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

Status and Prospective

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First observation of binary neutron star merger

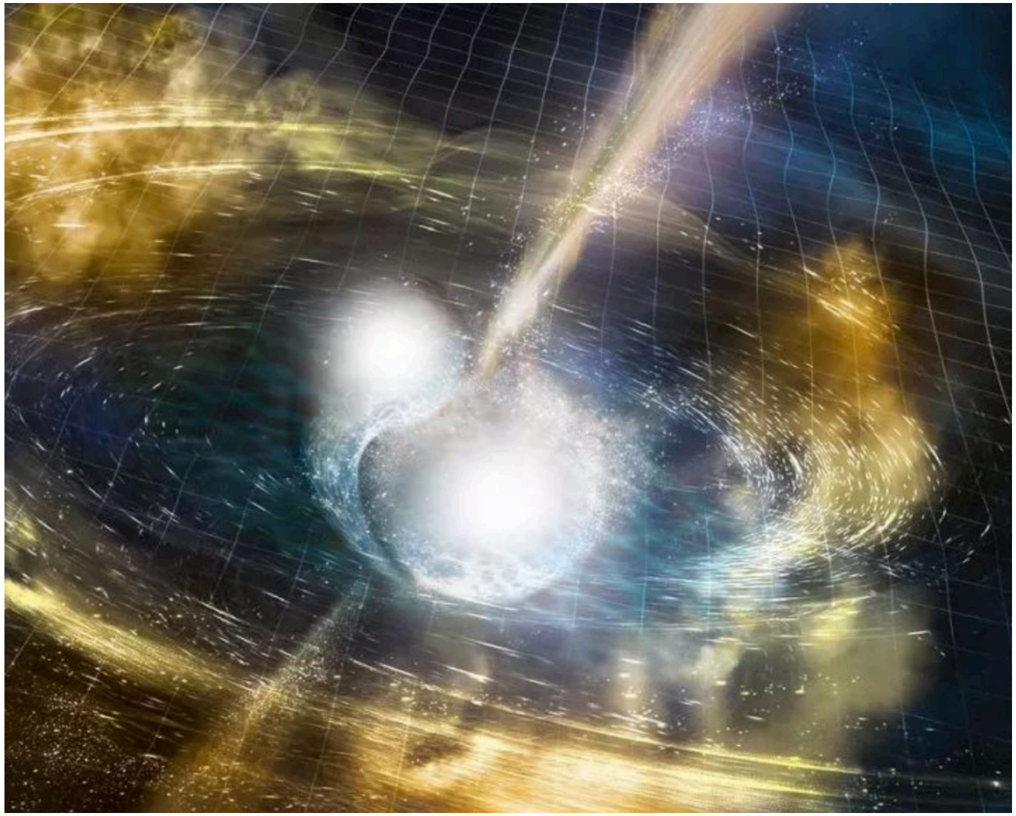
15 papers are published in Science, Nature, PRL

[1] Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119, 161101 (2017), Published October 16, 2017

[2] Arcavi et al., "Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger" Nature (16 October 2017)
[3] Troja et al., "The X-ray counterpart to the gravitational-wave event GW170817" Nature (16 October 2017)
[4] Pian et al., "Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger" Nature (16 October 2017)
[5] Kasen et al., "Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event" Nature (16 October 2017)
[6] Smartt et al., "A kilonova as the electromagnetic counterpart to a gravitational-wave source" Nature (16 October 2017)
[7] Abbott et al., "A gravitational-wave standard siren measurement of the Hubble constant" Nature (16 October 2017)

[8] Drout et al., "Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis," Science (16 October 2017)
[9] Shappee et al., "Early spectra of the gravitational wave source GW170817: Evolution of a neutron star merger," Science (16 October 2017)
[10] Kasliwal et al., "Illuminating gravitational waves: A concordant picture of photons from a neutron star merger," Science (16 October 2017)
[11] Hallinan et al., "A radio counterpart to a neutron star merger," Science (16 October 2017)
[12] Evans et al., "Swift and NuSTAR observations of GW170817: Detection of a blue kilonova," Science (16 October 2017)
[13] Bloom et al., "A cosmic multimessenger gold rush," Science (16 October 2017)
[14] Kilpatrick et al., "Electromagnetic evidence that SSS17a is the result of a binary neutron star merger," Science (16 October 2017)
[15] Coulter et al., "Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source," Science (16 October 2017)

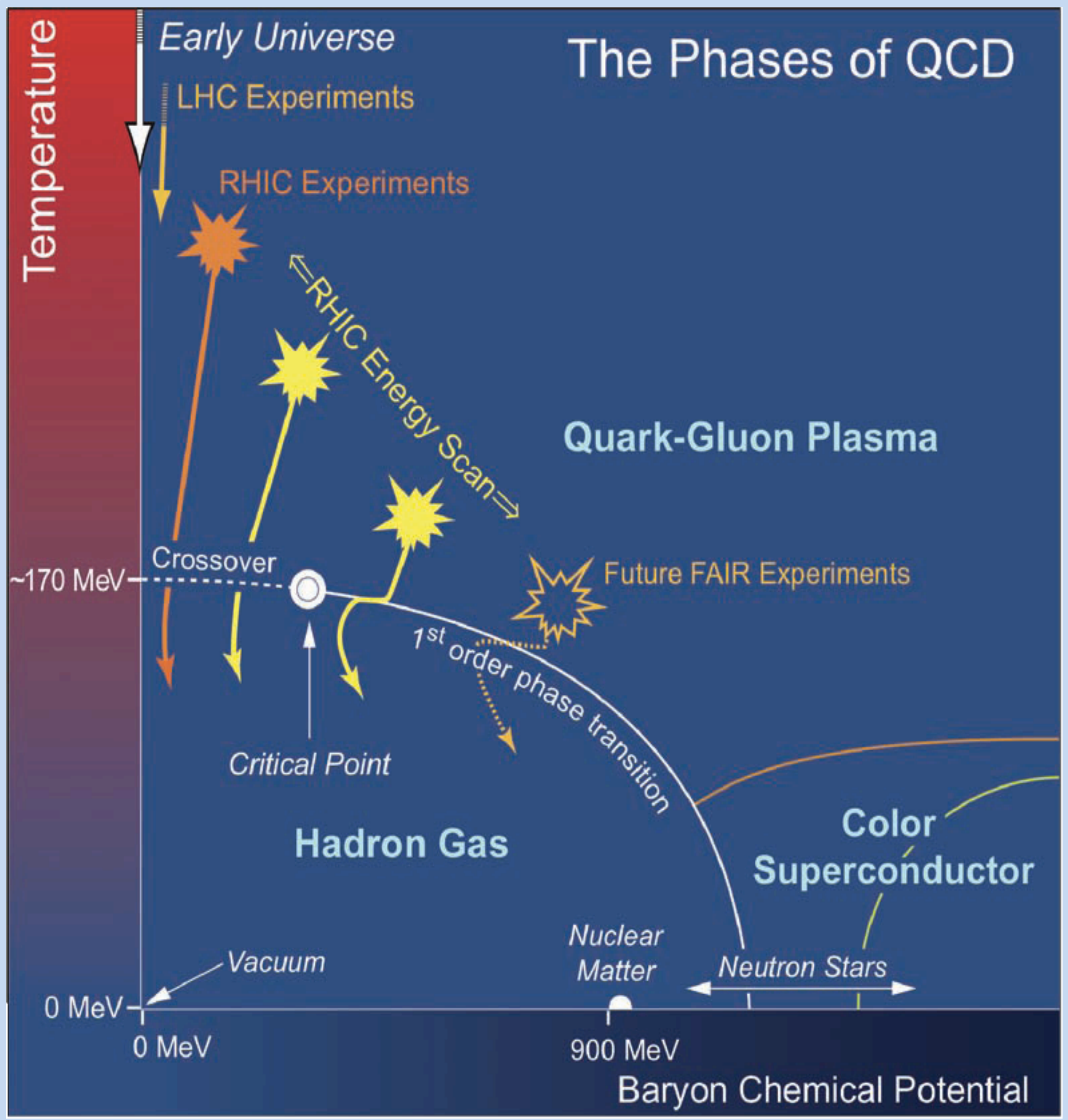
A scientific feast！(科学盛宴)

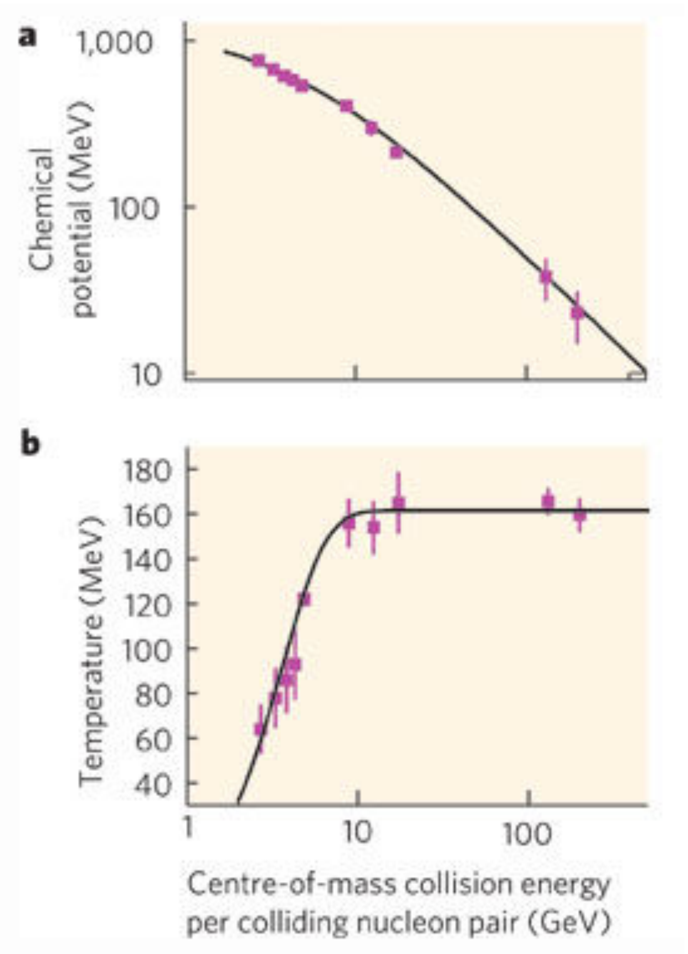


- Gravitation wave + EM radiation
- The origin of heavy elements
- Multi-messenger astronomy era

What’s the EoS of neutron star ?

QCD Phase Structure and Beam Energy Scan



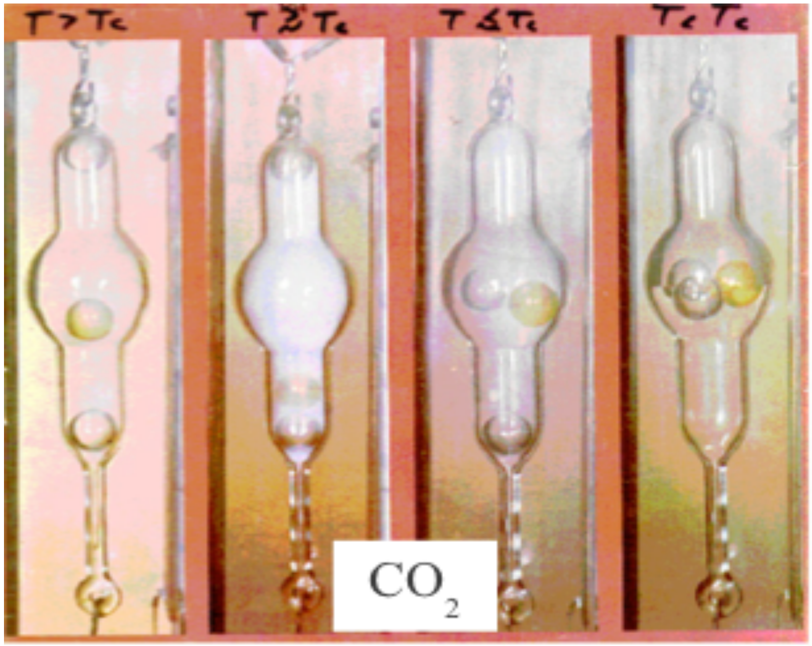


Scan the QCD phase diagram by tuning the colliding energies.

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

Critical Point and Critical Phenomena

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



First CP is discovered in 1869 for CO_2 by Andrews.

$T_c = 31°C$

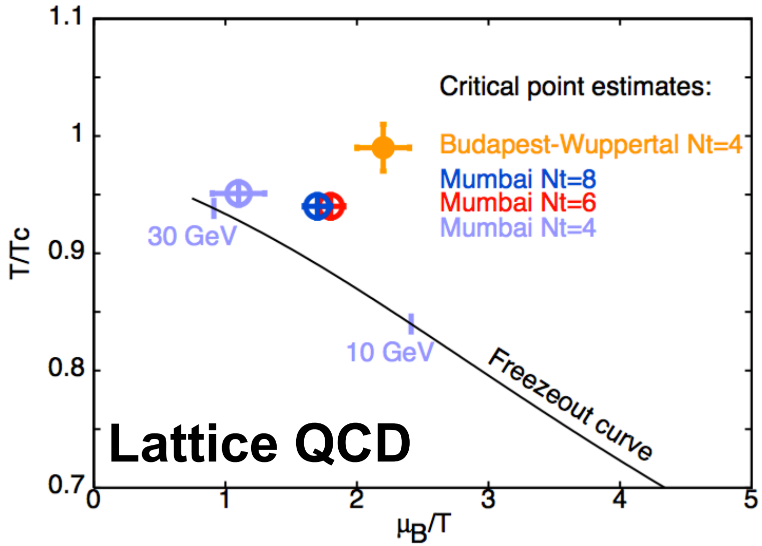
Critical Phenomena :

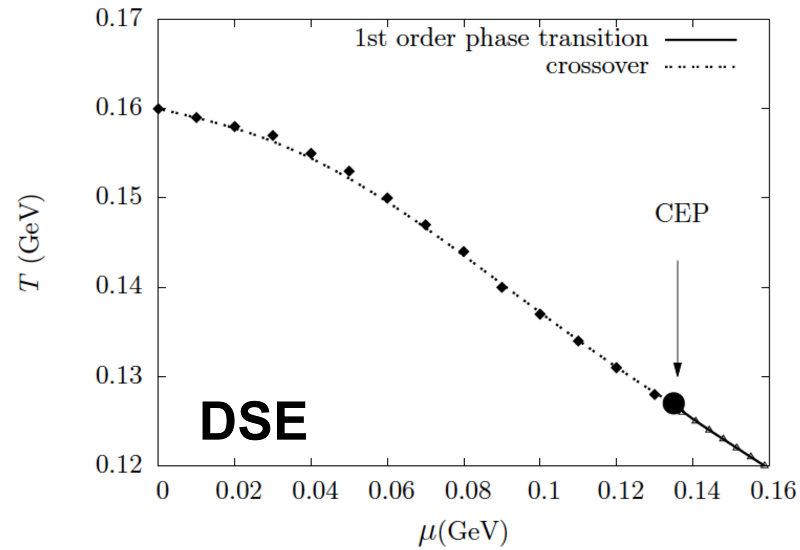
- Density fluctuations and cluster formations.
- Divergence of Correlation length (ξ).
  Susceptibilities (χ), heat capacity (C_V) , Compressibility (κ) etc.
  Critical opalescence.
- Universality and critical exponents are determined by the symmetry and dimensions of underlying system.

Heavy-ion collisions:

1) **Effects of finite time and size.**
2) **Non-equilibrium effects.**

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

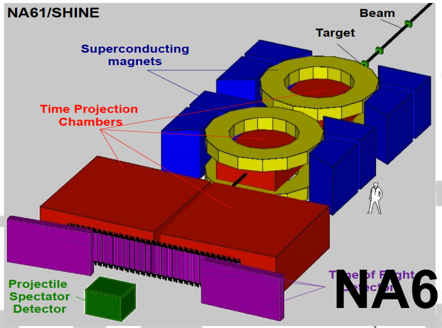
2): Hong-shi Zong et al., JHEP 07, 014 (2014).
$(\mu^E_B, T_E) = (405, 127)$ MeV

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

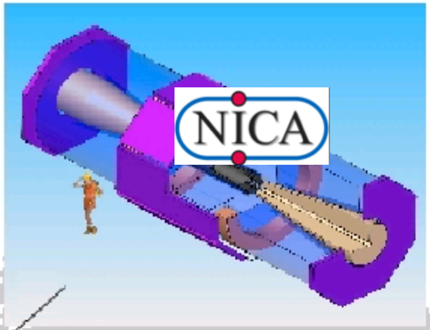


NA61/SPS

Fix target

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

Construction….



Collider

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

NICA

SIS

SPS

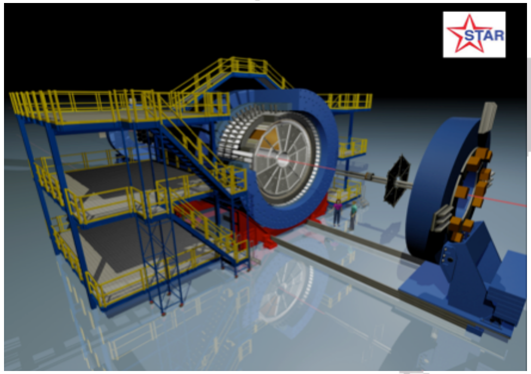
RHIC

CEE@Lanzhou

JPARC@Japan

RHIC Beam Energy Scan

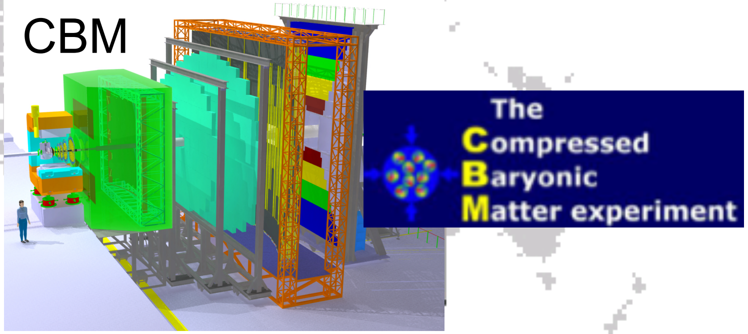
BES-I (2010-2014) is complete.



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

Construction….

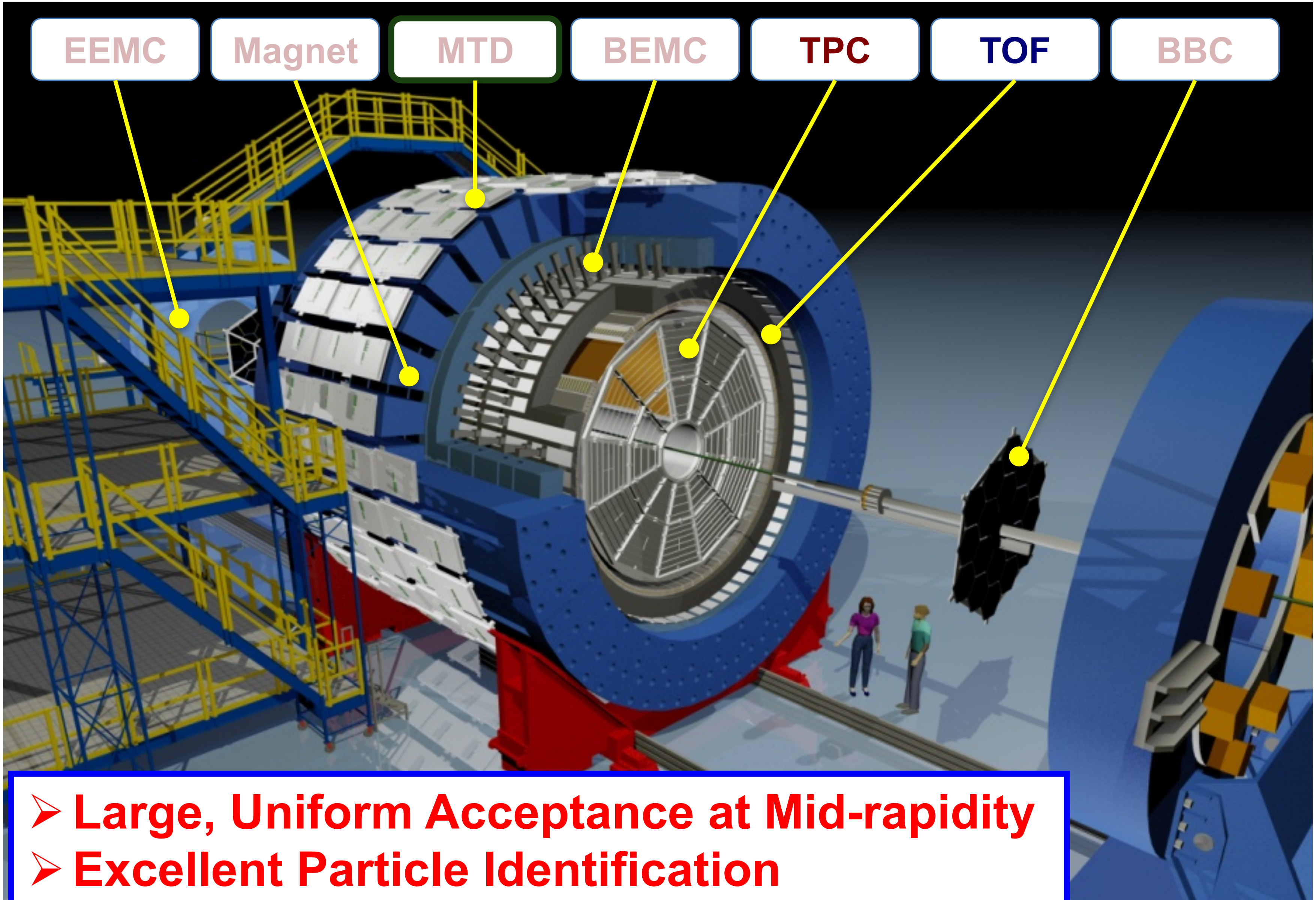
CBM



Fix target

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

STAR Detector

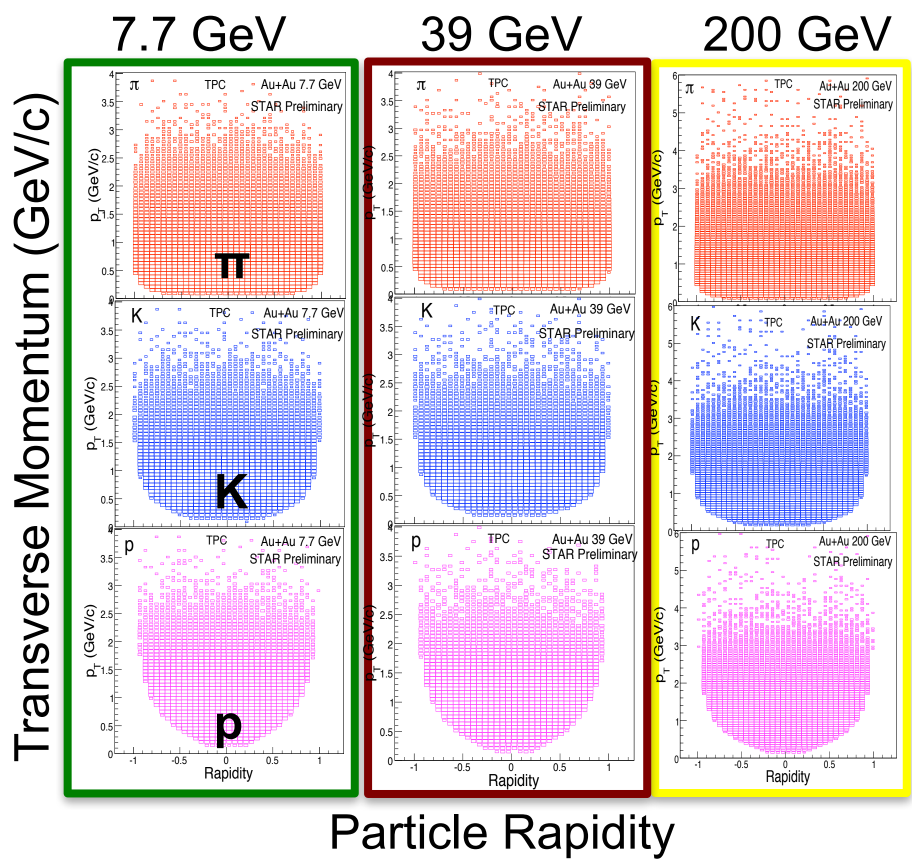


- **Large, Uniform Acceptance at Mid-rapidity**
- **Excellent Particle Identification**

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)



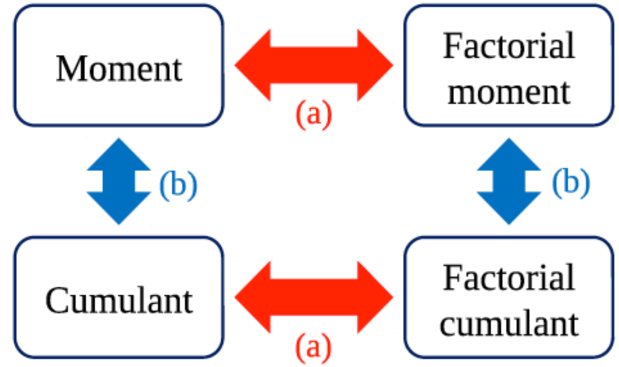
- ➢ Large and homogeneous acceptance at mid-rapidity.
- ➢ STAR has good opportunity to explore the QCD phase structure by accessing broad region of phase diagram.

Quantify the Fluctuations

Cumulants generating fun.:

$$G(\theta)=\sum_{n} e^{\theta n}P(n)=\left\langle e^{\theta n}\right\rangle \qquad \left\langle n^m\right\rangle_c=\left.\frac{\partial^m K(\theta)}{\partial\theta^m}\right|_{\theta=0}$$

- For Poisson distributions: $C_n = C_1$
- For Gaussian distributions: $C_n=0$, $(n>=3)$



M. Kitazawa, X. Luo, PRC96, 024910 (2017)

- Describe the shape of the distribution
- "Factorial": Remove self-correlations, easy efficiency correction.

Cumulants and Central Moments:

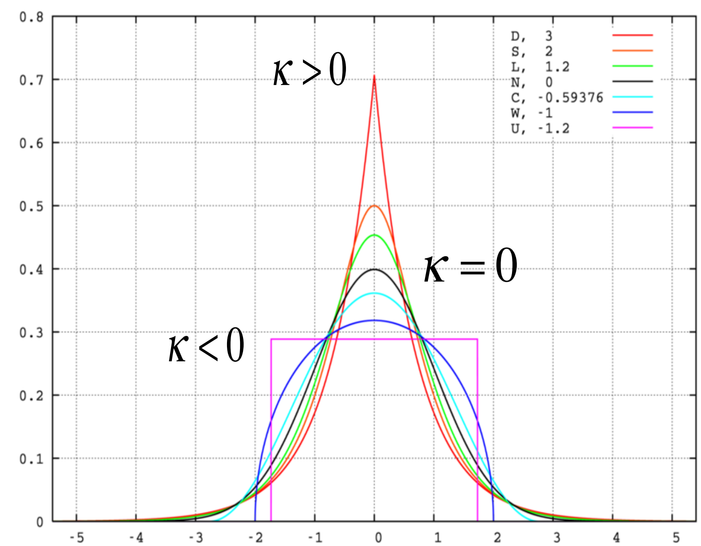
$$C_{1,N}=\langle N\rangle,\quad C_{2,N}=\left\langle(\delta N)^2\right\rangle$$

$$C_{3,N}=\left\langle(\delta N)^3\right\rangle,\quad C_{4,N}=\left\langle(\delta N)^4\right\rangle-3\left\langle(\delta N)^2\right\rangle^2$$

$$\delta N=N-\langle N\rangle$$

Variance, Skewness and Kurtosis:

$$\sigma^2=C_{2,N},\ S=\frac{C_{3,N}}{(C_{2,N})^{3/2}},\ \kappa=\frac{C_{4,N}}{(C_{2,N})^2}$$



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.

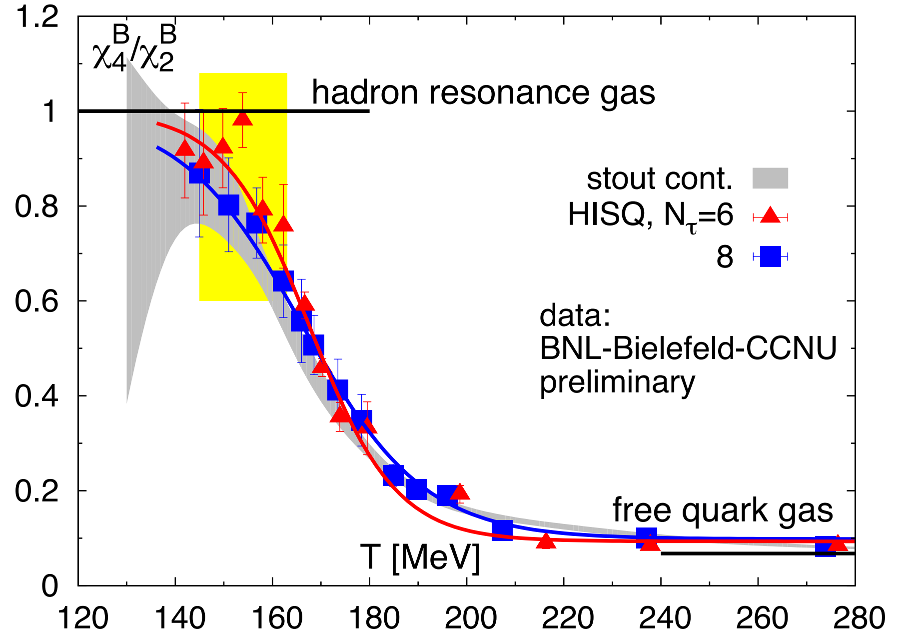
$$C_{n,q} = VT^3 \chi_q^{(n)} = \frac{\partial^n (p/T^4)}{\partial(\mu_q/T)^n}, \qquad q = B, Q, S$$

Cancel out the volume dependence by taking ratios of cumulants:

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

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

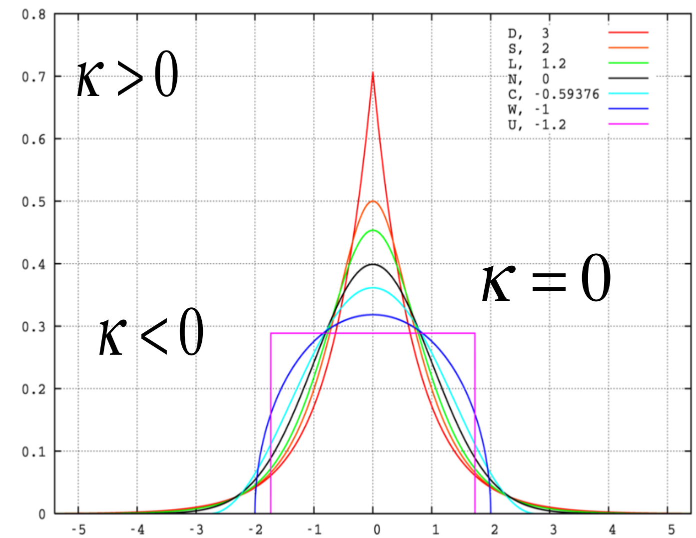
S. Ejiri et al, Phys.Lett. B 633 (2006) 275. B. Friman et al., EPJC 71 (2011) 1694. F. Karsch and K. Redlich , PLB 695, 136 (2011). S. Gupta, et al., Science, 332, 1525(2012).



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*)



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

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

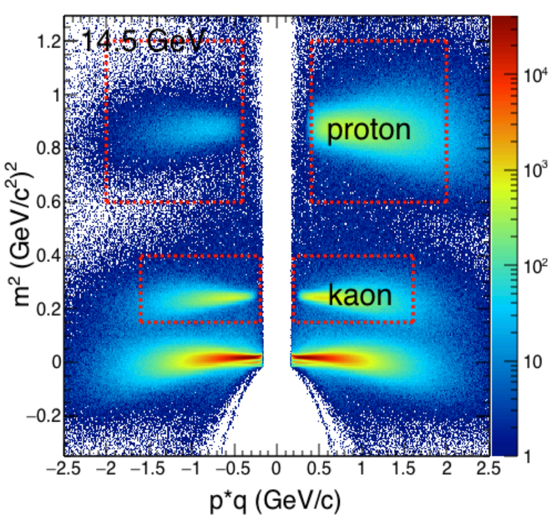
$$\frac{C_{3,q}}{C_{2,q}} = S\sigma \propto \xi^{9/4}$$

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

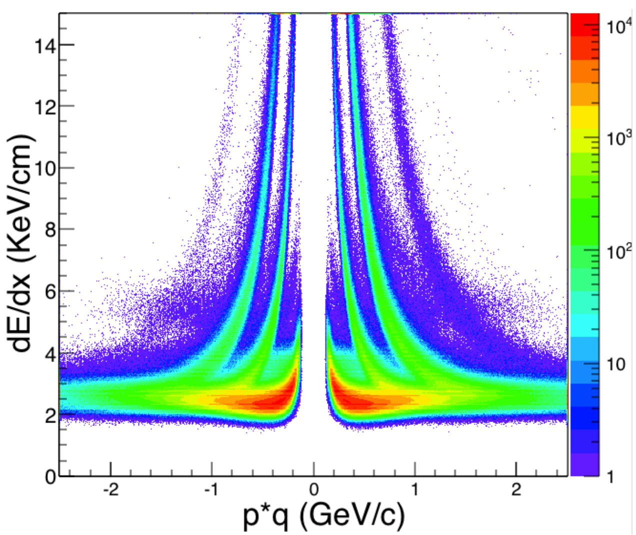
Analysis Details

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\lvert\eta\rvert < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\lvert y\rvert < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\lvert y\rvert < 0.5$
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
	$0.5 < \lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 1.0$

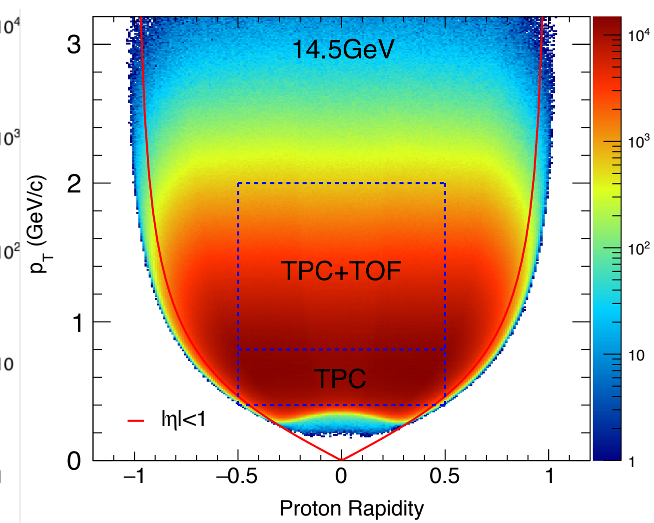
TOF PID



TPC PID

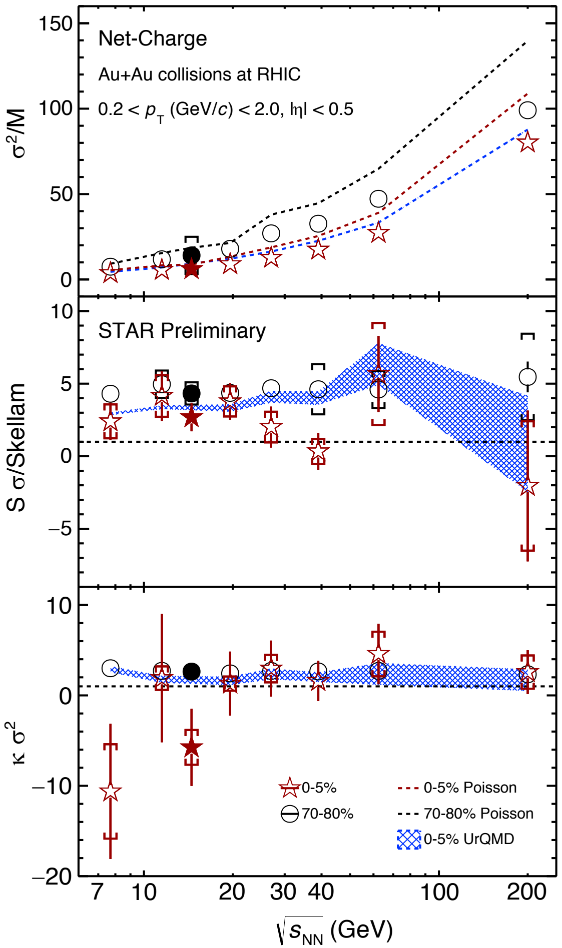


Phase Space



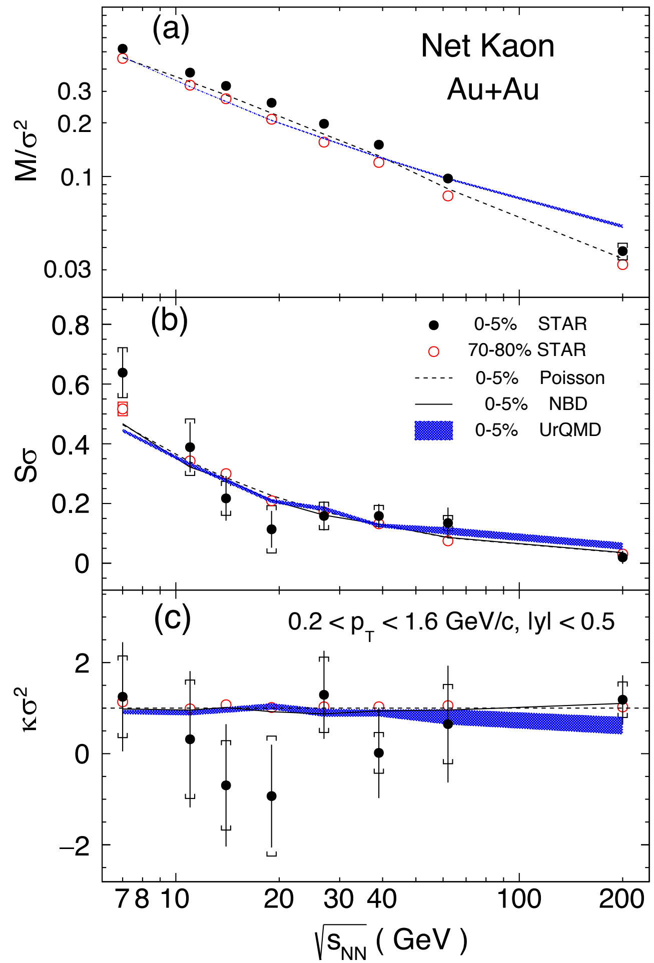
Experimental Results : Energy dependence

Net-Charge (Q)



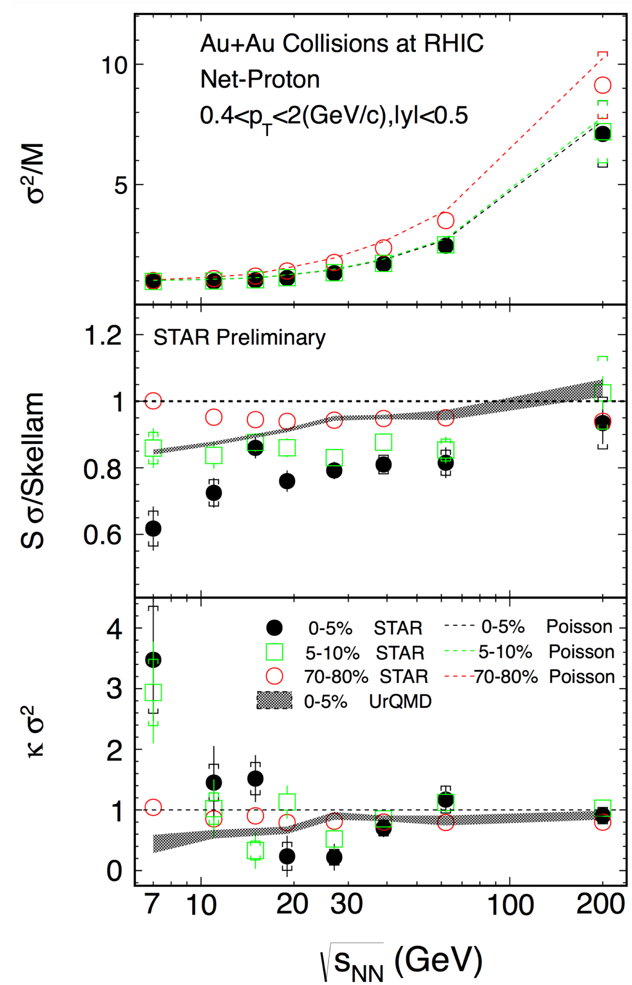
STAR, PRL113,092301 (2014)
STAR, QM 2015

Net-Kaon (S)



STAR, submitted to PLB [arXiv: 1709.00773]
STAR, QM 2015

Net-Proton (B)



STAR, PRL105,022302 (2010);
STAR, PRL112,032302 (2014).
STAR, CPOD 2014, QM 2015

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.

Three questions need to be addressed for CP search

1. Do we precisely measure the fluctuations in heavy-ion collisions (value and uncertainties) ? (experimental analysis methods)

2. What's the characteristic signature (model independent) of the QCD critical point for the fluctuation observable in heavy-in collisions ?

3. What's the background (non-CP) contributions to the experimental observables ?

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

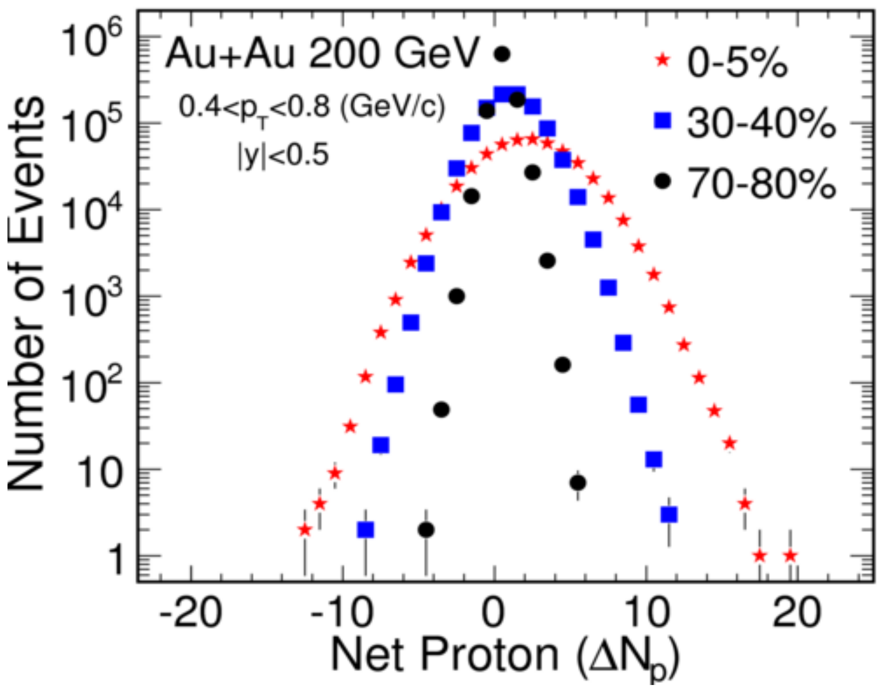
   Swagato et al, PRC92,034912 (2015). PRL117, 222301 (2016); M. Nahrgang, et al. EPJA 52, 240 (2016).
   C. herold Phys.Rev. C93 (2016) no.2, 021902 L. Jiang et al. arXiv: 1704.04765

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

Data Analysis Methods

Raw net-p prob. distribution



STAR, **PRL**105,022302 (2010);

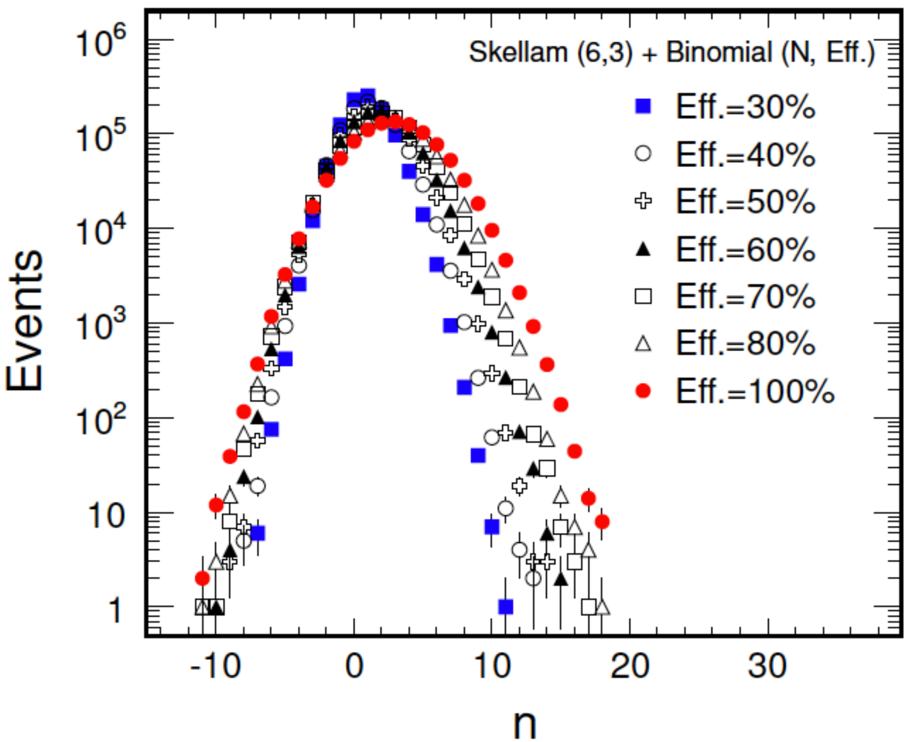
1. **Initial Volume Fluctuations.**
   centrality bin width correction.
2. **Remove auto-correlation.**
   New centrality definition.
3. **Efficiency Correction.**
   Binomial efficiency response
4. **Statistical Error Estimation.**
   Delta theorem and Bootstrap

$$error \propto O\left(\sigma^n / \varepsilon^\alpha\right)$$

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, PRC96, 024910 (2017).

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

Effects of Finite Detection Efficiency



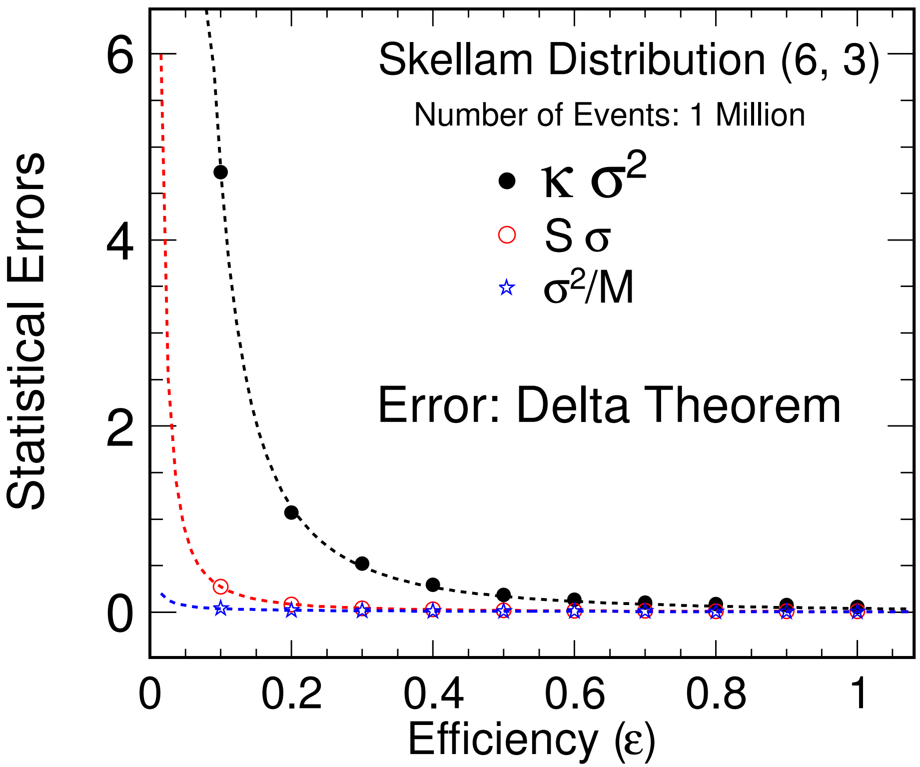
Efficiency Response Function :

$$B(n;N,\varepsilon)=\frac{N!}{n!(N-n)!}\varepsilon^{n}(1-\varepsilon)^{N-n}$$

With the total produced multiplicity N and the detector efficiency ε, the probability of detected number of particles can be treated as a binomial process.

$$p(n_p,n_{\bar{p}})=\sum_{N_p=n_p}^{\infty}\sum_{N_{\bar{p}}=n_{\bar{p}}}^{\infty}P(N_p,N_{\bar{p}})\times\frac{N_p!}{n_p!\,(N_p-n_p)!}(\varepsilon_p)^{n_p}(1-\varepsilon_p)^{N_p-n_p}$$
$$\times\frac{N_{\bar{p}}!}{n_{\bar{p}}!\,(N_{\bar{p}}-n_{\bar{p}})!}(\varepsilon_{\bar{p}})^{n_{\bar{p}}}(1-\varepsilon_{\bar{p}})^{N_{\bar{p}}-n_{\bar{p}}}$$

Efficiency Correction and Error Estimation



1. Error Estimation: Delta theorem or Bootstrap.

2. Efficiency Correction : Based on analytical formula derived from factorial moments by assuming binomial response function for detector efficiency

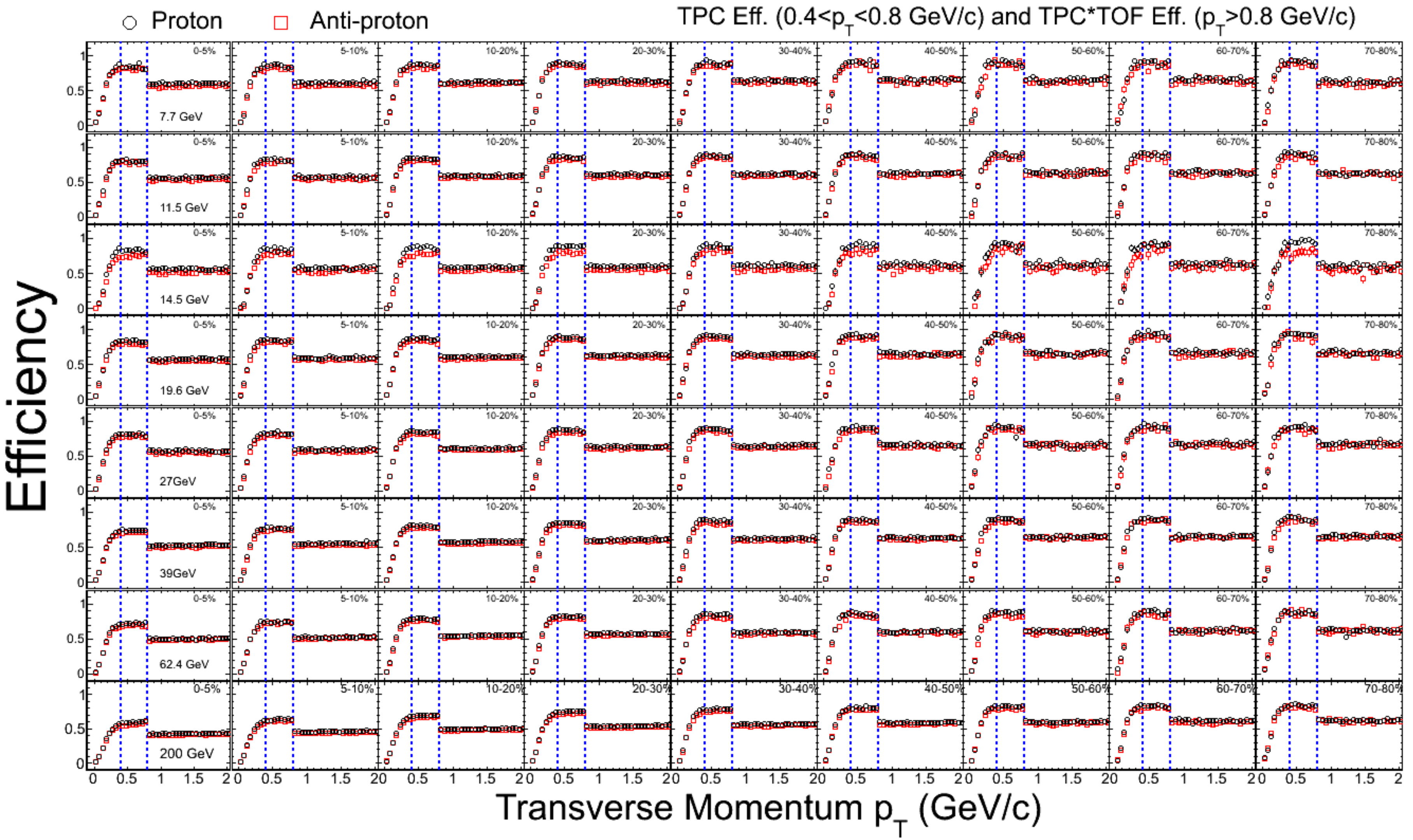
$$F_{u,v,j,k}(N_{p_1}, N_{p_2}, N_{\bar{p}_1}, N_{\bar{p}_2}) = \frac{f_{u,v,j,k}(n_{p_1}, n_{p_2}, n_{\bar{p}_1}, n_{\bar{p}_2})}{(\varepsilon_{p_1})^u (\varepsilon_{p_2})^v (\varepsilon_{\bar{p}_1})^j (\varepsilon_{\bar{p}_2})^k}$$

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

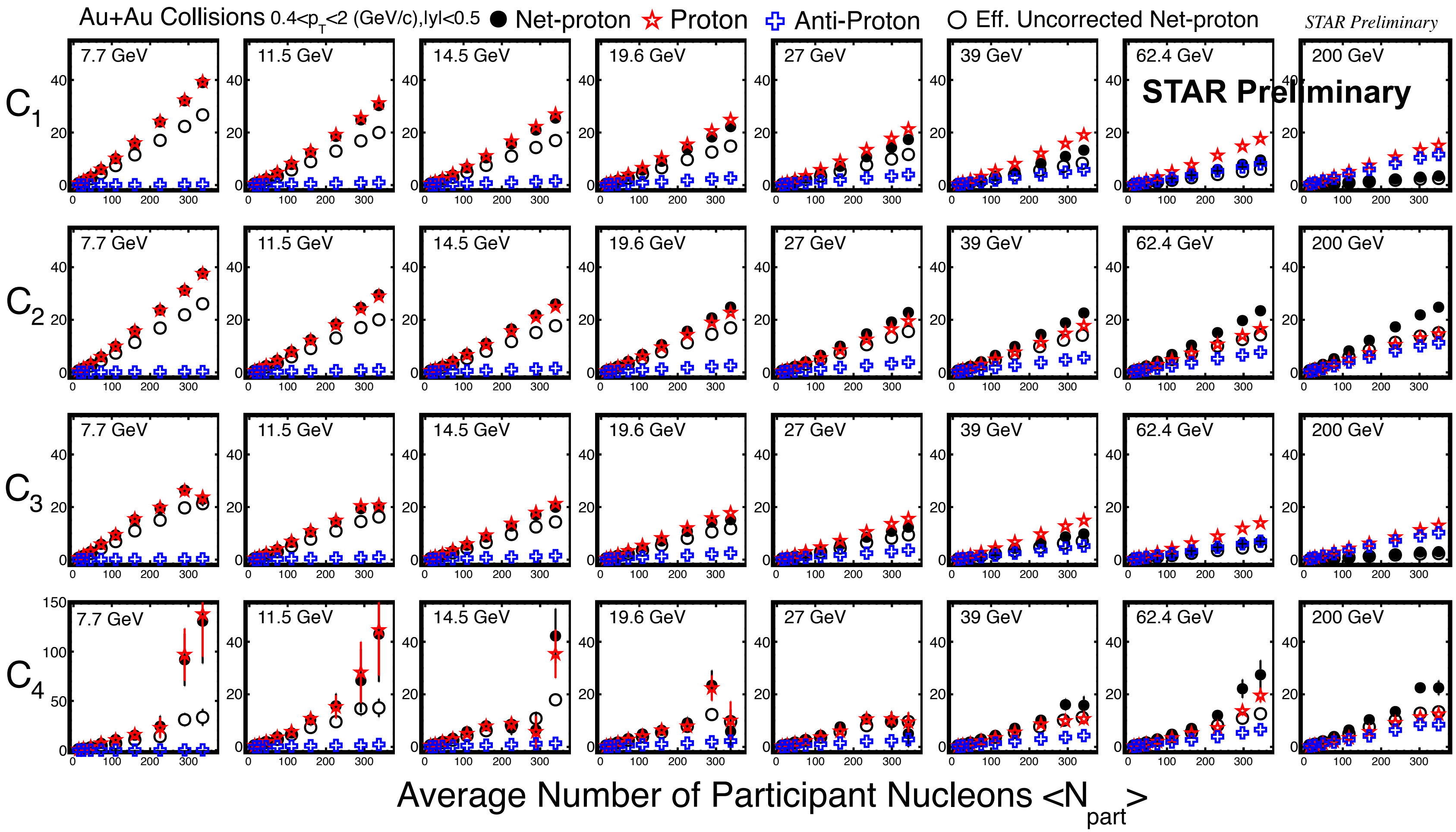
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}$$

A. Bzdak and V. Koch, PRC91,027901(2015), PRC86， 044904(2012).
X. Luo, PRC91, 034907 (2015).
T. Nonaka, et al., PRC95, 064912 (2017).

Efficiency for Proton and Anti-proton

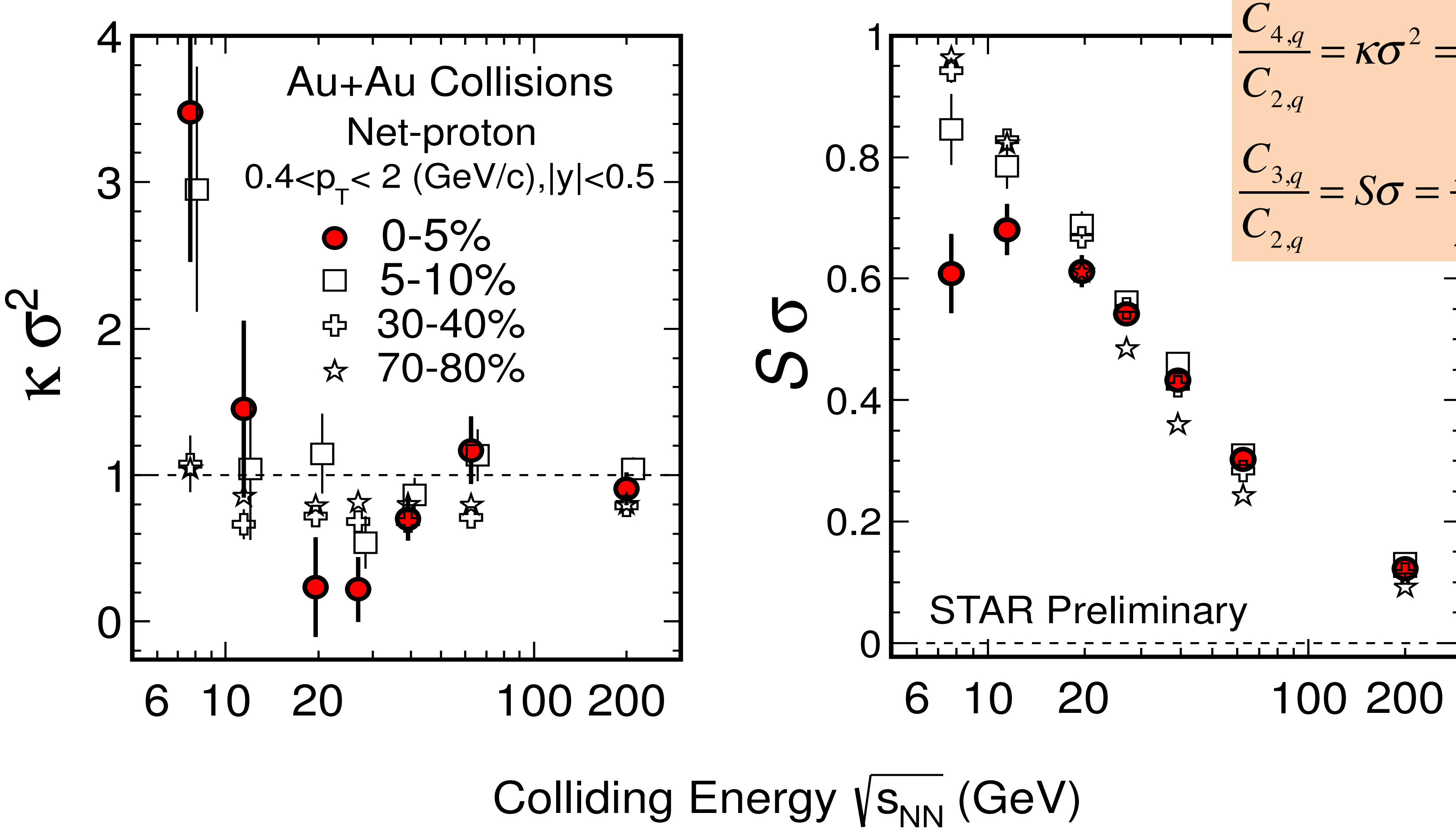


Net-Proton, Proton and Anti-Proton Cumulants ($C_1 \sim C_4$)



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

Energy Dependence of Net-Proton Fluctuations



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

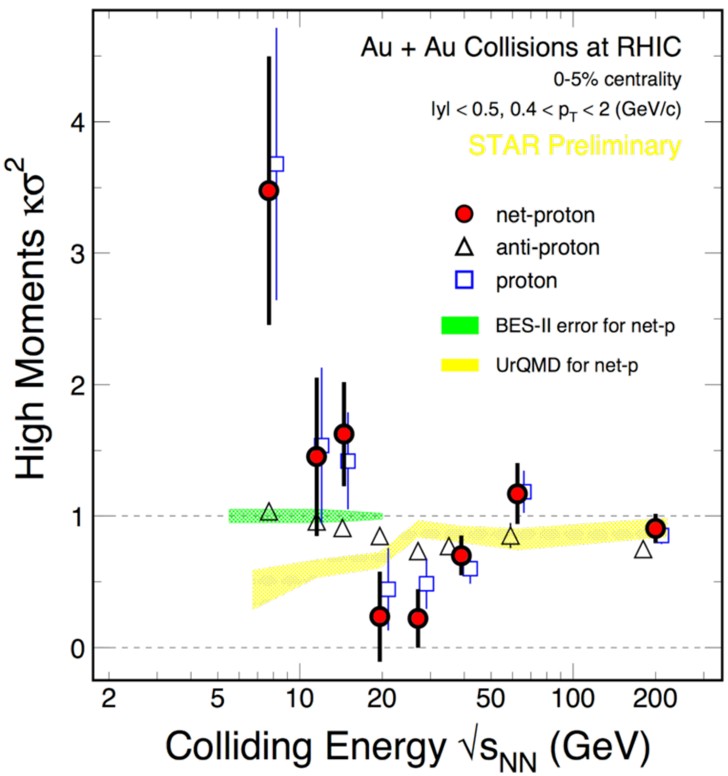
$$\frac{C_{3,q}}{C_{2,q}} = S\sigma = \frac{\chi_q^{(3)}}{\chi_q^{(2)}}$$

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

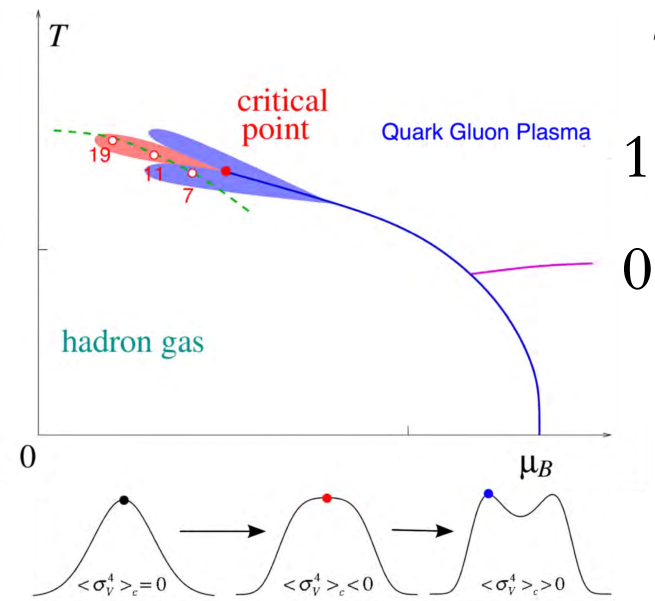
4^{th} order Net-Proton Fluctuations $\kappa\sigma^2 = C_4/C_2$

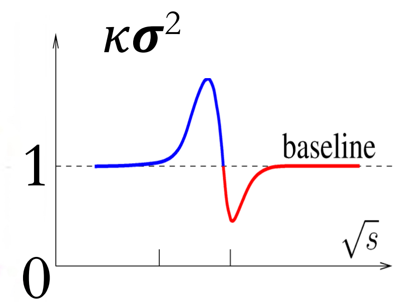
- First observation of the non-monotonic energy dependence of fourth order net-proton fluctuations. Hint of entering Critical Region ??

STAR Data



σ field Model





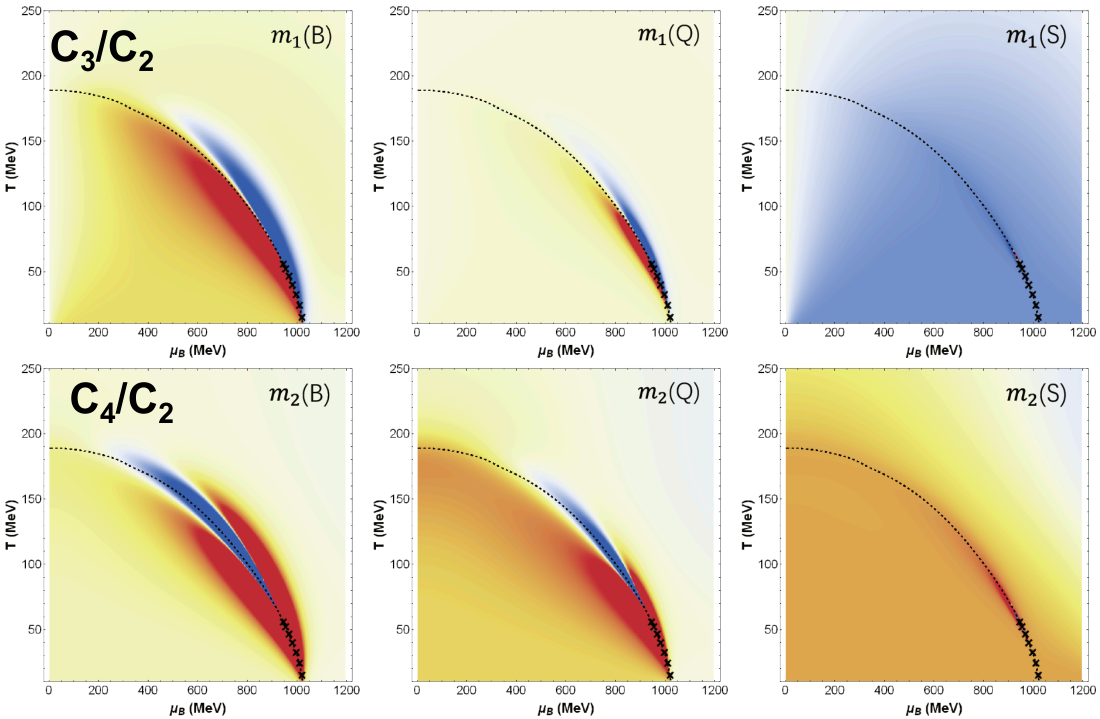
Critical signal: Oscillation Structure

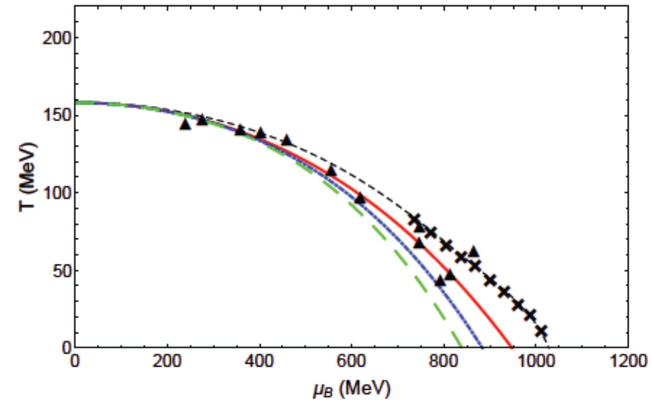
STAR, PRL105,022302 (2010); PRL112,032302 (2014).
STAR, CPOD2014 and QM2015

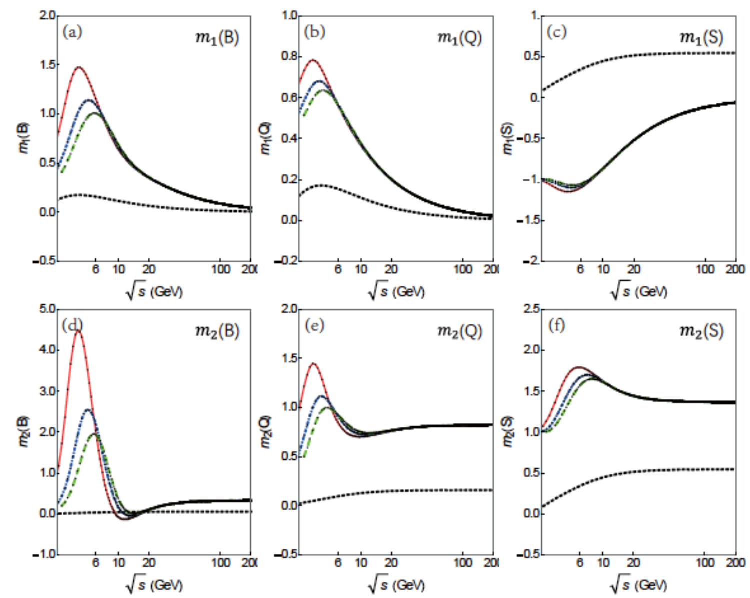
M. A. Stephanov, PRL102, 032301 (2009).
M. A. Stephanov, PRL107, 052301 (2011).

NJL Model Calculations

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





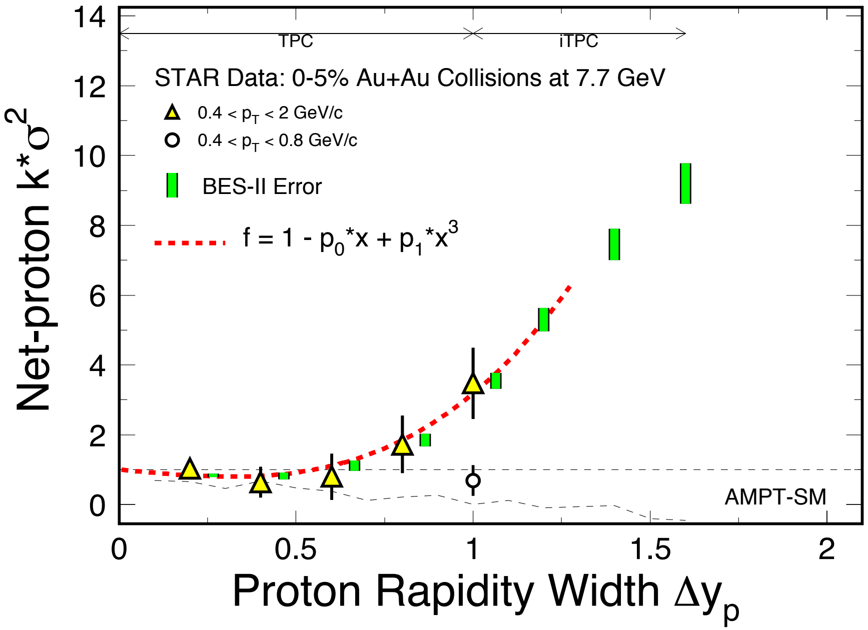


1) Due to large mass of s quark, CP Signals in Q and S are much smaller than B.
2) Forth and third order fluctuations have very different behavior.

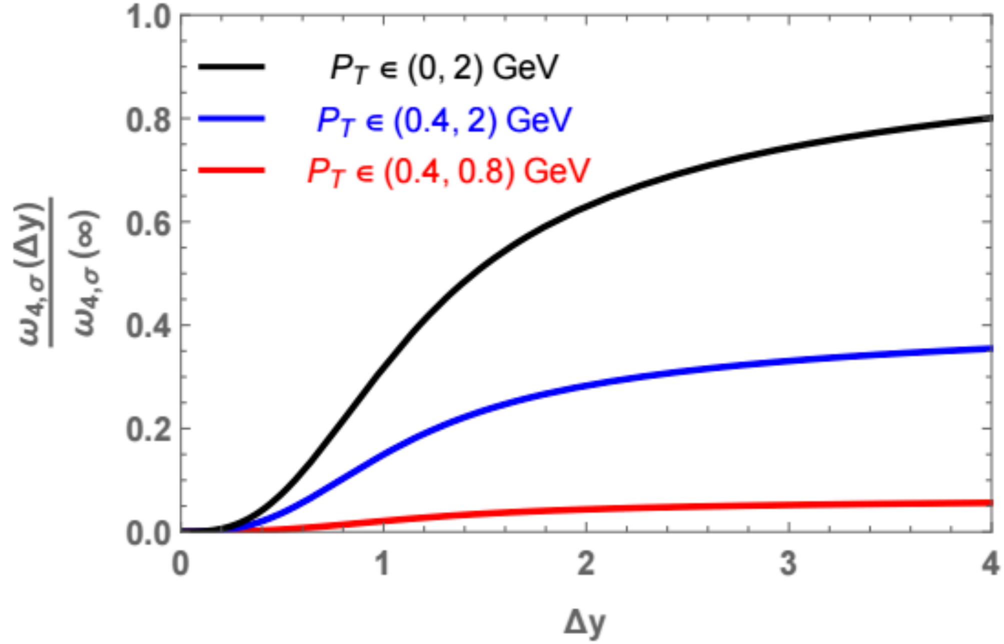
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017).
JW Chen, JDeng et al., PRD93, 034037 (2016), PRD95, 014038 (2017)

Acceptance dep. near CP

STAR Data



Model

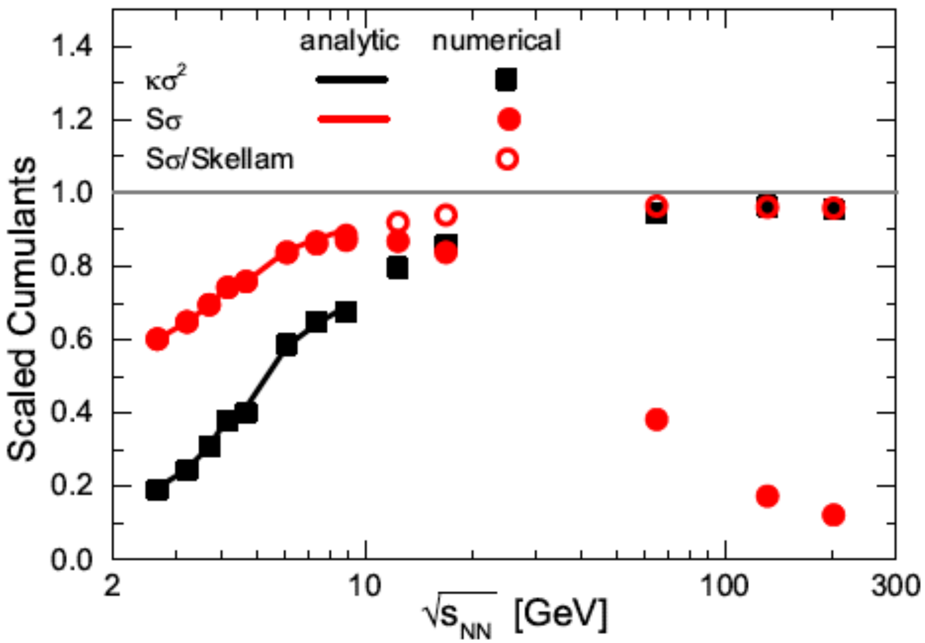


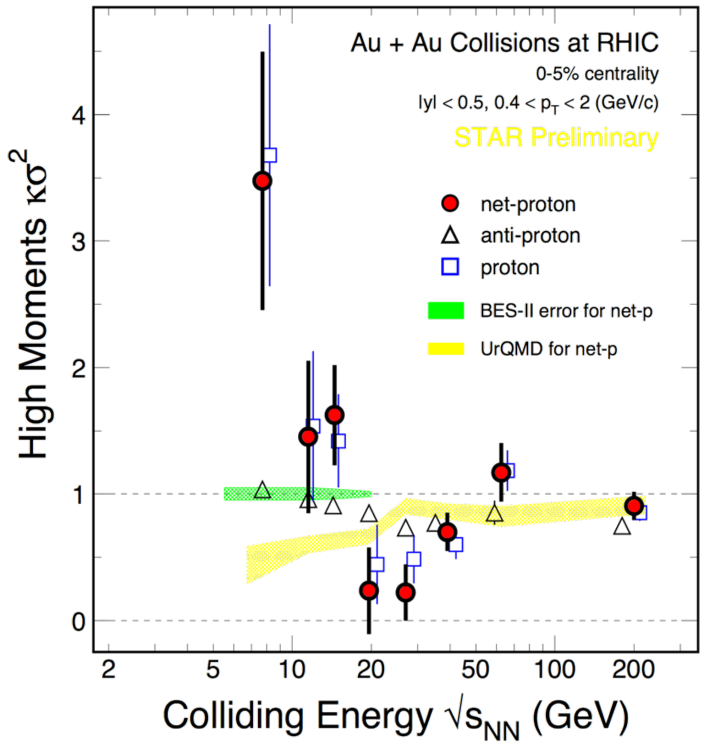
B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016).
A. Bzdak, V. Koch, Phys.Rev. C95, 054906 (2017)
M. Kitazawa, X. Luo, PRC96, 024910 (2017).

Signals can be enhanced by enlarging the acceptance.

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: **$\kappa\sigma^2 < 1$**

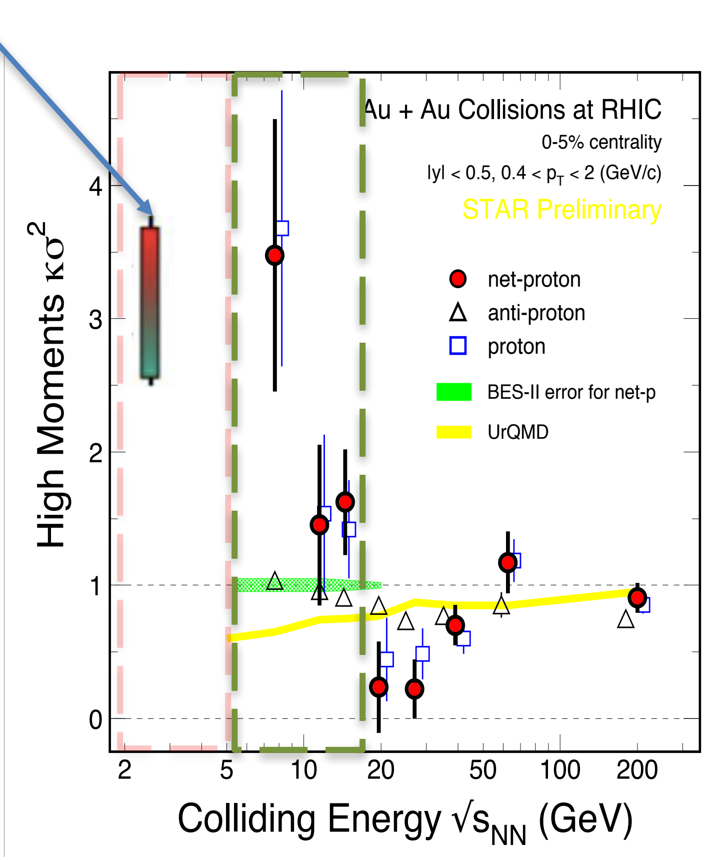
➢ Model simulation :*All suppress the net-proton fluctuations.*

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

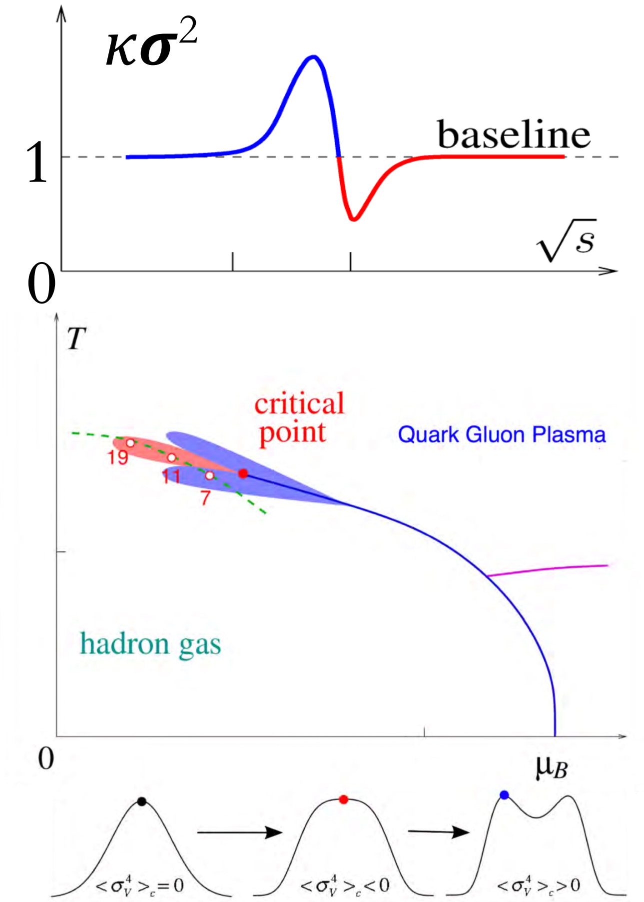
1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, PR**C92**, 064908(2015). J. Xu, S. Yu, F. Liu, X. Luo, PR**C94**, 024901(2016). X. Luo *et al*, NP**A931**, 808(14), P.K. Netrakanti *et al.* 1405.4617, NP**A947**, 248(2016), P. Garg *et al.* Phys. Lett. **B726**, 691(2013). S. He and X. Luo, PLB
2) **Baron Mean field:** S. He, X. Luo, Y. Nara, S. Esuimi, N. Xu, Phys.Lett. **B762** (2016) 296-300.
3) **Proton Cluster formation:** A. Bzdak, V. Koch, V. Skokov, Eur. Phys. J., C77, 288(2017)

Future Plan for QCD Critical Point Search

Preliminary HADES Results (QM2017)



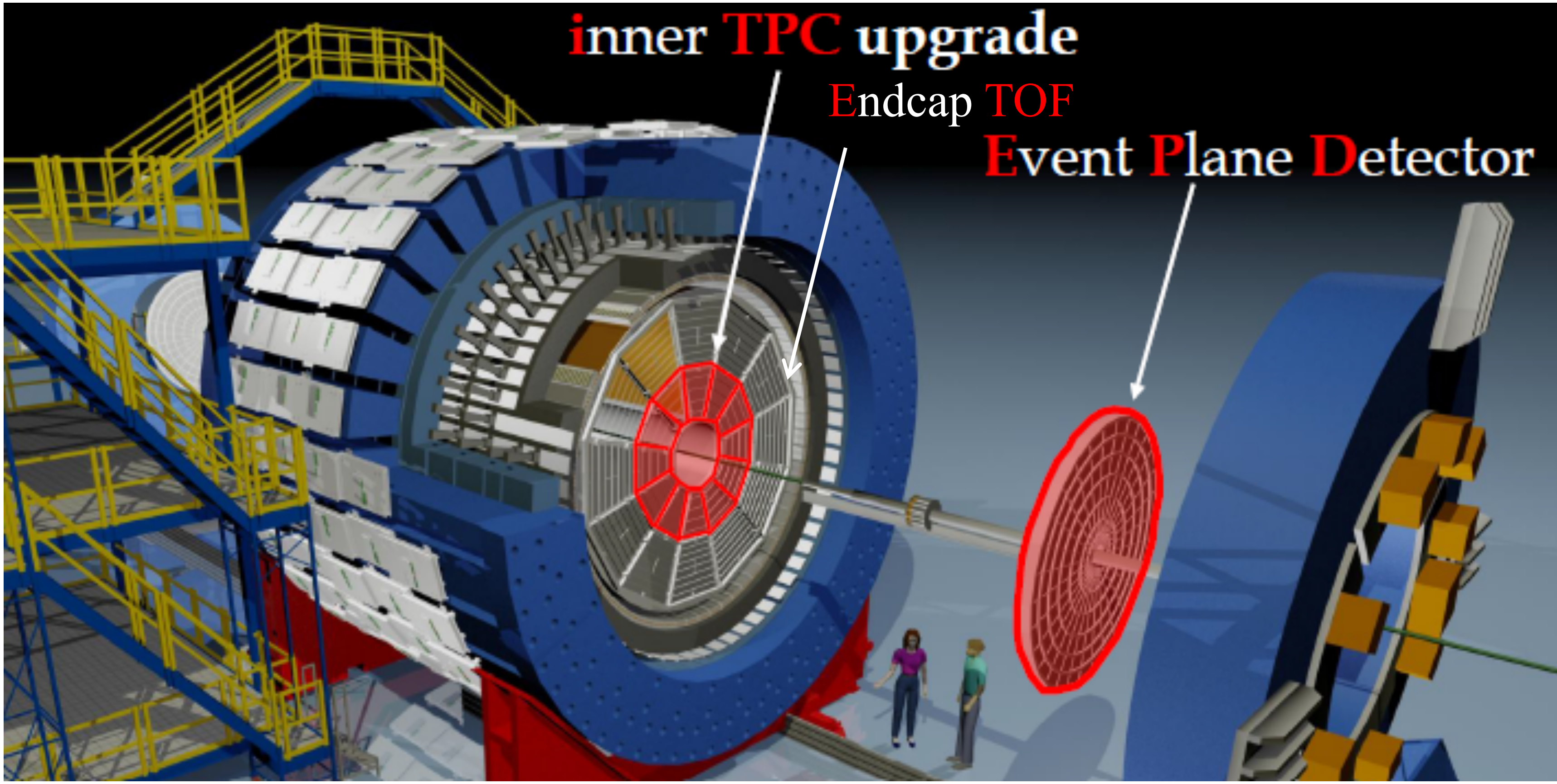
M. A. Stephanov, PRL107, 052301 (2011).



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

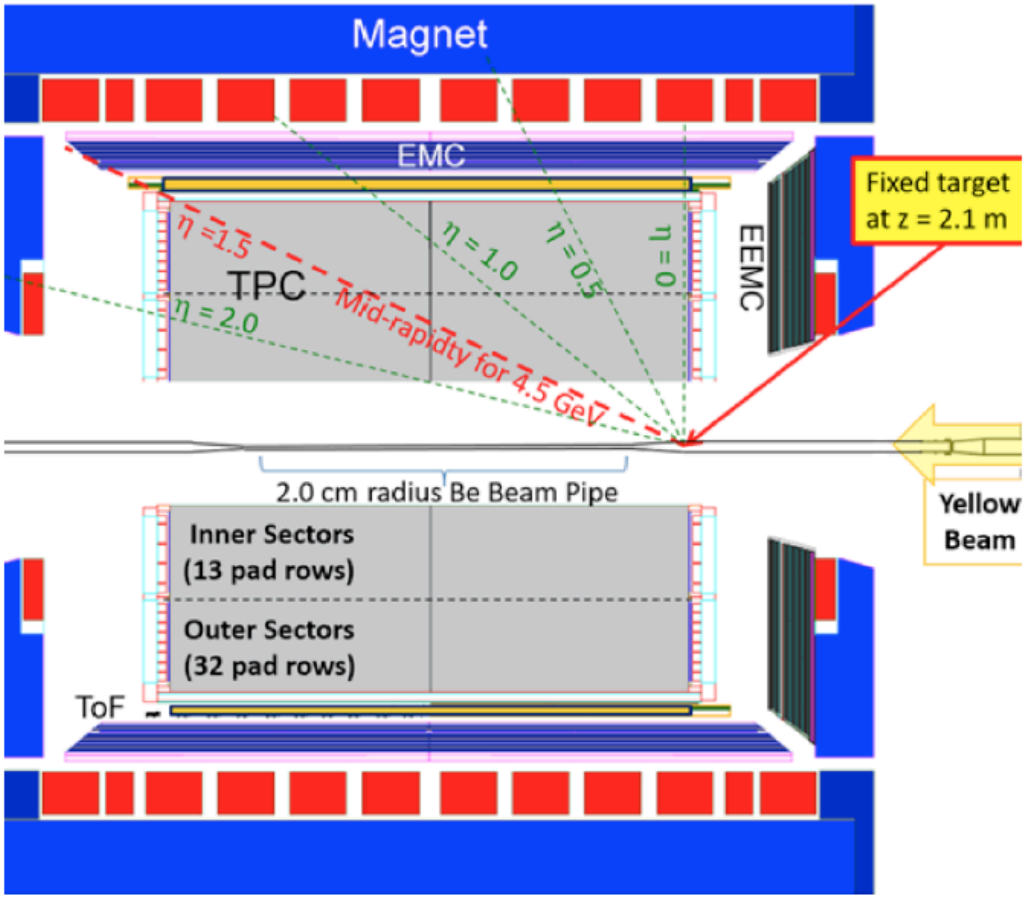
2019-2020: BES-II at RHIC

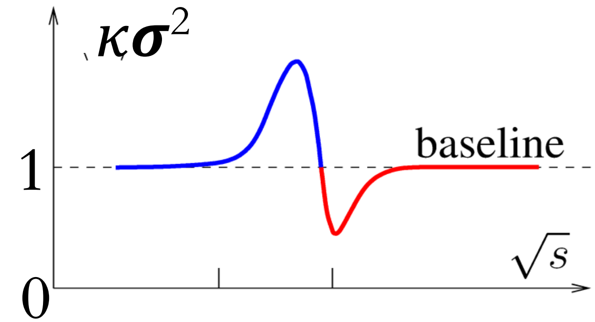
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	1200	2017	83	165
39	39	2010	112	164
27	70	2011	156	162
19.6	**400** / 36	**2019-20** / 2011	206	160
14.5	**300** / 20	**2019-20** / 2014	264	156
11.5	**230** / 12	**2019-20** / 2010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

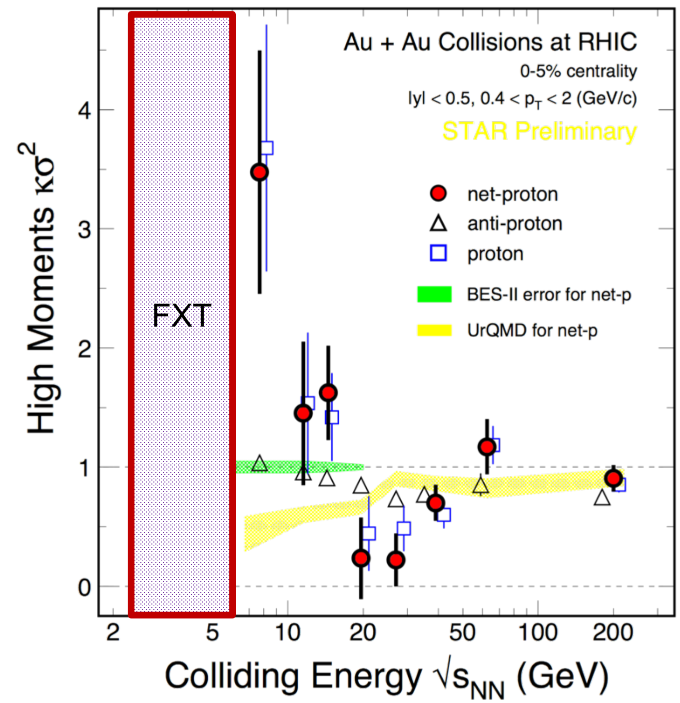
BES-II: Precise mapping the QCD phase diagram

$200 < \mu_B < 420$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 fluctautions in HIC.

Thank you !