Baryon-Strangeness Correlations in Au+Au Collisions at RHIC BES energies from UrQMD Model

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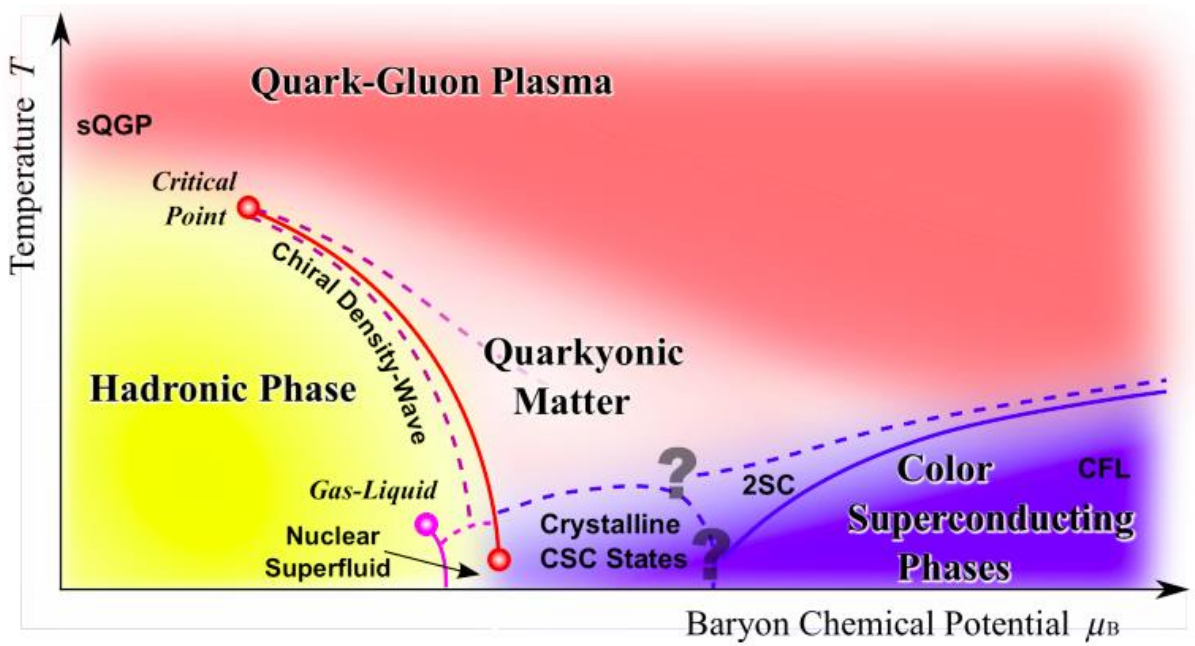
Motivation



- Fluctuations and correlations of conserved charges can be applied to search for the QCD critical point in the QCD phase diagrams.

- B=1/3Δu+1/3Δd+1/3Δs, Q=2/3Δu-1/3Δd-1/3Δs, S=-Δs.

- UrQMD model may provide a baseline for the experimental measure.

Mixed-Cumulants:Related to the Susceptibility

- Pressure: $$\frac{P}{T^4} = \frac{1}{VT^3}\ln Z\left(T,\ \mu_B, \mu_Q, \mu_S\right)$$

- Susceptibility: $$\chi_{mn}^{XY}\left(T,\vec{\mu}\right) = \frac{\partial^{(m+n)}\left[P/T^4\right]}{\partial\left(\mu_X/T\right)^m \partial\left(\mu_Y/T\right)^n}\Big|_{\vec{\mu}\ =\ 0}$$

  where X, Y = B、Q 、S， $\chi_{0n}^{XY} = \chi_n^Y$ and $\chi_{m0}^{XY} = \chi_m^X$.

- Mixed-cumulants of the conserved quantities :

$$C_{mn}^{XY} = VT^3\chi_{mn}^{XY}(T,\ \vec{\mu}).$$

Reference : Phys. Rev. Lett. 111, 082301 (2013).

Observables: Mixed-Cumulant Ratios

Reference : Phys. Rev. Lett. 111, 082301 (2013).

$$\chi_2^S = \frac{1}{VT^3} C_2^S$$

$$\chi_4^S = \frac{1}{VT^3} C_4^S$$

$$\chi_{mn}^{BS} = \frac{1}{VT^3} C_{mn}^{BS}$$

$$\frac{\chi_{mn}^{BS}}{\chi_{m+n}^S} = \frac{(-1)^n}{3^m},$$

where $m + n = 2, 4.$

Normalized correlation coefficients:

$$-3\frac{\chi_{11}^{BS}}{\chi_2^S} = R_{11}^{BS} = -3\frac{C_{11}^{BS}}{C_2^S}$$

$$-3\frac{\chi_{13}^{BS}}{\chi_4^S} = R_{13}^{BS} = -3\frac{C_{13}^{BS}}{C_4^S}$$

$$9\frac{\chi_{22}^{BS}}{\chi_4^S} = R_{22}^{BS} = 9\frac{C_{22}^{BS}}{C_4^S}$$

$$-27\frac{\chi_{31}^{BS}}{\chi_4^S} = R_{31}^{BS} = -27\frac{C_{31}^{BS}}{C_4^S}$$

Theory ⟷ Experiment

- In order to cancel volume dependence.
- In order to make the ratios unity in the QGP phase (B_S=-1/3S_S).

Mixed-Cumulant Ratios Calculation

- The joint cumulants of random variables, $X_1, X_2, \ldots X_n$ ($n \geq 2$):

$$C(X_1, X_2 \cdots X_n) = \sum_{\pi} \left(|\pi| - 1 \right)! \ \left(-1\right)^{|\pi|-1} \prod_{B \in \pi} E \left(\prod_{i \in B} X_i \right).$$

- The mixed-cumulant ratios of the random variables B,S are:

$$R_{11}^{BS} = -3 \frac{C_{11}^{BS}}{C_2^S} = -3 \frac{C(B, S)}{C(S, S)} = -3 \frac{\langle \delta B \delta S \rangle}{\langle (\delta S)^2 \rangle} = -3 \frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}.$$

$$R_{13}^{BS} = -3 \frac{C_{13}^{BS}}{C_4^S} = -3 \frac{C(B, S, S, S)}{C(S, S, S, S)} = -3 \frac{\langle \delta B (\delta S)^3 \rangle - 3 \langle \delta B \delta S \rangle \langle (\delta S)^2 \rangle}{\langle (\delta S)^4 \rangle - 3 \langle (\delta S)^2 \rangle^2}.$$

$$R_{22}^{BS} = 9 \frac{C_{22}^{BS}}{C_4^S} = 9 \frac{C(B, B, S, S)}{C(S, S, S, S)} = 9 \frac{\langle (\delta B)^2 (\delta S)^2 \rangle - 2 \langle \delta B \delta S \rangle^2 - \langle (\delta B)^2 \rangle \langle (\delta S)^2 \rangle}{\langle (\delta S)^4 \rangle - 3 \langle (\delta S)^2 \rangle^2}.$$

$$R_{31}^{BS} = -27 \frac{C_{31}^{BS}}{C_4^S} = -27 \frac{C(B, B, B, S)}{C(S, S, S, S)} = -27 \frac{\langle (\delta B)^3 \delta S \rangle - 3 \langle \delta B \delta S \rangle \langle (\delta B)^2 \rangle}{\langle (\delta S)^4 \rangle - 3 \langle (\delta S)^2 \rangle^2}.$$

Error Calculation

$$f_{m,n} = \langle B^m S^n \rangle,$$

$$F_{m,n} = \langle (\delta B)^m (\delta S)^n \rangle = \frac{\partial F_{m,n}}{\partial f_{i,j}} f_{i,j}$$

$$= \sum_{i=0}^{m} \sum_{j=0}^{n} C_m^i C_n^j (-1)^{m+n-i-j} f_{1,0}^{m-i} f_{0,1}^{n-j} f_{i,j}.$$

General Error propagation formula :

$$V(\phi) = \sum_{i=1,\ j=1}^{n} \frac{\partial \phi(X_1, \cdots X_n)}{\partial X_i} \frac{\partial \phi(X_1, \cdots X_n)}{\partial X_j} Cov(X_i, X_j).$$

The covariance of multivariate moments :

$$Cov(f_{i,j}, f_{k,h}) = \frac{1}{N} (f_{i+k,j+h} - f_{i,j} f_{k,h}).$$

Reference： Xiaofeng Luo, Phys. Rev. C. 91, 034907 (2015).

$$R_{11}^{BS} = -3 \frac{C_{11}^{BS}}{C_2^S} = -3 \frac{F_{1,1}}{F_{0,2}} = -3 \frac{f_{1,1} - f_{1,0} f_{0,1}}{f_{0,2} - f_{0,1}^2}$$

$$\frac{\partial R_{11}^{BS}}{\partial f_{i,j}} = \frac{\partial R_{11}^{BS}}{\partial F_{1,1}} \frac{\partial F_{1,1}}{\partial f_{i,j}} + \frac{\partial R_{11}^{BS}}{\partial F_{0,2}} \frac{\partial F_{0,2}}{\partial f_{i,j}} = \frac{-3}{C_{02}^{BS}} \frac{\partial F_{1,1}}{\partial f_{i,j}} + \frac{3 C_{11}^{BS}}{(C_{02}^{BS})^2} \frac{\partial F_{0,2}}{\partial f_{i,j}}$$

$$Error(R_{11}^{BS}) = \sqrt{V(R_{11}^{BS})} = \sqrt{\sum_{i,k=0}^{1} \sum_{j,h=0}^{2} \frac{\partial R_{11}^{BS}}{\partial f_{i,j}} \frac{\partial R_{11}^{BS}}{\partial f_{k,h}} Cov(f_{i,j}, f_{k,h})}.$$

Analysis Details

$\sqrt{s_{NN}}$(GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics(million)	72.5	105	106	81	133	38	56

- UrQMD (Ultra Relativistic Quantum Molecular Dynamics) model is a microscopic transport model.
- For centrality divided, charge particles ($0.5<|\eta|<1.0$) is used.
- For analysis method,
  - The particle multiplicities event-by-event .
  - The weighted mean values ($\langle B\rangle$ 、 $\langle S\rangle$ 、 $\langle B^m S^n\rangle$).
  - Observables: $C_{mn}^{BS}\left(C_{11}^{BS}、C_{13}^{BS}、C_{22}^{BS}、C_{31}^{BS}、C_{2}^{S}、C_{4}^{S}\right)$
    $R_{mn}^{BS}\left(R_{11}^{BS}、R_{22}^{BS}、R_{13}^{BS}、R_{31}^{BS}\right)$

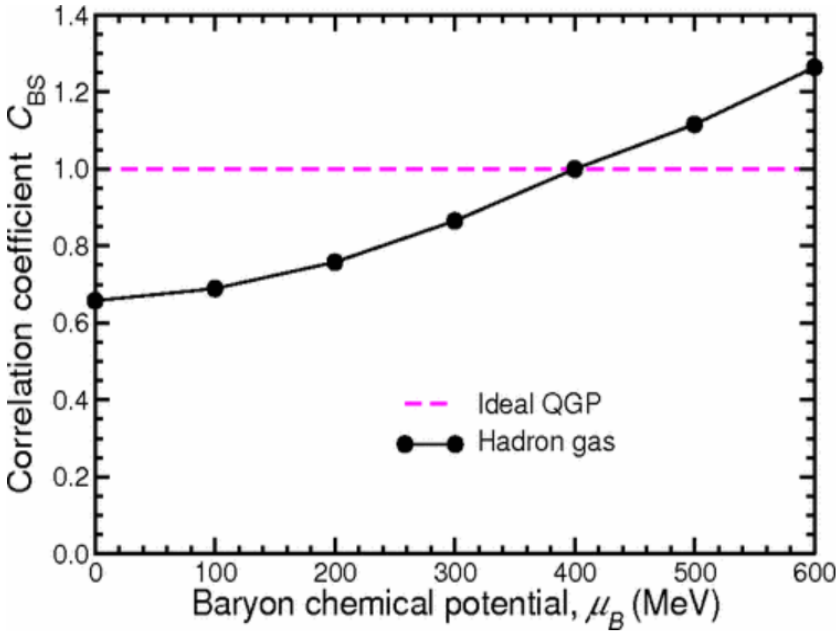
Reference：
Ji Xu, Shili Yu, Feng Liu, and Xiaofeng Luo, Phys. Rev. C.94, 024901(2016).

Particle Details

Particle	Component	Mass (GeV/c^2)	PID	Baryon Number	Strangeness
proton	uud	0.938	2212	1	0
neutron	udd	0.939	2112	1	0
K^+	$u\bar{s}$	0.493	321	0	1
K^0	$d\bar{s}$	0.497	311	0	1
Λ	uds	1.115	3122	1	-1
Σ^-	dds	1.197	3112	1	-1
Σ^0	uds	1.192	3212	1	-1
Σ^+	uus	1.189	3222	1	-1
Ξ^-	dss	1.321	3312	1	-2
Ξ^0	uss	1.314	3322	1	-2
Ω^-	sss	1.672	3334	1	-3

- For particle choose: p, n, K^+, K^0, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, Ω^- and corresponding anti-particles ($|\eta|<0.5$) are included.

Results from HRG Model



- For uncorrelated hadron gas:

$$R_{11}^{BS} = -3\frac{\sum_k \sigma_k^2 B_k S_k}{\sum_k \sigma_k^2 S_k^2} \overset{Poisson}{\approx} -3\frac{\sum_k \langle n_k \rangle B_k S_k}{\sum_k \langle n_k \rangle S_k^2}$$

  - At low μ_B, C_{BS} is smaller than unity.
  - As μ_B increases, population of strange baryons increases.

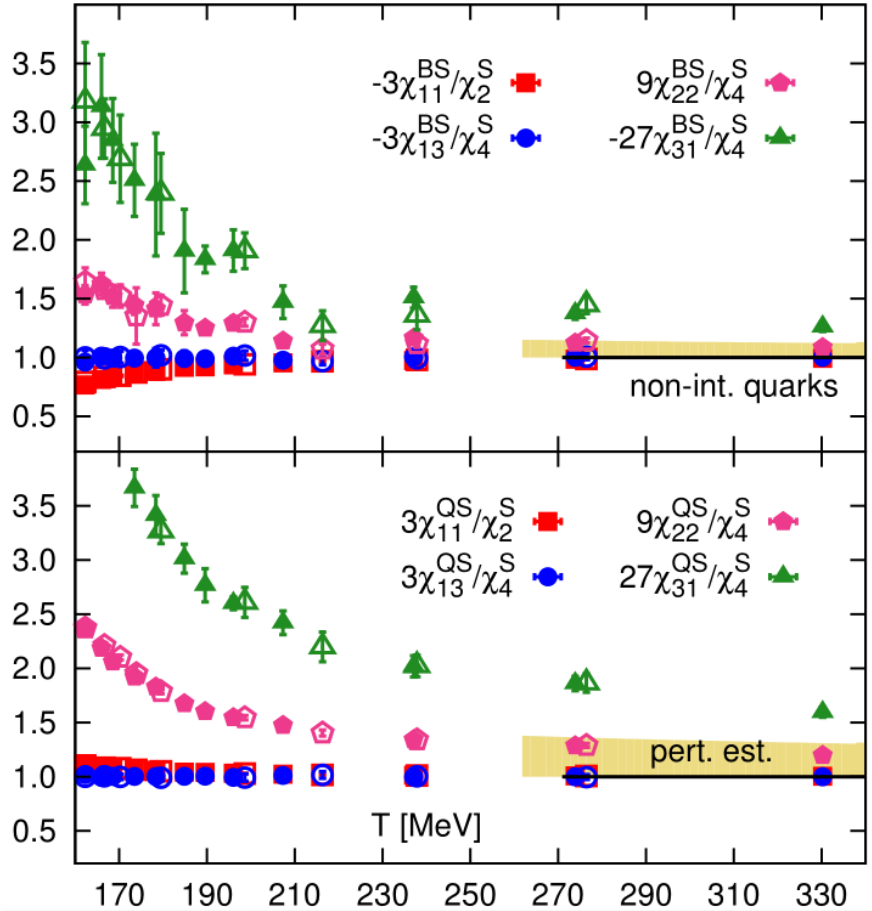
$$C_{BS} = R_{11}^{BS} = -3\frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2} \overset{\langle S \rangle = 0}{=} -3\frac{\langle BS \rangle}{\langle S^2 \rangle}$$

- For non-interacting quark-gluon plasma:

$$C_{BS} = R_{11}^{BS} = \frac{\langle (u+d+s)(s) \rangle}{\langle s^2 \rangle} = 1$$

Reference:V.Koch, A.Majumder, and J.Randrup,Phys.Rev.Lett.95,182301(2005).

Results From Lattice QCD



- B-S (top) and Q-S (bottom) correlations , properly scaled by the strangeness fluctuations and powers of the fractional baryonic and electric charges .
- In the non-interacting quark gas, all these ratios are unity (shown by the lines at high temperatures).
- Higher order ratios are more sensitive.

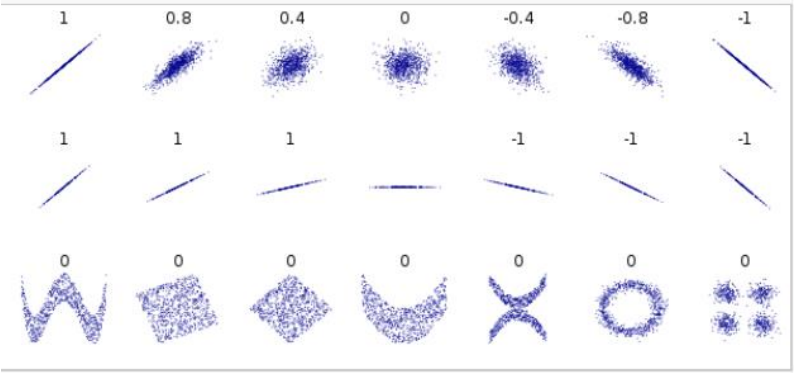
Reference : Phys. Rev. Lett. 111, 082301 (2013).

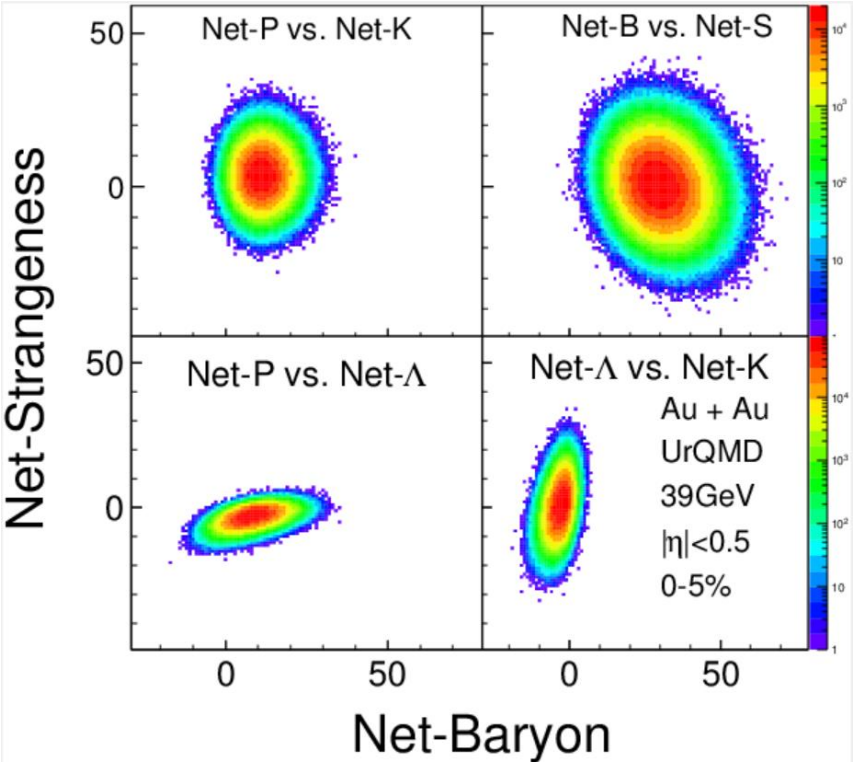
Results From UrQMD Model

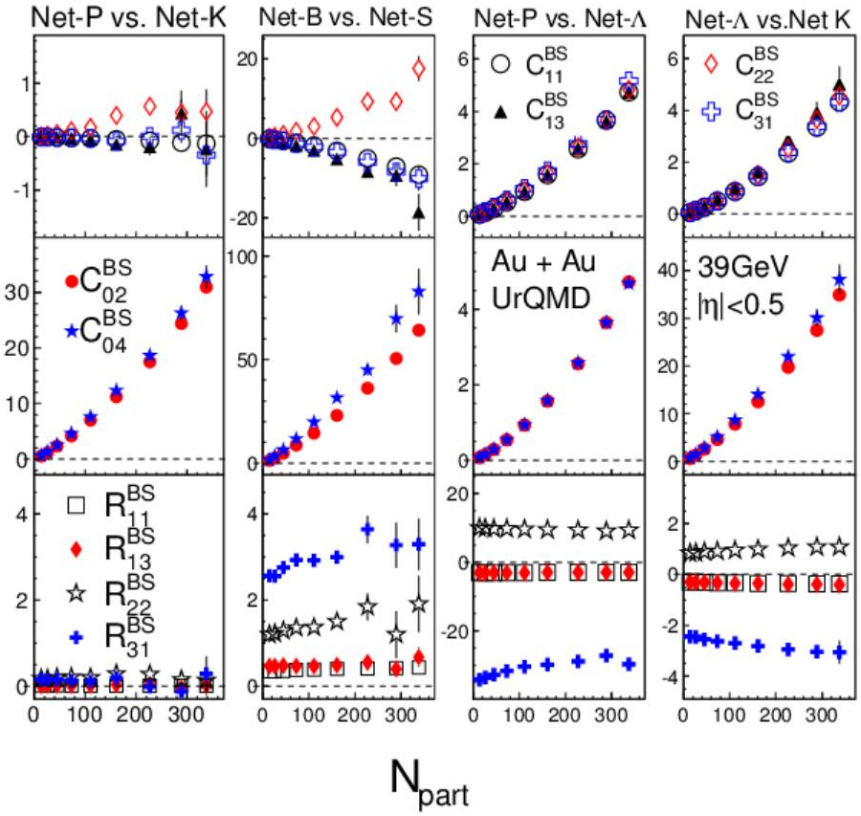
In order to study the contributions of different particle species to the B-S correlations, We consider ten situations: Anti-particles are also included.

Different situations	Particles included
(i) Net-Λ vs. Net-K	Λ, K^+
(ii) Net-P vs. Net-K	p, K^+
(iii) Net-P vs. Net-Λ	p, Λ
(iv) Net-B vs. Net-S	p, n, K^+, K^0, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, Ω^-
(v) B-S(excl. s-baryon)	p, n, K^+, K^0
(vi) B-S(excl. Λ)	p, n, K^+, K^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, Ω^-
(vii) B-S(excl. no-s-baryon)	K^+, K^0, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, Ω^-
(viii) B-S(excl. p)	n, K^+, K^0, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, Ω^-
(ix) B-S(excl. s-meson)	p, n, Λ, Σ^-, Σ^0, Σ^+,Ξ^-, Ξ^0, Ω^-
(x) B-S(excl. K^+)	p, n, K^0,Λ, Σ^-, Σ^0, Σ^+,Ξ^-, Ξ^0, Ω^-

Centrality Dependence(I): i-iv

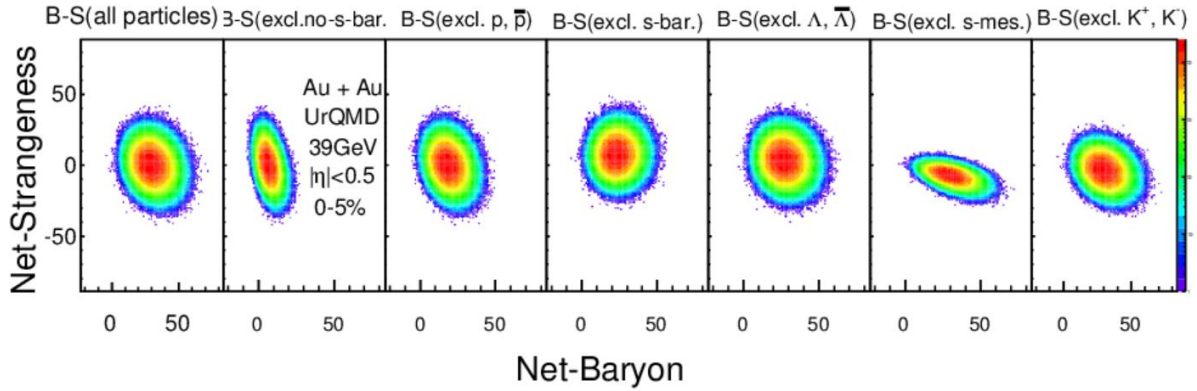


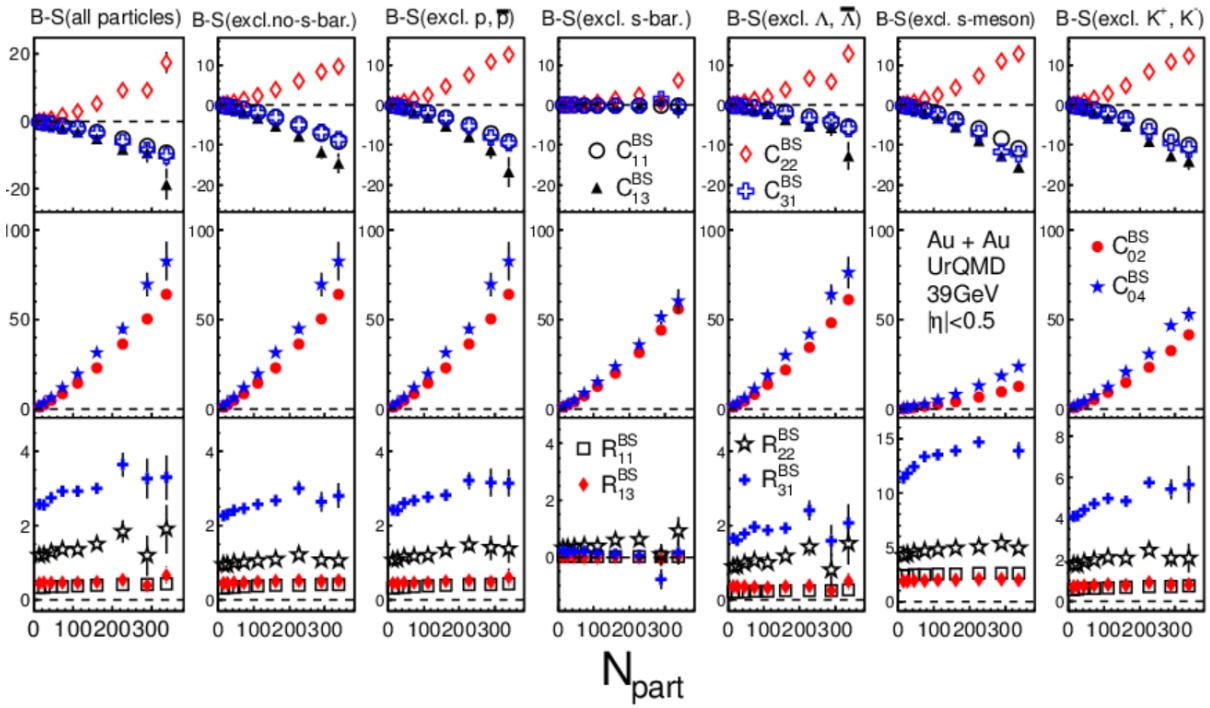




- Net-B and Net-S are anticorrelated;
- Net-P and Net-K are less correlated；
- Net-P and Net-Λ 、 Net-Λ and Net-K are correlated.

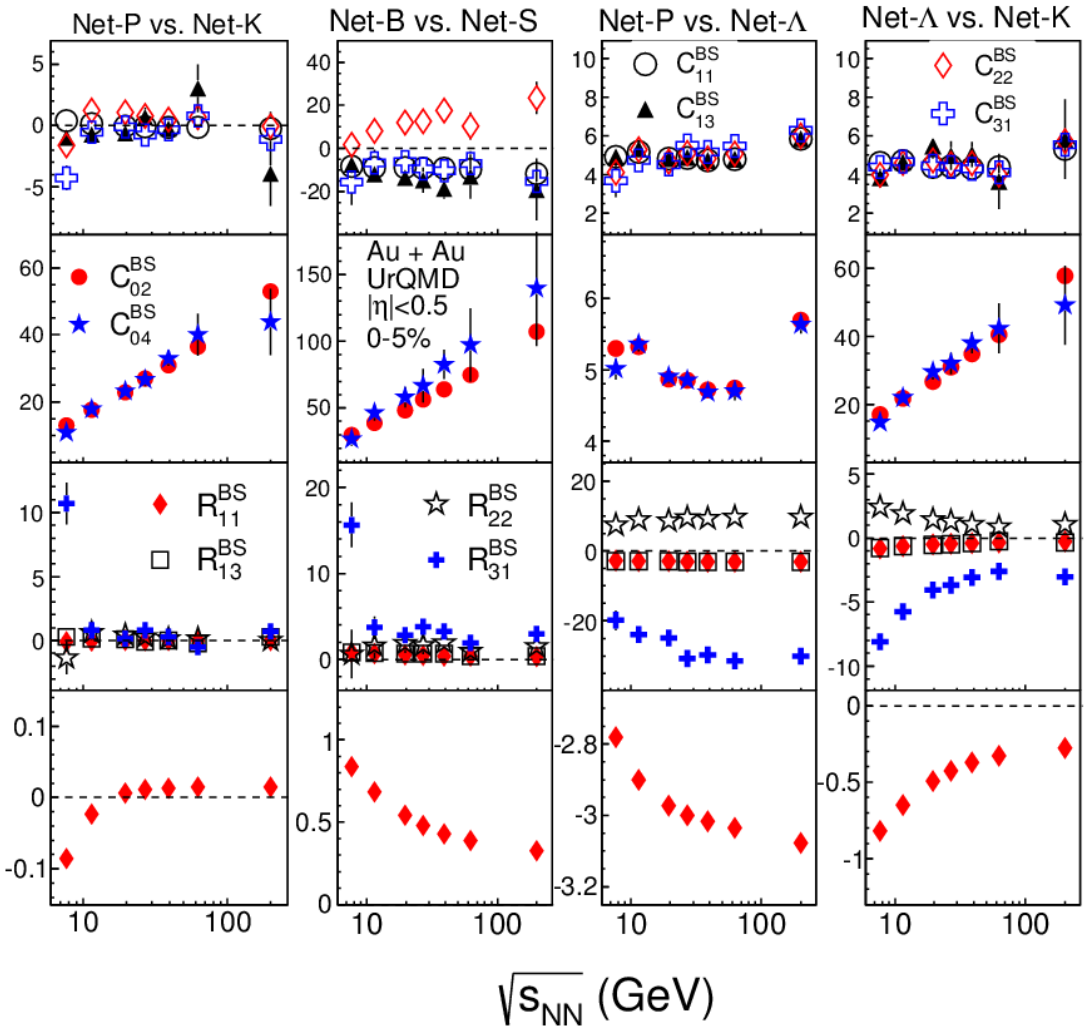
Centrality Dependence(II): iv-x





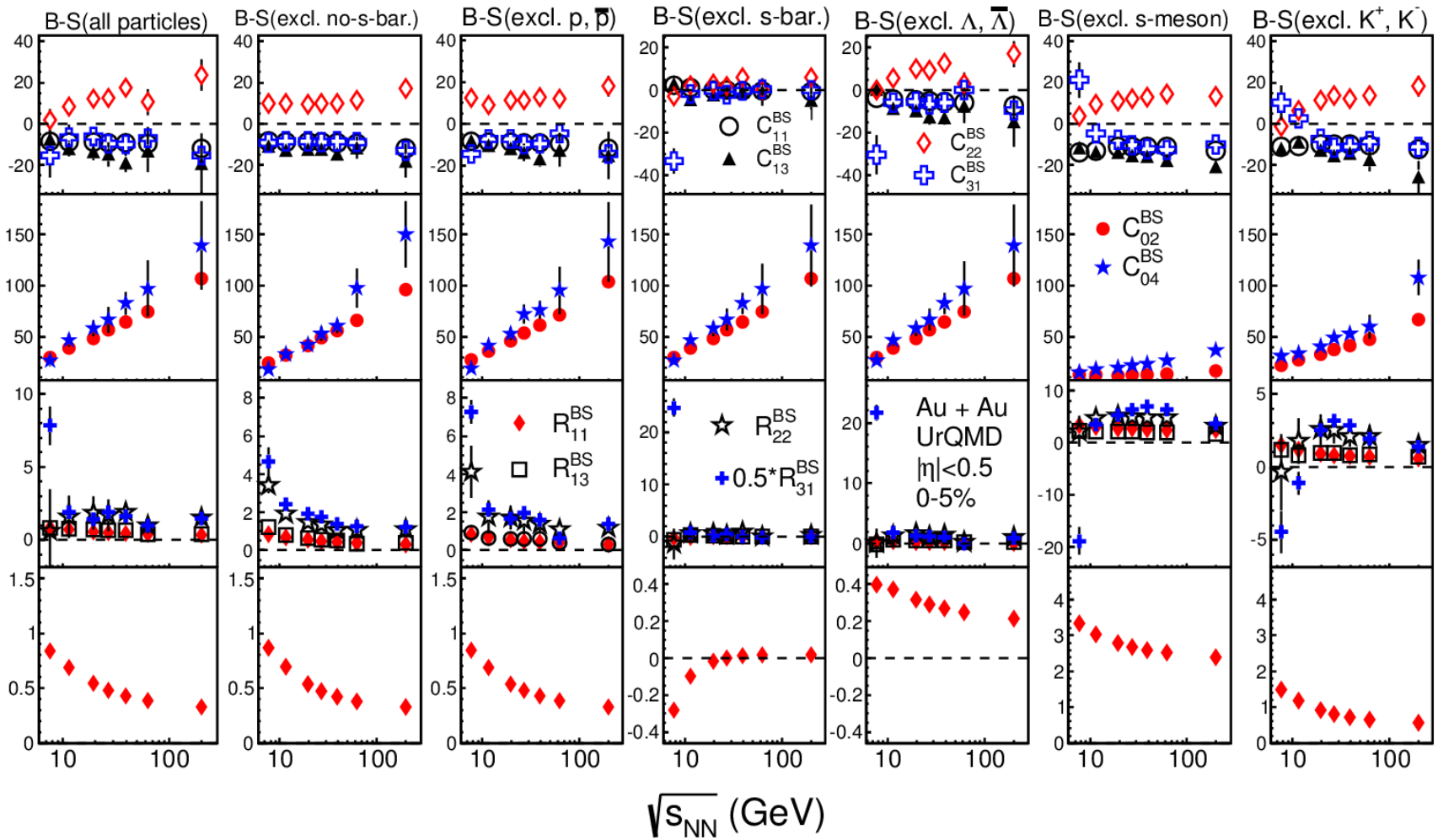
- S-baryons have contributions to B-S correlations.
- S-mesons have contributions to strangeness fluctuations.
- These ratios does not show any large centrality dependence.

Energy Dependence (I): i-iv



- The second order ratio is shown as a function of energy.
- The strangeness fluctuations of net- Λ is smaller than that of net-K.

Energy Dependence (II): iv-x



- The ratios have a strong species dependence.
- The higher order ratios are more sensitive to energy.

Summary

- **The centrality and energy dependence of B-S correlations.**
  - The ratios are comparable with the results from Lattice QCD.
  - The ratios show weakly centrality dependence.
  - The second order ratio is shown as a function of energy, higher order ratio is more sensitive to energy.

- **The contributions of particle species to the B-S correlations.**
  - Strange-baryons and Strange-mesons have contributions to the B-S correlations and strangeness fluctuations respectively.
  - The ratios have a strong species dependence.
  - Λ is at least included in the measurements.

Thanks for your listen!