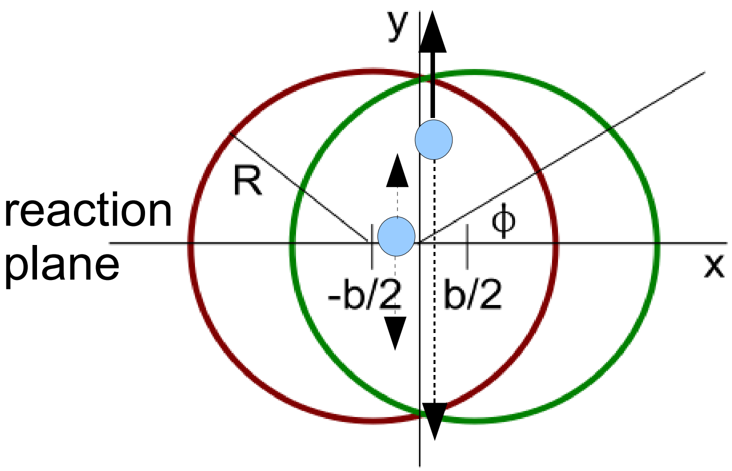
Excess of Negative Charge
on other side of Reaction Plane
around $\phi = 3\pi/2$

Charge conserved in hadronization:

More positively charged quarks implies more positively charged hadrons



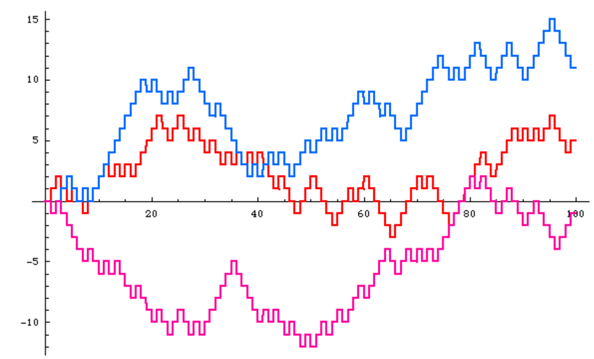
Computing observables



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

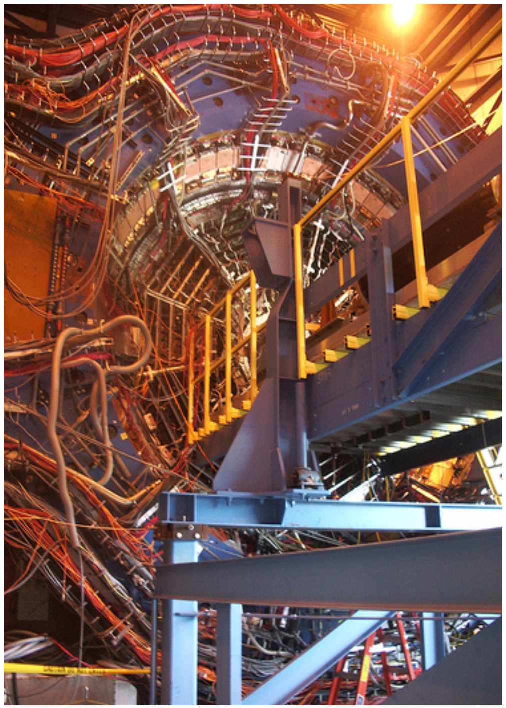
Variance of charge difference between both sides reaction plane:

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

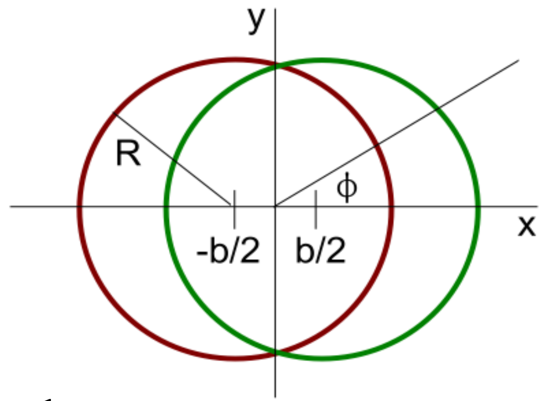
Time & Volume integral Overlap region	Rate of Transitions	Screening Functions	Square of Change Charge difference

Observables

Voloshin ('04)



STAR detector
Full azimuthal coverage



ϕ : angle between particle and reaction plane

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

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

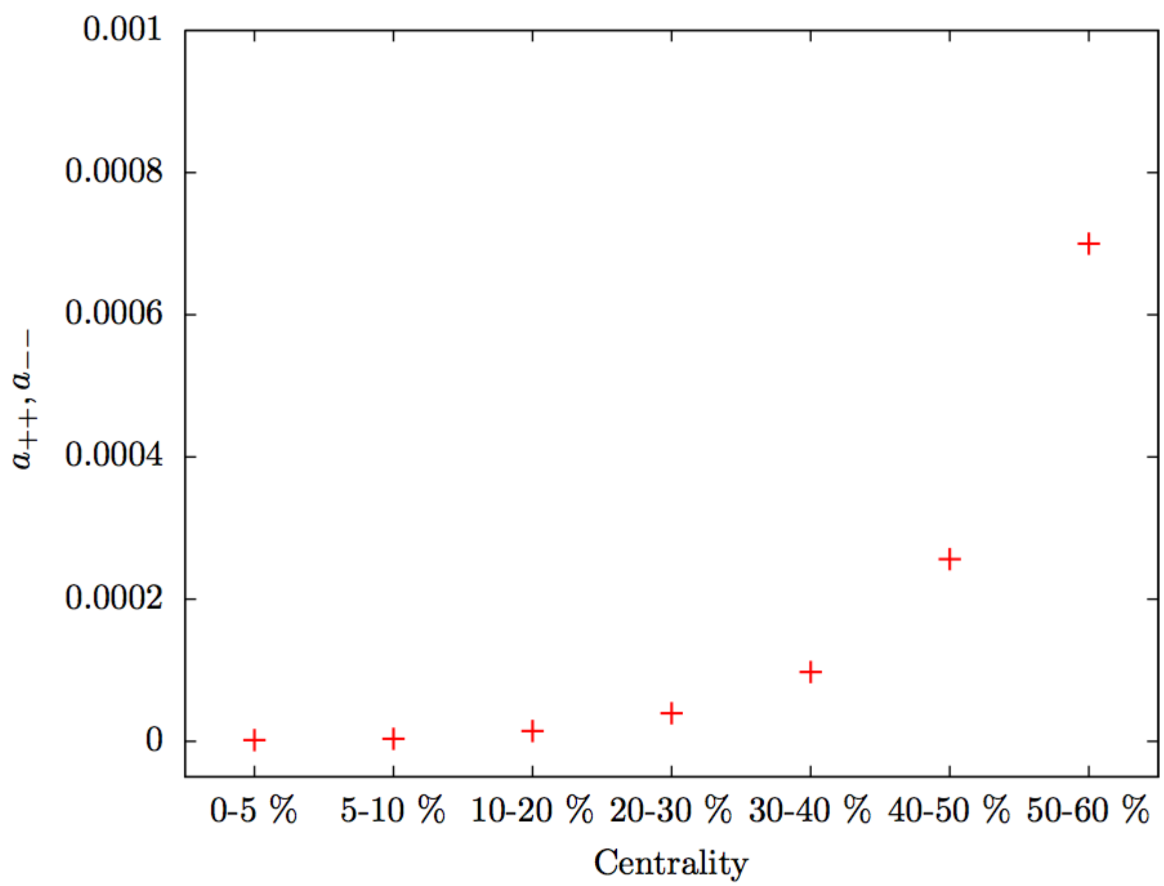
$\langle a_-^2 \rangle \sim \langle \Delta_-^2 \rangle$ Pref. emission negative on one side

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

Preliminary analysis performed by STAR collaboration

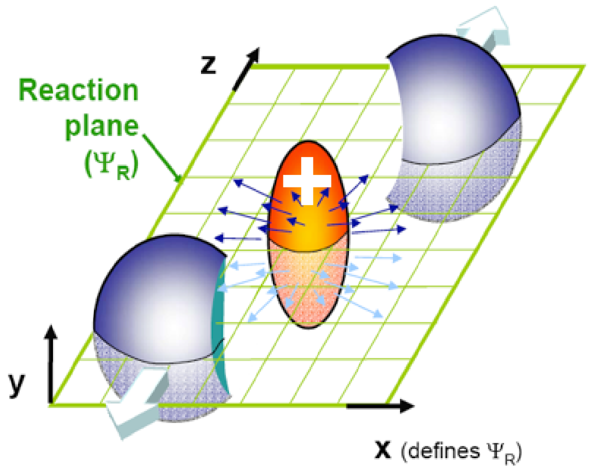
Observables are not P and CP-odd, understand possible backgrounds

Correlators vs. Centrality



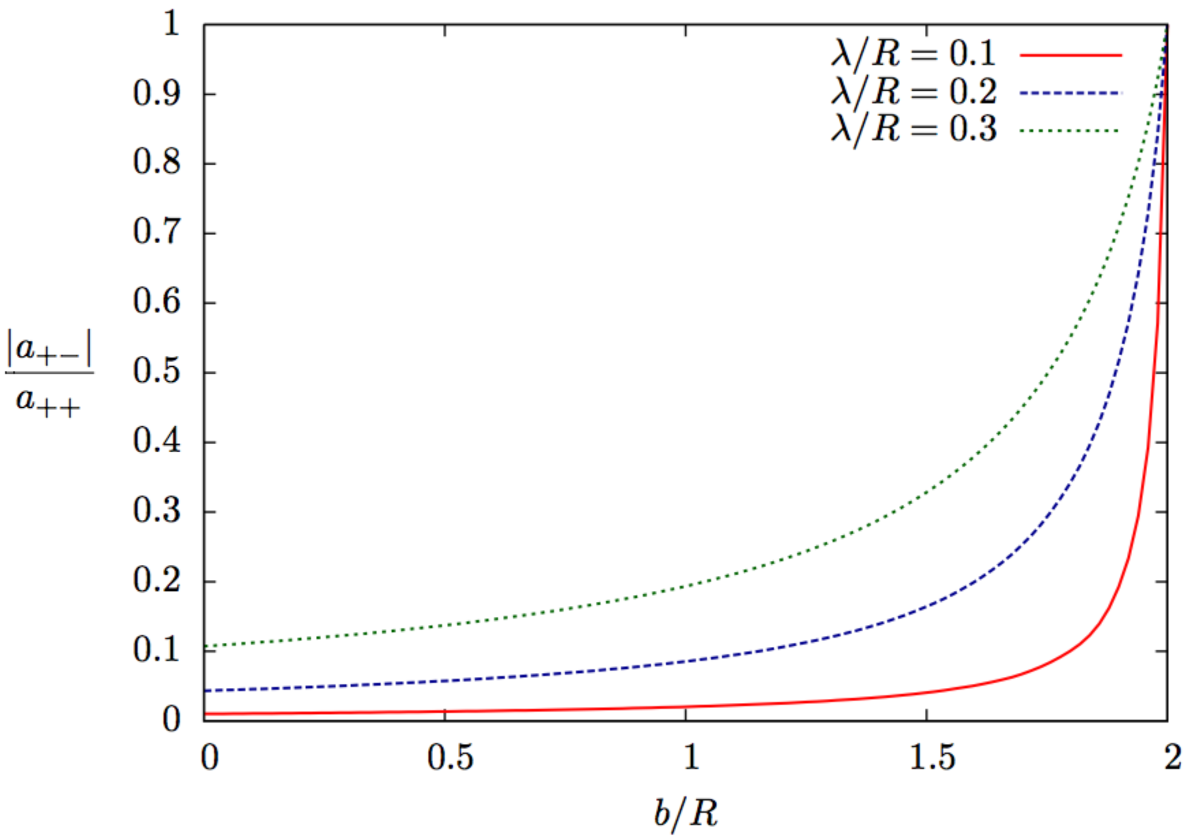
$\langle a_+^2 \rangle \sim \langle \Delta_+^2 \rangle$

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



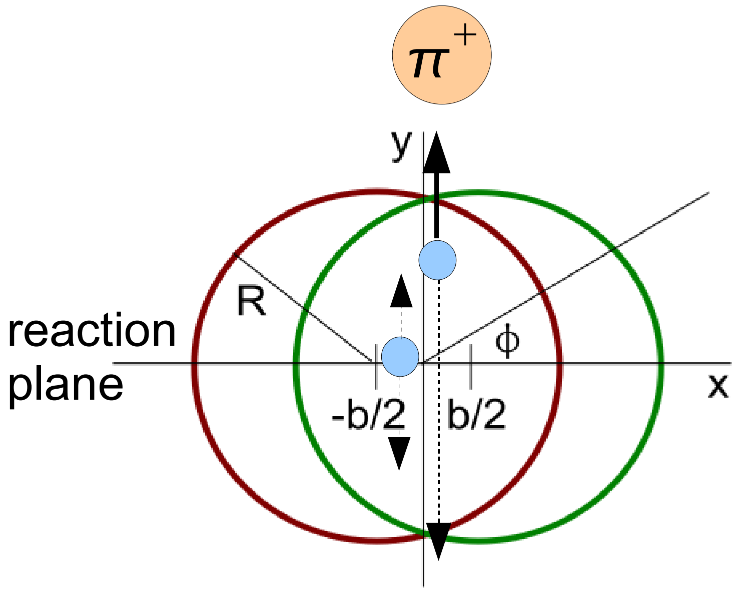
Suppression of correlations

between positively charged particles on one side and

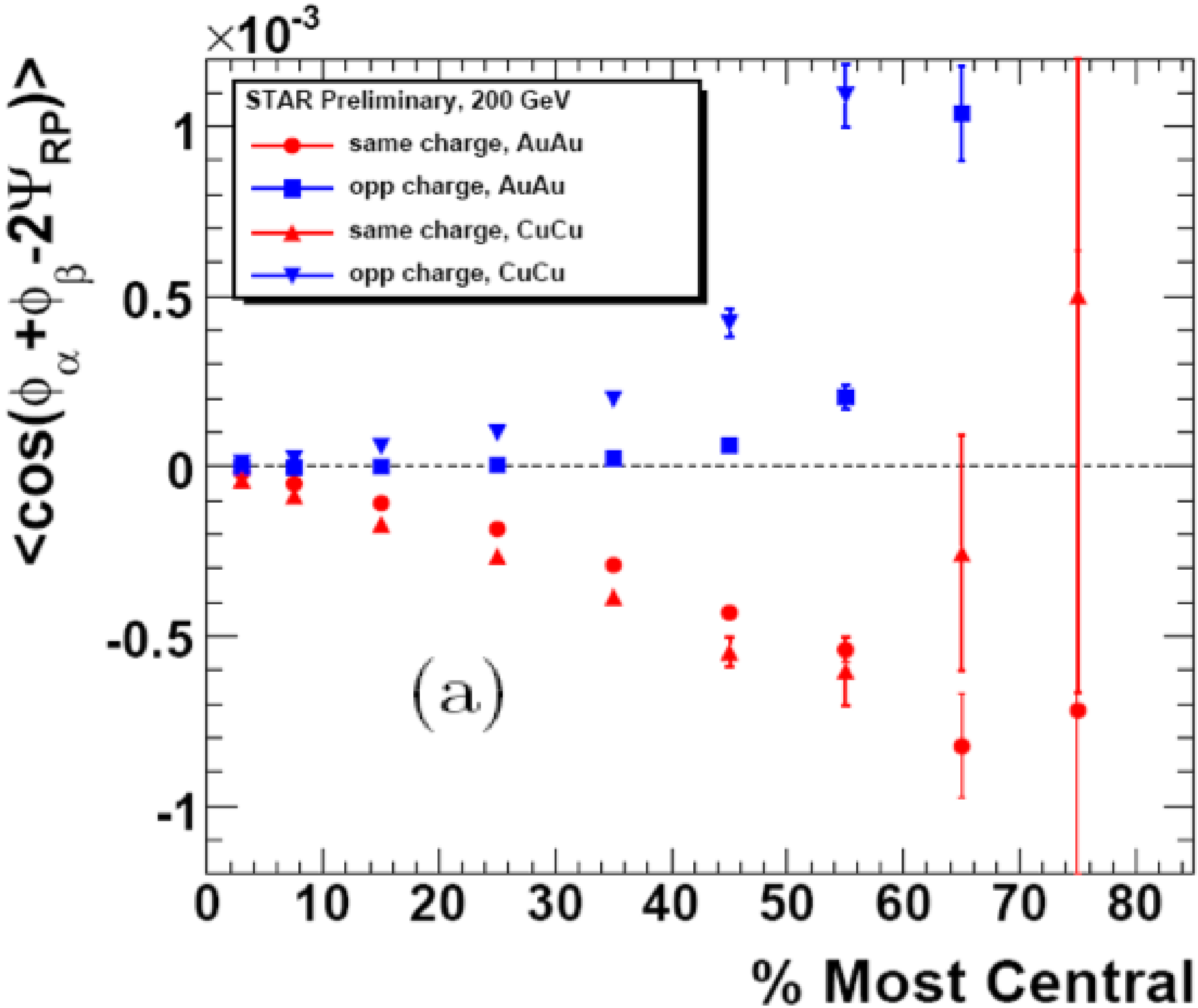
negatively charged particles on other side of reaction plane

due to screening.

A possible result of the Chiral Magnetic Effect

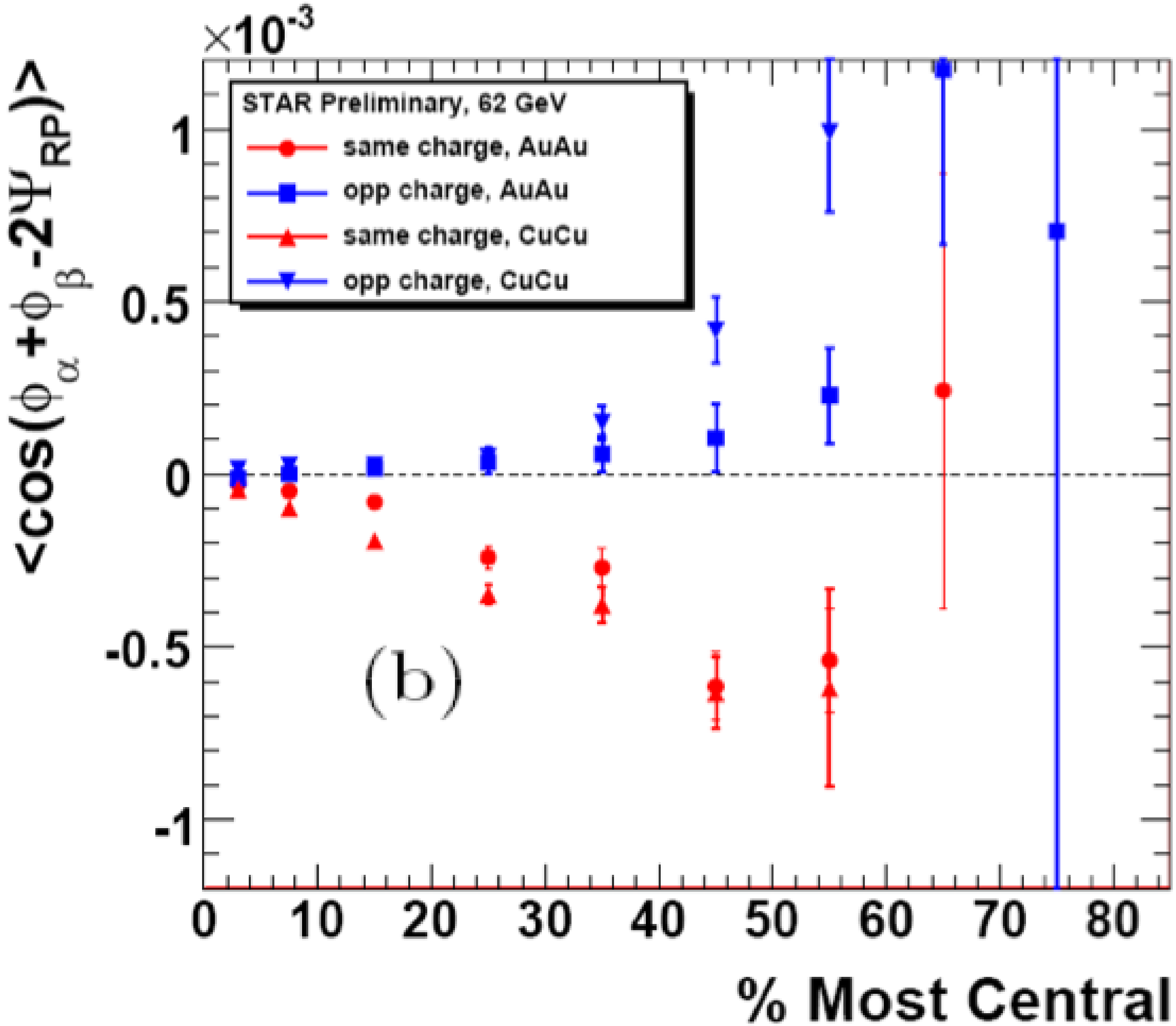


Measurements Au & Cu @ 200 GeV



Voloshin Quark Matter 2008

Measurements Au & Cu @ 62 GeV



Voloshin Quark Matter 2008

Measurements suggest

Preferential emission of charged particles perpendicular to the reaction plane.

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

Existence of screening effect.

About 1-3 % asymmetry

Asymmetry increases as a function of centrality

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

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

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
  Test: use nuclei with same A and different Z

- Order parameter for chiral symmetry restoration / deconfinement?
  Test: energy scan. If no QGP no signal

- Particle species dependence
  up quarks are more affected by chiral magnetic effect than down quarks
  Test: measure asymmetries for Delta resonances, charged Kaons vs Ks

Features of the Chiral Magnetic Effect

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

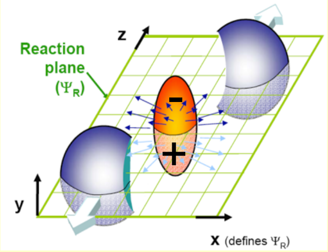
For now it seems that for intermediate energies we have $(Z/A)^2$ dependence

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

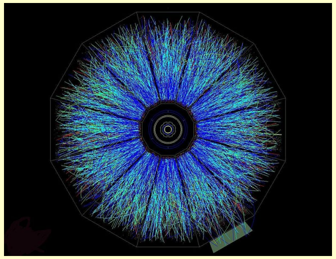
At LHC smaller asymmetries. Magnetic field decays faster.

Conclusions and outlook

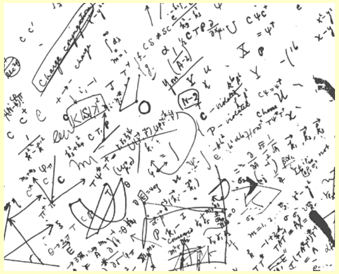
-The Chiral Magnetic Effect can be used to detect
P and CP-violation transitions in QCD.



- This can be done using Heavy Ion Collisions.
Preliminary STAR analysis

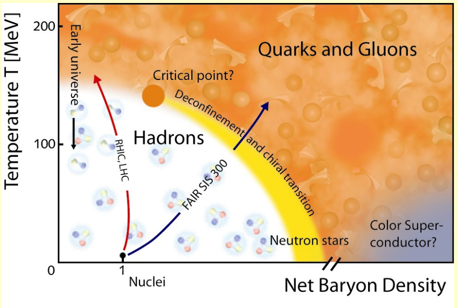


- We can make a number of predictions,
more precise possible.



- 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
- Larry McLerran

- Vasily Dzordzhadze
- Jianwei Qiu
- Ilya Selyuzhenkov
- Yannis Semertzidis
- Sergei Voloshin