# STAR measurements in search of the CME and the CMW

## -- a biased selection of STAR results

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# Outline

For the CME,
I will discuss different types of background in $\gamma$;
I will not cover
- alternative correlator (see Roy Lacey's talk)
- $\gamma$ as a function of invariant mass
- decomposition of $\gamma$ vs $\Delta\eta$

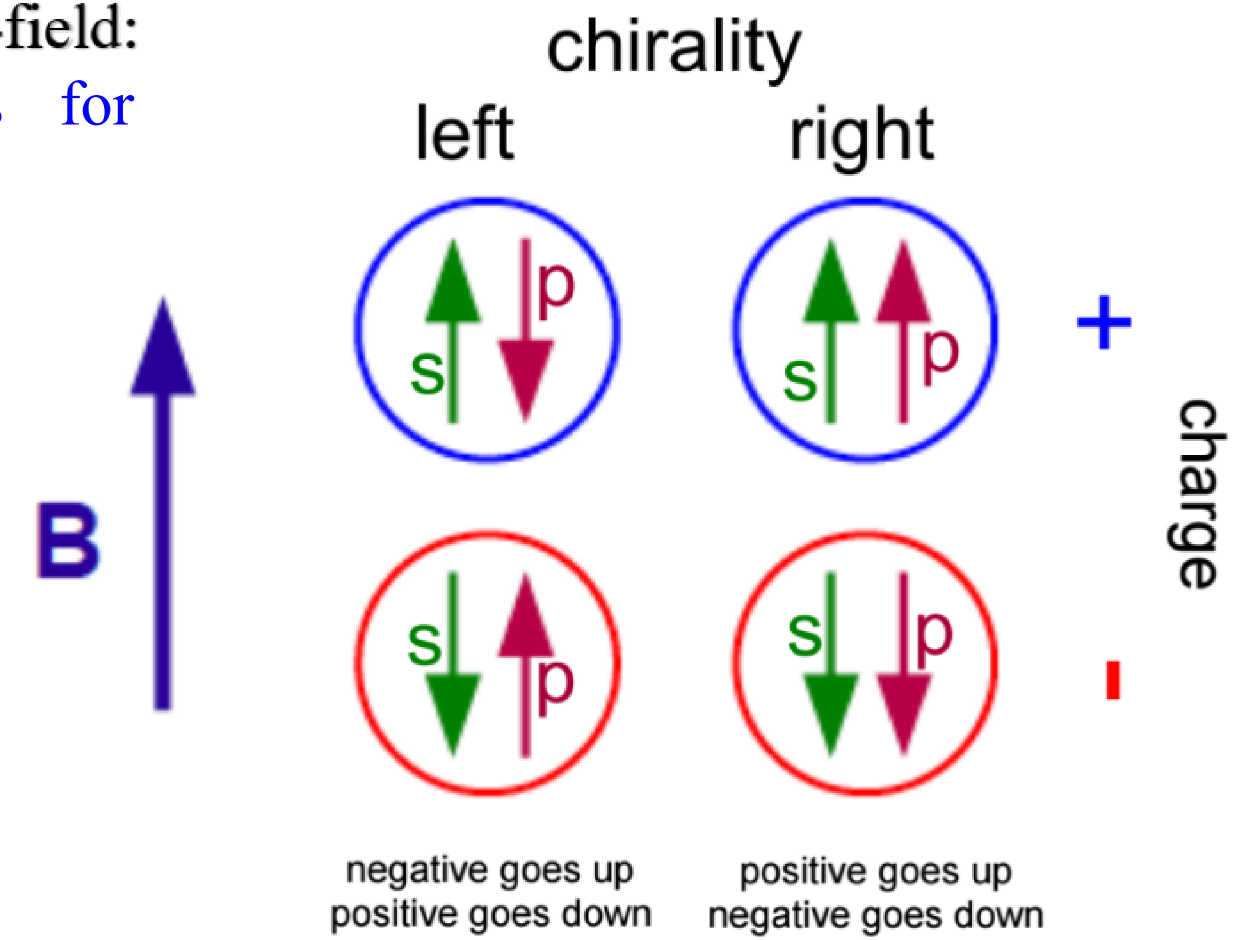
For the CMW,
I will discuss alternative interpretations, including
- hydro+isospin
- local charge conservation

# 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




courtesy of P.Sorensen

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

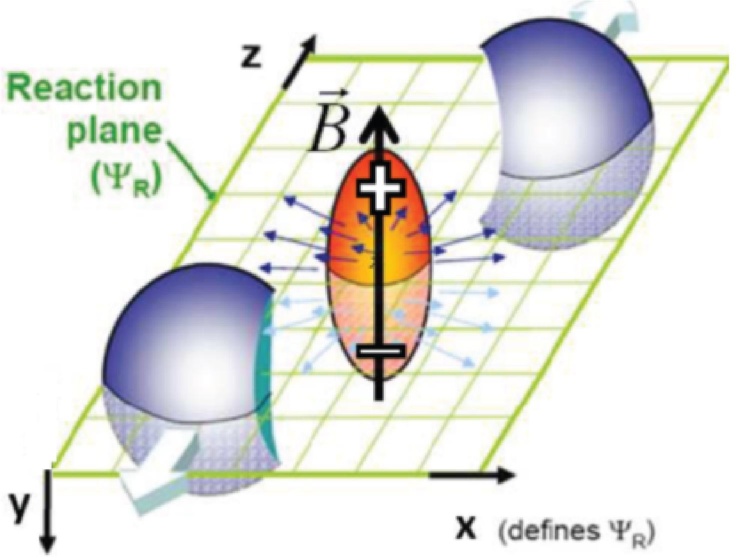
$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

# CME observable: γ correlator

S. Voloshin, PRC 70 (2004) 057901

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

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




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

background effects: largely cancel out

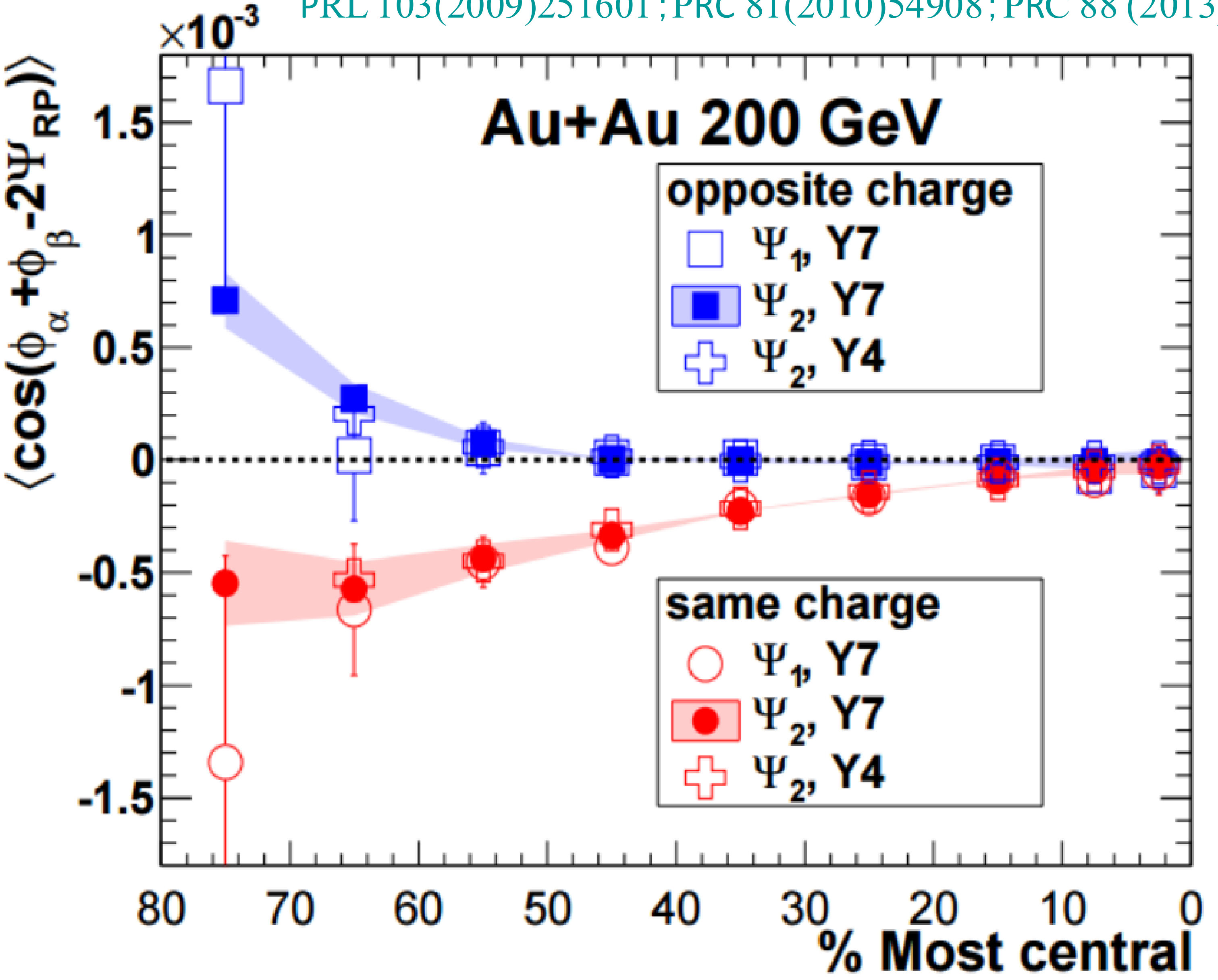
P-even quantity: still sensitive to charge separation

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

$v_2$ 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

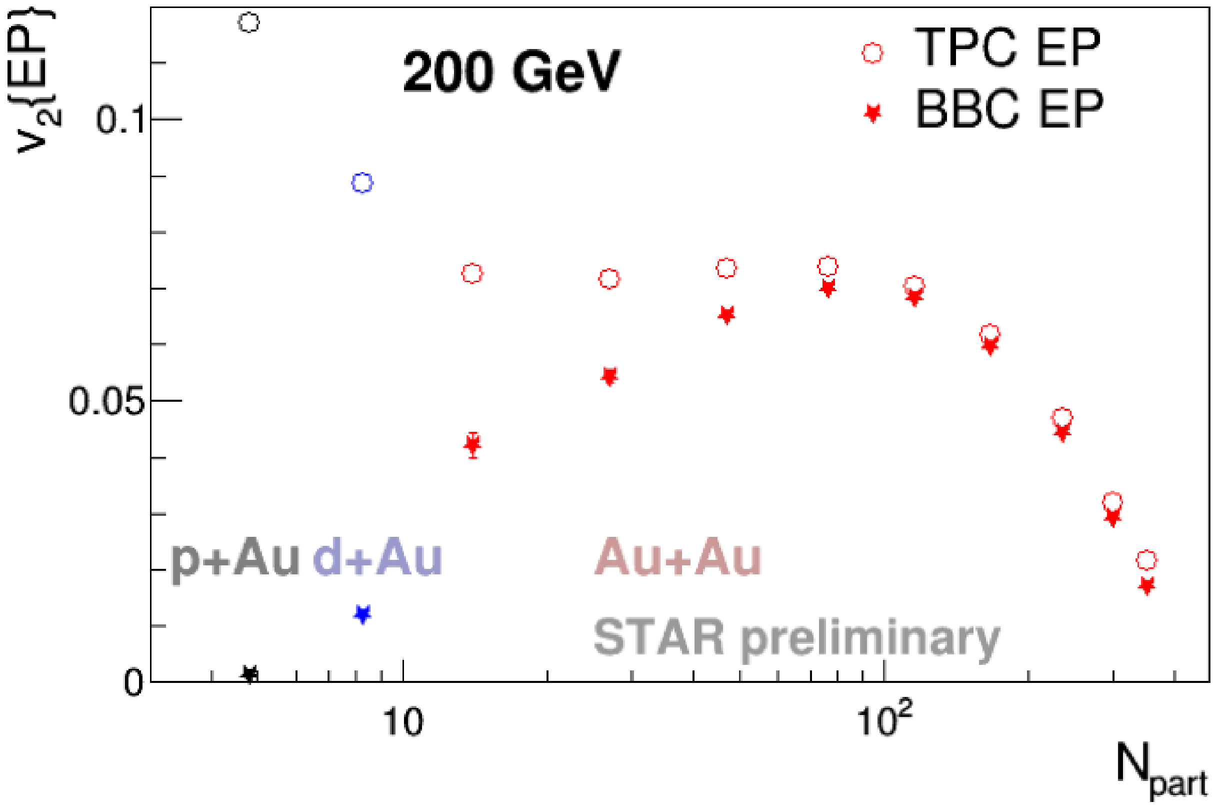


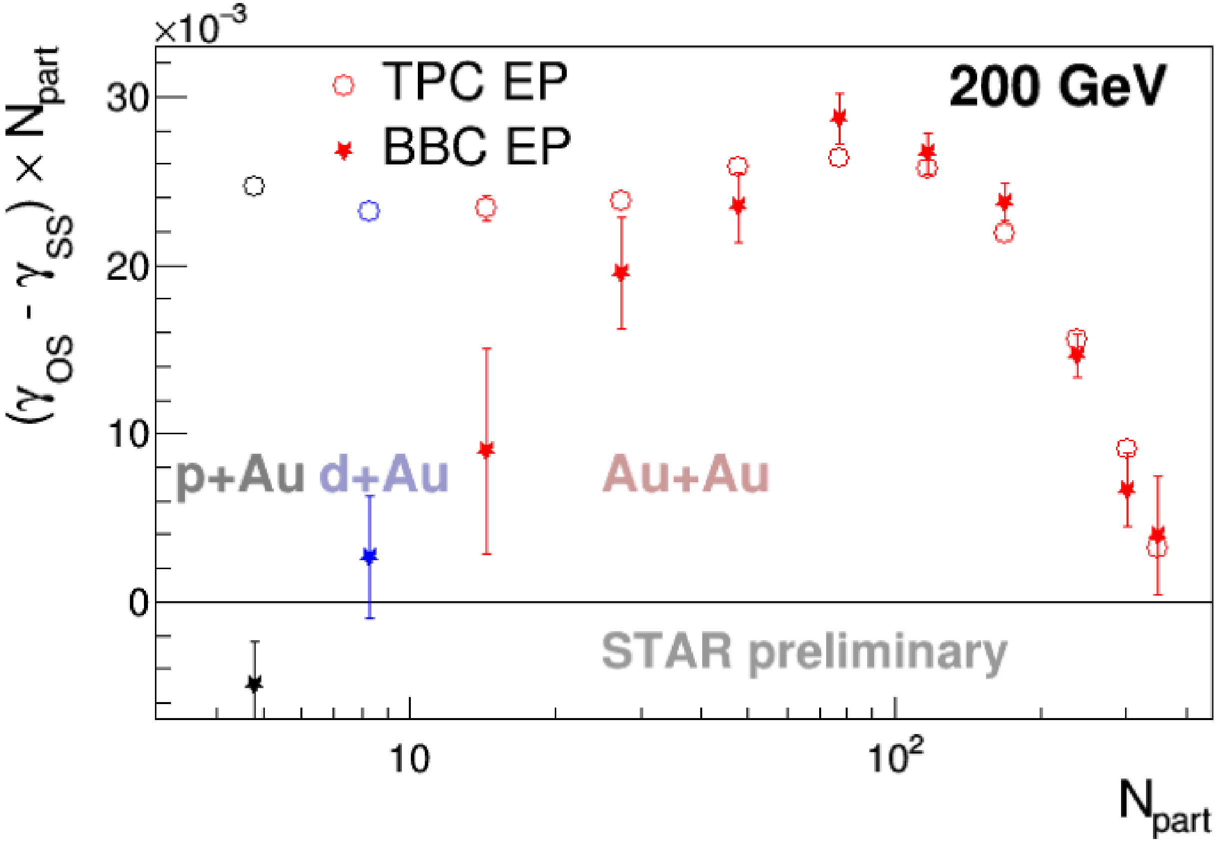

- $\gamma_{os}$ > $\gamma_{ss}$, consistent with CME expectation
- consistent between different years (2004 and 2007)
- confirmed with 1st-order EP (from spectator neutron $v_1$)

However, there are still different types of background:

1. nonflow (correlations unrelated to the reaction plane)
2. aparent anisotropy (final particles)
3. hidden anisotropy (resonances)

# Nonflow-related background




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

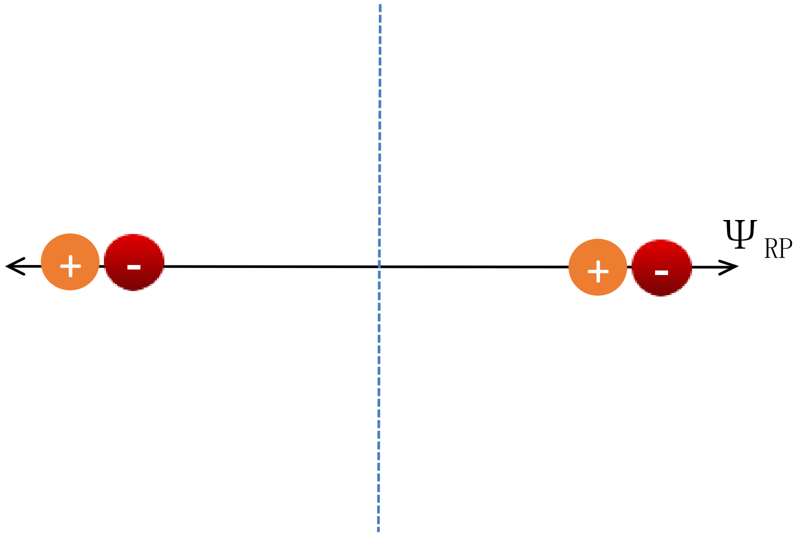
$|\eta_{TPC}| < 1$
$3.8 < |\eta_{BBC}| < 5.1$

# Anisotropy-related background

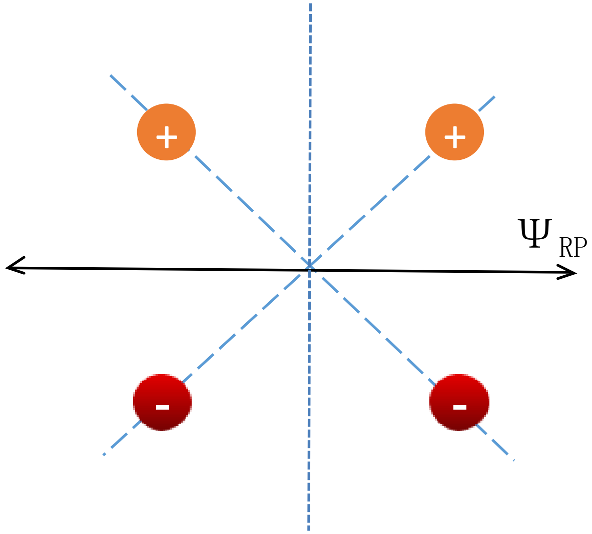
A specific configuration as shown below could solely come from statistical fluctuations.

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

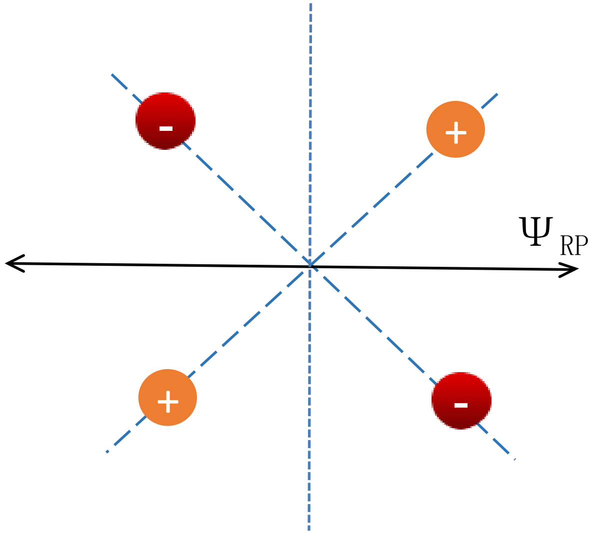
Hidden anisotropy:
implicit $v_2$ (of resonance parents).
real charge separation, but not CME




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




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




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

controllable with measured $v_2$

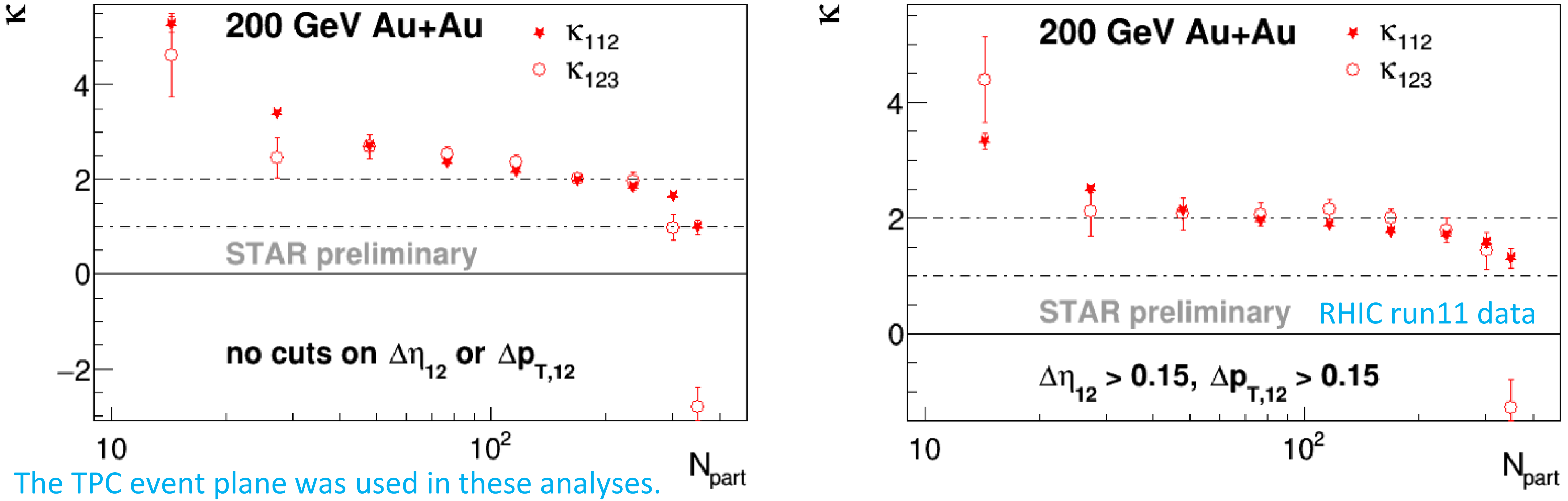
hard to control directly

# $v_2^{explicit}$-related background

$$\gamma_{1,n-1,n} = \langle \cos[\varphi_\alpha + (n-1)\varphi_\beta - n\Psi_{EP}] \rangle / res_{EP}$$
$$= \kappa_{1,n-1,n} \cdot v_{n,\beta} \cdot \delta$$

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

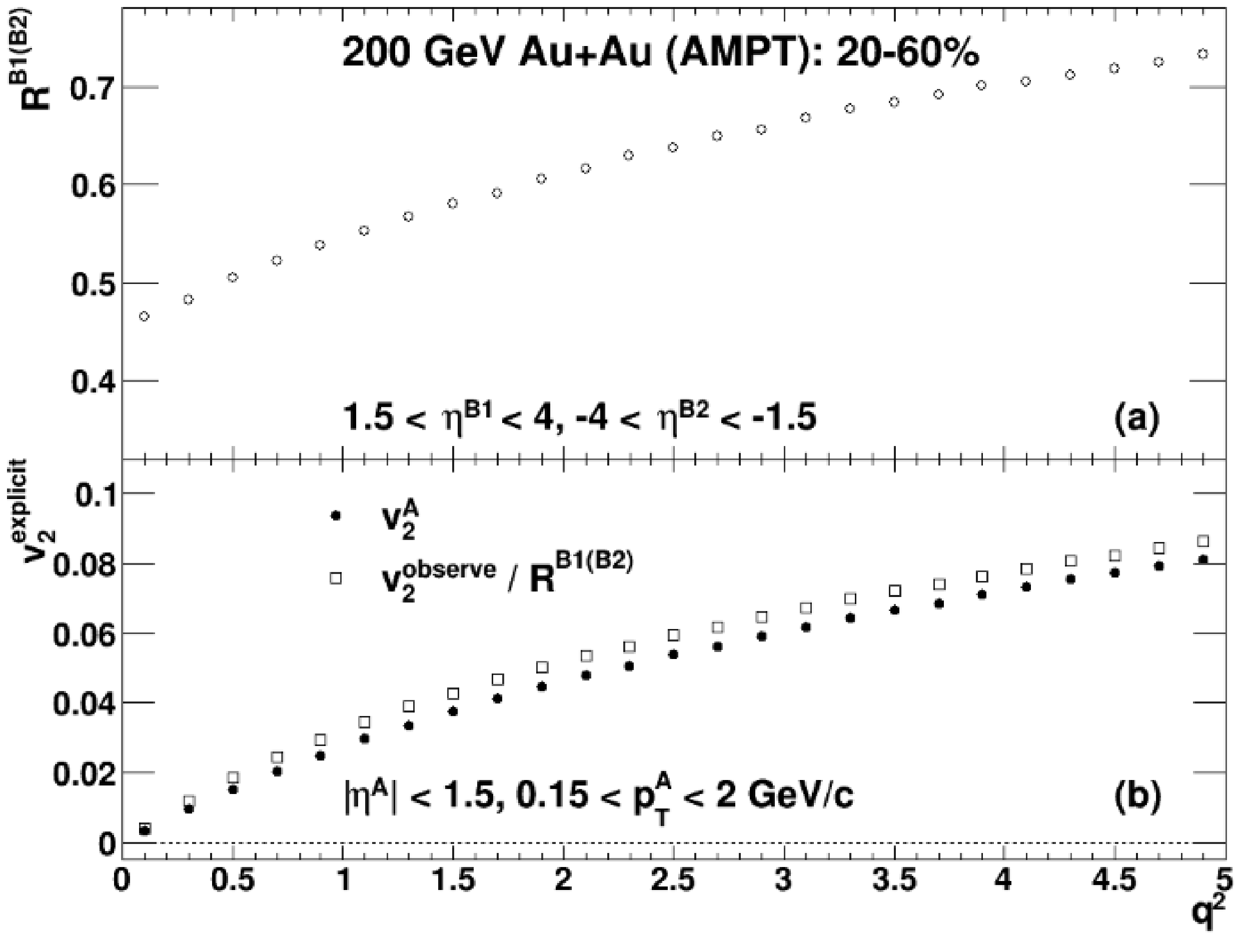
$\kappa_{1,n-1,n}$ is just $\gamma_{1,n-1,n}$ normalized by $v_n$ and δ.




The TPC event plane was used in these analyses.

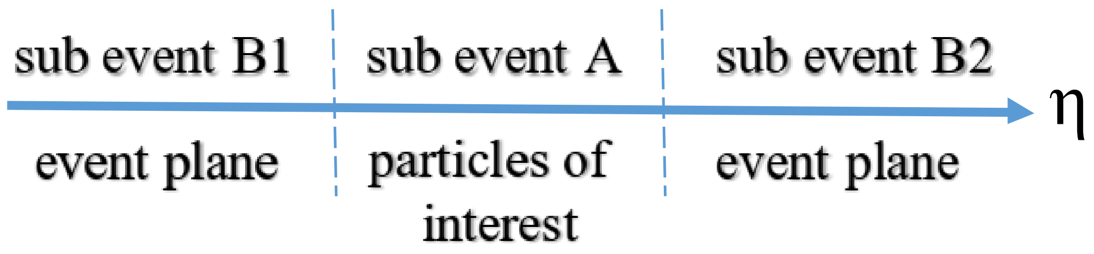
$\kappa_{112}$ and $\kappa_{123}$ are consistent with each other (except in the most collisions), especially after removing very-short-range correlations.

# Event-shape engineering




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

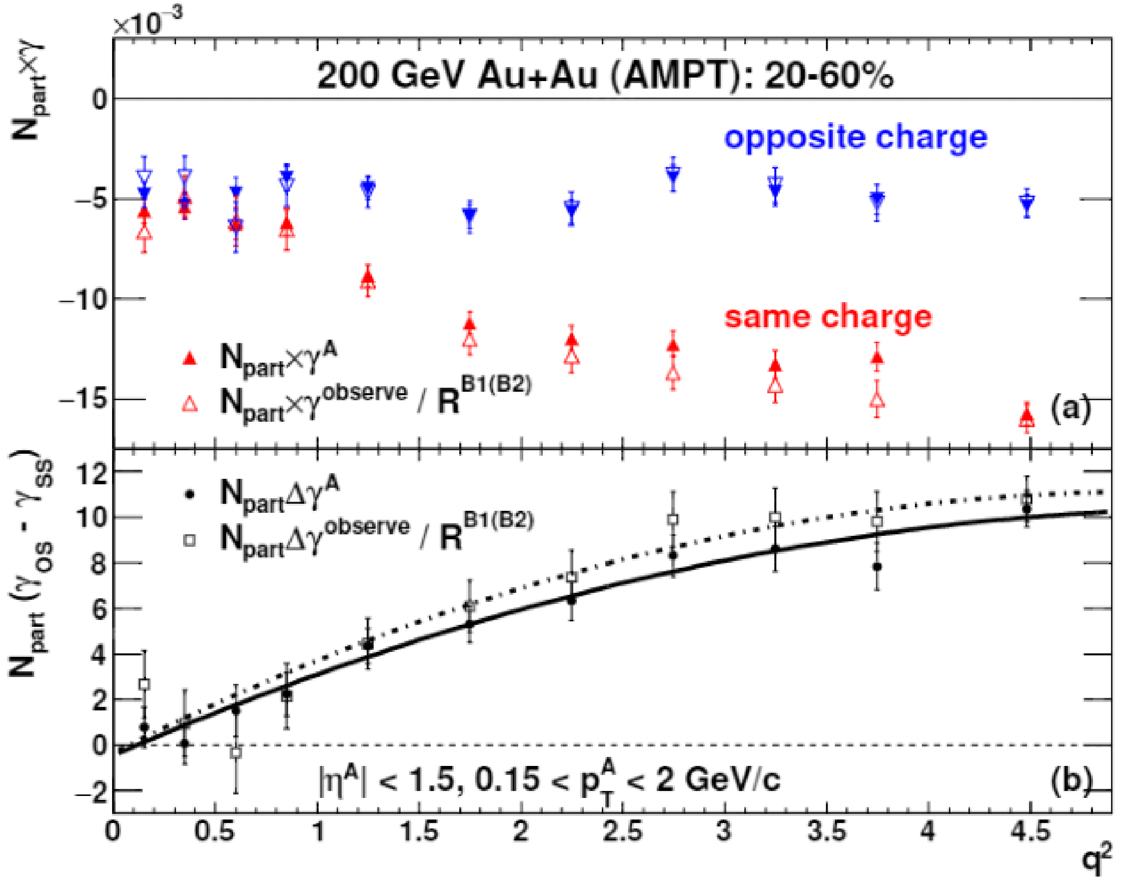
$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$




- 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




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

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

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

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

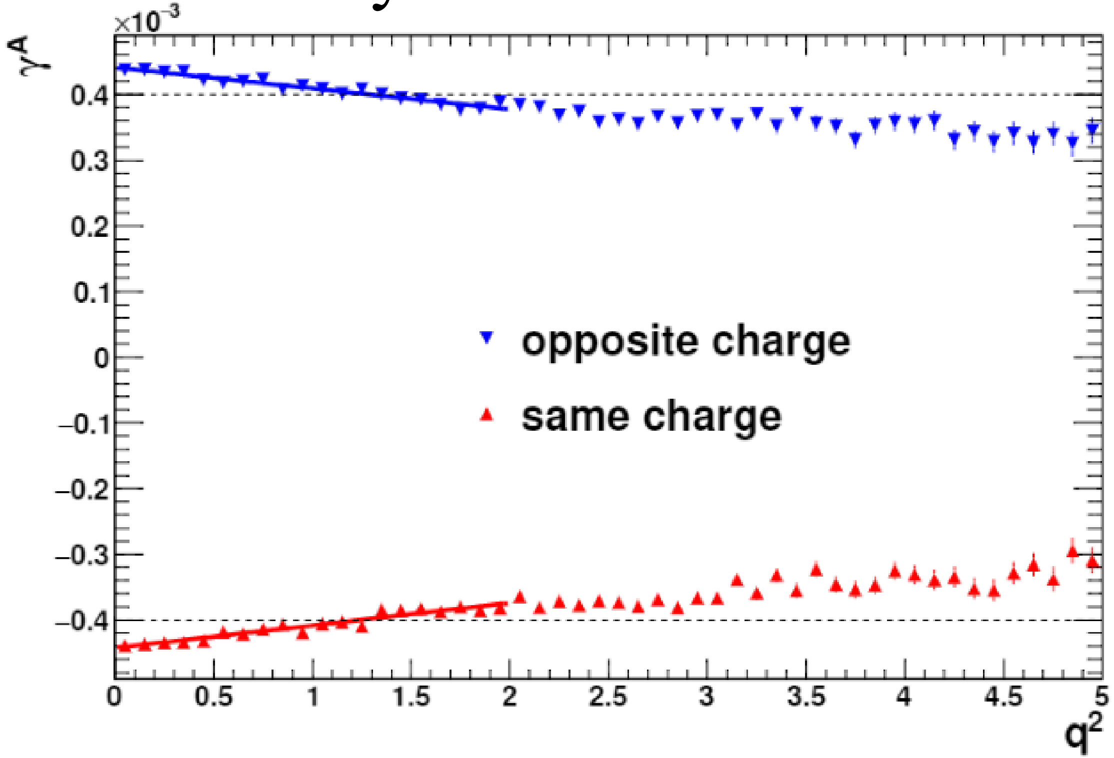
consistent with zero: $(-4.5 \pm 6.7) \times 10^{-4}$ for $N_{\rm part}\Delta\gamma^{\rm A}$ and $(-3.3 \pm 10.6) \times 10^{-4}$ for $N_{\rm part}\Delta\gamma^{\rm observe}/R^{\rm B1(B2)}$.

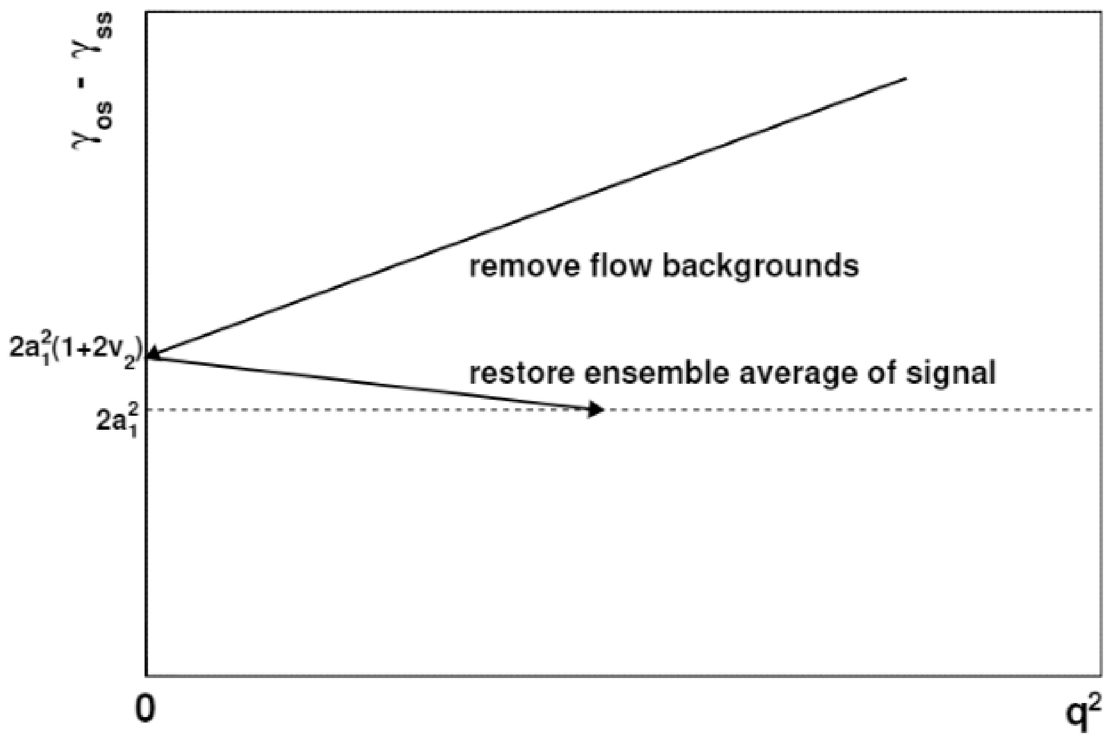
Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001

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

# Artificial effect

Toy model simulation

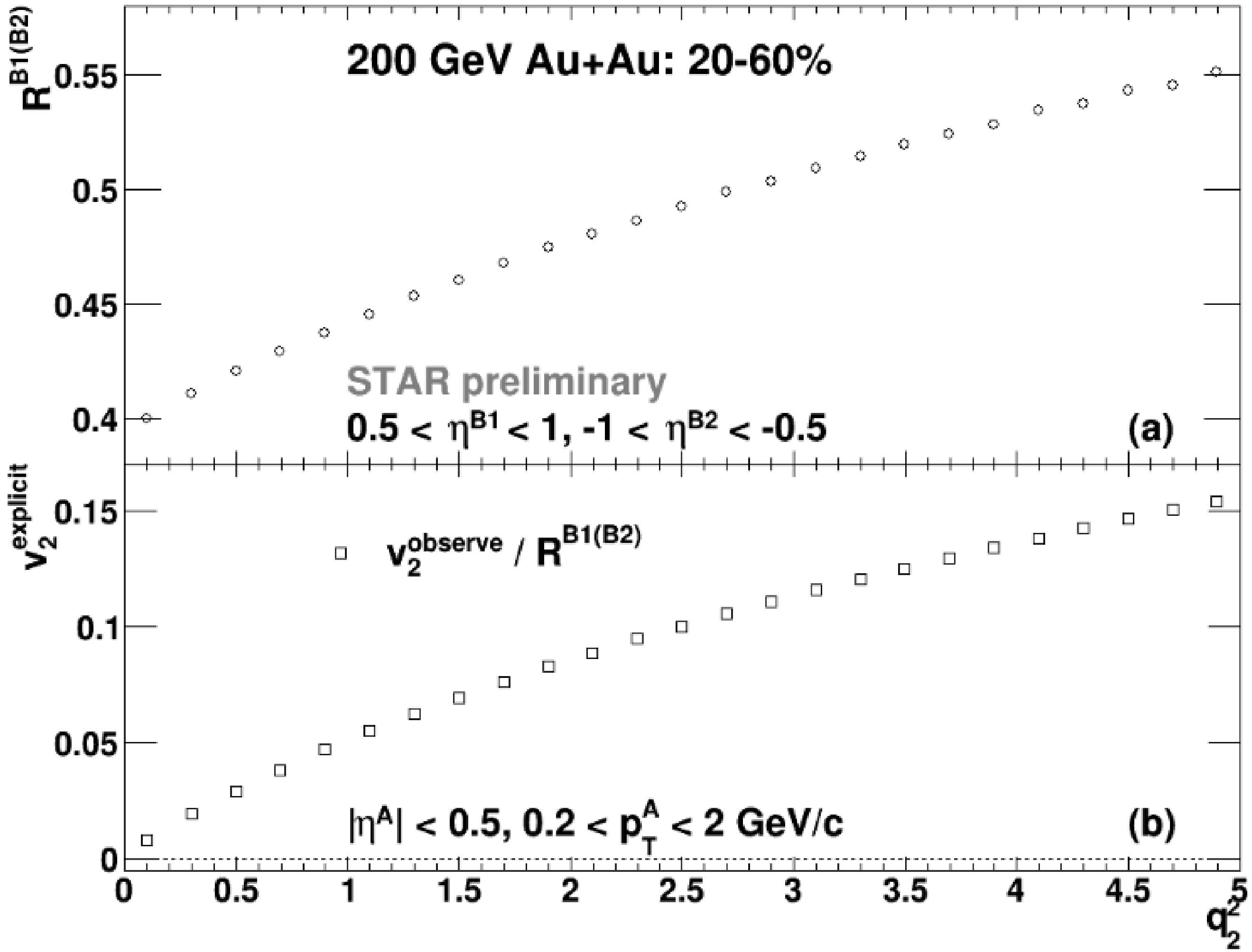


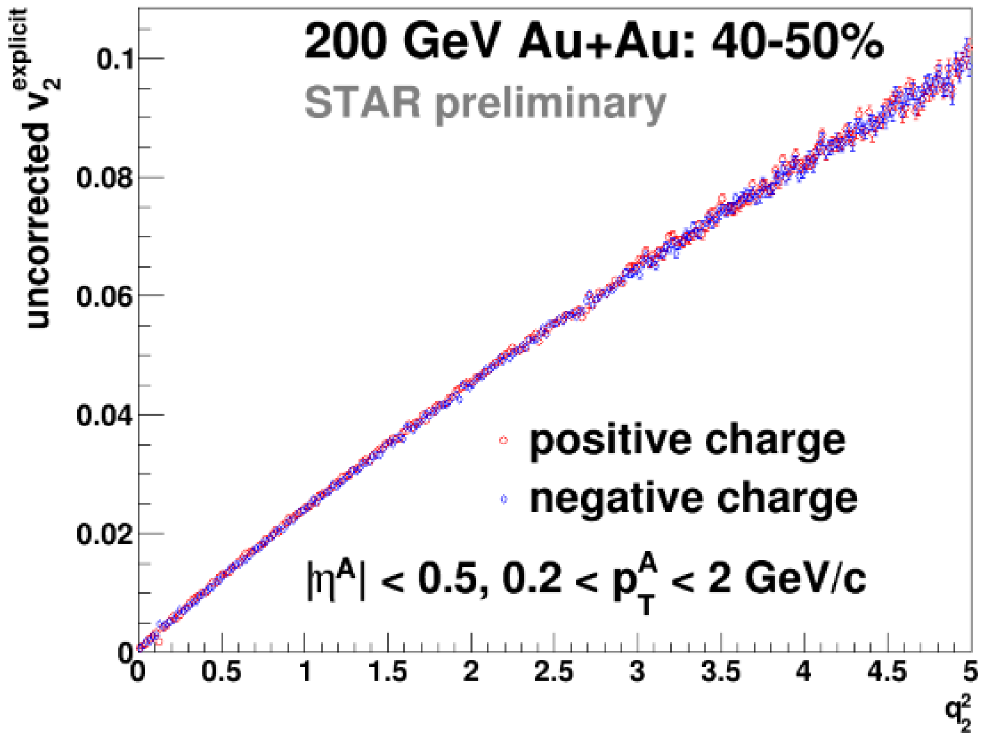

Fufang Wen, Jacob Bryon, Liwen Wen, Gang Wang, Chinese Phys. C 42(1) (2018) 014001

$\Delta\gamma|_{q=0}$ 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



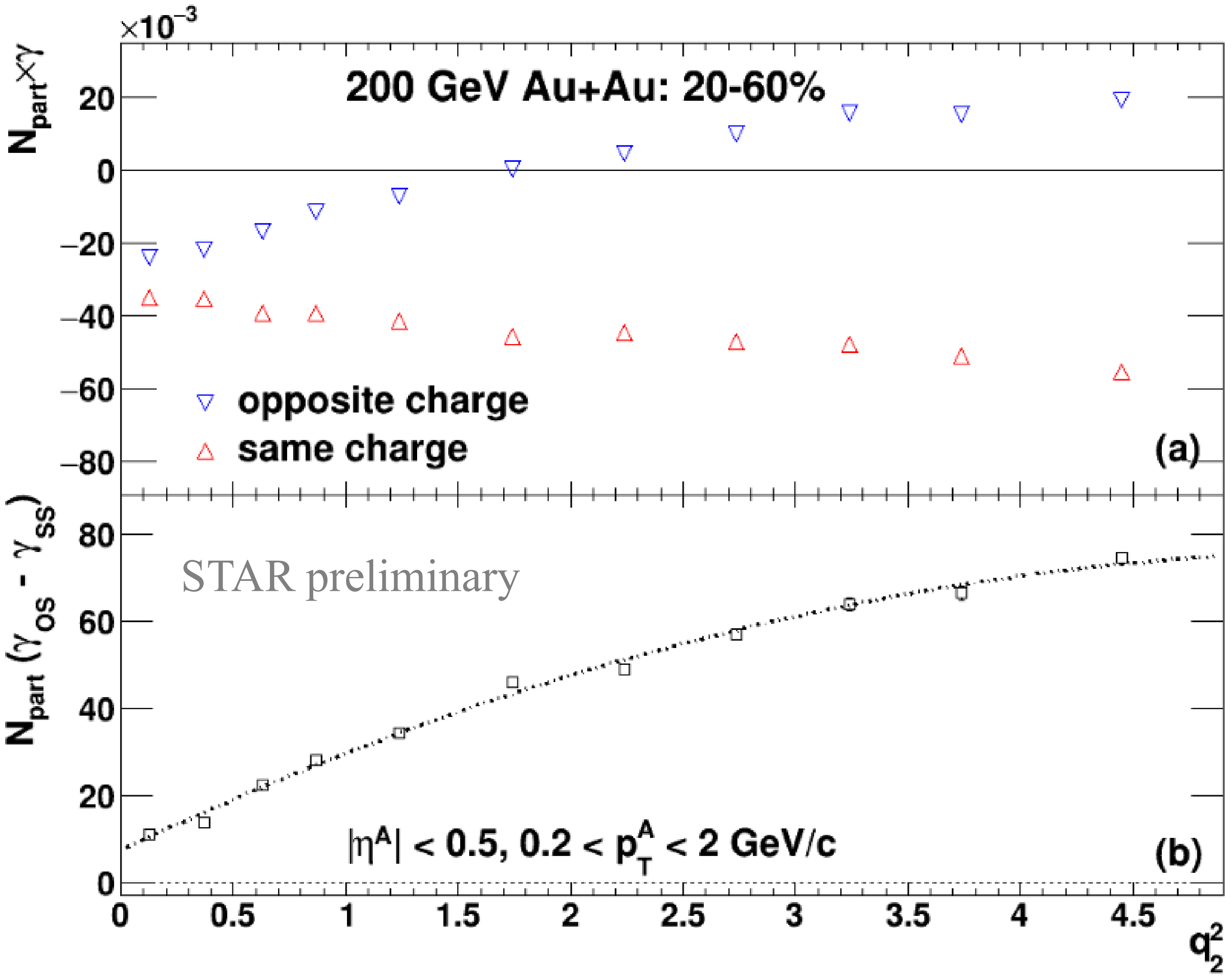

$$R^{B1(B2)} \equiv \sqrt{\langle \cos[2(\Psi_{EP}^{B1} - \Psi_{EP}^{B2})] \rangle_E}.$$




$q_2$ 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.

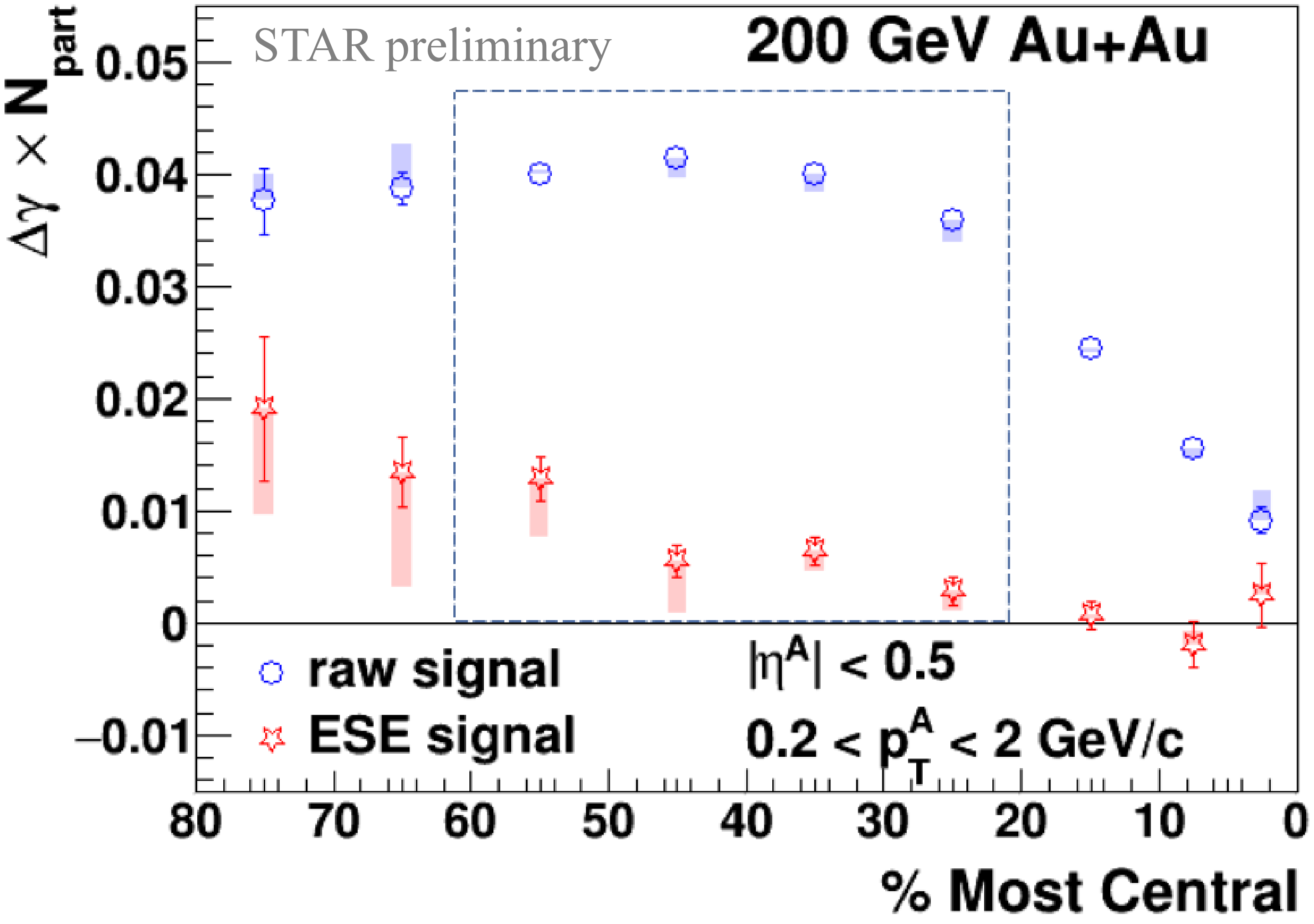
# $\gamma_{112}$: 200 GeV Au+Au




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

- 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 $\gamma_{123} = \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\psi_{RP})\rangle$

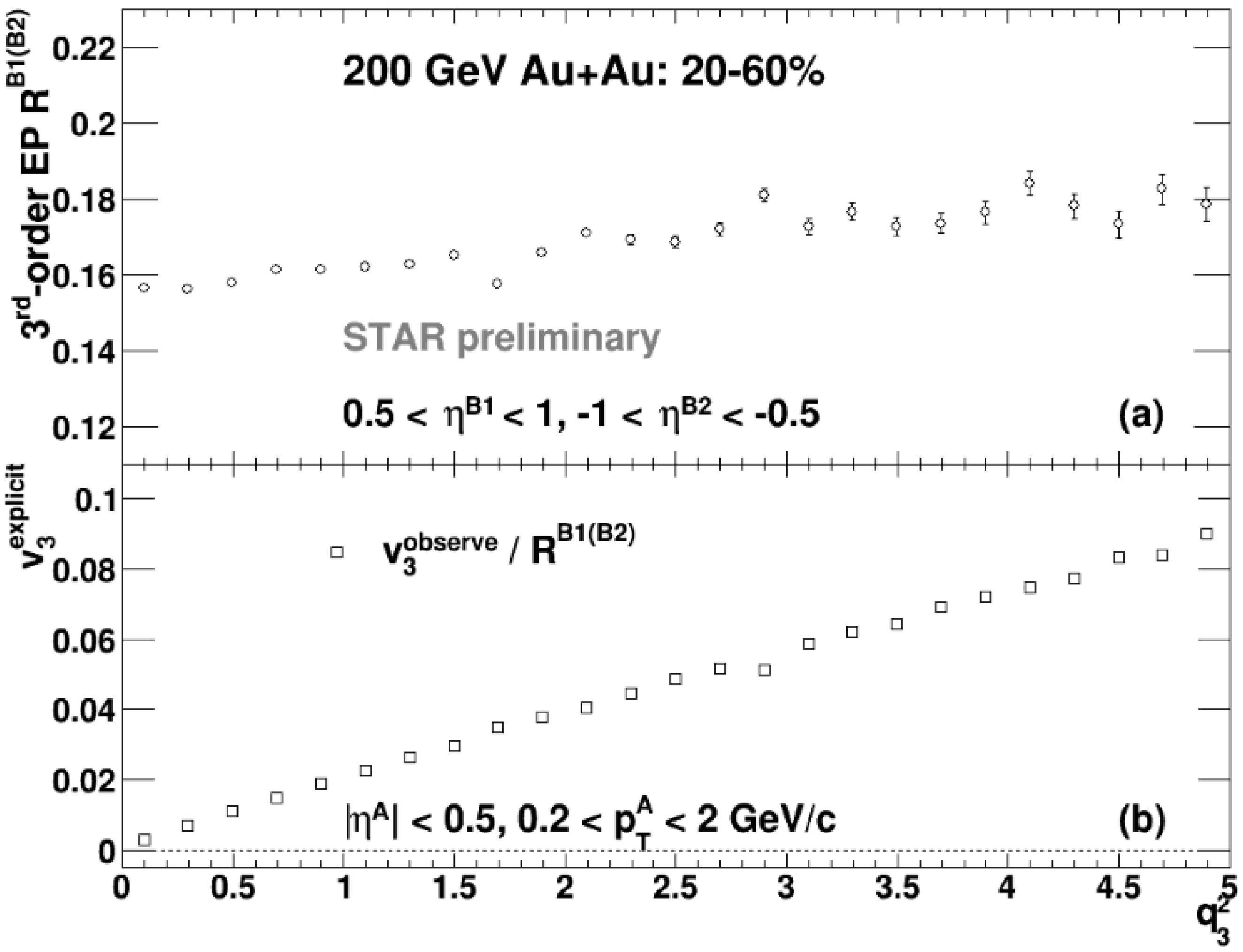
# Centrality dependence




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




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

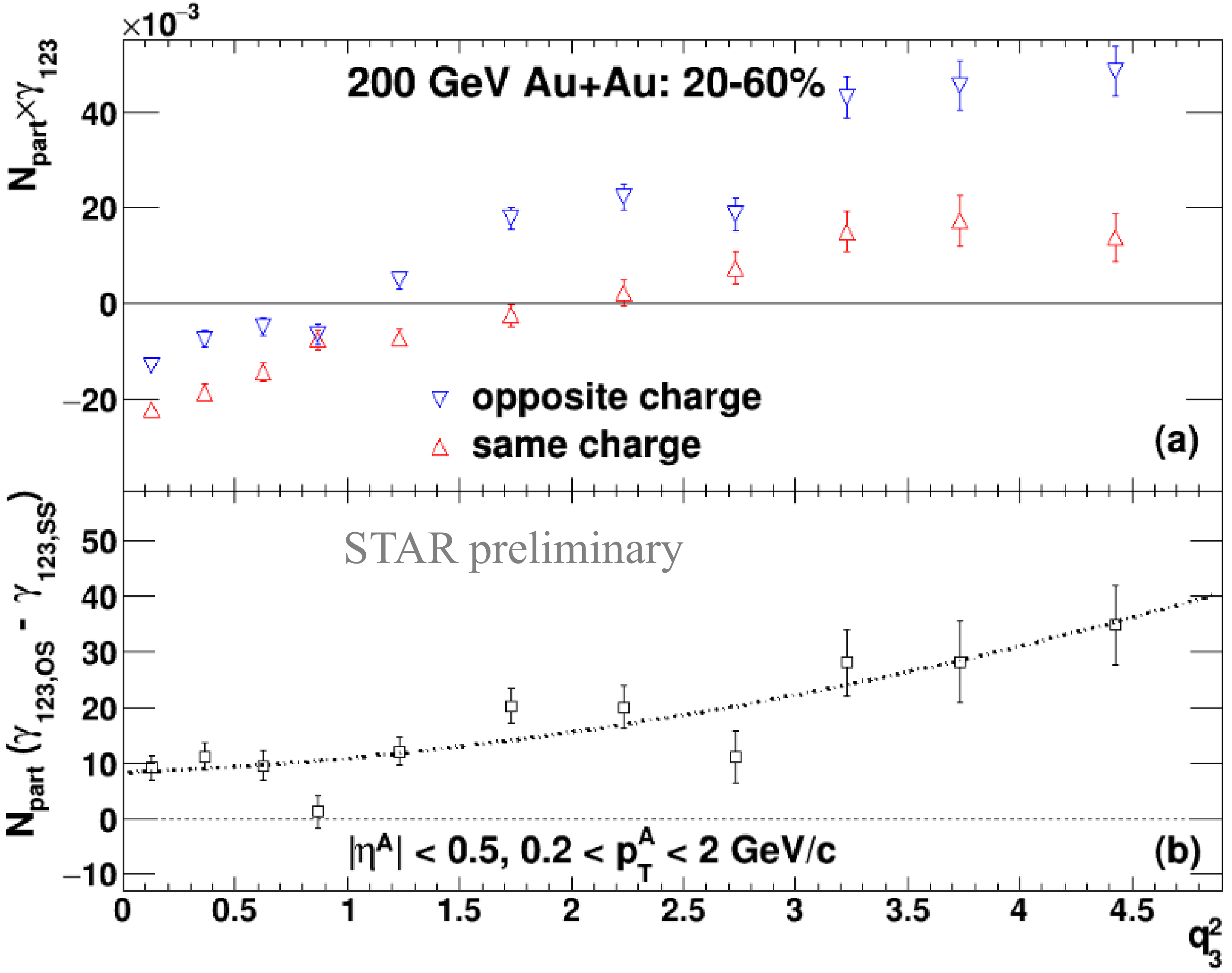
$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

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

3

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

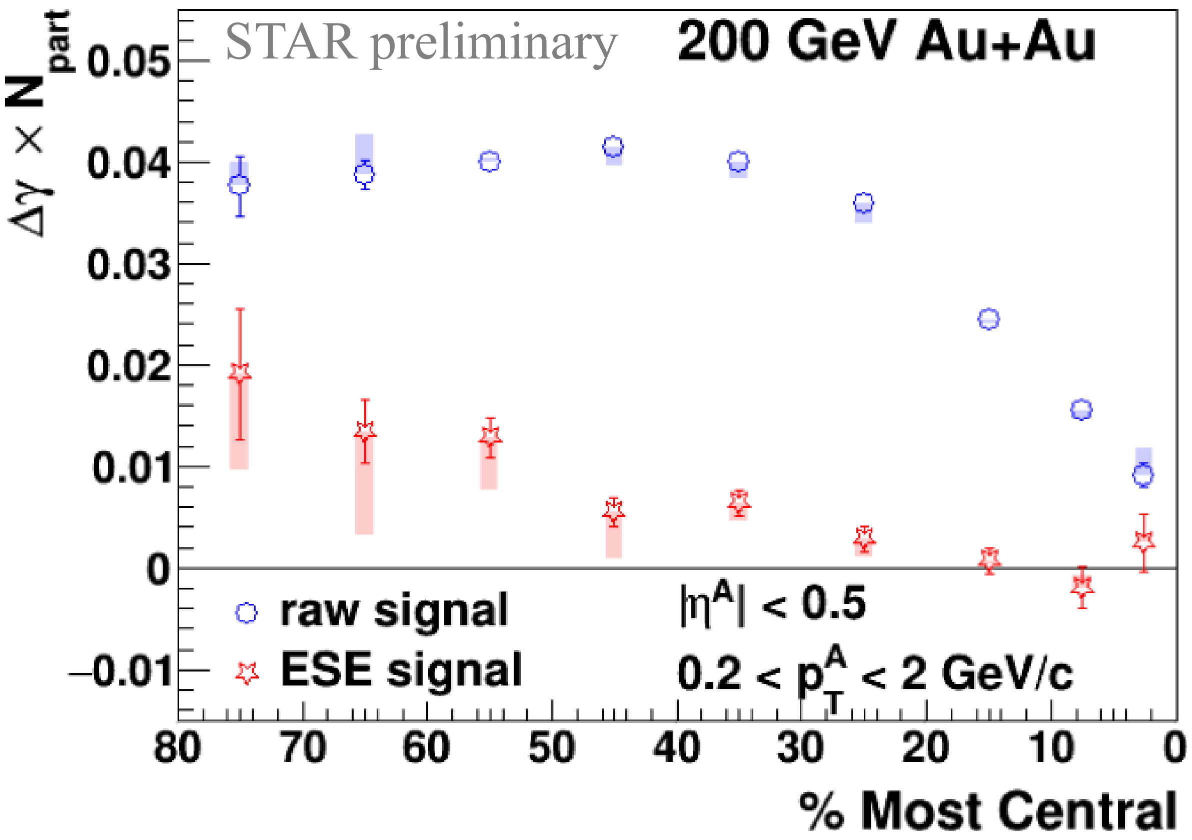
# $\gamma_{123}$: 200 GeV Au+Au

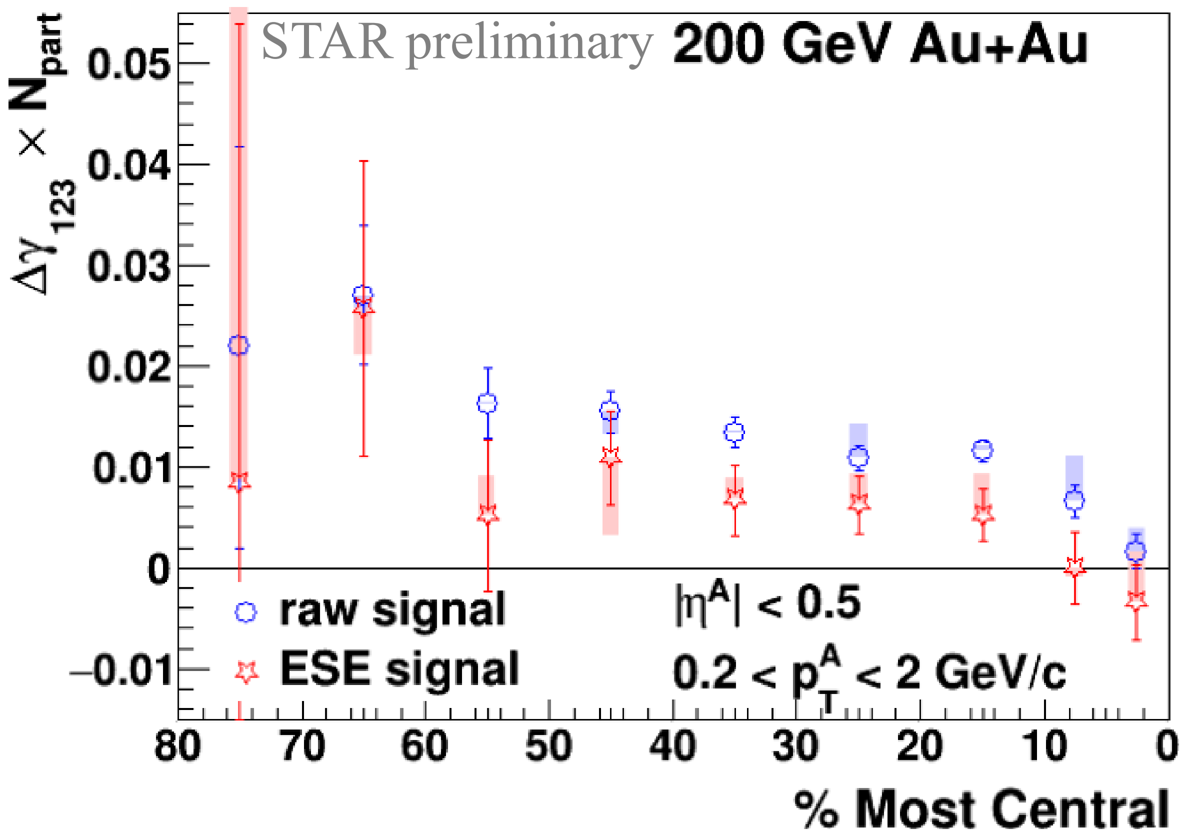



$\langle N_{part} \rangle$ for 20-60% collisions is roughly 98.

- $\gamma_{123}$ 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 $\gamma_{112}$ and $\gamma_{123}$ are consistent with each other. $(7.51 \pm 0.75)*10^{-3}$ for $\gamma_{112}$
- Should they scale with $v_2$ and $v_3$, instead of being the same? (if they are due to implicit $v_2$ or $v_3$)

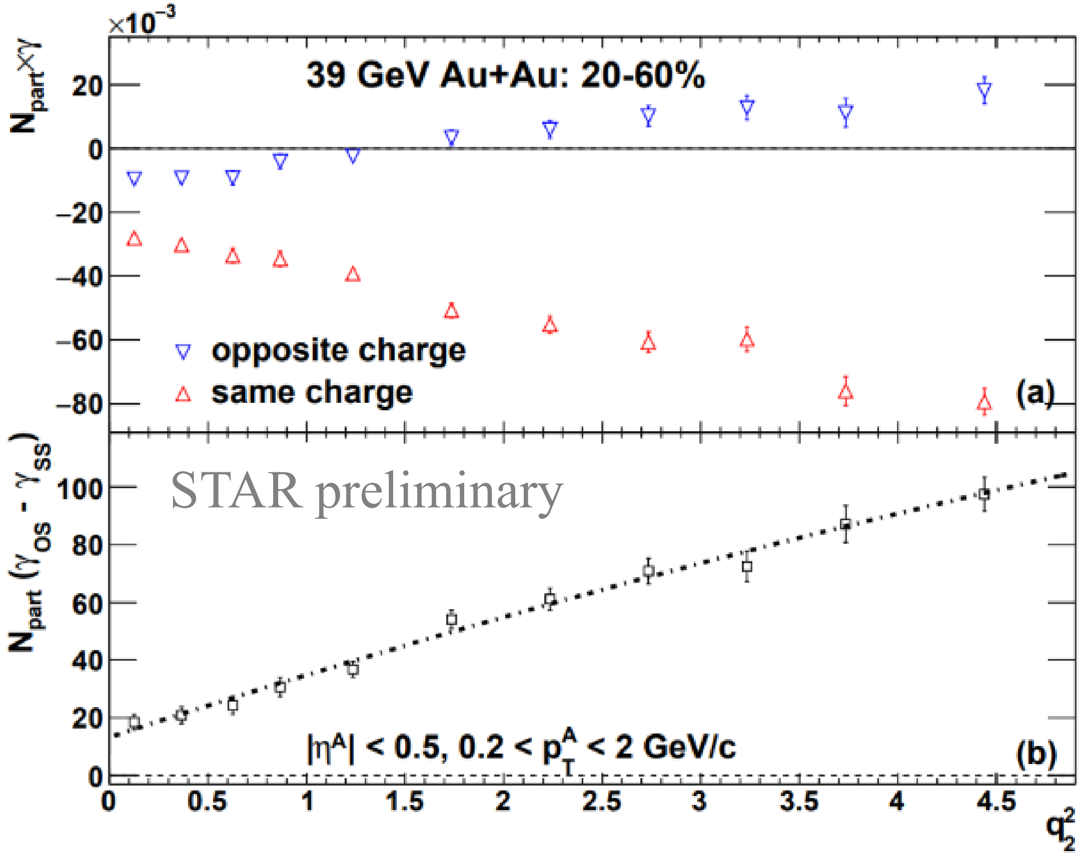
# Centrality dependence

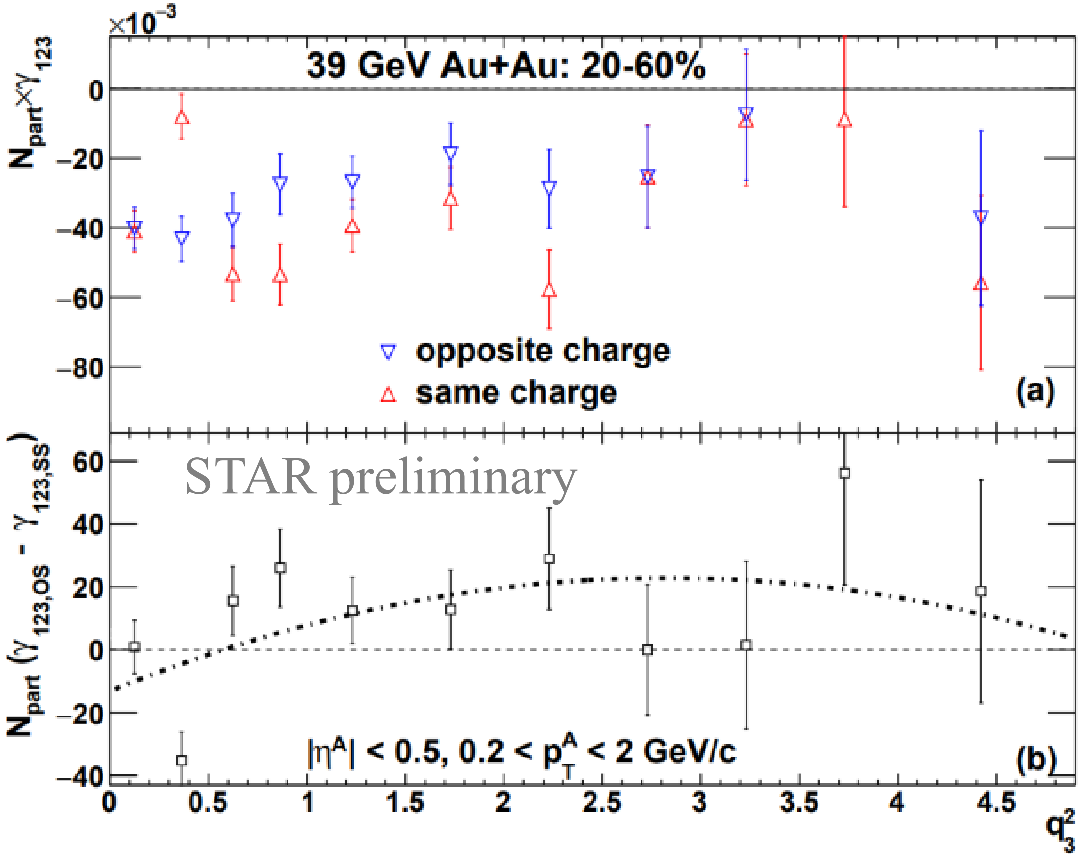



- The raw signals are different between $\gamma_{112}$ and $\gamma_{123.}$ (a factor of 3)
- The ESE signals are, however, similar for $\gamma_{112}$ and $\gamma_{123}$.
- Origin of these finite intercepts: residue nonflow? implicit $v_2$? CME?

# $\gamma_{112}$ and $\gamma_{123}$: 39 GeV Au+Au



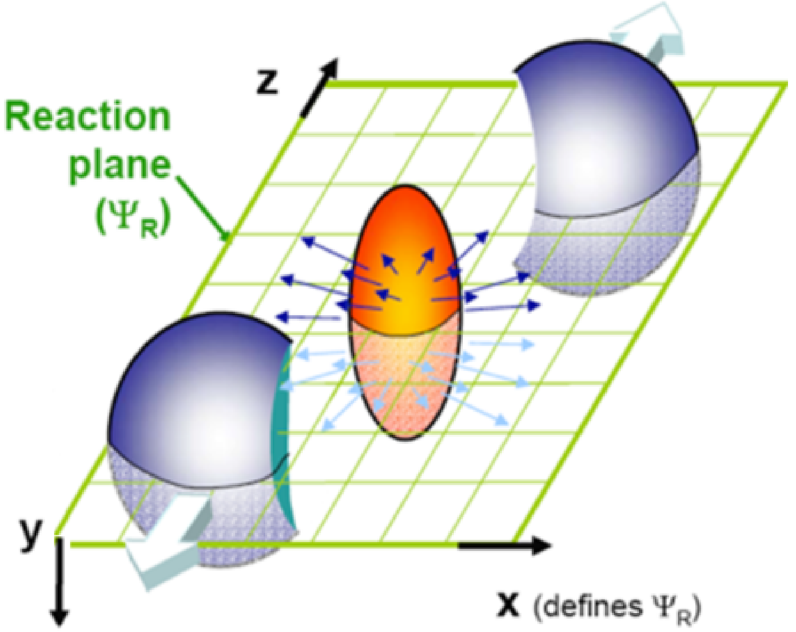

- $\gamma_{112}$: $(1.319 \pm 0.223)*10^{-2}$, 6σ effect
- $\gamma_{123}$: $(-1.316 \pm 0.756)*10^{-2}$, consistent with zero
- This year, 27 GeV data will provide a chance to confirm this.
- The newly installed EPD will help further suppress nonflow.

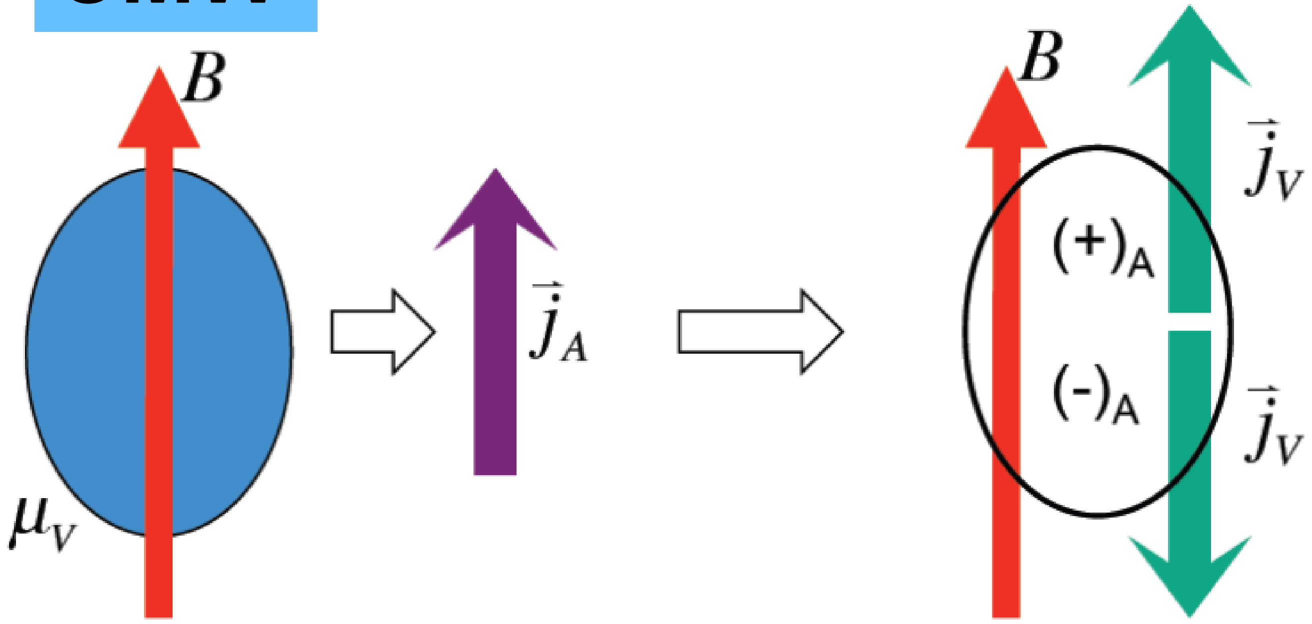
# Summary on CME

- Nonflow backgrounds are severe in small systems
  - suppressed with $\eta$ gap between EP and particles of interest
- Apparent-anisotropy background seems to be the major contribution
  - $\kappa_{112}$ and $\kappa_{123}$ are close to each other
  - ESE shows small but finite intercepts for both $\gamma_{112}$ and $\gamma_{123}$
  - 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)



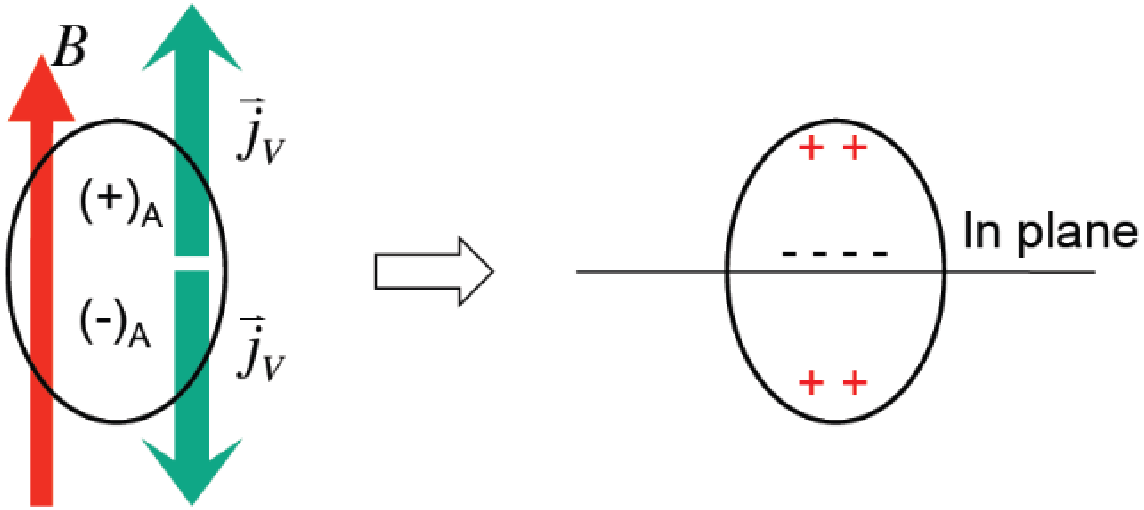

$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect

Chiral Magnetic Effect

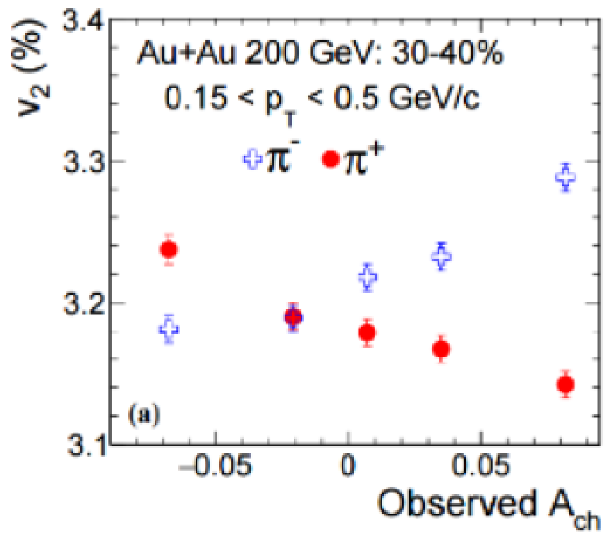
CSE + CME → Chiral Magnetic Wave:
collective excitation
signature of chiral symmetry restoration

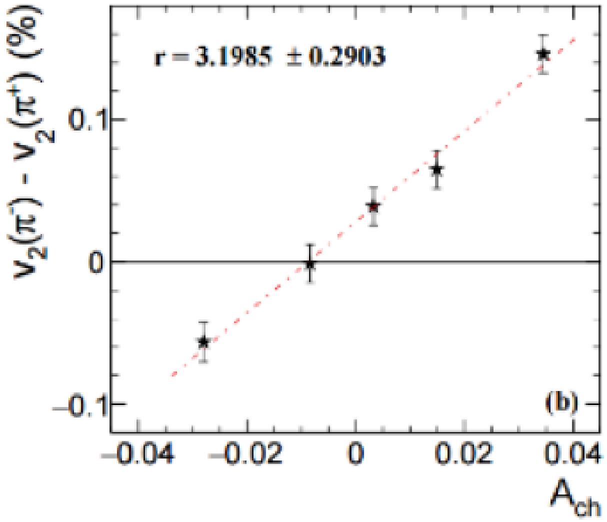
# Observable




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

STAR, PRL 114 (2015) 252302




quadrupole moment

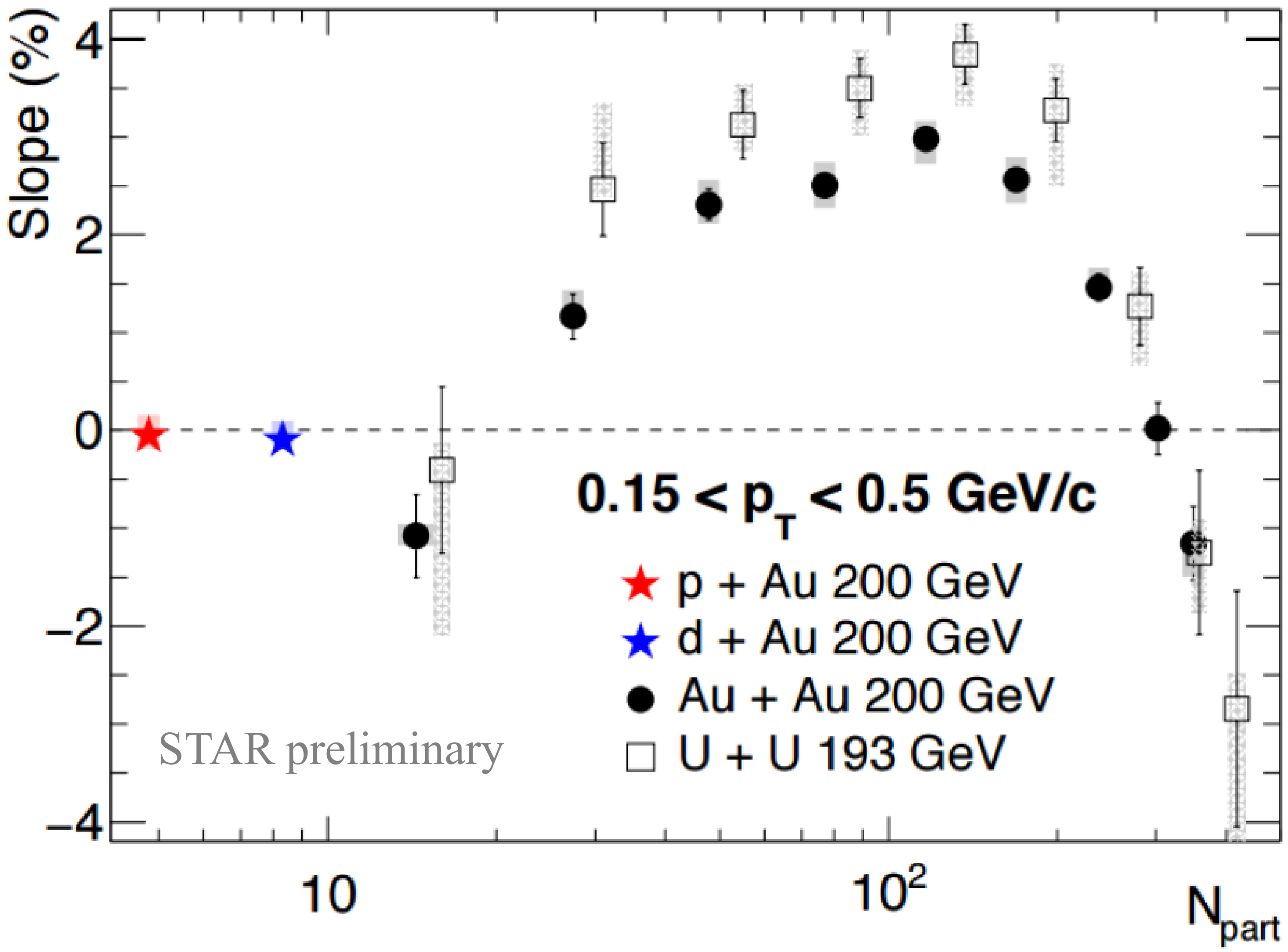
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{\text{ch}}$ ,

net charge density

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

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

# Different collision systems



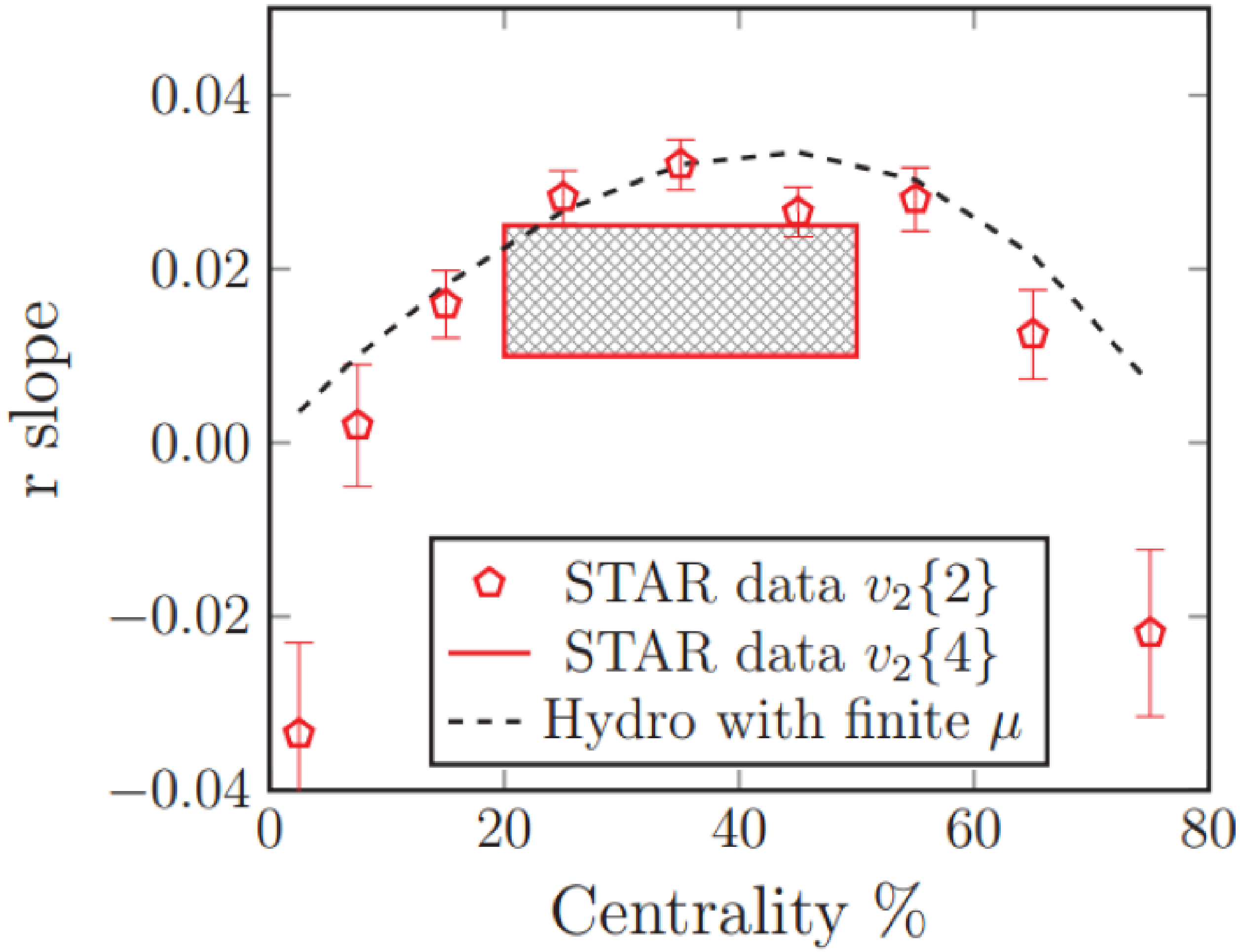

Nonflow effects are largely cancelled by the $v_2$ difference.

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

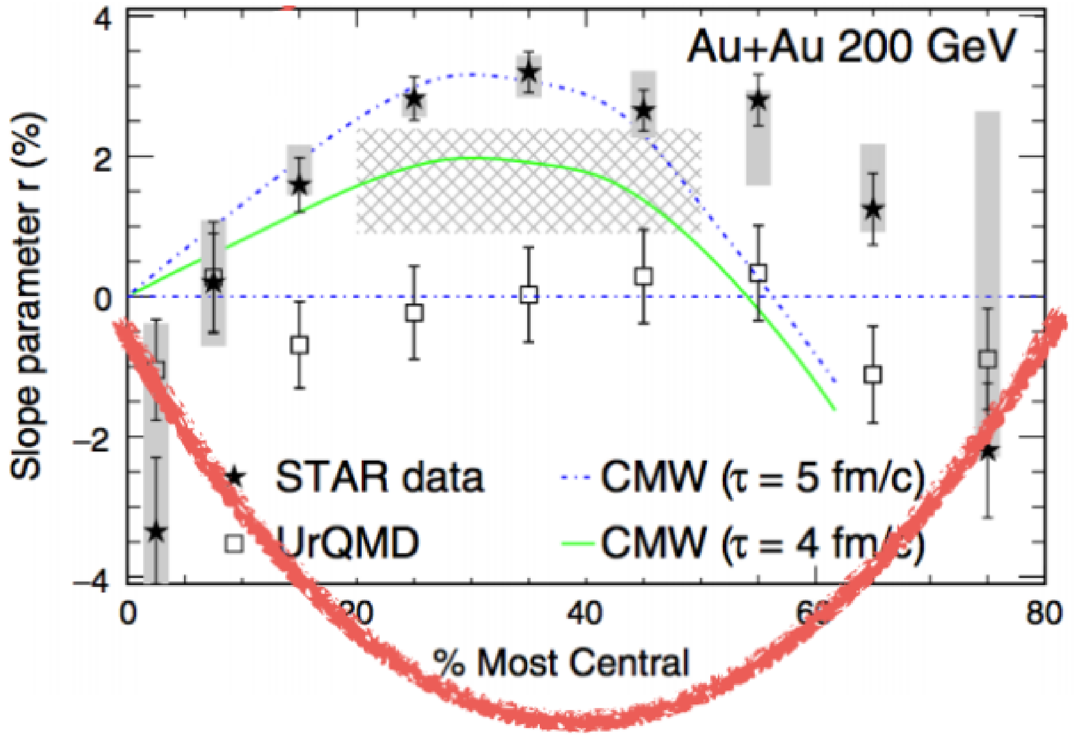
Larger signals in U+U than Au+Au for mid-central or mid-peripheral events (in line with the magnetic field difference?)

The TPC event plane was used in these analyses.

# Alternative interpretation: hydro+isospin



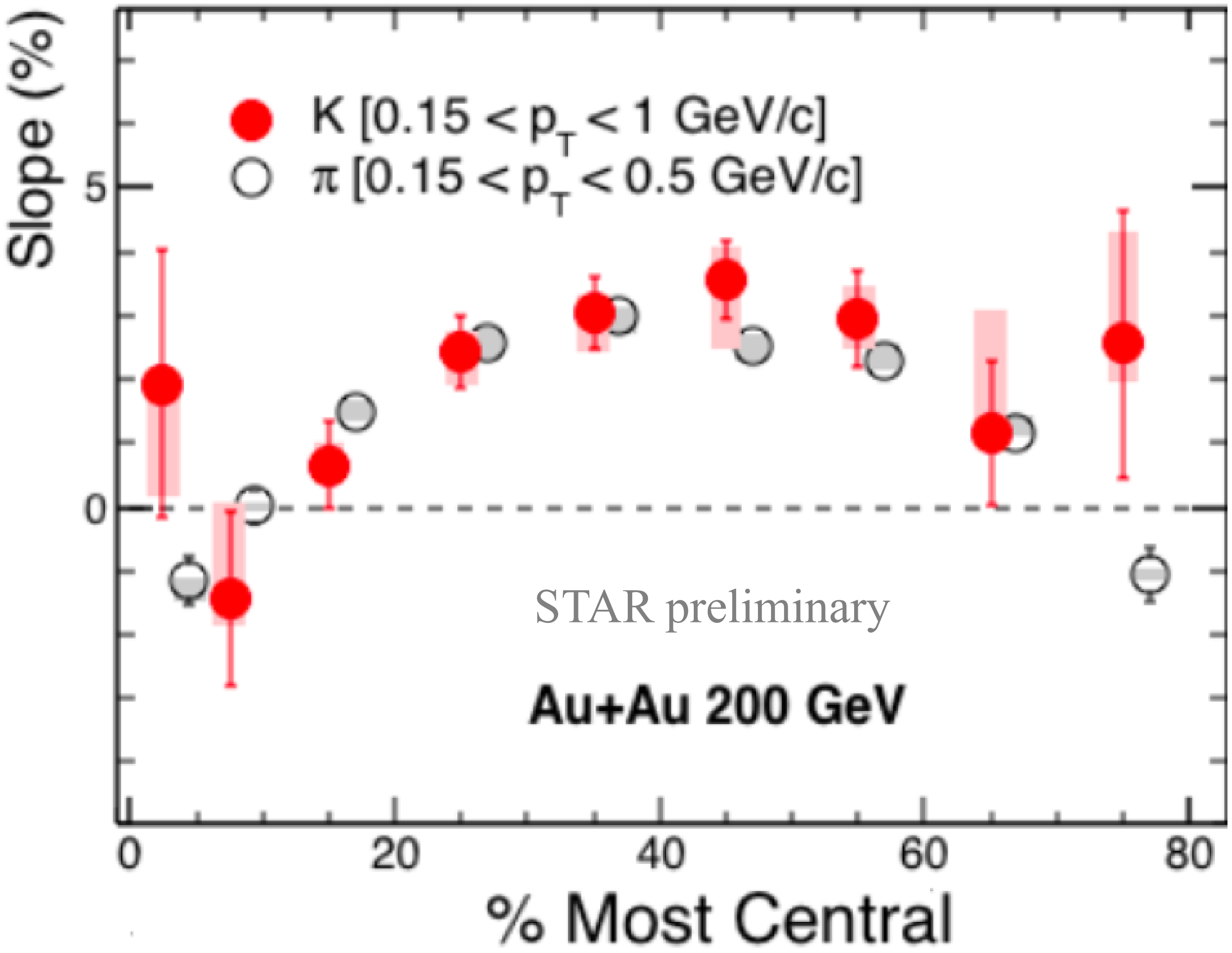

Y. Hatta et al. NPA 947 (2016) 155




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

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

# kaon $\Delta v_2$ slope

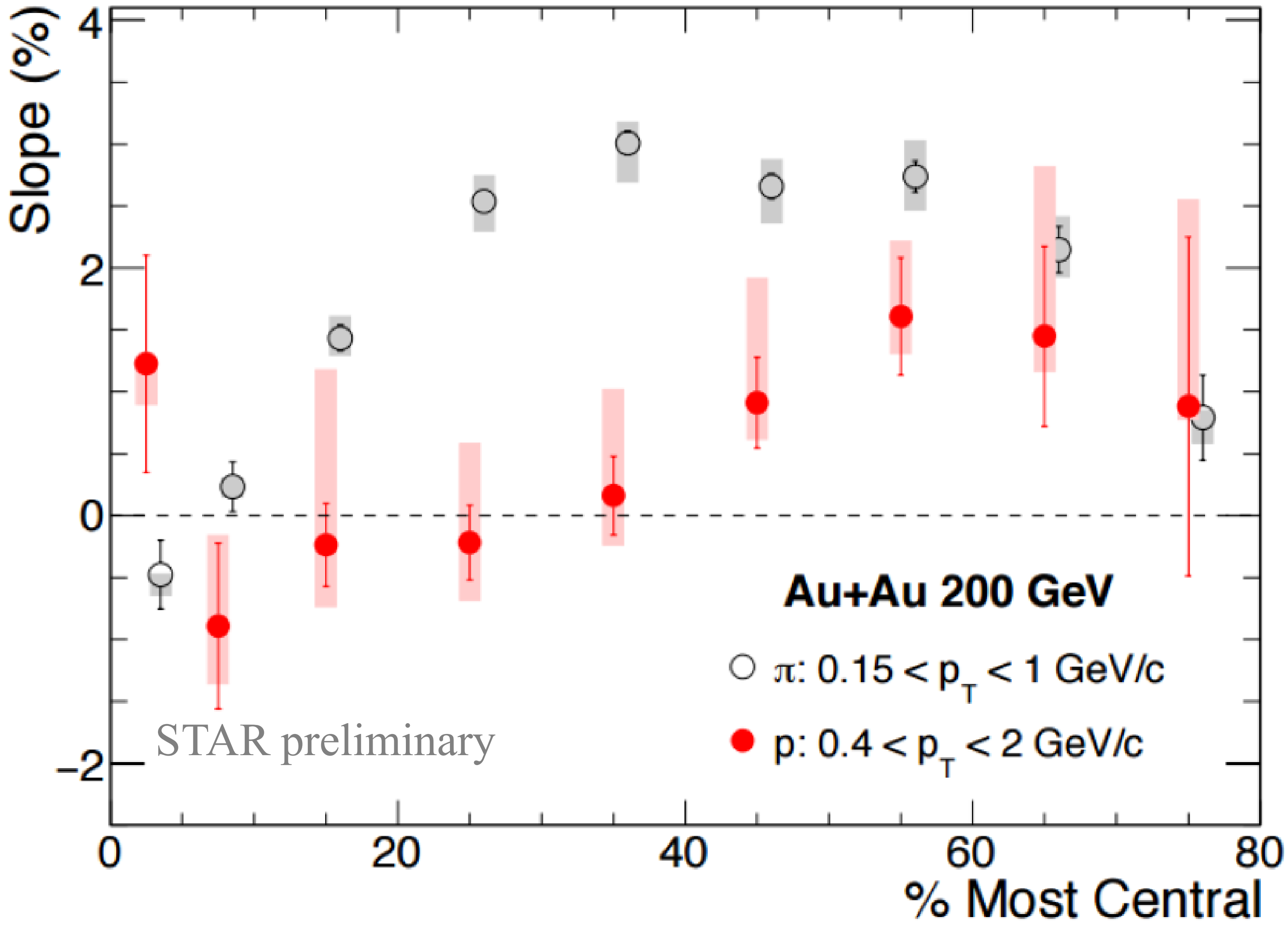



Hydrodynamics study (no CMW): kaon slope should be opposite to $\pi$ slope with larger magnitude, since

$$v_2(\boldsymbol{\pi}^+) < v_2(\boldsymbol{\pi}^-)$$
$$v_2(\mathbf{K}^+) > v_2(\mathbf{K}^-)$$

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

# proton $\Delta v_2$ slope



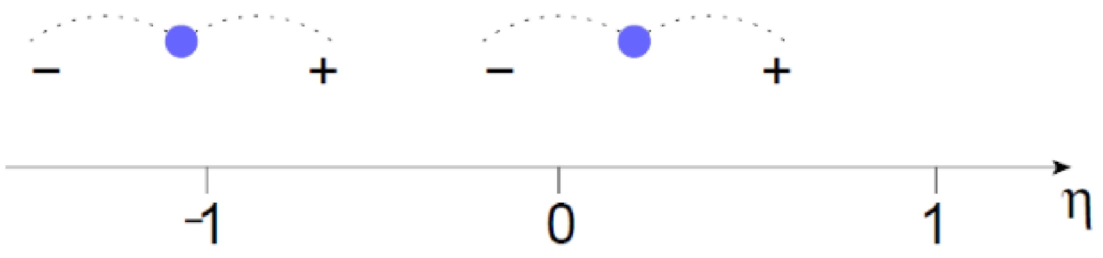

Hydrodynamics study (no CMW): proton slope should be opposite to π slope with larger magnitude, since

$v_2(\boldsymbol{\pi}^+) < v_2(\boldsymbol{\pi}^-)$

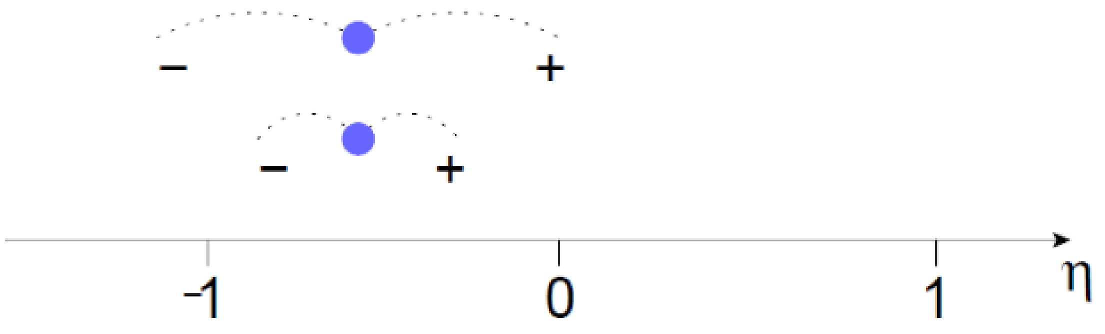
$v_2(\mathbf{p}) > v_2(\mathbf{p\text{-}bar})$

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.

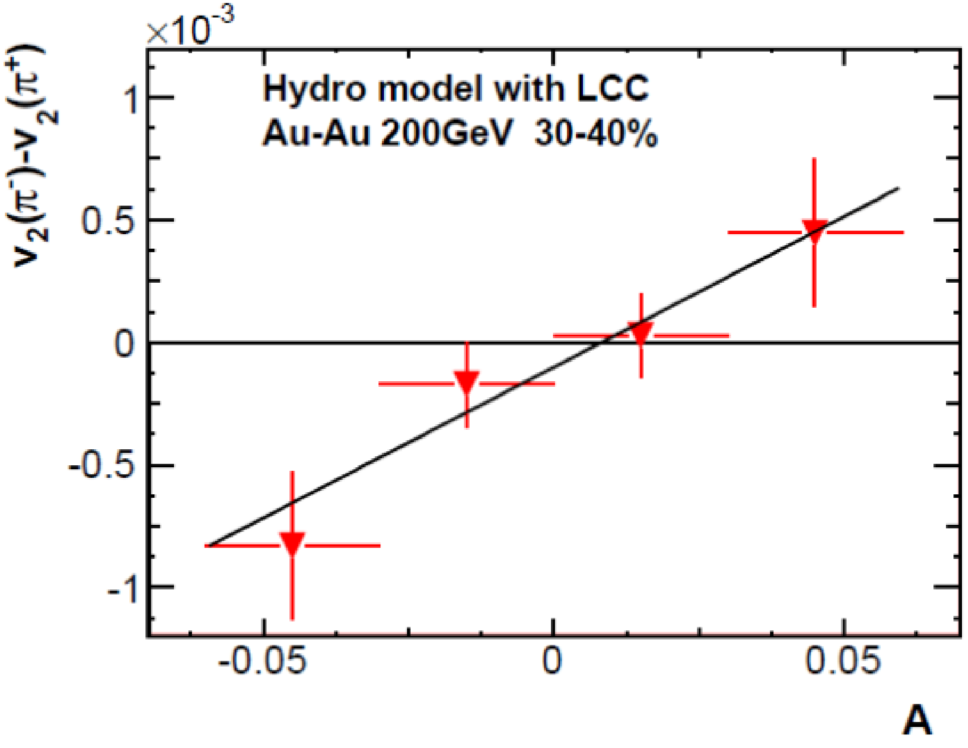
# Alternative interpretation: LCC




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 $p_T$.

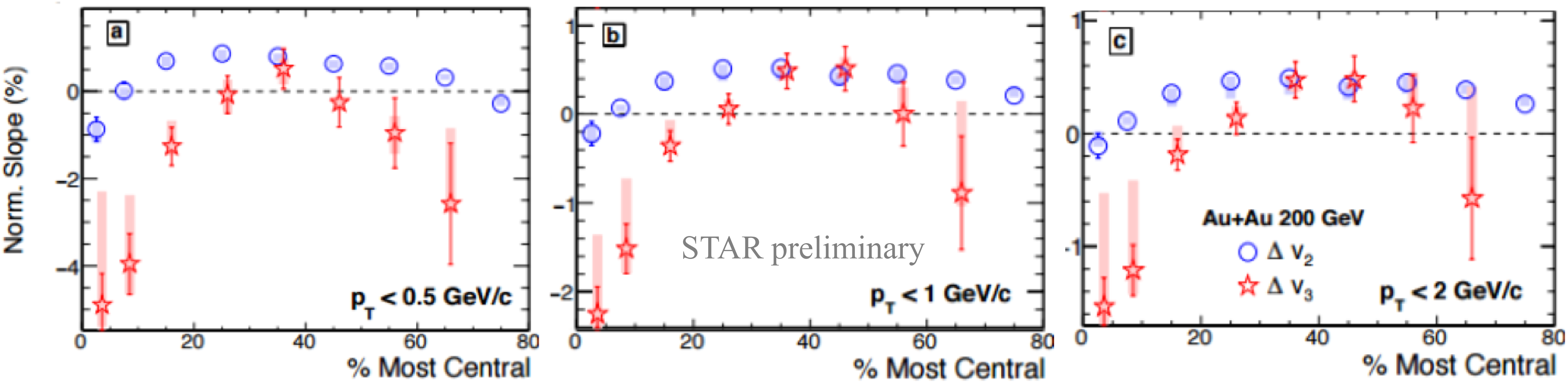



A. Bzdak and P. Bozek, Phys. Lett. B 726 (2013) 239

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.

# $\Delta v_3$ slope

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



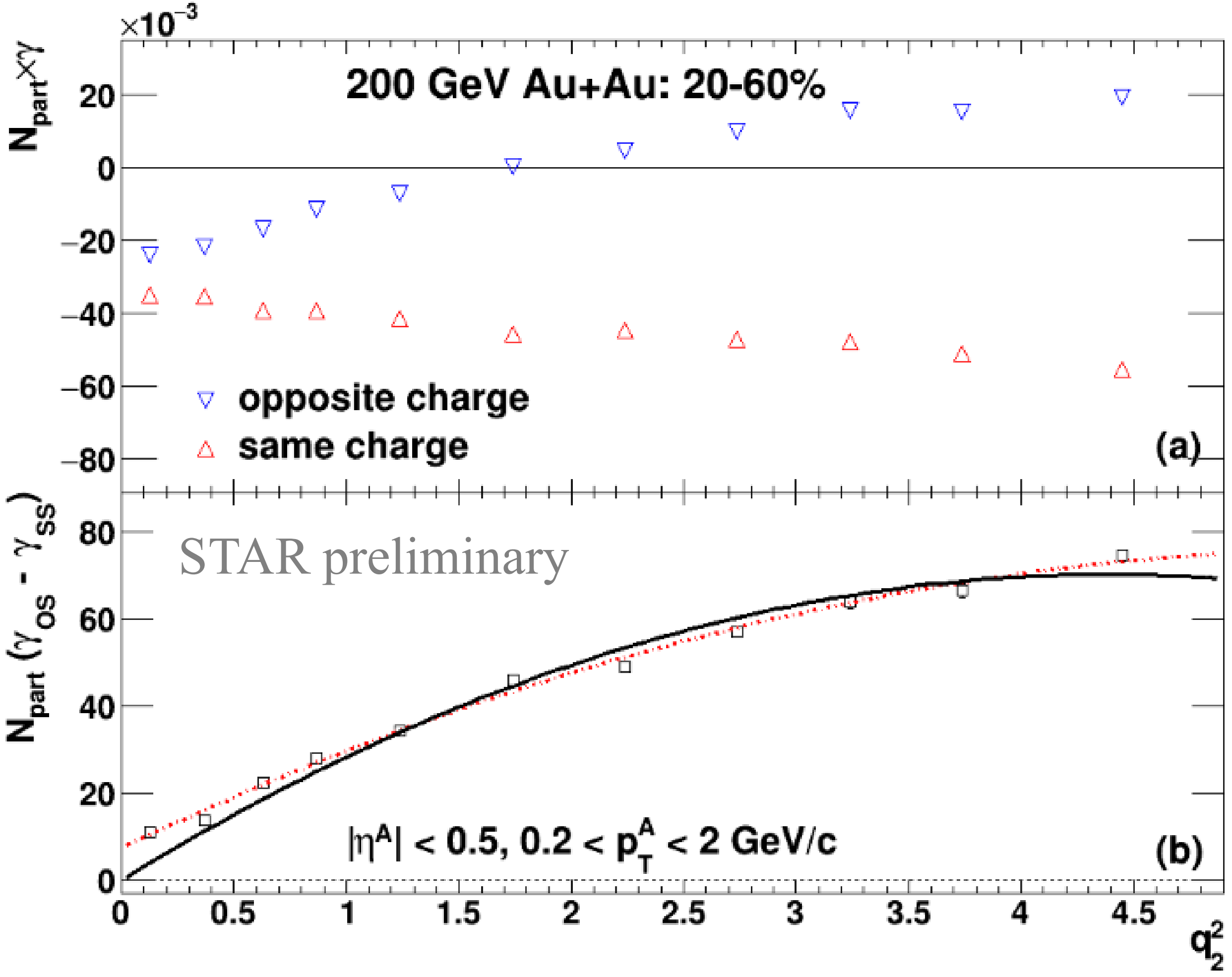

Local charge conservation may introduce $A_{ch}$ dependence of $\Delta v_2(\pi)$. Then one should see **Norm.$\Delta v_3$ ~ Norm.$\Delta v_2$**
(Bzak & Bozek PLB 726(2013)239).
STAR measurement: **Norm.$\Delta v_3$ < Norm.$\Delta v_2$** at low $p_T$. Closer at high $p_T$.
LCC mechanism alone cannot explain data.

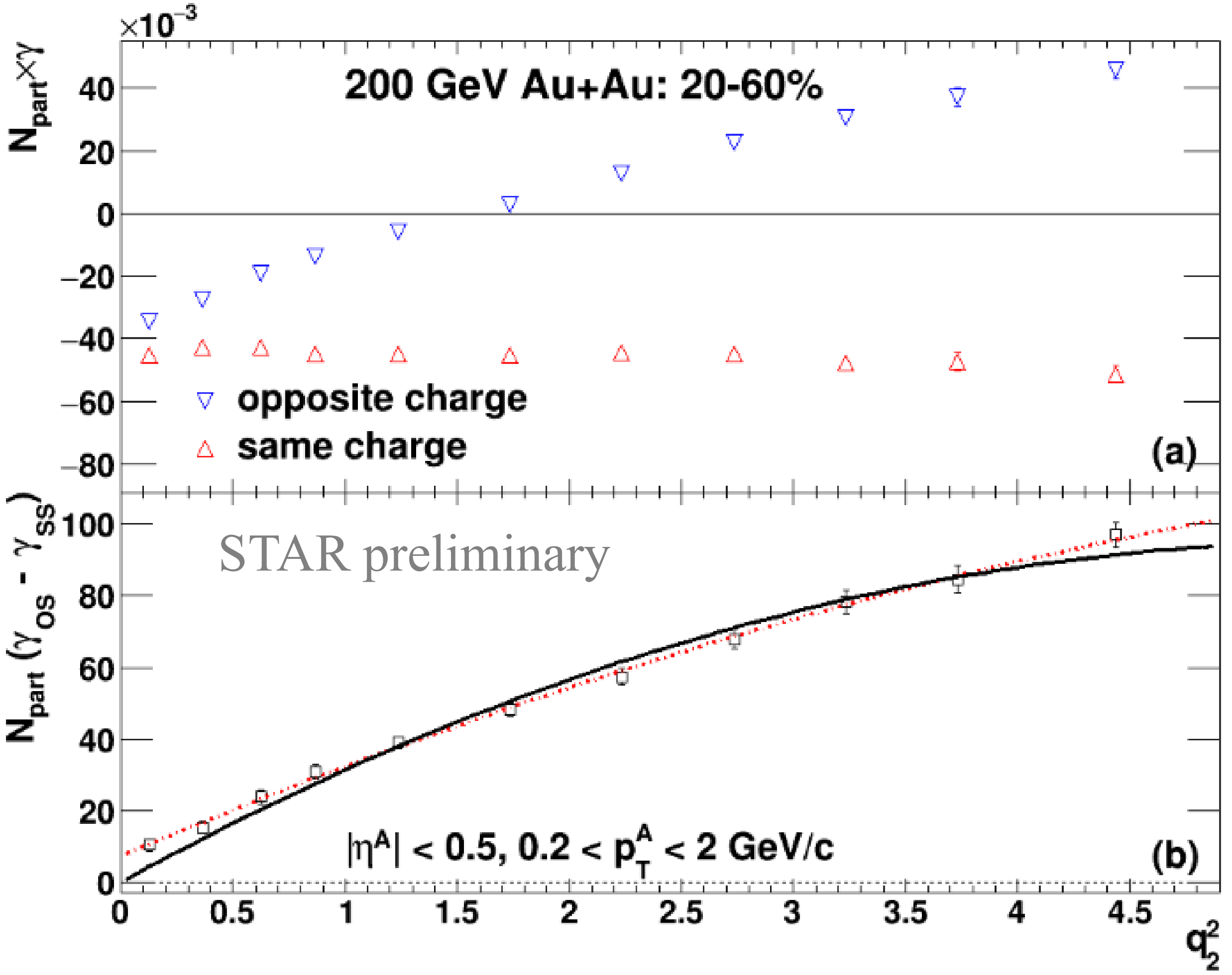
# Summary on CMW

- 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.$\Delta v_2$
- There is room for CMW.

# Backup slides

# $\gamma_{112}$: 200 GeV Au+Au

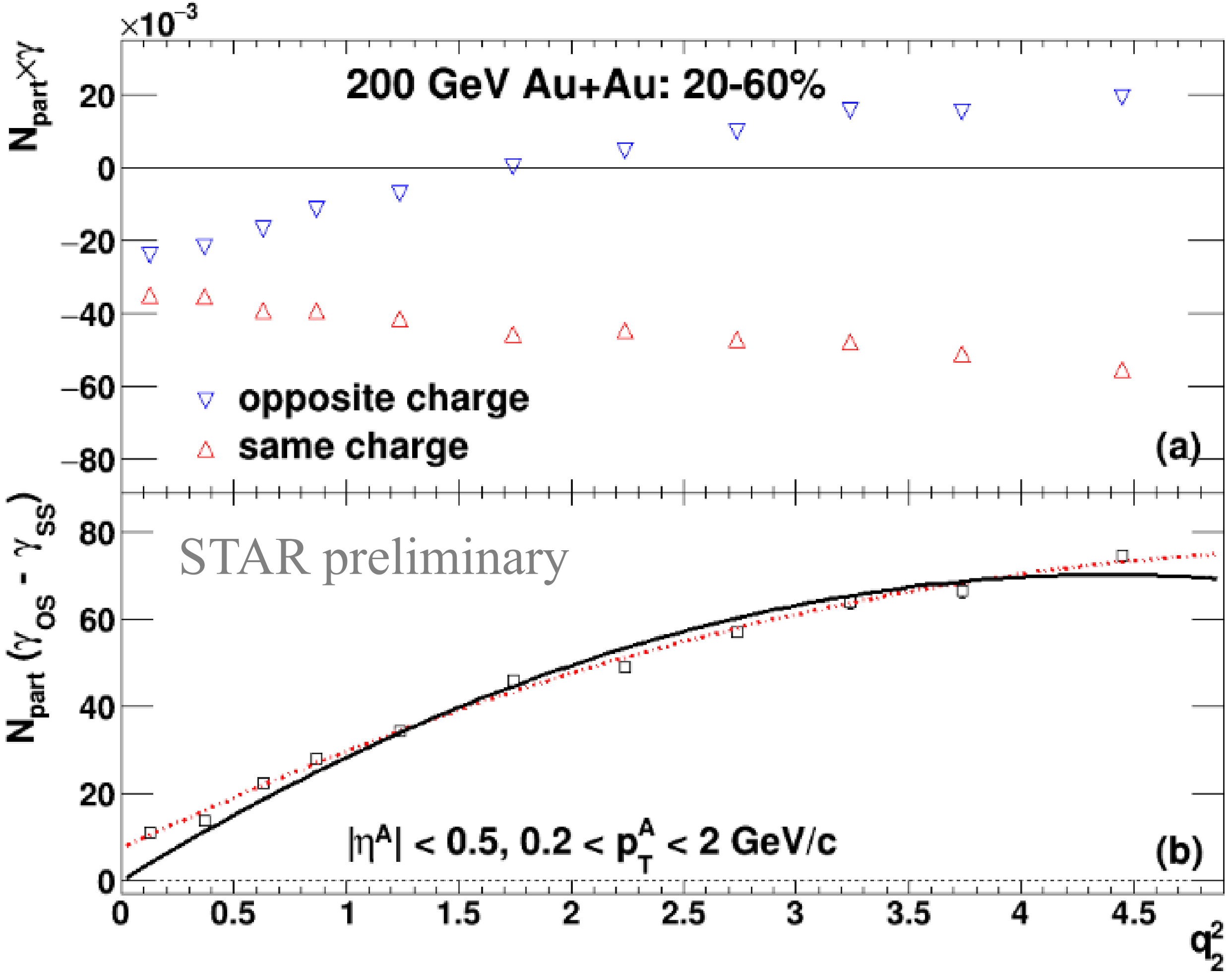


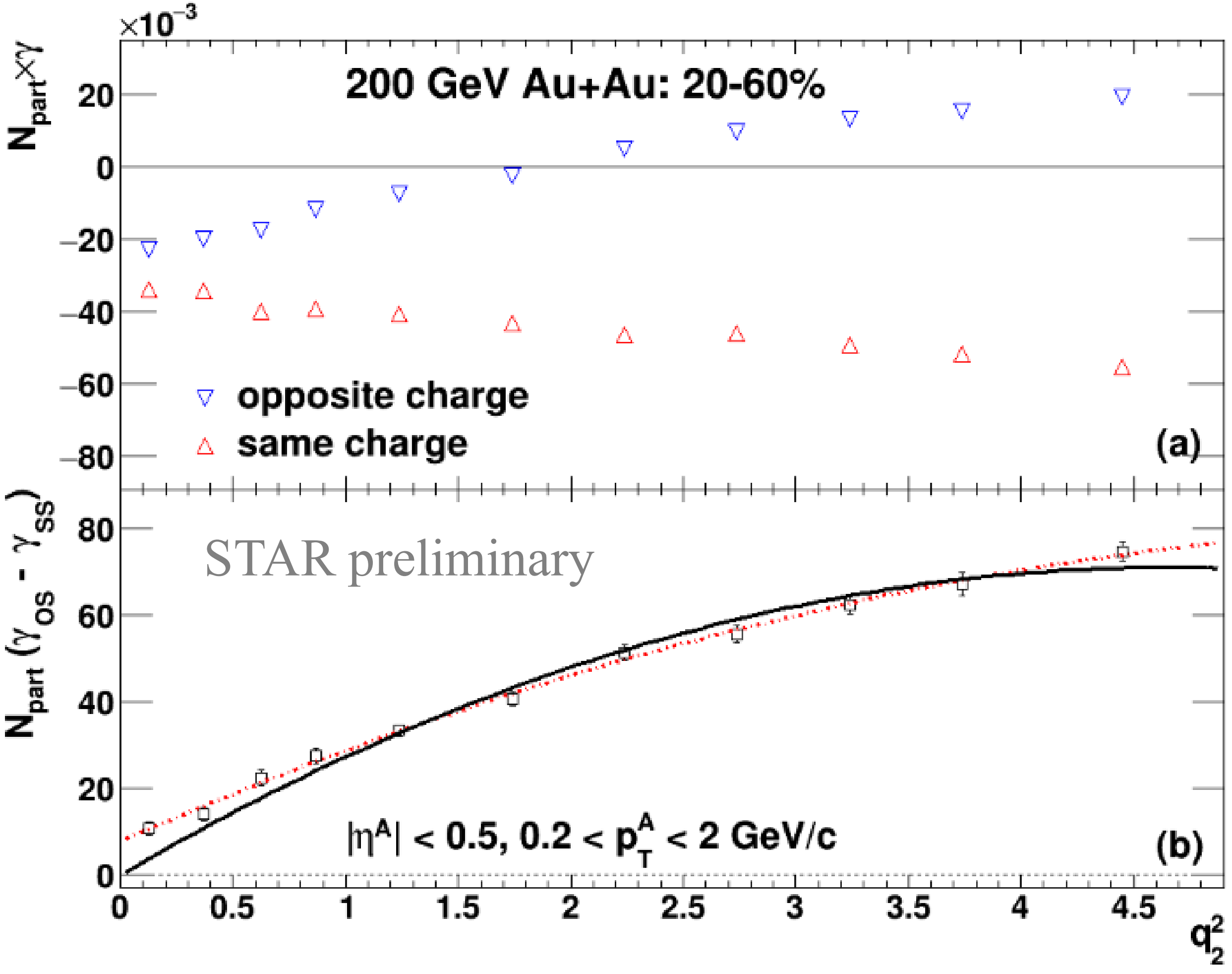




**Whole** multiplicity: $(7.51 \pm 0.75)*10^{-3}$  **Half** multiplicity: $(7.32 \pm 1.37)*10^{-3}$

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

# $\gamma_{112}$: 200 GeV Au+Au



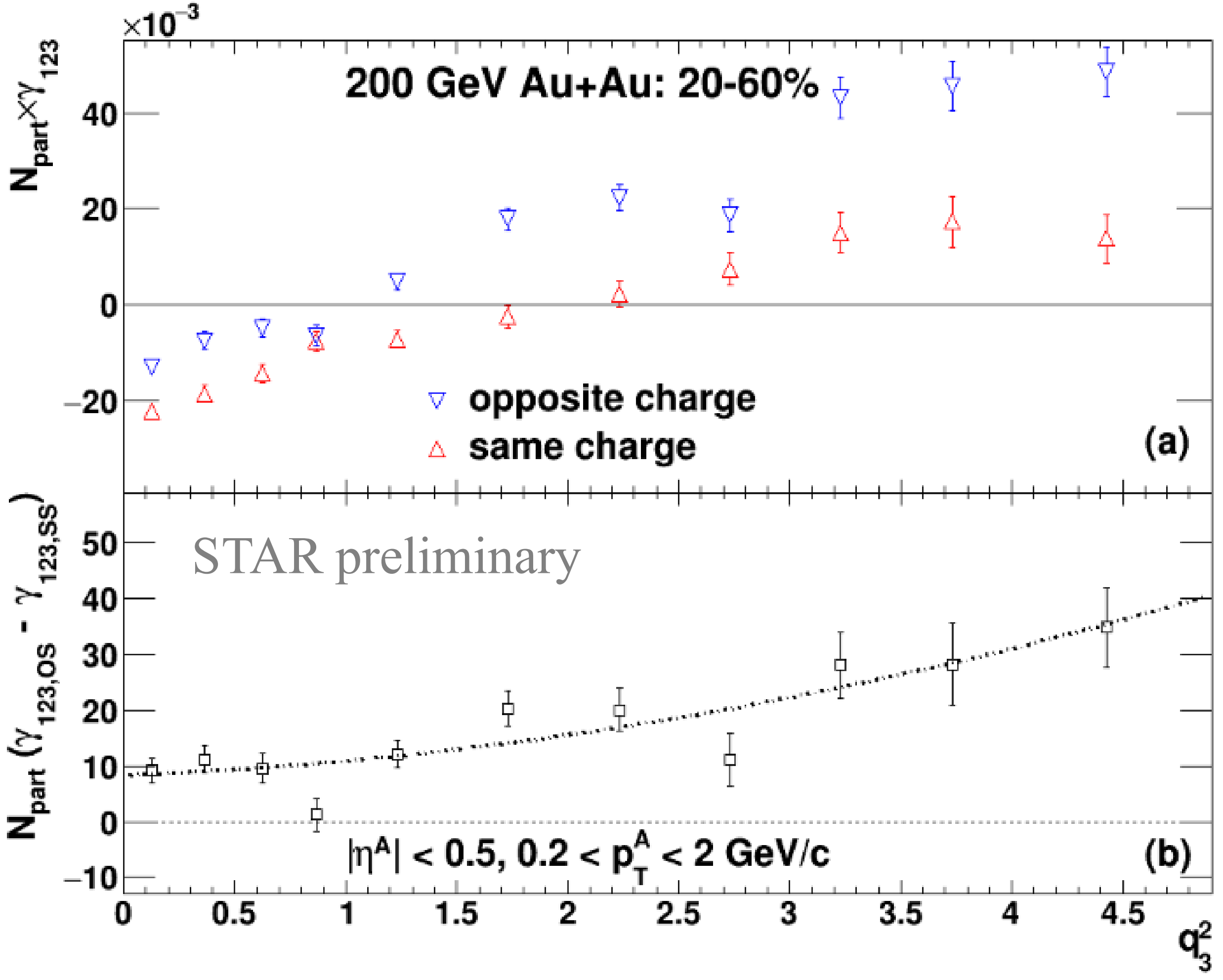



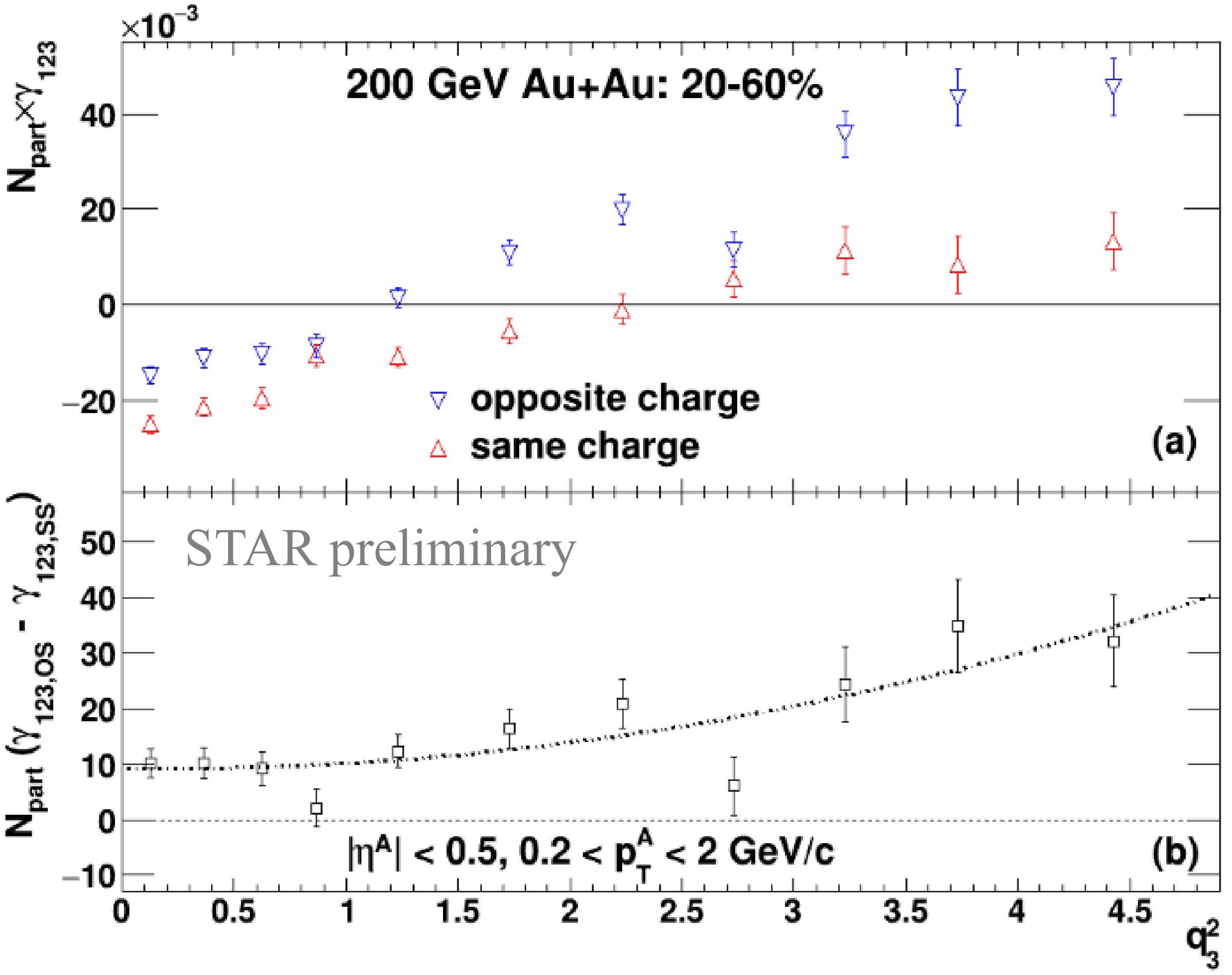

**No η gap**: $(7.51 \pm 0.75)*10^{-3}$ **η gap of 0.1**: $(7.81 \pm 1.22)*10^{-3}$

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 $\chi^2$.

# $\gamma_{123}$: 200 GeV Au+Au



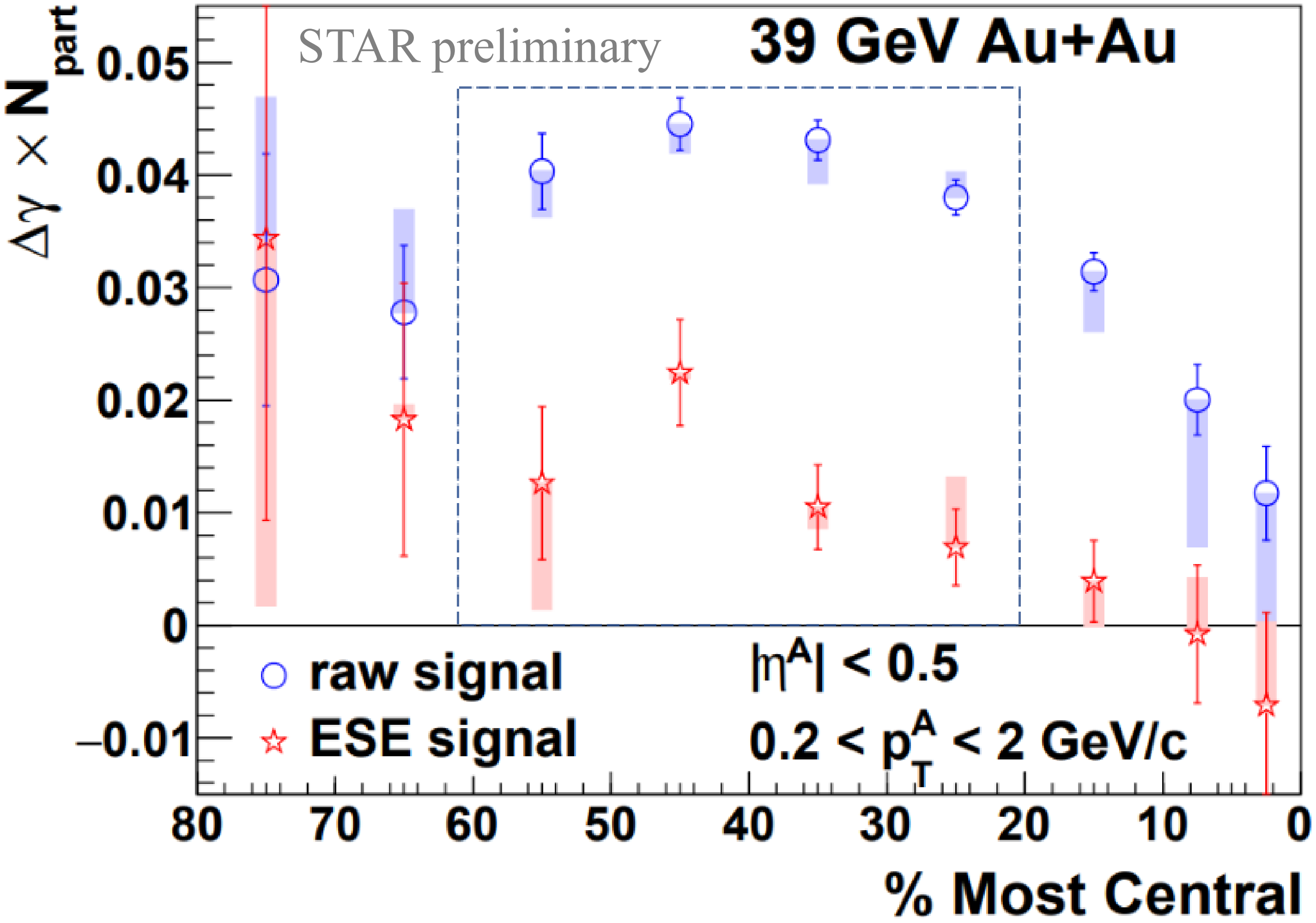




**No η gap**: $(8.32 \pm 1.92)*10^{-3}$

**η gap of 0.1**: $(9.27 \pm 2.20)*10^{-3}$

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!