Strong Parity Violation:

An Introduction to STAR Results on Charge Separation Measurements

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Looking for new physics – Strong Parity Violation

- The conventional point of view
  - "Parity is conserved in the strong and electromagnetic interactions"
    - See, for example, Perkins "Introduction to High Energy Physics"

- The less-conventional point of view
  - In the vicinity of a deconfining phase transition, the QCD vacuum can possess meta-stable domains leading to P and CP violation.
    - See, for example, Kharzeev, Pisarski, and Tytgat PRL 81, 512 (1998).

Thanks to wonderful talks given by Harmen Warringa at BNL, Sergei Voloshin QM2009 and Evan Finch CPOD

Explicit P and CP violation is allowed in QCD

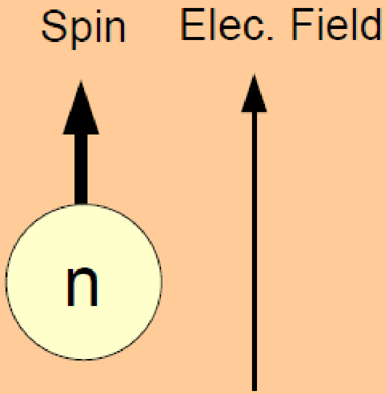
- **A very simple addition to the bare QCD Lagrangian is interesting**
  - $L_{QCD} \rightarrow L_{QCD} + \delta L$

Adding the theta term breaks P- and CP- explicitly

$$L_{QCD} \rightarrow L_{QCD} + \theta \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

This term gives rise to a neutron EDM

Experiment: $|\theta| \leq 10^{-10}$



- **Why is θ so small?**
  - **Perhaps due to Peccei-Quinn symmetry … which would imply the existence of axions.**

An old but still interesting problem …

Implicit P and CP violation is (also) allowed in QCD

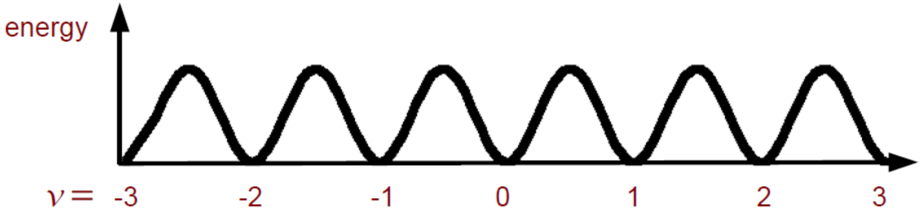
- **Vafa and Witten ('84) showed that if $\theta = 0$ then P and CP violation are not possible**
  - **Theorem valid for ground state QCD at zero temperature and zero density**

- **Heavy Ion Collisions aren't representative of ground state QCD**

- **Possibilities for implicit P and CP violation in QCD**
  - **Finite temperature**
  - **Finite density**
  - **Metastable vacua**
  - **Out of equilibrium**
  - **All of these are possible in a heavy ion collisions where, by hypothesis, Axial symmetry and Chiral symmetry are in transition.**

Summary: Hot QCD allows for Parity Violation

QCD has an infinite number of vacua which can distinguished by a winding number $\nu = 0, \pm 1, \pm 2, \ldots.$



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

In chiral limit (m=0): $[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2 N_f Q_w$

- **Moving from one vacuum state to another is the result of changing the topological charge of the system**
- **Topological charge flips helicity and thus counts the difference between the number of right and left handed quarks (a consequence of the axial Ward identity)**

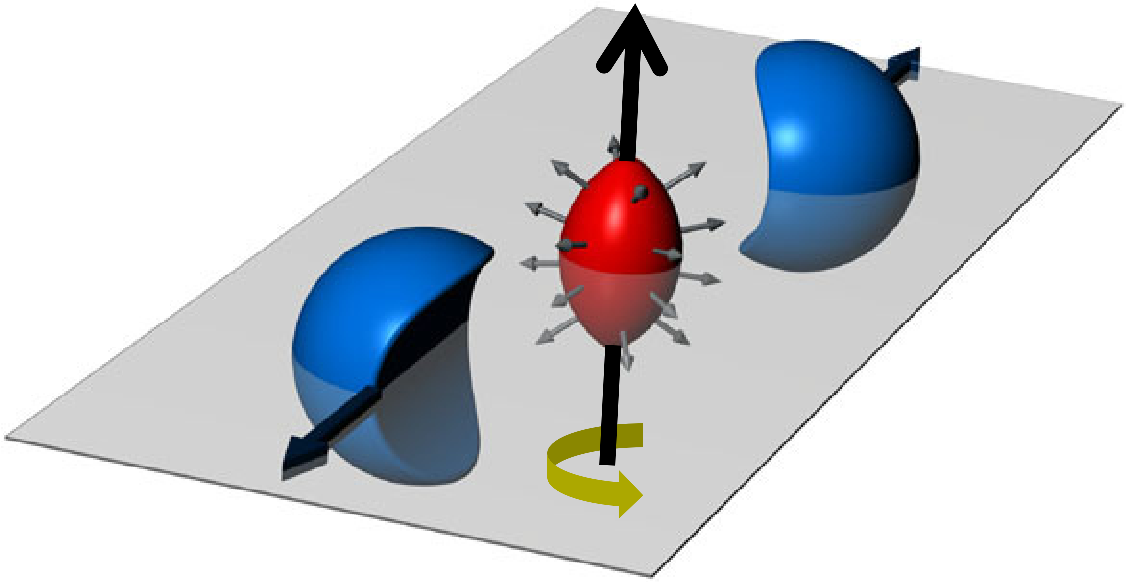
- **What every experimentalist likes to see in a theory publication …**
  - **"The consequences and magnitude of these effects are subject to experimental study and verification"**
    - **Kharzeev, McLerran, and Warringa arXiv:0711.0950 and Nucl. Phys. A803 (2008) 227.**

From a humble experimentalist's point of view … the theory appears to be fully vetted; these CP and P violating domains almost certainly occur in ultra-relativistic HI collisions. The question is whether the effects are large enough to be observed …

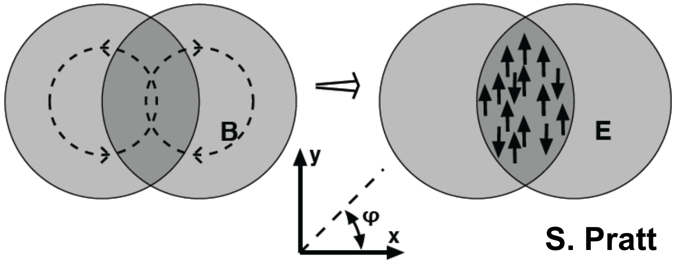
- **The hypothesis:**
  - The Chiral Magnetic Effect can cause a separation of charge, above and below the reaction plane
  - If the CME effect occurs in HI collisions, then it would be evidence for P and CP violation in the strong interaction

What I am going to describe, next, is a feat of nano-engineering that would make Richard Feyman proud …

The System Has Angular Momentum

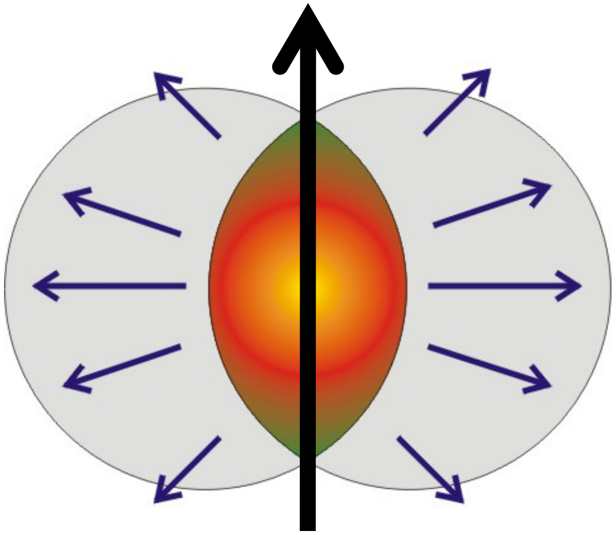


Kharzeev et al. have noted that angular momentum is conserved in HI collisions …



S. Pratt

so there is an angular momentum vector that lies perpendicular to the reaction plane



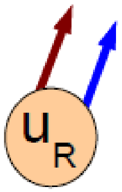
- Electromagnetic charges in motion lead to an electromagnetic magnetic field (not a color magnetic field)
- The magnetic fields can reach 10^{18} gauss. Stronger than on the surface of a neutron star.
- May be related to ridge formation etc.

Quarks interact with the B field via their spin

- **Assume: chiral symmetry is restored in a QGP**
- **Assume: quark masses drop to ~0 after chiral symmetry restoration**

In chiral limit:

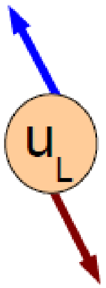
Particles/Antiparticles with right-handed helicity



have spin and momentum parallel

In chiral limit:

Particles/Antiparticles with left-handed helicity



have spin and momentum anti-parallel

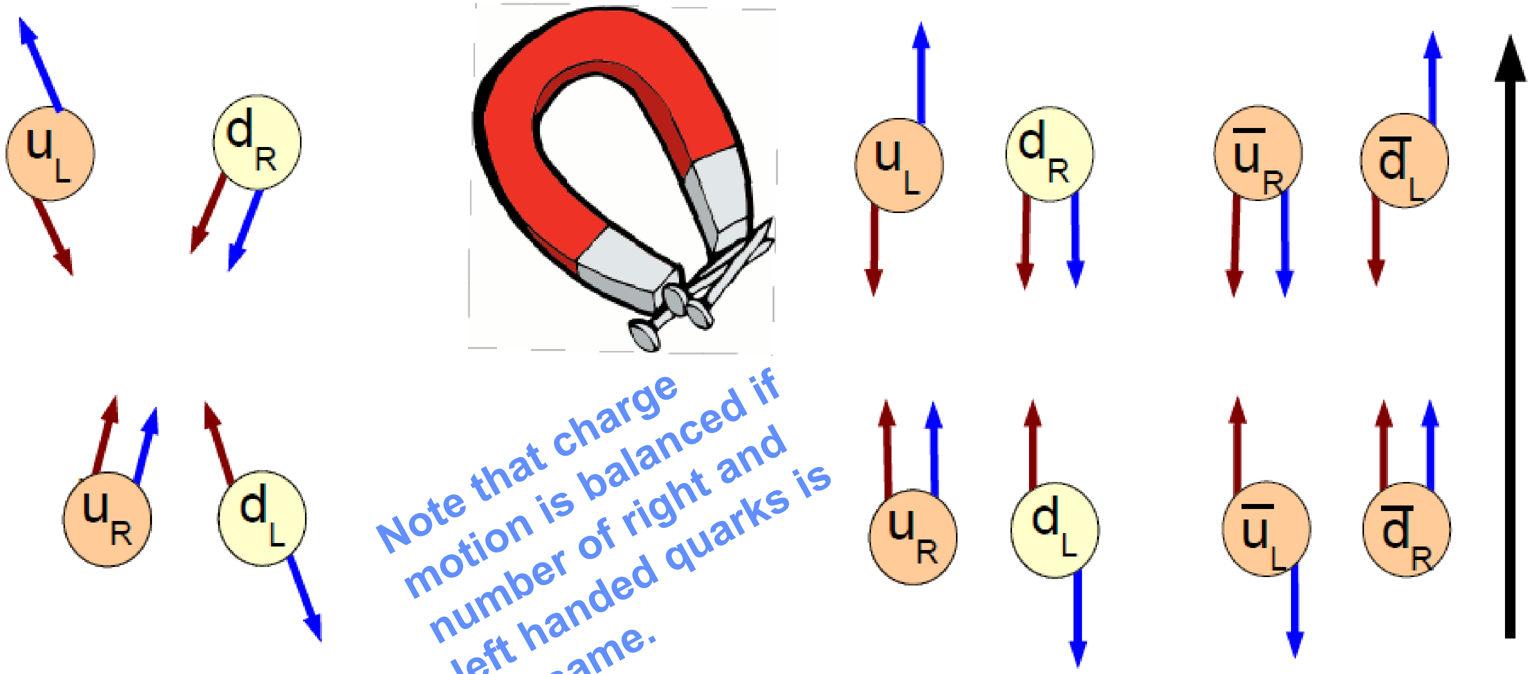
- **Chirality and helicity are the same for massless particles … so in the limit of zero mass, it is easy to define chirality (not so easy for non-zero mass).**

How does the B field affect the Quarks?

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

No Magnetic Field: No polarization

Magnetic field: Polarization *B*



Note that charge motion is balanced if number of right and left handed quarks is the same.

The momenta of the quarks align along the magnetic field

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

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

H. Warringa

How does the Magnetic field affect Chirality?

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

No Magnetic Field: No polarization

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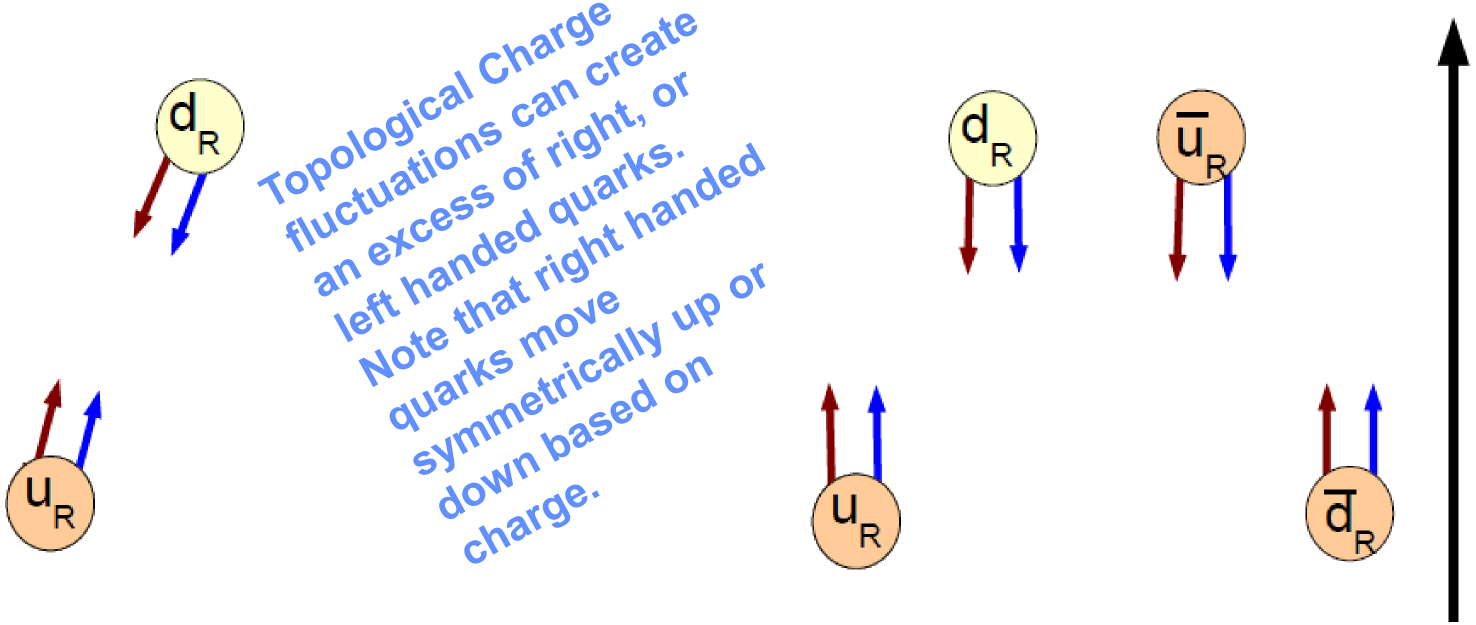


Topological Charge fluctuations can create an excess of right, or left handed quarks. Note that right handed quarks move symmetrically up or down based on charge.

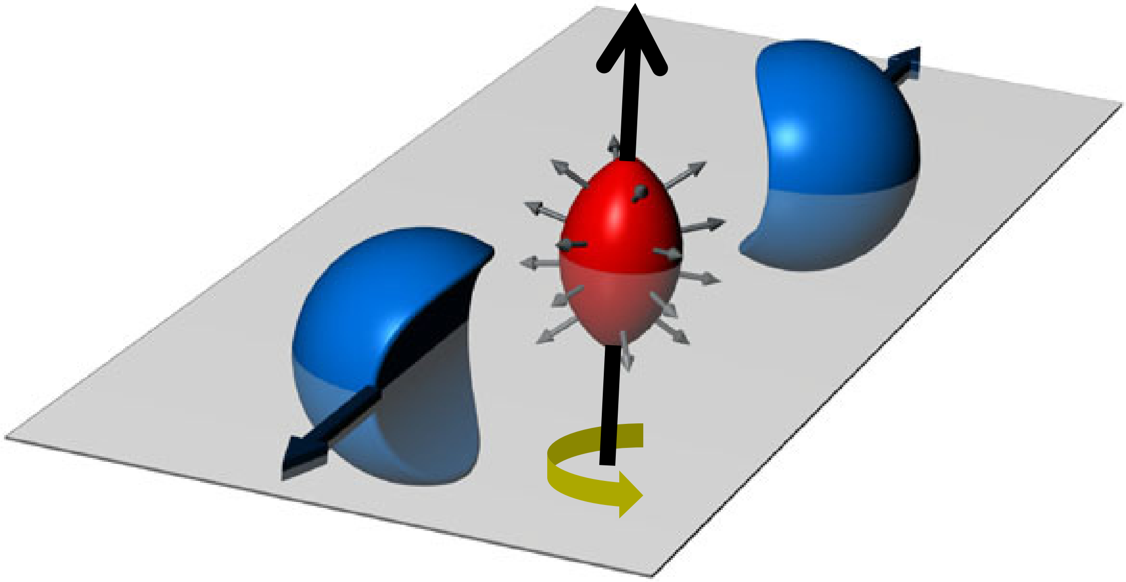
Positively charged particles move parallel the magnetic field

Negatively charged particles move to antiparallel to magnetic field

<u>An electromagnetic current is created along the magnetic field</u>

H. Warringa

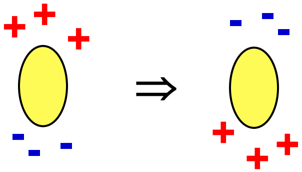
Separation of Charge wrt the reaction plane



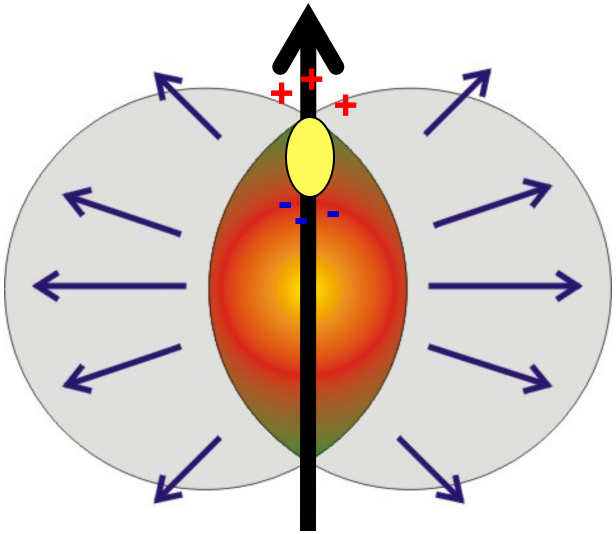
If a chirally restored bubble is created in a heavy ion collision, the positively charged quarks will go up … then hadronize … and yield an excess of positive pions above the plane

Unfortunately, it could be just the opposite in the next event depending on the topological charge in the bubble

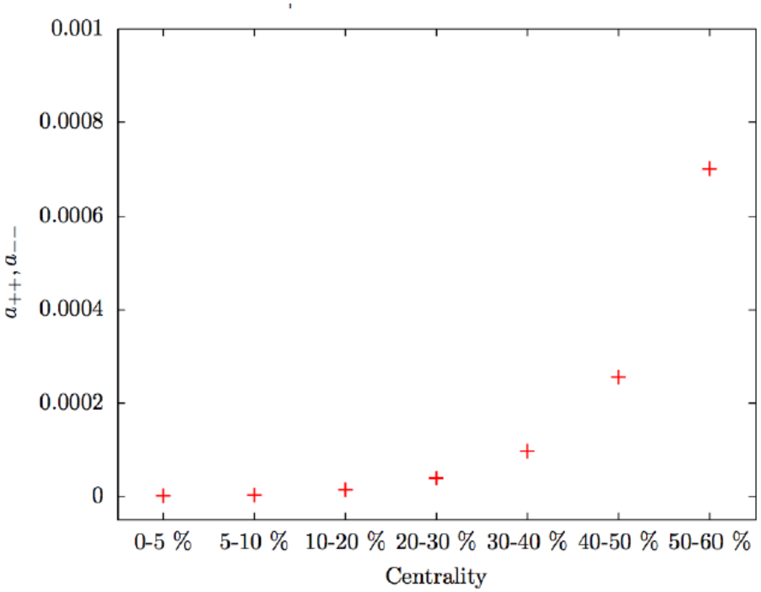
- The signal is manifestly parity odd
  x ⇒ -x , p ⇒ -p
  but the observable will be even

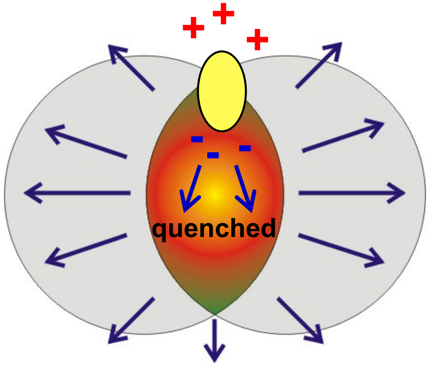


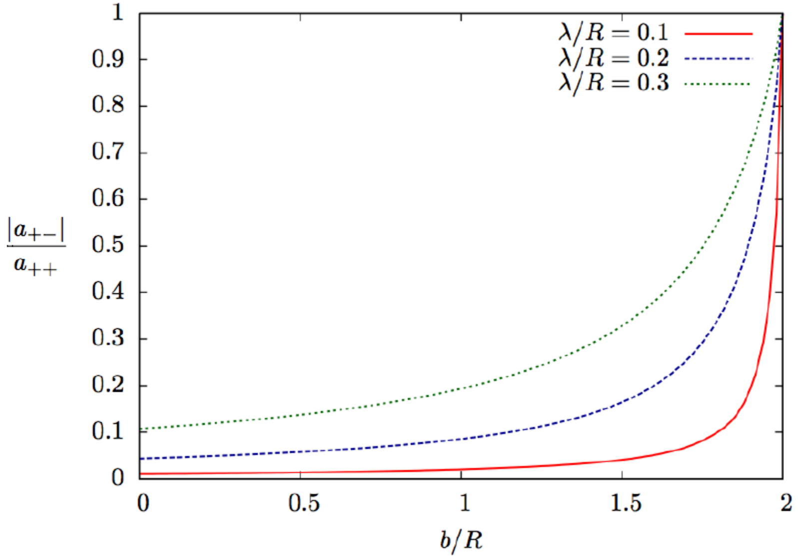
- The charge-flow asymmetry is too small to be seen in a single event but may be observable with correlation techniques



A Possible Result of the Chiral Magnetic Effect







- **Theory suggests ++ and -- correlations increase in peripheral collisions**
- **++ to +- correlations may be altered due to de-correlation in the medium**
  - **Kharzeev suggests ‘bubble’ on edge of collision zone and one side absorbed**

The Hypothesis

- **The hypothesis:**
  - **The Chiral Magnetic Effect can cause a separation of charge, above and below the reaction plane**

- **Lets look at STAR data taking capabilities … and finally look at the data**

The Relativistic Heavy Ion Collider at BNL

RHIC

- Two independent rings
- 3.83 km in circumference
- Accelerates everything, from p to Au

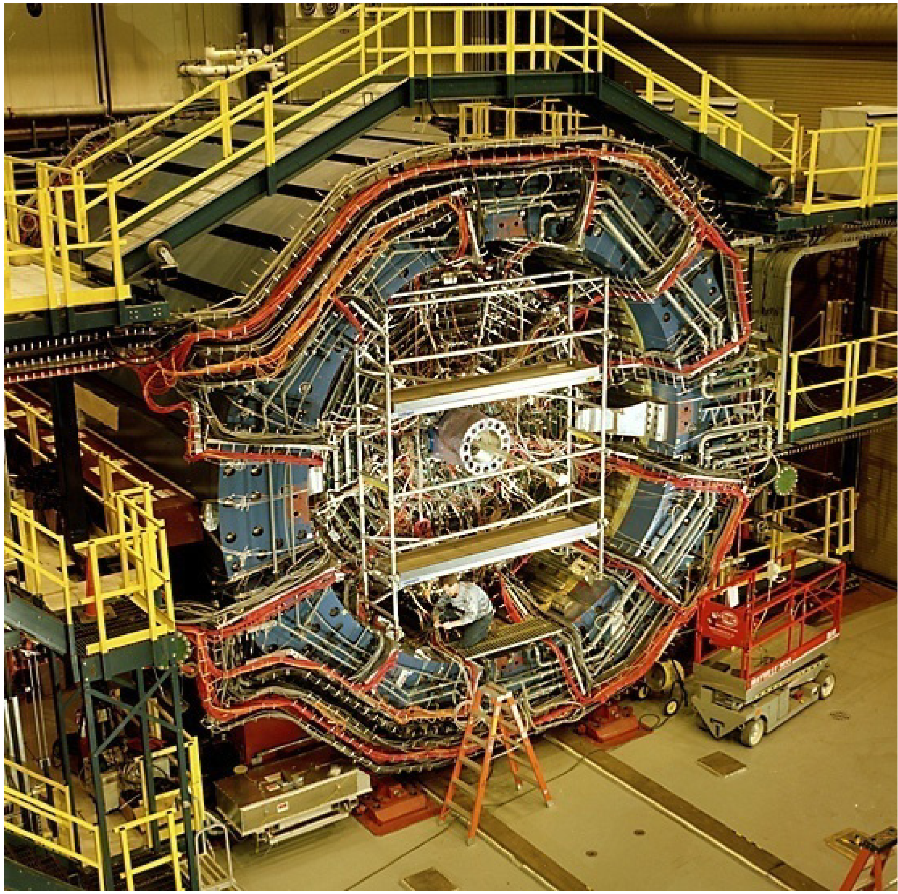
	$\sqrt{s}$	L
p-p	500	10^{32}
Au-Au	200	10^{27}

(GeV and $cm^{-2}\ s^{-1}$)

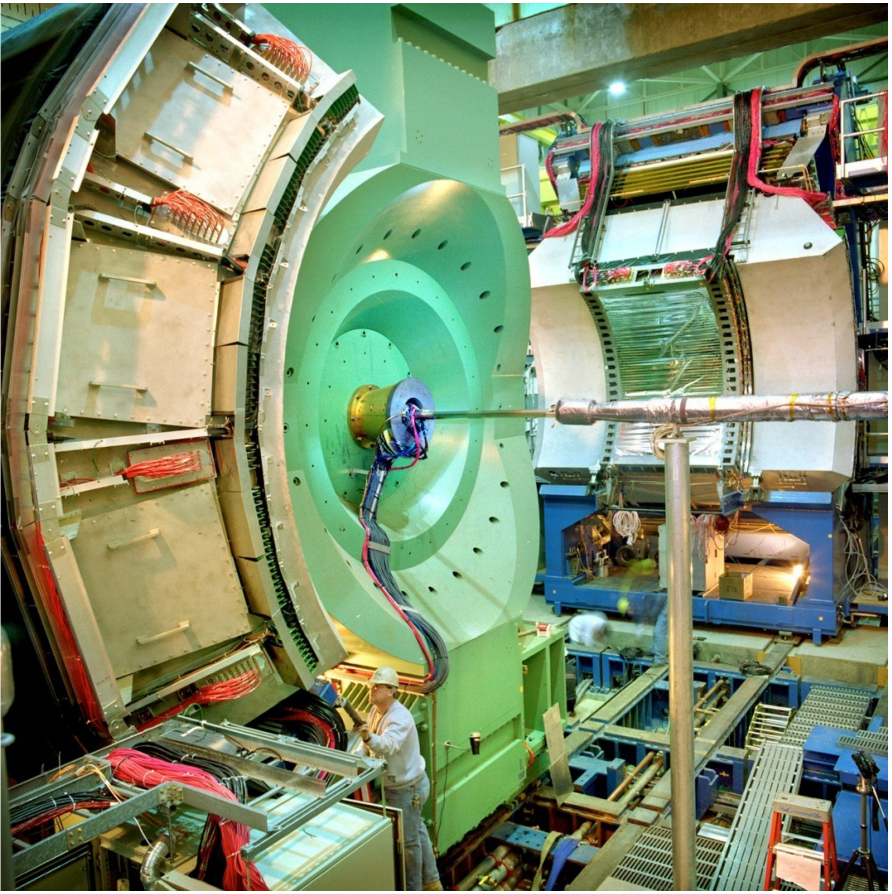
- Polarized protons
- Two Large and two small detectors were built

And for a few more days, it is the highest energy <u>heavy ion</u> collider in the world

The Large Detectors – PHENIX and STAR

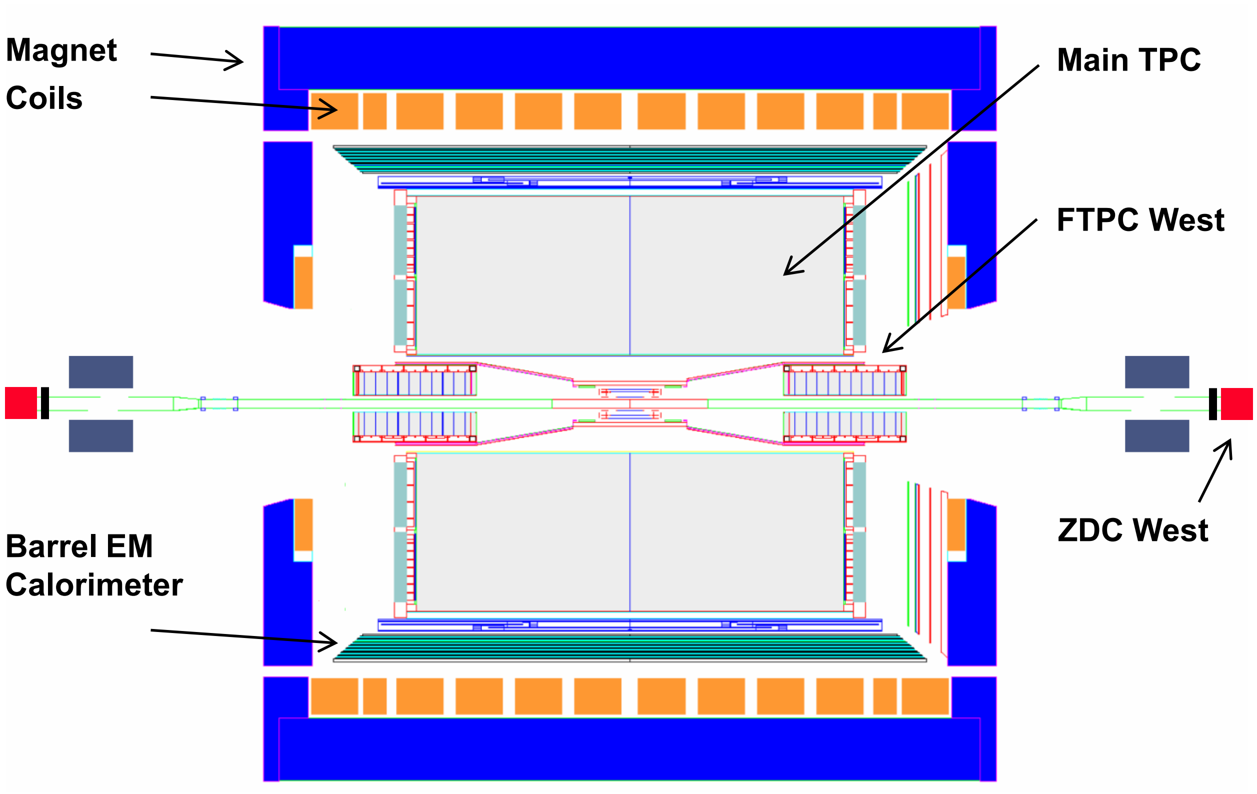


STAR



PHENIX

STAR Parity Data & Analysis



- Tracking is done by the **Main TPC** and independently by two **Forward TPCs**

- **ZDC-SMD** measures spectator neutrons and can be used to determine the first order reaction plane

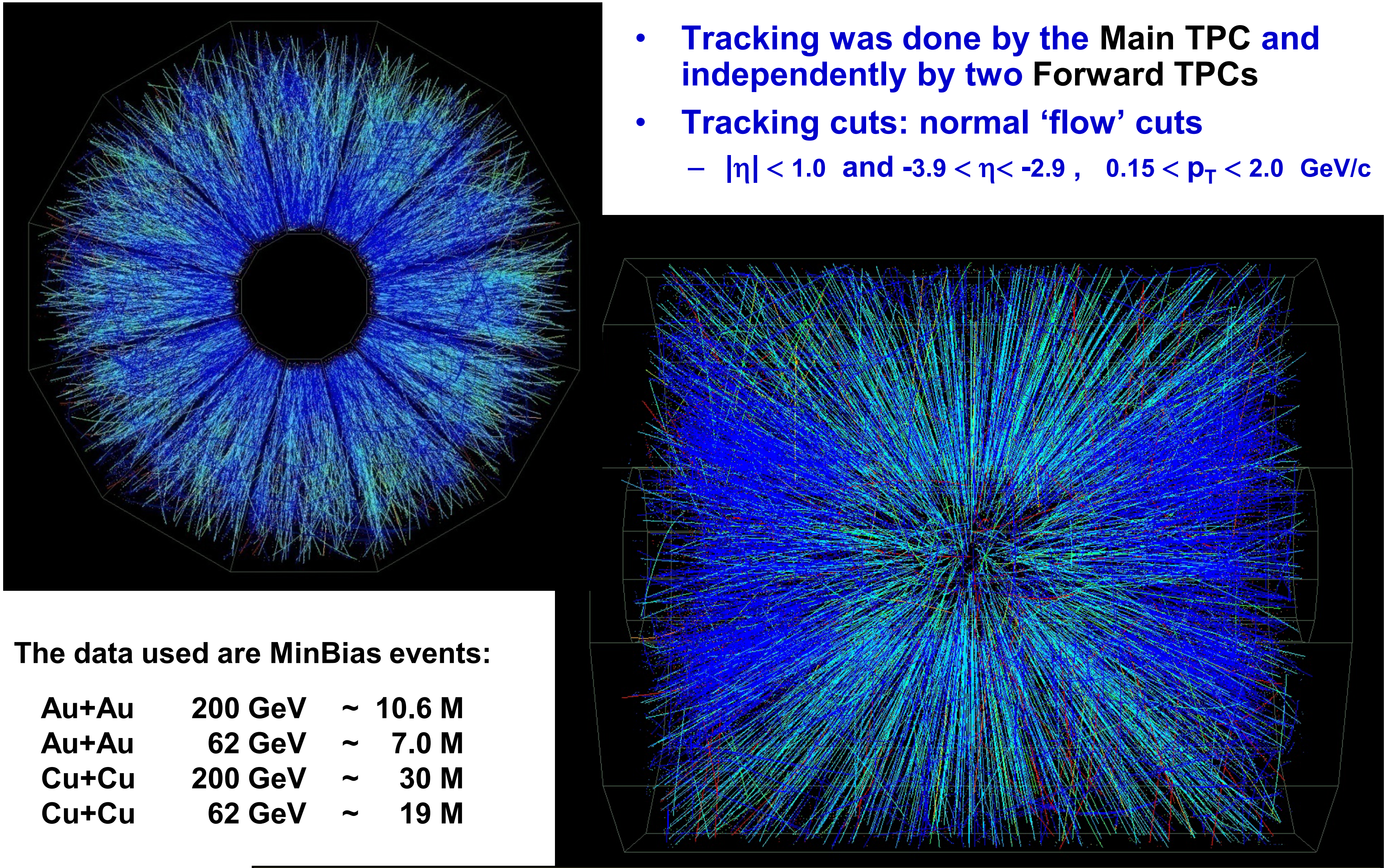
- Tracking cuts:
  - $|\eta| < 1.0$ (Main TPC)
  - $-3.9 < \eta < -2.9$
    $3.9 < \eta < 2.9$ (FTPCs)
  - $0.15 < p_T < 2.0$ GeV/c

The data presented here were taken during RHIC Run IV and are based on:

Au+Au	200 GeV	~	10.6 M Minimum Bias events
Au+Au	62 GeV	~	7.0 M Minimum Bias events
Cu+Cu	200 GeV	~	30 M Minimum Bias events
Cu+Cu	62 GeV	~	19 M Minimum Bias events

Cu-Cu and Au-Au Events at √s = 62 & 200 GeV

STAR



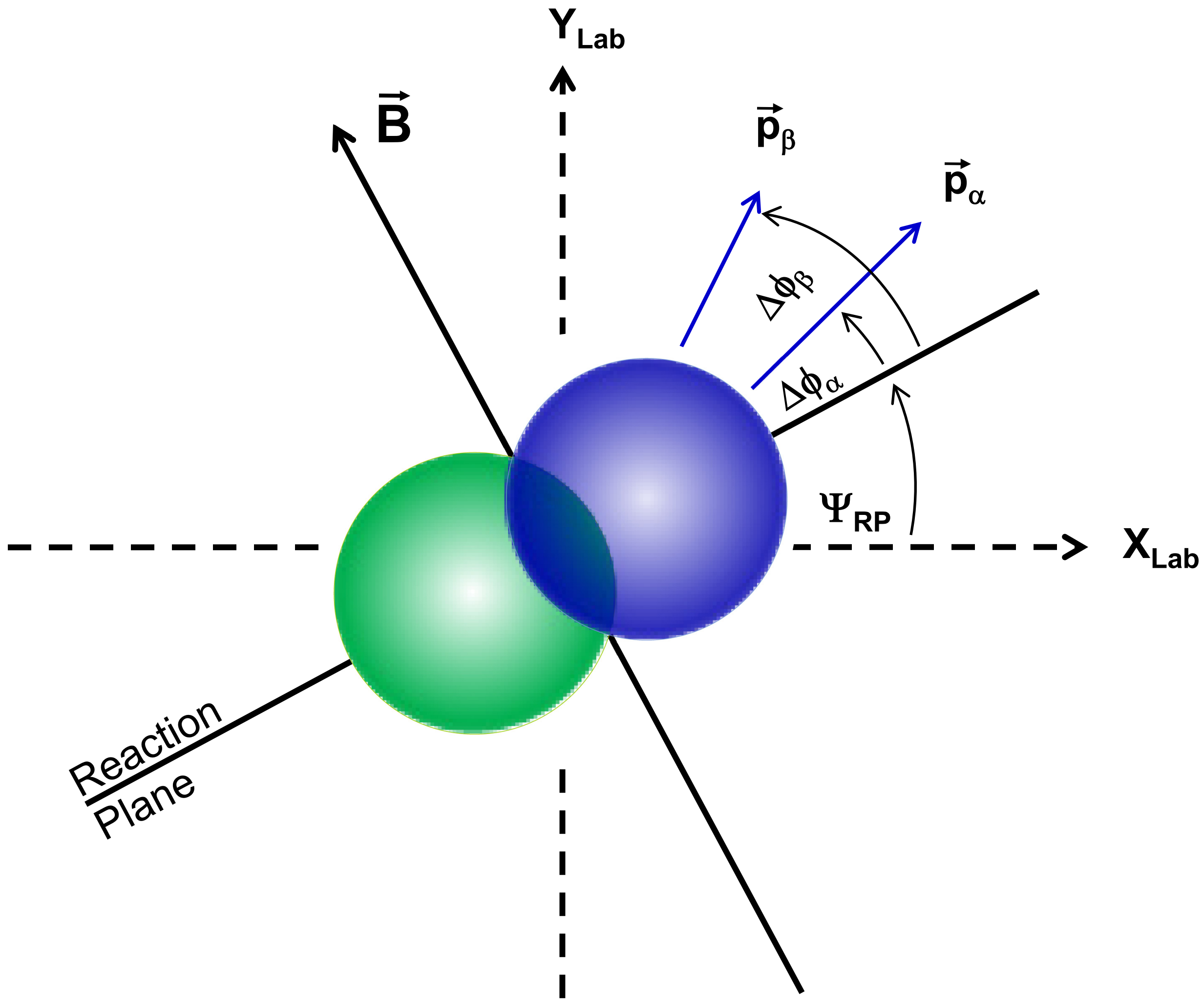
- Tracking was done by the **Main TPC** and independently by two **Forward TPCs**
- Tracking cuts: normal 'flow' cuts
  - – $|\eta| < 1.0$ and $-3.9 < \eta < -2.9$, $0.15 < p_T < 2.0$ GeV/c

The data used are MinBias events:

Au+Au	200 GeV	~	10.6 M
Au+Au	62 GeV	~	7.0 M
Cu+Cu	200 GeV	~	30 M
Cu+Cu	62 GeV	~	19 M

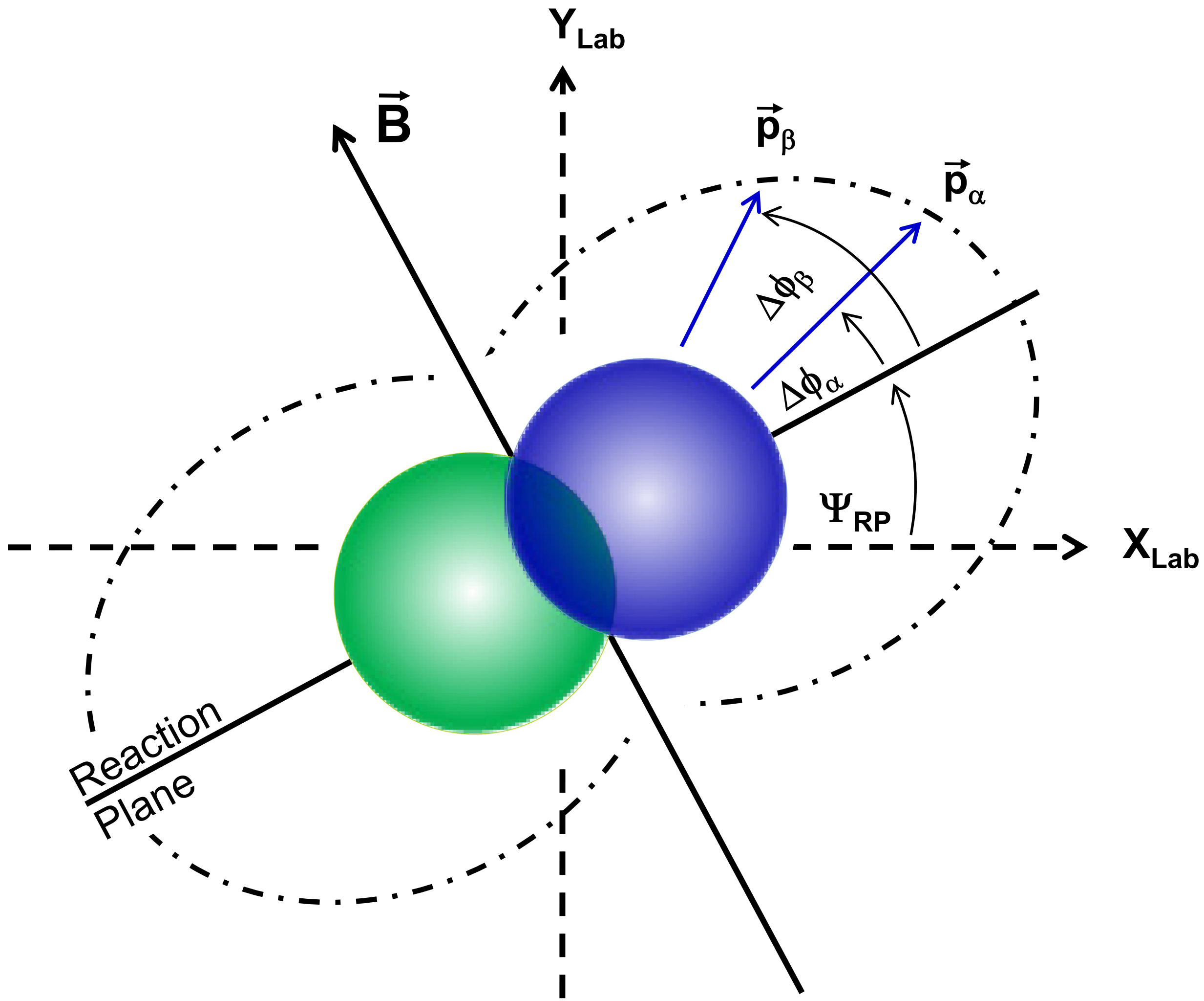
The P and CP analysis is done by looking at the angular distribution of tracks; ignoring mass, energy, and momentum. Only the angle of emission is used.

Analysis Uses Standard Flow Tools



- **The line between the centers of the nuclei and the beam axis define the reaction plane – perpendicular to angular momentum vector and B field**

Analysis Uses Standard Flow Tools



- The line between the centers of the nuclei and the beam axis define the reaction plane – perpendicular to angular momentum vector and B field

Full Fourier Transform of the Invariant Yield

$$f(\phi) = \frac{b'_0}{2} + \sum_{n=1}^{\infty} \left(a'_n \sin(n\phi) + b'_n \cos(n\phi) \right)$$

where

$$a'_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \sin(n\phi) \; d\phi \quad \text{for} \quad n = 1, 2, \ldots$$

$$b'_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \cos(n\phi) \; d\phi \quad \text{for} \quad n = 0, 1, 2, \ldots$$

If we want to test if parity is conserved then we should keep the extra terms

$$E \frac{dN^3}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + \underline{2a_1 \sin(\Delta\phi)} + 2b_1 \cos(\Delta\phi) + \underline{2a_2 \sin(2\Delta\phi)} + 2b_2 \cos(2\Delta\phi) + \ldots \right)$$

where

$$a_n = \pi a'_n = \sum_i \sin(n(\phi_i - \Psi_R)) \;, \qquad b_n = \pi b'_n = \sum_i \cos(n(\phi_i - \Psi_R))$$

The standard HI flow analysis assumes a = 0 and assigns $b_n \equiv v_n$

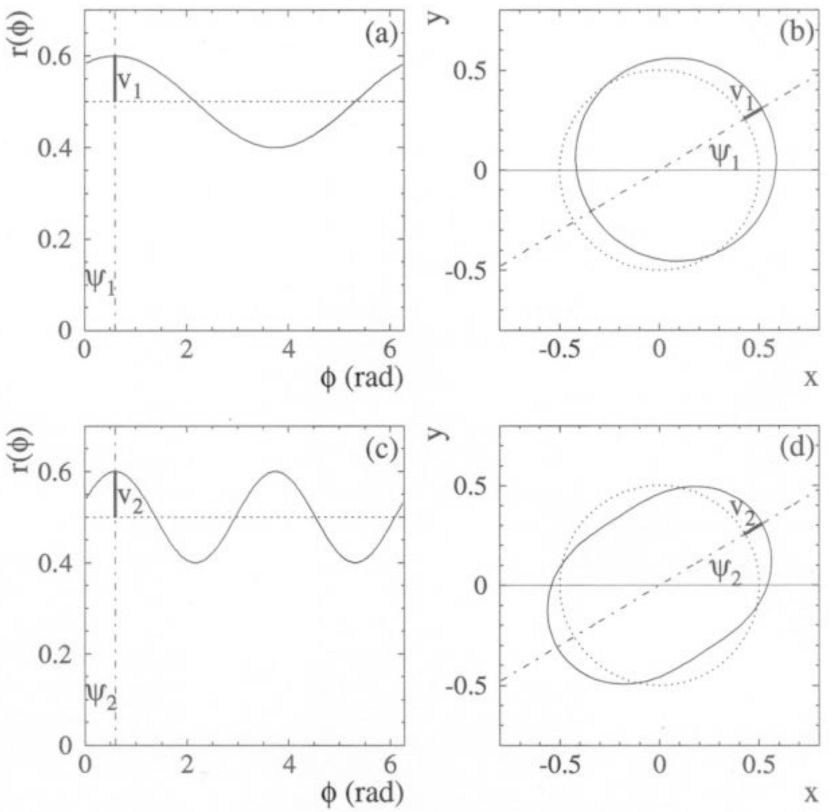
Interpreting Flow – order by order

n=1: Directed Flow has a period of 2π (only one maximum)

- ~~v_1 measures whether the flow goes to the left or right – whether the momentum goes with or against a billiard ball like bounce. For collisions of identical nuclei, symmetry forces v_1 to be an odd function of η~~

n=2: Elliptic flow has a period of π (two maximums)

- v_2 represents the elliptical shape of the momentum distribution. It is an even function of η for identical nuclei



Perform a Fourier Transform to isolate the coefficients

If parity is conserved, sin() terms drop out

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2a_1\sin(\Delta\phi) + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + 2v_4\cos(4\Delta\phi) + \ldots \right)$$

isotropic

parity non-conserving

directed

elliptic

higher order terms

The Experimental Observable

- **The coefficients for the Fourier expansion of the invariant yield are**

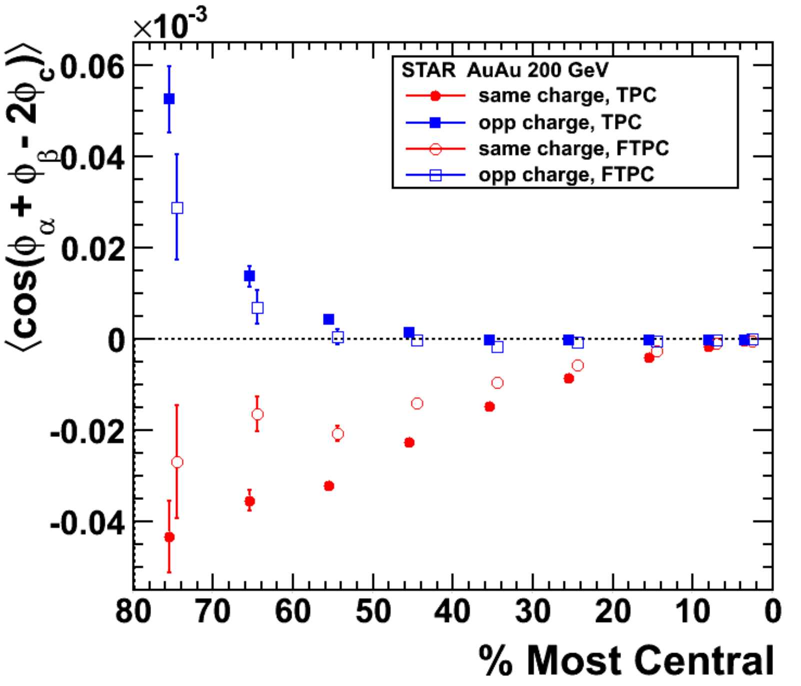
  $$v_n \equiv \left\langle \cos\left(n(\phi - \Psi_R)\right) \right\rangle \quad \textbf{or} \quad v_n^2 = \left\langle \cos\left(n(\phi_i - \phi_j)\right) \right\rangle$$

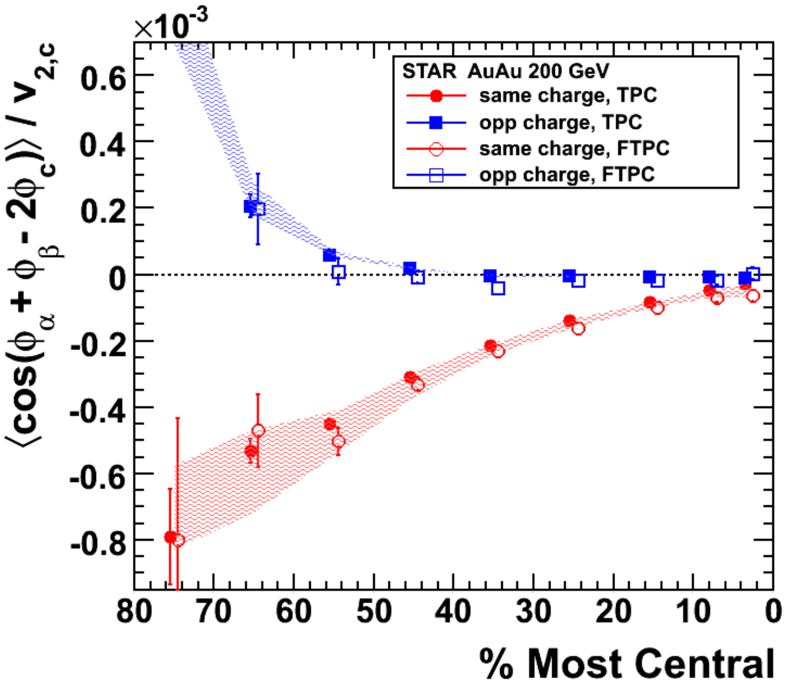
  - **where the average is taken over all particles in the event and ψ_R is the known reaction plane angle (e.g. from the FTPC if we are using TPC data)**
  - **The second method is a true two particle correlation (many details left out)**

- **Under certain assumptions v_1 is directed flow**
  - **Note that a 'normal' v_1 measurement for pions in a Au-Au reaction has an intrinsic symmetry that suggests weighting by sign(η)**
  - **Don't do this. We are looking for charge flow that goes up/down so choose to do the sum without sign(η) weighting and thus the 'normal' v_1 will cancel out. (See next bullet). This assumes symmetric η acceptance.**

- **A clever observable: $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$ … a triple correlation**
  - **Mixed Harmonics:** $\left\langle \cos(\phi_i - \phi_k)\cos(\phi_j - \phi_k) - \sin(\phi_i - \phi_k)\sin(\phi_j - \phi_k) \right\rangle = (v_1^2 - a_1^2)\, v_2$
  - **Measure $(v_1^2 - a_1^2) * v_2$ because v_2 is large and it amplifies the parity non-conserving signal, a_1, while preserving reasonable statistical errors.**
  - **The signal is parity odd, but the observable $(v_1^2 - a_1^2) * v_2$ is even. Best way to measure charge sensitive flow because $v_1 \Rightarrow 0$ and $\underline{(v_1^2 - a_1^2) * v_2 \quad \Rightarrow \quad -a_1^2 * v_2}$**

Like Sign and Opposite Sign Correlations





Abelev et al. (STAR Collaboration), PRL 103, 251601 (2009)

Abelev et al. (STAR Collaboration), PRC, 81, 054908 (2010)

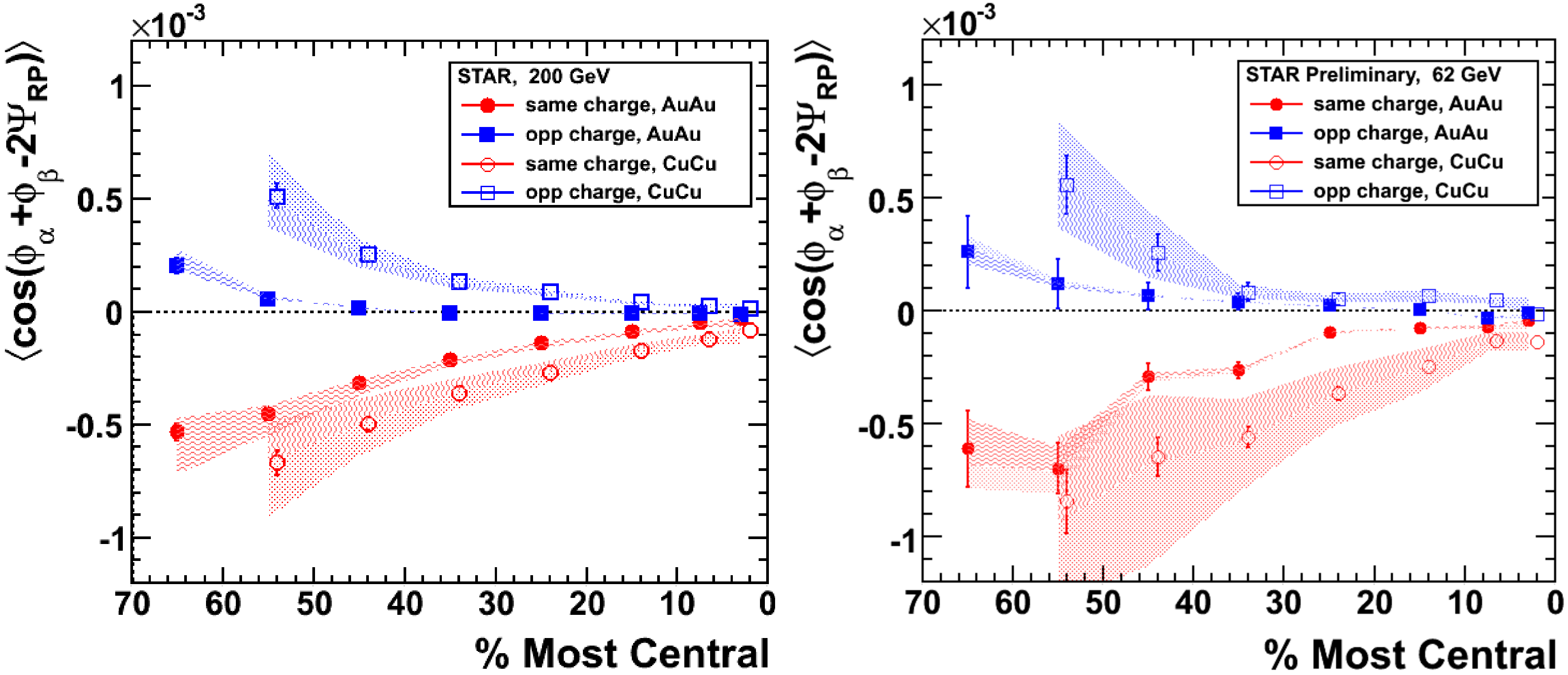
- **A charge separation signal appears in the data; independent of how we determine the reaction plane with different estimates of Ψ_R (i.e. ϕ_c)**
  - **Signal is present if Ψ_R is found with the TPC, FTPC, or even ZDC.**
  - **Systematic errors in panel II, above, cover the range introduced by using $v_2\{2\}$ or $v_2\{4\}$ in the calculation**
- $\left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle / \mathrm{v}_{2,c} \approx -1 * \left\langle a_{1,\alpha}\, a_{1,\beta} \right\rangle$ **and so is a candidate PV signal**
  - **Same sign $a_{i,\gamma}$ flow is negative … Opposite sign $a_{i,\gamma}$ flow is positive**

Expectations, if it is topologically induced PV

- Magnitude: $|a| \sim Q / N_{\pi+}$ where $Q = N_L - N_R = 0, \pm 1, \pm 2, \ldots$
  - ✓ $|a| \sim 10^{-2}$ or equivalently $|a|^2 \sim 10^{-4}$ and independent of how Ψ_R is found
- Charge Combinations for the observable $\left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle / \mathrm{v}_{2,c}$
  - ✓ $\left\langle a_+ a_+ \right\rangle = \left\langle a_- a_- \right\rangle = -1 * \left\langle a_+ a_- \right\rangle$
    - ✓ Same sign $a_{i,\gamma}$ flow is negative … Opposite sign $a_{i,\gamma}$ flow is positive
  - Particle interactions in the medium may cause suppression of the back to back correlations
    - Quenching is a possible and may be expected … more theoretical work req'd
- Species Dependence
  - Proportional to Z^2 but quenching may be smaller in smaller systems
- Centrality Dependence
  - If the P-violating domain does not change size with centrality, then correlator should depend on $1/N_{mult}$ times magnitude of B field
    - The effect should decrease with centrality faster than $1/N_{mult}$
- Rapidity dependence
  - Correlated particles come from a domain of ~ 1 fm, and $\Delta\eta \approx 1$

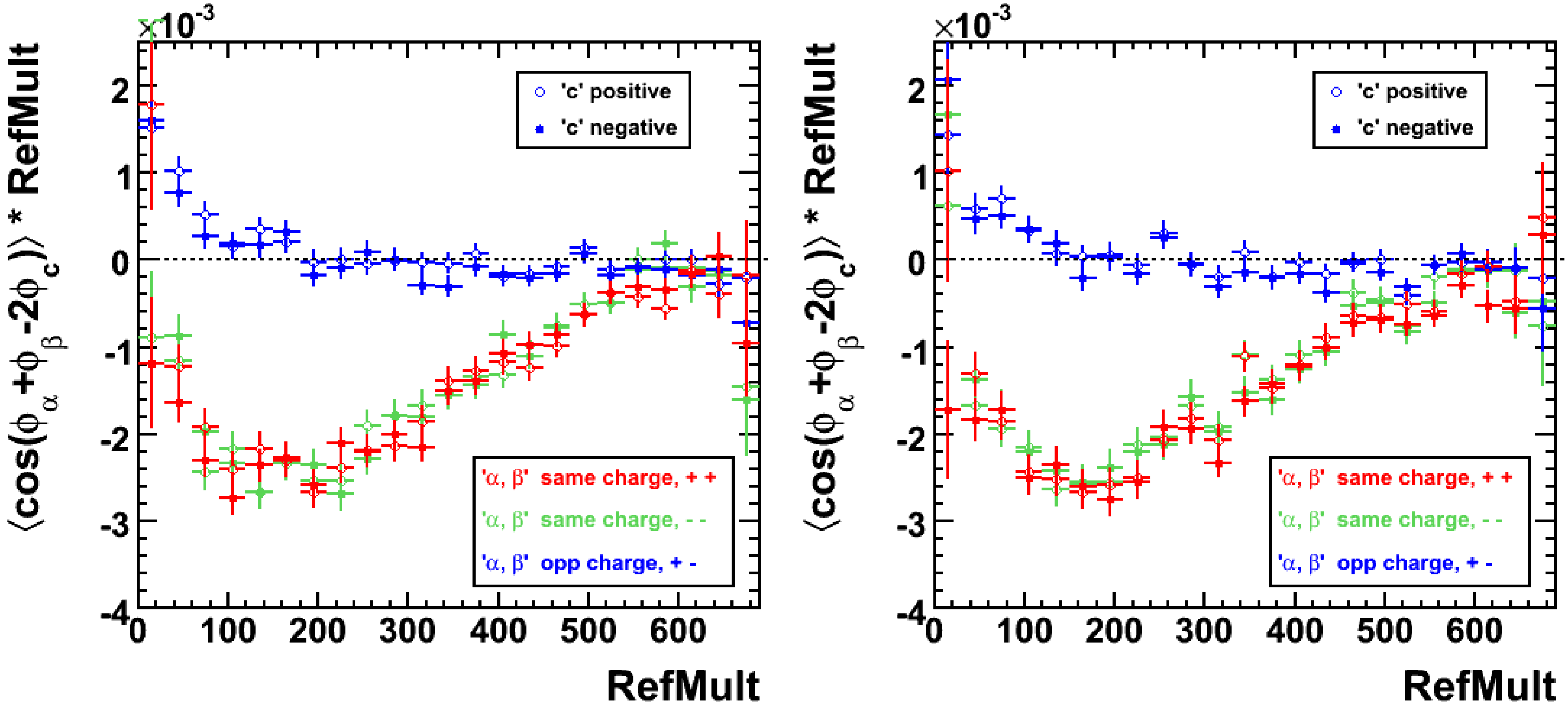
Lets look at some of these expectations to see if they hold true

Species and Energy Dependence



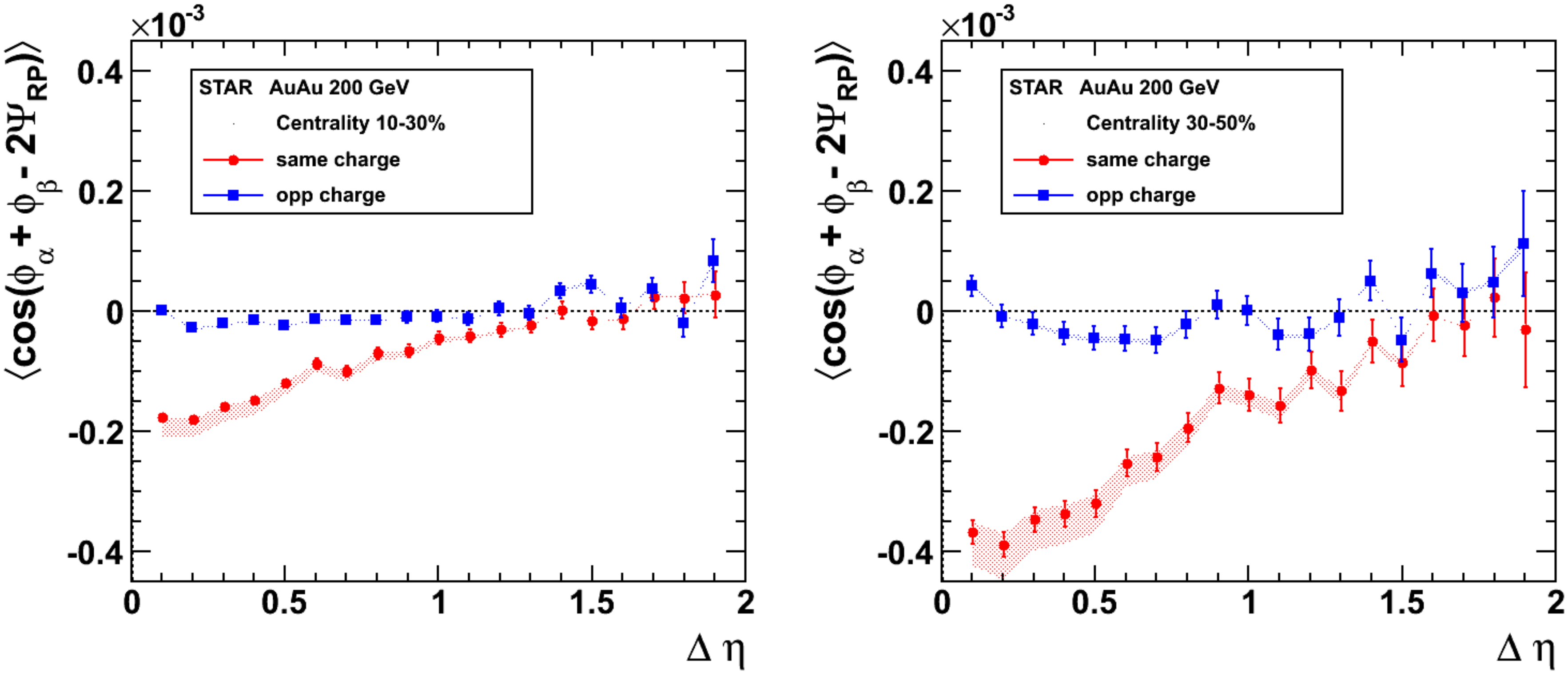
- **Au-Au data compared to Cu-Cu data**
    - Results suggests that Cu-Cu data, as a function of centrality, is larger
    - Possibly suggesting that a smaller system is less quenched
- **200 GeV data compared to 62 GeV data – signal is similar in both**
    - Shaded regions represent uncertainty in elliptic flow

Centrality and/or Multiplicity Dependence (& other systematics)



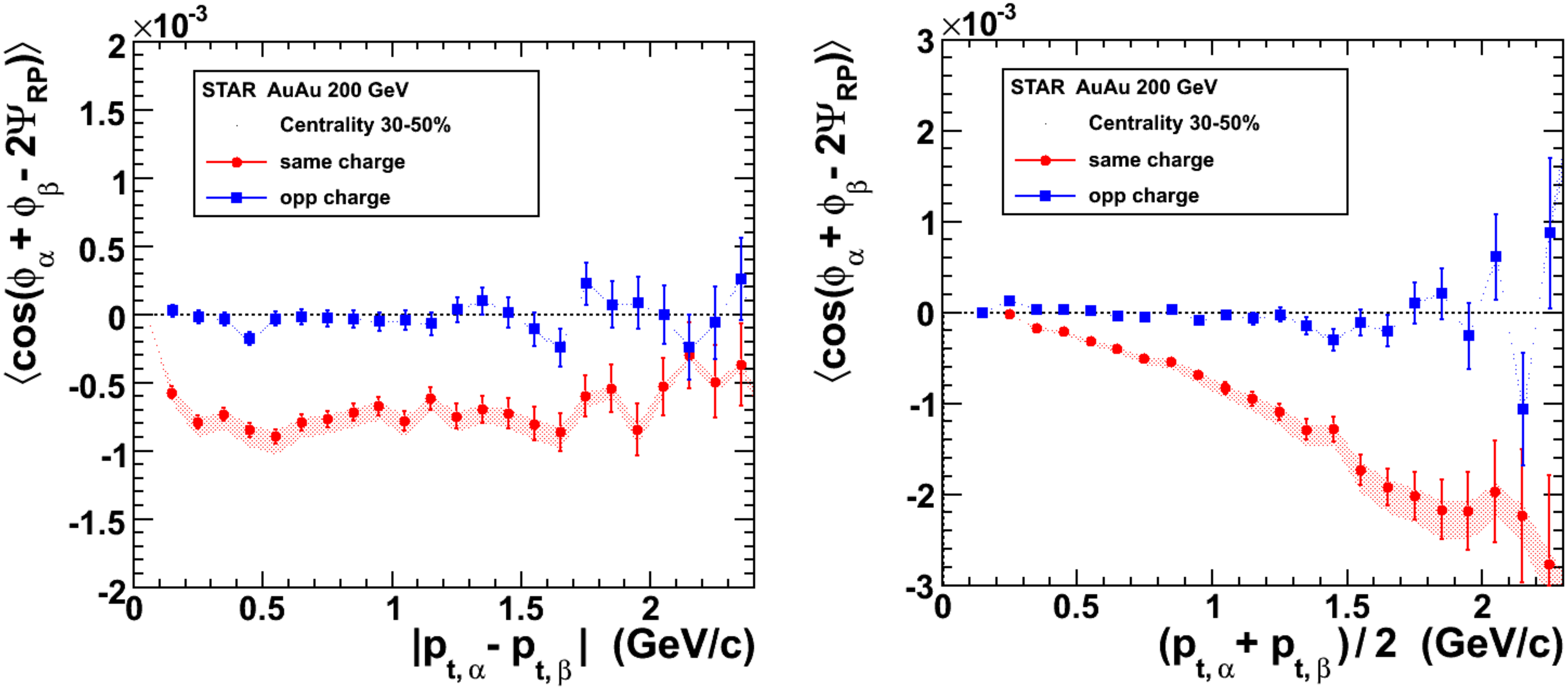
- **Au-Au 200 - Correlator decreases with centrality faster than $1/N_{mult}$ for same sign correlations**
  - Apologies for the use of RefMult … it is uncorrected multiplicity into ±0.5 unit of η
- **Correlator * RefMult .vs. RefMult … plotted for Positive (left) and Negative (right) polarity of the STAR magnet**
  - Good study of systematics of B field … also acceptance corrections (see PRC)

Rapidity Dependence



- **Rapidity dependence of the 10-30 and 30-50% centrality bins**
- **Typical hadronic width of about one unit of pseudo-rapidity**
- **Shaded bands indicate uncertainties in the v_2 measurements**
  - **Error bands estimated with 2 and 4 particle cumulants as bounds**

p_T Dependence of the Signal



- p_t difference
  - Signal is roughly constant for a p_t difference from 0 to 2 GeV/c.
- Average p_t :
  - Signal grows with p_t up to 2 GeV/c and then limited by statistics

p_T dependence is not as naively expected. Guidance from theory suggests that the phenomena are limited to p_T < 1 GeV/c. However, Koch et al. show that a boost of 150 MeV per correlated pair is consistent with the CME and the data.

Cumulants and full PID for pions

- Note that … $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$ = Re $\langle e^{i(\phi i + \phi j - 2\phi k)} \rangle$
  - This is the basis for the cumulant technique
  - A powerful tool that allows us to subtract two particles correlations from the three particle correlation that we are trying to measure
  - Automatically 're-centers' the data (i.e. acceptance corrections)

- So for example:

$$\begin{aligned}\left\langle\left\langle e^{i(\phi_i+\phi_j-2\phi_k)}\right\rangle\right\rangle &= \left\langle e^{i(\phi_i+\phi_j-2\phi_k)}\right\rangle \\ &- \left\langle e^{i(\phi_i+\phi_j)}\right\rangle\left\langle e^{i(-2\phi_k)}\right\rangle - \left\langle e^{i(\phi_i-2\phi_k)}\right\rangle\left\langle e^{i(\phi_j)}\right\rangle \\ &- \left\langle e^{i(\phi_i)}\right\rangle\left\langle e^{i(\phi_j-2\phi_k)}\right\rangle + \left\langle e^{i(\phi_i)}\right\rangle\left\langle e^{i(\phi_j)}\right\rangle\left\langle e^{i(-2\phi_k)}\right\rangle\end{aligned}$$

- Test acceptance corrections … but also to test full PID
  - All previous analyses were done for all-charged particles
  - Now select pions (± 2σ) and reject electrons (± 2σ)
  - Goal: to confirm that it is hadrons, not leptons, that show the PV signal

Full Cumulant – Analysis and Results

$$\begin{aligned}\left\langle\left\langle e^{i\left(\phi_i+\phi_j-2\phi_k\right)}\right\rangle\right\rangle &= \left\langle e^{i\left(\phi_i+\phi_j-2\phi_k\right)}\right\rangle \\ &- \left\langle e^{i\left(\phi_i+\phi_j\right)}\right\rangle\left\langle e^{i\left(-2\phi_k\right)}\right\rangle - \left\langle e^{i\left(\phi_i-2\phi_k\right)}\right\rangle\left\langle e^{i\left(\phi_j\right)}\right\rangle \\ &- \left\langle e^{i\left(\phi_i\right)}\right\rangle\left\langle e^{i\left(\phi_j-2\phi_k\right)}\right\rangle + \left\langle e^{i\left(\phi_i\right)}\right\rangle\left\langle e^{i\left(\phi_j\right)}\right\rangle\left\langle e^{i\left(-2\phi_k\right)}\right\rangle\end{aligned}$$

Real Terms

$$\begin{aligned}\mathrm{a}_1^2\,\mathrm{v}_2 &= \left\langle\cos(\phi_i+\phi_j-2\phi_k)\right\rangle \\ &- \left\langle\cos\left(\phi_i+\phi_j\right)\right\rangle\left\langle\cos\left(-2\phi_k\right)\right\rangle - \left\langle\cos\left(\phi_i-2\phi_k\right)\right\rangle\left\langle\cos\left(\phi_j\right)\right\rangle \\ &- \left\langle\cos\left(\phi_i\right)\right\rangle\left\langle\cos\left(\phi_j-2\phi_k\right)\right\rangle + 2\left\langle\cos\left(\phi_i\right)\right\rangle\left\langle\cos\left(\phi_j\right)\right\rangle\left\langle\cos\left(-2\phi_k\right)\right\rangle\end{aligned}$$

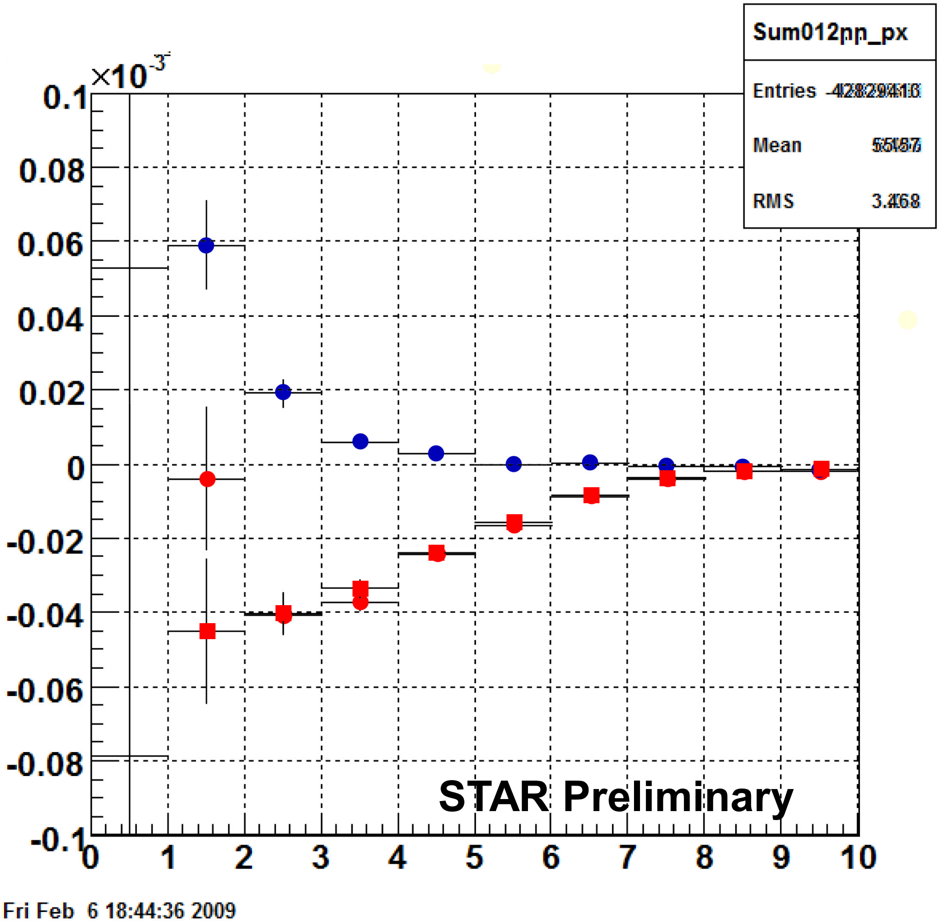
Imaginary Terms enter via cross-terms to create additional real terms

$$\begin{aligned}&+ \left\langle\sin\left(\phi_i+\phi_j\right)\right\rangle\left\langle\sin\left(-2\phi_k\right)\right\rangle + \left\langle\sin\left(\phi_i-2\phi_k\right)\right\rangle\left\langle\sin\left(\phi_j\right)\right\rangle \\ &+ \left\langle\sin\left(\phi_i\right)\right\rangle\left\langle\sin\left(\phi_j-2\phi_k\right)\right\rangle - 2\left\langle\sin\left(\phi_i\right)\right\rangle\left\langle\sin\left(\phi_j\right)\right\rangle\left\langle\cos\left(-2\phi_k\right)\right\rangle \\ &- 2\left\langle\sin\left(\phi_i\right)\right\rangle\left\langle\cos\left(\phi_j\right)\right\rangle\left\langle\sin\left(-2\phi_k\right)\right\rangle - 2\left\langle\cos\left(\phi_i\right)\right\rangle\left\langle\sin\left(\phi_j\right)\right\rangle\left\langle\sin\left(-2\phi_k\right)\right\rangle\end{aligned}$$

Acceptance corrections are crucial when doing full PID in STAR

Full 3 particle cumulant for Run IV Au-Au 200

Very good agreement with non-PID data and more conventional results



- \+ - opp sign
- ++ same sign
- \- - same sign

- **Full 3 particle cumulant**
  - Complete acceptance corrections used & required
- **With particle ID for pions**
  - Electrons rejected

Background – a few words

- Our observable is parity even and so may contain effects that are not related to strong parity violation

- Structure of correlator allows control of a wide class of backgrounds

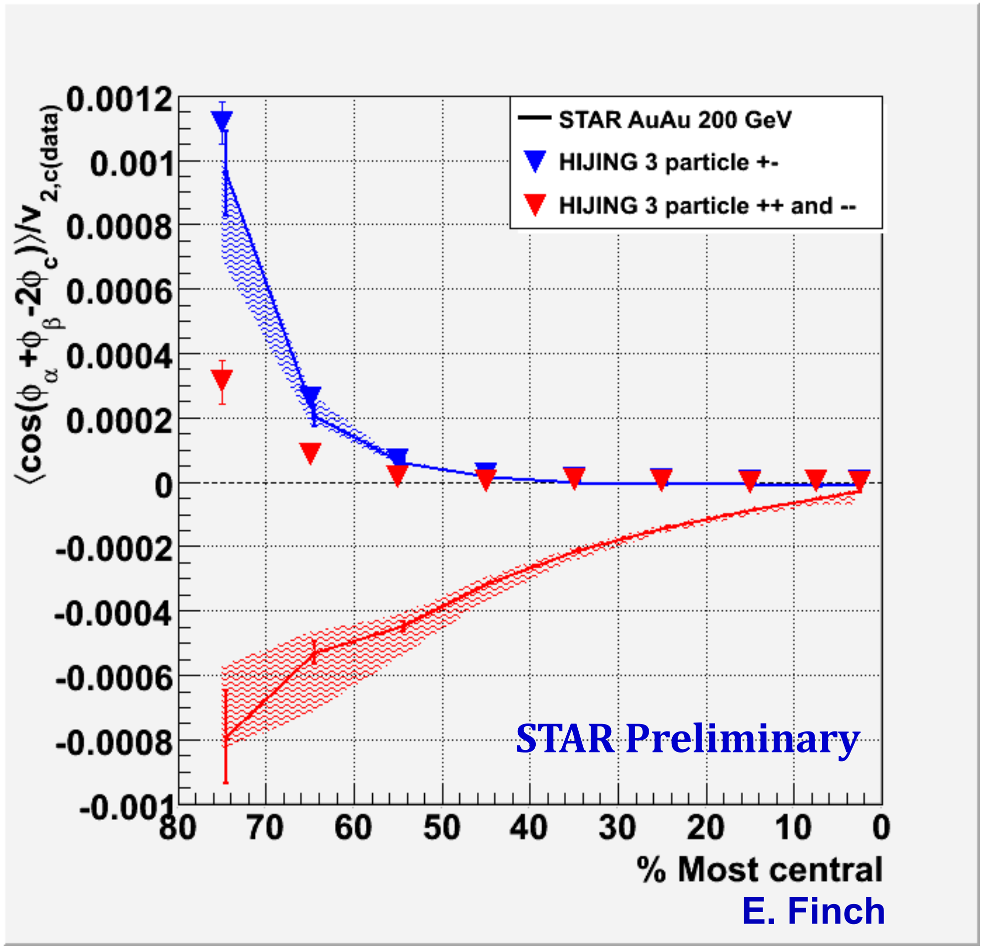
$$\left\langle \cos(\phi_i - \phi_k)\ \cos(\phi_j - \phi_k) \right\rangle - \left\langle \sin(\phi_i - \phi_k)\ \sin(\phi_j - \phi_k) \right\rangle = \left(\left(\mathrm{v}_1^2 + B_{in} \right) - \left(a_1^2 + B_{out} \right) \right) \mathrm{v}_2$$

- As previously noted, the magnitude of v_1 is small and the directed flow terms sum to zero due to our choice to *not* weight the sum by sign(η)

- The correlator represents the difference between correlations projected onto an axis in the reaction plane and an axis perpendicular to the reaction plane
  - This removes correlations among particles that are not related to the reaction plane orientation

- So a source of background that may persist in the data are particles from a cluster (resonance decay or jet) where the cluster is flowing with respect to the reaction plane
  - These studies, and other simulations studies, are a continuing effort

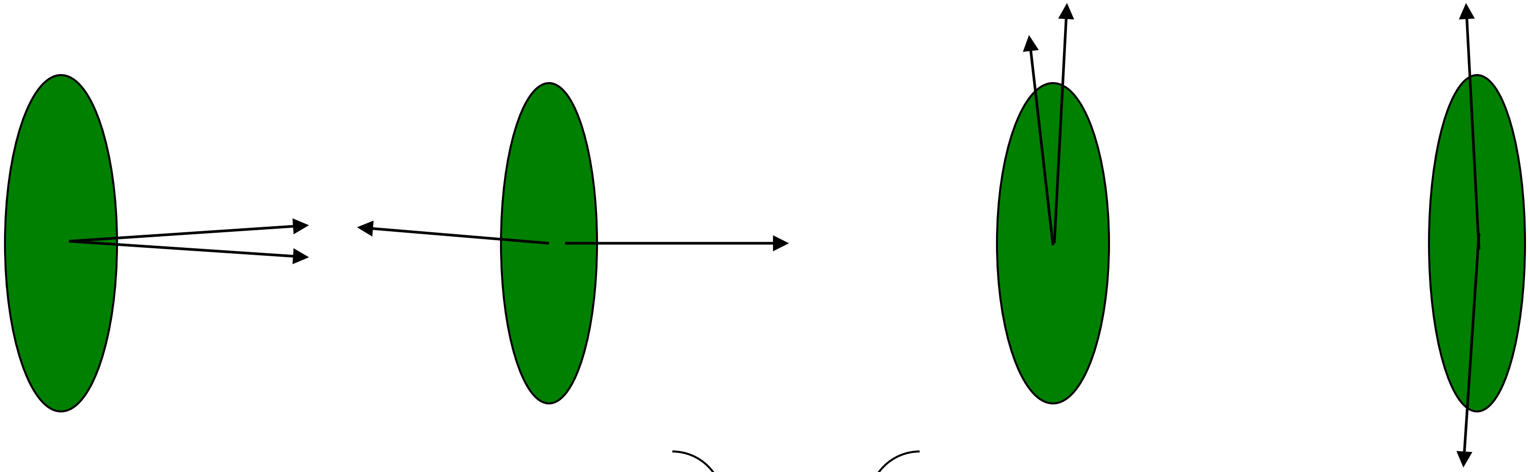
Reaction-plane independent background



- HIJING (quenching off) predicts that the 3 particle background is about as large as the measured signal for unlike-sign in several peripheral bins in all systems measured,
- Not a significant background for like-sign correlations over most of centrality range.
- UrQMD predicts a considerably smaller 3-particle cluster background.

Reaction-plane dependent backgrounds

$< \cos[(\Delta\varphi_a)+(\Delta\varphi_b)] >$ **measures, roughly speaking…**



(Same-side, in-plane pairs − Opposite-side, in-plane pairs) − (Same-side, out-of-plane pairs − Opposite-side, out-of-plane pairs)

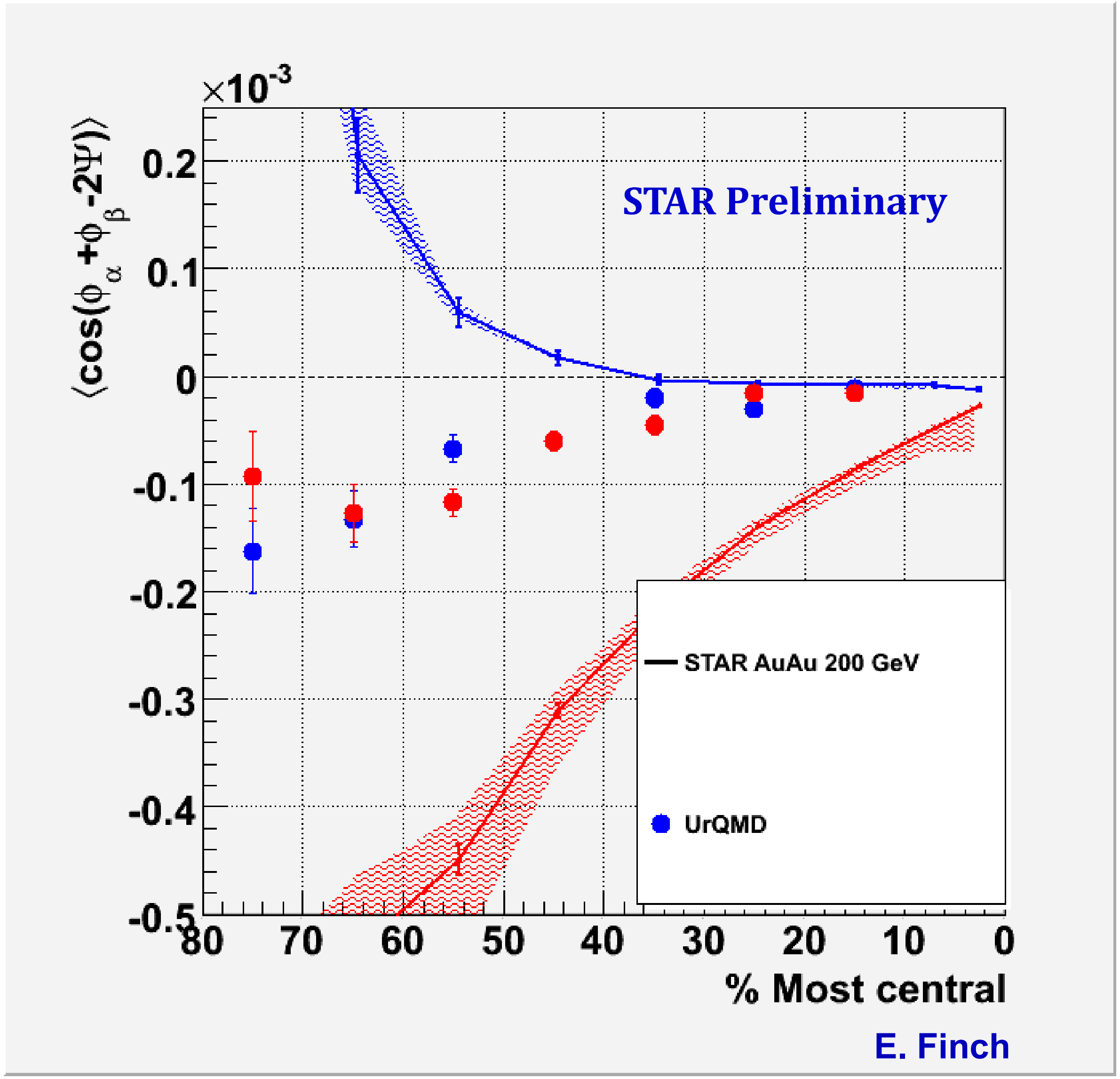
Potential problems include clusters (jets / minijets / resonances) whose production or properties depends on orientation with respect to the reaction plane. For example, a resonance which decays generally with a small opening angle and has positive v_2 gives a positive contribution.

$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{RP})\rangle =$$

$$= A_{clust}\,\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{clust})\rangle_{clust}\; v_{2,clust}$$

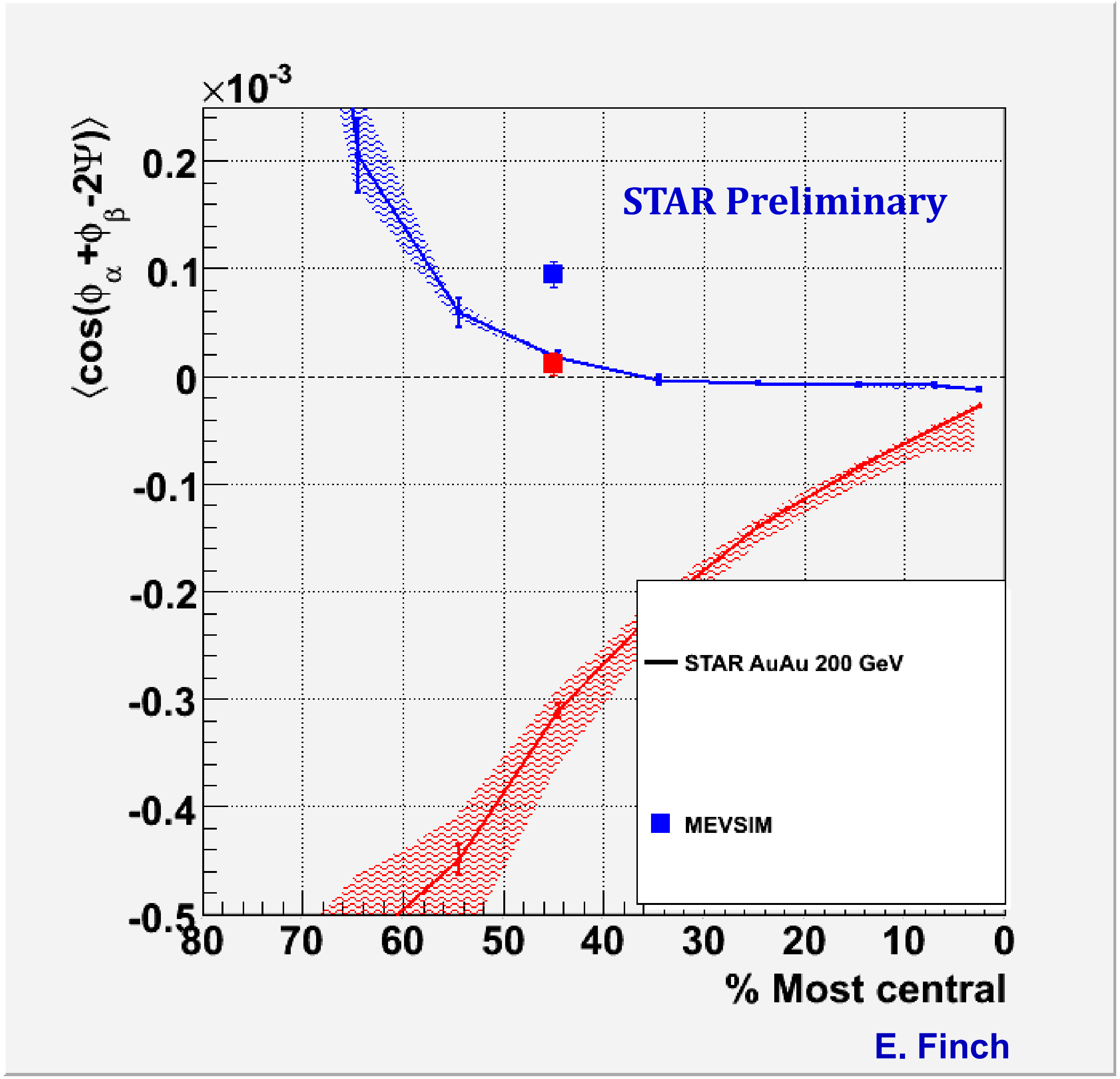
$$\boxed{\begin{aligned} A_{clust} &= (\text{probability that } \alpha \text{ is from a cluster}) \\ &\times\ (\text{probability that } \beta \text{ is from the same cluster}) \end{aligned}}$$

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



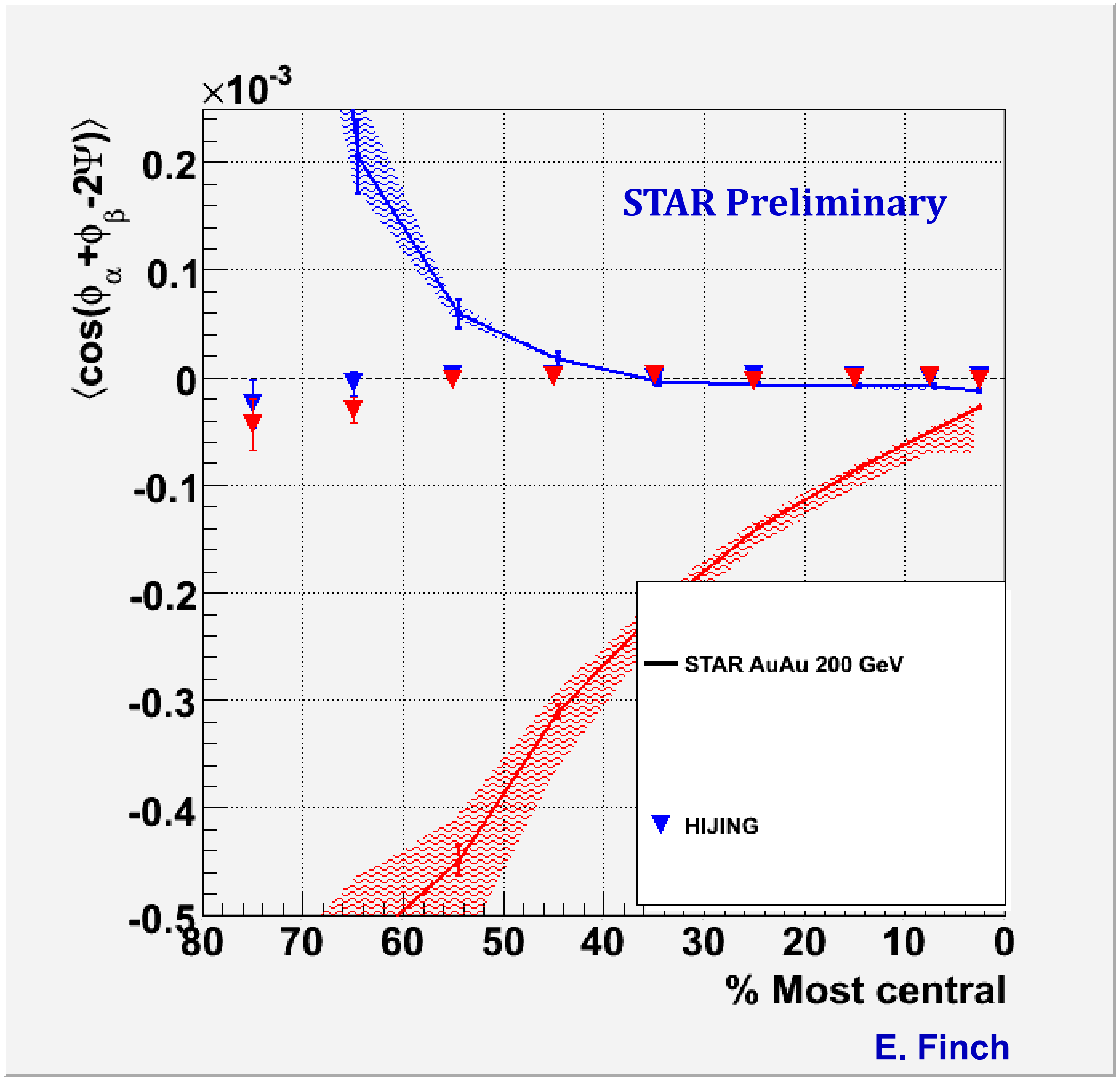
- **UrQMD**

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



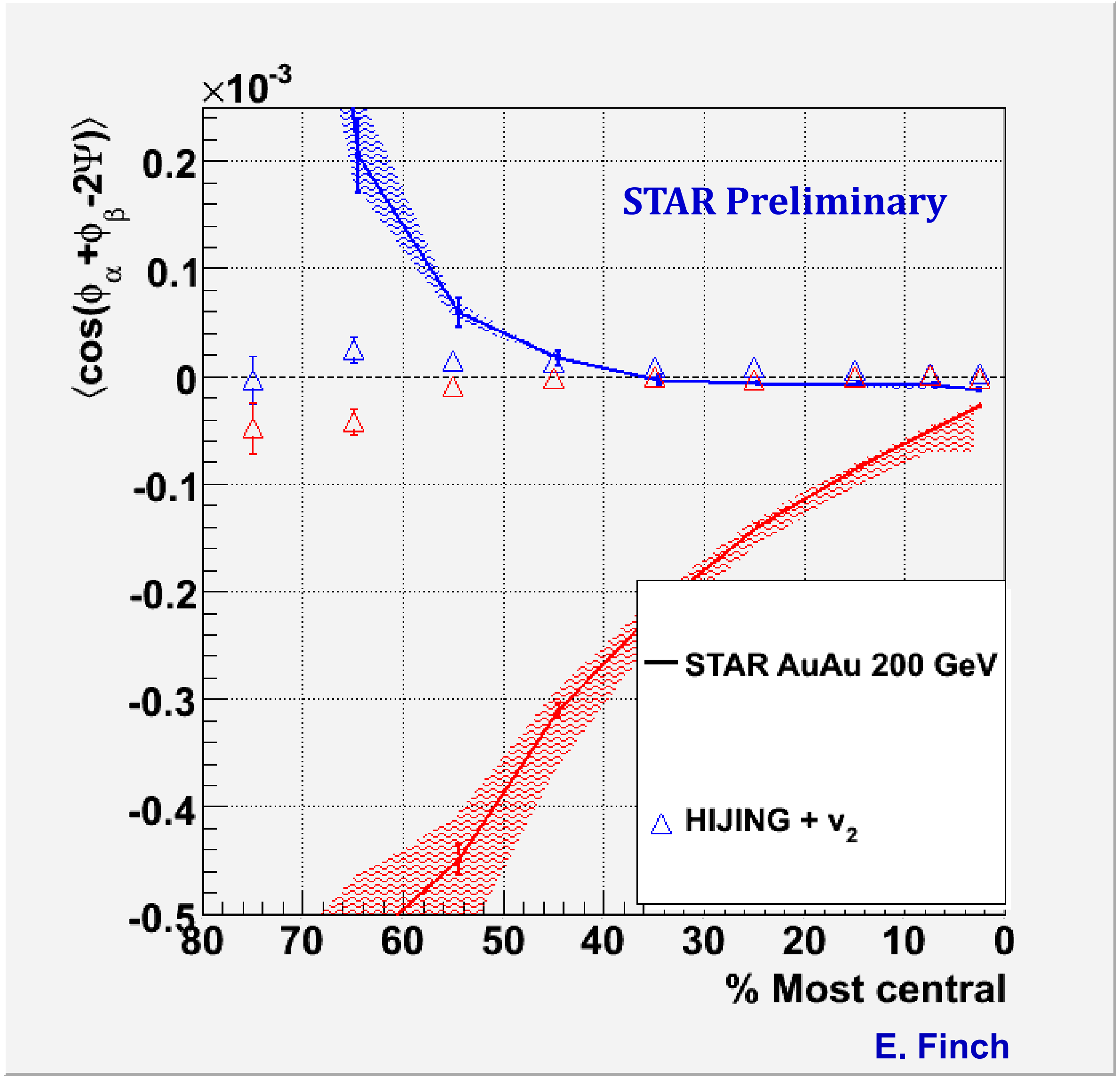
- **MEVSIM**

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



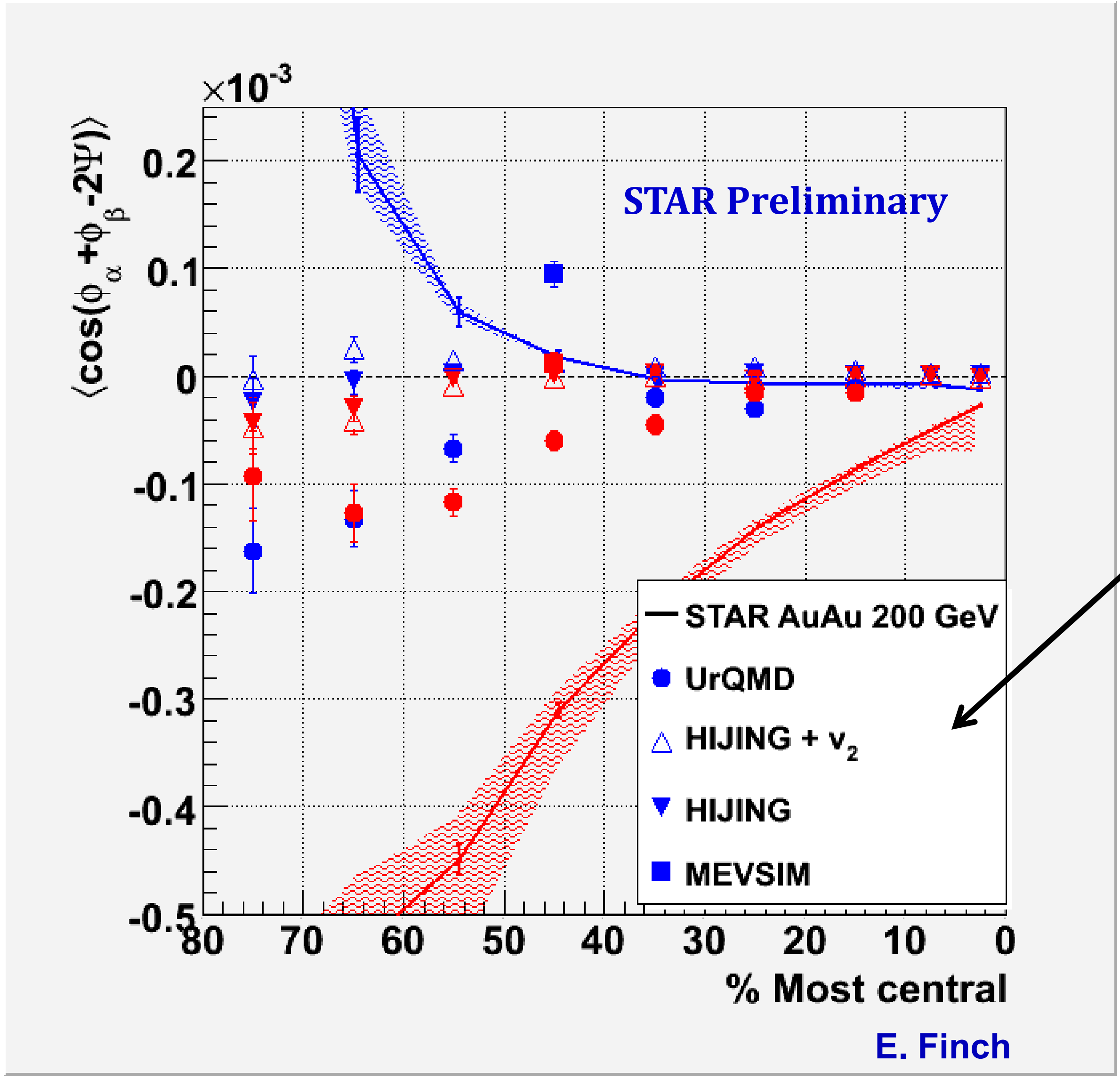
- **HiJing**

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



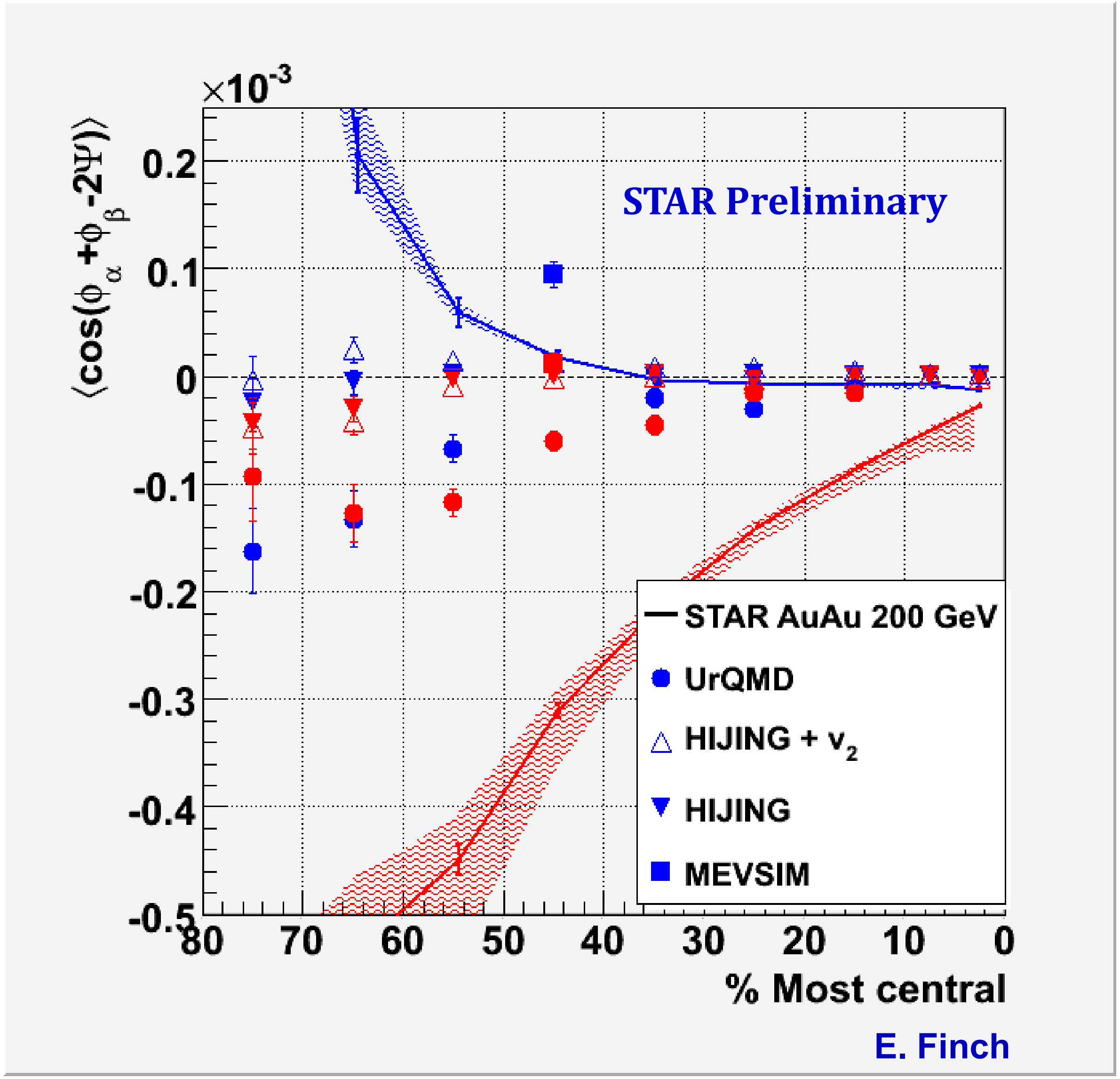
- HiJing + v_2

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



- All

$< \cos(\varphi_a+\varphi_b-2\Psi_{RP}) >$ (with Ψ_{RP} known)



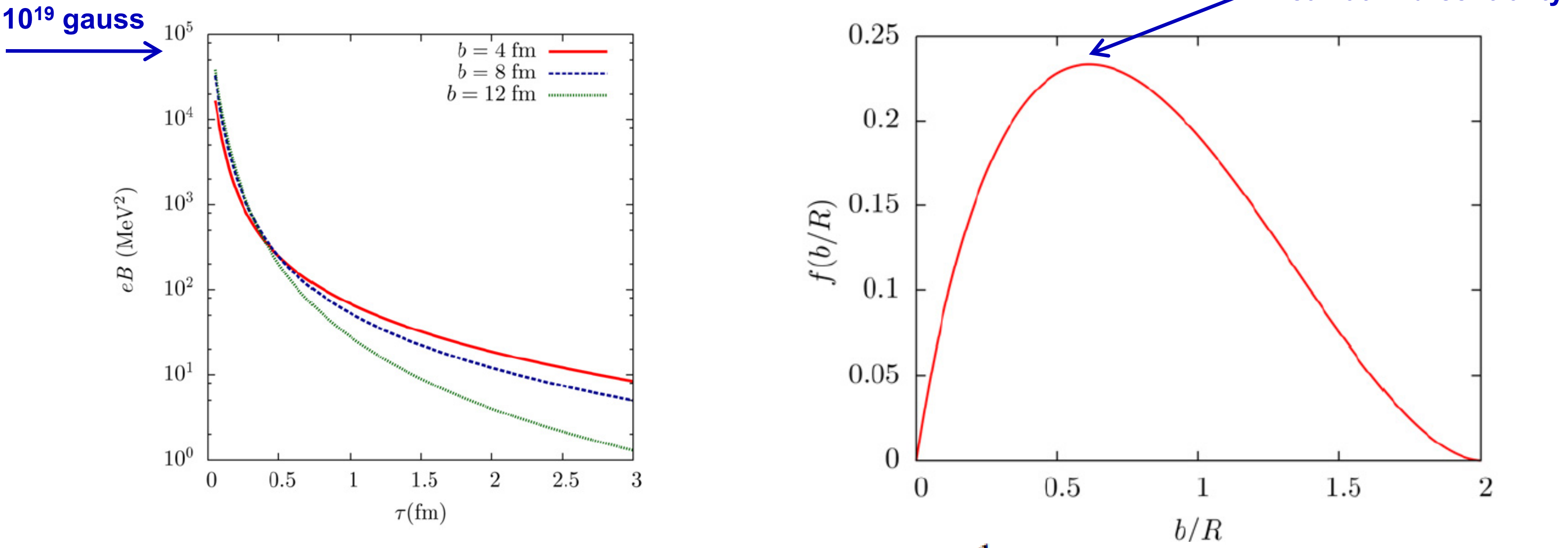
AMPT calculations also done but not shown due to lack of strict charge conservation.

Future Directions …

- **Goal: A true ‘smoking gun’ for Chiral Symmetry restoration and weird B field effects**
- **Theory – more robust estimates of the magnitude of the effect are highly desirable and better predictions for systematic trends**
  - **Many works in progress; see work by Kharzeev, McLerran, Warringa et al.**
- **Theory – show that the Chiral Magnetic Effect can be derived from first principles lattice calculations**
  - **This is work in progress; see for example T. Blum et al. arXiv: 0911.1348**
- **Experiment – three particle reaction plane dependent backgrounds**
  - **needs more work**
- **U-U collisions – study tip to tip collisions**
  - **The tricky part is triggering on a tip to tip collision**
- **Energy Scan to lower and higher energies**
  - **The Chiral Magnetic Effect depends on chiral symmetry restortion and a QGP … does the signal go away at lower energies?**
  - **Alice and the LHC: the signal could be of the same magnitude, or smaller**

Prospects for ALICE and the LHC

- Presumably, the domain size for topological charge fluctuations grows at higher energies … but the effect of the participant's magnetic field goes down as exp(-Y_0/2) (surprise!)



$$eB_p \approx cZ\alpha_{\mathrm{EM}} \exp(-Y_0/2) \frac{1}{R^{1/2}\tau^{3/2}} f(b/R)$$

- At 2.76 and 5.52 TeV, the beam rapidities are 7.98 and 8.68
  - Thus, the exponential attenuation diminishes the effect particpant contribution by a factor of 5, and spectator contribution by more …

Summary

- Kharzeev et al. have hypothesized that charge separation may be an indicator of Strong Parity Violation, Chiral Symmetry restoration, and very strong B fields

- The correlator $\left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle$ or equivalently

  $$\left\langle \cos(\phi_i - \phi_k)\ \cos(\phi_j - \phi_k)\ -\ \sin(\phi_i - \phi_k)\ \sin(\phi_j - \phi_k) \right\rangle\ =\ (\mathrm{v}_1^2 - a_1^2)\ \mathrm{v}_2$$

  is a parity even observable that is sensitive to charge separation effects, wrt the reaction plane, and is insensitive to many different backgrounds

- STAR sees clear evidence for charge separation in Au-Au and Cu-Cu collisions at 62 and 200 GeV
  - The signal is not so small … $|a| \sim 10^{-2}$, and is accessible with standard tools

- Qualitatively the STAR results agree with the magnitude and gross features of the theoretical predictions for parity violation in HI collisions
  - Lots of discussion in the community, both pro and con
  - The gentle art of proctology has begun …

- ALICE can test the CME hypothesis with Pb-Pb events

More studies are coming soon … it will be fun

Backup Slides

Additional Reading

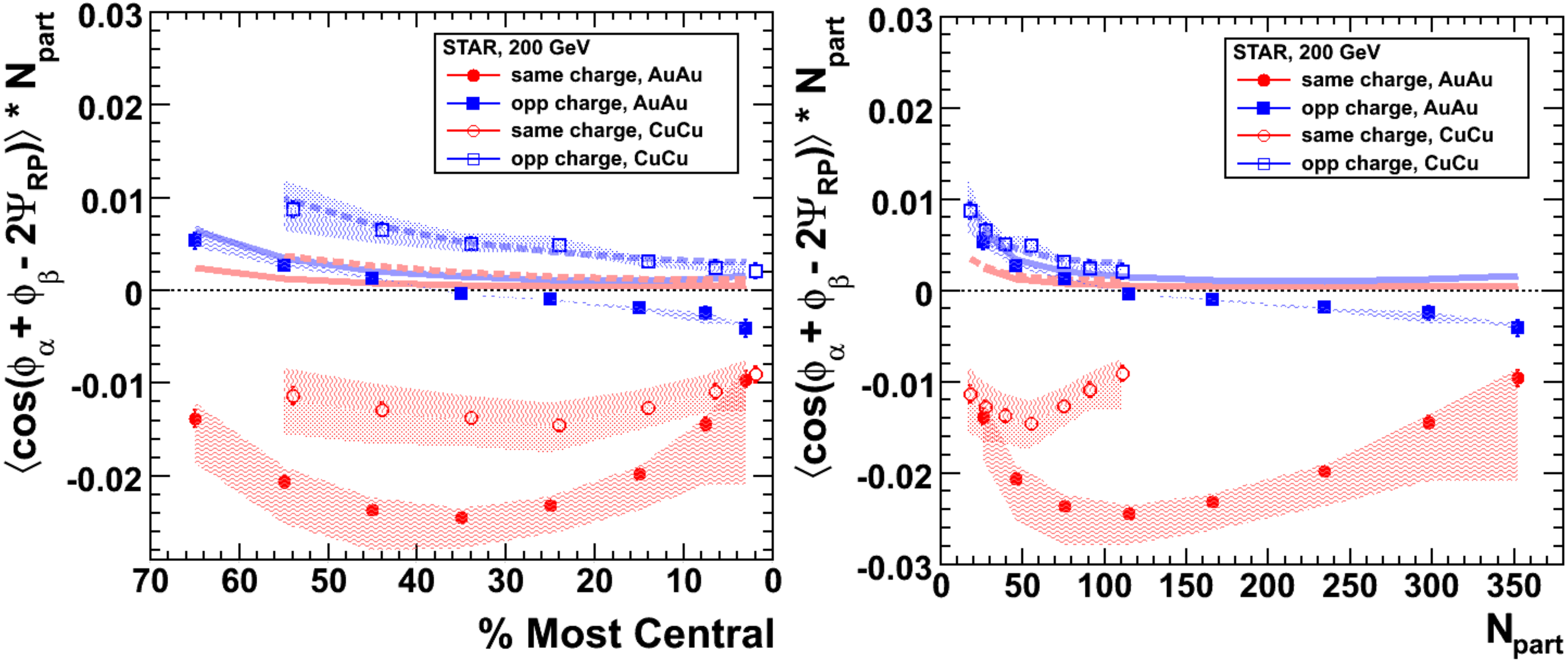
- Theoretical Papers Discussing PV and how to look for it
  - "Parity violation in hot QCD: Why it can happen, and how to look for it" D. Kharzeev, Phys.Lett. B633, 260-264, 2006.
  - Kharzeev, McLerran, and Warringa Nucl. Phys. A803 (2008) 227

- Experimental papers discussing PV and how to look for it
  - Voloshin, PRC 70, 057901 (2004).

- Experimental papers with our data
  - Abelev et al. (STAR Collaboration), PRL 103, 251601 (2009)
  - Abelev et al. (STAR Collaboration), PRC, 81, 054908 (2010)

- Criticism and commentary
  - Bzdak, Koch & Liao, PRC 81, 031901(R) (2010)
  - Pratt, arXiv 1002.1758
  - Wang, PRC 81, 064902 (2010)
  - Müller &Schäfer, arXiv 1009.1053
  - more on the way … :-)

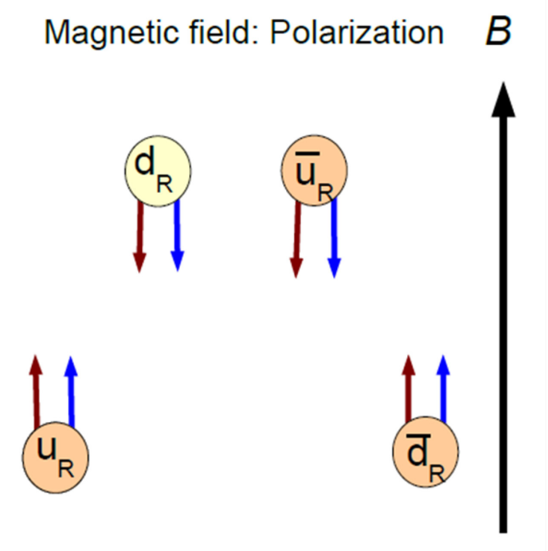
N_{part} Dependence



- Au-Au and Cu-Cu data at 200 GeV scaled by N_{part} vs Centrality
- Au-Au and Cu-Cu data at 200 GeV scaled by N_{part} vs N_{part}
  - Shaded regions represent uncertainty in the measured elliptic flow (v_2)

Making particles – neutral mesons won’t flow

- Only a specific set of quarks can flow “up” in our example
  - Upwards Flow: $u, \bar{d}, \bar{s}$
  - Downwards Flow: $\bar{u}, d, s$
  - Assuming that down and strange behave the same way in a B_{EM} field



- Meson flow is easy to understand
  - Upwards Flow: $u\,\bar{d}\,(\pi^+)$, $u\,\bar{s}\,(K^+)$
  - Downwards Flow: $\bar{u}\,d\,(\pi^-)$, $\bar{u}\,s\,(K^-)$
  - Just by coincidence … neutral mesons fail to <flow>, even those combinations that coalesce from the vacuum. Event average == 0.

- Baryons are trickier … assume that they proceed via a coalescing di-quark and pick up the third quark from the vacuum
  - Upwards Flow: $u\,u\,d\,(p)$, $\bar{u}\,\bar{d}\,\bar{s}\,(\bar{\Lambda}^0)$, $\bar{d}\,\bar{s}\,\bar{s}\,(\bar{\Xi}^-)$, $\bar{s}\,\bar{s}\,\bar{s}\,(\bar{\Omega}^-)$
  - Downwards Flow: $\bar{u}\,\bar{u}\,\bar{d}\,(\bar{p})$, $u\,d\,s\,(\Lambda^0)$, $d\,s\,s\,(\Xi^-)$, $s\,s\,s\,(\Omega^-)$
  - Di-quark combinations that coalesce one quark from the vacuum will have event average == 0.

Useful to study other mesons and baryons

CP Violation – all scenarios involve $\langle \vec{E}_a \bullet \vec{B}_a \rangle \neq 0$

- If the color B field has a component that is parallel to the color E field then

$$\left\langle F^a_{\mu\nu} \, \widetilde{F}^a_{\mu\nu} \right\rangle = 4 \left\langle \vec{E}_a \bullet \vec{B}_a \right\rangle \neq 0$$

and under P and CP transformations

$$\vec{E}_a \bullet \vec{B}_a \quad \rightarrow \quad -\vec{E}_a \bullet \vec{B}_a$$

which means that parity and CP symmetries are broken

- Finally, gauge field configurations exist with finite action and quantized topological charge
  - Q_w is the winding number .

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

These configurations are related to instanton and sphaleron transitions … but that topic is beyond the scope of my talk