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APS physics

STAR

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Search for the Chiral Magnetic Effect Using STAR BES-II Data with Event Shape Selection

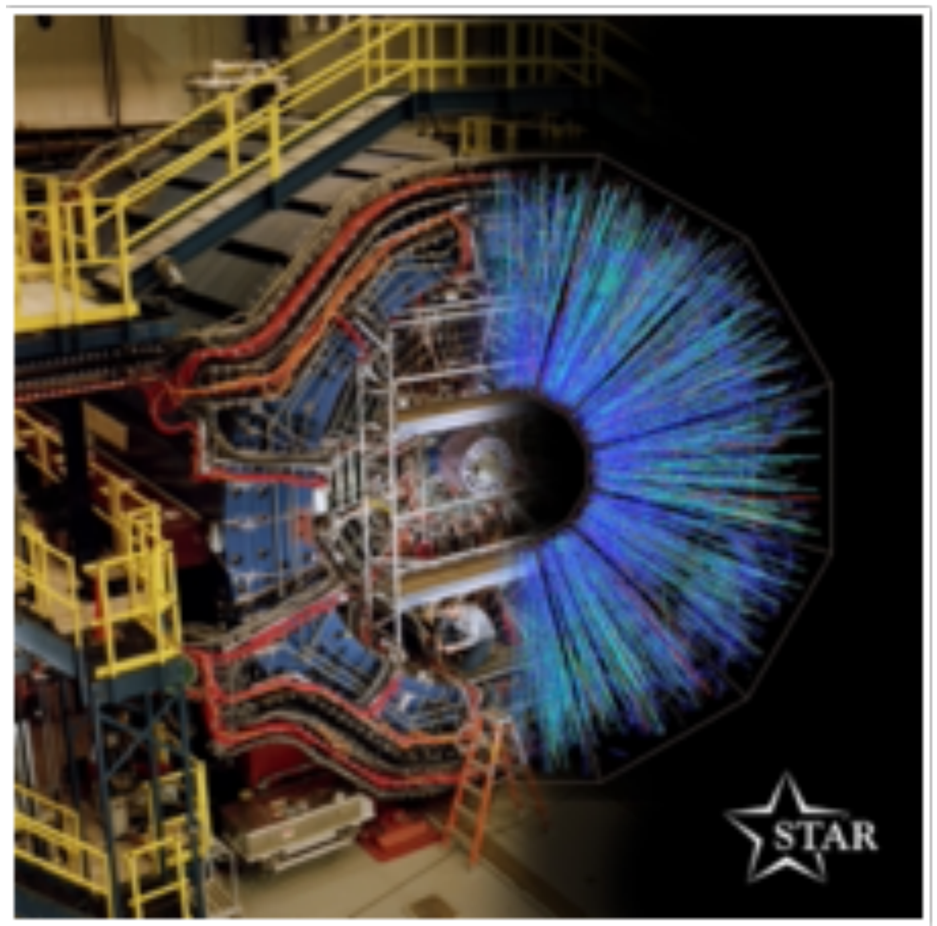
Zhiwan Xu (UCLA)

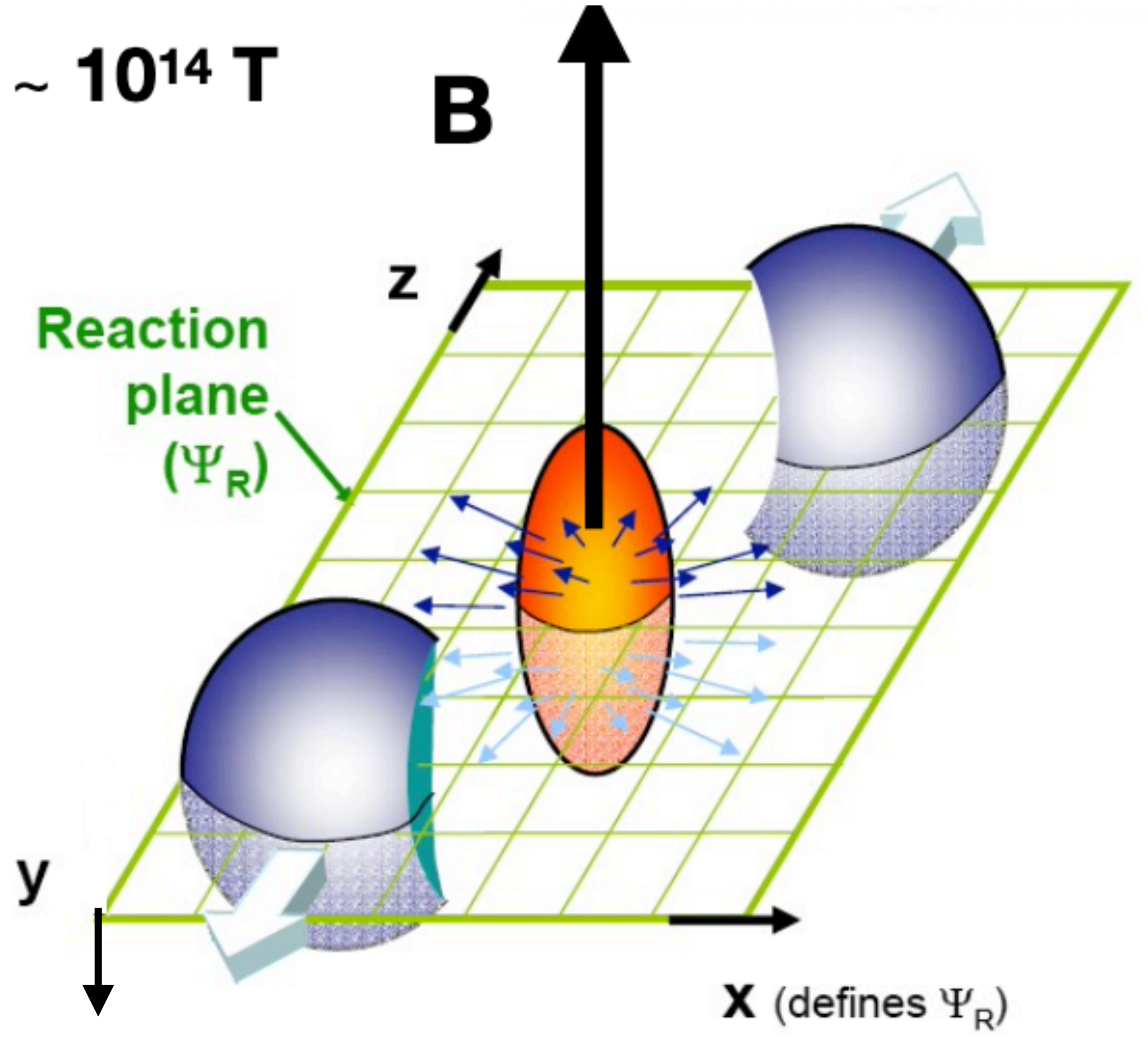
For the STAR Collaboration

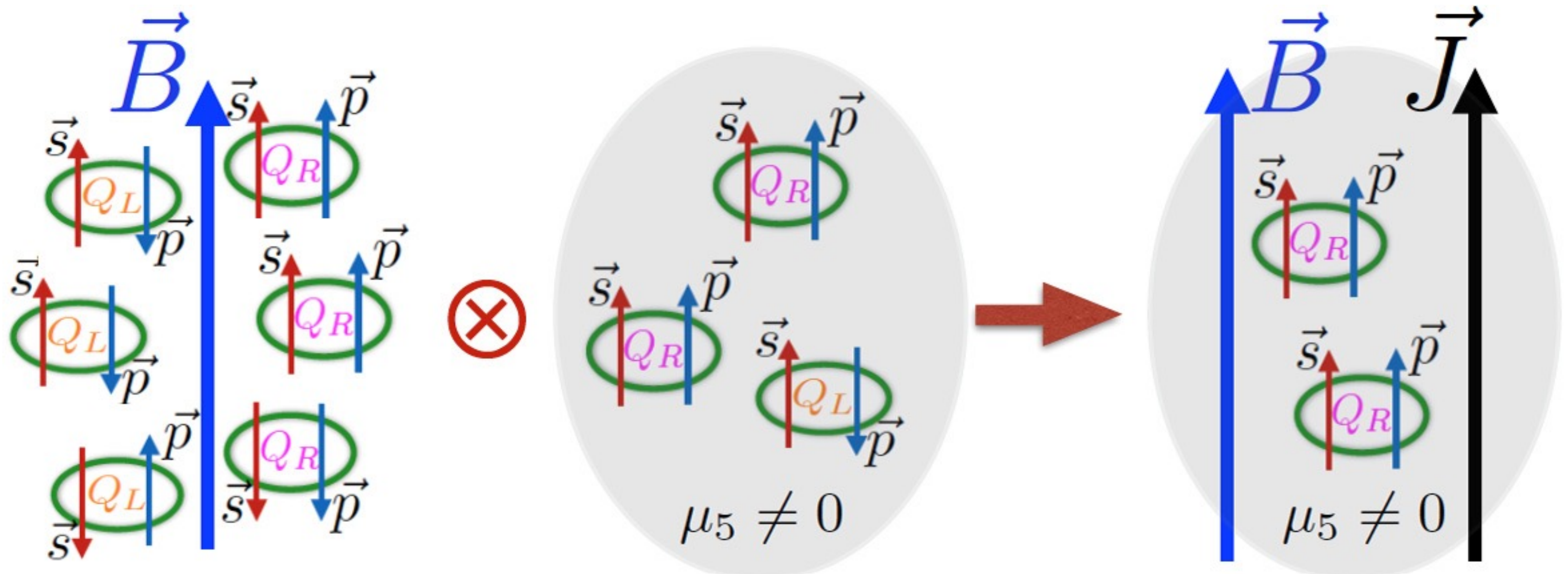
October 29, 2022

Chiral Magnetic Effect

D. Kharzeev, Phys. Lett. B 633, 260 (2006).
S. A. Voloshin, Phys. Rev. C 70, 057901 (2004).







- Chirality imbalance coupled with strong magnetic field induces a charge separation along the B field direction (violates Parity Symmetry dynamically in strong interaction!)
- To quantify the collective motions including the charge separation, we expand the particle azimuthal angle distribution as:

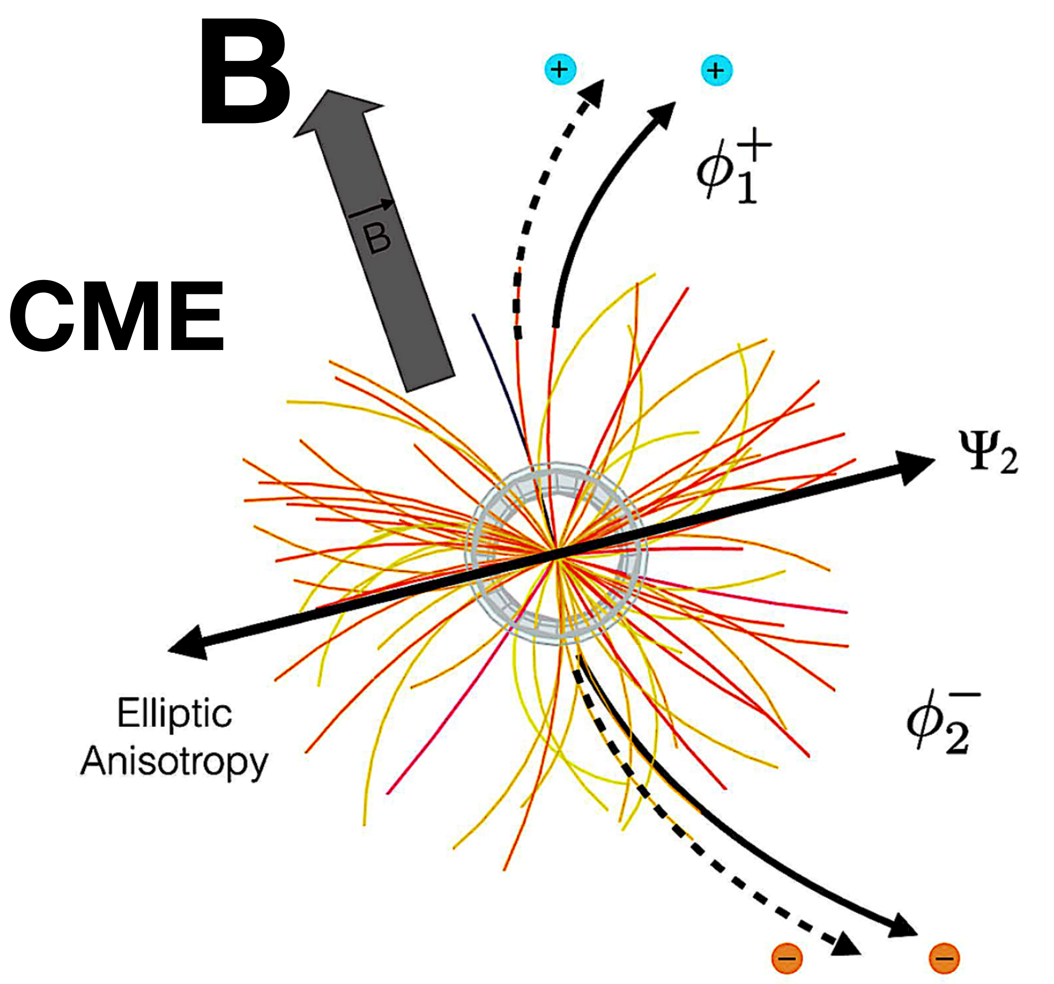
$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_{\mathrm{RP}}) + 2v_2 \cos[2(\phi - \Psi_{\mathrm{RP}})] + \cdots + 2a_\pm \sin(\phi - \Psi_{\mathrm{RP}}) + \cdots,$$

$$\propto \ \mu_5 |\vec{\mathbf{B}}|.$$

Chiral Magnetic Effect

D. E. Kharzeev, J. Liao, S. A. Voloshin, and G. Wang, Prog. Part. Nucl. Phys. 88, 1 (2016).

CME



$\propto a_1 \cdot a_1$

$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_{RP}) \rangle = \langle \cos(\phi_1 - \psi_{RP}) \cos(\phi_2 - \psi_{RP}) \rangle - \langle \sin(\phi_1 - \psi_{RP}) \sin(\phi_2 - \psi_{RP}) \rangle$$

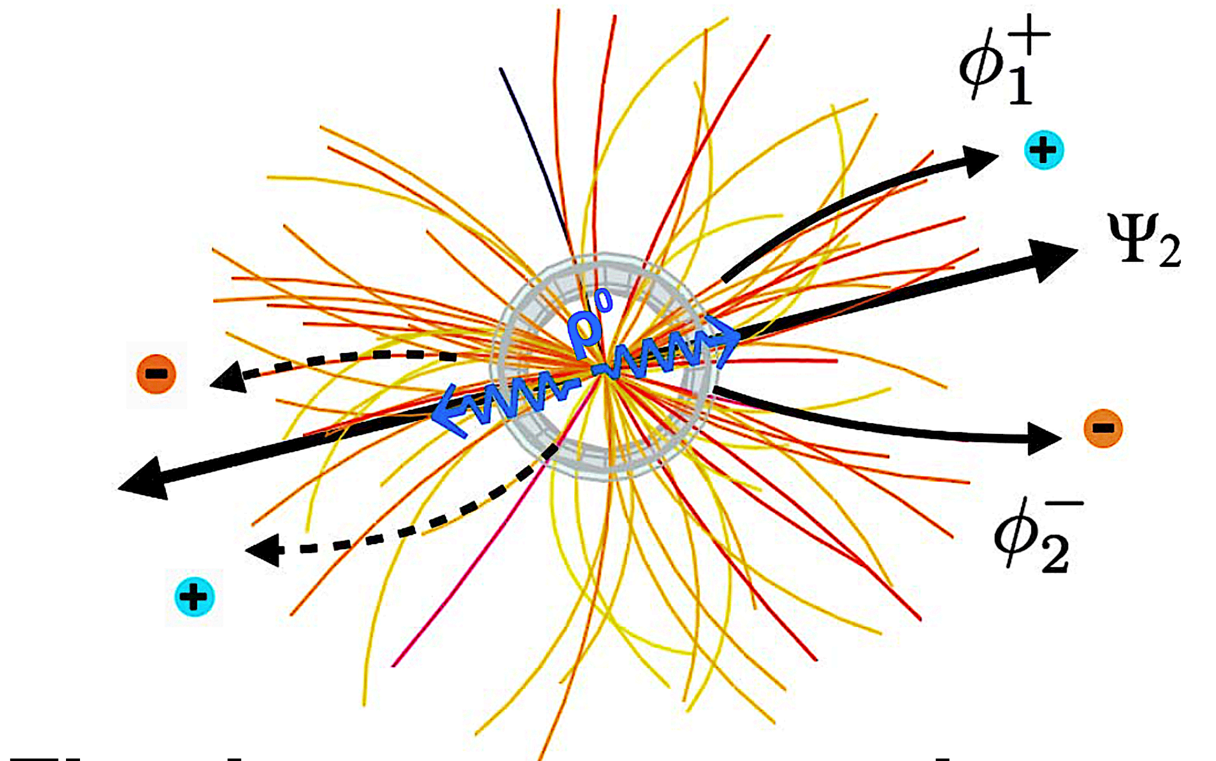
- **CME signal: difference between opposite-sign and same-sign correlation**

$$\Delta\gamma^{CME} = \gamma^{OS} - \gamma^{SS} > 0$$

- **Decay of flowing resonance** $\propto v_2$

$$\Delta\gamma^{reso} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2}{N}$$

Non-CME



Flowing resonance decay

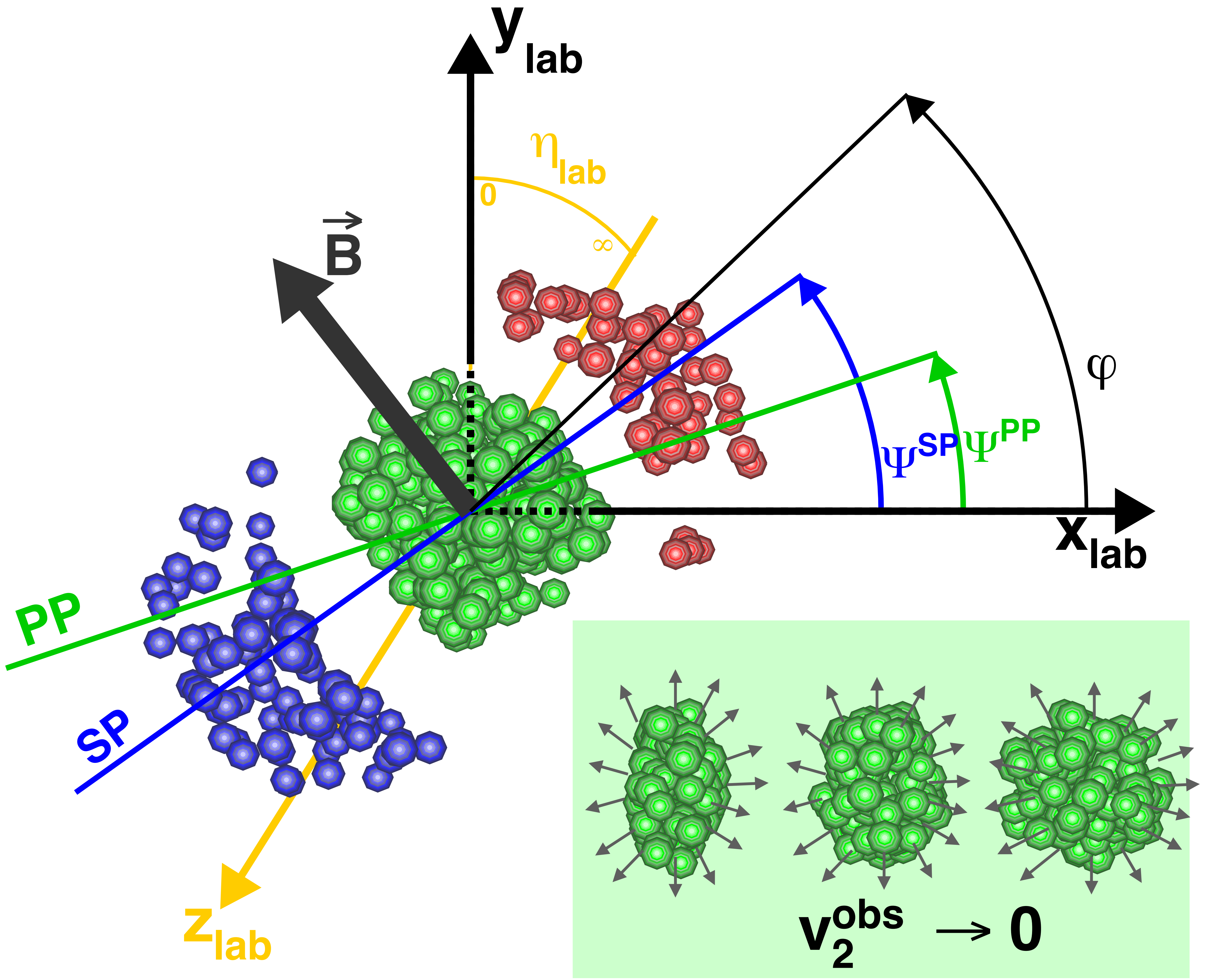
$$\Delta\gamma^{112} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measured **Signal** **Backgrounds**

- **Indicator of background** $\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_{RP}) \rangle \sim v_2\delta$
- **In experiment** $\psi_{RP} \rightarrow \psi_2$ or ψ_1

Event Shape Selection

R. Milton, G. Wang, M. Sergeeva, S. Shi, J. Liao, and H. Z. Huang, Phys. Rev. C 104, 064906 (2021).



- **Flow vector to control the event shape:**

$$\vec{q_n}^{A} = (q^{A}_{n,x}, q^{A}_{n,y})$$

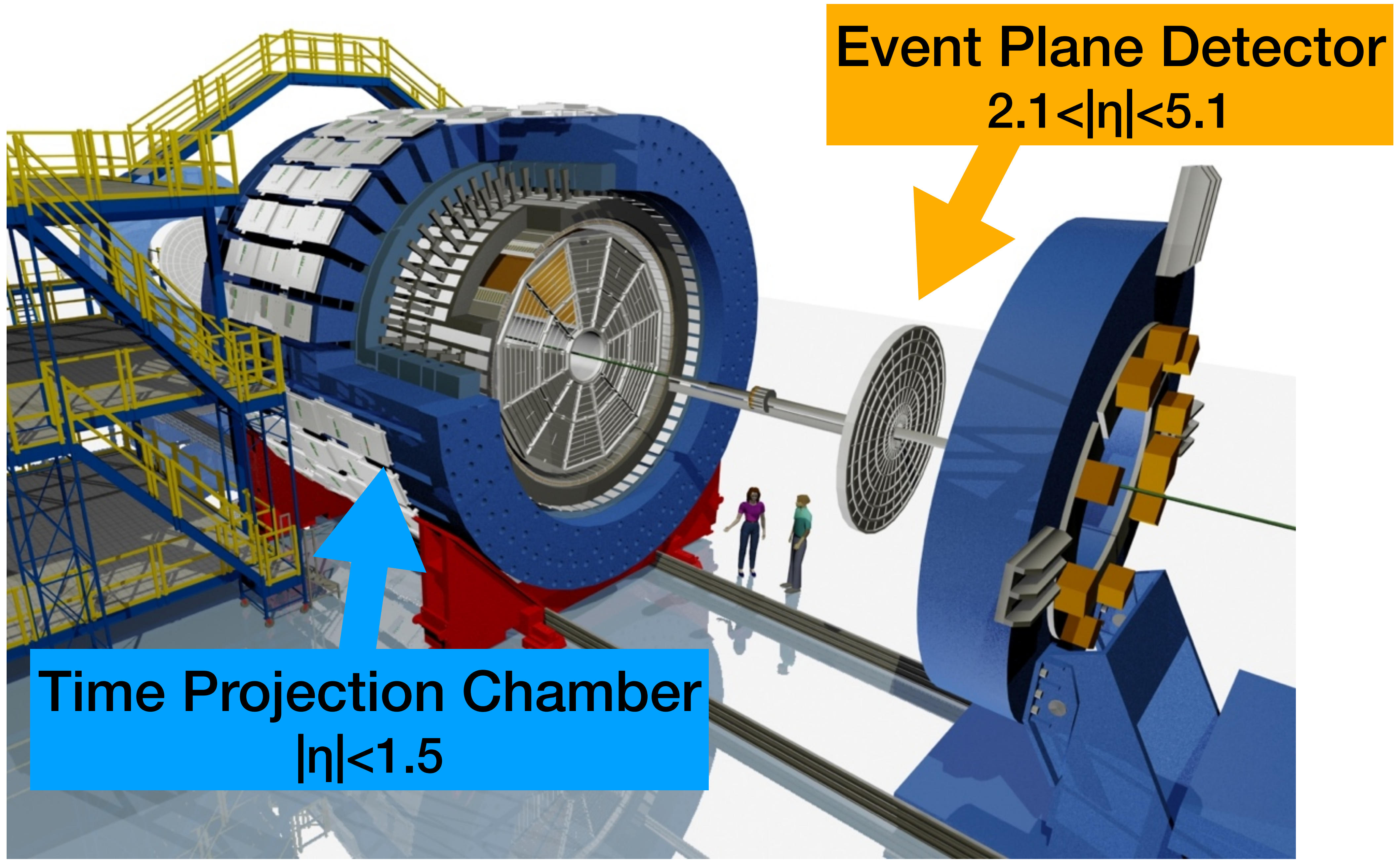
$$q^{A}_{n,x} = \frac{1}{\sqrt{N}}\sum_{i}^{N}\cos(n\phi_i^{A}),$$

$$q^{A}_{n,y} = \frac{1}{\sqrt{N}}\sum_{i}^{N}\sin(n\phi_i^{A}),$$

- **For events in each q^A class, v_2 and Δγ are measured using POIs in sub-event (A), and EP estimated from independent sub-event (B).**
    - $\Delta\gamma(q_2^2)$ **and** $v_2(q_2^2) \rightarrow \Delta\gamma(v_2)$
- **Event Shape Selection (ESS) approach**

$$\underset{\text{Measured}}{\underset{\downarrow}{\Delta\gamma^{112}}} = \underset{\text{Signal}}{\underset{\downarrow}{\Delta\gamma^{\text{CME}}}} + \underbrace{\cancelto{\text{ESS}}{k\frac{v_2}{N}} + \cancelto{\text{EPD plane}}{\Delta\gamma^{\text{non-flow}}}}_{\text{Backgrounds}}$$

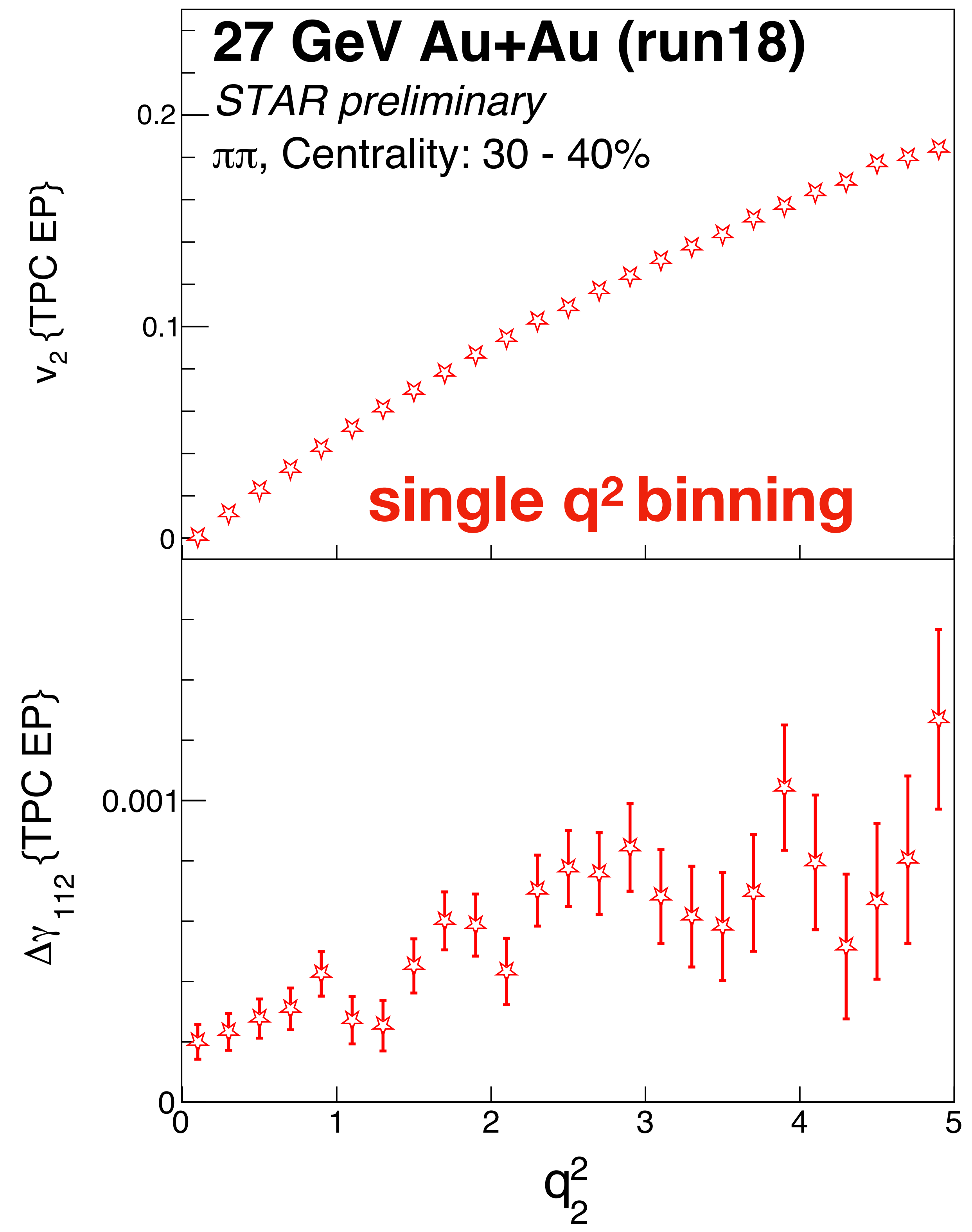
$\Delta\gamma^{112}$ and v_2 {TPC EP} at 27 GeV



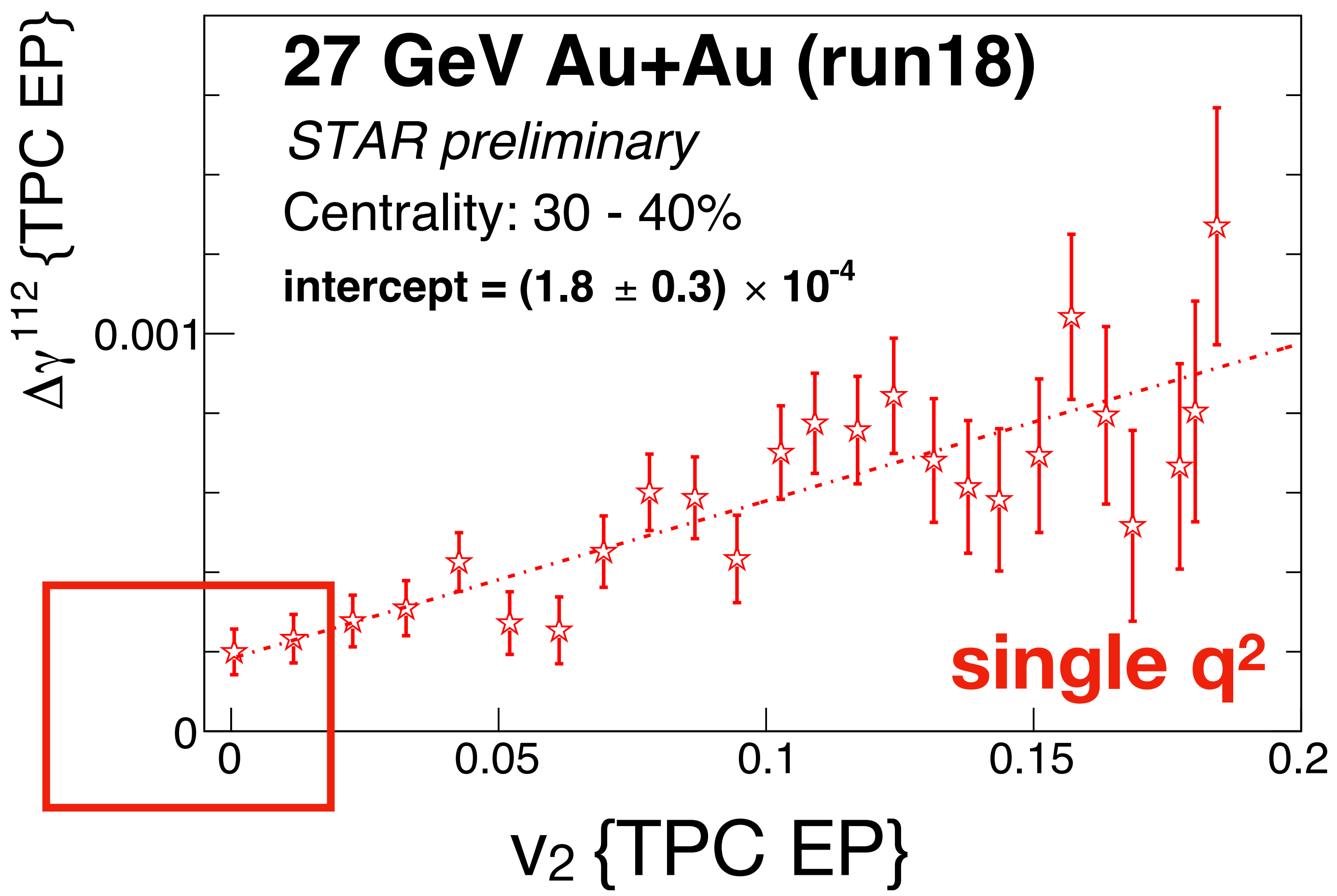
Event Plane Detector
$2.1<|\eta|<5.1$

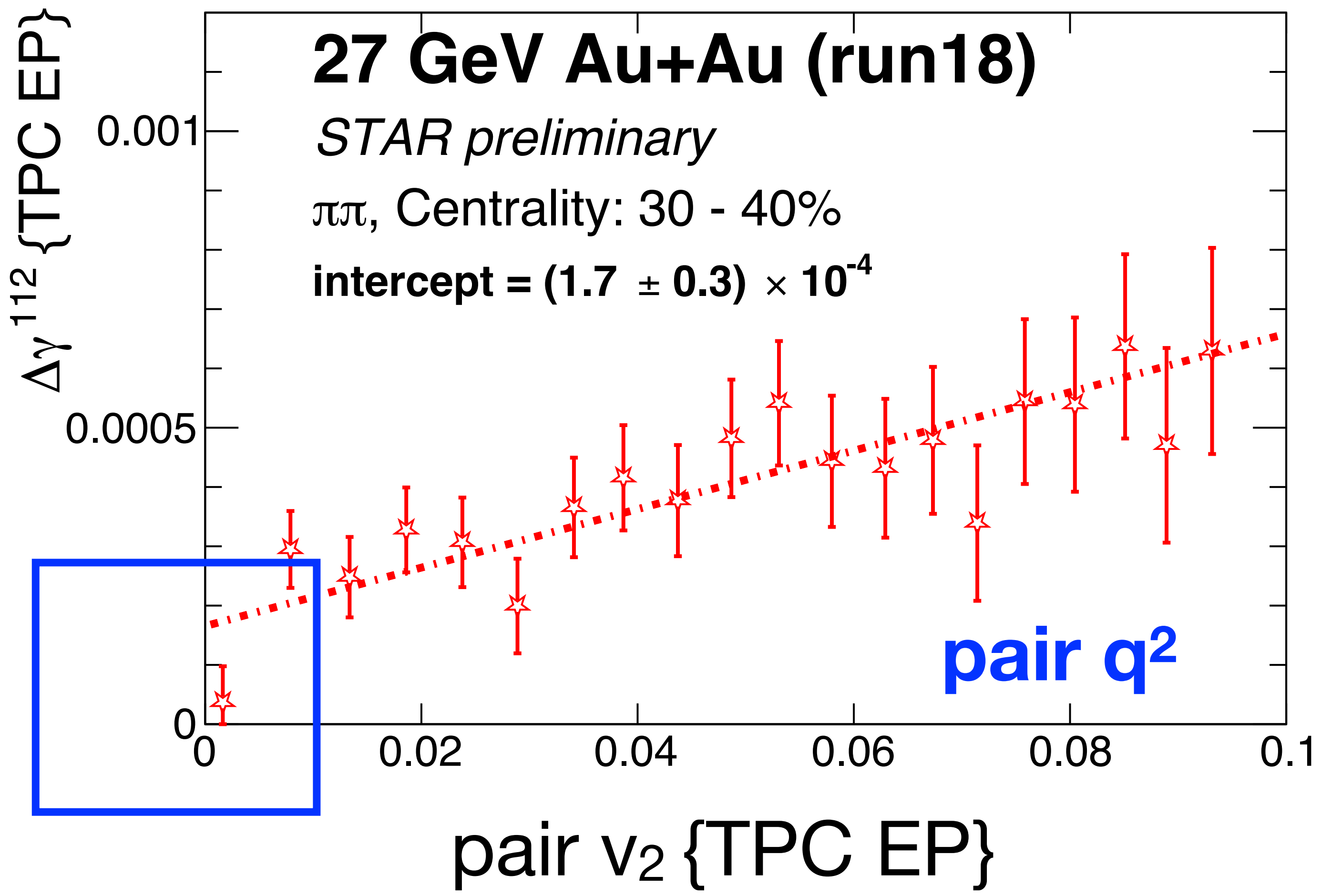
Time Projection Chamber
$|\eta|<1.5$

Current STAR detector



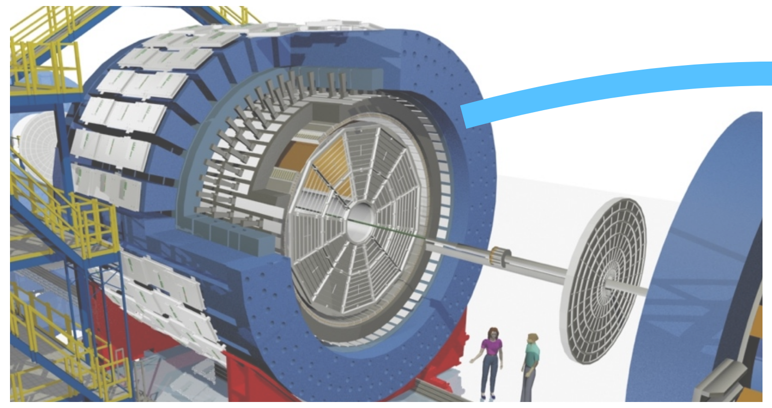
uncertainties are statistical





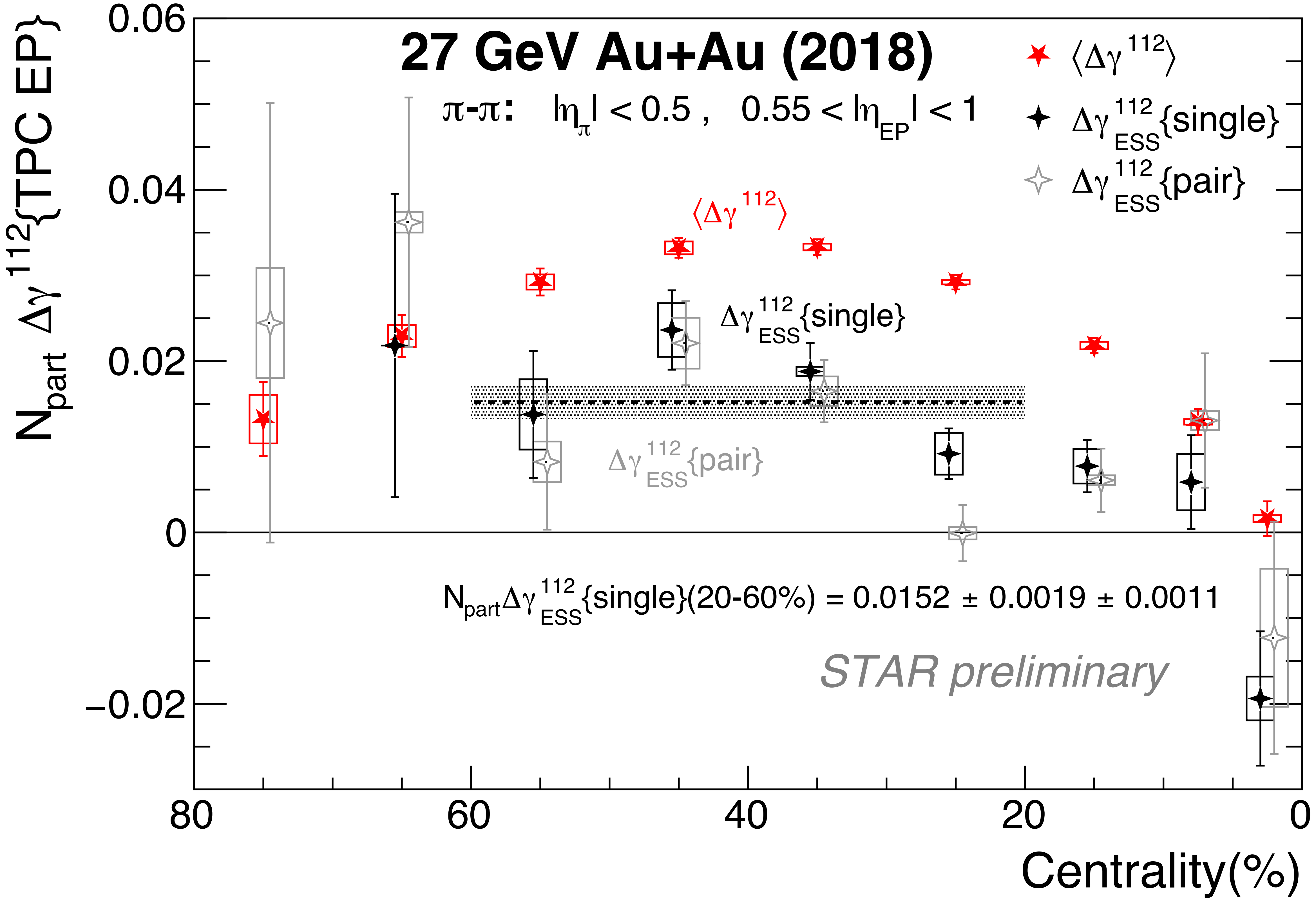
- **Event shape variables:**
  - single particle q^2 ~ primary particles
  - pair parent q^2 ~ resonance decay
  - pair parent obtained from adding momenta of two particles to mimic decay kinematics
- **Both ESS approaches can extrapolate** $\Delta\gamma^{112}_{ESS} = (1-2v_2)\cdot$ Intercept

ESS at 27 GeV : TPC EP

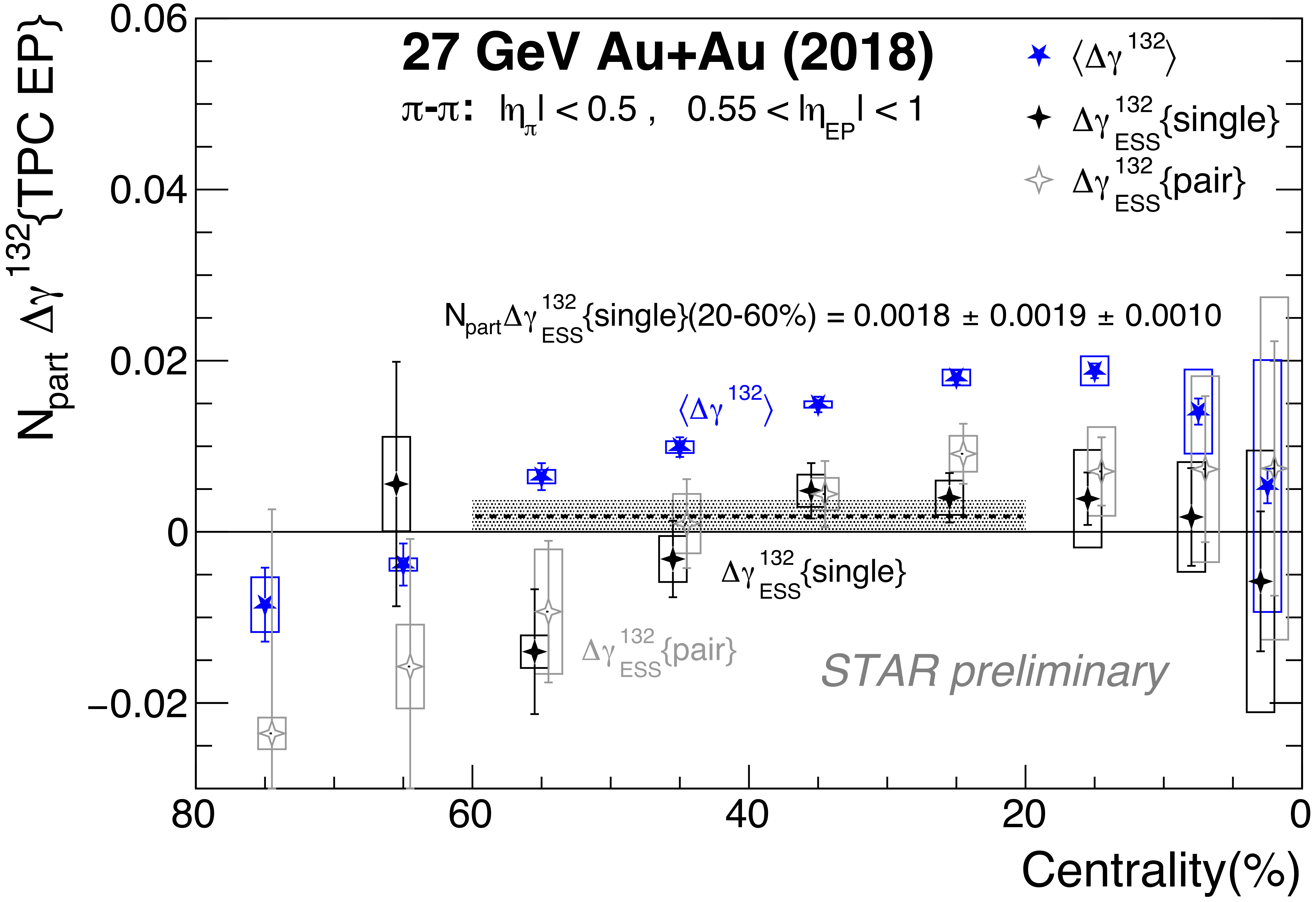


Time Projection Chamber
|η|<1

$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_2) \rangle$$

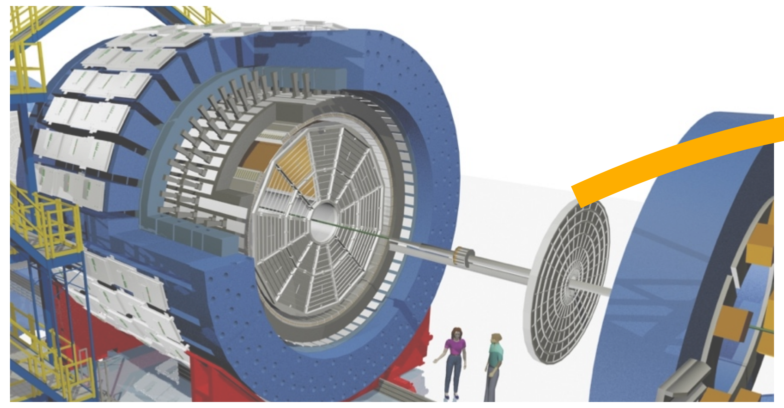


$$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_2) \rangle$$



- **ESS with TPC EP reduces the flow background, but residual non-flow correlation remains**
- $\Delta\gamma^{132}$ **(almost pure background) indicates ESS method removes substantial backgrounds**

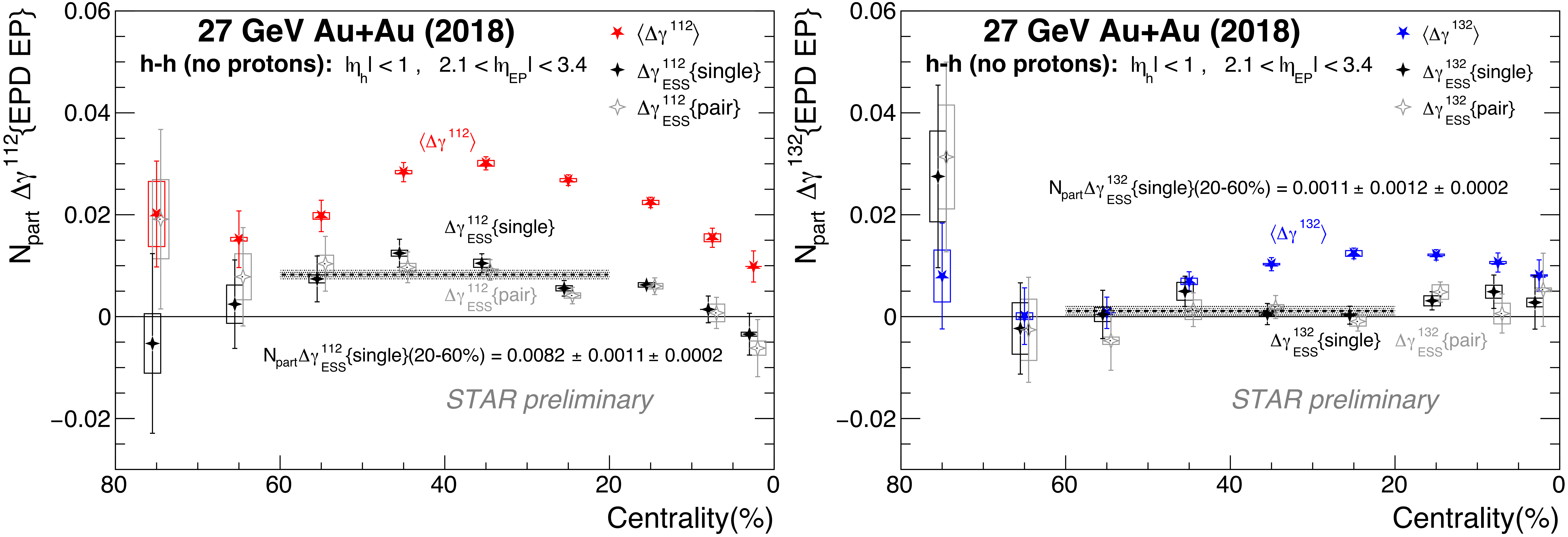
27 GeV : EPD 2nd-order EP



Event Plane Detector
2.1<|η|<5.1

$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_2) \rangle$$

$$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_2) \rangle$$

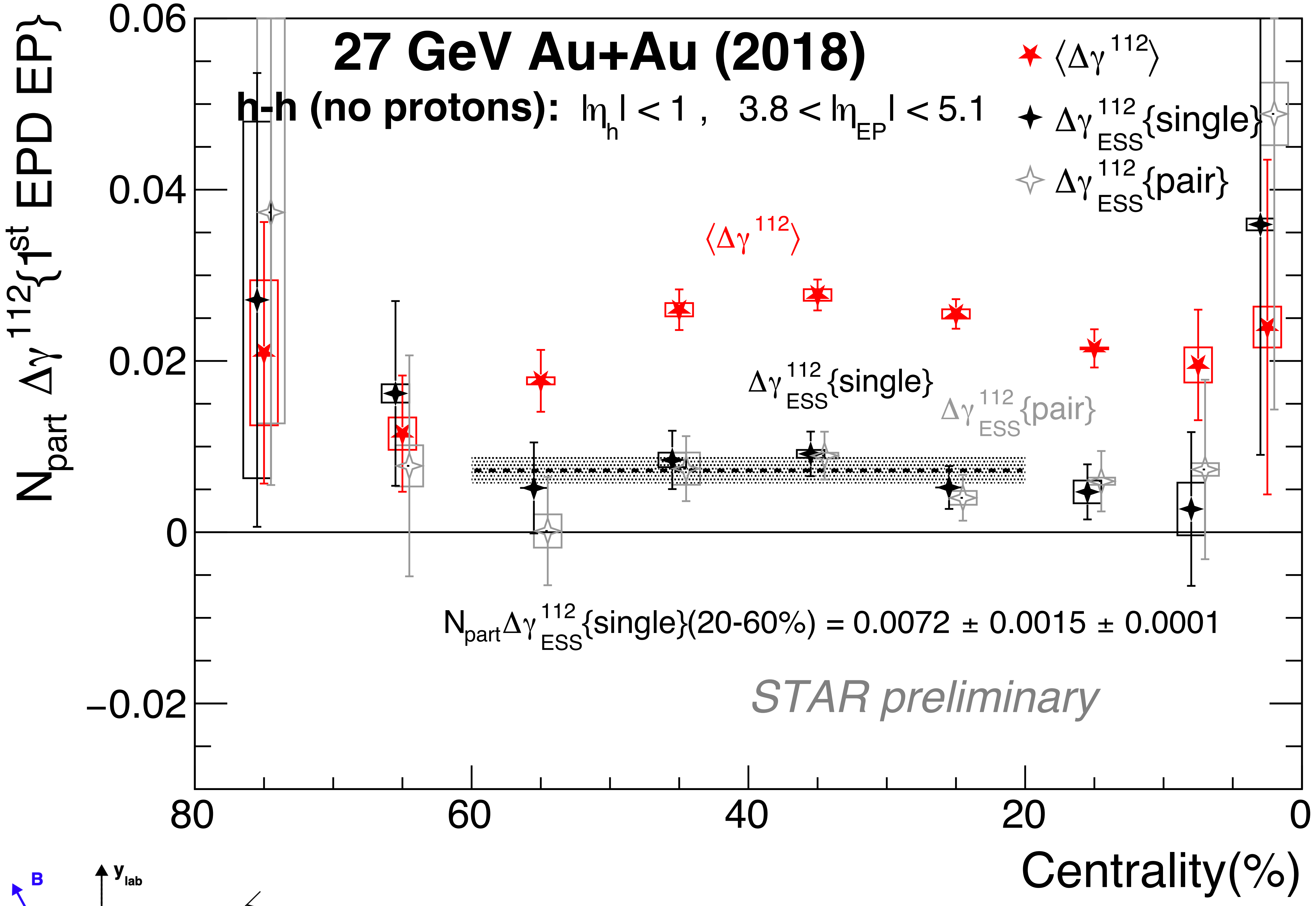


- Using EPD, short-range nonflow contribution is significantly suppressed
- Approaches with single and pair q_2^2 show similar results.
- Finite $\Delta\gamma^{112}_{ESS}$ in mid central events ; $\Delta\gamma^{132}_{ESS}$ consistent with zero for all centralities.

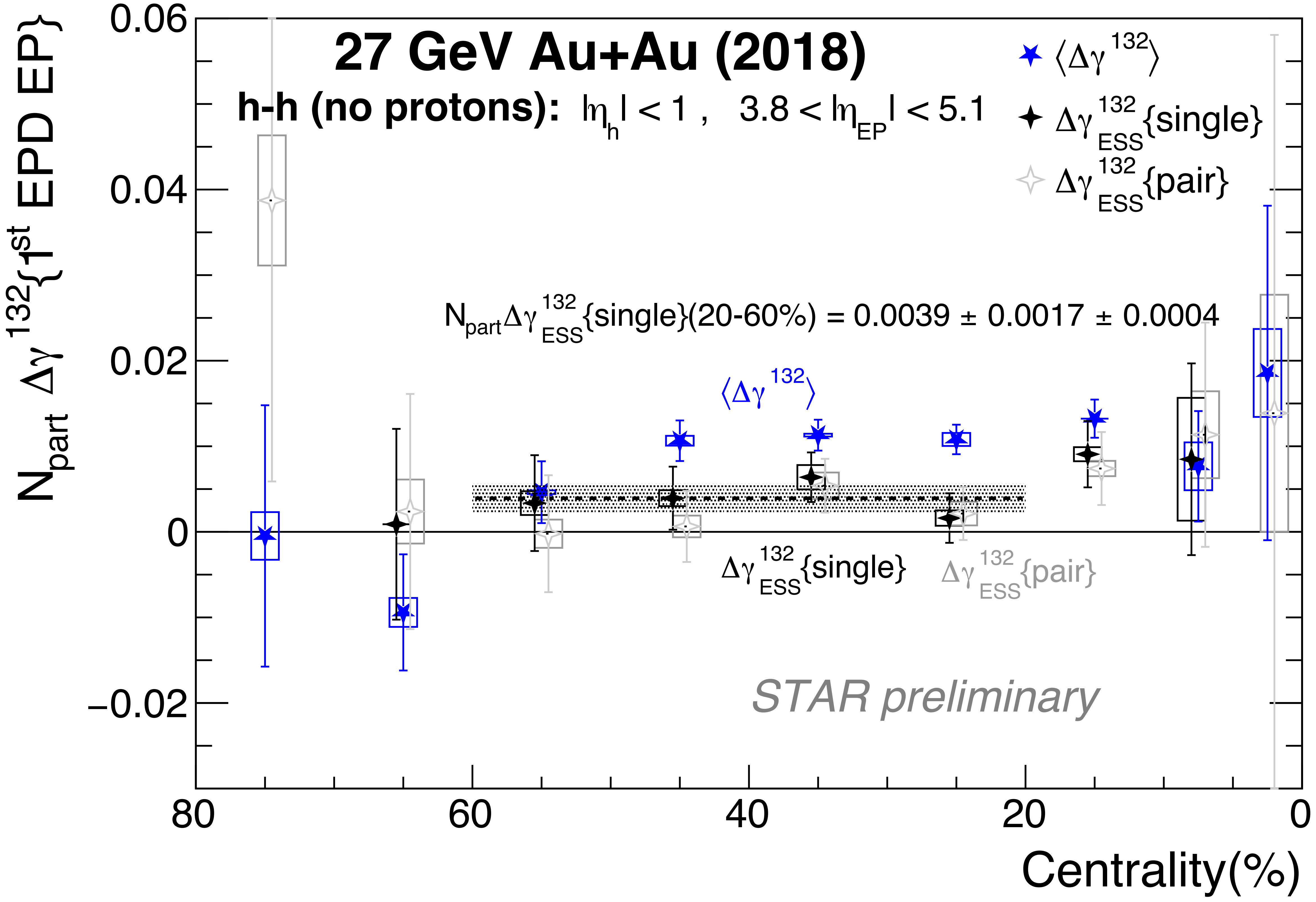
27 GeV : EPD spectator plane

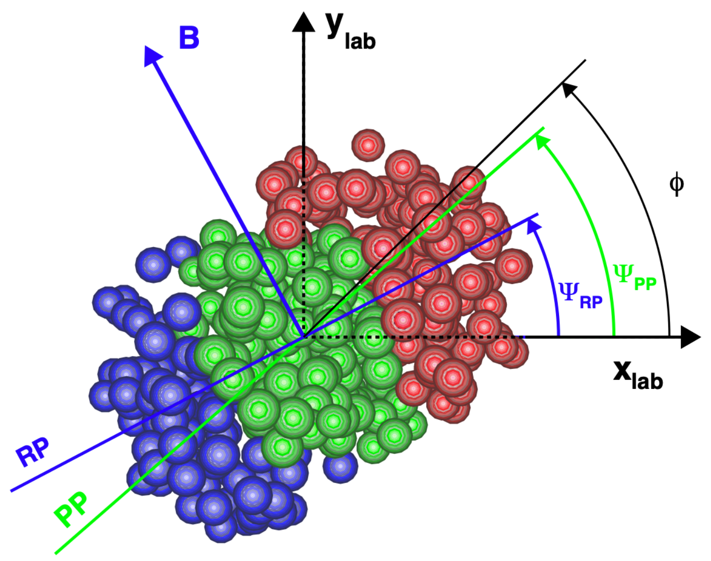
Event Plane Detector
2.1<|η|<5.1

$\gamma^{112} = \langle\cos(\phi_1 + \phi_2 - \psi_{1,e} - \psi_{1,w})\rangle$



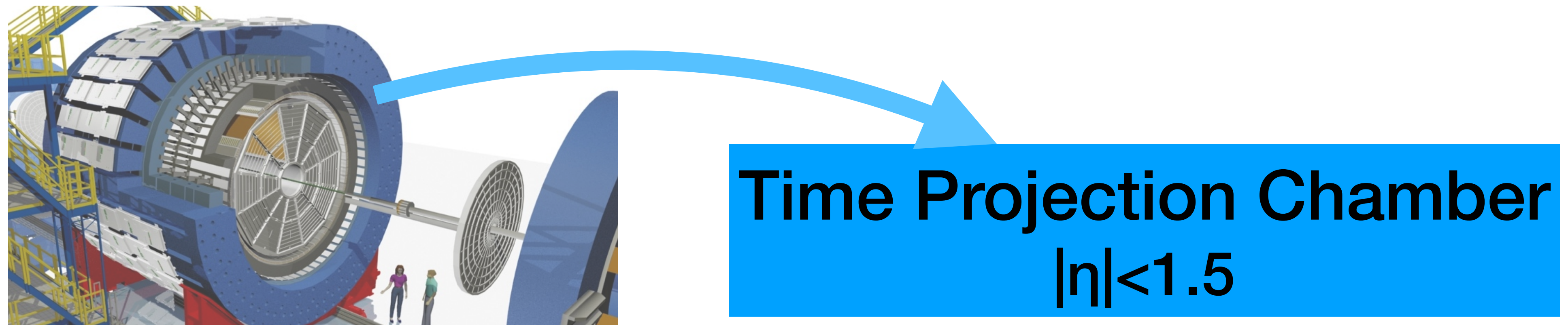
$\gamma^{132} = \langle\cos(\phi_1 - 3\phi_2 + \psi_{1,e} + \psi_{1,w})\rangle$



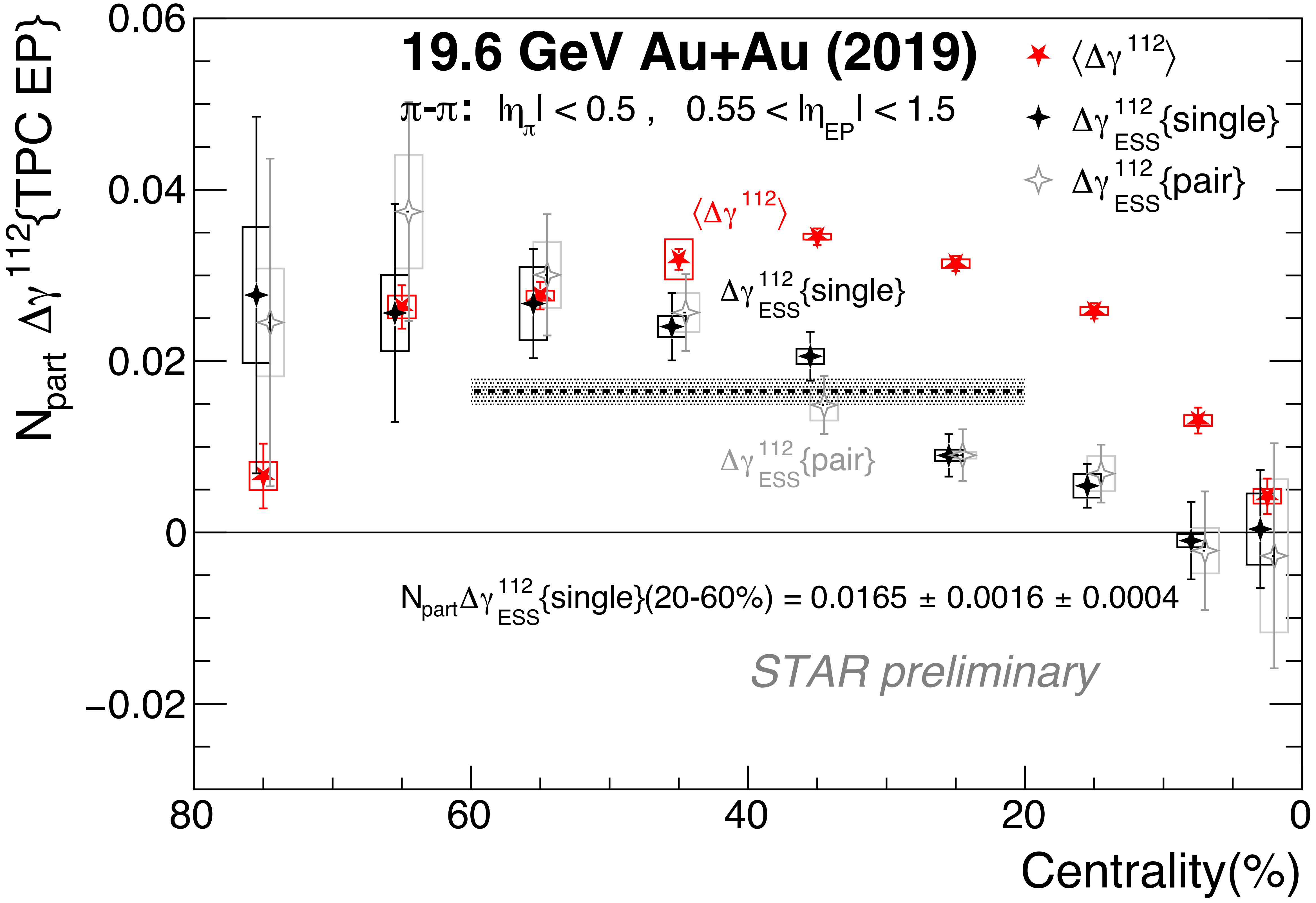


- **Spectator plane is more correlated to the magnetic field direction.**
- **Finite $\Delta\gamma^{112}_{ESS}$ in mid central events**
- **$\Delta\gamma^{132}_{ESS}$ consistent with zero (2 σ) for all centralities.**

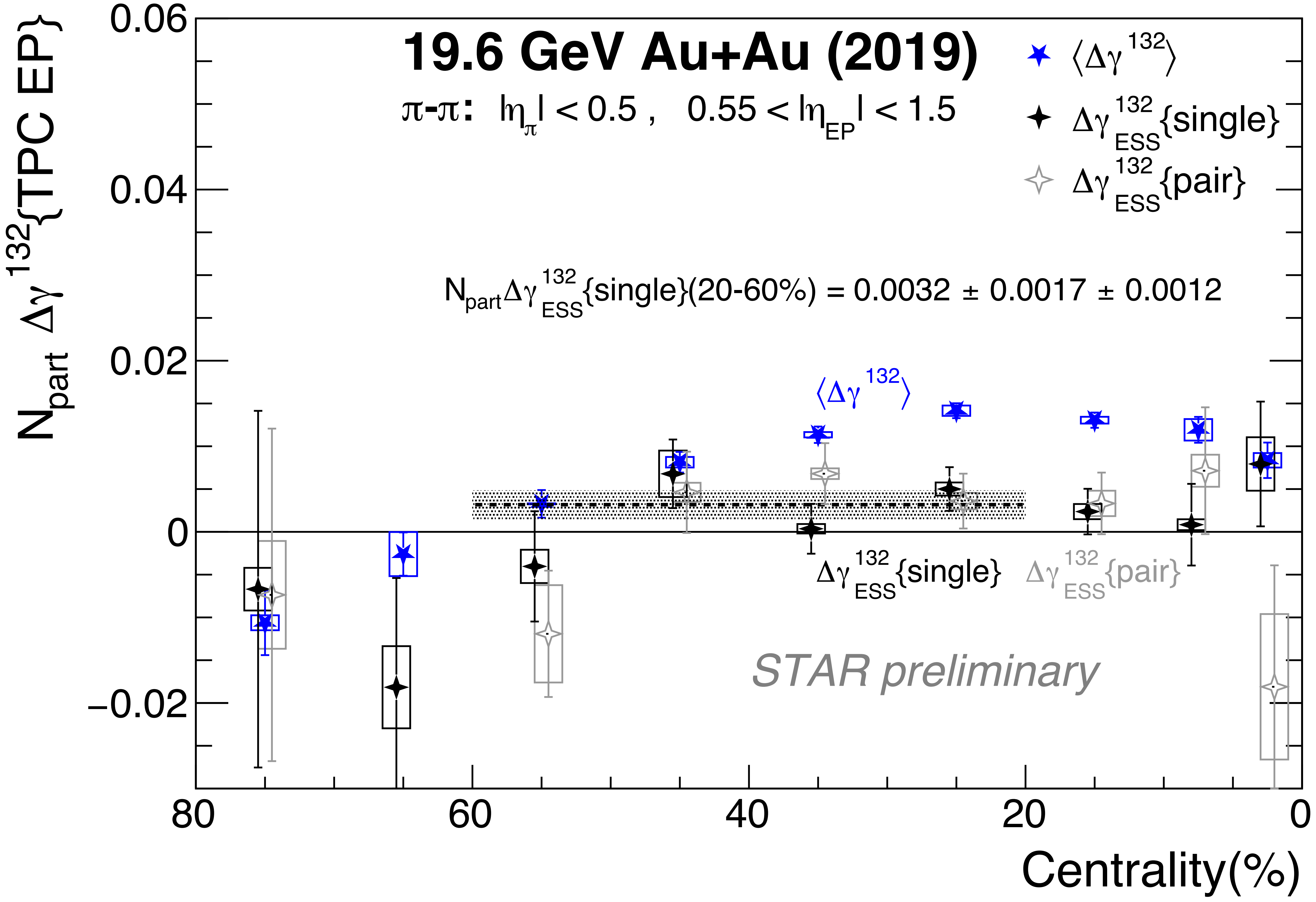
19.6 GeV : TPC EP



$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_2) \rangle$$

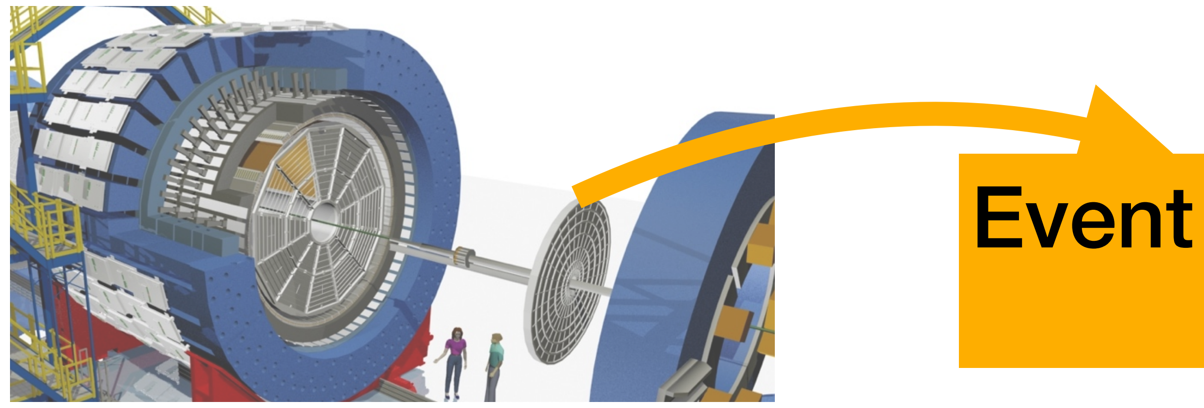


$$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + 2\psi_2) \rangle$$



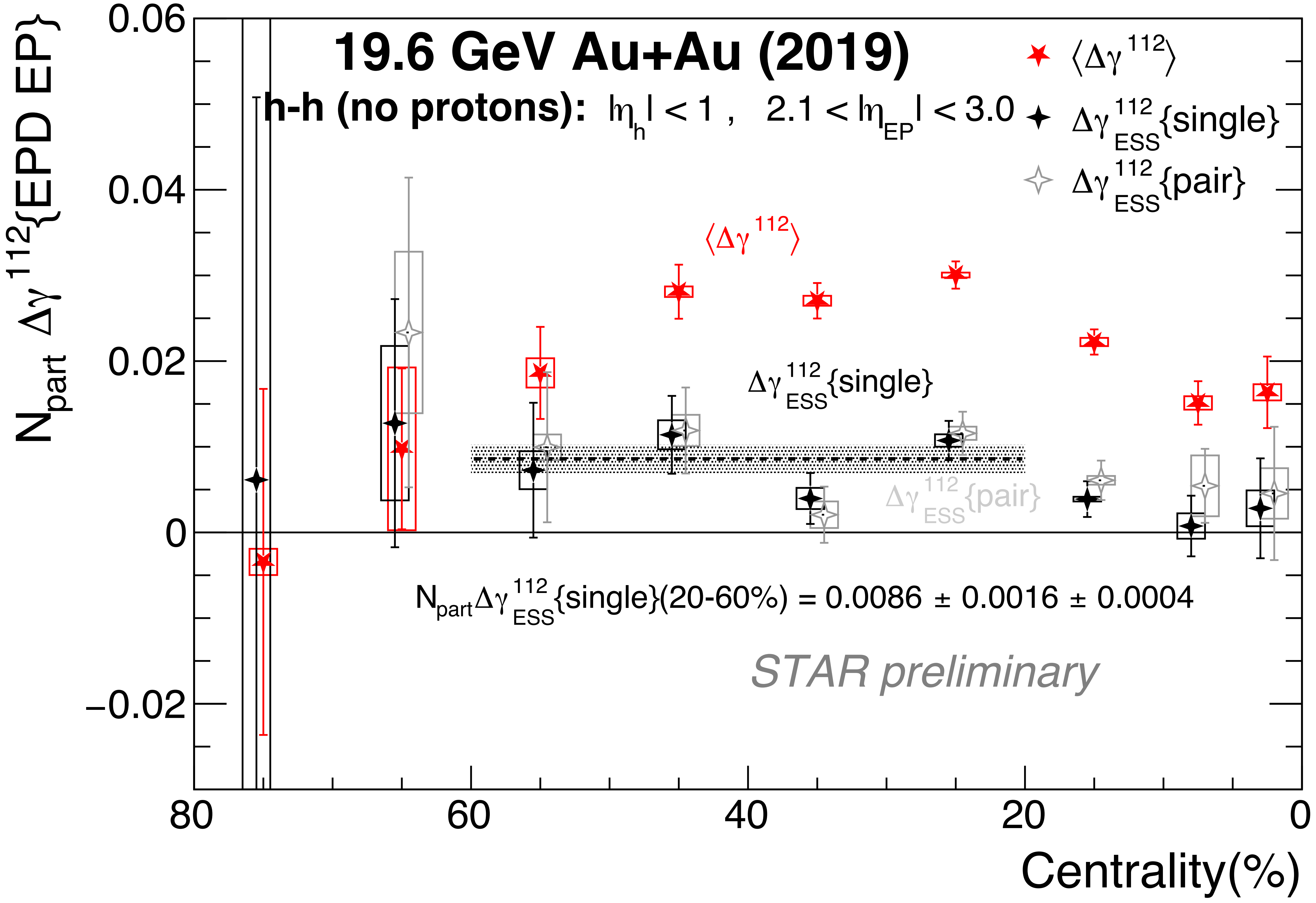
- **In general, 19.6 GeV data show similar behavior as 27 GeV.**
- **Finite $\Delta\gamma^{112}_{ESS}$ in mid-central, non-flow largely affects peripheral region.**

19.6 GeV : EPD 2nd-order EP

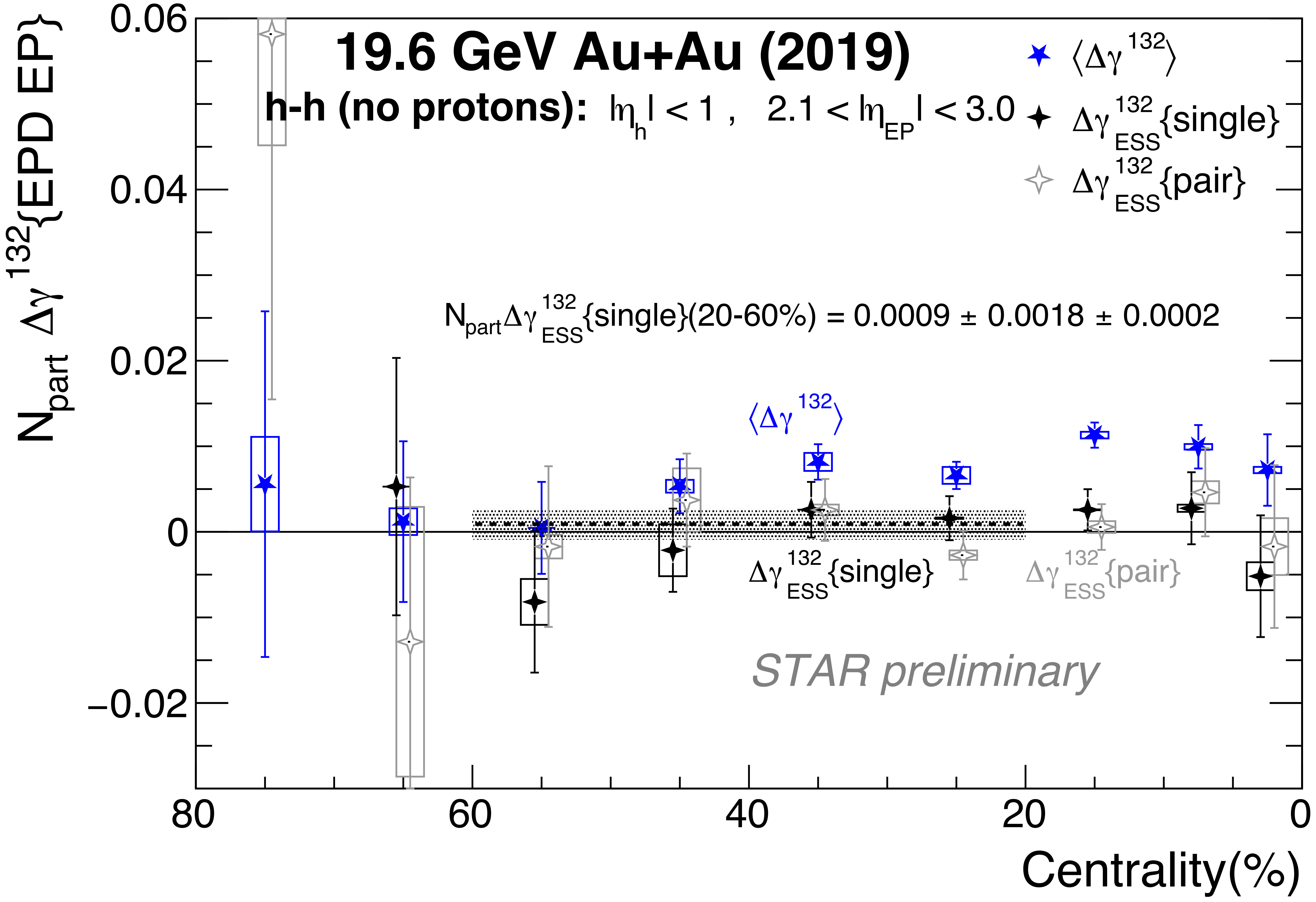


Event Plane Detector
2.1<|η|<5.1

$\gamma^{112} = \langle\cos(\phi_1 + \phi_2 - 2\psi_2)\rangle$

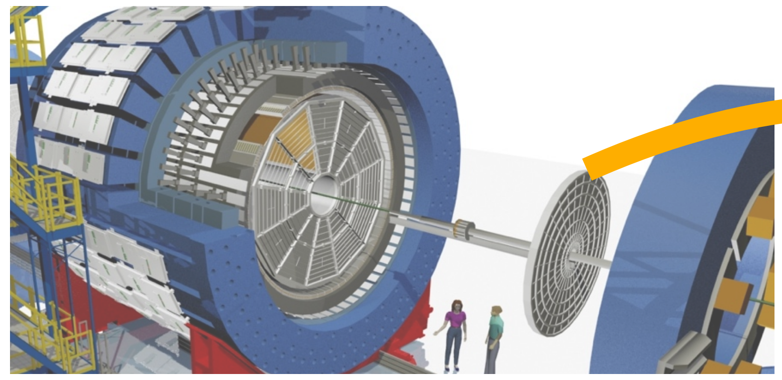


$\gamma^{132} = \langle\cos(\phi_1 - 3\phi_2 + 2\psi_2)\rangle$



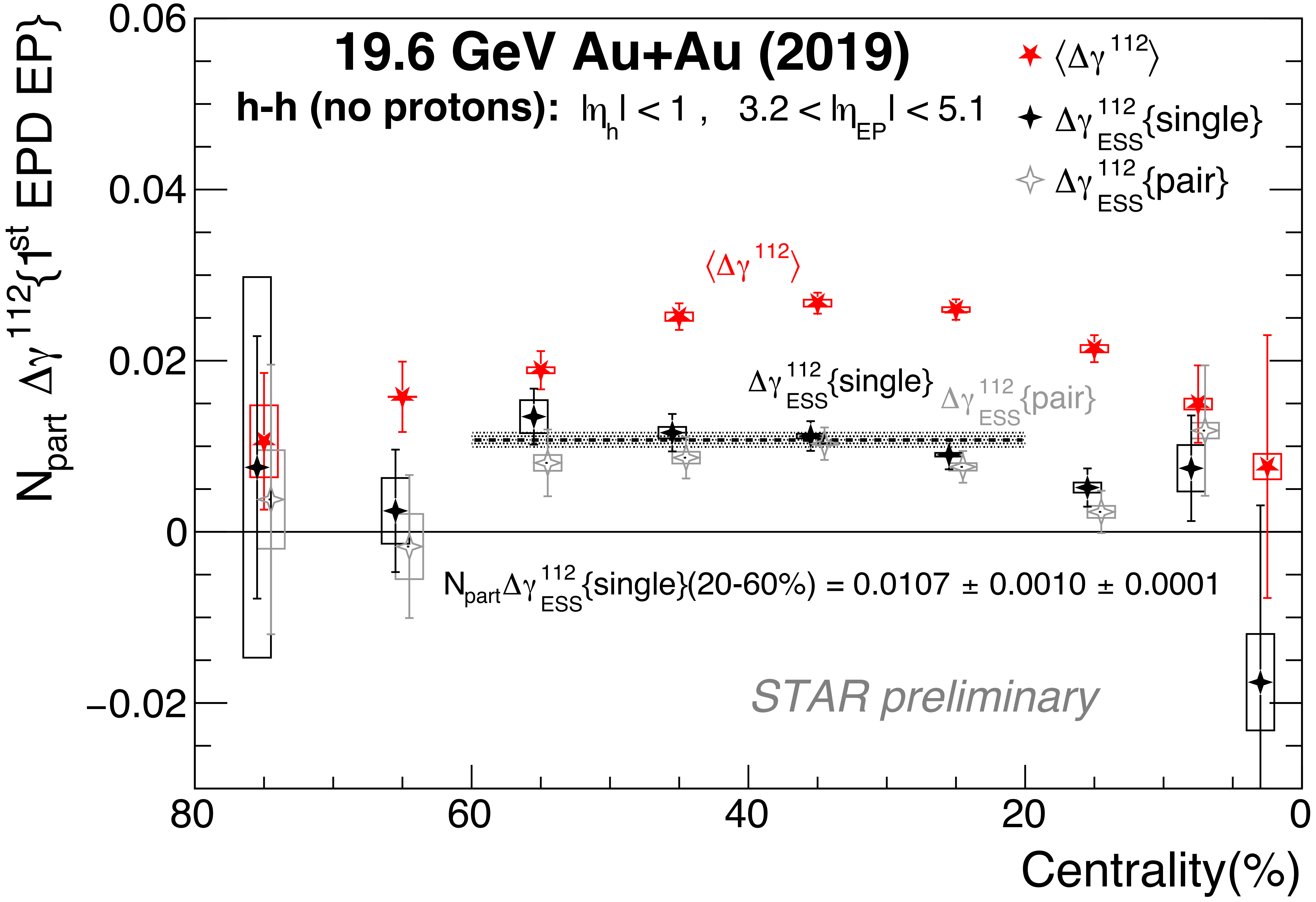
- **We use EPD in aid of nonflow background suppression in $\Delta\gamma^{112}_{ESS}$.**
- **Approaches with single and pair q_2^2 show similar results.**
- **Finite $\Delta\gamma^{112}_{ESS}$ at mid central collisions**

19.6 GeV : EPD spectator plane

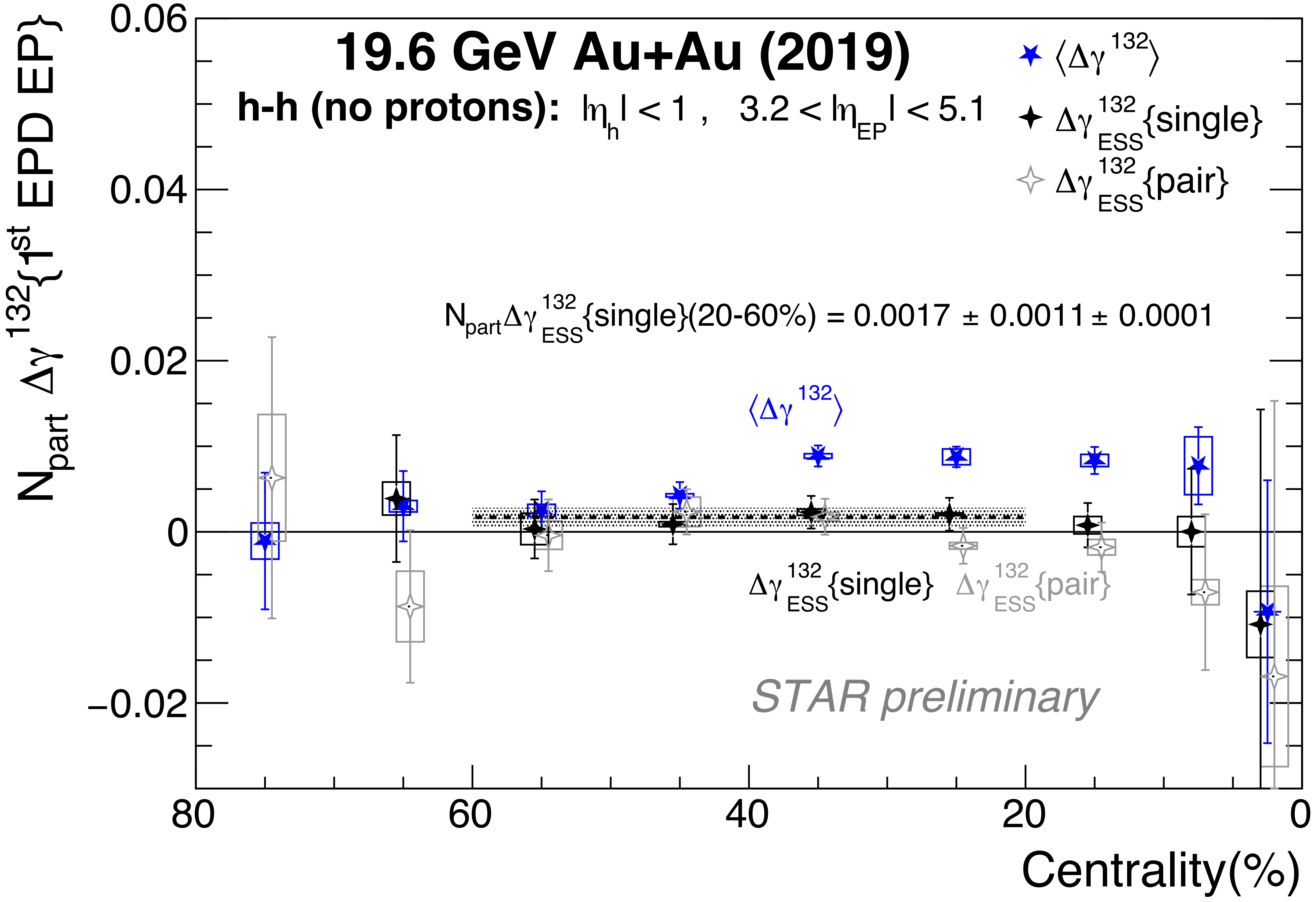


Event Plane Detector
2.1<|η|<5.1

$$\gamma^{112} = \langle \cos(\phi_1 + \phi_2 - \psi_{1,e} - \psi_{1,w}) \rangle$$



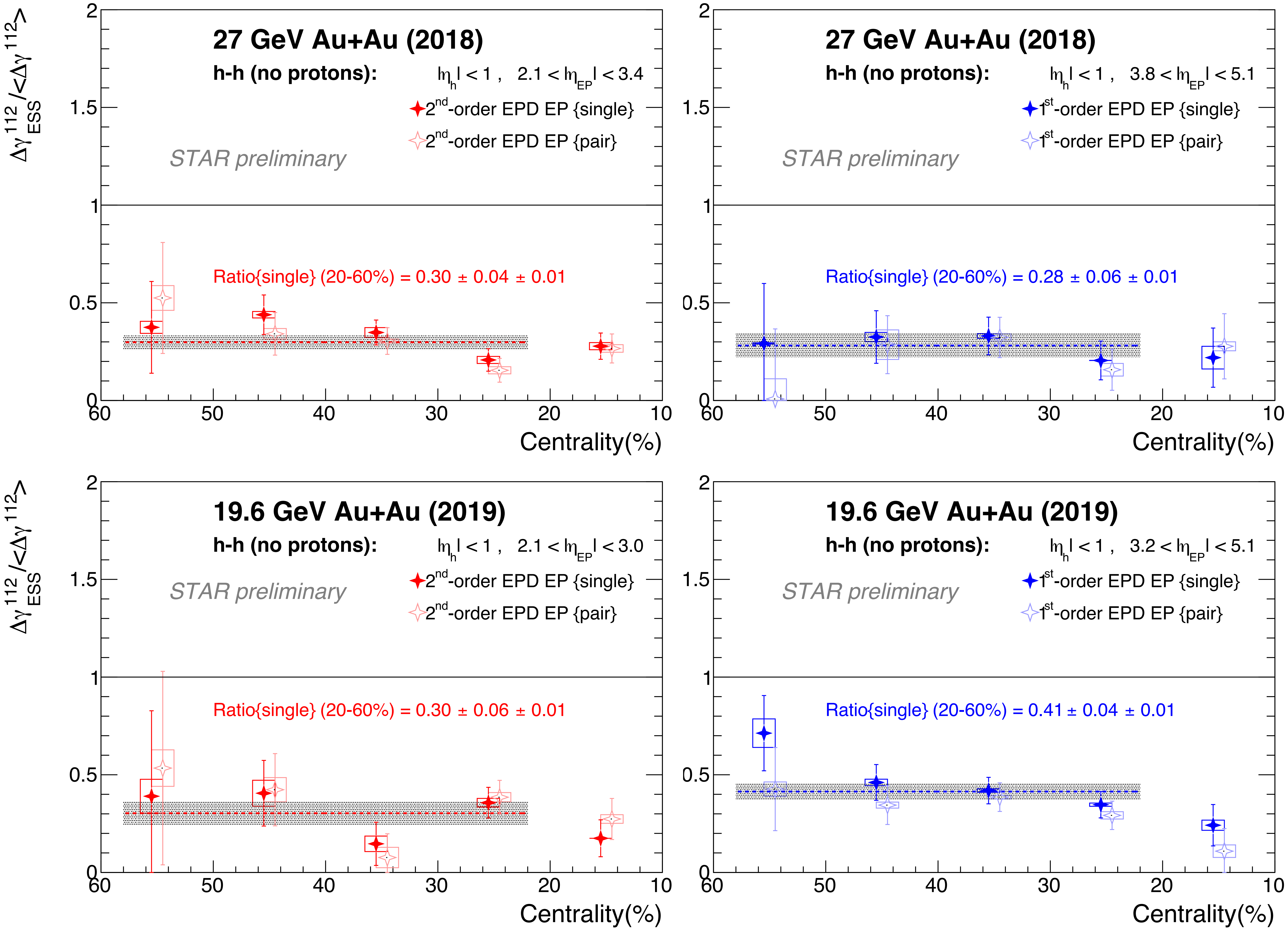
$$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + \psi_{1,e} + \psi_{1,w}) \rangle$$



- **Spectator plane is more correlated to the magnetic field direction.**
- **Finite $\Delta\gamma^{112}_{ESS}$ in mid central events**
- **$\Delta\gamma^{132}_{ESS}$ consistent with zero for all centralities.**

Ratio of $\Delta\gamma^{112}_{ESS}/\langle\Delta\gamma^{112}\rangle$

- **The ratio of ESS to inclusive $\Delta\gamma^{112}$ is ~ 30% for mid-centrality range at both energies.**
- **Flow (v_2-related) BKG and nonflow effects contribute to nearly 70% of $\langle\Delta\gamma^{112}\rangle$.**
- **Remaining 30% fraction may indicate possible CME in Au+Au, which needs further investigation!**

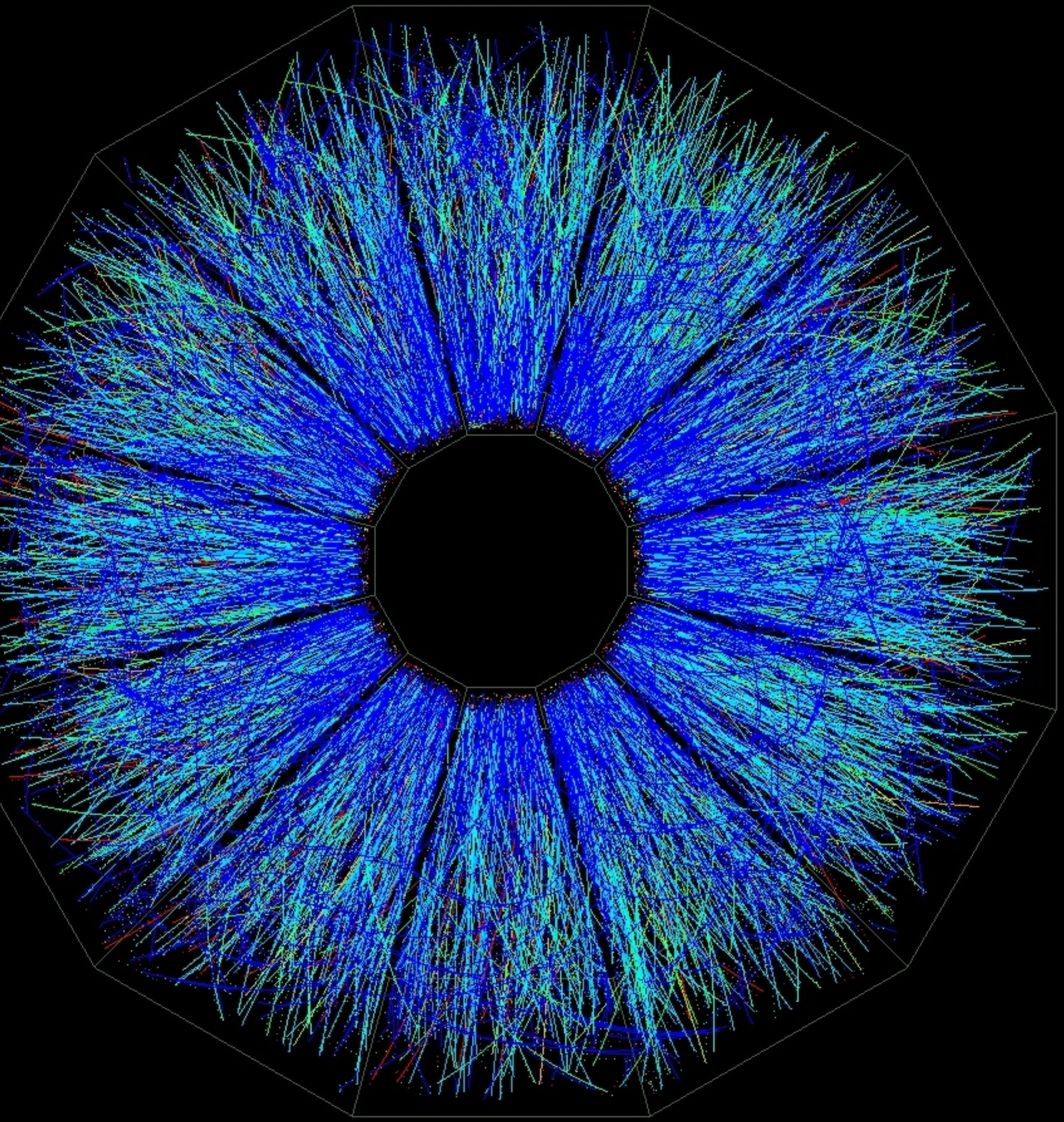


Conclusions

- **We demonstrate that event shape selection (ESS) approach substantially suppresses (by ~70%) v_2 related backgrounds, enhancing the CME signal portion.**
- **The choice of POI from TPC and EPD EPs is very effective for ESS to search for CME.**
- **Shape selections using single and pair q_2^2 showed similar results.**
- **The ESS method shows the CME contribution in inclusive $\Delta\gamma^{112}$ is lower than 30% in mid-central collisions for 19.6 GeV and 27 GeV.**

- **Next: go lower energy at 7.7 GeV…**

$$\underset{\textbf{Measured}}{\underset{\downarrow}{\Delta\gamma^{112}}} = \underset{\textbf{Signal}}{\underset{\downarrow}{\Delta\gamma^{\text{CME}}}} + \underbrace{\overset{\textbf{ESS}}{\cancel{k\frac{v_2}{N}}} + \overset{\textbf{EPD plane}}{\cancel{\Delta\gamma^{\text{nonflow}}}}}_{\textbf{Backgrounds}}$$



Thank you

Backups

Datasets and Cuts

27 GeV Au+Au 2018 (27GeV_production_2018)

Event level cuts

|Vz{TPC}| < 70
Vr < 2 cm
|Vz{VPD}-Vz{TPC}|< 4 cm

Track level cuts

nFitHits>=15
DCA < 2 cm,
0.2 < pT < 2 GeV/c,
|η|<1.

(TPC EP) using pions as POI:
TOF matching, TOF mass
DCA < 1 cm, |η|<0.9, pT > 0.2 GeV/c,
p < 1.6 GeV/c, $|n\sigma_{\pi}|<2$, nHitsDedx>15

For 0-80%, Before: 1.0×10^9 → After cut: 3.6×10^8 events.

19.6 GeV Au+Au 2019 (production_19GeV_2019)

Event level cuts

|Vz{TPC}| < 70
Vr < 2 cm
|Vz{VPD}-Vz{TPC}|< 10 cm

Track level cuts

nFitHits>=15
DCA < 3 cm,
0.2 < pT < 2 GeV/c,
|η|<1. (|η|<1.5 if construct TPC EP)

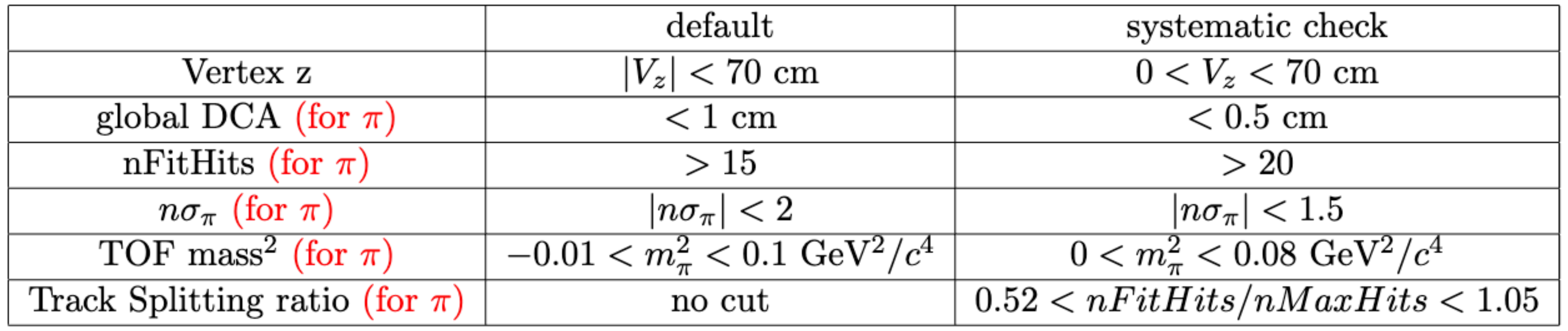
(TPC EP) using pions as POI:
cut same as 27 GeV.

For 0-80%, Before: 1.3×10^9 → After cut: 3.1×10^8 events.

Systematic Uncertainty

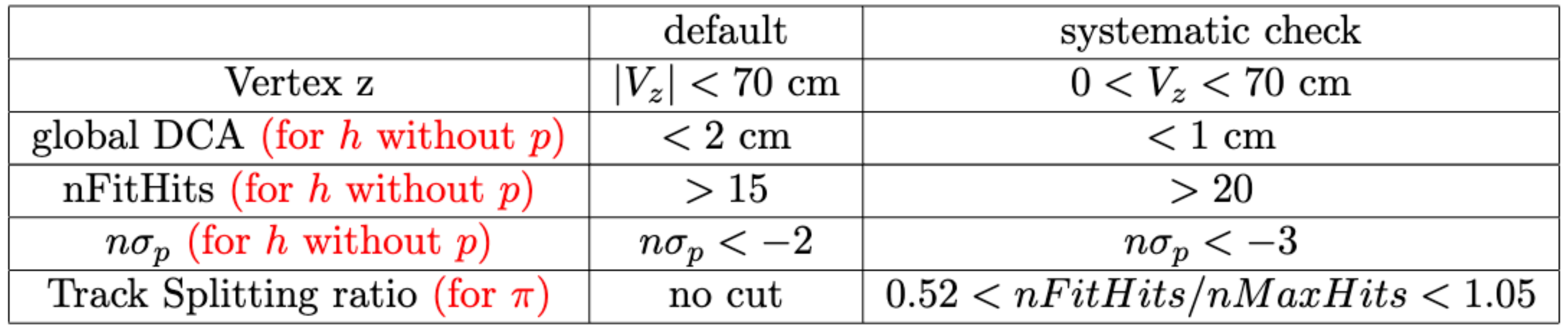
similar as Isobar blind analysis

(TPC EP)



	default	systematic check
Vertex z	$\|V_z\| < 70$ cm	$0 < V_z < 70$ cm
global DCA (for π)	< 1 cm	< 0.5 cm
nFitHits (for π)	> 15	> 20
$n\sigma_\pi$ (for π)	$\|n\sigma_\pi\| < 2$	$\|n\sigma_\pi\| < 1.5$
TOF mass^2 (for π)	$-0.01 < m_\pi^2 < 0.1$ GeV$^2/c^4$	$0 < m_\pi^2 < 0.08$ GeV$^2/c^4$
Track Splitting ratio (for π)	no cut	$0.52 < nFitHits/nMaxHits < 1.05$

(EPD EP)



	default	systematic check
Vertex z	$\|V_z\| < 70$ cm	$0 < V_z < 70$ cm
global DCA (for h without p)	< 2 cm	< 1 cm
nFitHits (for h without p)	> 15	> 20
$n\sigma_p$ (for h without p)	$n\sigma_p < -2$	$n\sigma_p < -3$
Track Splitting ratio (for π)	no cut	$0.52 < nFitHits/nMaxHits < 1.05$