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Investigation of the sensitivities of observables for CME search by the STAR experiment using AVFD framework

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arXiv:2105.06044

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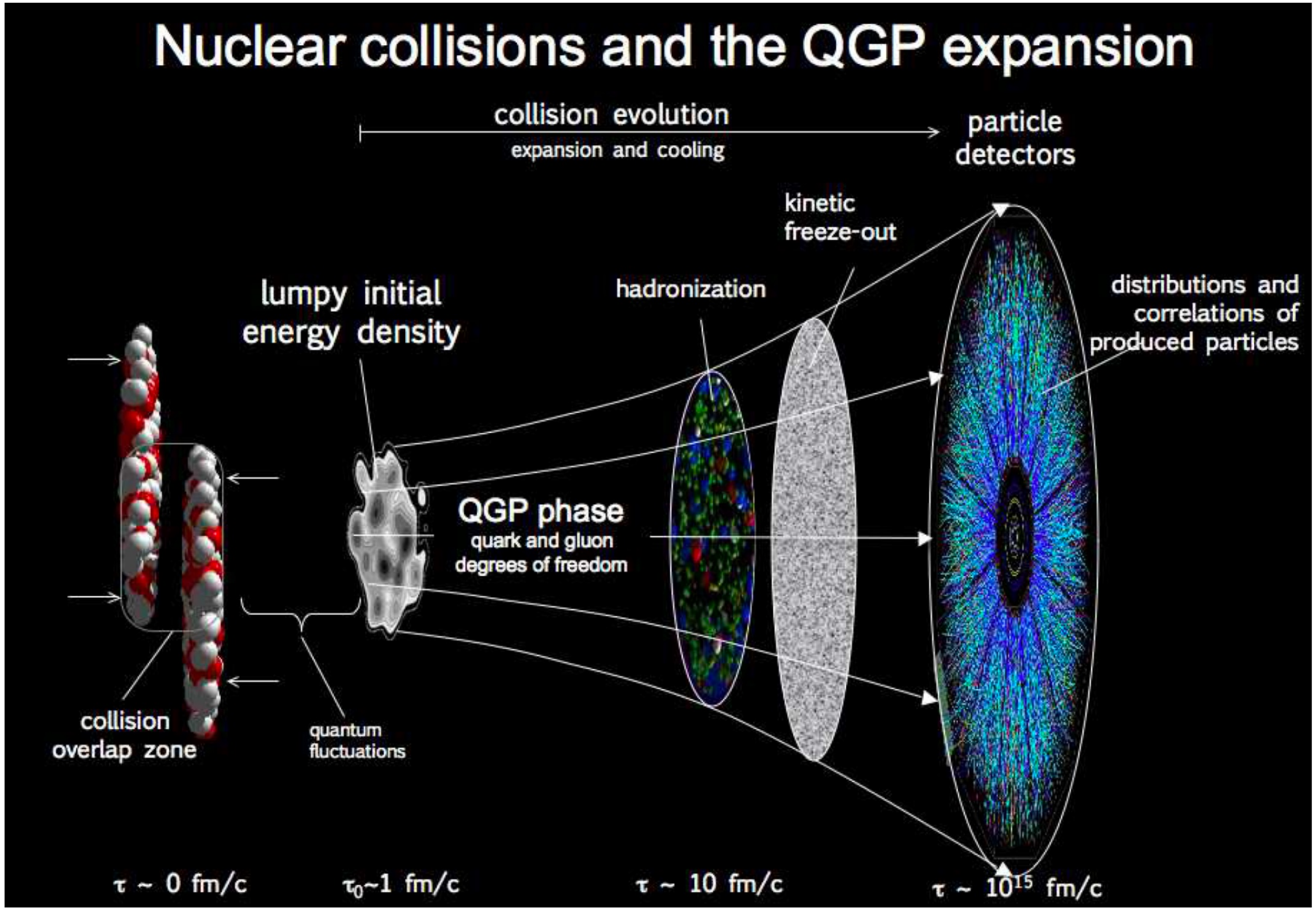
U.S. DEPARTMENT OF ENERGY | Office of Science

STAR

Outline

- Motivation
- CME observables and their Core-components
- Sensitivity Study with STAR's frozen code isobar blind-analysis, with EBE-AVFD events.
- Summary

Heavy-Ion Collisions



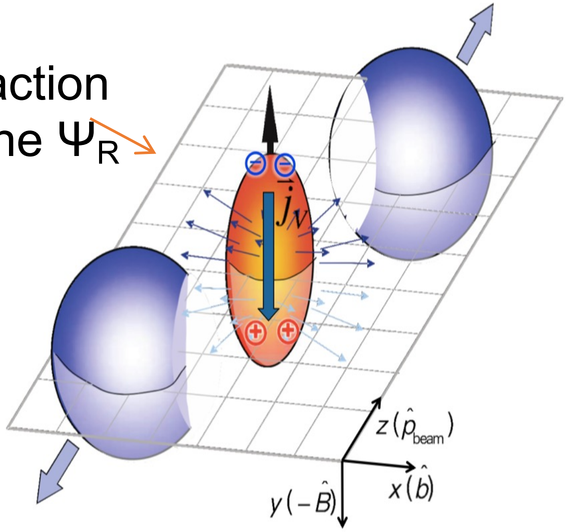
- The quark-gluon plasma (QGP) is created in heavy-ion collisions.

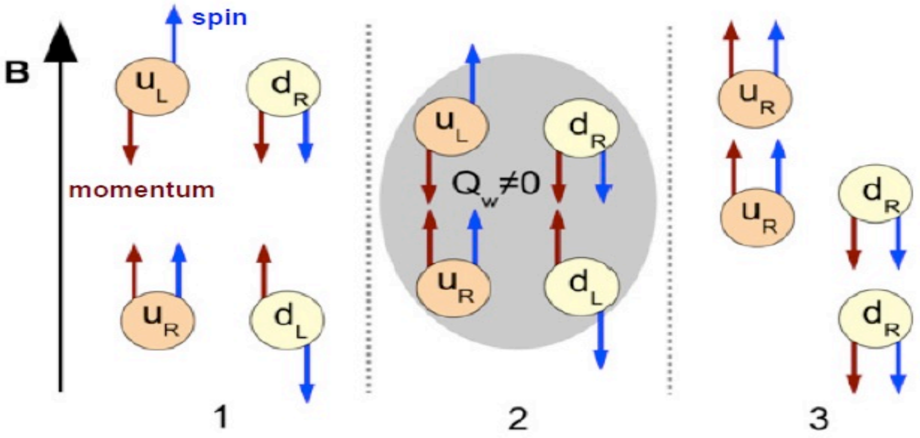
- According to QCD, if the topological solutions of the SU(3) gauge group are chiral, they can transfer chirality to quarks via chiral anomaly, forming local chiral domains in QGP

Chiral Magnetic Effects (CME)

In non-central collisions a strong magnetic field is produced ⊥ to Ψ_R

Reaction Plane Ψ_R





D. Kharzeev, Phys. Lett. B 633, 260 (2006)
D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A 797, 67 (2007).

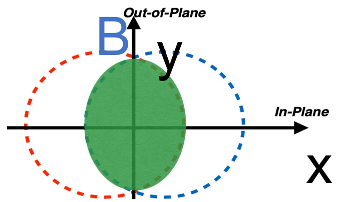
CME-induced charge separation shifts pos. and neg. particles in opposite directions (along B).

The azimuthal distribution of particles is Fourier-decomposed as:

$$\frac{dN_\alpha}{d\phi^*} \approx \frac{N_\alpha}{2\pi}[1 + 2v_{1,\alpha}\cos(\phi^*) + 2v_{2,\alpha}\cos(2\phi^*) + 2v_{3,\alpha}\cos(3\phi^*) + ... + 2a_{1,\alpha}\sin(\phi^*) + ...]$$

The CME is present due to finite n_5/s, measured as finite a_1 in experiment.

Experimental Observable: γ-correlator



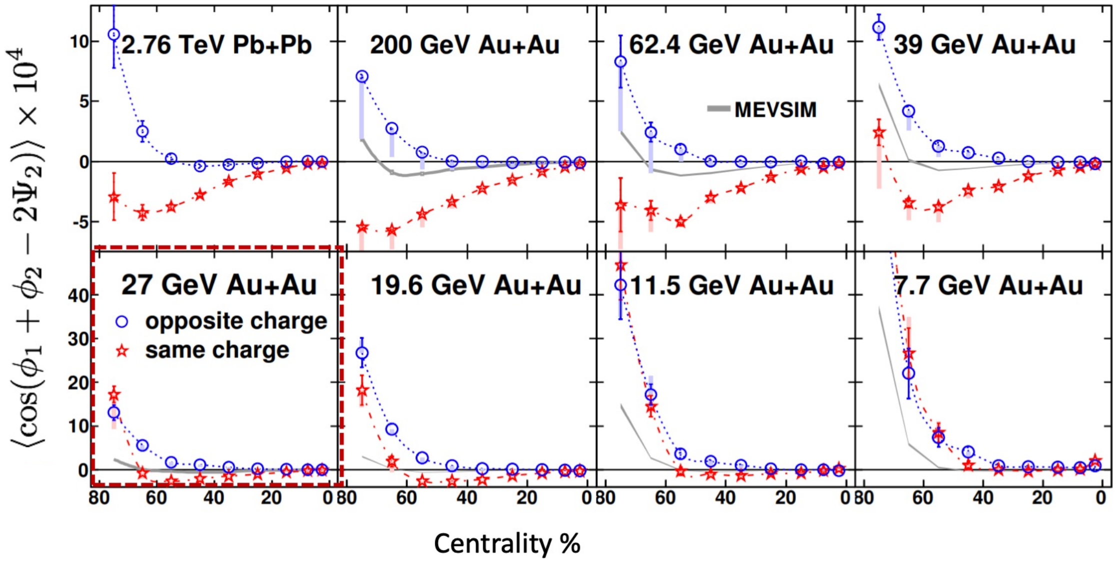
$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$
$$= \langle \cos(\Delta\phi_\alpha)\cos(\Delta\phi_\beta) - \sin(\Delta\phi_\alpha)\sin(\Delta\phi_\beta) \rangle$$
$$= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{IN}) - (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{OUT}),$$

Directed flow

background effects

Fluctuations of a_1

STAR PRL 113 (2014) 052302



$$\Delta\gamma_{112} \equiv \gamma_{112}^{OS} - \gamma_{112}^{SS},$$

the $\langle v_{1,\alpha} v_{1,\beta} \rangle$ terms cancel out, as well as a large portion of $(B_{IN} - B_{OUT})$.

$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$
$$= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{IN}) + (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{OUT}),$$

$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta}.$$

- **Backgrouds include the effects of resonance flow, momentum conservation and local charge conservation.**

Soren Schlichting, Scott Pratt, Phys. Rev. C 83 (2011) 014913.
Jie Zhao and Fuqiang Wang, Prog. Part. Nucl. Phys. 107, 200 (2019).

Experimental Observable: R-correlator

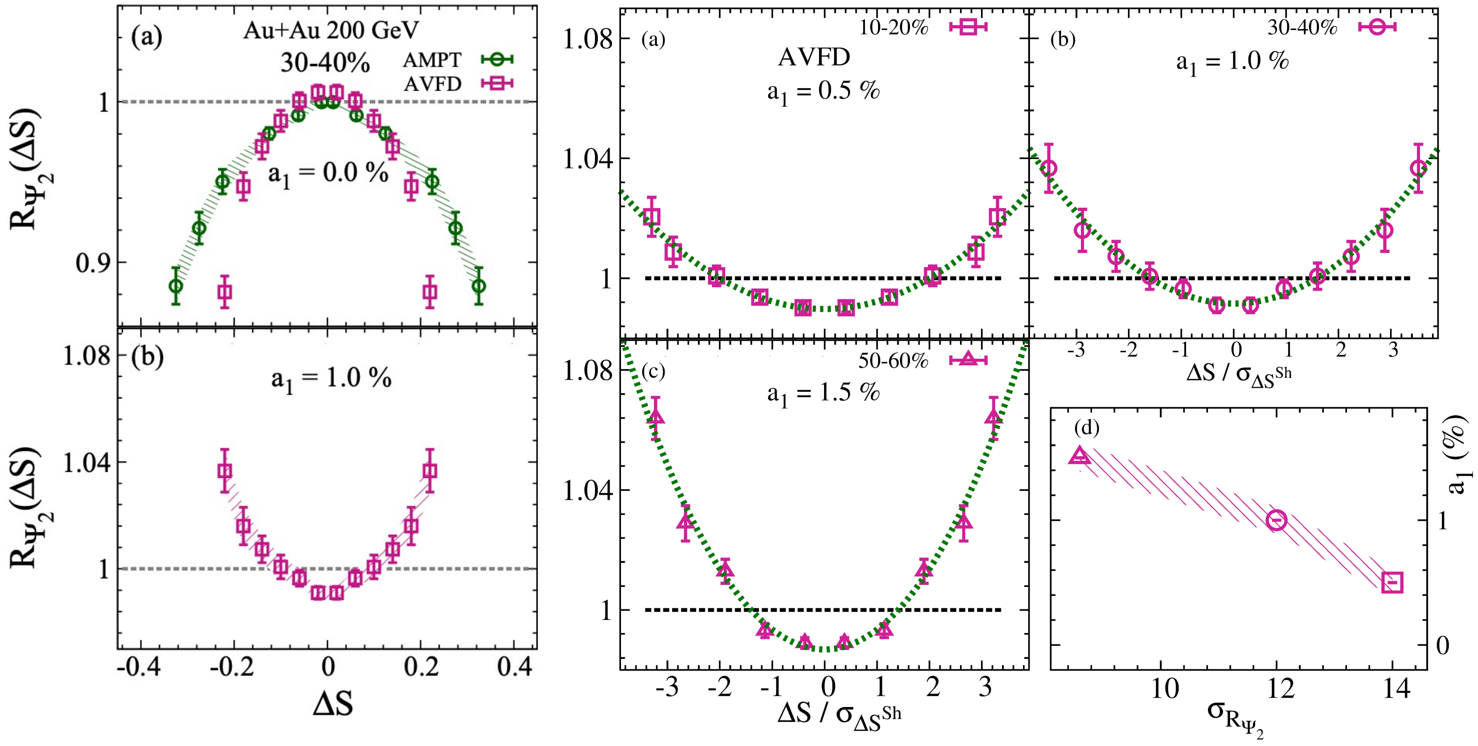
Phys. Rev. C **97**, 061901(R) (2018)
Phys. Rev. C **98**, 061902(R) (2018)

1) E-by-E a_1 difference between +/- charge ΔS.

2) Removal of trivial contribution: $C(\Delta S) = \frac{N_{real}(\Delta S)}{N_{shuffled}(\Delta S)}$

3) Look for out-of-plane excess: $R(\Delta S) = \frac{C^{\perp}(\Delta S)}{C(\Delta S)}$

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



- $R_{\Psi 2}$ is concave with CME signal.
- $R_{\Psi 2}$ is convex when backgrounds only.
- $R_{\Psi 2}$ getting more concave when the signal is larger.

➢ However, the interpretation of the shape of $R_{\Psi 2}$ is complicated by other effects.

Phys. Rev. C 97 034907(2018)
Phys. Rev. C 101, 024916 (2020)
Phys. Rev. C 103, 034912 (2021)

Experimental Observable: Signed Balance Function

A. Tang, Chinese Physics C Vol. 44, No. 5 (2020) 054101

Y. Lin, (for STAR Collaboration) QM2019

1) Count pair's momentum ordering in p_y :

$$B_{P,y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+},$$

$$B_{P,y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

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

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

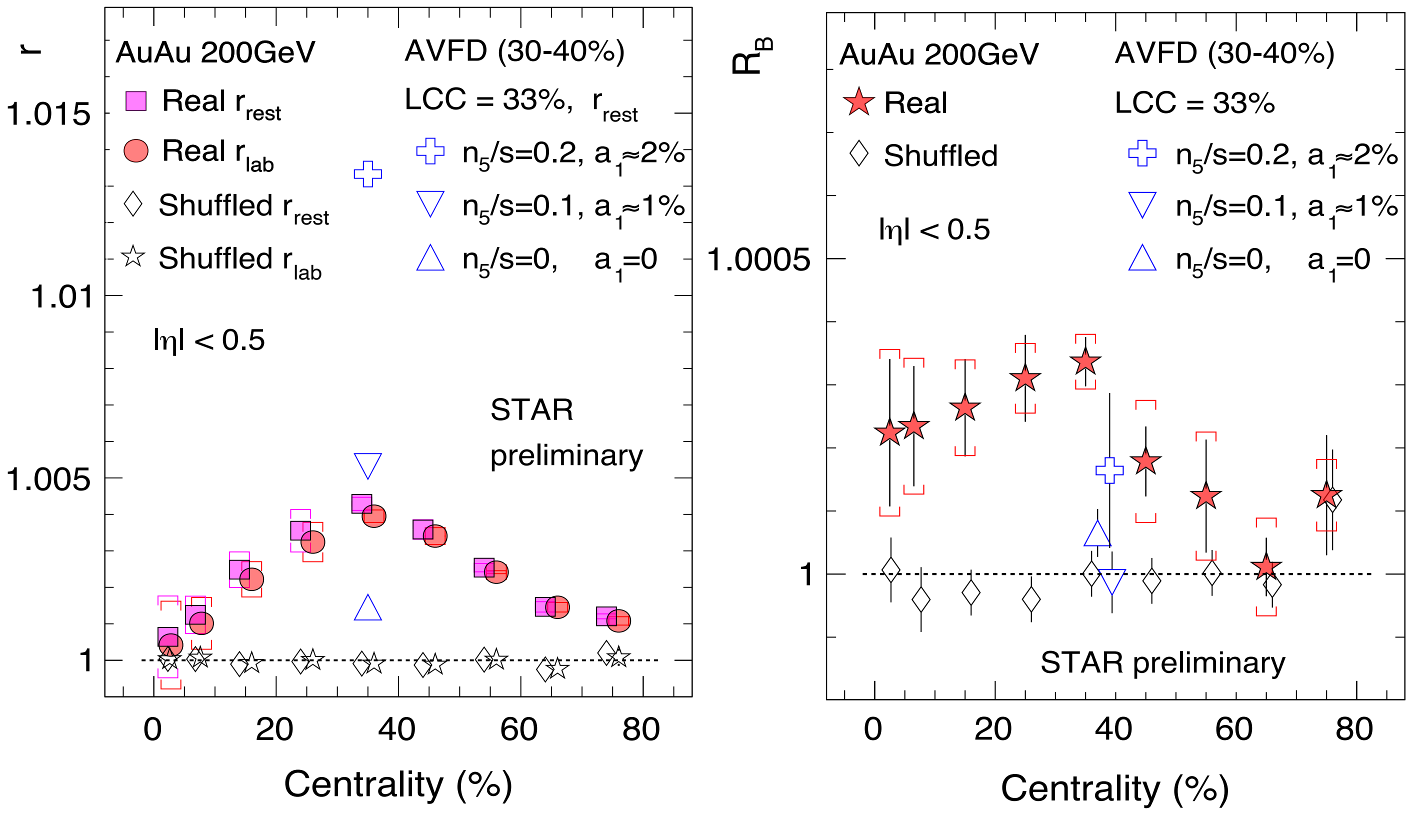
$$\Delta B_y(\pm 1) = \delta B_y(\pm 1) - \delta B_y(\pm 1)$$

$$= \frac{N_+ + N_-}{N_+ N_-}\left[N_{y(+-)} - N_{y(-+)}\right]$$

3) Look for enhanced event-by-event fluctuation of net ordering in y direction.

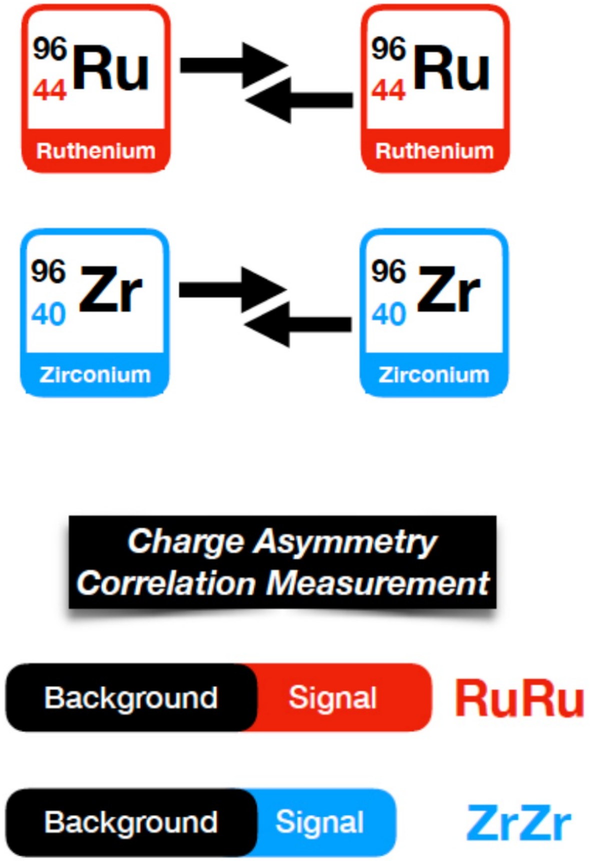
$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}$$ (>1 with CME)

$$R_B = \frac{r_{rest}}{r_{lab}}$$ (>1 with CME)



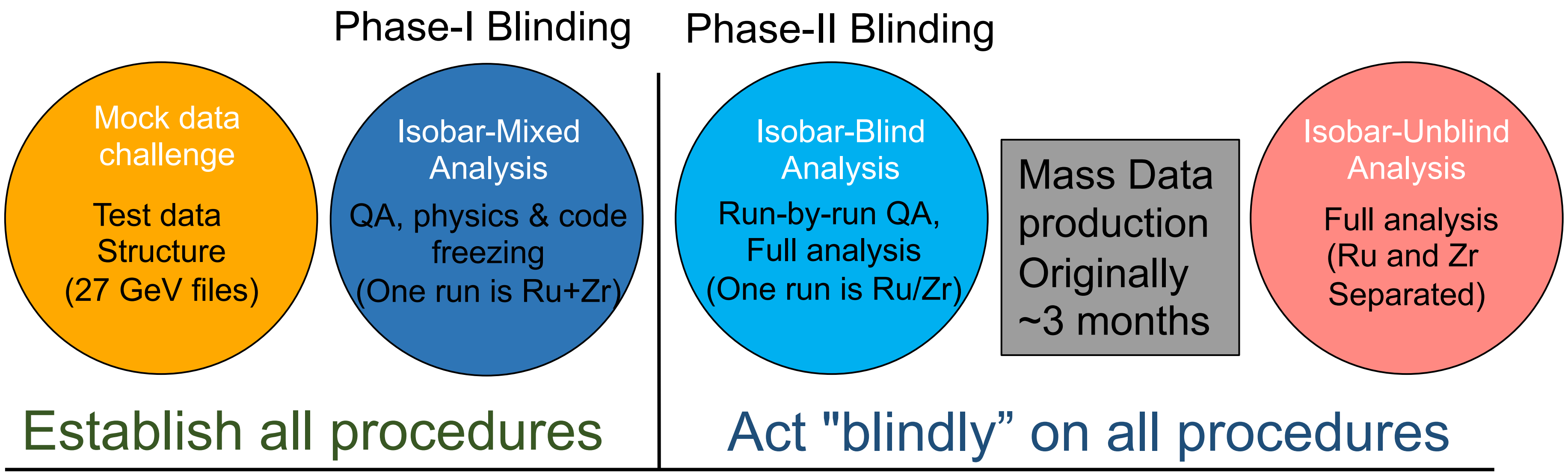
- Not participated in isobar blind-analysis, but included here for completeness.

Isobaric Collision and Blind-analysis at STAR



- The two isobaric systems: Difference in the CME signal but same flow backgrounds.

J. Adam, et al. Nuclear Science and Techniques, 32, 48 (2021);
J. Adam, et al. arXiv:2109.00131 [nucl-ex]

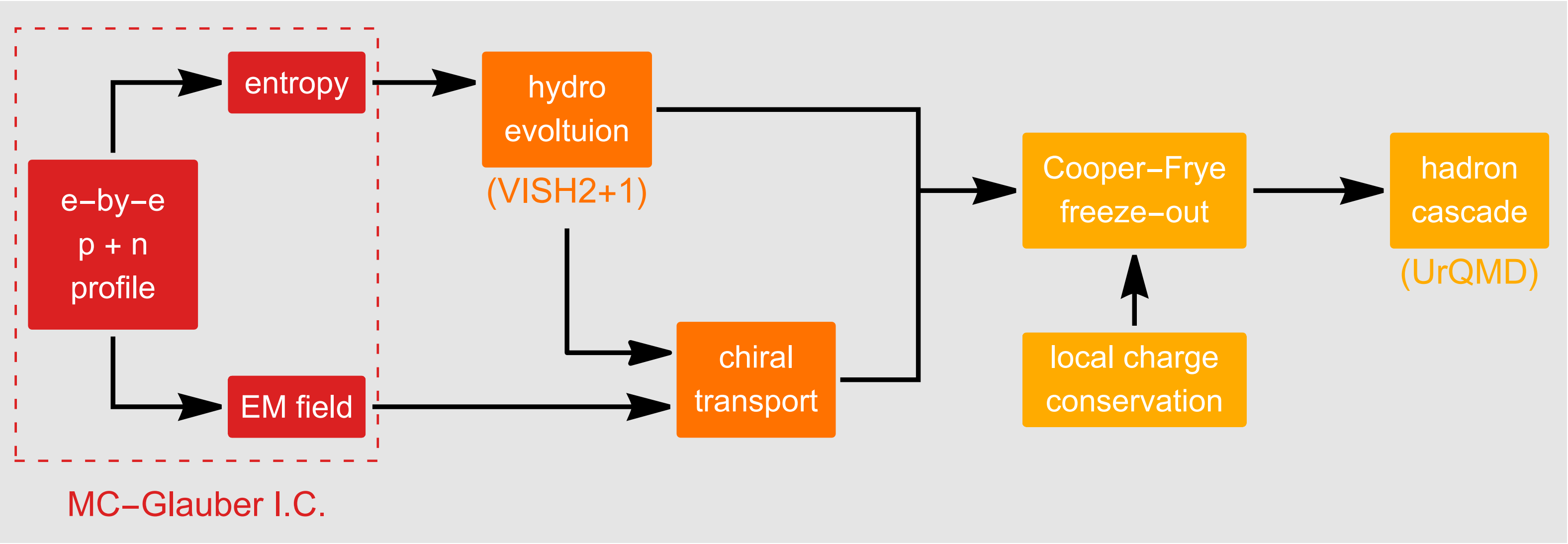


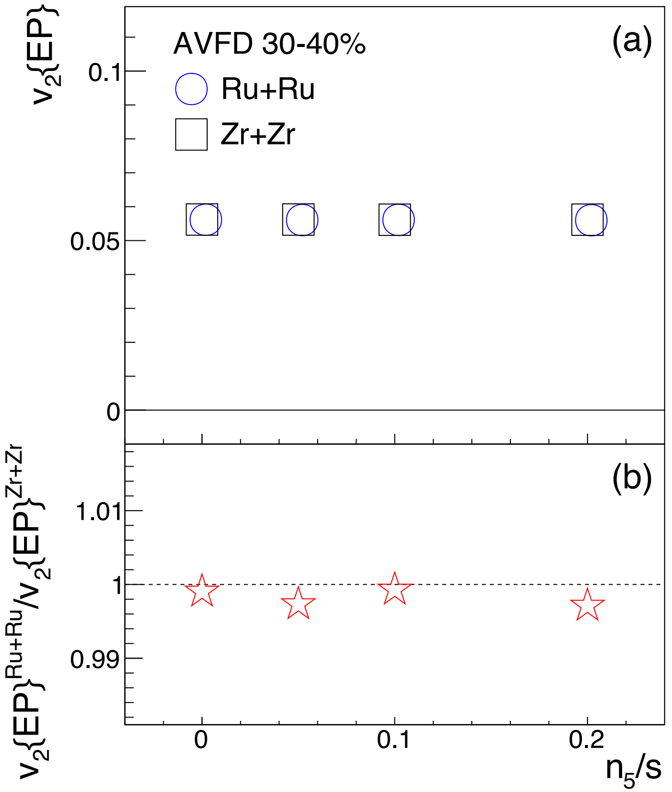
- The STAR has implemented a blind-analysis recipe in data analyses, and all the analysis codes have been frozen as part of the blinding procedure. Five institutional groups performed blind analyses of the isobar data, with various observables.
- It's desirable to study the connection and difference between various observables, as well as their sensitivities to the CME signals.

EBE-AVFD Beta1.0 with Isobars

EBE-AVFD: event-by-event anomalous-viscous fluid dynamics,

Phys. Rev. C **97**, 061901(R) (2018)
Phys. Rev. C **98**, 061902(R) (2018)





Y. Jiang, S. Shi, Y. Yin and J. Liao, Chin. Phys. C 42 No. 1 011001 (2018)
S. Shi, Y. Jiang, E. Lilleskov and J. Liao. Annals of Physics 394 50-72 (2018)
S. Shi, H. Zhang, D. Hou, and J. Liao. Phys. Rev. Lett. 125, 242301 (2020)

a_1 is obtained with RP

n_5/s	$a_{1,+}$ (%)		$a_{1,-}$ (%)	
	Ru+Ru	Zr+Zr	Ru+Ru	Zr+Zr
0	0	0	0	0
0.05	0.37	0.35	0.35	0.33
0.10	0.74	0.69	0.71	0.66
0.20	1.48	1.38	1.42	1.32

- a_1 (Ru) > a_1 (Zr)

- The major background (v_2) is identical.

Connection of CME methods

The relation between experimental observables via analytical derivation:

SBF:

$$\Delta_{\rm SBF} \equiv \sigma^2(\Delta B_y) - \sigma^2(\Delta B_x) \approx \frac{128M^2}{\pi^4}(\Delta\gamma_{112} - \frac{4}{3}v_2\Delta\delta).$$

R-correlator:

$$\Delta_{R2} \approx 2(1 - \frac{1}{M})\Delta\gamma_{112}$$

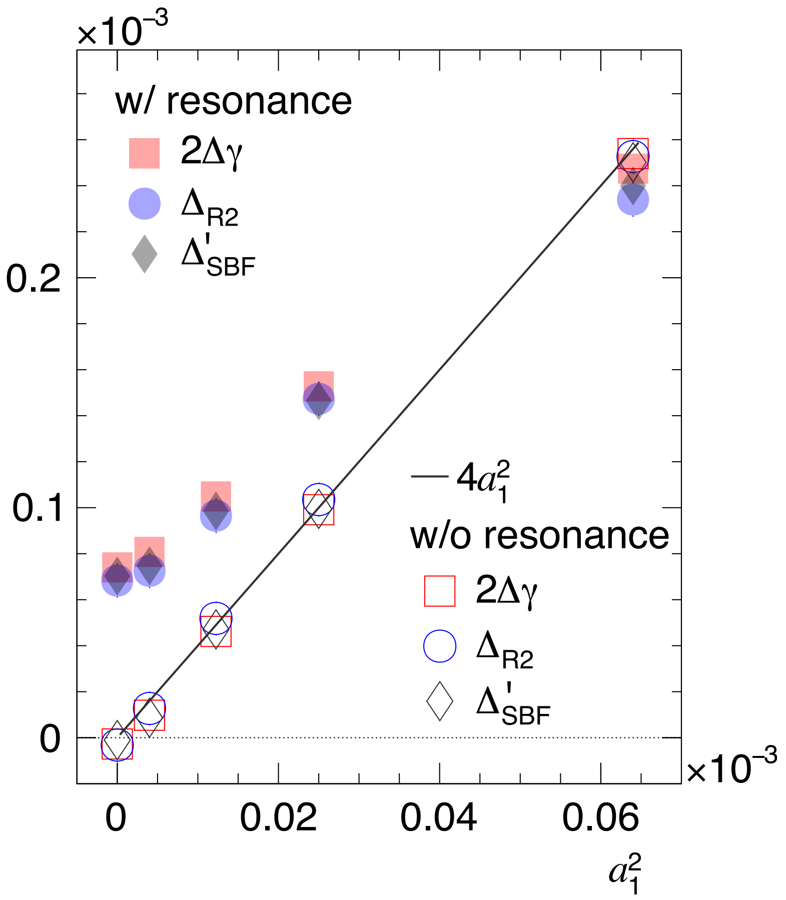
$$\frac{S_{\rm concavity}}{\sigma^2_{R2'}} = \frac{S_{\rm concavity}}{\sigma^2_{R2}}\langle(\Delta S_{2,\rm shuffled})^2\rangle \approx -M\Delta\gamma_{112}.$$

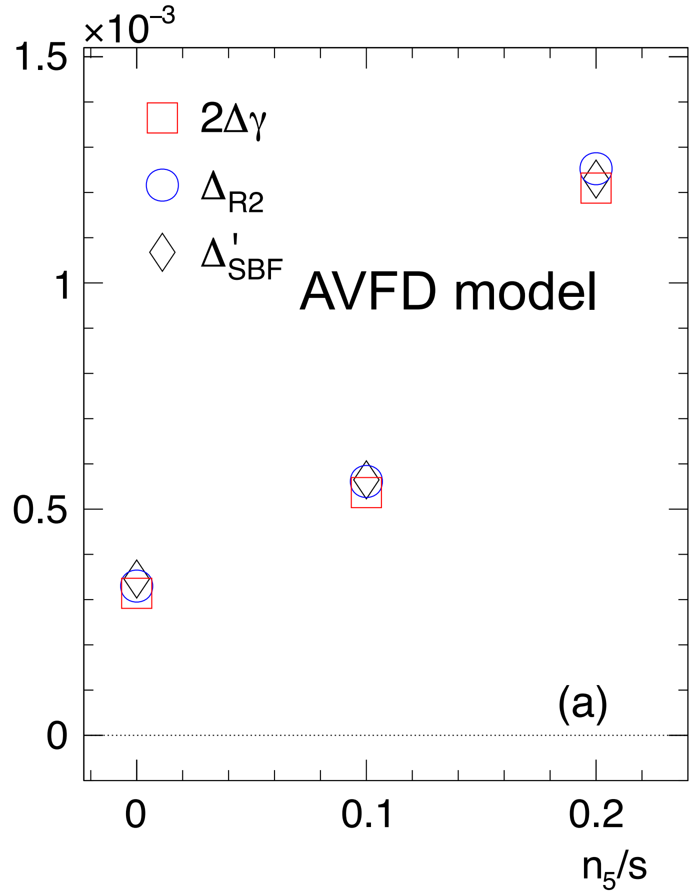
In following slides, we will study core-components $\Delta_{\rm SBF}$ and $\Delta_{\rm R2}$

S. Choudhury, et al. arXiv:2109.00131

Core-Component Comparisons of CME Observables

$$2\Delta\gamma_{112},\ \Delta_{R2} \text{ and } \Delta'_{\rm SBF} \equiv \left(\frac{\pi^4}{64M^2}\Delta_{\rm SBF} + \frac{8}{3}v_2\Delta\delta\right)$$

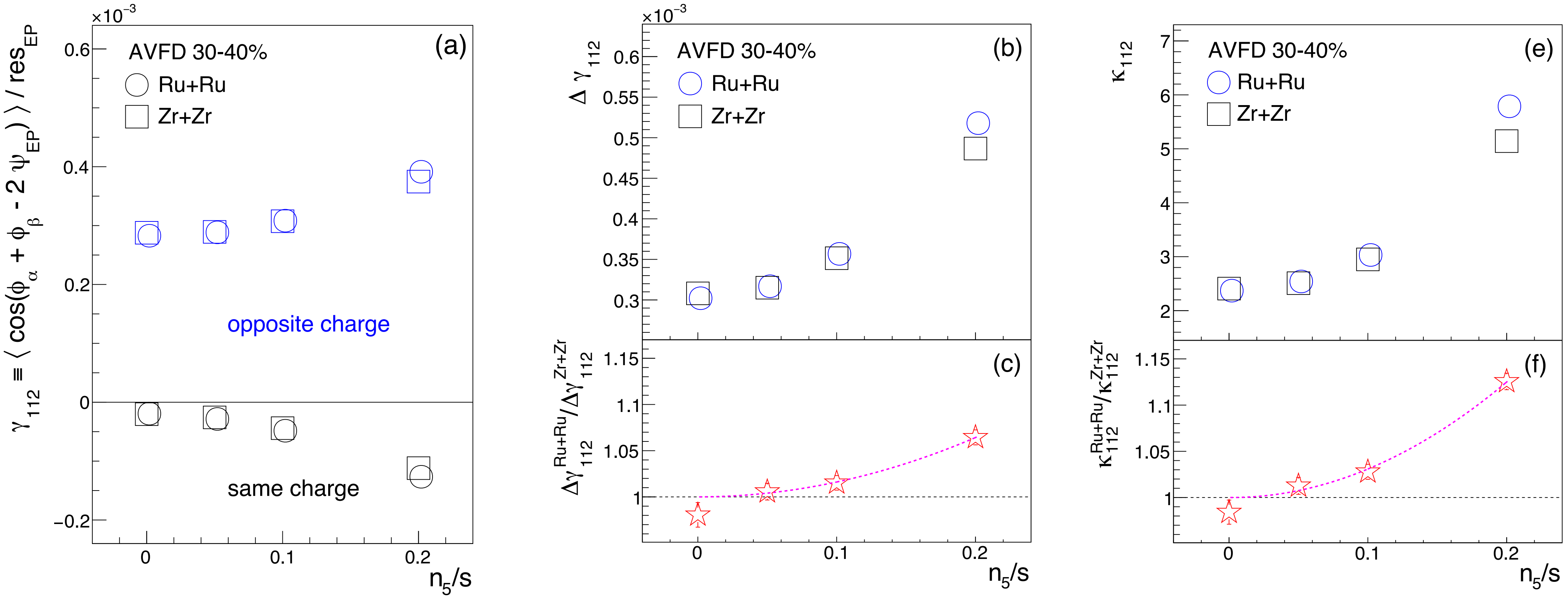




When comparing core components, all three observables have very similar responses to the signal and background.

γ Correlator with Frozen code

$0.2 < p_T < 2.0$
$|\eta| < 1.0$



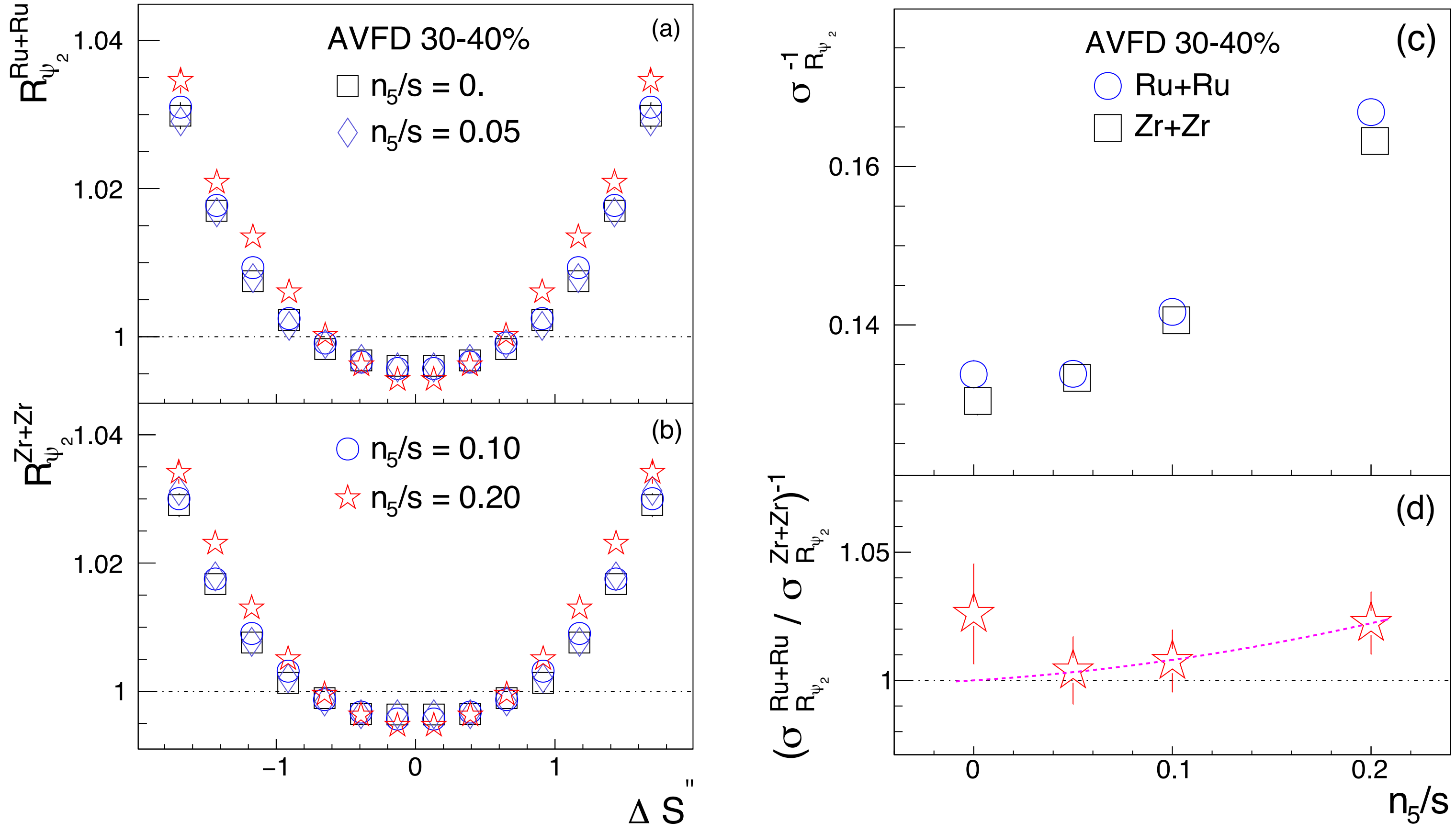
$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta}.$$

- $\Delta\gamma_{112}$ and κ_{112} show a finite background contribution at n_5/s=0, and increase with the CME signal.
- The ratio(Ru/Zr) is consistent with or below unity at n_5/s =0, and increases with n_5/s. and the ratio of κ_{112} shows more sensitivity.

The dotted lines are polynomial fit.

R(ΔS) -correlator with Frozen code

$0.35 < p_T < 2.0$
$|\eta| < 1.0$

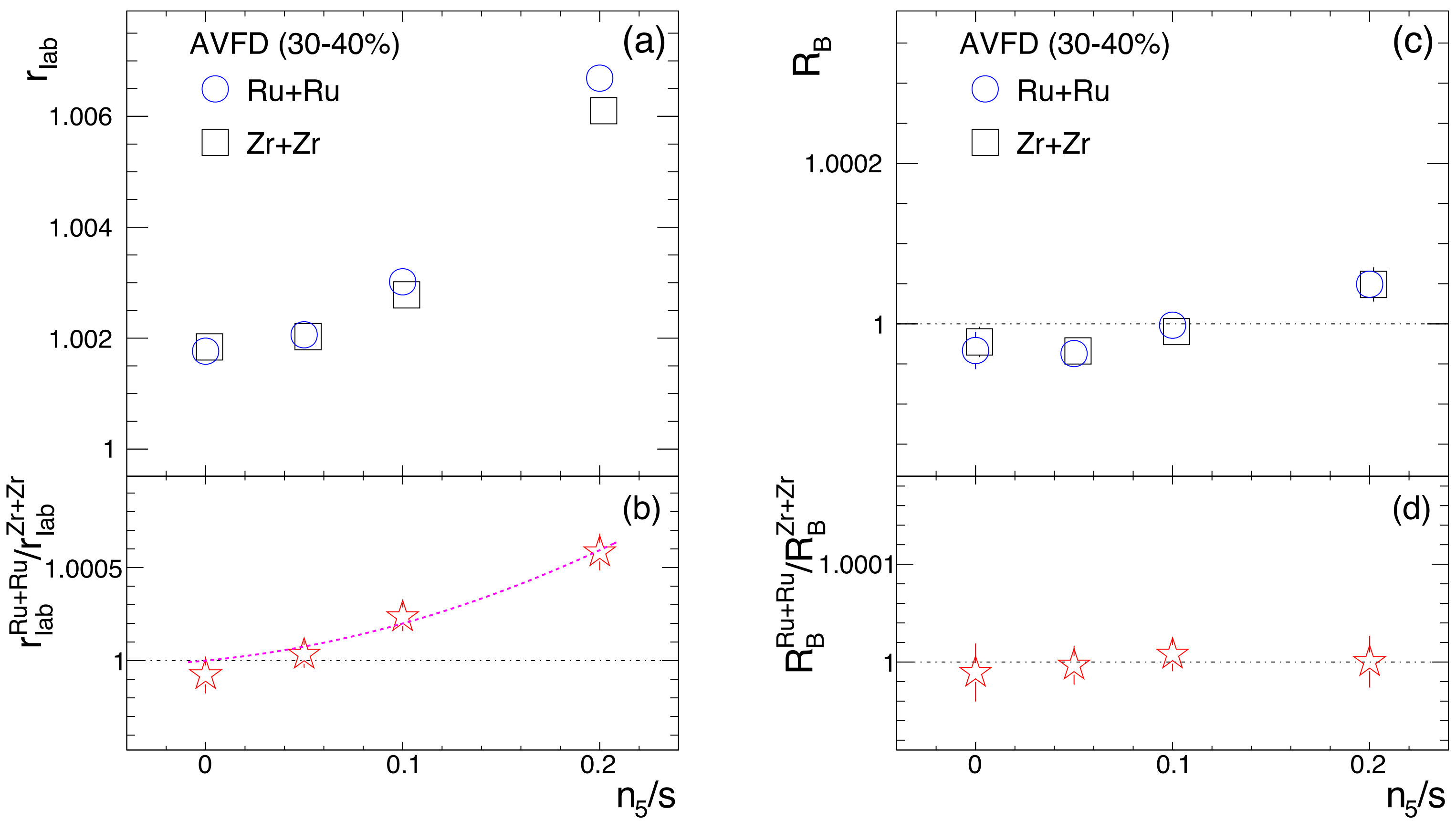


- As n_5/s increases, the R_{ψ_2} distribution becomes more concave.
- The $\sigma^{-1}_{R_{\psi_2}}$ value are increasing with n_5/s.
- R_{ψ_2}(Ru/Zr) shows no visible response to signal increase.

(However, if studied with true RP and same kinematic cuts, it shows similar sensitivity as $\Delta\gamma_{112}$).

Signed Balance Function

$0.2 < p_T < 2.0$
$|\eta| < 0.5$



r_{lab} shows compatible sensitivity to $\Delta\gamma$.

R_B (Ru/Zr) shows little sensitivity, due to worsen EP resolution and lower multiplicity (relative to AuAu).

No hope using R_B for isobar collisions due to its nature of statistics hungry.

Significance Study for Isobaric Collisions

n_5/s	$N_{\rm event}$	$\Delta\gamma_{112}$	$\Delta\delta$	κ_{112}	$r_{\rm lab}$	σ_{R2}^{-1}	$\Delta\gamma_{112}\{\rm RP\}$	$\sigma_{R2}^{-1}\{\rm RP\}$
0	2×10^8	-1.50	-2.89	-1.21	-0.77	1.33	0.67	0.56
0.05	4×10^8	0.62	-6.16	1.37	0.47	0.29	2.84	3.33
0.10	4×10^8	1.91	-16.81	3.43	3.11	0.62	11.78	10.85
0.20	2×10^8	7.73	-42.96	14.07	5.96	1.84	37.48	27.90

- The ratios of two isobars, $\Delta\gamma$ and r_{lab} show compatible and decent sensitivity
- $R_{\psi2}$ and R_B show flat response to signal increase.

The observable$_{RP}$: True RP and same kinematic cuts

Summary

- The relations among experimental observables have been established via analytical derivation, and the equivalence between the core-components of these observables have been verified.

- With EBE-AVFD events and STAR's frozen codes, we have studied $\Delta\gamma$, $R_{\psi n}$-correlator, and SBF's (not in frozen codes) response to same n_5/s for two isobars separately.
  - The results show that all three methods are sensitive to CME signal for each individual isobar species.
  - When studied as the ratio of two isobars, $\Delta\boldsymbol{\gamma}$ and r_{lab} show compatible and decent sensitivity, while R_{ψ_2} and R_B shows flat response to signal increase.

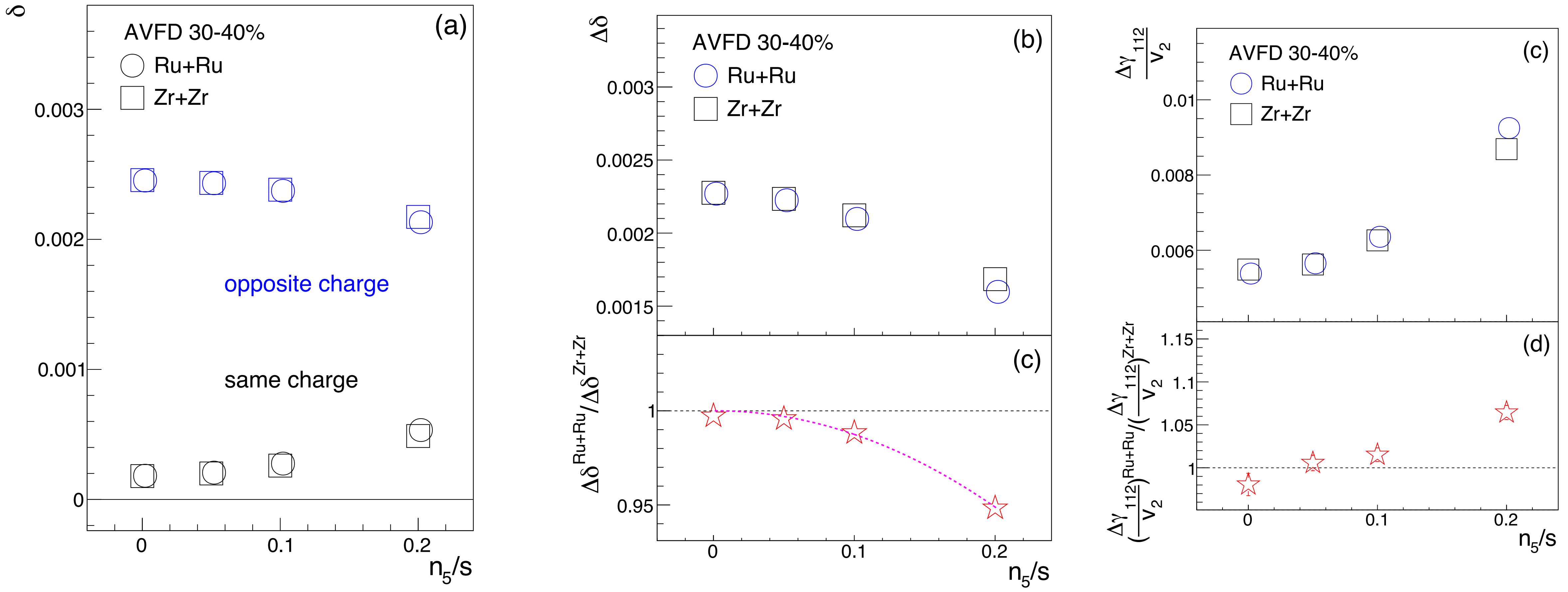
- This study provides a reference point to gauge the STAR isobaric-collision data.

BackUp: **Model Descriptions**

Model	Conditions	references
Toy model	A simplified Monte Carlo calculations, in which the signals and backgrounds can be controlled.	STAR, PRC 79 034909 (2009) STAR, PRL 92, 092301 (2004) F.Q. Wang , PRC 95, 051901 (2017)
AMPT	Version v2.25t4cu with string melting and charge conservation assured. No CME.	Lin, Ko, Li, Zhang & Pal, Phys. Rev. C 72 064901 (2005), and private communication with Z.W.Lin and G.L. Ma
EBE-AVFD	Signals and backgounds are both taken into account in more realistic way.	Y. Jiang, S. Shi, Y. Yin and J. Liao, Chin. Phys. C 42 No. 1 011001 (2018) S. Shi, Y. Jiang, E. Lilleskov and J. Liao. Annals of Physics 394 50-72 (2018) S. Shi, H. Zhang, D. Hou, and J. Liao. Phys. Rev. Lett. 125, 242301 (2020)

BackUp: γ Correlator with Frozen code

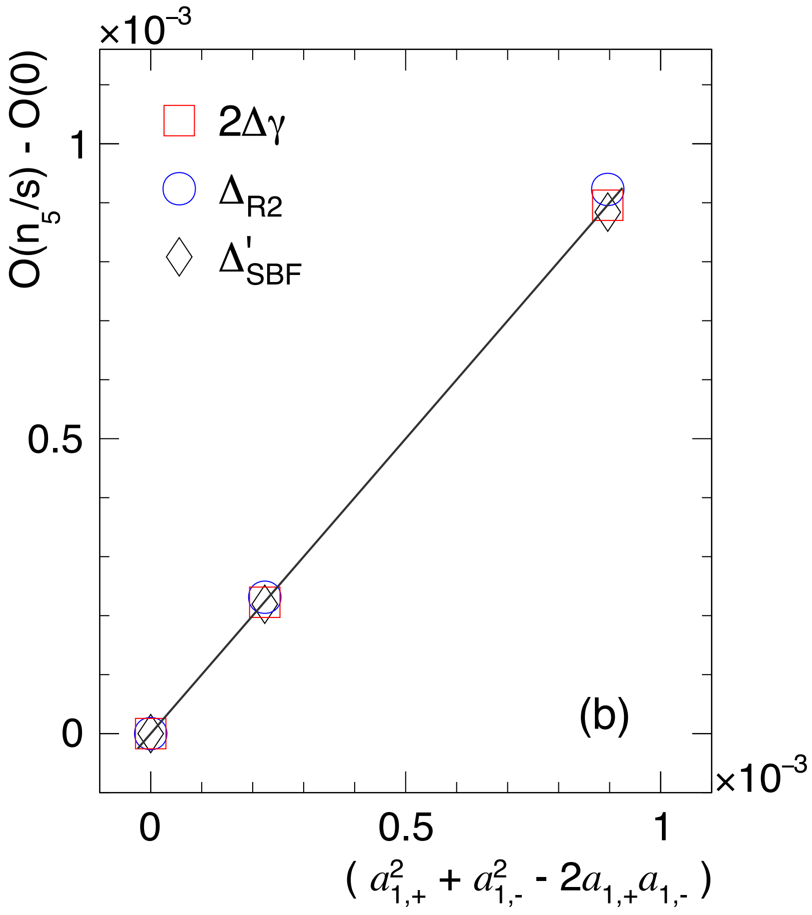
$0.2 < p_T < 2.0$
$|\eta| < 1.0$



Core-Component Comparisons of CME Observables

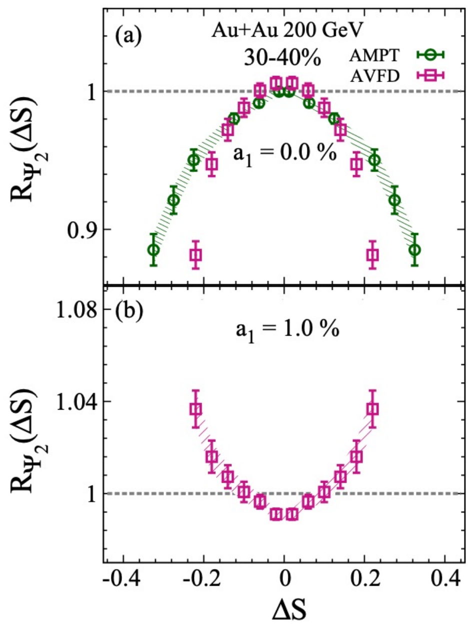
$2\Delta\gamma_{112}$, Δ_{R2} and $\Delta'_{\rm SBF} \equiv (\frac{\pi^4}{64M^2}\Delta_{\rm SBF} + \frac{8}{3}v_2\Delta\delta)$

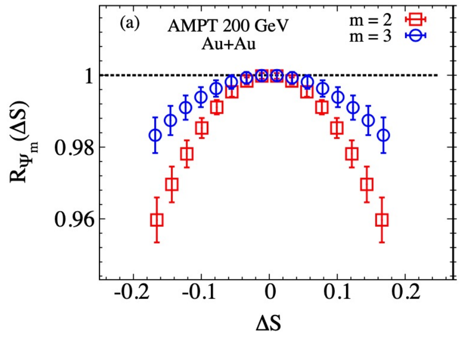
$$O(n_5/s) - O(0) = a_{1,+}^2 + a_{1,-}^2 - 2a_{1,+}a_{1,-}.$$



BackUp: Study Related the R-correlator

Studies	$R_{\psi 2}$ Shape	Shape Similarity in $R_{\psi 2}$ and $R_{\psi 3}$
Roy/Niseem's PRC, PLB AMPT with resonance decay, No LCC	Convex. 30-50% centrality	$R_{\psi 2}$ and $R_{\psi 3}$ Shape similar. Both convex
Huang/Nie/Ma. PRC 101, 024916 (2020) AMPT	Flat. 30-50% centrality	$R_{\psi 3}$ is slightly concave (may also consistent with being depending on viewing range)
P. Bozek, PRC 97 034907(2018)	Concave. All centralities	Both concave (after EO resolution correction, based on private comm. Between Roy/Niseem and Bozek)
Aihong Tang, STAR Collab. Mtg AVFD version beta1.0	Concave. 30-40% centrality	n/a
Yicheng Feng PRC 103, 034912 (2021) AMPT	Concave in 30-50% centrality. Other centrality may be flat or convex depending on viewing range	$R_{\psi 2}$ and $R_{\psi 3}$ Shape not similar, although both are concave.
Gang Wang, CME focus group Mtg 09/20/19 AMPT	Concave in 30-50% centrality. Other centrality may be flat or convex depending on viewing range	$R_{\psi 2}$ and $R_{\psi 3}$ Shape similar flat.





No clear conclusion about the Shape of R's observerbales.