Chiral Magnetic Effect

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Talk Plan

- Chiral Magnetic Effect ~ conventional explanation
- Current from infinity – *What really flows?*
- Chiral Magnetic Effect in a hadronic phase
- Is there a current... or not? *Signature of what??*
- Experimental challenges and theories

Chiral Magnetic Effect
~ conventional explanation ~

Basic Formula

Chiral Magnetic Effect

$$\boldsymbol{j} = N_c \sum_{\text{flavor}} \frac{q_f^2 \mu_5}{2\pi^2} \boldsymbol{B}$$

Basic Formula

Chiral Magnetic Effect

Hard to understand

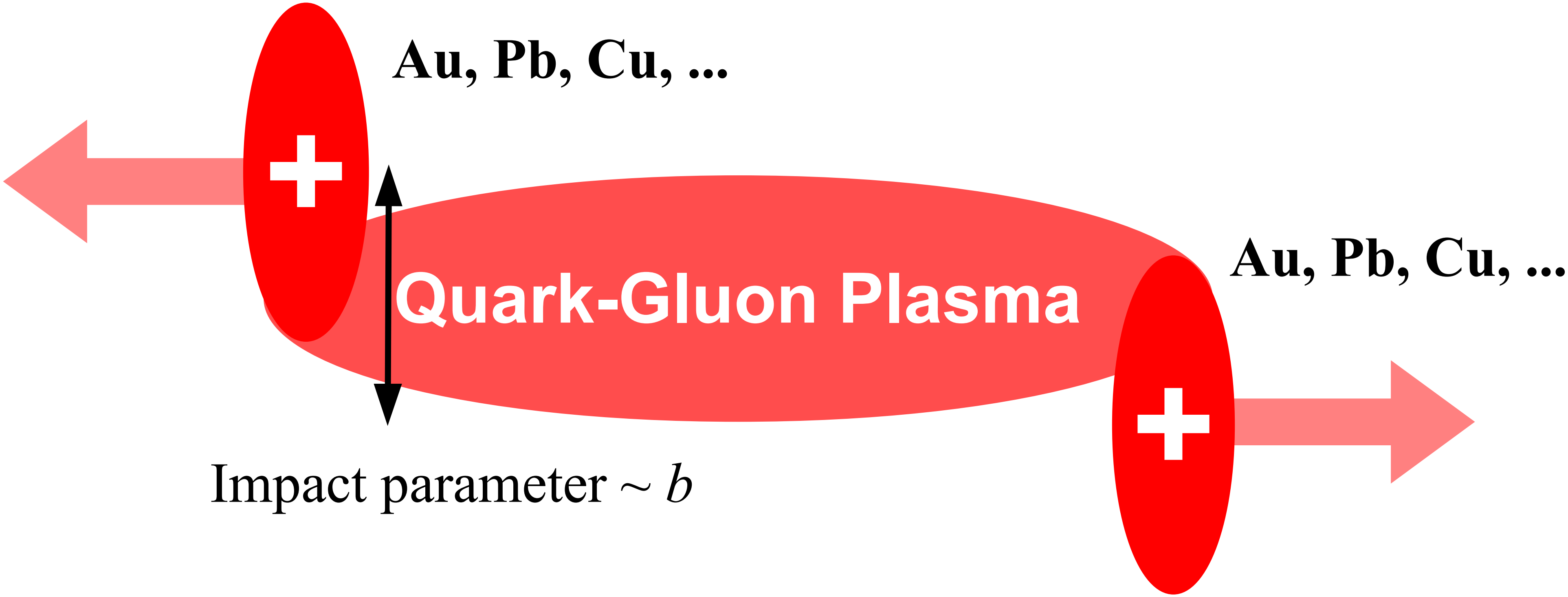
$$\boldsymbol{j} = N_c \sum_{\text{flavor}} \frac{q_f^2 \mu_5}{2\pi^2} \boldsymbol{B}$$

Easy to understand

Very hard to understand

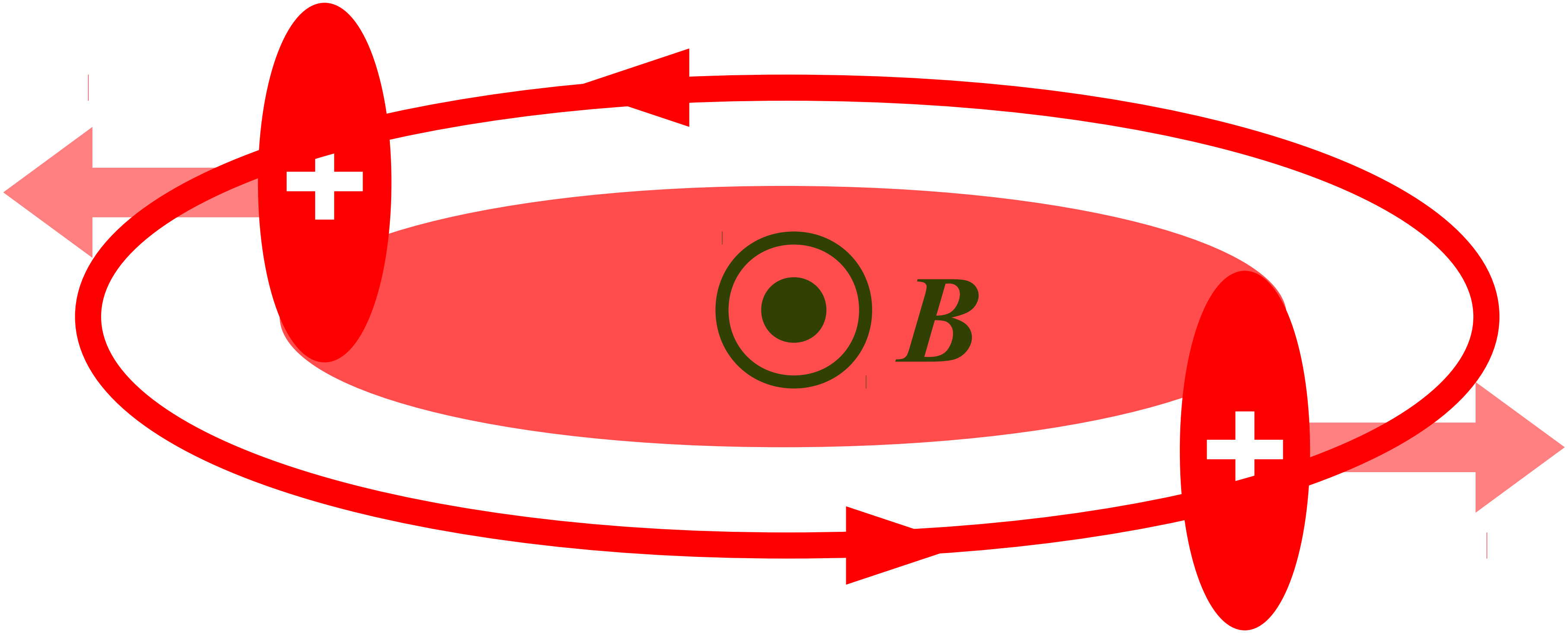
Origin of the Magnetic Field

Moving almost at the speed of light



Origin of the Magnetic Field

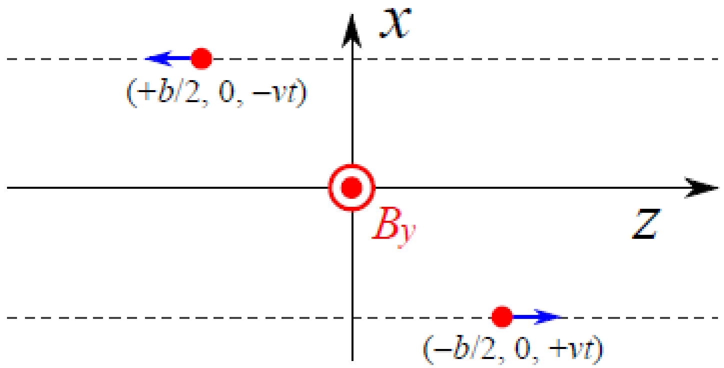
Strong B generated due to Electrodynamics

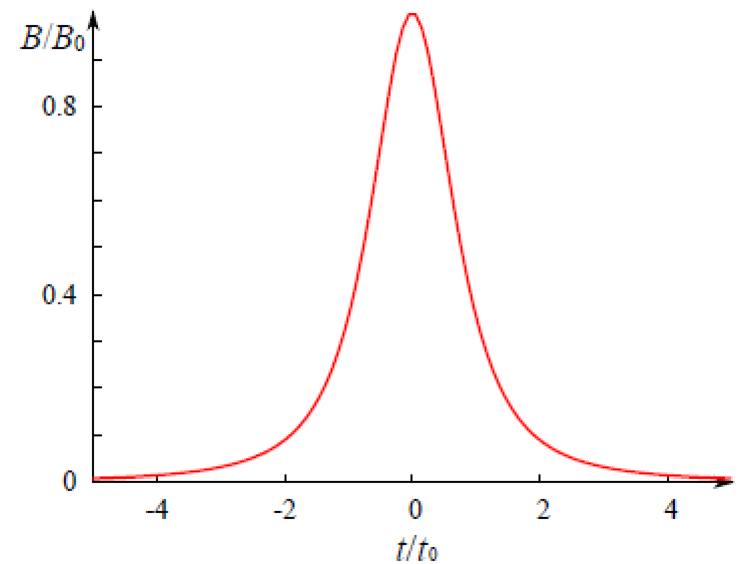


on top of the Quark-Gluon Plasma

Point-charge Approximation

Lienard-Wiechert potential





$$eB(t) = \frac{eB_0}{[1+(t/t_0)^2]^{3/2}}$$

$$eB_0 = (47.6\,\mathrm{MeV})^2 \left(\frac{1\,\mathrm{fm}}{b}\right)^2 Z \underbrace{\sinh(Y)}_{\sim\gamma} \quad , \qquad t_0 = \frac{b}{2\sinh(Y)}$$

Discussed by Rafelski, Mueller, … (~1976)

Physics of the Strong Magnetic Field

Magnetic field looks like a "medium"

A photon becomes massive.
Generally, the dispersion relations of photons with respective polarizations are distorted (Birefringence)

A photon on top of *B* decays into pair particles.

Chiral symmetry breaking is enhanced.

Not known how the phase diagram is affected.
Pion structural change is hardly understood...

Fukushima-Hidaka

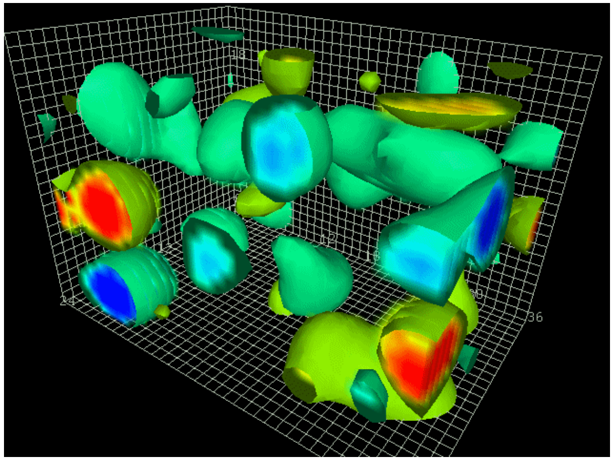
Origin of the Chiral Chemical Potential

Generation of the chiral charge

$$\frac{dN_5}{dt} = -\frac{g^2 N_f}{8\pi^2}\int d^3x\ \mathrm{tr}\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Chirality ⟵ Topological charge density

Topologically non-trivial gauge configuration



Derek's visual QCD

$\Rightarrow N_5 \Rightarrow \mu_5$

Origin of the Topological Charge Q_w

Topologically non-trivial gauge configurations

Instanton (tunneling under barrier)

Lives only in Euclidean space-time

Makes the η' meson heavy

Suppressed at high temperature $\chi \sim \exp[-c\rho^2 T^2]$

Sphaleron (excitations over barrier)

Lives in Minkowski space-time

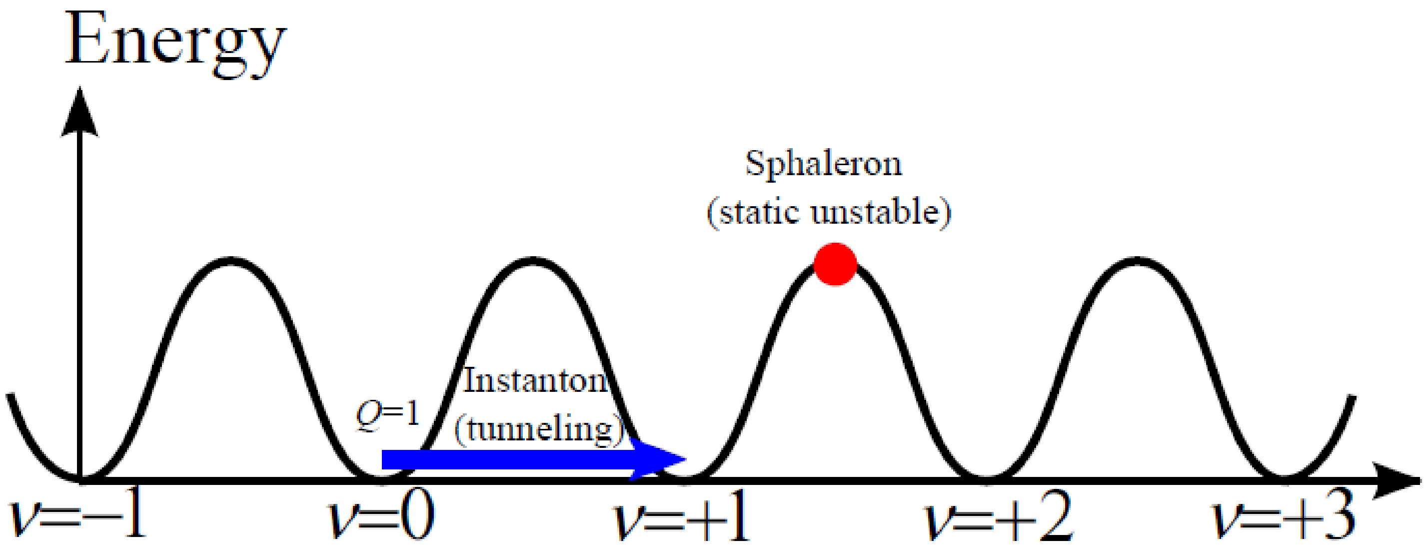
Breaks the baryon and lepton numbers (in the weak int.)

Enhanced at high temperature $\Gamma \sim T^4$ **Arnold-McLerran Kharzeev-McLerran--Warringa**

Sphalerons get excited (~1fm/c) only after *B* decays

Origin of the Topological Charge

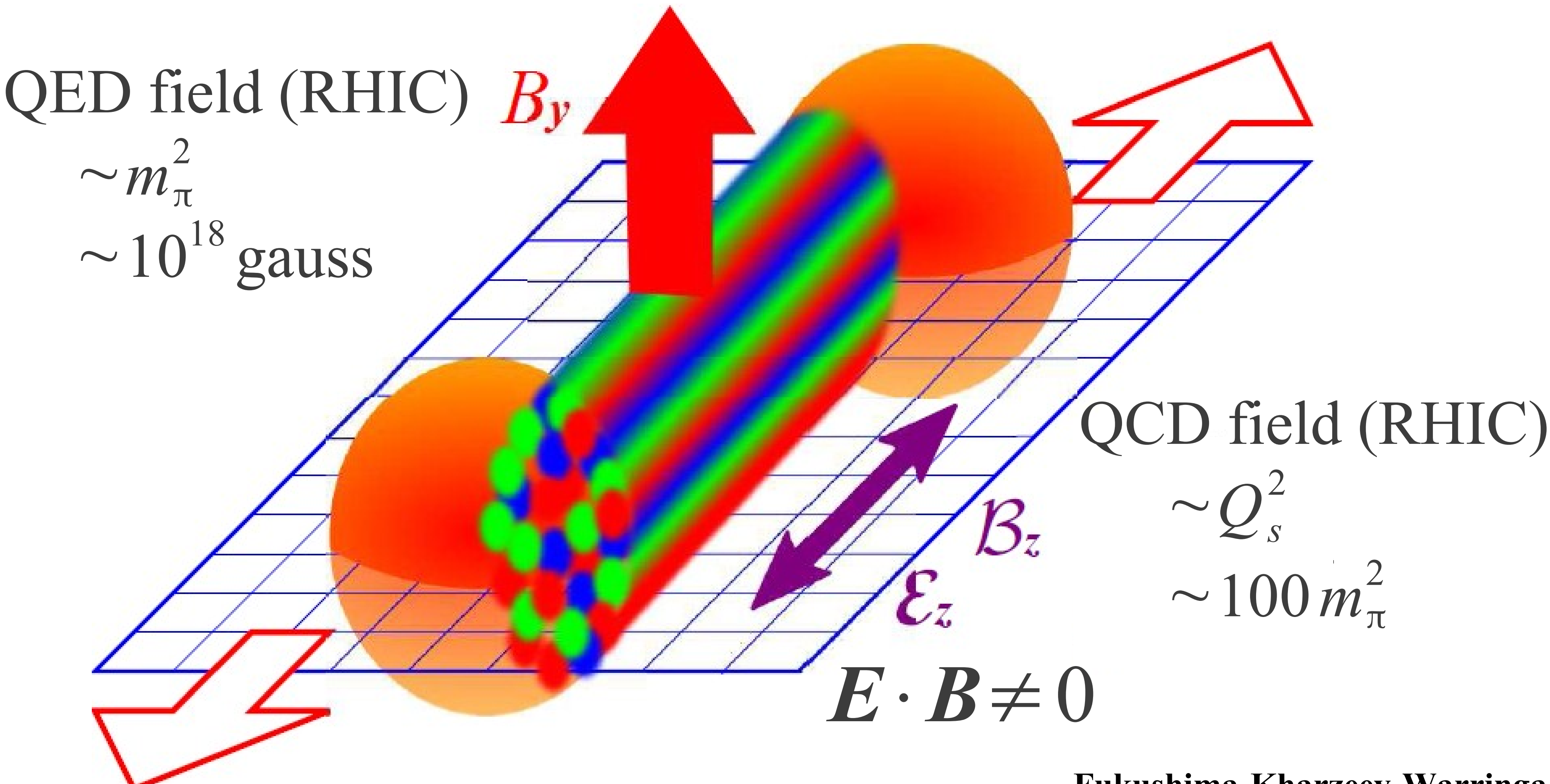
Difference between instanton and sphaleron



Instantons (Euclidean windings) are suppressed at high *T* but communications in real time are not and dominated by the contribution from the zero-winding sector.

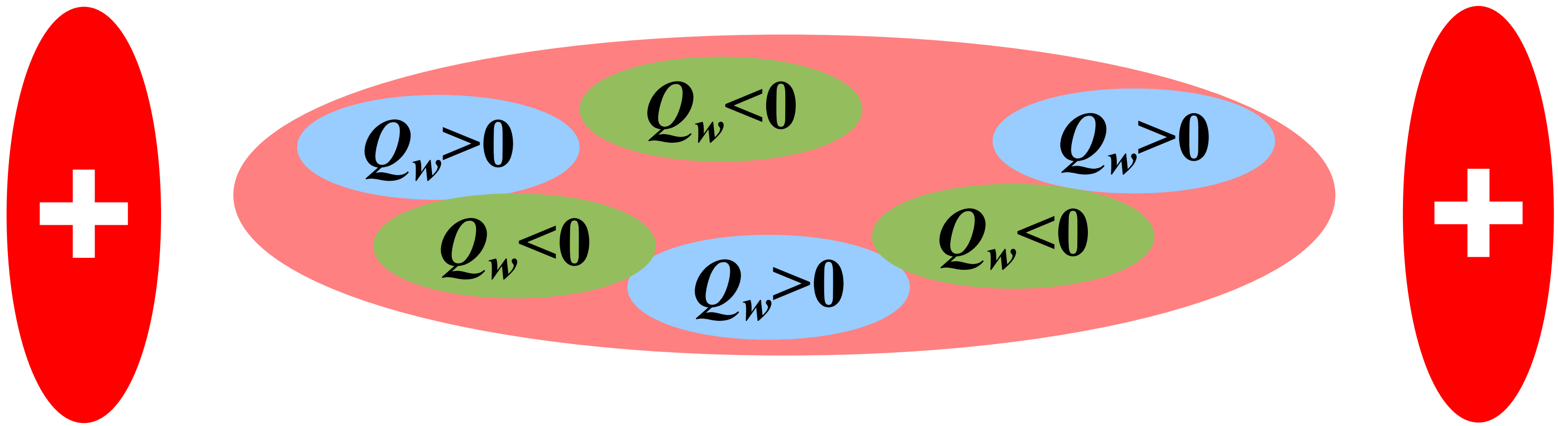
Origin of the Topological Charge

Color Glass Condensate



Fukushima-Kharzeev-Warringa

Local Parity Violation (LPV)



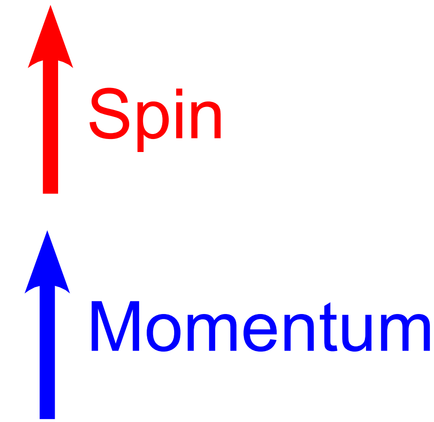
Physics Impact

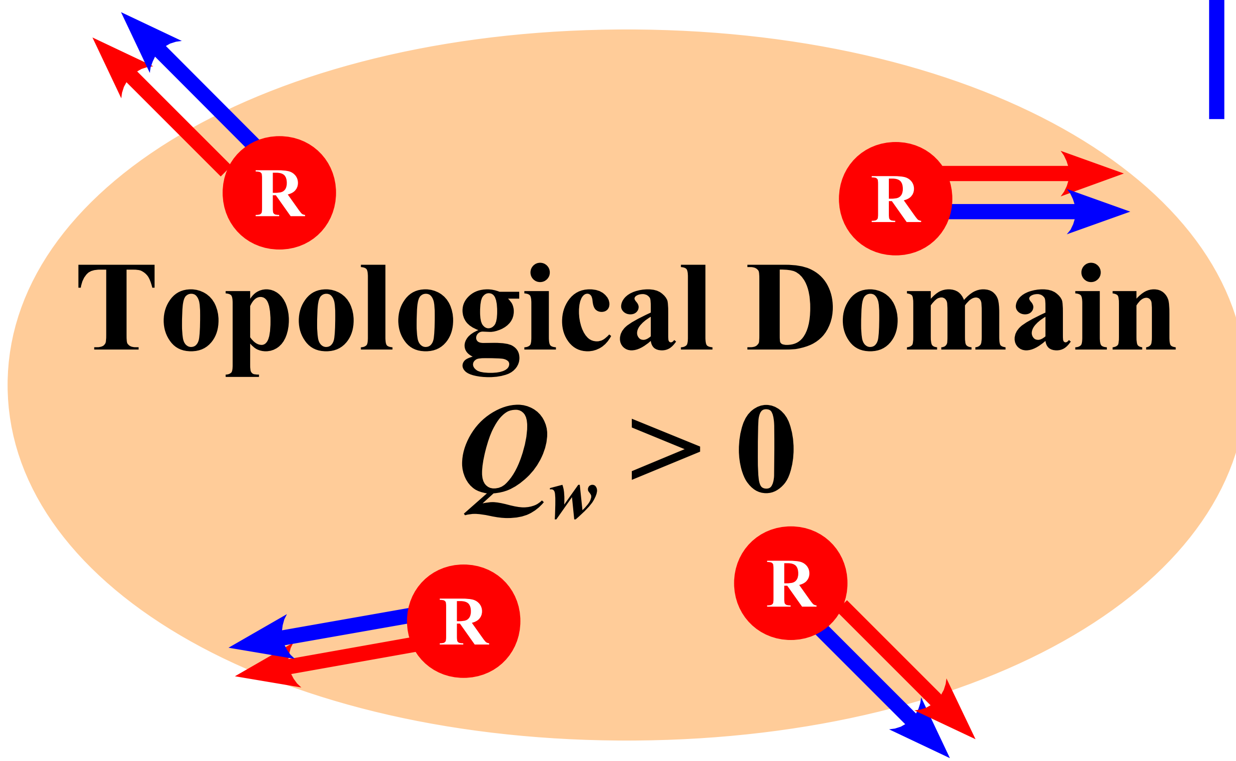
Experimental evidence for the quantum anomaly
Origin of the mass – QCD instanton never detected
Particle production from the CGC initial condition

Charge Separation

Without *B* Fields

Net Current $\langle J \rangle = 0$

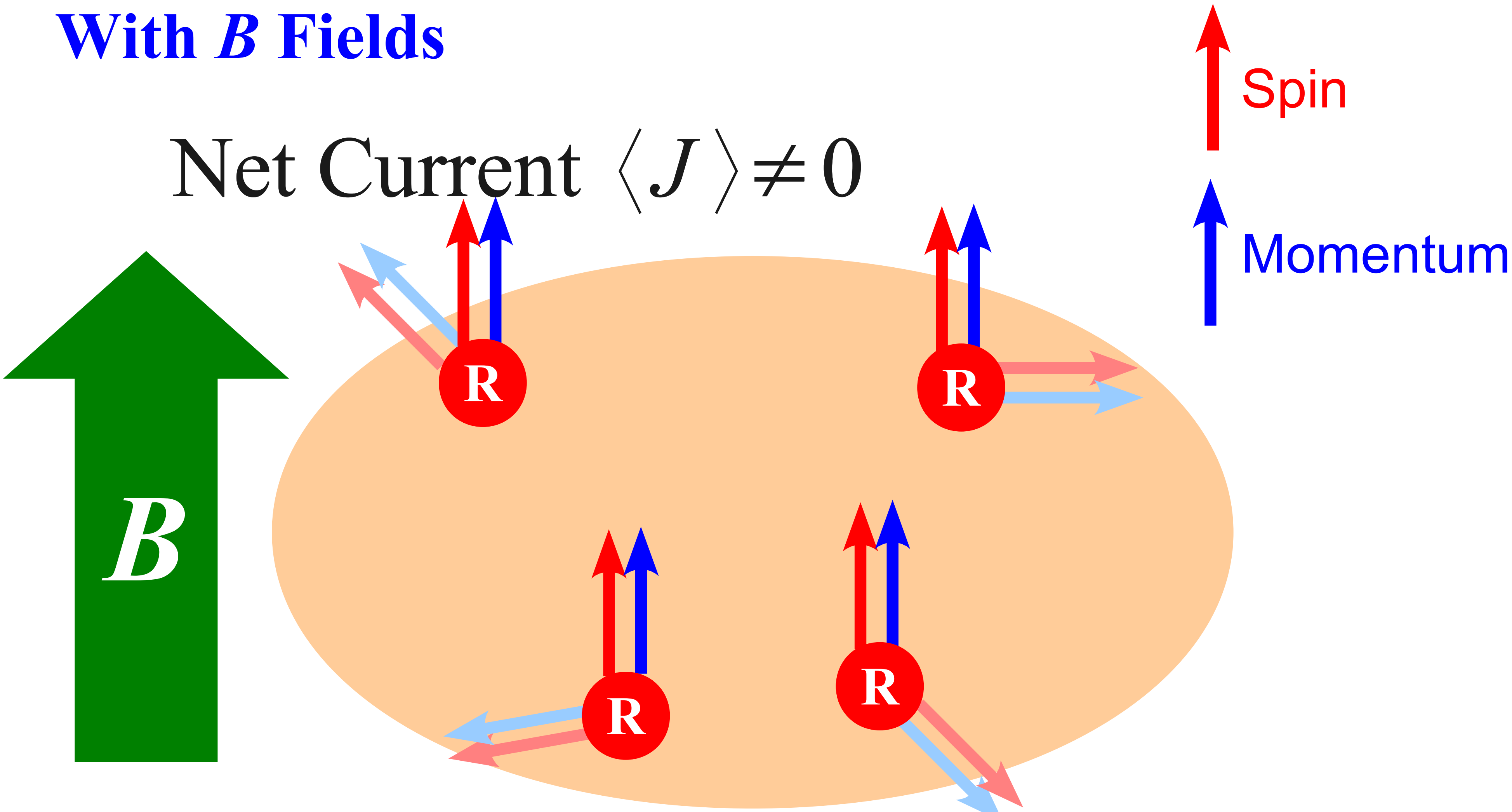




Charge Separation

With *B* Fields

Net Current $\langle J \rangle \neq 0$



Kharzeev-McLerran-Warringa

Caution!

Such a classical picture is not correct!

With the *B*-effect many phenomena (related to the Landau quantization) look classical, but their origin is purely quantum!

Caution!

Such a classical picture may easily lead people to a wrong interpretation of the chiral magnetic effect!

Deconfined and light (chiral-symmetric) quarks are seemingly necessary... but really so?

Current from infinity

– What really flows?

Landau Quantization

Energy dispersion relation in *B*

$$\omega^2 = p_z^2 + \underline{2|gB|(n+1/2)} + m^2 - 2sgB$$

Transverse motion = Harmonic Oscillator

- **Light fermions (s=1/2) have zero mode.**
  (Nearly) massless quarks at high T and/or μ
- **Light vector bosons have (Nielesen-Olesen) instability.**
  Gluons in the chromo-B / ρ in a superstrong B **(Chernodub)**
- **Charged scalar bosons are all massive.**
  π^+, π^-, … Explicit breaking of isospin symmetry

Etc, etc...

Quantum Anomaly

Formula insensitive to *M*, *T*, *μ* ← IR scales

Zero-point Oscillation

$$\Gamma = -N_c \sum_{\text{flavor}} \frac{|q_f B|}{2\pi^2} \sum_s \sum_{n=0}^{\infty} \alpha_{n,s} \int_{-\infty}^{\infty} \frac{dp_z}{2\pi} \omega_{n,s}$$

Landau degeneracy — spin — Landau level

Chirality

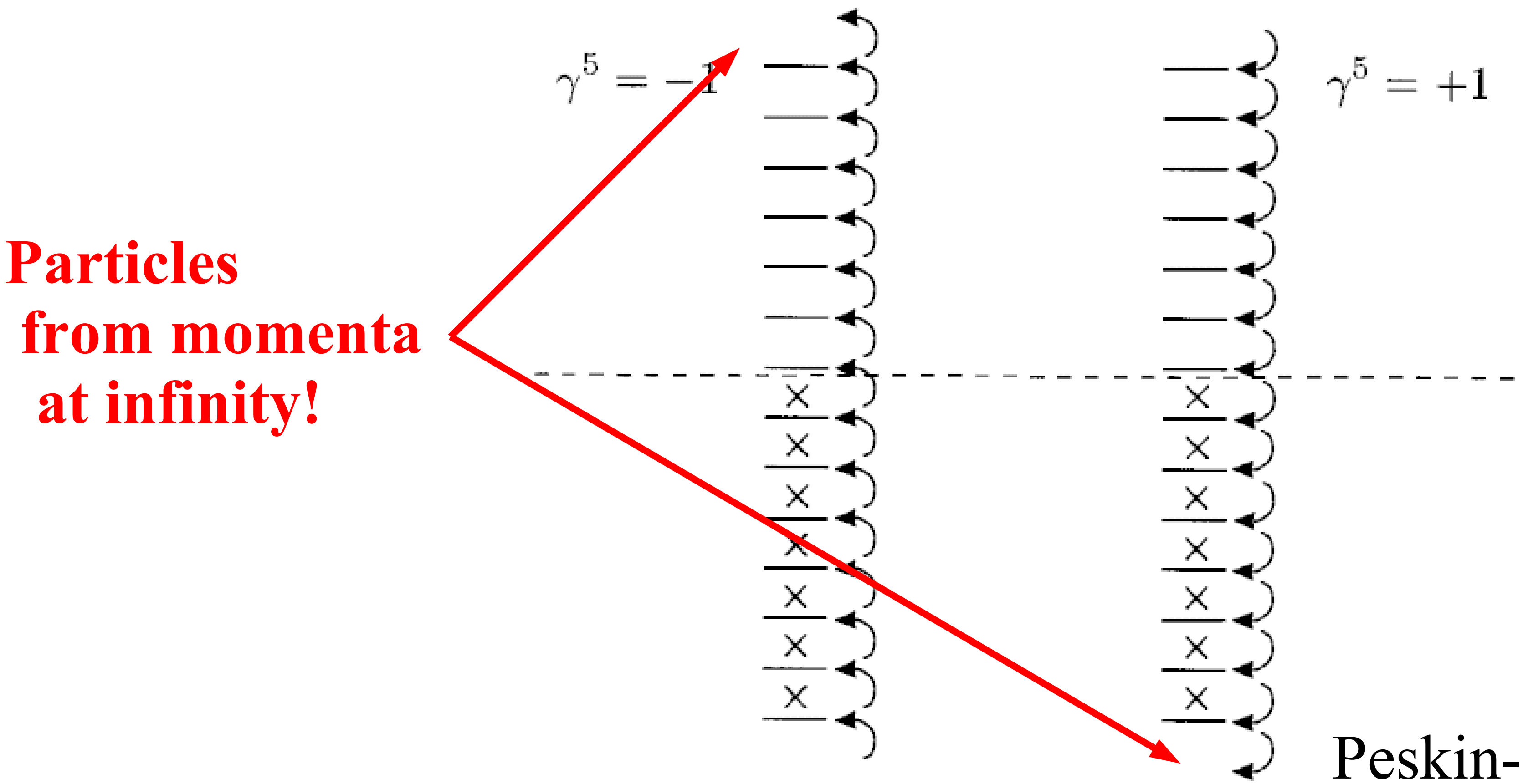
$$\omega_{n,s}^2 = \left(\sqrt{p_z^2 + 2|q_f B| n} + \text{sgn}(p_z) s \mu_5\right)^2 + M^2$$

$$j_z = \frac{d\Gamma}{dA_z} = q_f \frac{d\Gamma}{dp_z} = \#\left[\omega_{n,s}(p_z=\infty) - \omega_{n,s}(p_z=-\infty)\right]$$

$$= N_c \sum_{\text{flavor}} q_f \frac{|q_f B|}{2\pi^2} \sum_{n,s} \alpha_{n,s} s \mu_5 = N_c \sum_{\text{flavor}} \frac{q_f^2 B \mu_5}{2\pi^2}$$

(1+1)-dimensional Anomaly

Anomaly is a “surface” effect



Peskin-Schroeder

Current from the Chiral Magnetic Effect

Particles from infinitely large momentum components in virtual excitations of quarks!?

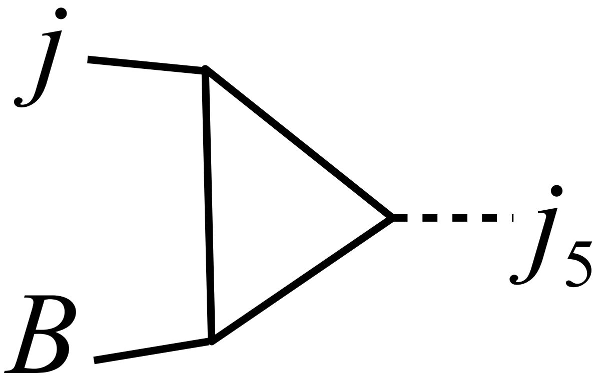
All soft scales (M, T, μ) are irrelevant!?

What would be seen in real experiments?

Let's take another example of quantum anomaly for a better intuition!

Triangle Anomaly

Anomaly Matching Condition ('t Hooft)

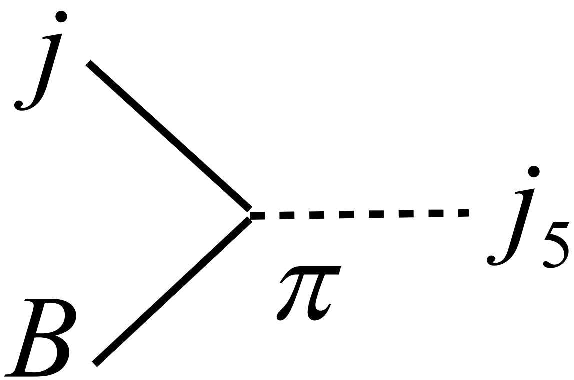


$$K^{AB}_{\mu\nu}(q) = i\int d^4x\, e^{iq\cdot x} \langle j^A_{5\mu}(x)\, j^B_\nu(0)\rangle_B$$

$$\sim -N_c \frac{eB}{2\pi^2} \frac{q_\mu \tilde{q}_\nu}{q^2} \frac{1}{2} \delta^{AB}$$

Equivalent to the chiral magnetic effect

If quarks are confined, how can be this singularity saturated?

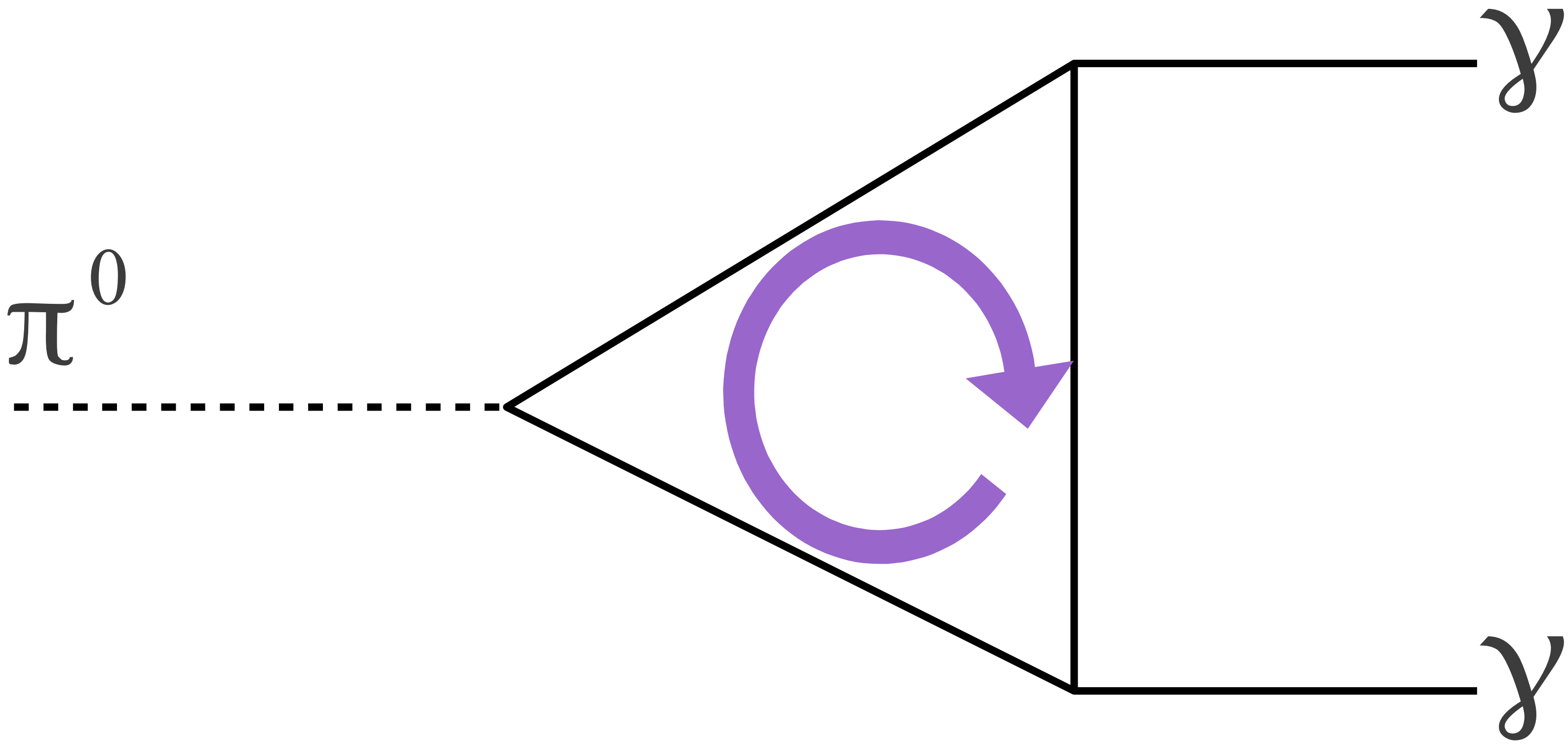


In the confined world there must be massless NG bosons (chiral broken).

For $N_f = 2$, massless proton and neutron could saturate the IR singularity...

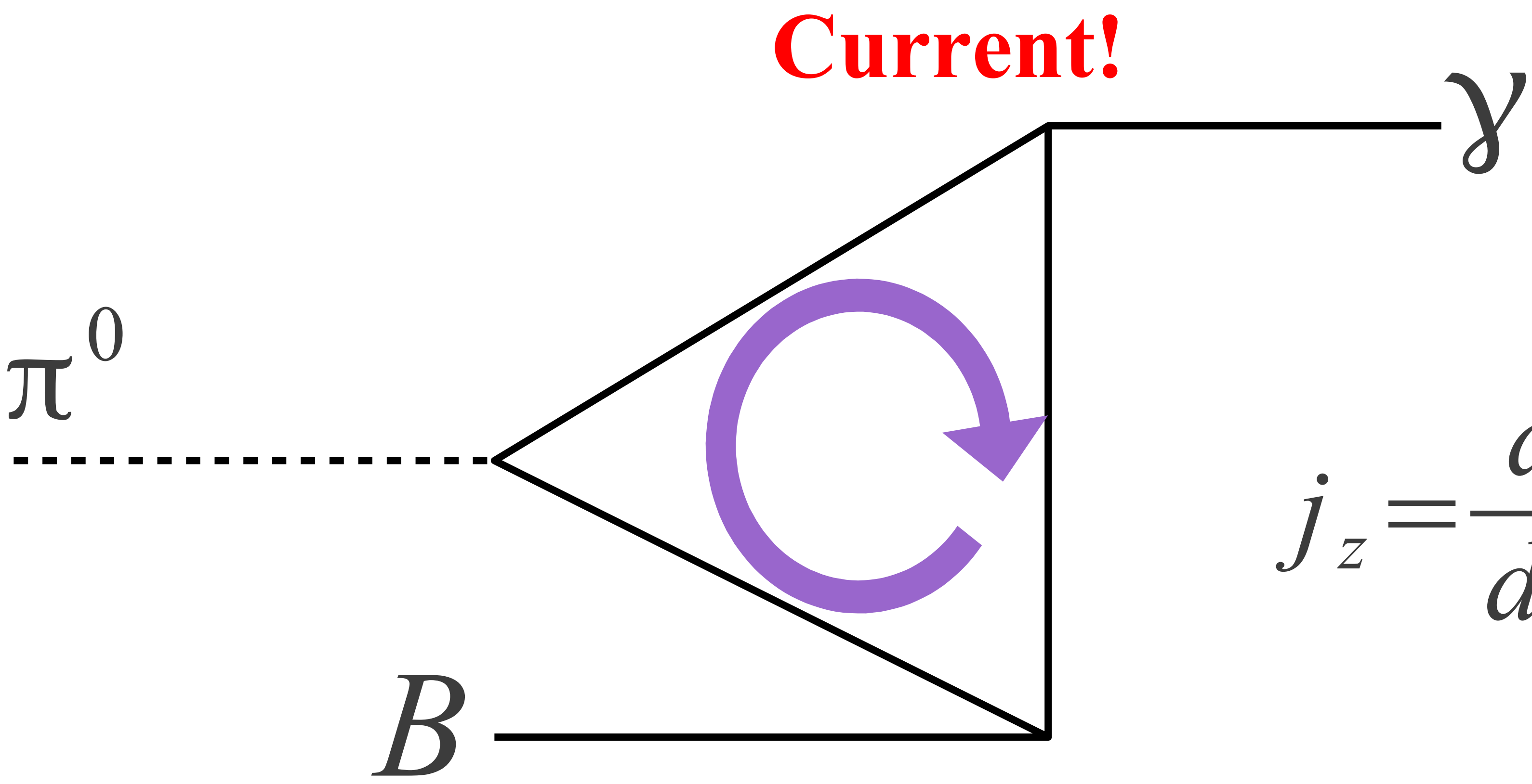
$\pi^o \rightarrow 2\gamma$

Typical example of the anomalous process



$B + \pi^{o} \rightarrow \gamma$

Typical example of the anomalous process



$$j_z = \frac{d\,\Gamma}{d\,A_z}$$

Asakawa-Majumder-Mueller

Current on top of pions

If π^0 distributes coherently (with condensation), microscopic currents in π^0 make a macroscopic current (similar to the Josephson current in SC).

- **π^0 domain wall and the current**

  (Son-Stephanov)

- **Skyrmion and induced charge**

  (Eto-Hashimoto-Iida-Ishii-Maezawa)

Chiral Magnetic Effect

in a hadronic phase

Chiral Lagrangian

$$L=\frac{f_\pi^2}{4}\mathrm{tr}\left[\partial_\mu U\,\partial^\mu U^\dagger+U^\dagger\chi+\chi^\dagger U\right]-\frac{N_f\chi_{\mathrm{top}}}{2}\left(-i\ln\det U-\theta\right)^2$$

Condensate: $U=\begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$ Mass: $\chi=\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}$

Potential: $V(\phi)=-\frac{f_\pi^2}{2}\sum_i m_i^2\cos\phi_i+\frac{N_f\chi_{\mathrm{top}}}{2}\left(\sum_i\phi_i-\theta\right)^2$

Physics is periodic in terms of θ (Dashen's phenomena)

Witten

θ = *Pseudo-scalar Condensate*

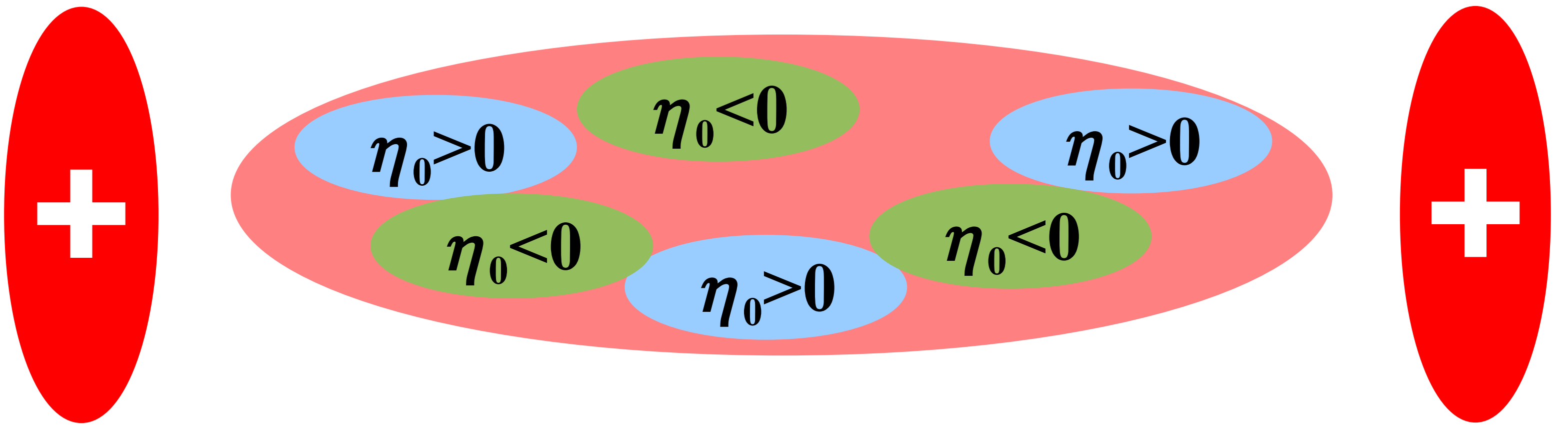
$\phi_1, \phi_2, \phi_3 = -\phi_1 - \phi_2$ describe η_0 and η_8

Potential: $V(\phi) = -\frac{f_\pi^2}{2}\sum_i m_i^2 \cos\phi_i + \frac{N_f \chi_{\rm top}}{2}\left(\sum_i \phi_i - \theta\right)^2$

If any of flavors is massless, θ-dependence is gone; Absorbed by the pseudo-scalar condensate

If any of flavors is massless, θ and the pseudo-scalar condensate are simply identifiable.

Local Parity Violation (LPV) again



Disoriented Chiral Condensate in not only the pion direction but also the iso-singlet direction.

Pionic DCC would also exhibit the LPV.

Spatially and temporally fluctuating η_0 condensates

→ Inhomogeneous (and non-zero) θ

Question

Calculate a current with B and $\theta(t)$

Do not use deconfined and massless quarks but just stick to the Chiral Lagrangian!

Anomaly in the Chiral Lagrangian

Wess-Zumino-Witten Action

$\pi^- \to e^- \bar{\nu}_e \gamma$

$$L_{WZW} = -\frac{N_c}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\Big\{\mathrm{tr}\Big[U^\dagger \hat{r}_\mu U \hat{l}_\nu - \hat{r}_\mu \hat{l}_\nu$$

$$+ i\Sigma_\mu \left(U^\dagger \hat{r}_\nu U + \hat{l}_\nu\right)\Big]\mathrm{tr}\left(v_{\rho\sigma}\right) + \frac{2}{3}\mathrm{tr}\left(\Sigma_\mu \Sigma_\nu \Sigma_\rho\right)\mathrm{tr}\left(v_\sigma\right)\Big\}$$

$\pi^0 \to 2\gamma$ $\qquad$ $\gamma\pi^0 \to \pi^+\pi^-$

$$\hat{r}_\mu = \hat{v}_\mu + \hat{a}_\mu, \quad \hat{l}_\mu = \hat{v}_\mu - \hat{a}_\mu, \quad \Sigma_\mu = U^\dagger \partial_\mu U$$

Axial vector field (traceless)

Vector field (traceless)

Kaiser-Leutwyler

Another WZW (Contact Term)

WZW term without dynamical *U* fields

$$L_P = \frac{N_c}{8 N_f \pi^2} \epsilon^{\mu\nu\rho\sigma} \left\{ \mathrm{tr}\left[v_\mu \left(\partial_\nu v_\rho - \frac{i}{3} [v_\nu, v_\rho] \right) \right] \partial_\sigma \theta + \mathrm{tr}\left(a_\mu D_\nu a_\rho \right) \left[\frac{4}{3} \mathrm{tr}\left(a_\sigma \right) + \partial_\sigma \theta \right] \right\} - \frac{N_c}{12 N_f^2 \pi^2} \mathrm{tr}\left(a_\mu \right) \mathrm{tr}\left(\partial_\nu a_\rho \right) \partial_\sigma \theta$$

QED fields: $v_\mu = eQ A_\mu = e \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} A_\mu$

Kaiser-Leutwyler

Current from the WZW Action

$$\Gamma_p = \int \frac{N_c}{8 N_f \pi^2} \epsilon^{\mu\nu\sigma\rho} \mathrm{tr}[v_\mu \partial_\nu v_\rho] \partial_\sigma \theta + \cdots$$

$$j_z = \frac{d\Gamma_p}{dA_z} = \frac{N_c}{4 N_f \pi^2} \epsilon^{zxyt} \mathrm{tr}(Q^2) B_z \partial_t \theta$$

$$= N_c \sum_f \frac{q_f^2 B_z}{2\pi^2} \cdot \frac{\partial_t \theta}{2 N_f}$$

Time-dependent DCC in the singlet channel

μ_5

Full Computation

Non-anomalous

Currents from π^+, π^- flows

Non-singlet anomalous (conventional DCC)

Currents from inhomogeneous π condensation

Singlet anomalous (CME)

Currents from inhomogeneous η_0 condensation

In completion (Fukushima-Mameda)

Similar Effects

$$j_\mu = \epsilon_{\mu\nu\sigma\rho} \left(\partial^\nu \theta \right) F^{\sigma\rho}$$

Derivative of a scalar quantity
η' condensate
Pseudo-scalar condensate
Strong θ angle

2nd-rank tensor
Field strength tensor
Angular momentum
Angular velocity

Chiral separation / vortical / … / effect

Is there a current... or not?

Signature of what?

What is necessary for the CME?

Is “quark deconfinement” necessary?

What is necessary for the CME?

Is "quark deconfinement" necessary?

NO!?

Anomaly should be saturated with quarks and hadrons

This is realized by the Wess-Zumino-Witten action.
WZW is used for similar phenomena (Son-Stephanov)
and can be for the CME.

What flows microscopically in a hadronic phase?
Through high-momentum quark component in the η_0 condensate??

What is necessary for the CME?

Is "quark deconfinement" necessary?

NO!?

Anomaly should be saturated with quarks and hadrons

This is realized by the Wess-Zumino-Witten action.
WZW is used for similar phenomena (Son-Stephanov)
and can be for the CME.

Dima says sphaleron transitions enhanced
in the deconfined phase at high temperature...

What is necessary for the CME?

Is "chiral symmetry restoration" necessary?

What is necessary for the CME?

Is "chiral symmetry restoration" necessary?

Probably Yes!?

WZW action does not require the chiral limit.
CME current is insensitive to the quark mass.

To form the DCC, far off-equilibrium matter from chiral symmetric (and $U(1)_A$ symmetric) state is implicitly assumed.

Picture in a hadronic phase

What is necessary for the CME?

Is "chiral symmetry restoration" necessary?

Probably Yes!?

IF, topological gauge configurations (sphaleron) are given, not μ_5 but N_5 is generated.
N_5 decays with the quark mass term.
(Chirality makes sense only for massless quarks)

Picture in a deconfined phase

Experimental Challenges and Theories

Difficulty

P-odd quantity is zero on average

What we can observe in physics of the strong interaction is:

NOT P (and CP) Violation
BUT *Local* P (and CP) Violation

Not *qualitative* but *quantitative*

Difficulty

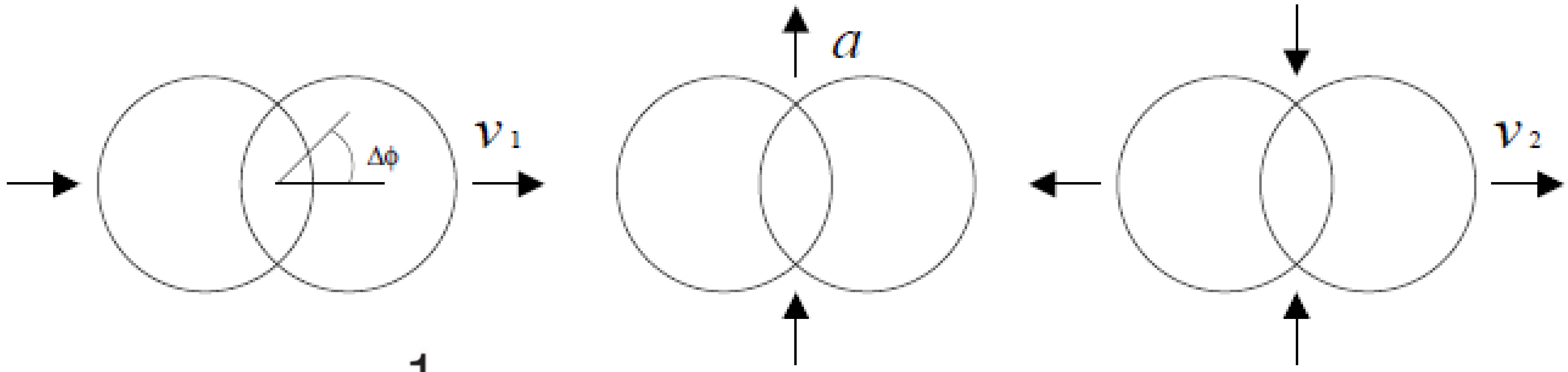
$$\langle (\text{P-odd Observable}) \rangle = 0$$

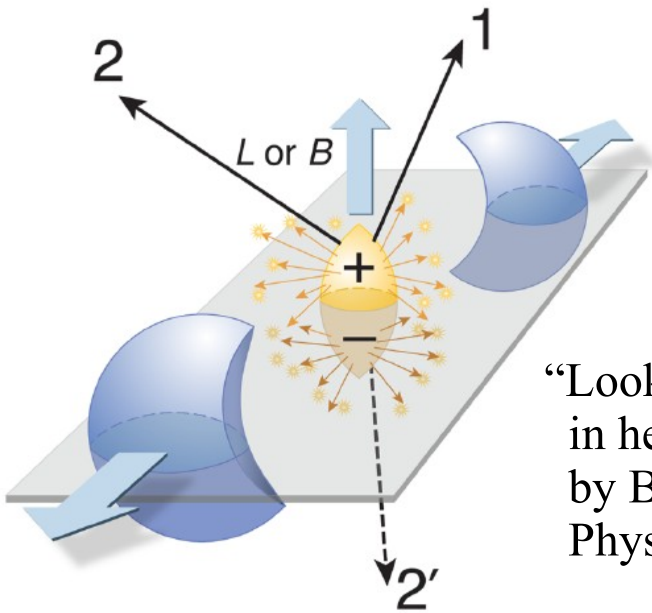
$$\langle (\text{P-odd Observable})^2 \rangle = \text{Large or Small?}$$

Even if we find the latter large, can we really say that we find the local parity violation?
Theoretical prediction needed...

Fluctuation of Charge Separation

$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_{1\pm}\cos(\Delta\phi) + 2a_\pm \sin(\Delta\phi) + 2v_{2\pm}\cos(2\Delta\phi) + \cdots$$





"Looking for parity violation in heavy-ion collisions" by Berndt Müller Physics 2, 104 (2009)

ϕ : Azimuthal angle

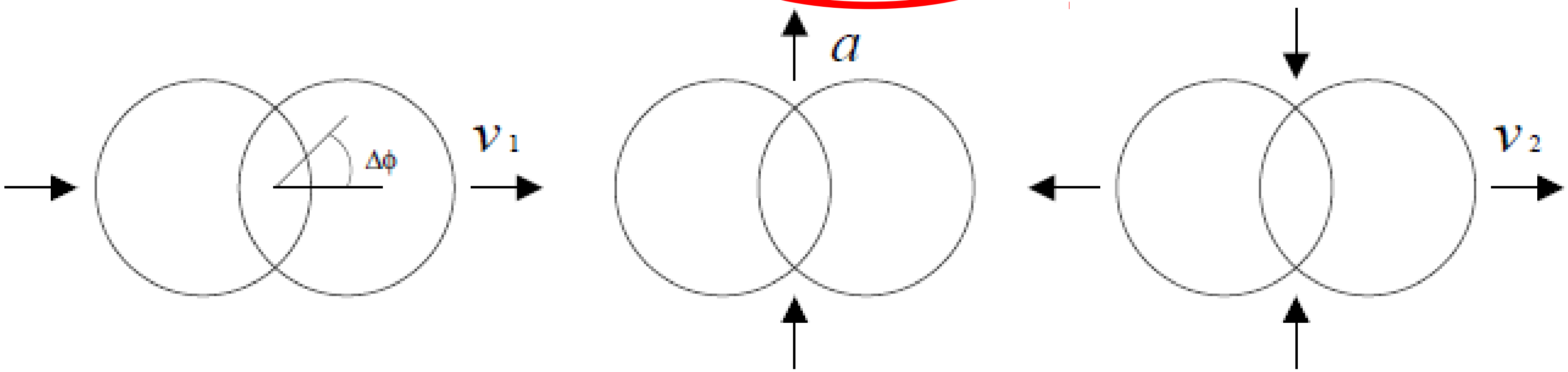
v_1 : Directed flow

v_2 : Elliptic flow

Interpretation

Parity-Odd (Charge Separation)

$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_{1\pm}\cos(\Delta\phi) + 2a_\pm \sin(\Delta\phi) + 2v_{2\pm}\cos(2\Delta\phi) + \cdots$$



$$\langle\langle \cos(\Delta\phi_\alpha + \Delta\phi_\beta) \rangle\rangle \equiv \left\langle\!\!\left\langle \frac{1}{N_\alpha N_\beta} \sum_{i=1}^{N_\alpha} \sum_{j=1}^{N_\beta} \cos(\Delta\phi_{\alpha,i} + \Delta\phi_{\beta,j}) \right\rangle\!\!\right\rangle$$

$(\alpha, \beta = +, -)$

$$= \langle\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle\rangle - \langle\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle\rangle$$

$$= \left(\langle\langle v_{1,\alpha} v_{1,\beta} \rangle\rangle + B^{\rm in}_{\alpha\beta} \right) - \left(\langle\langle a_\alpha a_\beta \rangle\rangle + B^{\rm out}_{\alpha\beta} \right).$$

Cancel? NO!

Famous (Infamous?) Results

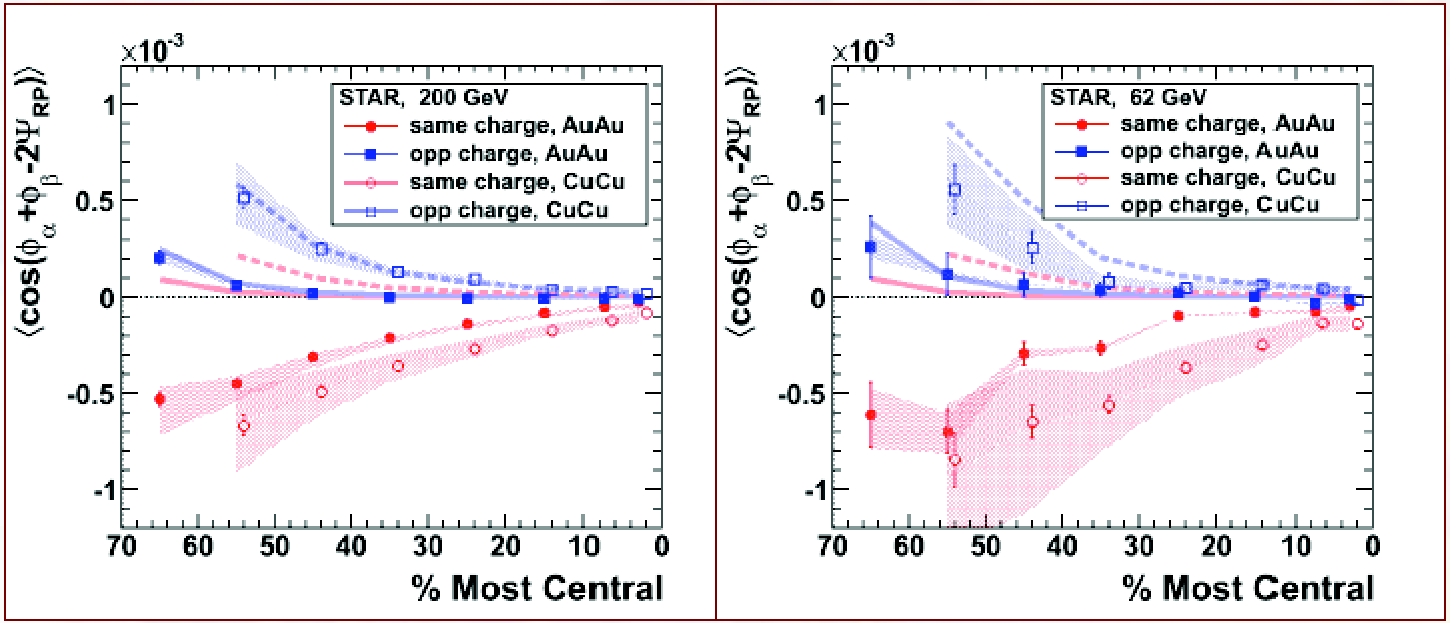
3-Particle Correlation (fluctuation measurement)

$$\langle\langle \cos(\Delta\phi_\alpha + \Delta\phi_\beta)\rangle\rangle \equiv \left\langle\!\!\left\langle \frac{1}{N_\alpha N_\beta}\sum_{i=1}^{N_\alpha}\sum_{j=1}^{N_\beta}\cos(\Delta\phi_{\alpha,i} + \Delta\phi_{\beta,j})\right\rangle\!\!\right\rangle$$

$$= \langle\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle\rangle - \langle\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle\rangle$$

$$= \left(\langle\langle v_{1,\alpha} v_{1,\beta}\rangle\rangle + B^{\mathrm{in}}_{\alpha\beta}\right) - \left(\langle\langle a_\alpha a_\beta\rangle\rangle + B^{\mathrm{out}}_{\alpha\beta}\right).$$

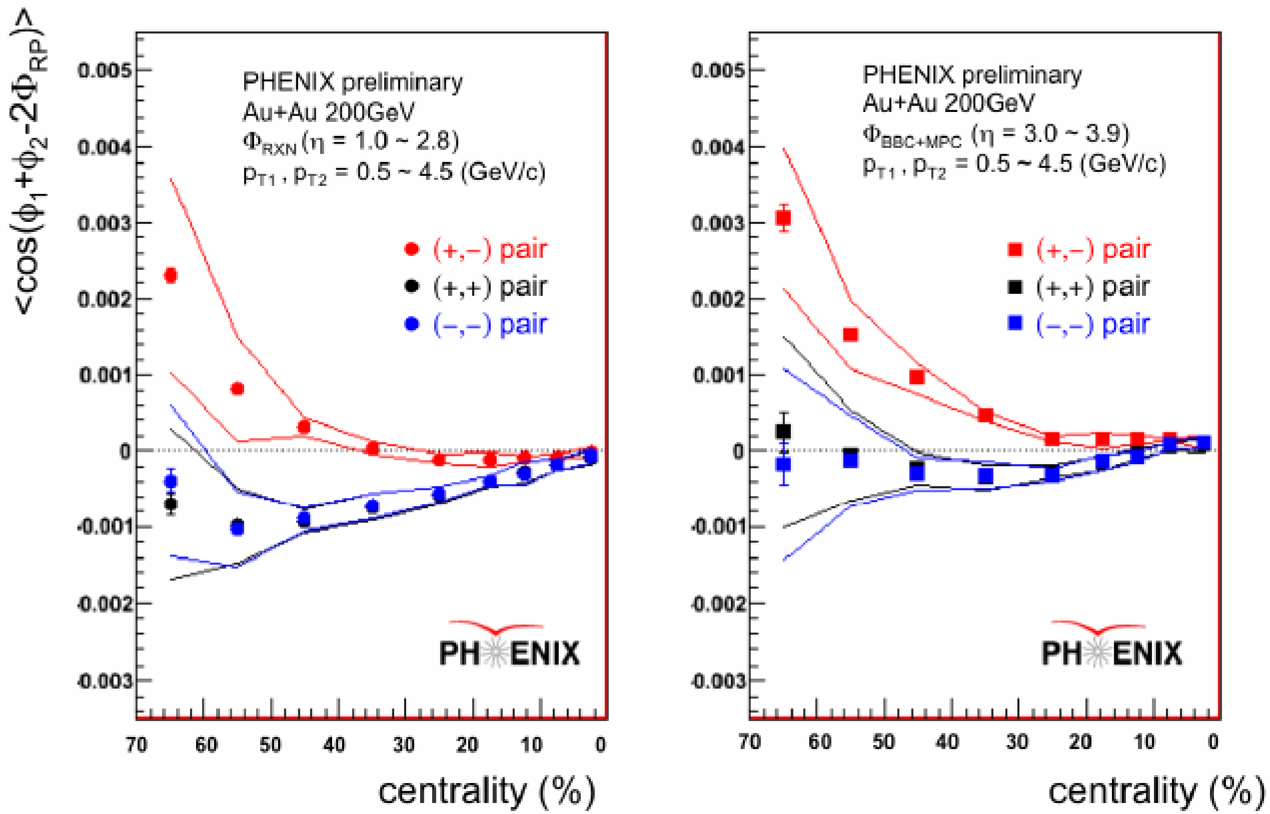
STAR Results



Voloshin STAR

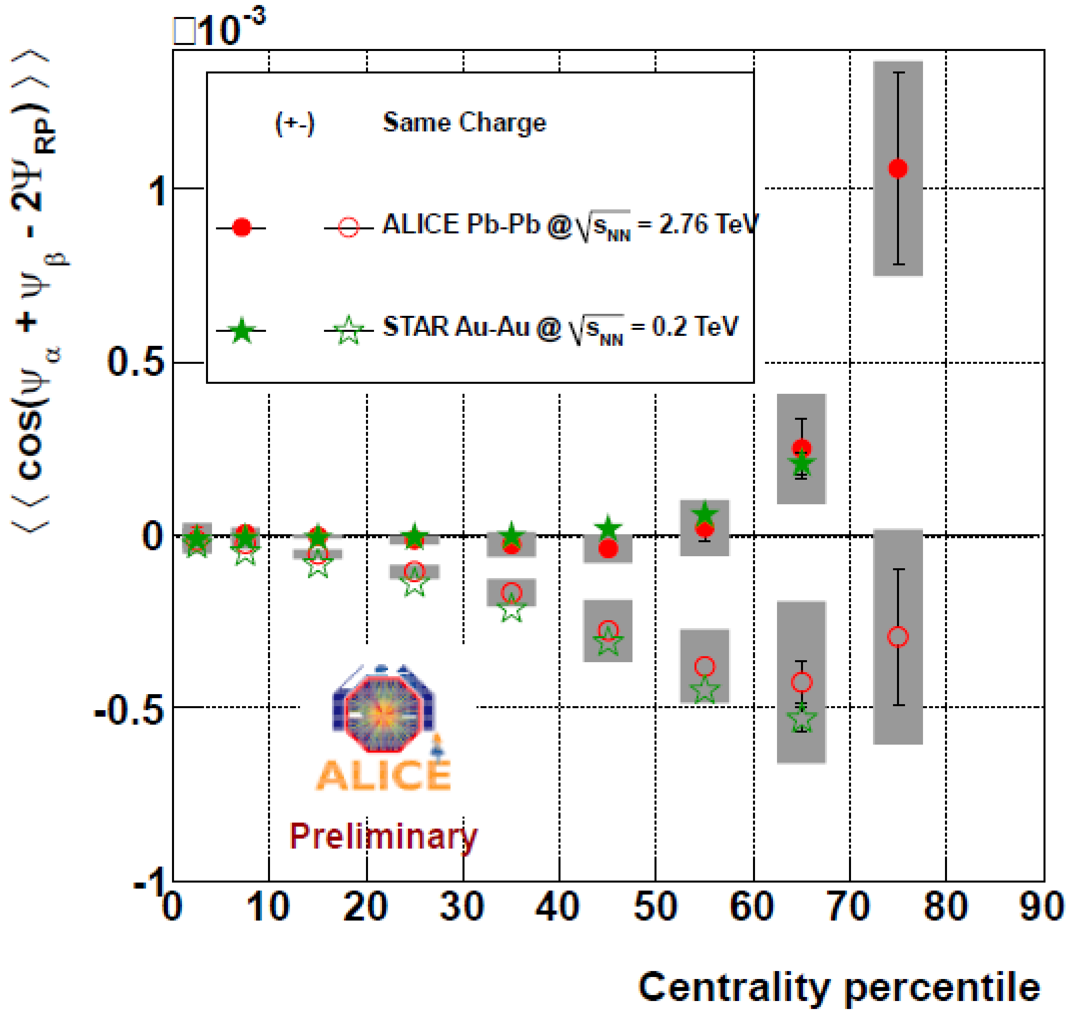
Followed up by RHIC (PHENIX)

Qualitative agreement with STAR



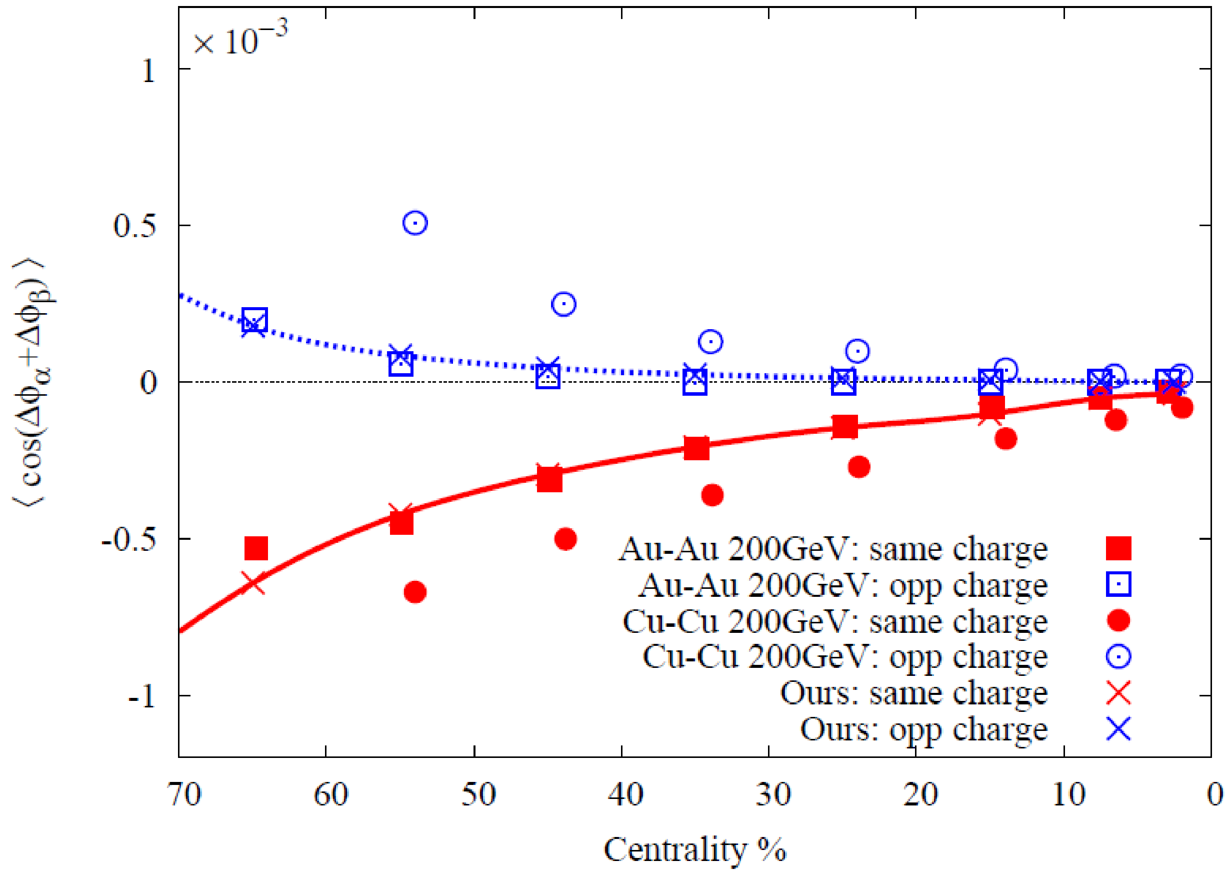
Figures from a talk by Lacey in CPODD

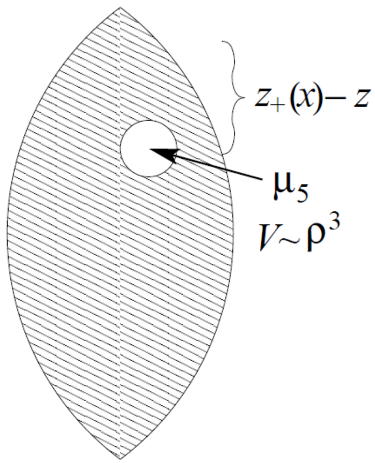
Further confirmation from ALICE



Data from ALICE

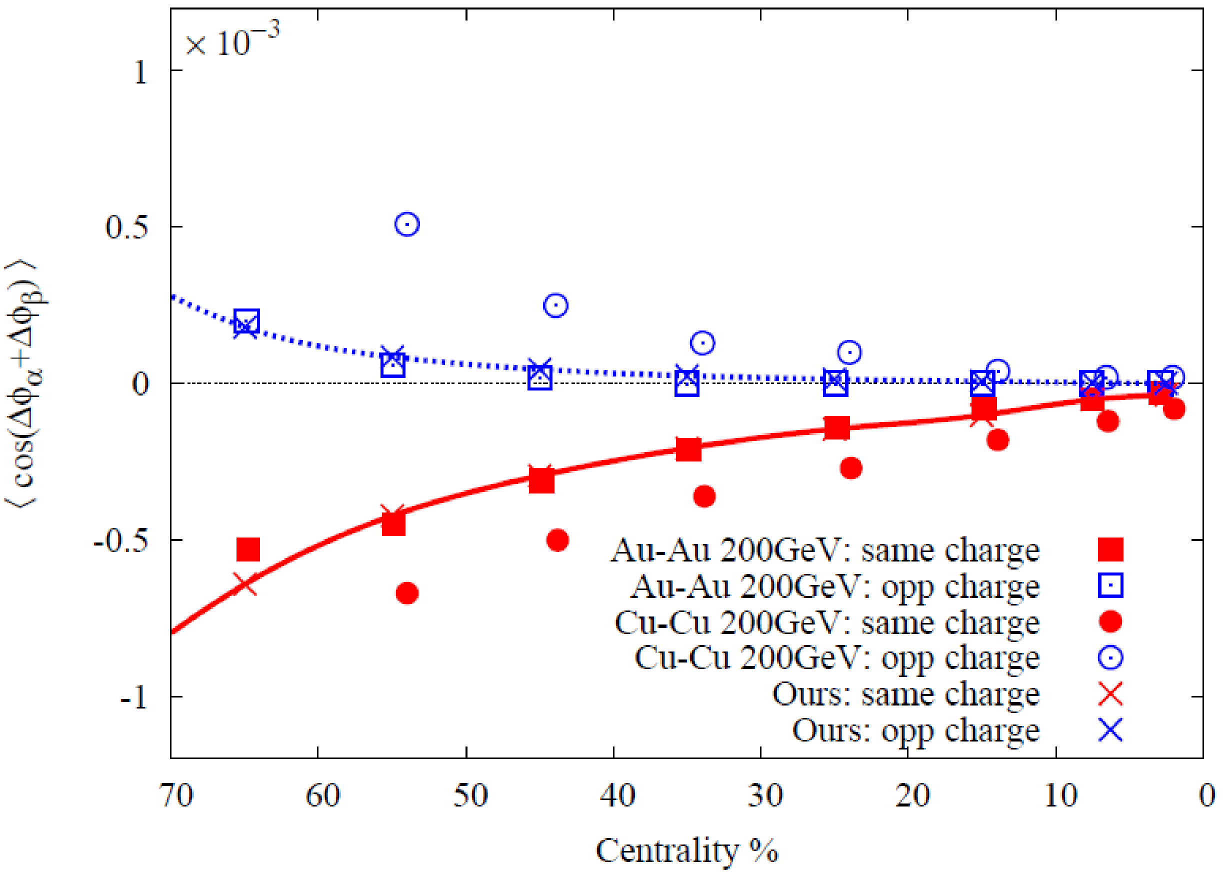
What really happens?





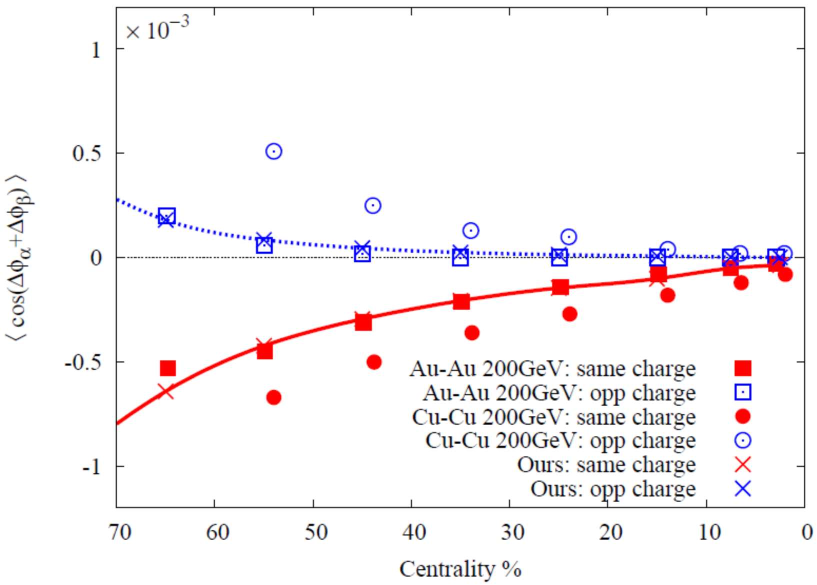
Theoretical fit I made three years ago but didn't publish and just threw away!

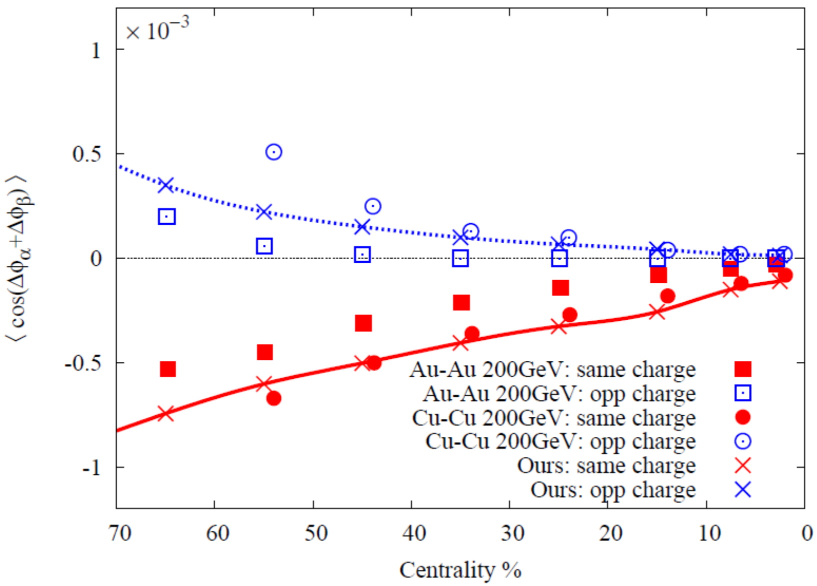
What really happens?



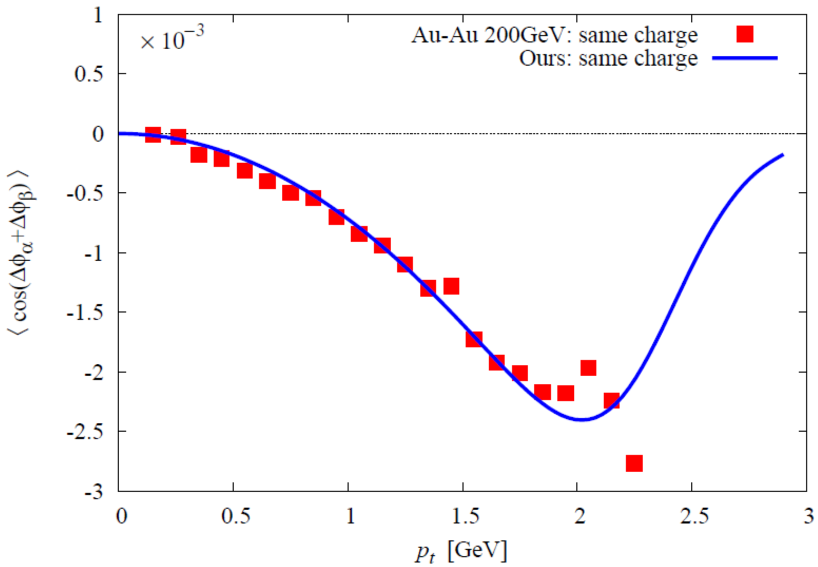
To fit the date, the CME is not necessary. If going to peripheral, less particles and larger fluctuations.... that's all!

Systematic fit possible?





Species dependence



***Pt* dependence**

Difficulty

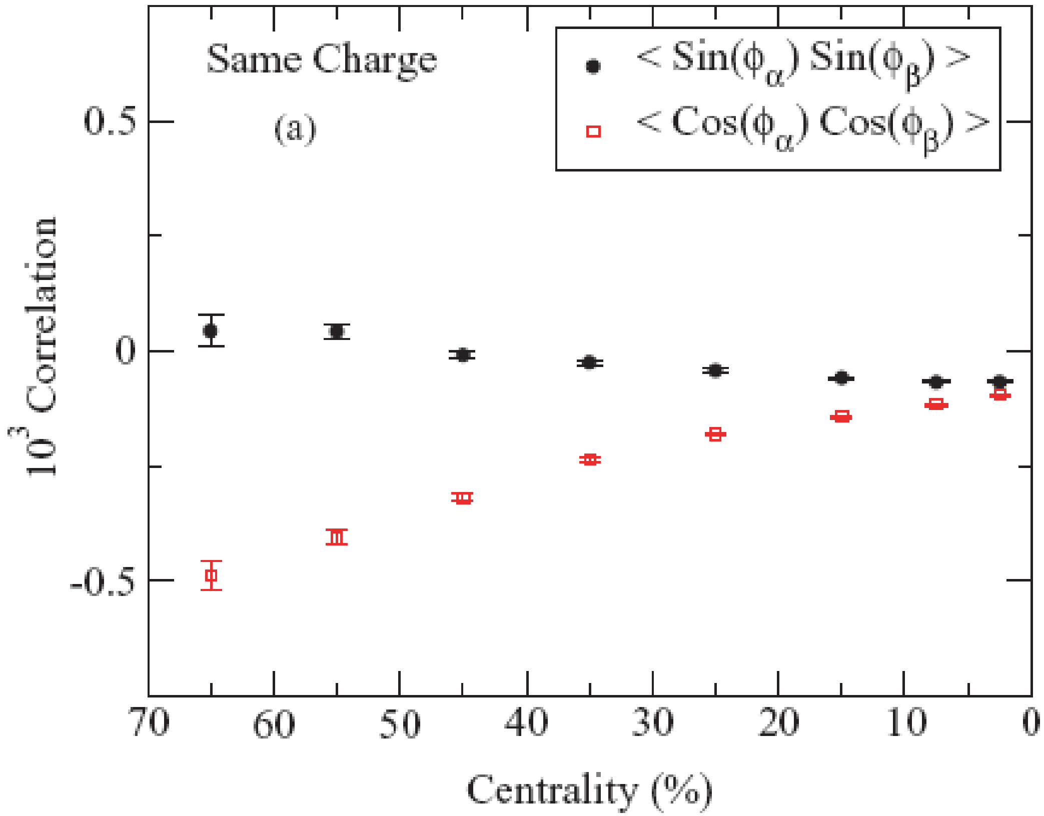
Theoretical fit is always possible.
But... so what?

We cannot conclude anything!

Decomposition (Background)

$$\langle \cos(\Delta\phi_\alpha + \Delta\phi_\beta)\rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$

$$\langle \cos(\Delta\phi_\alpha - \Delta\phi_\beta)\rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle + \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$



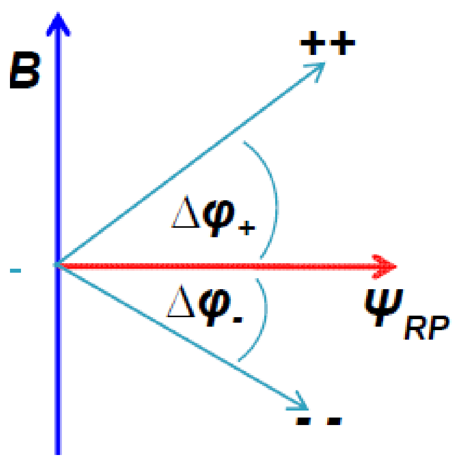
Bzdak-Koch-Liao (2009)

Not ruled out (yet?)

No longer considered as an evidence of anything...

Multi-Particle Correlation

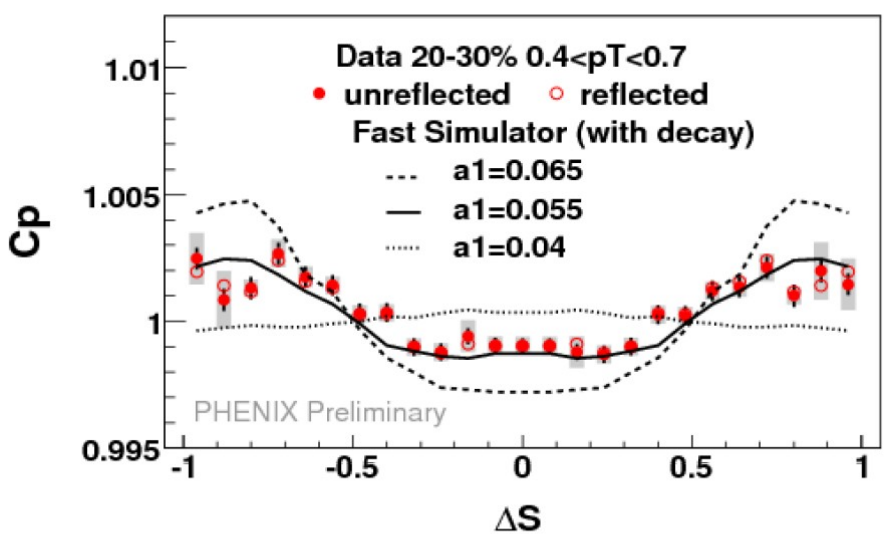
Two Distribution Functions

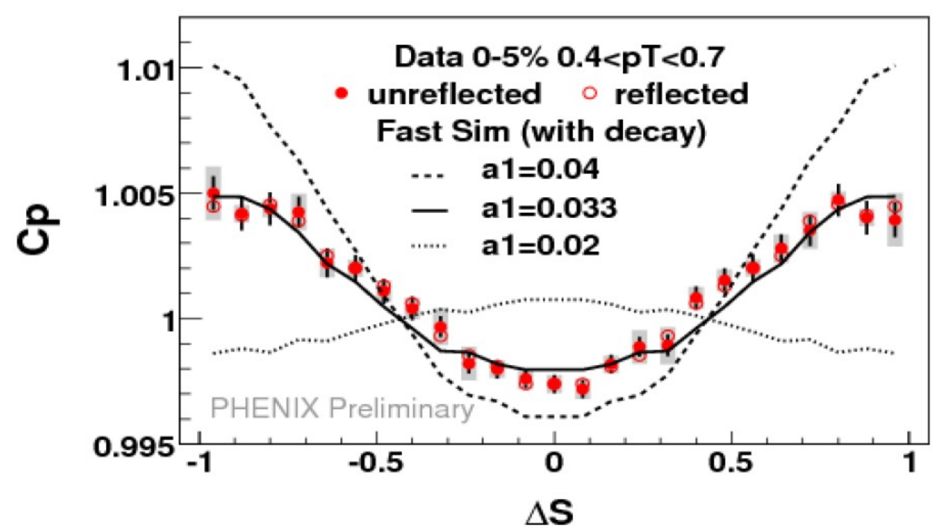


$$\left\langle S_p^{h+} = \sin\Delta\phi_{p+}\right\rangle \quad \left\langle S_n^{h-}\right\rangle \quad \left\langle S_p^{h\mp}\right\rangle \quad \left\langle S_n^{h\mp}\right\rangle$$

$$C_p(\Delta S) = \frac{N\left(\left\langle S_p^{h+}\right\rangle - \left\langle S_n^{h-}\right\rangle\right)}{N\left(\left\langle S_p^{h\mp}\right\rangle - \left\langle S_n^{h\mp}\right\rangle\right)}$$

PHENIX
Talk by Lacey
in CPODD





Summary

- Theory of the Chiral Magnetic Effect is robust, but phenomenological inputs have uncertainties...
- Parity Violation itself cannot be seen, and only its fluctuations are observed which are parity even! Subtraction of backgrounds is very hard...
- Important to look at physics observables with which flow effects are distinguishable (multi-particle corr.)
- More from forthcoming conferences:

  CPODD (BNL – June) QM (Washington D.C. – Aug.)
  QCD in a Strong B (ECT* – Nov.)