Methods and Results on Conserved Charge Fluctuations from RHIC BES & FXT

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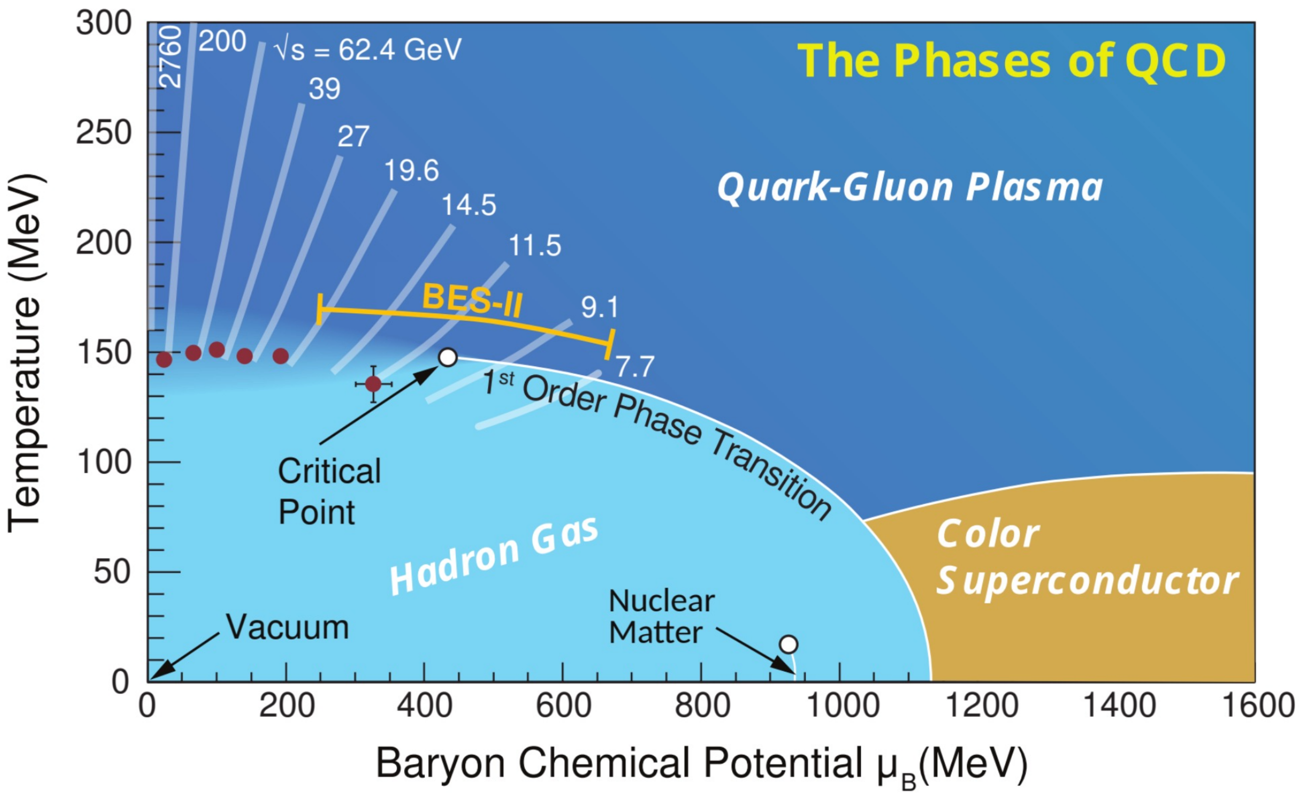
In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction
- Results from BES-I and FXT
- New analysis for baryon-strangeness correlations
  - Purity correction
  - Results
- Summary

“Conjectured” QCD phase diagram



A. Bzdak et al, Phys.Rep.853 pp1-87 (2020)

- Crossover at μ_B = 0 MeV
  - Y. Aoki et al, Nature 443,675(2006)
- 1st-order phase transition at large μ_B?
- Critical point?

Beam Energy Scan Phase-I (BES-I)

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)	T_{ch} (MeV)	μ_B (MeV)
200	238	164.3	28
62.4	47	160.3	70
54.4	550	160.0	83
39	86	156.4	160
27	30	155.0	144
19.6	15	153.9	188
14.5	20	151.6	264
11.5	6.6	149.4	287
7.7	3	144.3	398

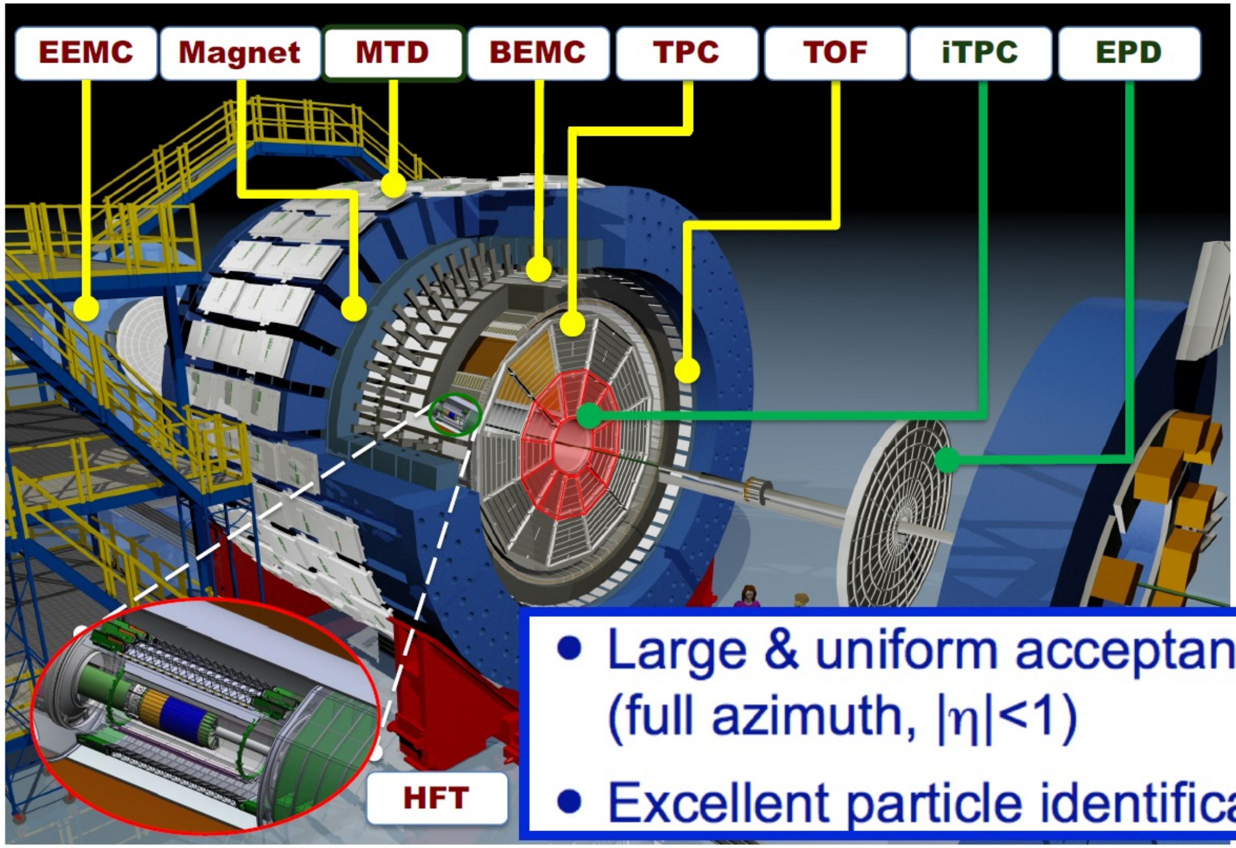
2010-2017

- Crossover at μ_B = 0 MeV
  - Y. Aoki et al, Nature 443,675(2006)
- 1^{st}-order phase transition at large μ_B?
- Critical point?

Fluctuations of conserved charges have been measured for BES-I data.

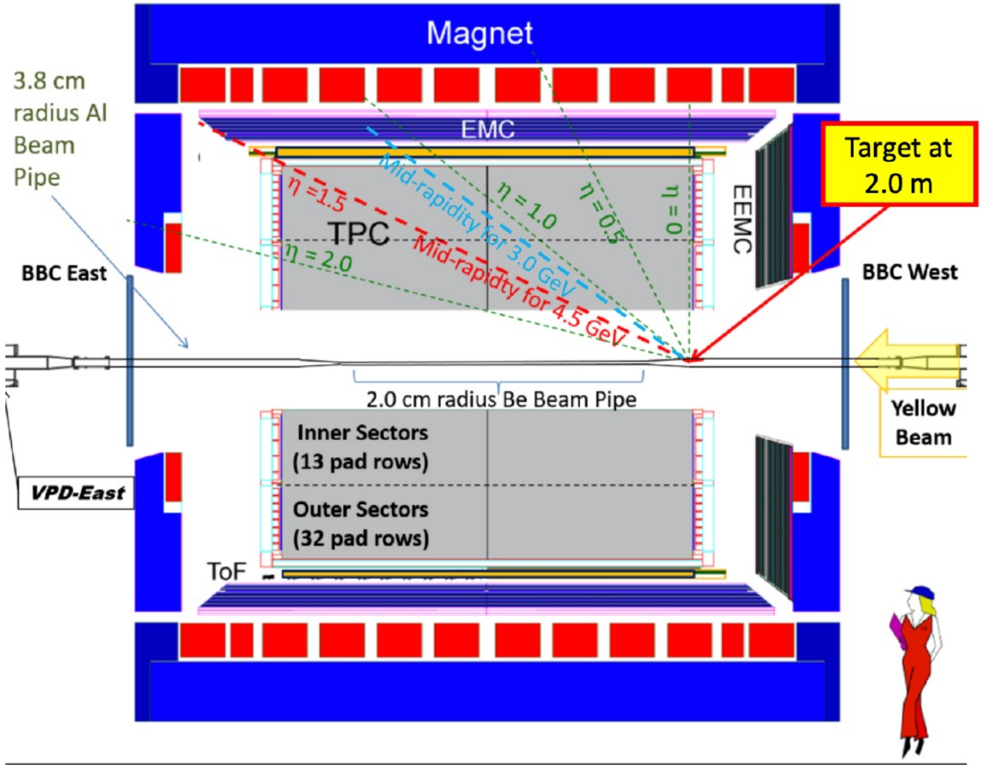
Complementary measurements at RHIC: BES-II, FXT (2019-2022)

STAR detectors



- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

FXT mode : μ_B=760 MeV @ 3GeV



Cumulants of conserved charges

- Measure event-by-event distributions of net-baryon, net-charge, and net-strangeness number

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

(1) Sensitive to the correlation length

$$C_2 = <(\delta N)^2>_c \approx \xi^2 \qquad C_5 = <(\delta N)^5>_c \approx \xi^{9.5}$$
$$C_3 = <(\delta N)^3>_c \approx \xi^{4.5} \qquad C_6 = <(\delta N)^6>_c \approx \xi^{12}$$
$$C_4 = <(\delta N)^4>_c \approx \xi^7$$

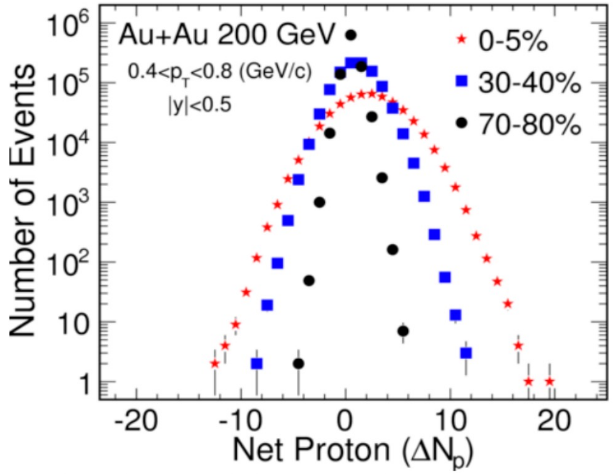
M. A. Stephanov, PRL102.032301(2009), PRL107.052301(2011)
M. Asakawa, S. Ejiri, and M. Kitazawa, PRL103262301(2009)

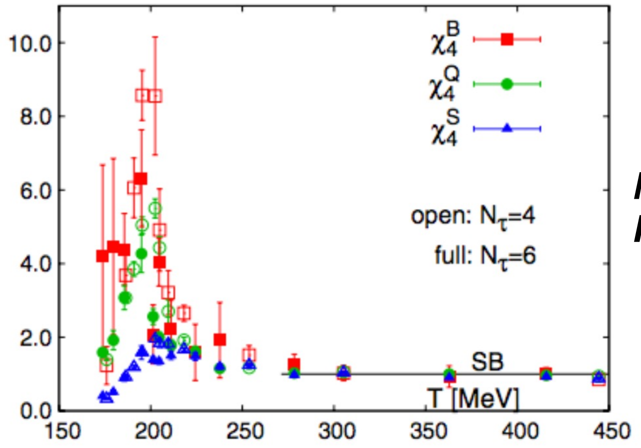
(2) Comparison with susceptibilities

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

STAR, PRL105.022302(2010)

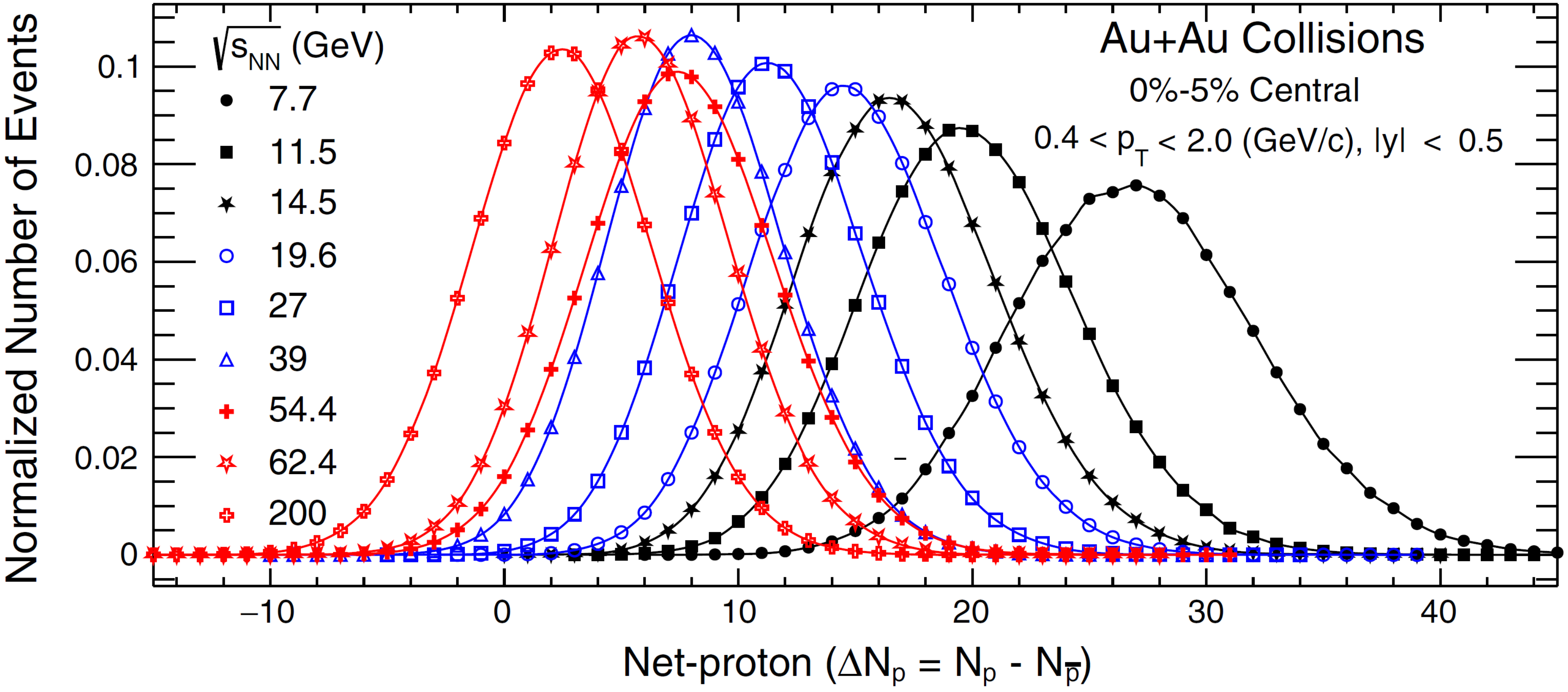




M.Cheng et al, PRD79.074505(2009)

Raw net-proton multiplicity distribution

- Need to consider various experimental effects.



STAR, PRL126.092301(2021), PRC104.024902(2021)

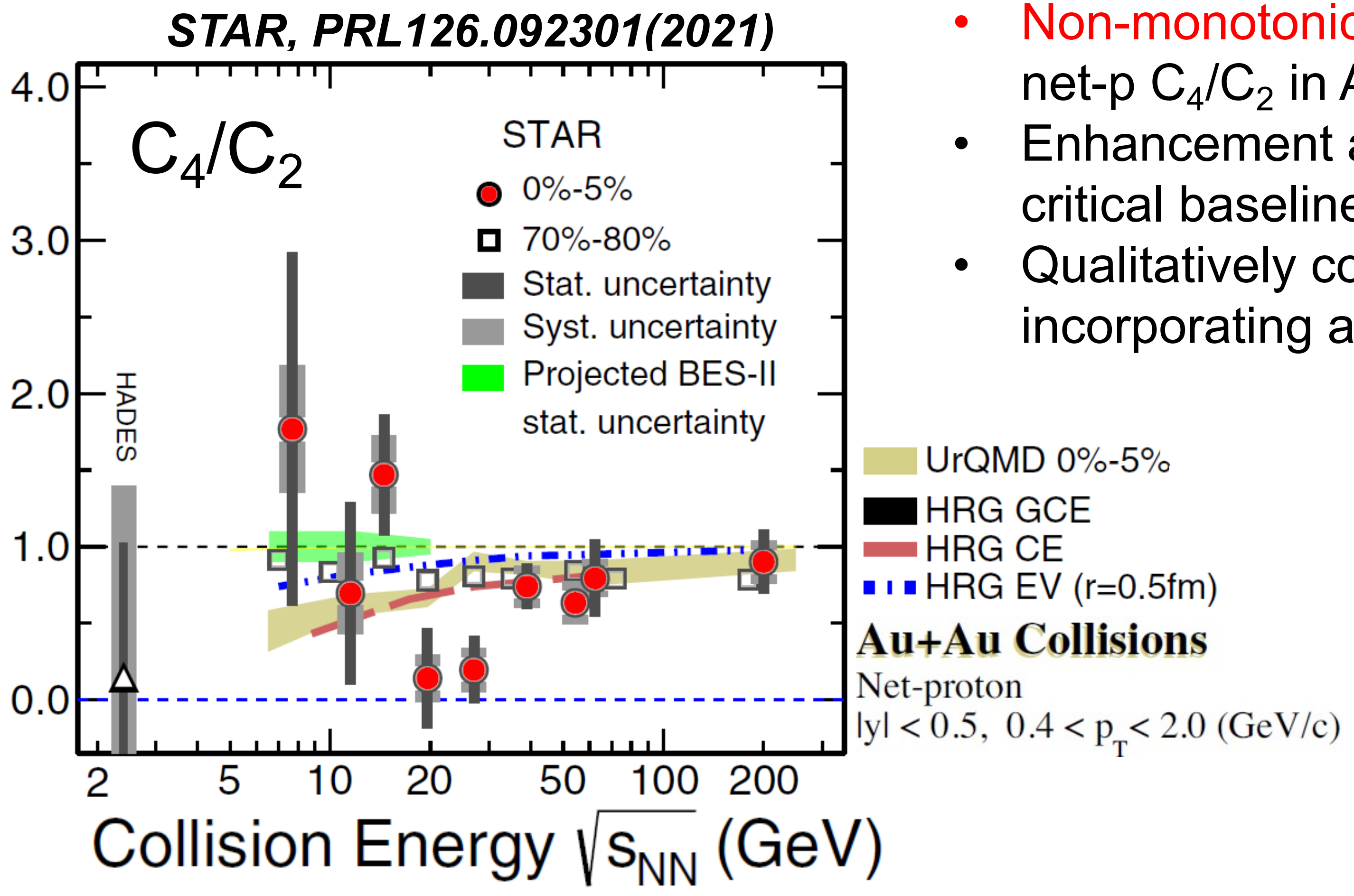
Experimental challenges

- Detector efficiency correction
  - ***Binomial distribution***
    - *M. Kitazawa and M. Asakawa, PRC86.024904(2012), A. Bzdak and V. Koch, PRC86.044904(2012), X. Luo, PRC91.034907(2016),*
    - *T. Nonaka, M. Kitazawa, S. Esumi, PRC95.064912(2017), X. Luo and T. Nonaka, PRC99.044917(2019)*
  - ***Non-binomial distribution***
    - *T. Nonaka, M. Kitazawa, S. Esumi, NIMA906 10-17(2018)*
    - *S. Esumi, K. Nakagawa, T. Nonaka, NIMA987.164802(2021)*
- Initial volume fluctuation
  - **M. I. Gorenstein and *M. Gaździcki, PRC84.014904 (2011)*, V. Skokov, B. Friman, and K. Redlich, PRC88,034911 (2013)**
  - **X. Luo, J. Xu, B. Mohanty, N. Xu, J. Phys. G40.105104 (2013), P. Munzinger, A. Rustamov, and J. Stachel, NPA960.114 (2017)**
  - **T. Sugiura, T. Nonaka, and S. Esumi, PRC100.044904 (2019)**
- Pileup events
  - *S. Sombun et al, J.Phys.G45.025101(2018), P. Garg and D. Mishra, PRC96.044908(2017)*
  - *T. Nonaka, M. Kitazawa, S. Esumi, NIMA984.164632(2020), Y. Zhang, Y. Huang, T. Nonaka, X. Luo, NIMA1026.166246(2022)*
- Particle identification
  - *M. Gaździcki, K. Grebieszkow, M. Maćkowiak, and S. Mrówczyński, PRC83.054907 (2011)*
  - *A. Rustamov and M. I. Gorenstein, PRC86.044906 (2012), M. I. Gorenstein, PRC84.024902 (2018)*
  - *M. Arslandok and A. Rustamov, NIMA946.162622 (2019)*
- More to be resolved…
  - Net-proton≠net-baryon, purity correction, acceptance dependence for comparison with theory, ….

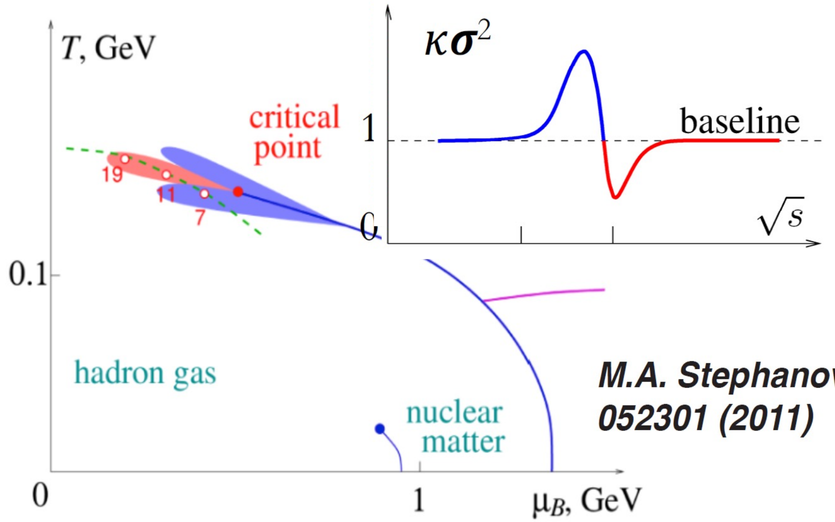
***Not all important studies are listed here**

Results from BES-I & FXT

Net-proton C_4/C_2

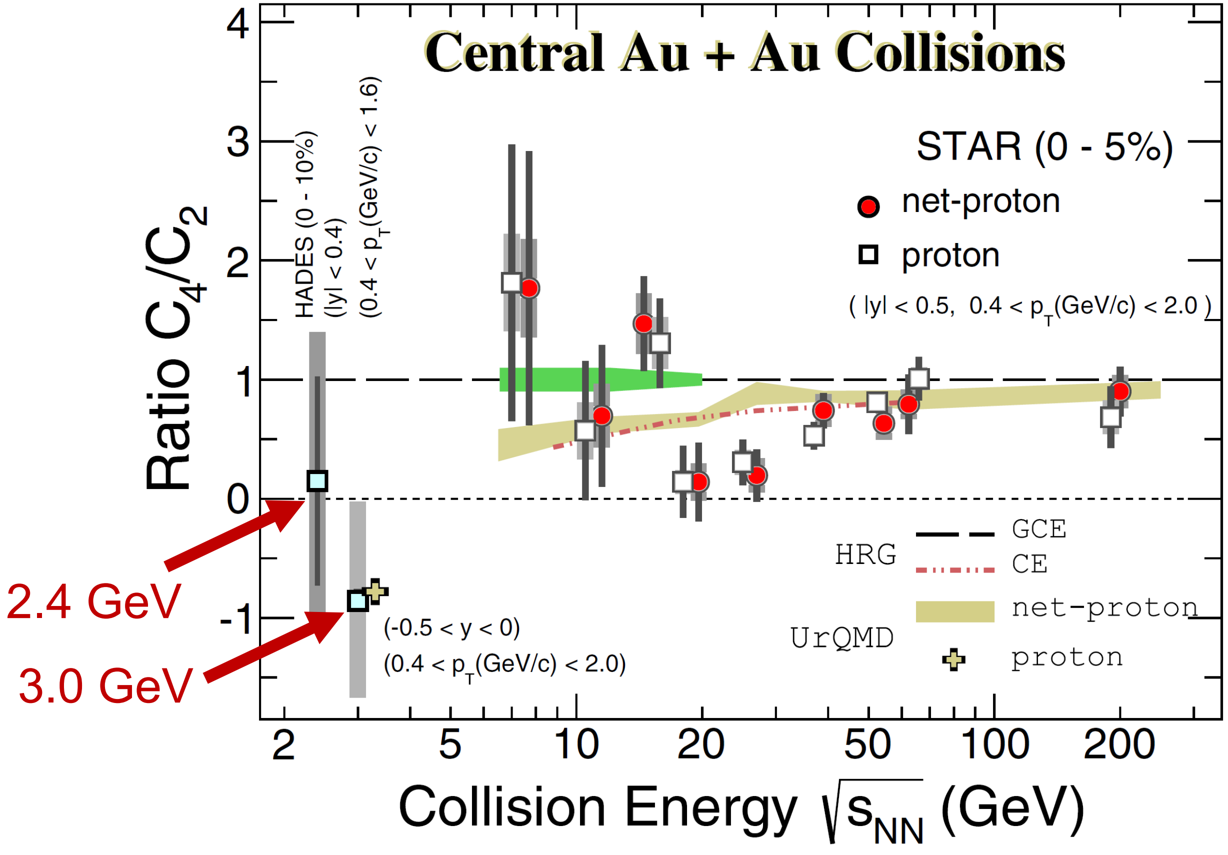


- Non-monotonic beam energy dependence (3.1σ) of net-p C_4/C_2 in Au+Au central collisions.
- Enhancement at ~7.7 GeV is not reproduced by non-critical baselines.
- Qualitatively consistent with the model prediction incorporating a critical point.

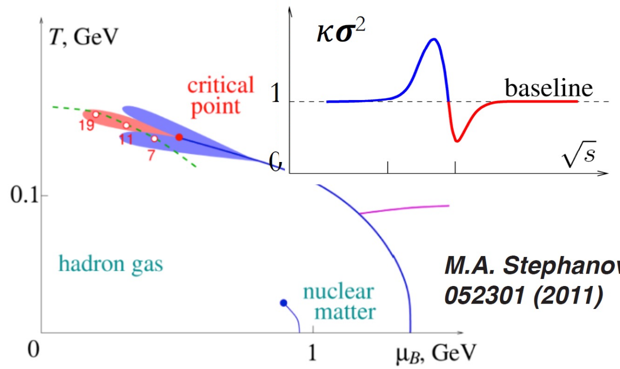


M.A. Stephanov, PRL107, 052301 (2011)

Collision energy dependence



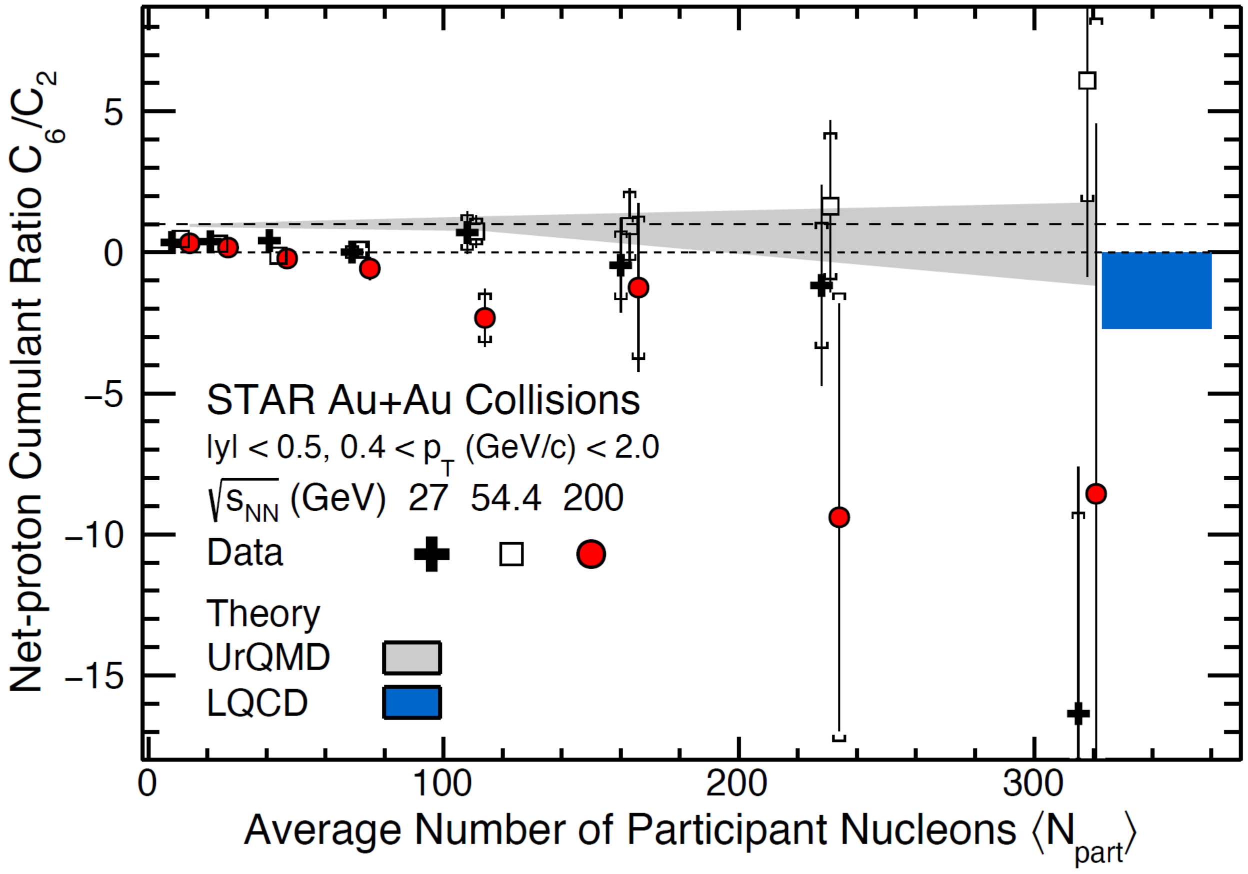
HADES, PRC102.024914(2020)
STAR, PRL128.202303(2022), PRC107.024908(2023)



M.A. Stephanov, PRL107, 052301 (2011)

- No clear enhancement is observed for 2.4 and 3.0 GeV data from HADES and STAR.
- Negative value at 3GeV is reproduced by UrQMD, which incorporates baryon number conservation.
- The data implies that the QCD critical region could only exist at energies > 3GeV.

Net-proton C_6/C_2 for crossover search

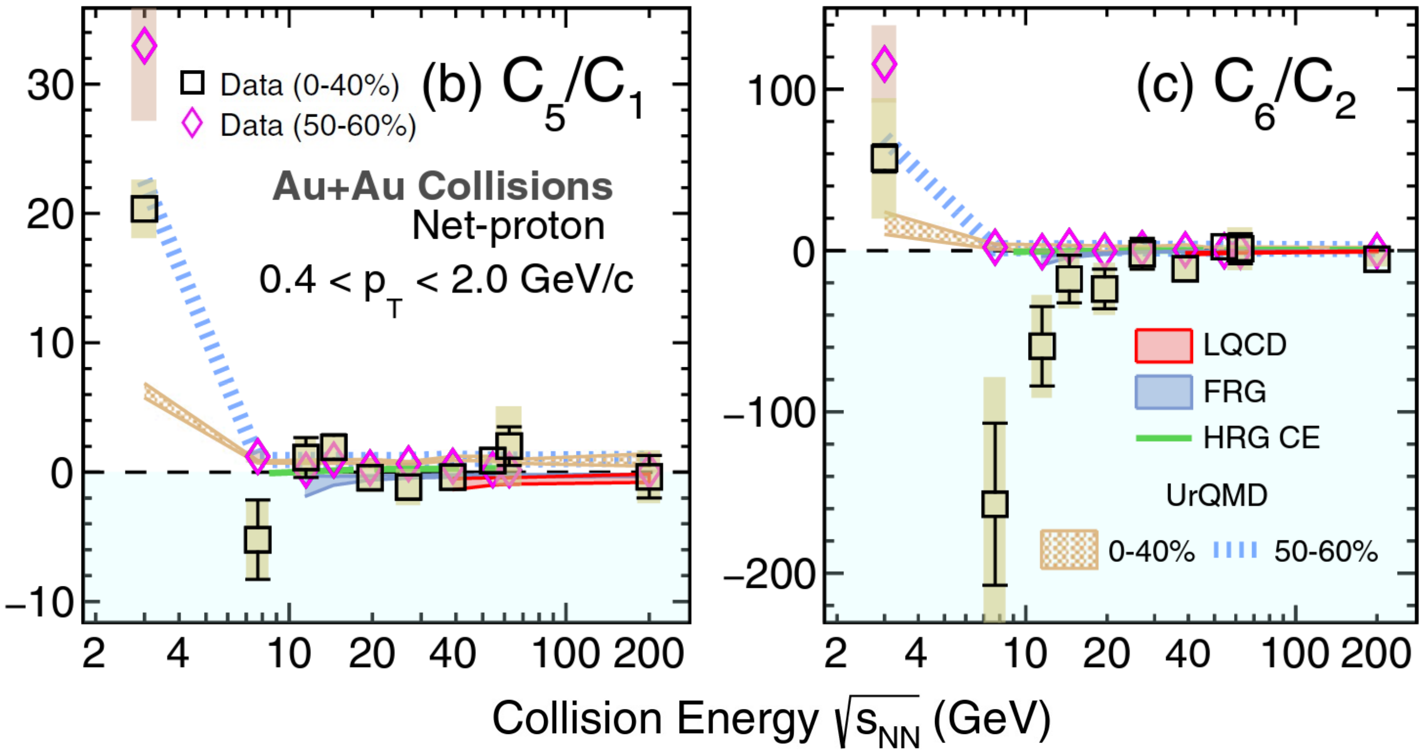


- C_6/C_2 values are progressively negative from peripheral to central collisions at 200 GeV, which is consistent with LQCD calculations.
- Could suggest a smooth crossover transition at top RHIC energy.

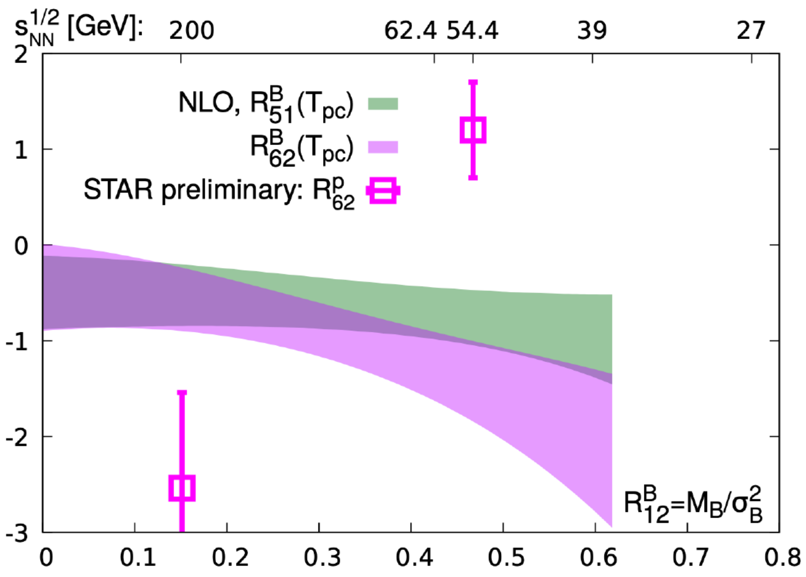
STAR, PRL127.262301(2021)

Energy dependence of C_5/C_1 and C_6/C_2

STAR, PRL130.082301(2023)



- The C_6/C_2 values decrease with decreasing the collision energy, which is quite similar to the LQCD calculation.



Bazavov et al, PRD101.074502(2020)

New results

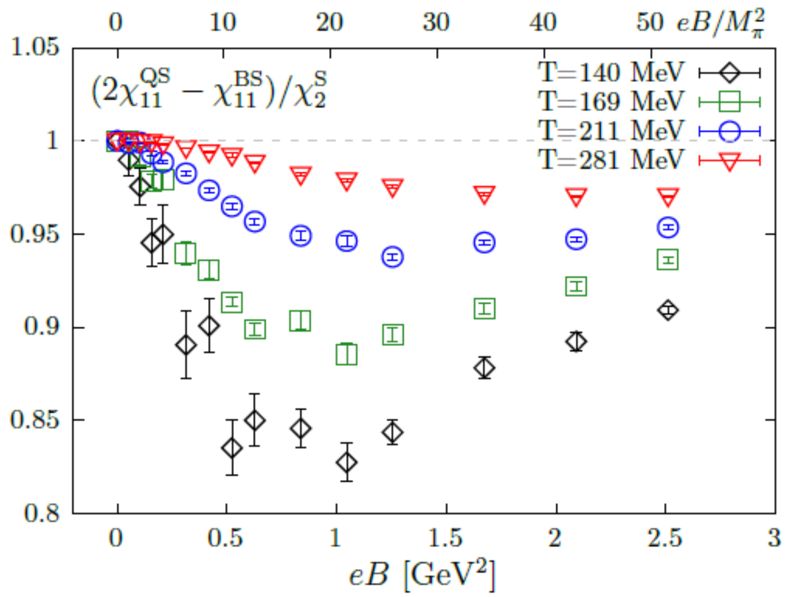
<u>Notation</u>

$\langle X^r \rangle_c$: r[th]-order cumulant of particle X
$\langle XY \rangle_c = \langle XY \rangle - \langle X \rangle \langle Y \rangle$: 2[nd]-order mix-cumulant b/w X and Y
$\langle BS \rangle_c$: 2[nd]-order mix-cumulant b/w net-baryon and net-strangeness
$\langle S^2 \rangle_c$: 2[nd]-order net-strangeness cumulant

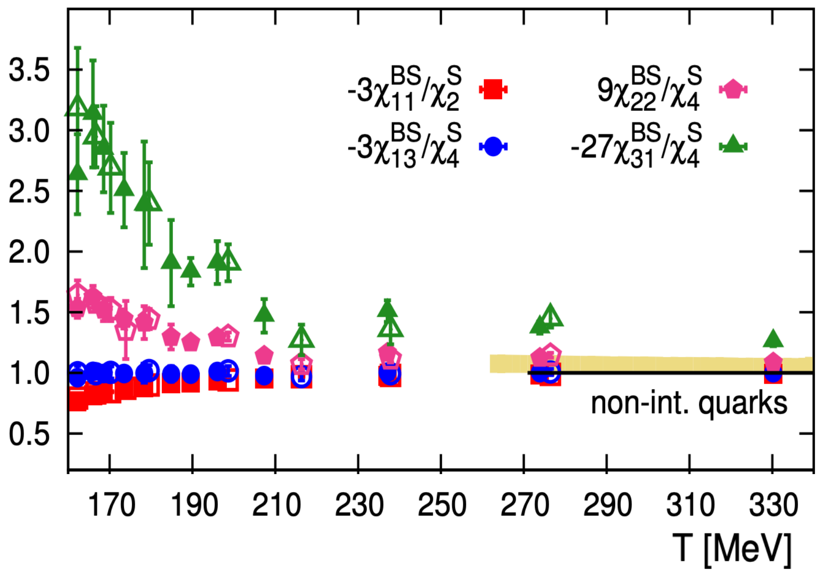
Revisiting 2nd-order fluctuations

- Mix-cumulants among conserved charges are suggested to be sensitive to the magnetic field as well as the temperature.
- Previous STAR measurements on baryon-strangeness correlations are far away from the theoretical guidance.

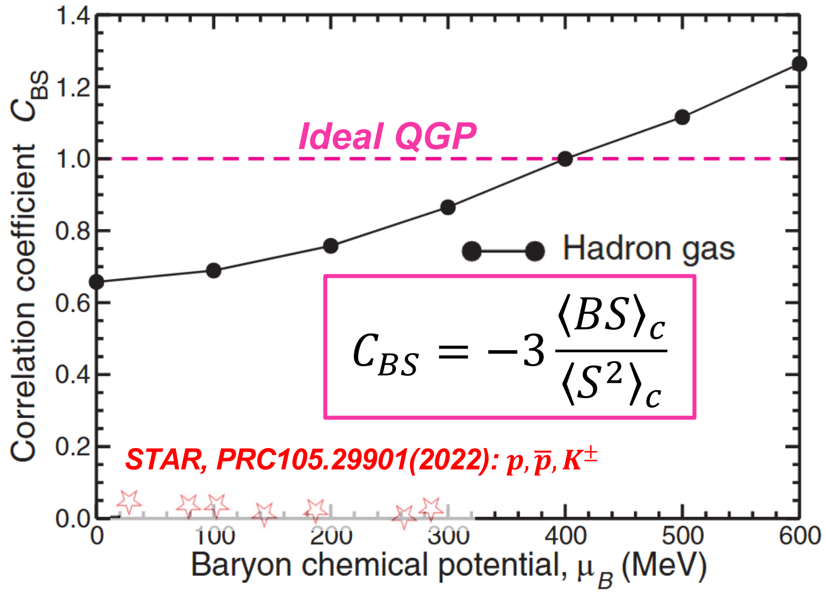
H-T.Ding et al, EPJA57.202(2021)



A. Bazavov et al, PRL111.082301(2013)

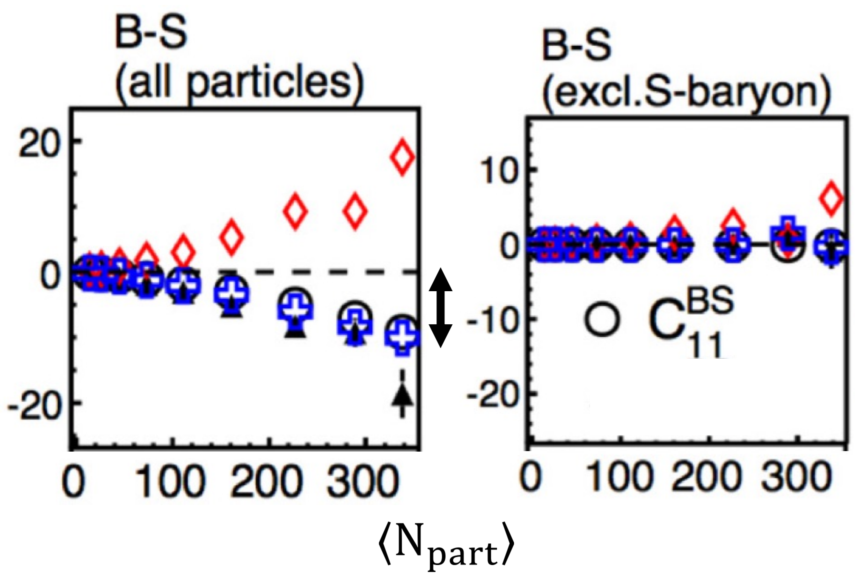


V. Koch et al, PRL95.182301(2005)

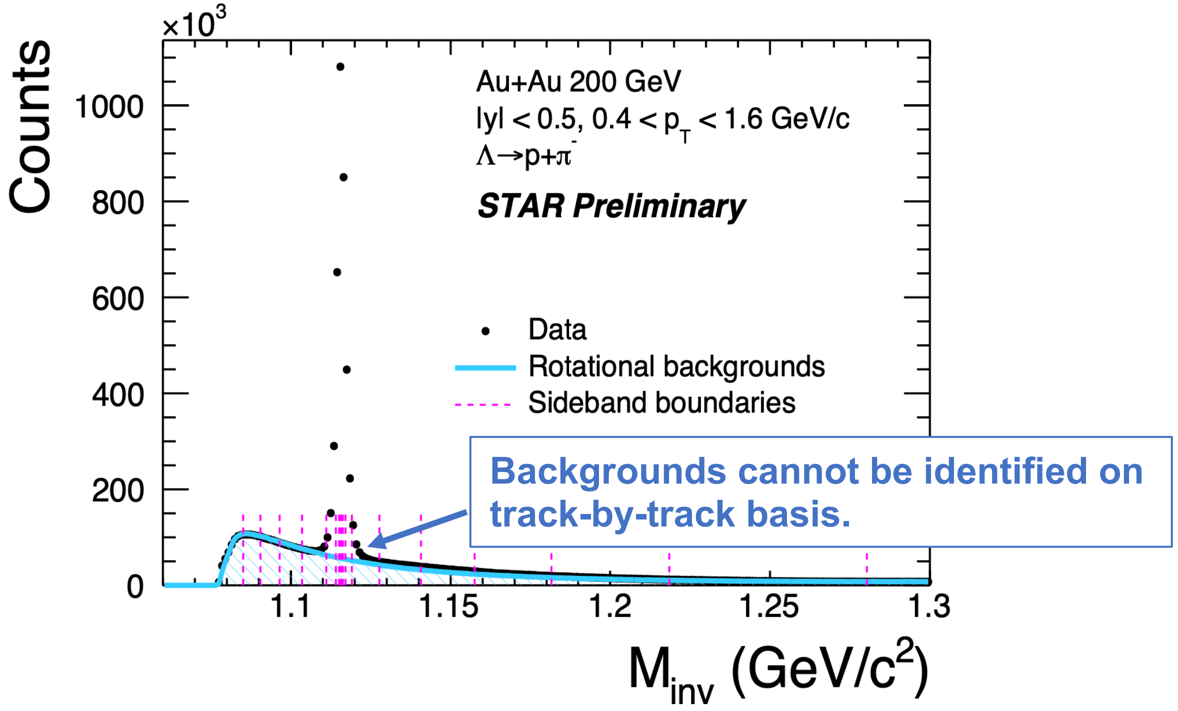


What is missing?

- Model studies indicate that the most of baryon-strangeness correlations are carried by hyperons.
- Measuring event-by-event fluctuations of hyperons is challenging, because of the combinatorial backgrounds and low reconstruction efficiency.



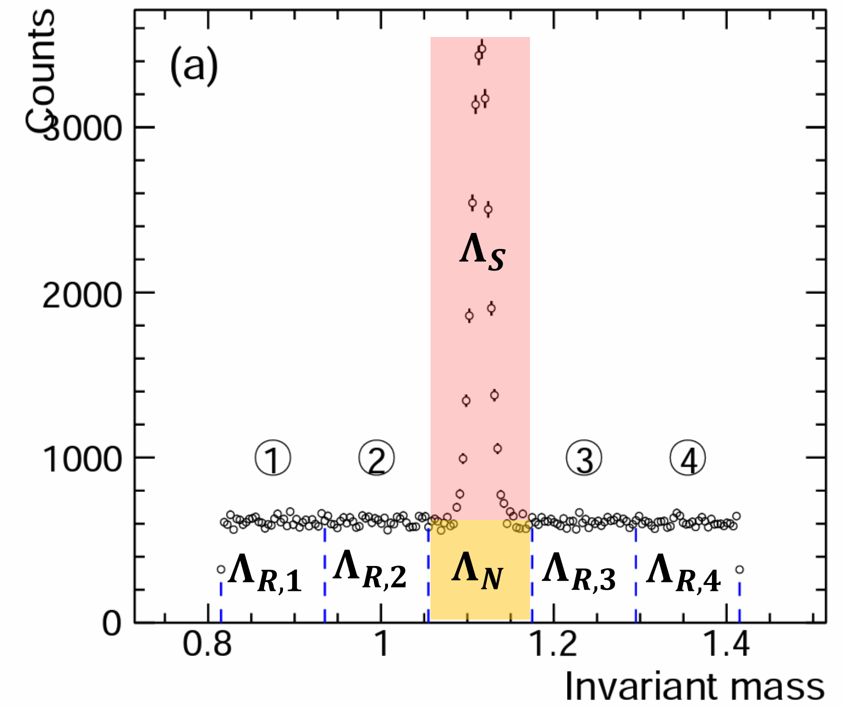
UrQMD: Z. Yang et al, PRC95.014914(2017)



Purity correction: methodology

T. Nonaka, NIMA.1039.167171(2022)

We can only measure $\Lambda_{SN} = \Lambda_S + \Lambda_N$



- Λ_S and Λ_N cannot be obtained directly.

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

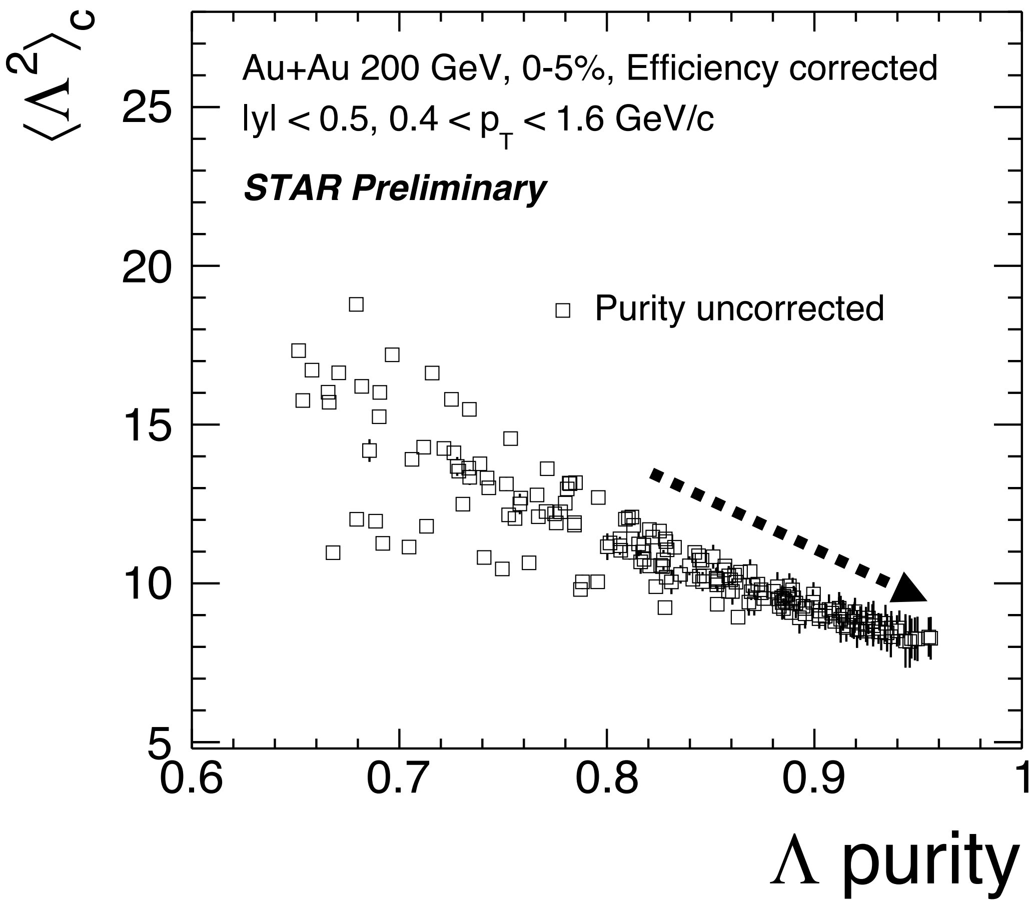
$$\langle\Lambda_S^2\rangle_c = \langle\Lambda_{SN}^2\rangle_c - \langle\Lambda_N^2\rangle_c - 2\langle\Lambda_S\Lambda_N\rangle_c$$

Assumption
Particle number distribution of the backgrounds under the signal peak is consistent with that in sideband.

$$\langle\Lambda_S^2\rangle_c = \langle\Lambda_{SN}^2\rangle_c - \langle\Lambda_{R,i}^2\rangle_c - 2\langle\Lambda_{SN}\Lambda_{R,i}\rangle_c + 2\langle\Lambda_{R,i}\Lambda_{R,j}\rangle_c \quad (i \neq j)$$

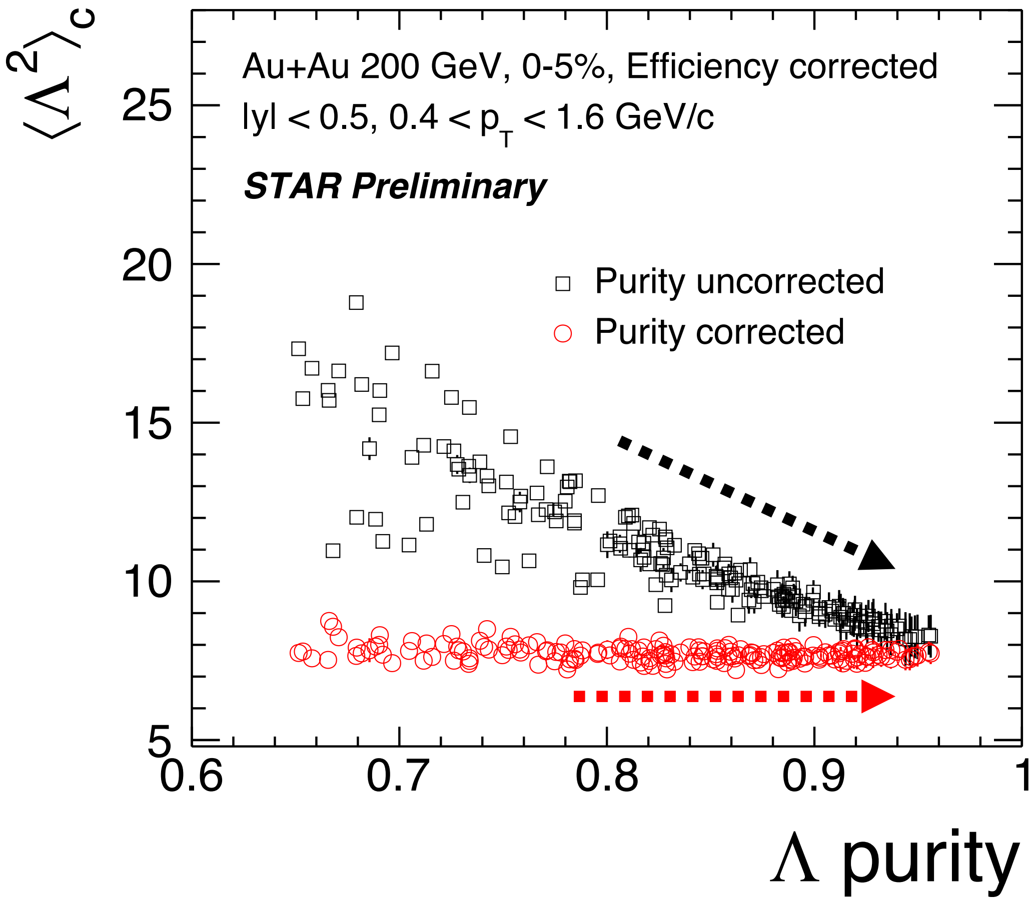
- **If purity correction works, the efficiency/purity corrected cumulants should be consistent w.r.t various topological cuts having different efficiency/purity.**

Purity correction: validation in STAR data



- The 2nd-order Λ cumulant is analyzed for various topological cut conditions having different purity/significance, which increases with decreasing the purity.

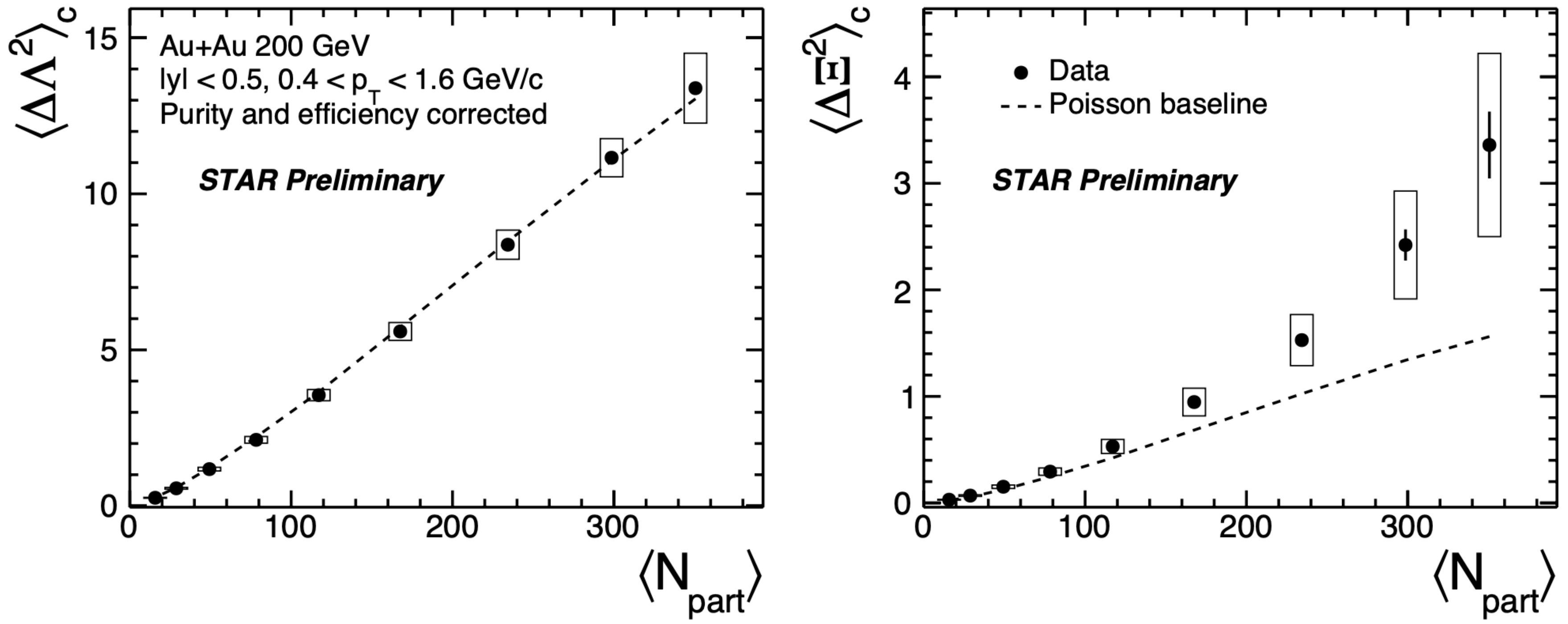
Purity correction: validation in STAR data



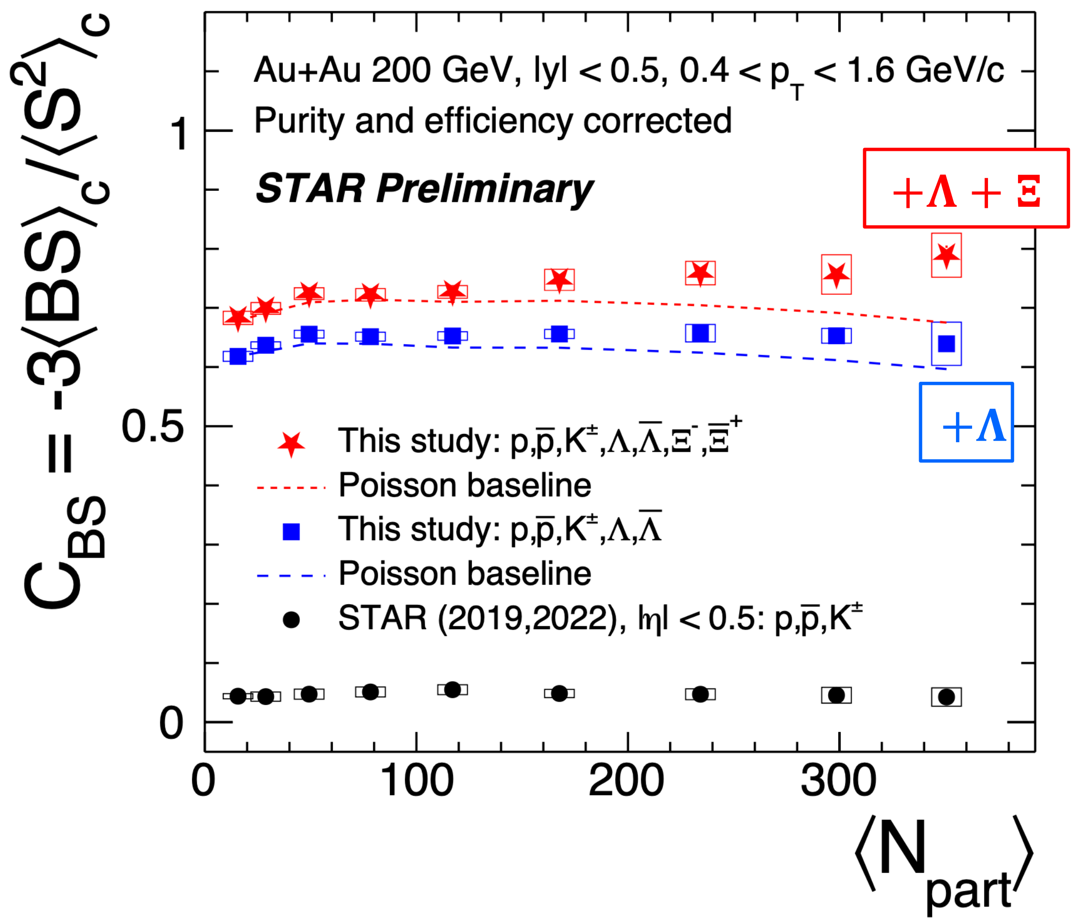
- The 2nd-order Λ cumulant is analyzed for various topological cut conditions having different purity/significance, which increases with decreasing the purity.
- Purity-corrected cumulants are flat w.r.t purity, and crosses with the uncorrected cumulants at the highest purity, indicating the validity of the methodology.
- First time to address the effect of combinatorial backgrounds on event-by-event hyperon fluctuations.

Net-hyperon cumulants

- First measurement of net-Ξ ($\Xi^- - \bar{\Xi}^+$) fluctuations.
- $\langle \Delta\Xi^2 \rangle_c$ is systematically enhanced w.r.t the Poisson baseline in central collisions, while $\langle \Delta\Lambda^2 \rangle_c$ is consistent with the Poissonian.

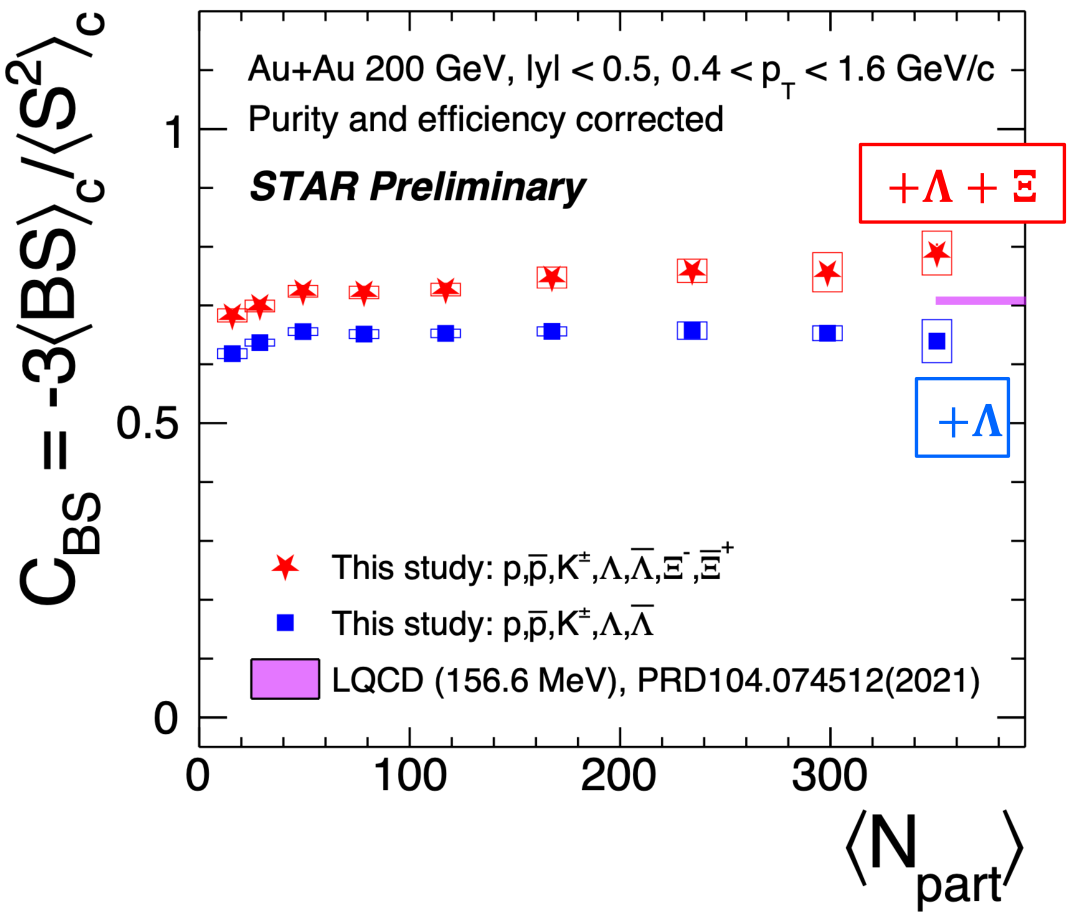


Results



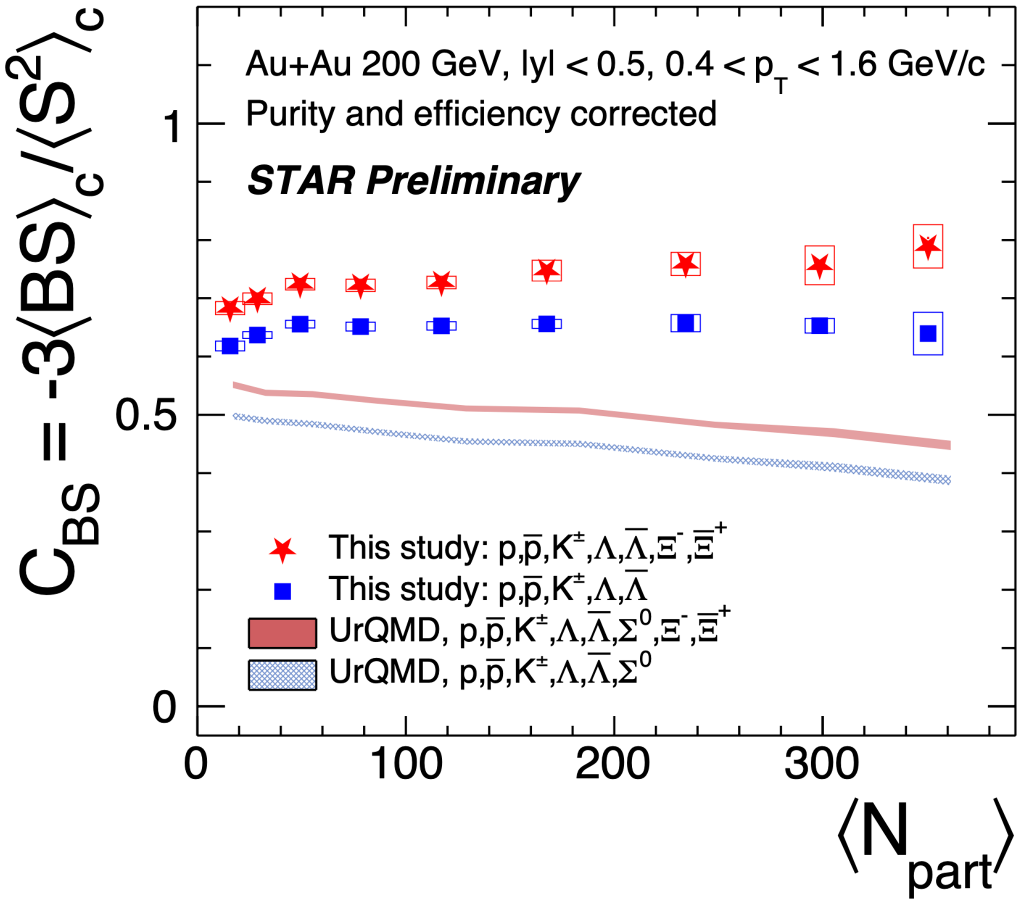
- The C_{BS} values are significantly enhanced by including Λ and Ξ hyperons compared to the previous measurements.
- The C_{BS} values are systematically larger than the Poisson baselines.
- The largest enhancement is seen in most central collisions in case including Ξ.

Comparison with LQCD



- Our measurements are consistent with LQCD calculations so far.
- <u>Caution</u>: the C_{BS} value strongly depends on particle types included in the measurements.

Comparison with UrQMD



- UrQMD is analyzed by using the same particle species (+ Σ^0) as the measurements.
- UrQMD underestimates the data.

Summary

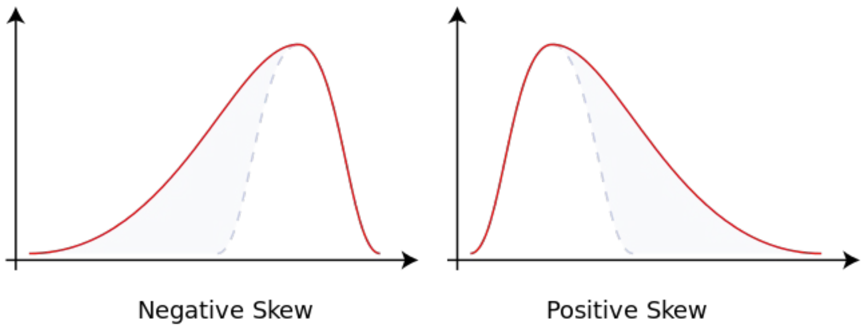
- Some interesting hints on the QCD critical point, crossover, and phase boundary have been obtained through the measurements of higher-order cumulants of net-proton distributions. Stay tuned for precise measurements for BES-II.
- Purity correction has been established to remove the effect of combinatorial backgrounds from hyperon number fluctuations.
- The values of baryon-strangeness correlations (C_{BS}) have been significantly enhanced by including Λ and Ξ hyperons.
- Theoretical inputs are needed to make physics conclusion.

Thank you for your attention

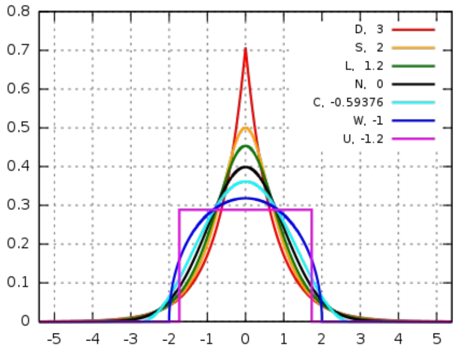
Higher-order fluctuation

- Moments and cumulants are mathematical measures of "shape" of a distribution, which probes fluctuations of an observable.

Skewness (S) → asymmetry



Kurtosis (κ) → sharpness



- Cumulant ↔ Central moment

$$C_1 = \langle N \rangle, \quad C_2 = \langle (\delta N)^2 \rangle \qquad \delta N = N - \langle N \rangle$$

$$C_3 = \langle (\delta N)^3 \rangle \quad C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2$$

$$C_5 = \langle (\delta N)^5 \rangle - 10 \langle (\delta N)^2 \rangle \langle (\delta N)^3 \rangle$$

$$C_6 = \langle (\delta N)^6 \rangle + 30 \langle (\delta N)^2 \rangle^3 - 15 \langle (\delta N)^2 \rangle \langle (\delta N)^4 \rangle$$

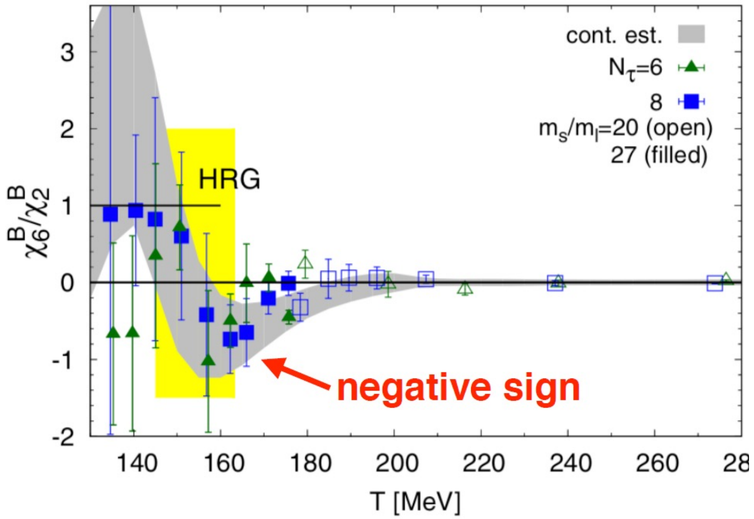
- Cumulants have additivity : proportional to the system volume

$$C_n(X+Y) = C_n(X) + C_n(Y)$$

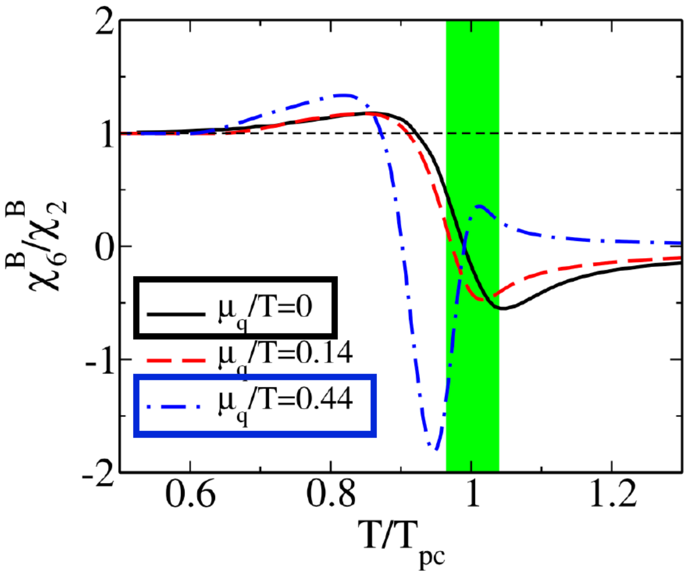
C_5 and C_6 for crossover search

- No direct experimental evidence for a smooth crossover at μ_B~0 MeV.
- **C_6/C_2 < 0** is predicted as a sign of crossover transition
- High-statistics data sets at 27, 54.4, 200 GeV were analyzed.

A. Bazavov et al, PRD.95.054504



B. Friman et al, Eur. Phys. J. C (2011) 71:1694

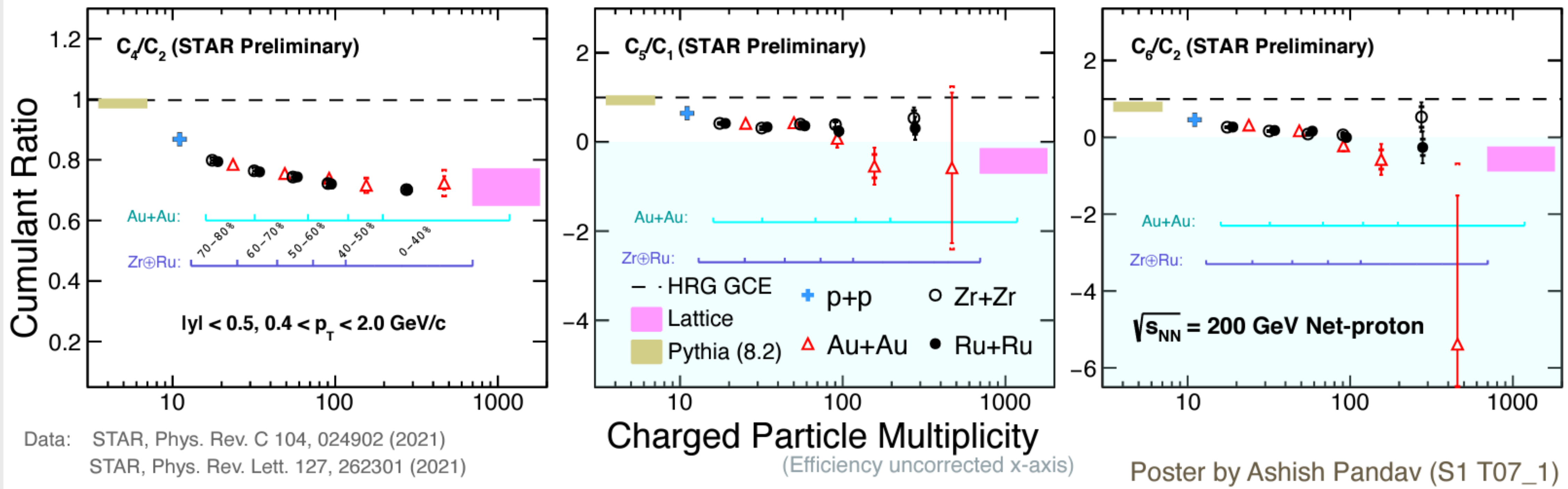


Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

Predicted scenario for this measurement

System size dependence

- Ratios approach LQCD calculations with increasing the multiplicity, which imply that the created system approach thermalized medium at high multiplicity region.



Data: STAR, Phys. Rev. C 104, 024902 (2021)
STAR, Phys. Rev. Lett. 127, 262301 (2021)

Poster by Ashish Pandav (S1 T07_1)

Ho-San Ko, QM2022

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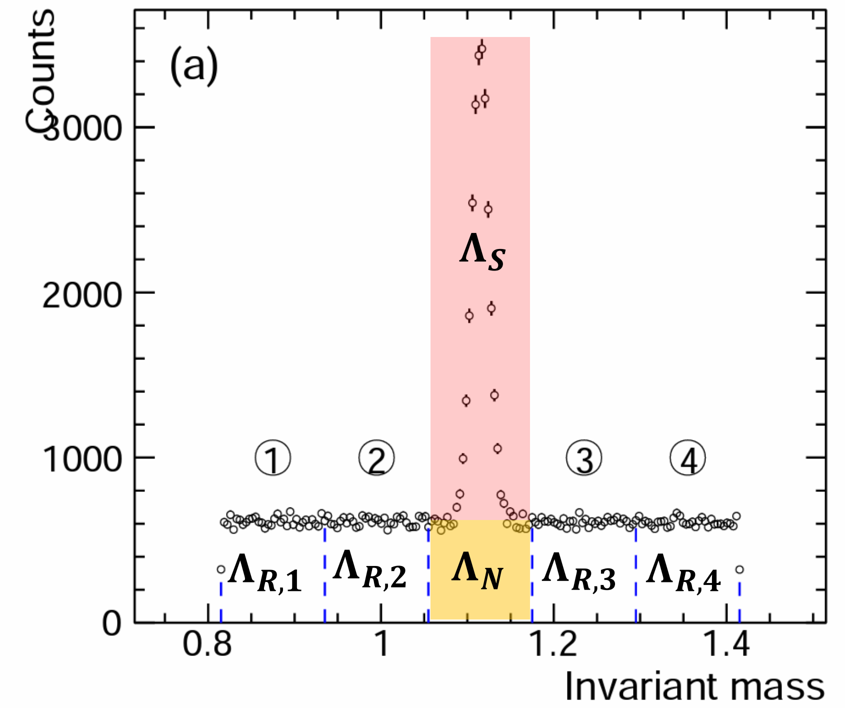
T. Nonaka, NIMA.1039.167171(2022)

We can only measure $\Lambda_{SN} = \Lambda_S + \Lambda_N$



- m_S and m_N cannot be obtained directly.

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

$$\langle \Lambda_S^2 \rangle_c = \langle \Lambda_{SN}^2 \rangle_c - \langle \Lambda_N^2 \rangle_c - 2\langle \Lambda_S \Lambda_N \rangle_c$$

Assumption

$$\langle \Lambda_N^2 \rangle_c = \langle \Lambda_{R,i}^2 \rangle_c$$

$$\langle \Lambda_S \Lambda_N \rangle_c = \langle \Lambda_S \Lambda_{R,i} \rangle_c$$

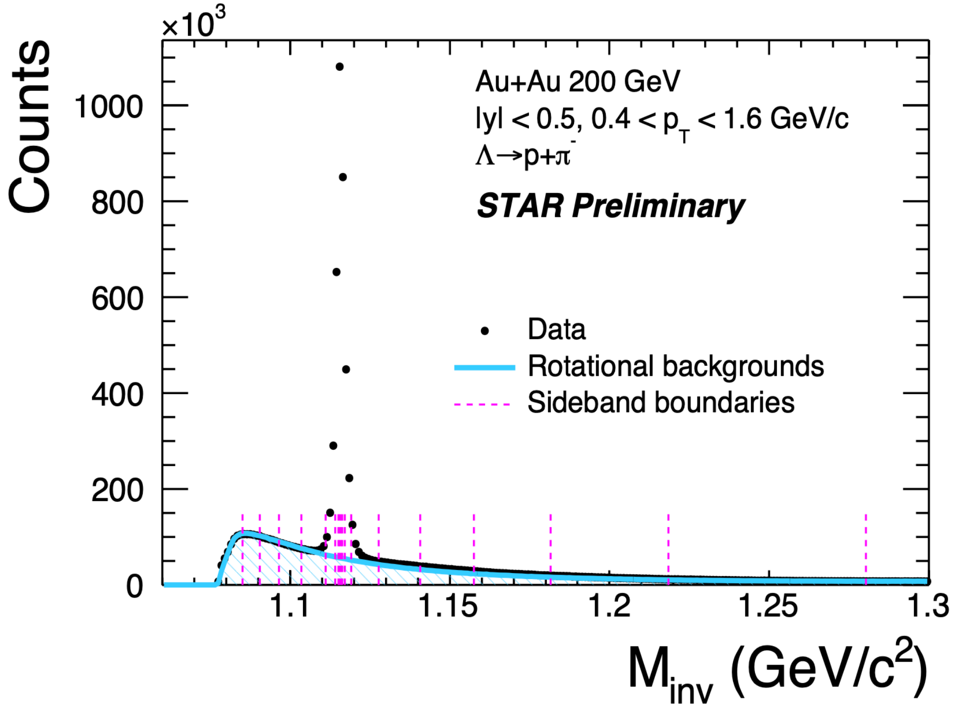
$$\langle \Lambda_N \Lambda_{R,i} \rangle_c = \langle \Lambda_{R,i} \Lambda_{R,j} \rangle_c \quad (i \neq j)$$

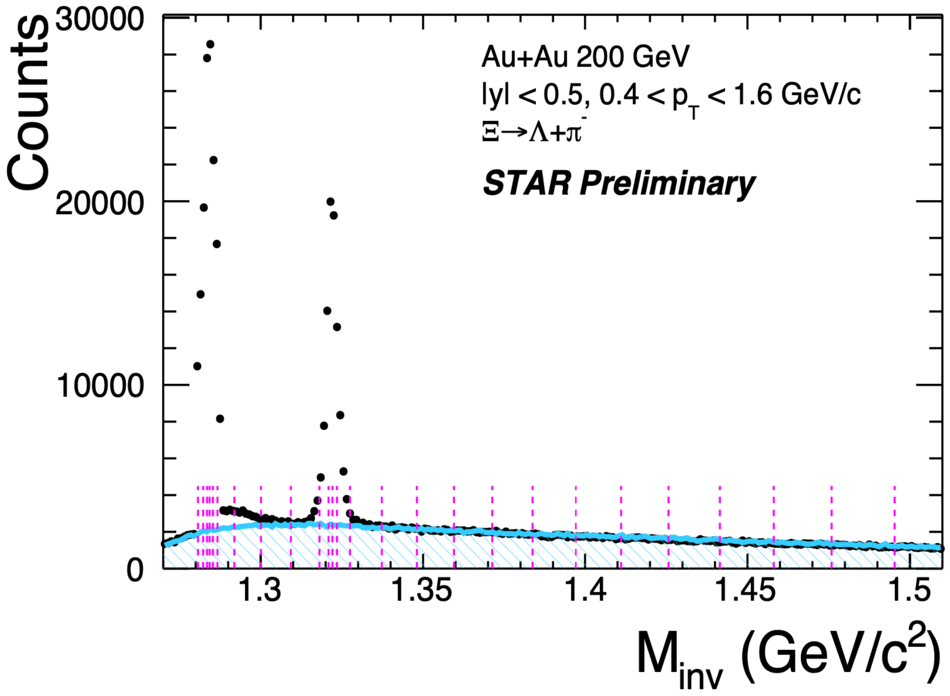
$$\langle \Lambda_S^2 \rangle_c = \langle \Lambda_{SN}^2 \rangle_c - \langle \Lambda_{R,i}^2 \rangle_c - 2\langle \Lambda_{SN} \Lambda_{R,i} \rangle_c + 2\langle \Lambda_{R,i} \Lambda_{R,j} \rangle_c \quad (i \neq j)$$

- **If purity correction works, the efficiency/purity corrected cumulants should be consistent w.r.t various topological cuts having different efficiency/purity.**

Sideband cumulants

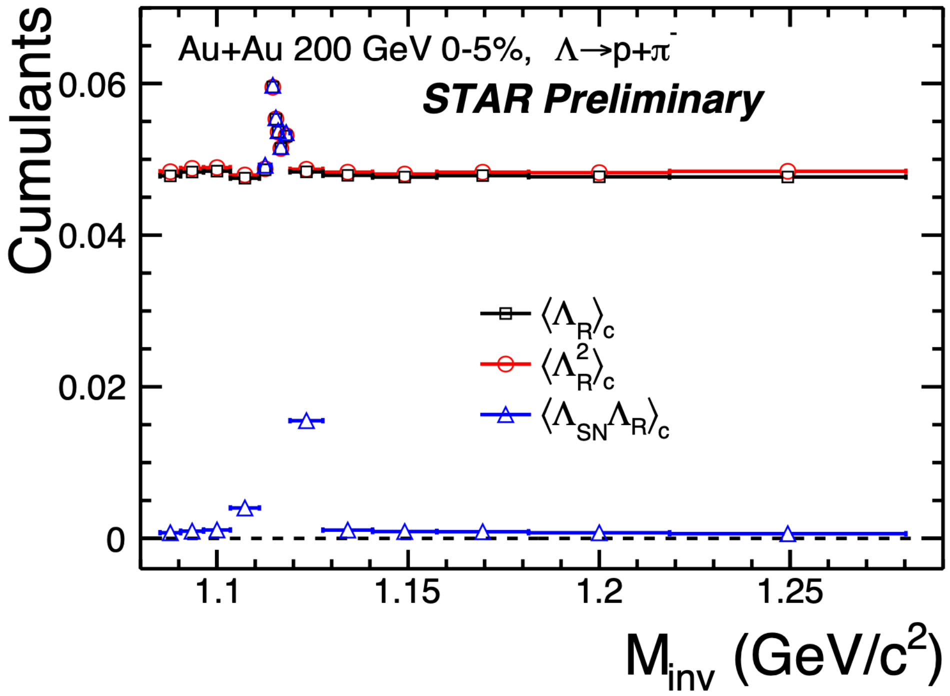
- Sidebands are divided into small windows based on the yield of the signal candidates.

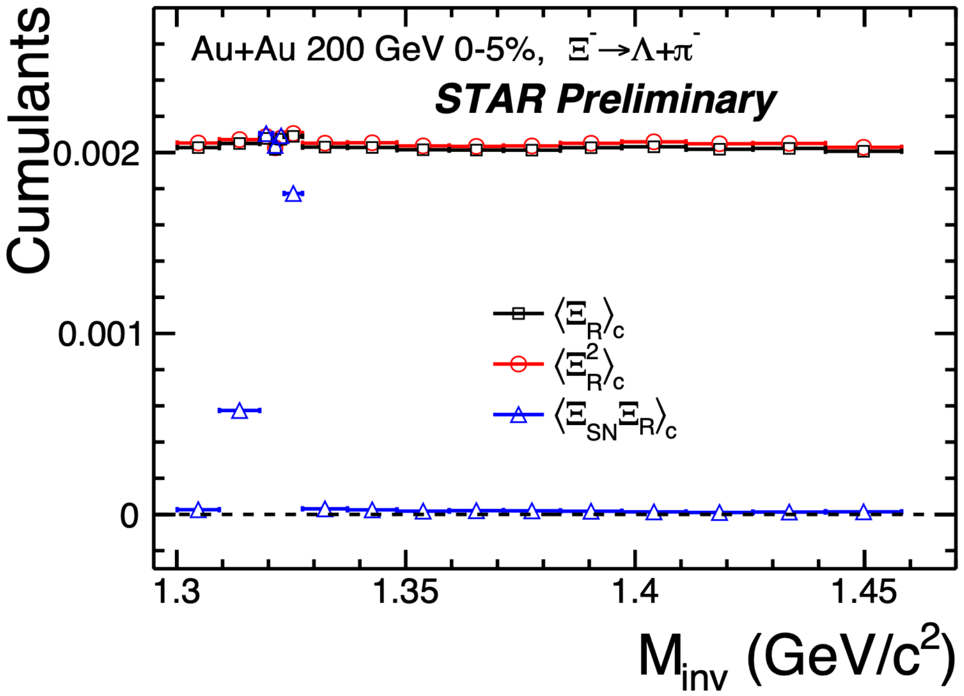




Sideband cumulants

- Sidebands are divided into small windows based on the yield of the signal candidates.
- The flatness seen in 2nd-order cumulants and correlation with signal candidates w.r.t the invariant mass imply the particle number distribution is similar for those regions.

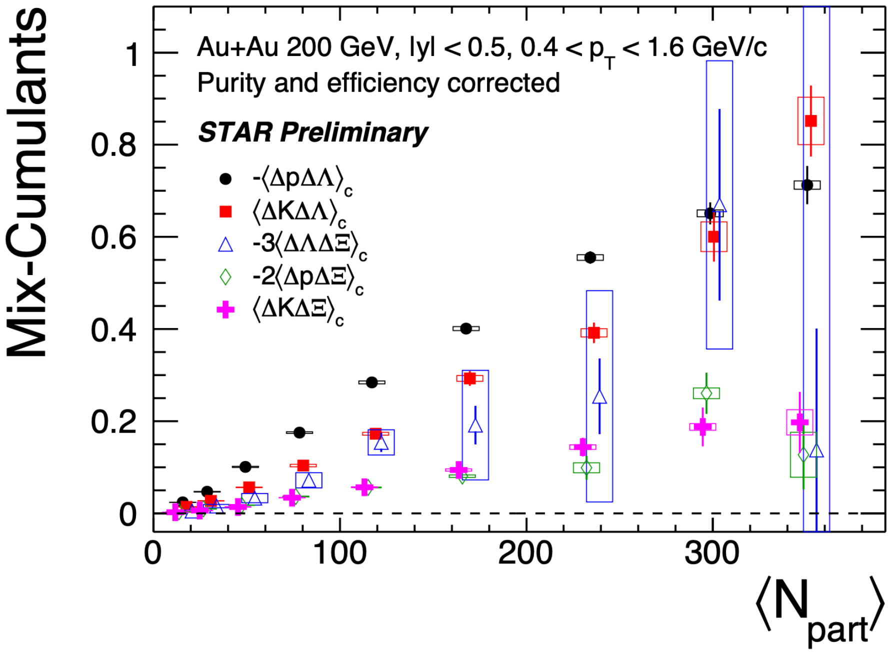




Correlation terms

- Most correlation terms have positive contribution on $\langle BS\rangle_c$.

$$\begin{aligned}\langle BS\rangle_c &= \langle(\Delta p+\Delta\Lambda+\Delta\Xi)(\Delta K-\Delta\Lambda-2\Delta\Xi)\rangle_c\\ &= \langle\Delta p\Delta K\rangle_c \boxed{-\langle\Delta p\Delta\Lambda\rangle_c} \boxed{-2\langle\Delta p\Delta\Xi\rangle_c} \boxed{+\langle\Delta\Lambda\Delta K\rangle_c} -\langle\Delta\Lambda^2\rangle_c \boxed{-3\langle\Delta\Lambda\Delta\Xi\rangle_c} \boxed{+\langle\Delta\Xi\Delta K\rangle_c} -2\langle\Delta\Xi^2\rangle_c\end{aligned}$$



STAR, PRC 105.029901(2022)