Search for the QCD Critical Point -

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

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July 26, 2017

Outline

1. Introduction

2. Experimental Results from STAR experiments

3. Model and Theoretical Calculations

   1):Signals from Criticality.

   - NJL, PQM, σ model etc.
   - DSE, Lattice QCD.

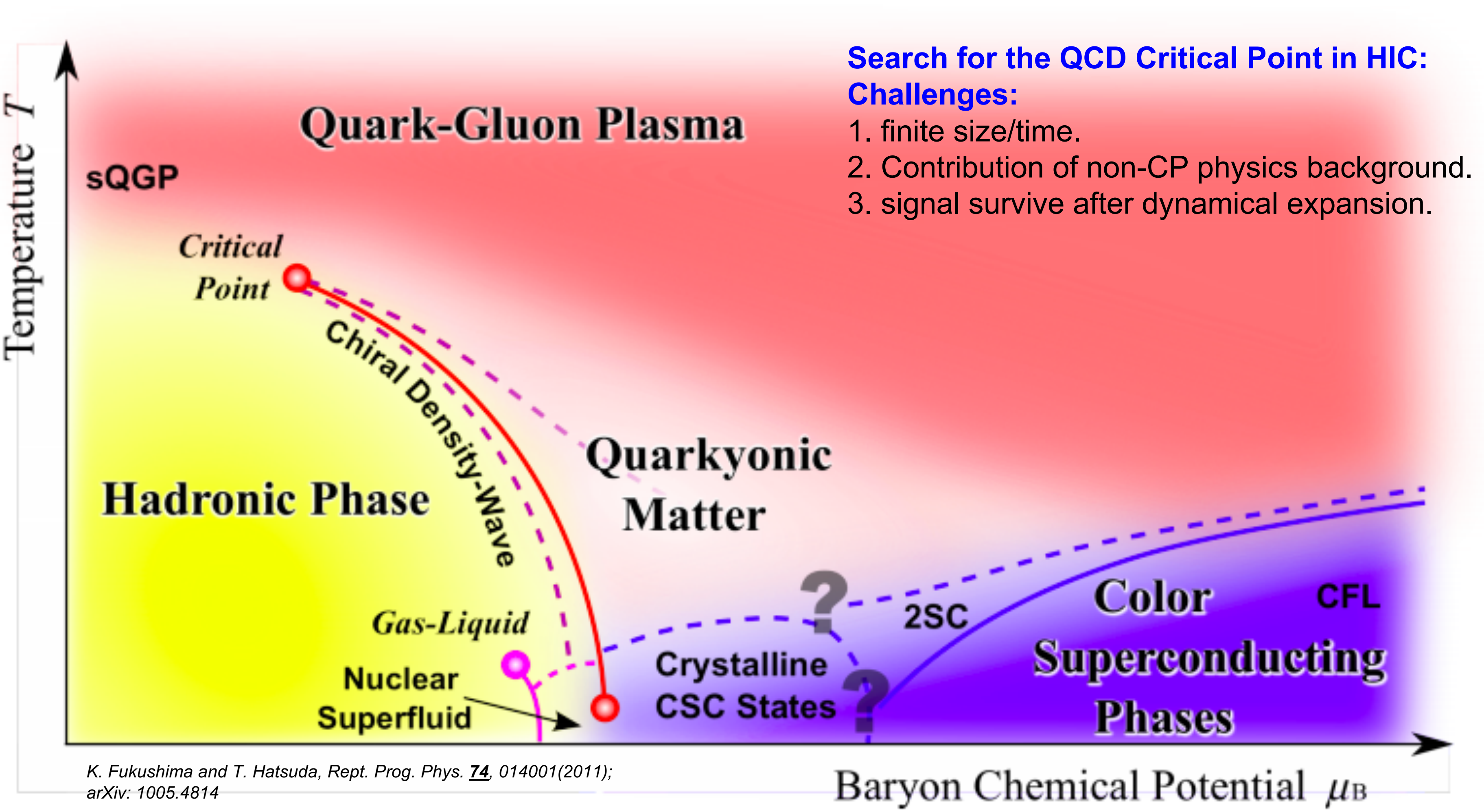
   2) Study non-CP background in HIC.

   - Transport model: UrQMD, JAM etc.

4. Summary and Outlook

QCD Phase Diagram (Conjectured)

QCD Phase Structure : Emergent properties of the strong interaction.



Search for the QCD Critical Point in HIC:

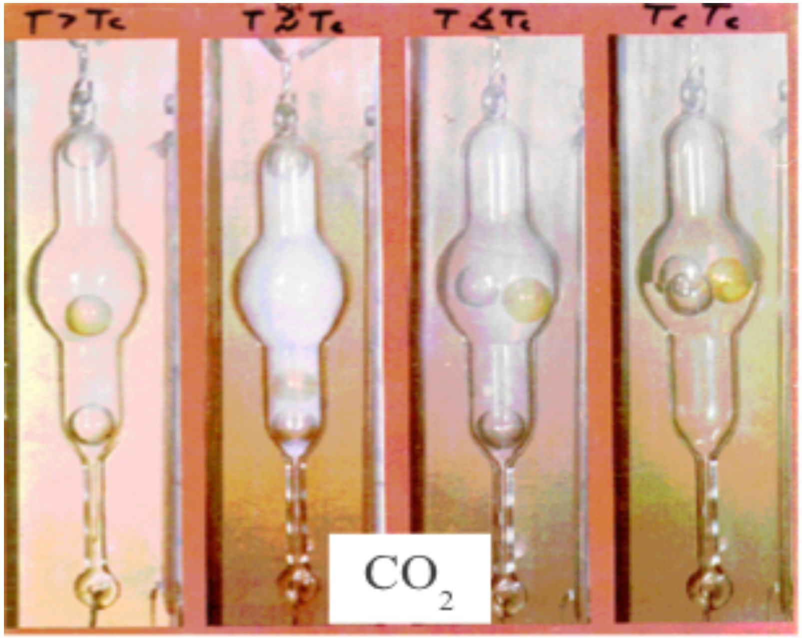
Challenges:

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

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

Critical Point and Critical Phenomena

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



Critical Phenomena :

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

  Susceptibilities (χ), heat capacity (C_V) ,
  Compressibility (κ) etc.

  Critical opalescence. (临界乳光)

- Universality (普适性) and critical exponents (临界指数) determined by the symmetry and dimensions of underlying system.

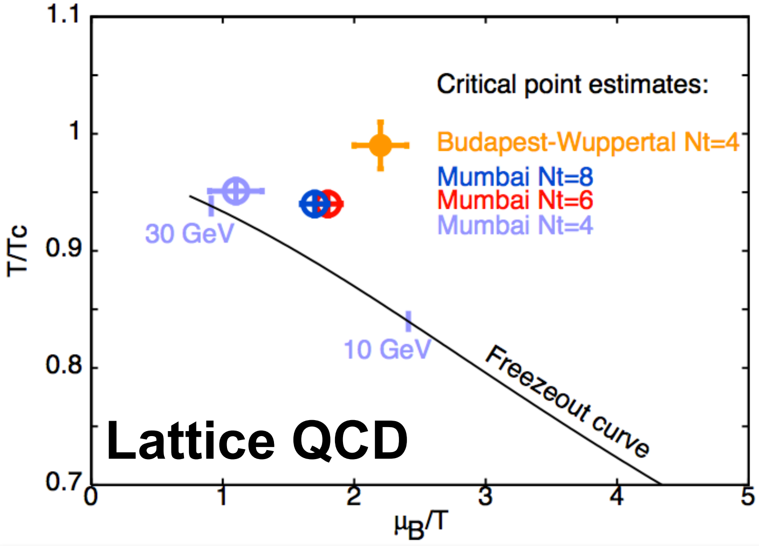
First CP is discovered in 1869 for CO_2 by Andrews.

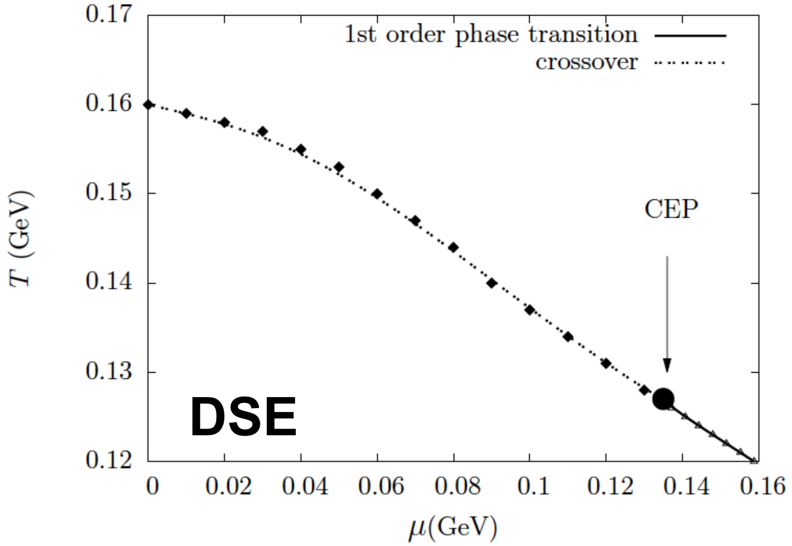
Can we discovery the Critical Point of Quark Matter ? (**Put a permanent mark in the QCD phase diagram in text book.**)

T_c = 31°C

T_c ~ Trillion (10^{12}) °C

Location of Critical Point: 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:

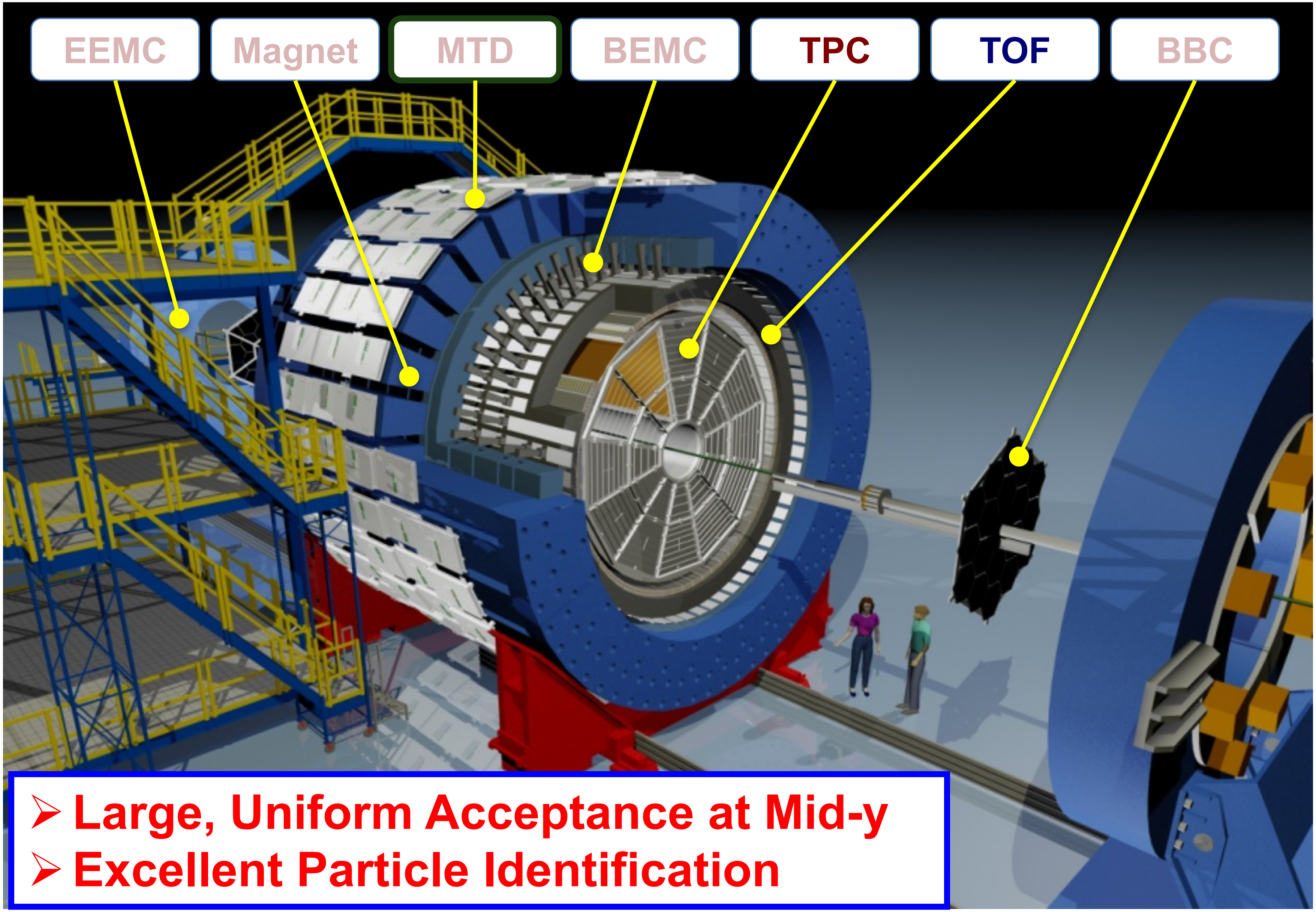
1): Y. X. Liu, et al., PRD90, 076006 (2014); 94, 076009 (2016).
$(\mu^E_B, T^E) = (372, 129)$; $(262.3, 126.3)$ MeV

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

$\mu^E_B = 262 \sim 504$ MeV, $T_E = 115 \sim 162$, $\mu^E_B / T_E = 1.74 \sim 4.38$

STAR Detector

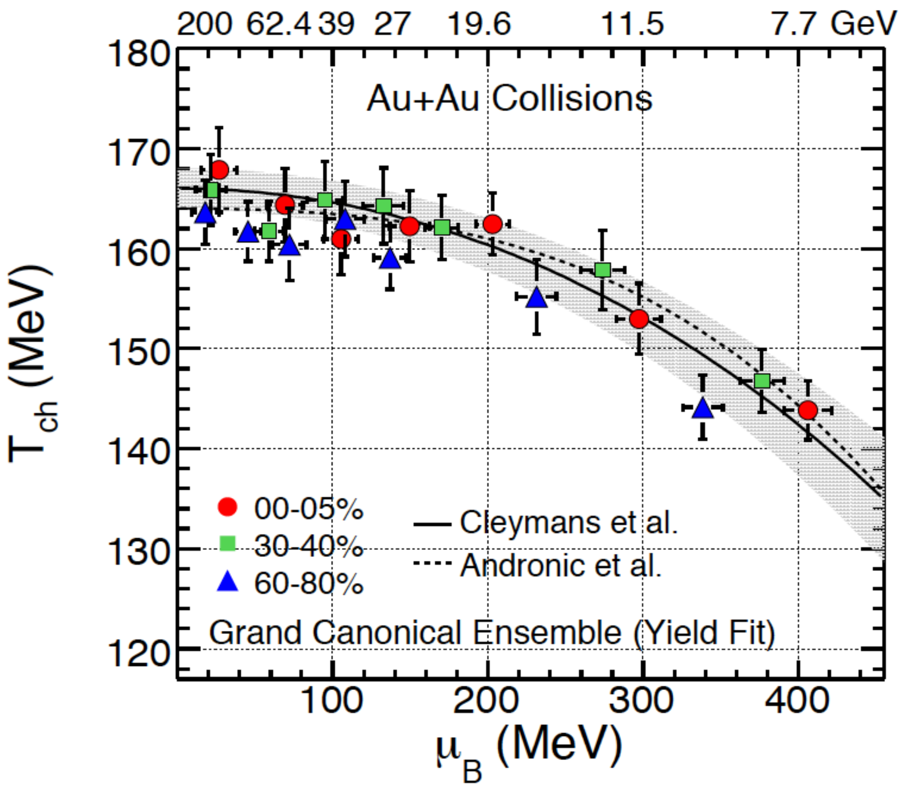


- ➢ **Large, Uniform Acceptance at Mid-y**
- ➢ **Excellent Particle Identification**

Bean Energy Scan - I (2010-2017)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*μ_B (MeV)	*T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	300	2017	83	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)

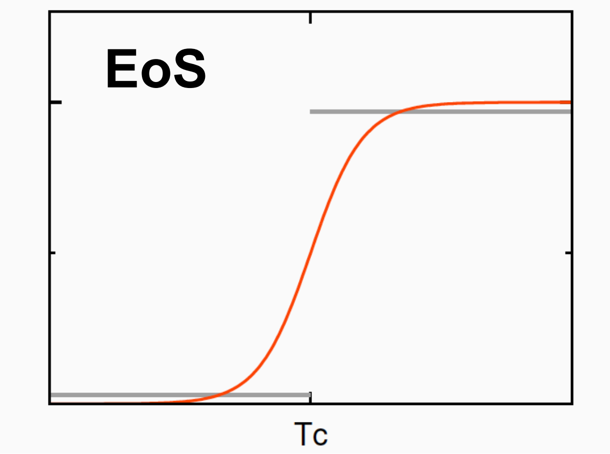


1) Access broad region of the QCD phase diagram.
2) STAR: Large and homogeneous acceptance, excellent PID capabilities.

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

Fluctuations as Signature of Phase Transition

Fluctuations are sensitive to the phase transition and critical point.



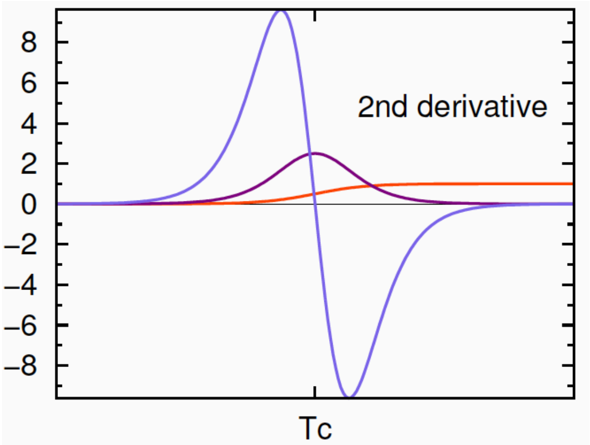
1. Derivations of thermodynamic quantities (EoS) are related to E-by-E fluctuations in HIC.

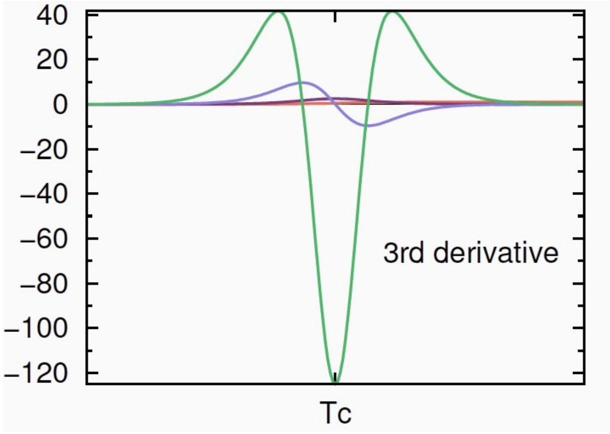
$$\chi_n = \frac{\partial^n (P/T^4)}{\partial(\mu/T)^n}\bigg|_T$$

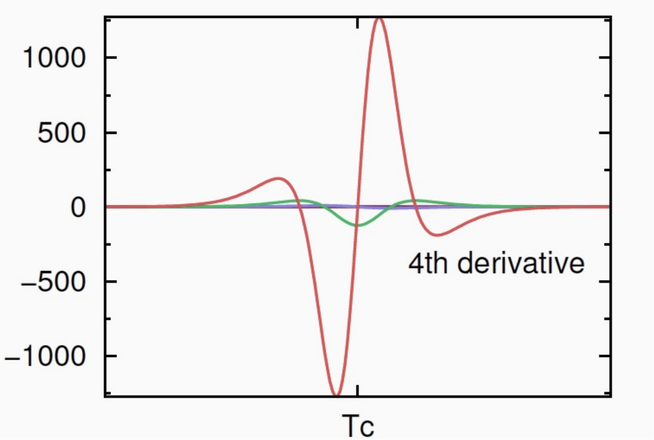
$$\chi_1 = \frac{1}{VT^3}\langle N\rangle\,, \quad \chi_2 = \frac{1}{VT^3}\langle(\Delta N)^2\rangle\,, \quad \chi_3 = \frac{1}{VT^3}\langle(\Delta N)^3\rangle\,,$$

$$\chi_4 = \frac{1}{VT^3}\langle(\Delta N)^4\rangle_c \equiv \frac{1}{VT^3}\left(\langle(\Delta N)^4\rangle - 3\langle(\Delta N)^2\rangle^2\right)\,.$$

2. It reveals more details: Sign change and diverge.







M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81, 4816 (1998). M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. D 60, 114028 (1999). S. Jeon and V. Koch, Phys. Rev. Lett. 83, 5435 (1999). S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076(2000). M. Asakawa, U. Heinz and B. Muller, Phys. Rev. Lett. 85, 2072 (2000). Y. Hatta, M. Stephanov， Phys. Rev. Lett. 91, 102003 (2003). V. Koch, A. Majumder, J. Randrup, Phys.Rev.Lett. 95, 182301 (2005). M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009). M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009). M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).

Higher Order Fluctuations of Conserved Quantities

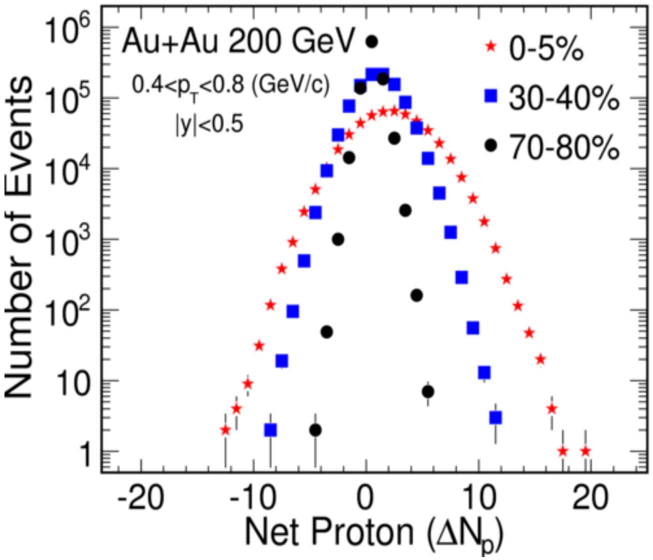
1. **Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations.**

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

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

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

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).

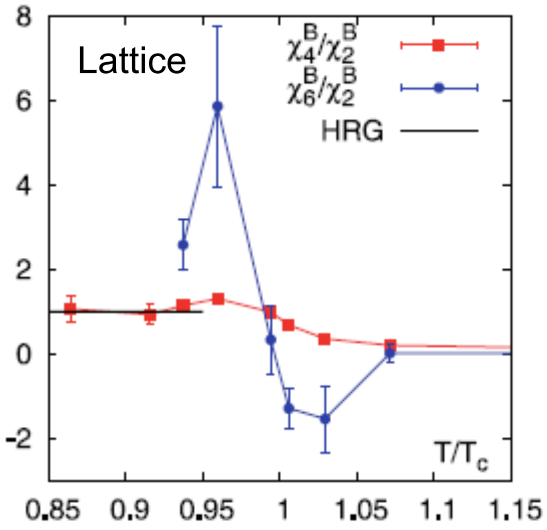


2. **Connection to the susceptibility of the system.**

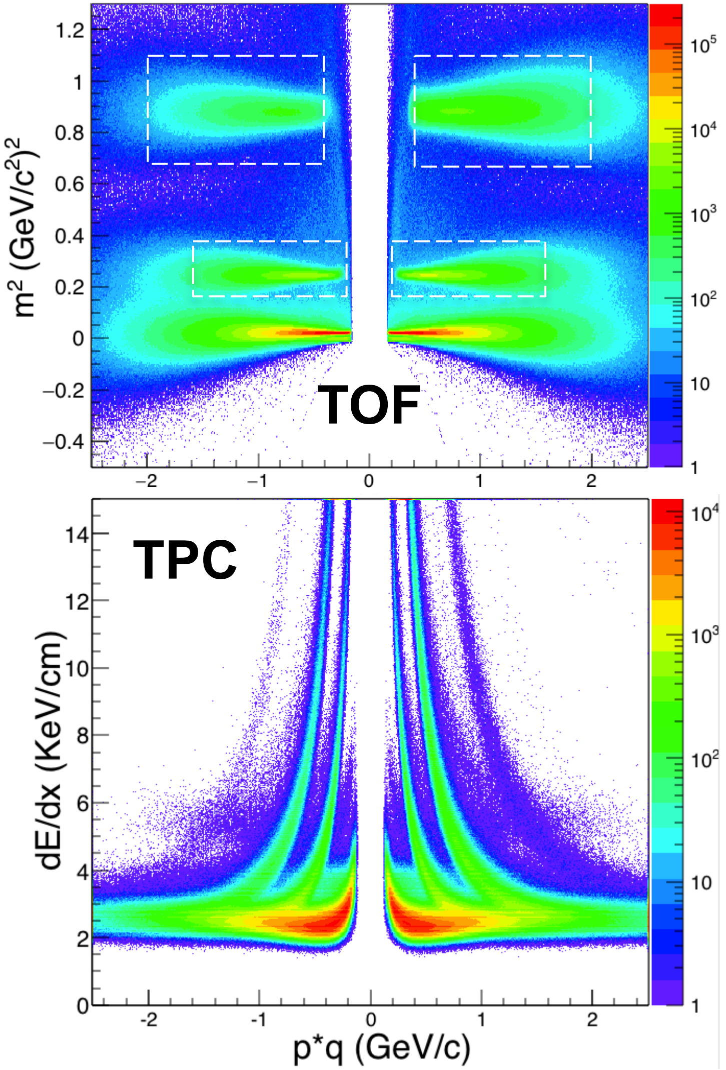
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

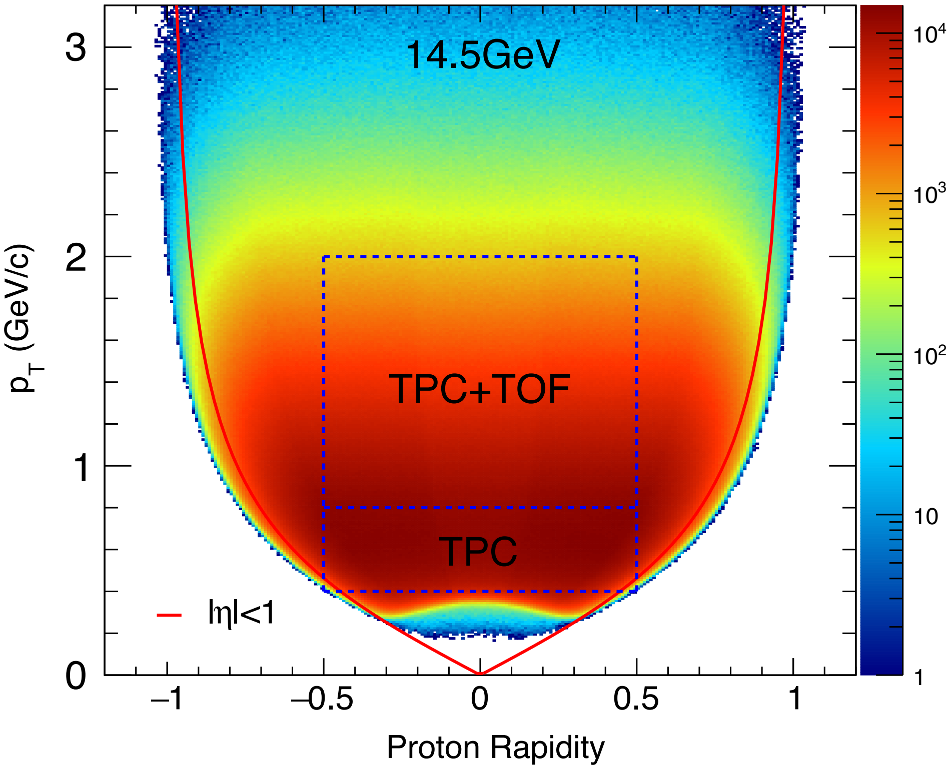
$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T\wedge 4)}{\partial(\mu_q)^n}, q = B, Q, S$$

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



Proton Identification





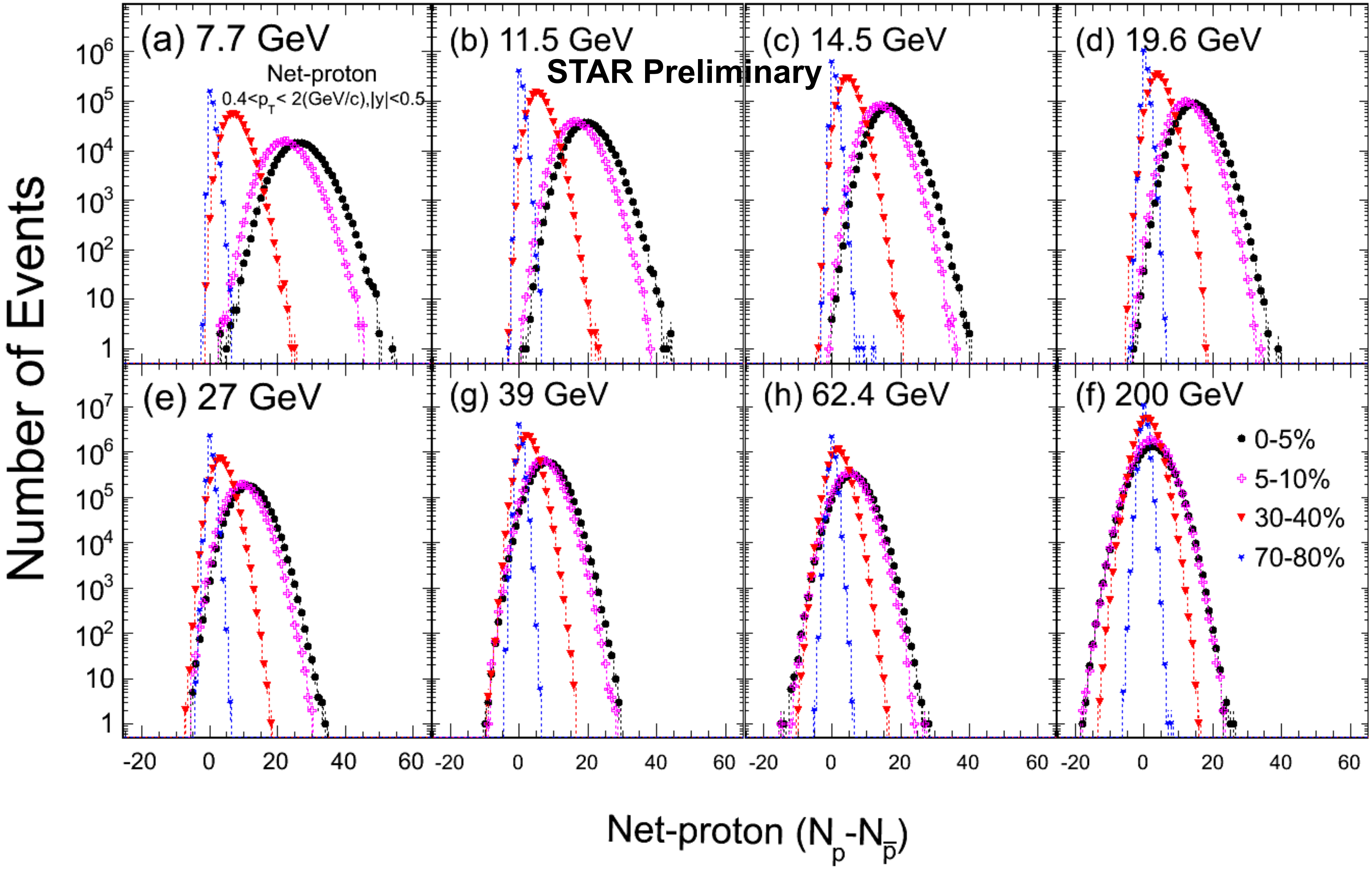
Acceptance: $|y| \le 0.5$, $0.4 \le p_T \le 2$ GeV/c

Efficiency corrections:

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

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

Raw Net-proton Multiplicity Distributions



Data Analysis Methods

1. Statistical errors estimation based on Delta theorem

X. Luo, J. Phys. G39, 025008 (2012).

2. Centrality Bin Width Correction: Suppress the volume fluctuations

X. Luo, J. Xu, B. Mohanty, N. Xu, et al, J. Phys. G40, 105104 (2013).

3. Unified efficiency correction and error estimation

X. Luo, Phys. Rev. C 91, 034907 (2015).

Have been used in the ALICE and Hades Collaboration.

Invited Review: X. Luo and Nu Xu, Nucl. Sci. Tech. 28, 112 (2017), **[arXiv: 1701.02105]**

Efficiency Correction 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.

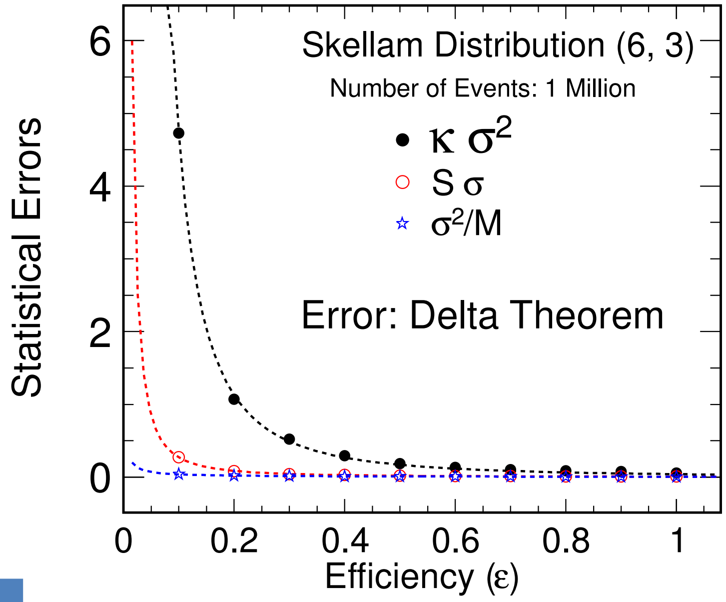
$$F_{u,v,j,k}(N_{p_1}, N_{p_2}, N_{\bar{p}_1}, N_{\bar{p}_2}) = \frac{f_{u,v,j,k}(n_{p_1}, n_{p_2}, n_{\bar{p}_1}, n_{\bar{p}_2})}{(\varepsilon_{p_1})^u (\varepsilon_{p_2})^v (\varepsilon_{\bar{p}_1})^j (\varepsilon_{\bar{p}_2})^k}$$

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)

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



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

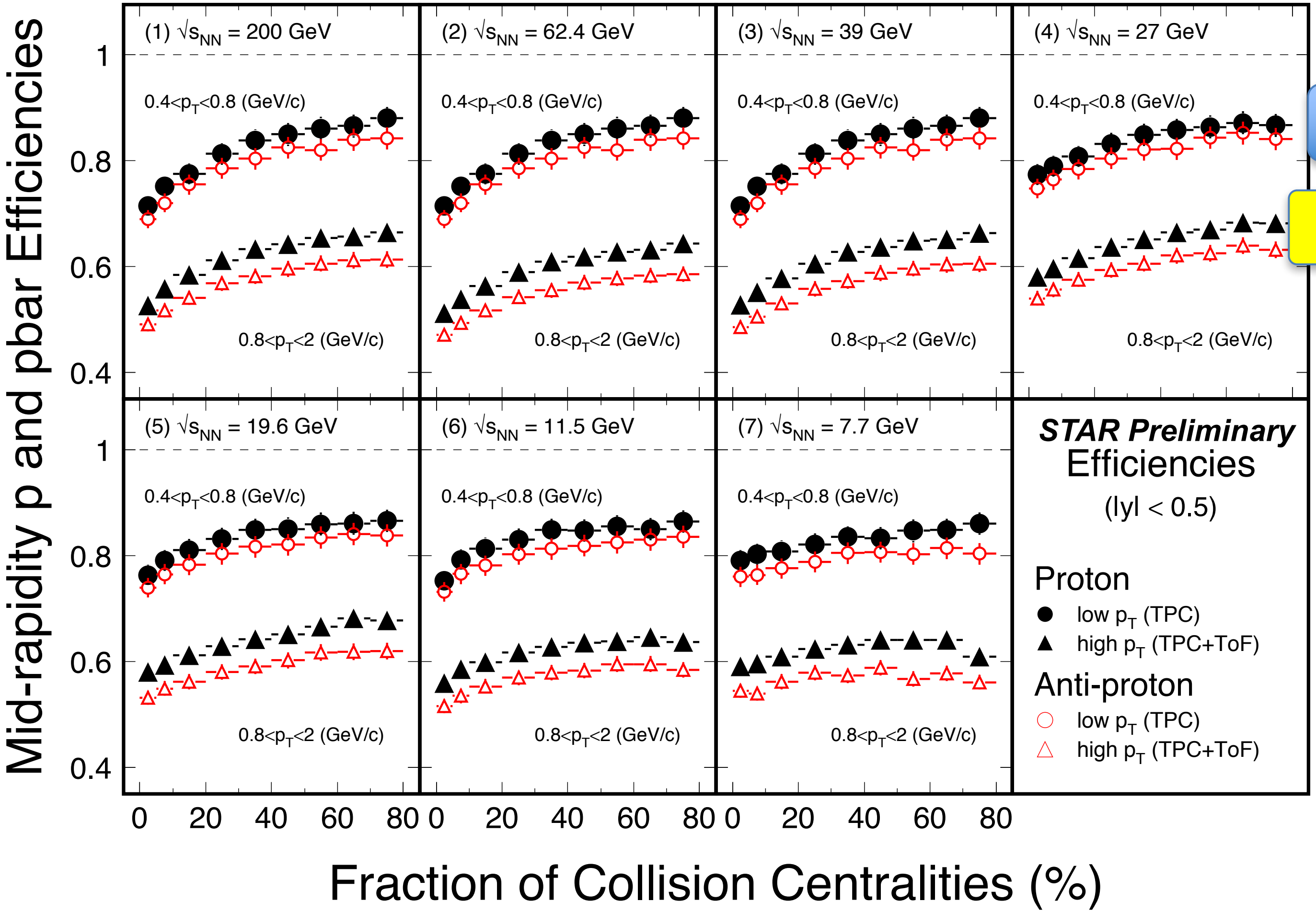
Those numbers are for illustration purpose and not used in actual analysis

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

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

Efficiencies for Protons and Anti-protons

Au + Au Collisions at RHIC

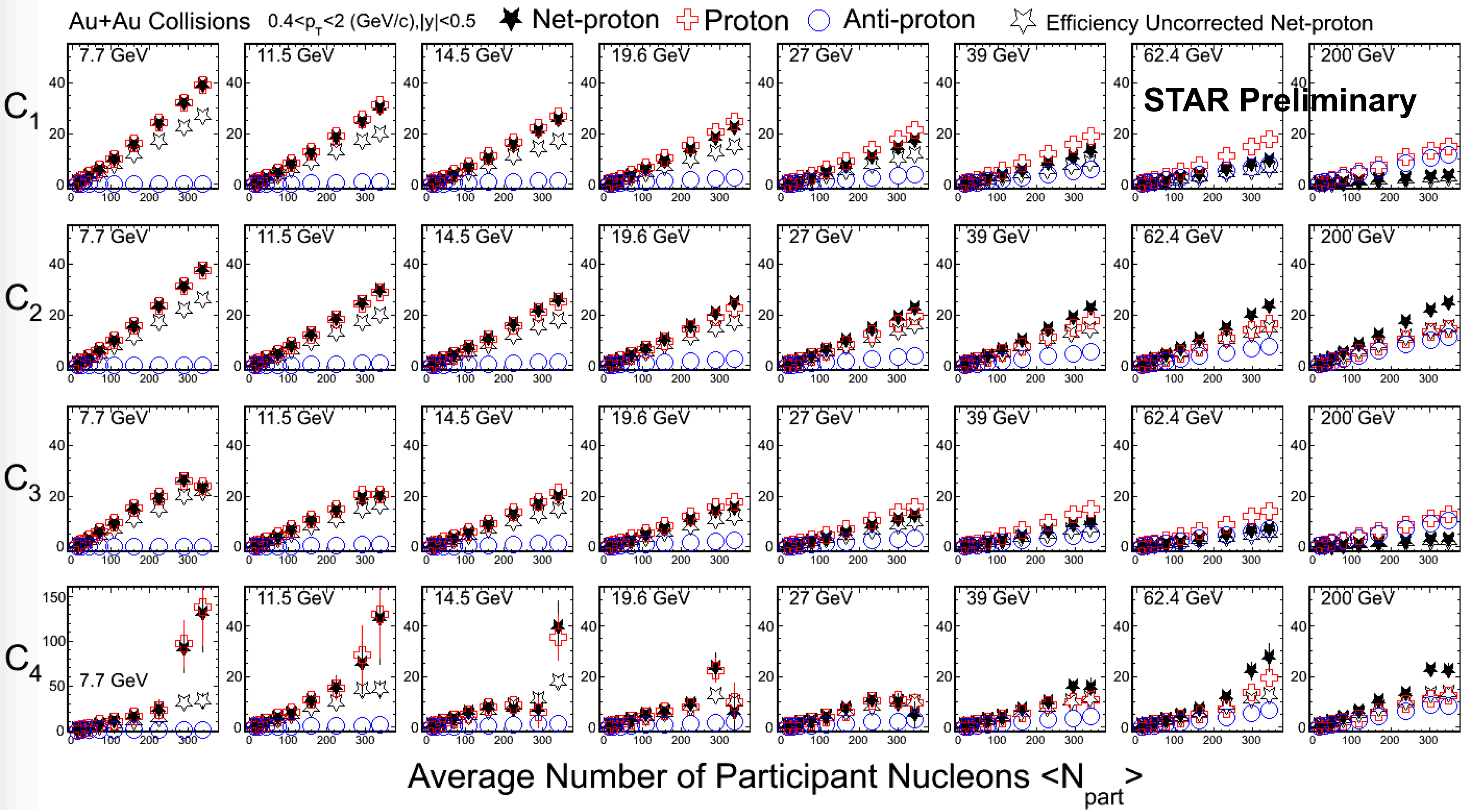


TPC

TPC + TOF

- ➢ 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

Cumulants: $C_1 \sim C_4$



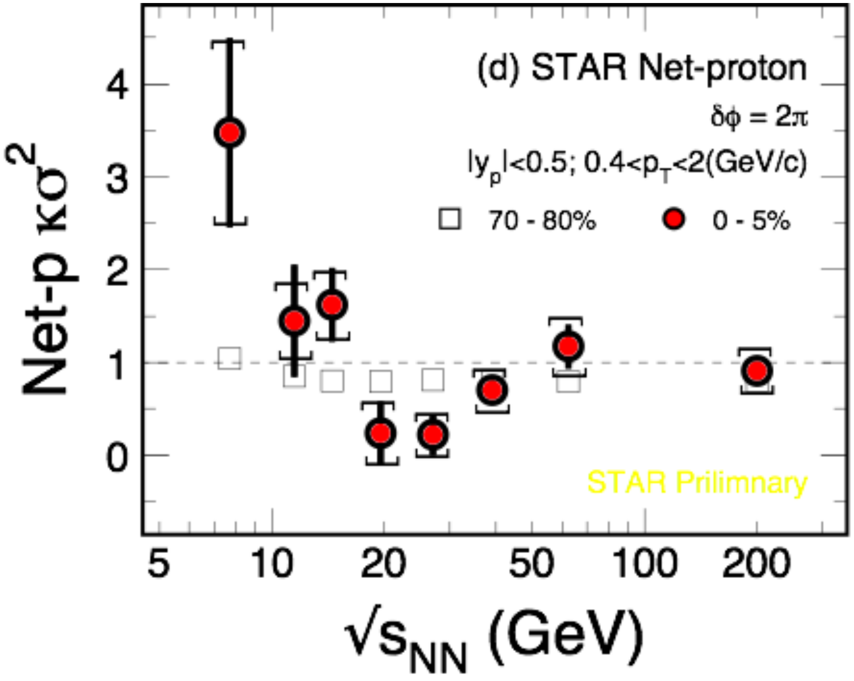
In general, cumulants are increasing with <N_{part}>.

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

Forth order Net-Proton Fluctuations $\kappa\sigma^2 = C_4/C_2$

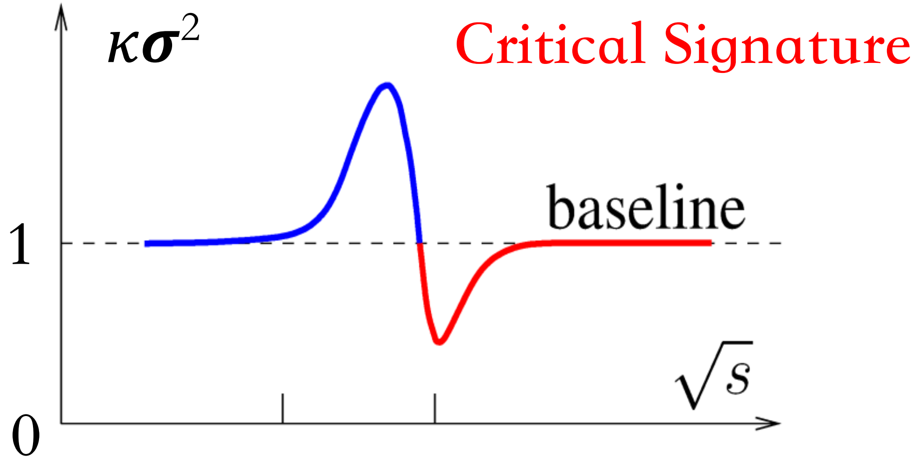
- First observation of the non-monotonic energy dependence of fourth order net-proton fluctuations. Hint of entering Critical Region ??

STAR Data



STAR, PRL112,032302 (2014).
X. Luo (STAR Coll.), PoS CPOD2014 (2015) 019
X. Luo, Plenary talk at QM15, Nucl. Phys. A956,75 (2016)
X. Luo and Nu Xu, Nucl. Sci. Tech. 28, 112 (2017)

Model

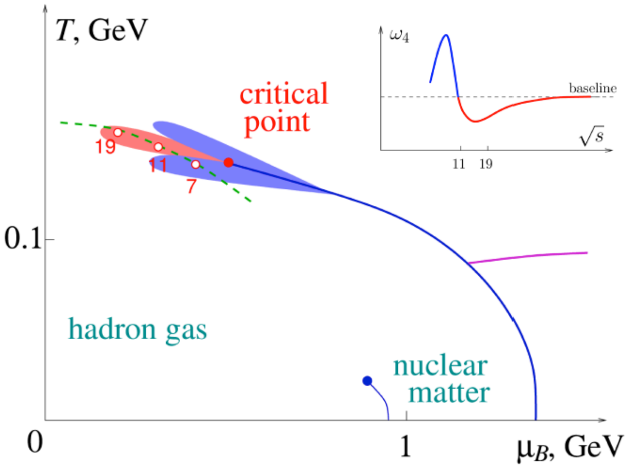


M.A. Stephanov, PRL107, 052301 (2011).
Vovchenko et al., PRC92, 054901 (2015)
Schaefer&Wanger,PRD 85, 034027 (2012)
JW Chen et al., PRD93, 034037 (2016), PRD95, 014038 (2017)
Weijie Fu et al, Phys.Rev. D94 (2016) , 116020
W. K. Fan, X. Luo, H. S. Zong, IJMPA 32, 1750061 (2017).

Sign of Kurtosis :Model and Theoretical Calculations

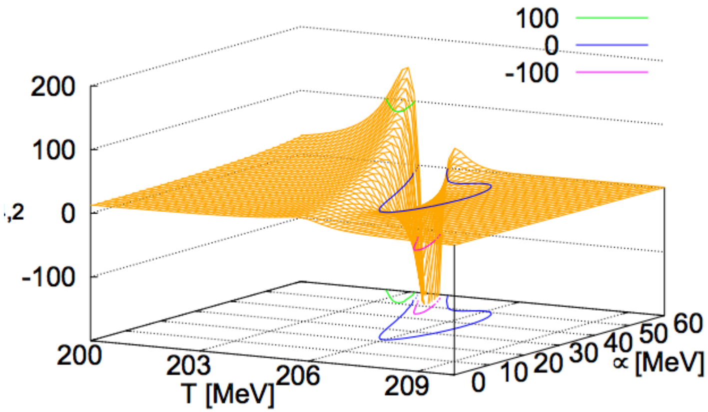
σ field

M.A. Stephanov,
PRL107, 052301 (2011).



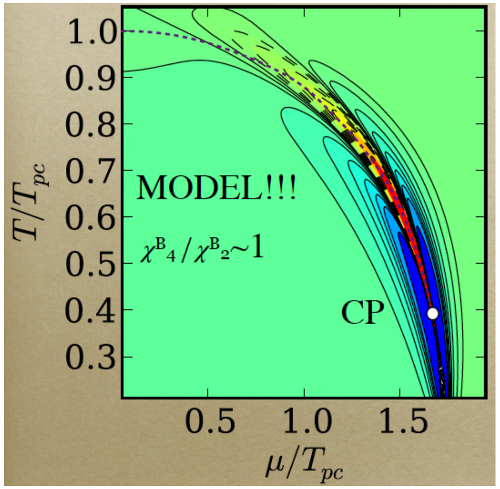
PQM

Schaefer&Wanger,
PRD 85, 034027 (2012)

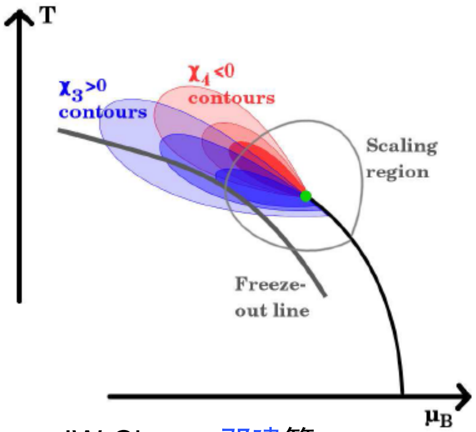


PQM

V. Skokov, QM2012

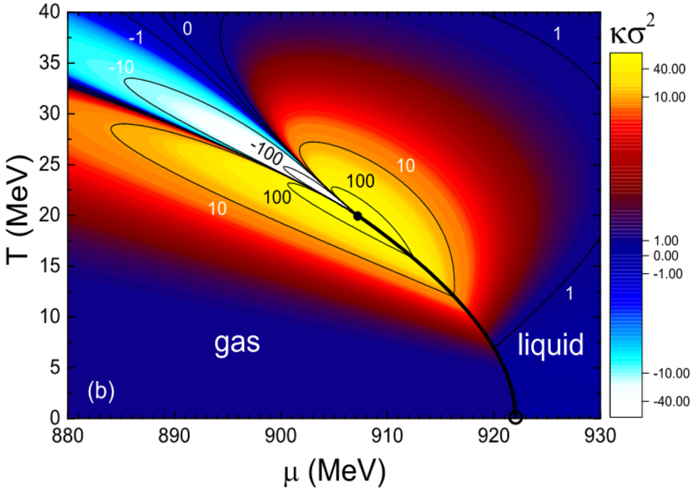


NJL



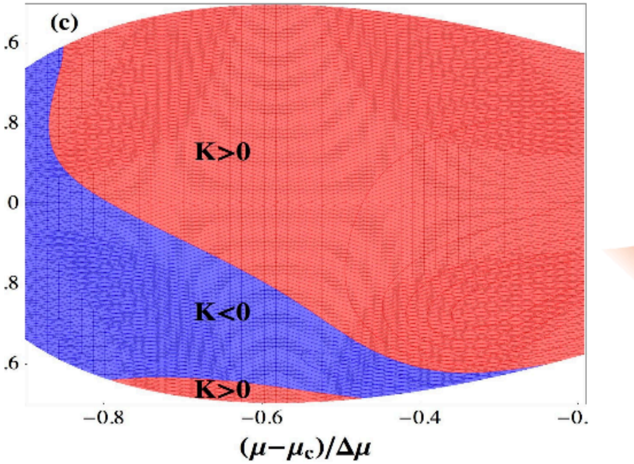
JW Chen，邓建等,
PRD93, 034037 (2016),
PRD95, 014038 (2017)

VDW



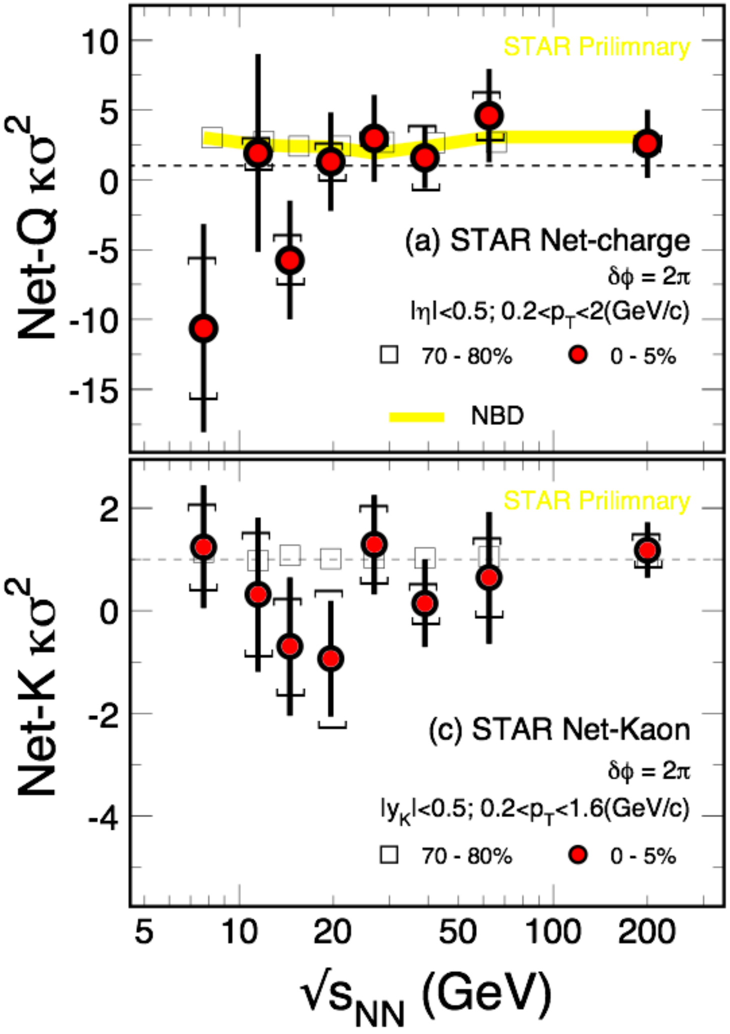
Vovchenko et al., PRC92,054901 (2015)
PRL118,182301 (2017)

Memory&non-equ. effects



Swagato,et al, PRC92,034912 (2015).
PRL

Net-charge and Net-kaon Fluctuations



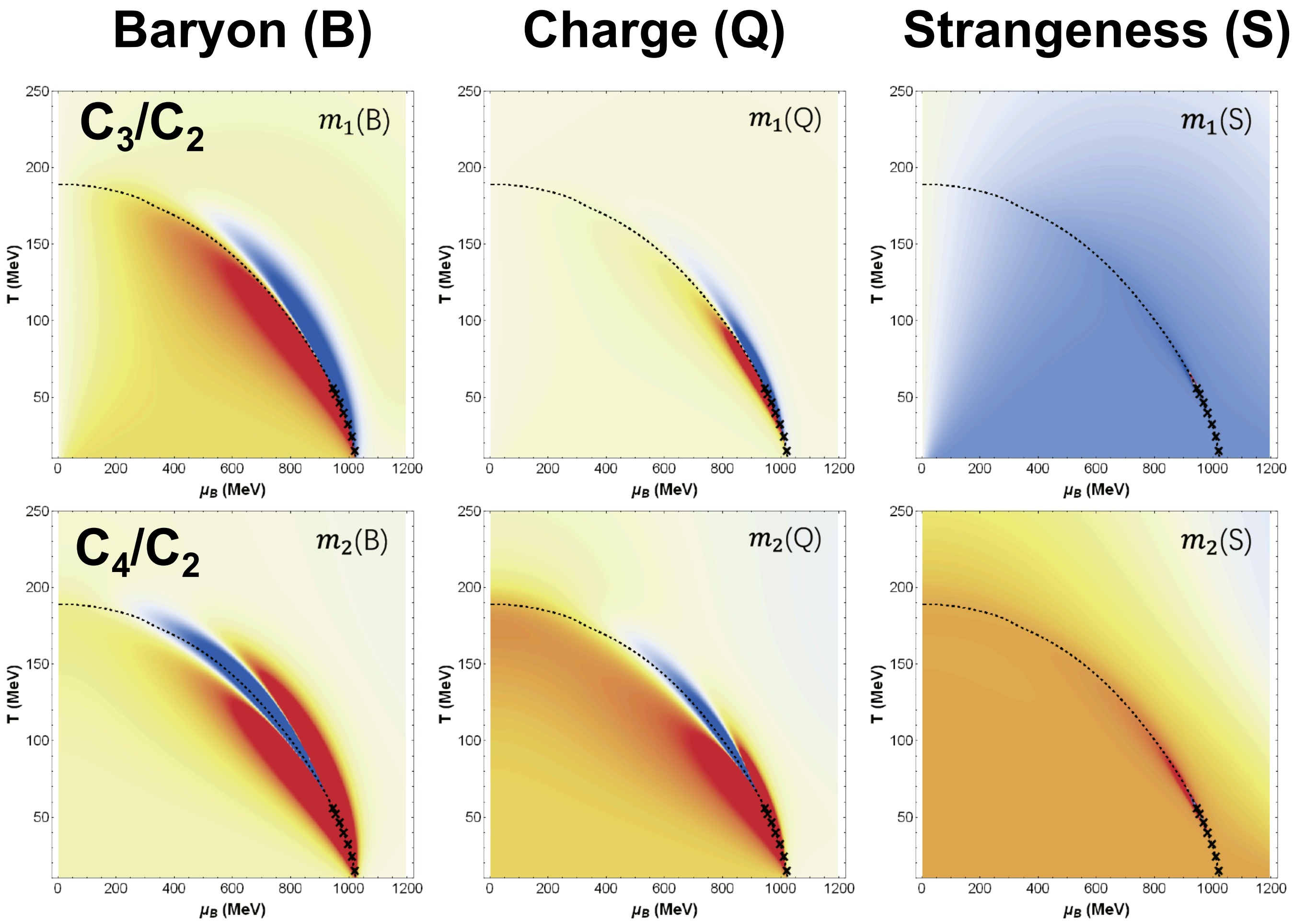
$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

In STAR:

σ(Q) > σ(K) > σ(p)

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

NJL Model Calculations



1) CP Signals from baryon fluctuations are much stronger than Q and S.
2): Forth and third order fluctuations have very different behavior.

W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017).

Model Calculations: UrQMD, JAM

- Study non-critical background effects on the Net-Proton and Proton fluctuations

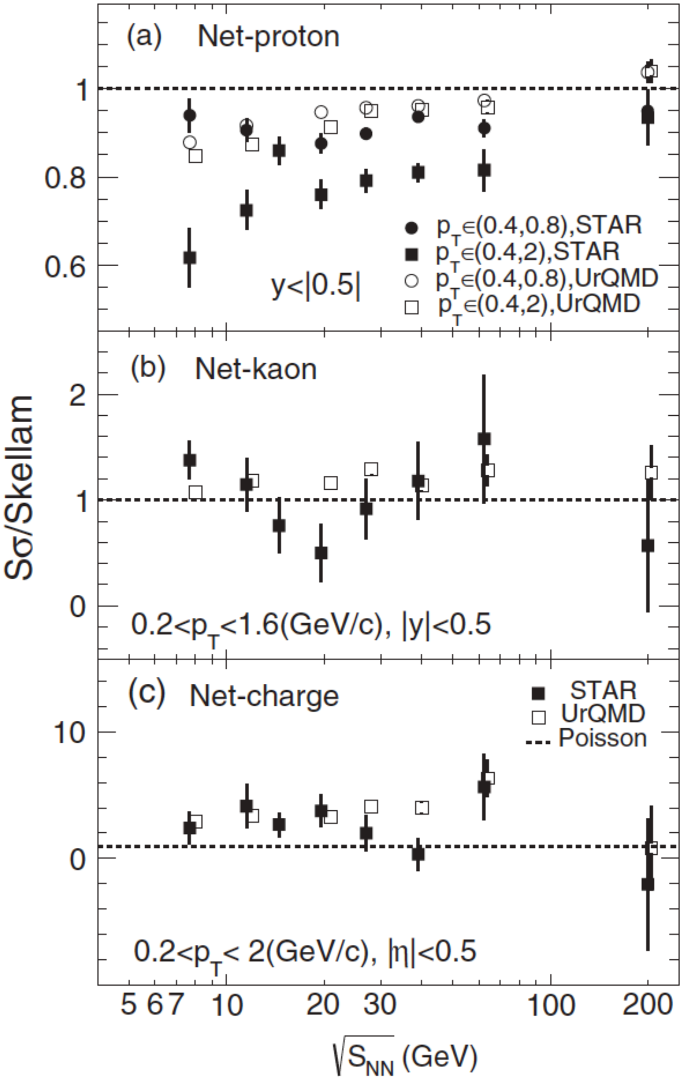
1) Baryon number conservations

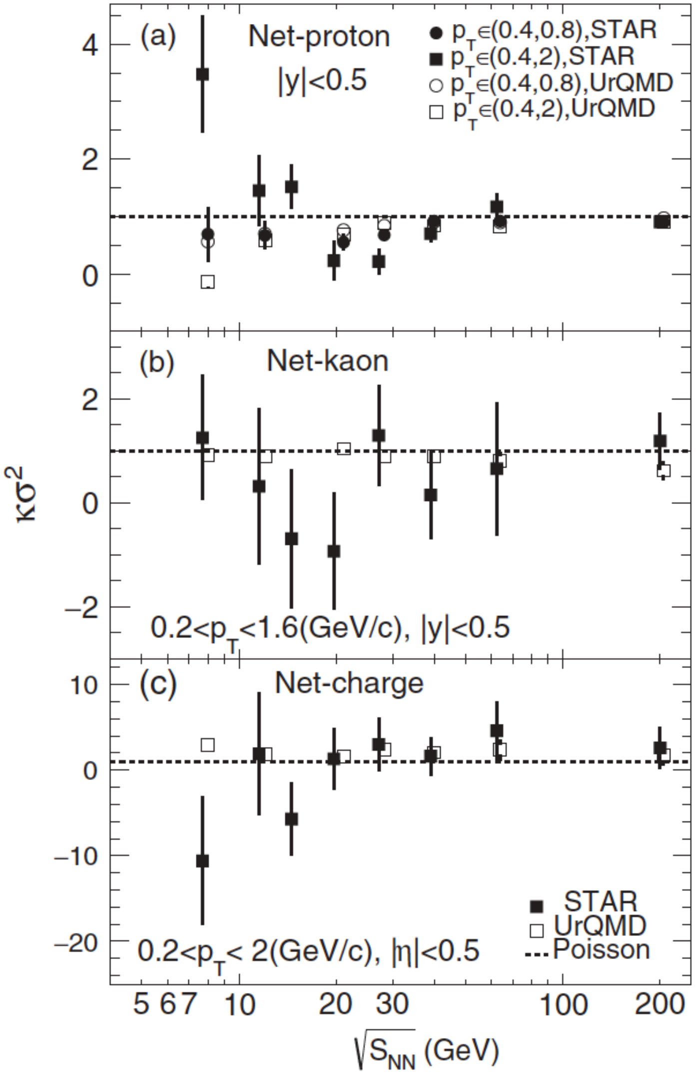
2) EoS (cascade, mean field, 1st order P.T.)

3) Resonance weak decay and hadronic scattering.

1. J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016)
2. S. He, X. Luo, arXiv:1704.00423
3. C. Zhou, J. Xu, X. Luo, F. Liu, PRC96, 014909 (2017).
4. S. He, X. Luo, Y. Nara, S. Esuimi, N. Xu, Phys.Lett. B762 (2016) 296-300
5. Y. Zhang, S. He, X. Feng, X. Luo, In preparation.

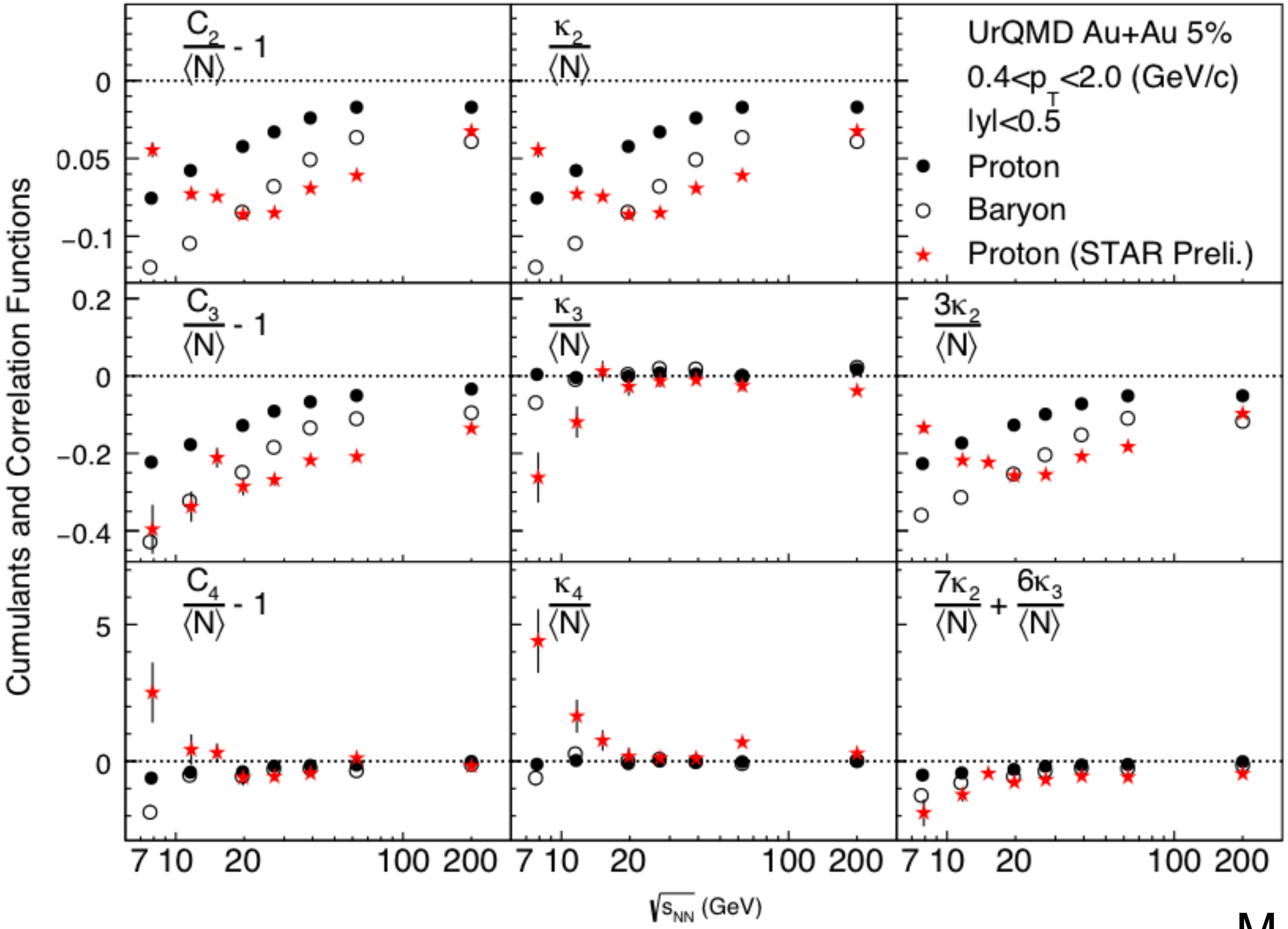
UrQMD Calculations





J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016)

Proton Cumulants and Correlation Functions



$$C_2 = <N> + \hat{\kappa}_2$$
$$C_3 = <N> + 3\hat{\kappa}_2 + \hat{\kappa}_3$$
$$C_4 = <N> + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

$\hat{\kappa}_2, \hat{\kappa}_3, \hat{\kappa}_4$:

2,3,4-particle correlation function

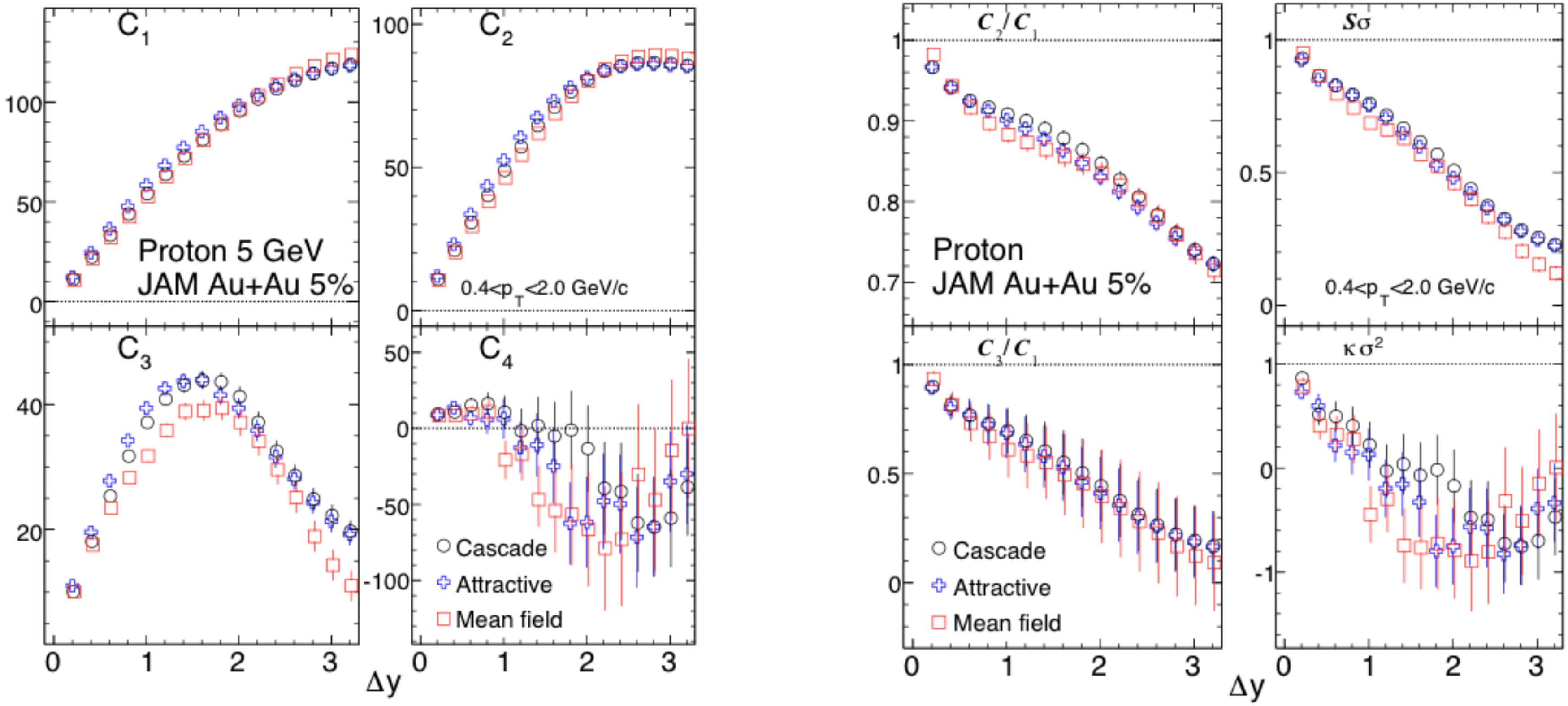
S. He, X. Luo arXiv:1704.00423

M. Kitazawa and X. Luo arXiv:1704.04909

Non-monotonic energy dependence of fourth order proton fluctuations is dominated by 4-particle correlation function.

Effects of EoS to Proton Cumulants

JAM Model: Au+Au collisions at 5 GeV

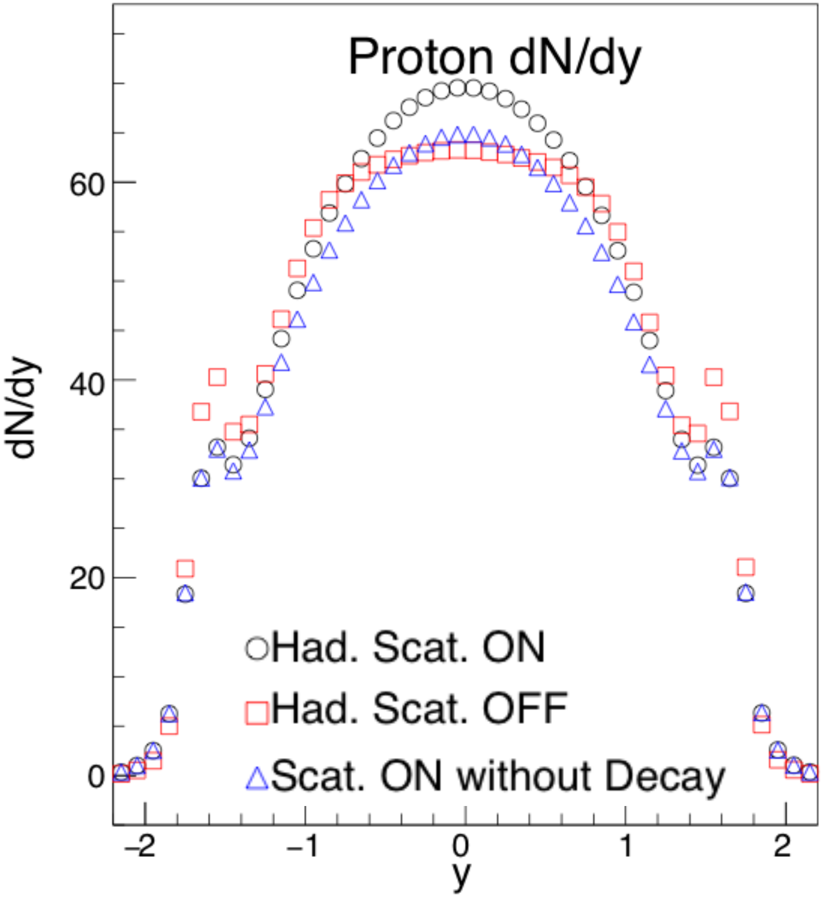


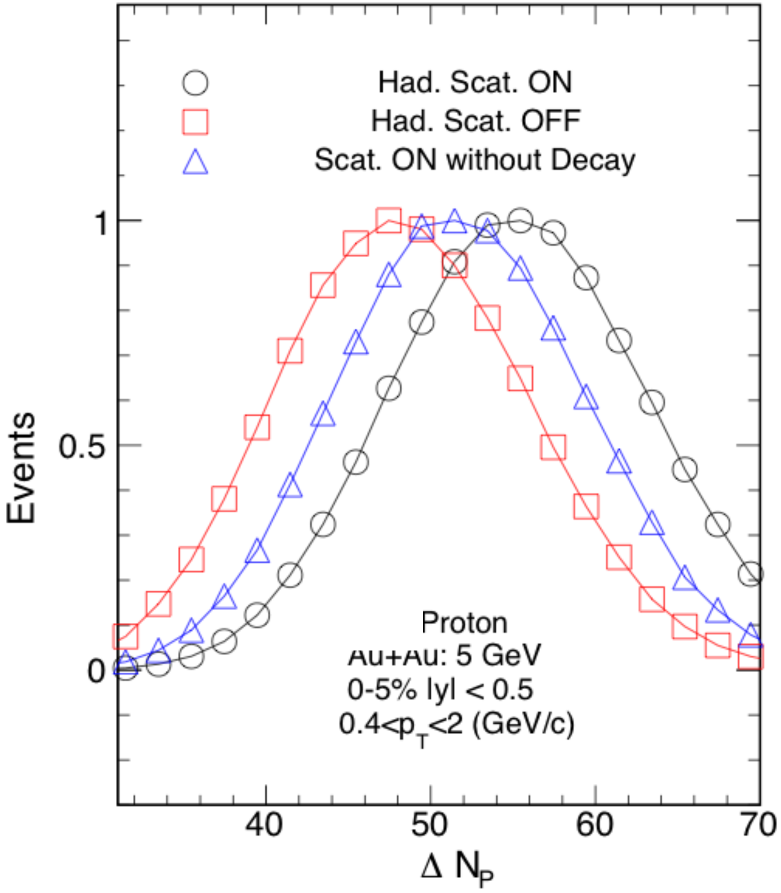
Similar trendss observed in all types of EoS.

Suppressions at large rapidity windows are due to the baryon number conservation

S. He, X. Luo, Y. Nara, S. Esumi and N. Xu, Phys. Lett. B762, 296 (2016)

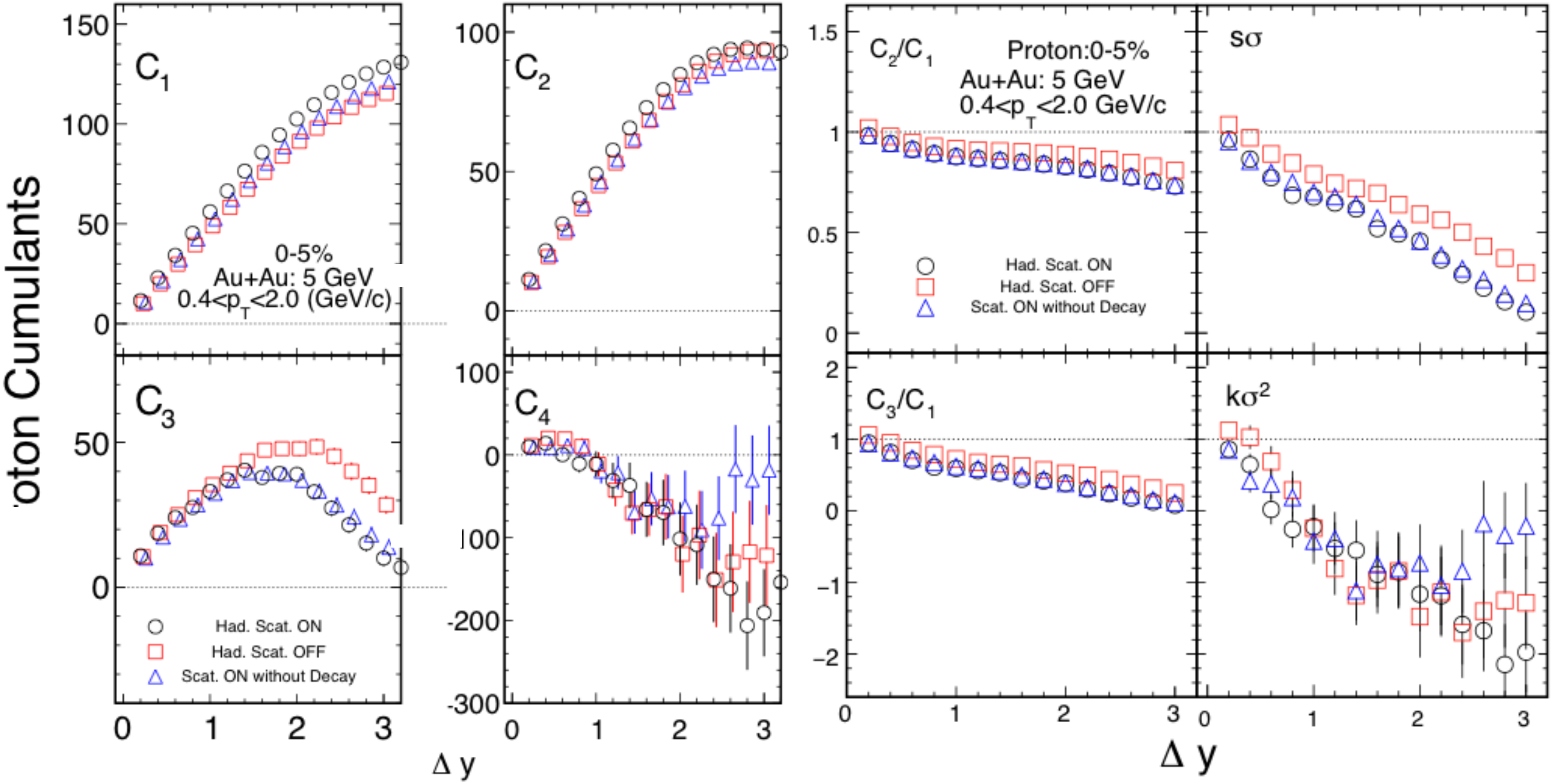
Weak Decay and Hadronic Scattering





1. Larger Proton dN/dy is observed at mid-rapidity when turning on hadronic scattering.

2. Weak decay increases the final state proton multiplicity

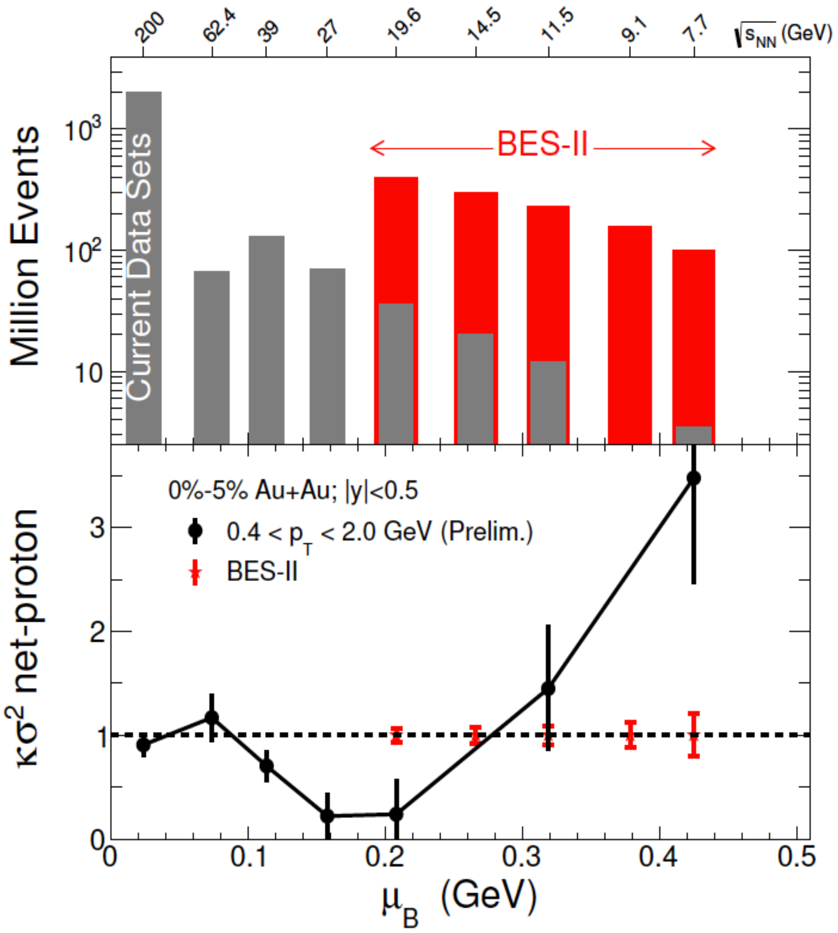


5. Y. Zhang, S. He, X. Feng, X. Luo, In preparation.

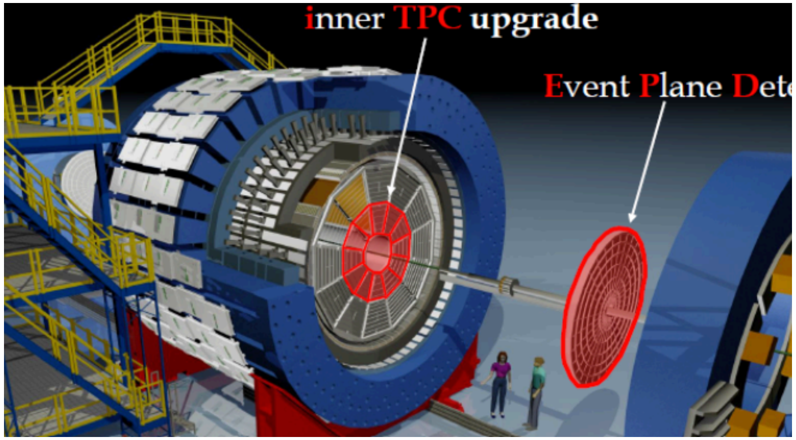
BES-II at RHIC (2019-2020)

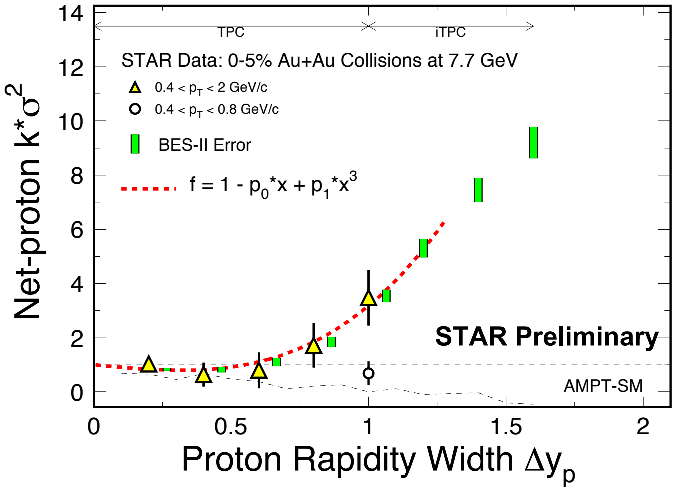
More Data

RHIC Luminosity Upgrade for Low Energies



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

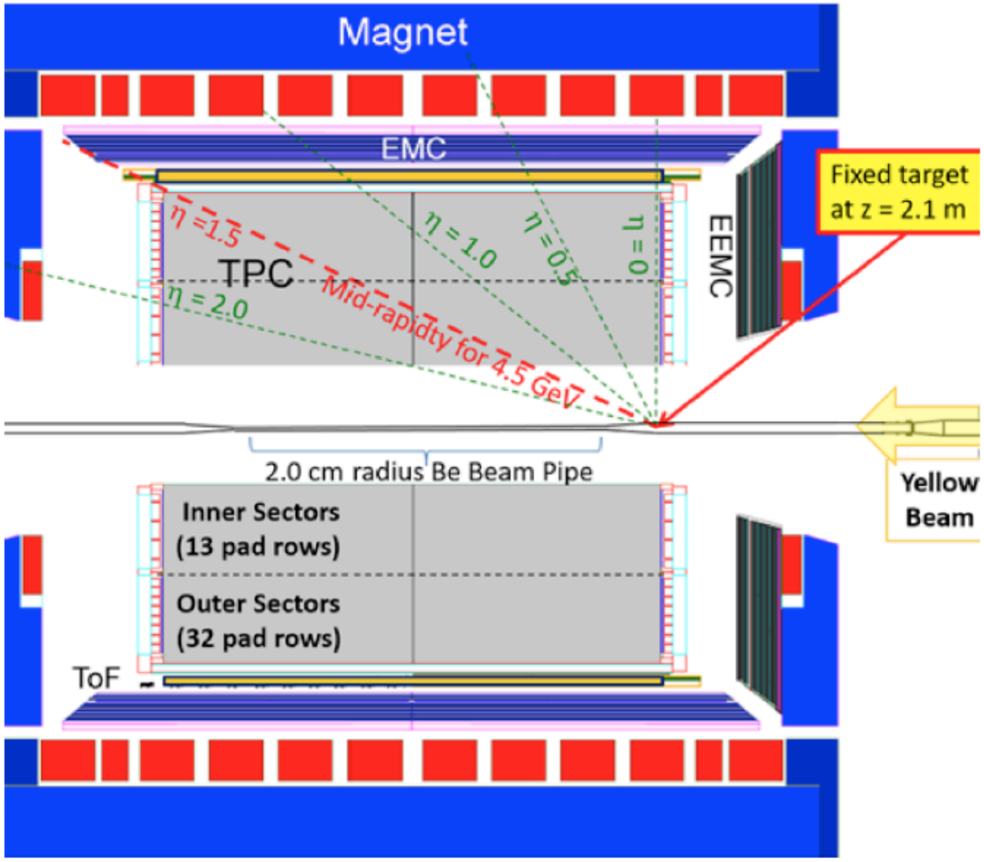


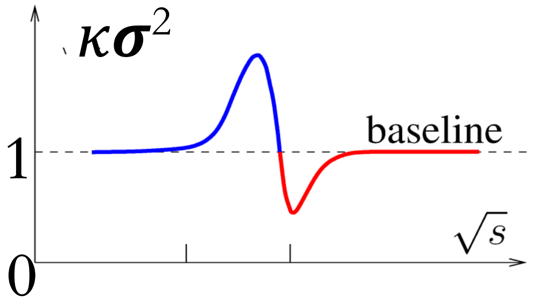


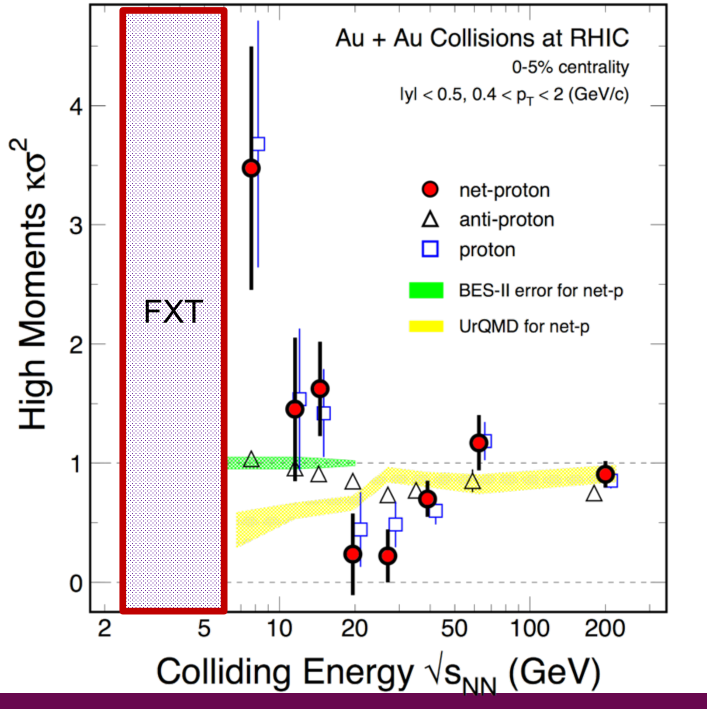
1) Event statistics driven by QCD CP search and di-electron measurements.
2) The STAR Fix-target mode is also planed in BESII. ($\sqrt{s_{NN}}$： 4.5, 3.9, 3.6, 3.0 GeV)

FXT Experiments at STAR (2018-2019)

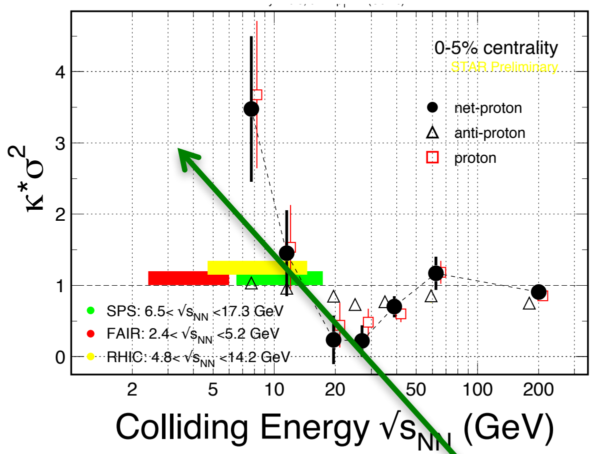
- Key step to confirm the signature of QCD critical point
- Center of Mass Energy Range (3 - 6.2 GeV)

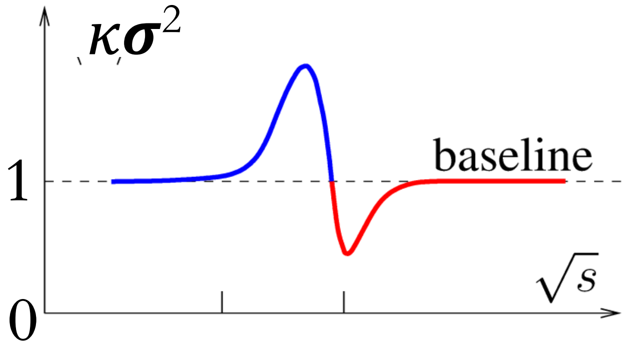


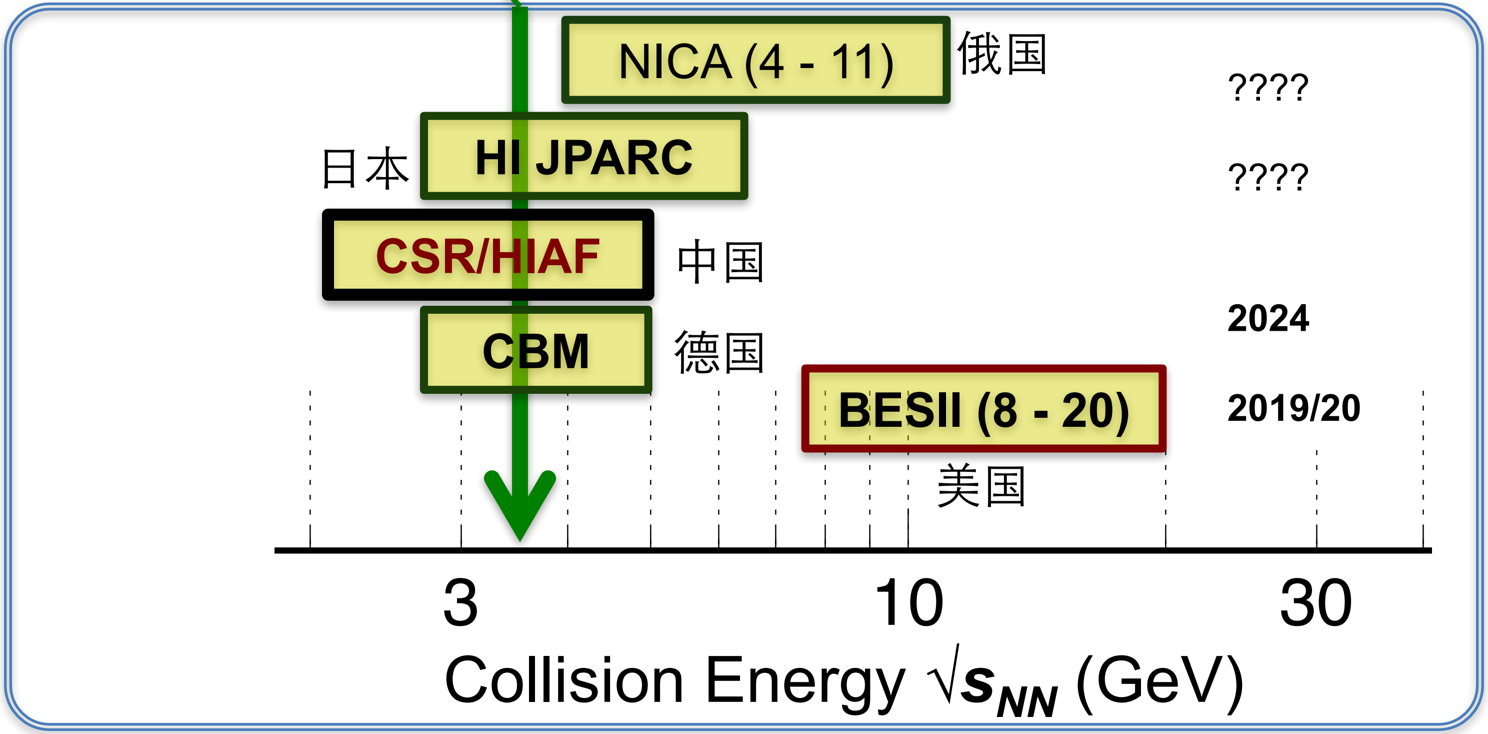




CP Search at $\sqrt{s_{NN}} \leqslant 8\,\text{GeV}$







NICA (4 - 11) 俄国 ????

日本 **HI JPARC** ????

CSR/HIAF 中国

CBM 德国 **2024**

BESII (8 - 20) 美国 **2019/20**

Collision Energy $\sqrt{s_{NN}}$ (GeV)

Summary

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

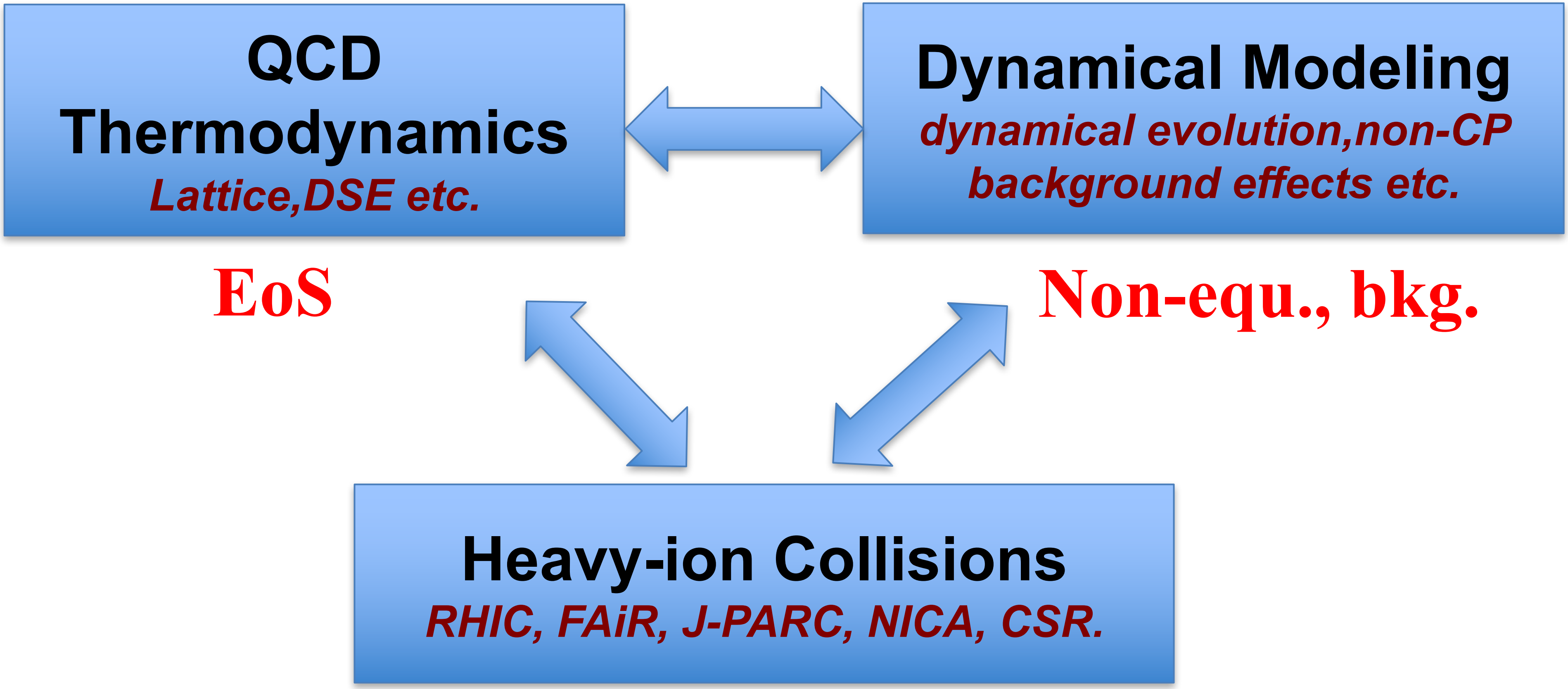
- Model simulation indicates: *Baryon conservations, Mean-field potential, hadronic scattering, Deuteron formation, Softening of EoS. All suppress the net-proton fluctuations.*

- 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 2024) etc.

Huge discovery Potential at high baryon density region

QCD critical point and 1st order P.T.

Outlook



QCD Thermodynamics

Lattice,DSE etc.

Dynamical Modeling

dynamical evolution,non-CP background effects etc.

EoS

Non-equ., bkg.

Heavy-ion Collisions

RHIC, FAiR, J-PARC, NICA, CSR.

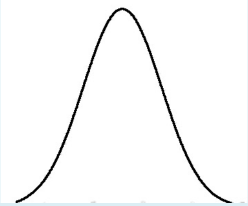
Precision measurements at high baryon density

Need close collaboration from both theorist and experimentalist !

Thank you !

临界点灵敏观测量：守恒荷分布的高阶矩

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
Y. Hatta, M. Stephanov， Phys. Rev. Lett. 91, 102003 (2003).
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)



系统

守恒荷涨落
对热力学性质敏感

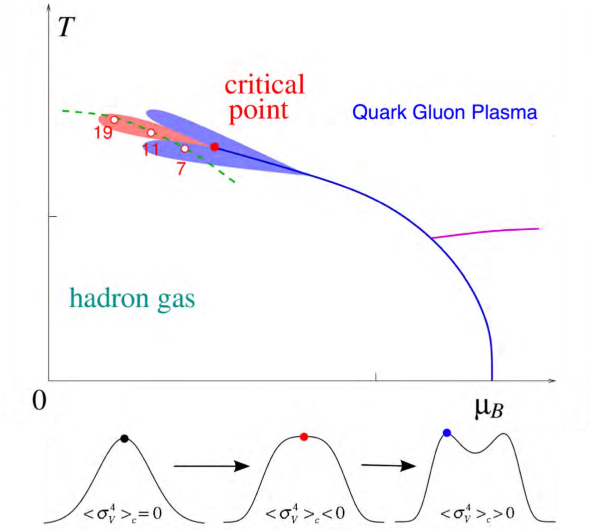
净重子 (B),
净电荷 (Q),
净奇异数 (S)

高阶矩(涨落的度量)

二阶：方差(σ^2)
三阶：偏度(S)
四阶：峰度 (κ)

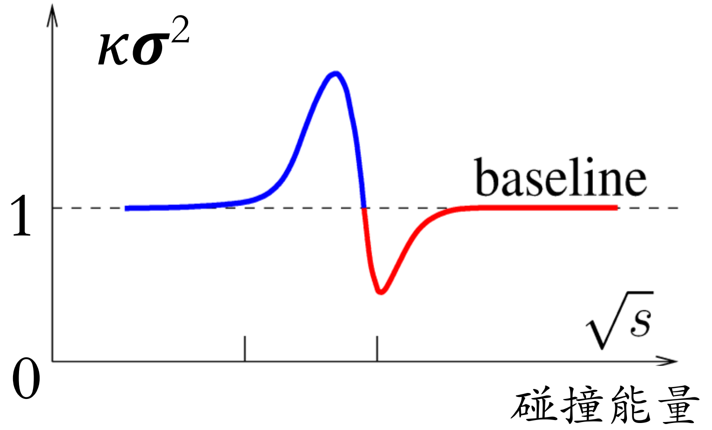
$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}} \propto \xi^5$$

与感应率(χ)直接相关
对关联长度(ξ)敏感



M.A. Stephanov, PRL107, 052301 (2011).

理论预言：临界点信号



观测量对碰撞能量的非单调“振荡”行为

1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, PRC92, 064908(2015).
2) P.K. Netrakanti et al, NPA947, 248(2016),
3) P. Garg et al. Phys. Lett. B726, 691(2013).
4) Jing-hua Fu, arXiv: 1610.07138; Phys.Lett. B722 (2013) 144-150
5) M. Bluhm, Eur.Phys.J. C77 (2017) no.4, 210.
6) J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016)
7) S. He, X. Luo, arXiv:1704.00423
8) C. Zhou, J. Xu, X. Luo, F. Liu, PRC96, 014909 (2017).
9) S. He, X. Luo, Y. Nara, S. Esuimi, N. Xu, Phys.Lett. B762 (2016) 296-300

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, hadronic scattering, Deuteron formation, Softening of EOS. All suppress the net-proton fluctuations.*