Higher Moments of Net-proton Multiplicity Distributions at STAR

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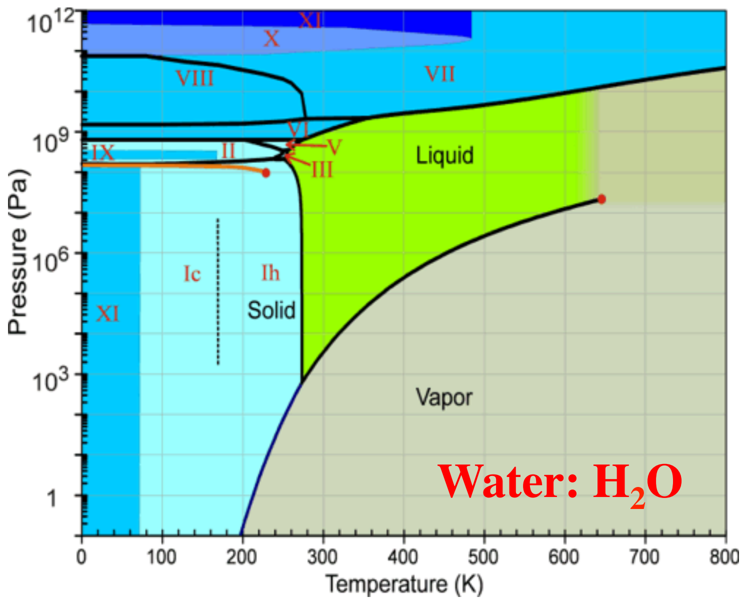
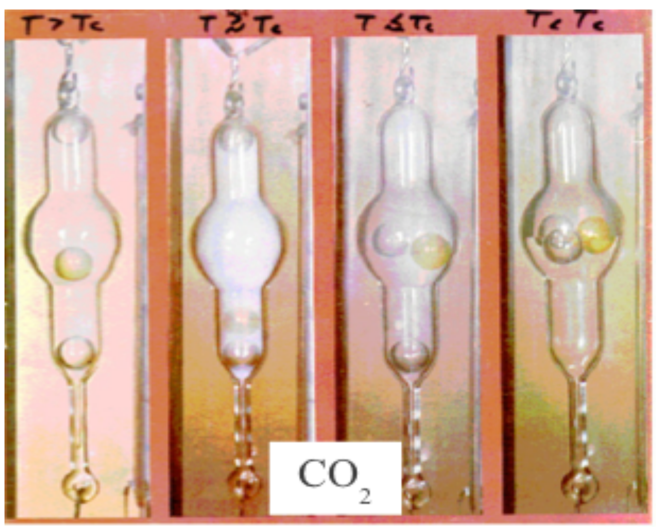
Outline

- **Introduction:**
- **Results from RHIC Beam Energy Scan-I:**
- **Theoretical Calculations: Lattice QCD and PQM Model.**
- **Techniques Used in the Moment Analysis.**
- **Summary**

Phase Transition and Critical Point



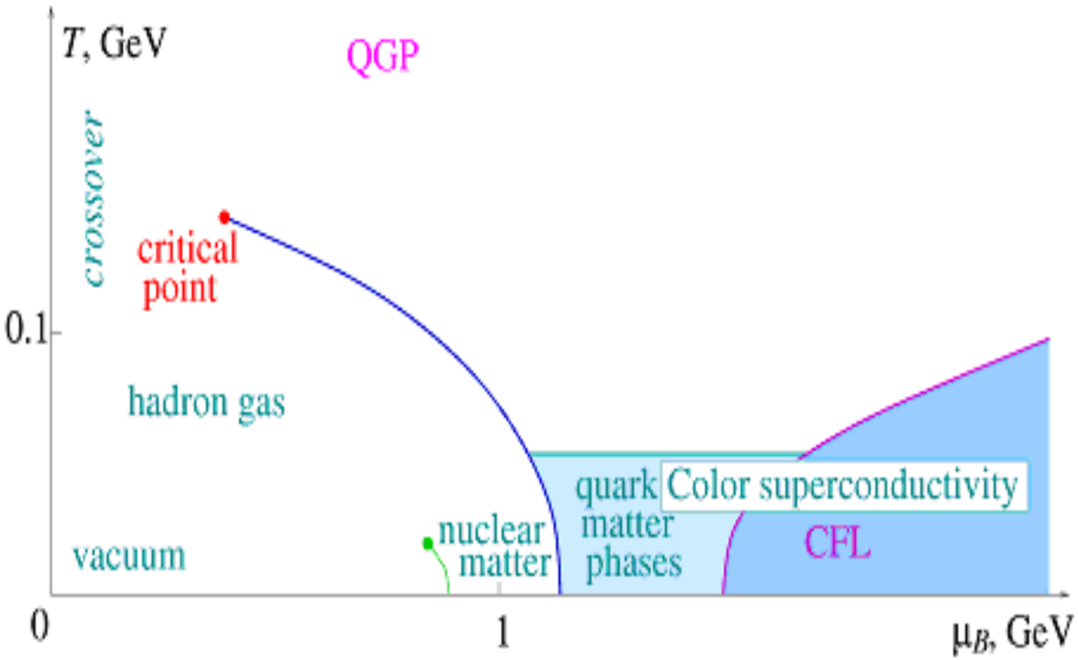


Matter may undergo phase transition when external condition (T, P etc.) are changed.

At the Critical Point (CP):

- 2nd order phase transition.
- Diverges of the thermodynamics quantities, such as correlation length (ξ), susceptibilities (χ), heat capacity (C_V).
- Long wavelength fluctuations comparable with the light wavelength: Critical Opalescence.

Explore the Phase Structure of Nuclear Matter



Lattice QCD :

➢ Crossover at μ_B =0, 1[st] order phase transition at large μ_B .

Y. Aoki, et al., Nature 443, 675 (2006).
S. Gupta, et al. Science 332, 1525 (2011).
A. Bazavov et al, PRD 85, 054503 (2012).
Y. Aoki et al., JHEP 0906, 088 (2009) .

➢ 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 Heavy Ion Collisions:

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

Observables:

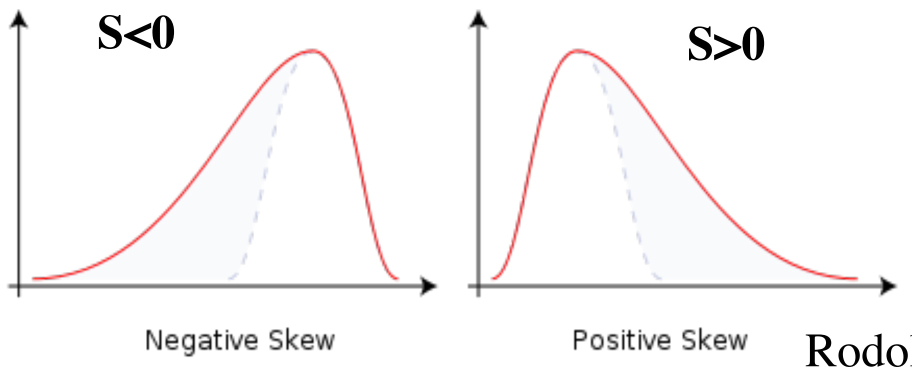
1. Flucutations and correlations.
2. Collective flow: v1, v2…
3. Others…

Higher Moments (I): Sensitive to the Correlation Length

Skewness:

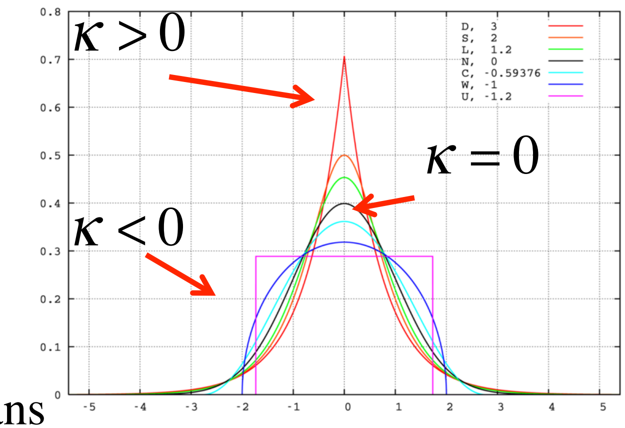
C_n: n^{th} order cumulants

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{<(N-<N>)^3>}{\sigma^3}$$



Kurtosis:

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$



Rodolfo Hermans

- Ideal probe of non-gaussian fluctuations.
- Sensitive to the correlation length (ξ).

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

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

Search for CP in Heavy Ion Collisions (ξ~2-3 fm)

M. A. Stephanov,
Phys. Rev. Lett. 102, 032301 (2009);
Phys. Rev. Lett. 107, 052301 (2011);

Higher Moments (II): Related to the Susceptibility

Theory: Lattice QCD, HRG… ⇔ Experiment: Heavy Ion Collisions

Pressure:

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V, T, \mu_B, \mu_Q, \mu_S)$$

Susceptibility:

$$\chi_q^{(n)} = \frac{1}{T^4} \frac{\partial^n}{\partial(\mu_q / T)^n} P\left(\frac{T}{T_C}, \frac{\mu_q}{T}\right)\Big|_{T/T_c},$$

$q = B, Q, S$ **(Conserved Quantum Number)**

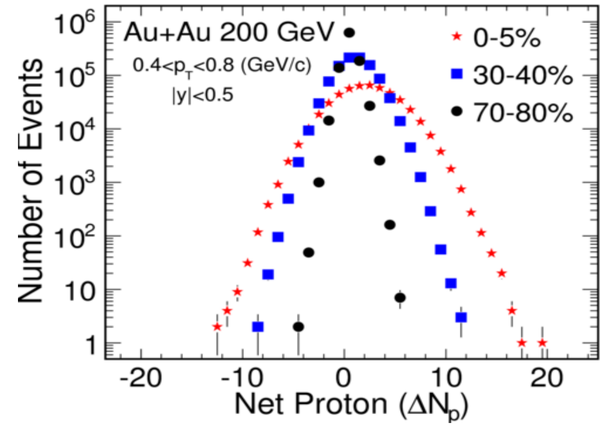
$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle, \chi_q^{(2)} = \frac{1}{VT^3}\left\langle (\delta N_q)^2 \right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle (\delta N_q)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle (\delta N_q)^4 \right\rangle - 3\left\langle (\delta N_q)^2 \right\rangle^2\right)$$

A. Bazavov et al .*arXiv::1208.1220. 1207.0784.*
F. Karsch et al, PLB 695, 136 (2011).
arXiv: 1203.0784; S. Borsanyi et al, JHEP1201,138(2011);

STAR Experiment: *PRL105, 022302(2010).*



➢ **Susceptibility ⇔ Moments**

$$\boxed{\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}, S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}, \frac{\sigma^2}{M} \sim \frac{\chi^{(2)}}{\chi^{(1)}}}$$

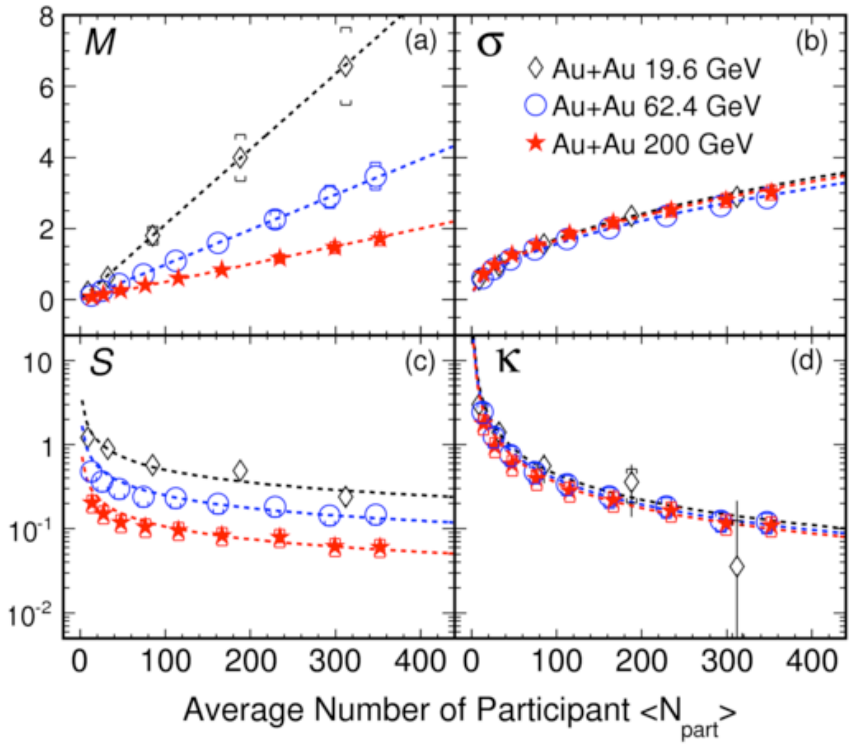
➢ Study Phase Transition and Bulk properties of QCD matter.

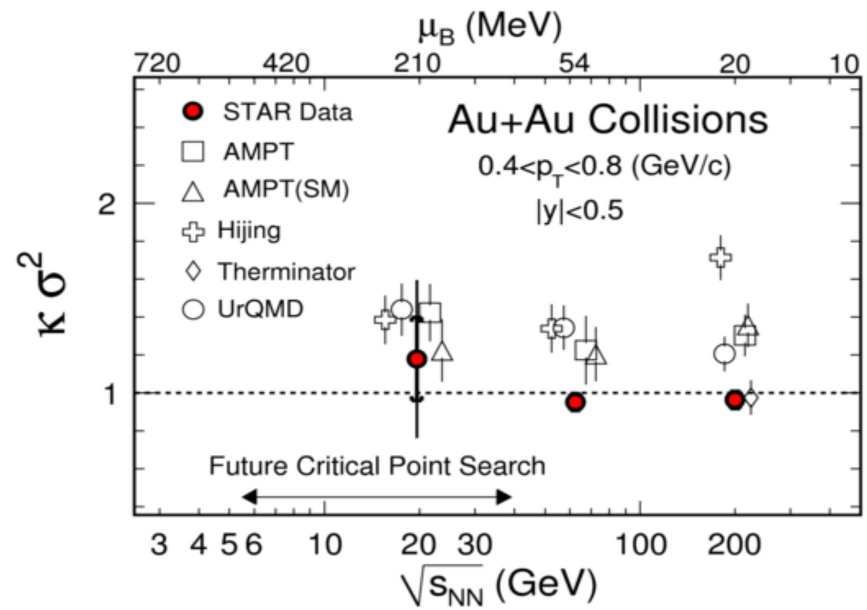
R.V. Gavai and S. Gupta, *PLB 696, 459 (2011).*
S. Gupta, et al., *Science, 332, 1525(2011).*
Y. Hatta, et al, *PRL. 91, 102003 (2003).*

Observable: Higher Moments of Net-proton Distributions

Net-proton fluctuations can reflect the diverges of baryon number fluctuations at CP and can be used to search for the CP.

Y. Hatta, et al., Phys.Rev.Lett. 91, 102003 (2003).

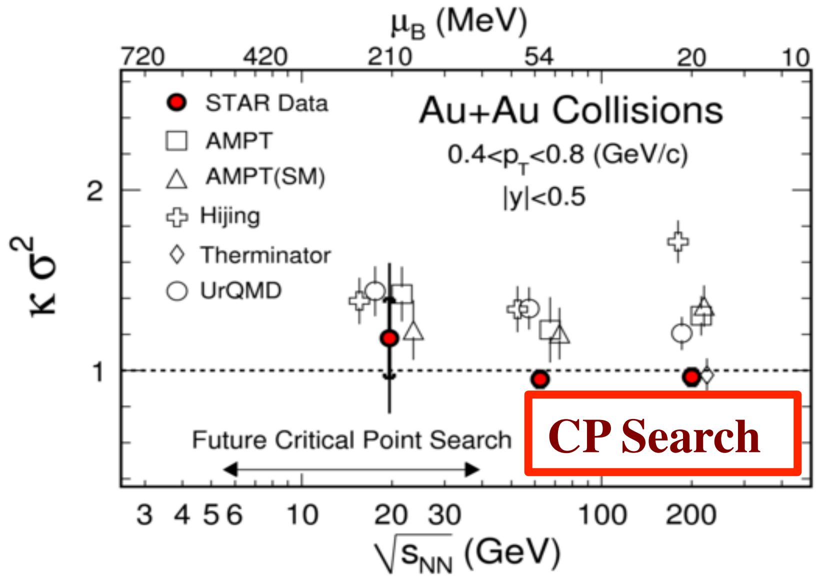




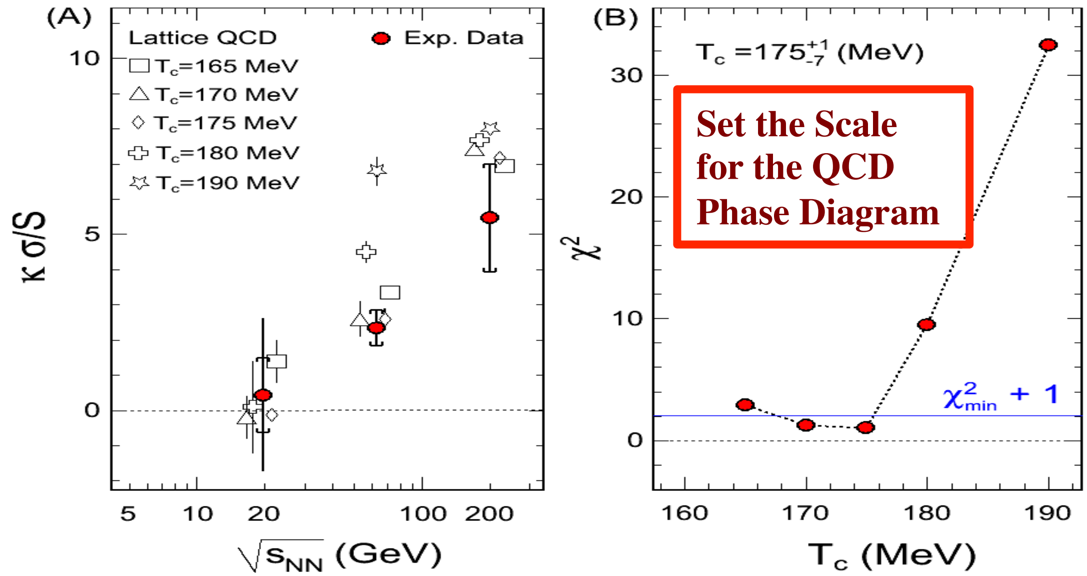
STAR: Physical Review Letters 105, 022302 (2010).

- First measurement of the higher moments of net-proton distributions at RHIC.
- There has no evidence for the existence of QCD critical point with μ_B <200 MeV.

Applications of Higher Moments Analysis

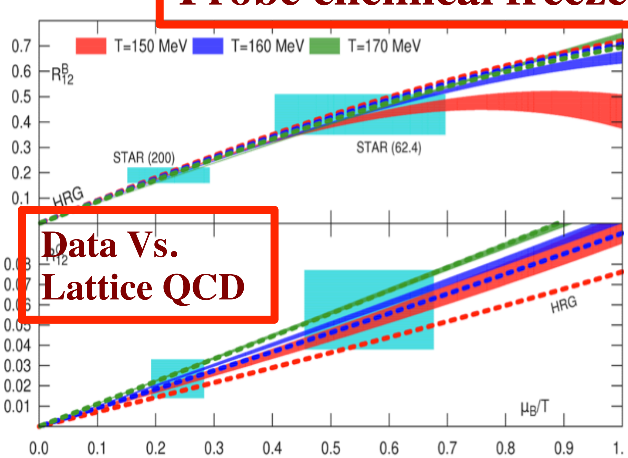


STAR, Phys. Rev. Lett. 105, 022302 (2010).

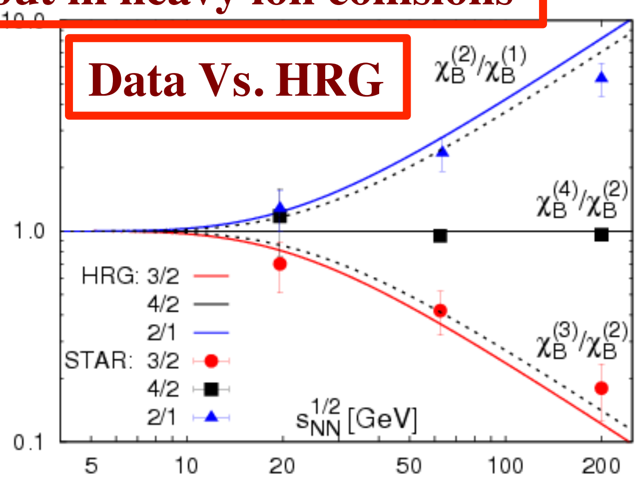


S. Gupta, et al, Science 332:1525 (2011).

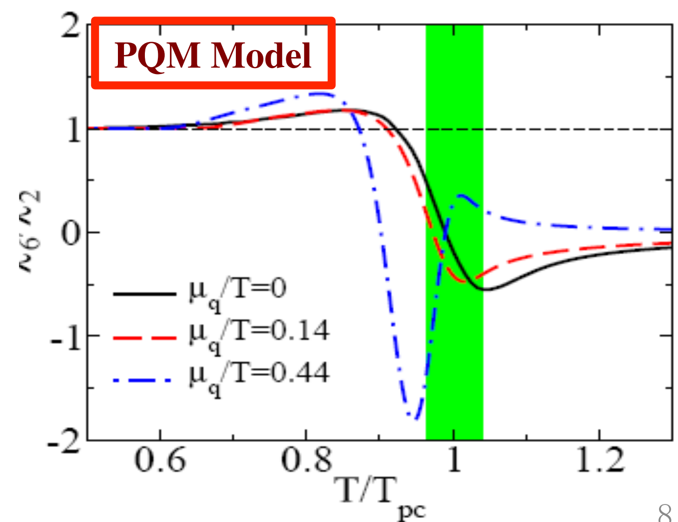
Probe chemical freeze out in heavy ion collisions



A. Bazavov et al., PRL109, 192302 (2012)



F. Karsch et al, PLB,695, 136 (2011).

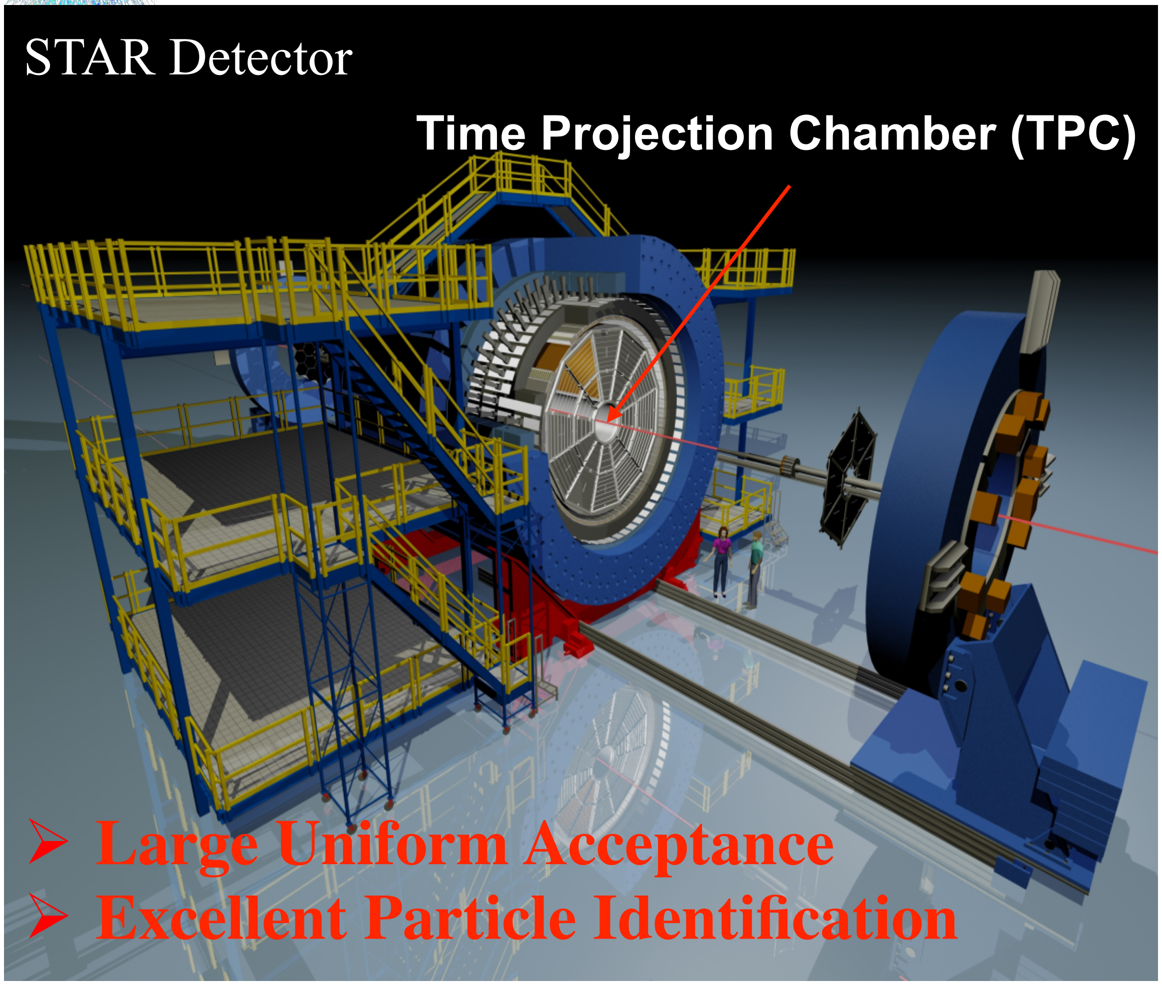


B. Friman, *et al, EPJC 71, 1694 (2011)*

Continue the story….

Search for the QCD Critical Point….

RHIC Beam Energy Scan-Phase I



Varying beam energy varies Temperature and Baryon Chemical Potential.
(RHIC BES-Phase I: Au+Au collisions at $\sqrt{s_{NN}}$=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)

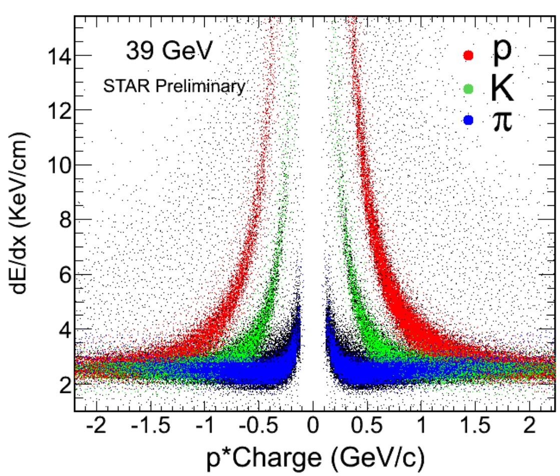
- Access a broad region of QCD phase diagram by RHIC BES program.
- STAR is an ideal detector to perform correlation and fluctuation analysis to study the QCD phase diagram.

Data Analysis

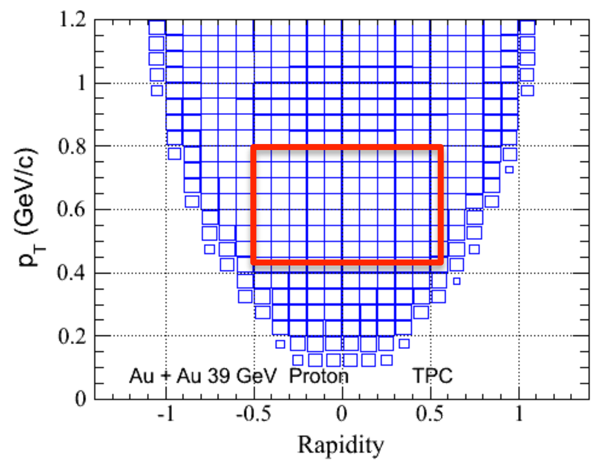
Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics (Million)	~3	~6.6	~15	~30	~87	~47	~242
Year	2010	2010	2011	2011	2010	2010	2010

➢ 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 $|y|<0.5$.

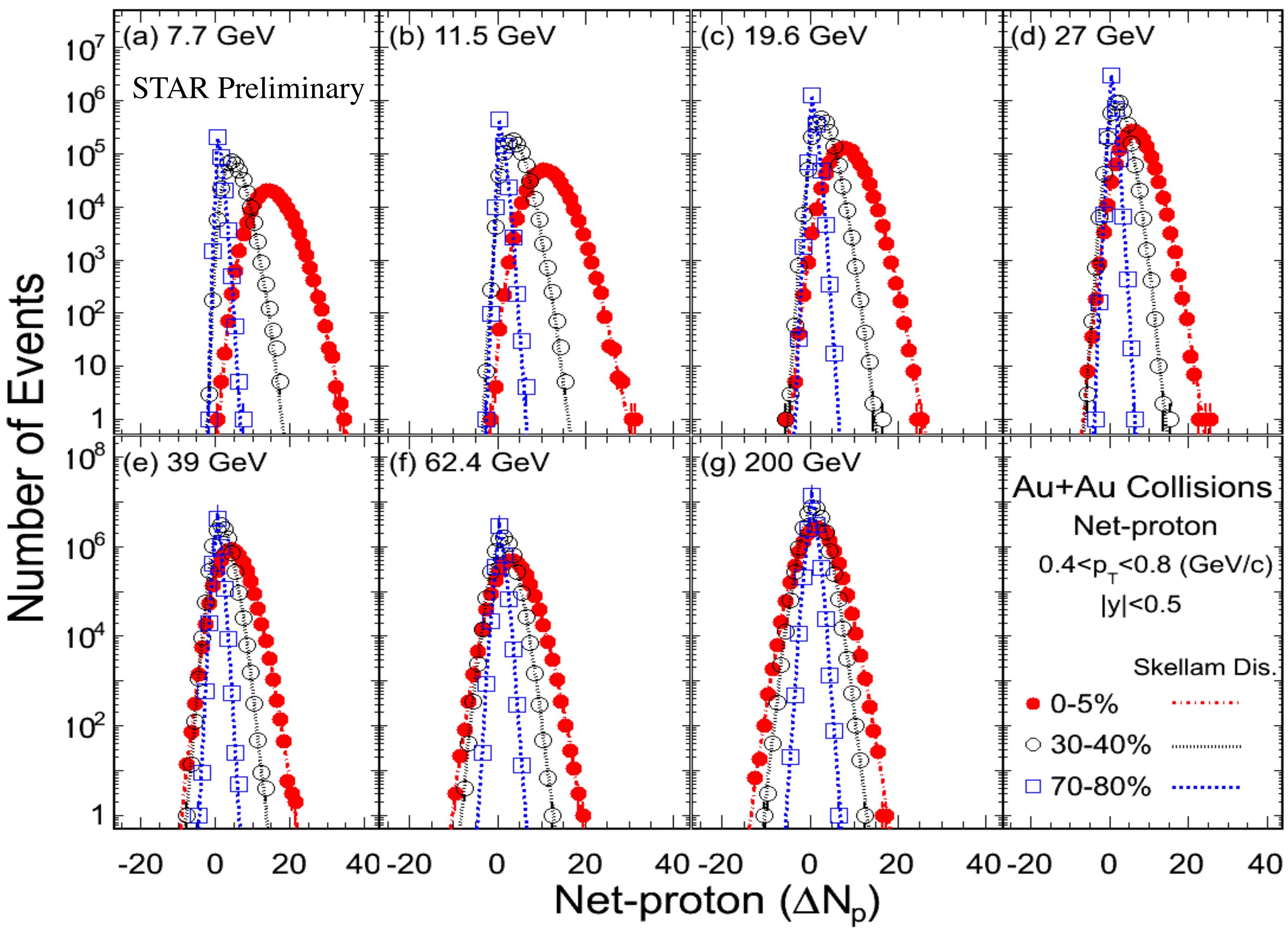
STAR TPC dE/dx PID



Proton Phase Space



Event-by-Event Net-proton Distributions



- Skellam distributions (dash lines) :assuming distributions of protons and anti-protons are indep. Poission.

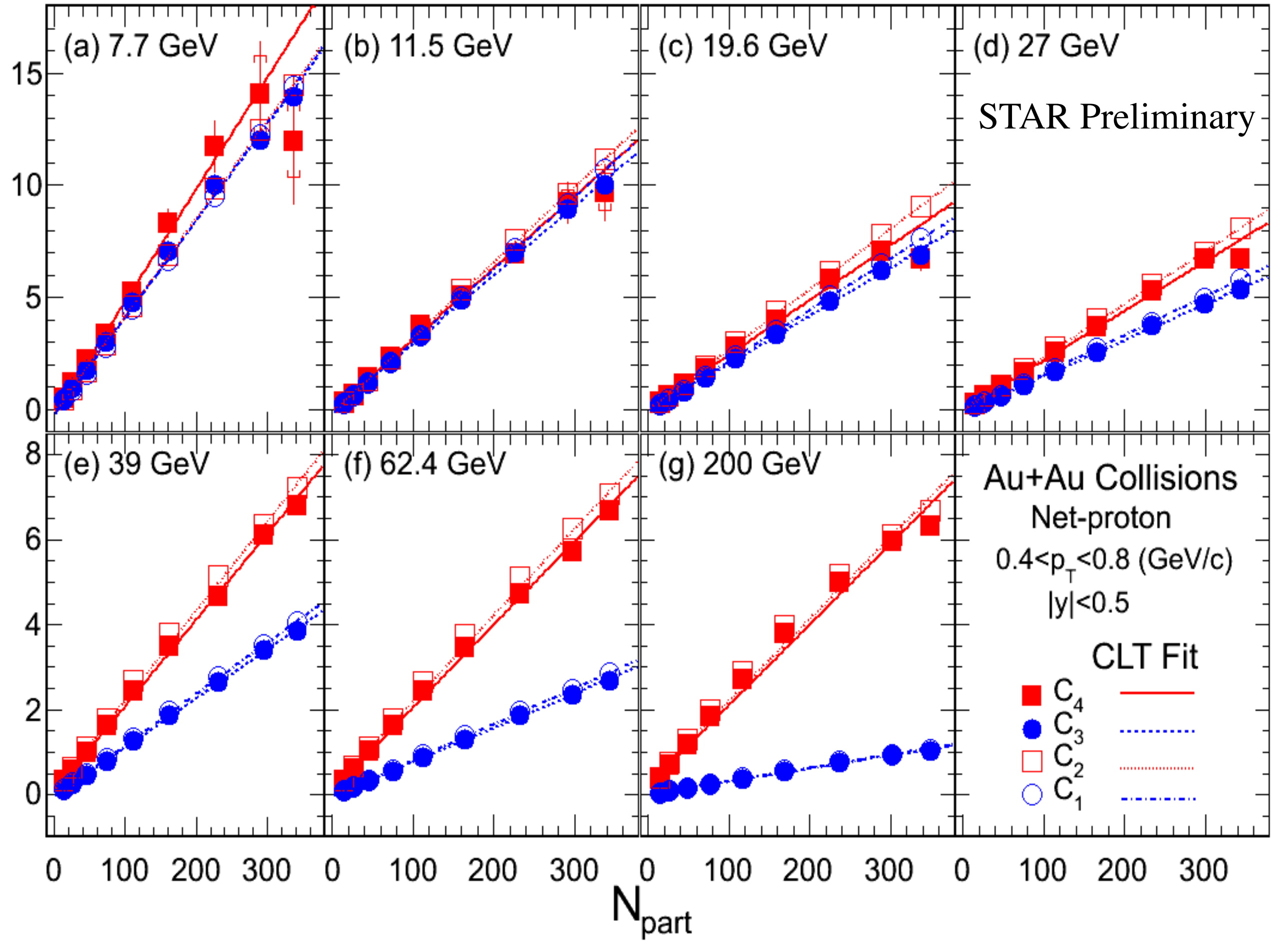
$$P(N)=\left(\frac{N_{\bar{p}}}{N_p}\right)^{N/2} I_N\left(2\sqrt{N_{\bar{p}}N_p}\right)e^{-(N_{\bar{p}}+N_p)}$$

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.

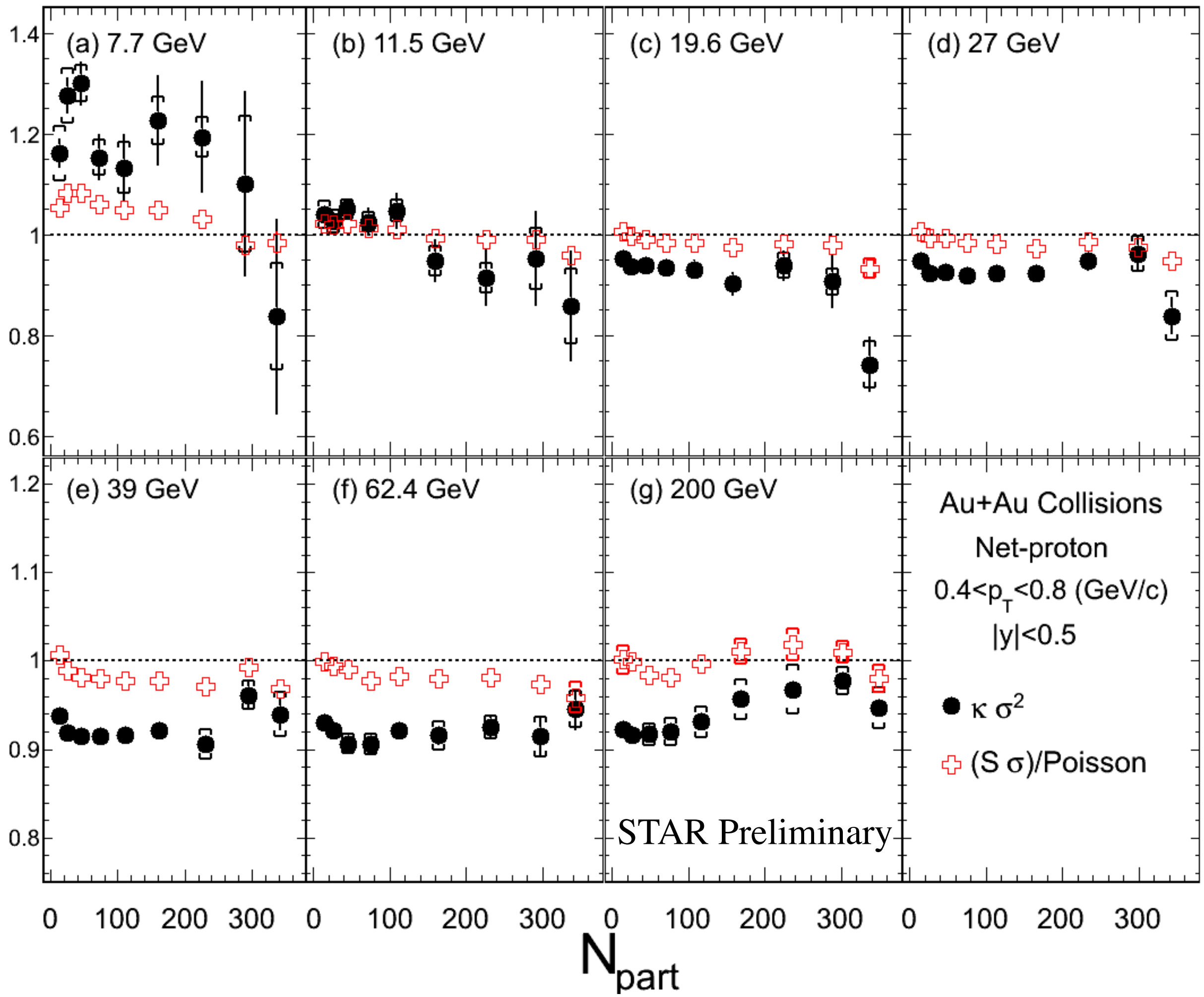
➢ All cumulants show general linear dependence on N_{part}.

➢ $C_1 \sim C_3$ (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.)

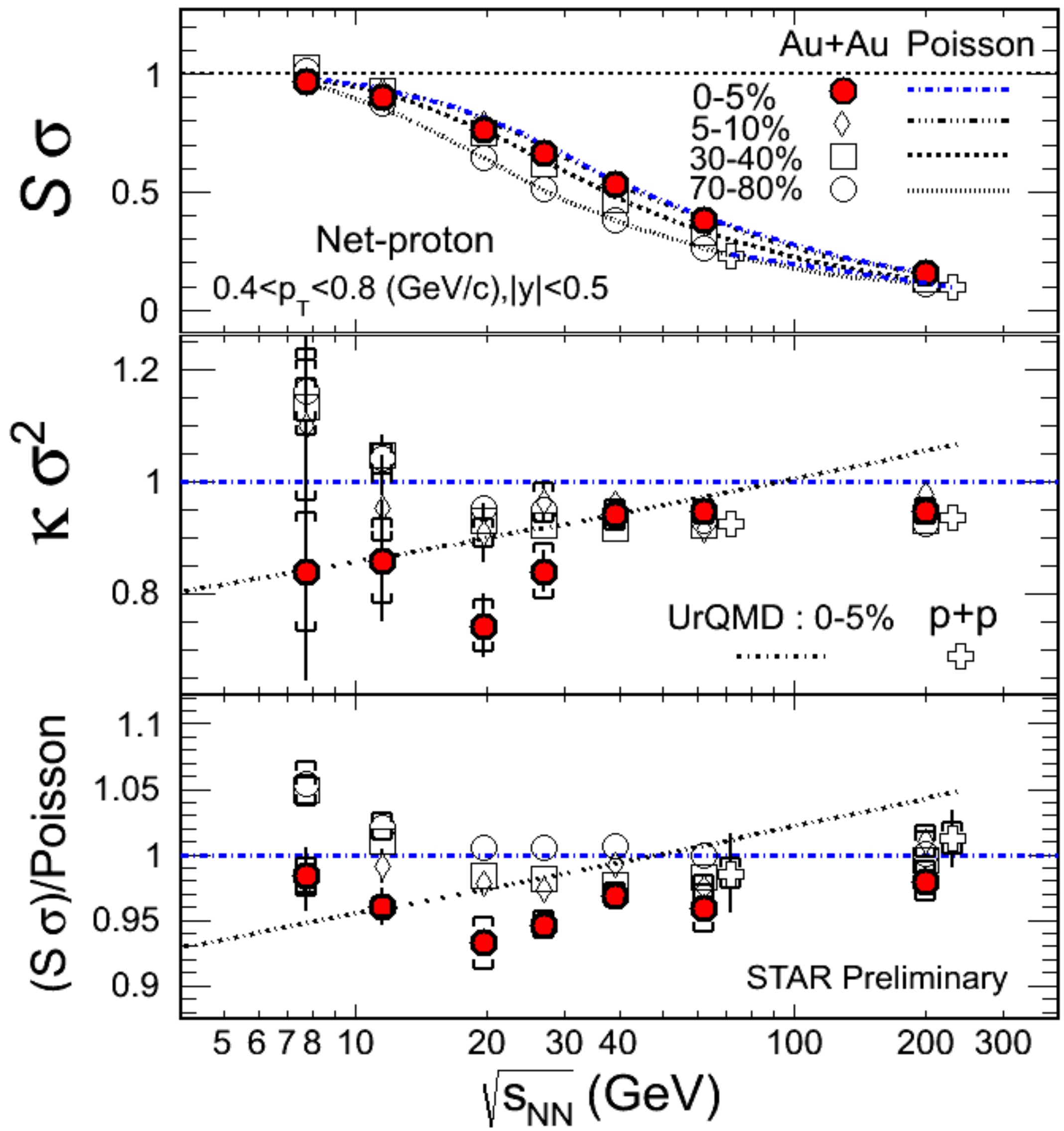
Moment Products: Centrality Dependence



- 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: Energy Dependence



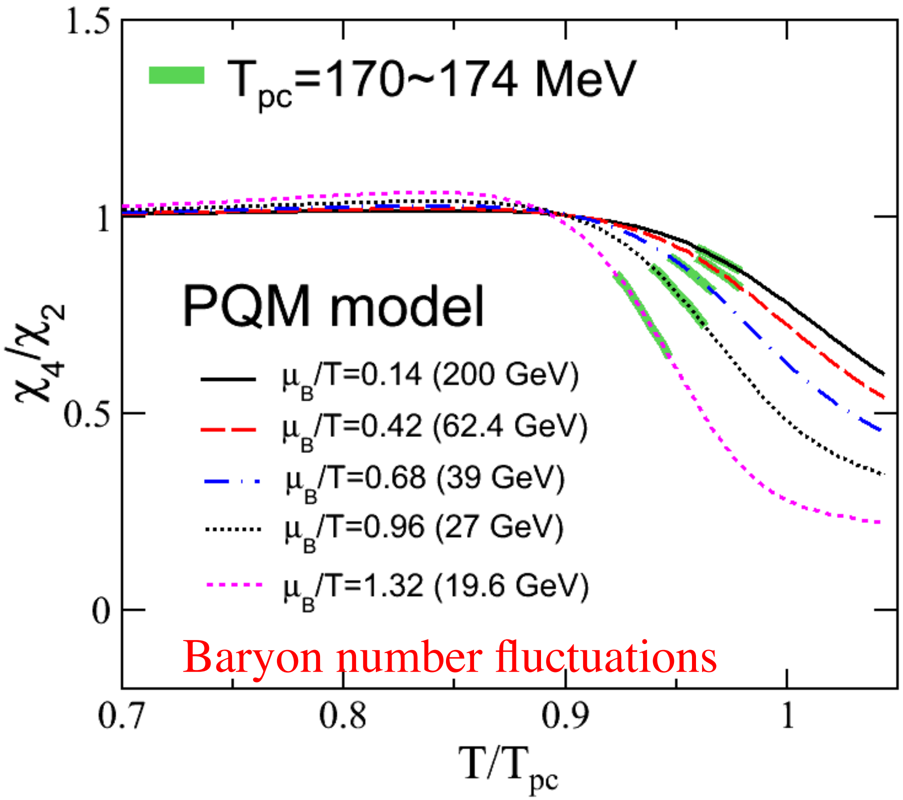
- Deviations below Poisson expectations are observed beyond statistical and systematic errors in 0-5% most central collisions for $\kappa\sigma^2$ and Sσ above 7.7 GeV.

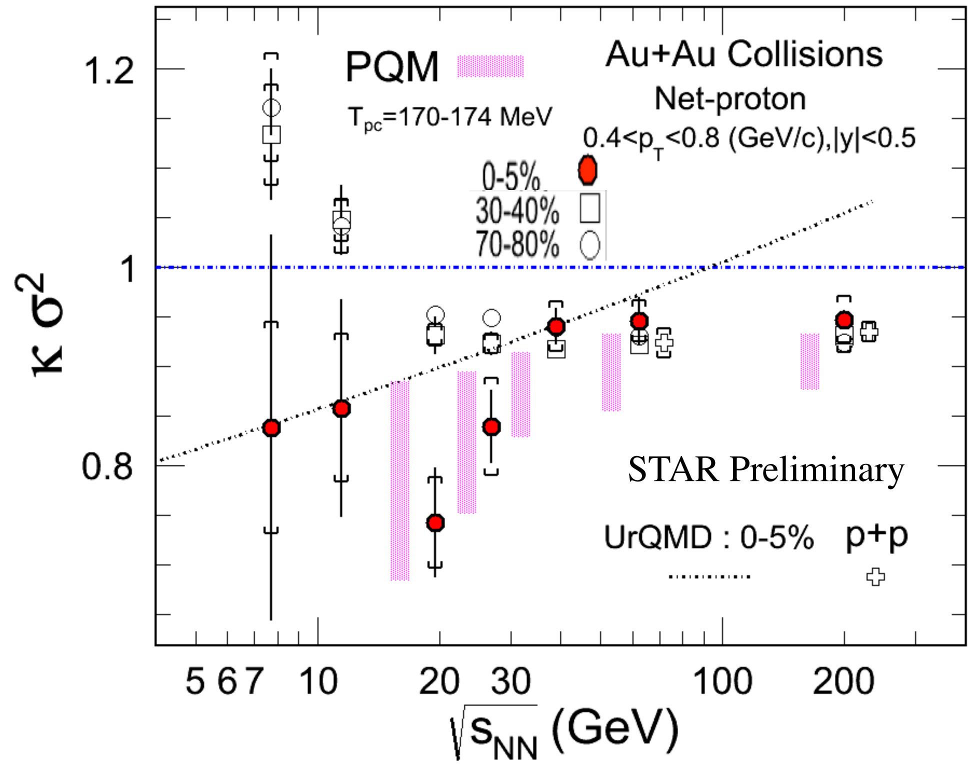
- UrQMD model show monotonic behavior for the moment products, in which non-CP physics, such as baryon conservation, hadronic scattering effects, are implemented.

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

STAR

Comparison between Data and PQM Model



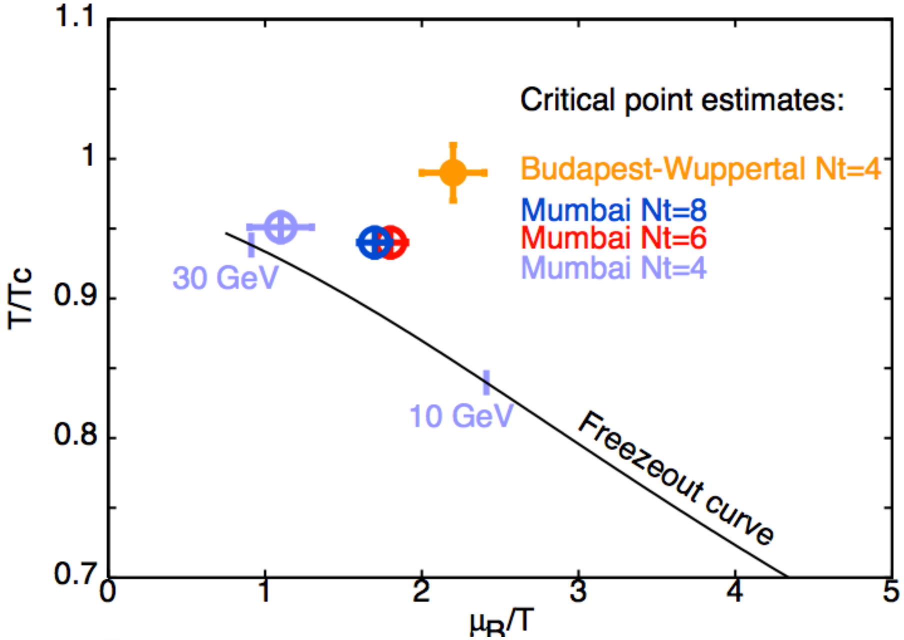


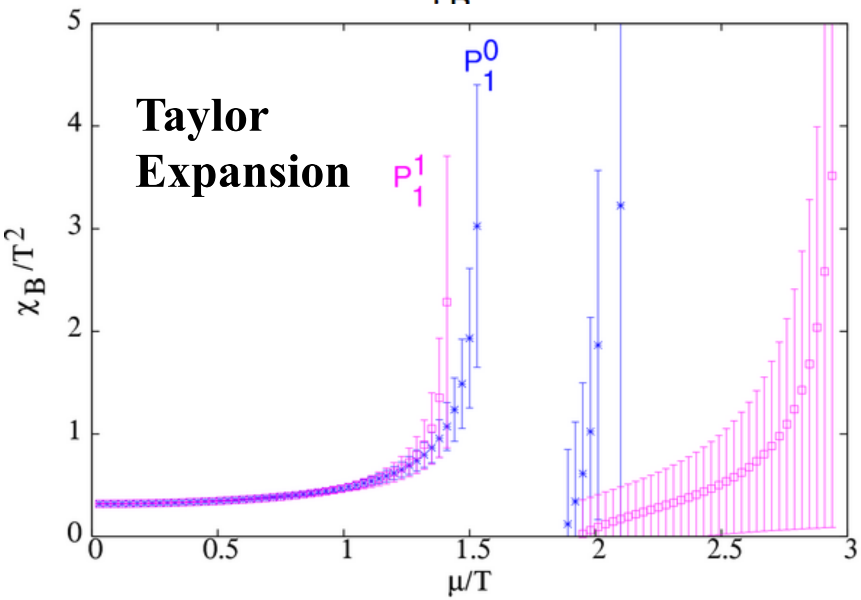
B. Friman, et al, EPJC 71, 1694 (2011).

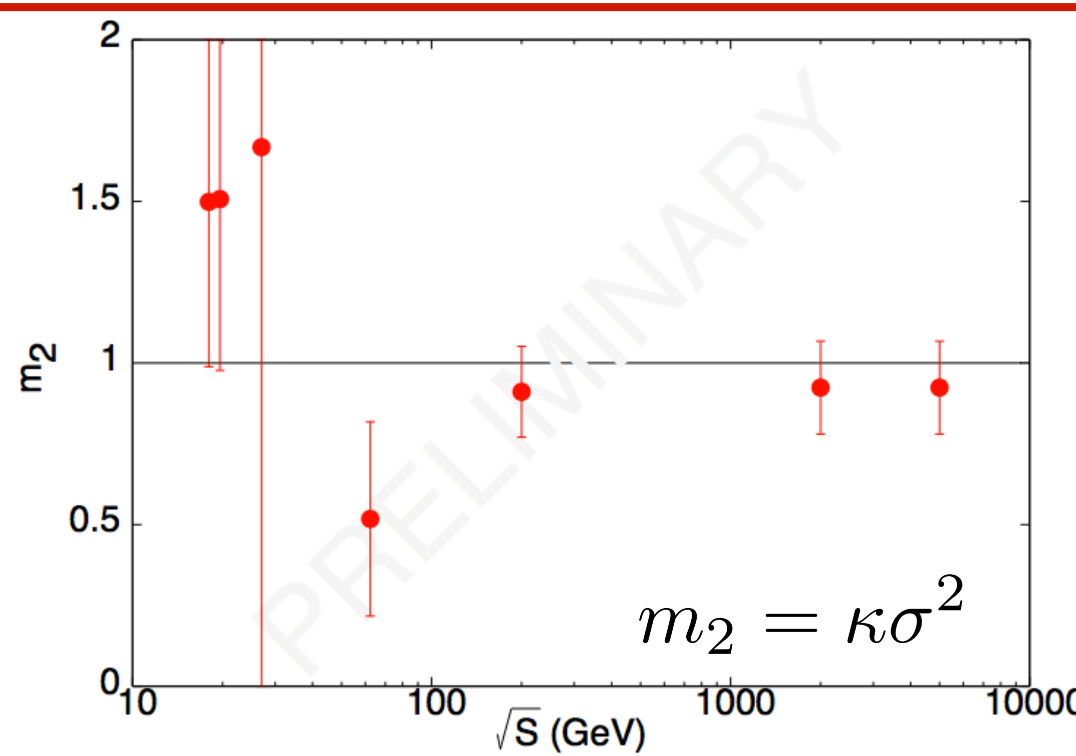
PQM Model: Polyakov Quark Meson Model

- PQM model calculations agree with data.
- Need more statistics at lower beam energies.

QCD Critical Point: Lattice Calculation







- ➢ μ^E_B/T^E~1-2.
- ➢ More statistic are needed.

S. Gupta, CPOD2013

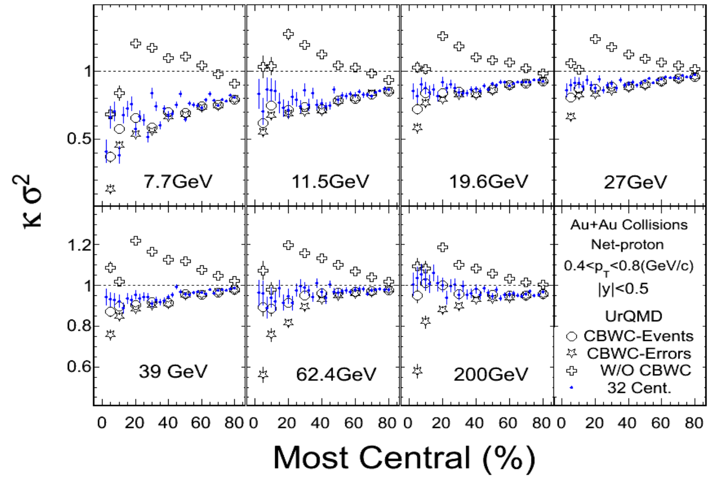
Techniques used in the Moment Analysis

X. Luo, et al, arXiv: 1302.2332

1. Centrality Bin Width Correction (CBWC):

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]

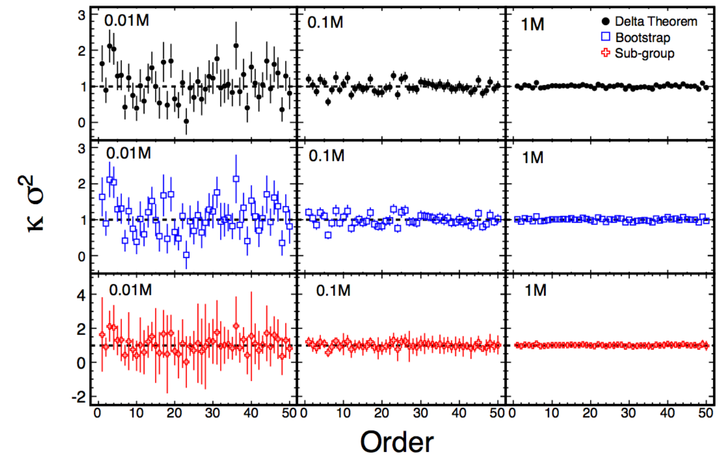


2. New Centrality: Refmult3

Determine the centrality using charged particles but excluding proton/anti-proton used in the analysis to avoid auto-correlation.

3. Statistical Error Estimations: Delta theorem method.

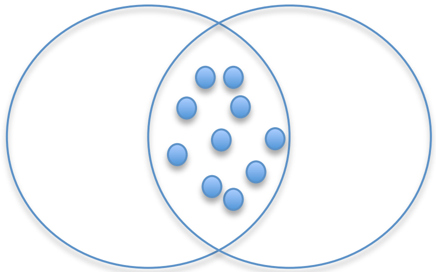
J. Phys. G 39, 025008 (2012) [arXiv: 1109.0593]



4. Centrality Resolution Effect.

This effect will be shown by model calculations and we are still investigating in data.

Initial geometry (volume) fluctuations



Initial geometry: $N_{part,}$ overlap volume…

How does the initial geometry fluctuations affect the higher order fluctuations analysis ?

Theoretical calculations:

The independent emission Source Model

Henning Heiselberg, nucl - th/0003046

- Multiplicity N arise from independent Source, such as participant nucleon (Np).

$$N = \sum_{i=1}^{N_p} n_i$$

n_i is the multiplicity from i^{th} source.

- Multiplicity Fluctuations:

$$\frac{\sigma_N^2}{M_N} = \frac{\sigma_n^2}{M_n} + <n> \frac{\sigma_{N_p}^2}{M_{N_p}}$$

N_{part} fluctuations.

Volume fluctuations (V)

arXiv: 1205.4756

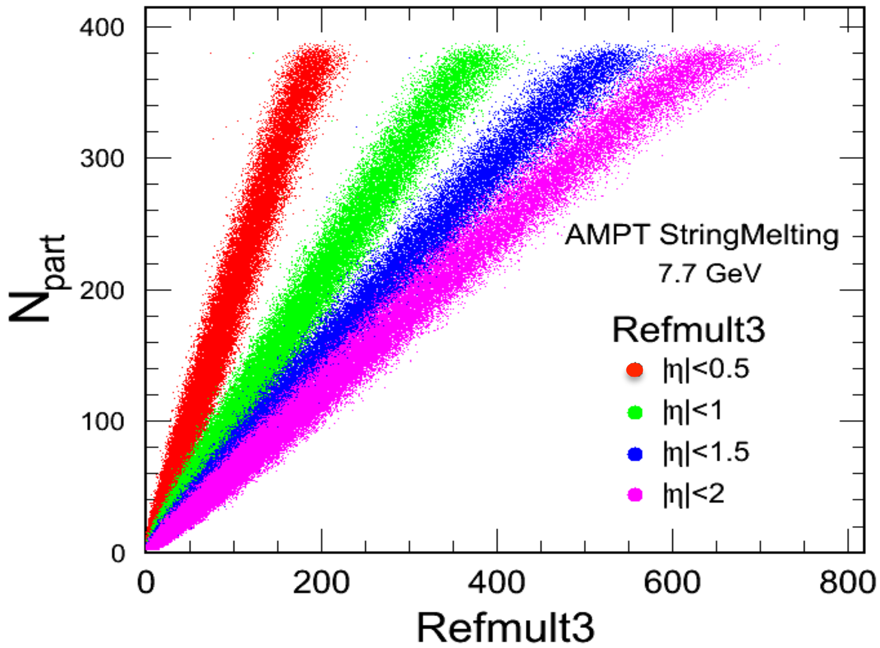
$$\sigma_N^2 = \sigma_n^2 * V + <n>^2 \frac{\sigma_V^2}{V}$$

Volume fluctuations.

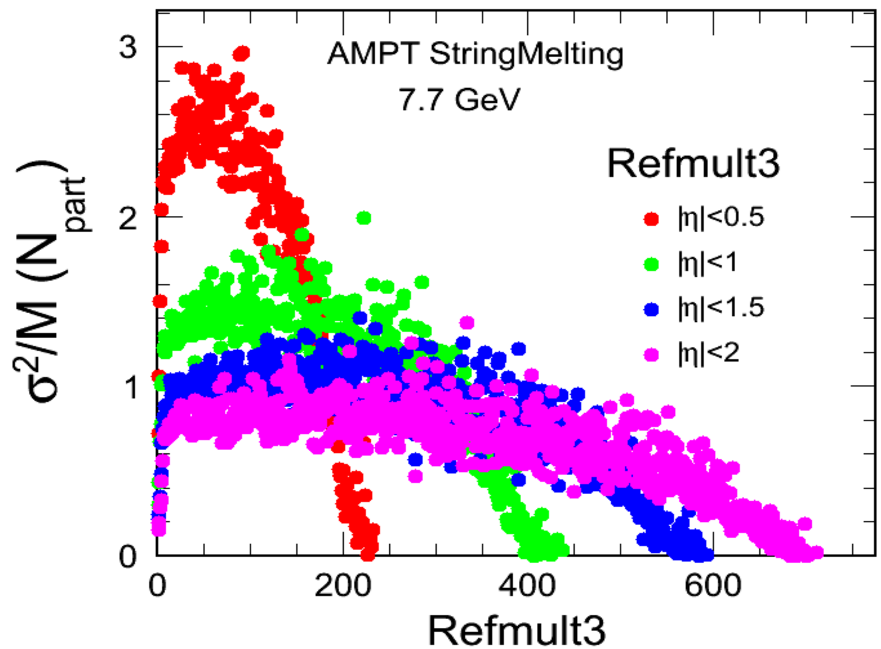
$\sigma_n^2, <n>$: Fluctuation per unit volume and independent of volume.

Centrality Resolution : Model Simulation

2D histogram



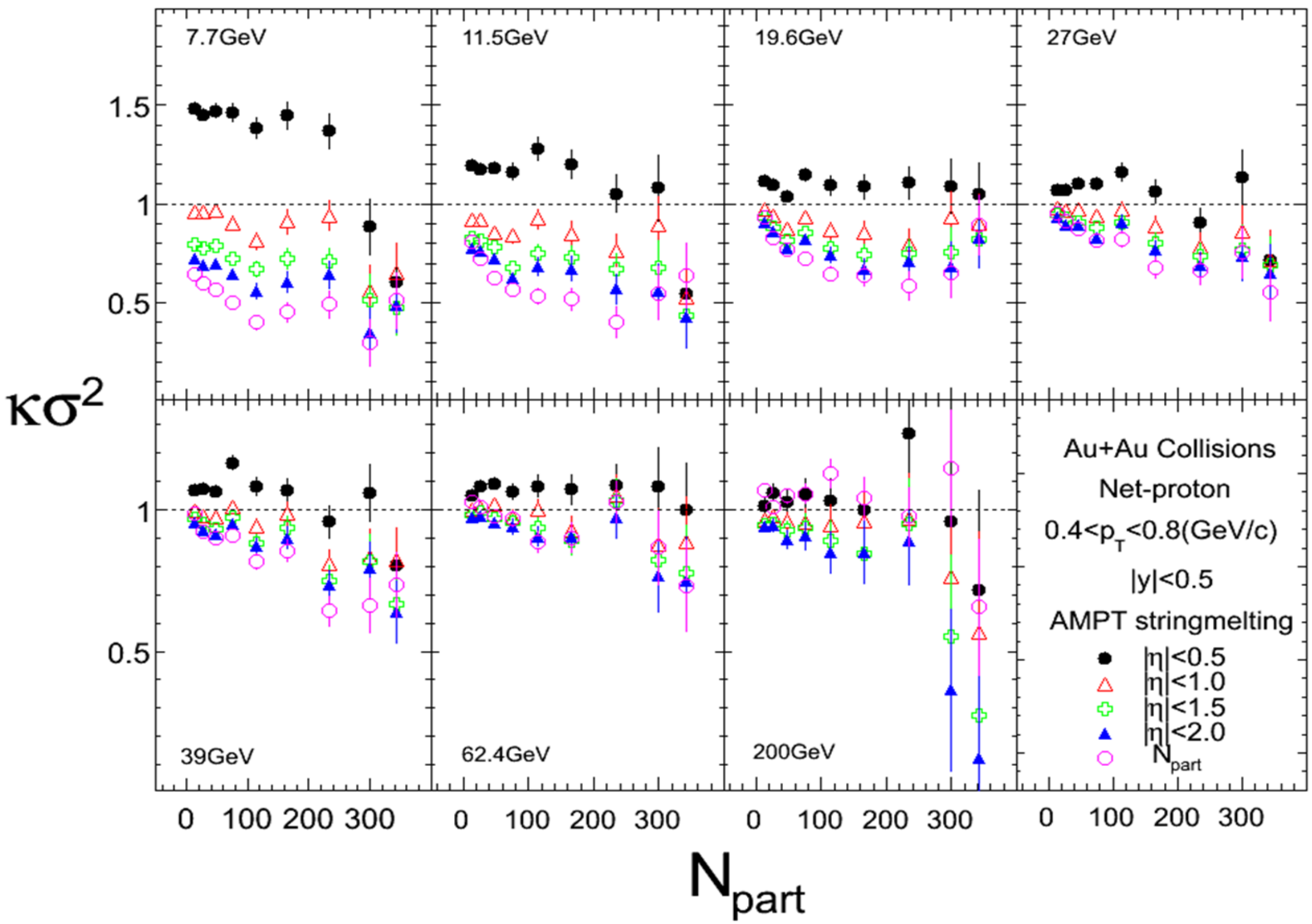
Fluctuations of N_{part} (Number of Participant)



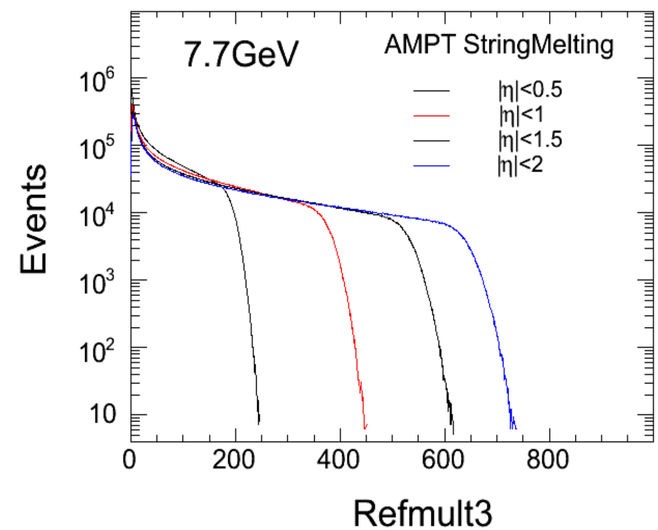
Refmult3 Definition in Model: Charged Kaon + Pion Multiplicities within certain η window.

- Central collisions has smaller N_{part} fluctuations (higher centrality resolution) than mid-central and peripheral collisions.
- N_{part} fluctuations will be largely suppressed at mid-central and peripheral collisions by increasing the particle multiplicities in centrality definition.

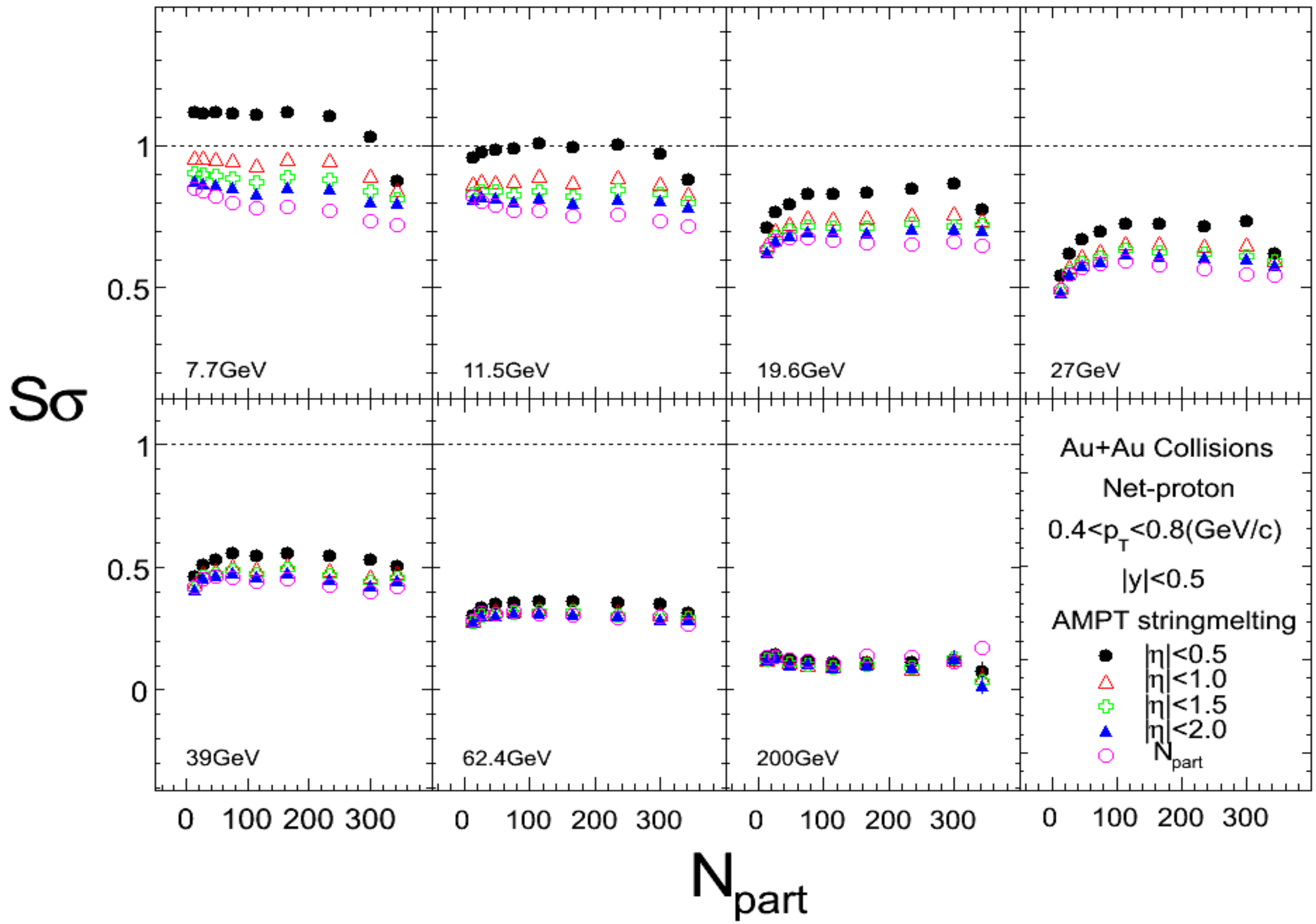
Model simulations: AMPT String Melting



Refmult3 Centrality :
|η|<0.5, |η|<1, |η|<1.5, |η|<2

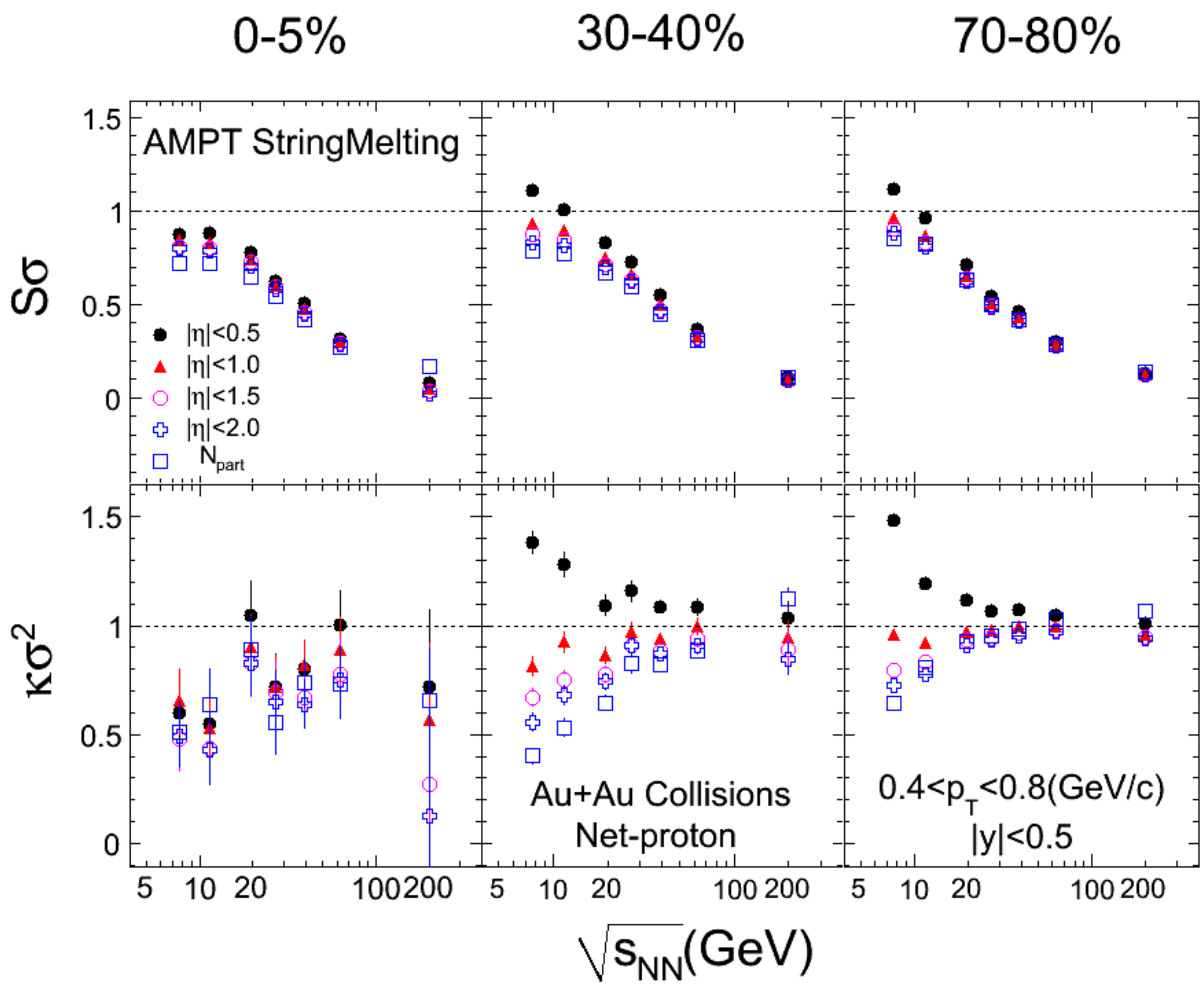


- Large difference are observed in mid-central /peripheral and low energies for different Refmult3 definition (different centrality resolutions).
- The saturation are reached around |η|<2 and are close to the results with the N_{part} centrality.



Similar behavior is observed as for Kurtosis*Variance.

Model Simulation: Energy Dependence



- ➢ Significant differences are found at mid-central/peripheral collisions and low energies.
- ➢ For 0-5% central collisions, results are consistent within errors.

Summary

Measurements:

- We present 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).

Comparisons with Skellam Expectations and Transport Model:

- Deviations below Skellam expectation are observed in Au+Au collisions beyond the statistics and systematics errors for the moment products $\kappa\sigma^2$ and $S\sigma$ above 7.7 GeV. Monotonic behavior for the moment products is observed in the UrQMD model.

Experimental results are compared with Lattice QCD and PQM Model Calculations. Centrality resolution effect has been discussed by model simulation and we are still investigating this effect in the data.

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

- The second phase of beam energy scan program at RHIC is planned.

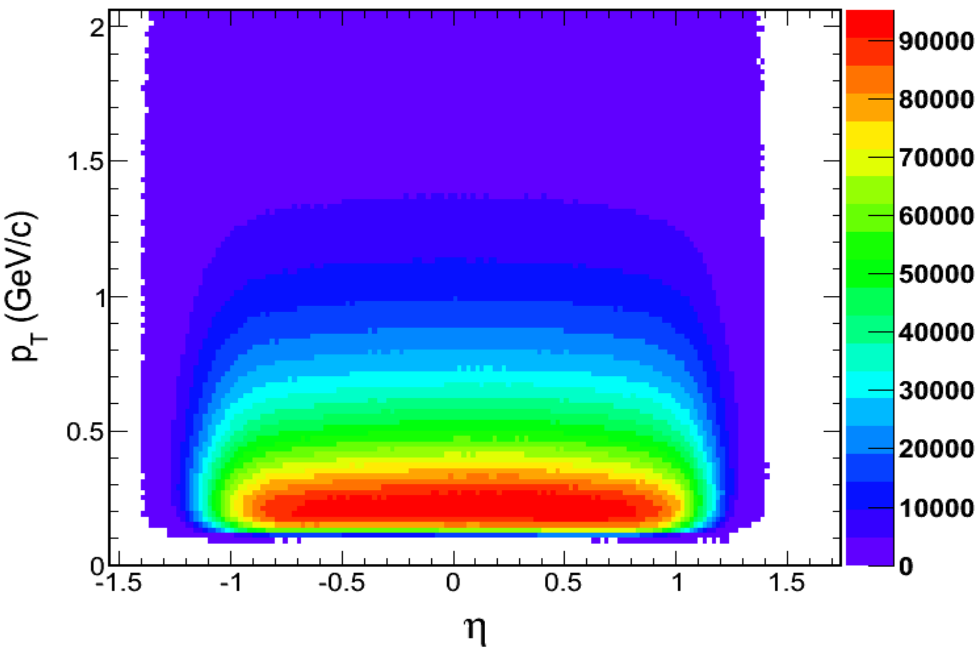
Backup Slides

What about the experimental data ?

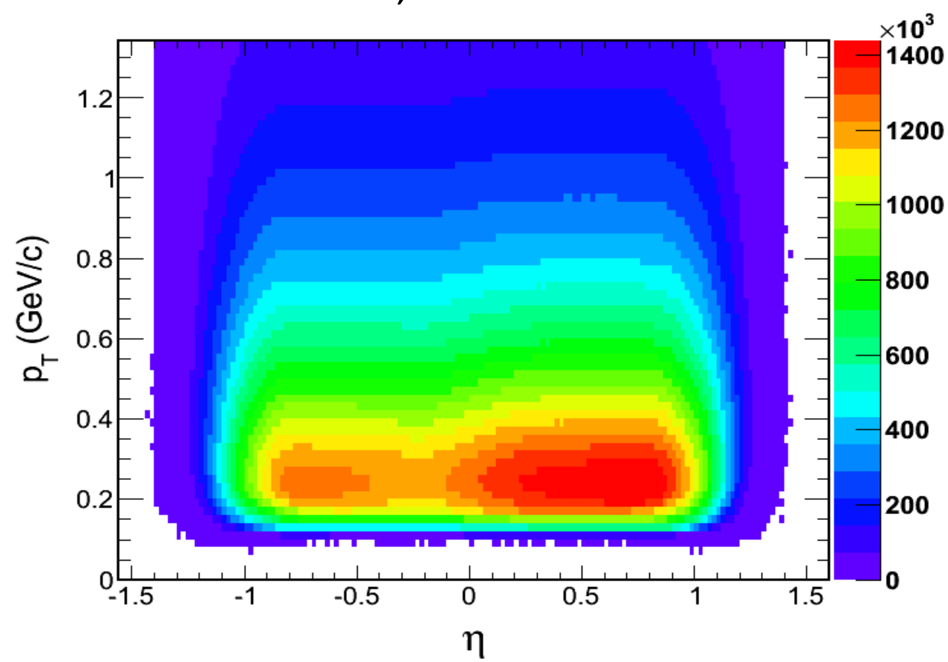
- We can not measure Npart or Volume but charged particles.
- Do the similar test as we have done in model.
  Vary the η window in the Refmult3 definition to suppress the Npart (volume) fluctuations .

η distributions for charged particles

Run 10, Au+Au 7.7 GeV

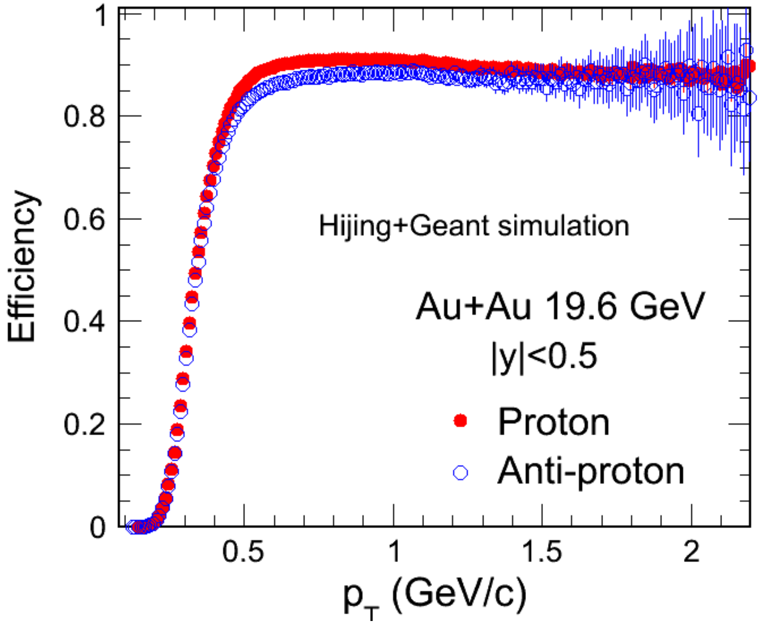


Run 10, Au+Au 200 GeV

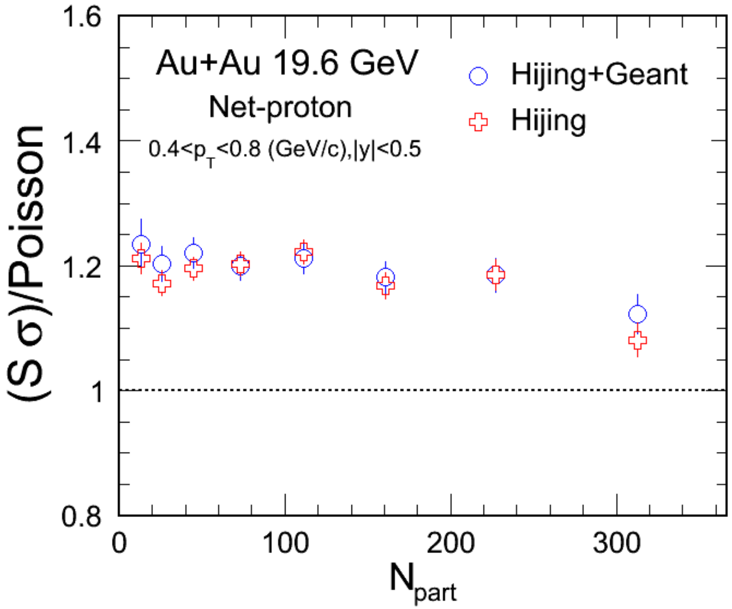


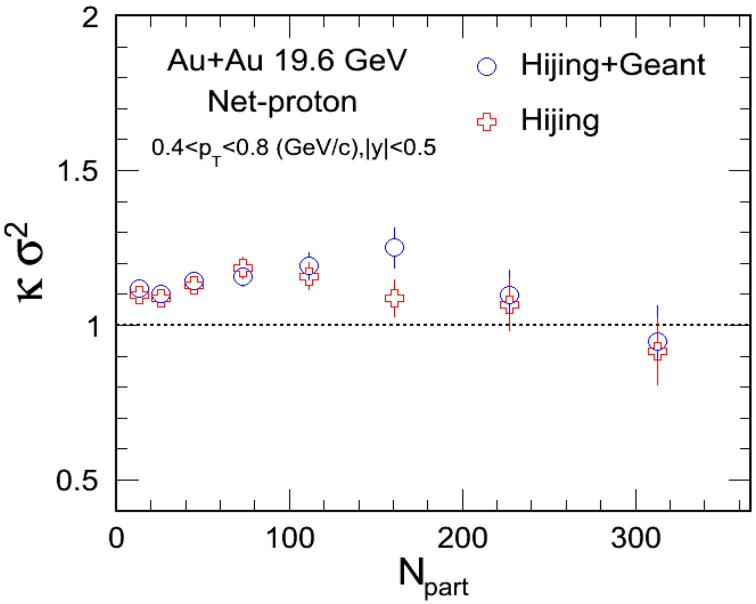
TPC acceptance limit, ~|η|<1.5, large efficiency drop beyond |η|<1

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.





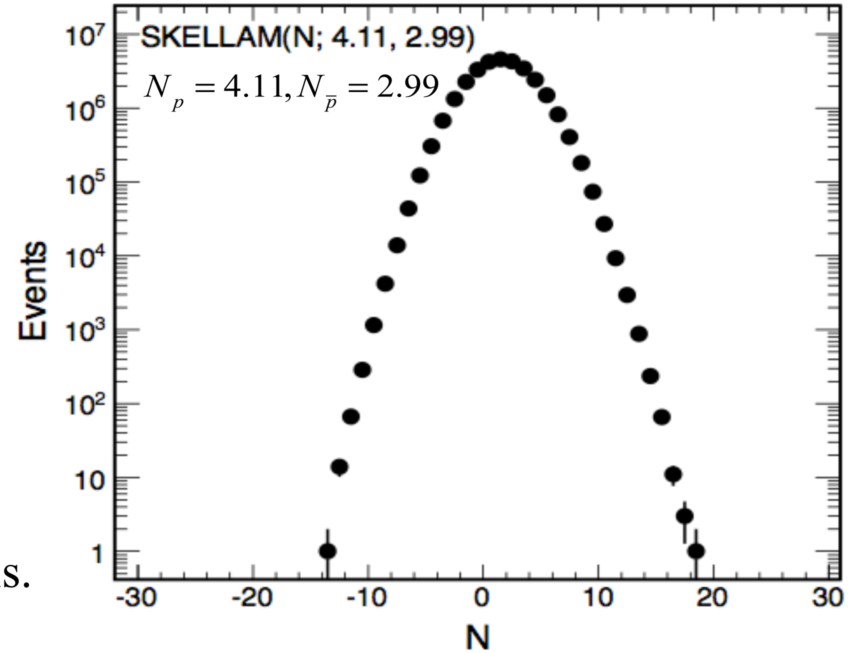
Skellam Expectations

- **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.**

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

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 skallam expectations for various moments/cumulants measurements:**

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

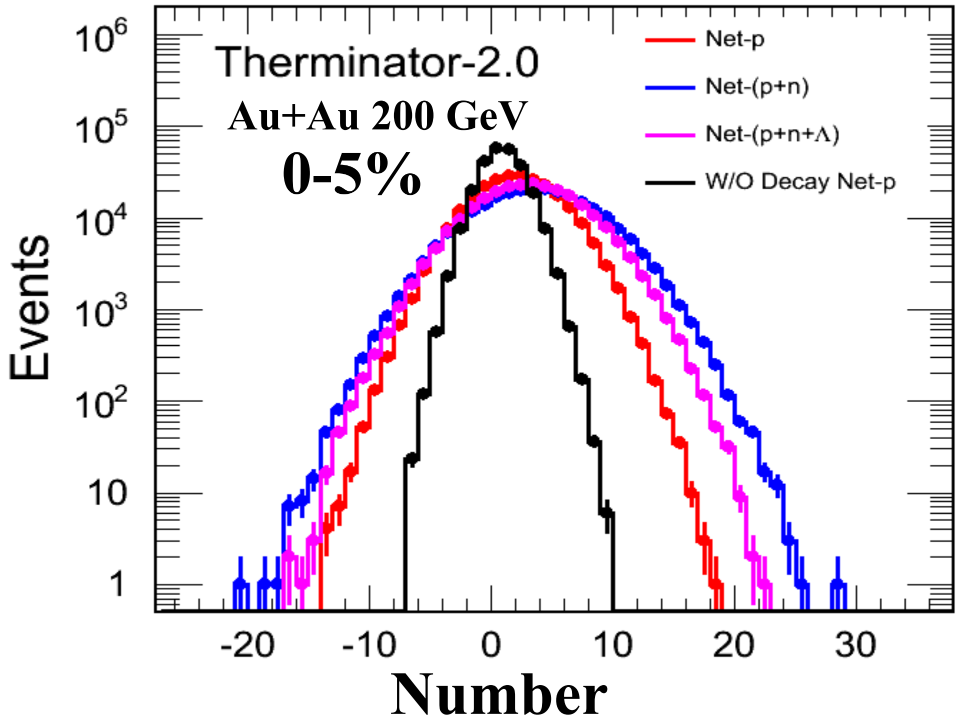
$$C_{2n-1} = N_p - N_{\bar{p}}, (n = 1, 2, 3 ...)$$

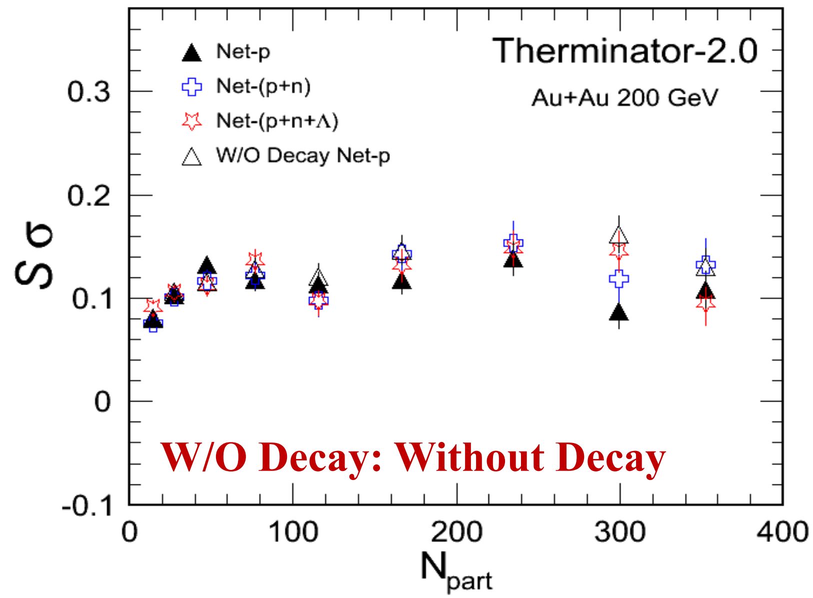
$$S\sigma = \frac{C_3}{C_2} = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}, \kappa\sigma^2 = \frac{C_4}{C_2} = 1$$

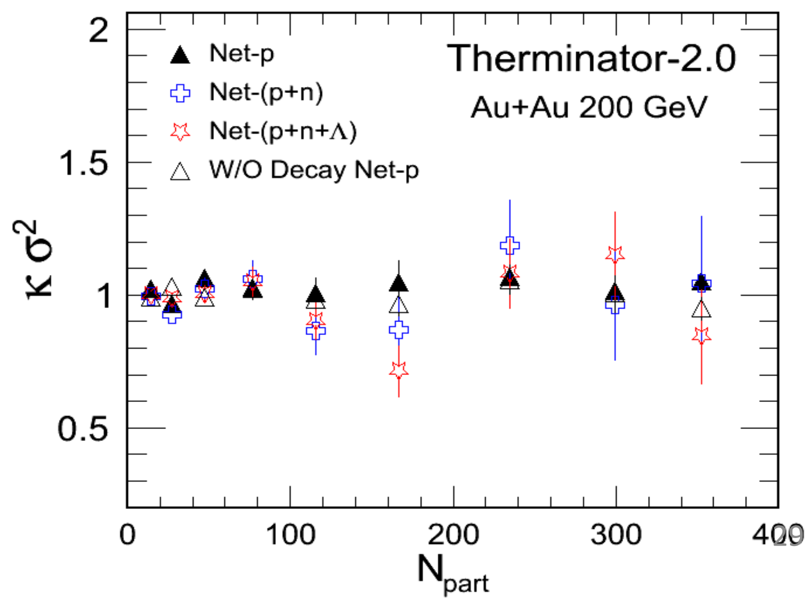
The skallam expectations may have energy and centrality dependence.

Resonance Decay and Neutron Effect

Model: Thermintor-2.0 (arXiv:1102.0273 **)**



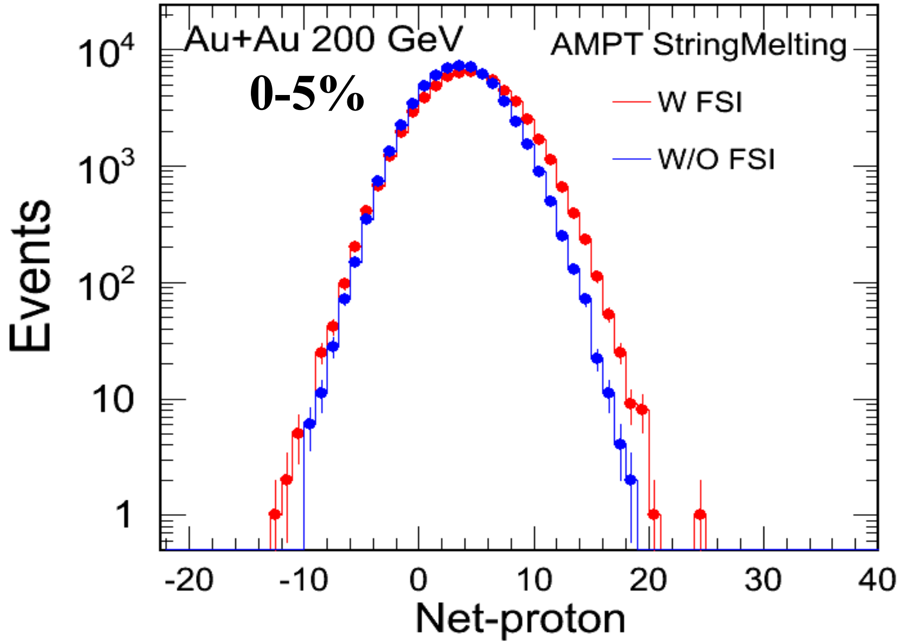


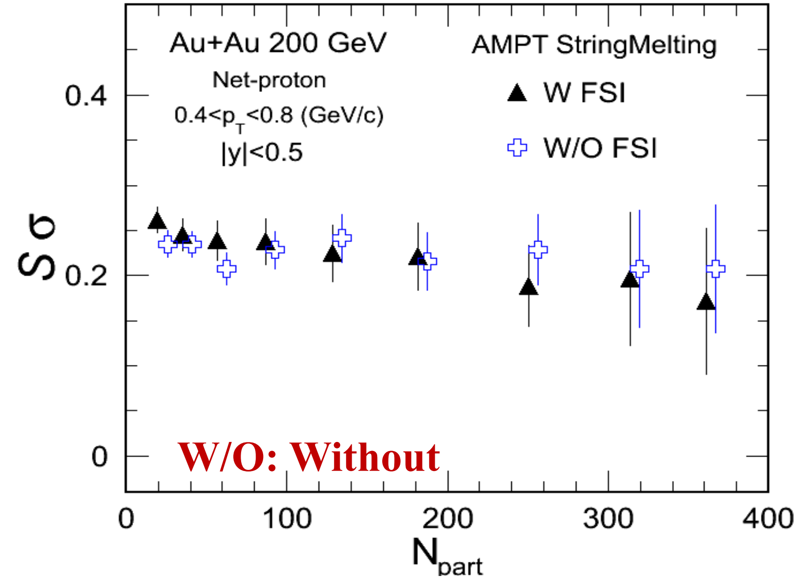


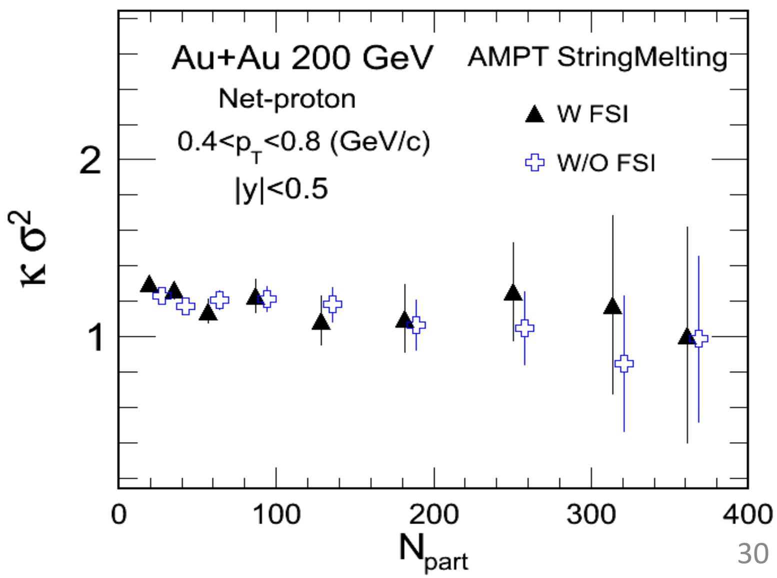
- Effect of resonance decay on $S\sigma$ and $\kappa\sigma^2$ is small. (based on the right two plots).
- Effect of inclusion of neutrons is small: Indicates: Net-proton fluctuation can reflect the net-baryon fluctuation.
- Error estimation: X. Luo, arXiv:1109.0593

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 $S\sigma$ and $\kappa\sigma^2$ are small. (based on the results in the right two plots).

Other Baryons

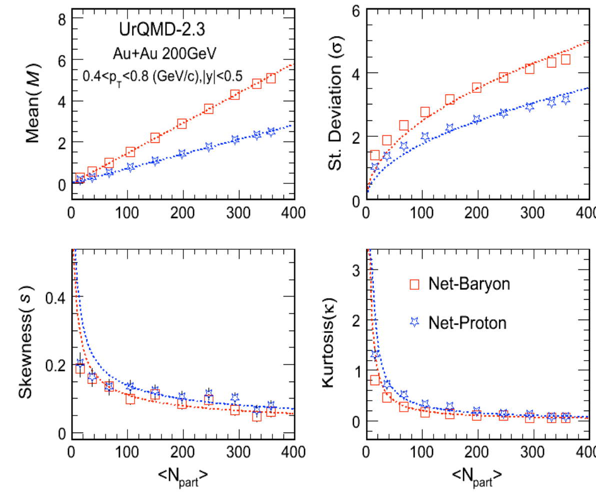
M. Kitazawa and M. Asakawa – arXiv: 1107.2755

(anti-)Proton number fluctuations modified in hadron phase.

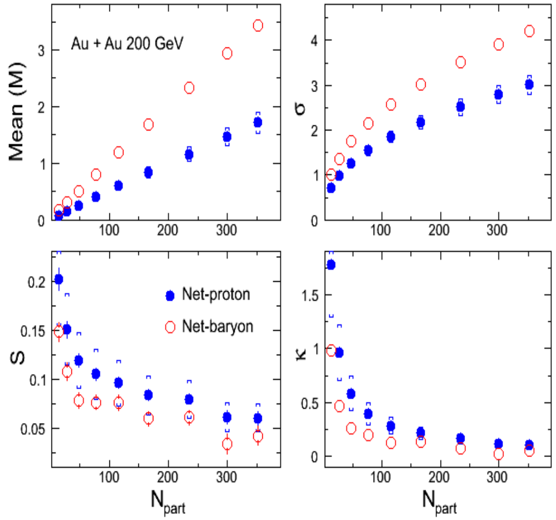
Random Isospin distribution of nucleons

$$p(n) + \pi \rightarrow \Delta^{+,0} \rightarrow n(p) + \pi$$

UrQMD



Data



Individual Moments change

Products of Moments similar

B. Mohanty, CPOD 2011.