A New Correlator to Detect and Characterize the Chiral Magnetic Effect

Roy A. Lacey
Stony Brook University

Outline

- Introduction
  - ✓ CME & Charge separation
  - ✓ Prior measurements & challenges
- New Correlator
  - ✓ Correlator essentials
  - ✓ Correlator details
  - ✓ Signal Quantification
- Correlator response
  - ✓ Response to background
  - ✓ Response to signal + background
  - ✓ STAR Experimental measurements presented by N. Magdy
- Summary

Anomalous Transport in the QGP

Chiral Magnetic Effect (CME)

Electric Current — *Chiral Magnetic Conductivity* — *Chiral Chemical potential*

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

$$\sigma_5 = C_A \mu_5$$

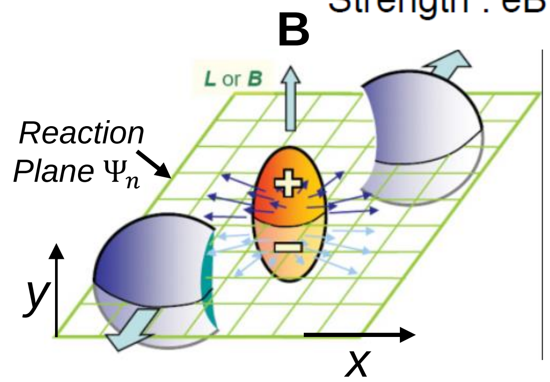
$$C_A = Q^2 / (4\pi^2)$$

Kharzeev hep-ph/0406125

The Chiral Magnetic Effect (CME) results from anomalous chiral transport of the chiral fermions in the QGP, leading to the generation of an electric current along the magnetic field generated in the collision:

→ Leads to charge separation along the B-field

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



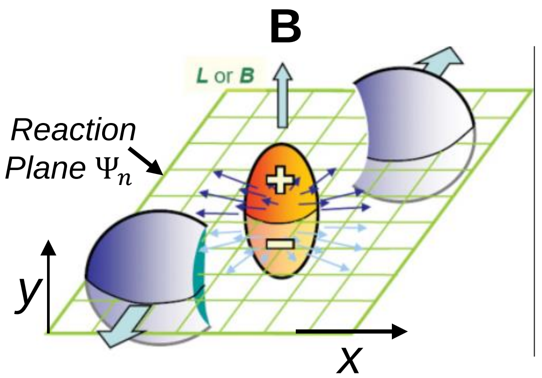
I. *CME detection & characterization could provide crucial insights on;*

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

II. The search for CME-driven charge separation is a major research theme especially at RHIC!

- ✓ **The isobar run is currently in progress**

Measuring Charge separation



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

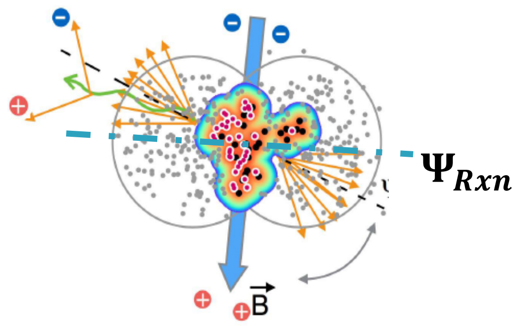
$$\frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_1^{ch} \sin\phi + ...]$$

$$a_1^{ch} \propto \mu_5 \vec{B}$$

<u>Objective:</u> identify & characterize this "dipole moment"

✓ ***The Gamma correlator and its variants, have been used extensively for experimental measurements***

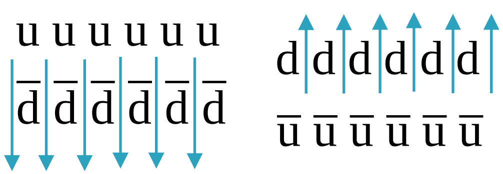
Gamma correlator & its Response



Voloshin, PRC 70 (2004) 057901

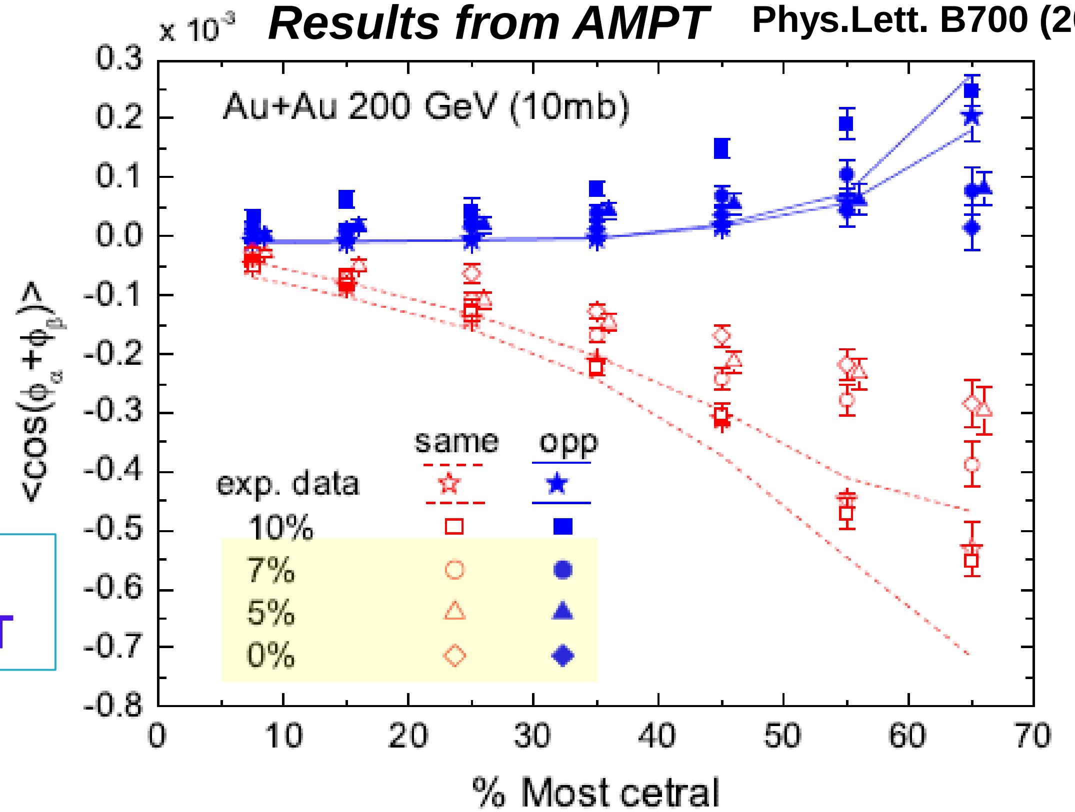
$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + \boxed{c\,\frac{v_2}{N}}$$

Tested with Input charge separation in AMPT



switch the p_y values of a fraction of each set

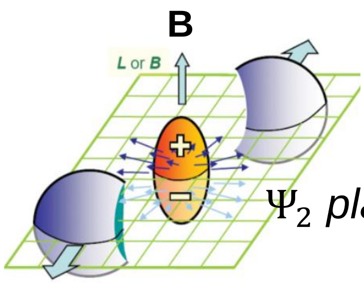
Ma, Zhang
Phys.Lett. B700 (2011) 39-43



- **The Gamma Correlator's response is similar for signal and background**
  - ✓ **Background-driven correlations complicate CME-driven signal extraction?**
- **Background can account for a <u>part</u>, or <u>all</u> of the observed charge separation signal?**

Recent CMS measurements for p+Pb and Pb+Pb at the LHC gives cause for pause!

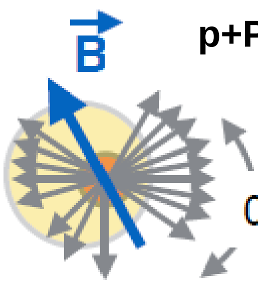
Pb+Pb



Ψ_2 *plane*

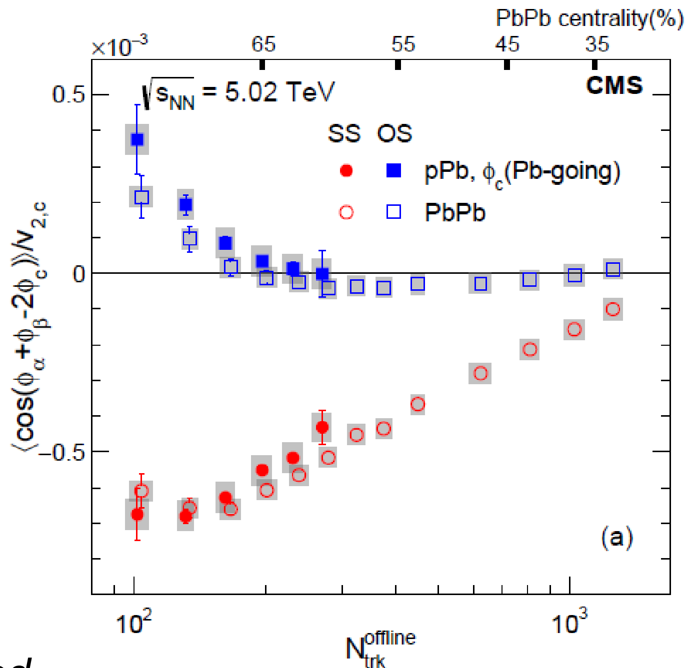
B and Ψ_2 *correlated*

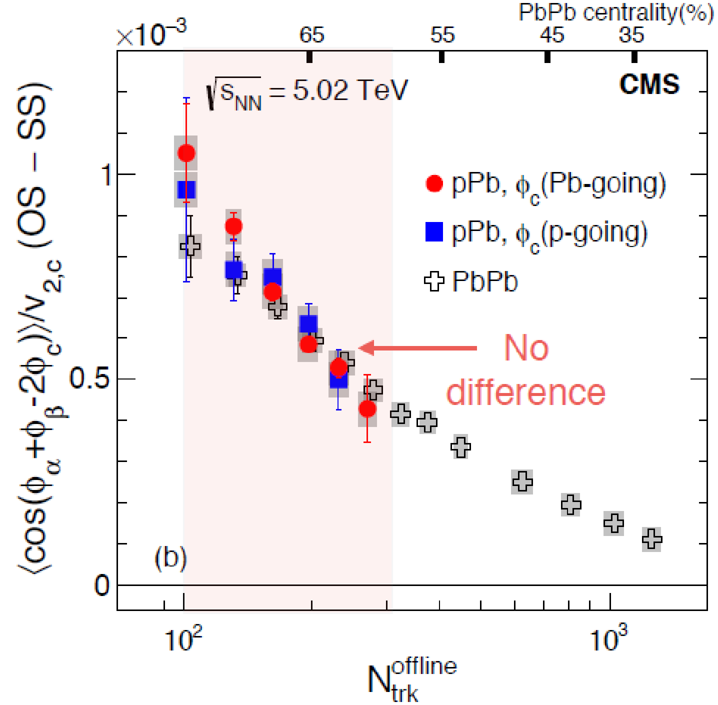
p+Pb



$0<\Psi_2<2\pi$ *plane*

B and Ψ_2 *~ uncorrelated*





- **The magnitudes of the scaled correlators for p+Pb and Pb+Pb are not expected to be the same**

→ **"Reduced" magnetic field strength for p+Pb?**

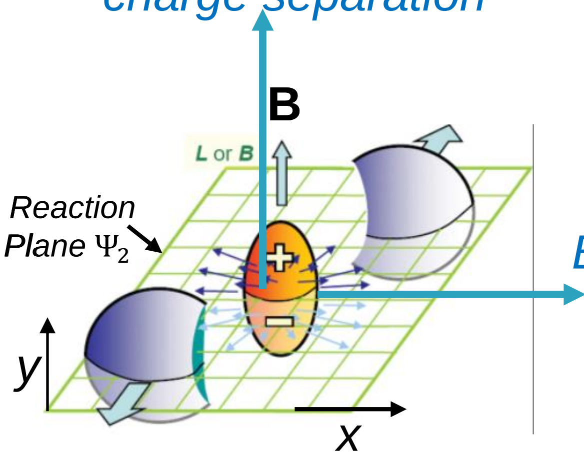
→ **Large dispersion of the B-field about Ψ_2 in p+Pb**

Why a new correlator?

To have better control over signal and background

Correlator essentials

CME-driven + Background-driven charge separation



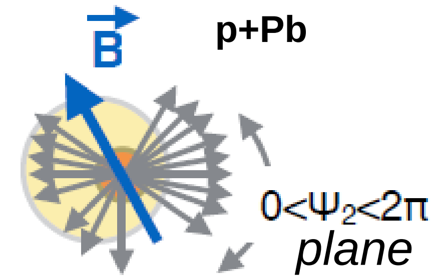
Background-driven charge separation only

Measure separately;

- ✓ *CME-driven + Background-driven charge separation*
- ✓ *Background-driven charge separation*

Then compare them

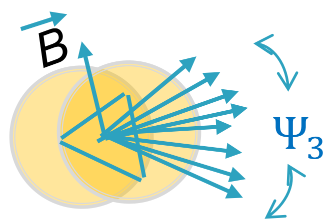
Leverage Small systems



B and Ψ_2 ~ uncorrelated

- ✓ *Measurement insensitive to B-field → "no signal"*
- ✓ *Excellent bench mark*

Leverage Ψ_3 measurements



B and Ψ_3 ~ uncorrelated

- ✓ *Ψ_3 measurements insensitive to B-field, but sensitive to background*
- ✓ *Compare with Ψ_2 measurements*

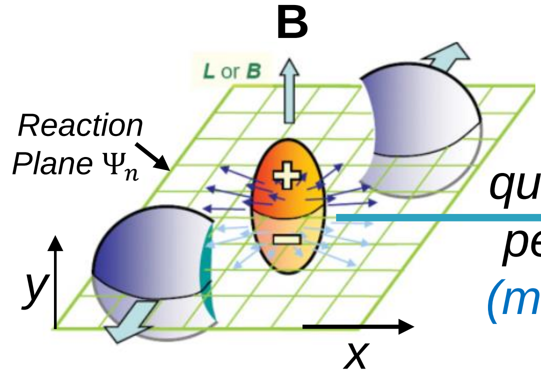
The "New" Correlator

The correlator is constructed for each event plane Ψ_m
via a ratio of two correlation functions

N. Magdy et al.
arXiv: 1710.01717

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \quad \mathrm{m} = 2, 3$$

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



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

The $R_{\Psi_m}(\Delta S)$ correlator measures the magnitude of charge separation parallel to the B-field, relative to that for charge separation perpendicular to the B-field

Note

$C_{\Psi_3}(\Delta S)$ *and* $C^{\perp}_{\Psi_3}(\Delta S)$ *are both insensitive to CME-driven charge separation*
(they measure only background)

The "New" Correlator – Correlation Functions

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \quad \mathrm{m} = 2, 3$$

N. Magdy et al.
arXiv: 1710.01717

Correlation functions are constructed from the ratio of two distributions

$N_{\mathrm{real}}(\Delta S)$

is the distribution over events, of the event-by-event averaged ΔS

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

$$\Delta S = \frac{\sum_1^p \sin(\frac{m}{2}\Delta\varphi_m)}{p} - \frac{\sum_1^n \sin(\frac{m}{2}\Delta\varphi_m)}{n}$$

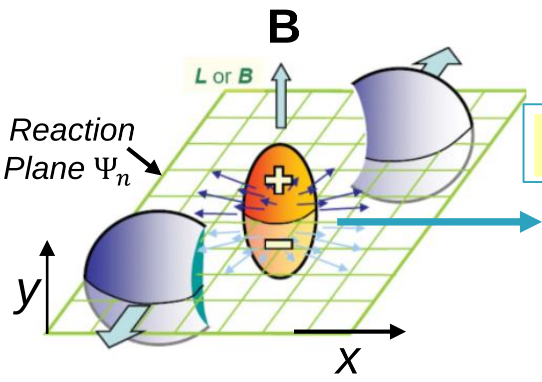
$$\Delta\varphi_m = \phi - \Psi_m$$

$p = \# h^+$ | $n = \# h^-$

ΔS **measures charge separation**

$N_{\mathrm{Shuffled}}(\Delta S)$

*is obtained from the same events, following random reassignment (shuffling) of **only** the charge of each particle in an event*



$$C^{\perp}_{\Psi_m}(\Delta S) = \frac{N_{\mathrm{real}}(\Delta S)}{N_{\mathrm{Shuffled}}(\Delta S)}$$

$$\Psi_m \longrightarrow \Psi_m + \pi / m$$

$N_{\mathrm{real}}(\Delta S)$ *carries charge separation response*

$N_{\mathrm{Shuffled}}(\Delta S)$ *carries the "null" response*

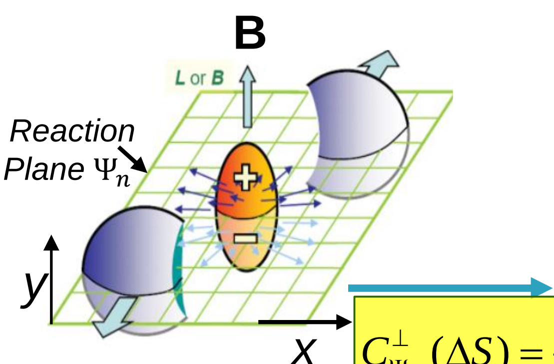
contributions from CME-driven charge separation, vanish for this correlation function

The "New" Correlator & Correlation Functions

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \quad \mathrm{m} = 2, 3$$

Correlation functions are constructed from Gaussian shaped distributions

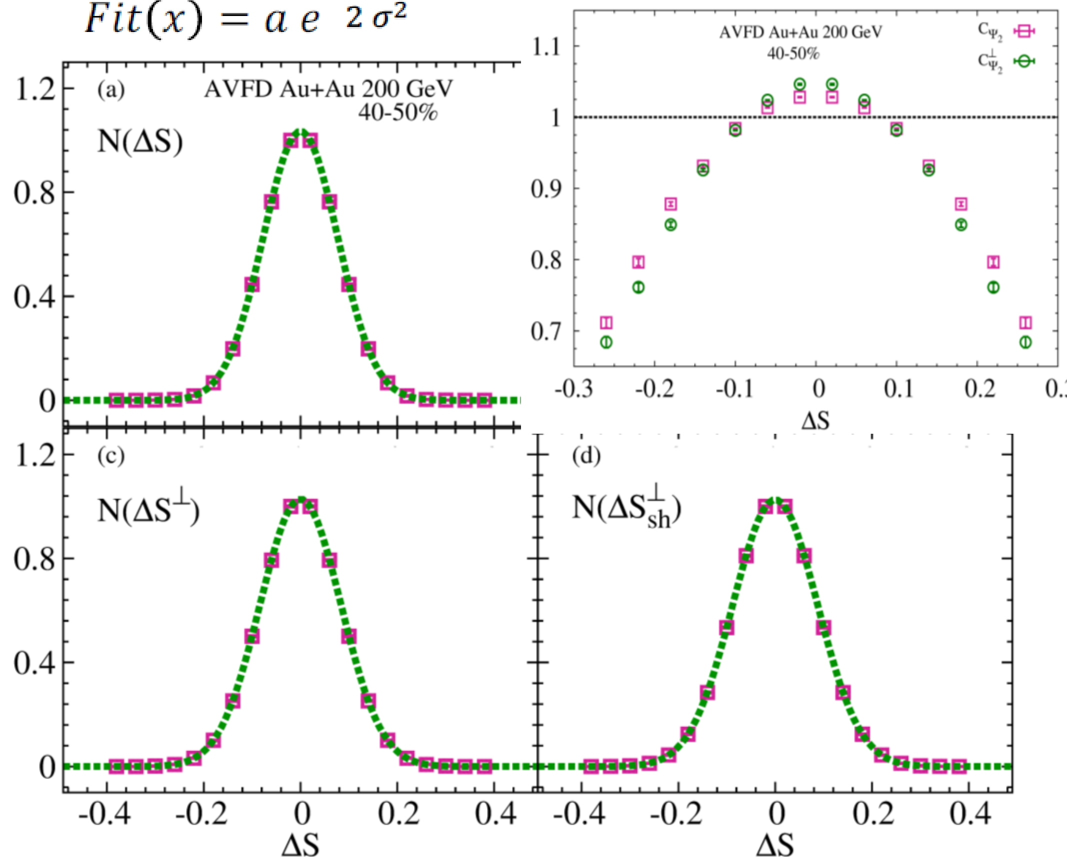
$$C_{\Psi_m}(\Delta S) = \frac{N_{\mathrm{real}}(\Delta S)}{N_{\mathrm{Shuffled}}(\Delta S)}$$



$$C^{\perp}_{\Psi_m}(\Delta S) = \frac{N_{\mathrm{real}}(\Delta S)}{N_{\mathrm{Shuffled}}(\Delta S)}$$

$$\Psi_m \longrightarrow \Psi_m + \pi / m$$

$$Fit(x) = a\, e^{\frac{(x-b)^2}{2\sigma^2}}$$



$C_{\Psi_m}(\Delta S)$, $C^{\perp}_{\Psi_m}(\Delta S)$ and $R_{\Psi_m}(\Delta S)$ *are* Gaussian

$\longrightarrow$ Convexity/Concavity of $R_{\Psi_m}(\Delta S)$ depends on the relative widths

New Correlator Response

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \quad \mathrm{m} = 2, 3$$

Correlator response investigated with several models

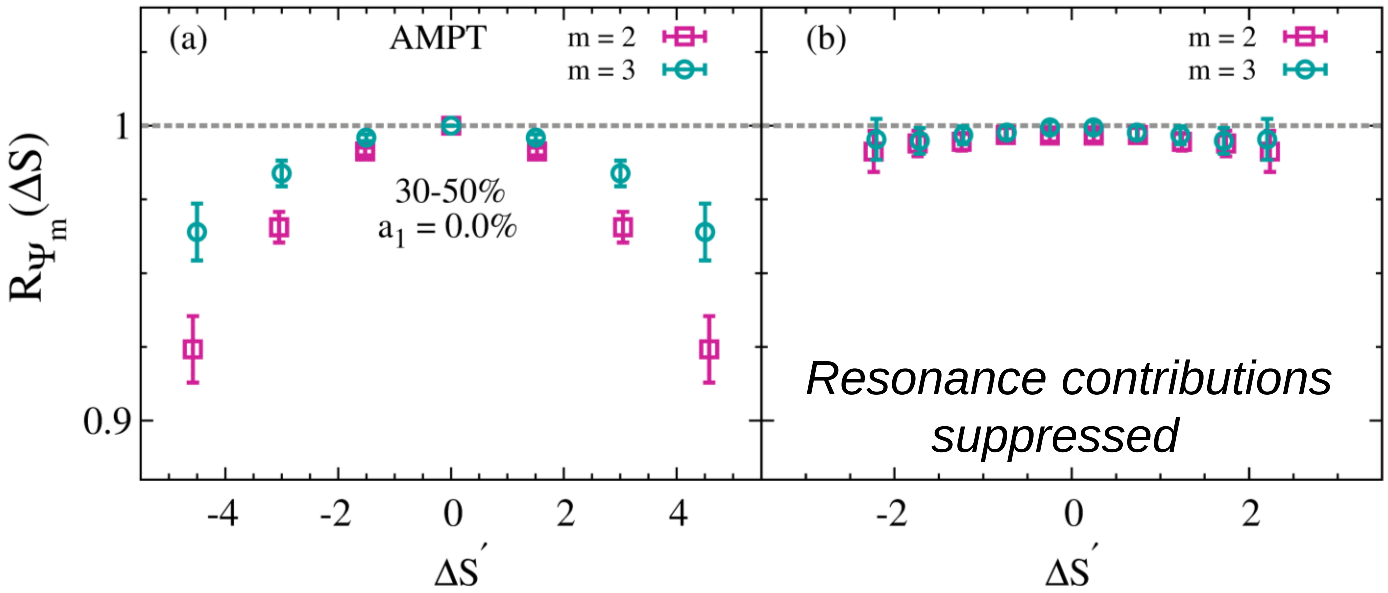
- ✓ *Toy Models*
- ✓ *AMPT (background only)*
- ✓ *AVFD (background + signal)*

Representative examples follow

Correlator Response – background models

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \ \ \mathrm{m} = 2, 3$$

N. Magdy et al.
arXiv: 1710.01717



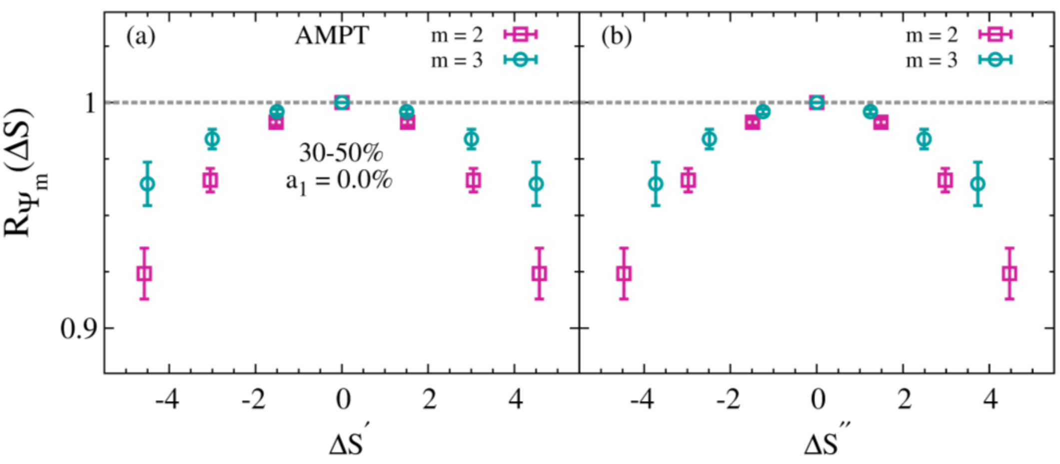
- **Validation of the expected similarity between the patterns for $R_{\Psi_2}(\Delta S)$ and $R_{\Psi_3}(\Delta S)$ for background-driven charge separation**

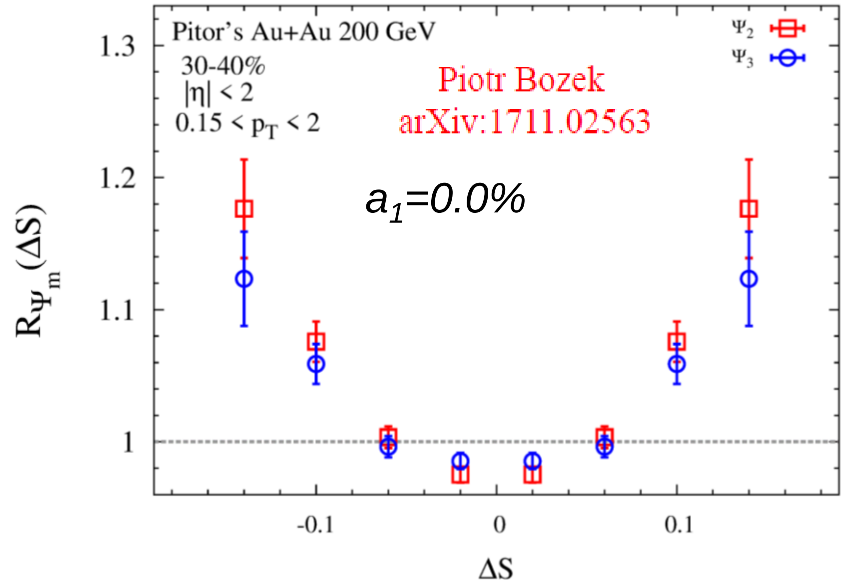
- **A discernible difference in the response for signal and background ($R_{\Psi_2}(\Delta S)$ and $R_{\Psi_3}(\Delta S)$) is a crucial and necessary requirement for unambiguous identification and characterization of CME-driven charge separation.**

Correlator Response – background models

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)},\ \ \mathrm{m} = 2, 3$$

N. Magdy et al.
arXiv: 1710.01717





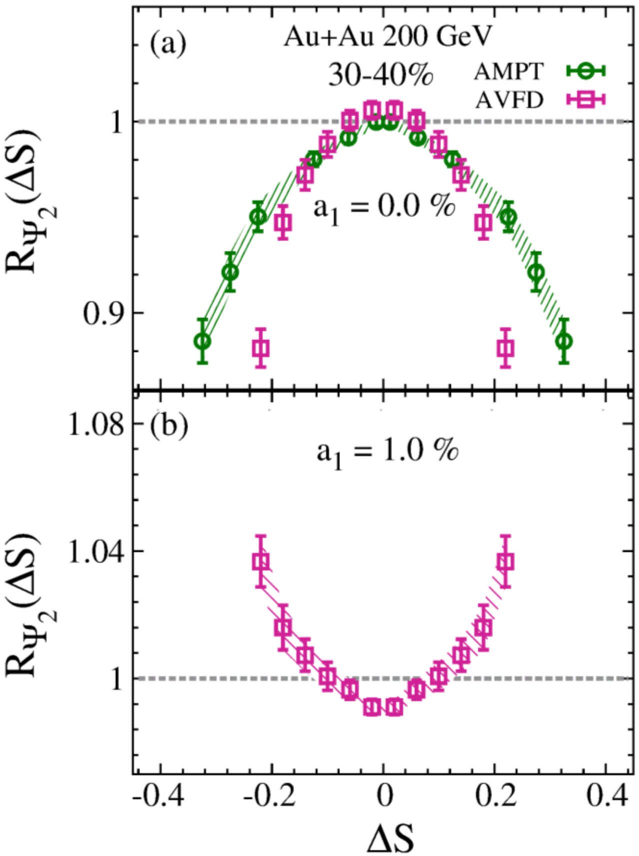
- **Validation of the expected similarity between the patterns for $R_{\Psi_2}(\Delta S)$ and $R_{\Psi_3}(\Delta S)$ for background-driven charge separation**

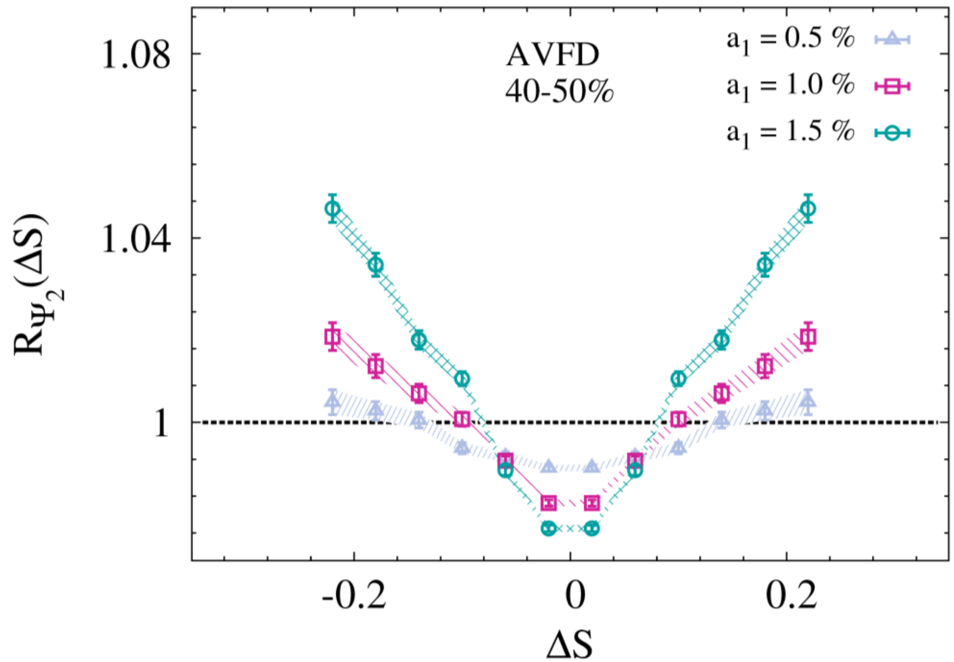
- **A discernible difference in the response for signal and background ($R_{\Psi_2}(\Delta S)$ and $R_{\Psi_3}(\Delta S)$) is a crucial and necessary requirement for unambiguous identification and characterization of CME-driven charge separation.**

New Correlator Response – Signal + background

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi}(\Delta S)}, \quad \mathrm{m} = 2, 3$$

N. Magdy et al.
arXiv: 1710.01717





Concaved-shape distribution for input charge separation

Signal magnitude reflected in the widths of the distributions

- ✓ *Smaller widths for larger input signal*

➢ **Validation of the expected concave-shaped response of $R_{\Psi_2}(\Delta S)$ to CME-driven charge separation input in AVFD events.**

Signal Quantification

Charge separation magnitude is reflected in the widths (σ) of the correlator distributions

N. Magdy et al. this workshop

The widths are also influenced by;

- ✓ *Number fluctuations*
- ✓ *Event plane resolution*

Both can be accounted for, via appropriate scaling

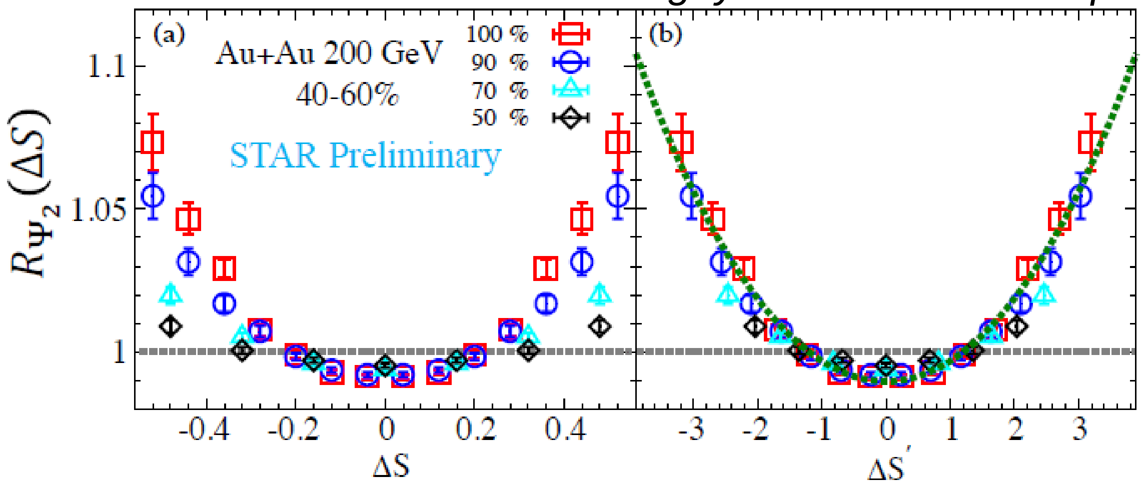
- ✓ *Number fluctuations*

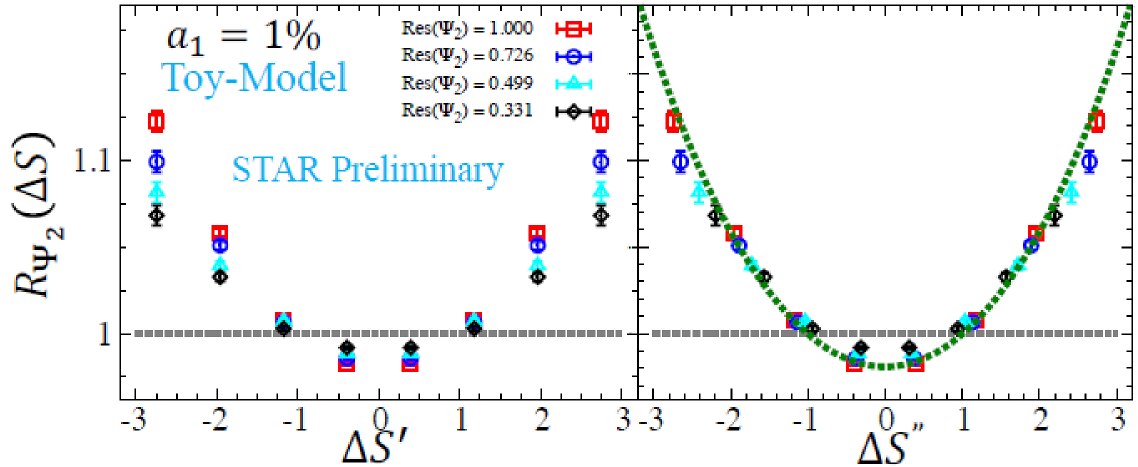
$$\Delta S' = \Delta S / \sigma_{\Delta S^{sh}}$$

- ✓ *Event plane resolution*

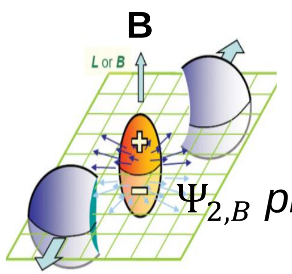
$$\Delta S'' = \Delta S' / \delta_{Res}$$

$$\delta_{Res} = e^{0.5(1-Res)^2}$$





Signal Identification & Characterization



$\Psi_{2,B}$ *planes*

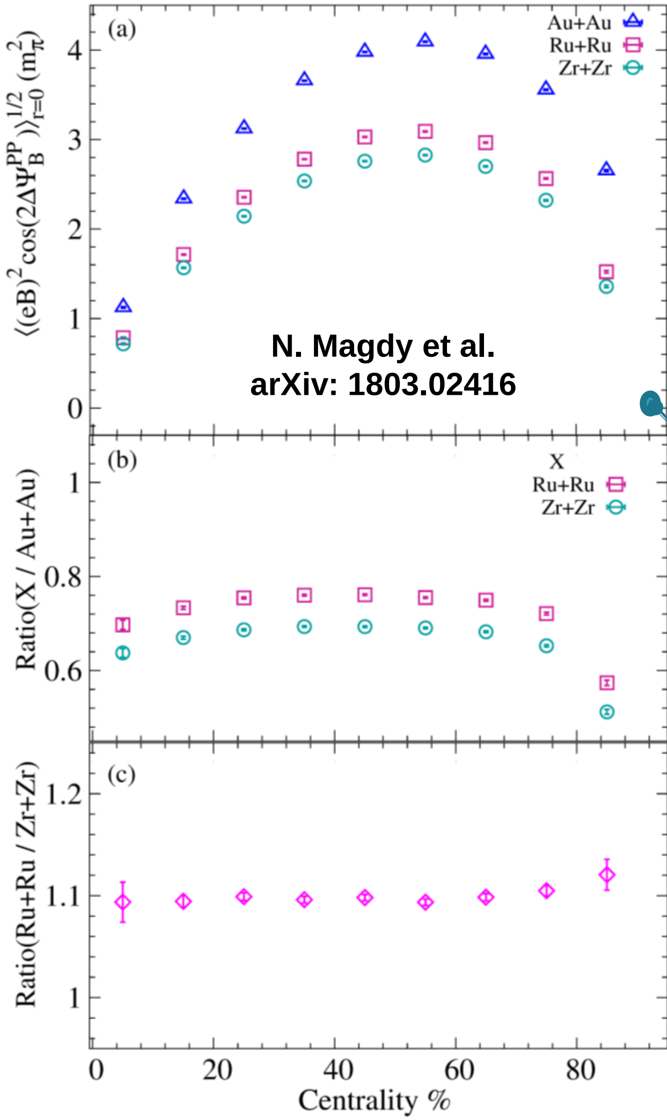
Ψ_B *and* Ψ_2 *correlated*
Ψ_B *and* Ψ_3 *correlated*

$\tau_B \propto 1/\sqrt{s}$

$B \propto \sqrt{s}$

Characteristic beam energy dependence expected

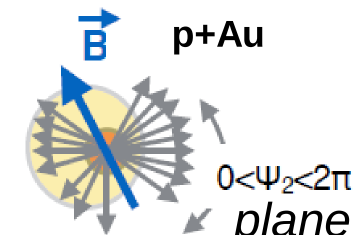
But need chiral quarks



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

$$a_1^{ch} \propto \mu_5 \vec{B}$$

Characteristic centrality and system dependence expected



Ψ_B *and* Ψ_2 *&* Ψ_3
~ uncorrelated

Characteristic difference between $R_{\Psi_2}(\Delta S)$ *and* $R_{\Psi_3}(\Delta S)$ *expected*

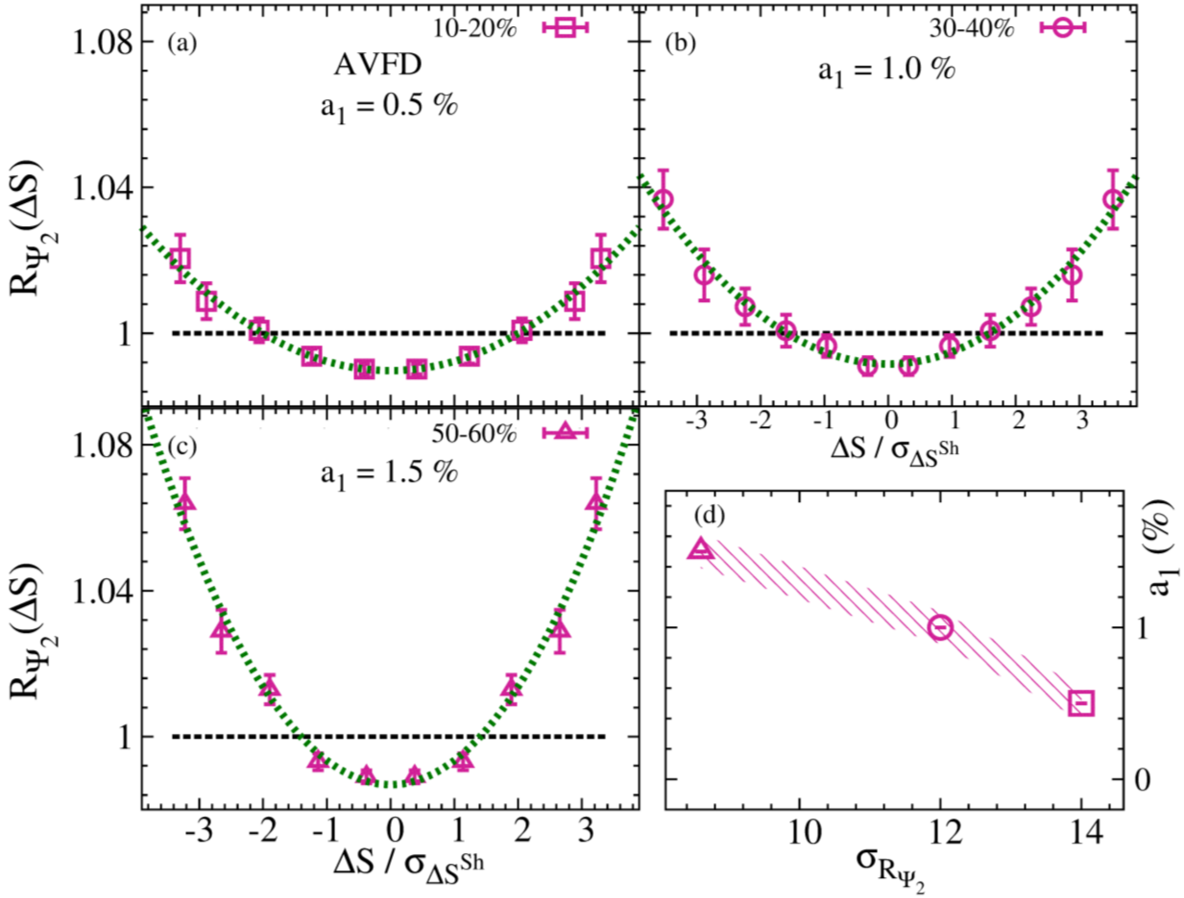
Characteristic isobaric-system dependence expected

➢ **We leverage the characteristic $\sqrt{s}$, centrality and system dependence to identify and characterize CME-driven charge separation**

New Correlator Response

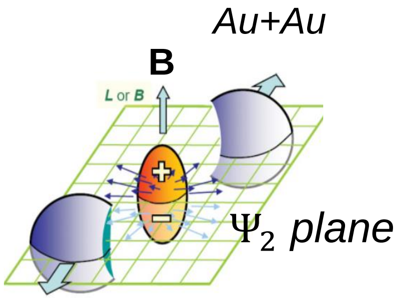
$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}, \ \ m = 2, 3$$

N. Magdy et al.
arXiv: 1710.01717



➢ **Validation of the expected centrality dependence of $R_{\Psi_2}(\Delta S)$ to CME-driven charge separation input in AVFD events.**

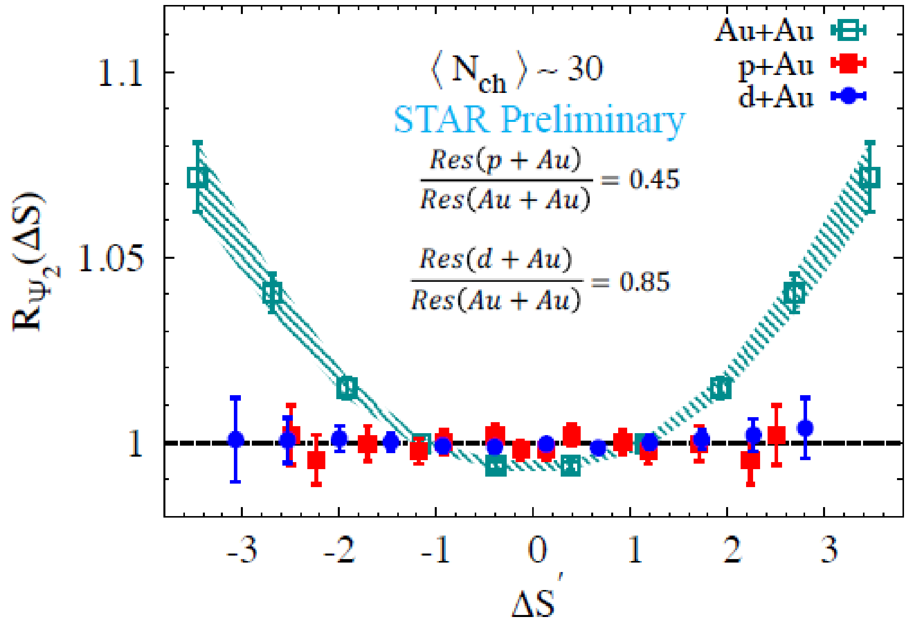
New Correlator Response – Data teaser

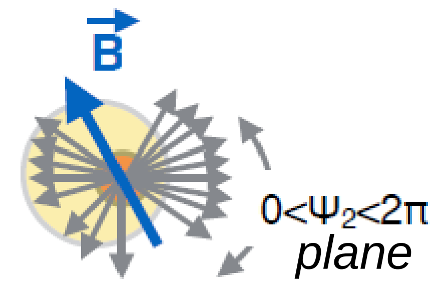


Ψ_B and Ψ_2 correlated

$$a_1^{ch} \propto \mu_5 \vec{B}$$

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





Ψ_B and Ψ_2 ~ uncorrelated

- **A decidedly "concave-shaped" distribution for peripheral Au+Au collisions**
  - ✓ ***Consistent with a CME-driven charge separation contribution in these collisions***

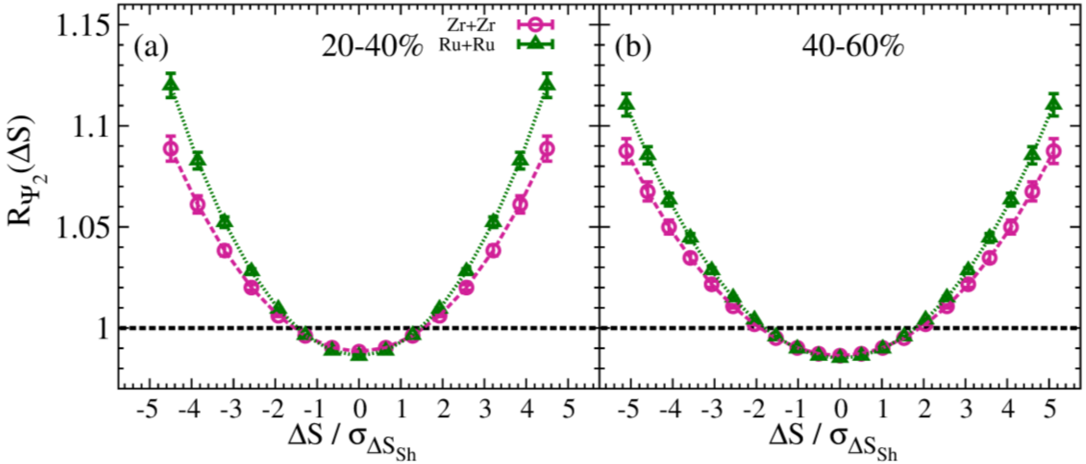
- **In contrast, an essentially flat distribution for p(d)+Au**
  - ❖ **Validates the**
    - ✓ *"reduced magnetic field strength"*
    - ✓ *random B-field orientations*

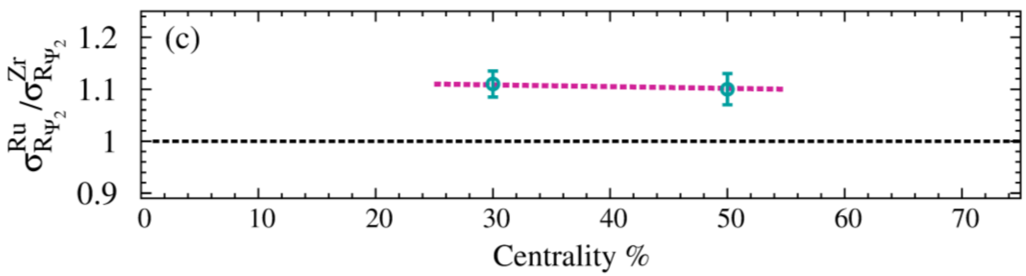
  in these collisions

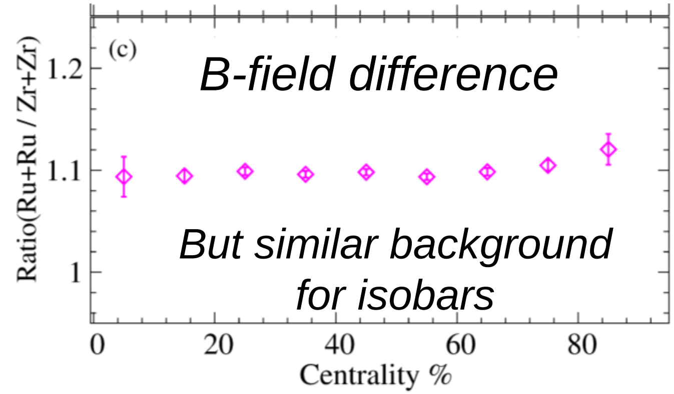
$R_{\Psi_m}(\Delta S)$ measurements are consistent with the expectations for CME-driven charge separation

New Correlator Response

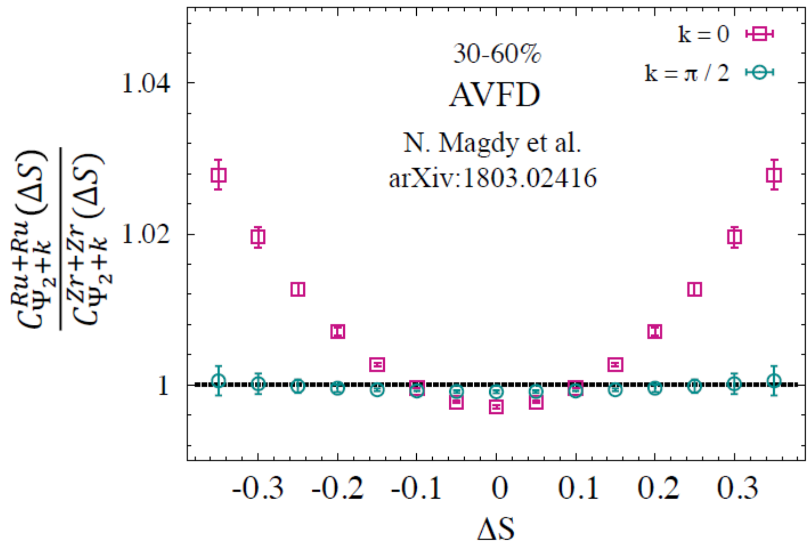
AVFD predictions for the Ru+Ru and Zr+Zr isobaric systems







$$C_{\Psi_2+k} = \frac{N(\Delta S^{\Psi_2+k})}{N(\Delta S^{\Psi_2+k}_{sh})}$$



- **Validation of the expected isobaric dependence of $R_{\Psi_2}(\Delta S)$ to CME-driven charge separation input in AVFD events.**

Isobaric ratios of the correlation function can be used to characterize both signal and background – crucial for isobar run!

Summary

- *New charge-sensitive $R_{\Psi_m}(\Delta S)$ correlators have been developed to identify and characterize CME-driven charge separation*
  - ✓ *This correlator suppresses, as well as measures the well known background contributions to the CME-driven charge separation signal*
- *Validation tests, performed with several models, indicate that the correlators can give;*
  - ✓ *discernible responses for background- and CME-driven charge separation which allows unambiguous identification and characterization of the CME*
  - ✓ *Crucial information to characterize both signal and background in the isobar data*
- ***The experimentally measured correlators (to date) suggests the presence of a CME-driven charge separation in Au+Au collisions.***

End

Chiral Magnetic Effect

Electric Current → $\vec{J}_Q$

Chiral Magnetic Conductivity → σ_5

Chiral Chemical potential → μ_5

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

$$\sigma_5 = C_A \mu_5$$

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

Kharzeev hep-ph/0406125

Jiang et al., arXiv:1611.04586

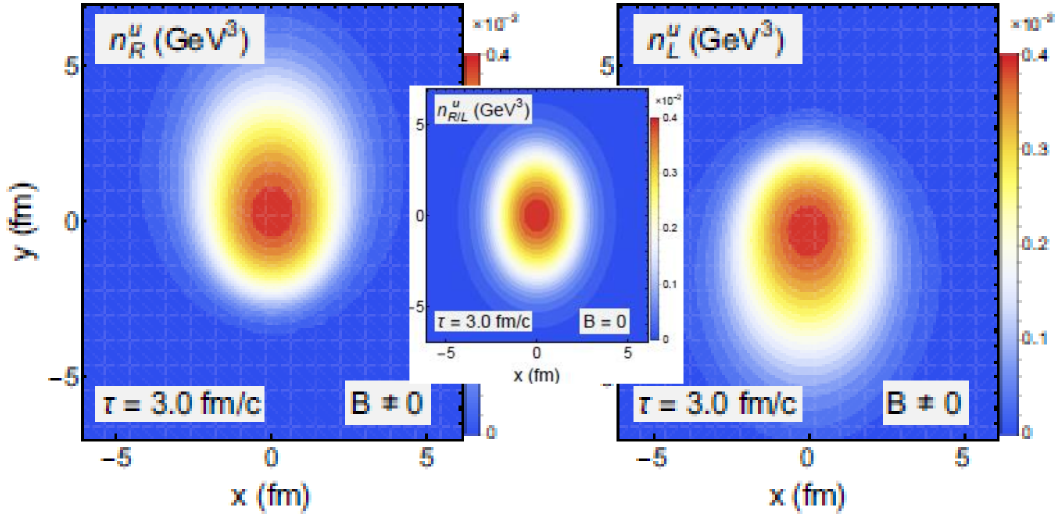


FIG. 1. Comparison of the evolution of the densities (n_R^u, n_L^u) for right-handed (left panel) and left-handed (right panel) u-flavor quarks at $\tau = 3.00$fm/c for a nonzero B field along the positive y-axis (i.e. perpendicular to the reaction plane). The figures, which show results from Anomalous Viscous Fluid Dynamics (AVFD) calculations, are taken from Ref. [8].

The Chiral Magnetic Effect (CME) results from anomalous chiral transport of the chiral fermions in the QGP, leading to the generation of an electric current $\vec{J}_Q$ *along the magnetic field* $\vec{B}$ *generated in the collision:*

→ **Leads to charge separation about the event plane**

Charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

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

Objective: identify & characterize this "dipole moment"

CME correlator status quo

Several measurements performed at RHIC and the LHC with the so-called **Gamma Correlator**;

Second order event plane

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

$\alpha, \beta = -, +$

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

3-particle-correlator :

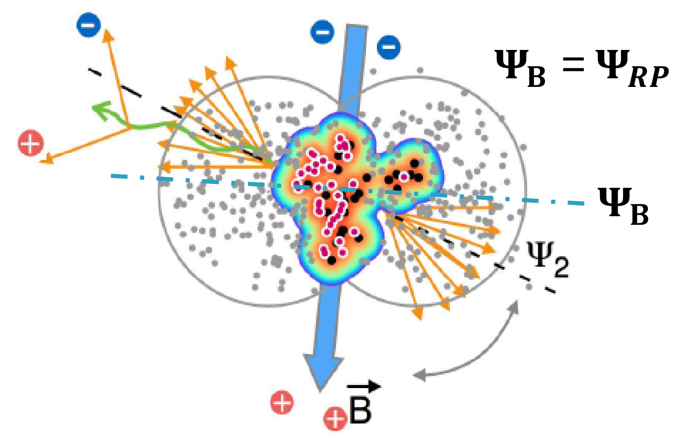
$$C_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$$

Voloshin, PRC 70 (2004) 057901

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

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

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\mathrm{IN}}] - [\langle a_\alpha a_\beta \rangle + B_{\mathrm{OUT}}]$$



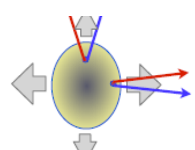
Directed flow (small at |η|<1)

In-plane background

Interesting Signal

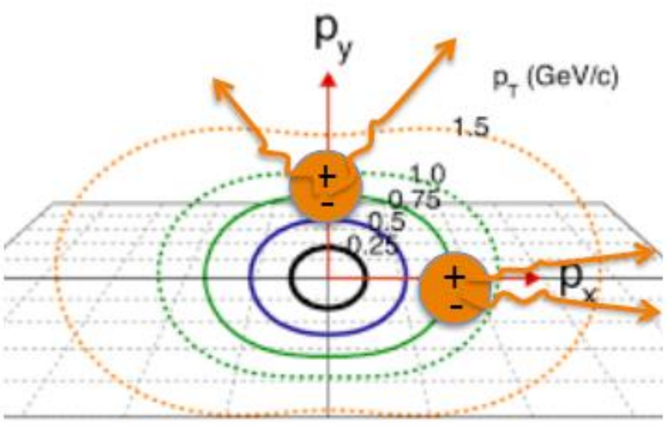
Out-of-plane background

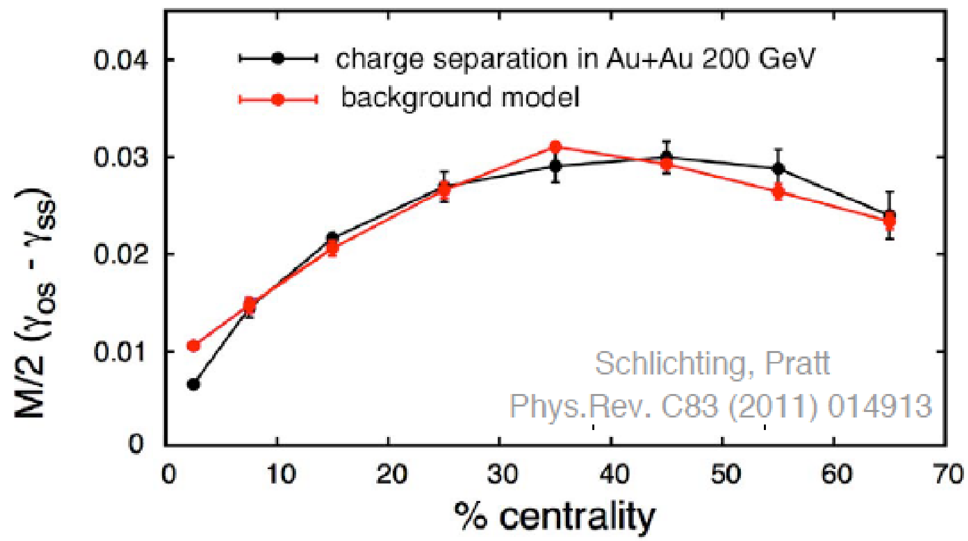
$(B_{IN} - B_{OUT}) \sim v_2/N$



$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\,\frac{v_2}{N}$$

Local charge conservation is an especially important background





$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + c\,\frac{v_2}{N}$$

||

0

- **Background-driven correlations can account for a <u>part</u>, or <u>all</u> of the observed charge separation signal?**