Investigating Event-Shape Methods in search for Chiral Magnetic Effect in Relativistic Heavy Ion Collisions

Based on: H. Li, Feng, Wang, arXiv:2407.14489

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Quark Matter 2025

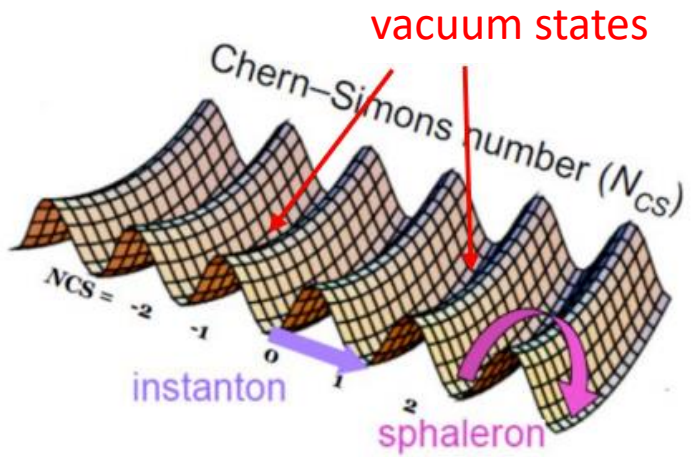
The Chiral Magnetic Effect (CME)

The CME

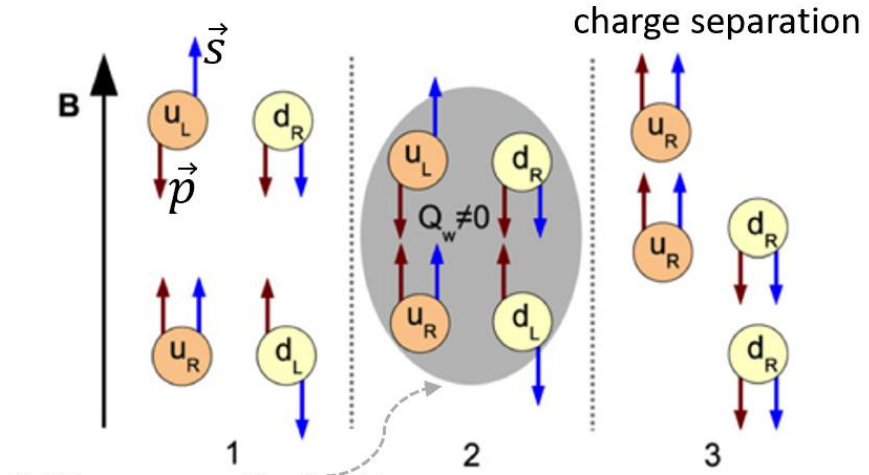
- QCD Vacuum fluctuations → Non-zero topological charge → Chirality imbalance
- Strong magnetic field → (anti-) parallel to B → Charge separation

Importance of the CME

- Approximate chiral symmetry restoration
- Local P/CP-violation in strong interaction
- It may resolve the strong CP problem of matter–antimatter asymmetry



Kharzeev,Pisarski,Tytgat,PRL81(1998)512

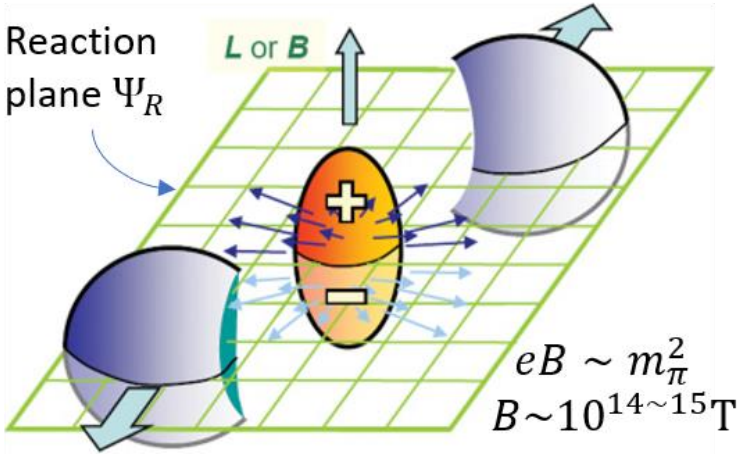


QCD vacuum fluctuation

Topological charge $Q_w \propto \int \vec{E}_c \cdot \vec{B}_c$

Heavy Ion collisions and Observables

- **Heavy ion collisions ideal to search for CME**
  - Deconfined quarks and gluons (QGP)
  - Strong magnetic field



- **Fourier series of particle azimuthal distributions**

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

- **The γ correlator**

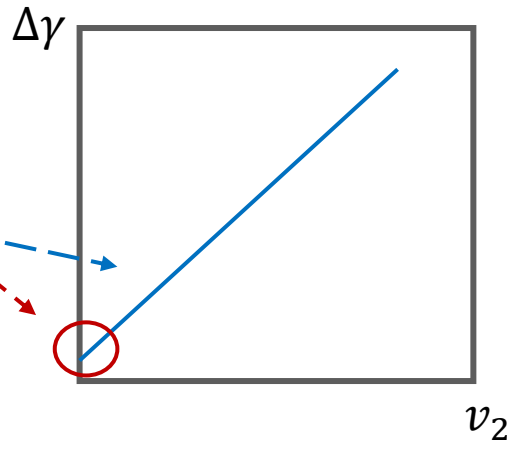
$$\gamma_{\alpha\beta} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$$

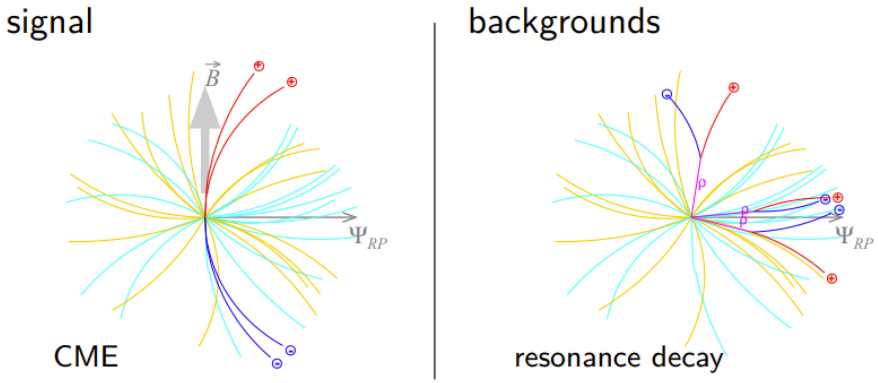
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS} \approx b_{bkg} * v_2 + 2a_1^2\ (CME)$$

Major flow background in $\Delta\gamma$.

Intercept more sensitive to CME.

S.A. Voloshin, Phys. Rev. C70(2004)057901





- **Event-Shape Engineering (ESE)**

A technique to remove flow background by linear extrapolation

Feng, Wang, Voloshin. *Experimental Search for the Chiral Magnetic Effect in Relativistic Heavy-Ion Collisions: A Perspective*, arXiv:2502.09742

Event Shape Methods

■ **Correlation** between **Event-shape quantity** and **Particle of interest (POI)** from each methods

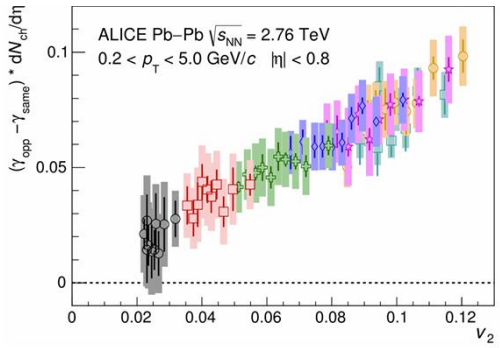
☐ Event Shape Engineering (ESE)

Event-shape variable

$$q_2 = \sqrt{\frac{\left[\left(\sum_i^M \cos 2\phi_i\right)^2 + \left(\sum_i^M \sin 2\phi_i\right)^2\right]}{M}}$$

POI
- $v_2 = \langle \cos 2(\phi_i - \psi) \rangle$
- $\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi) \rangle$

q_2 and POIs (v_2 and $\gamma_{\alpha\beta}$) calculated from *different* particles



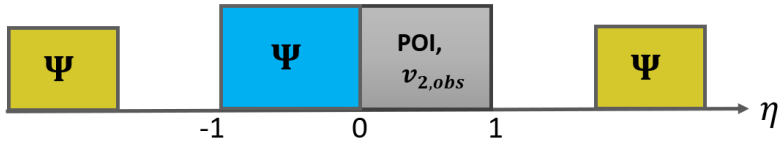
S. Acharya et al. (ALICE), Physics Letters B 777 (2018)

☐ Event Shape (ES)

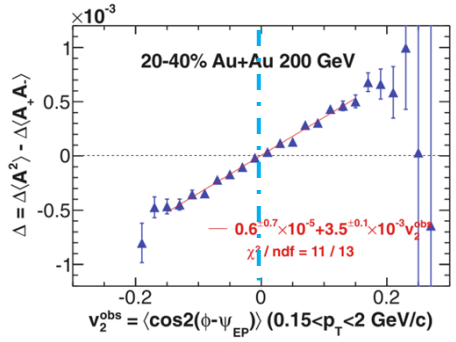
Event-shape variable

$$v_2^{obs} = \langle \cos 2(\phi_i - \psi) \rangle$$

POI
- $v_2^{obs} = \langle \cos 2(\phi_i - \psi) \rangle$
- $\Delta \approx \gamma_{os} - \gamma_{ss}$



Event-shape v_2^{obs} and Δ calculated from the *same* particles



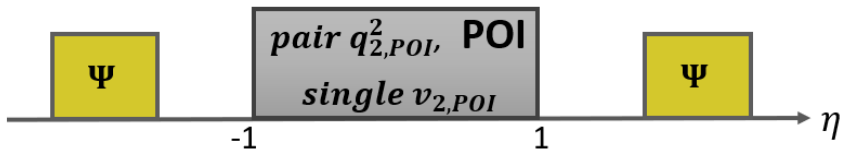
L. Adamczyk et al. (STAR), Phys. Rev. C **89**, 044908 (2014)

☐ Event Shape Selection (ESS)

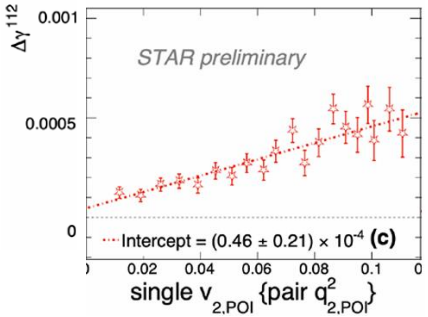
Event-shape variable

$$pair\ q^2_{2,POI} = \frac{\left(\sum_i^N \cos 2\phi_i\right)^2 + \left(\sum_i^N \sin 2\phi_i\right)^2}{N(1+Nv_2\{2\})}$$

POI
- $single\ v_{2,POI} = \langle \cos 2(\phi_i - \psi) \rangle$
- $\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi) \rangle$



$pair\ q^2_{2,POI}$ and POIs ($single\ v_{2,POI}$ and $\gamma_{\alpha\beta}$) calculated from the *same* particles



Z. Xu et al. (STAR), arXiv:2401.00317

General Expectations

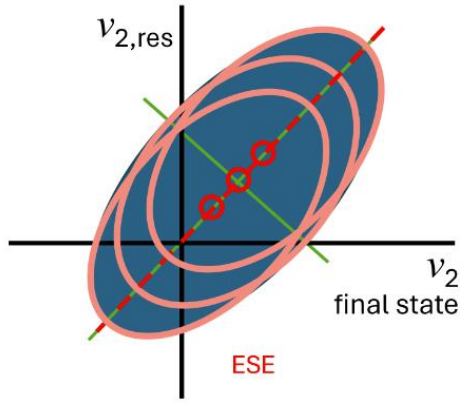
- Background from cluster correlations, e.g. resonance decay ($\Delta\gamma_{bkg} \propto v_{2,res}$)

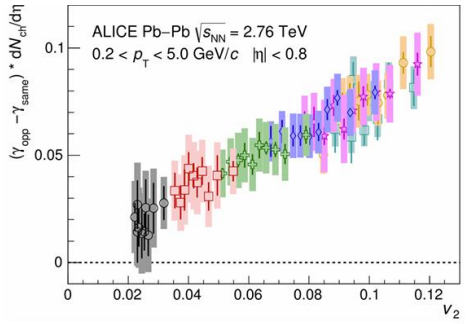
ESE Schukraft et al. PLB 719 (2013) 394

q_2 decoupled from POI

Average $\langle v_{2,res} \rangle \propto \langle v_2 \rangle$, unbiased

Dynamical fluctuation



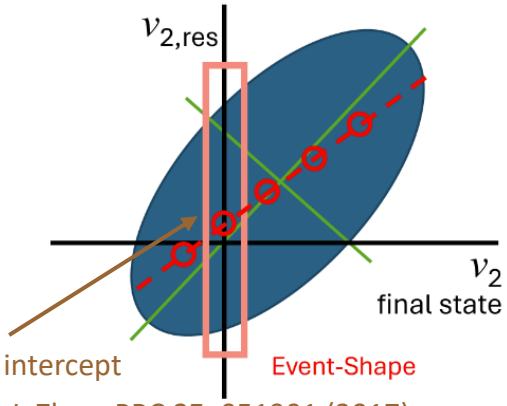


ES Adamczyk et al. (STAR), PRC **89**, 044908 (2014)

Biases from v_2^{obs} selections by using the same POI's

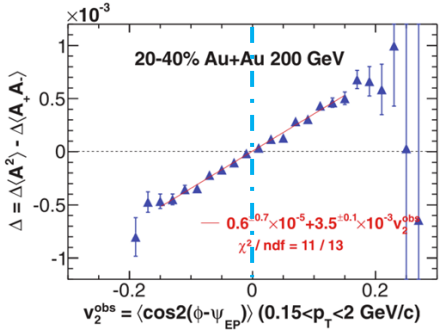
$v_{2,res}$ not strictly $\propto v_2^{obs}$

Statistical fluctuation



Positive intercept — Event-Shape

F. Wang, J. Zhao, PRC **95**, 051901 (2017)

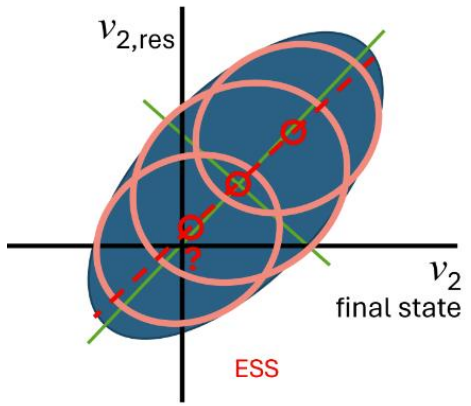


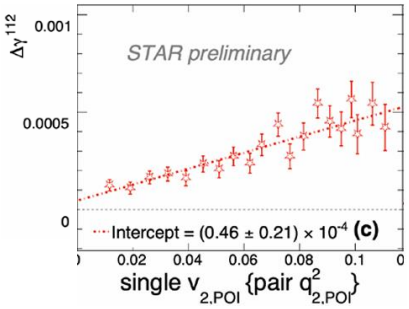
ESS Z. Xu et al. (STAR), arXiv:2401.00317

Biases from pair $q_{2,POI}^2$ selections by using the same POI's

$v_{2,res}$ unnecessarily $\propto v_2$

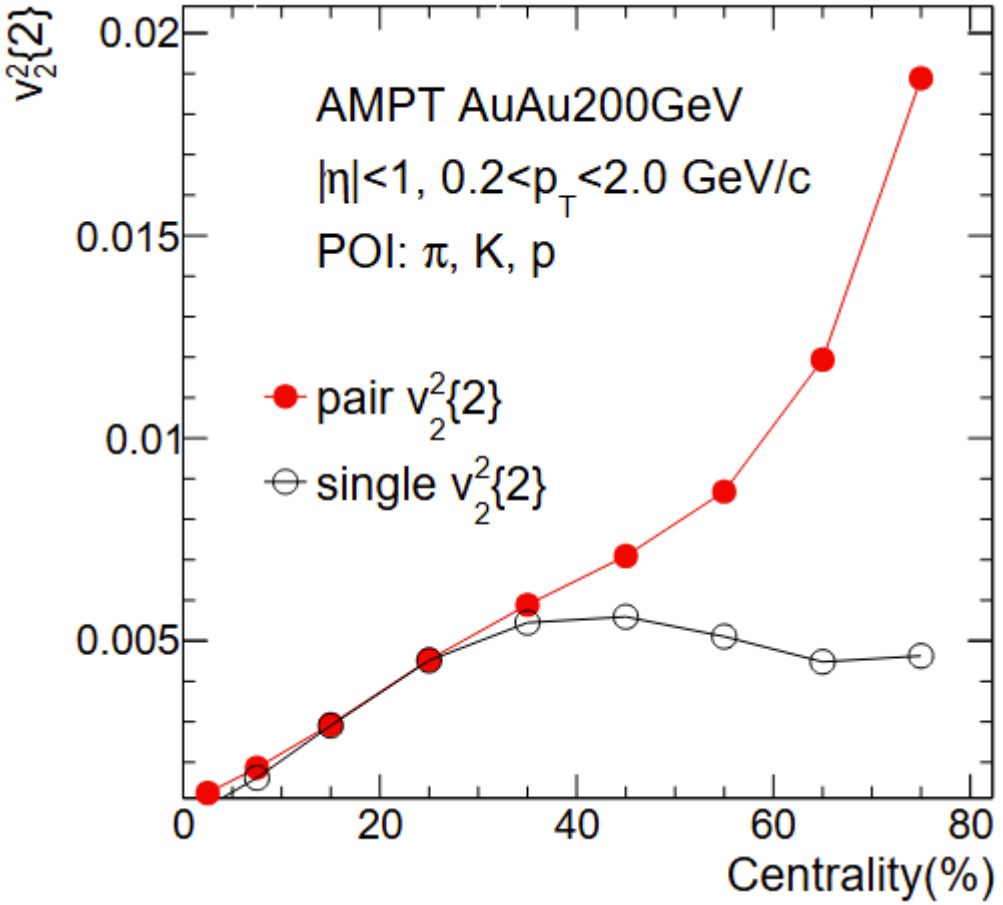
Statistical fluctuation





Event-shape variable: pair $q_{2,pair}^2$

$$\langle q_2^2 \rangle \approx 1 + N v_2^2\{2\}$$



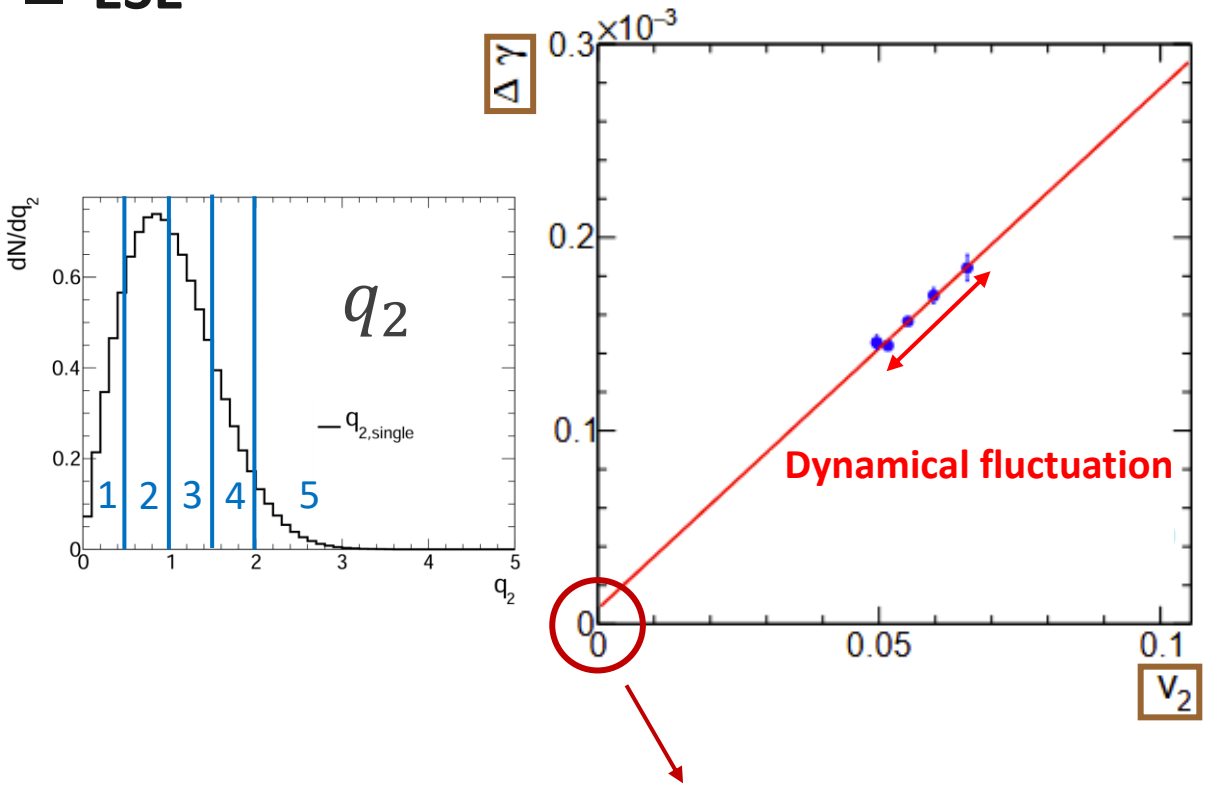
- What is pair q_2^2?
  - Flow
  - Nonflow
  - Self correlation: two pairs share one same particle

- **Pair q_2^2, single v_2, $\Delta\gamma$** using the same POIs, and are therefore entangled.

  Their statistical fluctuations are all correlated.

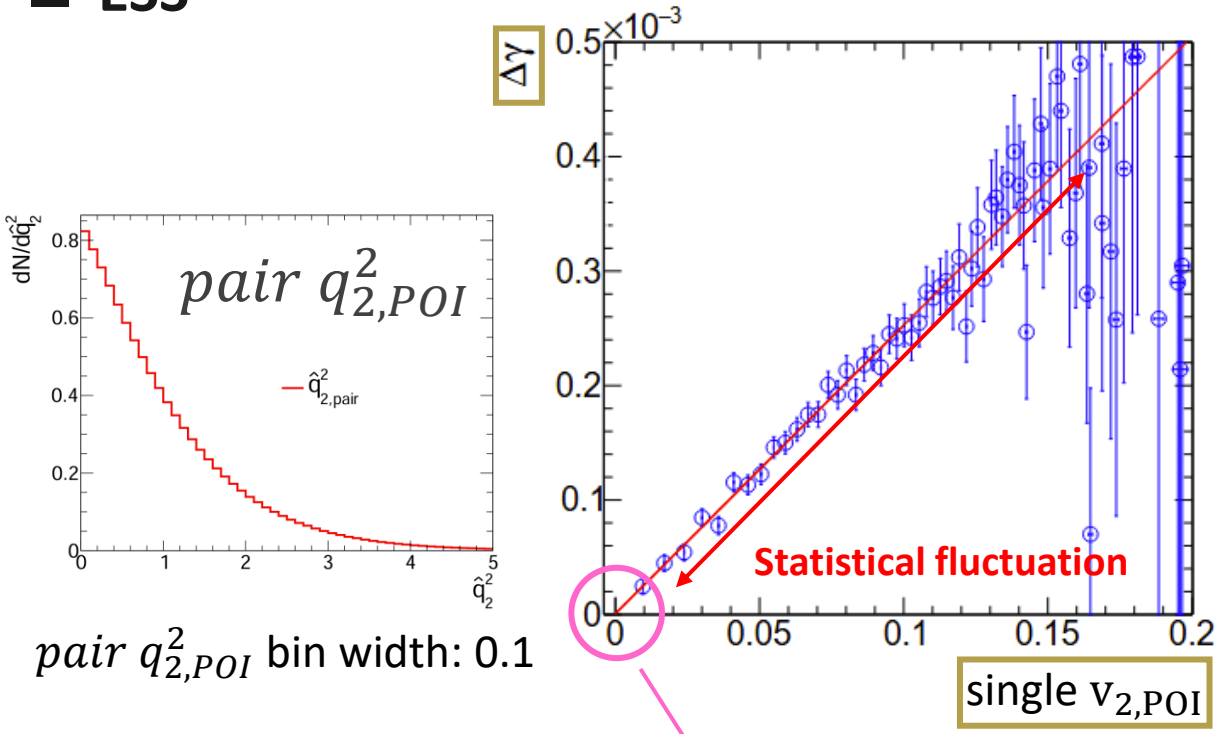
Analysis techniques, dyn. vs. stat. fluctuations

ESE



- $\Delta\gamma \approx b_{bkg} * v_2 +$ $\Delta\gamma_{\mathrm{ESE}}$ (CME signal)

ESS



$pair\ q^2_{2,POI}$ bin width: 0.1

- $\Delta\gamma \approx b_{bkg} *$ single $v_{2,\mathrm{POI}} + \Delta\gamma_{ESS}$ (CME signal?)

Physics model results (no CME included)

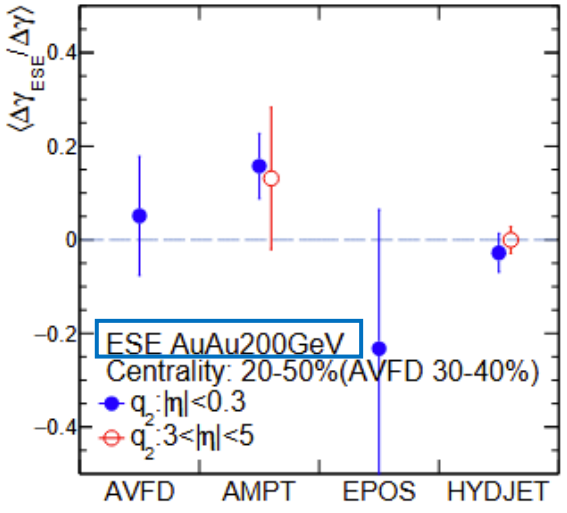
Physics models: AVFD, AMPT, EPOS, HYDJET

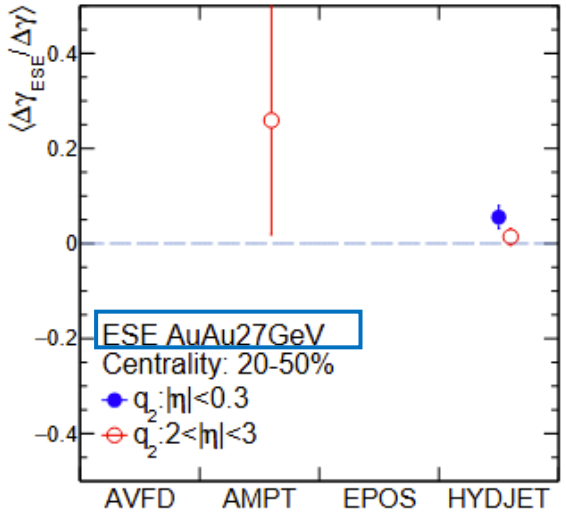
H. Li, Feng, Wang, arXiv:2407.14489

ESE

Ratio of ESE intercept over inclusive $\Delta\gamma$

POI acceptance: $0.3 < |\eta| < 1$



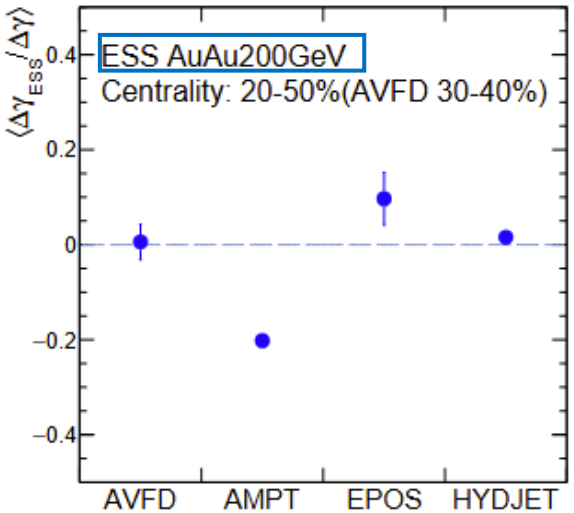


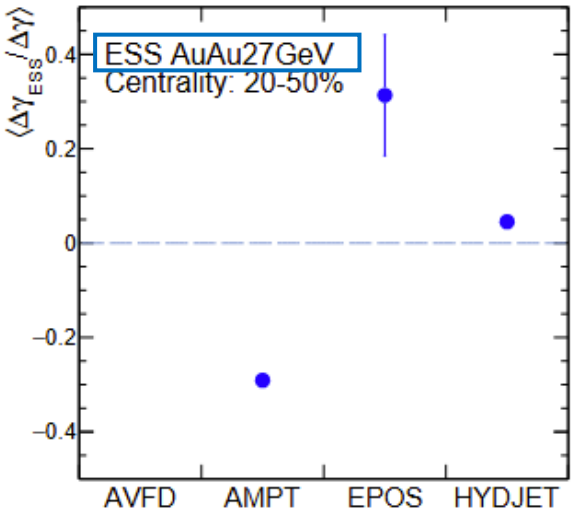
- ESE generally consistent with zero (relatively large error bar)

ESS

Ratio of ESS intercept over inclusive $\Delta\gamma$

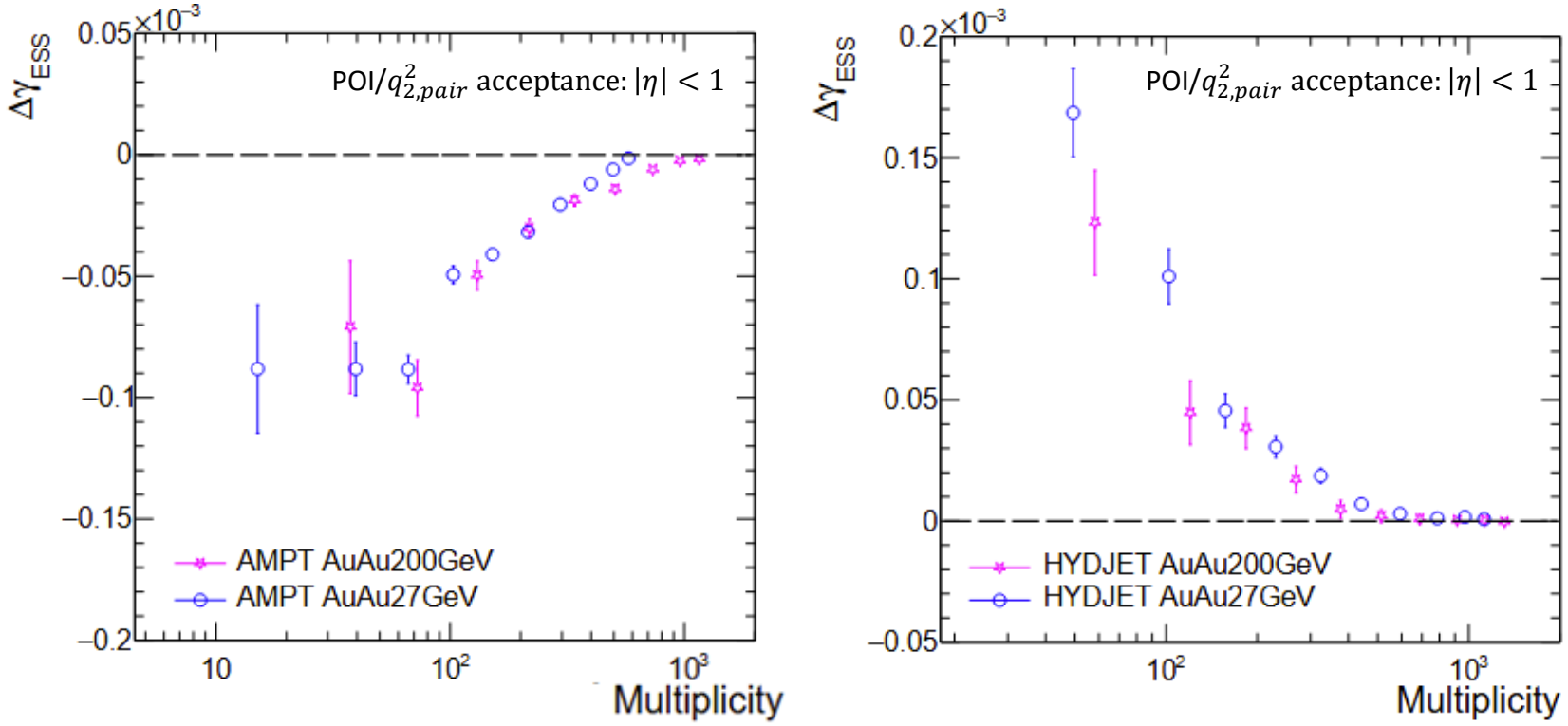
POI/$q^2_{2,pair}$ acceptance: $|\eta| < 1$





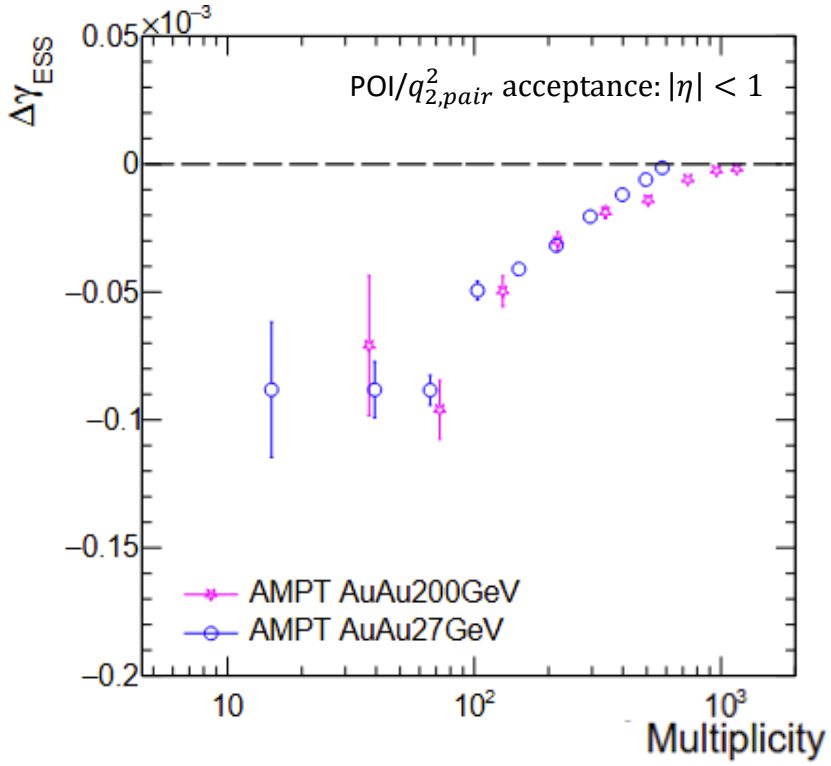
- ESS intercept inconsistent with zero depending on models (negative, positive)

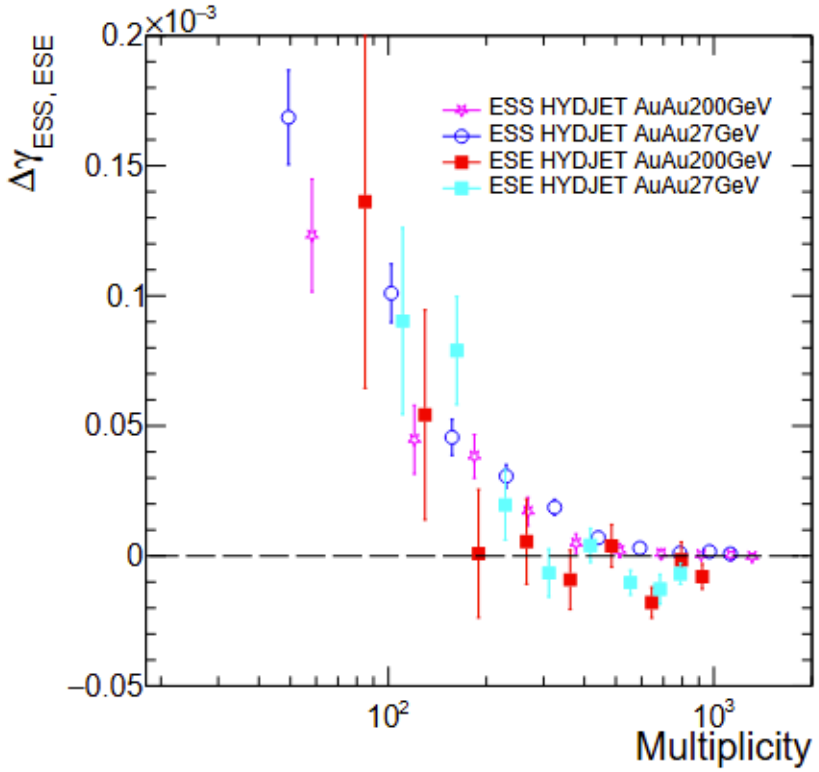
Intercept dependent on multiplicity



- $\Delta\gamma_{ESS}$ deviates from zero, more in peripheral collisions
- $\Delta\gamma_{ESS}$ depends on multiplicity, weak energy dependence

Intercept dependent on multiplicity



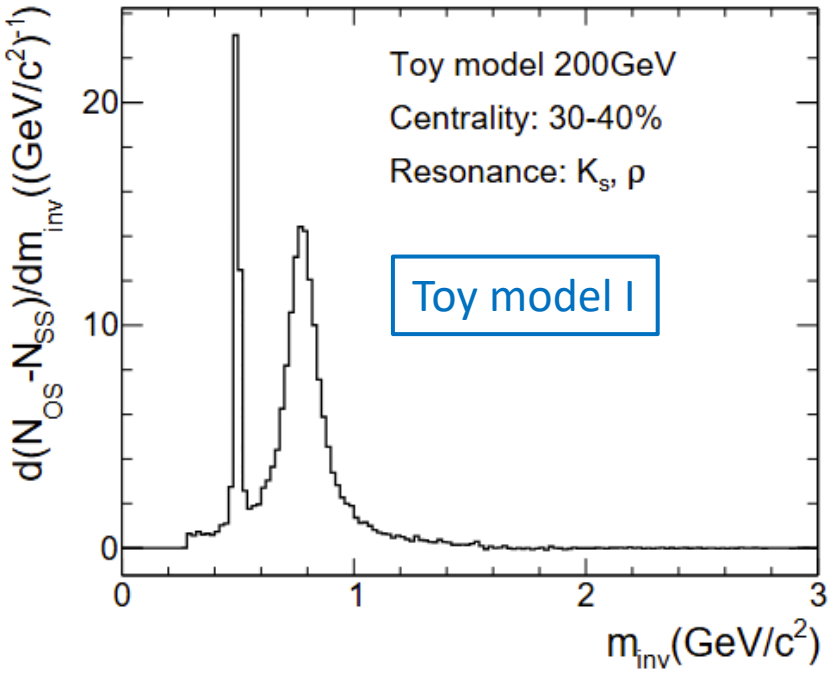


- $\Delta\gamma_{ESS}$ deviates from zero, more in peripheral collisions
- $\Delta\gamma_{ESS}$ depends on multiplicity, weak energy dependence
- $\Delta\gamma_{ESE}$ also deviates from zero, more in peripheral collisions, but relatively large error bars

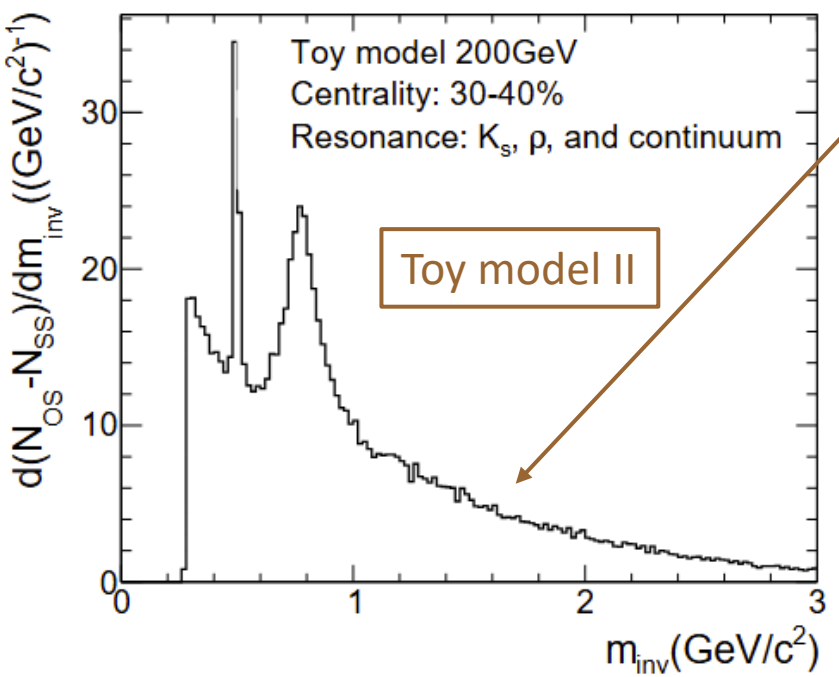
Toy model study to decipher the intercepts

- Particle/resonance spectra from measured data (STAR AuAu200GeV)
- To examine how the makeup of background affects intercepts

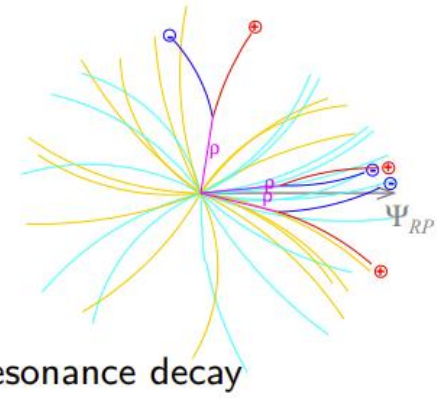
Varying the mixture of K_s/ρ_0



Adding a local charge conservation continuum

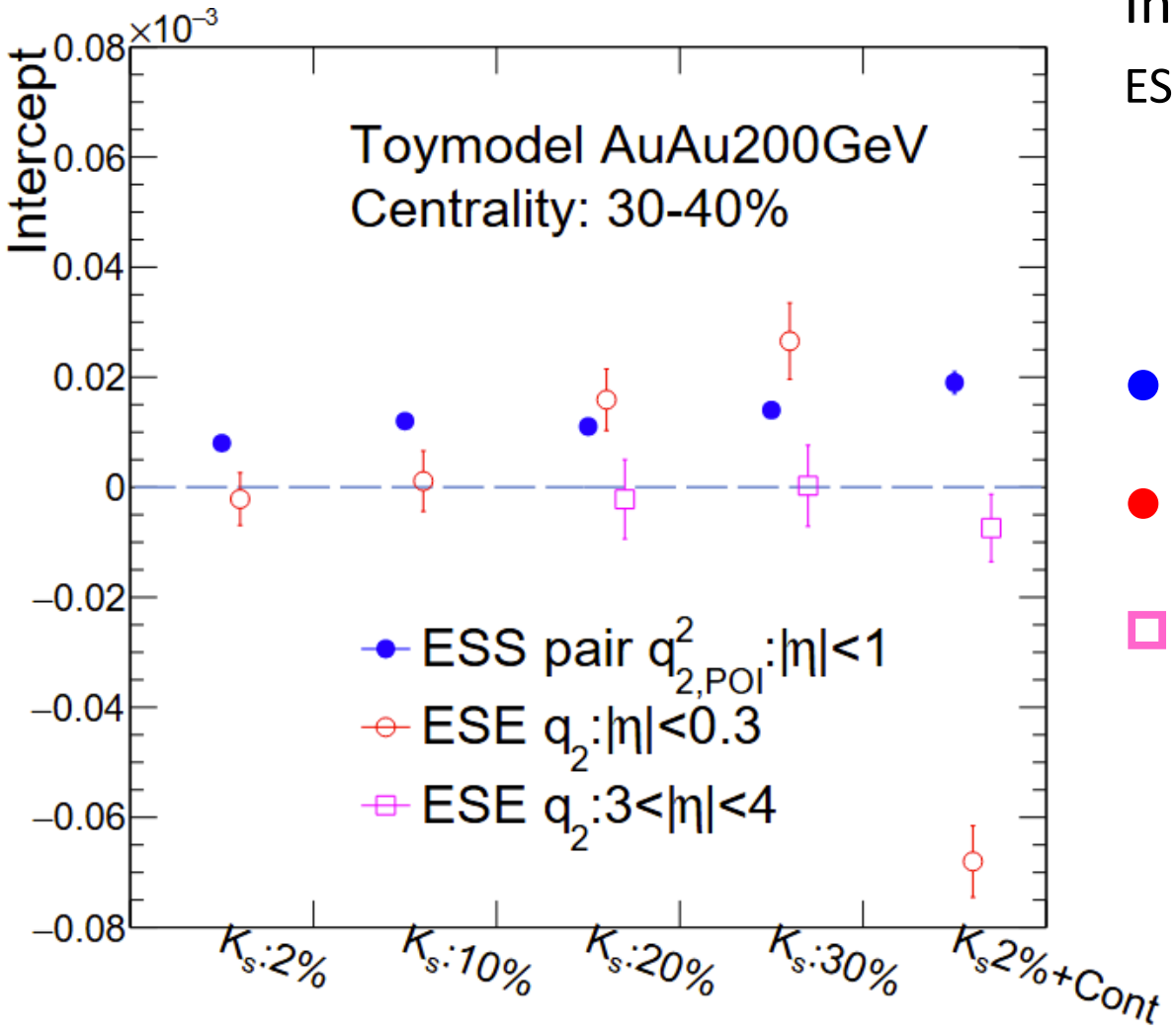


backgrounds



resonance decay

Toy model study to decipher the intercepts



Intercept vs. different K_s, ρ_0 mixture

ESE (ESS) POI acceptance: $0.3 < |\eta| < 1$ $(|\eta| < 1)$

- ESS intercept seems to increase with increasing K_s mixture
- q_2 from $|\eta| < 0.3$ is presumably affected by nonflow with POI
- Minimal non-flow using forward q_2

Summary

- Investigated ESS and ESE methods using physics and toy models

- ESE selects on dynamical fluctuations
  - Gap in projection to zero v_2 renders large uncertainties
  - Physics interpretation of intercept:
    May be complicated by nonflow between POI and q_2

- ESS selects on statistical fluctuations
  - $\boldsymbol{pair\ q_2^2}$, $\boldsymbol{single\ v_2}$, $\boldsymbol{\Delta\gamma}$ all use the same POI; intertwined, correlated stat. fluc.
  - Physics interpretation of intercept:
    Complicated by the fact that all variables are entangled
  - ESS intercept can be negative, zero, or positive, depending on details

The ESS method is not practical to search for CME:
It is unclear what the intercept is