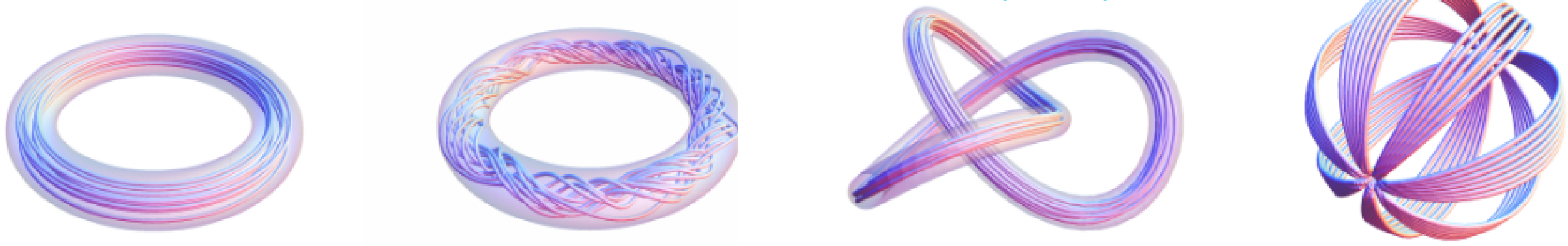
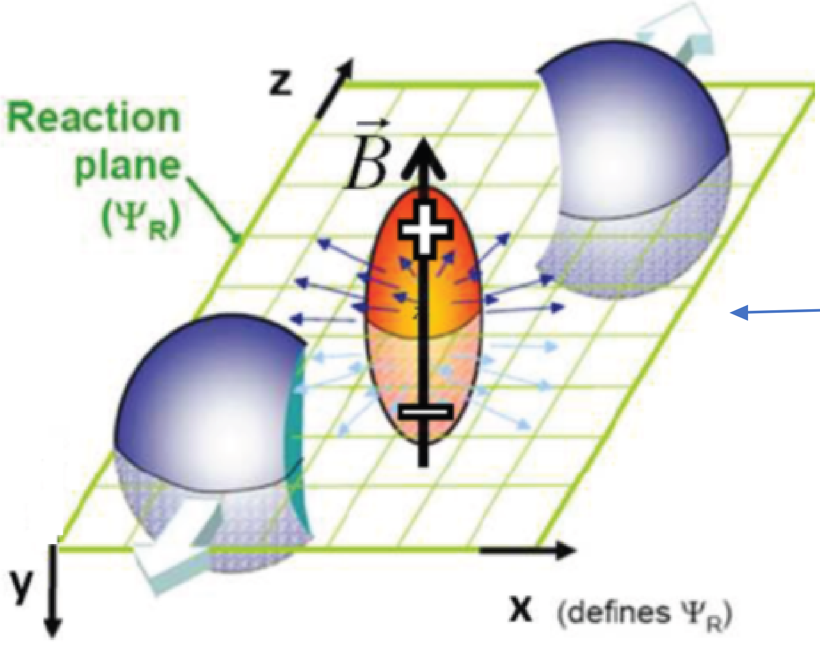
Background estimation in search of the CME at STAR

Gang Wang (for STAR Collaboration)
UCLA

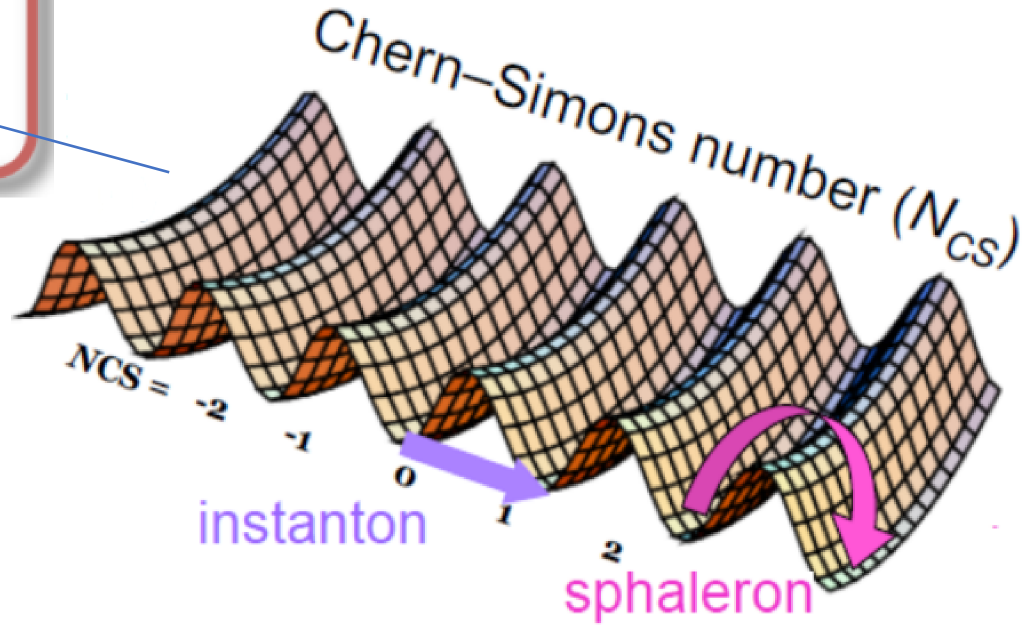
Chiral Magnetic Effect: magnetic field + chirality = current

Y. Hirono, D. E. Kharzeev and Y. Yin PRD 92,125031 (2015)





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



D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

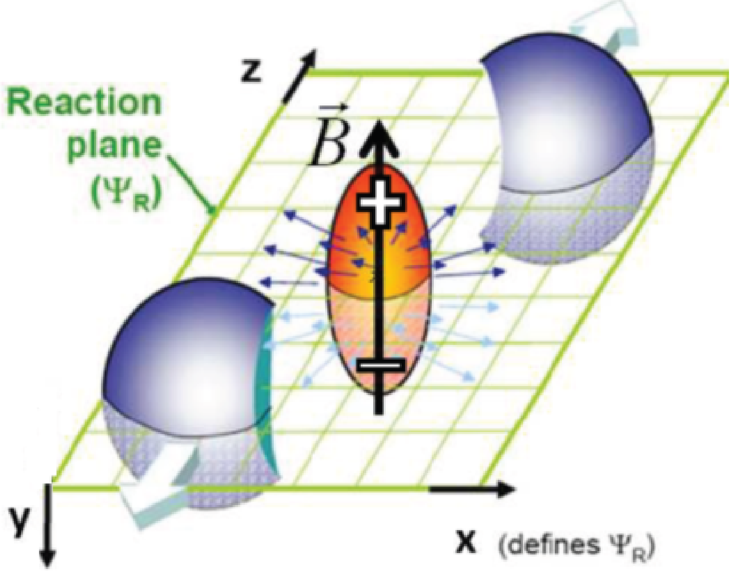
An excess of right or left handed quarks lead to a current flow along the magnetic field.

CME observable: γ correlator

A way to quantify the extra charge fluctuation.

S. Voloshin, PRC 70 (2004) 057901

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



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

background effects: largely cancel out

P-even quantity: still sensitive to charge separation

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

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

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

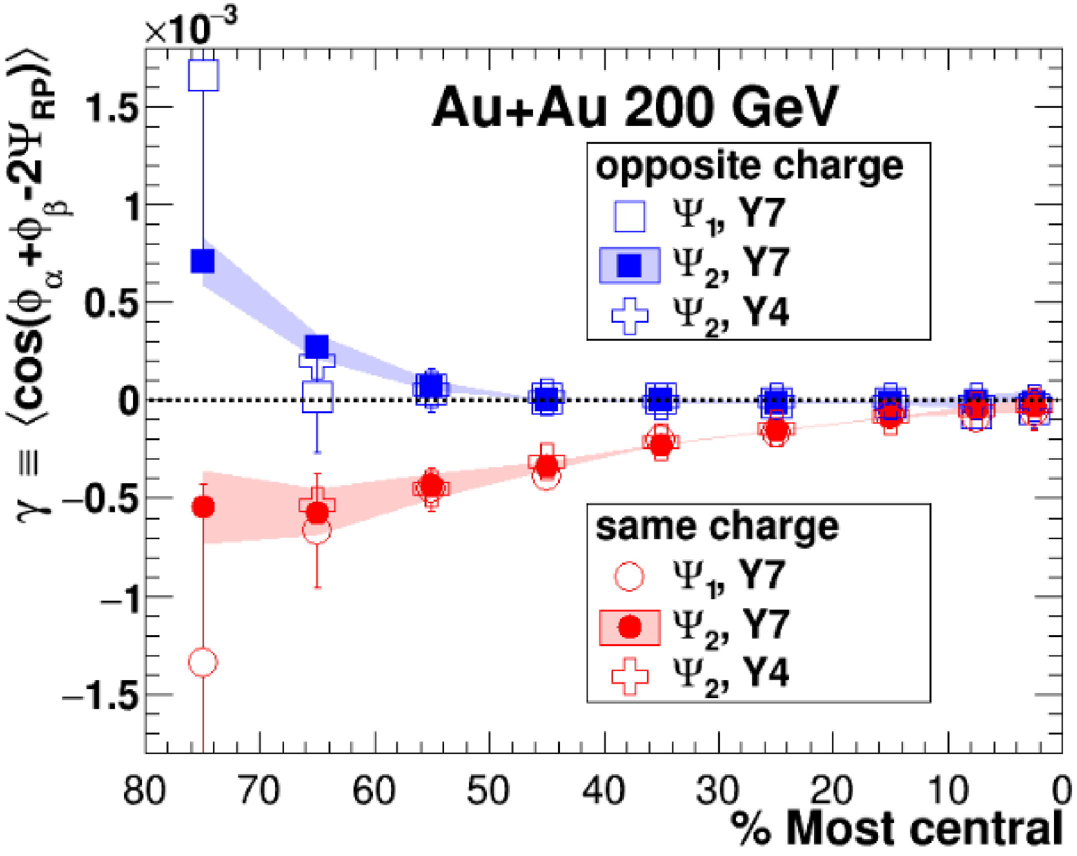
Charge separation signal

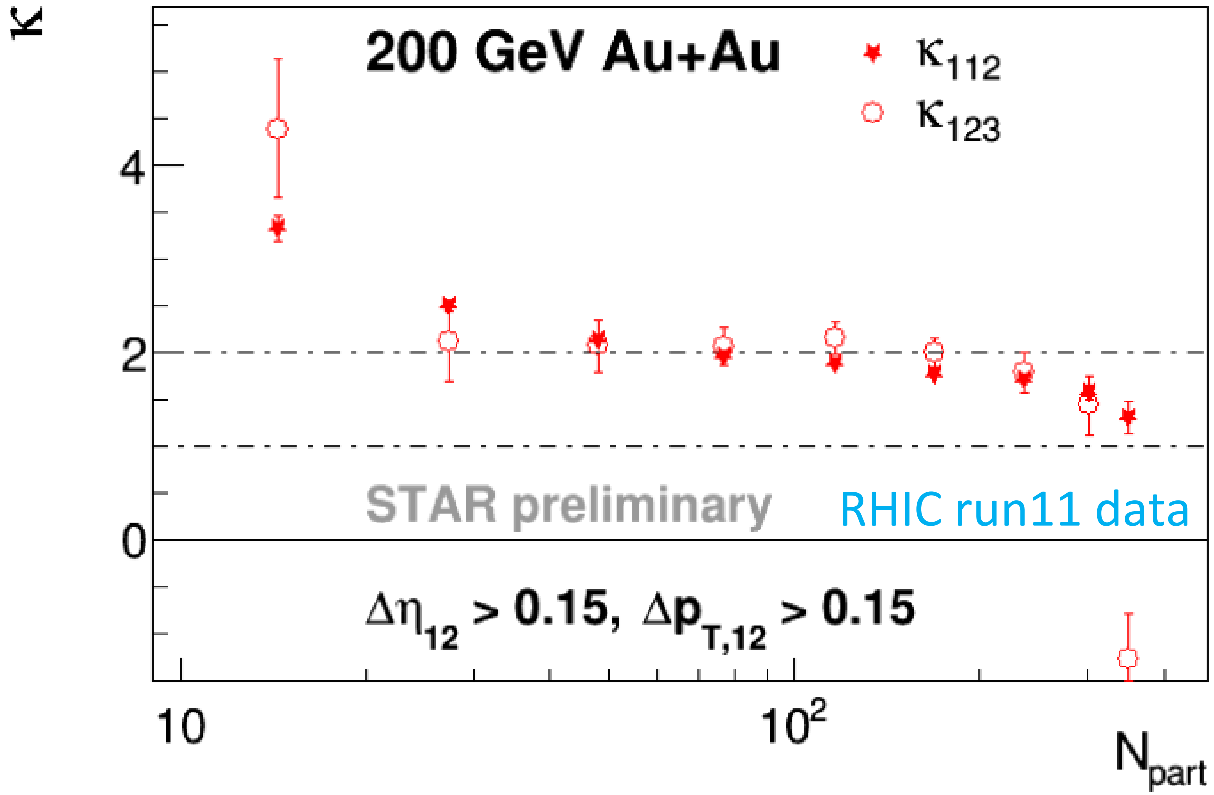
$\gamma_{1,n-1,n} = \langle\cos[\varphi_\alpha + (n-1)\varphi_\beta - n\Psi_{EP}]\rangle/res_{EP}$

$\Delta\gamma_{1,n-1,n} = \kappa_{1,n-1,n}\, v_n\, \Delta\delta$

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

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

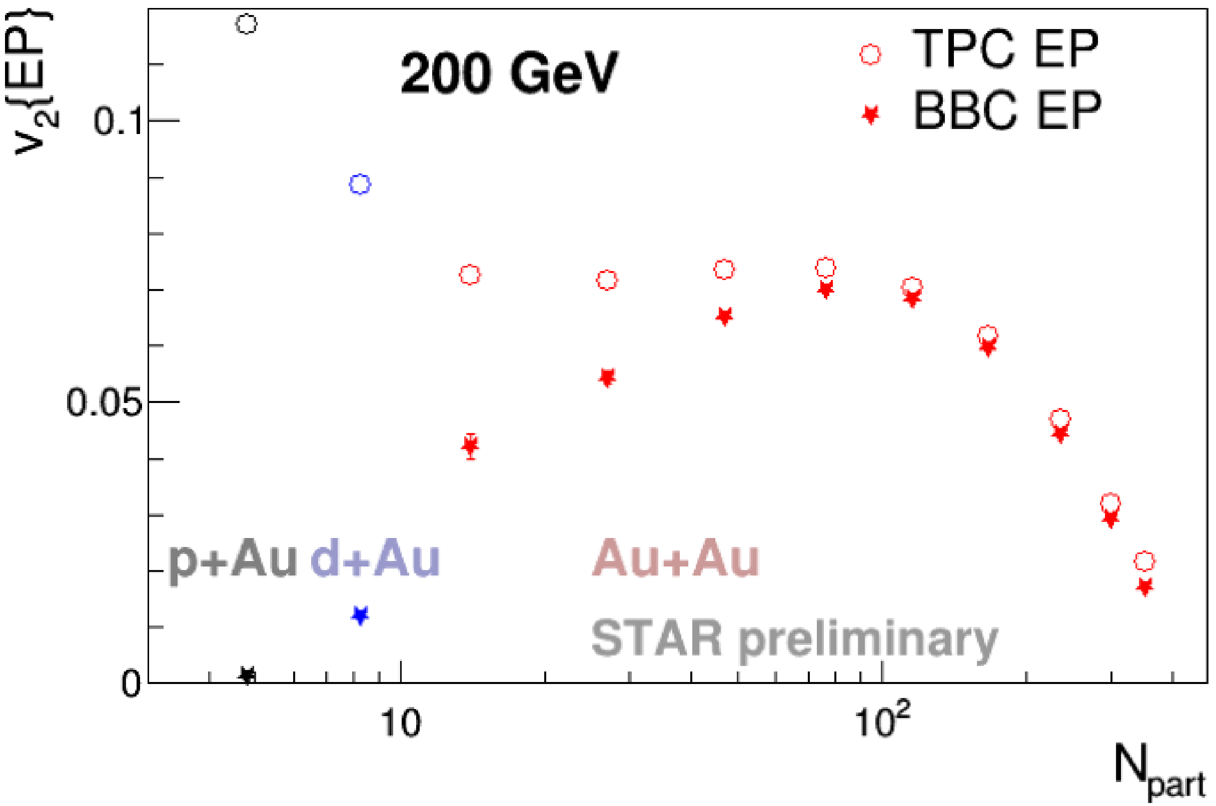


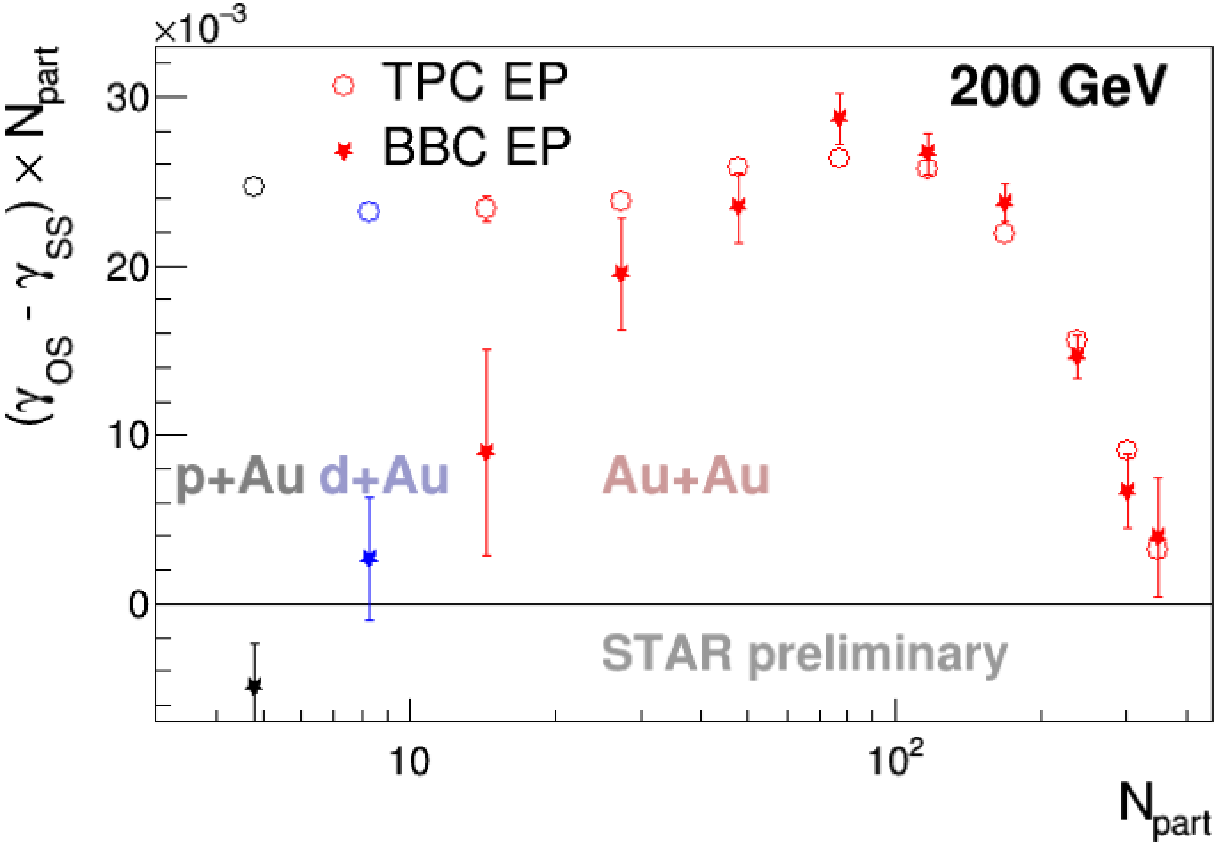


STAR, PRL 103(2009)251601;
PRC 81(2010)54908;
PRC 88 (2013) 64911

Charges seem to be separated according to $\Delta\gamma_{112}$.
However, κ_{112} and κ_{123} are mostly consistent with each other, especially after removing very-short-range correlations.

Nonflow-related BG





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

$|\eta_{TPC}| < 1$

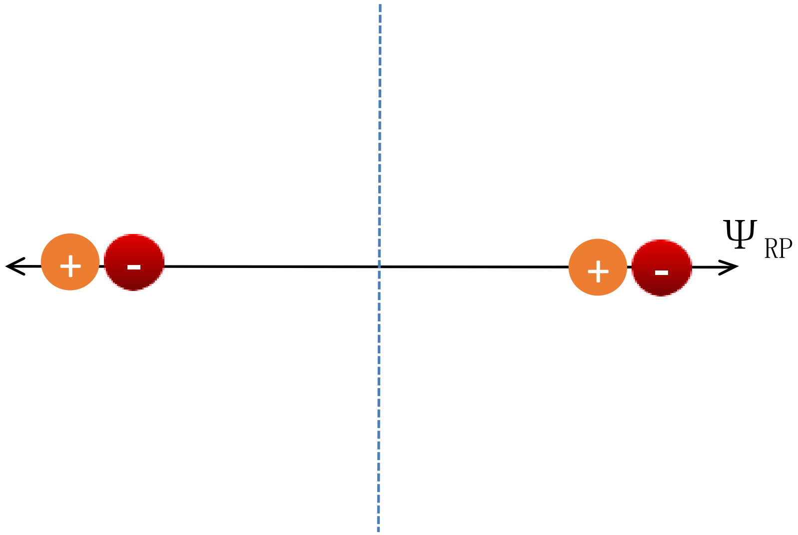
$3.8 < |\eta_{BBC}| < 5.1$

Flow-related background

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

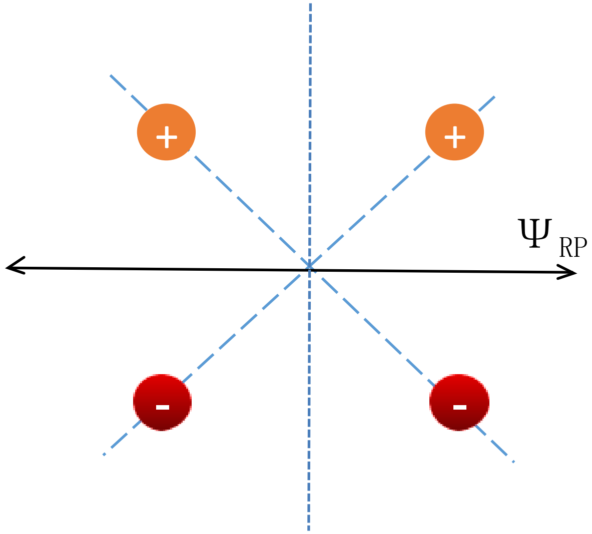
Aparent anisotropy:
explicit v_2 (of final-state particles).
even w/o visual charge separation

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

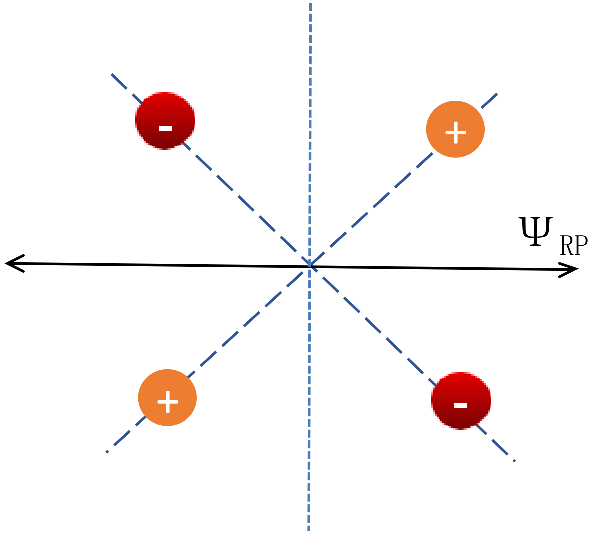


$v_2 = 1$
$\gamma_{SS} = -1$
$\gamma_{OS} = 0$

controllable with measured v_2



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



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

hard to control directly

γ_{112} vs γ_{132}

Consider flowing resonances that decay:

$$\gamma_{112} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res} + 2\varphi_{res} - 2\Psi)\rangle$$
$$\approx f_{res}/N_\pi \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res})\rangle\, v_{2,res}$$

$$\gamma_{132} = \langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi)\rangle$$
$$= \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res} + 2\varphi_{res} - 2\Psi)\rangle$$
$$\approx f_{res}/N_\pi \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res})\rangle\, v_{2,res}$$

Assume ...... then ......

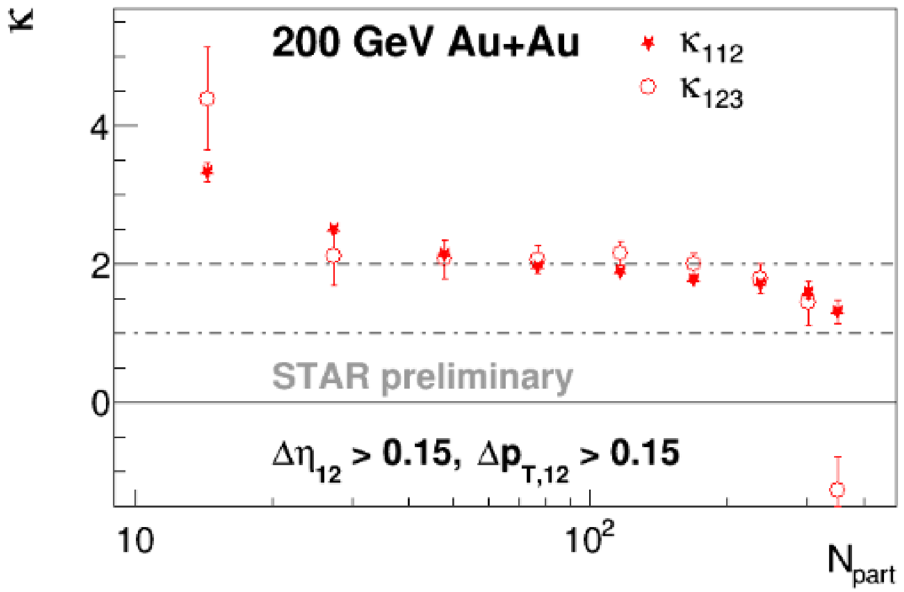
$$\varphi_\alpha \approx \varphi_\beta \rightarrow \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res})\rangle \approx \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res})\rangle$$

$$\gamma_{112}^{BG} \approx \gamma_{132}^{BG}$$

How wrong can that be?

… and γ_{123}

Consider flowing resonances that decay:



$$\gamma_{112} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res} + 2\varphi_{res} - 2\Psi)\rangle$$
$$\approx f_{res}/N_\pi \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res})\rangle\, v_{2,res}$$

$$\gamma_{132} = \langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi)\rangle$$
$$= \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res} + 2\varphi_{res} - 2\Psi)\rangle$$
$$\approx f_{res}/N_\pi \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res})\rangle\, v_{2,res}$$

$$\gamma_{123} = \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\Psi)\rangle$$
$$= \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\varphi_{res} + 3\varphi_{res} - 3\Psi)\rangle$$
$$\approx f_{res}/N_\pi \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\varphi_{res})\rangle\, v_{3,res}$$

Assume …… then ……

$$\varphi_\alpha \approx \varphi_\beta \rightarrow \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res})\rangle \approx \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res})\rangle \approx \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\varphi_{res})\rangle$$

$$\gamma_{112}^{BG}/v_2 \approx \gamma_{132}^{BG}/v_2$$
$$\approx \gamma_{123}^{BG}/v_3$$

How wrong can that be? →

γ_{112} vs γ_{132}

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

Aparent anisotropy:
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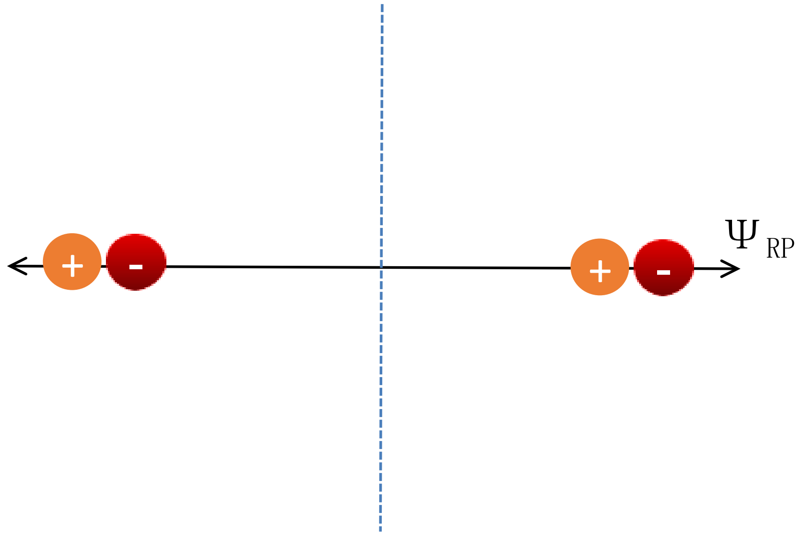
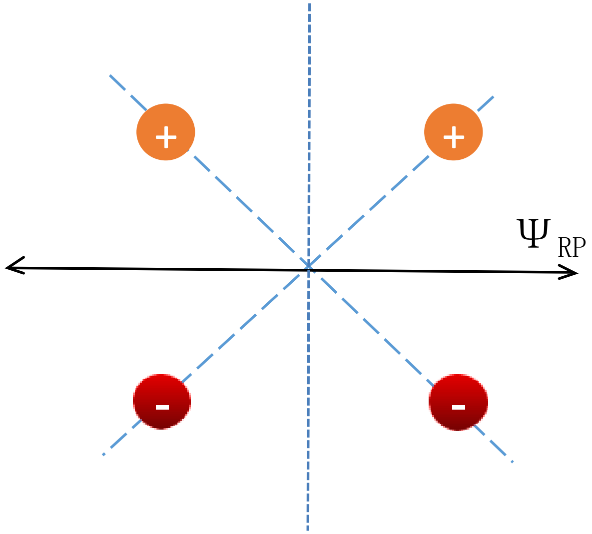


$v_2 = 1$

$\gamma_{112,SS} = -1$ $\gamma_{132,SS} = -1$

$\gamma_{112,OS} = 0$ $\gamma_{132,OS} = 0$

$\Delta\gamma_{112} = \Delta\gamma_{132} \rightarrow$ flow background

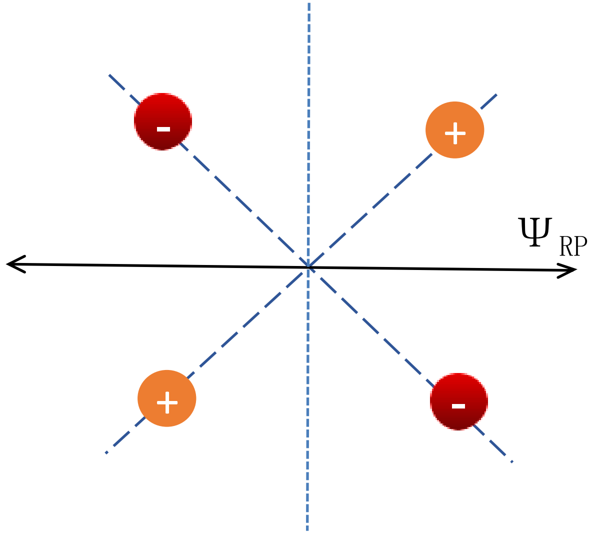


$v_2 = 0$

$\gamma_{112,SS} = -1$ $\gamma_{132,SS} = 1$

$\gamma_{112,OS} = 1/2$ $\gamma_{132,OS} = -1/2$

negative contribution to $\Delta\gamma_{132}$



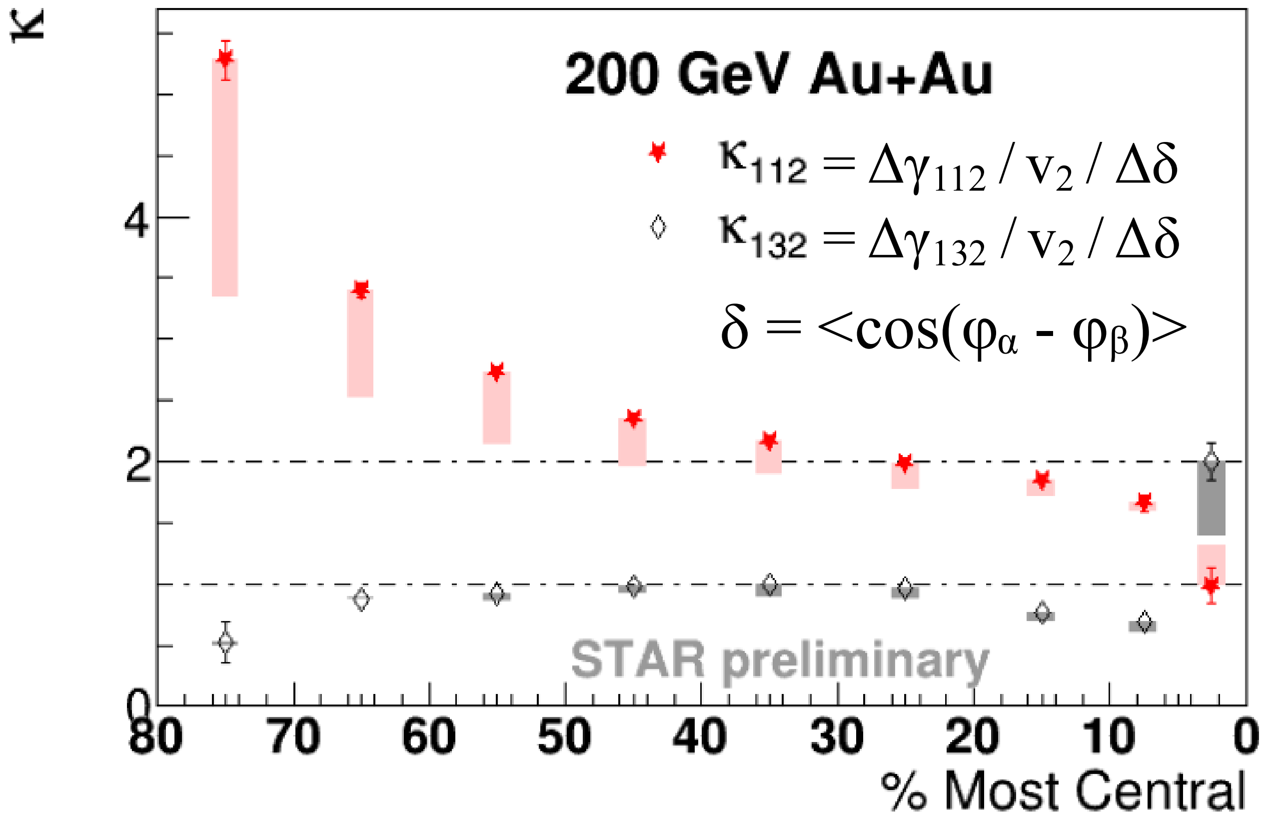
$v_2 = 0$

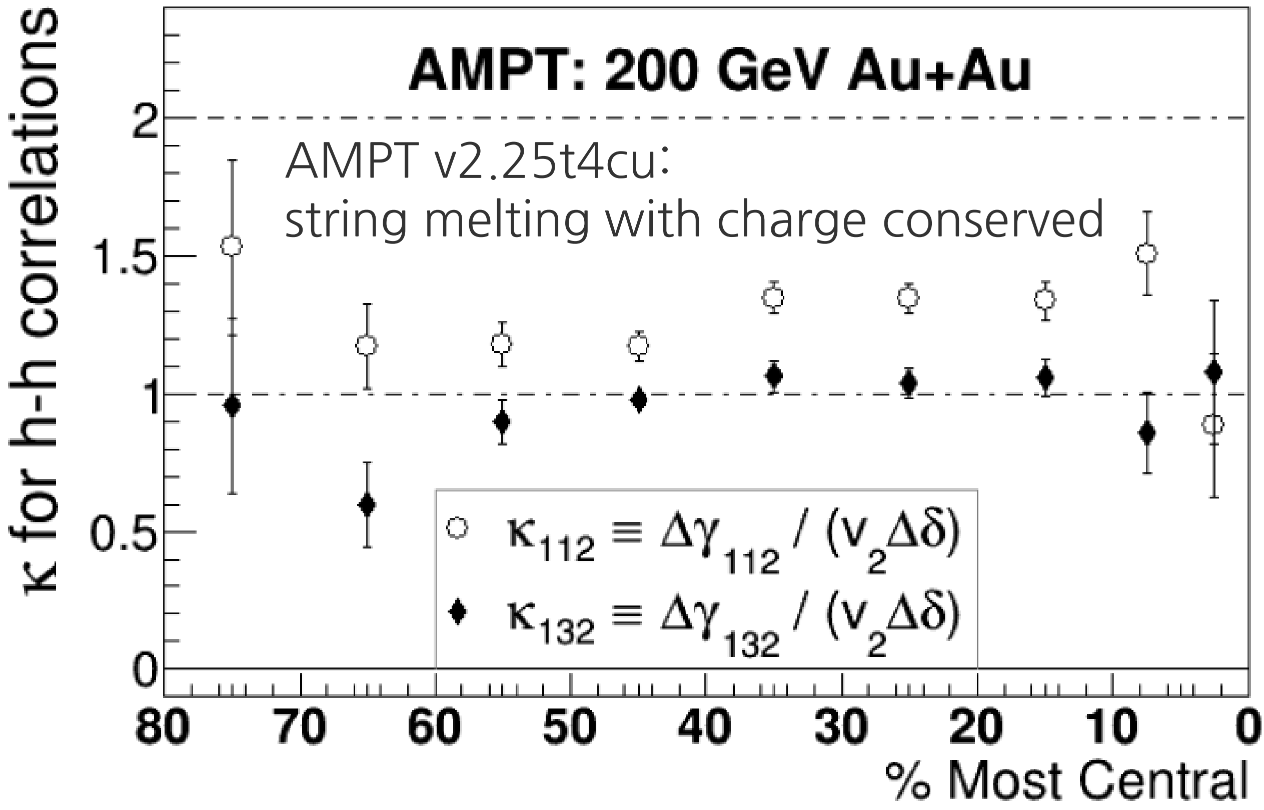
$\gamma_{112,SS} = 0$ $\gamma_{132,SS} = 0$

$\gamma_{112,OS} = 0$ $\gamma_{132,OS} = 0$

$\Delta\gamma_{112} = \Delta\gamma_{132}$

κ_{112} VS κ_{132}





- κ_{132} from data is close to 1 for 20 - 70% most central events.
- AMPT also confirms that. κ_{132} connects data and model.
- AMPT has κ_{112} above κ_{132} (so $\varphi_\alpha \neq \varphi_\beta$), but not as high as data.
- If AMPT is trustable, then data show extra correlations beyond flow.

Why is κ_{132} close to 1?

Cumulant: $\langle\langle A*B\rangle\rangle = \langle A*B\rangle - \langle A\rangle*\langle B\rangle$

$$\gamma_{132} = \langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\beta - \varphi_\alpha + 2\varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\beta - \varphi_\alpha)\cos(2\varphi_\beta - 2\Psi)\rangle - \langle\sin(\varphi_\beta - \varphi_\alpha)\sin(2\varphi_\beta - 2\Psi)\rangle$$
$$= \delta*v_2 + \langle\langle\cos(\varphi_\beta - \varphi_\alpha)\cos(2\varphi_\beta - 2\Psi)\rangle\rangle - \langle\langle\sin(\varphi_\beta - \varphi_\alpha)\sin(2\varphi_\beta - 2\Psi)\rangle\rangle$$

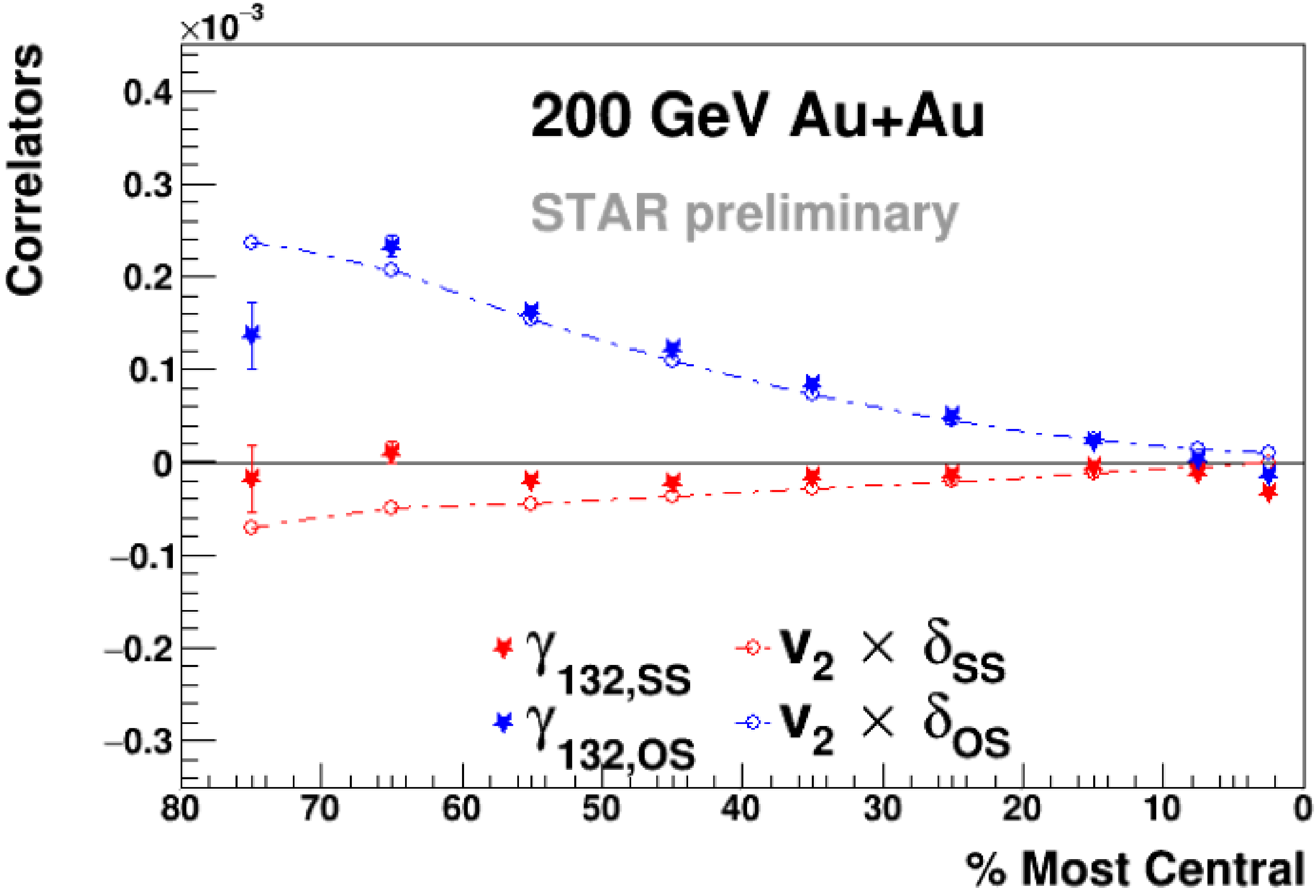
fluctuations could cancel in sin*sin and cos*cos

$$\gamma_{112} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\alpha - \varphi_\beta + 2\varphi_\beta - 2\Psi)\rangle$$
$$= \langle\cos(\varphi_\beta - \varphi_\alpha)\cos(2\varphi_\beta - 2\Psi)\rangle + \langle\sin(\varphi_\beta - \varphi_\alpha)\sin(2\varphi_\beta - 2\Psi)\rangle$$
$$= \delta*v_2 + \langle\langle\cos(\varphi_\beta - \varphi_\alpha)\cos(2\varphi_\beta - 2\Psi)\rangle\rangle + \langle\langle\sin(\varphi_\beta - \varphi_\alpha)\sin(2\varphi_\beta - 2\Psi)\rangle\rangle$$

CME signal or other physics adds up here

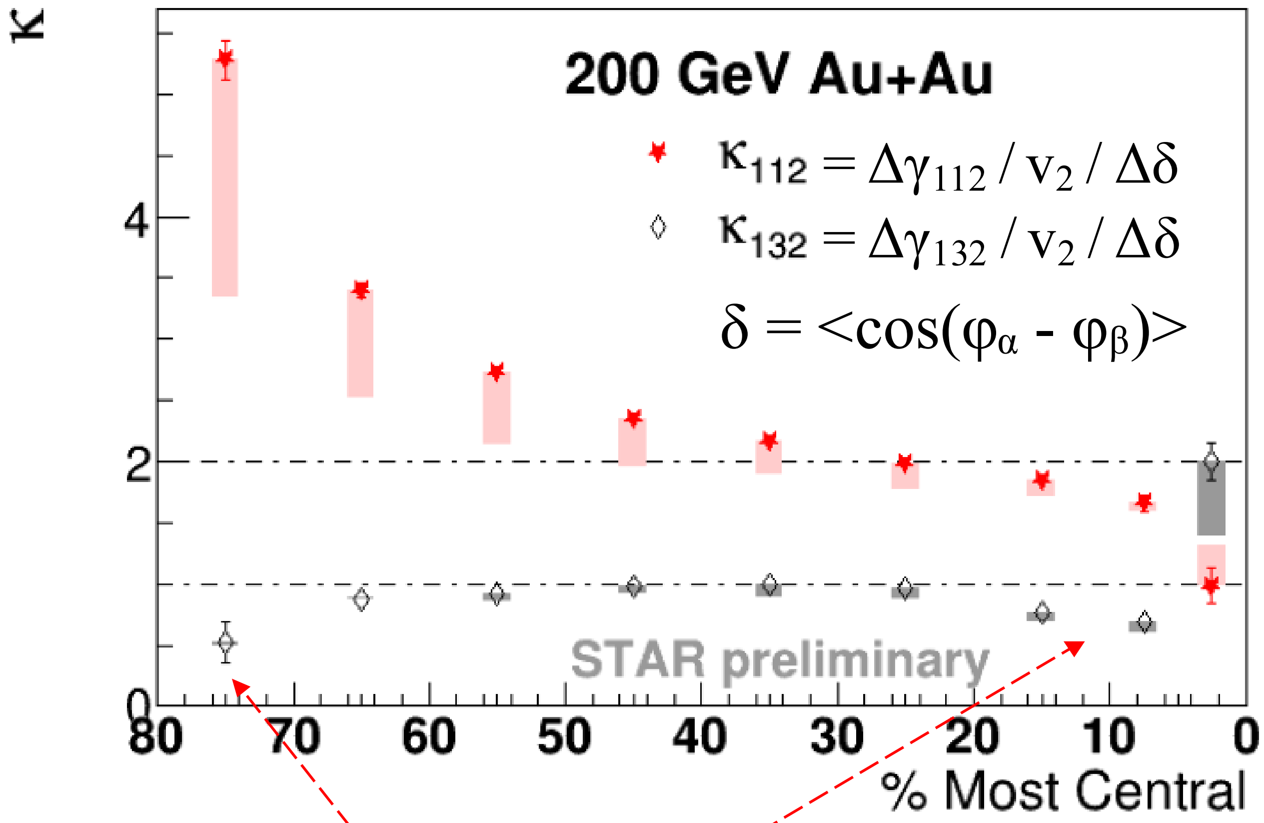
$\delta = \langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ also contains CME,
but is contaminated with other effects, and scaled down by v_2.

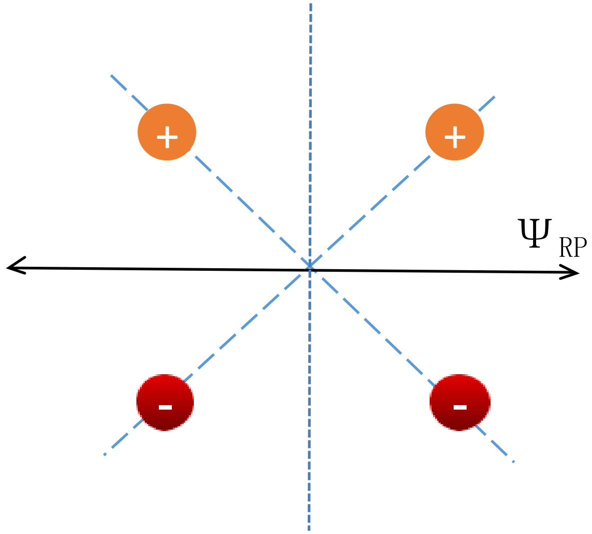
γ_{132}: SS and OS



($\gamma_{132} \approx \delta^* v_2$) qualitatively holds for both same charge and oppoite charge.

γ_{132}: further understanding





$v_2 = 0$

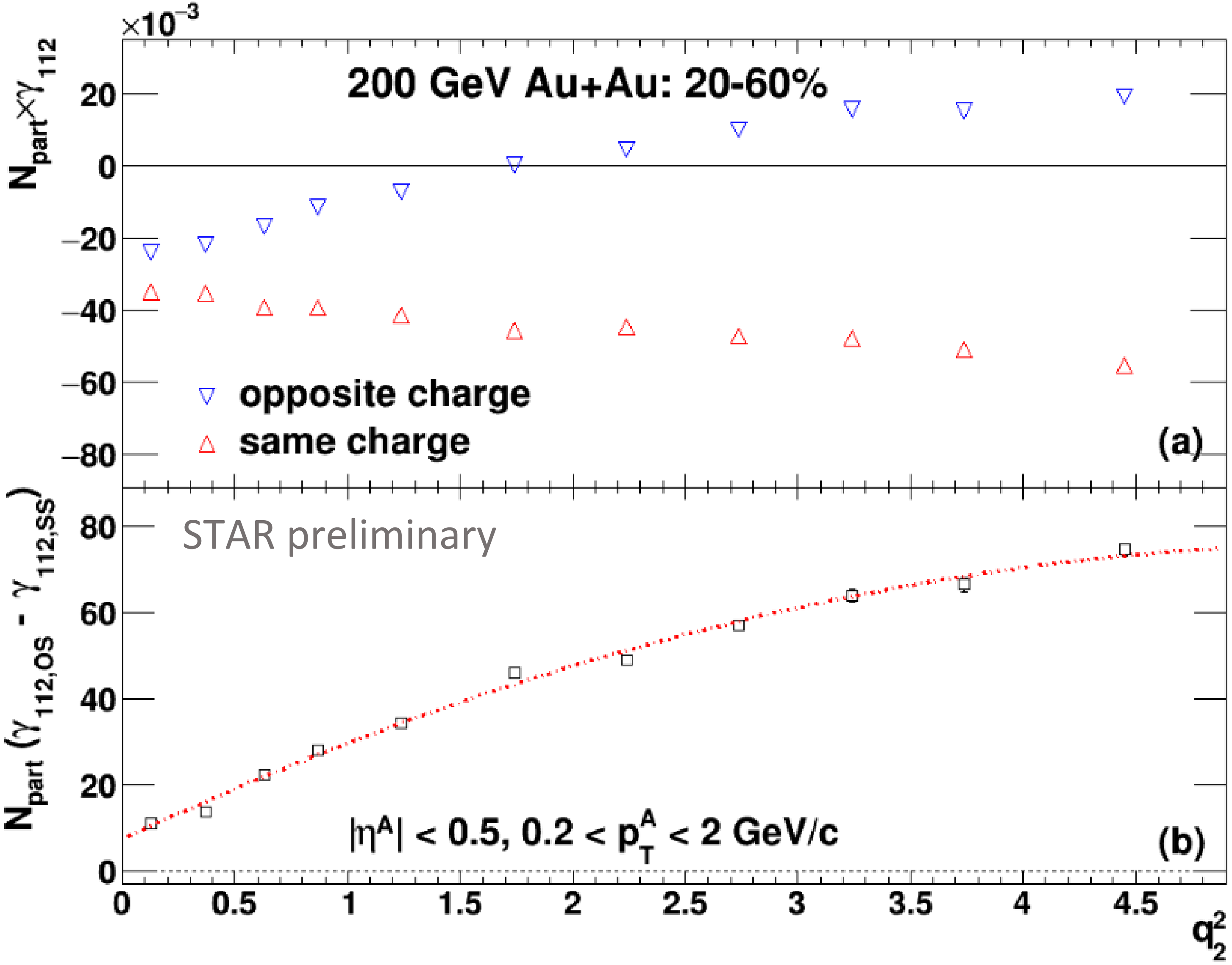
$\gamma_{112,SS} = -1$ $\gamma_{132,SS} = 1$

$\gamma_{112,OS} = 1/2$ $\gamma_{132,OS} = -1/2$

positive contribution to $\Delta\gamma_{112}$
negative contribution to $\Delta\gamma_{132}$

- κ_{132} goes below 1 for peripheral and central collisions.
- Could be pulled down by "hidden anisotropy" or non-flow.
- 20 - 70% collisions seem to be a robust zone.

Event-shape Engineering



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

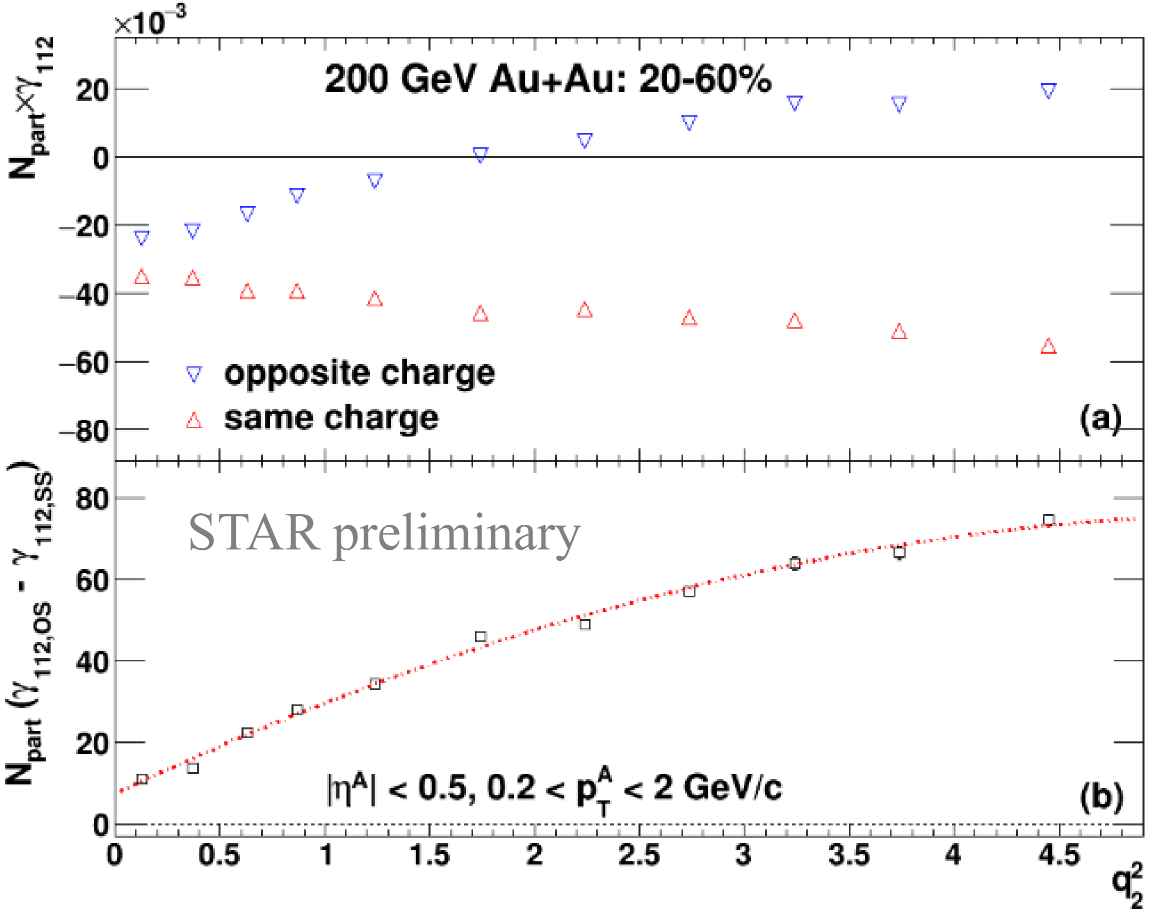
$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

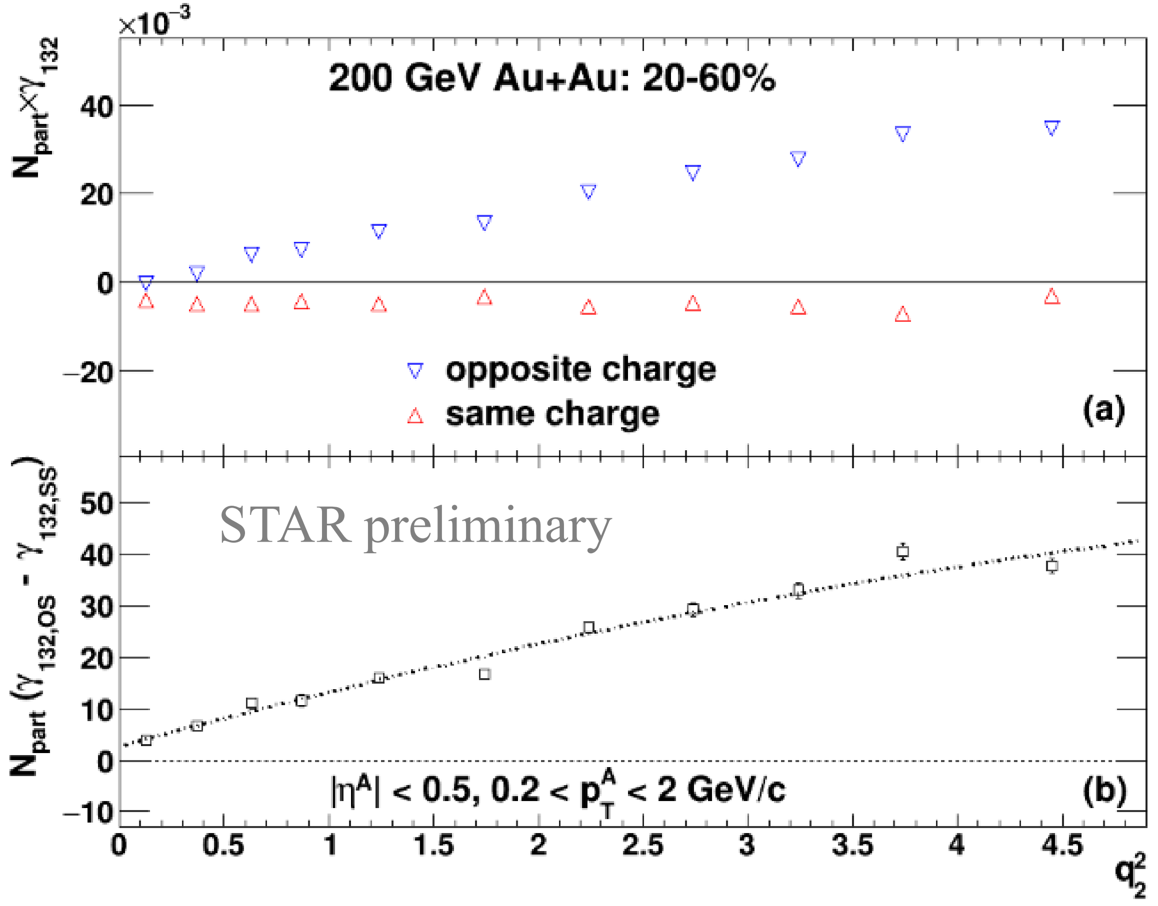
$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$

- OS and SS approach each other at small q.
- When q^2 is extrapolated to 0, there is a finite intercept: $(7.51 \pm 0.75)*10^{-3}$
- What about other correlators?

$<N_{part}>$ for 20-60% collisions is roughly 98.

Extension of ESE to γ_{132}

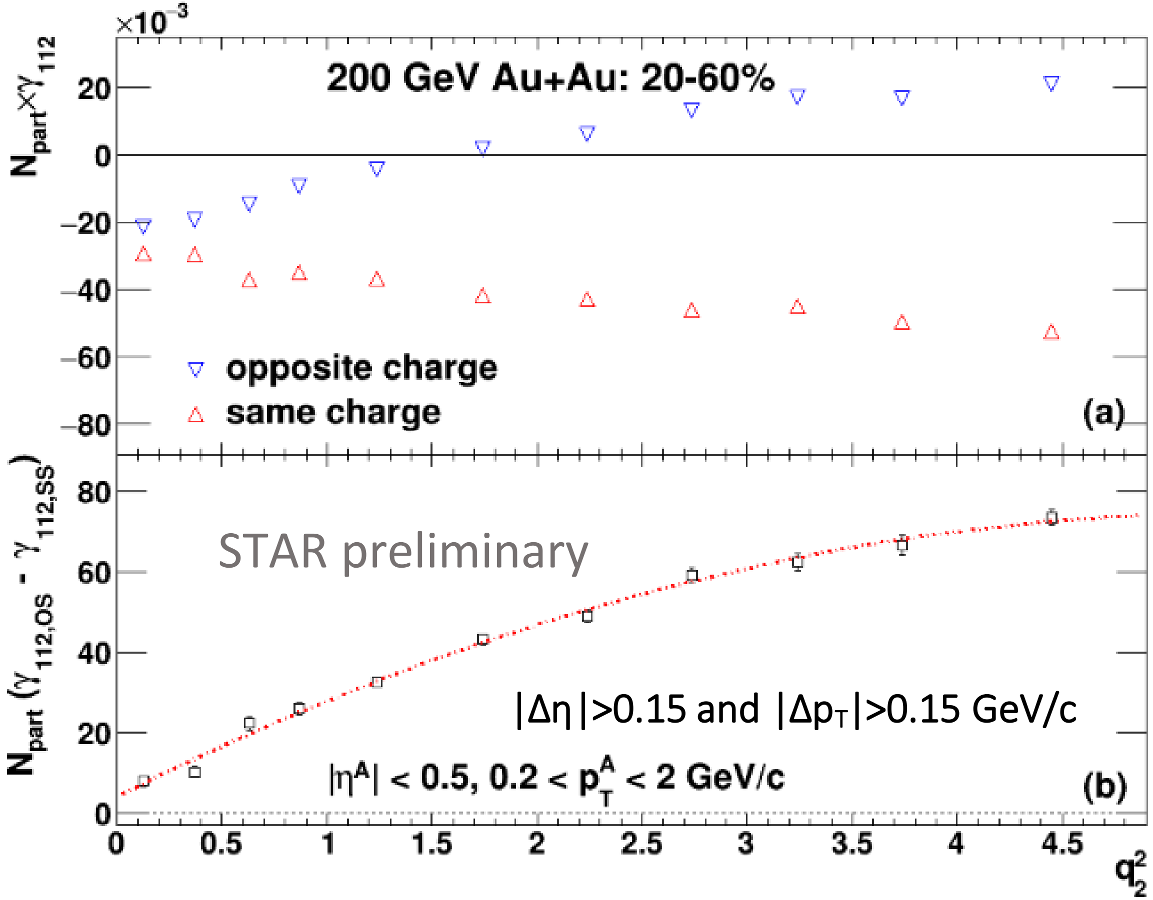


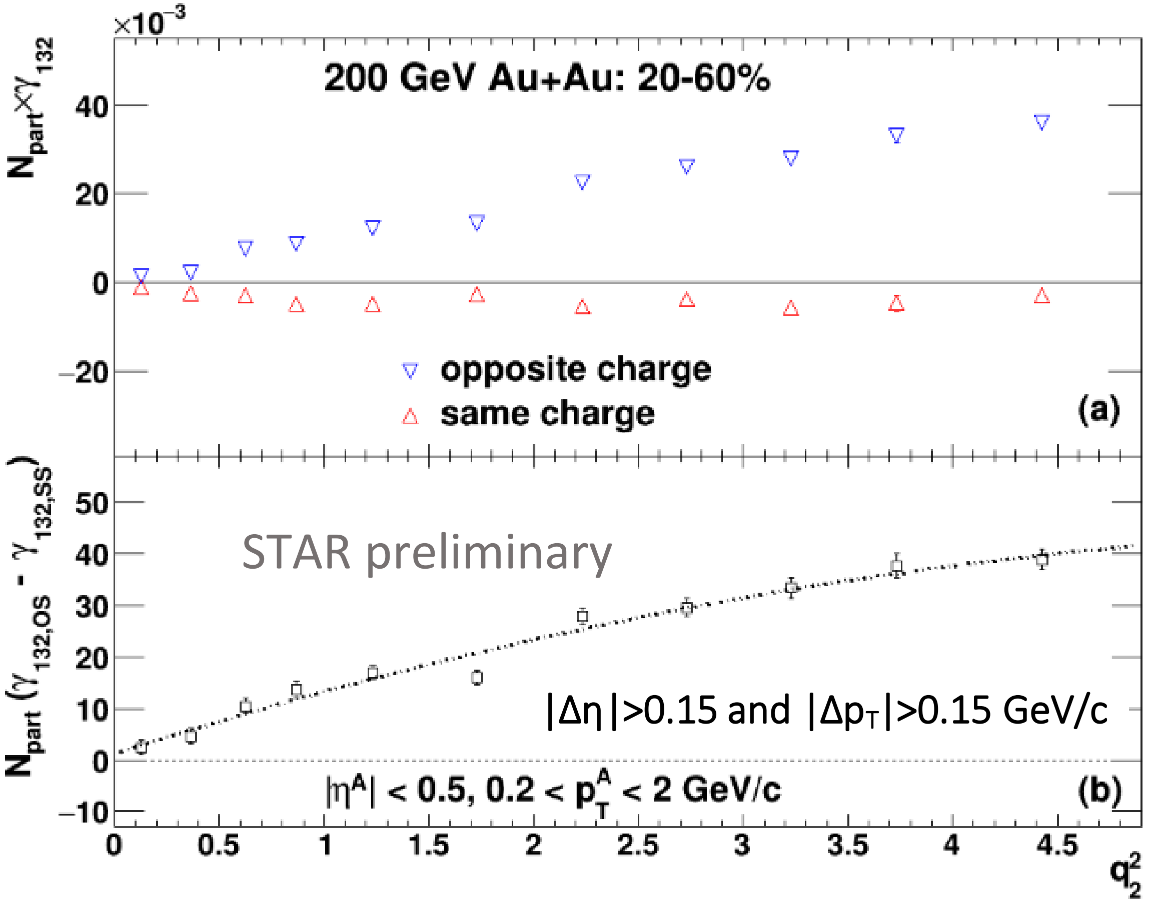


At q=0 (including very-short-range correlations):

- $N_{part}*\gamma_{112} = (7.51 \pm 0.75)*10^{-3}$
- $N_{part}*\gamma_{132} = (2.65 \pm 0.77)*10^{-3}$

Extension of ESE to γ_{132}

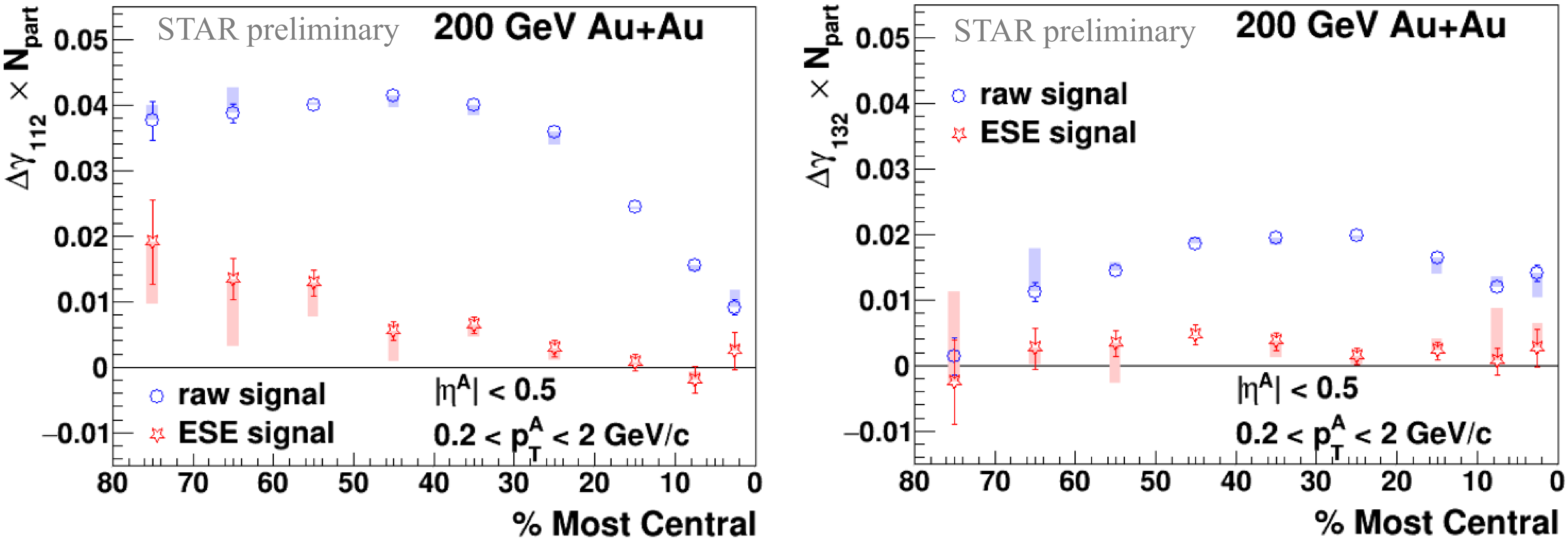




At q=0 (excluding very-short-range correlations):

- $N_{part}*\gamma_{112} = (4.15 \pm 1.08)*10^{-3}$
- $N_{part}*\gamma_{132} = (1.24 \pm 1.10)*10^{-3}$

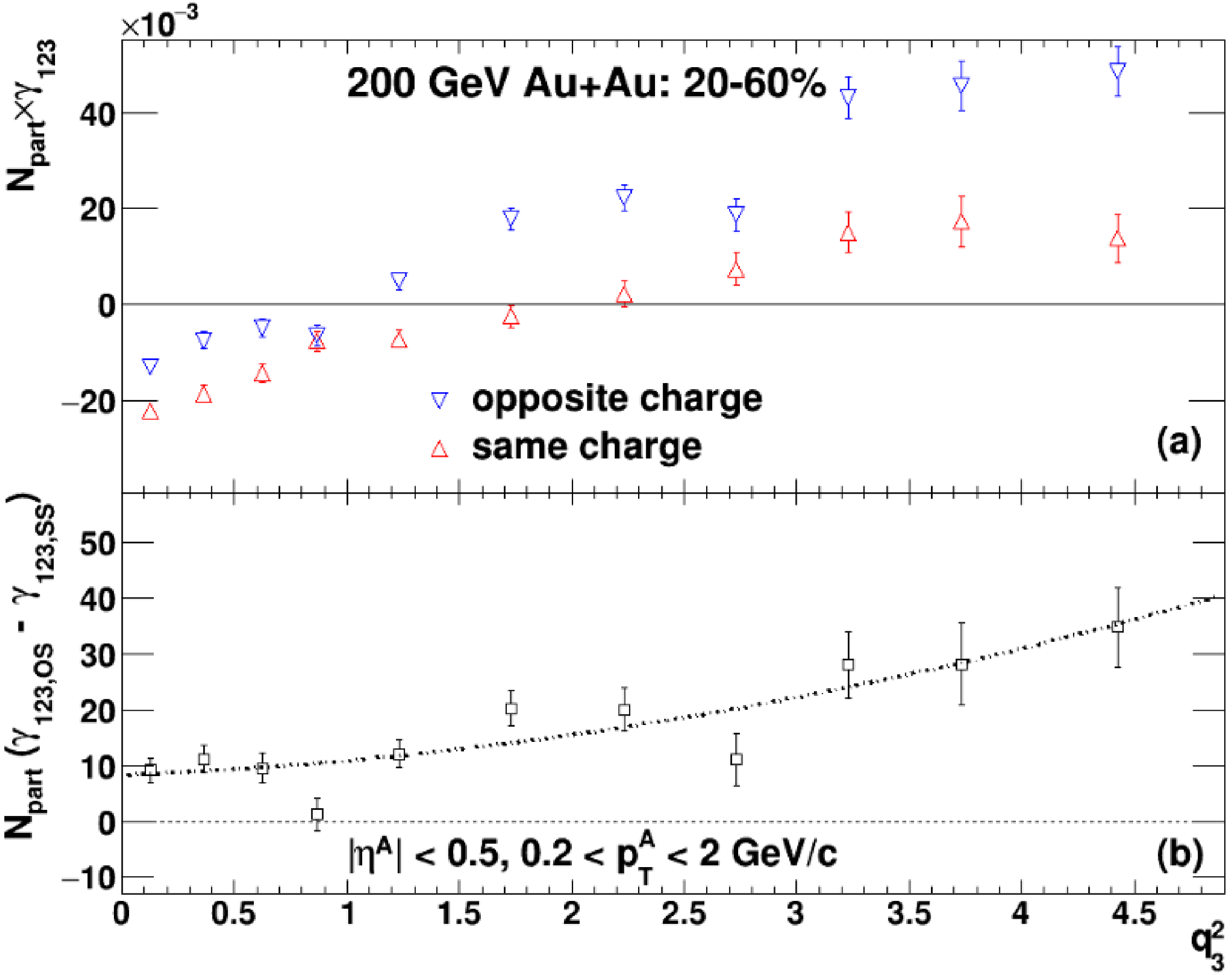
ESE: centrality dependence



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

- Both $\Delta\gamma_{112}$ and $\Delta\gamma_{132}$ are substantially reduced with this ESE approach.
- $\Delta\gamma_{132}$ almost vanishes: still possible residue BKG.

Extension of ESE to γ_{123}



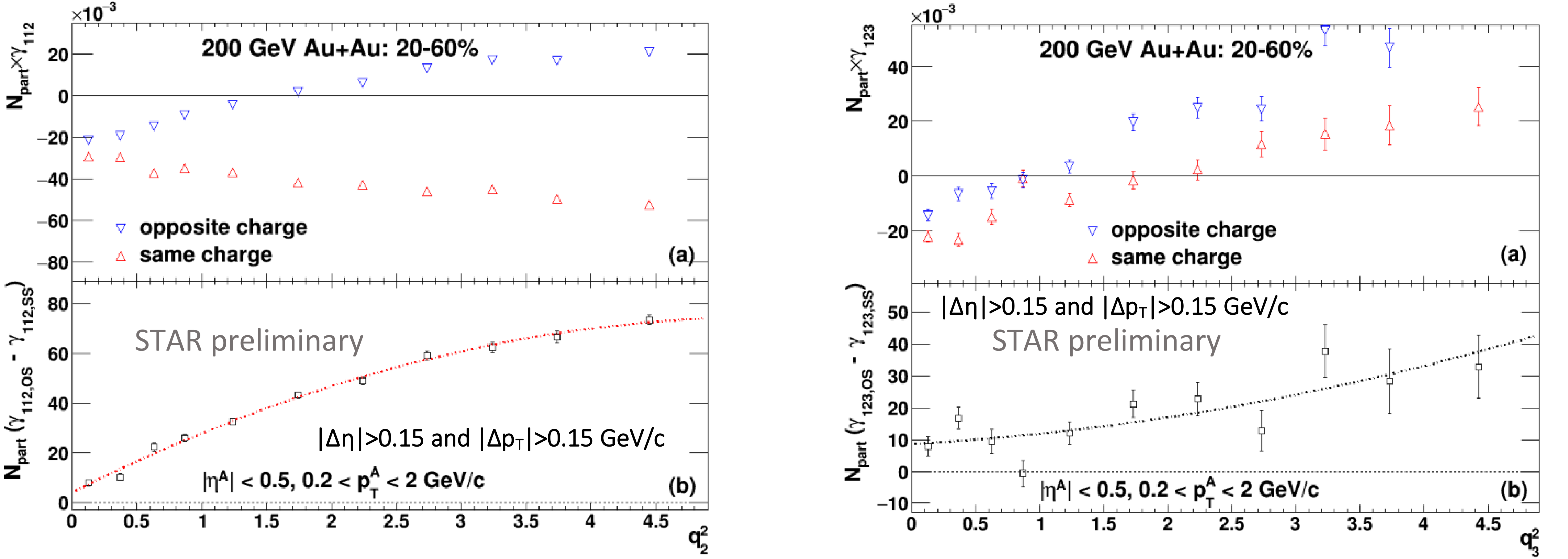
<N_{part}> for 20-60% collisions is roughly 98.

- γ_{123} can be studied via the 3rd-order flow vector, q_3.
- When q_3 is extrapolated to 0, there is a finite intercept:
  $(8.32 \pm 1.92)*10^{-3}$ for γ_{123}
  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}
- Being the same means overshooting. Should scale with v_2 and v_3 (due to implicit v_2 or v_3)?

$$\gamma_{112}^{BG}/v_2 \approx \gamma_{132}^{BG}/v_2 \approx \gamma_{123}^{BG}/v_3$$

Extension of ESE to γ_{123}

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



At q=0 (excluding very-short-range correlations):

- $N_{part}*\gamma_{112} = (4.15 \pm 1.08)*10^{-3}$
- $N_{part}*\gamma_{123} = (8.67 \pm 2.65)*10^{-3}$ even higher

Summary on γ_{132}

γ_{132} is a good starting point to study the coupling between v_2 and δ.

$$\gamma_{132} = \delta^* v_2 + \langle\langle\cos(\varphi_\beta - \varphi_\alpha)\cos(2\varphi_\beta - 2\Psi)\rangle\rangle - \langle\langle\sin(\varphi_\beta - \varphi_\alpha)\sin(2\varphi_\beta - 2\Psi)\rangle\rangle$$

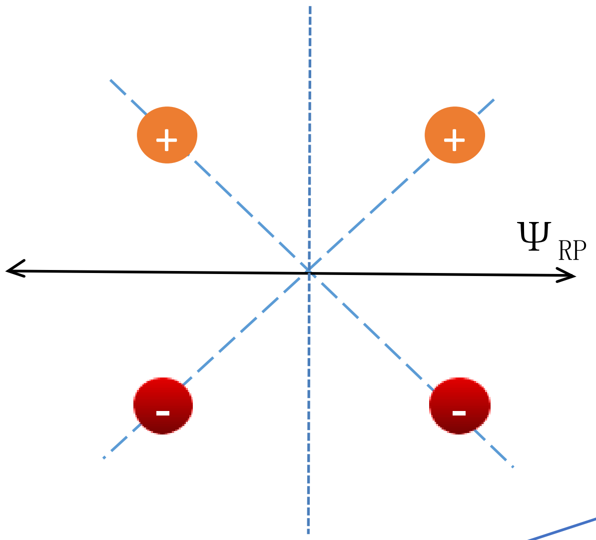
Cancellation qualitatively holds, especially in 20-70% events

$$\varphi_\alpha \approx \varphi_\beta \rightarrow \langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{res})\rangle \approx \langle\cos(3\varphi_\alpha - \varphi_\beta - 2\varphi_{res})\rangle \approx \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\varphi_{res})\rangle$$

$$\gamma_{112}^{BG}/v_2 \approx \gamma_{132}^{BG}/v_2 \approx \gamma_{123}^{BG}/v_3$$

violated by 20-40% according to AMPT

oveshooting when using ESE



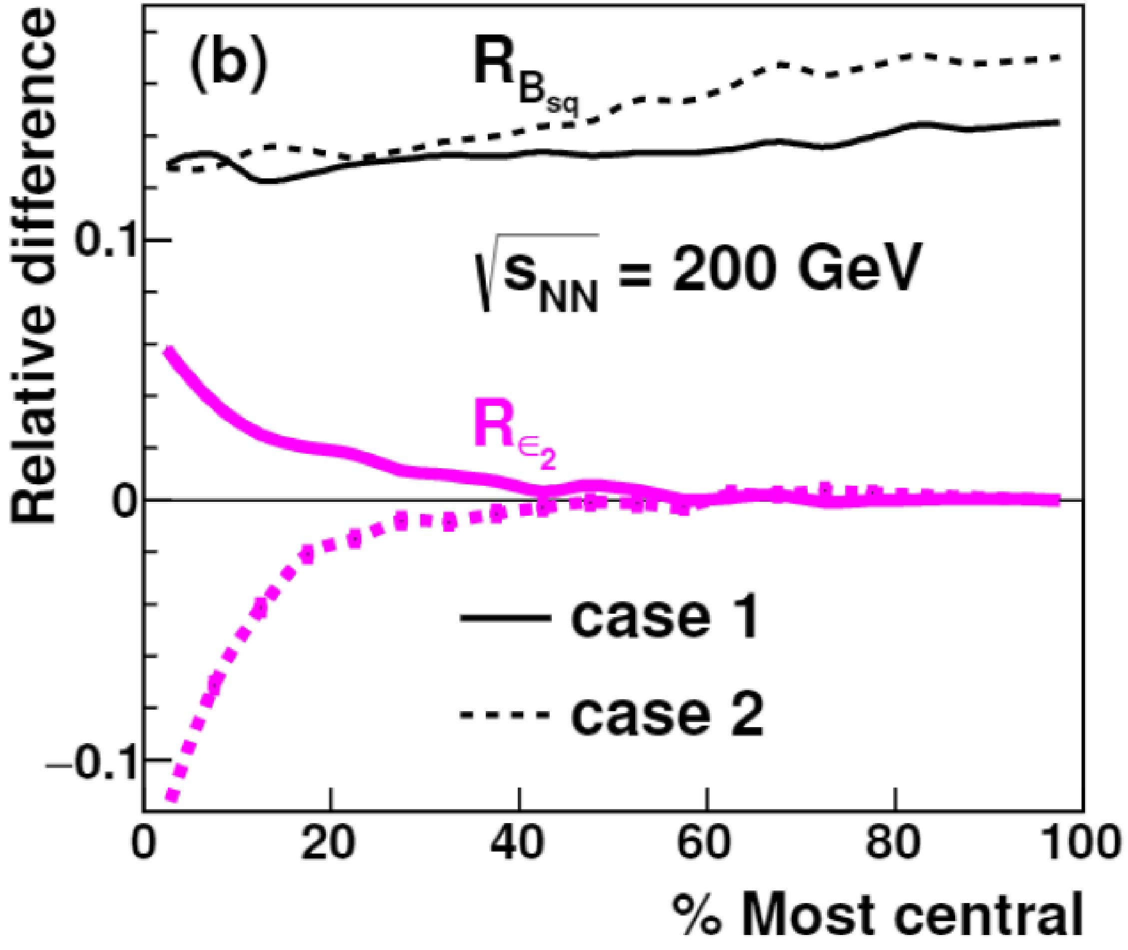
$v_2 = 0$

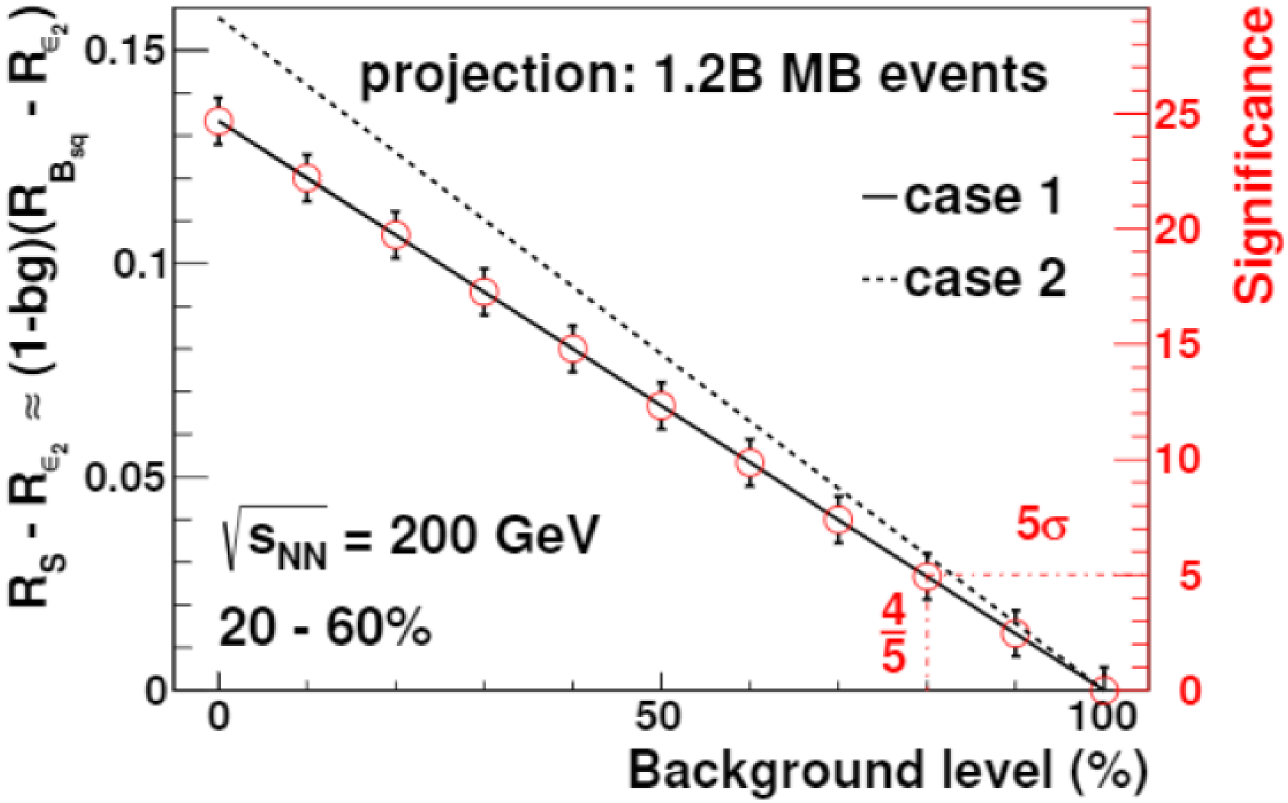
$\gamma_{112,SS} = -1$ $\gamma_{132,SS} = 1$

$\gamma_{112,OS} = 1/2$ $\gamma_{132,OS} = -1/2$

- κ_{132} goes below 1 for peripheral and central collisions:
  - could be a sign of "implicit v_2" or nonflow.
- ESE substantially reduces $\Delta\gamma_{112}$ and $\Delta\gamma_{132}$
  - but residue BKG and over-subtraction could both exist.
- Isobar is still the best solution.

Isobar: Ru+Ru vs Zr+Zr





Required 1.2B events per collision type.
Data acquisation doubled this number.

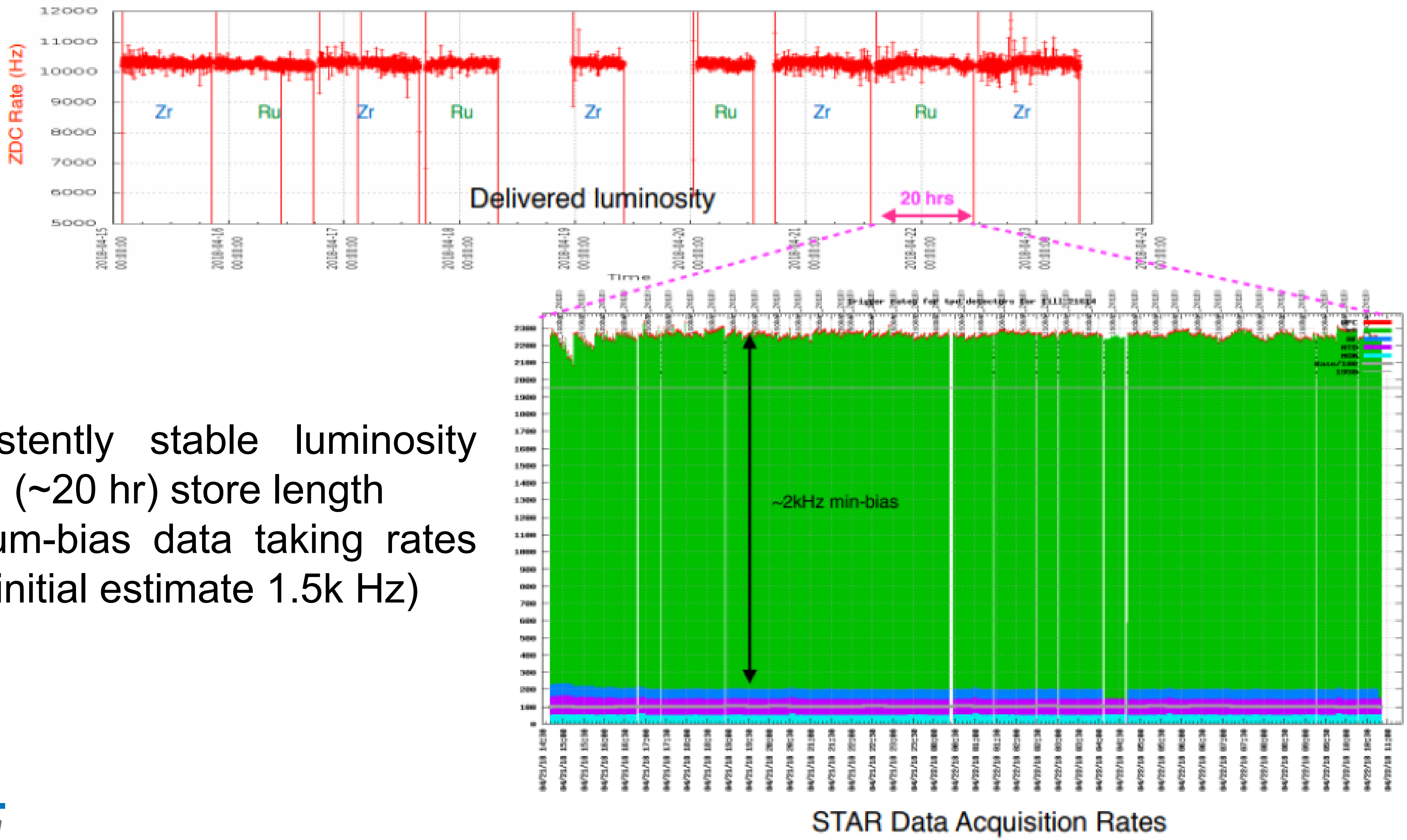
- Significant difference in the magnetic field between the two collision systems.
- Flow-background gives similar contributions for intermediate centralities.

Data taking for isobaric collisions

Requested and performed

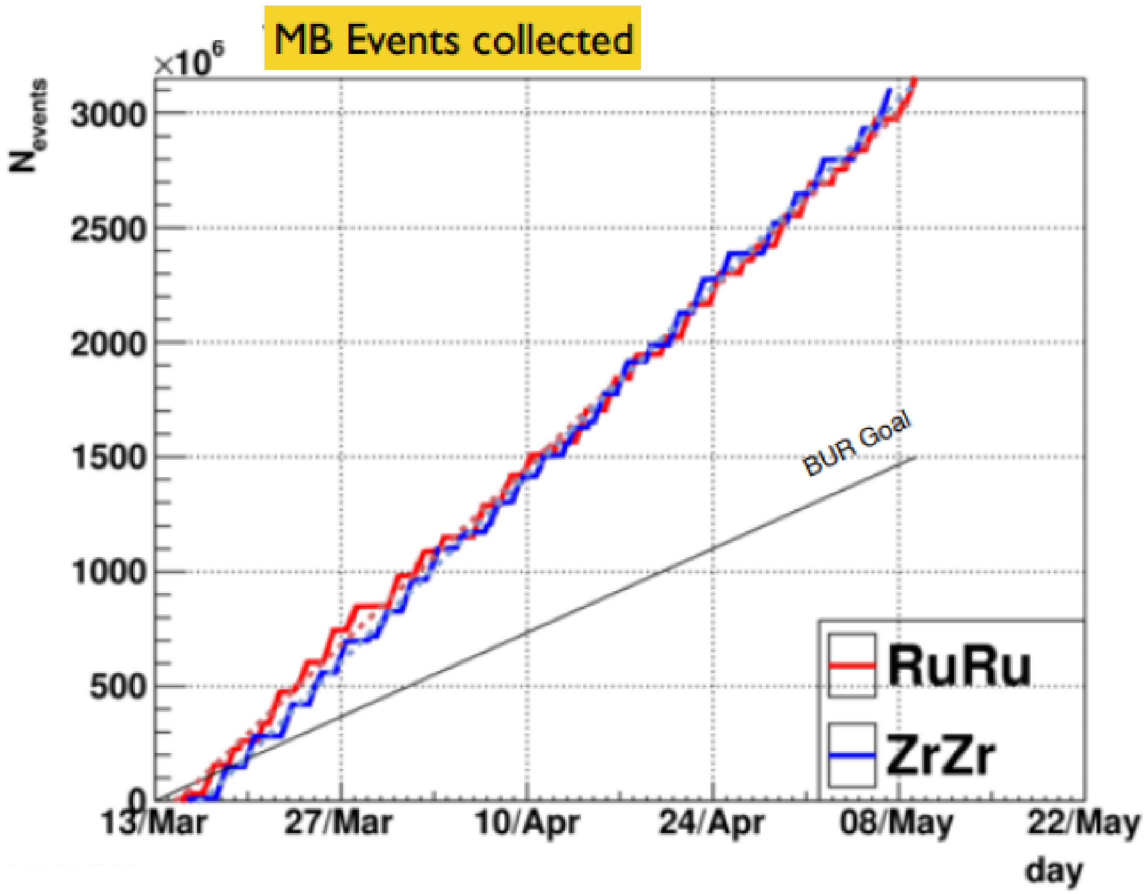
- Optimized luminosity: maximum STAR data acquisition rate and minimum background and pile-up
  - Stable luminosity leveling at ZDC ~10K Hz (L ~ 2.2 x 10^{27}cm^{-2}s^{-1})
  - Stochastic beam cooling to control emittance
- Rapid (~daily) switching between Ru and Zr: minimize systematic uncertainties
  - 20 hr/store/isobar
- Maximize the purity and reconstruction efficiency: minimum-bias trigger with tight vertex cut (with VPD ±30cm)

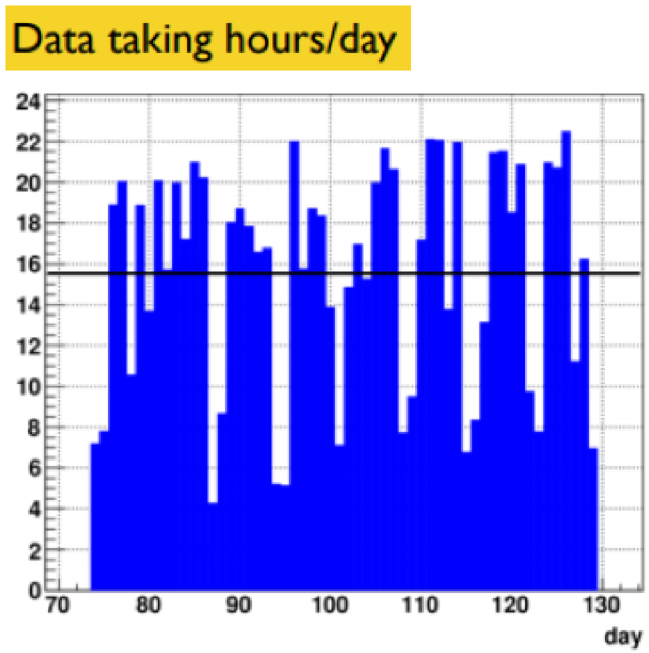
Data taking for isobaric collisions

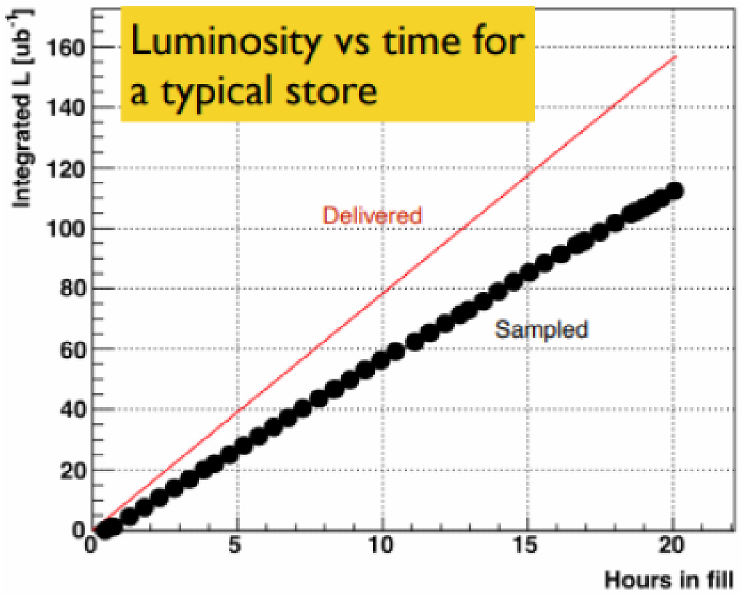


- Consistently stable luminosity with long (~20 hr) store length
- Minimum-bias data taking rates ~2k Hz (initial estimate 1.5k Hz)

Data taking for isobaric collisions

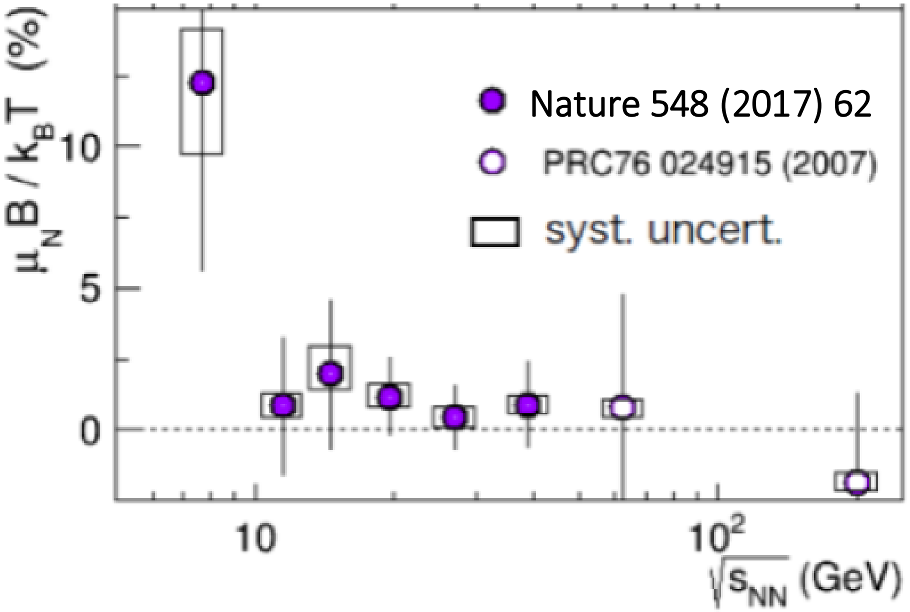






- Collected 3.1B minimum-bias events for both Ru+Ru and Zr+Zr (vs goal 1.5B) [3/15-5/9]
- Good event fraction ~ 95%

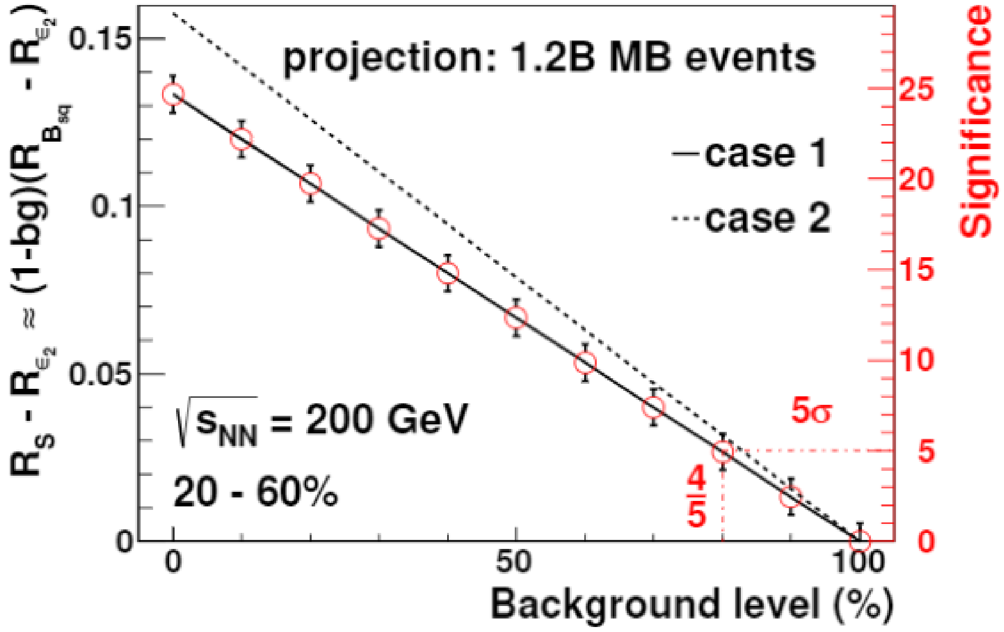
My personal outlook: new possibility (isobars at 27 GeV)

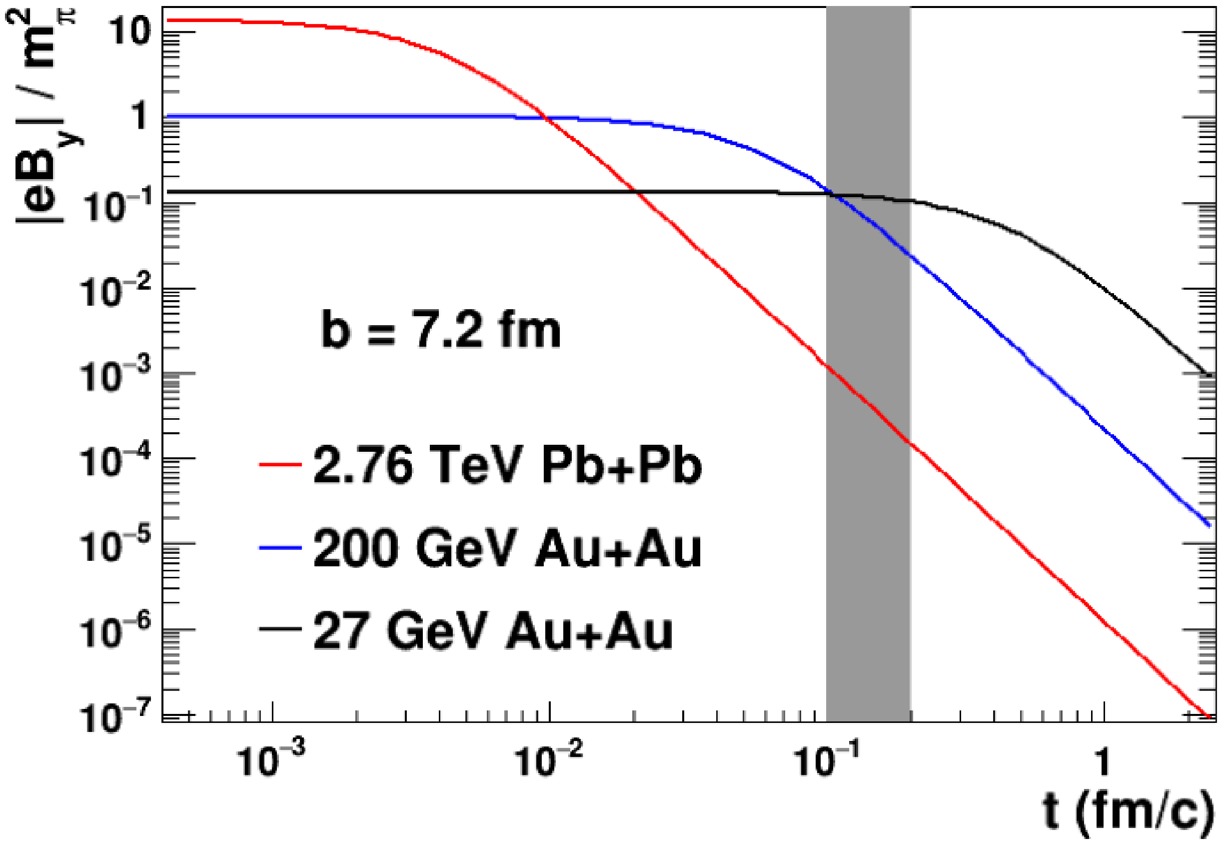


If one of the following conditions is met, then I would advocate Ru+Ru and Zr+Zr at 27 GeV:

1) Au+Au at 27 GeV: significant B-field

2) Ru+Ru and Zr+Zr at 200 GeV: significant CME signal





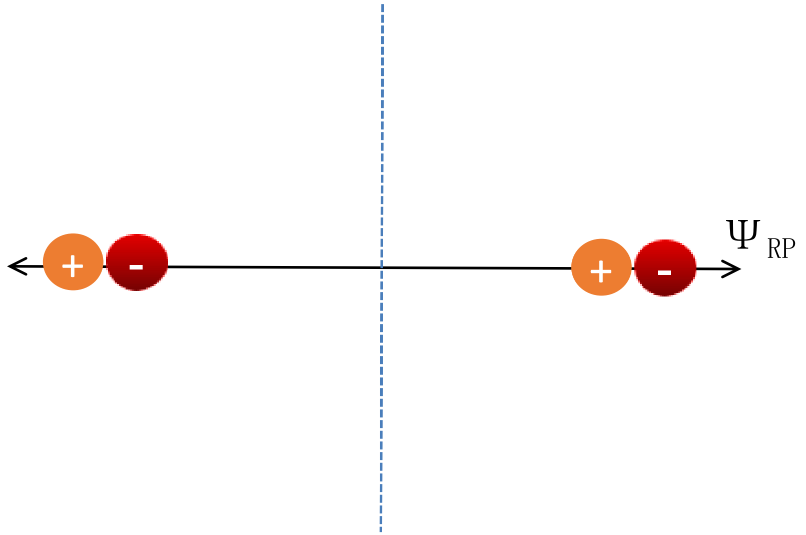
Backup

γ_{112} vs γ_{123}

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

Aparent 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

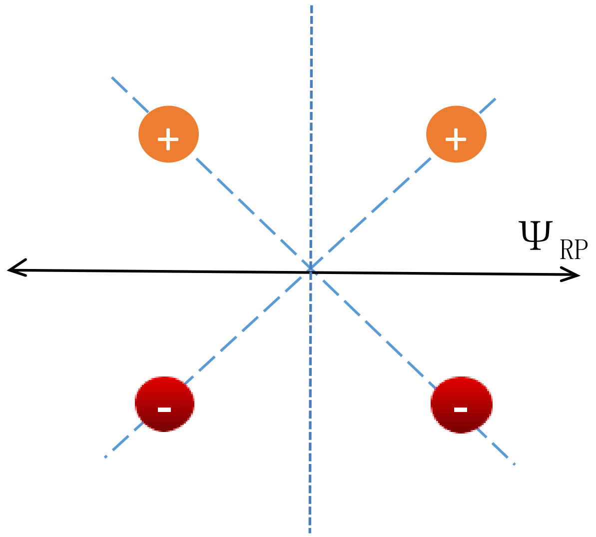


$v_2 = 1$ $\quad v_3 = 0$

$\gamma_{112,SS} = -1$ $\quad \gamma_{123,SS} = 0$

$\gamma_{112,OS} = 0$ $\quad \gamma_{132,OS} = 0$

$\Delta\gamma_{112} = 1 \quad \Delta\gamma_{123} = 0$

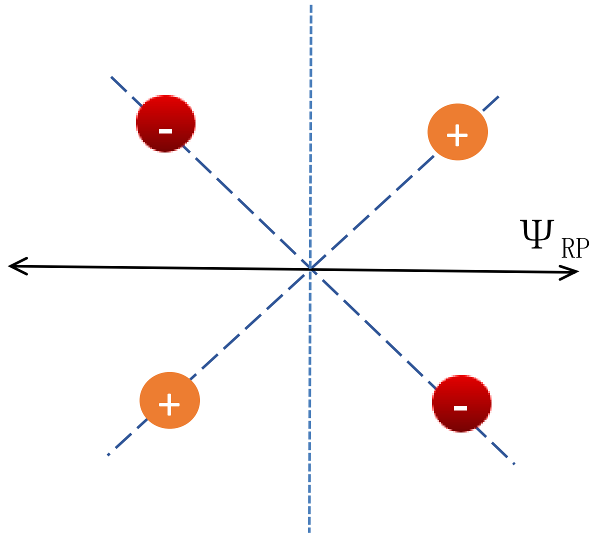


$v_2 = 0$ $\quad v_3 = 0$

$\gamma_{112,SS} = -1$ $\quad \gamma_{123,SS} = 0$

$\gamma_{112,OS} = 1/2$ $\quad \gamma_{123,OS} = 0$

$\Delta\gamma_{112} = 3/2 \quad \Delta\gamma_{123} = 0$



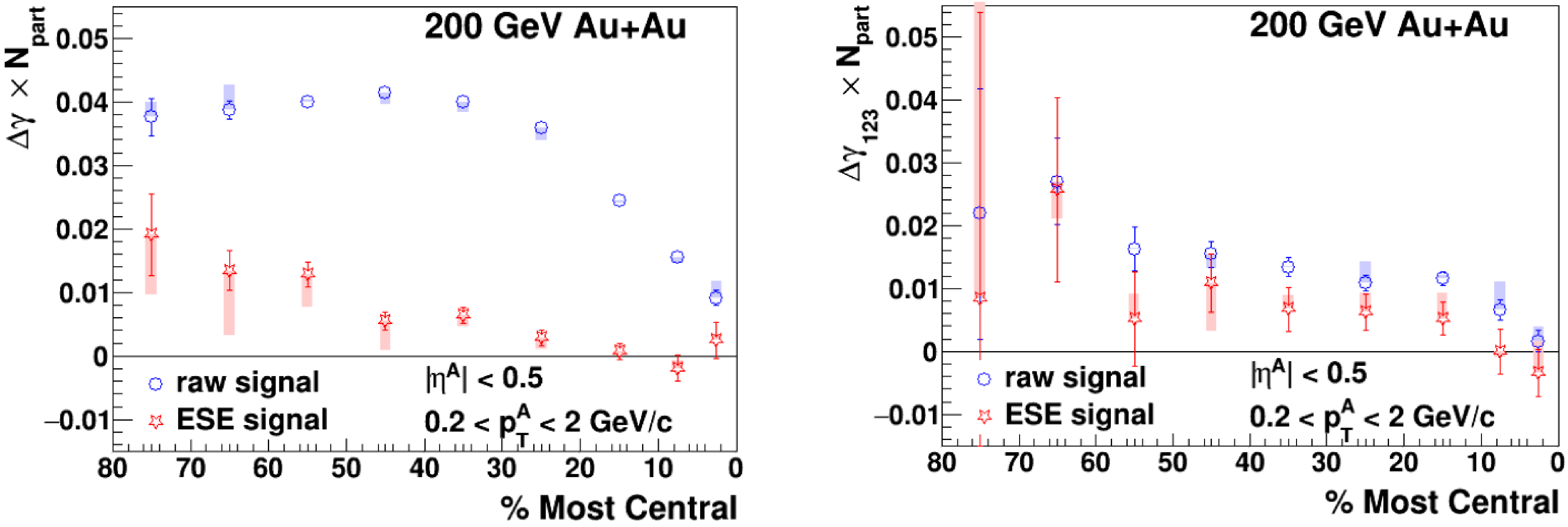
$v_2 = 0$ $\quad v_3 = 0$

$\gamma_{112,SS} = 0$ $\quad \gamma_{123,SS} = 0$

$\gamma_{112,OS} = 0$ $\quad \gamma_{123,OS} = 0$

$\Delta\gamma_{112} = \Delta\gamma_{123} = 0$

ESE: γ_{123}



- The raw signals are different between γ_{112} and γ_{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 $v_{2(3)}$? CME?