Supported in part by U.S. DEPARTMENT OF ENERGY

Lessons from Isobar and Event Shape Selection Analysis for Search of CME with RHIC Beam Energy Scan Data

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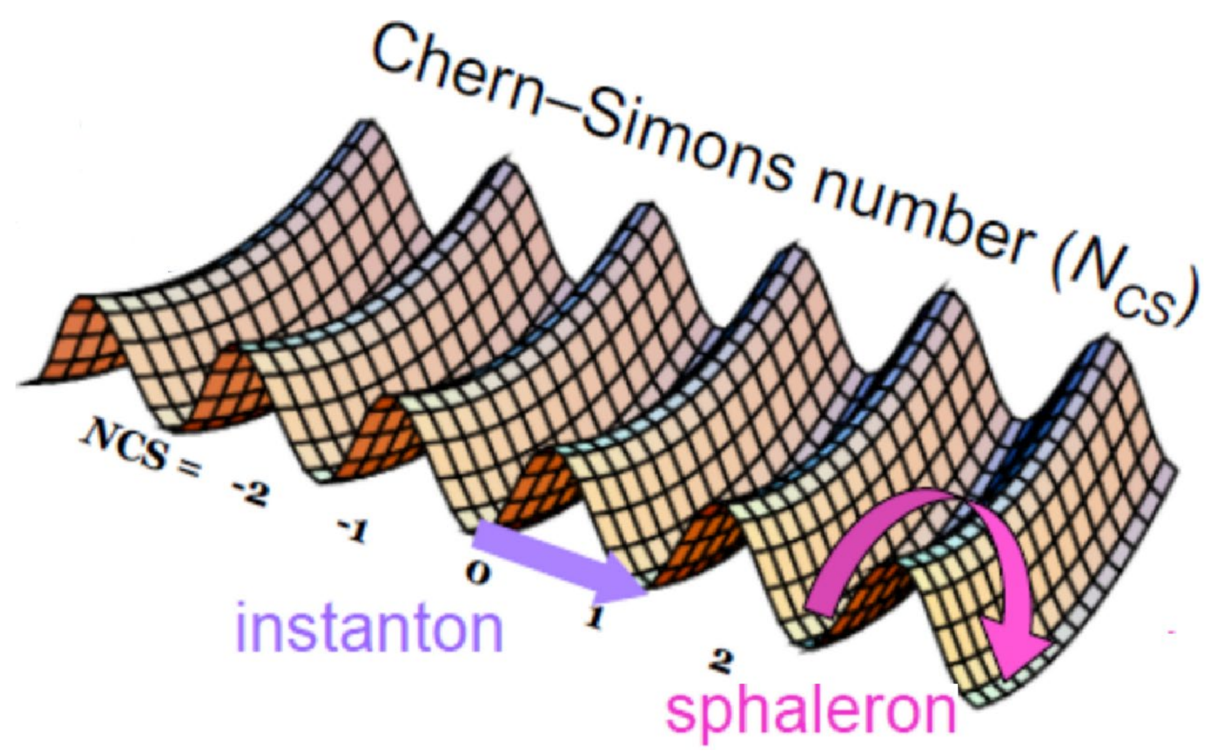
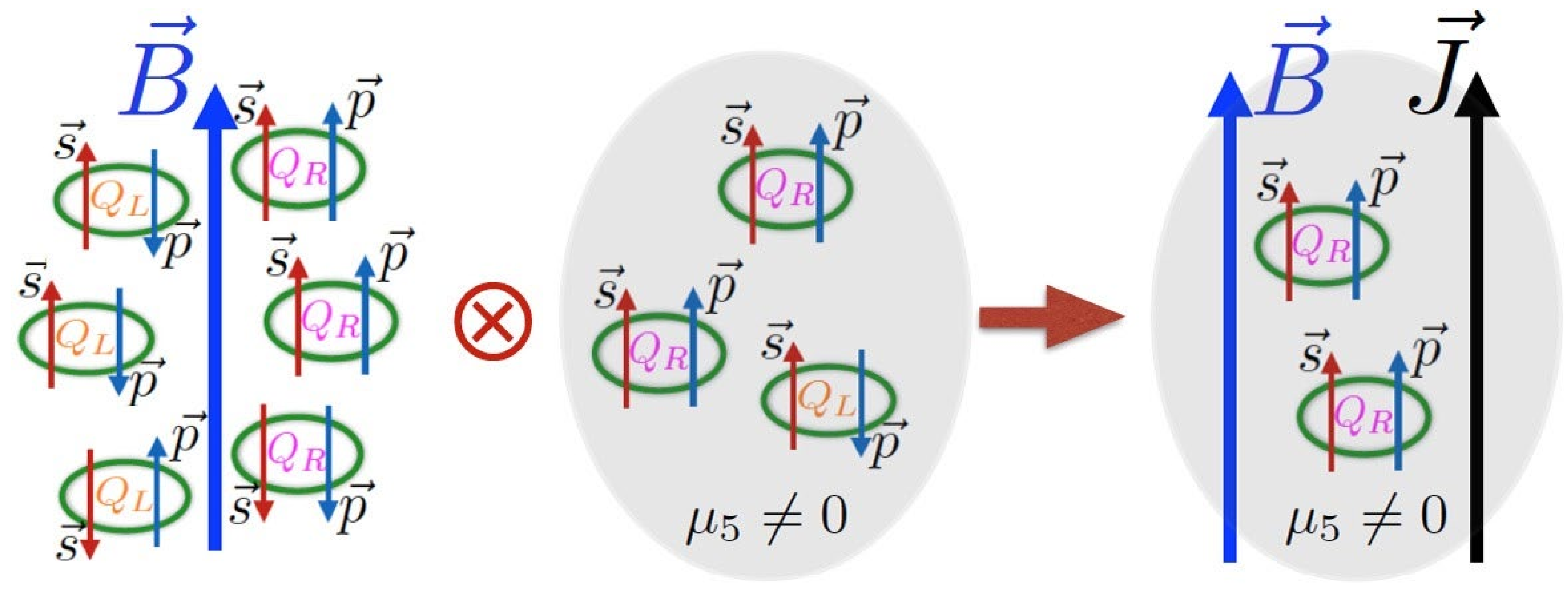
Thanks to Zhiwan Xu, Brian Chan, Gang Wang and Jinfeng Liao and his group for AVFD and Discussions

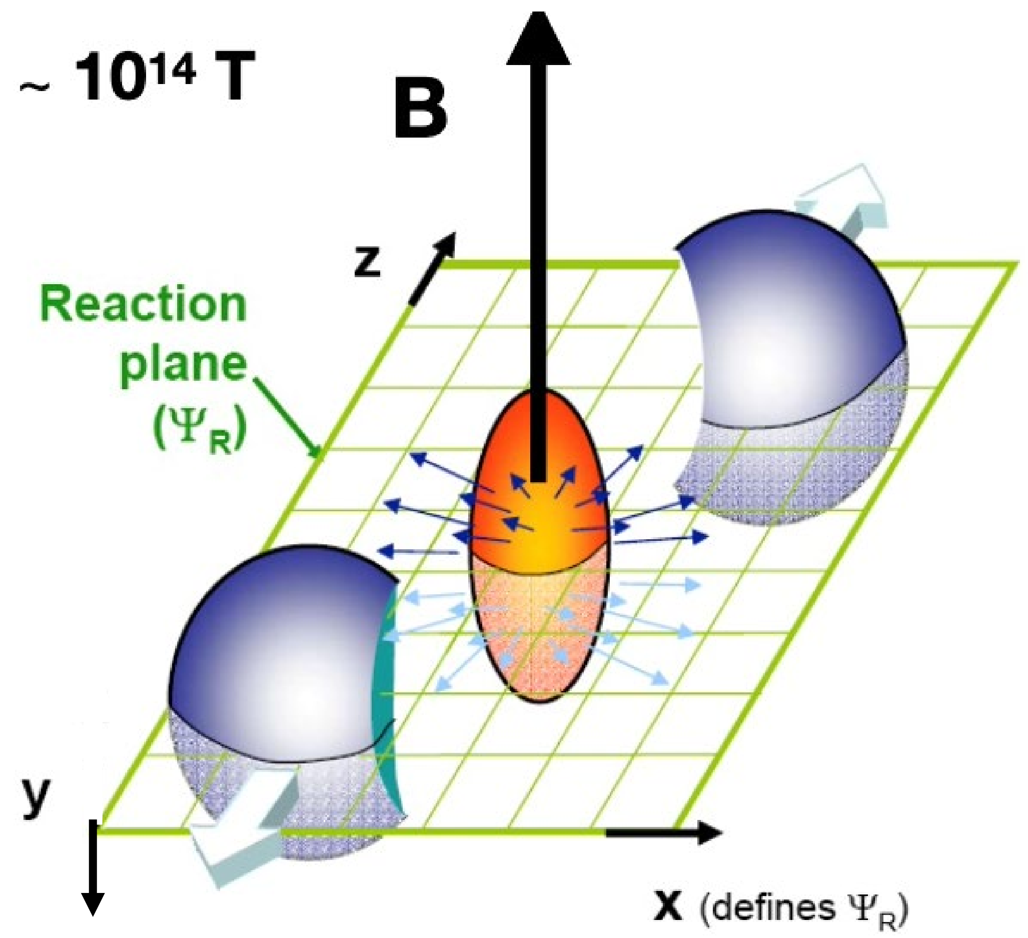
Chiral Magnetic Effect

D. Kharzeev, Phys. Lett. B 633, 260 (2006).

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





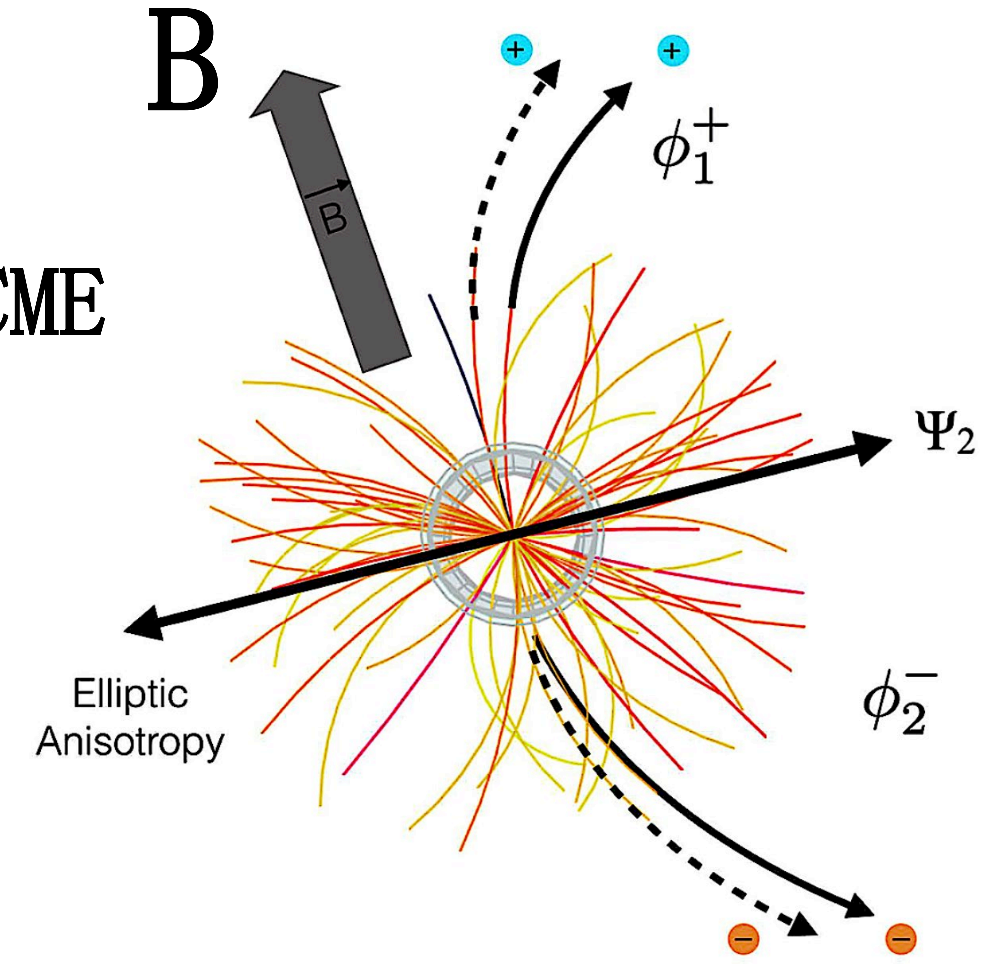


- Chirality imbalance coupled with strong magnetic field induces a charge separation along the B field direction (violates Parity Symmetry dynamically in strong interaction!)
- Heavy-Ion Collision provides an opportunity to observe an intrinsic QCD toplogical phenomenon experimentally.

Chiral Magnetic Effect

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

CME



- To quantify the collective motions including the charge separation, we expand the particle azimuthal angle distribution as:

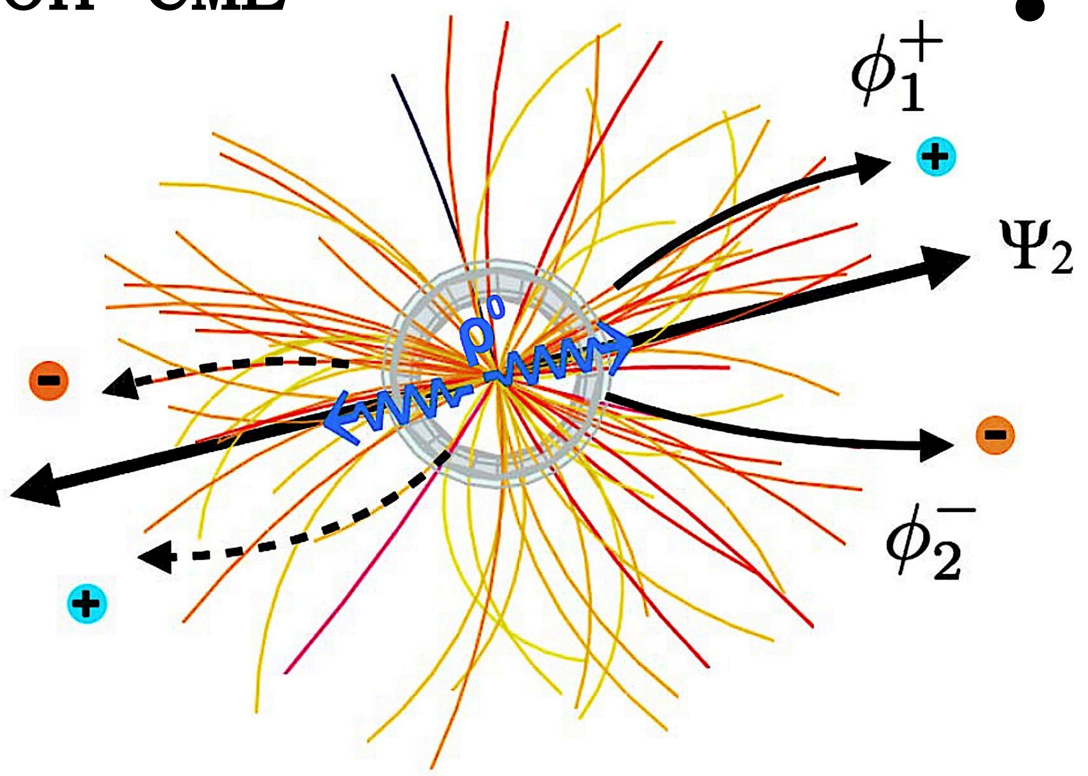
$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1\cos(\phi - \Psi_{RP}) + 2v_2\cos[2(\phi - \Psi_{RP})] + \cdots + \underbrace{2a_\pm}_{\propto\ \mu_5|\vec{\mathbf{B}}|}\sin(\phi - \Psi_{RP}) + \cdots$$

- Experiment observable:

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

$$\gamma^{112} = \langle\cos(\phi_1 + \phi_2 - 2\psi_{RP})\rangle = \langle\cos(\phi_1 - \psi_{RP})\cos(\phi_2 - \psi_{RP})\rangle - \underbrace{\langle\sin(\phi_1 - \psi_{RP})\sin(\phi_2 - \psi_{RP})\rangle}_{\propto\ a_1 \cdot a_1}$$

Non-CME



Flowing resonance decay

- Decay of flowing resonance

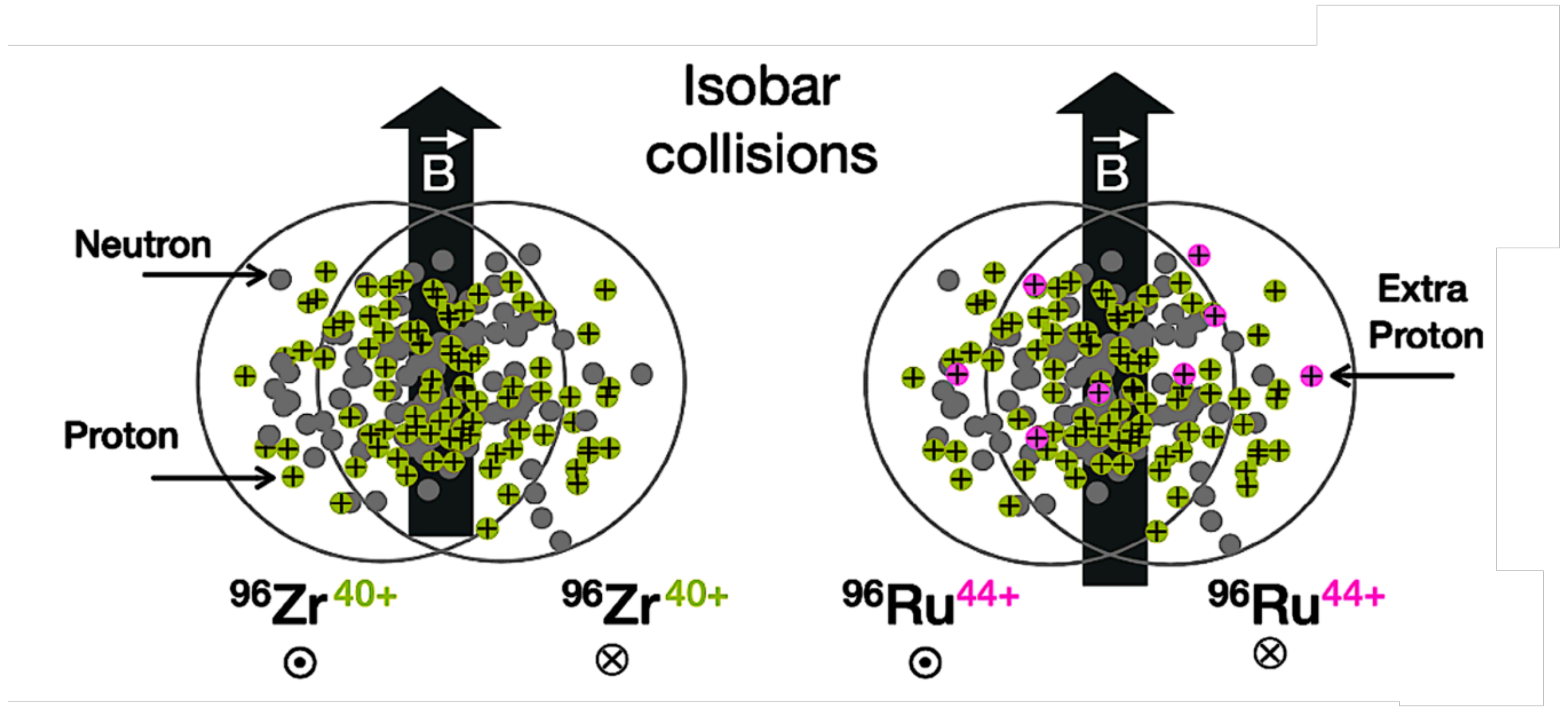
$$\Delta\gamma^{reso} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2}{N}$$

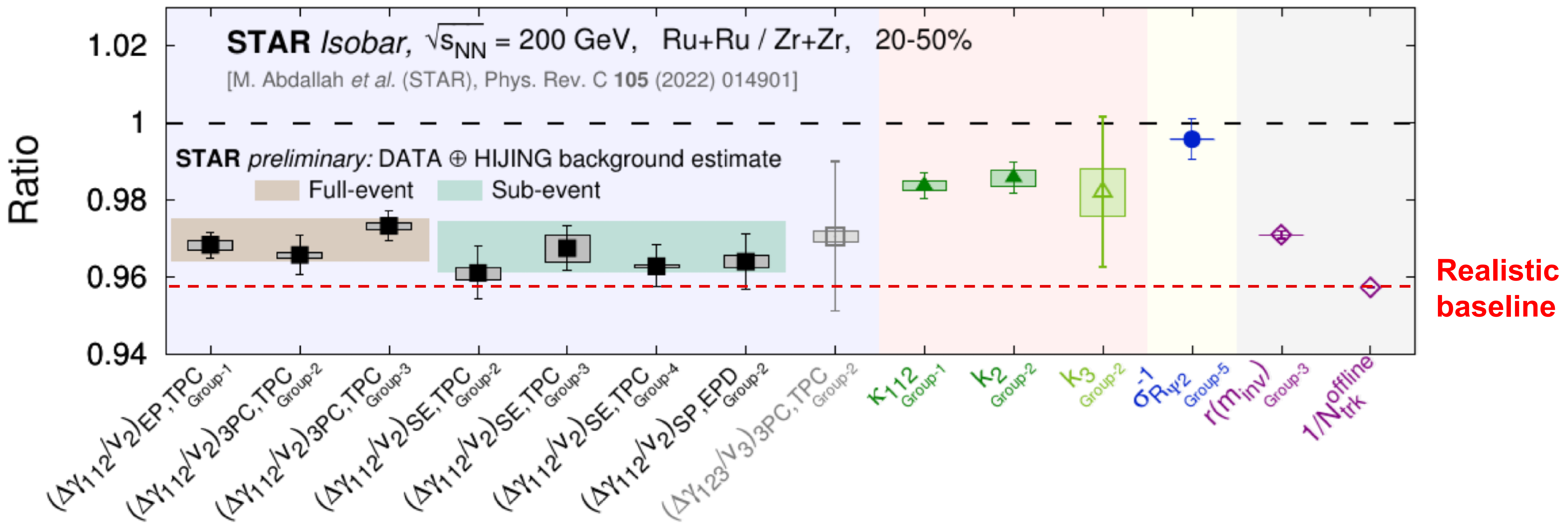
$$\boxed{\underbrace{\Delta\gamma^{112}}_{\text{Measured}} = \underbrace{\Delta\gamma^{CME}}_{\text{Signal}} + \underbrace{k\frac{v_2}{N} + \Delta\gamma^{non-flow}}_{\text{Backgrounds}}}$$

Lessons from Isobar Collisions

Phys. Rev. C 105, 014901

- Isobar data did not observe the predefined CME signatures.
- Why? BKG difference: multiplicity mismatch. v_2 ~ 2%





Isobar collisions sensitive to potential difference in CME observable due to different Magnetic Field

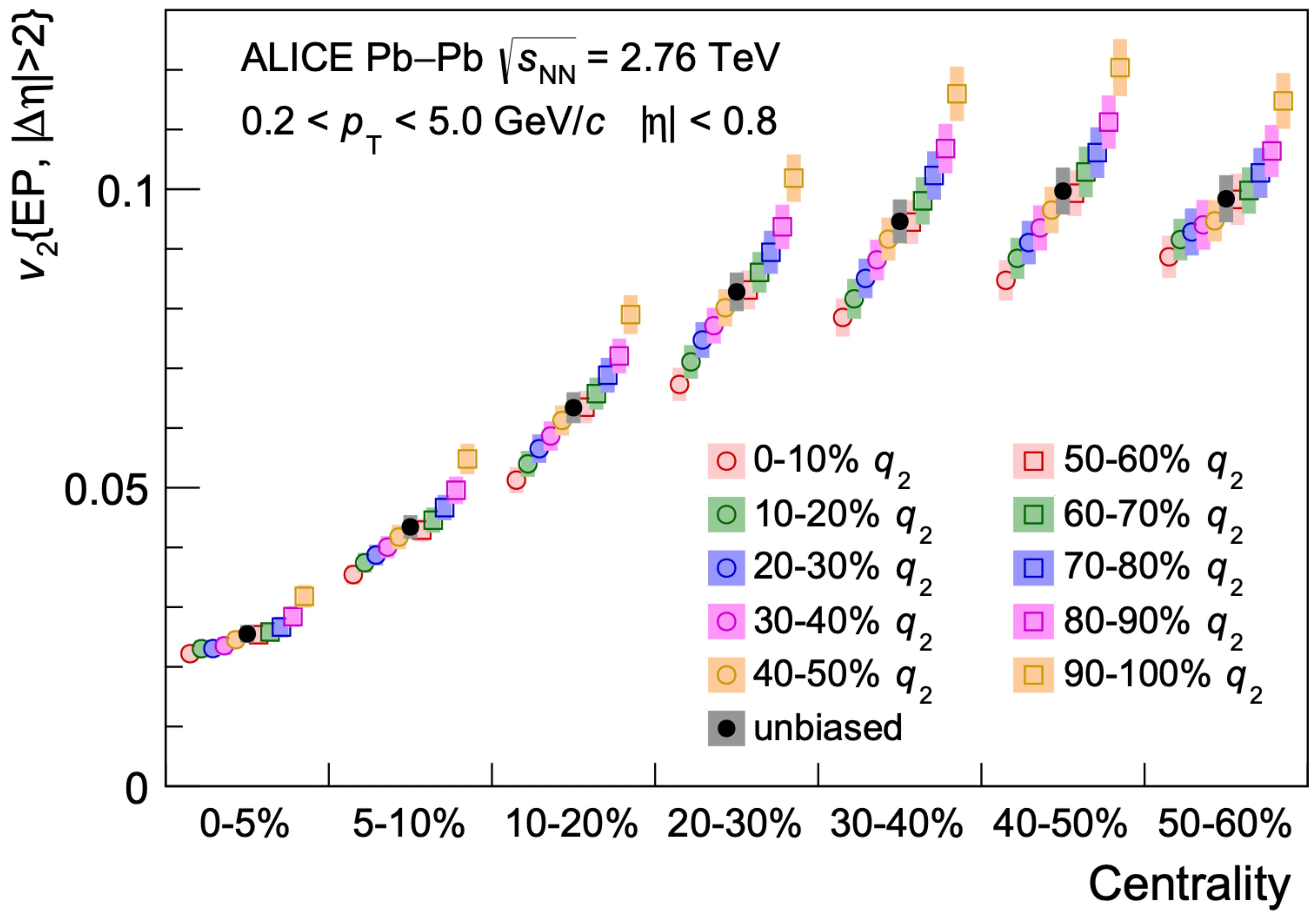
Ru+Ru/Zr+Zr isobars are not exactly the same within sub-percent level to achieve the accuracy needed

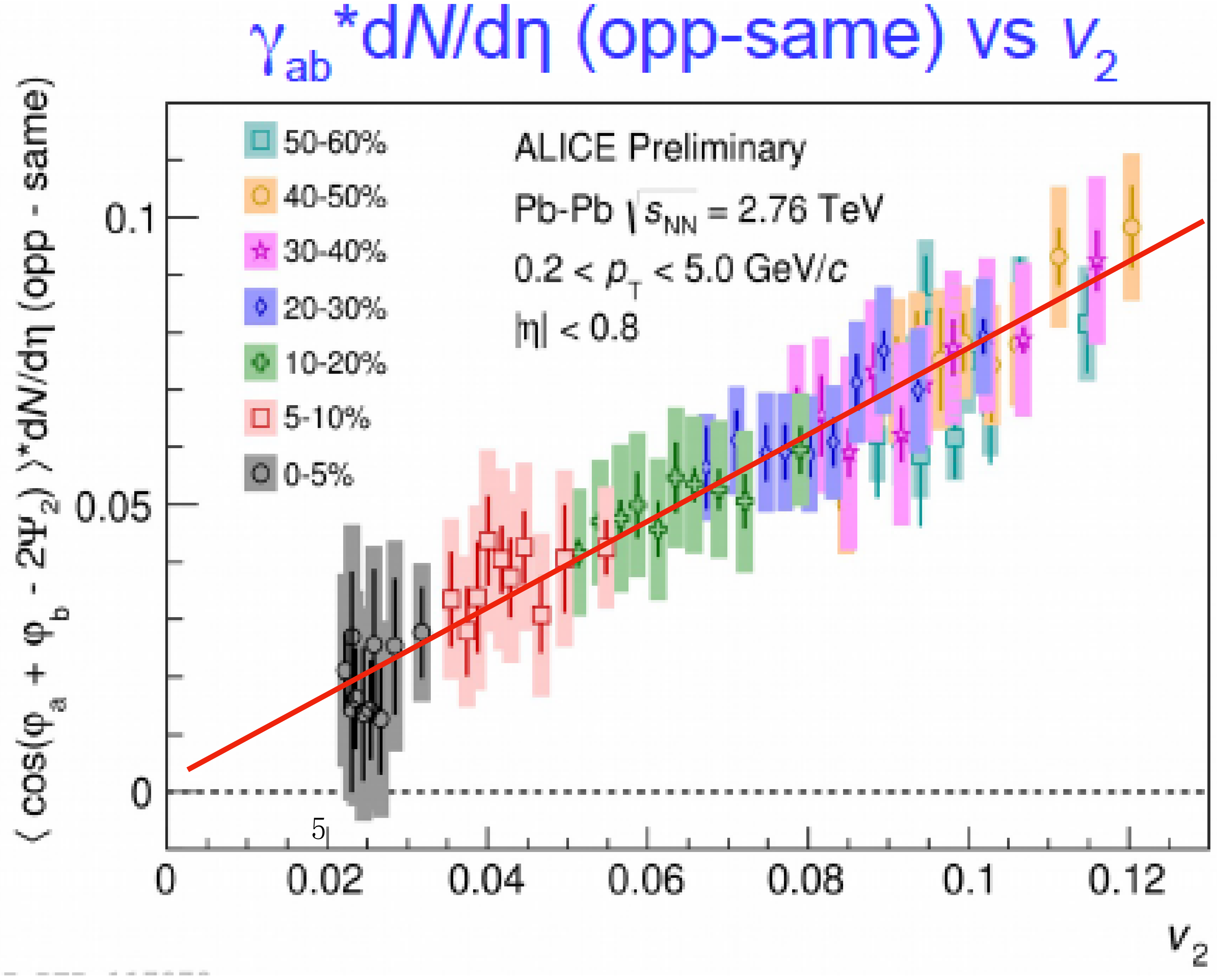
These isobars are also small in Z, not favorable for CME searches

Isobar data → CME signal is probably small, not necessarily zero ! → how small?

Event Shape Selection (Engineering)
Large Colliding Nuclei Pb+Pb at LHC and Au+Au at RHIC

Phys. Lett. B 777, 151 (2018)





Unable to select a spherical event shape sample **AND with finite Magnetic Field** to search for CME

q_2 from an eta region different from particle of interest

So selected q_2 not effective in selecting the shape of emission for particles of interest

If the selection is such that v2 →0 when the events corresponding to the most central collisions, then the number of spectator protons are minimum and not favorable for CME

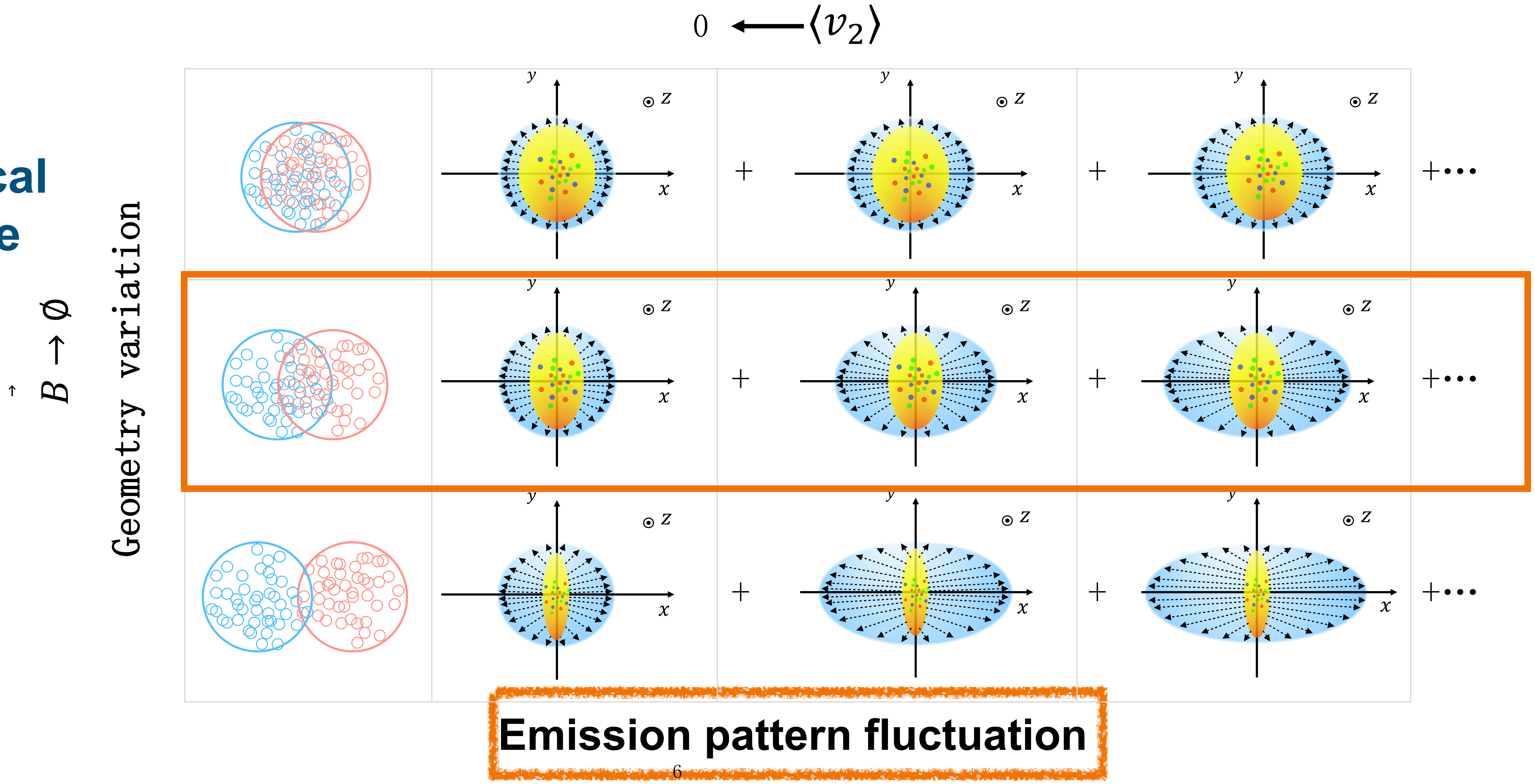
Event Shape Selection to control v_2?

q2 or v2 has contributions:

- **participant shape distribution – likely long range and correlated over large eta gaps**
- **emission pattern fluctuations – short eta range, uncorrelated for different eta regions**

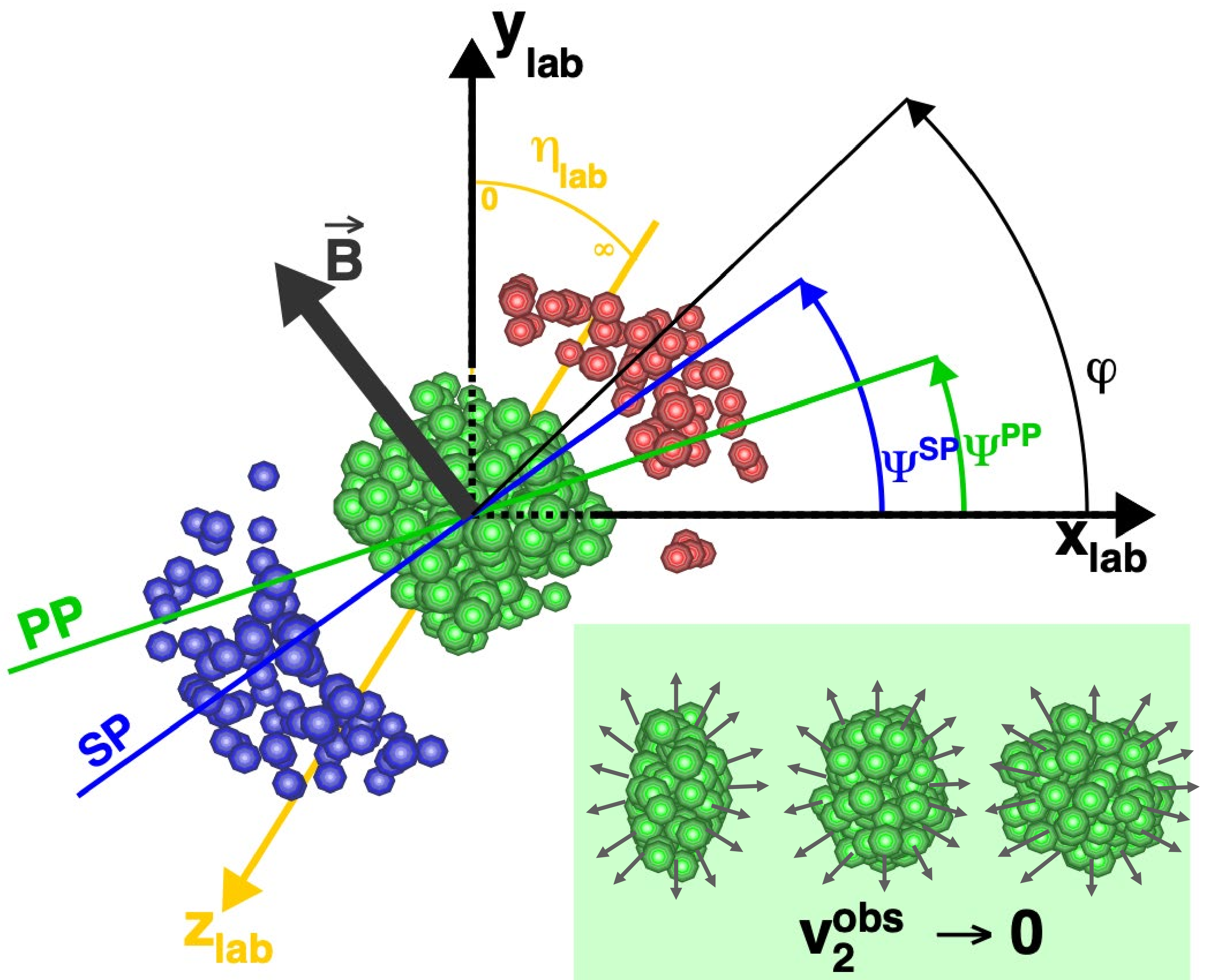
CME Search:

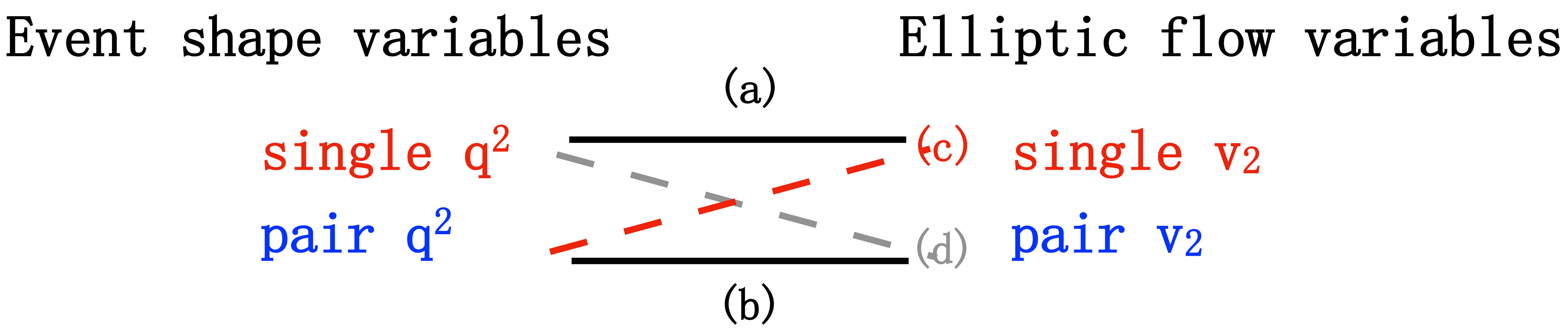
- **POI – spherical**
- **B field -- finite**



Event Shape Selection Variables

- Single q^2 and single v_2 are constructed from final particles
- Pair q^2 and pair v_2 are calculated based on pair momentum
  - Pair momentum is obtained from adding momenta of two particles to mimic decay kinematics ~ more related to $\Delta\gamma$ background



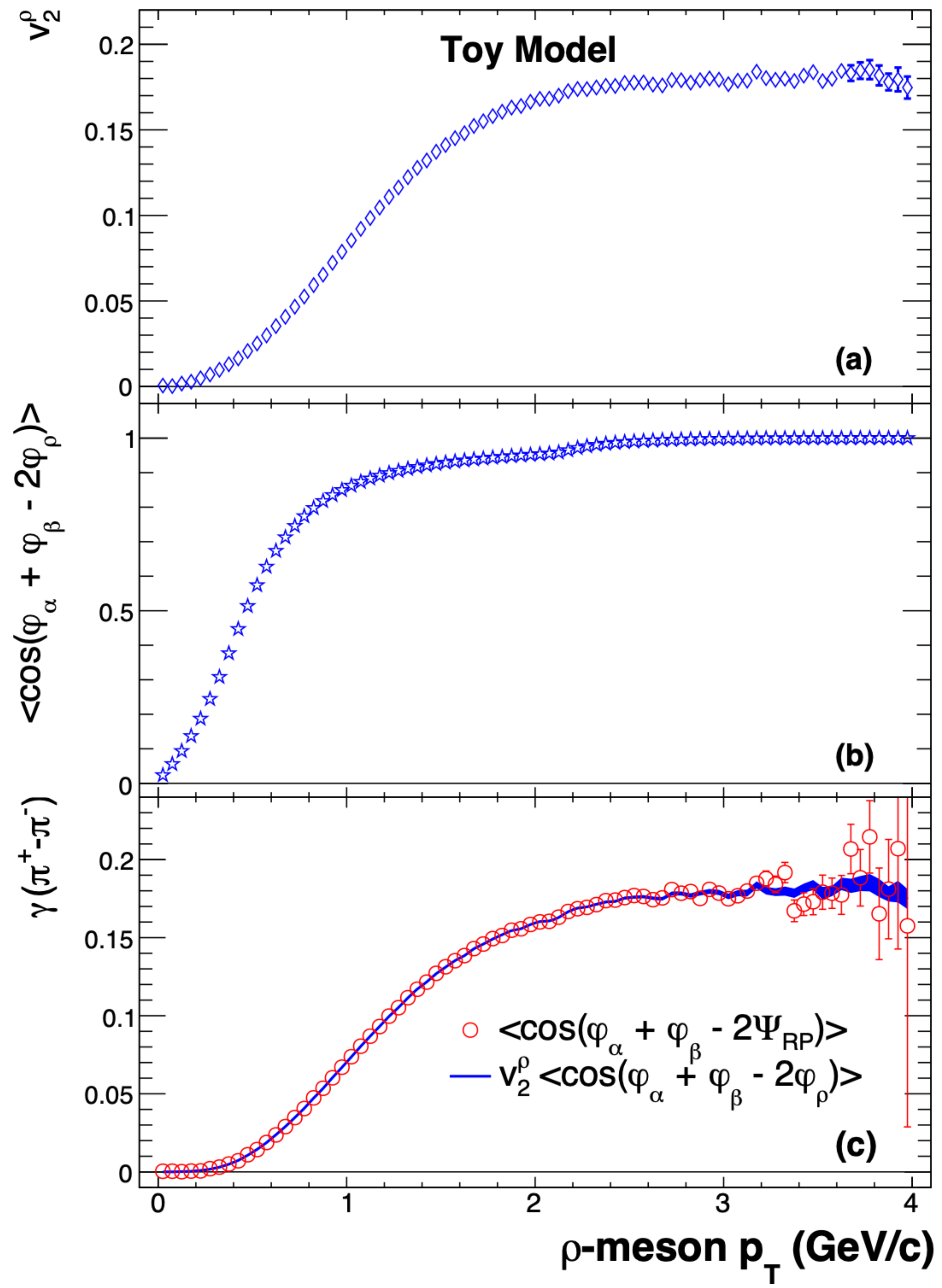


Which one of the above four ESS is the best?

Origins of BKG ~ v_2^{res}

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

- The BKG from resonance flowing decay in $\Delta\gamma$ is well-represented by product of



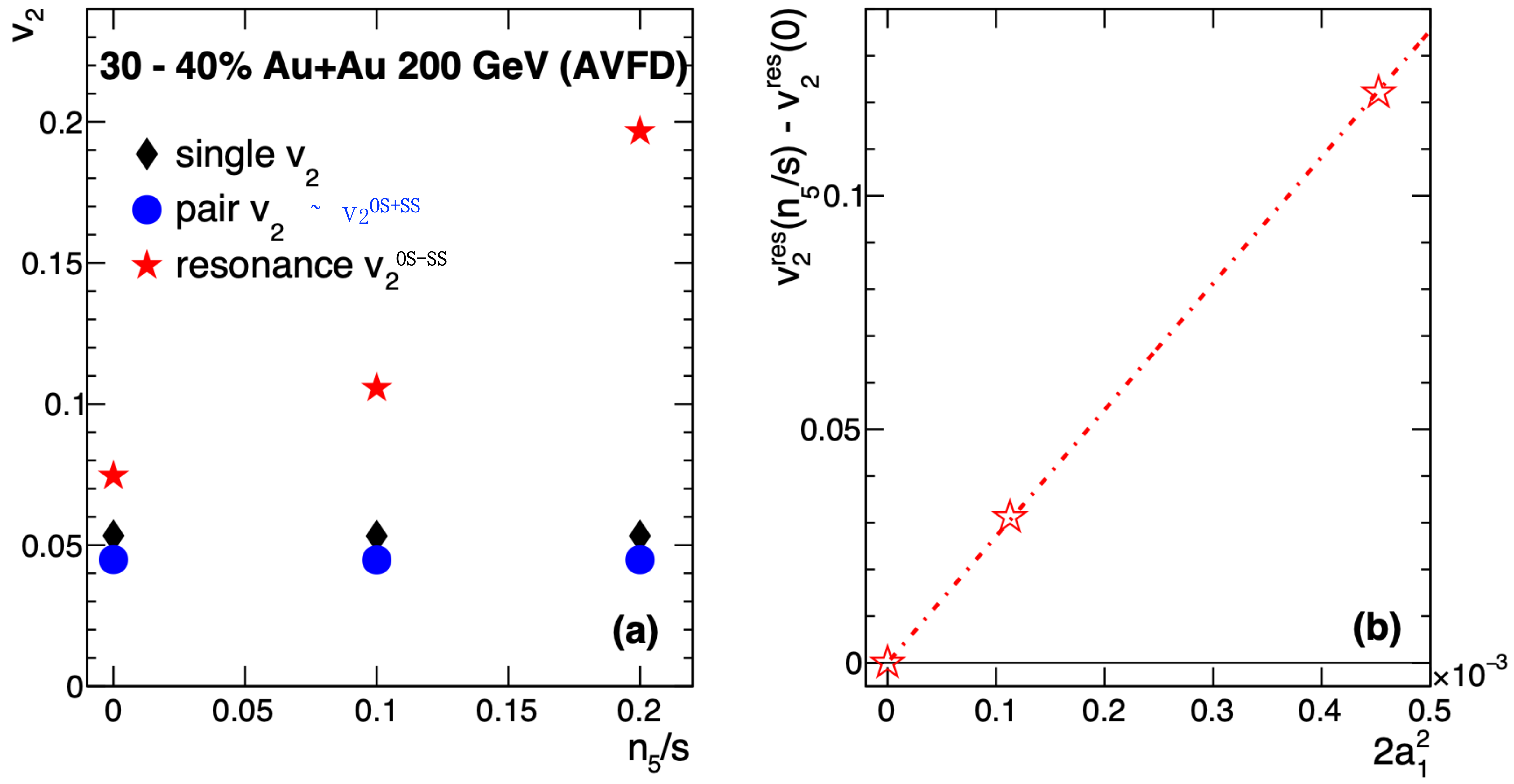
$$\Delta\gamma\{BG\} = v_2^{res}\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$$

- A toy model targeted $\rho \rightarrow \pi^+ \pi^-$ resonance decay confirms the above relation.

- Can we use v_2^{res} directly to control the BG?

- NO. Why? v_2^{res} is modified by the CME existence.

Optimal ESS Approach



$$v_2^{res} \sim v_2^{\pi} + \frac{N^{SS}}{N^{OS} - N^{SS}}(\Delta\gamma - v_2^{\pi}\Delta\delta)$$

Comparable

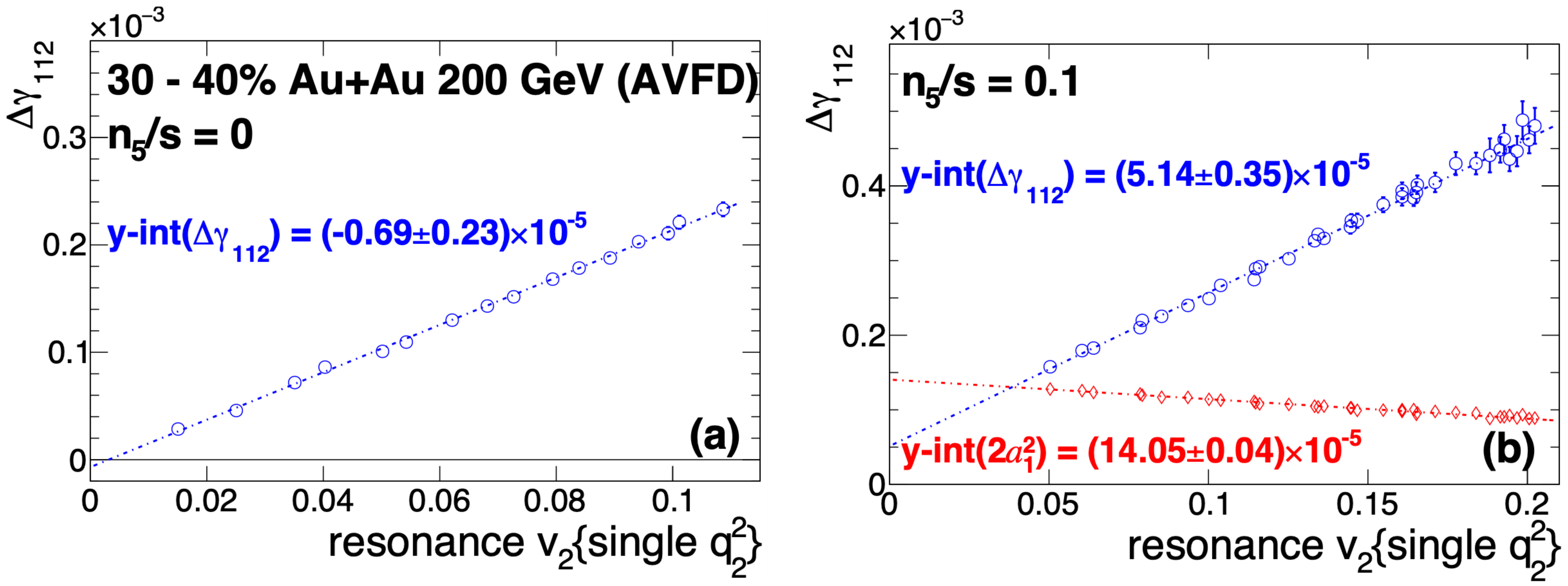
Not good for ESS!

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

Dominant

- **Resonance v_2^{res} is significantly modified under the CME.**
- **The increase is proportional to a_1^2**
- **Single v_2 and pair v_2 are almost constant.**

Optimal ESS Approach



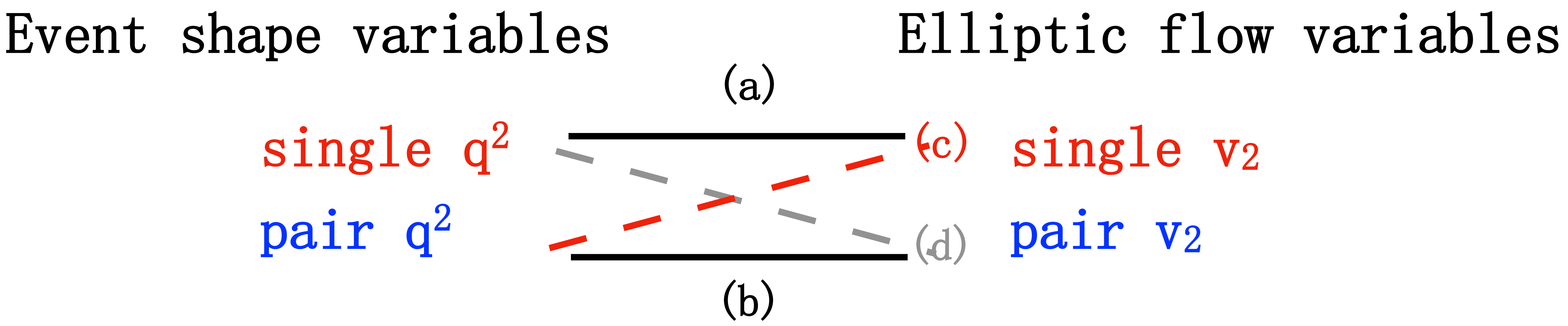
$$v_2^{res} \sim v_2^{\pi} + \frac{N^{SS}}{N^{OS} - N^{SS}}(\Delta\gamma - \ v_2^{\pi}\Delta\delta)$$

Comparable

Severe Over Subtraction

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

Dominant

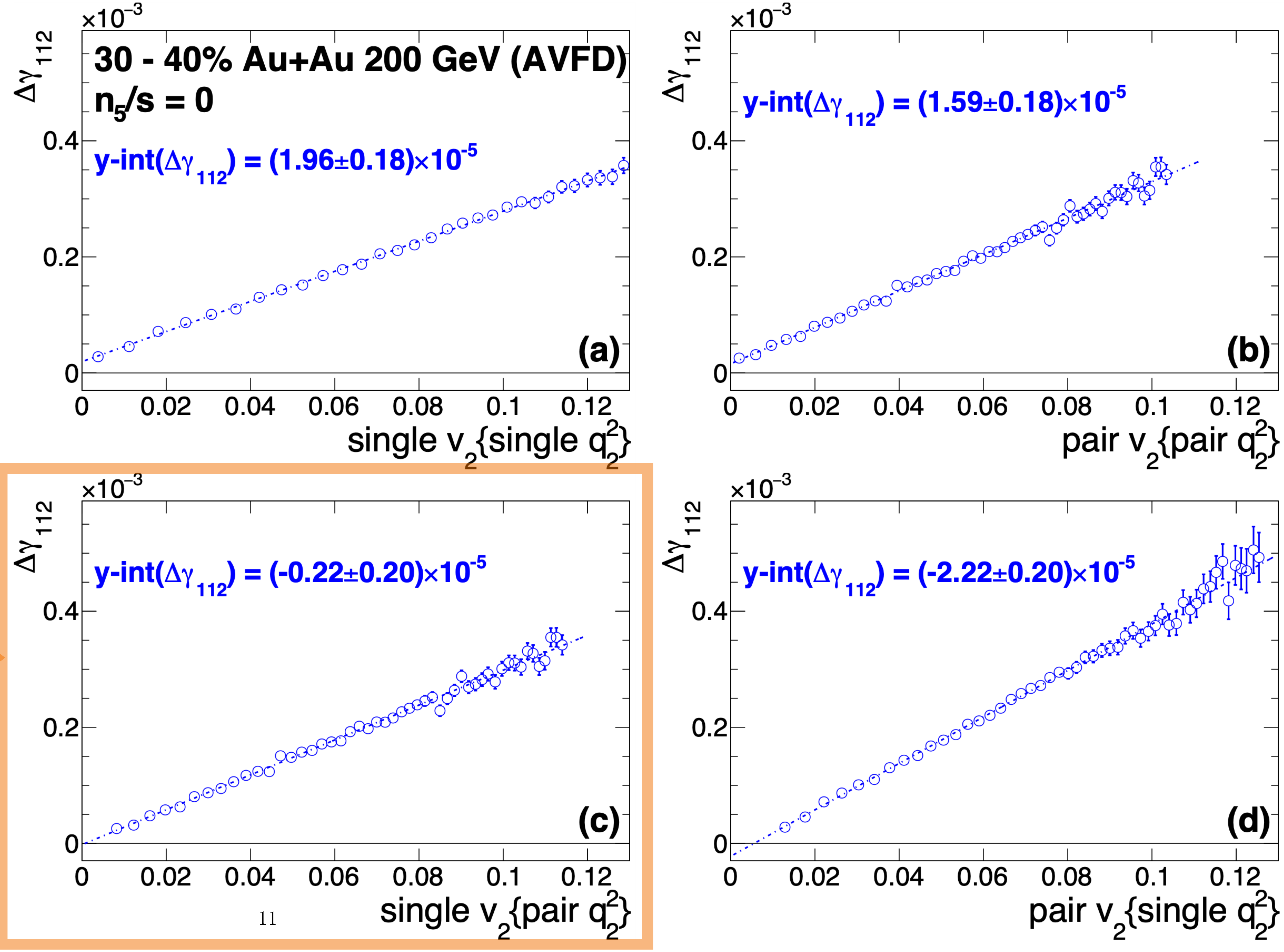


- **Unmixed recipes cause residual background near zero-flow region**
- **Mixed recipes have advantage that the v_2 and binning q^2 are less correlated.**
- **However, pair v2 contains true CME signal, which may lead to over subtraction.**

Scenario (c) – pair q^2, single v_2 is the optimal solution.

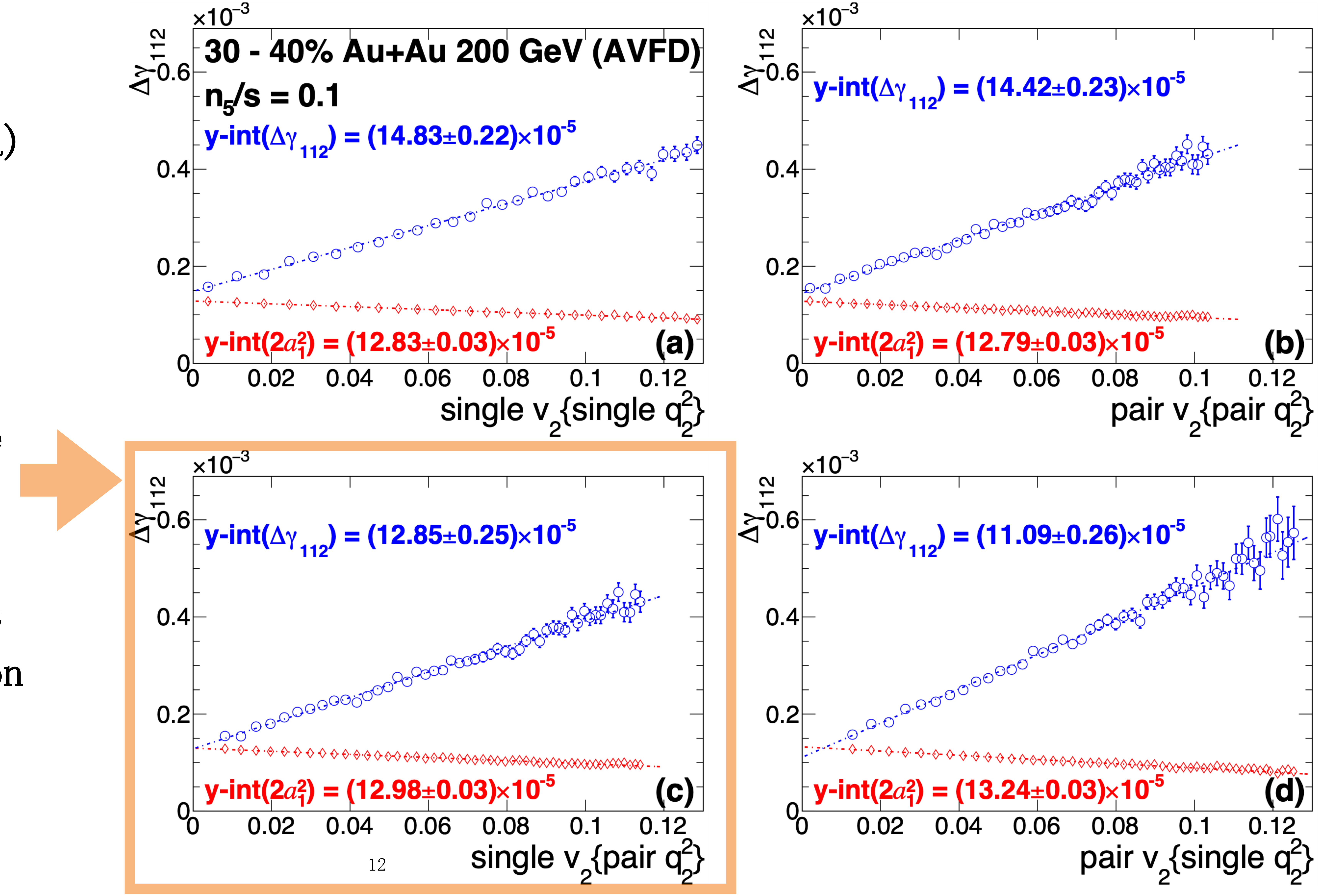
ESS for AVFD Events: $n_5/s = 0$ (pure BKG)

- AVFD model confirms possible residual background in (a) and (b) unmixed recipes.
- Mixed combination can remove residual BKG and predict over-subtraction in scenario (d)
- ESS (c) using single v2 and binning by pair q2 can well reproduce BKG.



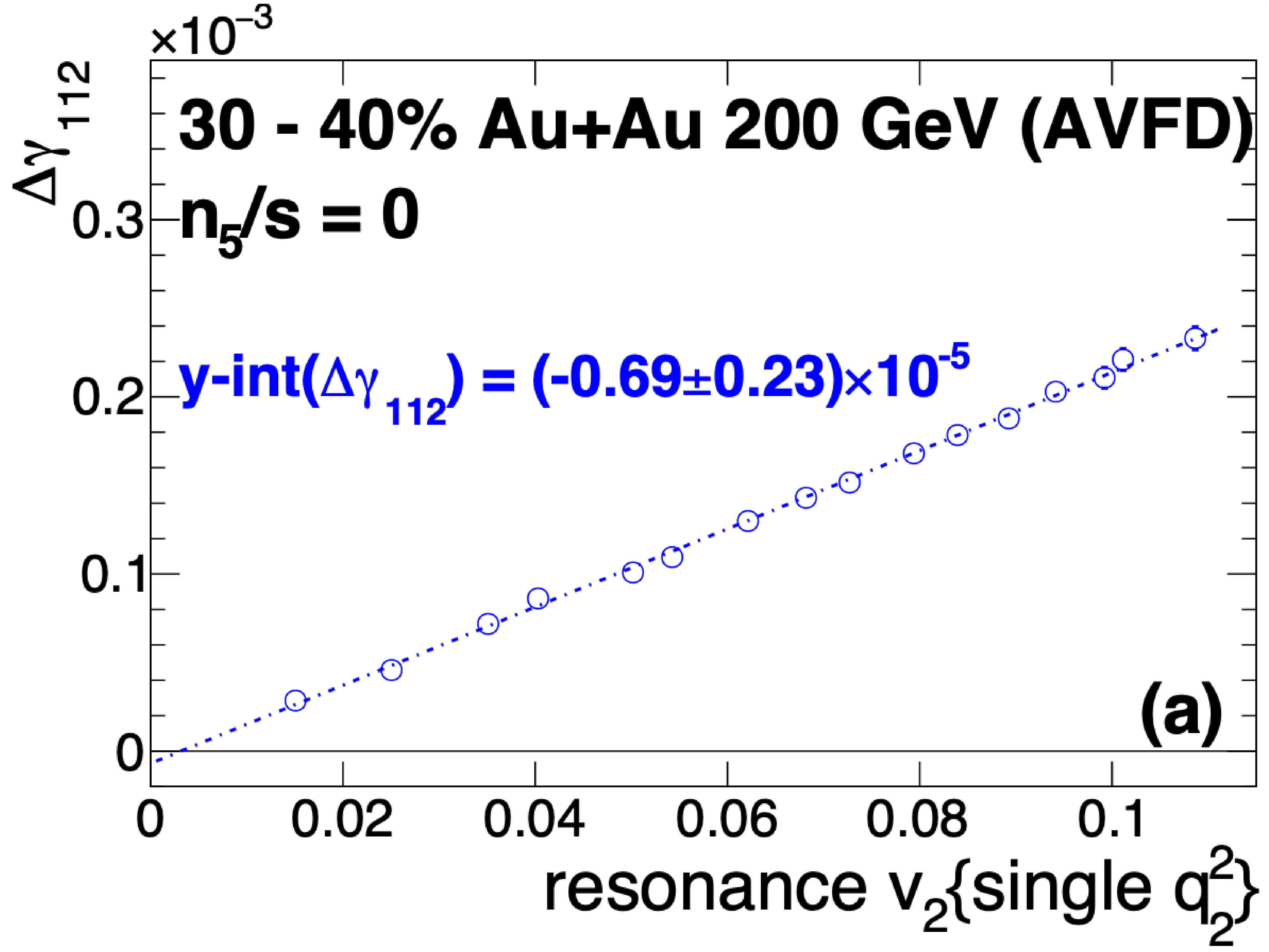
ESS for AVFD: $n_5/s = 0.1$ (moderate CME)

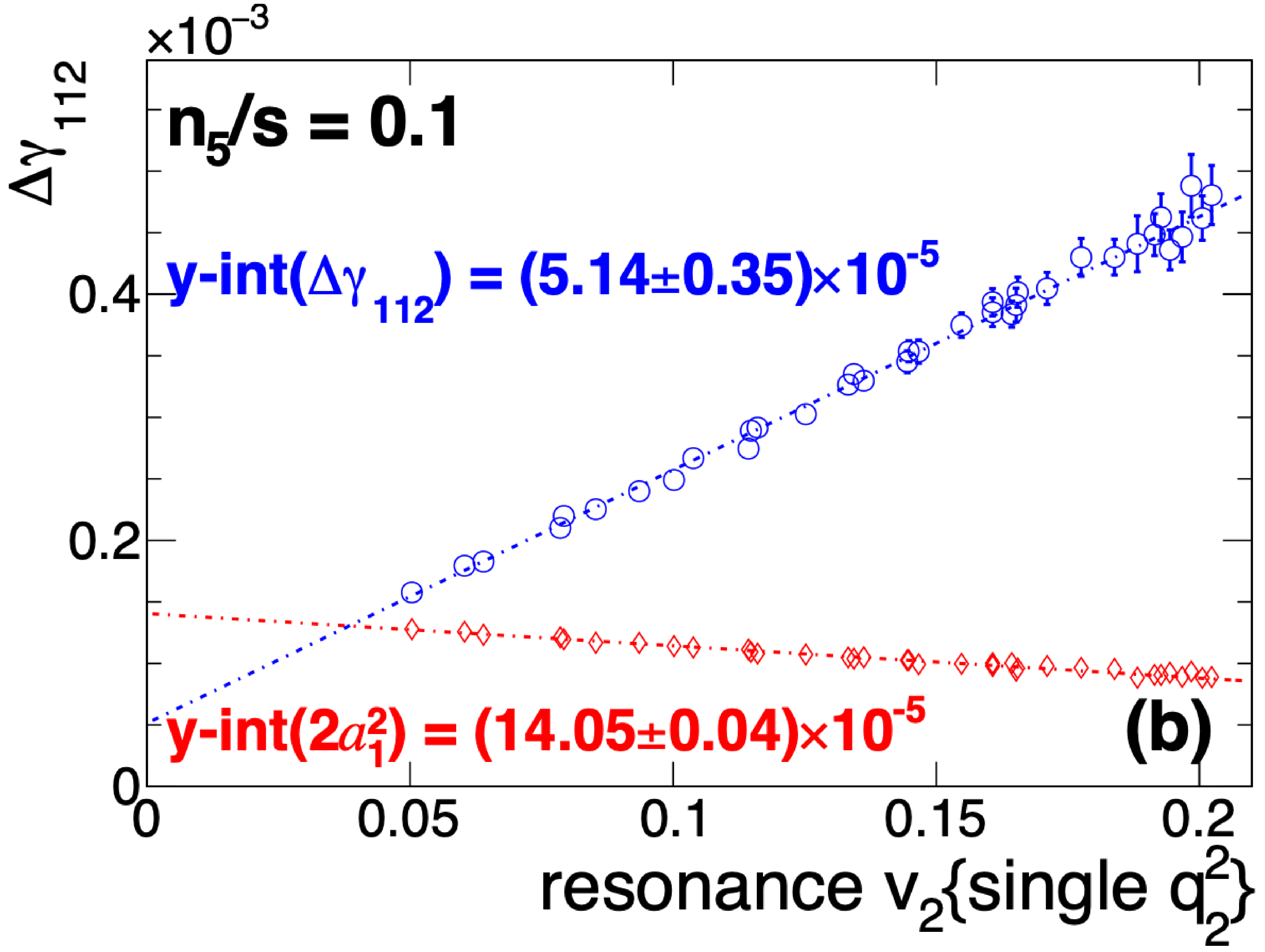
- With CME signal, residual background preserves in (a) and (b) unmixed recipes.
- AVFD confirms that ESS (c) suppress the residual BKG, and successfully match the true signal.
- Over-subtraction of BKG as predicted in (d) projection



Why Over-subtraction in ESS using v_2(resonance)

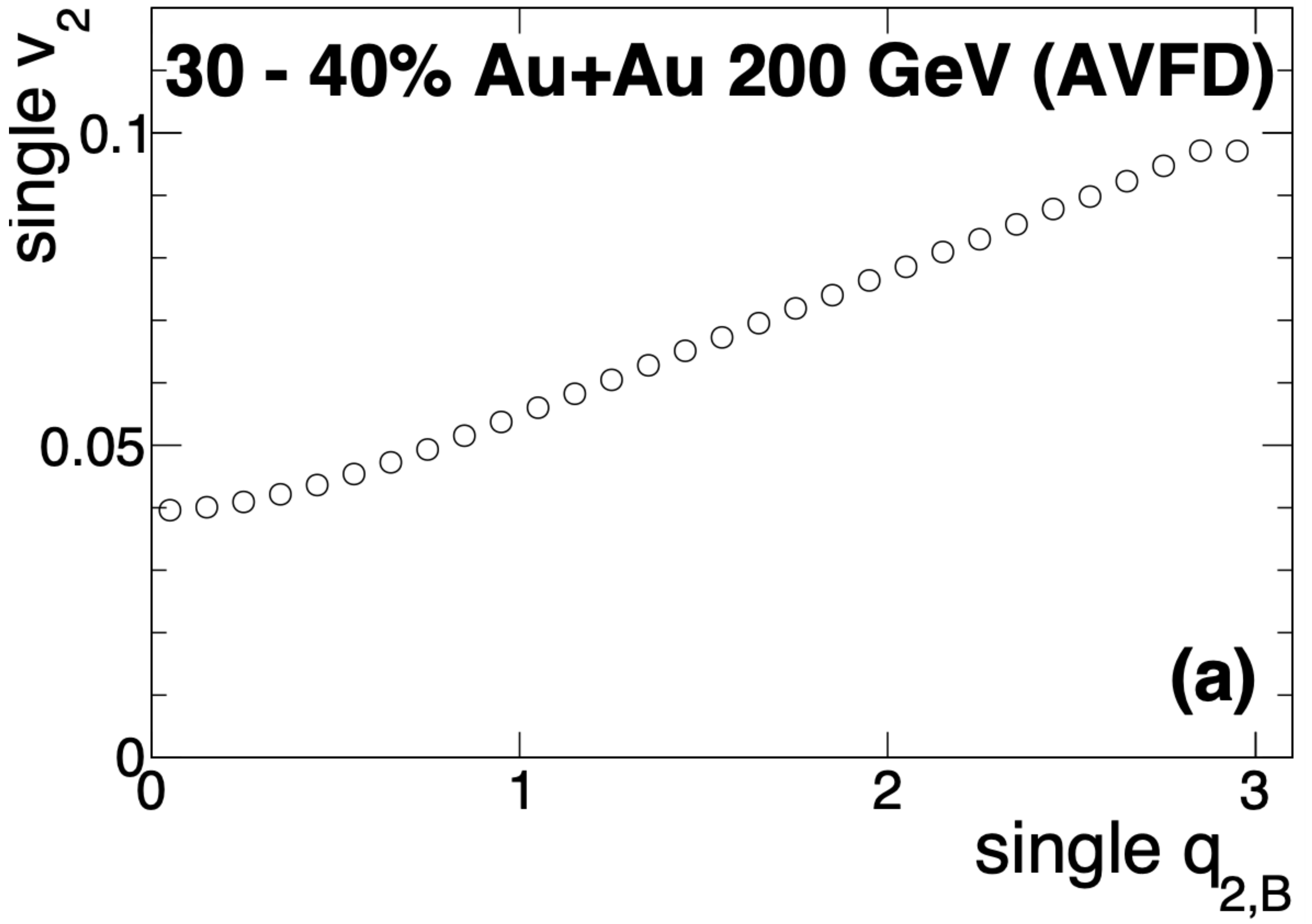
- Using v_2^{res} will cause severe over-subtraction.
- Explains that ESS (d) pair v2 that contains possible CME signal also cause over-subtraction.

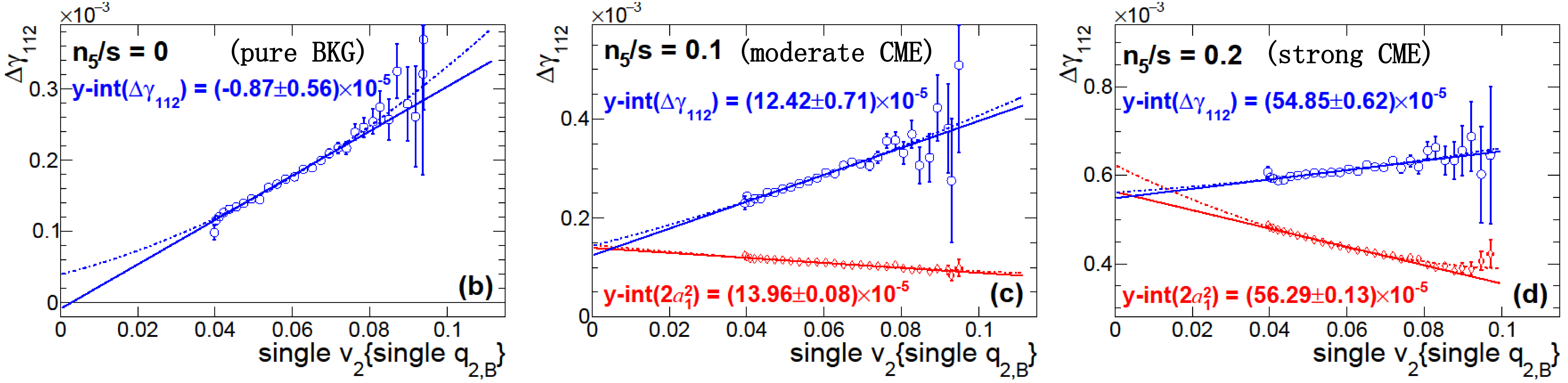




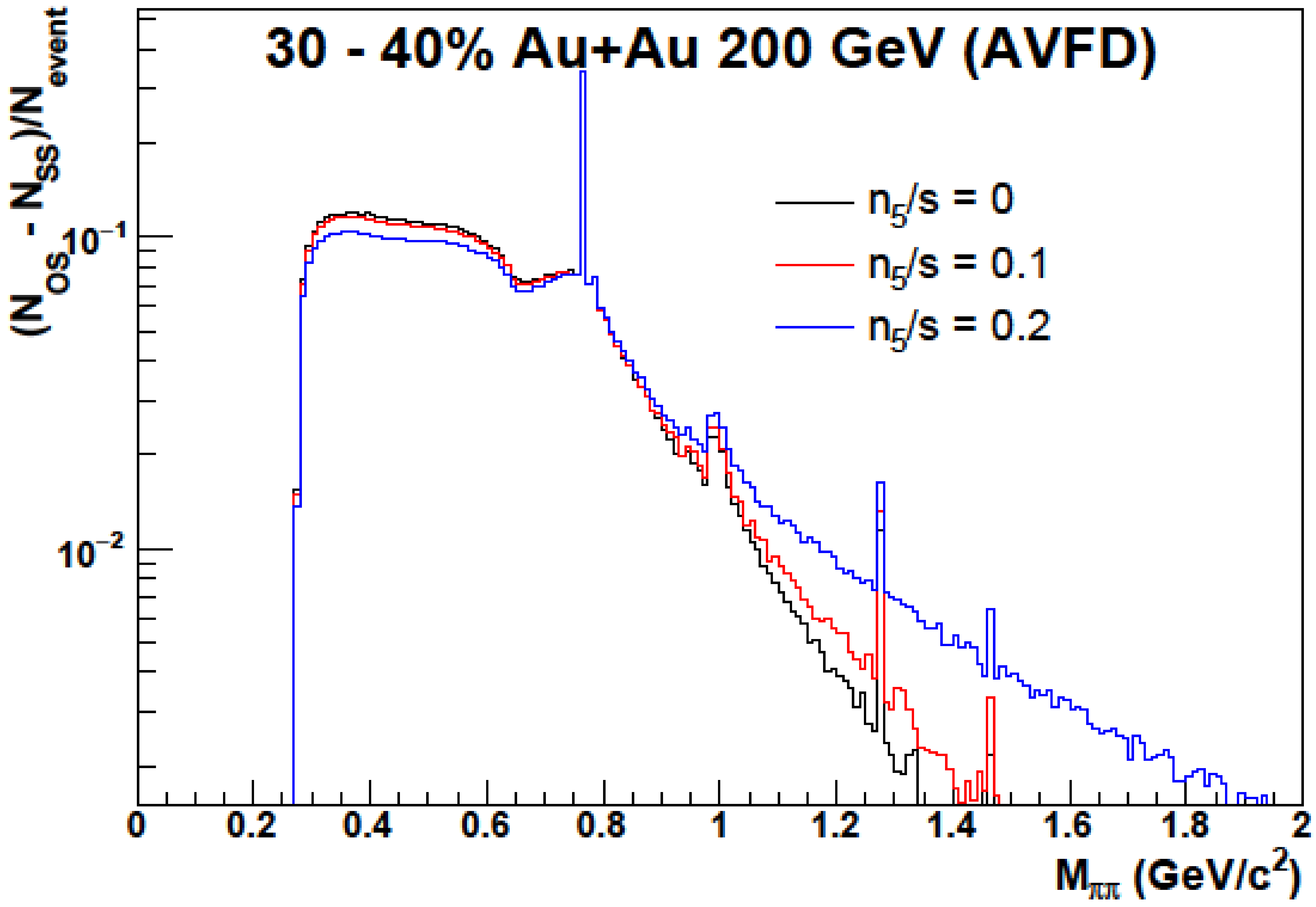
Using separate region Qb – Not Effective

- Separate region q_2 has weak correlation with the POI's v_2
- This cause a gap in $\Delta\gamma$- v_2 plot that leads to less reliable results:
  - Statistic errors are 3 times larger than ESS involving POI.
  - Systematic uncertainties demonstrated by 2nd-order polynomial have large variation, even exceed statistic errors.





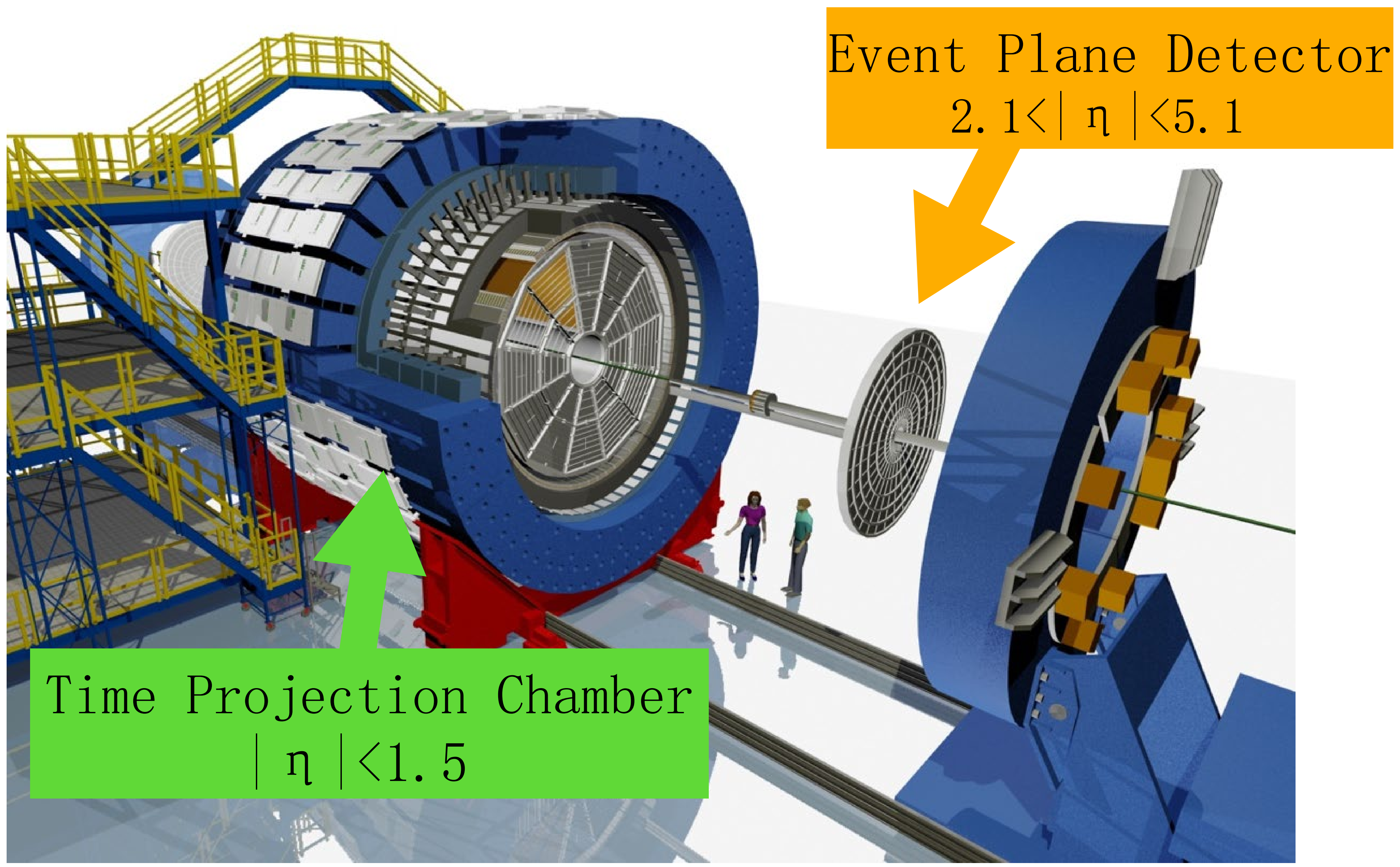
CME changes the invariant mass distribution



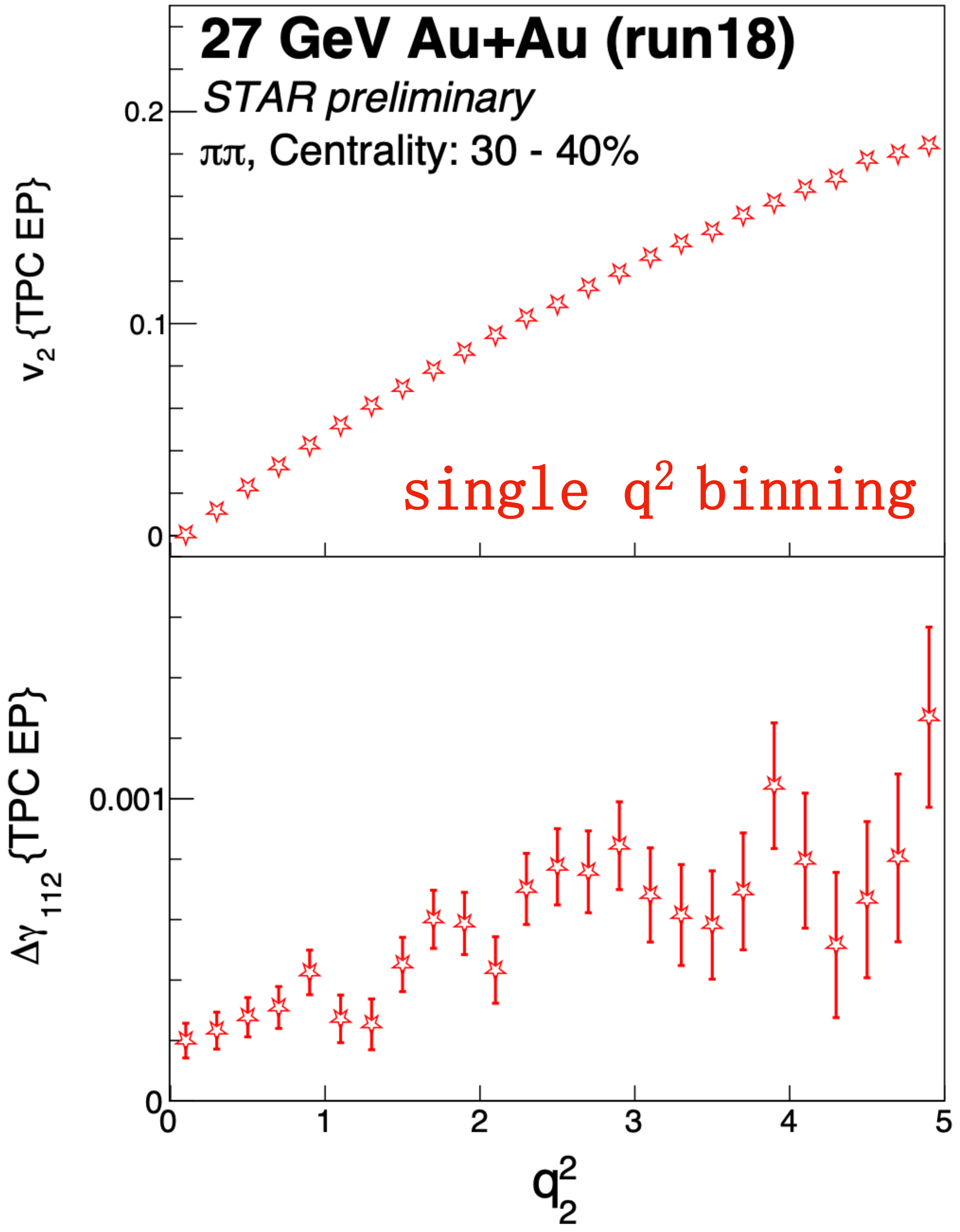
There is no clear region of signal vs background in invariant mass distribution

Application to STAR data

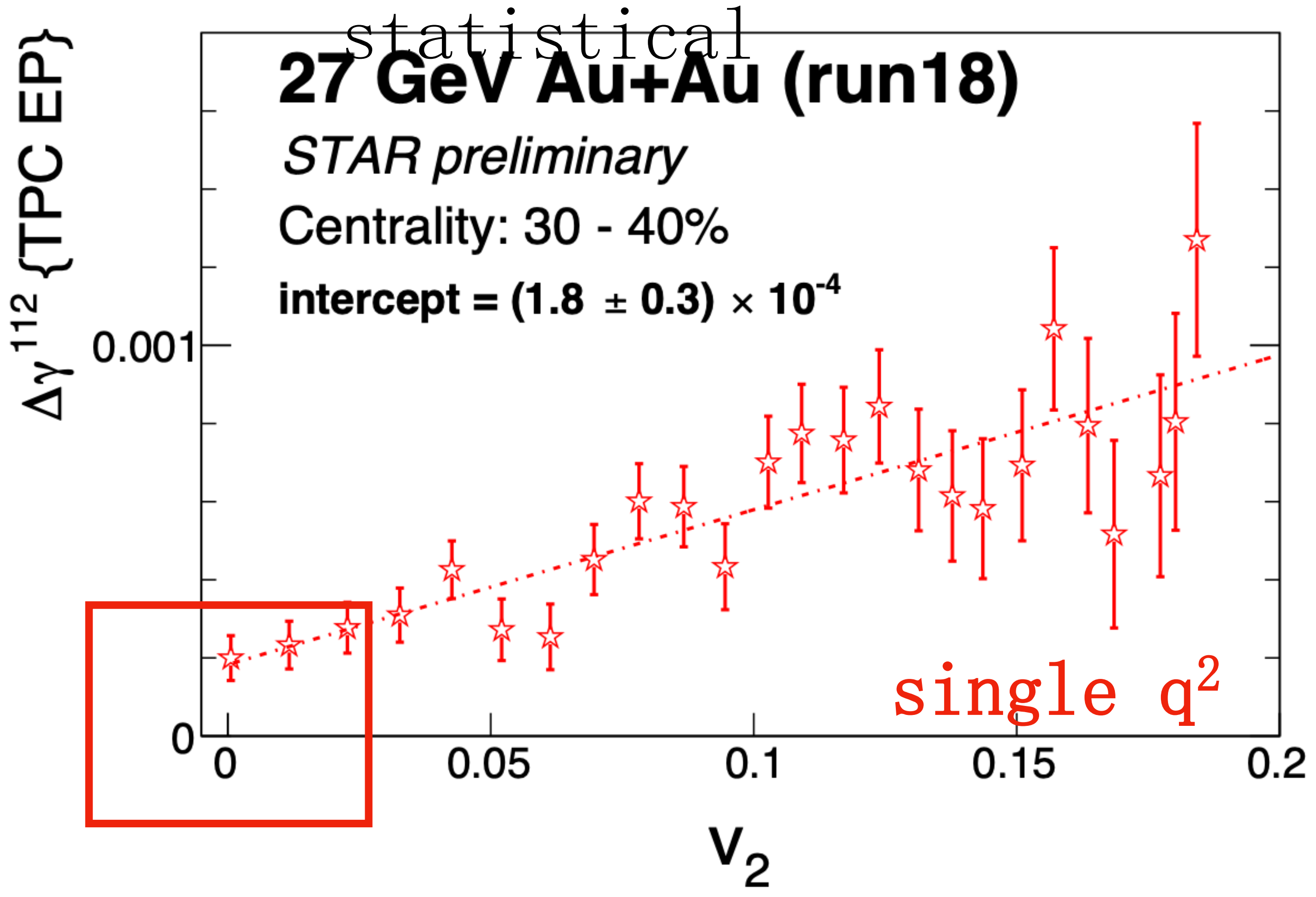
DNP2022. Z.Xu.

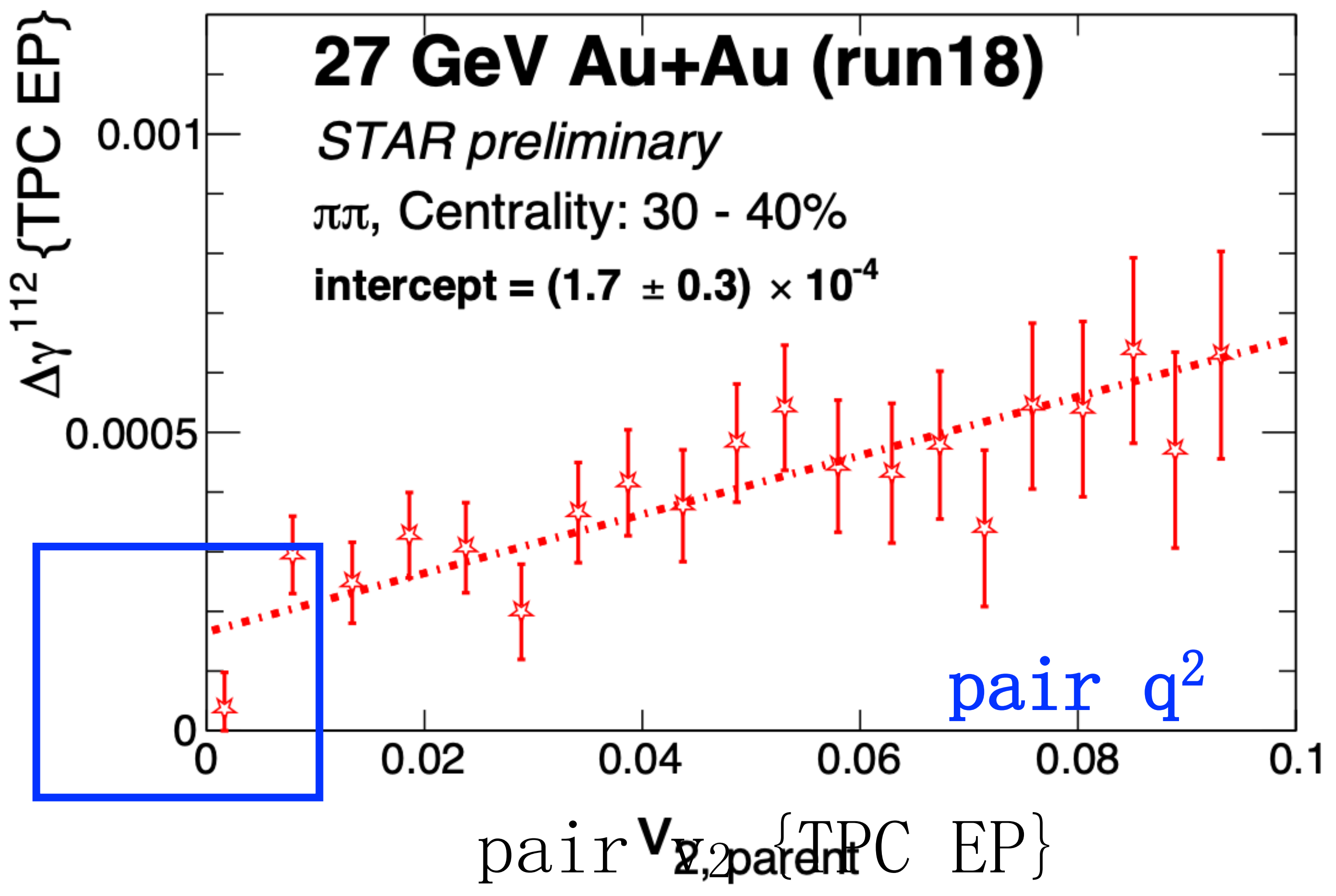


Current STAR detector



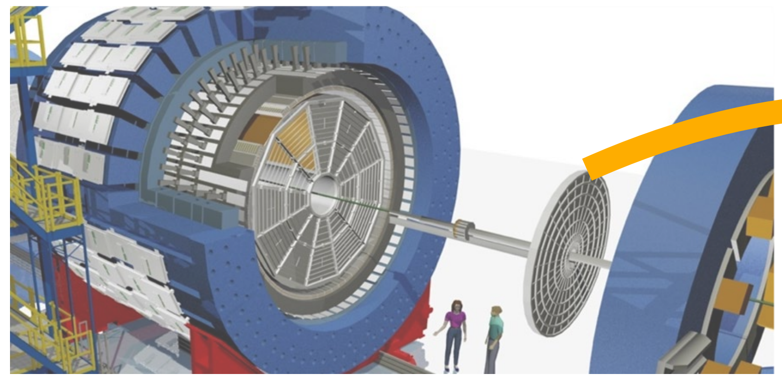
uncertainties are statistical





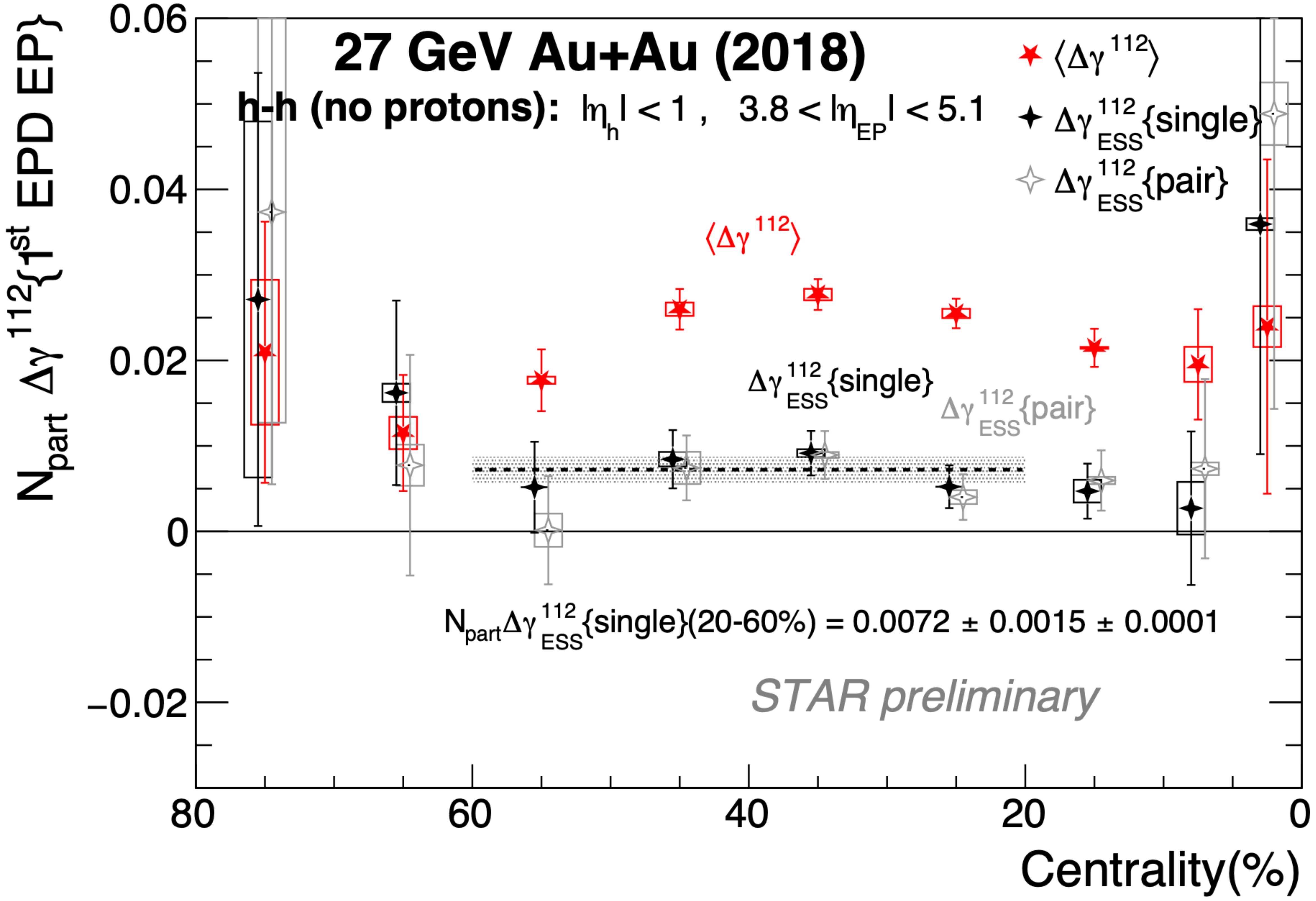
- Both ESS approaches can extrapolate $\Delta\gamma_{ESS}^{112} = (1 - 2v_2)\cdot$Intercept

27 GeV : EPD spectator plane

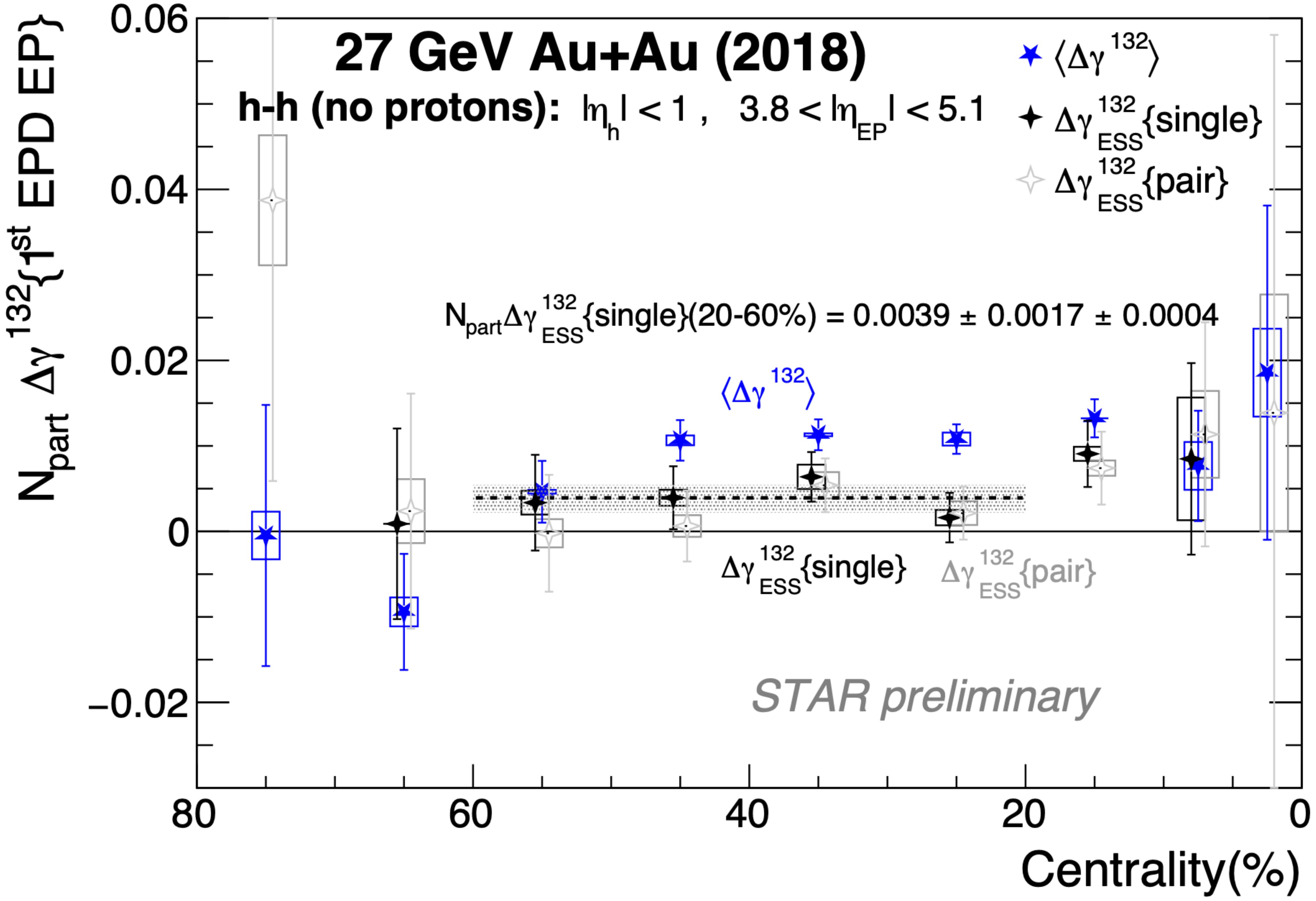


Event Plane Detector
2.1<|η|<5.1

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

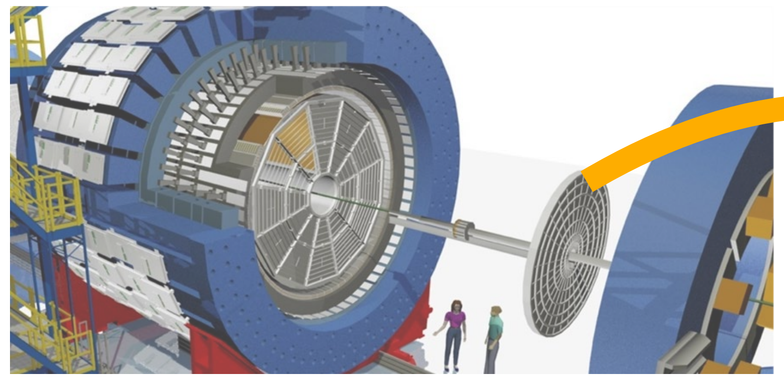


$\gamma^{132} = \langle \cos(\phi_1 - 3\phi_2 + \psi_{1,e} + \psi_{1,w}) \rangle$



- 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 for all centralities.
- The precision of STAR measurement after ESS is controlled to be 5.4% of ensemble average $\Delta\gamma^{112}$.

19.6 GeV : EPD spectator plane



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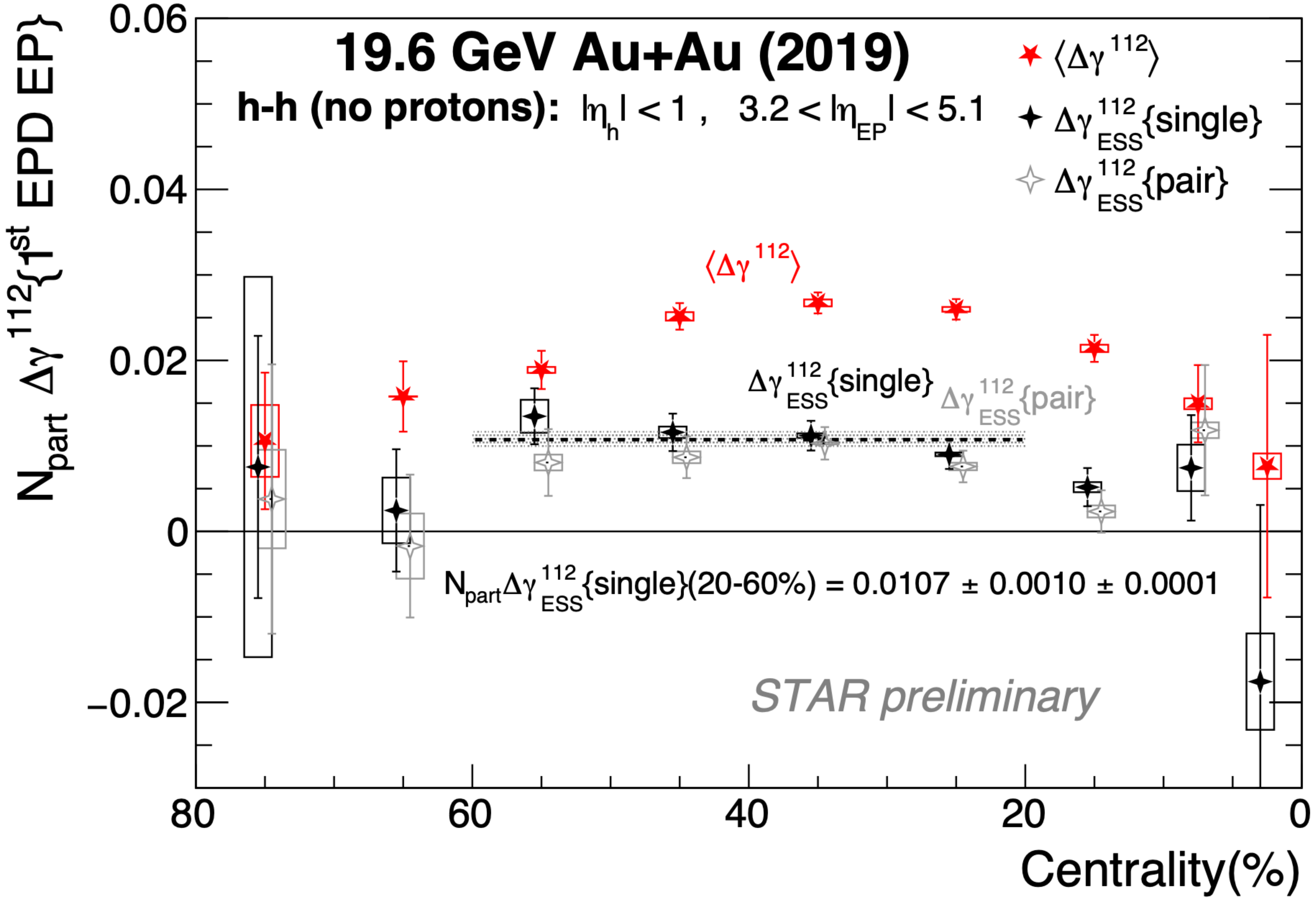
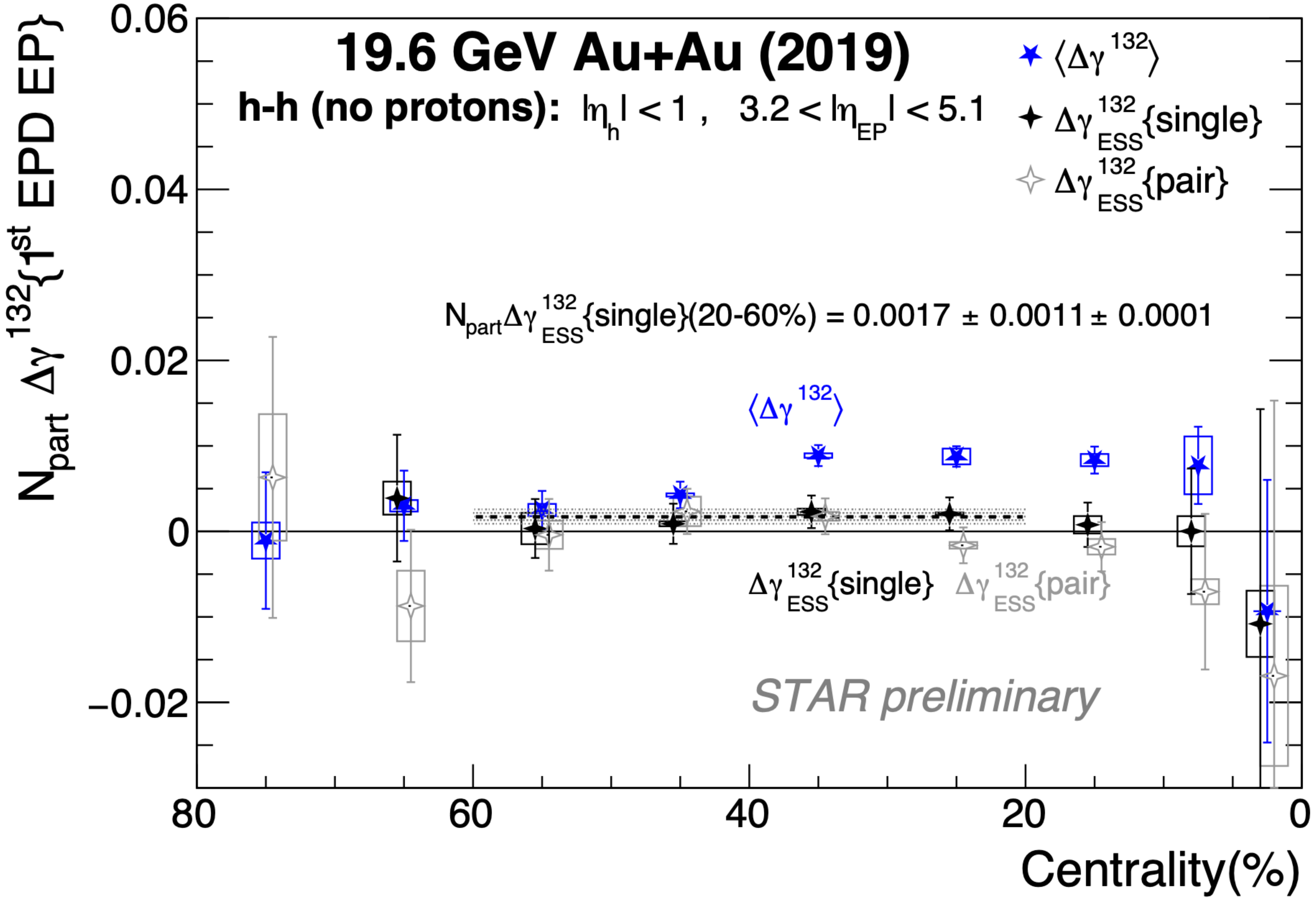
Event Plane Detector
2.1<|η|<5.1

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

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





- Spectator plane is more correlated to the magnetic field direction.
- Finite $\Delta\gamma_{ESS}^{112}$ in mid central events; $\Delta\gamma_{ESS}^{132}$ consistent with zero for all centralities.
- The precision of STAR measurement after ESS is controlled to be 3.6% of ensembled average $\Delta\gamma^{112}$.

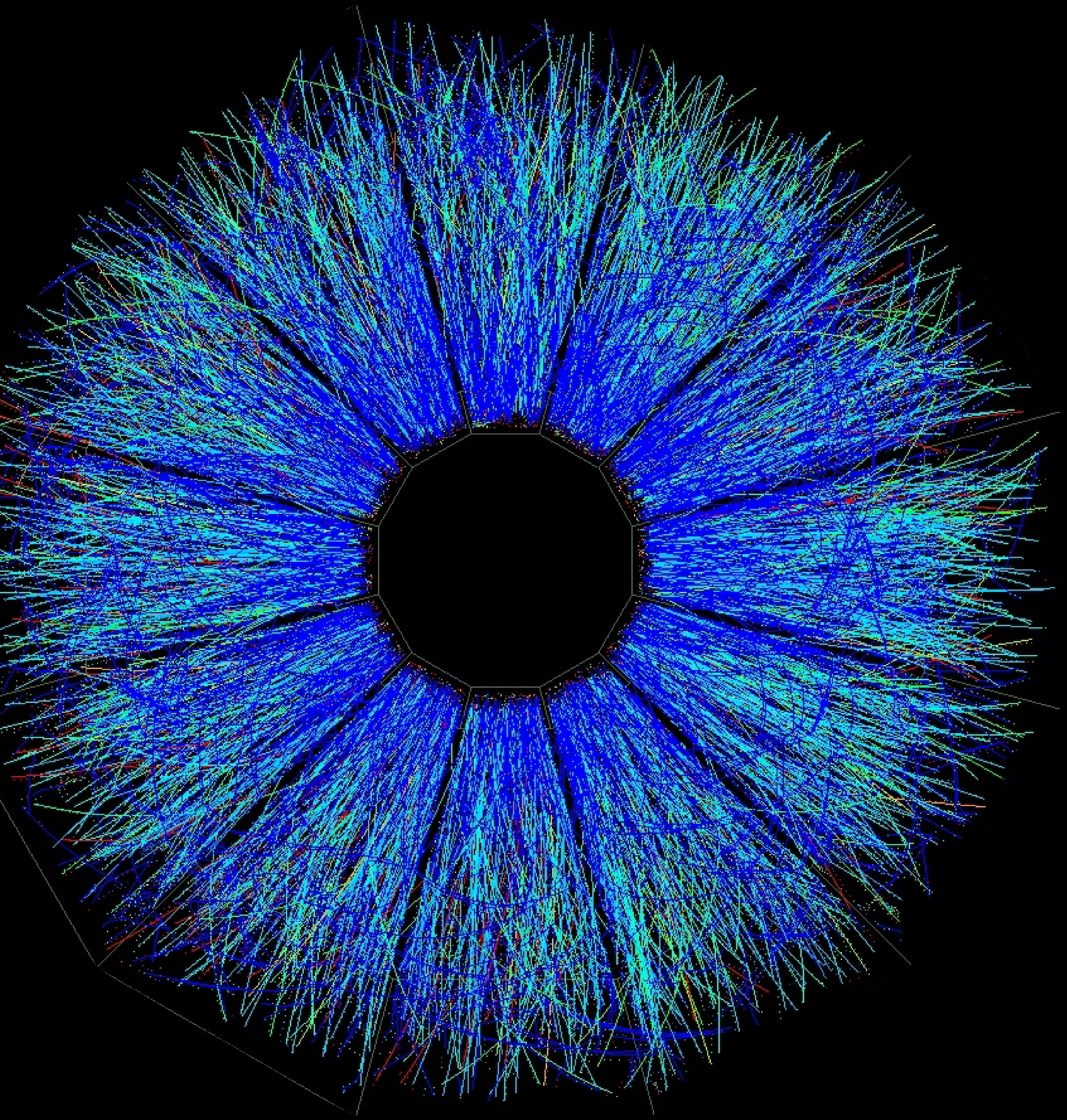
Perspectives

- Resonance v_2 turns out to be a CME sensitive observable
- We developed an optimized Event Shape Selection method —single v_2 and pair q^2, that utilize pair particle information to further suppress residual BKG
- We demonstrate that event shape selection (ESS) approach substantially suppresses (over five-fold) v_2 related backgrounds, enhancing the CME search sensitivity considerably.
- Using 1st-order EPD spectator plane, we can achieve a 4-5% precision in ESS measurement of $\Delta\gamma^{112}\{hh\}$ in RHIC' s BES-II data.

$$\boxed{\begin{aligned}&\Delta\gamma^{112}\\&=\underbrace{\Delta\gamma^{\mathrm{CME}}}_{\text{Signal}}+\underbrace{k\frac{v_2}{N}+\Delta\gamma^{\mathrm{non-flow}}}_{\text{Backgrounds}}\end{aligned}}$$

Measured

ESS spectator plane



Thank you!