Search for the QCD Critical Point -
Fluctuations of Conserved Quantities in High-Energy Nuclear Collisions at RHIC

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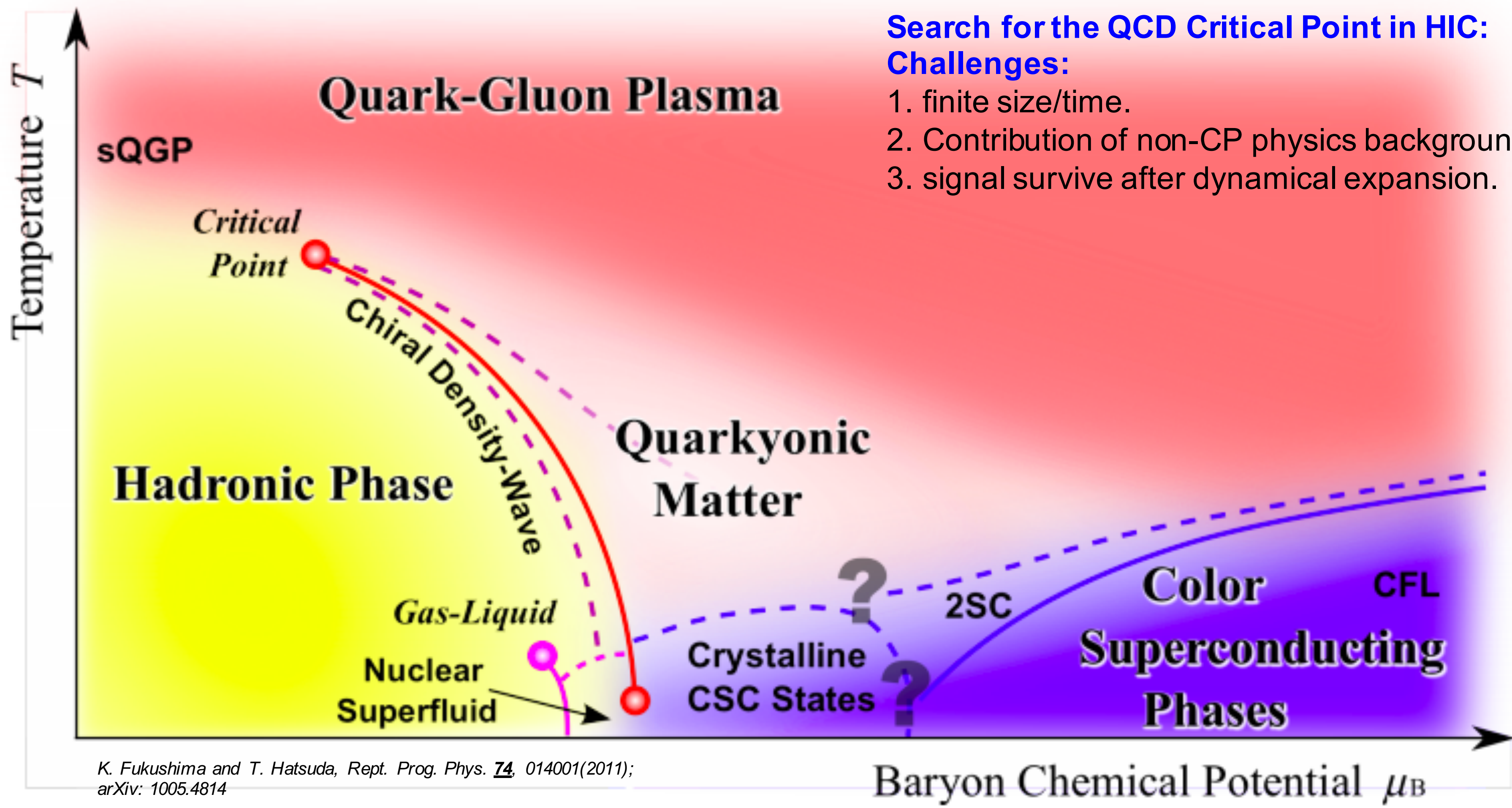
Aug. 31, 2016

QCD Phase Diagram (Conjectured)

QCD Phase Structure : Emergent properties of the strong interaction.

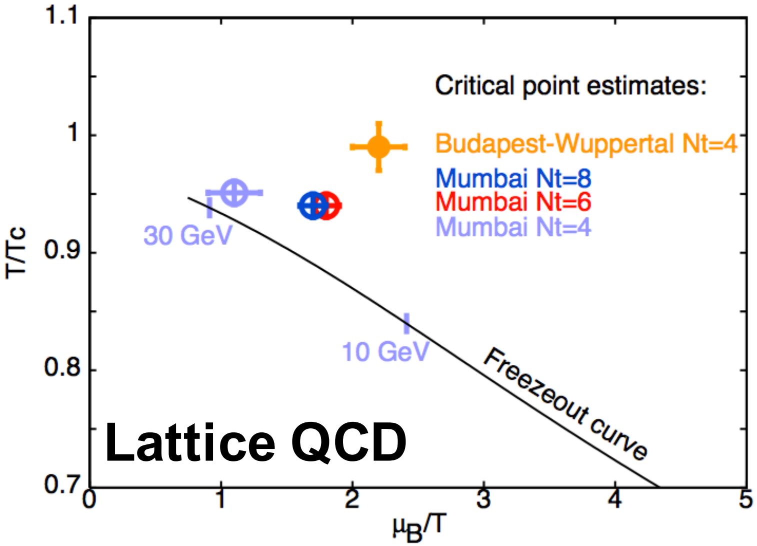


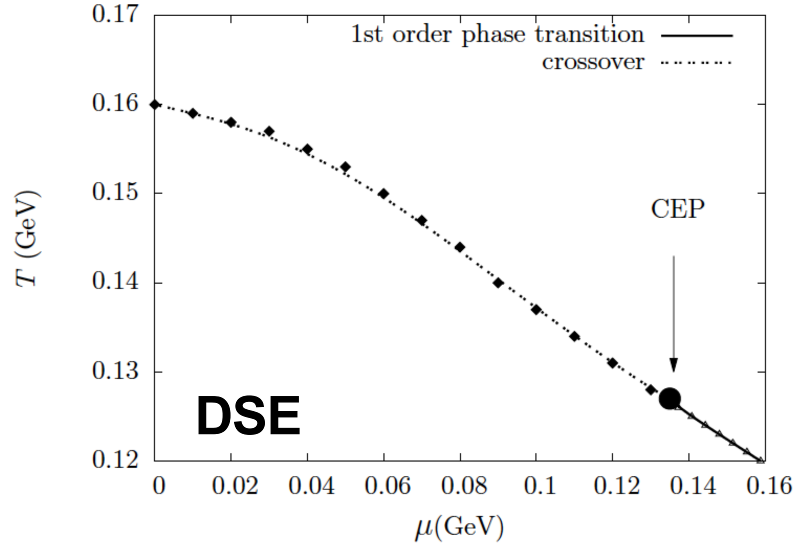
*K. Fukushima and T. Hatsuda, Rept. Prog. Phys. **74**, 014001(2011); arXiv: 1005.4814*

Search for the QCD Critical Point in HIC:
Challenges:

1. finite size/time.
2. Contribution of non-CP physics background.
3. signal survive after dynamical expansion.

Location of CEP: Theoretical Prediction





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

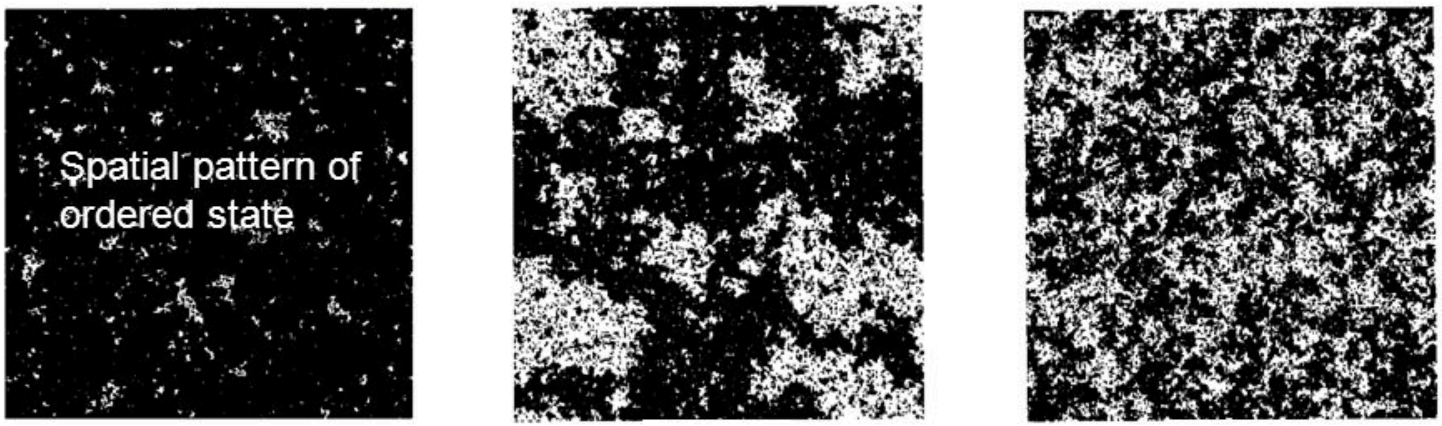
2): Hong-shi Zong et al., JHEP 07, 014 (2014).
$(\mu^E_B, T_E) = (405, 127)$ MeV

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

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

Critical Point and Critical Phenomena

Ordered $T=0.995T_c$ | Critical $T=T_c$ | Disordered $T=1.05T_c$



2D-Ising model simulation from ISNB4-563-02435-X C33421

Critical Phenomena :

- Density fluctuations and cluster formations.
- Divergence of Correlation length (ξ).

  Susceptibilities (χ), heat capacity (C_V) ,

  Compressibility (κ) etc.

  Critical opalescence.

- Universality and critical exponents determined by the symmetry and dimensions of underlying system.

First CP is discovered in 1869 for CO_2

T_c = 31°C

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

T_c ~ Trillion (10^{12}) °C

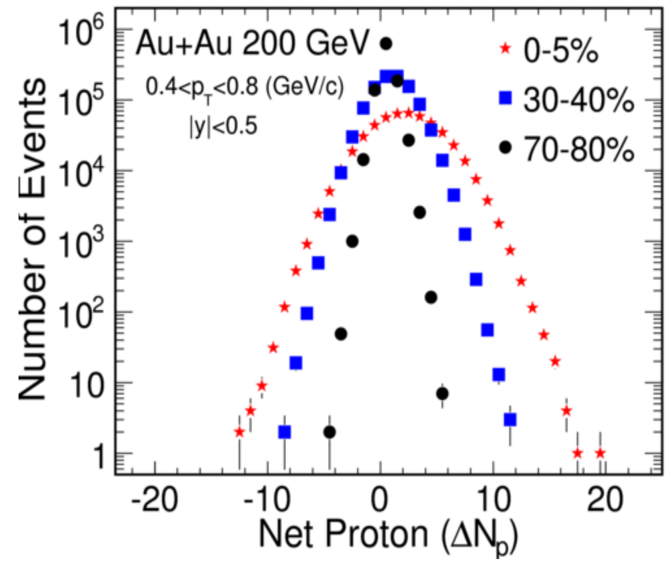
Fluctuations of Conserved Quantities

1. **Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations.**

$$C_{1,x} = < x >, C_{2,x} = < (\delta x)^2 >,$$
$$C_{3,x} = < (\delta x)^3 >, C_{4,x} = < (\delta x)^4 > -3 < (\delta x)^2 >^2$$

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

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).
Y. Hatta, M. Stephanov, Phys. Rev. Lett. 91, 102003 (2003).

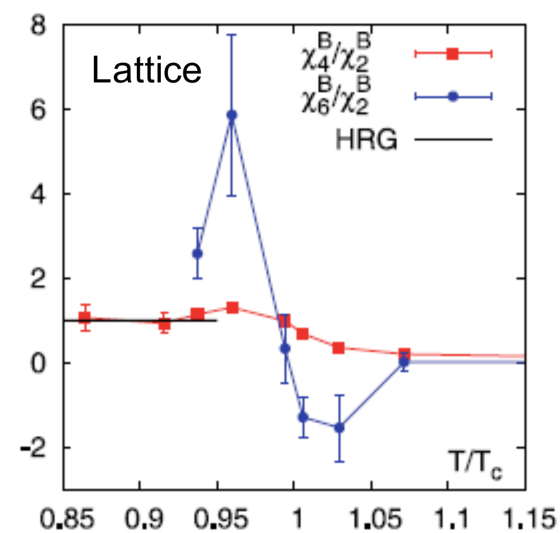


2. **Connection to the susceptibility of the system.**

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

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

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



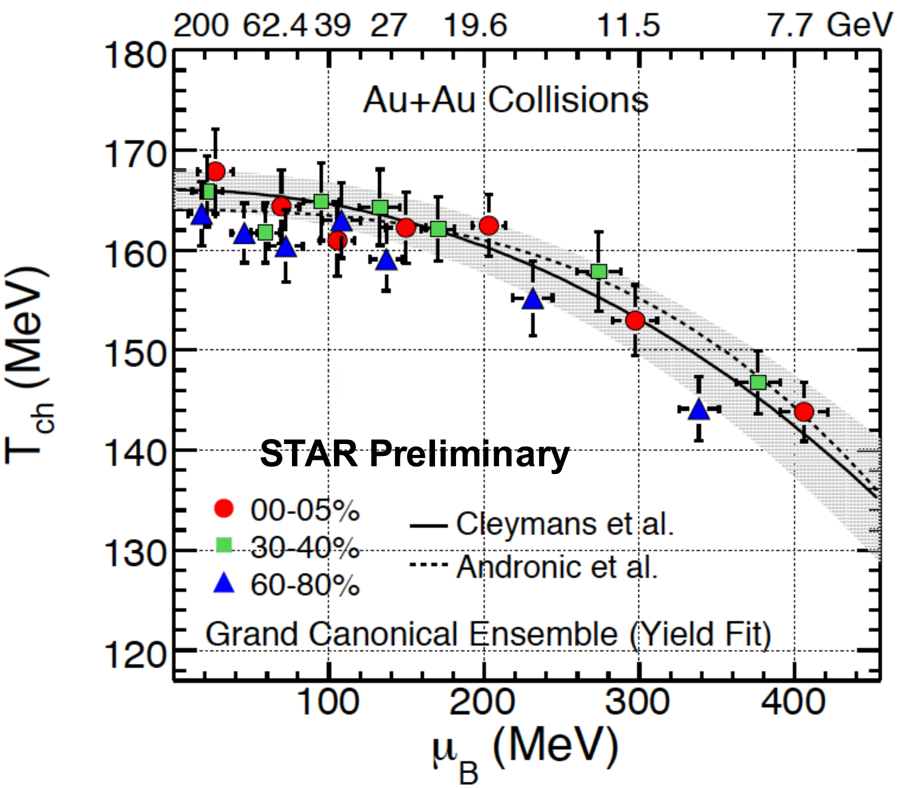
STAR Detector System

- Large, Uniform Acceptance at Mid-y
- Excellent Particle Identification

RHIC Beam Energy Scan- I (2010-2014)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*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	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140

*(μ_B, T_{CH}) : J. Cleymans et al., PR**C73**, 034905 (2006)



1) Access broad region of the QCD phase diagram.
2) STAR: Large and homogeneous acceptance, excellent PID capabilities.

STAR is a unique detector with huge discovery potential in exploring the QCD phase structure at high baryon density.

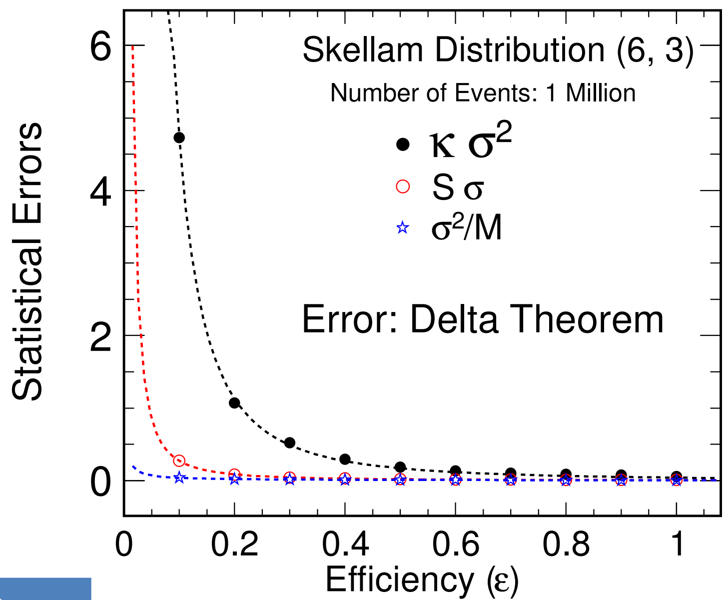
Efficiency Correlation and Error Estimation

- We can express the cumulants in terms of the factorial moments, which can be easily efficiency corrected by assuming binomial response function for efficiency.

$$f(\varepsilon) = \frac{1}{\sqrt{n}} \frac{a}{\varepsilon^b}$$

$$F_{u,v,j,k}(N_{p_1}, N_{p_2}, N_{\bar{p}_1}, N_{\bar{p}_2}) = \frac{f_{u,v,j,k}(n_{p_1}, n_{p_2}, n_{\bar{p}_1}, n_{\bar{p}_2})}{(\varepsilon_{p_1})^u (\varepsilon_{p_2})^v (\varepsilon_{\bar{p}_1})^j (\varepsilon_{\bar{p}_2})^k}$$

A. Bzdak and V. Koch, PRC91, 027901 (2015).
X. Luo, PRC91, 034907 (2015);



- Statistical Errors based on Delta Theorem.
  With same N events: error(net-charge) > error(net-kaon) > error(net-proton)

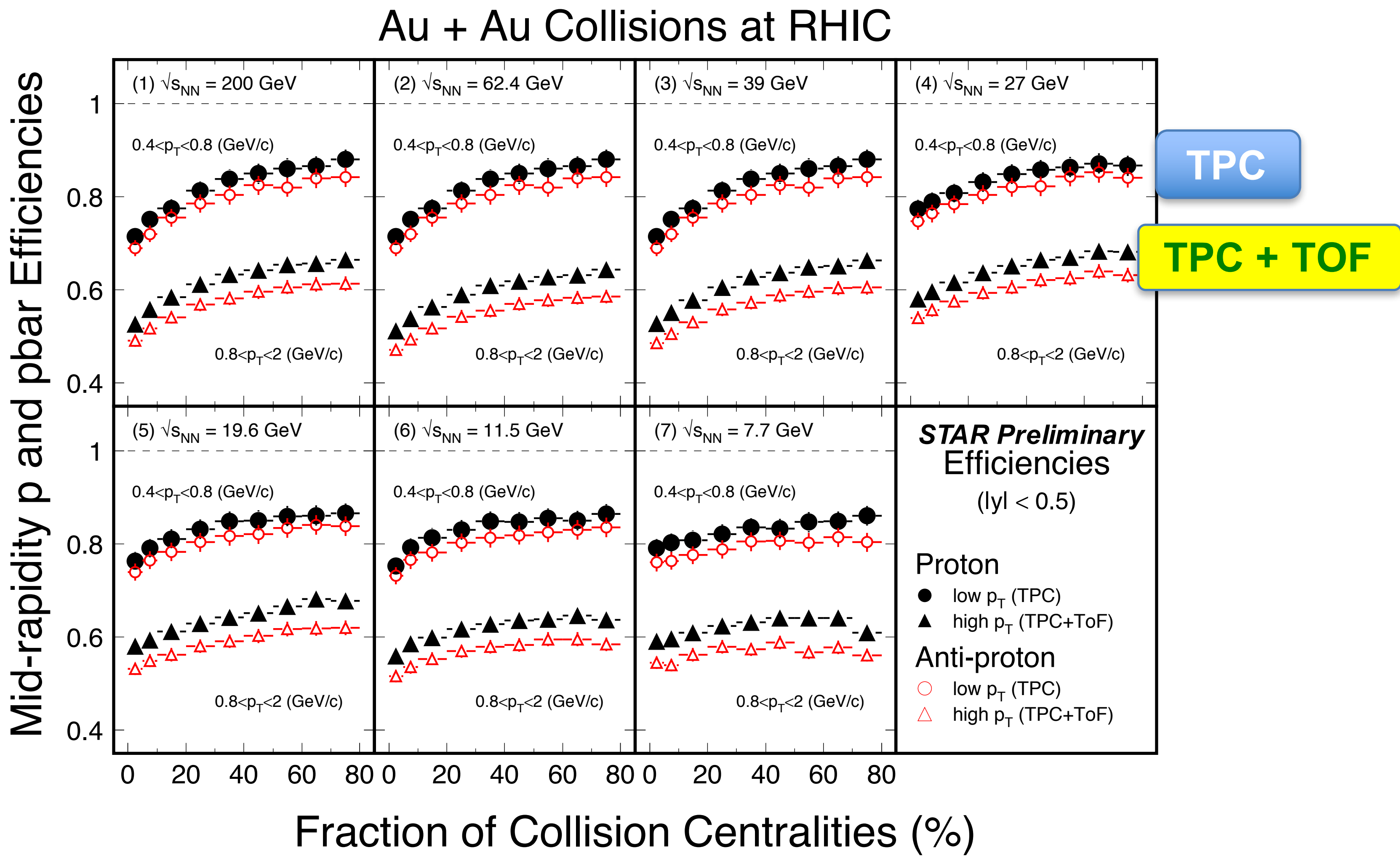
Au+Au 14.5GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width(σ)	12.2	4.2	3.4
Average efficiency(ε)	65%	75%	38%
σ^2/ε^2	355	32	82

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

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

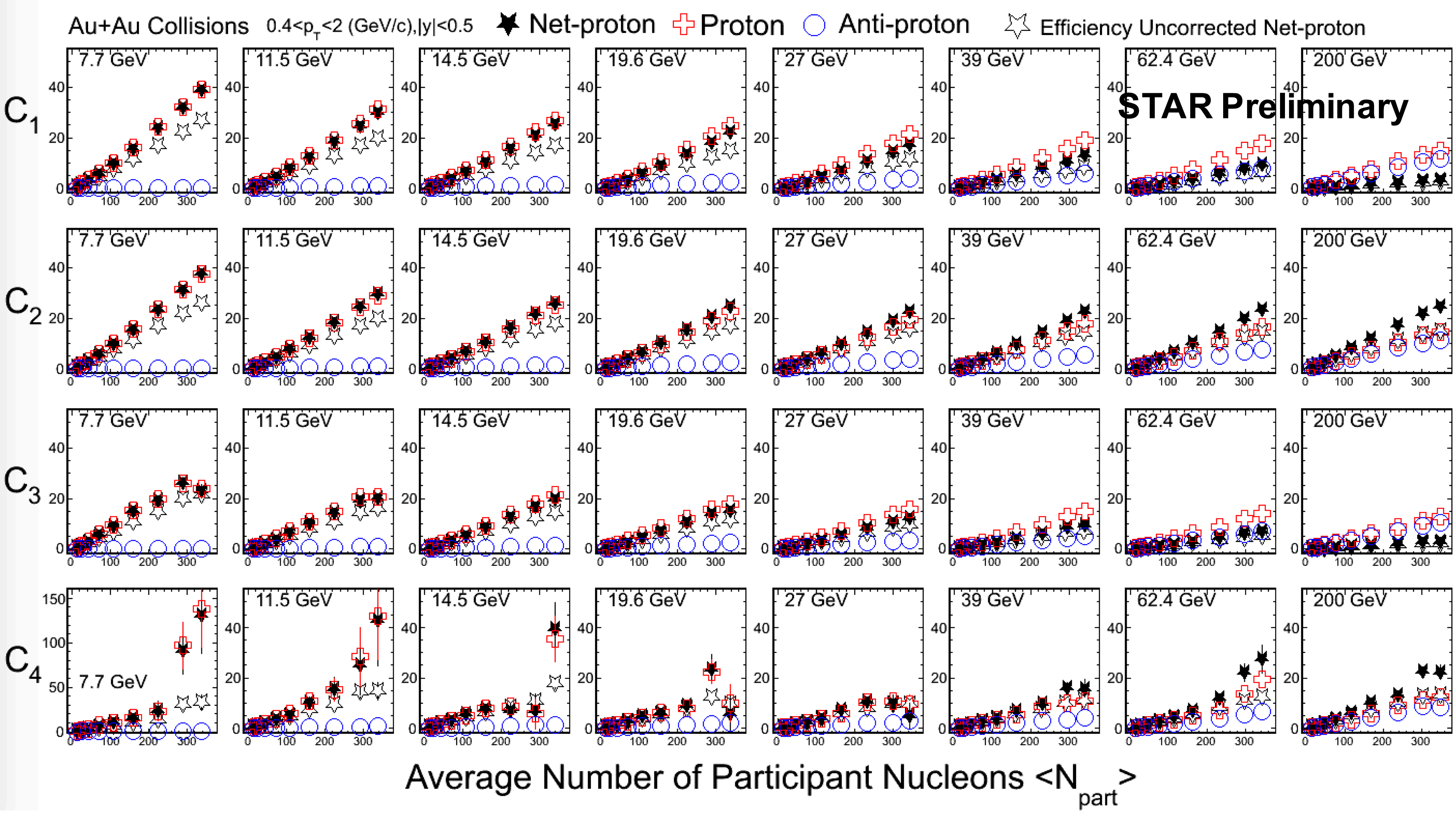
Those numbers are for illustration purpose and not used in actual analysis

Efficiencies for Protons and Anti-protons



- Due to TOF matching eff., high p_T efficiency (~50%) are smaller than low p_T (~80%).
- Efficiency decrease with increasing energies and centralities.
- Proton Efficiency > Anti-proton Efficiency

Net-Proton Cumulants (C_1~C_4) Vs. Centrality

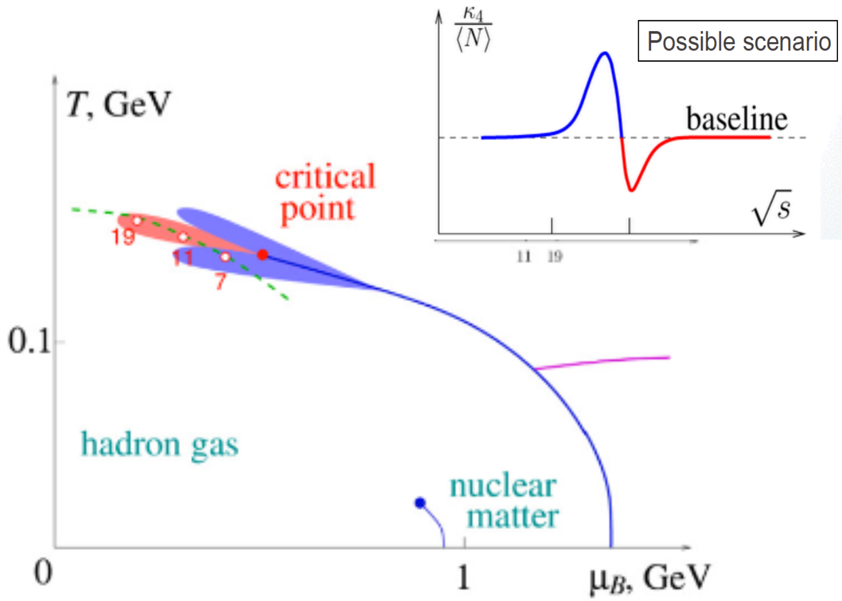


1. In general, cumulants are linearly increasing with <N_{part}>.
2. Efficiency corrections are important.
3. At low energies, the proton cumulants are close to net-proton.

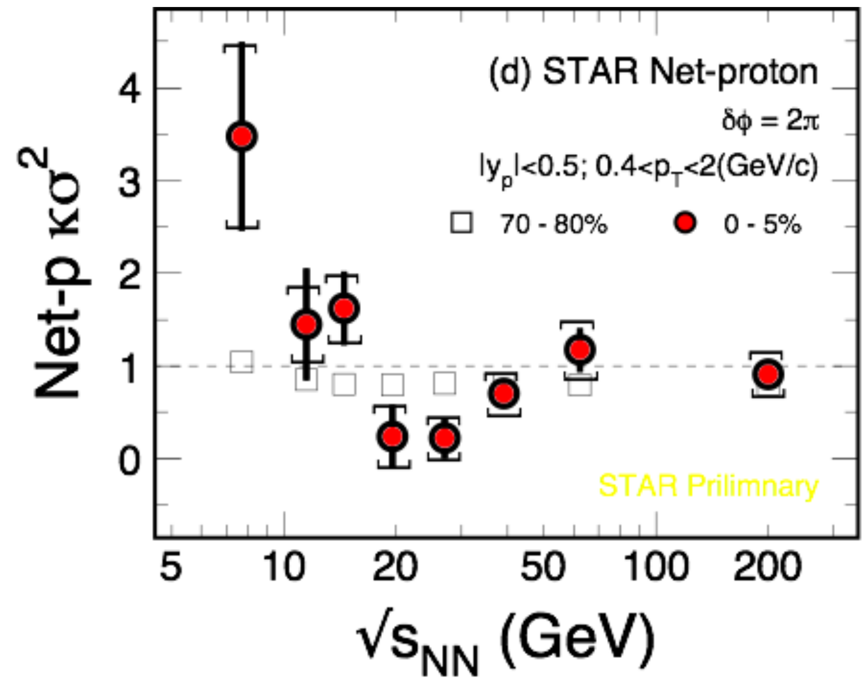
Forth Order Fluctuations: Net-proton

$$\kappa\sigma^2 = C_4/C_2$$

Model



STAR BES Data

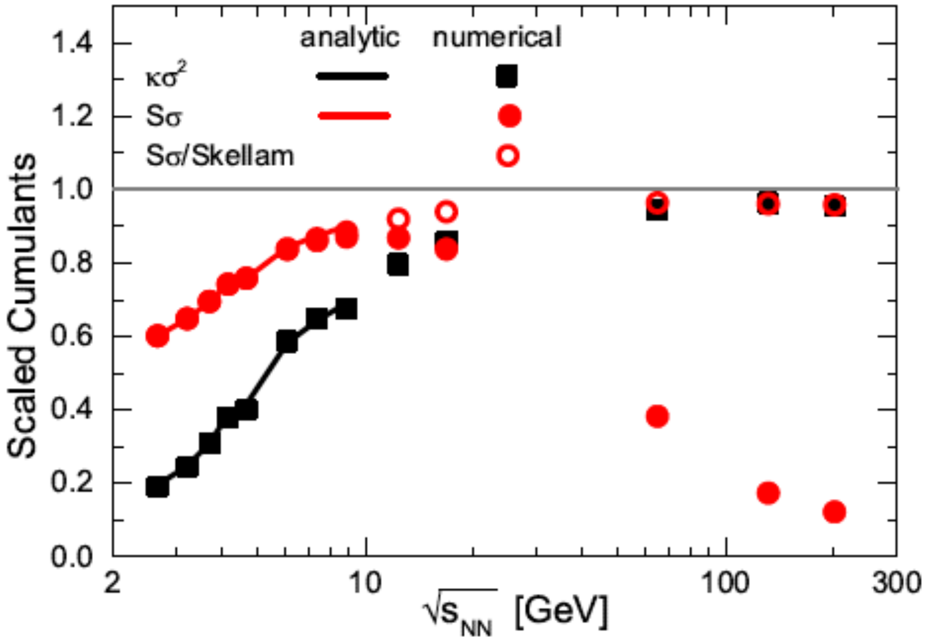


M.A. Stephanov, PRL107, 052301 (2011).
Schaefer&Wanger,PRD 85, 034027 (2012)
Vovchenko et al., PRC92, 054901 (2015)
JW Chen et al., PRD93, 034037 (2016)
arXiv: 1603.05198.

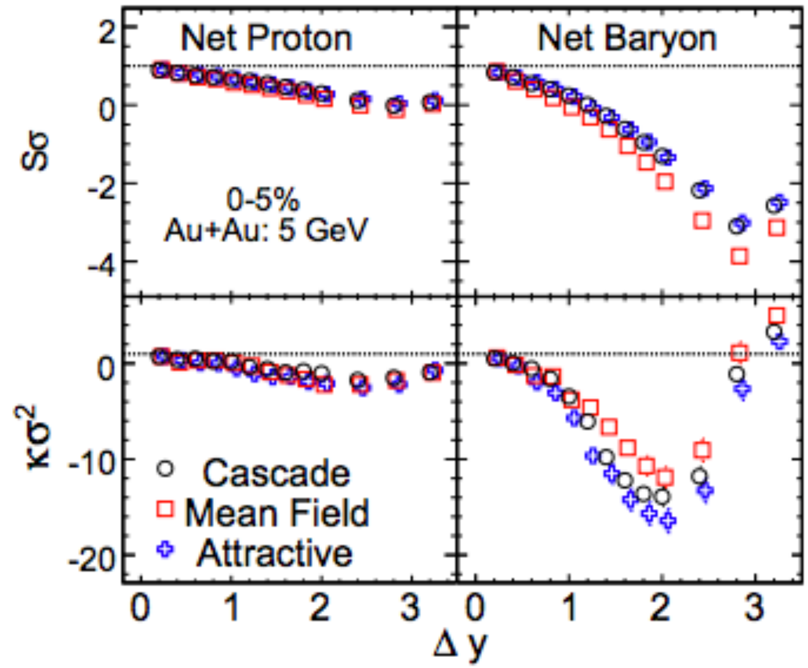
Non-monotonic energy dependence is observed for 4th order net-proton fluctuations in most central Au+Au collisions.

Model Results : Net-Proton $\kappa\sigma^2$

UrQMD



JAM

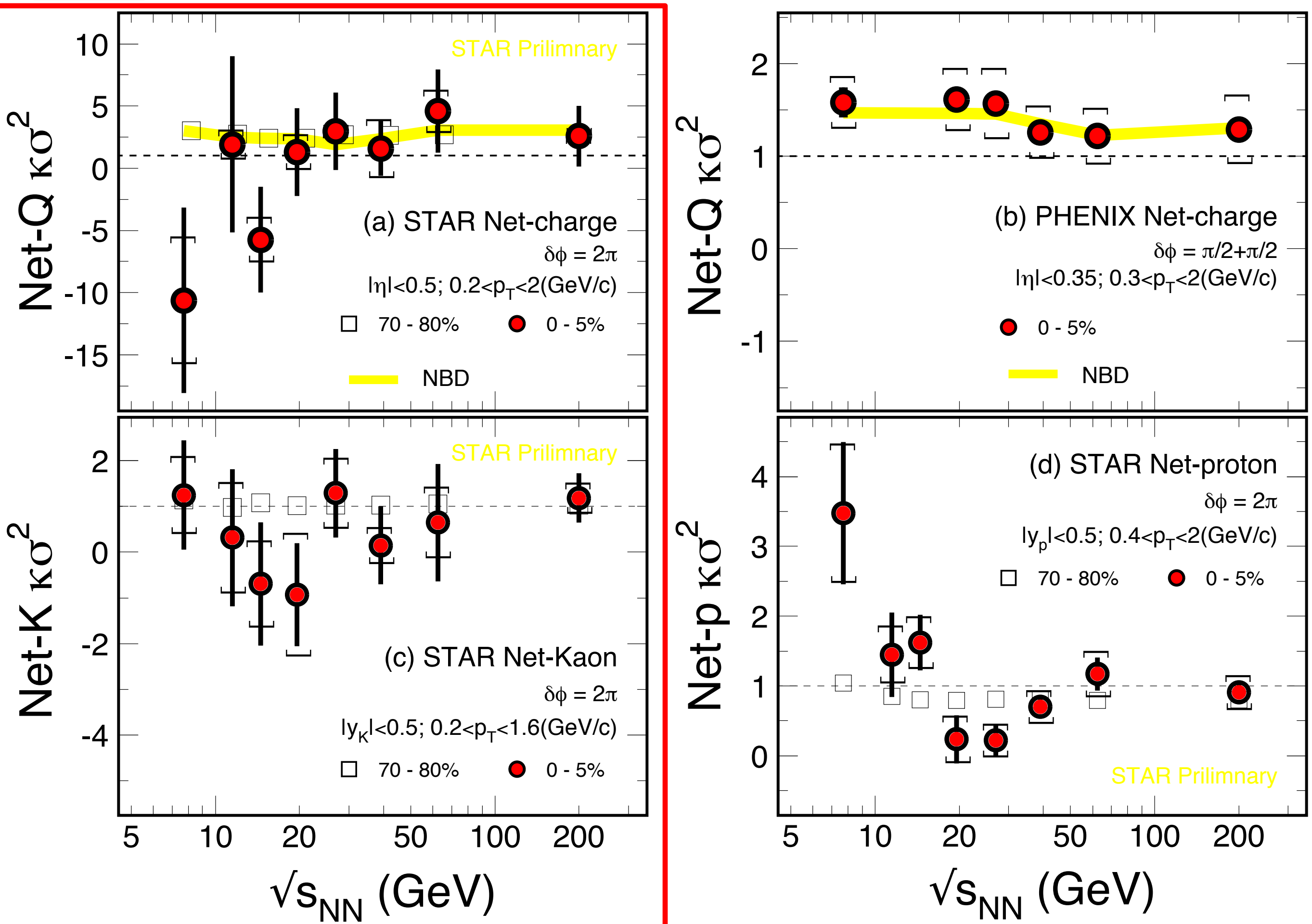


At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$** Model: **$\kappa\sigma^2 < 1$**

- Model simulation indicates: *Baryon conservations, Mean-field potential, Deuteron formation, Softening of EOS. All suppress the net-proton fluctuations.*

1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, PR**C92**, 064908(2015). J. Xu, S. Yu, F. Liu, X. Luo, PR**C94**, 024901(2016). X. Luo *et al*, NP**A931**, 808(14), P.K. Netrakanti *et al.* 1405.4617, NP**A947**, 248(2016), P. Garg *et al.* Phys. Lett. **B726**, 691(2013).
2) S. He, X. Luo, Y. Nara, S. Esuimi, N. Xu, arXiv: 1607.06376.

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



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

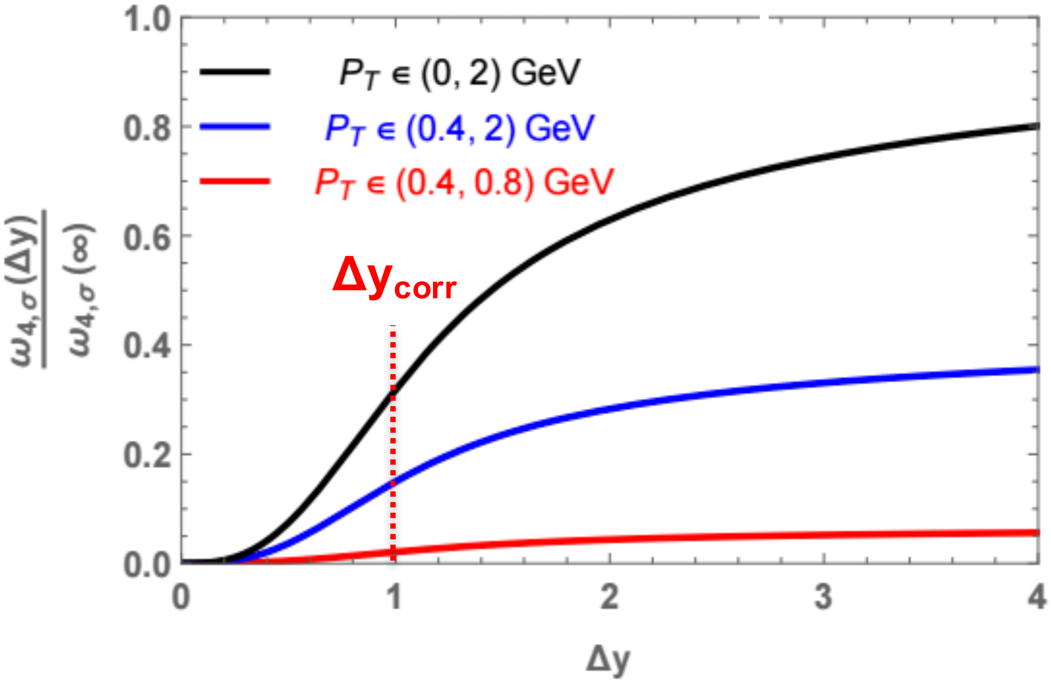
In STAR:

$\sigma(Q) > \sigma(K) > \sigma(p)$

1) Within errors, the results of net-Q and net-Kaon show flat energy dependence.
2) More statistics are needed at low energies.

Acceptance Dependence : Test the power law behavior

Acceptance dependence of the critical contribution



Δy_{corr} : The correlation range in rapidity

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

$$C_1 = <N>$$

$$C_2 = <N> + \hat{\kappa}_2$$

$$C_3 = <N> + 3\hat{\kappa}_2 + \hat{\kappa}_3$$

$$C_4 = <N> + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

$\hat{\kappa}_2, \hat{\kappa}_3, \hat{\kappa}_4$: 2,3,4-particle correlation function

Generating function for the factorial cumulants: $\hat{\kappa}_n$ (corr. fun.):

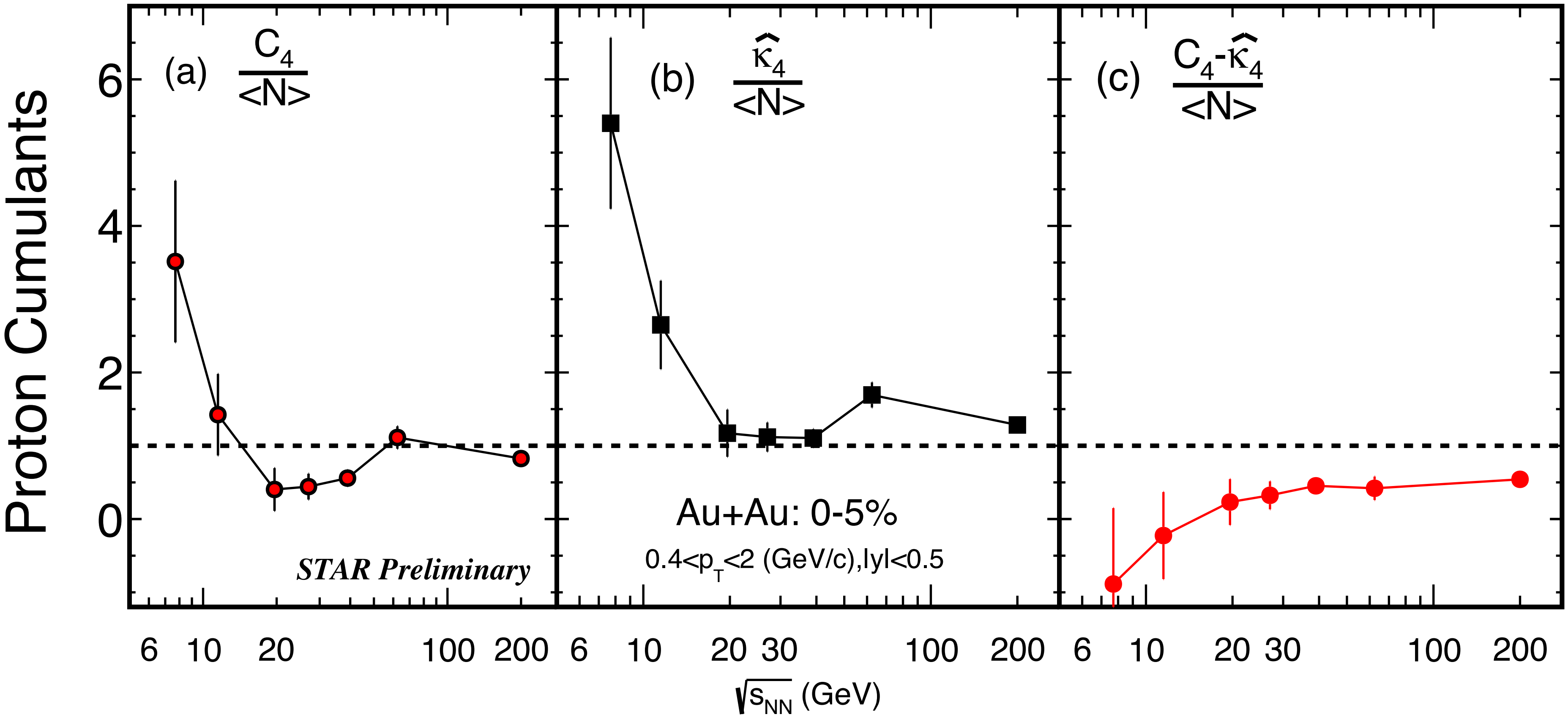
$$g(x) \equiv \sum_{k=1}^{\infty} \hat{\kappa}_k \frac{x^k}{k!} = \ln \langle (1+x)^N \rangle .$$

If $\Delta y << \Delta y_{corr}$: $C_n \propto \hat{\kappa}_n \propto <N>^n \sim (\Delta y)^n$ **(Critical dominate)**

If $\Delta y >> \Delta y_{corr}$: $C_n \propto \hat{\kappa}_n \propto <N> \sim (\Delta y)$ **(Non-critical dominate)**

Contributions from Four- Particle Correlation

X. Luo (for the STAR Collaboration), PoS(CPOD2014)019 [arXiv:1503.02558].

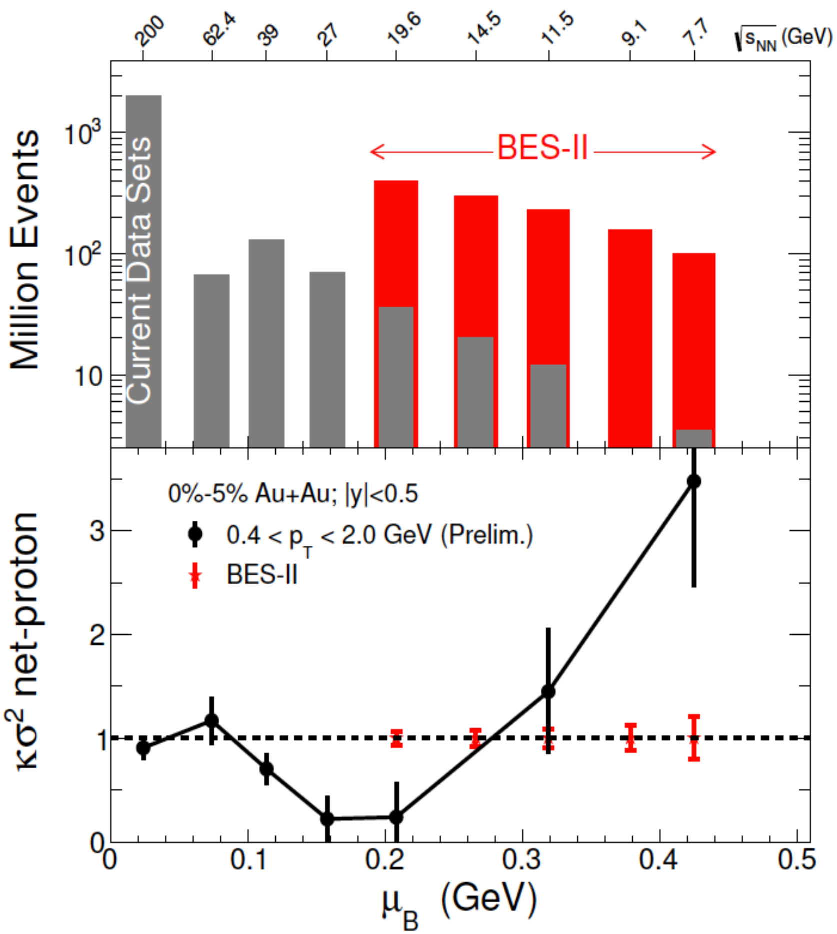


Without the four particle correlation, the non-monotonic behavior observed in forth order net-proton fluctuations disappears.

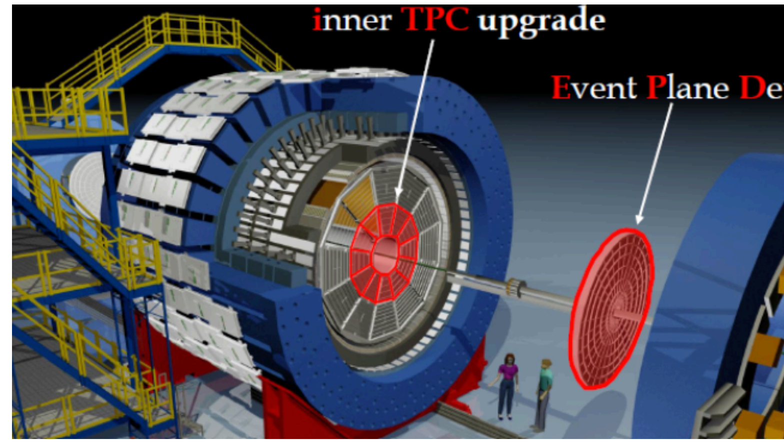
BES II at RHIC (2019-2020)

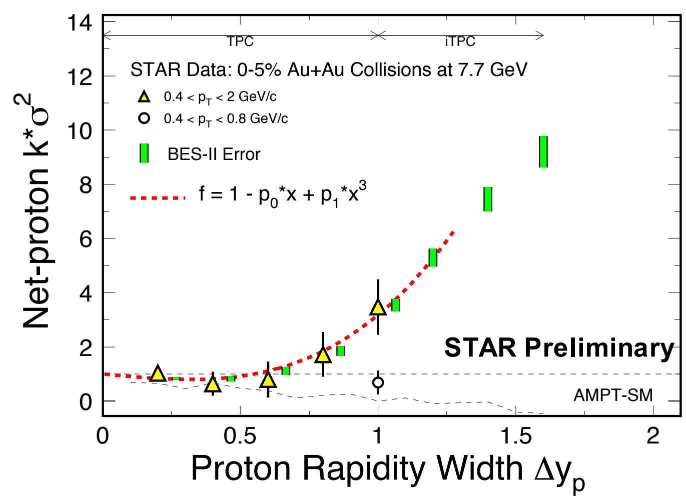
More Data

RHIC Luminosity Upgrade for Low Energies



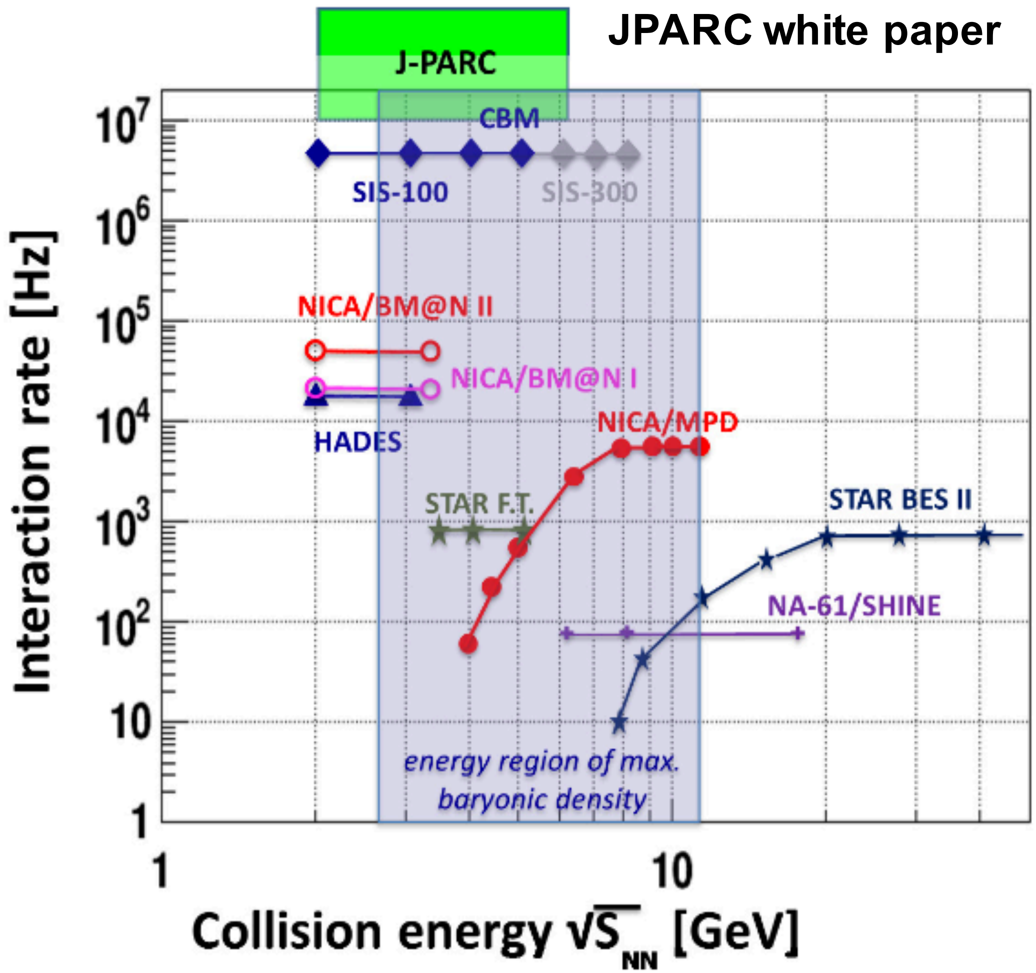
iTPC upgrade extends the rapidity coverage to $\Delta y = 1.6$

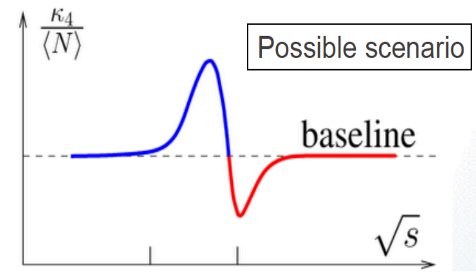


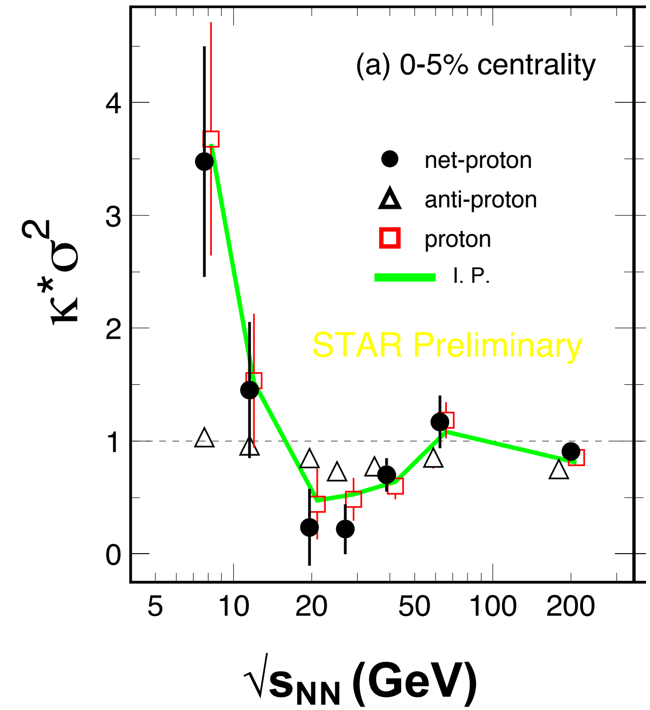


1) Event statistics driven by QCD CP search and di-electron measurements.
2) The STAR Fix-target mode is also planed in BESII. ($\sqrt{s_{NN}}$: 4.5, 3.9, 3.6, 3.0 GeV)

Future Experiments for High Baryon Density







Longer future: search for the "peak structure" of CP at lower energies

$350 < \mu_B < 750$ MeV ($2 < \sqrt{s_{NN}} < 8$ GeV). FXT experiment is more effective.

Summary

- We show cumulants of net-proton, net-K and net-Q for Au+Au collisions at 7.7,11.5,14.5, 19.6, 27, 39, 62.4 and 200 GeV.

- *Non-monotonic energy dependence is observed at central Au+Au collisions for net-proton kurtosis, which is consistent with the presence of critical point.* Observation of the criticality ?

- Acceptance (p_T and y) studies : *Looking for the non-linear power law behavior.*

- Study the QCD phase structure at high baryon density with high precision:
  (1) BES-II at RHIC (2019-2020, both collider and fix target mode).
  (2) Fix-target at low energies: : FAIR/CBM(starting at 2022).

Thank you !