Search for the QCD Critical Point with Higher Moments of Net-proton Distributions

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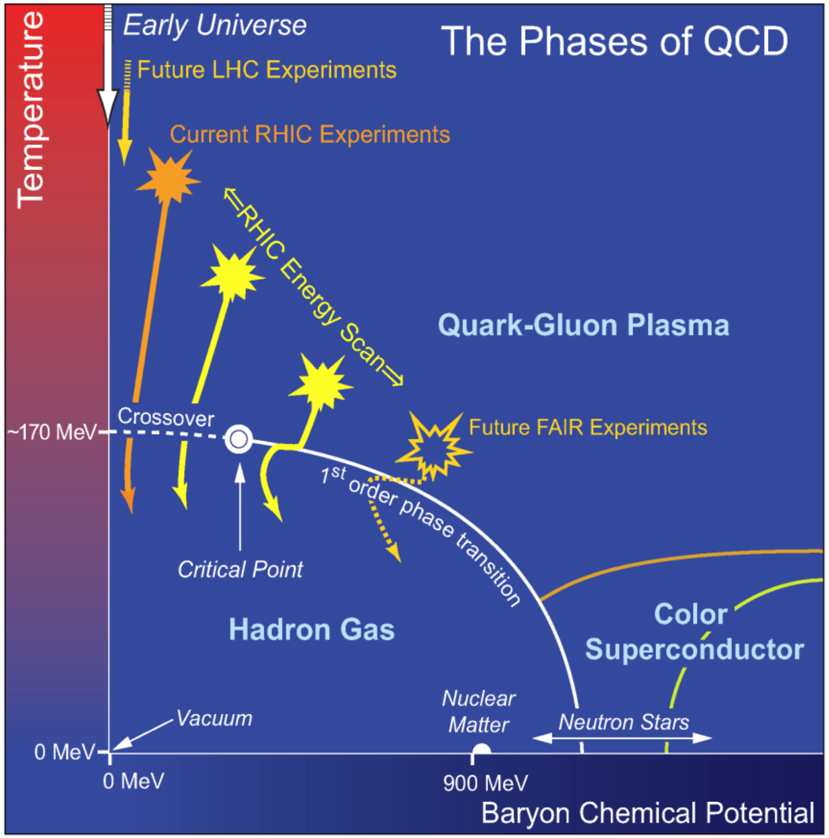
QCD Phase Diagram



Lattice QCD:

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

➢ QCD Citical Point: The end point of first order phase transition boundary.

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

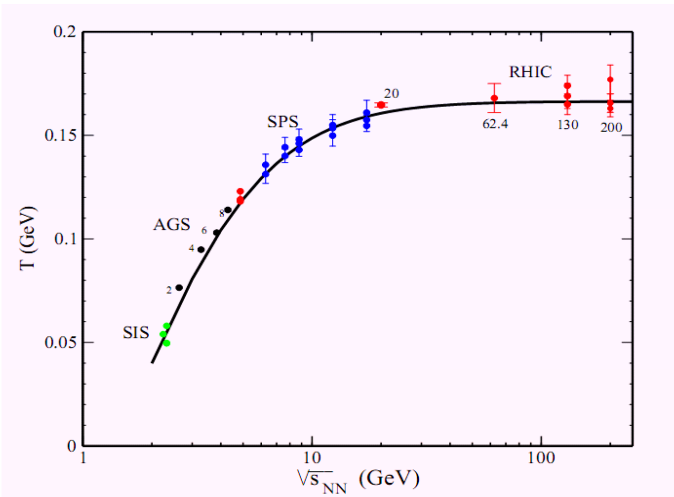
Motivations :

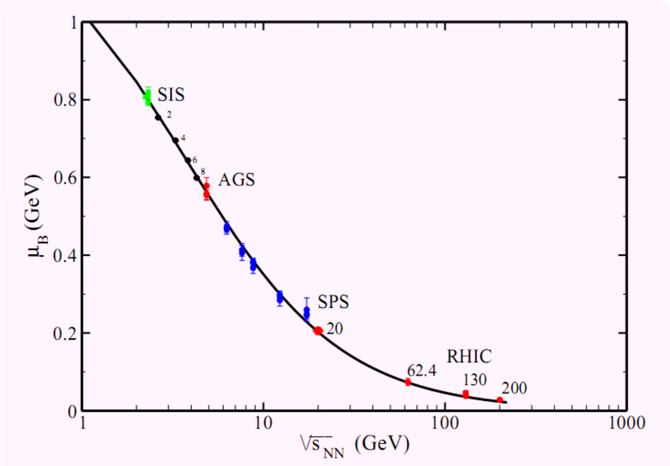
➢ Map the QCD Phase Boundary.
➢ Search for the QCD Critical Point.

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 is ongoing)

➢ **STAR Detector : Large Uniform Acceptance.**

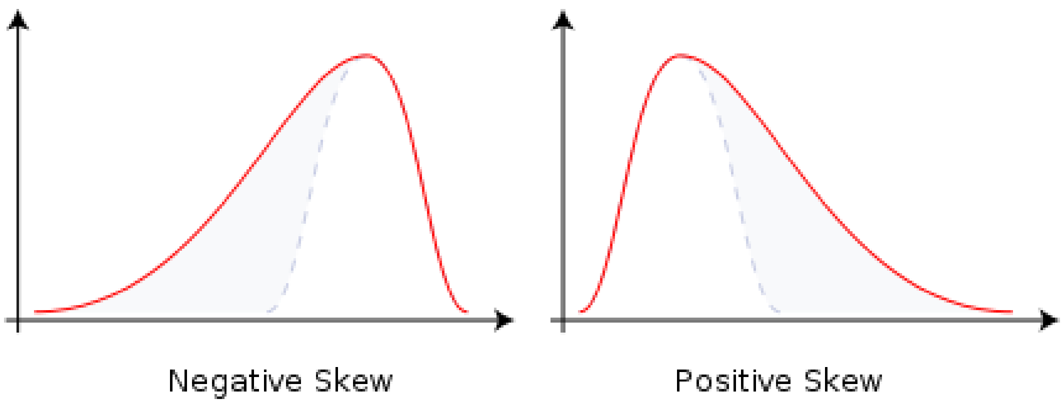
STAR is the ideal detector for the QCD critical point search.

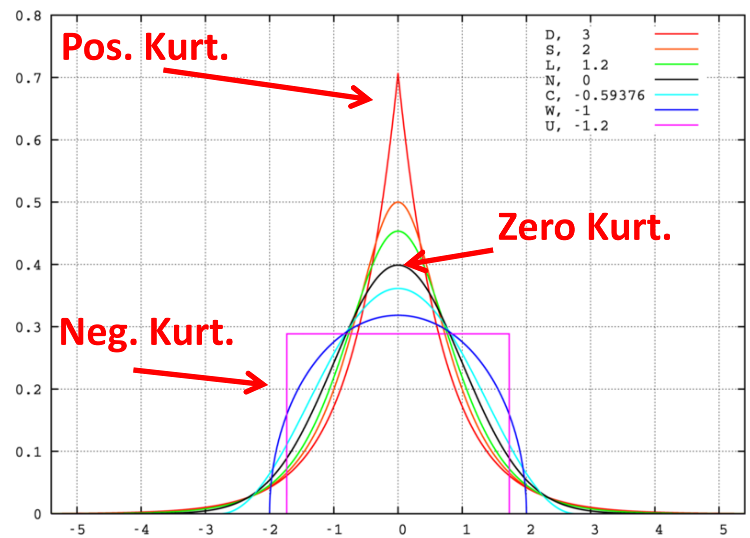
Higher Moments: Non-Gaussian Fluctuation Measure

Definition : N: **Event by Event Multiplicity Distribution**

Mean: $M = \langle N \rangle$ **St. Deviation:** $\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$

Skewness: $s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$ **Kurtosis:** $\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$





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

X. Luo, arXiv: 1106.2926.

Importance of Higher Moments Method

➢ **Link to Thermodynamic Susceptibilities in Lattice QCD and Hadron Resonance Gas (HRG) Model:**

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

M.Cheng et al, Phys. Rev. D 79, 074505 (2009)

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

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

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

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

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

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

Volume Cancel Out

Net-proton numbers fluctuations can reflect baryon and charge number fluctuations.

Y. Hatta et al,PRL 91, 102003 (2003)

➢ **Sensitive to Correlation Length (ξ) : Sigma Model Calculations.**

Due to finite size, finite time effects.

in heavy ion collisions. ξ~2-3 fm.

$$< (\delta N)^2 > \approx \xi^2$$

$$< (\delta N)^3 > \approx \xi^{4.5}$$

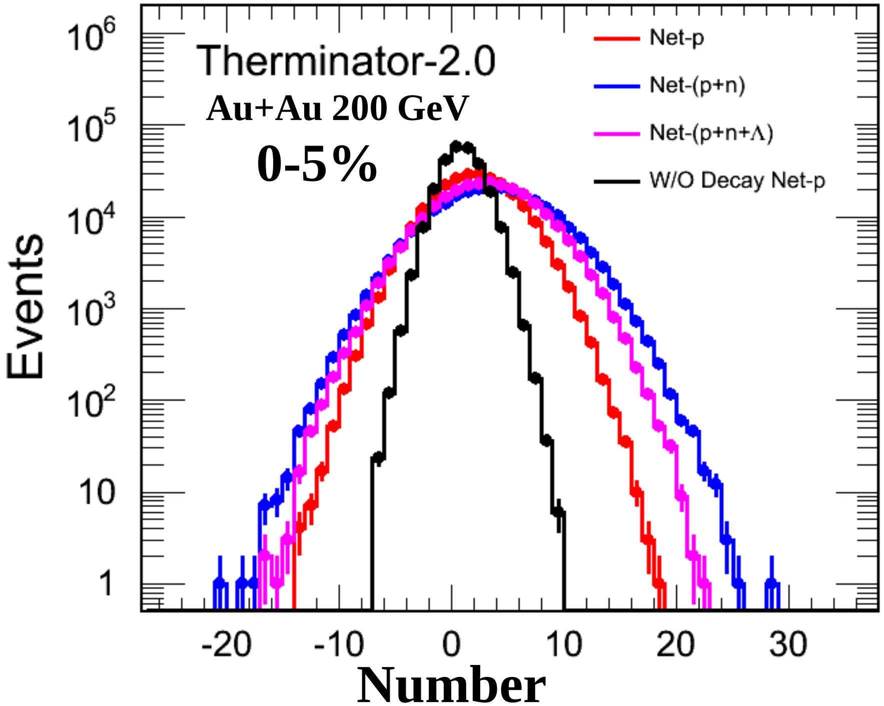
$$< (\delta N)^4 > - 3 < (\delta N)^2 >^2 \approx \xi^7$$

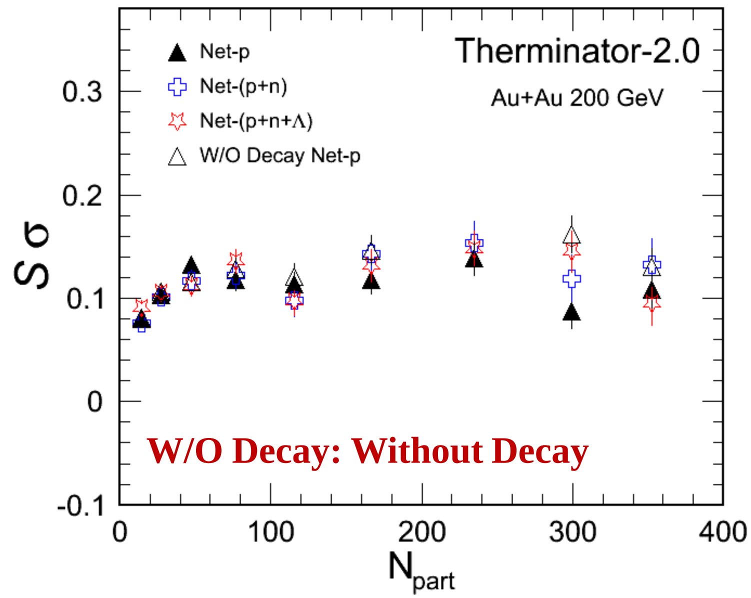
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)

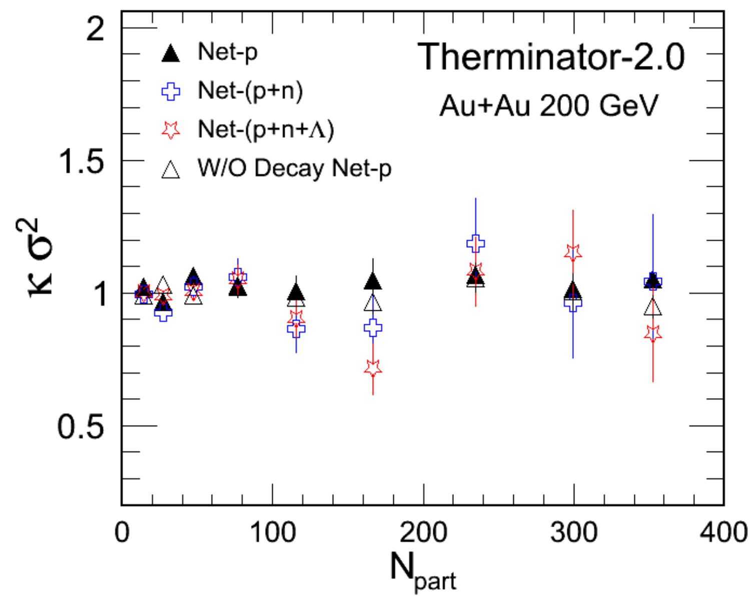
C. Athanasiou,M. Stephanov, K. Rajagopal, Phys. Rev. D 82, 074008 (2010)

Resonance Decay and Neutron Effect

Model: Therminator-2.0 (arXiv:1102.0273)



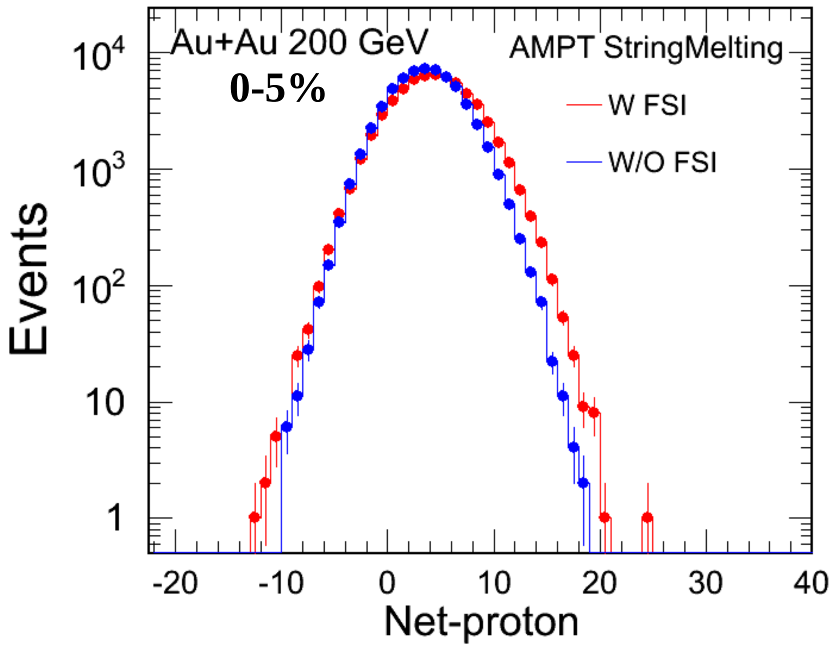


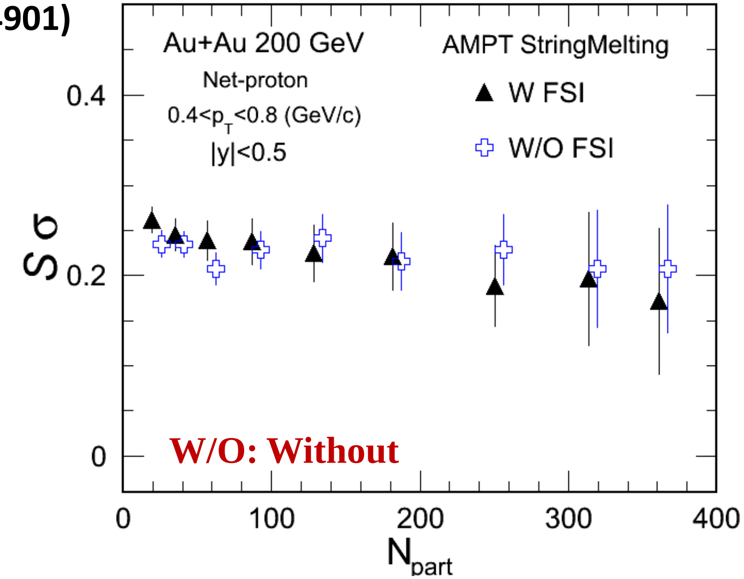


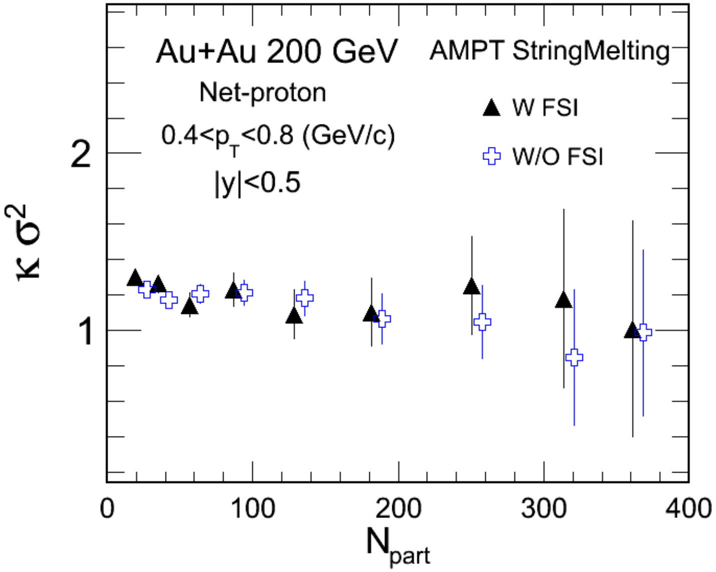
- **Effect of resonance decay on Sσ and κσ² is small.** **(based on the right two plots).**
- **Effect of inclusion of neutrons is small:** **Indicates: Net-proton fluctuation can reflect the net-baryon fluctuation.**
- **Error estimation: X. Luo, arXiv:1109.0593**

Final State Interaction (FSI) Effect

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



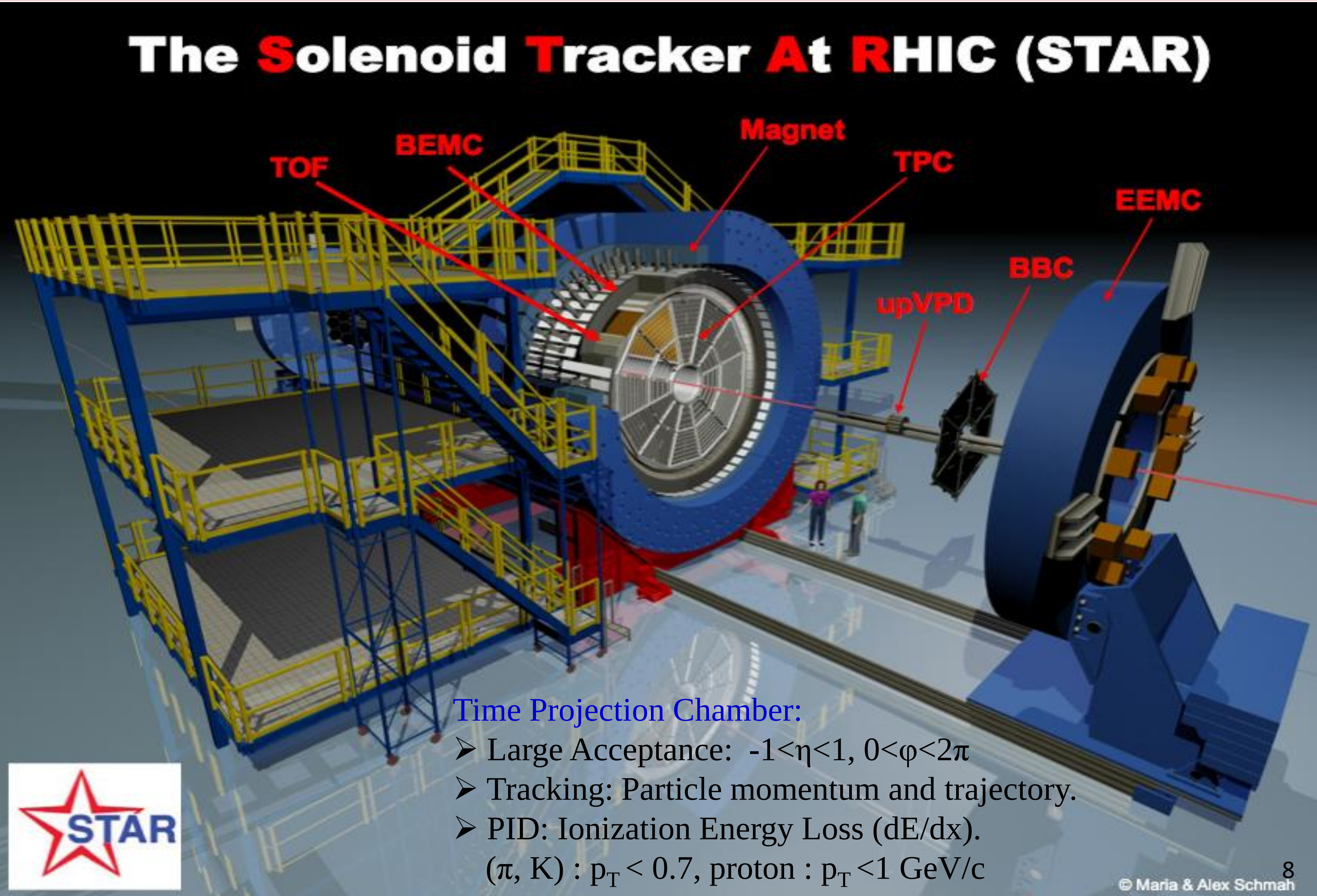




- **Effects of Final State Interaction (FSI) on Sσ and $\kappa\sigma^2$ are small.**

(based on the results in the right two plots).

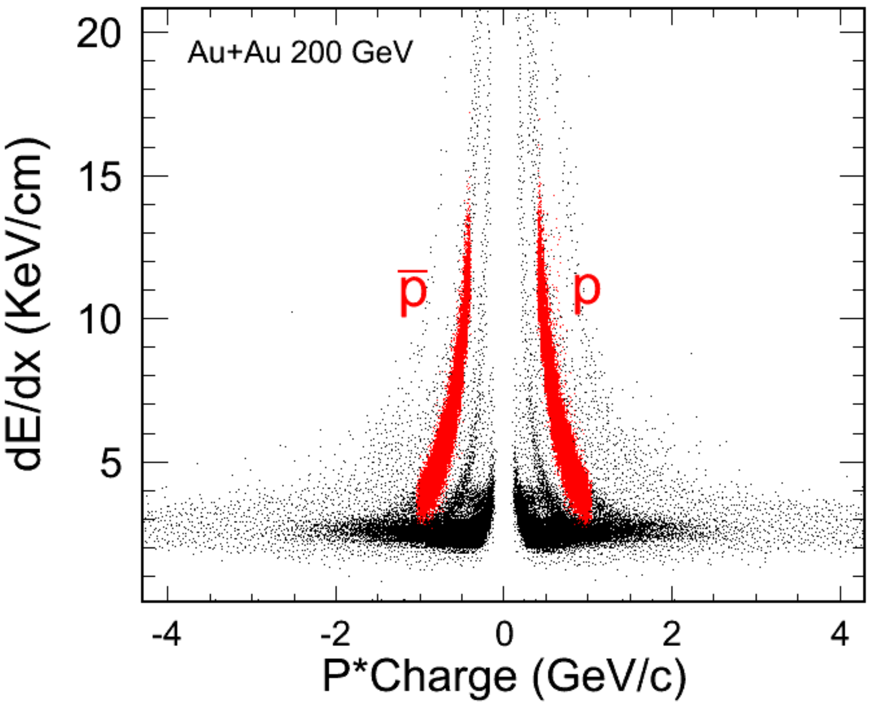
STAR Detector-3D Picture



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) : $p_T < 0.7$, proton : $p_T <1$ GeV/c

Particle Identification with TPC dE/dx



- **Track Quality Cuts:**
  Nfits>20,
  Nfits/NFitPoss>0.52.
  gDca<1 cm.

- **PID Cut: dE/dx**
  $|Z_p|<2$

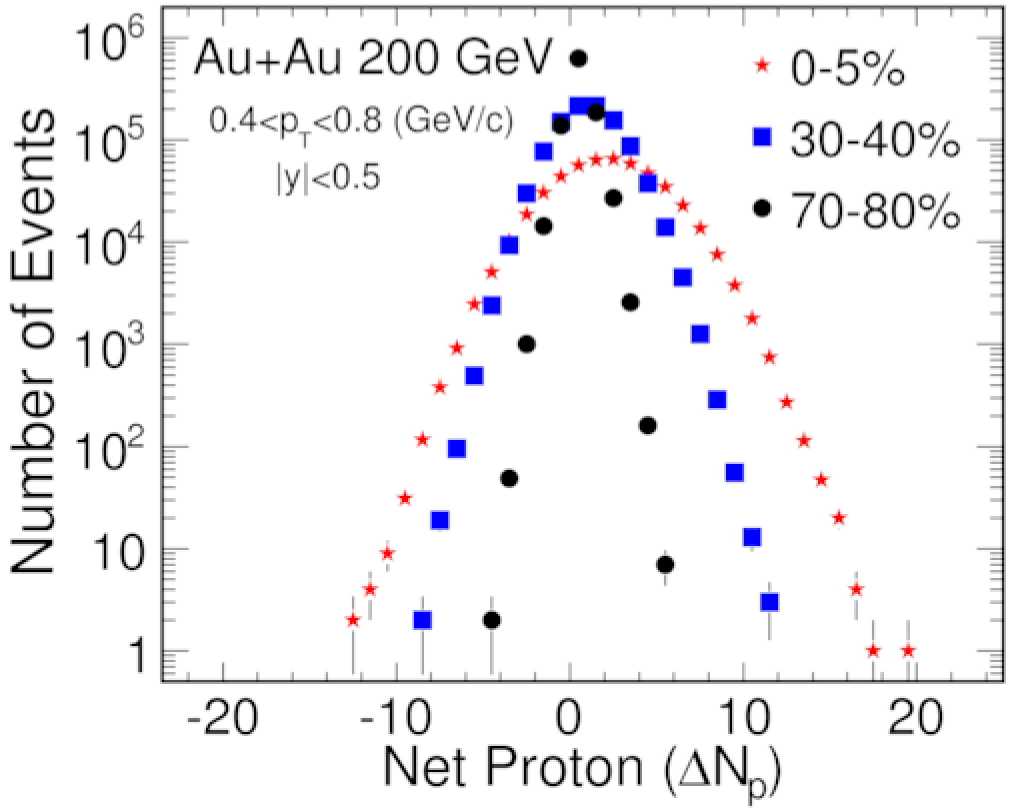
$$Z = \frac{\log[(dE/dx)|_{measure} / (dE/dx)|_{expected}]}{\sigma_E}$$

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.
- Larger long wavelength critical fluctuations developed in low p_T.

M. Stephannov, K. Rajagopa, E. Shuryak, Phys. Rev. D 60, 114028 (1999)

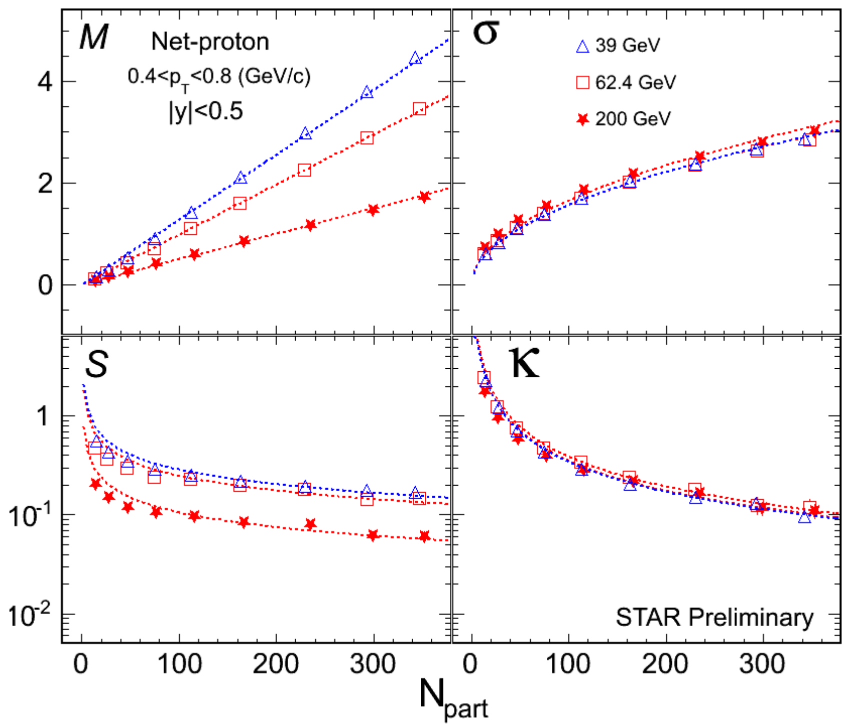
Event-by-Event Net-proton Multiplicity Distributions

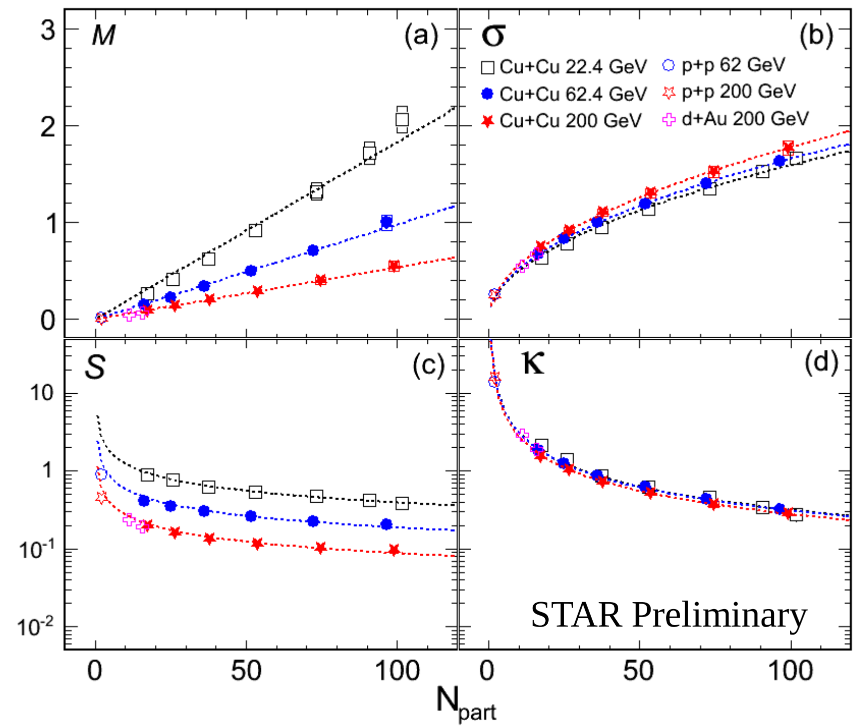


STAR: Phys. Rev. Lett. 105 (2010) 022302

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

Centrality Dependence (I): Higher Moments





Central Limit Theorem (CLT)

X. Luo, arXiv:1106.2926

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

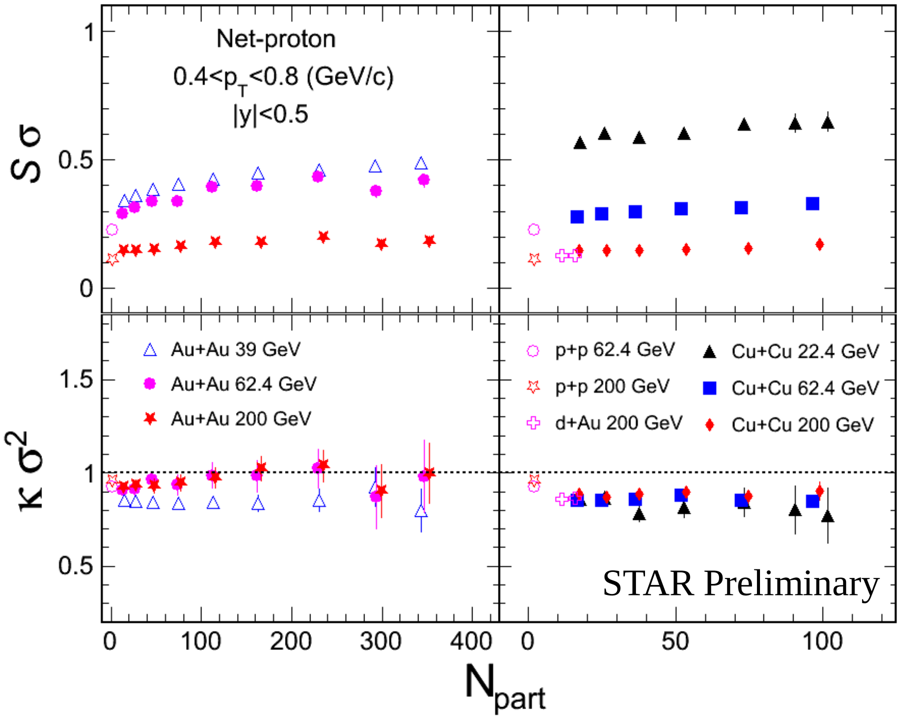
$$S_i = S_x \Big/ \sqrt{C \times N_{part}}, \kappa_i = \kappa_x \Big/ (C \times N_{part})$$

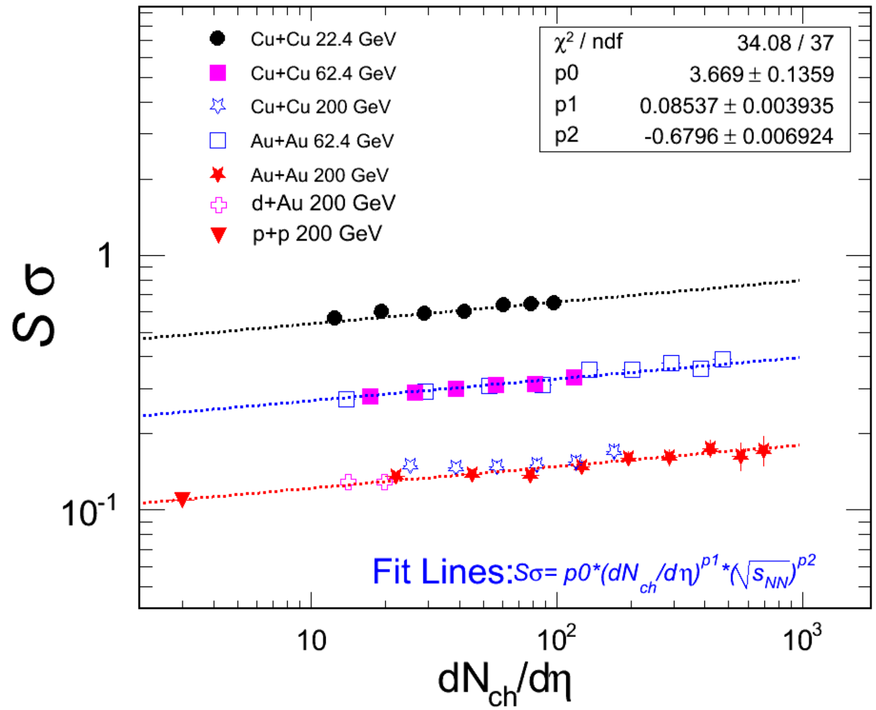
Consistent with CLT Expectations (lines).

Indicates many identical, independent particle emission sources.

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

Centrality Dependence (II): Moment Products



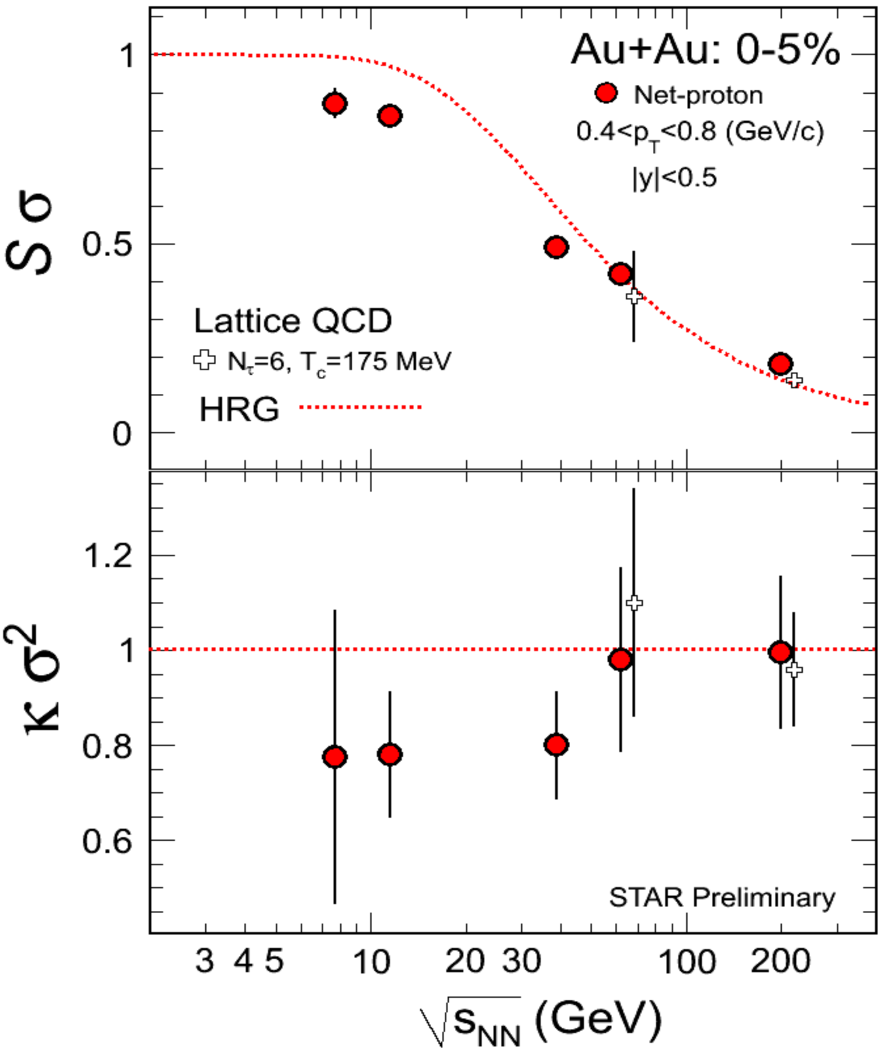


The 62.4 and 200 GeV data are published
in PRL 105 (2010) 022302

X. Luo, arXiv:1106.2926

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

Energy Dependence of Moment Products



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

- Consistent with HRG and Lattice QCD results at high energy.

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

- Deviations from HRG model. from 39 GeV.

Possible Reasons of the deviations:

1. Link to the chiral phase transition and/or critical point.

B. Friman et al., Eur. Phys. J. C71, 1694 (2011)
M. A. Stephanov, arXiv:1104.1627

2. Non-applicable of Grand Canonical Ensemble (GCE).

Analysis of 19.6 and 27 GeV data with high statistics are ongoing….

Summary

- **Higher moments are directly related to thermodynamic susceptibilities in Lattice QCD and HRG model. It opens a new domain of probing bulk properties of nuclear matter.**

- **Higher moments of net-proton distributions in heavy ion collisions are applied to search for the QCD critical point. Preliminary results from STAR BES data are obtained.**

- **Deviations from HRG model for $S\sigma$ and $\kappa\sigma^2$ are observed . The possible reasons are discussed.**

Outlook: The results for 19.6 and 27 GeV high statistics data will come soon.