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Fluctuations and Correlations of Conserved Charges in Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV with STAR Detector

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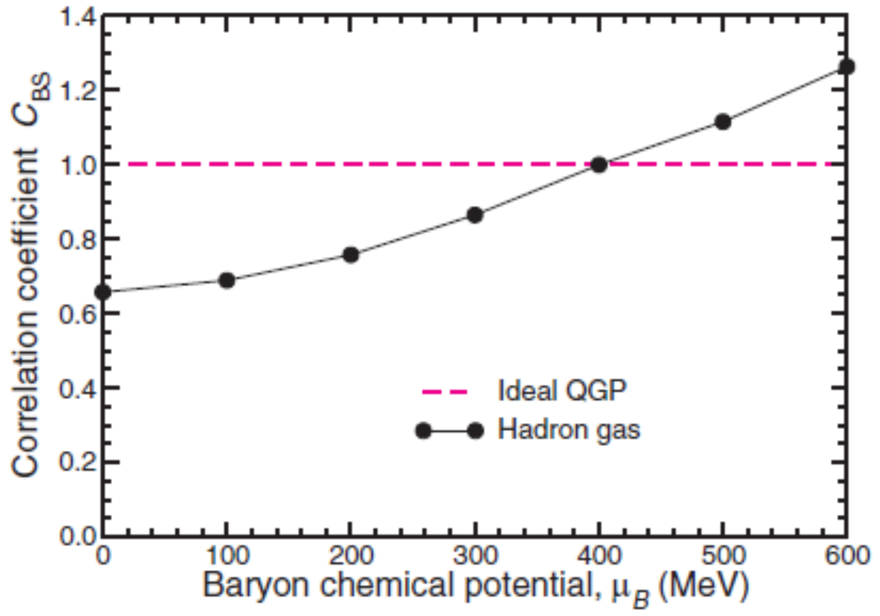
Outline

- Motivation
- Analysis Details
- Results
- Summary and Outlook

Motivation

- Baryon-Strangeness Correlation can be used to study the degree of freedom of QGP

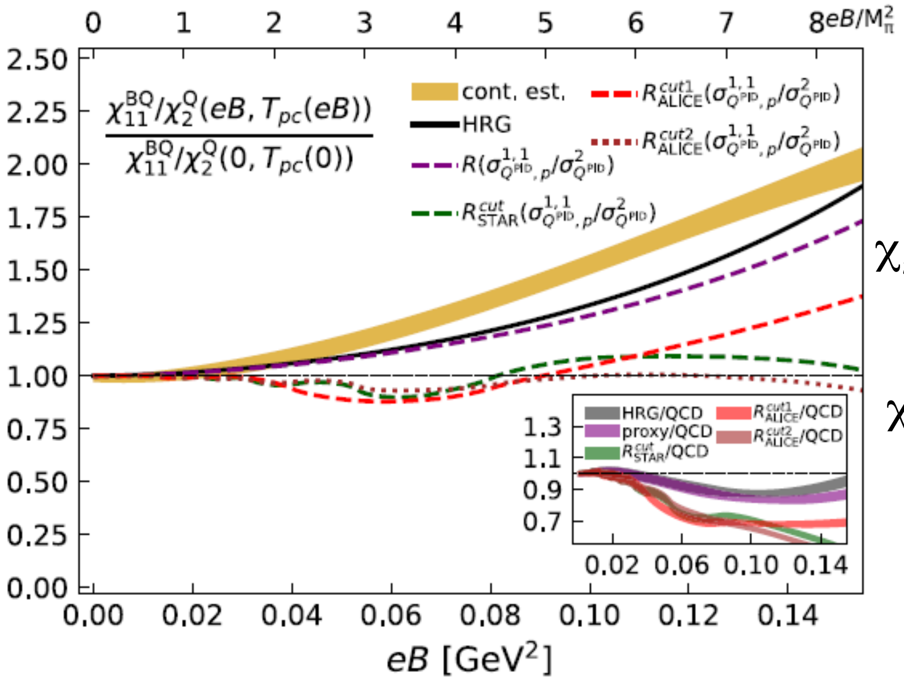
$$C_{BS} \equiv -3\frac{\sigma_{BS}}{\sigma_S^2} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$



V. Koch, A. Majumder, and J. Randrup, PRL 95, 182301 (2005)

- Baryon electric charge correlation as a magnetometer of QCD
- From LQCD， Sensitivity to Magnetic field B obey ordering :

$$\frac{\langle BQ\rangle_c}{\langle QS\rangle_c} > \frac{\langle BQ\rangle_c}{\langle Q^2\rangle_c} > \frac{\langle BQ\rangle_c}{\langle B^2\rangle_c} > \frac{\langle B^2\rangle_c}{\langle Q^2\rangle_c}$$



$$\chi_{i,j}^{BQ} = \frac{\partial^{i+j}(P/T^4)}{\partial\hat{\mu}_B^i\partial\mu_Q^j} = \frac{\sigma_{1,1}^{BQ}}{VT^3},$$

$$\chi_2^Q = \frac{\partial^2(P/T^4)}{\partial\hat{\mu}_Q^2} = \frac{\sigma_2^Q}{VT^3}$$

H.-T. Ding et al, PRL 111, 114522 (2025)

Observable

- A previous STAR publication (PRC 100, 014902 (2019)) reported correlations of conserved charges using p, K, and π as proxies
- Λ hyperons are included in this analysis as better proxies for conserved charges

	p		K^+	K^-	π^+	π^-	Λ	
B	+1	-1	0	0	0	0	+1	-1
S	0	0	+1	-1	0	0	-1	+1
Q	+1	-1	+1	-1	+1	-1	0	0

$$\Delta p \equiv p - \bar{p},\quad \Delta\Lambda \equiv \Lambda - \bar{\Lambda},\quad \Delta K \equiv K^+ - K^-,\quad \Delta\pi \equiv \pi^+ - \pi^-$$

$$\langle BS\rangle_c = \langle(\Delta p + \Delta\Lambda)(\Delta K - \Delta\Lambda)\rangle_c = \langle\Delta p\Delta K\rangle_c - \langle\Delta p\Delta\Lambda\rangle_c + \langle\Delta\Lambda\Delta K\rangle_c - \langle\Delta\Lambda^2\rangle_c$$

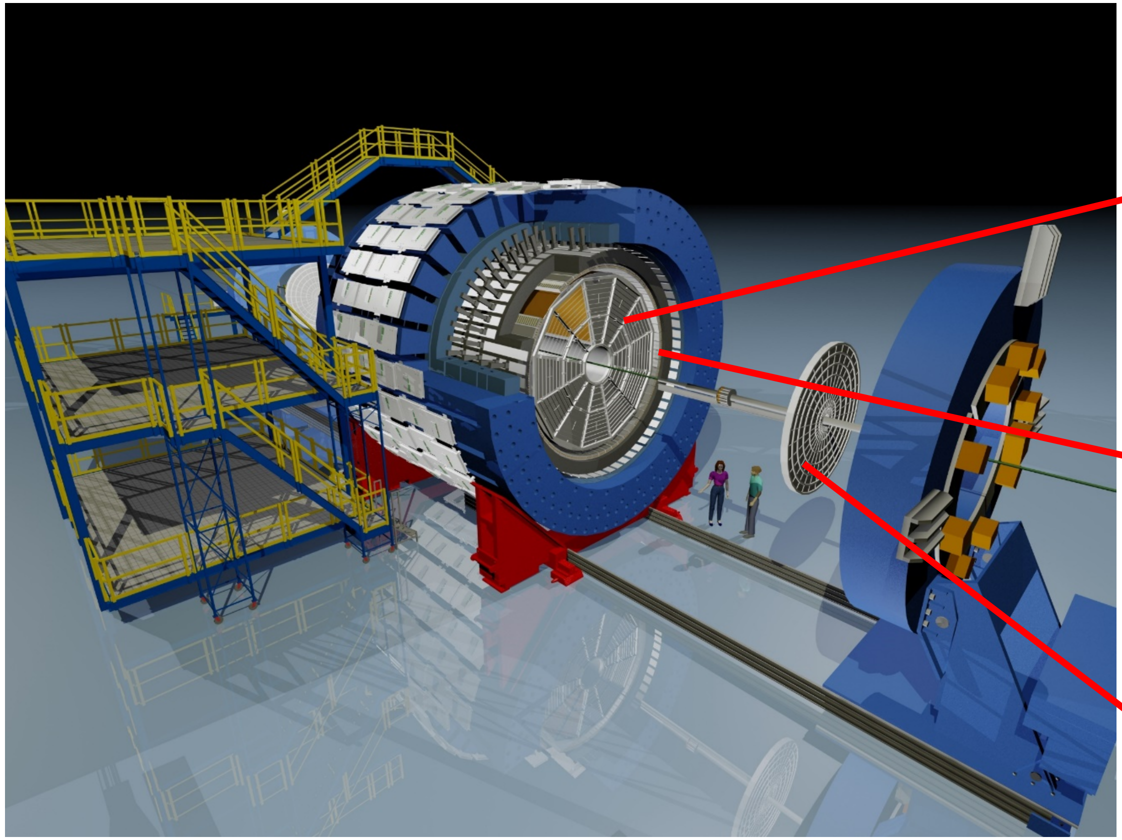
$$\langle BQ\rangle_c = \langle\Delta p^2\rangle_c + \langle\Delta p\Delta K\rangle_c + \langle\Delta p\Delta\pi\rangle_c + \langle\Delta\Lambda\Delta p\rangle_c + \langle\Delta\Lambda\Delta K\rangle_c + \langle\Delta\Lambda\Delta\pi\rangle_c$$

$$\langle QS\rangle_c = \langle\Delta p\Delta K\rangle_c - \langle\Delta p\Delta\Lambda\rangle_c + \langle\Delta K^2\rangle_c - \langle\Delta K\Delta\Lambda\rangle_c + \langle\Delta\pi\Delta K\rangle_c - \langle\Delta\pi\Delta\Lambda\rangle_c$$

$$\langle Q^2\rangle_c = \langle\Delta p^2\rangle_c + \langle\Delta K^2\rangle_c + \langle\Delta\pi^2\rangle_c + 2\langle\Delta p\Delta K\rangle_c + 2\langle\Delta p\Delta\pi\rangle_c + 2\langle\Delta K\Delta\pi\rangle_c$$

$$\frac{\chi_{1,1}^{BQ}}{\chi_{1,1}^{QS}} = \frac{\langle BQ\rangle_c}{\langle QS\rangle_c},\qquad \frac{\chi_{1,1}^{BQ}}{\chi_2^{Q}} = \frac{\langle BQ\rangle_c}{\langle Q^2\rangle_c},\qquad \frac{\chi_{1,1}^{BQ}}{\chi_2^{B}} = \frac{\langle BQ\rangle_c}{\langle B^2\rangle_c},\qquad \frac{\chi_2^{B}}{\chi_2^{Q}} = \frac{\langle B^2\rangle_c}{\langle Q^2\rangle_c}$$

The STAR Detector



Collision systems	Ru+Ru 200 GeV	Zr+Zr 200 GeV

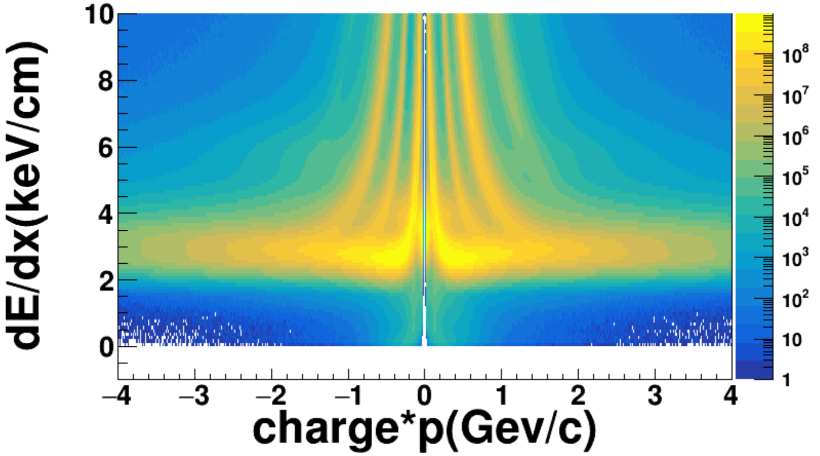
Sub-system relevant to this analysis:

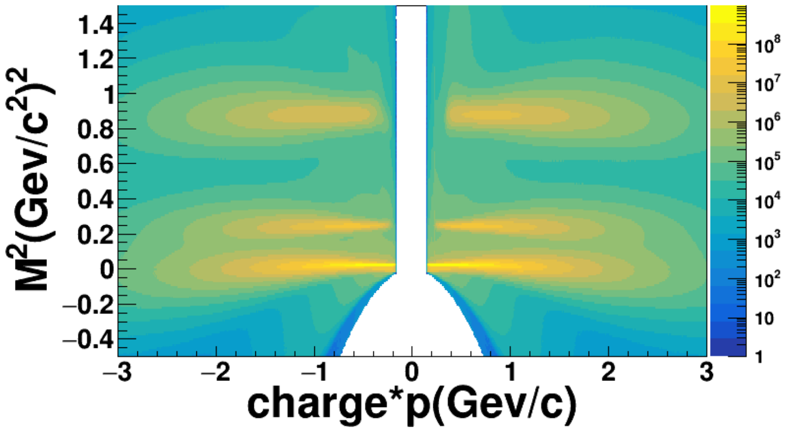
- Time Projection Chamber
    - Full azimuthal coverage, $|\eta| < 1.0$
    - Particle identification utilizing ionization energy loss
- Time Of Flight
    - Full azimuthal coverage, $|\eta| < 0.9$
    - Particle identification at high momentum region
- Event Plane Detector
    - $2.1< |\eta| <5.1$
    - EPD is used for the centrality determination to avoid auto-correlation

Particle Identification and Acceptance

Particle identification :

Particle	TPC	TPC+TOF
p()	0.4< p_T <0.8(GeV/c) $\|n\sigma_p\| < 2$	0.8< p_T <1.6 (GeV/c) 0.6< m^2 <1.2 (GeV^2/c^4)
$K^+(K^-)$	$\|n\sigma_K\| < 2$	0.4< p_T <1.6 (GeV/c) 0.15< m^2 <0.4 (GeV^2/c^4)
$\pi^+(\pi^-)$	$\|n\sigma_\pi\| < 2$	0.4< p_T <1.6 (GeV/c) -0.15< m^2 <0.14 (GeV^2/c^4)

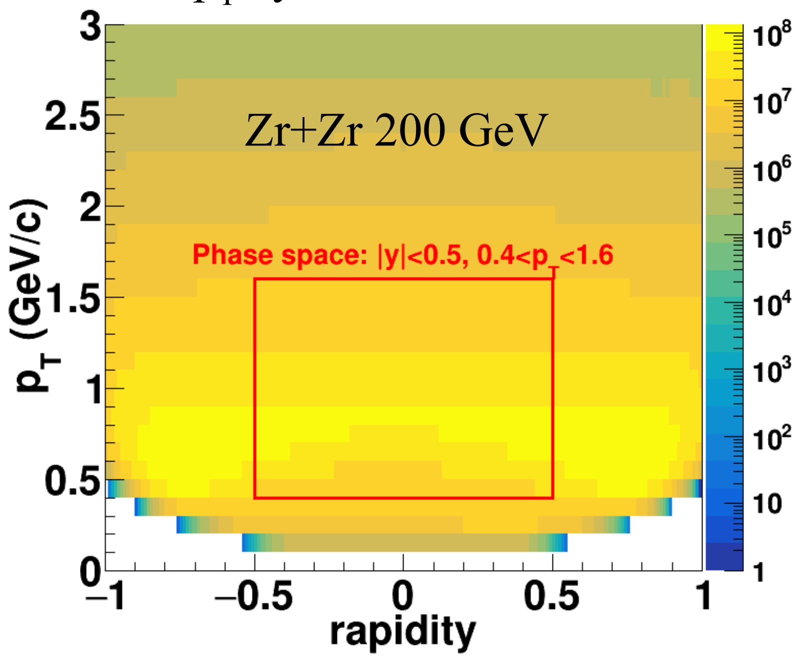




Phase space:

- p_T range: 0.4 to 1.6 GeV/c
- $|y| < 0.5$

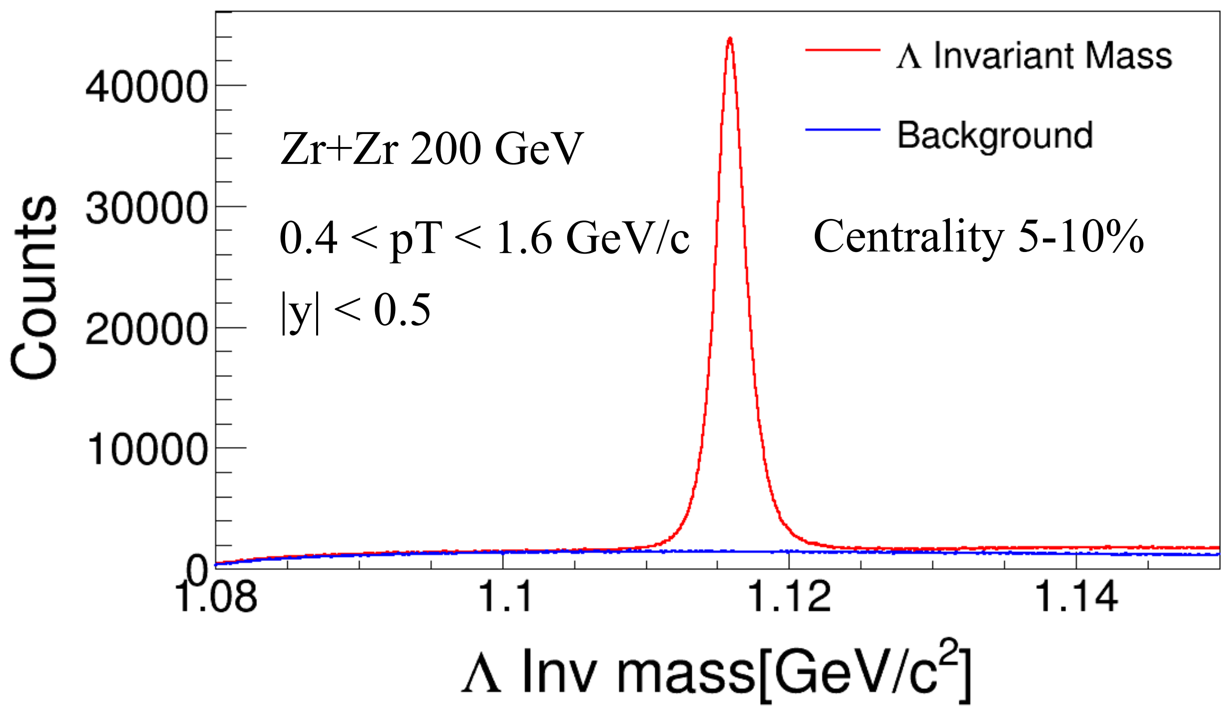
p_T - y distribution of K^+

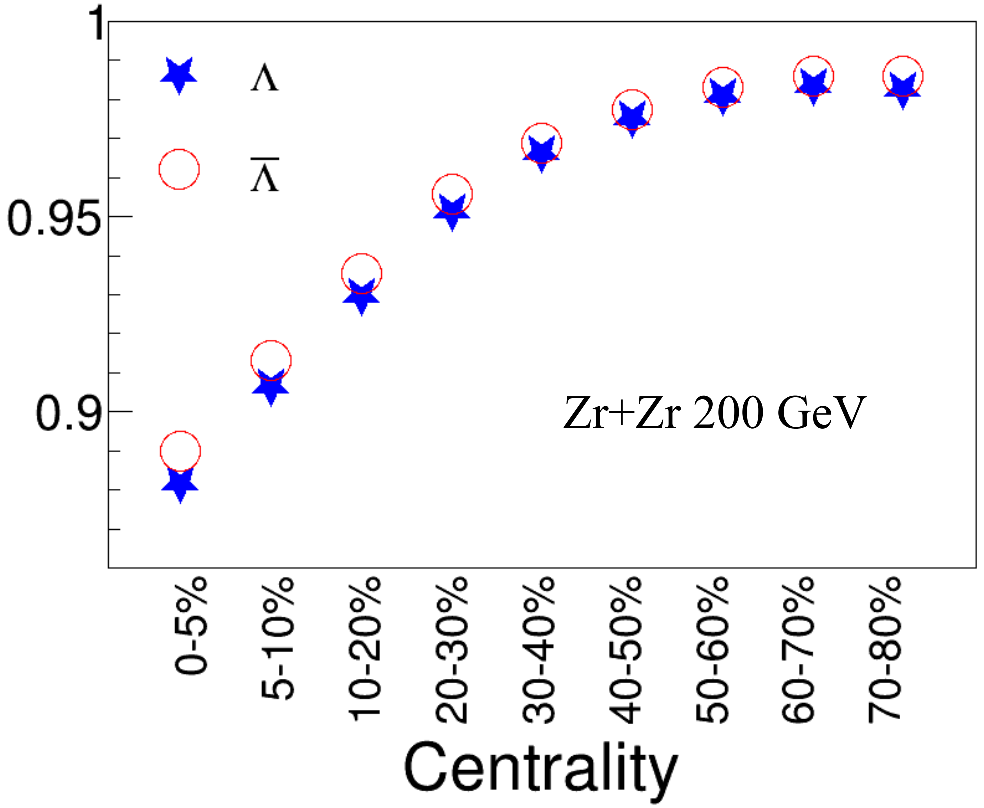


Invariant Mass Distribution and Purity of Λ

Λ decays to proton and pion with a branching ratio of 63.9%:

$$\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+)$$





Analysis Workflow

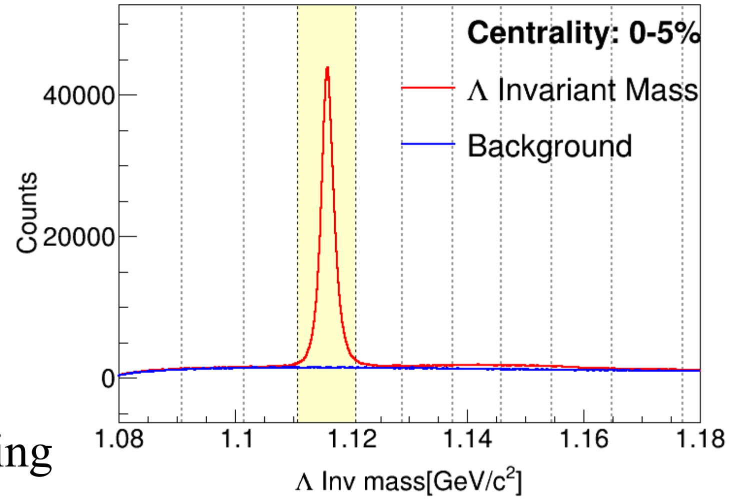
Purity correction

Sidebands are used to subtract the effect of combinatorial background from cumulants

T. Nonaka, NIMA 1039 (2022) 167171

$$\Lambda_{SN} = \Lambda_S + \Lambda_N$$

$$\langle \Lambda_S^2 \rangle_c = \langle \Lambda_{SN}^2 \rangle_c - \langle \Lambda_{R_i}^2 \rangle_c - 2\langle \Lambda_{SN}\Lambda_{R_i} \rangle_c + 2\langle \Lambda_{R_i}\Lambda_{R_j} \rangle_c$$



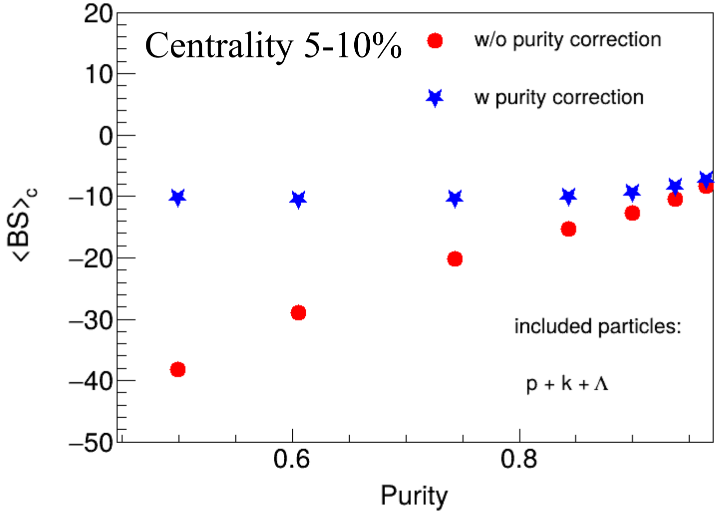
Efficiency correction

Include feeddown correction for Λ, p, π

The feeddown fraction α_f was estimated from the embedding

T. Nonaka et al, PRC95.064912(2017)
X. Luo, T. Nonaka , PRC 99, 044917 (2019)
Arghya et al, CPC 45 104001(2021)

Use modified efficiency: $\varepsilon' = \dfrac{\varepsilon}{1-\alpha_f}$



CBWC

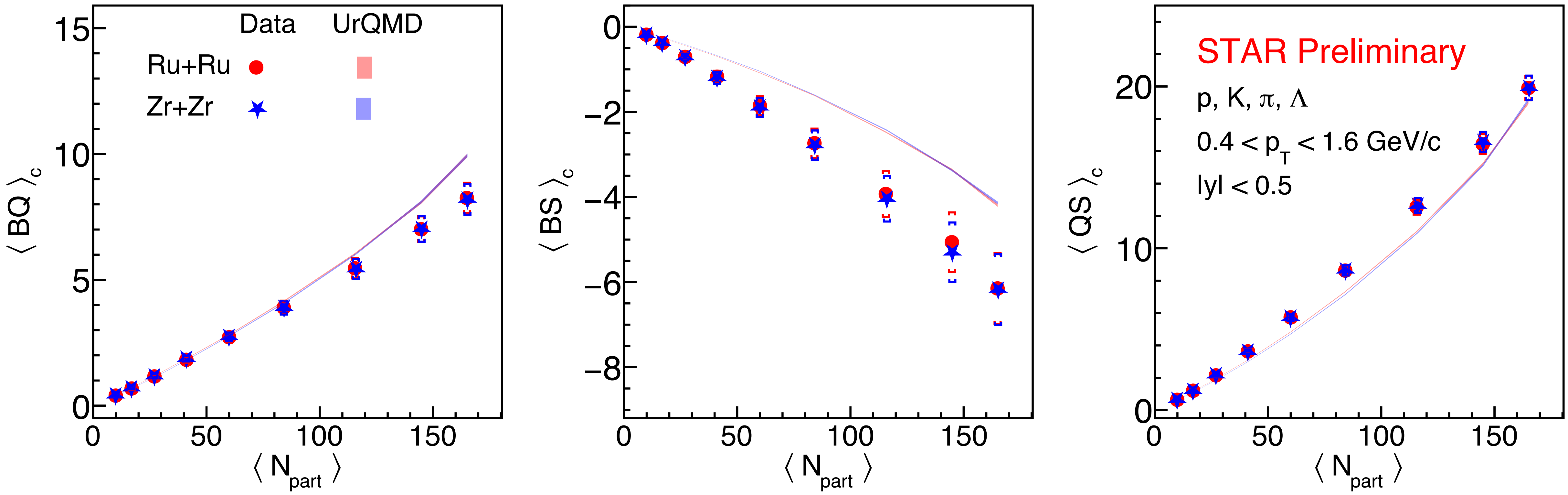
X.Luo et al, J. Phys. G 40, 105104 (2013)

$$\langle N_1 N_2 \rangle_c = \frac{\langle n_1 n_2 \rangle_c}{\varepsilon_1 \varepsilon_2} = \frac{\langle n_1 n_2 \rangle}{\varepsilon_1 \varepsilon_2} - \frac{\langle n_1 \rangle \langle n_2 \rangle}{\varepsilon_1 \varepsilon_2}$$

$$\langle N^2 \rangle_c = \frac{\langle n^2 \rangle_c}{\varepsilon^2} + \frac{\langle n \rangle_c}{\varepsilon} - \frac{\langle n \rangle_c}{\varepsilon^2}$$

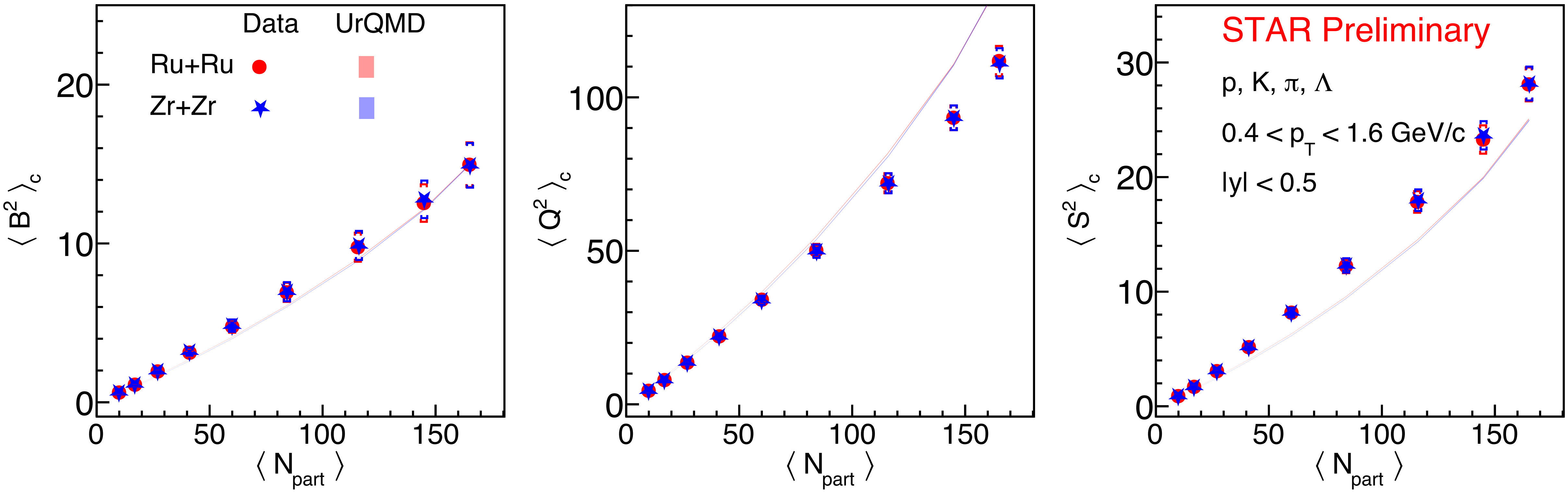
Result

Correlations of Conserved Charges



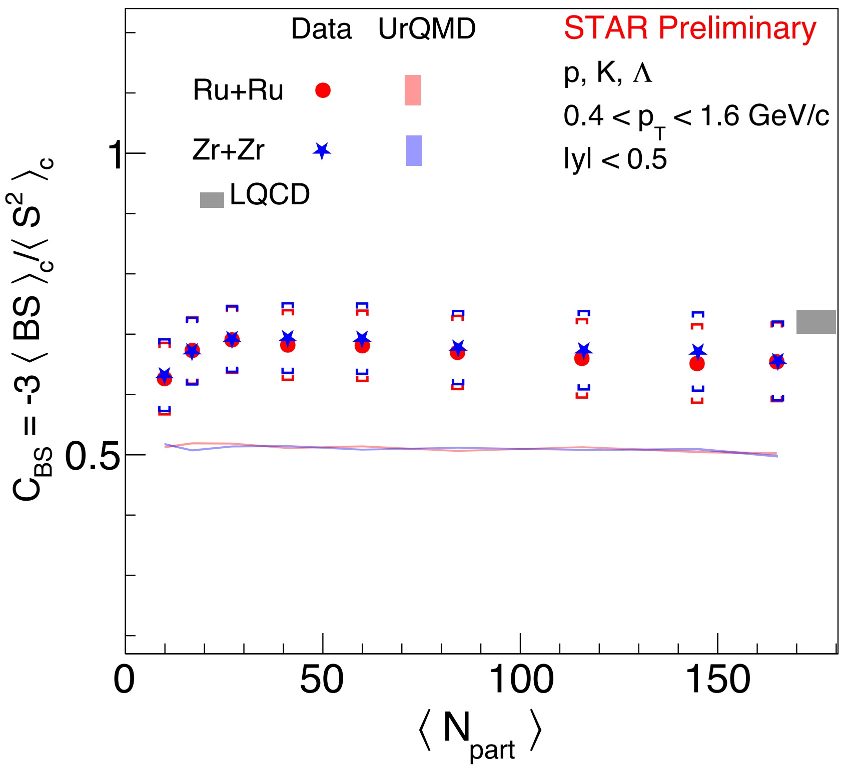
- The correlations increase with $\langle N_{part} \rangle$, and UrQMD can qualitatively describe the trends
- The correlations are consistent within uncertainties for the Ru+Ru and Zr+Zr systems

Variances of Conserved Charges



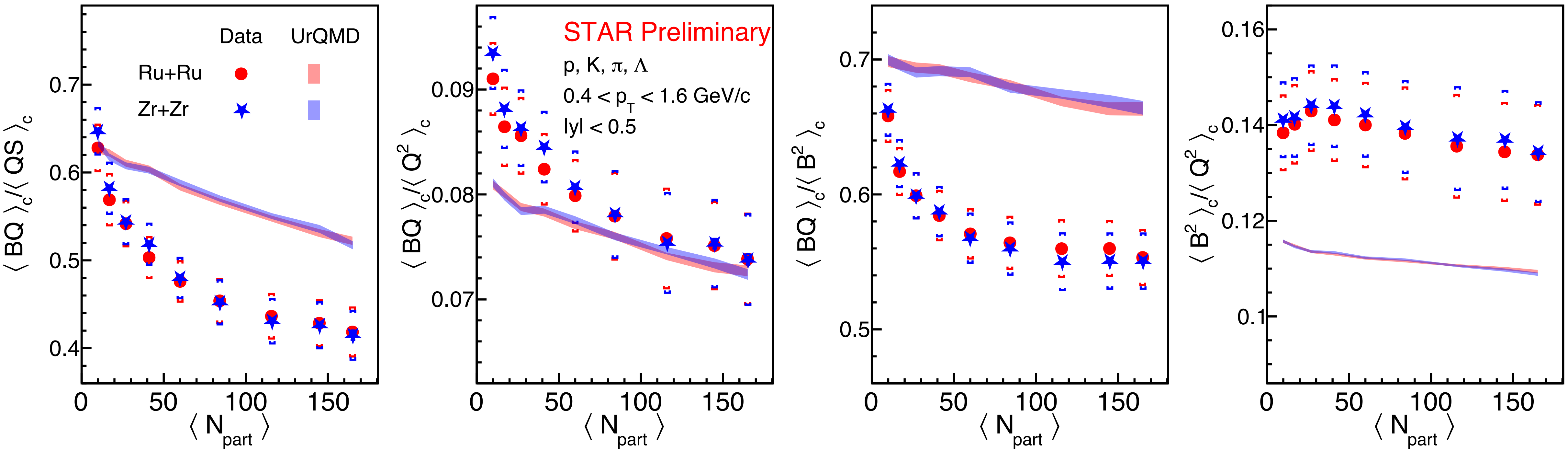
- Variances increase with $\langle N_{part} \rangle$ and UrQMD can qualitatively describe the trends
- Results are consistent within uncertainties for the Ru+Ru and Zr+Zr systems

Baryon-strangeness correlation



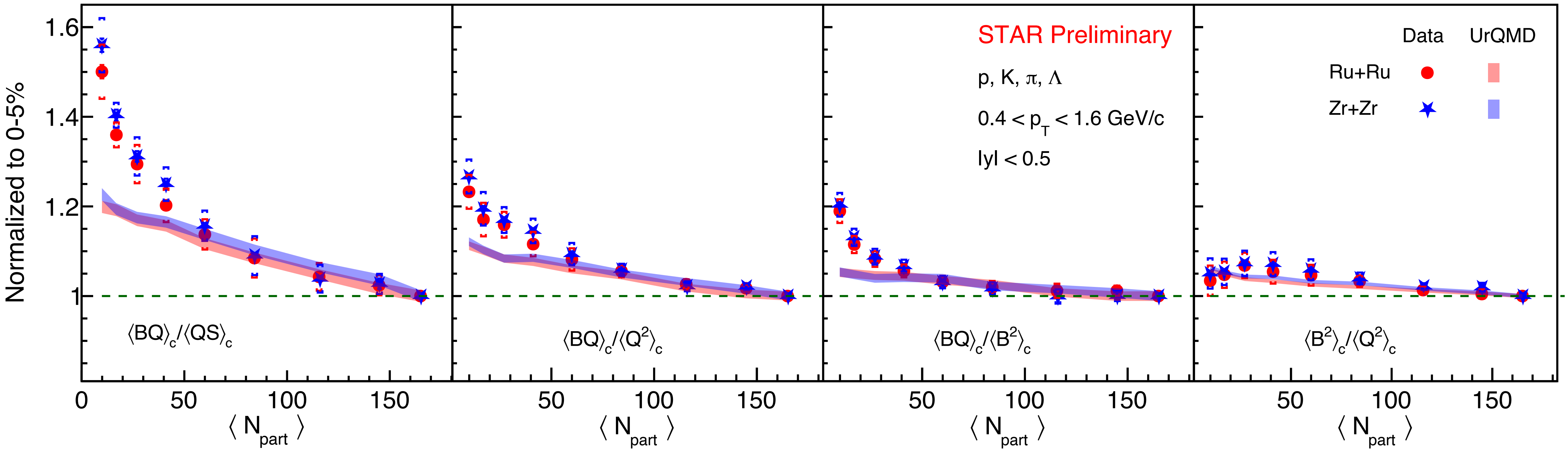
- C_{BS} is consistent with the LQCD result within uncertainties and higher than the UrQMD result
- C_{BS} is consistent within uncertainties for the Ru+Ru and Zr+Zr systems

The cumulant ratios of conserved charges



- The first three cumulant ratios decrease with $\langle N_{part} \rangle$ increasing, showing a strong centrality dependence, while the last one exhibits a weak centrality dependence
- The cumulant ratios increase more rapidly than UrQMD from central to peripheral

The cumulant ratios normalized to the 0-5% centrality



- The cumulant ratios increase more rapidly than UrQMD from central to peripheral
- In peripheral collisions, the peripheral-to-central ratios follow the order:

$$\frac{\langle BQ\rangle_c}{\langle QS\rangle_c} > \frac{\langle BQ\rangle_c}{\langle Q^2\rangle_c} > \frac{\langle BQ\rangle_c}{\langle B^2\rangle_c} > \frac{\langle B^2\rangle_c}{\langle Q^2\rangle_c}$$

Summary and Outlook

Summary:

- We presented the correlations and 2nd-order cumulants of conserved charges (B, Q, S) in Ru+Ru 200 GeV and Zr+Zr 200 GeV
- The correlations and 2nd-order cumulants are consistent within uncertainties for these two systems
- The correlation increase more rapidly than UrQMD from central to peripheral
- In peripheral collisions, the peripheral-to-central ratios follow the order:

$$\frac{\langle BQ\rangle_c}{\langle QS\rangle_c} > \frac{\langle BQ\rangle_c}{\langle Q^2\rangle_c} > \frac{\langle BQ\rangle_c}{\langle B^2\rangle_c} > \frac{\langle B^2\rangle_c}{\langle Q^2\rangle_c}$$

Outlook:

- Measure higher-order correlations and fluctuations
- Measure correlations at lower energies (both collider and fixed-target)