The Chiral Magnetic Effect

Or.... how to find P- and CP-odd interactions in the quark-gluon plasma

Or.... how to find topological charge changing transitions in the quark-gluon plasma

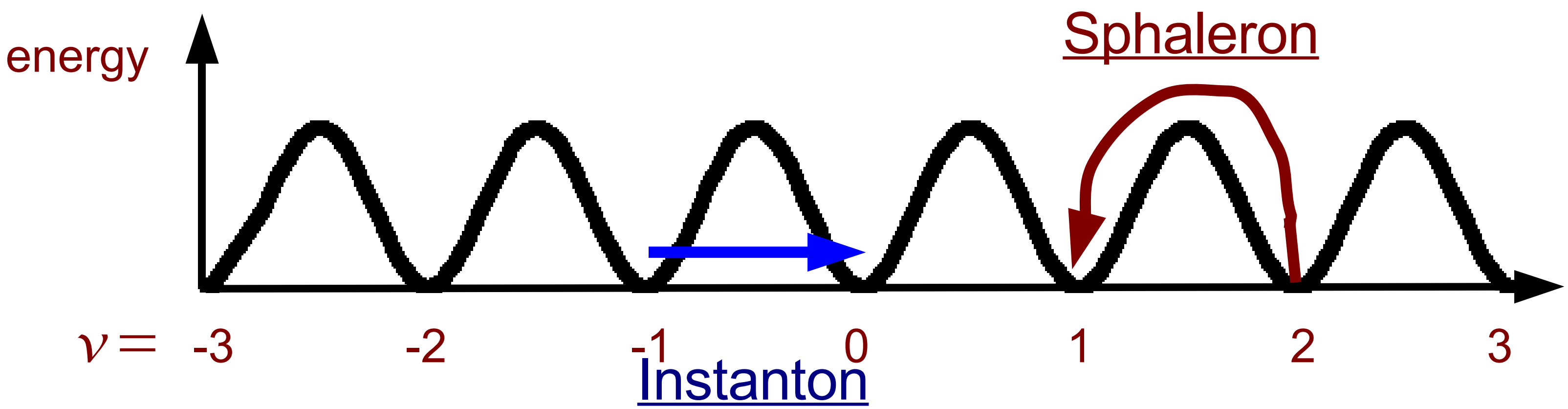
Harmen Warringa, Brookhaven National Laboratory

Based on: Kharzeev, McLerran and HJW, arXiv:0711.0950,
Fukushima, Kharzeev and HJW, arXiv:0808.3382

QCD: Gluon fields can be winded

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

Stable under smooth deformations
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, look for it in QGP!

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

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

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

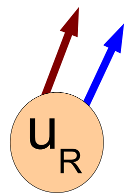
Not only in QGP, also in Glasma Lappi and McLerran ('06)

Winded gluon fields induce chirality P- and CP-odd effect

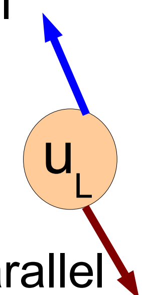
Induce difference between number of left- and right-handed fermions.

In chiral limit:

Right-handed particles

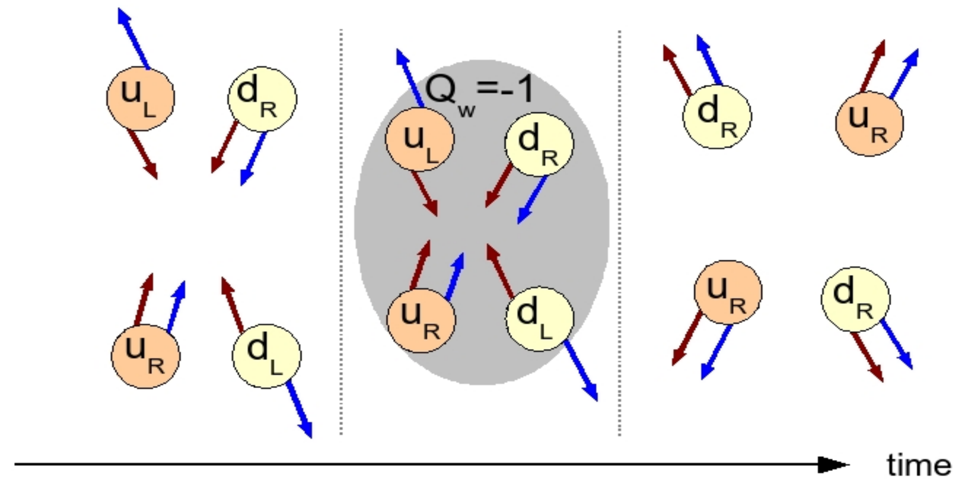


have spin and momentum parallel



Left-handed particles

have spin and momentum anti-parallel



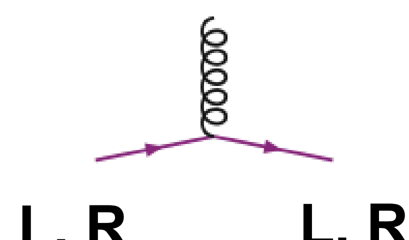
$$[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2N_f Q_w$$

Axial Anomaly, Exact relation!

Adler ('69), Bell and Jackiw ('69)

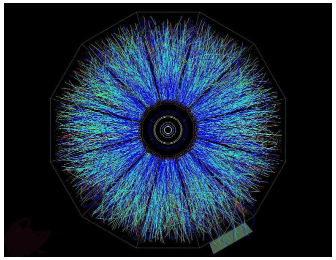
Nonperturbative P- and CP-violating effect

Not possible with ordinary quark-gluon interactions



Strong & ElectroWeak Matter

Strong matter produced
in heavy ion collisions

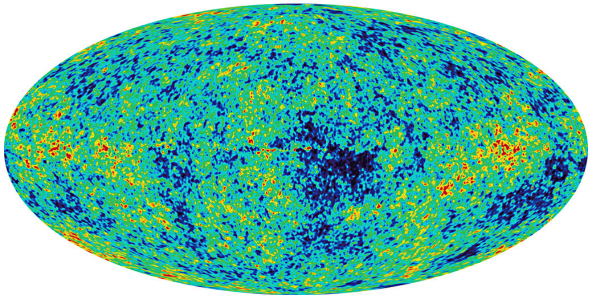


Topological charge changing transitions

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

P- and CP-violating

Electroweak matter produced
in the early universe



Topological charge changing transitions

induce nonzero baryon + lepton number

C- and CP-violating

At high temperatures these transitions are unsuppressed (sphalerons)

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

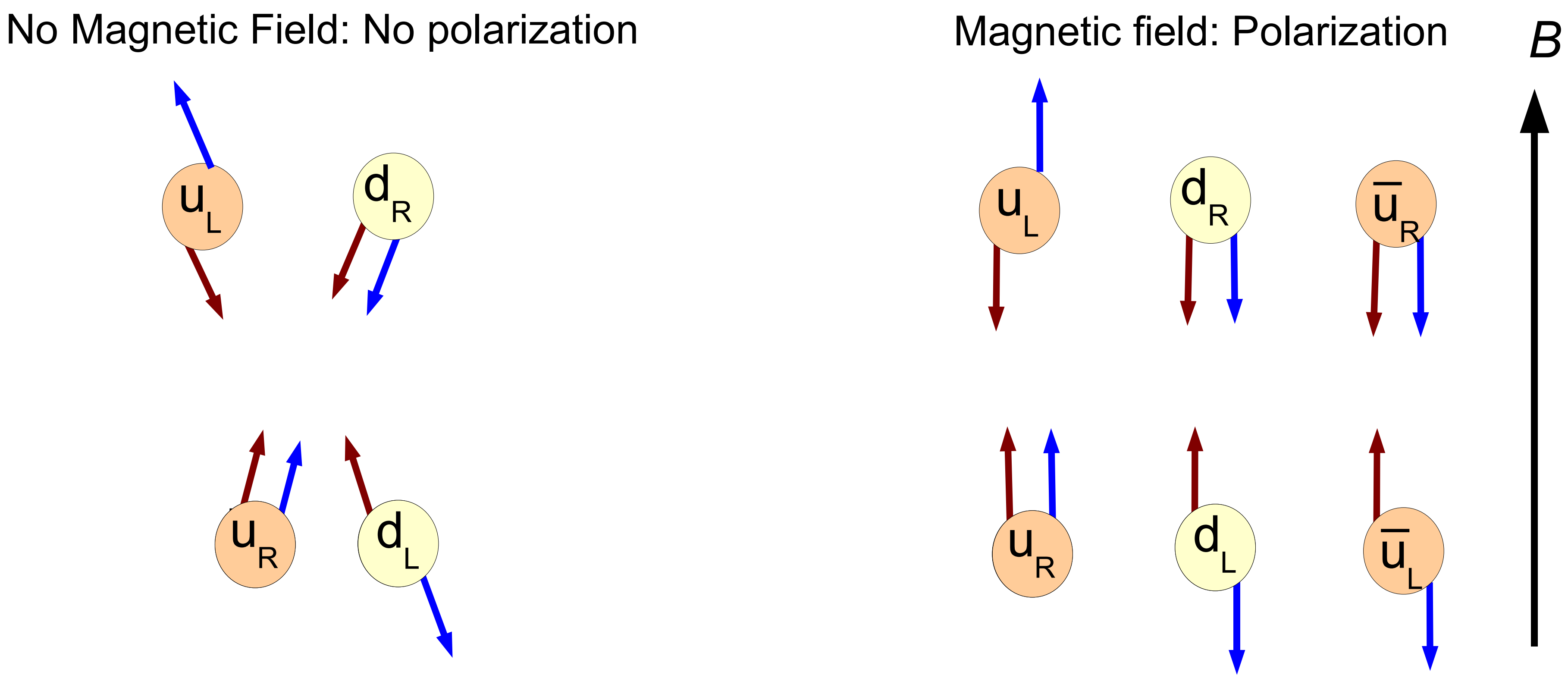
How to observe topological charge changing transitions in hot quark matter?

We observe an asymmetry between matter and antimatter

Kuzmin, Rubakov, Shaposhnikov ('85)

Use Magnetic field to observe Chirality

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

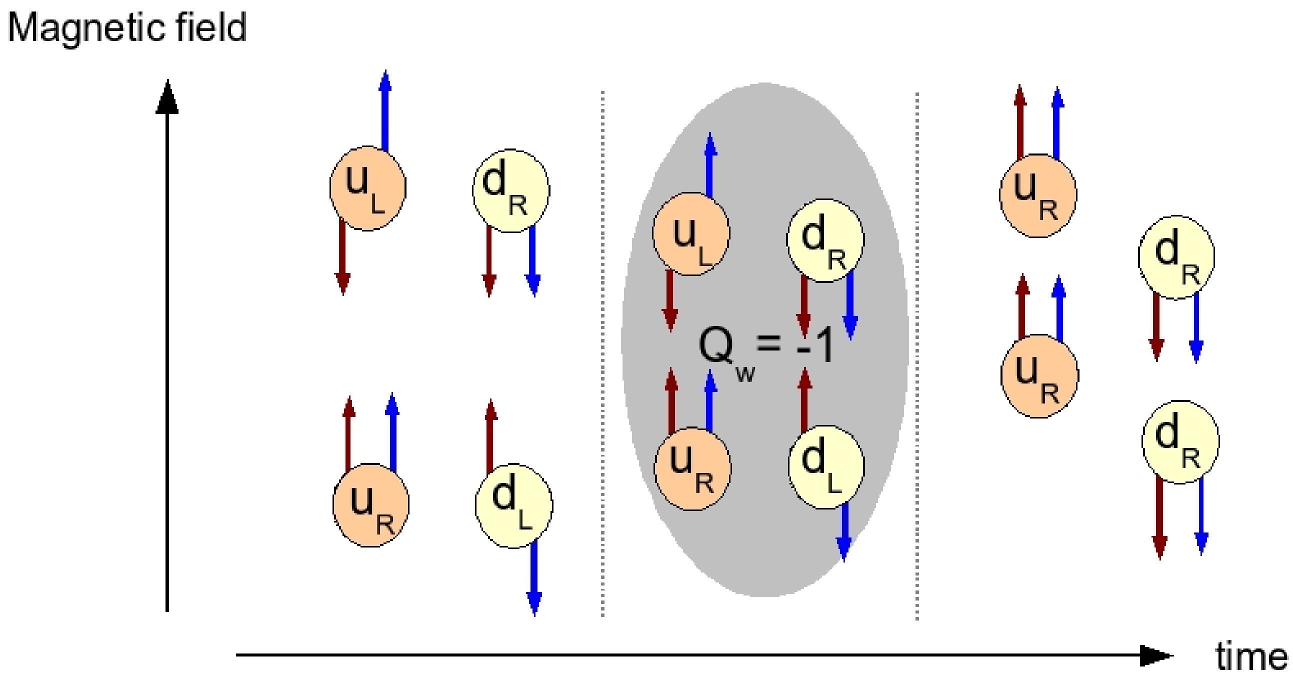


The momenta of the quarks align along the magnetic field

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!

Sphaleron -> quark anti-quark pairs leads to same current

Topological charge charging transitions induces Chirality

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

In finite volume this causes separation of positive from negative charge

Kharzeev, McLerran & HJW ('07)

Reasonable polarization of quarks requires: $e B \sim \frac{1}{\rho^2} \sim \alpha_s^2 T^2 \sim 10^3 - 10^4 \text{ MeV}^2$

The Chiral Magnetic Effect

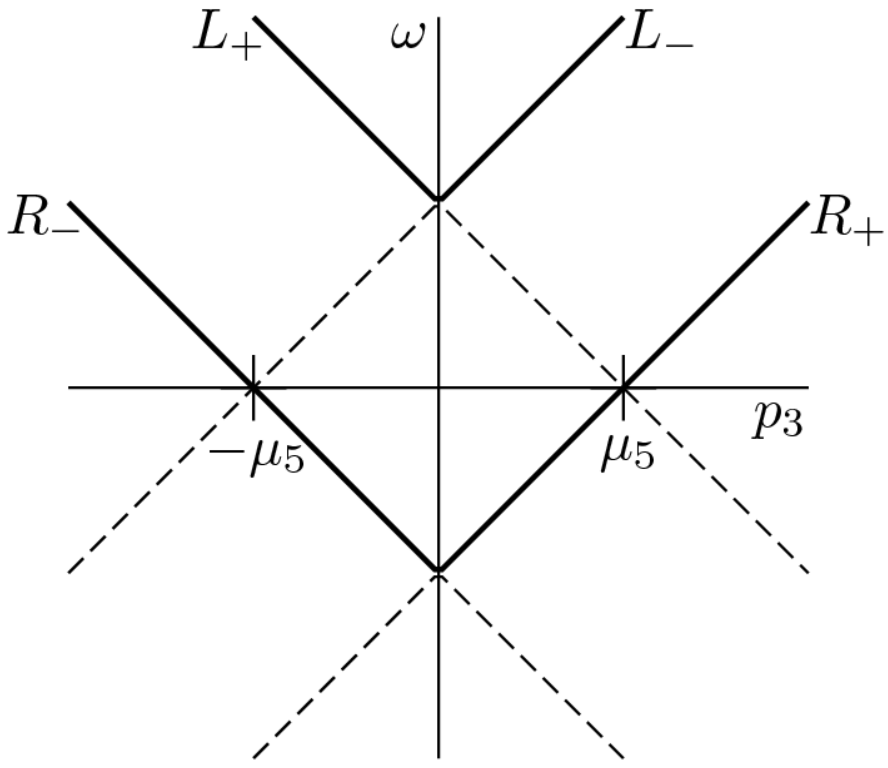
Introduce Chiral Chemical Potential μ_5 to obtain nonzero Chirality
Study equilibrium response to Magnetic Field

$$J^{\mu}=\int d^3x \langle \bar{\psi}\gamma^{\mu}\psi\rangle$$

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

Vecror Current induced
due to Electromagnetic Anomaly

Goldstone and Wilczek ('81),
Nielsen and Ninomiya ('83),
D'Hoker and Goldstone ('85)



Spectrum Massless Fermions with
Nonzero Chiral Chemical Potential

The Chiral Magnetic Effect:

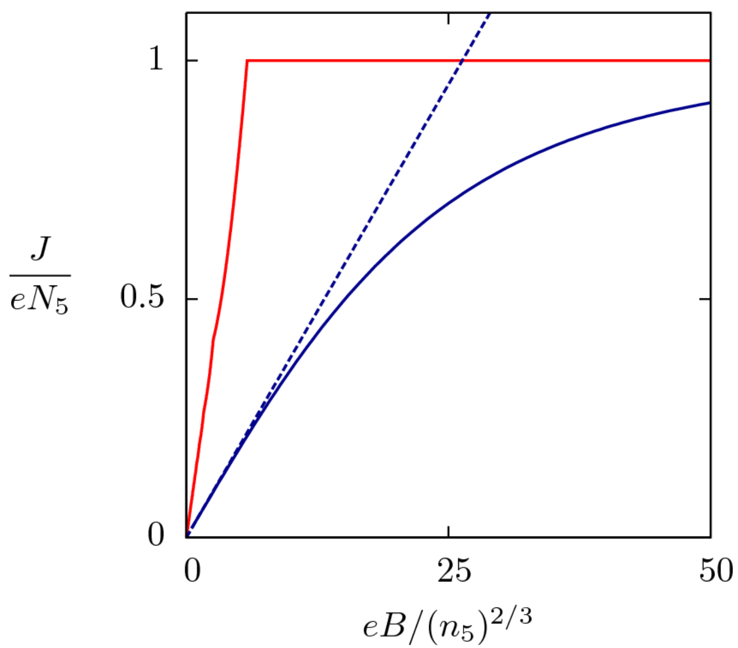
QCD anomaly provides chirality
EM anomaly provides current

Kharzeev, Fukushima & HJW ('08)

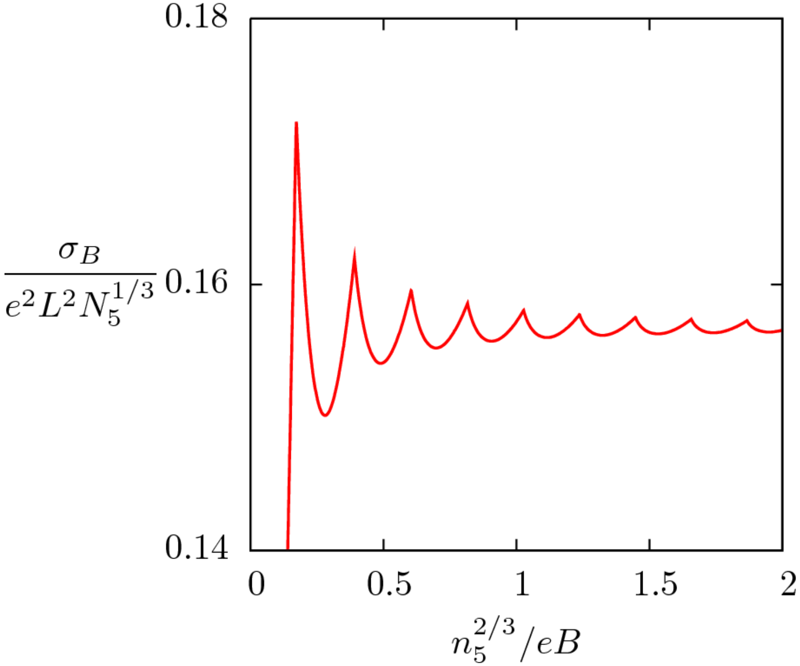
The Chiral Magnetic Effect

Introduce Chiral Chemical Potential to Induce Chirality
Study equilibrium response to Magnetic Field

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



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

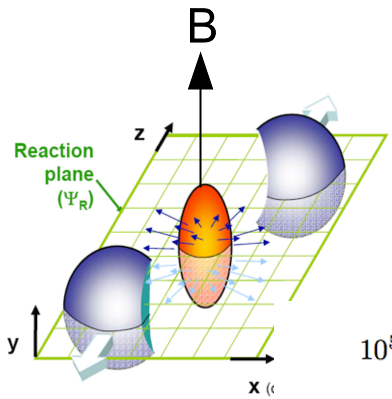


Conductivity vs. inverse magnetic field
at zero temperature (not valid for QCD)

$$J = \frac{3e^2}{2\pi^2} \frac{N_5}{N_f} \frac{1}{T^2 + \mu^2/\pi^2} B \sum_f q_f^2$$

Kharzeev, Fukushima & HJW ('08)

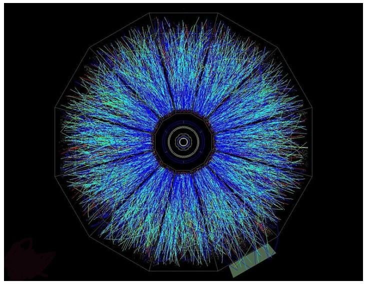
Magnetic Field in Heavy Ion Collisions

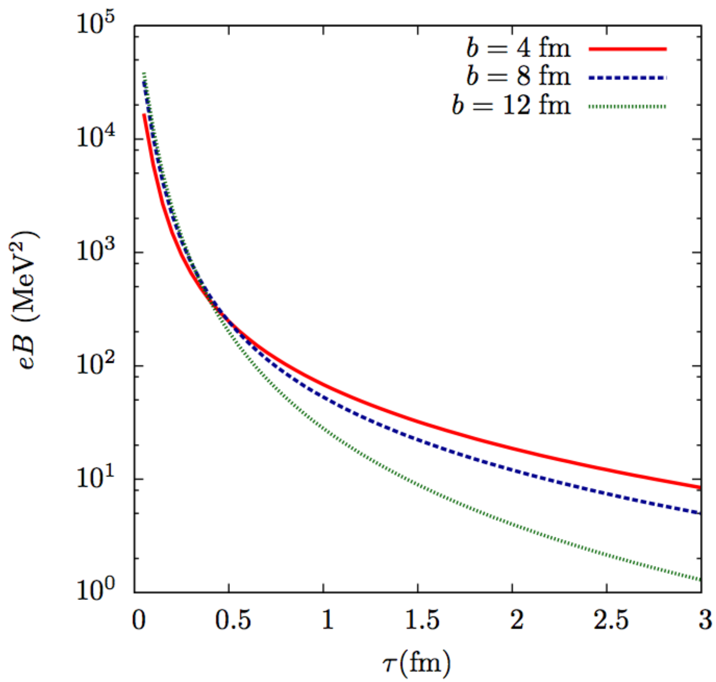


Computed numerically at origin in pancake approximation

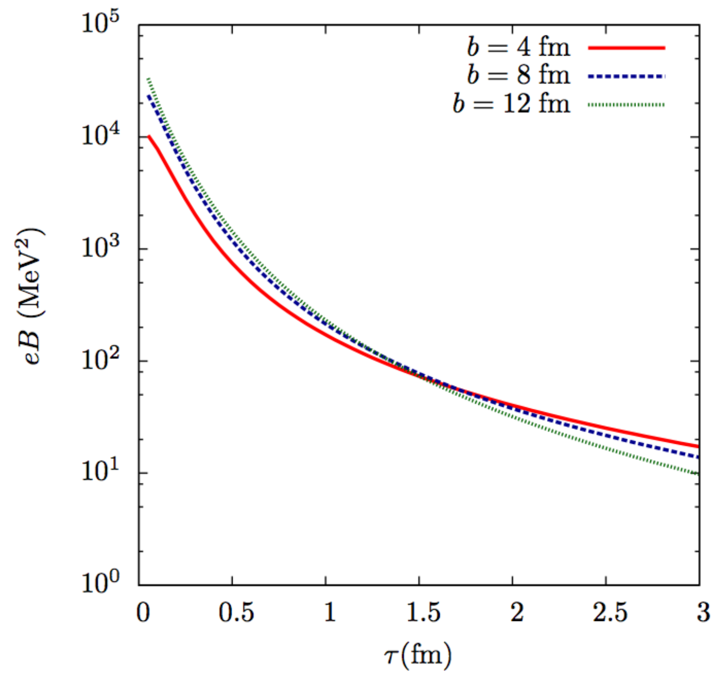
RHIC@BNL

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





100 GeV per Nucleon



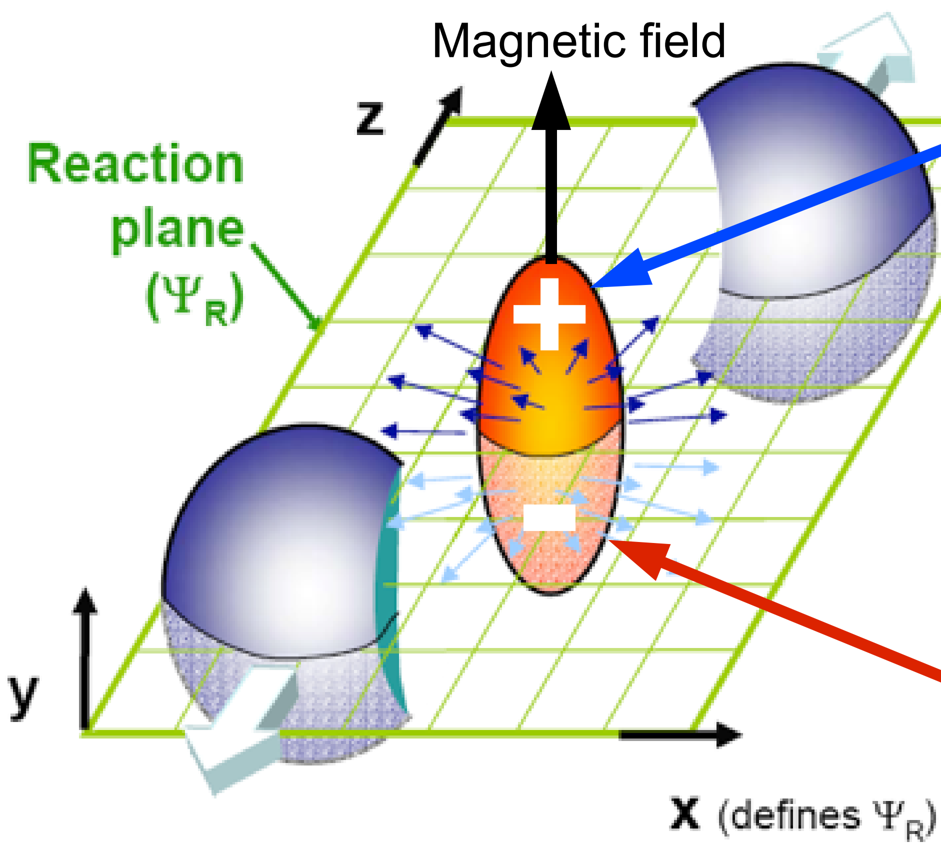
31 GeV per Nucleon

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 $\phi=\pi/2$

Caused by sphalerons in quark-gluon plasma
In combination with Magnetic Field heavy ions

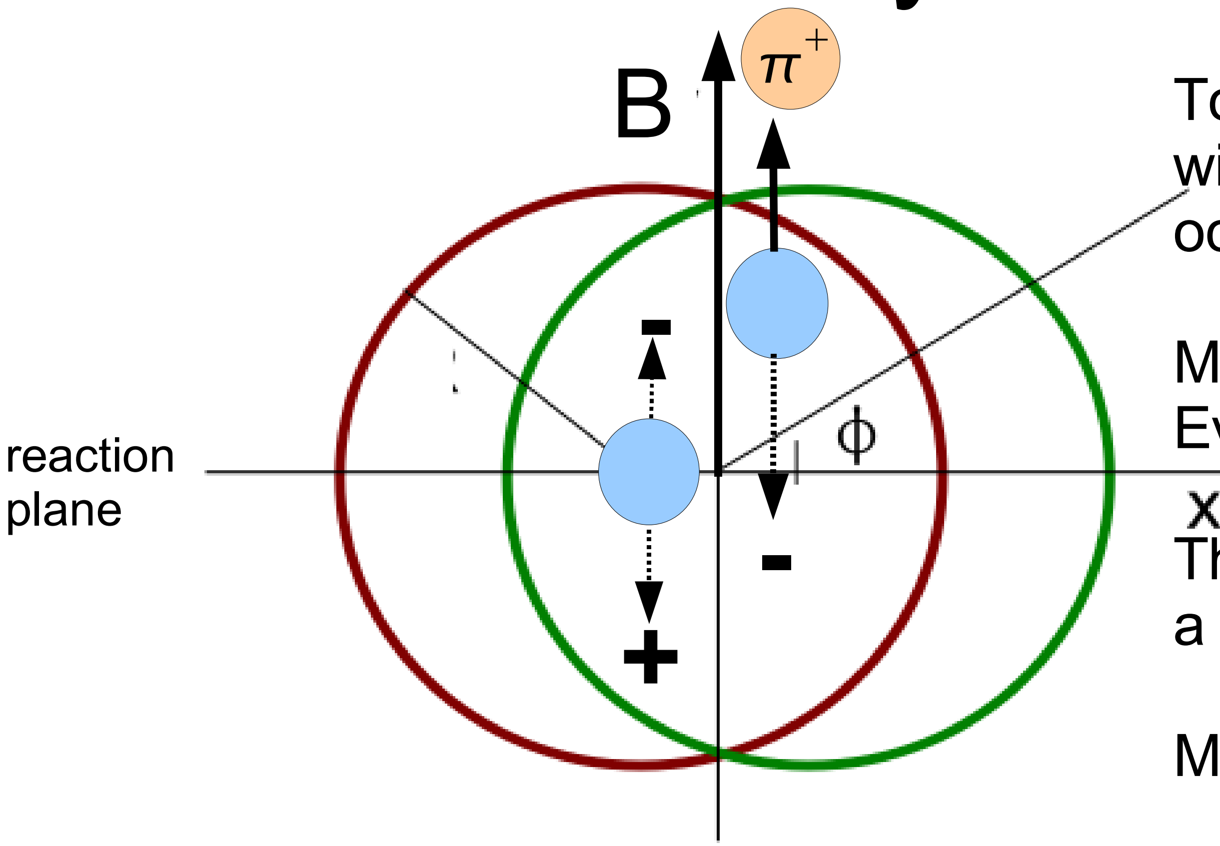
Excess of Negative Charge on other side of Reaction Plane around $\phi=3\pi/2$

Charge conserved in hadronization:

More positively charged quarks implies more positively charged hadrons

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

The Chiral Magnetic Effect in Heavy Ion Collisions



Topological transitions with fluctuating winding number occur anywhere in the QGP

Measure: Variances -> nonzero Event-by-Event P- and CP-violation

The Chiral Magnetic Effect is a near the surface effect

Medium causes screening

Variance of charge difference between both sides reaction plane:

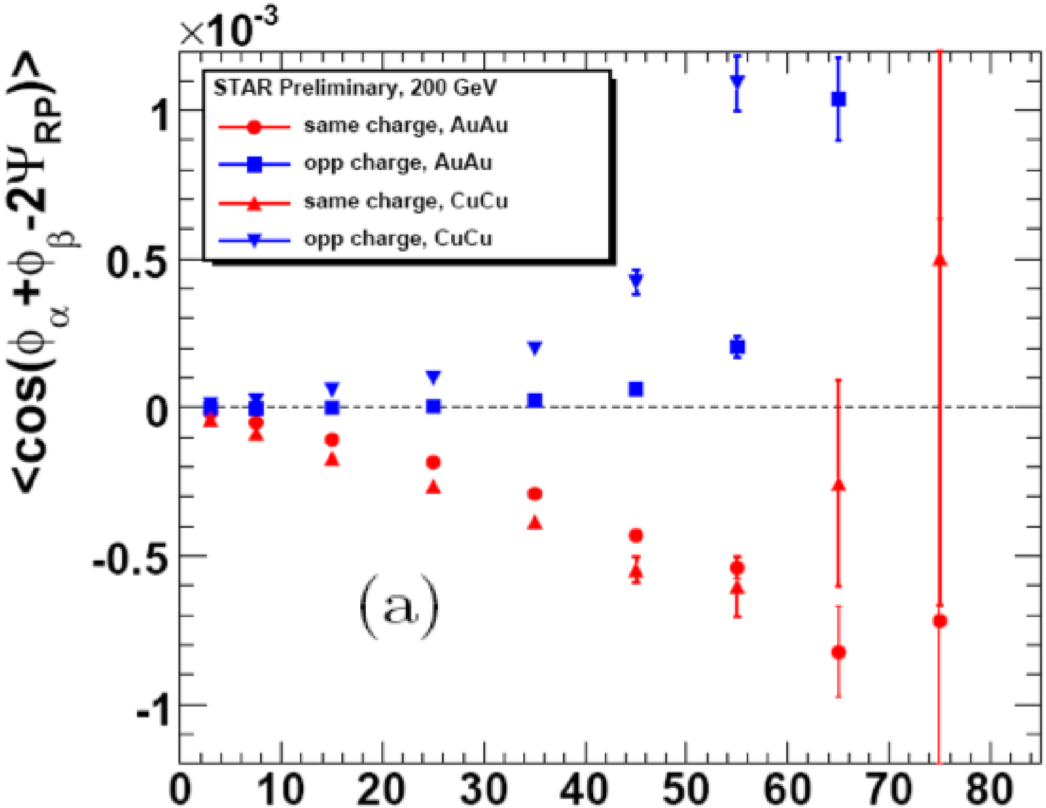
$$\langle \Delta_{\pm}^2 \rangle = 2\int_{t_i}^{t_f} \mathrm{d}t \int_V \mathrm{d}^3 x \; \frac{\mathrm{d} N_t}{\mathrm{d}^3 x \, \mathrm{d} t} \; [\xi_+^2(x_\perp)+\xi_-^2(x_\perp)] \; \left(\sum_f q_f^2 e B \rho\right)^2$$

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

Estimate magnitude asymmetry for large impact paramater 10^{-4} with 1-2 orders of magnitude uncertainty.

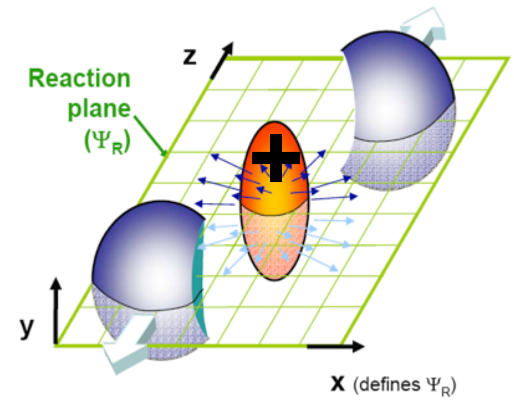
Preliminary data Au & Cu 200 GeV

minimum bias

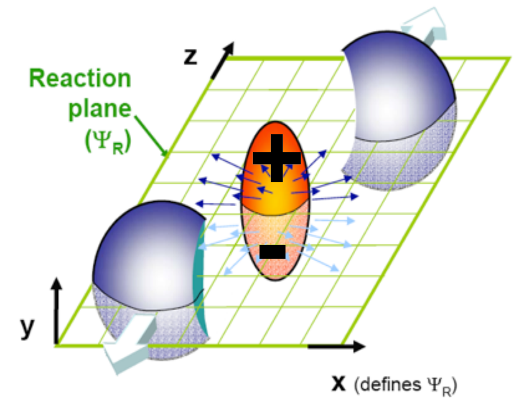


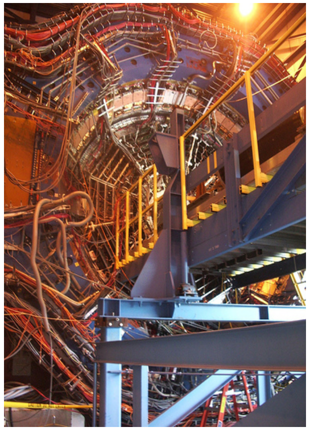
Most Central % Centrality Most peripheral

Red points:



Blue points:





Sergei Voloshin
(STAR Collaboration)
Quark Matter 2008

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

Features of the Chiral Magnetic Effect

An order parameter for Confinement / Deconfinement

If quarks are confined quarks cannot be separated over long distances.

Hence Chiral Magnetic Effect does not work.

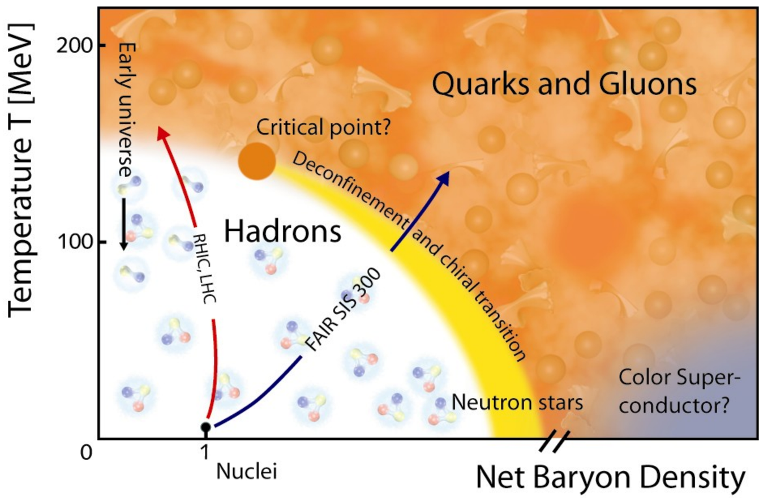
An order parameter for Chiral Symmetry Breaking / Restoration

If chiral symmetry is broken: a nonzero chirality will be quickly removed by the chiral condensate

Hence Chiral Magnetic Effect does not work

No QGP: No Chiral Magnetic Effect

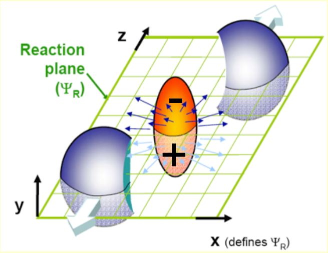
Test: Energy scan



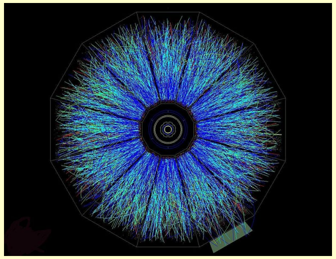
The correlators are proportional to Z^2

Test: use nuclei with same A and different Z, isobars

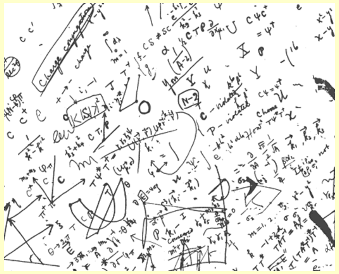
Conclusions and outlook



- The Chiral Magnetic Effect can be used to detect topological charge changing transitions in QCD (sphalerons, ...). Event-by-event P- and CP-violation.

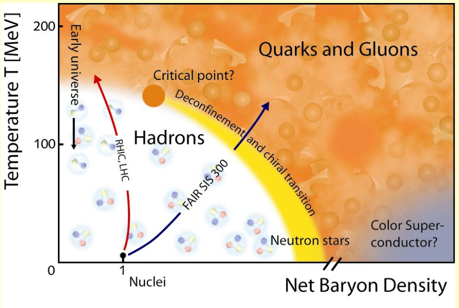


- This can be done using Heavy Ion Collisions. Preliminary STAR analysis show interesting results



- 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 and confinement/deconfinement.

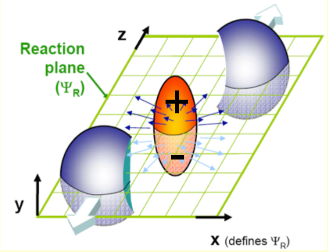
Thanks for your attention

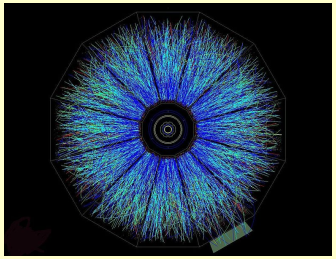
And thanks to:

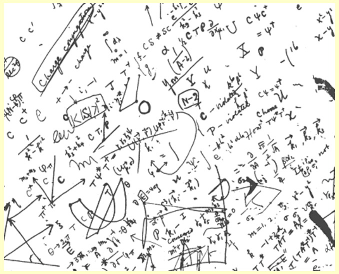
- The organizers of SEWM 08

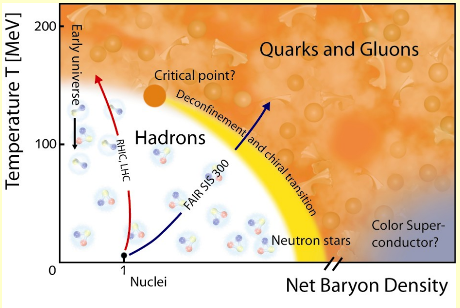
- Dmitri Kharzeev
- Larry McLerran
- Kenji Fukushima

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

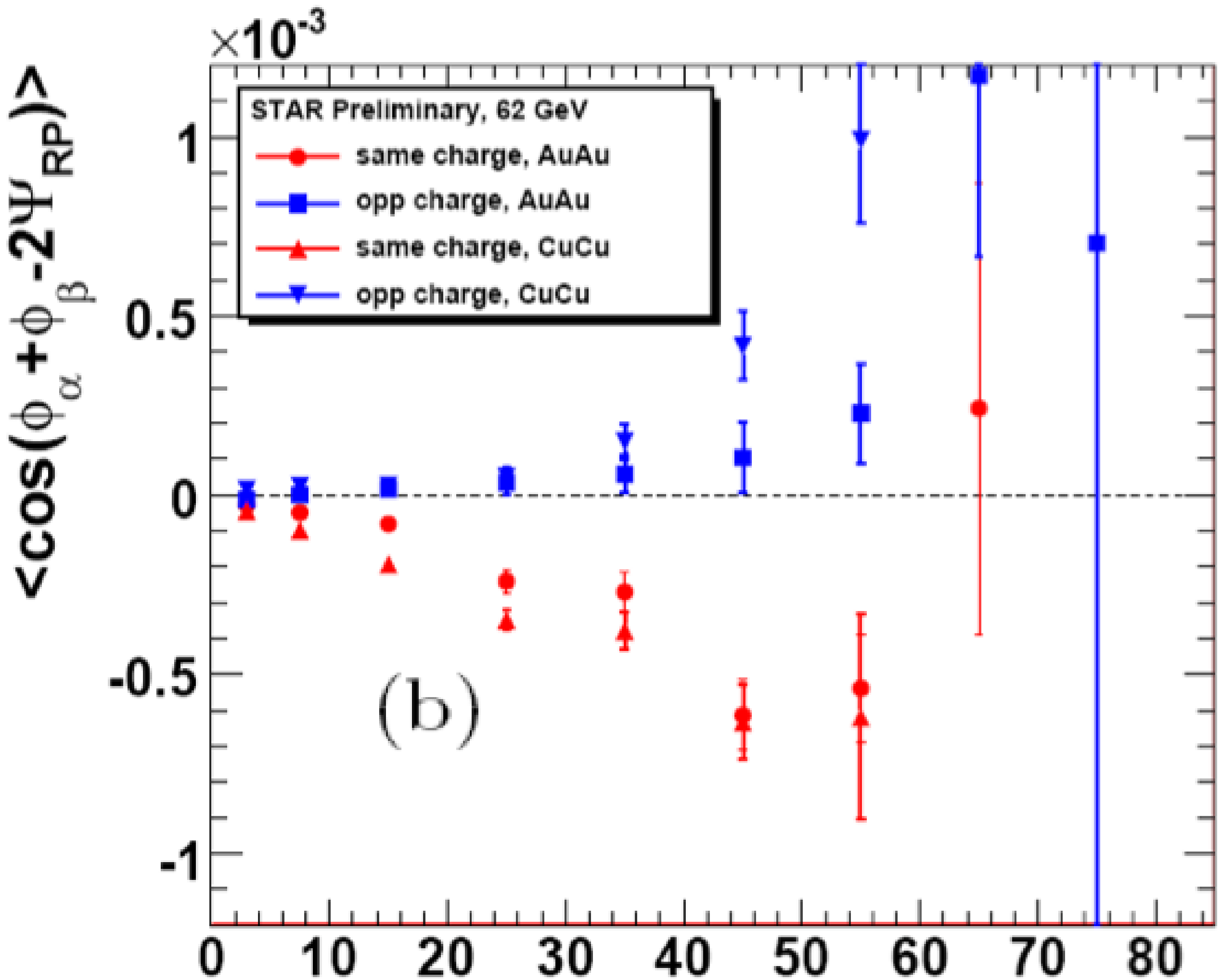






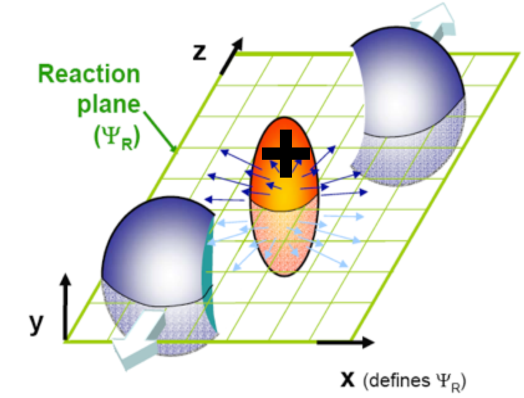


Preliminary data Au & Cu 62 GeV

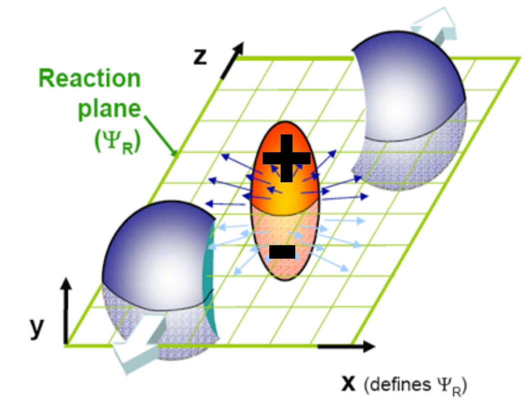


Most Central % Centrality Most peripheral

Red points:



Blue points:



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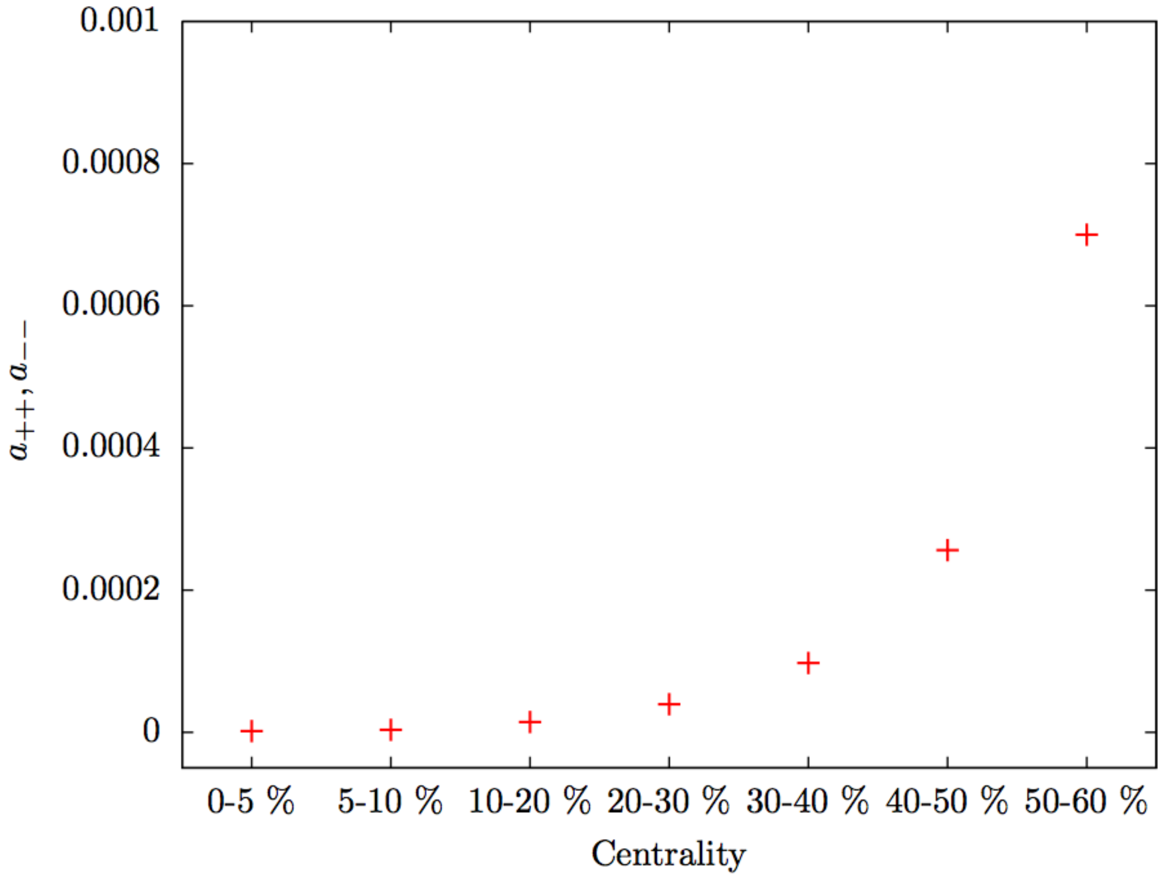
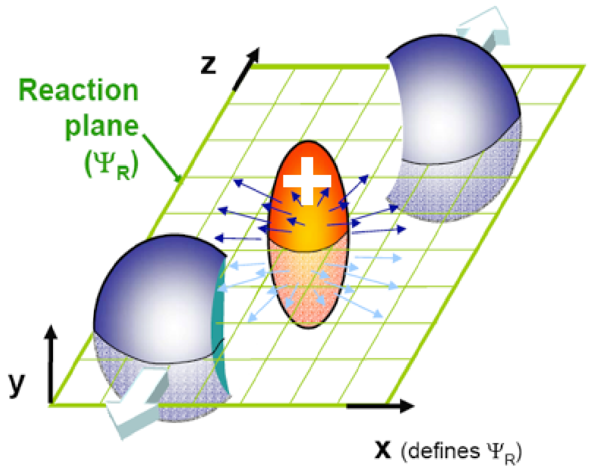
Chiral Magnetic Effect prediction: Correlators vs. Centrality



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

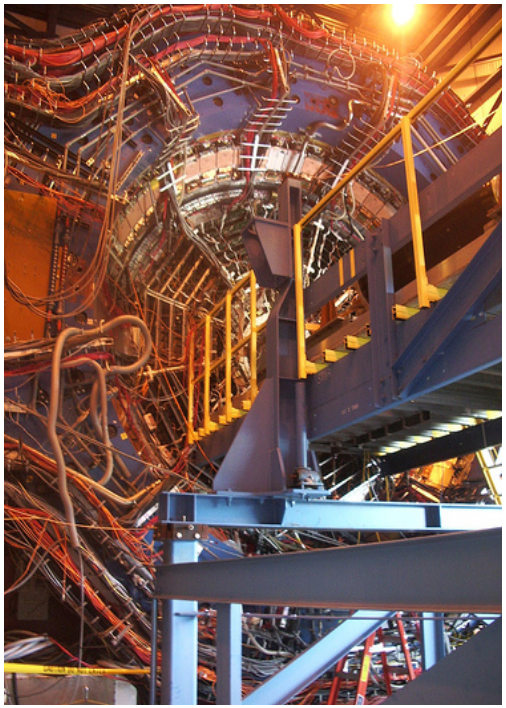
Preferential emission of positively charged particles around $\phi = \pi/2$ or $\phi = \pi/2$



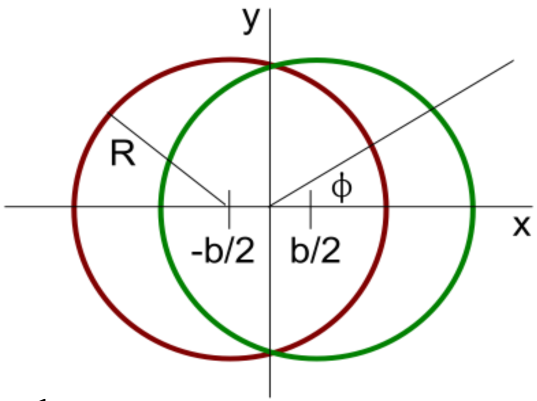
A possible result of the Chiral Magnetic Effect in Gold-Gold collisions at 130 GeV per nucleon

Observables

Voloshin ('04)



STAR detector
Full azimuthal coverage



ϕ : angle between particle and reaction plane

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

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

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.

Measurements suggest

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

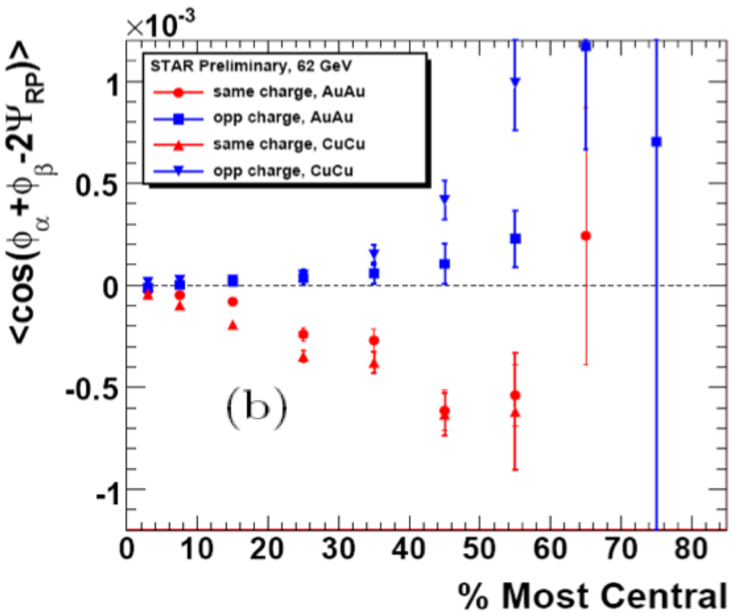
Correlations between positively charged particles and negatively charged particles on opposite sides.

Existence of screening effect.

About 1-3 % asymmetry

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.



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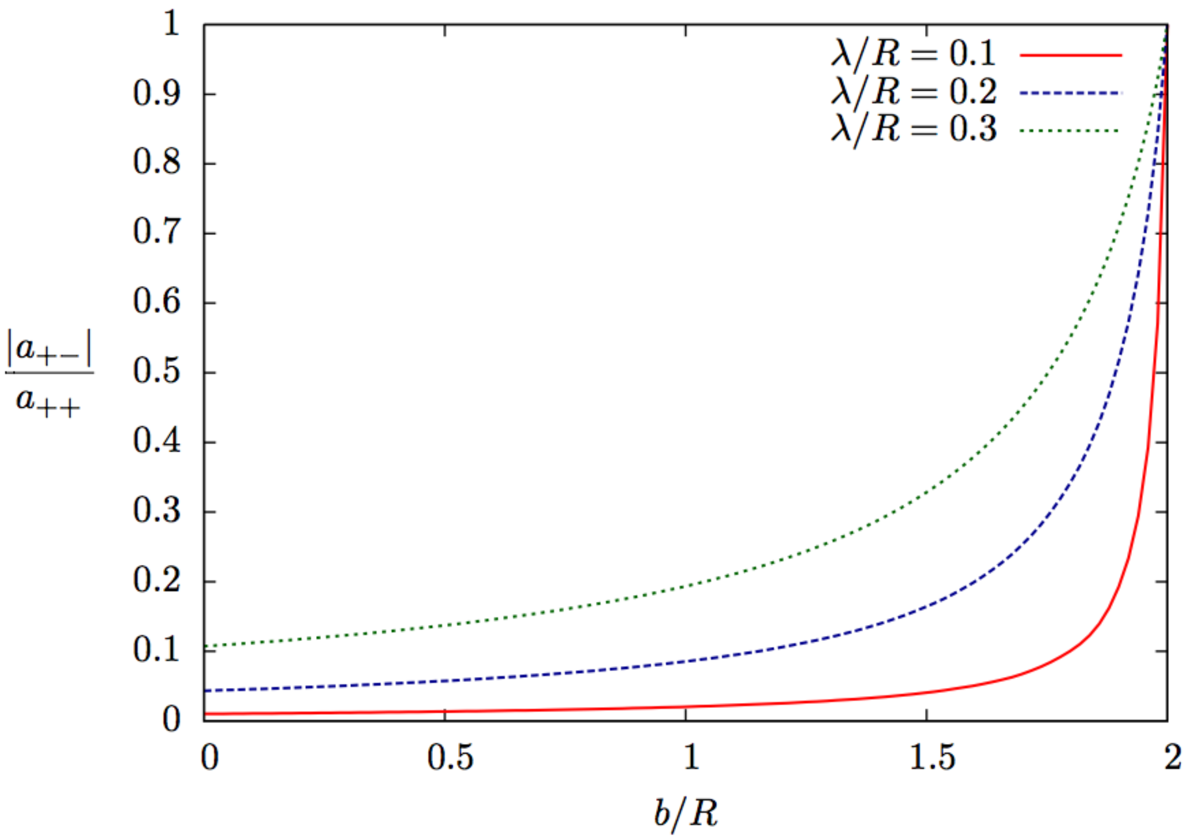
Is it due to the Chiral Magnetic Effect or due to something else, and how to find out?

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