Search for QCD Critical Point with Fluctuations of Conserved Quantities in Heavy-ion Collisions

Status and Prospective

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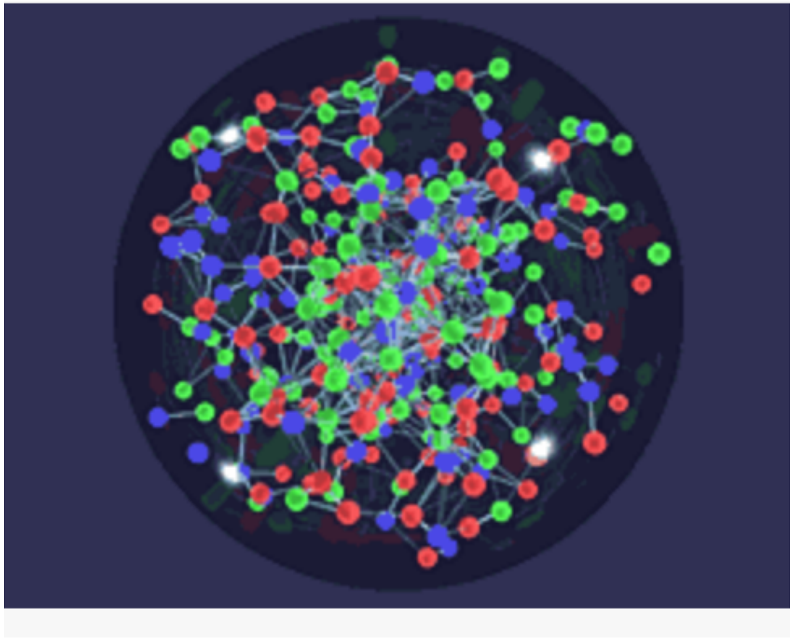
Heating to Trillion Degrees

Steam engine and Industry Revolution

Quark-gluon engine ??



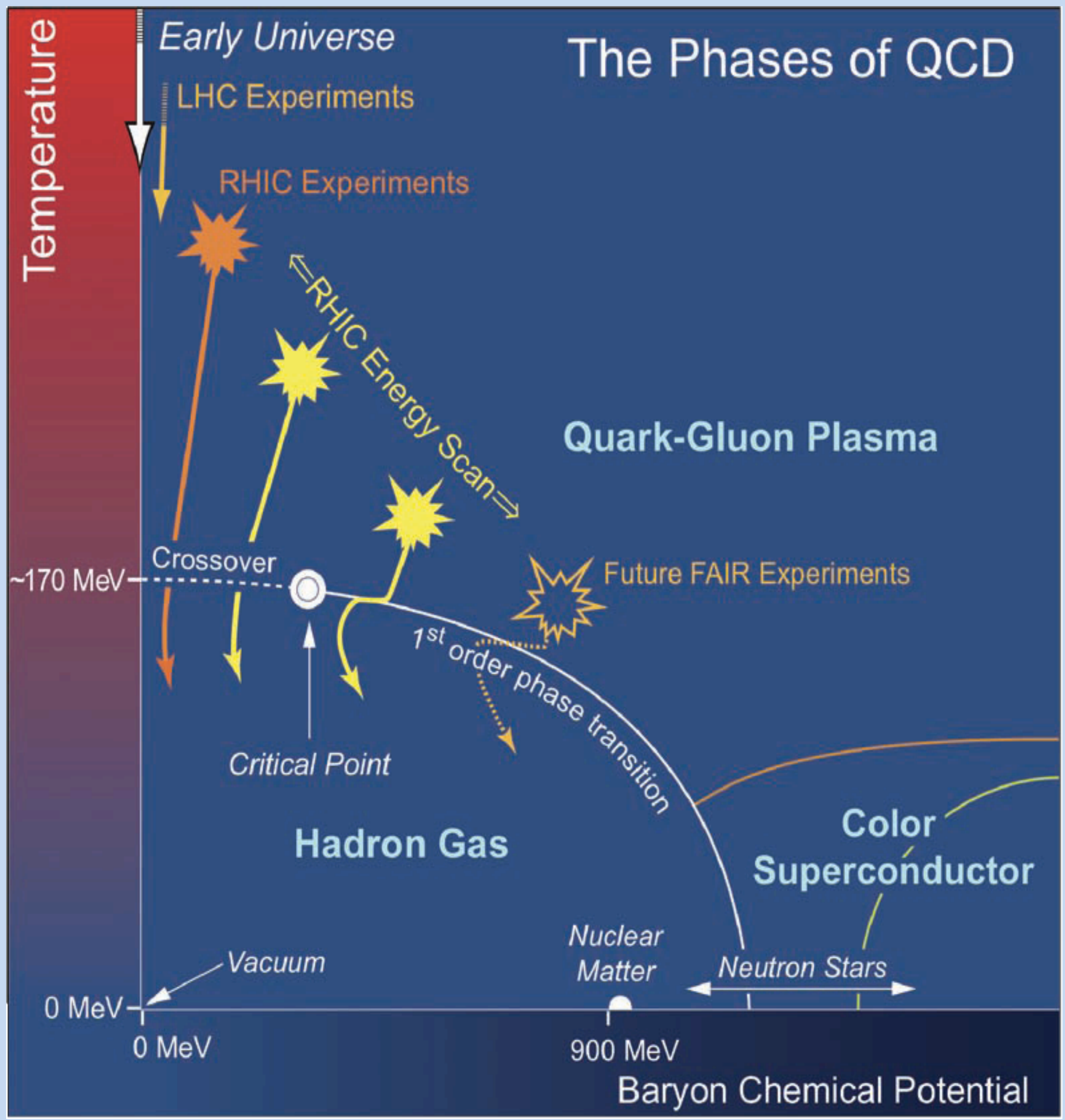
Heat the Water -> Vapor

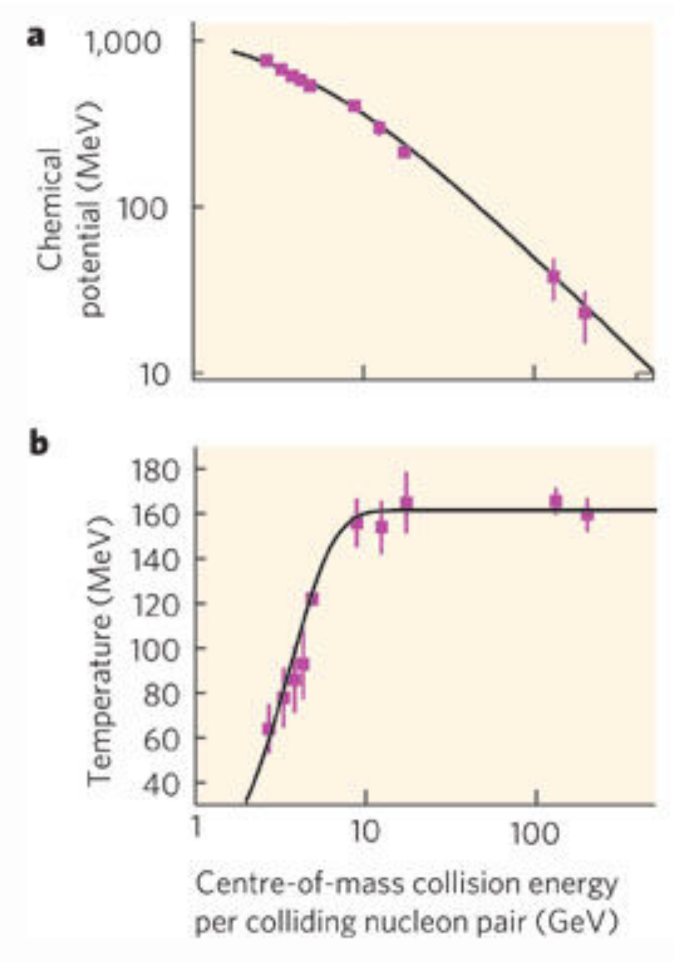
100°C

Quark-gluon plasma

10^{12} °C

QCD Phase Structure and Beam Energy Scan

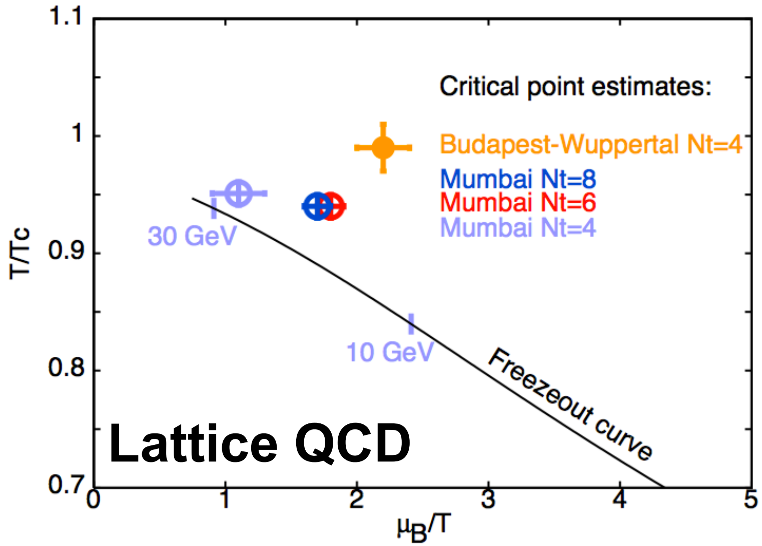


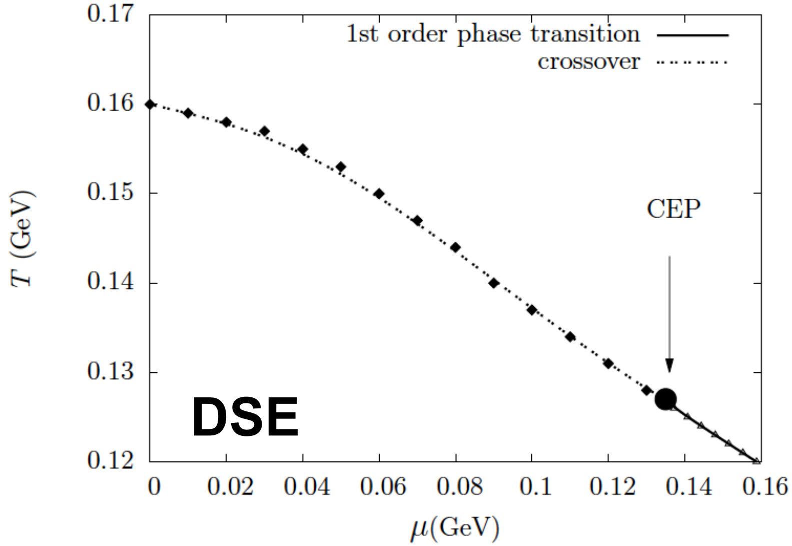


Scan the QCD phase diagram by tuning the colliding energies.

PBM&Johanna, Nature **448**, 302-309 (2007)

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 et al. NPA 956, 352 (2016).
$(\mu^E_B / T_E > 2)$

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

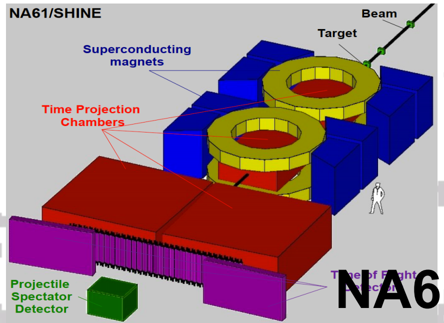
2): Hong-shi Zong et al., JHEP 07, 014 (2014).
$(\mu^E_B, T_E) = (405, 127)$ MeV

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

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

Experimental facility to study the high baryon density region

Started at 2009

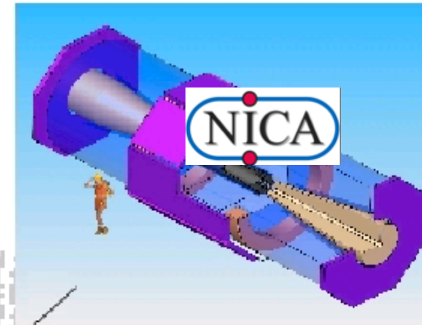


NA61/SPS

Fix target

$\sqrt{s_{NN}}$ = 5-17 GeV

Construction….



Collider

$\sqrt{s_{NN}}$ = 4-11 GeV (2023-)

NICA

SIS

SPS

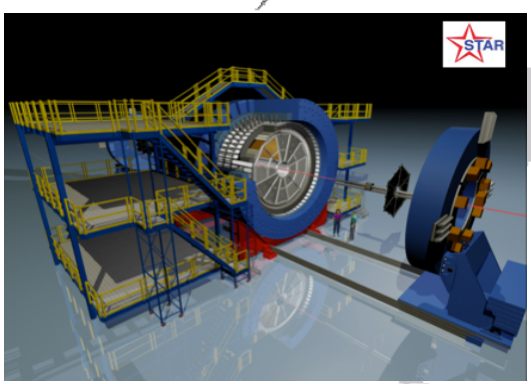
CEE@Lanzhou

JPARC@Japan

RHIC Beam Energy Scan

RHIC

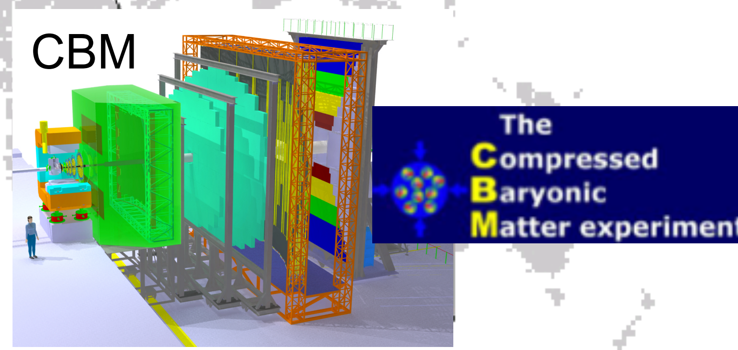
BES-I (2010-2014) is complete.



Collider $\sqrt{s_{NN}}$ = 7.7-200 GeV

Construction….

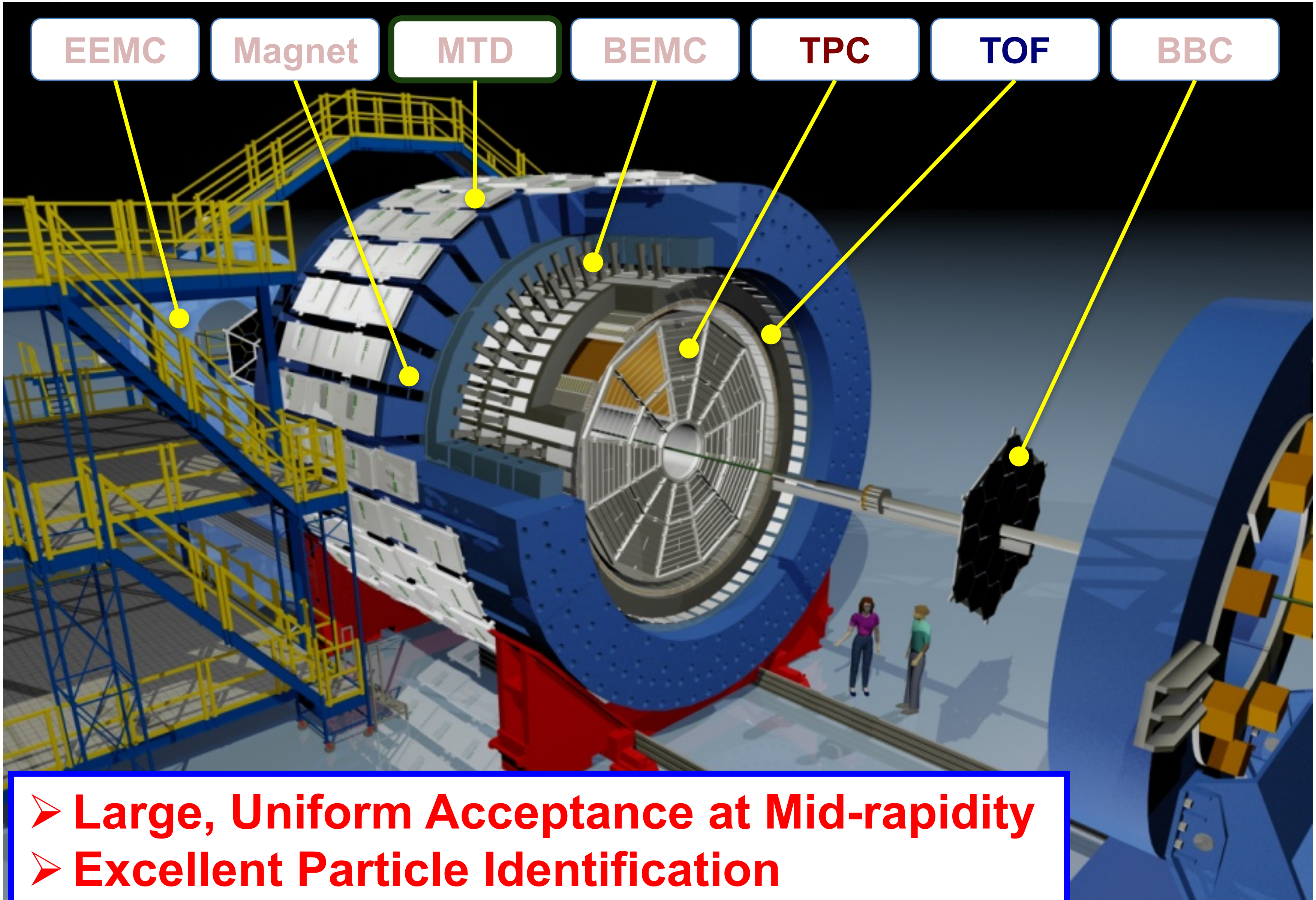
CBM



Fix target

$\sqrt{s_{NN}}$ = 2-8 GeV (2025-)

STAR Detector

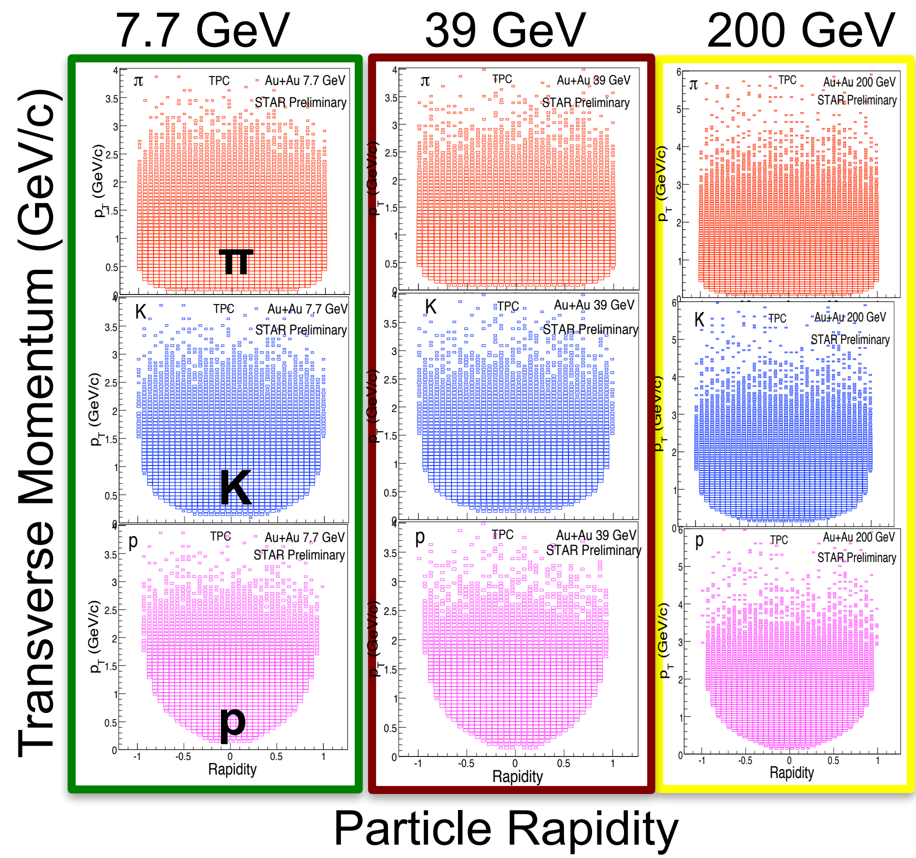


- Large, Uniform Acceptance at Mid-rapidity
- Excellent Particle Identification

Beam Energy Scan - I (2010-2017)

$\sqrt{s_{NN}}$ (GeV)	Events ($X10^6$)	Year	$^*\mu_B$ (MeV)	$^*T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	1200	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)



- ➢ Large and homogeneous acceptance at mid-rapidity.
- ➢ STAR has good opportunity to explore the QCD phase structure by accessing broad region of phase diagram.

Cumulants of Conserved Charges Distributions

The cumulants of conserved charges (B, Q, S) in grand canonical ensemble are extensive variables, and are directly connected to the susceptibility of the system.

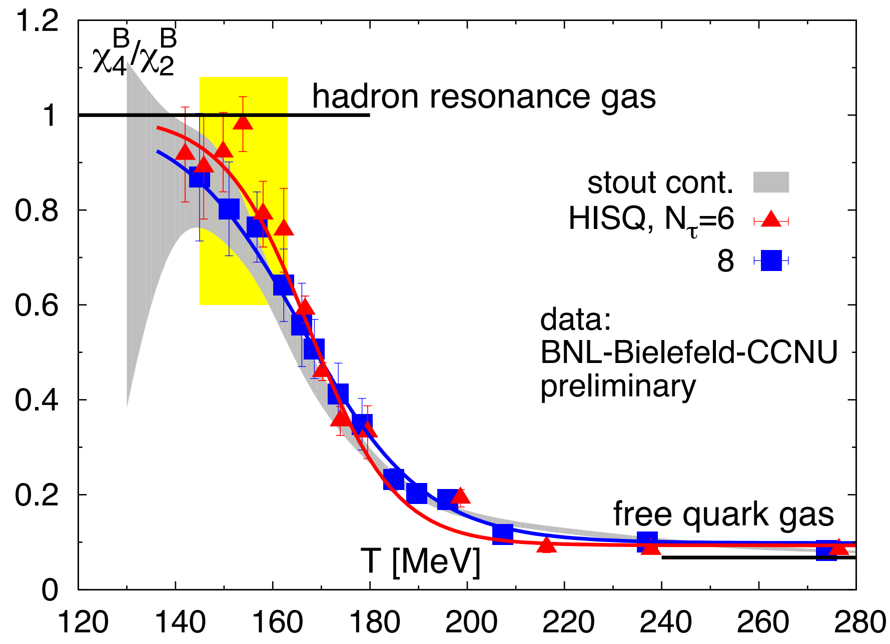
$$C_{n,q} = VT^3 \chi_q^{(n)} = \frac{\partial^n (p/T^4)}{\partial(\mu_q/T)^n}, \qquad q = B, Q, S$$

Cancel out the volume dependence by taking ratios of cumulants:

$$\frac{C_{4,q}}{C_{2,q}} = \kappa\sigma^2 = \frac{\chi_q^{(4)}}{\chi_q^{(2)}}$$

$$\frac{C_{3,q}}{C_{2,q}} = S\sigma = \frac{\chi_q^{(3)}}{\chi_q^{(2)}}$$

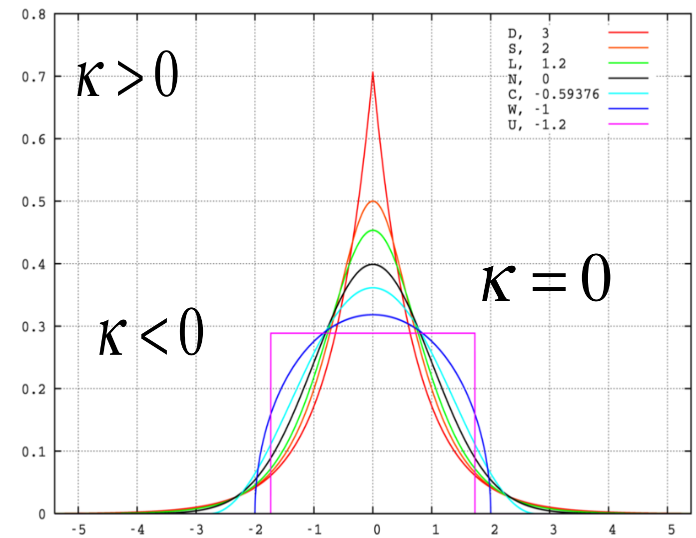
S. Ejiri et al,Phys.Lett. B 633 (2006) 275. B. Friman et al., EPJC 71 (2011) 1694. F. Karsch and K. Redlich , PLB 695, 136 (2011). S. Gupta, et al., Science, 332, 1525(2012).



Observables measured at STAR

Cumulants of the event-by-event net-proton, net-charge and net-kaon distributions.

- **Net-Proton:** $N_p - N_{\bar{p}}$
  (Net-Baryon, *B*)
- **Net-Charge:** $N_{Q^+} - N_{Q^-}$
- **Net-Kaon:** $N_{K^+} - N_{K^-}$
  (Net-Strangeness, *S*)



$$C_{2,q} \propto \xi^2, C_{3,q} \propto \xi^{4.5}, C_{4,q} \propto \xi^7$$

$$\frac{C_{4,q}}{C_{2,q}} = \kappa\sigma^2 \propto \xi^5$$

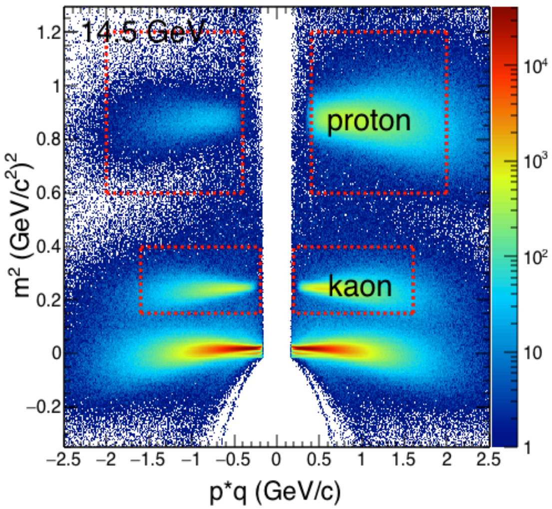
$$\frac{C_{3,q}}{C_{2,q}} = S\sigma \propto \xi^{9/4}$$

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

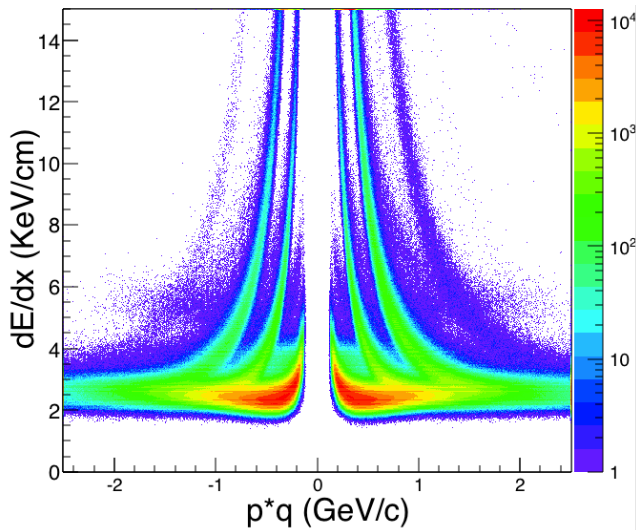
Analysis Details

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *to avoid auto-correlations*	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$

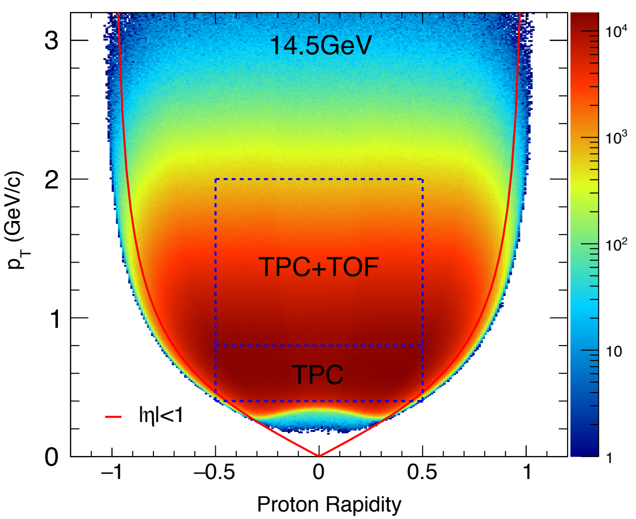
TOF PID



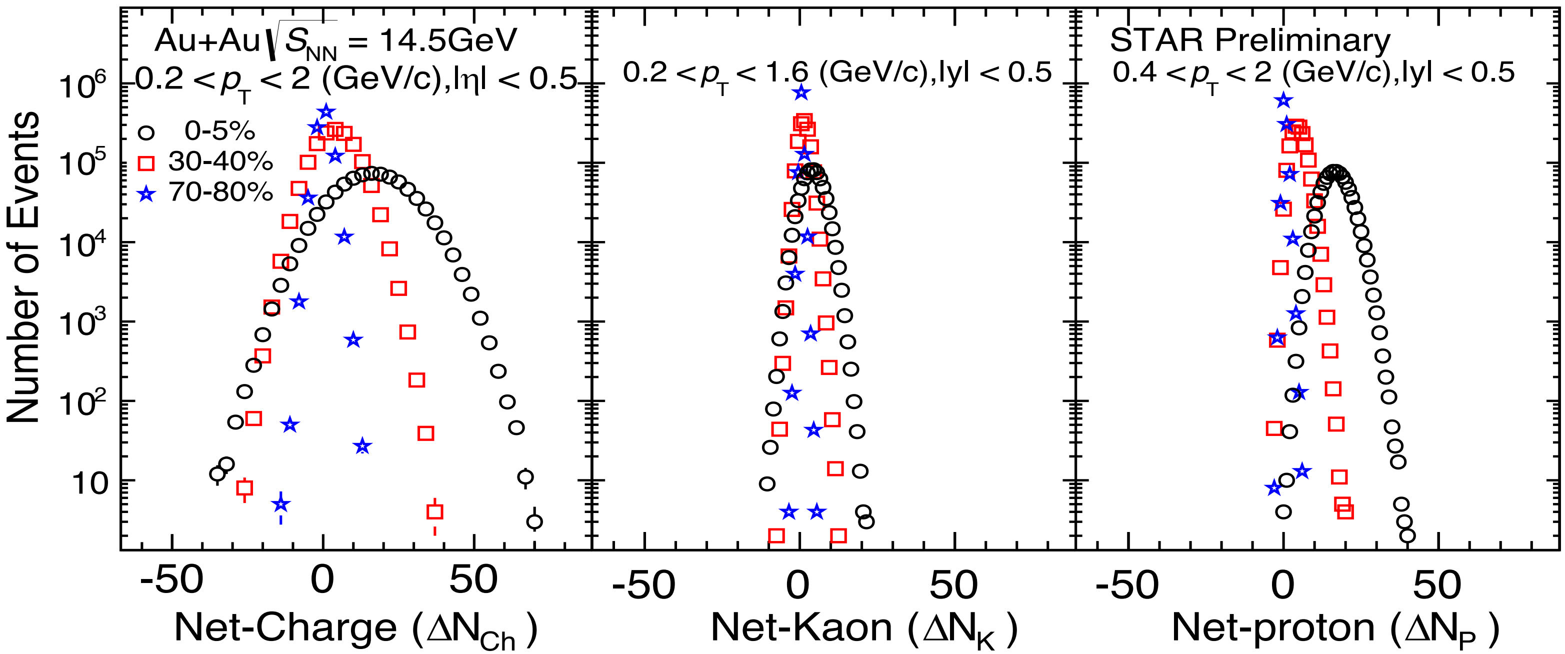
TPC PID



Phase Space



Data Analysis Methods



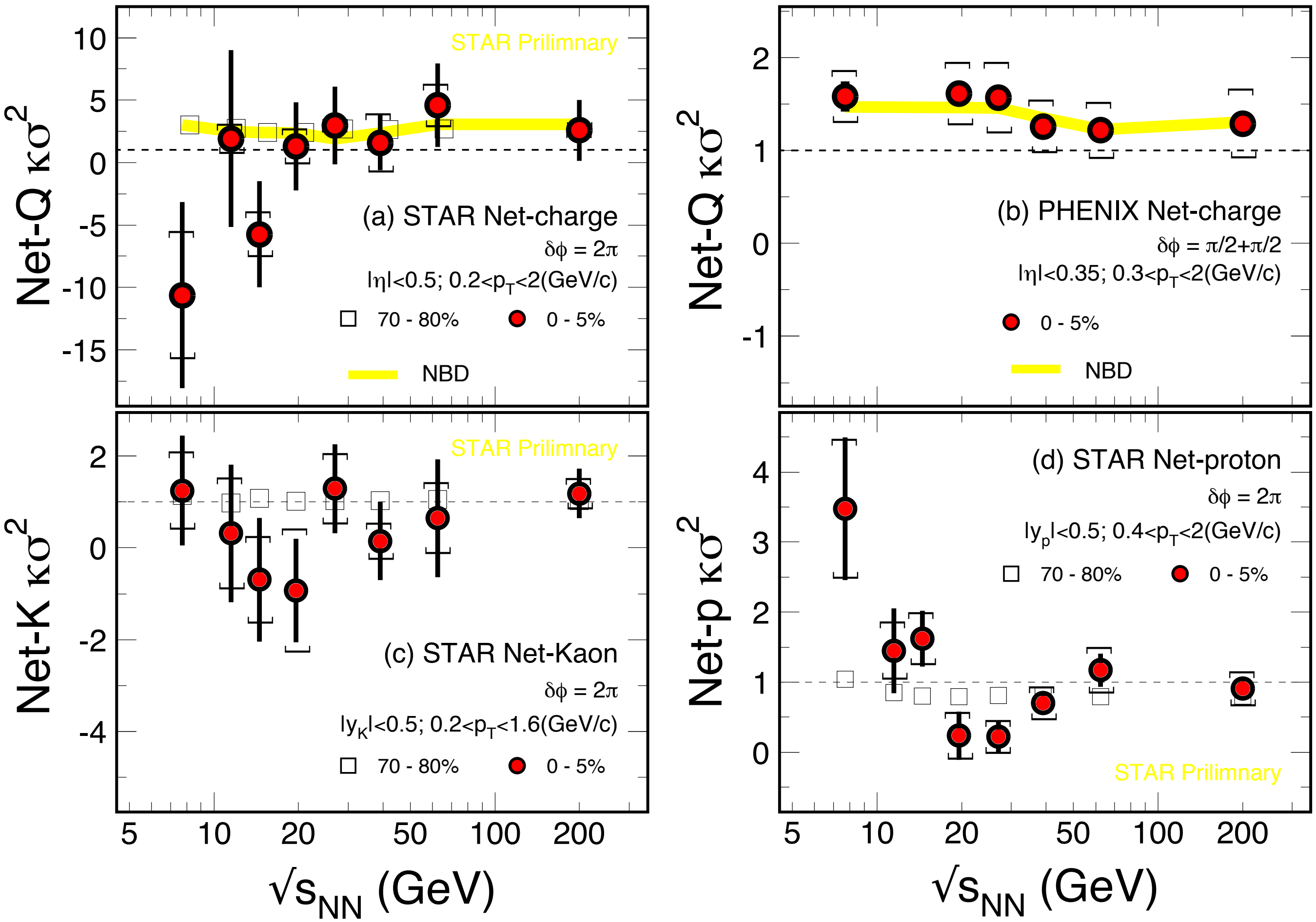
Effects needed to be addressed to get final moments/cumulants:

1. Avoid auto-correlation effects: New centrality definition.
2. Suppress volume fluctuation：Centrality bin width correction
3. Finite detector efficiency correction

X.Luo, et al. J. Phys. G39, 025008 (2012); *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). T. Nonaka et al., PRC95, 064912 (2017). M. Kitazawa and X. Luo, PRC*96, 024910 (2017).

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

Forth Order Fluctuations of Net-P, Net-Q, Net-K



STAR, PRL105,022302 (2010);
STAR, PRL112,032302 (2014).
STAR, CPOD 2014, QM 2015
STAR, PRL113,092301 (2014)
STAR, to PLB [arXiv: 1709.00773]

1. Large errors are observed in Q and S fluctautions, Statistical Errors: Q > S > B.
2. Non-monotonic energy dependence observed in 4th order net-proton fluctuations.

Towards Understanding Experimental Data

1. **Effective model calculations (Static):** σ field Model, NJL, PNJL, PQM, VDW+HRG, Mean field

   M. A. Stephanov, PRL107, 052301 (2011). Schaefer&Wanger,PRD 85, 034027 (2012);
   JW Chen, JDeng et al., PRD93, 034037 (2016), PRD95, 014038 (2017)
   W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017); arXiv: 1702.08674
   Vovchenko et al., PRC92,054901 (2015); PRL118,182301 (2017)
   K. Fukushima, Phys.Rev. C91 (2015) no.4, 044910; Weijie, Fu et al, Phys.Rev. D94 (2016) , 116020
   M. Huang et al., arXiv:1706.02238, Ju Xu et al, arXiv:1709.05178, Guoyun Shao et al.,arXiv:1708.04888

2. **Dynamical evolution of critical fluctuations:** Study non-equilibrium effects

   Swagato et al, PRC92,034912 (2015). PRL117, 222301 (2016); M. Nahrgang, et al. EPJA 52, 240 (2016).
   C. herold Phys.Rev. C93 (2016) no.2, 021902 L. Jiang et al. arXiv: 1704.04765

3. **Non-critical background:** HRG, UrQMD, JAM, AMPT, Hydro+UrQMD

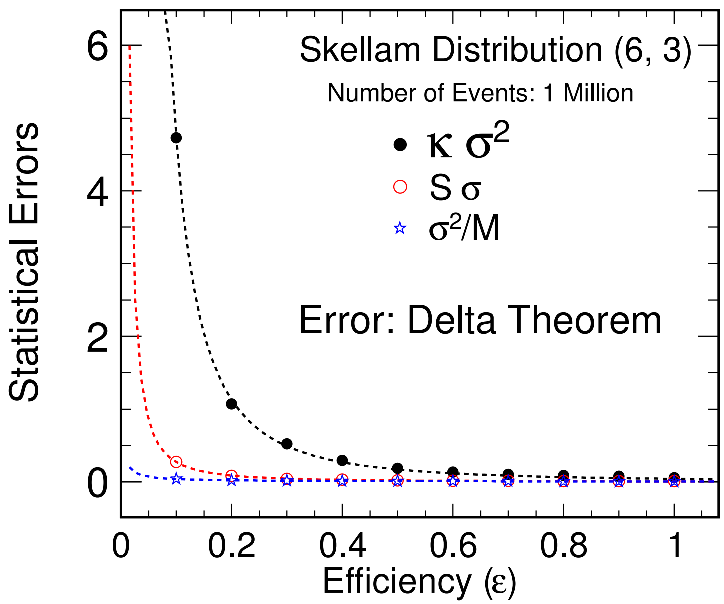
   Z. Feckova,et al., PRC92, 064908(2015). P.K. Netrakanti et al, NPA947, 248(2016), P. Garg et al. Phys. Lett. B726, 691(2013).J.H. Fu, arXiv: 1610.07138; Phys.Lett. B722 (2013) 144-150; M. Bluhm, EPJC77, 210 (2017). J. Xu, YSL, X. Luo, F. Liu, PRC94, 024901 (2016) ; S. He, X. Luo, arXiv:1704.00423, C. Zhou, et al., PRC96, 014909 (2017). S. He, et al., PLB762, 296 (2016). L. Jiang et al., PRC94, 024918 (2016). H.J. Xu, PLB 2017. Huichao et al., arXiv:1707.09742

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.

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

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)

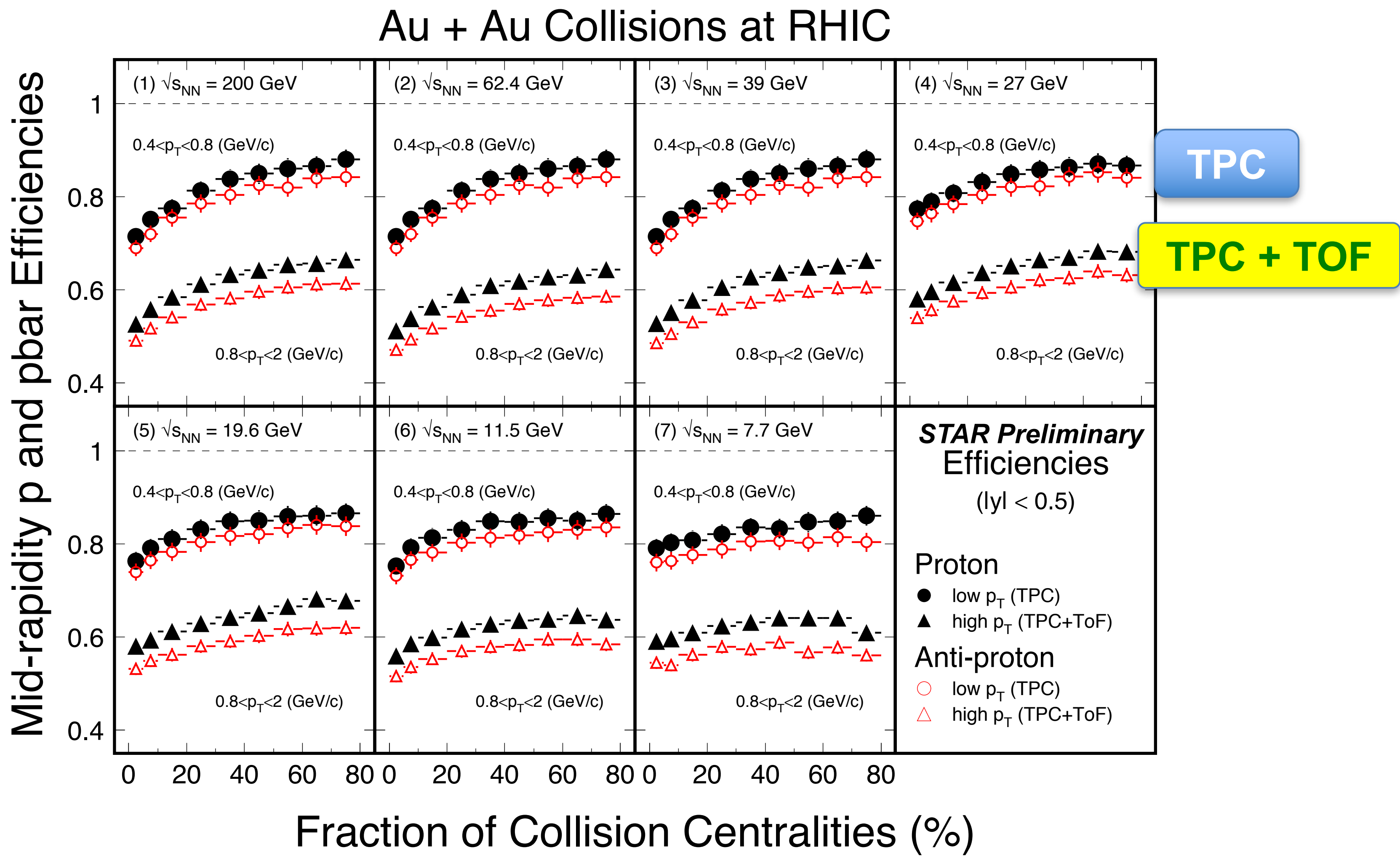
Au+Au 14.5GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width(σ)	12.2	4.2	3.4
Average efficiency(ε)	65%	75%	38%
σ^2/ε^2	355	32	82

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

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

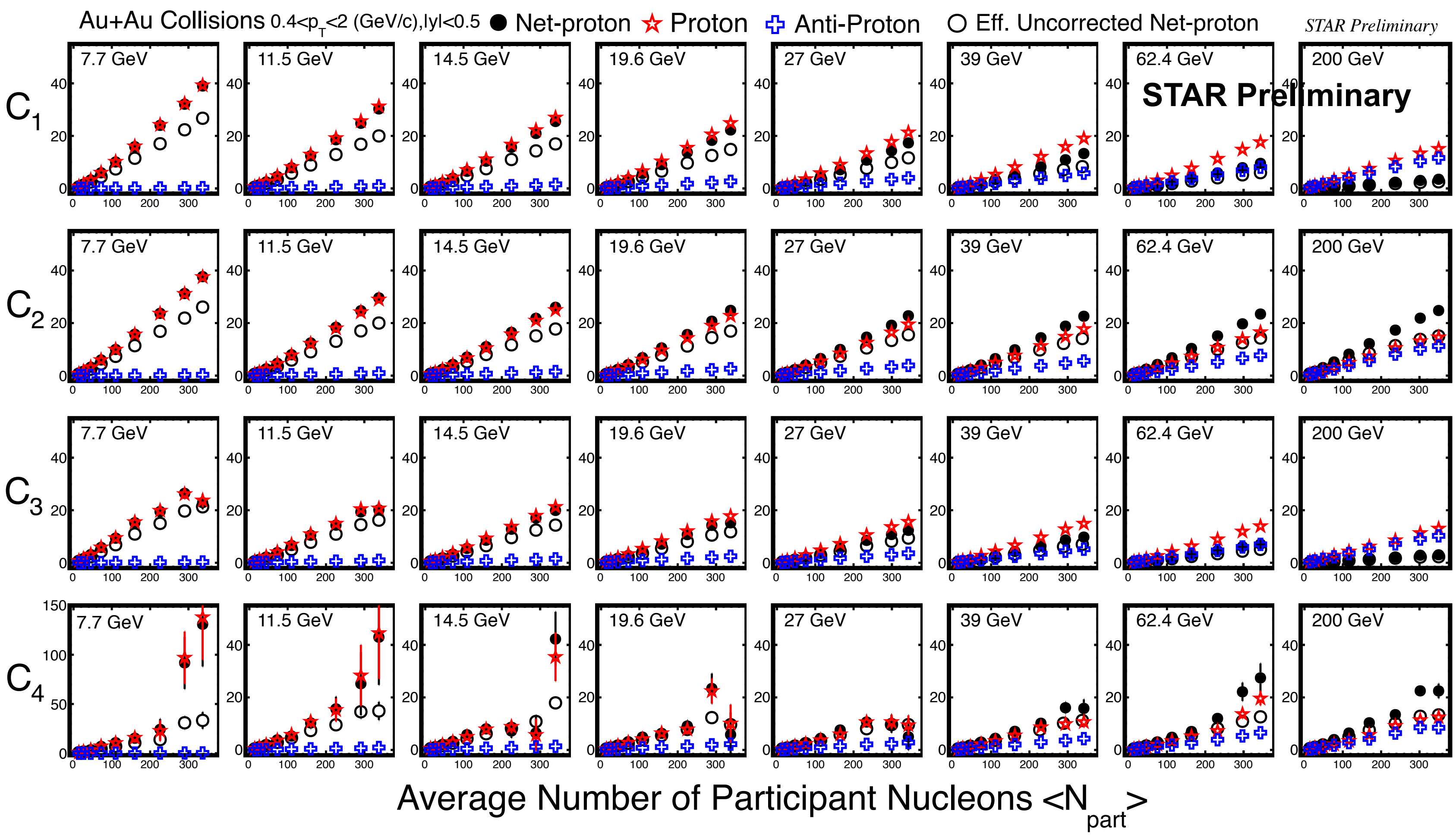
Those numbers are for illustration purpose and not used in actual analysis

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, Proton and Anti-Proton Cumulants (C_1~C_4)

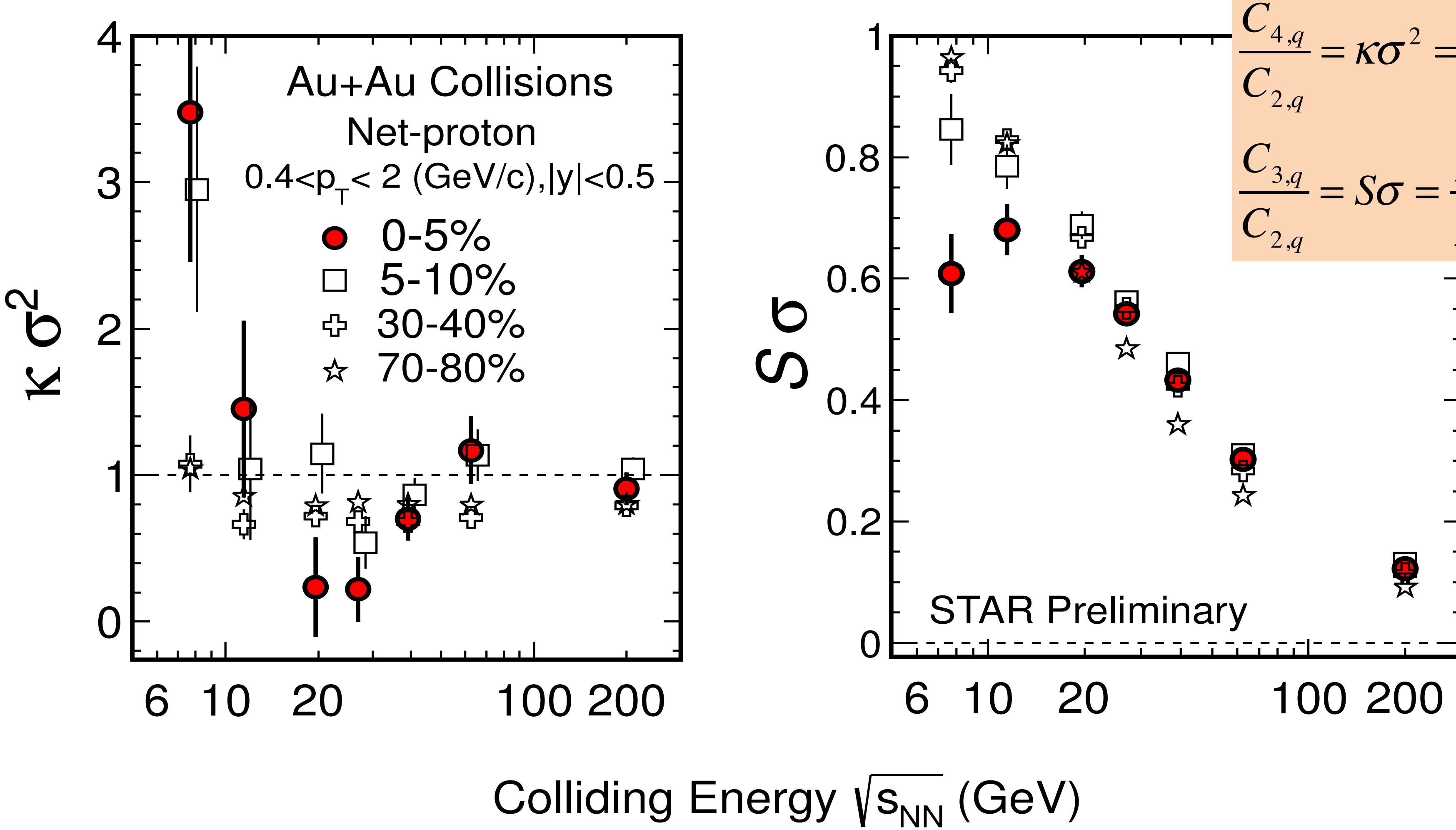


1. Efficiency corrections are important for both value and statistical errors.
2. Generally, cumulants are linearly increasing with $<N_{part}>$.
3. At low energies, the proton cumulants are close to net-proton.

Energy Dependence of Net-Proton Fluctuations

$$\frac{C_{4,q}}{C_{2,q}} = \kappa\sigma^2 = \frac{\chi_q^{(4)}}{\chi_q^{(2)}}$$

$$\frac{C_{3,q}}{C_{2,q}} = S\sigma = \frac{\chi_q^{(3)}}{\chi_q^{(2)}}$$

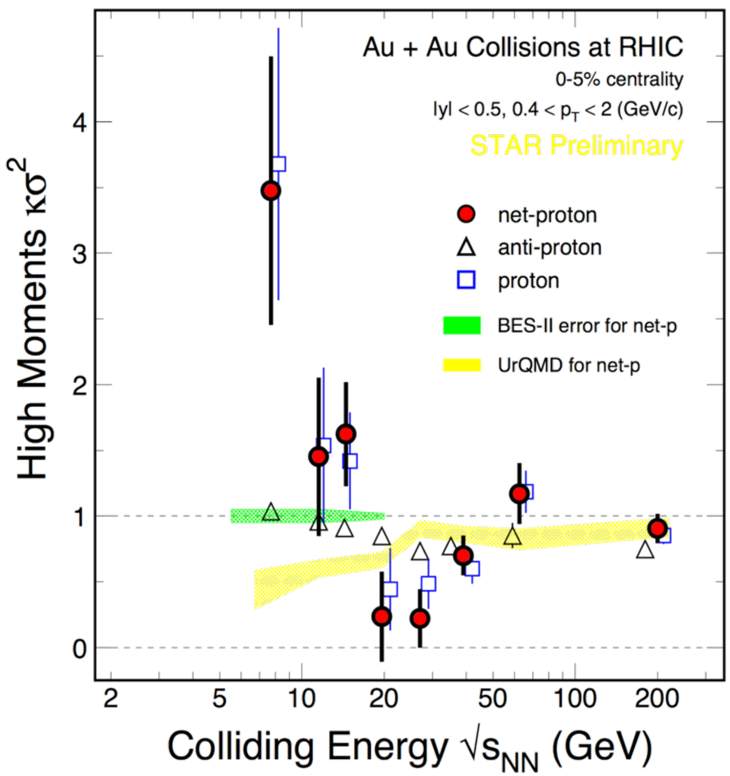


Clear non-monotonic energy dependence is observed in the fourth order net-proton fluctuations in 0-5% central Au+Au collisions.

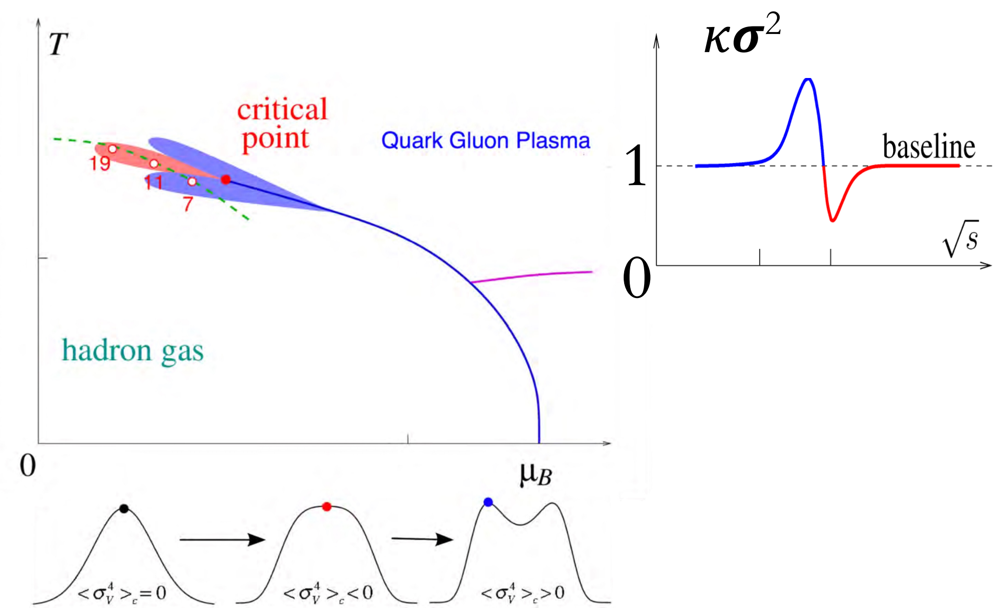
4^{th} order Net-Proton Fluctuations $\kappa\sigma^2 = C_4/C_2$

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

STAR Data



σ field Model



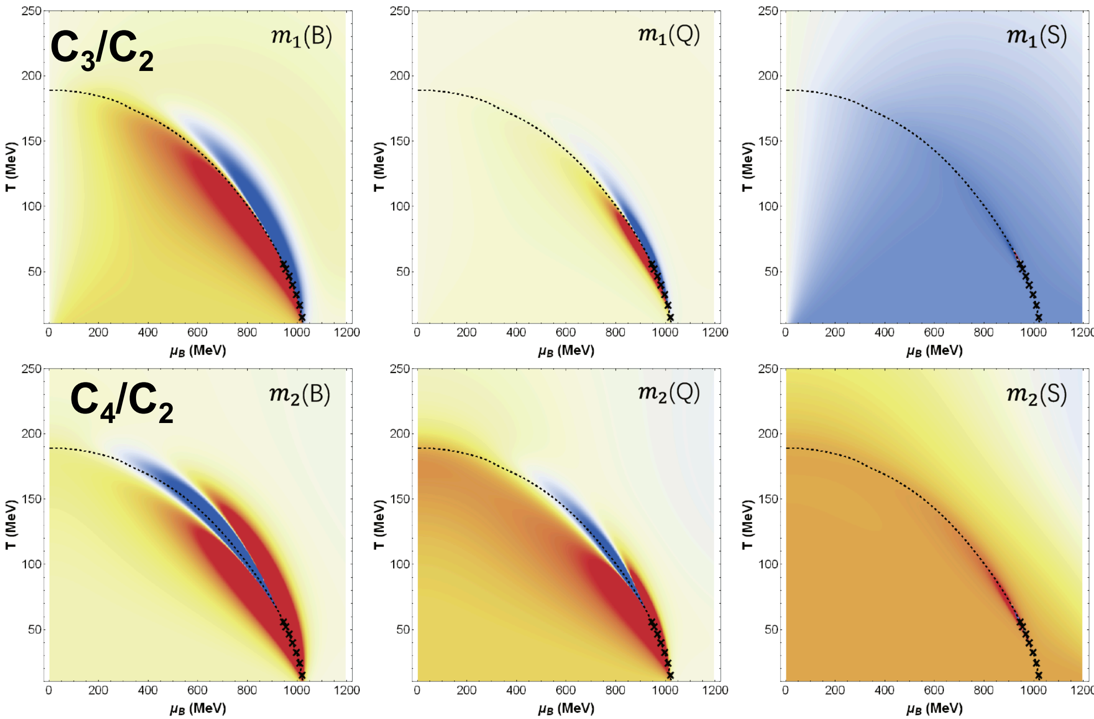
Critical signal: Oscillation Structure

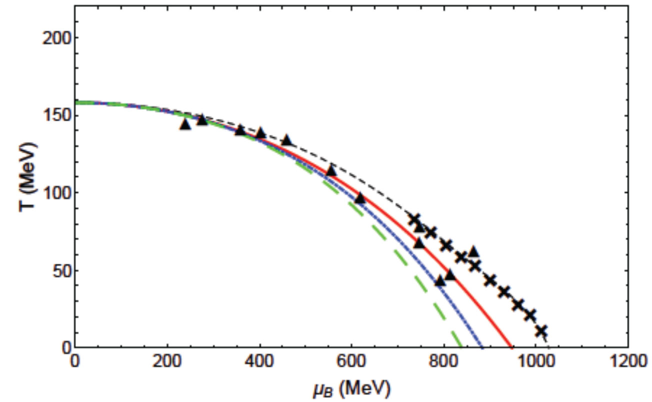
STAR, PRL105,022302 (2010); PRL112,032302 (2014).
STAR, CPOD2014 and QM2015

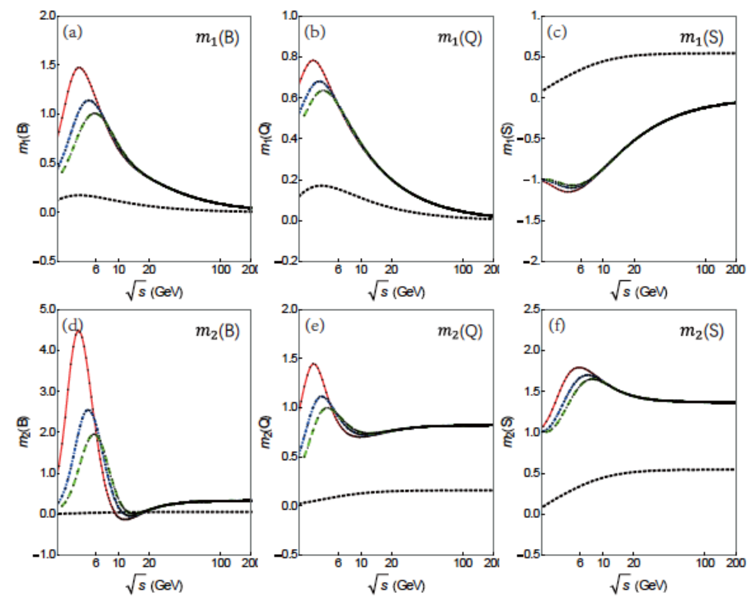
M. A. Stephanov, PRL102, 032301 (2009).
M. A. Stephanov, PRL107, 052301 (2011).

NJL Model Calculations

Baryon (B) **Charge (Q)** **Strangeness (S)**







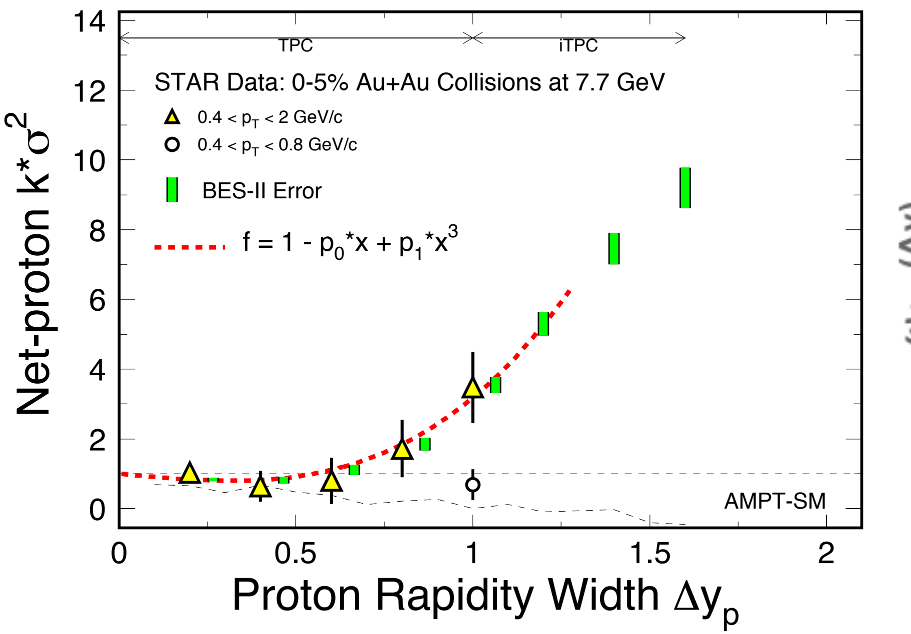
1) Due to large mass of s quark, CP Signals in Q and S are much smaller than B.
2) Forth and third order fluctuations have very different behavior.

W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017).
JW Chen, JDeng et al., PRD93, 034037 (2016), PRD95, 014038 (2017)

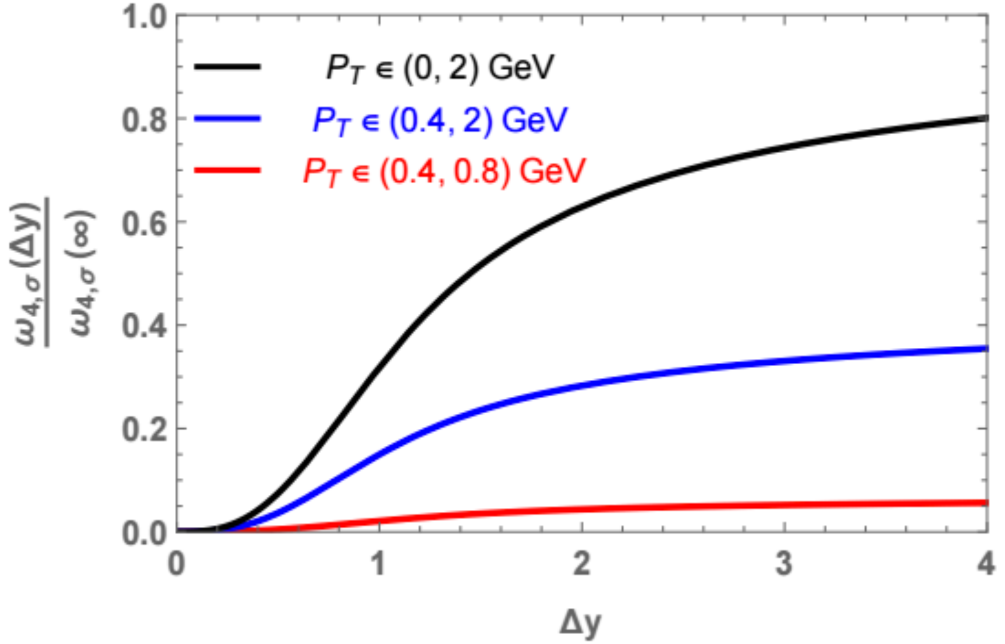
Acceptance Dependence

Acceptance dep. near CP

STAR Data



Model

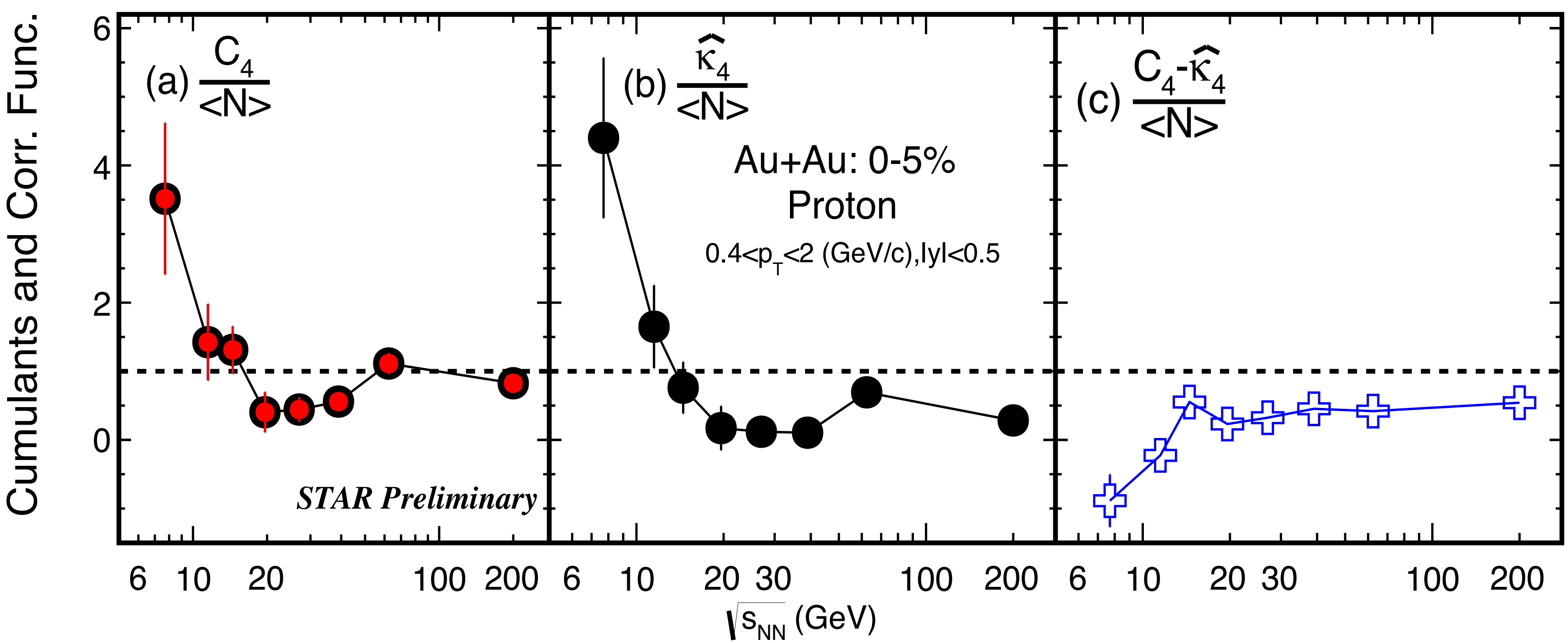


B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016).
A. Bzdak, V. Koch, Phys.Rev. C95, 054906 (2017)
M. Kitazawa, X. Luo, PRC96, 024910 (2017).

Signals can be enhanced by enlarging the acceptance.

Proton Cumulants and Correlation Functions

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



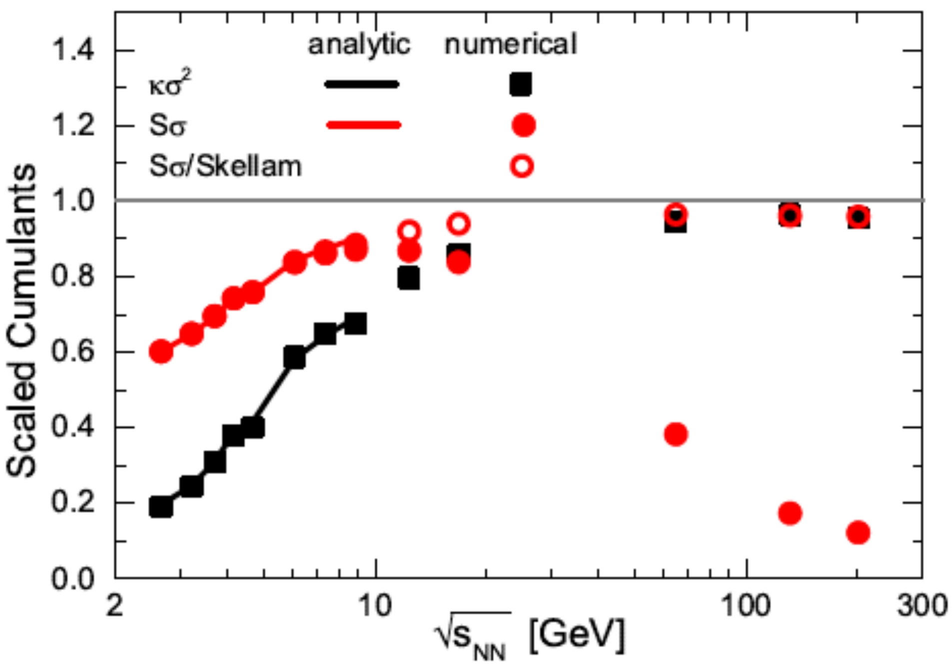
Four particle correlation dominated the non-monotonic behavior observed in forth order net-proton fluctuations.

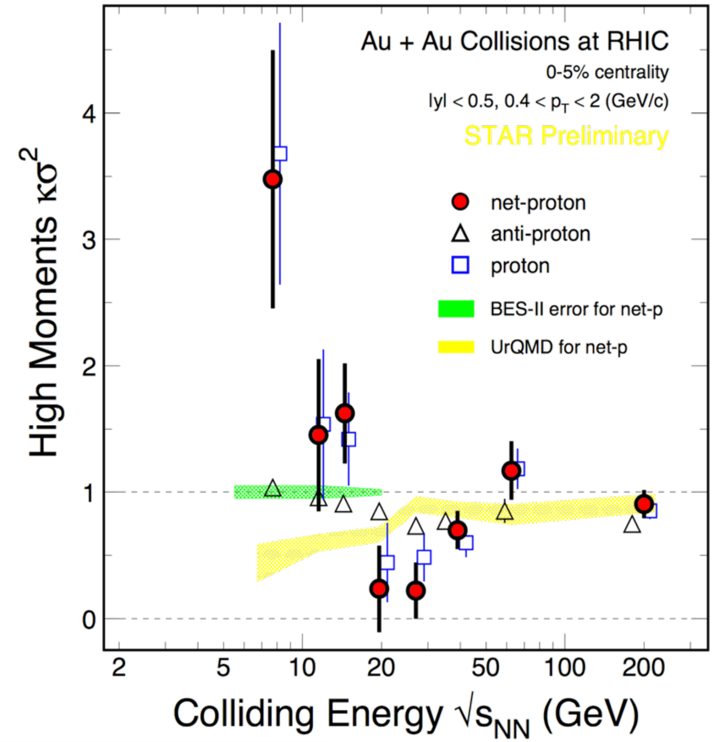
$$C_2 = \langle N \rangle + \hat{\kappa}_2$$
$$C_3 = \langle N \rangle + 3\hat{\kappa}_2 + \hat{\kappa}_3$$
$$C_4 = \langle N \rangle + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

Proton Cluster formation: A. Bzdak, V. Koch, V. Skokov, Eur. Phys. J., C77, 288(2017)

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

UrQMD (with Deuteron Formation)





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

- Model simulation :*All suppress the net-proton fluctuations.*

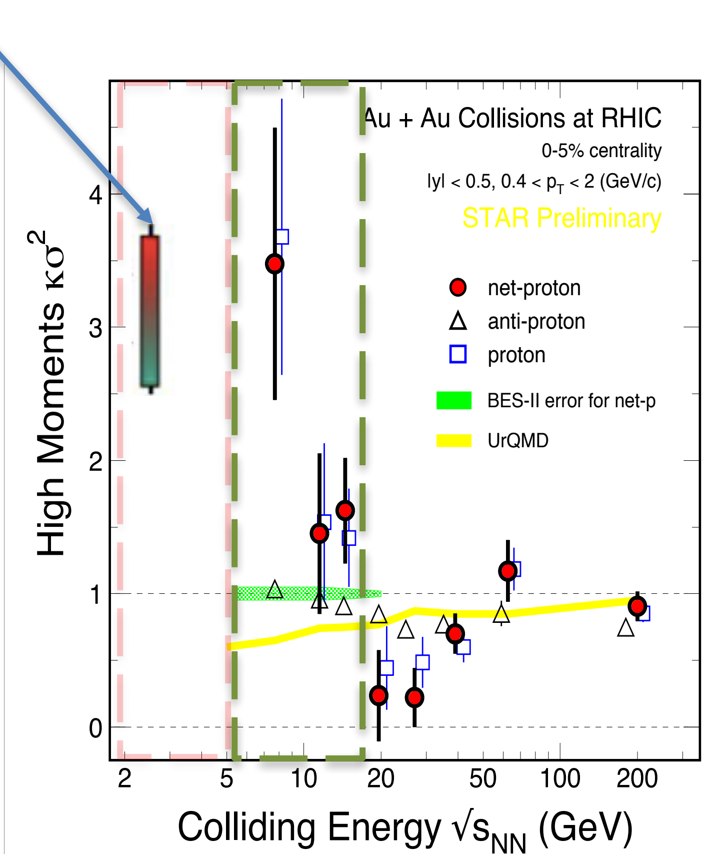
(UrQMD, AMPT, HRG, JAM cannot reproduce data)

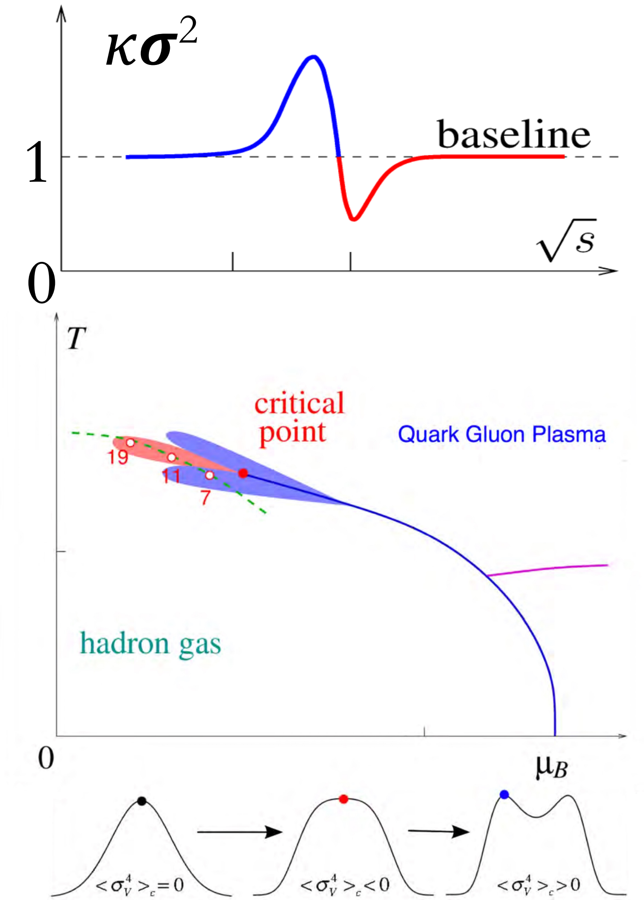
1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, PR**C92**, 064908(2015). J. Xu, S. Yu, F. Liu, X. Luo, PR**C94**, 024901(2016). X. Luo *et al*, NP**A931**, 808(14), P.K. Netrakanti *et al.* 1405.4617, NP**A947**, 248(2016), P. Garg *et al.* Phys. Lett. **B726**, 691(2013).
2) S. He, X. Luo, Y. Nara, S. Esuimi, N. Xu, Phys.Lett. **B 762**, 296 (2016).
3) S. He and X. Luo, , Phys.Lett. **B 774**, 623 (2017).

Future Plan for QCD Critical Point Search

Preliminary HADES Results (QM2017)

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

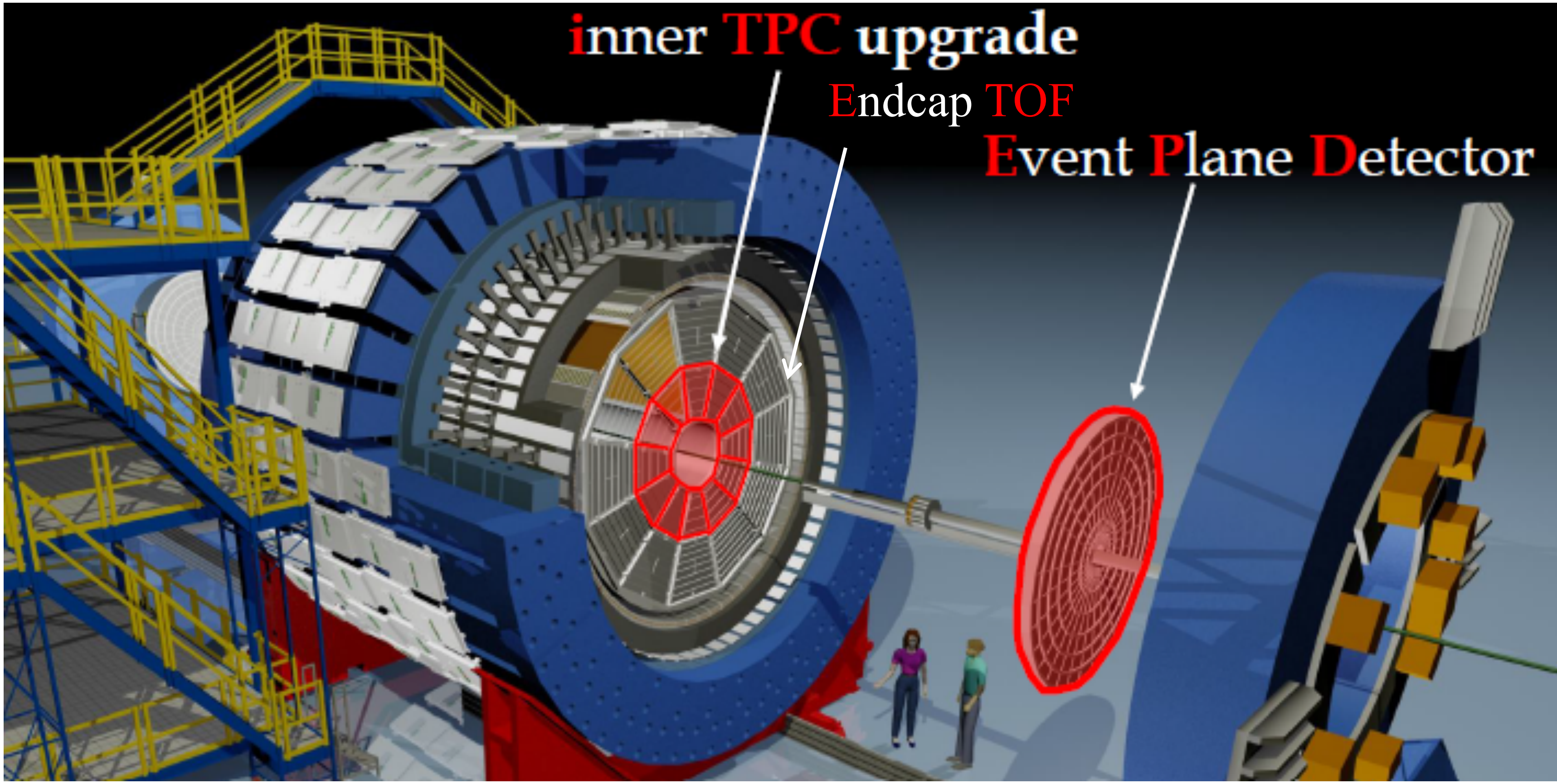




1. Need precision measurement between 7.7 to 20 GeV
2. Need lower energy data points.

CBM/STAR FXT/HADES/NICA Experiments

STAR Upgrades for BES Phase-II



1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/EP resolution

iTPC, EPD, eTOF
Dedicated two runs at RHIC: 2019 & 2020

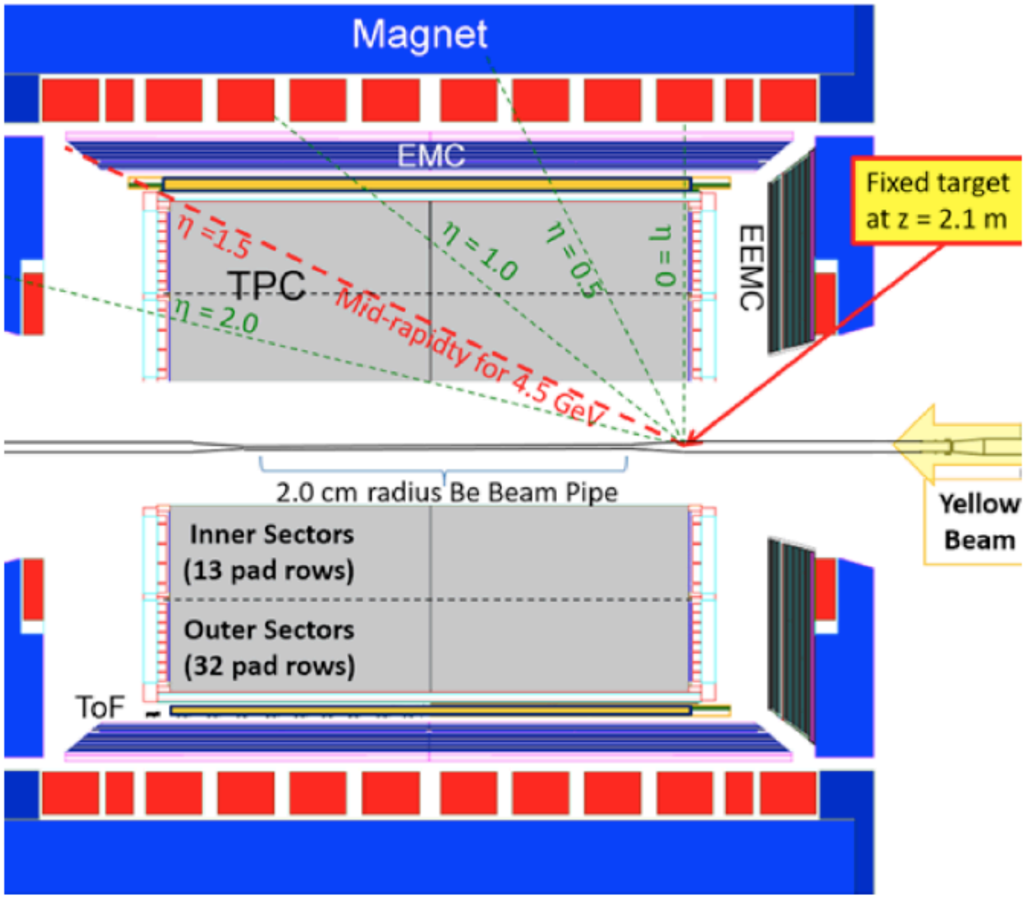
2019-2020: BES-II at RHIC

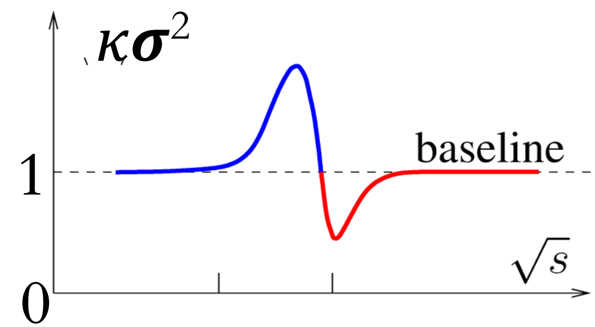
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	1200	2017	83	165
39	39	2010	112	164
27	70	2011	156	162
19.6	**400** / 36	**2019-20** / 2011	206	160
14.5	**300** / 20	**2019-20** / 2014	264	156
11.5	**230** / 12	**2019-20** / 2010	315	152
9.2	**160** / 0.3	**2019-20** / 2008	355	140
7.7	**100** / 4	**2019-20** / 2010	420	140

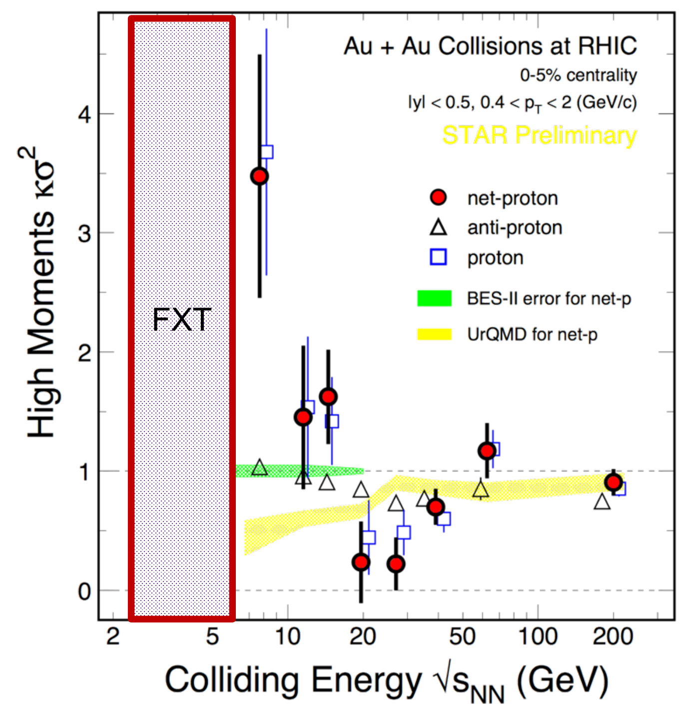
BES-II: Precise mapping the QCD phase diagram

$200 < \mu_B < 420$MeV

FXT Experiments at STAR (2018-2019)







FXT Data Taking Plan：
2018: Au+Au :3 GeV (100 million events)
2019-2020: Au+Au: 6.2, 5, 4.5, 4, 3.5 GeV

Summary and Outlook

- Clear non-monotonic energy dependence is observed in the net-proton kurtosis at most central Au+Au collision.
  A hint of entering critical region.
  Need to confirm with more statistics and lower energies data.

- Model simulation (No CP) indicates: *Baryon conservations, Mean-field potential, hadronic scattering, Deuteron formation.*
  All suppress the net-proton fluctuations.

- Within current uncertainties, net-charge and net-kaon fluctuations show flat energy dependent. Need more statistics.

- 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 (BES-III): CBM, NICA, CEE, JPARC.
  (3) Need dynamical modeling of the critical fluctuations in HIC.

Thank you !