The 4th Asian Triangle Heavy Ion Conference (ATHIC2012) in Pusan, South Korea on November 14-17, 2012

Baryon Number Fluctuations from RHIC Beam Energy Scan

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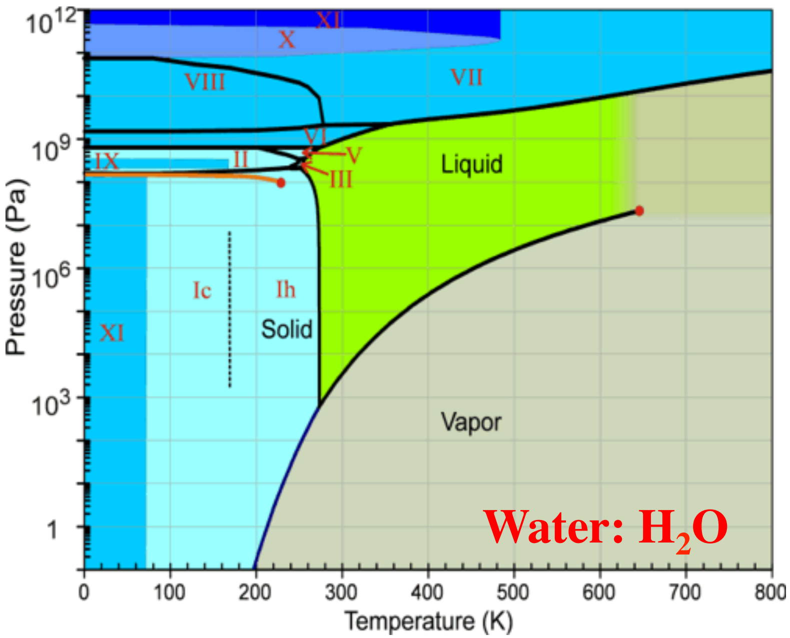
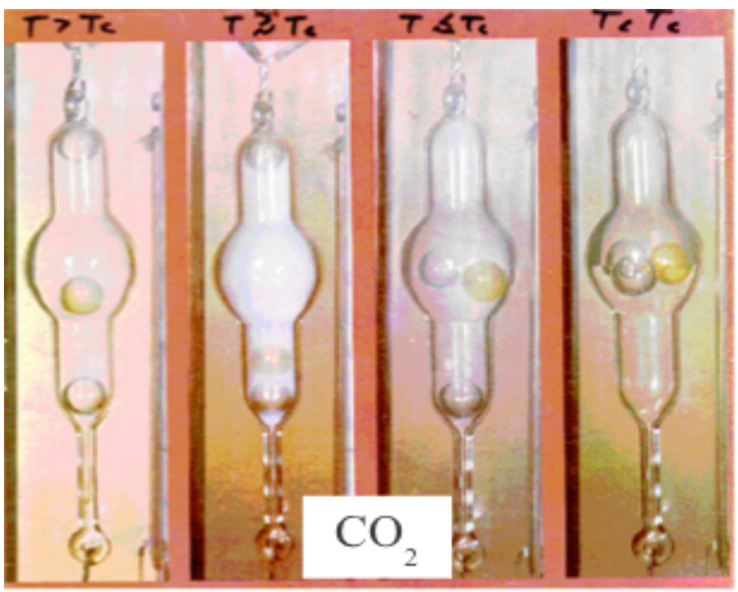
Outline

- **Introduction:**
- **Applications of the Higher Moments analysis.**
- **Results from RHIC Beam Energy Scan-I:**
- **Theoretical Calculations: Lattice QCD and PQM Model.**
- **Summary**

Phase Transition and Critical Point



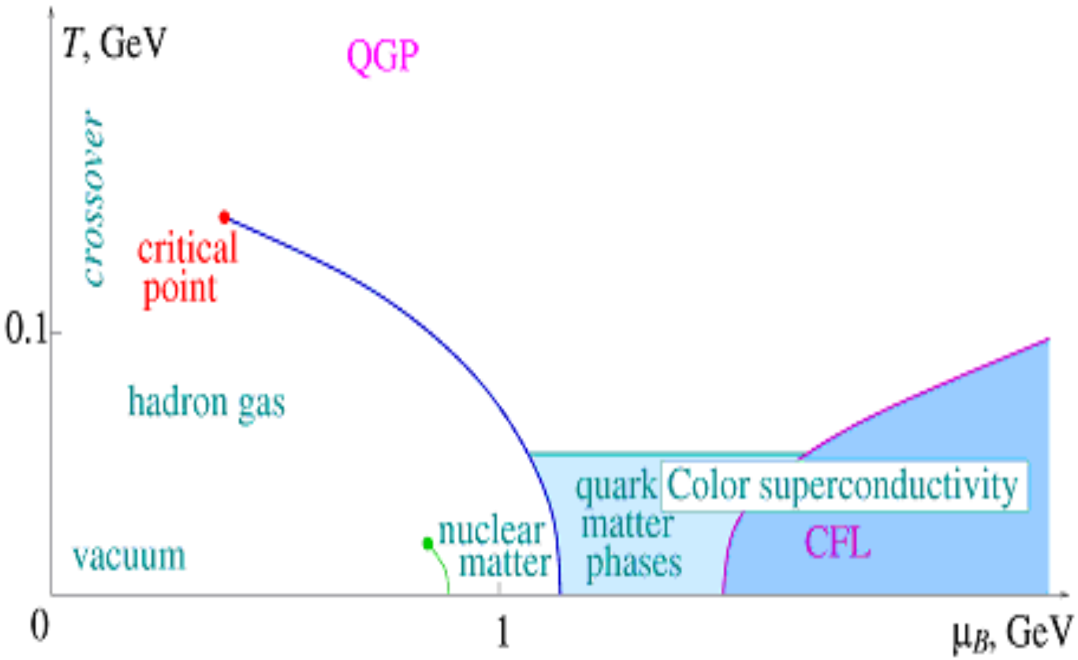


Matter may undergo phase transition when external condition (T, P etc.) are changed.

At the Critical Point (CP):

- 2nd order P.T..
- 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, 1st 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:

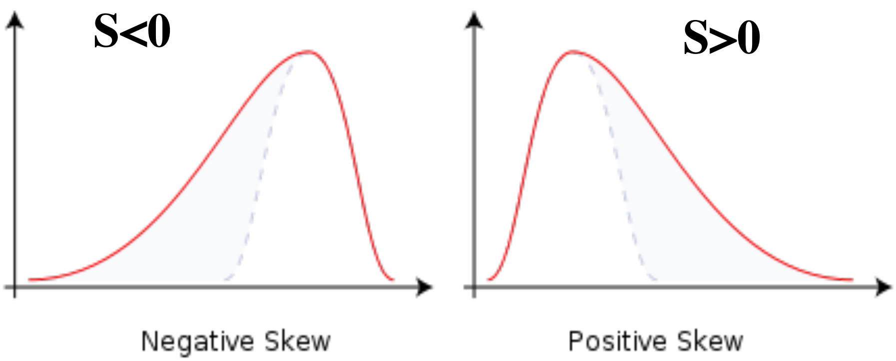
1. Flucutations and correlations.
2. Collective flow: v1, v2…
3. Others…

Higher Moments (I): Sensitive to the Correlation Length

Skewness:

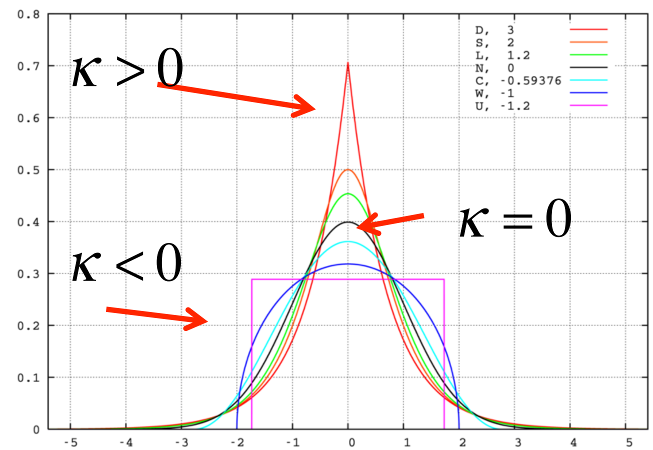
C_n: nth order cumulants

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



Kurtosis:

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



- ➢ 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)**

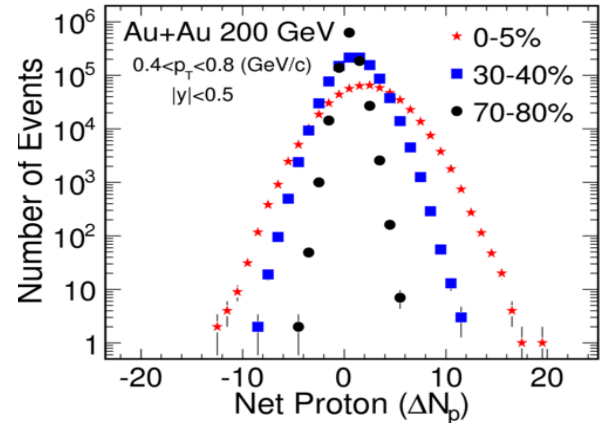
$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q\rangle, \chi_q^{(2)} = \frac{1}{VT^3}\left\langle (\delta N_q)^2\right\rangle$$

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

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

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, 22303(2010).*



➢ **Susceptibility ⇔ Moments**

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

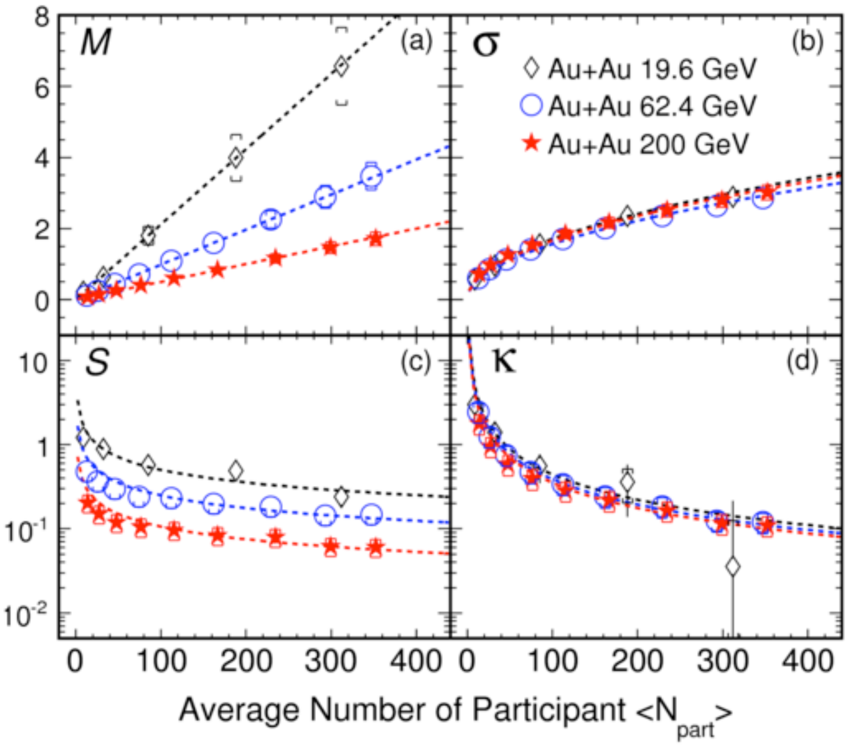
➢ Study Phase Transition and Bulk properties of QCD matter.

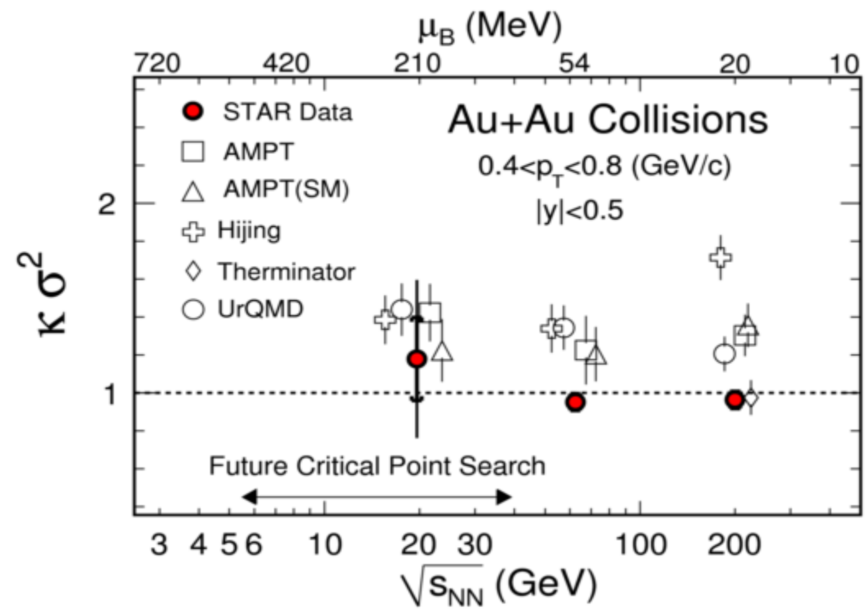
R.V. Gavai and S. Gupta, *PLB 696, 459 (2011).*
S. Gupta, et al., *Science, 332, 1525(2011).*
Y. Hatta, et al, *PRL. 91, 102003 (2003).*

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).

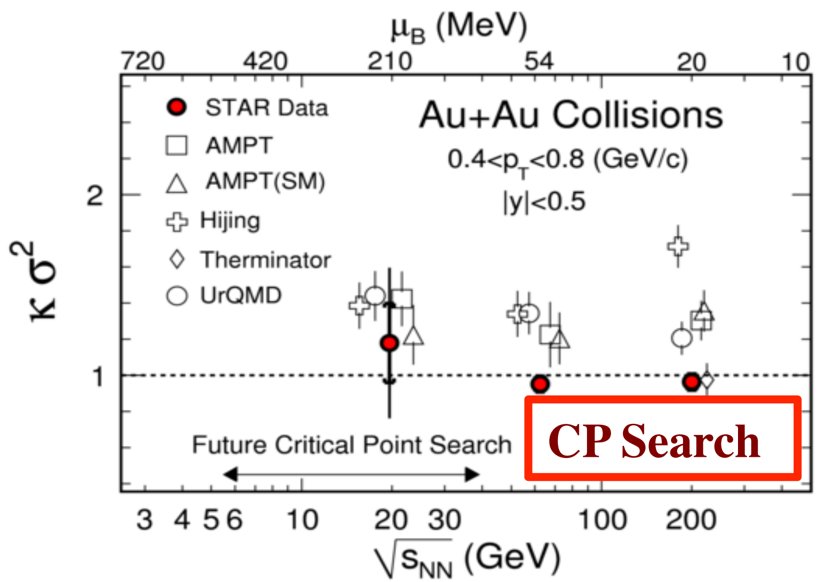




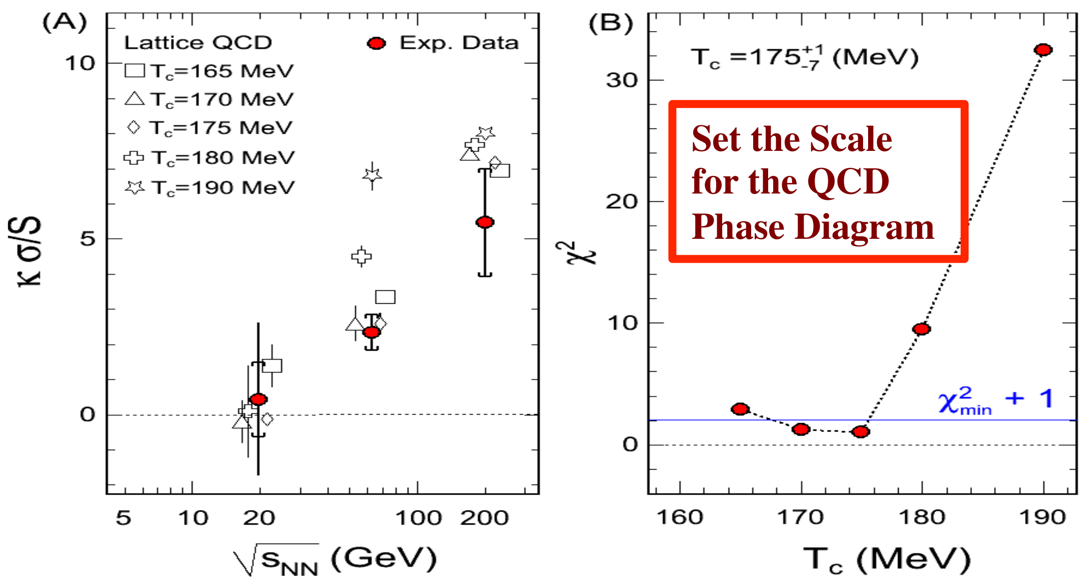
STAR: Physical Review Letters 105, 022302 (2010).

- 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

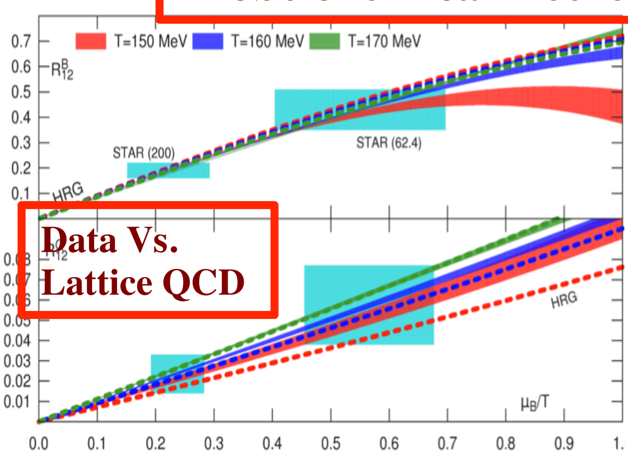


STAR, Phys. Rev. Lett. 105, 22302 (2010).

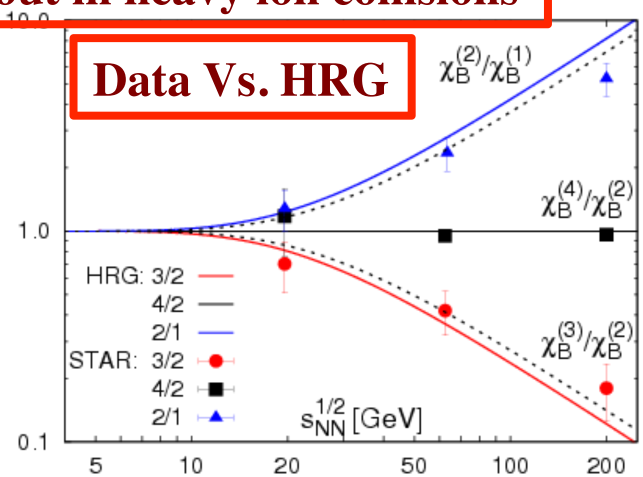


S. Gupta, et al, Science 332:1525 (2011).

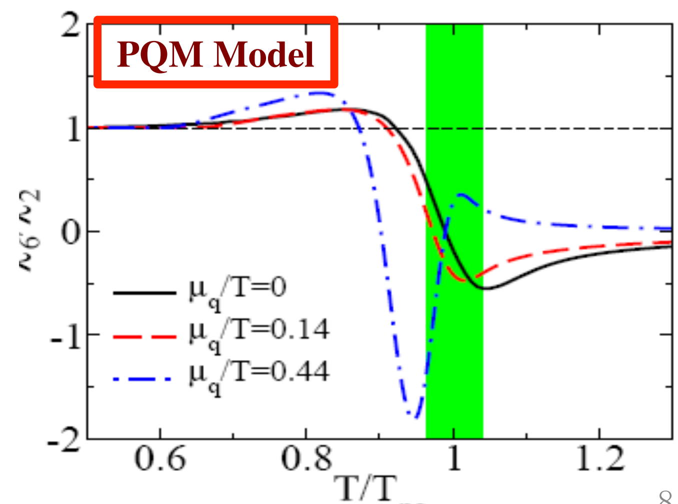
Probe chemical freeze out in heavy ion collisions



A. Bazavov et al.,*arXiv:1208.1220.*



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

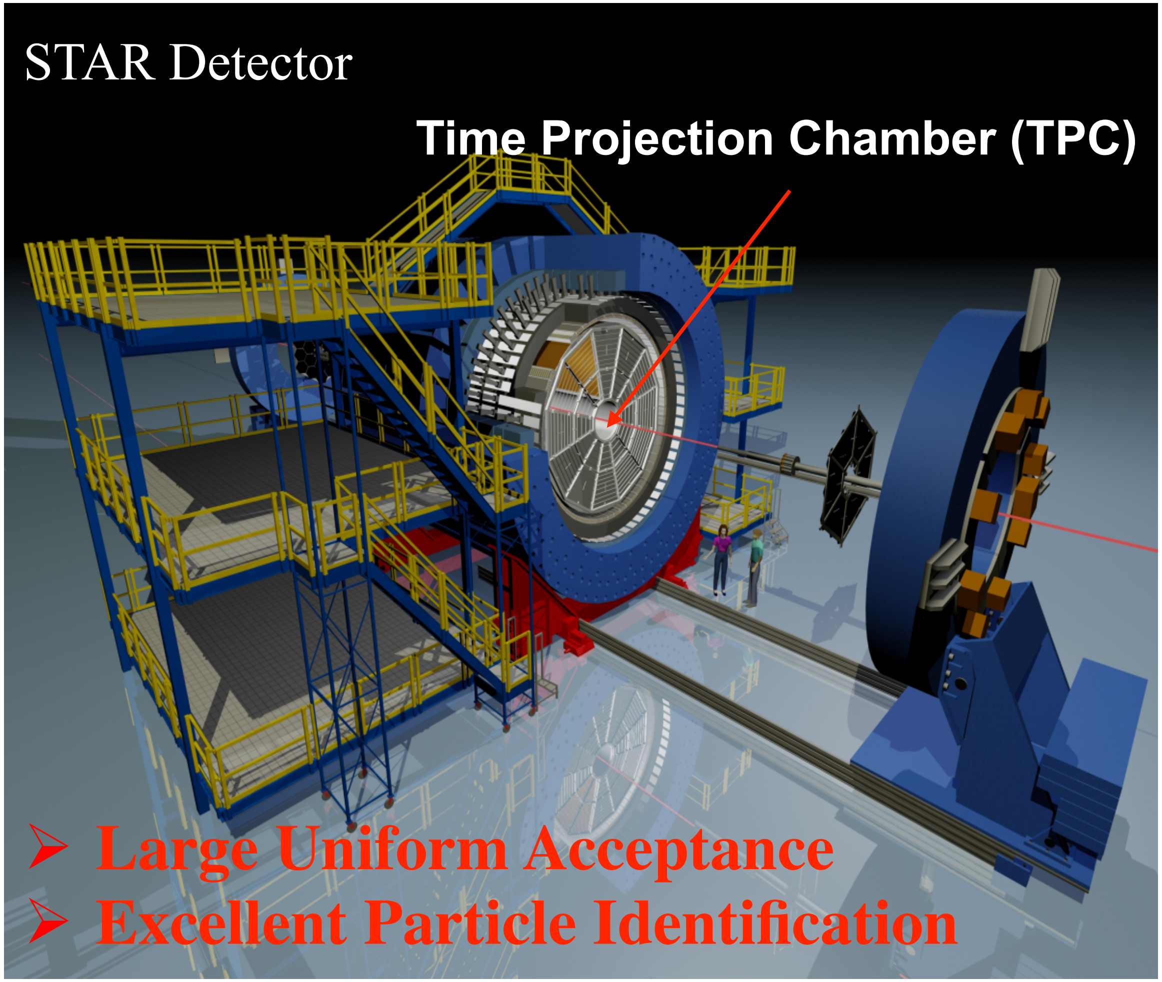


B. Friman, *et al, EPJC 71, 1694 (2011)*

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 √s=7.7, 11.5, 19.6, 27, 39, 62.4, 200 GeV) M. M. Aggarwal, arXiv:1007.2613 (2010).

√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)

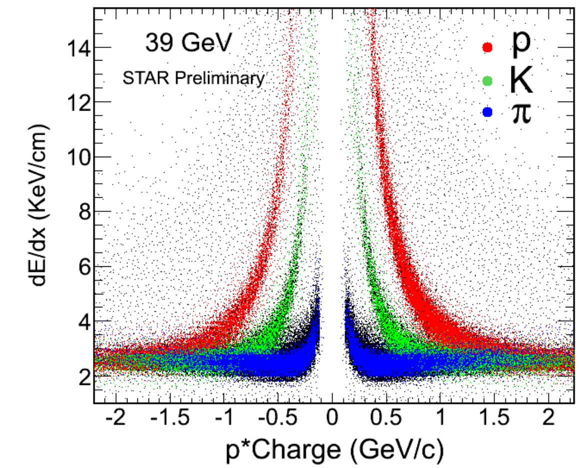
- Access a broad region of QCD phase diagram by RHIC BES program.
- STAR is an ideal detector to perform correlation and fluctuation analysis to study the QCD phase diagram.

Data Analysis 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 $|y|<0.5$.

STAR TPC dE/dx PID



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

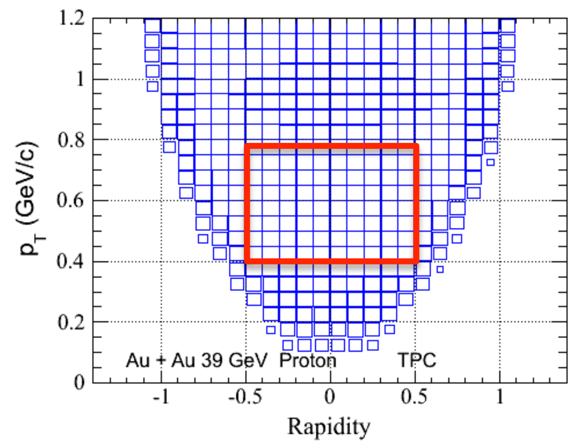
1. Centrality Bin Width Correction:
 (To suppress the volume fluctuations):
 Moments are corrected for centrality bin-width effects by using the weighted average of the moments inside each centrality bin.
 J. Phys.: Conf. Ser. 316, 012003 (2011) [arXiv: 1106.2926]

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

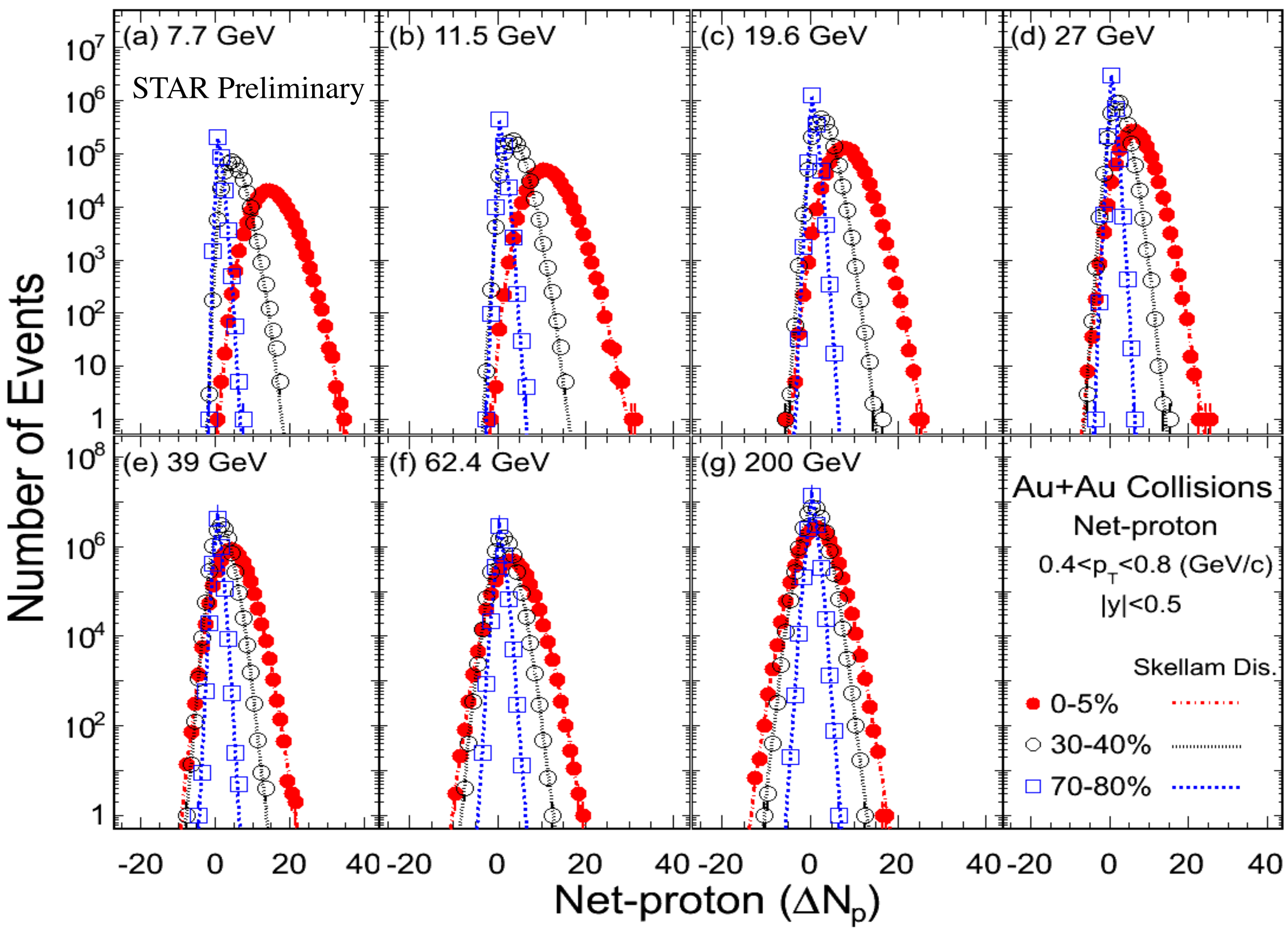
2. Statistical Error Estimations: Delta theorem method.
 J. Phys. G 39, 025008 (2012) [arXiv: 1109.0593]

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.

Proton Phase Space



Event-by-Event Net-proton Distributions



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

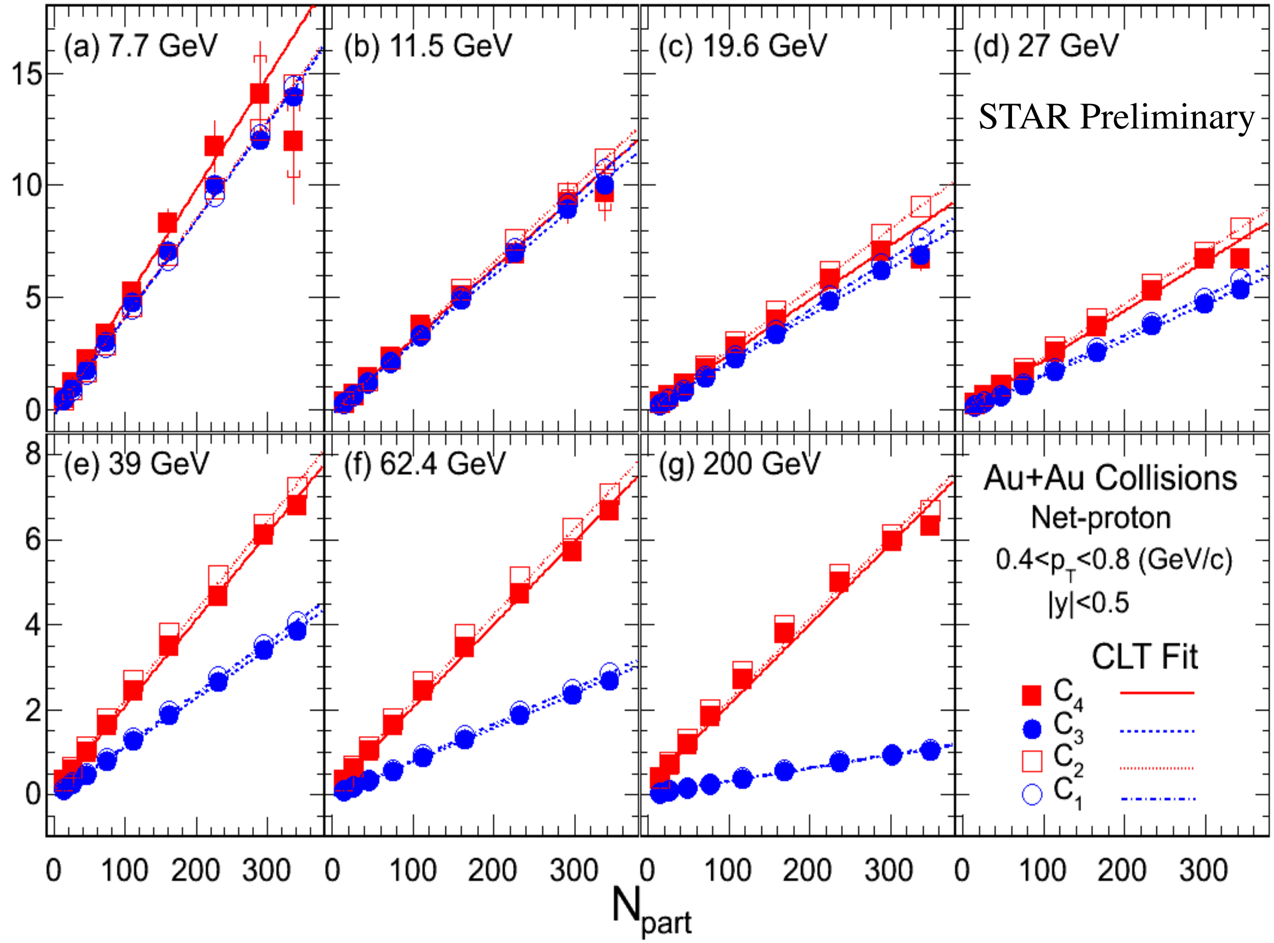
$$P(N) = \left(\frac{N_{\bar{p}}}{N_p}\right)^{N/2} I_N\left(2\sqrt{N_{\bar{p}} N_p}\right) e^{-(N_{\bar{p}}+N_p)}$$

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.

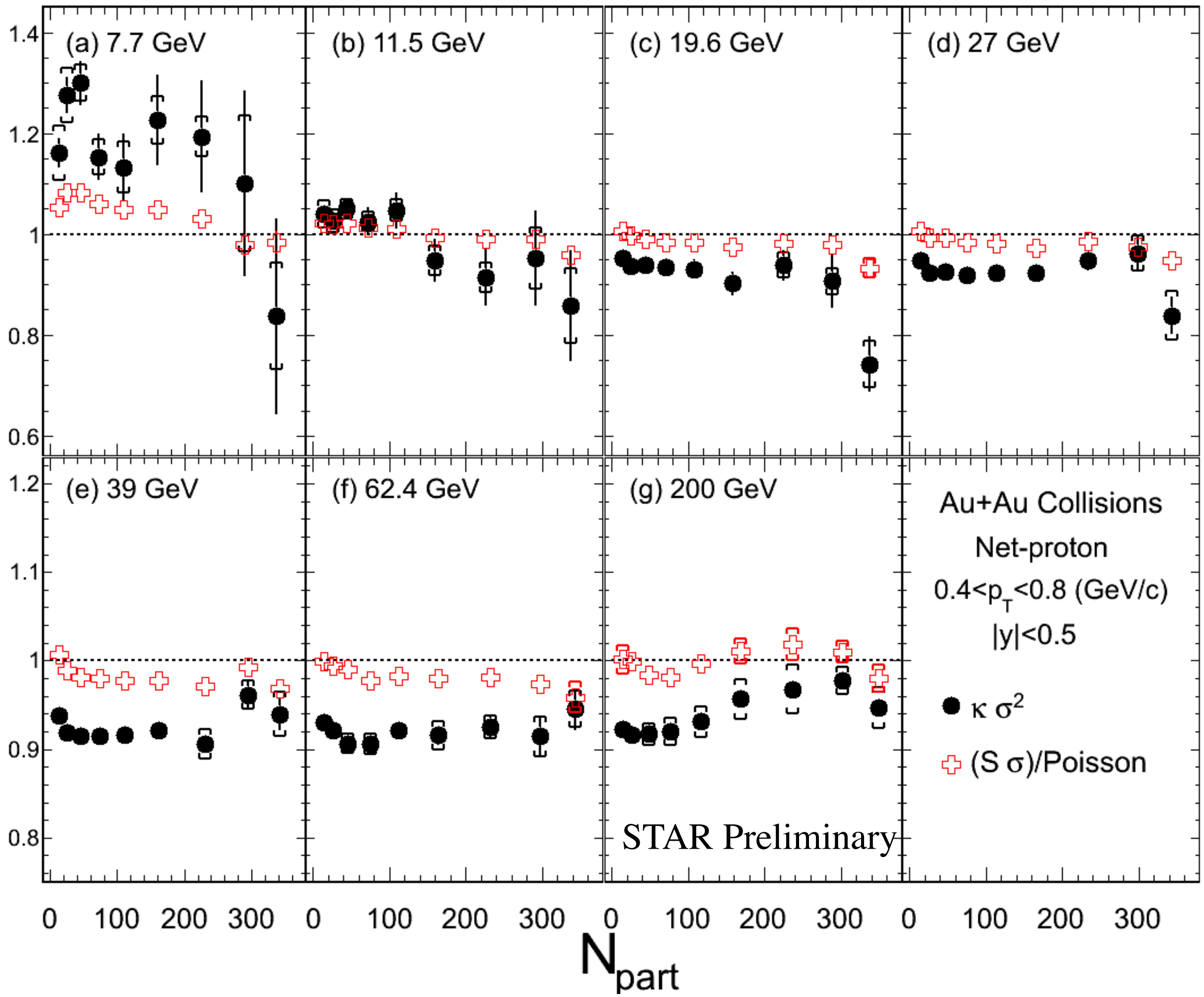
$$C_n \propto V$$

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.)

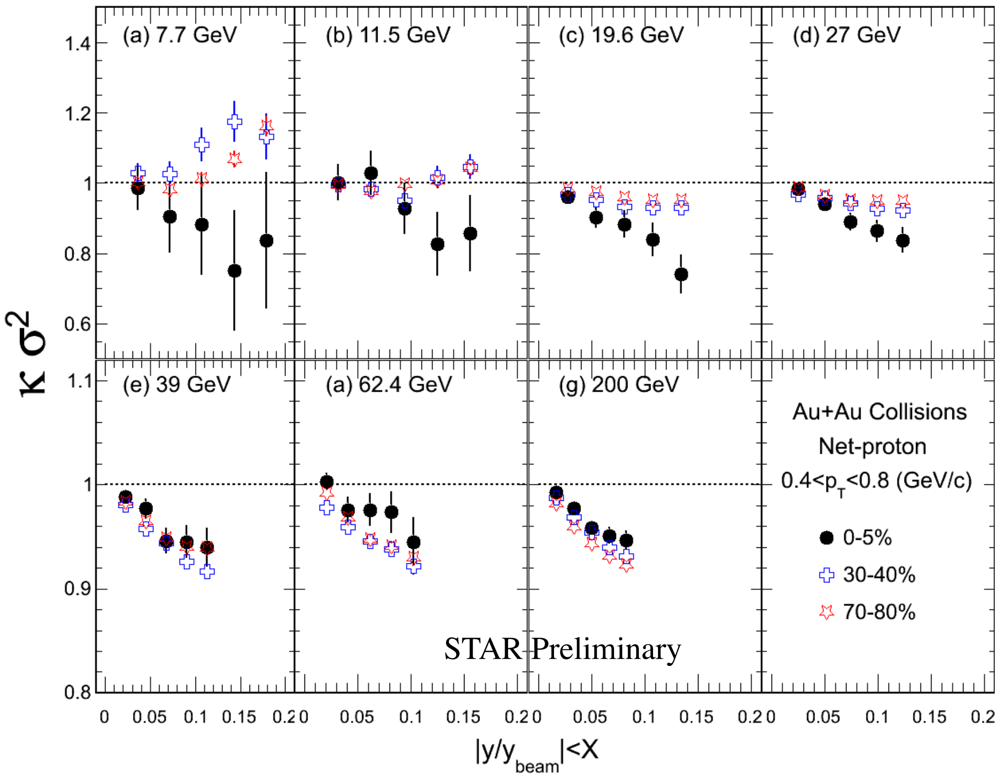
Moment Products: Centrality Dependence

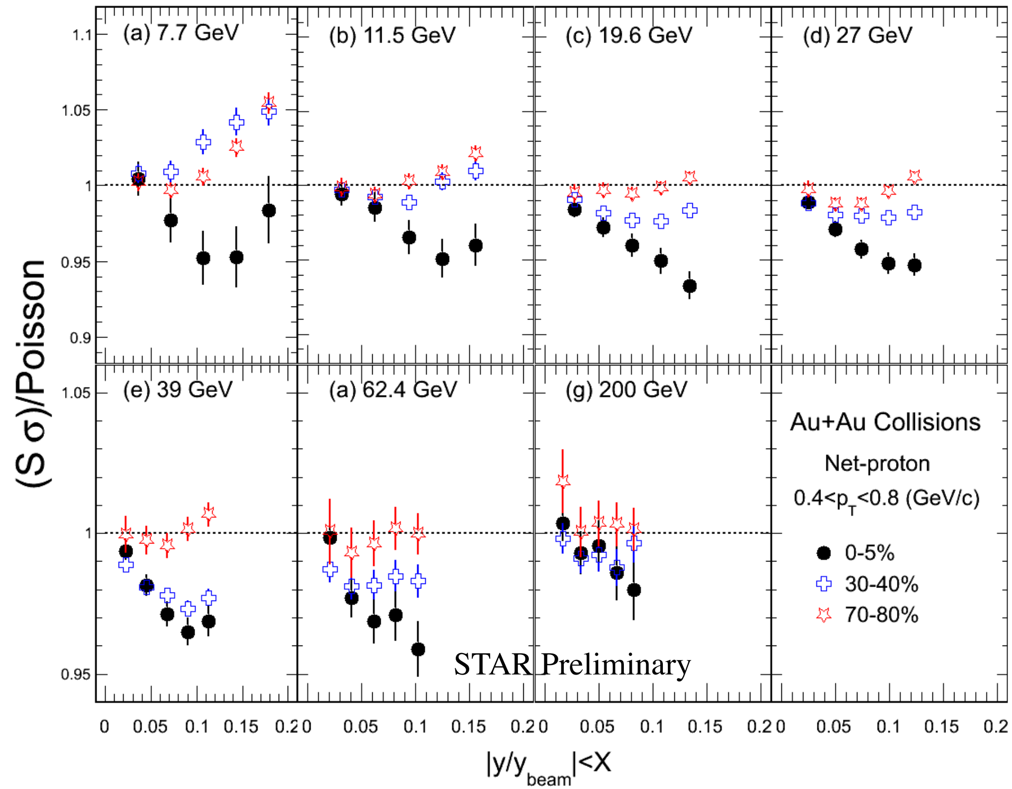


- Moment products are related to the susceptibility ratios:
  $\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(3)}$
  $S\sigma \sim \chi^{(3)}/\chi^{(2)}$
- Deviations below Poisson expectations are observed in most of the energies and centralities.
- Below 19.6 GeV, moment products are larger than Poisson expectations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

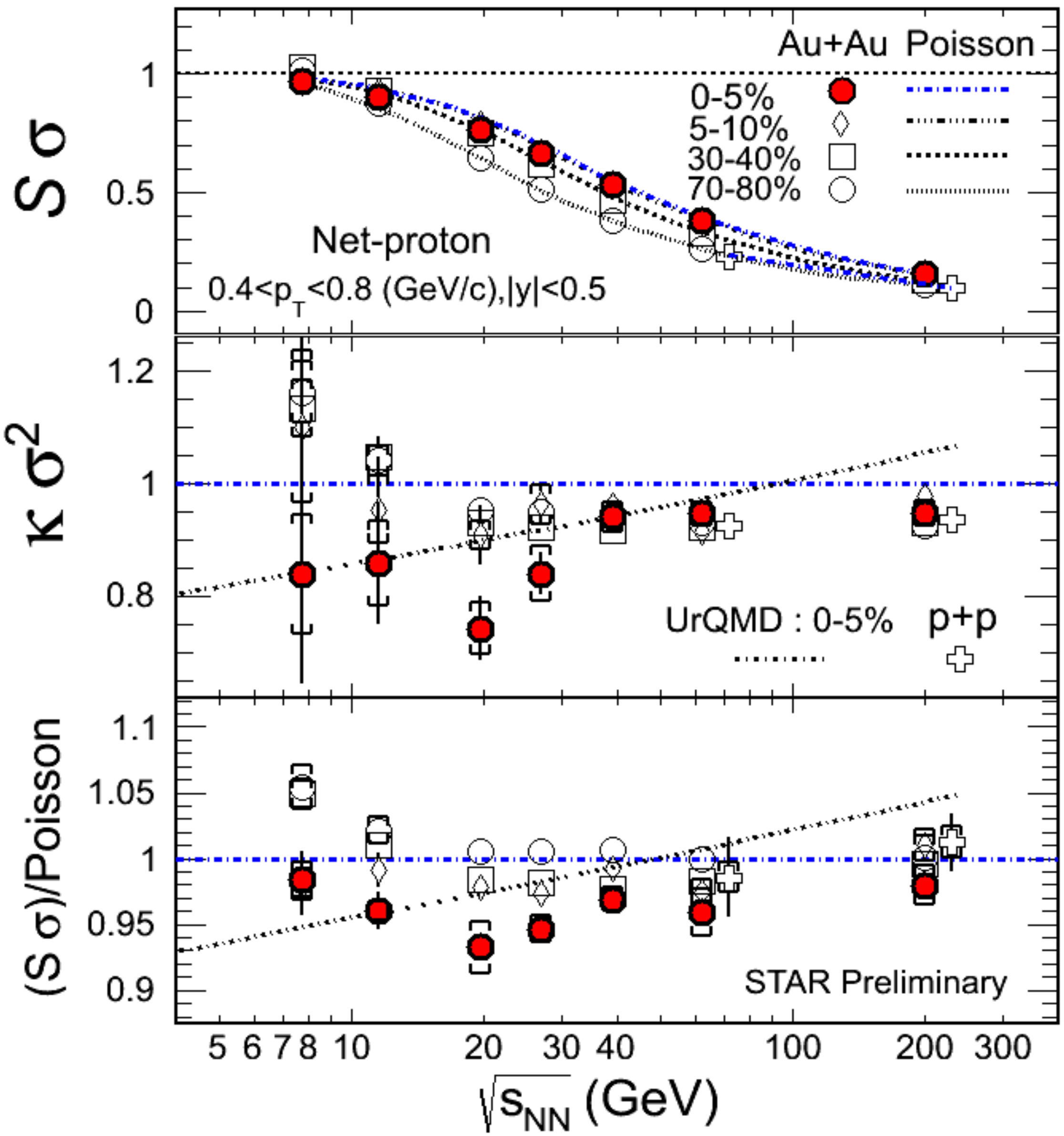




Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
y_{beam}	2.79	3.20	3.73	4.05	4.42	4.89	6.05

- $\kappa\sigma^2$ 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

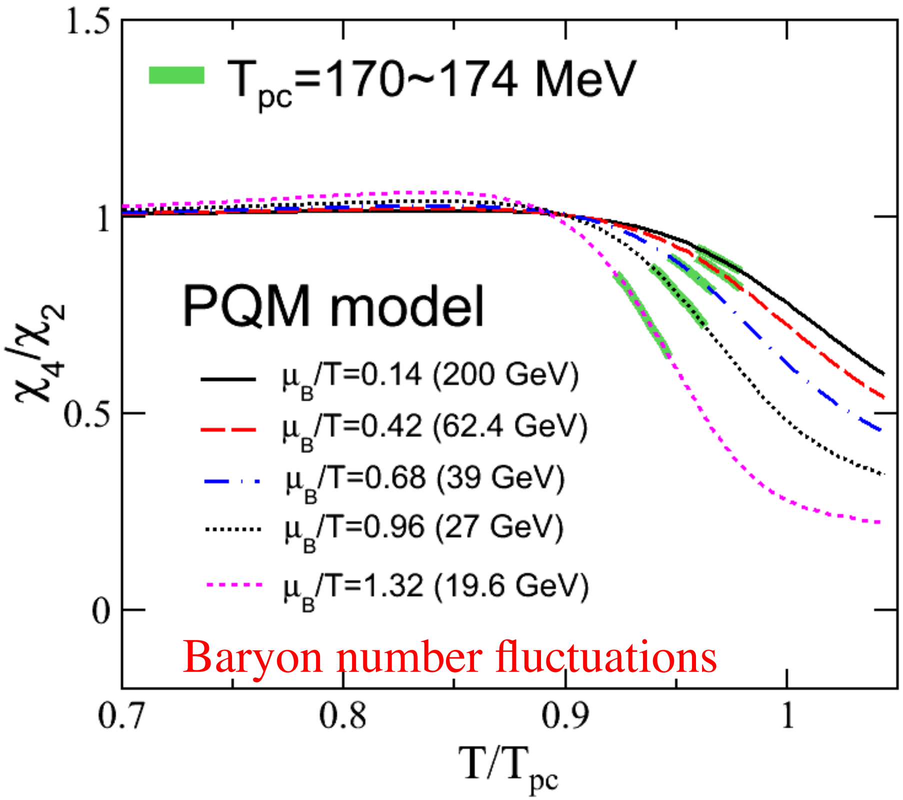


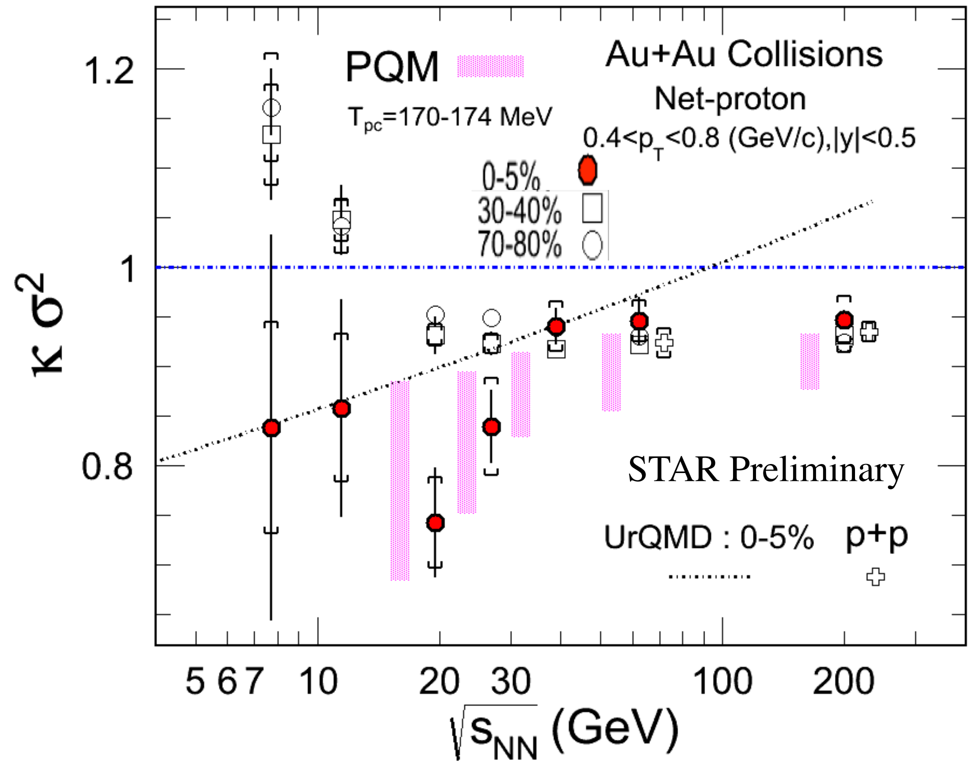
➢ Deviations below Poisson expectations are observed beyond statistical and systematic errors in 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ above 7.7 GeV.

➢ 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.

PQM Model Expectations



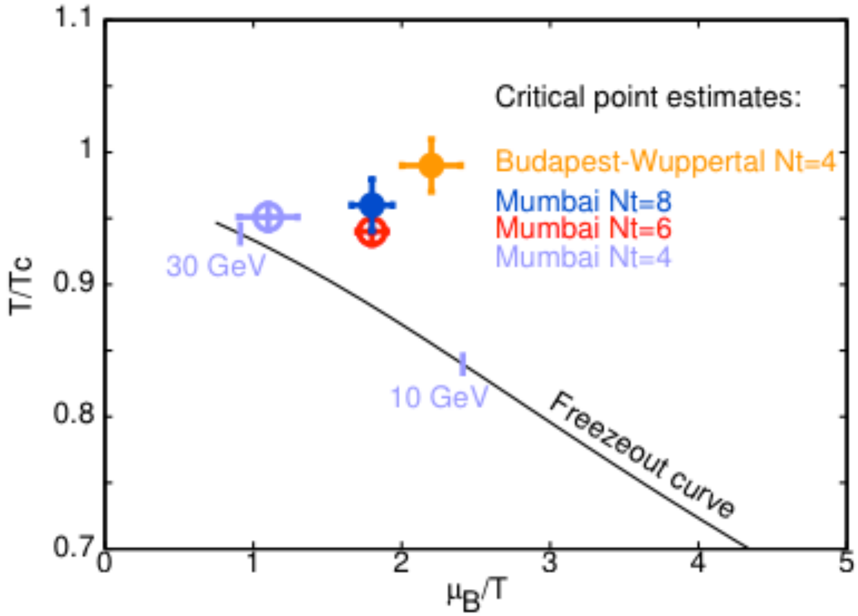


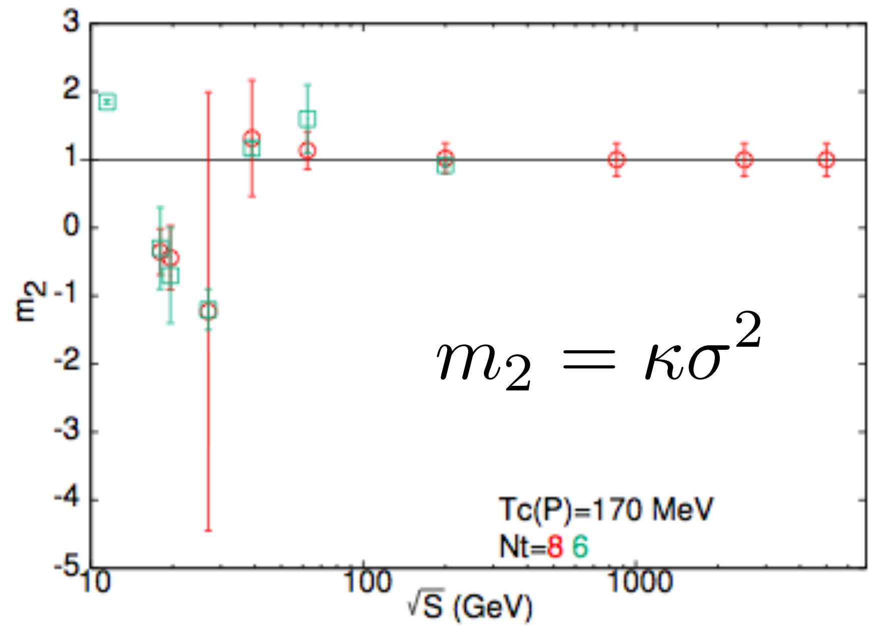
B. Friman, *et al, EPJC 71, 1694 (2011)*

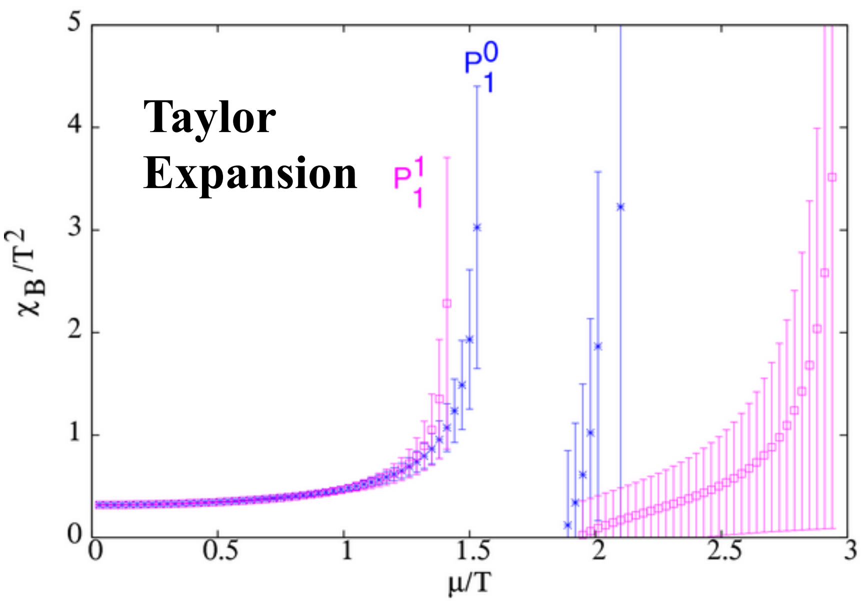
PQM Model: Polyakov loop Quark Meson Model

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

QCD Critical Point: Lattice Calculation







- Nt=8 results are consistent with Nt=6.
- μ^E_B/T^E~1-2.

Rajiv Gavai& S. Gupta, QM2012

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.

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. Monotonic behavior for the moment products is observed in the UrQMD model.

Experimental results are compared with Lattice QCD and PQM Model Calculations.

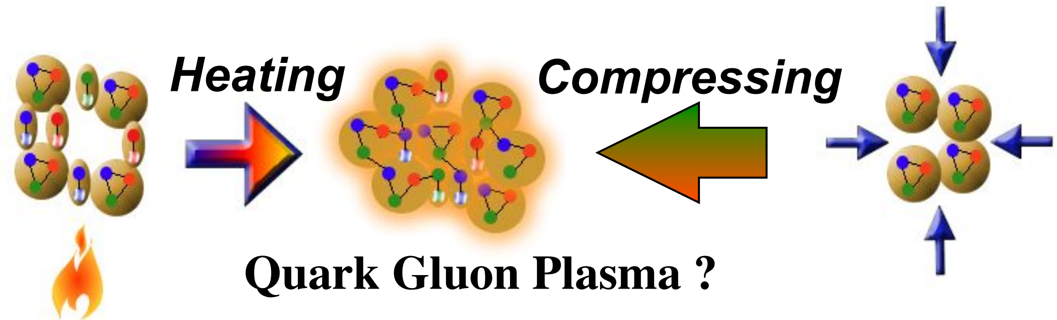
Higher statistics are needed in order to draw physics conclusion at lower beam energies.

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

Backup Slides

Explore the Phase Structure of Nuclear Matter

Create new form of nuclear matter by colliding two nuclei !



Questions about QCD Phase Diagram:

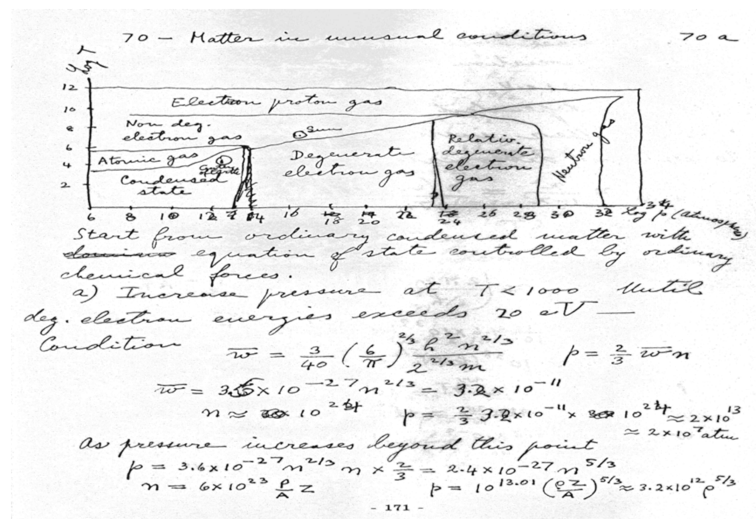
1. Is there a Partonic Phase ?
   What's Properties?

2. Where is the phase boundary between hadronic matter and partonic matter ?

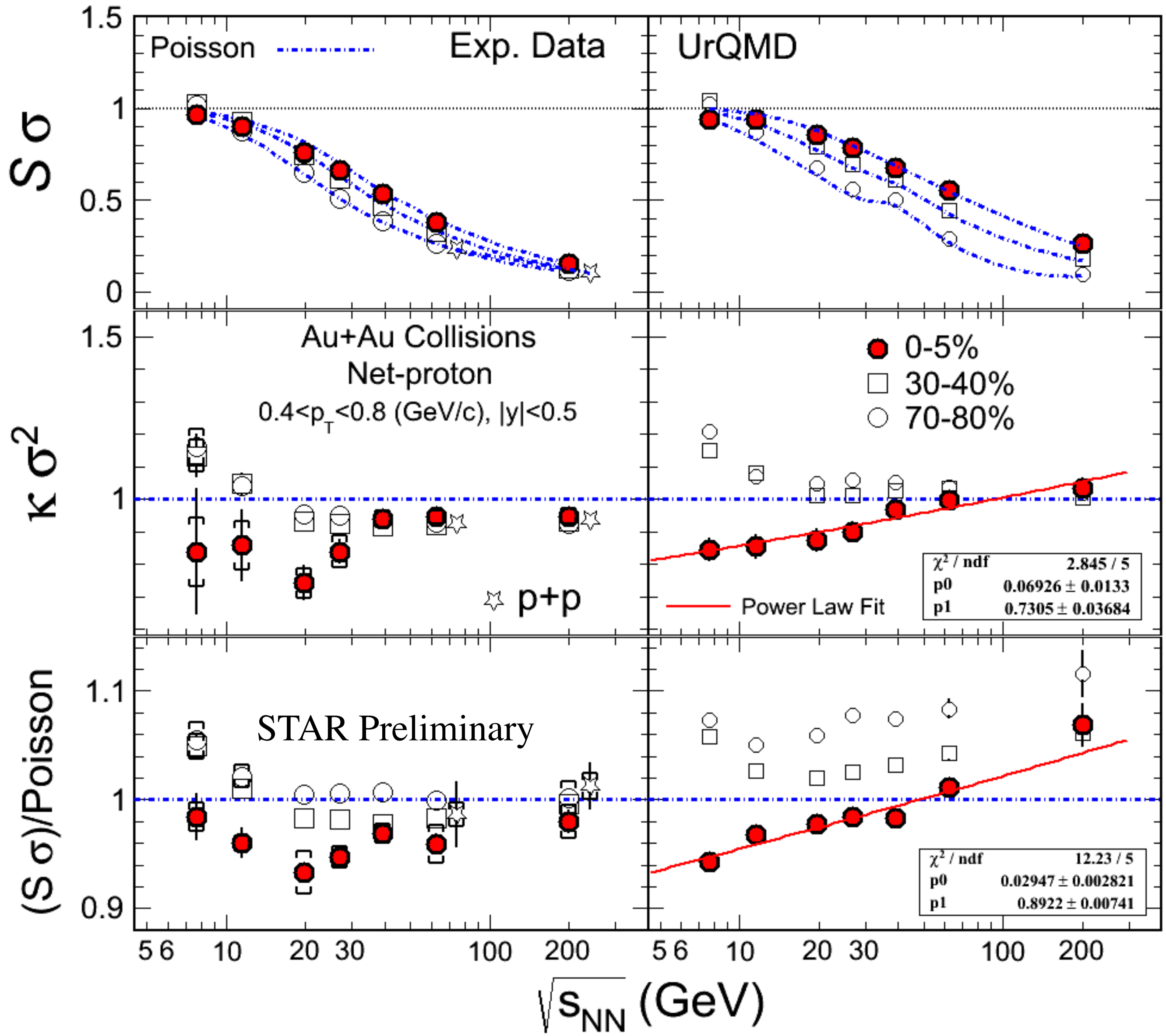
3. Is there a Critical Point ?

E. Fermi

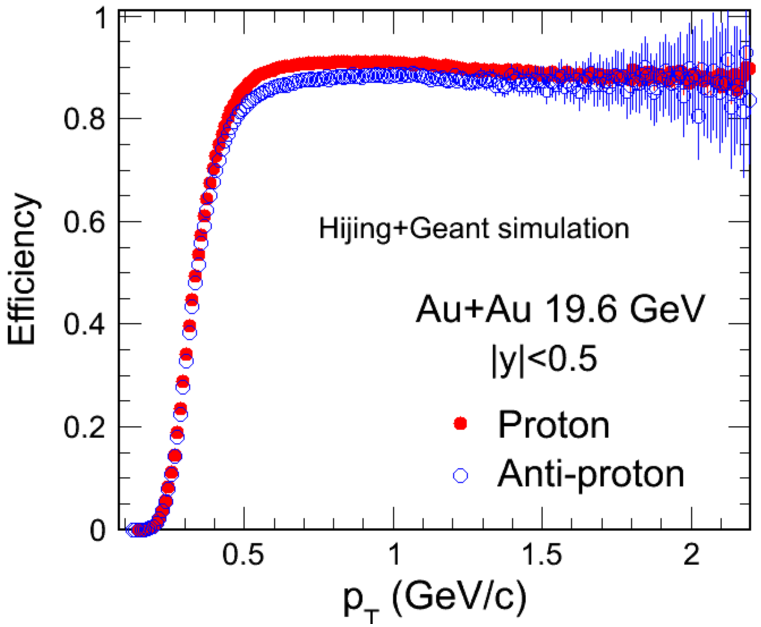
E. Fermi: *"Notes on Thermodynamics and Statistics " (1953)*



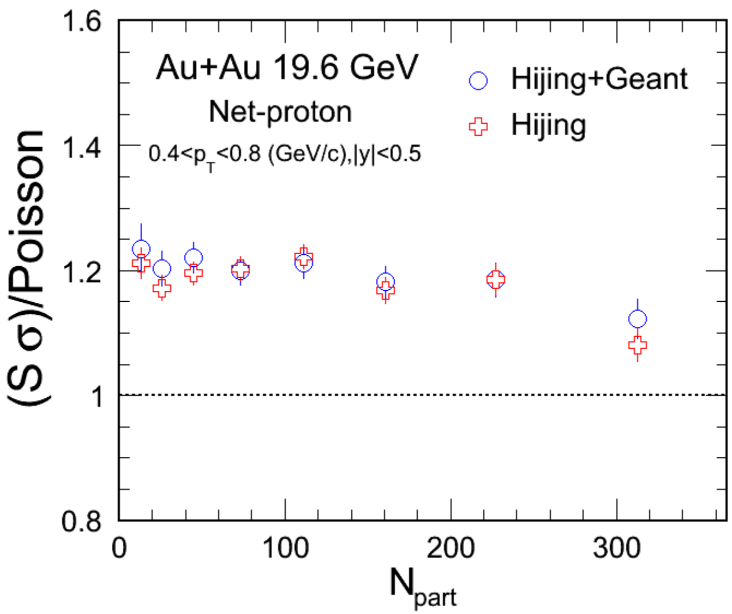
Moment Products/Poisson Ratio: Energy Dependence

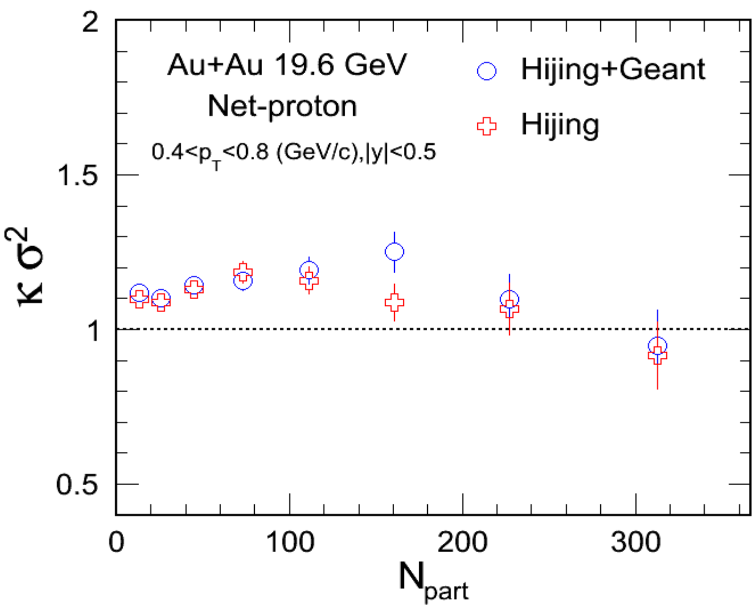


Hijing+Geant Simulation



- 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.



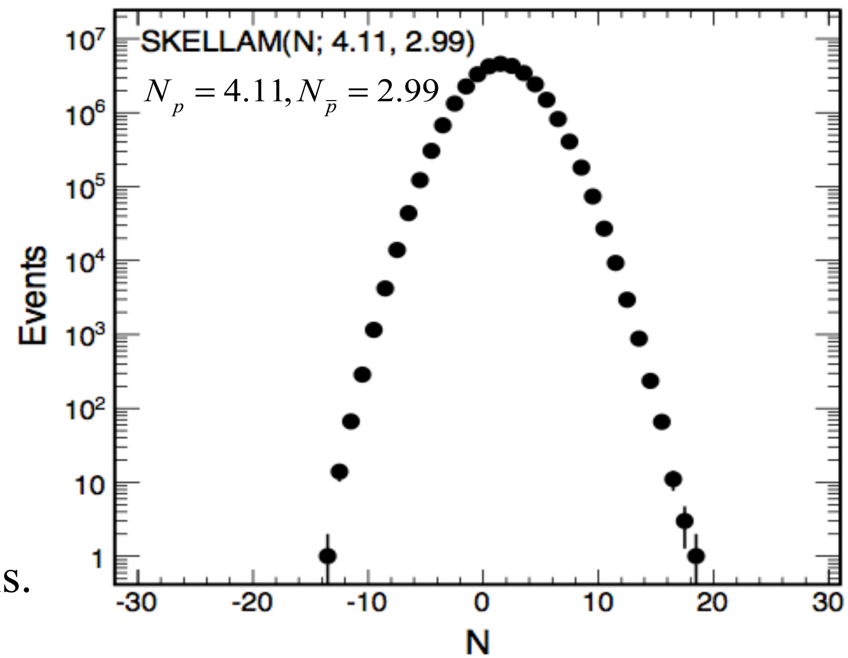


Poisson Baseline

- **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:**

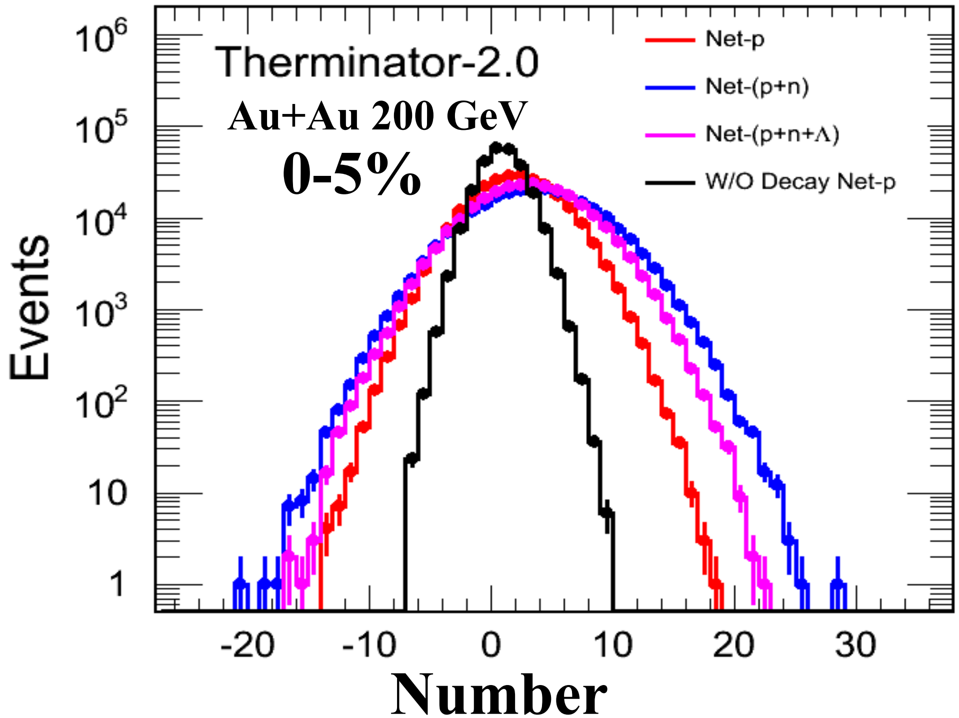
$$C_{2n} = N_p + N_{\bar{p}}$$
$$C_{2n-1} = N_p - N_{\bar{p}}, (n = 1,2,3...)$$

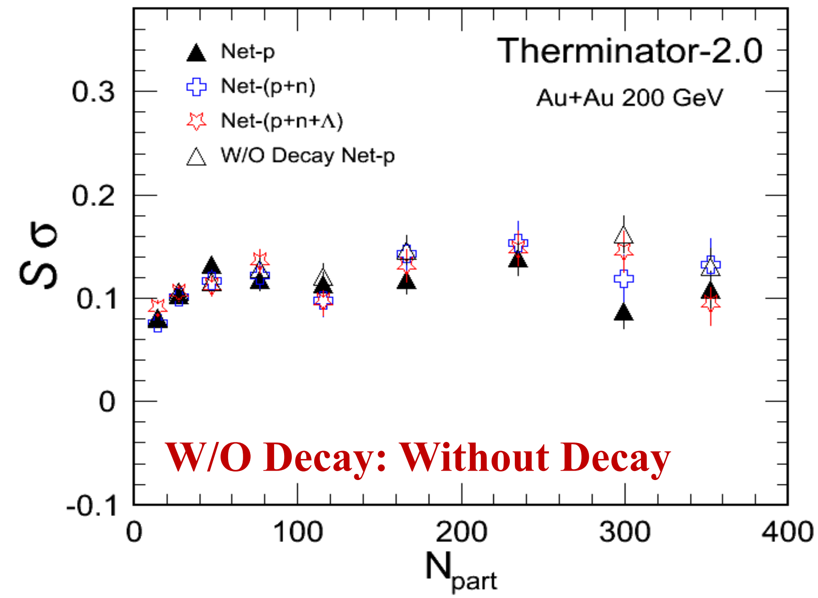
$$S\sigma = \frac{C_3}{C_2} = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}, \kappa\sigma^2 = \frac{C_4}{C_2} = 1$$

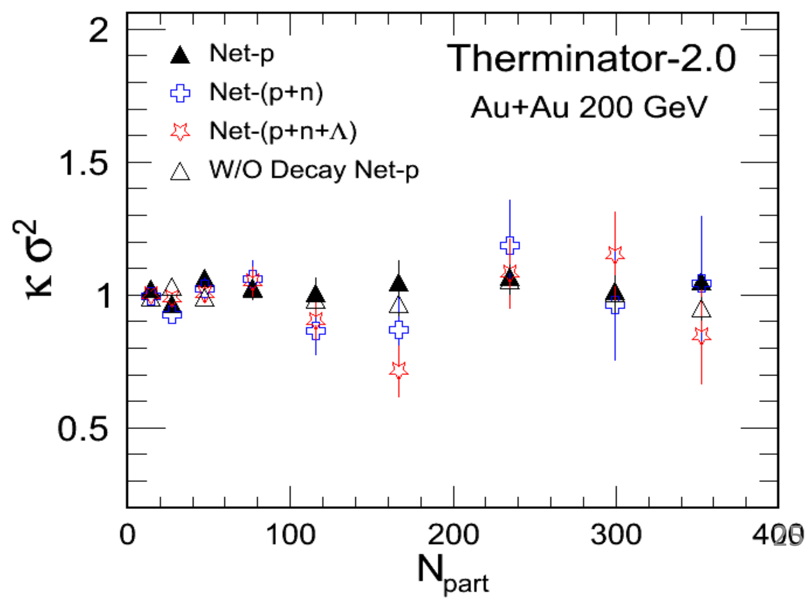
The Poisson expectations may have energy and centrality dependence.

Resonance Decay and Neutron Effect

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



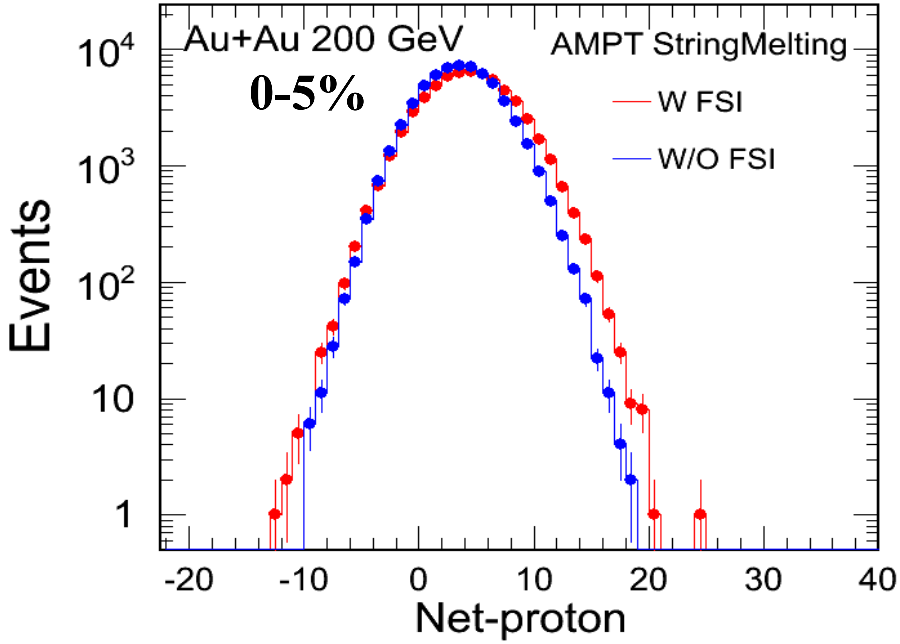


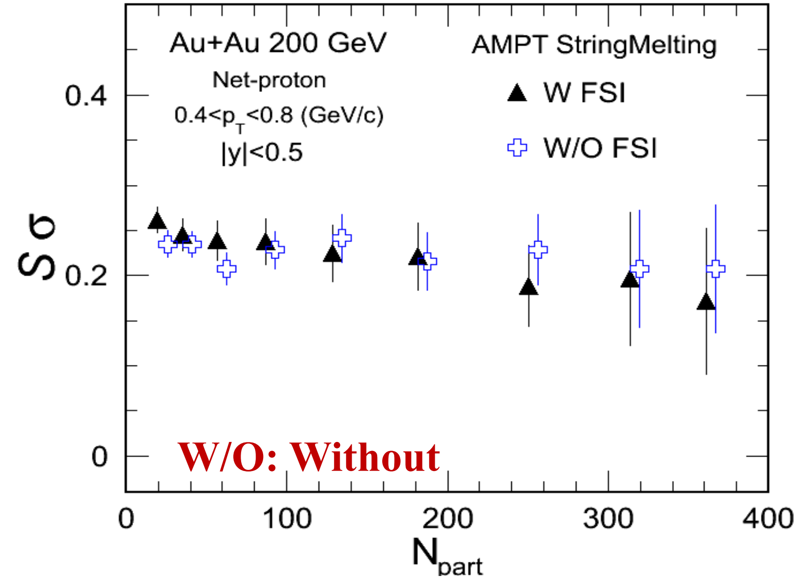


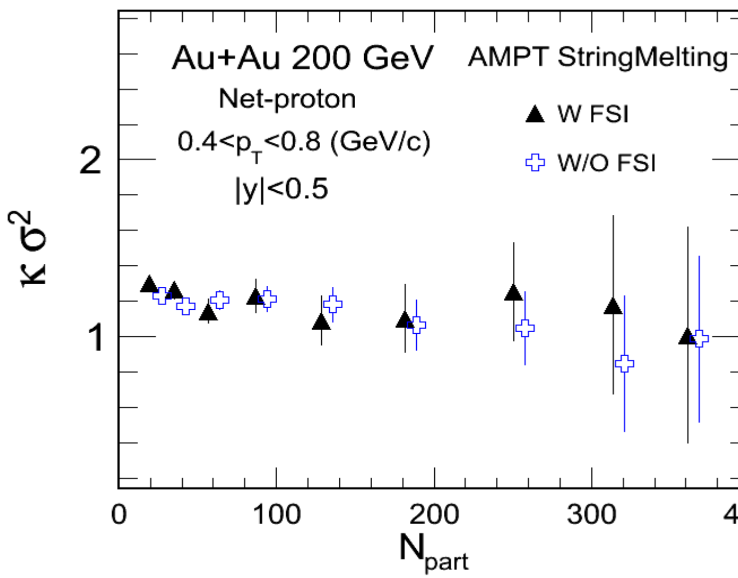
- Effect of resonance decay on $S\sigma$ and $\kappa\sigma^2$ is small. (based on the right two plots).
- Effect of inclusion of neutrons is small: Indicates: Net-proton fluctuation can reflect the net-baryon fluctuation.
- Error estimation: X. Luo, arXiv:1109.0593

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).

Other Baryons

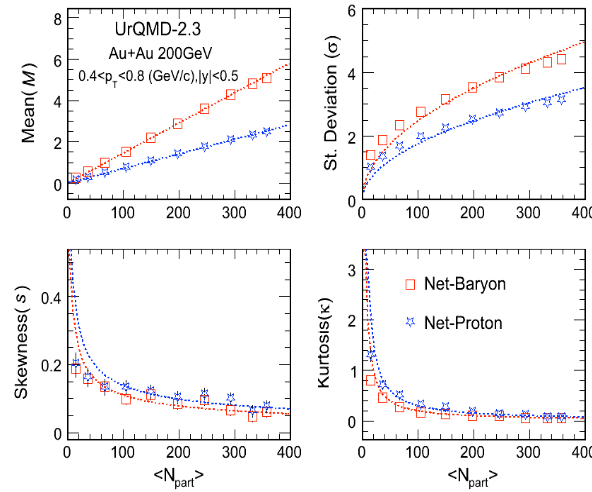
M. Kitazawa and M. Asakawa – arXiv: 1107.2755

UrQMD

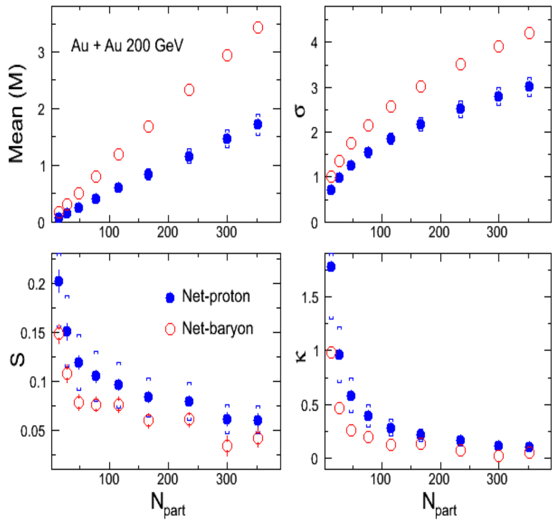
(anti-)Proton number fluctuations modified in hadron phase.

Random Isospin distribution of nucleons

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



Data



Individual Moments change

Products of Moments similar

B. Mohanty, CPOD 2011.