Search for the QCD Critical Point -

Fluctuations of Conserved Quantities in High-Energy Nuclear Collisions at RHIC

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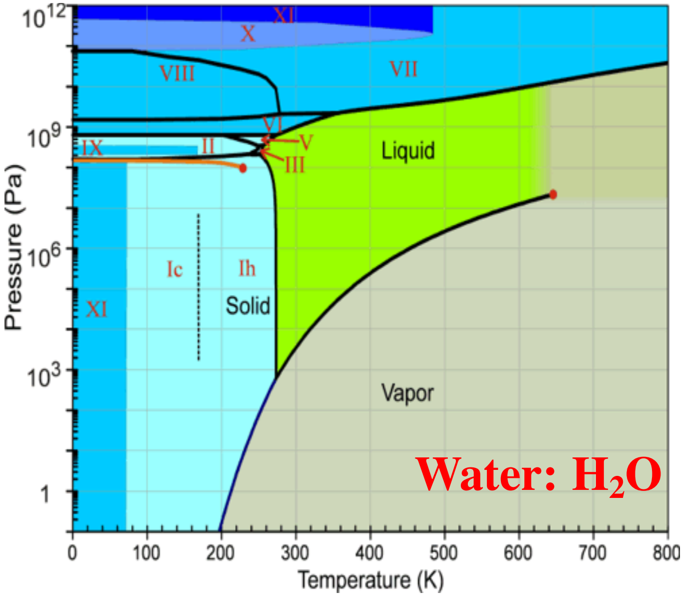
QCD Phase Structure III, Wuhan, June 6-9, 2016

Work with Feng Liu and Nu Xu.

Critical Point



T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869

Matter	Critical Tem. (T_c)	Critical Pre. (P_c)
CO_2	31 °C	72.8 atm
Water	374 °C	217.7 atm
Gold	6,977 °C	5,000 atm

Critical Phenomena:

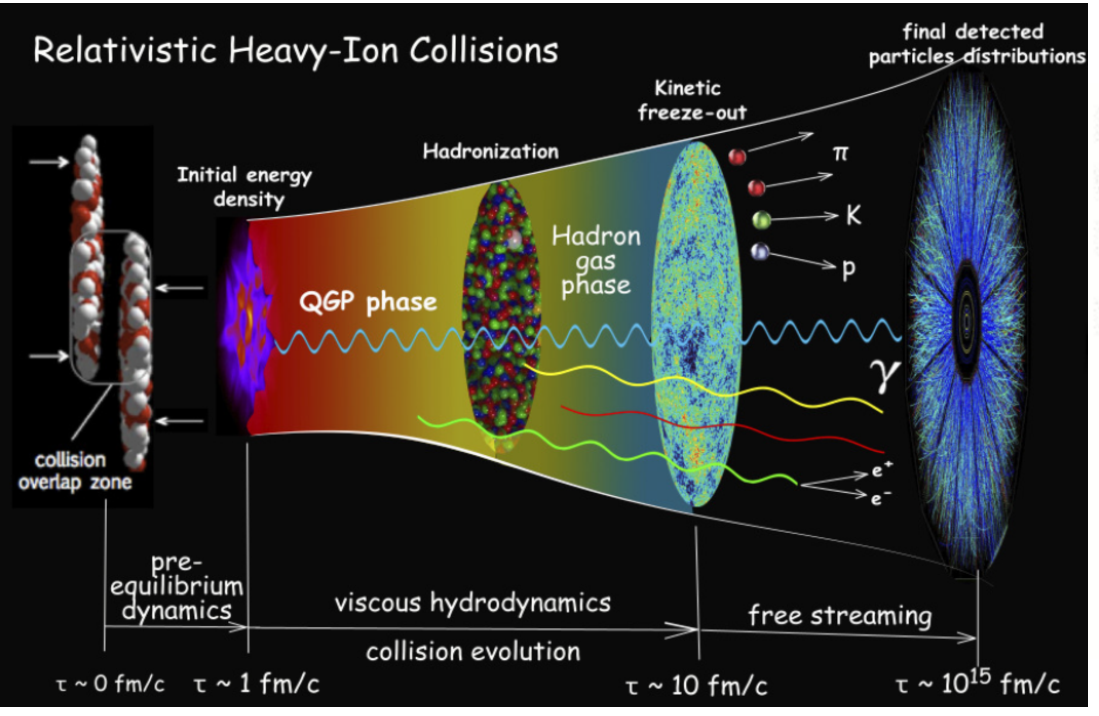
(Power law divergences of thermodynamics quantities, described by critical exponents, universality.)

- Correlation length (ξ), Susceptibilities (χ), heat capacity (C_V) , Compressibility (κ) etc.
- Critical Opalescence.

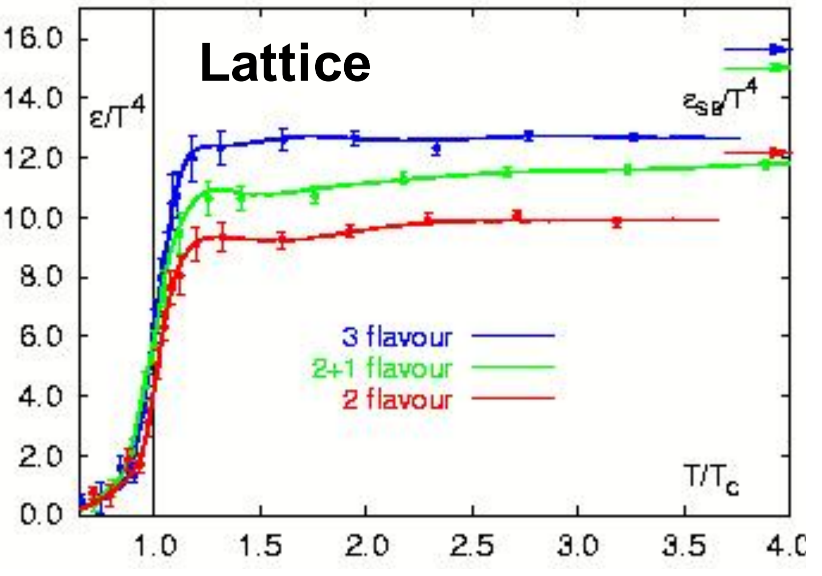
Can we discovery the Critical Point of Quark Matter ? (Put a permanent mark in the QCD phase diagram in the text book.)

T_c ~ Trillion (10^{12}) °C

Little Bang



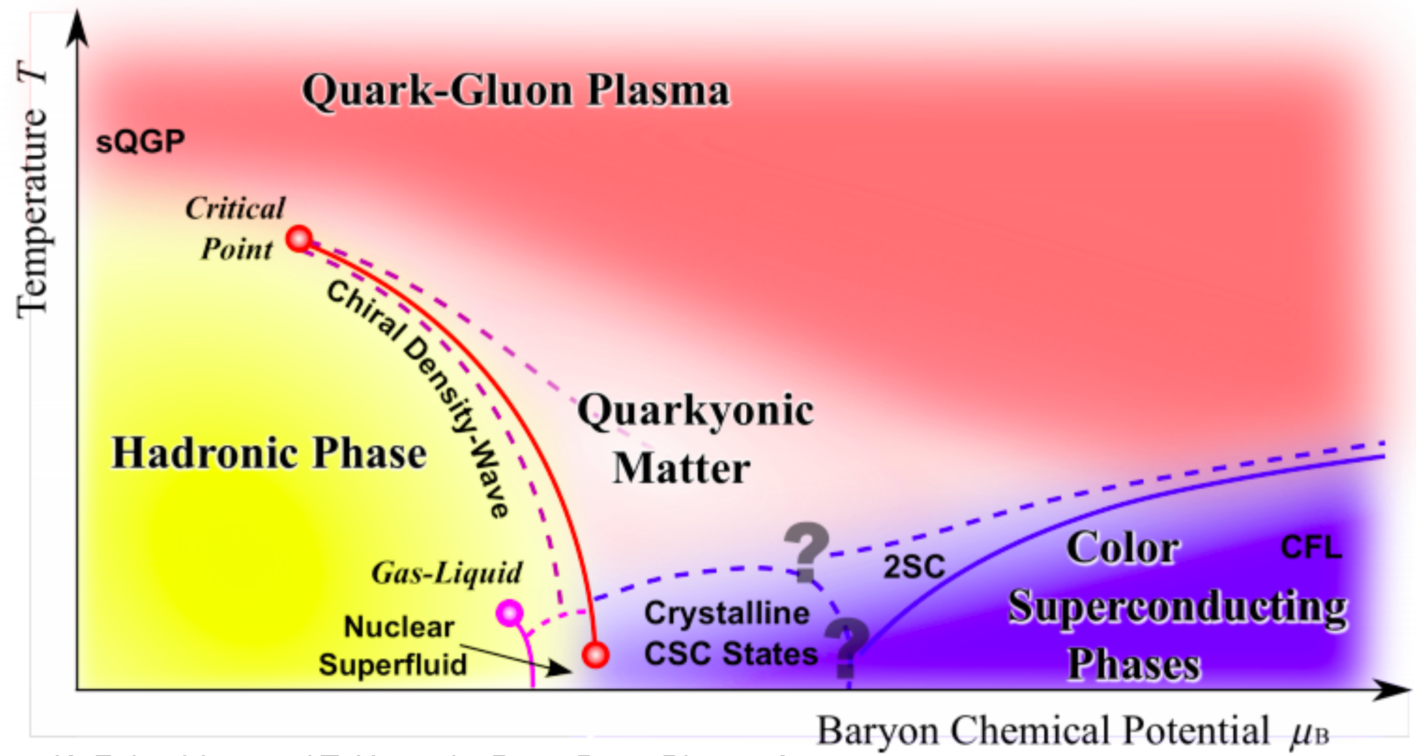
Energy Density Vs. T



T_c=154 +/- 9 MeV

- **Theory:** Transition from hadrons to quarks – release of new DOF ! QGP – not an ideal Boltzmann gas !
- **Experiment:** Indirect evidences for strongly couple and liquid like QGP formed in high energy nuclear collisions, such as Jet quenching etc.

QCD Phase Diagram (Conjectured)



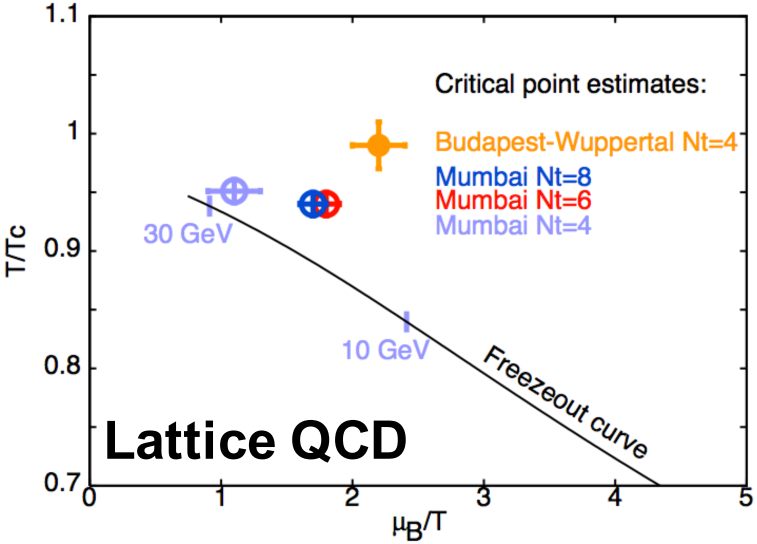
Hatsuda and Fukushima

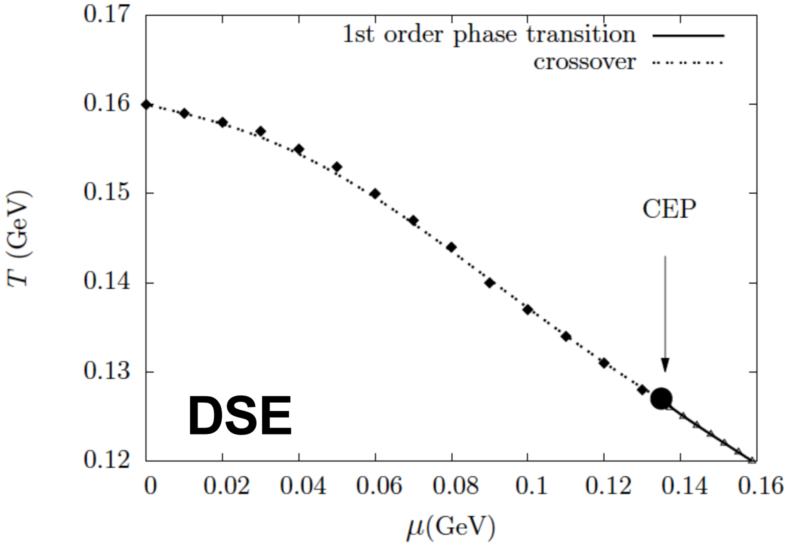
K. Fukushima and T. Hatsuda, Rept. Prog. Phys. ***74****, 014001(2011); arXiv:1005.4814*

Search for the QCD Critical Point in Heavy-ion Collisions:
Challenges:

1. finite size/time.
2. Non-CP physics background.
3. Phase transition signal survive after dynamical expansion.

Location of QCD Critical Point: Theory





Lattice QCD:

1): Fodor&Katz, JHEP 0404,050 (2004):
$(\mu^E_B, T_E) = (360, 162)$ MeV (Reweighting)

2): Gavai&Gupta, NPA 904, 883c (2013)
$(\mu^E_B, T_E) = (279, 155)$ MeV (Taylor Expansion)

3): F. Karsch ($\mu^E_B / T_E > 2$, CPOD2016)

DSE:

1): Y. X. Liu, et al., PRD90, 076006 (2014).
$(\mu^E_B, T^E) = (372, 129)$ MeV

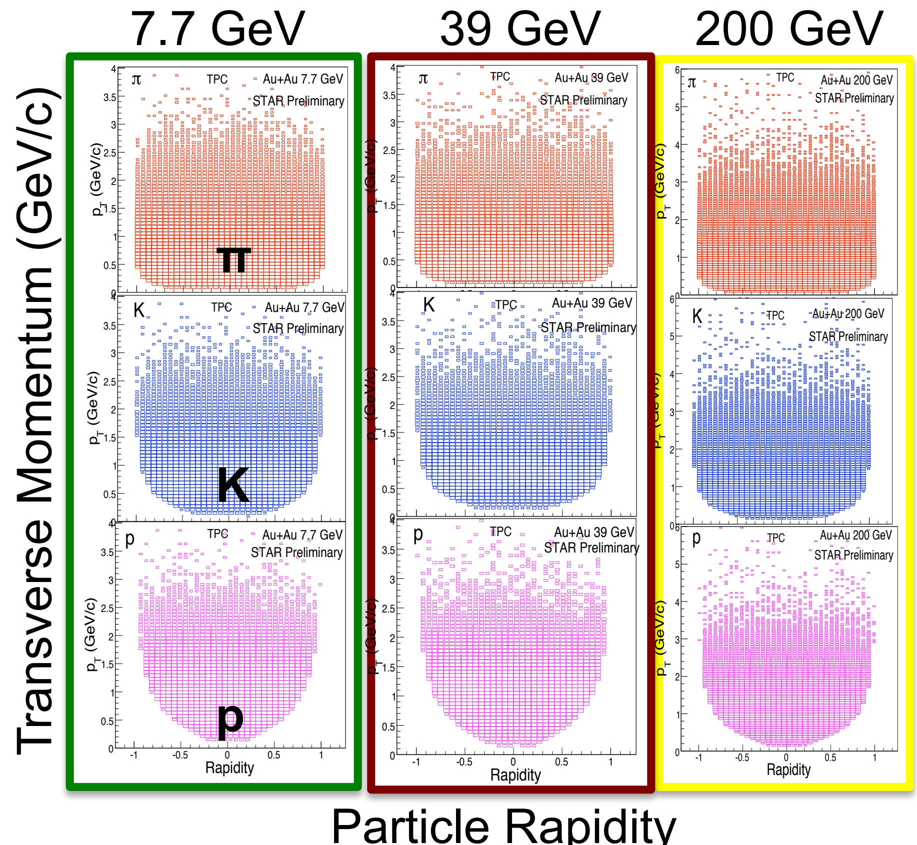
2): Hong-shi Zong et al., JHEP 07, 014 (2014).
$(\mu^E_B, T_E) = (405, 127)$ MeV

3): C. S. Fischer et al., PRD90, 034022 (2014).
$(\mu^E_B, T^E) = (504, 115)$ MeV

$\mu^E_B = 266 \sim 504$ MeV, $T_E = 115 \sim 162$, $\mu^E_B / T_E = 1.8 \sim 4.38$

RHIC Beam Energy Scan- I (2010-2014)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	$^*\mu_B$ (MeV)	$^*T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140



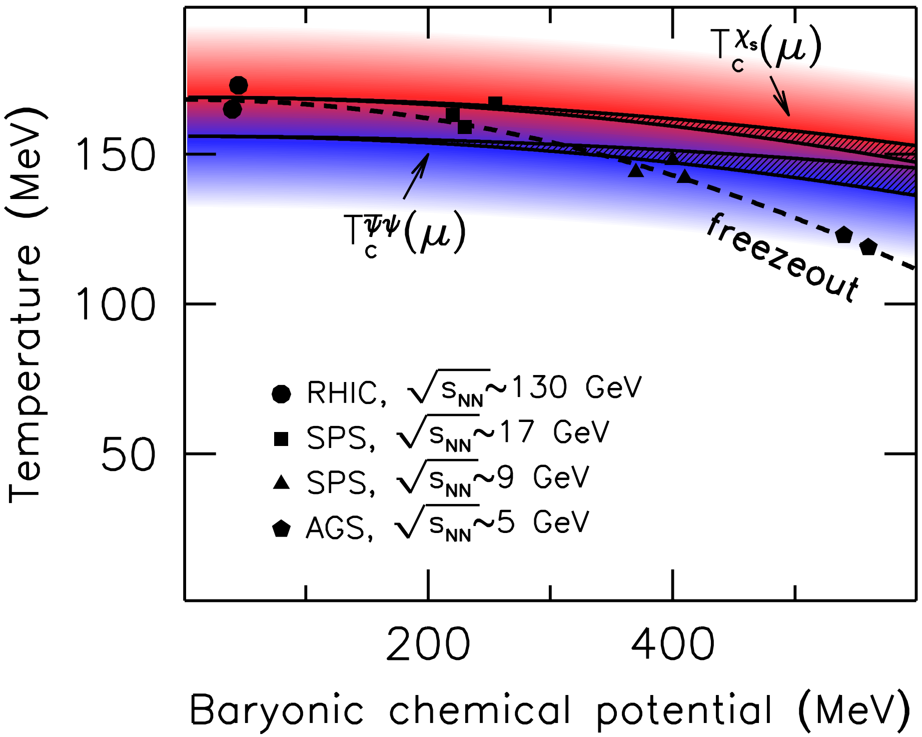
1) Access broad region of the QCD phase diagram.
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Important for fluctuation analysis!

$^*(\mu_B, T_{CH})$: J. Cleymans et al., PR**C73**, 034905 (2006)

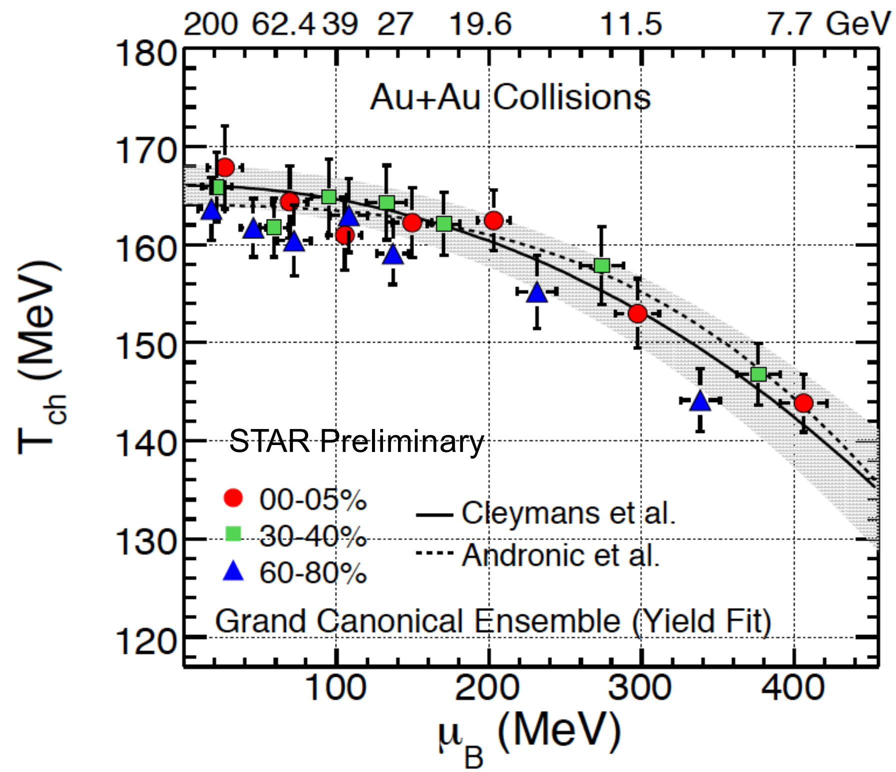
The RHIC Beam Energy Scan Phase-II has been planed (2019-2020).

$\sqrt{s_{NN}}$=19.6, 14.5, 11.5, 7.7 GeV with high statistics

Freeze Out Lines Vs. Phase Transition Boundary



JHEP 1104 (2011) 001



✧ **Width of transition line wide.**

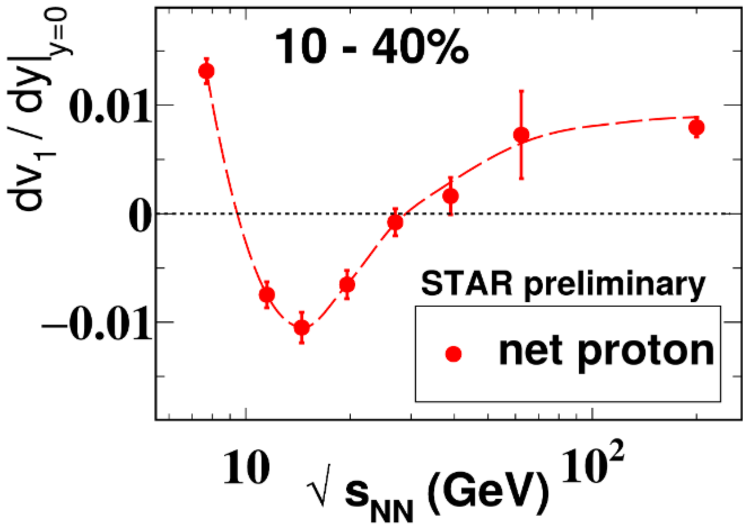
✧ **Freeze-out line close to transition line.**

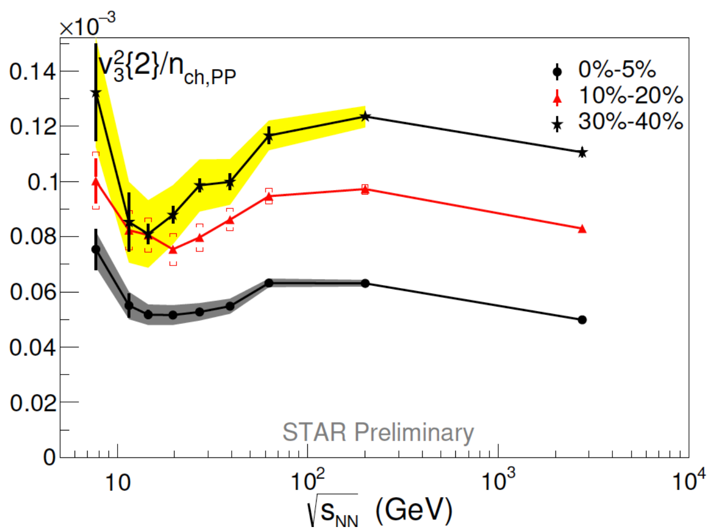
Chemical Freeze-out: (GCE)

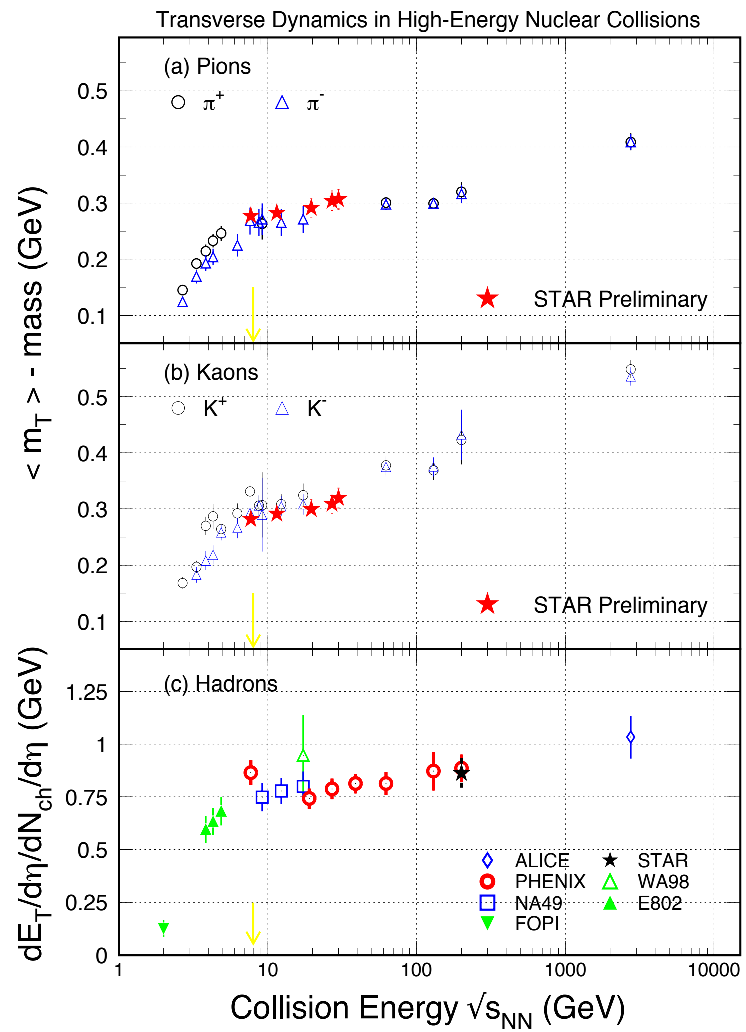
- Weak temperature dependence
- Centrality dependence μ_B!

STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

Softening of EoS ?







D.H. Rischke et al. HIP1, 309(1995) H. Stoecker, NPA750, 121(2005).
J. Steinheimer et al., arXiv:1402.7236 P. Konchakovski et al., arXiv:1404.276

Fluctuations Probes the QCD Phase Transition

Fluctuations are sensitive to the thermodynamic properties of the system and can be used to probe the QCD phase transition.

1. Fluctuations signals the QCD Critical Point.

M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998). Cited:928
M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999). Cited:708

Probe singularity of the equation of state: Divergence of the fluctuations.

2. Fluctuations signals the Quark Deconfinement.

S. Jeon and V. Koch, Phys. Rev. Lett. 83, 5435 (1999). Cited: 193.
S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000). Cited: 470.
M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000). Cited:443.

Proposed experimental observables:

1. **Pion multiplicity fluctuations.**
2. **Mean p_T fluctuations.**
3. **Particle ratio fluctuations**
4. **Fluctuations of conserved quantities.**

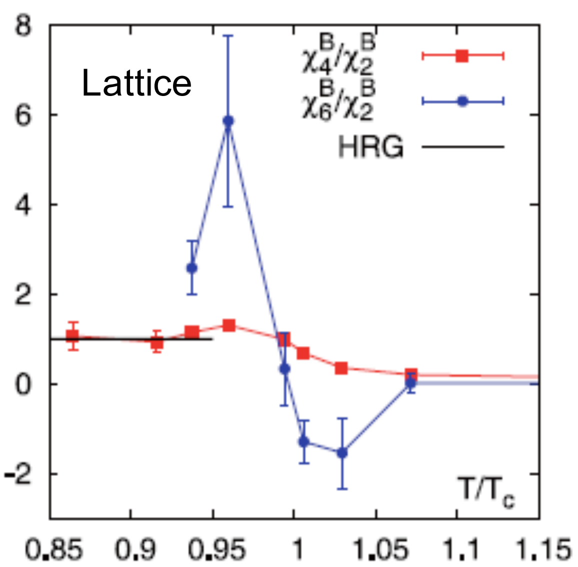
Higher Order Fluctuations of Conserved Quantities

1. Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

$$\left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \qquad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^{7}$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

2. Direct connection to the susceptibility of the system.



$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T\wedge 4)}{\partial(\mu_q)^n}, q = B, Q, S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

Observables: Higher Moments (fluctuations)

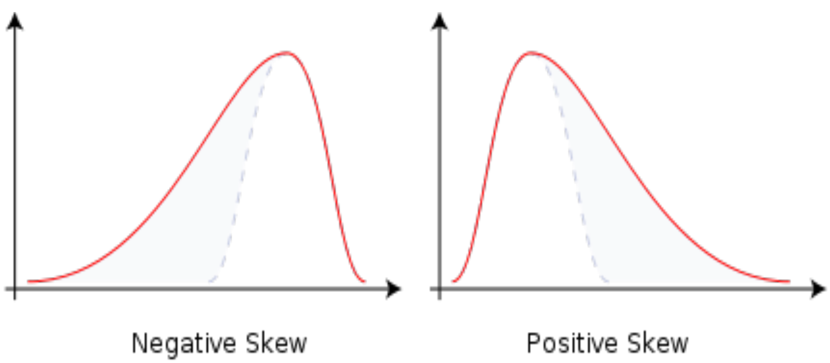
"Shape" of the fluctuations can be measured: non-Gaussian moments.

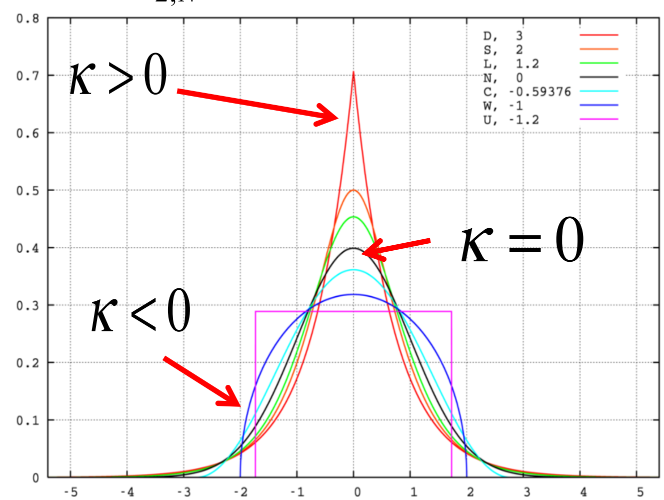
$$C_{1,x} = < x >, C_{2,x} = < (\delta x)^2 >,$$

$$C_{3,x} = < (\delta x)^3 >, C_{4,x} = < (\delta x)^4 > -3 < (\delta x)^2 >^2$$

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{< (N - < N >)^3 >}{\sigma^3}$$

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{< (N - < N >)^4 >}{\sigma^4} - 3$$



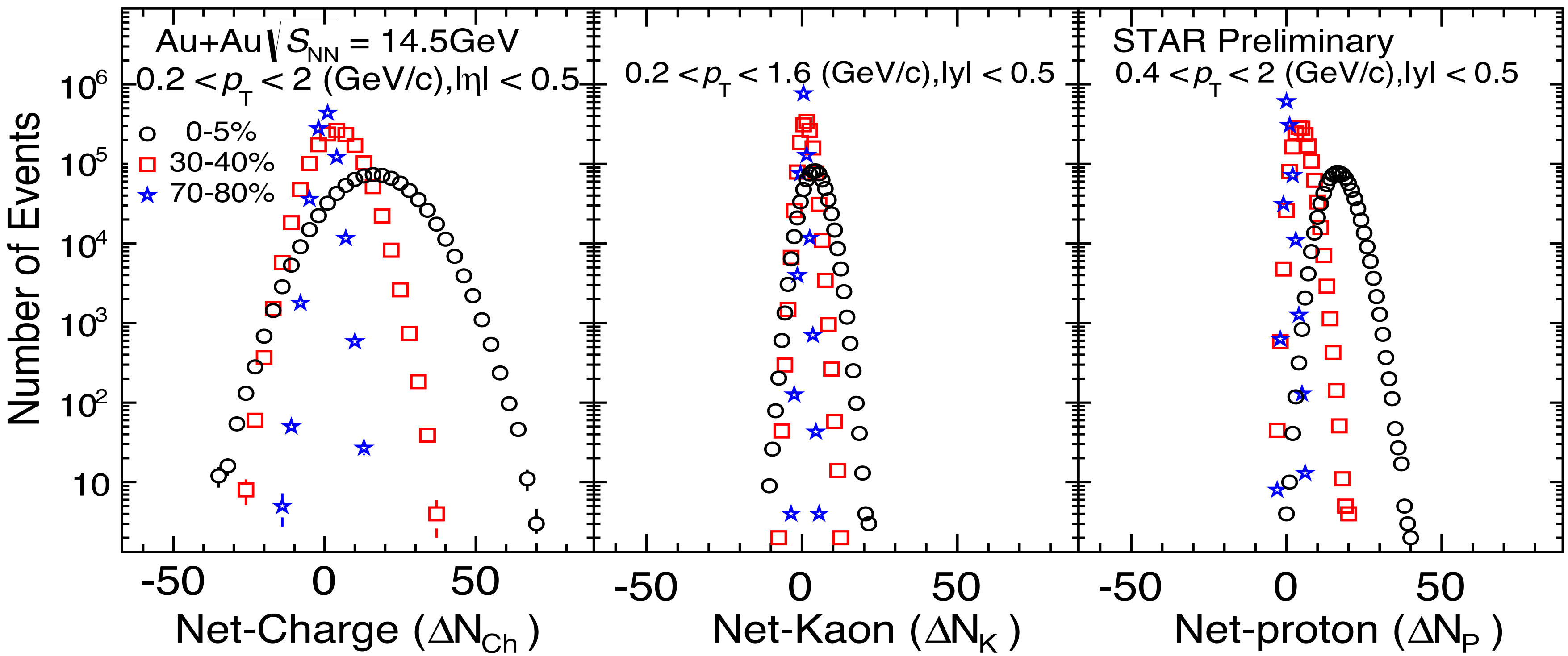


➢ **Susceptibility ratios ⇔ Cumulant Ratios (Cancel V dependence)**

$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

(q=B, Q, S)

Raw Event-By-Event Net-Particle Multiplicity Distribution



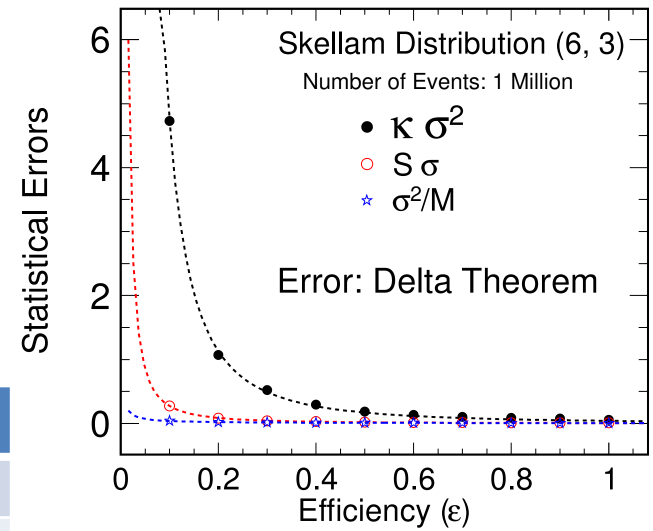
Effects needed to be addressed to get final moments/cumulants:

1. Auto-correlation effects.
2. Effects of volume fluctuations.
3. Finite detector efficiency .

A. Bzdak and V. Koch, PRC86, 044904 (2012)
X.Luo, et al. J. Phys. G40,105104(2013)
X.Luo, Phys. Rev. C 91, 034907 (2015)
A . Bzdak and V. Koch, PRC91, 027901 (2015)

Efficiency Correlation and Error Estimation

- We can express the moments and cumulants in terms of the factorial moments, which can be easily efficiency corrected.
  X. Luo, PRC91, 034907 (2015);
  A. Bzdak and V. Koch, PRC91, 027901 (2015)
- Statistical Errors based on Delta Theorem. With same N events: error(net-charge) > error(net-kaon) > error(net-proton)



Au+Au 14.5GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width(σ)	12.2	4.2	3.4
Average efficiency(ε)	65%	75%	38%
σ^2/ε^2	355	32	82

Those numbers here not used in actual analysis

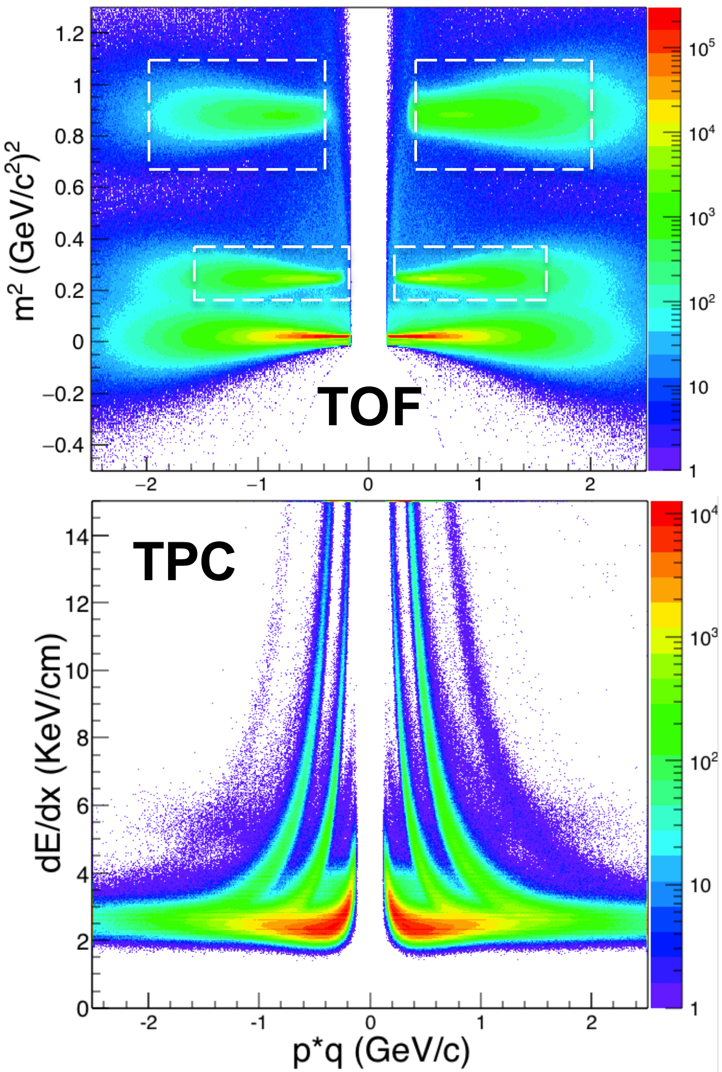
$$error(S\sigma) \propto \frac{\sigma}{\varepsilon^{3/2}}$$

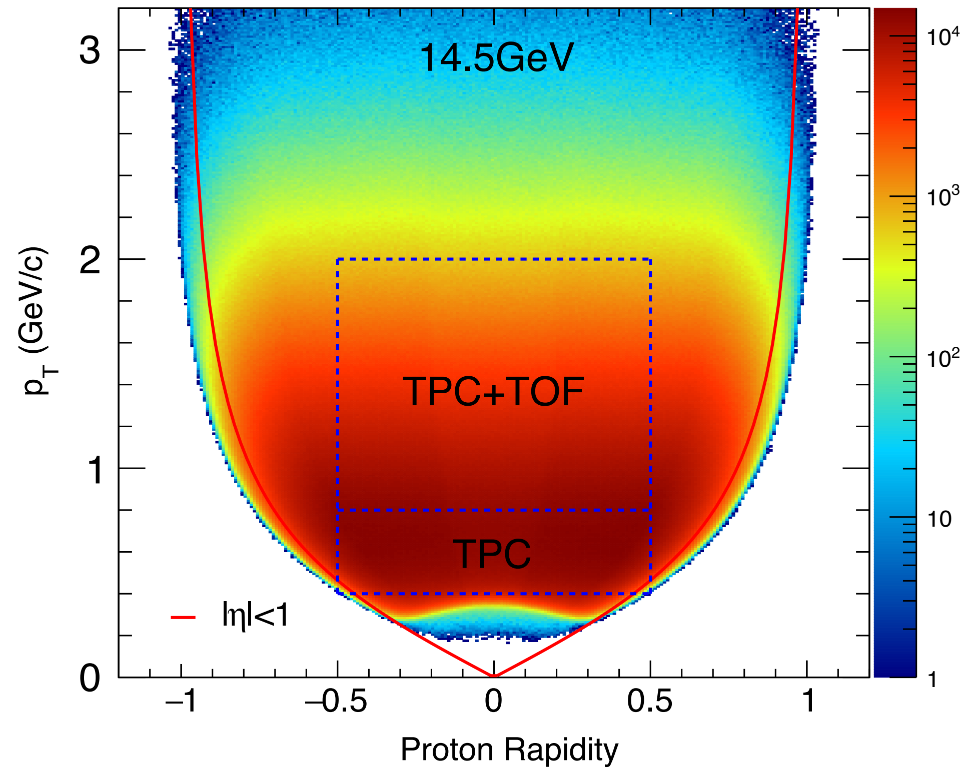
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}$$

- Systematic error estimation
  - Includes uncertainties on efficiency and efficiency fluctuations
  - PID and track cuts

Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.





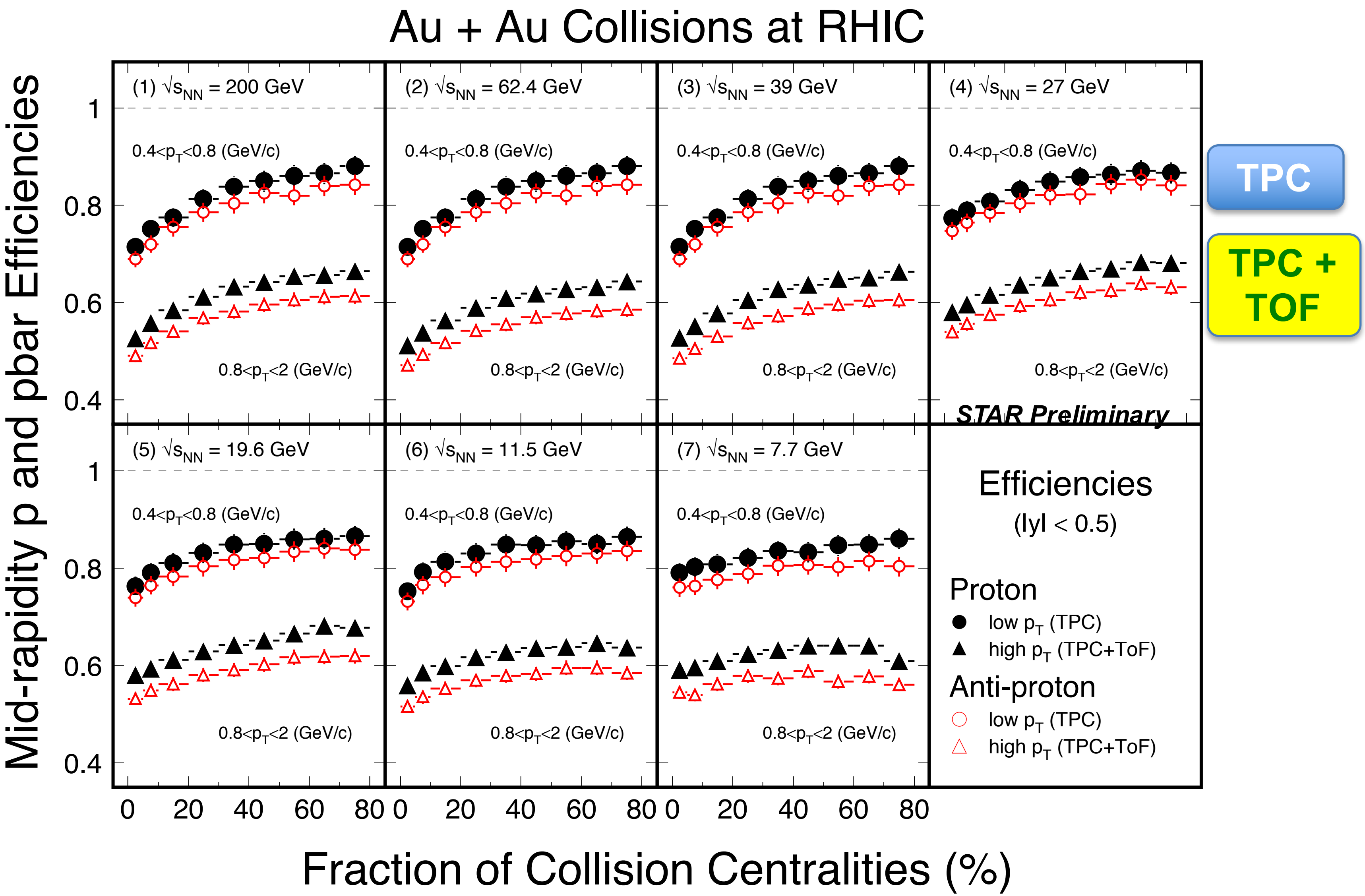
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

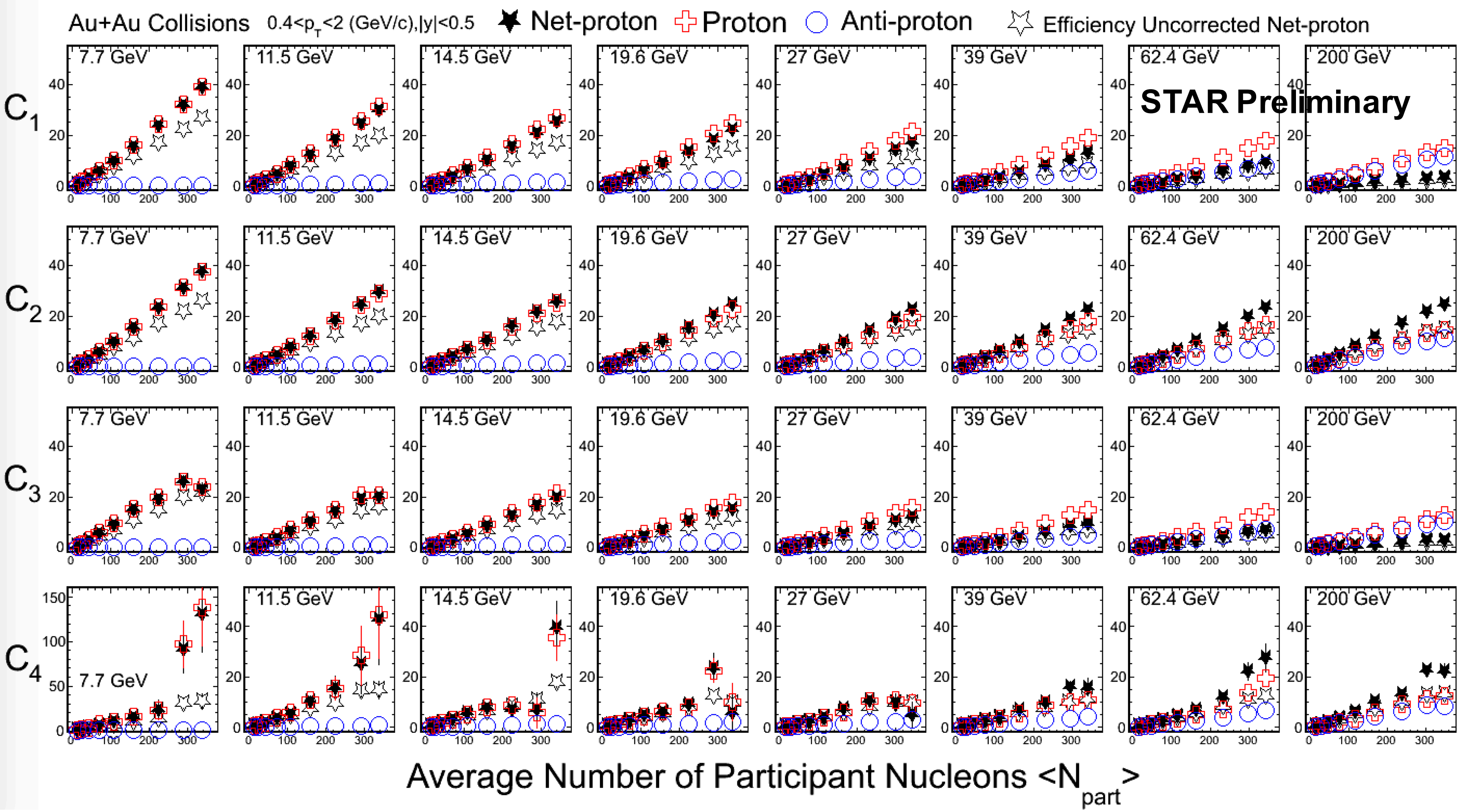
TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

Efficiencies for Protons and Anti-protons



Efficiency correction and error estimation methods : X. Luo, PRC91, 034907 (2015).

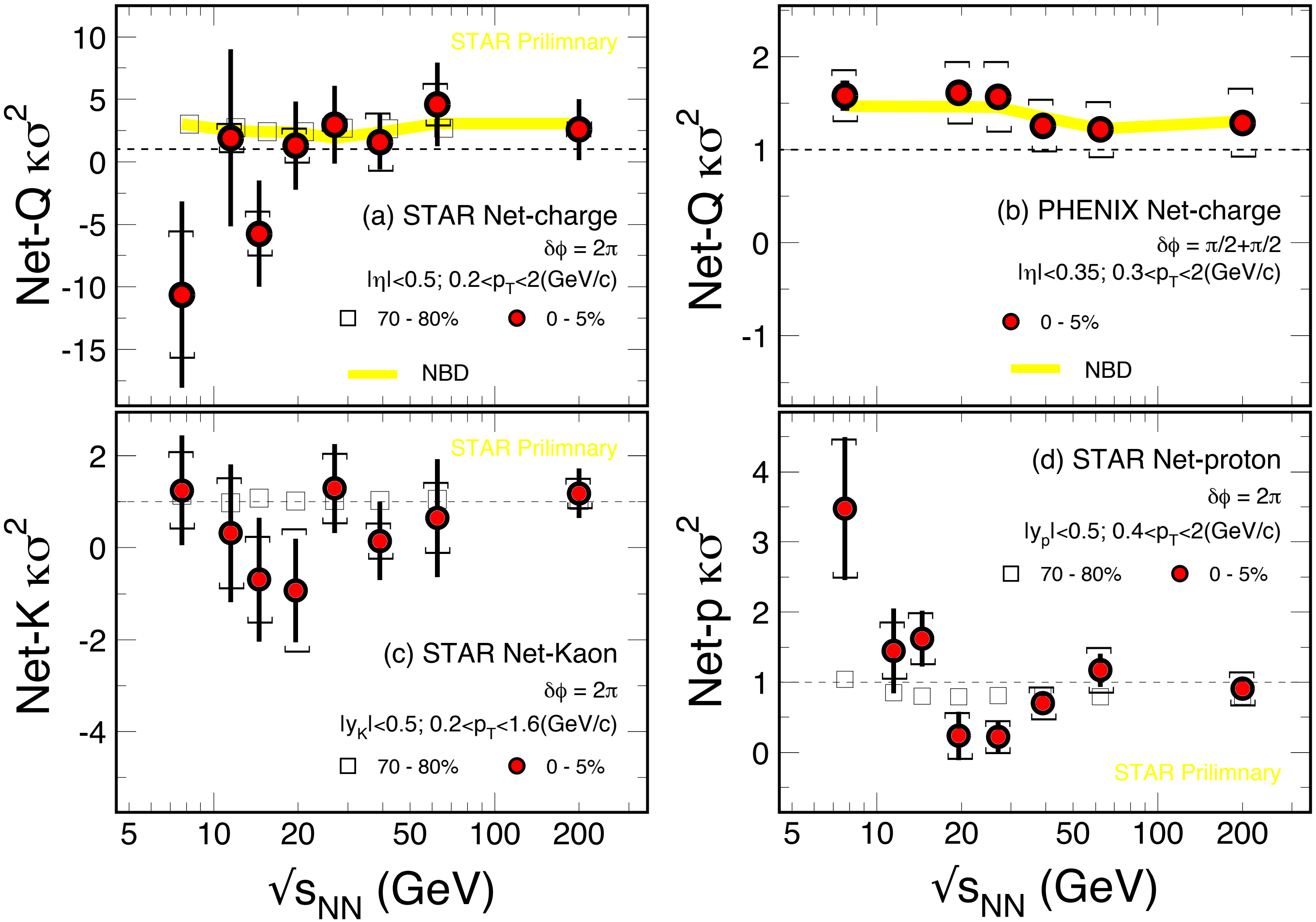
Net-Proton Cumulants: C1~C4



In general, cumulants are increasing with <N_{part}>.

Significant increase for C4 at most two central bin at 7.7 GeV.

Higher Moments of Net-Q, -K, -p



$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

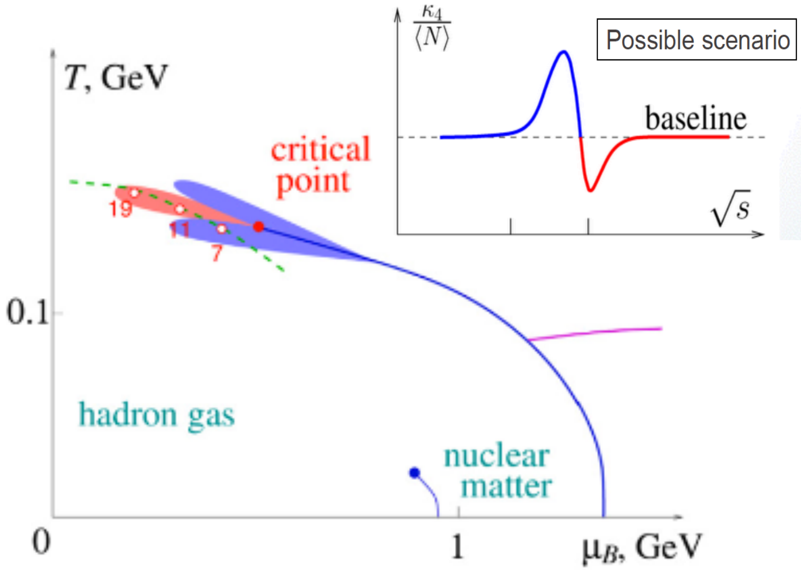
In STAR:

σ(Q) > σ(K) > σ(p)

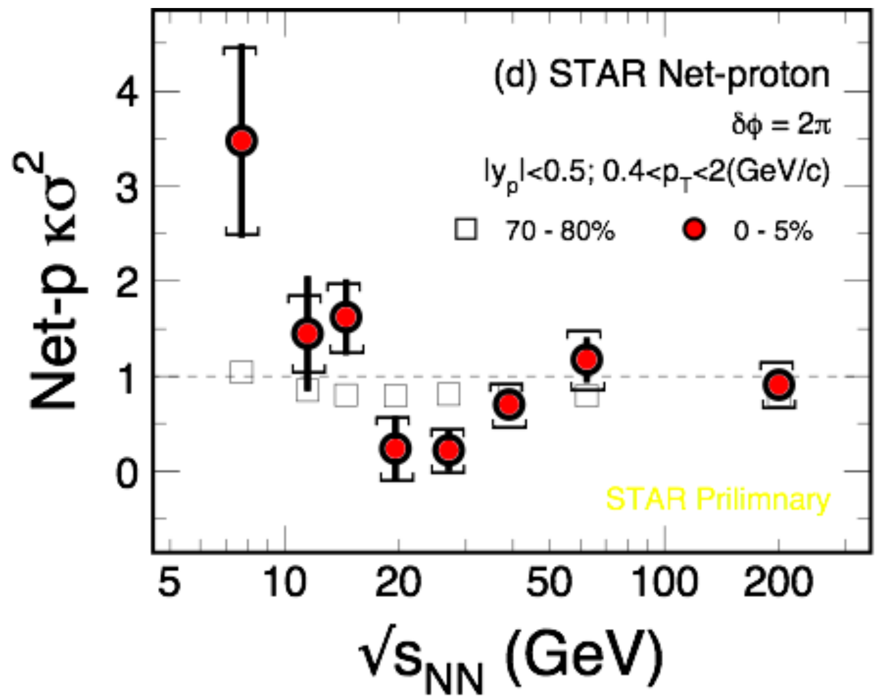
1) The results of net-Q and net-Kaon show flat energy dependence.
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions showing a minimum around $\sqrt{s_{NN}}$ = 20 GeV !

Expectation from Calculations

Model



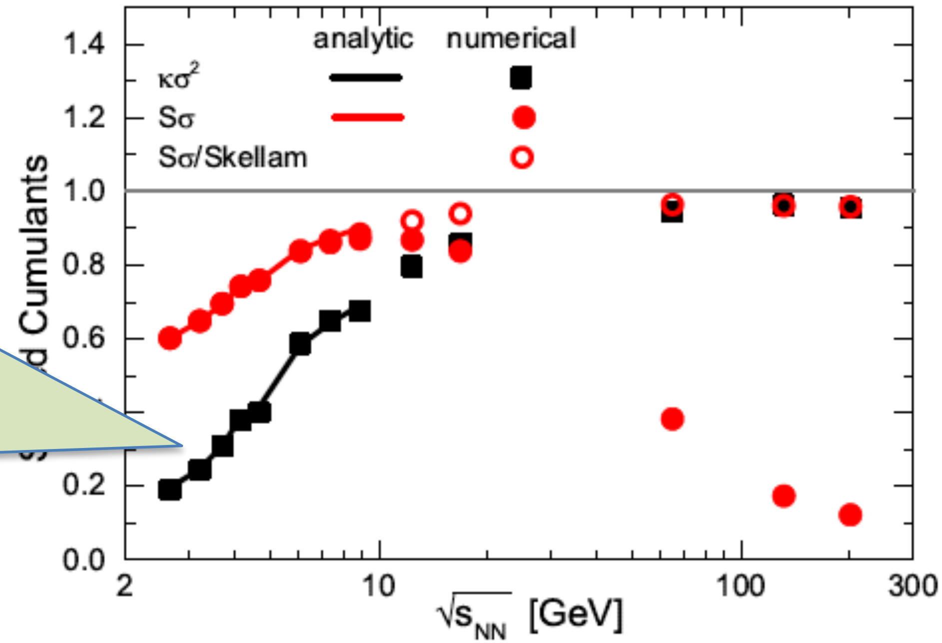
STAR BES Data



M.A. Stephanov, PRL107, 052301 (2011).
Schaefer&Wanger,PRD 85, 034027 (2012)
Vovchenko et al., PRC92, 054901 (2015)
JW Chen et al., PRD93, 034037 (2016)
arXiv: 1603.05198

Non-monotonic energy dependence is observed for 4th order net-proton fluctuations in most central Au+Au collisions.

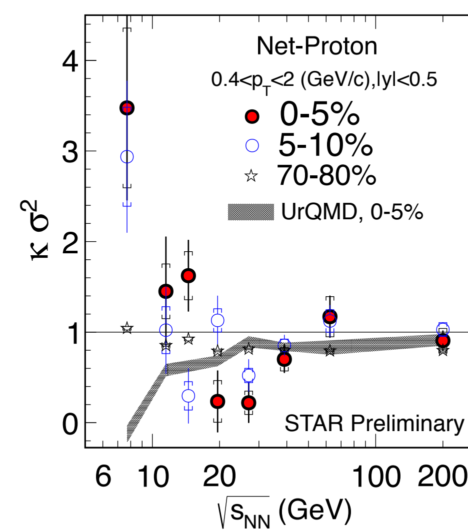
Model Simulation Results



At $\sqrt{s_{NN}} \leq 10$ GeV:

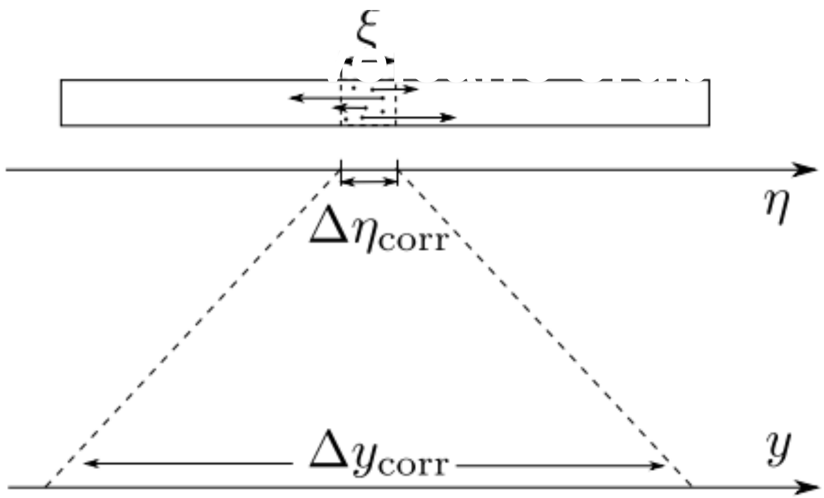
- Data: **$\kappa\sigma^2 > 1$!**
- Model: **$\kappa\sigma^2 < 1$!**
  - Baryon conservations
  - Mean-field
  - Deuteron formation

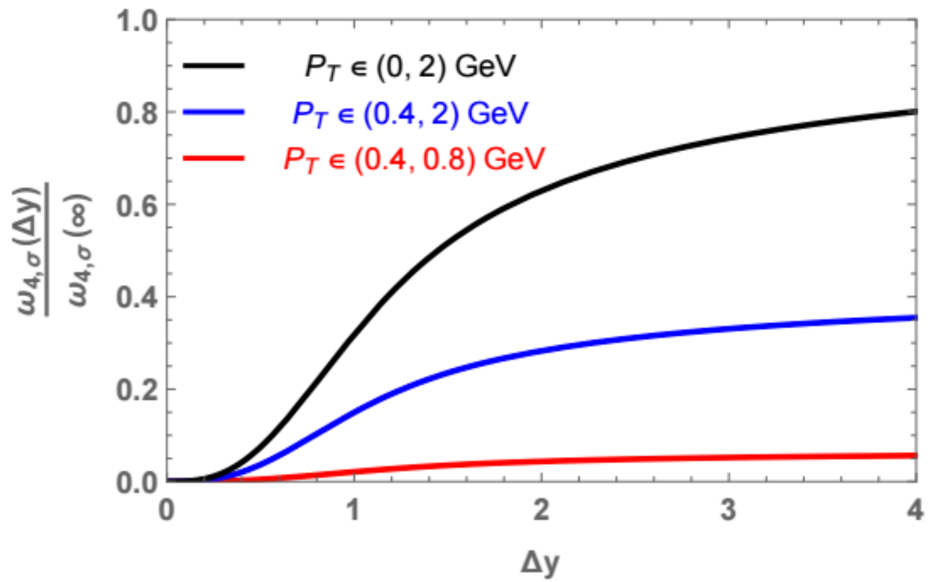
  All suppress higher order net-proton fluctuations



1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PR**C92**, 064908(15)
2) X.F. Luo *et al*, NP **A931**, 808(14)
3) P.K. Netrakanti *et al.* 1405.4617, NP **A947**, 248(16)
4) P. Garg *et al.* Phys. Lett. **B726**, 691(13)
5) Baryon mean-field effect (repulsive): also suppression in JAM.

Acceptance Dependence Study is Important !





Δy_{corr} : The correlation range in rapidity

Determined by the momentum distribution of the particles at freeze-out.

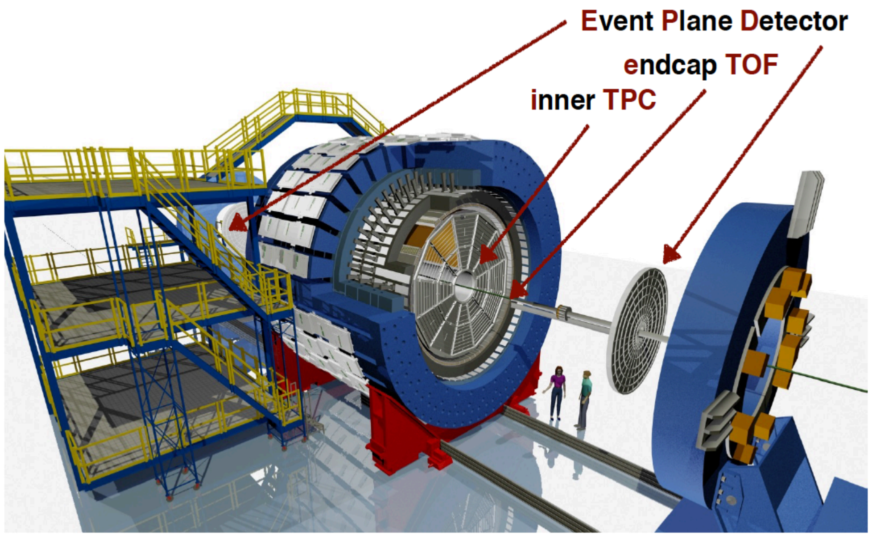
-- Diffusion + thermal Blurring effects.

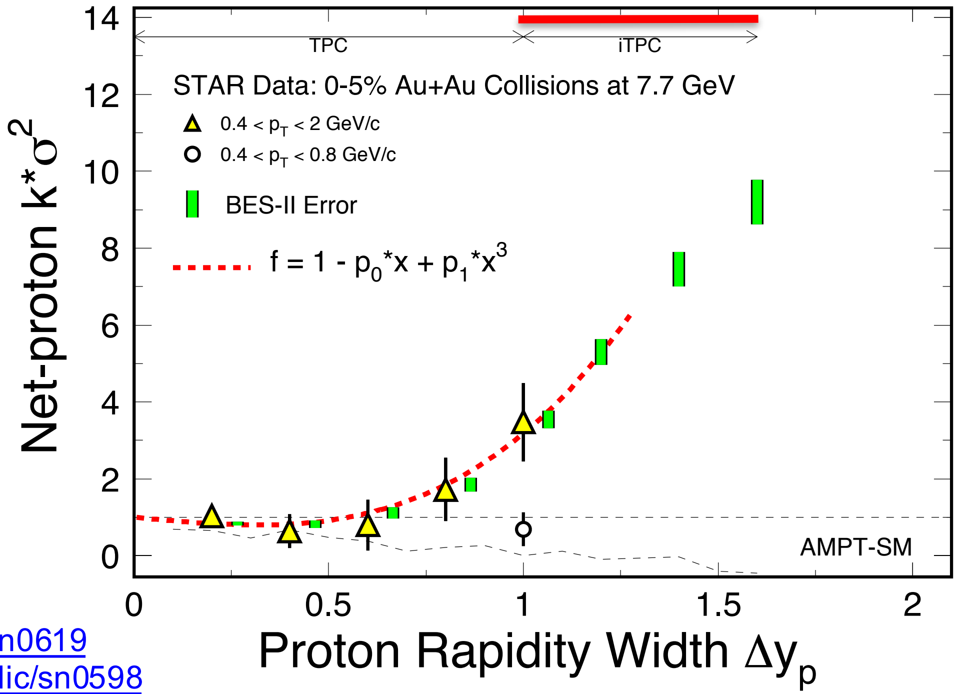
$$\kappa_4[M] = \underbrace{\langle M \rangle}_{\text{Poisson}} + \kappa_4[\sigma_V] \times g^4 \underbrace{\left(\text{(diagram)} \right)^4}_{\sim M^4} + \ldots \propto \begin{cases} M^4 & \textbf{Critical} \\ \langle M \rangle & \textbf{Thermal} \end{cases}$$

Test the non-linear power law behavior for Net-p Cumulsnts

B. Ling, M. Stephanov, *Phys. Rev. C 93, 034915 (2016)*

Rapidity Dependence





iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

1) BES-I results: Poisson + Baryon conservation + N^3,

2) BES-II: iTPC extend the rapidity coverage to $\Delta y = 1.6$, allowing us to studying kinematic dependence and test the non-linear power law behavior (criticality ?).

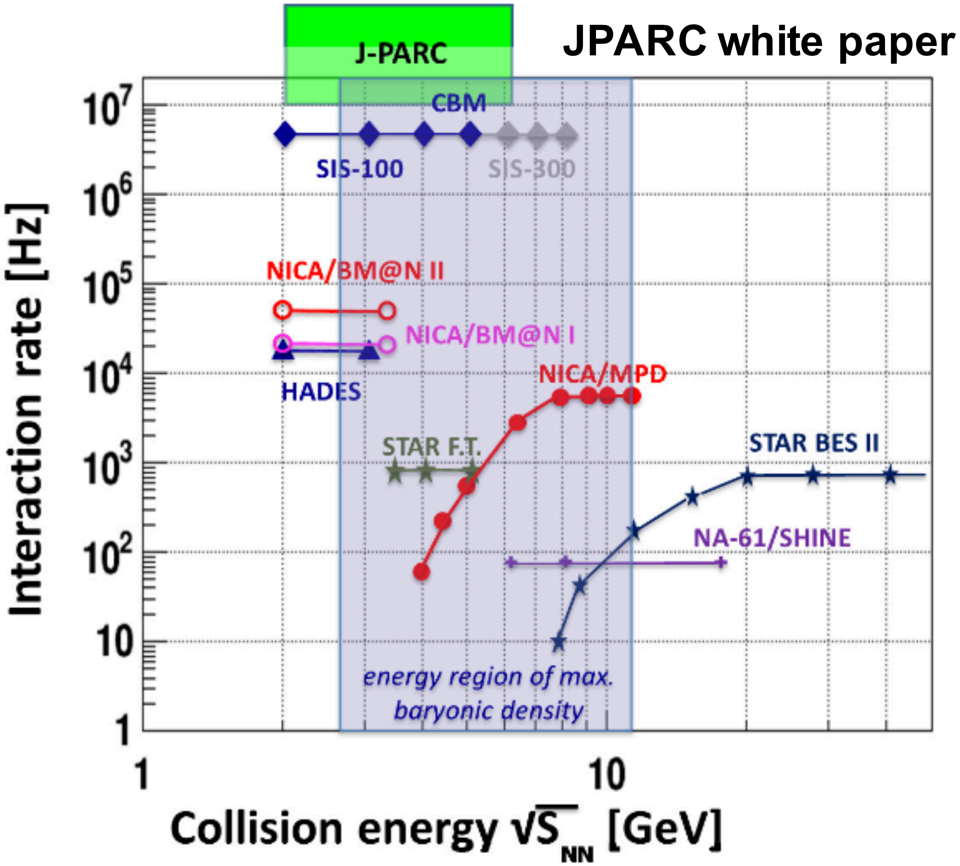
Event Statistics for BES II at RHIC

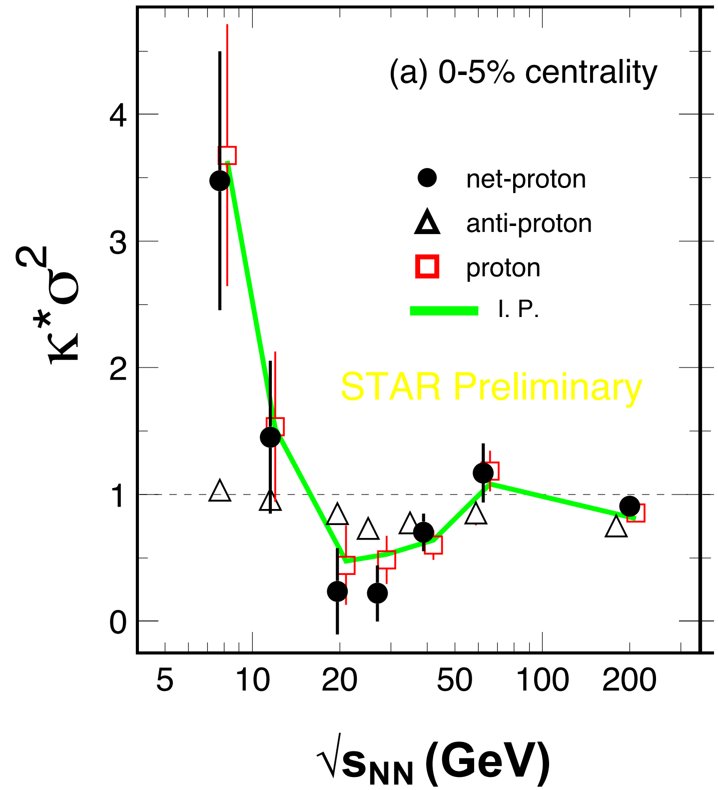
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

1) Event statistics driven by QCD CP search and di-electron measurements
2) STAR detector operated in the Fix-target mode is also planed in BESII.

FXT: $\sqrt{s_{NN}}$: 4.5, 3.9, 3.6, 3.0 GeV

BES-III: Nu's Order





Longer Future: fixed-target experiment (FXT) at extreme large net-baryon density, 350 < μ_B < 750 MeV (2 < $\sqrt{s_{NN}}$ < 8 GeV). At low energies, FXT experiment is more effective.

FXT: the Beam Energy Scan-III is needed for **QCD Critical Point !**

Summary

- We show cumulant and cumulant ratios for net-proton, net-K and net-charge for Au+Au collisions at 7.7,11.5,14.5, 19.6, 27, 39,62.4 and 200 GeV.

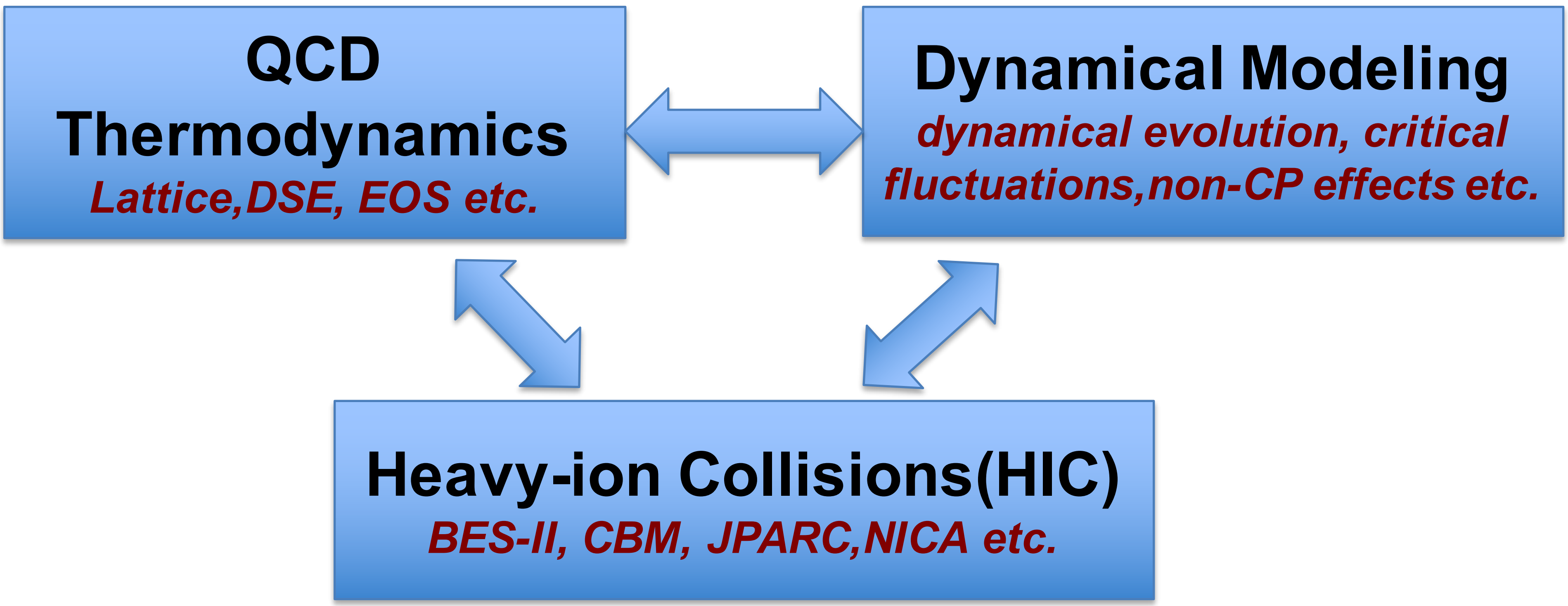
- *Non-monotonic behavior is observed at most central collisions for net-proton kurtosis.* Observation of the criticality ?

- Acceptance (p_T and y) studies indicate large acceptance is crucial for fluctuation measurements. Test the non-linear power law increase near the critical point.

- *Study the QCD phase structure at high baryon density region with high precision*: BES-II at RHIC (2019-2020, both collider and fix target mode). Beyond 2020-: CBM, JPARC (fix-target).

Outlook

Search for the QCD Critical Point in HIC



1. Confirm the observation of criticality in heavy-ion collisions !
2. Pin down the exact location of CP in the phase diagram.

Huge potential for discoveries !
Let us do it together !