



RHIC

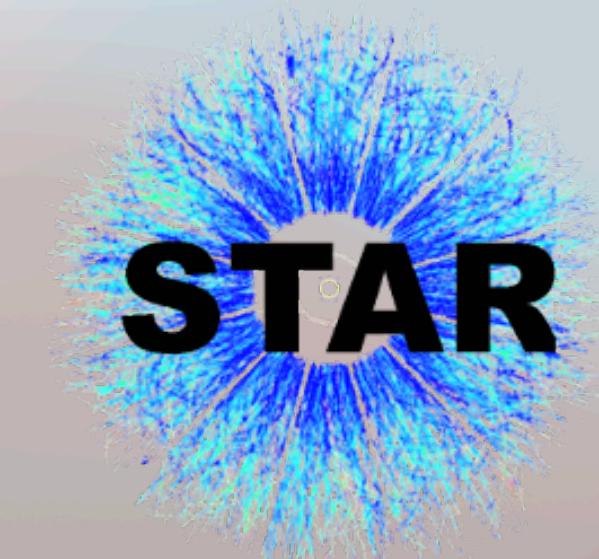
Brookhaven
National Laboratory

Supported in part by
U.S. DEPARTMENT OF
ENERGY

STAR

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

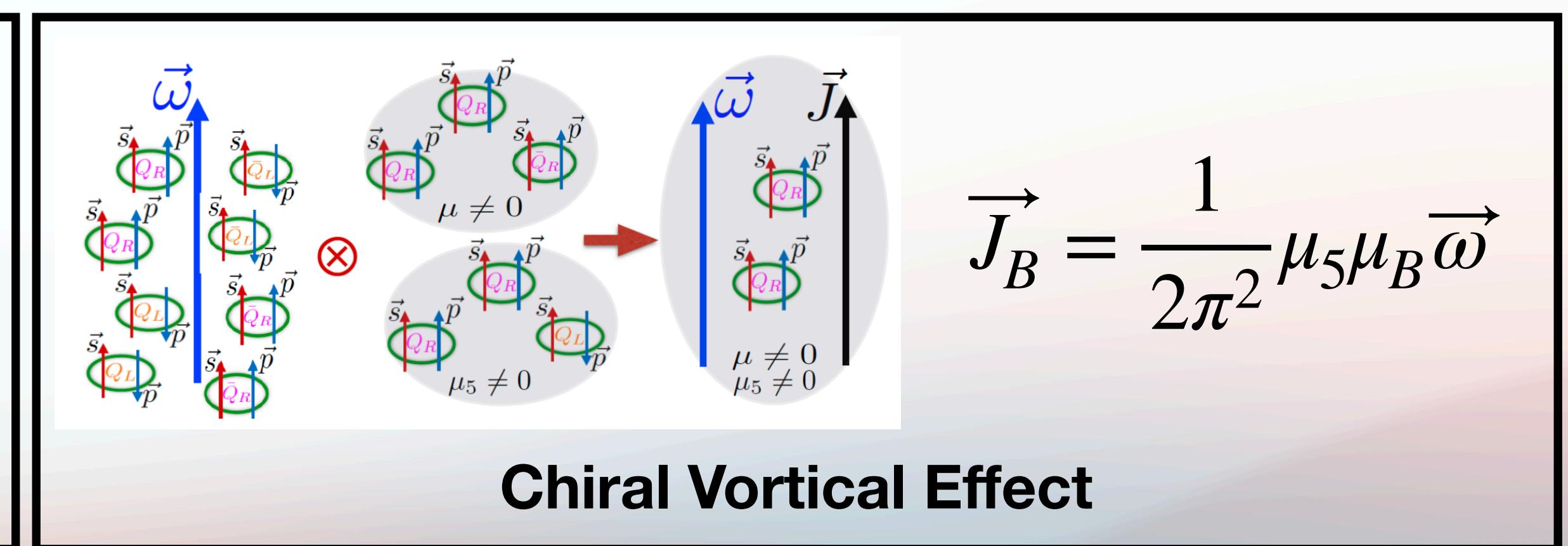
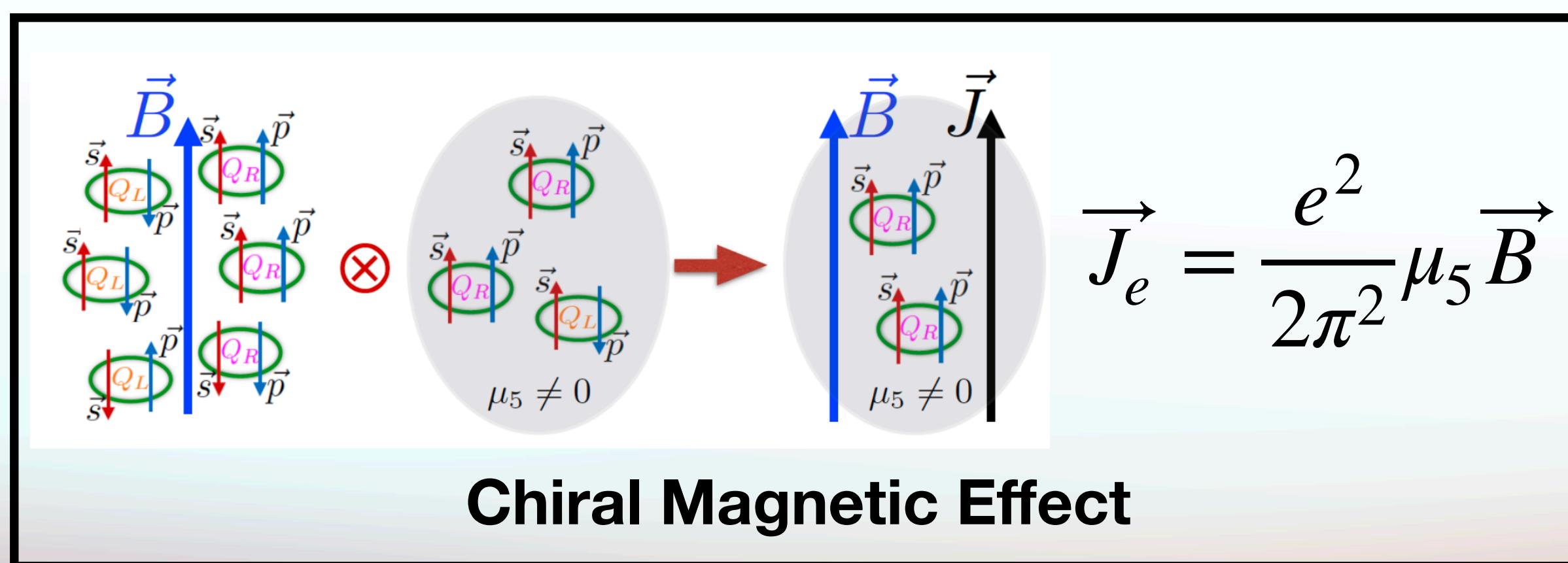
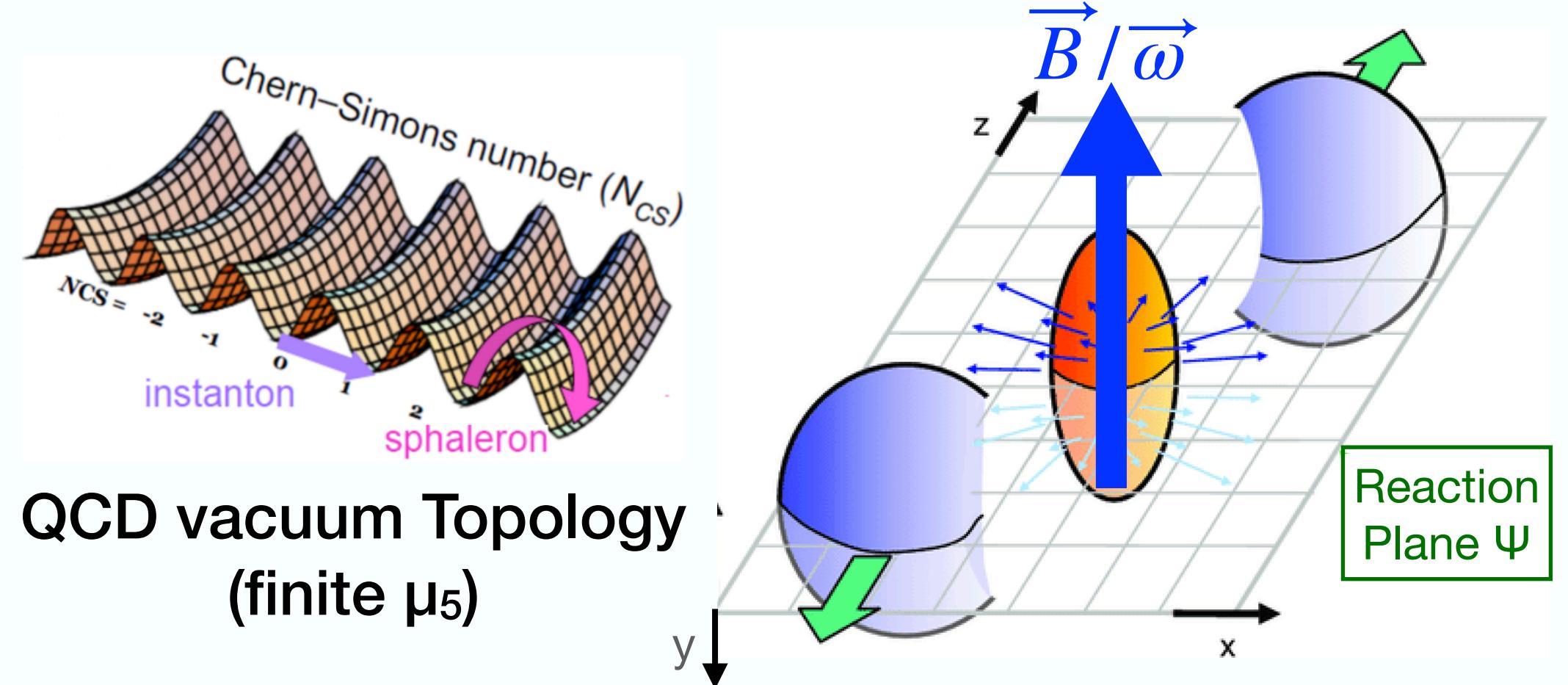
Zhiwan Xu (for the STAR Collaboration)
University of California, Los Angeles
Sep 5, 2023



Chiral Magnetic and Vortical Effect

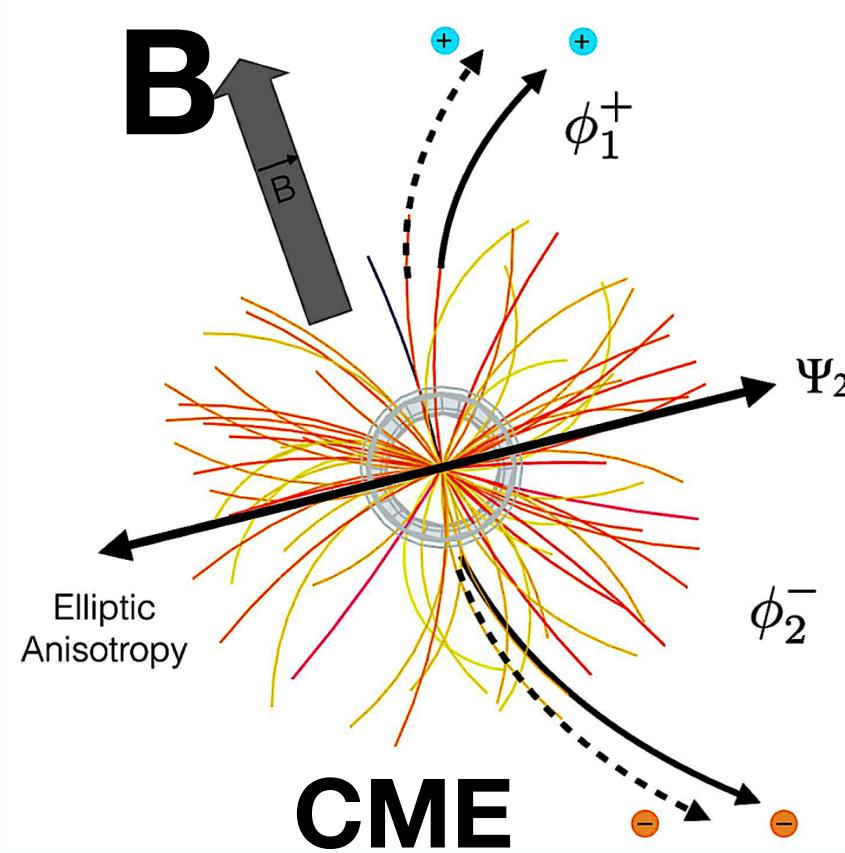
Kharzeev, Pisarski, Tytgat, PRL 81(1998) 512
S.A. Voloshin, Phys. Rev. C, 70, 057901 (2004)

- 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!



Experimental Observables

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



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

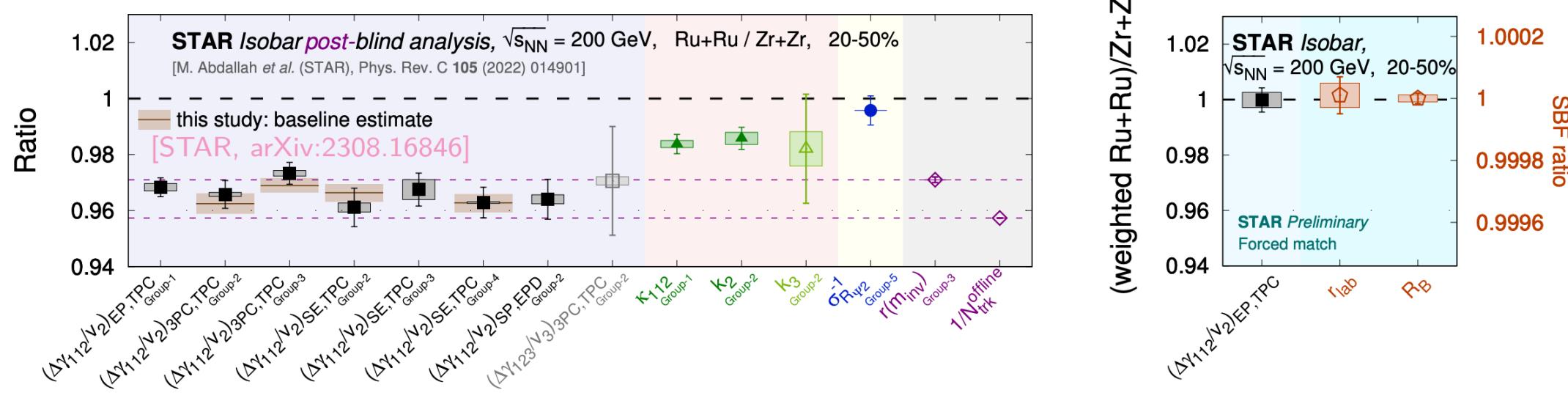
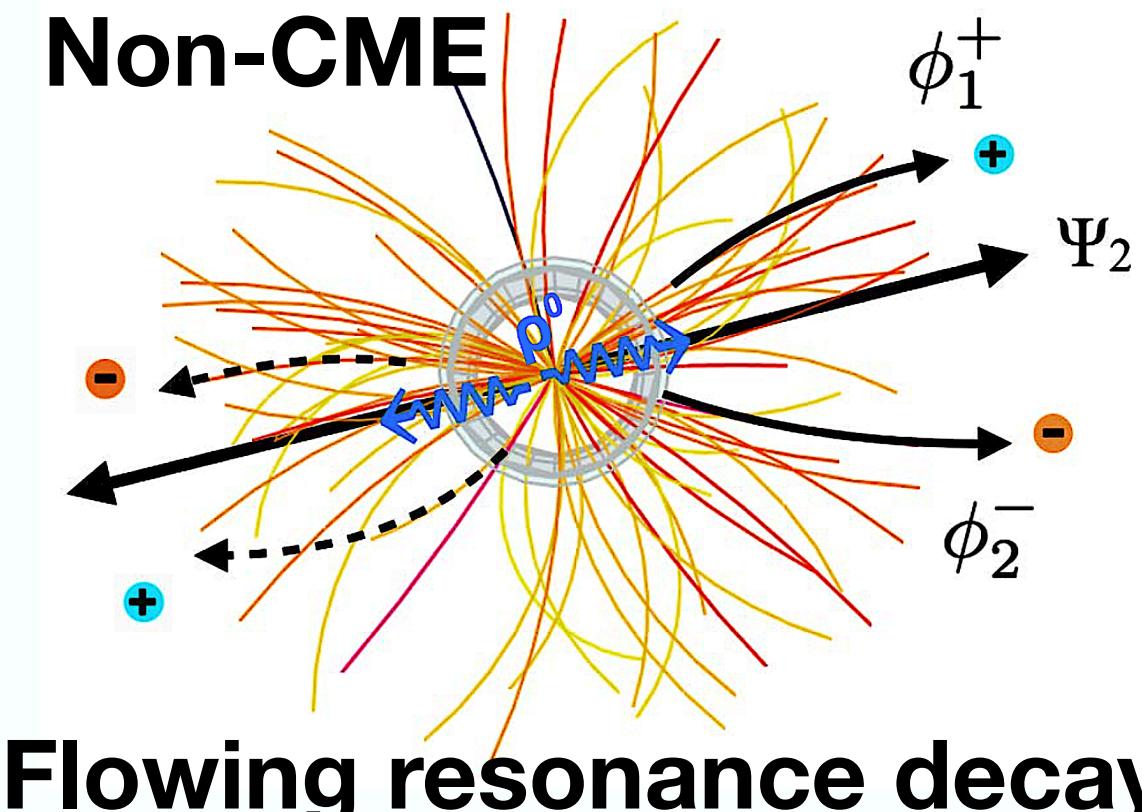
Parity Odd, can not directly observe $\propto \mu_5 B$ ($\mu_5 \mu_B \omega$)

Parity Even, sensitive to charge separation

Observables: $\gamma^{112} = \langle \cos(\varphi_1 + \varphi_2 - 2\Psi_{RP}) \rangle = \langle v_1 v_1 \rangle - \langle a_1 a_1 \rangle + BG(v_2^{cl})$

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

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



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.

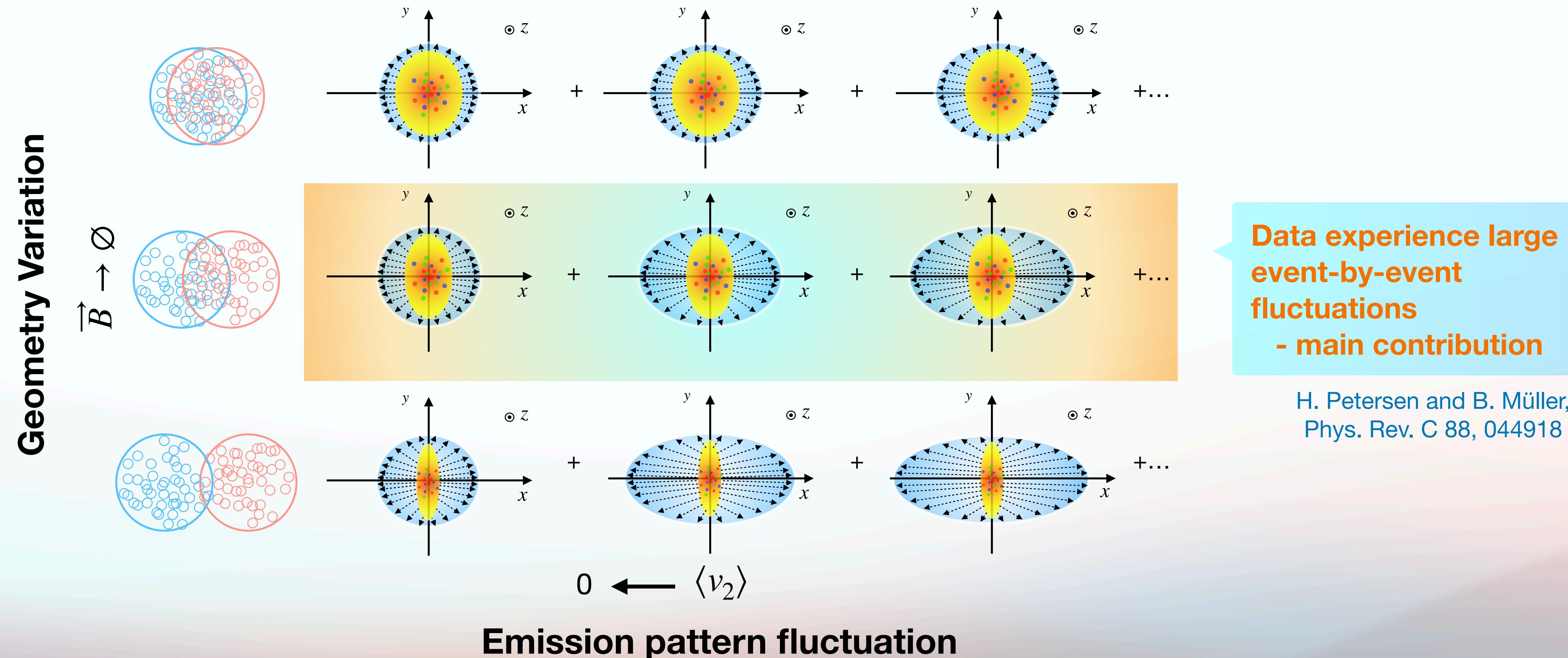
See Yicheng Feng's talk on Sep 6

Schematic Diagram of Event Shape

Z. Xu et al, arXiv:2307.14997

Observable based on final-state particles (v_2 , flow vector \mathbf{q}_2) has contributions from:

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

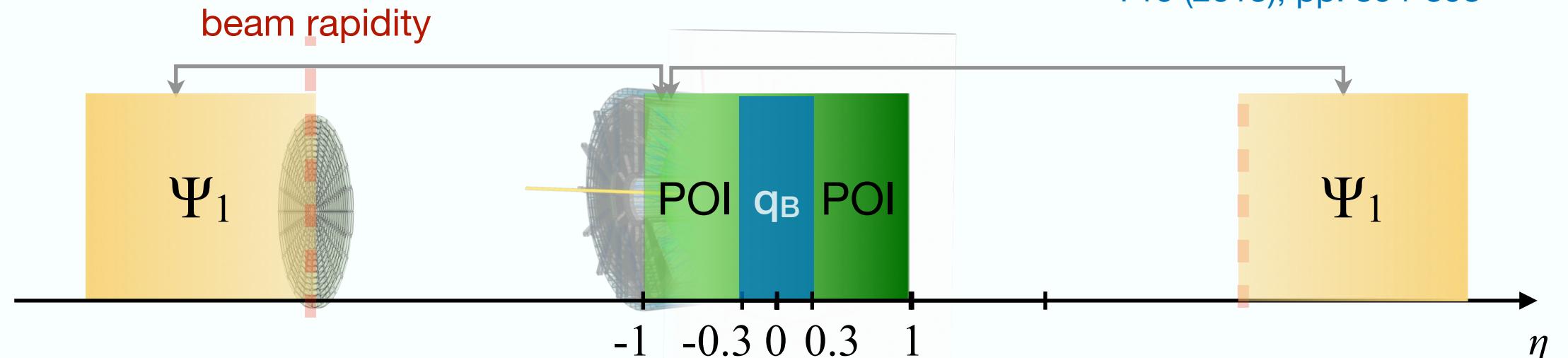


Event Shape Selection and Engineering

new

Event Shape Engineering

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



Event shape variable

q_B (no POI)

Elliptic flow variable

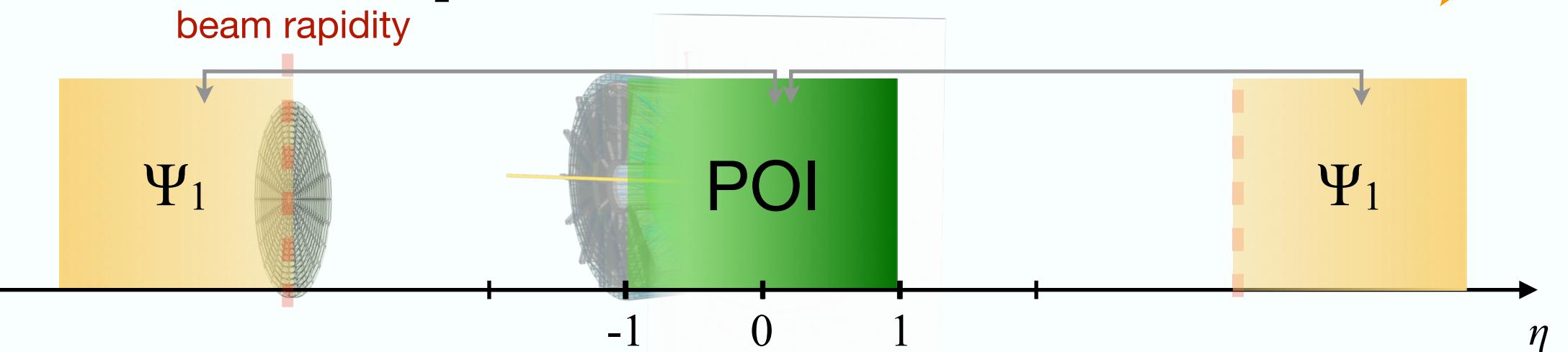
v_2 (POI)

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

q_B excludes POI

Event Shape Selection

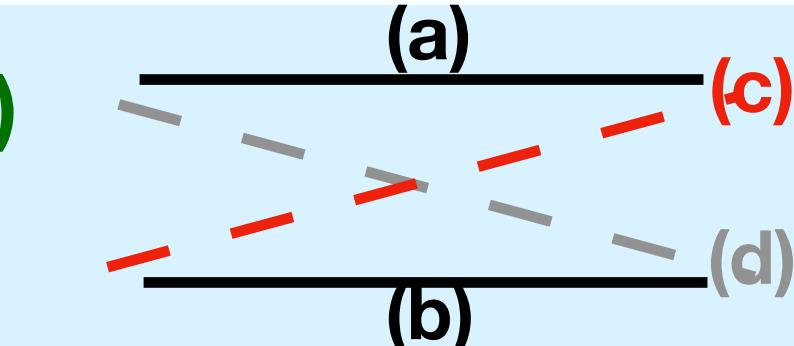
Z. Xu et al, arXiv:2307.14997



Event shape variable

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

Elliptic flow variable



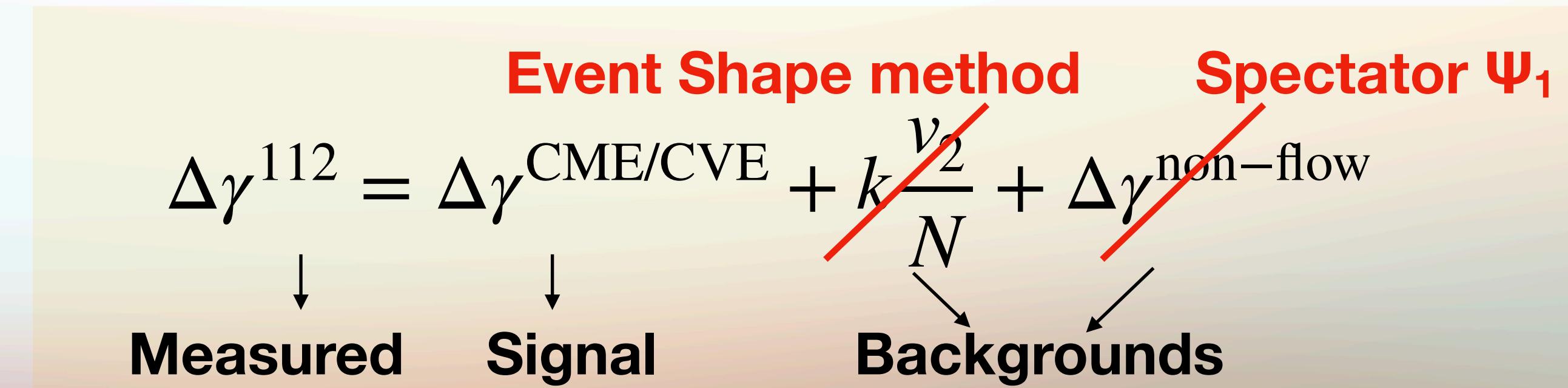
single v_2 (POI)
pair v_2 (POI)

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

Pair from adding momenta
of two POI particles.

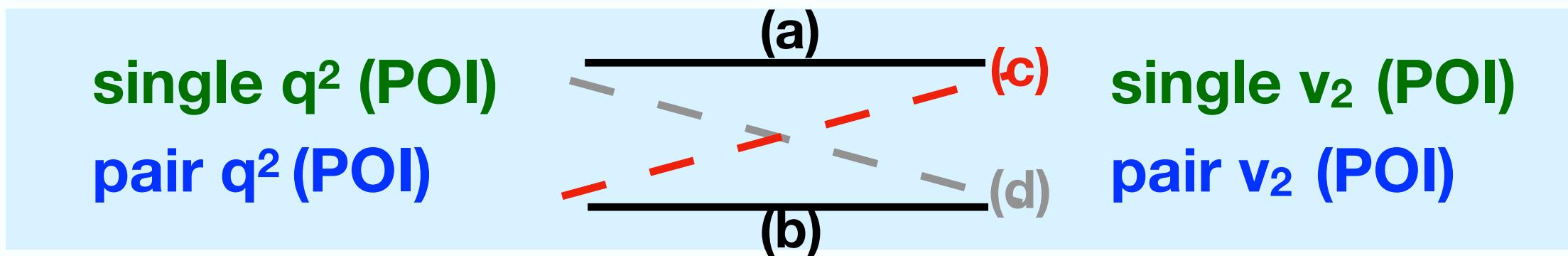
Rely on long η range correlation from initial shape

Rely on emission pattern and geometry shape

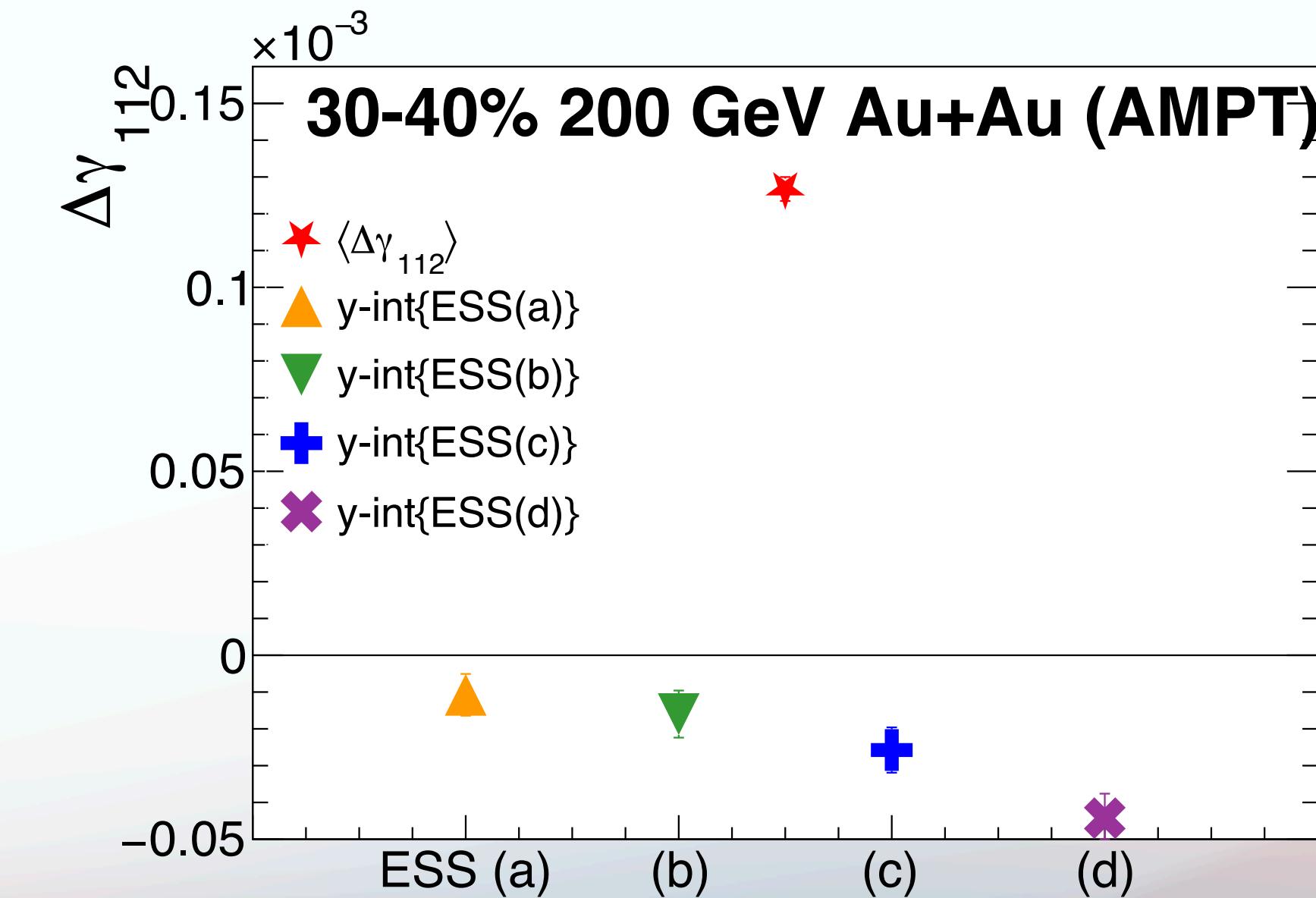
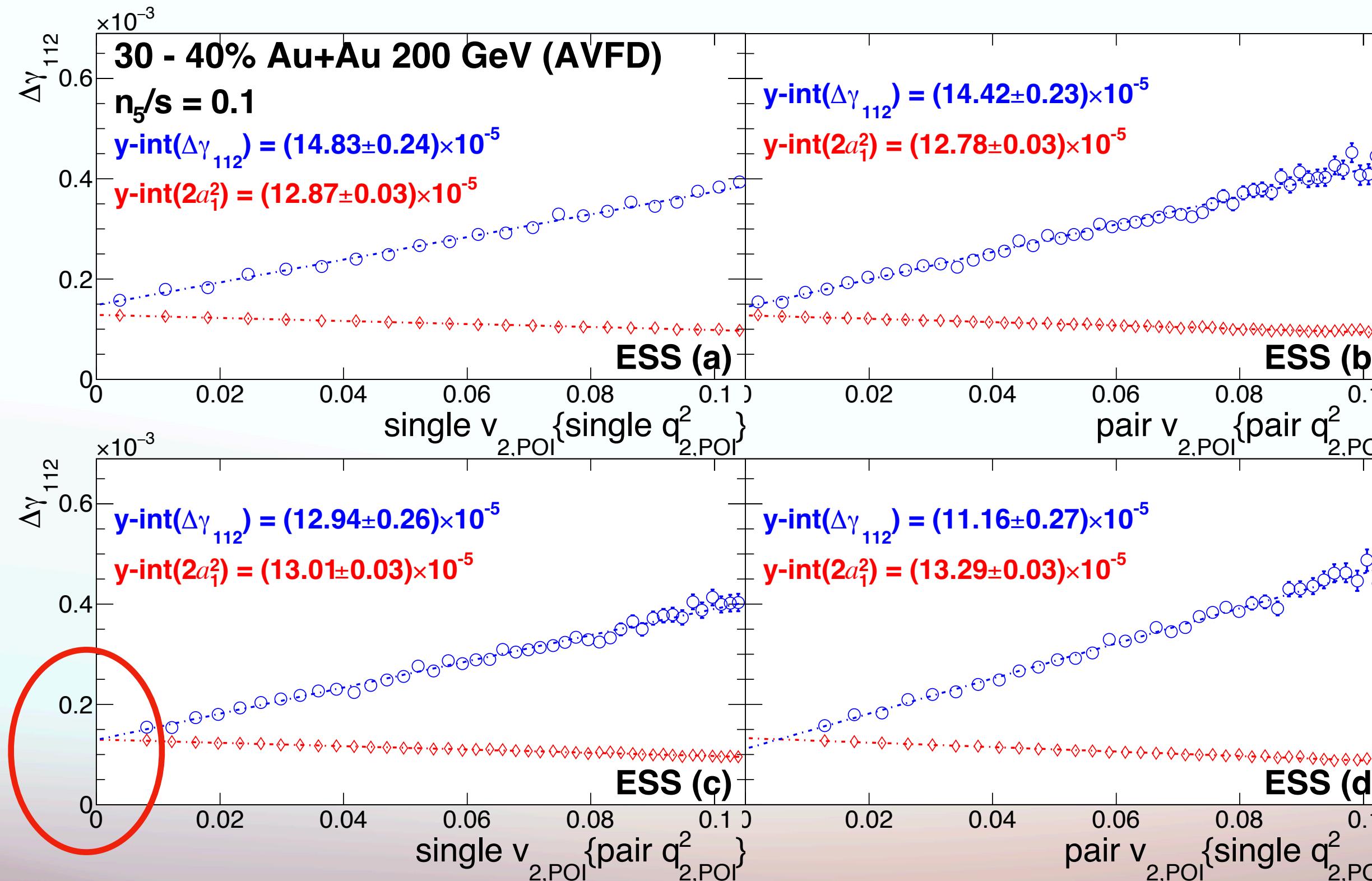


Simulation results for Event Shape Selection

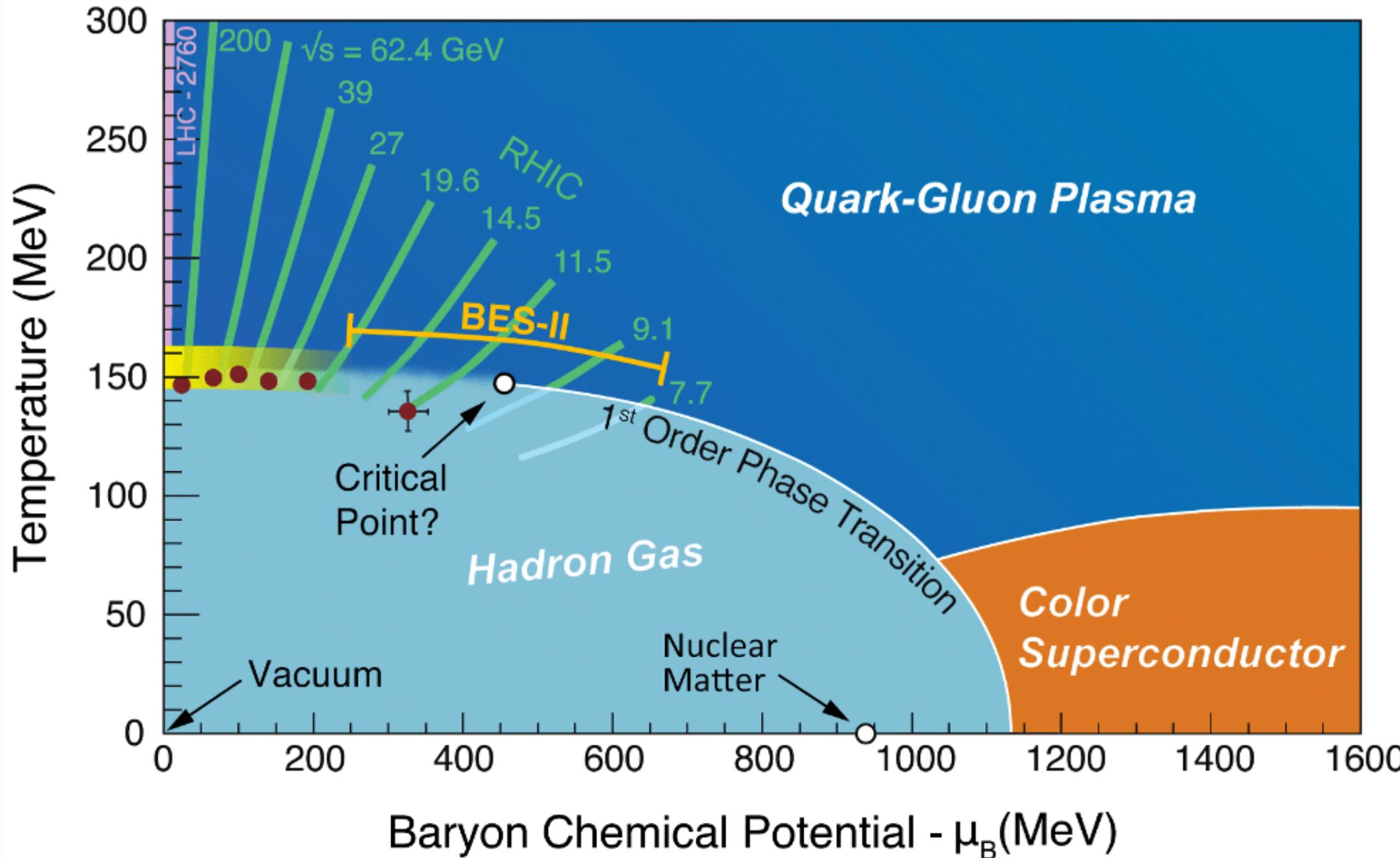
Z. Xu et al, arXiv:2307.14997



- 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.

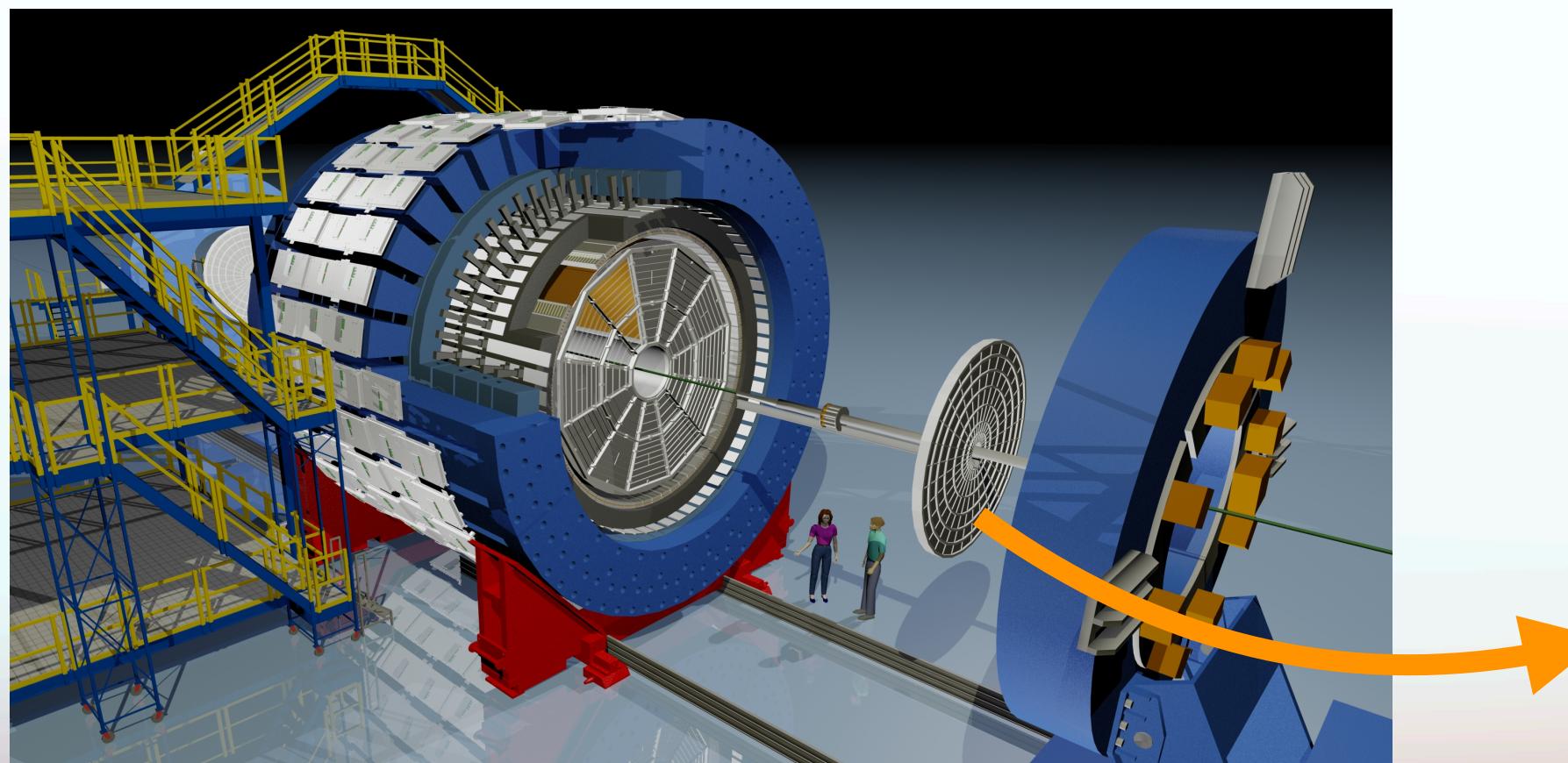


New Analyses at STAR



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 ($2.1 < \eta < 5.1$) for BES-II energies.

200 GeV Au+Au - Event Shape Engineering

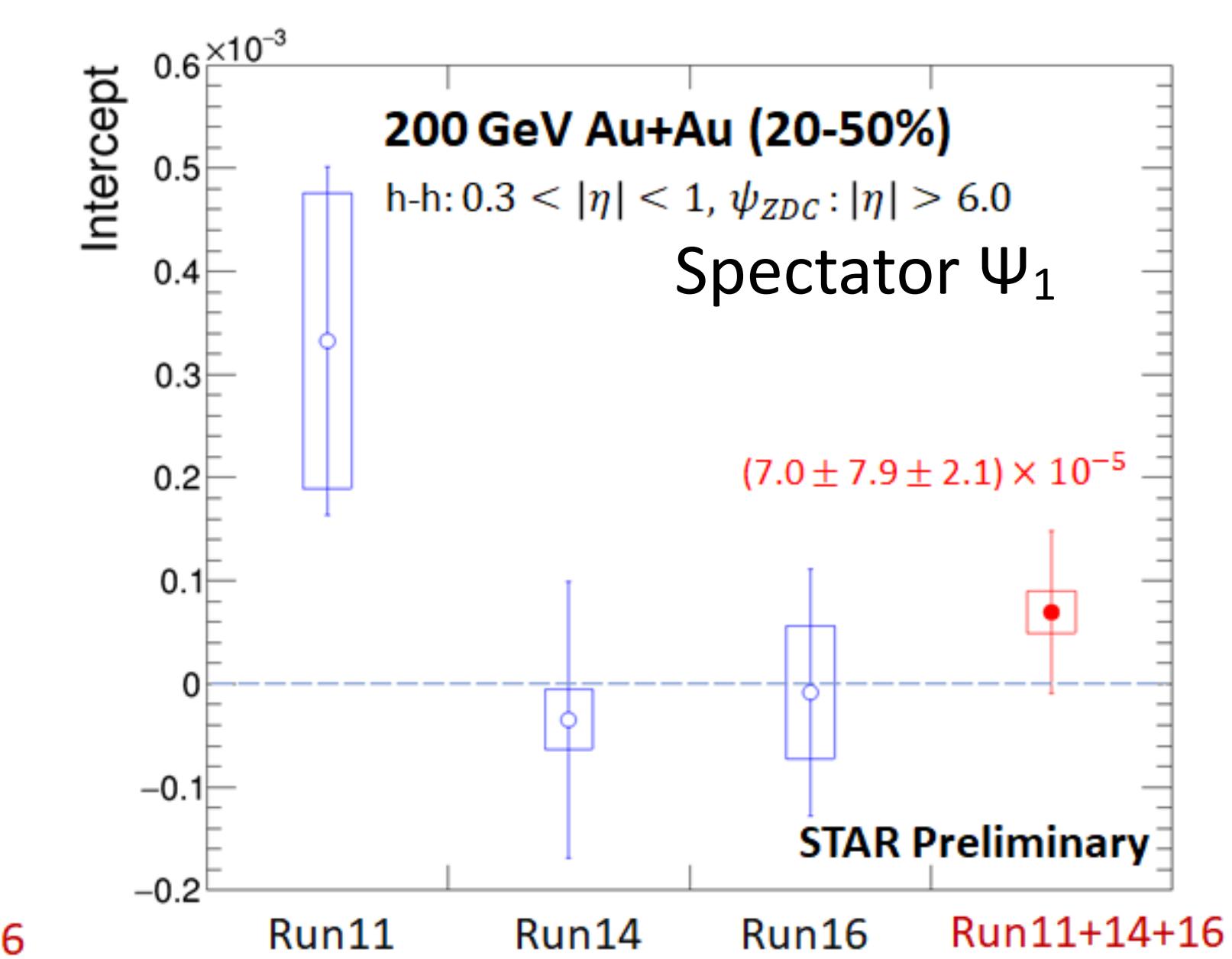
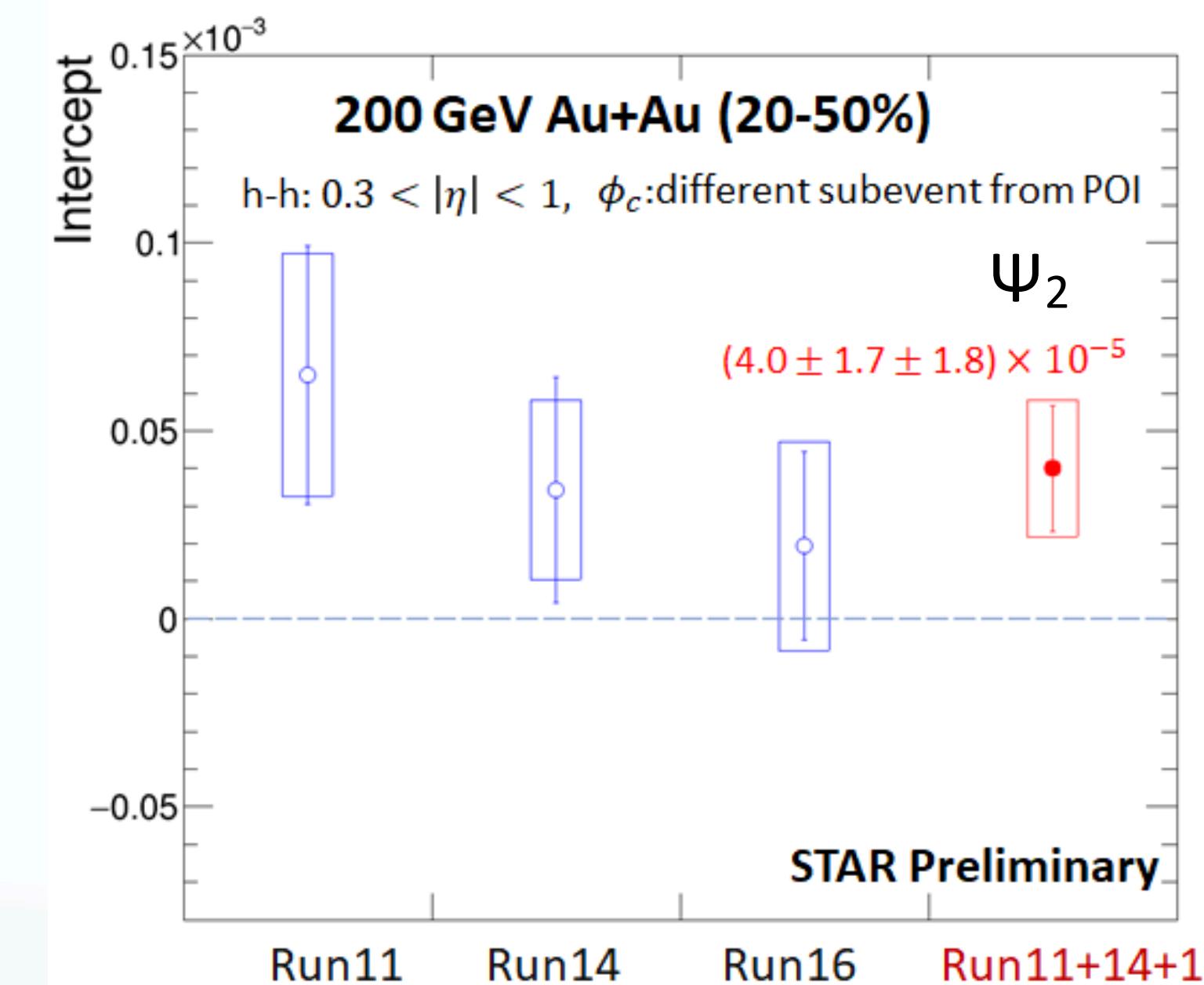
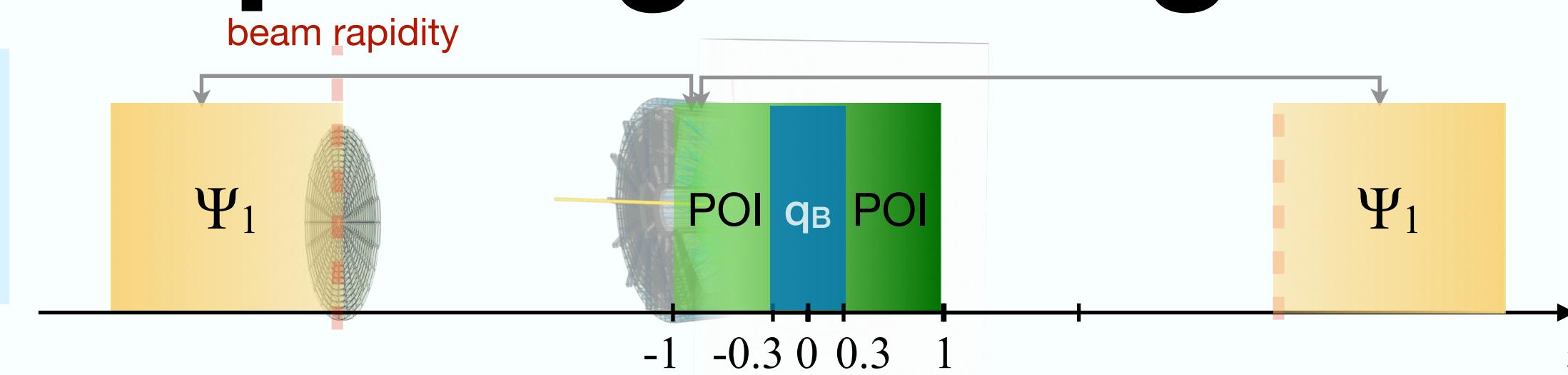
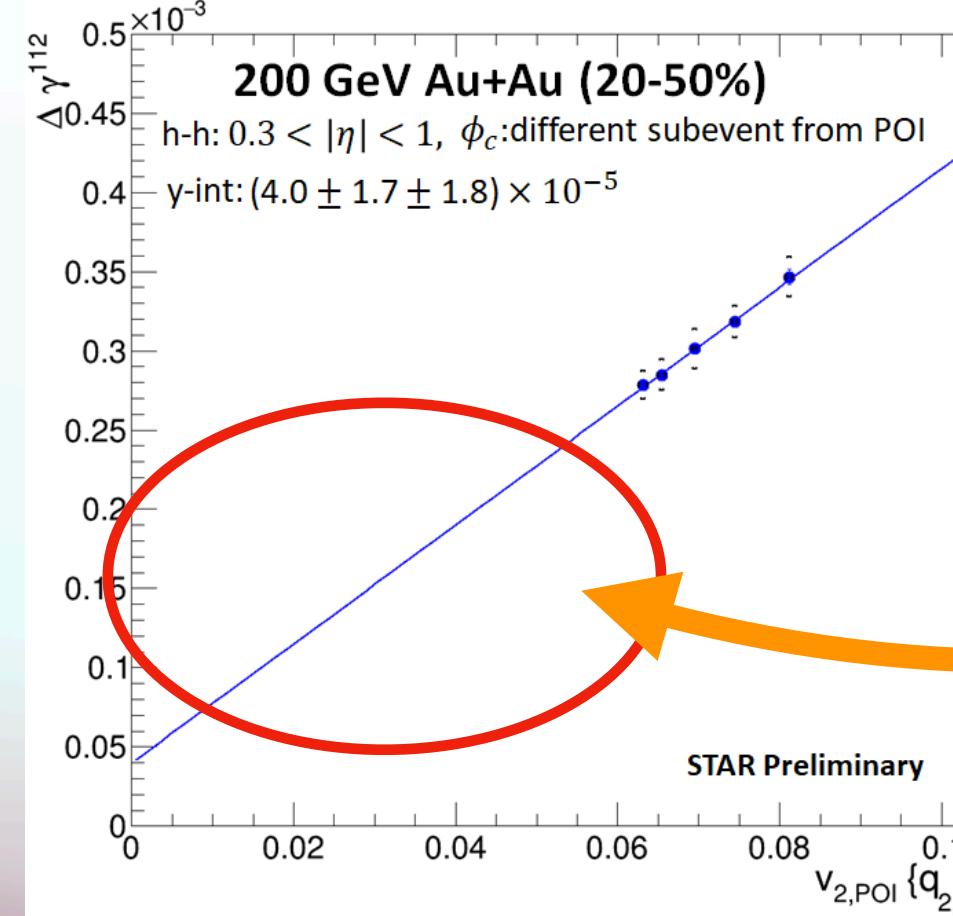
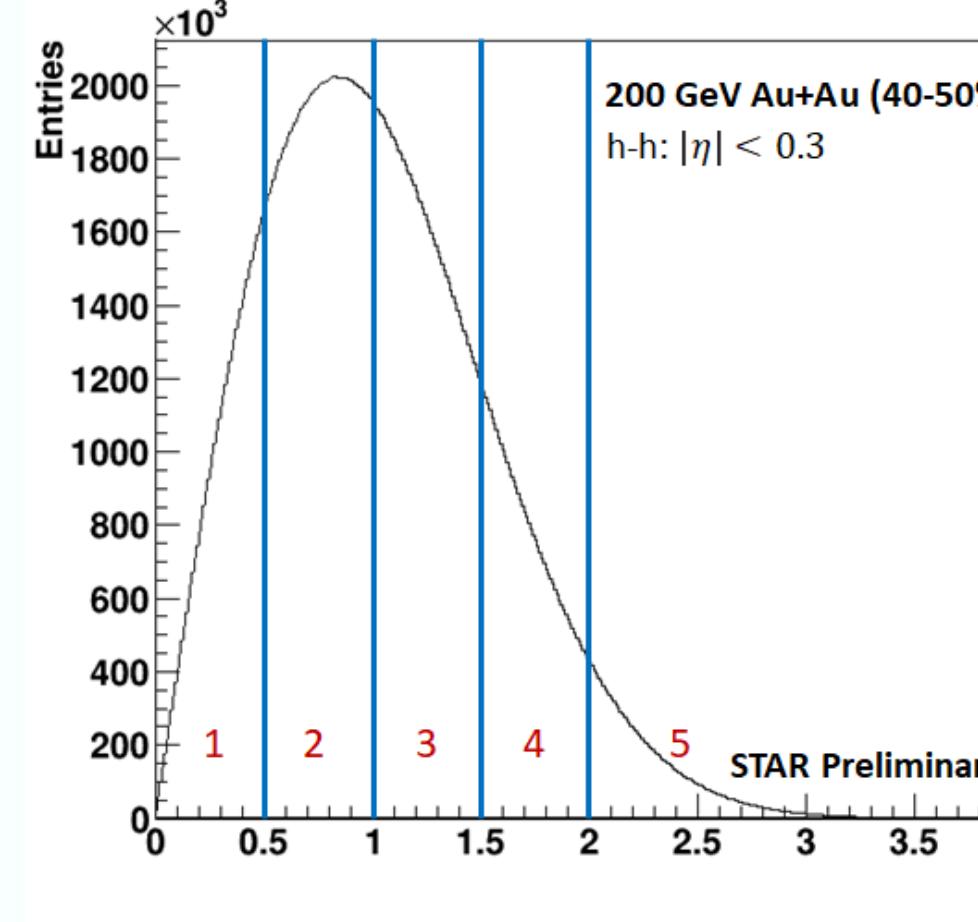
See Poster #437 of
Han-Sheng Li

Event shape variable

q_B (no POI)

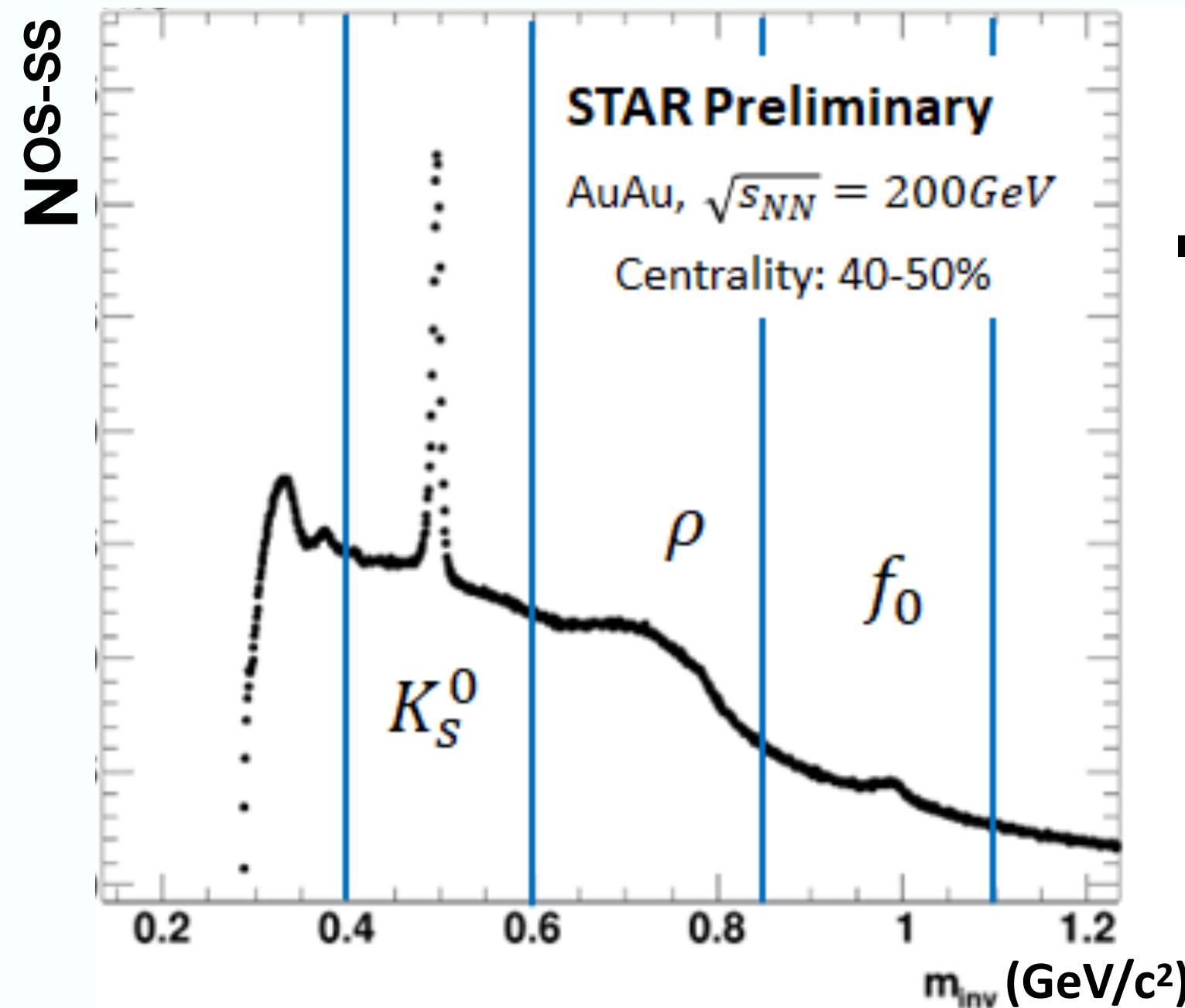
Elliptic flow variable

v_2 (POI)

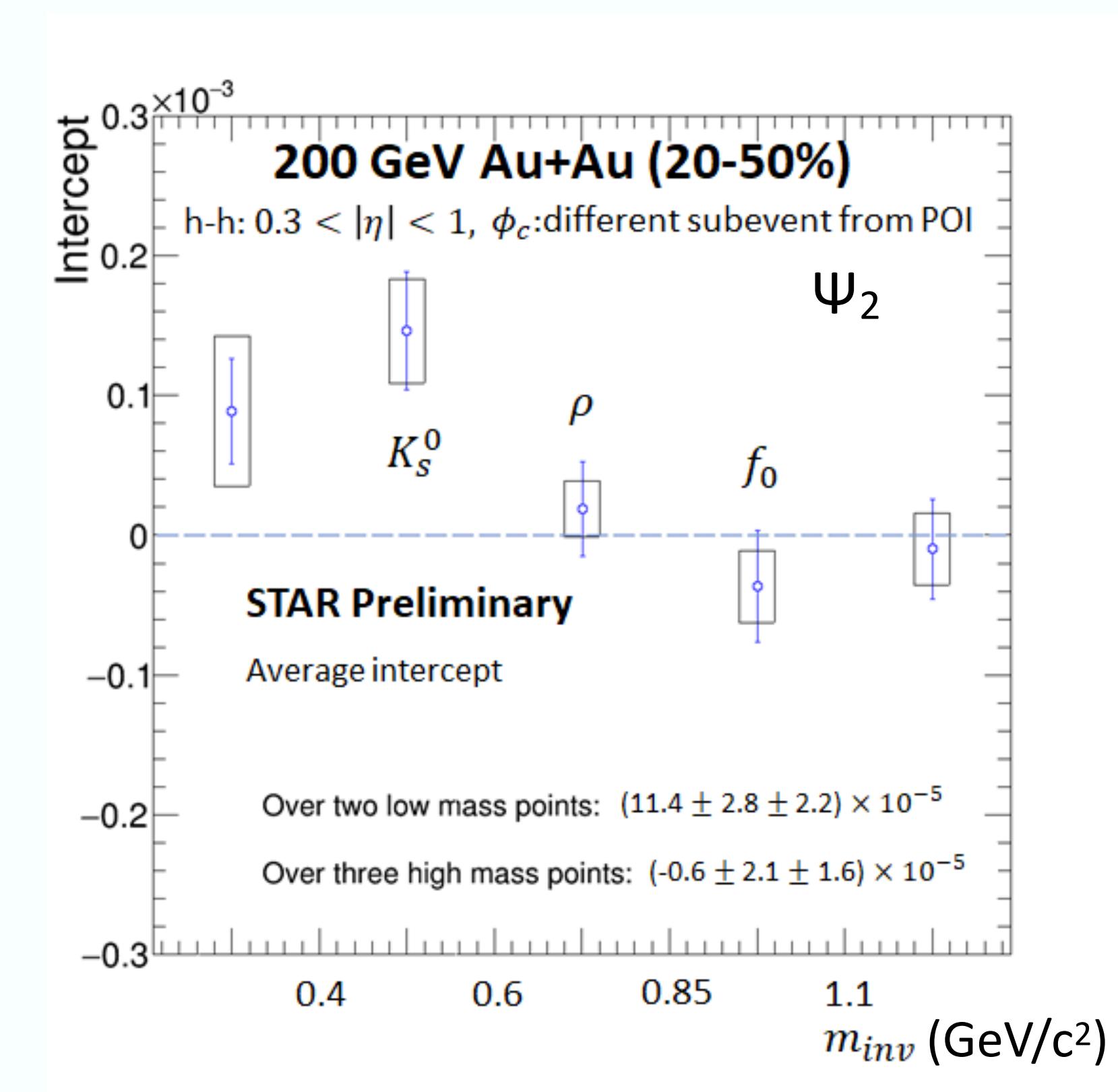


- The large statistical error arises from the gap near zero flow.
- Results with Ψ_2 yield 1.5σ , nonflow effects to be assessed.
- Results using $\Psi_{1,ZDC}$ is less than 1σ significance.

200 GeV Au+Au - Invariant Mass dependence with ESE



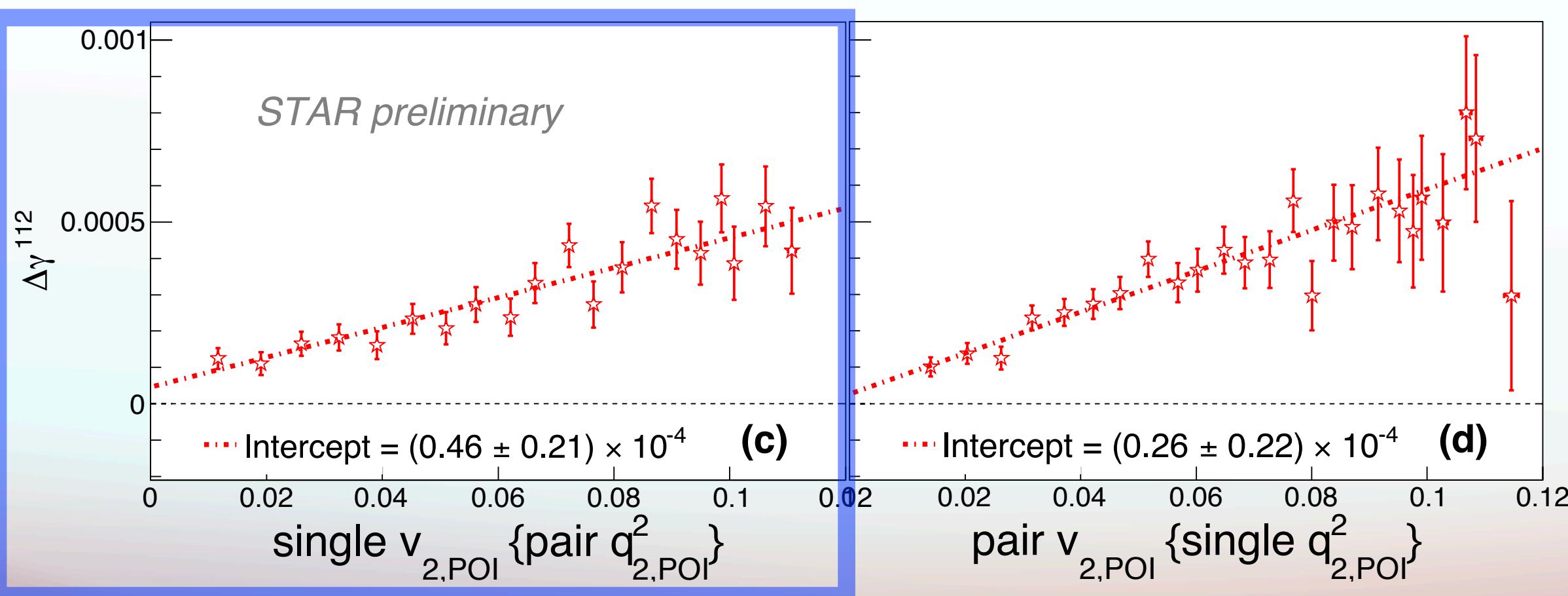
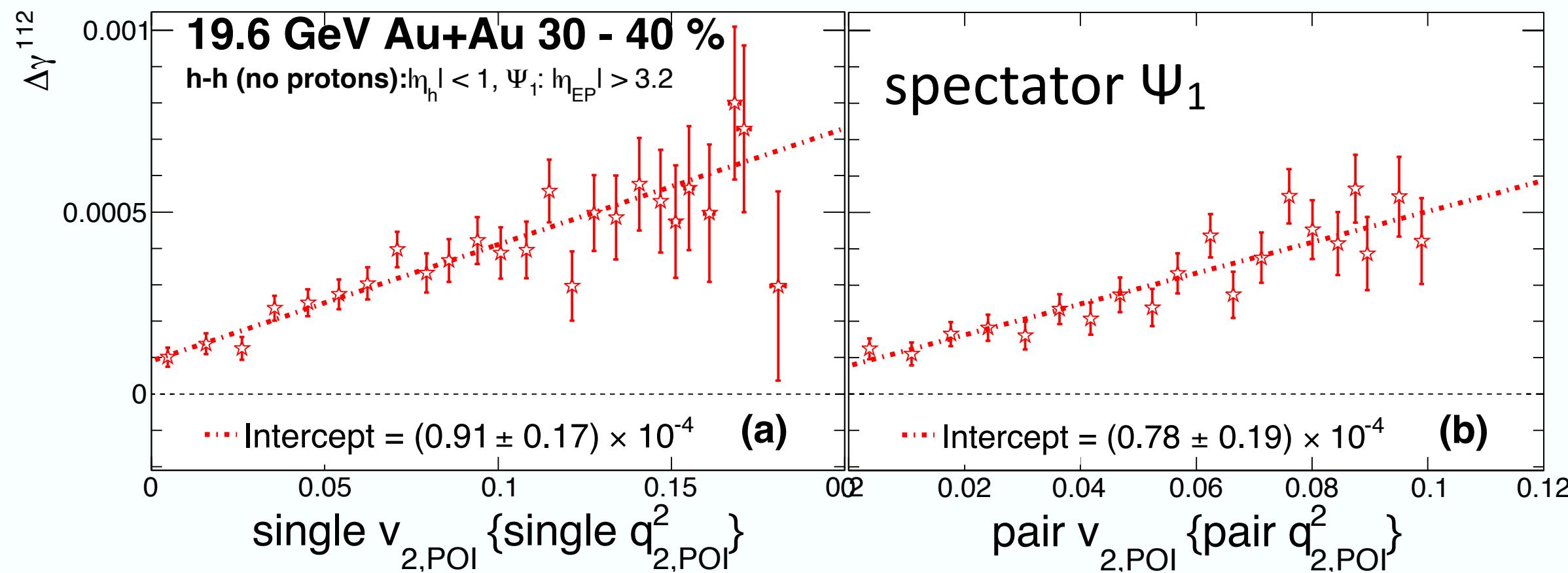
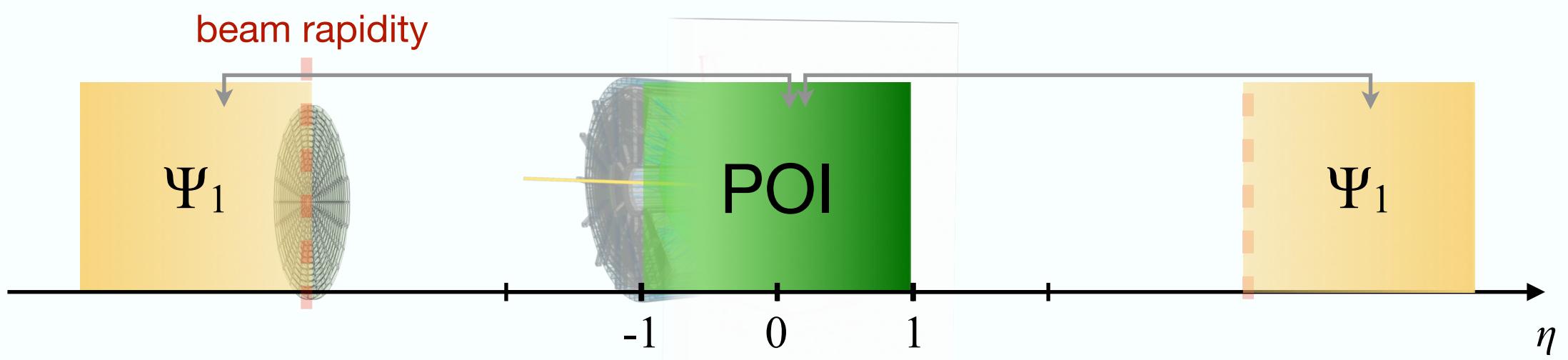
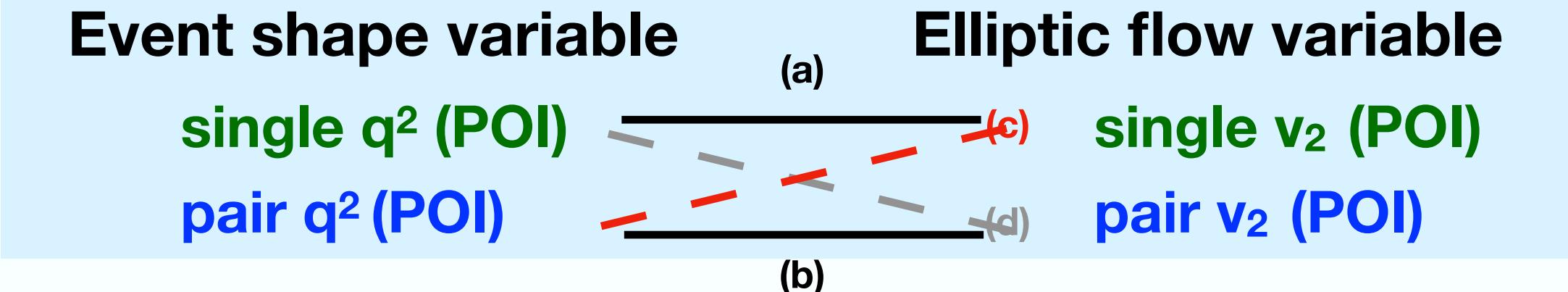
- **Mass windows (GeV/c²)**
- Low mass: $m_{inv} < 0.4$
- K_s^0 region: $0.4 < m_{inv} < 0.6$
- ρ region: $0.6 < m_{inv} < 0.85$
- f_0 region: $0.85 < m_{inv} < 1.1$
- High mass: $1.1 < m_{inv}$



- 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

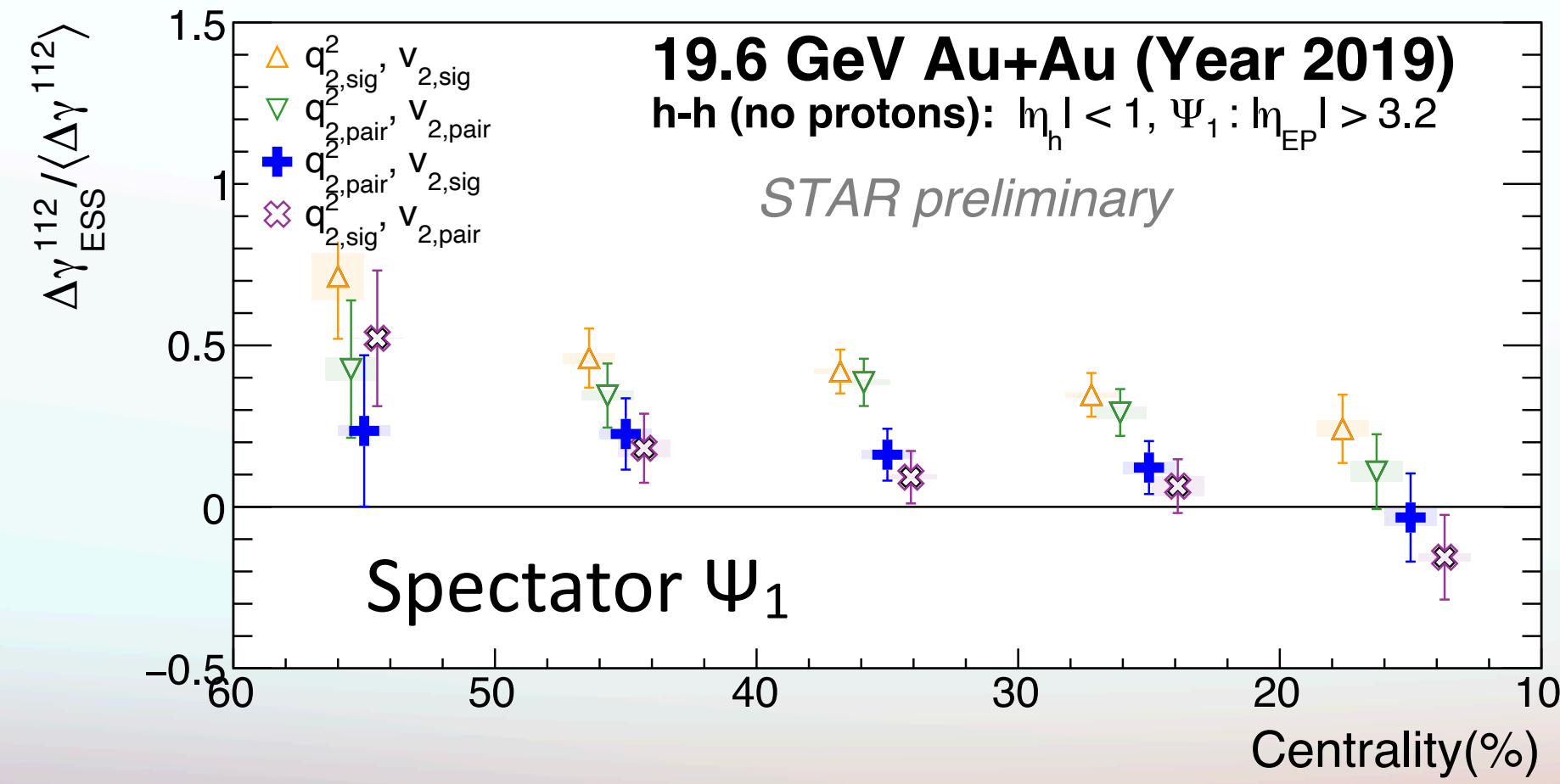
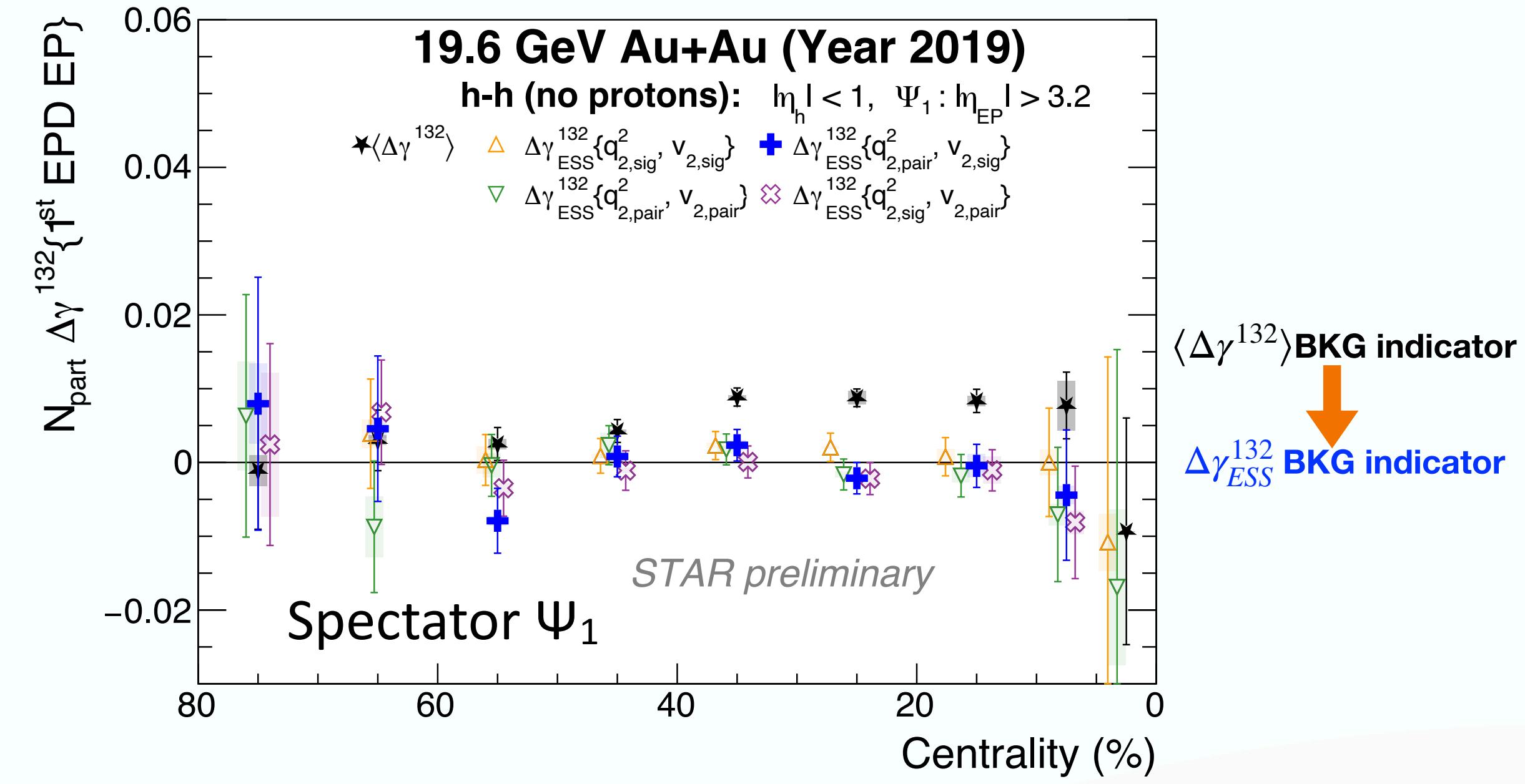
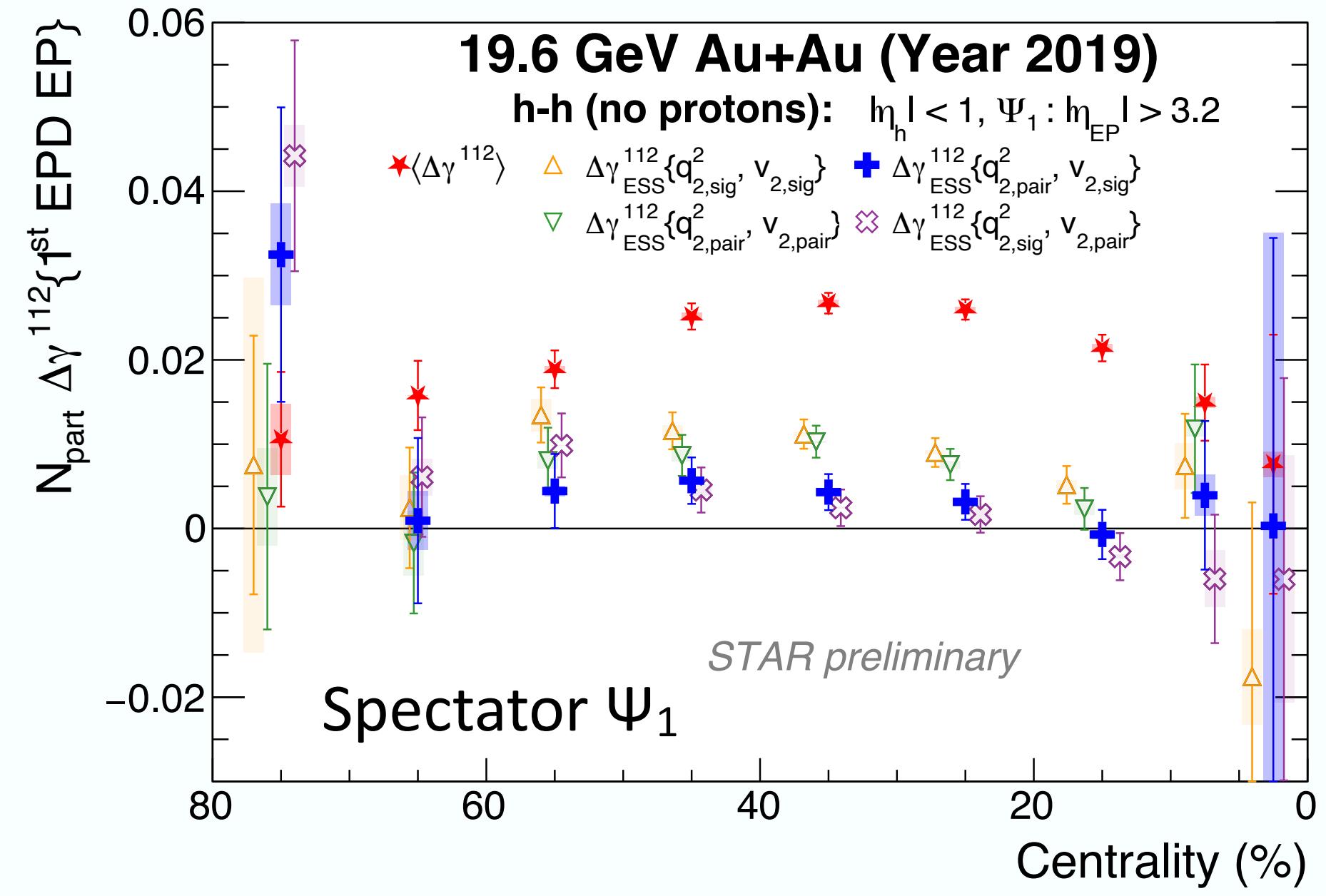


- ESS using POI allows much shorter extrapolation to zero v_2 .
- The ordering of y-intercepts follows predictions from both AVFD and AMPT
- The y-intercept needs a correction to restore the CME signal:

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

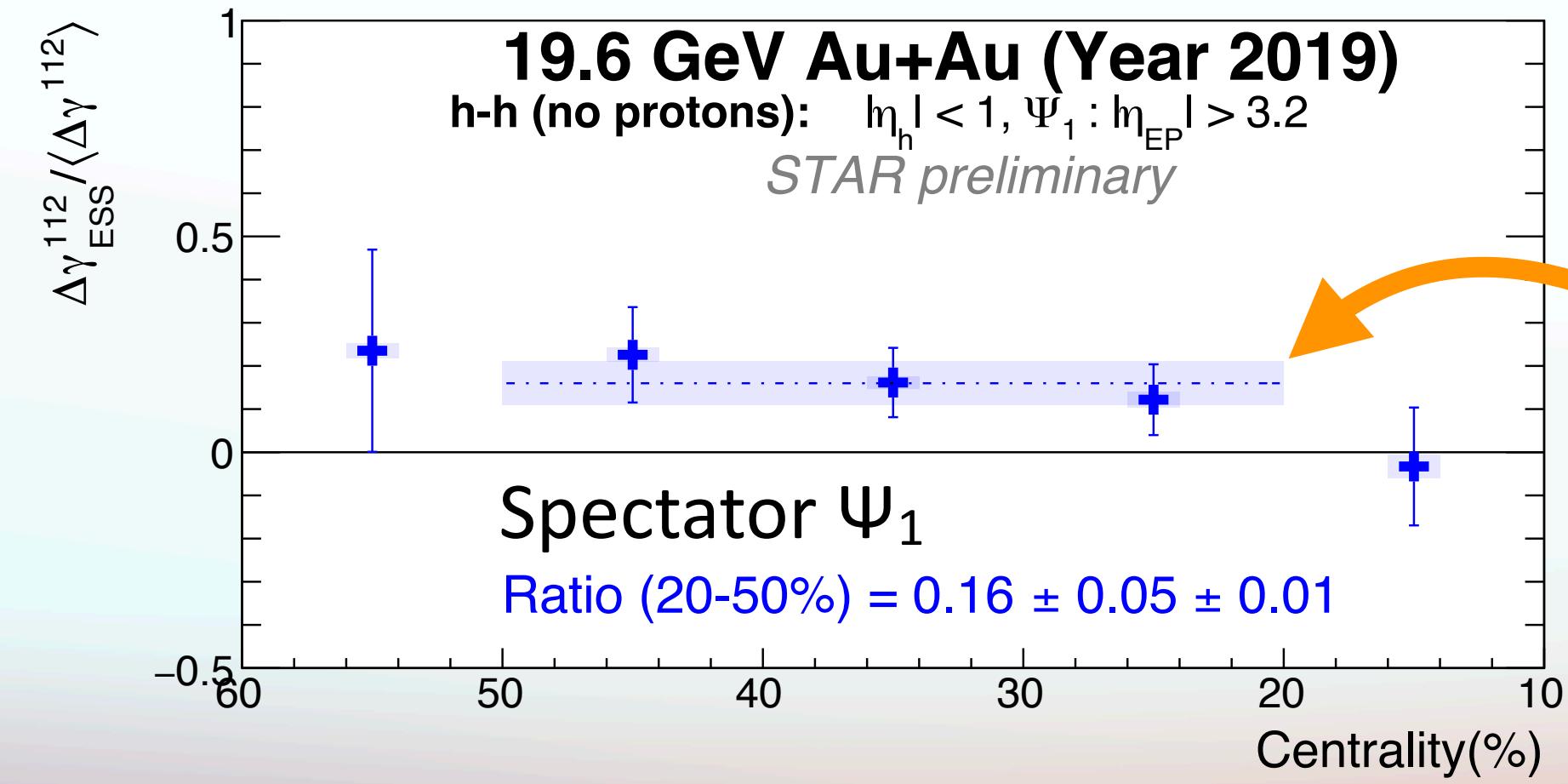
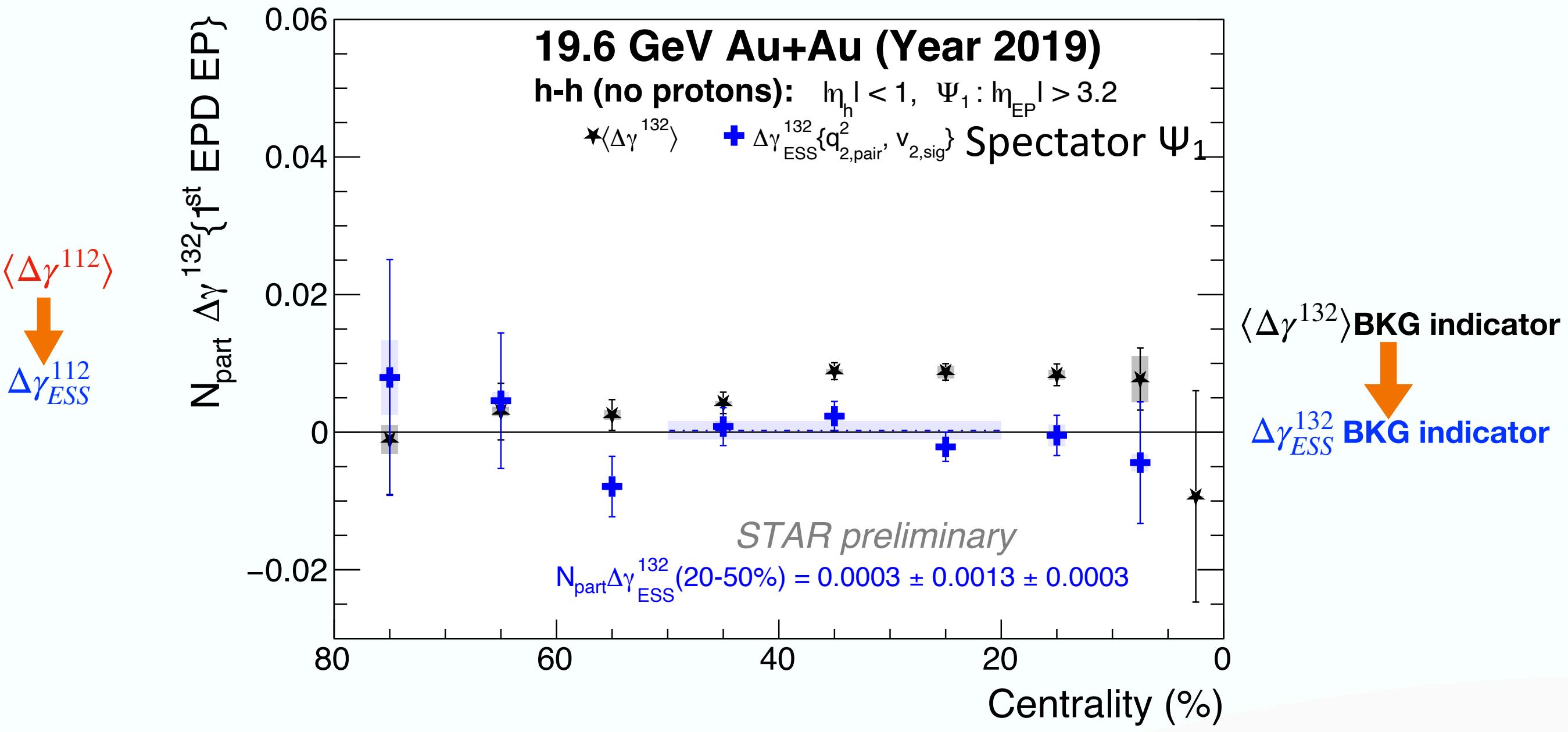
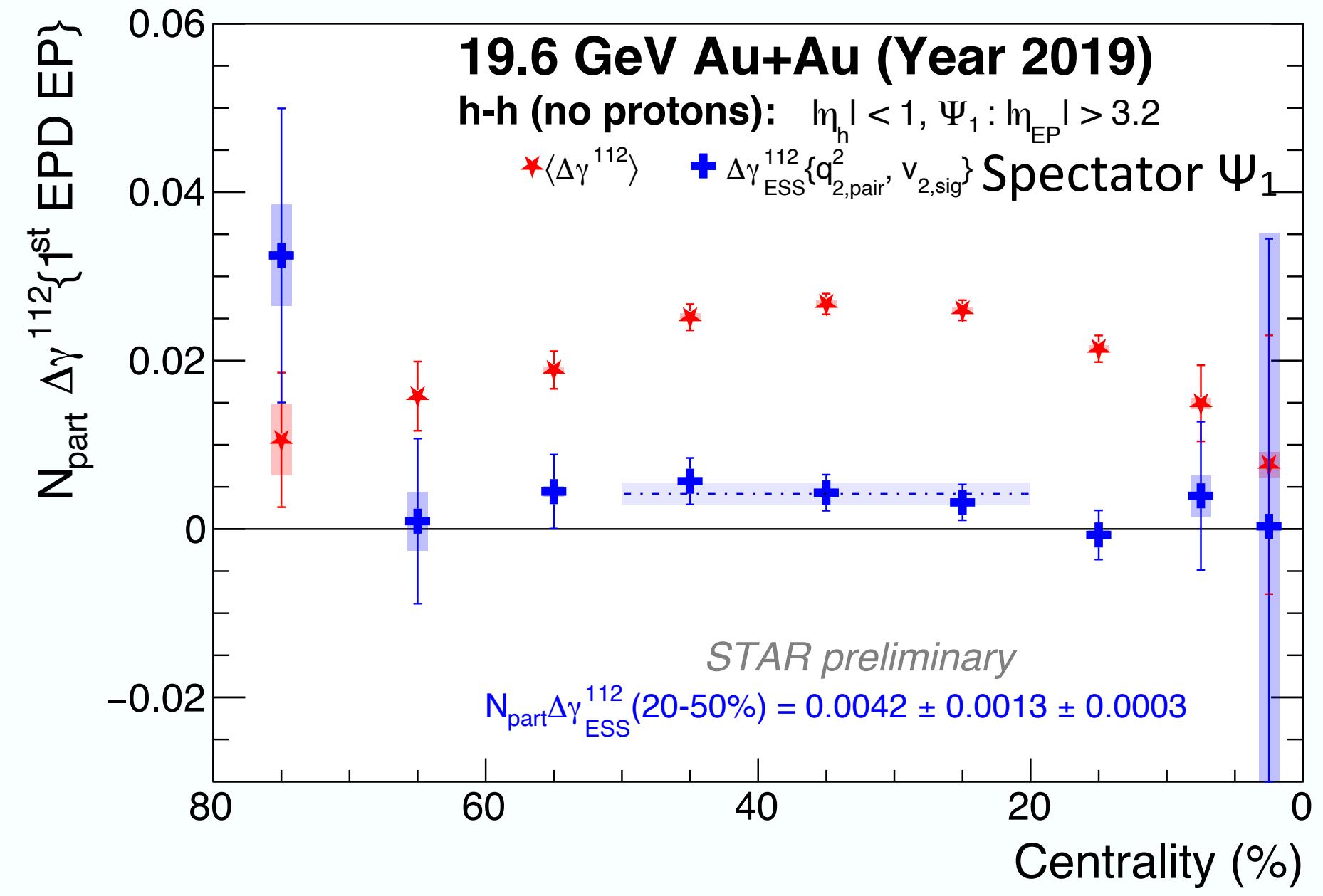
Z.Xu et al Phys. Rev. C 107, L061902

Beam Energy Scan II - Event Shape Selection



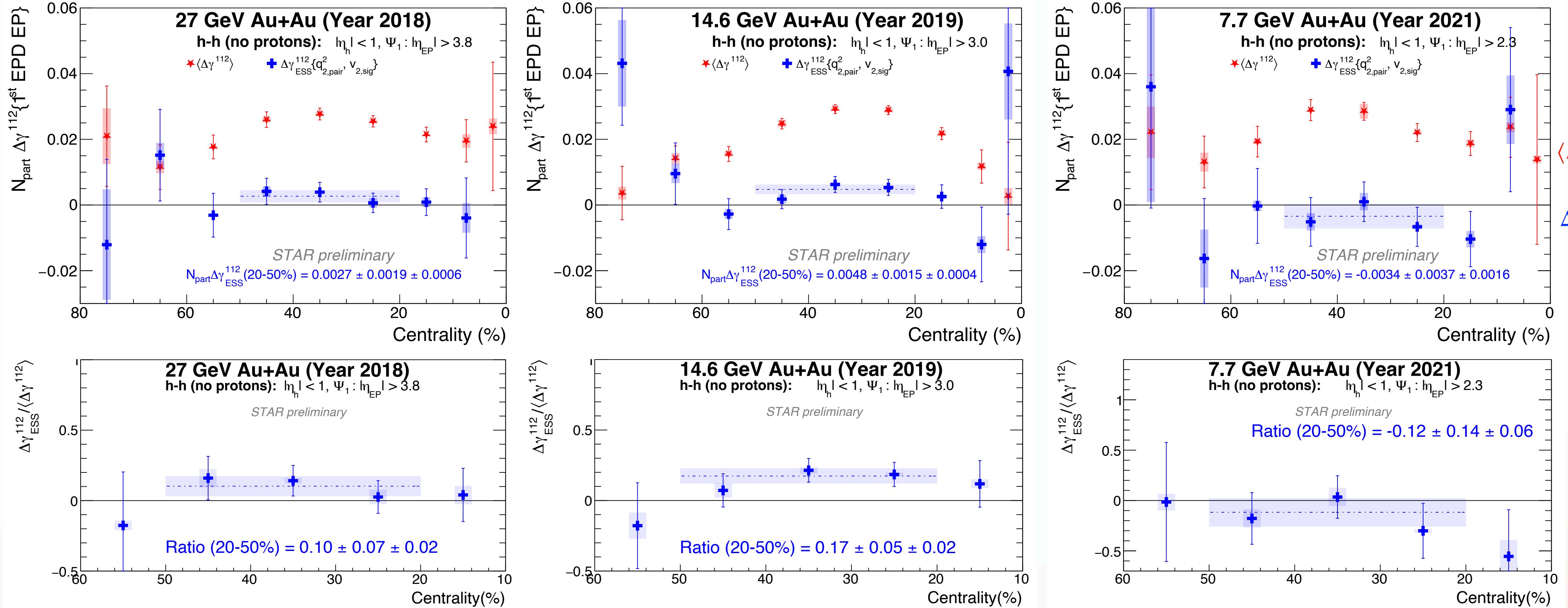
- The ESS is applied to different centralities.
- Ordering of four $\Delta\gamma_{ESS}^{112}$ follows prediction from model.
- We will focus on the optimal recipe ESS(c).

Beam Energy Scan II - Event Shape Selection



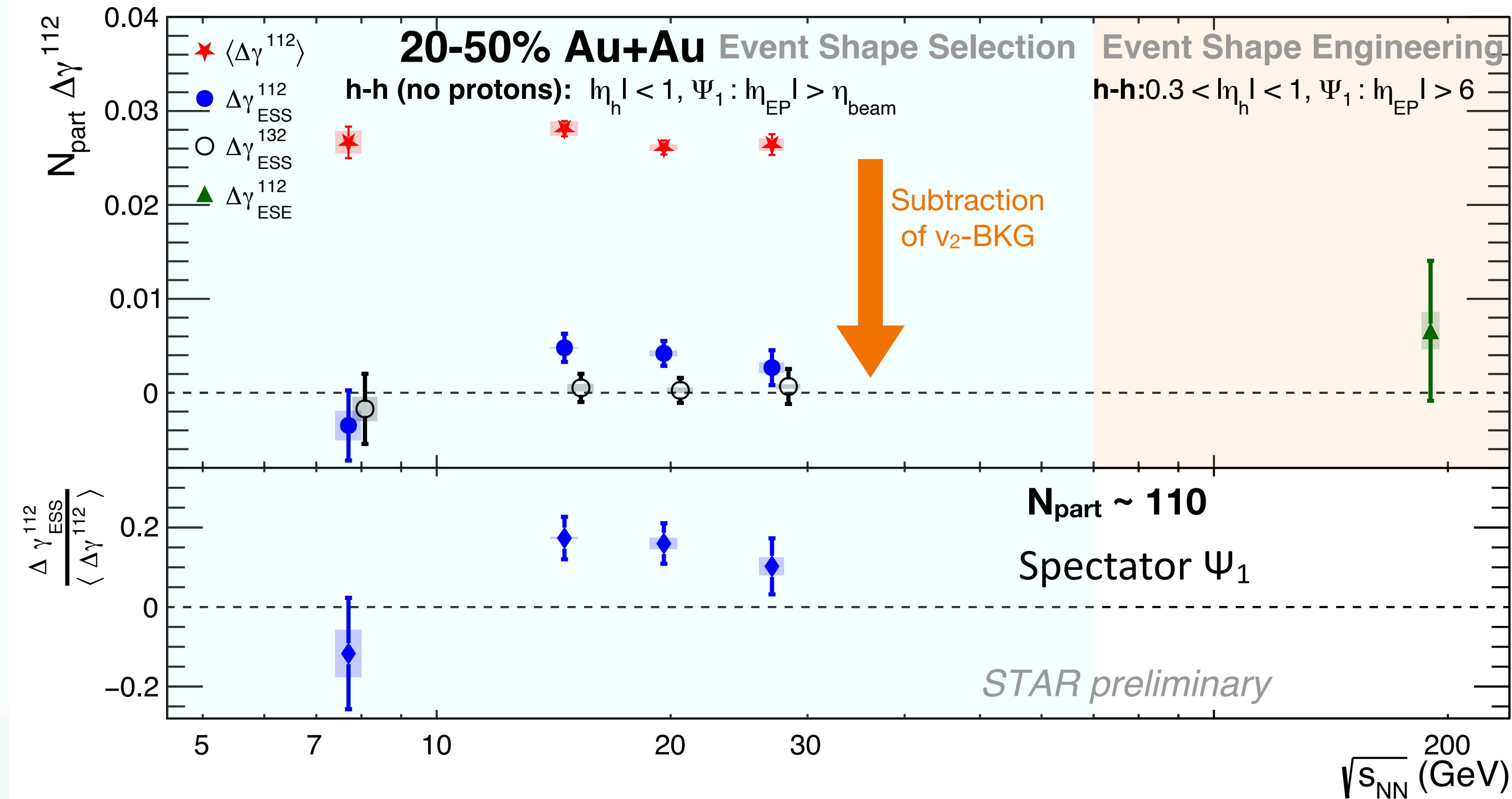
- After v_2 -BKG subtraction, a finite signal in mid-central events.
- Ratio from the optimal ESS (c), pair q^2 and single v_2 , yields a 3σ significance for 20-50% at 19.6 GeV.
- From BKG indicator $\Delta\gamma^{132}$, ESS successfully removes v_2 -BKG.

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.

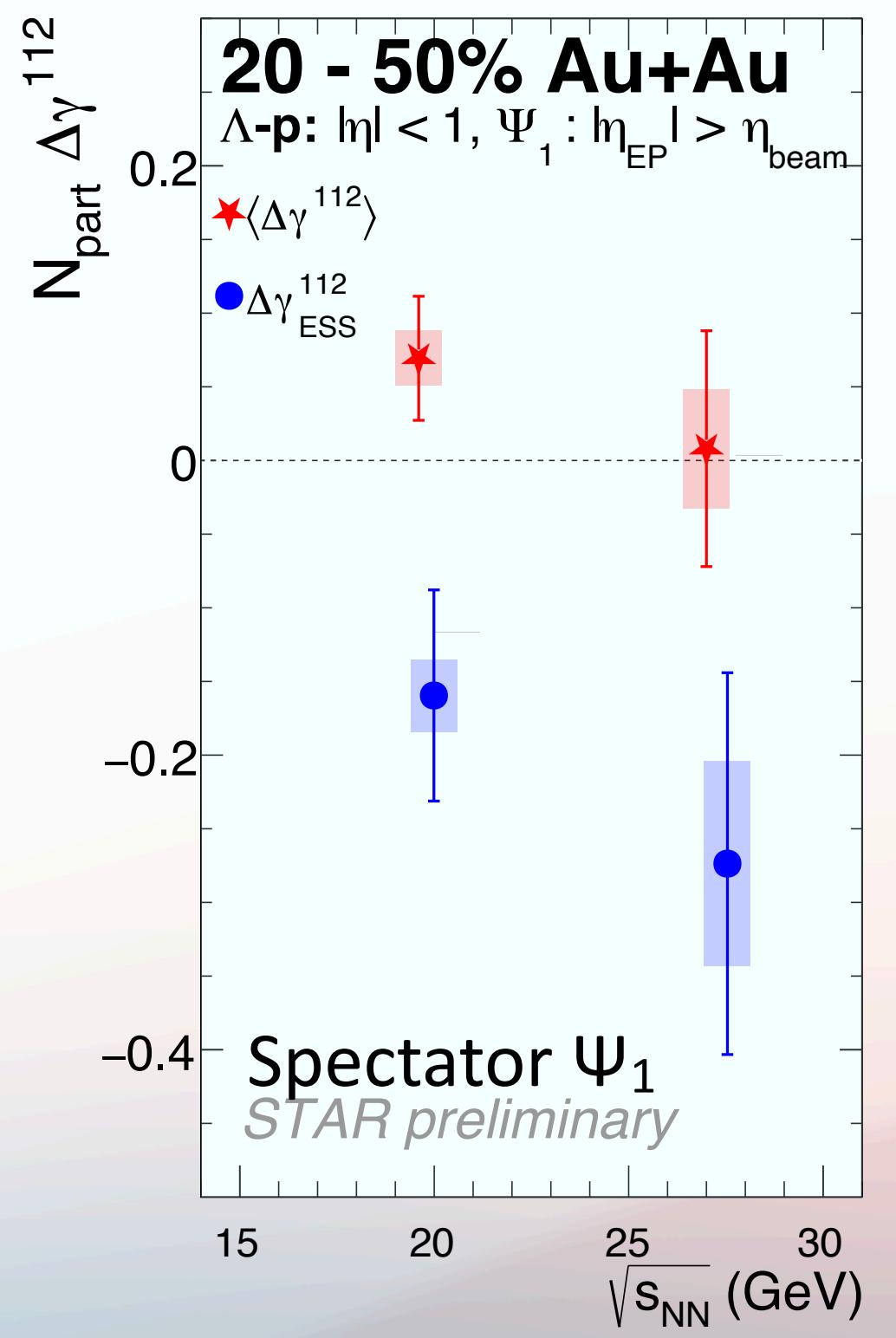
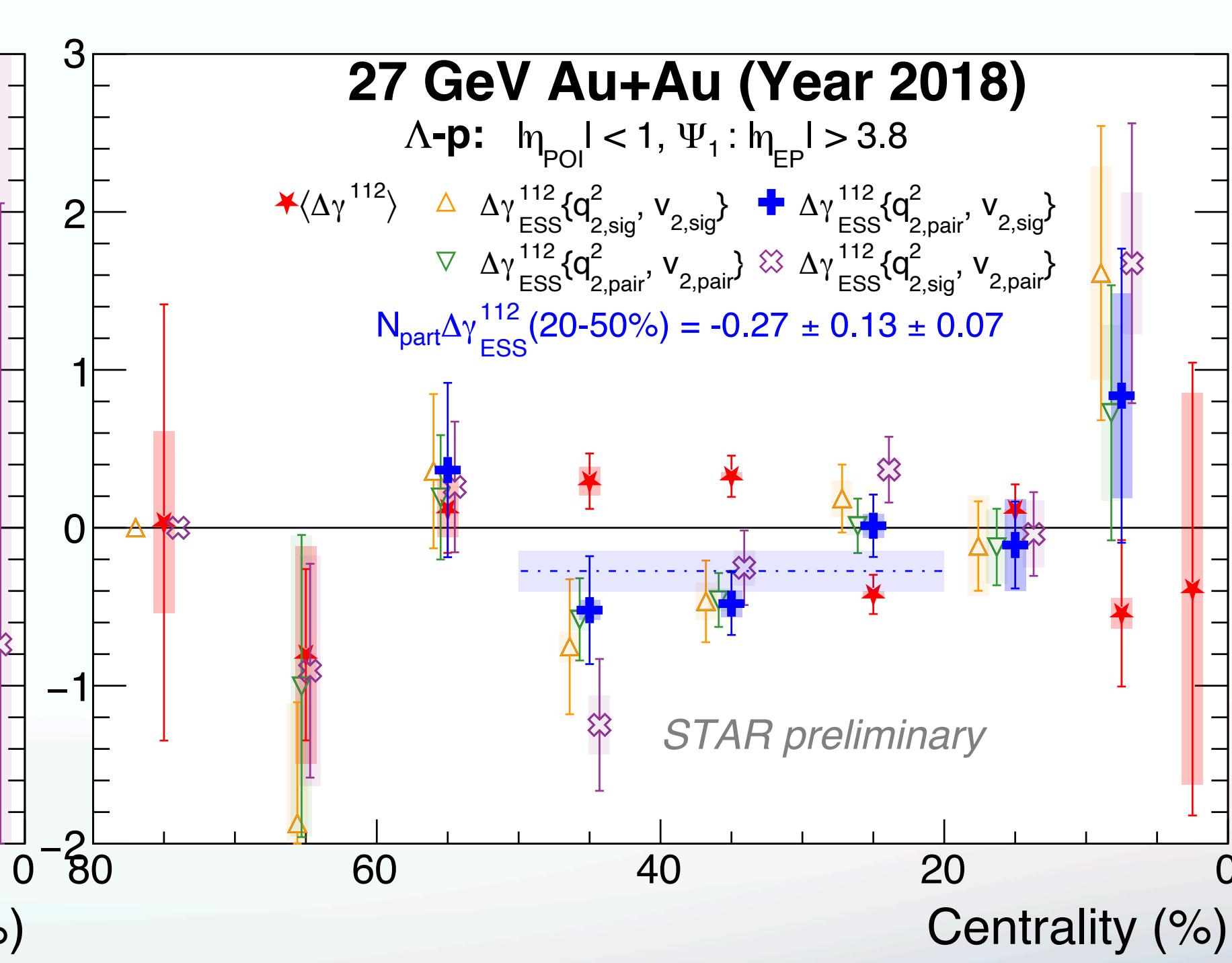
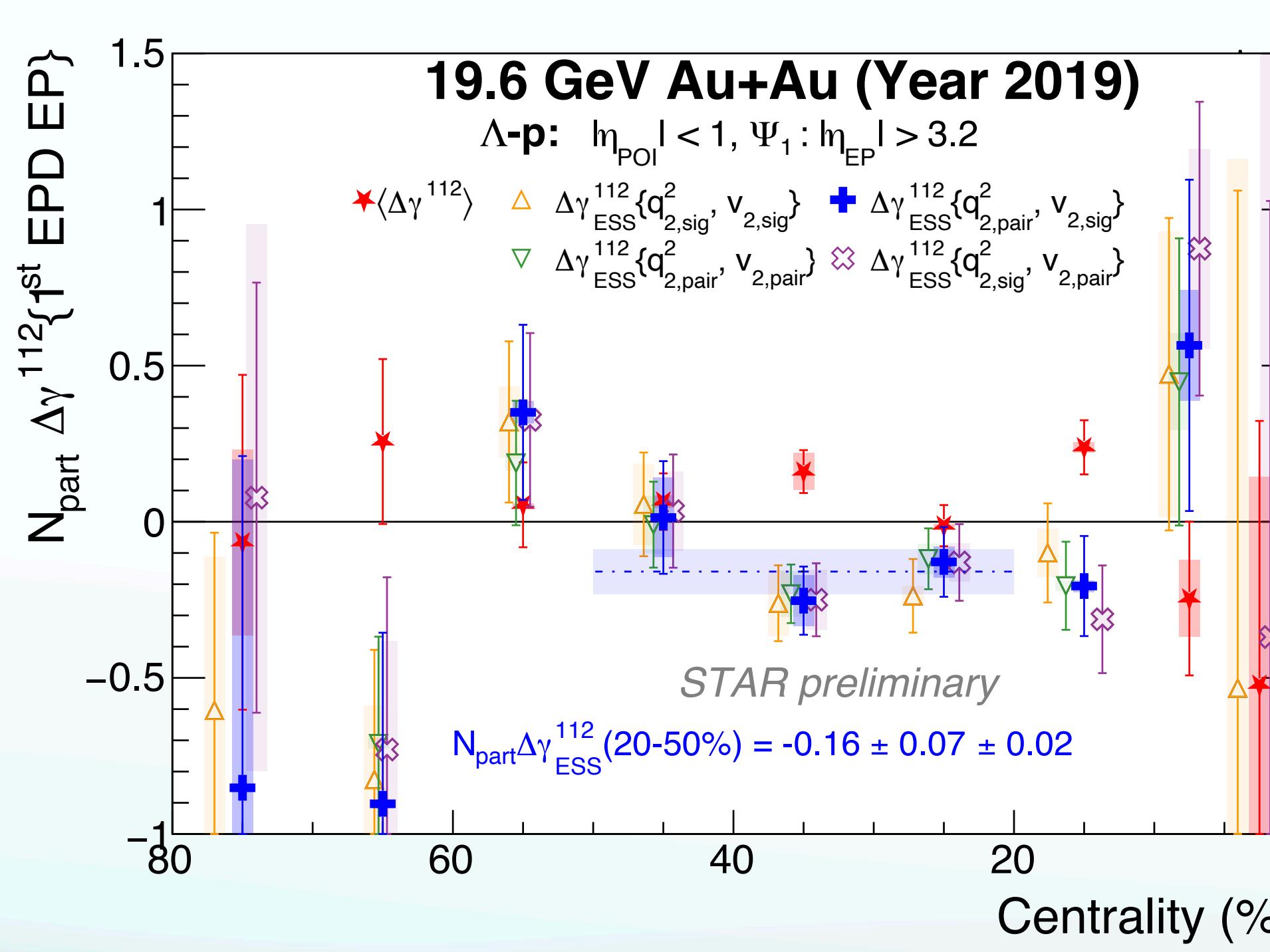
Beam Energy Dependence of CME observable



- 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 $\Delta\gamma$ correlator w.r.t. Ψ_1 are consistent with zero.
- Results lack of significance due to low hyperon statistics.

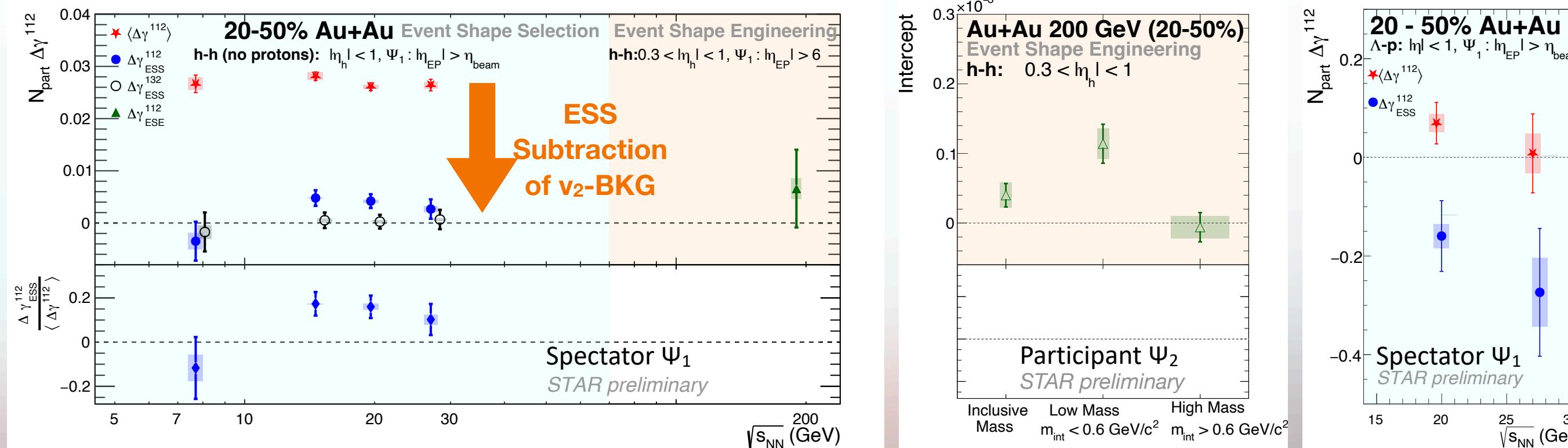


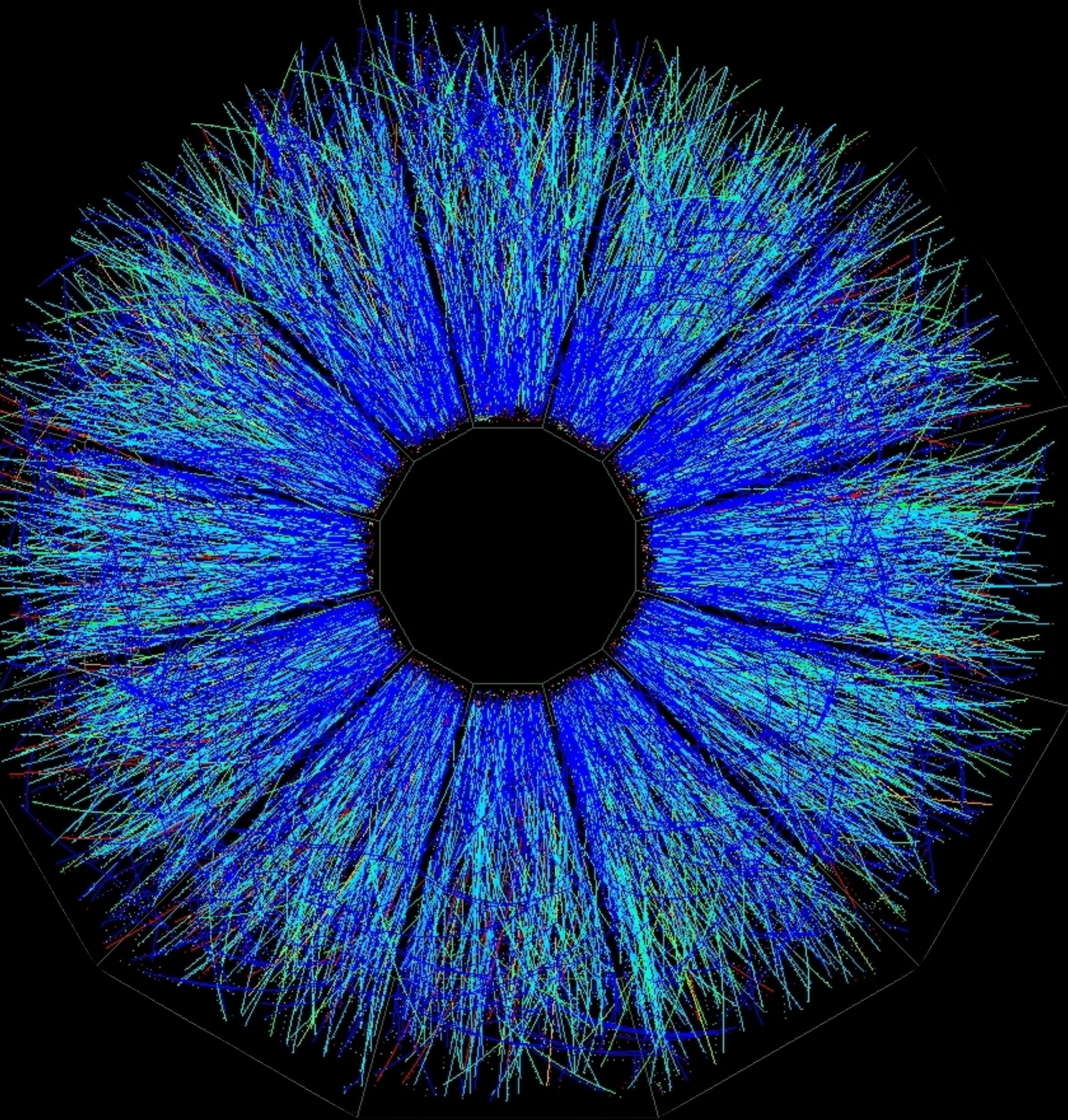
Summary

Event Shape method Spectator Ψ_1

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

- 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 ($> 3\sigma$ 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.



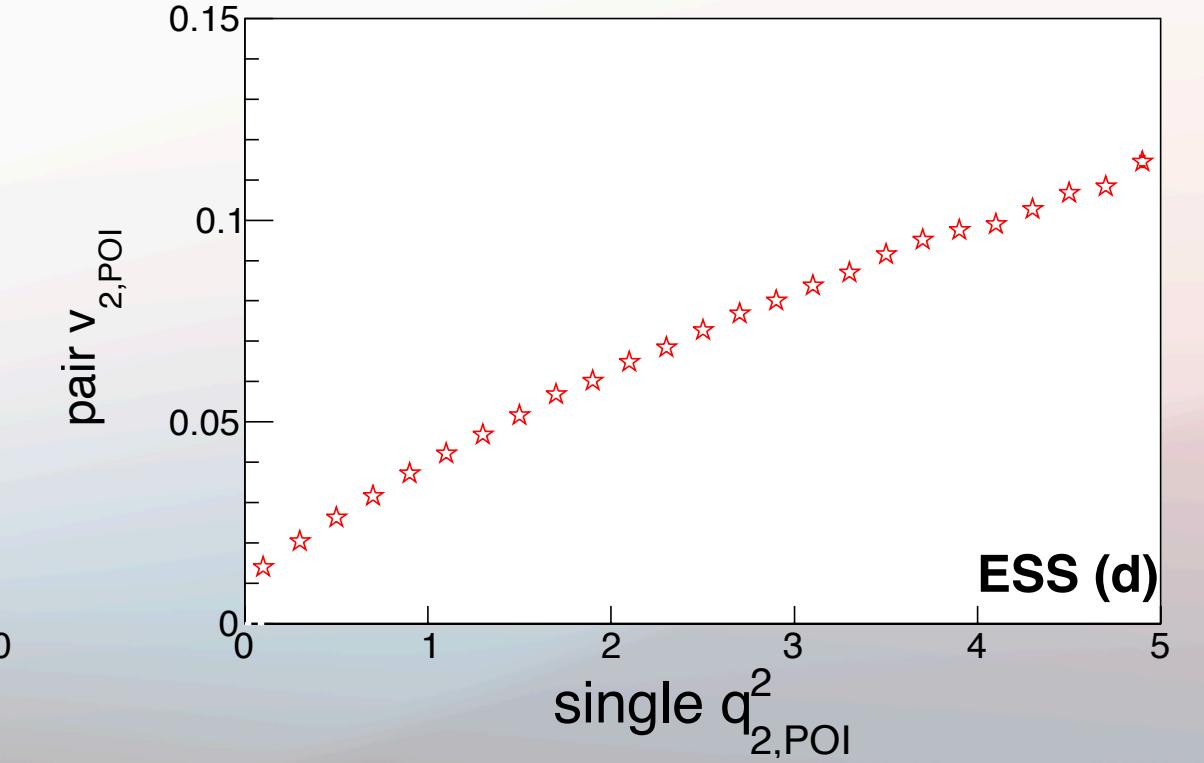
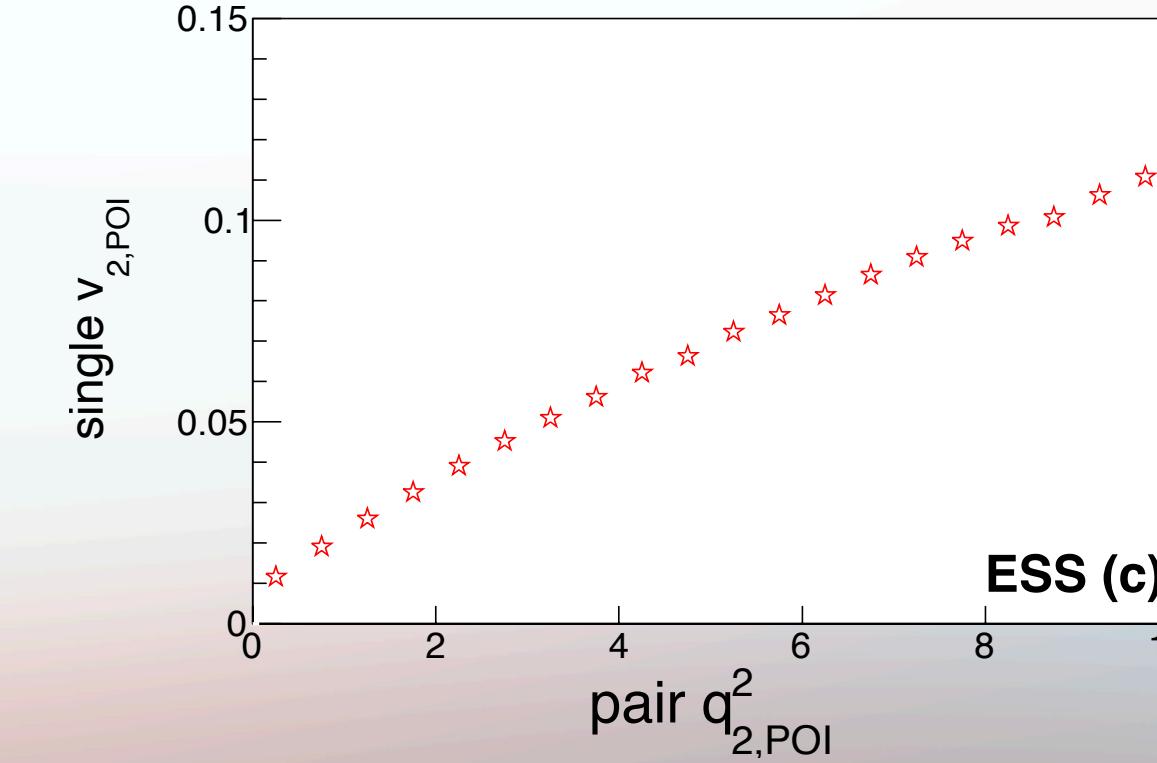
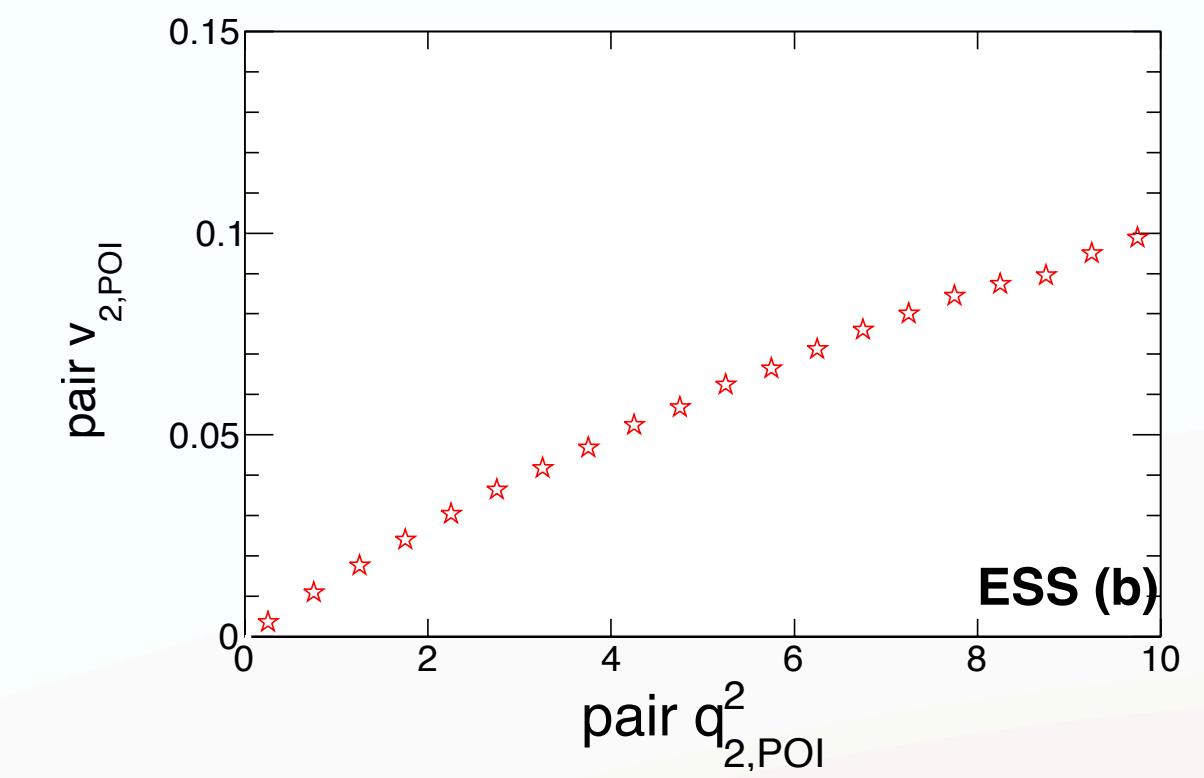
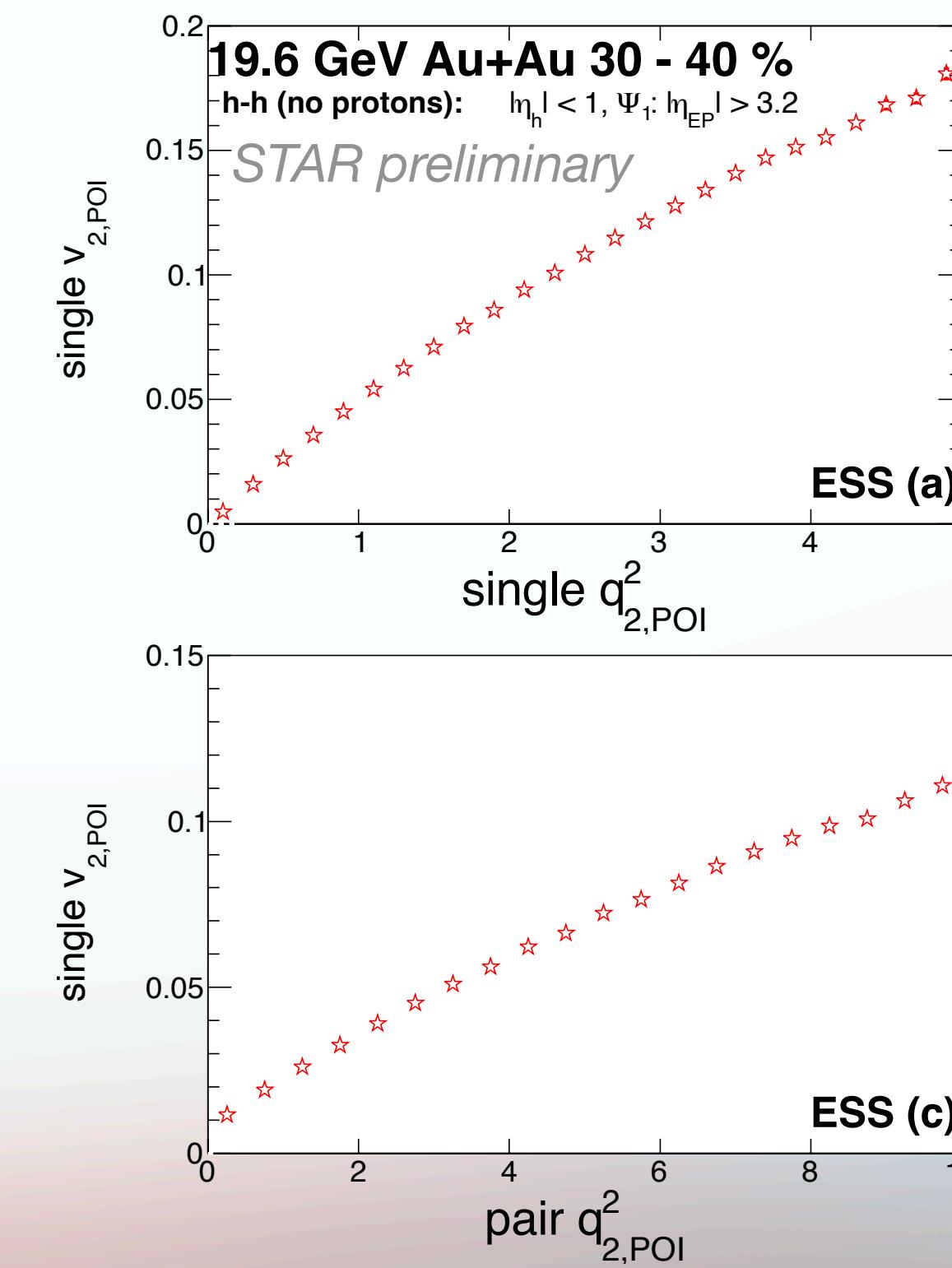
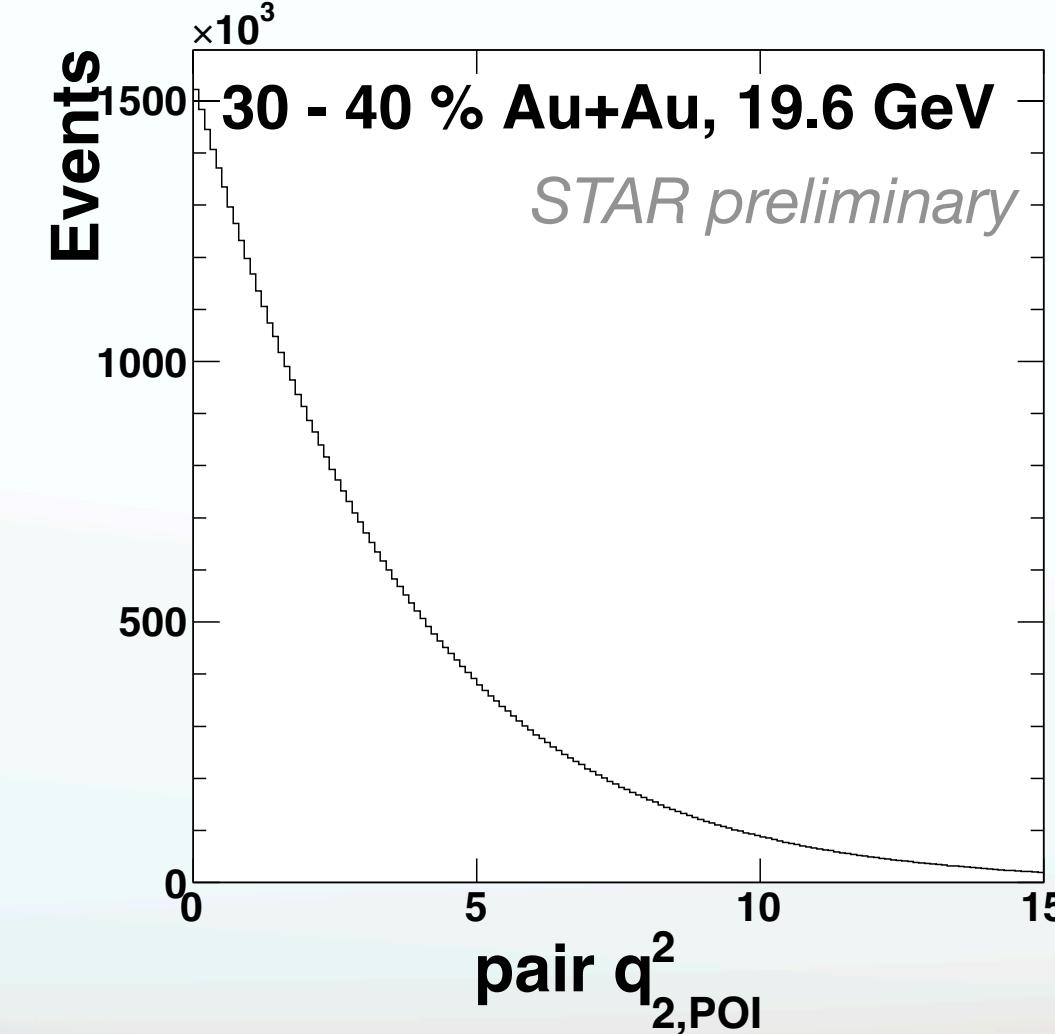
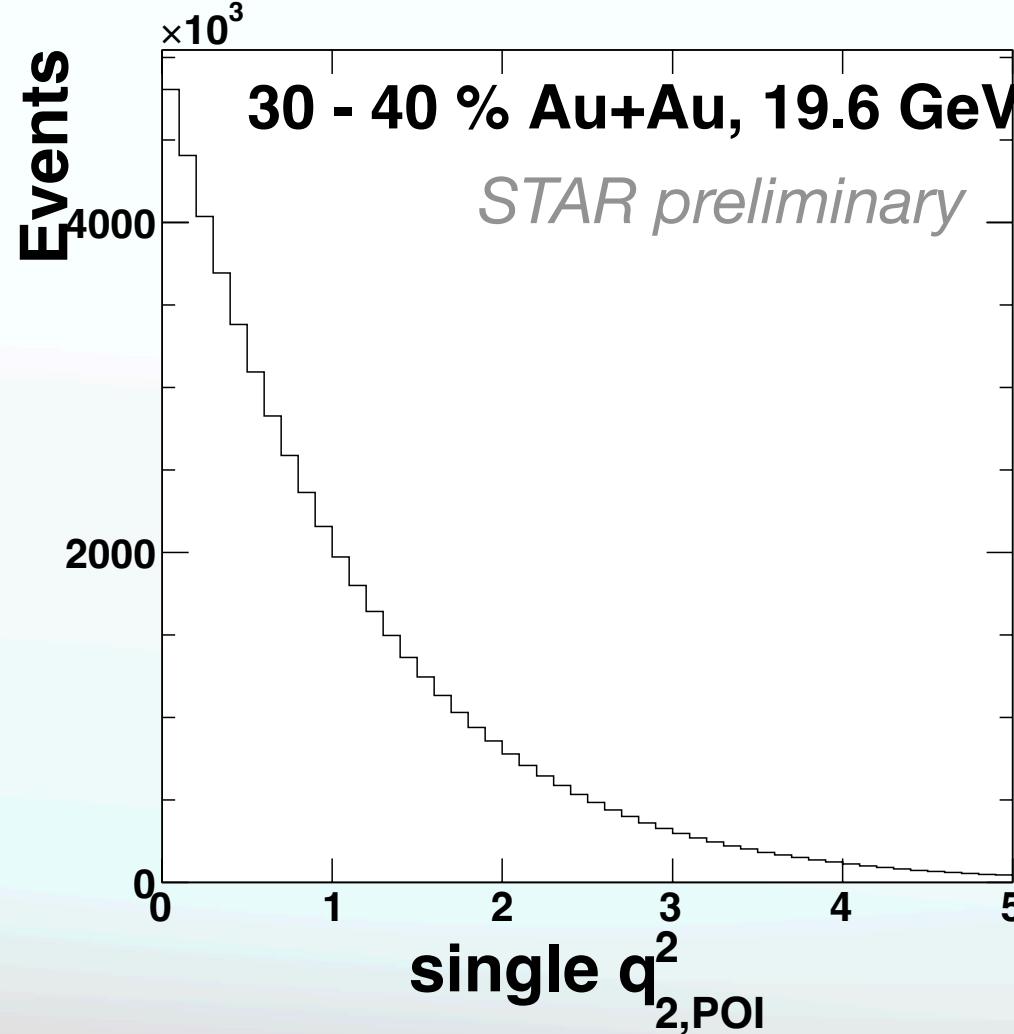


Thank you!

Analyses Details for Event Shape Selection

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

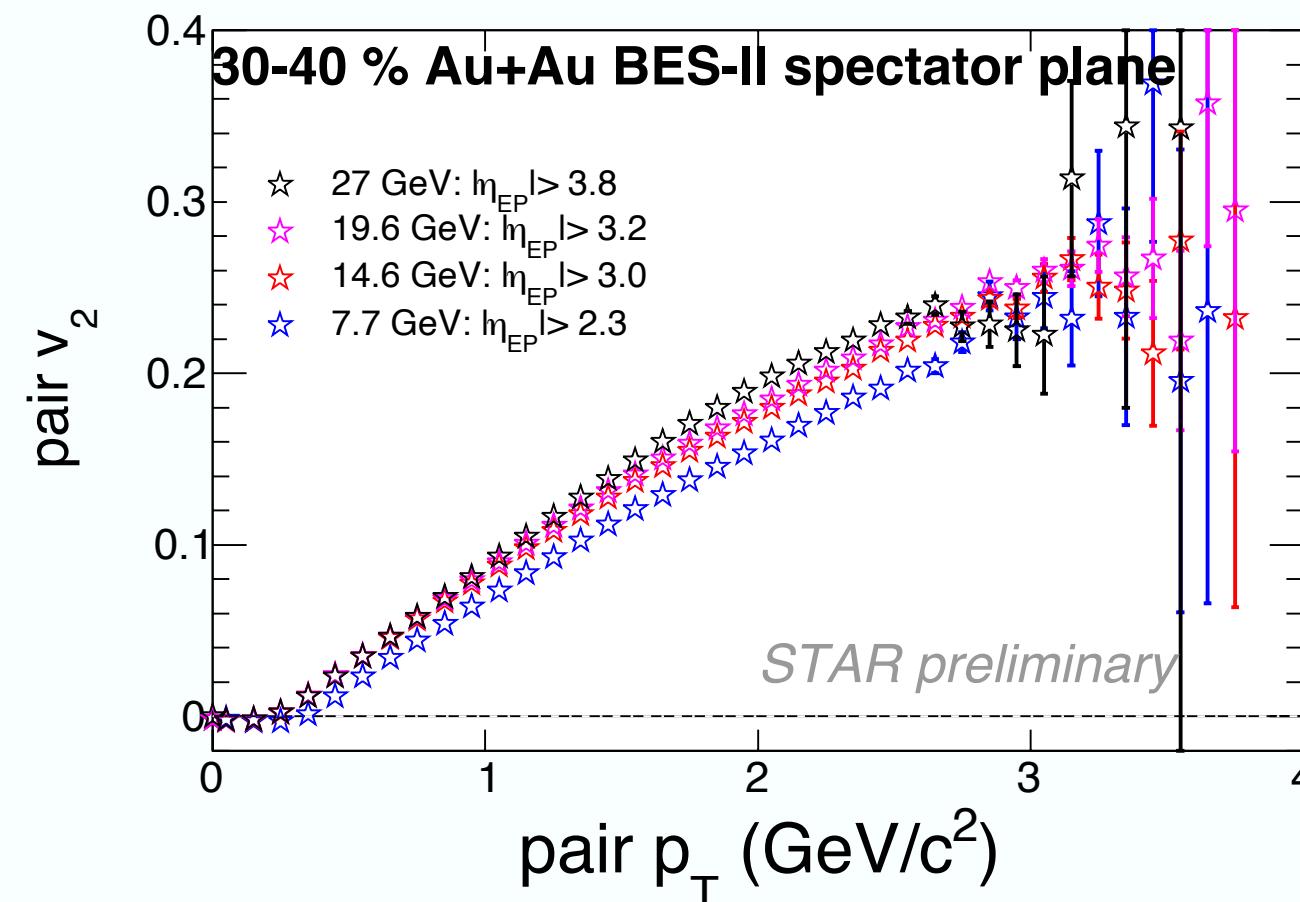
$$v_2\{single(pair)\} = \frac{\langle \cos(2\varphi_{i(p)} - \Psi_{1,\text{EPDe}} - \Psi_{1,\text{EPDw}}) \rangle}{\text{res}_{1,\text{sub}}^2}$$



ESS and Pair v_2

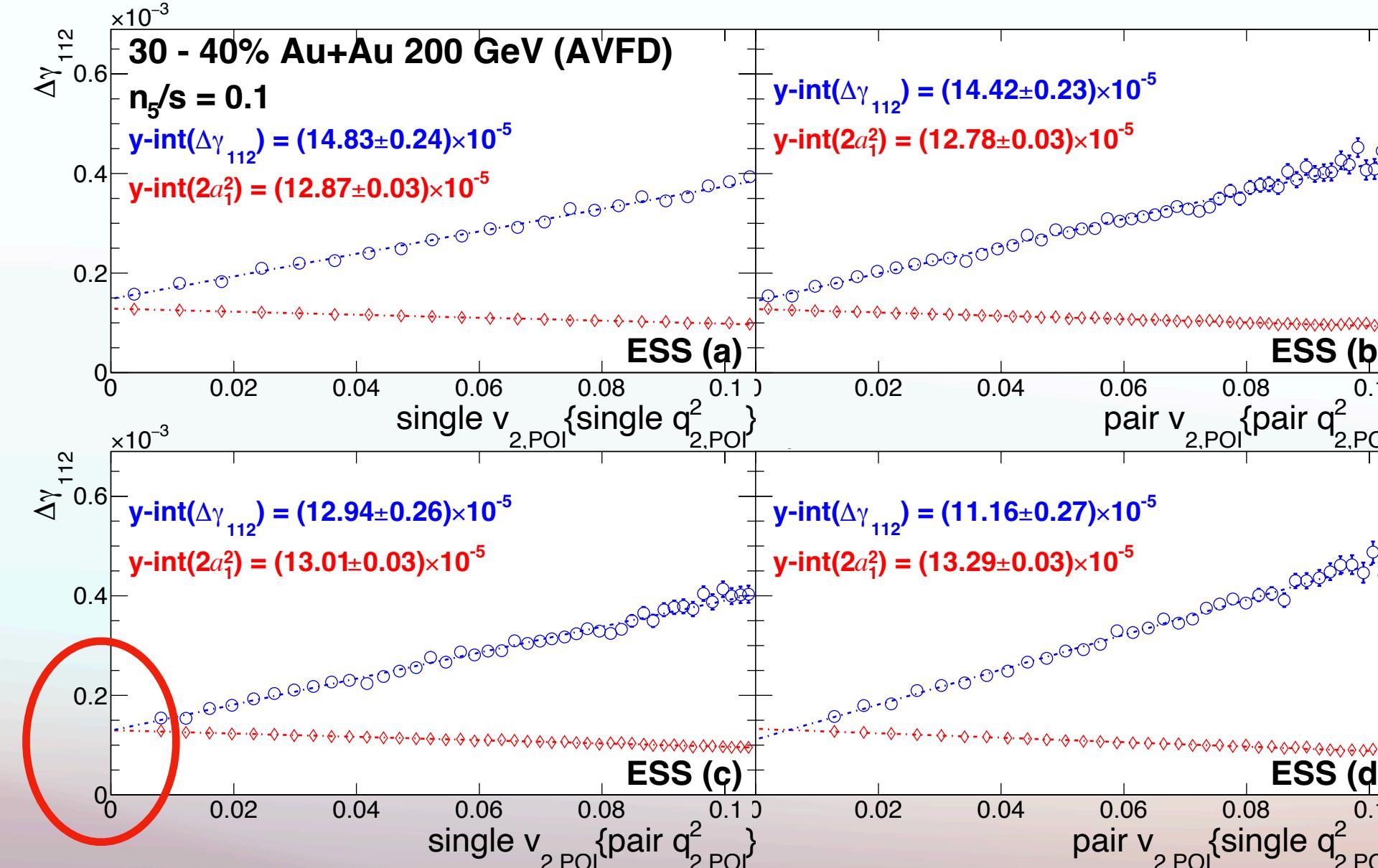
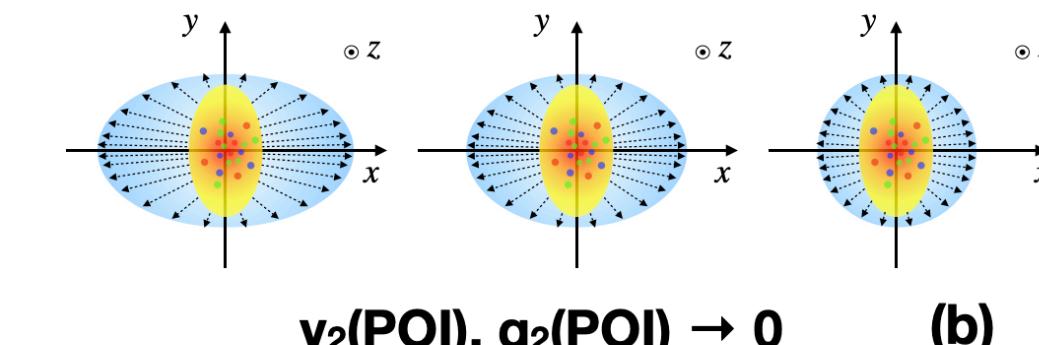
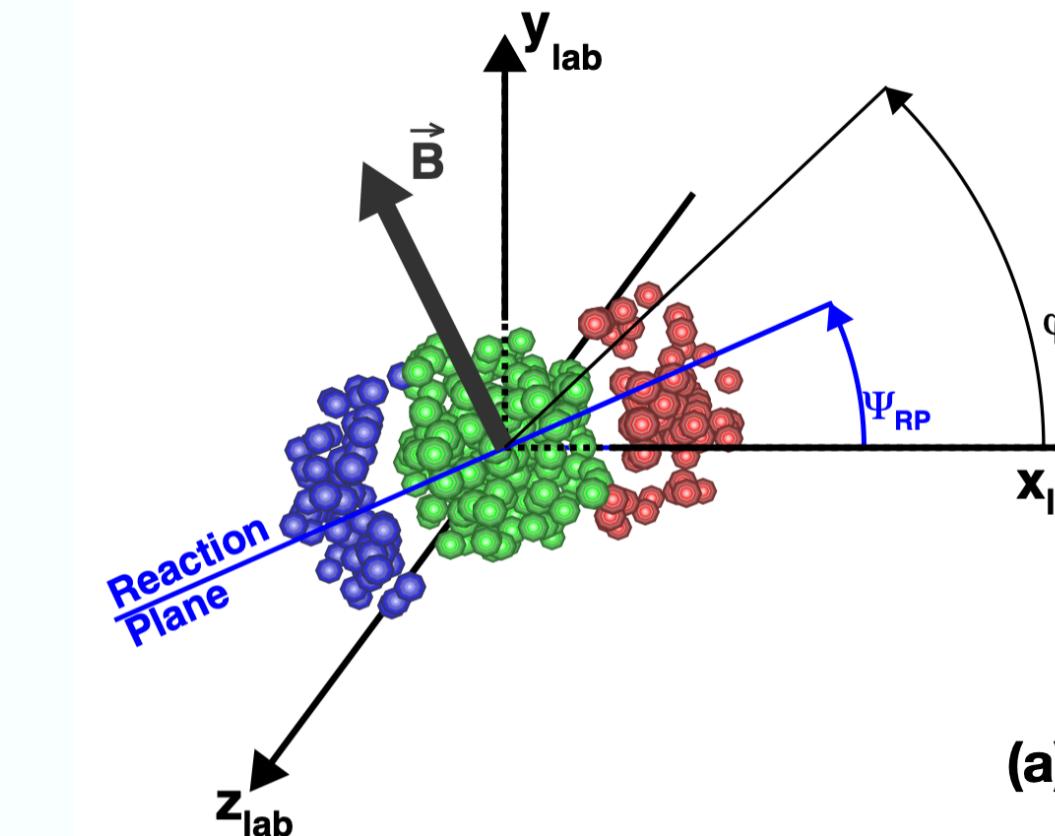
Z. Xu et al, arXiv:2307.14997

- 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



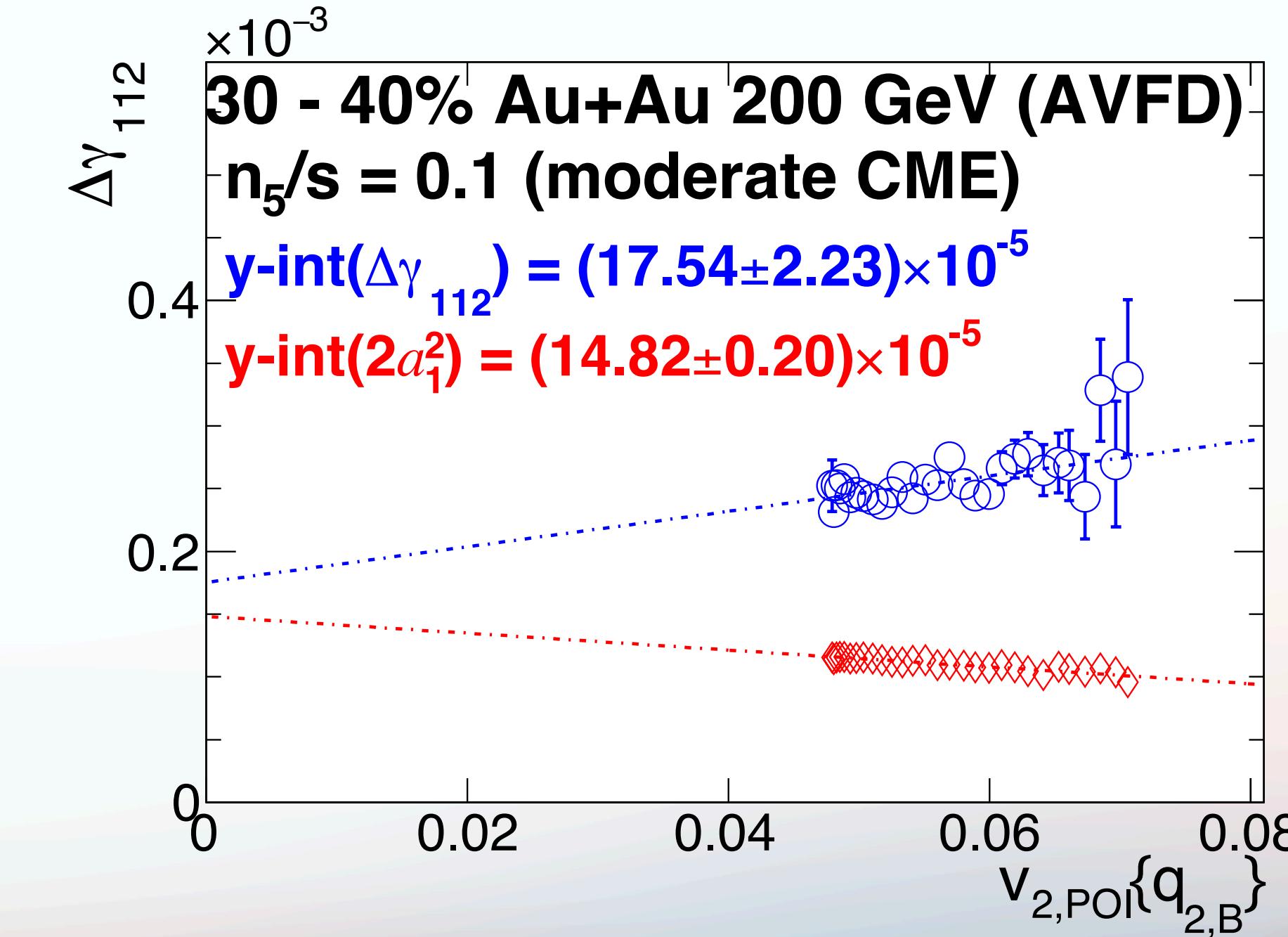
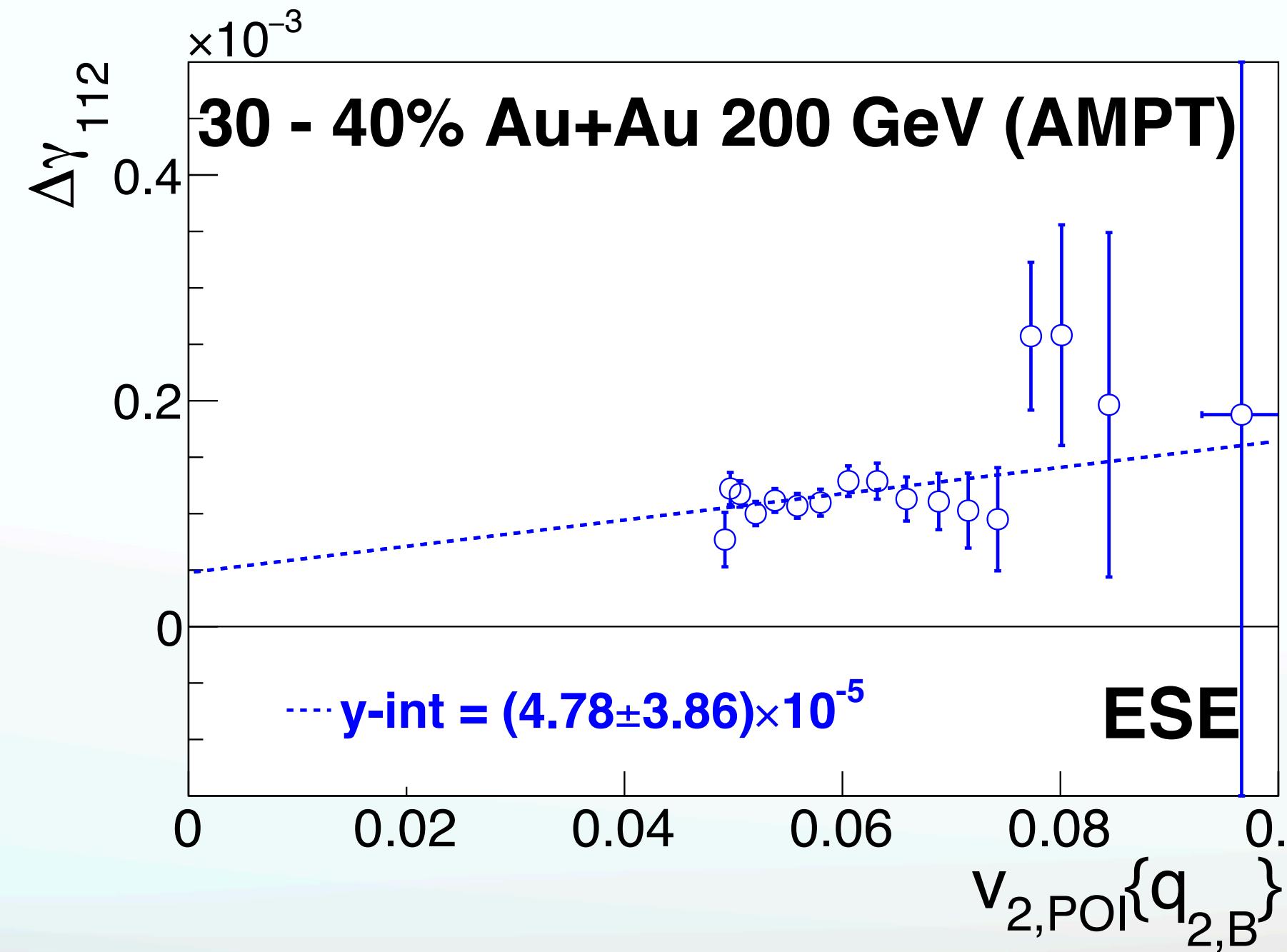
- Unmixed recipes (a) and (b) cause residual background near zero-flow region
- Mixed recipes have advantage that the v_2 and binning q^2 are less correlated.
- However, pair v_2 contains true CME signal, which may lead to over subtraction for (d).

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

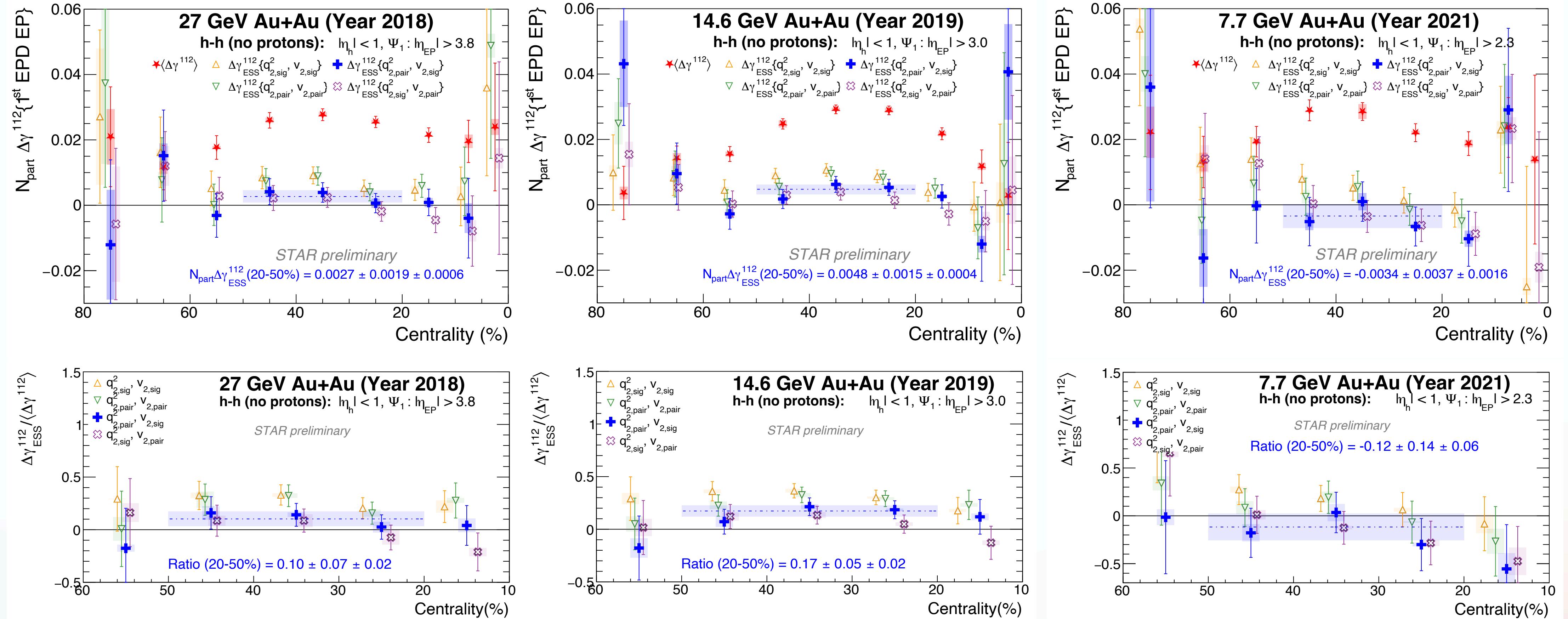
Simulation for q_B from Event Shape Engineering

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

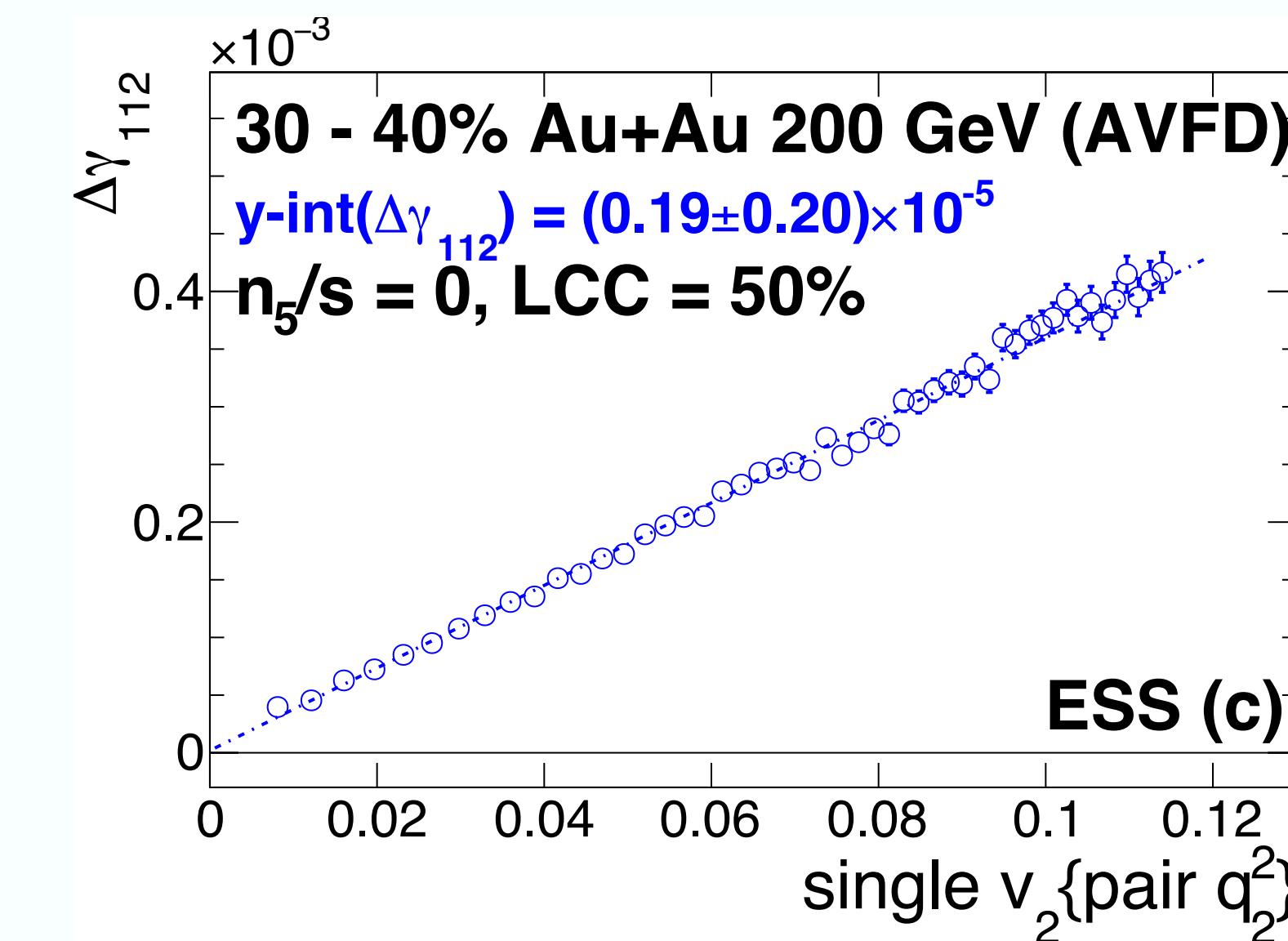
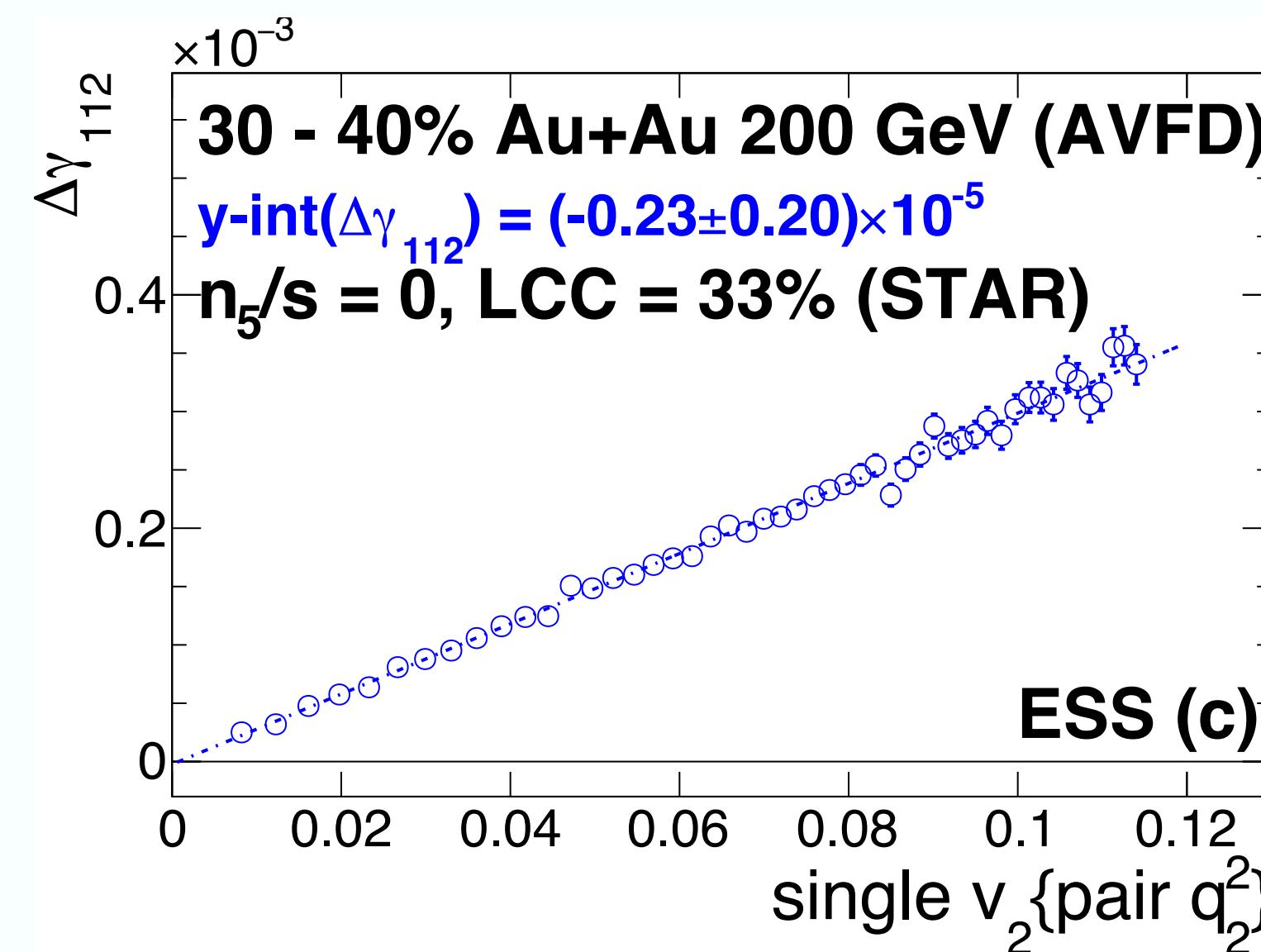


Beam Energy Scan II - Event Shape Selection



- 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%