QM 2023

Brookhaven National Laboratory

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Search for the Chiral Magnetic and Vortical Effects Using Event Shape Variables in Au+Au Collisions at STAR

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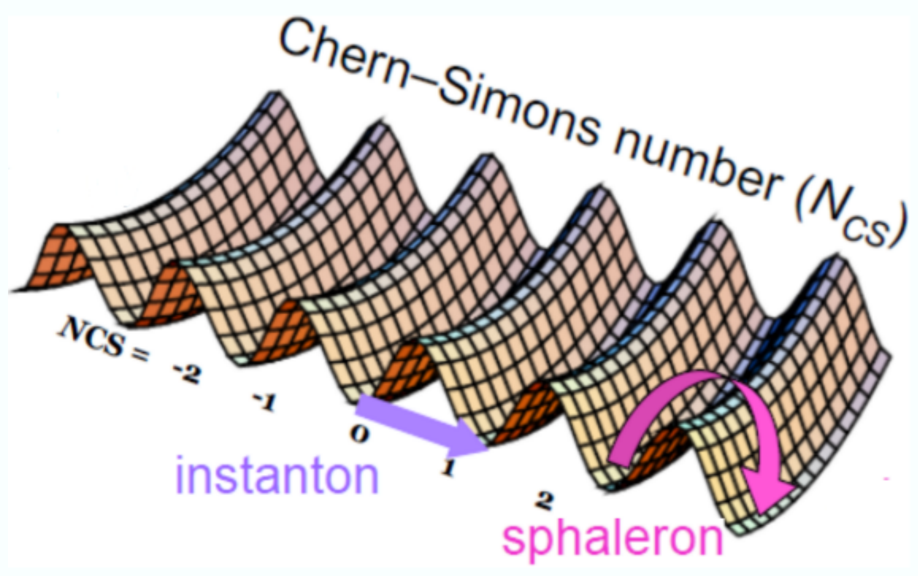
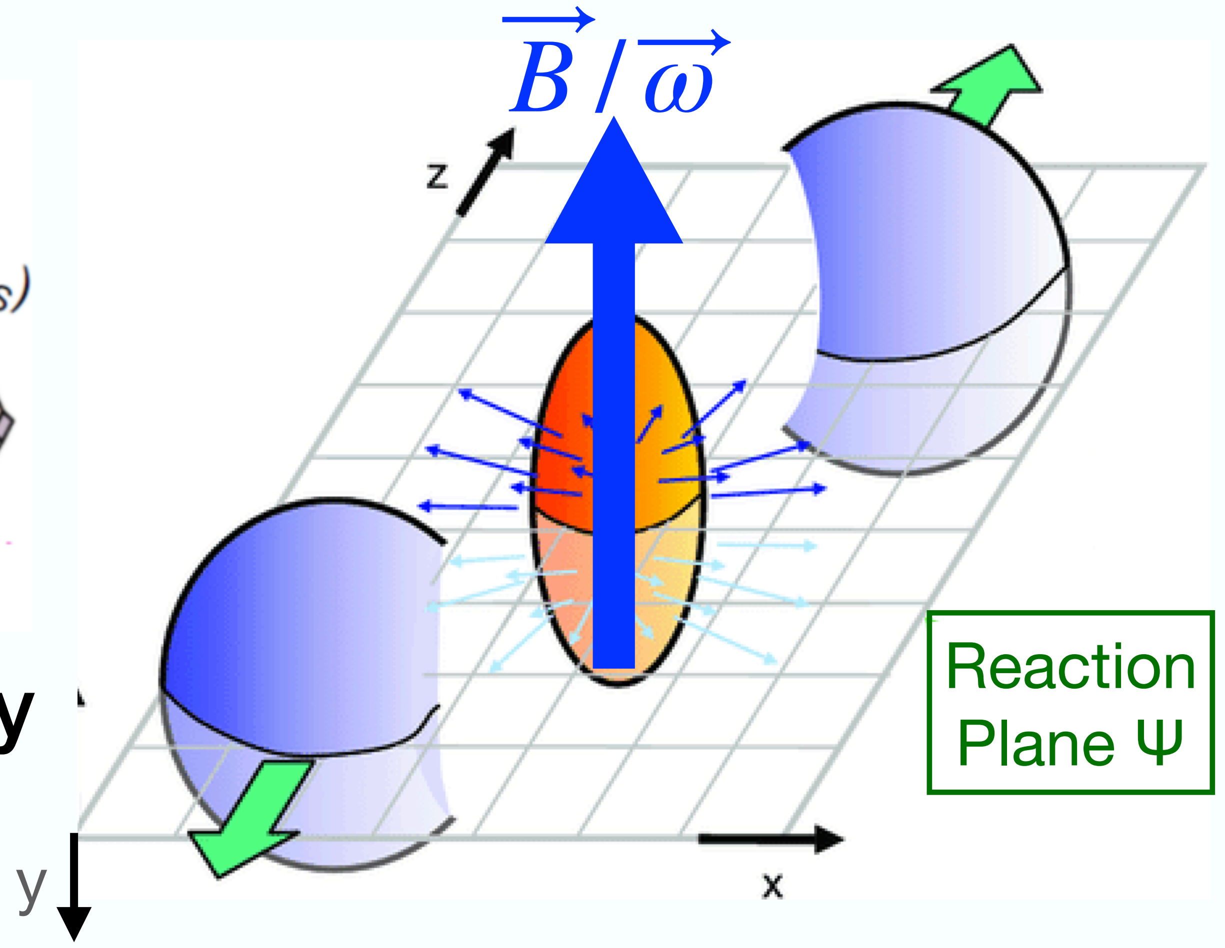
Chiral Magnetic and Vortical Effect

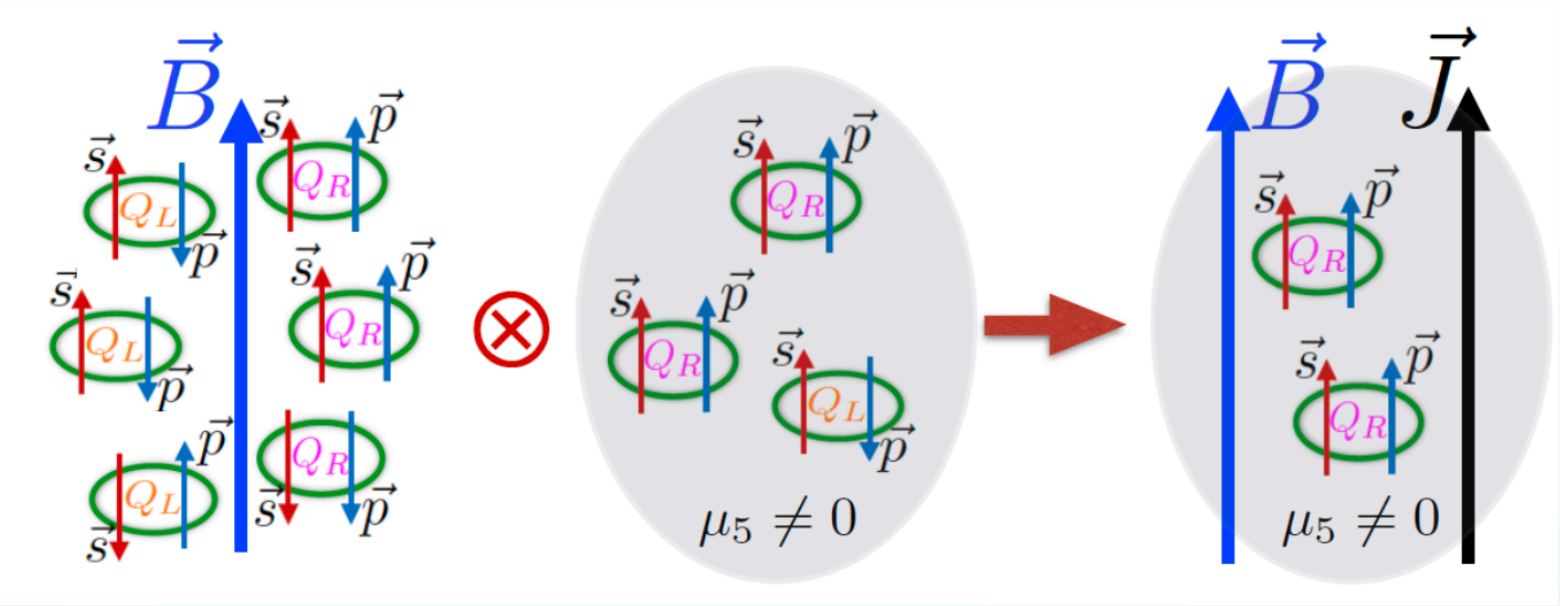
Kharzeev, Pisarski, Tytgat, PRL 81(1998) 512
S.A. Voloshin, Phys. Rev. C,70, 057901 (2004)

- **QCD vacuum transition leads to chirality imbalance.**
- **CME: Chirality imbalance of quarks coupled with strong magnetic field induces an electric charge separation with respect to reaction plane.**
- **CVE: Chirality imbalance and net baryon density under large vorticity induces a baryonic charge separation.**
- **CME (CVE) violates local Parity Symmetry and CP Symmetry!**



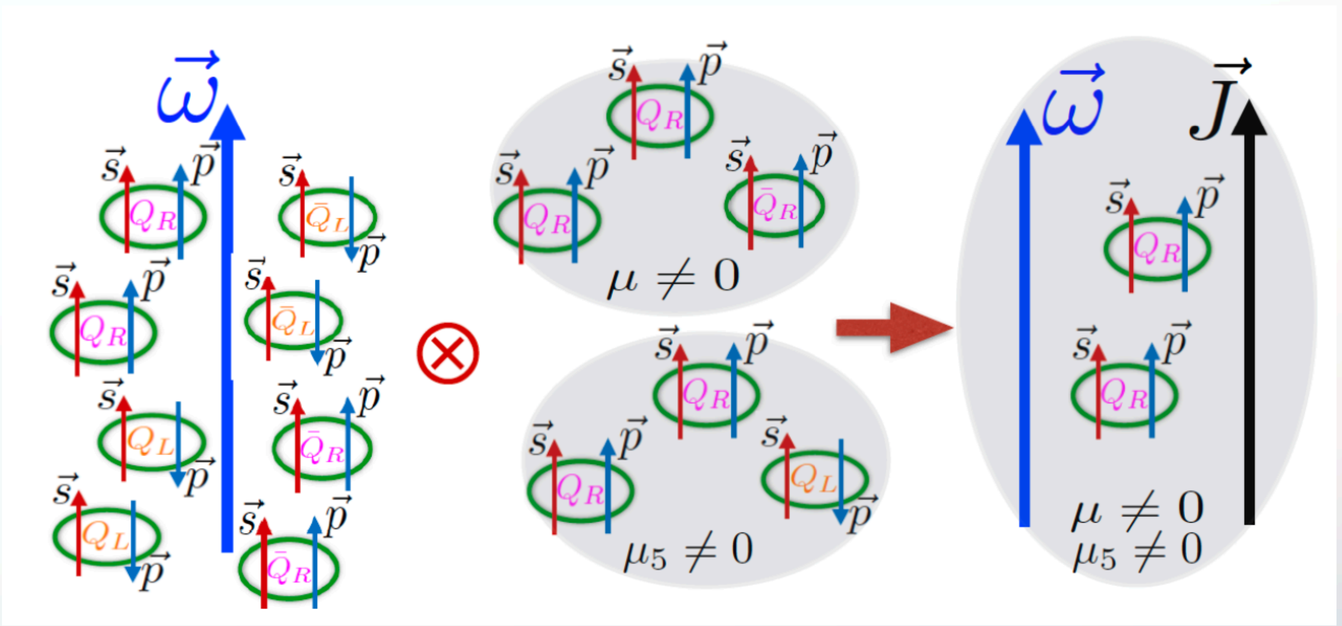
QCD vacuum Topology
(finite μ_5)





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

Chiral Magnetic Effect

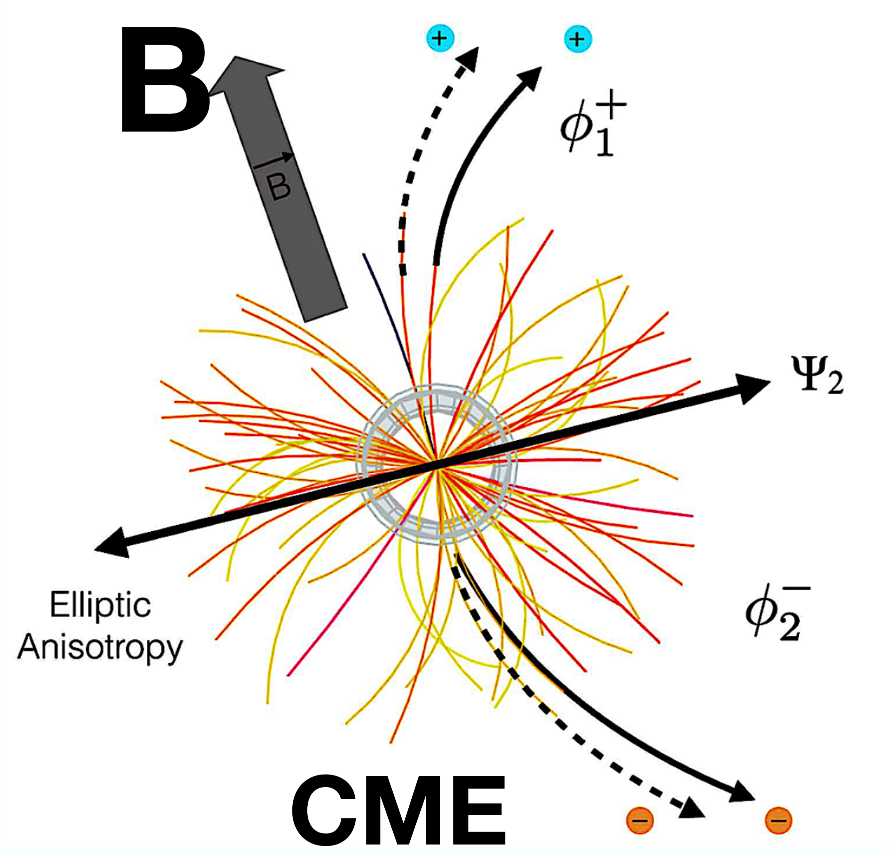


$$\vec{J}_B = \frac{1}{2\pi^2}\mu_5 \mu_B \vec{\omega}$$

Chiral Vortical Effect

Experimental Observables

S.A. Voloshin, Phys. Rev. C,70, 057901 (2004)



$$\frac{dN_{\pm}}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2a_1^{\pm}\sin(\varphi - \Psi_{RP}) + 2v_2\cos(2\varphi - 2\Psi_{RP}) + \ldots$$

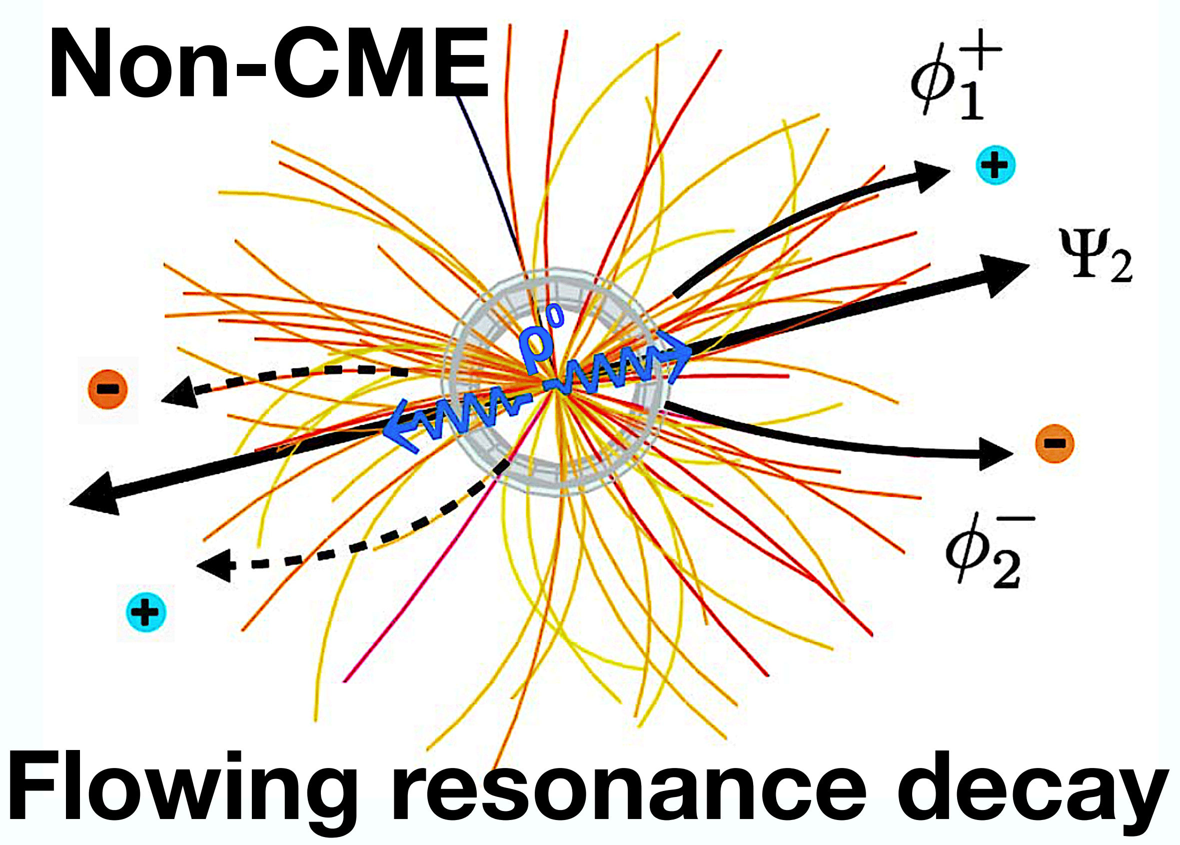
Parity Odd, can not directly observe $\propto \mu_5 B \quad (\mu_5\mu_B\omega)$

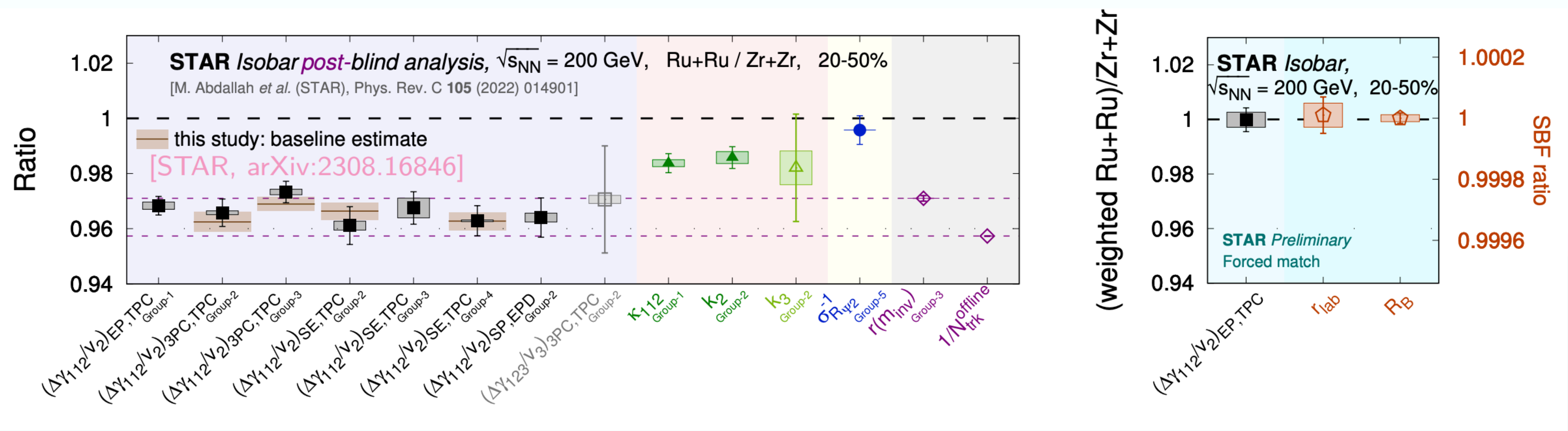
Parity Even, sensitive to charge separation

Observables: $\gamma^{112} = \langle\cos(\varphi_1 + \varphi_2 - 2\Psi_{RP})\rangle = \langle v_1v_1\rangle - \langle a_1a_1\rangle + \mathrm{BG}(v_2^{cl})$

$$\Delta\gamma^{112} = \gamma^{OS} - \gamma^{SS} = \Delta\gamma^{\mathrm{CME/CVE}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{nonflow}}$$

BKG indicator: $\gamma^{132} = \langle\cos(\varphi_1 - 3\varphi_2 + 2\Psi_{RP})\rangle \quad \rightarrow \Delta\gamma^{132}$





See Yicheng Feng's talk on Sep 6

Important points from Isobar blind analysis:

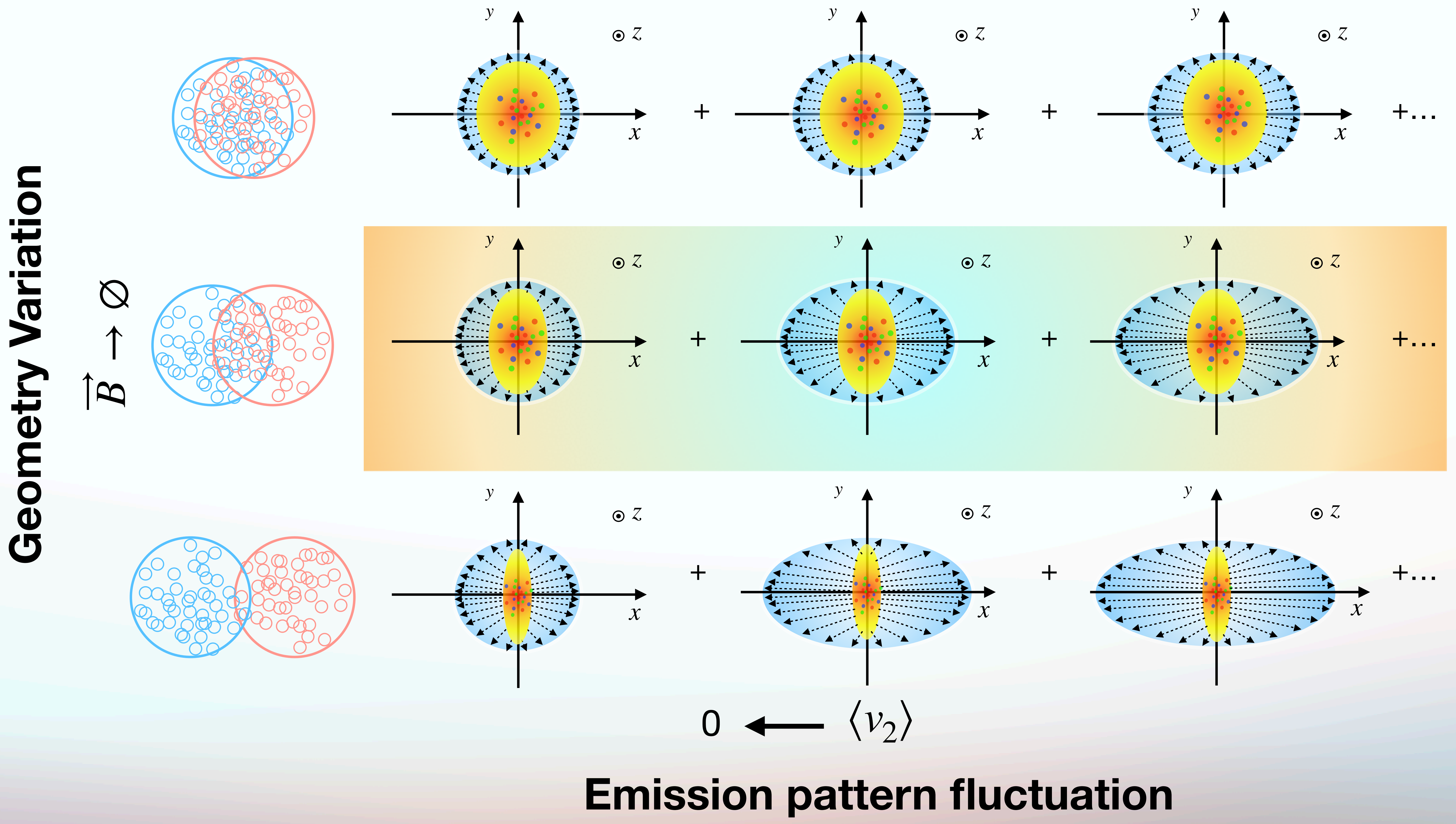
- **The v_2-related background is large.**
- **The possible CME signal is small. Fraction of CME signal is likely not as large in Au+Au.**
- **Using participant plane (TPC) entails large nonflow BKG (can be avoided with spectator plane Ψ_1)**
- **We need better a method.**

Schematic Diagram of Event Shape

Z. Xu et al, arXiv:2307.14997

Observable based on final-state particles (v_2, flow vector q_2) has contributions from:

- **participant zone geometry – expected to be long ranged in rapidity**
- **emission pattern fluctuations – more localized, less correlated over rapidity**



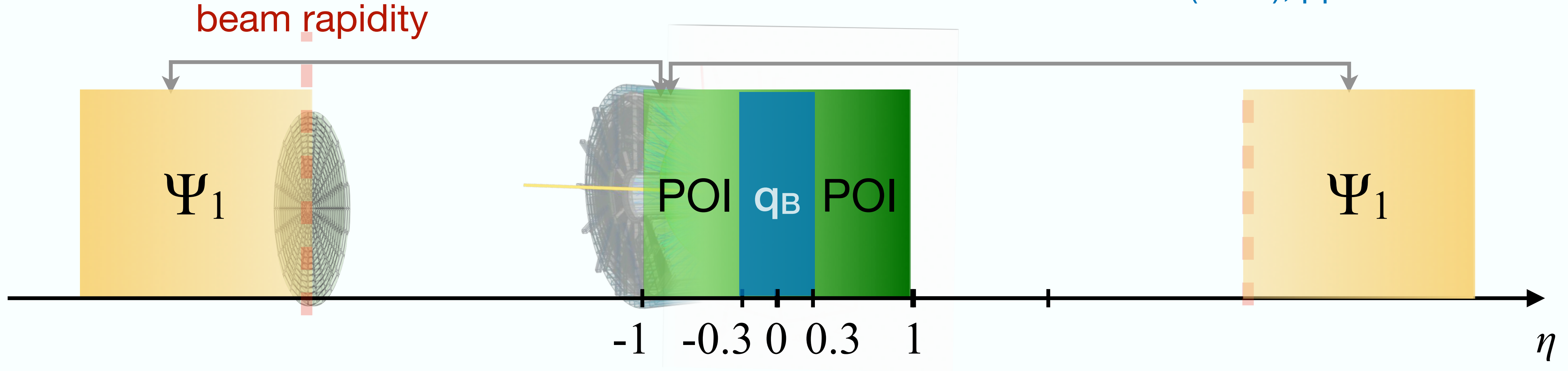
Data experience large event-by-event fluctuations - main contribution

H. Petersen and B. Müller, Phys. Rev. C 88, 044918

Event Shape Selection and Engineering

Event Shape Engineering

J. Schukraft et al, Phys. Lett. B, 719 (2013), pp. 394-398



Event shape variable | **Elliptic flow variable**

q_B (no POI) ——— **v_2 (POI)**

$$q_B = \sqrt{\frac{\left(\sum_{i=1}^{N} \sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N} \cos 2\varphi_i\right)^2}{N}}$$

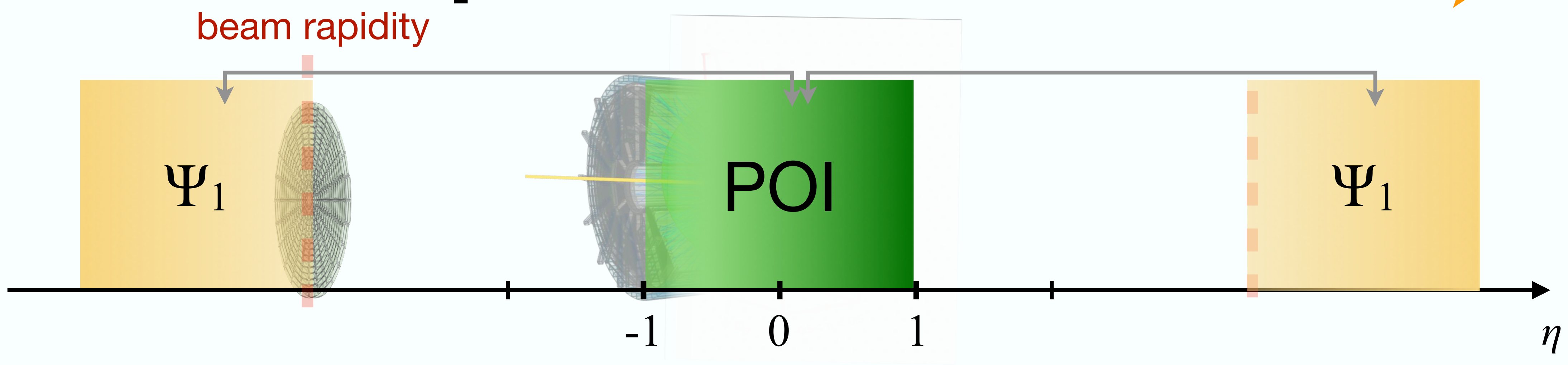
q_b excludes POI

Rely on long η range correlation from initial shape

Event Shape Selection

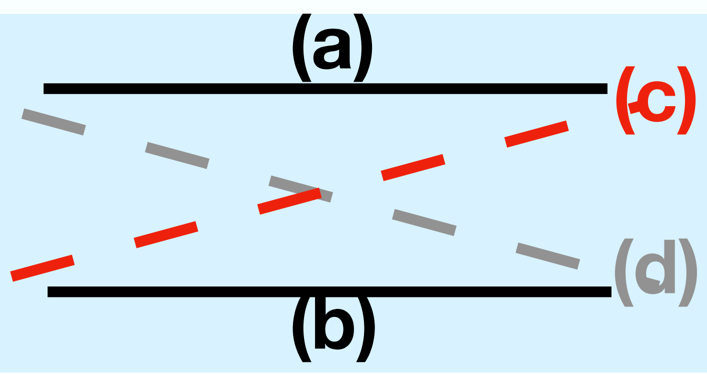
new

Z. Xu et al, arXiv:2307.14997



Event shape variable | **Elliptic flow variable**

single q^2 (POI)
pair q^2 (POI)



single v_2 (POI)
pair v_2 (POI)

$$q_2^2 = \frac{\left(\sum_{i=1}^{N} \sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N} \cos 2\varphi_i\right)^2}{N(1 + N\langle v_2 \rangle)}$$

Pair from adding momenta of two POI particles.

Rely on emission pattern and geometry shape

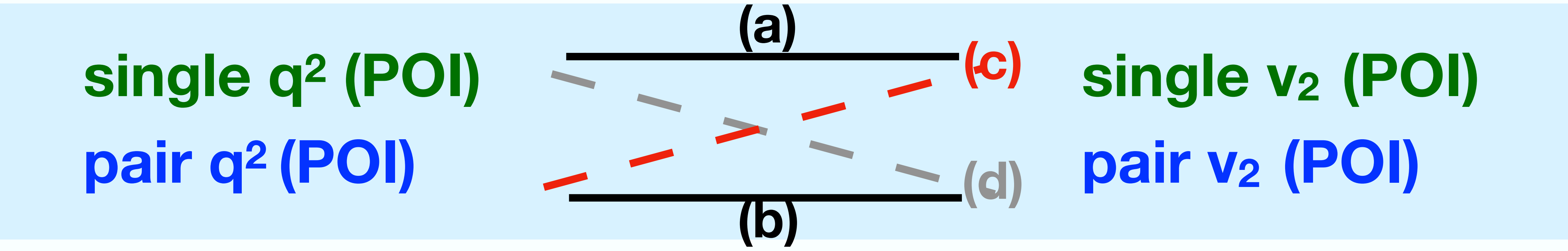
Event Shape method **Spectator Ψ_1**

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

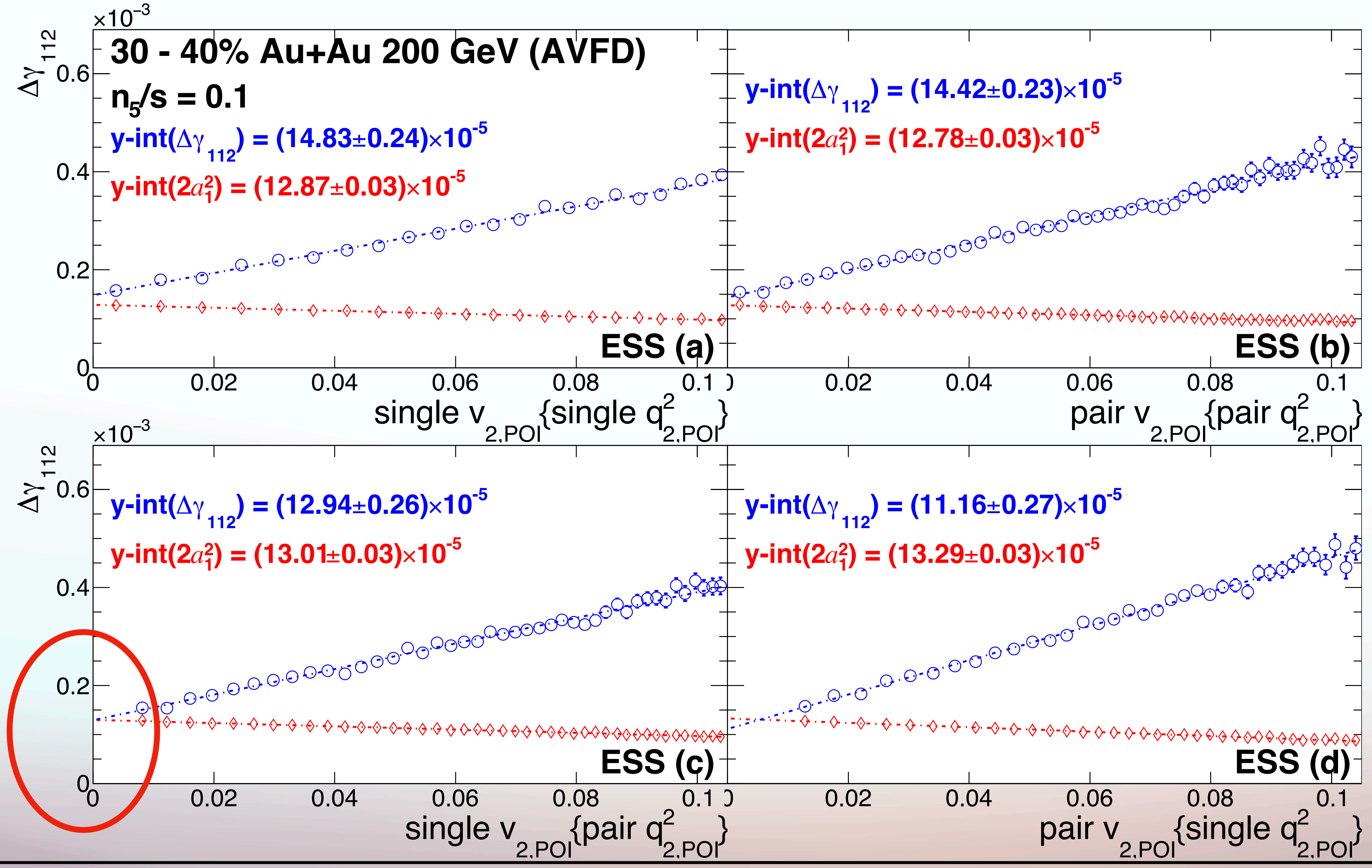
Measured **Signal** **Backgrounds**

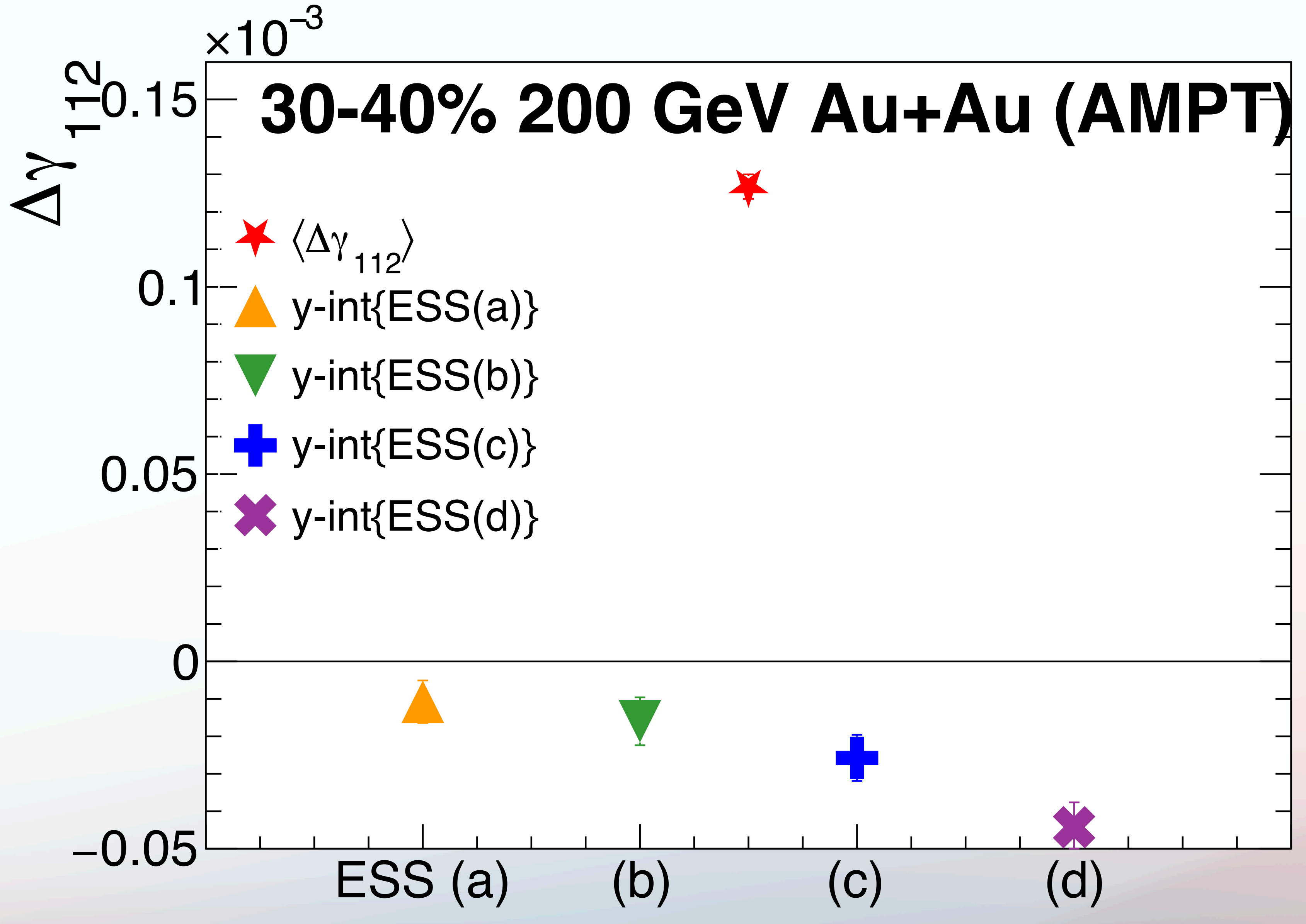
Simulation results for Event Shape Selection

Z. Xu et al, arXiv:2307.14997

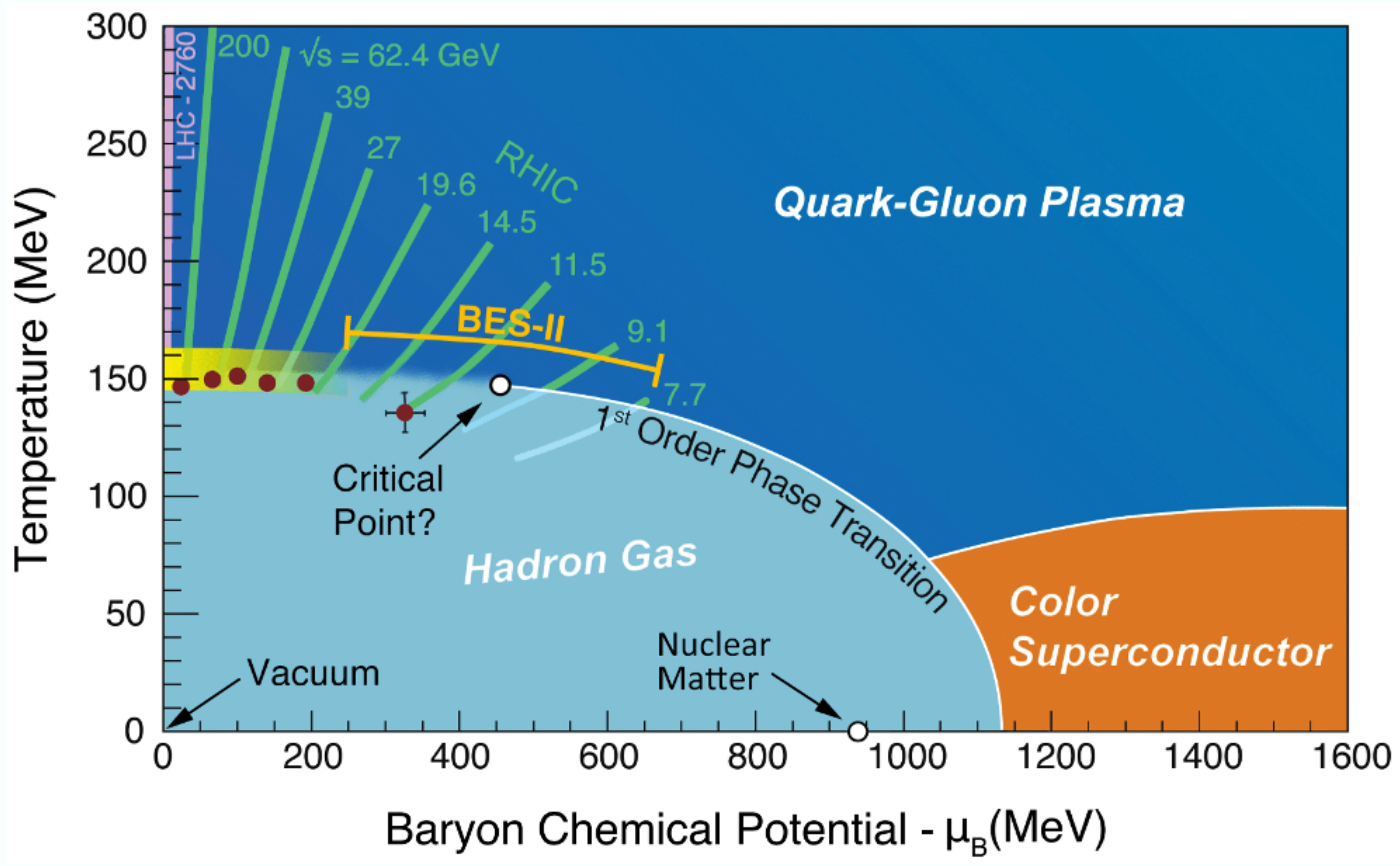


- The optimal ESS recipe (c) accurately matches the input true CME signal.
- Mixed combinations further suppress residual BKG: intercepts follow an ordering (a)>(b)>(c)>(d)
- With AMPT, all ESS schemes seem to over-subtract the BKG.



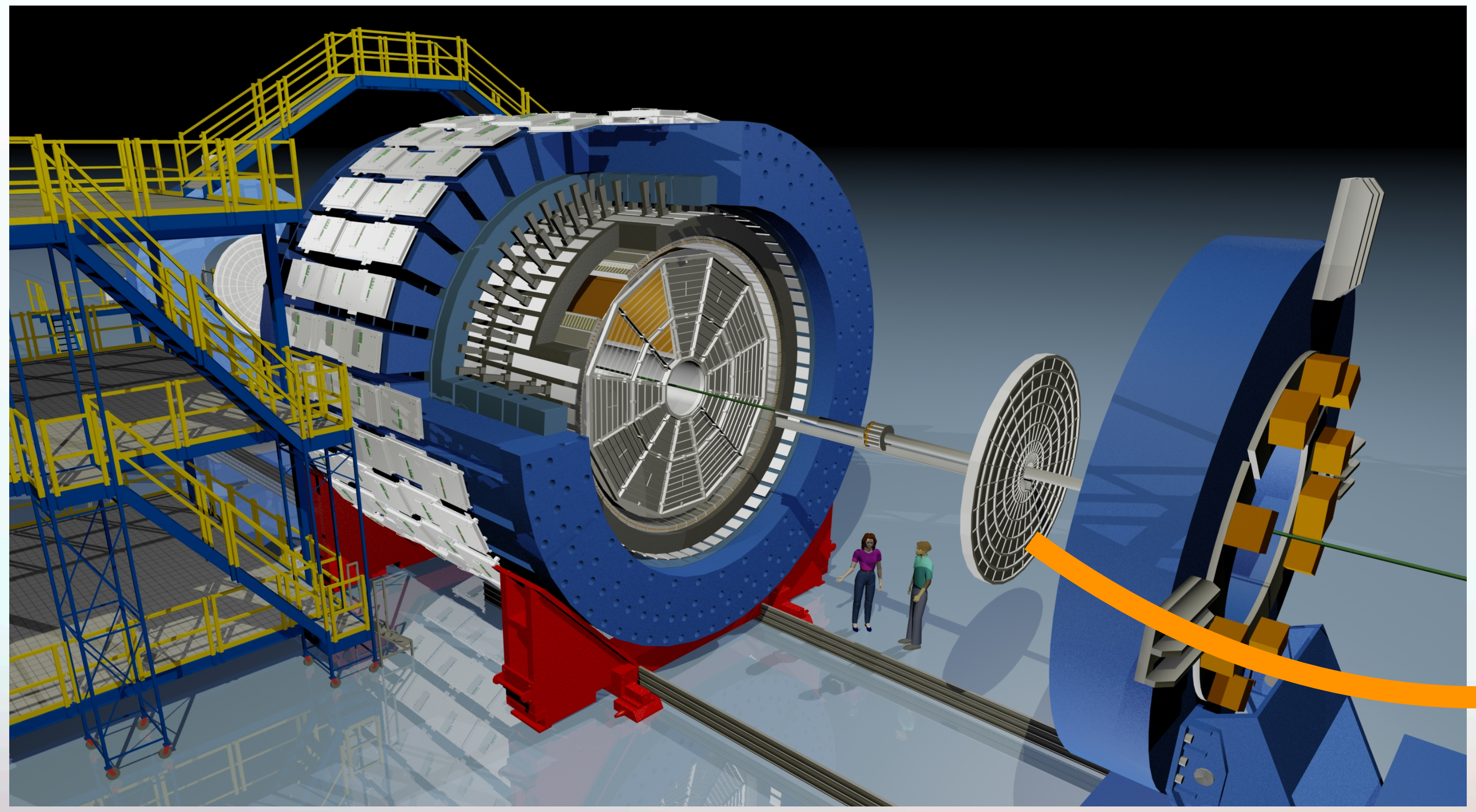


New Analyses at STAR



BES-II Au+Au	Events
27 GeV	555 M
19.6 GeV	478 M
14.6 GeV	324 M
7.7 GeV	101 M

200 GeV Au+Au	Events
run 11+14+16	2.1 B



Advantage:

- **Au+Au: Larger system has a stronger B field.**
- **Lower energy: longer B lifetime.**
- **BES-II achieved higher statistics than BES-I.**
- **200 GeV Au+Au data have accumulated 2.1B events.**

Detector Upgrades:

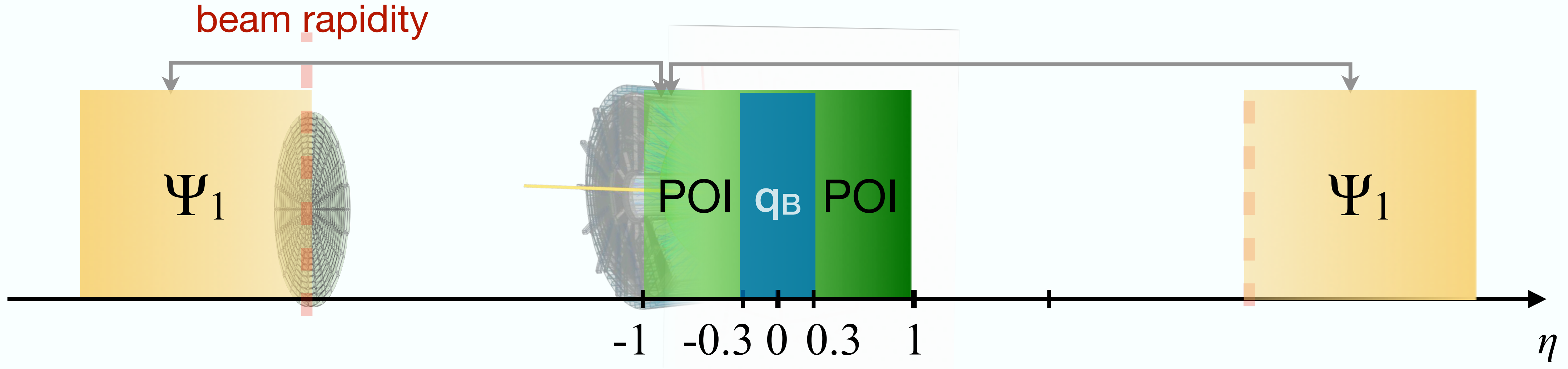
- **2018 EPD : high EP resolution into spectator region Ψ_1 (2.1<η<5.1) for BES-II energies.**

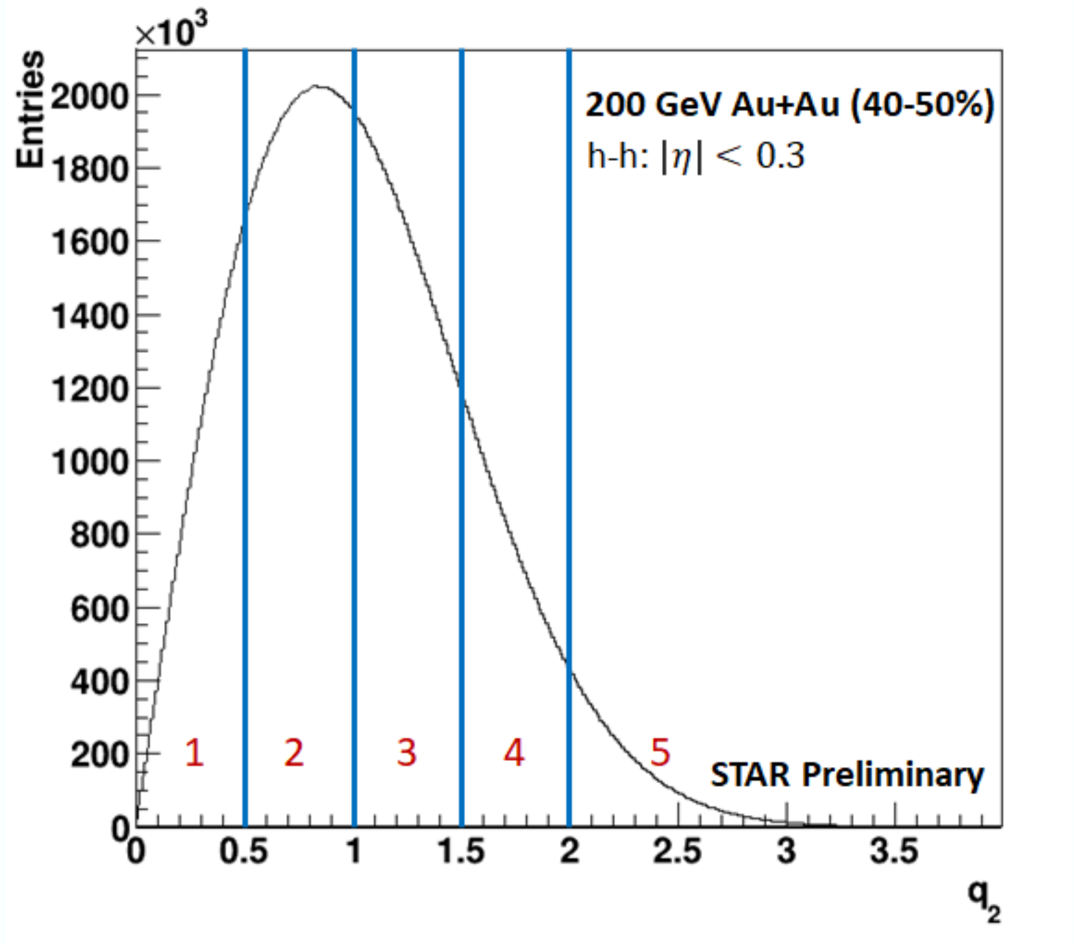
200 GeV Au+Au - Event Shape Engineering

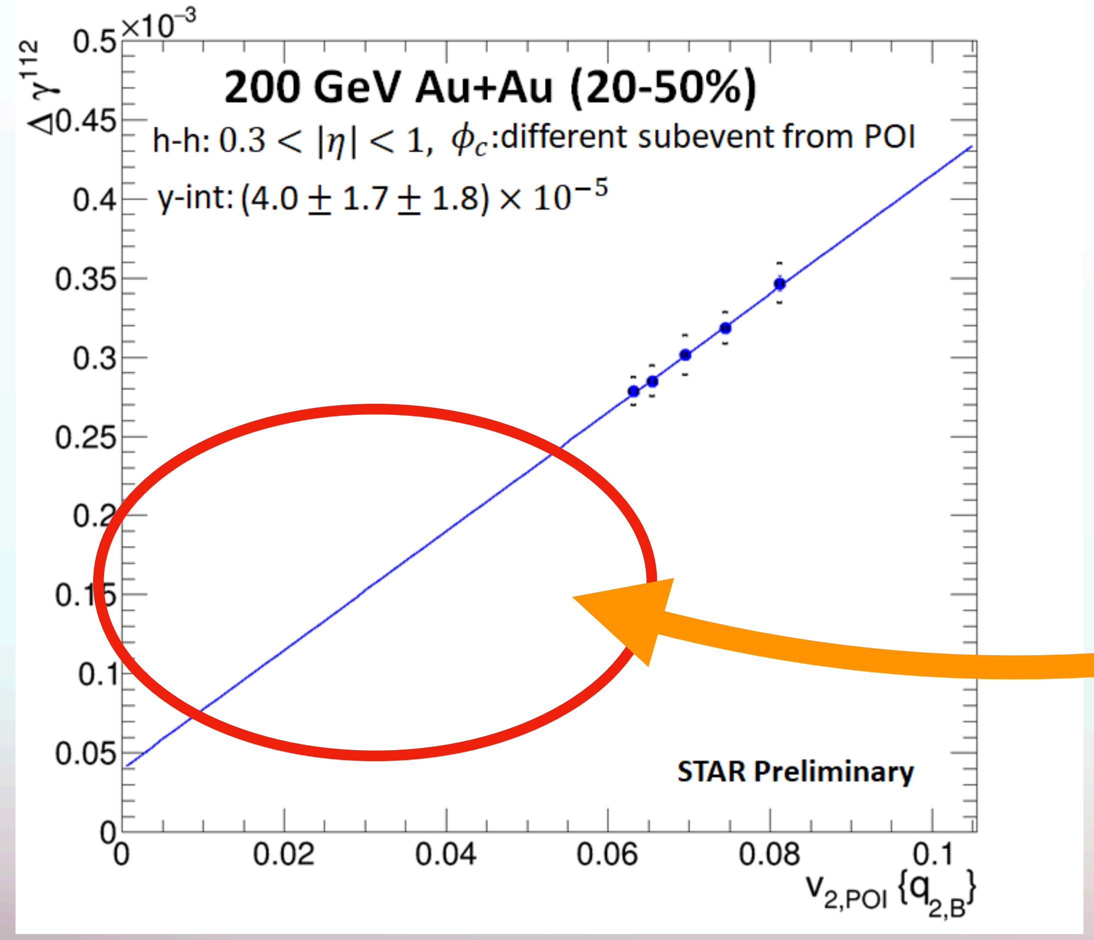
See Poster #437 of Han-Sheng Li

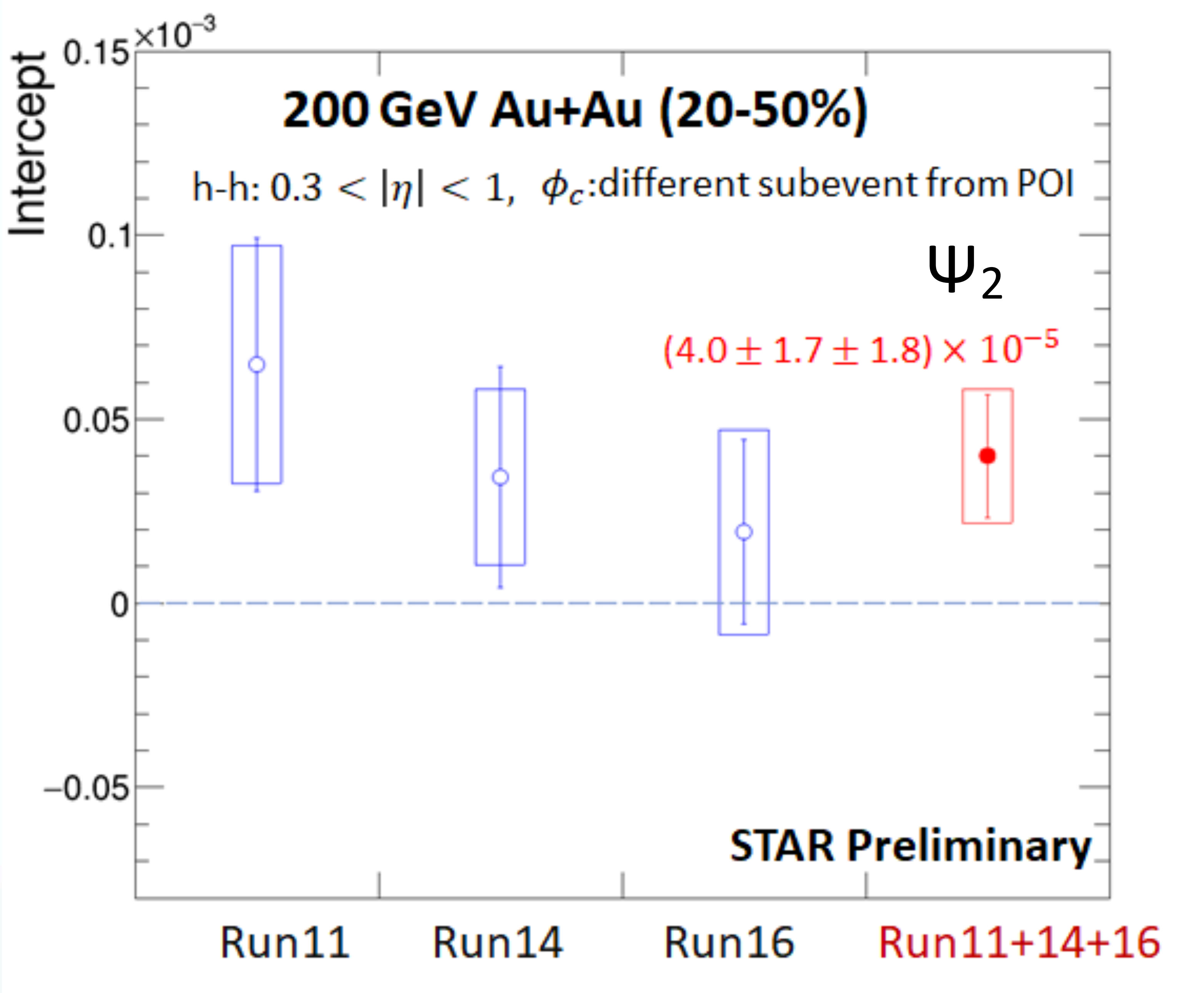
Event shape variable — **Elliptic flow variable**

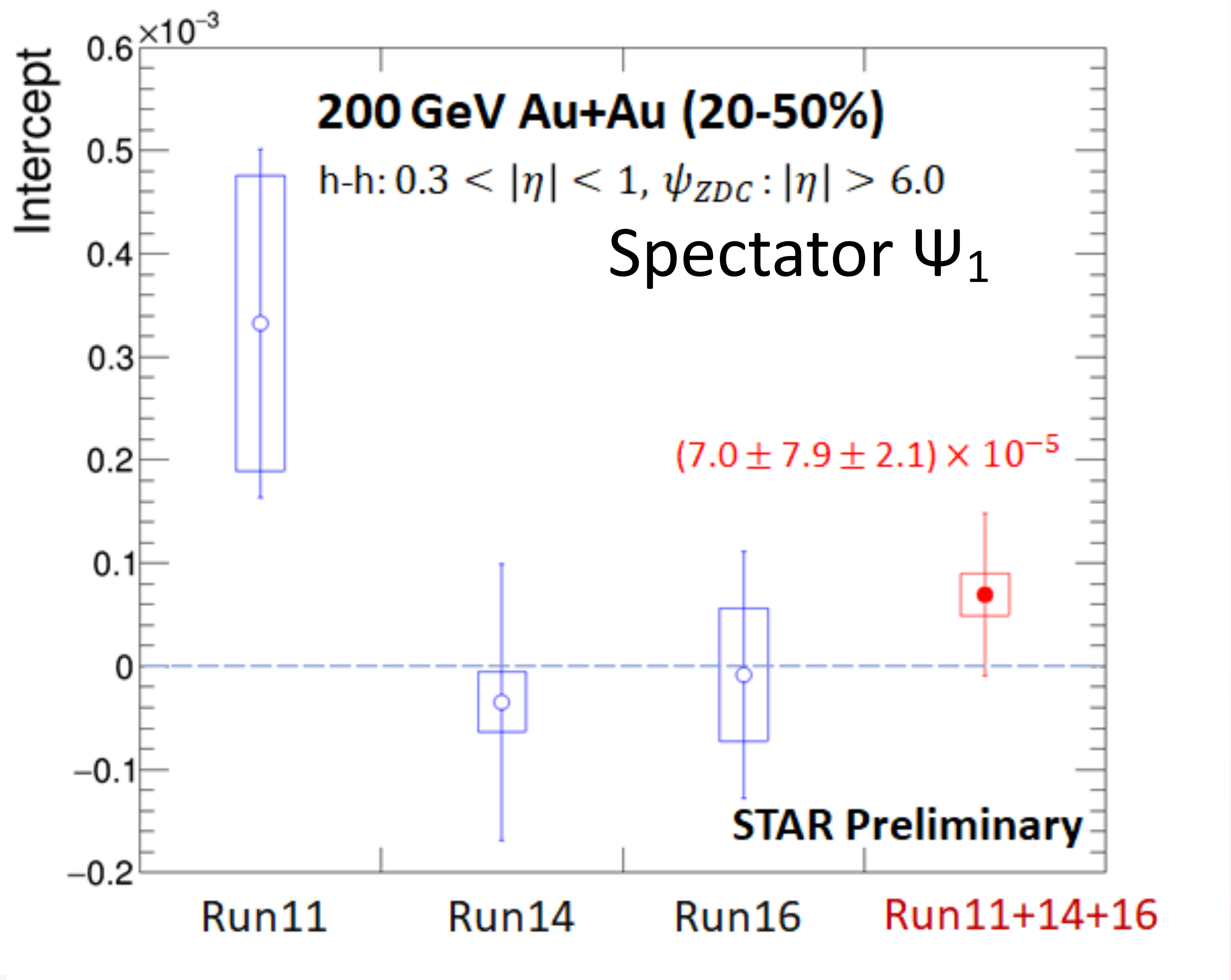
q_B (no POI) ——— v_2 (POI)





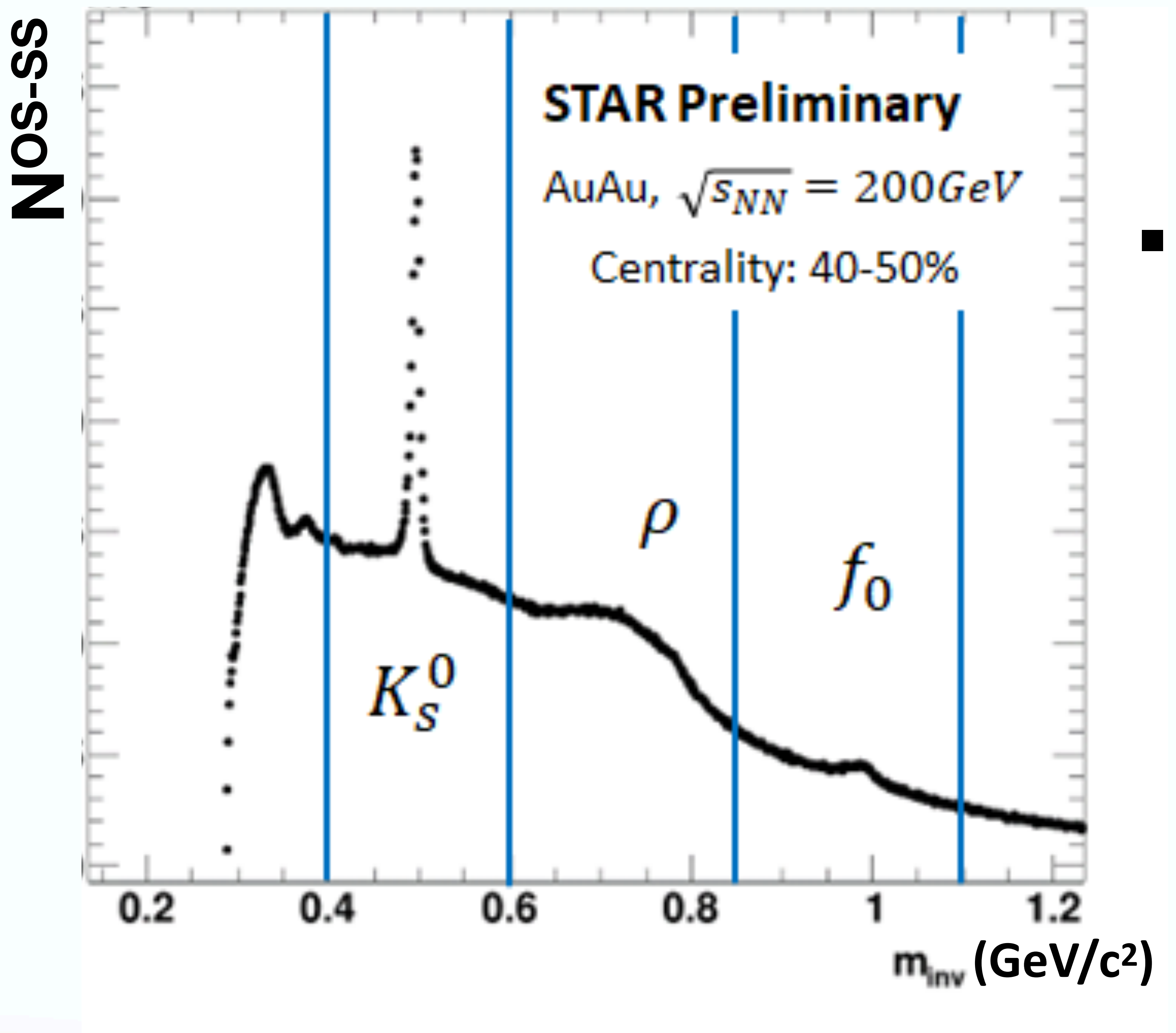




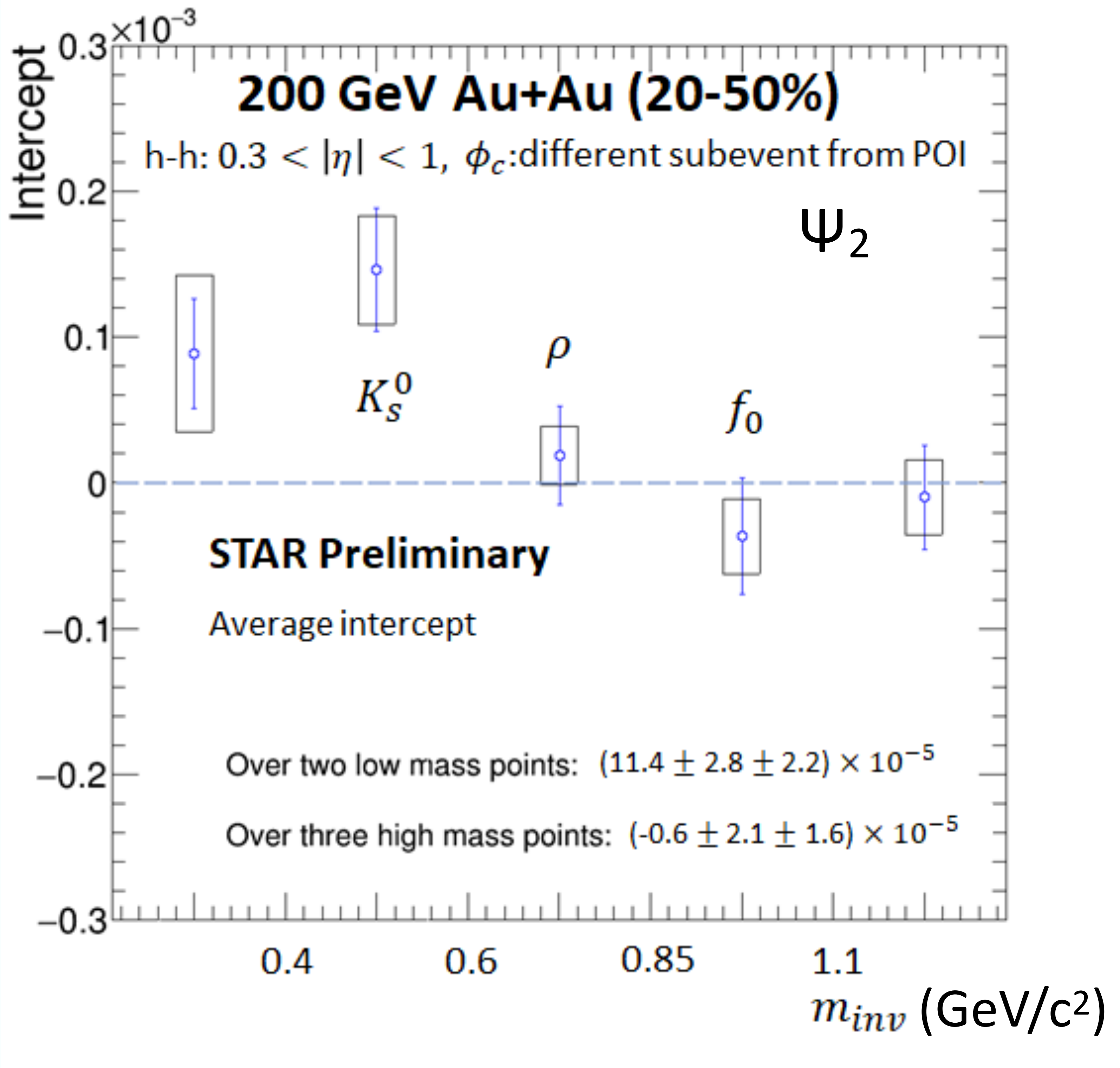


- **The large statistical error arises from the gap near zero flow.**
- **Results with Ψ_2 yield 1.5σ, nonflow effects to be assessed.**
- **Results using $\Psi_{1,ZDC}$ is less than 1σ significance.**

200 GeV Au+Au - Invariant Mass dependence with ESE



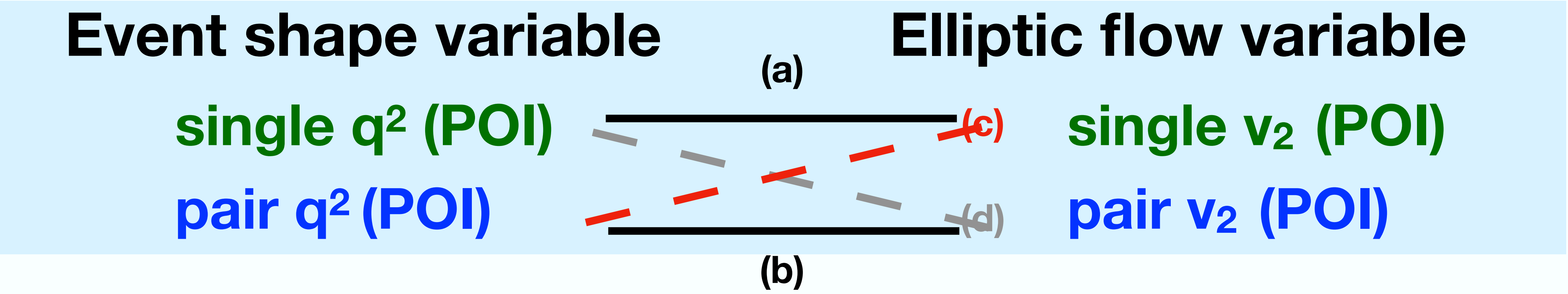
- **Mass windows (GeV/c²)**
  - Low mass: $m_{inv} < 0.4$
  - K_s^0 region: $0.4 < m_{inv} < 0.6$
  - ρ region: $0.6 < m_{inv} < 0.85$
  - f_0 region: $0.85 < m_{inv} < 1.1$
  - High mass: $1.1 < m_{inv}$

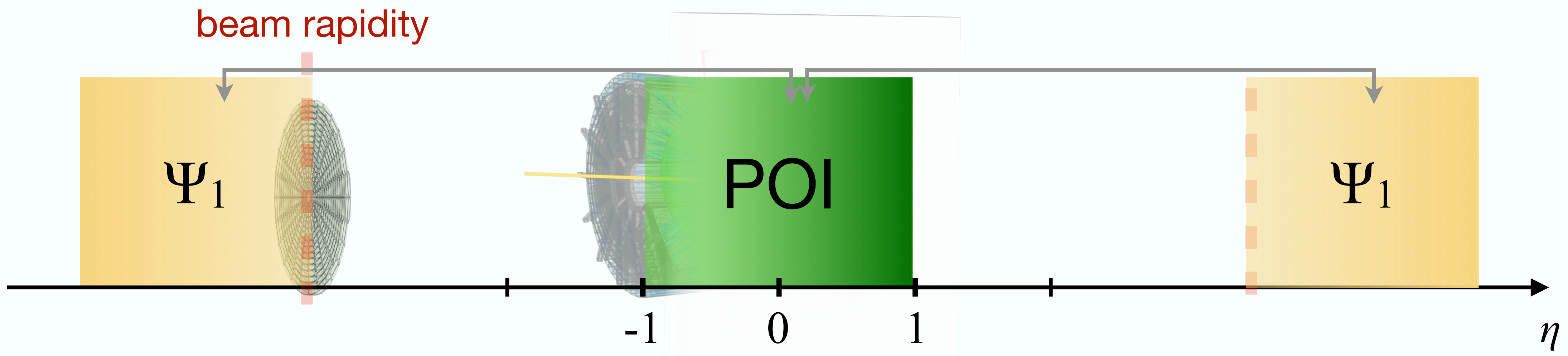


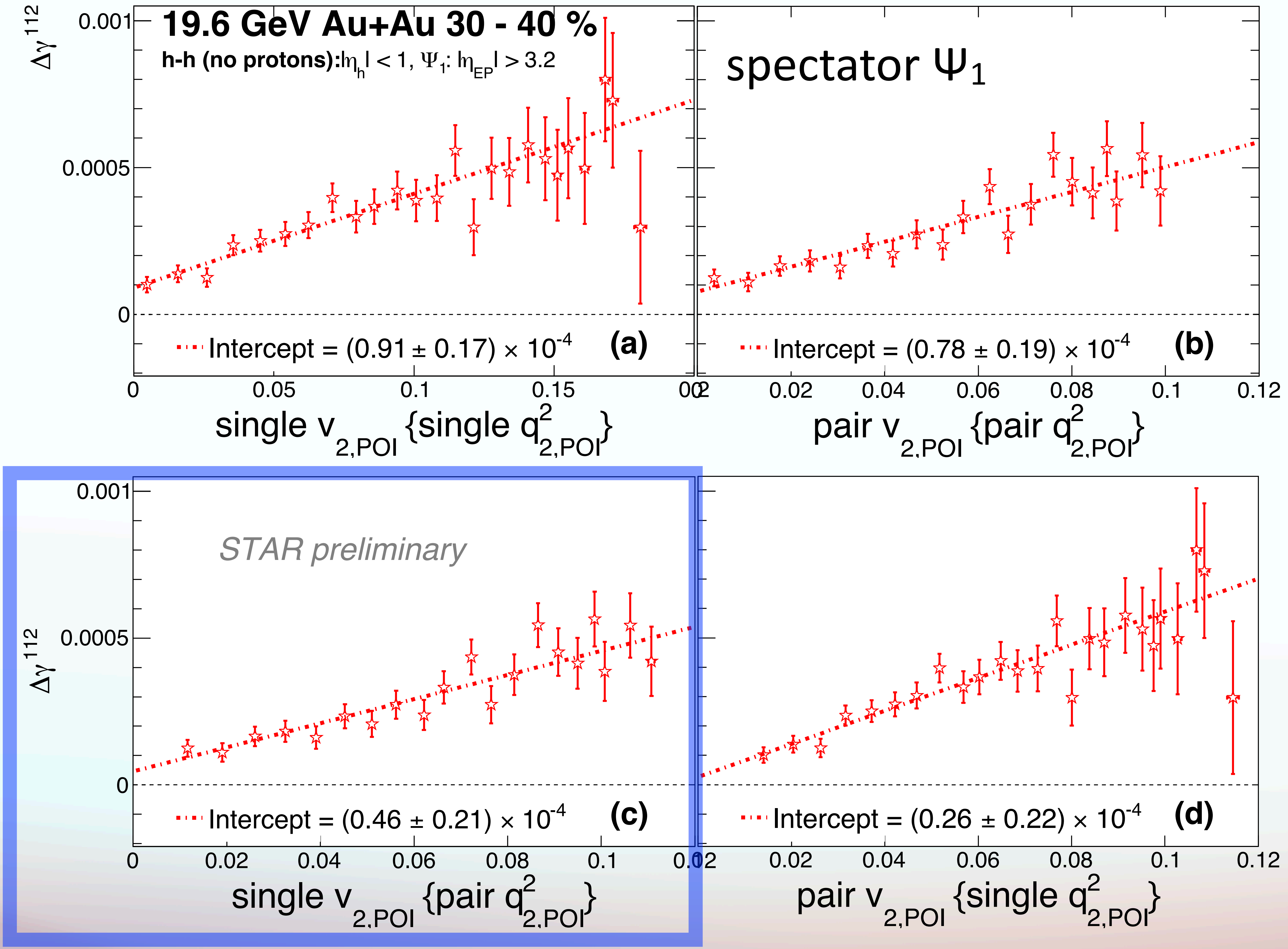
- **Low-mass region appears to have a larger charge separation(3σ) than high-mass region (consistent with zero).**
- **Measurement relative to Ψ_2, Residual nonflow effects to be accessed.**

See Poster #437 of Han-Sheng Li

Beam Energy Scan II - Event Shape Selection





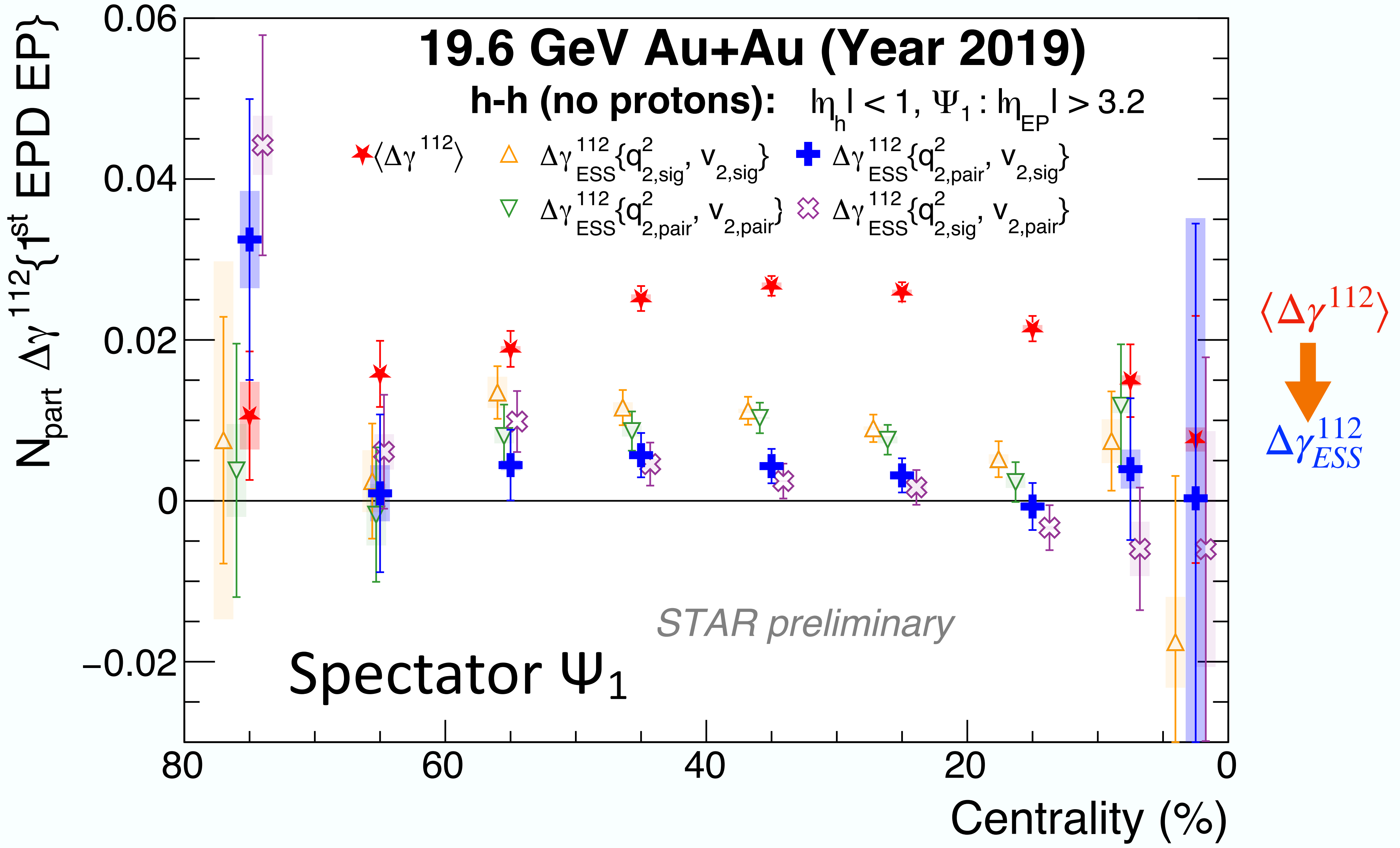


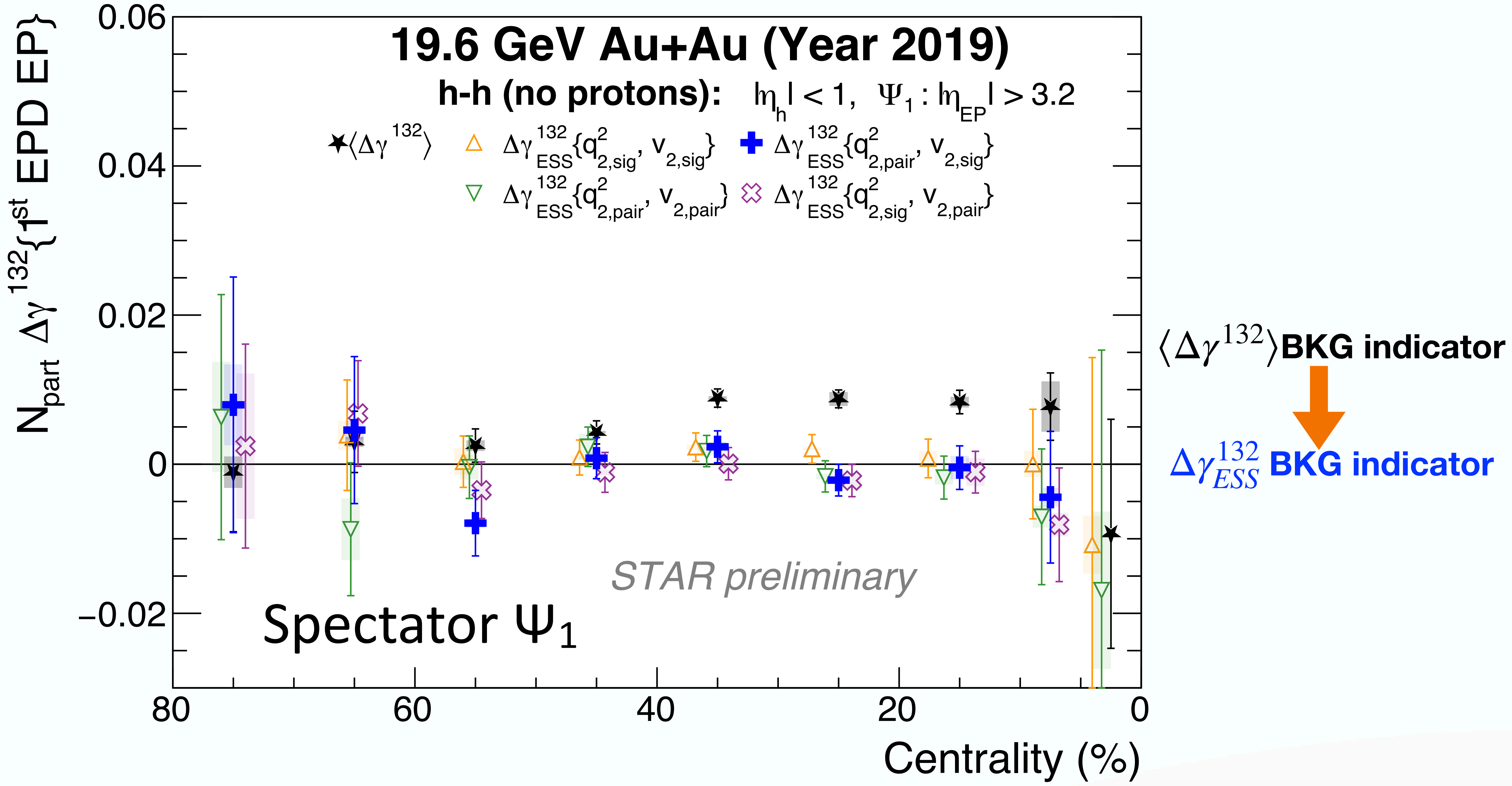
- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT**
- **The y-intercept needs a correction to restore the CME signal:**

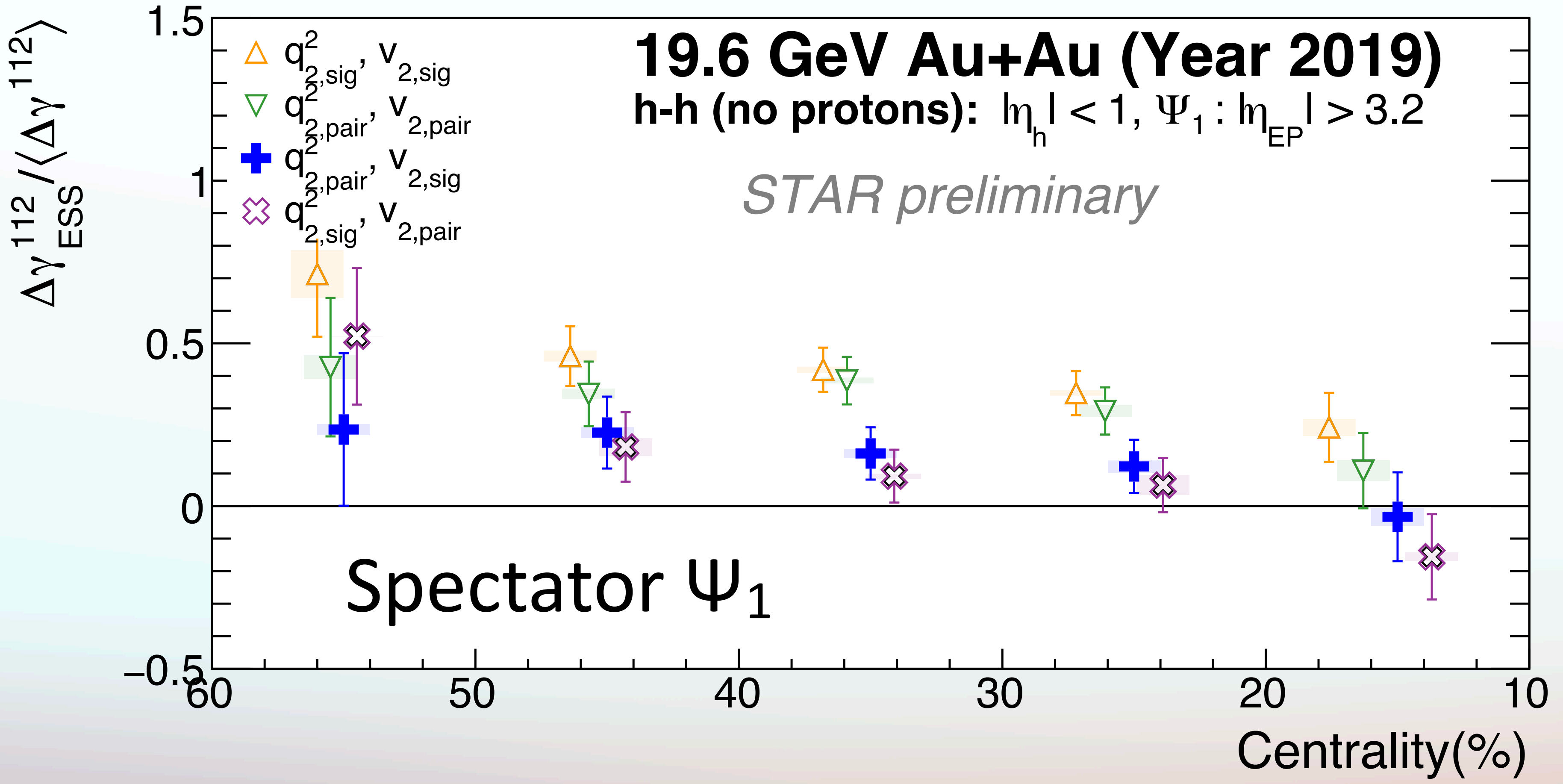
$$\Delta\gamma^{112}_{ESS} = Intercept \times (1 - v_2)^2$$

Z.Xu et al Phys. Rev. C 107, L061902

Beam Energy Scan II - Event Shape Selection

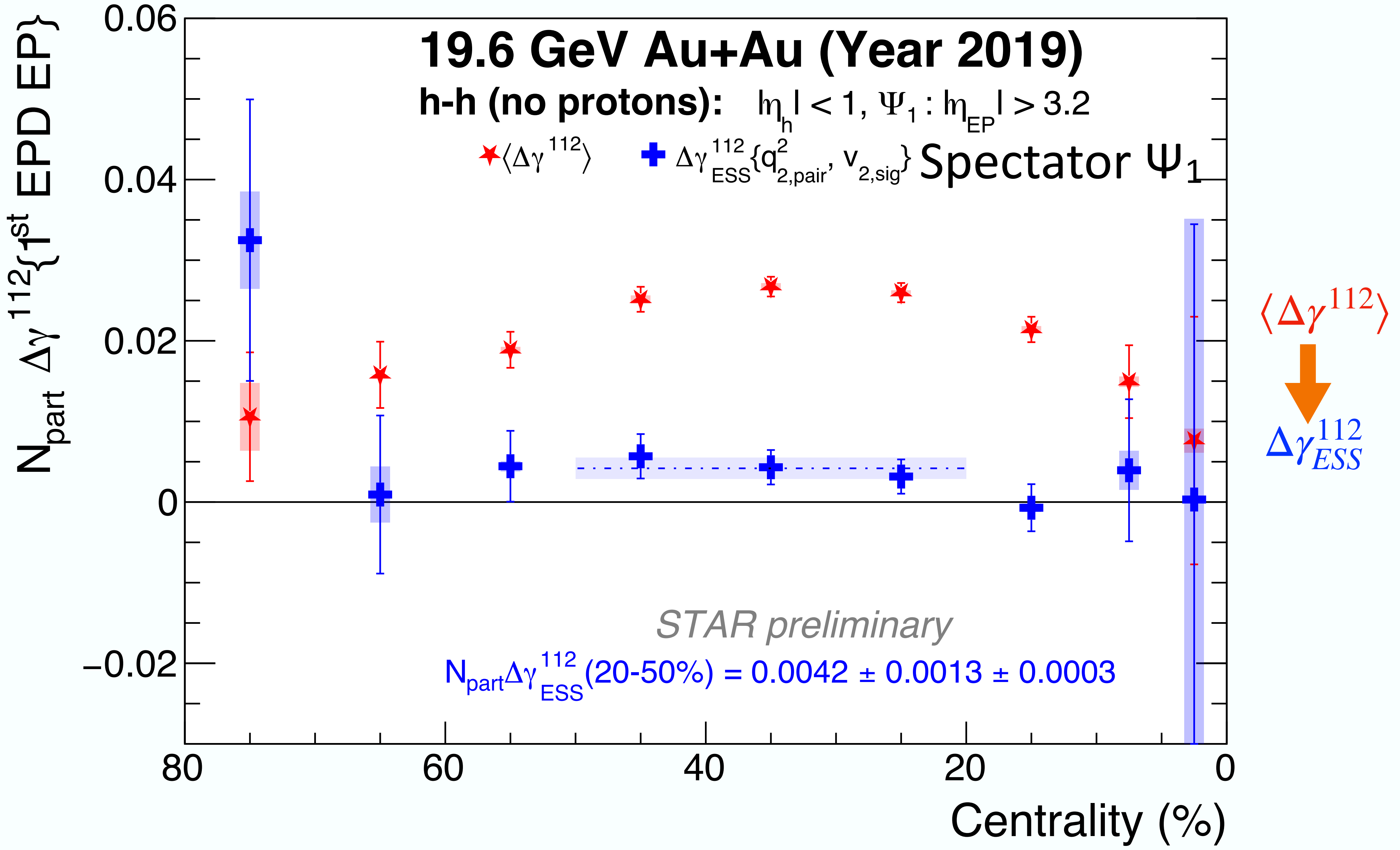


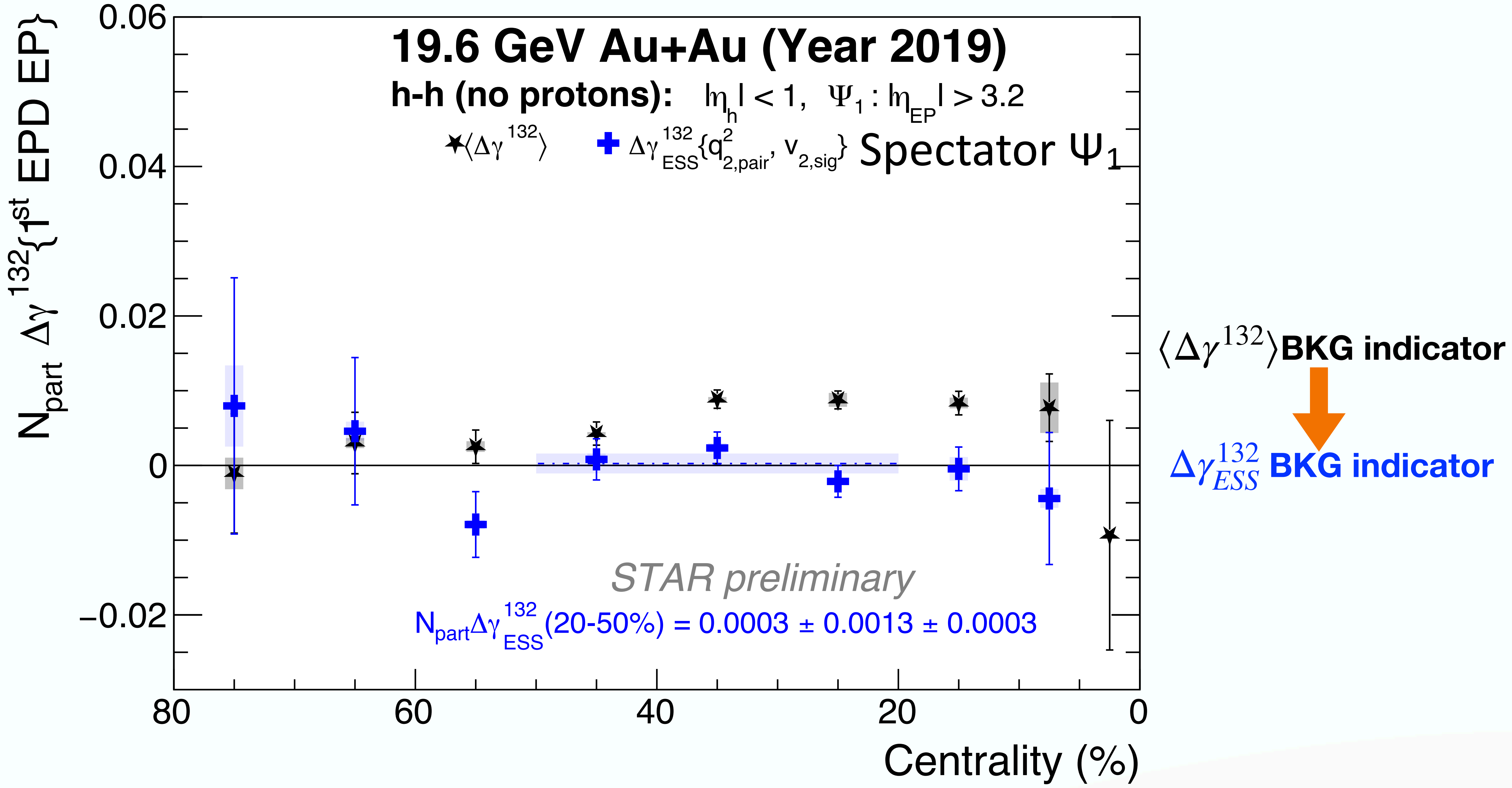


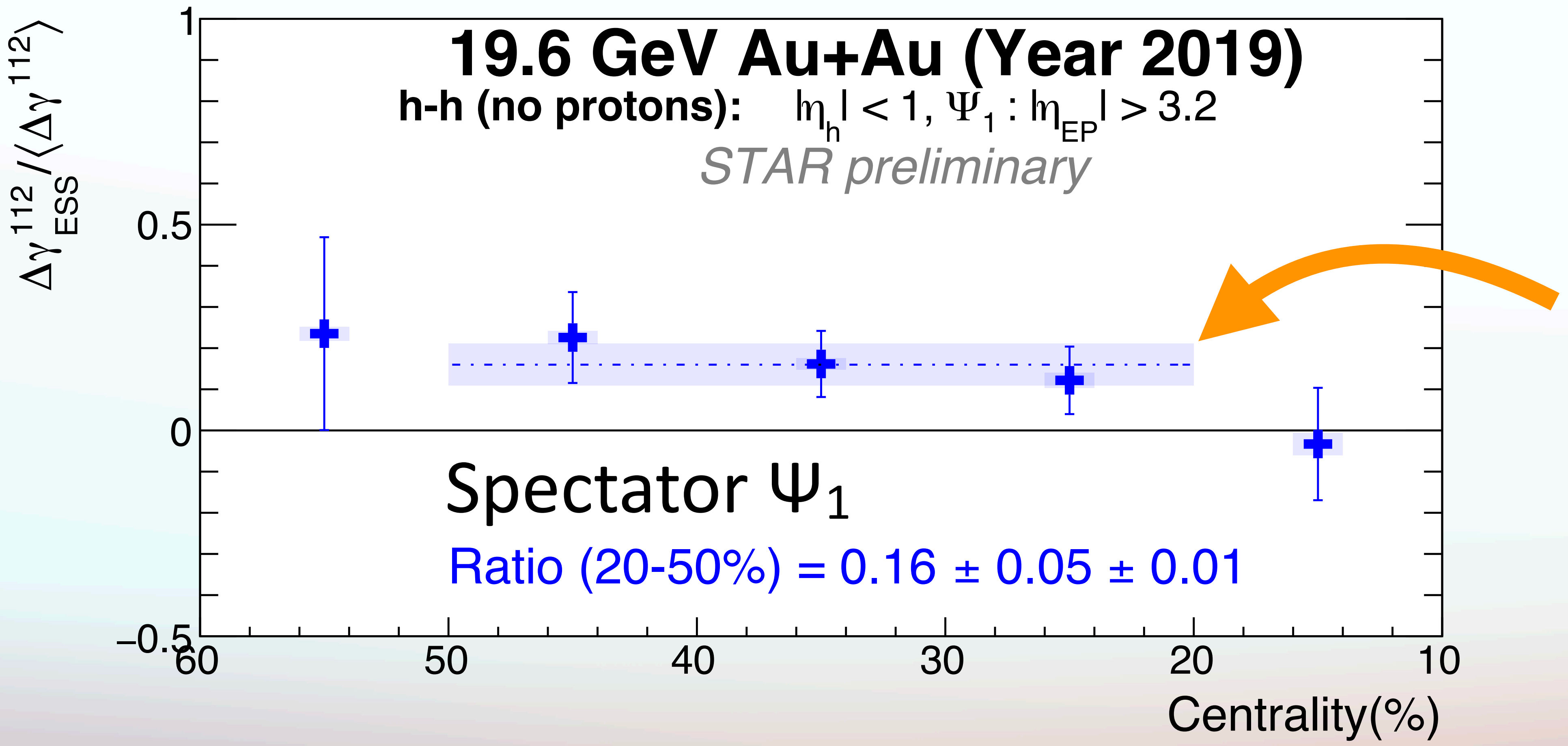


- The ESS is applied to different centralities.
- Ordering of four $\Delta\gamma_{ESS}^{112}$ follows prediction from model.
- We will focus on the optimal recipe ESS(c).

Beam Energy Scan II - Event Shape Selection

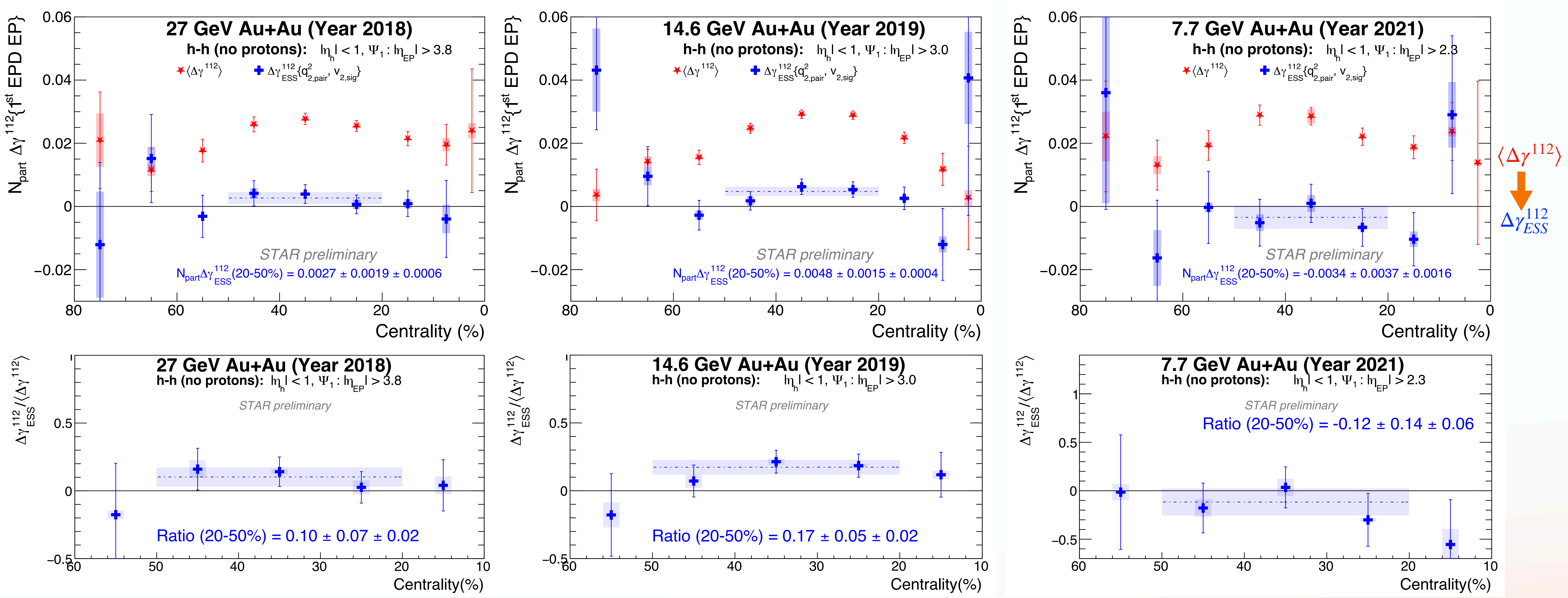






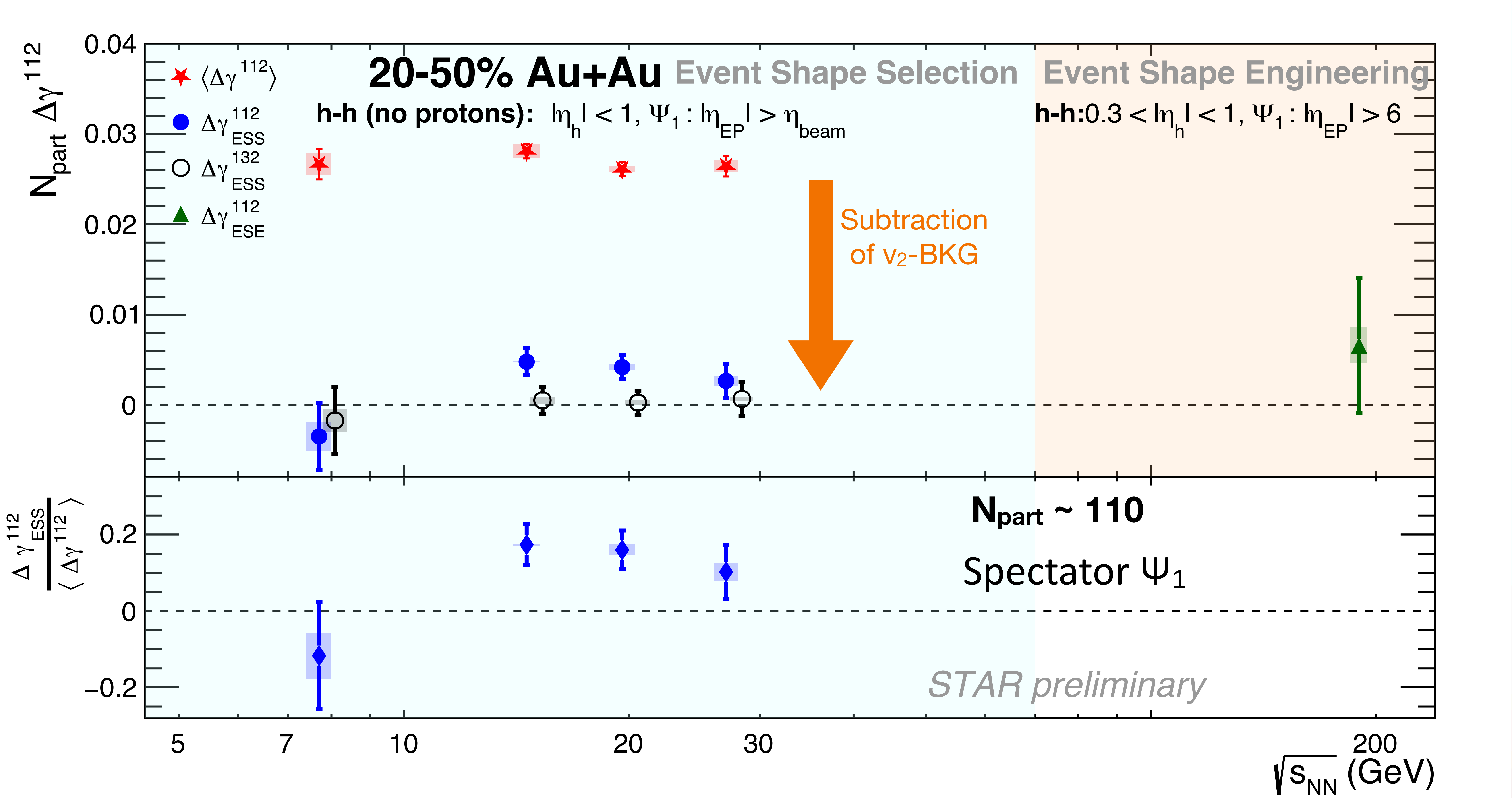
- **After v_2-BKG subtraction, a finite signal in mid-central events.**
- **Ratio from the optimal ESS (c), pair q^2 and single v_2, yields a 3σ significance for 20-50% at 19.6 GeV.**
- **From BKG indicator $\Delta\gamma^{132}$, ESS successfully removes v_2-BKG.**

Beam Energy Scan II - Event Shape Selection



- Results from the optimal ESS (c), pair q^2 and single v_2:
  - At 27 GeV, uncertainties too large to conclude.
  - At 14.6 GeV, the ratio for 20-50% has a 3σ significance.
  - At 7.7 GeV, the current results favor the zero-CME scenario.

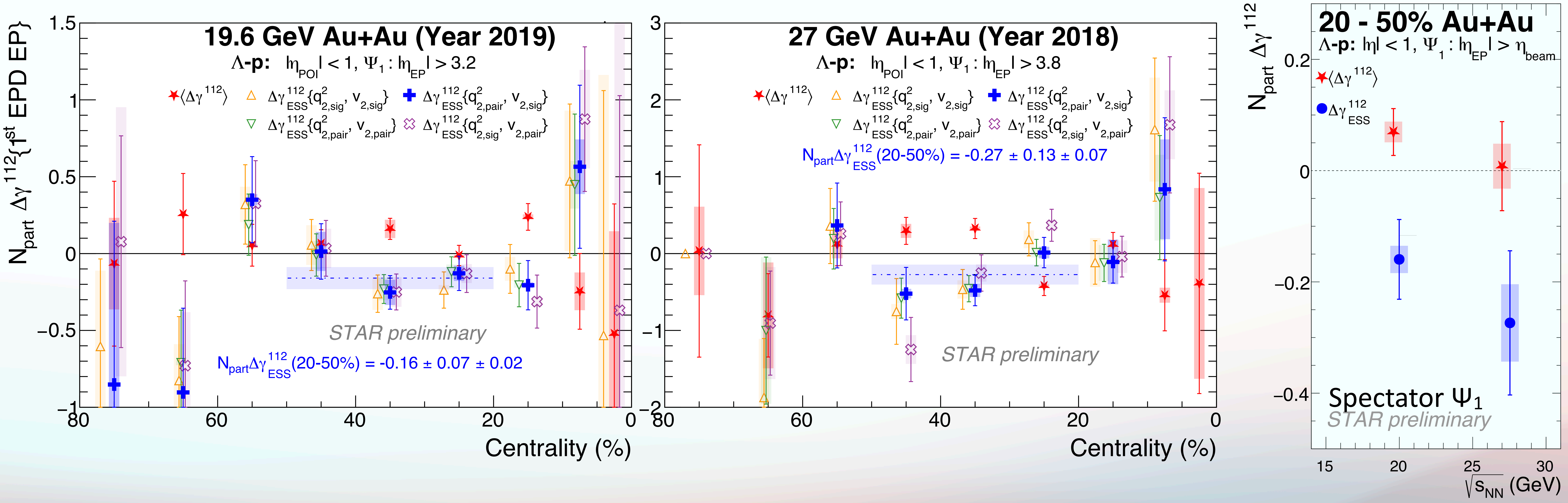
Beam Energy Dependence of CME observable



- After v_2-BKG subtraction with Event Shape variables, and nonflow suppression with Ψ_1
  - At 14.6 and 19.6 GeV, a 3σ effect.
  - At 7.7, 27, 200 GeV, the current results have large uncertainties.
- More BES-II data analyses for 11.5 GeV and 9.2 GeV are on the way.

CVE measurement at BES-II

- At 19.6 and 27 GeV, CVE measurements of Λ-p using Δγ correlator w.r.t. Ψ_1 are consistent with zero.
- Results lack of significance due to low hyperon statistics.

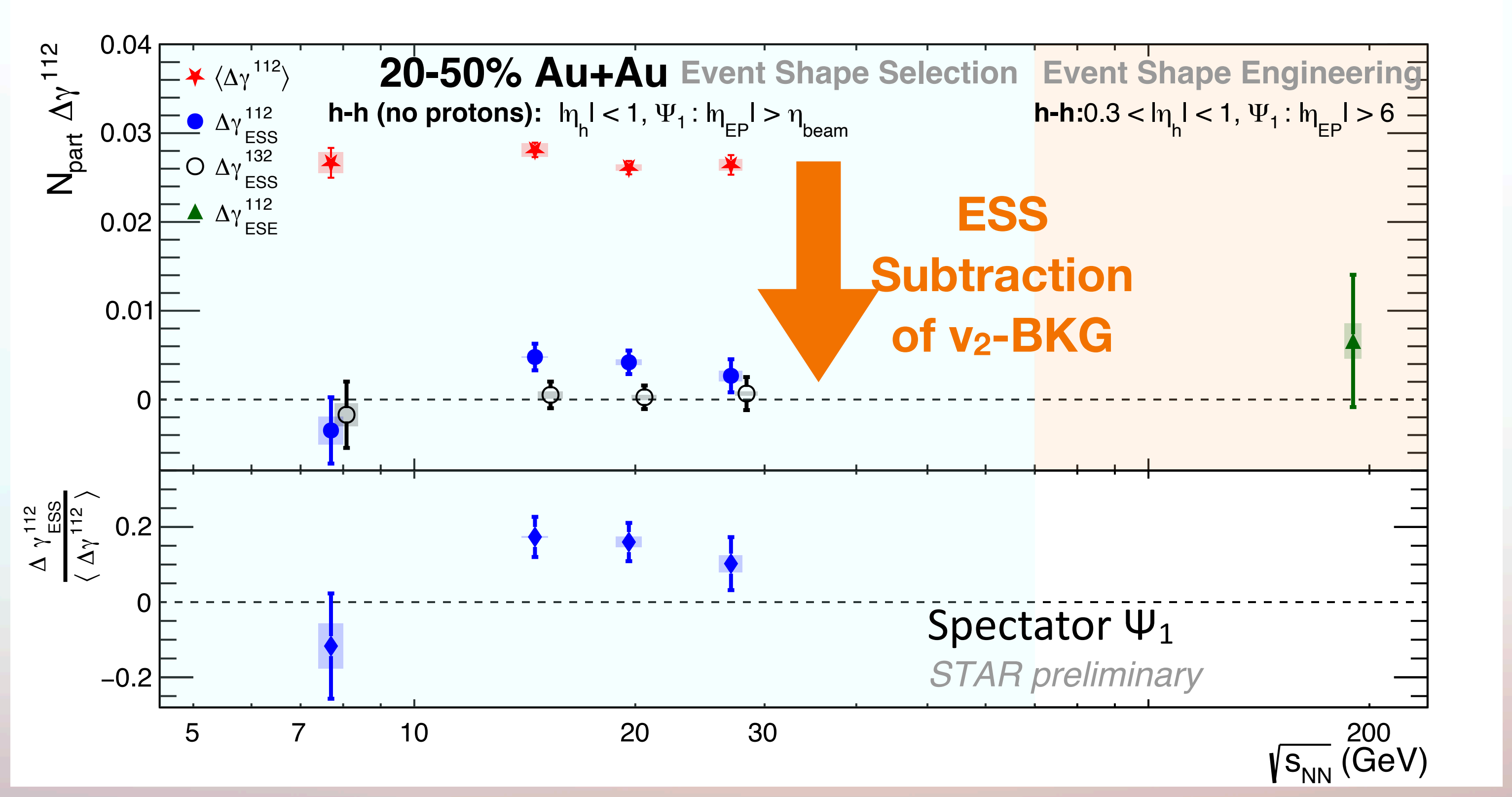


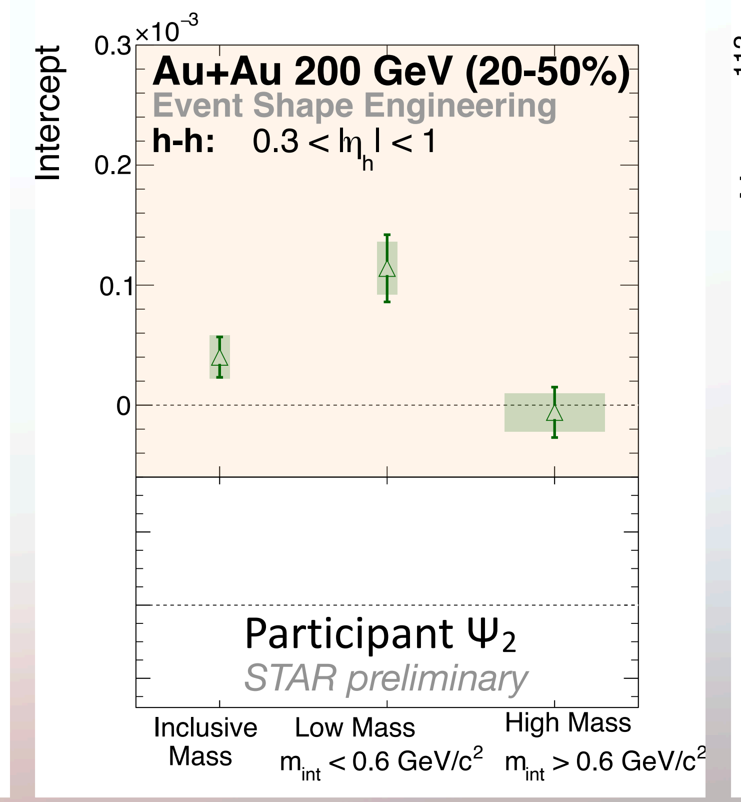
Summary

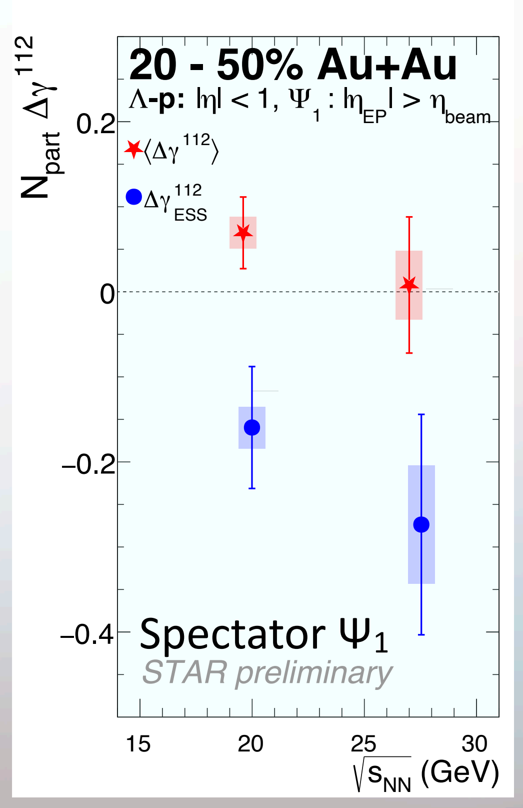
Event Shape method Spectator Ψ_1

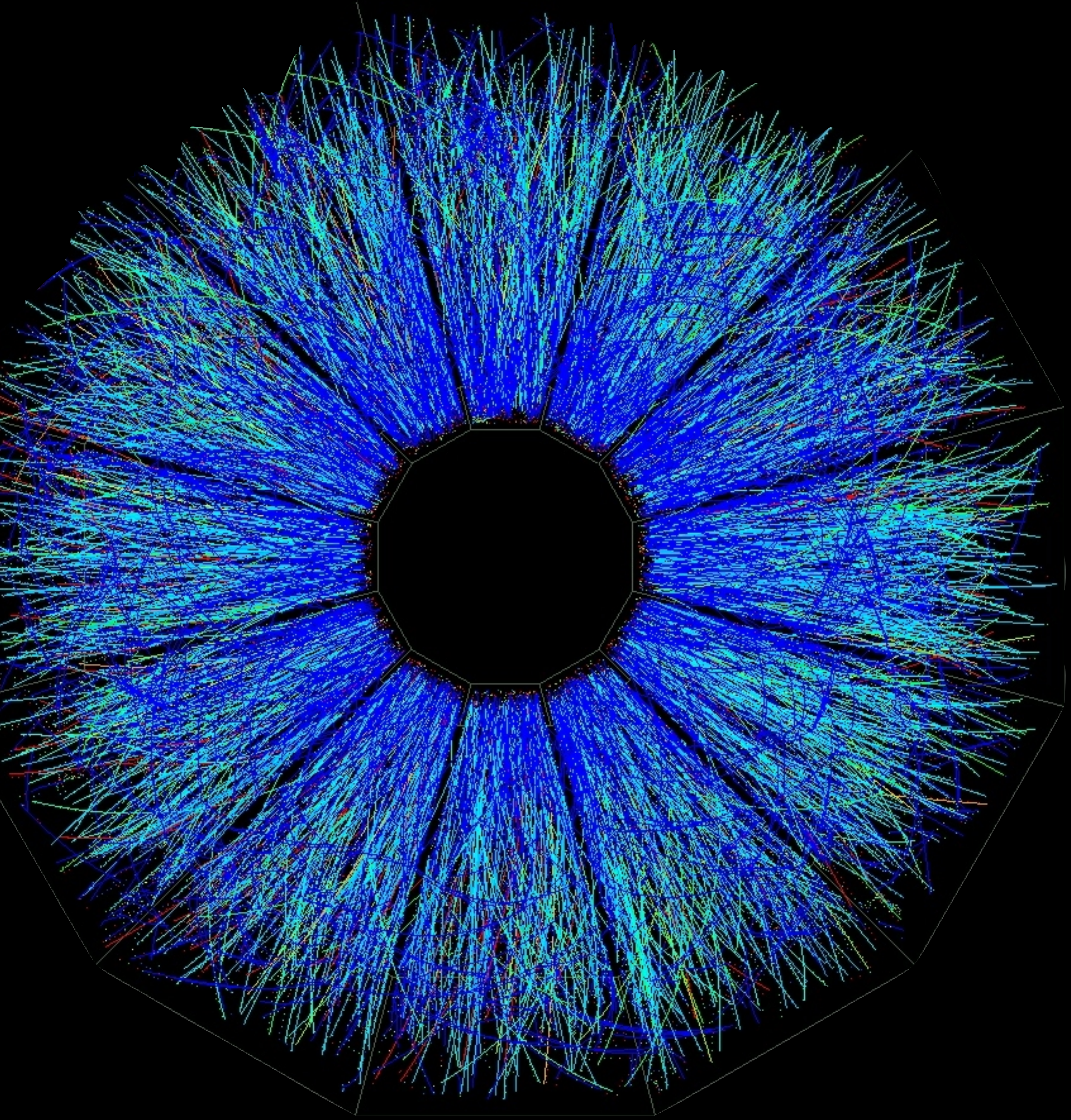
$$\Delta\gamma^{112} = \Delta\gamma^{\mathrm{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{non-flow}}$$

- The search for the CME and CVE addresses an intrinsic topological property of QCD.
- We use Event Shape Selection to extrapolate $\Delta\gamma^{112}$ to zero-flow limit, and use spectator plane Ψ_1 to suppress the non-flow background.
    - The CME-sensitive $\Delta\gamma^{112}$ after BKG subtraction is finite (3σ) at 14.6 and 19.6 GeV.
    - The data interpretation requires further assessment on the new ESS methodology:
        - According to AVFD, the method is accurate (3σ signal);
        - According to AMPT, there is over-subtraction of BKG (> 3σ signal).
- At 200 GeV, using ESE with Ψ_2, low-invariant-mass region appears to have a larger ESE intercept (3σ) than high-mass region. Residual nonflow effects to be assessed.
- No CVE effects have been observed in Au+Au at 19.6 and 27 GeV.







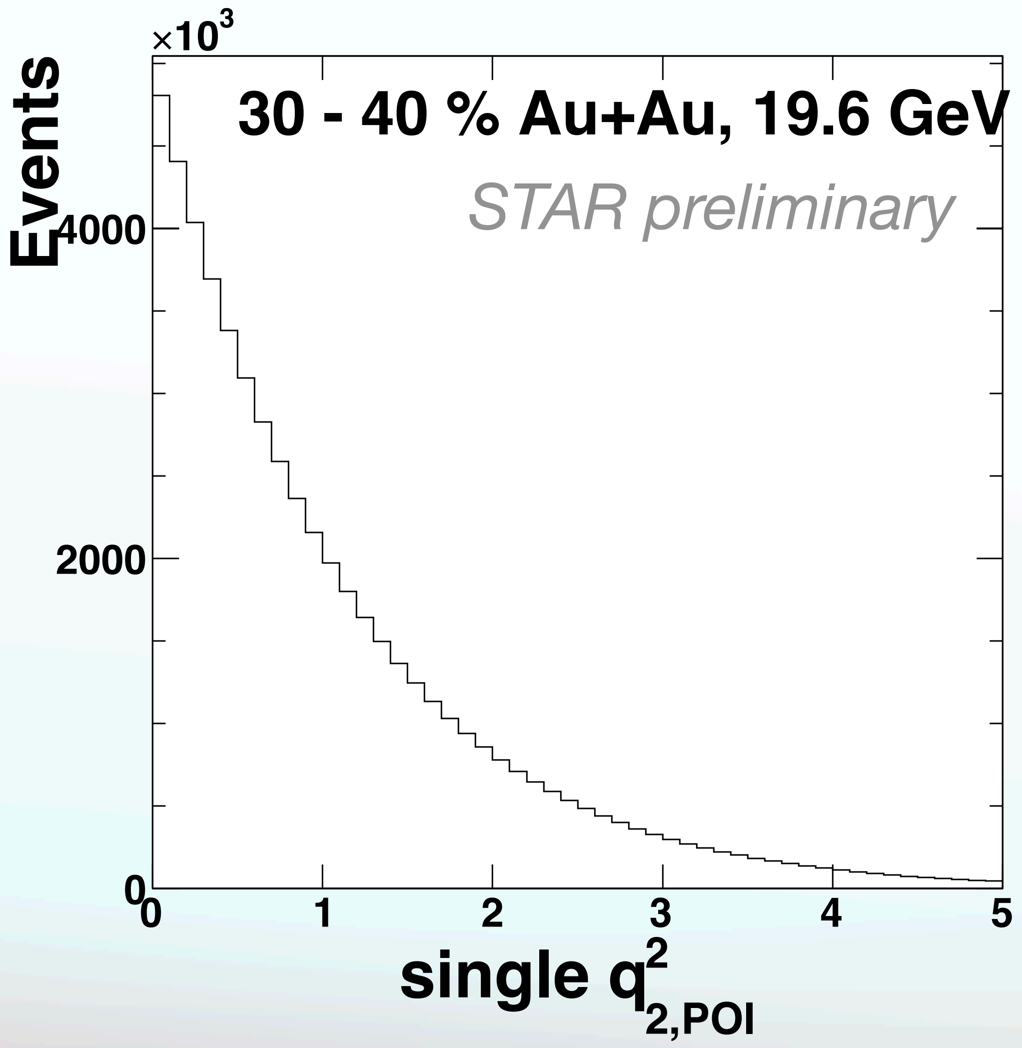


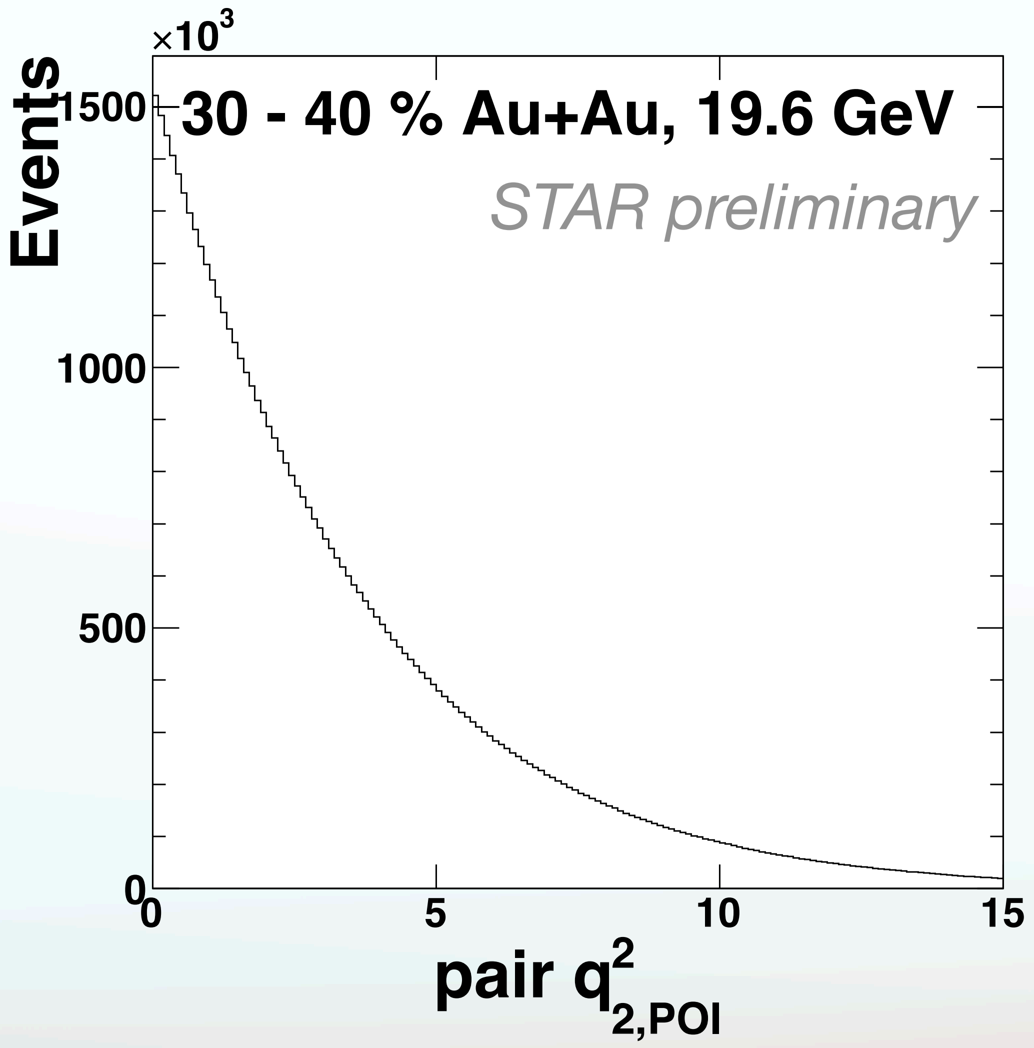
Thank you!

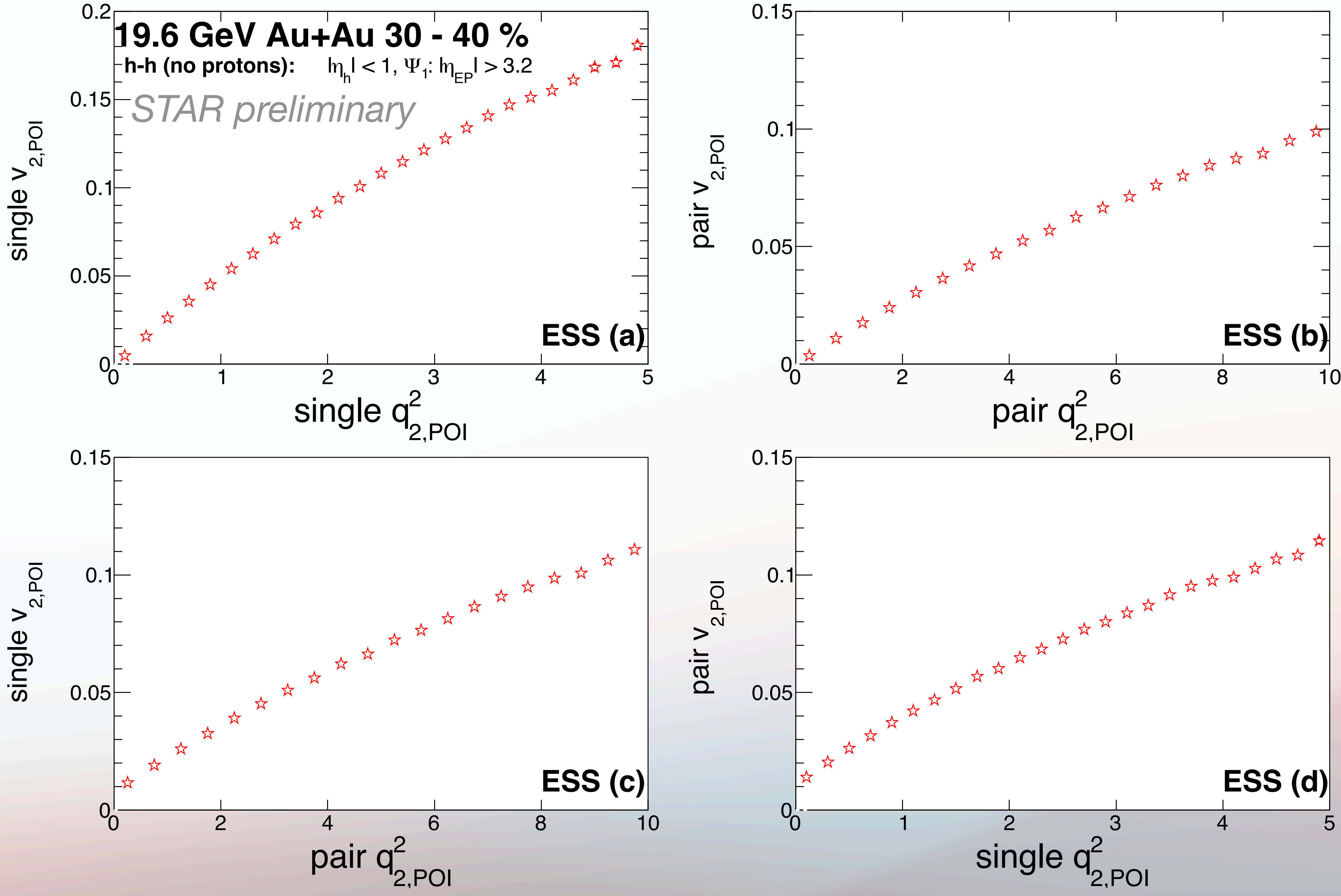
Analyses Details for Event Shape Selection

- φ_i **from TPC hadron (excluding proton) |η|<1**
- **Pair** $\varphi_p = \tan^{-1}\dfrac{p_{T,1}\sin\varphi_1 + p_{T,2}\sin\varphi_2}{p_{T,1}\cos\varphi_1 + p_{T,2}\cos\varphi_2}$ **constructed on** φ_i **from TPC hadron (excluding proton) |η|<1.**
- **q^2 : Event Shape variable for binning events** $q_2^2\{single(pair)\} = \dfrac{\left(\sum_{i=1}^{N}\sin 2\varphi_{i(p)}\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_{i(p)}\right)^2}{N(1+N\langle v_{2,s(p)}\rangle)}$
- **At each single (pair) q^2_{POI} bin, measure the selected event averaged observable v_2 and $\Delta\gamma^{112}$**

$$v_2\{single(pair)\} = \frac{\langle\cos(2\varphi_{i(p)} - \Psi_{1,EPDe} - \Psi_{1,EPDw})\rangle}{res^2_{1,sub}}$$

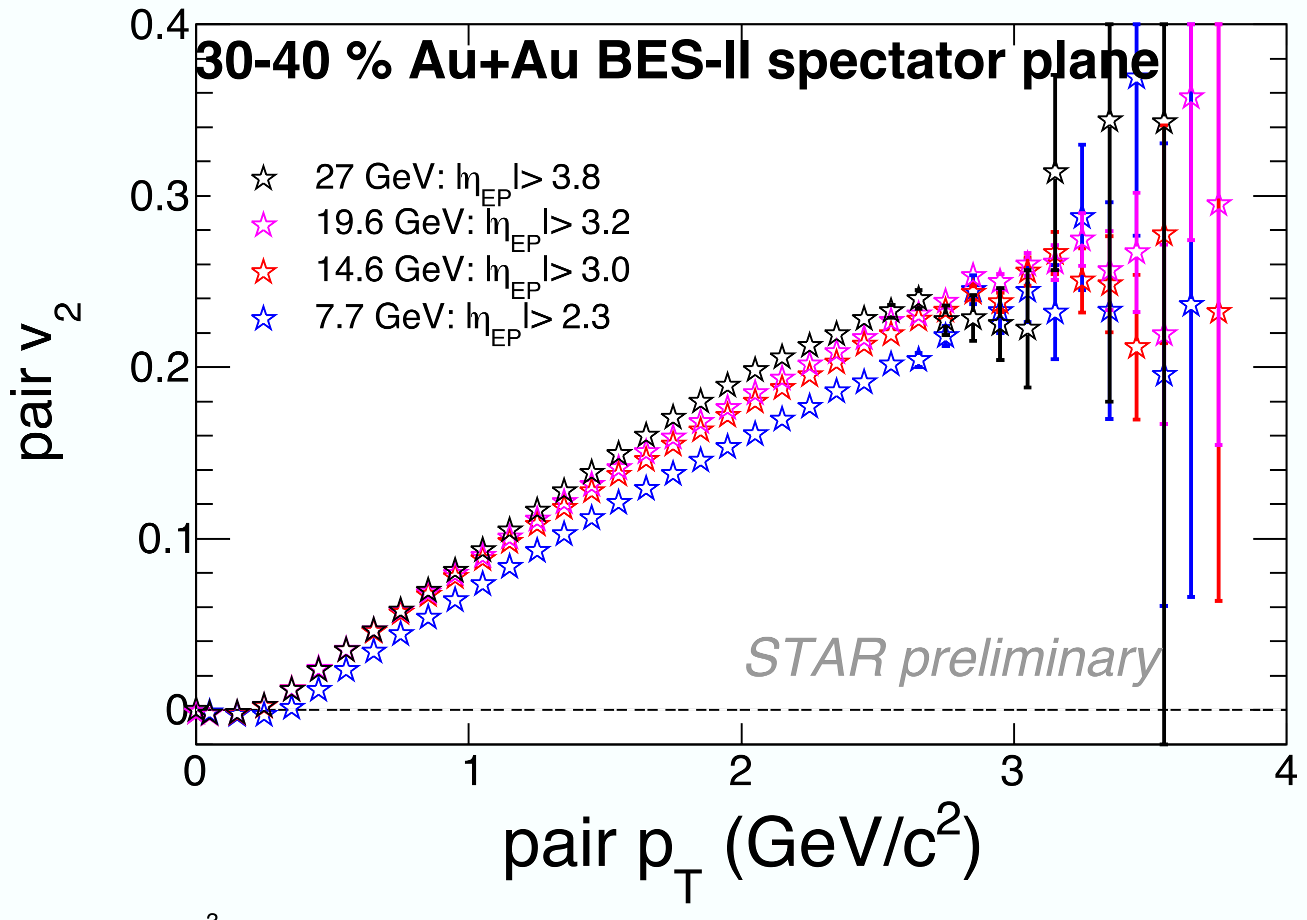






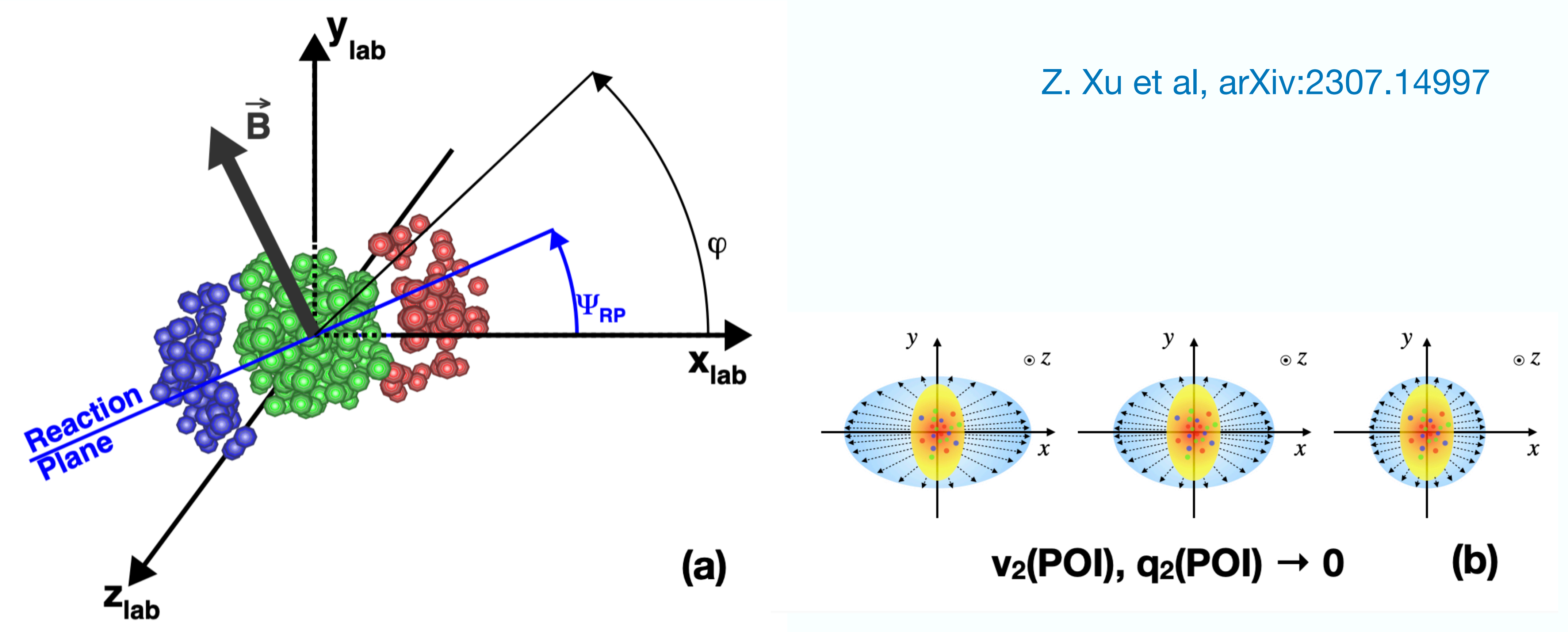
ESS and Pair v_2

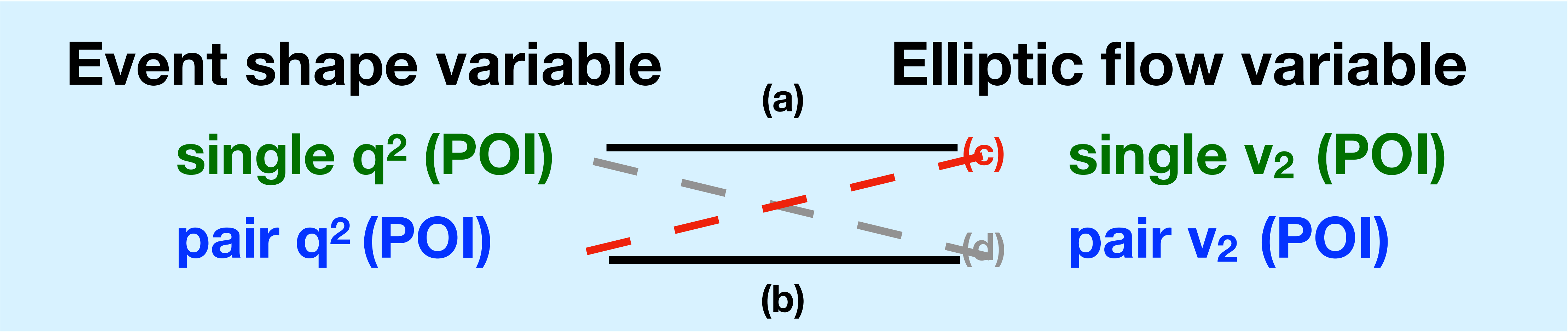
- **Pair v_2 from adding momenta of two POI particles.**

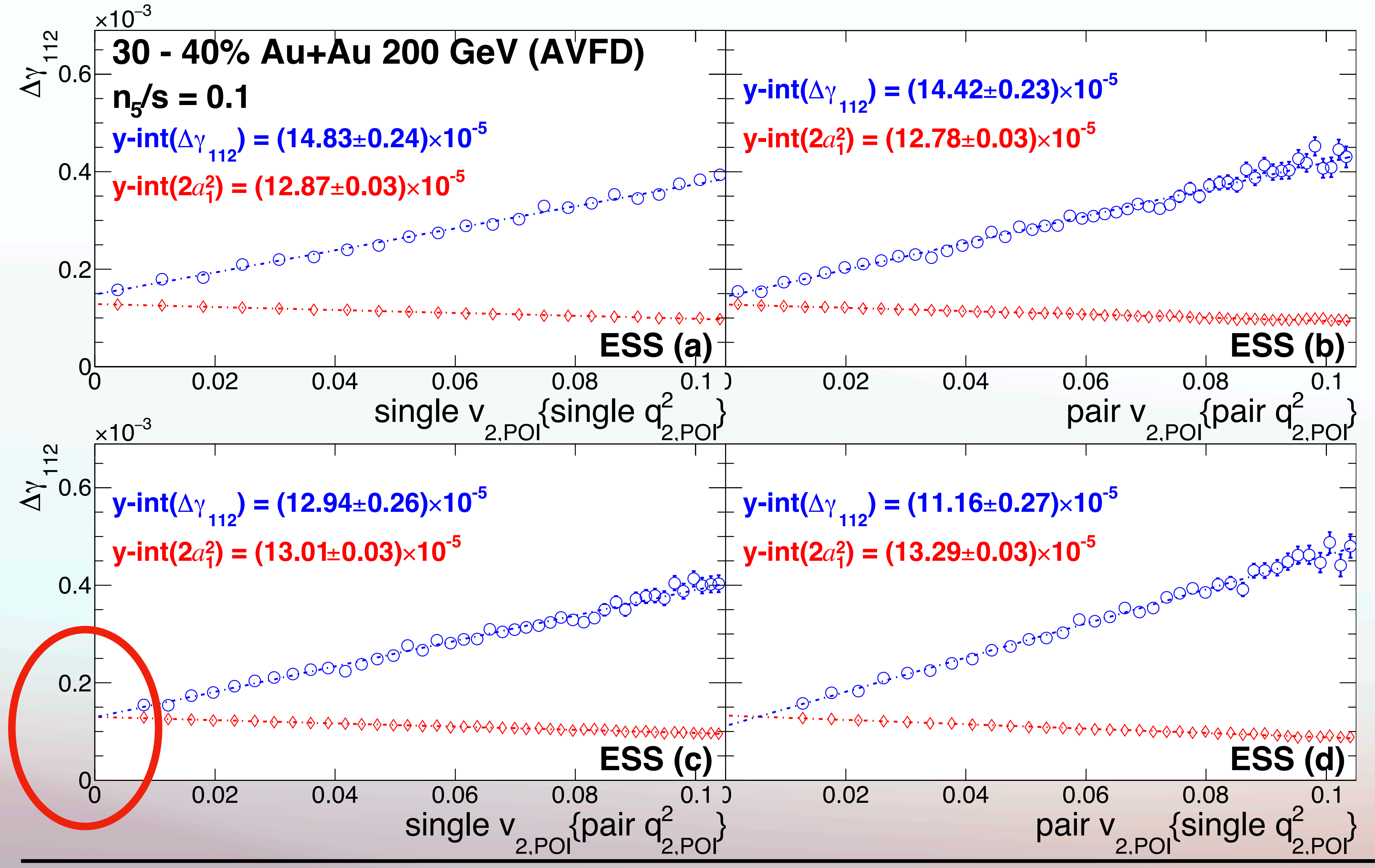


$$\text{pair } v_2 \sim \cos 2\phi - \frac{N^{SS}}{N^{OS}+N^{SS}}(\Delta\gamma - v_2^{\pi}\Delta\delta)$$

↑ **Dominant**







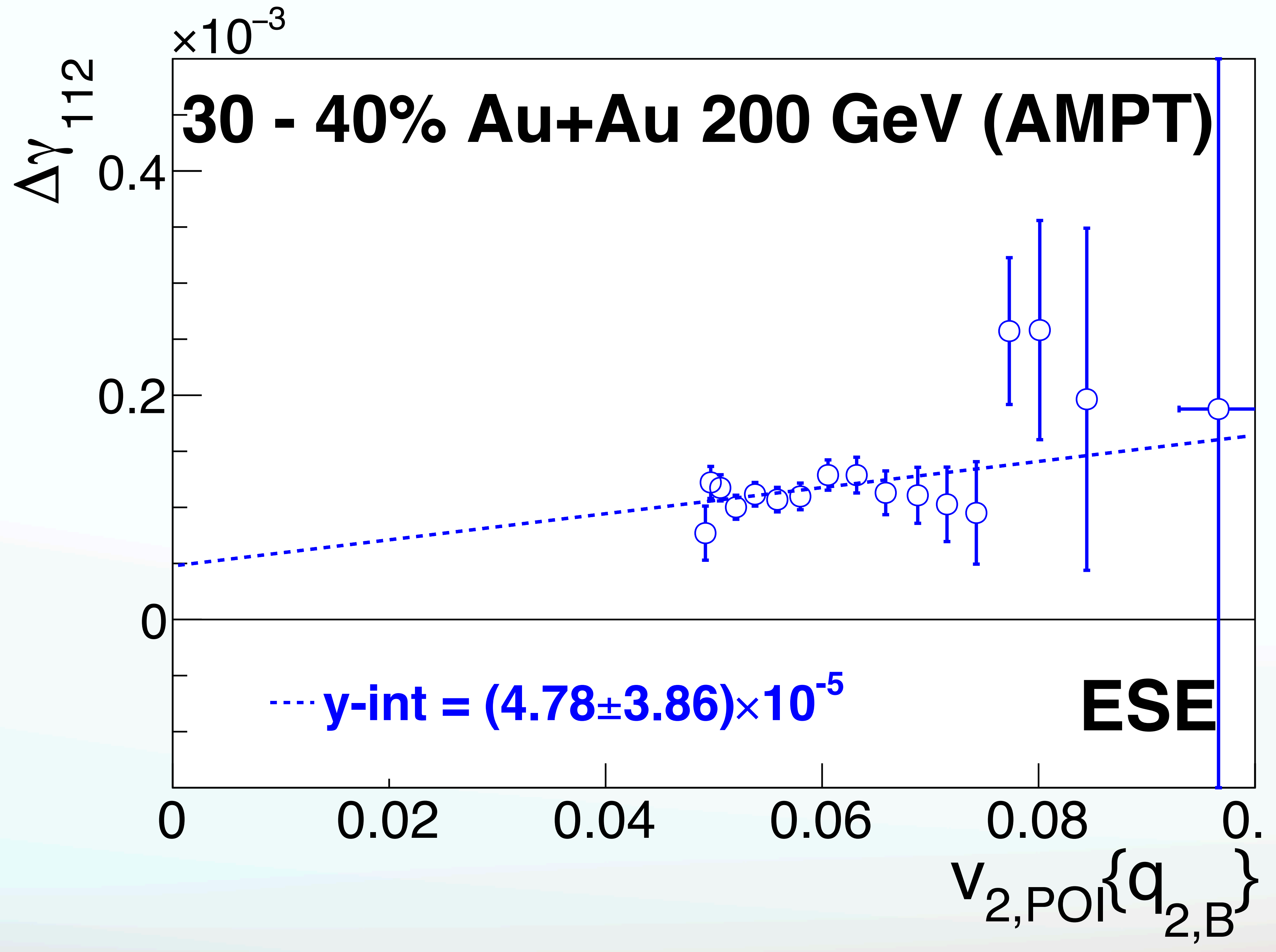
- **Unmixed recipes (a) and (b) cause residual background near zero-flow region**
- **Mixed recipes have advantage that the v_2 and binning q^2 are less correlated.**
- **However, pair v_2 contains true CME signal, which may lead to over subtraction for (d).**

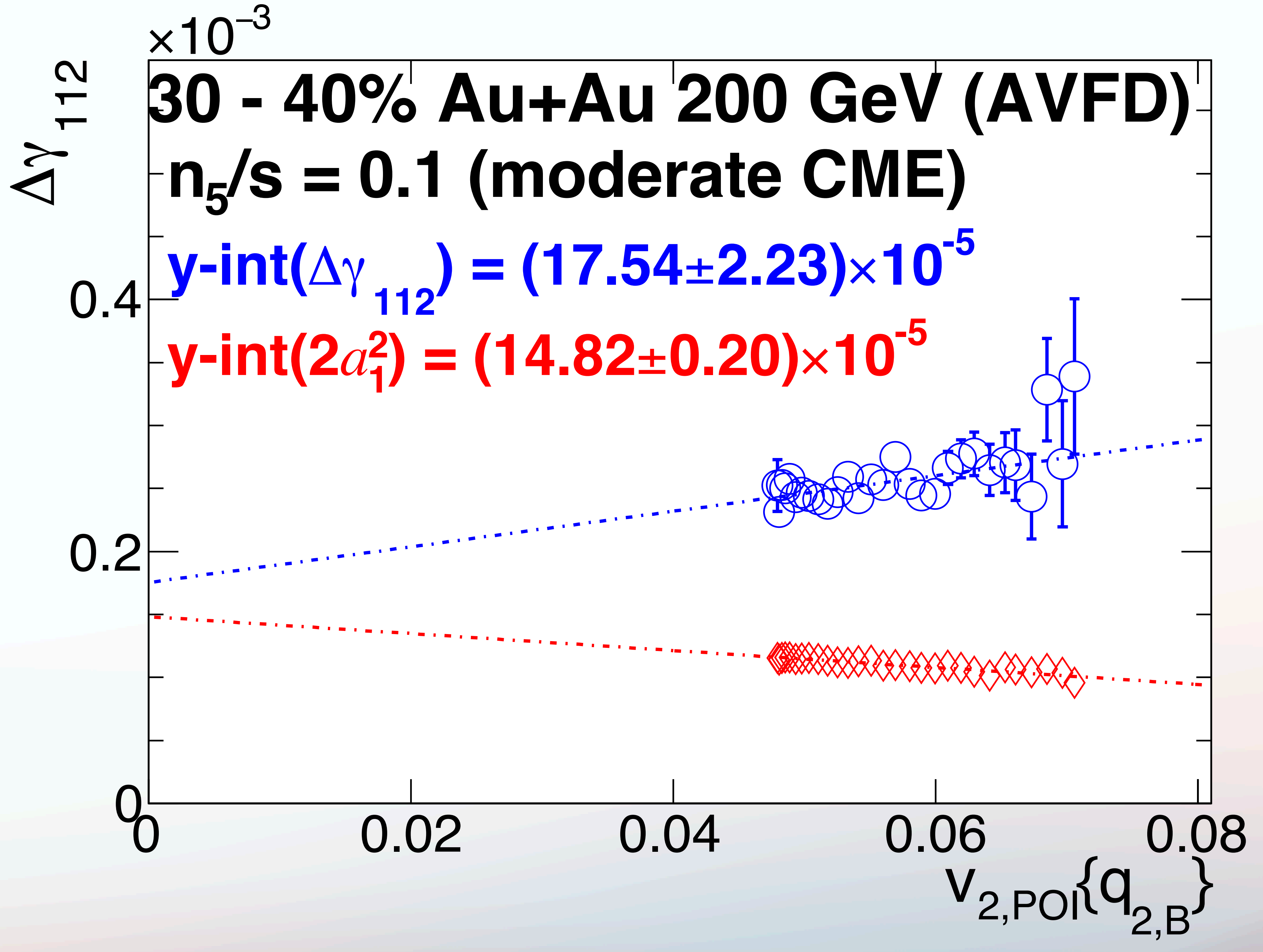
Scenario (c) — pair q_2, single v_2 is the optimal solution!

Simulation for q_B from Event Shape Engineering

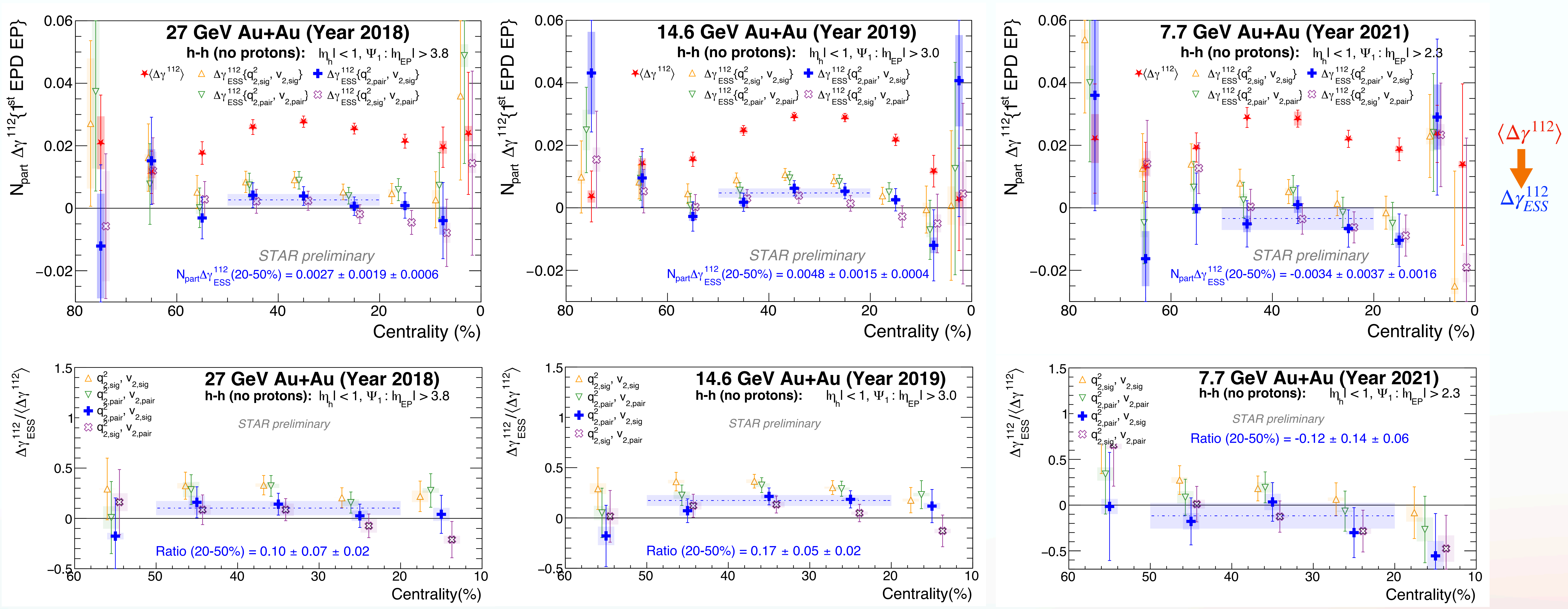
q_B (no POI) —— v_2 (POI)

- ESE works effectively with mid-rapidity q_B ($|\eta|<0.3$) and POI ($0.3<|\eta|<1$)
- The errors become many times larger than those on slide 19



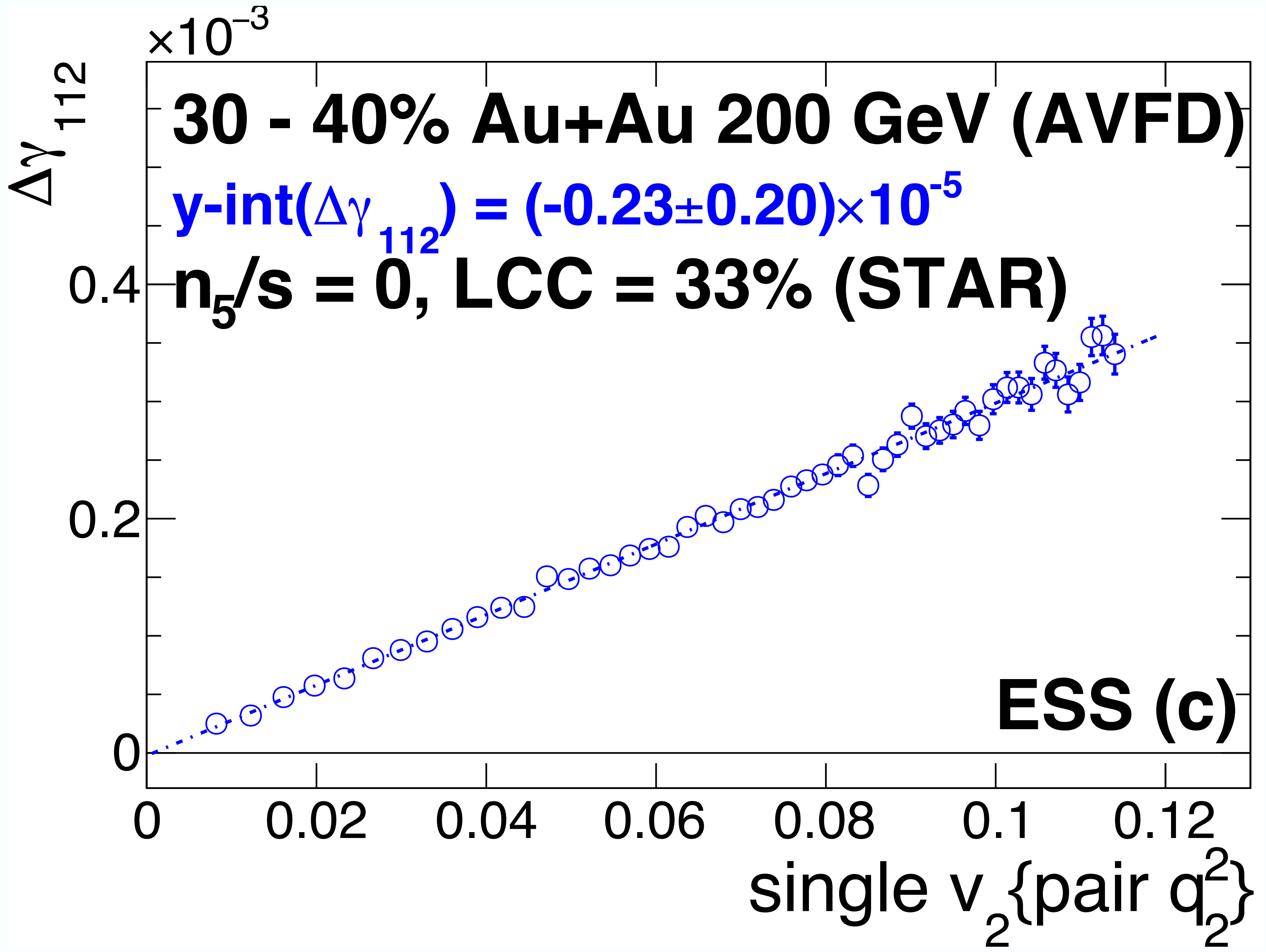


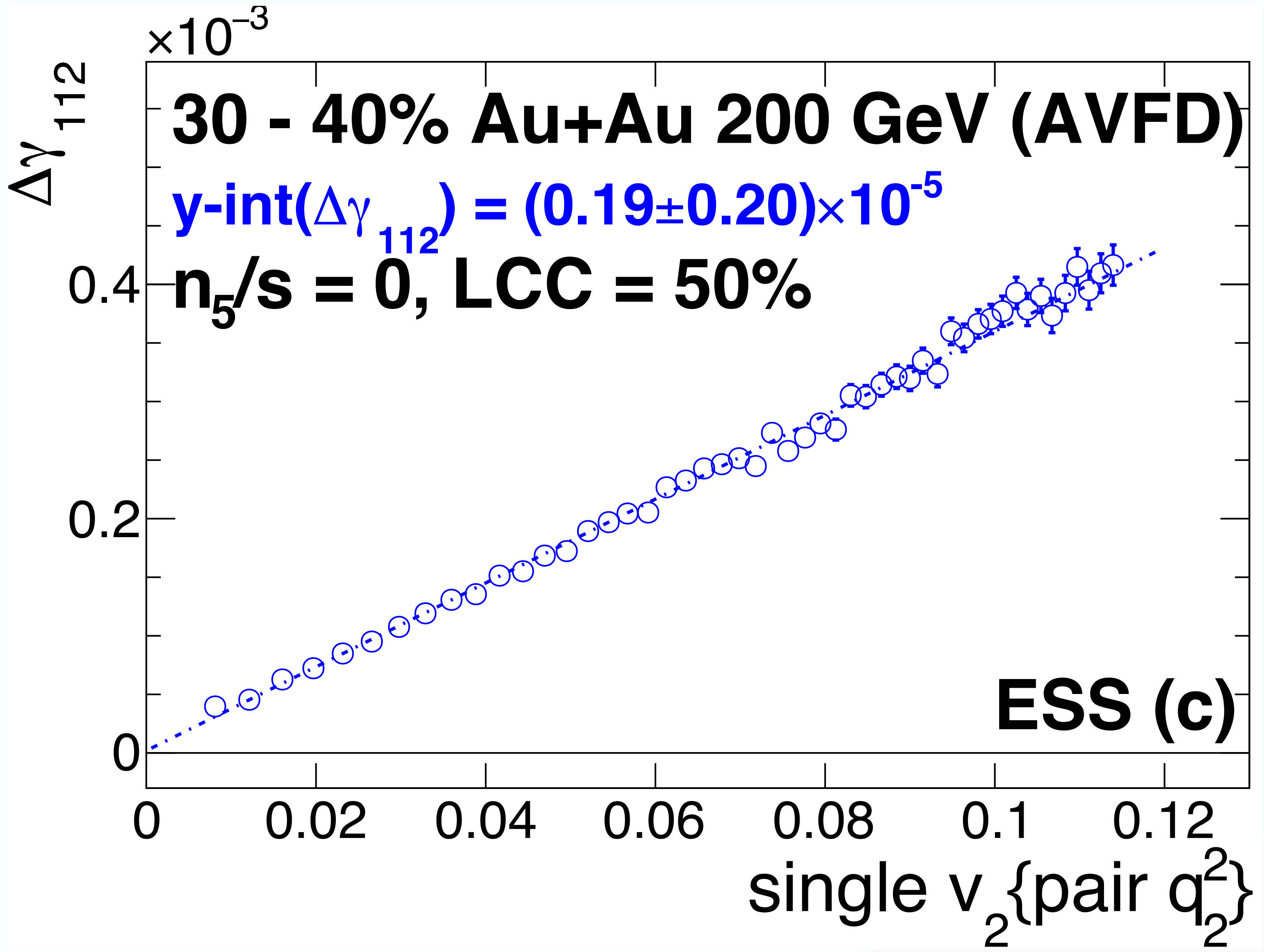
Beam Energy Scan II - Event Shape Selection



- At 27 GeV, the results from the optimal ESS (c), pair q^2 and single v_2 have uncertainties too large to conclude.
- At 14.6 GeV, the ratio for 20-50% using optimal ESS has a 3σ significance.
- At 7.7 GeV, the current results favor the zero scenario.

ESS: AVFD at different LCC





- **AVFD check at different Local Charge Conservation (LCC) tuning confirms that ESS(c) can well restore zero BKG.**
  - **Experiment data LCC is 33%**