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

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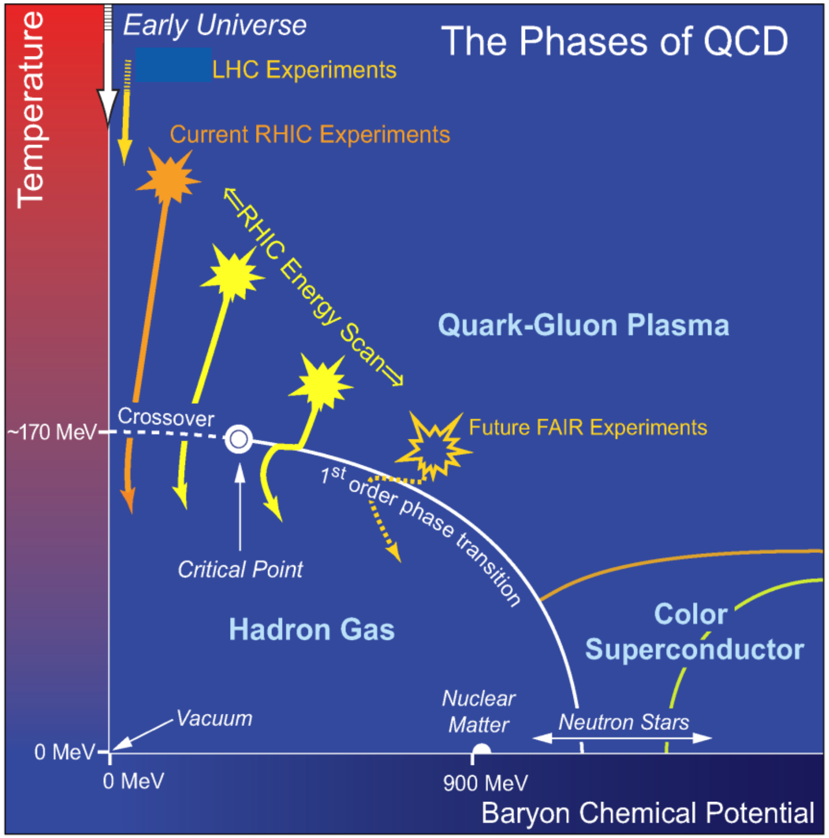
QCD Phase Diagram



Lattice QCD:

➢ Crossover at 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).

➢ QCD Citical 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).

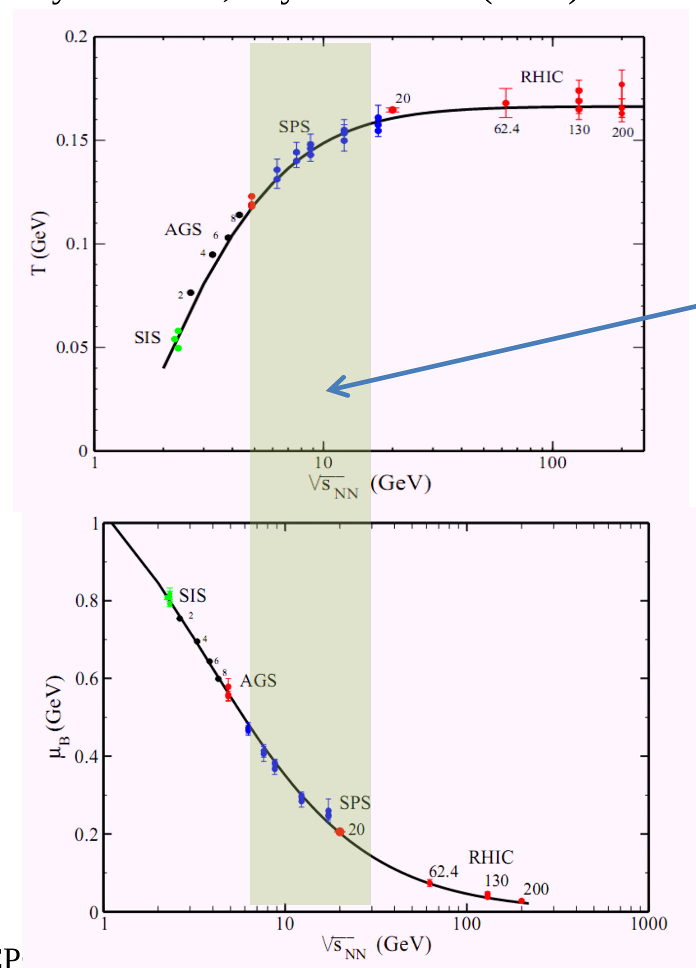
Main Motivation:

➢ Map the QCD Phase Boundary.
➢ Search for the QCD Critical Point.

Access the QCD Phase Diagram

➢ Particle ratio fitted by thermal model to extract Chemical freeze-out temperature (T) and baryon chemical potential (μ_B).

J. Cleymans et al, Phys. Rev. C73 (2006) 034905



➢ **RHIC Beam Energy Scan (BES) Program.**

Au+Au Collisions

Year	$\sqrt{s_{NN}}$ (GeV)
2010	7.7, 11.5, 39
2011	19.6*, 27*

*Analysis are ongoing

➢ **Advantages for STAR Detector :**

(a) Large uniform acceptance.

(b) Excellent particle identification.

(c) (a) and (b) will not change with energy.

➢ **STAR is the ideal detector for the QCD critical point search.**

STAR, arXiv: 1007.2613

Moments and Cumulants

In statistics, moments and cumulants are used to characterize the properties of probability distribution.

Central Moments ↔ **Moments**

$$\mu_n = <(N - <N>)^n>.$$

$$\mu_2 = \sigma^2, \mu_1 = 0$$

$$\mu_n' = <N^n>.$$

$$\mu_1' = <N>$$

Central Moments ↔ **Cumulants** ↔ Moments

$$C_n = \mu_n - \sum_{m=2}^{n-2} \binom{n-1}{m-1} C_m \mu_{n-m}$$

$$C_n = \mu_n' - \sum_{m=1}^{n-1} \binom{n-1}{m-1} C_m \mu'_{n-m}$$

$$C_1 = <N>, C_2 = \mu_2 = \sigma^2$$

$$C_3 = \mu_3, C_4 = \mu_4 - 3\mu_2^2$$

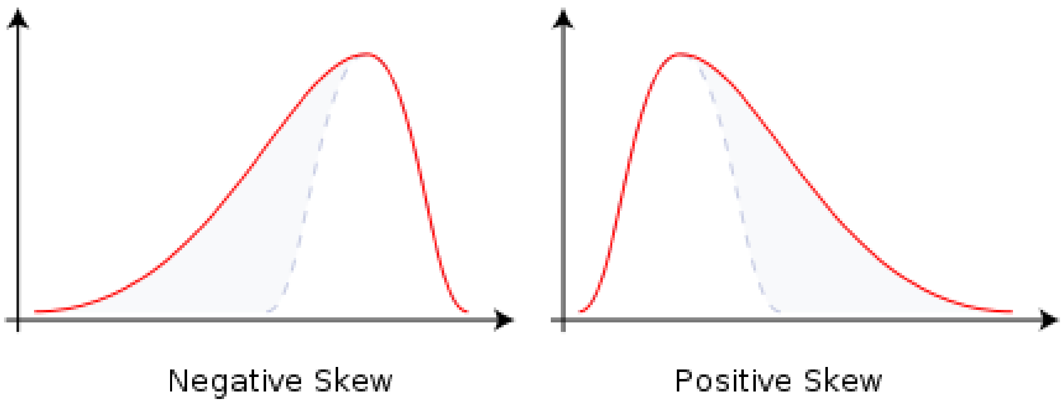
Non-Gaussian Measure: Skewness and Kurtosis

Normalized Central Moments : Skewness (3rd order) and Kurtosis (4th order).

Skewness:

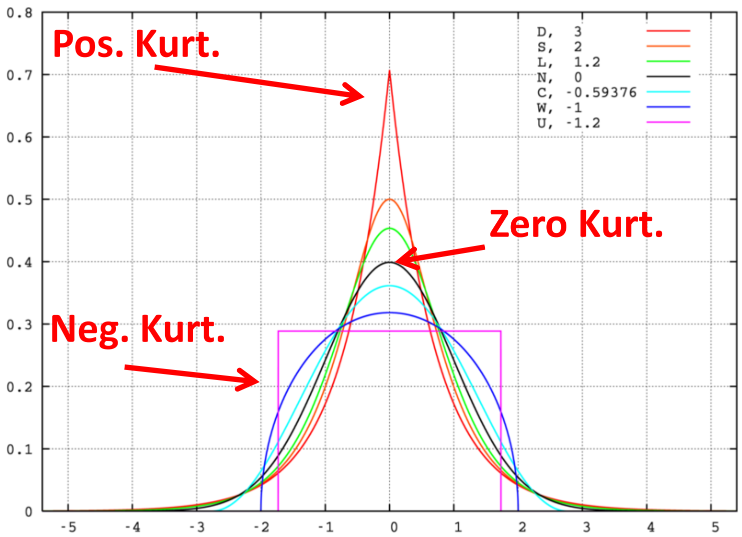
$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{<(N-<N>)^3>}{\sigma^3}$$

N: Event by Event Multiplicity



Kurtosis:

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



- **For Gaussian distribution, the skewness and kurtosis are equal to zero. Ideal probe of the non-Gaussian fluctuations near critical point.**

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).

Importance of Higher Moments Method (I)

➢ **Fluctuations of conserved quantities link to thermodynamic susceptibilities, for eg. in Lattice QCD and Hadron Resonance Gas (HRG) Model:**

Net-baryon: B

$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

F. Karsch et al, Phys. Lett. B 695, 136 (2011).
M.Cheng et al, Phys. Rev. D 79, 074505 (2009).

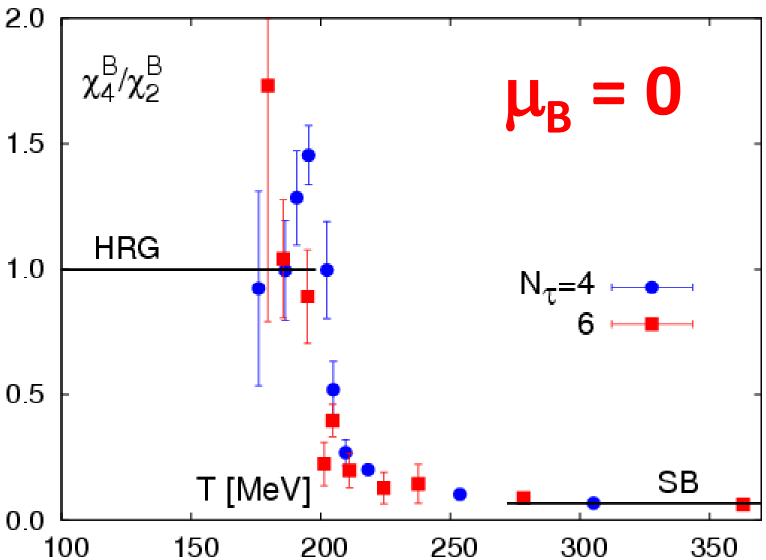
$$\chi_B^{2} = \frac{1}{VT^3} < \delta N_B^{2} >$$

$$\chi_B^{3} = \frac{1}{VT^3} < \delta N_B^{3} >$$

$$\chi_B^{4} = \frac{1}{VT^3} (< \delta N_B^{4} > -3 < \delta N_B^{2} >^2)$$

$$\chi_B^3 / \chi_B^2 = C_{3,B}/C_{2,B} = (S\sigma)_B$$
$$\chi_B^4 / \chi_B^2 = C_{4,B}/C_{2,B} = (\kappa\sigma^2)_B$$

Volume Cancel Out



Experimental measurable net-proton numbers fluctuations can reflect baryon and charge number fluctuations.

Y. Hatta et al,Phys. Rev. Lett. 91, 102003 (2003).
M. Kitazawa, M. Asakawa, arXiv:1107. 2755

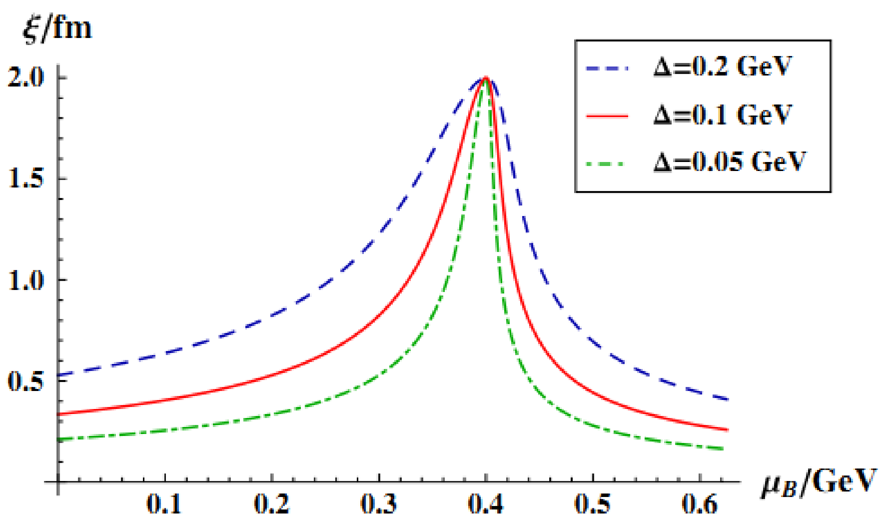
Importance of Higher Moments Method (II)

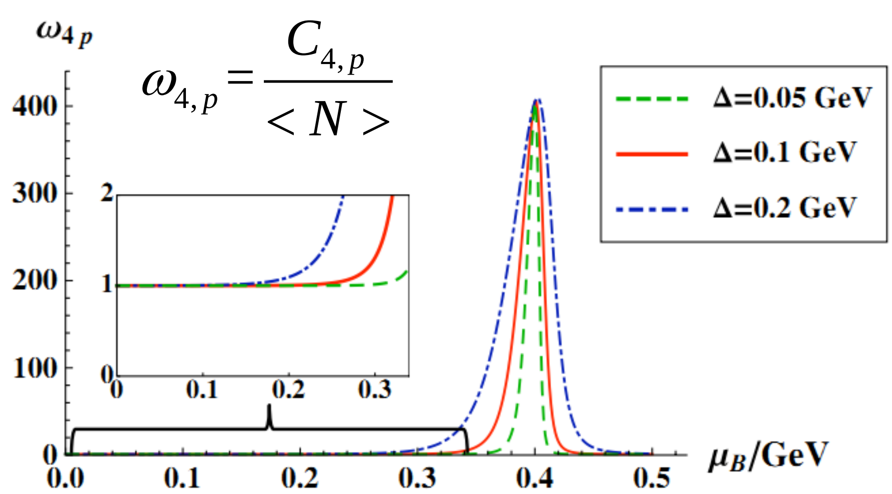
- **More sensitive to the correlation length (ξ) :**

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).

Due to finite size, finite time effects.
in heavy ion collisions.
ξ~2-3 fm at CP.

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





Assume μ_{CP} =400 MeV.

C. Athanasiou, M. Stephanov, K. Rajagopal, Phys. Rev. D 82, 074008 (2010)

Predictions from Hadron Resonance Model

- With the Boltzmann approximation, thermodynamic pressure in the HRG model (Grand Canonical Ensemble):

$$\frac{P}{T^4} = \frac{1}{\pi^2} \sum_i d_i (m_i / T)^2 K_2(m_i / T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q) / T]$$

- Consider:

$\mu_S \ll \mu_B$

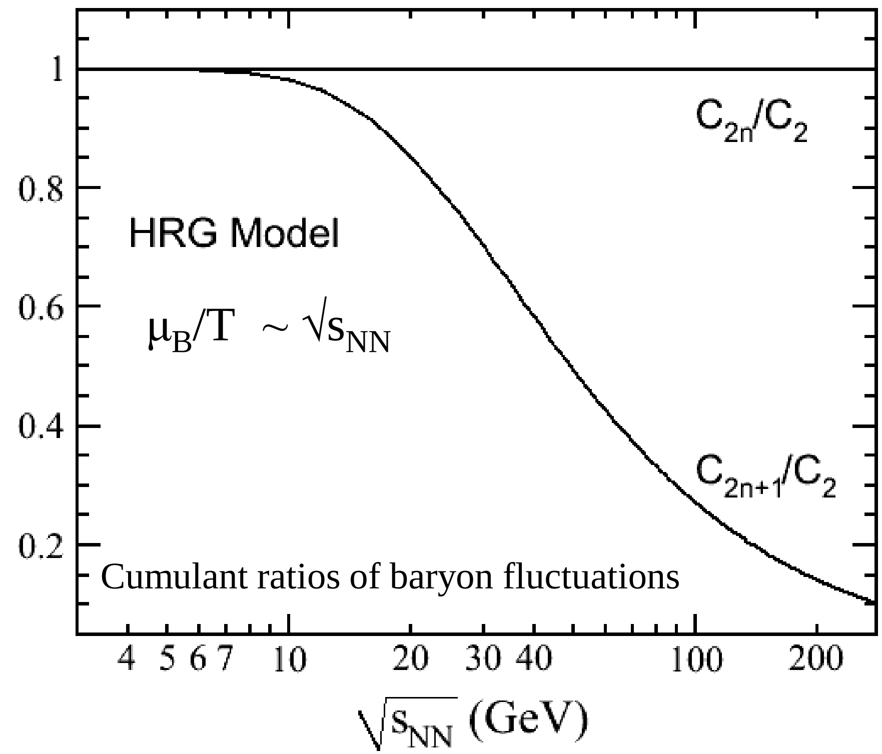
$\mu_Q \ll \mu_B$

$$\frac{C_{2n+1,B}}{C_{2,B}} = \frac{\chi_B^{(2n+1)}}{\chi_B^2} = \tanh(\mu_B / T),$$

$$\frac{C_{2n,B}}{C_{2,B}} = \frac{\chi_B^{(2n)}}{\chi_B^2} = 1 \quad (n = 1, 2, 3 \cdots)$$

$(S\sigma)_B = \chi_B^3 / \chi_B^2 = \tanh(\mu_B/T)$

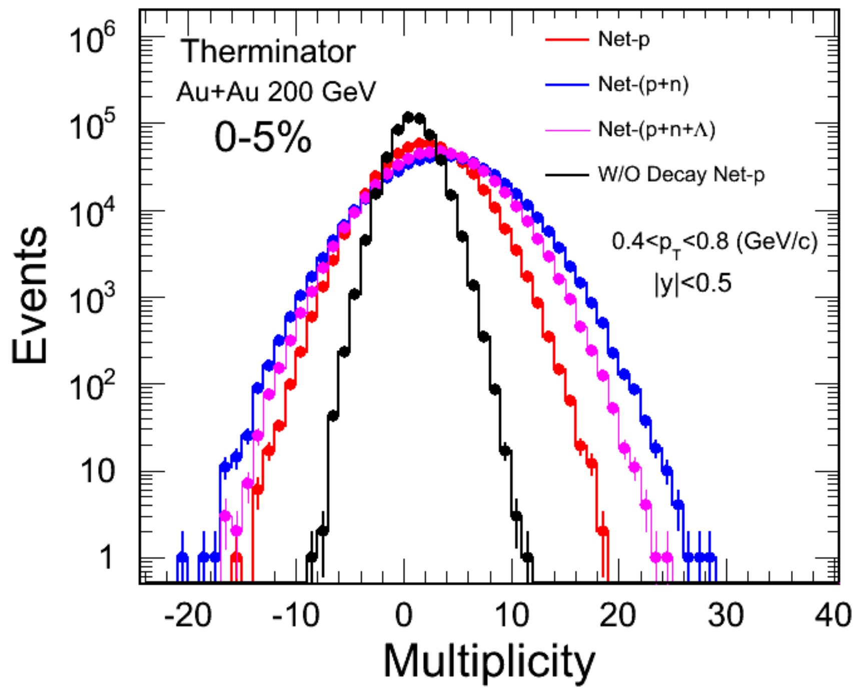
$(\kappa\sigma^2)_B = \chi_B^4 / \chi_B^2 = 1$

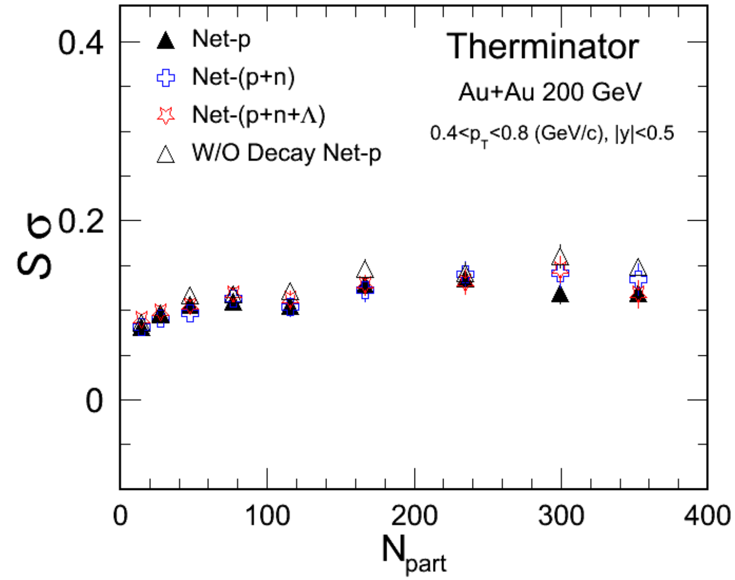


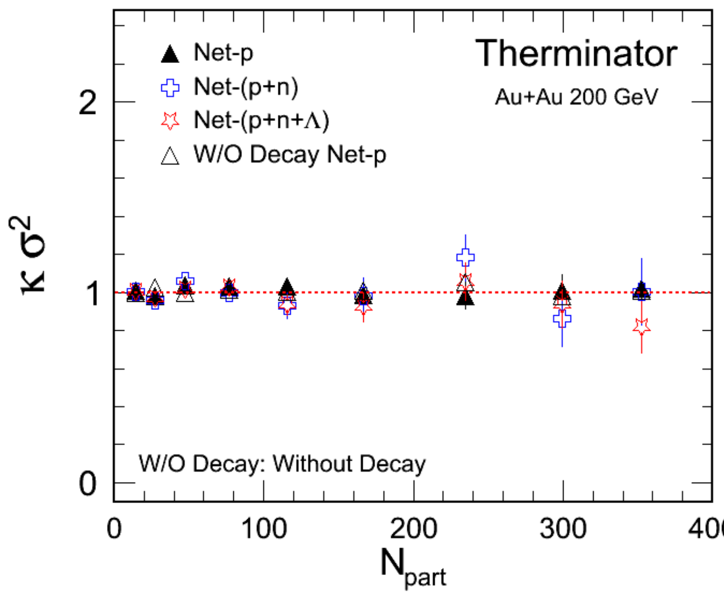
F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)

Resonance Decay and Neutron Effect

Model: Therminator (arXiv:1102.0273)





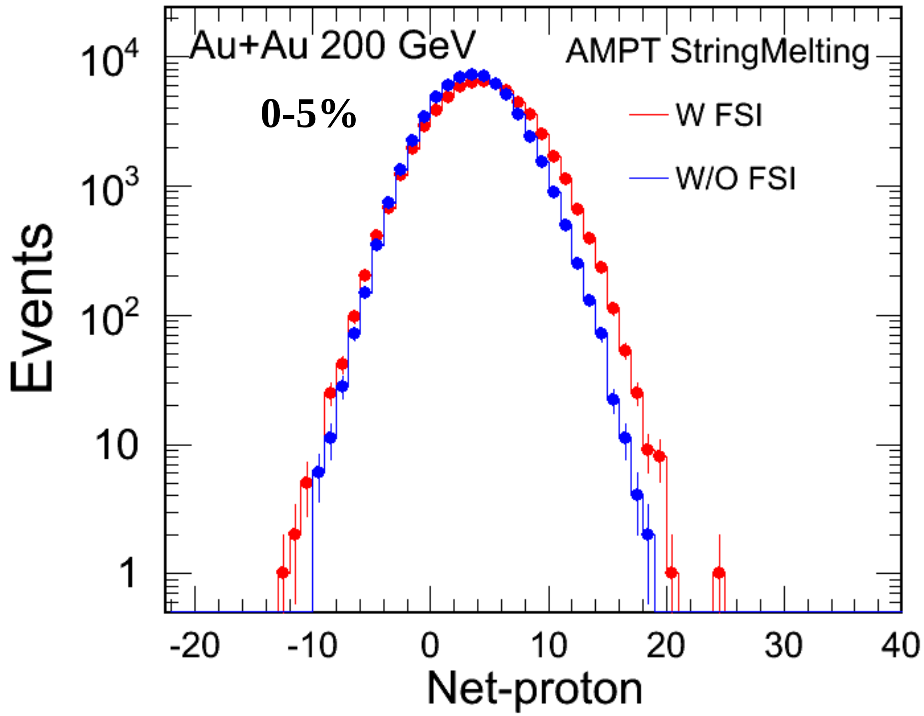


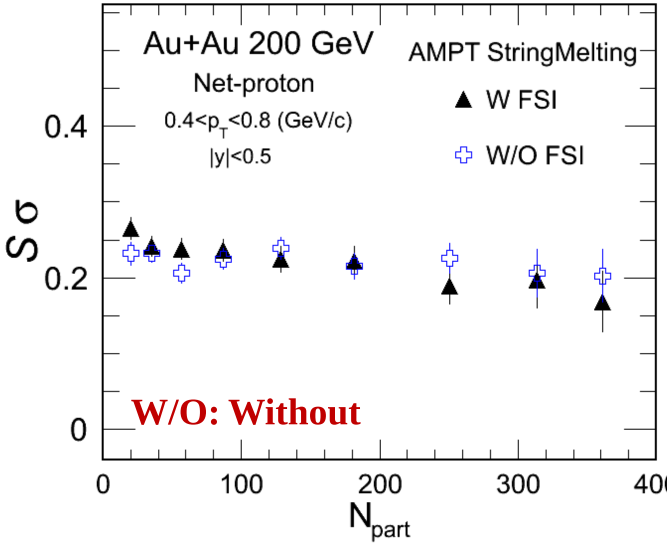
- Results of $S\sigma$ and $\kappa\sigma^2$ are consistent within errors indicating effects of resonance decay and inclusion of neutrons and/or Λ are small.

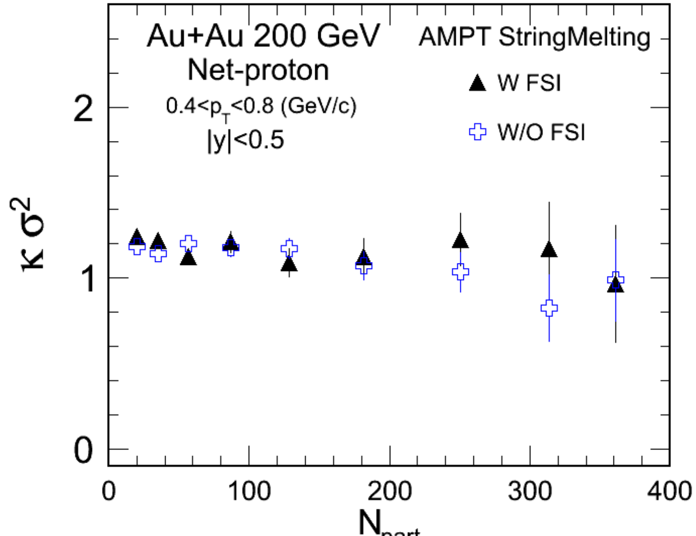
- Statistical error based on delta theorem method:
  X. Luo, arXiv:1109.0593

Final State Interaction (FSI) Effect

Model: AMPT String Melting **(Phys. Rev. C 72, 064901)**

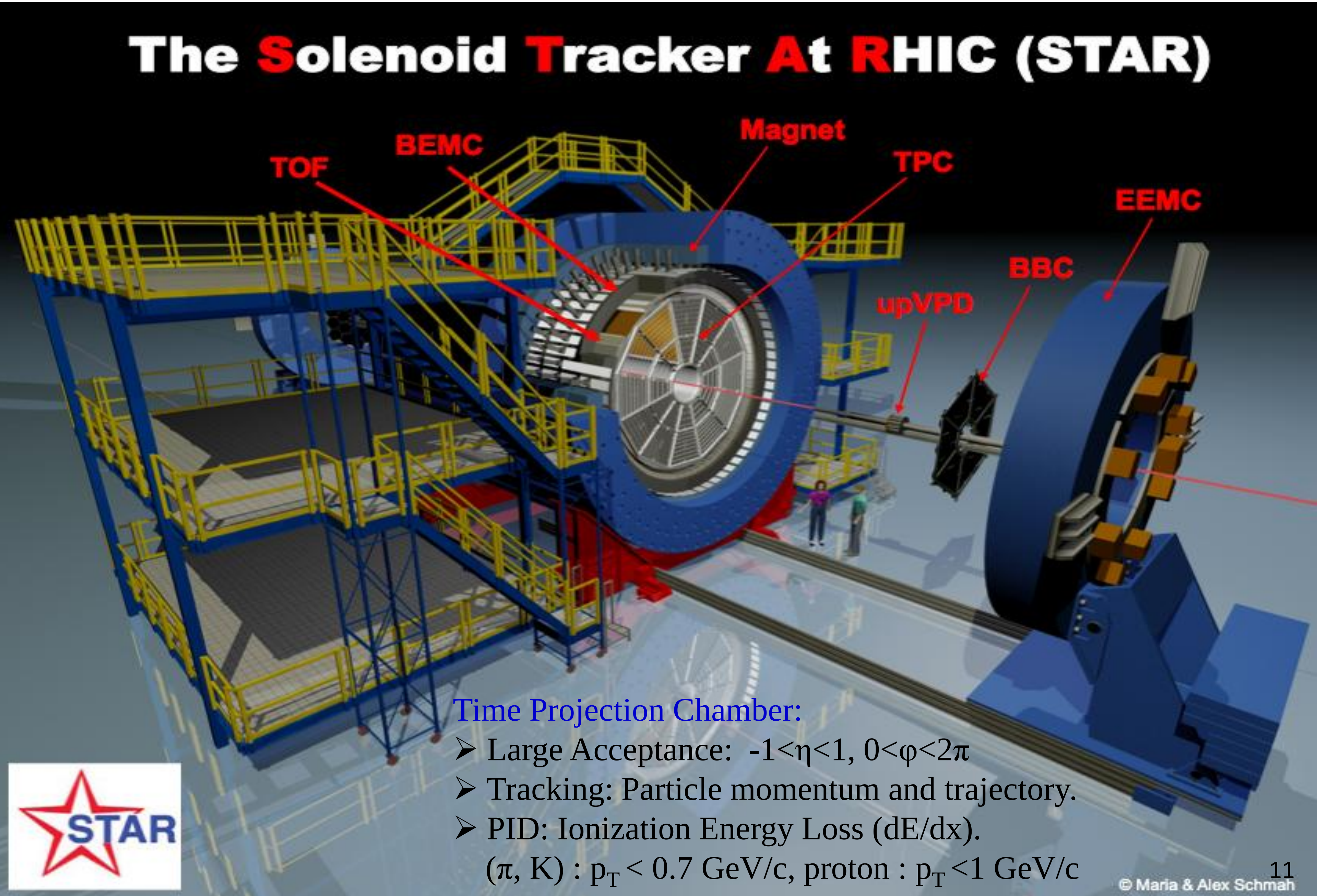






- Results of Sσ and κσ^2 are consistent within errors indicating effects of final state interaction on Sσ and κσ^2 are small.

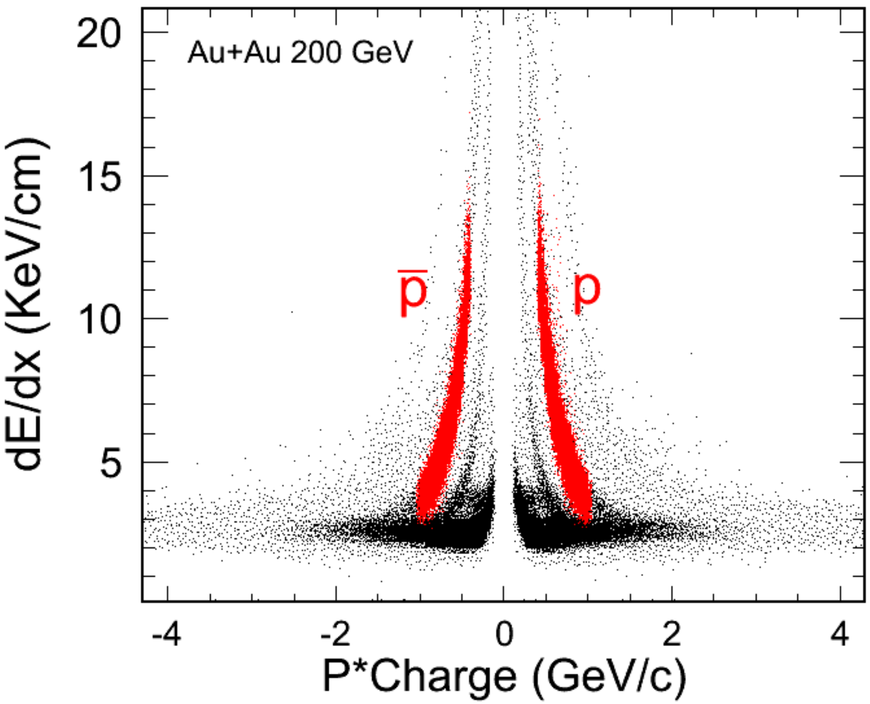
STAR Detector



Time Projection Chamber:

- Large Acceptance: $-1<\eta<1$, $0<\varphi<2\pi$
- Tracking: Particle momentum and trajectory.
- PID: Ionization Energy Loss (dE/dx).
  (π, K) : $p_T < 0.7$ GeV/c, proton : $p_T <1$ GeV/c

Particle Identification with TPC dE/dx



- **Track Quality Cuts:**

  NFits>20,
  NFits/NFitsPoss>0.52,
  gDca<1 cm.

- **PID Cut: dE/dx**

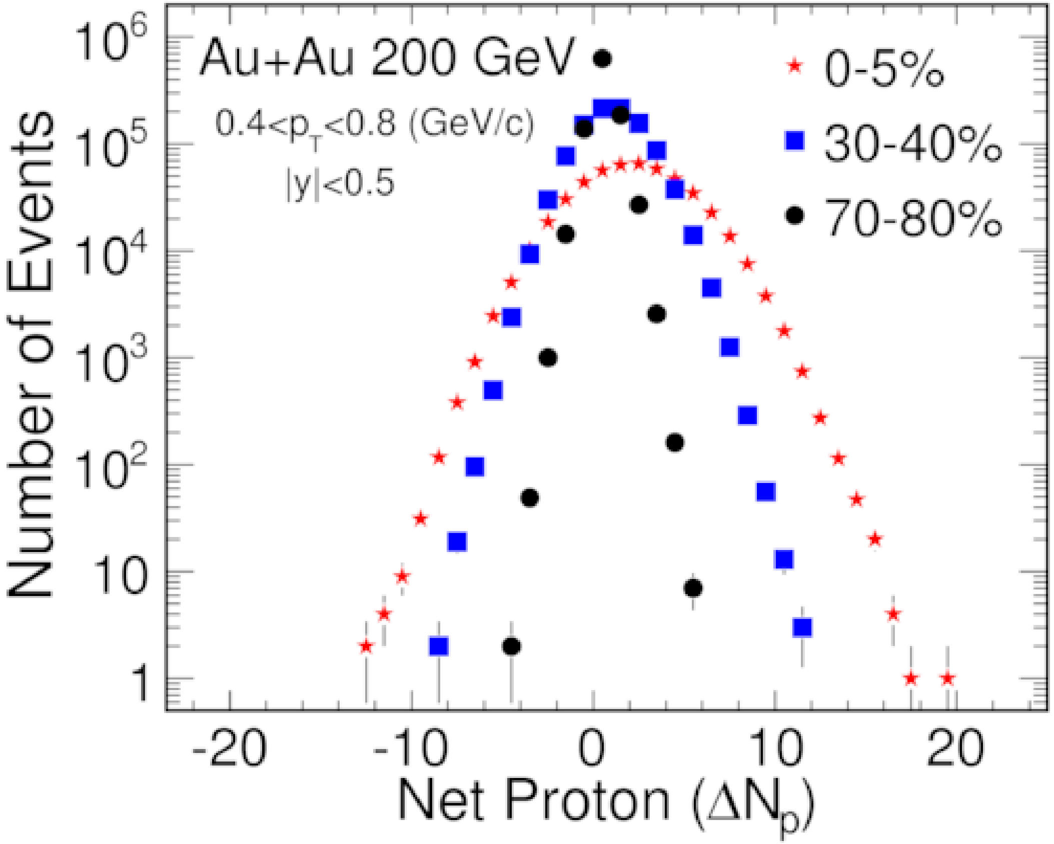
  $|Z_p|<2$

$$Z = \frac{\log[(dE/dx)|_{measure} / (dE/dx)|_{expected}]}{\sigma_E}$$

Advantages for using $0.4< p_T <0.8$ (GeV/c) and $|y_p|<0.5$:

- Clean proton and antiproton identification with TPC dE/dx.
- Similar detection efficiency for proton and anti-proton.

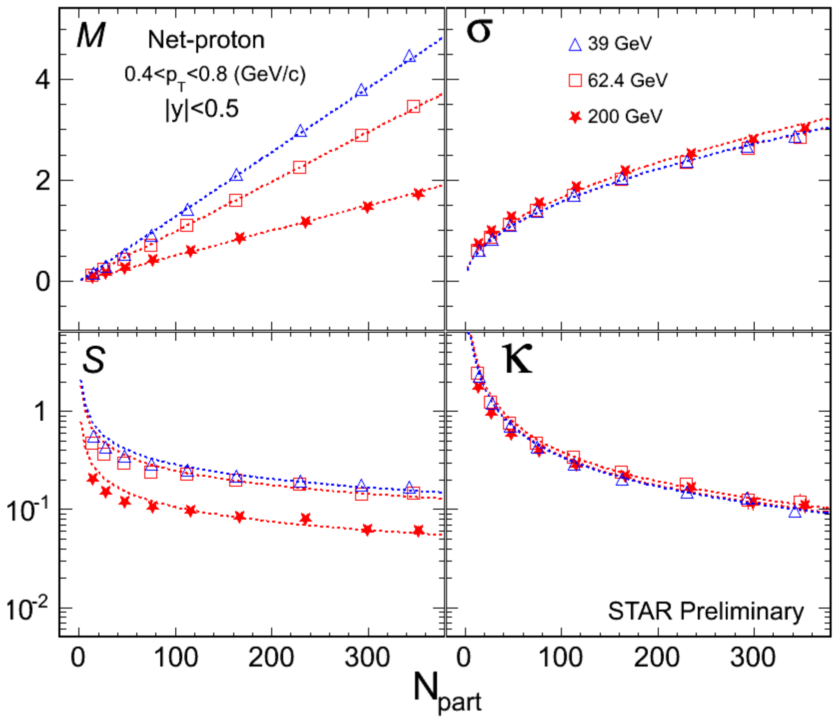
Event-by-Event Net-proton Multiplicity Distributions

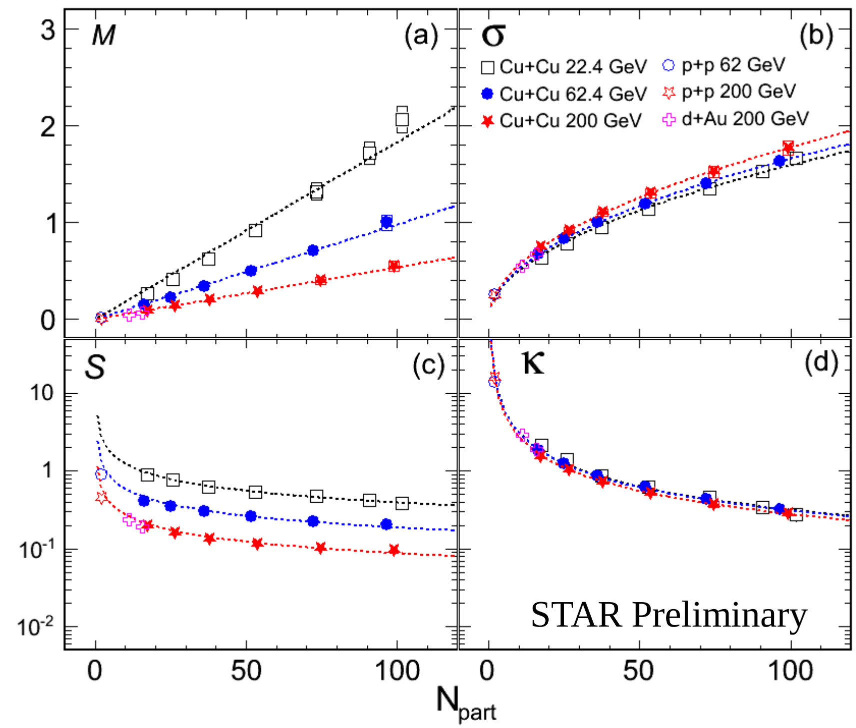


STAR: Phys. Rev. Lett. 105 (2010) 022302

- The event-by-event net-proton distributions are more symmetrical in central collision than peripheral.

Centrality Dependence (I): Various Moments





X. Luo (STAR Collabration)
WWND Proceedings, arXiv:1106.2926

Central Limit Theorem (CLT)

$$M_i = M_x \times C \times N_{part}, \sigma_i^2 = \sigma_x^2 \times C \times N_{part}$$

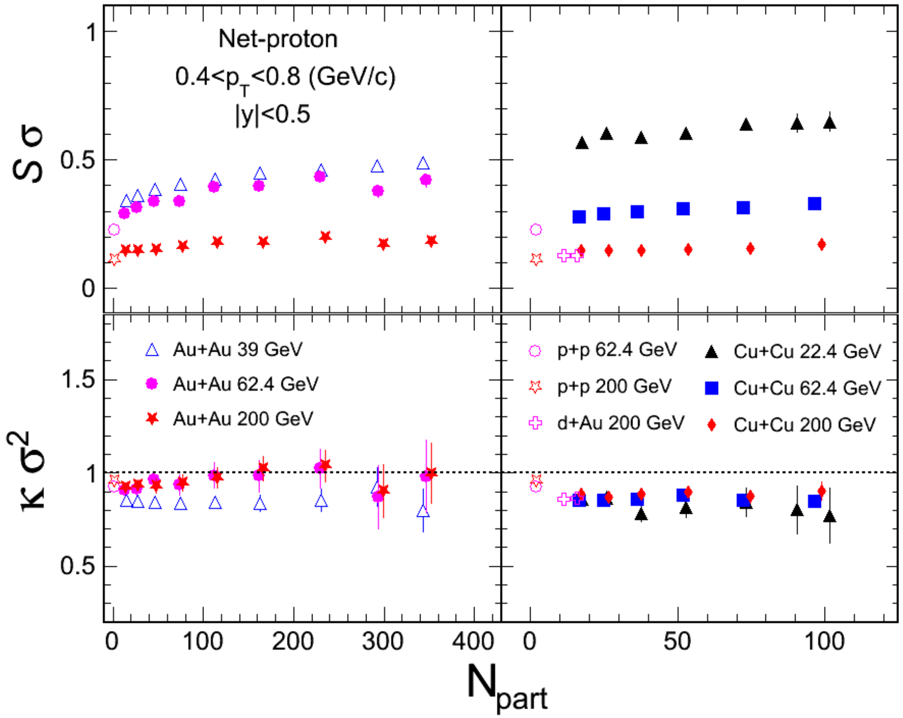
$$S_i = S_x \Big/ \sqrt{C \times N_{part}}, \kappa_i = \kappa_x \Big/ (C \times N_{part})$$

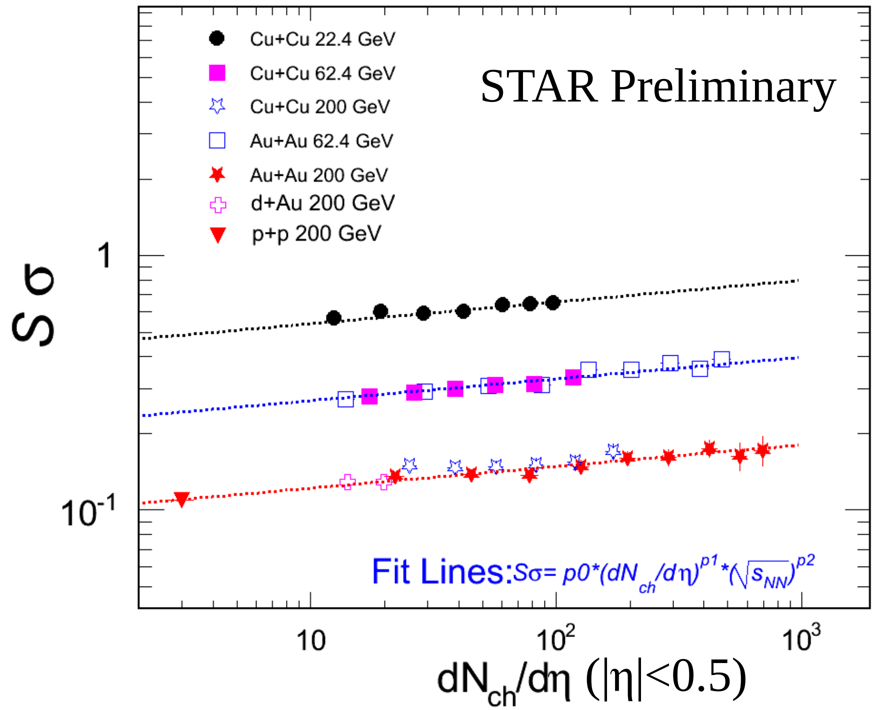
The 62.4 and 200 GeV data are published in PRL 105 (2010) 022302

Consistent with CLT Expectations (lines).

Indicates many identical, independent particle emission sources.

Centrality Dependence (II): Moment Products



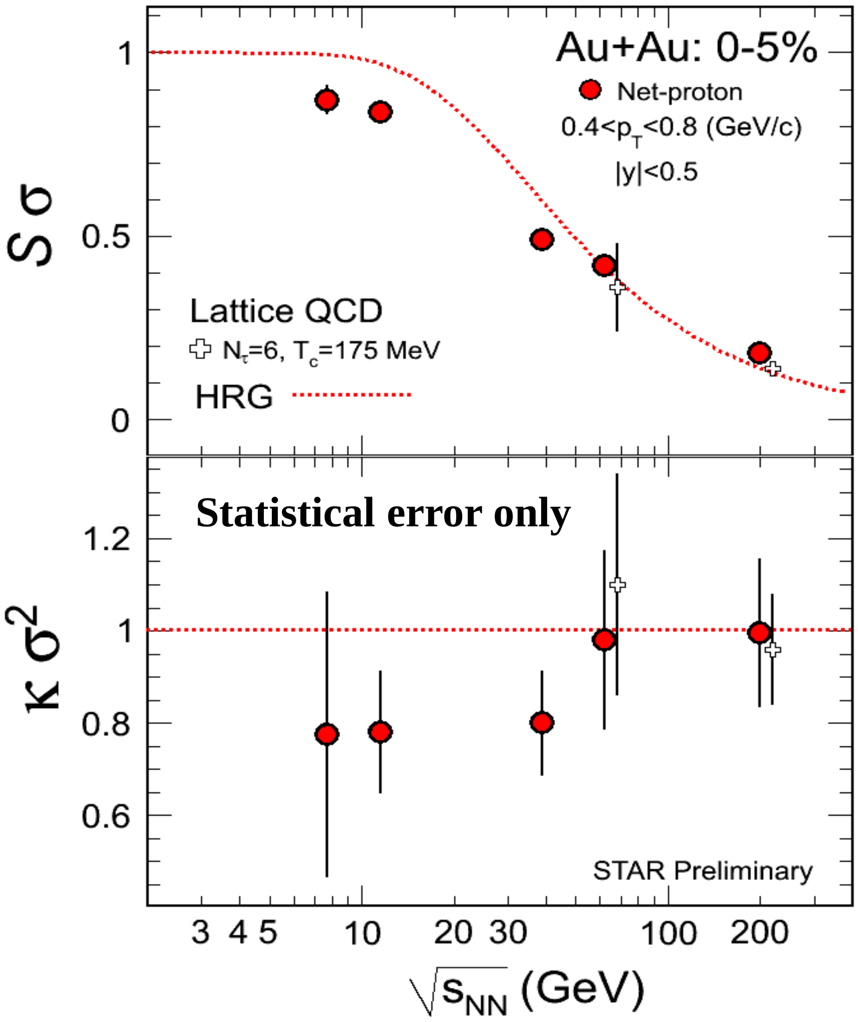


The 62.4 and 200 GeV data are published
in PRL 105, 022302 (2010) .

X. Luo (STAR Collabration)
WWND Proceedings, arXiv:1106.2926

- Sσ : 1. Slightly increase with centrality and strong energy dependence.
  2. Scale with the dN/dη for fixed energy.
- $\kappa\sigma^2$: Weak centrality and energy dependence.

Energy Dependence



- Consistent with HRG and Lattice QCD at high energies (62.4 and 200 GeV).

  F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011).
  R. Gavai and S. Gupta, Phys. Lett. B 696, 459 (2011).

- Systematic effects, such as auto-correlation between centrality selection and net-proton fluctuations, PID methodology (rapidity , p_T and PID cuts) are under study.

- More accurate statistical error propagation study is ongoing. X. Luo, arXiv:1109.0593

62.4 and 200 GeV data are published in PRL 105, 022302 (2010) .

Summary

➢ Higher moments of conserved quantities are sensitive to the correlation length and direct connected to thermodynamic susceptibilities. It opens a new domain of probing bulk properties of nuclear matter.

➢ Measurements of higher moments of net-proton distribution presented for 7.7, 11.5, 39, 62.4 and 200 GeV Au+Au collisions.

➢ Agreements of measured net-proton $\kappa\sigma^2$ and $S\sigma$ with HRG model and Lattice calculations are observed for 62.4 and 200 GeV.

Outlook: 1. Study the systematic effects.
2.The results from 19.6, 27 GeV data will come soon.