Brookhaven National Laboratory

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

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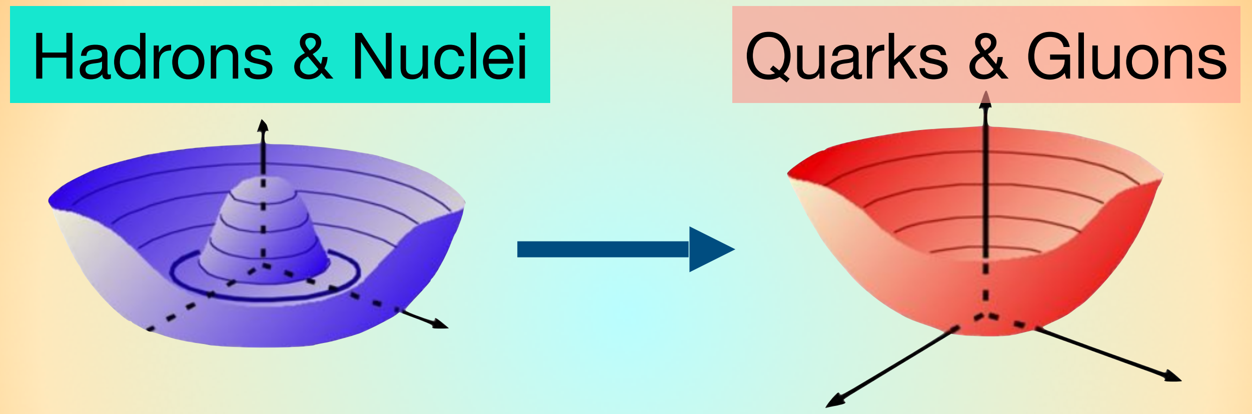
Nov 26, 2023

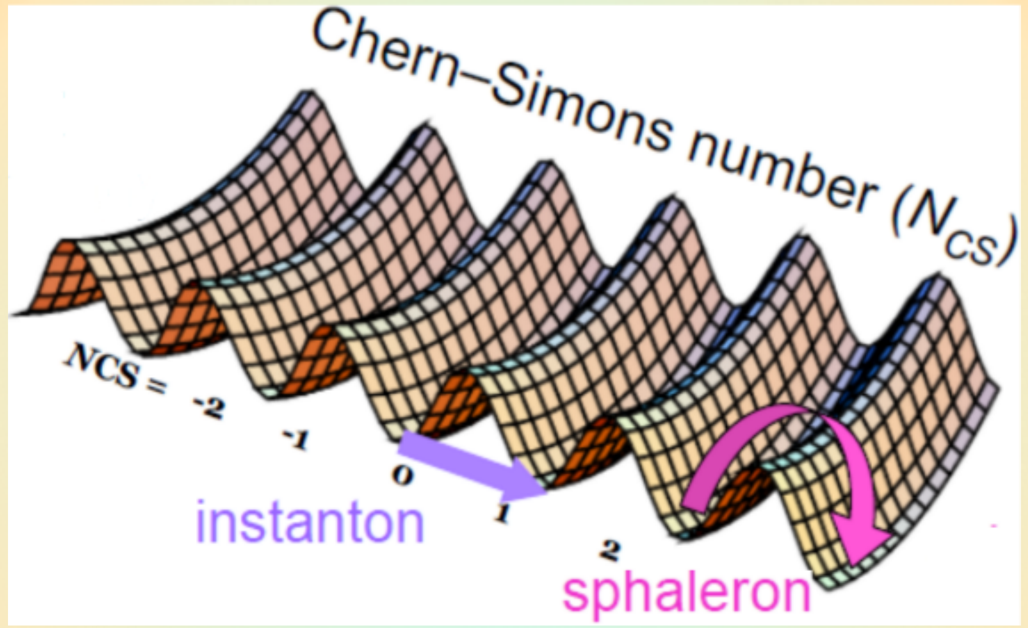
STAR

Chiral Magnetic Effect

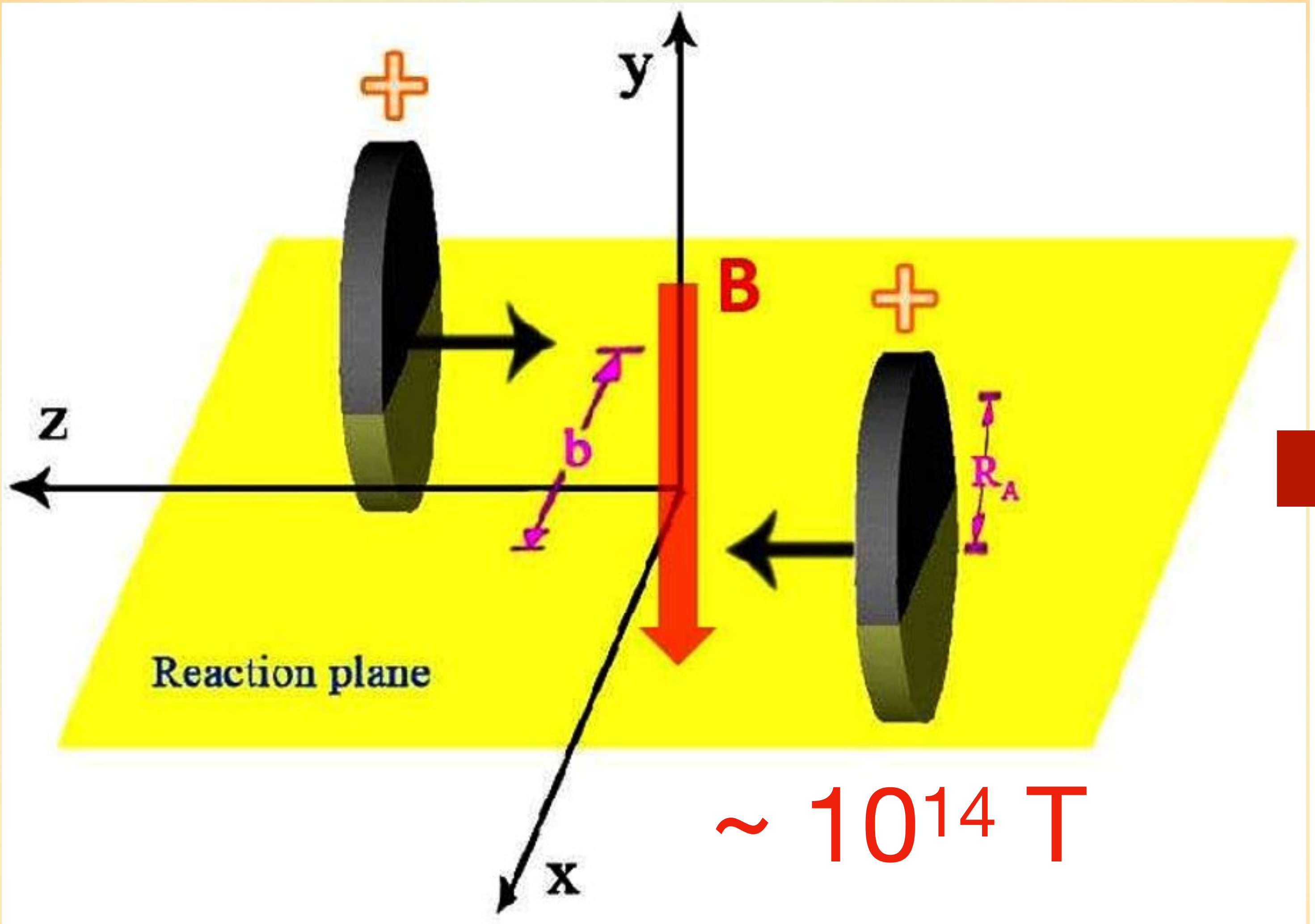
Kharzeev, Pisarski, Tytgat, PRL 81(1998) 512
Voloshin, PRC 70 (2004) 057901



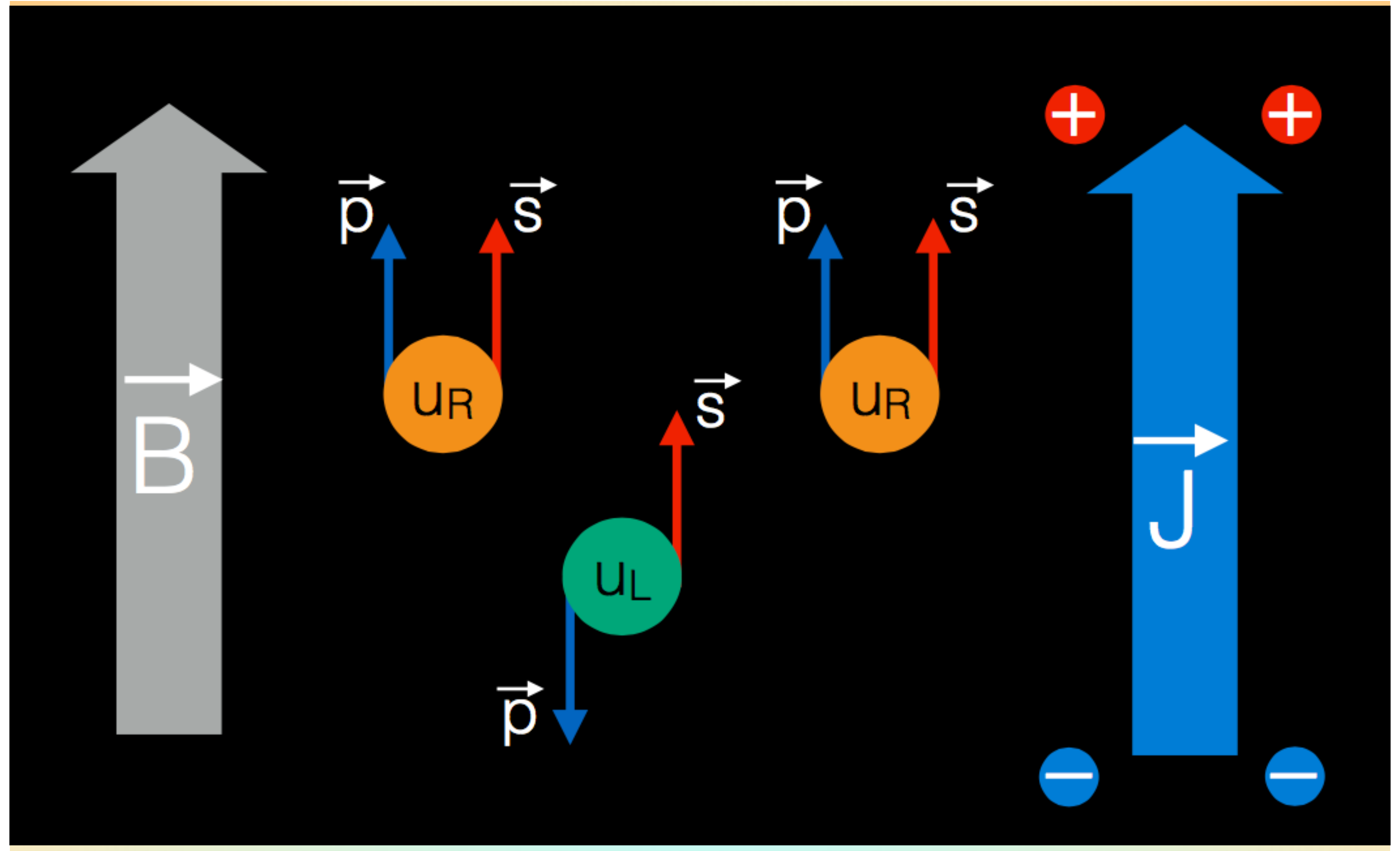
Chiral symmetry restoration (massless quarks)



Chirality imbalance (finite μ_5)



Strong magnetic field (B)



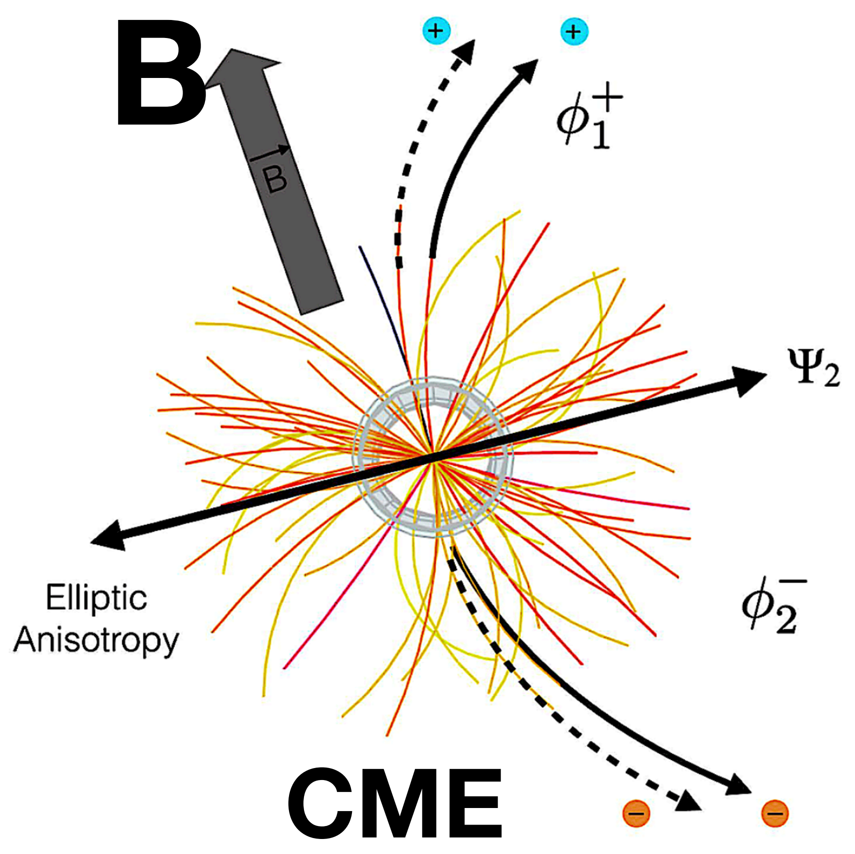
Chiral Magnetic Effect (J || B)

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

- **QCD vacuum transition leads to nonzero topological charge.**
- **Chirality imbalance of quarks coupled with strong magnetic field induces an electric charge separation along the B field direction (violates local Parity Symmetry and CP Symmetry!)**

Experimental Observables

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

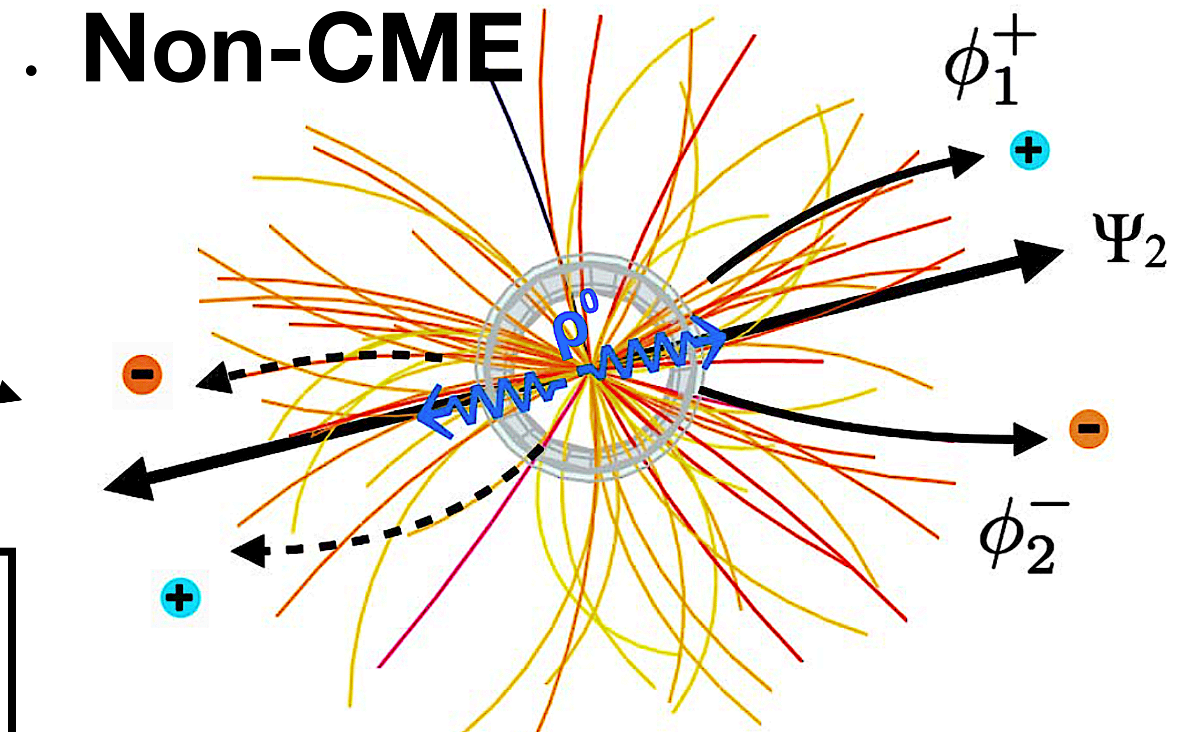


$$\frac{dN_\pm}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2a_1^\pm \sin(\varphi - \Psi_{RP}) + 2v_2\cos(2\varphi - 2\Psi_{RP}) + \ldots$$

Parity Odd, can not directly observe $\propto \mu_5 B$

Parity Even, sensitive to charge separation

Non-CME

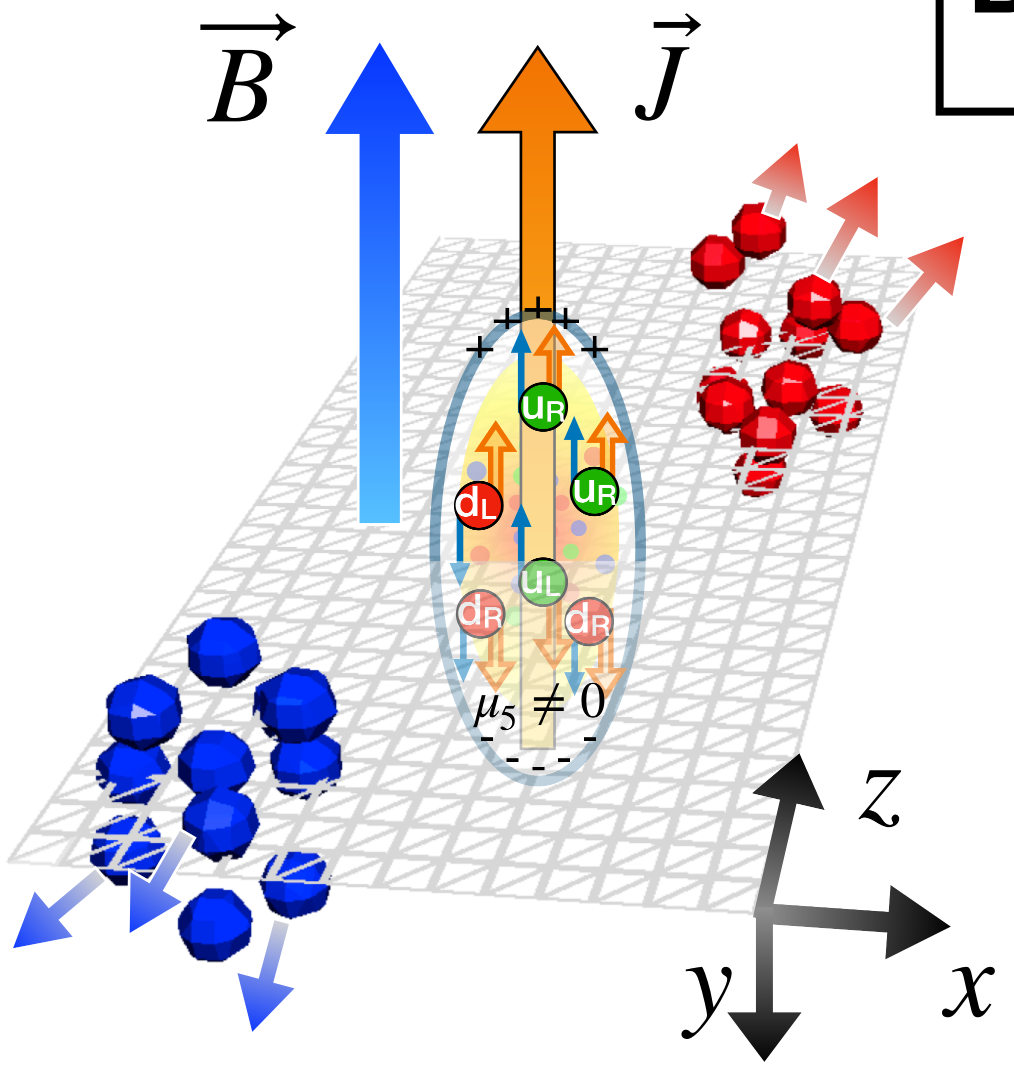


Flowing resonance decay

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

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

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



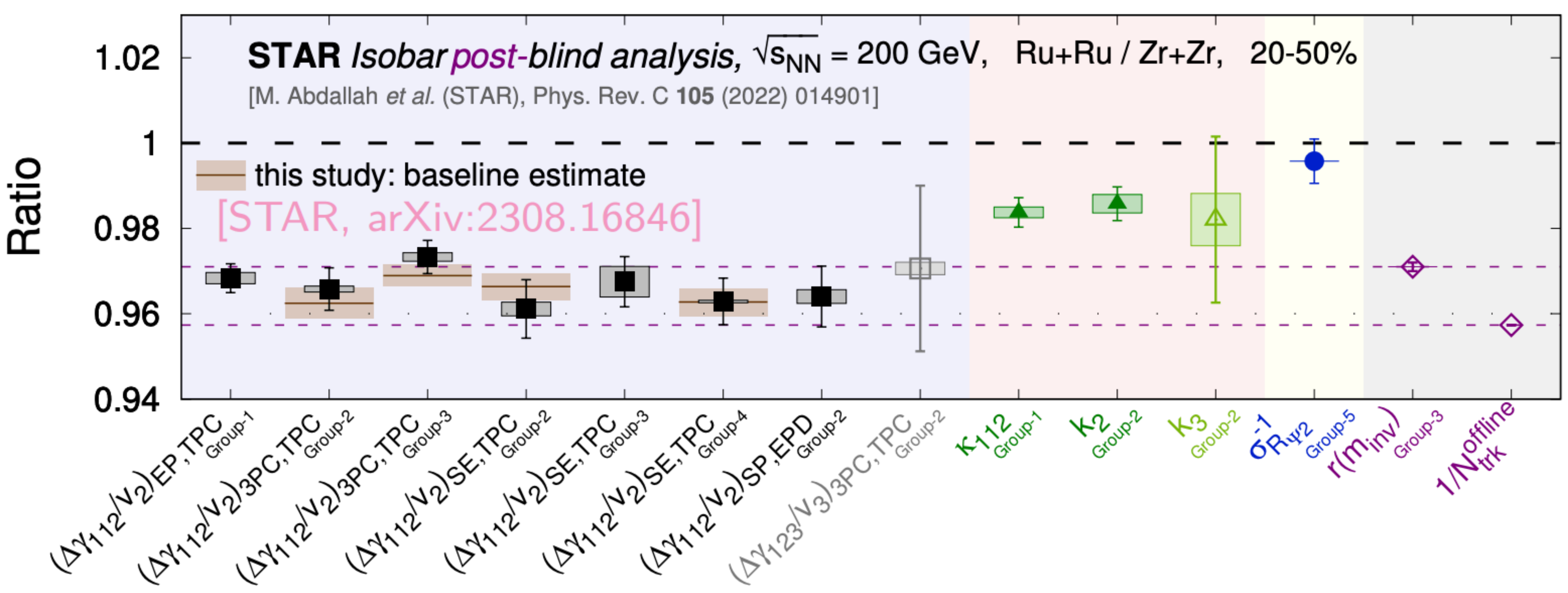
In experiment, Spectator Plane serves as a proxy for the Reaction Plane: $\Psi_1 \rightarrow \Psi_{RP}$

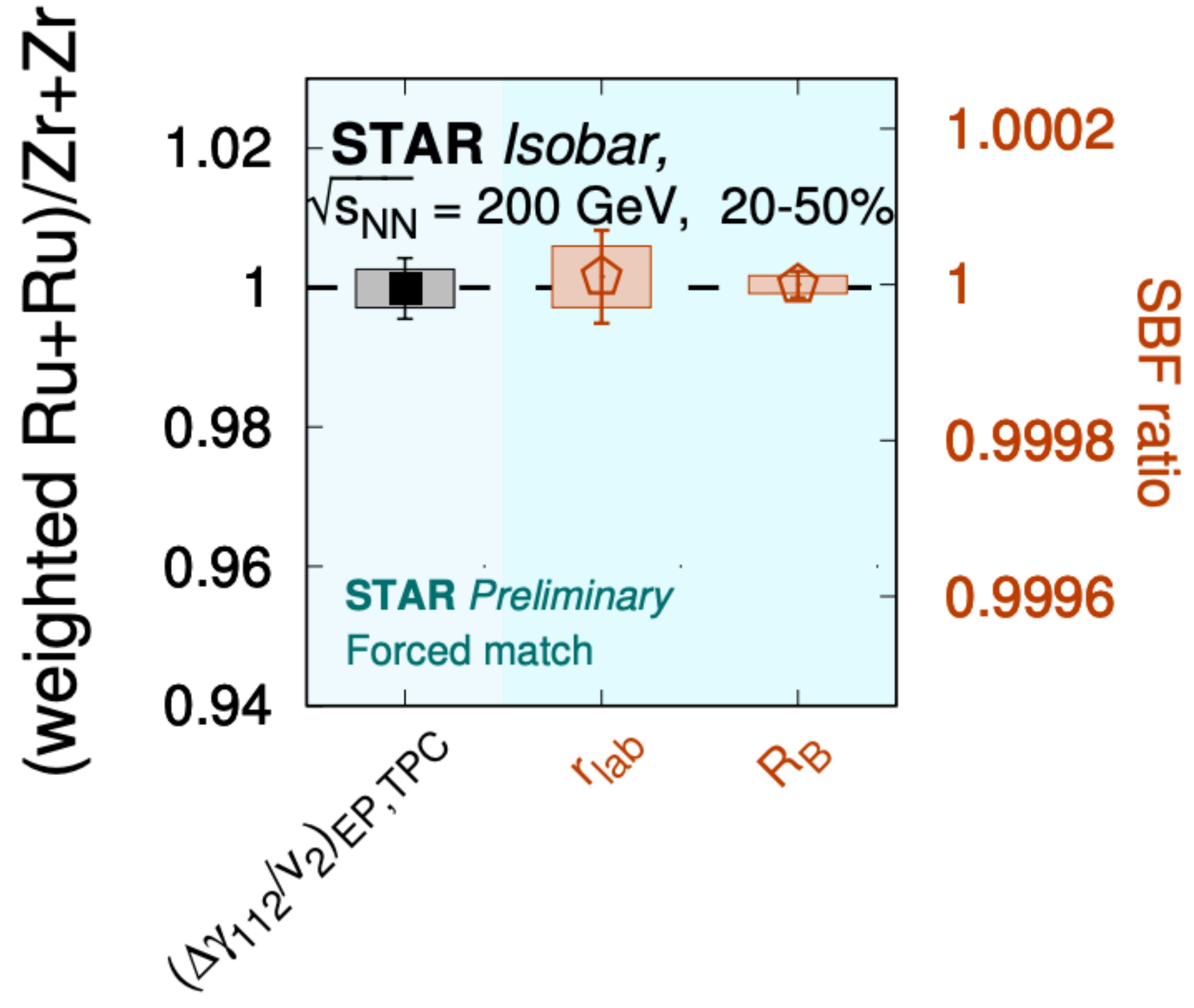
- **More correlated with the B field**
- **Minimizes the nonflow background**

To control the v_2-related BKG, various approaches have been developed.

Search for the CME in Isobar collisions

- Goal is to look for the signal difference in CME between isobar systems (Ru+Ru and Zr+Zr)





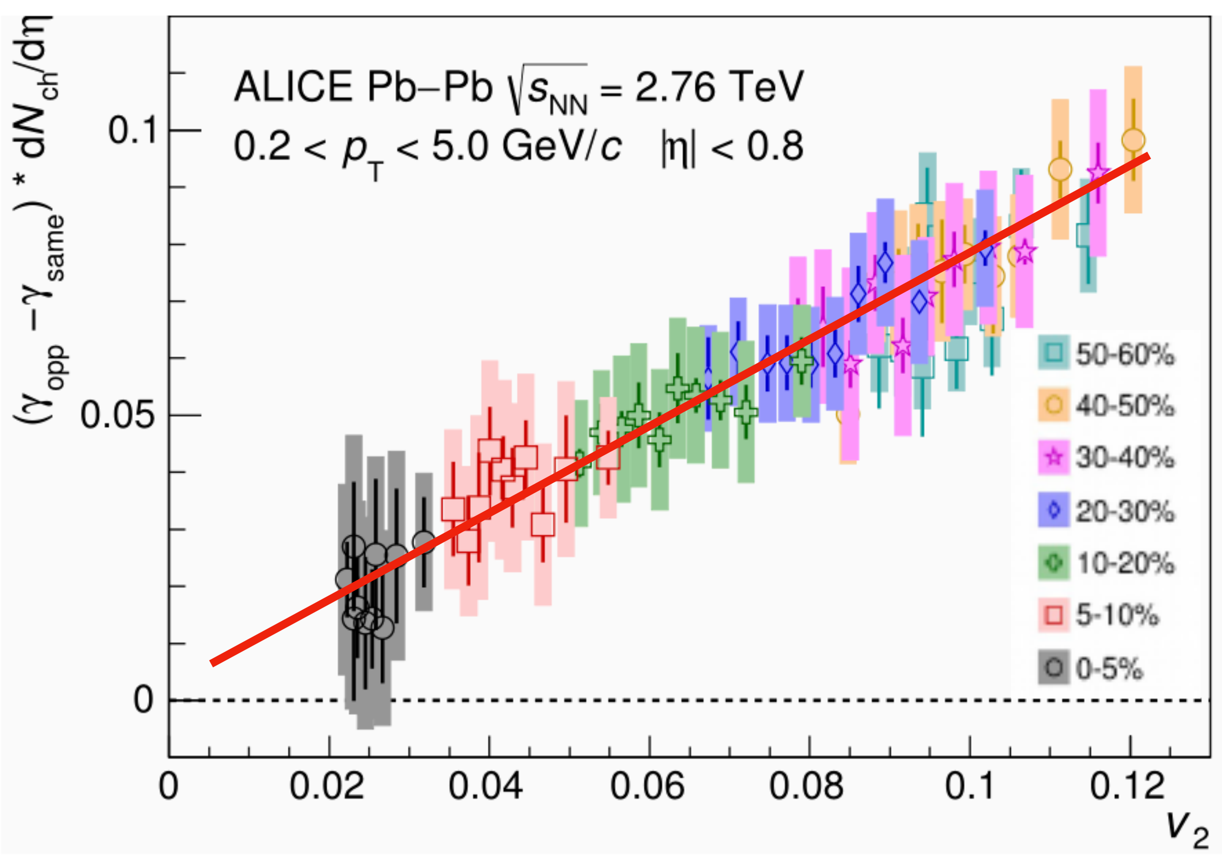
Lessons from Isobar blind analysis:

- The v_2-related background is large.
- The possible CME signal is small.
- Using participant plane (TPC) entails large nonflow BKG (can be avoided with spectator plane Ψ_1)

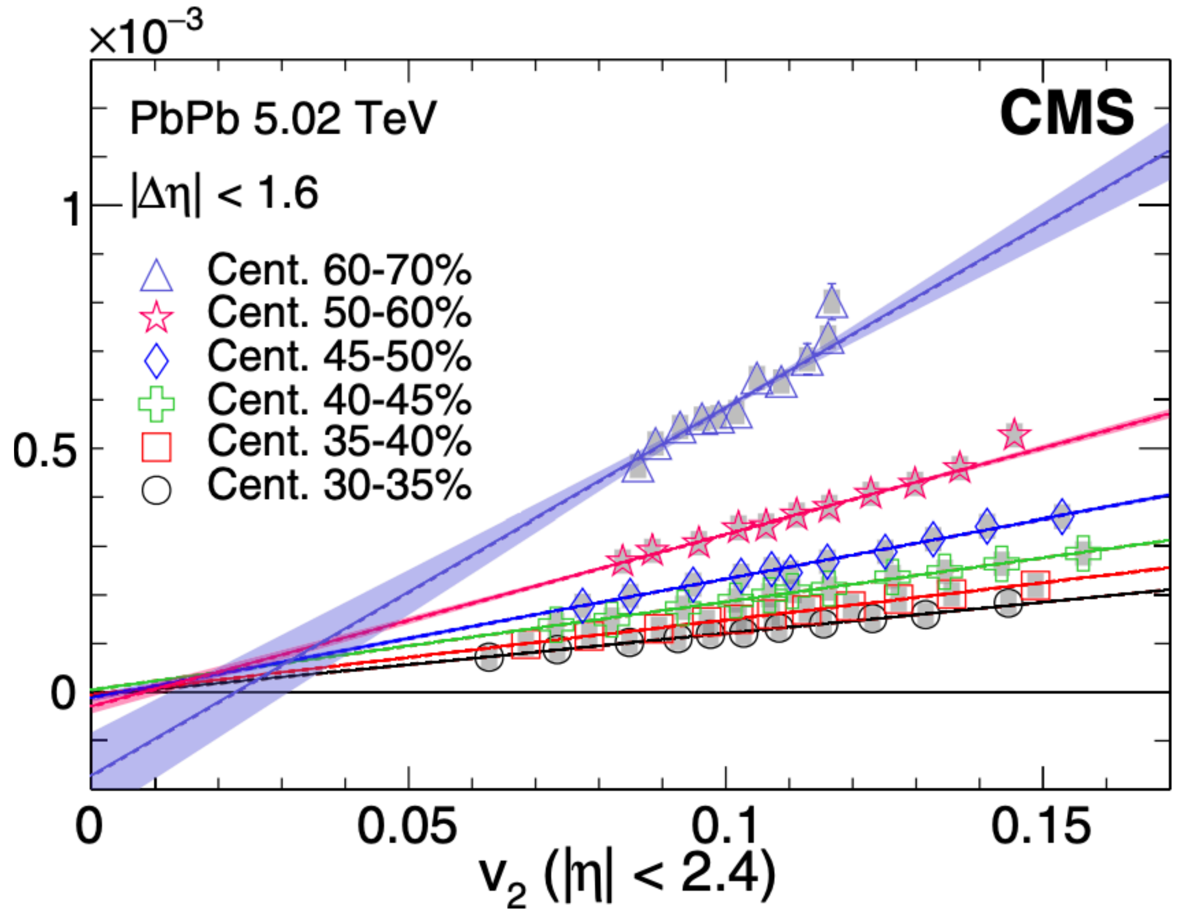
Search for the CME at LHC

- Goal is to extrapolate to zero-flow limit by categorizing events based on event shapes q_2 (non-POI) to control over eccentricity

ALICE, Phys. Lett. B, 777, 151 (2018)



CMS Phys. Rev. C 97, 044912 (2018)



Important points from ESE at ALICE and CMS:

- At LHC energies, $\Delta\gamma^{112}$ could be explained by v_2 related BKG.
- Event Shape Engineering (ESE) based on variables excluding POI is unstable.

Why Search for the CME with Au+Au Beam Energy Scan?

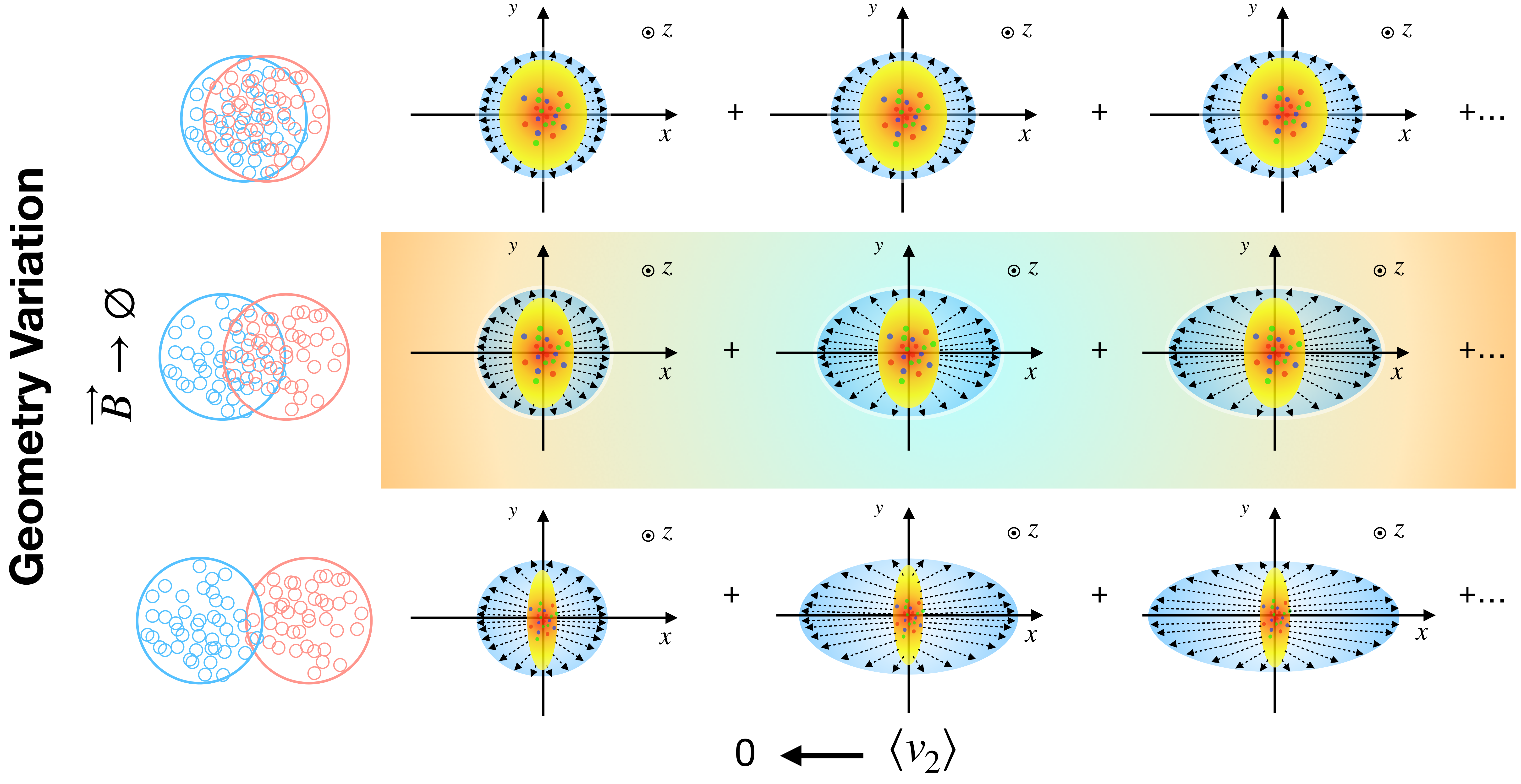
- Prerequisites for CME changes with energy. Advantage: longer lasting B field.
- Possible to see the turn-off effect where QGP signatures vanishes
- We need a more effective method to mitigate v_2-BKG.

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 range in rapidity**
- **emission pattern fluctuations – more localized, less correlated over rapidity**



Emission pattern fluctuation

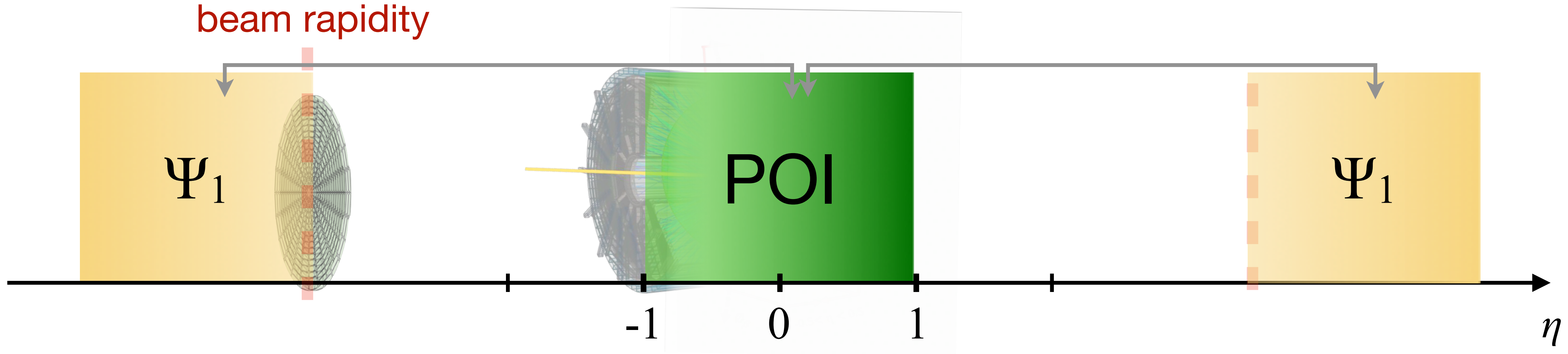
Data experience large event-by-event fluctuations - main contribution

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

Event Shape Selection

Z. Xu et al, arXiv:2307.14997

- Goal is to directly extrapolate to zero-flow limit by utilizing event shapes of POI that are **sensitive to both emission pattern and geometry**



Event shape variable | **Elliptic flow variable**

Flow vector

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

(a)

single q^2 (POI) — single v_2 (POI)

pair q^2 (POI) — pair v_2 (POI)

(b)

(c)

(d)

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

$$\varphi_p = \tan^{-1}\frac{p_{T,1}\sin\varphi_1 + p_{T,2}\sin\varphi_2}{p_{T,1}\cos\varphi_1 + p_{T,2}\cos\varphi_2}$$

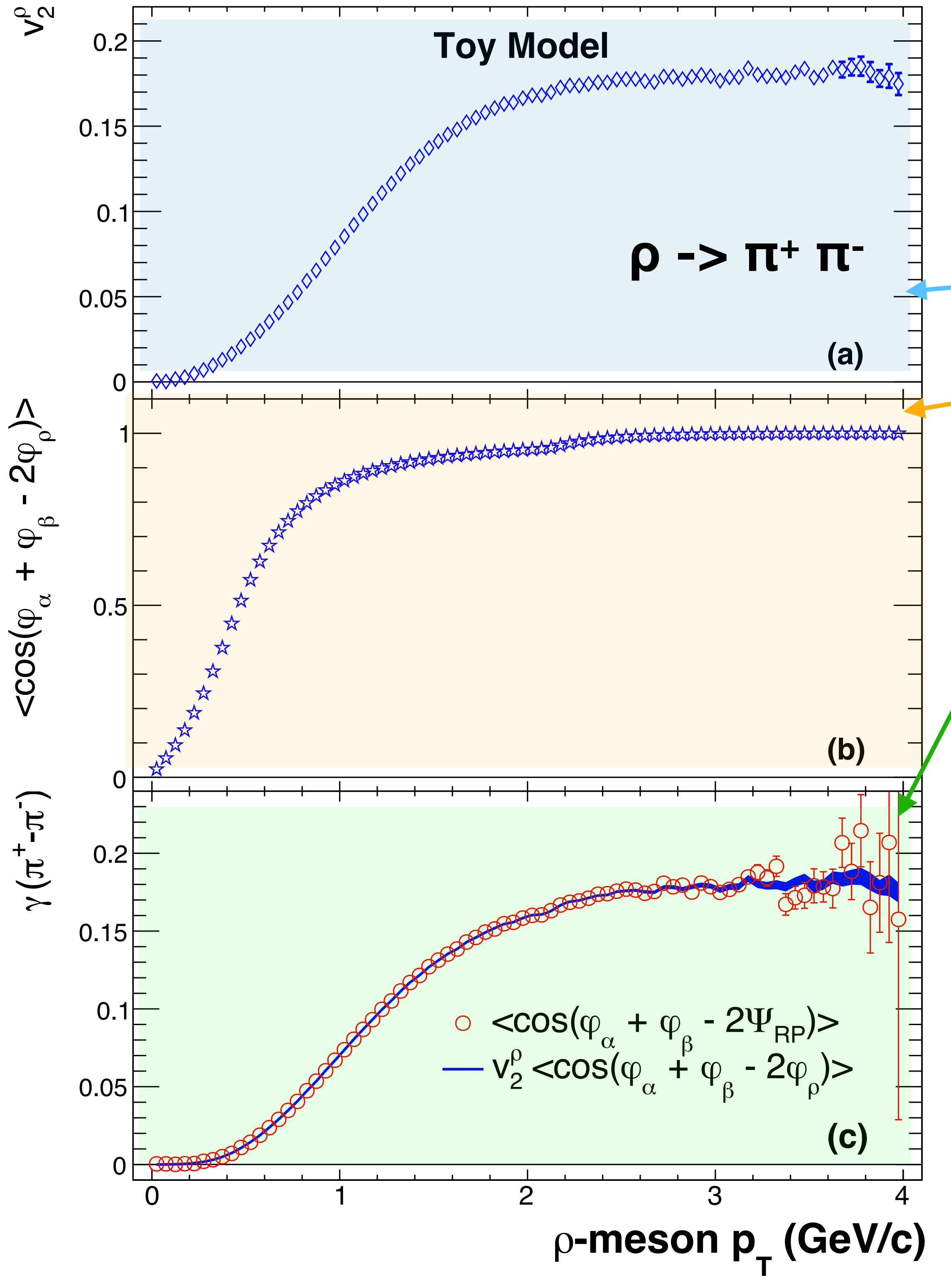
Event Shape Selection — **Spectator Ψ_1**

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

Measured — **Signal** — **Backgrounds**

Flow background in the CME measurement

Z. Xu et al, arXiv:2307.14997



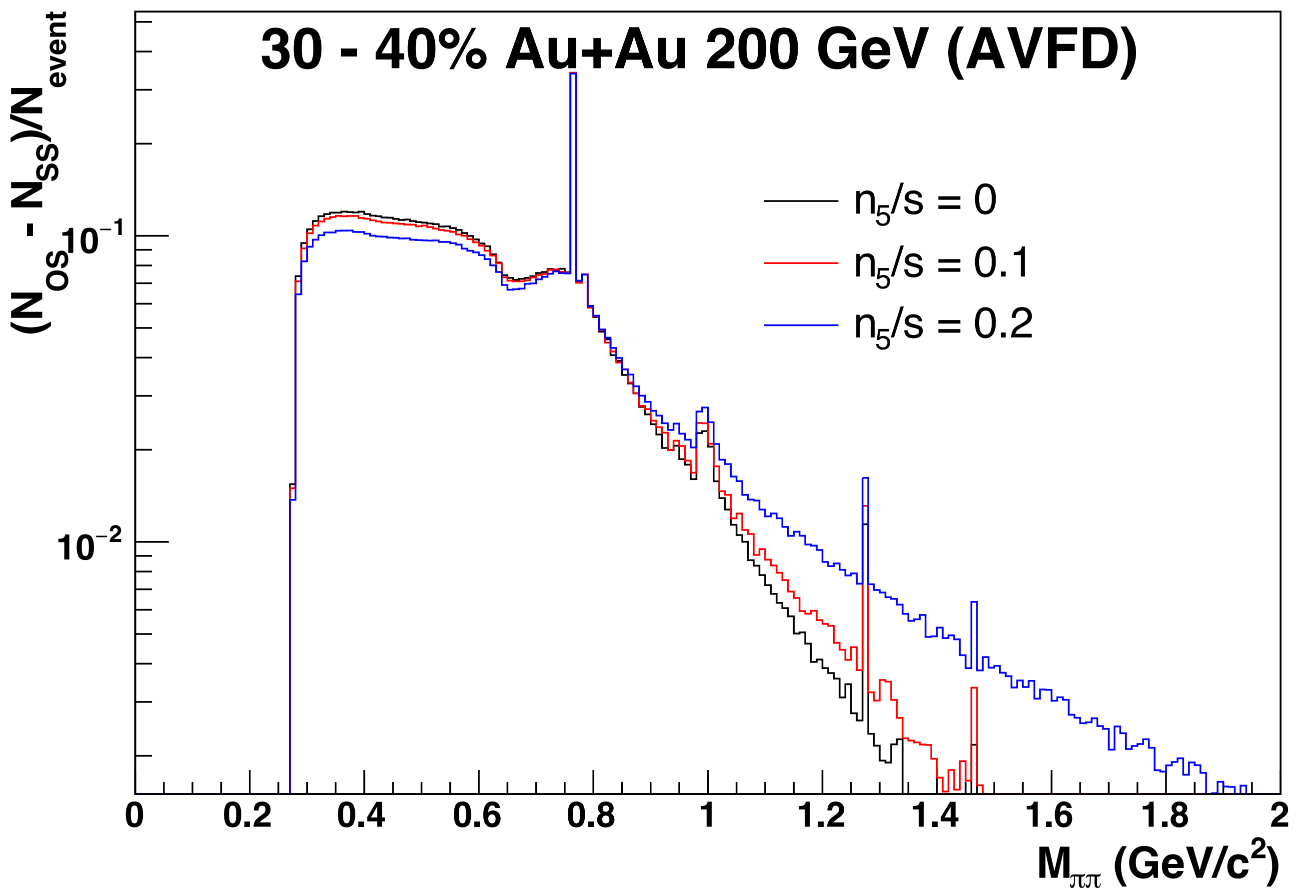
- **The BKG from flowing resonance decay in Δγ is well-represented by the relation**

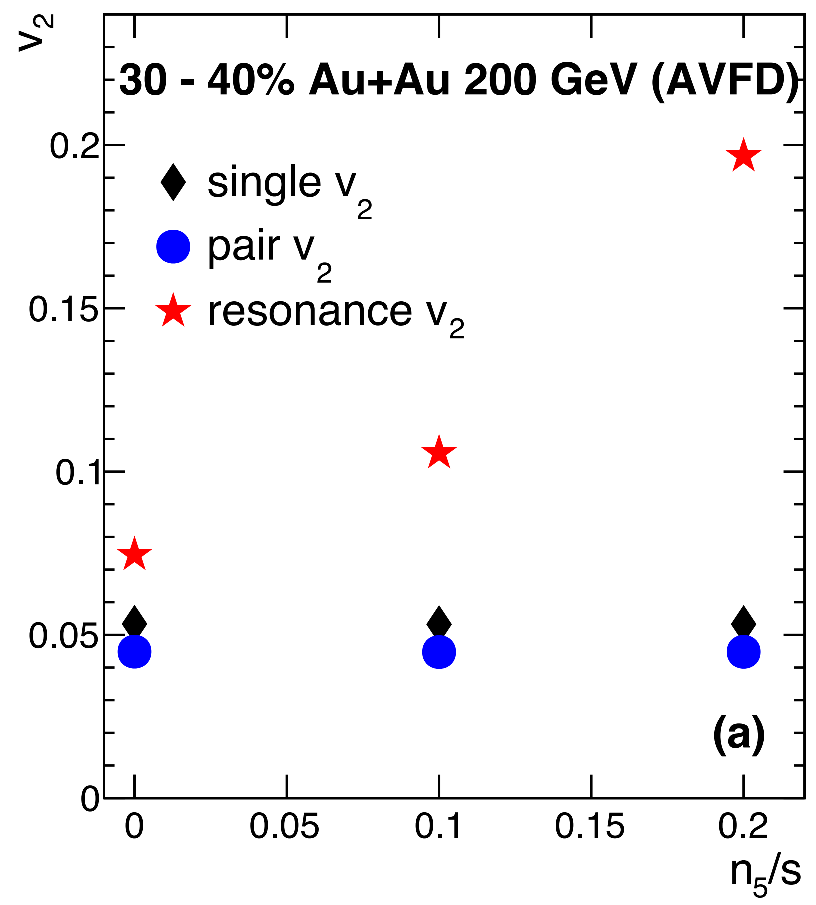
$$\Delta\gamma\{BG\} = v_2^{res}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\rangle$$

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

- **AVFD calculations show v_2^{res} itself is sensitive to input CME signal**
- **The Invariant mass spectrum is modified under the presence of CME.**
- **On the contrary, single and pair v_2 is relatively constant.**

The Toy Model uses PYTHIA to decay resonances





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

Comparable

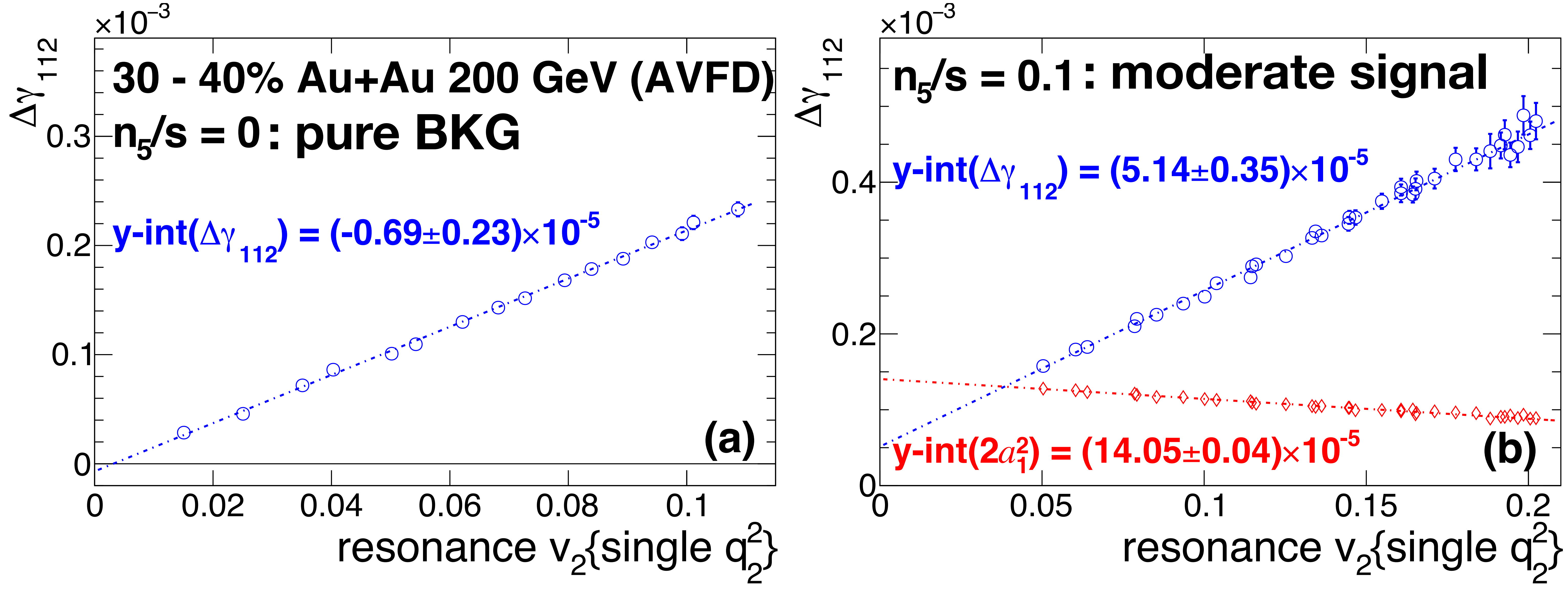
$$\text{pair } v_2 \sim \cos 2\phi - \frac{N^{SS}}{N^{OS} + N^{SS}}(\Delta\gamma - v_2^{\pi}\Delta\delta)$$

Dominant

$$\Delta\delta = \delta^{OS} - \delta^{SS}, \quad \delta = \langle\cos(\varphi_1 - \varphi_2)\rangle$$

v_2^{res} not suitable for Event Shape Selection

Z. Xu et al, arXiv:2307.14997



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

Comparable

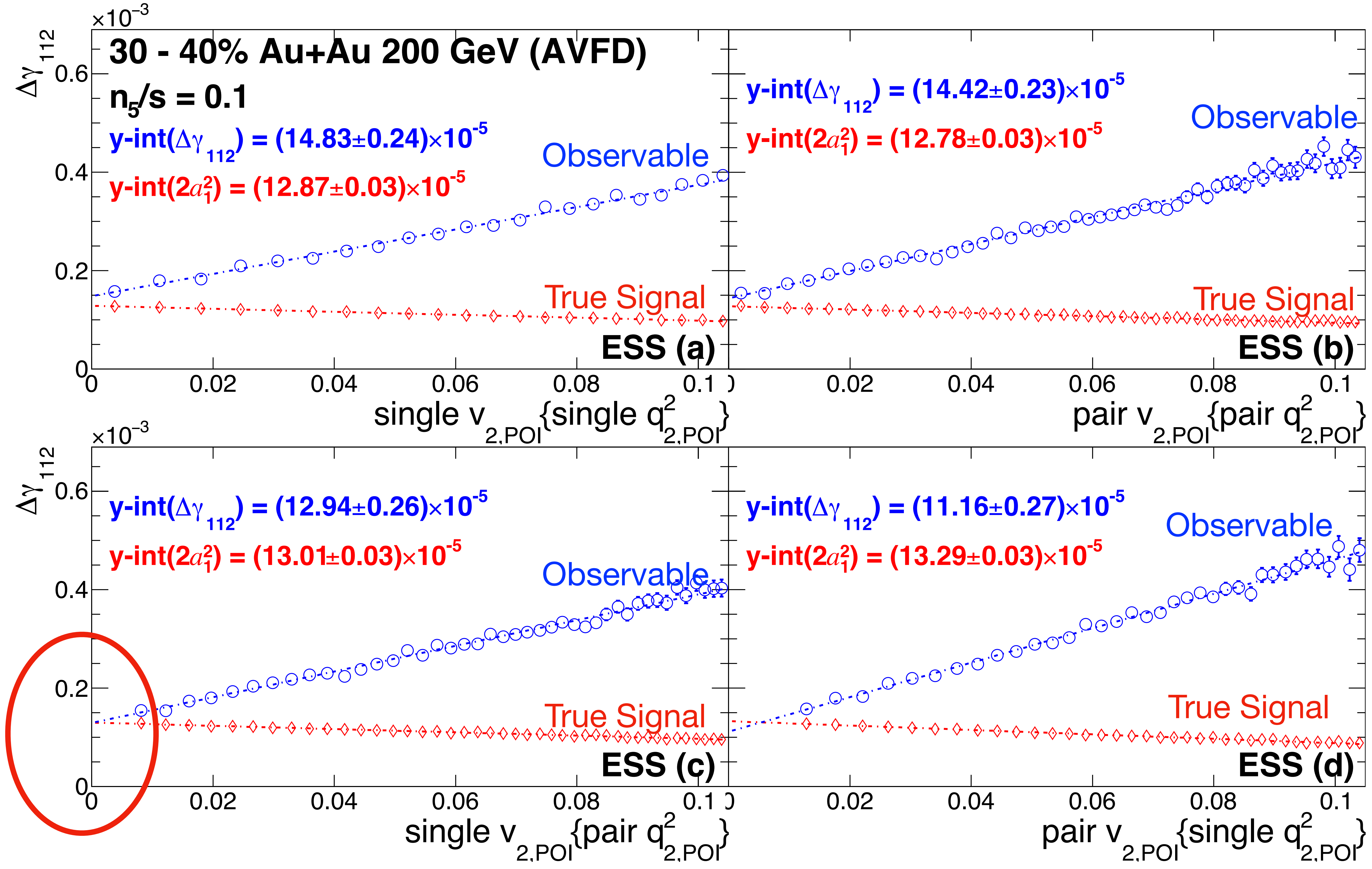
$$\text{pair } v_2 \sim \cos 2\phi - \frac{N^{SS}}{N^{OS} + N^{SS}}(\Delta\gamma - v_2^{\pi}\Delta\delta)$$

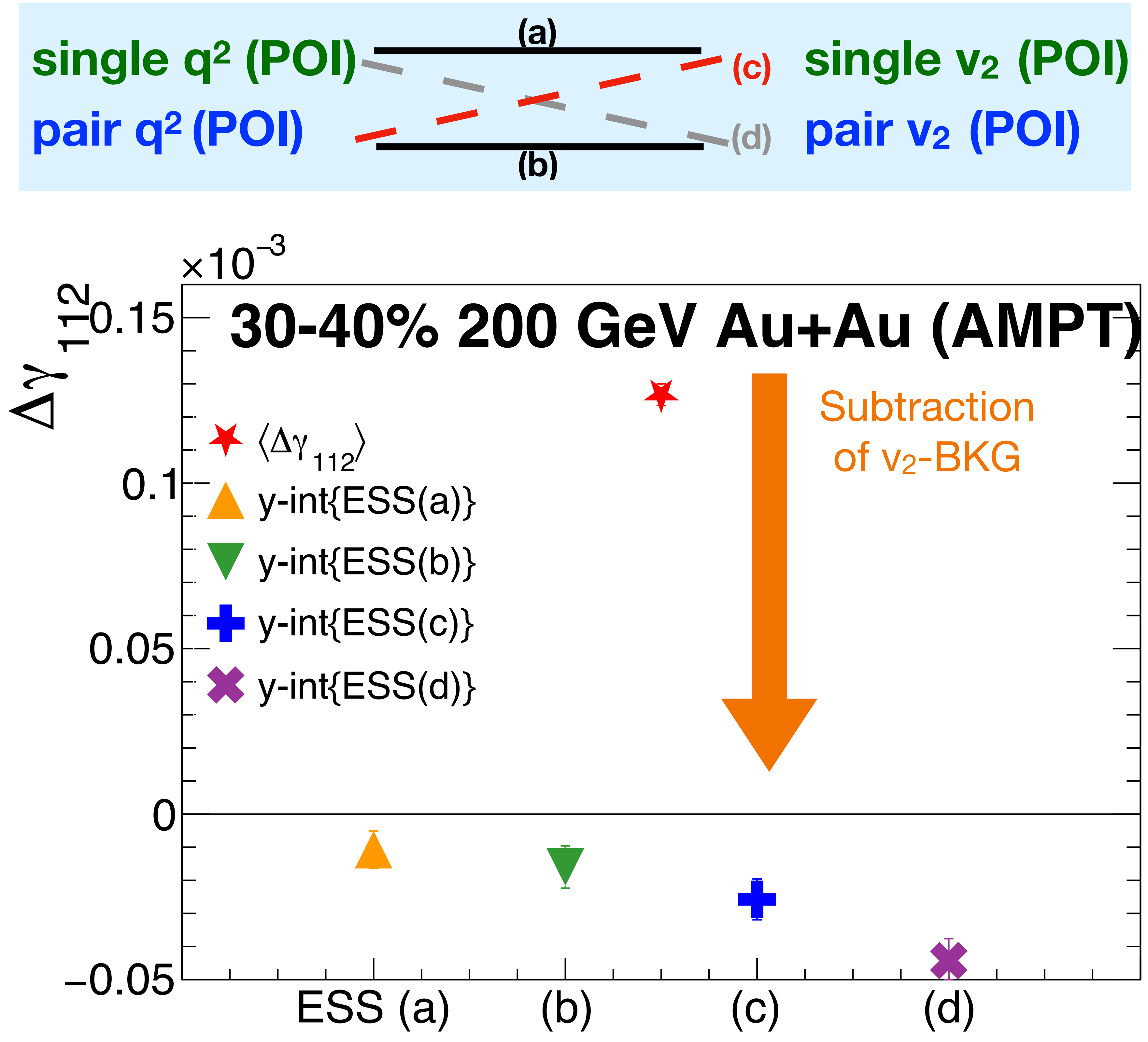
Dominant

- **Under moderate CME signal input, AVFD demonstrates that using v_2^{res} could cause severe over-subtraction.**
- **It indicates that using pair v_2 (average of charged pairs) may cause small over-subtraction.**

Simulation results for Event Shape Selection

Z. Xu et al, arXiv:2307.14997



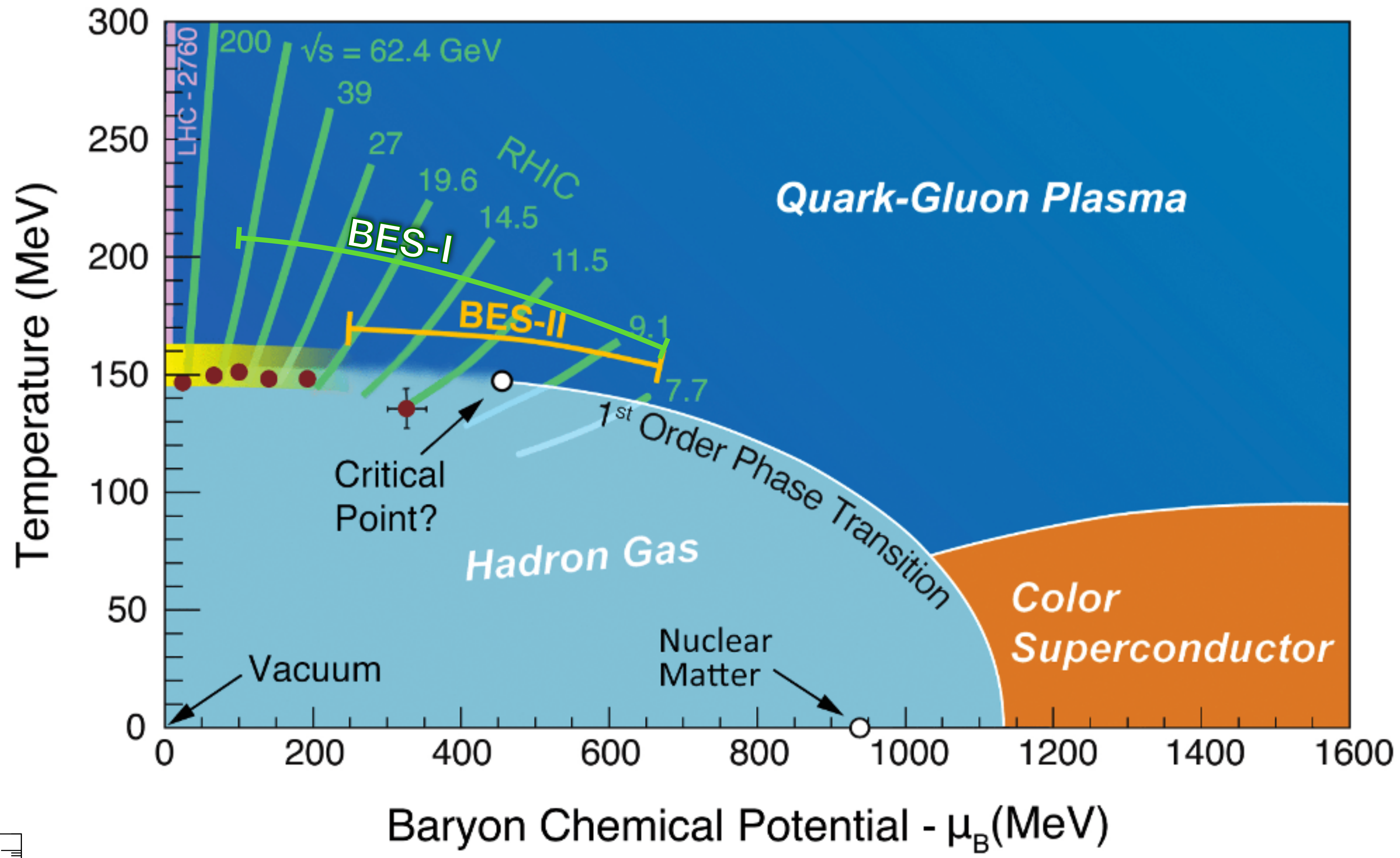


- With AVFD, the **optimal ESS recipe (c)** accurately matches the input true CME signal.
- Mixed combinations further suppress residual BKG: intercepts follow an ordering (a)>(b)>(c)>(d)
- With AMPT, all ESS schemes seem to over-estimate the BKG (same ordering as AVFD).

Beam Energy Scan at RHIC

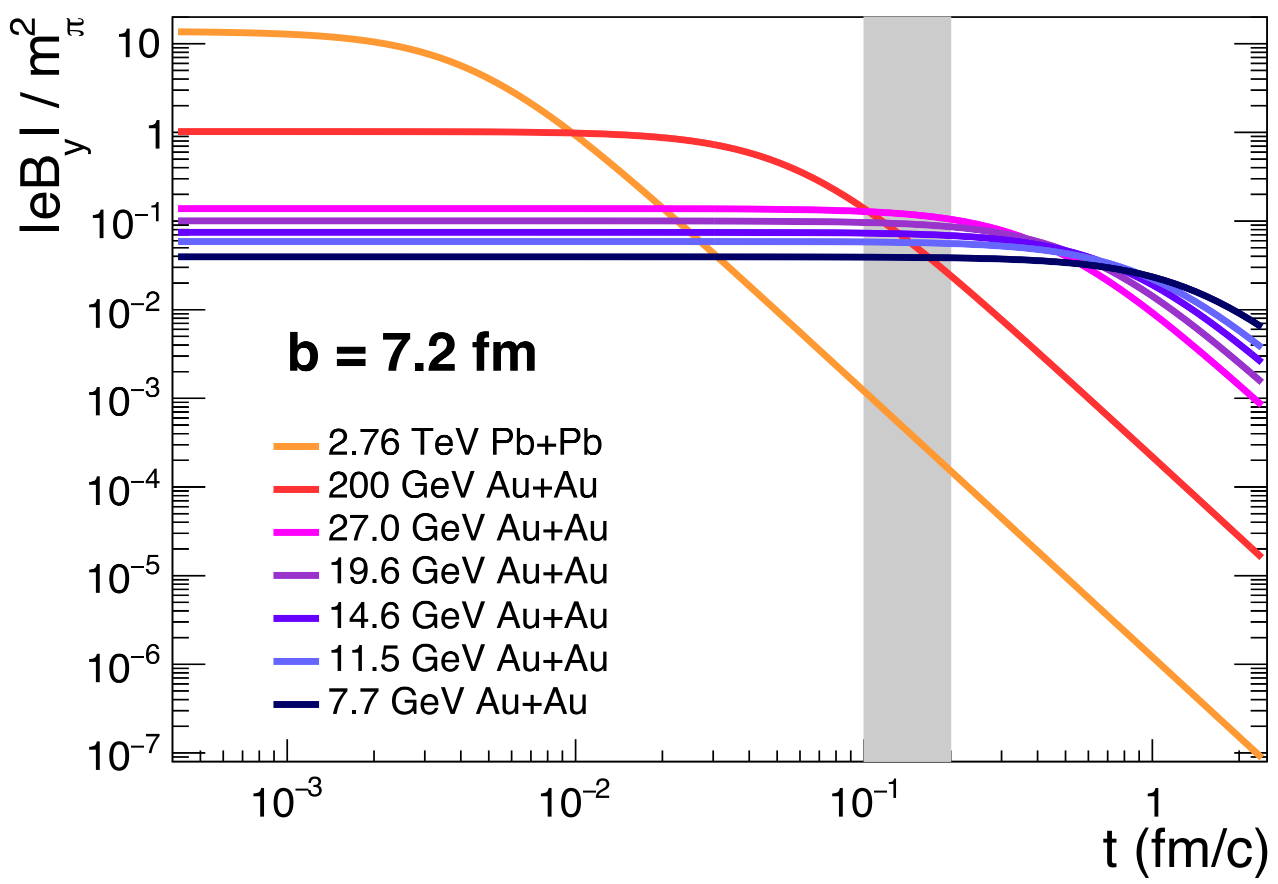
BES-I

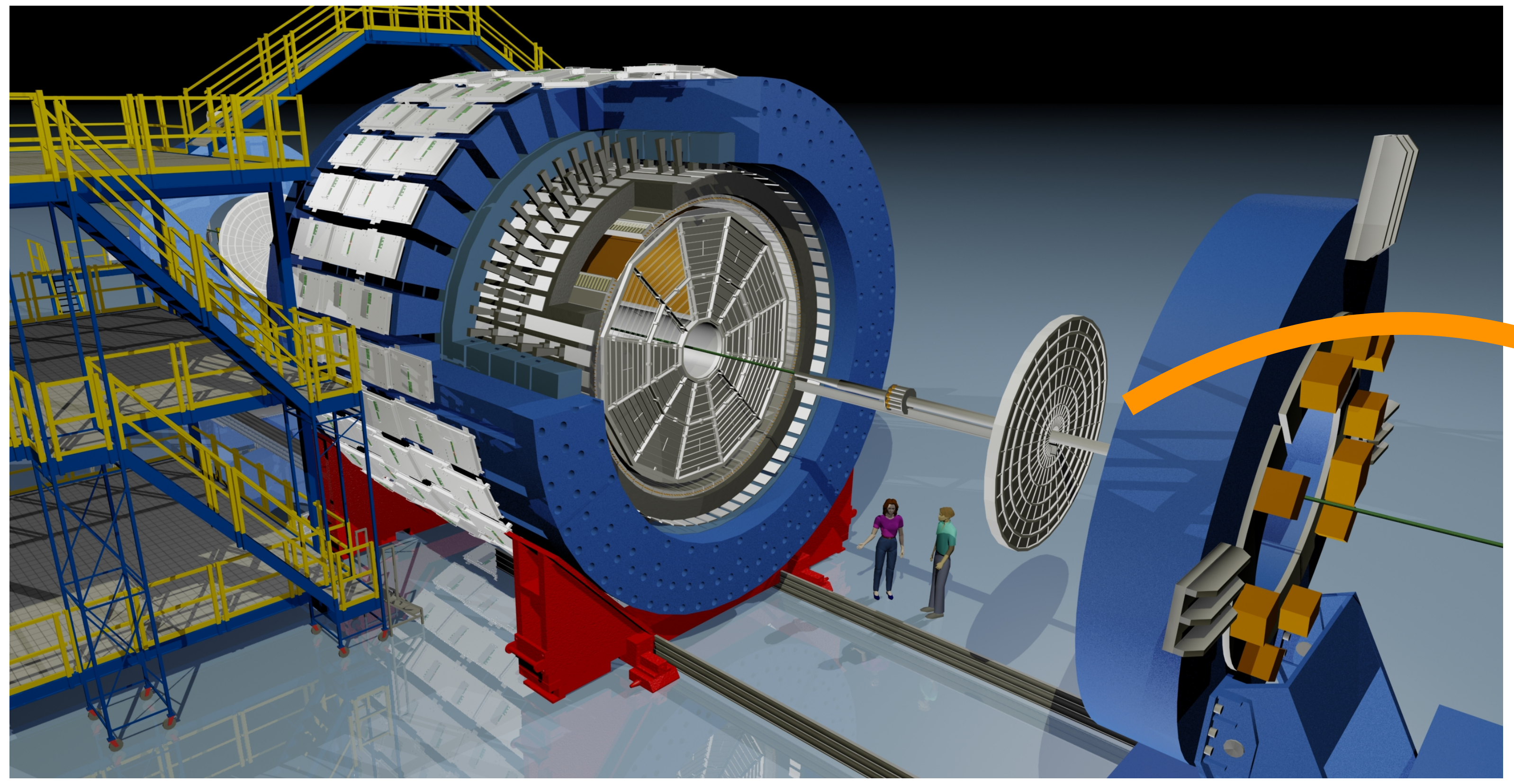
$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
62.4	46	2010
39	86	2010
27	30	2011
19.6	15	2011
14.6	13	2014
11.5	7	2010
9.2	0.3	2008
7.7	4	2010



BES-II

$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
27	555	2018
19.6	478	2019
14.6	324	2019
11.5	230	2020
9.2	160	2020
7.7	101	2021

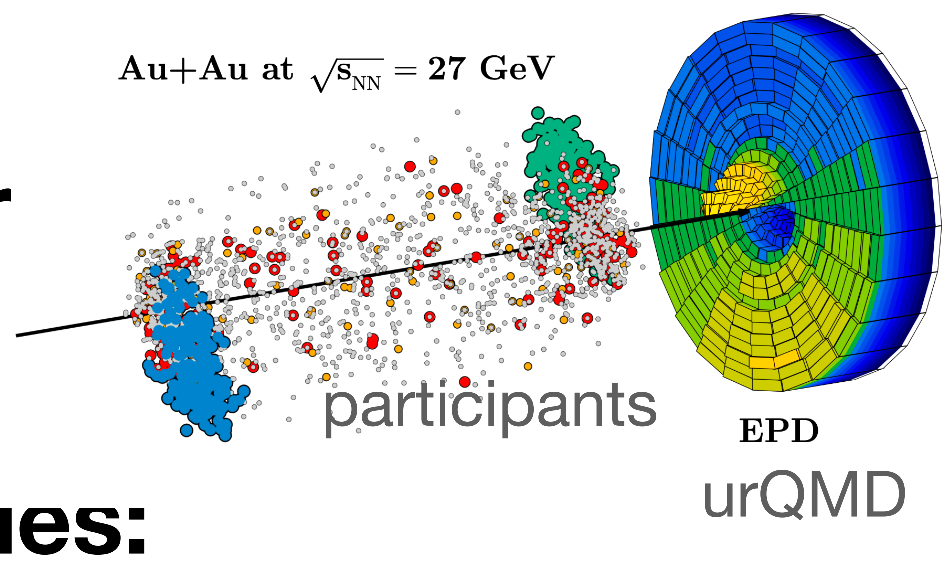




Statistics:

- **20 times higher**

$\eta > y_{beam}$: Forward spectators



Detector Upgrades:

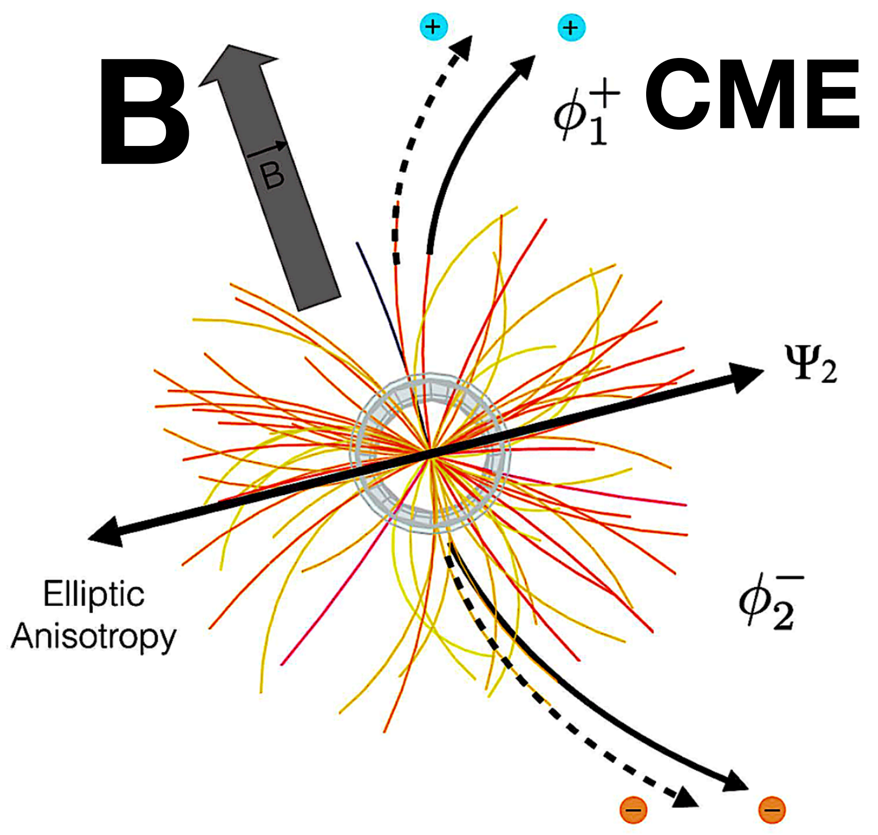
- **2018 EPD : high EP resolution into spectator region (2.1<η<5.1)**

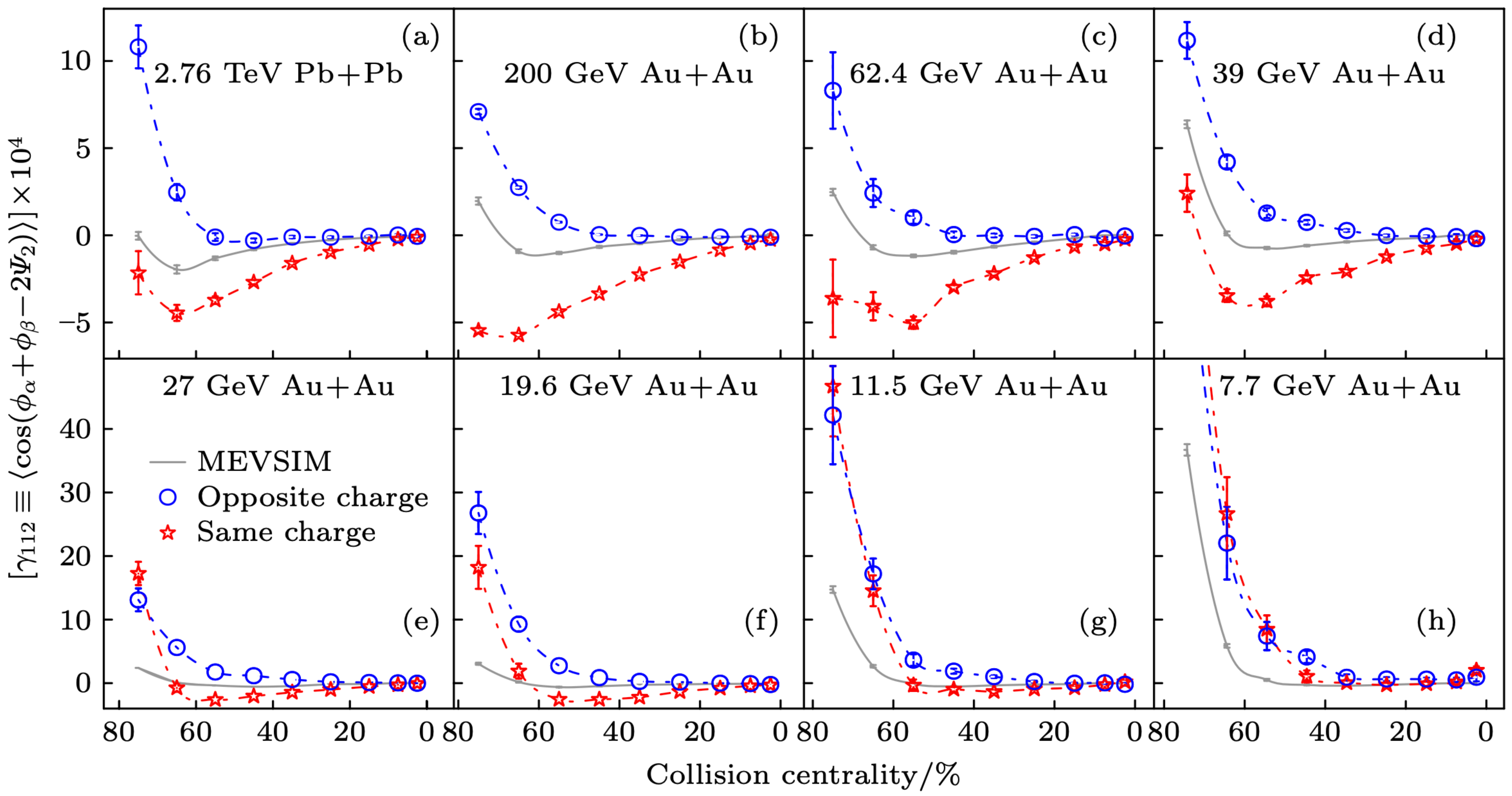
Beam Energy Scan I

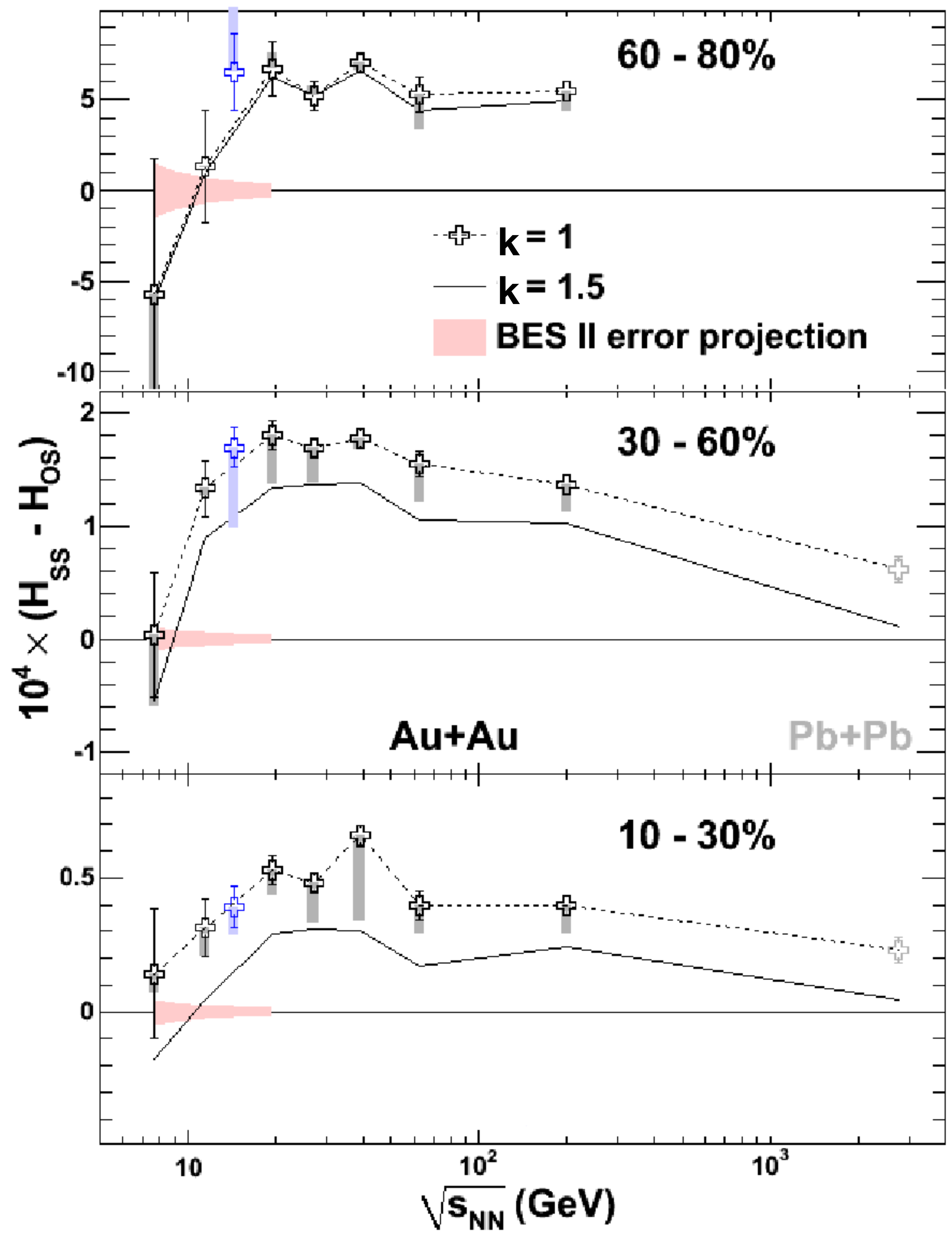
ALICE, Phys. Rev. Lett. 110, 012301 (2013)

STAR, PRL 113 (2014) 052302

$H^k = (kv_2\delta - \gamma)/(1 + kv_2) \quad k = 1,\ 1.5\ \ldots,\ \delta = \langle\cos(\varphi_1 - \varphi_2)\rangle$



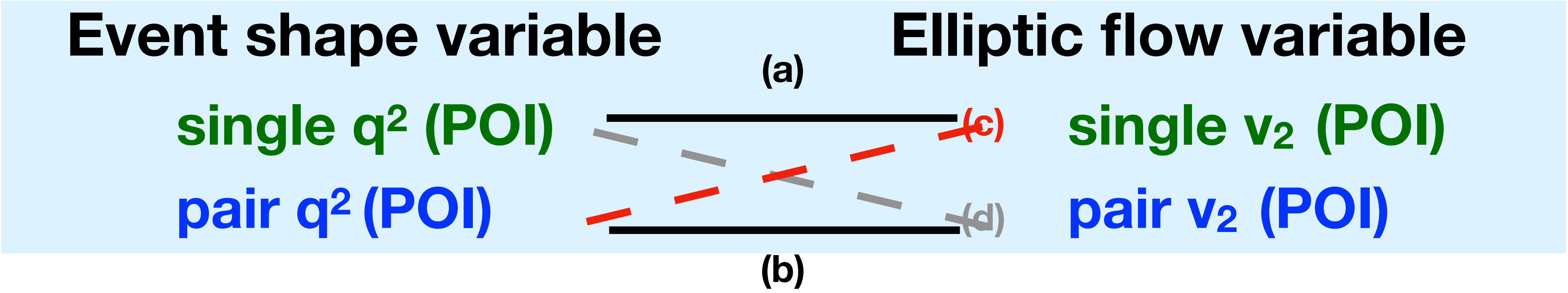


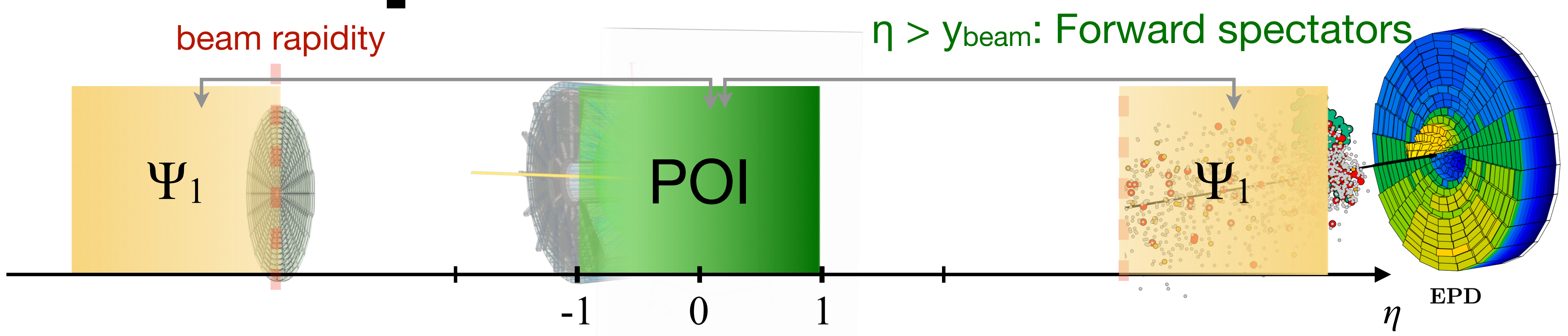


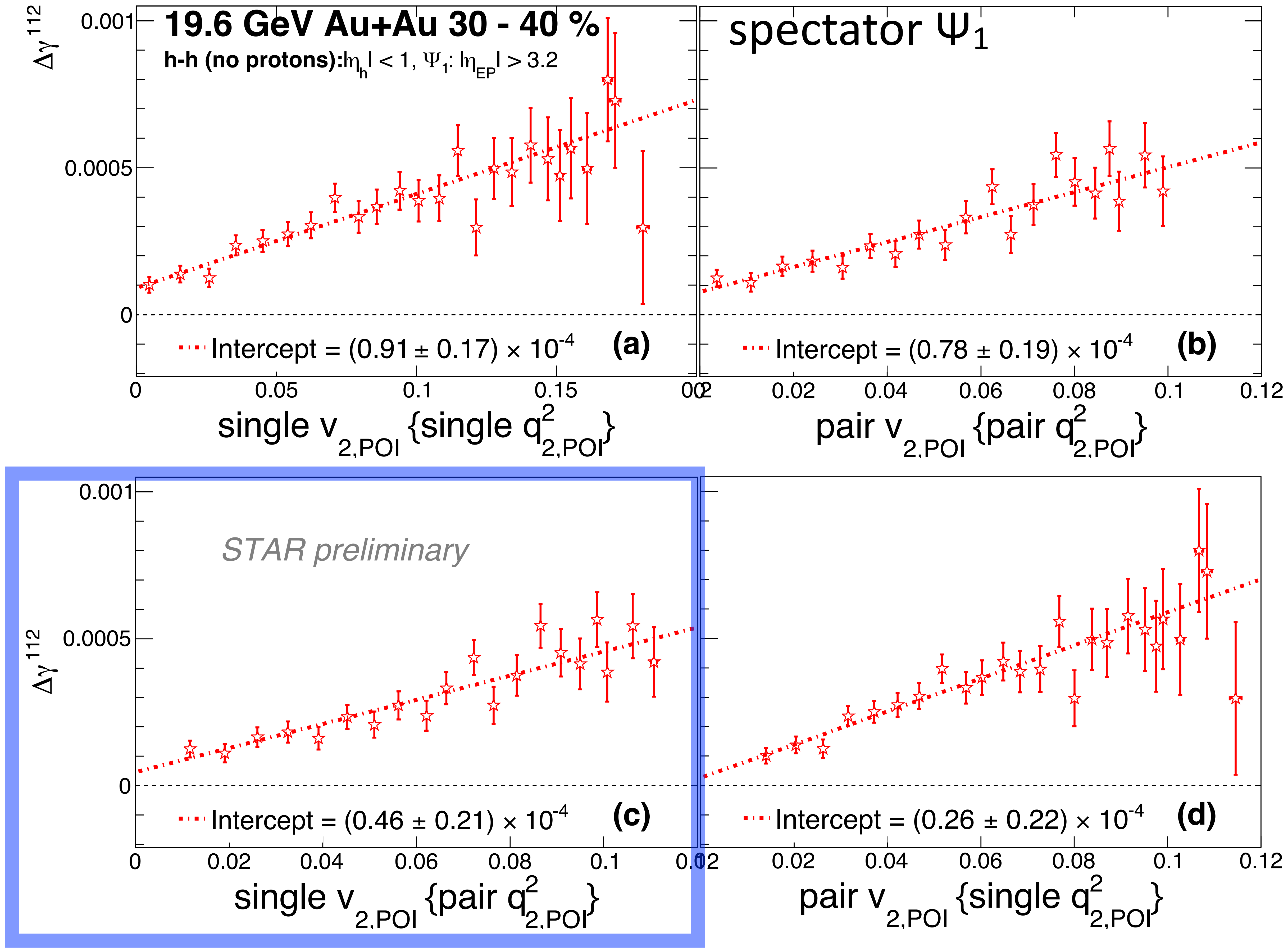
- $\Delta\gamma^{112}$ **measurement using participant plane (TPC) entails large nonflow BKG.**
- **ΔH disappears at the lowest and highest energies. The vanishing at 7.7 GeV indicates the domination of hadronic interactions over partonic ones.**

BES-II provides unique opportunity to search for the CME!

Beam Energy Scan II - Event Shape Selection





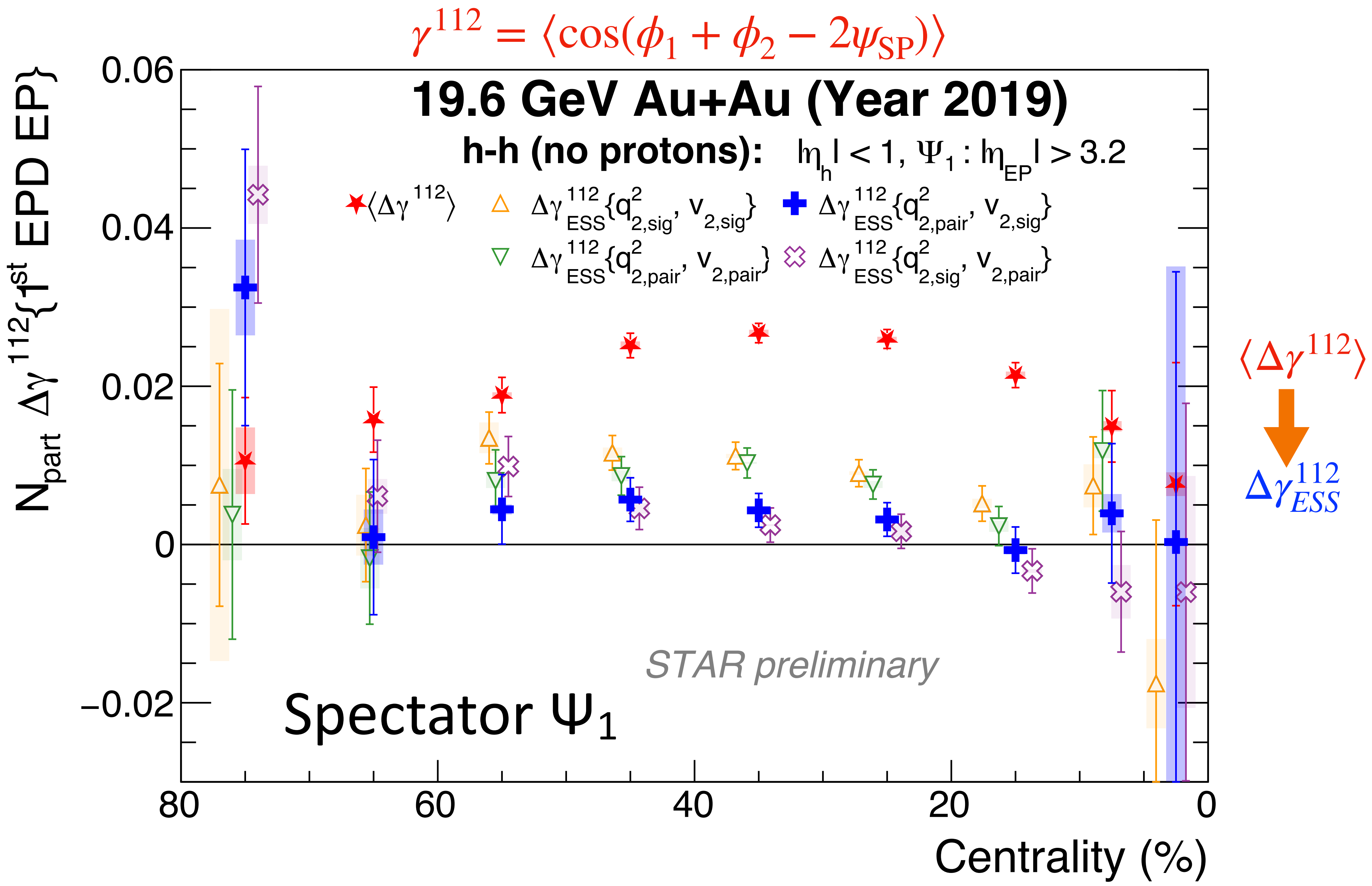


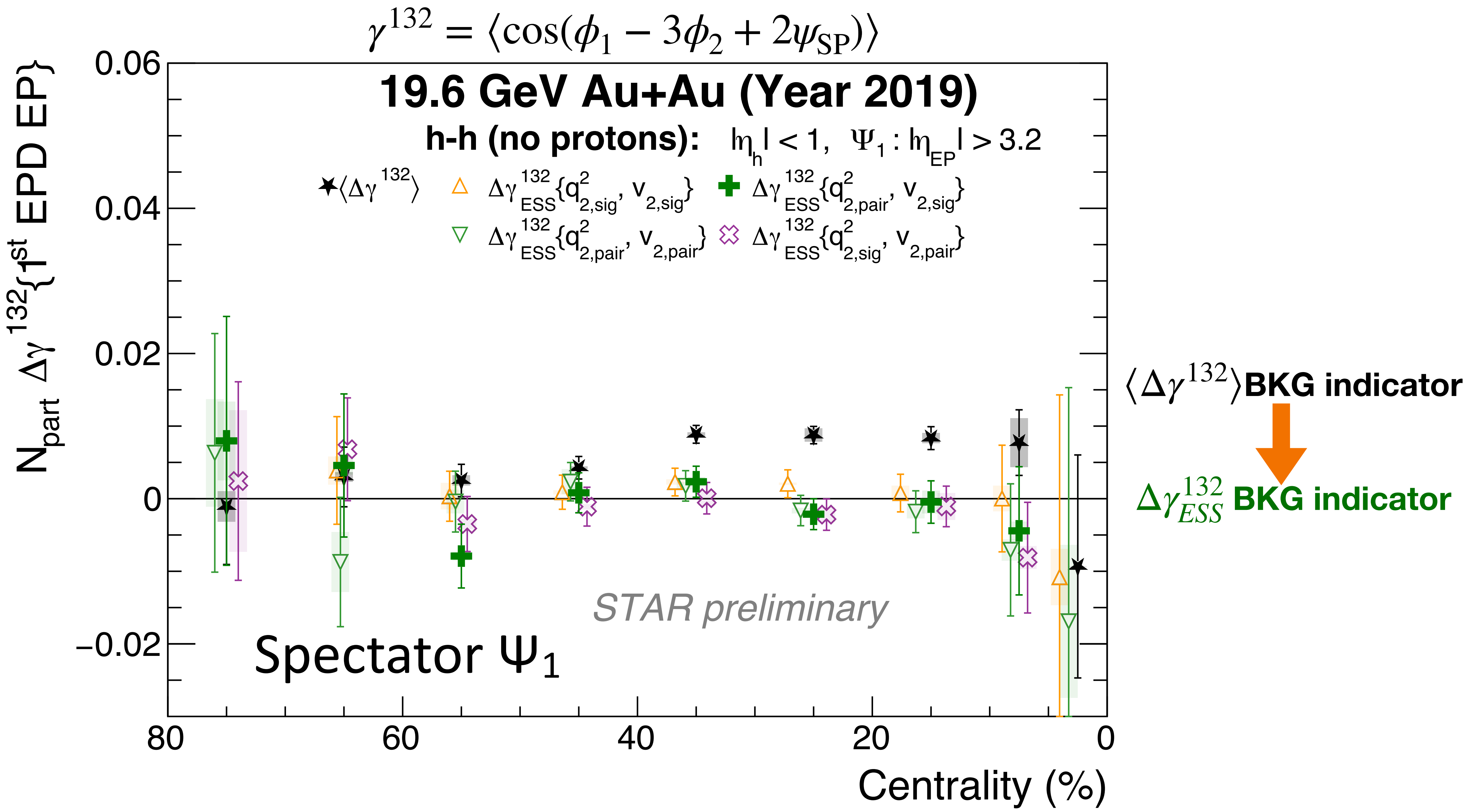
- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT**
- **The y-intercept requires a small correction to restore the CME signal:**

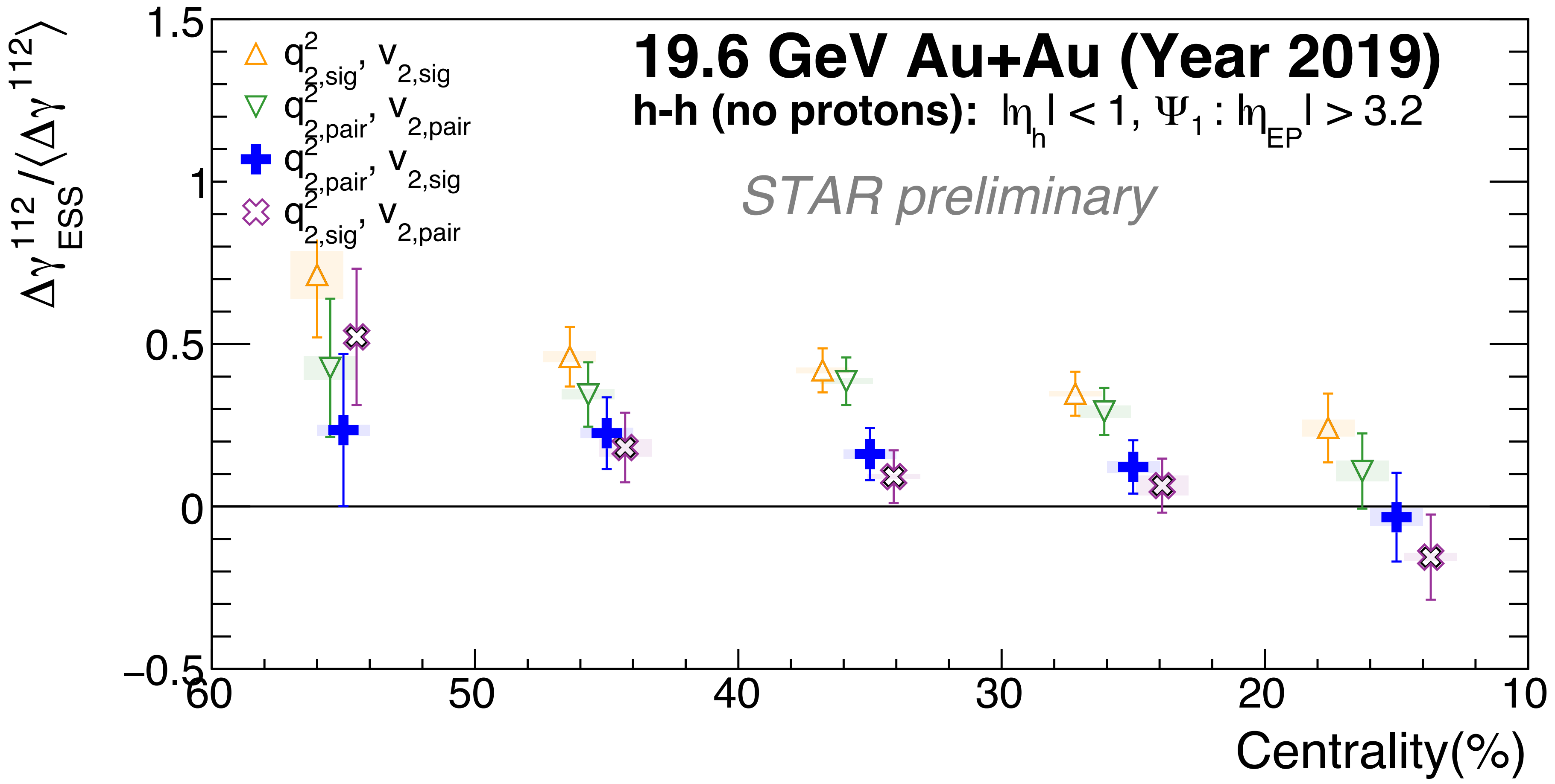
$$\Delta\gamma_{ESS}^{112} = Intercept \times (1 - v_2)^2$$

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

Beam Energy Scan II - Event Shape Selection

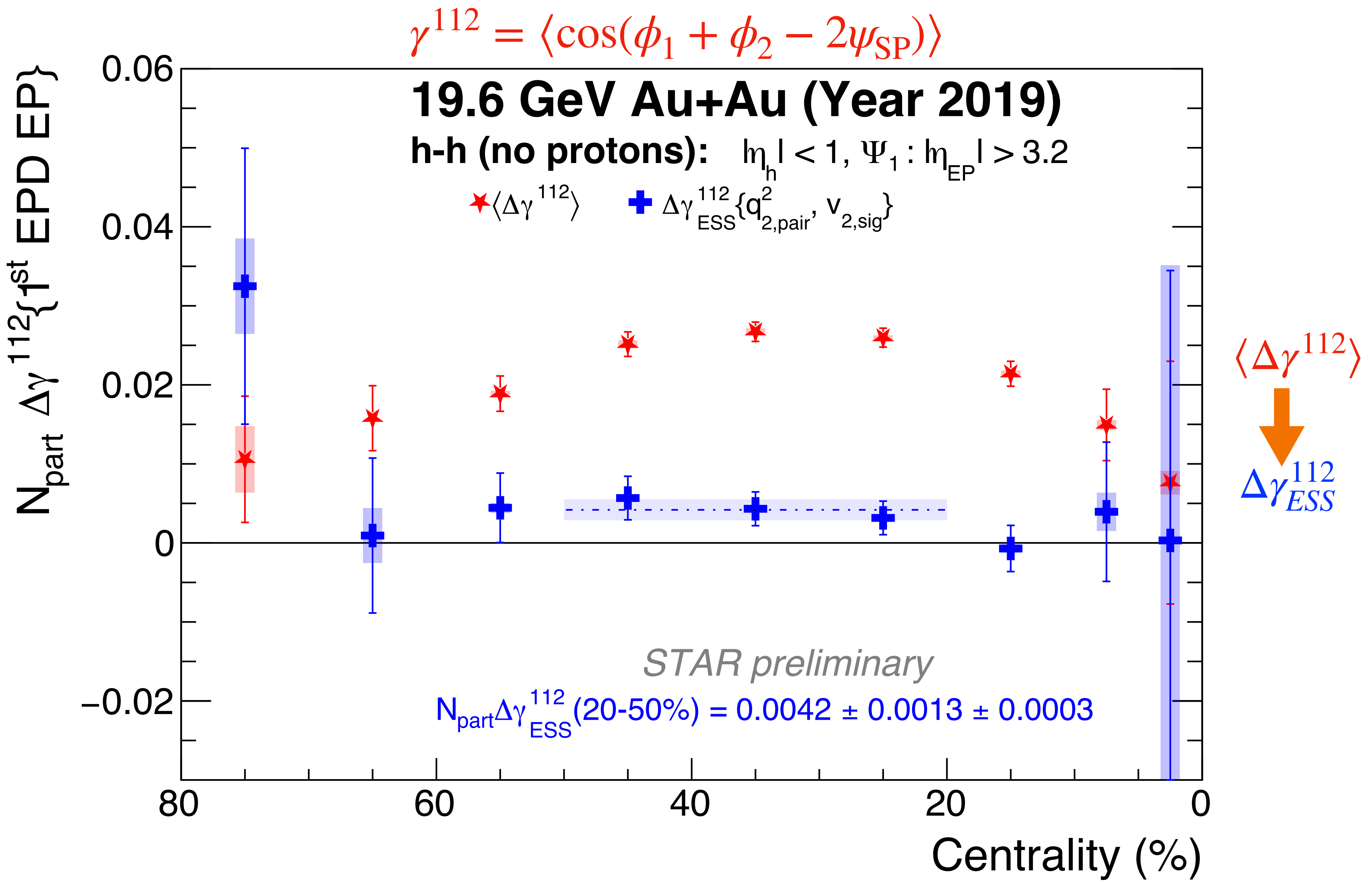


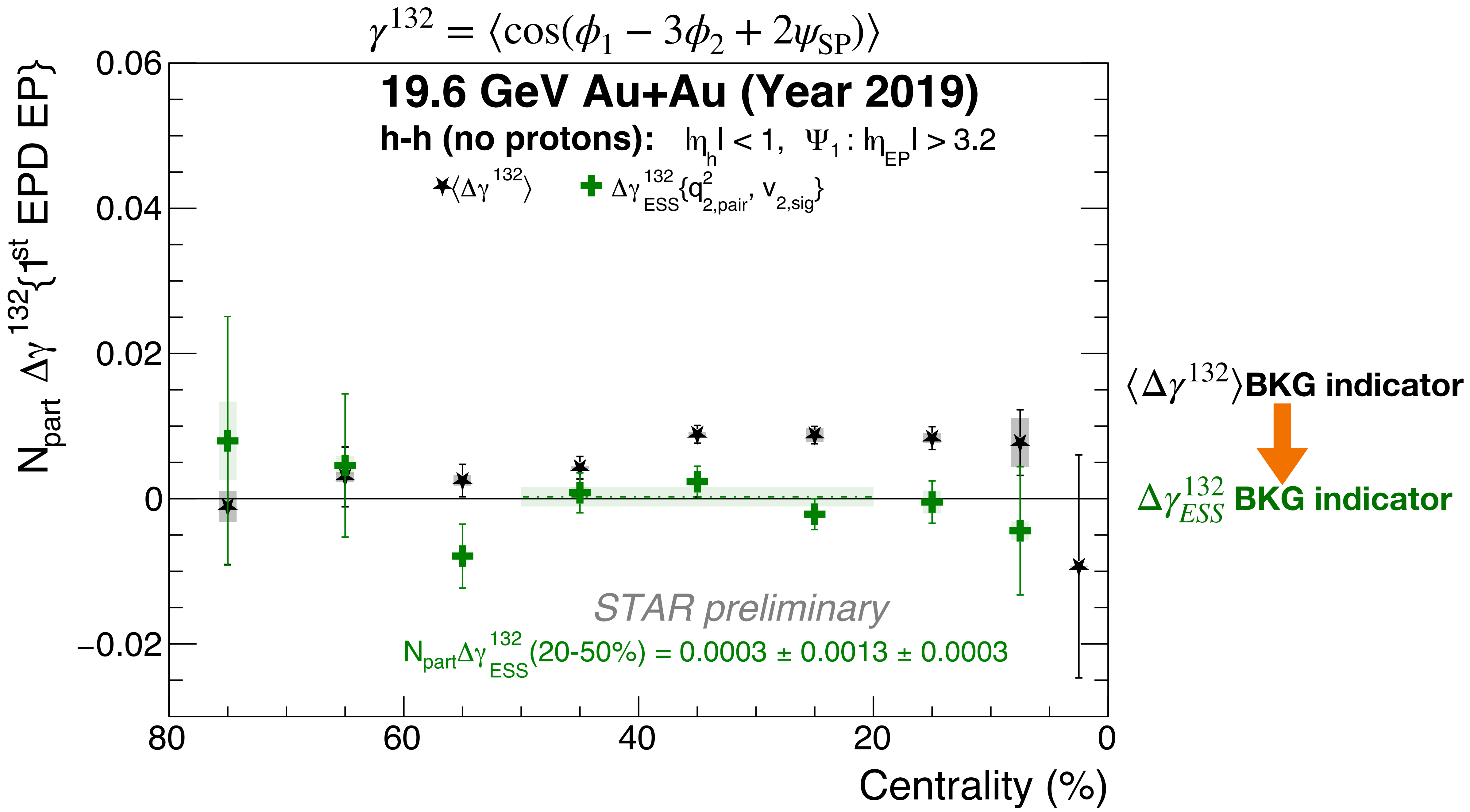


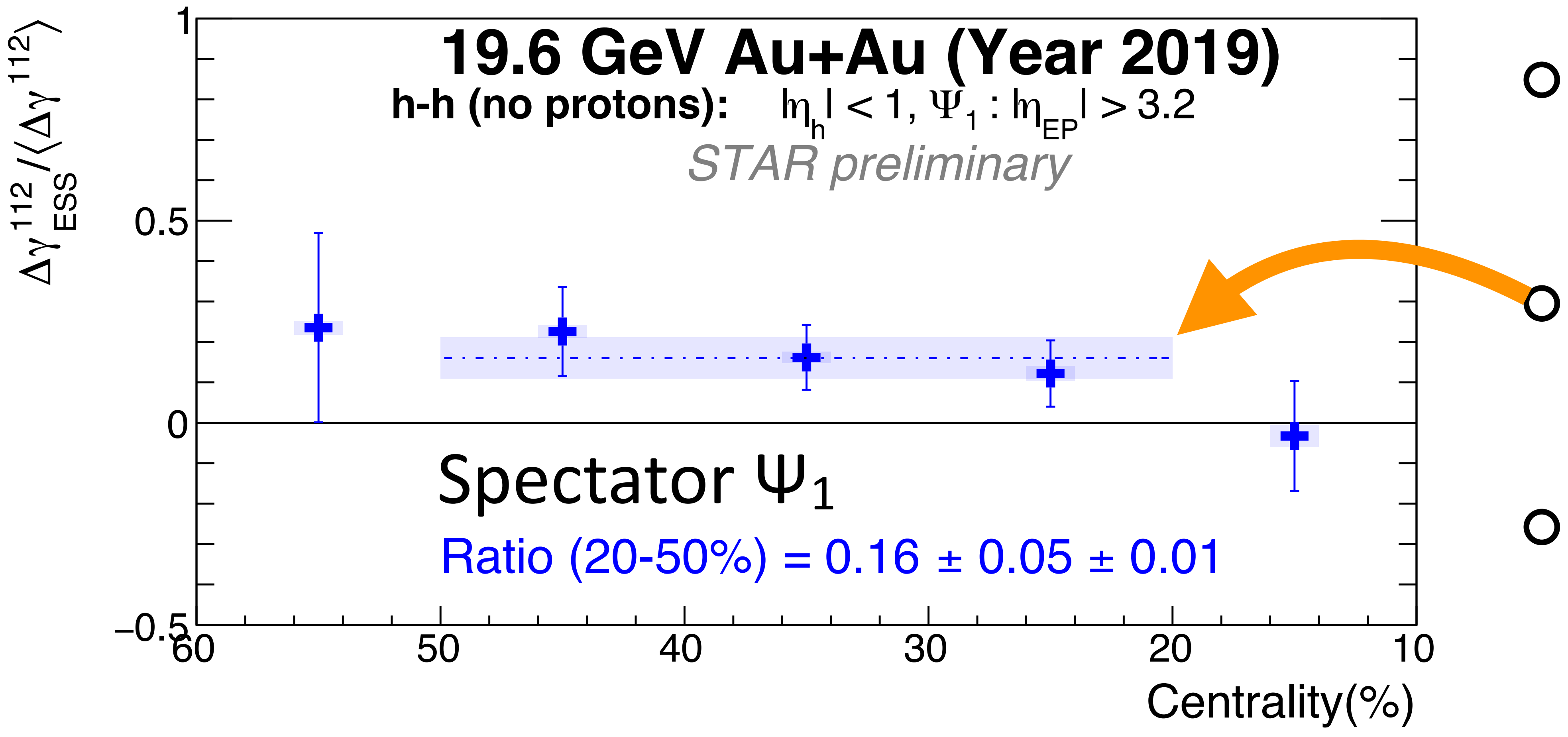


- **The ESS is applied to different centralities.**
- **Ordering of four $\Delta\gamma^{112}_{ESS}$ follows prediction from model.**

Beam Energy Scan II - Event Shape Selection

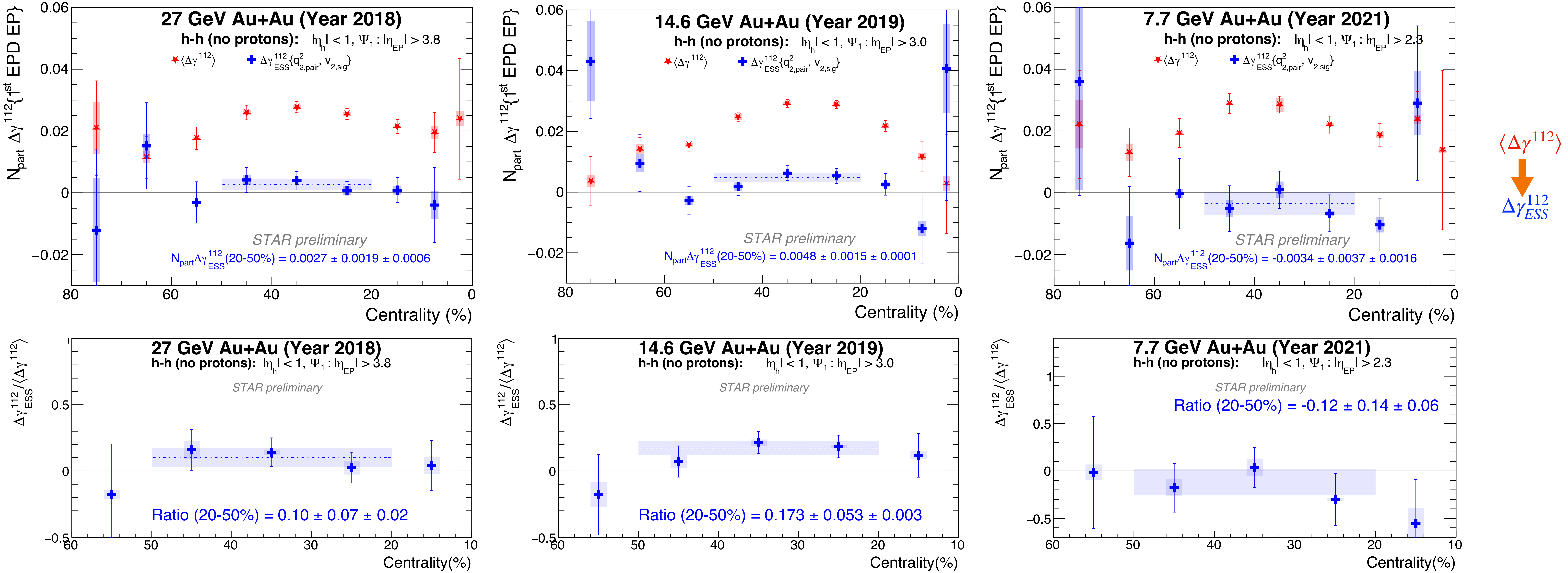






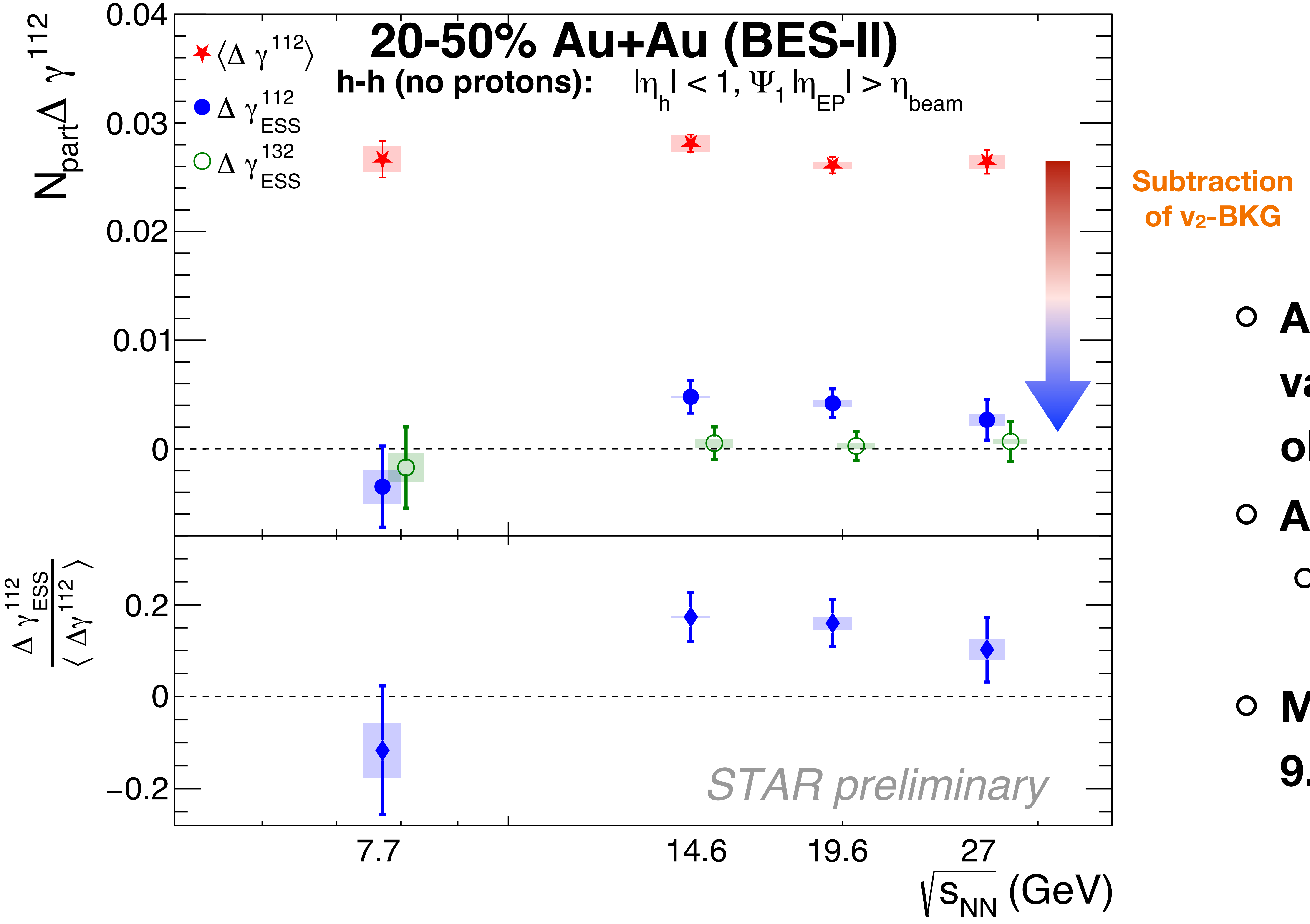
- **After v_2-BKG subtraction, a finite signal in mid-central 20-50% events.**
- **Ratio from the optimal ESS (c), pair q^2 and single v_2, yields a 3σ significance for 20-50% centrality at 19.6 GeV.**
- **From BKG indicator $\Delta\gamma^{132}$, ESS successfully removes v_2-BKG.**

Beam Energy Scan II - Event Shape Selection



- Results from the optimal ESS (c), pair q^2 and single v_2:
  - At 27 GeV, uncertainties dominate.
  - At 14.6 GeV, the ratio for 20-50% centrality has a 3σ significance of CME sensitive $\Delta\gamma^{112}_{ESS}$
  - At 7.7 GeV, the current results favor the zero-CME scenario.

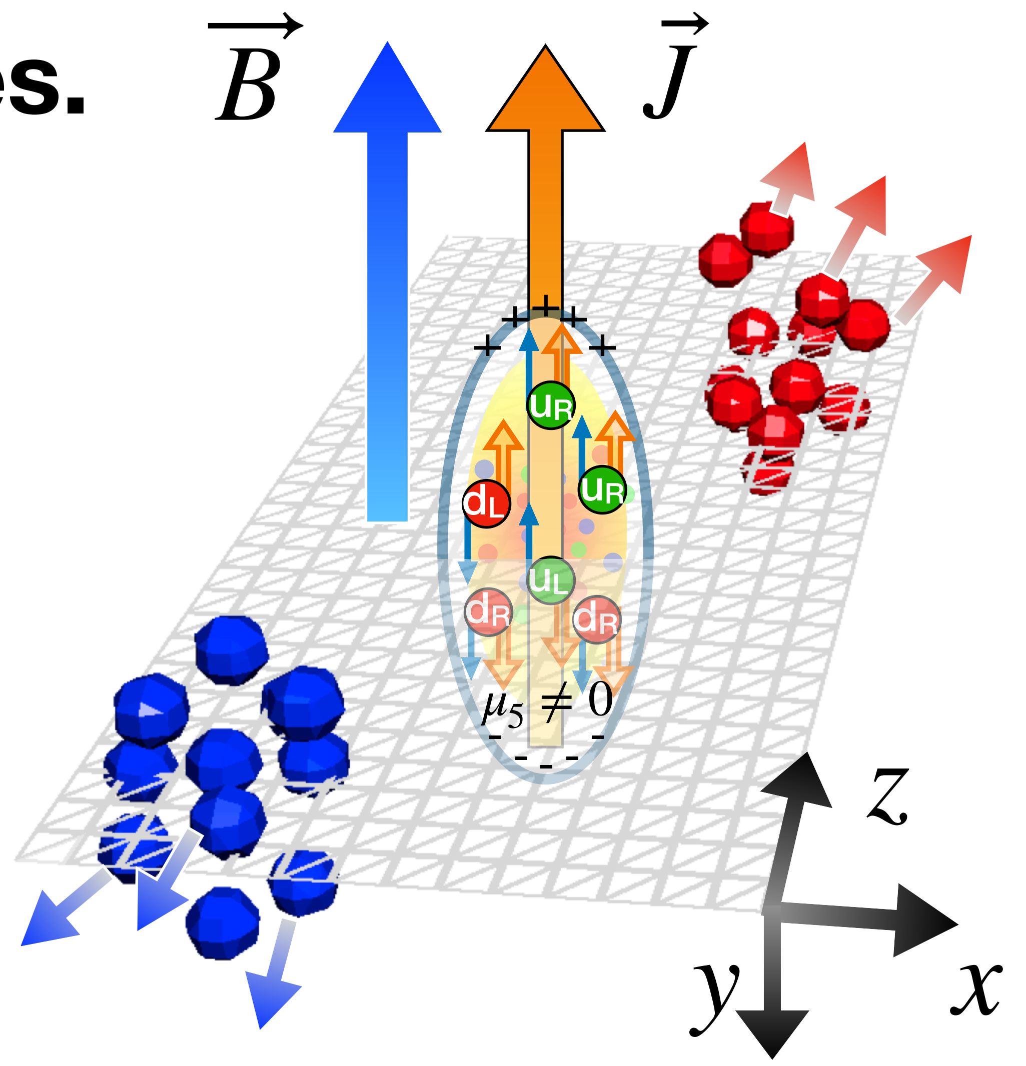
Beam Energy Dependence of CME observable

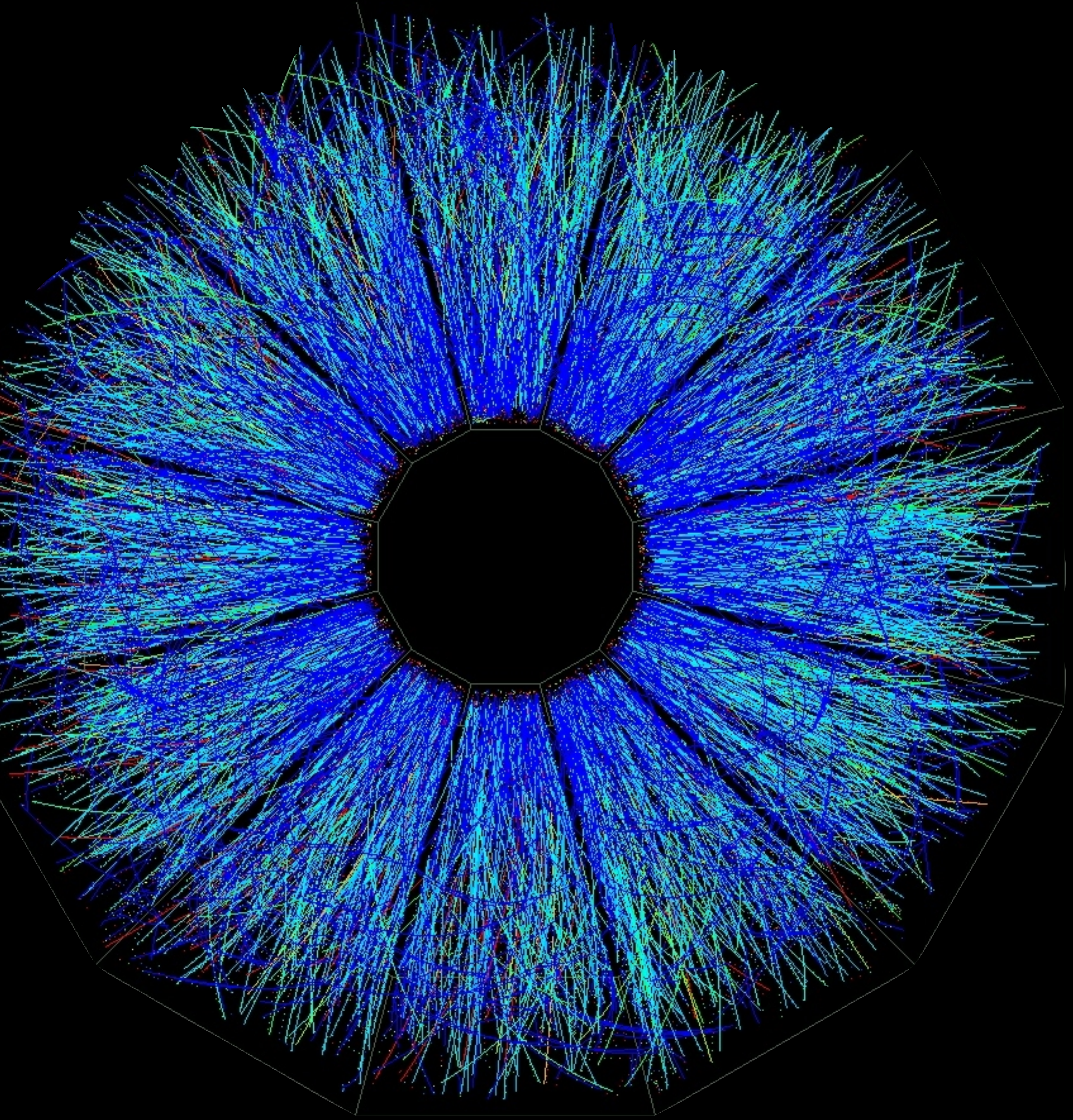


- After v_2-BKG subtraction with Event Shape variables, and nonflow supression with Ψ_1, obtained $\Delta\gamma^{112}_{ESS}/\langle\Delta\gamma^{112}\rangle$ that shows
- At 14.6 and 19.6 GeV, a 3σ effect.
  - At 7.7 GeV and 27 GeV, consistent with zero based upon the large statistic error.
- More BES-II data analyses for 11.5 GeV and 9.2 GeV are on the way.

Summary

- The search for the CME addresses an intrinsic topological property of QCD.
- We use a novel Event Shape Selection method to extrapolate $\Delta\gamma^{112}$ to zero-flow limit, and use spectator plane Ψ_1 to minimize the nonflow background.
    - The CME-sensitive $\Delta\gamma^{112}_{ESS}/\langle\Delta\gamma^{112}\rangle$ after BKG subtraction is finite (3σ) in Au+Au at 14.6 and 19.6 GeV.
- Above 14.6 GeV, our finding favors the scenario that the chirality imbalance and magnetic filed may coexist to induce the CME.
- Approaching 7.7 GeV, current result hints zero CME within uncertainties.





Thank you!