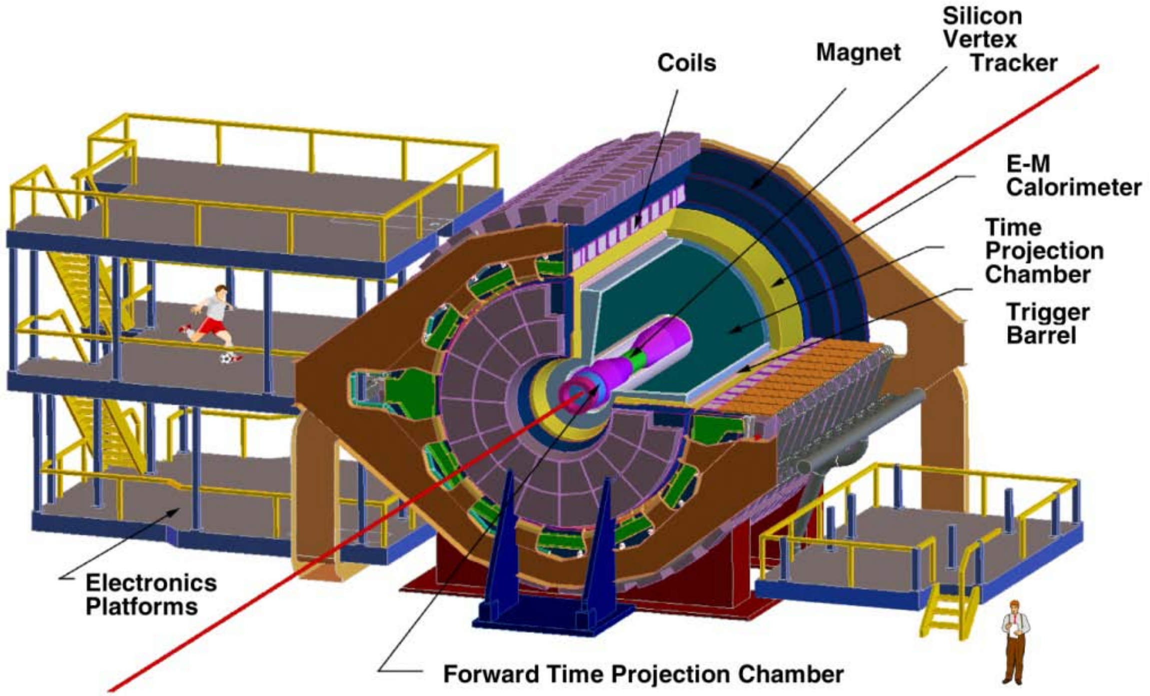
STAR Results on Charge Separation Measurements



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Looking for new physics – Strong Parity Violation

STAR

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

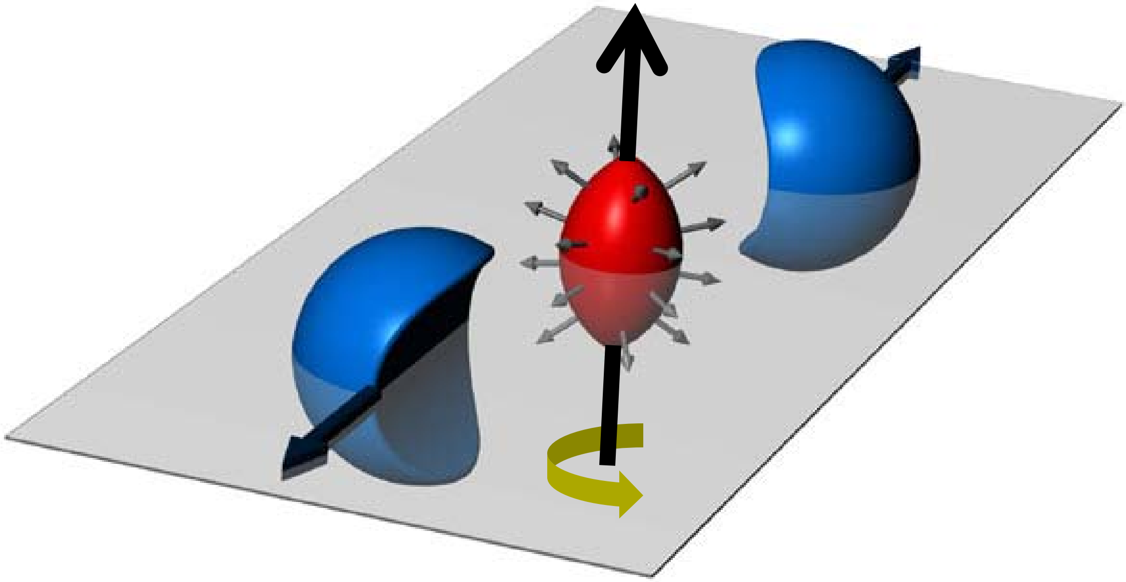
- **The less-conventional point of view**
  - **It is proposed that in the vicinity of a deconfining phase transition, the QCD vacuum can possess meta-stable domains leading to P and CP violation.**
    - **See, for example, Kharzeev, Pisarski, and Tytgat PRL 81, 512 (1998).**

- **From a humble experimentalist's point of view …**
  - **The theory appears to be fully vetted and there is no reason why these metastable domains can't be formed in HI collisions at RHIC**
  - **The consequences and magnitude of these effects are subject to experimental study and verification**
    - **See, for example, Kharzeev, McLerran, and Warringa arXiv:0711.0950**

I will present a bit of theory to motivate the observations and then the data

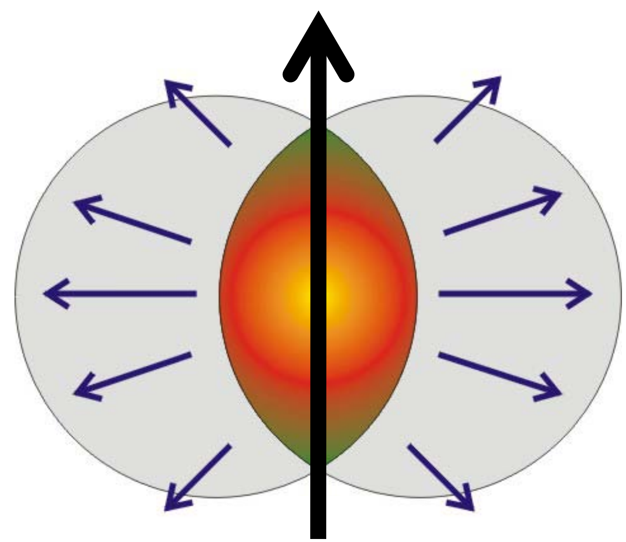
Thanks to wonderful talks by Harmen Warringa at BNL and Sergei Voloshin at QM2009

Conservation of Global Angular Momentum



Kharzeev et al. have proposed that angular momentum is (globally) conserved in a heavy ion collision and does not beakup into smaller pieces

If this is true, then there should be an angular momentum vector that lies perpendicular to the reaction plane



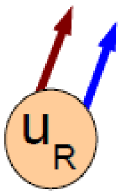
- Electromagnetic charges in motion lead to an electromagnetic magnetic field (not a color magnetic field)
- The magnetic fields can reach 10^{17} gauss. Stronger than on the surface of a neutron star.
- May be related to ridge formation etc.

Quarks interact with the B field via their spin

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

In chiral limit:

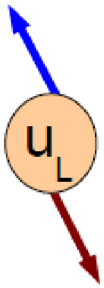
Particles/Antiparticles
with right-handed helicity



have spin and momentum parallel

In chiral limit:

Particles/Antiparticles
with left-handed helicity



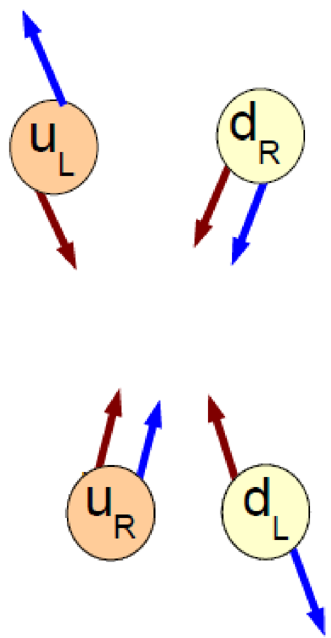
have spin and momentum anti-parallel

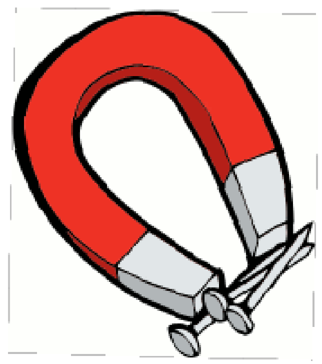
- **Kharzeev et al. assume massless quarks in this study**
- **Chirality and helicity are the same for massless particles … so in the limit of zero mass, it is easy to define chirality (not so easy for non-zero mass).**

How does the B field affect the Quarks?

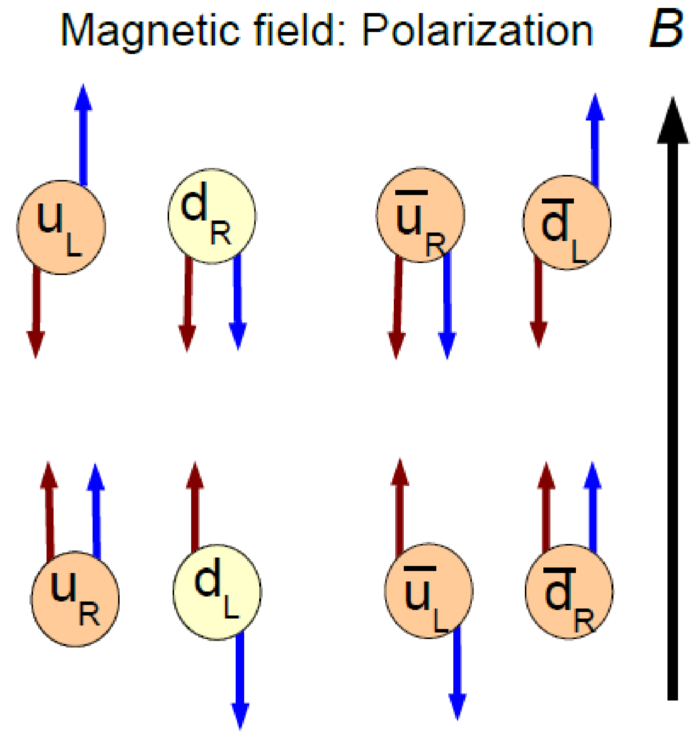
A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization





Magnetic field: Polarization



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

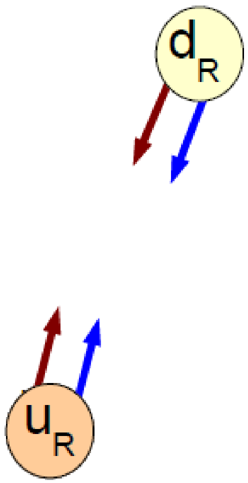
In this way the magnetic field can distinguish between right and left

H. Warringa

How does the Magnetic field affect Chirality?

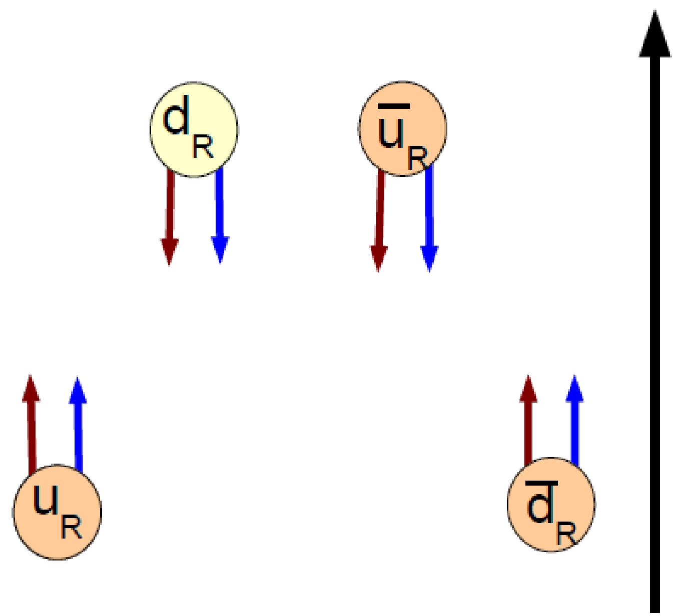
A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization



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.

Magnetic field: Polarization B



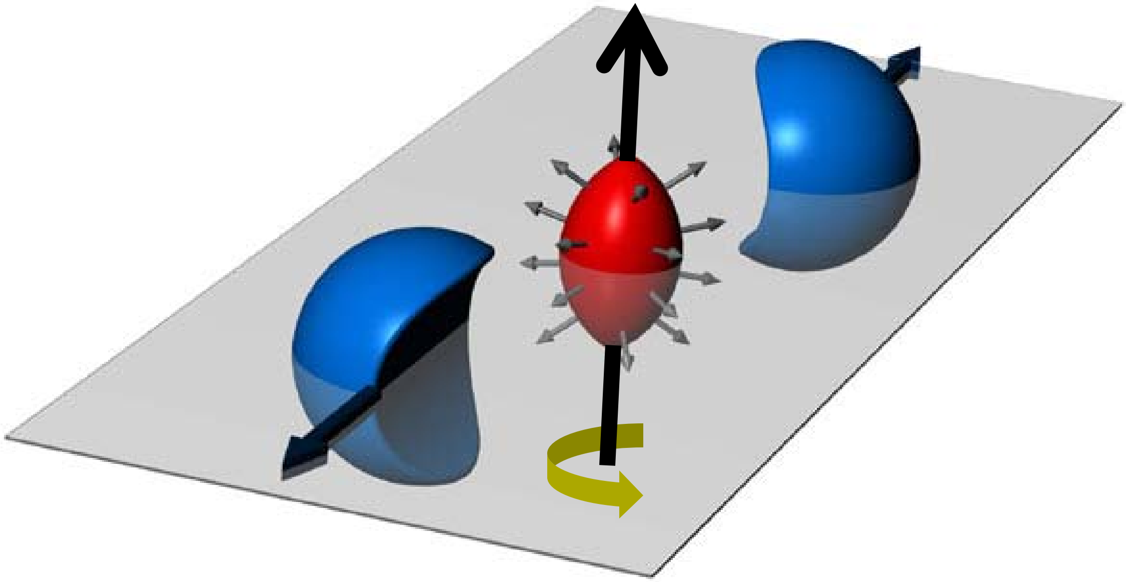
Positively charged particles move parallel the magnetic field

Negatively charged particles move to antiparallel to magnetic field

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

H. Warringa

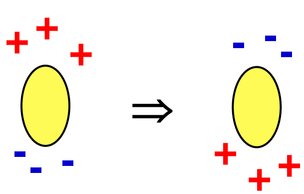
Separation of Charge wrt the reaction plane

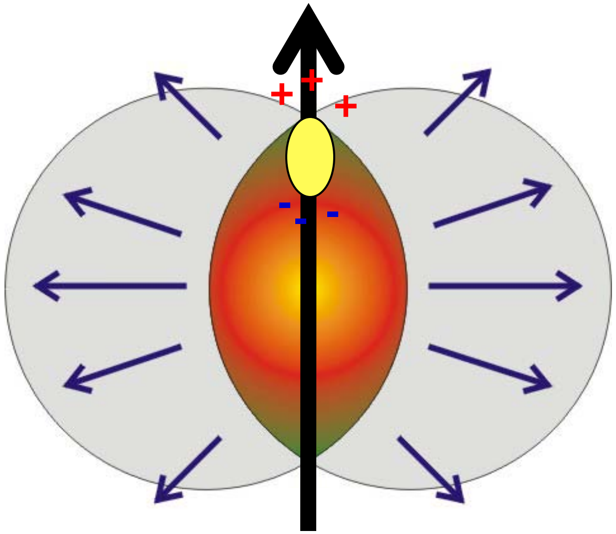


If a chirally restored bubble is created in a heavy ion collision, the positively charged quarks will go up … then hadronize … and yield an excess of positive pions above the plane

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

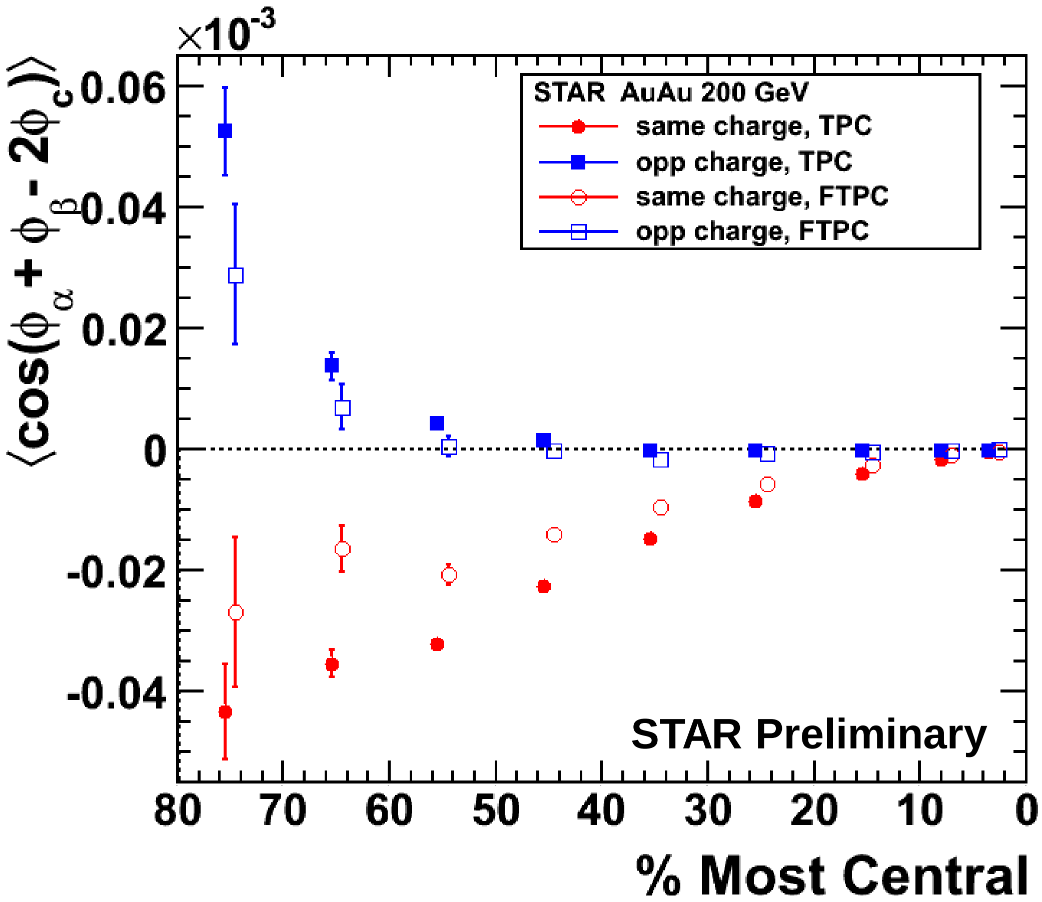
- The signal is manifestly parity odd
  $x \Rightarrow -x$, $p \Rightarrow -p$

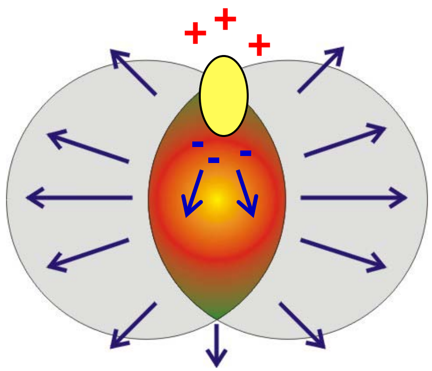




- The charge-flow asymmetry is too small to be seen in a single event but may be observable with correlation techniques

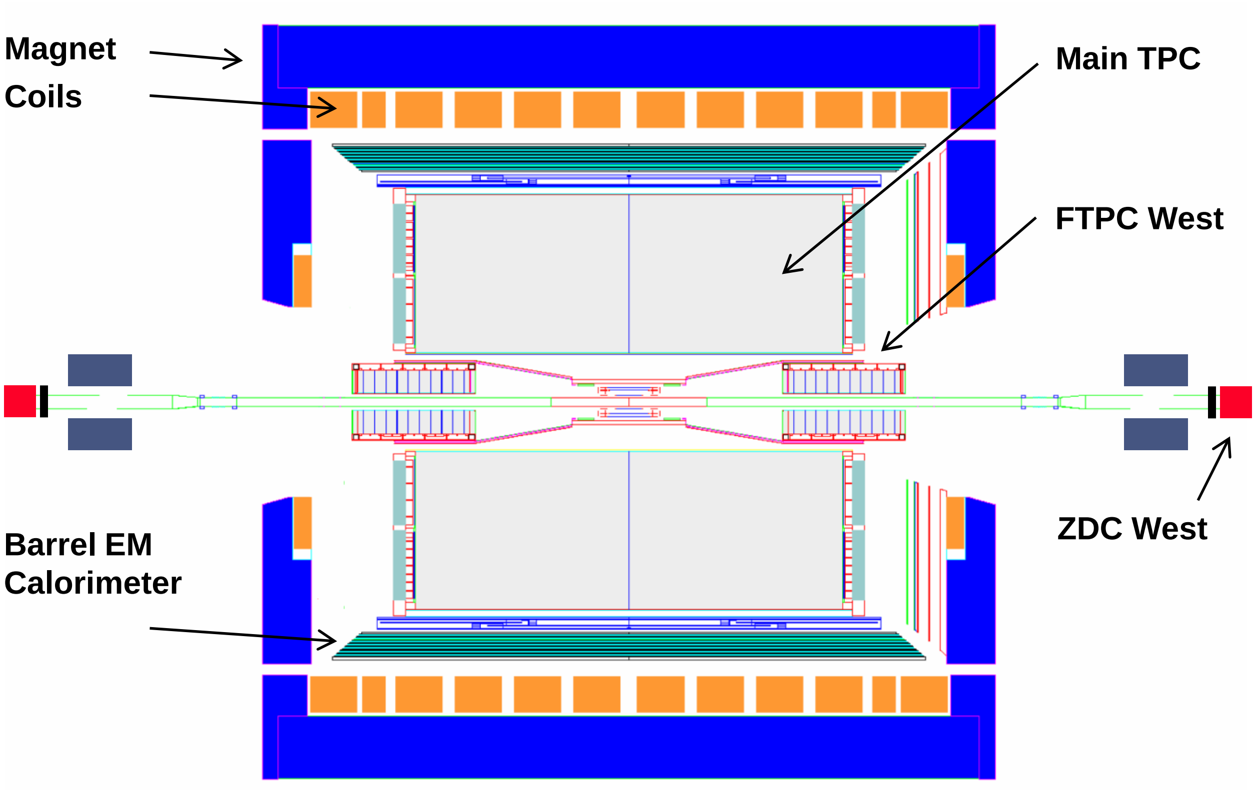
A signal is present in the STAR data





- **Naively, theory suggests ++, -- correlations equal and opposite in sign to +-**
  - **Kharzeev suggests 'bubble' on edge of collision zone and one side absorbed**
- **But all of this requires careful explanation …**

The STAR Detector at RHIC



- 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

Full Fourier Transform of the Invariant Yield

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$$f(\phi) = \frac{b_0'}{2} + \sum_{n=1}^{\infty} \left(a_n' \sin(n\phi) + b_n' \cos(n\phi) \right)$$

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 $b_n \equiv v_n$

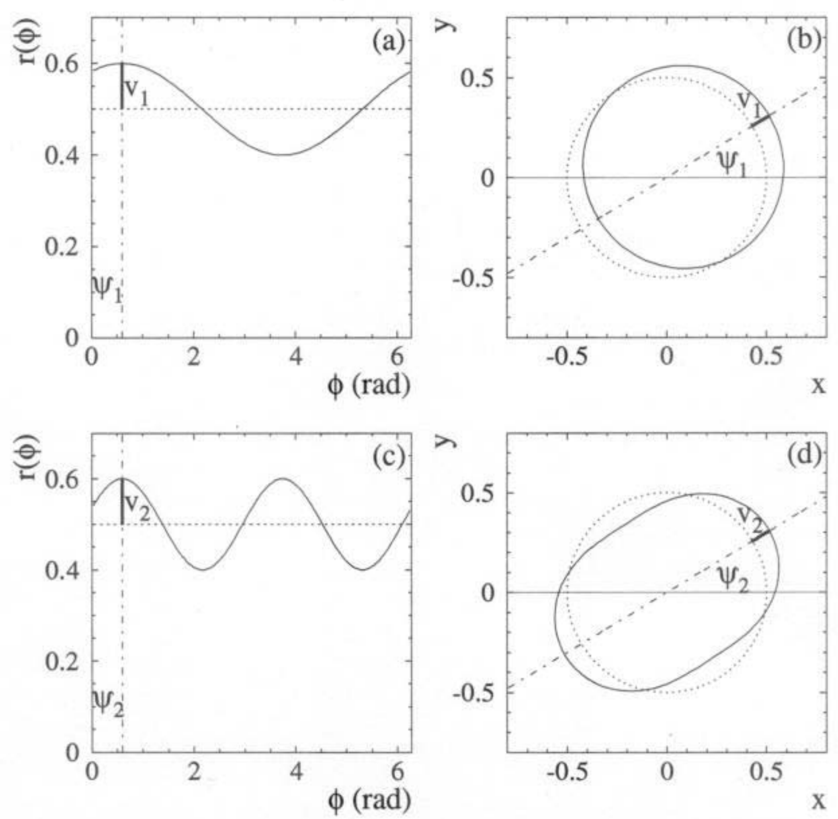
Interpreting Flow – order by order

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 off the collision zone

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

- v_2 represents the elliptical shape of the momentum distribution



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

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

  $$\mathrm{v}_n \equiv \left\langle \cos(n(\phi - \Psi_R)) \right\rangle \qquad \textbf{or} \qquad \mathrm{v}_n^2 = \left\langle \cos(n(\phi_i - \phi_j)) \right\rangle$$

  – 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.

- **The signal is small … so S.V. proposed a clever observable to help find it**

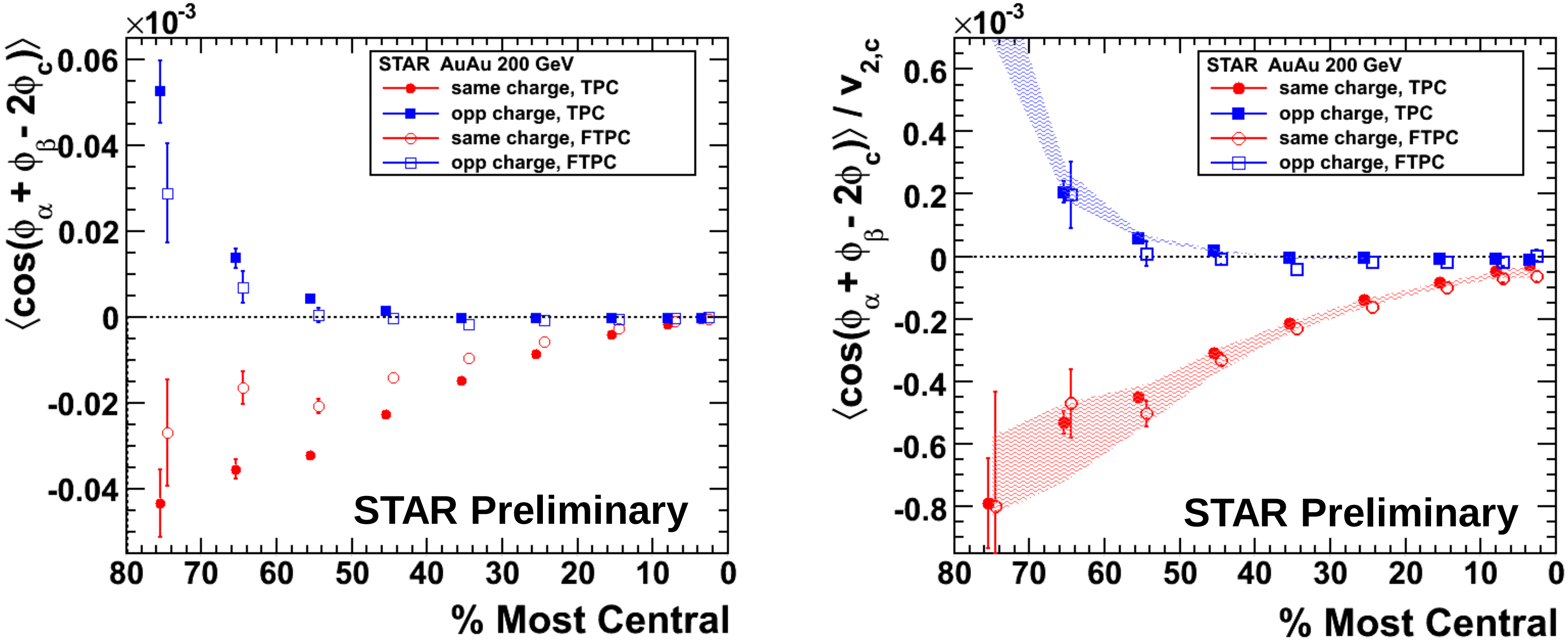
  – Mixed Harmonics: $\left\langle \cos(\phi_i - \phi_k)\, \cos(\phi_j - \phi_k) - \sin(\phi_i - \phi_k)\, \sin(\phi_j - \phi_k) \right\rangle = (\mathrm{v}_1^2 - a_1^2)\, \mathrm{v}_2$

  – 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 observable $(v_1^2 - a_1^2) * v_2$ is not parity odd, but it is a good way to measure charge sensitive flow because $v_1 \Rightarrow 0$ and $(v_1^2 - a_1^2) * v_2 \Rightarrow -a_1^2 * v_2$

The observable: $-1 * \left\langle a_{1,\alpha}\, a_{1,\beta} \right\rangle \mathrm{v}_{2,c} \approx \left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle$

Like Sign and Opposite Sign Correlations



- **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

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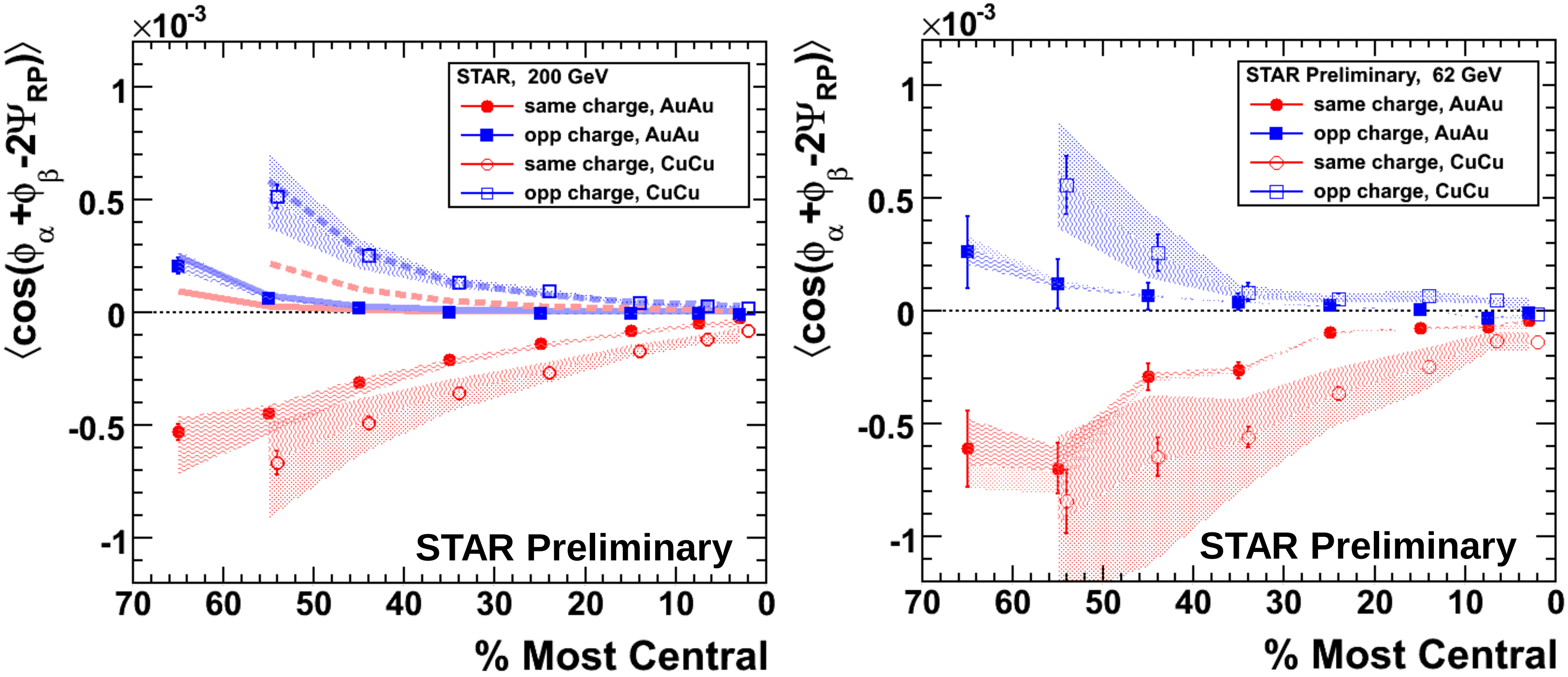
- **Magnitude: $|a| \sim Q / N_{\pi+}$ where $Q = N_L - N_R = 0, \pm1, \pm2, \ldots$**
  - ✓ **$|a| \sim 10^{-2}$ or equivalently $|a|^2 \sim 10^{-4}$ and independent of how Ψ_R is found**
- **Charge Combinations for the observable $\left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle / v_{2,c}$**
  - ✓ $\left\langle a_+ a_+ \right\rangle = \left\langle a_- a_- \right\rangle = -1 * \left\langle a_+ a_- \right\rangle$
    - ✓ **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 $\Delta\eta \approx 1$**

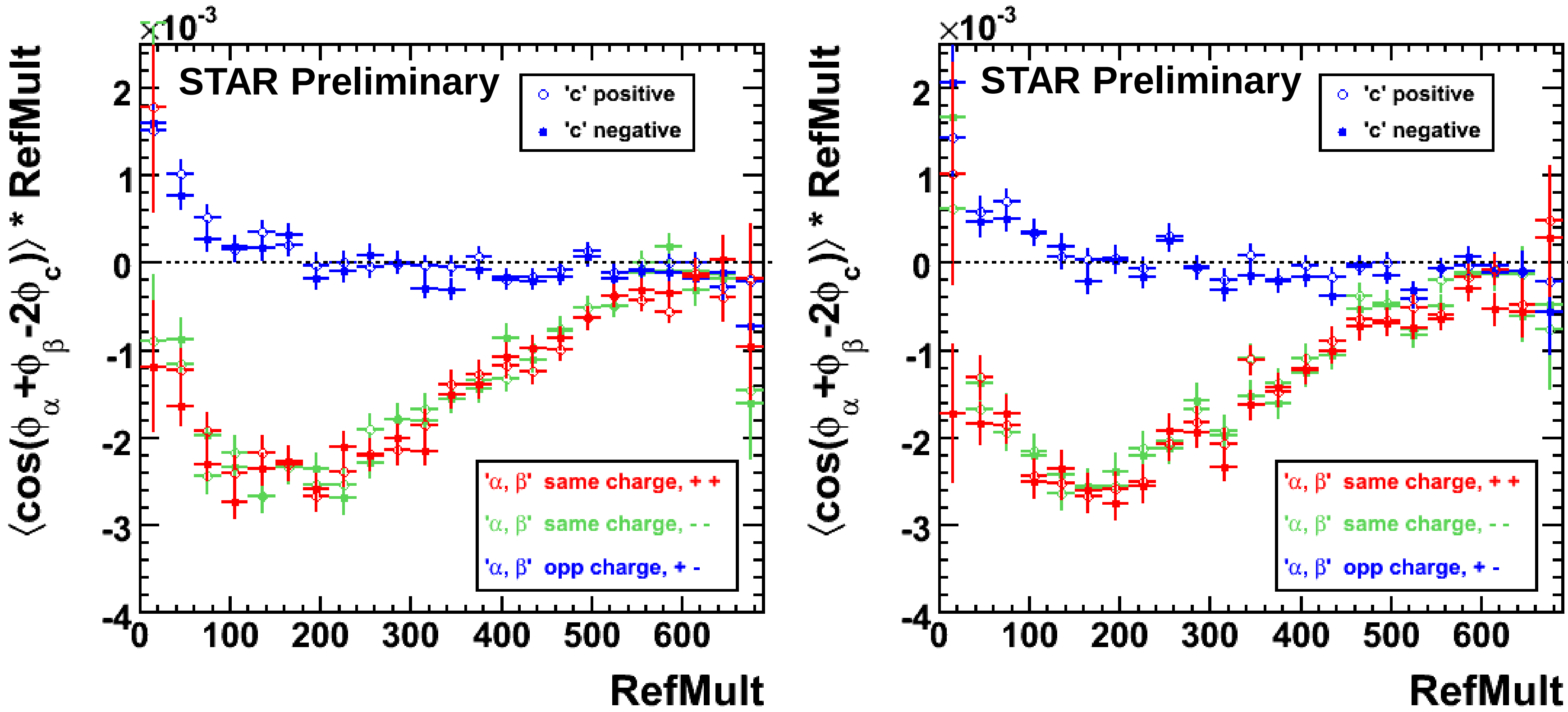
Lets look at some of these expectations to see if they hold true

Species and Energy Dependence



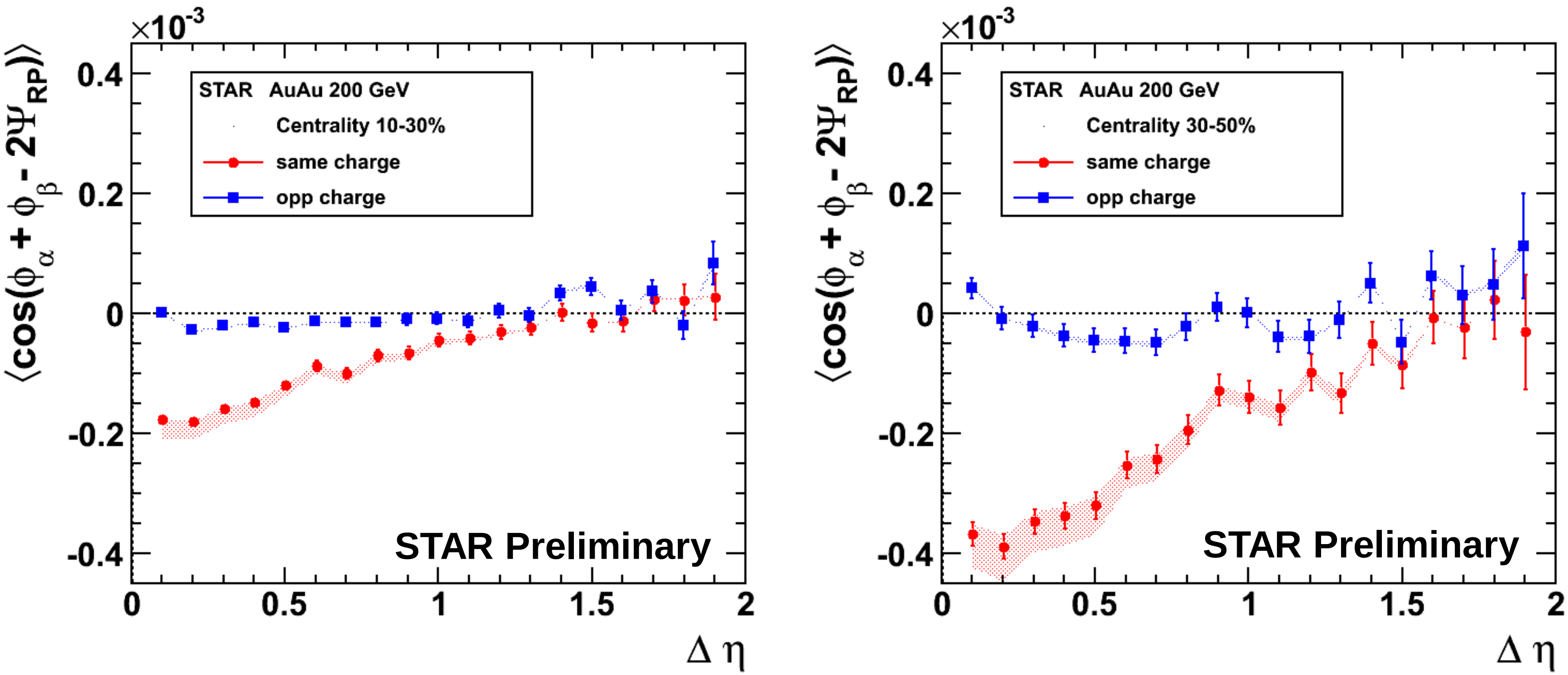
- **Au-Au data compared to Cu-Cu data**
  - Results suggests that Cu-Cu data, as a function of centrality, is larger
  - Possibly suggesting that a smaller system is less quenched
- **200 GeV data compared to 62 GeV data – signal is similar in both**
  - Shaded regions represent uncertainty in elliptic flow
  - Solid and dashed lines are possible backgounds (see talk by E. Finch)

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

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**

$$\left\langle \cos(\phi_i - \phi_k)\ \cos(\phi_j - \phi_k) \right\rangle - \left\langle \sin(\phi_i - \phi_k)\ \sin(\phi_j - \phi_k) \right\rangle = \left(\left(v_1^2 + B_{in} \right) - \left(a_1^2 + B_{out} \right) \right) v_2$$

- **As previously noted, the directed flow terms, v_1, 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 plan 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, will be presented by E. Finch**

Summary

- **D. K. et al. have hypothesized that charge separation may be an indication of Strong Parity Violation in heavy ion collisions**

- **The correlator**

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

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

- **STAR sees clear evidence for charge separation in Au-Au and Cu-Cu collisions at 62 and 200 GeV**
  - **The signal is small … few * 10^{-4}**
  - **The signal is stronger in smaller systems and approximately independent of collision energy**

- **Qualitatively the results agree with the magnitude and gross features of the theoretical predictions for parity violation in heavy ion collisions**

Backup Slides

Full Cumulant – Analysis and Results

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

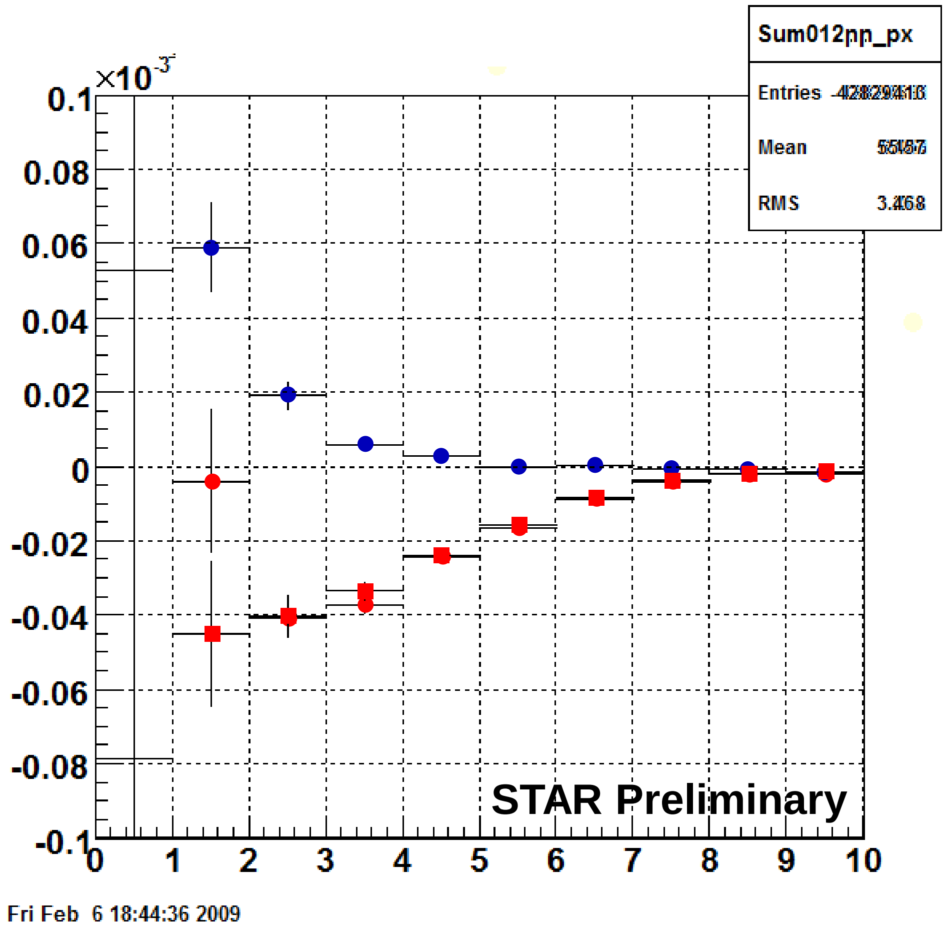
Real Terms

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

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

$$+ \left\langle \sin(\phi_i + \phi_j)\right\rangle \left\langle \sin(-2\phi_k)\right\rangle + \left\langle \sin(\phi_i - 2\phi_k)\right\rangle \left\langle \sin(\phi_j)\right\rangle$$
$$+ \left\langle \sin(\phi_i)\right\rangle \left\langle \sin(\phi_j - 2\phi_k)\right\rangle - 2\left\langle \sin(\phi_i)\right\rangle \left\langle \sin(\phi_j)\right\rangle \left\langle \cos(-2\phi_k)\right\rangle$$
$$- 2\left\langle \sin(\phi_i)\right\rangle \left\langle \cos(\phi_j)\right\rangle \left\langle \sin(-2\phi_k)\right\rangle - 2\left\langle \cos(\phi_i)\right\rangle \left\langle \sin(\phi_j)\right\rangle \left\langle \sin(-2\phi_k)\right\rangle$$

Full 3 particle cumulant for Run IV Au-Au 200



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