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

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Outline

- **Introduction:**
  1) QCD Phase Diagram.
  2) Higher Moments Method.
  3) Baseline Studies.

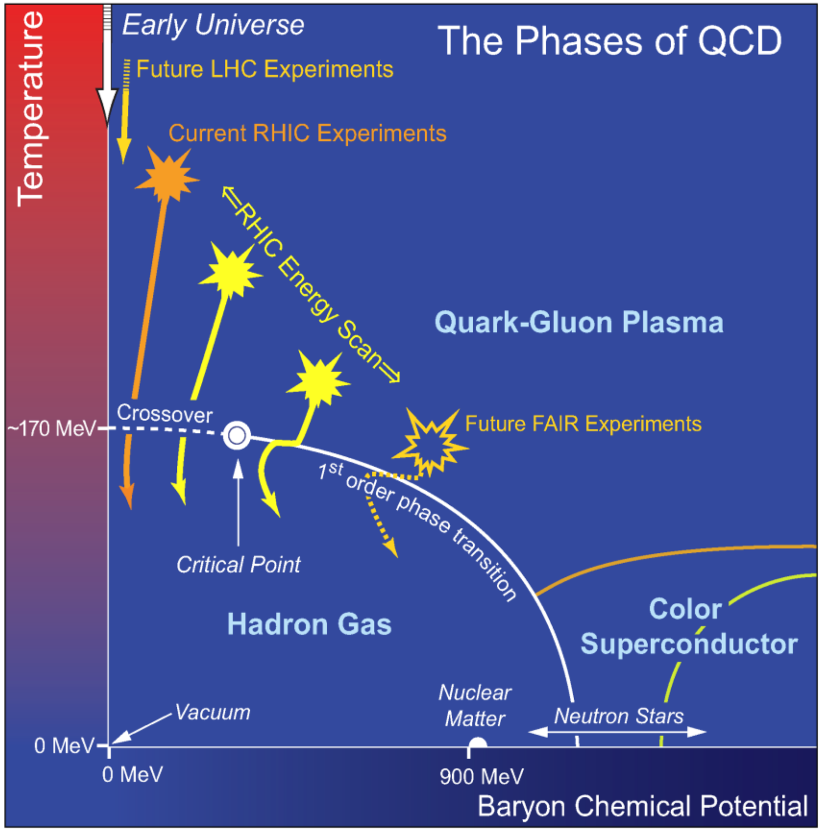
- **Data Analysis:**
  1) System: p+p, d+Au, Cu+Cu and Au+Au.
     Energy: 19.6, 22.4, 39, 62.4 and 200 GeV.
  2) Centrality Dependence.
  3) Energy Dependence.

- **Comparison with Lattice QCD and Thermal Model.**

- **Summary and Outlook.**

QCD Phase Diagram

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



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 443:675-678, 2006

Exploring the phase structure.

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

Where is the QCD Critical Point?

Theoretical Calculations:

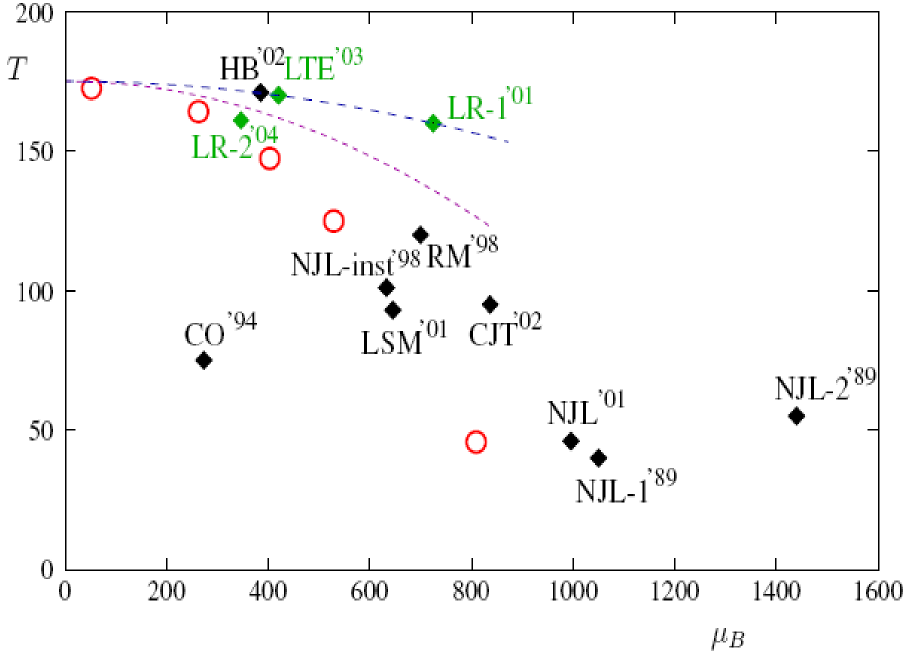
- Lattice QCD
- QCD Based Models

Vs

Experimental measurements

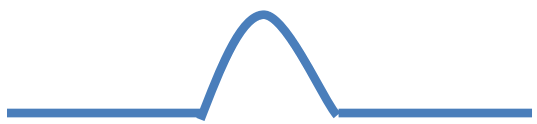
- **Sensitive Observable.**

Large uncertainties of theoretical calculation.



Approach to QCD Critical Point (CP):

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



Non-monotonic signal expected around CP.

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

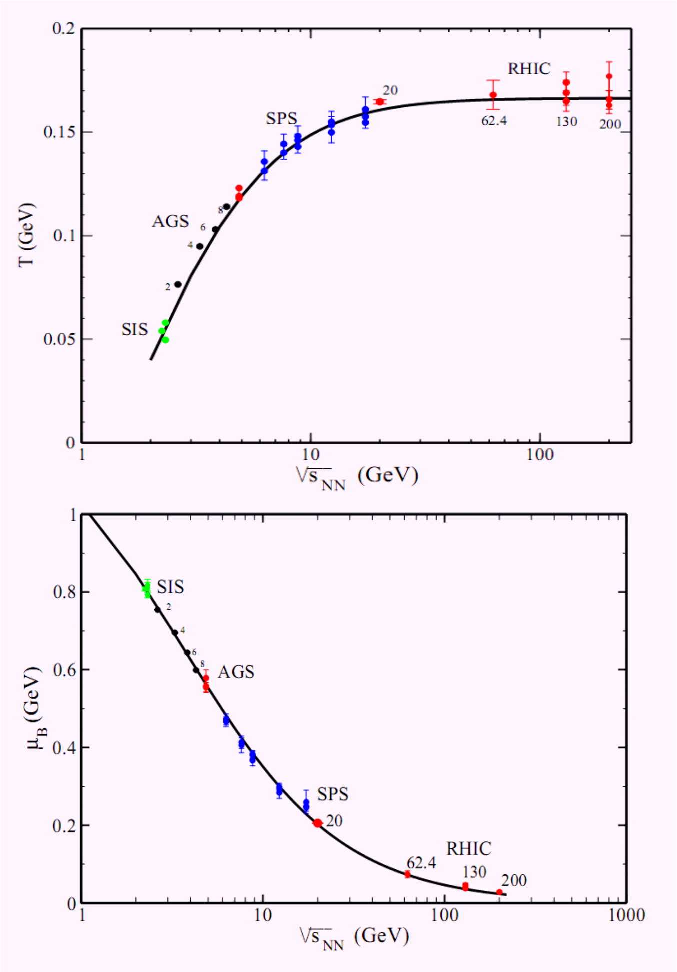
M. Stephanov, Acta Phys.Polon.B35:2939-2962,2004
PoSLAT2006:024,2006 (hep-lat/0701002)

Z. Fodor, S. D. Katz, hep-lat/0106002, het-lat/0401023.
hep-lat/0402006.

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 regions (T, μ_B) on the QCD phase diagram.

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

Year	$\sqrt{s_{NN}}$ (GeV)
2010	**7.7, 11.5, 39, 62.4, 200** **(μ_B Coverage : 20~420 MeV)**
2011	5 (Test Run) , 18, 27, 200

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

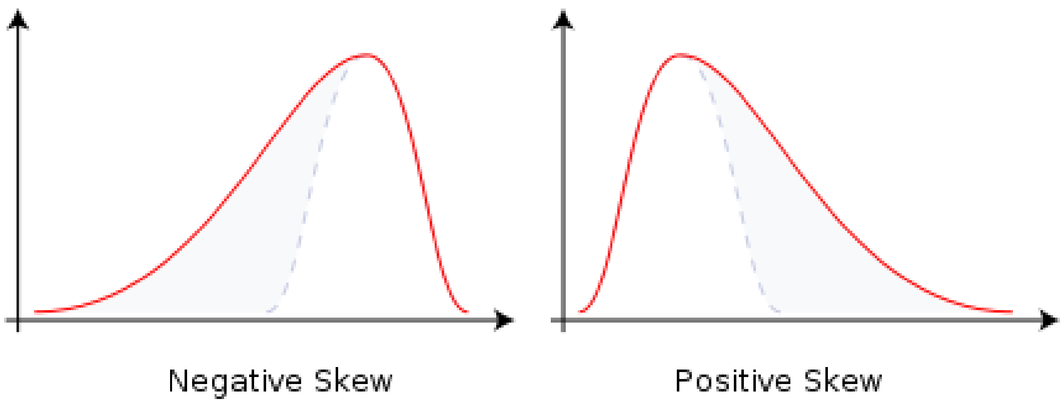
Good opportunities to search for CP !

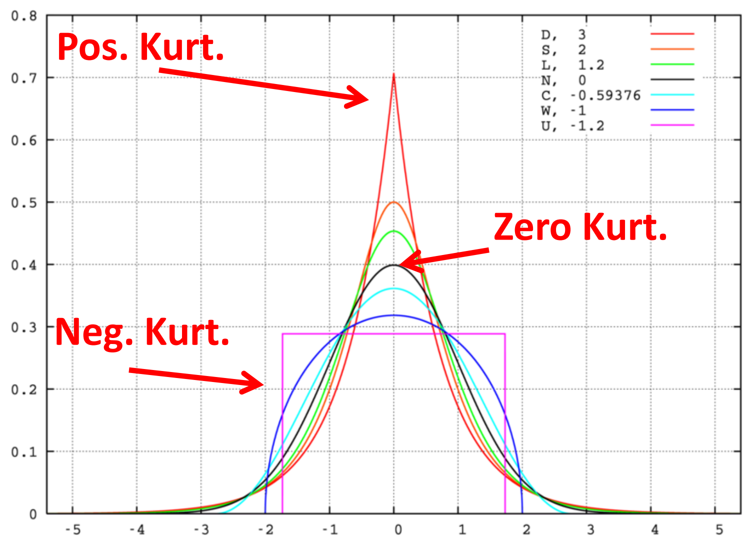
Higher Moments: Non-Gaussian Fluctuation Measure

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 fluctuations at CP.**

Importance of the 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)

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

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

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

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

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

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) : QCD Based Model Calculation.**

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)

Baseline (I): Thermal Fluctuations

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

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

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

Consider the net-proton fluctuations reflect the net-baryon fluctuations.

$$\kappa\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}} = 1$$

$$S\sigma = \frac{\chi_B^{(3)}}{\chi_B^{(2)}} = \tanh(\mu_B/T) < 1$$

$$\mu_S \ll \mu_B$$

$$\mu_Q \ll \mu_B$$

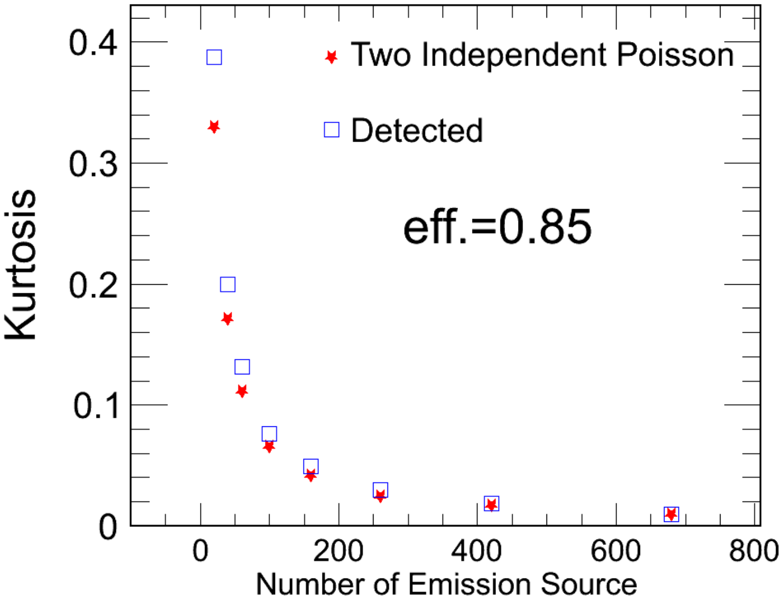
- **$\kappa\sigma^2$ is unity and $S\sigma$ is related to μ_B /T ratio of the thermal system.**

Baseline (II): Detector Efficiency Effect

- **Binomial Process of Detected Particles:** With the total produced multiplicity N and the detector efficiency ε.

$$B(n;N,\varepsilon)=\frac{N!}{n!(N-n)!}\varepsilon^{n}(1-\varepsilon)^{N-n} \Rightarrow T(k)=\sum_{N}B(k;N,\varepsilon)P(N)$$

- **Monto Carlo:** Input two Independent Poisson Distribution: $N=N_1-N_2$



$$\sigma_k^{\ 2}=\varepsilon\sigma_N^{\ 2}$$

$$S_k=\frac{S_N}{\sqrt{\varepsilon}}$$

$$K_k=\frac{K_N}{\varepsilon}$$

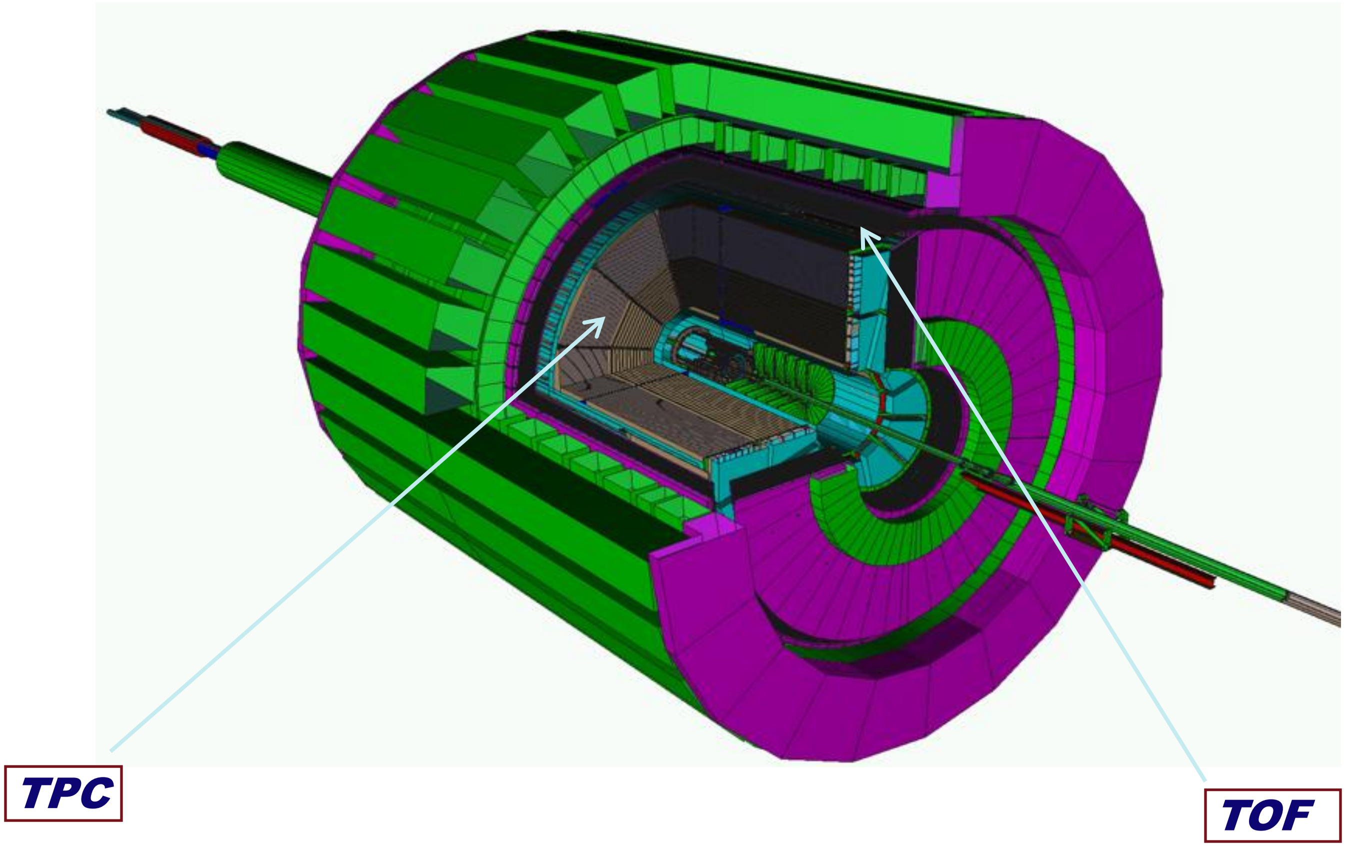
$$\Rightarrow$$

$$S_k\sigma_k=\frac{S_N}{\sqrt{\varepsilon}}*\sqrt{\varepsilon}\sigma_N=S_N\sigma_N$$

$$K_k\sigma_k^{\ 2}=\frac{K_N}{\varepsilon}*\varepsilon\sigma_N^{\ 2}=K_N\sigma_N^{\ 2}$$

- **For this case, the efficiency effects are simple and will be cancelled out for moment products.**

STAR Detector



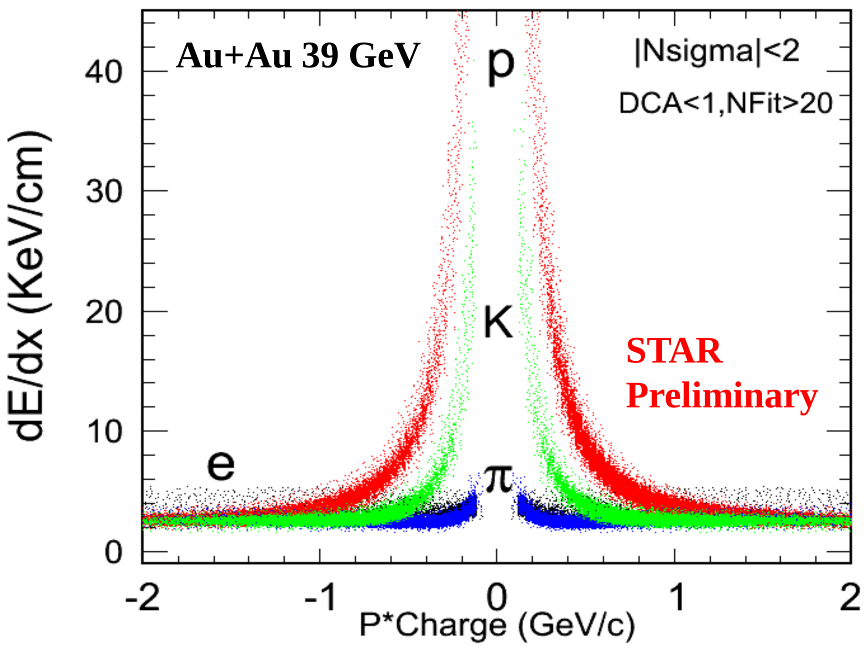
Time Projection Chamber:

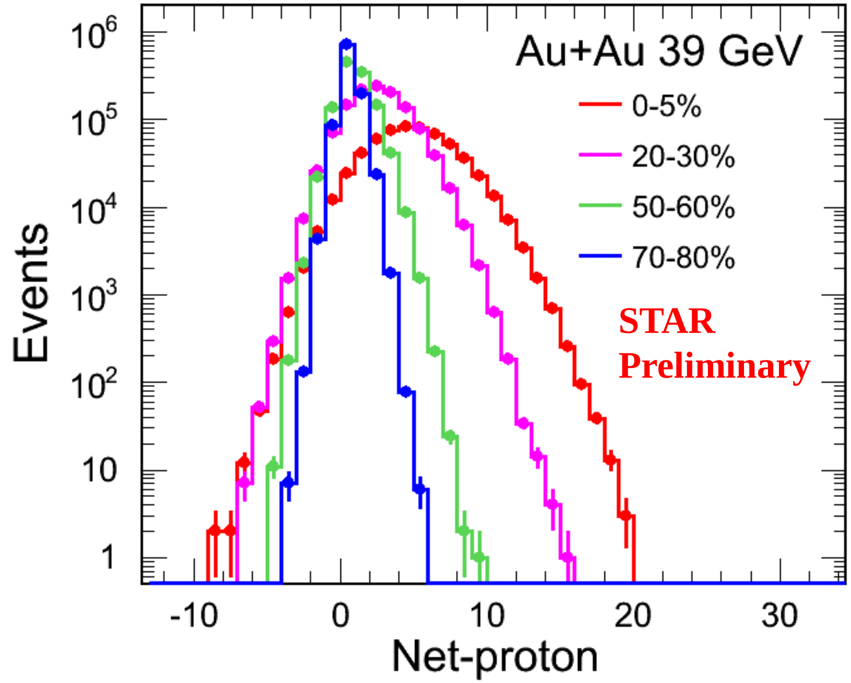
- Acceptance: $-1<\eta<1$, $0<\varphi<2\pi$
- Tracking: Particle momentum and trajectory.
- PID: Ionization Energy Loss (dE/dx).
  (π, K) : $p_T < 0.7$, proton : $p_T < 1$ GeV/c

Time Of Flight:

- 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

Event-by-Event Net-proton Multiplicity Distributions

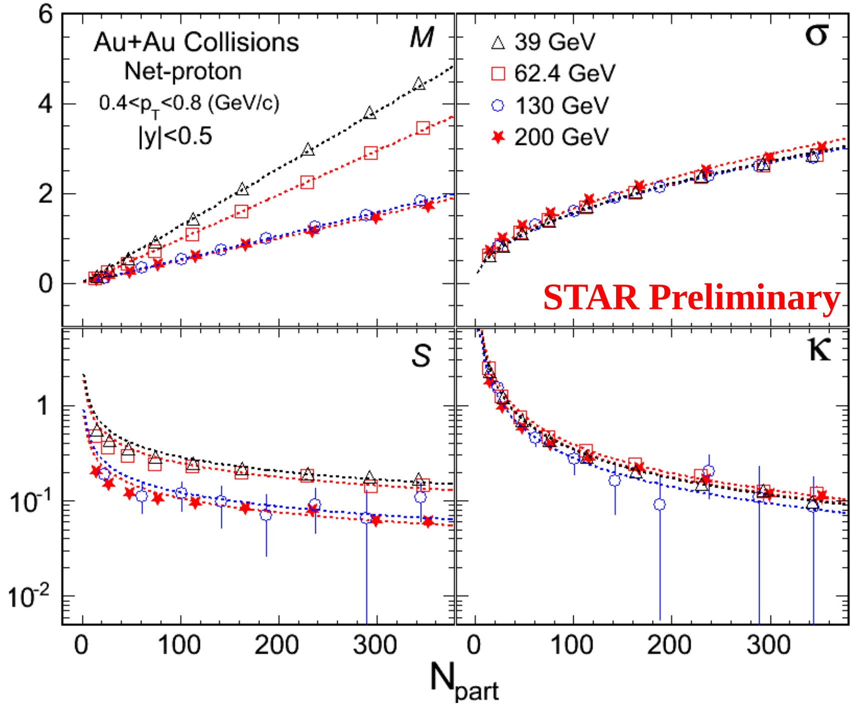


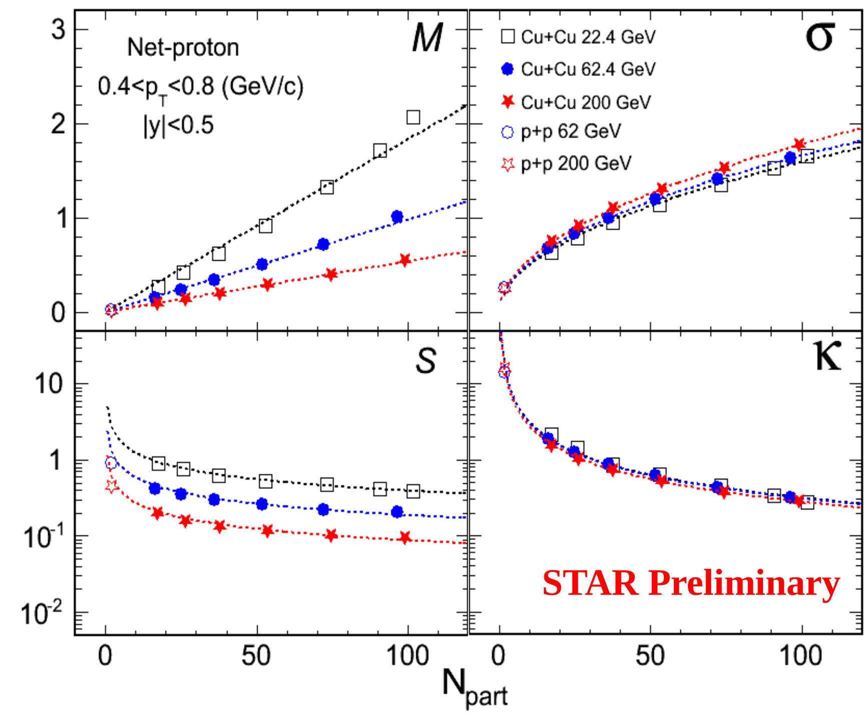


- ➢ Clean Proton and antiproton identification with TPC dE/dx. for 0.4< p_T <0.8 (GeV/c) and |y|<0.5.

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

Centrality Dependence (I): Higher Moments





Central Limit Theorem (CLT)

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

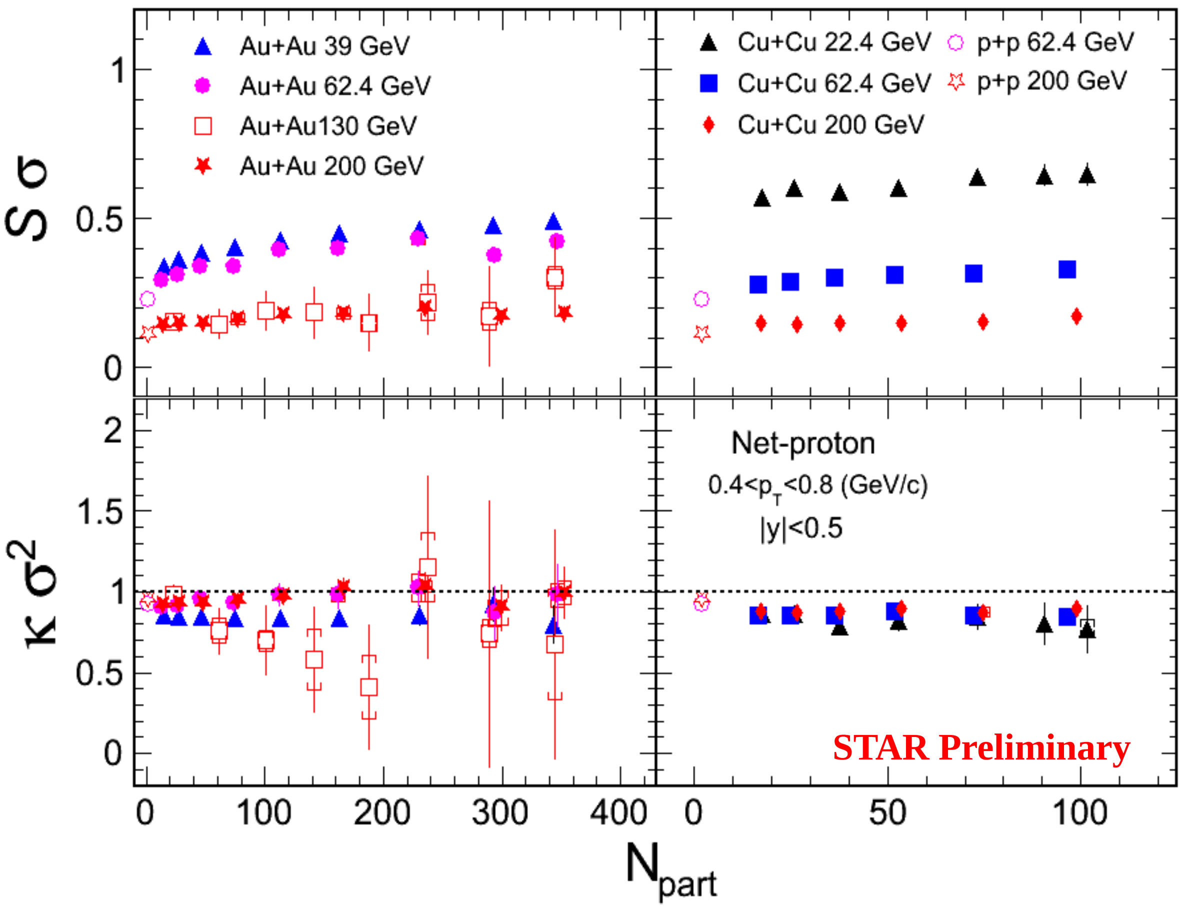
$$S_i = S_x \Big/ \sqrt{C \times N_{part}}, \kappa_i = \kappa_x \Big/ (C \times N_{part})$$

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:

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

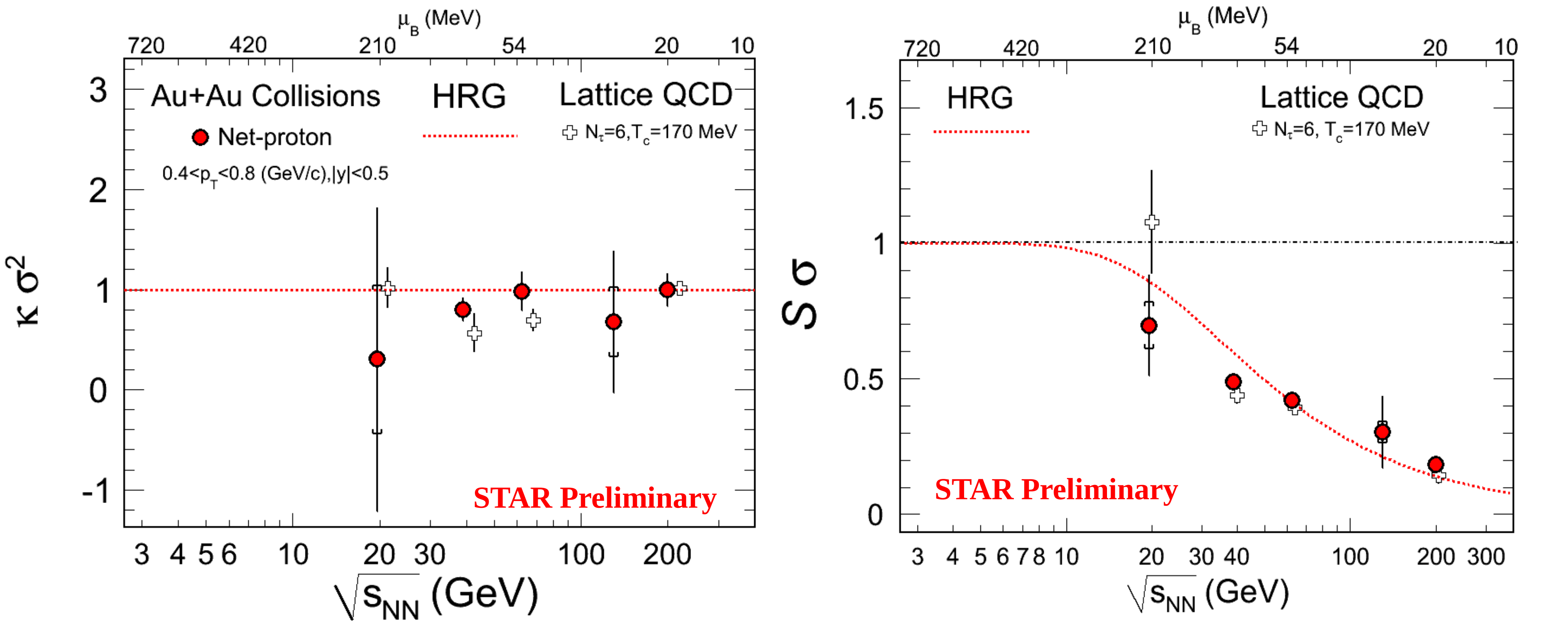
$$(\kappa\sigma^2)_B = \chi_B^4 / \chi_B^2$$

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.

Energy Dependence: Moment Products (Central Collision)

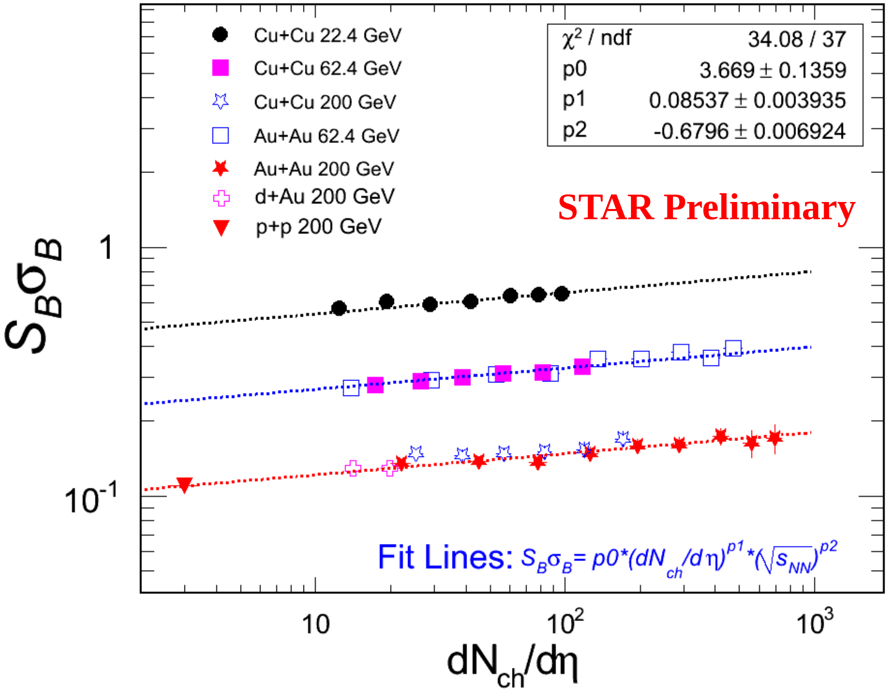


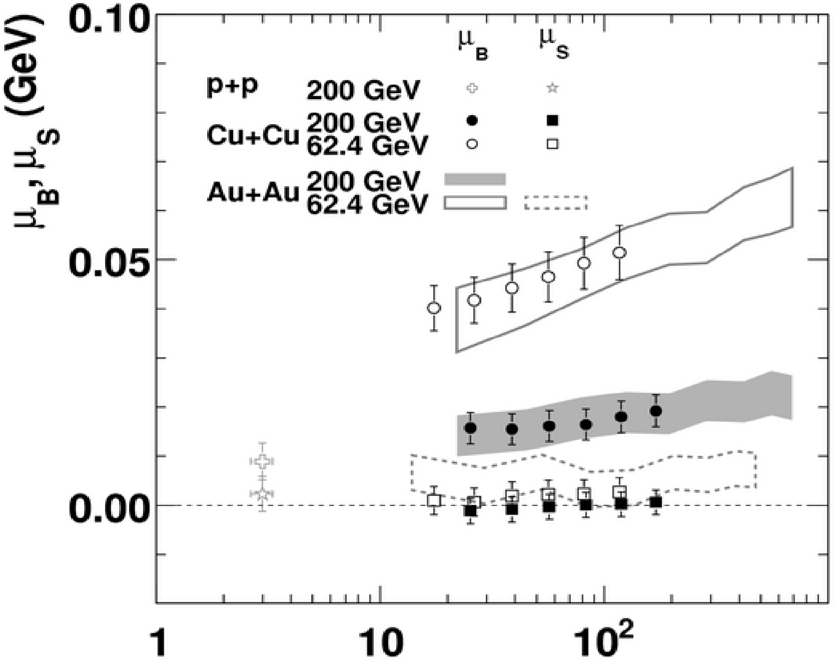
➢ 62.4, 130 and 200 GeV data are consistent with Lattice QCD and HRG Model. 39 GeV data starts to deviate from HRG model.

➢ Non-monotonic signals for CP are not observed at μ_B < 200 MeV region.

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

Scaling Properties for Sσ





STAR Paper, arXiv:1008.3133

Fit: $S_B\sigma_B = \frac{11}{3}*(\frac{1}{s^4}\frac{dN_{ch}}{d\eta})^{\frac{1}{12}}$

HRG: $S_B\sigma_B = \tanh[\frac{\mu_B}{T}]$

At high energy :

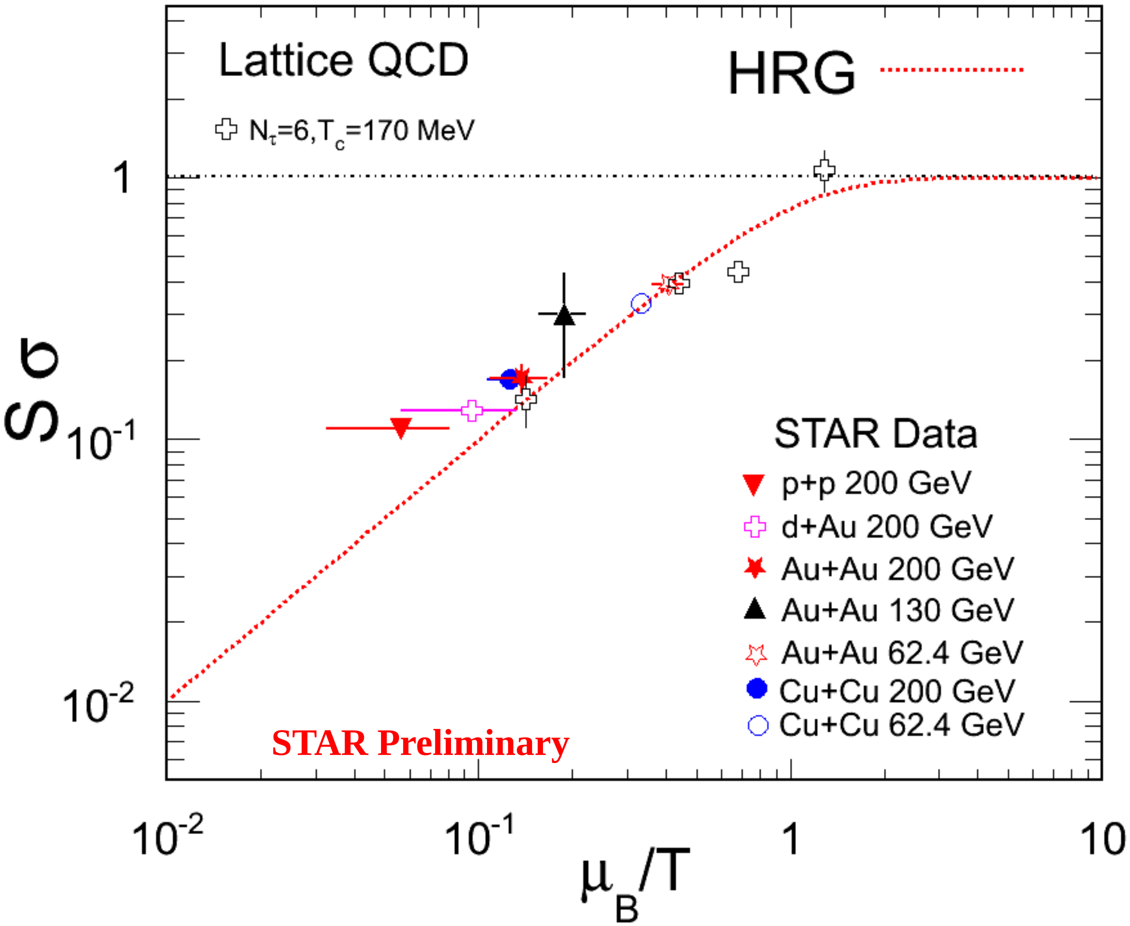
$\mu_B/T \ll 1$

$$\frac{\mu_B}{T} \approx tanh[\frac{\mu_B}{T}] = \frac{11}{3}(\frac{1}{s^4}\frac{dN_{ch}}{d\eta})^{\frac{1}{12}}$$

- Reflect connection between fluctuations, thermodynamic parameter and charged particle density.

s: Square of center of mass energy.
$dN_{ch}/d\eta$: Charged particle density.

Comparison with Lattice QCD and HRG Model



Caveat: p+p and d+Au system may not be described by Grand Canonical Ensemble.

- All HI results are consistent with the thermal model prediction, except the small systems from p+p and d+Au collisions.
- The issue of thermalization is discussed with fluctuation data from high-energy nuclear collisions at RHIC for the first time.

Summary and Outlook

- **Higher moments and moment products are expected to be sensitive to the QCD critical point related correlation and fluctuations.**

- **$S\sigma$ and $\kappa\sigma^2$ are found to be consistent with Lattice QCD and HRG model for high energy data. Non-monotonic signals for QCD critical point are not observed at μB < 200 MeV region.**

- **For the first time, we address the issue of thermalization with high order fluctuation data from high-energy nuclear collisions at RHIC.**

Outlook:
1. **Run 11 are running. More BES data are coming….**
2. **TOF will be used for PID in future analysis.**