Search for the QCD Critical Point by Higher Moments of Net-proton Multiplicity Distributions at STAR

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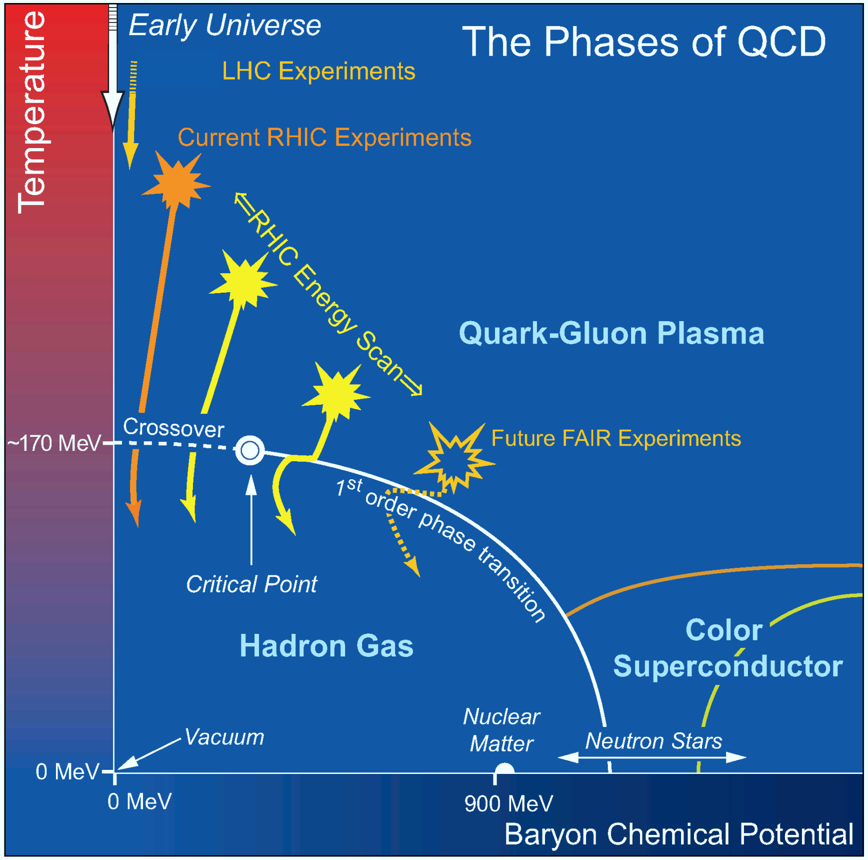
QCD Phase Diagram



Lattice QCD :

➢ Crossover at $\mu_B = 0$, 1st order phase transition at large μ_B .

Y. Aoki, et al., Nature 443, 675 (2006).
S. Gupta, et al. Science 332, 1525 (2011).

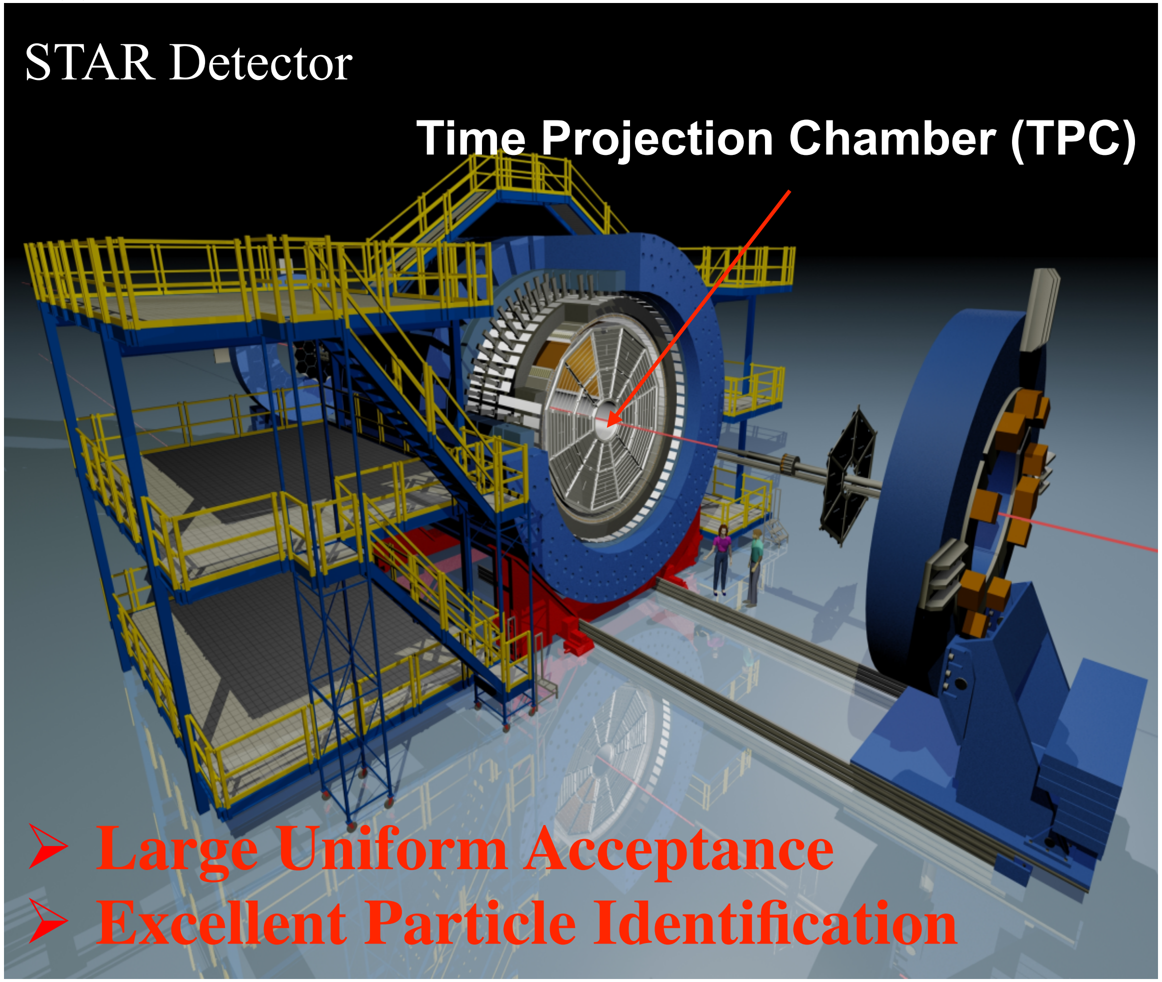
➢QCD Critical Point (CP): The end point of first order phase transition boundary.

Z. Fodor, et al, JHEP04, 050 (2004) (hep-lat/0402006)
M. A. Stephanov, Int. J. Mod. Phys. A 20, 4387 (2005) (hep-ph/0402115).

Main Goals of RHIC Beam Energy Scan (BES):

- Signals for phase transition/phase boundary.
- Search for Critical Point (CP).
- Bulk properties of QCD matter.

Experiment: Access the QCD Phase Diagram



Varying beam energy varies Temperature and Baryon Chemical Potential.
(RHIC BES-Phase I: Au+Au collisions at $\sqrt{s}$=7.7, 11.5, 19.6, 27, 39, 62.4, 200 GeV) M. M. Aggarwal, arXiv:1007.2613 (2010).

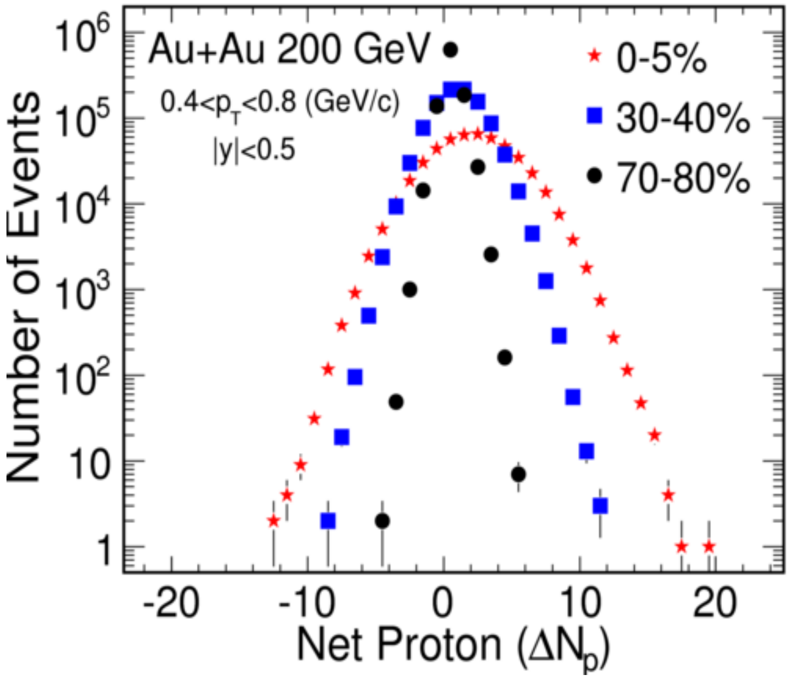
$\sqrt{s}$ (GeV)	μ_B (MeV)	T (MeV)
7.7	422	140
11.5	316	152
19.6	206	160
27	156	163
39	112	164
62.4	73	165
200	24	166

J. Cleymans et al., Phys. Rev. C 73, 034905 (2006)

- Access a broad region of QCD phase diagram by RHIC BES program.
- STAR is an ideal detector to perform correlation and fluctuation analysis to study the QCD phase diagram.

Observable: Higher Moments of Net-proton Distributions.

Typical net-proton distributions



STAR: Physical Review Letters 105, 022302 (2010).

Moments/Cumulants: Describe shape and fluctuations.

$$S\sigma = \frac{C_3}{C_2} = \frac{<(\delta N)^3>}{<(\delta N)^2>}, \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{<(\delta N)^4>}{<(\delta N)^2>^2} - 3$$

S: skewness, κ: kurtosis, C_n: n^{th} order cumulants

- Moments sensitive to correlation length (ξ): (Study phase transition and Critical Point.)

$$<(\delta N)^2> \sim \xi^2 \qquad <(\delta N)^3> \sim \xi^{4.5}$$
$$<(\delta N)^4> - 3<(\delta N)^2>^2 \sim \xi^7$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107 052301 (2011) . C. Athanasiou, et al., Phys. Rev. D 82, 074008 (2010).

- Moments products relates to baryon number susceptibility ratio : (Study Bulk properties of QCD matter.)

$$\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(3)} \quad S\sigma \sim \chi^{(3)}/\chi^{(2)} \quad \sigma^2/M \sim \chi^{(2)}/\chi^{(1)}$$

Product of moments cancel volume effect.
Net-protons are used to approximate Net-baryons.

F. Karsch et al, Phys. Lett. B 695, 136 (2011). arXiv: 1203.0784;
M.Cheng et al, Phys. Rev. D 79, 074505 (2009).
Y. Hatta, et al, Phys.Rev.Lett. 91, 102003 (2003).

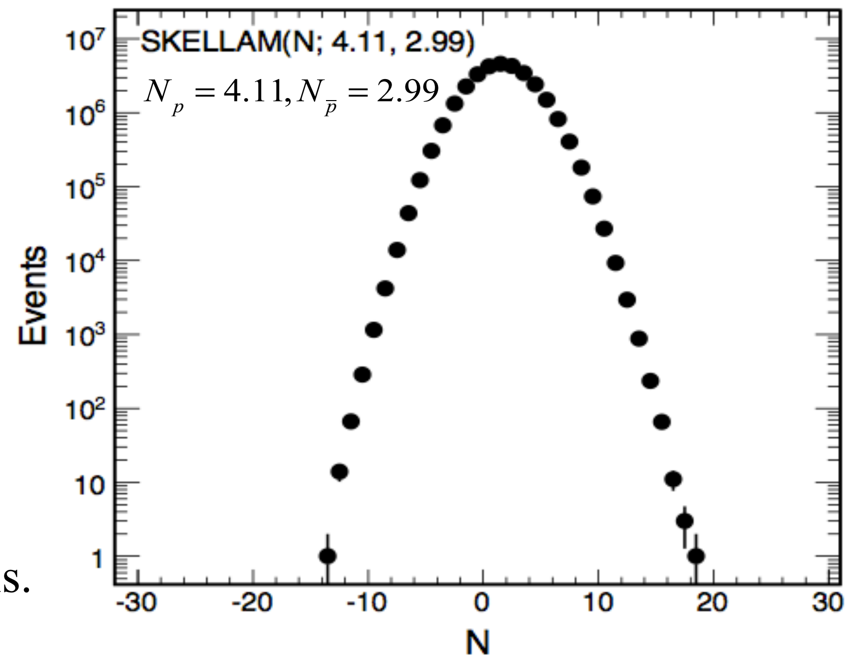
Poisson Baseline

- **If proton and anti-proton are independent Poissonian distributions, the distributions of net-protons is Skellam distributions, which is the case in Hadron Resonance Gas Model.**

$$P(N) = \left(\frac{N_{\bar{p}}}{N_p}\right)^{N/2} I_N(2\sqrt{N_{\bar{p}}N_p})e^{-(N_{\bar{p}}+N_p)}$$

N_{pbar} : Mean number of anti-protons
N_p : Mean number of protons

The Poisson baselines (skellam distributions) are only determined by measured average number of protons and anti-protons. This baseline will be used in our data analysis.



- **Then we have the Poisson baseline for various moments/cumulants measurements:**

$$C_{2n} = N_p + N_{\bar{p}}$$

$$C_{2n-1} = N_p - N_{\bar{p}}, (n = 1,2,3...)$$

$$S\sigma = \frac{C_3}{C_2} = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}, \kappa\sigma^2 = \frac{C_4}{C_2} = 1$$

The Poisson expectations may have energy and centrality dependence.

Data Analysis Details

Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics (Million)	~3	~6.6	~15	~30	~87	~47	~242
Year	2010	2010	2011	2011	2010	2010	2010

- **PID** : Energy loss (dE/dx) in Time Projection Chamber of STAR detector is used to identify protons with high purity within $0.4<p_T<0.8$ (GeV/c) and at mid-rapidity $|y|<0.5$.

- **Techniques Used in the Moments Analysis:**

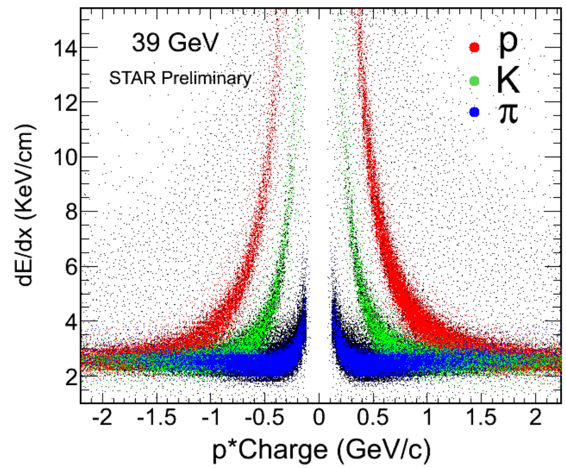
1. Centrality Bin Width Correction:
   (To suppress the volume fluctuations):
   Moments are corrected for centrality bin-width effects by using the weighted average of the moments inside each centrality bin.
   J. Phys.: Conf. Ser. 316, 012003 (2011) [arXiv: 1106.2926]

(Items 2 and 3 are updated techniques since QM 2011.)

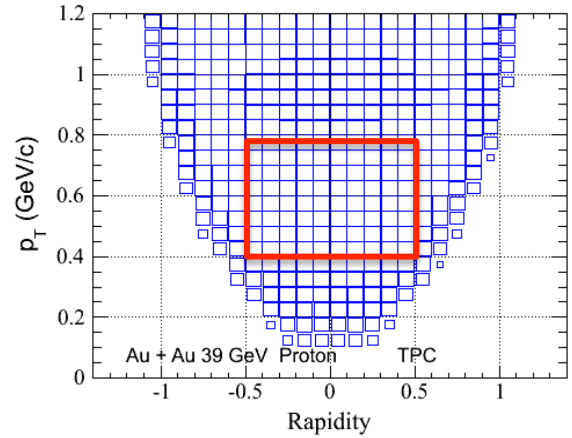
2. Statistical Error Estimations: Delta theorem method.
   J. Phys. G 39, 025008 (2012) [arXiv: 1109.0593]

3. Centrality (To avoid auto-corrections)
   Determine the centrality using charged particles within $|\eta|<0.5$. but excluding proton/anti-proton used in the analysis.

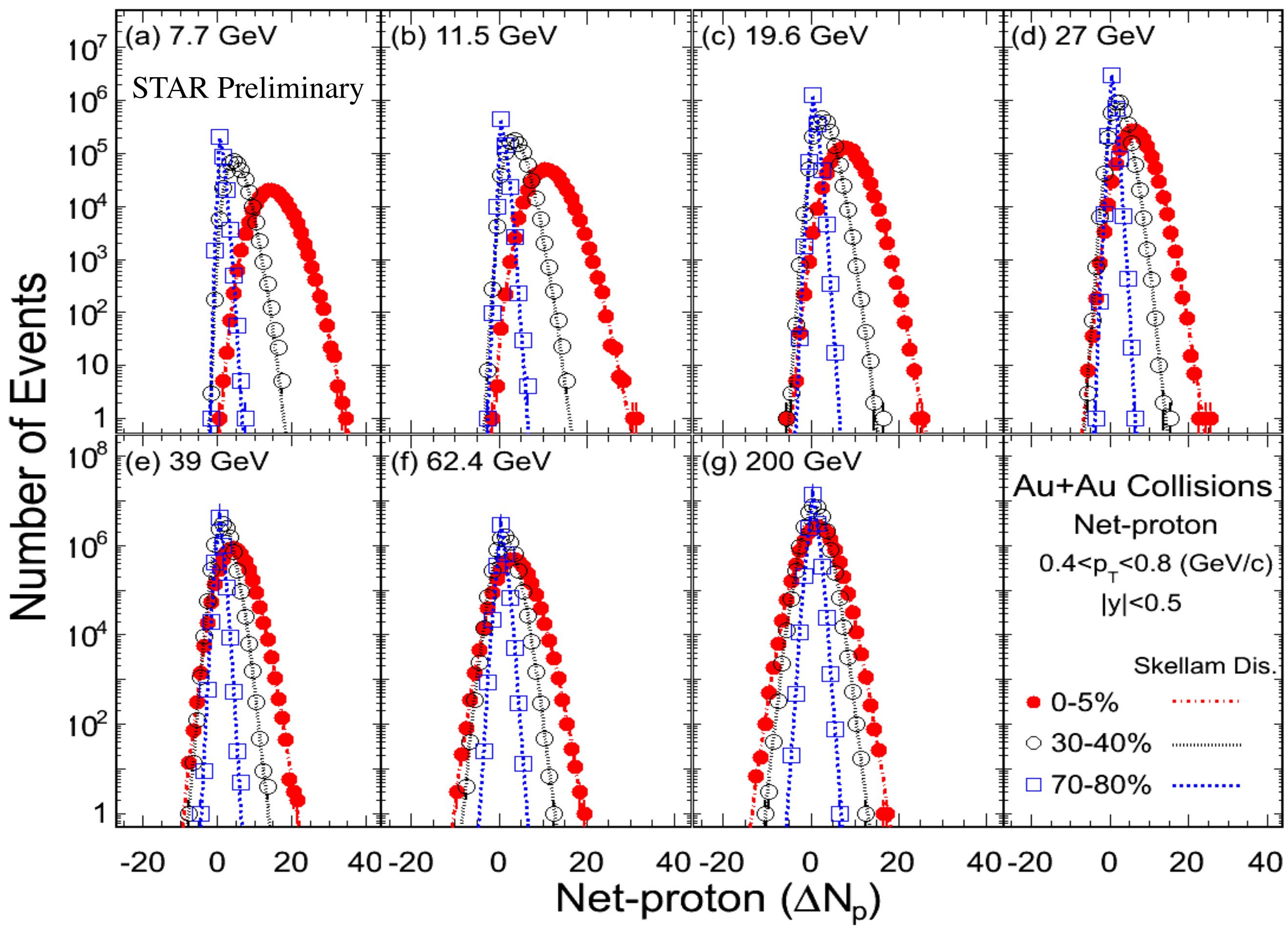
STAR TPC dE/dx PID



Proton Phase Space



Event-by-Event Net-proton Distributions



- Skellam distributions (dash lines)

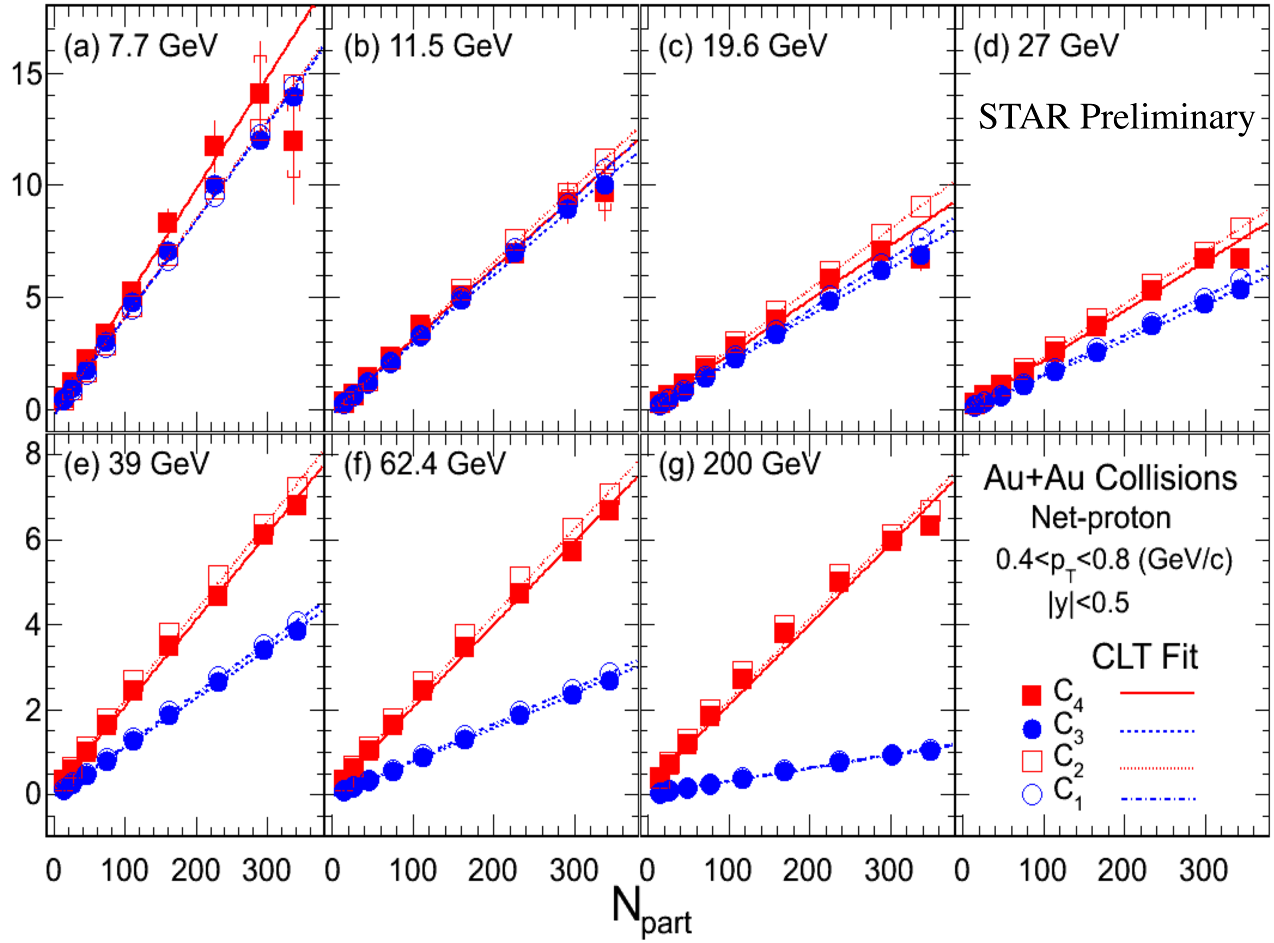
$$P(N) = \left(\frac{N_{\bar{p}}}{N_p}\right)^{N/2} I_N\left(2\sqrt{N_{\bar{p}} N_p}\right) e^{-(N_{\bar{p}}+N_p)}$$

Input parameters :measured average number of protons and anti-protons.

- The shape of the net-proton distributions vary with the centrality and energy.

- These are uncorrected event-by-event distributions of net-protons and the moments beyond mean are obtained by correcting for the finite centrality bin width effect.

Centrality Dependence of Various Order Cumulants



- 1st order polynomial fit: Central Limit Theorem (CLT) expectations for Cumulants.

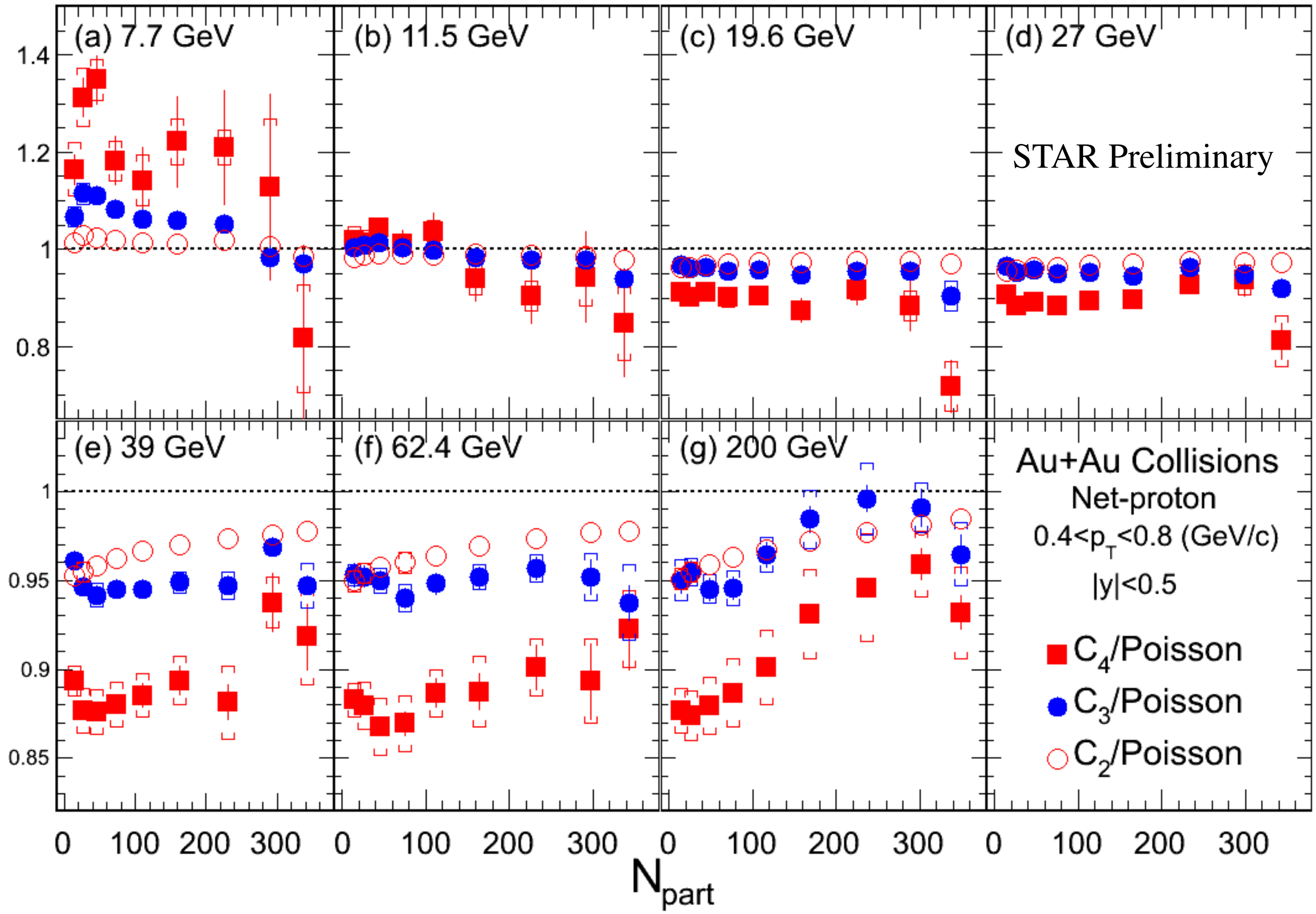
$$C_n \propto V$$

V: Volume of the system.

- All cumulants show general linear dependence on N_{part}.
- $C_1 \sim C_3$ (odd order) and $C_2 \sim C_4$ (even order).
- The differences between odd and even order cumulants decrease when the energy decrease.

(The produced number of anti-protons decrease with decreasing energy.)

Cumulants/Poisson Ratio: Centrality Dependence



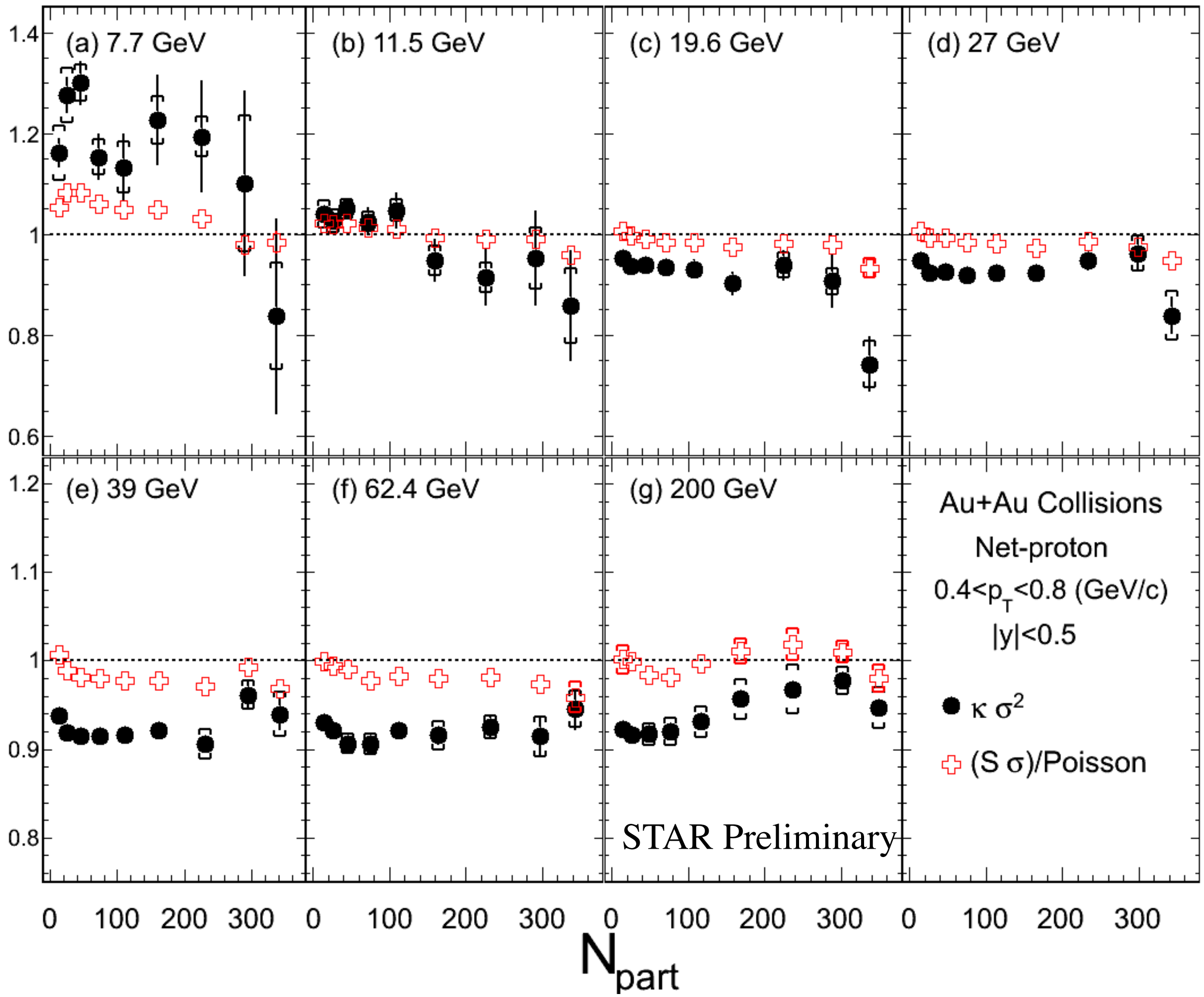
$C_4(\text{Poisson}) = \langle N_p \rangle + \langle N_{pbar} \rangle$

$C_3(\text{Poisson}) = \langle N_p \rangle - \langle N_{pbar} \rangle$

$C_2(\text{Poisson}) = \langle N_p \rangle + \langle N_{pbar} \rangle$

- For most of the energies and centralities, deviations below Poisson expectations are observed and the higher order cumulants, the larger deviation from Poisson baselines.
- Below 19.6 GeV, cumulants are larger than Poisson expectations for the peripheral collisions.

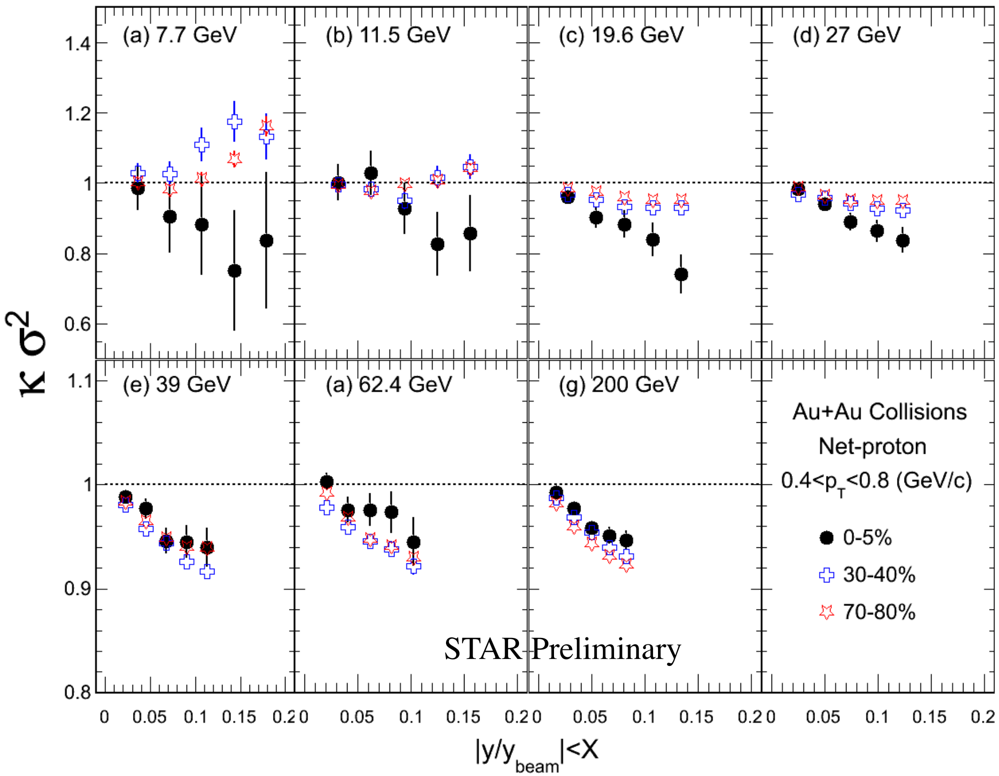
Moment Products: Centrality Dependence

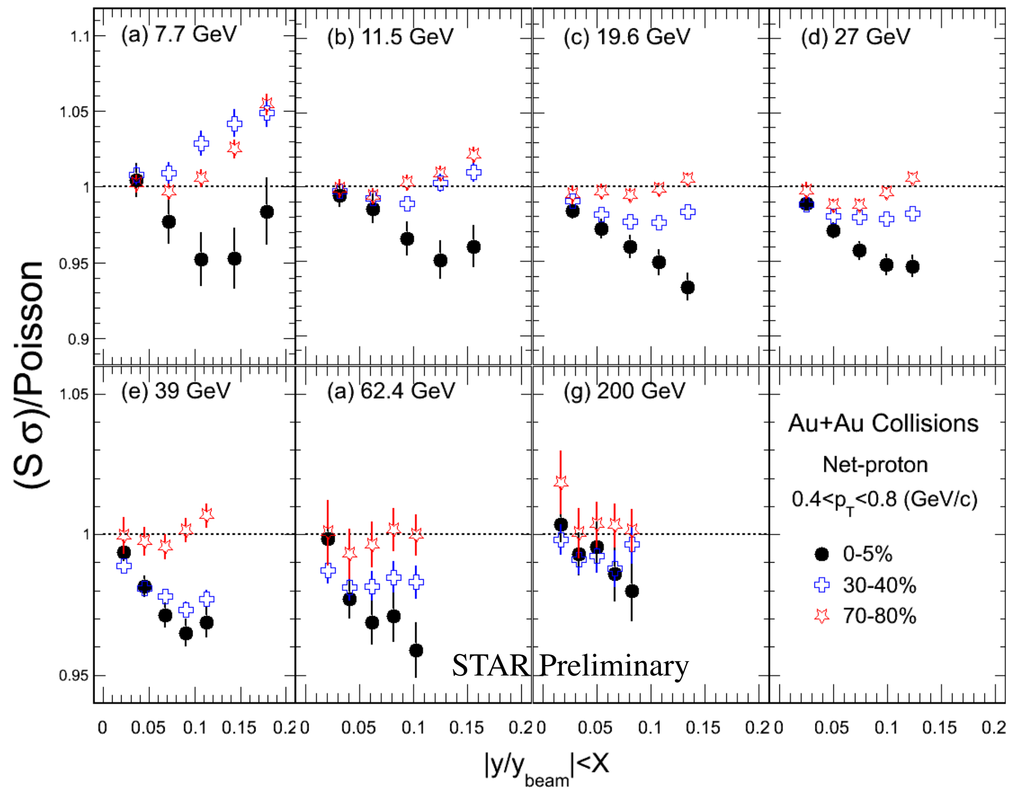


- Moment products are related to the susceptibility ratios:
  $\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(3)}$
  $S\sigma \sim \chi^{(3)}/\chi^{(2)}$
- Deviations below Poisson expectations are observed in most of the energies and centralities.
- Below 19.6 GeV, moment products are larger than Poisson expectations in peripheral collisions.

Poisson baseline: $S\sigma(Poisson) = \frac{C_3}{C_2} = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}, \kappa\sigma^2(Poisson) = \frac{C_4}{C_2} = 1$

Moment Products: Rapidity Window Dependence

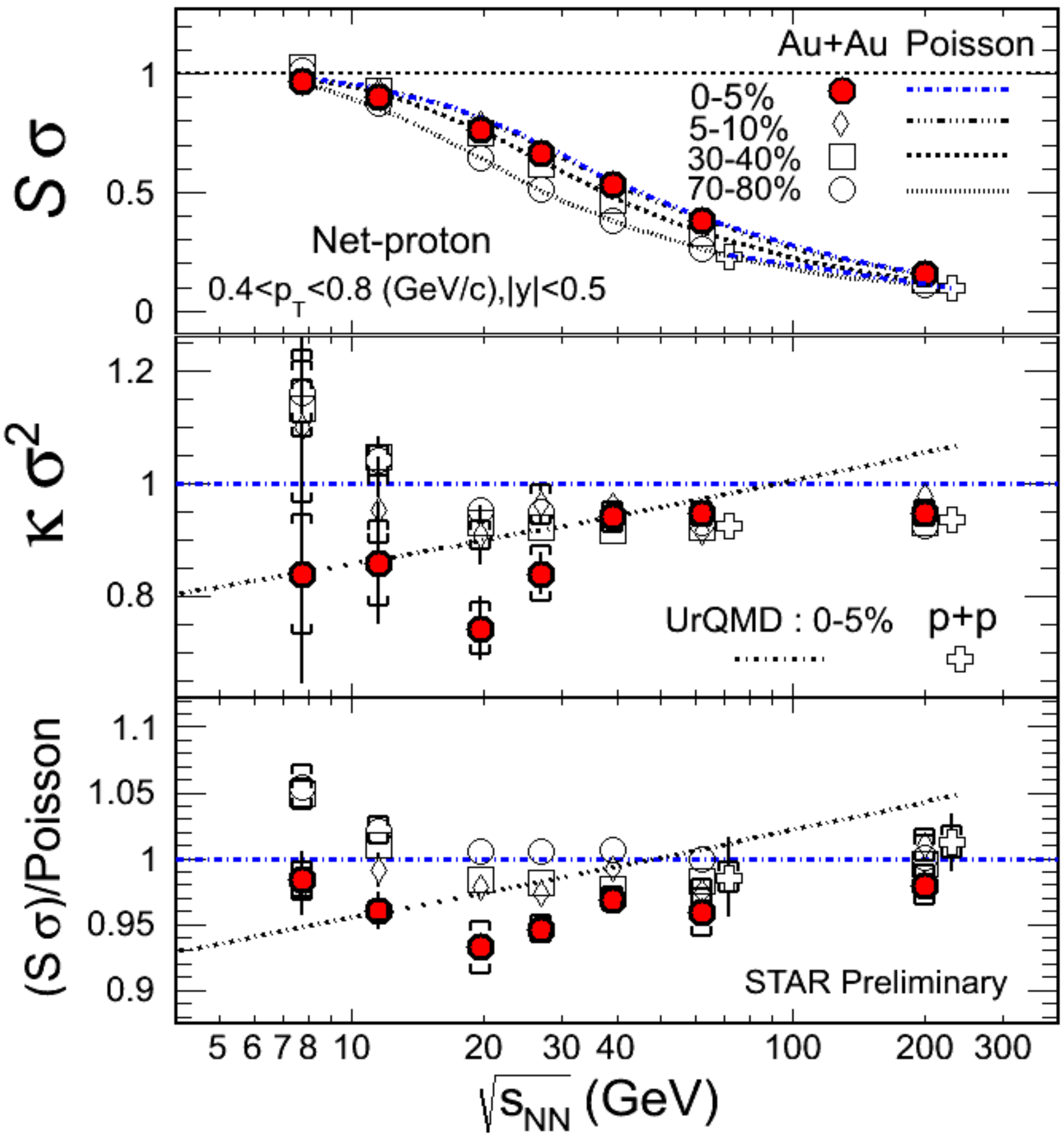




Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
y_{beam}	2.79	3.20	3.73	4.05	4.42	4.89	6.05

- $\kappa\sigma^2$ and Sσ/Poisson are below unity (Poisson baseline) and approach the baseline as the rapidity acceptance is decreased at 0-5% most central collisions. (|y|<0.1, 0.2, 0.3, 0.4, 0.5)
- Experimental values approach Poisson expectations as the rapidity acceptance is decreased.

Moment Products: Energy Dependence



➢ Deviations below Poisson expectations are observed beyond statistical and systematic errors in 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ above 7.7 GeV.

➢ For peripheral collisions, the deviations above Poisson expectations are observed below 19.6 GeV.

➢ UrQMD model show monotonic behavior for the moment products, in which non-CP physics, such as baryon conservation, hadronic scattering effects, are implemented.

Summary

Measurements:

- The centrality and energy dependence for the first four moments/cumulants of the net proton multiplicity distributions in Au+Au collisions at RHIC BES-Phase I energies (7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV) have been presented.

Expectations from Central Limit Theorem:

- Various order cumulants shows a general linear increase with increase in number of participant nucleons (system volume), which is expected by Central Limit Theorem.

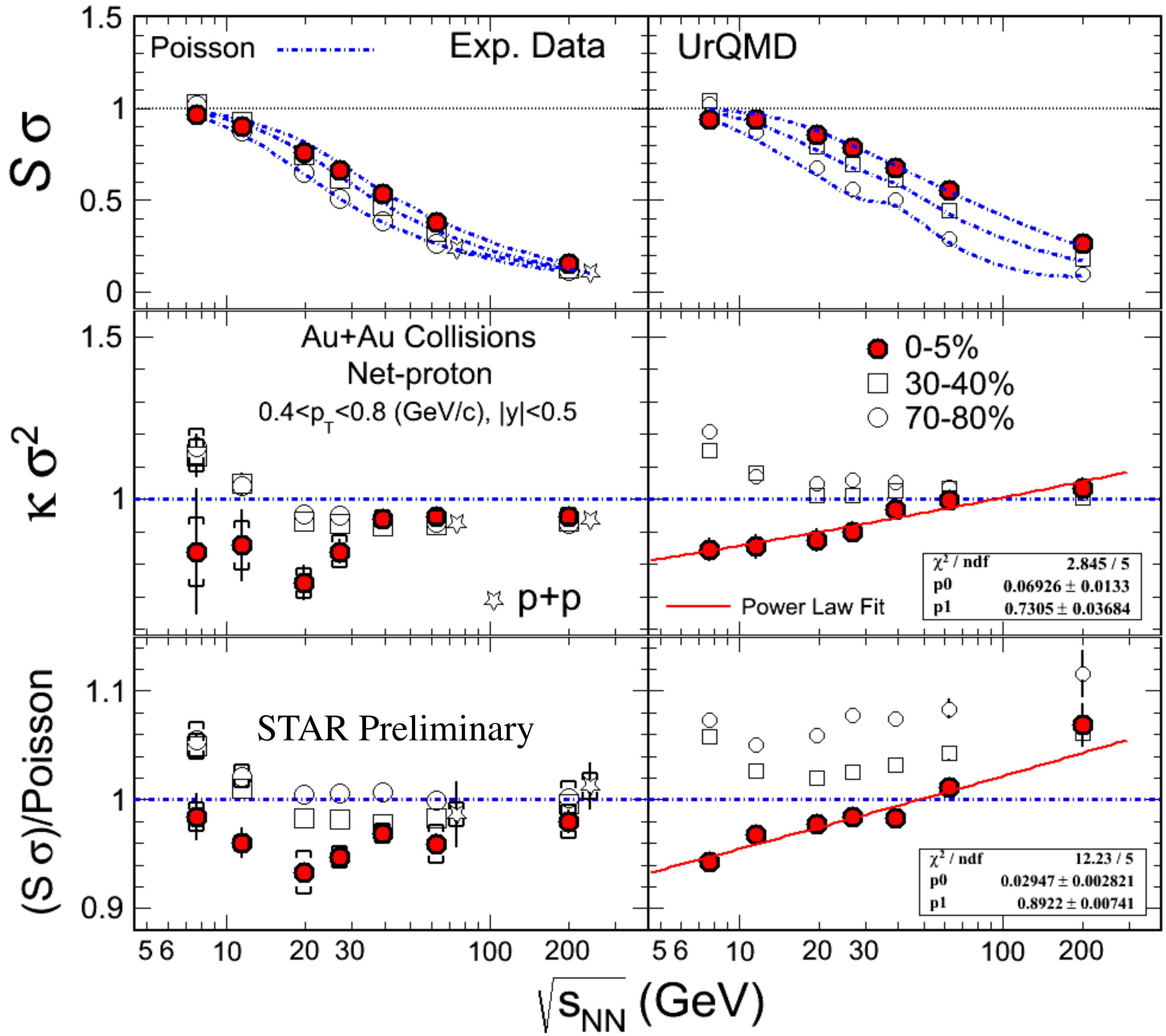
Comparisons with Poisson Baselines and Transport Model:

- Deviations below Poissonian expectation are observed in 0-5% most central Au+Au collisions beyond the statistics and systematics errors for the moment products $\kappa\sigma^2$ and $S\sigma$ above 7.7 GeV. For peripheral collisions, the deviations above Poisson expectations are observed below 19.6 GeV. Monotonic behavior for the moment products is observed in the UrQMD model.

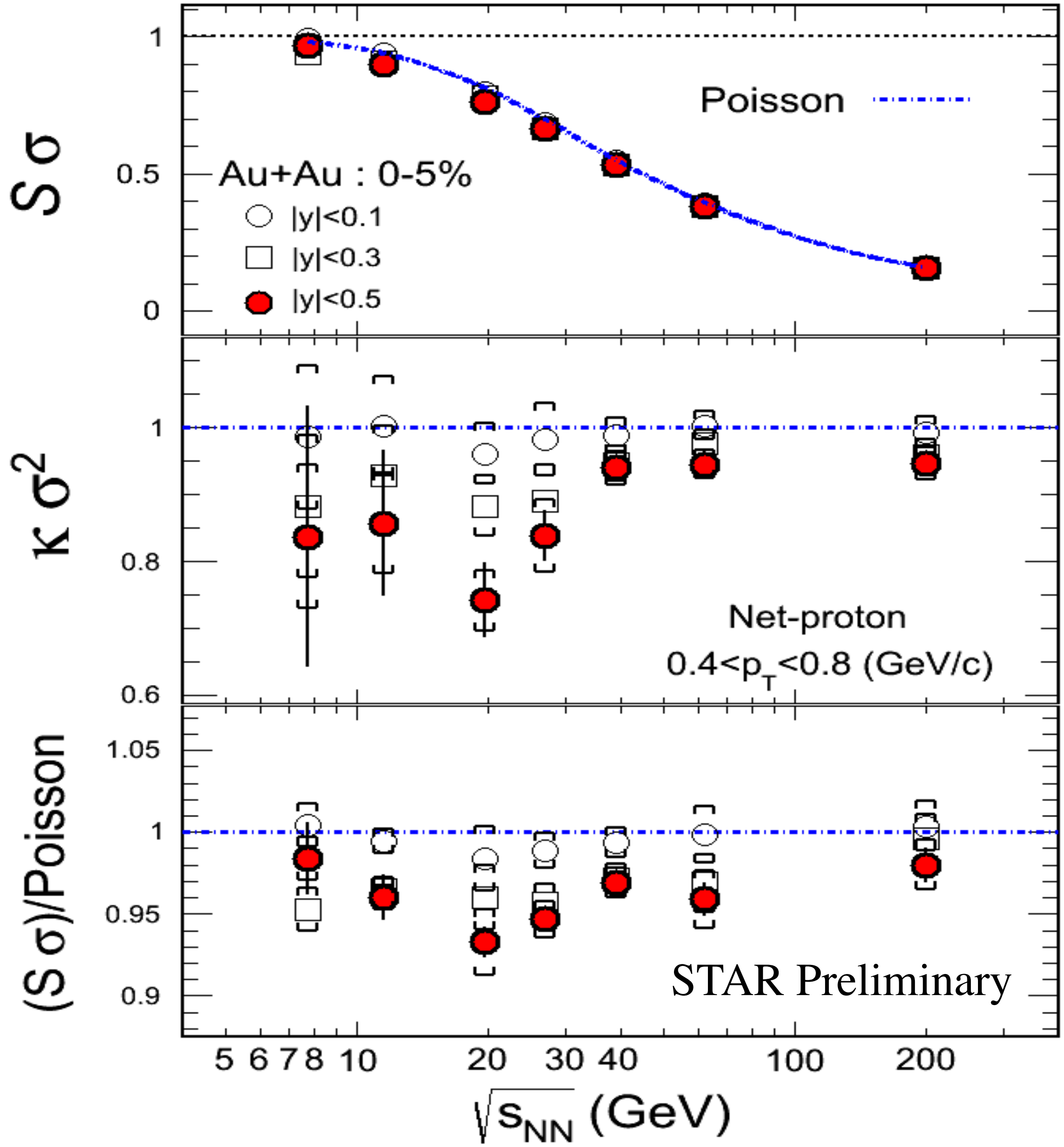
- Higher statistics are needed in order to draw physics conclusion at lower beam energies.

Backup Slides

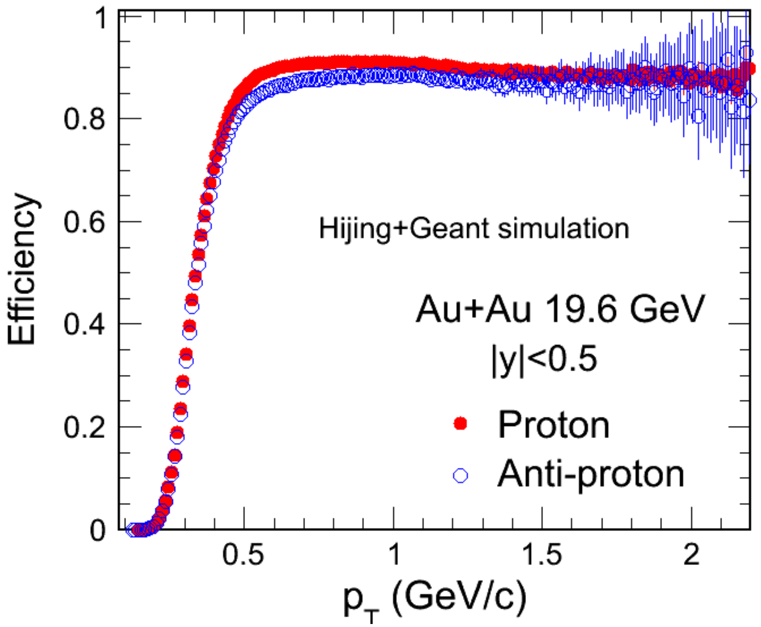
Moment Products/Poisson Ratio: Energy Dependence



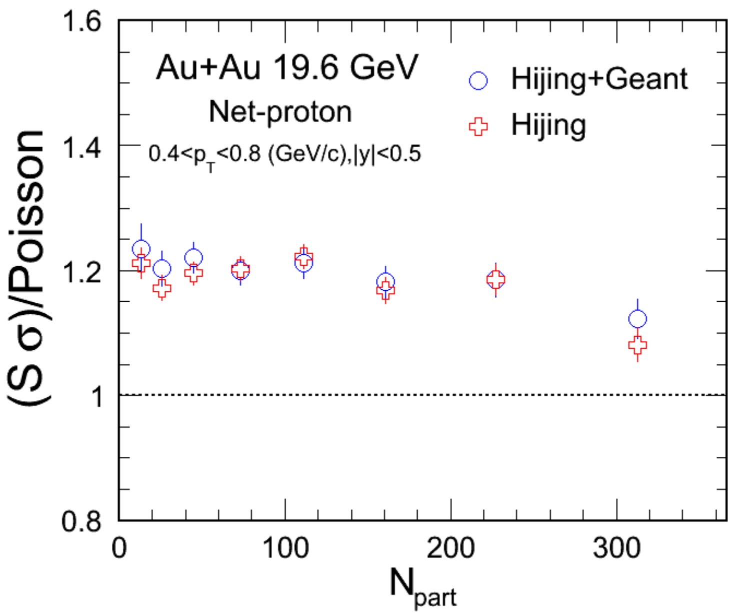
Moment Products/Poisson Ratio: Energy Dependence

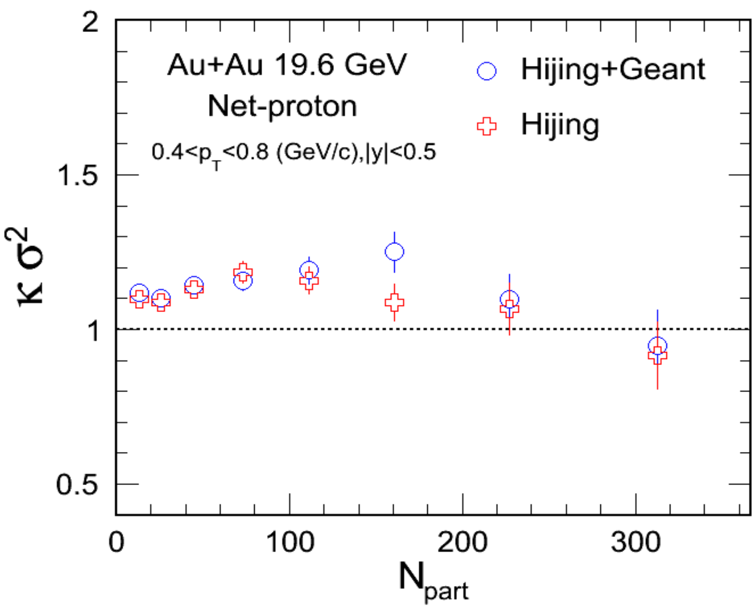


Hijing+Geant Simulation

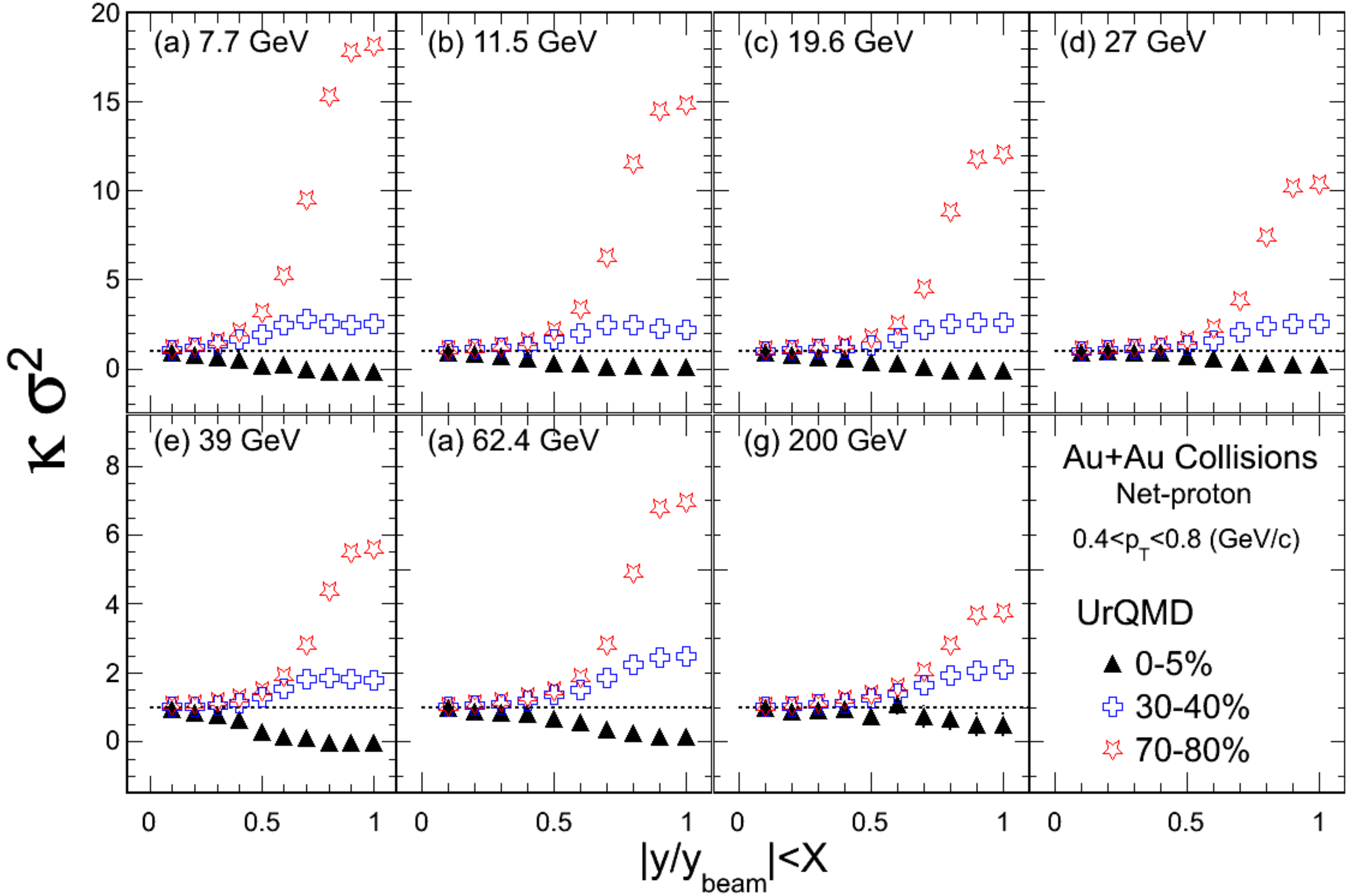


- The efficiency of proton and anti-proton as obtained for HIJING+GEANT simulations.
- The detector effects (efficiency, acceptance etc) seems small based on the Hijing+Geant simulations.



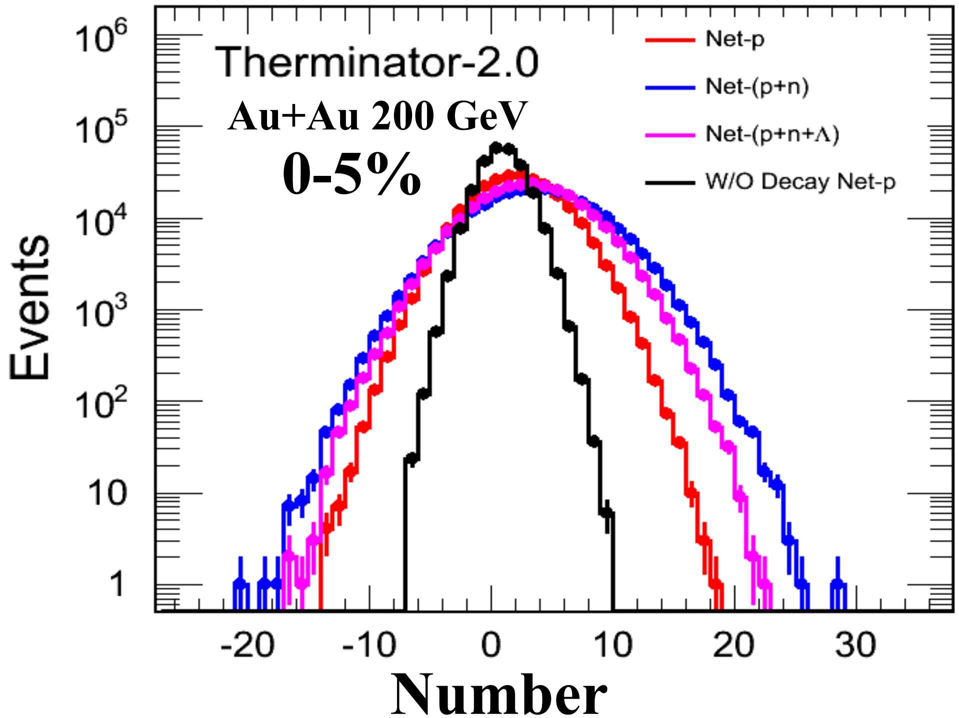


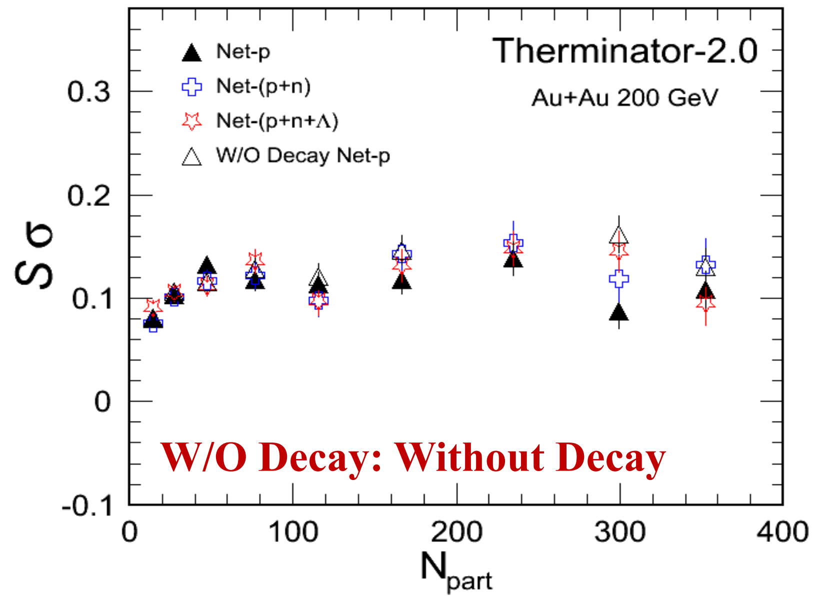
Rapidity Window Dependence: UrQMD Cal.

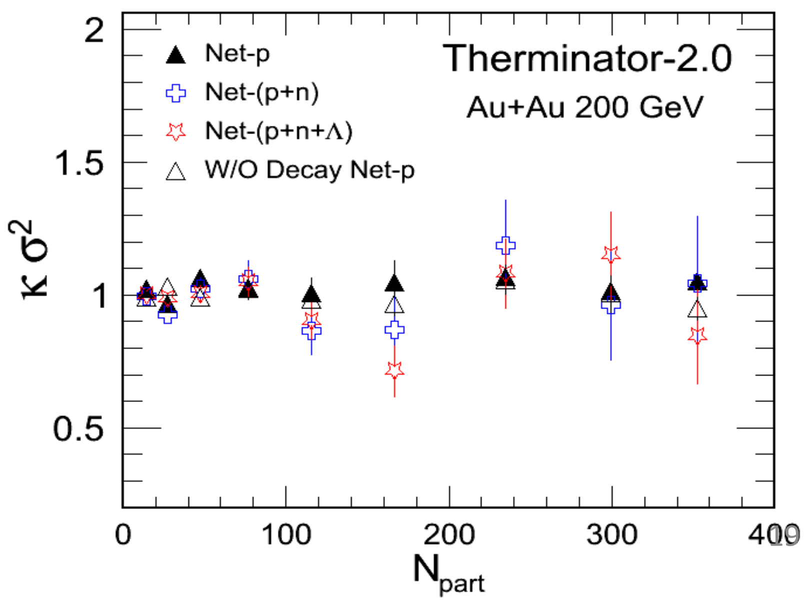


Resonance Decay and Neutron Effect

Model: Therminator-2.0 (arXiv:1102.0273)



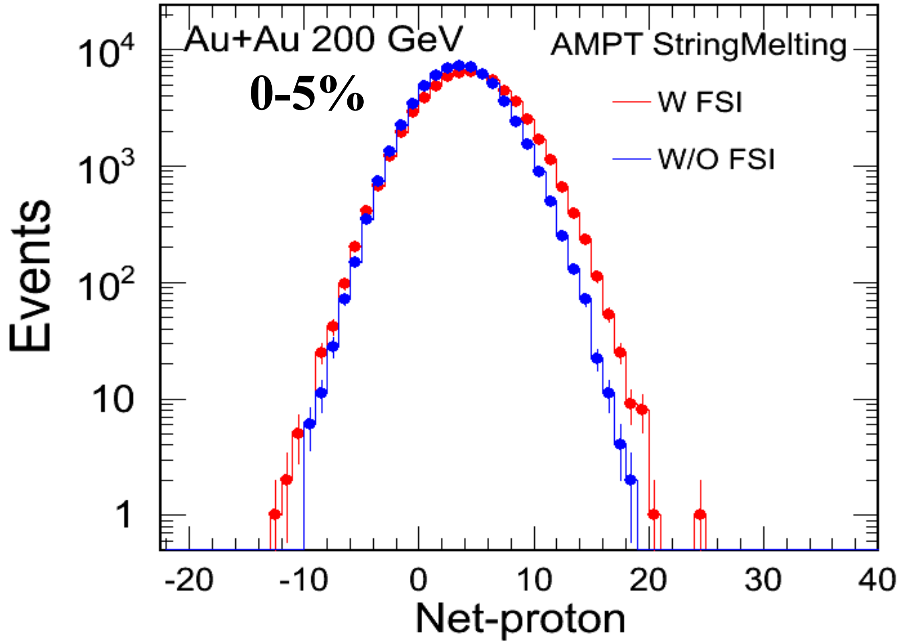


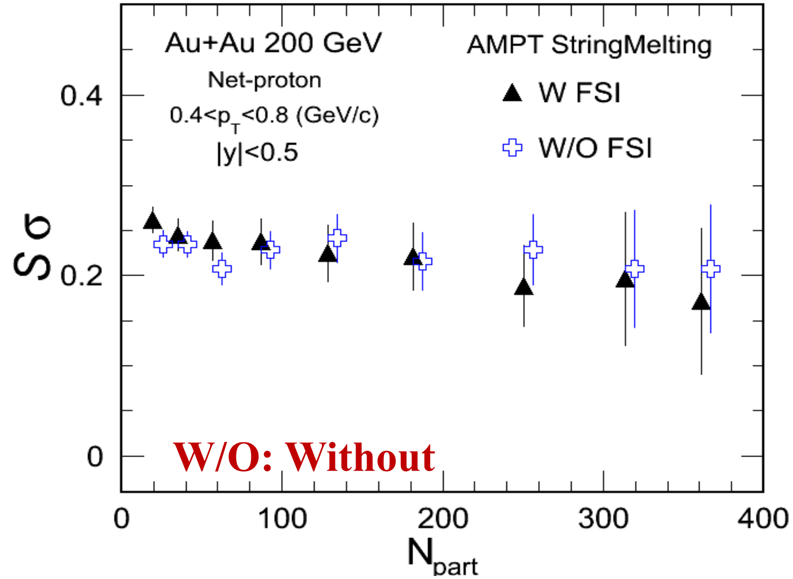


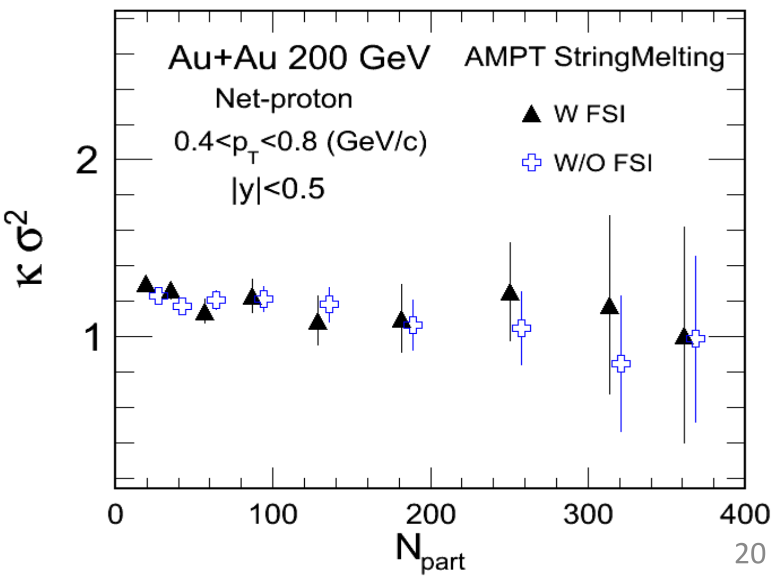
- Effect of resonance decay on $S\sigma$ and $\kappa\sigma^2$ is small. (based on the right two plots).
- Effect of inclusion of neutrons is small: Indicates: Net-proton fluctuation can reflect the net-baryon fluctuation.
- Error estimation: X. Luo, arXiv:1109.0593

Final State Interaction (FSI) Effect

Model: AMPT StringMelting (Phys. Rev. C 72, 064901)







- Process Final State Interaction (FSI) between hadrons or not can be controlled by "ART" program in the AMPT model.
- Effects of Final State Interaction (FSI) on Sσ and $\kappa\sigma^2$ are small. (based on the results in the right two plots).