Results from a modified R_{Ψ_2} observable in isobar collisions at STAR

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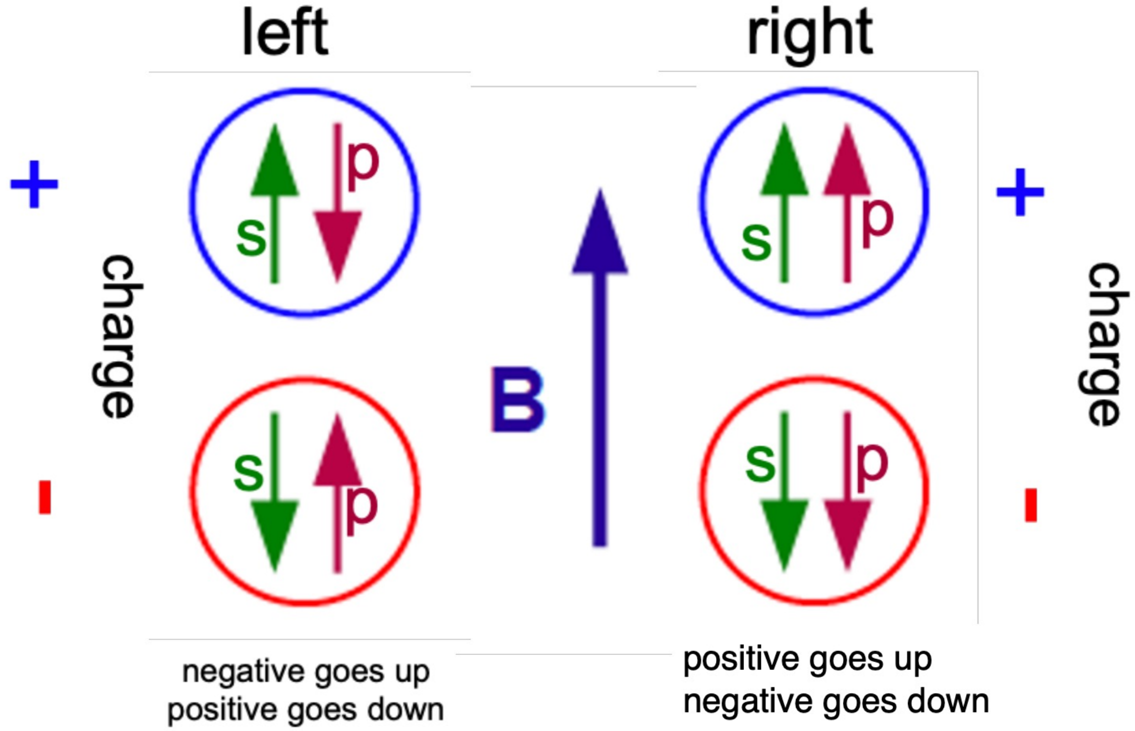
Chiral Magnetic Effect (CME) Introduction

- **Quantum Chromodynamics (QCD**) chiral anomaly **can produce an excess of right/left handed quarks in vacuum**

- Charges separate in magnetic field due to spectator protons

- Experimentally, observe **charge separation in final state particles** [1,2]



$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

[1] D. Kharzeev, R. Pisarski, and M. H. Tytgat, Phys.Rev.Lett. 81, 512 (1998)
[2] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl.Phys. A803, 227 (2008),

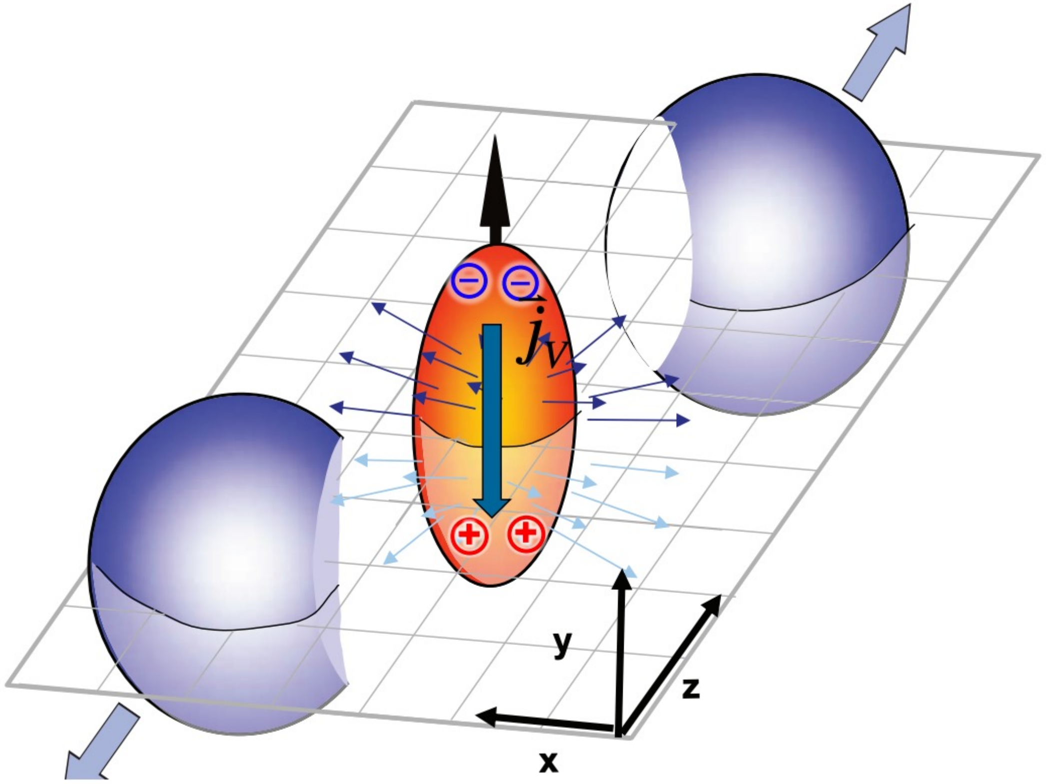
CME Introduction

- **B field** and **J** are aligned perpendicular to reaction plane (Ψ_{RP})

- The azimuthal distribution of particles can be expressed as:

$$\frac{dN^{\pm}}{d\phi} \propto 1 \pm 2a_1 \sin(\phi - \Psi_{RP}) + 2v_2 \cos 2(\phi - \Psi_{RP}) + \dots$$

  - $\boldsymbol{a_1}$ Charge dependent **CME signal**
  - v_2 Elliptic flow coefficient
  - Ψ_{RP} RP azimuthal angle

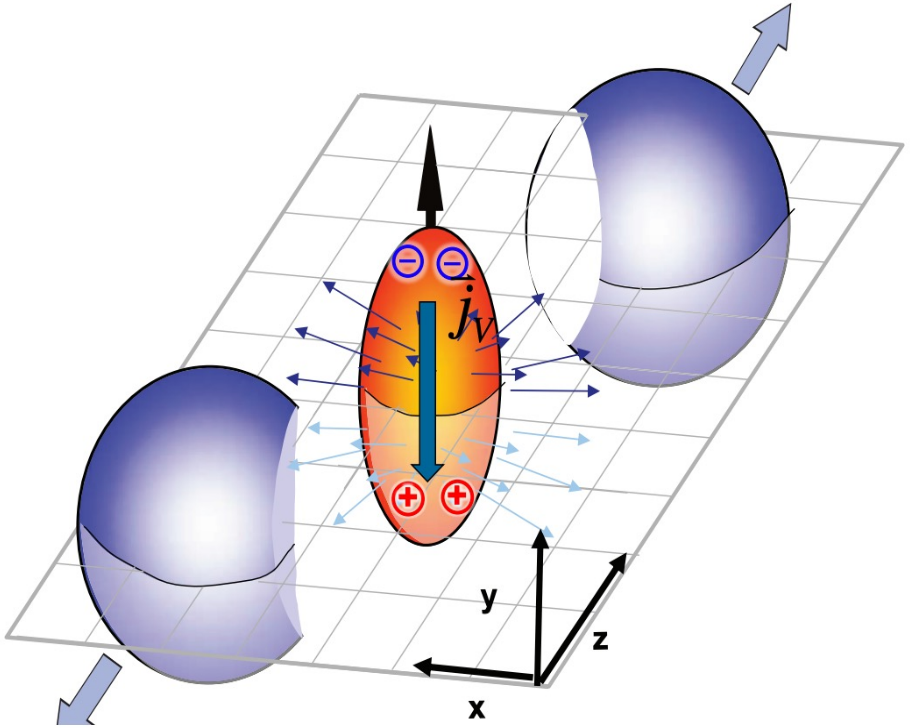


R Observable for CME

- Break an event into two subevents (East and West), by $0.1 < |\eta| < 1.0$
  - **Event Plane,** using empirical resolution correction [3]:
  - **POI -- Charge Separation (ΔS)**

- ΔS are calculated **parallel** and **perpendicular** to the **EP**
  - Example: Parallel ΔS for the West subevent
  - $\Delta S_m^w = \frac{1}{n_w^+}\sum_i^{n_w^+} \sin(\frac{m}{2}(\phi_i^+ - \Psi_m^E)) - \frac{1}{n_w^-}\sum_i^{n_w^-} \sin(\frac{m}{2}(\phi_i^- - \Psi_m^E))$

- **Can keep ΔS separate or take the average**



[3] M. Abdallah et al. (STAR Collaboration), Phys. Rev. C **105**, 014901 (2022)

R Observable for CME

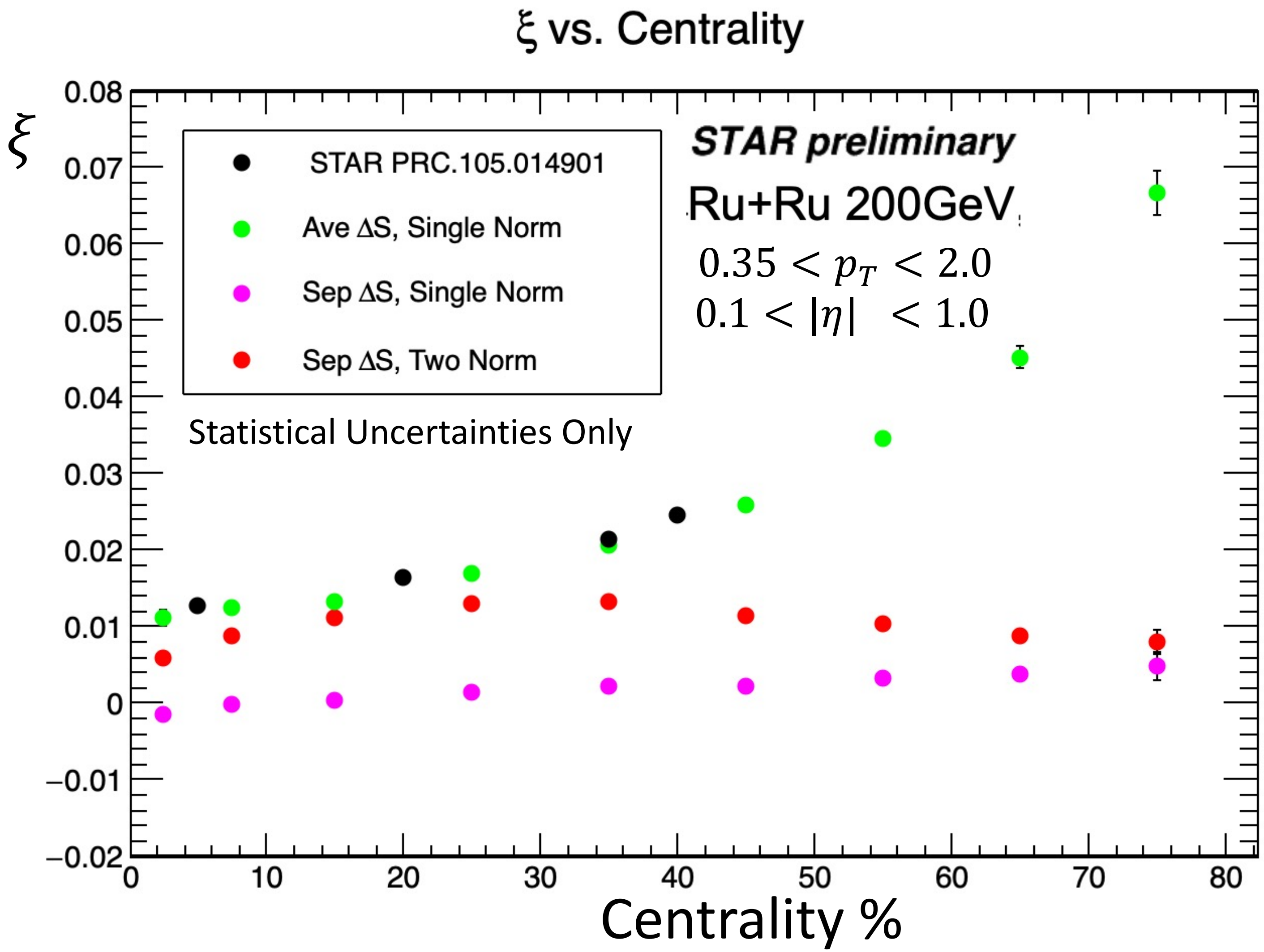
- The **R observable** is defined as the **ratio** between the **parallel** and **perpendicular** ΔS **distributions.**

- $$\boldsymbol{R_{\Psi_m} = \frac{\frac{\Delta S_m}{\Delta S_{m,sh}}}{\frac{\Delta S_m^{\perp}}{\Delta S_{m,sh}^{\perp}}} = Ce^{\xi x^2/2}}$$

- Contributions from **CME in** $\boldsymbol{R_{\Psi_m}}$ should be **concave**

- Width of R distribution, from ΔS distributions: $\frac{1}{\sigma^2} = (\frac{1}{\sigma_m^2} - \frac{1}{\sigma_{m,sh}^2}) - (\frac{1}{\sigma_{m\perp}^2} - \frac{1}{\sigma_{m\perp,sh}^2})$
  - $\boldsymbol{\xi = \frac{1}{\sigma'^2} = (\frac{\sigma_{m,sh}^2}{\sigma_m^2} - 1) - (\frac{\sigma_{m,sh}^2}{\sigma_{m\perp}^2} - \frac{\sigma_{m,sh}^2}{\sigma_{m\perp,sh}^2})}$: Single (Shuffled) Normalization
  - $\boldsymbol{\xi = \frac{1}{\sigma'^2} = (\frac{\sigma_{m,sh}^2}{\sigma_m^2} - \frac{\sigma_{m\perp,sh}^2}{\sigma_{m\perp}^2})}$: Two (Shuffled) Normalization
    - "Shuffled" Delta S distributions ($\Delta S_{m,sh}$) are formed by randomly shuffling particle charges

Results

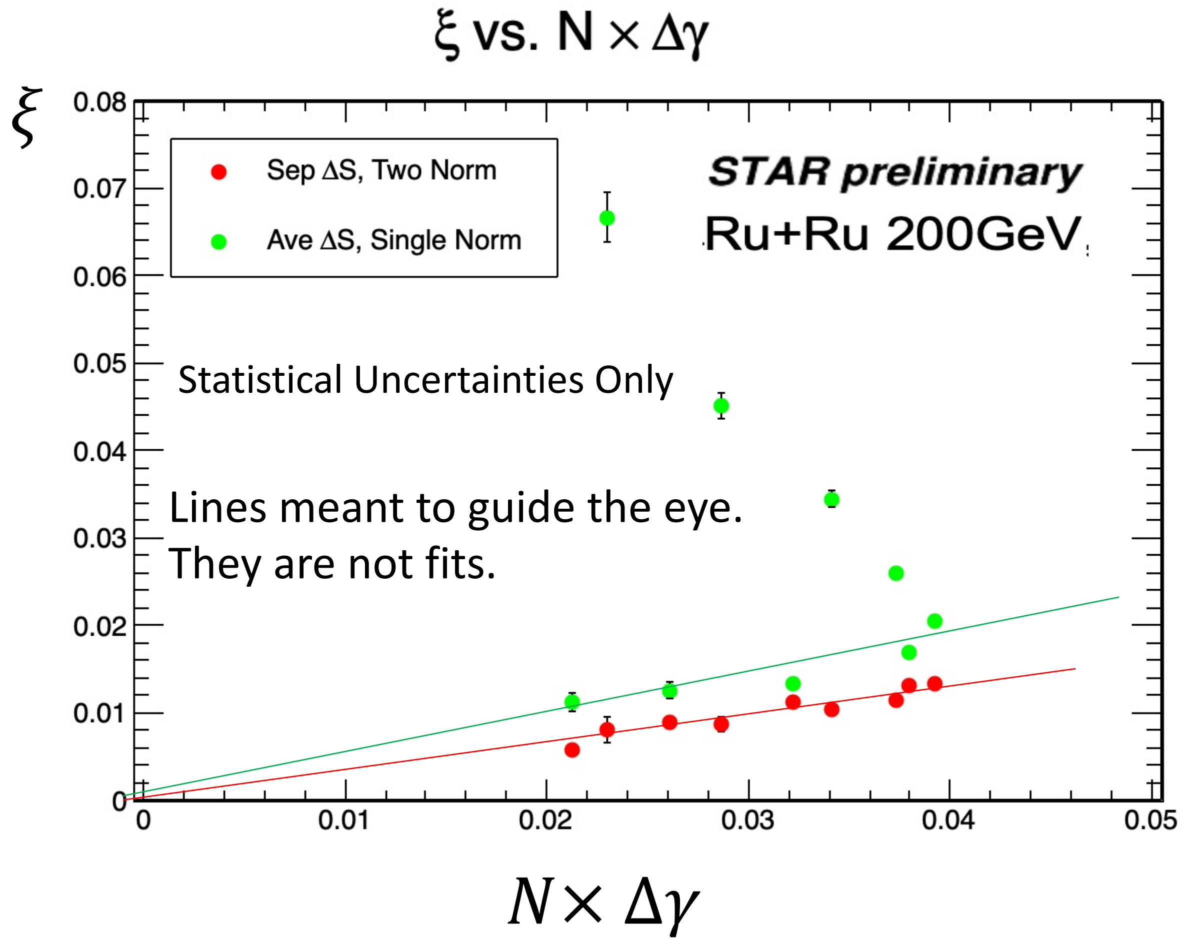


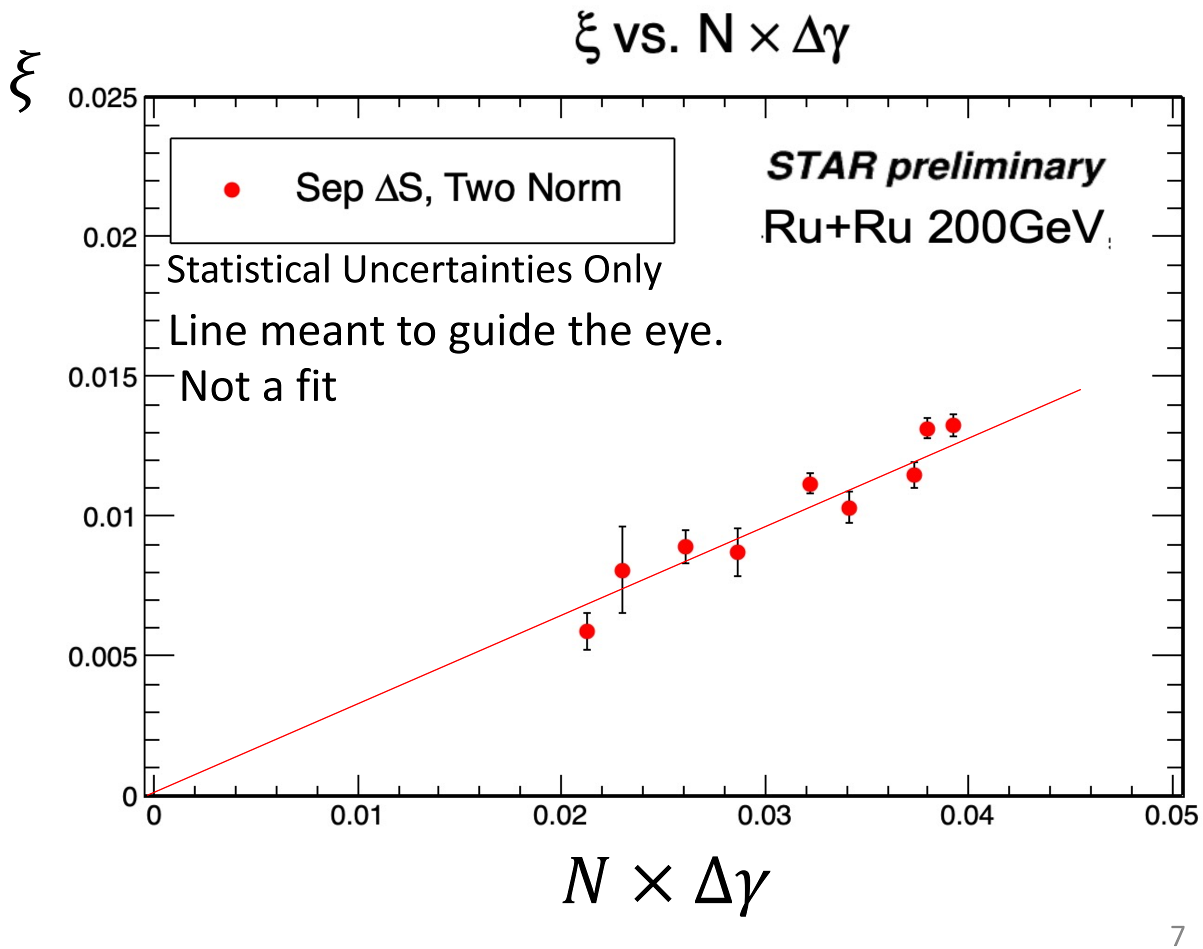
- Averaging ΔS between two sub-events can introduce autocorrelation, that is centrality dependent [4]
  - $Var[\Delta S] = \frac{1}{4}\langle \Delta S_E^2 \rangle + \frac{1}{4}\langle \Delta S_W^2 \rangle + \frac{1}{2}\langle \Delta S^E \Delta S^W \rangle$
- **Not expected in separate sub-event ΔS**
  - $\xi = \frac{1}{\sigma'^2} = (\frac{\sigma_{m,sh}^2}{\sigma_m^2} - 1) - (\frac{\sigma_{m,sh}^2}{\sigma_{m\perp}^2} - \frac{\sigma_{m,sh}^2}{\sigma_{m\perp,sh}^2})$
    - Single (Shuffled) Normalization
- Normalizations can make a difference
  - $\xi = \frac{1}{\sigma'^2} = (\frac{\sigma_{m,sh}^2}{\sigma_m^2} - \frac{\sigma_{m\perp,sh}^2}{\sigma_{m\perp}^2})$
    - Two (Shuffled) Normalization

[4] Y. Feng et al., Decipher the R_{Ψ_m} in search for the chiral magnetic effect in heavy ion collisions, Phys. Rev. C 103, 034912 (2021)

Correlation between ξ and $\mathrm{N} \times \Delta\gamma$

Separate or Average ΔS affect the correlation between ξ and $N \times \Delta\gamma$



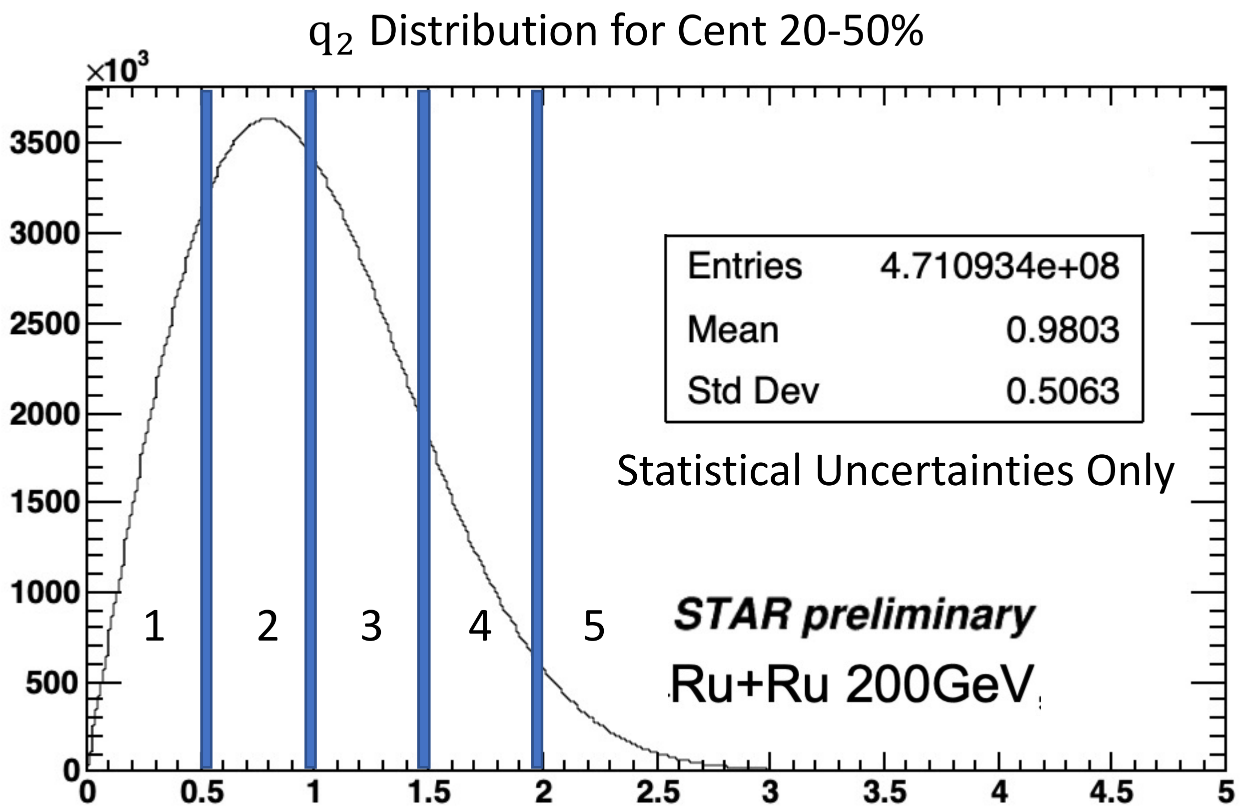


Now, onto to Event Shape Engineering (ESE) Analysis[5]

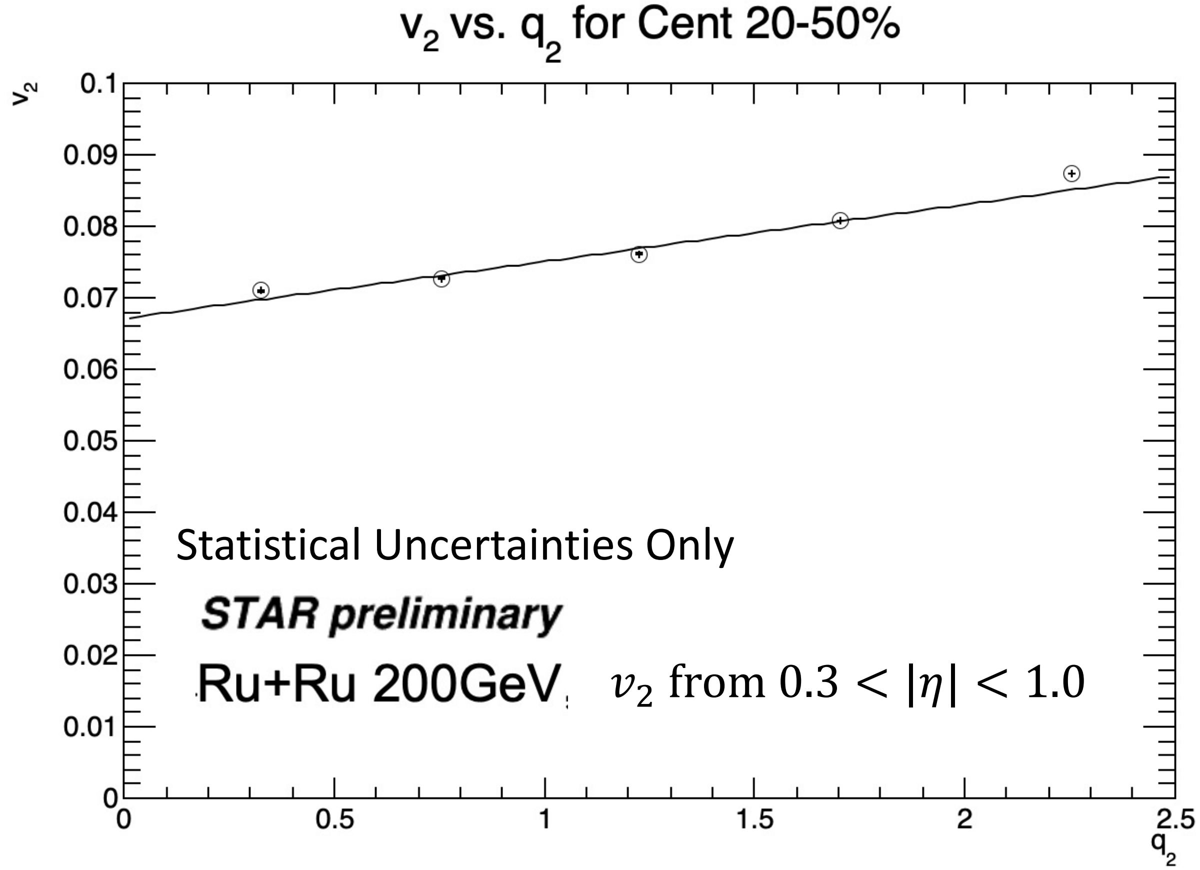
- ξ is expected to similar to N $\times$ $\Delta\gamma$, which is proportional to v_2[6]
  - $\boldsymbol{\xi}$ was **observed to be roughly independent of $\boldsymbol{v_2}$ with non-zero intercept**[3]
  - Want to **examine modified $\boldsymbol{\xi}$ vs. $\boldsymbol{v_2}$ in ESE**

[5] J. Schukraft, A. Timmins, and S. A. Voloshin,
Ultrarelativistic nuclear collisions: event shape engineering, Phys. Lett. B719, 394 (2013)
[6] S. Choudhury et al. , Investigation of experimental observables in search of the chiral magnetic effect in heavy-ion collisions in the STAR experiment, Chinese Phys. C 46 014101 (2022)

v_2 $vs.$ q_2

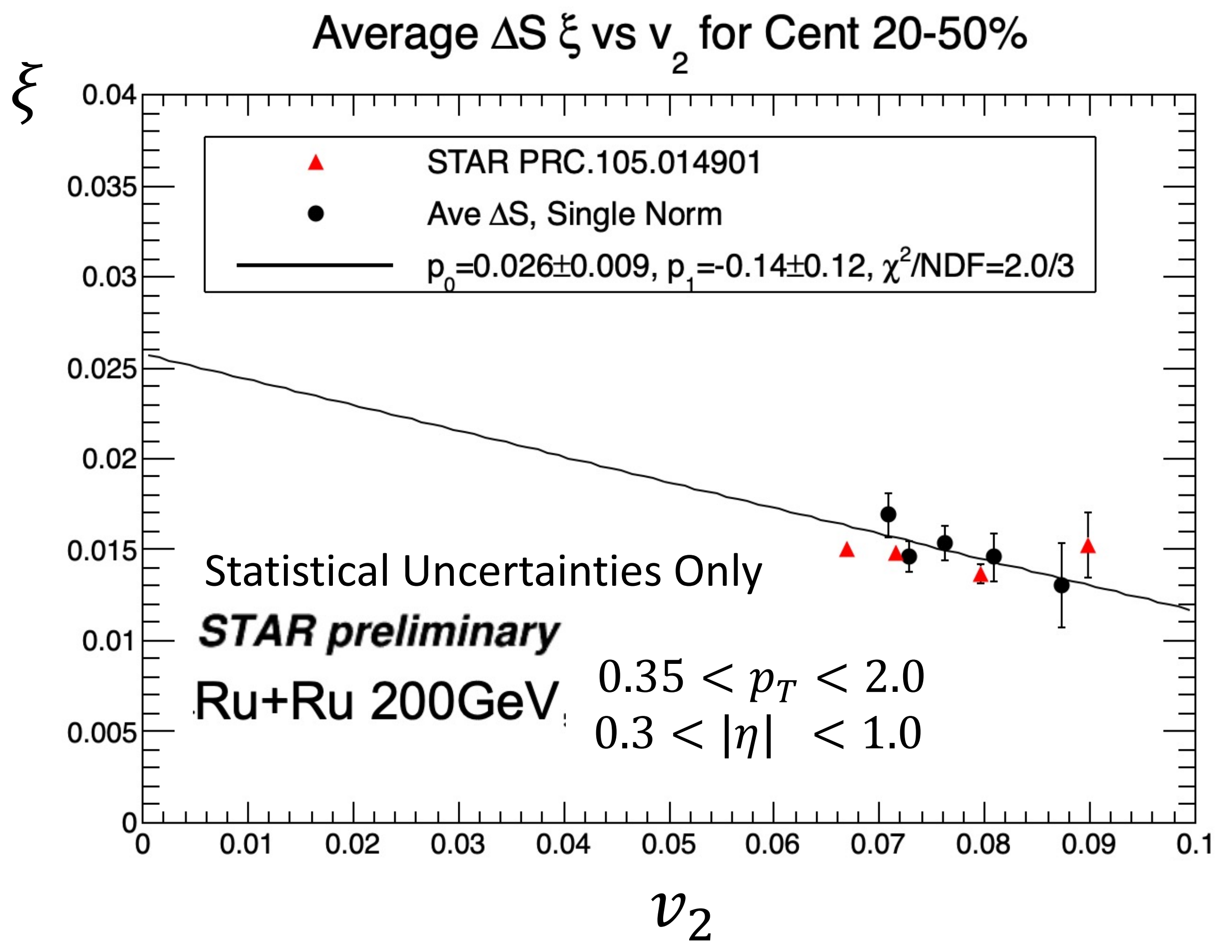


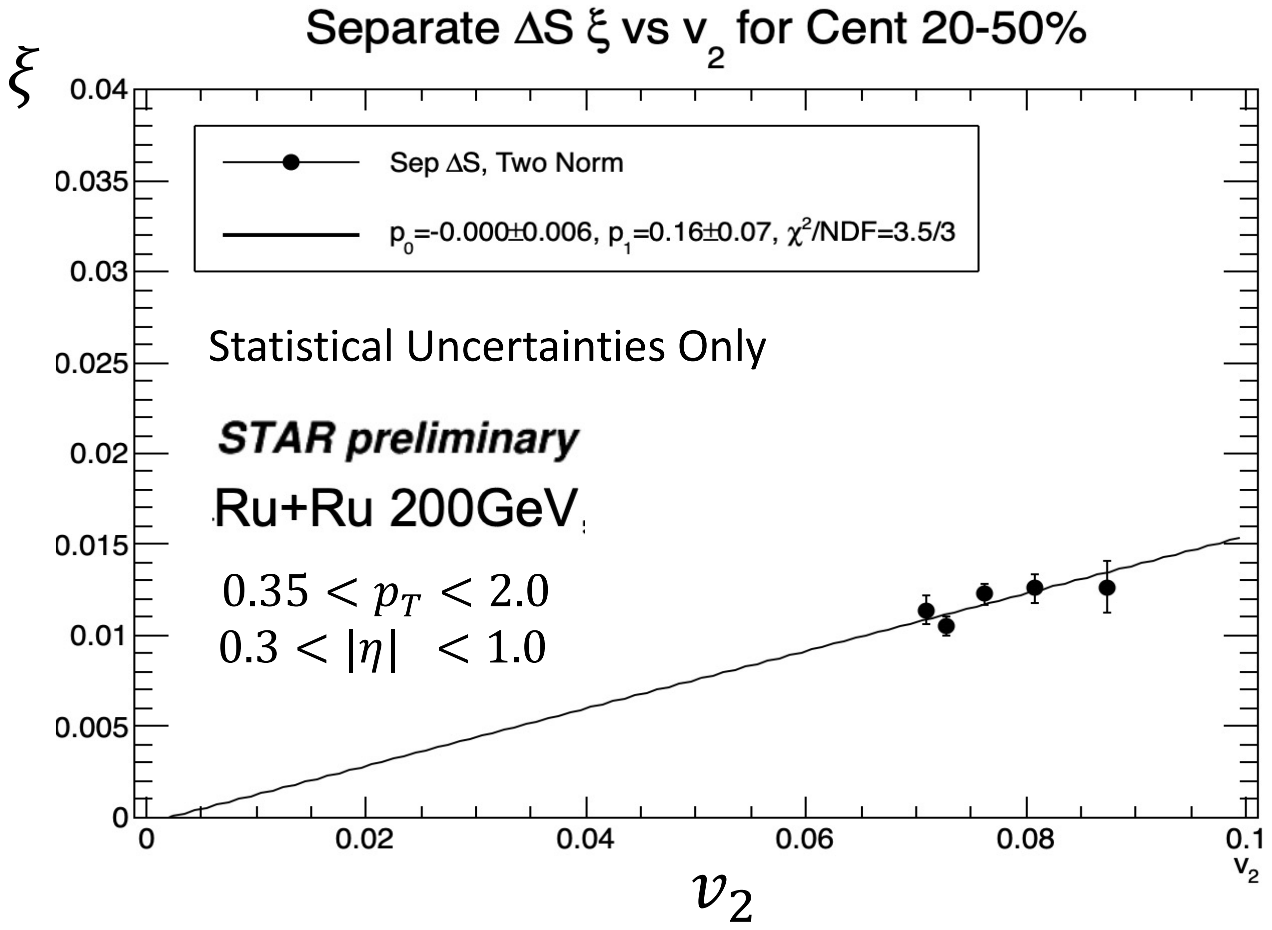
q_2 calculated from middle subevent $|\eta| < 0.3$ with particles satisfying $0.2 < p_T < 2.0$



Weighted average of q_2, and v_2 over the Centrality 20-50% range, each weighted by the number of events

ξ vs v_2 for Cent 20-50%





The Average ΔS introduces an autocorrelation yielding a non-zero intercept.
This intercept is not present in the Separate ΔS case.

Conclusions

A modified R-observable developed for CME search.

- In previous analyses, STAR data are normalized using a **single shuffled distribution**
  - Normalizing by **both perpendicular and parallel** shuffled distributions **makes a difference**

- STAR data **average** the **ΔS distributions** of the subevents
  - This averaging introduces an **autocorrelation** which **increases signal**
  - Yields a **non-zero intercept** in ESE analysis

- Our results (separate subevents, two shuffled normalizations) indicate **weak centrality dependence** of the modified ξ, similar to v_2. Modified ξ observed to be proportional to N $\times$ $\Delta\gamma$

Backup

ESE Analysis Procedure

1) 3 separate centrality bins: 20-30%, 30-40%, 40-50%
2) Event Shape Engineering (ESE) procedure: Each event is split into three subevents east (-1 < η <-0.3), middle (-0.3 < η < 0.3), and west (0.3 < η < 1.0)
3) $q2 = \sqrt{[\left(\sum_i^M \cos(2\phi_i)\right)^2 + \left(\sum_i^M \sin(2\phi_i)\right)^2]/M}$ calculated from the middle subevent (M is the number of particles). Each centrality bin has 5 equal width q2 bins (q2 cuts are the same for all centralities).
4) Accumulate $\cos\left(2(\phi_1 - \phi_2)\right)$. One phi from $-1 < \eta < -0.3$ and the other is from $0.3 < \eta < 1.0$
5) Event Plane (EP) from $-1 < \eta < -0.3$ and four ΔS distributions (real event, shuffled, both perpendicular and parallel to RP) using POI from $0.3 < \eta < 1.0$, and vice versa
6) EP Resolution from $\sqrt{\left\langle\cos\left(2(\Psi_1 - \Psi_2)\right)\right\rangle}$

[Steps 4, 5, 6 are done for each q2 bin in each centrality]

ESE Analysis Procedure II

7) Add $\cos\left(2(\phi_1 - \phi_2)\right)$ for each q2 bin over the 3 centrality bins and calculate

   $v_2 = \sqrt{\left\langle \cos\left(2(\phi_1 - \phi_2)\right)\right\rangle}$

8) For each q2 bin in each centrality calculate $\xi = \frac{1}{\sigma'^2}$ via RMS method

   - $\xi = \frac{1}{\sigma'^2} = (\frac{\sigma^2_{m,sh}}{\sigma^2_m} - 1) - (\frac{\sigma^2_{m,sh}}{\sigma^2_{m\perp}} - \frac{\sigma^2_{m,sh}}{\sigma^2_{m\perp,sh}})$: Single (Shuffled) Normalization
   - $\xi = \frac{1}{\sigma'^2} = (\frac{\sigma^2_{m,sh}}{\sigma^2_m} - \frac{\sigma^2_{m\perp,sh}}{\sigma^2_{m\perp}})$: Two (Shuffled) Normalization

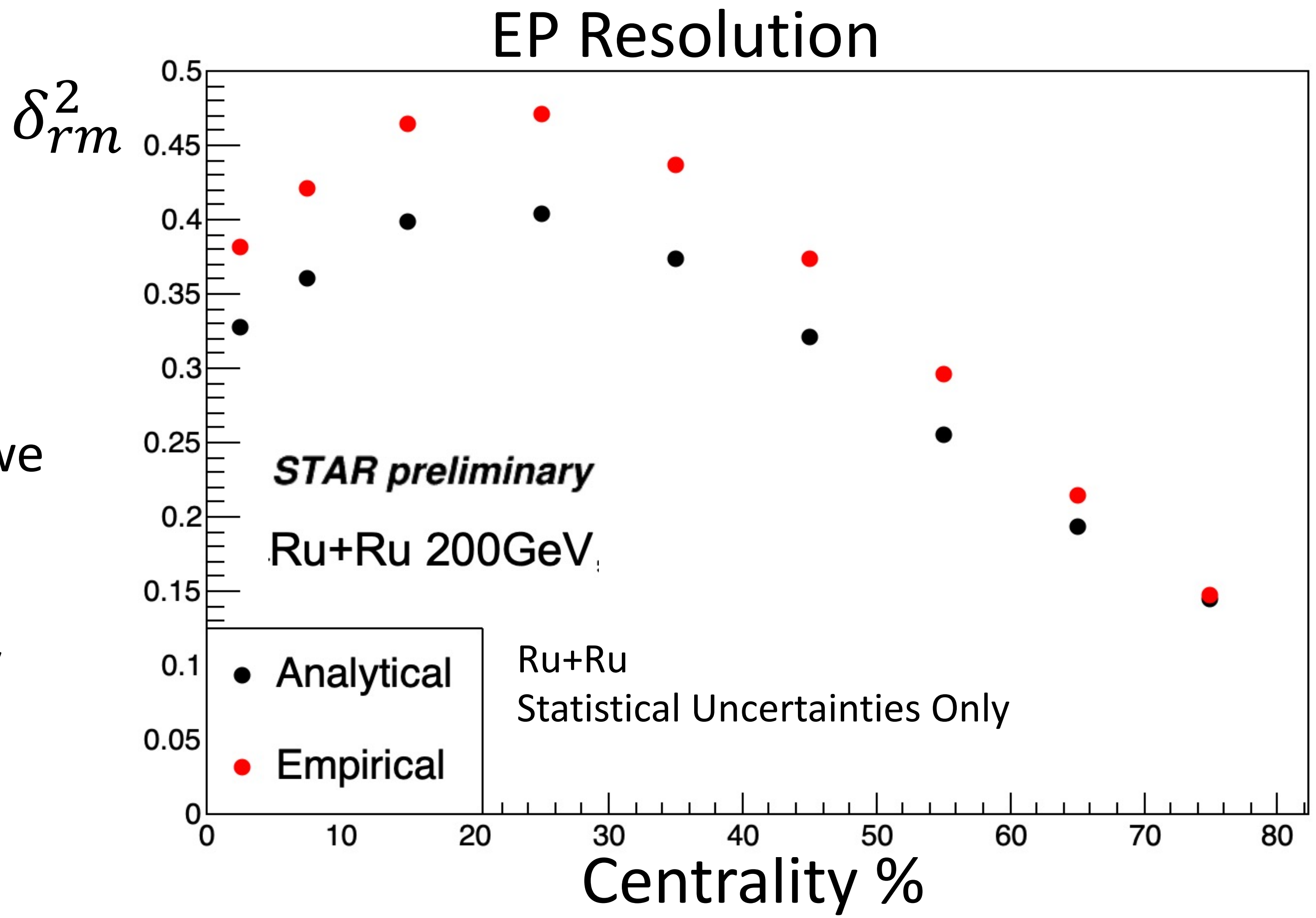
9) Correct by EP resolution (δ^2_{rm}): $\xi^{Cor} = \xi \times \frac{-1}{\delta^2_{rm}}$

10) For each q2 bin, take the average ξ^{Cor} over the three centrality bins weighted by the number of events. This is for the ξ^{Cor}vs. v_2 plot.

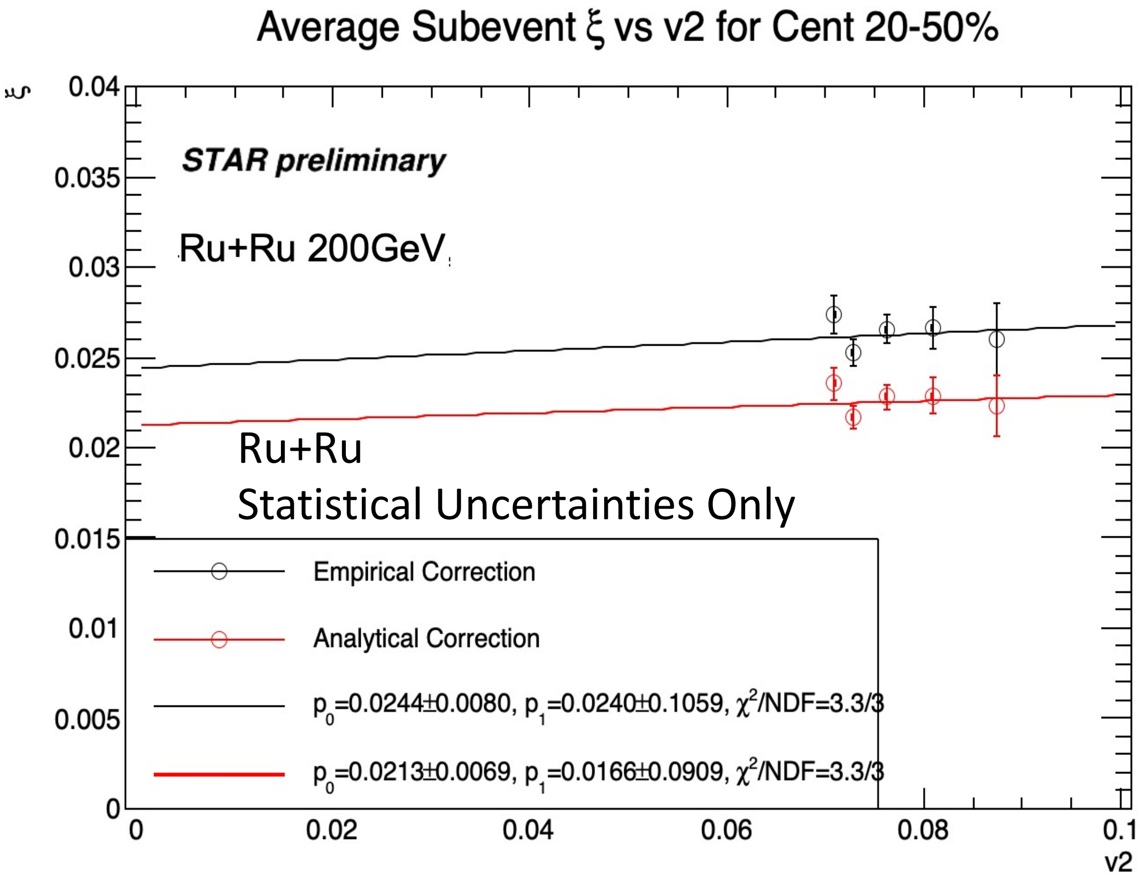
11) All $\xi's$ on all plots are already corrected for EP Resolution, so we only use ξ^{Cor} for backup slides discussing EP Resolution Correction

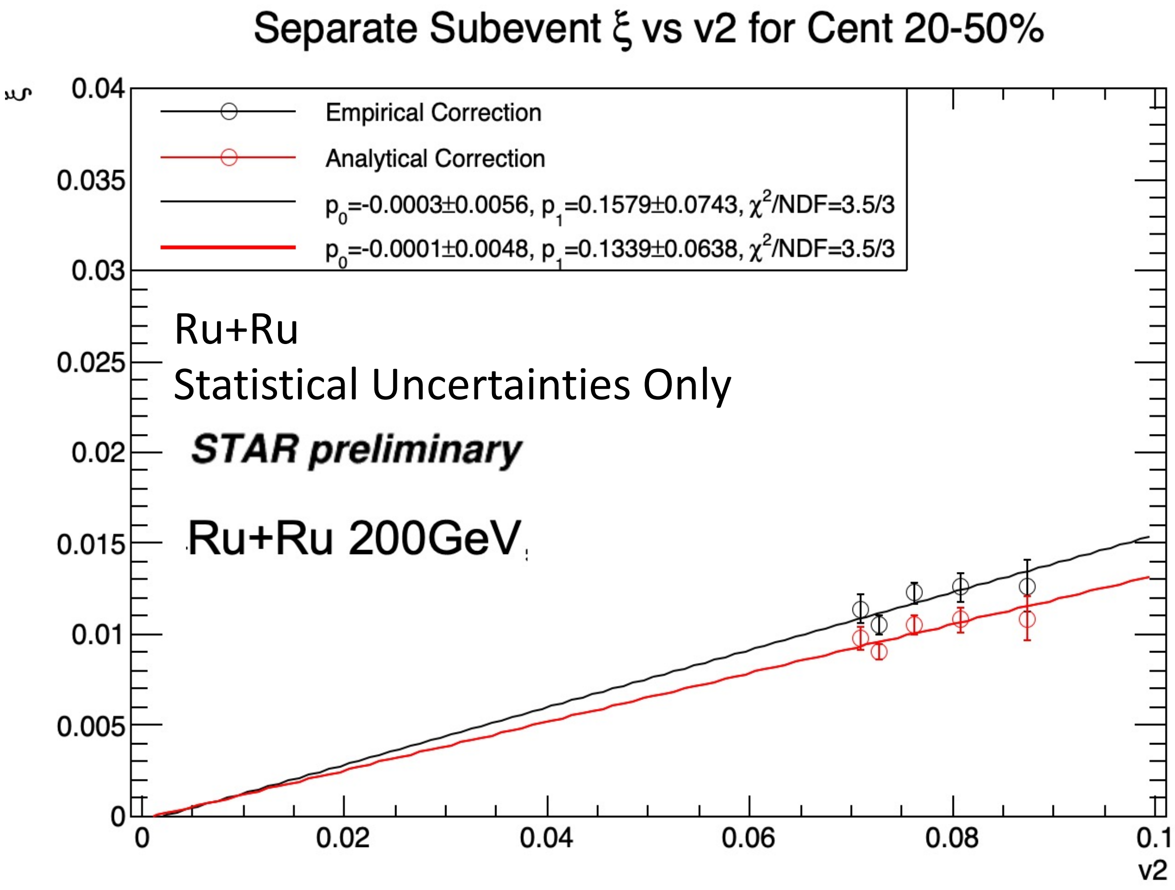
Event Plane Resolution Correction

- ξ also affected by EP Resolution (δ_{rm}^2):
  - $\xi^{Cor} = \xi \times \frac{-1}{\delta_{rm}^2}$
  - 2 ways to get EP Resolution, we use empirical in this study
  - All $\xi's$ on all plots are already corrected for EP Resolution



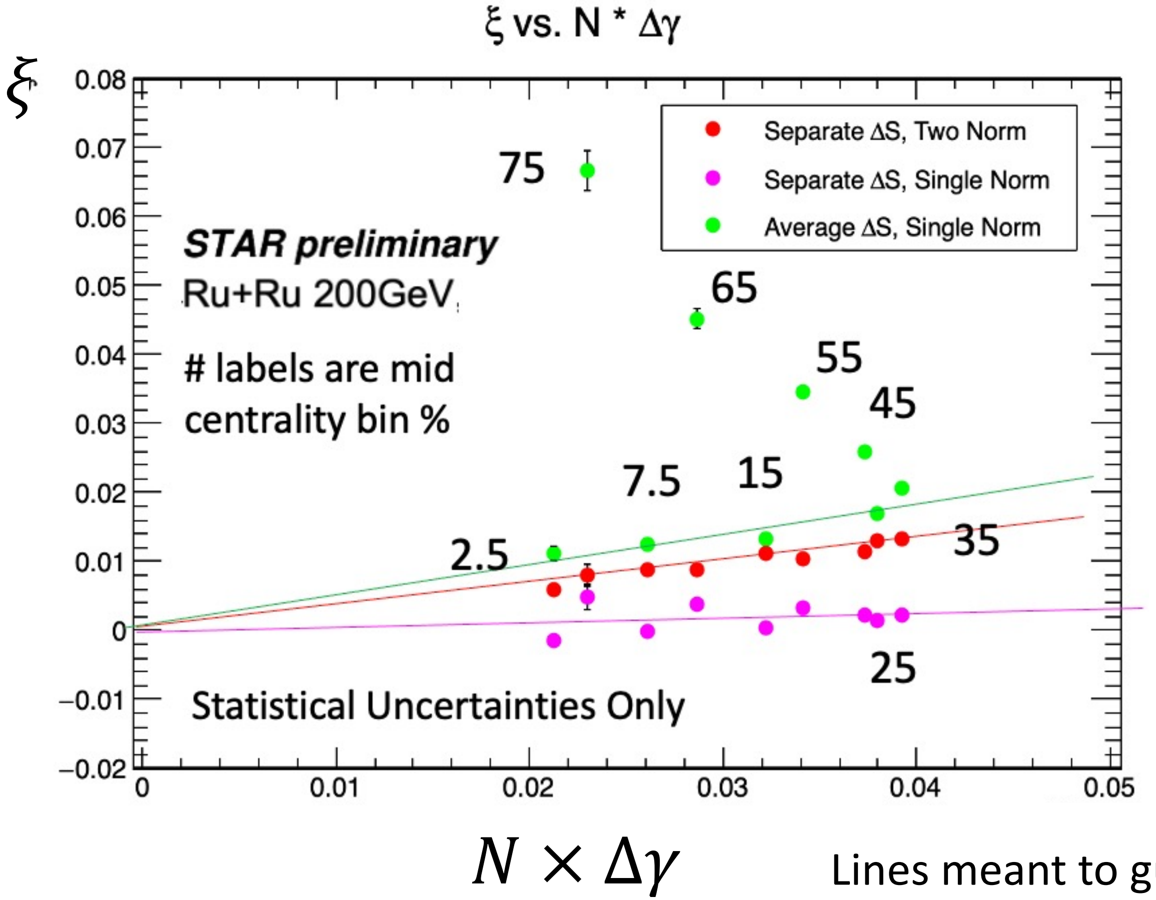
EP Resolution Correction Comparison: ξ vs v_2 for Cent 20-50%

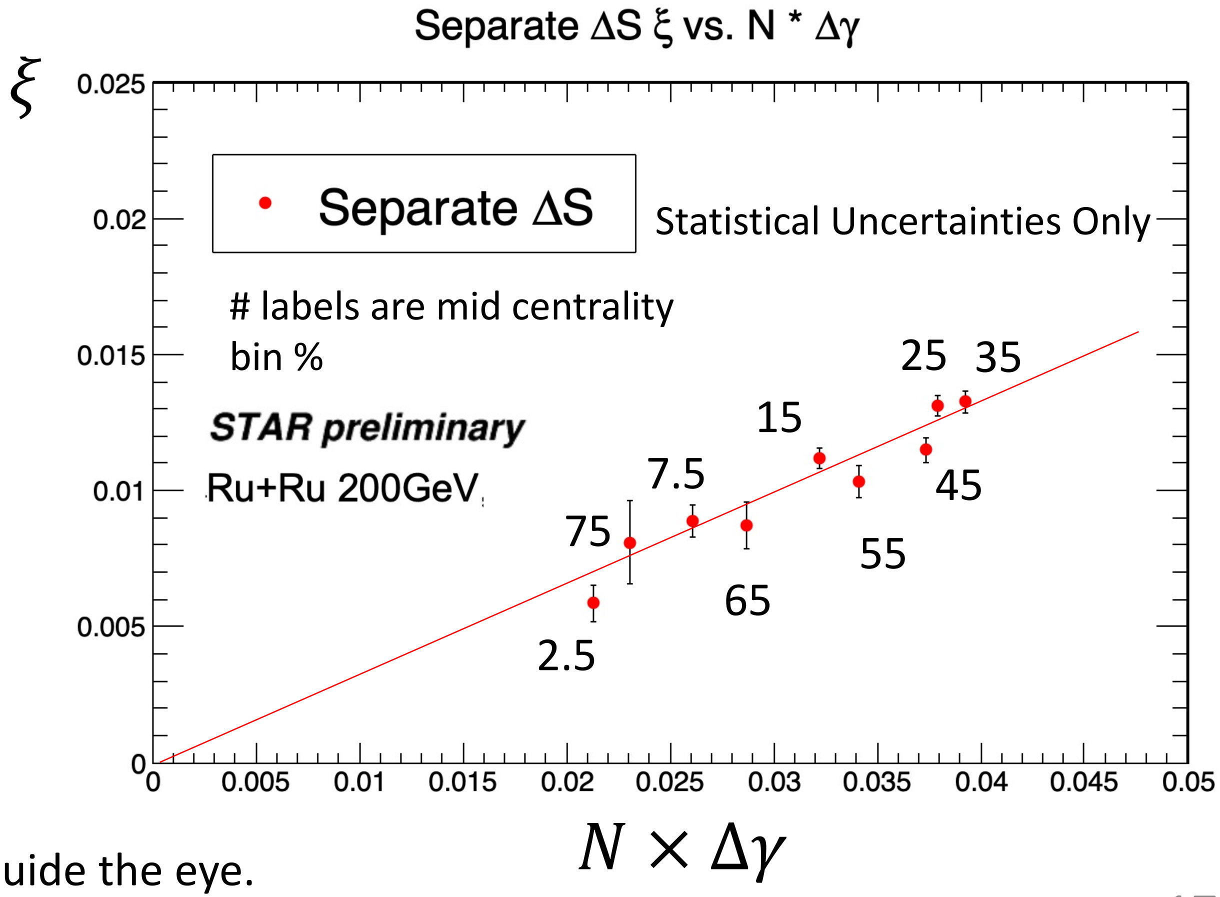




ξ vs $\langle N_{offline} \rangle \times \Delta\gamma$ Check

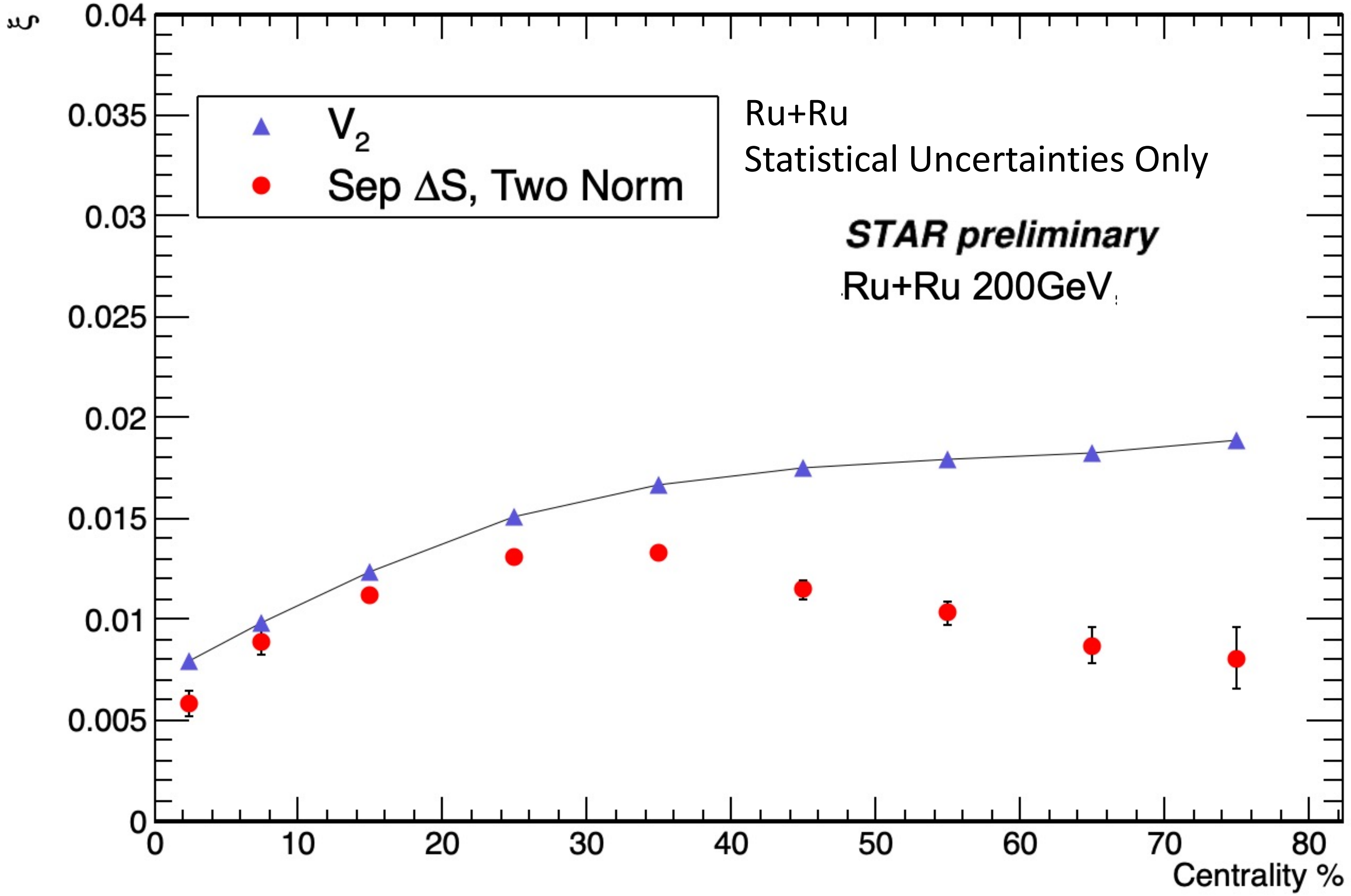
Separte ΔS and different treatments of normalization affect the correlation between ξ and $N * \Delta\gamma$





Lines meant to guide the eye.
They are not fits.

ξ and v_2 vs. Centrality



v_2 scaled by 0.25 to plot on same scale with ξ

Only interested in shape of v_2 *and* ξ vs. centrality in this plot

Normalization and EP Resolution effects on ξ