RECENT RESULTS ON EVENT-BY-EVENT FLUCTUATIONS FROM RHIC BEAM ENERGY SCAN PROGRAM AT STAR EXPERIMENT

Nihar R. Sahoo
(for the STAR Collaboration)
Texas A&M University,
USA

TEXAS A&M UNIVERSITY

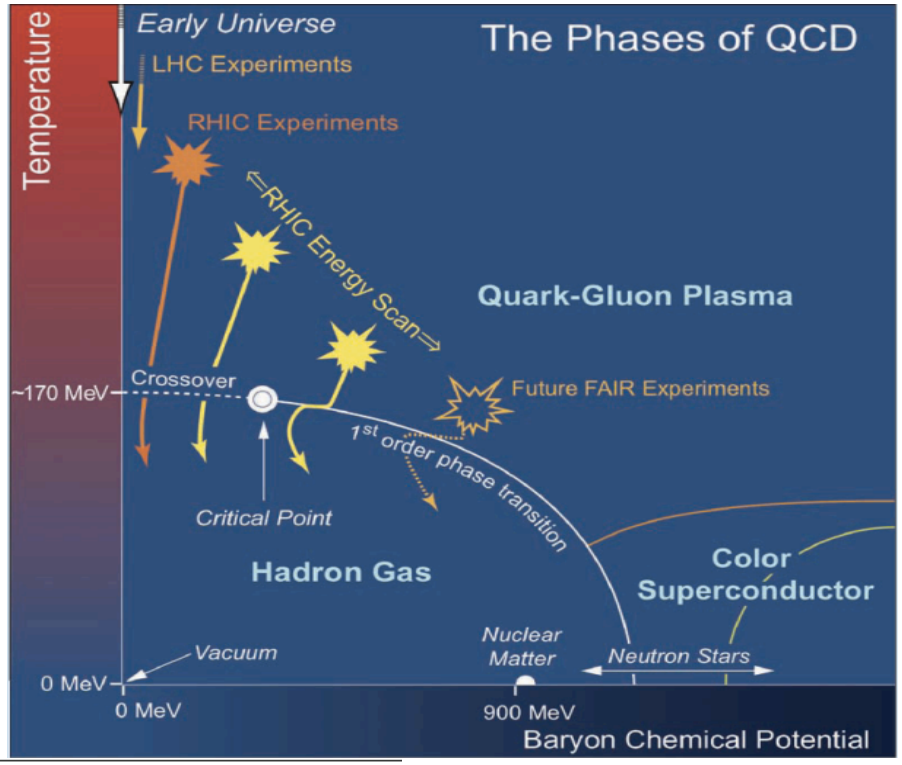
Outline

- **RHIC Beam Energy Scan Program**
  - **Search for QCD Critical Point**
    - **Higher moments of conserved charge distribution**
    - **Other signatures**
- **Signature of QGP**
- **Signature of Disoriented Chiral Condensate**
- **Future perspective for BES-II and upgrades**
- **Summary**

RHIC Beam Energy Scan program (BES)

Main Goal

- Search for the QCD Critical Point
- Evidence of 1st order phase transition in the QCD Phase diagram
- Understand the properties of the QGP as a function of μ_B



Beam Energy (in GeV)	Baryon Chemical Potential (in MeV)	Year of data taking	Event Statistics (Millions)	Beam time (weeks)
62.4	70	2010	67	1.5
39	115	2010	130	2.0
27	155	2011	70	1.0
19.6	205	2011	36	1.5
14.6	260	2014	20	2.0
11.5	315	2010	12	2.0
7.7	420	2010	4	4.0

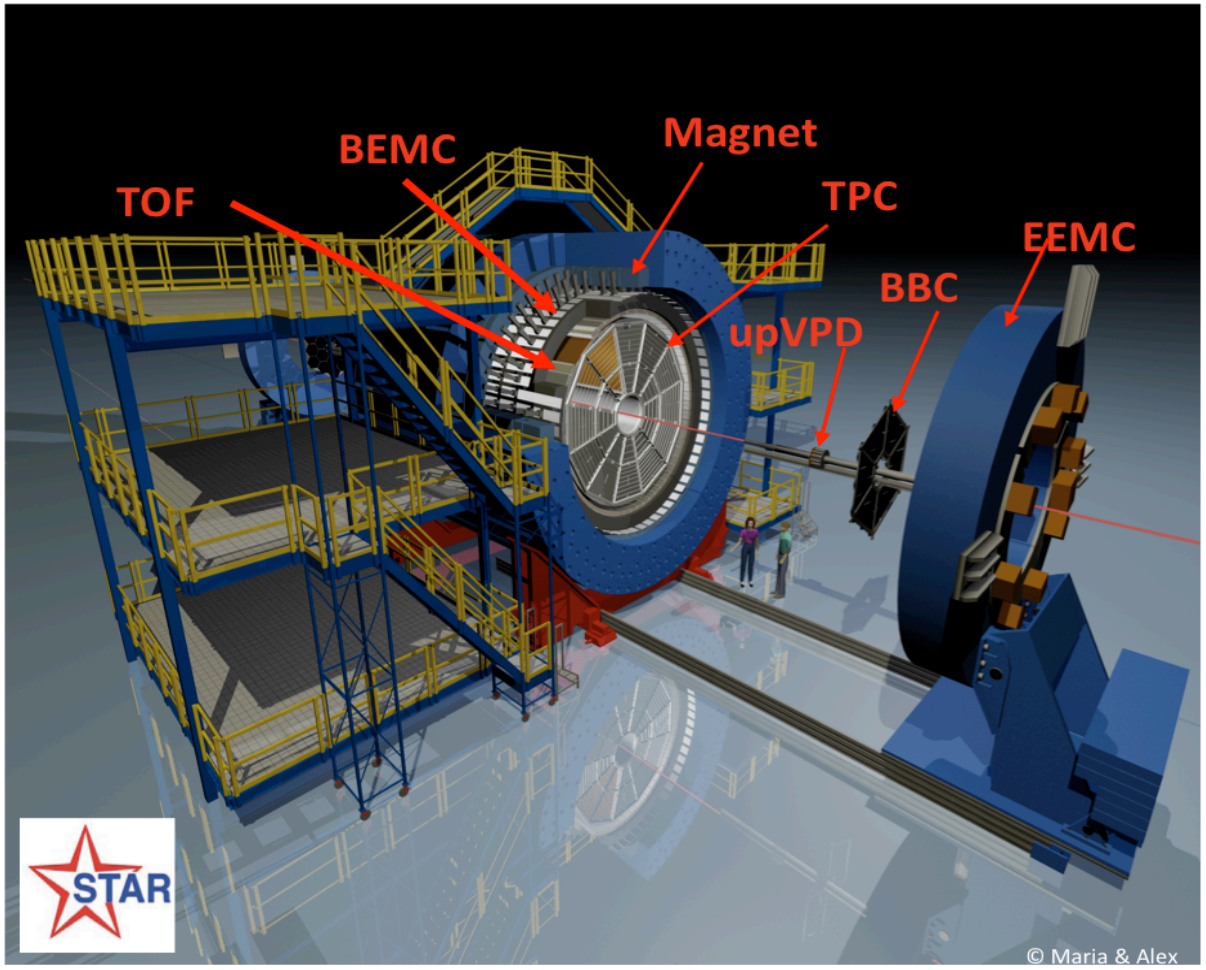
BES-I

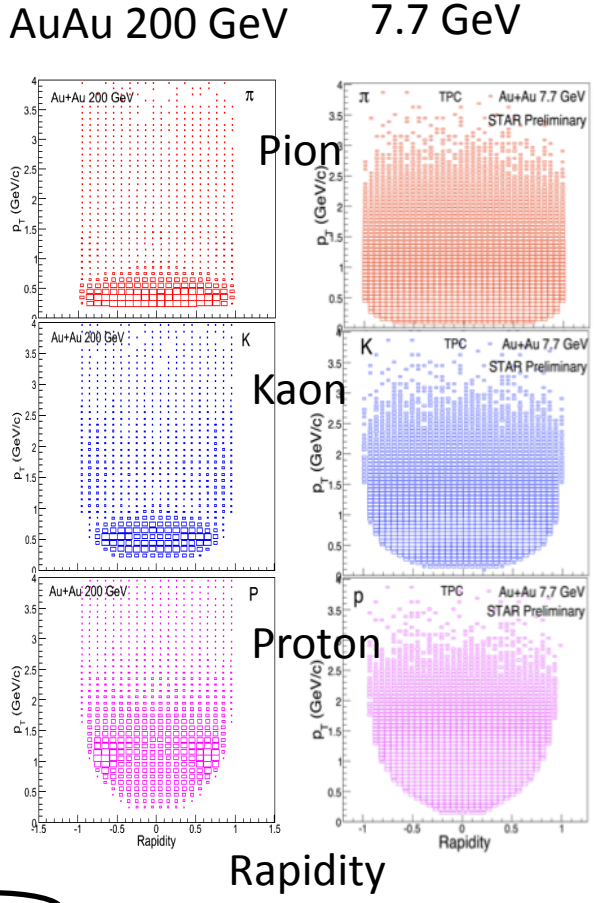
http://www.agsrhichome.bnl.gov/RHIC/Runs/

BES E-by-E fluctuation analysis

Physics Phenomena	Observables
QCD Critical Point	•**Higher moments of conserved charge distribution like,** • **Net-charge** • **Net-proton** (proxy of net-baryon) • **Net-kaon** (proxy of net strangeness) (Skewness, Kurtosis, etc) •**p_T fluctuation** (two particle p_T correlation) •**Particle Ratio fluctuation** ($\nu_{k/\pi}$, $\nu_{p/\pi}$, $\nu_{k/p}$)
Signature of QGP	**Dynamical charge fluctuation** ($\nu_{+/-}$)
DCC signature	**Charged particles-Y correlation** ($r_{m,n}$)

STAR Experiment at RHIC





- Uniform p_T and rapidity acceptance.
- Full 2π coverage
- Very good particle identification capabilities (TOF and TPC)

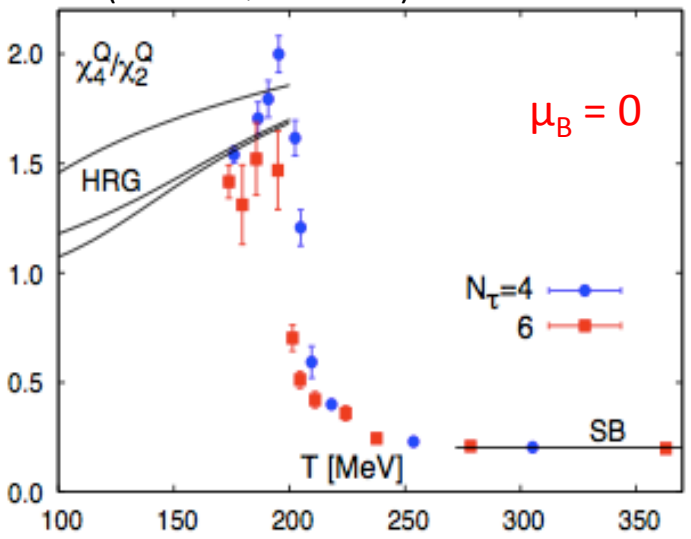
Important tools for any fluctuation analysis

QCD Critical Point

- **Signature of CP**
  - Divergence of the correlation $\chi_n \sim \xi^{5n/2-3}$
  - Divergence of the thermodynamic susceptibility (QCD based calculation)

M. Cheng et al, PRD 79, 074505 (2009)

(Lattice QCD results)



- **Bridge between**

  Theory and Experiment

$$VT^3\chi_2^Q = <(\delta N_Q)^2> \quad (\sigma)$$
$$VT^3\chi_3^Q = <(\delta N_Q)^3) > \quad (S)$$
$$VT^3\chi_4^Q = <(\delta N_Q)^4) > -3<(\delta N_Q)^2)>^2 \quad (\kappa)$$

Thermodynamic susceptibility ⟷ **Moments of the conserved quantities distribution**

net-charge, net-baryon and net-strangeness

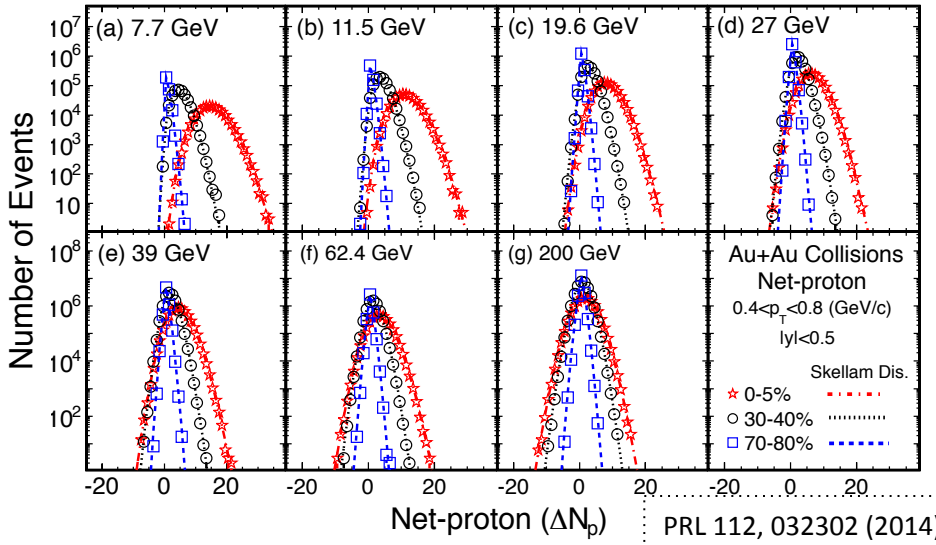
- **Various baseline measurements (Like, Poisson dist., NBD, etc.)**

Caveats: finite size and time effect, critical slowing down etc.

Higher moments of the distribution of conserved quantities as a function of beam energy may give signature of Critical Point.

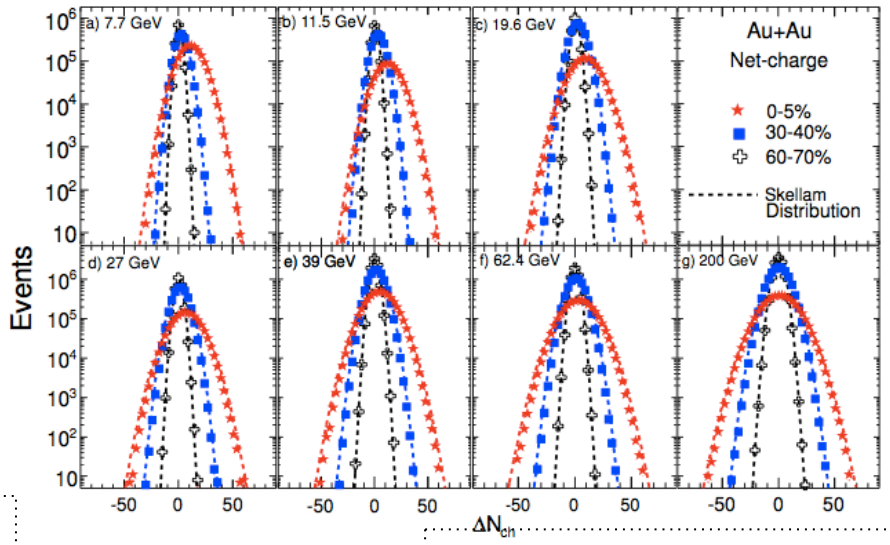
Higher moments analysis: Experimental techniques

Net-proton distribution



PRL 112, 032302 (2014).

Net-charge distribution



Acta Phys.Polon.Supp. 6 (2013) 437-444

Various sophisticated analysis techniques are used

- Extensive event quality assurance
- Centrality Bin width effect
- Efficiency correction of higher moments

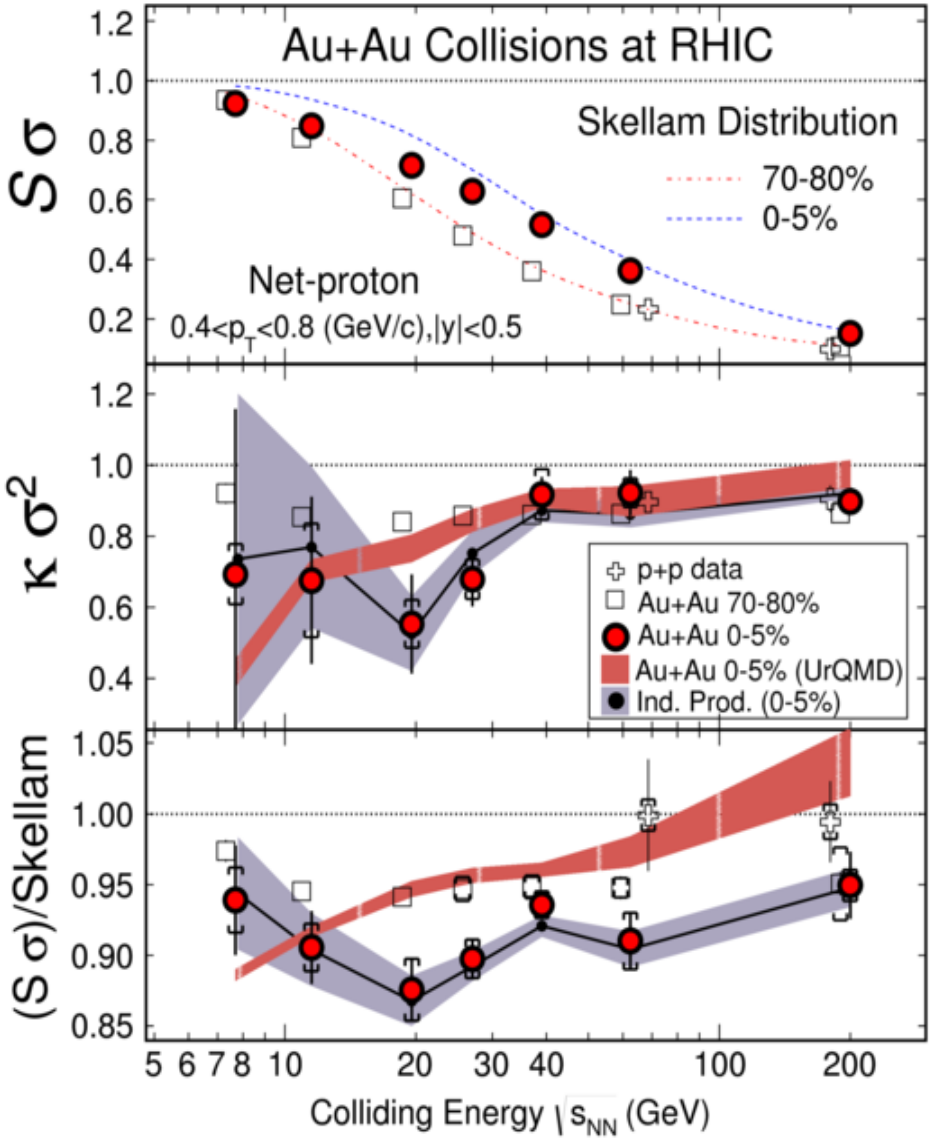
Various effects have been studied

- Auto-correlation effect
- Centrality resolution effect

Critical Analysis for Critical Point

•Various baseline measurements including different MC model simulations

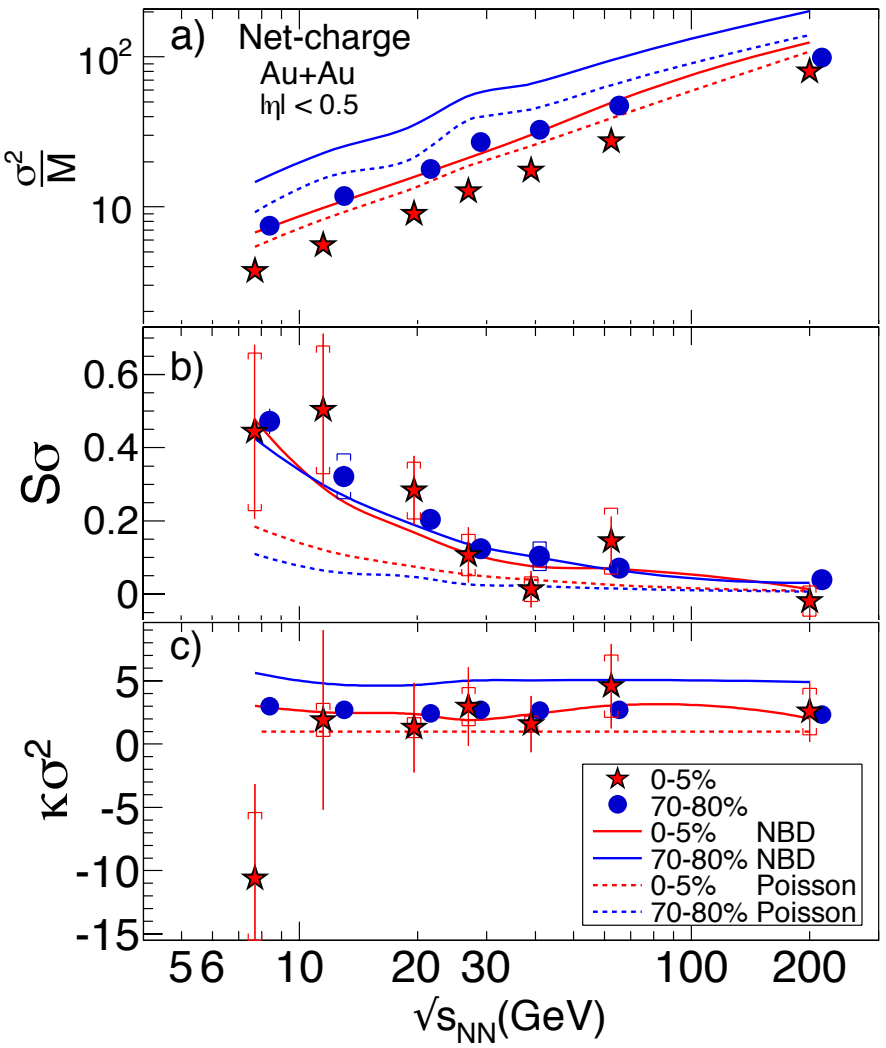
BES Results of Higher moments : Net-Proton



- Deviations for both $\kappa\sigma^2$ and $S\sigma$ from HRG and Skellam expectations are observed for $\sqrt{s_{NN}} \leq 27$ GeV
- At low energies, large statistical error
- Various model estimations are compared
  - Independent Production (no correlation between proton and anti-proton)
  - UrQMD

PRL 112, 032302 (2014).

BES Results of Higher moments: Net-Charge

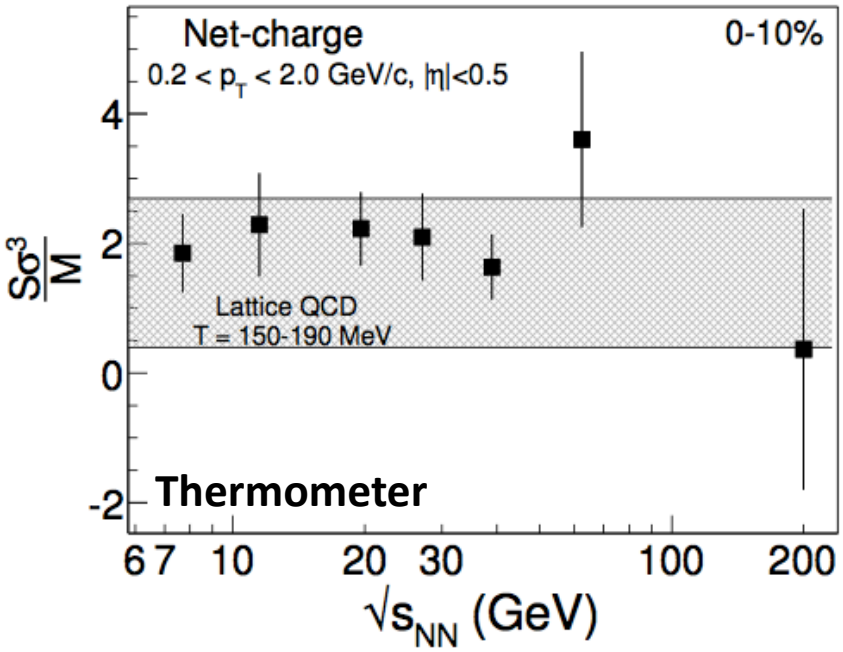


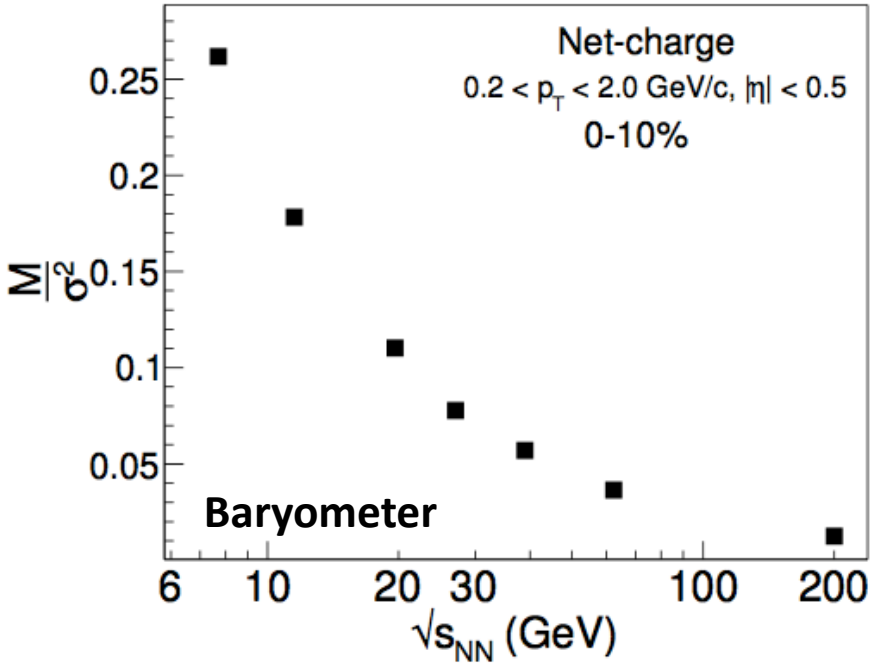
arXiv:1402.1558

- Within the present uncertainty, no non-monotonic behavior is observed as a function of beam energy
- More statistics at low energies is needed for better understanding
- Baseline measurements have been compared
  - Poisson (input: mean of Pos. and Neg. dist)
  - NBD
    (input: mean and width of Pos. and Neg. dist)
- These results can be used to extract the freeze-out parameters by comparing with lattice results

Extraction of Freeze-out parameter

- **Lattice QCD calculation and Experiment**



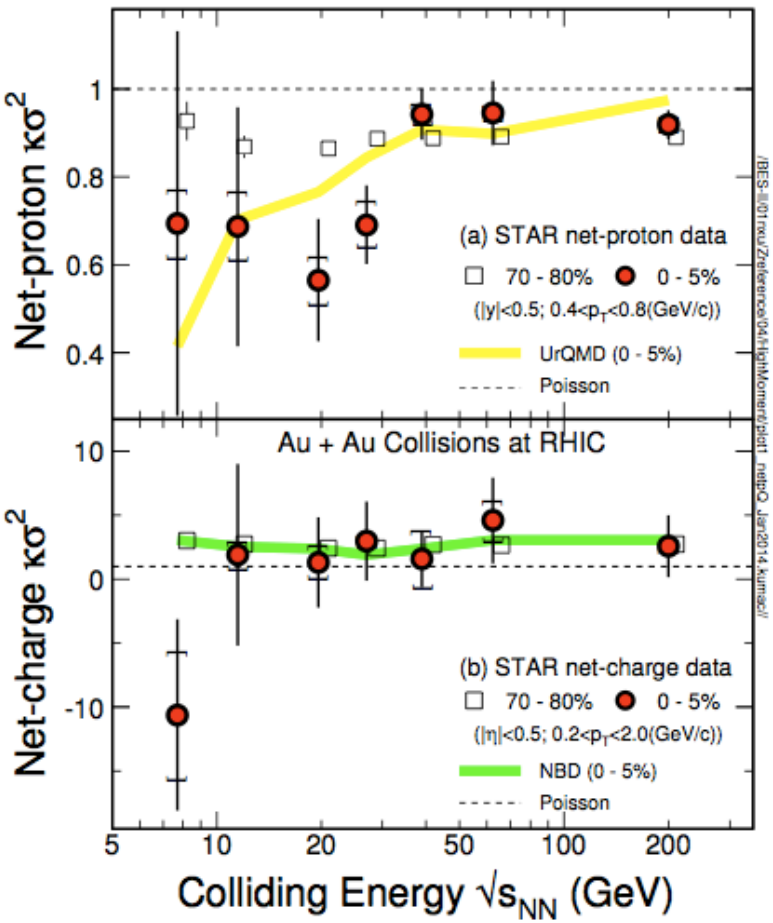


- **Recent lattice measurements**
  - **Estimation of T_f and μ_{B_f} : comparing experimentally measured higher moments of Net-charge distribution**

(A. Bazavov, et al., PRL 109, 192302 (2012), S. Borsanyi et al., PRL 111, 062005 (2013) , arXiv:1403.4576)

- **Exploring more about QCD phase diagram**
- **$S\sigma^3/M$: T_f lies between 150-190 MeV (with uncertainty)**
- **M/σ^2 decreases with increased beam energy as μ_B**

QCD Critical Point *vs* BES program



STAR white paper on BES-I

Within large stat. uncertainty,

- **Net-proton**

Deviations for $\kappa\sigma^2$ from UrQMD and Poisson expectations for $\sqrt{s_{NN}} \leq 27$ GeV

- **Net-charge**

No deviation is observed for $\kappa\sigma^2$ from NBD and Poisson

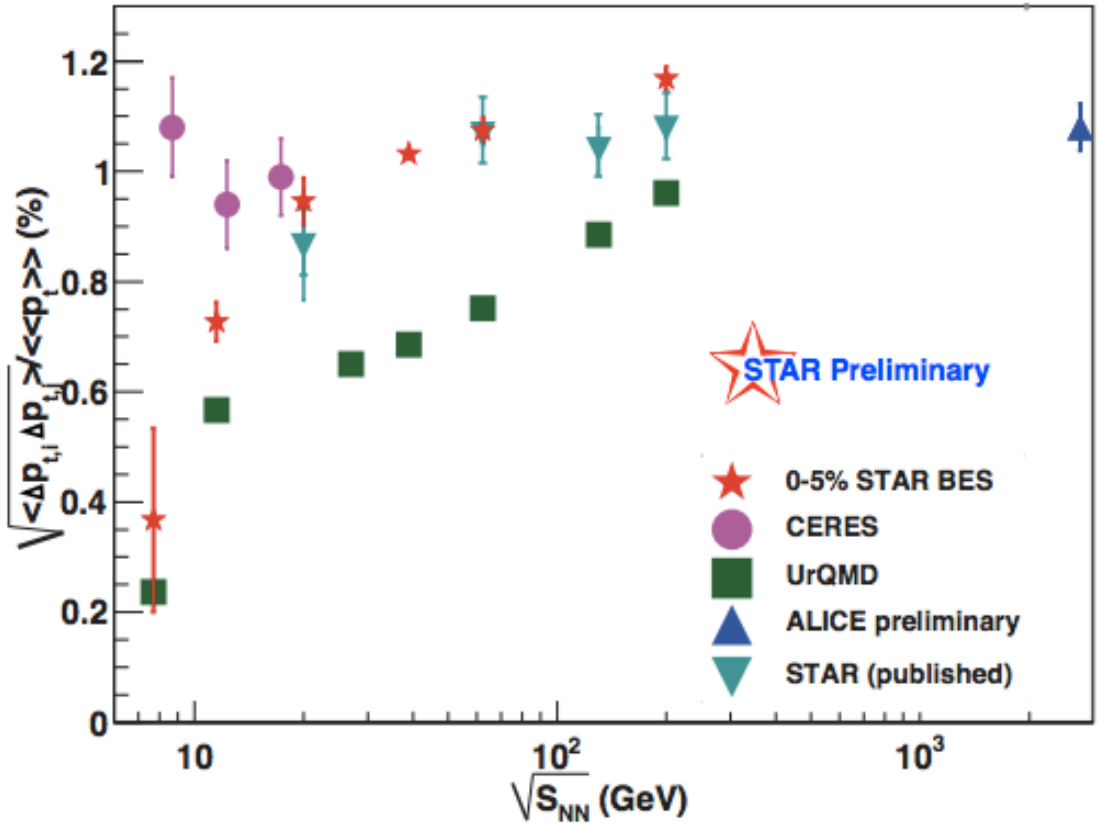
- Net-kaon (ongoing analysis)
- **Large Statistics is required at low energies**

- **Besides expt. challenges, required more understanding on**
  - Various final state effects (Resonance decay, diffusion of charge fluct. etc)
  - Finite volume and time effect
  - Effect of baryon stopping at low energies…, etc

Other Observables for Critical Point search ?

Transverse momentum fluctuation

- Two-particle transverse momentum correlation

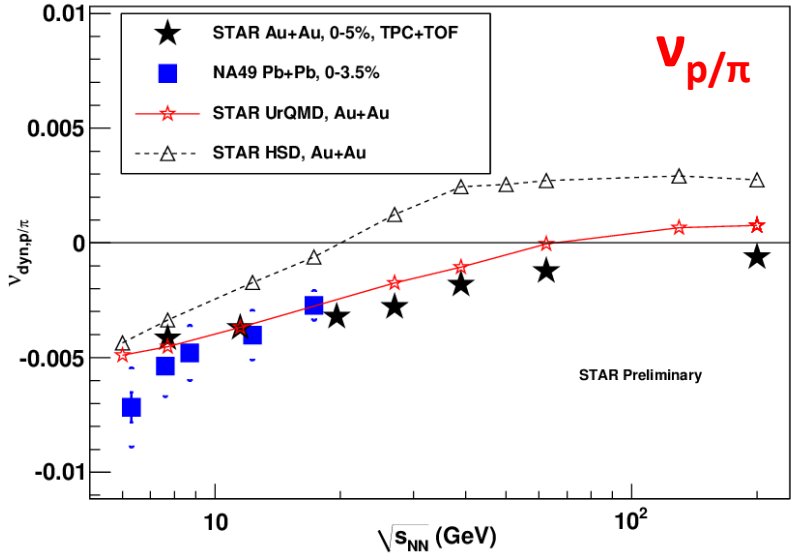


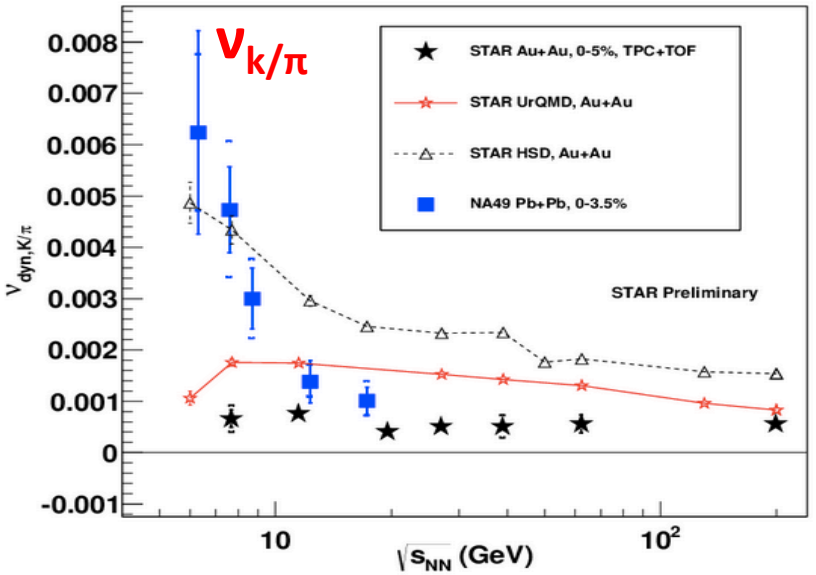
Related to specific heat of the system

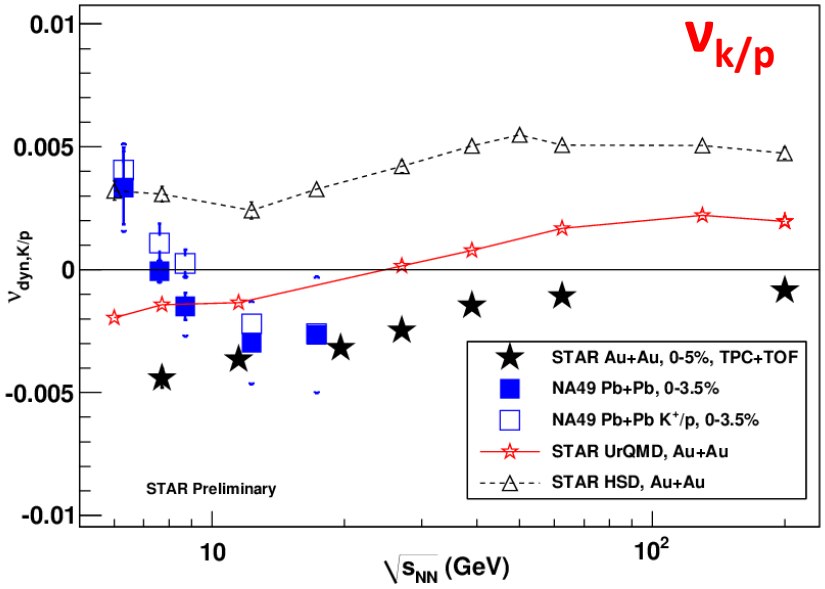
$$\frac{\sqrt{< \Delta p_{t,i}, \Delta p_{t,j} >}}{<< p_t >>} \propto \frac{1}{C_v}$$

- No non-monotonic behavior is observed as a function of collision energy
- Two particles p_T correlation decreases with decreased collision energy
- Rapid increase of p_T correlation below 39 GeV and a plateau above it

Particle Ratio Fluctuations







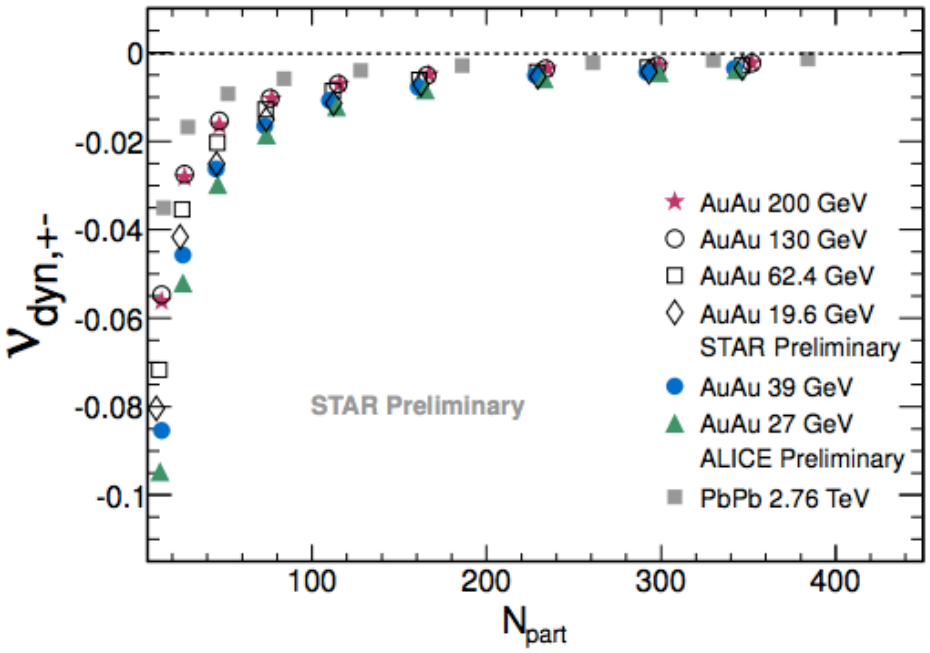
- Dynamical p/π and k/p fluctuation are negative and decreases with decreased collision energy

- Dynamical K/π fluctuation remains independent of collision energy.

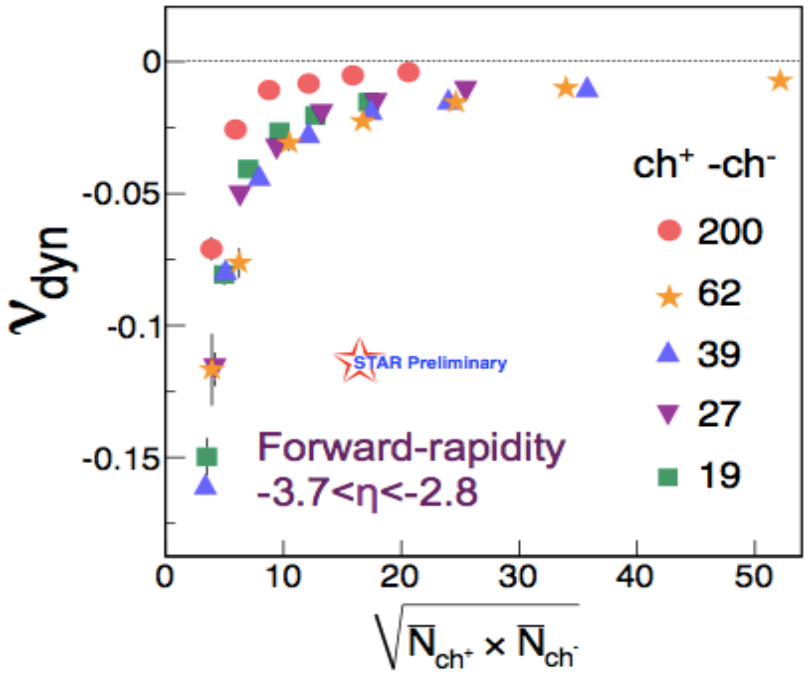
- **No non-monotonic behavior is observed as a function of collisions energy**

Dynamical charge fluctuation

Mid rapidity: -0.5 < η < 0.5



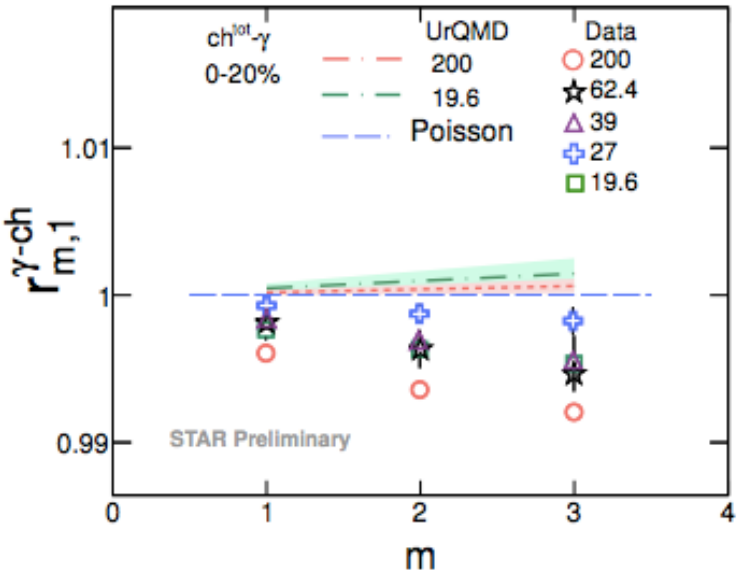
Forward rapidity: -3.7 < η < -2.8



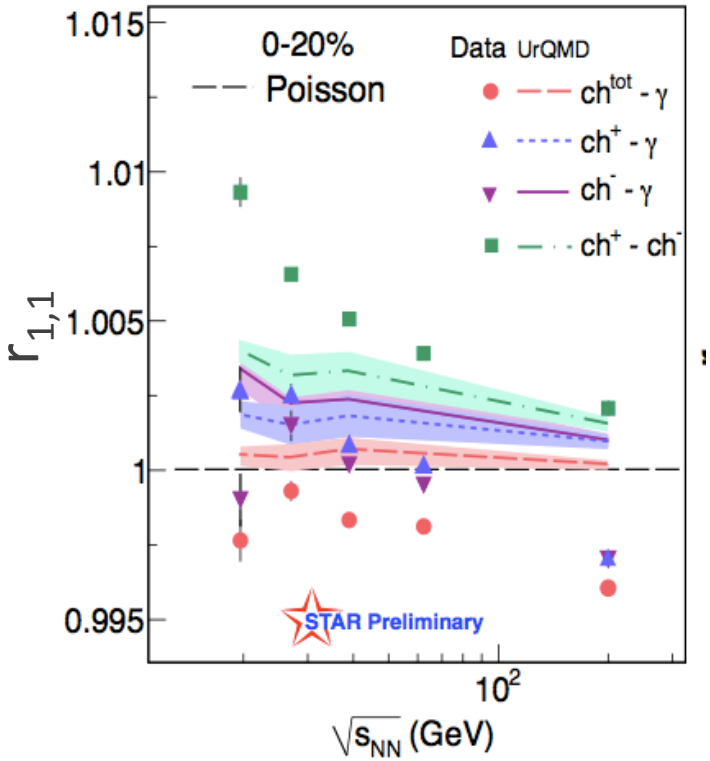
- **With decrease in collision energy, dynamical charge fluctuation decreases and becomes more negative**
  - Correlation between positive and negative charged particles increases with decreased beam energy

DCC signature

- **Photons are counted at forward detector PMD**



$$r_{m,1}^{\gamma-\mathrm{ch}} = \frac{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m+1)\ N_\gamma\rangle\,\langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m)\rangle\,\langle N_\gamma\rangle}$$



- **DCC signature: presence of very large e-by-e flut. in fraction of π^0 production**
  - Photons (Y) mostly from π^0 decay
- **Anomalous pion production as signature of DCC domain formation**
- **$r_{1,1}^{\text{Y-ch}}$ is a robust variable for DCC search**
- **More systematic study is needed (on going work)**

Where do we stand, so far ?

Observables	Signature of	Observation	Remarks
Net-proton higher moments	QCD Critical Point	Deviation below 27 GeV	Large Statistical Error
Net-charge higher moments		No clear deviation	Large Statistical Error
Particle ratio Fluctuation		No Deviation	Statistically sound
Two particle pT fluctuation		No Deviation	Statistically sound
v-dynamic : positive-neg. charged particles	QGP	Systematically decrease of dyn. fluc.	Ongoing analysis
v-dynamic : charge-neutral particles	DCC	No conclusive signature	Ongoing analysis

More statistics is required for the higher moment analysis to close the chapter on Critical Point at STAR Experiment.

(Let's give one more try!)

Future BES-II program

Collision Energy (GeV)	7.7	9.1	11.5	14.6	19.6
μB (MeV) 0-5% central collisions	420	370	315	260	205
BES-I (10^6 Events)	4	-	12	20 (y2014)	36
BES-II (10^6 Events)	100	160	230	300	400

Expected 2018-2019

Detector Upgrades

future E-by-E fluct. Analysis will improve

- **iTPC (Rebuilding of inner-sector of STAR TPC)**
  - **Improve dE/dX,**
  - **η coverage (from 1.0 to 1.7)**
  - **accessible for low p_T.**
- **EPD (Event Plane and centrality Detector)**
- **End-cap Time-Of-Flight (ETOF)**

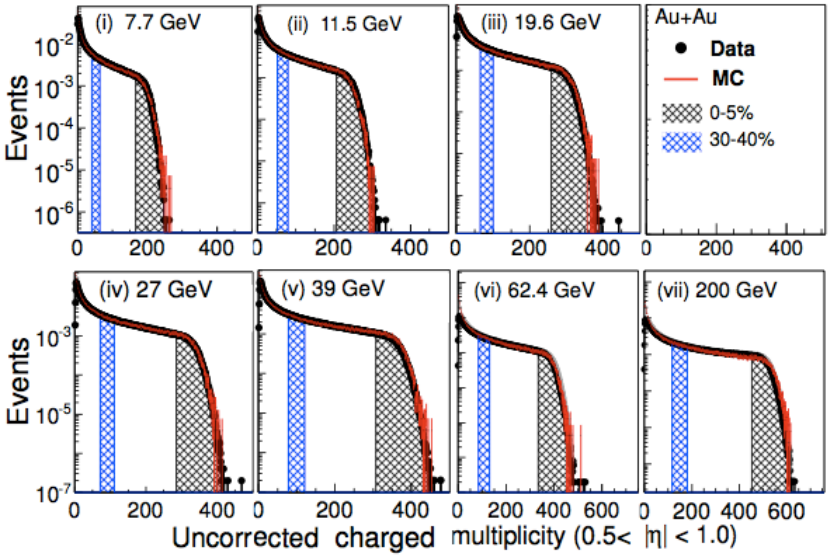
Summary

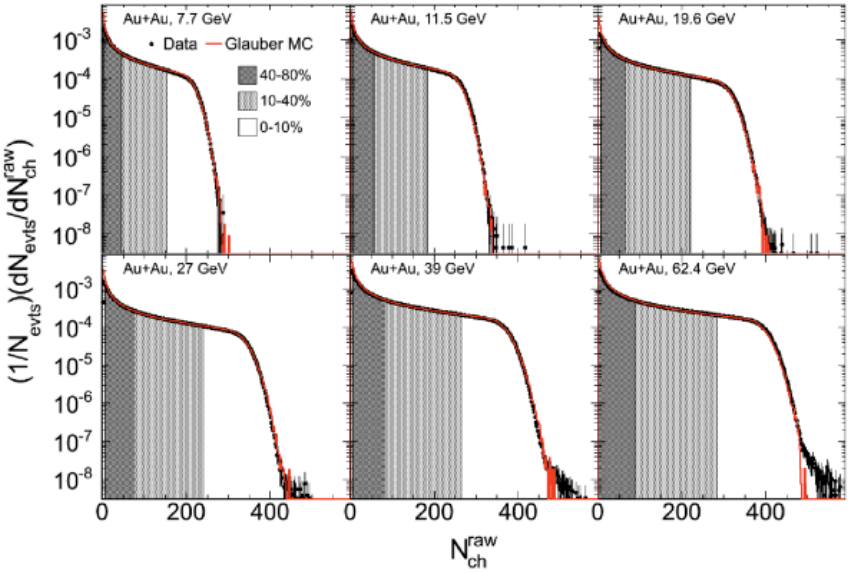
- STAR experiment has successfully completed BES-I program
- With large stat. uncertainty
  - Net-proton higher moments show deviation below 27 GeV from UrQMD and Poisson baseline
  - No clear deviation is observed from Net-charge higher moments

- More statistics and energy points are needed for final conclusion on Critical Point

- BES-II program with large statistics and detector upgrade may resolve the clear existence of Critical point in QCD phase Diagram

Back Up


(i) 7.7 GeV
(ii) 11.5 GeV
(iii) 19.6 GeV
Au+Au
Data
MC
0-5%
30-40%
(iv) 27 GeV
(v) 39 GeV
(vi) 62.4 GeV
(vii) 200 GeV
Events
Uncorrected charged multiplicity (0.5< |η| < 1.0)


Au+Au, 7.7 GeV
Data
Glauber MC
40-80%
10-40%
0-10%
Au+Au, 11.5 GeV
Au+Au, 19.6 GeV
Au+Au, 27 GeV
Au+Au, 39 GeV
Au+Au, 62.4 GeV
$(1/N_{evts})(dN_{evts}/dN_{ch}^{raw})$
N_{ch}^{raw}