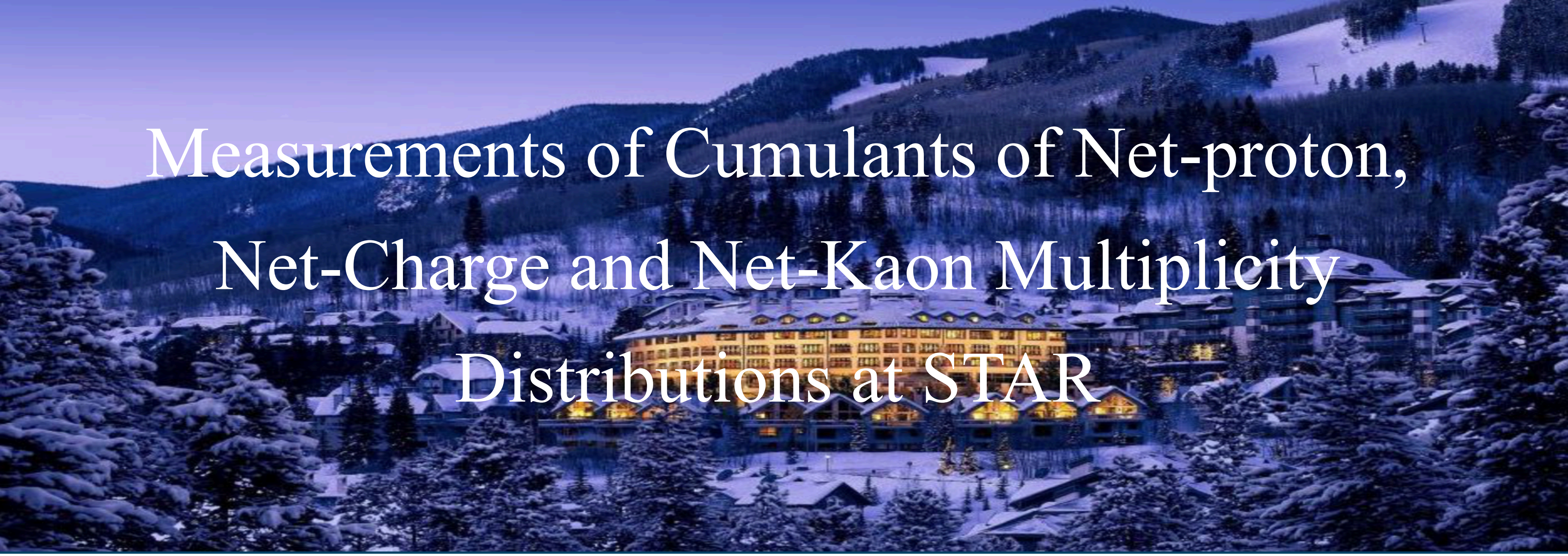
Measurements of Cumulants of Net-proton, Net-Charge and Net-Kaon Multiplicity Distributions at STAR



Zhenzhen Yang

(for the STAR Collaboration)

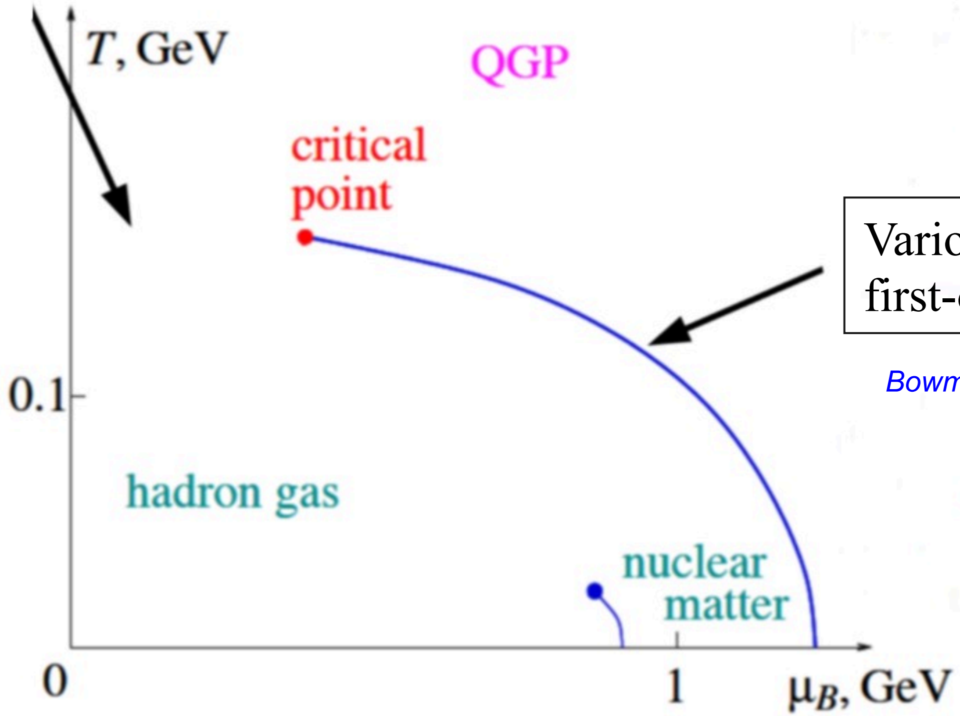
Central China Normal University

Lawrence Berkeley National Laboratory

The 35th Winter Workshop on Nuclear Dynamics, Beaver Creek

QCD Phase Diagram and Critical Point

Crossover transition



Various models predict the first-order phase transition

Bowman and Kapusta, PRC 79, 015202(2009)

Stephanov, Int.J.Mod Phys, A20, 4387

Thus, a critical point (CP) might be exist at the end point of the first-order phase transition.

Fluctuations of Conserved Quantities

- Net charge, net proton (proxy for net baryon), net kaon (proxy for net strangeness)

$$\Delta N_i = N_i - N_{\bar{i}},\ i = B, Q, S$$

- Higher moments: describe the shape of distributions:

$$M = C_1 \quad \sigma^2 = C_2 \qquad S = \frac{C_3}{(C_2)^{3/2}} \quad \kappa = \frac{C_4}{(C_2)^2}$$

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

$$C_1 = \langle N \rangle \quad C_3 = \langle (\delta N)^3 \rangle \quad C_2 = \langle (\delta N)^2 \rangle \quad C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

Sensitive to the correlation length (ξ):

$$\langle (\delta N)^3 \rangle \approx \xi^{4.5} \quad \langle (\delta N)^4 \rangle \approx \xi^7$$

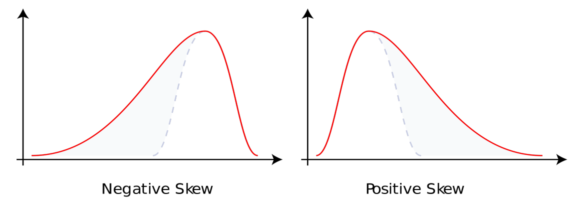
Directly related to susceptibilities:

$$\frac{\chi_i^4}{\chi_i^2} = \kappa\sigma^2 = \frac{C_{4,i}}{C_{2,i}}, \quad \frac{\chi_i^3}{\chi_i^2} = S\sigma = \frac{C_{3,i}}{C_{2,i}} \qquad \chi_i^n = \frac{1}{VT^3} C_{n,i} = \frac{\partial^n (p/T)}{\partial (\mu_q)^n}, i = B, Q, S$$

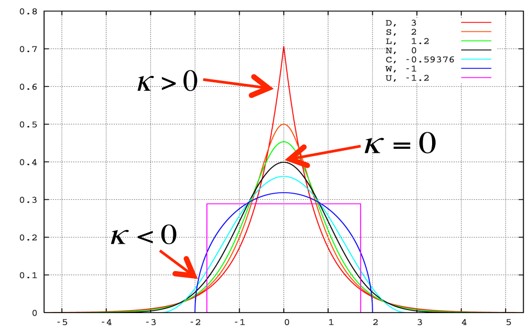
Volume dependence can be canceled by forming the ratio.

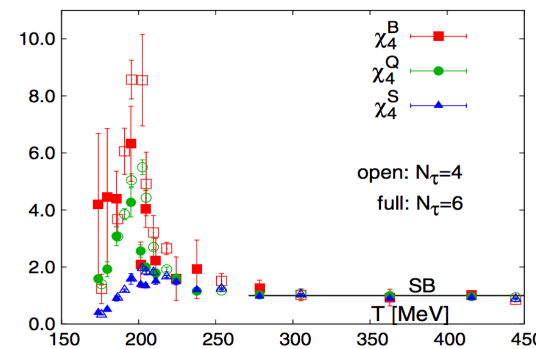
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
Y. Hatta, M. Stephanov, Phys. Rev. Lett. 91, 102003 (2003).

Skewness(S) → Asymmetry



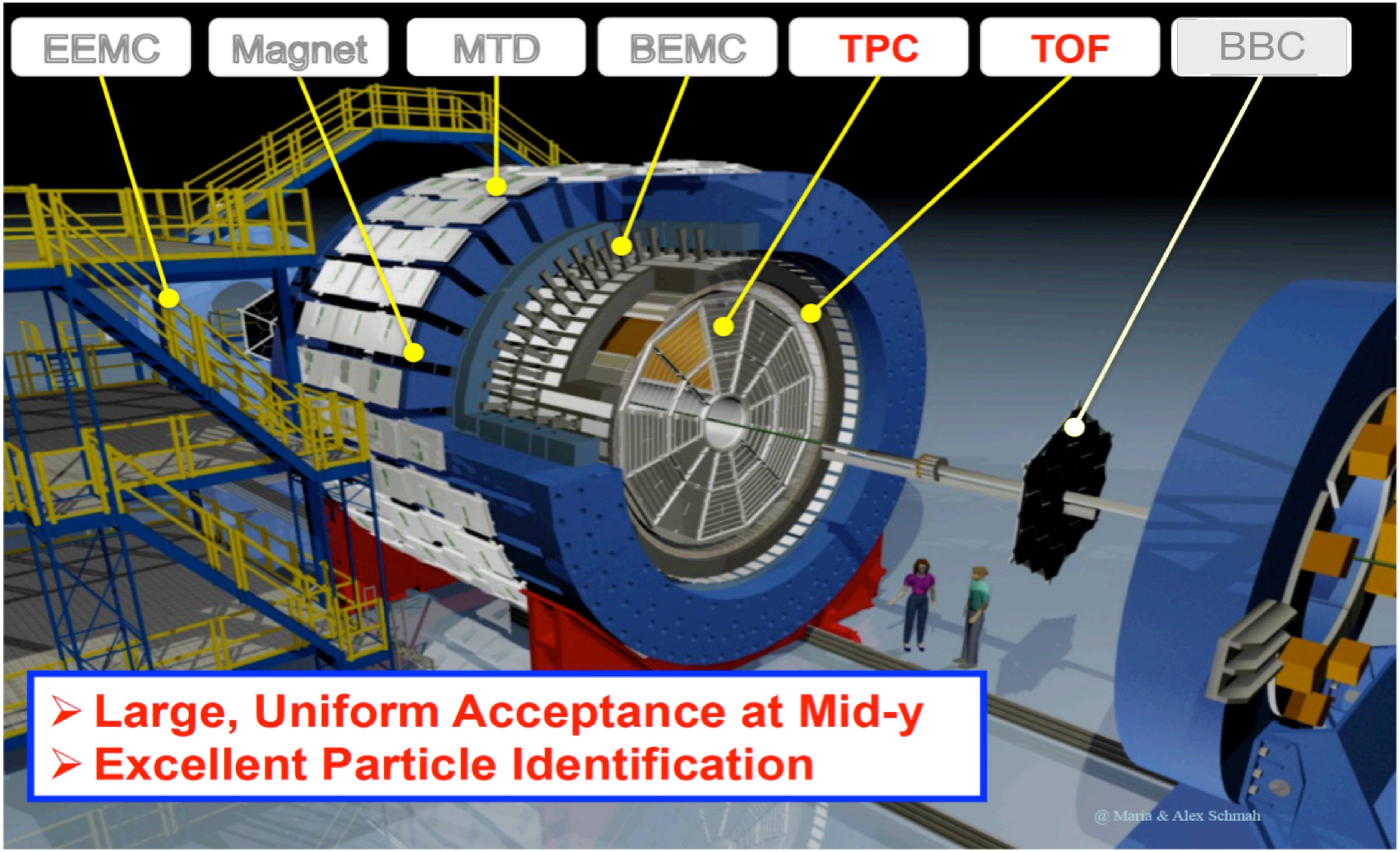
Kurtosis(κ) → Sharpness





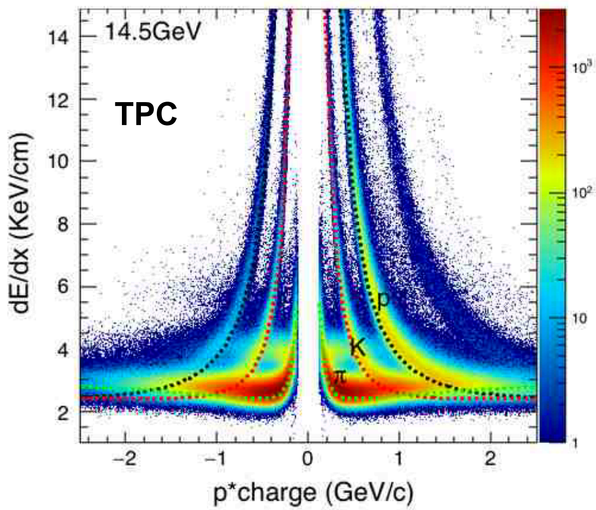
M.Cheng et sl, PRD 79, 074505(2009).

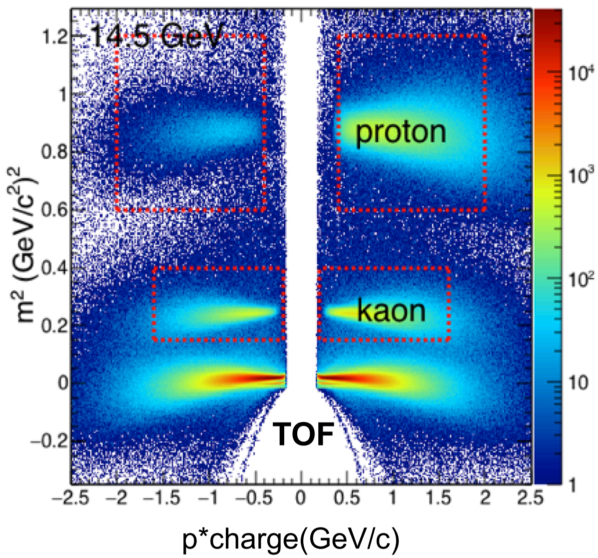
The STAR Detector

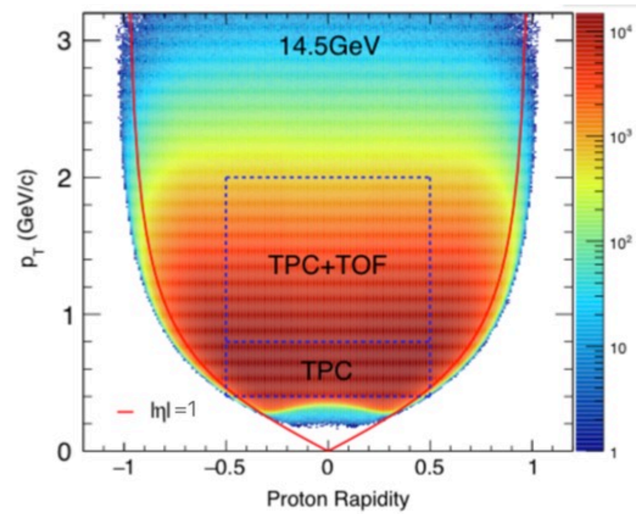


- Large, Uniform Acceptance at Mid-y
- Excellent Particle Identification

Particle Identification

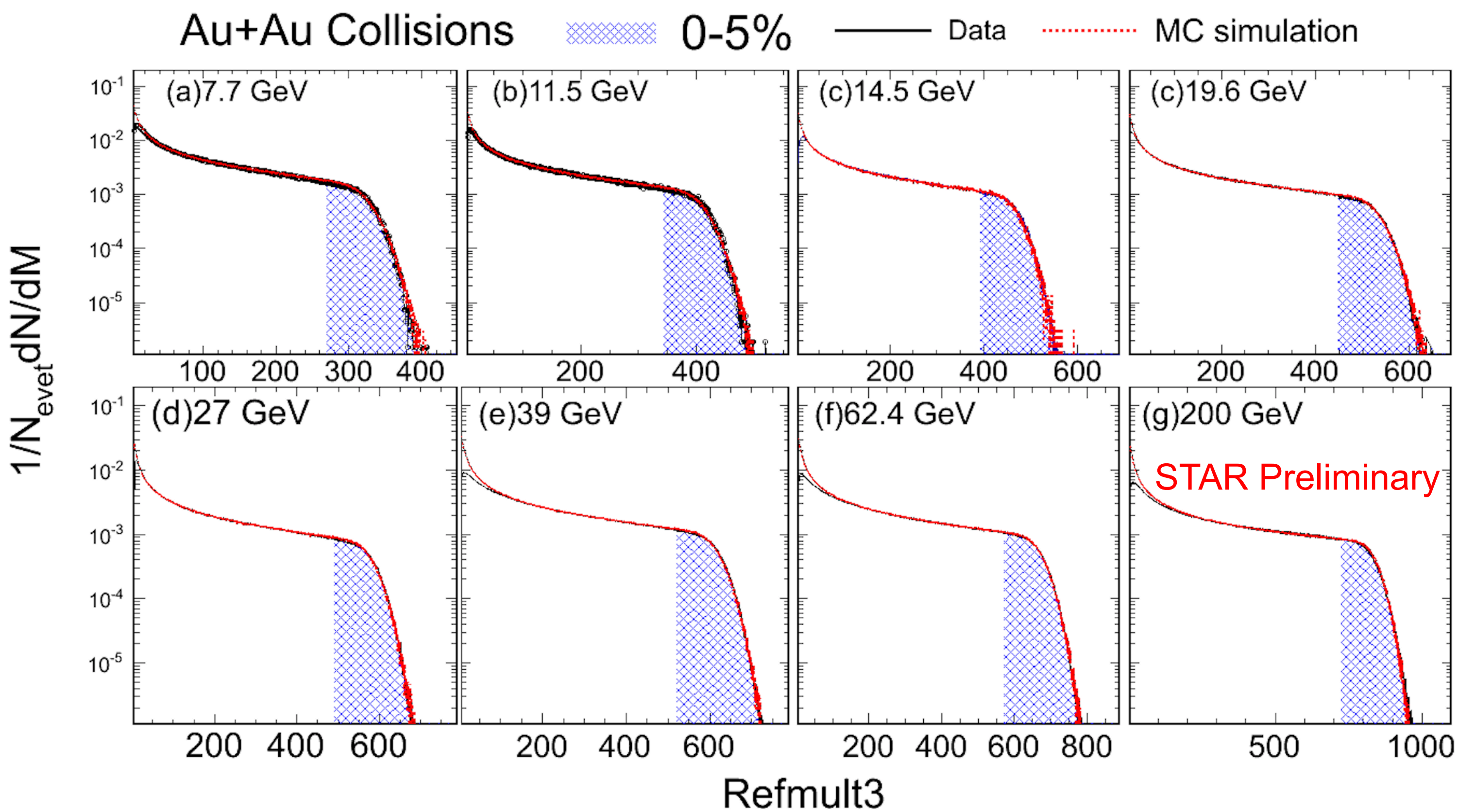






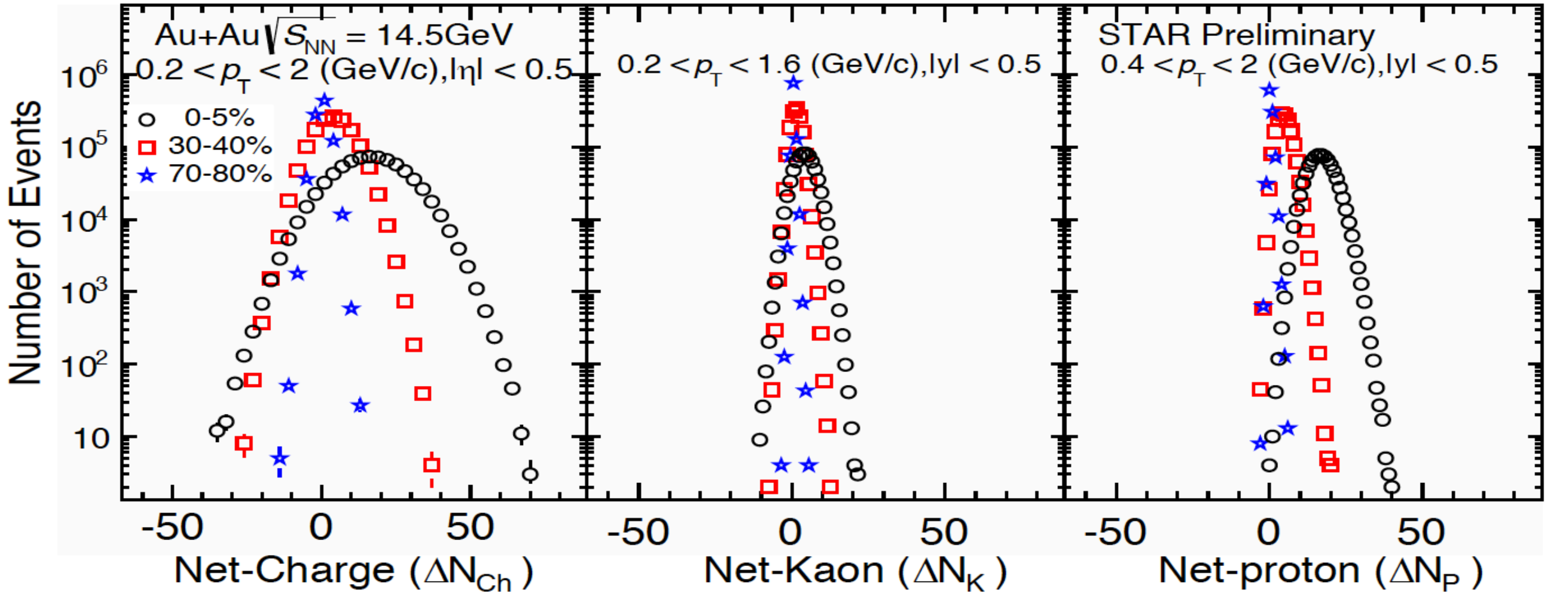
	Net-Proton	Net-Kaon	Net-Charge
Kinematic cuts	$0.4<p_T$ (GeV/c) <2.0 $\lvert y\rvert<0.5$	$0.2<p_T$ (GeV/c) <1.6 $\lvert y\rvert<0.5$	$0.2<p_T$ (GeV/c) <2 $\lvert\eta\rvert<0.5$
Particle Identification	$0.4<p_T$ (GeV/c) <0.8:TPC $0.8<p_T$ (GeV/c) <2.0:TPC+TOF	$0.2<p_T$ (GeV/c) <0.4:TPC $0.4<p_T$ (GeV/c) <1.6:TPC+TOF	Reject protons within $p_T<0.4$ GeV/c

Centrality Determination



	Net-Proton (Refmult3)	Net-Kaon (Refmult4)	Net-Charge (Refmult2)
Centrality definition (Avoid auto-correlations)	Charged kaons and pions, $\|\eta\|<1.0$, DCA<3 cm, NHitsFit>10	Charged protons and pions, $\|\eta\|<1.0$, DCA<3 cm, NHitsFit>15	Uncorrected charged primary particles multiplicity distributions $0.5<\|\eta\|<1.0$

Efficiency Uncorrected Net-Particle Multiplicity Distribution



- Mean value of net-particle increases from peripheral to central collisions.
- Net-charge distribution has the largest value of standard deviation (σ) in comparison to net-kaon and net-proton at the fixed centrality.
- Effects that need to be addressed to get final cumulants.

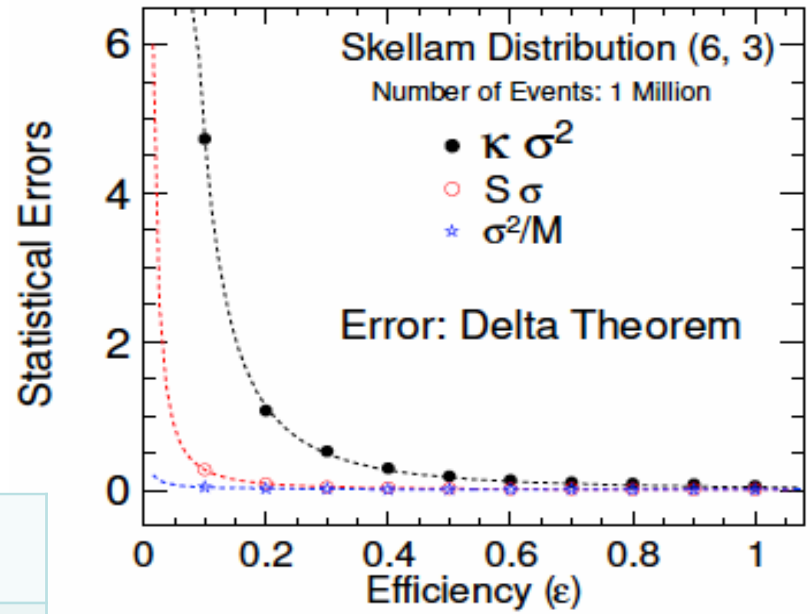
1. Auto-correlation effects.
2. Finite detector efficiency.

X.Luo,Phys. Rev.C91,034907(2015)
X.Luo,et al.J.Phys.G40,105104(2013)

Efficiency Calculation and Error Estimation

- We can express the cumulants in terms of the factorial moments, which can be easily efficiency corrected.
  - A.Bzdak and V.Koch,PRC91,027901(2015)
  - X.Luo, T.Nonaka, arXiv:1812.10303.
  - 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);
  - T. Nonaka et al., PRC95, 064912 (2017).
  - M. Kitazawa and X. Luo, PRC96, 024910 (2017),
  - X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017),

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



- Statistical errors based on Delta Theorem. With same N events: $\text{error}_{(\text{net-charge})} > \text{error}_{(\text{net-kaon})} > \text{error}_{(\text{net-proton})}$

Au+Au 14.5 GeV	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	365	32	82

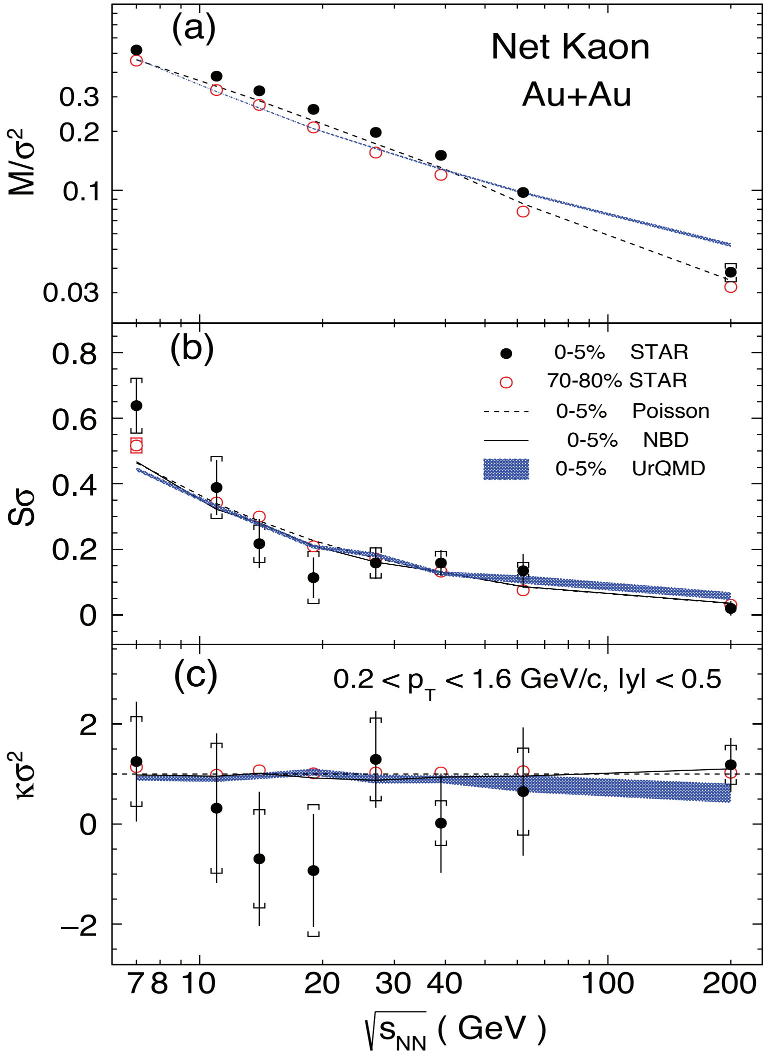
$$error(S\sigma) \propto \frac{\sigma}{\varepsilon^{3/2}}$$

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

- Systematic error estimation

Includes uncertainties on efficiency and efficiency fluctuations
PID and track cuts

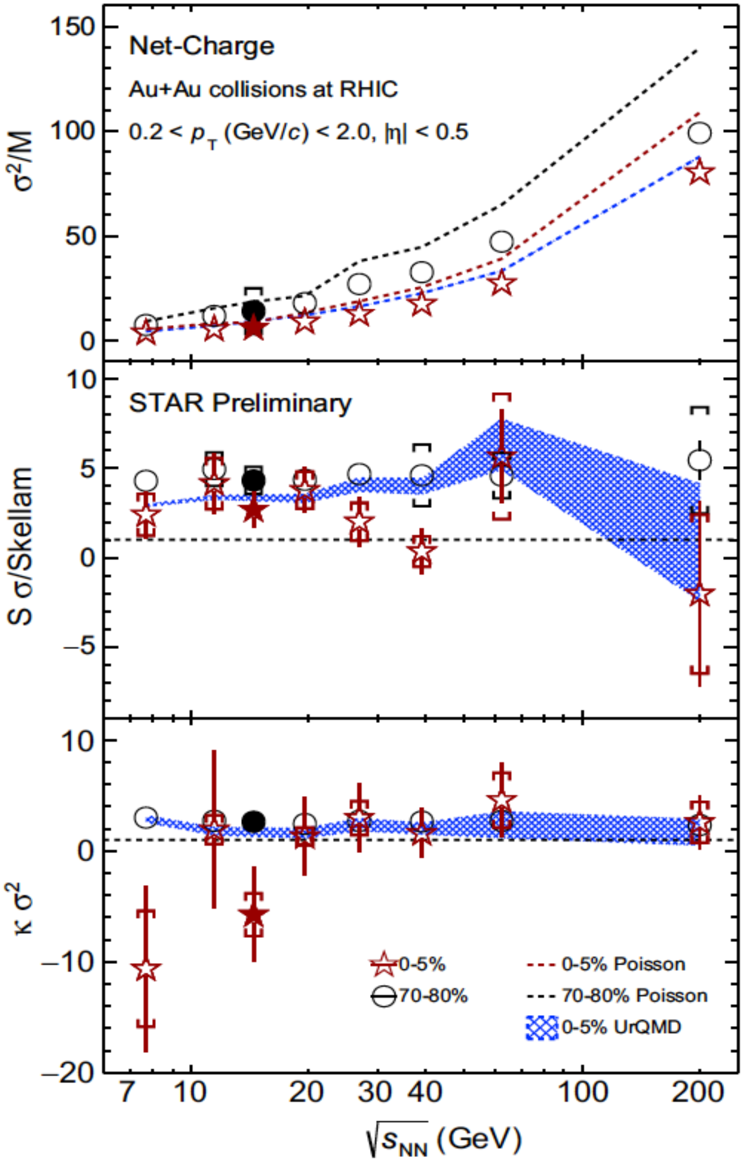
Energy Dependence: Net-Kaon



- The measured M/σ^2 decrease monotonically with increasing collision energy.
- The measured $\kappa\sigma^2$ are consistent with both the Poisson and NBD baselines within uncertainties.
- UrQMD calculations for $S\sigma$ and $\kappa\sigma^2$ are consistent with the data for the most central collisions.

L.Adamczyk, et al. Phys. Lett B, 785 (2018) 551-560 (for the STAR Collaboration)

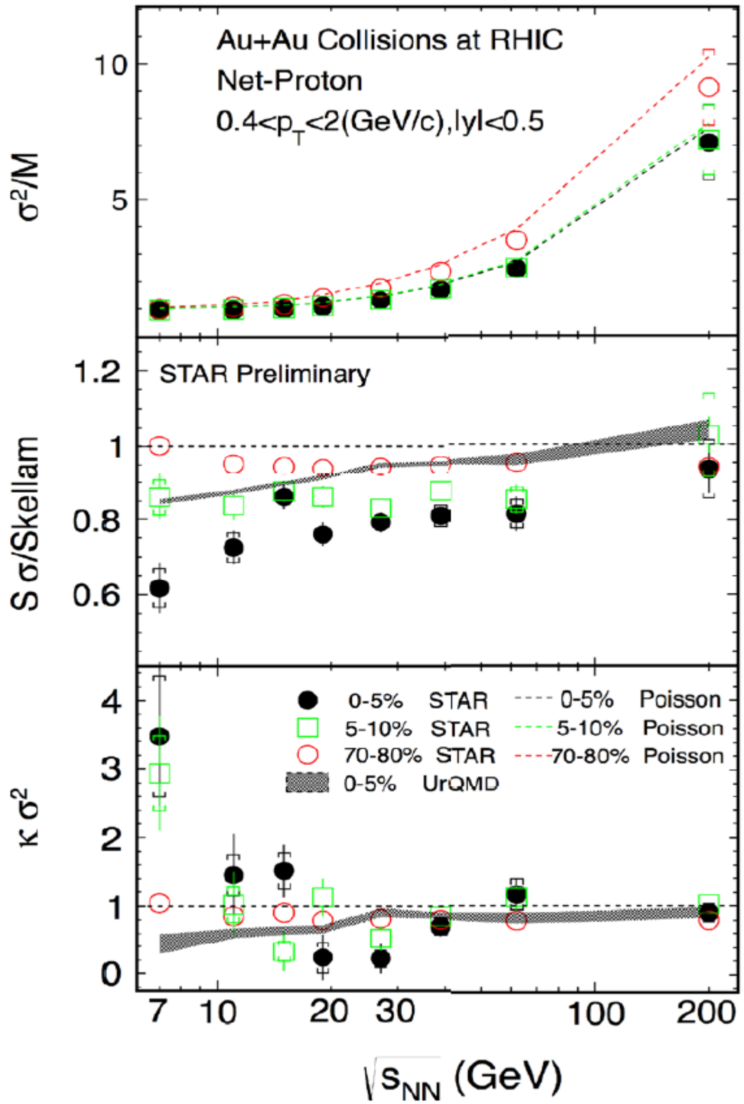
Energy Dependence: Net-Charge



- The σ^2/M increase when increasing the collision energy.
- Both the Sσ/Skellam and $\kappa\sigma^2$ show weak energy dependence.
- No significant deviations from the Poisson expectations and UrQMD calculation are observed for Sσ/Skellam and $\kappa\sigma^2$ within uncertainties.

L.Adamczyk, et al. Phys. Rev. Lett. 113, 092301 (2014) (for the STAR Collaboration)

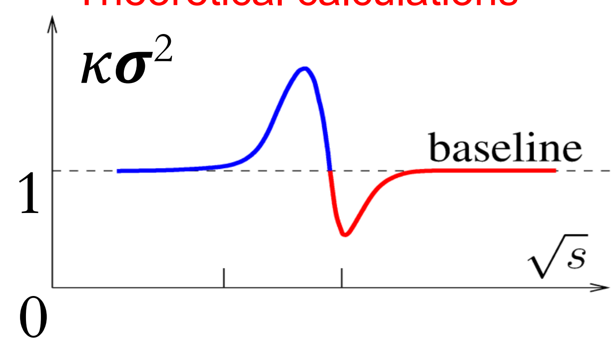
Energy Dependence: Net-proton



- The measured σ^2/M decrease monotonically with increasing collision energy.
- The UrQMD calculations of net-proton $\kappa\sigma^2$ show a strong suppression at low energies.
- Non-monotonic energy dependence of net-proton $\kappa\sigma^2$ in top 0–5% central collisions.
  A hint of entering the critical region.

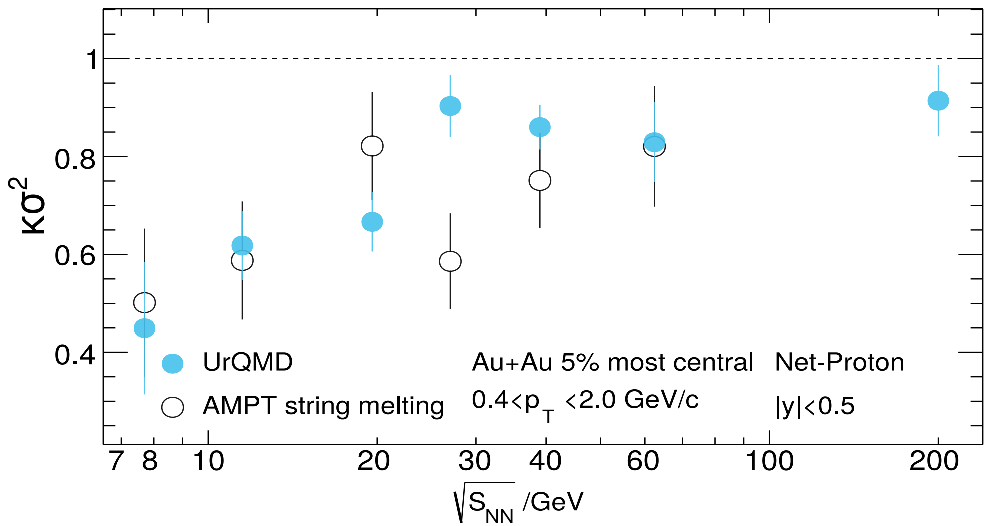
X. Luo and N. Xu, 10.1007/s41365-017-0257-0(2017)
M.A. Stephanov, PRL107, 052301 (2011)
Schaefer, Wanger, PRD 85, 034027 (2012)

Theoretical calculations



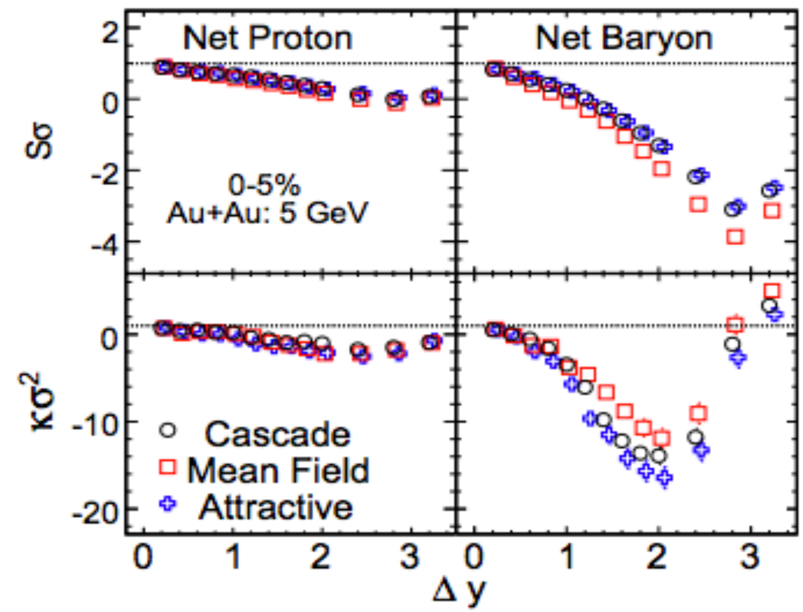
Non-Critical Contributions: Transport Model Studies

UrQMD and AMPT models

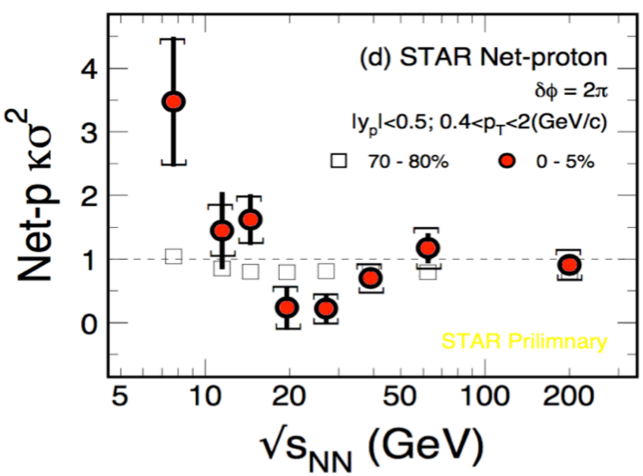


Z. Feckova, et al., PRC92, 064908(2015). J. Xu, et. al., PRC94, 024901(2016). X. Luo et al., NPA931, 808(14),
P.K. Netrakanti et al. 1405.4617, NPA947, 248(2016),

JAM model



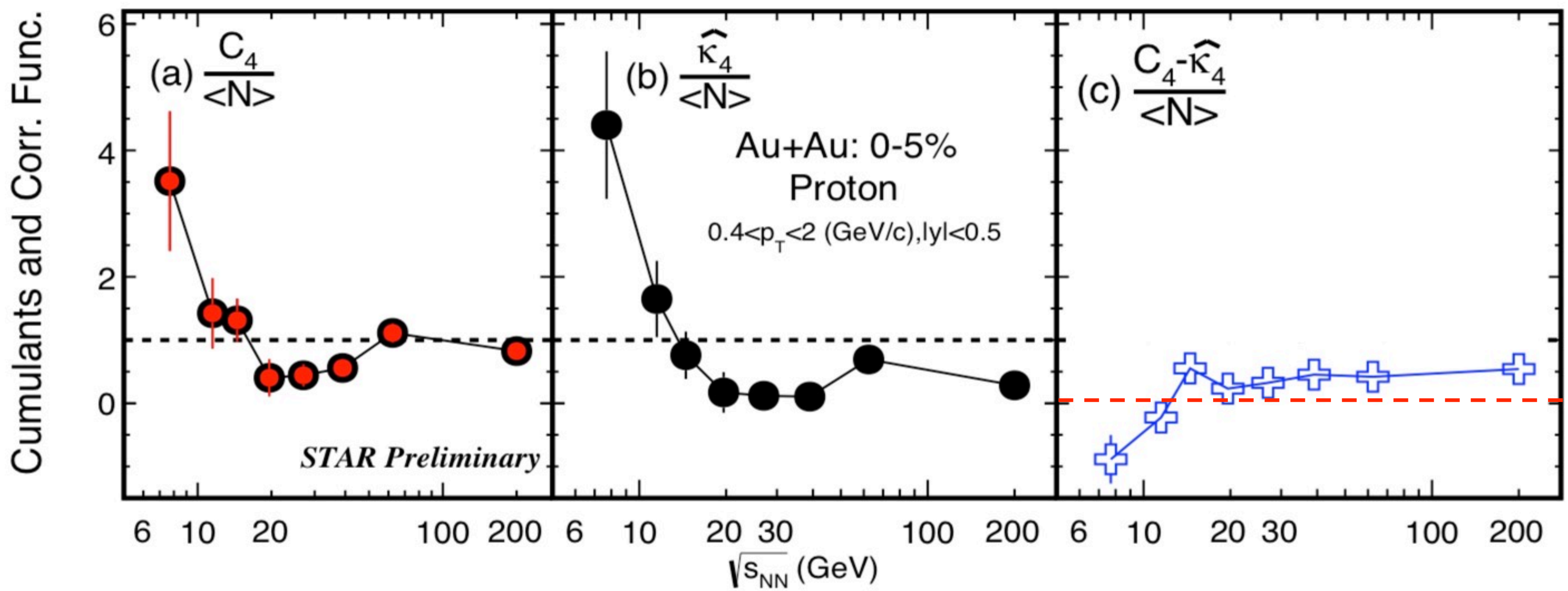
S. He, et. al., PLB762, 296 (2016).
S. He, X. Luo, PLB 774, 623 (2017).



- For net-proton, at $\sqrt{s_{NN}} \leq 10$ GeV:
  Data: **$\kappa\sigma^2 > 1$** Modesl: **$\kappa\sigma^2 < 1$**
- Model simulations: *suppression of the forth-order net-proton fluctuations.*

STAR: Phys. Rev. Lett. 105, 022302 (2010). Phys. Rev. Lett. 112, 032302 (2014).

Proton Cumulants and Correlation Function



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

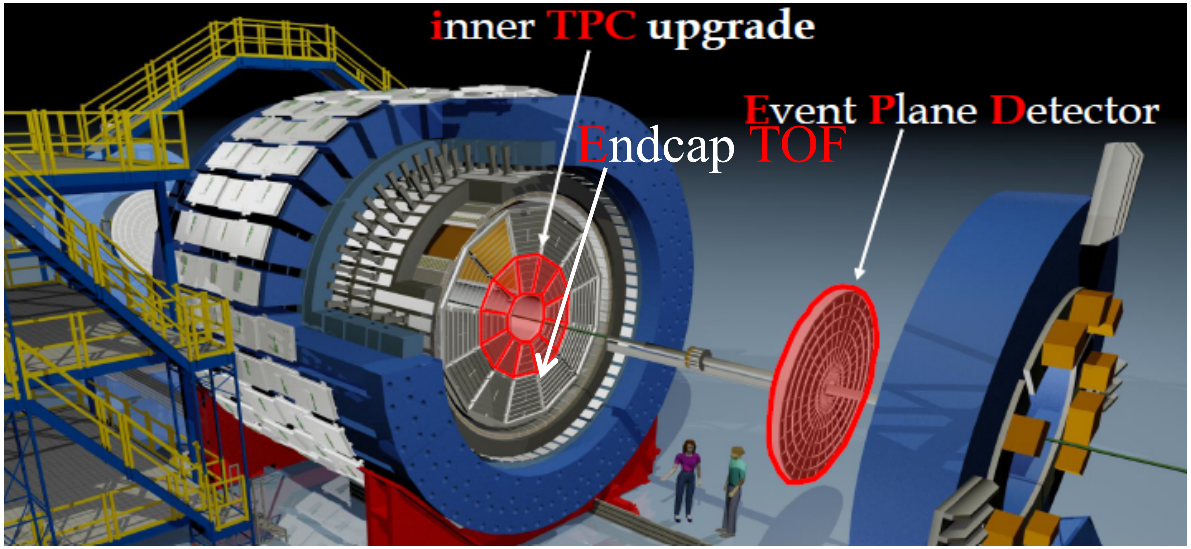
$$C_2 = <N> + \hat{\kappa}_2$$
$$C_3 = <N> + 3\hat{\kappa}_2 + \hat{\kappa}_3$$
$$C_4 = <N> + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

Possible interpretation:

A. Bzdak, V. Koch, V. Skokov, Eur. Phys. J., C77, 288(2017)

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

STAR Upgrades for BES-II (2019-2021)



iTPC proposal:https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF proposal:https://drupal.star.bnl.gov/STAR/starnotes/public/sn0665
EPD proposal:https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666
BES-II whitepaper:https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

iTPC	EPD	eTOF
$|\eta|<1.5$	$2.1<|\eta|<5.1$	$-1.6<\eta<-1$
Better dE/dx resolution	Better centrality and event plane resolution	Extend forward PID capablity
Fully operational in 2019	Fully operational in 2018	Fully operational in 2018

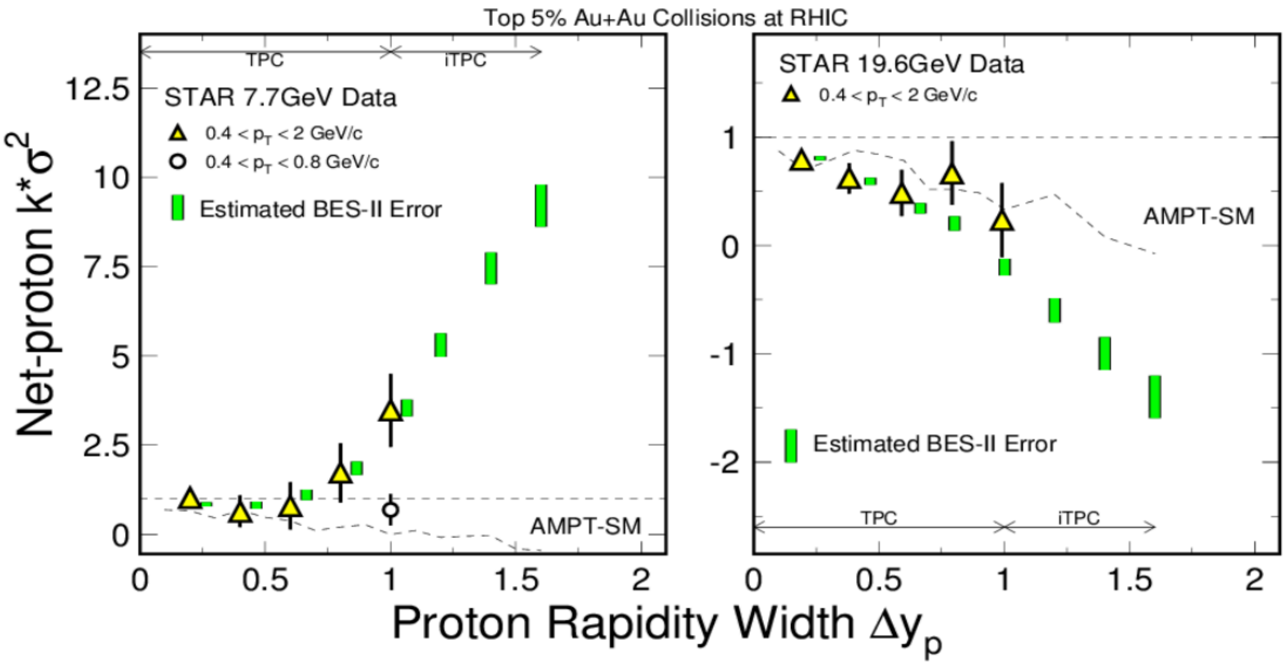
RHIC Beam Energy Scan II (2019-2021)

$\sqrt{s_{NN}}$(GeV)	μ_B(MeV)	T_{ch}(MeV)	Events(10^6)	BES-II / BES-I
200	20	166	350	2010
62.4	70	165	67	2010
54.4			1200	2017
39	115	164	130	2010
27	155	162	500/70	2018/2011
19.6	205	160	400/36	2019/2011
14.5	266	156	300/20	2019/2014
11.5	315	152	230/12	2020/2011
9.1	370	140	160	2020
7.7	420	140	100/4	2021/2010

- BES-II:10-20 times higher statistics than BES-I.
- BES-II: Precise mapping of the QCD phase diagram. $20<\mu_B<420$ MeV.

iTPC Impact on Net-proton Kurtosis

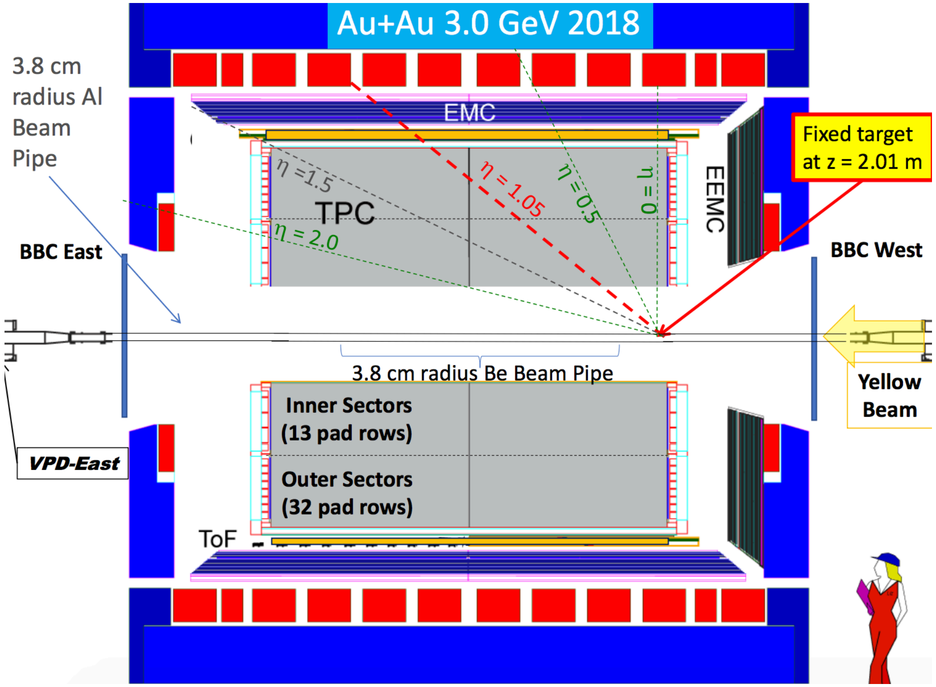
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619



- Measure multiplicity distributions of net-proton in a larger rapidity range.
- Extension of rapidity coverage should amplify the magnitude of fluctuations near the critical point.

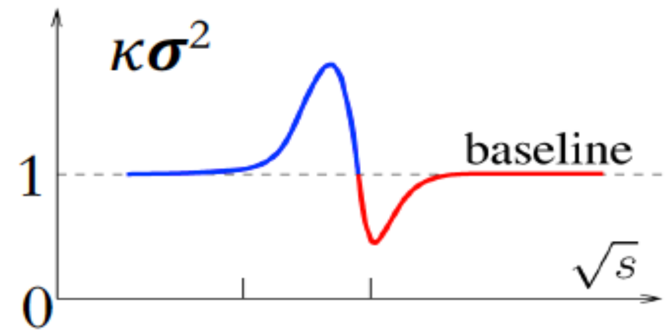
B.Ling and Mikehail A.Stephanov, Phys.Rev.C93(2016)034915

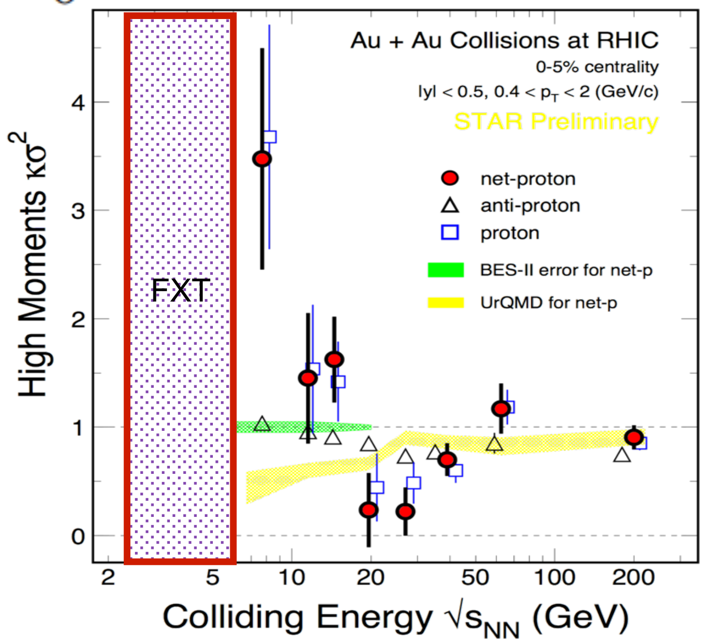
Fixed-Target (FXT) Experiments at STAR



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0696

$\sqrt{s_{NN}}$(GeV)	μ_B(MeV)	Events(10^6)	Run Year
7.7 (FXT)	420	100	2019
6.2 (FXT)	487	100	2020
5.2 (FXT)	541	100	2020
4.5 (FXT)	589	100	2019
3.9 (FXT)	633	100	2019
3.5 (FXT)	666	100	2020
3.2 (FXT)	699	100	2020
3.0(FXT)	721	100	2020





- FXT will be an ideal experiment to search for the QCD critical point at low energy with high precision.

Summary and Outlook

- Non-monotonic energy dependence is observed in net-proton C_4/C_2 at most central Au+Au collisions.
  Need to confirm with more statistics and lower energies data.

- Transport model (no CP) results show suppression of net-proton fluctuations at low energies.

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

- Study the QCD phase structure with high precision: BES-II at RHIC (2019-2021, both collider and fixed-target modes).
  The run starts February and is scheduled to run until July, all detectors are currently installed and commissioning starts during the WWND!