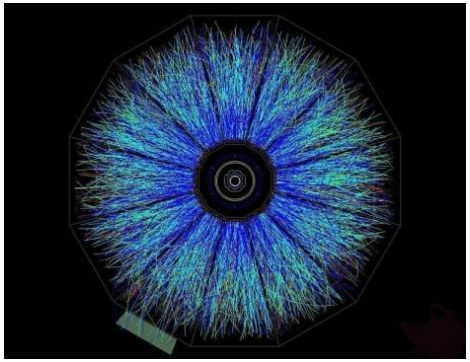
Higher Moments of Net-proton Multiplicity Distributions at RHIC



Xiaofeng Luo

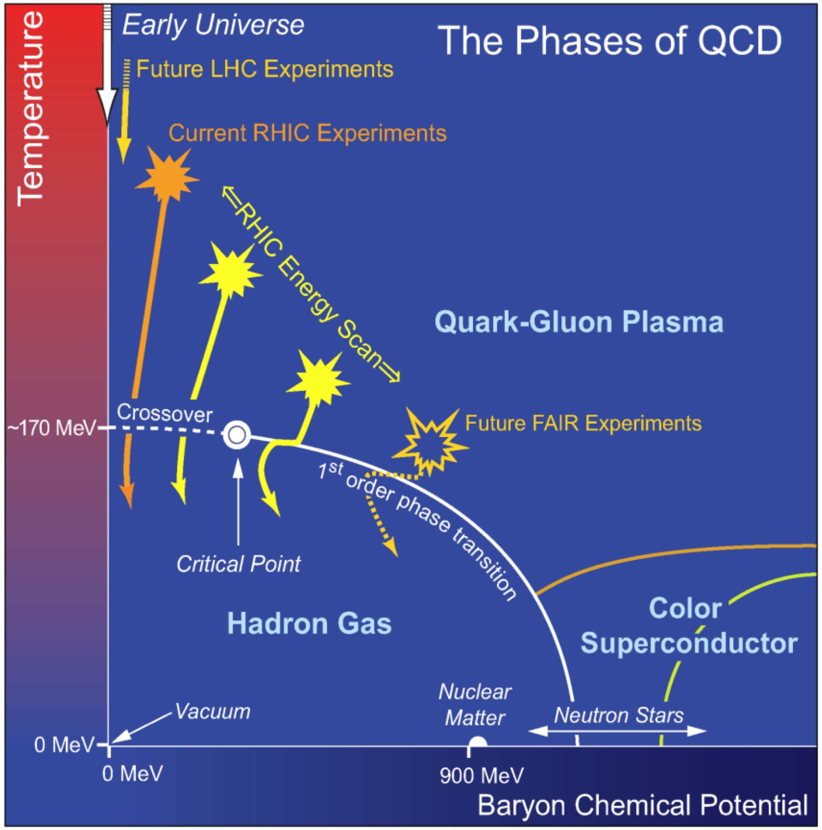
for the STAR Collaboration

Institute of Particle Physics, Central China Normal University
University of Science and Technology of China

7/18/2011

QCD Phase Diagram

Shows condition at which thermodynamically distinct phases can occur at equilibrium.



Lattice QCD:

- Crossover at $\mu_B = 0$, 1st order phase transition at large μ_B .
- QCD Citical Point: The end point of first order phase transition boundary.

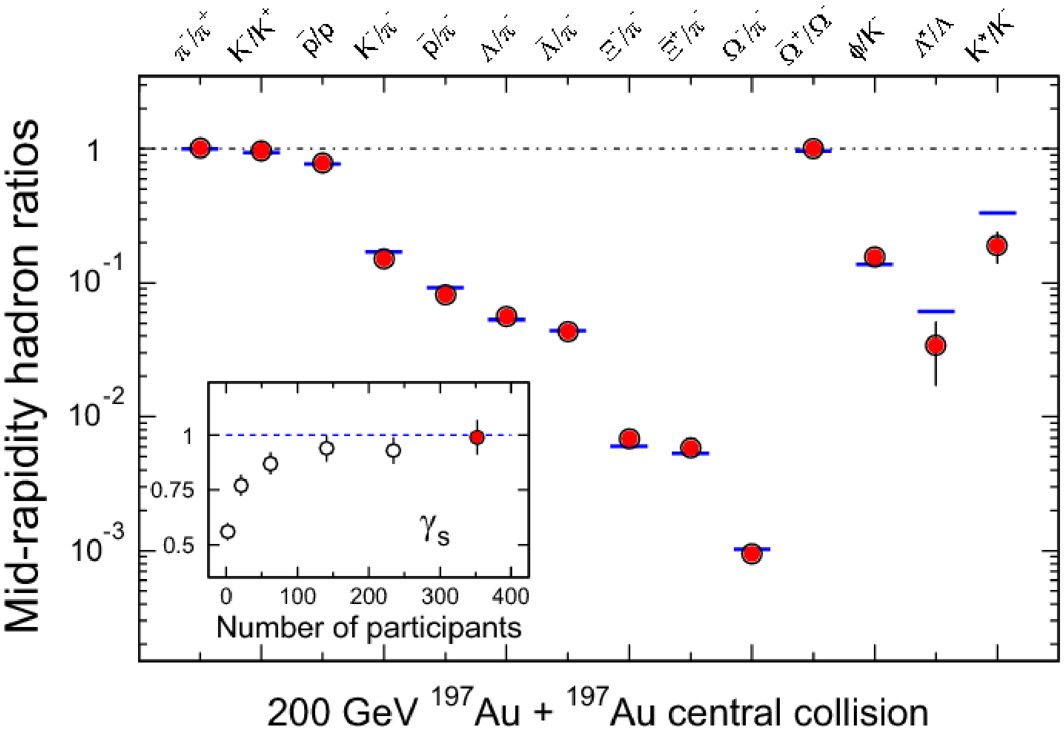
Y. Aoki et al., Nature 443:675-678, 2006

Motivations:

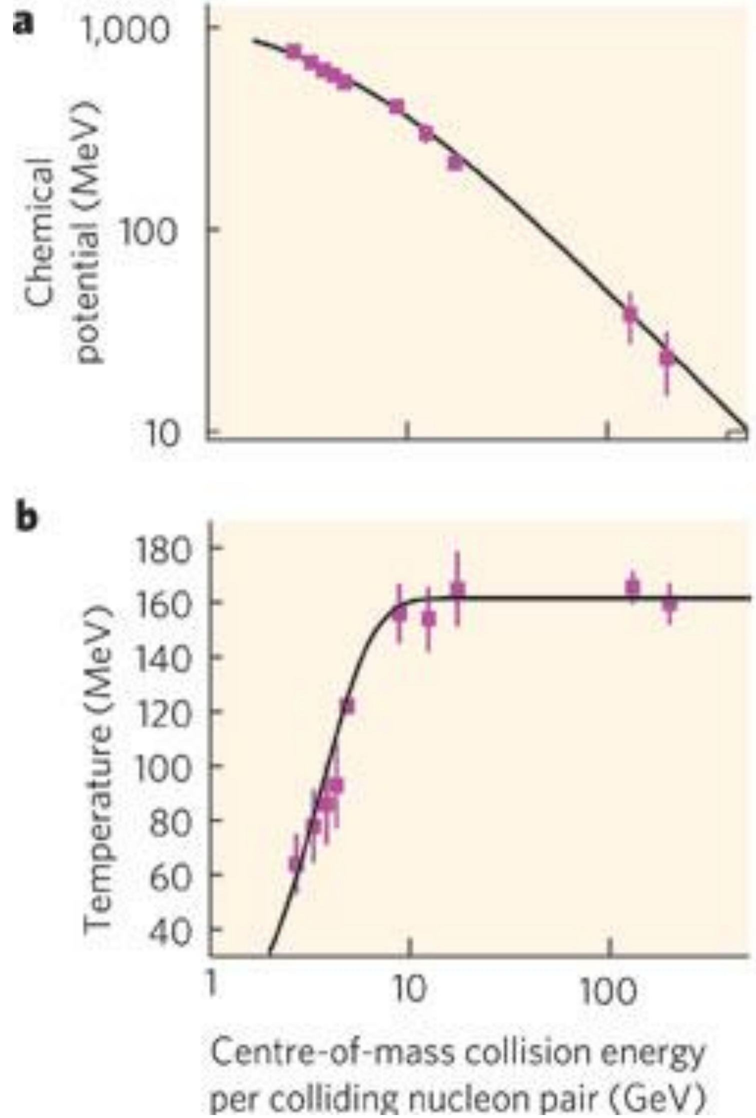
- Map the QCD Phase Boundary.
- Search for the QCD Critical Point.

Statistical Particle Production

➢ Particle ratio fit with Thermal Model: Chemical freeze out temperature (T) and baryon chemical potential (μ_B). Nucl. Phys. A757,102 (2005);



Nature 448:302-309 (2007)

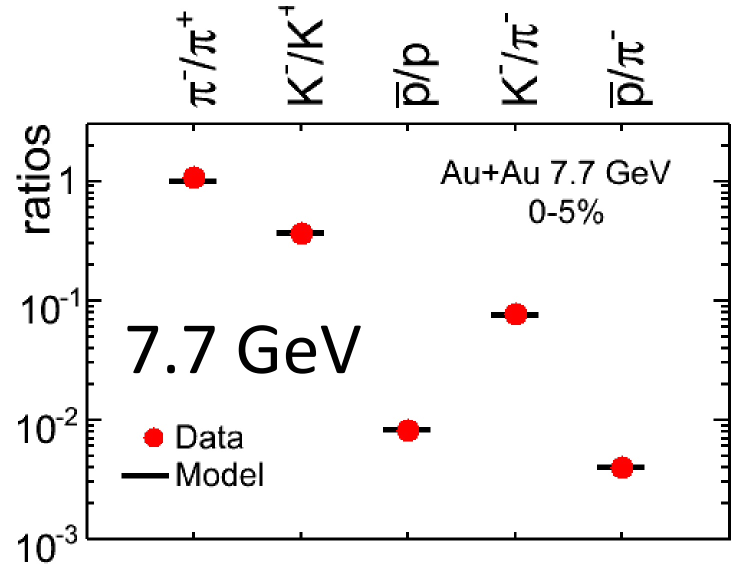


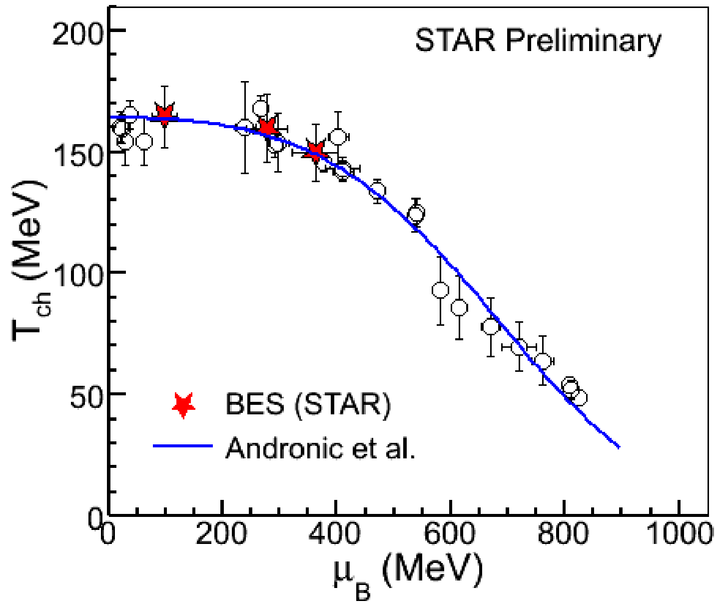
➢ Varying the colliding energy, we can access different regions (T, μ_B) on the QCD phase diagram.

Access the QCD Phase Diagram

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

$\sqrt{s_{NN}}$ (GeV)	Good events in Million MB
5.0	?
7.7	~ 5
11.5	~ 11
19.6	~ 17
27	~ 33
39	~ 170





- **STAR Detector : Large Uniform Acceptance. Ideal detector to perform fluctuation and correlation measurements.**

Good opportunities to search for the QCD critical point !

QM2011 talk: Lokesh

Locating the QCD Critical Point

Theoretical Calculations:

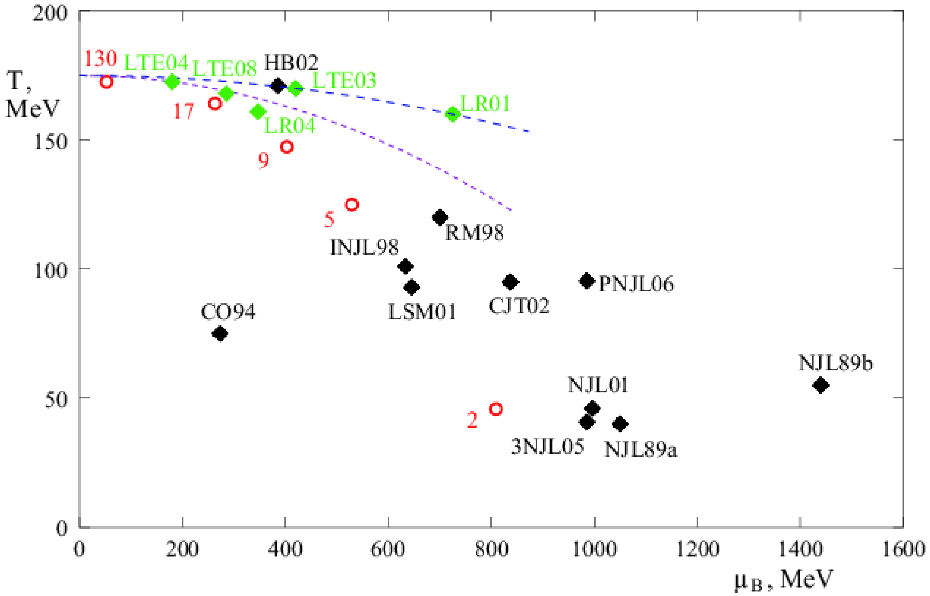
- Lattice QCD.
- QCD Based Models.

Vs

Experimental measurements

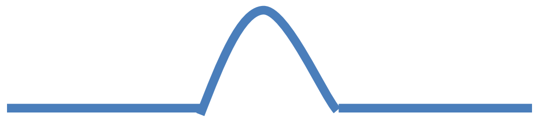
- **Access the QCD Phase Diagram.**
- **Find Sensitive Observable.**

Large uncertainties of theoretical calculation.



Signatures of QCD Critical Point:

- **Diverge of the Correlation length (ξ)**
- **Non-Gaussian fluctuations.**



Non-monotonic signal expected around QCD Critical Point.

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

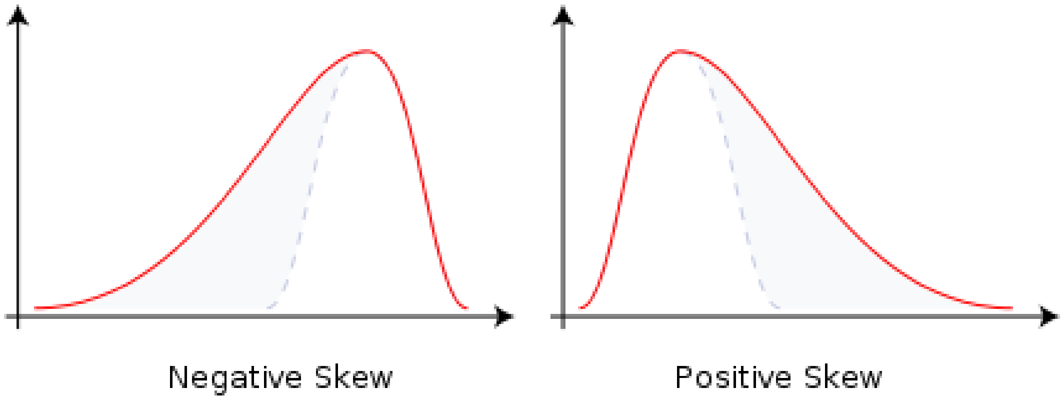
M. Stephanov, PoSLAT2006:024,2006 (hep-lat/0701002)
Z. Fodor, S. D. Katz, hep-lat/0106002, het-lat/0401023. hep-lat/0402006.
R. V. Gavai and S. Gupta, Phys. Rev. D 78, 114503 (2008).

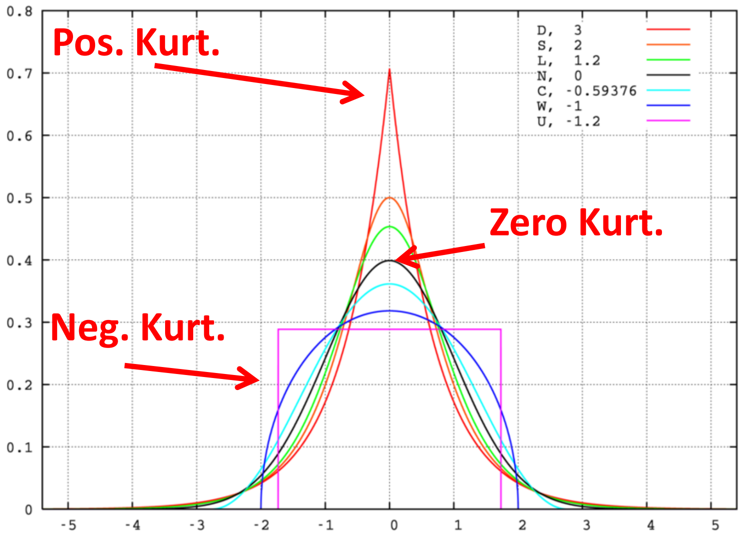
Higher Moments: Non-Gaussian Fluctuation Measure

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

Mean: $M = < N >$ **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 fluctuations at CP.**

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

Experimental measurable 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.

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

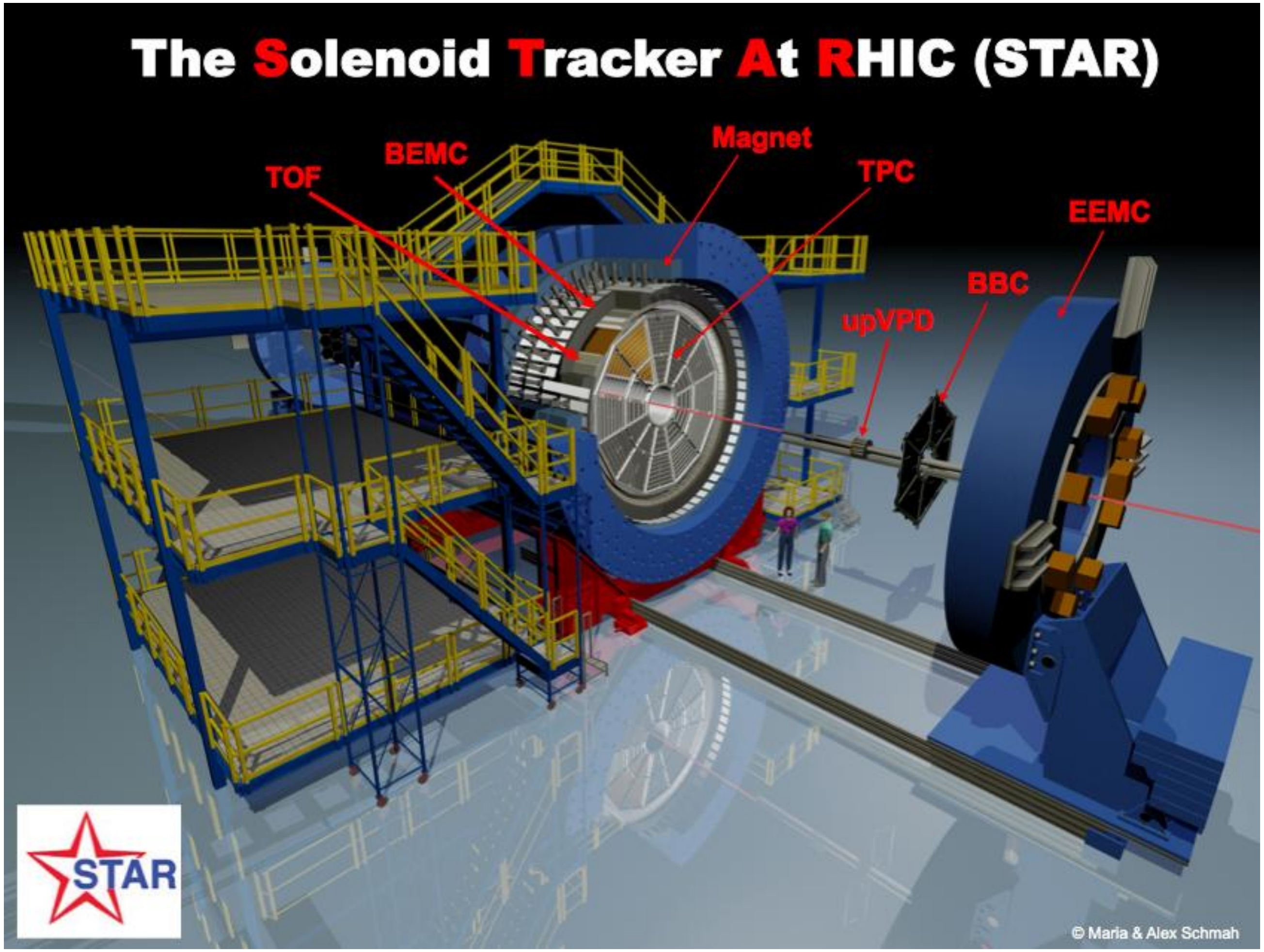
$$< (\delta N)^3 > \approx \xi^{4.5}$$

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

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

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

STAR Detector-3D Picture



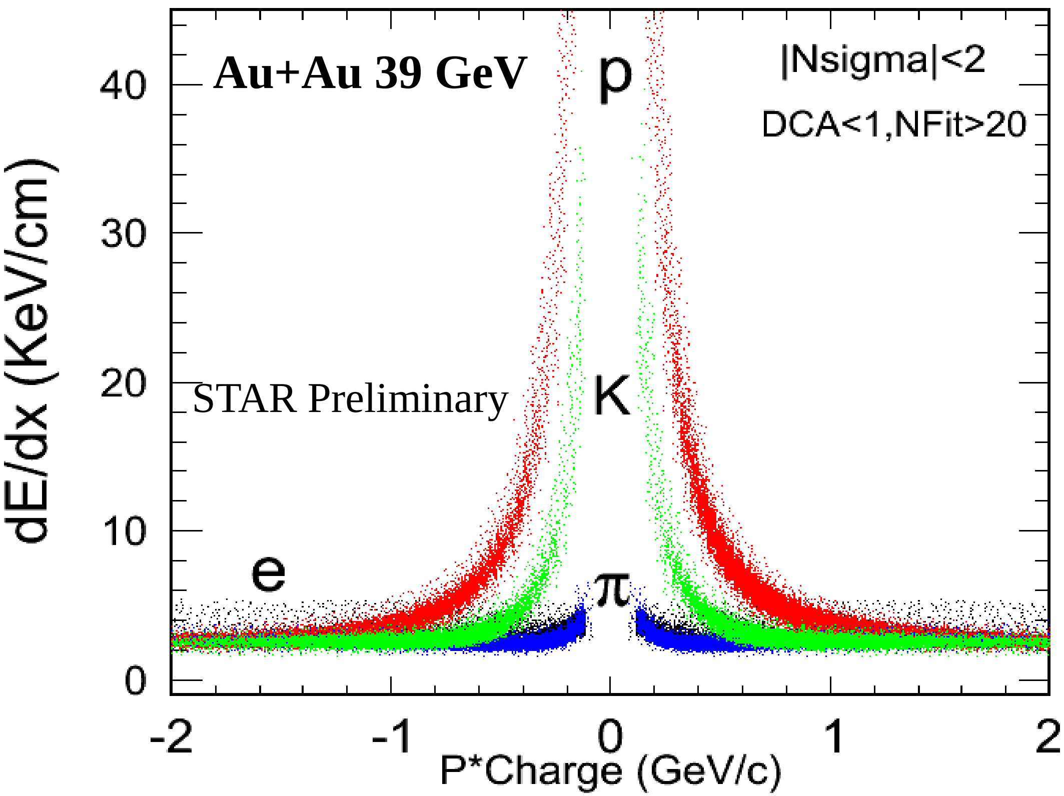
Time Projection Chamber:

- 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

Time Of Flight: (Full install in Run 10)

- Acceptance: $-0.9<\eta<0.9$, $0<\varphi<2\pi$
- Timing Resolution < 100ps.
- PID: (π, K): $p_T < 1.6$, proton: $p_T < 3$ GeV/c

Particle Identification with TPC dE/dx



- **Track Quality Cut:**

  Nfits>20,
  Nfits/NFitPoss>0.52.
  Dca<1 cm.

- **PID Cut: dE/dx**

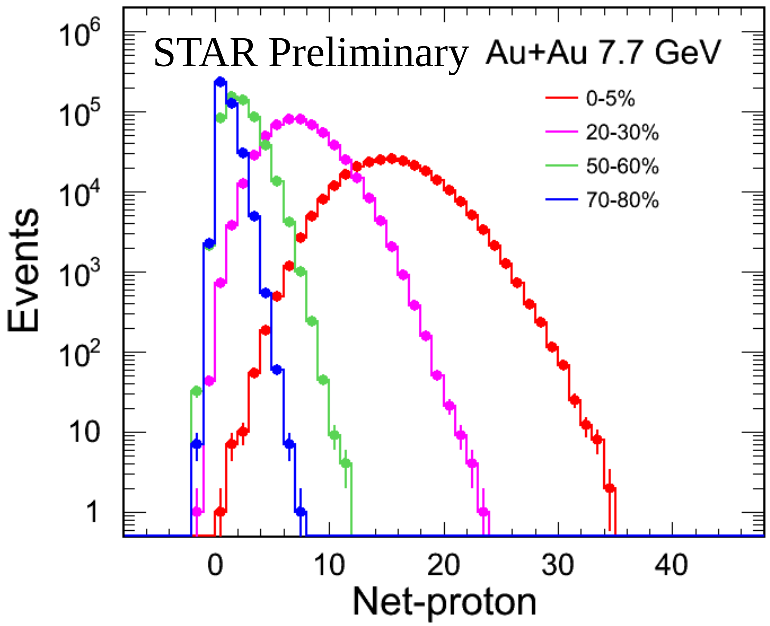
  $|Z_p|<2$

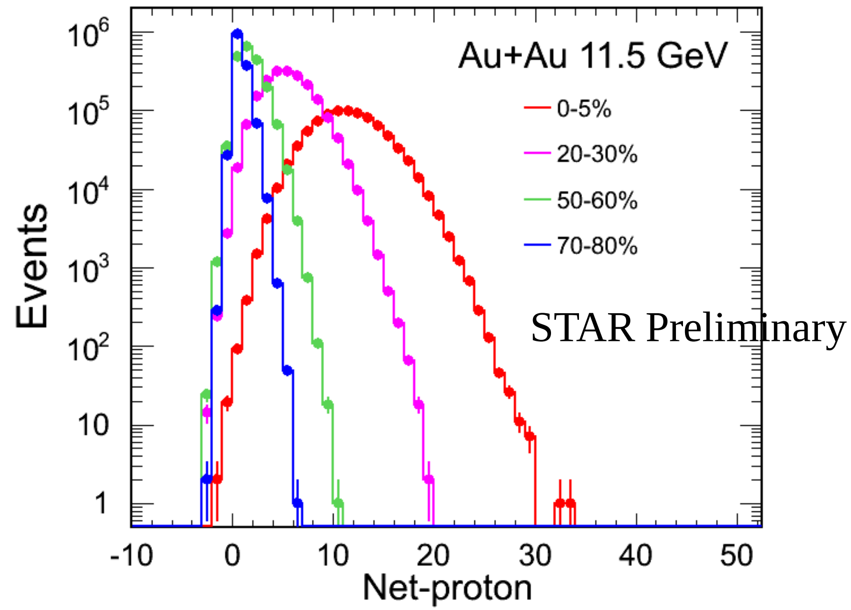
$$Z = \frac{\log[(dE/dx)|_{measure} / (dE/dx)|_{theory}]}{\sigma_E}$$

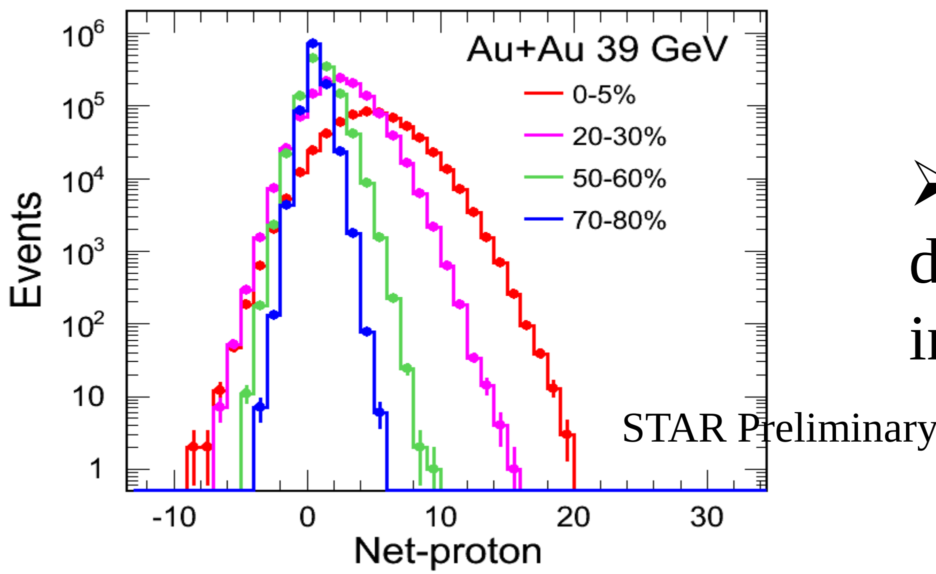
Within $0.4 < p_T < 0.8$ (GeV/c) and $|y|<0.5$:

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

Event-by Event Net-proton Multiplicity Distributions

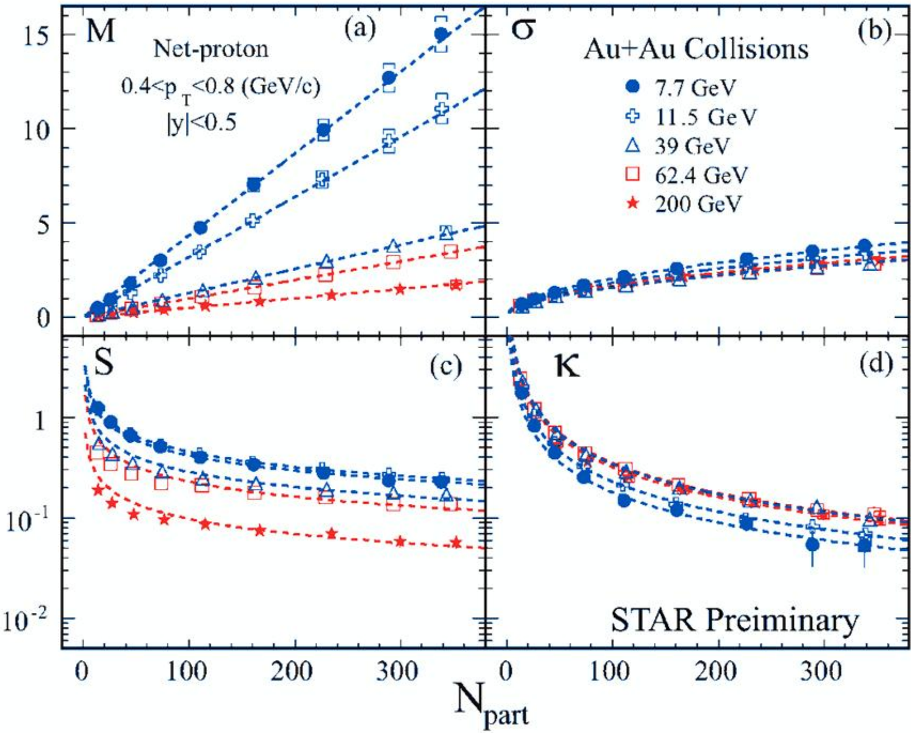


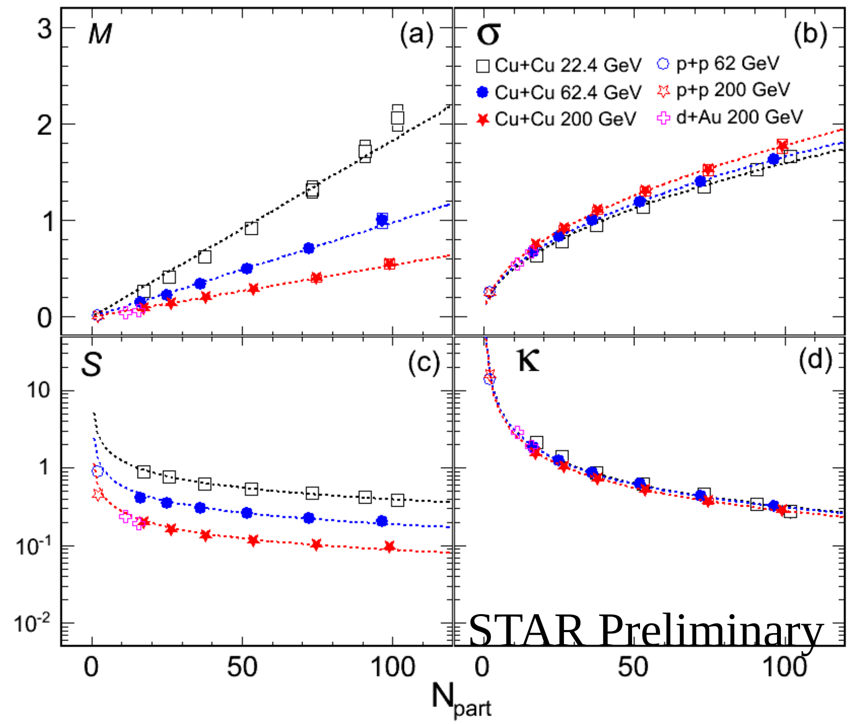




➢ The event-by-event net-proton distributions are more symmetrical in central collision than peripheral.

Centrality Dependence (I): Higher Moments





Central Limit Theorem (CLT)

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

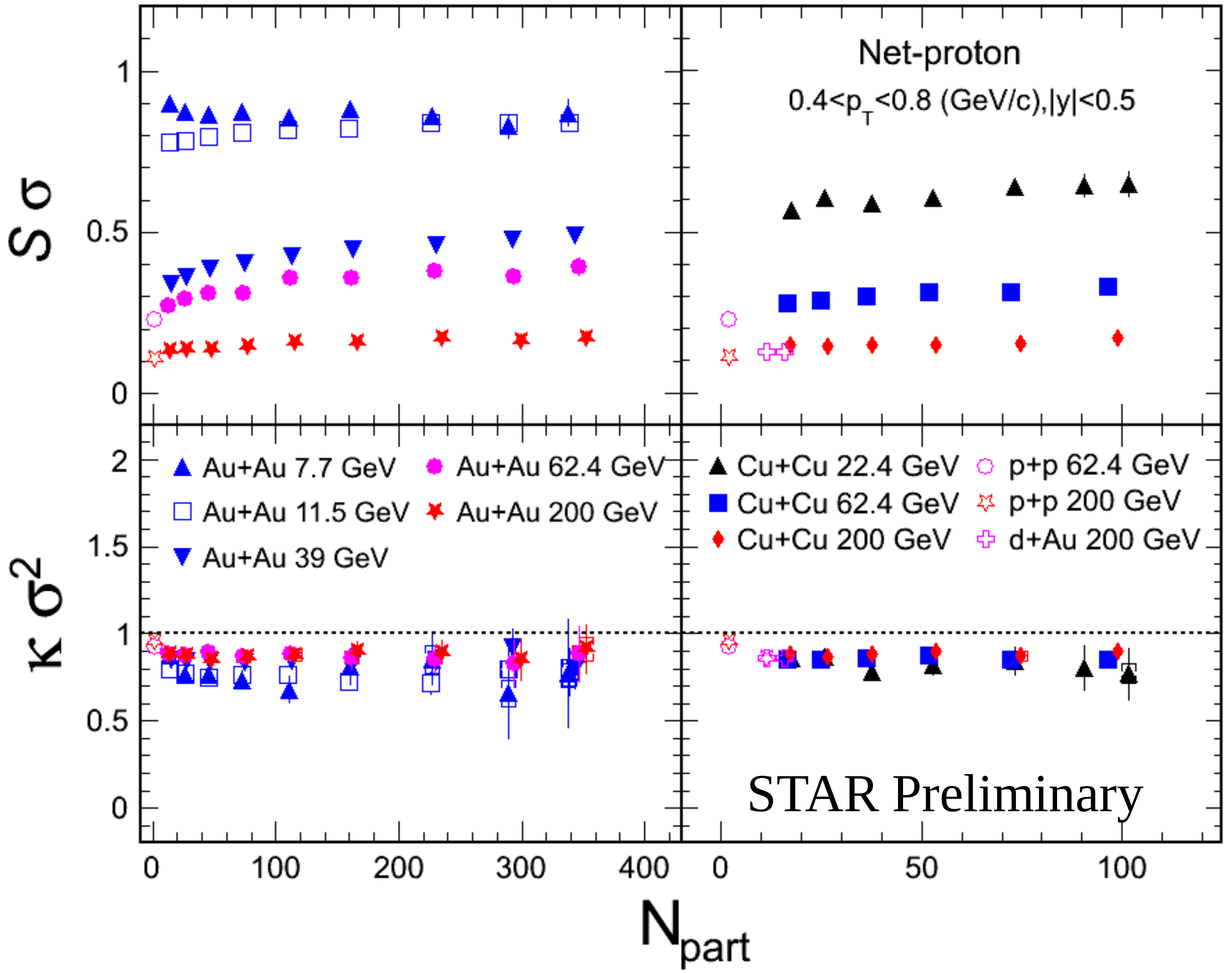
$$S_i = S_x \Big/ \sqrt{C \times N_{part}}, \kappa_i = \kappa_x \Big/ (C \times N_{part})$$

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

Consistent with CLT Expectations (lines).

Indicates many identical, independent particle emission sources.

Centrality Dependence (II): Moment Products



Related to baryon number susceptibility ratio:

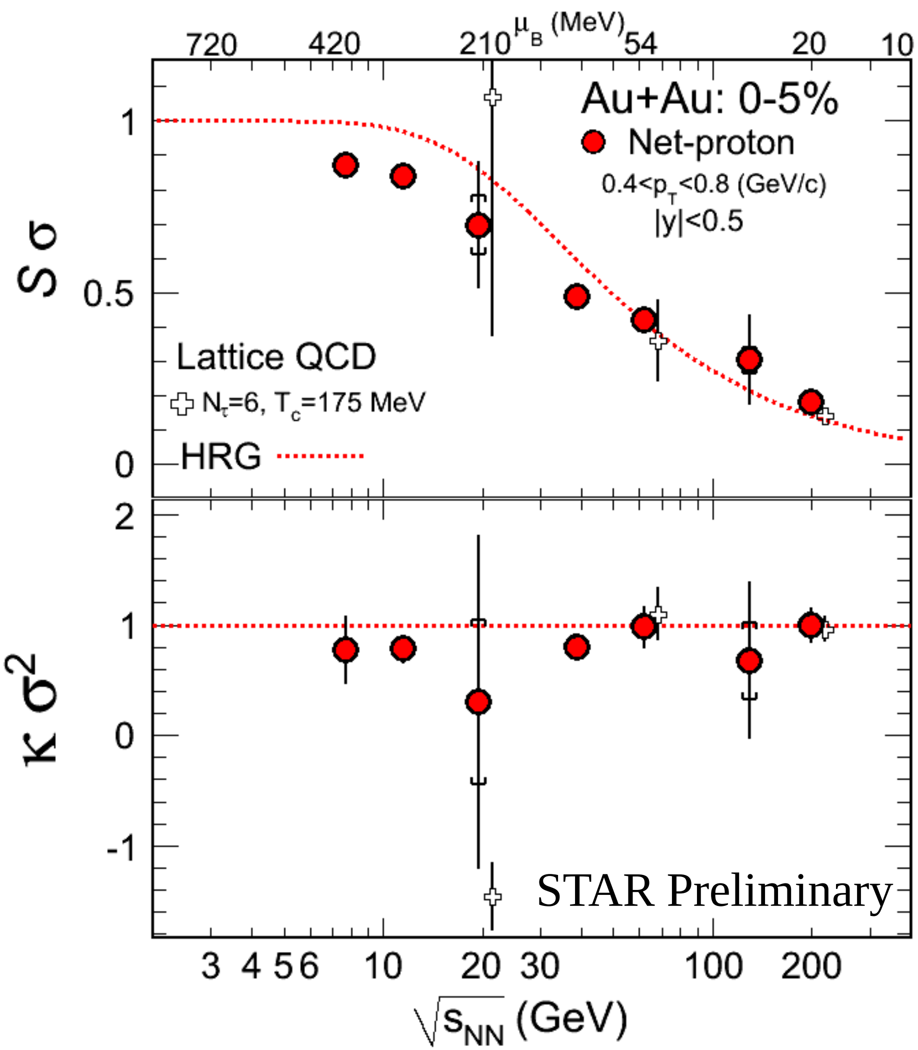
$$(S\sigma)_B = \chi_B^3 / \chi_B^2$$
$$(\kappa\sigma^2)_B = \chi_B^4 / \chi_B^2$$

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

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

- $S\sigma$: Weak centrality dependence.
- $\kappa\sigma^2$: No centrality dependence.

Search for the QCD Critical Point



R. Gavai and S. Gupta, Phys. Lett. B 696, 459 (2011)
F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)
B. Mohanty, QM 2011 talk , X. Luo QM2011 poster

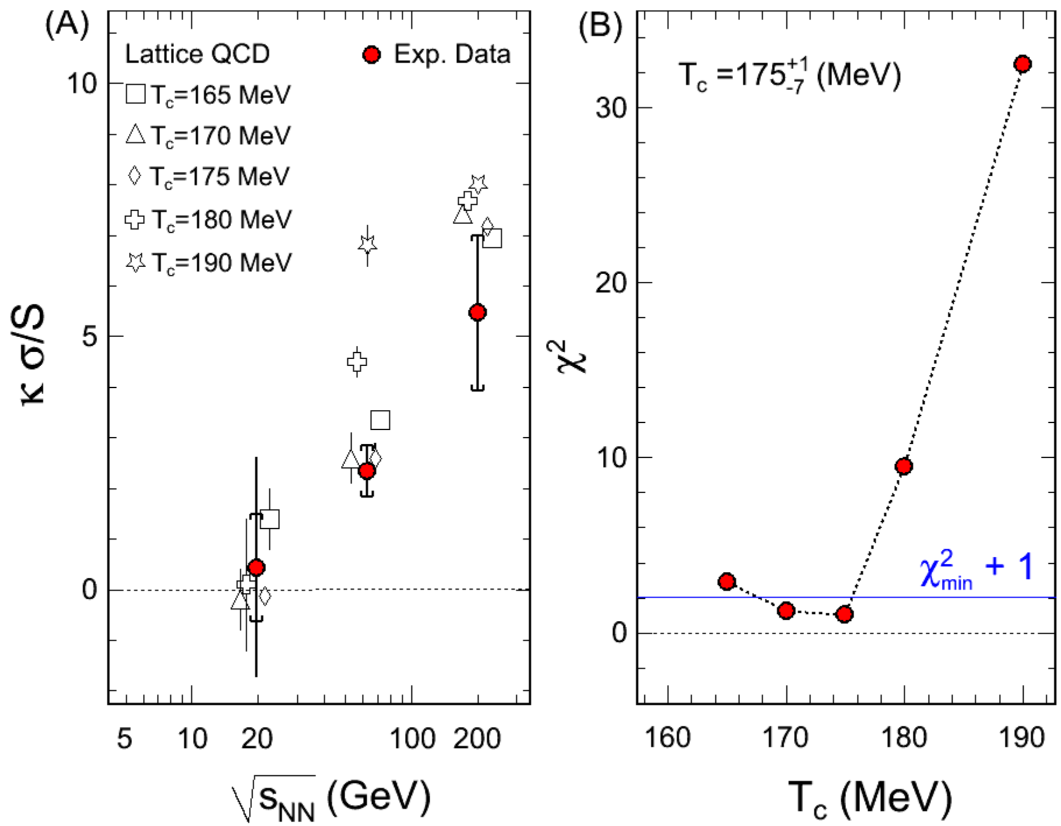
- Consistent with Lattice QCD and Hadron Resonance Gas (HRG) model at higher energies.
- Low energies (7.7, 11. 5, 19.6 and 39 GeV) deviate from HRG model.

Reasons are still not clear :

1. Linked to the chiral phase transition and QCD critical point ?
2. Non-applicable of Grand Canonical Ensemble at low energy ?

B. Friman et al., arXiv:1103.3511
M. A. Stephanov, arXiv:1104.1627

Determining the Scale (T_c) for QCD Phase Diagram



- For the first time, direct comparison between experimental data with Lattice QCD.
- Open an new domain for probing bulk properties of nuclear matter.
- This temperature sets a scale of QCD phase diagram. We conclude that the phase transition tempeartue T_c at μ_B=0 is **175 (+1) (-7) MeV**

$$\kappa\ \sigma\ /S = \chi_B^{(4)} / \chi_B^{(3)}$$

S. Gupta, X. Luo，
B. Mohanty, H. G. Ritter, N. Xu.
Science 332,1525 (2011)

Science
AAAS

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 and testing the non-perturbative QCD.

- First time, the higher moments of net-proton distributions are used to search for QCD critical point. Deviations from HRG model are observed at low energies.

- First time, transition temperature T_c at μ_B=0 is determined by comparing the experimental higher moments results with Lattice QCD results. We conclude that T_c =175 (+1) (-7) MeV.

Outlook: 19.6 and 27 GeV high statistic data have been taken this year. New results will come soon.