Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions 2018

STAR measurements in search of the CME and the CMW

-- a biased selection of STAR results

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UCLA

Outline

For the CME,
I will discuss different types of background in γ;
I will not cover

- alternative correlator (see Roy Lacey's talk)
- γ as a function of invariant mass
- decomposition of γ vs $\Delta\eta$

For the CMW,
I will discuss alternative interpretations, including

- hydro+isospin
- local charge conservation

Chiral Magnetic Effect:

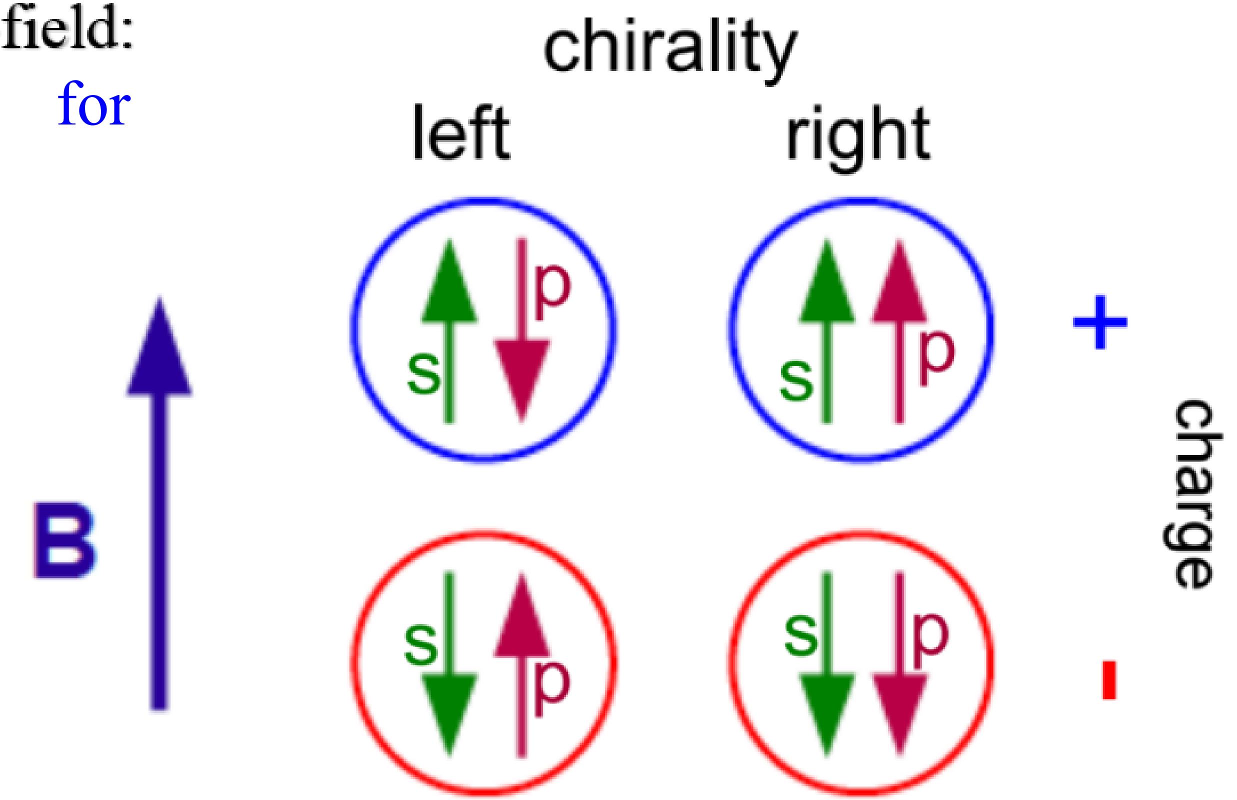
magnetic field + chirality = current

spin alignment in B-field:

opposite directions for opposite charges

handedness:

momentum and spin, aligned or anti-aligned



negative goes up
positive goes down

positive goes up
negative goes down

courtesy of P.Sorensen

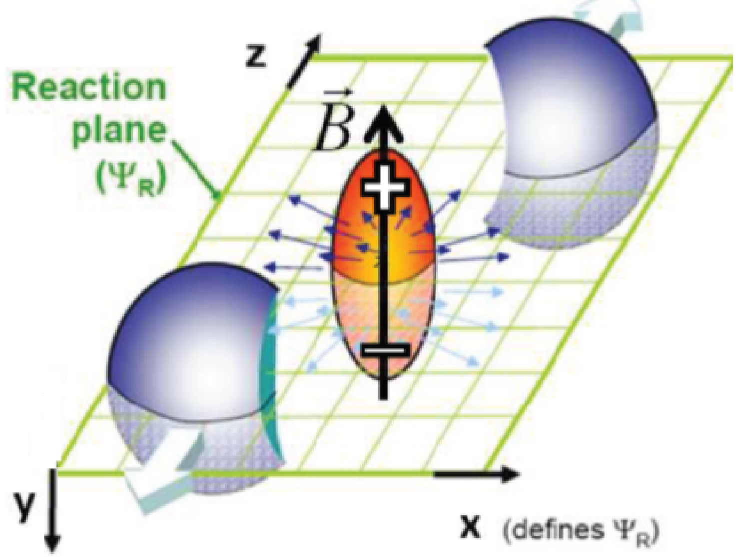
An excess of right or left handed quarks lead to a current flow along the magnetic field.

$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

CME observable: γ correlator

S. Voloshin, PRC 70 (2004) 057901

$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin\left(\phi^\pm - \Psi_{RP}\right)$$



$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$
$$= \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in}\right] - \left[\left\langle a_\alpha a_\beta \right\rangle + B_{out}\right]$$

background effects: largely cancel out

P-even quantity: still sensitive to charge separation

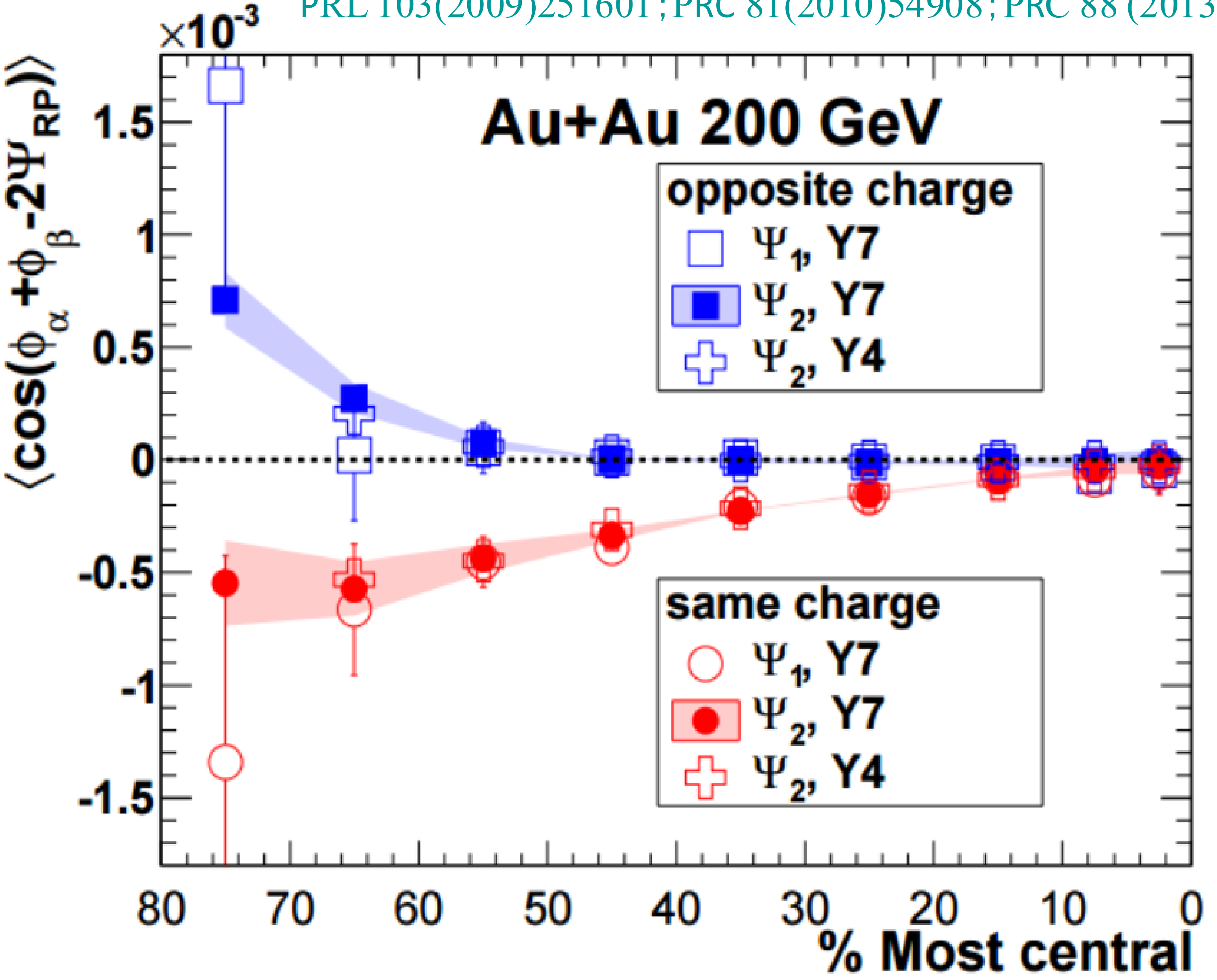
directed flow: expected to be the same for SS and OS

$$\frac{B_{in} - B_{out}}{B_{in} + B_{out}} = v_{2,cl} \frac{\left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{cl}) \right\rangle}{\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle}$$

v_2 of clusters/resonances, not final particles, containing both flow and nonflow.

Charge separation signal

PRL 103(2009)251601 ; PRC 81(2010)54908 ; PRC 88 (2013) 64911

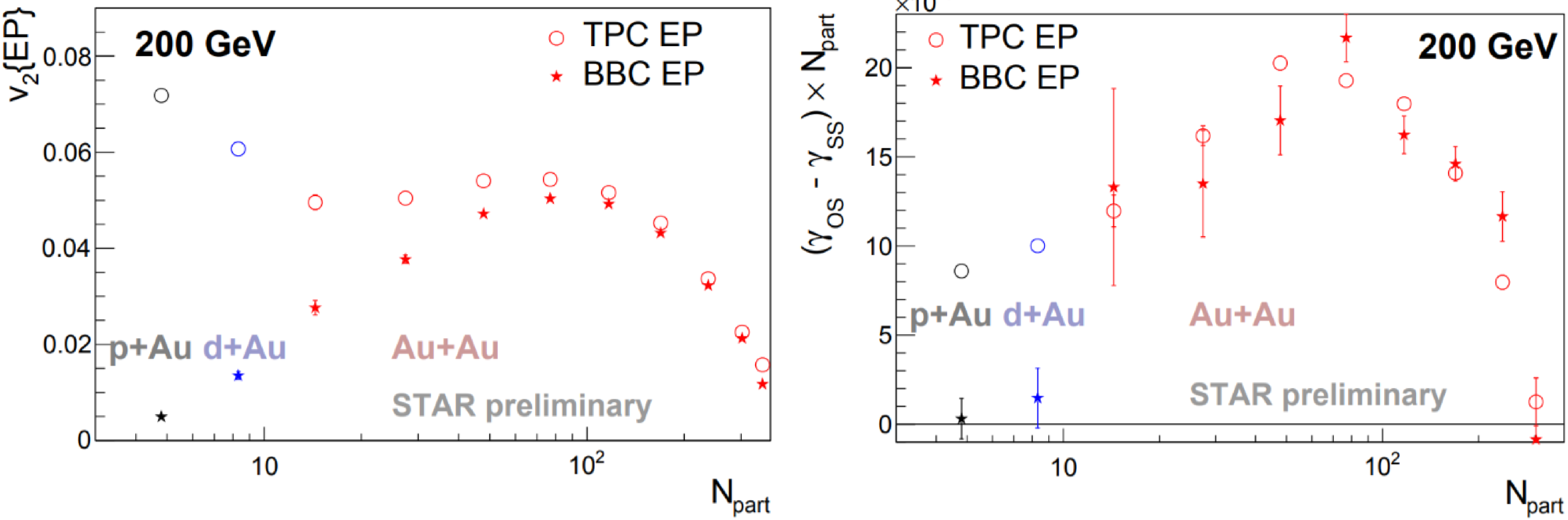


- γ_{os} > γ_{ss}, consistent with CME expectation
- consistent between different years (2004 and 2007)
- confirmed with 1st-order EP (from spectator neutron v_1)

However, there are still different types of background:

1. Non-flow (correlations unrelated to the reaction plane)
2. apparent anisotropy (final particles)
3. hidden anisotropy (resonances)

Non-flow background



$|\eta_{TPC}| < 1$

$3.8 < |\eta_{BBC}| < 5.1$

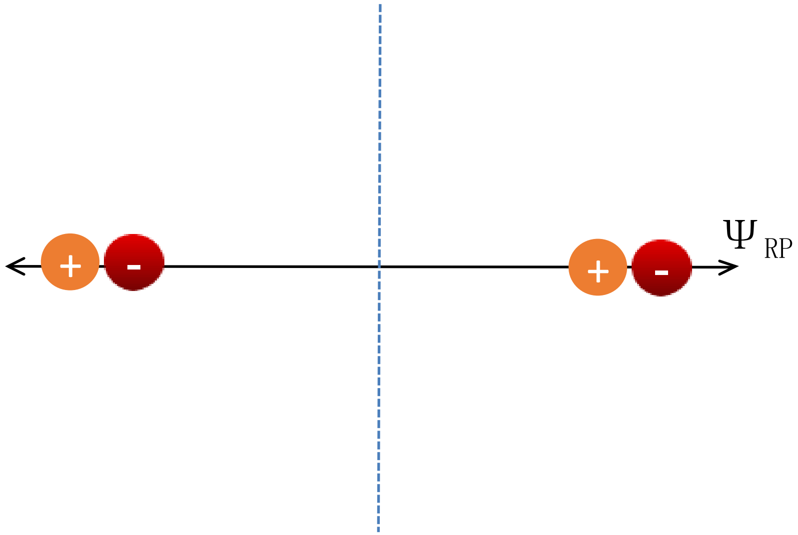
- Comparison between TPC EP and BBC EP shows significant non-flow effects in small systems.
- Non-flow effects are present in both v_2 and $\Delta\gamma$
- Safer in larger systems (more central Au+Au collisions)

Anisotropy-related background

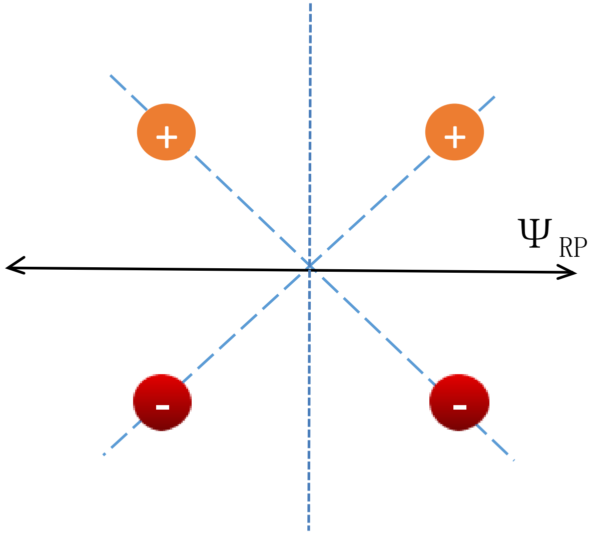
A specific configuration as shown below could solely come from statistical fluctuations.

Apparent anisotropy:
explicit v_2 (of final-state particles).
even w/o visual charge separation

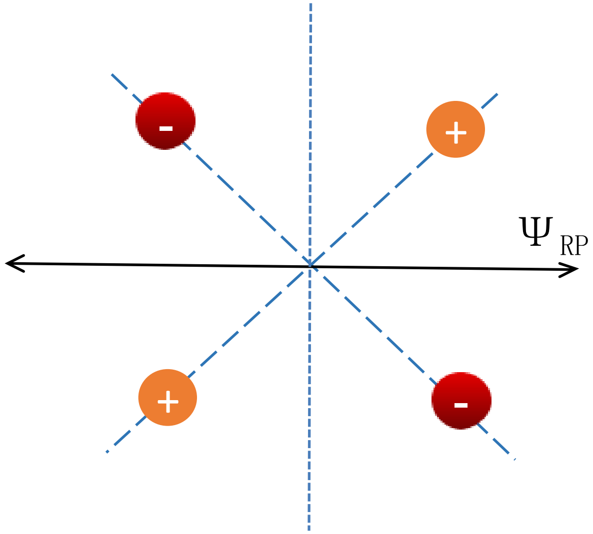
Hidden anisotropy:
implicit v_2 (of resonance parents).
real charge separation, but not CME



$v_2 = 1$
$\gamma_{SS} = -1$
$\gamma_{OS} = 0$



$v_2 = 0$
$\gamma_{SS} = -1$
$\gamma_{OS} = 1/2$



$v_2 = 0$
$\gamma_{SS} = 0$
$\gamma_{OS} = 0$

controllable with measured v_2

hard to control directly

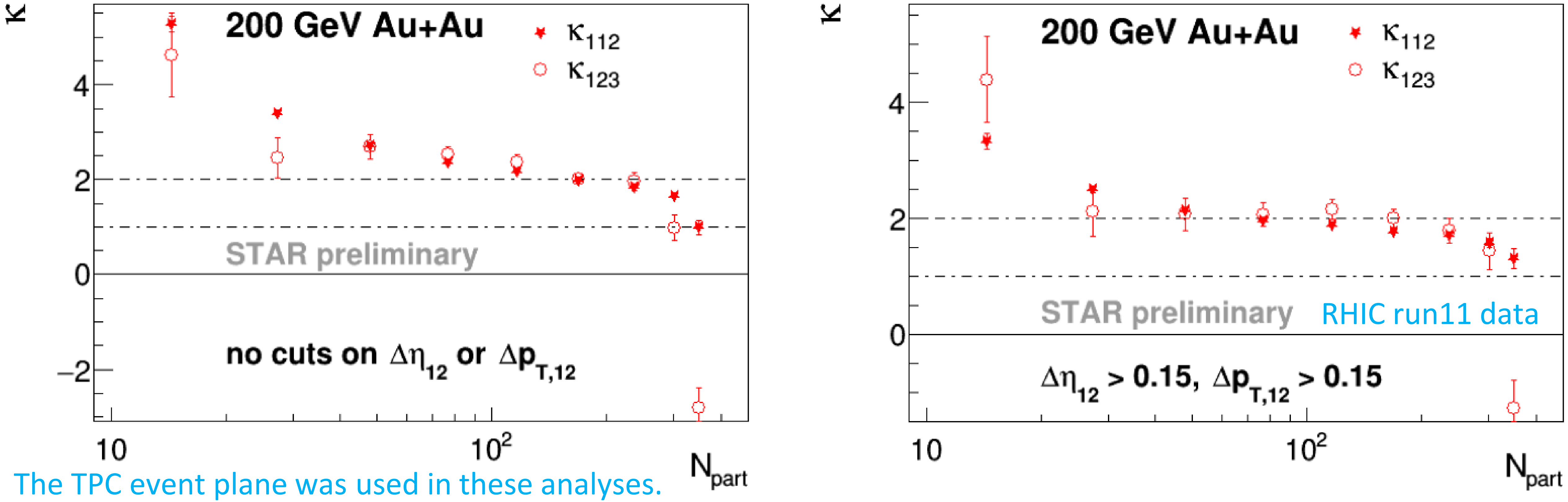
v_2^{explicit}-related background

$$\gamma_{1,n-1,n} = \left\langle \cos[\varphi_\alpha + (n-1)\varphi_\beta - n\Psi_{\mathrm{EP}}] \right\rangle / res_{\mathrm{EP}}$$

$$= \kappa_{1,n-1,n} \cdot v_{n,\beta} \cdot \delta$$

$$\delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$

$\kappa_{1,n-1,n}$ is just $\gamma_{1,n-1,n}$ normalized by v_n and δ.

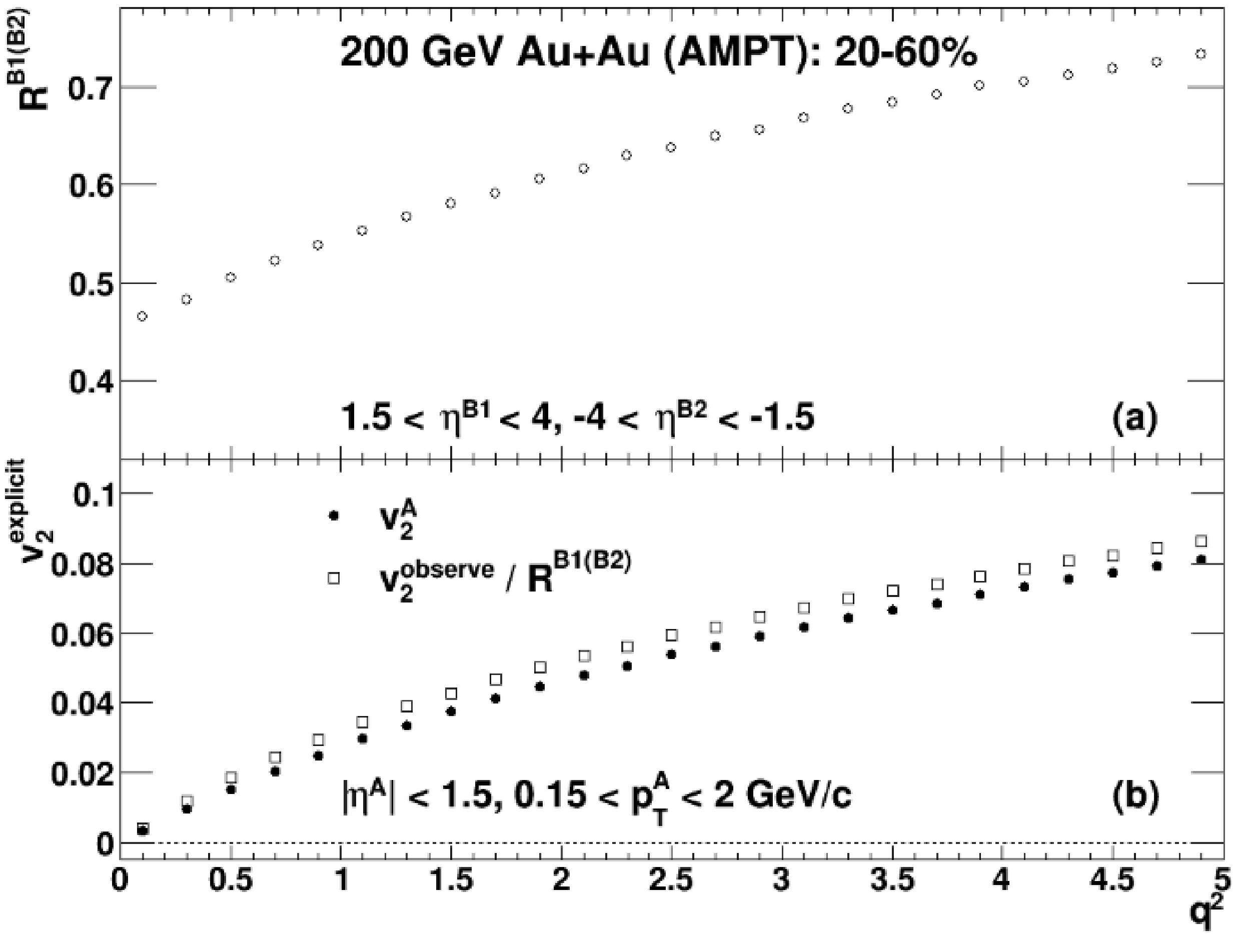


RHIC run11 data

The TPC event plane was used in these analyses.

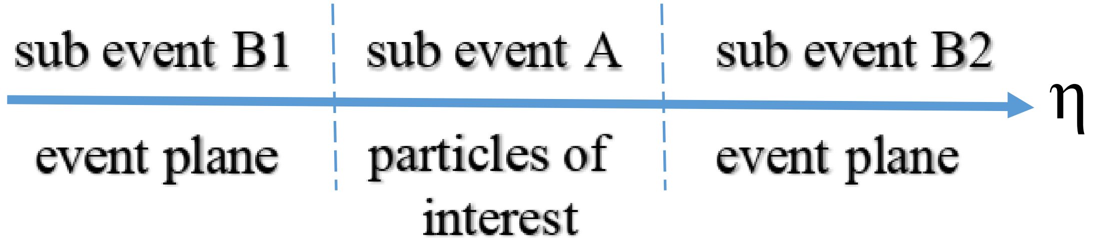
κ_{112} and κ_{123} are consistent with each other (except in the most central collisions), especially after removing very-short-range correlations.

Event-shape engineering



$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$



sub event B1 | sub event A | sub event B2

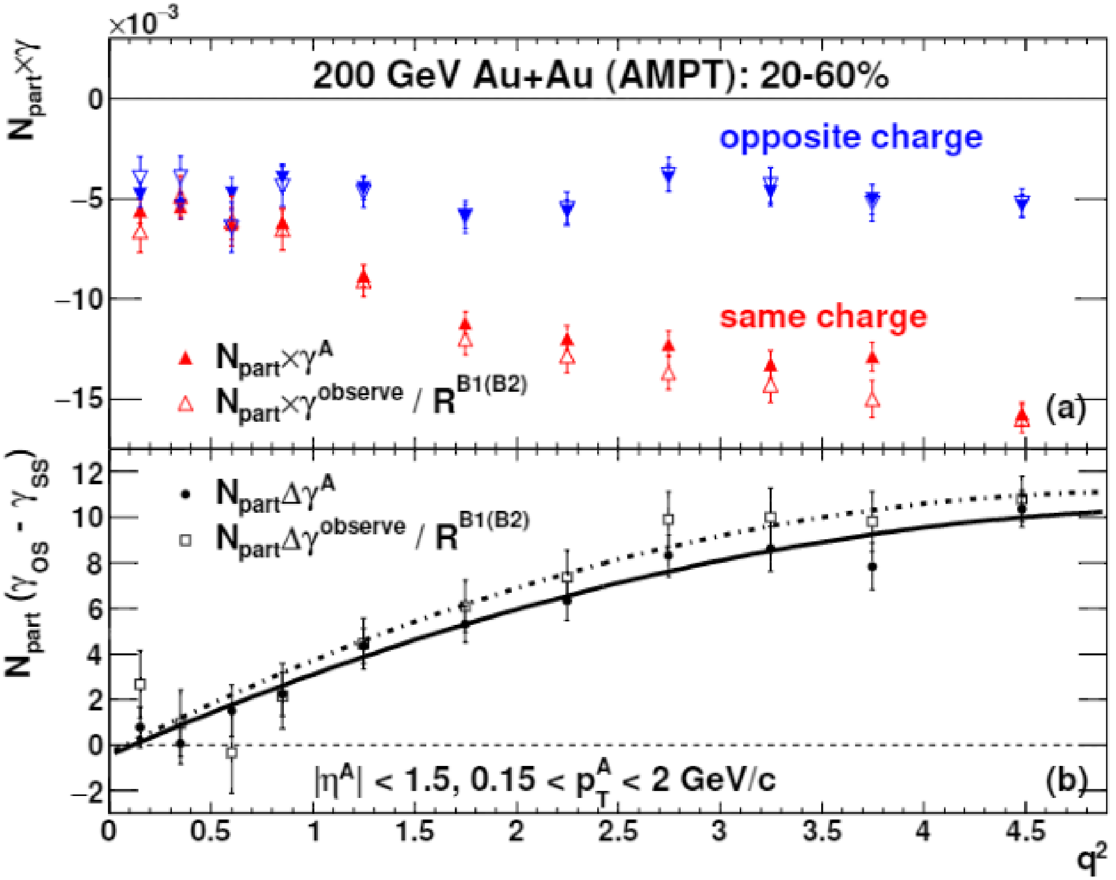
η

event plane | particles of interest | event plane

- divide each event into 3 sub-events.
- q, flow vector of particles of interest, provides a handle on the event shape.
- data point in each q bin is averaged over that specific event sample.
- AMPT shows that $v_2^{explicit}$ disappears when projecting q to 0, which is expected by construction.

Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001

Event-shape engineering



$$\overrightarrow{q} = (q_x, q_y)$$

$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$

- q, flow vector of particles of interest, provides a handle on the event shape.
- AMPT shows that γ_{OS} and γ_{SS} approach each other at small q.
- The background in $\Delta\gamma$ disappears when projecting q to 0.

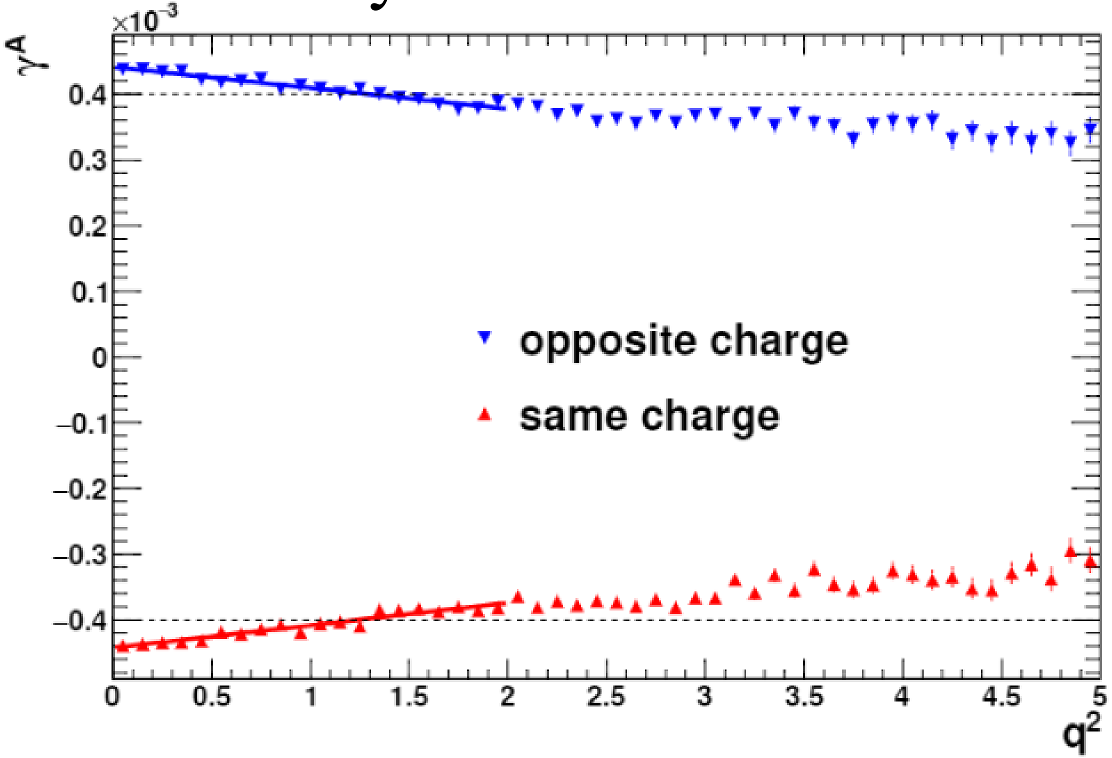
consistent with zero: $(-4.5 \pm 6.7) \times 10^{-4}$ for $N_{\rm part}\Delta\gamma^{\rm A}$ and $(-3.3 \pm 10.6) \times 10^{-4}$ for $N_{\rm part}\Delta\gamma^{\rm observe}/R^{\rm B1(B2)}$.

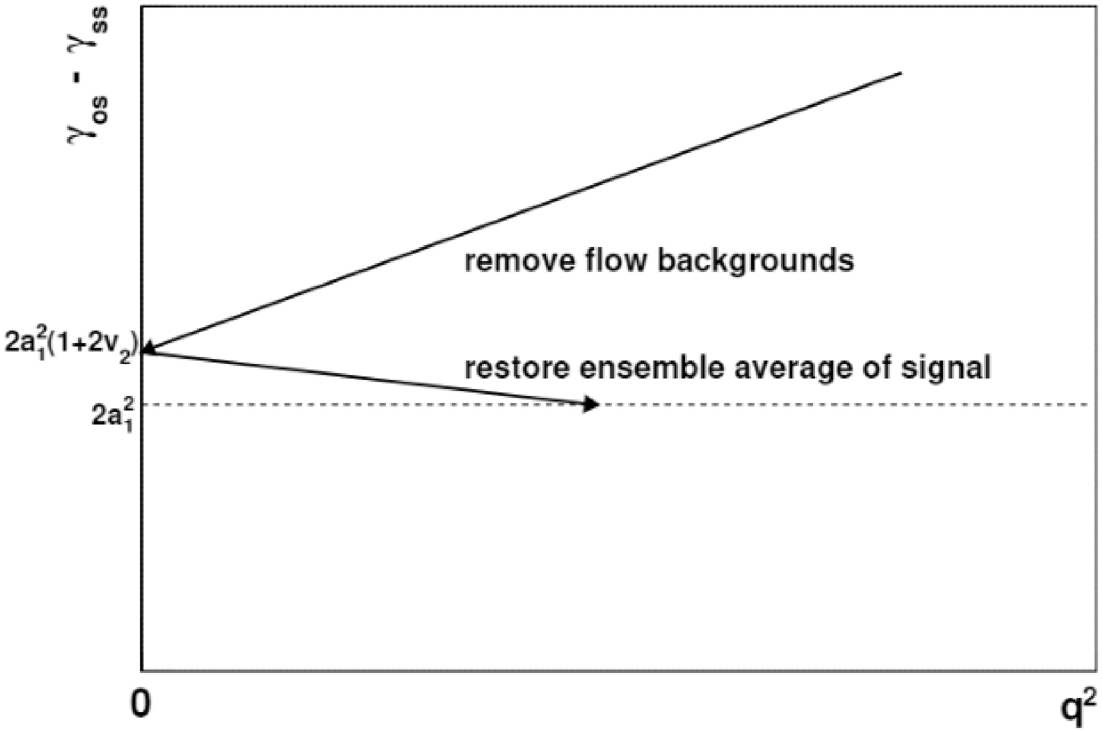
Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang,
Chinese Phys. C 42(1) (2018) 014001

This approach only takes care of the background due to the explicit v_2.

Artificial effect

Toy model simulation

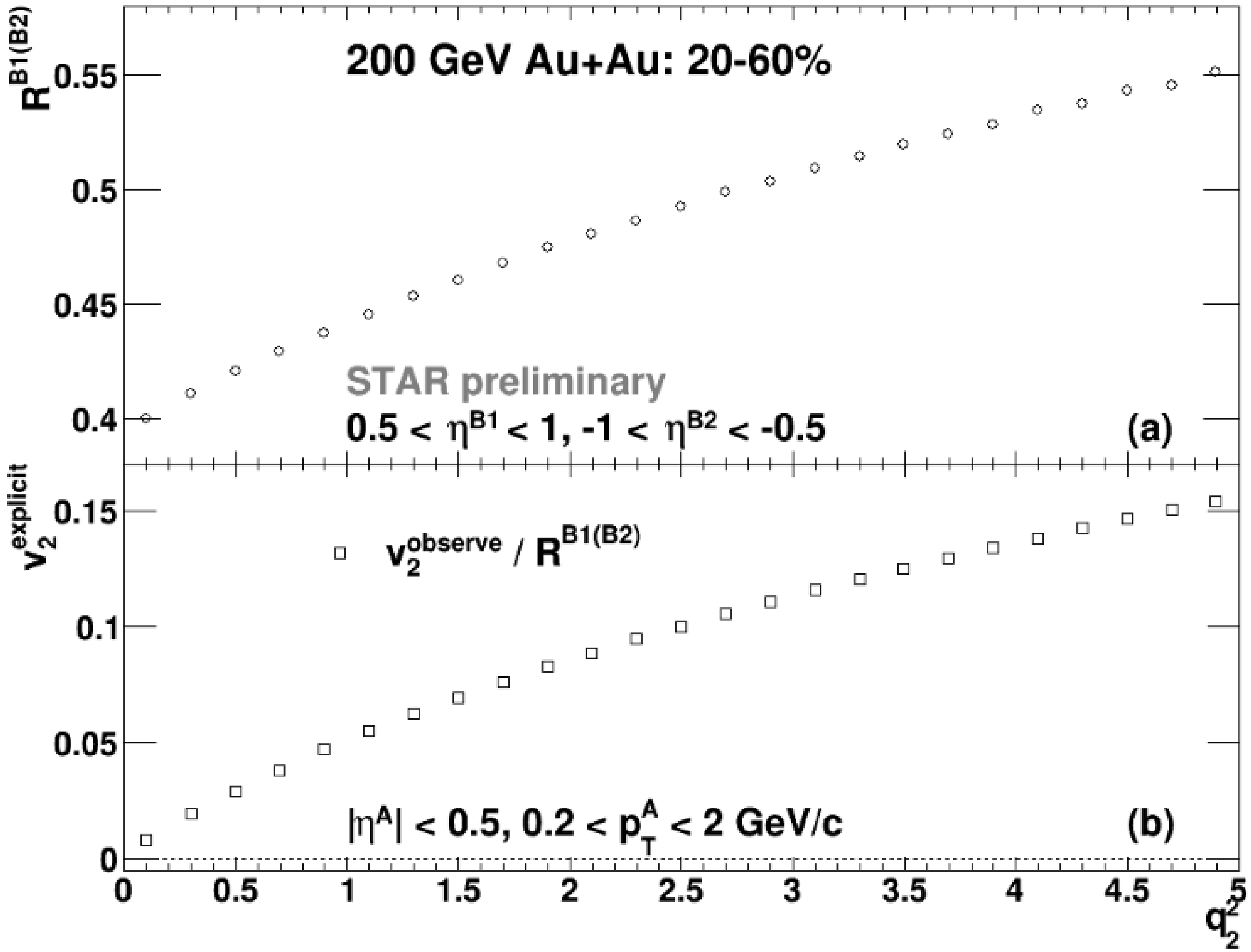




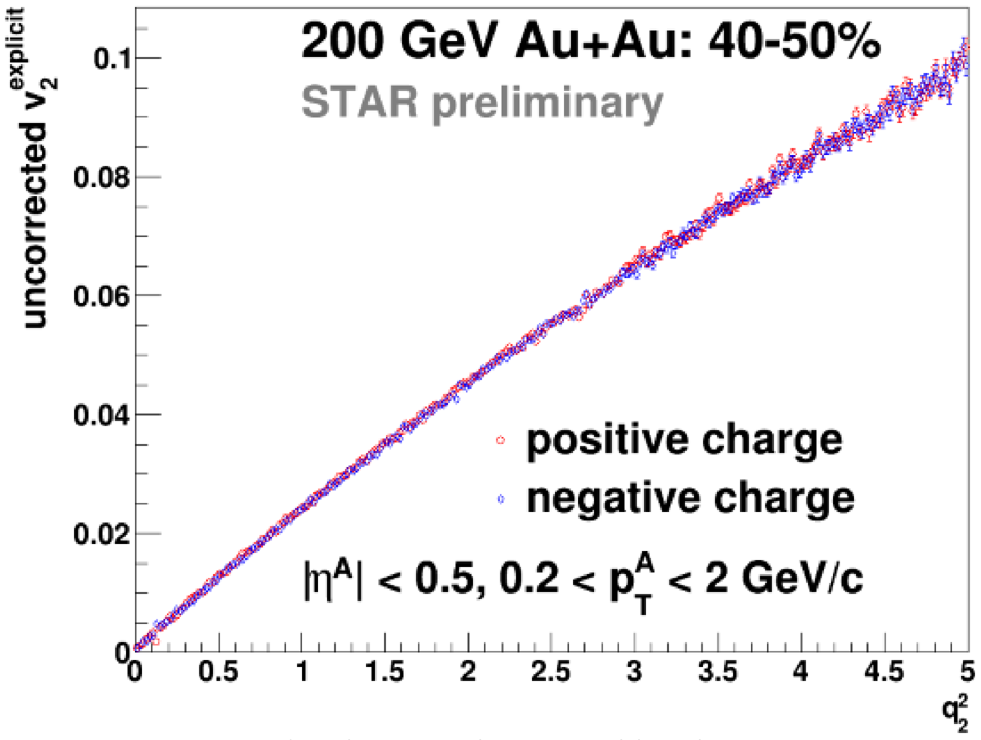
Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001

$\Delta\gamma|_{q=0}$ will not artificially diminish the CME signal, but will exaggerate it by a factor of $2v_2$, a roughly 10% effect.

v_2: 200 GeV Au+Au



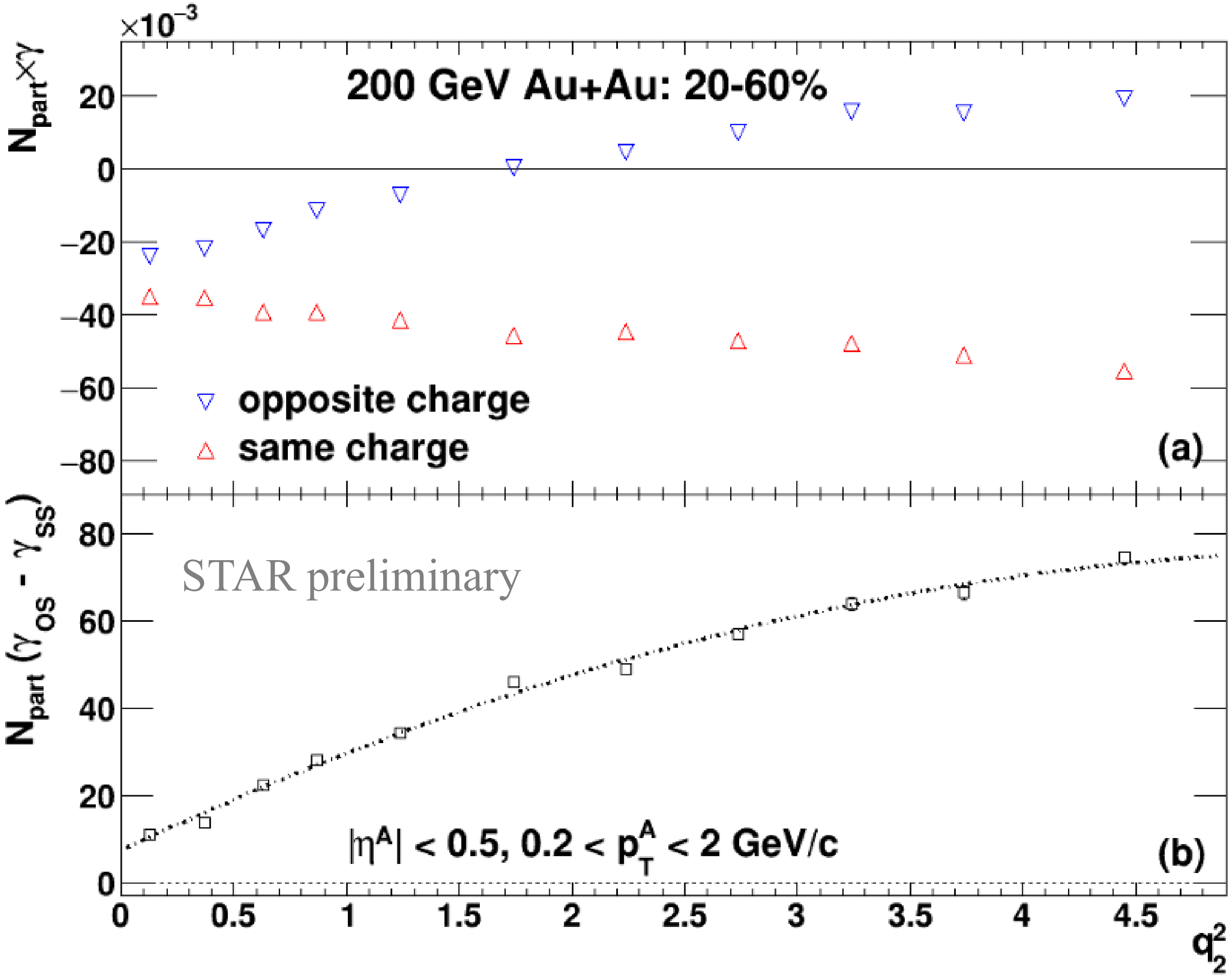
$$R^{B1(B2)} \equiv \sqrt{\langle \cos[2(\Psi_{EP}^{B1} - \Psi_{EP}^{B2})] \rangle_E}.$$



q_2 is based on all charges.

- The 2nd-order EP resolution depends on q.
- $v_2^{explicit}$ goes to zero at zero q (also true for separate charges), which is expected by construction.

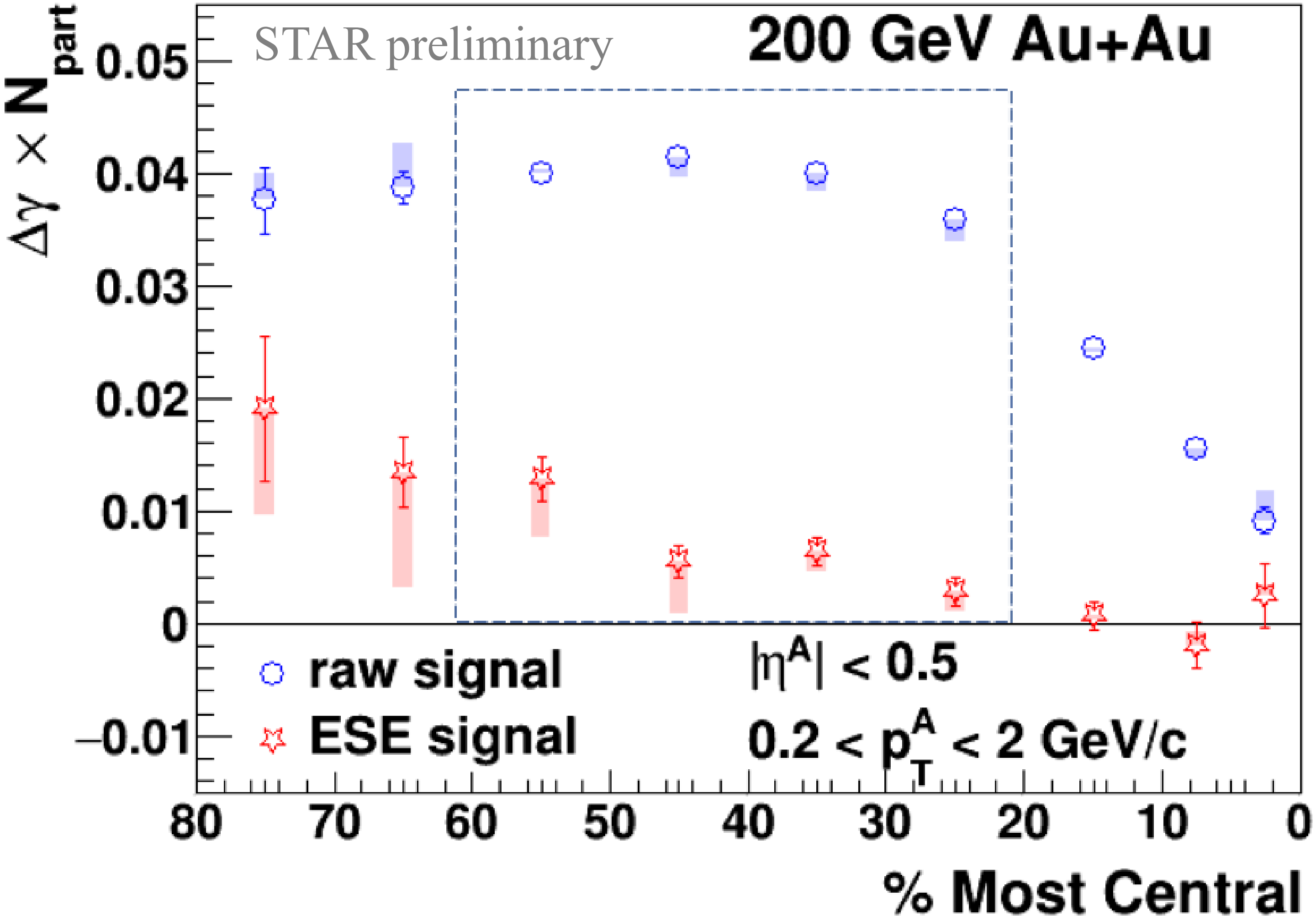
γ_{112}: 200 GeV Au+Au



- OS and SS approach each other at small q.
- When q^2 is extrapolated to 0, there is a finite intercept: $(7.51 \pm 0.75)*10^{-3}$ A 10σ effect for 20-60% events.
- IF this is due to CME, then a_1 is on ~ 1% level.
- The intercept may come from some implicit-v_2 backgrounds. Need to apply the method to $\gamma_{123} = \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\psi_{RP})\rangle$

$\langle N_{part} \rangle$ for 20-60% collisions is roughly 98.

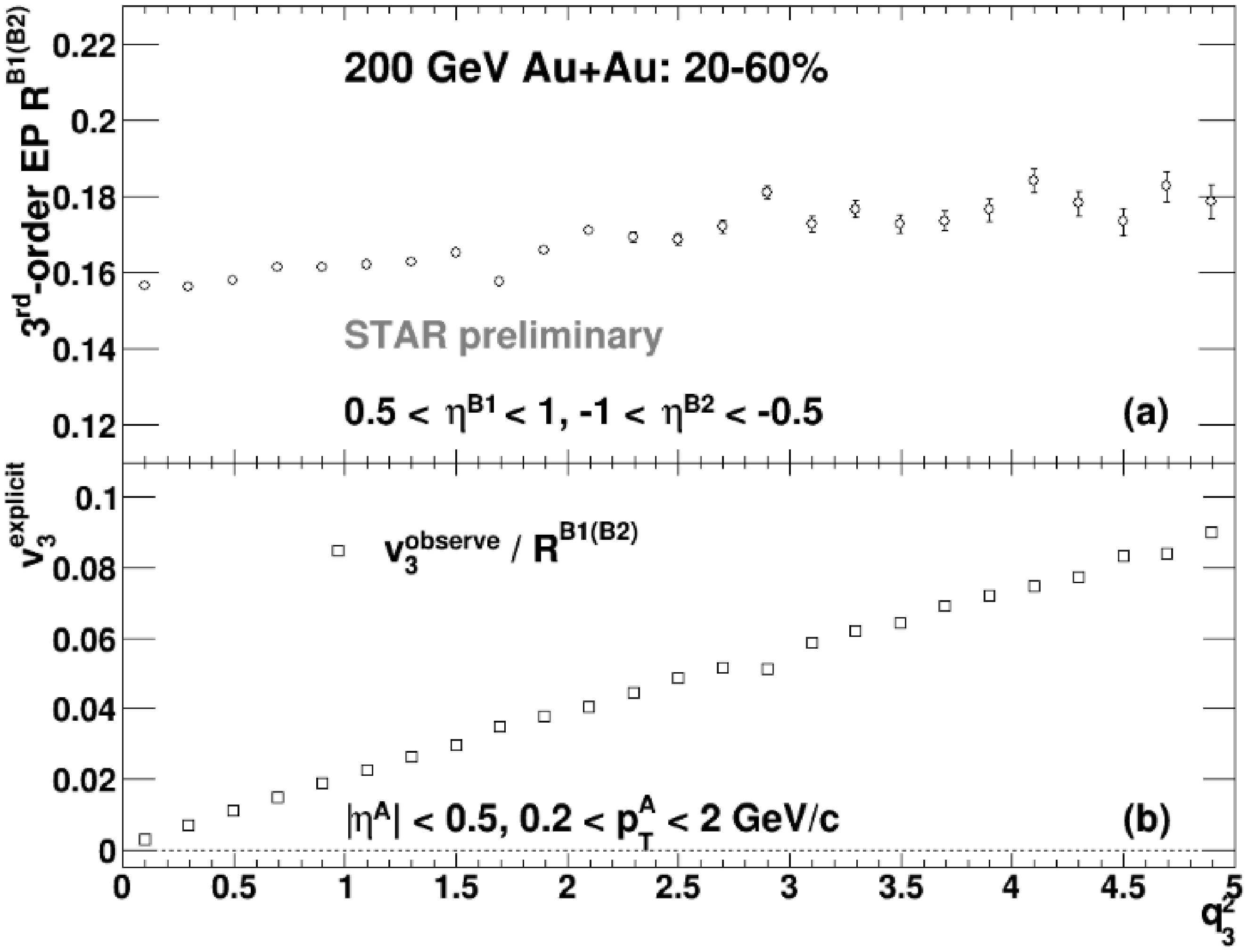
Centrality dependence



The shaded boxes reflect the cuts of $|\Delta\eta|>0.15$ and $|\Delta p_T|>0.15$ GeV/c.

- For 20-60% collisions, the raw signal is typically reduced to a 10-20% level with this ESE.
- It's worth trying this ESE method for Ru+Ru and Zr+Zr, if it does remove a large portion of BG.
- Still not sure whether the ESE signal is the true CME signal.

v_3: 200 GeV Au+Au



$$\overrightarrow{q} = (q_x, q_y)$$

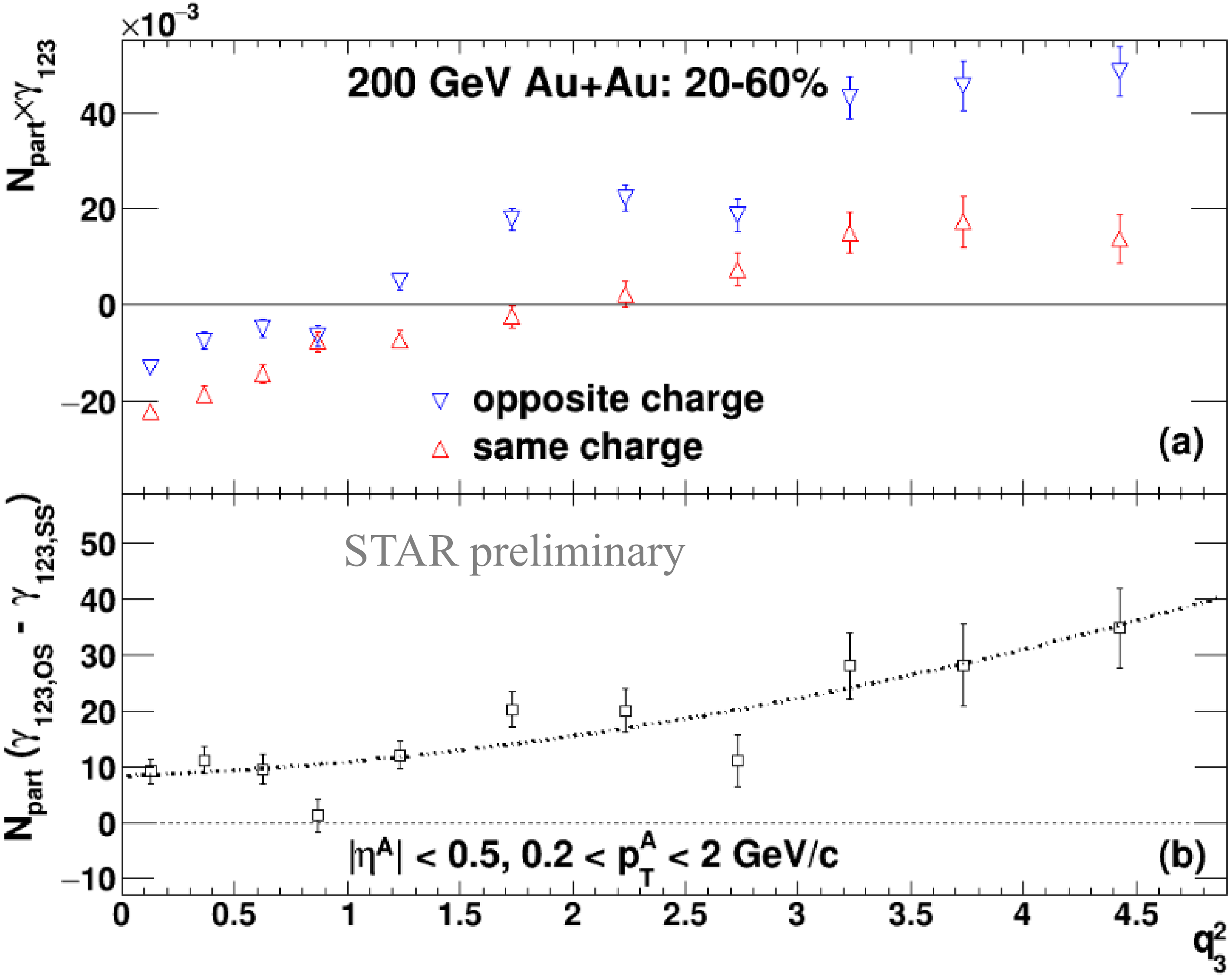
$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$

3

- The 3rd-order EP resolution depends on q_3.
- v_3^{explicit} goes to zero at zero q_3.

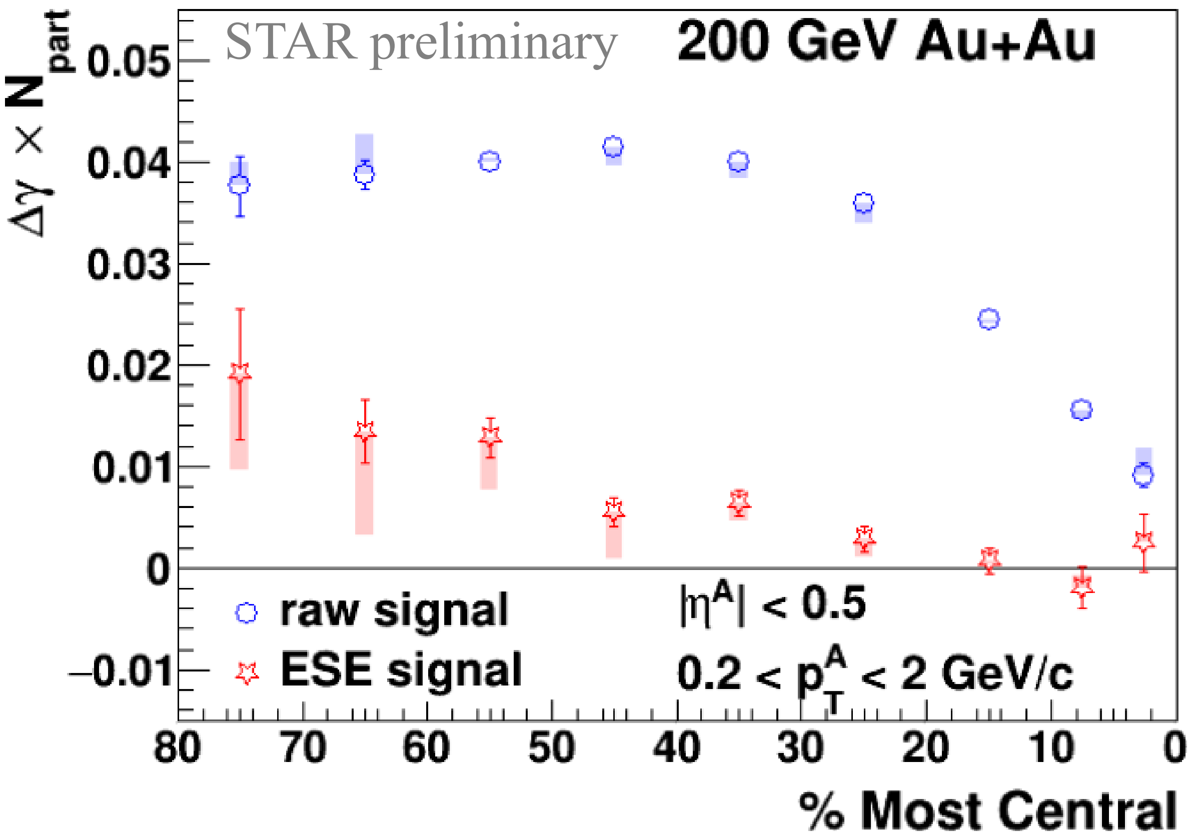
γ_{123}: 200 GeV Au+Au

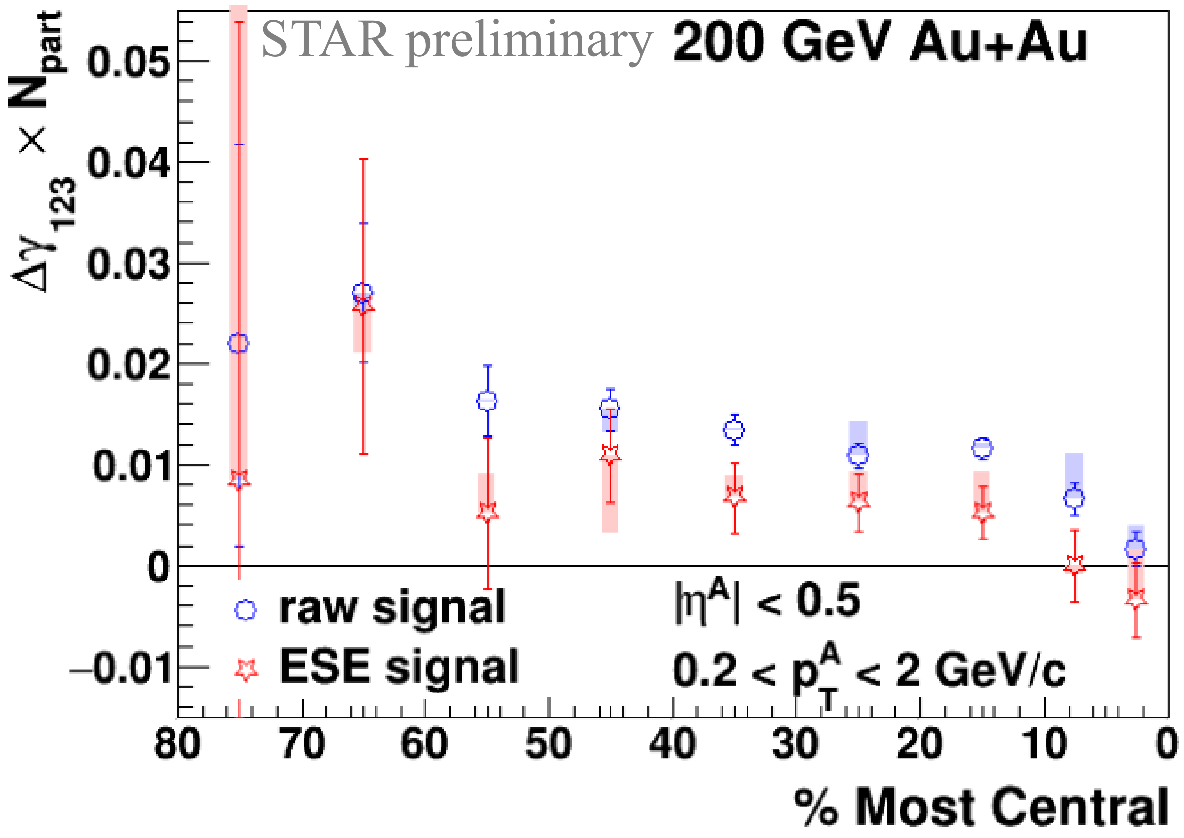


$\langle N_{part}\rangle$ for 20-60% collisions is roughly 98.

- γ_{123} can be studied via the 3rd-order flow vector, q_3.
- When q_3^2 is extrapolated to 0, there is a finite intercept: $(8.32 \pm 1.92)*10^{-3}$ A 4σ effect for 20-60% events.
- the intercepts for γ_{112} and γ_{123} are consistent with each other. $(7.51 \pm 0.75)*10^{-3}$ for γ_{112}
- Should they scale with v_2 and v_3, instead of being the same? (if they are due to implicit v_2 or v_3)

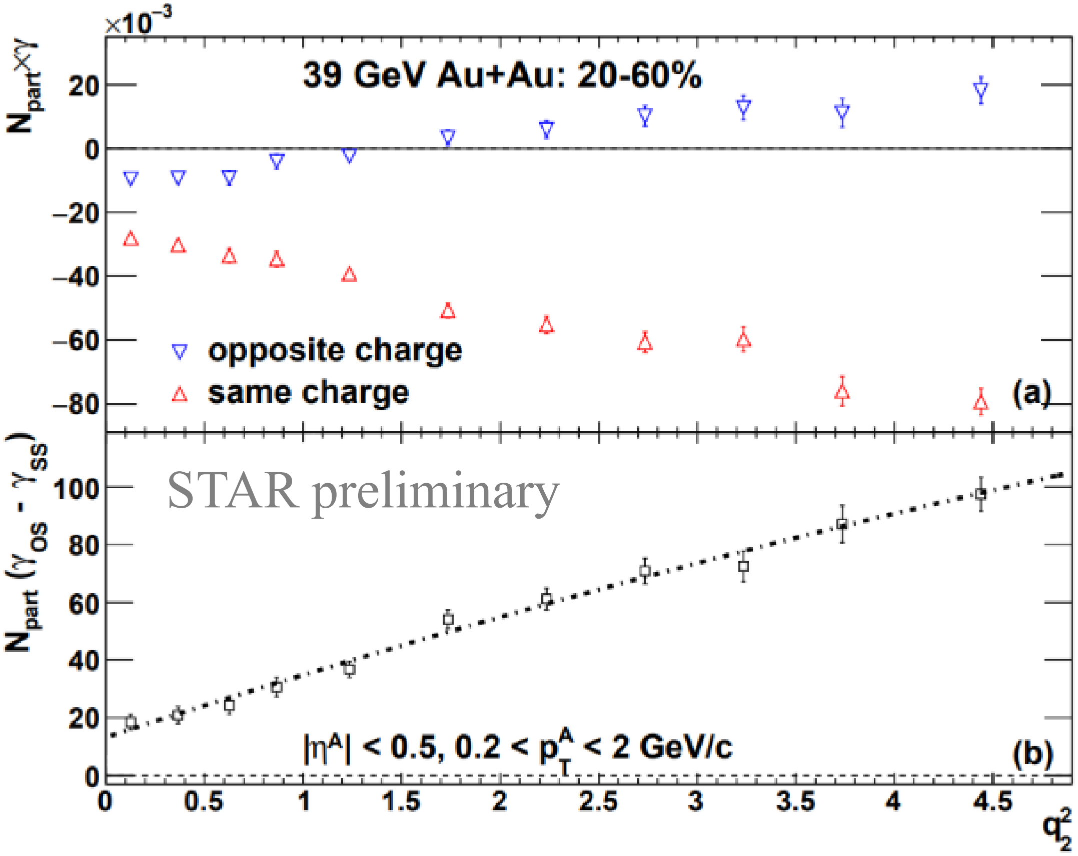
Centrality dependence

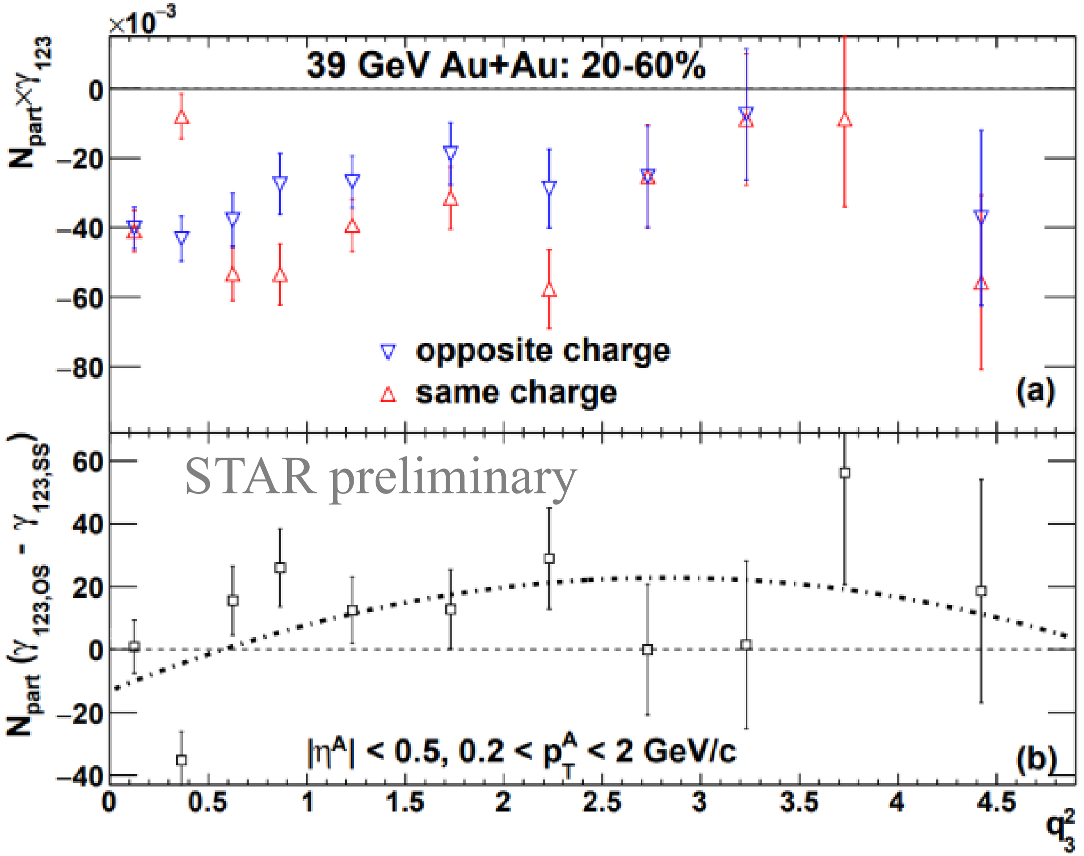




- The raw signals are different between γ_{112} and $\gamma_{123.}$ (a factor of 3)
- The ESE signals are, however, similar for γ_{112} and γ_{123}.
- Origin of these finite intercepts: residue nonflow? implicit v_2? CME?

γ_{112} and γ_{123}: 39 GeV Au+Au





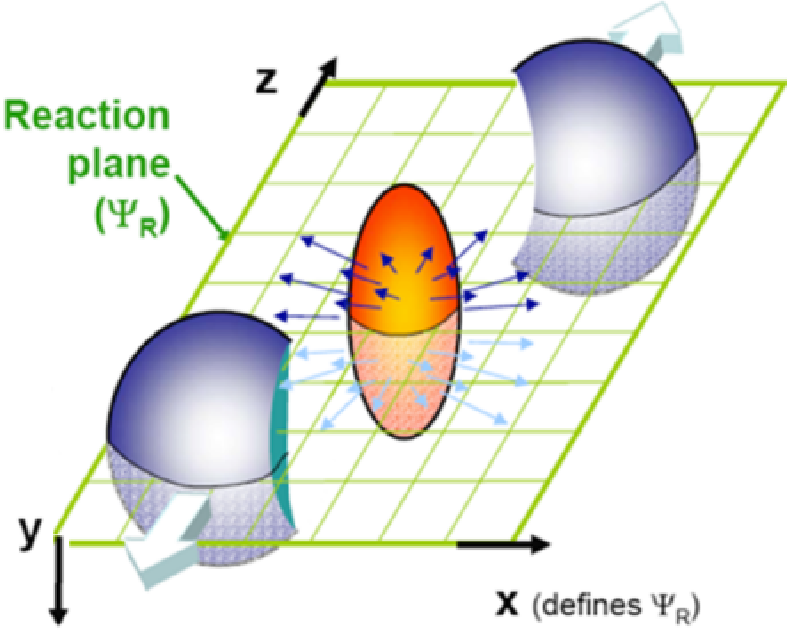
- γ_{112}: $(1.319 \pm 0.223)*10^{-2}$, 6σ effect
- γ_{123}: $(-1.316 \pm 0.756)*10^{-2}$, consistent with zero
- This year, 27 GeV data will provide a chance to confirm this.
- The newly installed EPD will help further suppress nonflow.

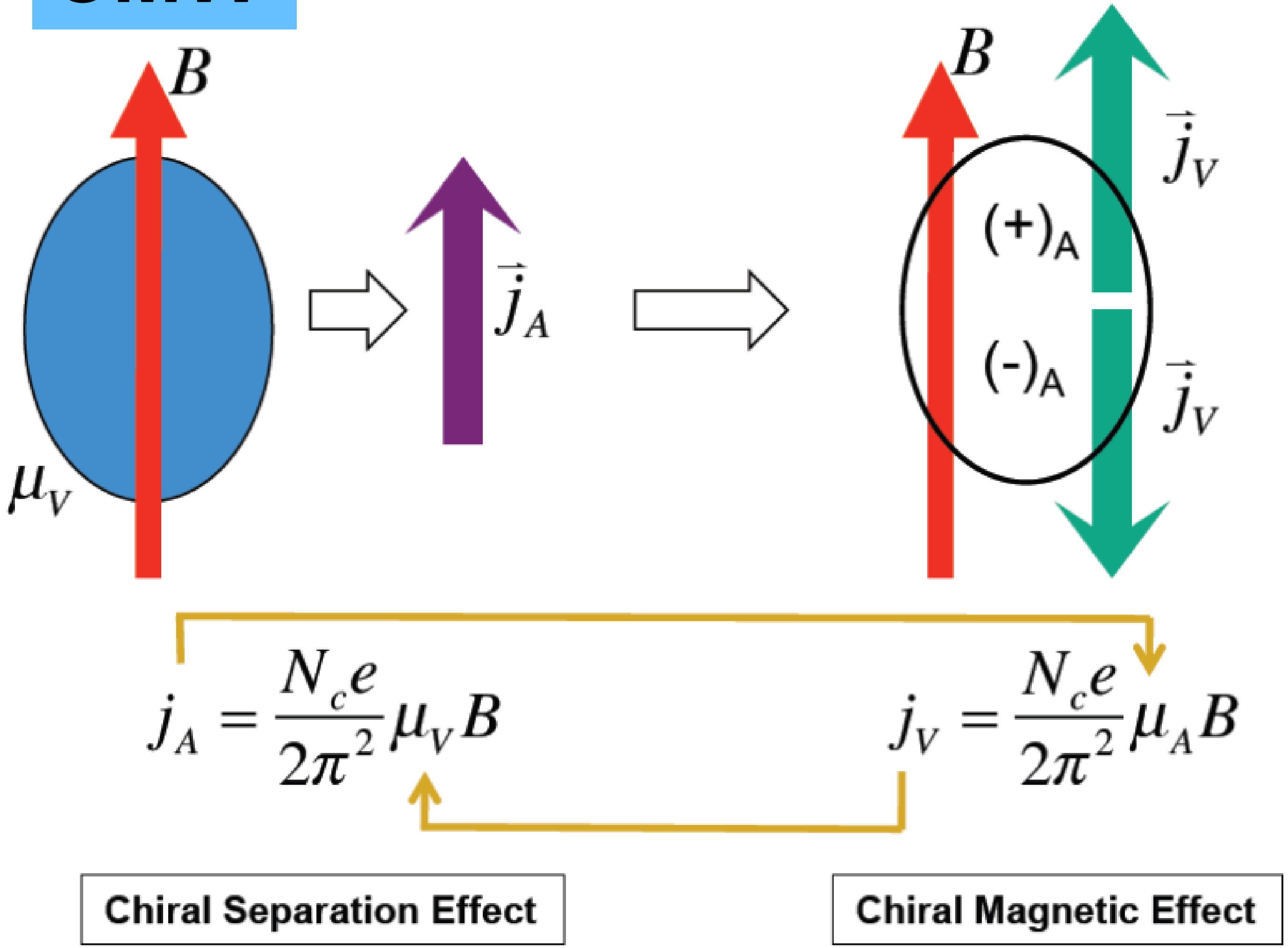
Summary on CME

- Non-flow backgrounds are severe in small systems
    - suppressed with η gap between EP and particles of interest
- Apparent-anisotropy background seems to be the major contribution
    - κ_{112} and κ_{123} are close to each other
    - ESE shows small but finite intercepts for both γ_{112} and γ_{123}
    - what if CME and v_2 are strongly correlated as functions of centrality
- Hidden-anisotropy background may be small
    - but hard to handle directly
- Isobaric collisions will clarify whether B field plays a role
    - will do blinding analysis
- High-statistics BES data and the EPD will further help

CMW

Peak magnetic field ~ 10^{15} Tesla !
(**Kharzeev et al. NPA 803 (2008) 227**)





$$j_A = \frac{N_c e}{2\pi^2}\mu_V B$$

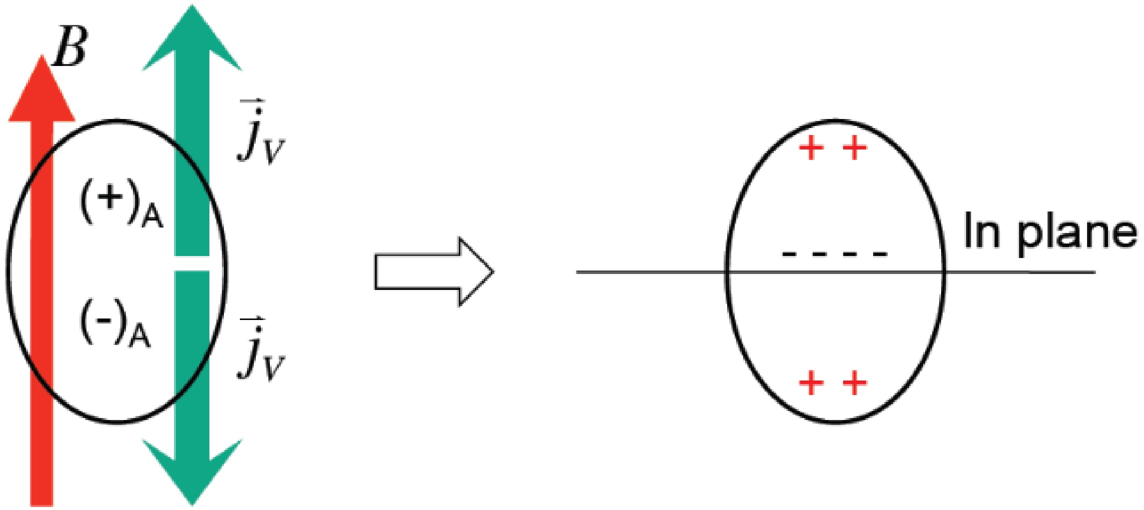
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect

Chiral Magnetic Effect

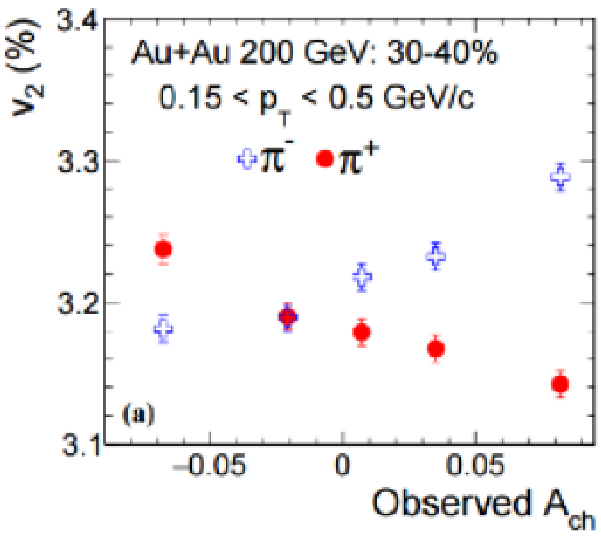
CSE + CME → Chiral Magnetic Wave:
collective excitation
signature of chiral symmetry restoration

Observable



**Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee,
PRL 107, 052303 (2011)**

STAR, PRL 114 (2015) 252302



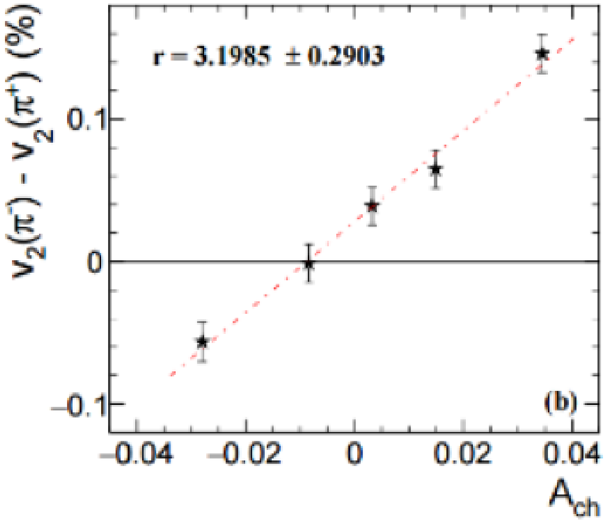
quadrupole moment

Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{\text{ch}}$,

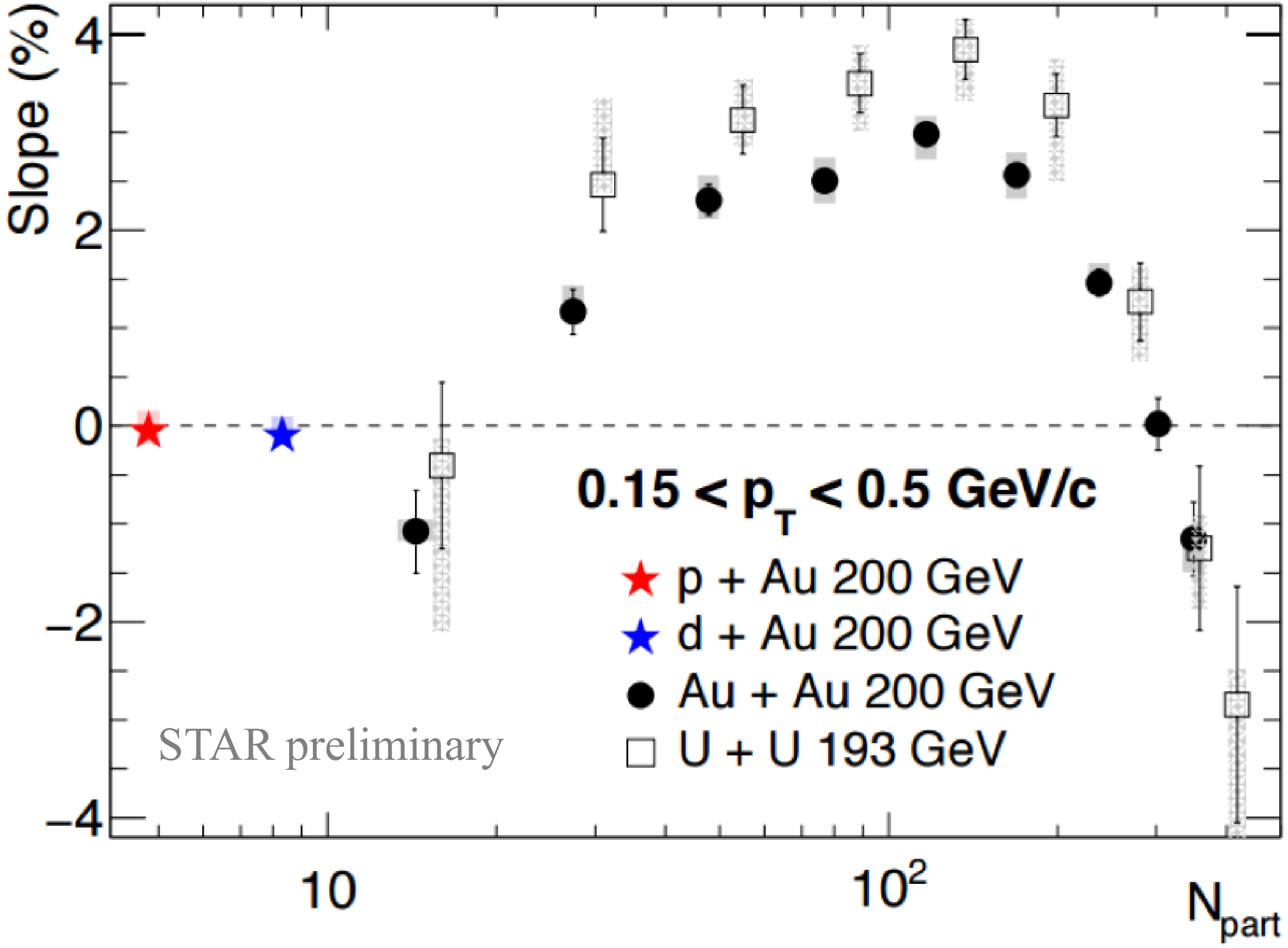
net charge density

where charge asymmetry is defined as $A_{\text{ch}} = \frac{N^+ - N^-}{N^+ + N^-}$.

Then π^- v_2 should have a positive slope as a function of A_{ch},
and π^+ v_2 should have a negative slope with the same magnitude.



Different collision systems



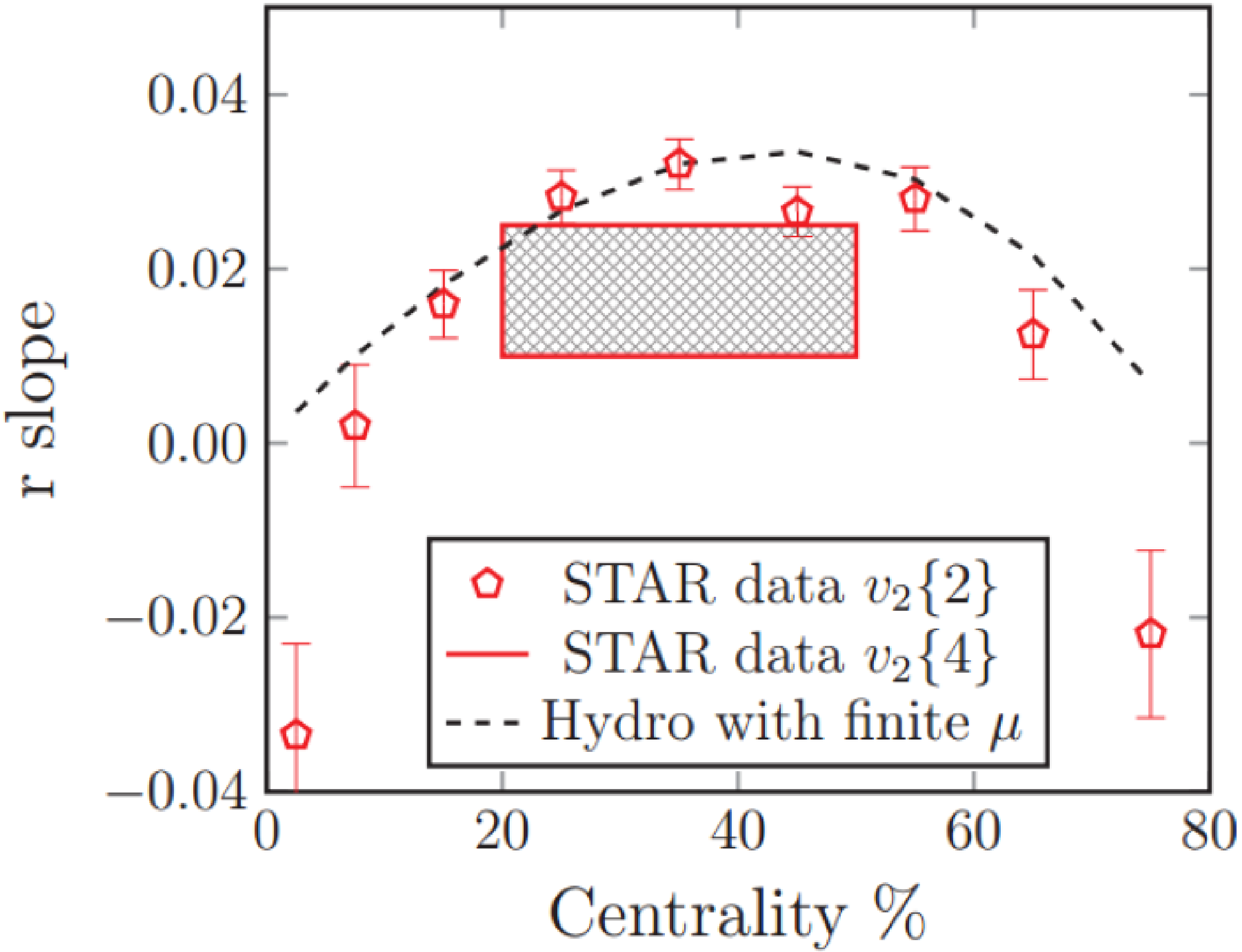
Nonflow effects are largely cancelled by the v_2 difference.

The slope for π is consistent with zero in 200 GeV p+Au and d+Au, close to peripheral Au+Au or U+U collisions.

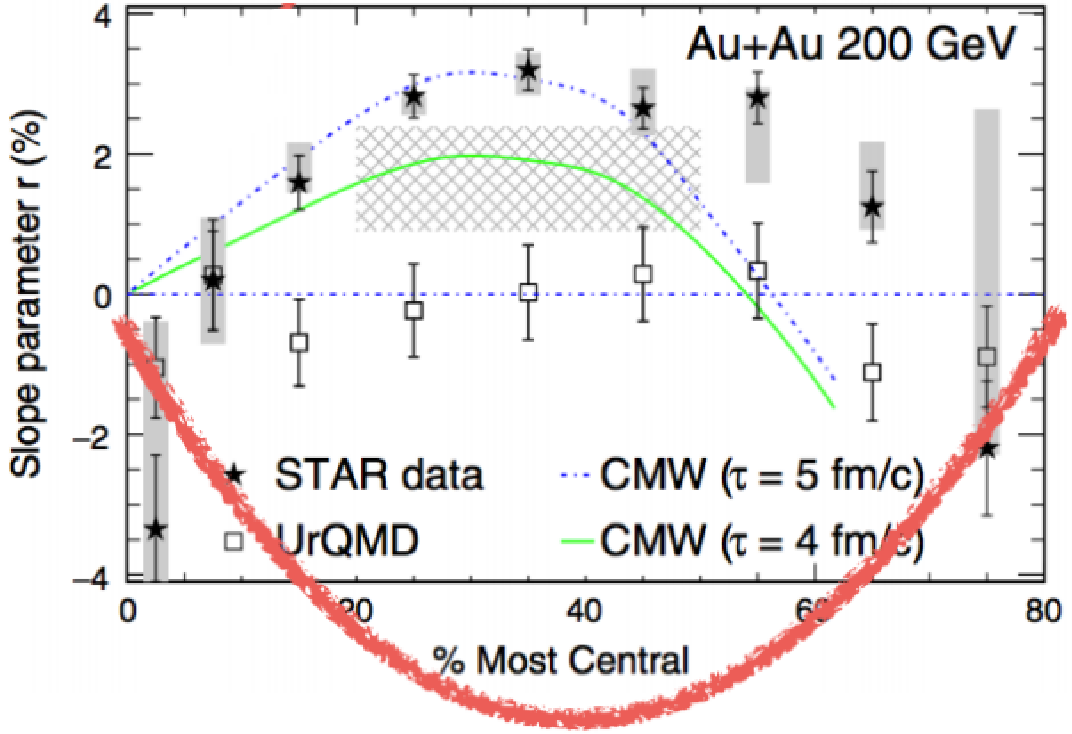
Larger signals in U+U than Au+Au for mid-central or mid-peripheral events (in line with the magnetic field difference?)

The TPC event plane was used in these analyses.

Alternative interpretation: hydro+isospin



Y. Hatta et al. NPA 947 (2016) 155



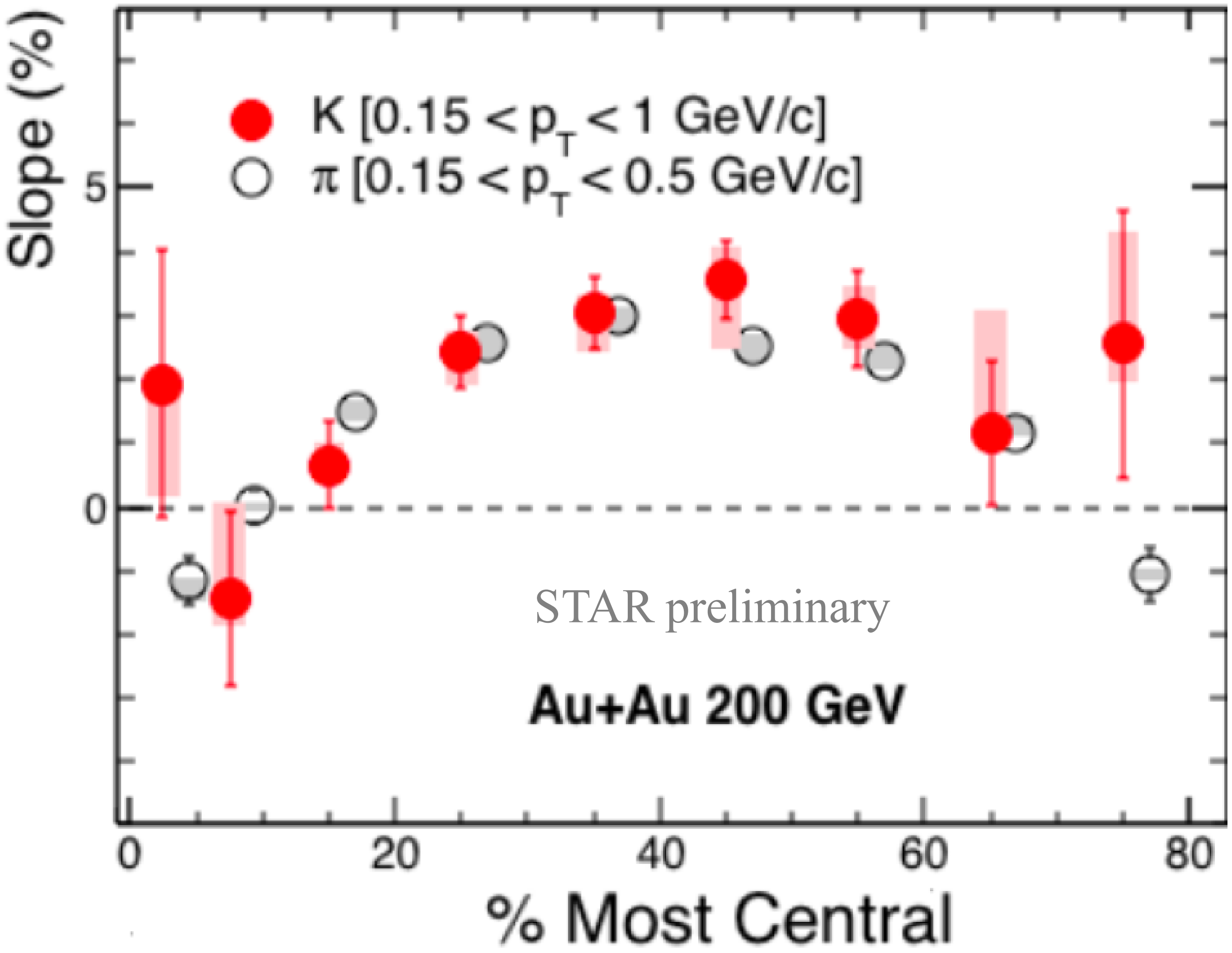
Hydrodynamics study (no CMW): kaon/proton slope should be opposite to π slope with larger magnitude, since

$v_2(\pi^+) < v_2(\pi^-)$

$v_2(K^+) > v_2(K^-)$

$v_2(p) > v_2(\text{p-bar})$

kaon Δv_2 slope

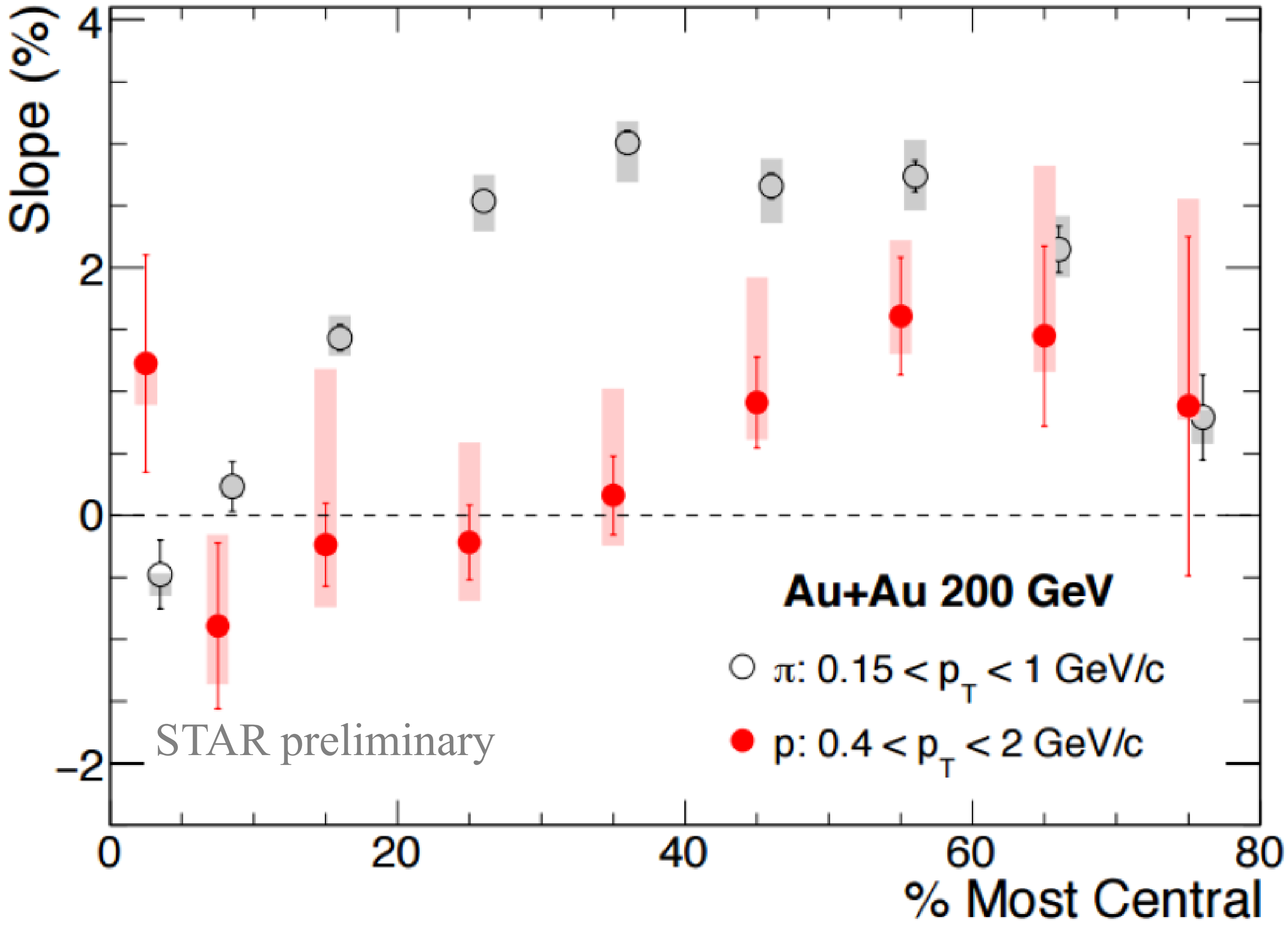


Hydrodynamics study (no CMW): kaon slope should be opposite to π slope with larger magnitude, since

$$v_2(\pi^+) < v_2(\pi^-)$$
$$v_2(K^+) > v_2(K^-)$$

STAR measurements show that kaon slope parameters behave similarly to those of π, not opposite: the isospin effect is not the dominant contribution to the pion or kaon slopes.

proton Δv_2 slope

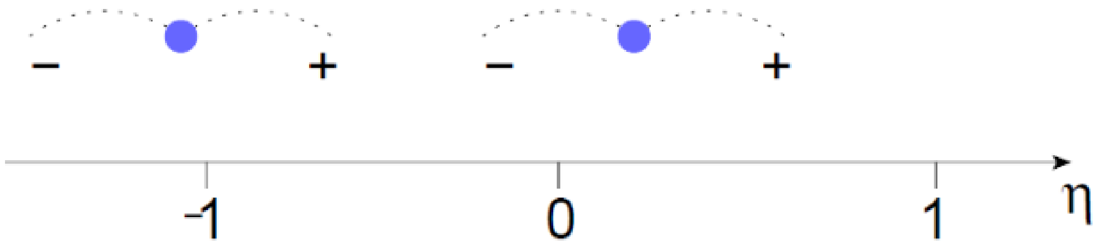


Hydrodynamics study (no CMW): proton slope should be opposite to π slope with larger magnitude, since

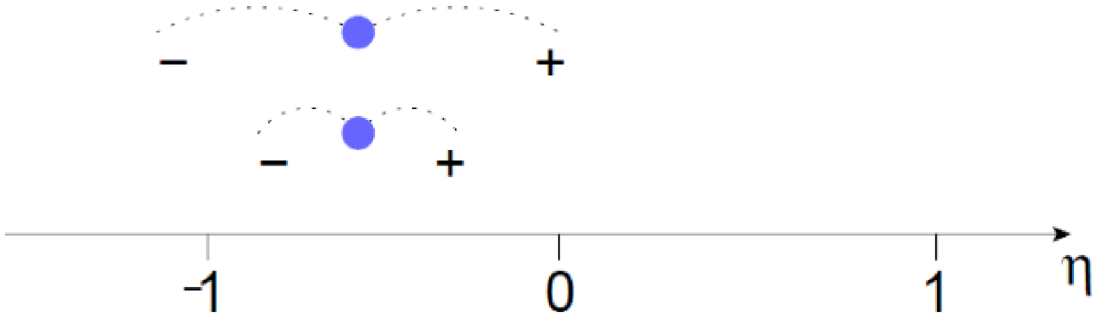
$$v_2(\boldsymbol{\pi}^+) < v_2(\boldsymbol{\pi}^-)$$
$$v_2(\mathbf{p}) > v_2(\textbf{p-bar})$$

STAR measurements: proton slopes behave differently from π and *K*: a mixed scenario without an obvious dominant mechanism, where the positive contribution of the CMW (CVW) and/or the LCC effect is reduced by the absorption effect, and/or is counterbalanced by the isospin effect.

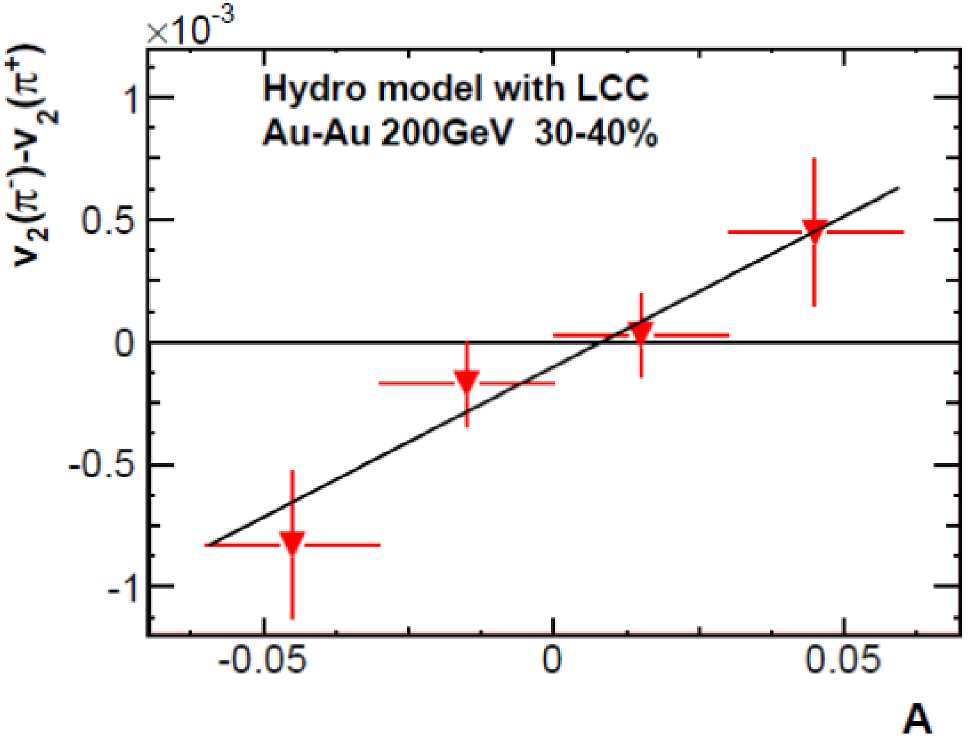
Alternative interpretation: LCC



Clusters located close to acceptance boundary produce one pion outside boundary. v_2 decreases with $|\eta|$.



Clusters with low p_T have particles more separated in η than high-p_T clusters. v_2 increases with p_T.

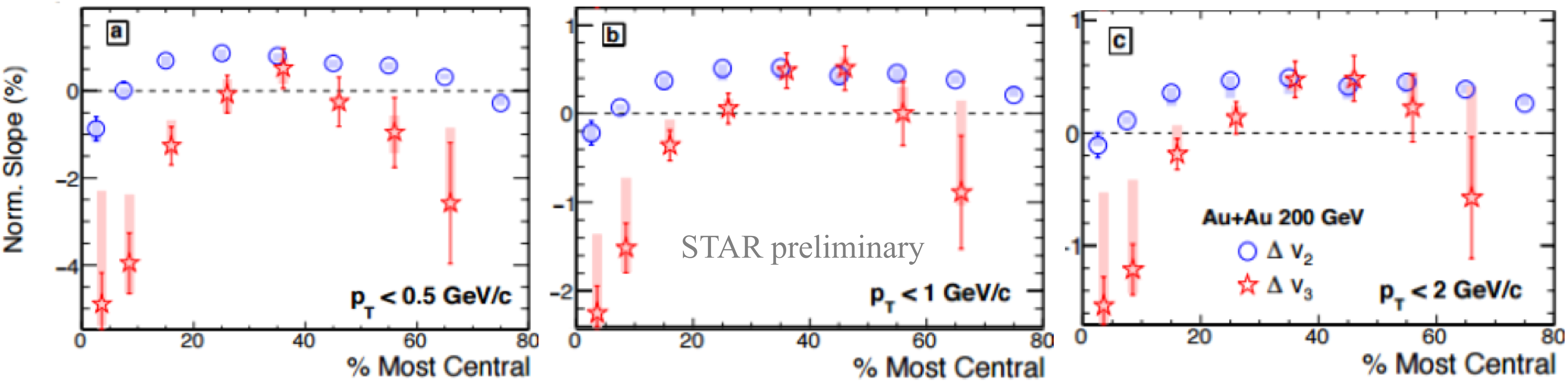


A. Bzdak and P. Bozek, Phys. Lett. B 726 (2013) 239

η dependence of v_2 is weaker than what this paper used; mean p_T in data is constant vs A_{ch} (no 2nd effect); the LCC effect is estimated to be 10 times smaller than data.

Δv_3 slope

$$\text{Norm.}\Delta v_n = 2\frac{v_n^- - v_n^+}{v_n^- + v_n^+}$$



Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then one should see **Norm.Δv_3 ~ Norm.Δv_2** (Bzak & Bozek PLB 726(2013)239).

STAR measurement: **Norm.Δv_3 < Norm.Δv_2** at low p_T. Closer at high p_T.

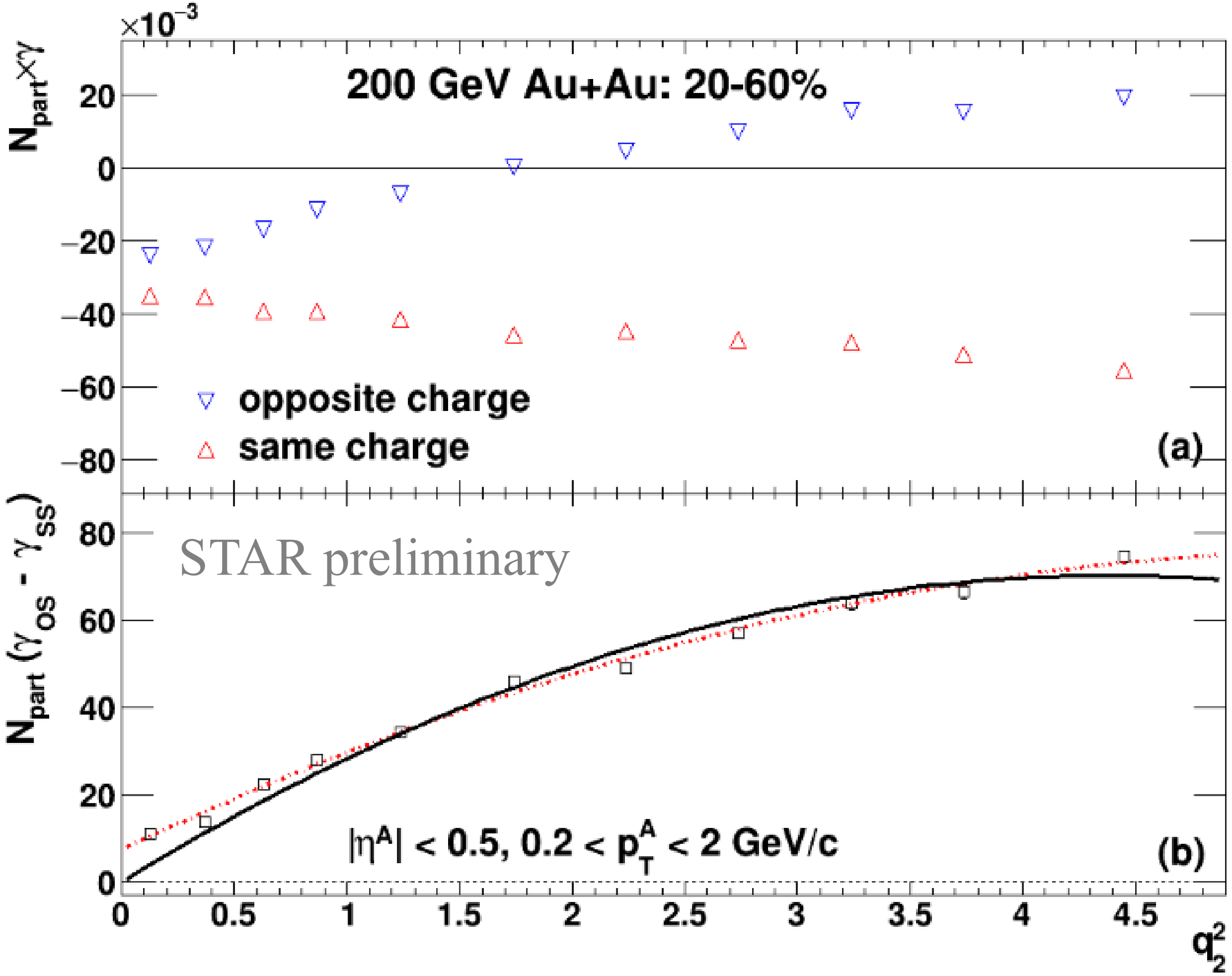
LCC mechanism alone cannot explain data.

Summary on CMW

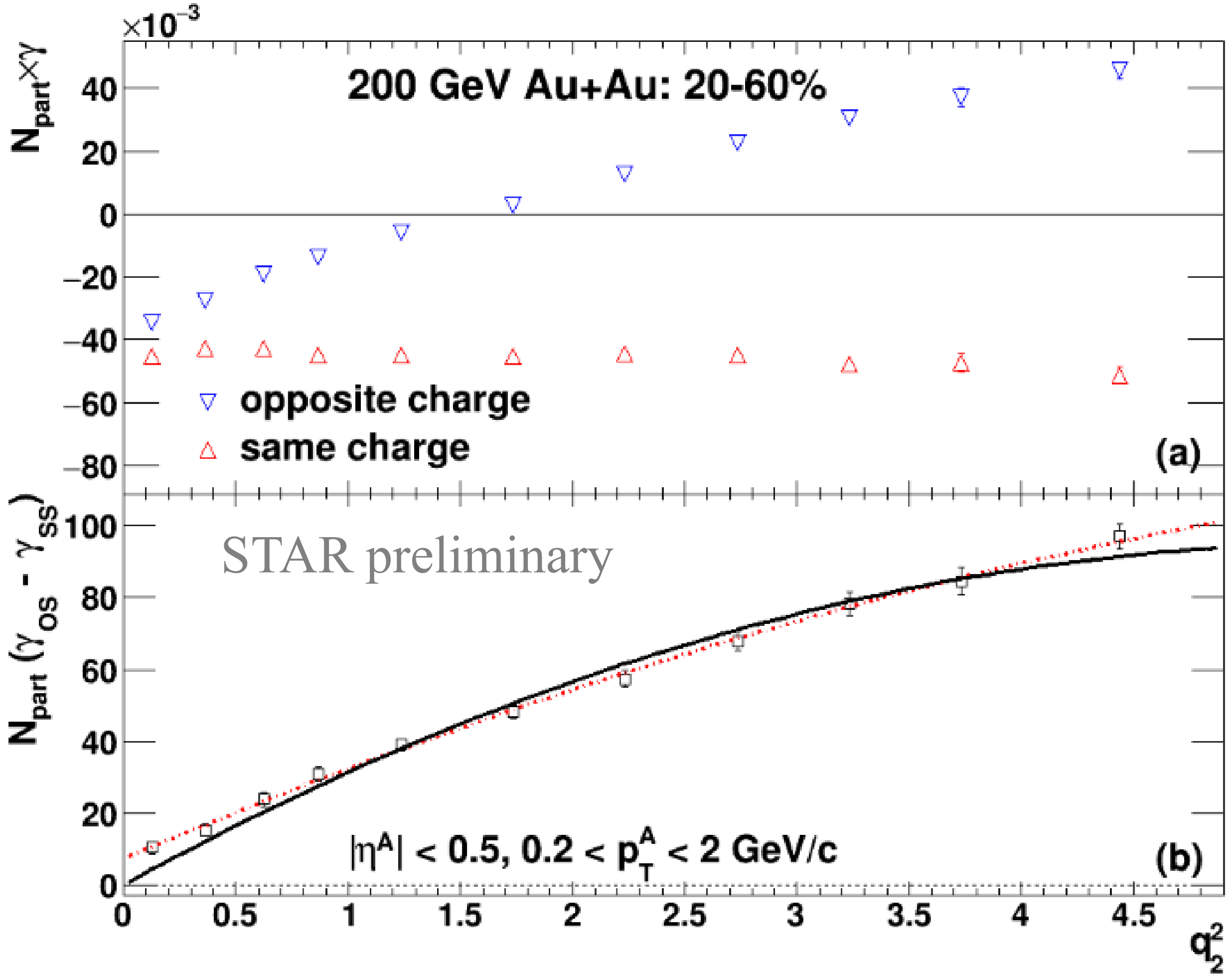
- No signals in p+Au, d+Au or peripheral Au+Au/U+U
- Signals in U+U larger than Au+Au
  - magnetic field difference?
- Hydro+isospin interpretation
  - not significant in pion or kaon slopes
  - may contribute to proton slopes
- LCC interpretation alone can not explain
  - Norm.$\Delta v_3 <$ Norm.Δv_2
- There is room for CMW.

Backup slides

γ_{112}: 200 GeV Au+Au



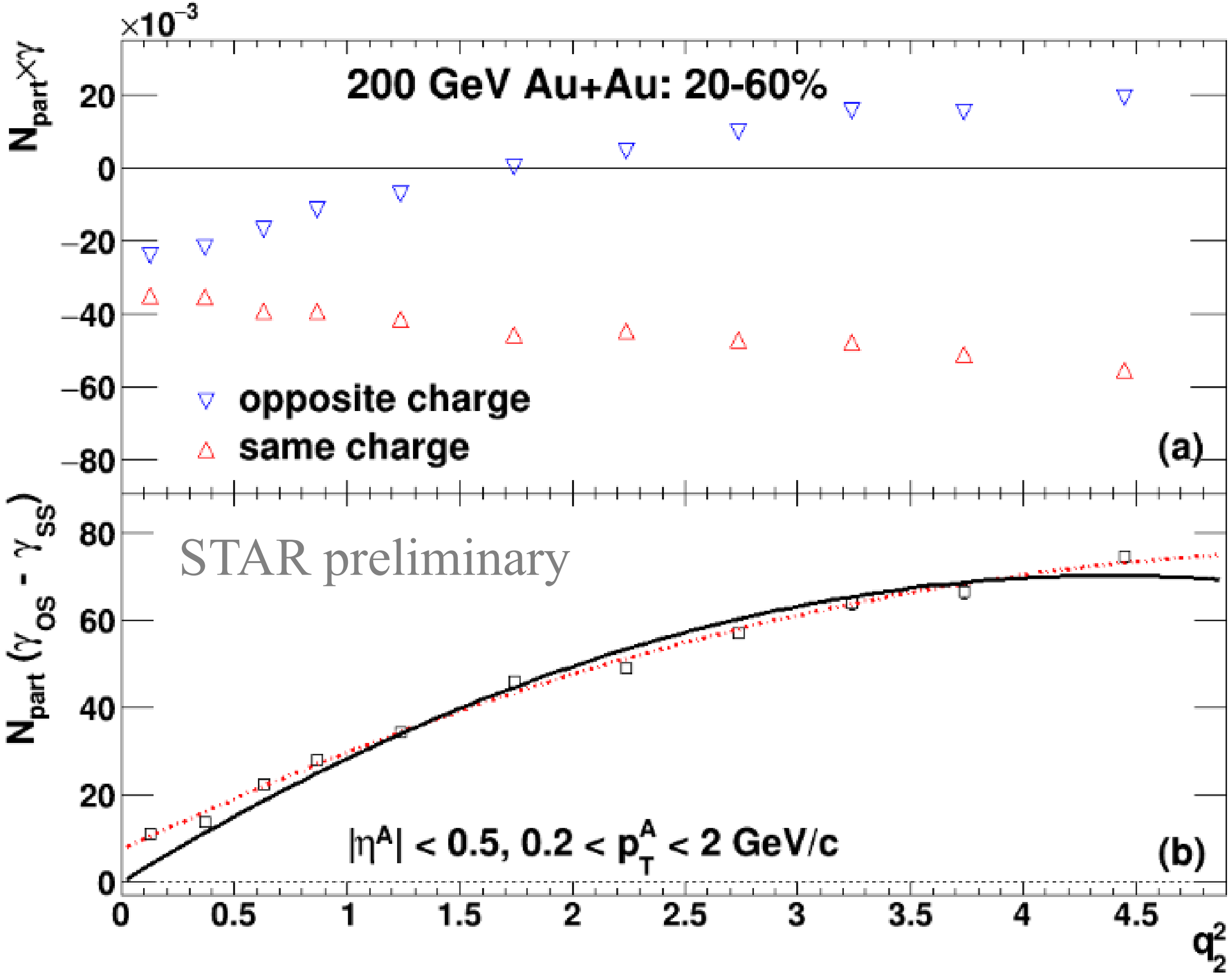
Whole multiplicity: (7.51 ± 0.75)*10^{-3}



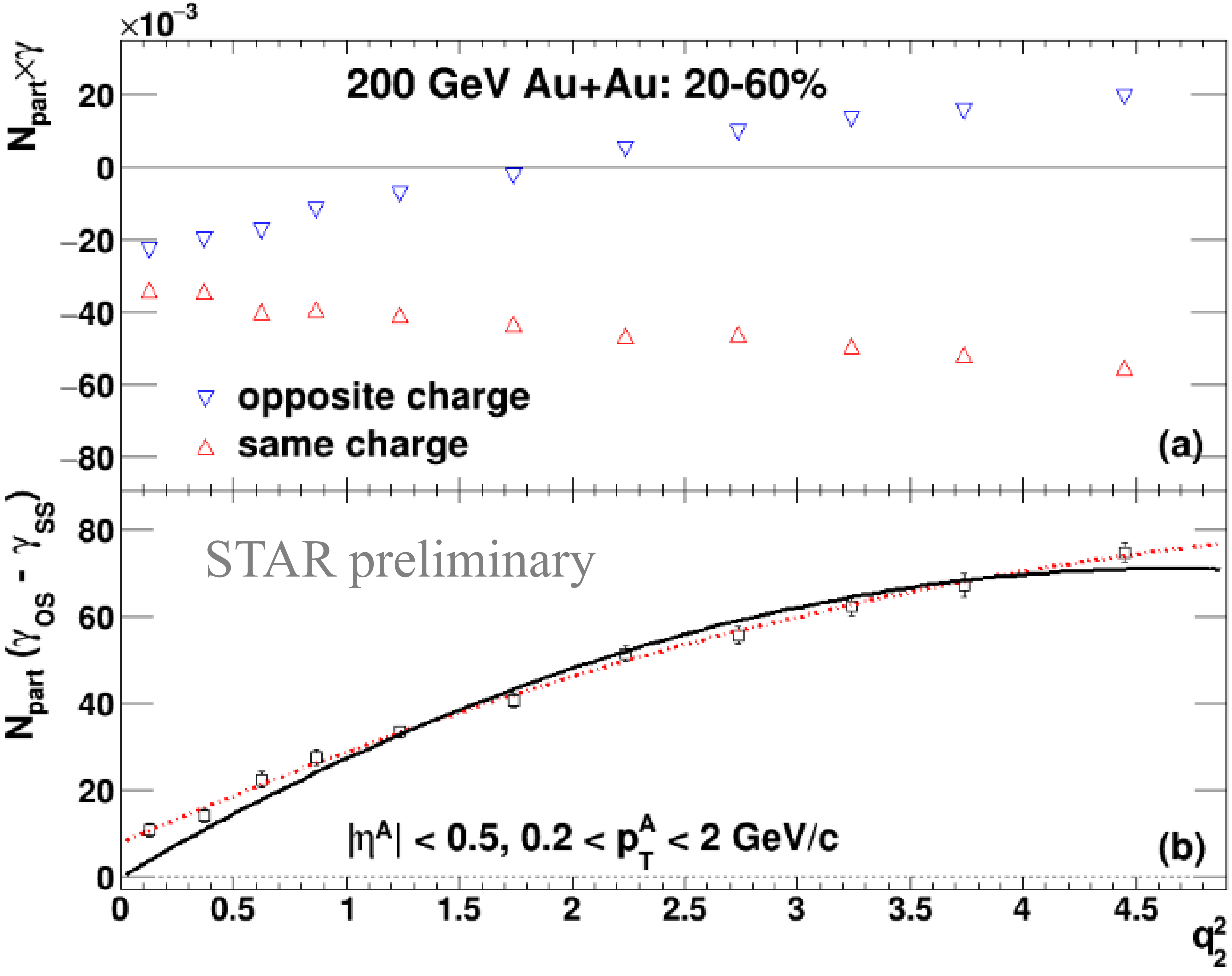
Half multiplicity: (7.32 ± 1.37)*10^{-3}

After randomly rejecting half of the particles, the q-dependence becomes stronger, but the intercept remains the same.

γ_{112}: 200 GeV Au+Au



No η gap: (7.51 ± 0.75)*10^{-3}

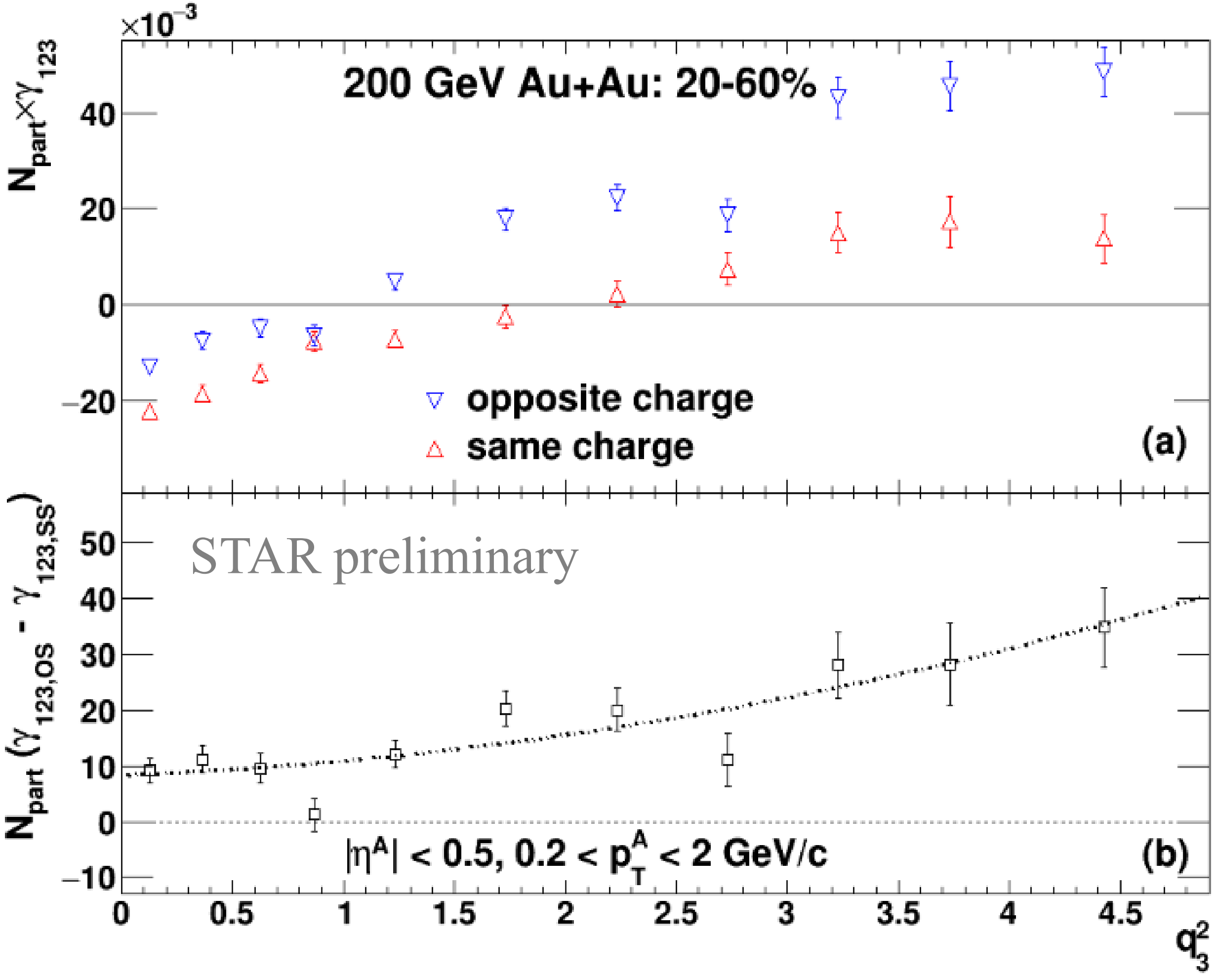


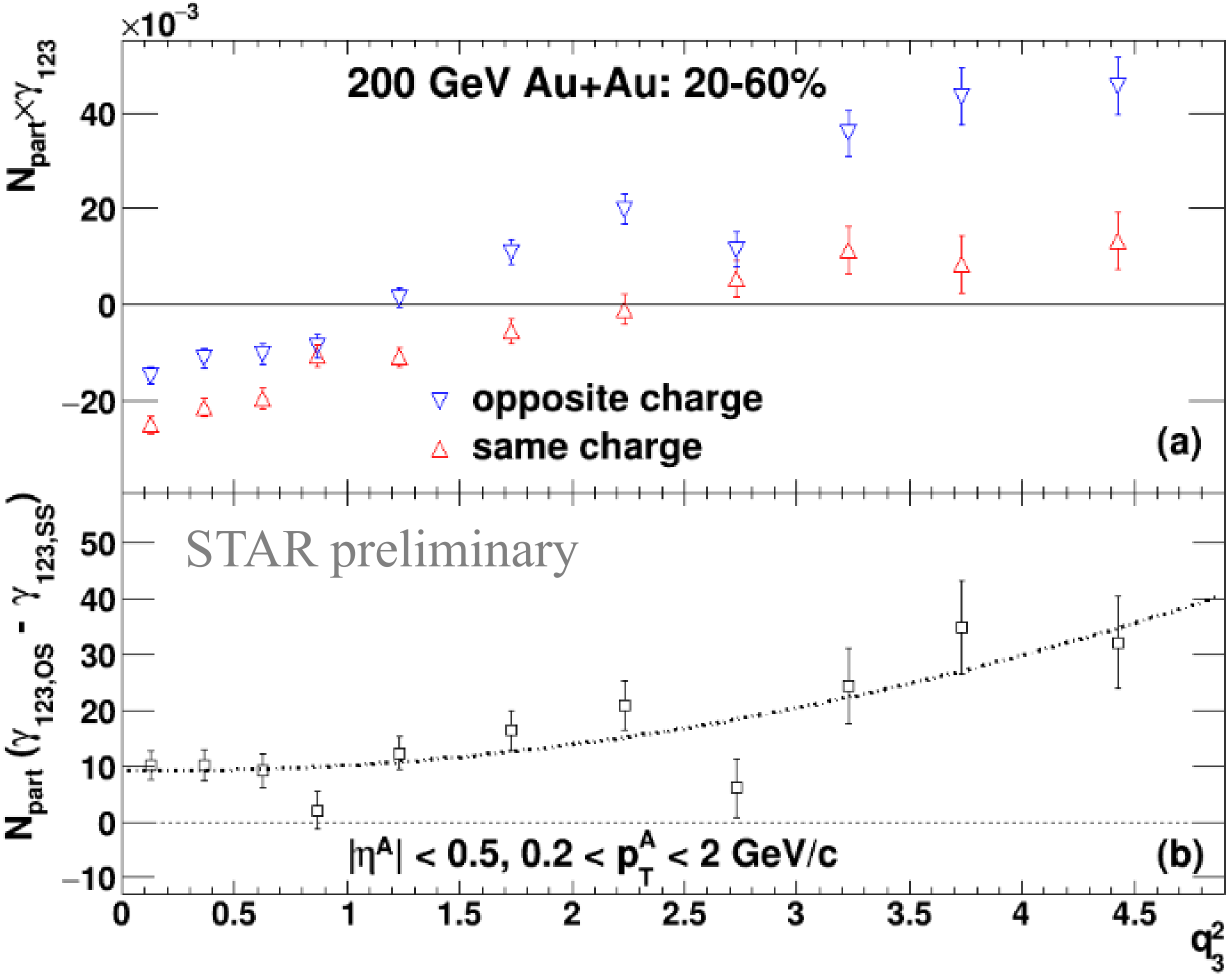
η gap of 0.1: (7.81 ± 1.22)*10^{-3}

When introducing η gap of 0.1, the q-dependence and the intercept are stable.

Forcing the fit to (0,0) gives ~6 times larger χ^2.

γ_{123}: 200 GeV Au+Au



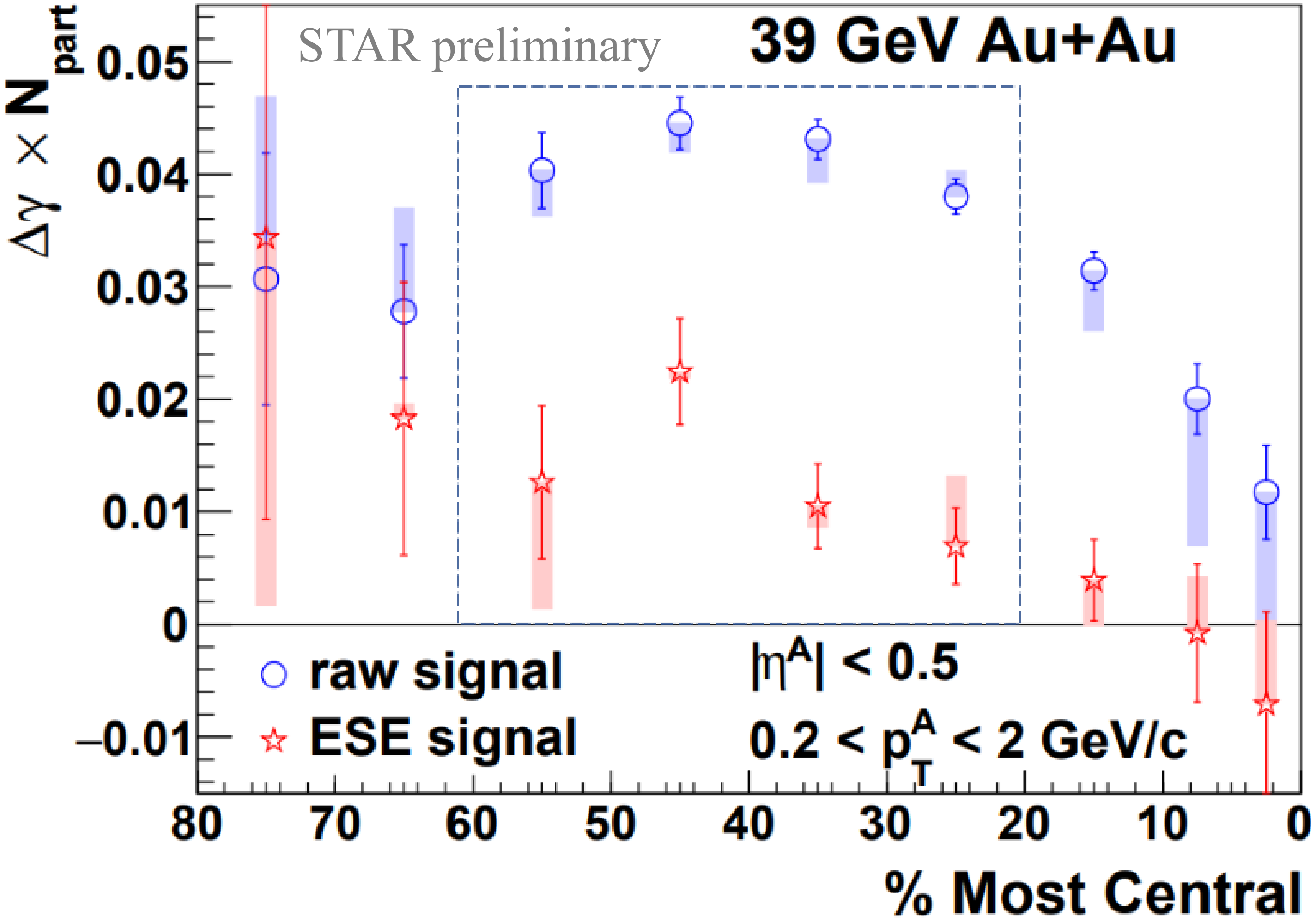


No η gap: (8.32 ± 1.92)*10^{-3}

η gap of 0.1: (9.27 ± 2.20)*10^{-3}

When introducing η gap of 0.1, the q-dependence and the intercept are stable.

Centrality dependence



The shaded boxes reflect the cuts of $|\Delta\eta|>0.15$ and $|\Delta p_T|>0.15$ GeV/c.

- For 20-60% collisions, this "BG" level is typically 75-80% of the raw signal.
- If the CME is there, and if this ESE really works, we expect a better significance in the difference between Ru+Ru and Zr+Zr, because a large portion of BG has been removed.
- Considering the increased error bars, we could still double the significance. Worth trying!