Scaling properties of background- and chiral-magnetically-driven charge separation in heavy ion collisions

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I. Introduction
II. Correlators used for measurements
III. Scaling properties & their implication

Important take aways:

I. The scaling properties of background- and chiral-magnetically-driven charge separation provides a potent tool for characterizing the CME.

II. Current results indicate;
- ✓ a robust CME signal in Au+Au and isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200\ GeV$.
- ✓ no CME signal in p+Au and d+Au collisions @ $\sqrt{s_{NN}} = 200\ GeV$
- ✓ no CME signal in p+Pb ($5.02\ TeV$) and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\ and\ 5.02\ TeV$

Anomalous Transport in the QGP

Chiral Magnetic Effect (CME)

Electric Current

Chiral Magnetic Conductivity

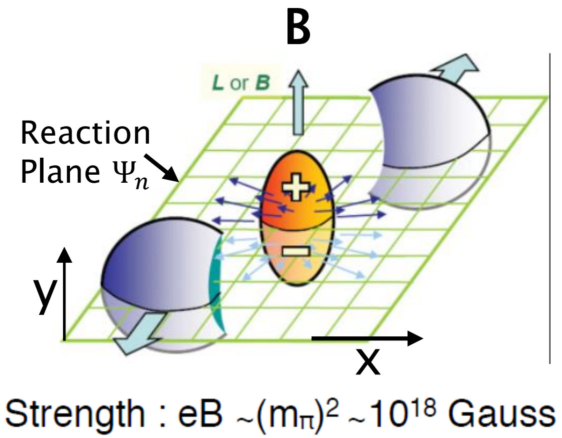
Chiral Chemical potential

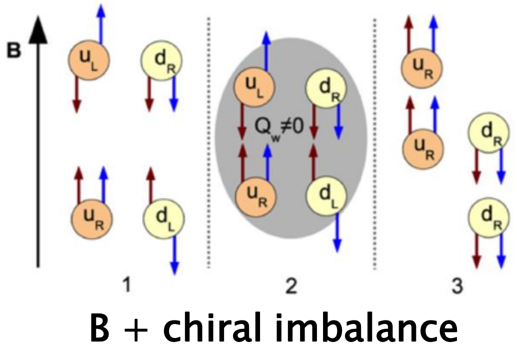
$$\vec{J}_Q = \sigma_5 \vec{B}$$

$$\sigma_5 = C_A \mu_5$$

$$C_A = Q^2 / (4\pi^2)$$

Kharzeev
hep-ph/0406125





The CME results from anomalous transport of chiral fermions in the QGP, leading to the generation of an electric current along the B-field generated in the collision:

- ✓ Results in charge separation along the B-field

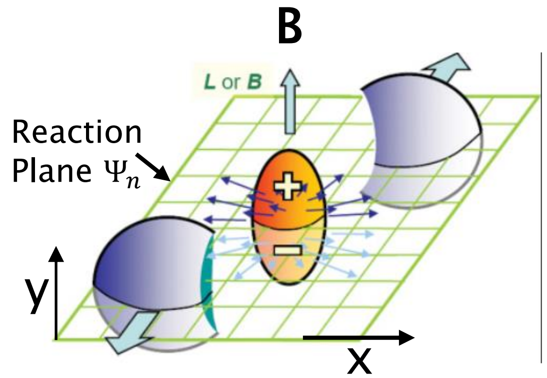
Why an interest in the CME?

CME detection & characterization could provide crucial insights on;

- ✓ Anomalous transport
- ✓ The interplay of chiral symmetry restoration, axial anomaly, and gluonic topology in the QGP

Measuring Charge separation

Strength : eB ~$(m_\pi)^2$ ~10^{18} Gauss



CME-induced charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

$$a_1^{ch} \equiv \left\langle a_1^2 \right\rangle^{1/2} \propto \mu_5 \vec{B}$$

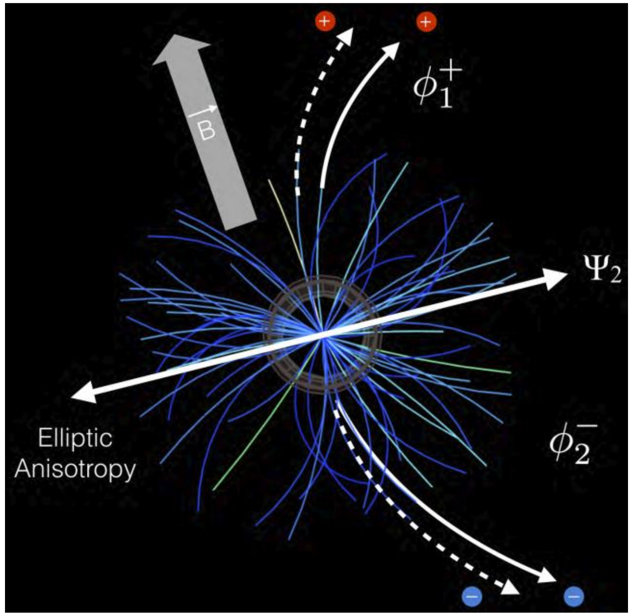
Central objective: identify & characterize this "dipole moment"

- This requires correlators that:
  - ✓ are sensitive to charge separation
  - ✓ can mitigate the influence of backgrounds
- Measurements designed to reduce the background influence
  - ✓ Isobars

Focus on two of the primary correlators

Primary Correlators

Voloshin, PRC 70 (2004) 057901



$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

$$\gamma^{ss} \neq \gamma^{os}$$

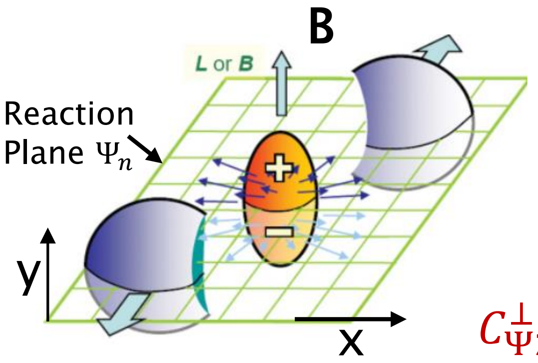
$$\Delta\gamma \sim \Delta\gamma^{CME} + k\frac{v_2}{N_{ch}}$$

$$R_{\Psi 2}(\Delta S) = \frac{C_{\Psi_2}(\Delta S)}{C^{\perp}_{\Psi_2}(\Delta S)}$$

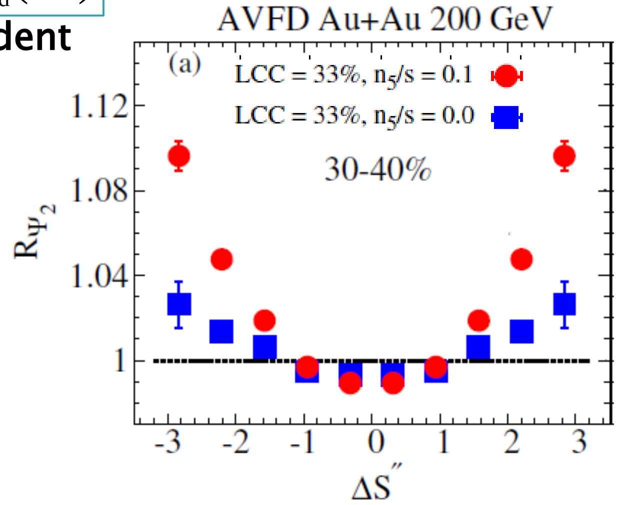
$$C_{\Psi_2}(\Delta S) = \frac{N_{real}(\Delta S)}{N_{Shuffled}(\Delta S)}$$

Charge-dependent

$C_{\Psi 2}(\Delta S)$ quantifies charge separation along the B-field



N. Magdy, et al.
PRC 97, 061901 (2018)



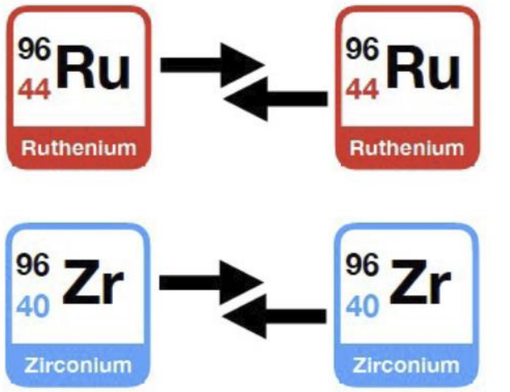
$C^{\perp}_{\Psi 2}(\Delta S)$ quantifies charge separation perpendicular to the B-field (only background)

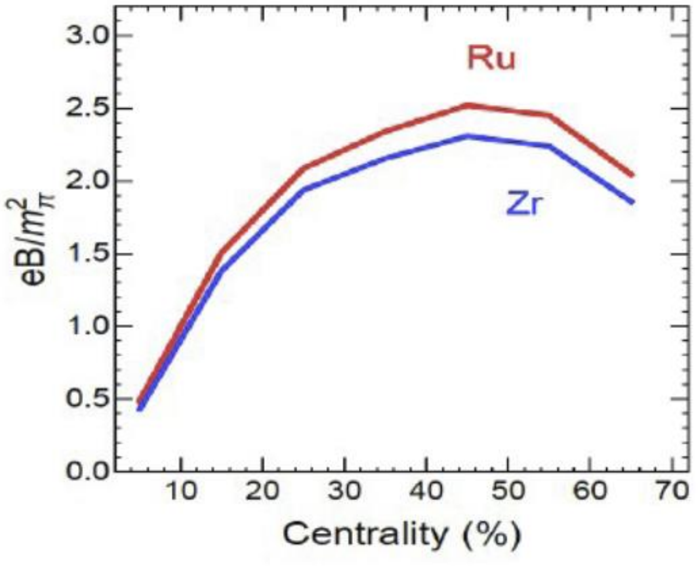
- ➢ The charge separation magnitude is reflected in the inverse variance $\frac{1}{\sigma^2}$, of the $R_{\Psi 2}(\Delta S)$ distribution which is corrected for:
  - ✓ Number fluctuations $\Delta S' = \Delta S/\sigma_{\Delta S^{sh}}$
  - ✓ Event plane resolution $\Delta S'' = \Delta S' \delta_{res}$

$$\frac{1}{\sigma^2} \sim \frac{1}{\sigma^2_{CME}} + \frac{\kappa}{N_{ch}}$$

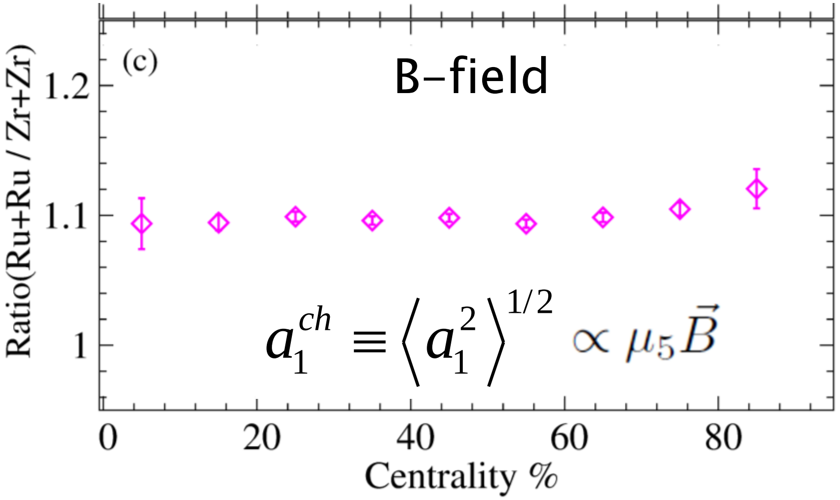
➢ **The scaling property of both correlators can be leveraged to characterize the CME**

Isobar collisions





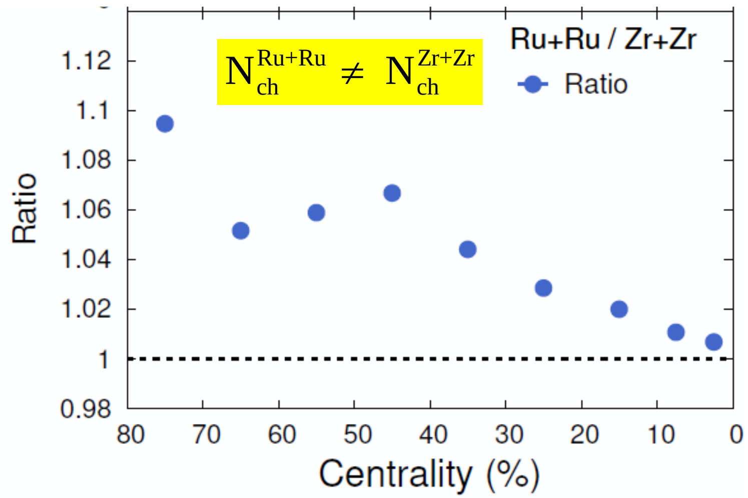
N. Magdy et al., *Phys.Rev.C* 9 (2018) 6, 061902,
e-Print: 1803.02416



- ✓ B-field difference
- ✓ Similar background

$$\Delta\gamma \sim \Delta\gamma^{\rm CME} + k\frac{v_2}{N_{\rm ch}}$$

$$\Delta\gamma^{\rm CME}_{\rm Ru+Ru} > \Delta\gamma^{\rm CME}_{\rm Zr+Zr}$$



$$\frac{1}{\sigma^2} \sim \frac{1}{\sigma^2_{\rm CME}} + \frac{\kappa}{N_{\rm ch}}$$

$$\left(\sigma^{-2}_{\rm CME}\right)_{\rm Ru+Ru} > \left(\sigma^{-2}_{\rm CME}\right)_{\rm Zr+Zr}$$

$$\frac{N_{\rm ch}^{\rm Ru+Ru}\left(\Delta\gamma/v_2\right)_{\rm Ru+Ru}}{N_{\rm ch}^{\rm Zr+Zr}\left(\Delta\gamma/v_2\right)_{\rm Zr+Zr}} > 1 \text{ (for CME)}$$

$$\frac{N_{\rm ch}^{\rm Ru+Ru}\left(\sigma^{-2}\right)_{\rm Ru+Ru}}{N_{\rm ch}^{\rm Zr+Zr}\left(\sigma^{-2}\right)_{\rm Zr+Zr}} > 1 \text{ (for CME)}$$

- ➢ Correction for N_{ch} difference necessary
- ➢ Correlator must be sensitive to a small signal difference

Scaling properties of the correlators

Stratedgy

Use the Anomalous Viscous Fluid Dynamics (AVFD) model to chart the scaling properties of background and signal + background

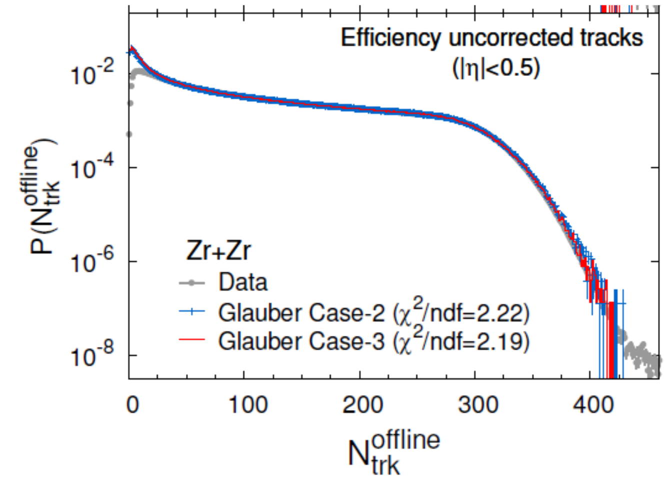
AVFD features:

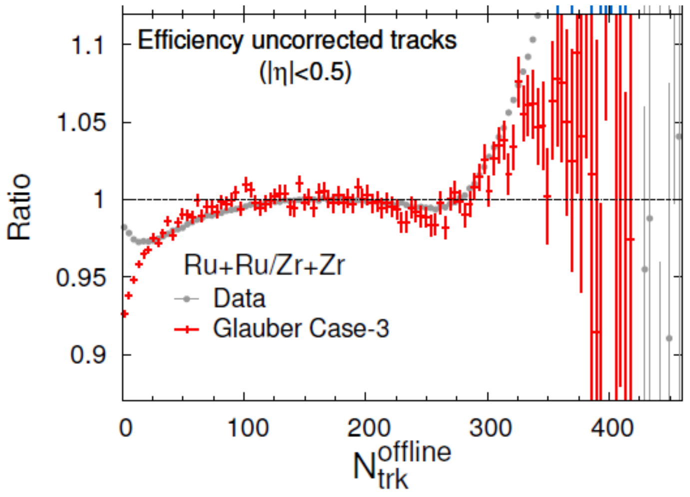
- ✓ Realistic representations of the experimentally measured particle yields, spectra, v_n, etc
- ✓ Includes CME signal (can be turned on/off)
- ✓ realistic estimates of charge-independent and charge-dependent backgrounds
  - ✓ resonance decays
  - ✓ local charge conservation (LCC)
- ✓ **Signal & background can be regulated**

Comprehensive set of results generated to study scaling properties of both correlators

- ✓ centrality dependence for each system for
  - ✓ Background
  - ✓ Background + signal

- Tunable Glauber parameters to reproduce constraint measurements
  - ✓ Multiplicity
  - ✓ V_n





Scaling property of the Background

$$R_{\Psi 2}(\Delta S) = \frac{C_{\Psi_2}(\Delta S)}{C^{\perp}_{\Psi_2}(\Delta S)}$$

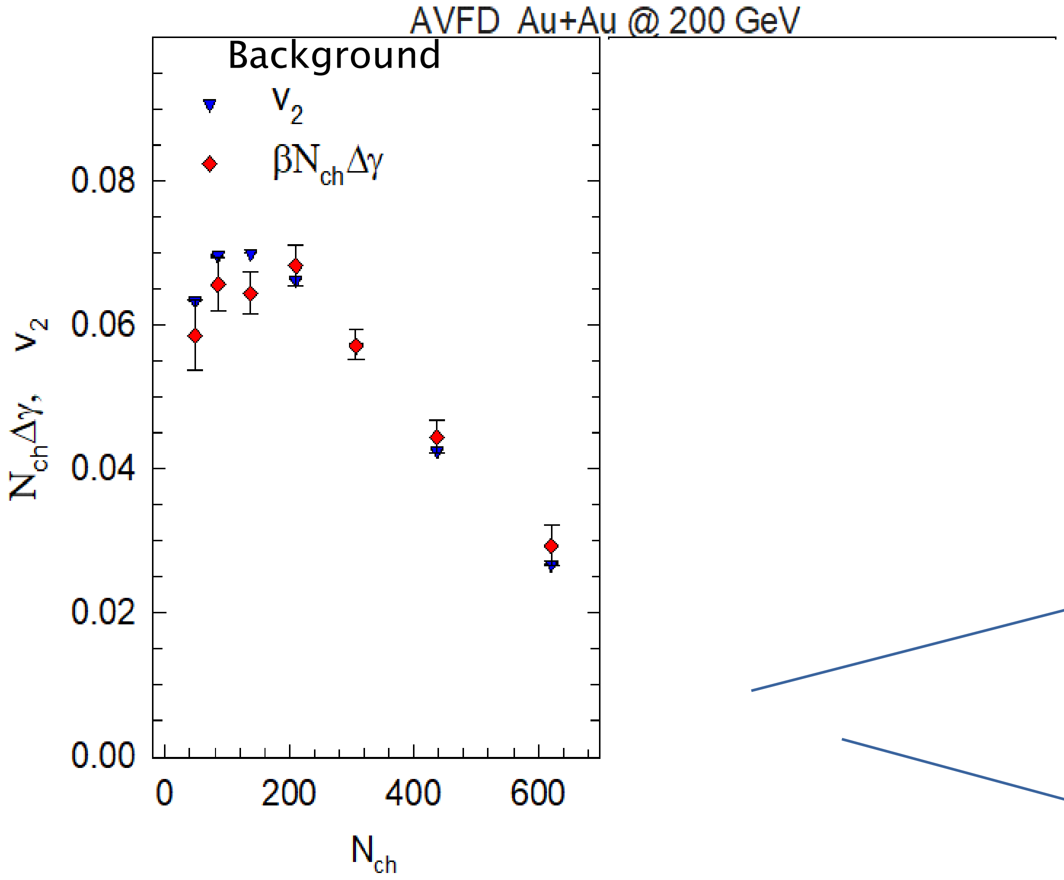
$$C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{Shuffled}}(\Delta S)}$$

$$\Delta\gamma \sim k\frac{v_2}{N_{ch}}$$ ✗

$$N_{ch}\Delta\gamma \propto v_2$$

or

$$\frac{\Delta\gamma}{v_2} \propto \frac{1}{N_{ch}}$$



$$\frac{1}{\sigma^2} \sim \frac{\kappa}{N_{ch}}$$ ✗

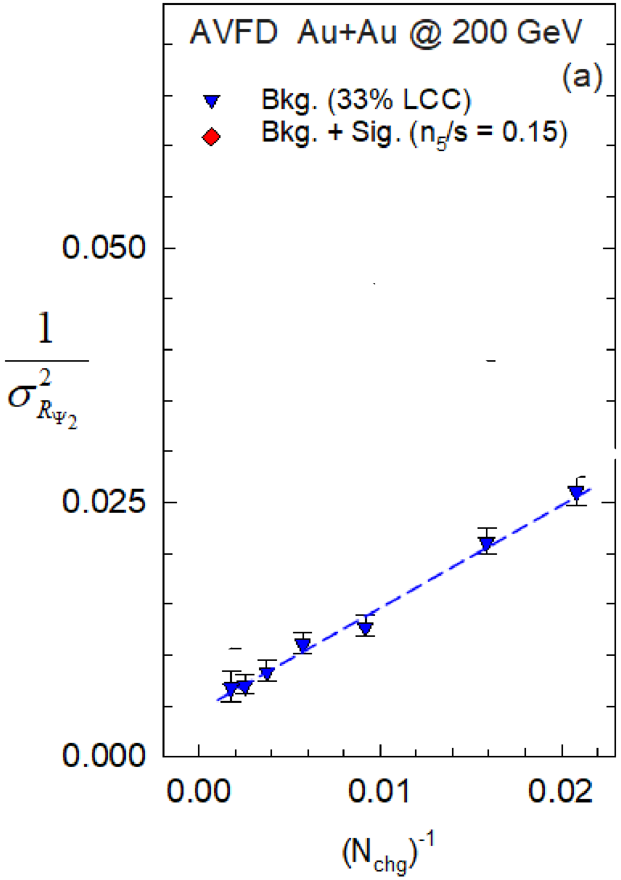
$$\frac{1}{\sigma^2} \propto \frac{1}{N_{ch}}$$

$$\frac{\Delta\gamma}{v_2} \propto \frac{1}{N_{ch}}$$

- $\frac{1}{\sigma^2} \sim N_{ch}\Delta\gamma$ ✗ This claim is incorrect
- The $\frac{1}{N_{ch}}$ dependence of $\frac{1}{\sigma^2}$ is well studied and well understood

Scaling property of background and signal

$$\frac{1}{\sigma^2} \sim \times + \frac{\kappa}{N_{ch}}$$



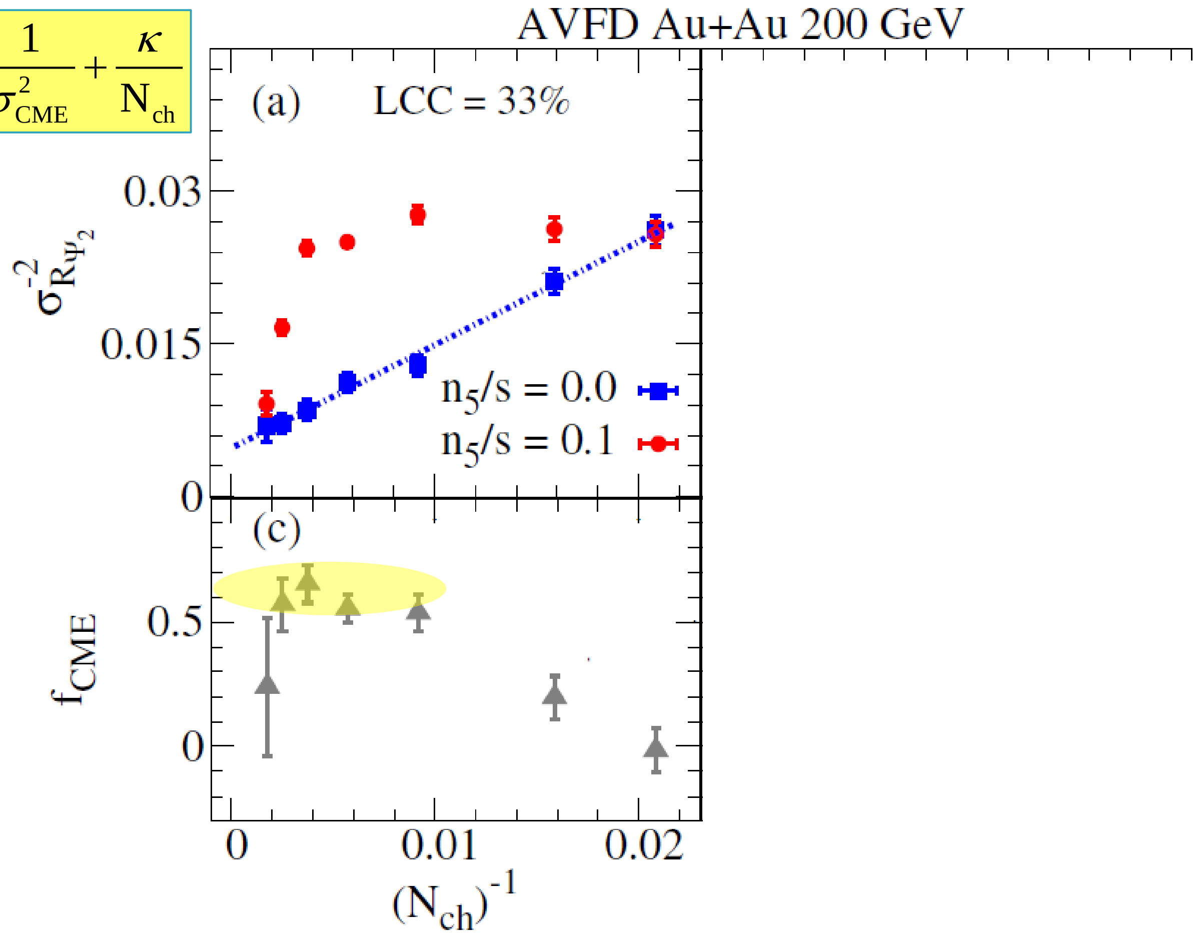
- 1 / N_{chg} scaling for background
  - ✓ **Experimental observation of $1/N_{chg}$ scaling would be a clear indication for no CME**

- Scaling violation for signal + background
  - ✓ f_{CME} benchmarks the signal

$$f_{\mathrm{CME}} = \frac{[\sigma^{-2}_{R_{\Psi_2}}(Sig.+Bkg.) - \sigma^{-2}_{R_{\Psi_2}}(Bkg.)]}{[\sigma^{-2}_{R_{\Psi_2}}(Sig.+Bkg.)]}$$

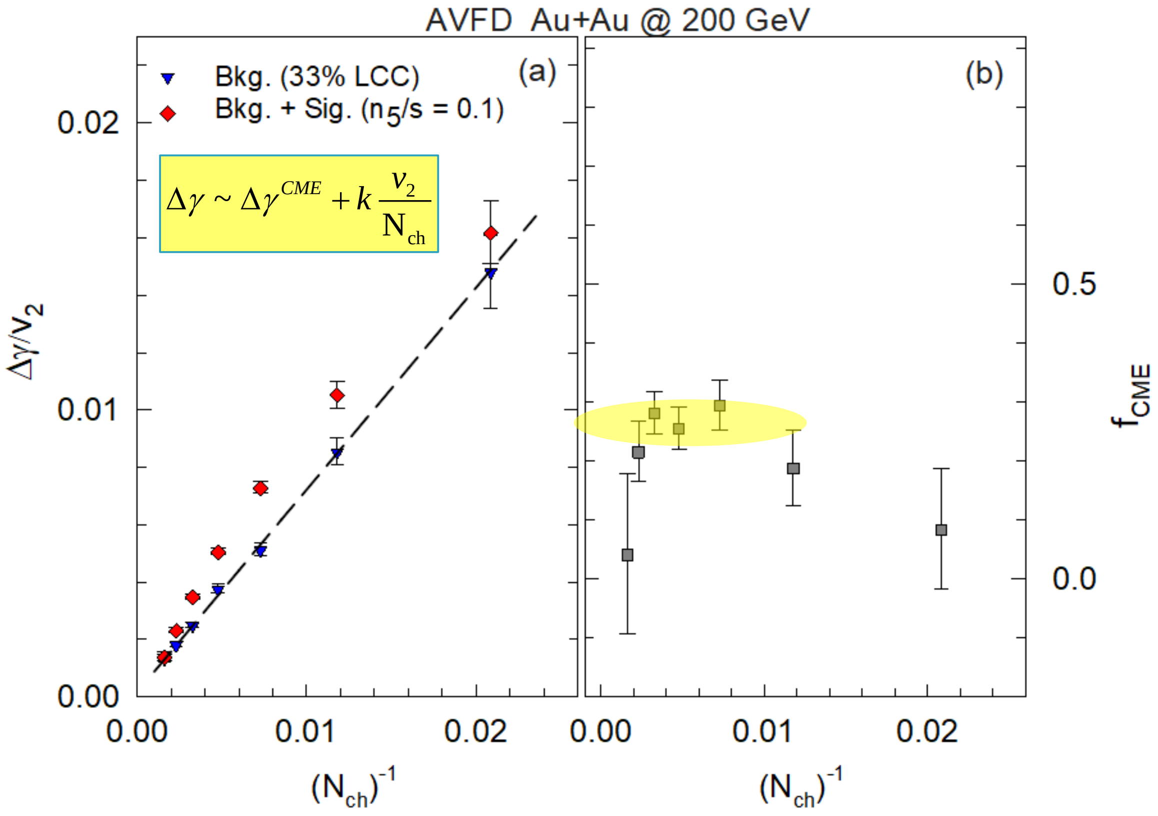
Scaling property of background and signal

$$\frac{1}{\sigma^2} \sim \frac{1}{\sigma^2_{\rm CME}} + \frac{\kappa}{\rm N_{ch}}$$



$$f_{\rm CME} = \frac{[\sigma^{-2}_{R_{\Psi_2}}(Sig. + Bkg.) - \sigma^{-2}_{R_{\Psi_2}}(Bkg.)]}{[\sigma^{-2}_{R_{\Psi_2}}(Sig. + Bkg.)]}$$

- Experimental observation of $1/N_{ch}$ scaling would be an indication for no CME



✓ Sensitivity difference

$$f_{\rm CME} = \frac{\Delta\gamma/v_2(Sig.+Bkg.) - \Delta\gamma/v_2(Bkg.)}{\Delta\gamma/v_2(Sig.+Bkg.)}$$

- $1/N_{ch}$ scaling for background
- Scaling violation for signal + background
  - ✓ Insensitivity to signal in very central & peripheral collisions → Bkg. constraint

These scaling properties can be leveraged to characterize the CME in data

Scaling property of the Data – $R_{\Psi 2}(\Delta S)$ correlator

$$\frac{N_{ch}^{Ru+Ru}\left(\sigma^{-2}\right)_{Ru+Ru}}{N_{ch}^{Zr+Zr}\left(\sigma^{-2}\right)_{Zr+Zr}} > 1 \text{ (for CME)}$$

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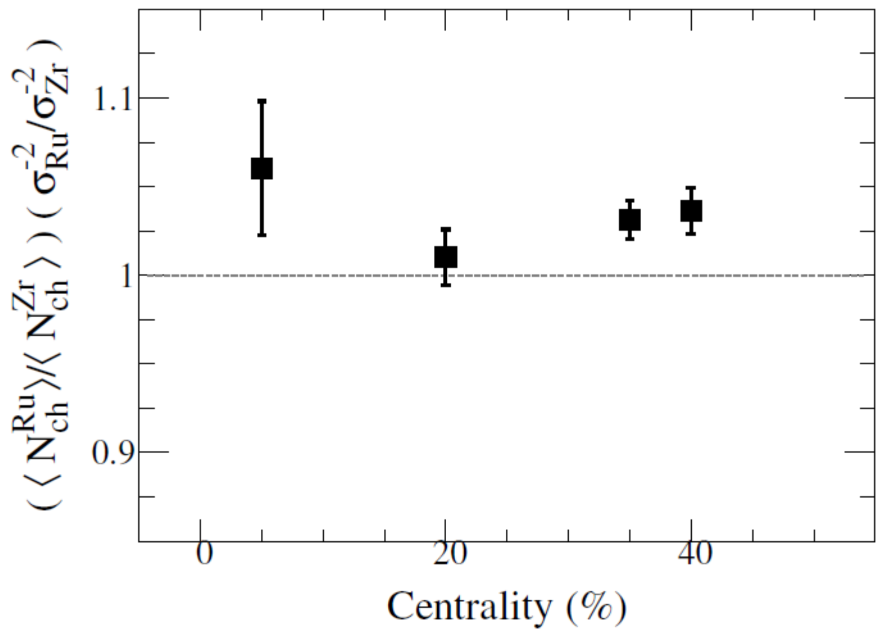
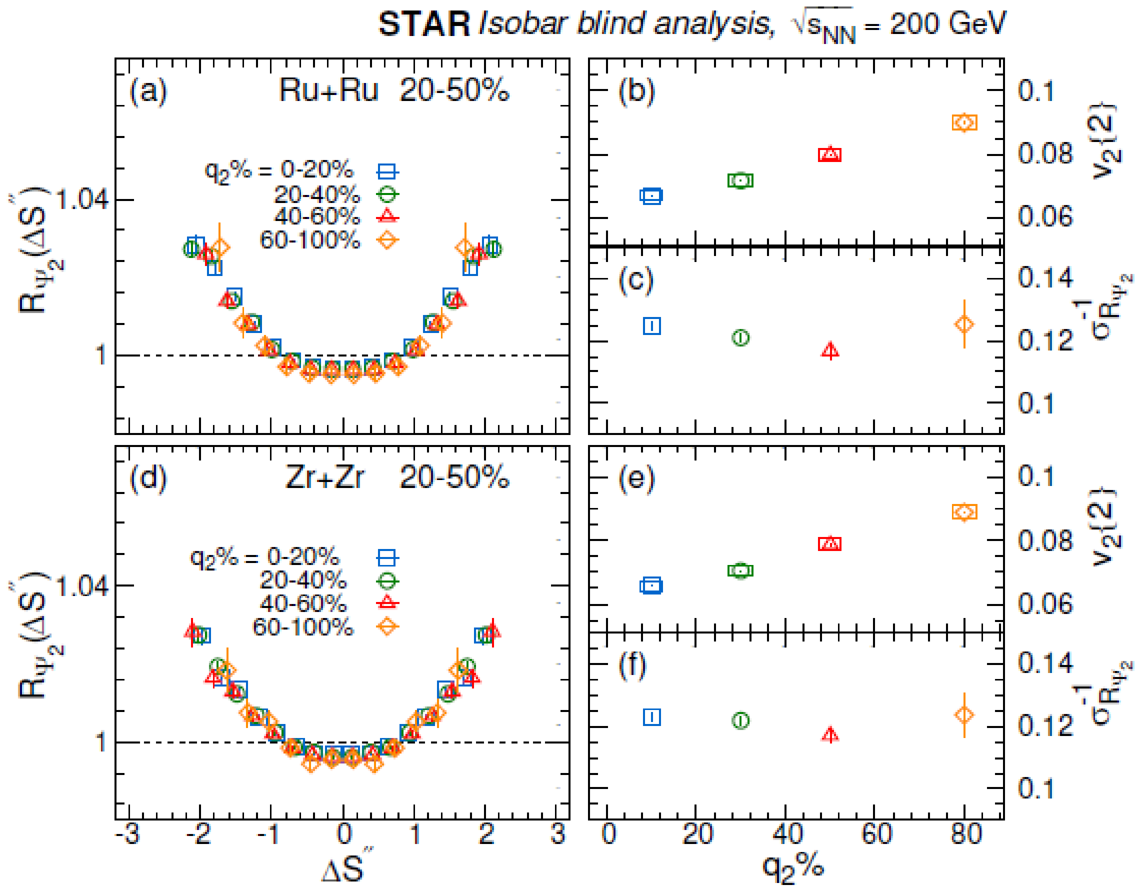




- ➢ **Small charge separation difference between the isobars**
  - ❖ **Compatible with the CME**
    - ✓ **small signal difference**

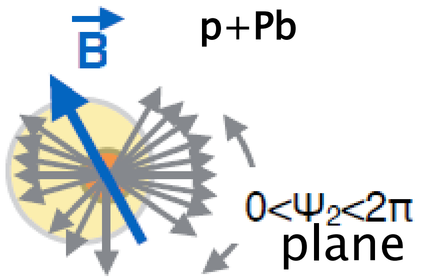
- ➢ **q_2–independent inverse variance validated for isobars**
  - ✓ This insensitivity spans a v_2 difference (between high and low q_2) that is much larger than the measured v_2 difference between the two isobars

Scaling property of the Data – $\Delta\gamma$ correlator

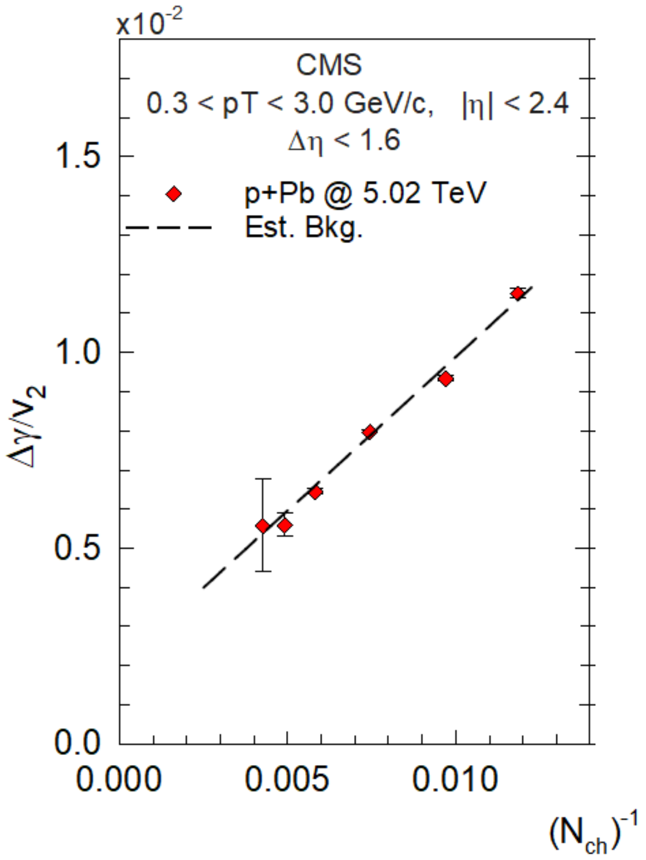
Data from *Phys.Rev.Lett.* 118 (2017) 12, 122301

$$\Delta\gamma \sim \Delta\gamma^{\text{CME}} + k\frac{v_2}{\text{N}_{\text{ch}}}$$

p+Pb



B and Ψ_2 ~ uncorrelated
CME **not** expected



- Experimental observation of $1/\text{N}_{\text{ch}}$ scaling would be an indication for no CME

- **No indication for CME in p+Pb collisions @ 5.02 TeV**

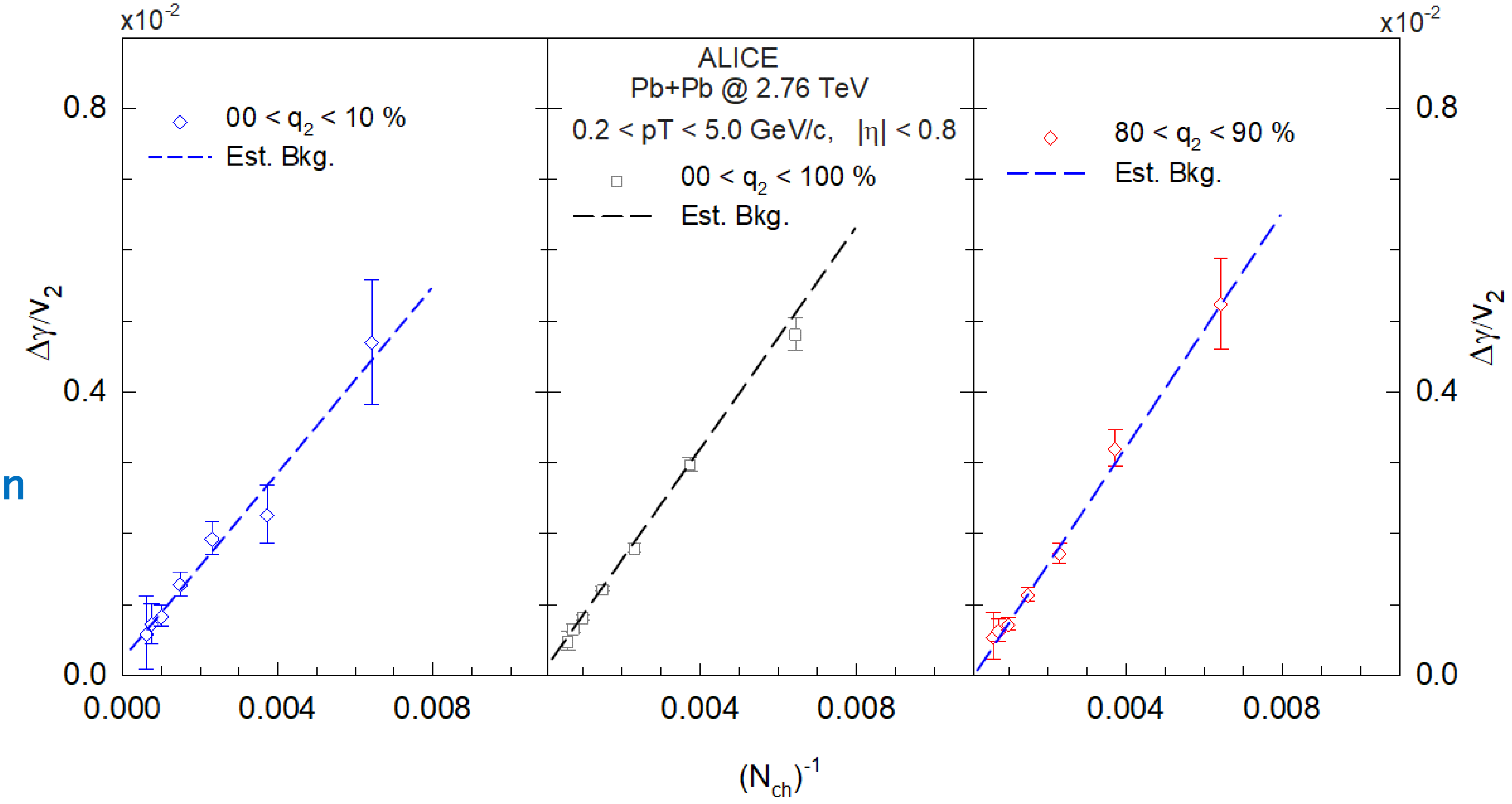
- **No indication for CME in Pb+Pb collisions @ 5.02 TeV**

Scaling property of the Data – $\Delta\gamma$ correlator

Data from Phys.Lett.B **777 (2018) 151-162**

$$\Delta\gamma \sim \Delta\gamma^{CME} + k\frac{v_2}{N_{ch}}$$

- **The experimental observation of $1/N_{ch}$ scaling would be an indication for <u>no</u> CME**



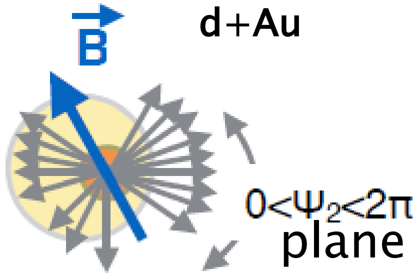
- **$1/N_{ch}$ scaling observed for q_2-selected Pb+Pb collisions @ 2.76 TeV**
  - ✓ **No indication for CME in Pb+Pb collisions @ 2.76 TeV**

Scaling property of the Data – $\Delta\gamma$ correlator

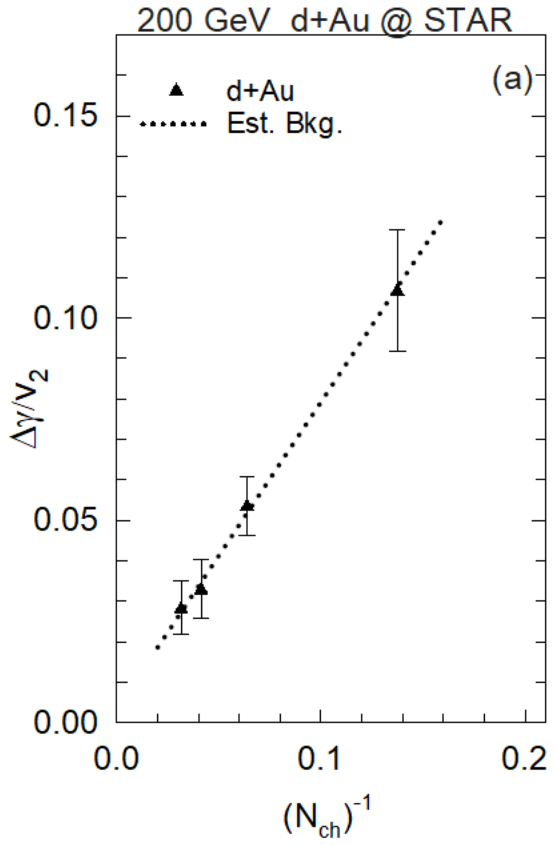
Data from Phys.Lett.B 798 (2019) 134975
Phys.Rev.C 77 (2008) 054901, *Phys.Rev.C* 88 (2013) 6, 064911

$$\Delta\gamma \sim \Delta\gamma^{\text{CME}} + k\frac{v_2}{\text{N}_{\text{ch}}}$$

d+Au



B and Ψ_2 ~ uncorrelated
CME <u>**not**</u> expected



- **$1/N_{ch}$ scaling observed for d+Au (similar for p+Au) collisions @ 200 GeV**
  - ✓ **No indication for CME**

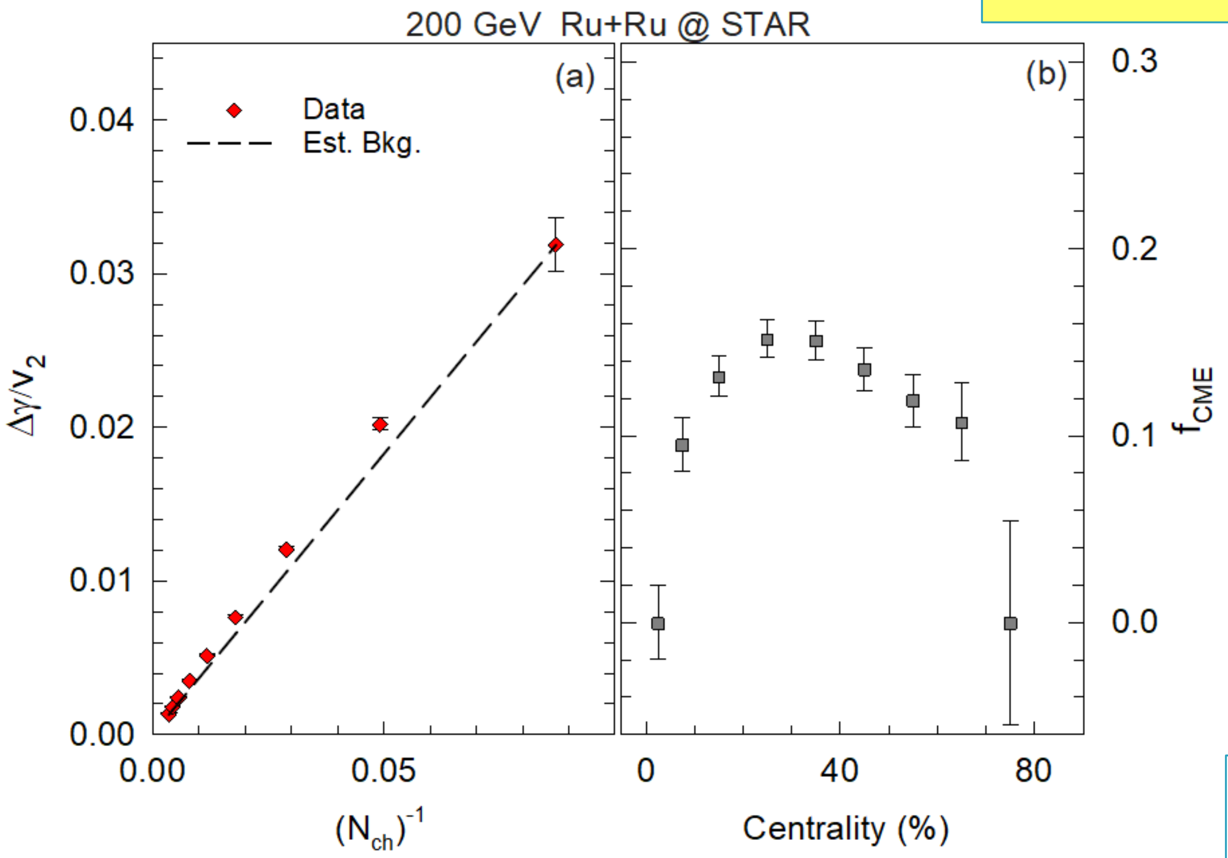
$$f_{\text{CME}} = \frac{\Delta\gamma/v_2\,(Sig.+Bkg.) - \Delta\gamma/v_2\,(Bkg.)}{\Delta\gamma/v_2\,(Sig.+Bkg.)}$$

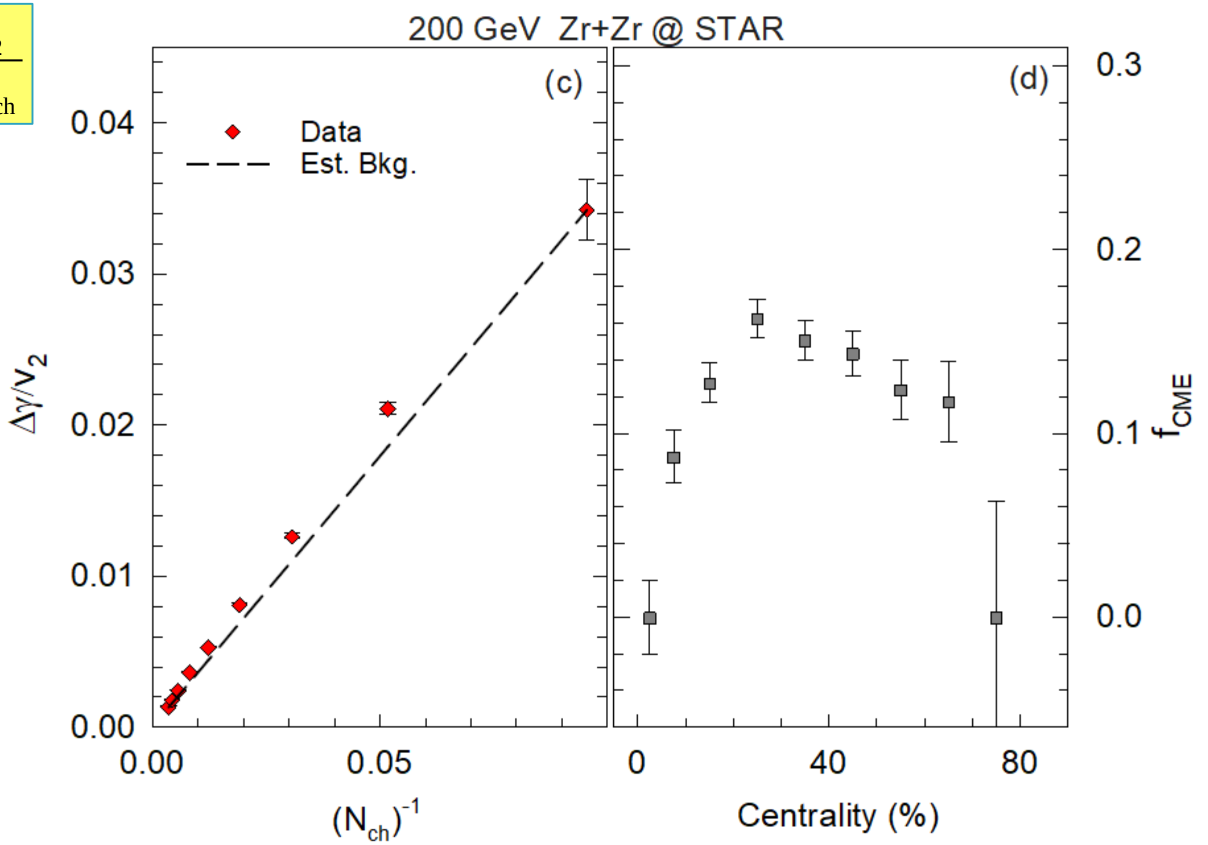
- **Scaling violations observed for Au+Au collisions @ 200 GeV**
  - ✓ **Indication for the CME**
  - ✓ **$f_{CME} \sim 27\%$ in mid-central collisions**

Scaling property of the Data – $\Delta\gamma$ correlator

Data from Phys.Rev.C **105 (2022) 1, 014901**

$$\Delta\gamma \sim \Delta\gamma^{\mathrm{CME}} + k\,\frac{v_2}{\mathrm{N_{ch}}}$$





$$f_{\mathrm{CME}} = \frac{\Delta\gamma/v_2\,(Sig. + Bkg.) - \Delta\gamma/v_2\,(Bkg.)}{\Delta\gamma/v_2\,(Sig. + Bkg.)}$$

- **Scaling violations observed for Ru+Ru and Zr+Zr collisions @ 200 GeV**
  - ✓ $f_{CME} \sim 14\%$ **in mid-central collisions**
  - ✓ **Similar magnitudes for the two isobars (in sensitivity to signal difference?)**
    - ❖ **Small signal difference implied from f_{CME} magnitude**

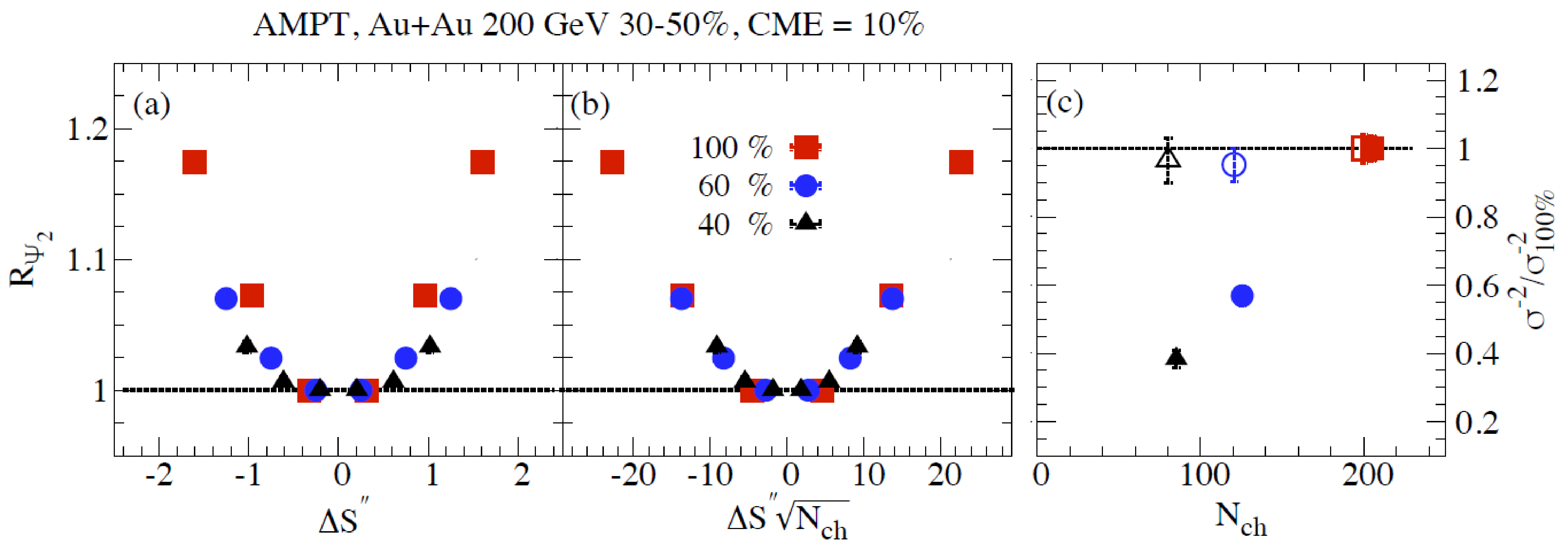
Summary

I. The scaling properties of background- and chiral-magnetically-driven charge separation give unique insight for characterizing the CME.

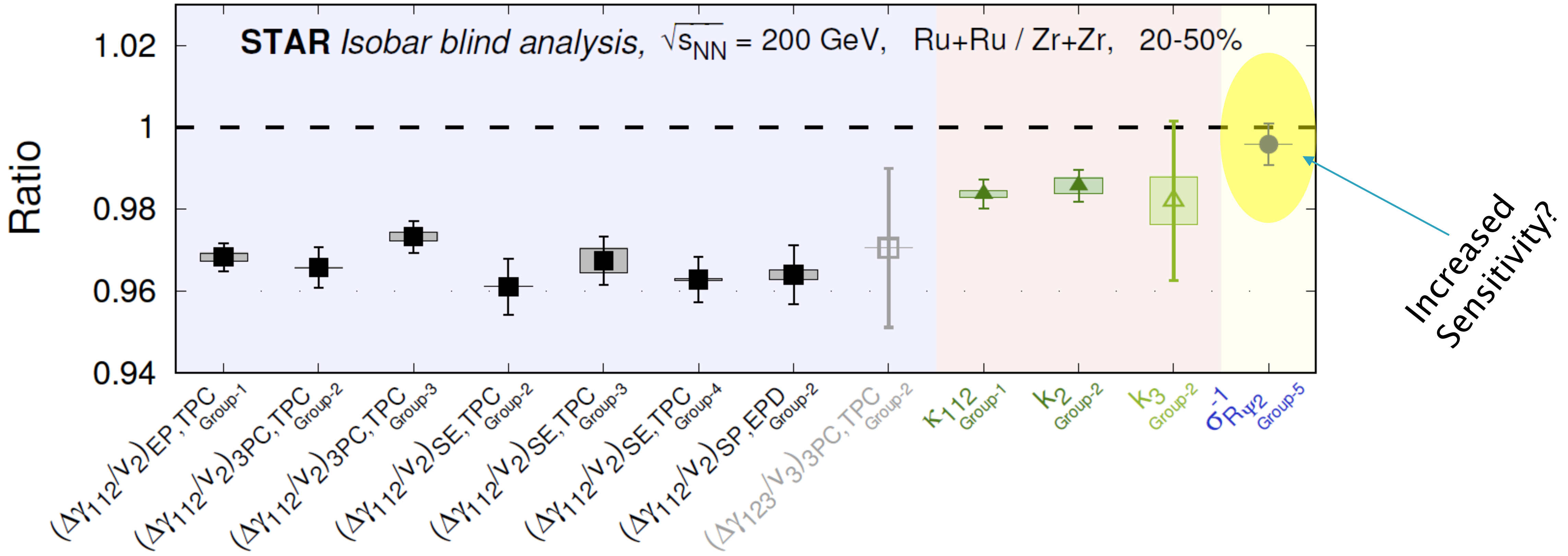
II. Ongoing analysis indicates
- ✓ a robust CME signal in Au+Au and isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200\ GeV$.
- ✓ no CME signal in p+Au and d+Au collisions @ $\sqrt{s_{NN}} = 200\ GeV$
- ✓ no CME signal in p+Pb and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\ and\ 5.02\ TeV$

Thank You

Scaling property of the Background

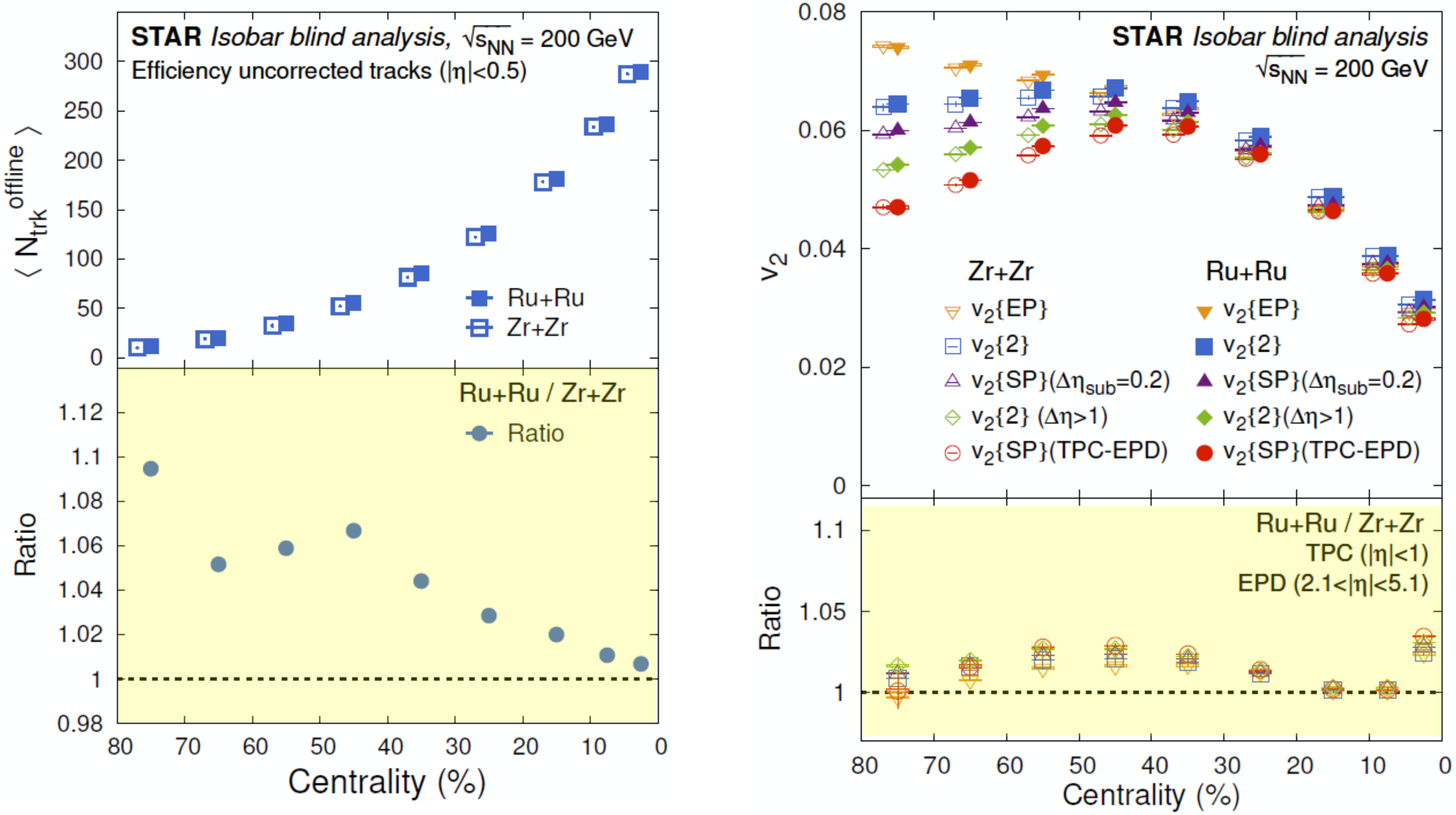


The blind analysis result



- ➢ **The predefined case for CME (Ratios > 1) are not observed!**
- ➢ Caveats:
  - ✓ Ratios < 1.0, indicating background difference for isobars
    - ❑ Implied ambiguity for presence/absence of CME

The blind background



The $R_{\Psi m}(\Delta S)$ Correlator

$$R_{\Psi 2}(\Delta S) = \frac{C_{\Psi 2}(\Delta S)}{C^{\perp}_{\Psi 2}(\Delta S)}$$

N. Magdy, et al.
PRC 97, 061901 (2018)

$$C_{\Psi 2}(\Delta S) = \frac{N(\Delta S)}{N(\Delta S_{sh})}$$

$$C^{\perp}_{\Psi 2}(\Delta S) = \frac{N(\Delta S^{\perp})}{N(\Delta S^{\perp}_{sh})}$$

$$\Delta\varphi = \varphi - \Psi_{\mathrm{m}}$$

$N(\Delta S)$

$$\langle S^{+}_{\Psi 2}\rangle = \frac{\sum_1^p w_p \sin(\Delta\varphi)}{\sum_1^p w_p}$$

$$\langle S^{-}_{\Psi 2}\rangle = \frac{\sum_1^n w_n \sin(\Delta\varphi)}{\sum_1^n w_n}$$

$$\Delta S = \langle S^{+}_{\Psi 2}\rangle - \langle S^{-}_{\Psi 2}\rangle$$

$N(\Delta S_{Sh})$

$$\Delta S_{Sh} = \langle S^{+}_{\Psi 2}\rangle_{Sh} - \langle S^{-}_{\Psi 2}\rangle_{Sh}$$

Sensitive to charge separation
(CME and Background)

w_i: charge dependent
detector acceptance.

Charge shuffling within an event breaks the charge separation sensitivity

$N(\Delta S^{\perp})$

$$\langle S^{+}_{\Psi 2}\rangle^{\perp} = \frac{\sum_1^p w_p \cos(\Delta\varphi)}{\sum_1^p w_p}$$

$$\langle S^{-}_{\Psi 2}\rangle^{\perp} = \frac{\sum_1^n w_n \cos(\Delta\varphi)}{\sum_1^n w_n}$$

$$\Delta S^{\perp} = \langle S^{+}_{\Psi 2}\rangle^{\perp} - \langle S^{-}_{\Psi 2}\rangle^{\perp}$$

$N(\Delta S^{\perp}_{sh})$

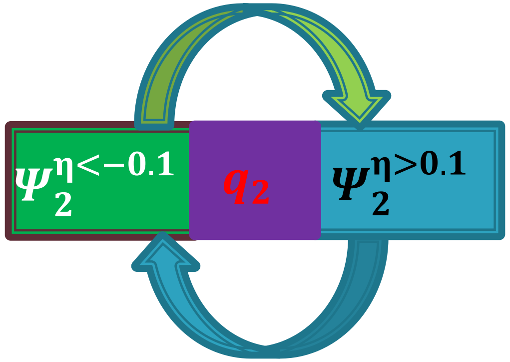
$$\Delta S^{\perp}_{Sh} = \langle S^{+}_{\Psi 2}\rangle^{\perp}_{Sh} - \langle S^{-}_{\Psi 2}\rangle^{\perp}_{Sh}$$

Shape-selected events

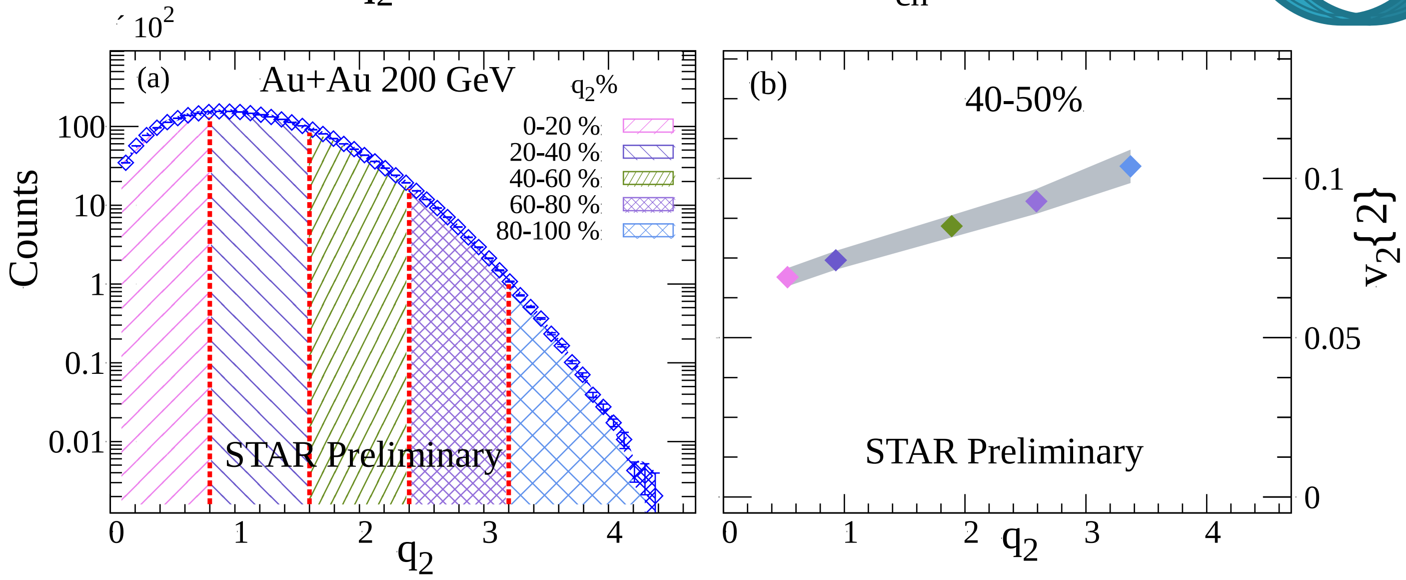
- Event-shape selections (Data)
  - ✓ Events are further subdivided into groups with different q_2 magnitude:

$$Q_{2,x} = \sum_{i=1}^{M} \cos(2\,\varphi_i) \qquad Q_{2,y} = \sum_{i=1}^{M} sin(2\,\varphi_i)$$

$$|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2} \qquad q_2 = \frac{|Q_2|}{\sqrt{M}}$$



  - ✓ The q_2 was created for each N_{ch}



- $v_2\{2\}$ increases linearly with q_2
- ✓ q_2 is good event-shape selector