Particle Production and Fluctuations at FAIR energies by using PHQMD model

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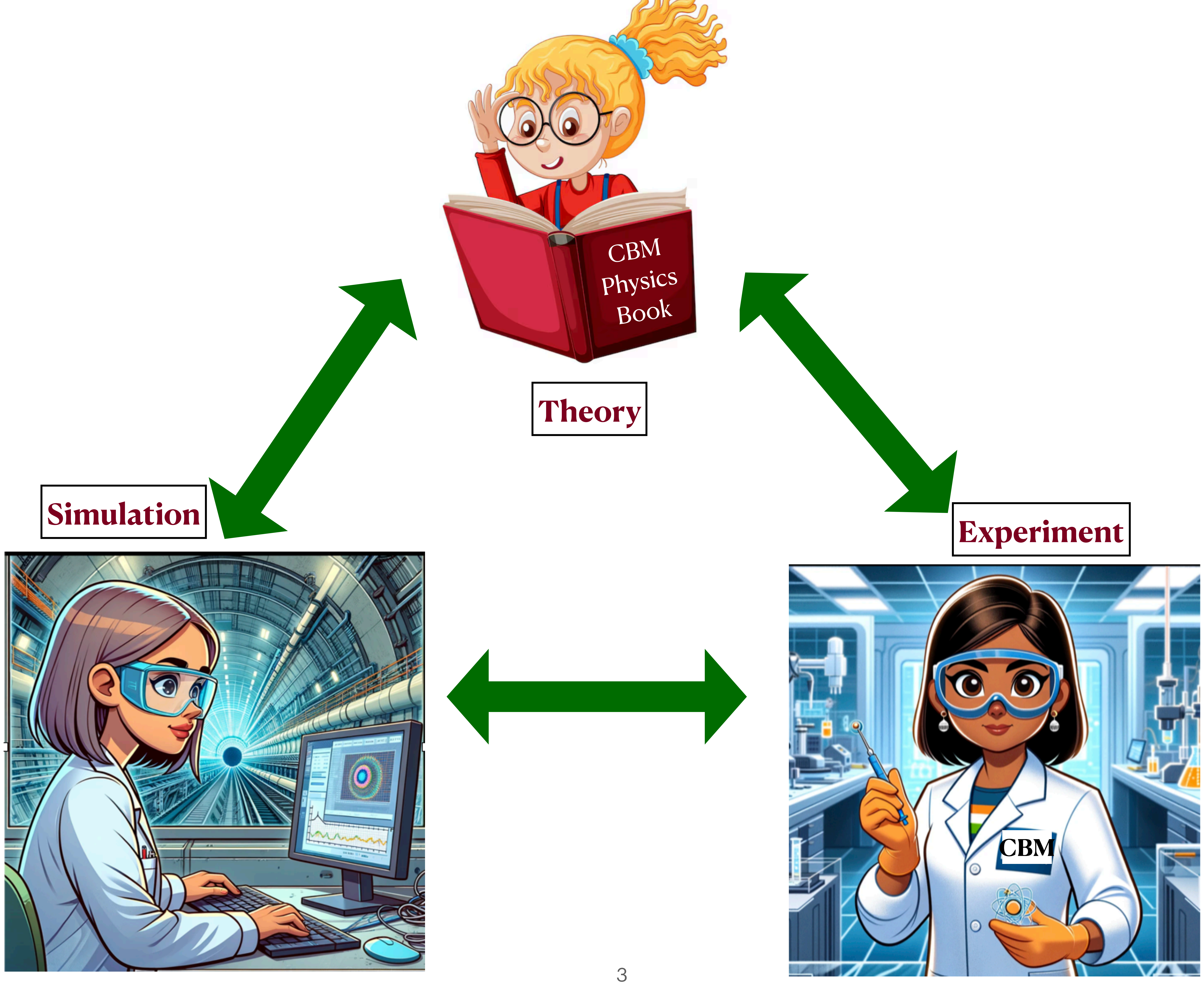
Outline

- Introduction
- Particle production
- Fluctuations of net-proton and net-kaon from minimum bias events
  - I. Using STAR acceptance and CBM acceptance
  - II.Energy dependence and Centrality dependence
  - III. Comparison between QGP ON and QGP OFF data for 7.7 GeV energy
- Summary


CBM
Physics
Book
Theory
Simulation
Experiment
CBM

Fluctuations in heavy-ion collisions

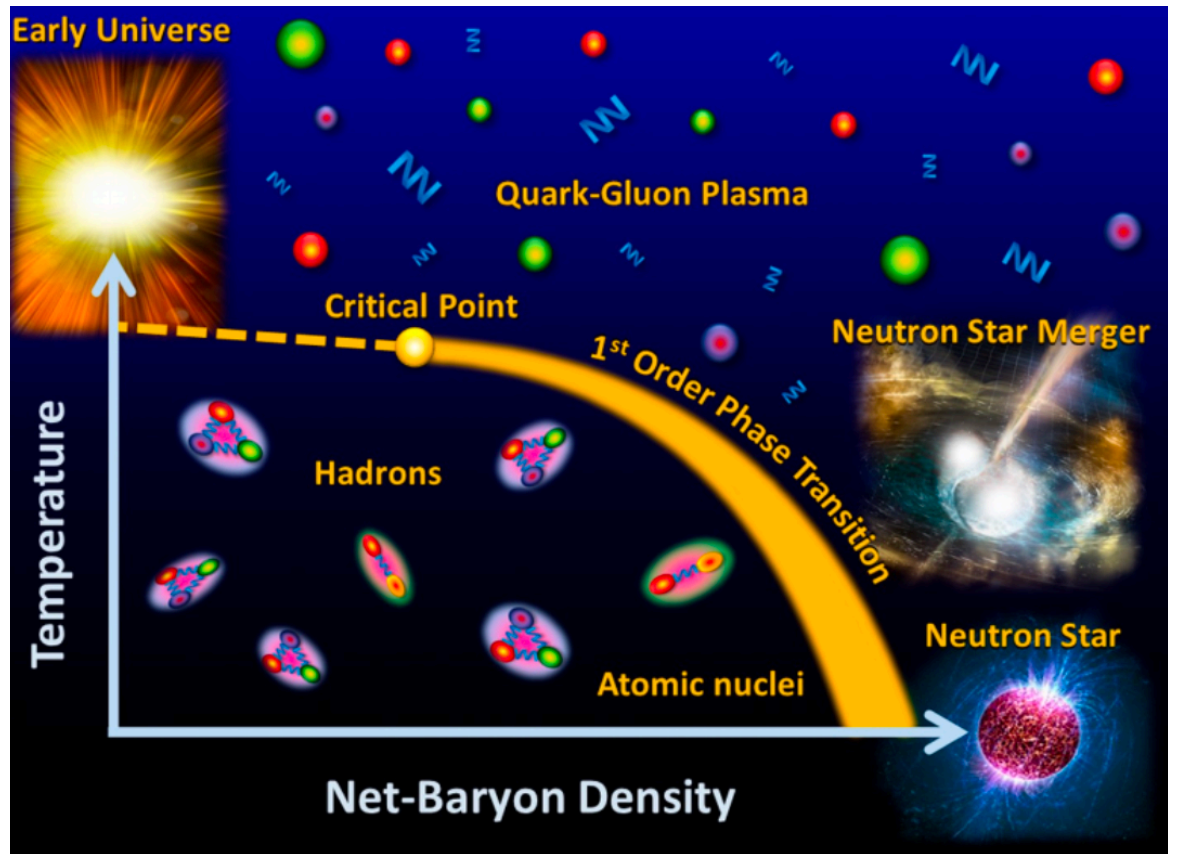
- Fluctuations are measured on event-by-event basis.
- The fluctuations are small, but measurable.
- Close to Gaussian, but non-Gaussianity is also measurable.
- If there is a critical point, fluctuation measures must be non-monotonic with collision energy (√s).
- Non-monotonic behavior is a necessary but not sufficient condition for the CEP.
- Correlation length diverges near critical point.

Experimental Observables

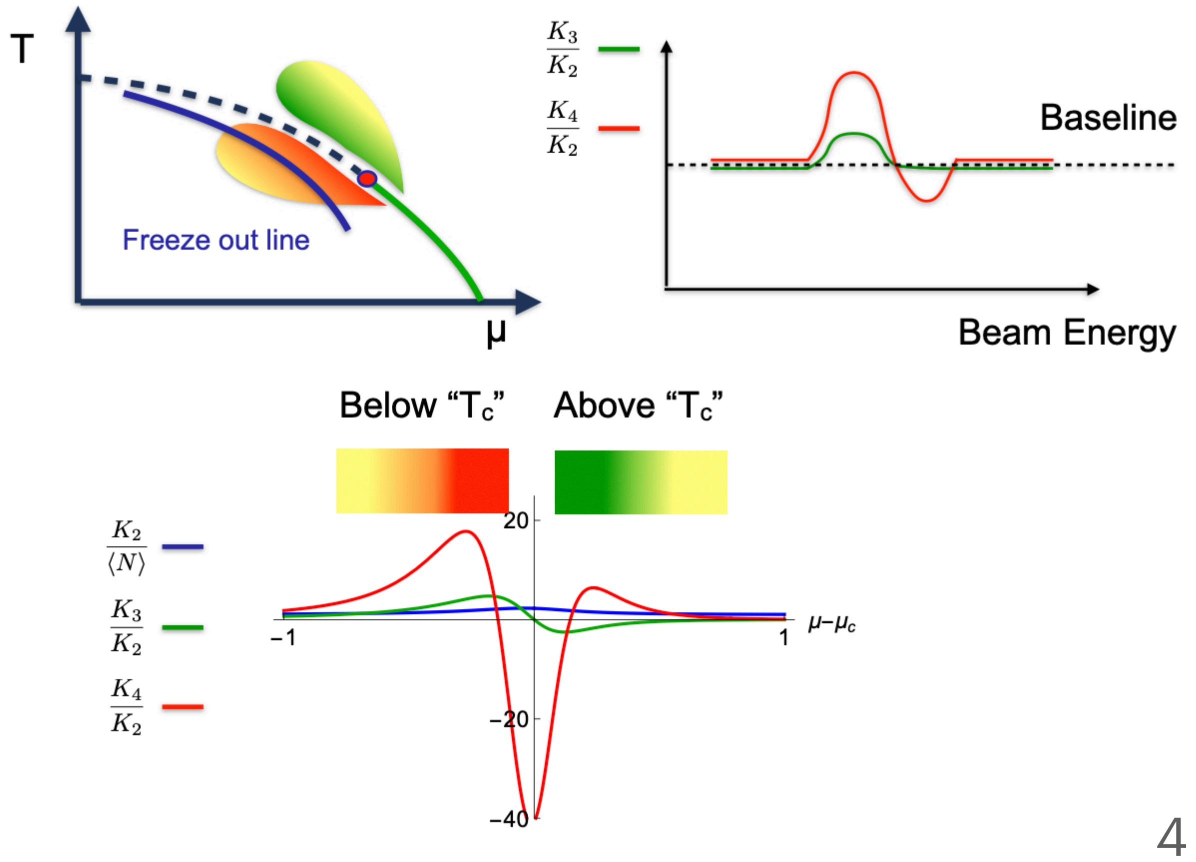
- Higher-order cumulants of net-particle multiplicities
  - Proxies for conserved charges (B, Q, S)
  - $\mu_r = \langle (N - \langle N \rangle)^r \rangle$: rth-order central moment
  - $C_1 = M = \langle N \rangle = VT^3\chi_1^q$
  - $C_2 = \sigma^2 = \mu_2 = VT^3\chi_2^q \sim \xi^2$
  - $C_3 = S\sigma^3 = \mu_3 = VT^3\chi_3^q \sim \xi^{4.5}$
  - $C_4 = \kappa\sigma^4 = \mu_4 - 3\mu_2^2 = VT^3\chi_4^q \sim \xi^7$
  - $C_5 = \mu_5 - 10\mu_3\mu_2 = VT^3\chi_5^q \sim \xi^{9.5}$
  - $C_6 = \mu_6 - 15\mu_4\mu_2 - 10\mu_3^2 + 30\mu_2^3 = VT^3\chi_6^q \sim \xi^{12}$
  - Sensitive to correlation length (ξ)

Lattice uses grand canonical ensemble

- Directly connected to susceptibilities (χ_r^q, $q = B, Q, S$)
  - $\frac{C_3^q}{C_2^q} = S\sigma = \frac{\chi_3^q}{\chi_2^q}$, $\frac{C_4^q}{C_2^q} = \kappa\sigma^2 = \frac{\chi_4^q}{\chi_2^q}$



What to expect?



Ref: M.A. Stephanov, PRL 102, 032301 (2009)
Picture taken from Volker Koch, titled - "Exploring the QCD phase diagram with fluctuations and correlations" presented in 63rd Cracow School, Zakopane, Poland

Motivation of our work

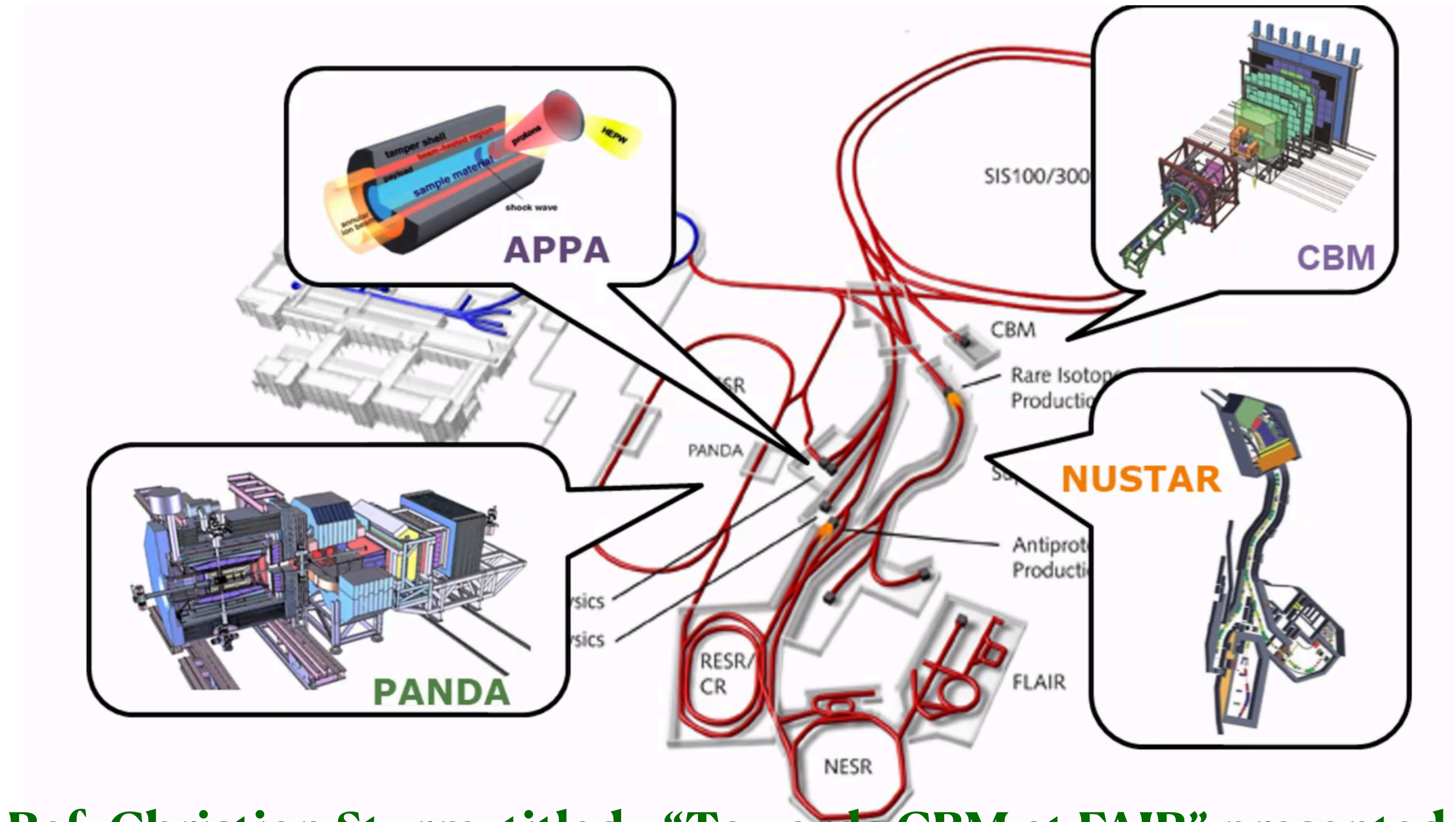
- **Study Net-Proton and Net-Kaon Number Fluctuations in the CBM energy range.**

Looking for the non-monotonicity of the moments of net-baryon number with collision energy which is suggested as a signature for QCD critical point.

Higher-order cumulants will be studied for enhanced critical signals.

- **Looking into the strangeness enhancement which is an indicator of QGP formation.**

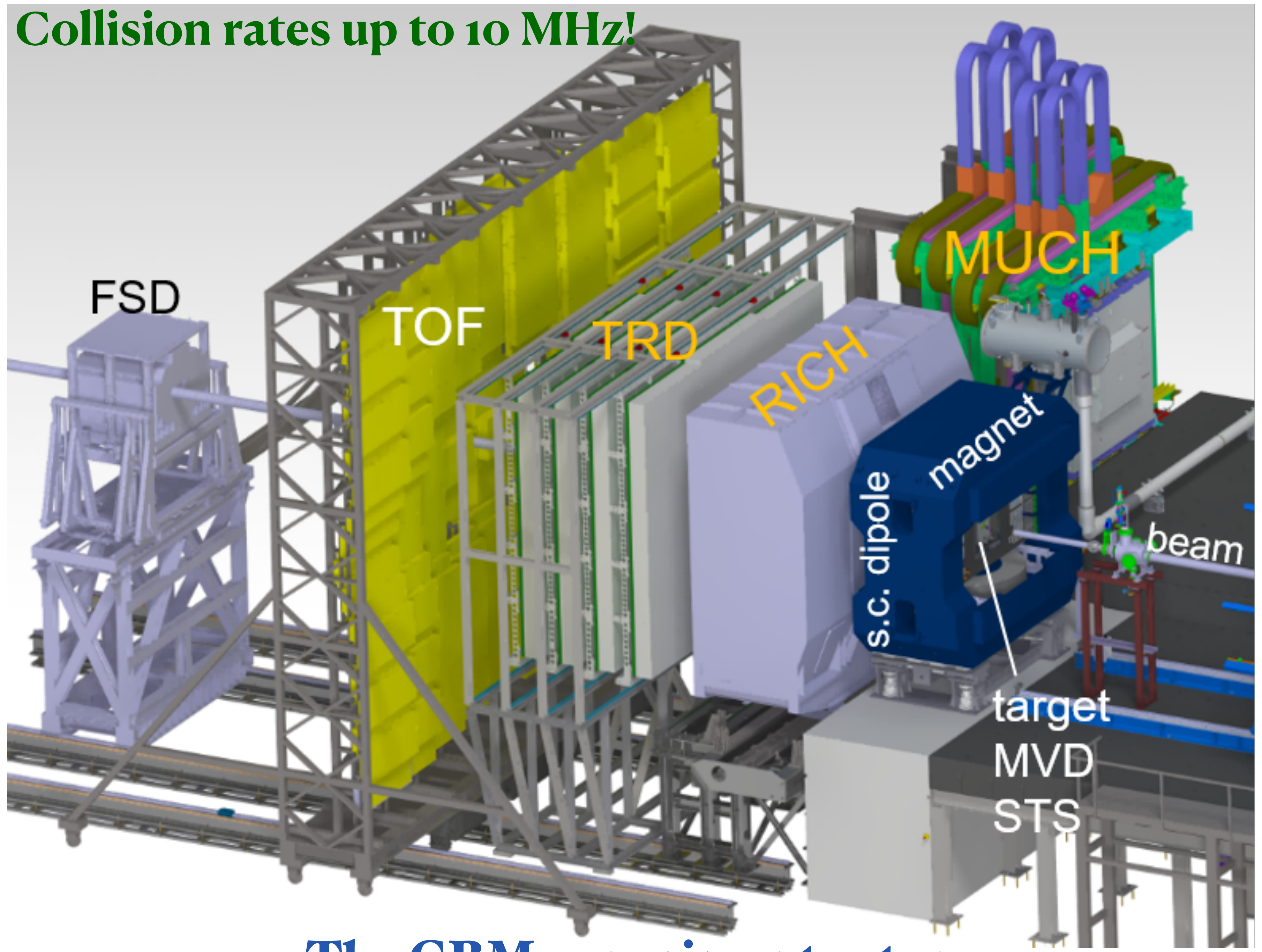
Facility for Antiproton and Ion Research (FAIR) and Compressed Baryonic Matter (CBM) Experiment



- 1. APPA (Atomic Plasma Physics Applications)
- 2. PANDA (antiProton ANnihilation at DArmstadt)
- 3. CBM (Compressed Baryonic Matter)
- 4. NUSTAR (NUclear STructure, Astrophysics and Reactions)

Ref: Christian Sturm, titled - “Towards CBM at FAIR” presented in MPACS, VECC, Kolkata

Collision rates up to 10 MHz!



The CBM experiment setup

- Equation-of-state (EOS) at high net baryon densities in neutron star cores.
- In-medium properties of hadrons.
- Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities.
- Study of strange dibaryons, hypernuclei, and massive strange objects.
- Mechanisms of charm production, propagation, and in-medium properties in nuclear matter.

Parton-Hadron-Quantum-Molecular Dynamics (PHQMD)

PHSD + QMD + MST

Relativistic considerations

but: mean-field potentials
=> correlations are smeared out

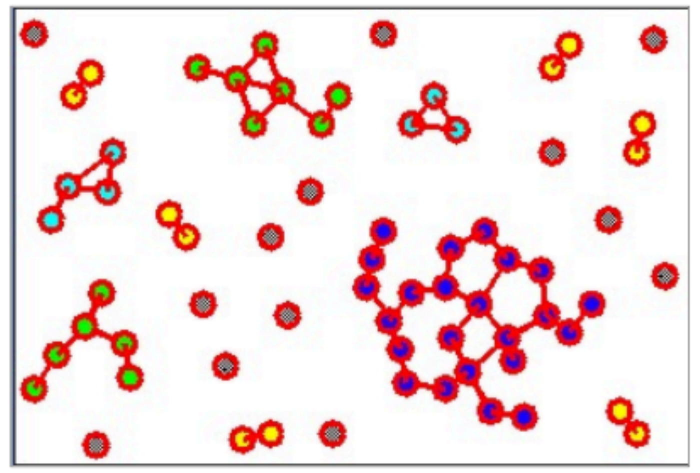
Correlations between baryons

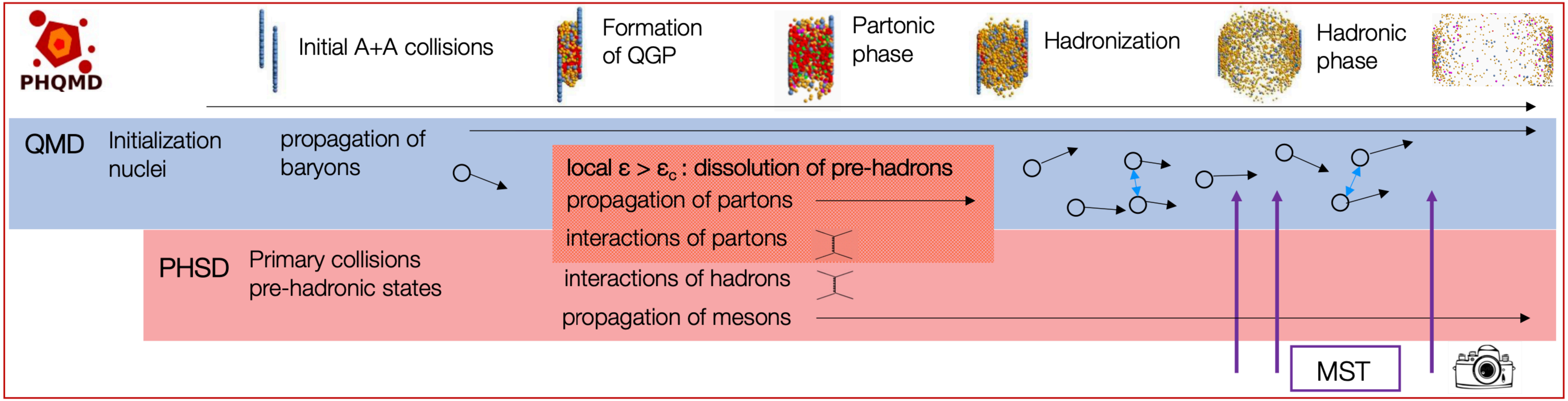
n-body transport approach

=> formation of clusters due to potential interactions

Cluster recognition

search for accumulations of particles in coordinate space



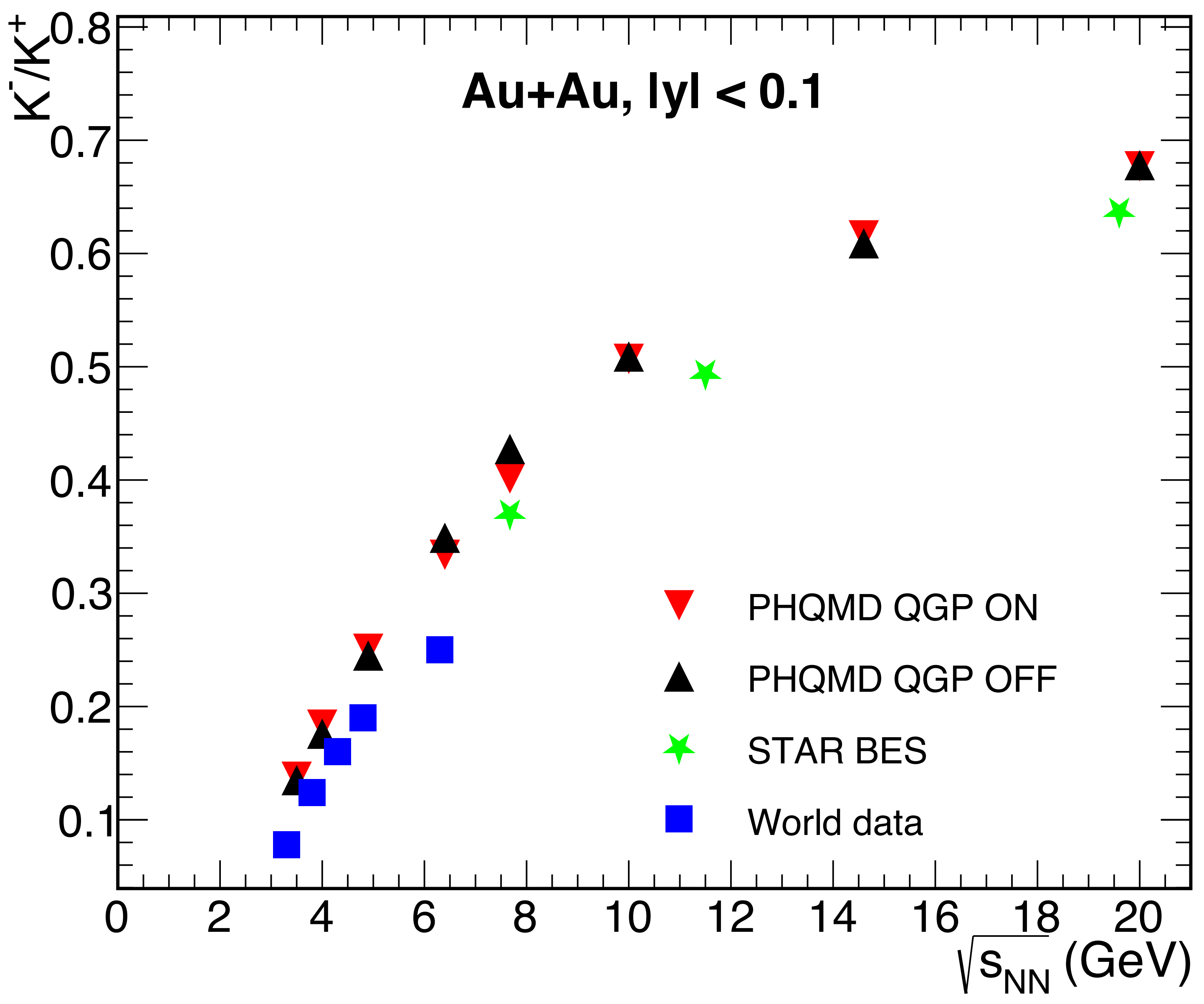


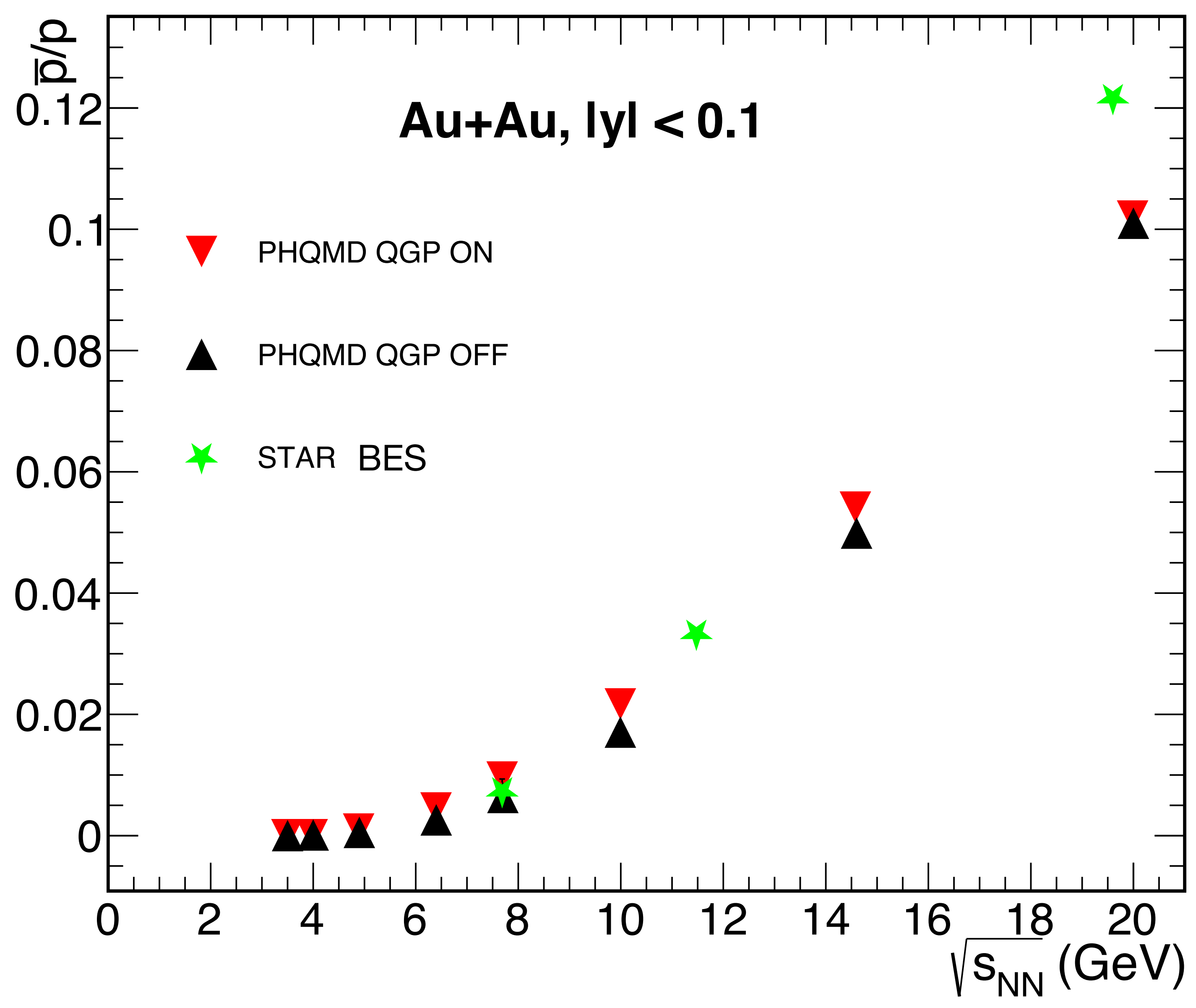
Ref: J. Aichelin et al., PRC 101 (2020) 044905 PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168(20039)
Slide taken from Susanne Gläßel, IKF Frankfurt,titled - "Update on the hypertriton 3-body-decay reconstruction" presented in 42nd CBM Collaboration meeting, Bucharest

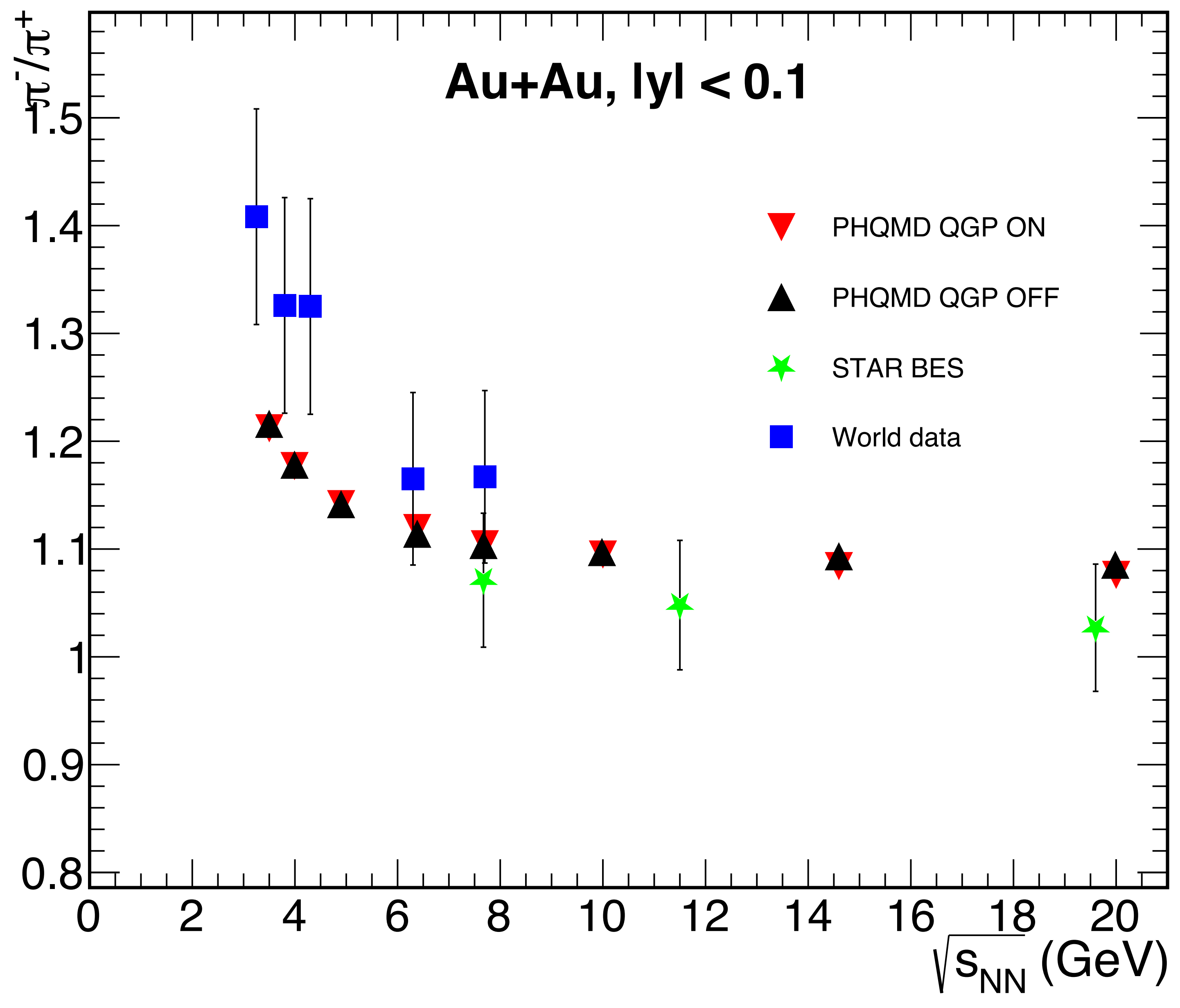
Two approaches have been considered

1. PHQMD minimum bias events (**2 Million**) for Au+Au collisions; centrality is estimated from all particle multiplicity distribution.
2. PHQMD data sets considering b_{max}=3.2 fm for Au+Au collisions are also generated for different energies.

Particle Ratio vs Energy







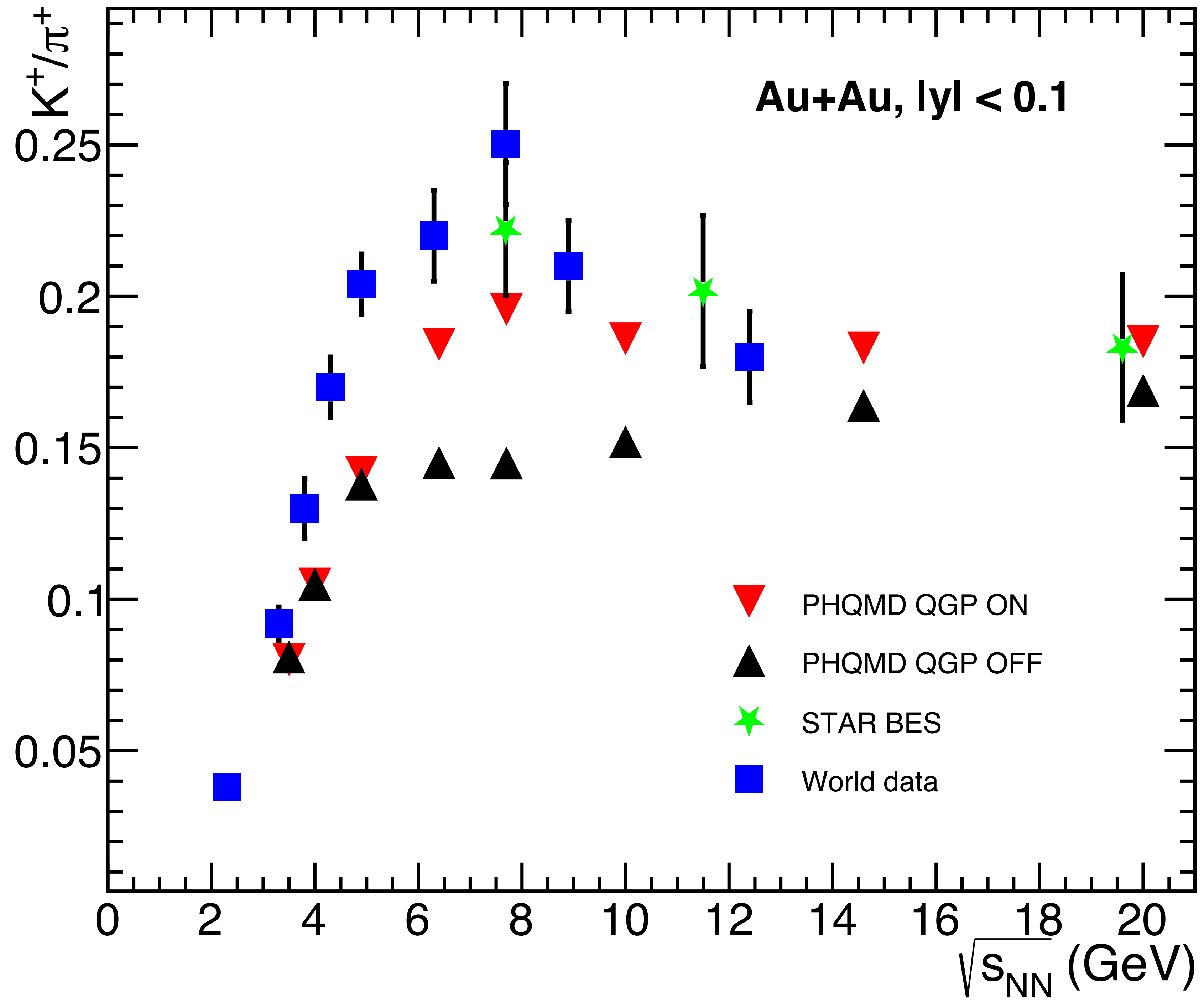
K^-/K^+ , $\bar{p}/p$ & π^-/π^+ratio of PHQMD model at mid-rapidity considering b_{max}=3.2 fm and compared with 0-5% central mid-rapidity data

- K^-/K^+ at BES energies are significantly less than unity.
- Suppression of K^- occurs due to associated production with hyperons like Λ.
- Strangeness is conserved, but s quarks favor anti-kaons and hyperons, while $\bar{s}$ quarks primarily form kaons.

- With increasing $\sqrt{s_{NN}}$, the $\bar{p}/p$ ratio rises, nearing unity at top RHIC energies. Higher beam energies lead to greater collision transparency, with mid-rapidity proton and antiproton production mainly from pair production.

Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

Strangeness enhancement



K^+/π^+ratio of PHQMD model at mid-rapidity considering b_{max}=3.2 fm and compared with 0-5% central mid-rapidity data

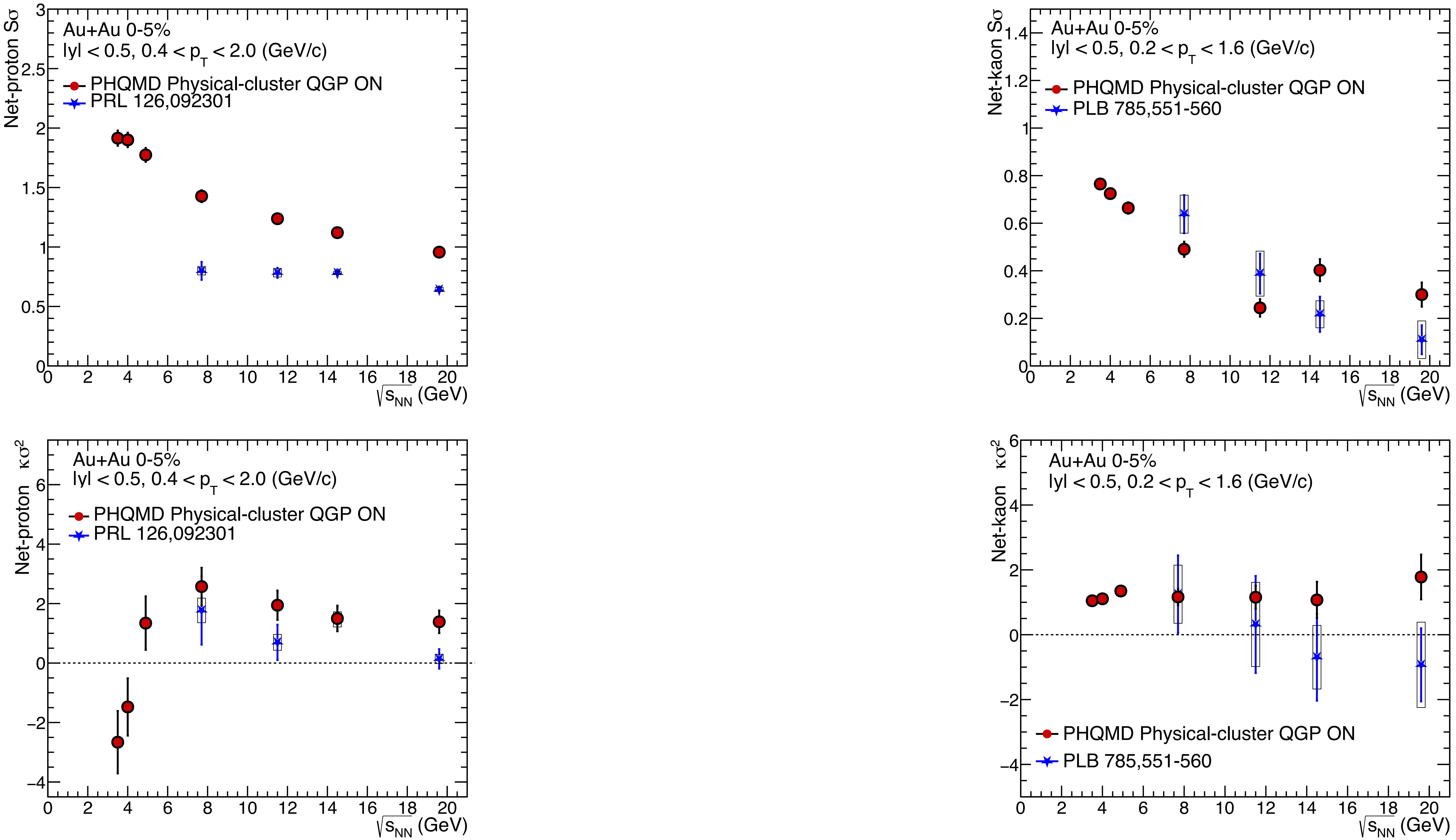
- A clear distinction is observed between QGP ON and OFF states in the K^+/π^+ ratio within 6-10 GeV.
- QGP ON scenario: K^+/π^+ ratio aligns well with experimental data.
- QGP OFF scenario: No "horn" structure observed, highlighting the impact of QGP on particle ratios.

Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

Energy Dependence of $s\sigma$ and $\kappa\sigma^2$ for Protons and Kaons for STAR acceptance

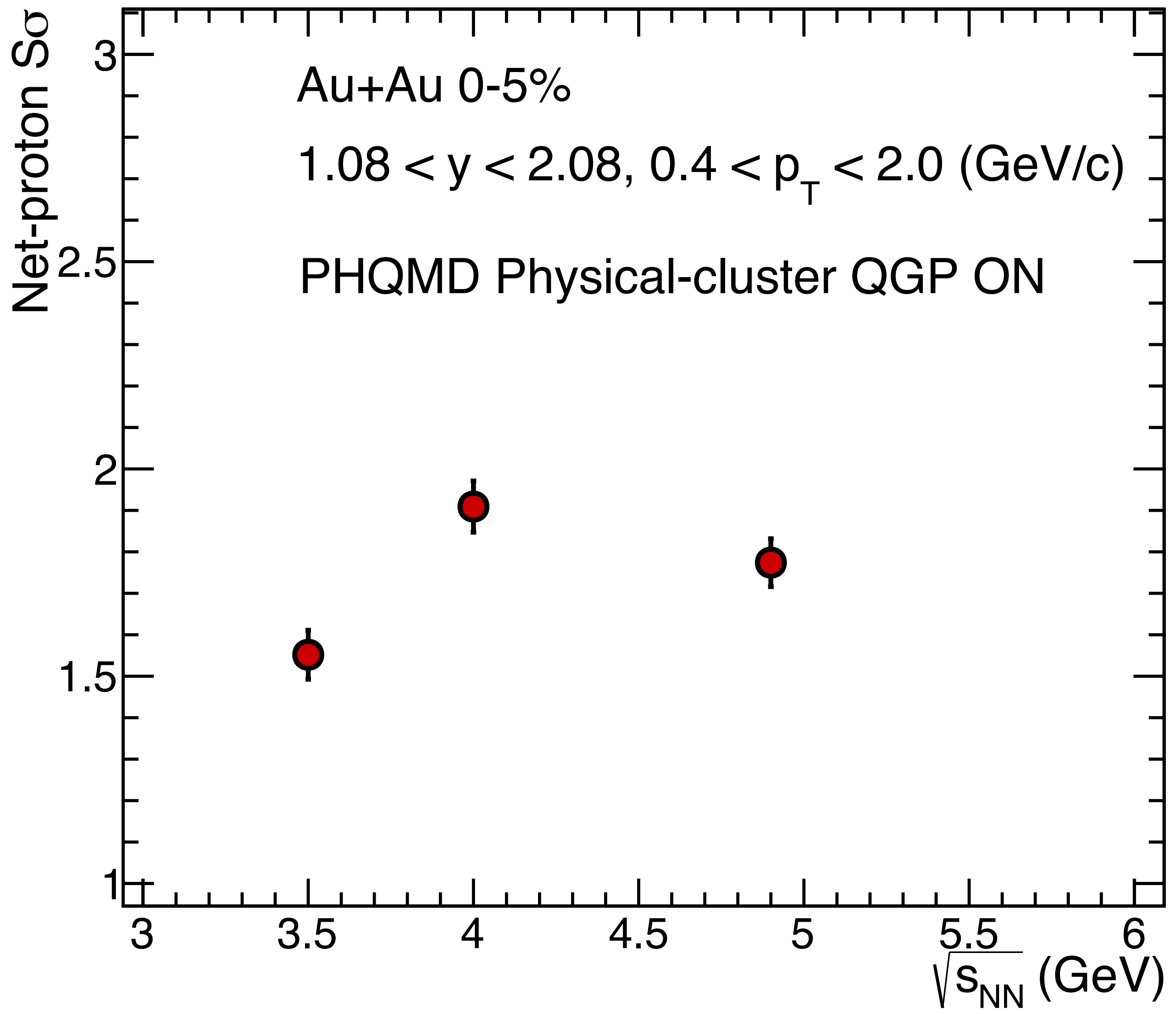
Proton

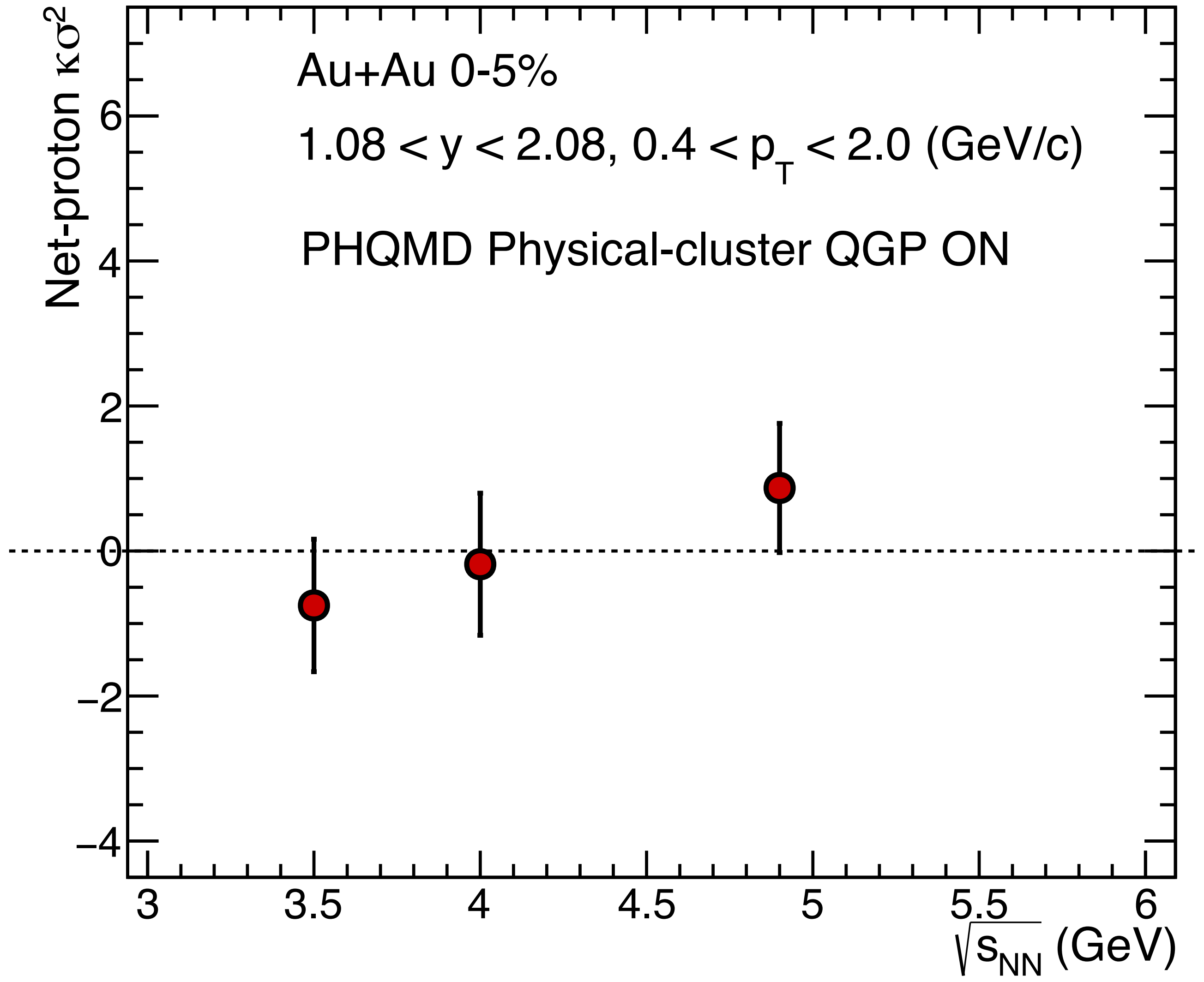
Kaon



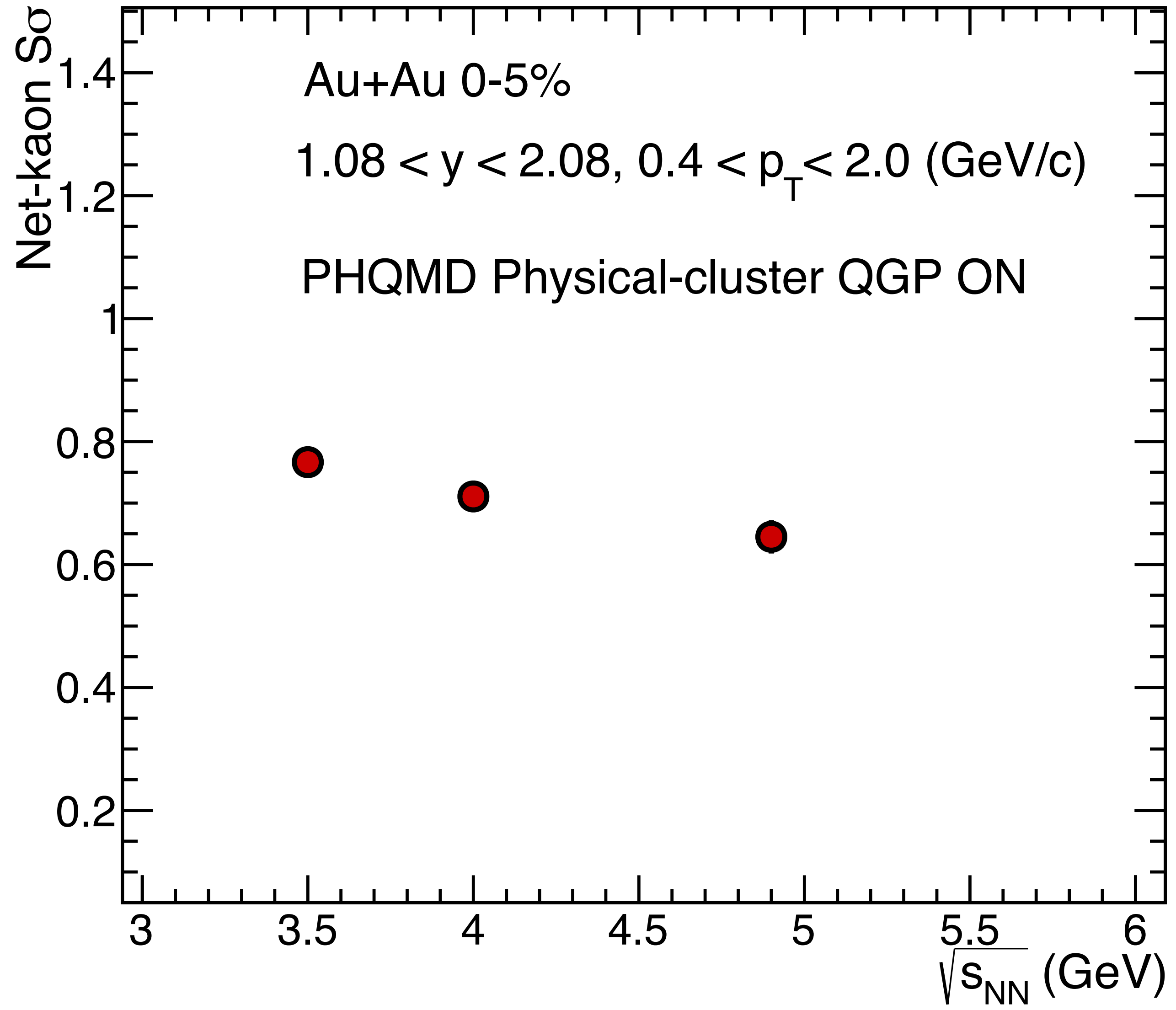
Energy Dependence of $s\sigma$ and $\kappa\sigma^2$ for Protons and Kaons for CBM acceptance

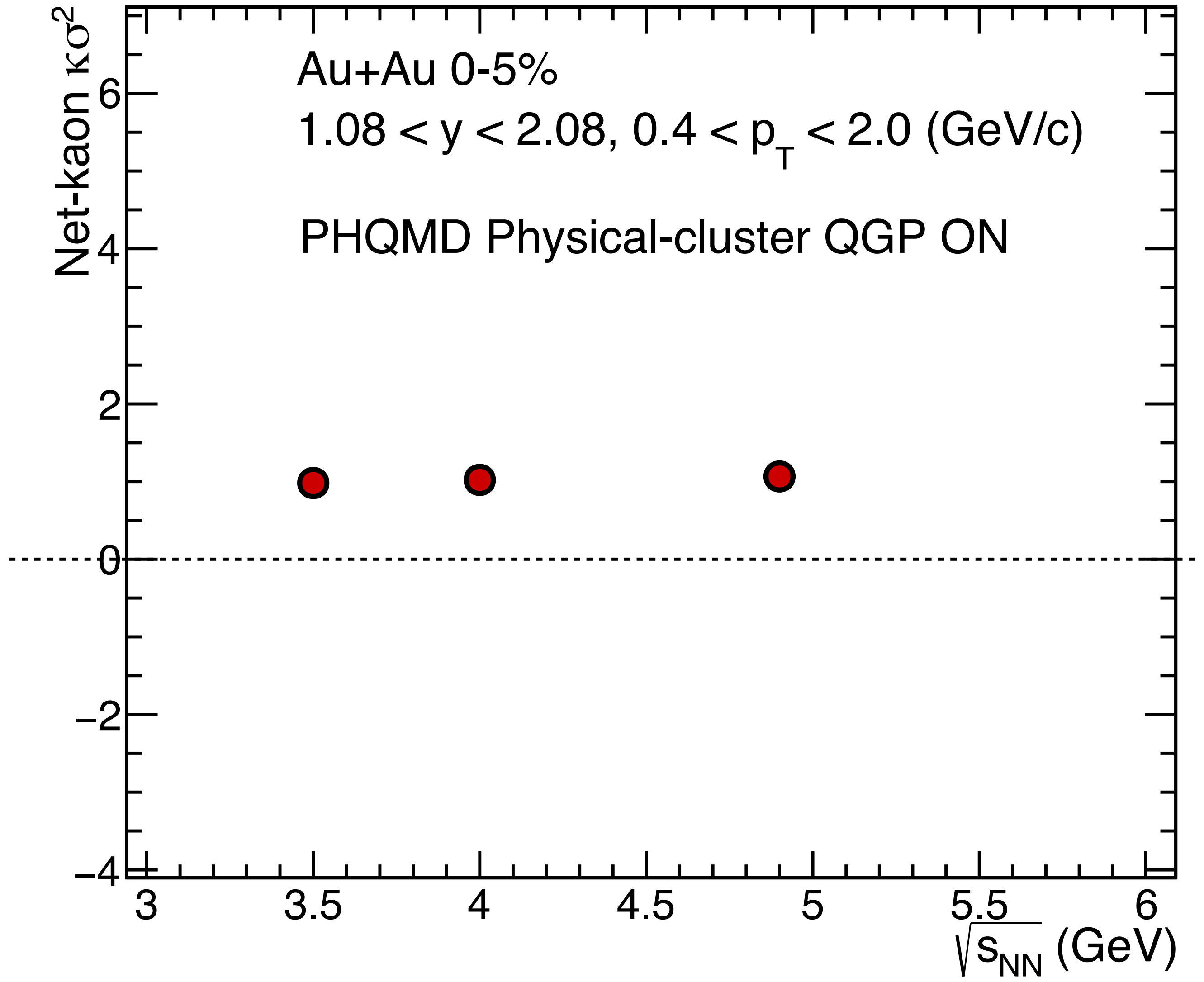
Proton





Kaon

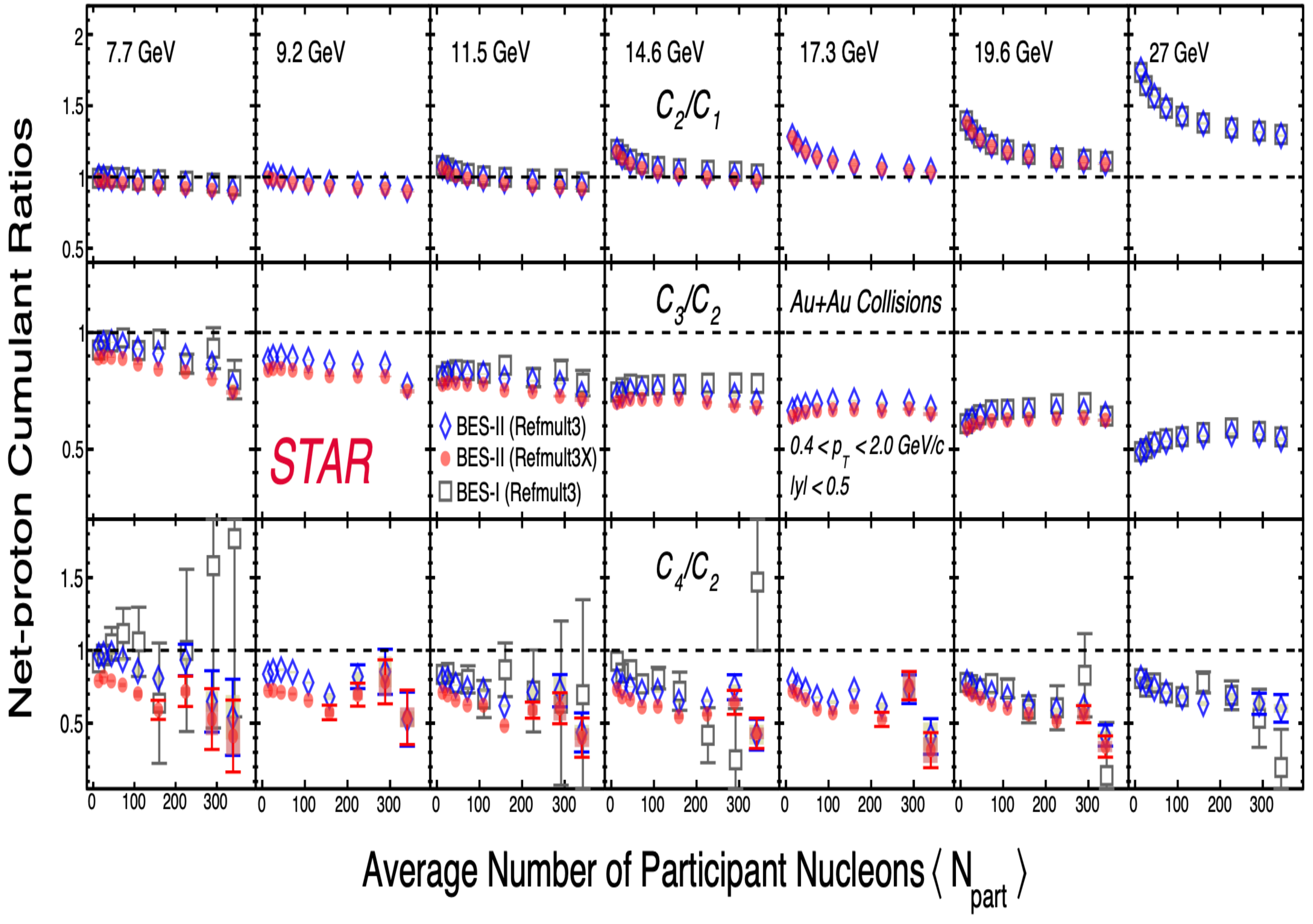




Centrality Dependence of $s\sigma$ and $\kappa\sigma^2$ for Protons

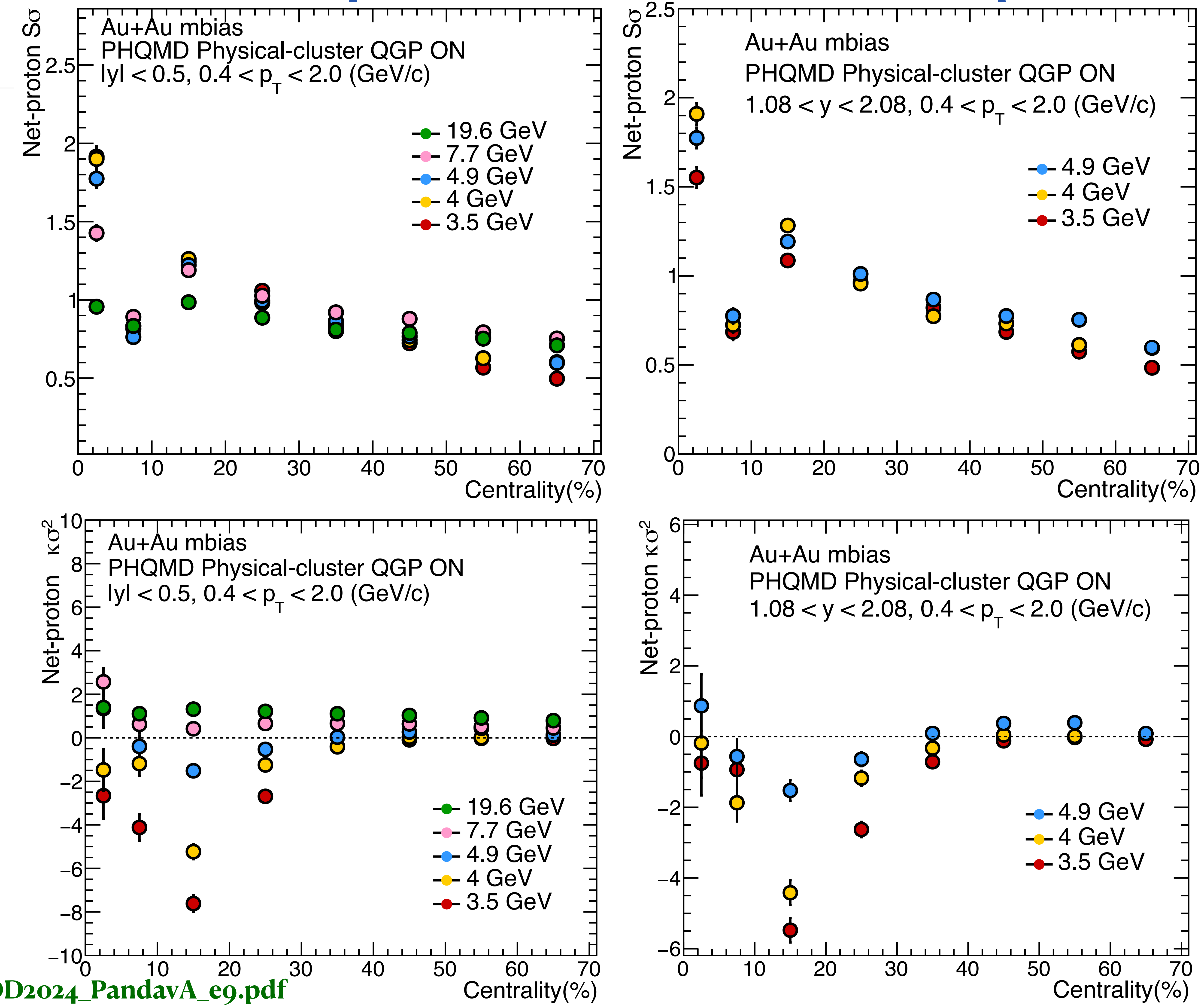
STAR Results

CENTRALITY DEPENDENCE AND COMPARISON WITH BES-I



PHQMD Results

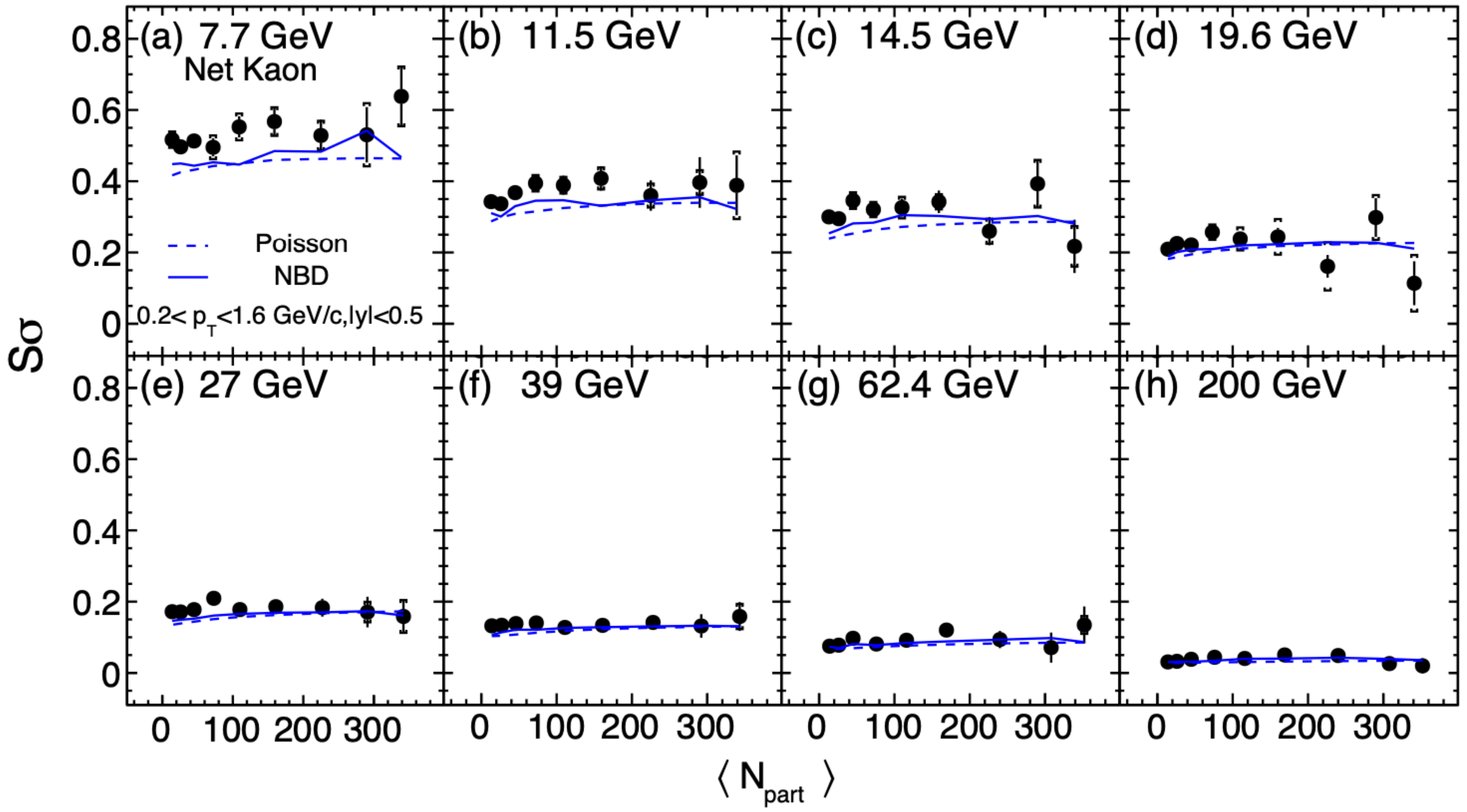
STAR acceptance | CBM acceptance

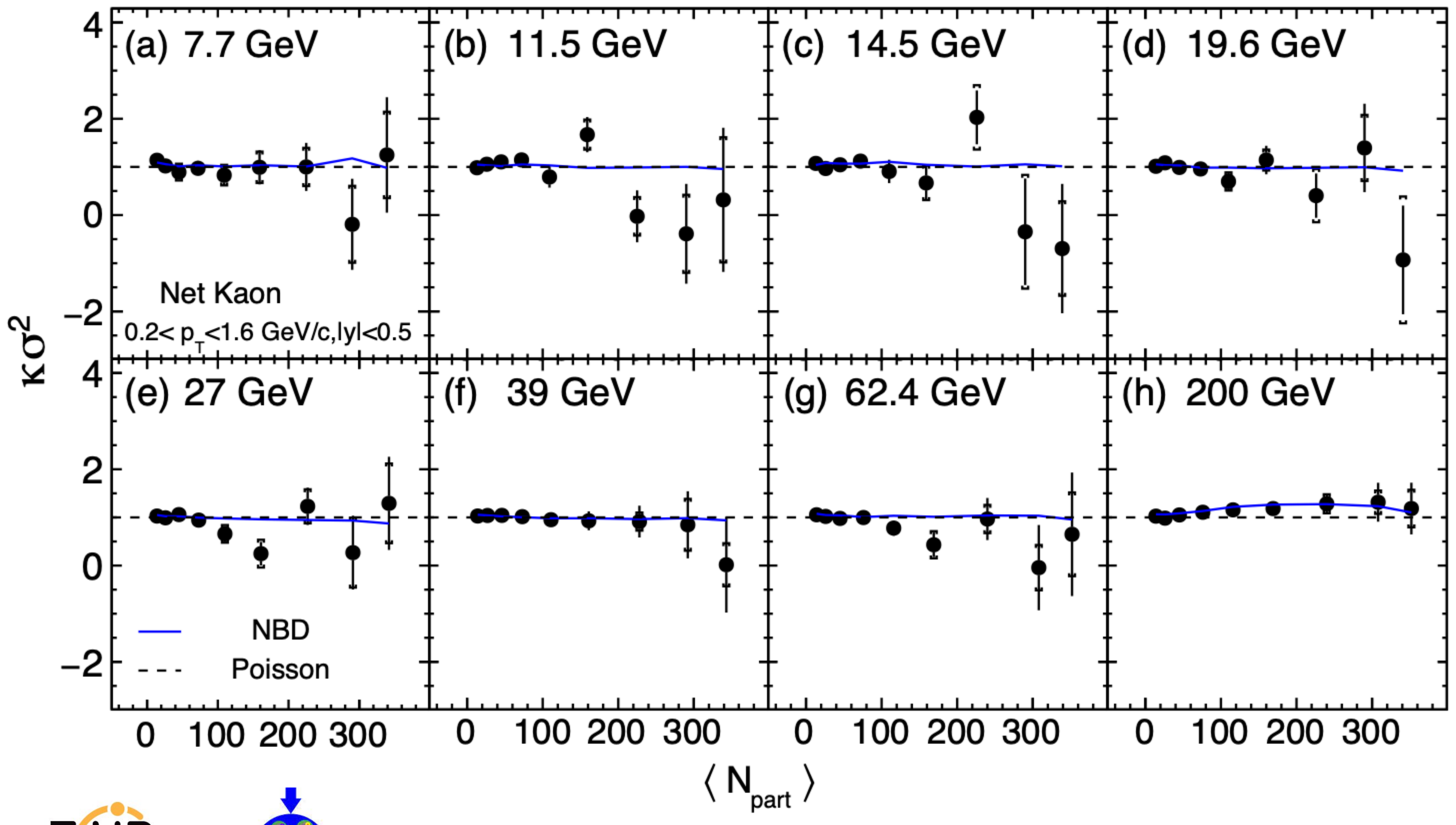


Ref: https://conferences.lbl.gov/event/1376/contributions/8772/attachments/5163/4984/CPOD2024_PandavA_e9.pdf

Centrality Dependence of *sσ* and *κσ²* for Kaons

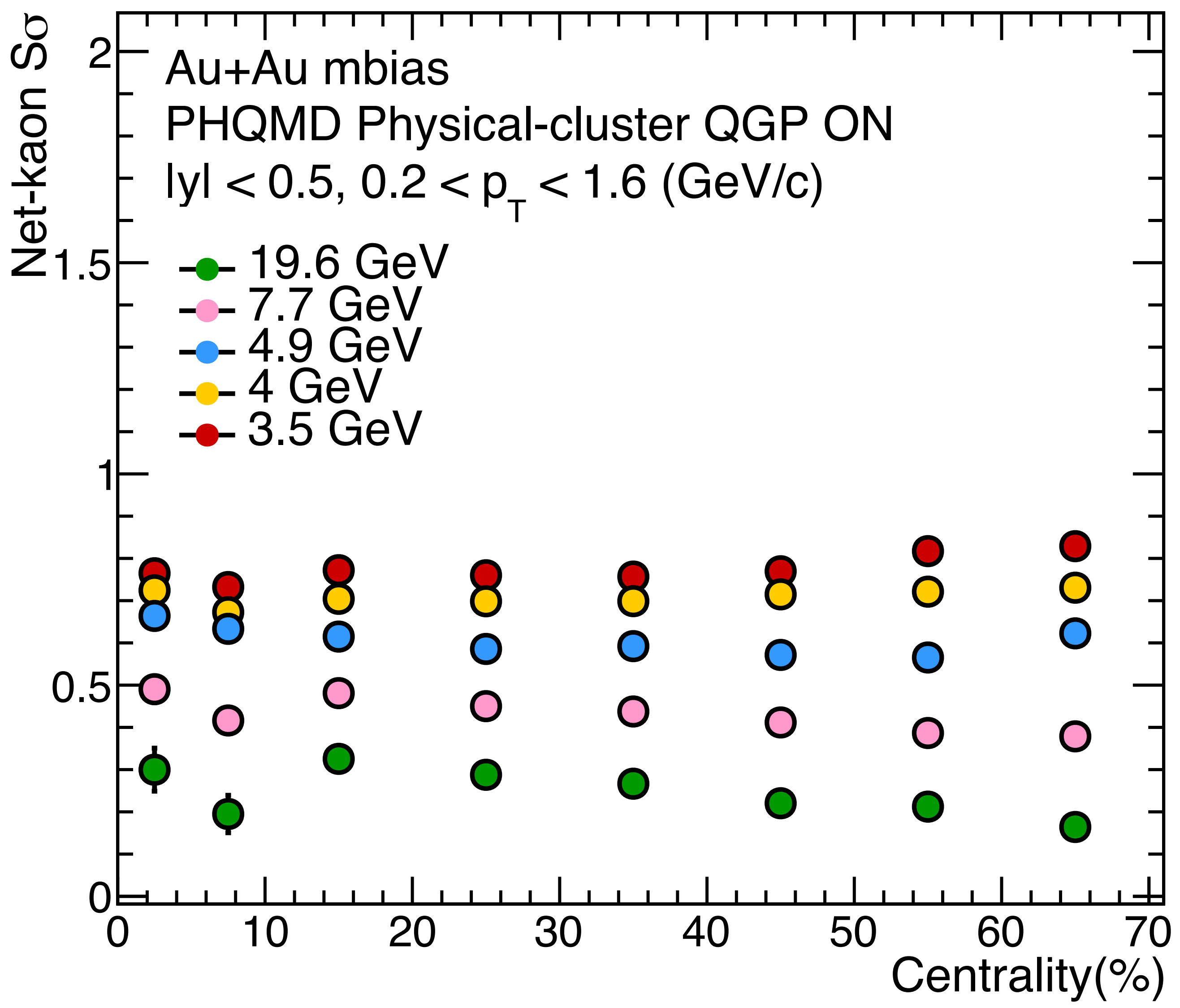
STAR Results

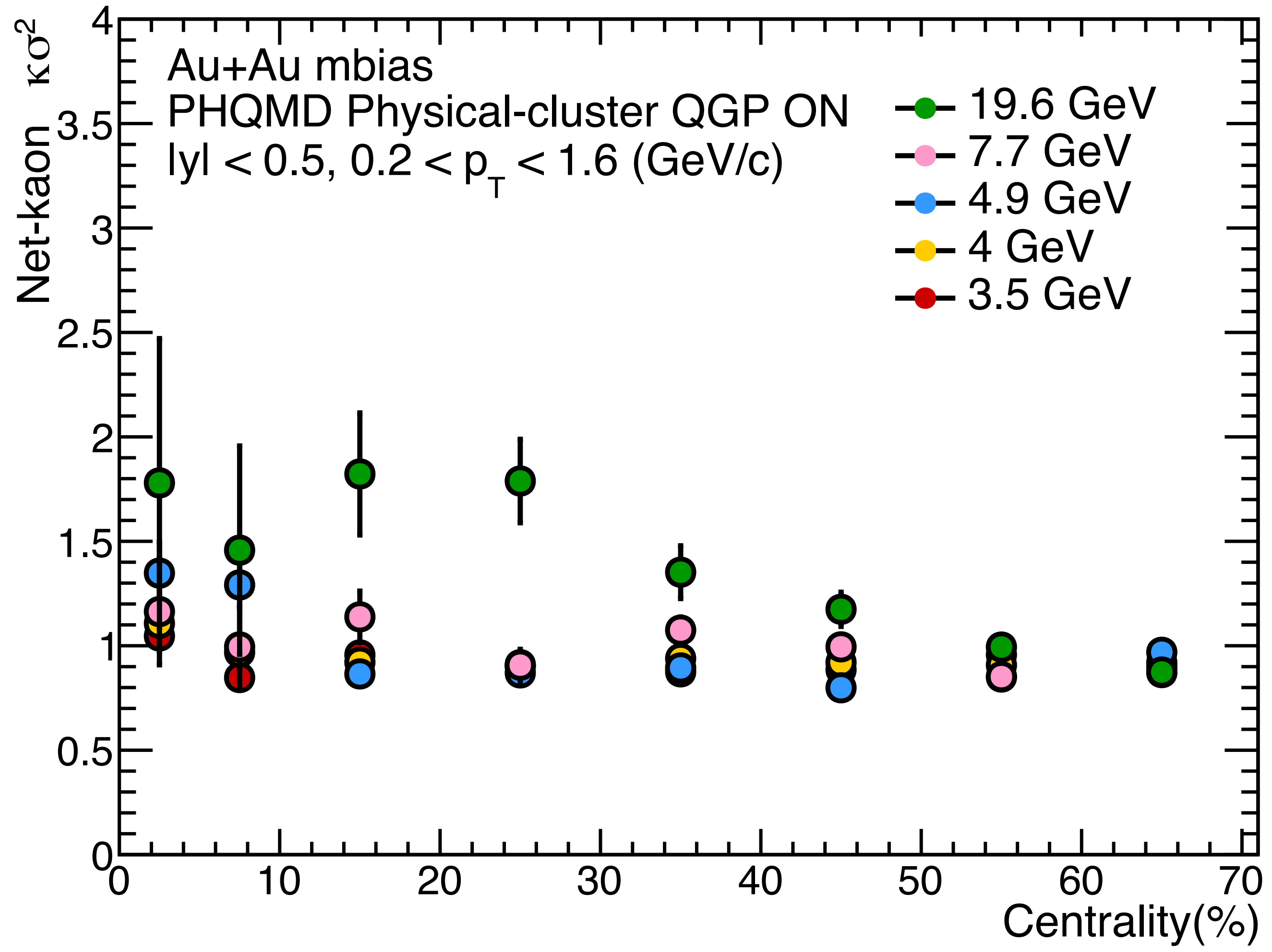




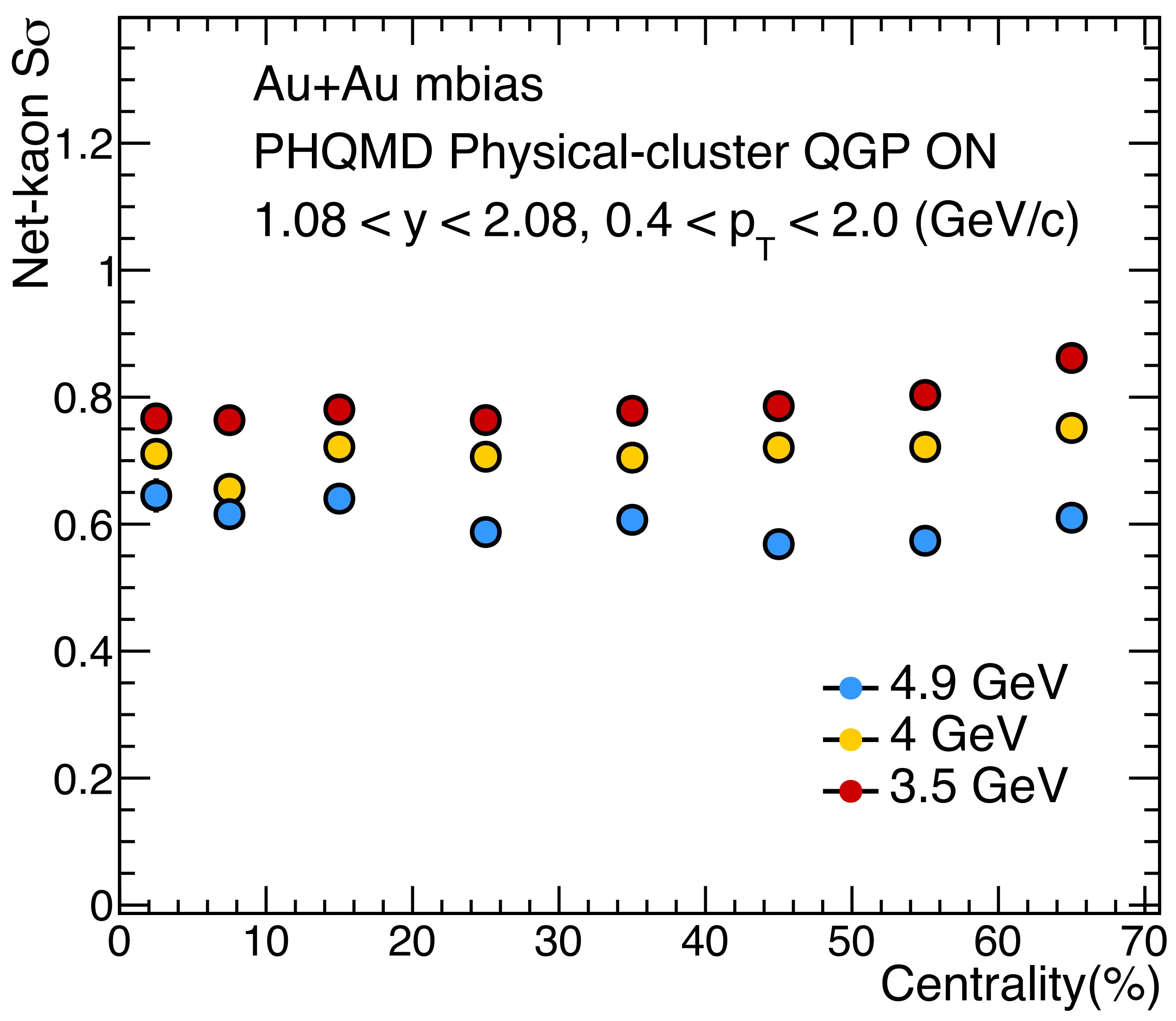
PHQMD Results

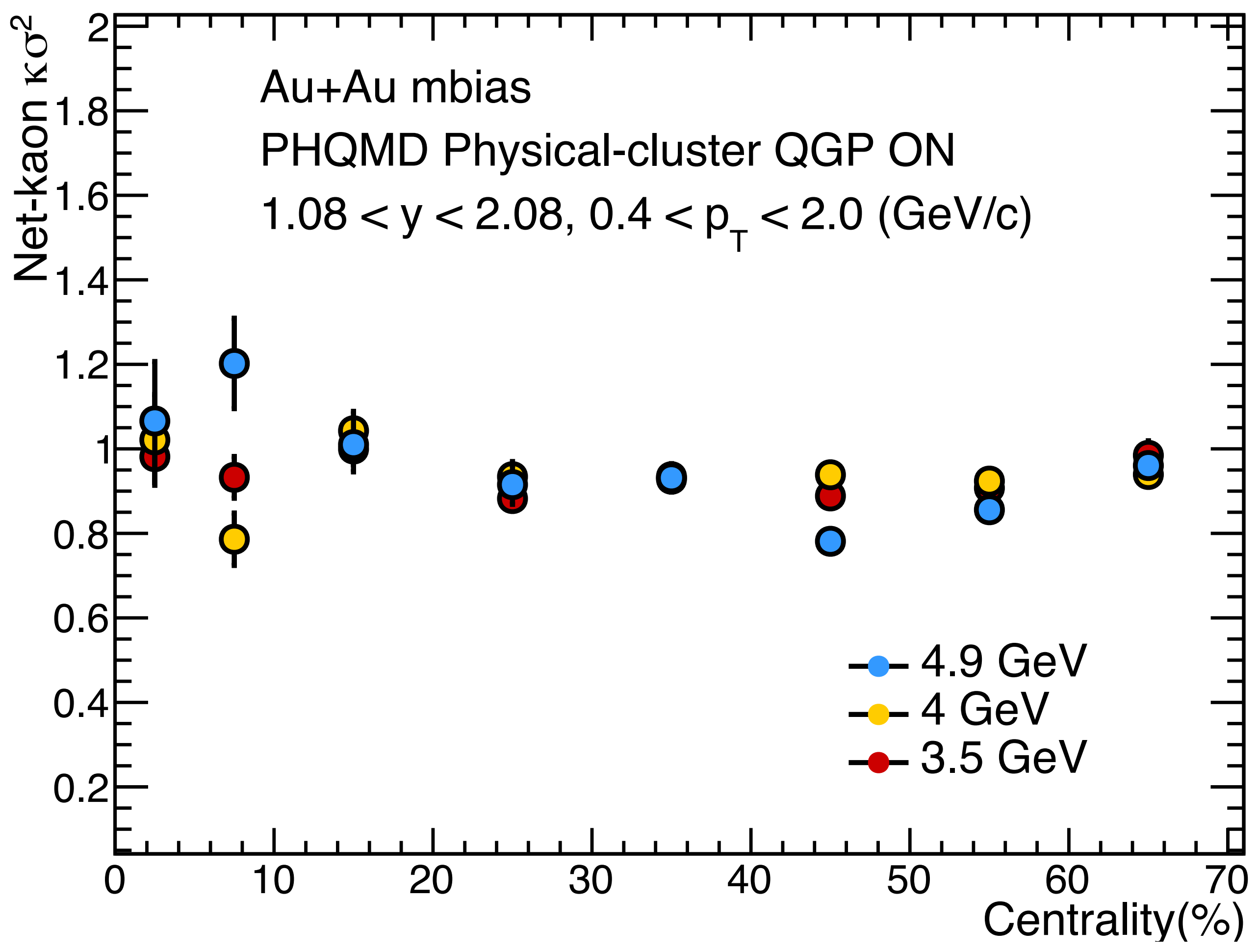
STAR acceptance





CBM acceptance

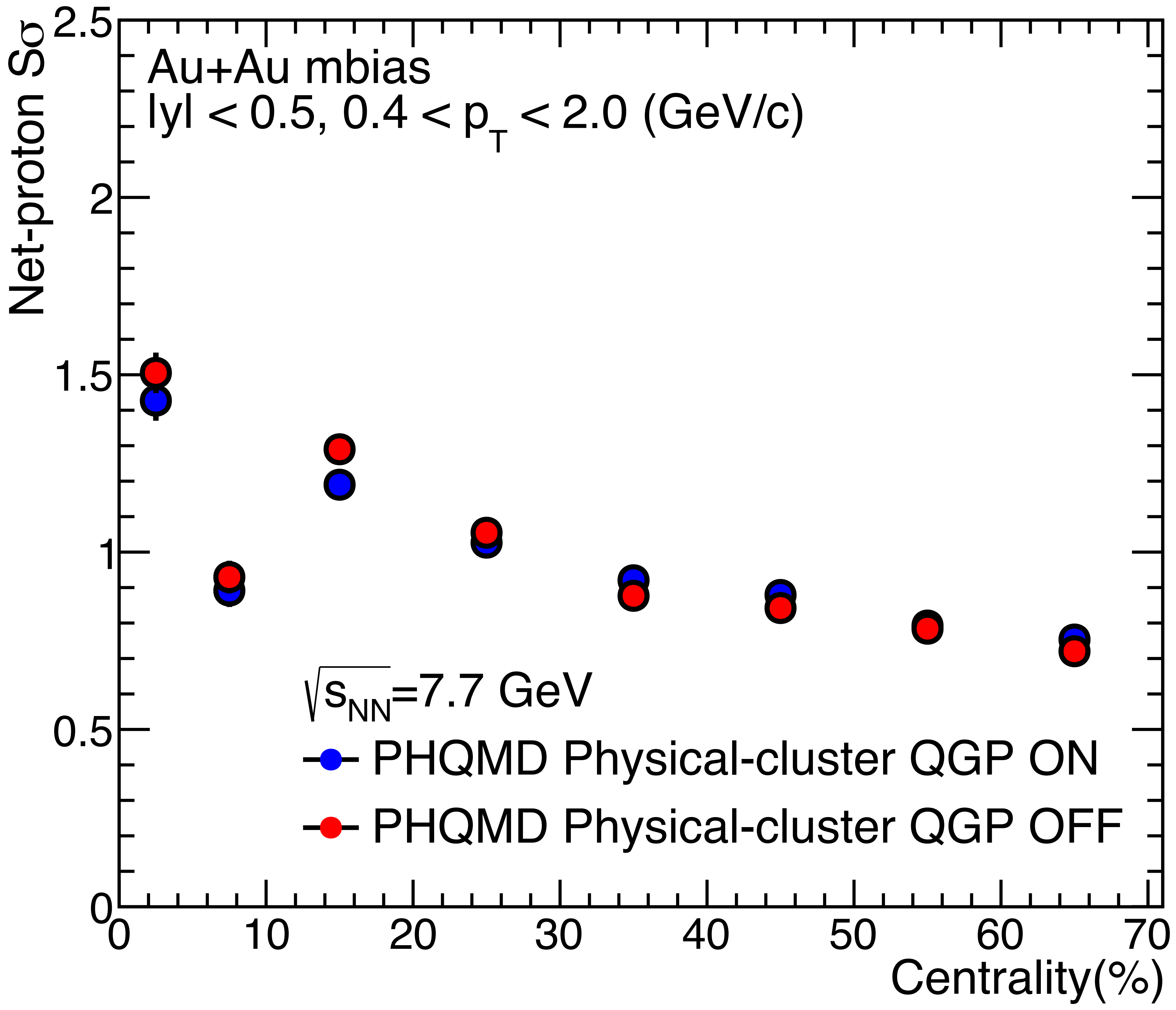


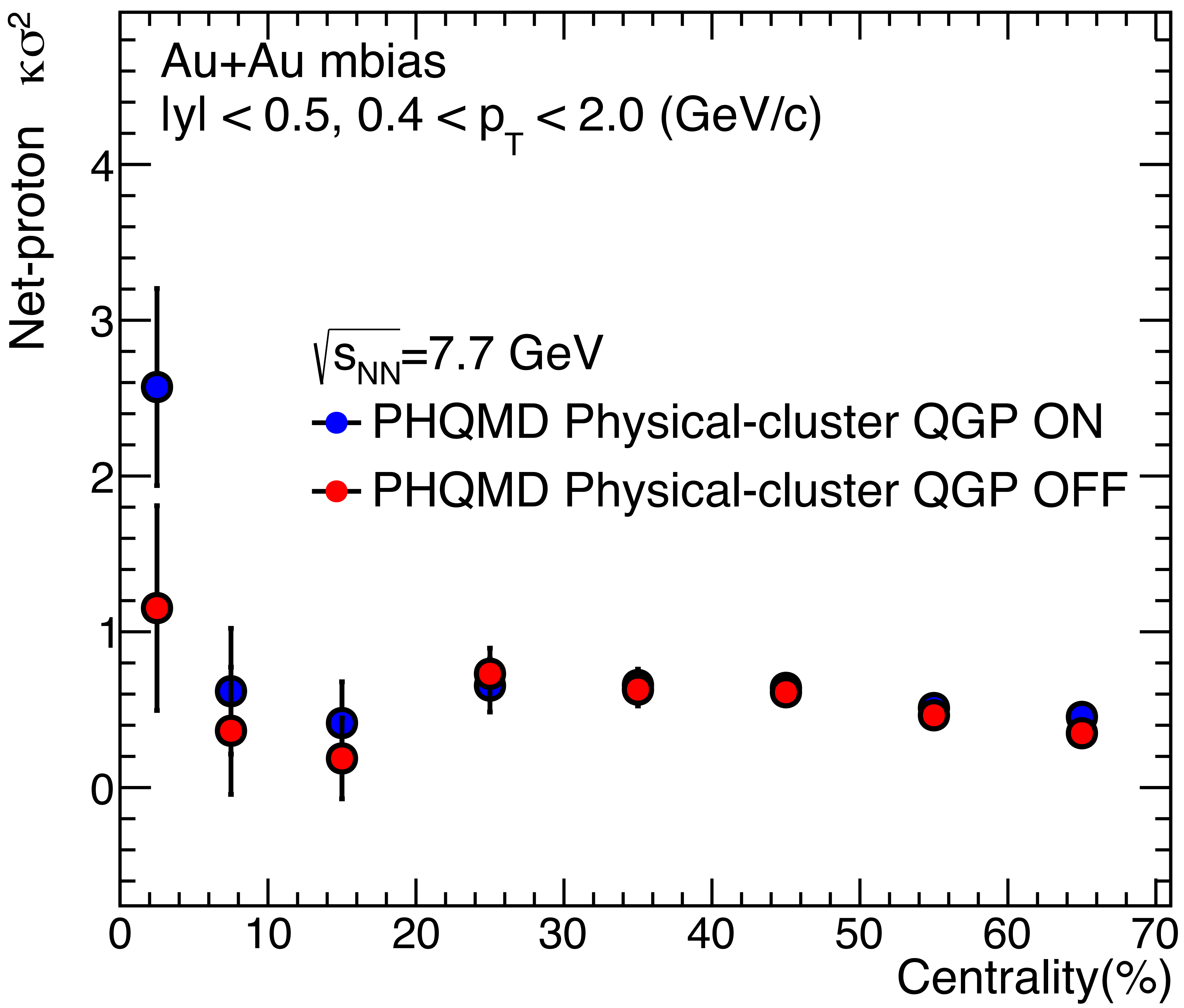


Ref: Phys. Lett. B, 785, 551–560 (2018)

Centrality Dependence of $s\sigma$ and $\kappa\sigma^2$ of Protons for QGP OFF and QGP ON

STAR acceptance





Summary

- **For the first time, PHQMD model has been applied to study for net-proton and net-kaon fluctuations.**
- $\kappa\sigma^2$ of proton matches well with the published data from the STAR whereas $S\sigma$ of proton differs.
- Similarly kaon $S\sigma$ of PHQMD data is in good agreement with the STAR data however $\kappa\sigma^2$ shows significant difference for higher energies (14.5, 19.6 GeV).
- No difference is observed for net-proton and net-kaon fluctuations between QGP ON and QGP OFF cases although statistics for this study is ~.1 Million events.

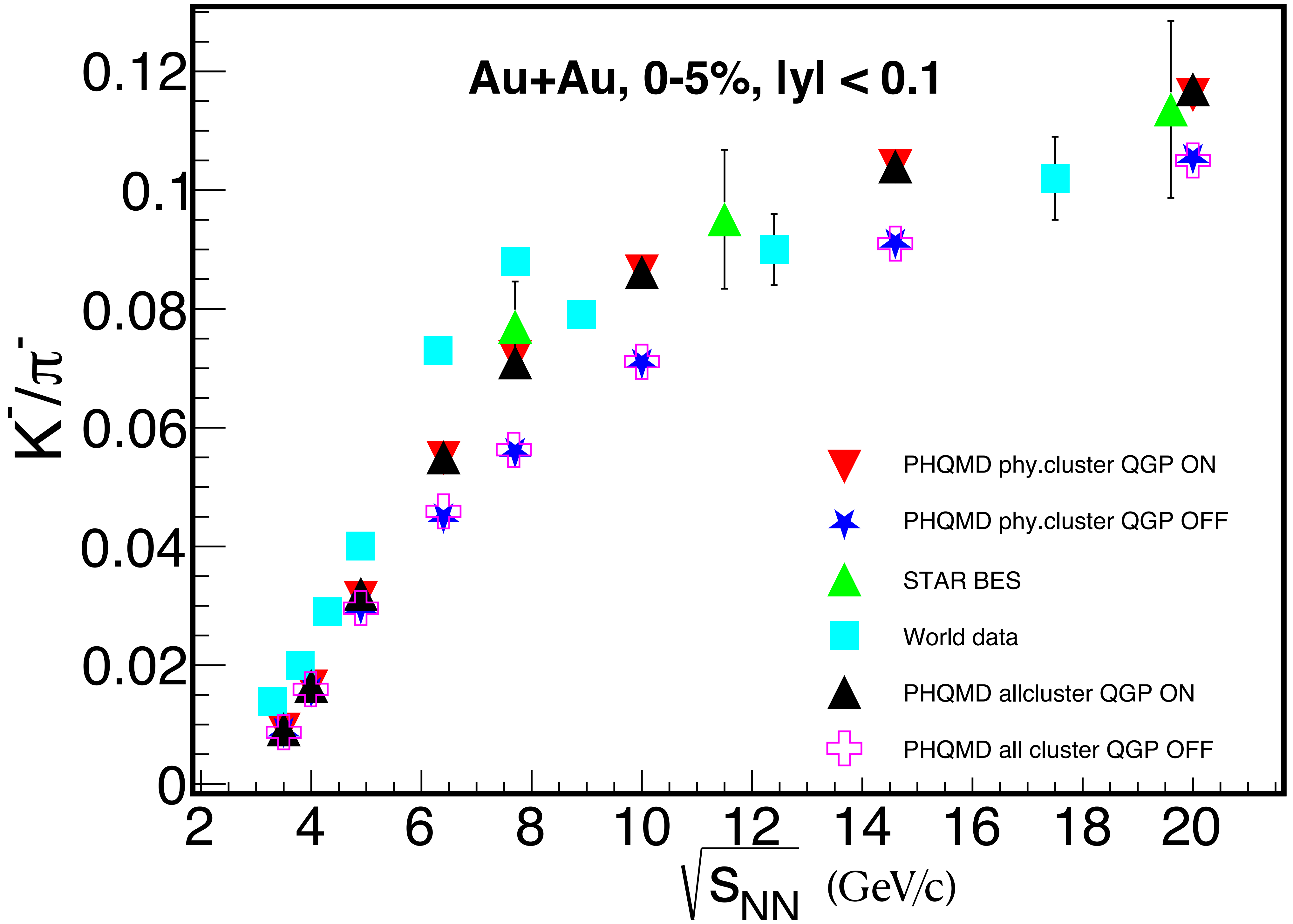
Future plan

Fluctuation analysis after passing through the CBM detector setup and identifying hadrons after reconstruction.

Thank you for your attention :)

Backup

Particle Ratio vs Energy



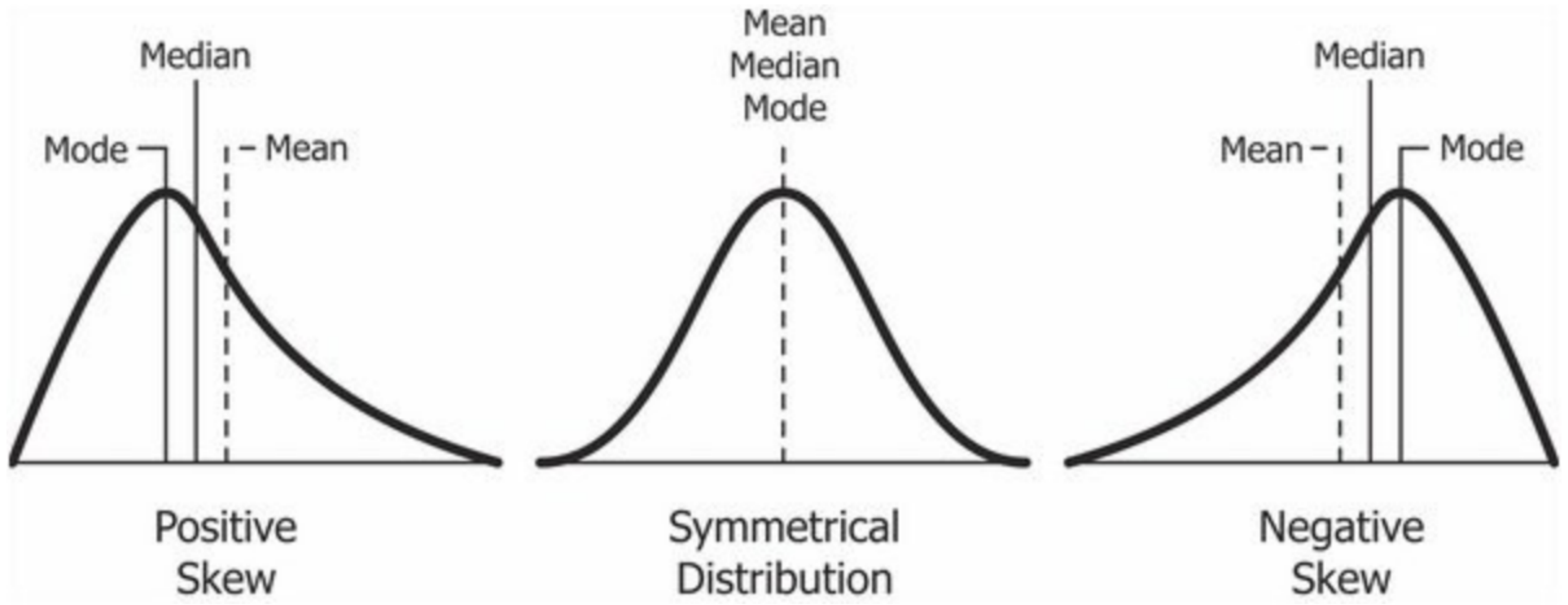
K^-/π^- **ratio of PHQMD model at mid-rapidity considering** b_{max}**=3.2 fm and compared with 0-5% central mid-rapidity data**

- **PHQMD K^-/π^- ratio increases monotonically with collision energy and match with the data.**

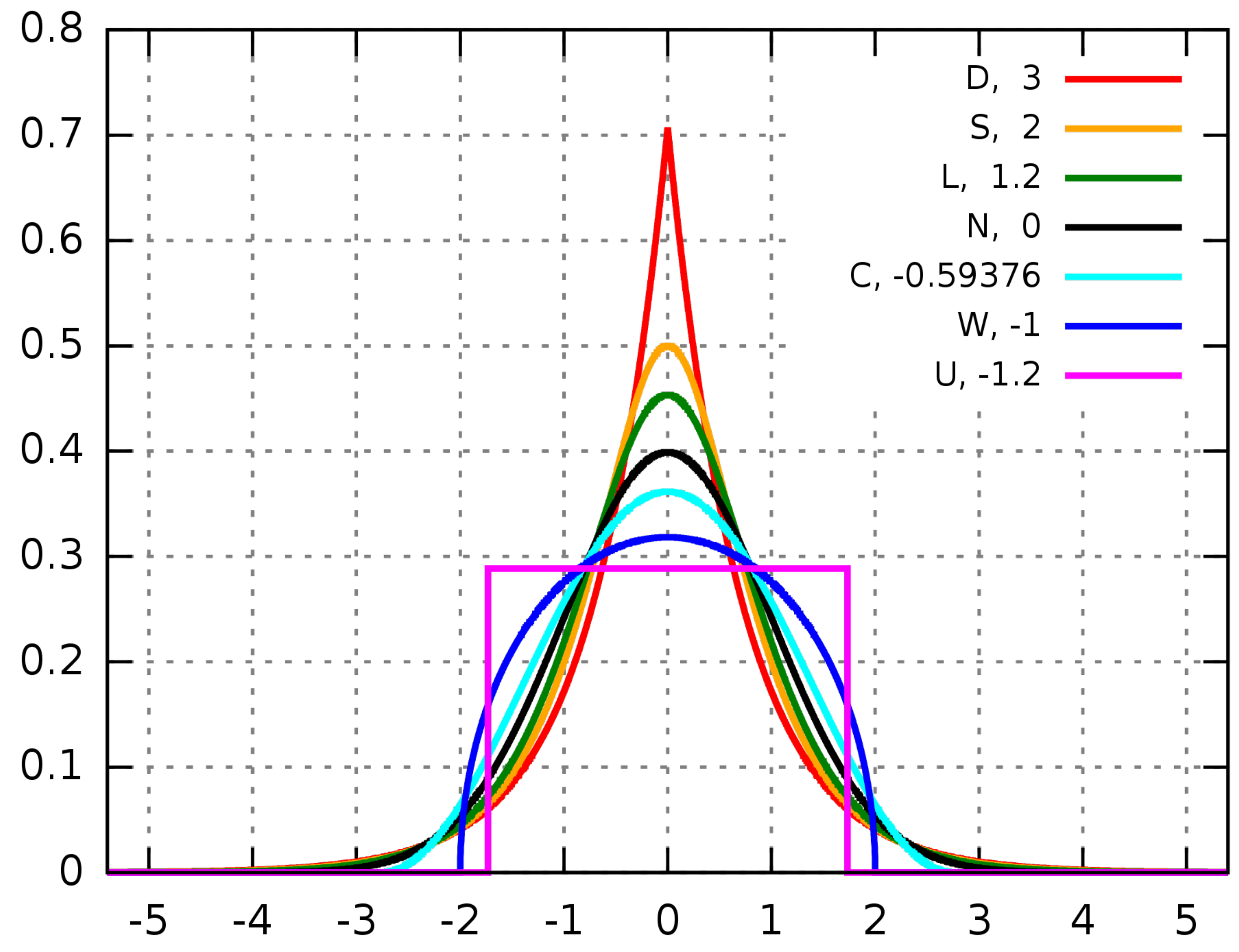
Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

Skewness and Kurtosis

- A frequency distribution is said to be skewed if the frequencies are not equally distributed on both the sides of the central value
- Kurtosis is another measure of the shape of a frequency curve. It signifies the extent of asymmetry, measures the degree of peakedness of a frequency distribution.



Skewness



Kurtosis

How to measure derivative

$$Z = tr\, e^{-\hat{E}/T+\mu/T\hat{N}_B}$$

$$\langle E\rangle = \frac{1}{Z}\, tr\, \hat{E}\, e^{-\hat{E}/T+\mu/T\hat{N}_B} = -\frac{\partial}{\partial 1/T}\ln(Z)$$

$$\langle(\delta E)^2\rangle = \langle E^2\rangle - \langle E\rangle^2 = \left(-\frac{\partial}{\partial 1/T}\right)^2 \ln(Z) = \left(-\frac{\partial}{\partial 1/T}\right)\langle E\rangle$$

$$\langle(\delta E)^n\rangle = \left(-\frac{\partial}{\partial 1/T}\right)^{n-1}\langle E\rangle$$

Cumulants of Energy measure the temperature derivatives of the EOS

Cumulants of Baryon number measure the chem. pot. derivatives of the EOS

Cumulants of (Baryon) Number

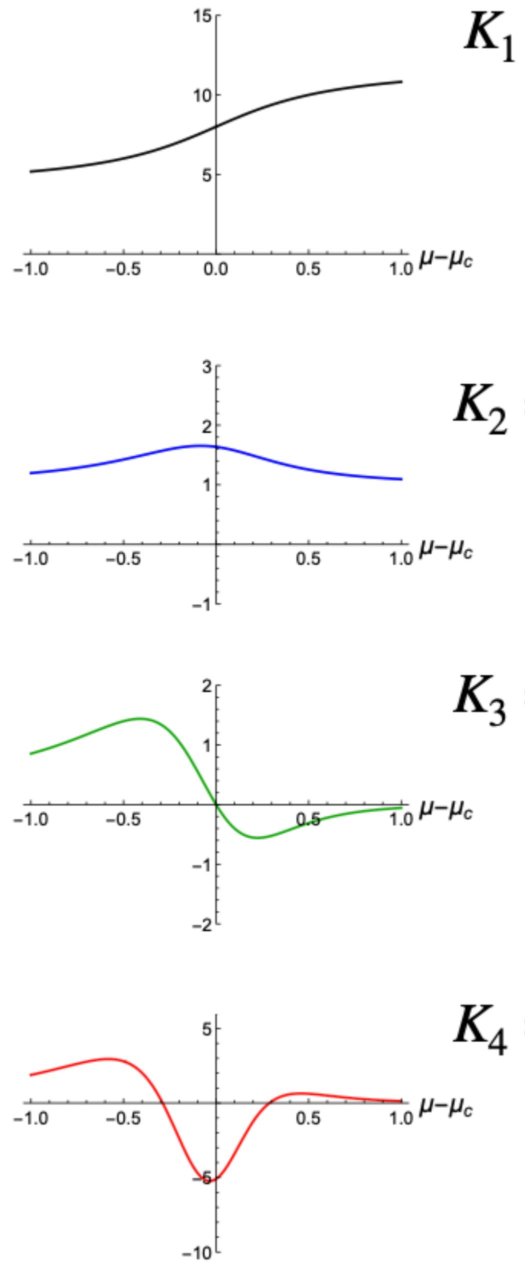
$$K_n = \frac{\partial^n}{\partial(\mu/T)^n}\ln Z = \frac{\partial^{n-1}}{\partial(\mu/T)^{n-1}}\langle N\rangle$$

$$K_1 = \langle N\rangle, \quad K_2 = \langle N - \langle N\rangle\rangle^2, \quad K_3 = \langle N - \langle N\rangle\rangle^3$$

Cumulants scale with volume (extensive): $K_n \sim V$

Volume not well controlled in heavy ion collisions

Cumulant Ratios: $\frac{K_2}{\langle N\rangle}, \frac{K_3}{K_2}, \frac{K_4}{K_2}$



$K_1 = \langle N\rangle$

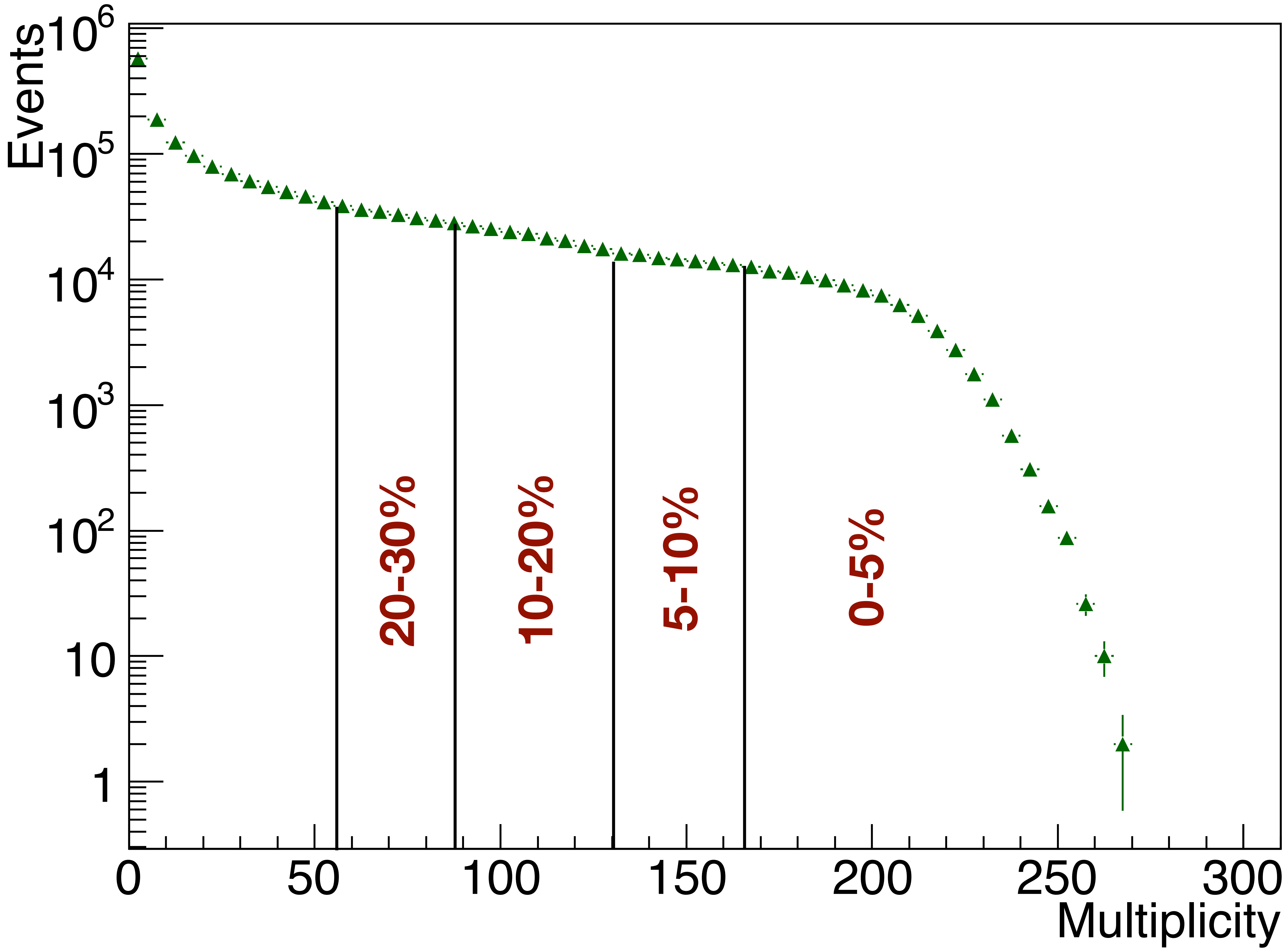
$K_2 = \frac{\partial}{\partial(\mu/T)}K_1$

$K_3 = \frac{\partial}{\partial(\mu/T)}K_2$

$K_4 = \frac{\partial}{\partial(\mu/T)}K_3$

Centrality Selection

CBM acceptance @ 4.9 GeV



PHQMD minimum bias events (2 Million); Then applied STAR or CBM acceptance cut and created modified root files; then centrality is estimated from all particle multiplicity distribution.

Centrality Selection

PHQMD minimum bias events (2 Million); Then applied STAR or CBM acceptance cut and produced modified root files; then centrality is estimated from all particle multiplicity distribution.

STAR acceptance @ 3.5 GeV

Centrality	N_mult
0-5%	165
5-10%	128
10-20%	83
20-30%	52
30-40%	32
40-50%	18
50-60%	10
60-70%	5

STAR acceptance @ 19.6 GeV

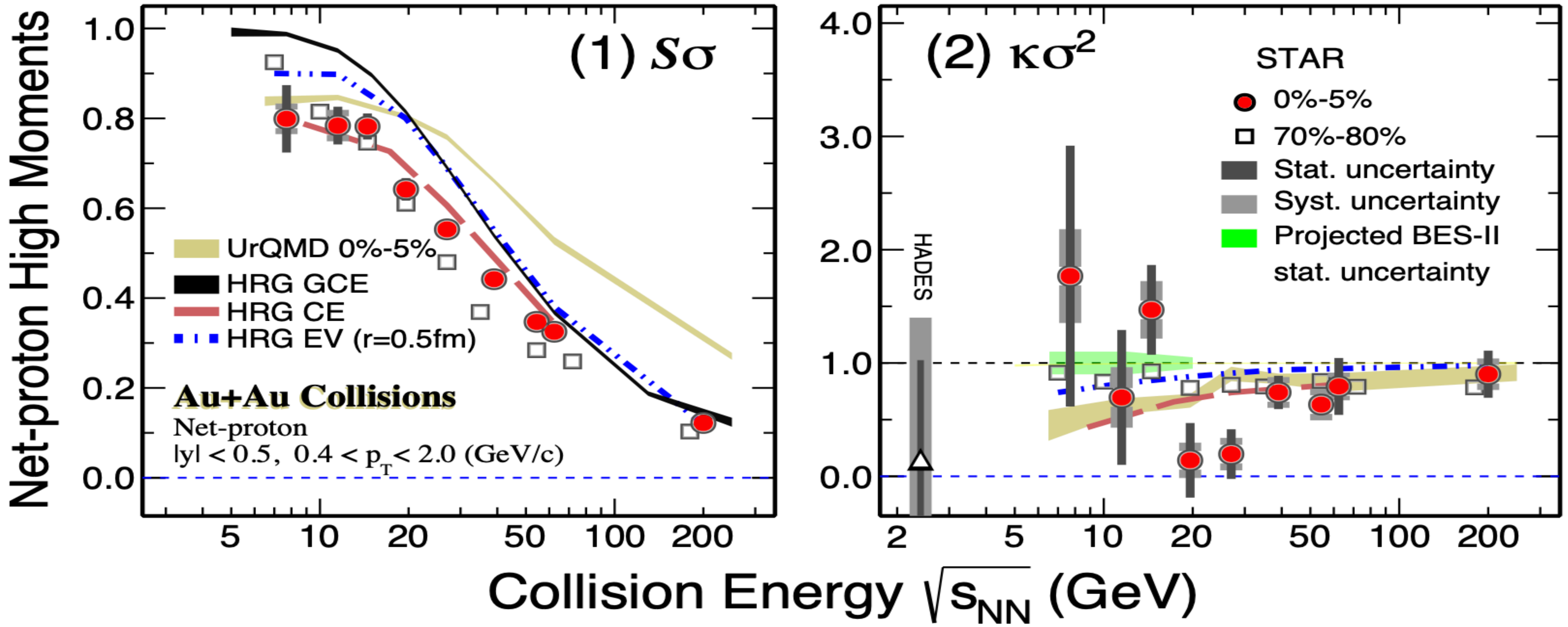
Centrality	N_mult
0-5%	269
5-10%	217
10-20%	145
20-30%	94
30-40%	58
40-50%	33
50-60%	18
60-70%	9

Second Approach

Net-proton & Net-kaon fluctuations calculation of PHQMD data sets considering b_{max}=3.2 fm

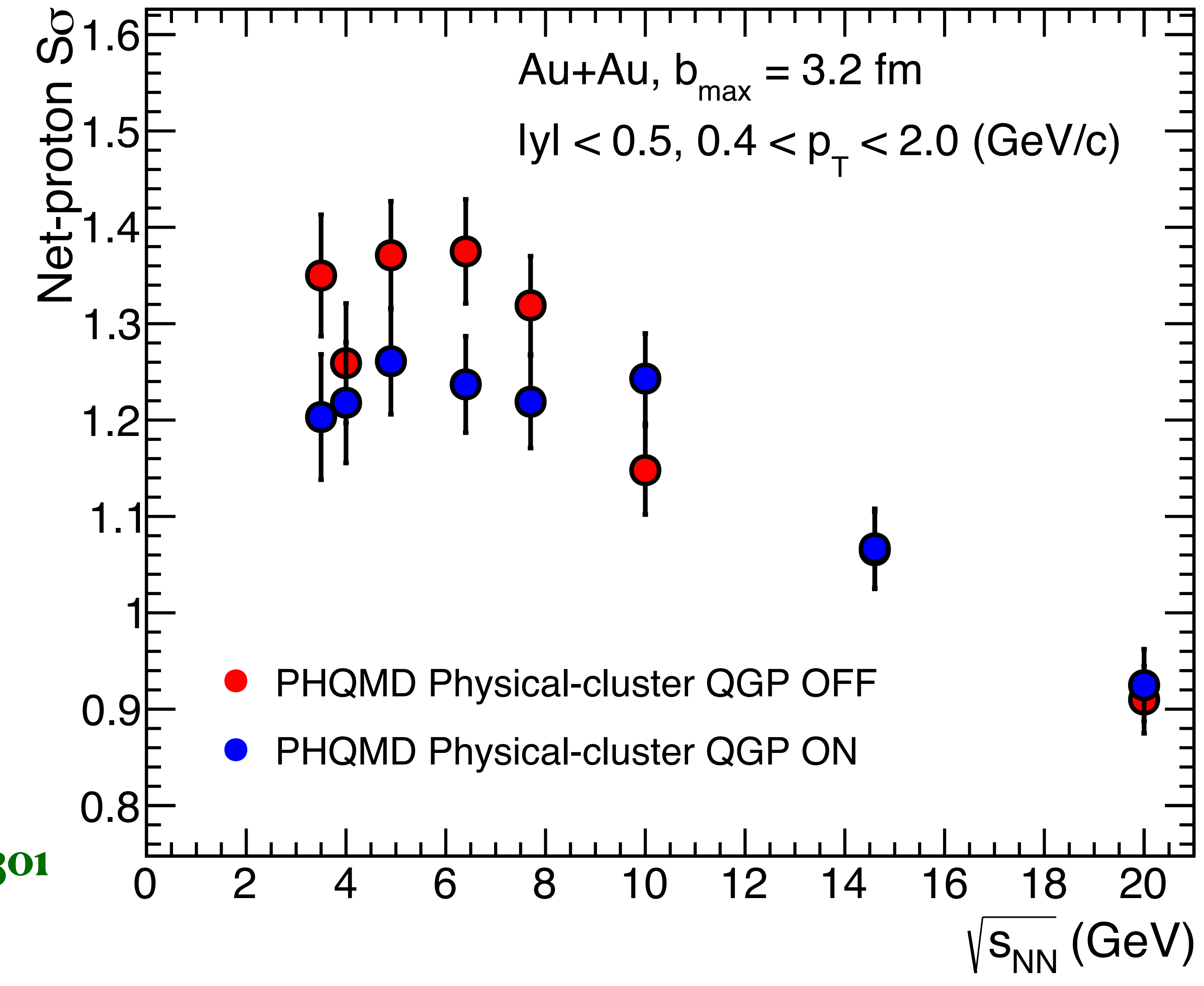
Net-proton number fluctuations in STAR acceptance

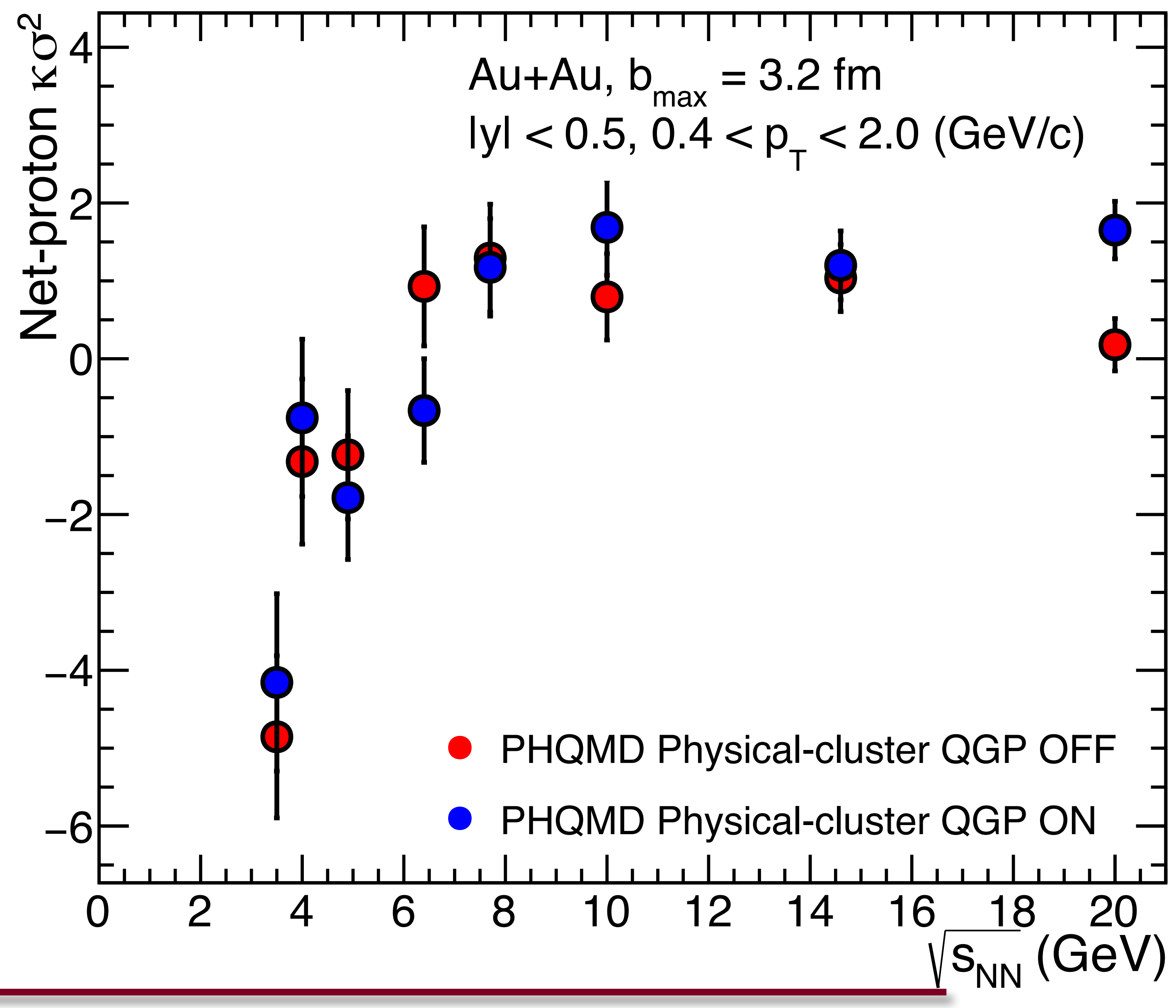
STAR Results



PHQMD Results

Statistics - 0.1 Million events

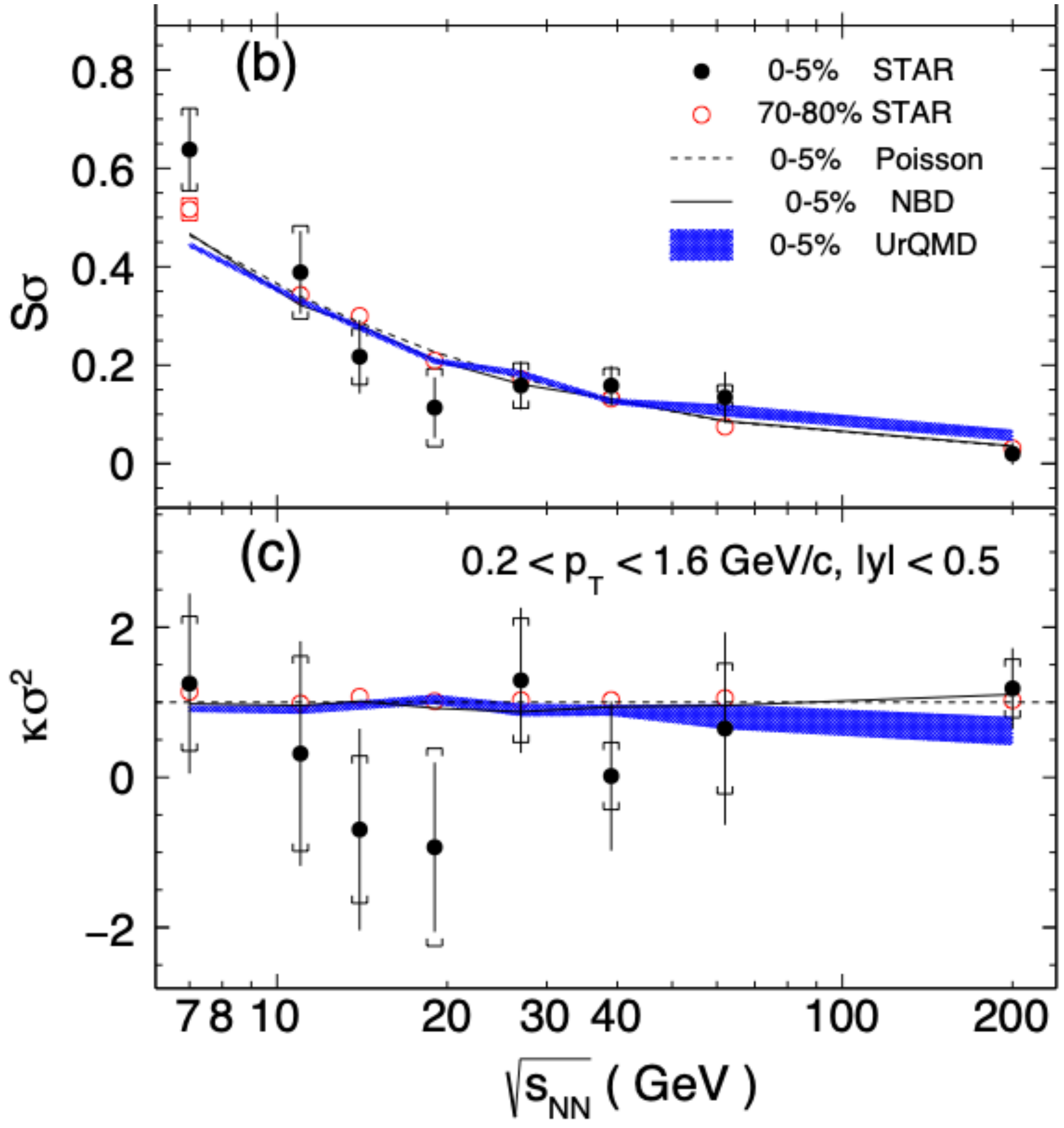




Ref: Phys.Rev.Lett. 126 (2021) 9, 092301

Net-kaon number fluctuations in STAR acceptance

STAR Results



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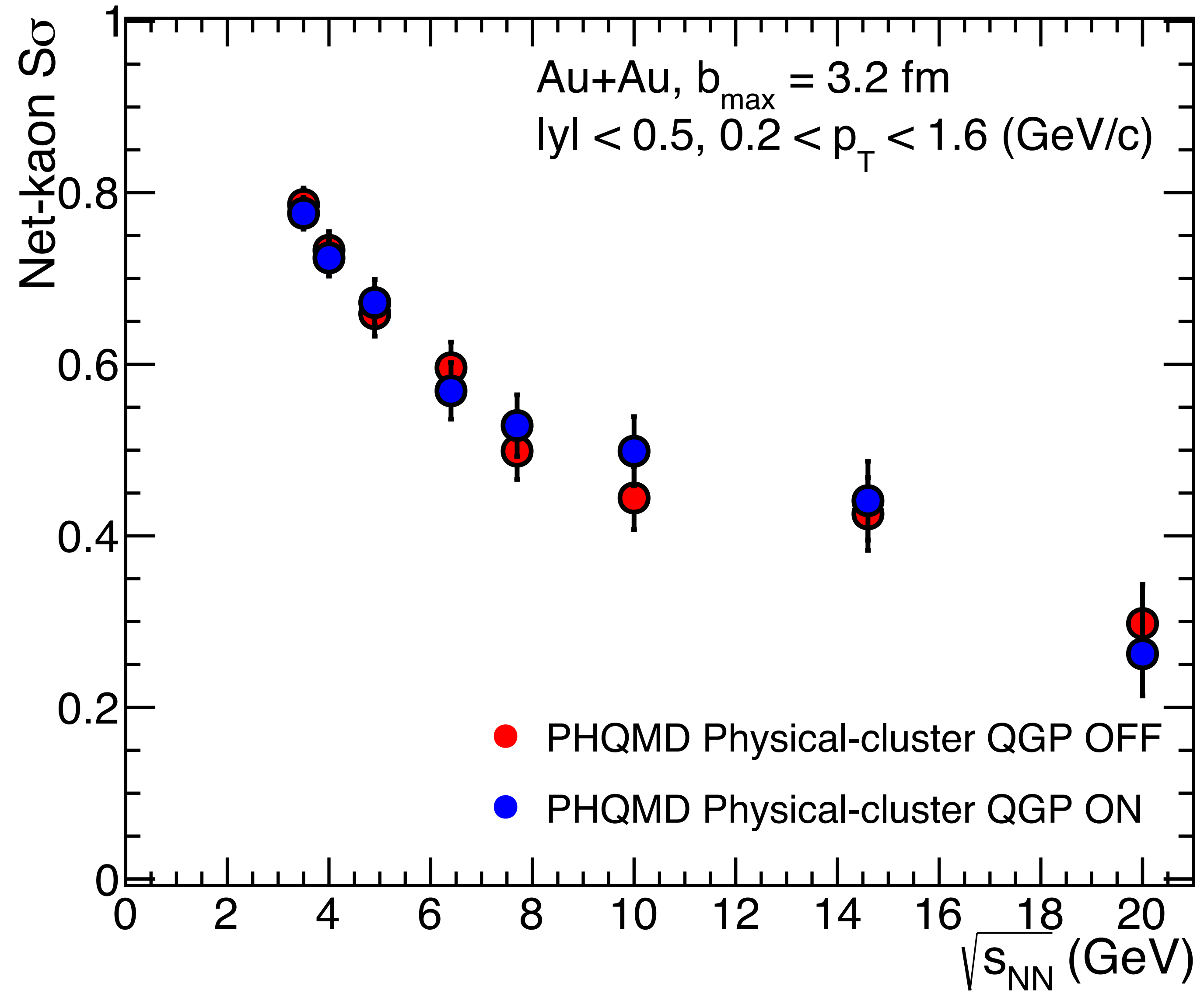

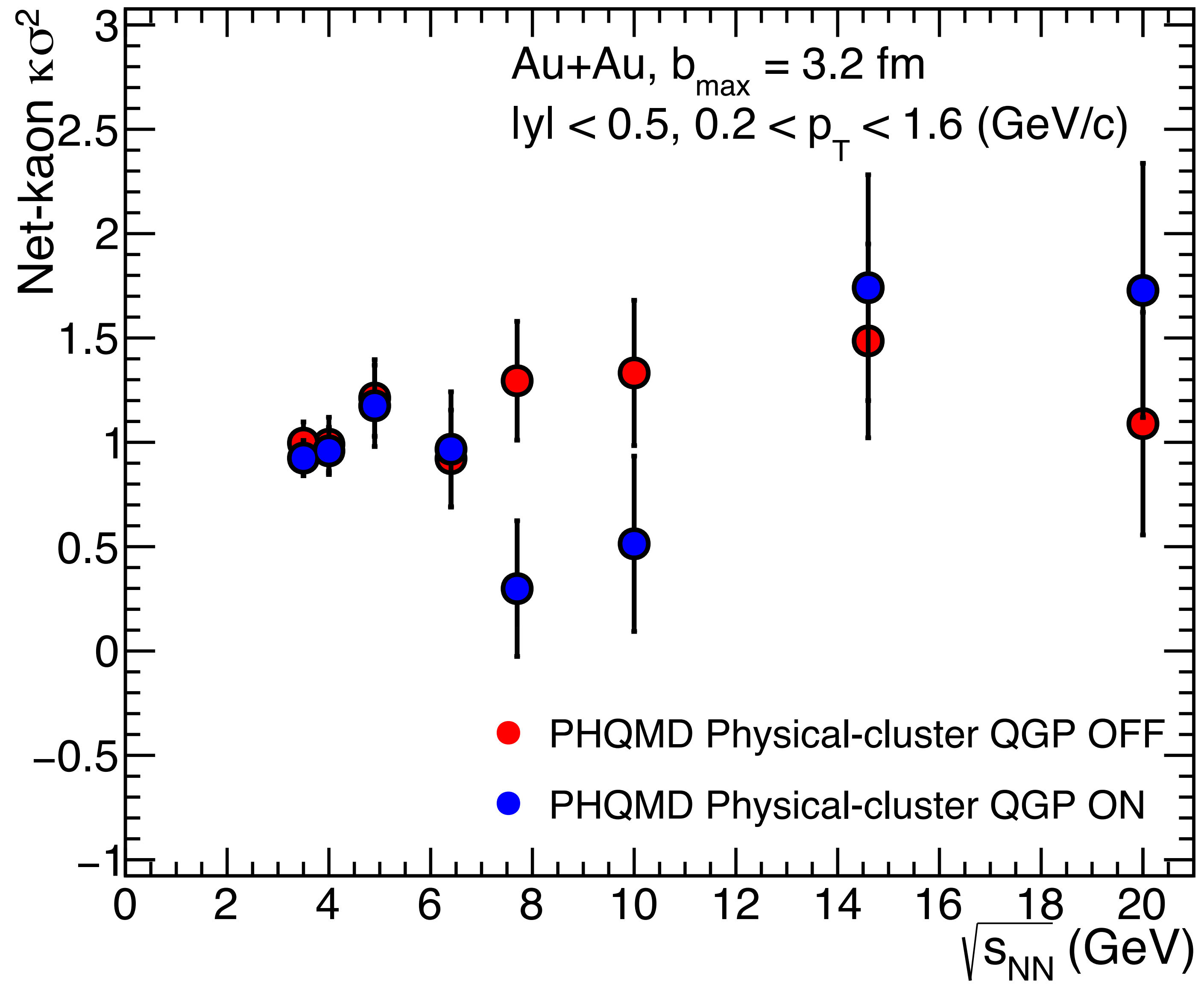

PHQMD Results

Statistics - 0.1 Million events