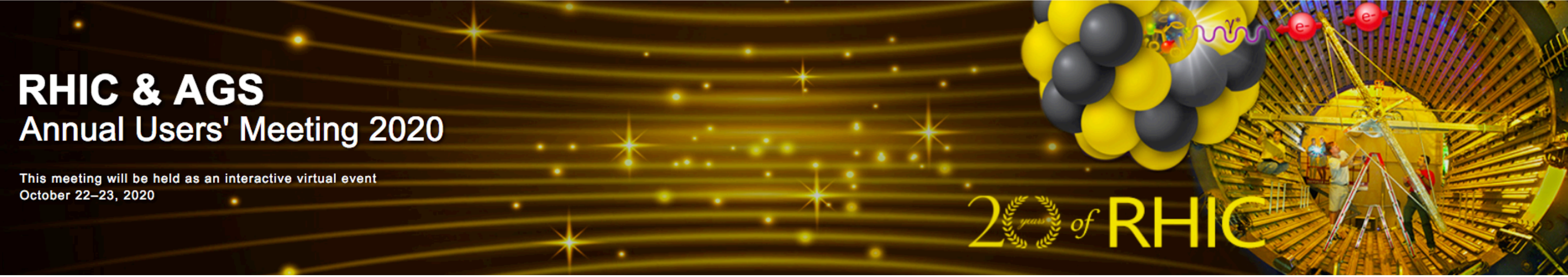

Status of the Chiral Magnetic Effect search at RHIC

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UIC

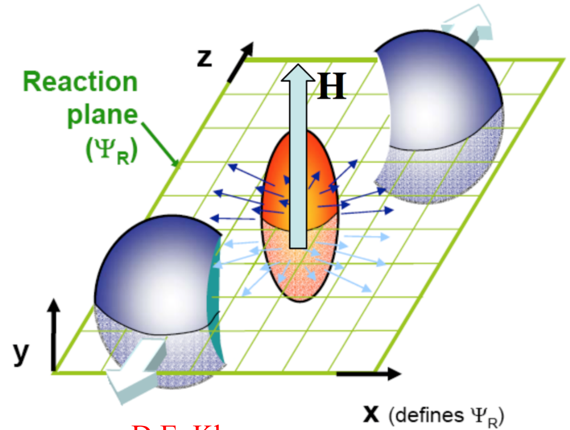
Status of the Chiral Magnetic Effect search at RHIC

- Outline:

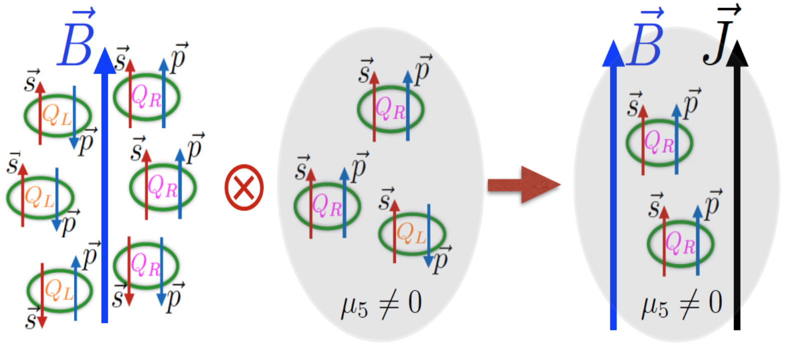
  - Introduction
  - Dipole charge separation correlators
  - Experimental Measurements
  - Isobar Analysis

❖ Introduction:

✓ Anomalous Transport in the QGP



D.E. Kharzeev
Prog.Part.Nucl.Phys. 75 (2014) 133-151



D.E. Kharzeev et al.
Prog.Part.Nucl.Phys. 88 (2016) 1-28

Chiral Chemical potential

- In non-central collisions a strong magnetic field is created ⊥ to Ψ_{RP}

- Magnetic field acts on the chiral fermions with $\mu_5 \neq 0$ leads to an electric current along the magnetic field which leads to a charge separation

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

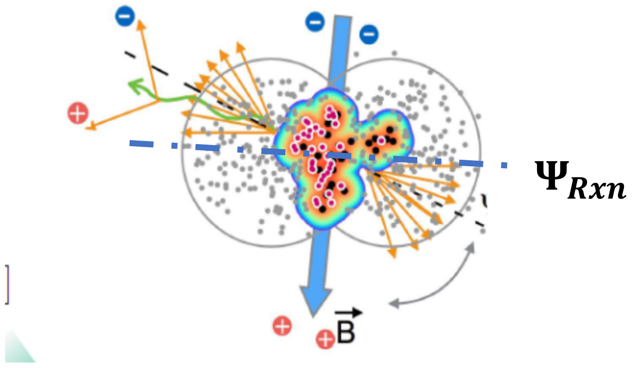
$$\frac{dN^{ch}}{d\phi} \propto 1 \pm 2\, a_1^{ch} \sin(\phi) + \cdots \qquad a_1^{ch} \propto \mu_5 \vec{B}$$

Can we identify & characterize this dipole moment?

❖ Dipole charge separation measurements correlators:

A well-known approach is to use the γ correlator to measure the dipole charge separation

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



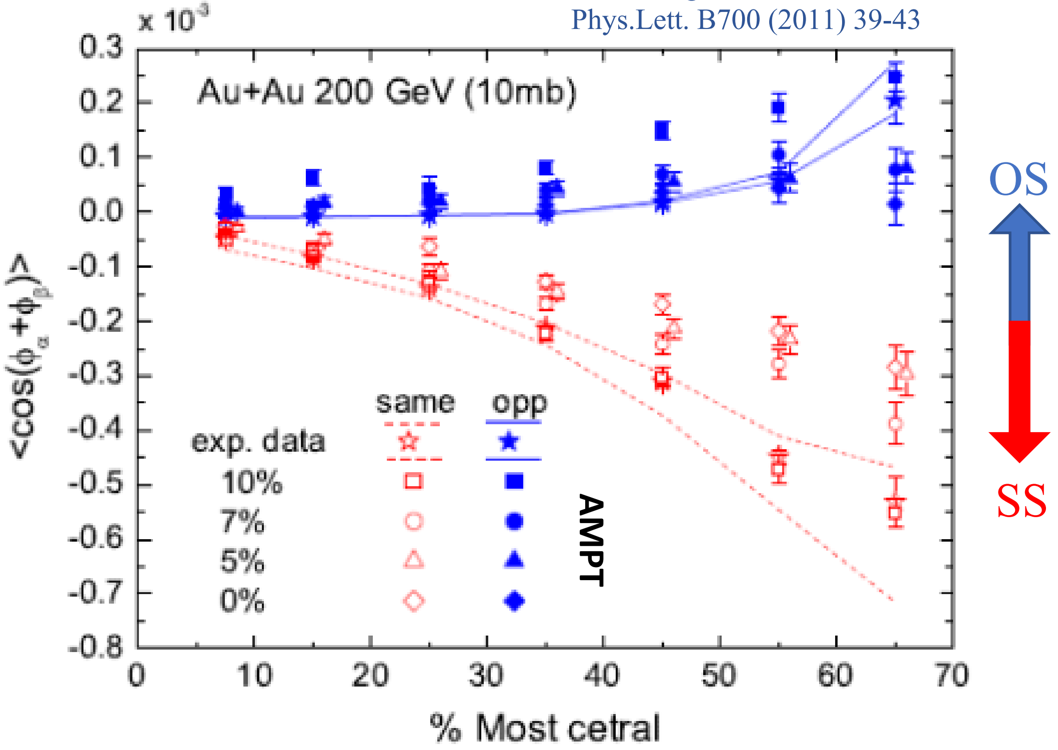
Voloshin, PRC 70 (2004) 057901

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

background

The background complicates signal extraction

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



➢ Background can account for a sizeable part of the observed charge separation

❖ Dipole charge separation measurements correlators:

A well-known approach is to use the γ correlator to measure the dipole charge separation

- ➢ Constraining the background effect on the γ correlator:
- ➢ Comparing and contrasting the:
  - ✓ γ_{112} vs. γ_{123}
    - B-field and Ψ_3 are uncorrelated
  - ✓ γ_{112} for small and large systems
    - B-field and Ψ_2 are uncorrelated
  - ✓ γ_{112} for different event shape selections
    - Constraining the v_n background
  - ✓ γ_{112} with pair invariant mass cut
    - Constraining the resonances contributions
  - ✓ γ_{112} along the participant and the spectators E-P
    - PKG is large (small) in measurements relative to PP (SP), CME signal is opposite

STAR collaboration,
Phys.Lett.B 798 (2019) 134975

Fufang Wen , et al,
CPC 42, 014001 (2018)

J. Zhao, H. Li and F. Wang,
Eur. Phys. J. C79 168 (2019)

Voloshin, Phys. Rev. C 98, 054911 (2018)
H-J. Xu, et al, CPC 42, 084103 (2018)

❖ Dipole charge separation measurements correlators:

A. Tang, Chinese Phys. C 44 054101 (2020)
Yufu Lin (QM-2019)

A new approach is to use the signed balance function to measure the dipole charge separation

- Count pair's momentum ordering in p_y

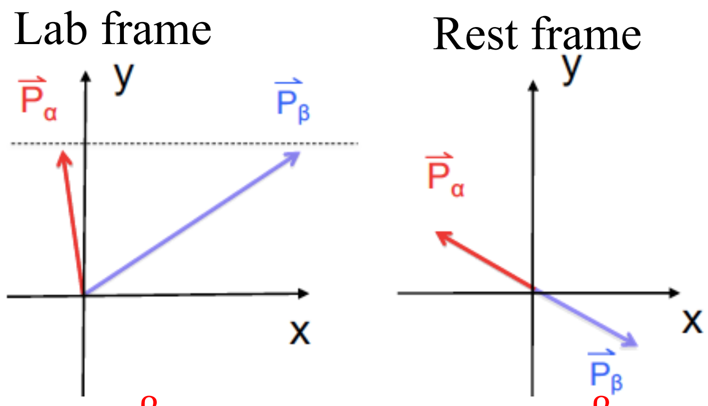
$$B_{P,y}(S_y) = [N_{+-}(S_y) - N_{++}(S_y)]/N_+$$

$$B_{N,y}(S_y) = [N_{-+}(S_y) - N_{--}(S_y)]/N_-$$

where $N_{\alpha\beta}$ denotes the number of positive/negative pairs with a sign of S_y in an event. S_y is labeled as +1 if $p_y^\alpha > p_y^\beta$, and -1 if vice versa.

- Count net-ordering (e.g. excess of pos. leading neg.) for each event

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1) \qquad \Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

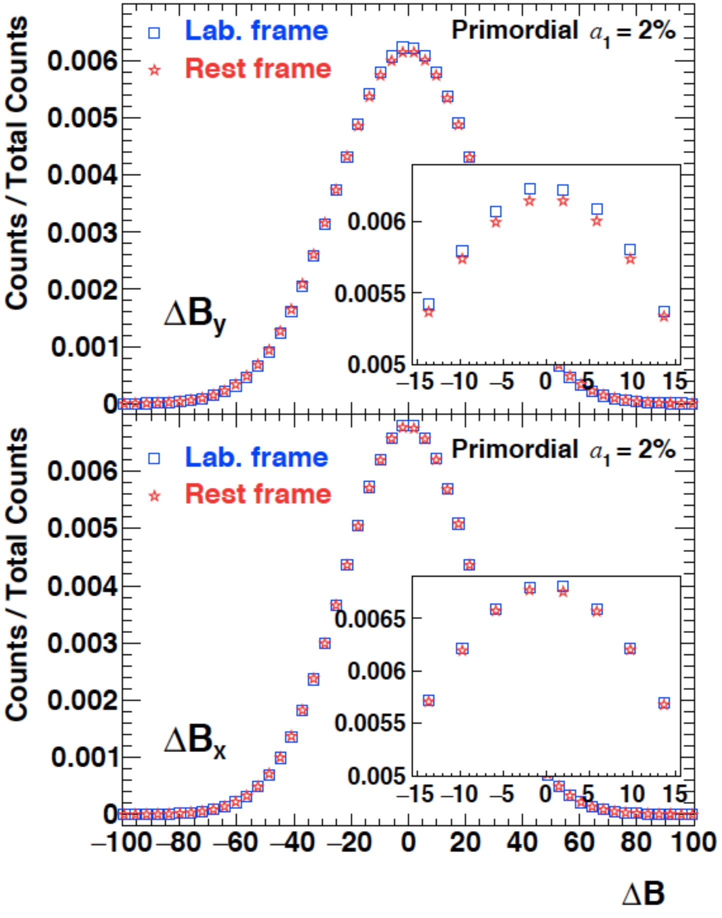


$p_y^\alpha = p_y^\beta$ $\qquad$ $p_y^\alpha > p_y^\beta$

$$r = \Delta B_y / \Delta B_x$$

$$R_B = r_{rest} / r_{lab}$$

Rest frame has the best sensitivity to momentum ordering



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A. Tang, Chinese Phys. C 44 054101 (2020)
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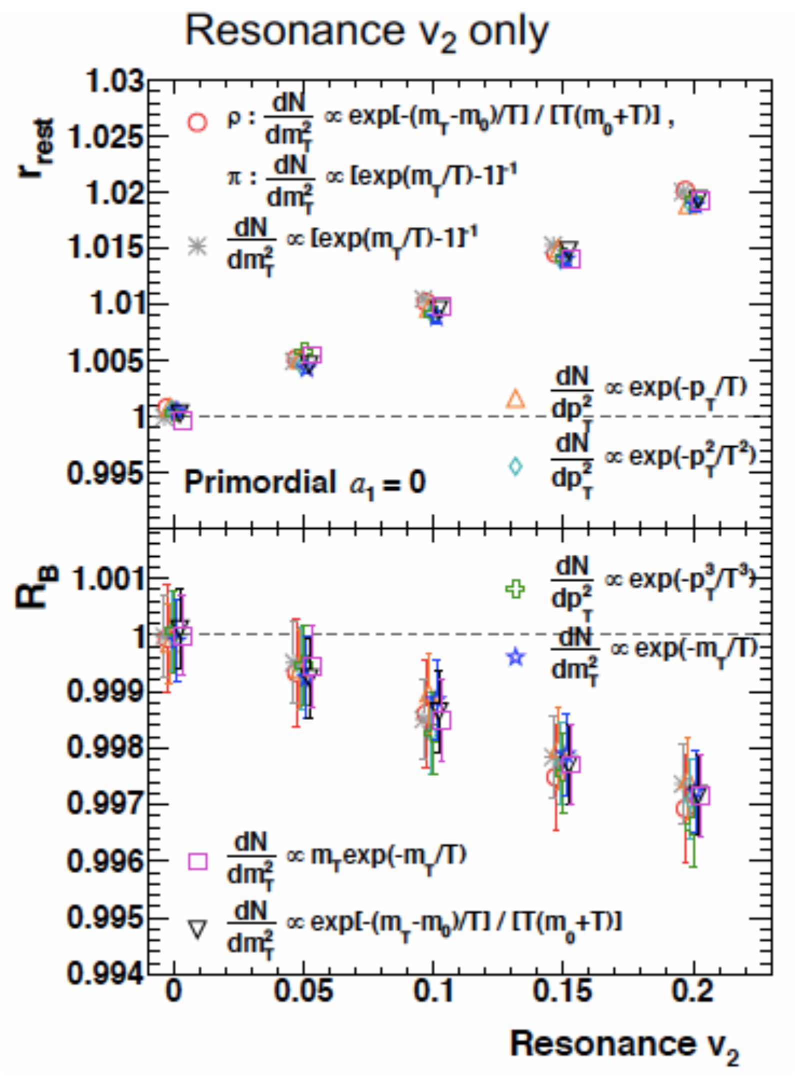
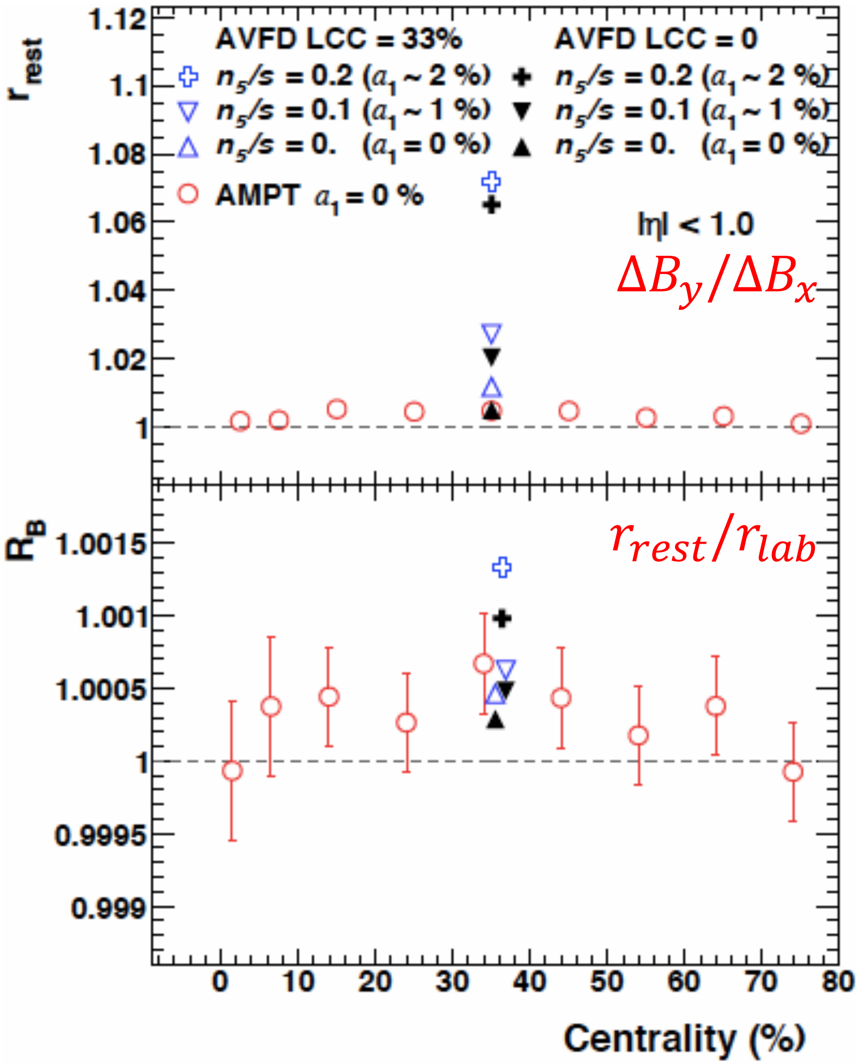




- In Toy model
  - ✓ r_{rest} and R_B responds in opposite directions to the change of resonance v_2

- In AVFD:
  - ✓ LCC shifts both r_{rest} and R_B upwards.
  - ✓ Limited response to LCC, when changing from 0% to 33%.

Sensitivity to the CME input signal?

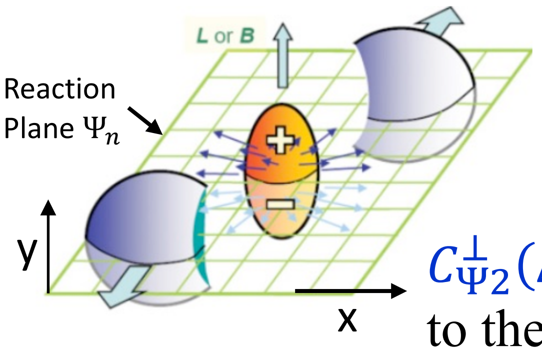
❖ Dipole charge separation measurements correlators:

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

A recent approach is to use the R_{Ψ_m} correlator to measure the dipole charge separation

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

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



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

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

m^{th} order event plane

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

<u>Note that</u> $R_{\Psi_3}(\Delta S)$ is insensitive to the CME-driven charge separation (but sensitive to background)

❖ Dipole charge separation measurements correlators:

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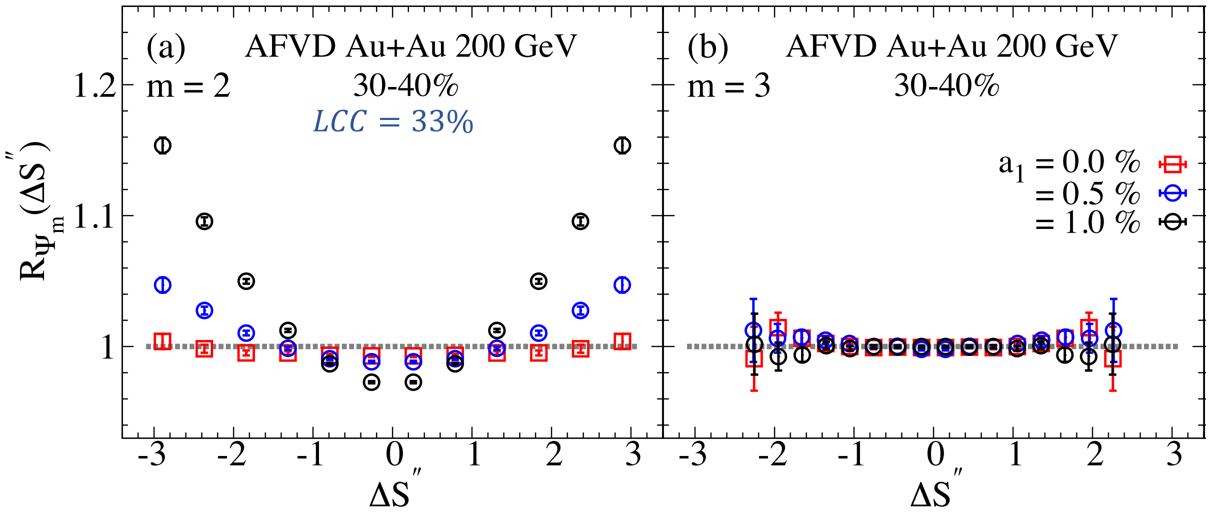
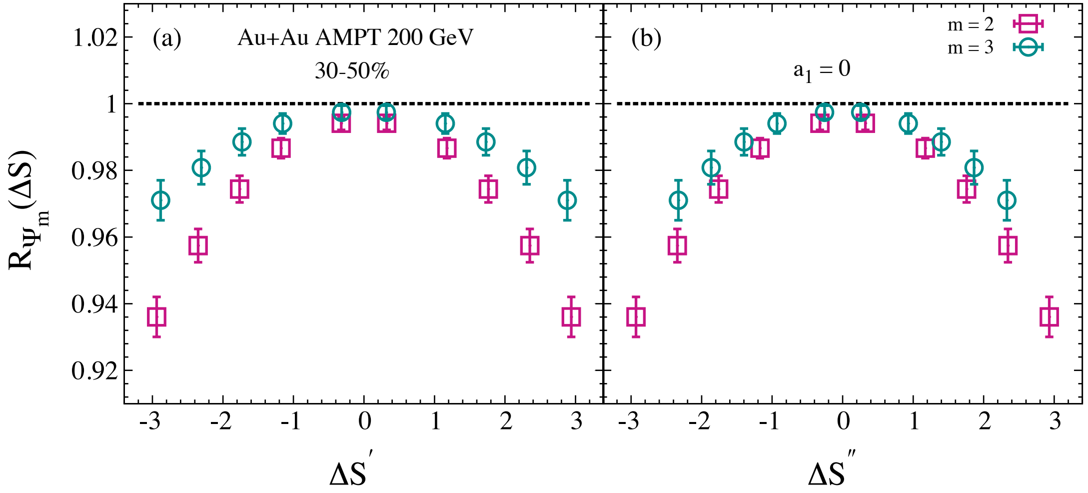
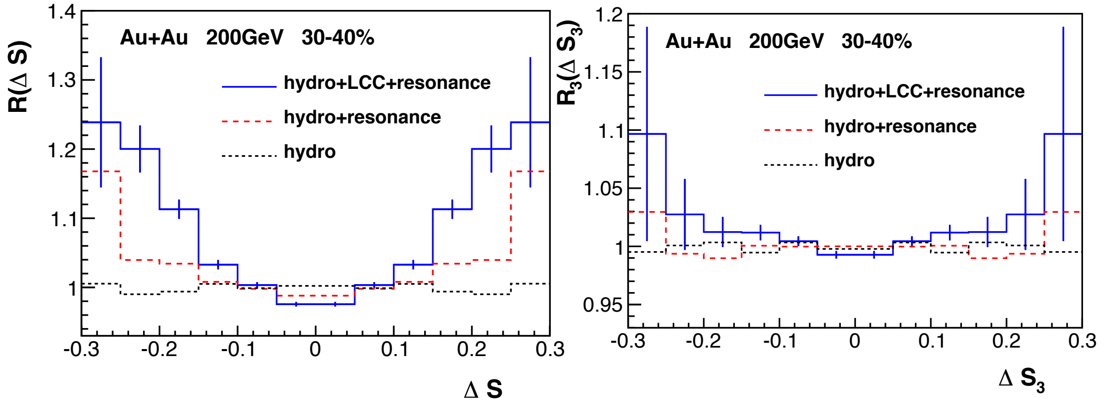


✓ Validation of the expected concave-shaped response of $R_{\Psi_2}(\Delta S)$ to the CME-driven charge separation input in CME-events



Piotr Bozek
PRC 97, 034907 (2018)

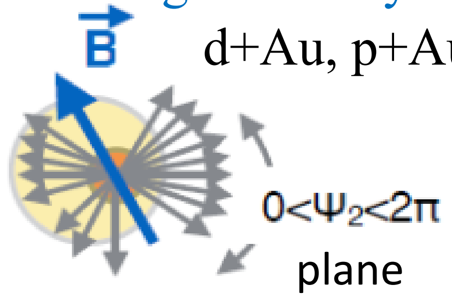


✓ The R_{Ψ_2} and R_{Ψ_3} give similar response to the background irrespective of the correlator shape

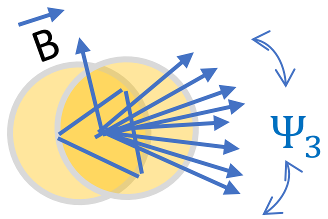
❖ Experimental Measurements

- Bench-mark measurements:
  - Leverage Small systems
  - Leverage Ψ_3 measurments

d+Au, p+Au, …



B-field and Ψ_2 ~ uncorrelated

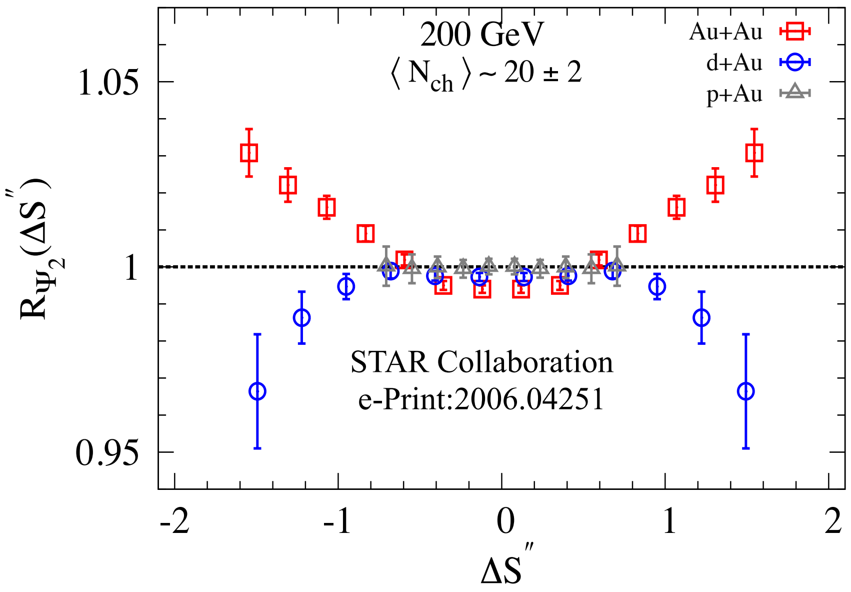


B-field and Ψ_3 ~ uncorrelated

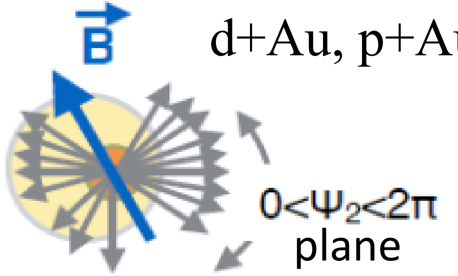
- Constraining the CME-signal to background via:
  - ✓ Different event shape selections
  - ✓ Pair invariant mass cut
  - ✓ Correlation along PP and SP
  - ✓ Using the signed balance function
  - ✓ Using the R_{Ψ_m} correlator

❖ Experimental Measurements:

Measurements for small and large systems:



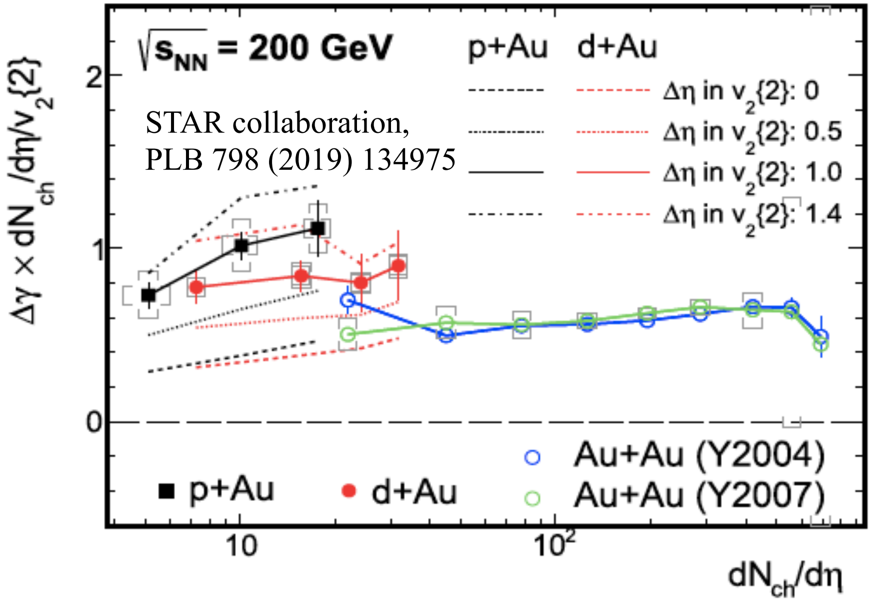
➢ Leverage Small systems



d+Au, p+Au, …

B-field and Ψ_2 ~ uncorrelated

✓ Excellent bench-mark



➢ Measurements for $R_{\Psi 2}$ show:
Different response for small (p(d)+Au) and large (Au+Au) systems

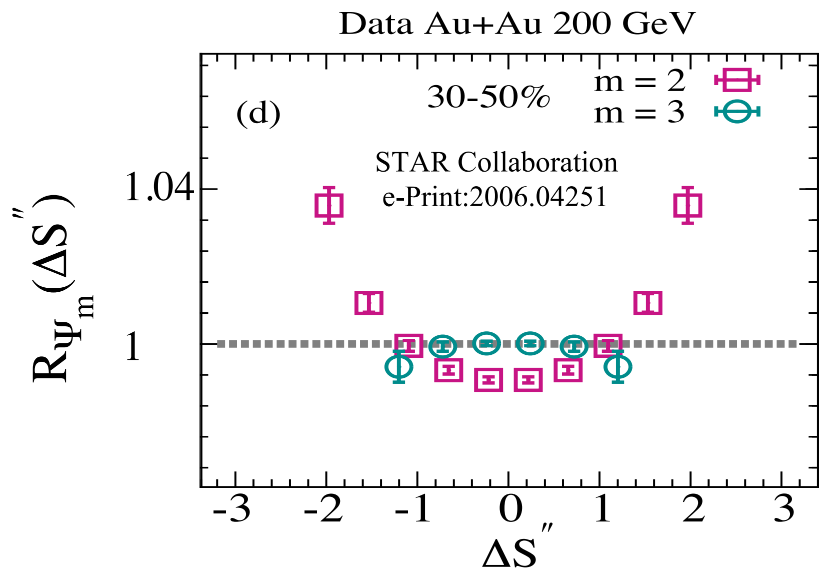
➢ Depending on the $\Delta\eta$ the $\Delta\gamma$ show:
Similar response for small (p(d)+Au) and large (Au+Au) systems

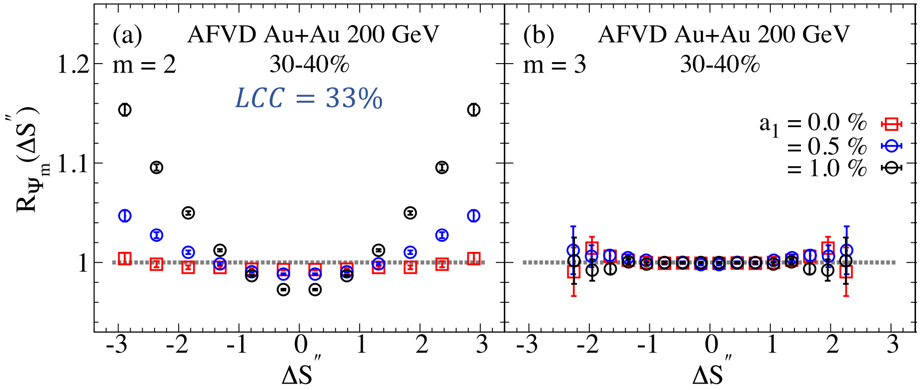
➢ $R_{\Psi 2}$ and $\Delta\gamma$ responded differently for small systems

✓ Back-ground driven charge separation?

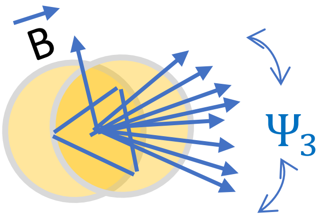
❖ Experimental Measurements:

Measurements for different event planes:





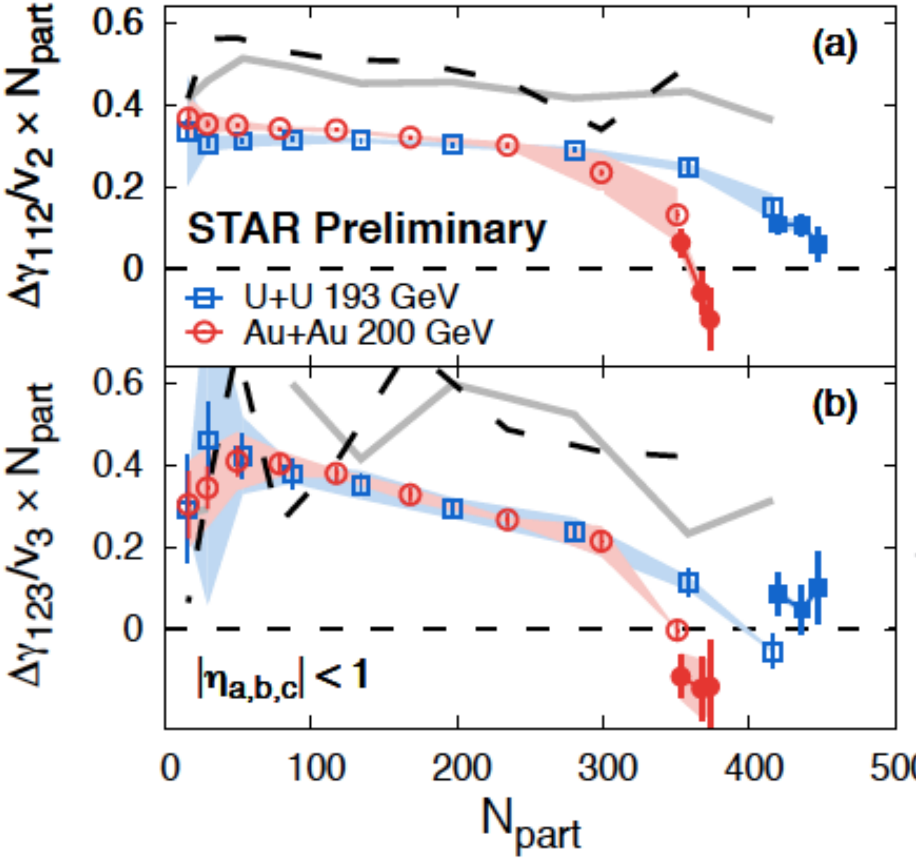
➢ Leverage Ψ_3 measurments



B-field and Ψ_3 ~ uncorrelated

✓ Excellent bench-mark

P.Tribedy, WWND 2020



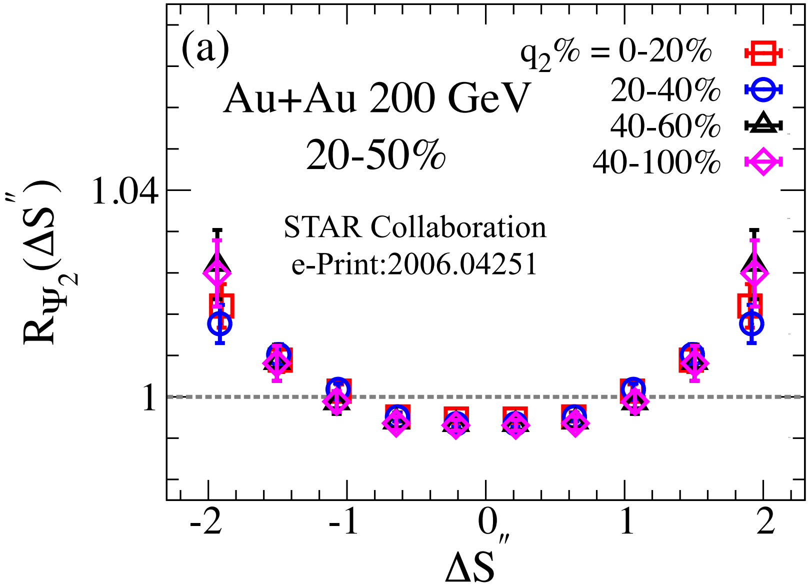
➢ $R_{\Psi 2}$ for Au+Au collisions is concave-shaped ($R_{\Psi 3}$ is flat-shaped)

✓ Difference shape between $R_{\Psi_2}(\Delta S)$ & $R_{\Psi_3}(\Delta S)$

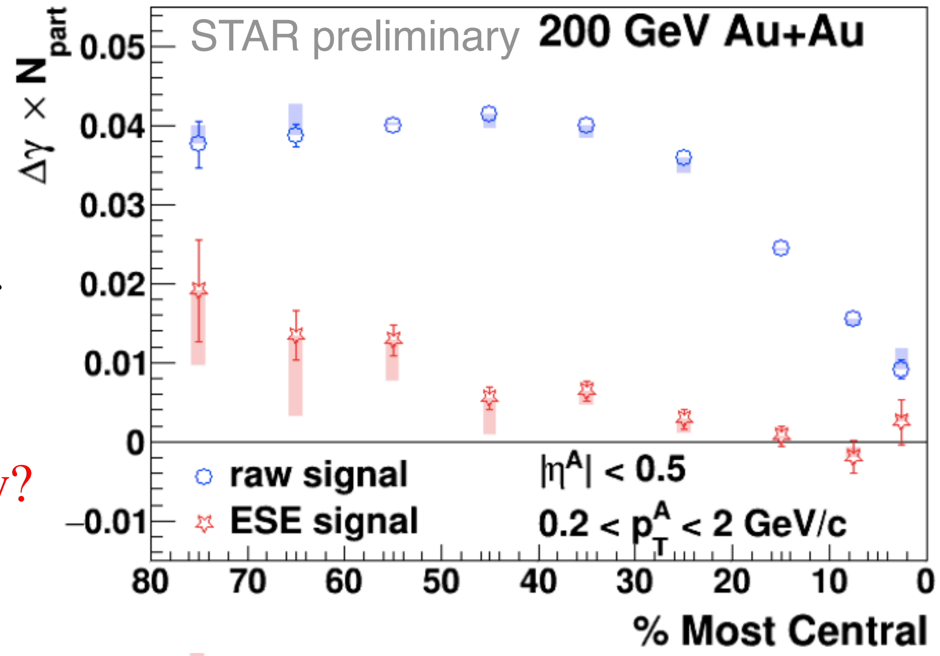
➢ γ_{123} (100% background) provides data-driven baseline

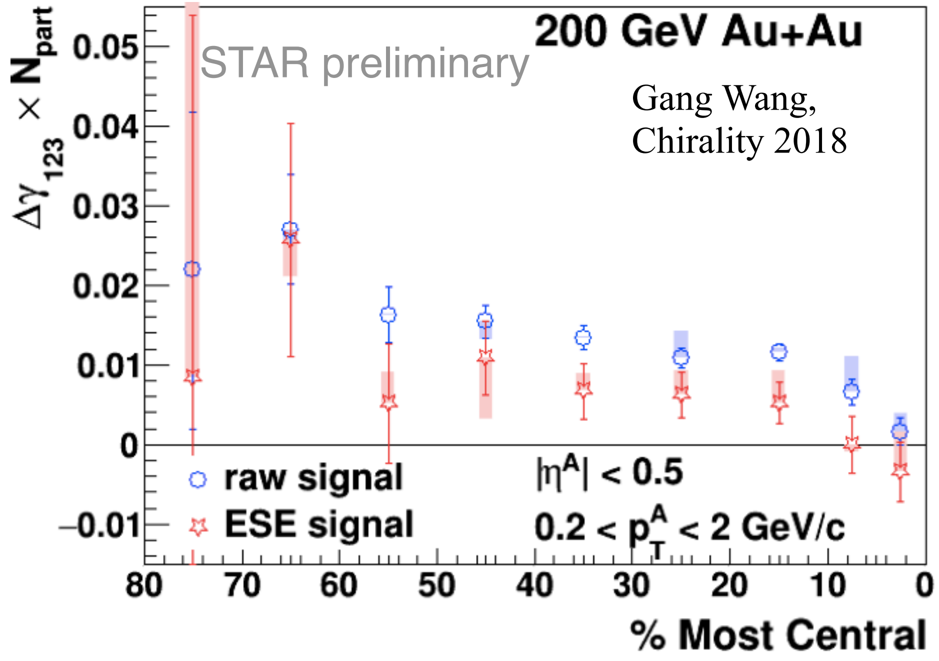
❖ Experimental Measurements:

Measurements for different event shape selections:



- ➢ The ESE signals are similar for γ112 and γ123.
  - ✓ Origin of these finite intercepts: residue nonflow? implicit v2? CME?



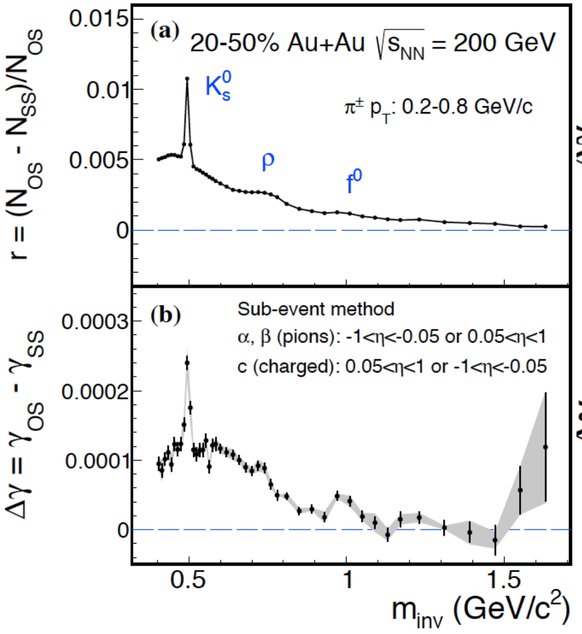


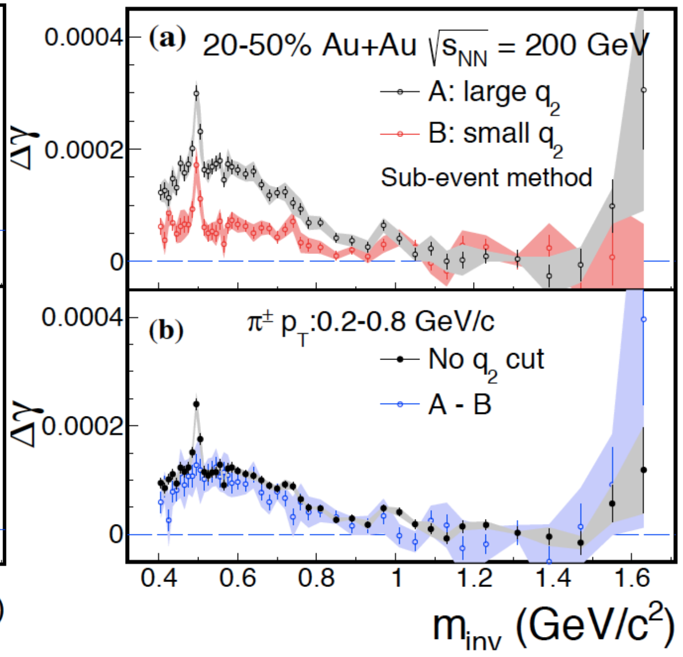
- ➢ The $R_{\Psi_2}(\Delta S)$ are not strongly influenced by the q_2-selections
  - ✓ Not strongly influenced by the v_2 -driven background charge separation?

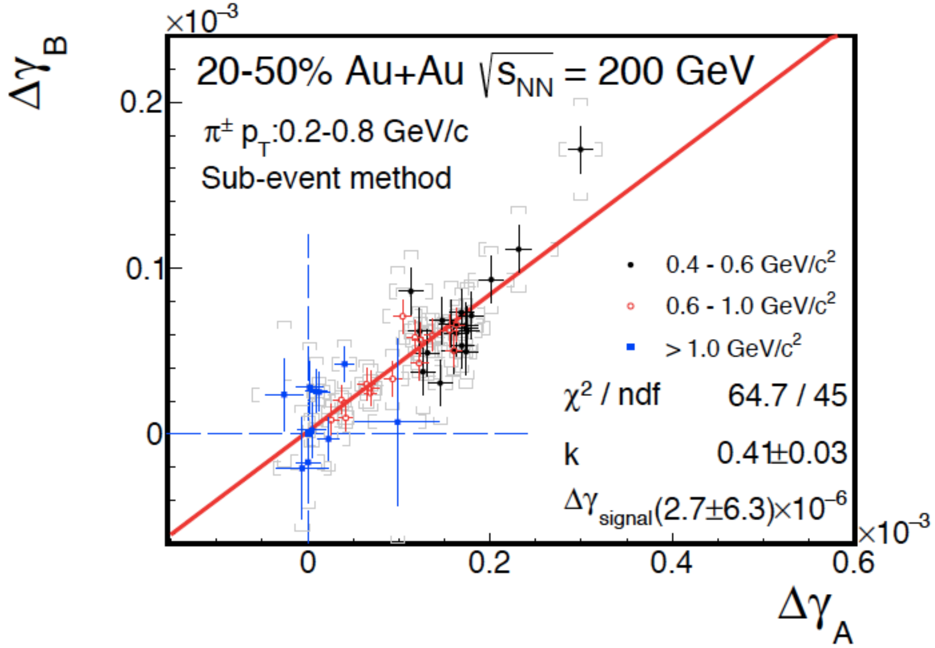
STAR collaboration, e-Print: 2006.05035
J. Zhao, H. Li and F. Wang, Eur. Phys. J. C79 168 (2019)

❖ Experimental Measurements:

The pair invariant mass to isolate the CME background:







$$\Delta\gamma(m_{\rm inv}) = \boxed{r(m_{\rm inv})\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{\rm res.})\rangle v_{2,\rm res.}} + \Delta\gamma_{\rm signal}$$

- ➢ ESE select events with diff. v_2 by q_2 class (A, B)
  - ✓ CME the same for events from different q_2 classes
  - ✓ Bkg $\Delta\gamma$ mass shape: $\Delta\gamma_A$-$\Delta\gamma_B$

$$\Delta\gamma_B = k\Delta\gamma_A + (1-k)\Delta\gamma_{\rm signal}$$

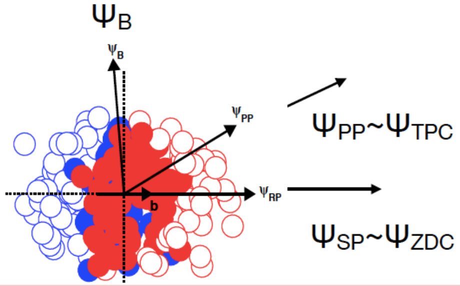
- ➢ The results indicate that the possible CME signal is small in the inclusive $\Delta\gamma$, consistent with zero with current precision. This presents an upper limit of 15% of the inclusive result at 95% confidence level.

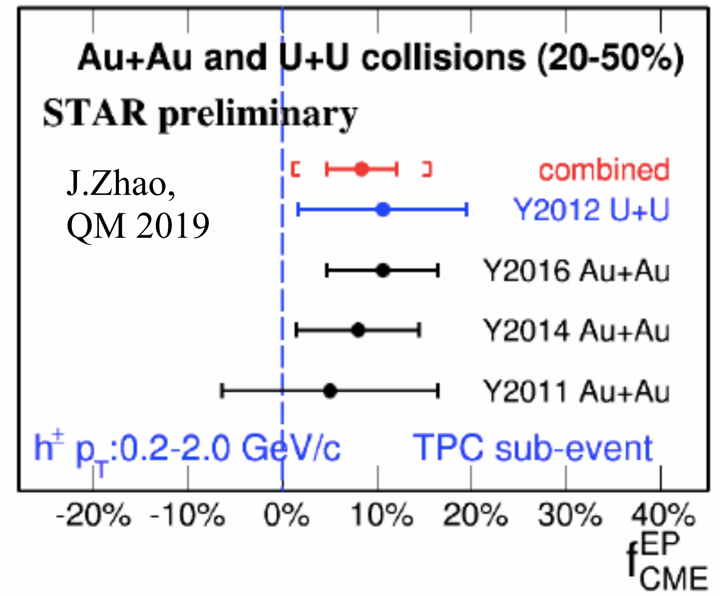
❖ Experimental Measurements:

Correlation along participant vs. spectators planes:

Voloshin, Phys. Rev. C 98, 054911 (2018)
H-J. Xu, et al, CPC 42, 084103 (2018)

- Fraction of CME-like signals can be extracted based on:



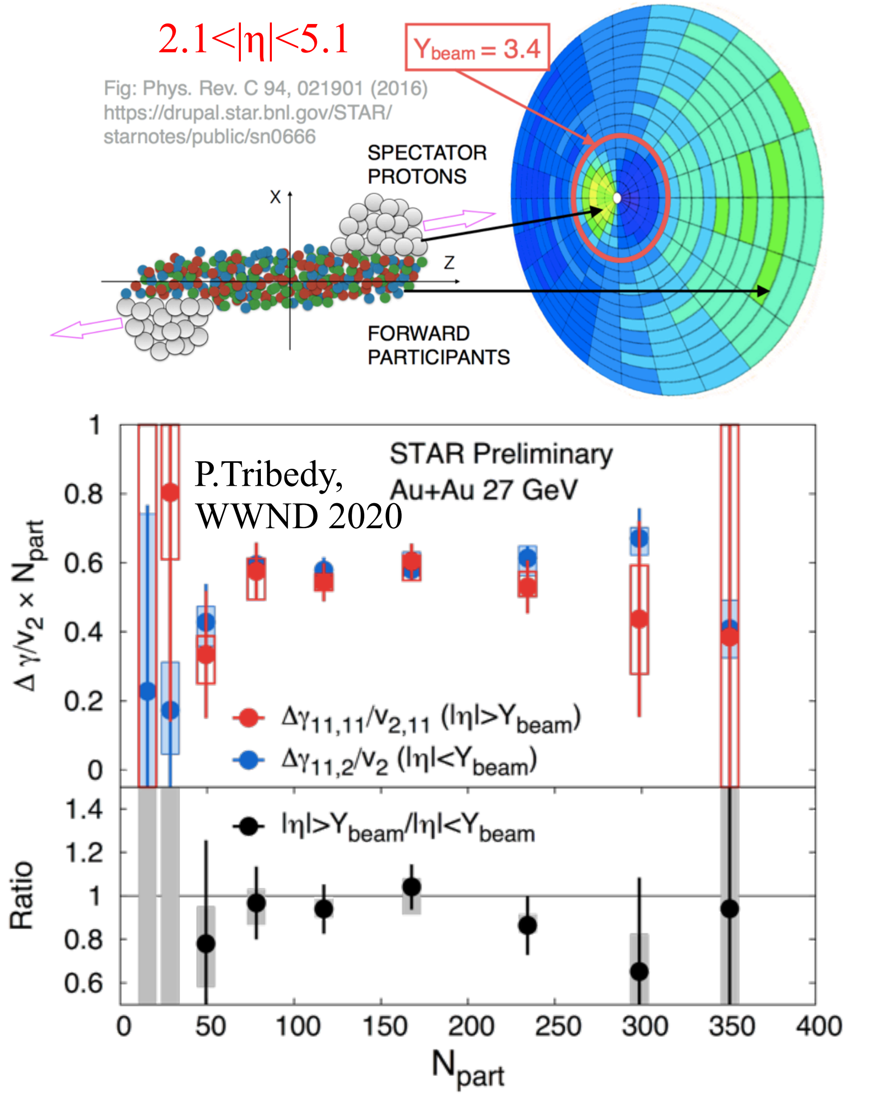


$$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\}$$
$$A = \Delta\gamma\{\psi_{ZDC}\} / \Delta\gamma\{\psi_{TPC}\}$$

$$f_{EP}(\mathrm{CME}) = \mathrm{CME}\{\psi_{TPC}\} / \Delta\gamma\{\psi_{TPC}\} = (A/a - 1)/(1/a^2 - 1)$$

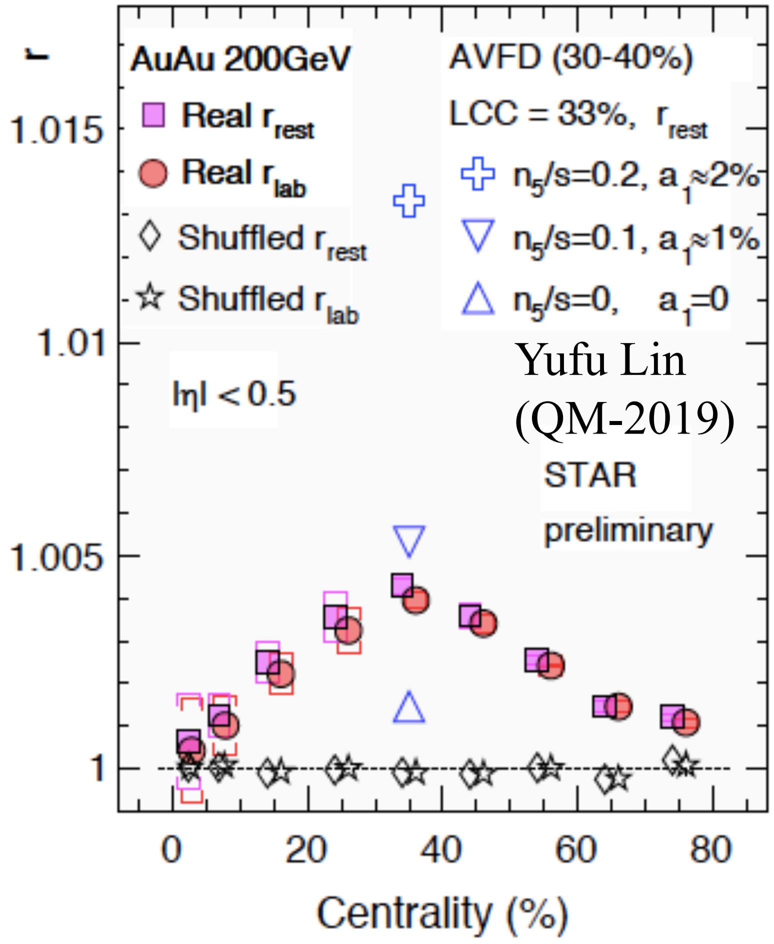
- CME fractions are extracted with $\Delta\gamma$ using Ψ_{PP}/Ψ_{RP} in U+U and Au+Au:
  - ✓ The combined result is (8±4±8)%
- At 27 GeV no significant difference in the scaled charge separation w.r.t. spectator proton & produced particle event planes.

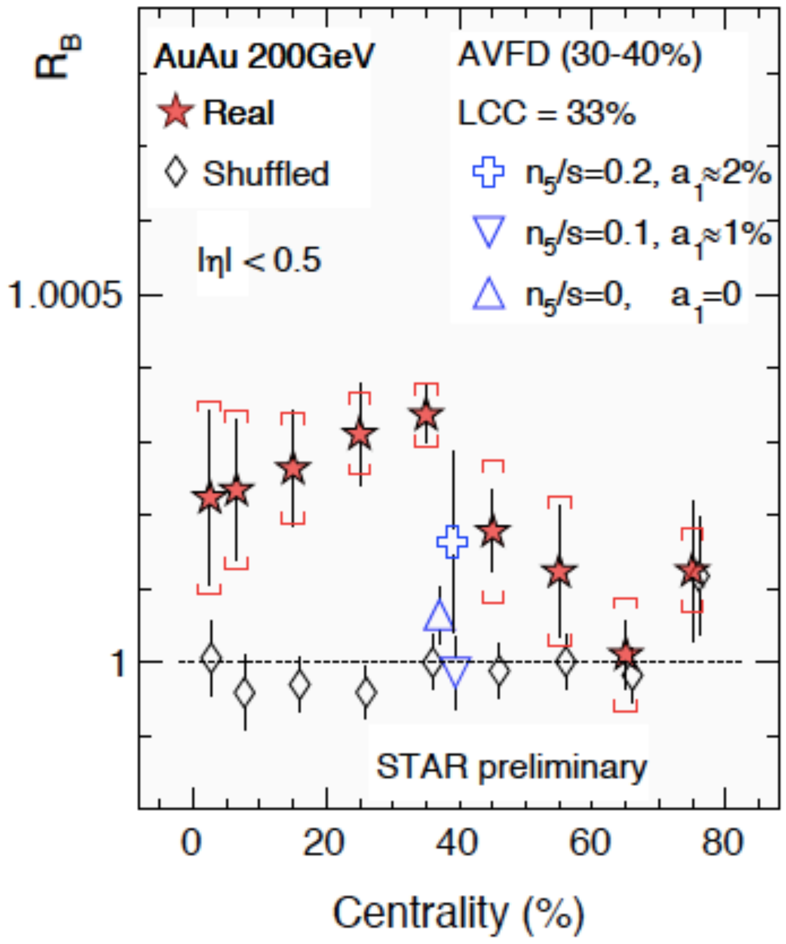
- Unique advantage of EPD at 27 GeV



❖ Experimental Measurements:

Measurements using the signed balance function:





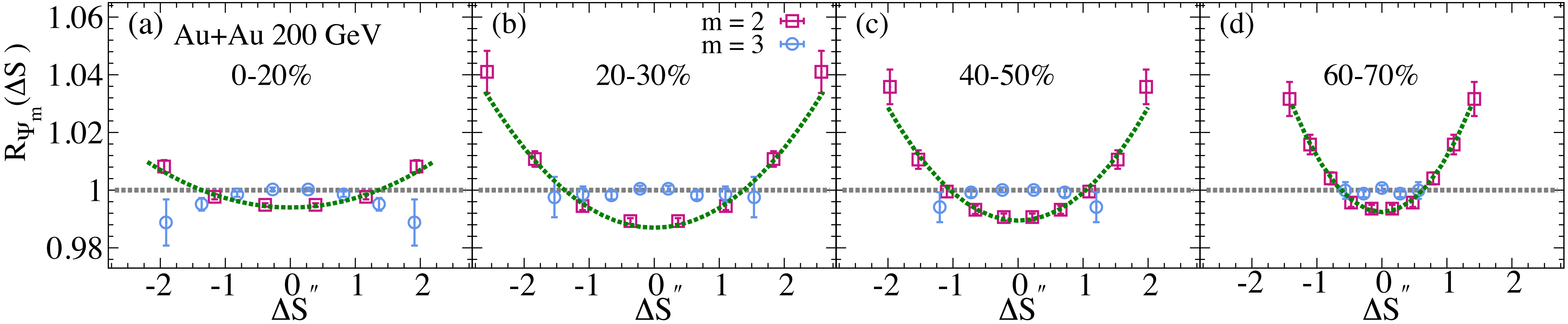
- Data points are not EP resolution corrected. Instead, they smeared reaction plane in AVFD with measured EP resolution in order to compare with data.
- The efficiency is also applied on AVFD events for a fair comparison.

Both r_{rest} and R_B are larger than unity in all centralities, and larger than model calculation with no CME.

❖ Experimental Measurements:

Measurements using the R_{Ψ_m} correlator:

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

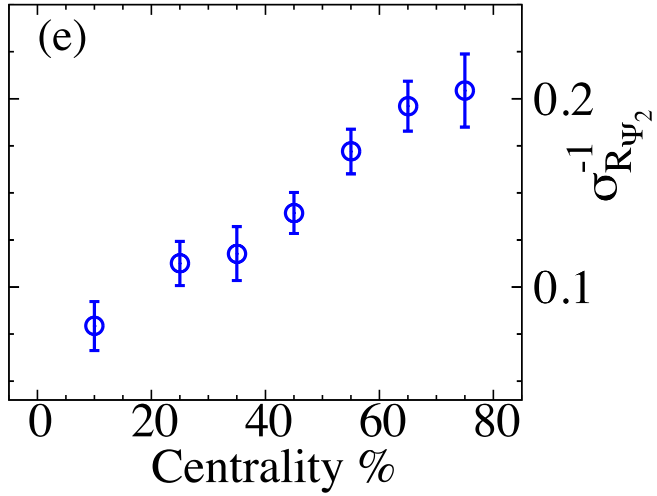


➢ $R_{\Psi 2}$ for Au+Au collisions is concave-shaped

✓ Difference shape between $R_{\Psi_2}(\Delta S)$ & $R_{\Psi_3}(\Delta S)$

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

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



❖ Experimental Measurements:
Implications

- Major efforts to reduce the background effect on the inclusive $\Delta\gamma$ using the pair invariant mass and f_{CME} methods,
  - ✓ The measurements, with large uncertainties, suggest that 15% of the inclusive result could be attributed to CME-signal?
- The $R_{\Psi_m}(\Delta S)$ measurements show:
  - Difference shape between R_{Ψ_2} & R_{Ψ_3} and between small and large systems
  - The $R_{\Psi_2}(\Delta S)$ are not strongly influenced by the q_2-selections
    - ✓ Background scenarios cannot provide a simultaneous description of the R_{Ψ_m} measurements.
      - CME?
- The signed balance function measurements show:
  - ✓ Both r_{rest} and R_B are larger than unity and larger than AVFD with CME-signal

➢ Optimistic point of view:

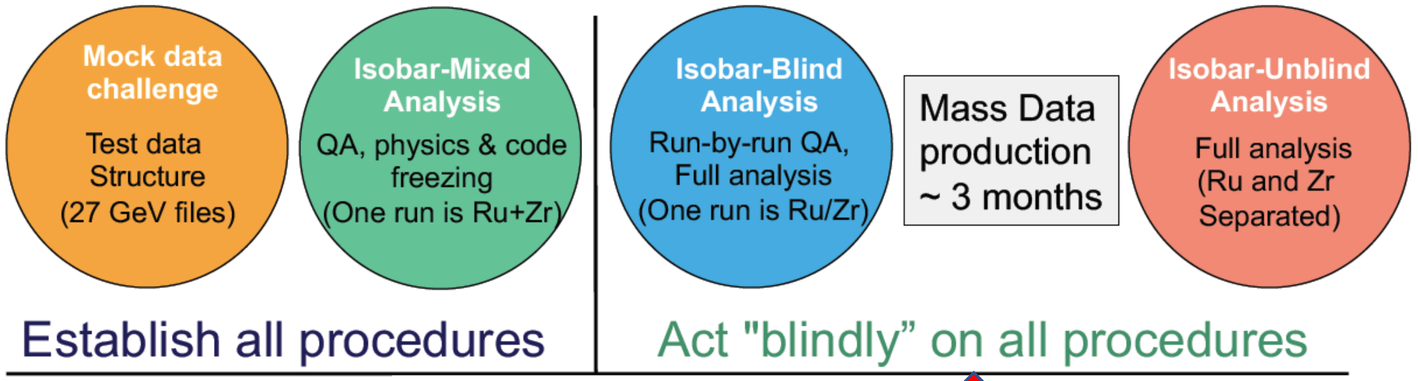
The experimental measurements reflect a charge separation that could be CME-driven

❖ Isobar Analysis:

A large, collective effort

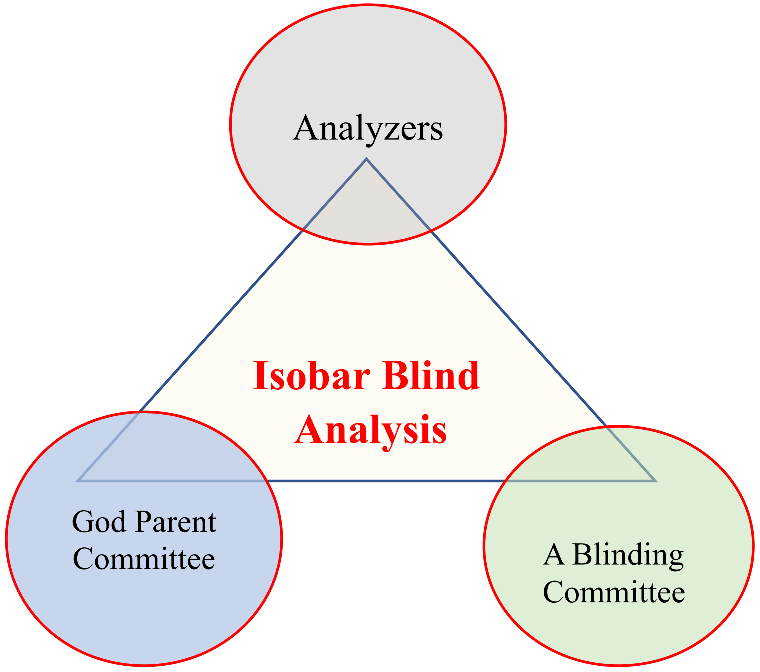
P. Tribedy
WWND 2020

A. Tang
PAC meeting, Sept 2020



STAR, arXiv:1911.00596 (2019)

We are here



5-Isobar Blind Analyses

- $\Delta\gamma, \Delta\delta$ and κ
- $\Delta\gamma, \Delta\delta$ and $\Delta\gamma(\Delta\eta)$
- $\Delta\gamma$ in PP/SP and $\Delta\gamma(\mathrm{M_{inv}})$
- $\Delta\gamma$ in PP/SP
- $R(\Delta S)$ Correlator.

1-Isobar Unblinded Analysis

- The signed balance function

Case for CME:

- $\Delta\gamma$ and its derivatives
  $\Delta\gamma/\mathrm{v_2}(\mathrm{Ru/Zr}) > 1$
  $\Delta\gamma_{112}/\mathrm{v_2}(\mathrm{Ru/Zr}) > \Delta\gamma_{123}/\mathrm{v_3}(\mathrm{Ru/Zr})$
  $\kappa(\mathrm{Ru/Zr}) > 1$
  $\Delta\gamma^{\mathrm{Ru}} - \mathrm{a'r'}\Delta\gamma^{\mathrm{Zr}} > 0$
- $R(\Delta S)$ (Ru/Zr) show concave shape
- $f_{CME}^{Ru} > f_{CME}^{Zr} > 0$

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC and Wayne State

Thank You