Anomalous transport in the Quark Gluon Plasma

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Focus: Experimental measurement of anomalous transport
(excellent theory presentations given in this series - eg. Landsteiner +)

N. Magdy, et. al, e-Print: 2003.02396
N. Magdy, et. al, e-Print: 2002.07934
N. Magdy, Phys.Rev.C 98 (2018) 6, 061902
N. Magdy, et al, Phys.Rev.C 97 (2018) 6, 061901

STAR Collaboration, e-Print:2006.04251

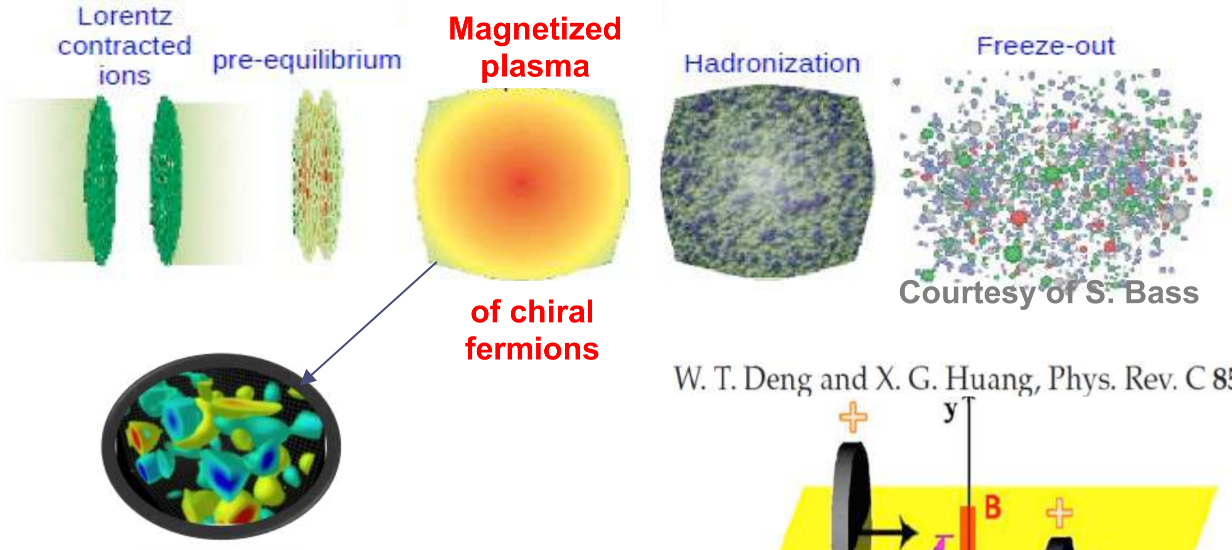
Outline

- *Introduction*
  - ✓ *Anomalous transport*
- **Observables for anomalous transport**
  - ✓ *Dipole charge separation*
  - ✓ *Quadrupole charge separation*
- **Correlator response and sensitivity**
  - ✓ *Background-only models*
  - ✓ *Background + signal models*
- **Experimental Results**
  - ✓ *Dipole*
  - ✓ *Quadrupole?*
- *Epilogue*

Essential takeaway

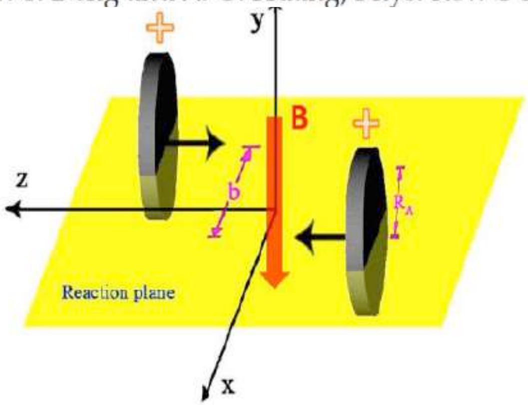
Precision measurements with a new charge-sensitive correlator, indicates anomalous transport in the quark gluon plasma created in RHIC collisions

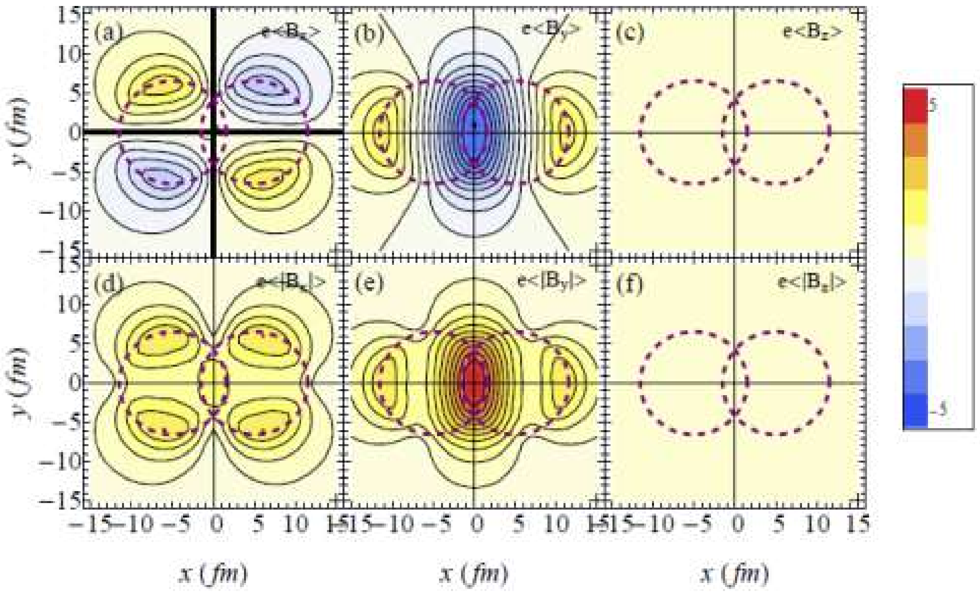
Magnetized QGP production

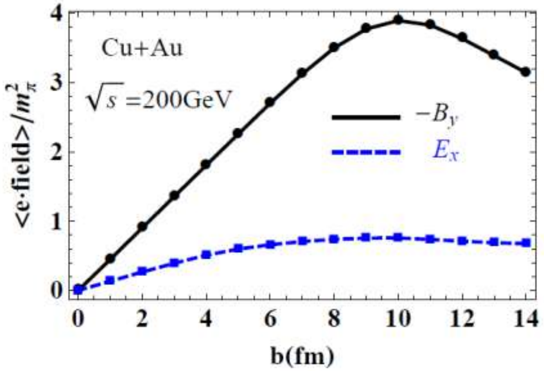


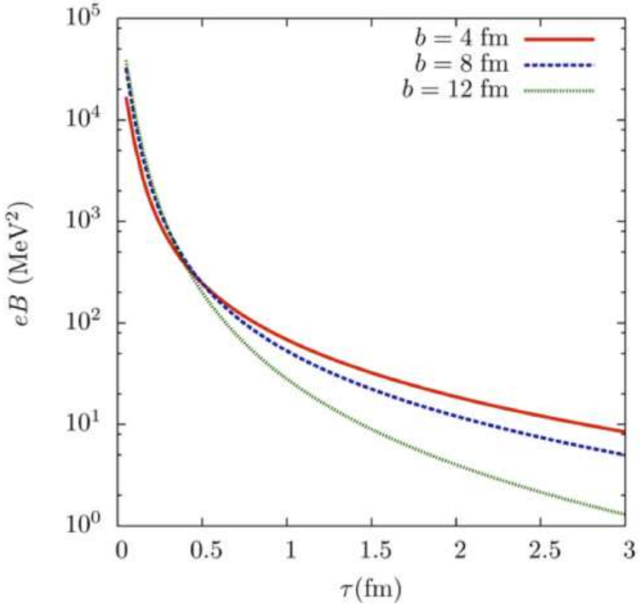
Topology-changing transitions can lead to a chiral imbalance characterized by (μ_A)

W. T. Deng and X. G. Huang, Phys. Rev. C **85**, 044907









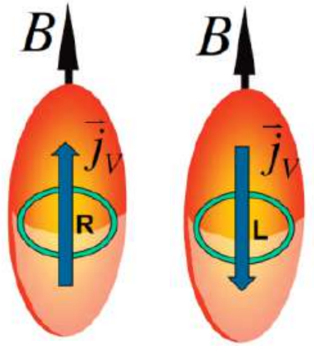
- ❖ *A chiral imbalance in the presence of a strong magnetic field, drives anomalous transport*

- ➢ **The QGP is subject to very strong B fields**
  - ✓ **10^{18} G (RHIC)**
  - ✓ **10^{20} G (LHC)**

D. Kharzeev, L. McLerran and H. Warringa, Nuclear Physics A 803, 227 (2008)

Anomalous Transport

Two principal anomalous processes are expected in the magnetized plasma [for $\mu_{V,A} \neq 0$]



<u>*Chiral Separation Effect (CSE)*</u>

$$\vec{J}_A = \frac{e\vec{B}}{2\pi^2}\mu_V\,, \text{for } \mu_V \neq 0$$

Vector chemical potential

Derived from the induction of a non-dissipative chiral axial current

<u>*Chiral Magnetic Effect (CME)*</u>

$$\vec{J}_V = \frac{e\vec{B}}{2\pi^2}\mu_A\,, \text{for } \mu_A \neq 0$$

Axial chemical potential

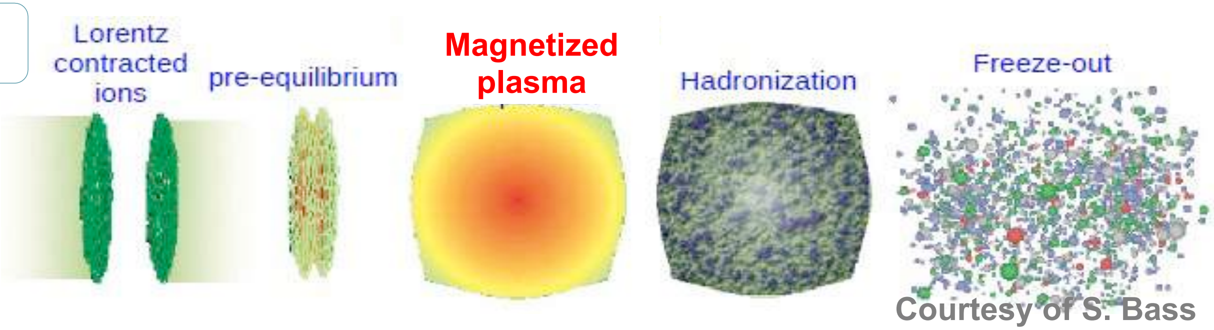
Characterized by a chiral vector current

(the lowest Landau level is chiral)

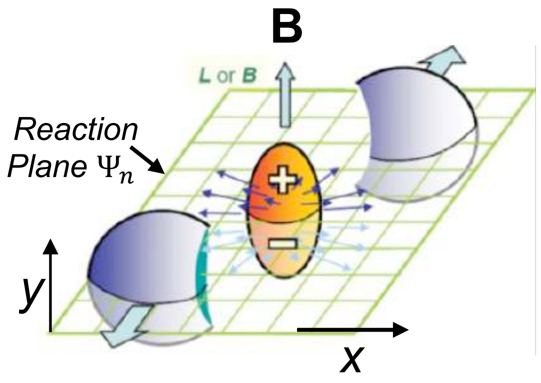
Experimental confirmation of the CME;

- ✓ *Would be a direct observation of topological effects in QCD.*
- ✓ *Would manifest the restoration of chiral symmetry in the QGP*

Anomalous Transport –Signals



CME



- *The CME drives a dipole charge separation along the* **B**-*field*
  - ✓ *leads to a "dipole moment" in the azimuthal distribution of the produced charged hadrons:*

$$\frac{dN}{d\Delta\phi} \propto [1 \pm 2a_1 \sin(\Delta\phi) + ...]$$

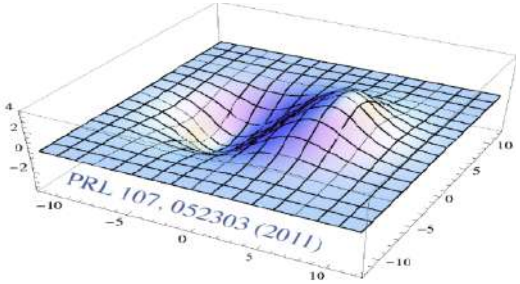
$$\tilde{a}_1 = \langle a_1^2 \rangle^{1/2} \propto \mu_5 B$$

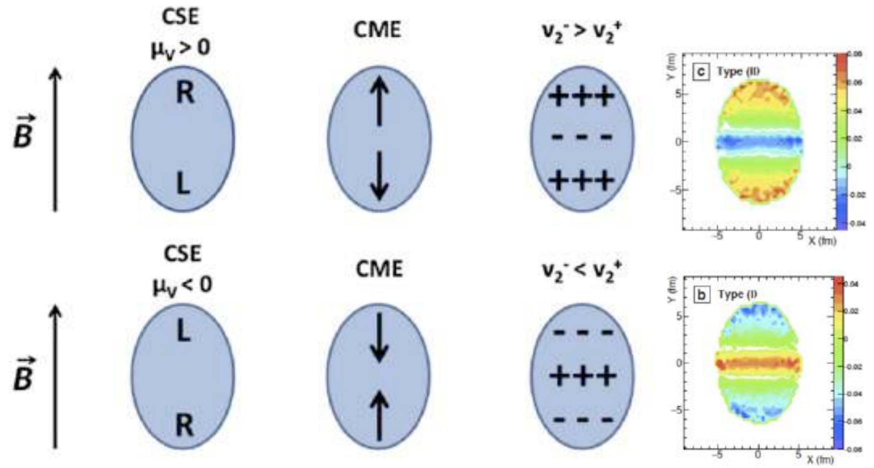
CMW

The interplay between the CSE and CME can lead to the production of a gapless collective mode or Chiral Magnetic Wave (CMW)

- ✓ Stems from the coupling between the density waves of the electric and chiral charges

Dmitri E. Kharzeev and Ho-Ung Yee, Phys. Rev. D83, 085007 (2011)





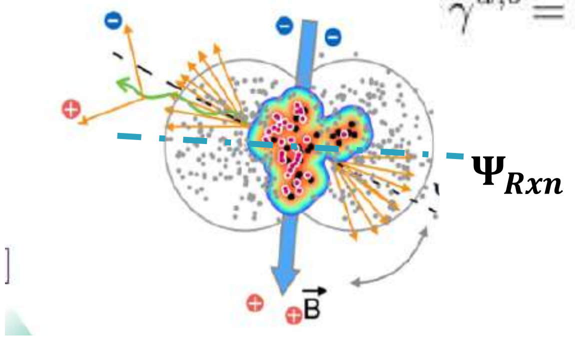
The CMW transports positive (negative) charges out-of-plane and negative (positive) charges in-plane to form an electric quadrupole.

- **The detection and characterization of both the dipole and quadrupole charge separation is paramount**

Prior/ongoing dipole charge separation measurements

A well known approach is to use the gamma (γ) correlator to measure the dipole charge separation

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

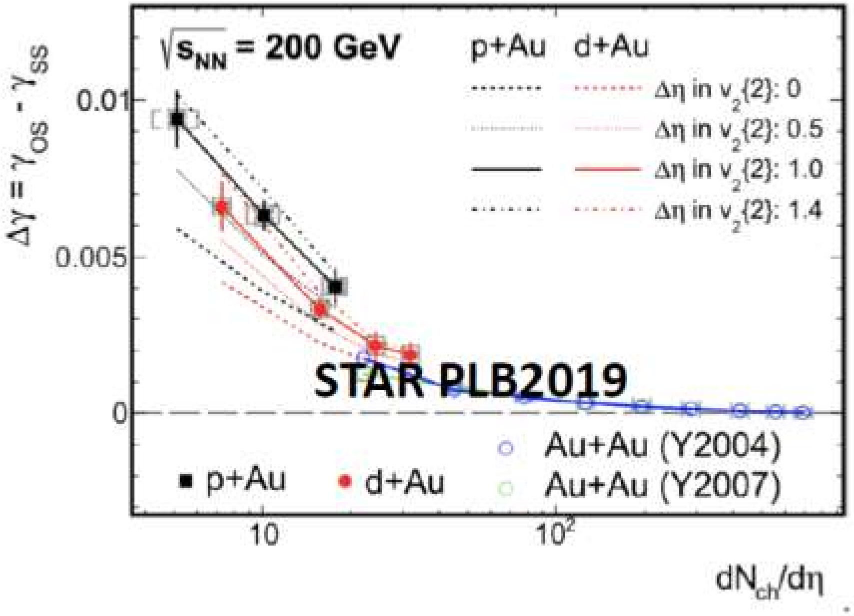


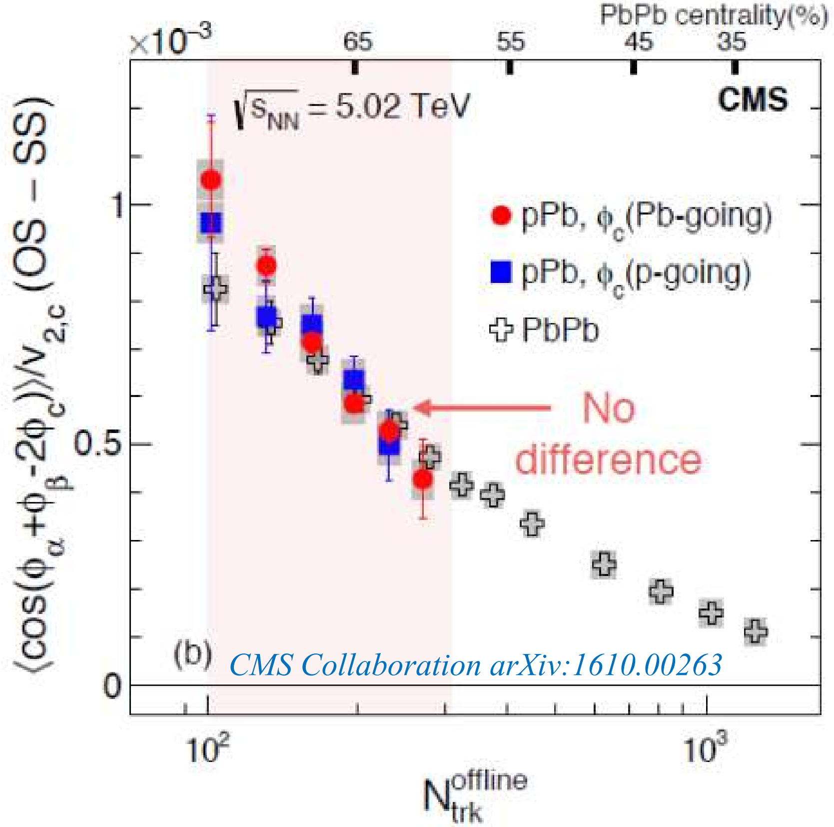
Voloshin, PRC 70 (2004) 057901

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

background

The background complicates signal extraction





Background can account for a sizeable part, if not all, of the observed charge separation

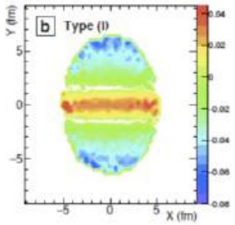
- ✓ **Could one make more discerning measurements with a different correlator?**

Prior/ongoing quadrupole charge separation measurements

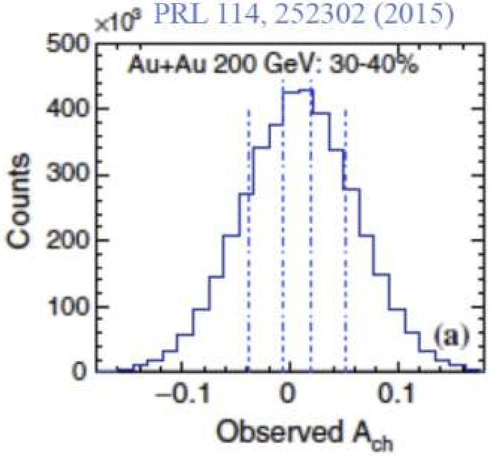
A pervasive approach is to measure the elliptic flow difference between negatively- and positively charged particles as a function of charge asymmetry

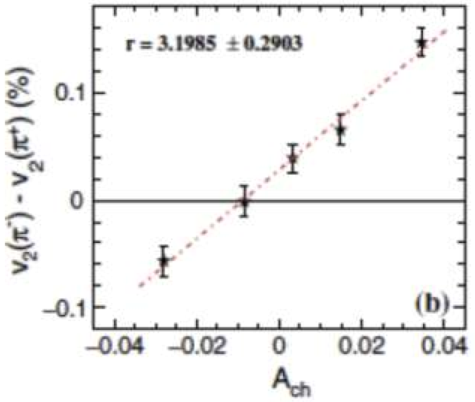
$$\Delta v_2 \equiv v_2^- - v_2^+ \simeq r A_{ch}$$

$$A_{ch} = \frac{(N^+ - N^-)}{(N^+ + N^-)}$$

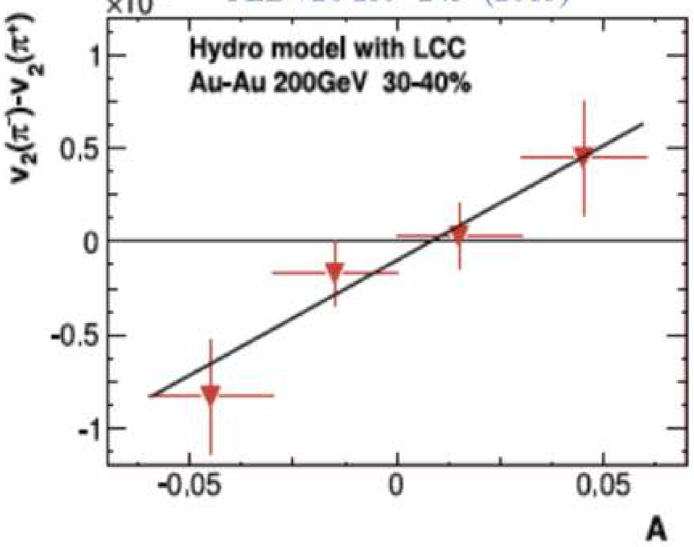


STAR
PRL 114, 252302 (2015)

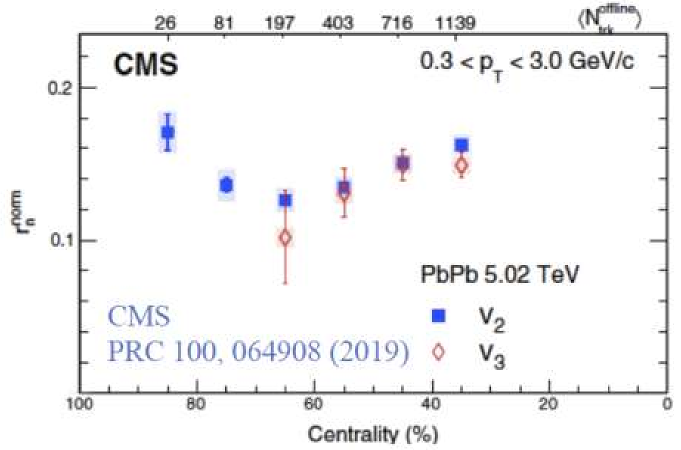


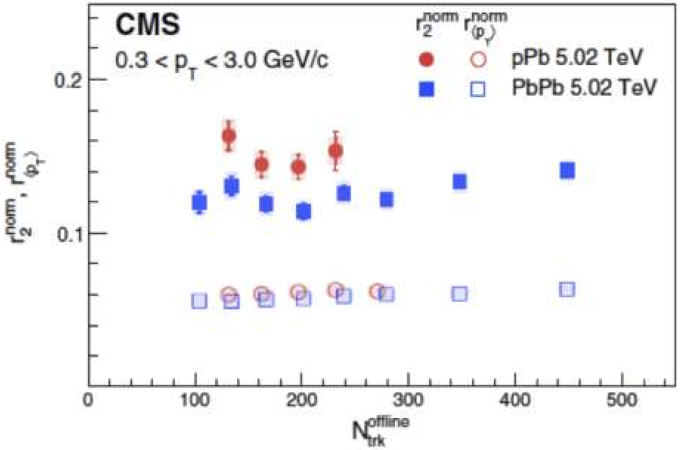


A.Bzdaka and P.Bozekb
PLB 726 239–243 (2013)



A purely background scenario can give a similar dependence





- ➢ Similar slope parameter for:
  - ✓ v_2 and v_3
  - ✓ Small and large systems

Background can account for a part, if not all, of the observed charge separation signal with this correlator

- ✓ **Could one make more discerning measurements with a different correlator?**

The $R^{(d)}_{\Psi_m}(\Delta S_d)$ Correlator - Rudiments

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

N. Magdy, et al. arXiv:2003.02396

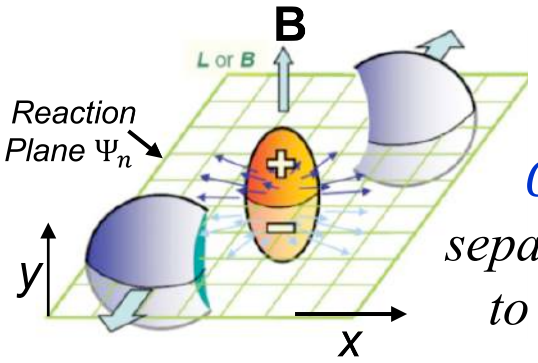
- *The correlator is constructed for a given event plane Ψ_m via a ratio of two correlation functions*

$$R^{(d)}_{\Psi_m}(\Delta S_d) = \frac{C_{\Psi_m}(\Delta S_d)}{C^{\perp}_{\Psi_m}(\Delta S_d)}, m = 2 \text{ and } 3$$

d=*1 - dipole*
d=*2 – quadrupole*
Charge separation

m[th] order event plane

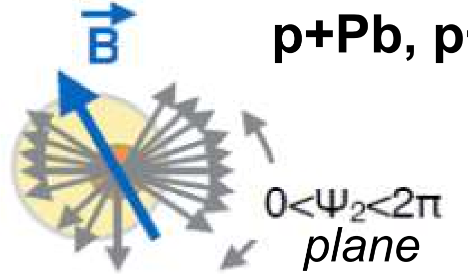
$C_{\Psi 2}(\Delta S_d)$ *quantifies charge separation of order* **d** *along the B-field*



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

- **Leverage Small systems**

p+Pb, p+Au, …



B-field and Ψ_2 ~ uncorrelated

- ✓ $R^{(d)}_{\Psi_2}(\Delta S_d)$ *measurements insensitive to B-field → "no signal"*
- ✓ *Excellent bench mark*

The $R^{(d)}_{\Psi_m}(\Delta S_d)$ correlator measures the magnitude of charge separation of order **d** *parallel to the B-field, relative to that for charge separation perpendicular to the B-field*

Note that $R^{(d)}_{\Psi_3}(\Delta S_d)$ ***is insensitive to the CME- and CMW-driven charge separation (but sensitive to background)***

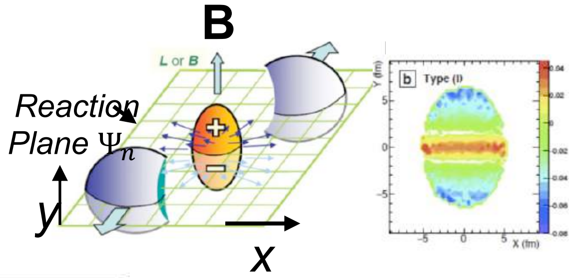
The $R^{(d)}_{\Psi_m}(\Delta S_d)$ Correlator - Operational

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

N. Magdy, et al.
arXiv:2003.02396

$$R^{(d)}_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S_d)}{C^{\perp}_{\Psi_m}(\Delta S_d)}$$

d=1 - dipole
d=2 - quadrupole



$$C_{\Psi_m}(\Delta S) = \frac{N(\Delta S_d)}{N(\Delta S_d)_{Sh}}$$

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

Sensitive to charge separation (Signal and Background):

$$C^{\perp}_{\Psi_m}(\Delta S) = \frac{N(\Delta S_d)^{\perp}}{N(\Delta S_d)_{Sh}{}^{\perp}}$$

$$N(\Delta S_d) = \mathrm{N}(\langle S^{+}_{\Psi_m}\rangle_d - \langle S^{-}_{\Psi_m}\rangle_{\mathrm{d}})$$

$$N(\Delta S_d)^{\perp} = \mathrm{N}(\langle S^{+}_{\Psi_m}\rangle^{\perp}_d - \langle S^{-}_{\Psi_m}\rangle^{\perp}_d)$$

w_i: charge-dependent detector acceptance

$$\langle S^{+}_{\Psi_m}\rangle_d = \frac{\Sigma_1^p\, w_p \sin\left[\frac{m^d}{2}\,(\Delta\varphi)\right]}{w_p}$$

$$\langle S^{+}_{\Psi_m}\rangle^{\perp}_d = \frac{\Sigma_1^p\, w_p \cos\left[\frac{m^d}{2}\,(\Delta\varphi)\right]}{w_p}$$

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

$$\langle S^{-}_{\Psi_m}\rangle_d = \frac{\Sigma_1^n\, w_n \sin\left[\frac{m^d}{2}\,(\Delta\varphi)\right]}{w_n}$$

$$\langle S^{-}_{\Psi_m}\rangle^{\perp}_d = \frac{\Sigma_1^n\, w_n \cos\left[\frac{m^d}{2}\,(\Delta\varphi)\right]}{w_n}$$

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

$$N(\Delta S_d)_{Sh} = \mathrm{N}(\langle S^{+}_{\Psi_m}\rangle_d - \langle S^{-}_{\Psi_m}\rangle_{\mathrm{d}})_{\mathrm{Sh}}$$

$$N(\Delta S_d)^{\perp} = N(\langle S^{+}_{\Psi_m}\rangle^{\perp}_d - \langle S^{-}_{\Psi_m}\rangle^{\perp}_d)_{Sh}$$

- **The correlator employs a common operational framework for both the dipole and quadrupole charge separation measurements**

Models used to "calibrate" the correlators

- *The response and the sensitivity of the correlators were studied with several models;*
  - ✓ AMPT with varying degrees of proxy CME- and CMW-driven charge separation **+ background**
  - ✓ AVFD with varying degrees of CME-driven charge separation **+ background**
  - ✓ Hydro events with **only background** **background = well known backgrounds**

AVFD - CME

The AVFD model, simulates the evolution of fermion currents in the QGP on top VISHNU bulk hydrodynamic flow

Yin Jiang, Shuzhe Shi, Yi Yin, and Jinfeng Liao
Chin.Phys.C 42 (2018) 1, 011001
e-Print: 1611.04586

AMPT - CME **Guo-Liang Ma and Bin Zhang** ***Phys. Lett. B700, 39–43 (2011)***

CME-induced charge separation generated By switching the p_y values of a fraction of the downward moving u ($\bar{d}$) quarks with those of the upward moving $\bar{u}$(d) quarks to produce a net charge-dipole separation in the initial-state

Signal strength $f_0 = \frac{N^{+(-)}_{\uparrow(\downarrow)} - N^{+(-)}_{\downarrow(\uparrow)}}{N^{+(-)}_{\uparrow(\downarrow)} + N^{+(-)}_{\downarrow(\uparrow)}}, \quad f_0 = \frac{4}{\pi} a_1$

$$\frac{dN}{d\Delta\phi} \propto [1 \pm 2a_1 \sin(\Delta\phi) + ...] \qquad \tilde{a}_1 = \langle a_1^2 \rangle^{1/2} \propto \mu_5 B$$

AMPT - CMW ***G.-L. Ma, Phys. Lett. B 735, 383 (2014)***

CMW-induced quadrupole charge separation generated by interchanging the position coordinates (x, y, z) for a fraction (f_q) of the in-plane light quarks (u, d and s) carrying positive (negative) charges with out-of-plane quarks carrying negative (positive) charges, at the start of the partonic stage.

Signal strength f_q

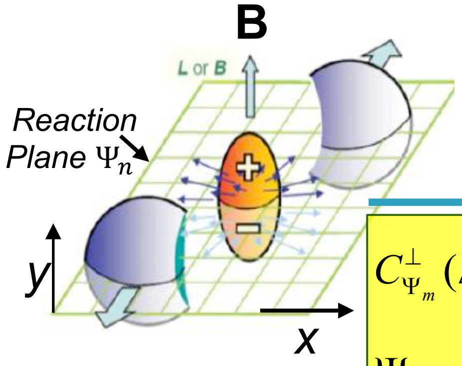
- **Note::**
  - ✓ **The input and output signals should not be the same, due to signal loss**
  - ✓ **The magnitude of the AVFD output signal should be larger than the AMPT output signal**

The $R^{(1)}_{\Psi_m}(\Delta S_1)$ [dipole correlator] - Operational

$$R^{(1)}_{\Psi_m}(\Delta S_1) = \frac{C_{\Psi_m}(\Delta S_1)}{C^{\perp}_{\Psi_m}(\Delta S_1)}, \quad m = 2, 3$$

Correlation functions are constructed from Gaussian shaped distributions

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



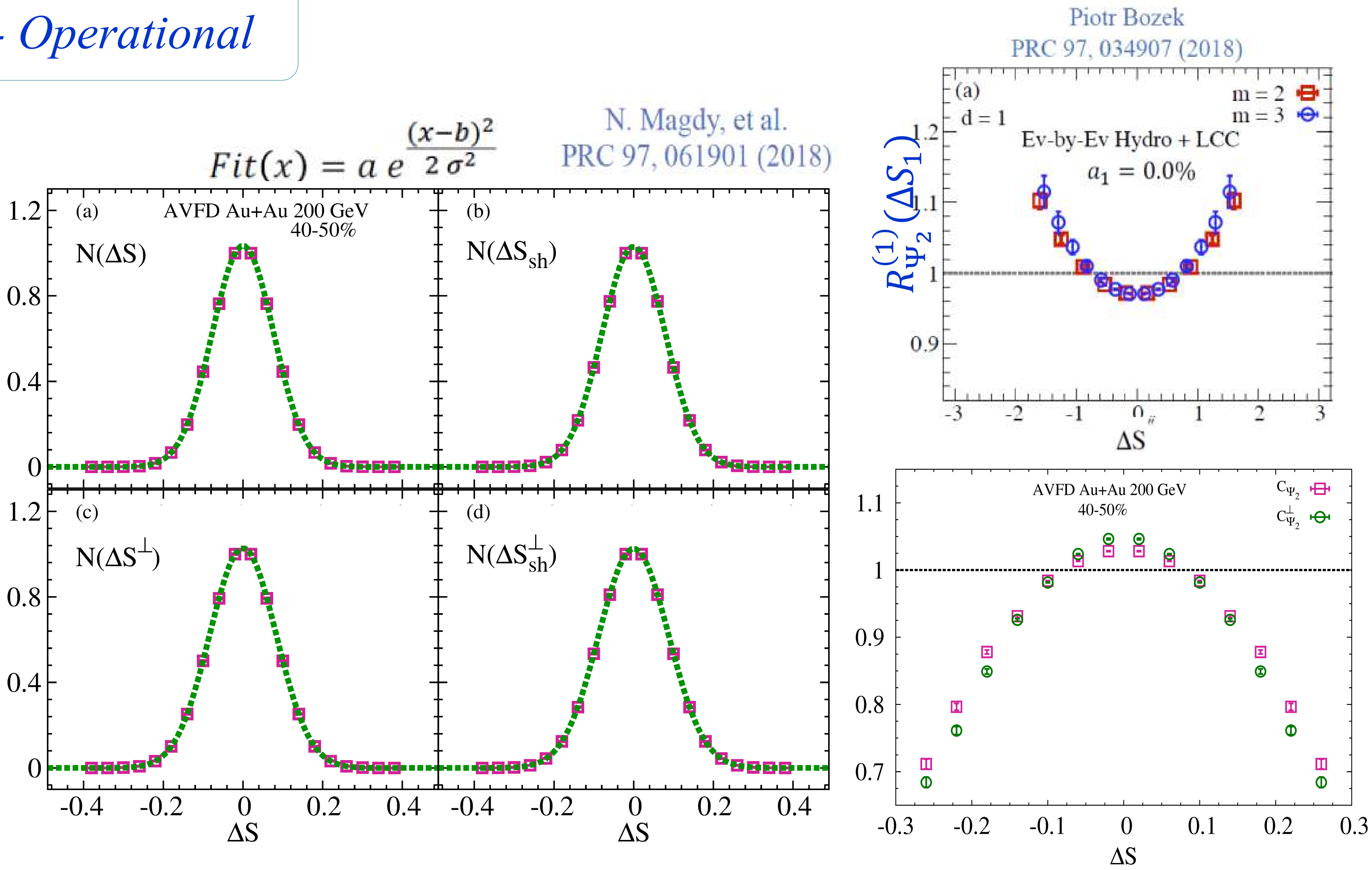
$$C^{\perp}_{\Psi_m}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{Shuffled}}(\Delta S)}$$

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

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

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

Piotr Bozek PRC 97, 034907 (2018)



$C_{\Psi_m}(\Delta S)$, $C^{\perp}_{\Psi_m}(\Delta S)$ and $R^{(1)}_{\Psi_m}(\Delta S)$ *are* Gaussian

$\longrightarrow$ Convexity/Concavity of $R^{1}_{\Psi_m}(\Delta S)$ depends on the relative widths

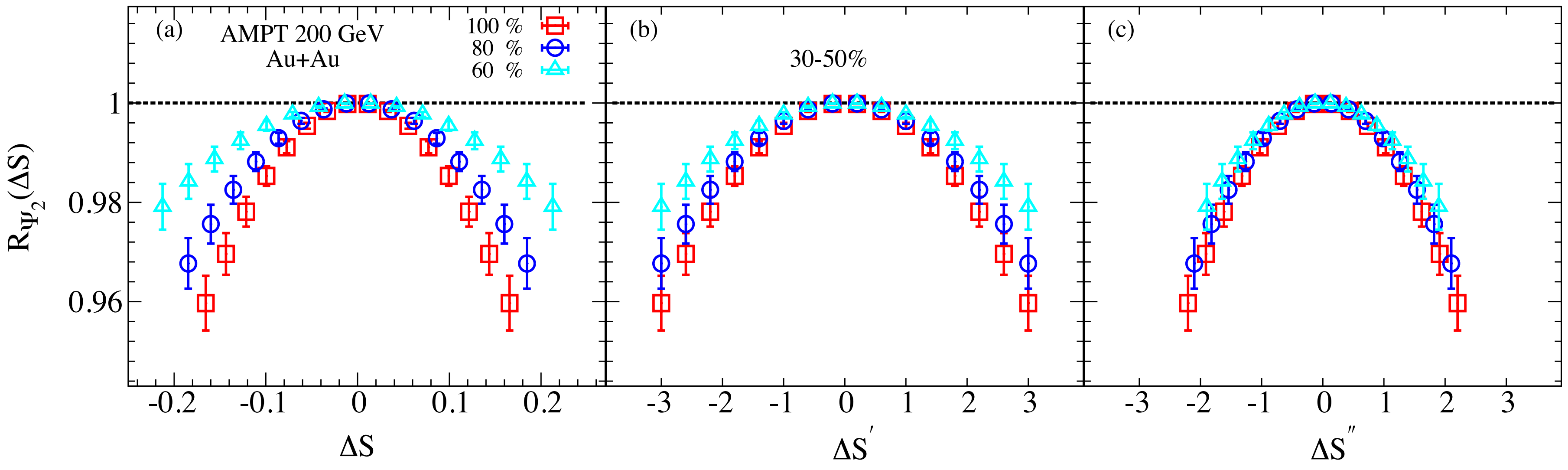
$\rightarrow$ The width of the distribution encodes the magnitude of charge separation

The $R_{\Psi_m}^{(1)}(\Delta S_1)$ [dipole correlator] - Operational

- *The charge separation magnitude is reflected in the width of the $R_{\Psi_m}^{(1)}(\Delta S_1)$ distribution which is affected by:*
  - ✓ *Number fluctuations*
  - ✓ *Event plane resolution*

Straightforward to mitigate

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



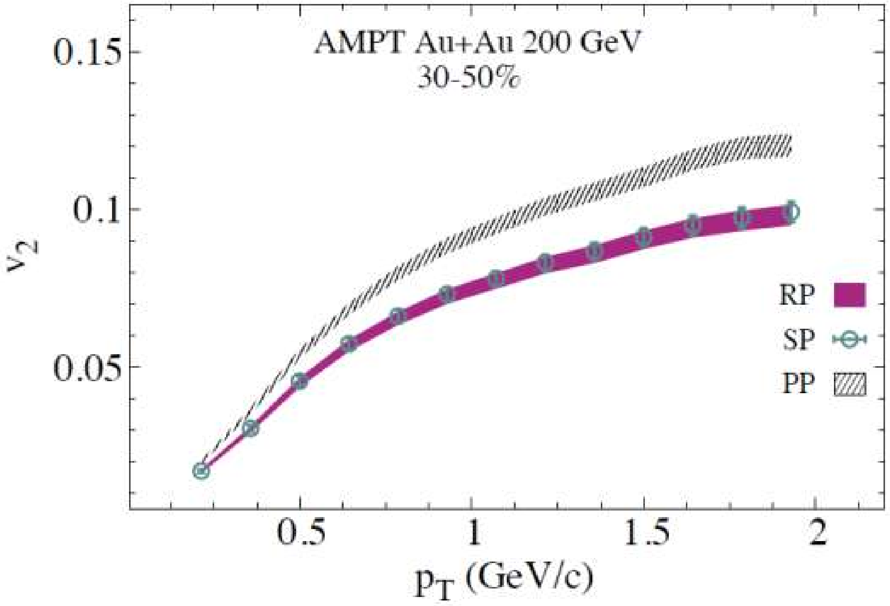
- ***Corrections for the effects of both number fluctuations and EP-resolution are necessary, but straightforward***

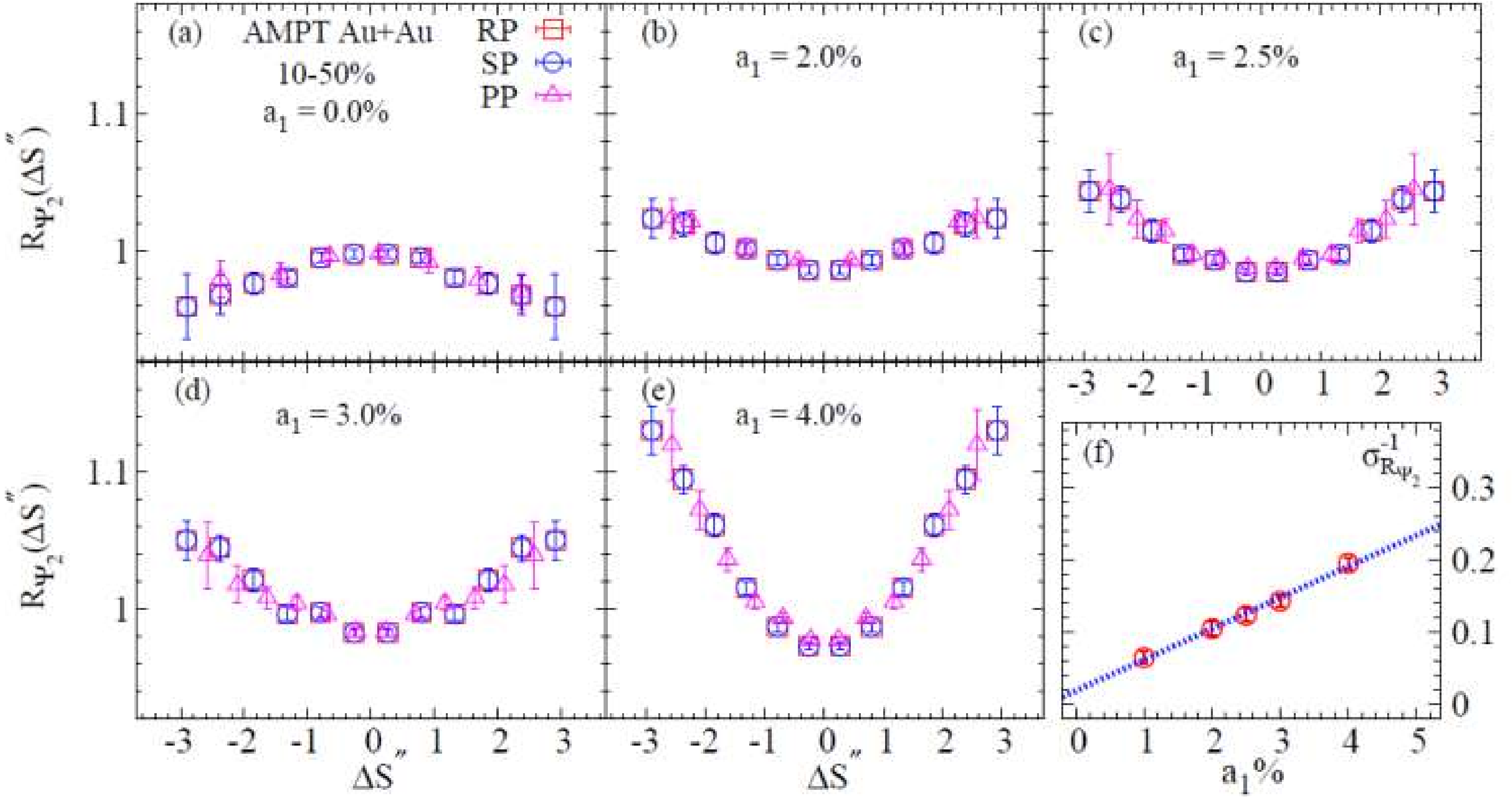
Sensitivity to signal – $R_{\Psi_m}^{(1)}(\Delta S_1)$ [dipole]

N. Magdy et. al., arXiv:2002.07934

The sensitivity of $R_{\Psi_m}^{(1)}(\Delta S_1)$ to different signal inputs + background, measured relative to several event planes, studied

$v_2 = \langle \cos(\phi - 2\,\psi_{XX}) \rangle$ XX =RP, SP and PP





- Similar $v_2(p_T)$ for RP & SP
  - ✓ $v_2(p_T)$ difference between RP and PP inline with fluctuations expectation

Characteristic response of the correlator

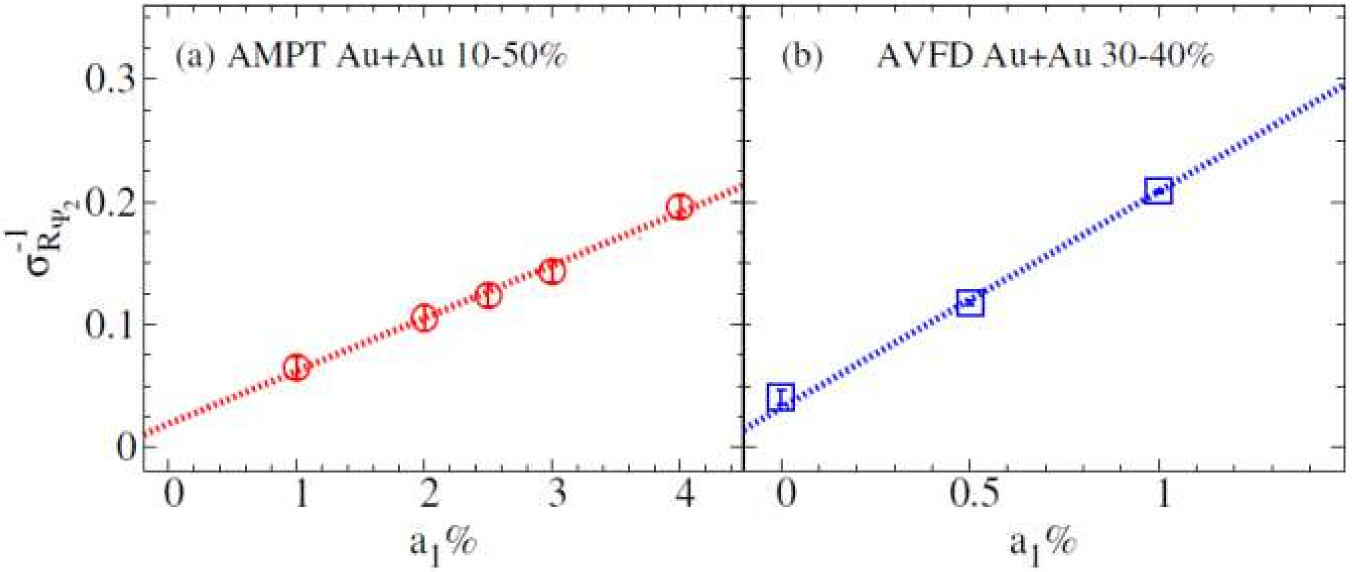
$\tilde{a} = \left\langle a_1^2 \right\rangle^{1/2} \propto \mu_5 B$

- ✓ $R_{\Psi_{XX}}^{(1)}$ is essentially event plane independent
  - ✓ Correction factors for number fluctuations & event plane resolution under control
- ✓ The inverse widths are proportional to a_1

Very good sensitivity down to small signals

Sensitivity to signal – $R_{\Psi_m}^{(1)}(\Delta S_1)$ [dipole]

Comparison of the correlator response for AMPT and AVFD events



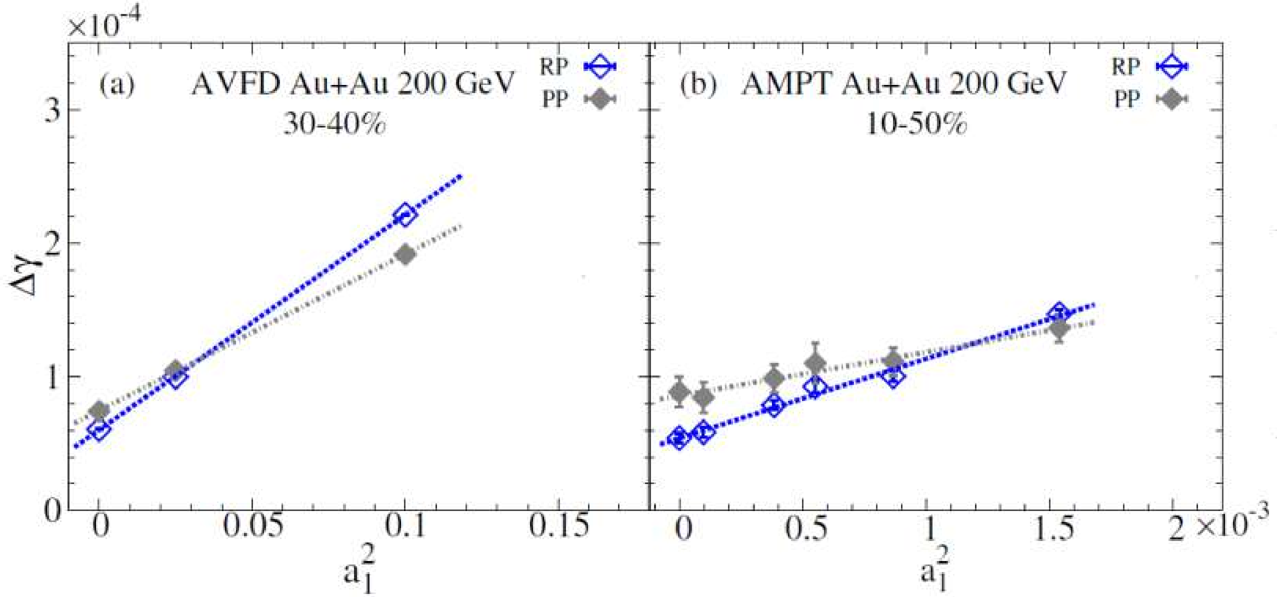
The inverse widths are proportional to the input a_1

- ✓ **Different slopes as expected**

$$a_1^{\mathrm{AMPT}} \sim 4a_1^{\mathrm{AVFD}}$$

Sensitivity to signal – $R^{(1)}_{\Psi_m}(\Delta S_1)$ [dipole]

Comparison of the correlator response for AMPT and AVFD events



The inverse widths are proportional to the input a_1^2

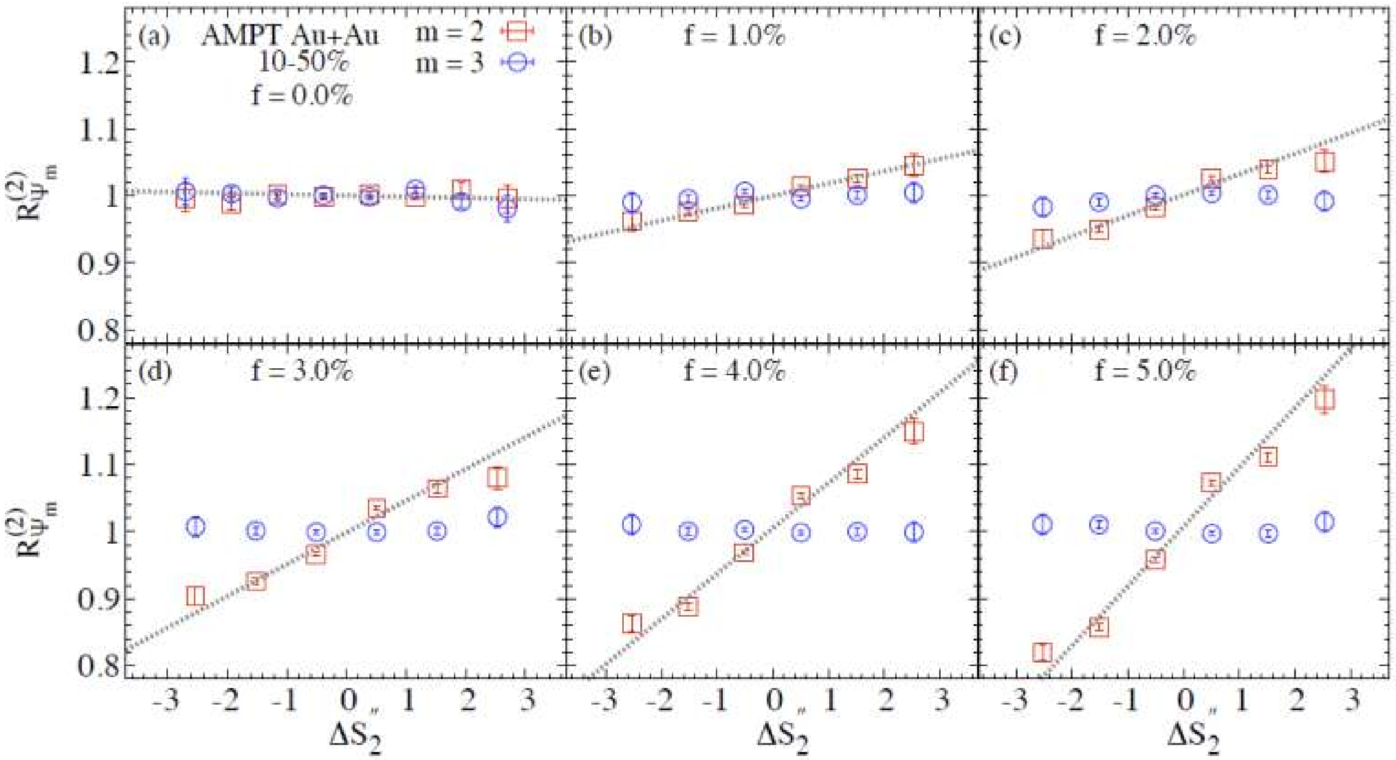
✓ **Different slopes as expected**

$a_1^{\mathrm{AMPT}} \sim 4a_1^{\mathrm{AVFD}}$ over range of interest

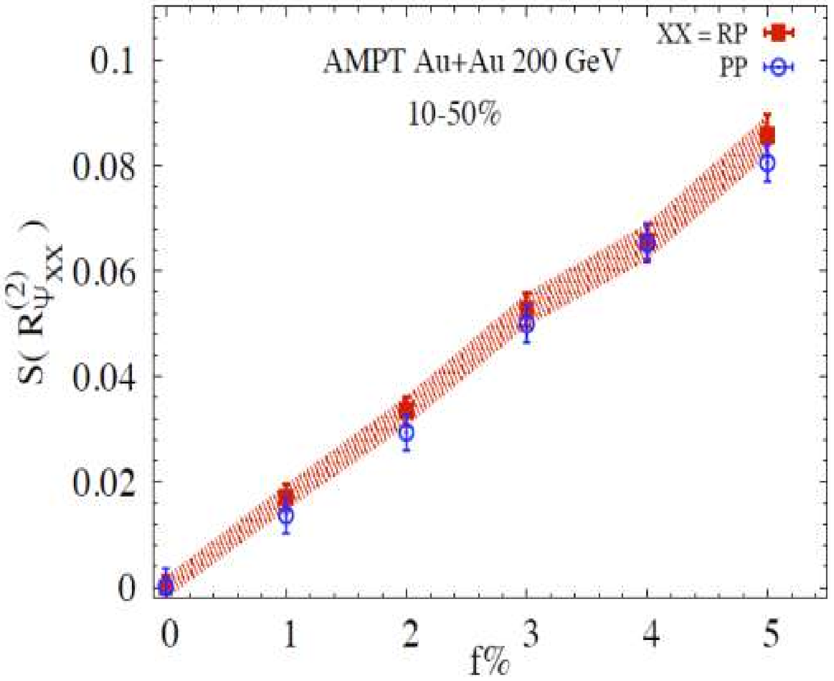
Sensitivity to signal – $R^{(2)}_{\Psi_m}(\Delta S_2)$ [quadrupole]

N. Magdy, et al. arXiv:2003.02396

The sensitivity of $R^{(2)}_{\Psi_m}(\Delta S_2)$ to different signal inputs + background, measured relative to several event planes



Slope vs. input signal f



Characteristic response of the $R^{(2)}_{\Psi_m}(\Delta S_2)$ correlator

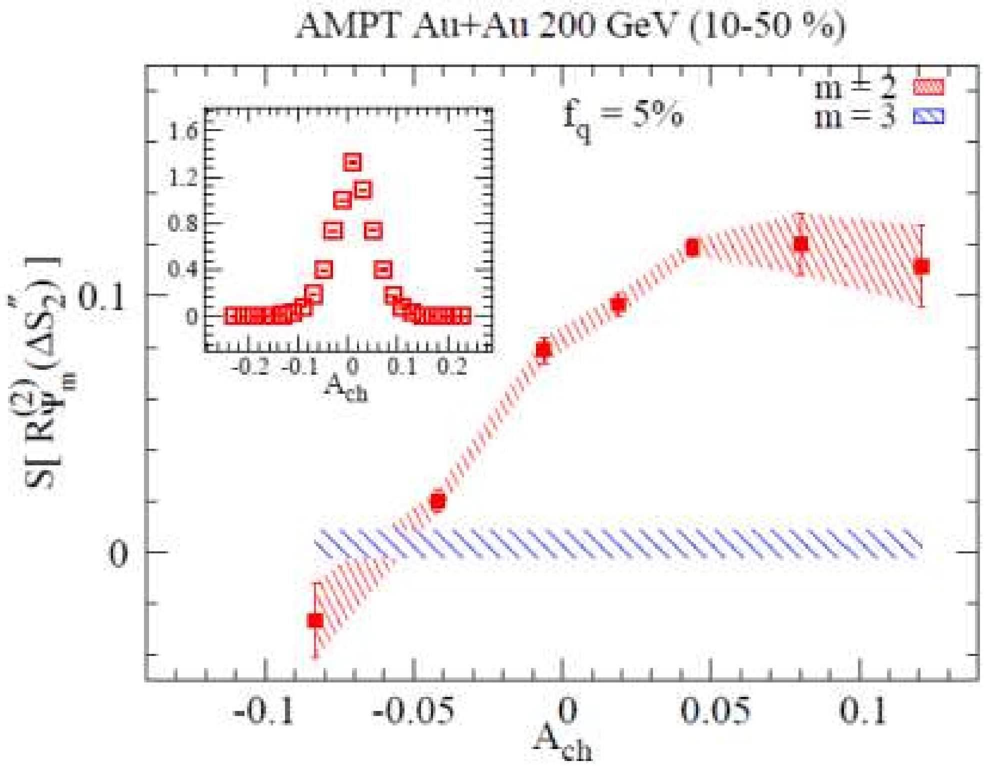
- ✓ $R^{(2)}_{\Psi_3}(\Delta S_2)$ **shows little, if any, sensitivity to background**

- ✓ *The extracted slopes are event-plane independent*
- ✓ *The extracted slopes are proportional to the input signals*

✓ **Very good sensitivity down to small input signals**

Sensitivity of the $R_{\psi_m}^{(2)}(\Delta S_2)$ correlator

N. Magdy, et al.
arXiv:2003.02396



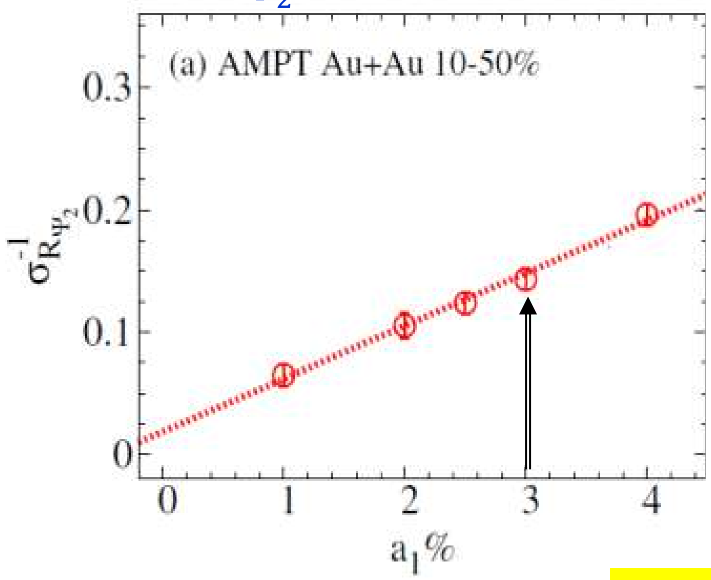
$$A_{ch} = \frac{(N^+ - N^-)}{(N^+ + N^-)}$$

Validation of the expected sensitivity to charge asymmetry

Sensitivity of the $R_{\Psi_m}^{(d)}(\Delta S_d)$ and $\Delta\gamma$ correlators

Calibrations for the $R_{\Psi_2}^{(1)}(\Delta S_1)$ and $\Delta\gamma$ correlators performed with the same events

$R_{\Psi_2}^{(1)}(\Delta S_1)$ *correlator*

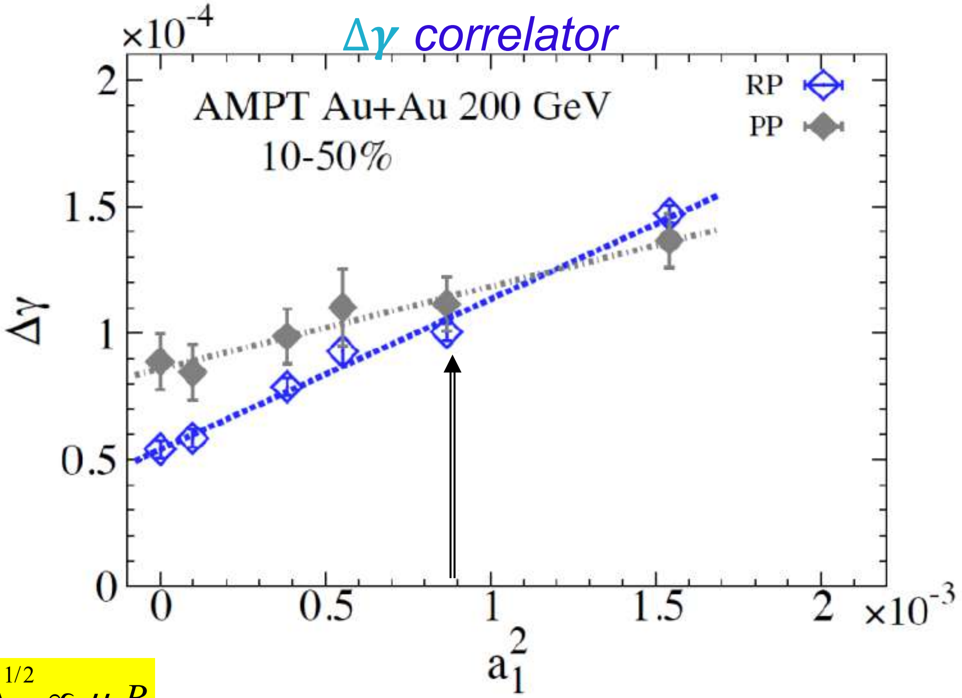


The inverse widths are proportional to a_1

$\tilde{a}_1 = \langle a_1^2 \rangle^{1/2} \propto \mu_5 B$

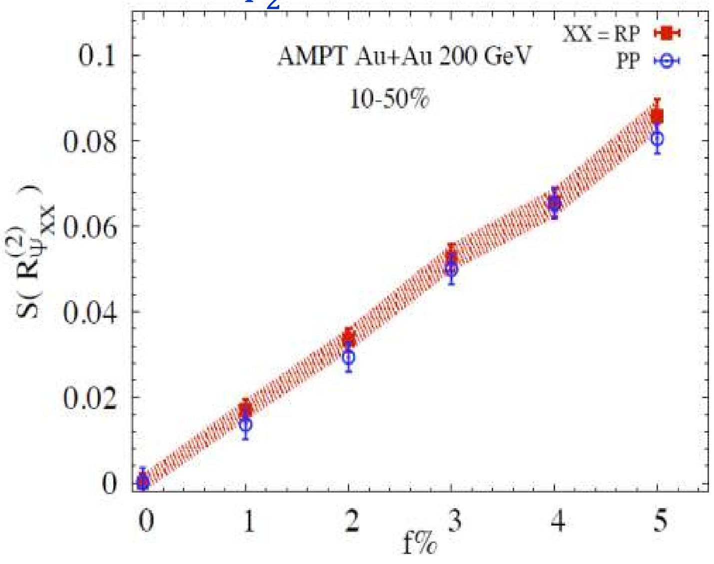
- ✓ **good sensitivity in the presence of background**

$\Delta\gamma$ correlator



- ➢ *$\Delta\gamma$ is proportional a_1^2*
  - ✓ **event plane dependence**
  - ✓ **sizeable intercept**
  - ✓ **$\Delta\gamma \neq 2a_1^2$ (due to losses)**
    f_{cme} ~ 15% (for PP)

$R_{\Psi_2}^{(2)}(\Delta S_2)$ *correlator*



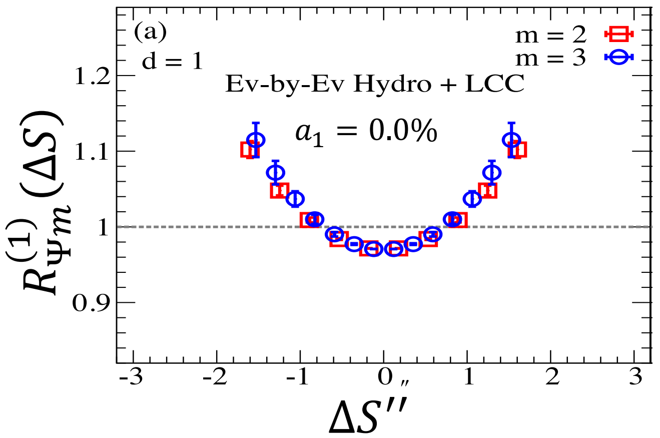
The extracted slopes are proportional to the input signals

- ✓ **good sensitivity in the presence of background**

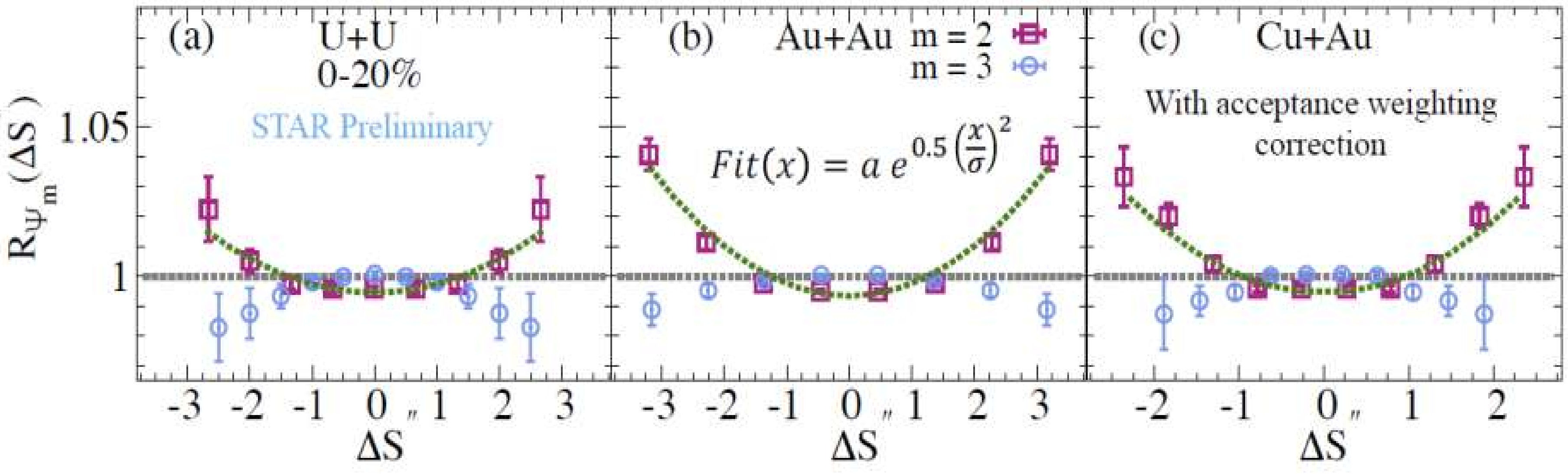
- ➢ **f_{cme} is NOT a good estimator of the magnitude of the CME signal when the background is significant**

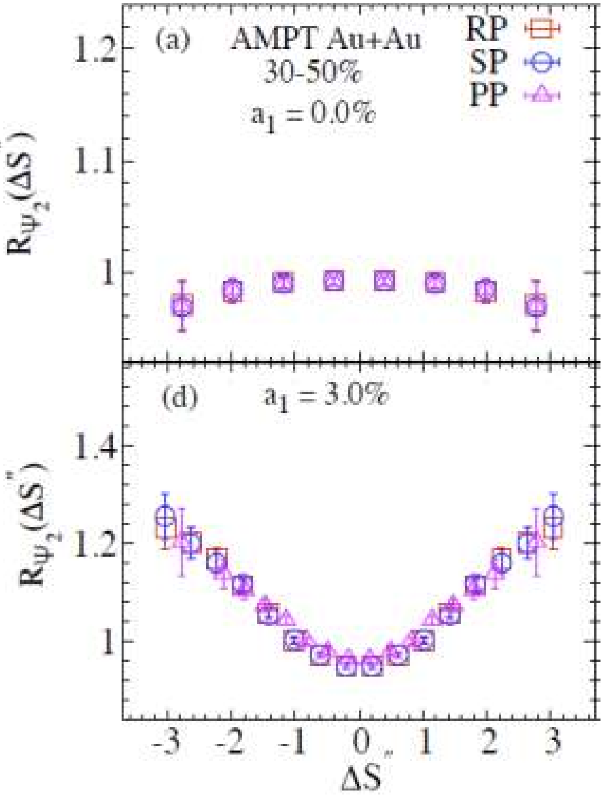
Representative results from data – $R^{(1)}_{\Psi_m}(\Delta S_1)$ [dipole]

Piotr Bozek
PRC 97, 034907 (2018)



- **$R_{\Psi_2}(\Delta S'')$ *and* $R_{\Psi_3}(\Delta S'')$ *measurements for 0-20% central collisions for different collision systems***



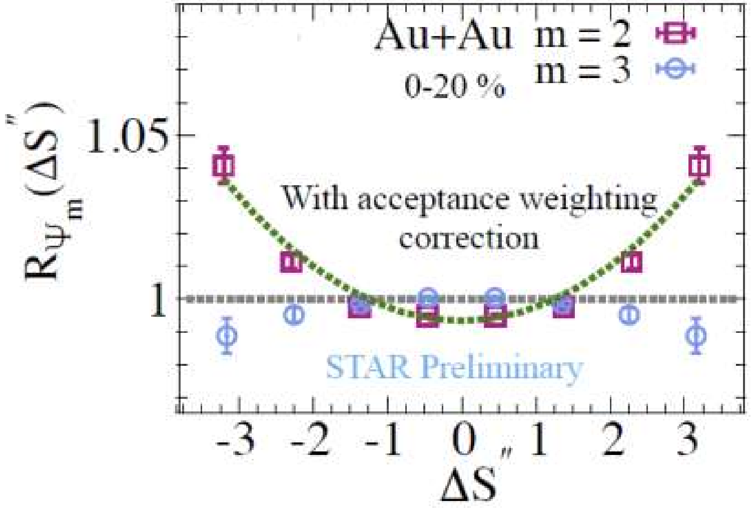


- *The $R_{\Psi_2}(\Delta S'')$ correlators are concave-shaped while the $R_{\Psi_3}(\Delta S'')$ correlators are convex-shaped.*
  - ✓ *This stark difference is **incompatible** with a purely background-driven charge separation*

The experimental patterns for $R_{\Psi_{2,3}}(\Delta S'')$ are consistent with CME-driven charge separation in these collisions

Representative results from data – $R^{(1)}_{\Psi_m}(\Delta S_1)$ [dipole]

- *$R_{\Psi 2}$ for Au+Au collisions is concave-shaped*
  ($R_{\Psi 3}$ is convex-shaped)
  - ✓ *Significant difference between $R^{(1)}_{\Psi_2}(\Delta S_1)$ & $R^{(1)}_{\Psi_3}(\Delta S_1)$*
  - ✓ *consistent with the expectation for CME-driven charge separation.*



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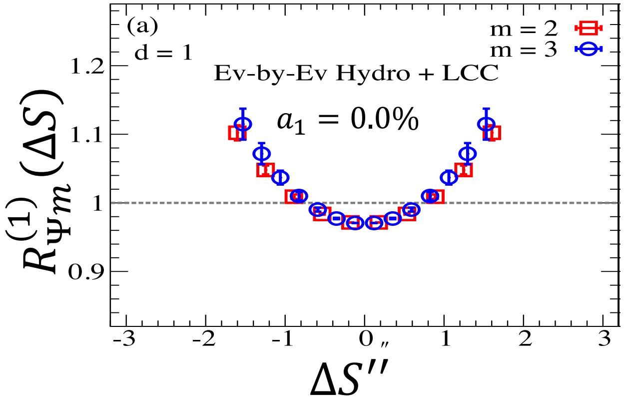
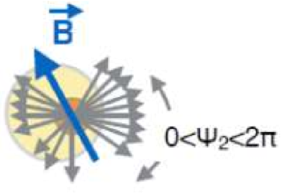
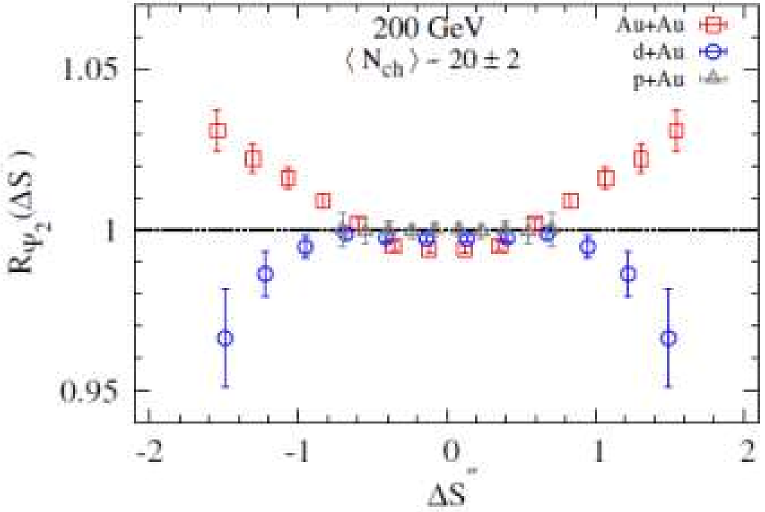
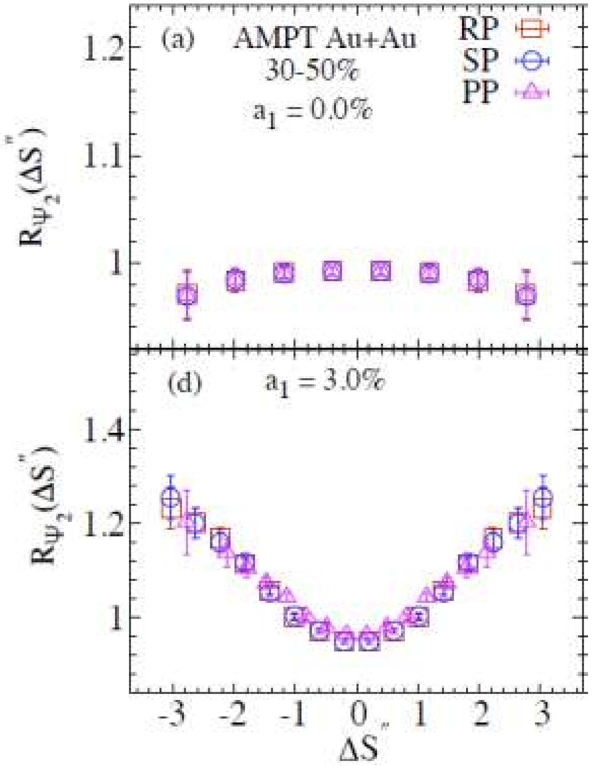


- *$R^{(1)}_{\Psi_2}(\Delta S_1)$ for p/d+Au collisions consistent with the expected pattern of **background-driven** charge separation*
  - ✓ *Similar to $R^{(1)}_{\Psi_3}(\Delta S_1)$ for Au+Au*



B-field and Ψ_2 ~ uncorrelated for p/d+Au

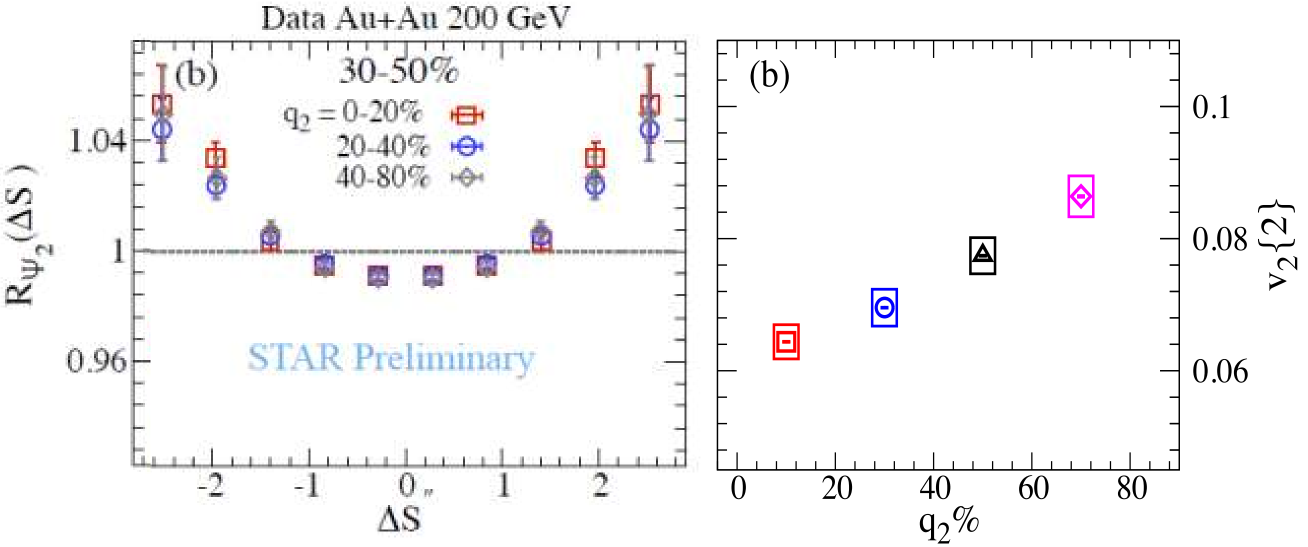


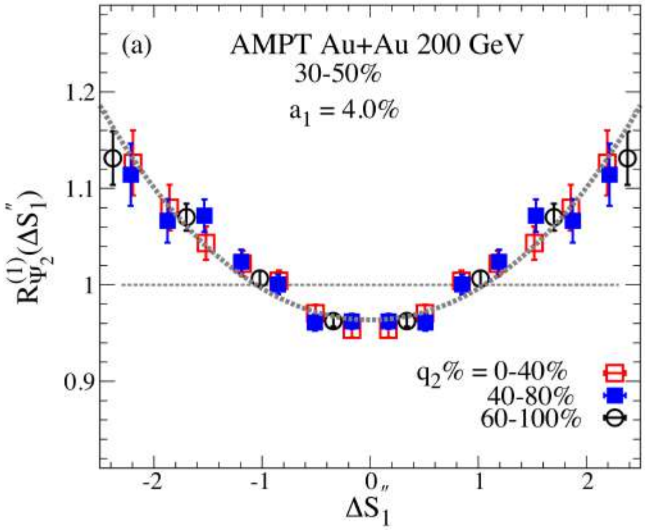


Representative results from data – $R_{\Psi_m}^{(1)}(\Delta S_1)$ *[dipole]*

- *Event shape selection*

Comparison of the $R_{\Psi_2}^{(1)}(\Delta S_1)$ *correlators for* q_2 *selected events for 30−50% central, Au+Au collisions at 200 GeV*



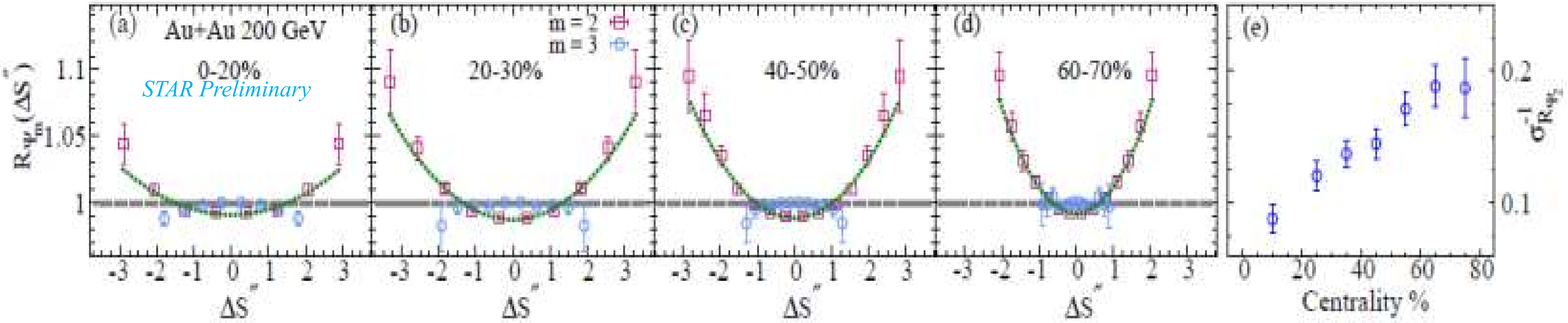


For modest CME signal + background, $R_{\Psi_2}^{(1)}(\Delta S_1)$ ***is insensitive to*** q_2 ***selection***

- *The* q_2*-selected* $R_{\Psi_m}^{(1)}(\Delta S_1)$ *correlators are not strongly influenced by the* q_2*-dependent* v_2*-driven background.*
  - ✓ *consistent with the absence of strong* v_2*-driven background influence.*

Representative results from data – $R^{(1)}_{\Psi_m}(\Delta S_1)$ [dipole]

➢ *$R^{(1)}_{\Psi_2}(\Delta S_1)$ and $R^{(1)}_{\Psi_3}(\Delta S_1)$ measurements vs. centrality for Au+Au Collisions at 200 GeV*



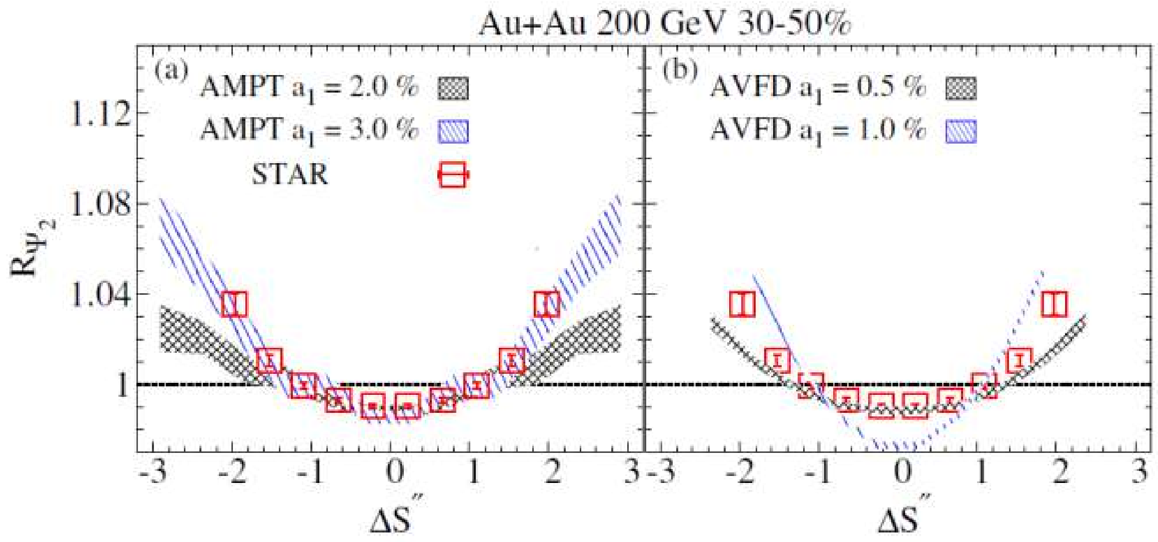
➢ *$\sigma^{-1}_{R_{\Psi_2}}$ indicates a sizable centrality dependence,*

- ✓ *Recall that $R^{(1)}_{\Psi_2}(\Delta S_1)$ is essentially independent of q_2 selection*

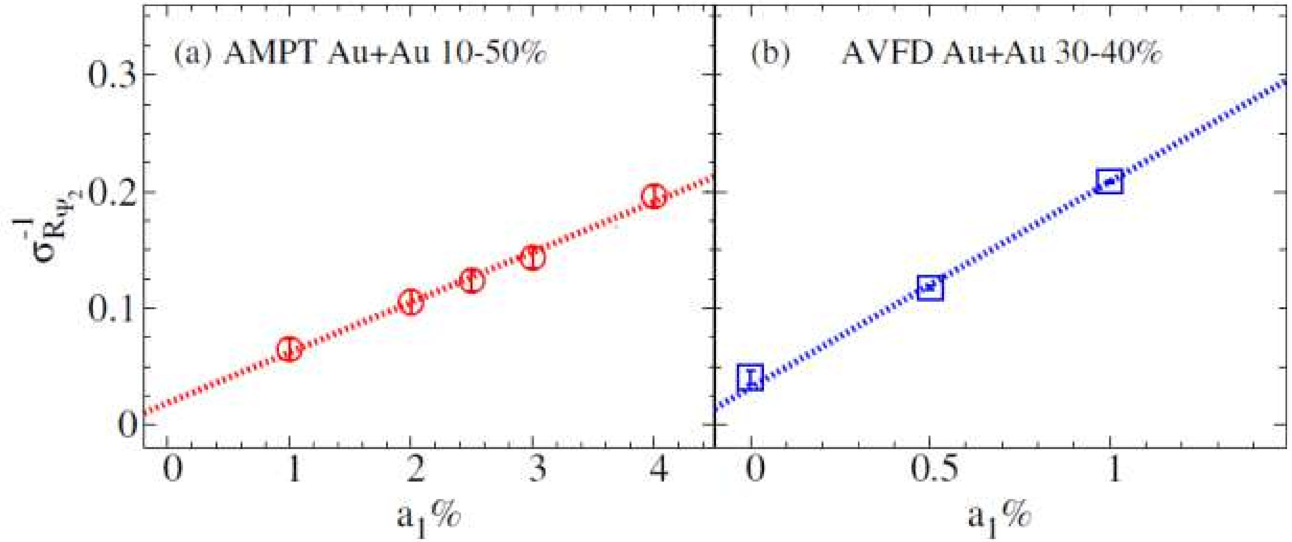
➢ *The data trends are in line with the expected increase in the magnitude of CME-driven charge separation (from central to peripheral collisions) resulting from:*

- ✓ *an increase in the $\vec{B}-$field*
- ✓ *stronger correlation between the $\vec{B}-$field and the event plane*
- ✓ *enhanced axial charge per entropy*

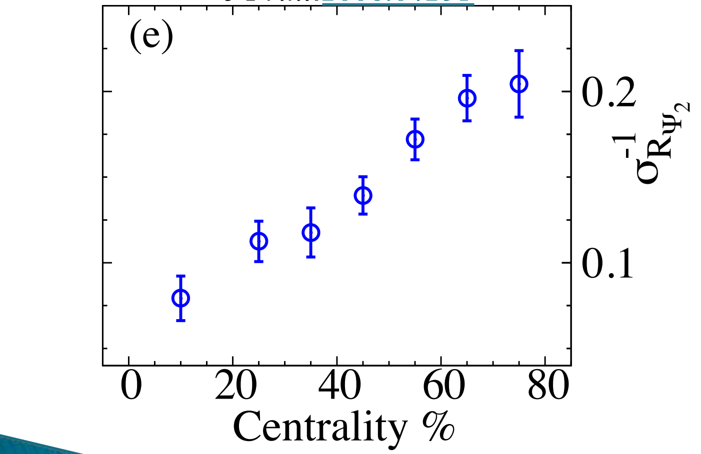
CME signal quantification



Representative calibration curves used to estimate a_1



STAR Collaboration,
e-Print:2006.04251



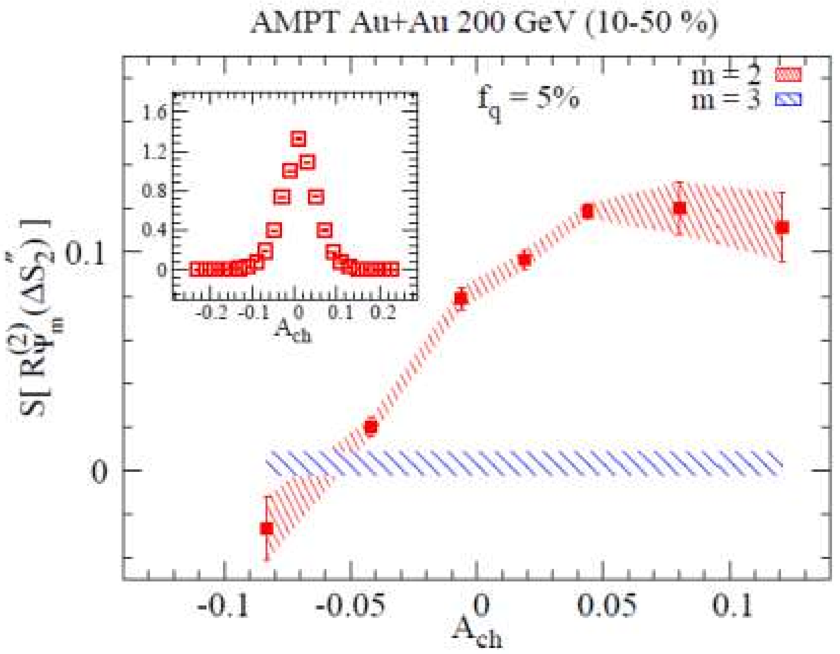
	Central	Mid-central	Peripheral
$\boldsymbol{a_1 - AVFD}$ (%)	0.250 ± 0.013	065 ± 0:033	1.0 ± 0.05
$\boldsymbol{a_1 - AMPT}$ (%)	1.00 ± 0.050	2.6 ± 0.130	4.0 ± 0.2

Implied f_{CME} ~ 15%
(from $\Delta\gamma$ correlator for Mid-central collisions)

✓ **Consistent with current estimates**

➢ **No glaring inconsistency with current f_{cme} measurements**

Ongoing $R^{(2)}_{\psi_m}(\Delta S_2)$ experimental measurement

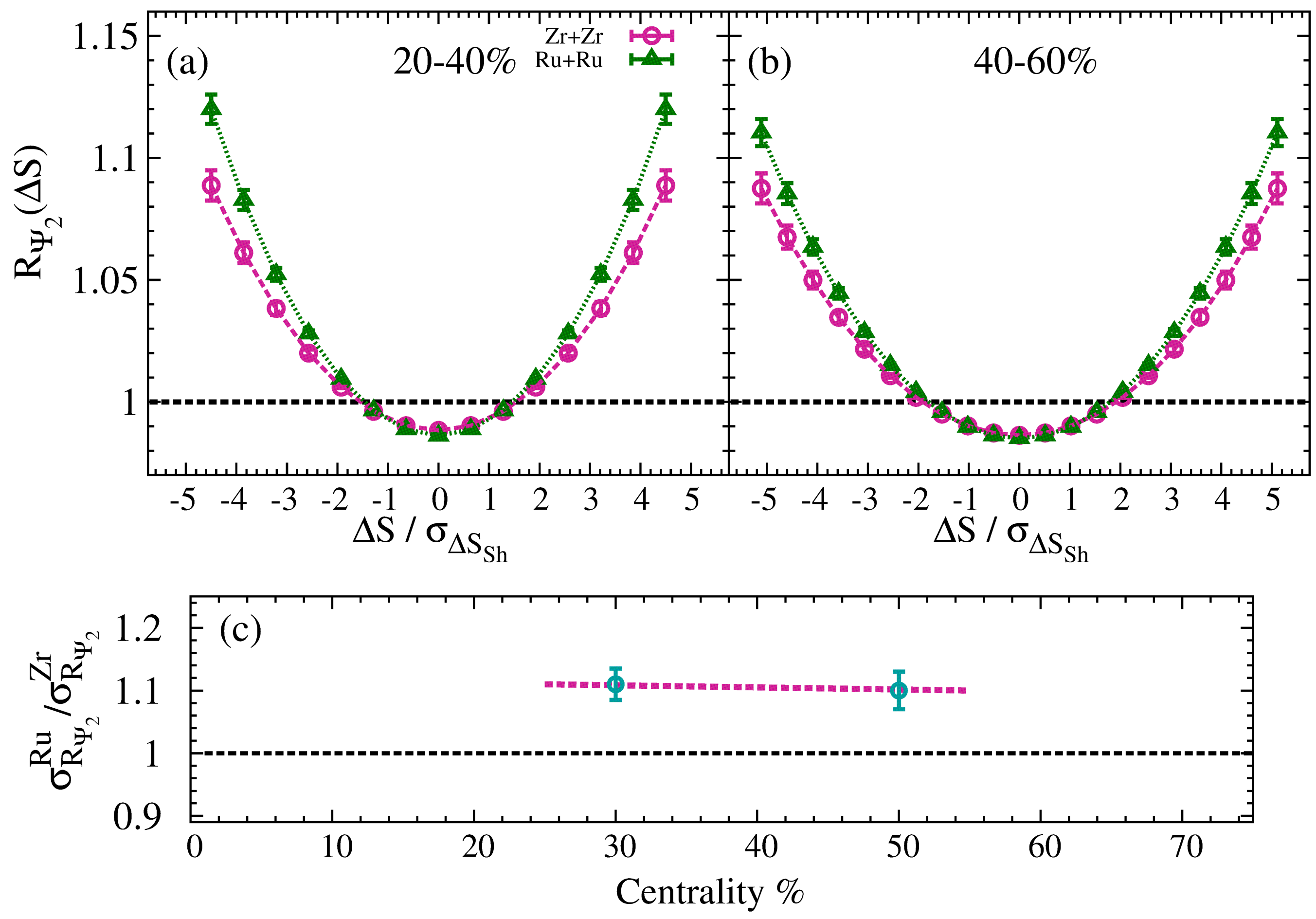


Measurements are complete

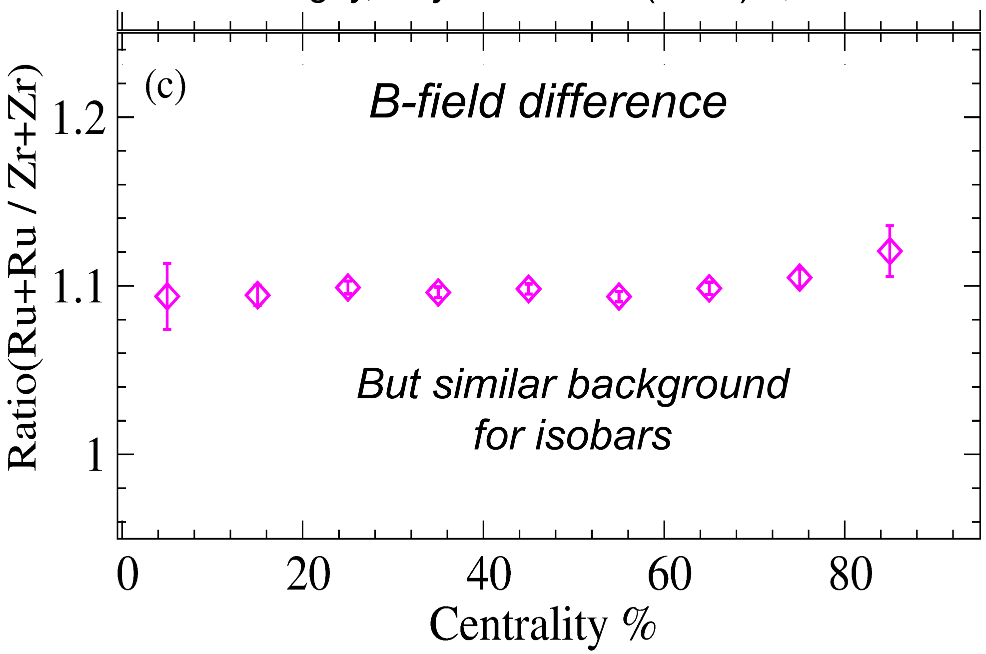
- ✓ *Will be reported shortly*
- ✓ *The observed patterns and trends are suggestive*

The $R_{\Psi_m}^{(1)}(\Delta S_1)$ Correlator - Isobars

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



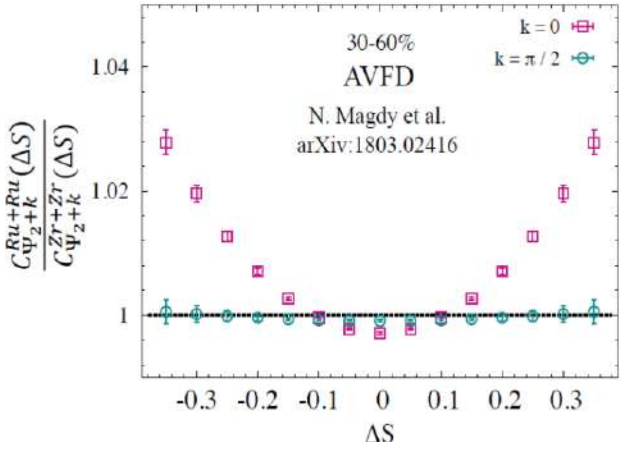
N. Magdy, Phys.Rev.C 98 (2018) 6, 061902

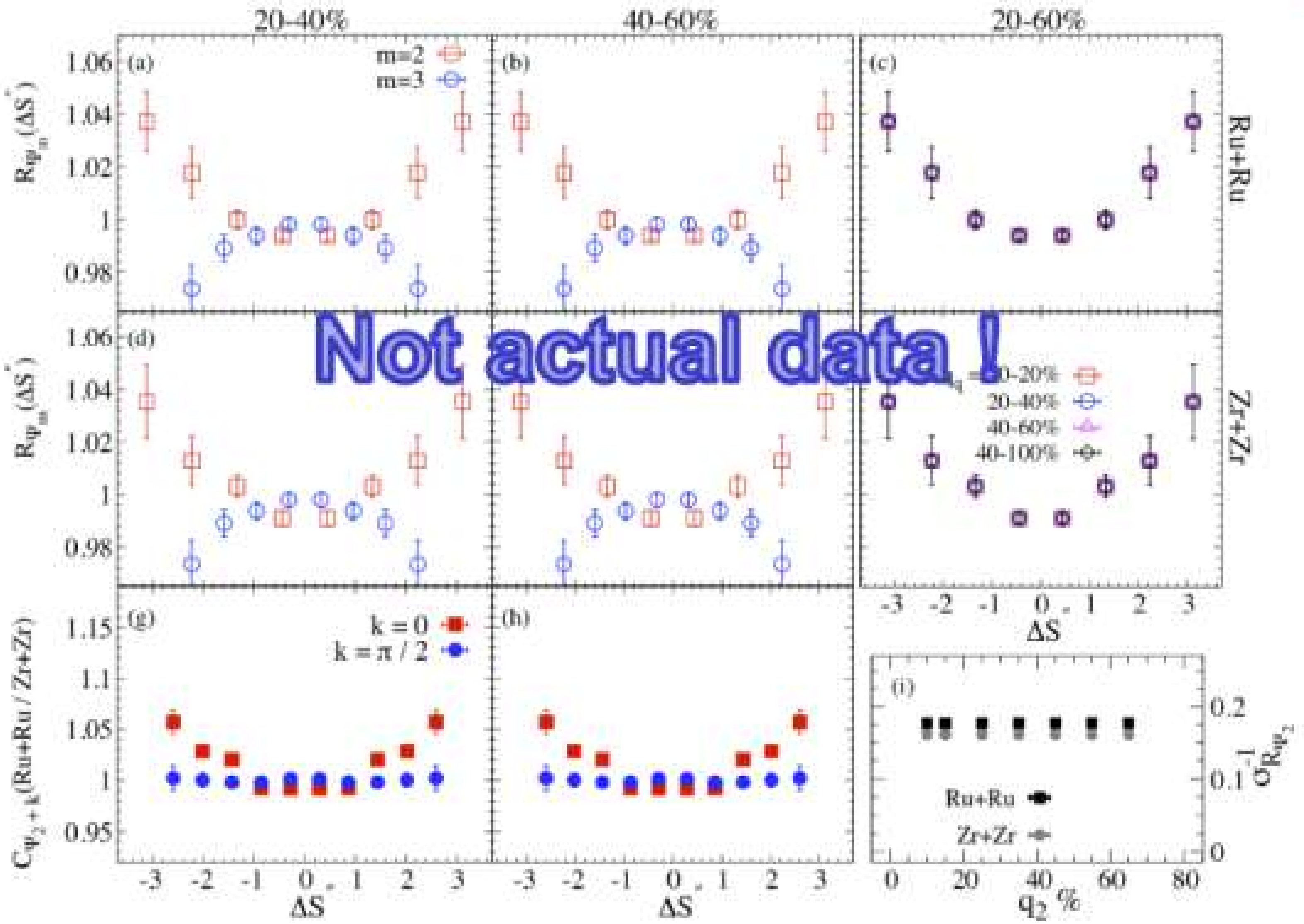


➢ **Validation of the expected isobaric dependence of $R_{\Psi_2}(\Delta S)$ to CME-driven charge separation input in AVFD events.**

Ongoing $R_{\psi_m}^{(d)}(\Delta S_d)$ *experimental* measurements for Isobars

- *Strategy*
  - ✓ *Measure the signal for each isobar*
  - ✓ *Measure the relative signal strength of the isobars*
  - ✓ *Measure the relative background strength of the isobars*





Measurements are underway

Summary

- A correlator $R_{\psi_m}^{(d)}(\Delta S_d)$, has been developed to enable identification and characterization of both CME- and CMW-driven charge separation
  - ✓ The correlator suppresses, as well as measures the well known background contributions to the CME- and CMW-driven charge separation signal
- Validation tests, performed with several models, indicate that the correlators can give;
  - ✓ discernible responses for background- and CME/CMW-driven charge separation which allows unambiguous identification and characterization of the respective signals
- ***The experimentally measured correlators (to date) suggests the presence of a CME-driven charge separation in A+A collisions.***
  - ✓ ***Experimental CMW measurements are complete and results will be released soon***
  - ***The experimental measurements for isobars are in progress with great anticipation***

End