Studying the QCD Phase Diagram in RHIC-BES at STAR

Toshihiro Nonaka for the STAR Collaboration
Central China Normal University

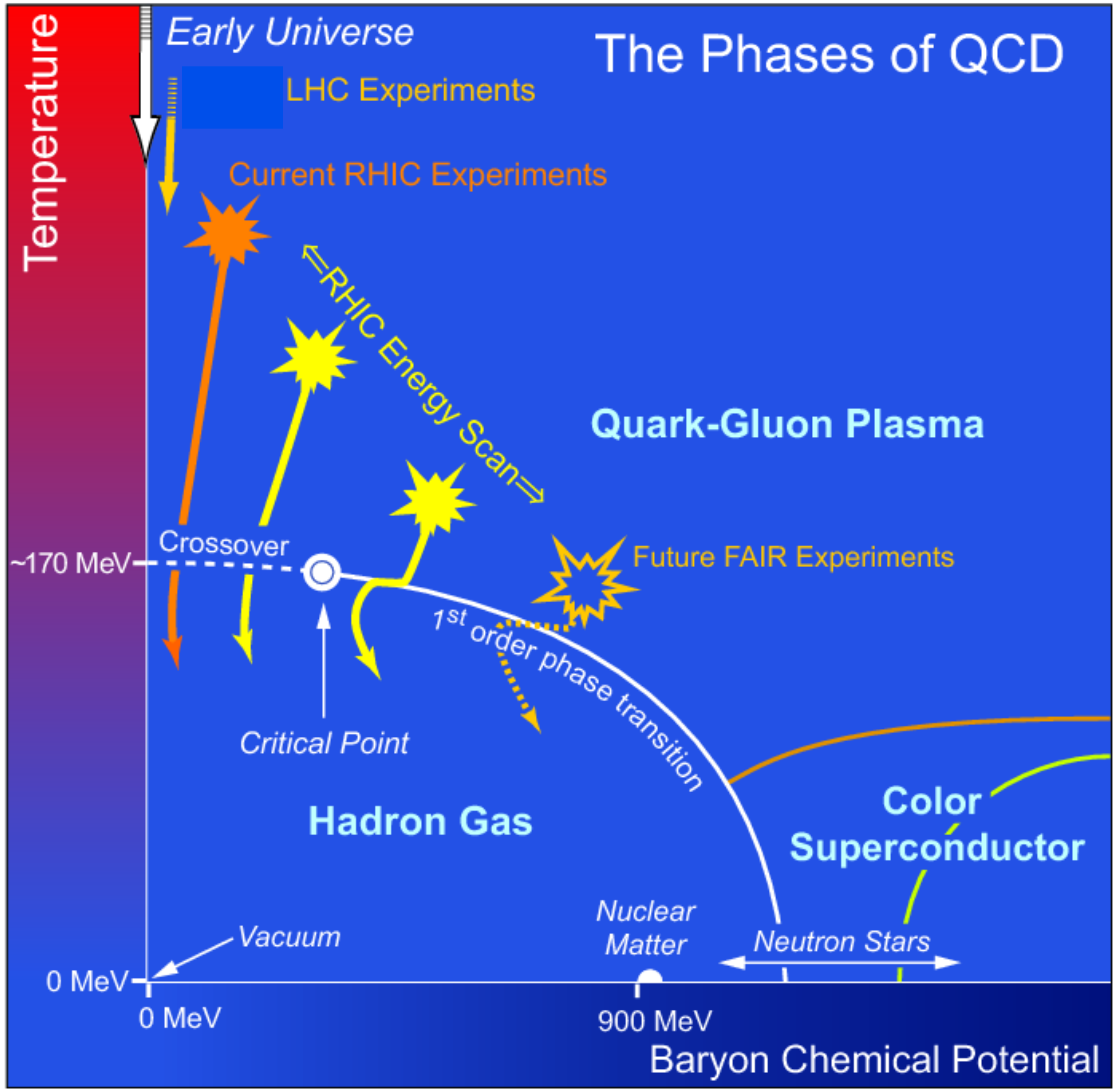
Nov. 13, 2018
QNP2018, Tsukuba, Japan

Outline

- ✓ **Introduction**
  - Beam Energy Scan
  - The STAR detector
- ✓ **Experimental results**
  - Freeze-out condition
  - The 1st-order phase transition
  - **Critical point**
  - Crossover
- ✓ **BES-II**
- ✓ **Summary**

Higher-order fluctuations of net-particle distributions

QCD phase diagram



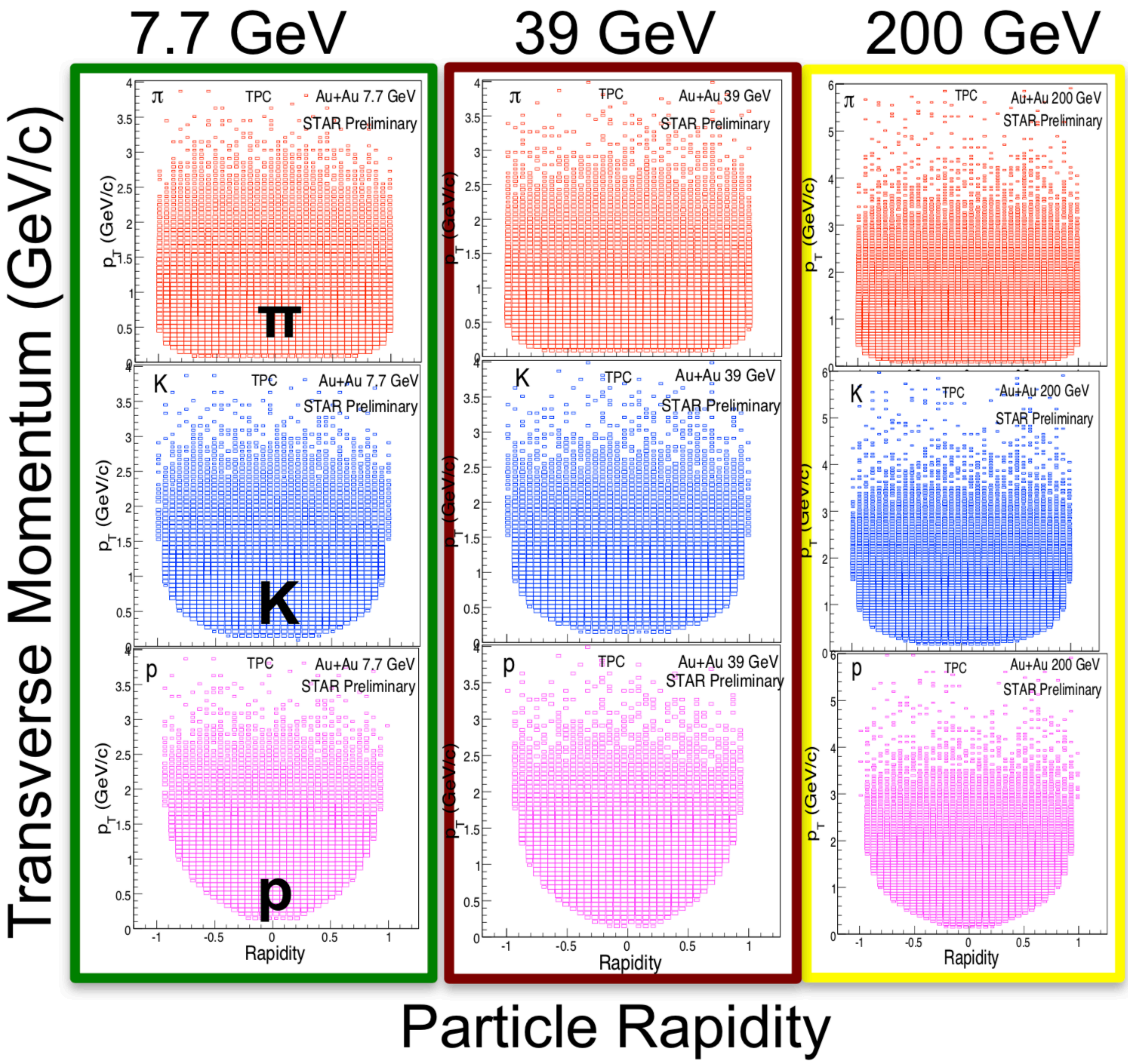
✓ **Need to investigate the QCD phase structure in wide (μ_B,T) region.**

- **Crossover at μ_B=0**
  Y. Aoki et al, Nature 443, 675(2006)
- **1st-order phase transition at large μ_B?**
- **Critical point?**

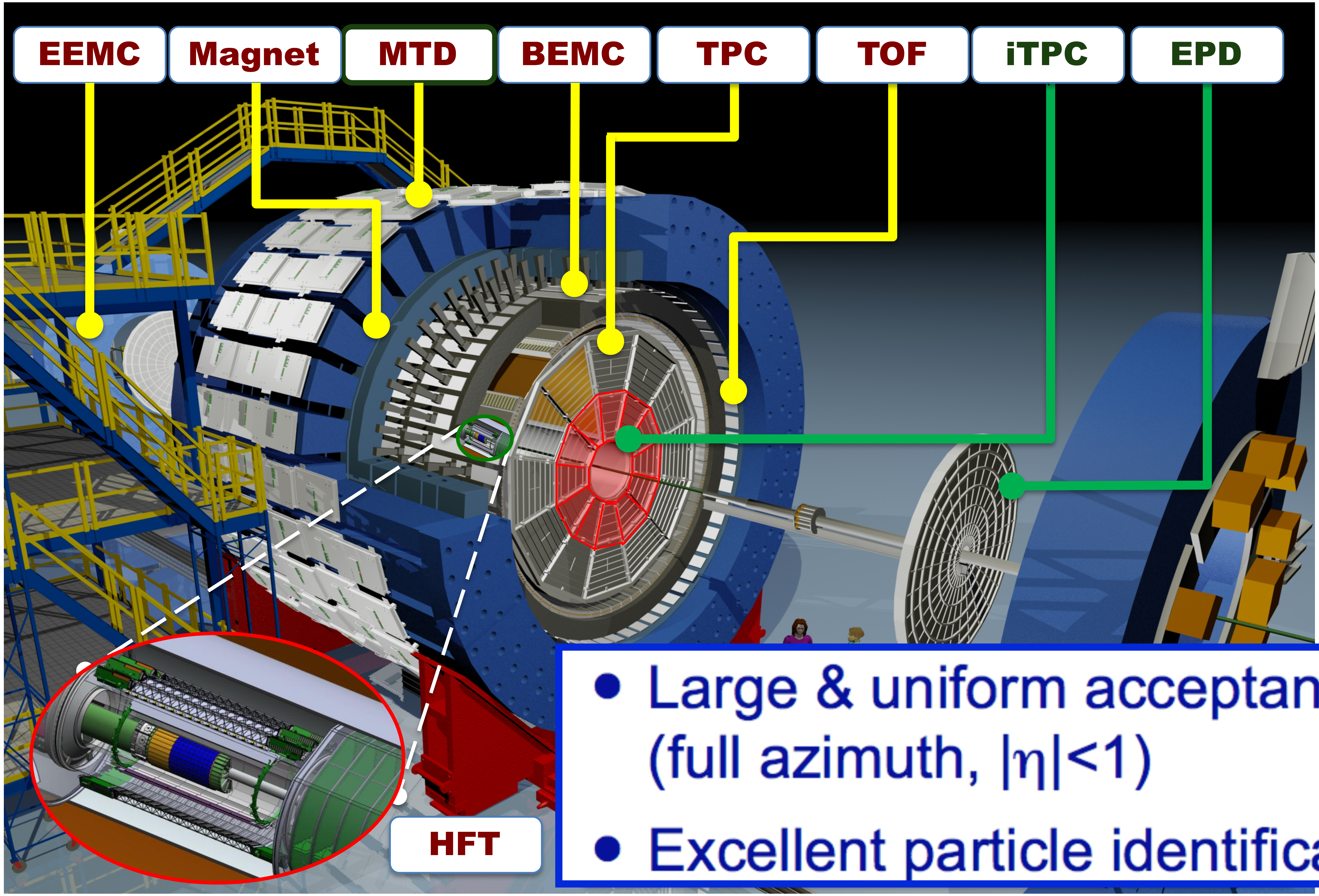
Beam Energy Scan

- ✓ **Large data sets in various collision energies.**
- ✓ **Large and homogeneous acceptance, especially important for fluctuation analysis.**

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	**1200**	**2017**
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



The STAR detector

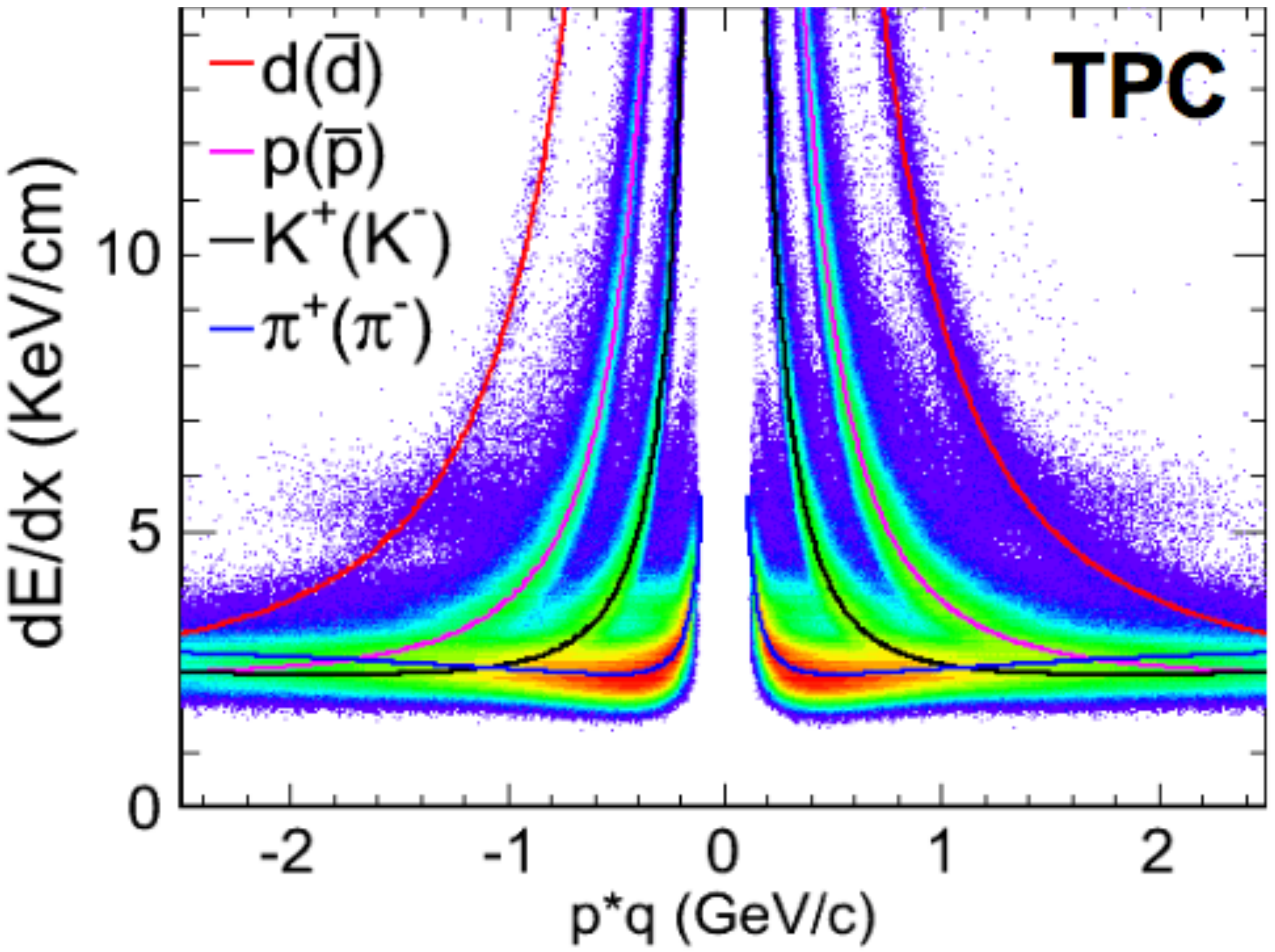


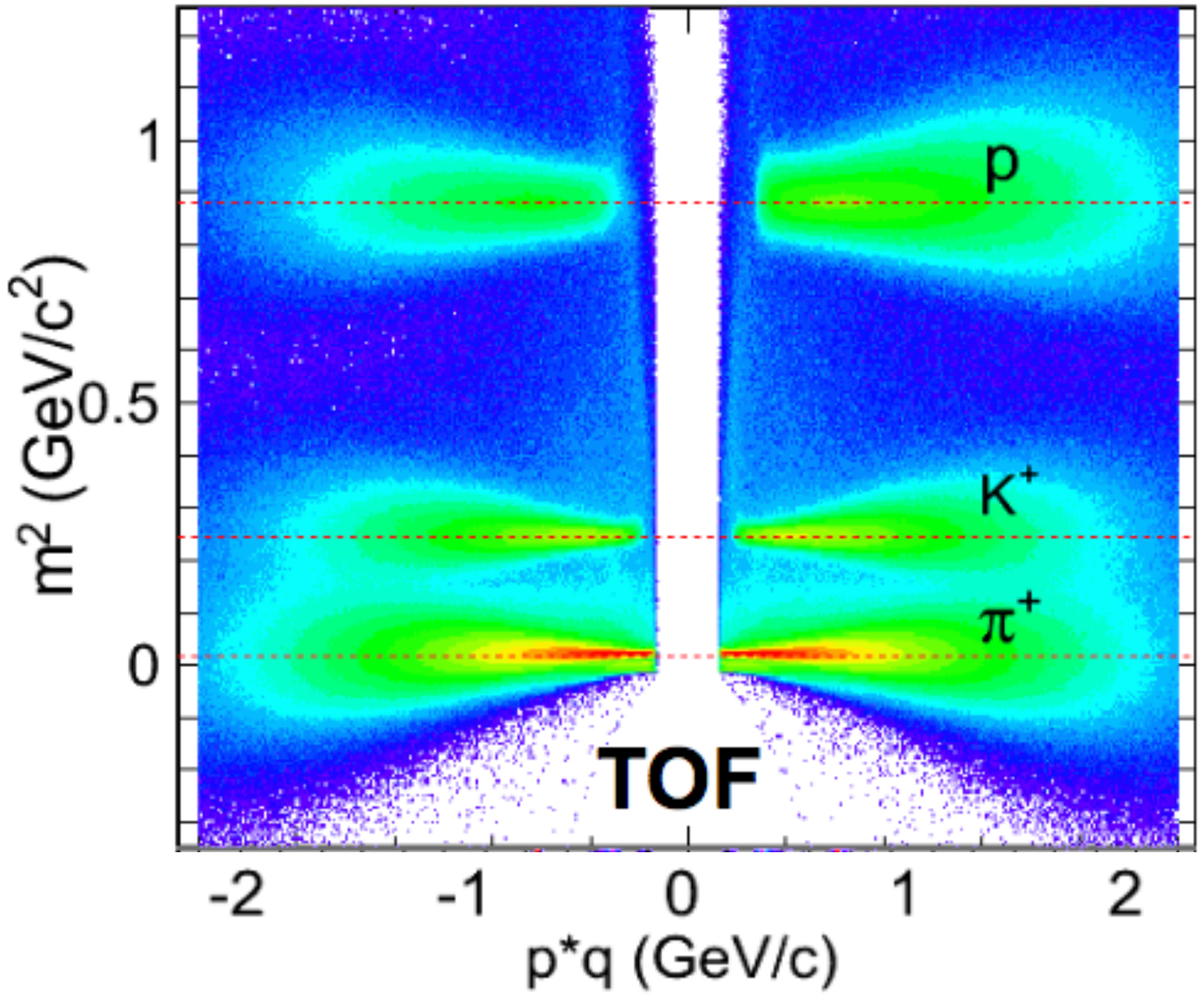
- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

Particle identification

✓ dE/dx measured with TPC is used for proton identification at low p_T region.

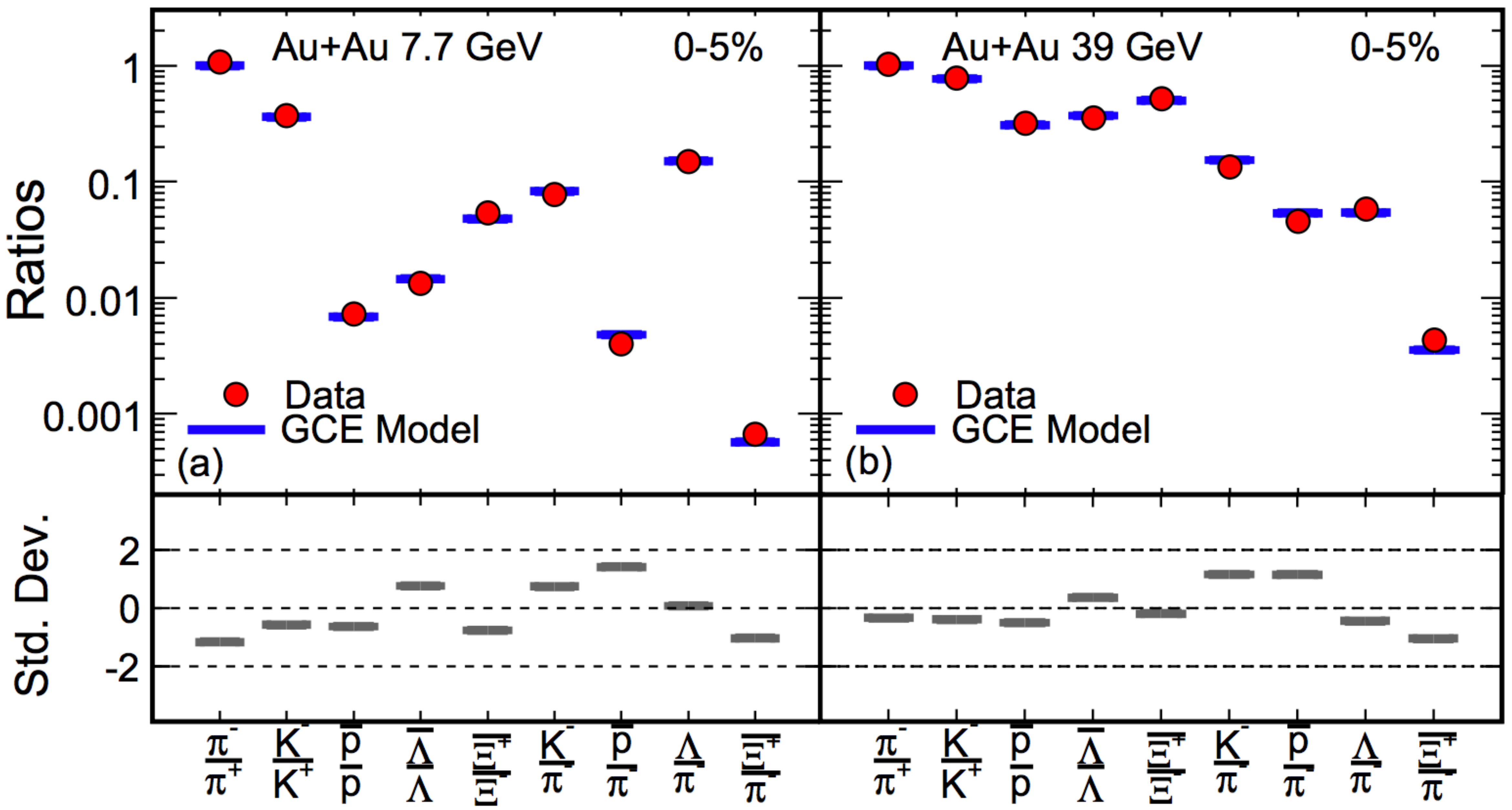
✓ The combined PID with m^2 from TOF is used at high p_T region.

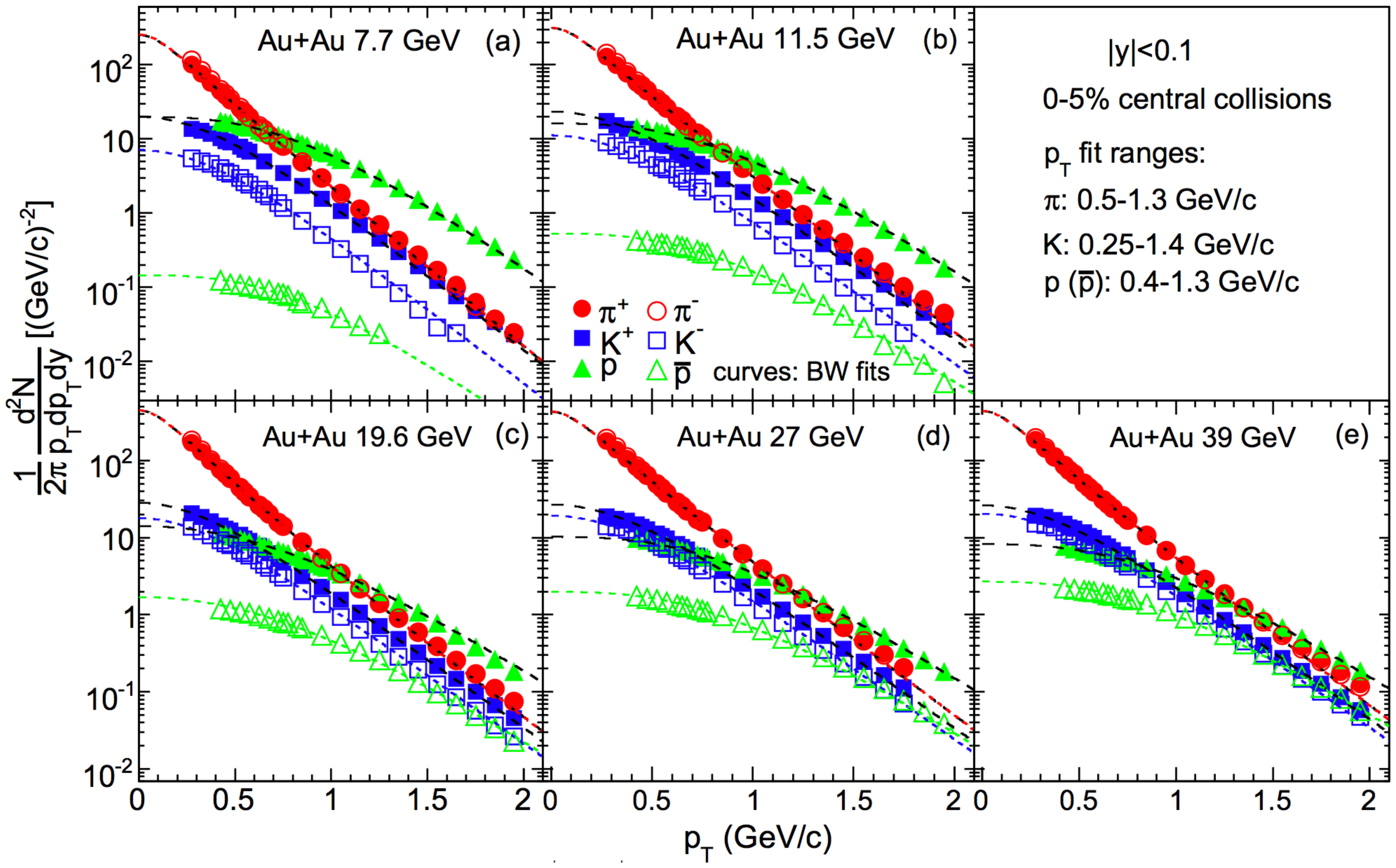




Hadron yield/spectra

✓ **Particle ratios and p_T spectra are measured at BES, from which the freeze-out conditions can be extracted.**



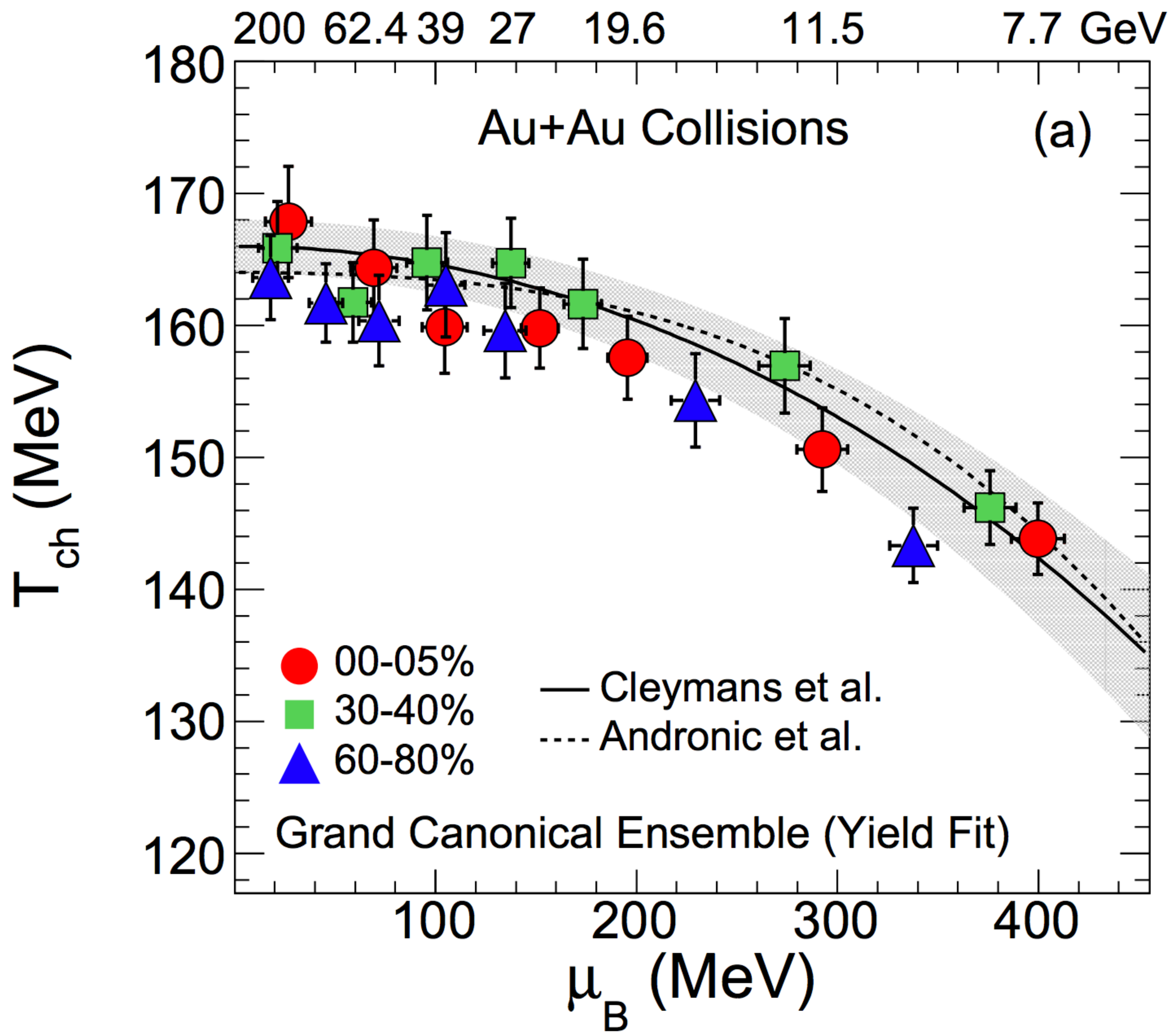


PRC96, 44904(2017) : STAR Collaboration

Freeze-out condition

✓ ***Chemical freeze-out***

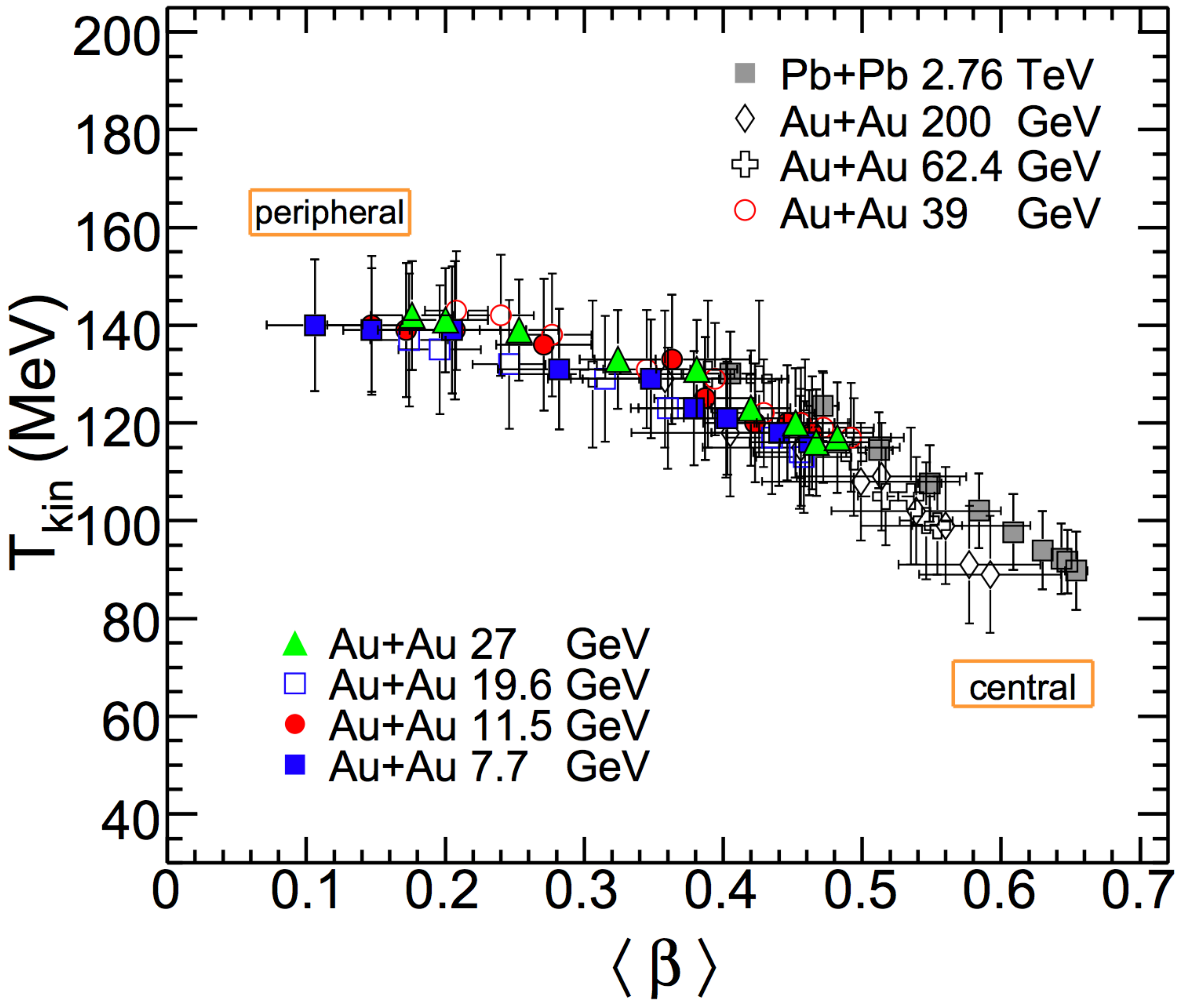
- Weak temperature dependence
- Centrality dependence of μ_B



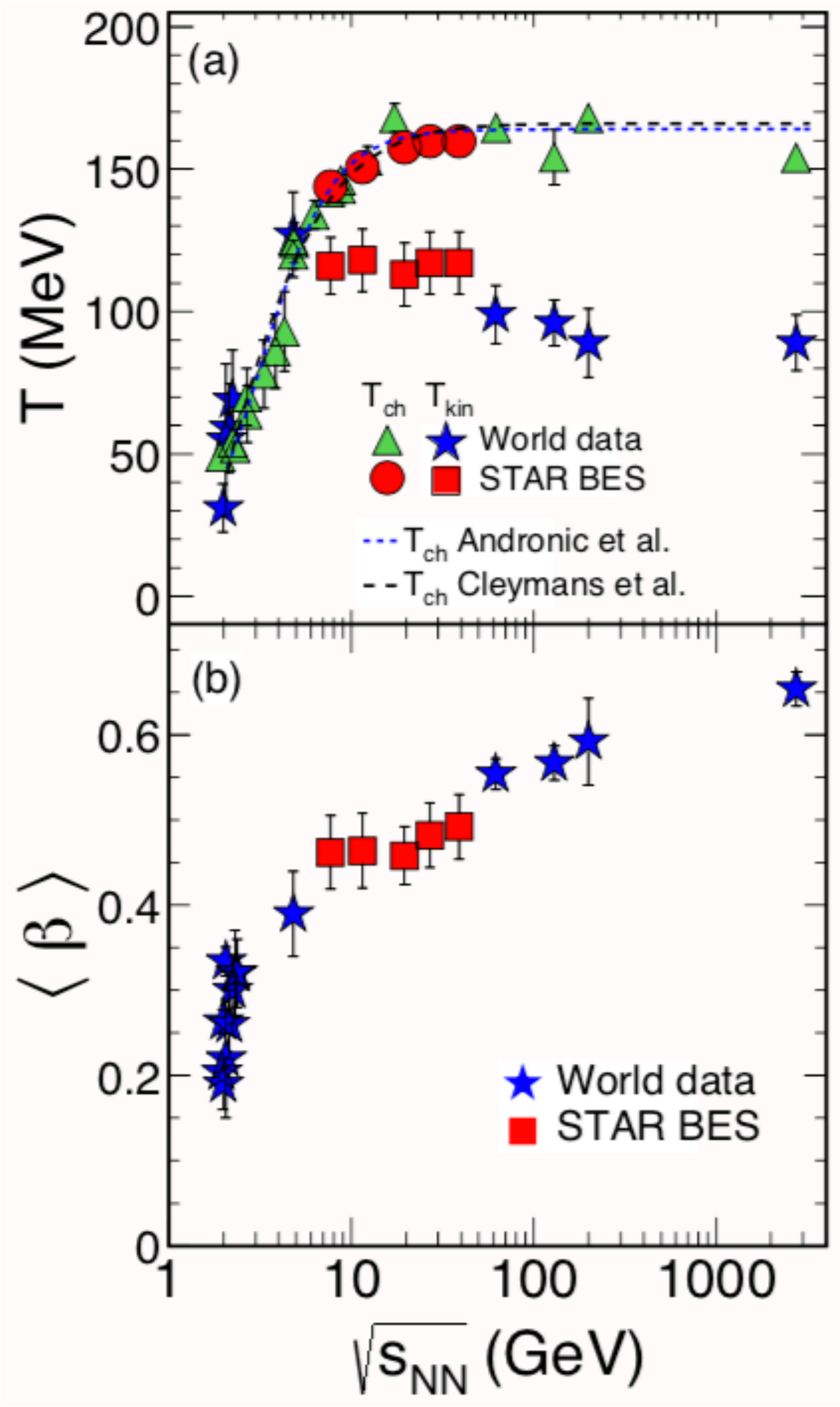
PRC96, 44904(2017) : STAR Collaboration

✓ ***Kinetic freeze-out***

- Central collisions→lower value of T_{kin} and larger collectivity <β>
- Stronger collectivity at higher energy, even for peripheral collisions.



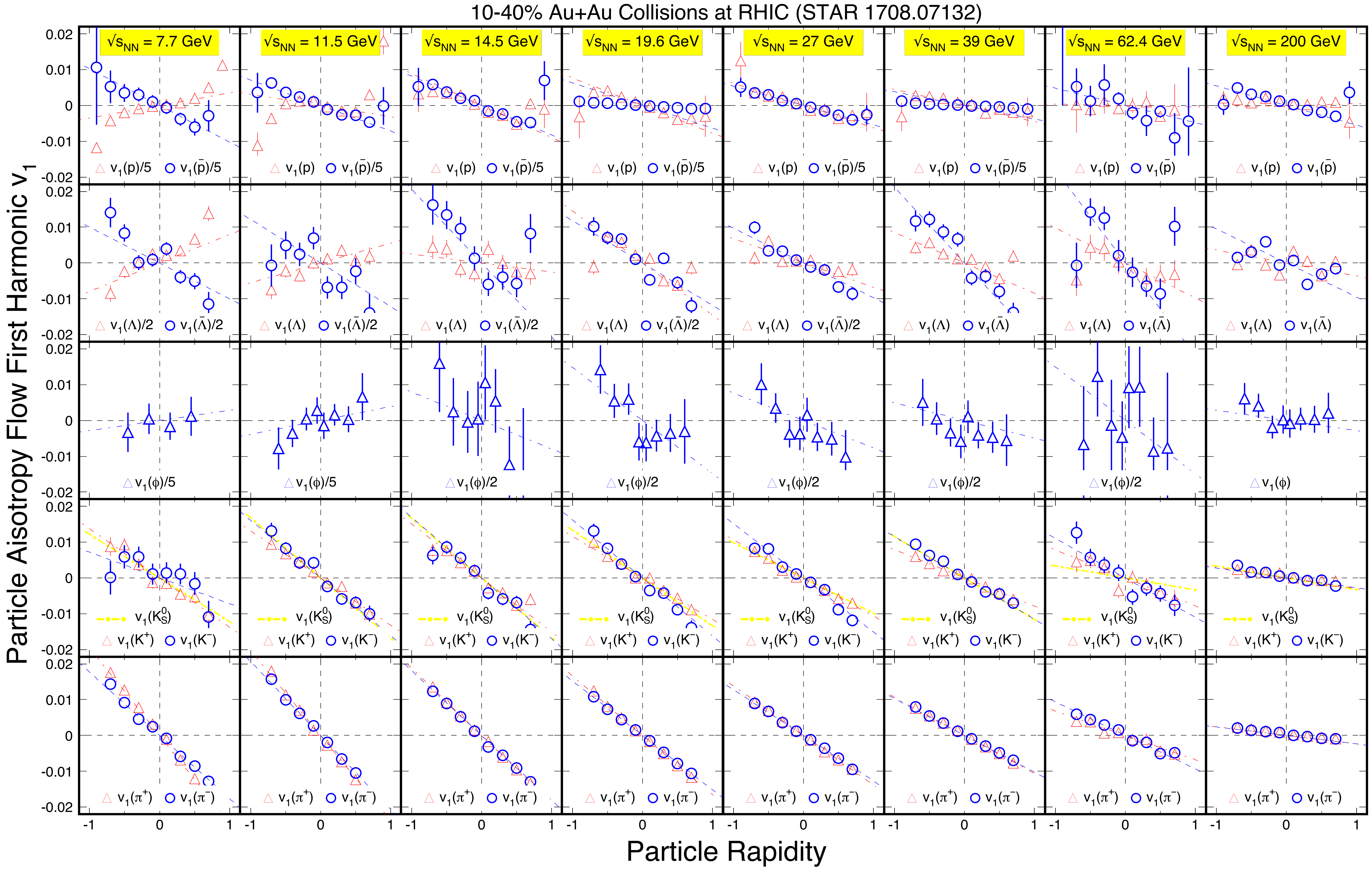
Freeze-out condition



- ✓ **Collectivity increases with beam energy for central collisions**
- ✓ **Gap between chemical and kinetic freeze-out temperatures increases with beam energy, which suggests hadronic system interacts for longer duration in high energy collisions.**

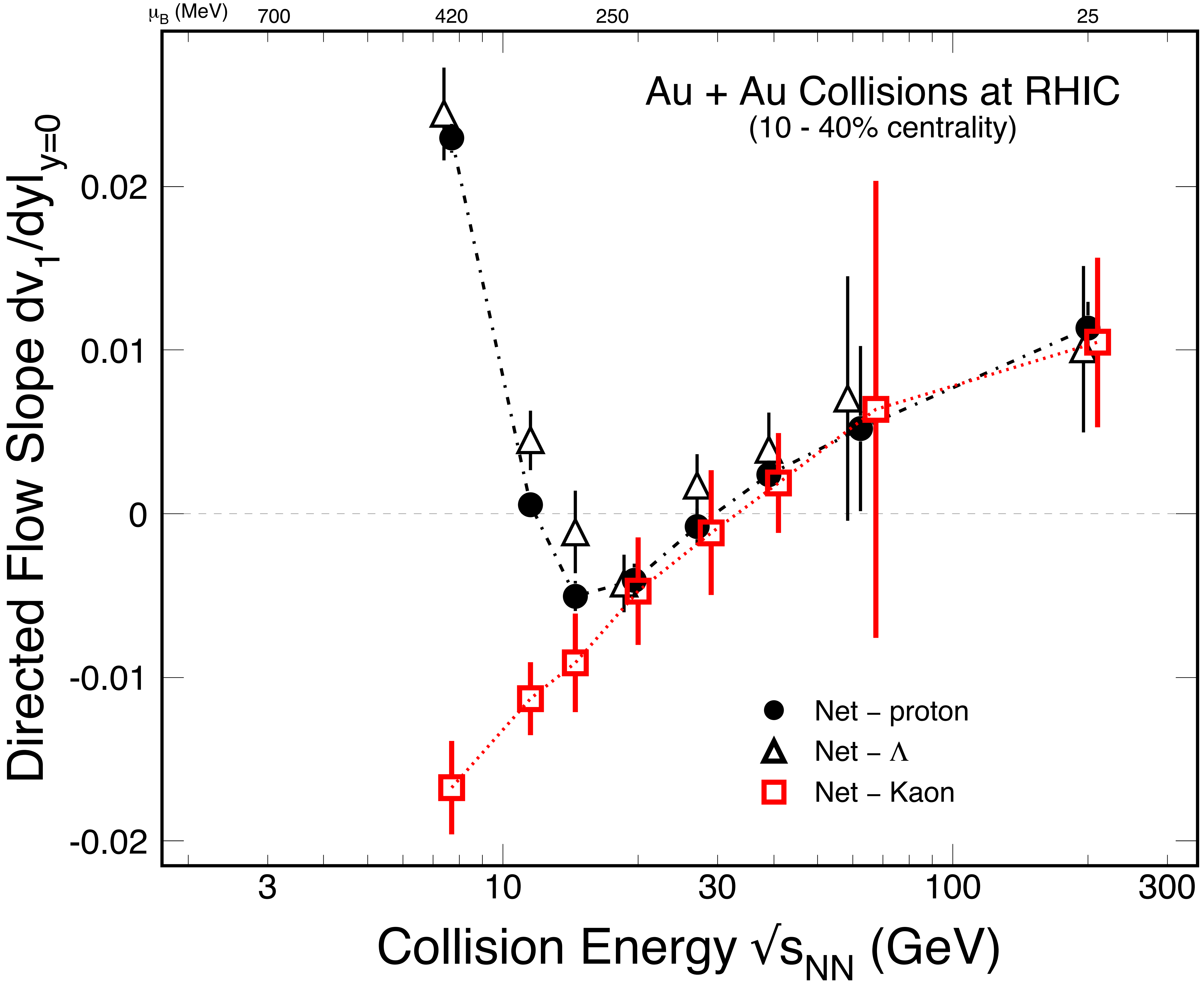
PRC96, 44904(2017) : STAR Collaboration

v_1 versus collision energy



PRL120, 62301(2018) : STAR Collaboration

v_1 versus collision energy



- ✓ Minimum at $\sqrt{s_{NN}}$ = 10 GeV for net-proton and net-Λ, but net-kaon data continue decreasing as energy decreases.
- ✓ At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive.
- ✓ Softest point only for baryons?
- ✓ Need model to explain

M. Isse, A. Ohnishi et al, PRC72, 064908(05)
Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16)

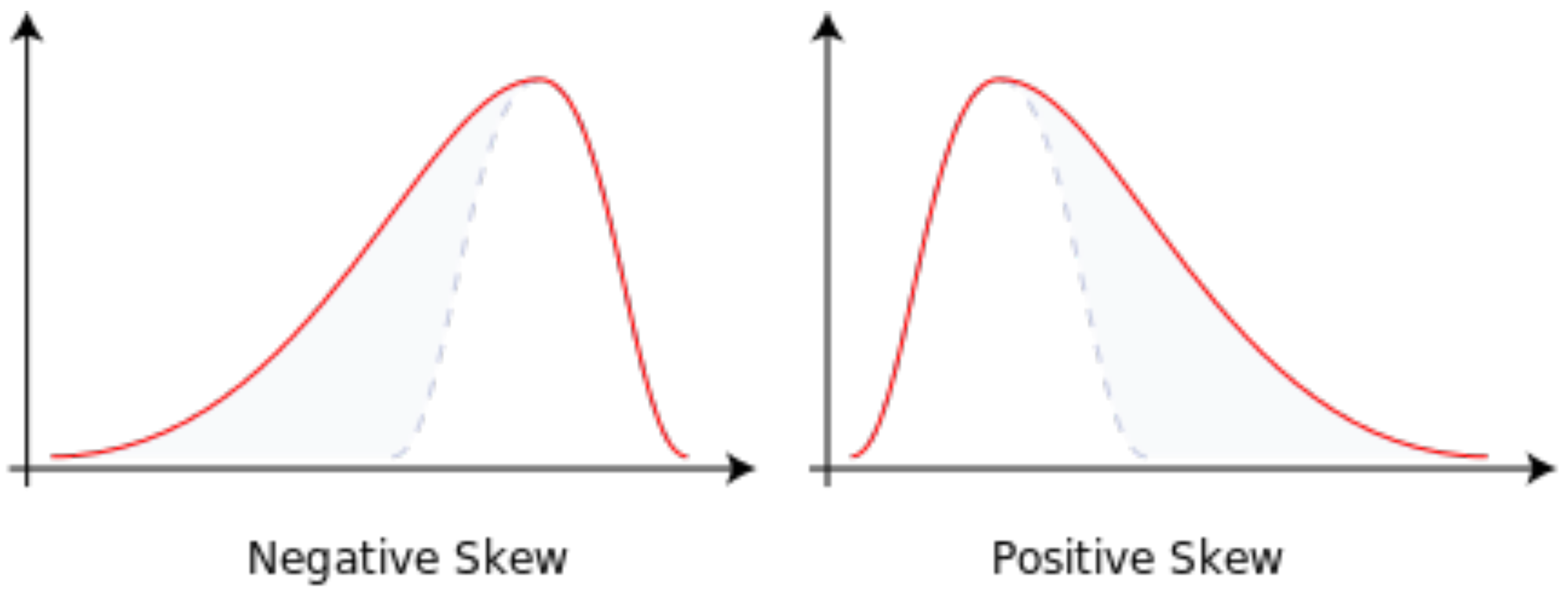
● STAR: PRL**112**, 162301(2014)
□ △ STAR: 1708.07132; **PRL120**, 62301(2018)

Searching for the critical point and crossover with higher-order fluctuations of net-particle distributions

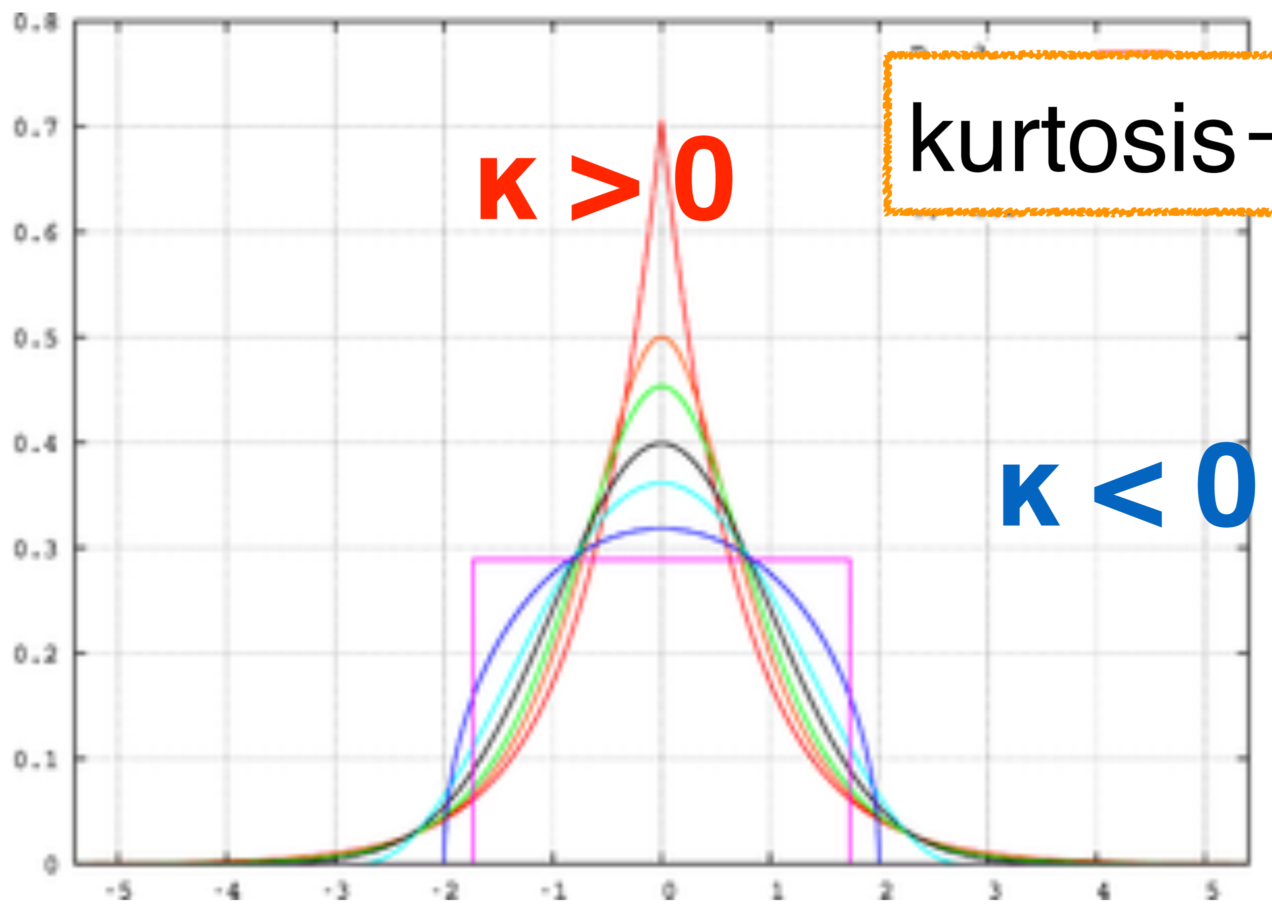
Higher-order fluctuations

- ✦ **Moments and cumulants are mathematical measures of "shape" of a distribution which probe the fluctuation of observables.**
  - ✓ **Moments: mean (*M*), standard deviation (*σ*), skewness (*S*) and kurtosis (κ).**
  - ✓ ***S and κ are non-gaussian* fluctuations.**

skewness→asymmetry



kurtosis→sharpness



from wikipedia

✓ **Cumulant ⇄ Moment**

$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

✓ **Cumulant : additivity**

$$C_n(X+Y) = C_n(X) + C_n(Y)$$

➞ **proportional to volume**

Fluctuations of conserved quantities

PRL 112, 032302 (2014) : STAR Collaboration

✦ Net baryon, net charge and net strangeness

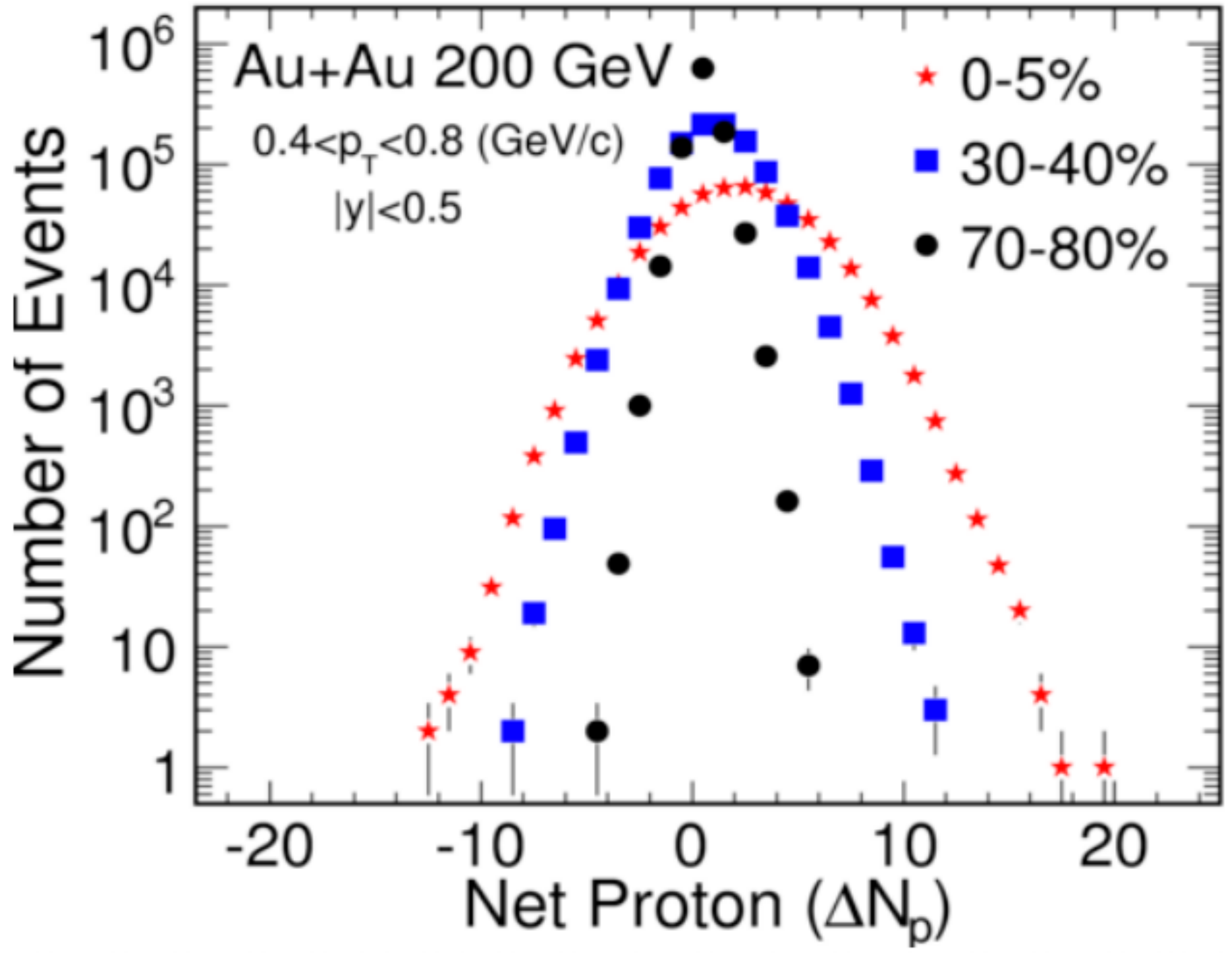
"Net" : positive - negative

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

No. of positively charged particles in one collision

No. of negatively charged particles in one collision

Fill in histograms over many collisions



→neutrons cannot be measured

(1) Sensitive to correlation length

$$C_2 = <(\delta N)^2>_c \approx \xi^2 \qquad C_5 = <(\delta N)^5>_c \approx \xi^{9.5}$$

$$C_3 = <(\delta N)^3>_c \approx \xi^{4.5} \qquad C_6 = <(\delta N)^6>_c \approx \xi^{12}$$

$$C_4 = <(\delta N)^4>_c \approx \xi^7$$

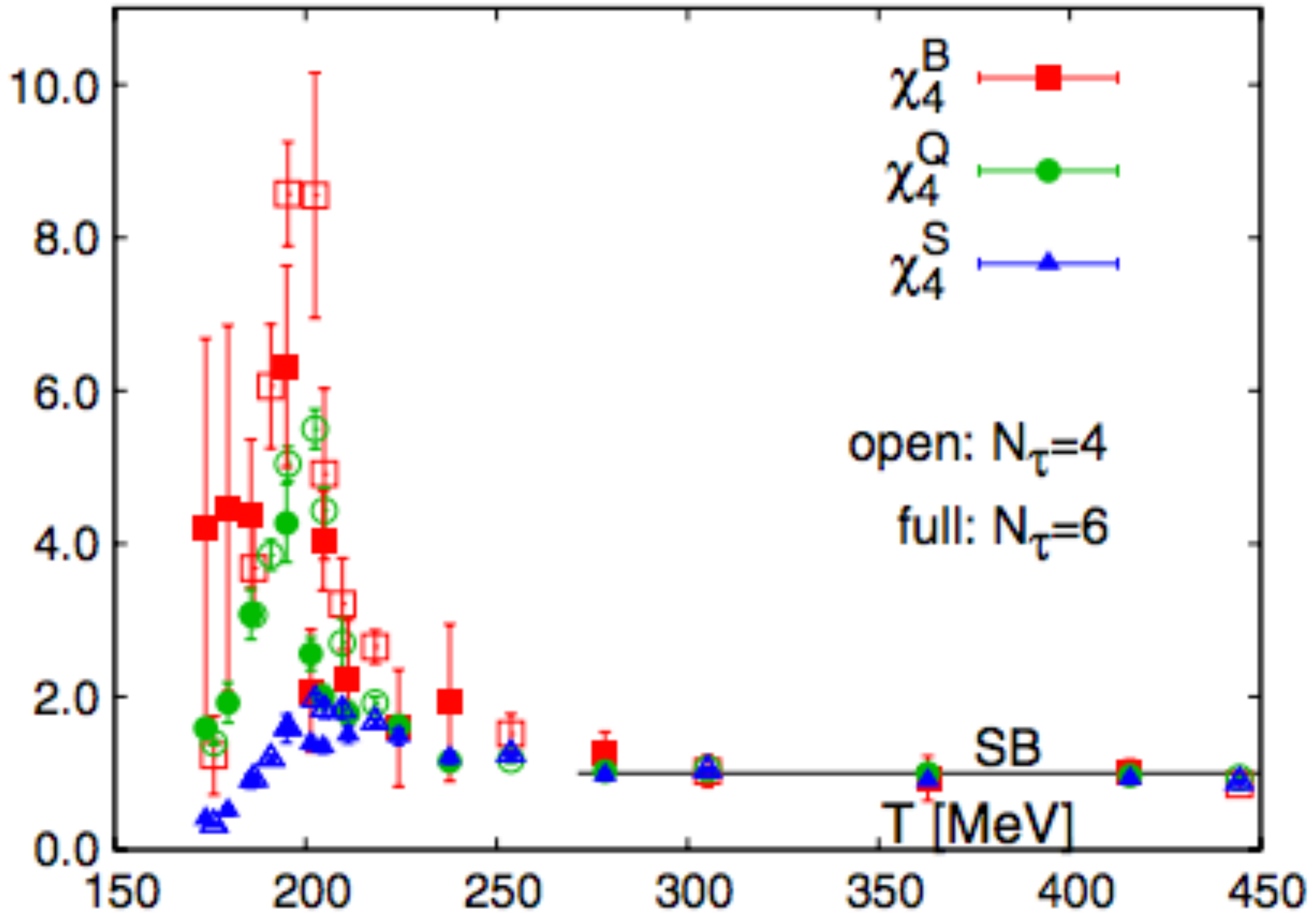
(2) Direct comparison with susceptibilities.

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

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

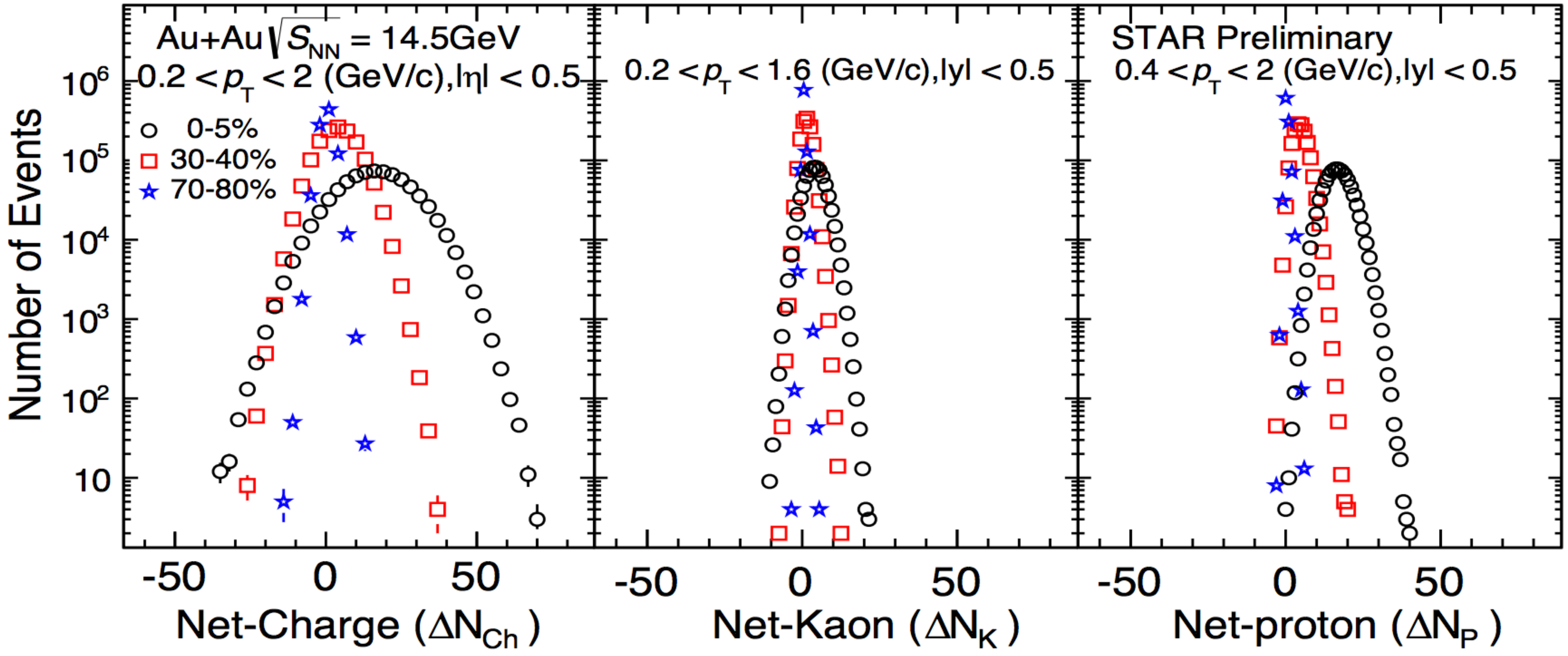
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

Volume **dependence can be canceled by taking ratio.**



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

Data analysis method

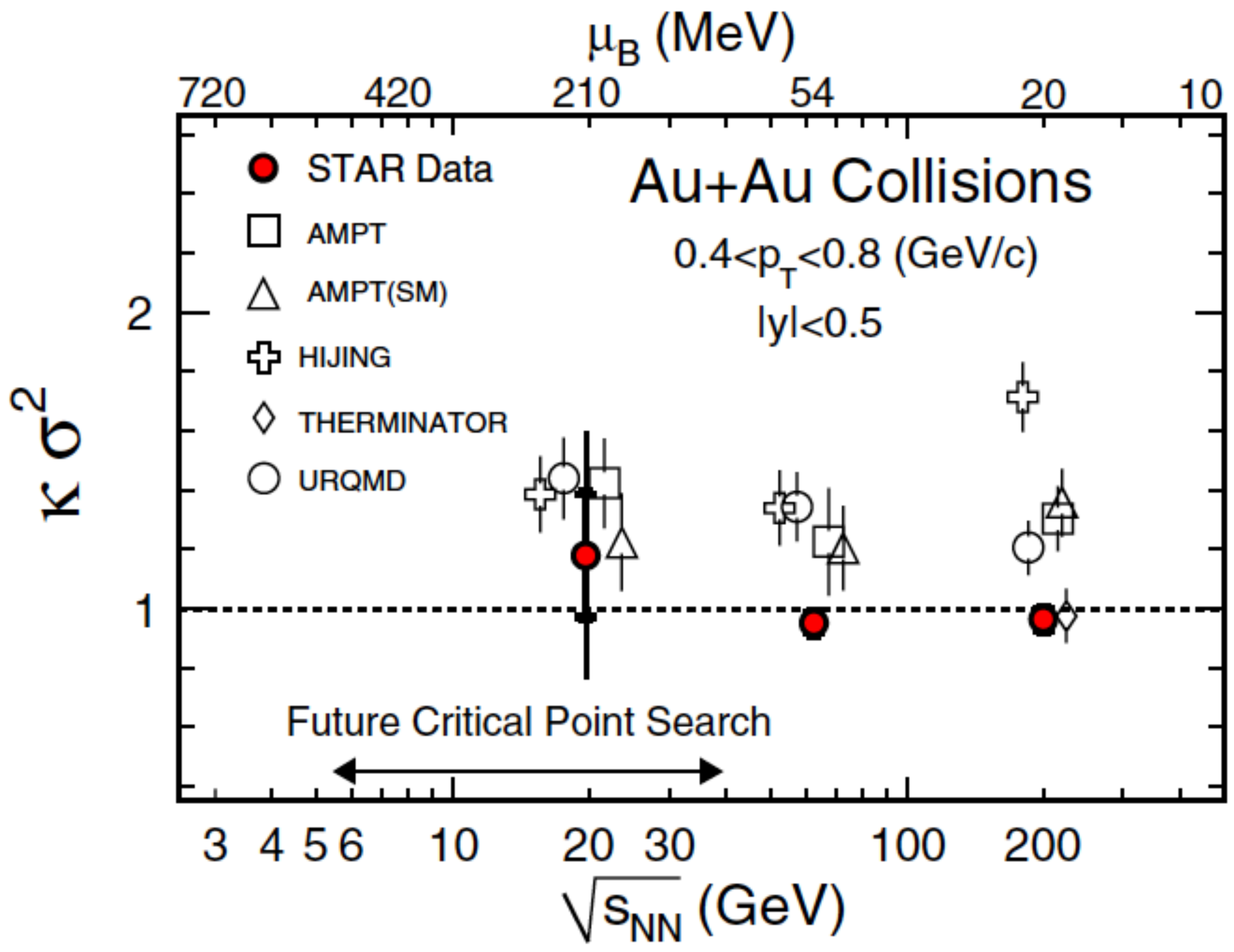


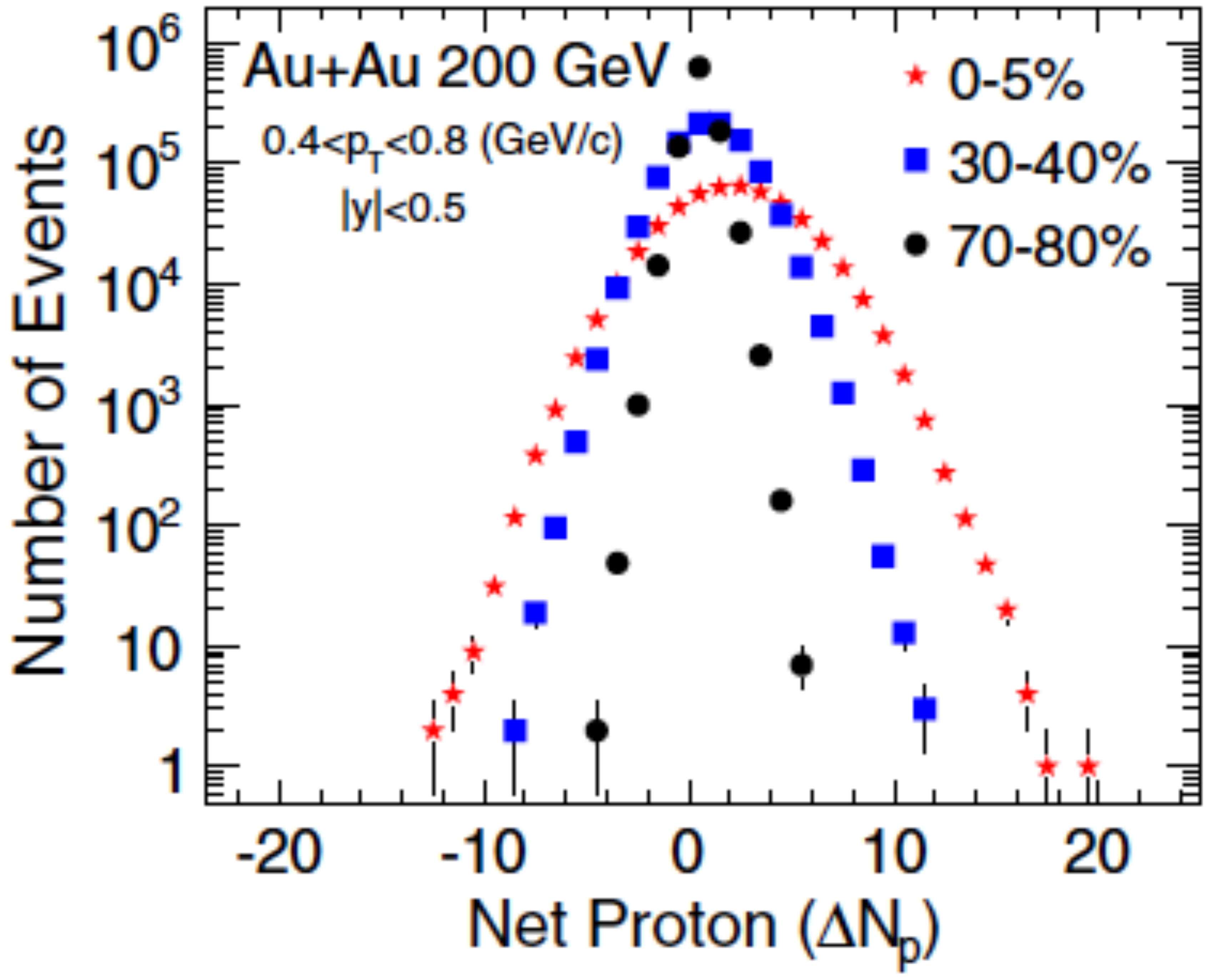
- ✓ **Statistical error estimation : Delta theorem or bootstrap**
- ✓ **Avoid auto-correlation effects : New centrality definition**
- ✓ **Suppress initial volume fluctuation : Centrality bin width correction**
- ✓ **Detector efficiency correction : Binomial model**

- ***X.Luo, J. Xu, B. Mohanty and N. Xu. J. Phys. G40,105104(2013)***
- ***M. Kitazawa : PRC.86.024904, M. Kitazawa and M. Asakawa : PRC.86.024904***
- ***A. Bzdak and V. Koch : PRC.86.044904, PRC.91.027901, X. Luo : PRC.91.034907***
- ***T. Nonaka, M. Kitazawa, S. Esumi : PRC.95.064912***

First measurement of net proton

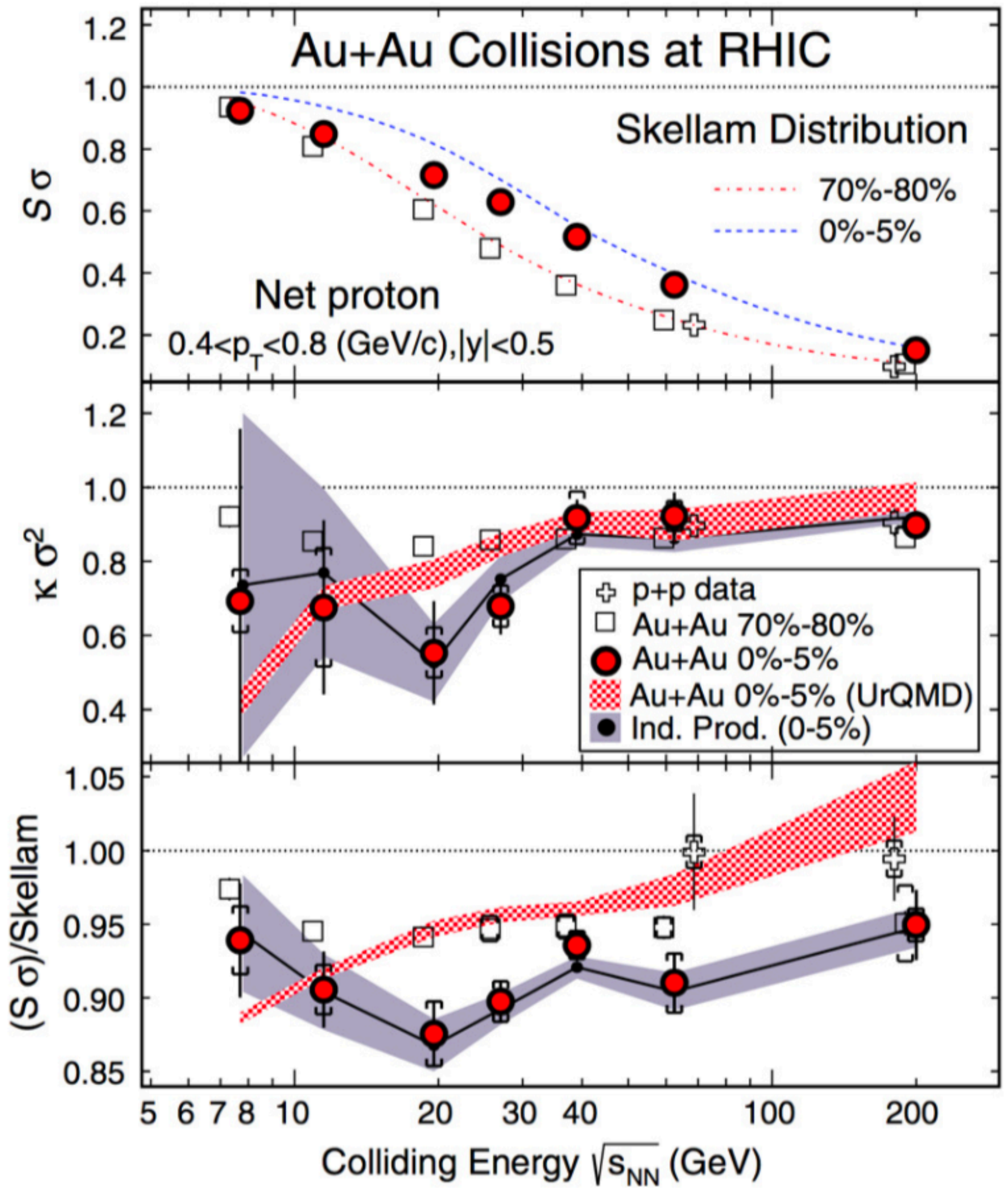
✓ **At μ_B < 210 MeV, the 4th-order fluctuation is found to be flat as a function collision energy.**





PRL105, 022302(2010): STAR Collaboration

Net proton from BES-I

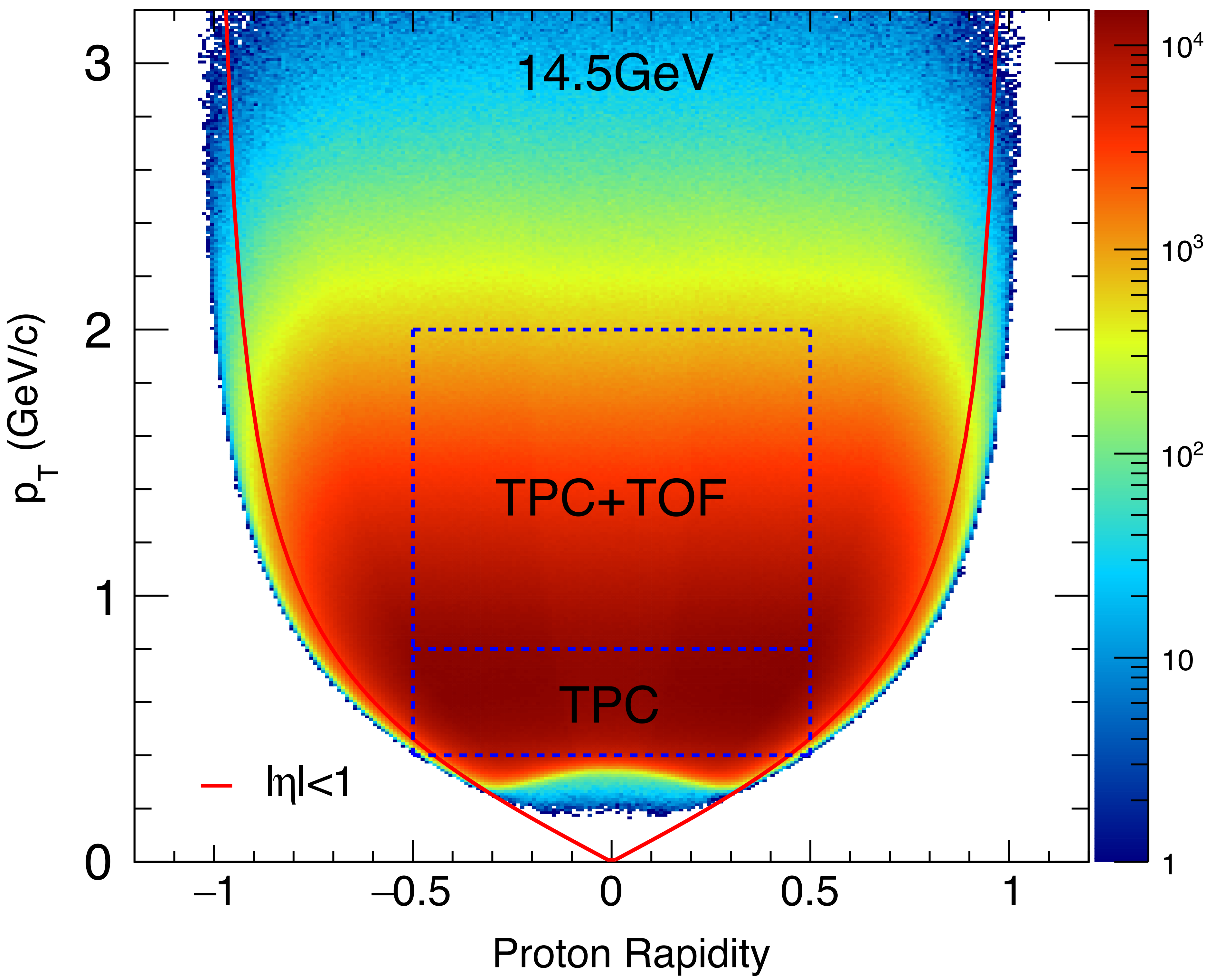


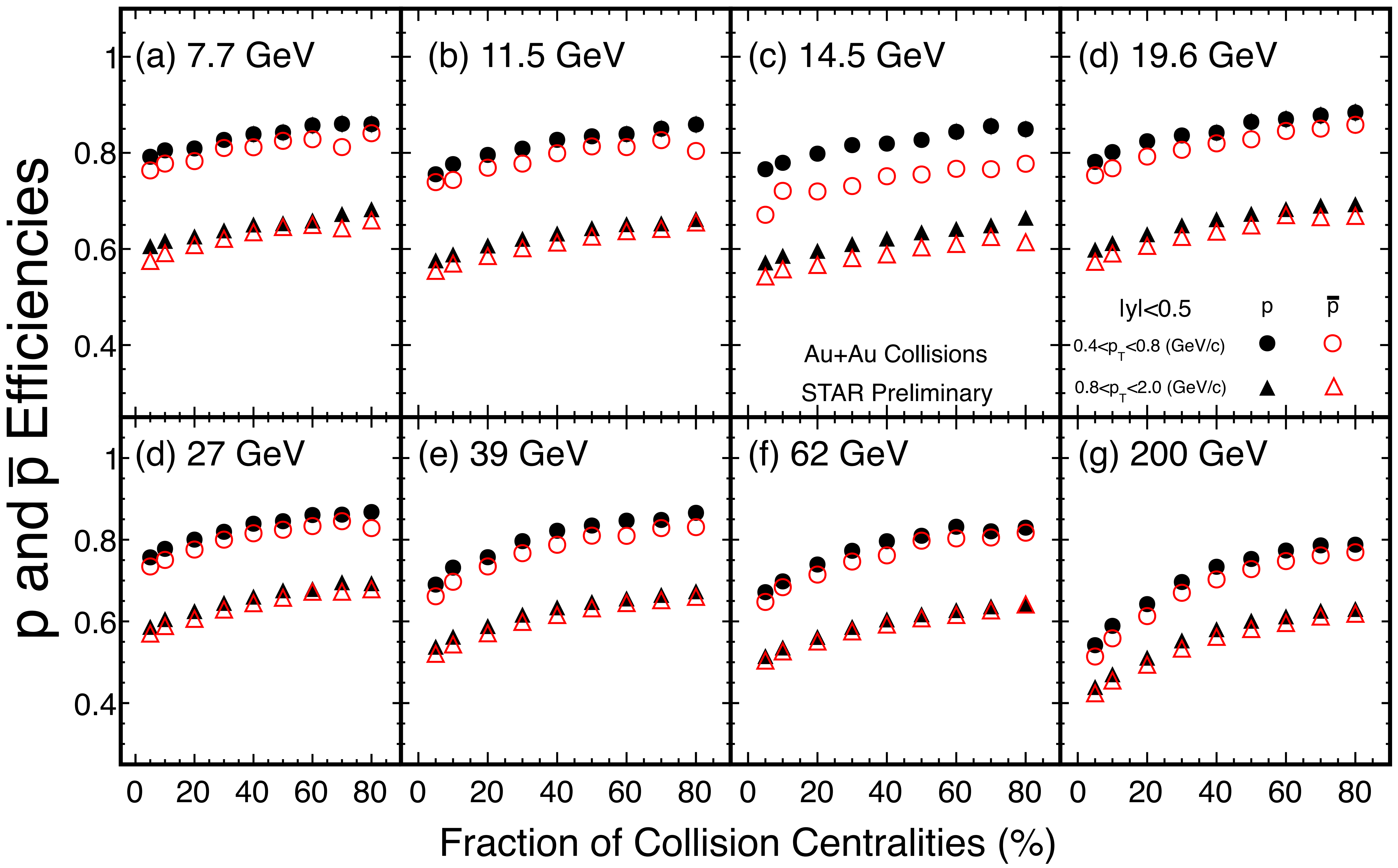
- ✓ **Deviation below Poisson baseline (unity).**
- ✓ **Both 3rd- and 4th-order fluctuations have their minimals at $\sqrt{s_{NN}}$ = 19.6 GeV.**

PRL112, 032302(2014): STAR Collaboration

Extend p_T coverage

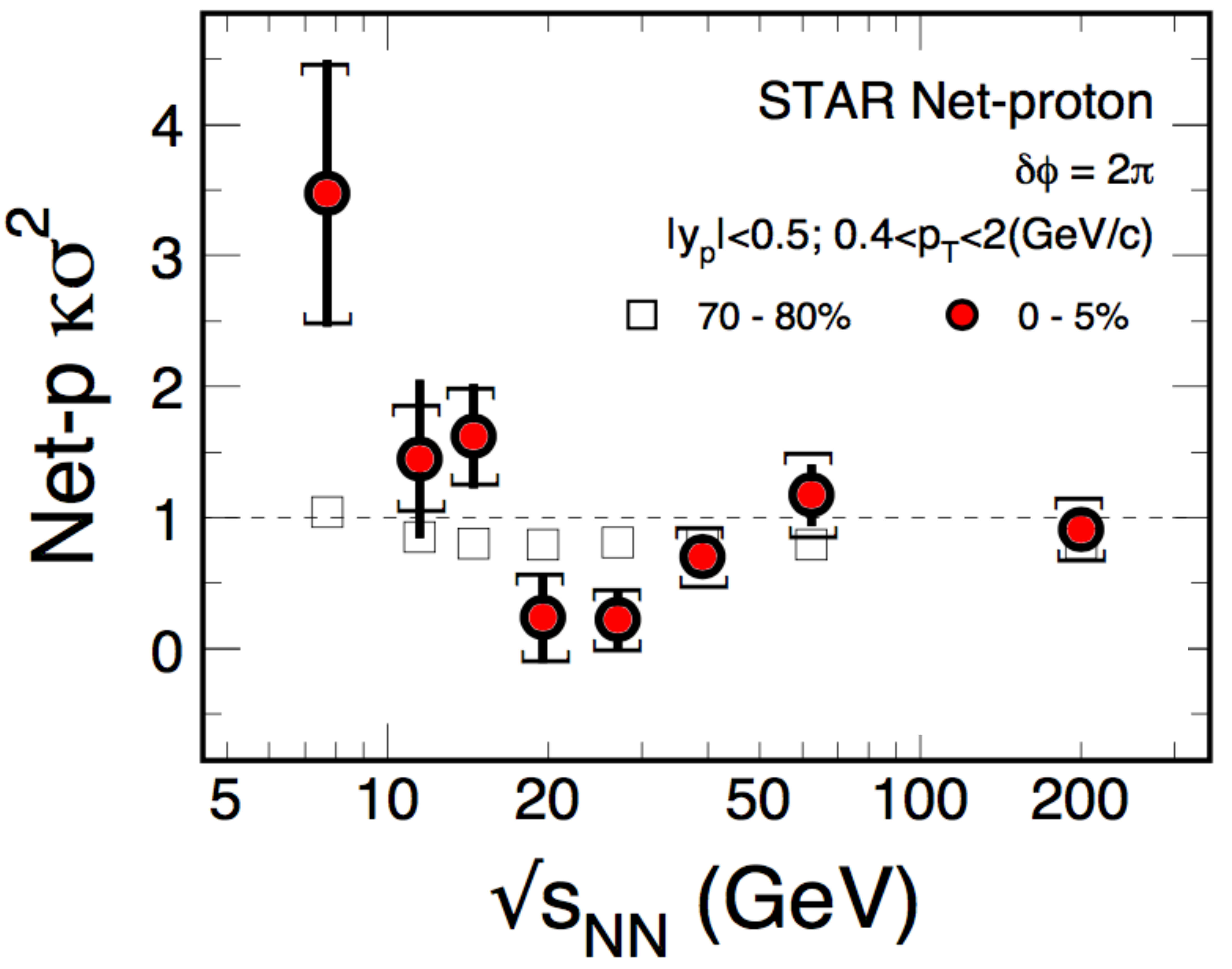
- ✓ p_T region can be extended up to 2.0 GeV by using TOF as well as TPC.
- ✓ We gain factor two (anti)protons with respect to the published results.



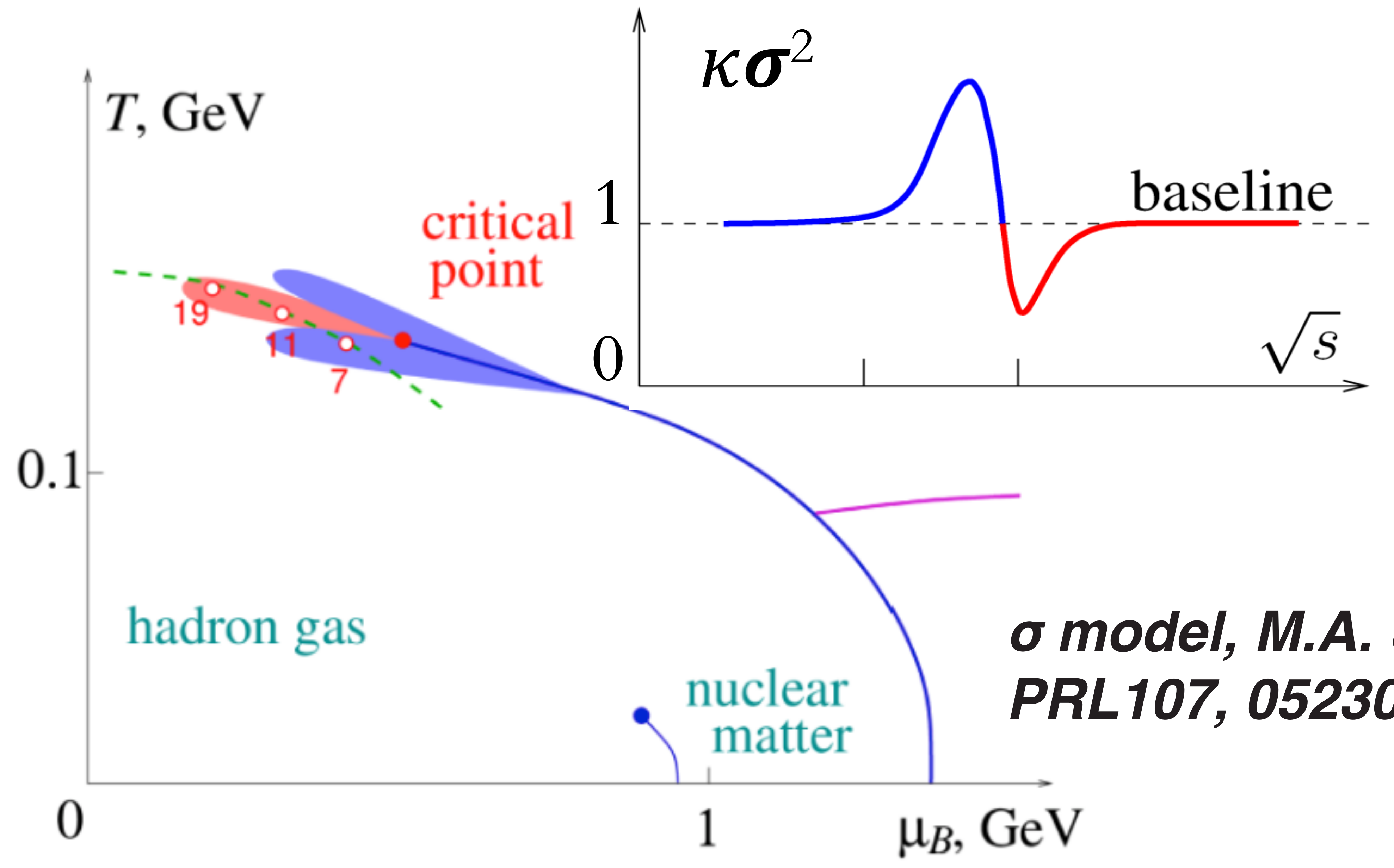


Non-monotonic behavior

PoS CPOD2014 (2015)019 : STAR



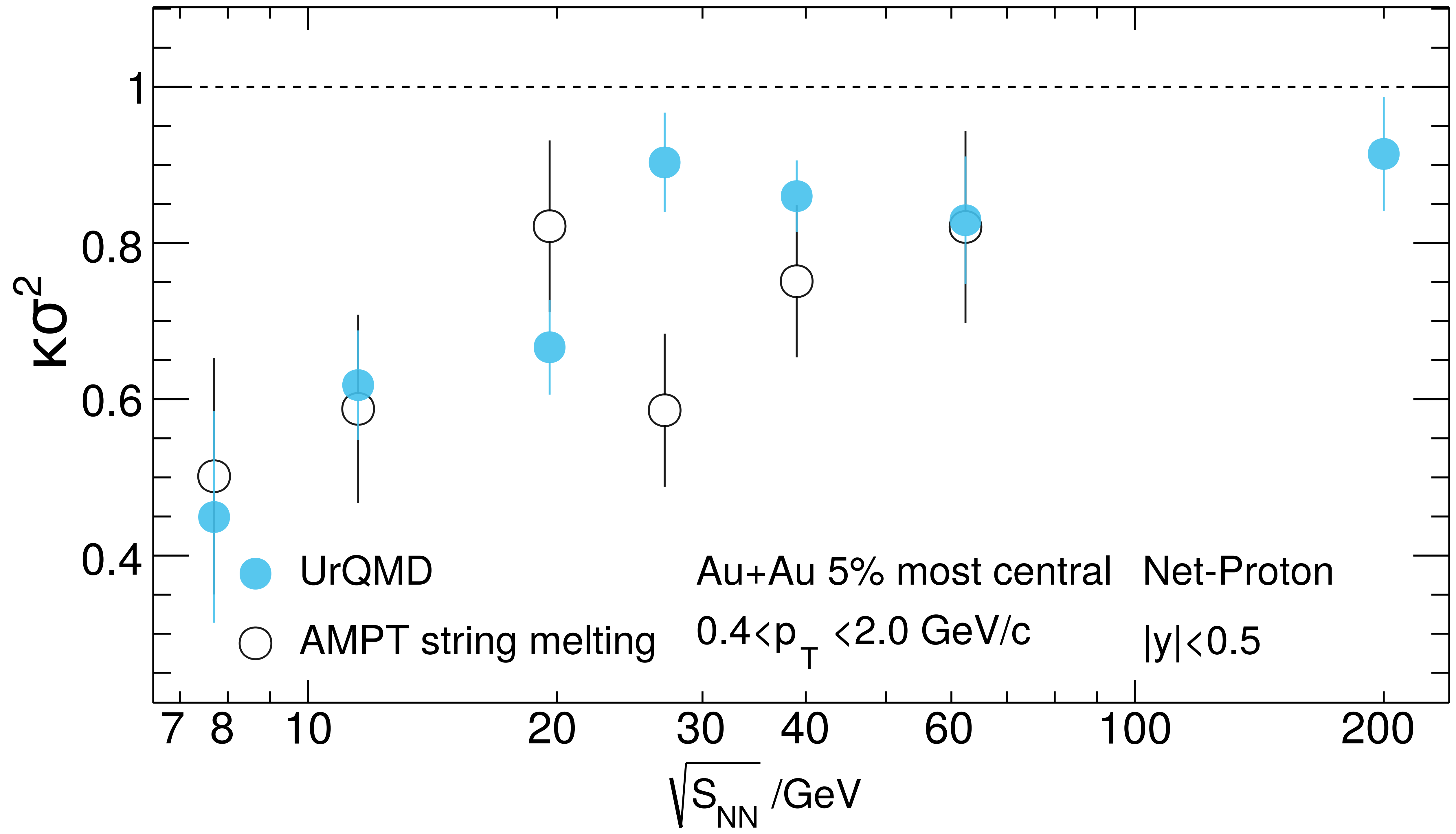
- ✓ $\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the theoretical calculation.
- ✓ Measurement at the lower energy is important.

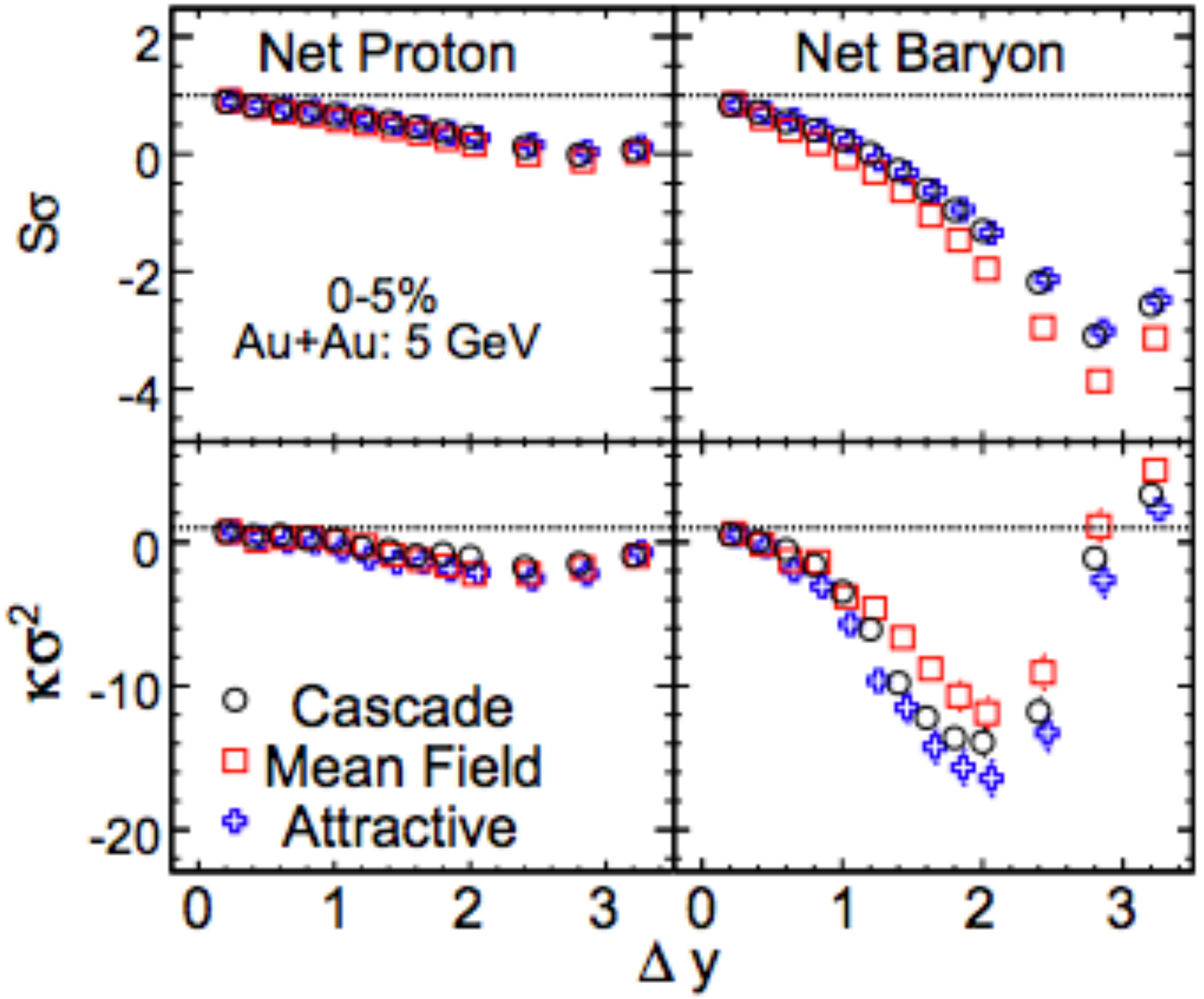


σ model, M.A. Stephanov, PRL107, 052301 (2011)

Non-critical contributions

- ✓ At $\sqrt{s_{NN}}$<10 GeV, data shows $\kappa\sigma^2$>1, while model shows $\kappa\sigma^2$<1
- ✓ No model simulations can explain the enhancement at low beam energies.

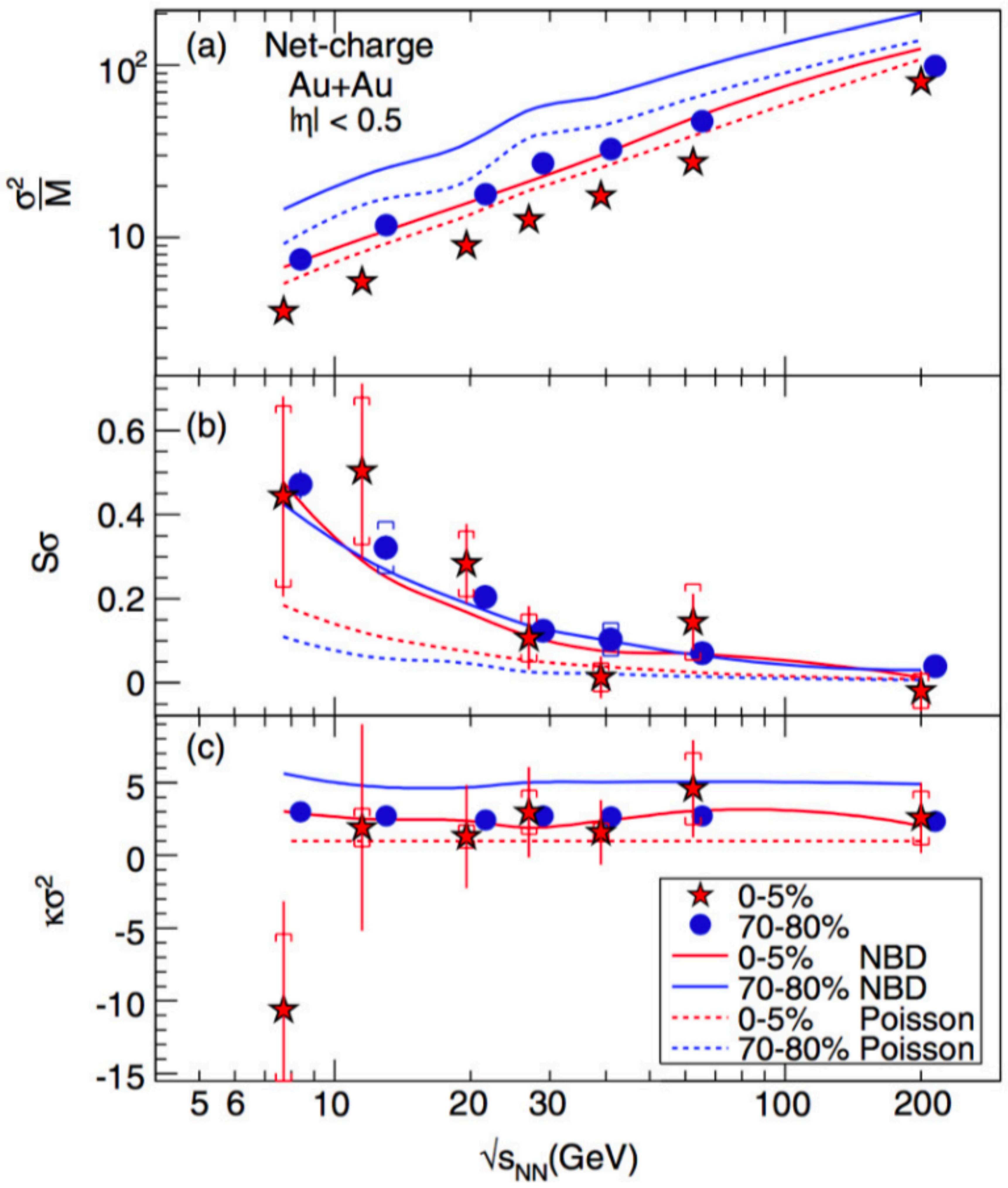




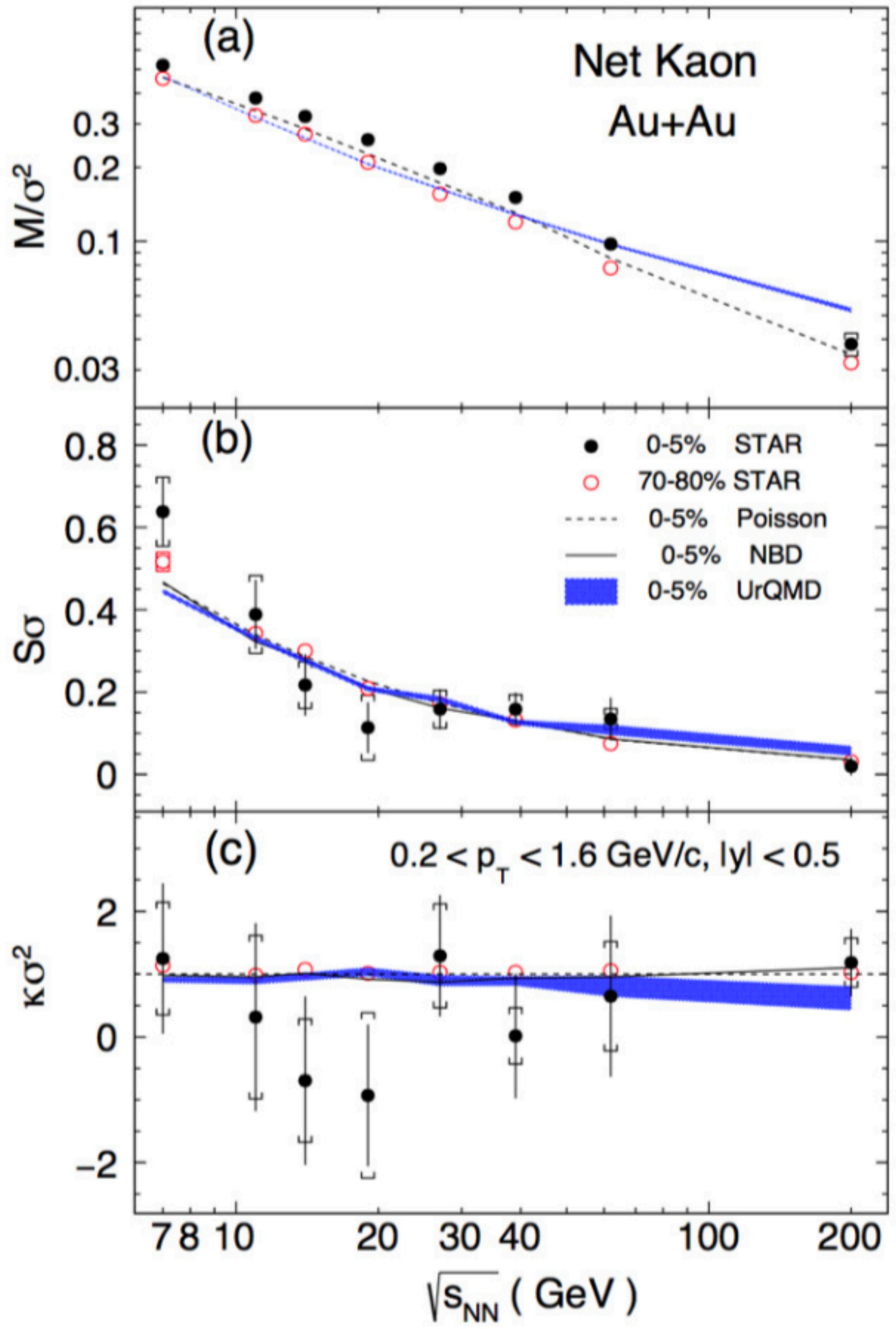
Z. Feckova, et al., PRC92, 064908(2015). J. Xu, et. al., PRC94, 024901(2016). X. Luo et al., NPA931, 808(14), P.K. Netrakanti et al. 1405.4617, NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016). S. He, X. Luo, PLB 774, 623 (2017).

Net charge and net kaon

PRL113, 092301(2014): STAR



PLB, 785, 551(2018): STAR



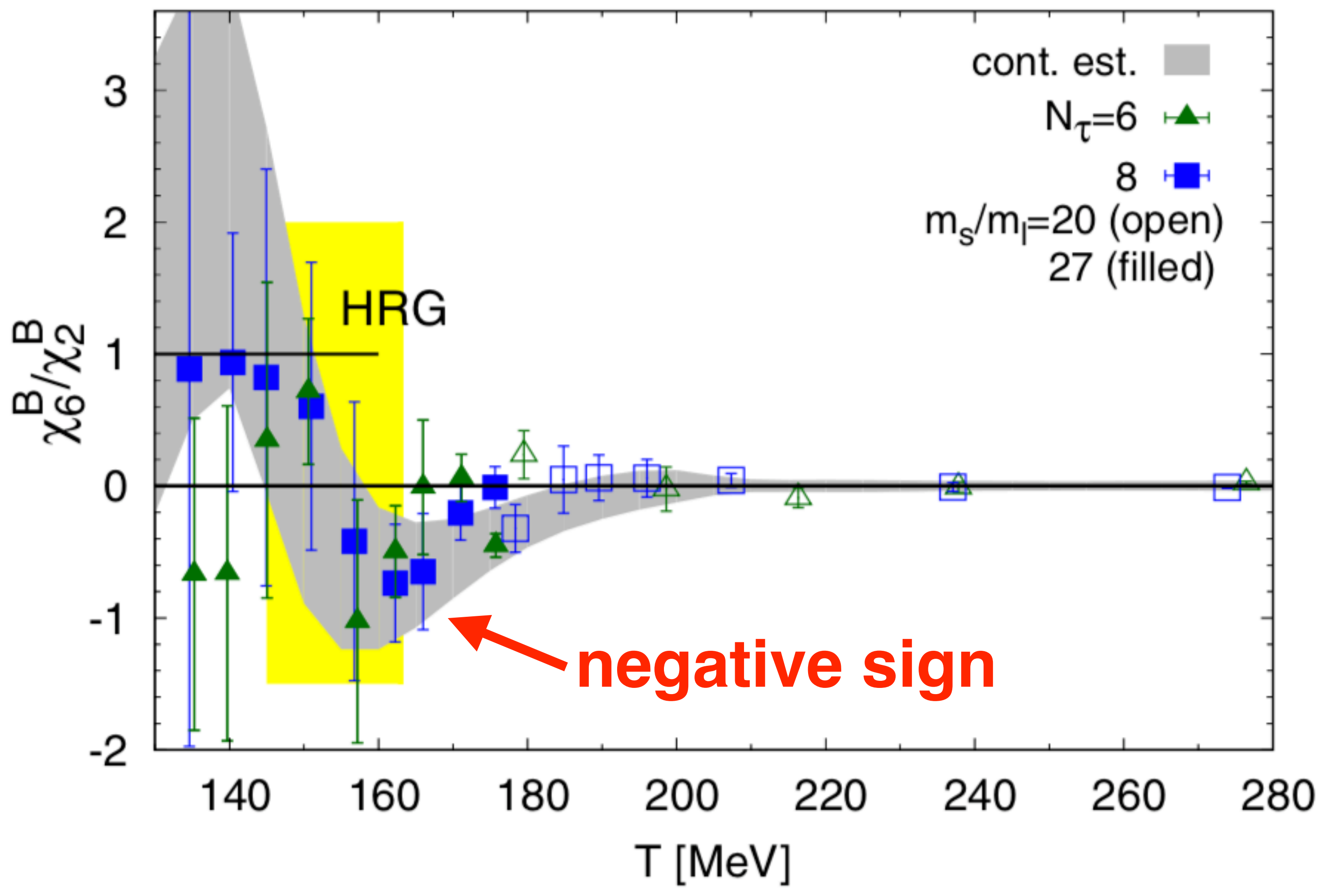
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}\frac{1}{\sqrt{N_{evts}}}$$

✓ **Large statistical uncertainties, need more data.**

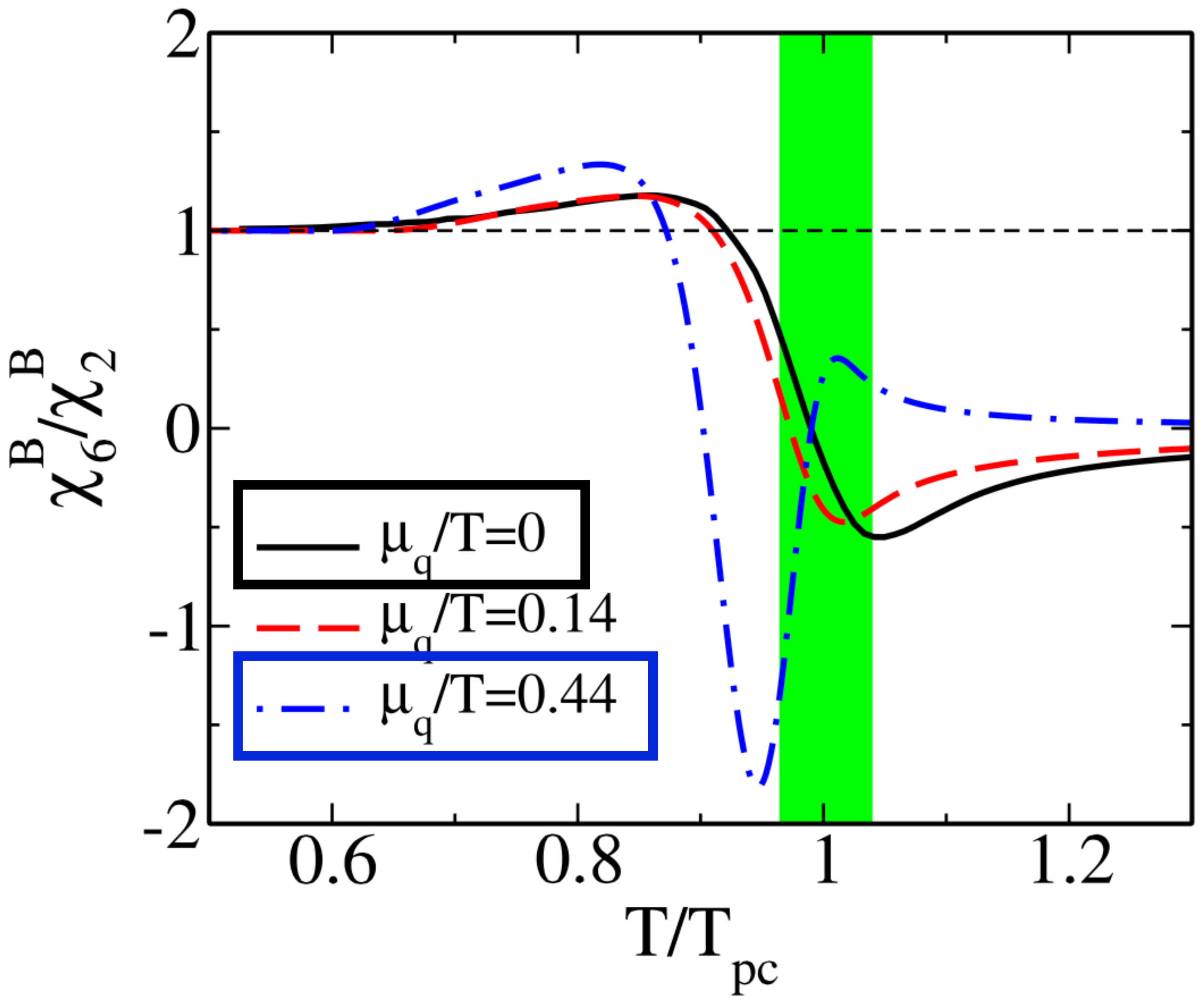
Sixth-order cumulants

- ✓ There isn't yet any experimental evidence for the smooth crossover at μ_B~0 MeV.
- ✓ Sixth-order cumulants of net-charge and net-baryon distributions are predicted to be negative if the chemical freeze-out is close enough to the phase transition, which is the characteristic signal for $\sqrt{s_{NN}}$>60 GeV.

A. Bazavov et al, PhysRevD. 95.054504 : LQCD



Friman et al, Eur. Phys. J. C (2011) 71:1694 : PQM model



Positive sign is predicted in $\sqrt{s_{NN}}$<60 GeV

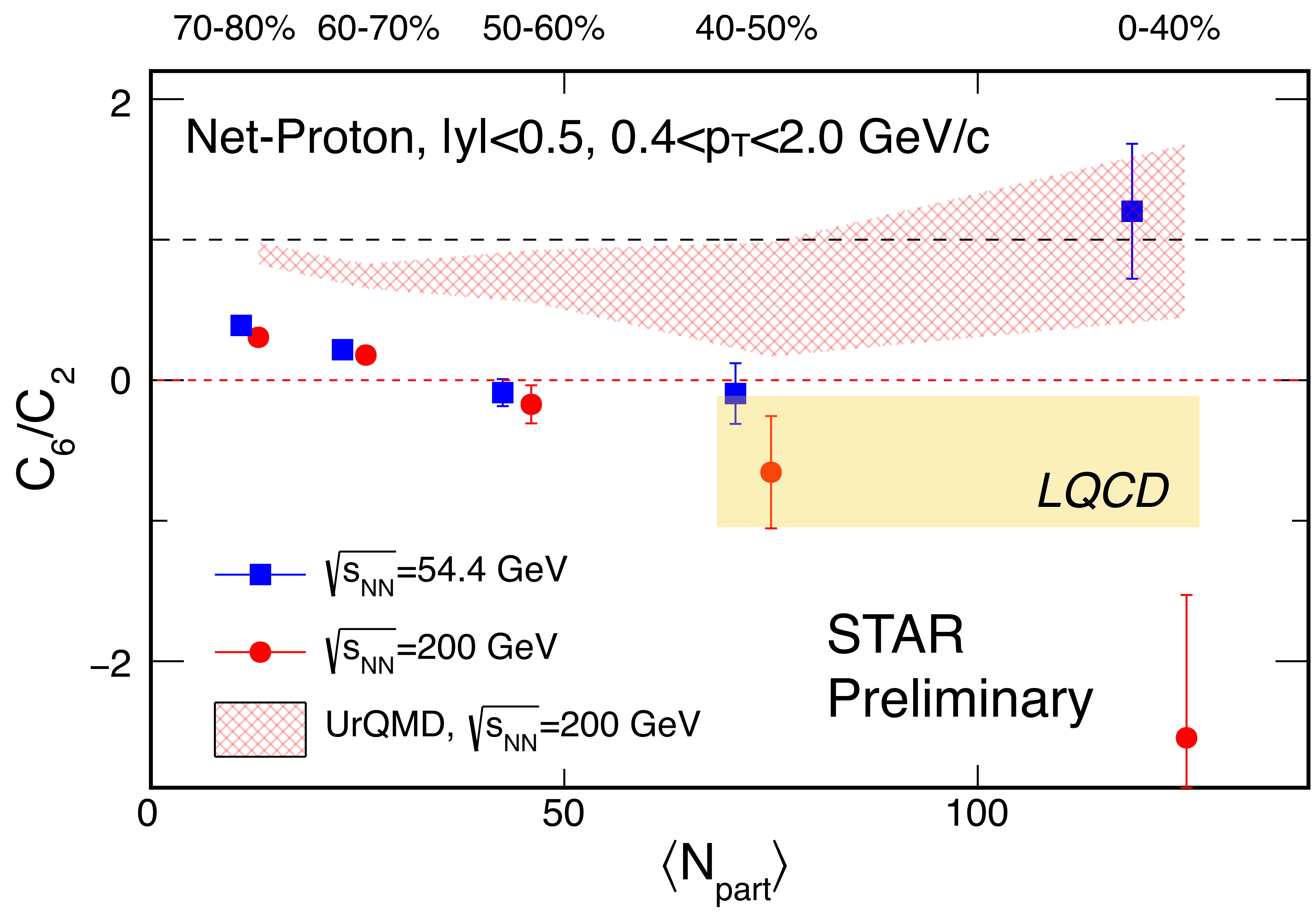
C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

Predicted scenario for this measurement

Sixth-order cumulants

- ✓ Clear separation and opposite signs between two energies in 0-40%.
- ✓ UrQMD cannot describe the experimental data at $\sqrt{s_{NN}}$ = 200 GeV.
- ✓ 200 GeV results are consistent with LQCD results.



LQCD : A. Bazavov et al, PhysRevD.95.054504

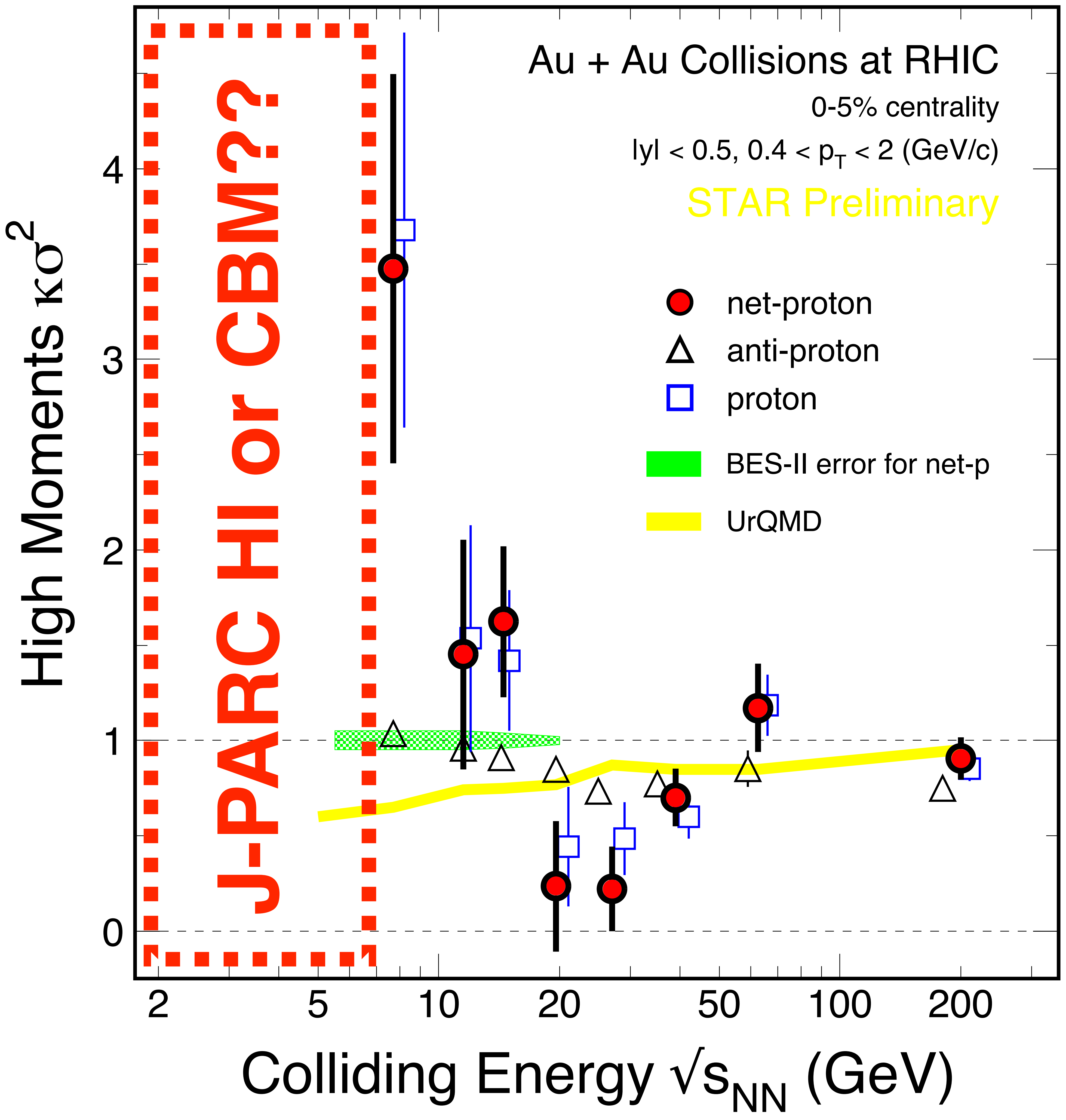
Beam Energy Scan Phase II

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES-II / BES-I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	**1200**	**2017**			
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-21** / 2011	**3**	206	160
14.5	**300** / 20	**2019-21** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-21** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-21** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-21** / 2010	**14**	420	140

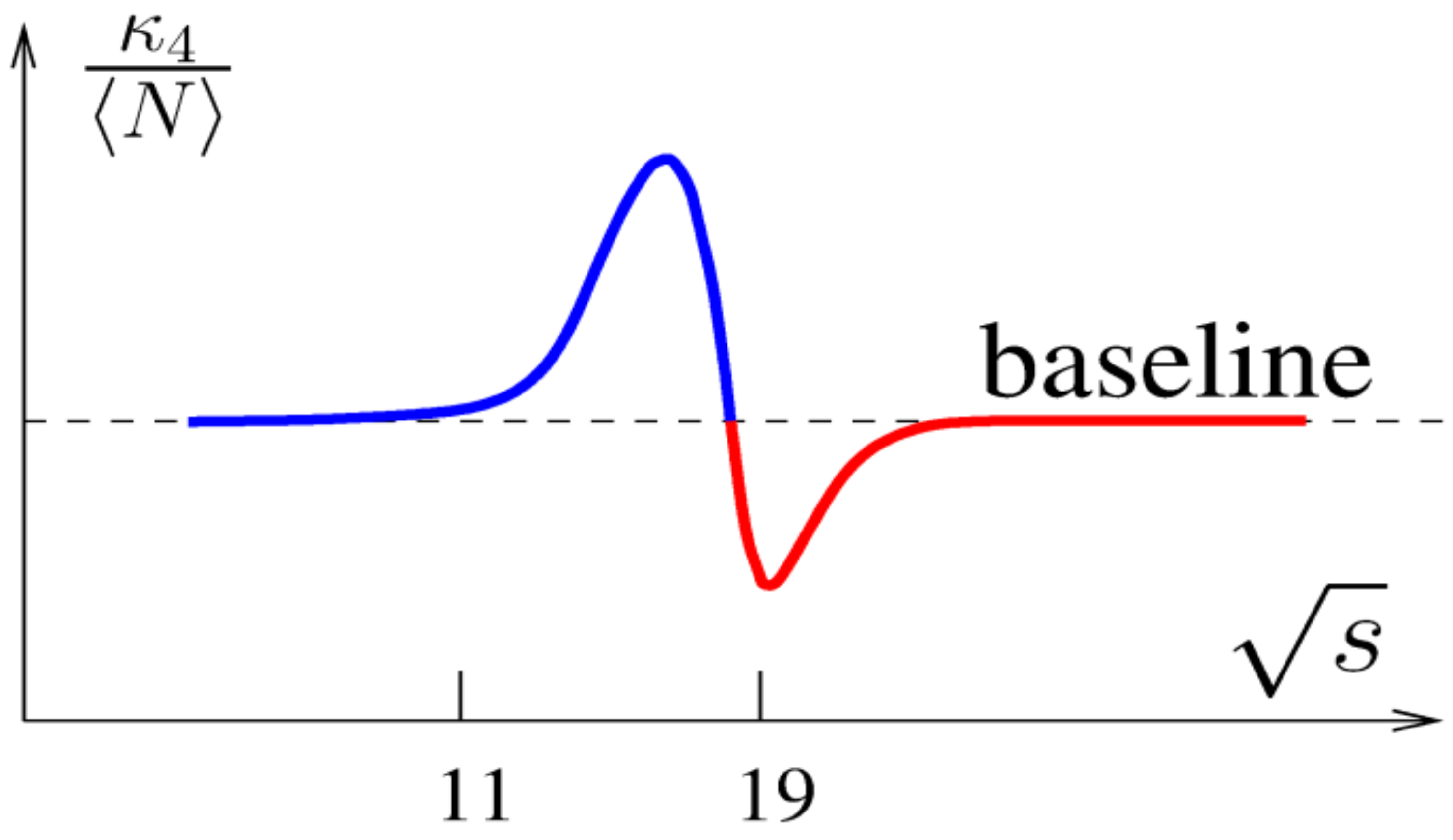
- ✓ **BES-II will start this winter.**
- ✓ **Luminosity will be improved with electron cooling system.**
- ✓ **Some detector upgrades will be done by BES-II. Pseudorapidity coverage will be extended from 1.0 to 1.5.**
- ✓ **Higher-order fluctuation measurement with small errors and large acceptance.**

Critical point search in BES-II

STAR Data : PoS CPOD2014 (2015)019



- ✓ **Statistical uncertainties will be dramatically reduced.**
- ✓ **Can we measure a possible "peak" structure?**



Summary

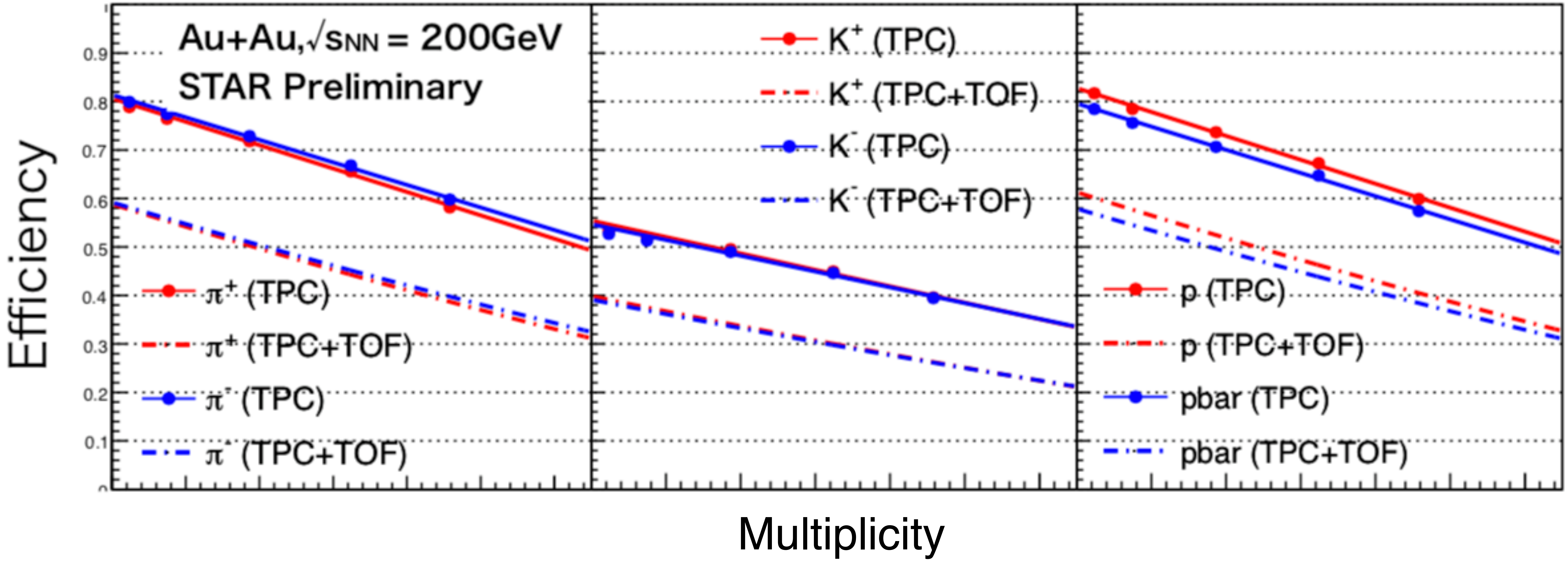
- Freeze-out conditions have been determined in terms of chemical/kinetic freeze-out in various collision energies.
- Searching for the softest point as a signal from the 1^{st}-order phase transition, by measuring v_1 slope in various collision energies.
- Non-monotonic behavior has been observed for net-proton $\kappa\sigma^2$ in the central Au+Au collisions as a function fo collision energy, which is qualitatively similar to the theoretical prediction.
- Enhancement at low beam energies cannot be explained by non-critical contributions in model simulations.
- BES-II will shrink the statistical uncertainties at 7.7—19.6 GeV region.

Thank you for your attention

Back up

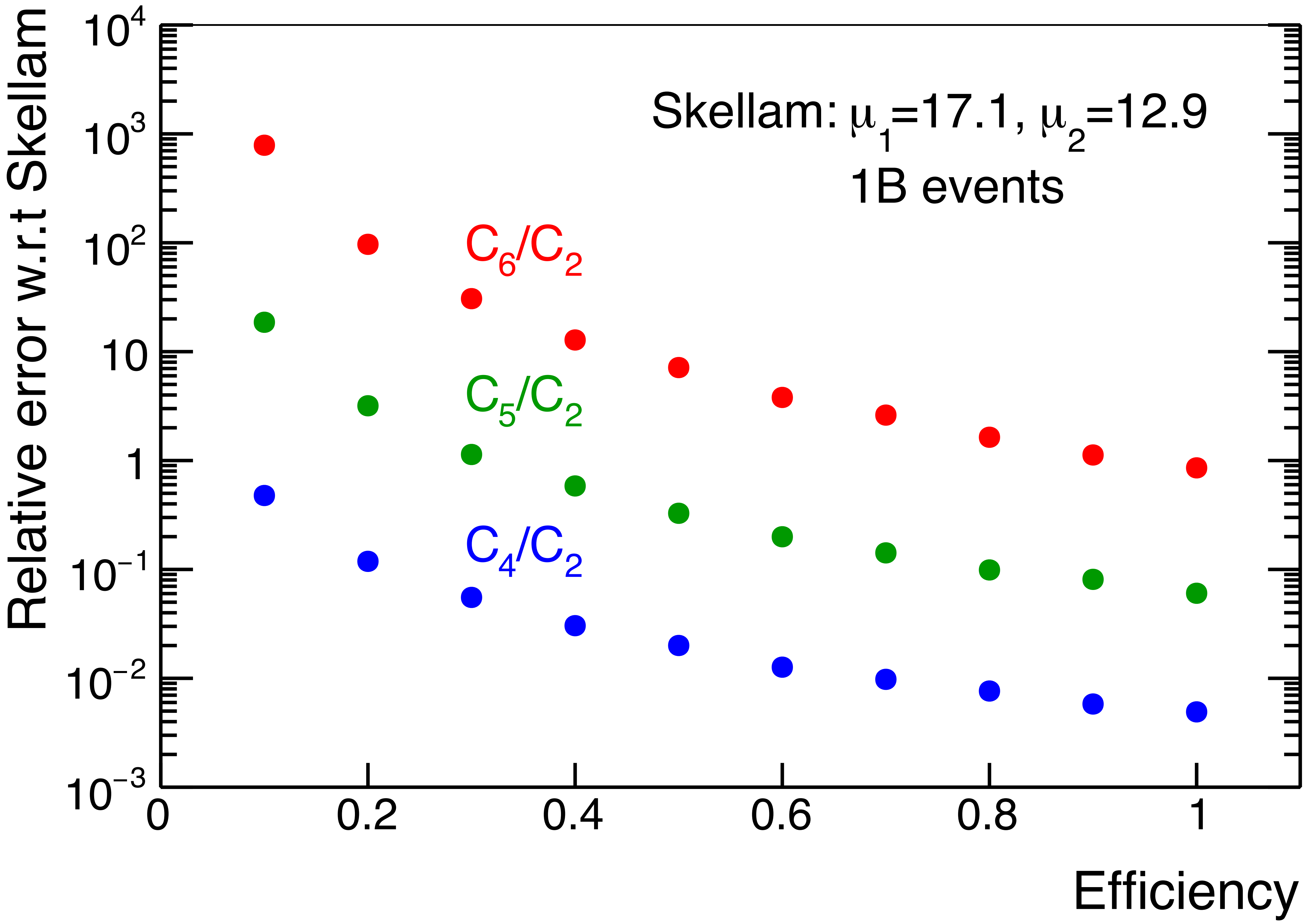
Efficiency

- ✓ **Single-particle tracking efficiencies for π/K/p have been estimated by embedding simulation.**
- ✓ **TOF matching efficiency is obtained from the real data.**



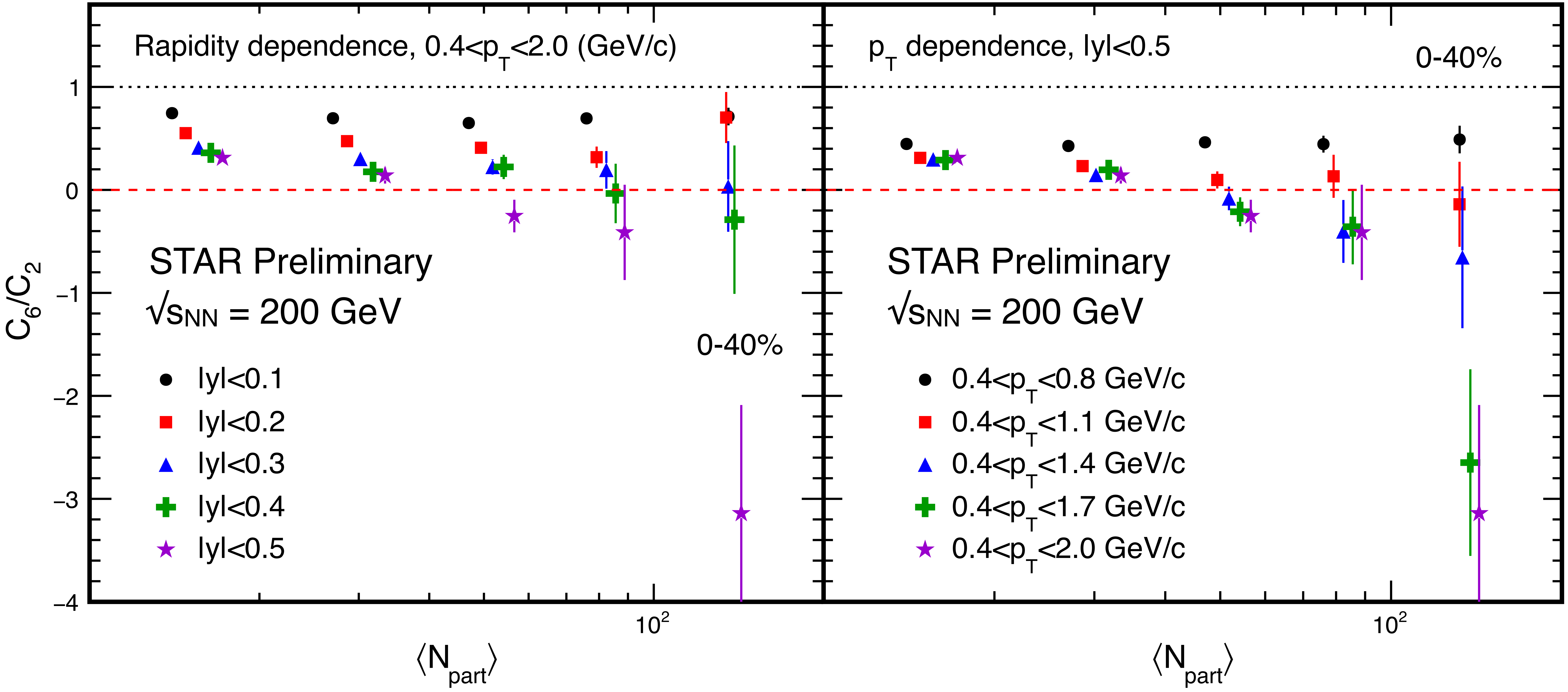
Statistical errors

- ✓ One order of cumulant increases, statistical errors becomes x10. ($C_4 \rightarrow C_6$: x100 err)
- ✓ Strongly depends on the efficiency. (60%→50% makes the error double)
- ✓ Smaller error bars at lower beam energies.



Acceptance dependence

- ✓ Monotonic decrease with enlarging the acceptance.
- ✓ p_T dependence seems to be saturated in $0.4<p_T<1.7$ GeV/c.

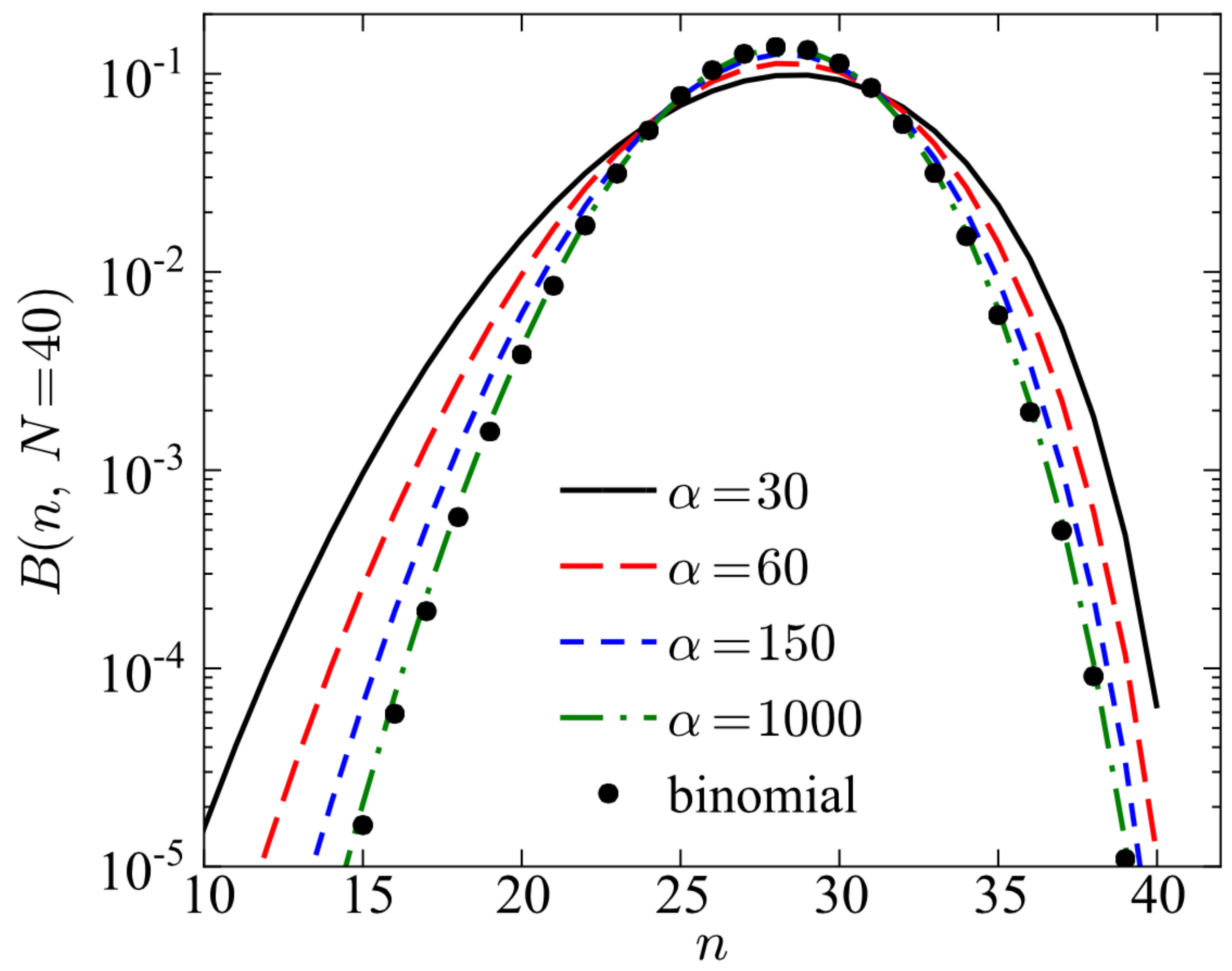


Non-binomial efficiencies

A. Bzdak, R. Holzmann, V. Koch : PRC.94.064907

1. Experimental effects

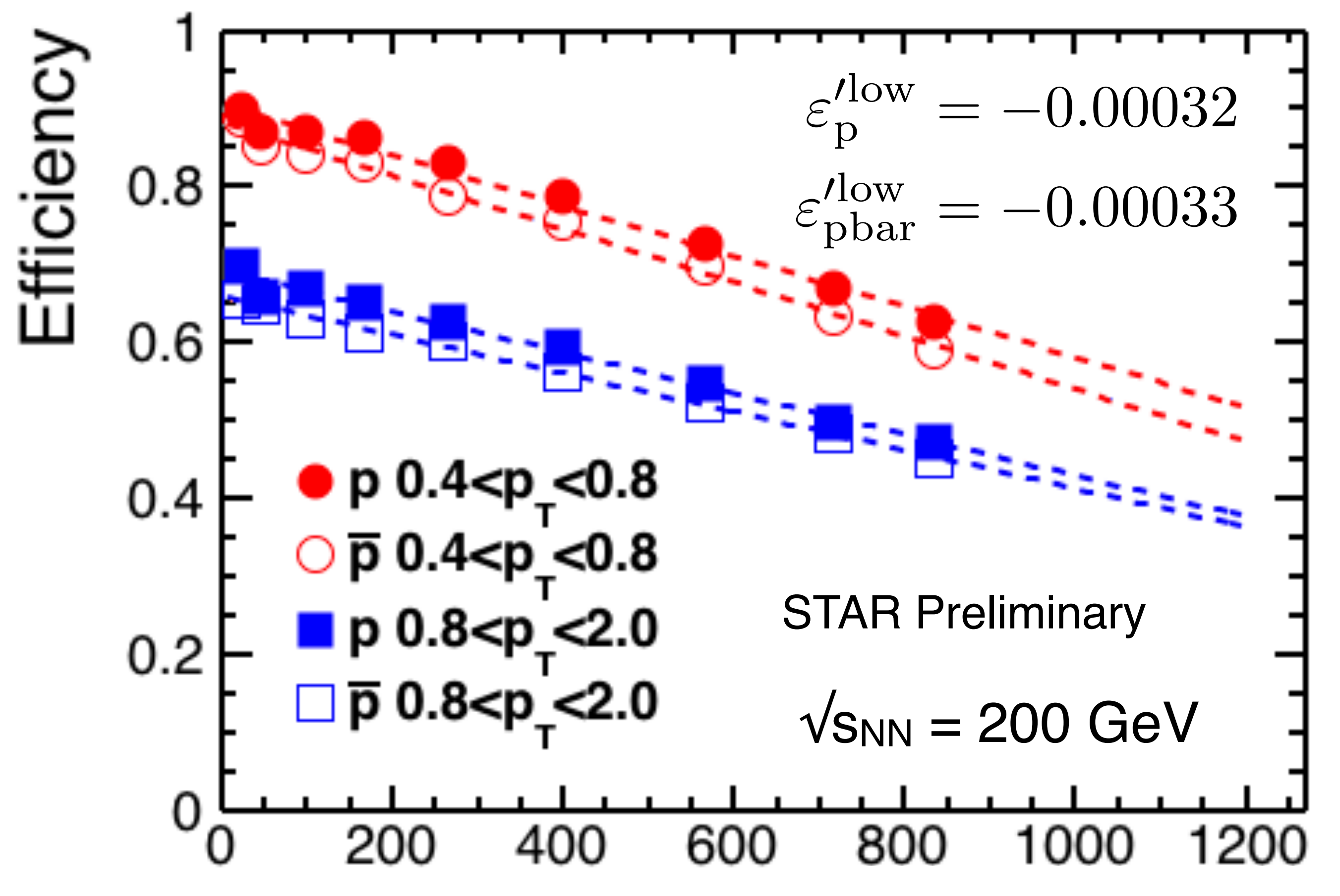
✓ **The detector efficiency may not be binomial, which would be due to the particle mis-identification, track splitting/merging effects, and many other reasons.**



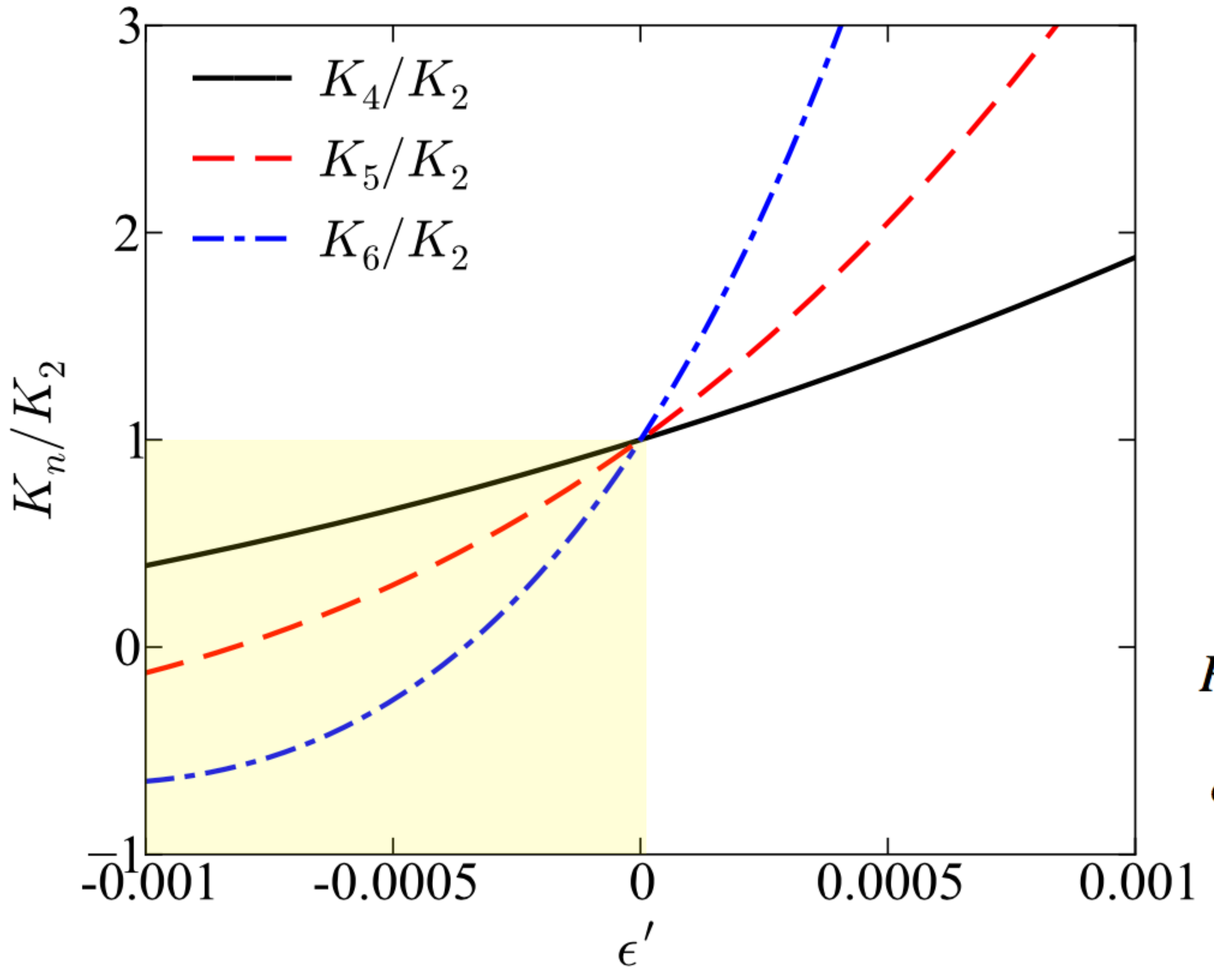
➡ *One example of non-binomial distribution, Beta-binomial, is wider distribution than binomial*

2. Multiplicity dependent efficiency

✓ **Residual dependence of efficiency inside one multiplicity bin (for centrality) needs to be taken into account.**



T. Nonaka, WPCF2017



A. Bzdak, R. Holzmann, V. Koch : PRC.94.064907

$$P(N) = \frac{\langle N\rangle^N}{N!}e^{-\langle N\rangle},$$

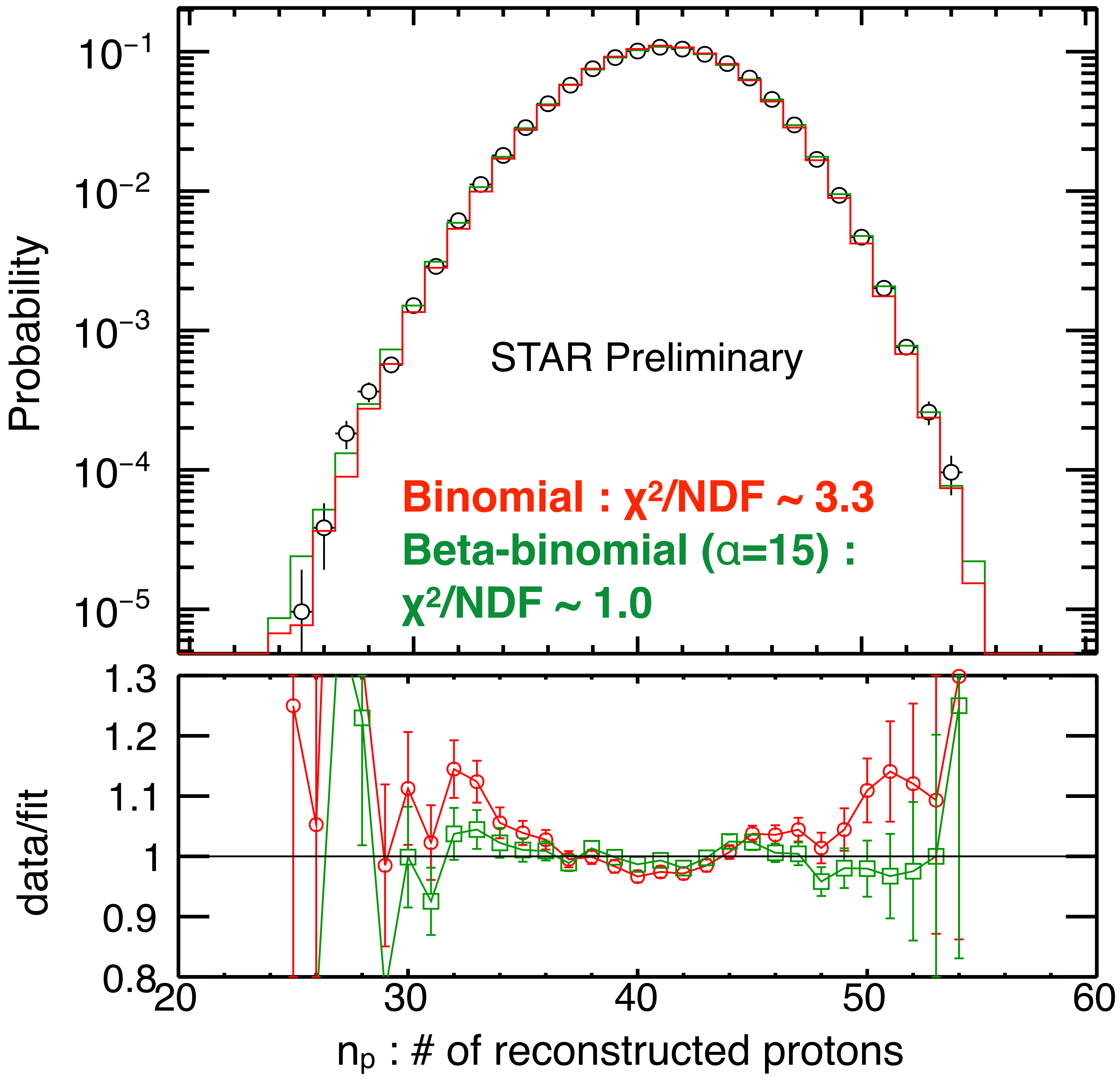
$$\epsilon(N) = \epsilon_0 + \epsilon'(N - \langle N\rangle),$$

Unfolding

- ✓ **We performed MC simulations by embedding protons and antiprotons, e.g., N_p=60 and N_{pbar}=15 (which would be an extreme number), and see whether those particles can be reconstructed or not.**
- ✓ **The response matrix is close to the beta-binomial distribution, which is wider than binomial.**
  - ➡ "Urn model" for beta-binomial distribution, where the parameter α controls the deviation from binomial.

> N_w : white balls, N_b: black balls, ε: efficiency
>
> $N_w = \alpha N_p \quad \varepsilon = N_w/(N_w + N_b)$

$\mathcal{R}(n_p; N_p, N_{pbar})$ $\sqrt{s_{NN}}$ = 19.6 GeV, 0-2.5% centrality



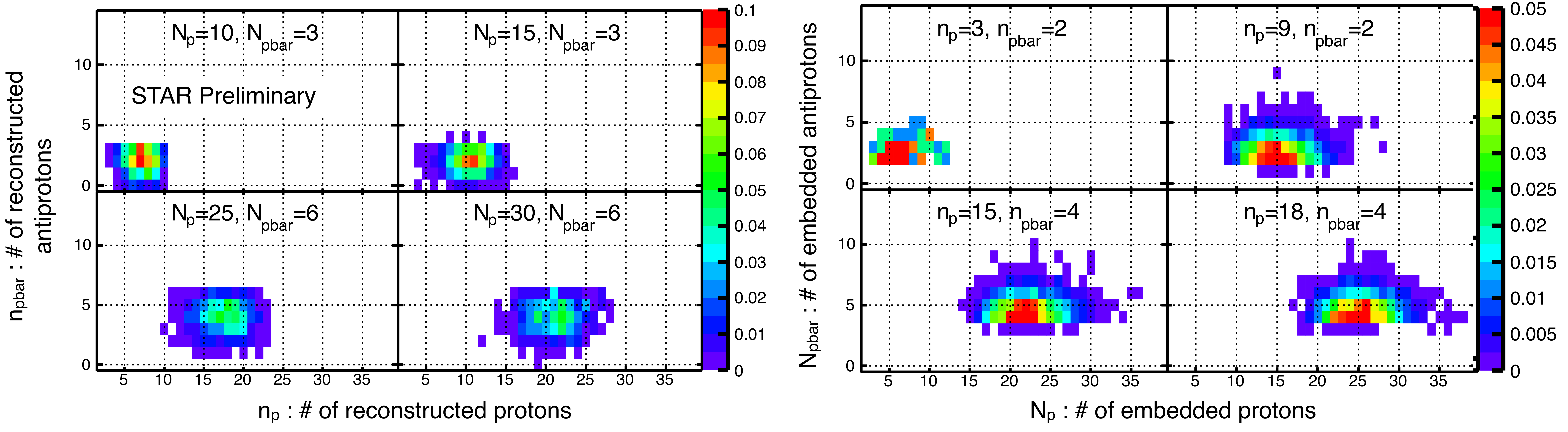
Response matrices

✓ **The deviation from binomial would depend on the # of embedded protons and antiprotons.**

✓ **4-D response matrices are determined by embedding simulation, which can be directly used for unfolding in order to reconstruct the distribution itself.**

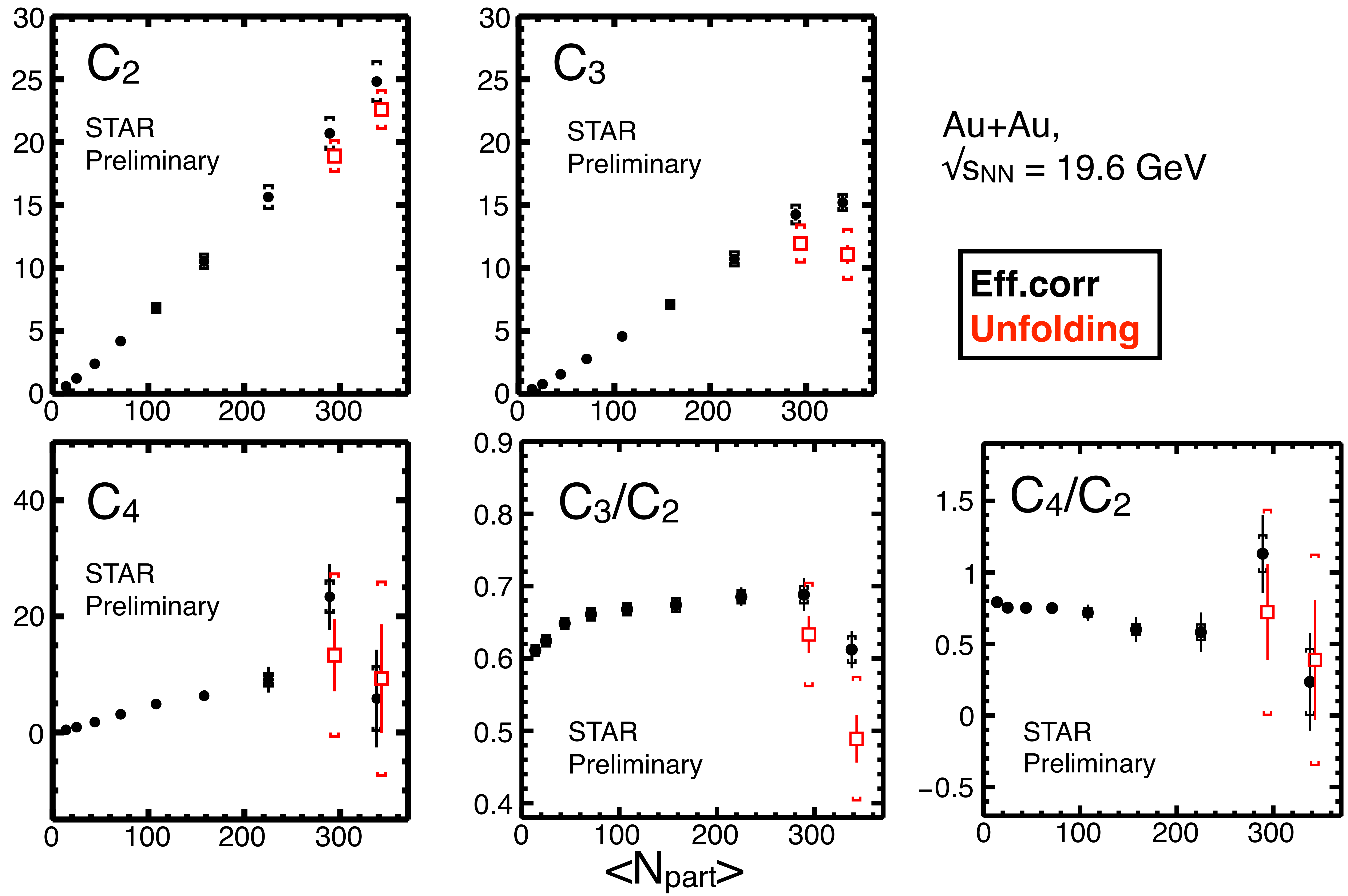
$\mathcal{R}(n_p, n_{pbar}; N_p, N_{pbar})$ **Forward response matrix**

$\mathcal{R}(N_p, N_{pbar}; n_p, n_{pbar})$ **Reversed response matrix**



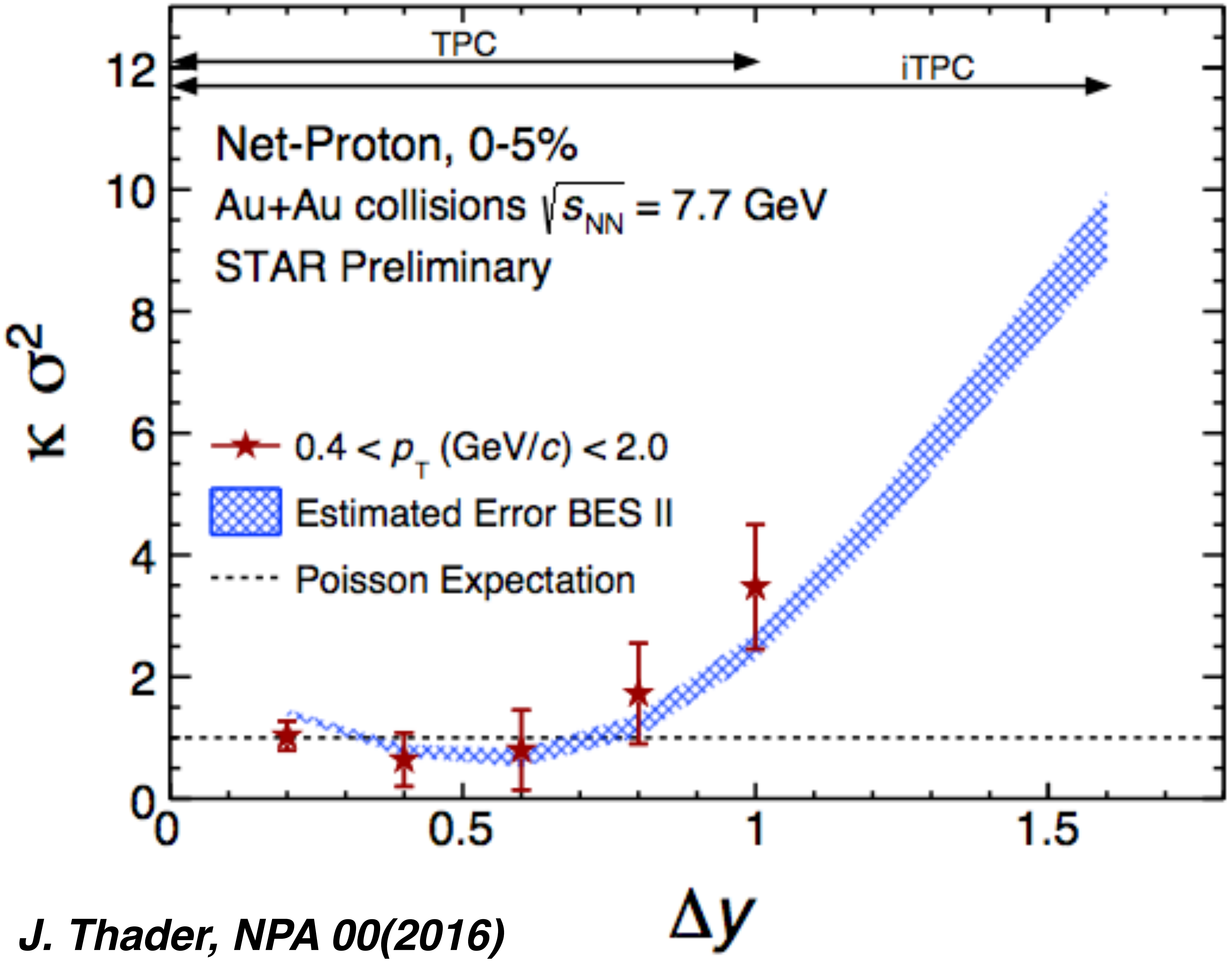
$\sqrt{s_{NN}}$ = 19.6 GeV, 0-5% centrality, |y|<0.5,
0.4 < p_T < 2.0, embedding simulation

Unfolding



- ✓ **For unfolding, 2.5% centrality width averaging has been done.**
- ✓ **Systematic suppression is observed for C_2 and C_3 with respect to the results of efficiency correction assuming binomial efficiencies.**
- ✓ **C_4, C_3/C_2 and C_4/C_2 are consistent within large systematic uncertainties limited by embedding samples.**

Beam Energy Scan Phase II



J. Thader, NPA 00(2016)

- ✓BES-II will start this winter.
- ✓Luminosity will be improved with electron cooling system.
- ✓Some detector upgrades will be done by BES-II. Pseudorapidity coverage will be extended from 1.0 to 1.5.
- ✓Higher-order fluctuation measurement with small errors and large acceptance.