Collision-system dependence of charge separation relative to the second- and third-order event planes; Implications for the Chiral Magnetic Effect in STAR

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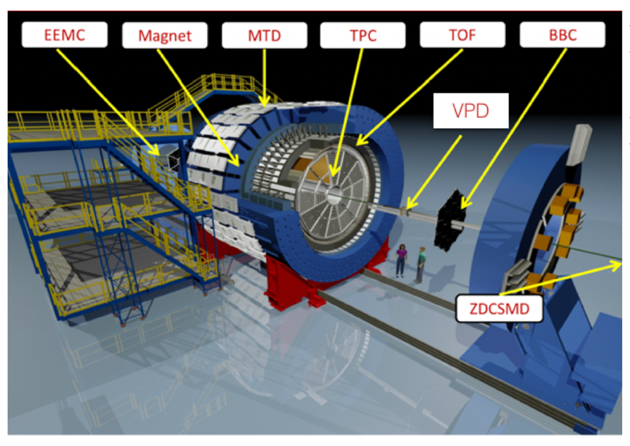
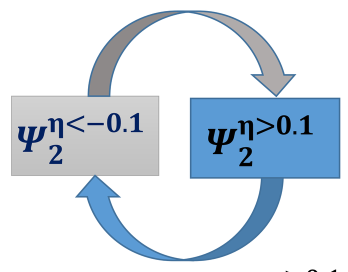
Abstract

A charge-sensitive correlator ($R_{\Psi_m}(\Delta S)$) is used to detect and characterize charge separation associated with the Chiral Magnetic Effect (CME) in heavy-ion collisions. The correlator gives a concave-shaped response relative to the second-order event plane, Ψ_2, and a null response relative to the third-order plane, Ψ_3, for CME-driven charge separation [1]. We present and discuss $R_{\Psi_m}(\Delta S)$ measurements relative to Ψ_2 and Ψ_3, for collisions of U+U at $\sqrt{s_{NN}}$ = 193 GeV, Au+Au, Cu+Au and p(d)+Au at $\sqrt{s_{NN}}$ = 200 GeV. The $R_{\Psi_2}(\Delta S)$ measurements are also presented for different event-shape selections.

The STAR experiment at RHIC



- The TPC detector is used in the current analysis
- Charged hadrons with $0.2 < p_T < 2.0$ GeV/c are used to construct $\Psi_2^{\eta>0.1}$ and $\Psi_2^{\eta<-0.1}$



- Particles with $0.35 < p_T < 2.0$ GeV/c and $\eta < 0$ are analyzed using $\Psi_2^{\eta>0.1}$
- Particles with $0.35 < p_T < 2.0$ GeV/c and $\eta > 0$ are analyzed using $\Psi_2^{\eta<-0.1}$

$R_{\Psi_m}(\Delta S)$ correlator

As outlined in Ref. [1], the correlators can be expressed as the ratio:

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

$$C_{\Psi m}(\Delta S) = \frac{N(\Delta S)}{N(\Delta S_{sh})} \qquad \Delta\varphi = \varphi - \Psi_m \qquad C^{\perp}_{\Psi m}(\Delta S) = \frac{N(\Delta S^{\perp})}{N(\Delta S^{\perp}_{sh})}$$

Sensitive to charge separation (CME and Background):

$$N(\Delta S) = N(\langle S^{+}_{\Psi m}\rangle - \langle S^{-}_{\Psi m}\rangle) \qquad N(\Delta S^{\perp}) = N(\langle S^{+}_{\Psi m}\rangle^{\perp} - \langle S^{-}_{\Psi m}\rangle^{\perp})$$

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

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

w_i: charge-dependent detector acceptance

p/n: number of positive/negative hadrons per event

Shuffling of charges within an event breaks the charge separation sensitivity:

$$N(\Delta S_{sh}) = N(\langle S^{+}_{\Psi m}\rangle_{sh} - \langle S^{-}_{\Psi m}\rangle_{sh}) \qquad N(\Delta S_{sh}) = N(\langle S^{+}_{\Psi m}\rangle^{\perp}_{Sh} - \langle S^{-}_{\Psi m}\rangle^{\perp}_{Sh})$$

$$\langle S^{+}_{\Psi m}\rangle_{sh} = \frac{\sum_1^p w_p \sin(\frac{m}{2}\Delta\varphi)}{w_p^{sh}} \qquad \langle S^{+}_{\Psi m}\rangle^{\perp}_{Sh} = \frac{\sum_1^p w_p \cos(\frac{m}{2}\Delta\varphi)}{w_p^{sh}}$$

$$\langle S^{-}_{\Psi m}\rangle_{sh} = \frac{\sum_1^n w_n \sin(\frac{m}{2}\Delta\varphi)}{w_n^{sh}} \qquad \langle S^{-}_{\Psi m}\rangle^{\perp}_{Sh} = \frac{\sum_1^n w_n \cos(\frac{m}{2}\Delta\varphi)}{w_n^{sh}}$$

Corrections for number fluctuations and the event plane resolution effects on the $R_{\Psi_m}(\Delta S)$

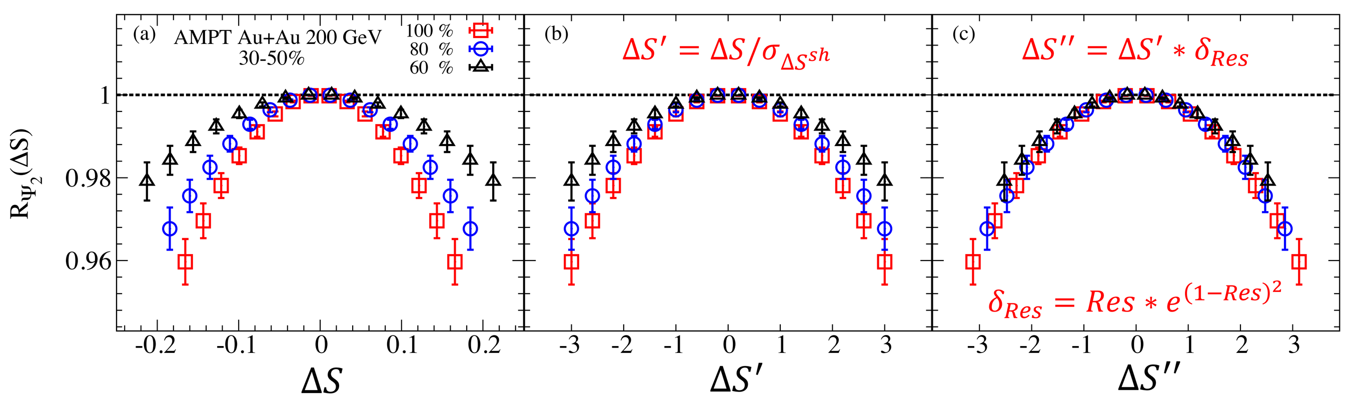
Charge separation magnitude is reflected in the width of the $R_{\Psi m}(\Delta S)$ distribution which is influenced by number fluctuations and event plane resolution. A scaling procedure was developed to mitigate both of these effects. This procedure was validated with the Au+Au data by selectively modifying the number fluctuations and the event plane resolution. Such modifications were accomplished by selecting a fraction of the particles in the sub-events used to (i) evaluate the event plane, (ii) measure charge separation relative to the event plane and (iii) both. Here we show a similar example using the AMPT model for case (iii).

✓ Number fluctuations

The influence of the particle number fluctuations can be minimized by empirically scale the ΔS by $\sigma_{\Delta S^{sh}}$ to be $\Delta S'$.

✓ Event plane resolution

The influence of the event plane resolution can be minimized by empirically scaling the $\Delta S'$ by δ_{Res} to be $\Delta S''$.



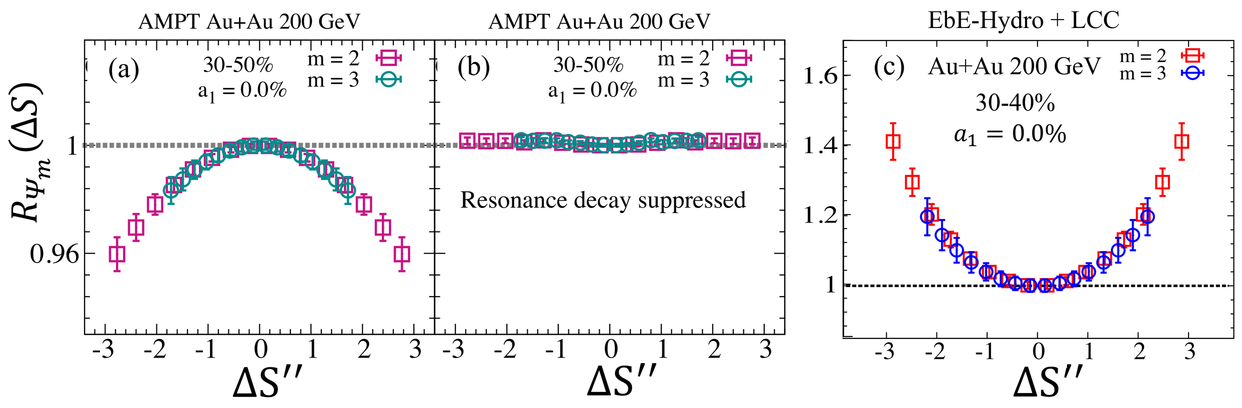
The different percentage represent the fraction of the event statistics used to create the $R_{\Psi m}(\Delta S)$ correlator. The empirical formula suggested can account for both the number fluctuations and the plane resolution effects on $R_{\Psi m}(\Delta S)$ [1].

Reference

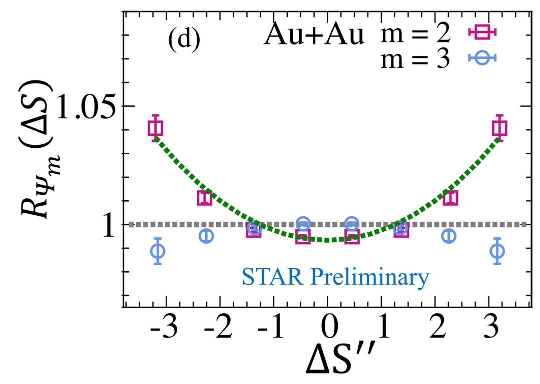
[1] N. Magdy, et al., Phys. Rev. C97, 061901 (2018)

[2] V. Khachatryan et al. (CMS Collaboration) Phys. Rev. Lett. 118, 122301 (2017)

$R_{\Psi_m}(\Delta S)$ response



➢ The $R_{\Psi 2}(\Delta S)$ and $R_{\Psi 3}(\Delta S)$ give similar response to the background irrespective of the correlator shape.

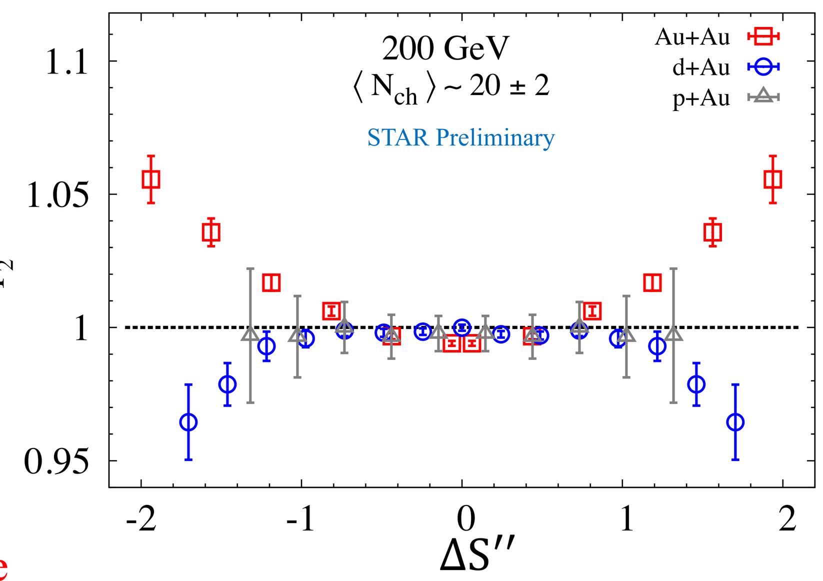


➢ The distinct difference in the measured response for $R_{\Psi 2}(\Delta S)$ and $R_{\Psi 3}(\Delta S)$ panel (d) are in contrast with the CME-driven charge separation.

$R_{\Psi_m}(\Delta S)$ response for small and large systems

- The noticeably flat/convex distributions for p(d)+Au collisions are consistent with the reduced magnetic field strength and the approximately random $\vec{B}$-field orientations (relative to Ψ_2) expected in these collisions. The distribution for peripheral Au+Au collisions is decidedly concave-shaped.
- These observations contrast with the large background-driven signal observed for p+Pb and peripheral Pb+Pb collisions at the LHC [2], with the γ correlator.

➢ These results suggest that the $R_{\Psi 2}(\Delta S')$ correlator is less sensitive to the backgrounds than the γ correlator.

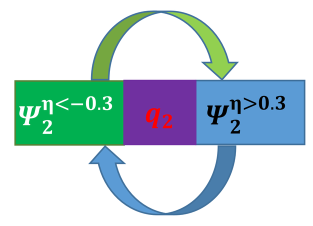


$R_{\Psi_m}(\Delta S)$ response to event-shape selections

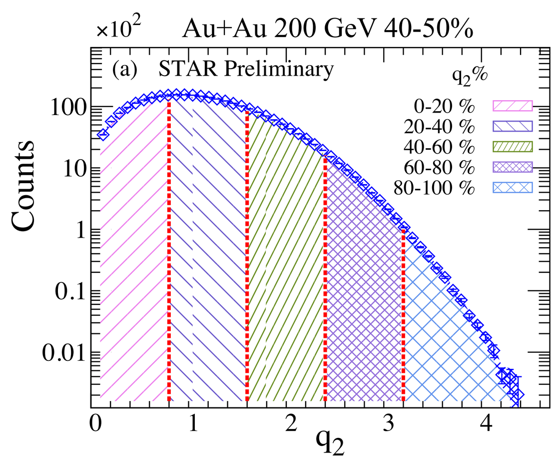
- Events are further subdivided into groups with different q_2 magnitude:

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

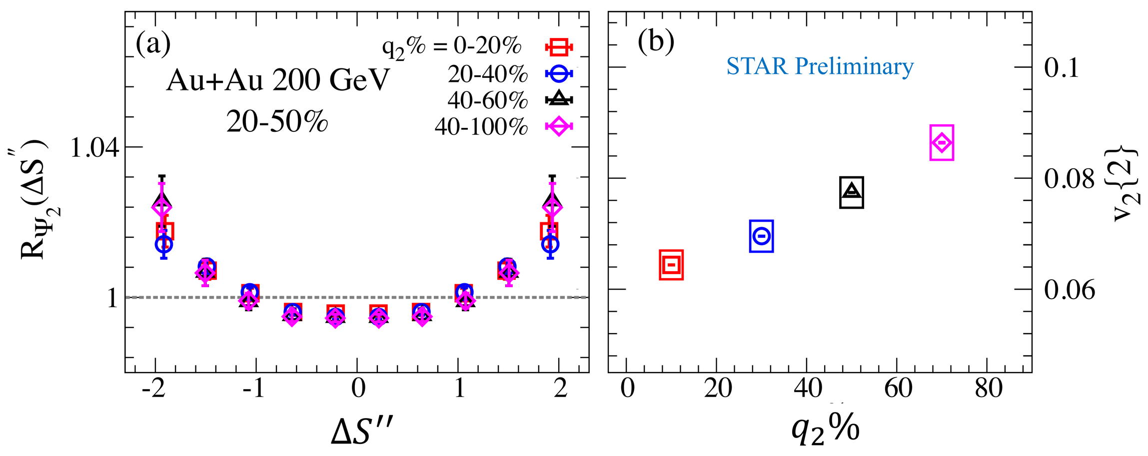
$$|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2} \qquad q_2 = \frac{|Q_2|}{\sqrt{M}}$$



- The q_2 distribution for 40-50% Au+Au collisions at 200 GeV, for the sub-event sample with $|\eta| < 0.3$



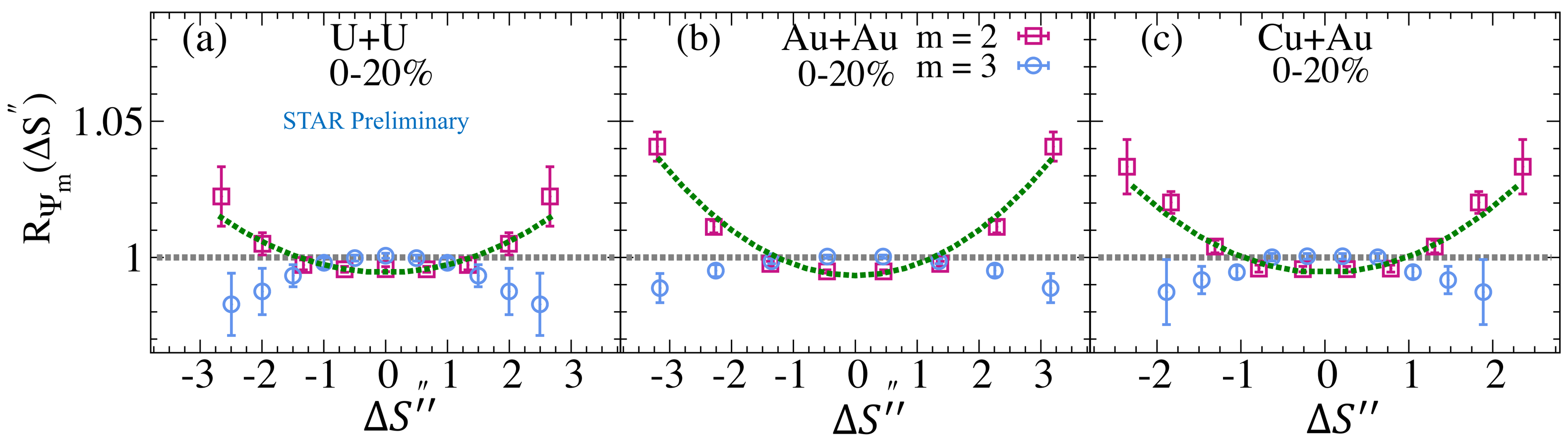
- $R_{\Psi 2}(\Delta S)$ correlators obtained for 20-50% central Au+Au collisions, for different q_2 selections.



➢ Different q_2 selections (right panel) suggests that $R_{\Psi 2}(\Delta S)$ is not strongly influenced by the v_2 background-driven charge separation.

Collision-system dependence of the $R_{\Psi_m}(\Delta S)$

The $R_{\Psi_2}(\Delta S)$ and $R_{\Psi_3}(\Delta S)$ for 0-20% centrality selection in different collision systems.



- The $R_{\Psi_2}(\Delta S)$ correlators for different collision systems is strikingly different from those for $R_{\Psi_3}(\Delta S)$ correlators.

➢ The $R_{\Psi_2}(\Delta S)$ decidedly concave-shaped, as would be expected for CME-driven charge separation with limited influence from background-driven charge separation.

Conclusions

Charge separation correlator, $R_{\Psi m}$(for m = 2,3), is investigated in, U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, Au+Au, Cu+Au and p(d)+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV using the STAR detector.

- $R_{\Psi m}$ measurements show:
  - ✓ Expected difference in the response for Ψ_2 and Ψ_3
  - ✓ Expected difference in the response for small (p(d)+Au) and large systems (Au+Au)
  - ✓ $R_{\Psi 2}$ width is q_2 independent (weak v_2−driven background sensitivity)

The presented $R_{\Psi m}$ results are consistent with the expectation for CME-driven charge separation.

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The STAR Collaboration https://drupal.star.bnl.gov/STAR/presentations

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