Search for QCD Critical Point: Higher Moments of Net-proton Multiplicity Distributions at RHIC

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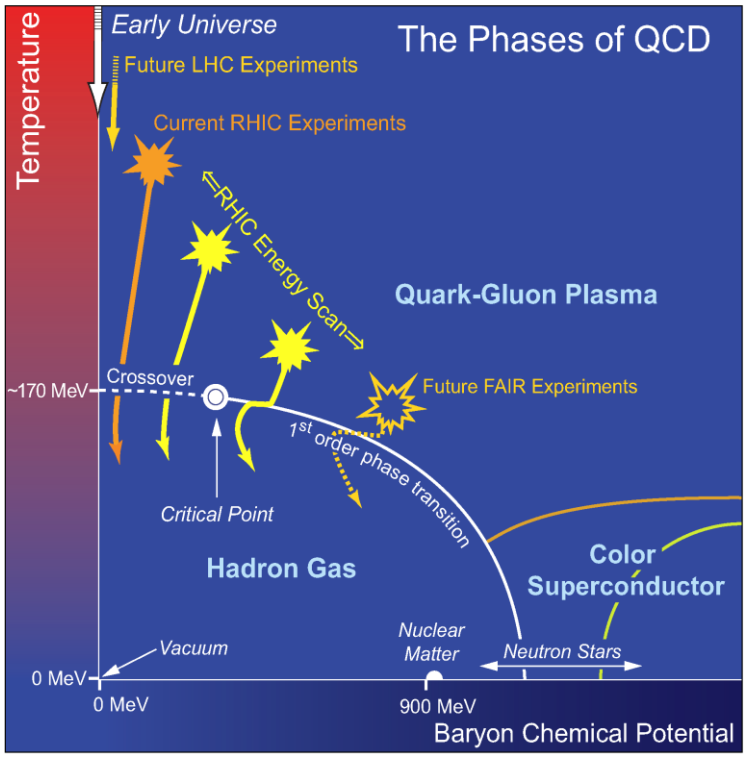
QCD Phase Diagram

A type of chart to show condition at which thermodynamically distinct phases can occur at equilibrium.



Schematic QCD Phase diagram of Nuclear Matter

Explore the structure of the QCD phase diagram.

- Map the QCD Phase Boundary.
- Find the QCD Critical Point (CP).

Signatures of the QCD Critical Point (CP):

- **Divergence of the correlation length (ξ) and thermodynamic susceptibilities.**
- **Non-Gaussian fluctuations.**

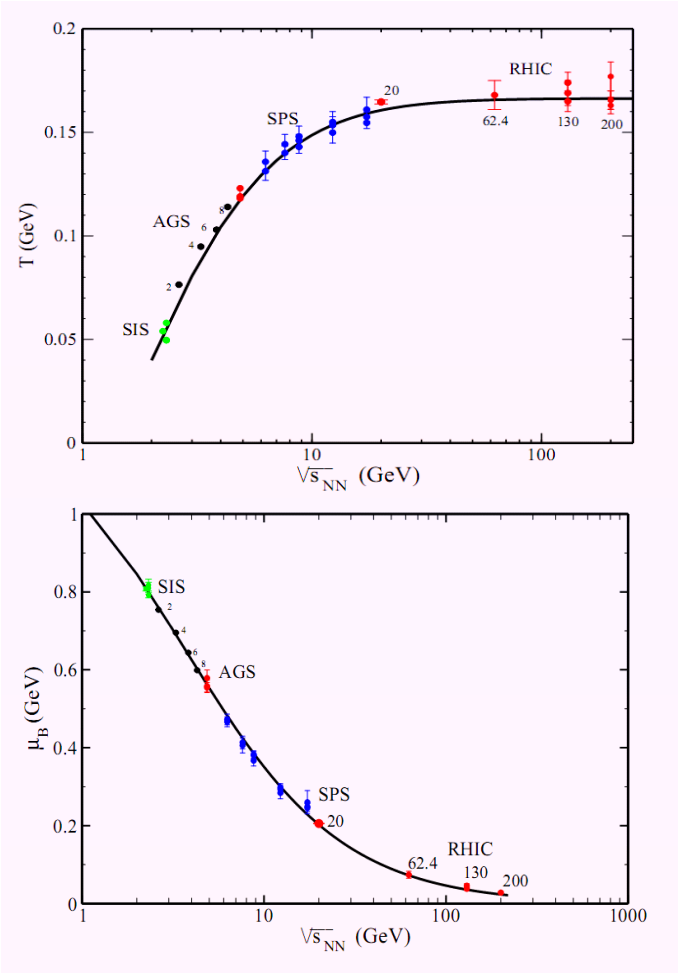
Observable (T, μ_B):

No-monotonic signal is need for CP.

Experimental Method: Heavy Ion Collisions

- Particle ratio fit with Thermal Model: Chemical freeze out temperature (T) and baryon chemical potential (μ_B).

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



- Varying the colliding energy, we can access different region (T, μ_B) on the QCD phase diagram.

- **RHIC Bean Energy Scan Program:**

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

Year	$\sqrt{s_{NN}}$ (GeV)
2010	**7.7, 11.5, 39, 62.4, 200** (μ_B **Coverage : 20~550 MeV**)
2011	6 (?), 18, 27, 200

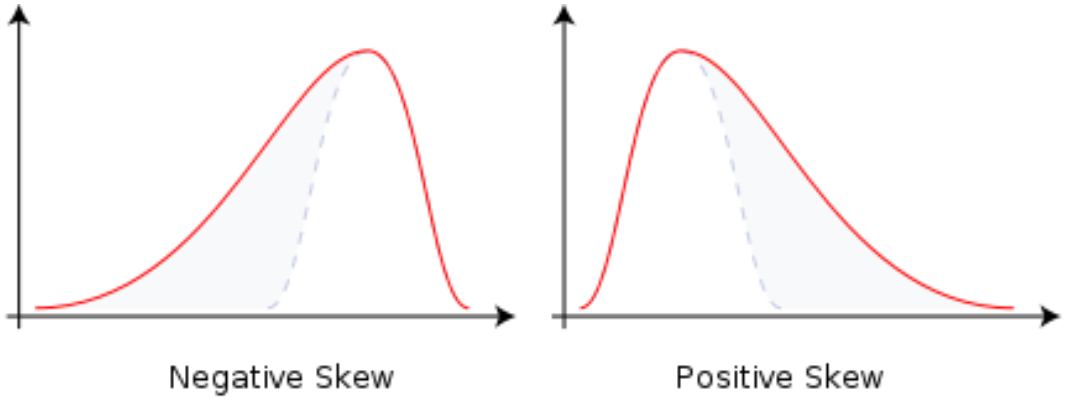
Good opportunities to search for CP !

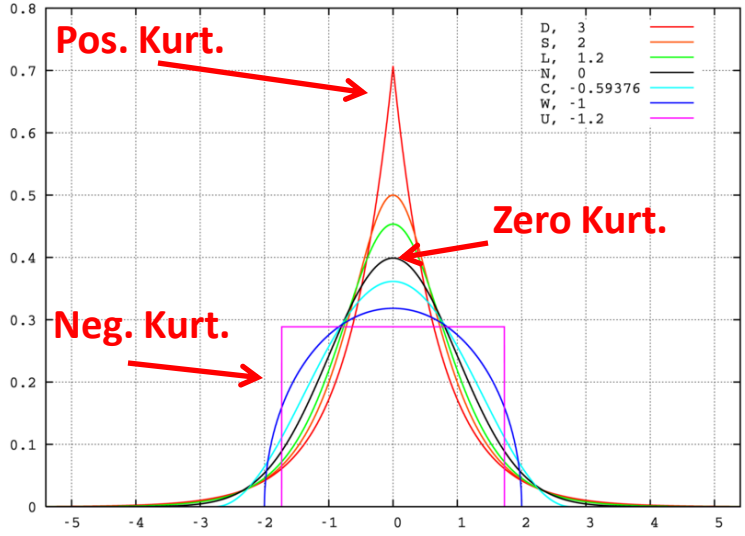
Higher Moments: Non-Gaussian Fluctuation Measure

Definition : N: Event by Event Multiplicity Distribution

Mean: $Y = < N >$ **St. Deviation:** $\sigma = \sqrt{< (N - < N >)^2 >}$

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





➢ **For Gaussian Distribution, the skewness and kurtosis are equal to zero. Ideal probe of the non-Gaussian fluctuation at CP.**

Theoretical Prediction of Higher Moments

(I): Link to Thermodynamics Susceptibilities in Hadron Resonance Gas (HRG) Model and Lattice QCD.

$$\chi_q^2 = \frac{1}{VT^3} < \delta N_q^2 >$$

$$\chi_q^3 = \frac{1}{VT^3} < \delta N_q^3 >$$

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

q=Conserved Quantities.
such as Charge, Baryon, Strangeness Number

$$(\kappa\sigma^2)_q = \chi_q^4 / \chi_q^2$$
$$(S\sigma)_q = \chi_q^3 / \chi_q^2$$

M.Cheng et al, arXiv: 0811.1006

F. Karsch and K. Redlich, arXiv:1007.2581

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

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

(II): Link to Correlation Length (ξ) :

Due to Finite size effects , Finite time and Critical slowing down effects, ξ~2-3 fm.

QCD Based Model:

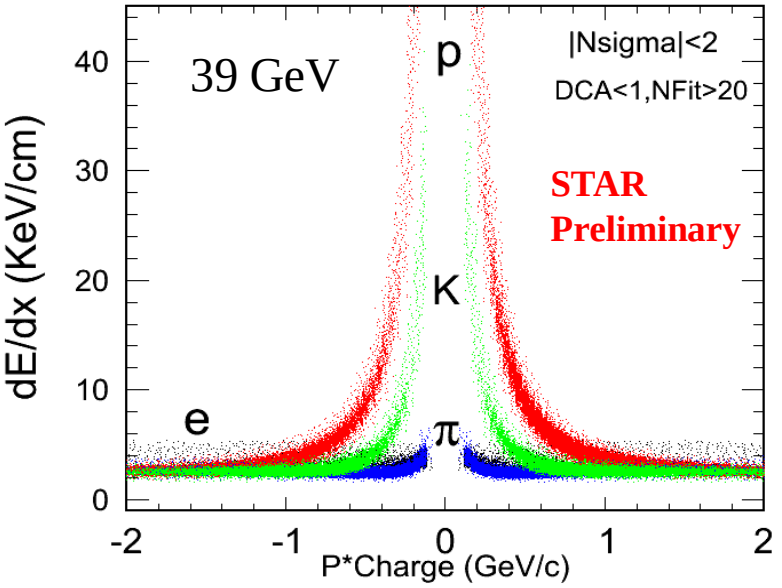
$$< (\delta N)^2 > \approx \xi^2, < (\delta N)^3 > \approx \xi^{4.5}$$

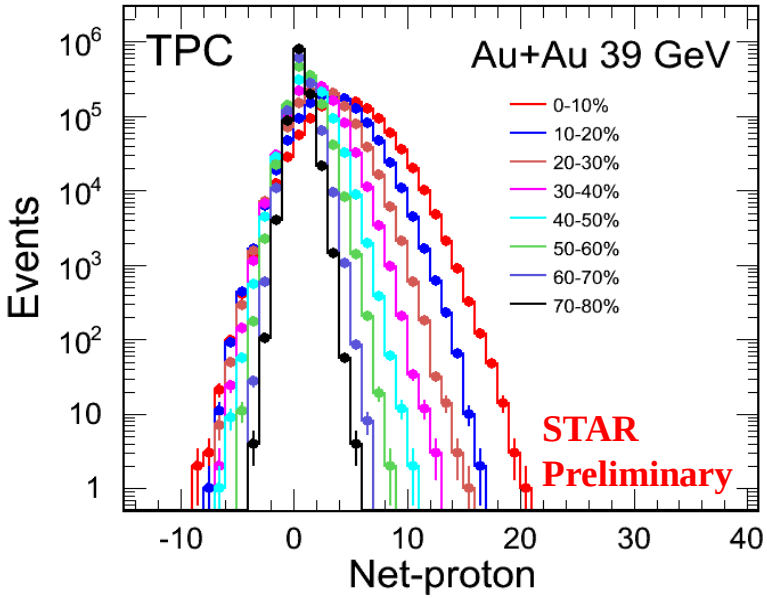
$$< (\delta N)^4 > -3 < (\delta N)^2 >^2 \approx \xi^7$$

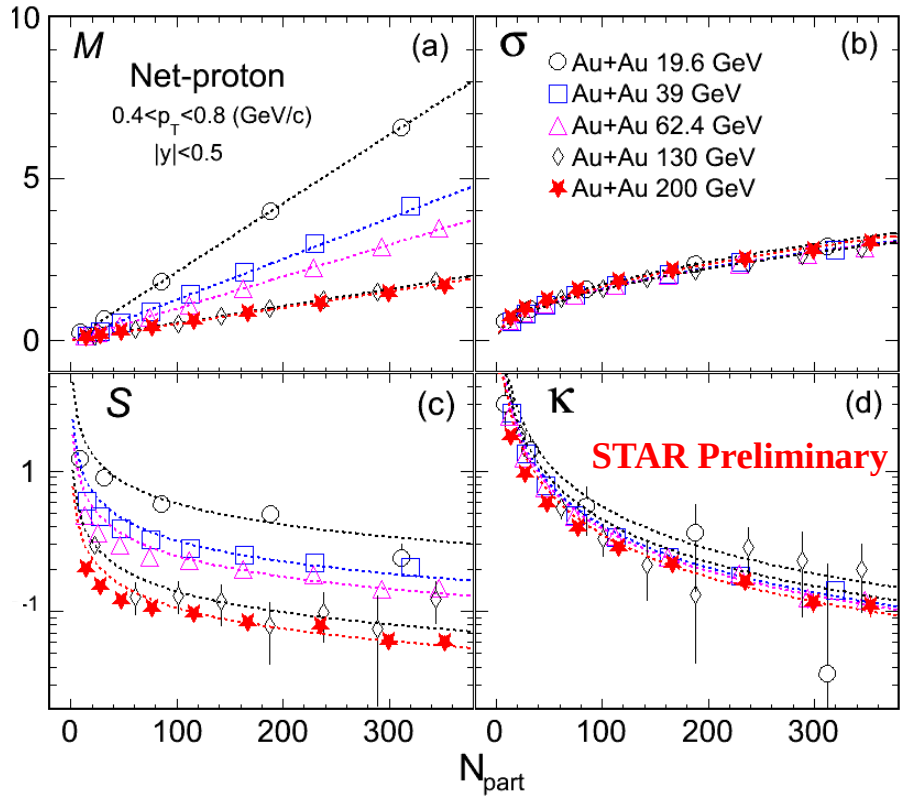
Higher Order Moments with Higher Sensitivity.

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
C. Athanasiou,M. Stephanov, K. Rajagopal, Phys. Rev. D 82, 074008 (2010)

Higher Moments of Net-proton Distributions



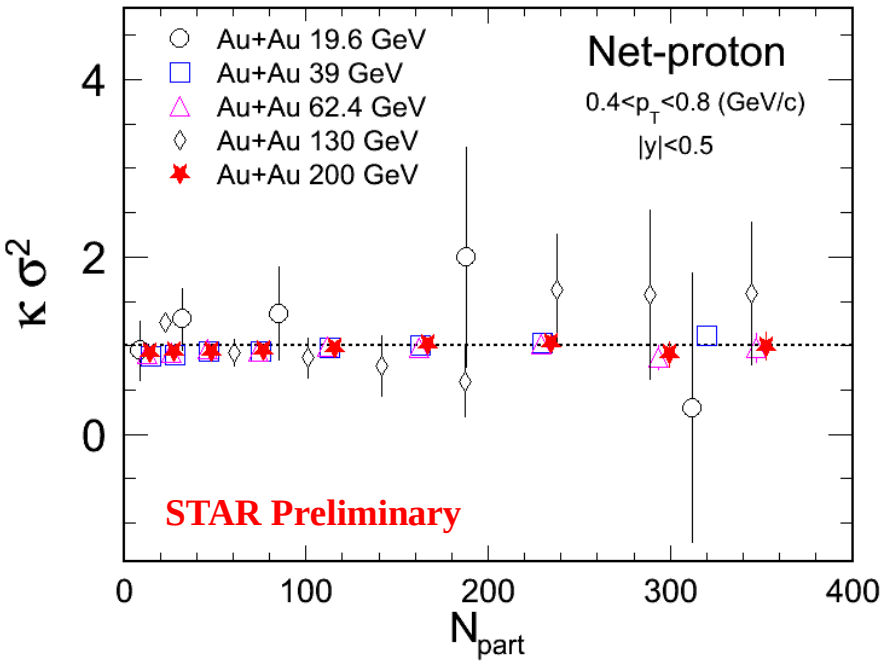


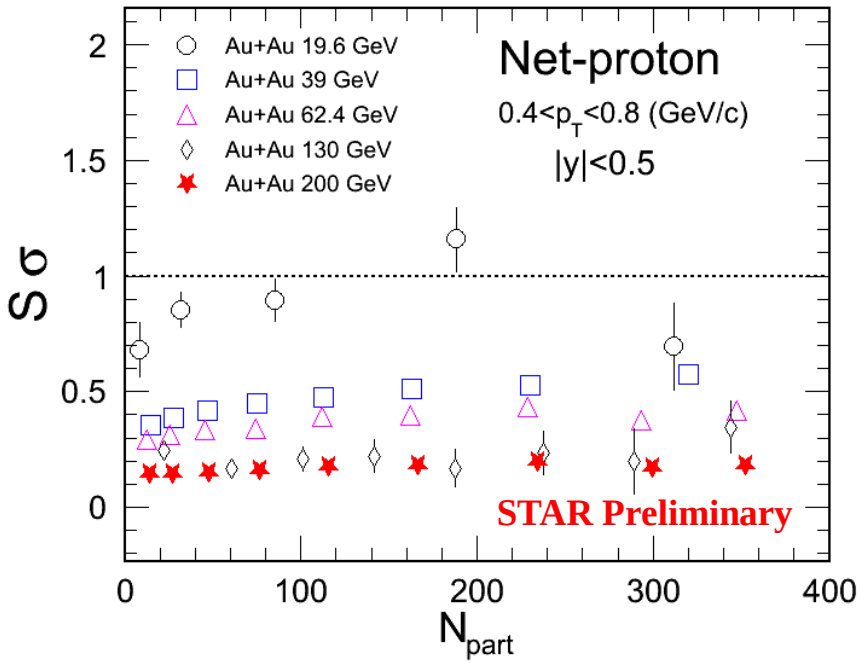


STAR: PRL 105 (2010) 022302

- **TPC dE/dx: Clean Proton and Anti-proton Identification at 0.4<pT<0.8 (GeV/c),|y|<0.5.**
- **Various moments of net-proton distributions vary with number of participants.**

Moments Product of Net-proton Distributions

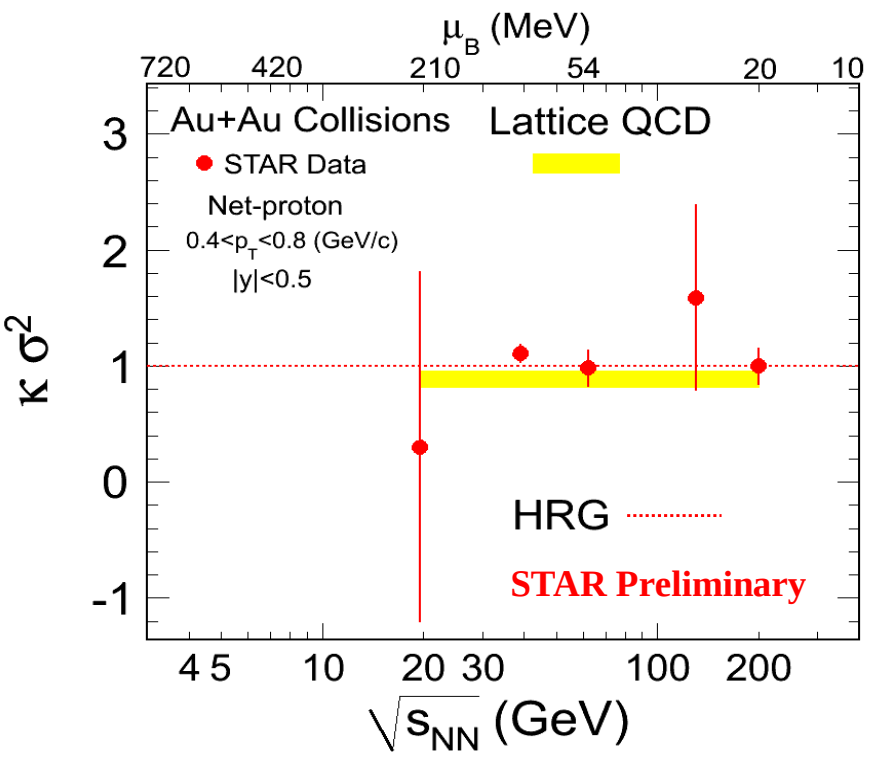




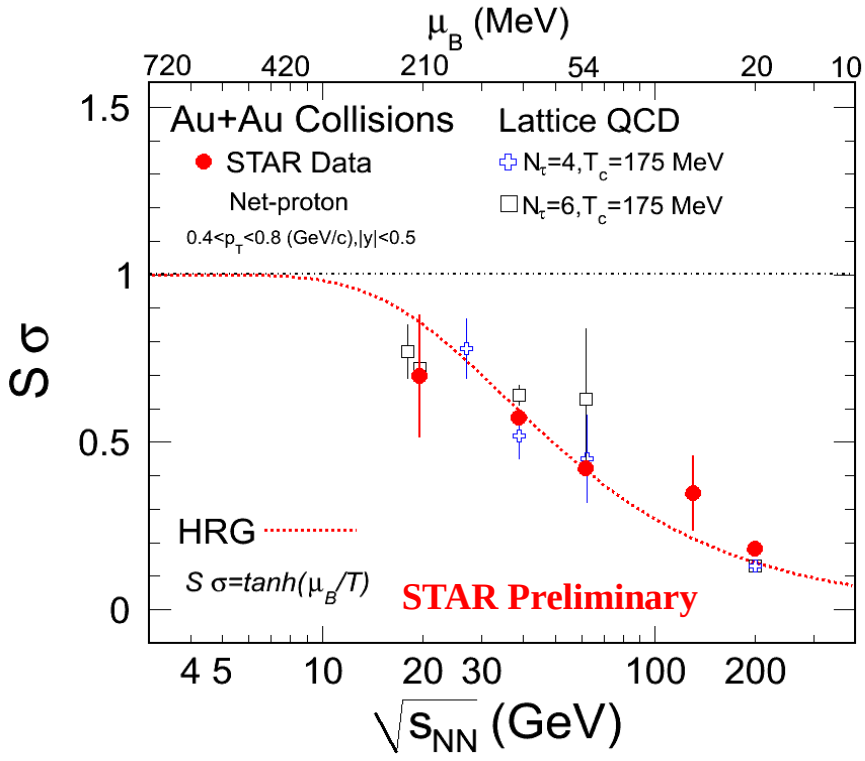
- Moment products of net-proton distribution are directly related to the baryon number susceptibility ratio and sensitive to the correlations length.

- Kurtosis*Variance: No energy dependence and small system size dependence.
  Skewness*Sigma: With energy dependence and small system size dependence.

Excitation Function of Sσ and κσ² for Central Net-proton Distributions



$$\mathrm{HRG}: \kappa_B \sigma_B^{\,2} = \frac{\chi_B^{(4)}}{\chi_B^{(2)}} = 1$$



$$\mathrm{HRG}: S_B \sigma_B = \frac{\chi_B^{(3)}}{\chi_B^{(2)}} = \tanh\left[\frac{\mu_B}{T}(\sqrt{s})\right] < 1$$

- **Currently, the STAR Au+Au high energy data are agreement with Lattice QCD and HRG model. Analysis is on going for √s=11.5 and 7.7 GeV.**

F. Karsch and K. Redlich, arXiv:1007.2581
R. Gavai & S. Gupta arXiv:1001.3796

Summary

- **Higher moments of net-proton distributions are sensitive to QCD critical point related non-Gaussian fluctuations and correlation length.**

- **Higher moments and moment products of net-proton distributions are presented for STAR Au+Au data with colliding energy down to $\sqrt{s}$=19.6 GeV.**

- **Moment products of $S\sigma$ and $\kappa\sigma^2$ for Net-proton distributions are found to be consistent with Lattice QCD and HRG model for high energy data. Looking for non-monotonic signature for CP at lower energy ($\sqrt{s}$=11.5 , 7.7 GeV…) .**