Studying the QCD Phase Diagram in RHIC-BES at STAR

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Outline

✓ **Introduction**

- Beam Energy Scan
- The STAR detector

✓ **Experimental results**

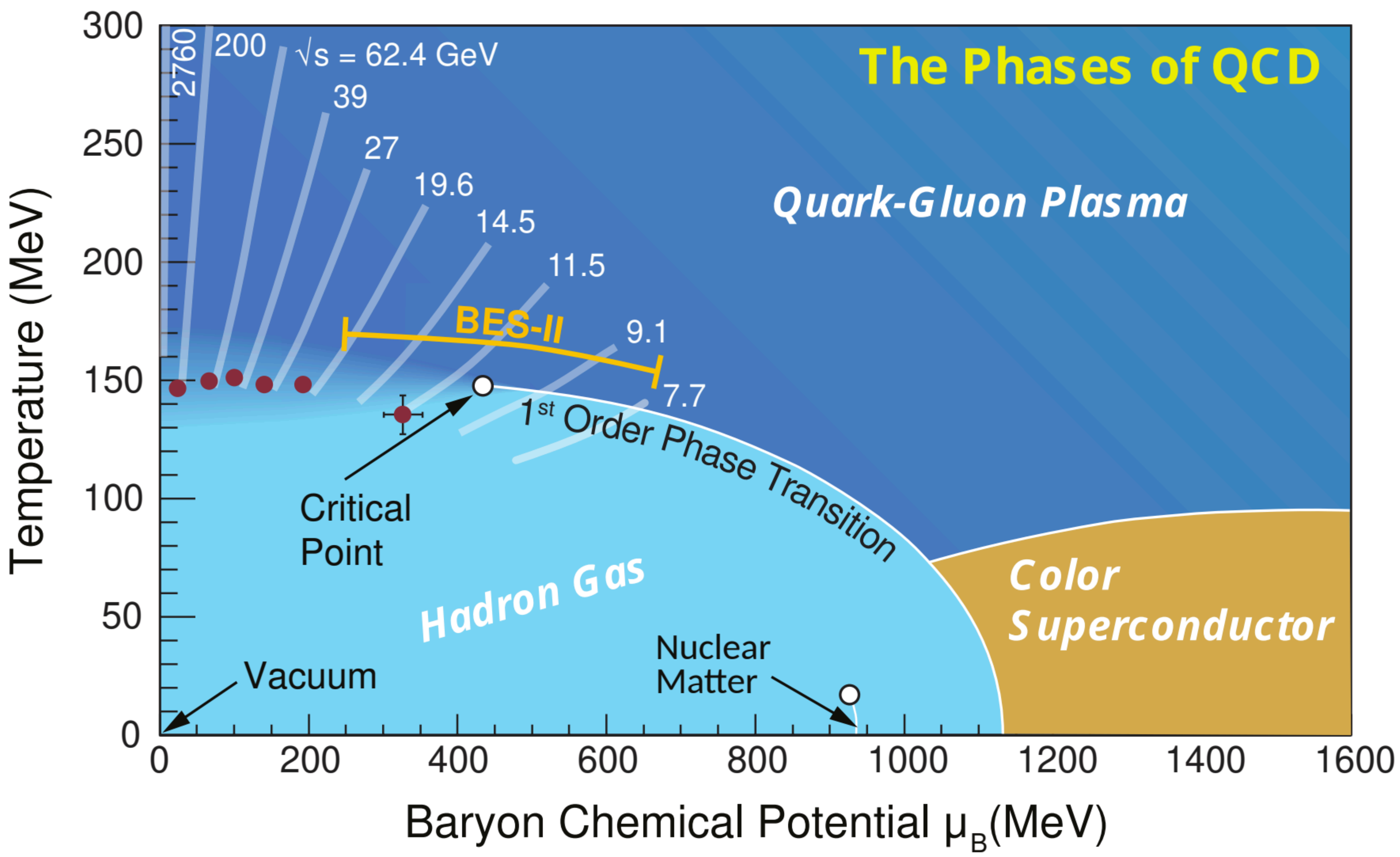
- Freeze-out conditions
- The 1st-order phase transition
- **Critical point**
  - **Higher-order fluctuations**
  - Light nuclei production
- Crossover

✓ **BES-II**

✓ **Summary**

QCD phase diagram

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



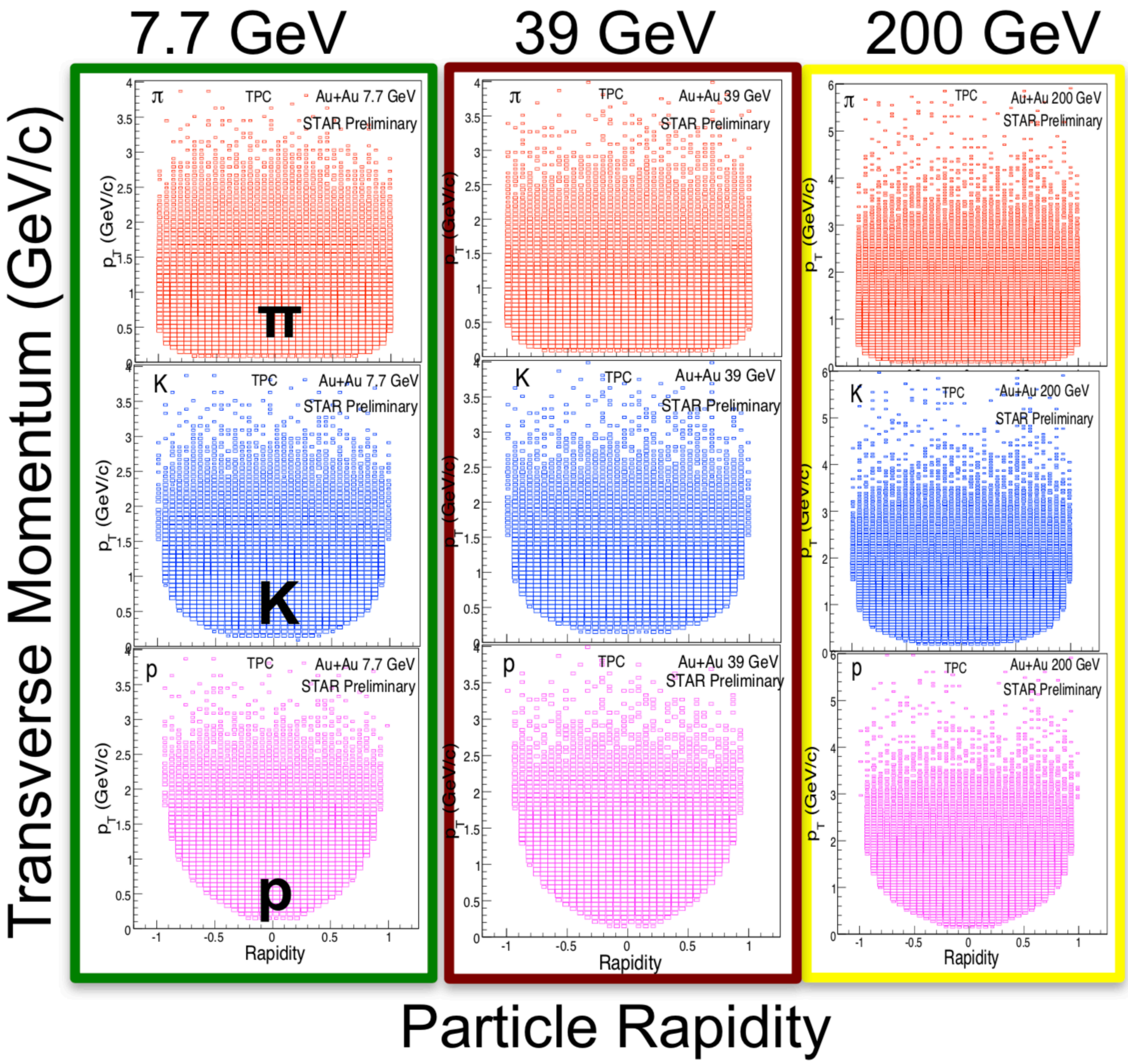
A. Bzdak et al, 1906.00936

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

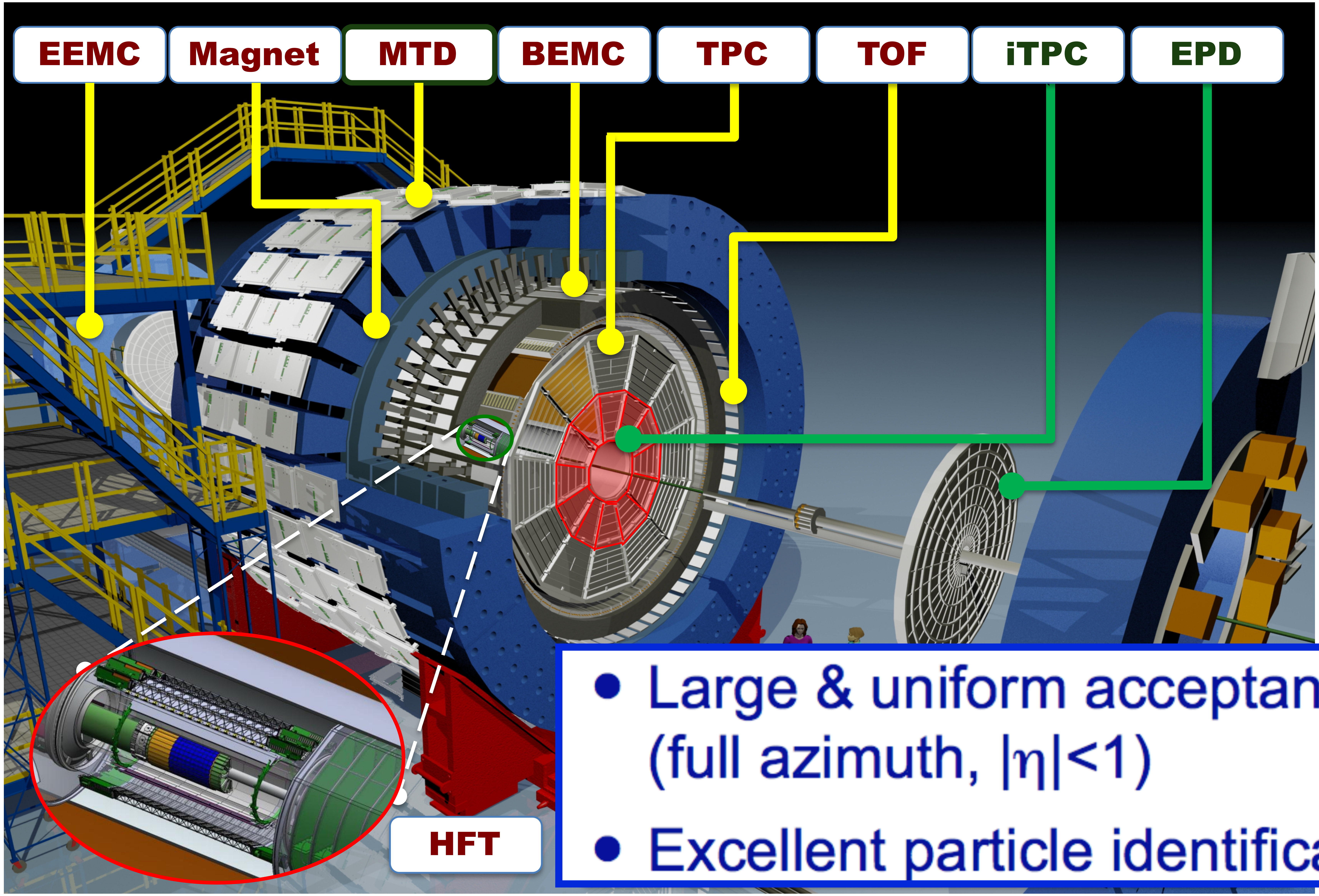
Beam Energy Scan

- ✓ **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



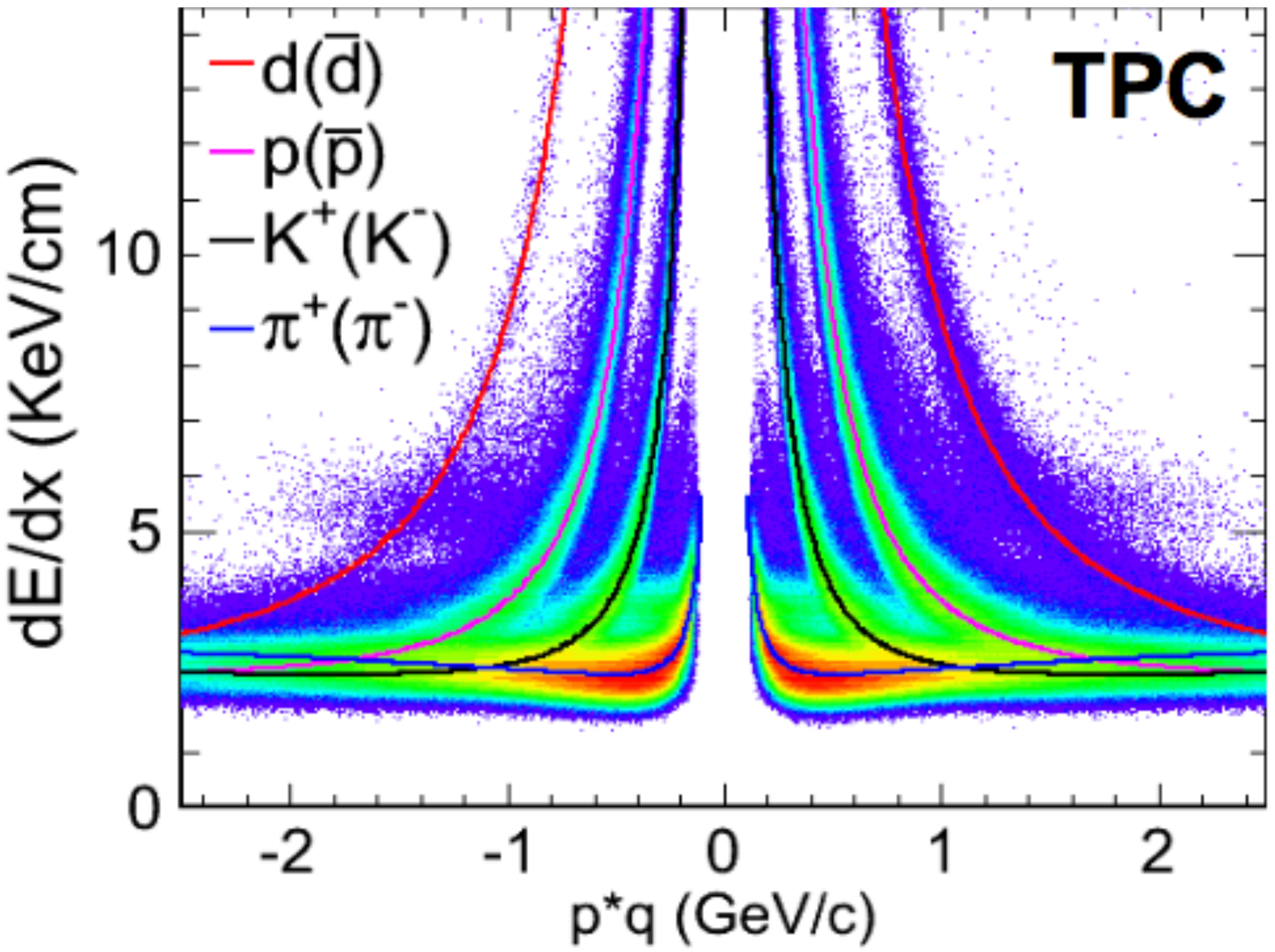
The STAR detector

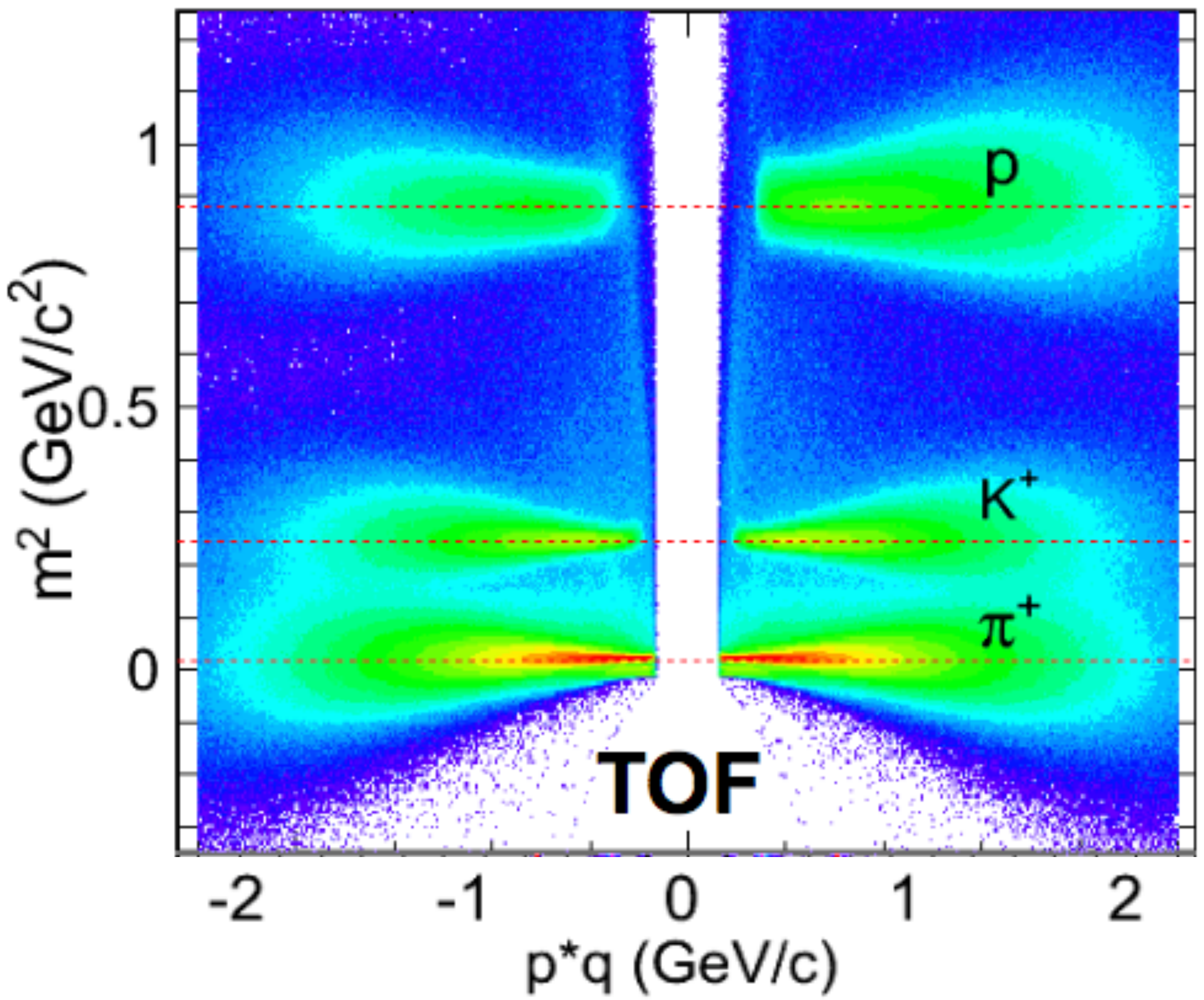


- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

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.

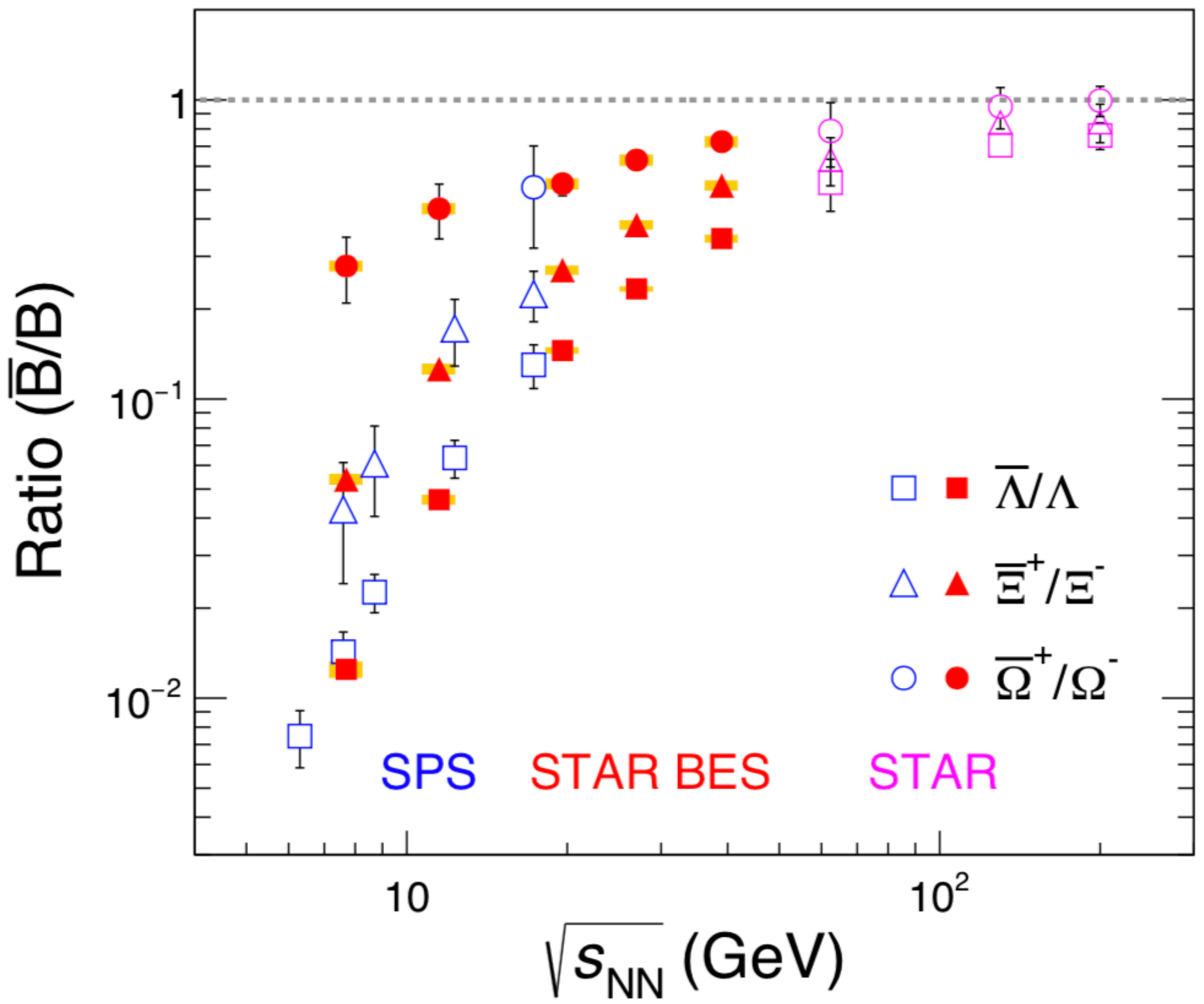


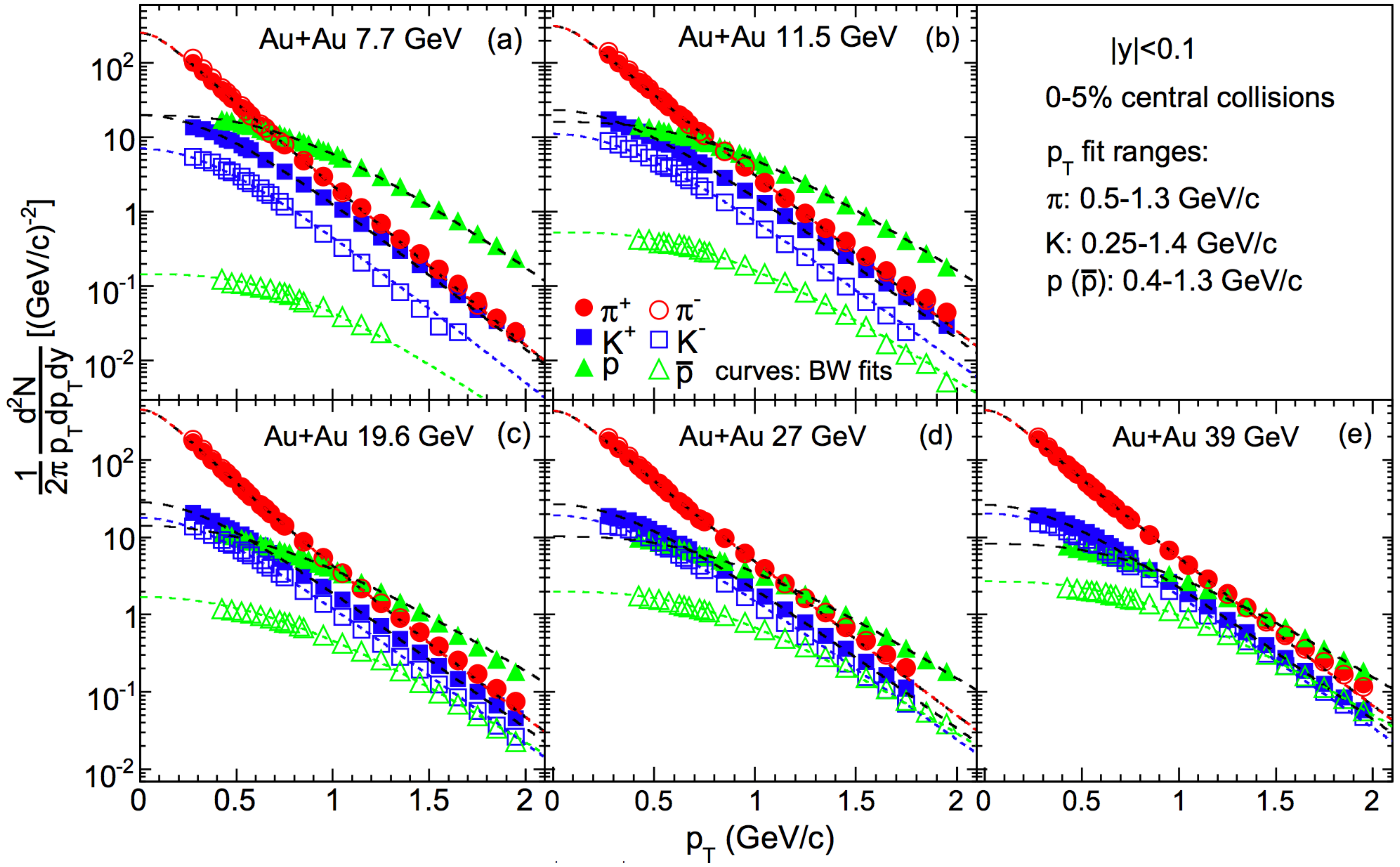


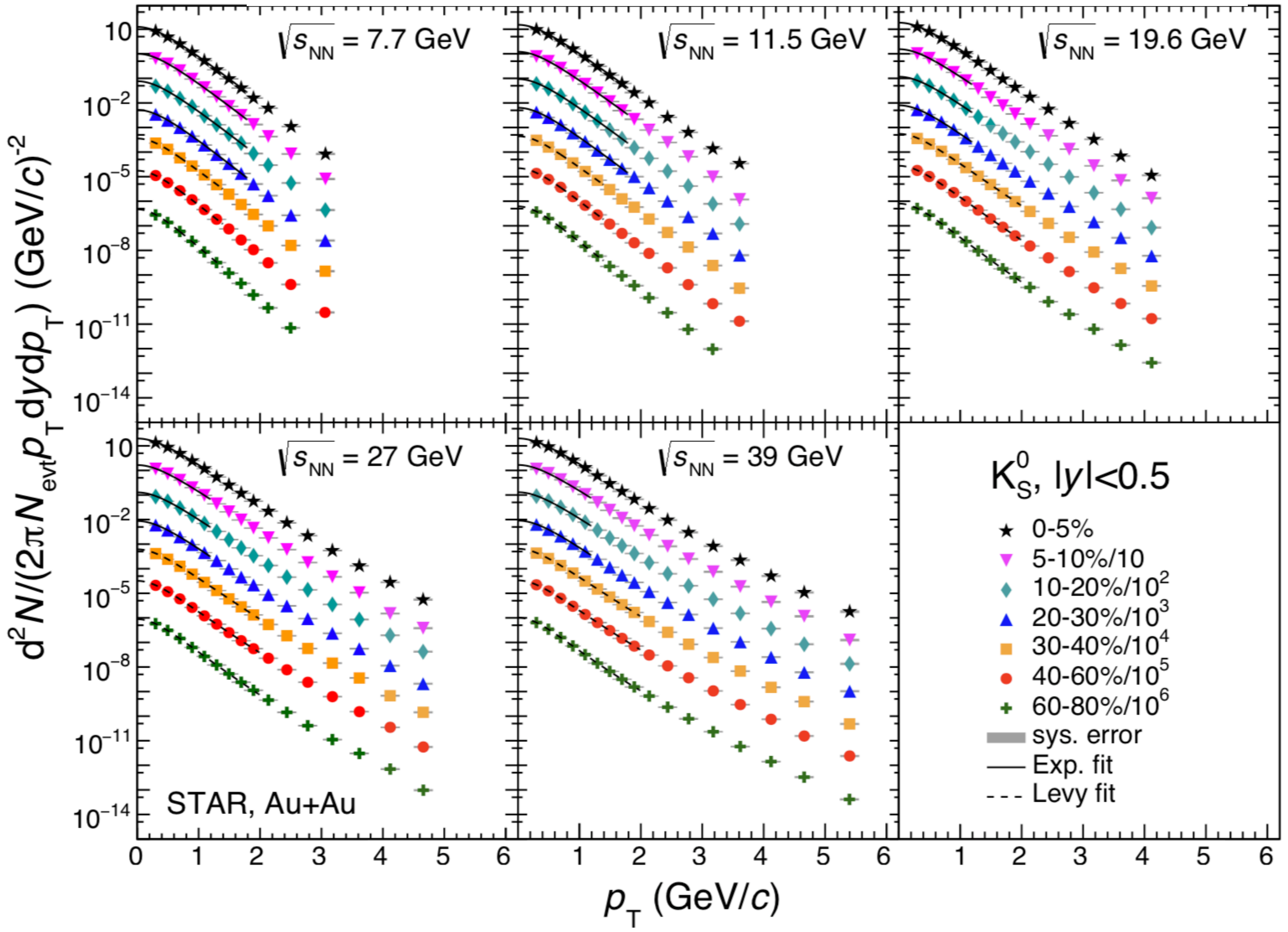
Hadron spectra

✓ **Particle spectra is measured in BES-I.**

PRC96, 44904(2017), 1906.03732 : STAR Collaboration



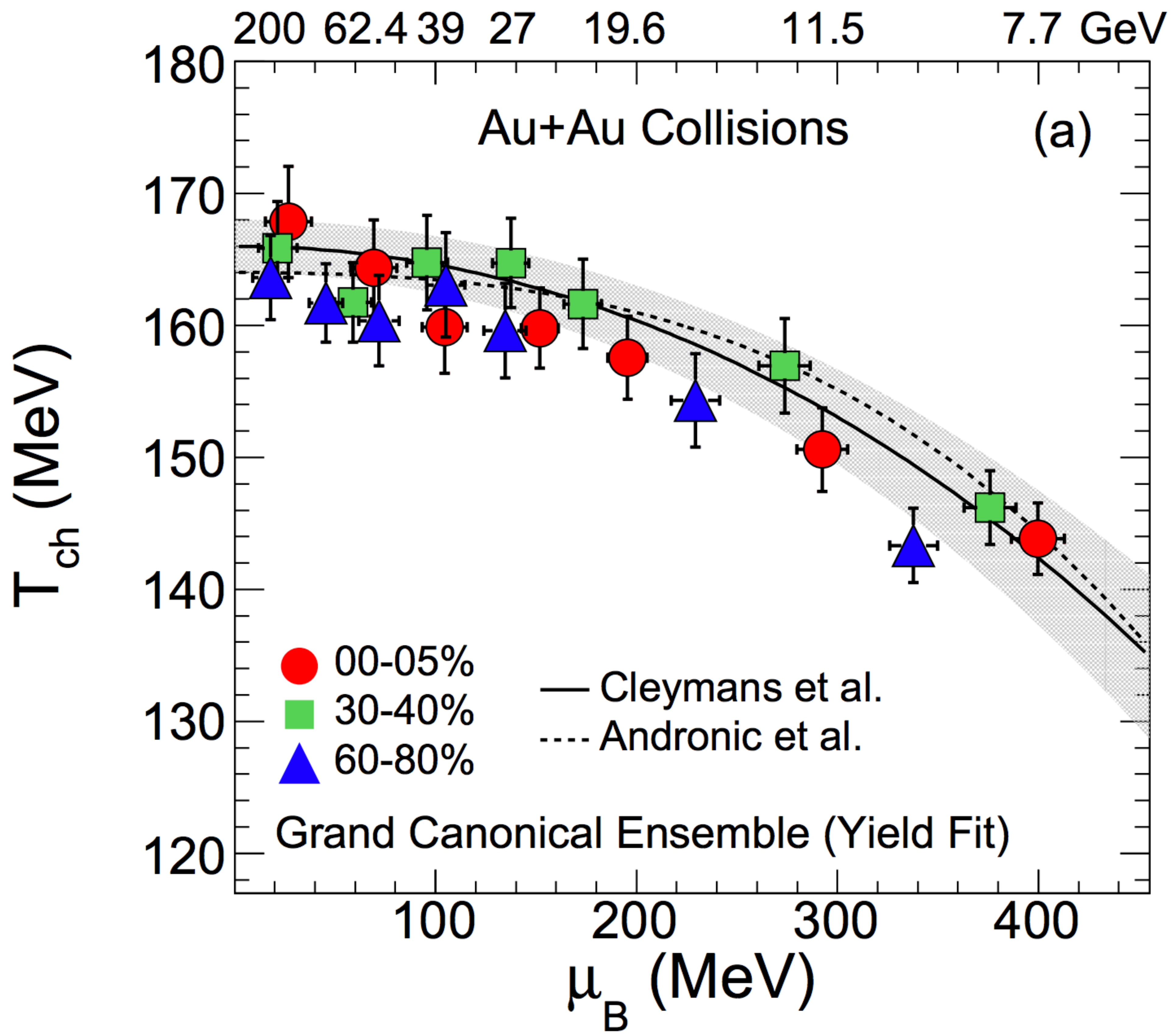


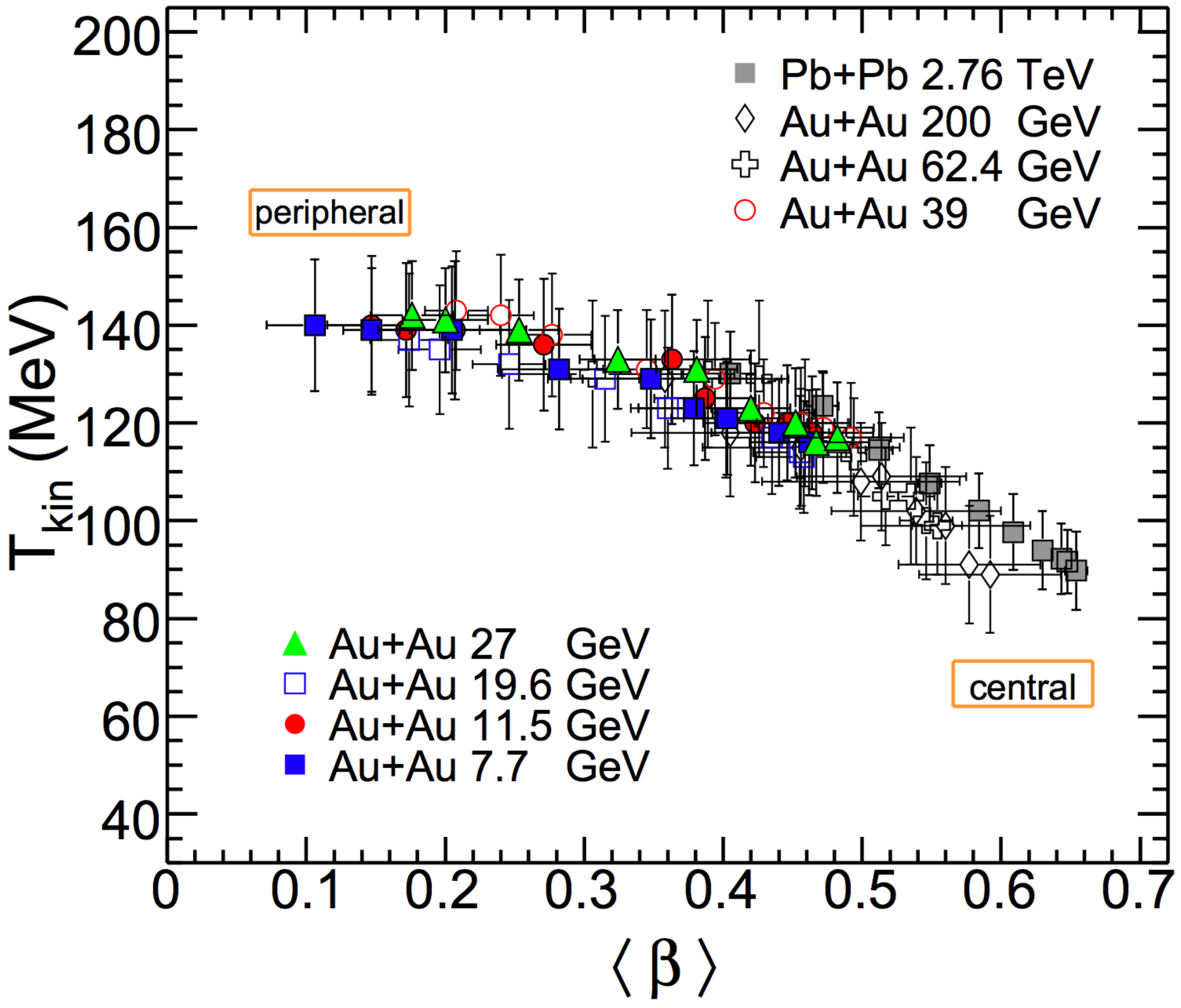


Freeze-out conditions

✓ ***Chemical freeze-out***
- Weak temperature dependence
- Centrality dependence of μ_B

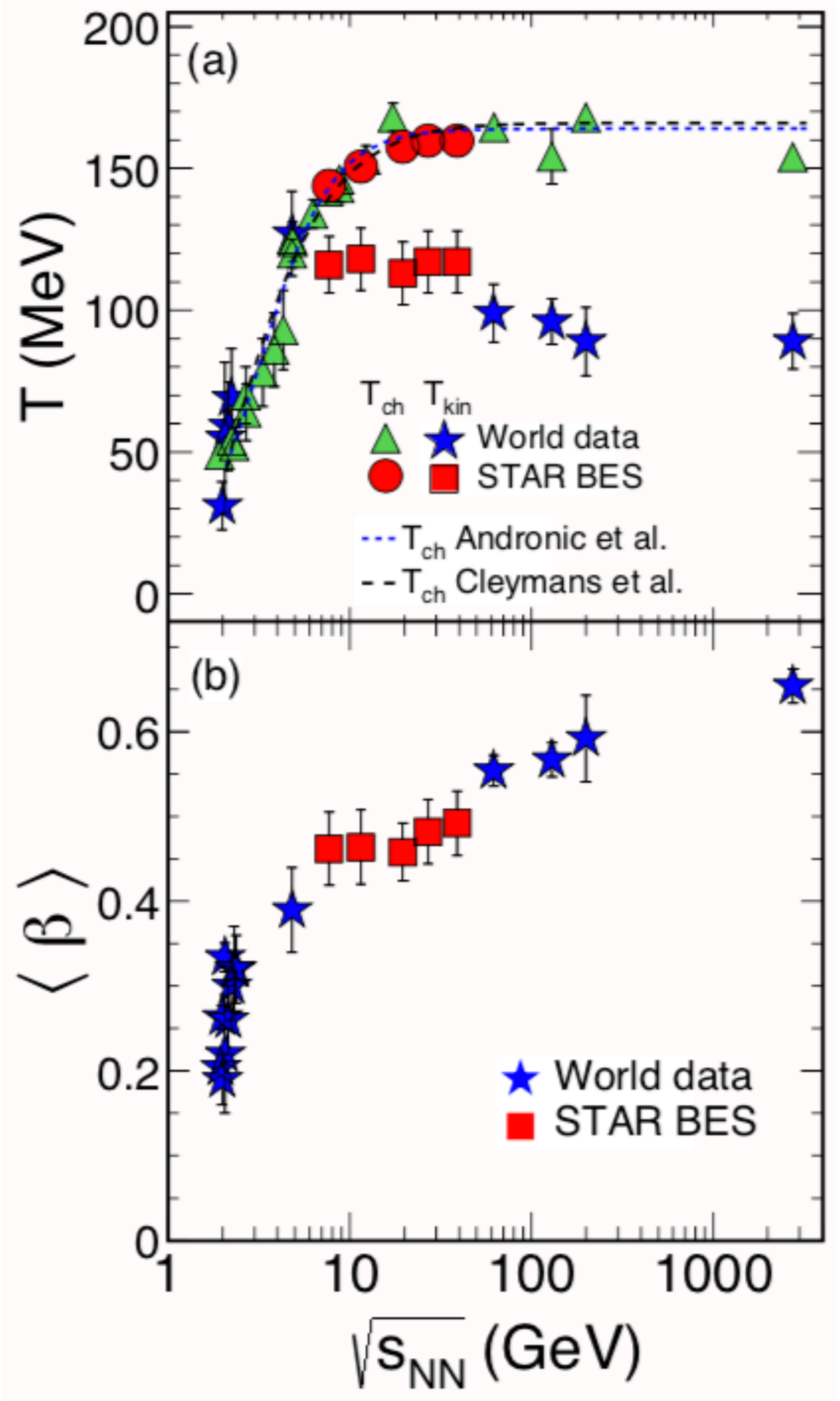
✓ ***Kinetic freeze-out***
- Central collisions→lower value of T_{kin} and larger collectivity <β>
- Stronger collectivity at higher energy, even for peripheral collisions.





PRC96, 44904(2017) : STAR Collaboration

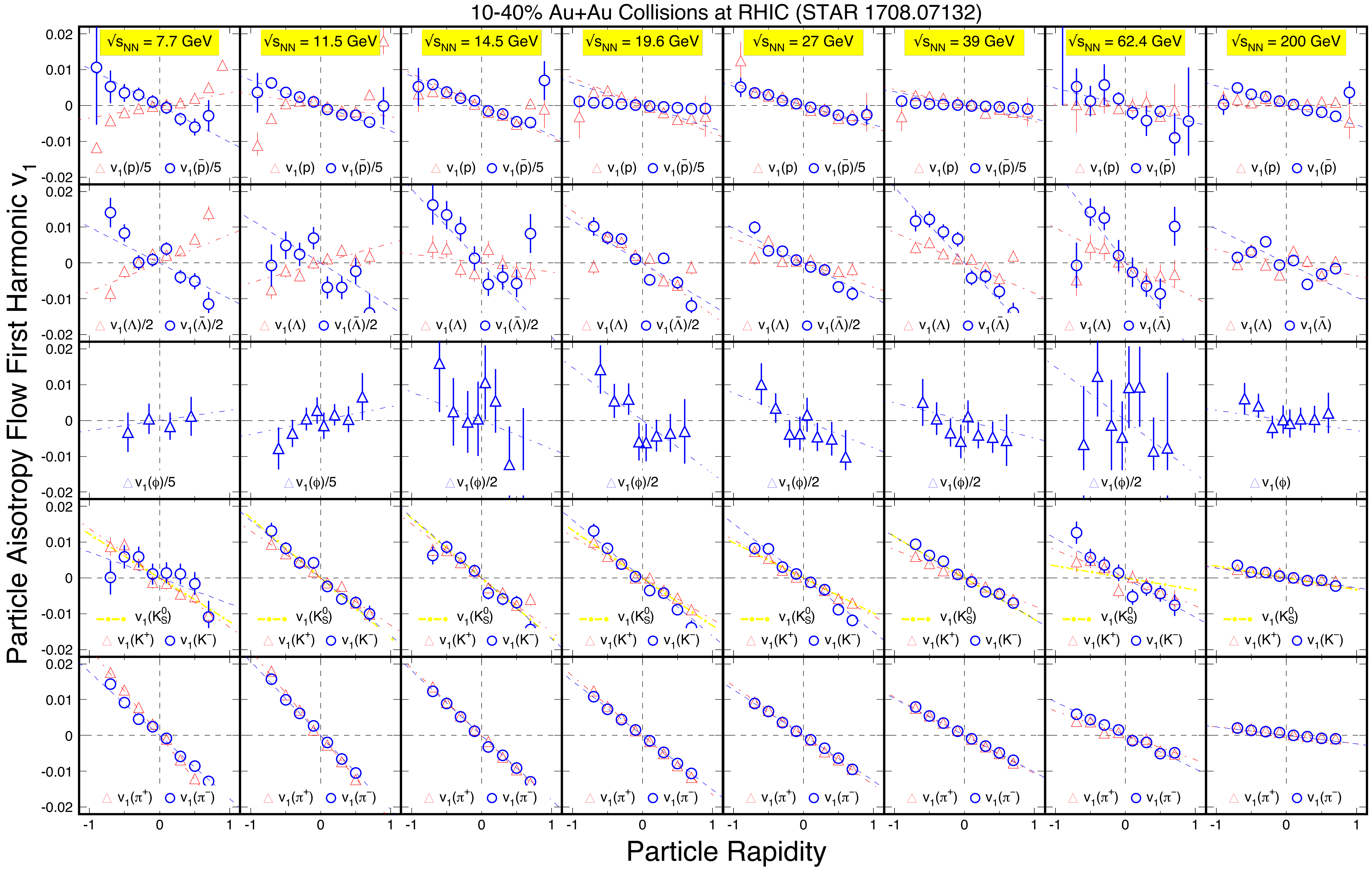
Freeze-out conditions



✓ **Both the larger separation of the freeze-out temperature (T_{ch}-T_{kin}) and stronger collectivity imply a longer hadronic interactions at higher collision energies.**

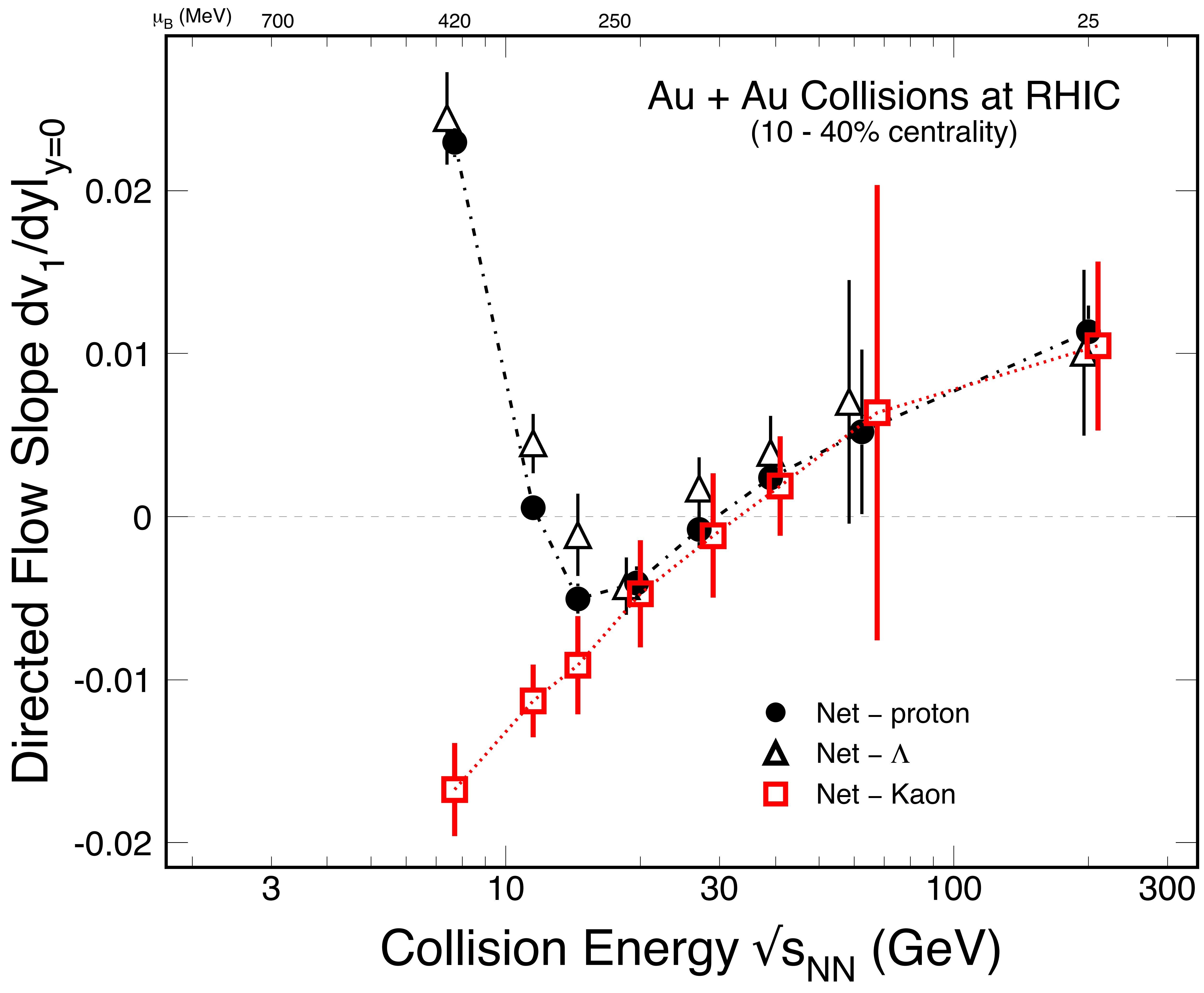
PRC96, 44904(2017) : STAR Collaboration

v_1 versus collision energy



PRL120, 62301(2018) : STAR Collaboration

v_1 slope versus collision energy



- ✓ Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton and net-Λ, but net-kaon v_1 slope 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

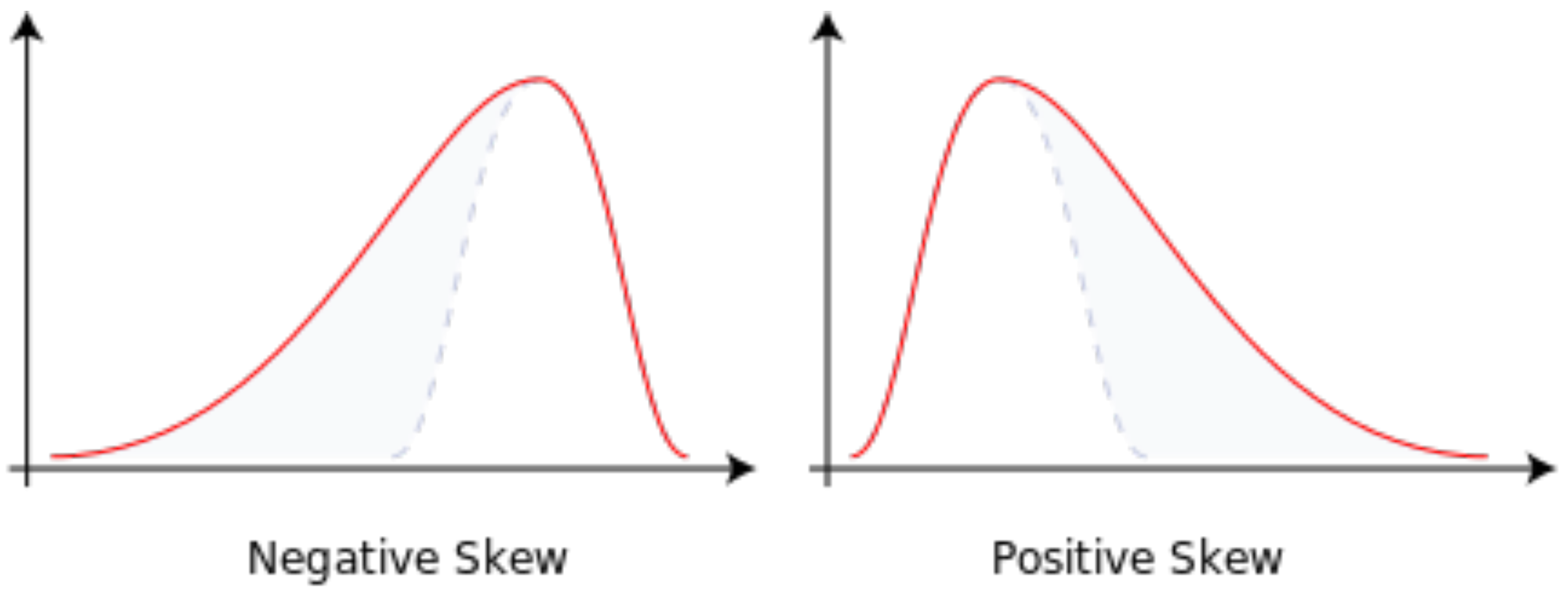
M. Isse, A. Ohnishi et al, PRC72, 064908(05)
Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16)

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

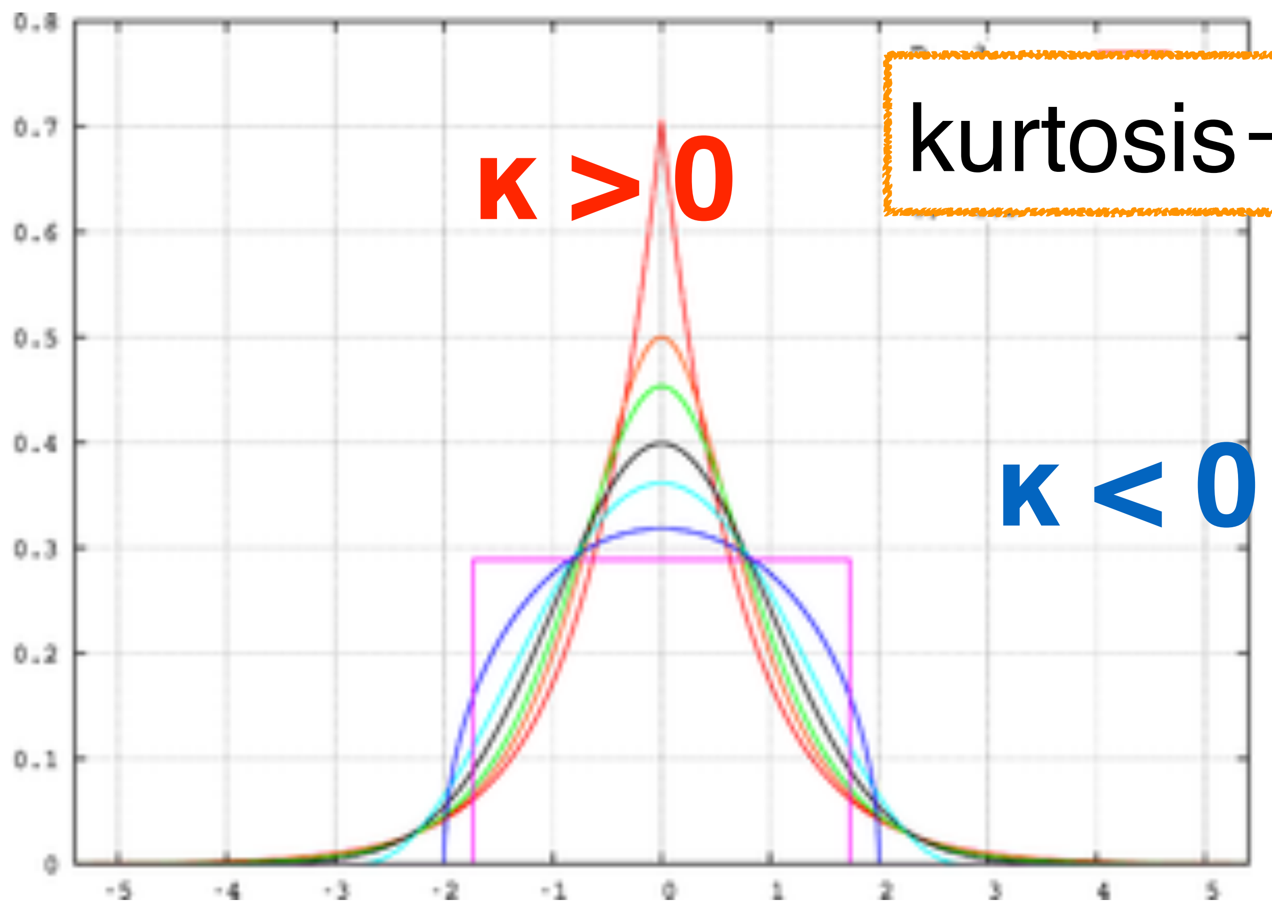
Higher-order fluctuations

- 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

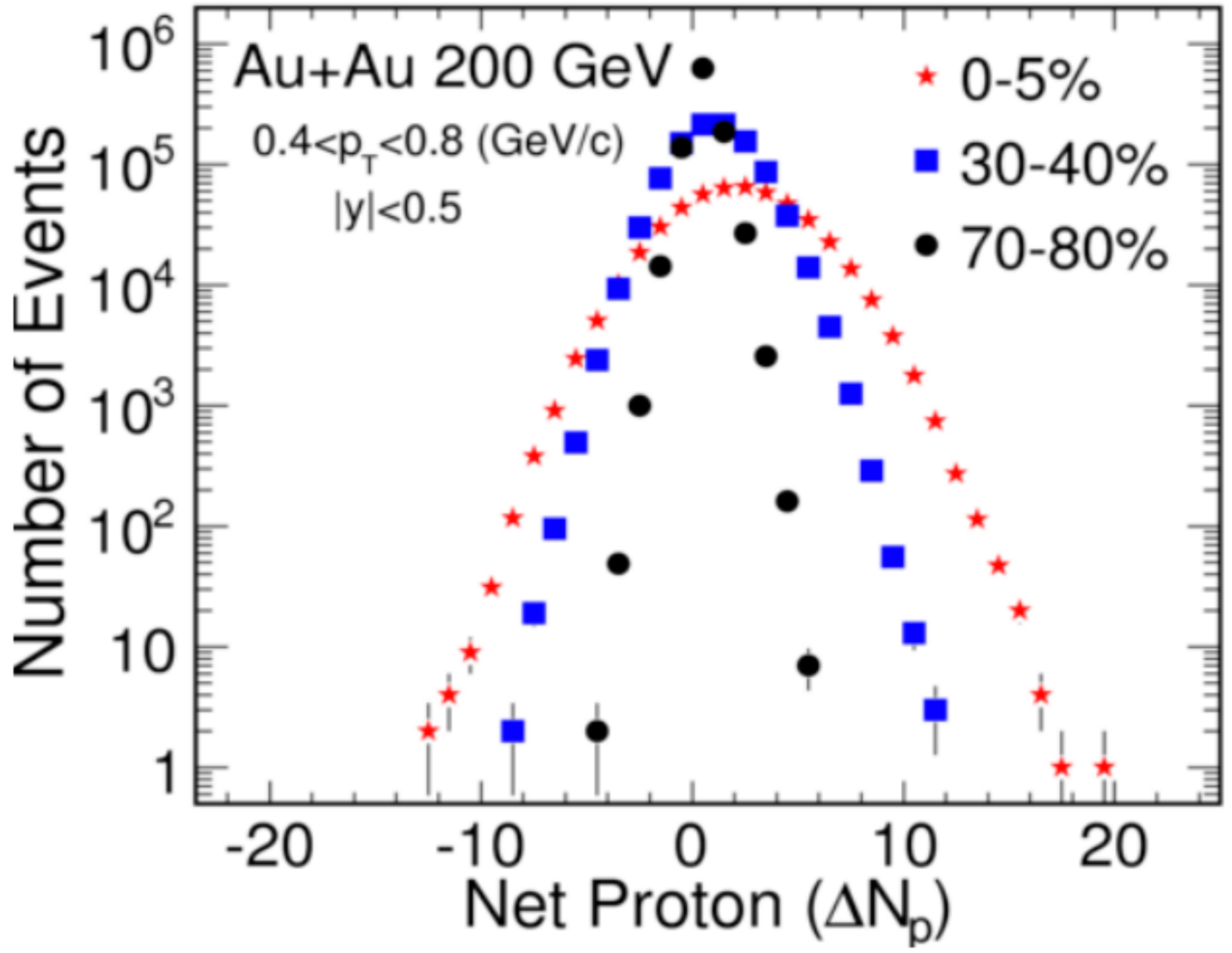
"Net" : positive - negative

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

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

$$C_2 =< (\delta N)^2 >_c \approx \xi^2 \qquad C_5 =< (\delta N)^5 >_c \approx \xi^{9.5}$$
$$C_3 =< (\delta N)^3 >_c \approx \xi^{4.5} \qquad C_6 =< (\delta N)^6 >_c \approx \xi^{12}$$
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

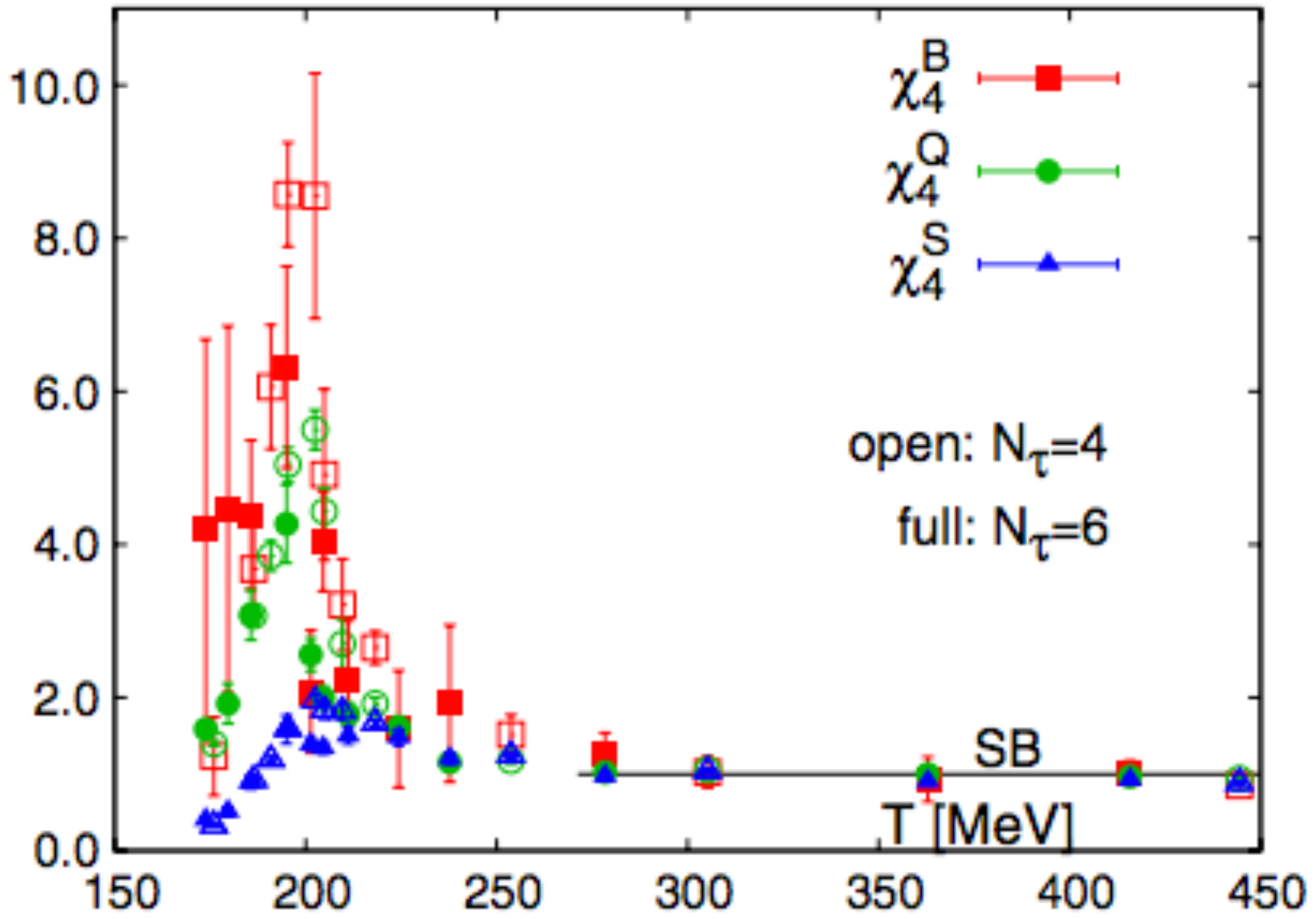
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
MAsakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

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

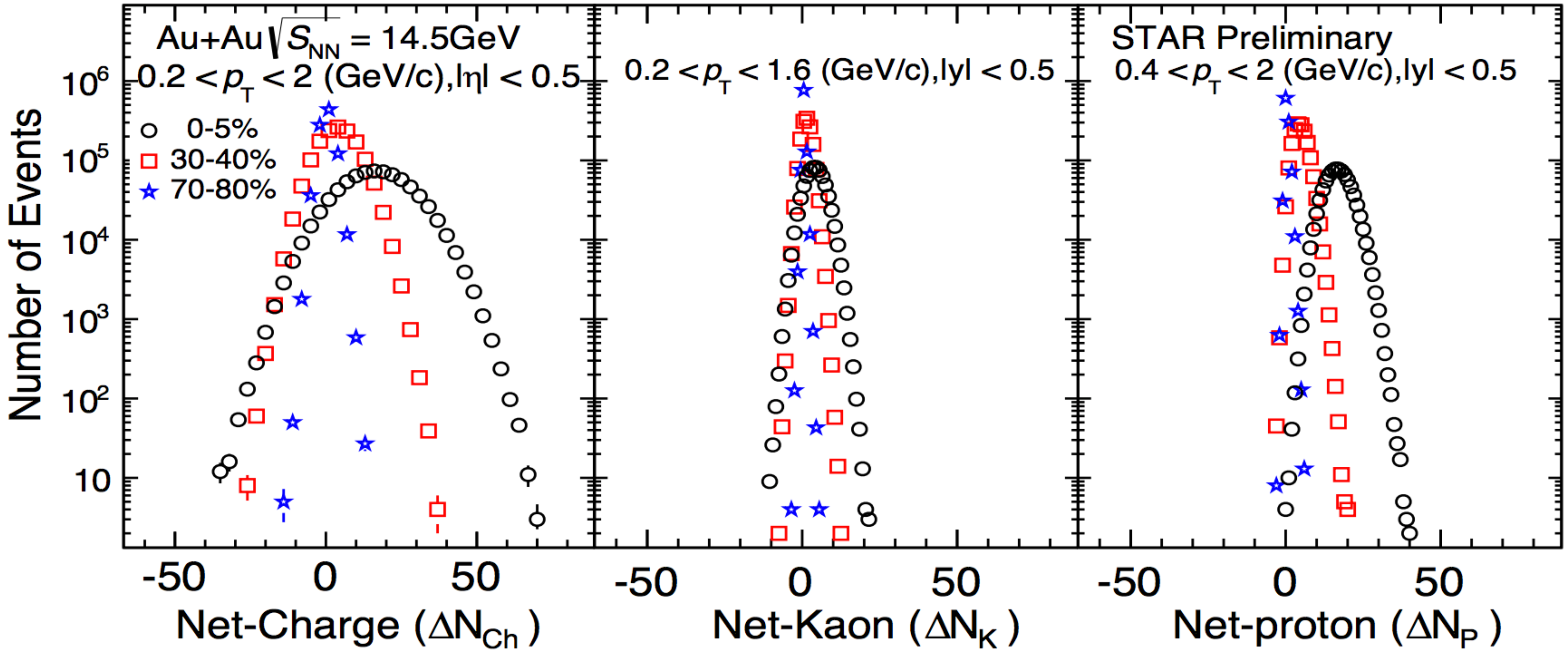
$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

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



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

Data analysis method

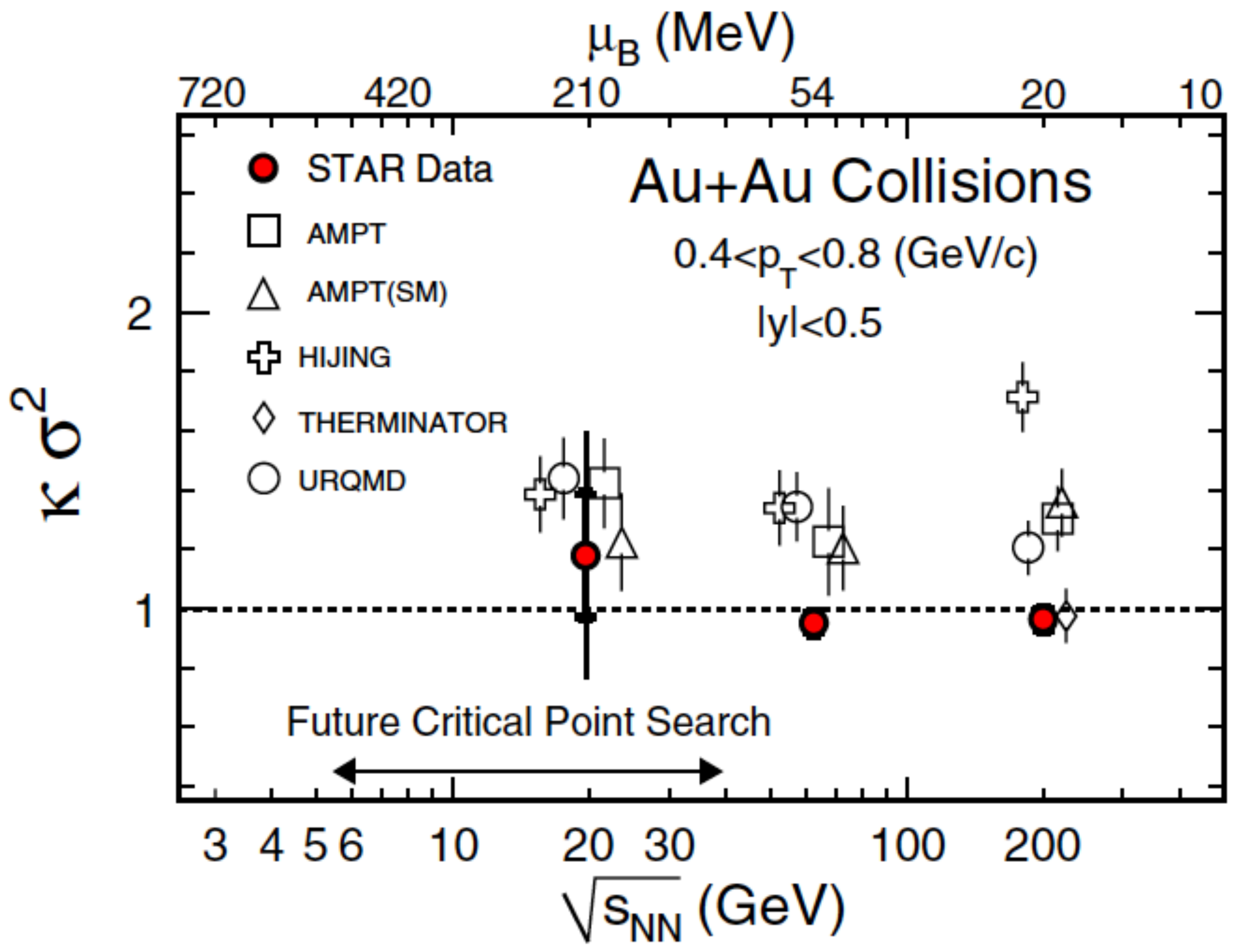


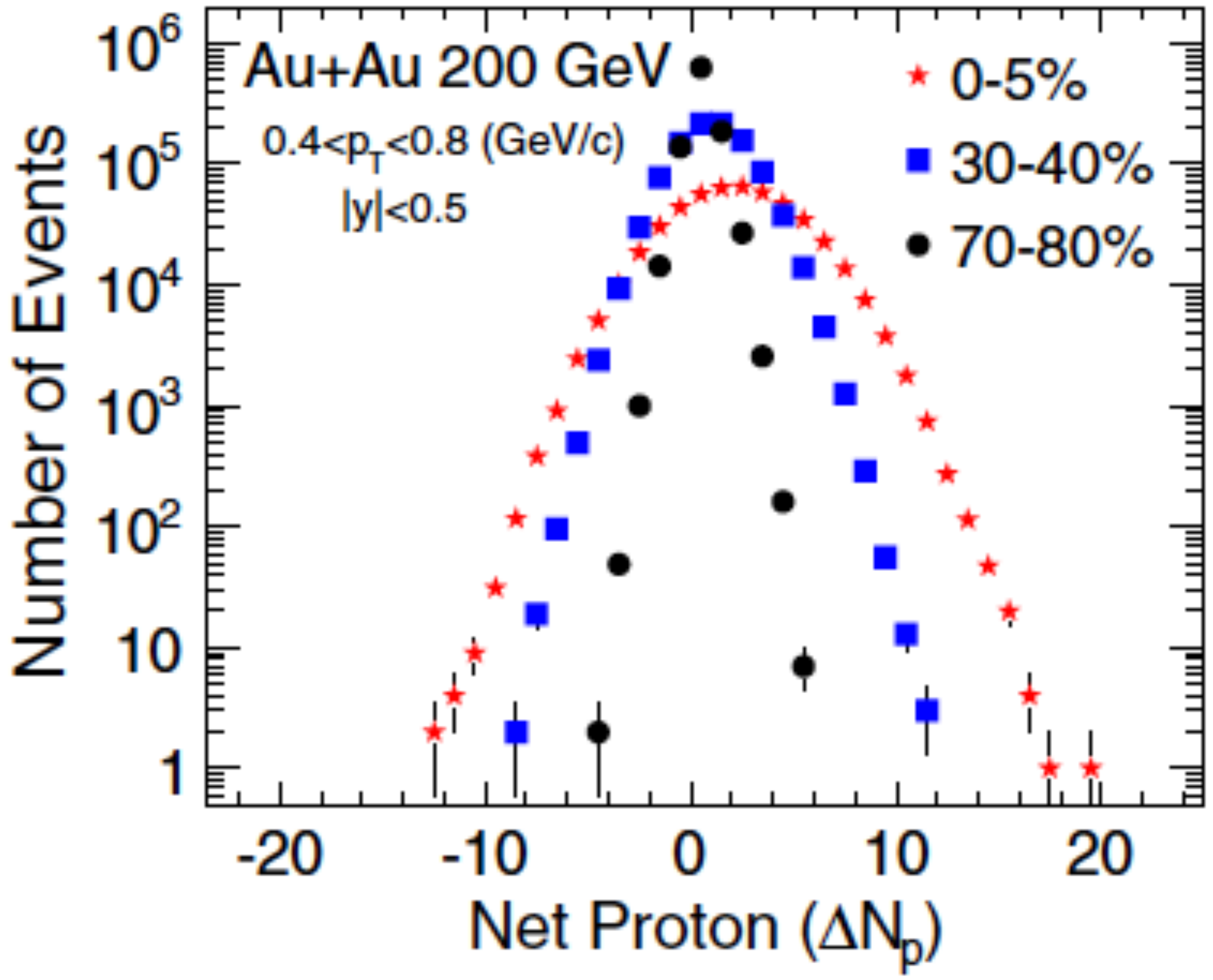
- ✓ **Statistical error estimation : Delta theorem or bootstrap**
- ✓ **Avoid auto-correlation effects : New centrality definition**
- ✓ **Suppress initial volume fluctuation : Centrality bin width correction**
- ✓ **Detector efficiency correction : Binomial model**

- *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*
- *X. Luo, T. Nonaka : PRC.99.044917*

First measurement of net proton

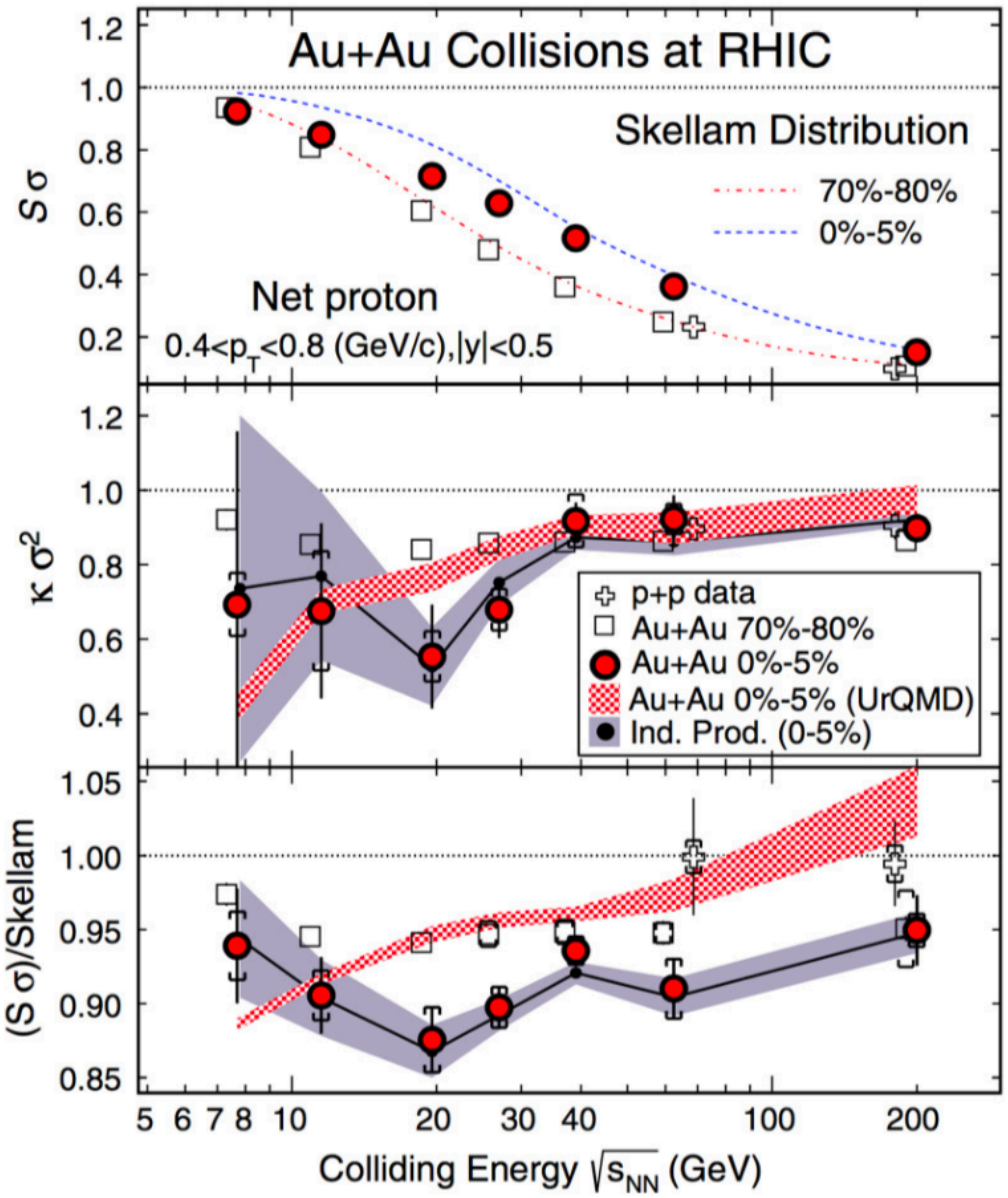
✓ **At μ_B < 210 MeV, the 4th-order fluctuation is found to be flat as a function of collision energy.**





PRL105, 022302(2010): STAR Collaboration

Net proton from BES-I

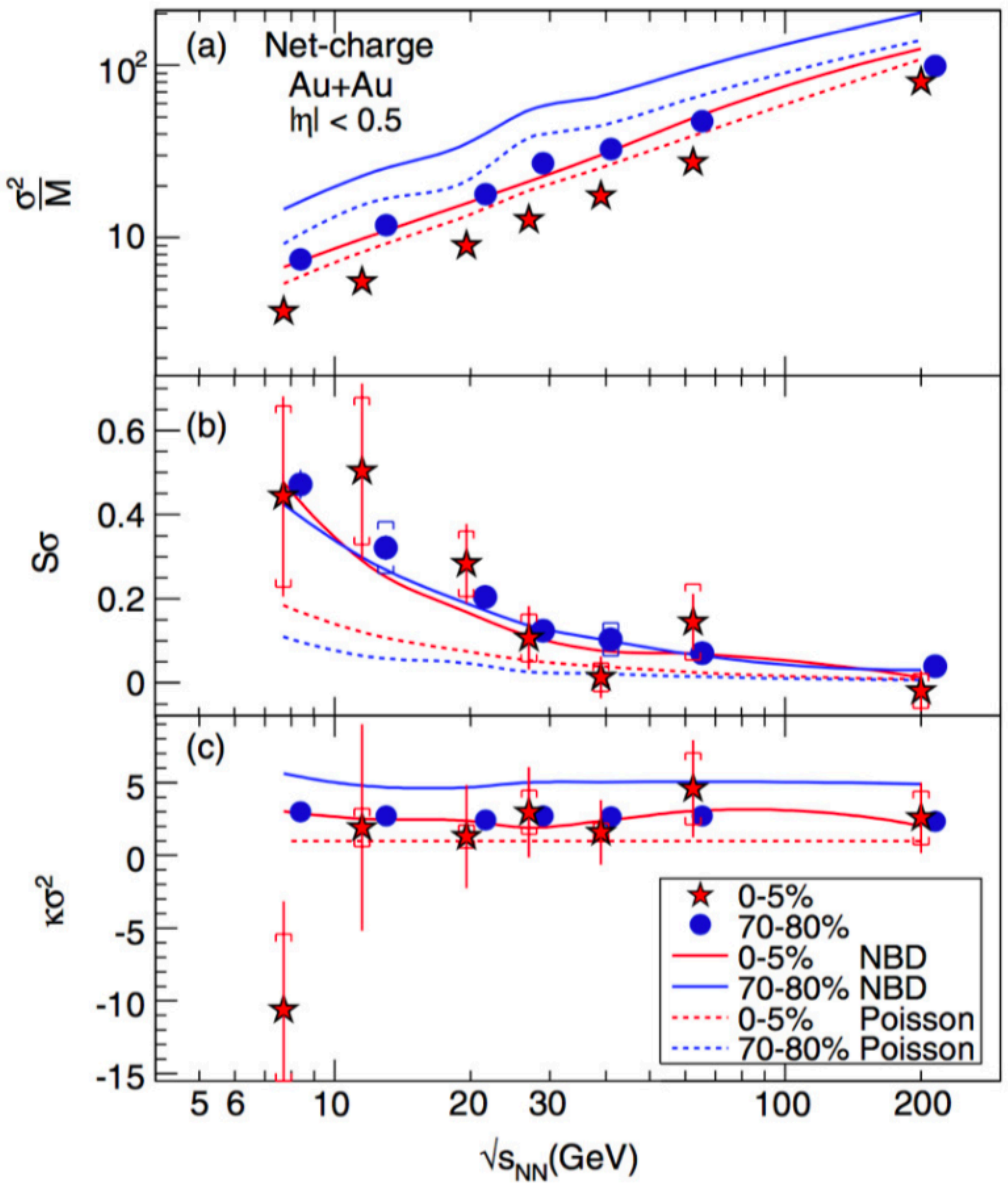


- ✓ **Deviation below Poisson baseline (unity).**
- ✓ **Both 3rd- and 4th-order fluctuations have their minima at $\sqrt{s_{NN}}$ = 19.6 GeV.**

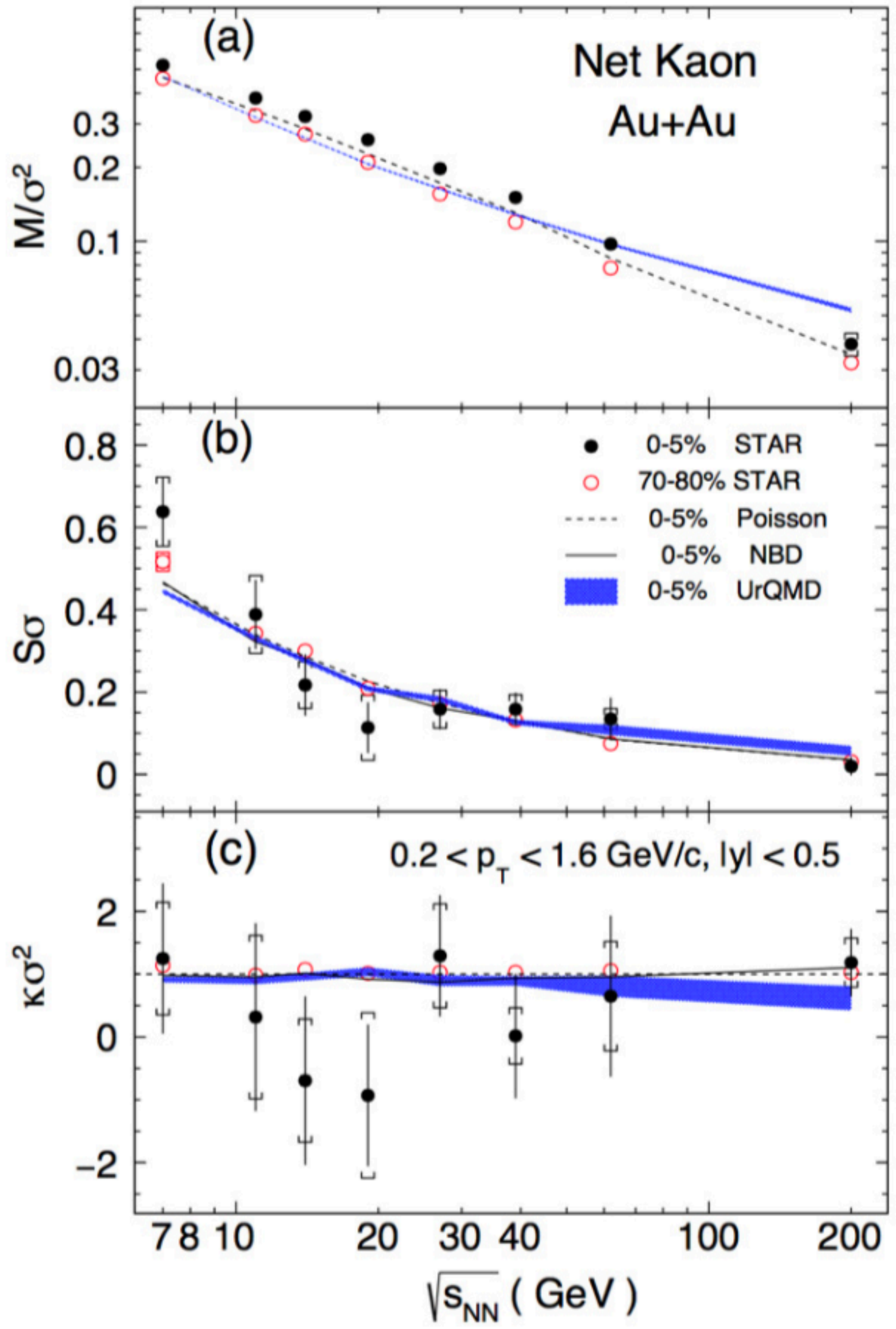
PRL112, 032302(2014): STAR Collaboration

Net charge and net kaon

PRL113, 092301(2014): STAR



PLB, 785, 551(2018): STAR



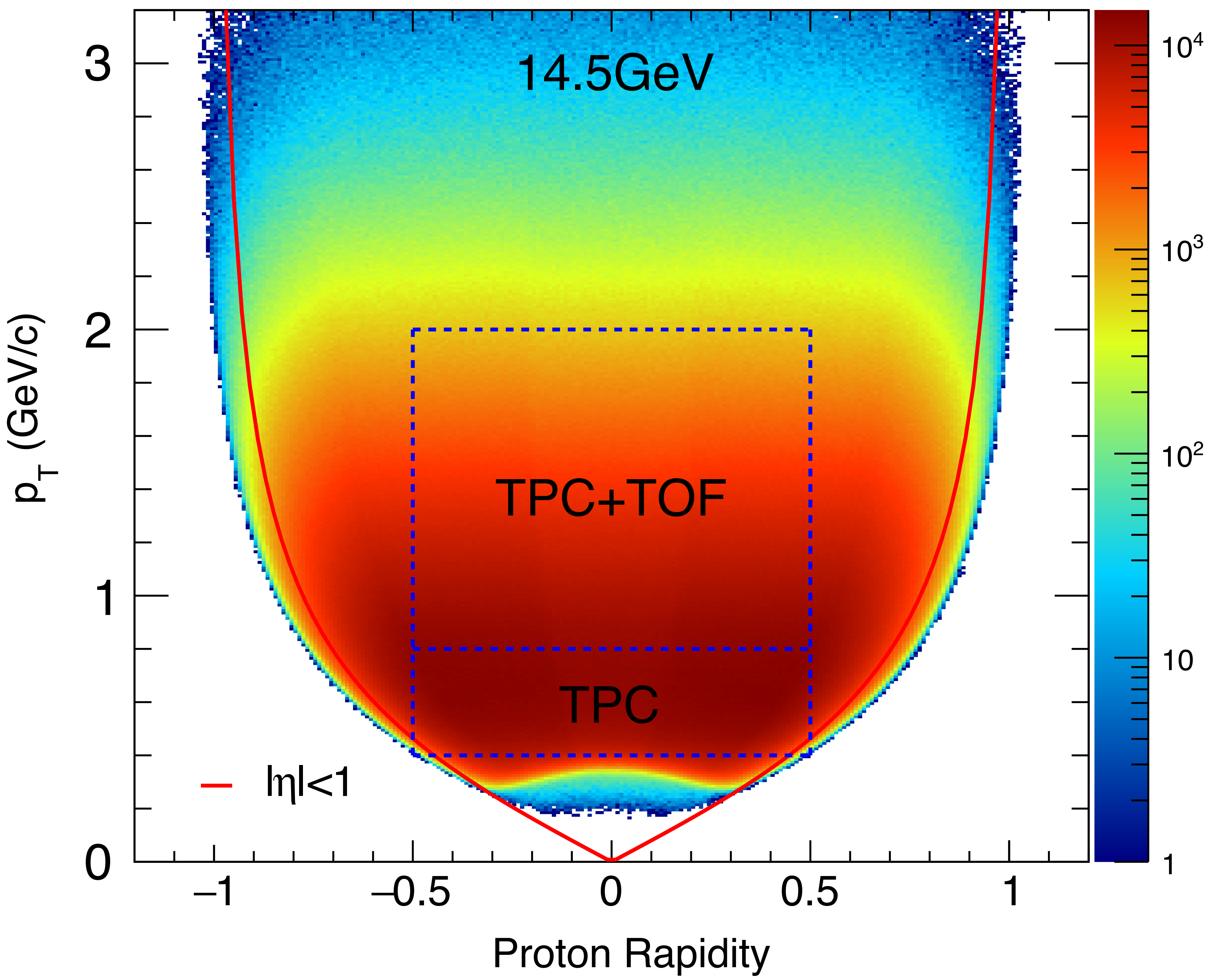
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}\frac{1}{\sqrt{N_{evts}}}$$

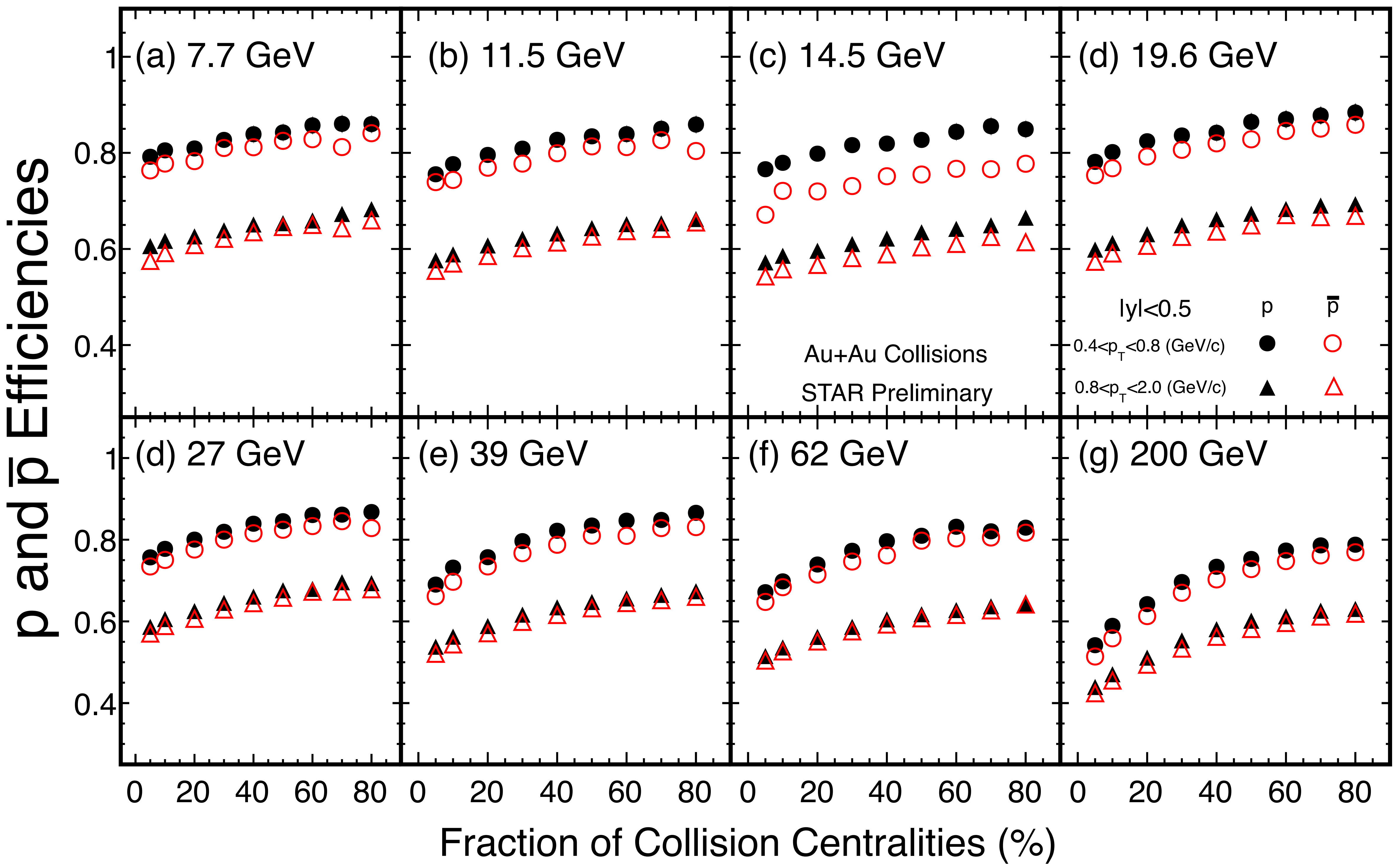
- ✓ **Large statistical uncertainties, need more data.**

Extend p_T coverage

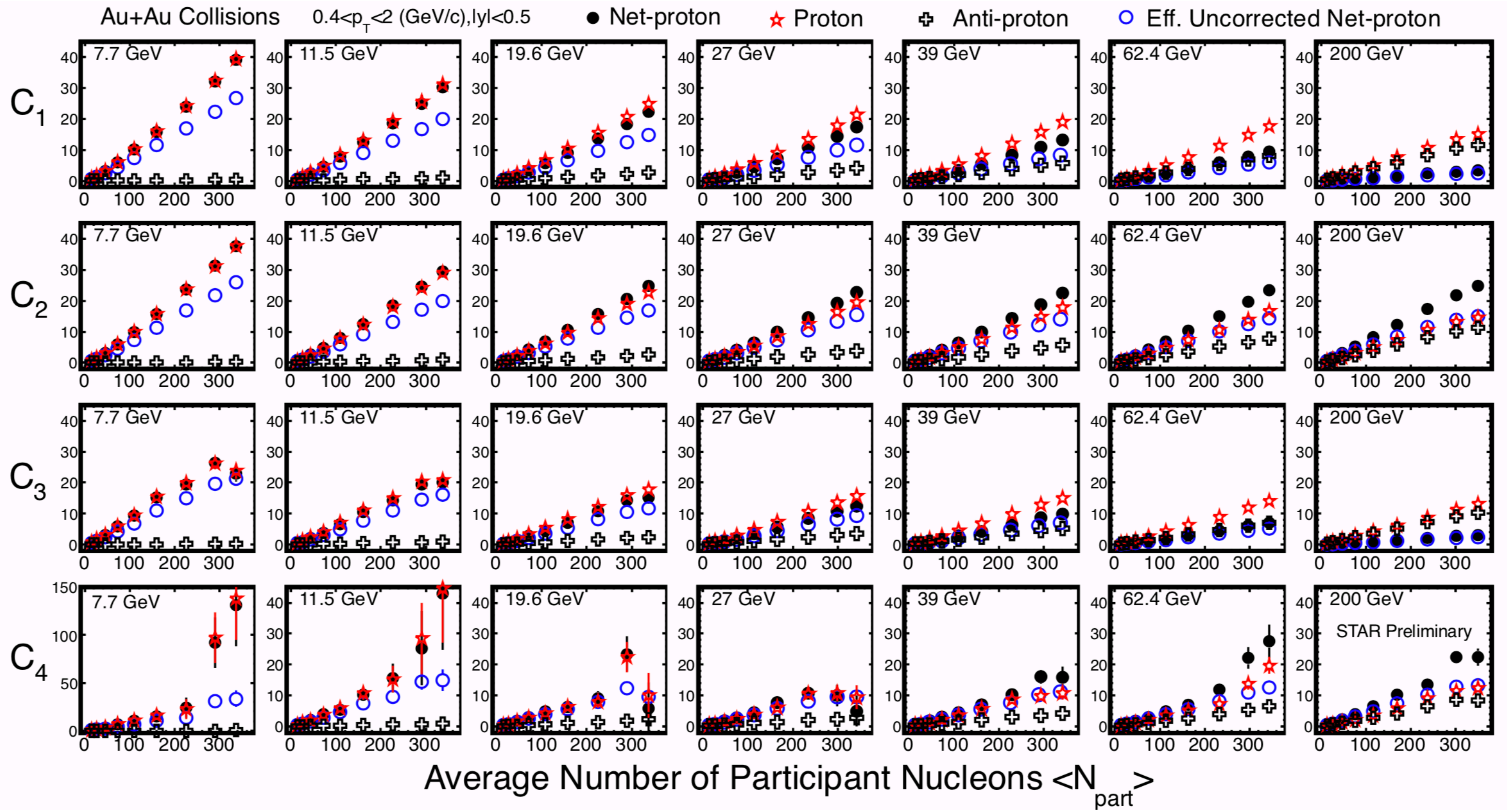
✓ p_T region can be extended up to 2.0 GeV by using TOF as well as TPC.

✓ (Anti)proton statistics is doubled with respect to the published results.





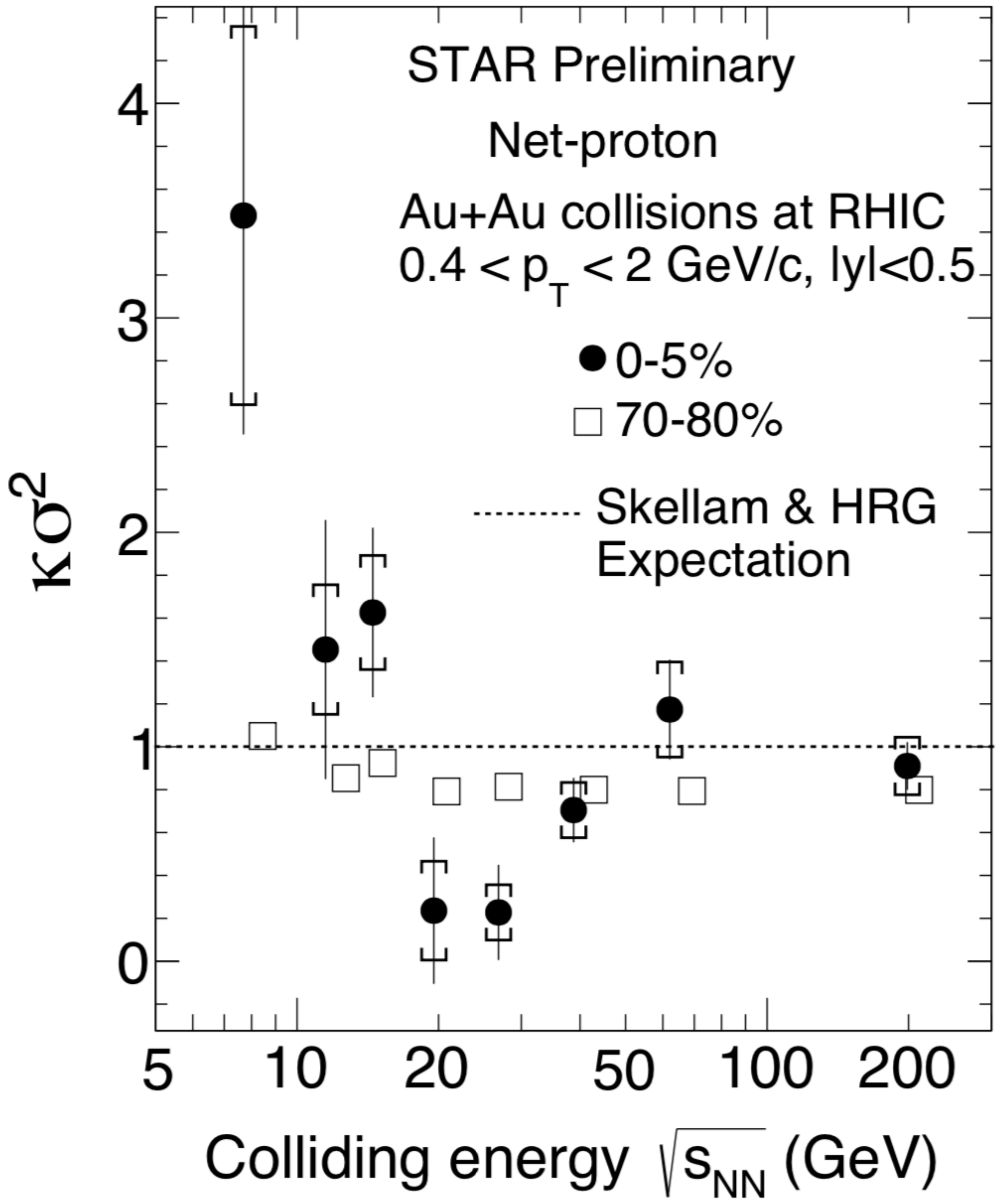
Cumulants in BES-I energies



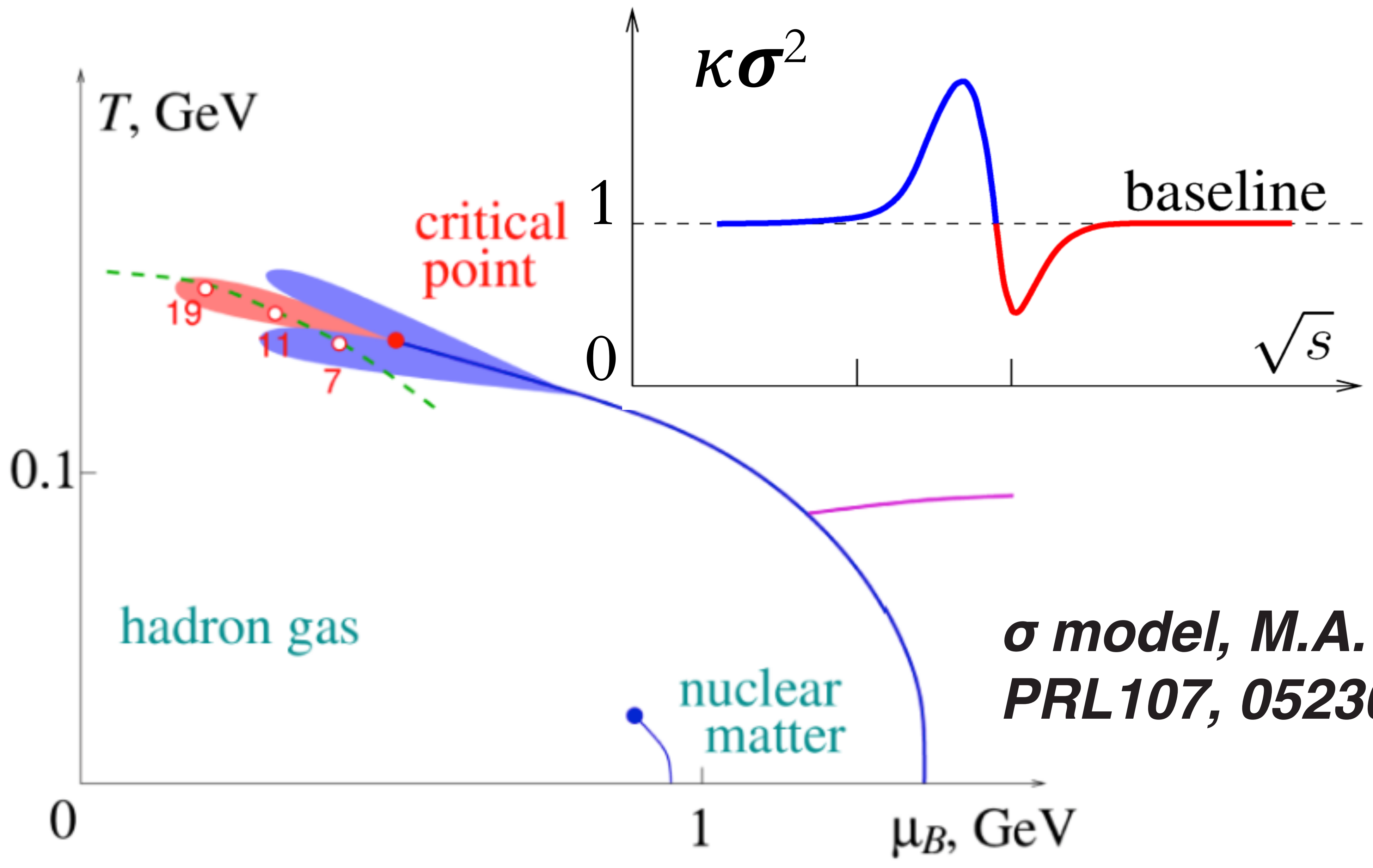
STAR, PoS CPOD2014 (2015)019

Non-monotonic behavior

STAR, PoS CPOD2014 (2015)019



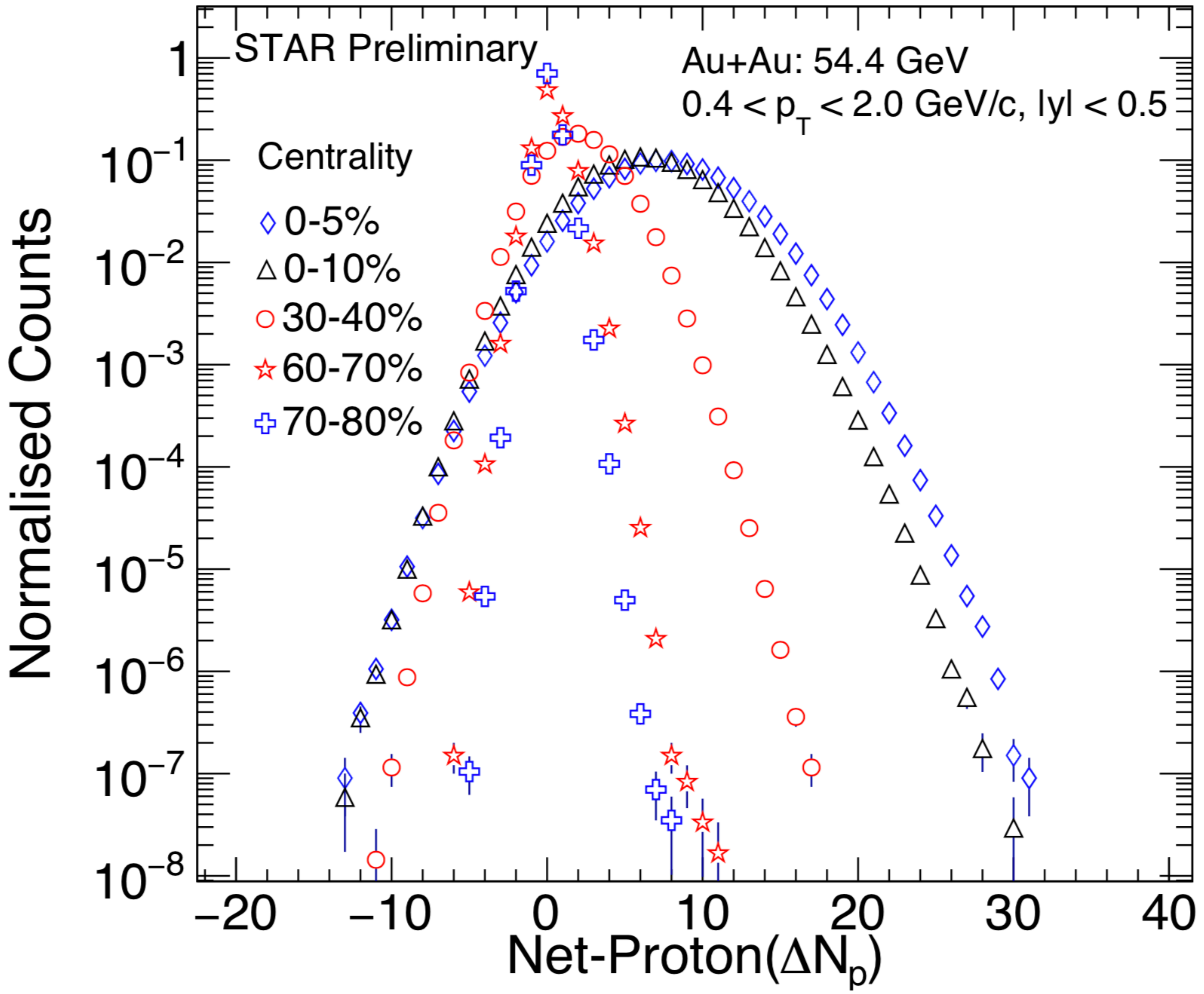
- ✓ **$\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the theoretical calculation.**
- ✓ **Measurement at lower energies are important.**



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

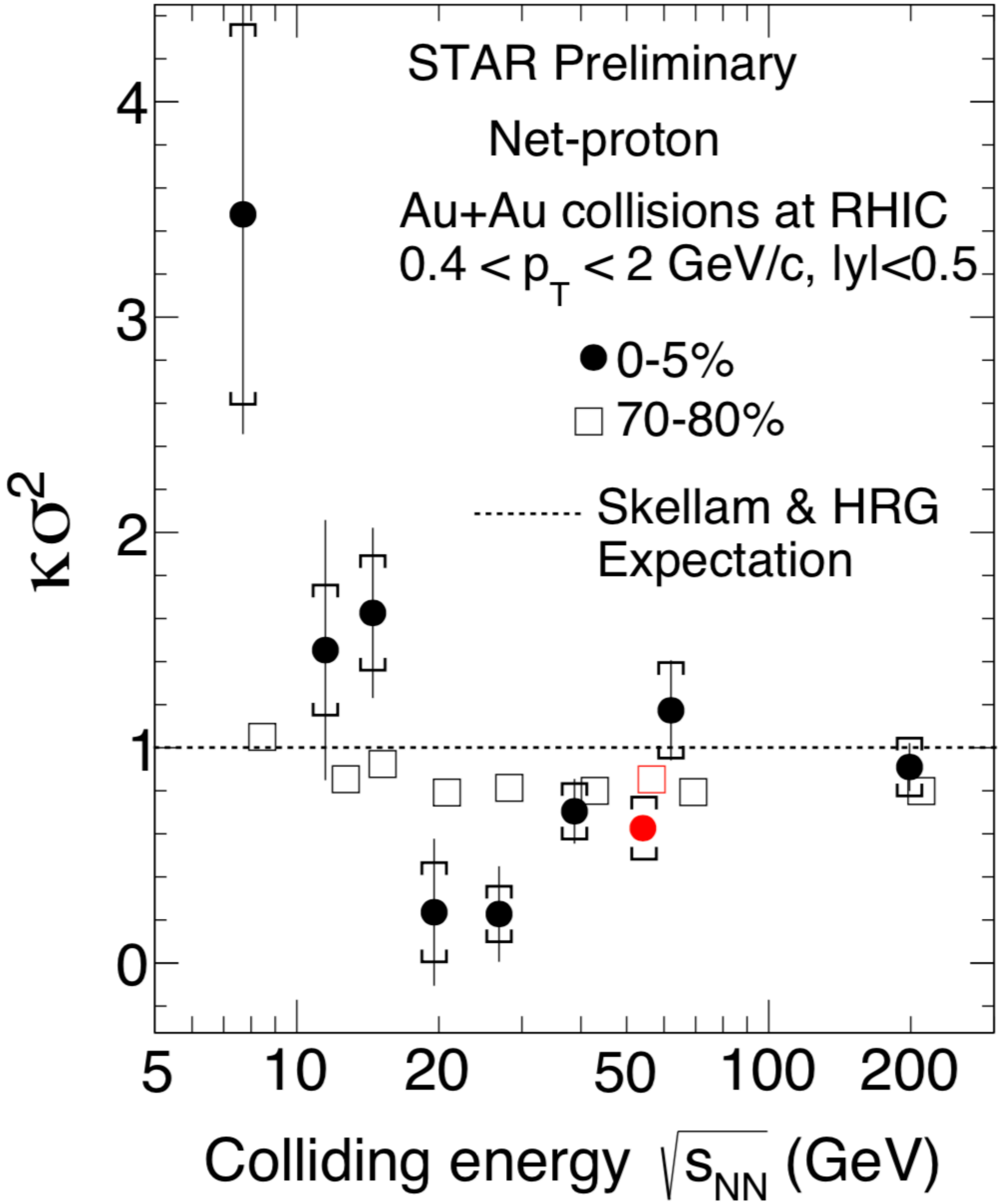
New data set : 54.4 GeV

Collision system and energy	Au+Au and 54.4 GeV
Baryon Chemical Potential	~ 90 MeV
No. of events	~ 553 M
Collision centrality	0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%
Centrality	$\lvert\eta\rvert < 1$; charged particles other than protons and antiprotons
Z Vertex	+/- 30 cm
Vertex radial position	2 cm
Detectors	Time Projection Chamber and Time-of-Flight
Particle Type	Proton and antiprotons
Rapidity	+/- 0.5
Transverse Momentum Range	0.4 to 2.0 GeV/c
Secondary proton backgrounds	|DCA| < 1cm



New data sets : 54.4 GeV

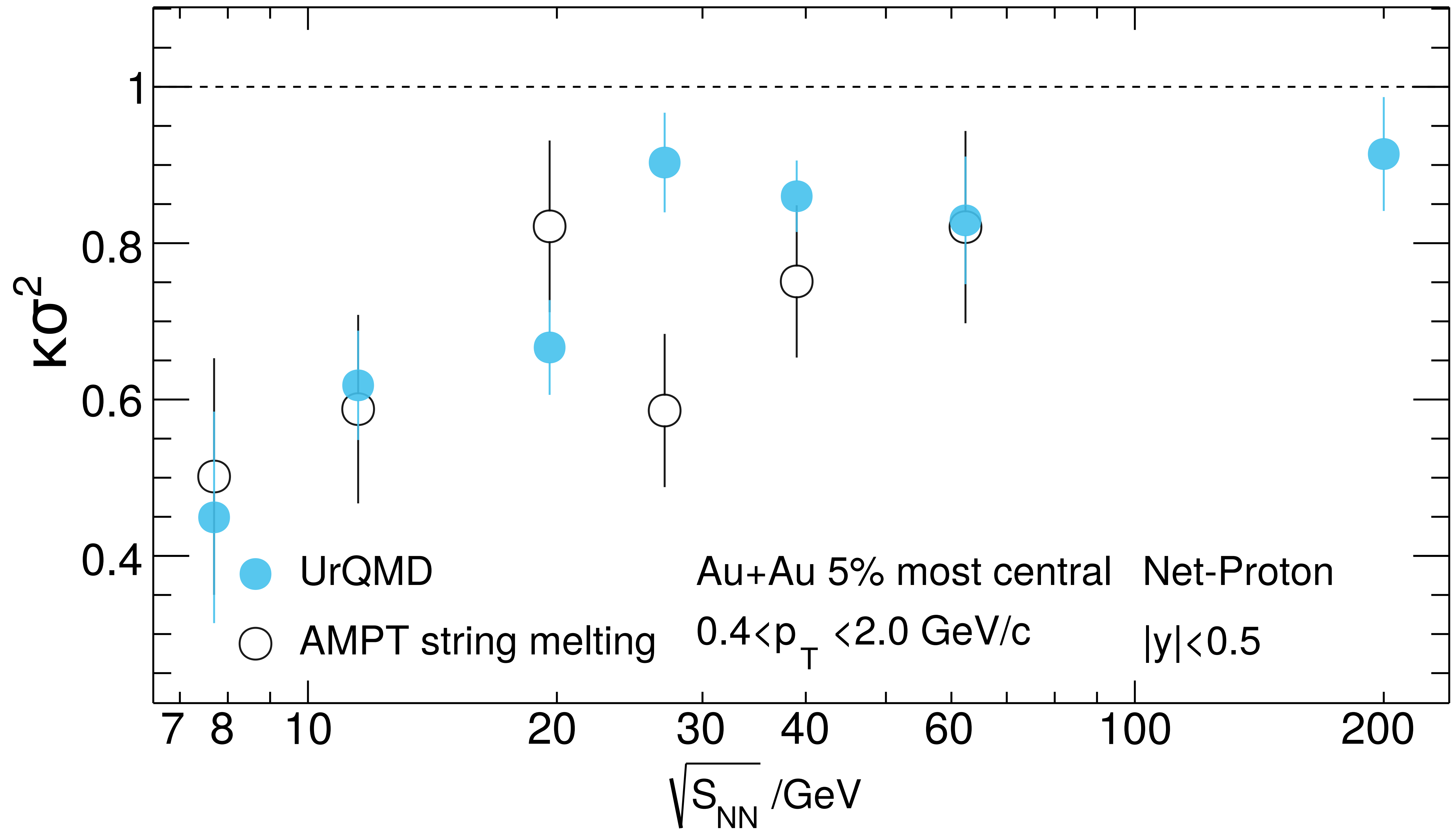
STAR, PoS CPOD2014 (2015)019

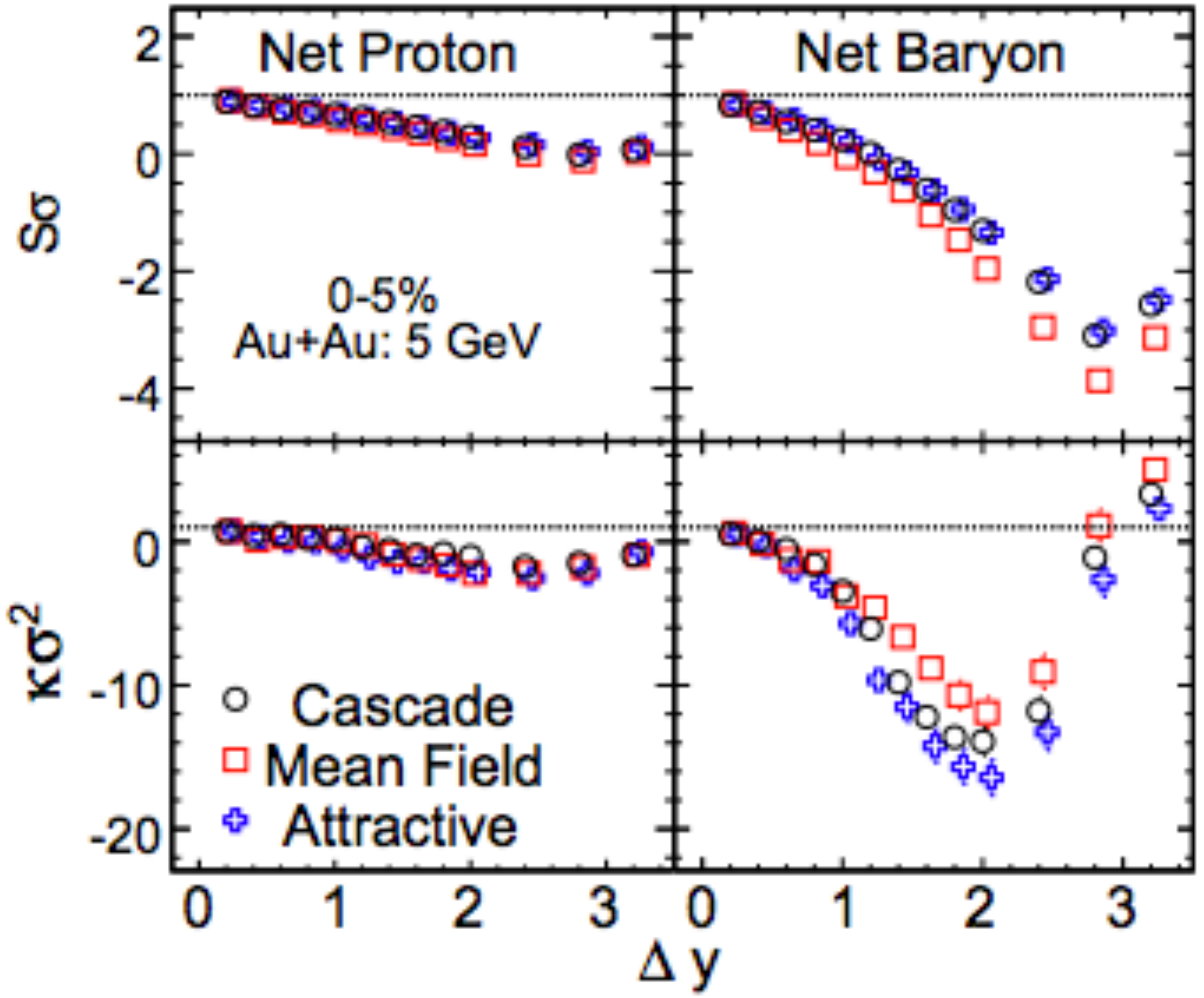


✓ **Results at 54.4 GeV follow the trend very well.**

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.



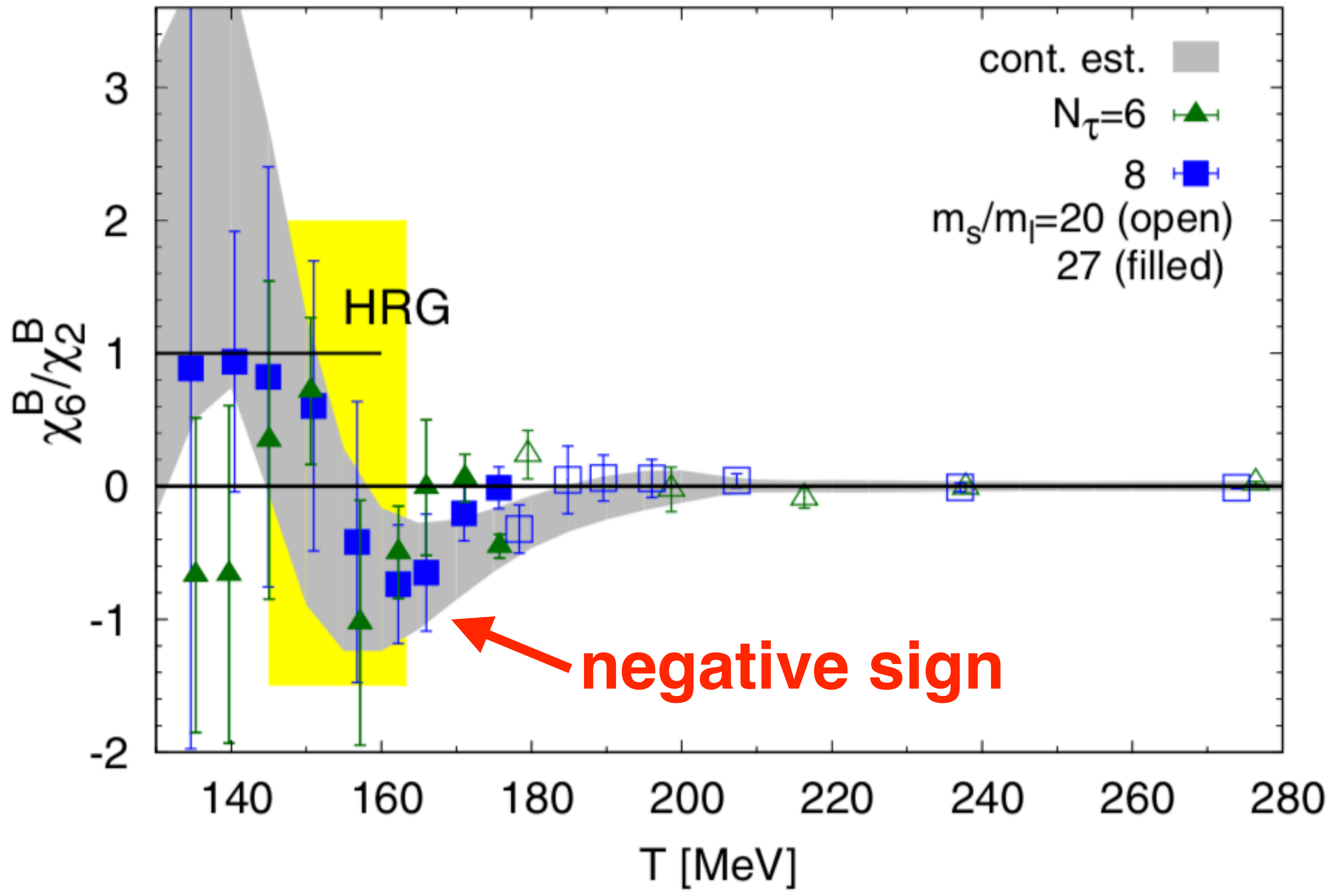


Z. Feckova, et al., PRC92, 064908(2015). J. Xu, et. al., PRC94, 024901(2016). X. Luo et al., NPA931, 808(14), P.K. Netrakanti et al. 1405.4617, NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016). S. He, X. Luo, PLB 774, 623 (2017).

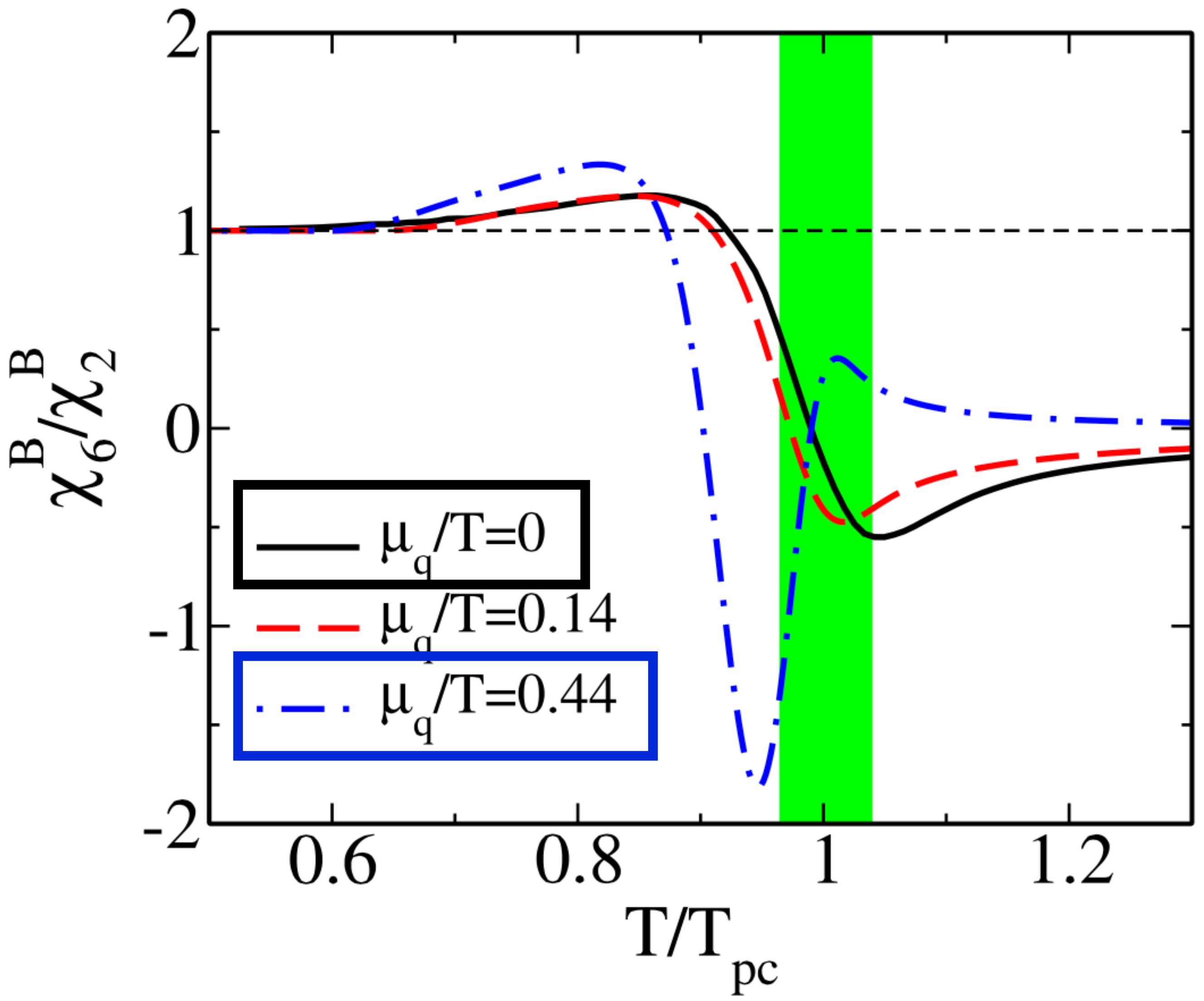
Sixth-order cumulants

- ✓ 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

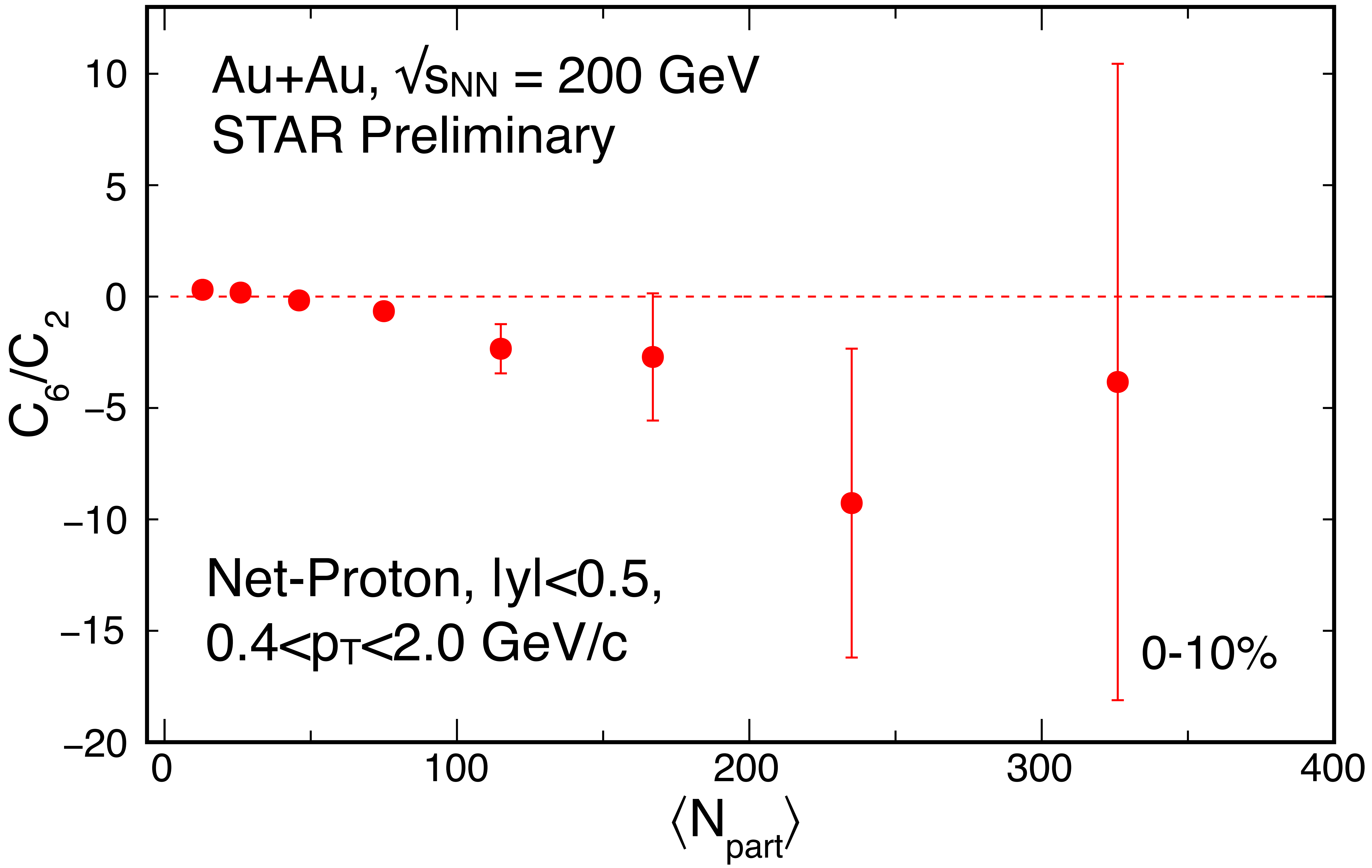
C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

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

Net-proton at $\sqrt{s_{NN}}$ = 200 GeV

- ✓ **Much better precision as compared to net-charge.**
- ✓ **Negative values are observed systematically from midcentral to central collisions, which seems consistent with the theoretical prediction.**



$$error(C_r) \propto \frac{\sigma^r}{\sqrt{N_{\rm eve}}}$$

Used statistics

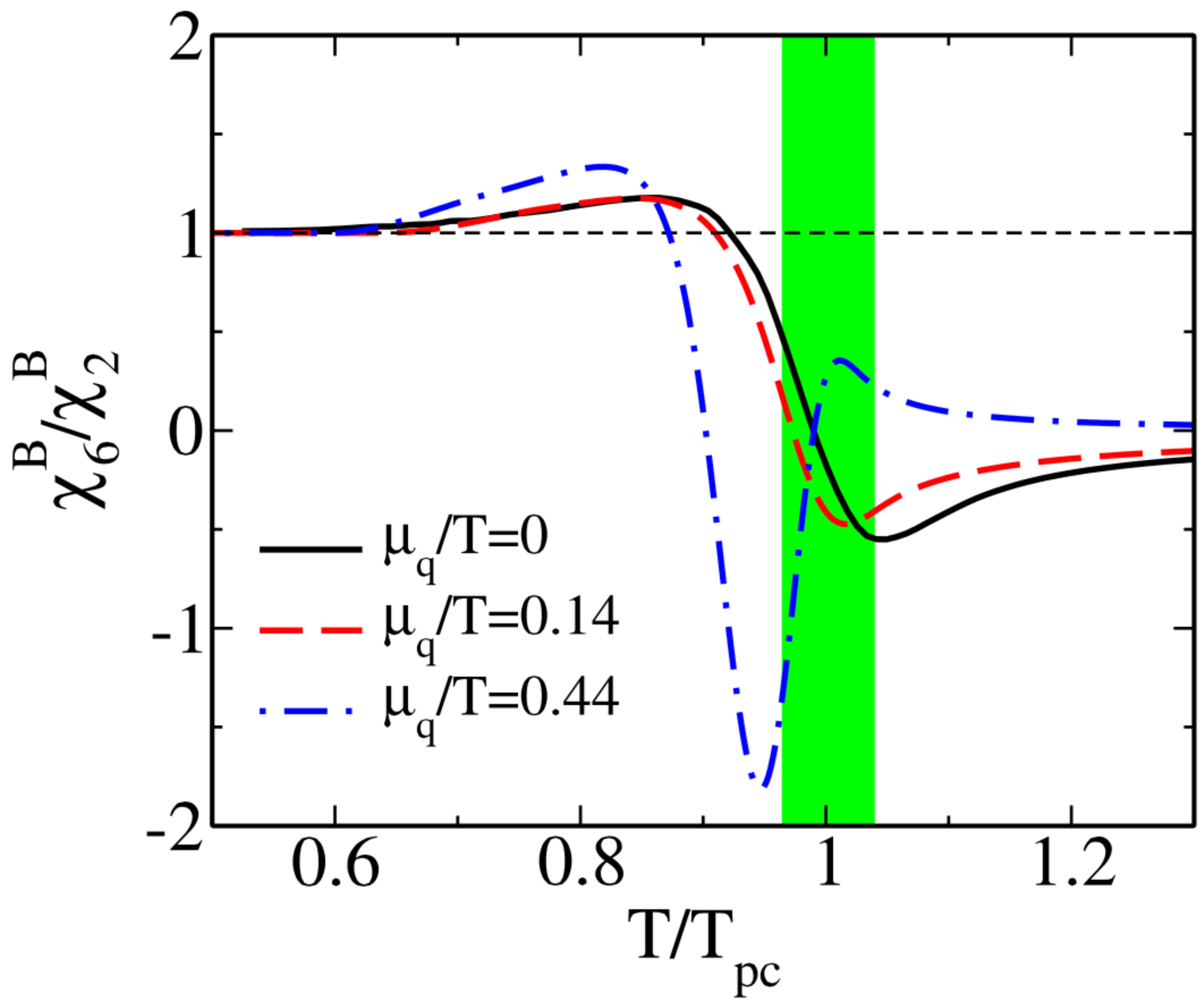
	0-10%	10-80%
Run10	~160M	~200M
Run11	~50M	~450M

Lower beam energy?

- ✓ Positive C_6 is predicted in $\sqrt{s_{NN}}<60$ GeV ($\mu_B/T<0.5$).
- ✓ STAR collected ~550M events at $\sqrt{s_{NN}}$ = 54.4 GeV in 2017.

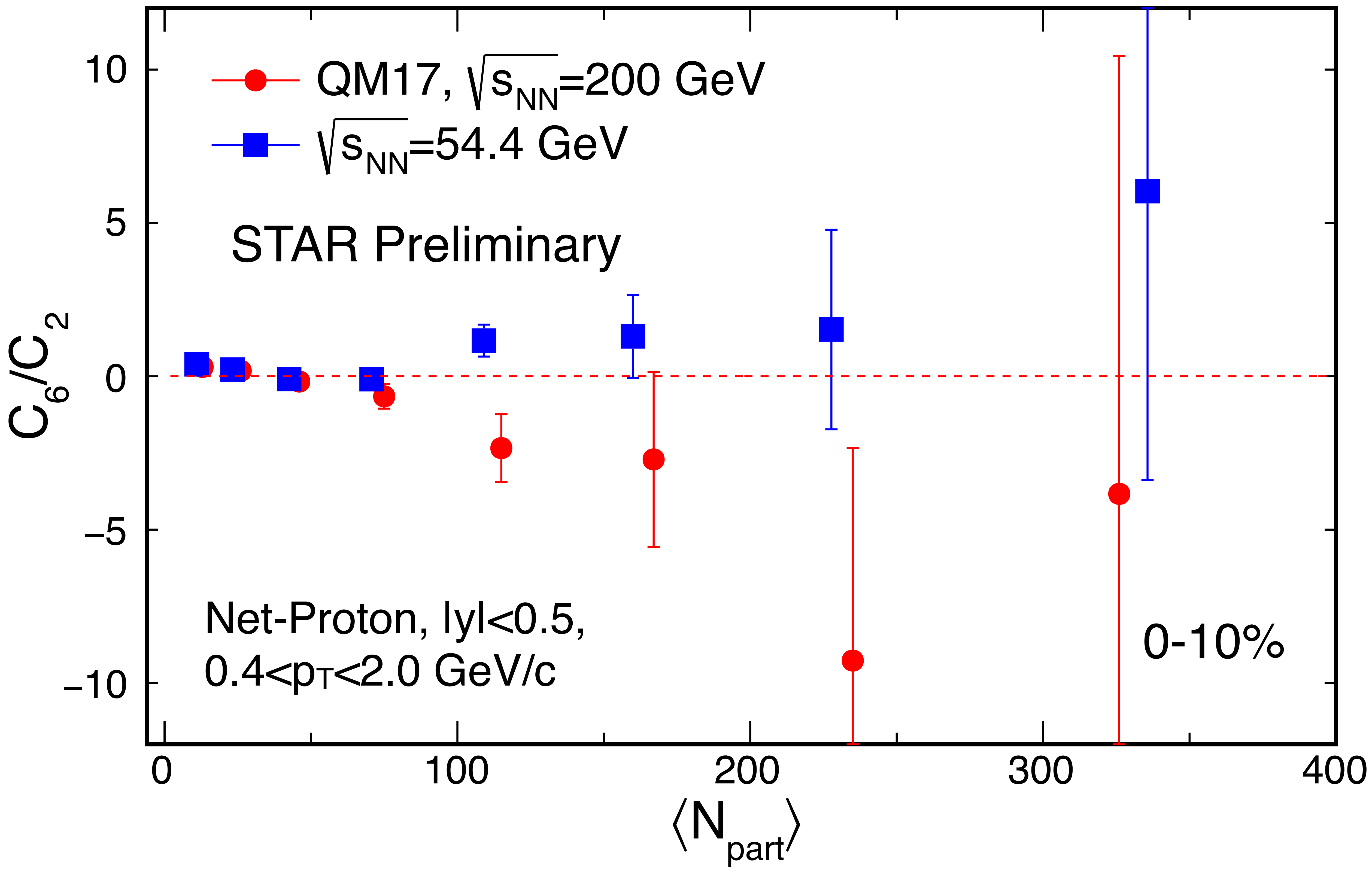
Friman et al, Eur. Phys. J. C (2011) 71:1694

If freeze-out occurs close to the chiral crossover temperature the sixth order cumulant of the net baryon number fluctuations will be negative at LHC energies as well as for RHIC beam energies $\sqrt{s_{NN}} \gtrsim 60$ GeV, corresponding to $\mu_B/T \lesssim 0.5$. This is in contrast to hadron resonance gas model calculations which yield a positive sixth order cumulant.



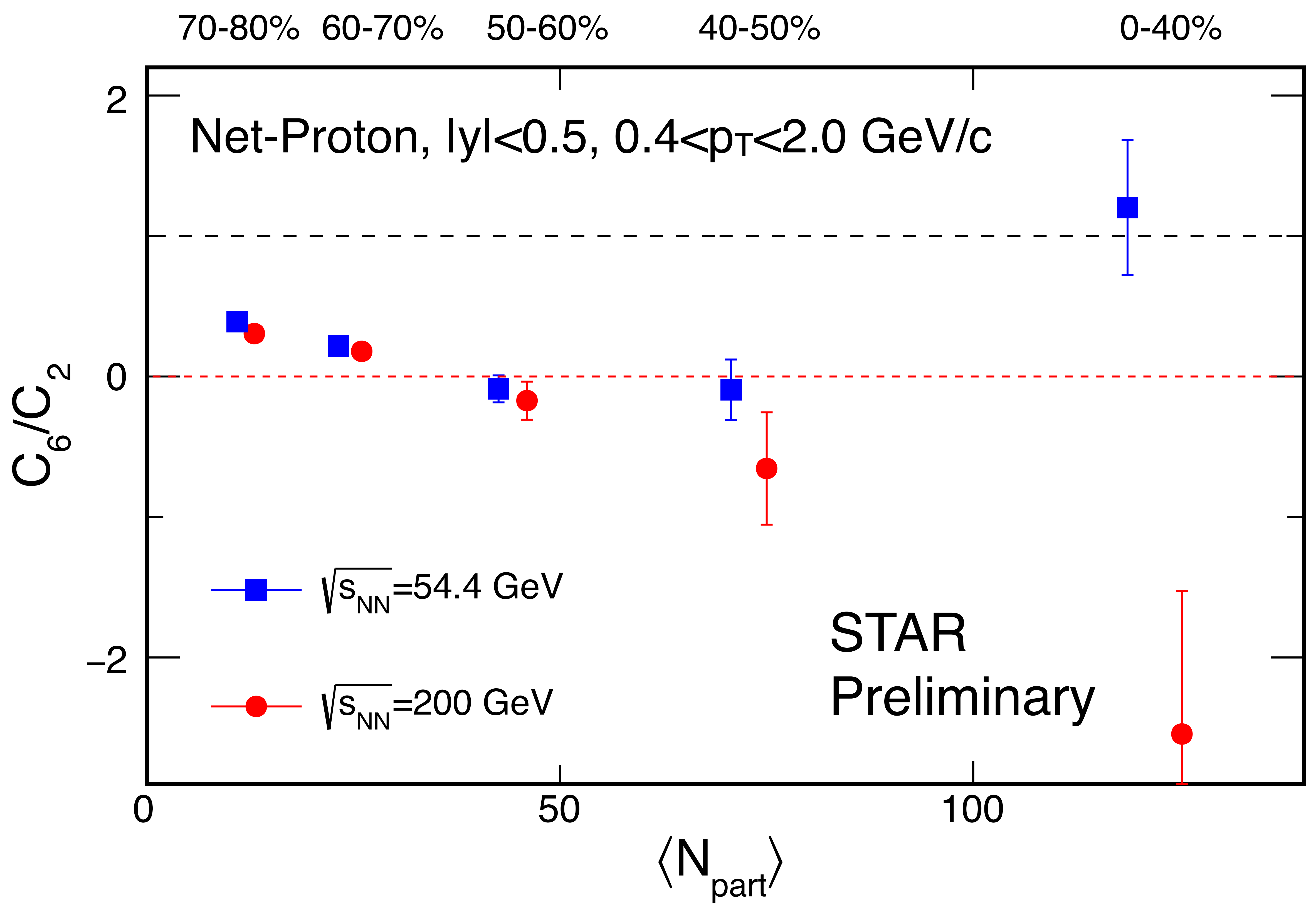
Net-proton C_6/C_2 at $\sqrt{s_{NN}}$ = 54.4 GeV

✓ Positive values are observed systematically from peripheral to central collisions.



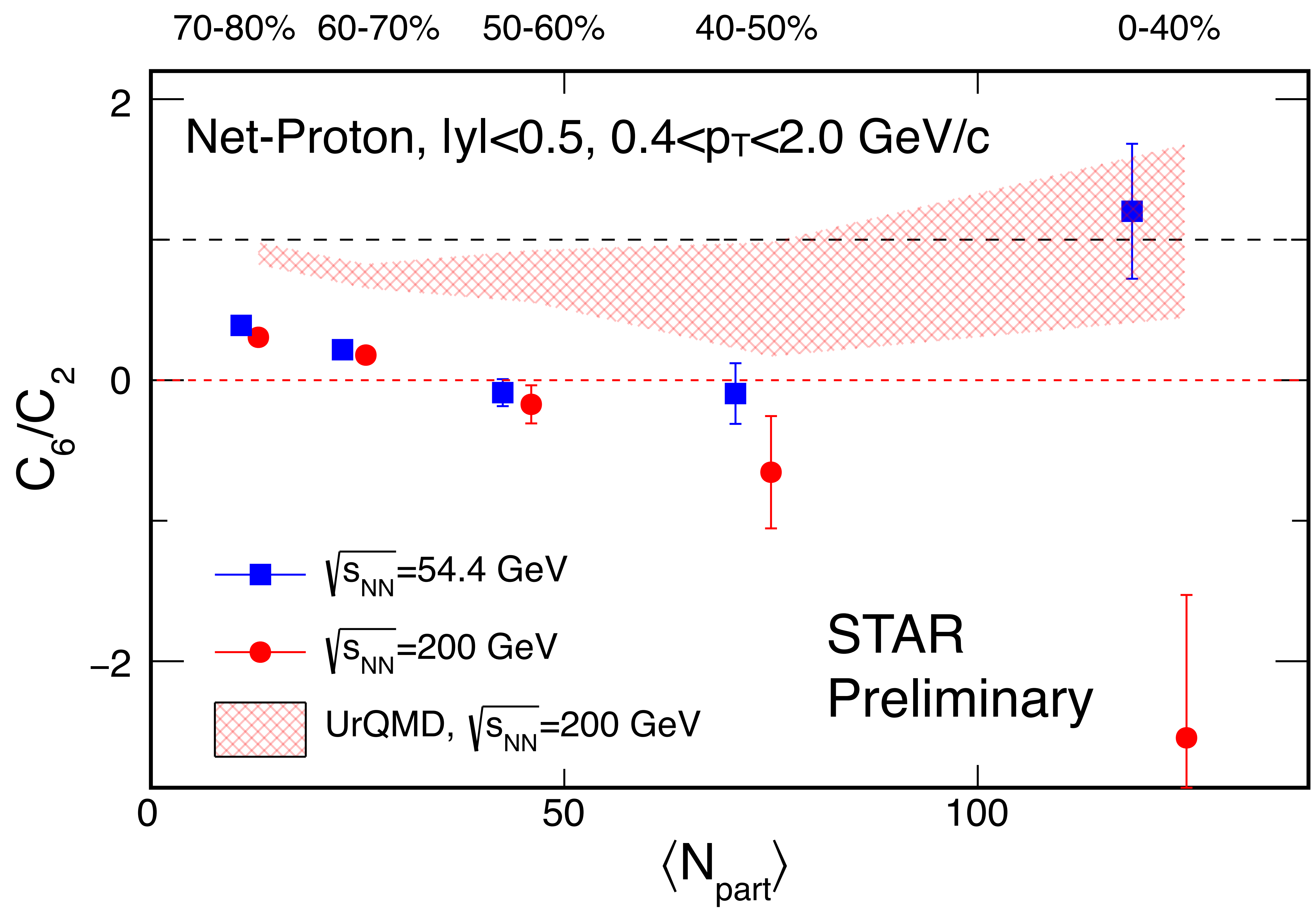
0-40% centrality

✓ Clear separation and opposite signs between two energies in 0-40%.



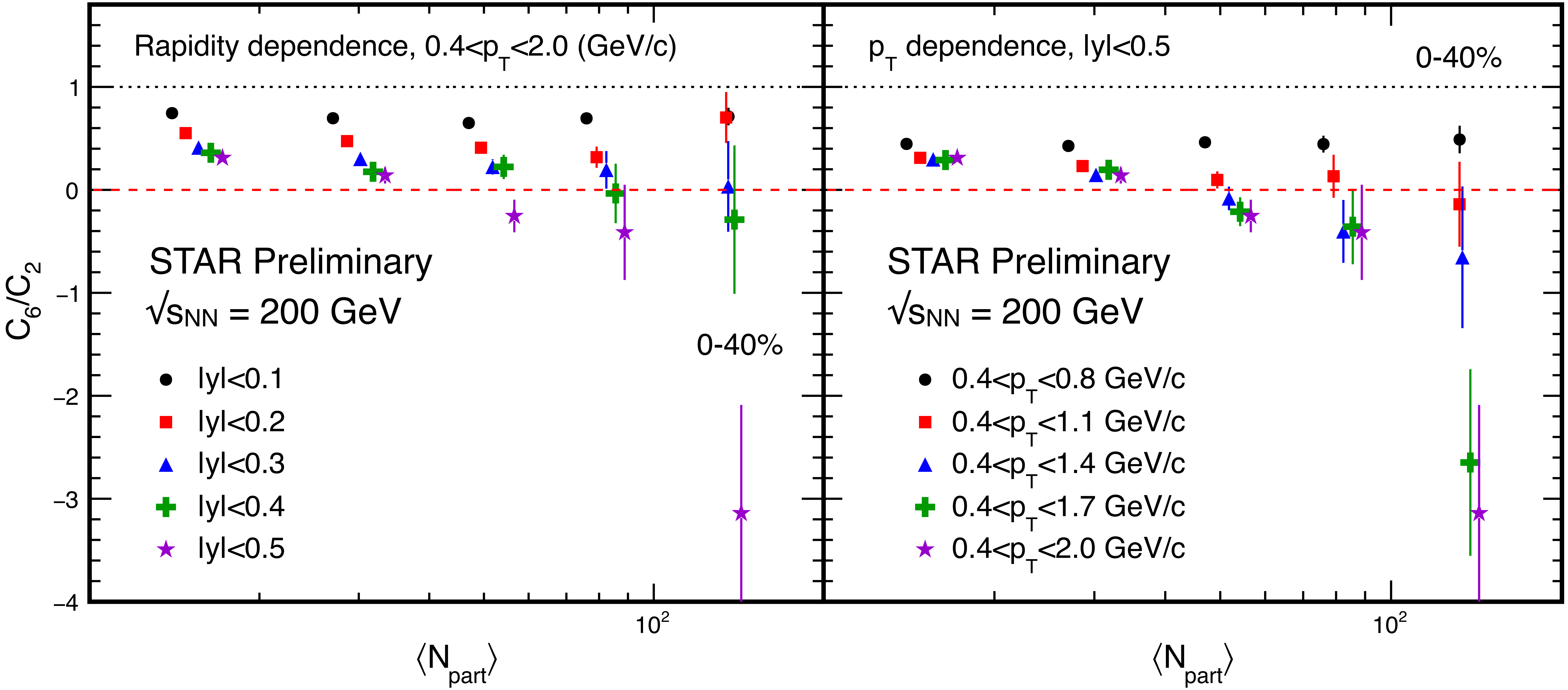
UrQMD

- ✓ Clear separation and opposite signs between two energies in 0-40%.
- ✓ UrQMD result shows positive signs for all centralities at $\sqrt{s_{NN}}$ = 200 GeV.



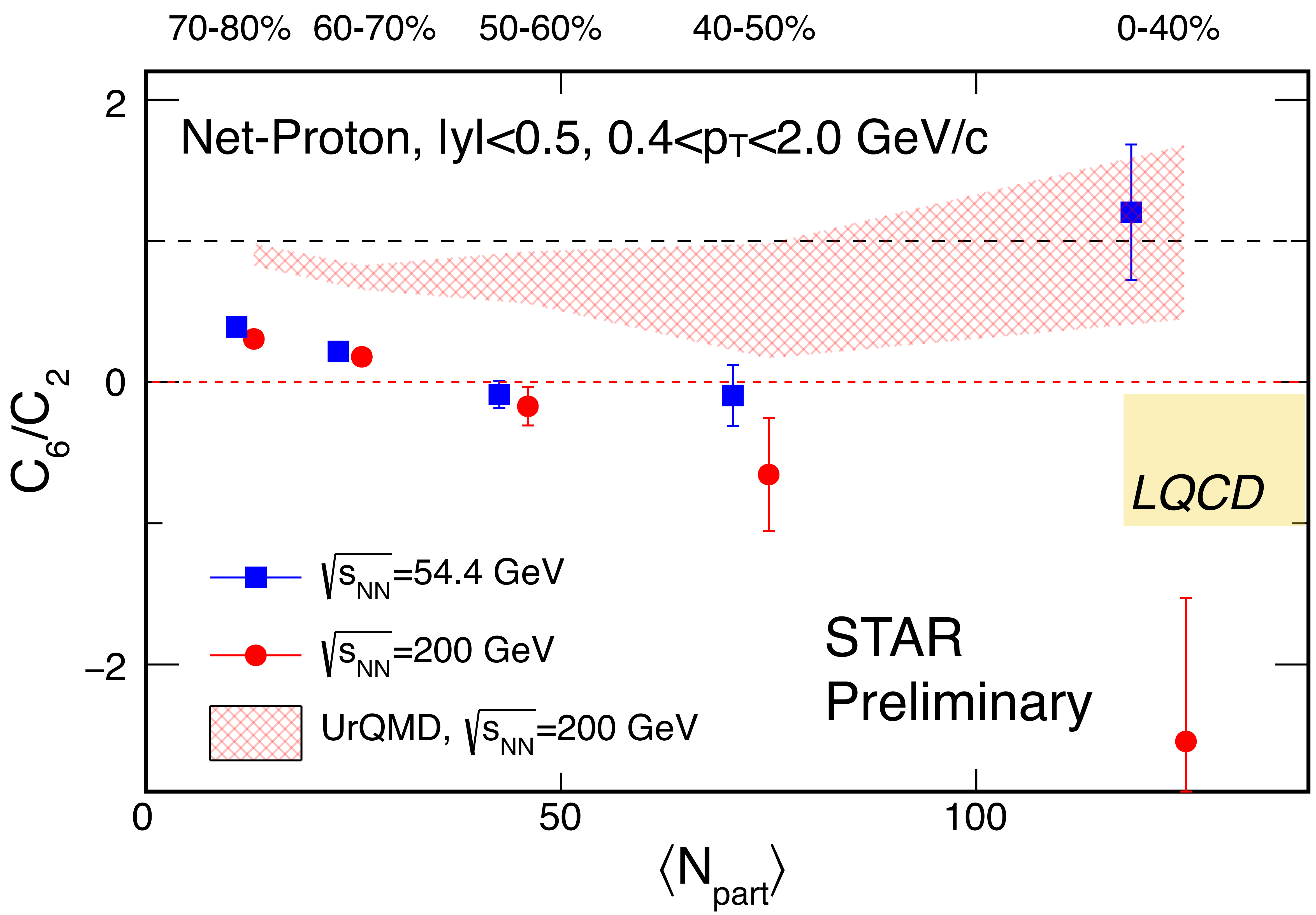
Acceptance dependence

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



0-40% centrality

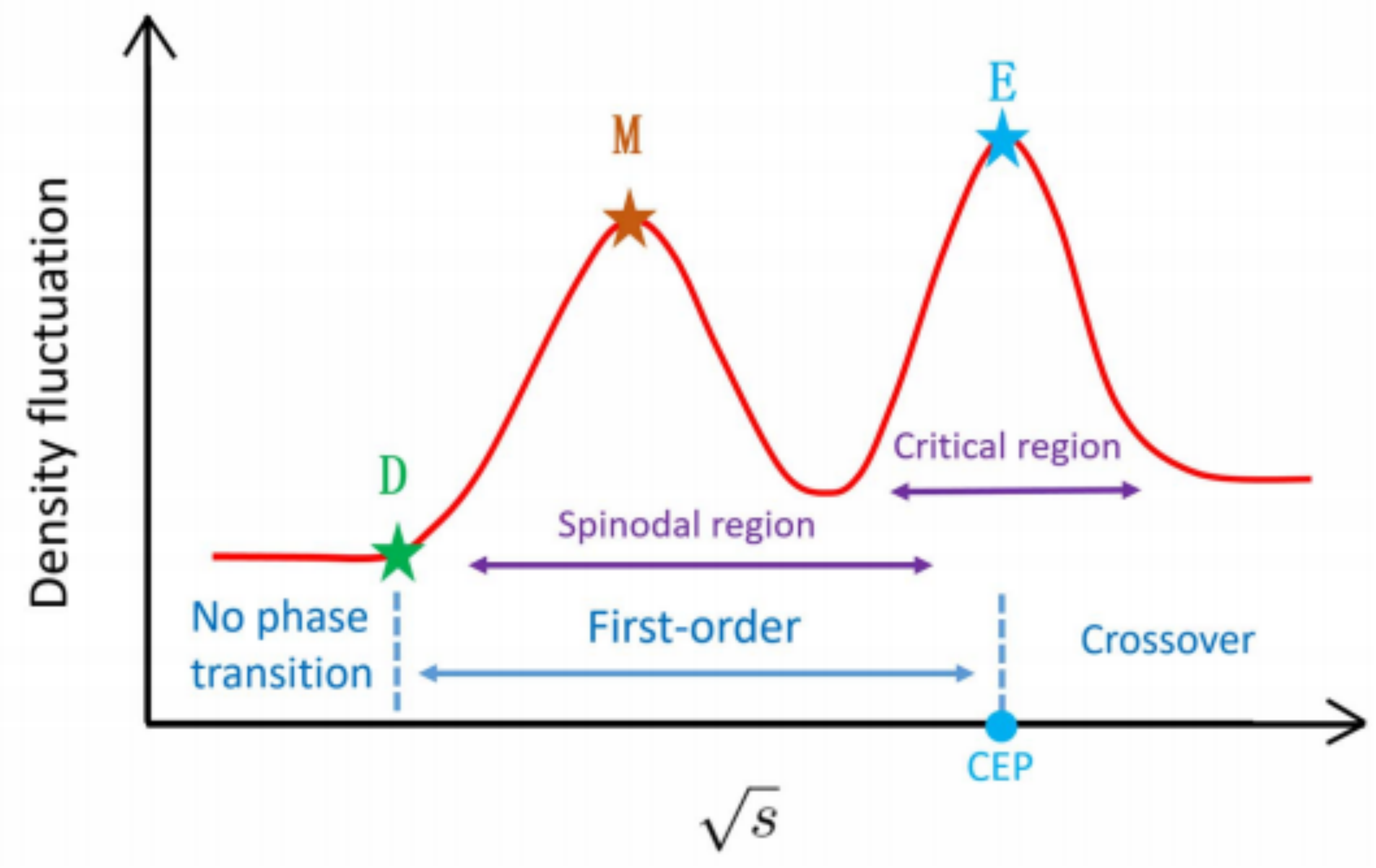
✓ Results from the central bin of 200 GeV Au+Au collisions are consistent with the LQCD prediction → remittance of chiral phase transition?



LQCD : A. Bazavov et al, PhysRevD.95.054504

Light nuclei production

✓ **Baryon density fluctuation becomes large near the critical point or 1st-order phase transition**



Coalescence + nucleon density fluctuation

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3/2} N_p\langle n\rangle(1+\alpha\Delta n),$$

$$N_{^3H} = \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3} N_p\langle n\rangle^2[1+(1+2\alpha)\Delta n],$$

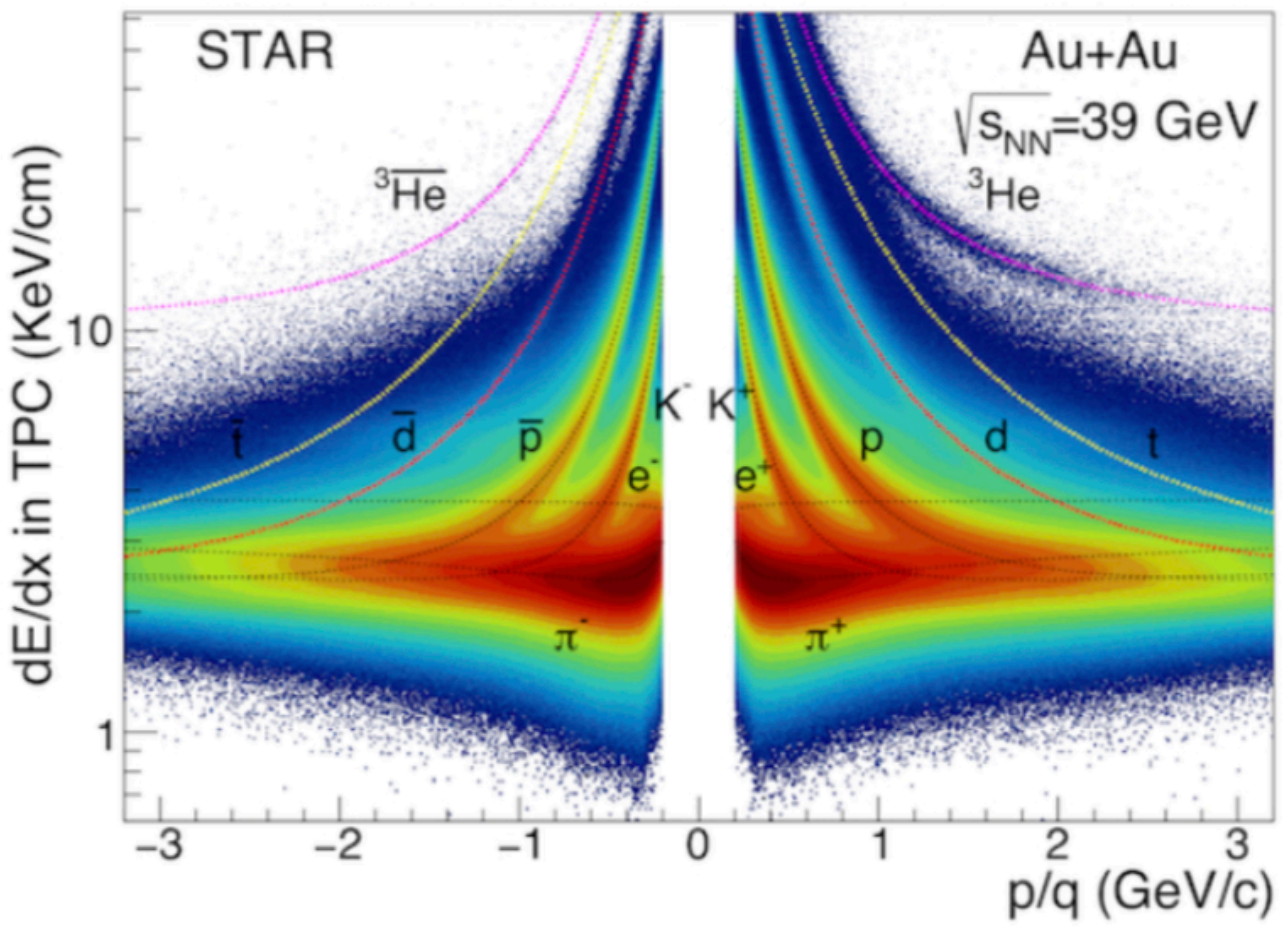
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

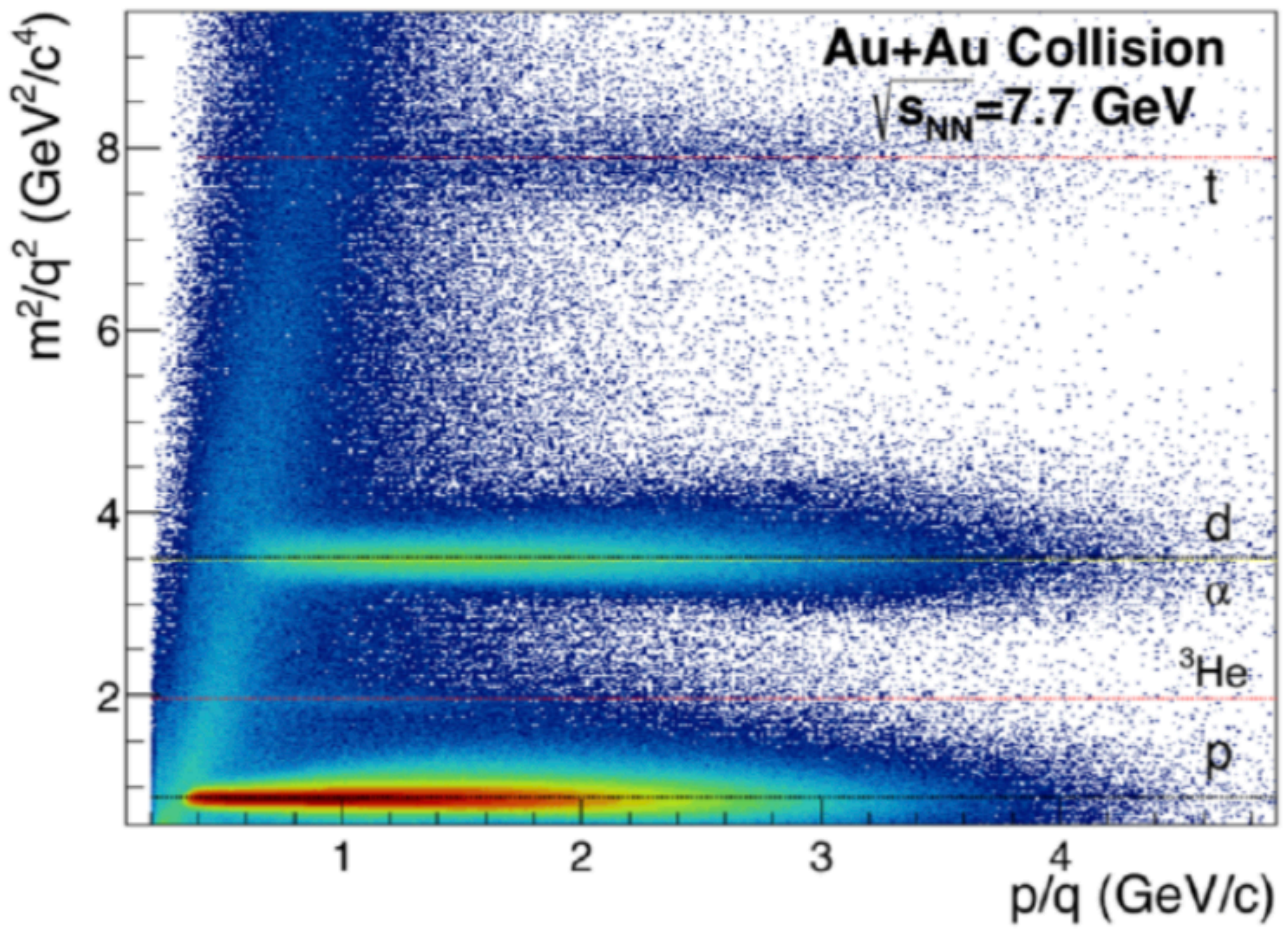
Neutron density fluctuation

$$\Delta n = \langle(\delta n)^2\rangle / \langle n\rangle^2$$

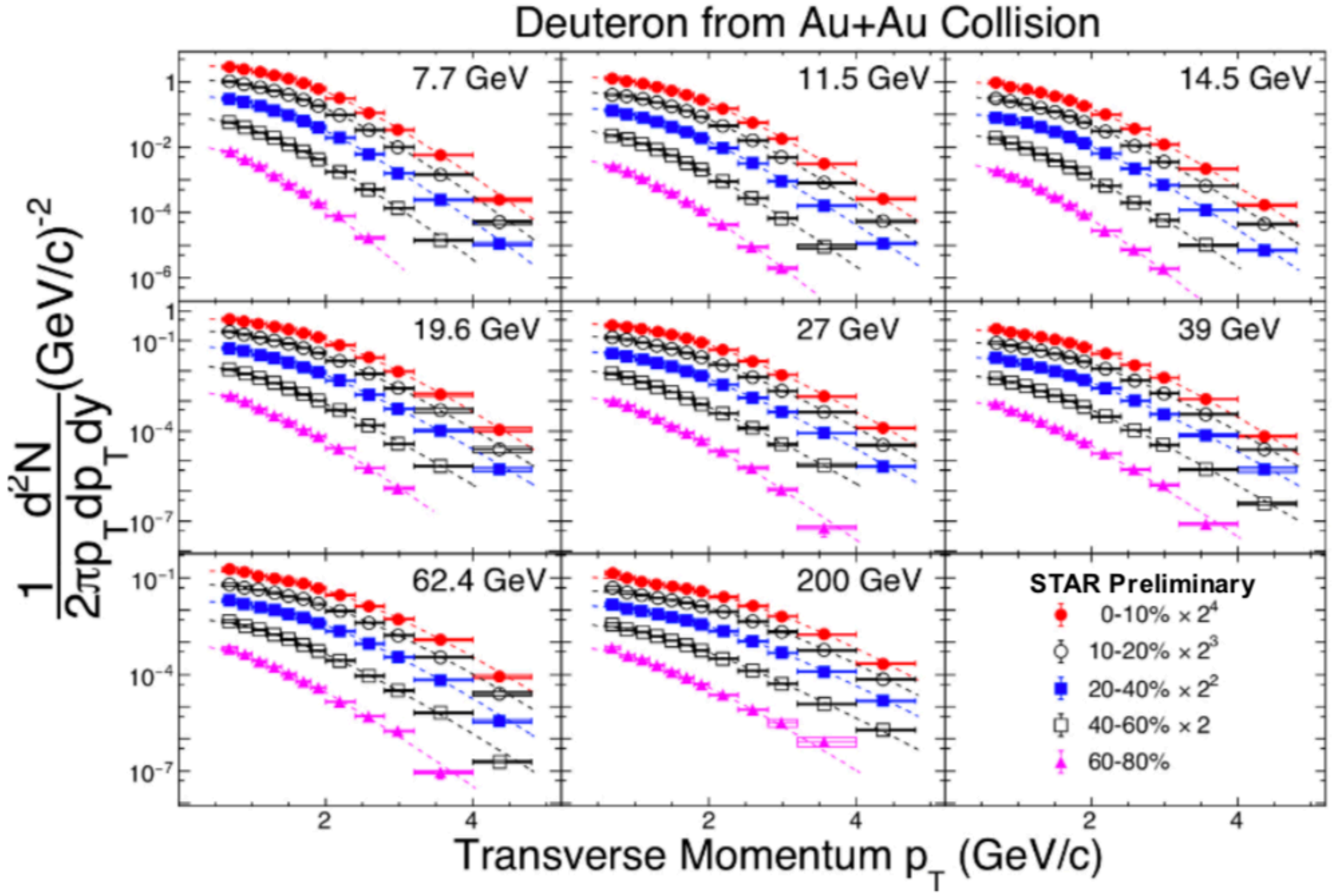
K. J. Sun, L.W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L.W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

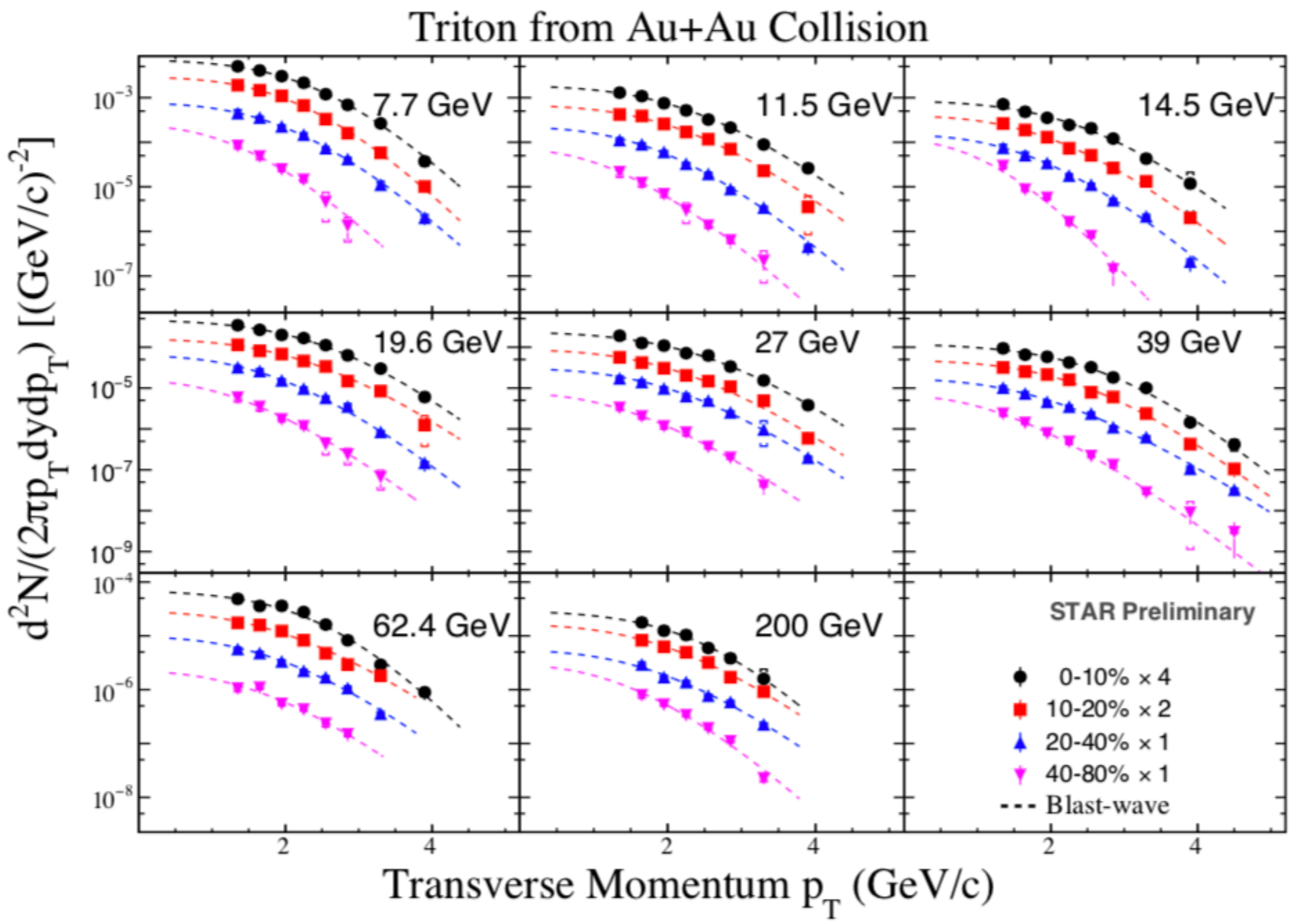
Light nuclei production





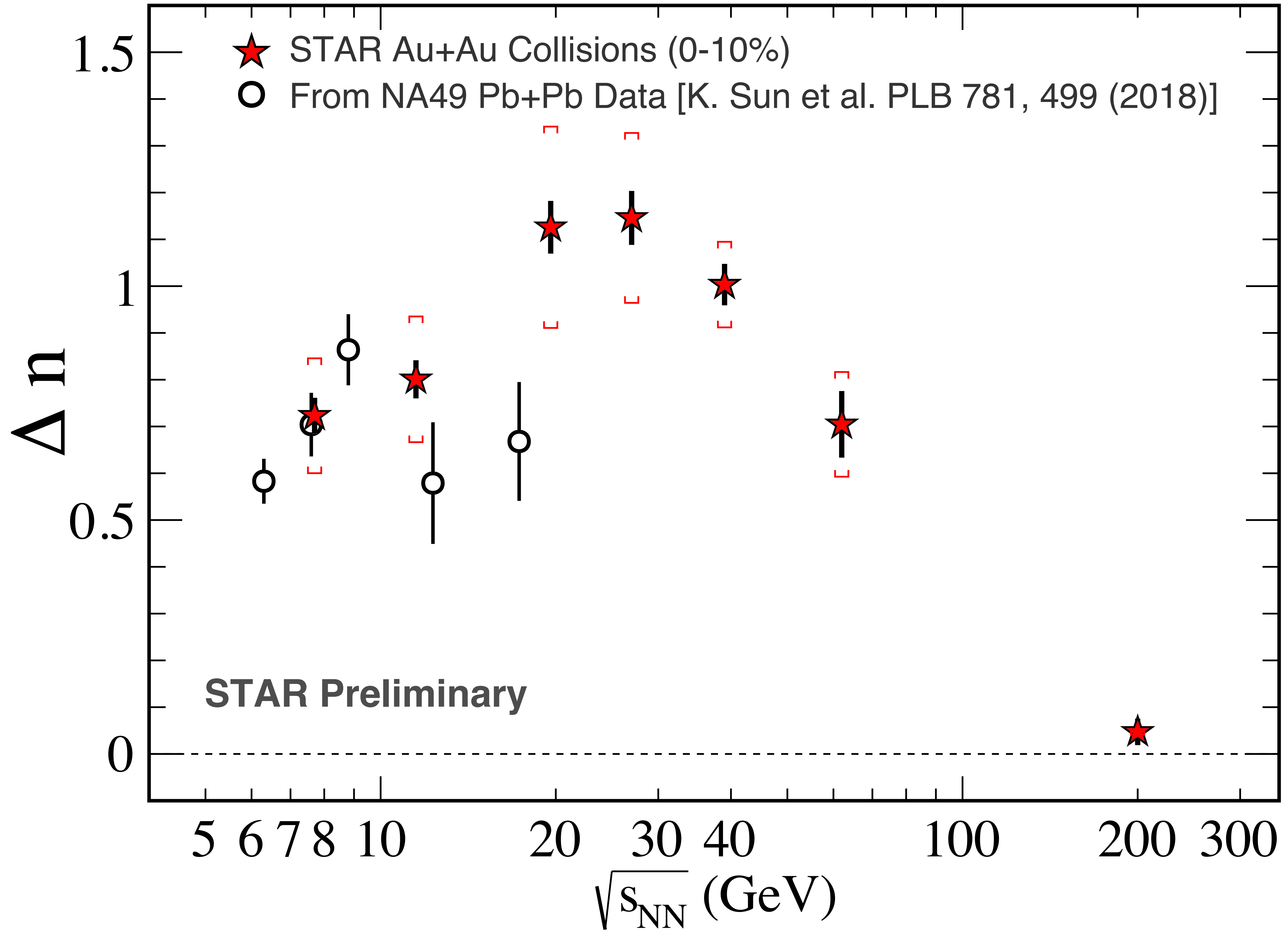
✓ **Deuteron and triton yields have been measured in BES-I energies.**





Neutron density fluctuation

✓ **Non-monotonic energy dependence is observed in Au+Au collisions with a peak around 20-30 GeV.**



$$\frac{\langle(\delta n)^2\rangle}{\langle n\rangle^2} = \Delta n = \frac{1}{g}\frac{N_t N_p}{N_d^2} - 1$$

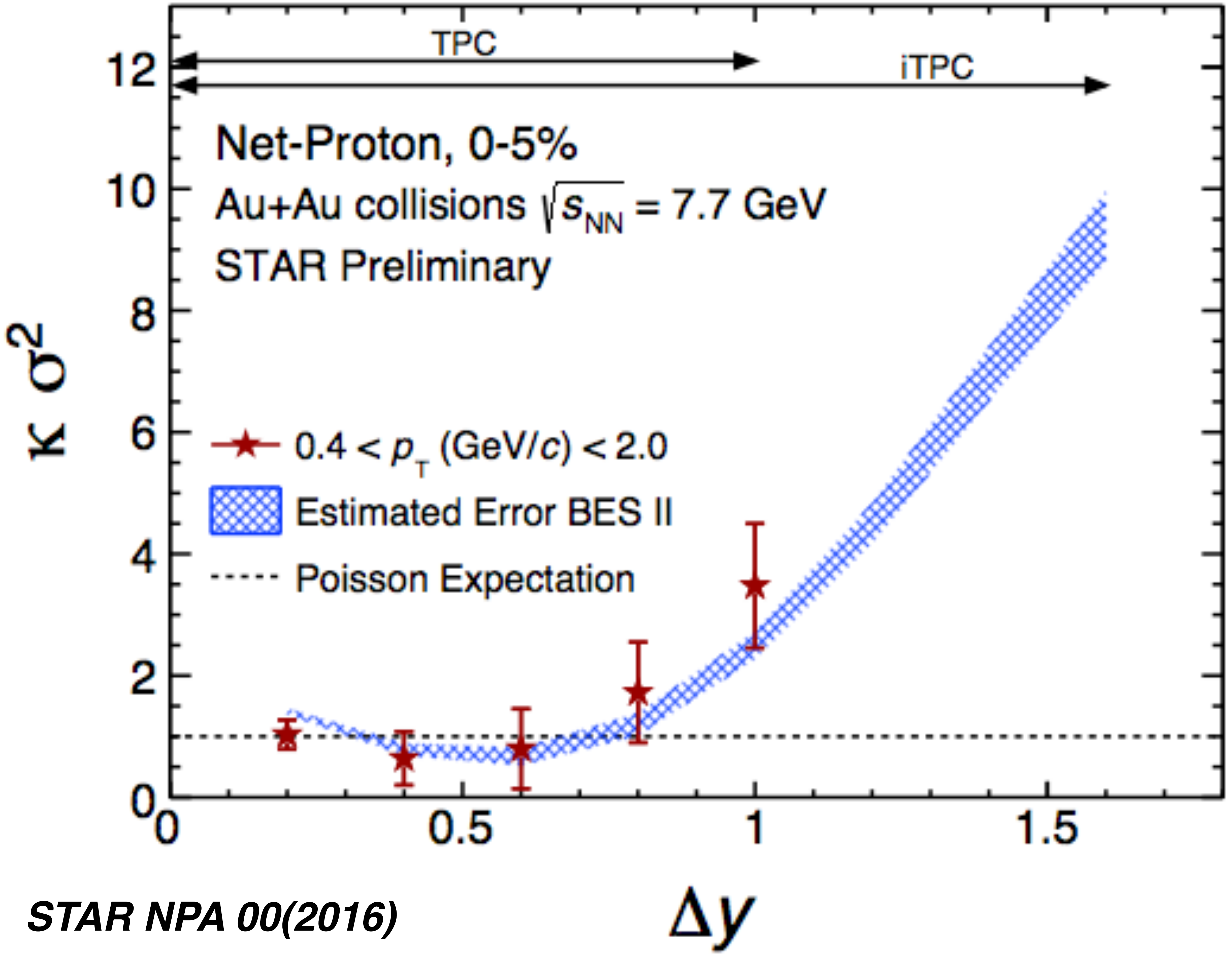
N_t : Triton yield
N_d : Deuteron yield
N_p : Proton yield

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 has started this year.**
- ✓**Luminosity has been improved with the electron cooling system.**
- ✓**Inner TPC has been fully integrated, which extends the pseudorapidity coverage from 1.0 to 1.5**
- ✓**New centrality definition by EPD.**
- ✓**eTOF for fixed-target program**
- ✓**Higher-order fluctuation measurement with small errors and large acceptance.**

Beam Energy Scan Phase II



STAR NPA 00(2016)

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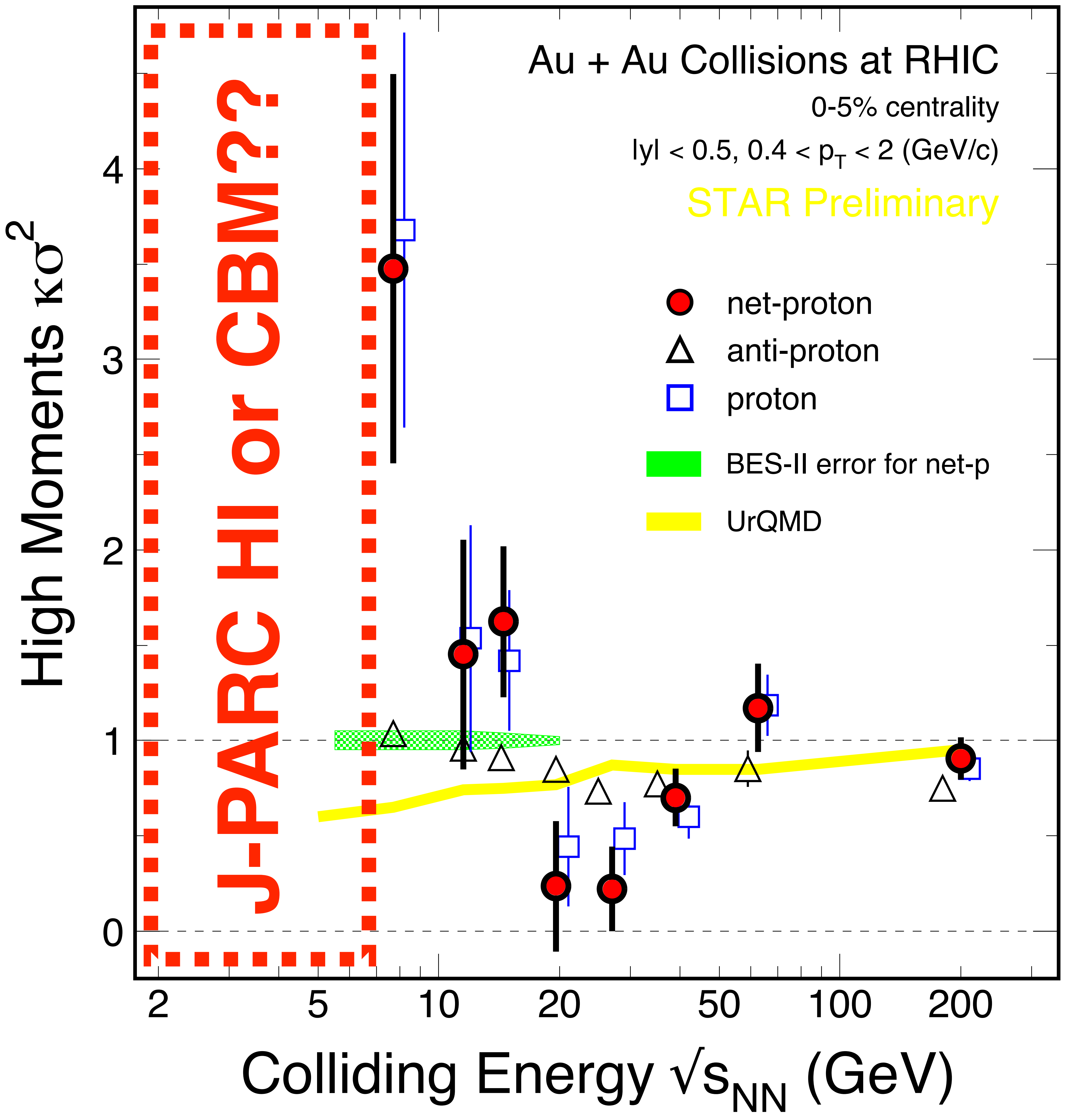
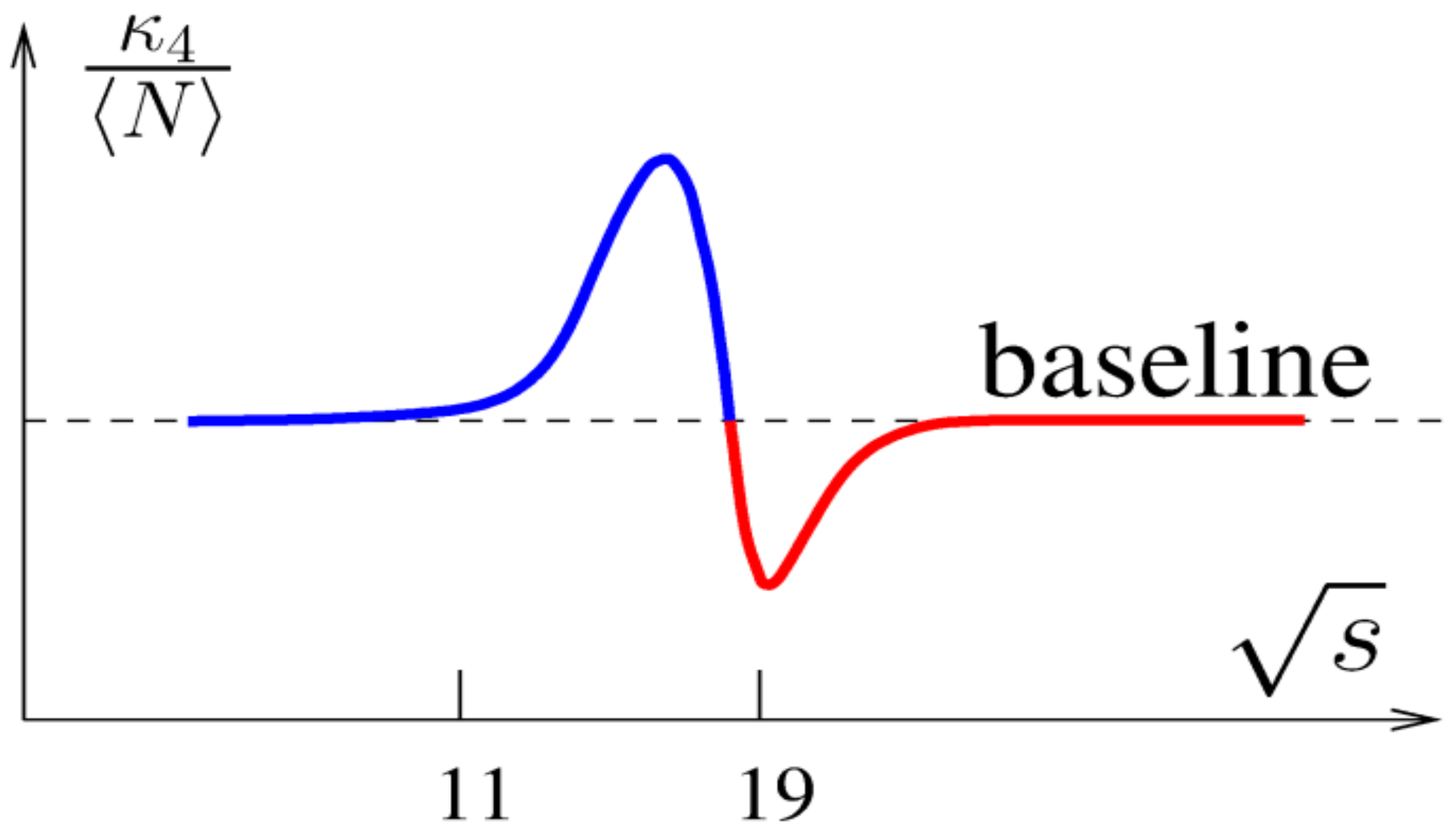
Critical point search in BES-II

STAR Data : PoS CPOD2014 (2015)019



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



Summary

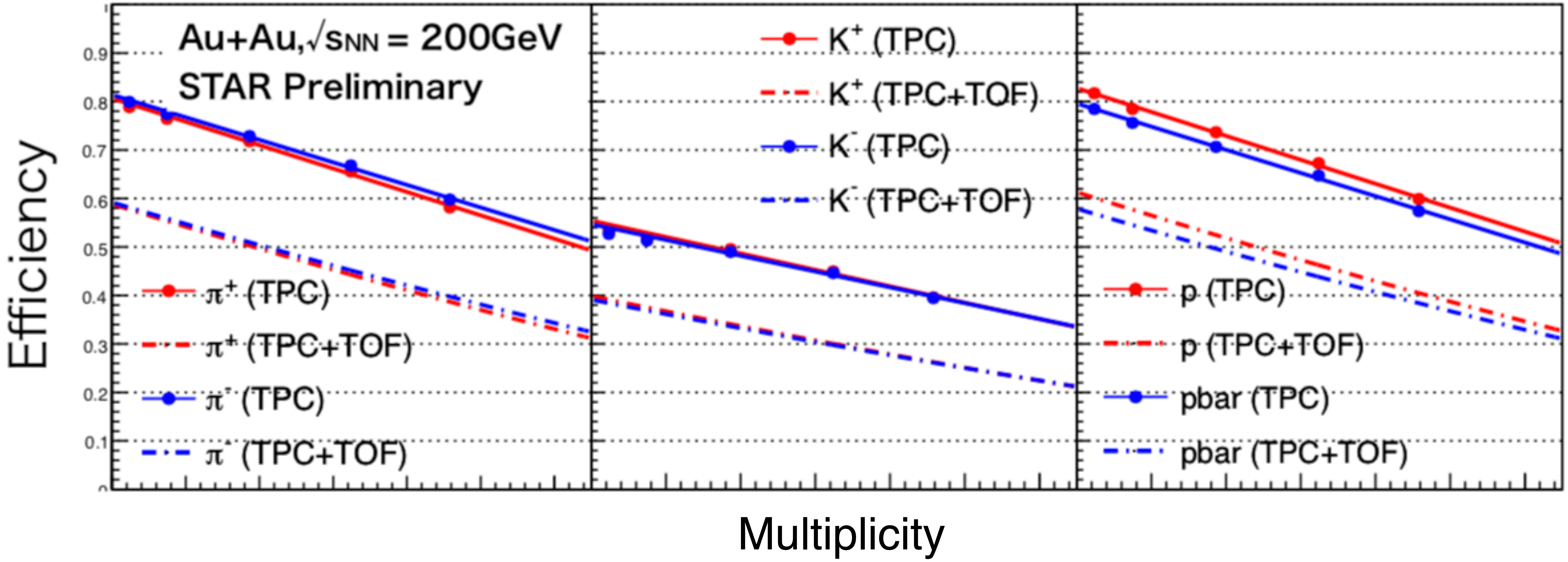
- Freeze-out conditions have been determined in terms of chemical/kinetic freeze-out in various collision energies.
- Search for the softest point as a signal from the 1st-order phase transition, by measuring v_1 slope in various collision energies.
- Non-monotonic behavior has been observed for net-proton $\kappa\sigma^2$ in the central Au+Au collisions as a function of collision energy, which is qualitatively similar to the theoretical prediction.
- Non-monotonic energy dependence is observed for neutron density fluctuation in central Au+Au collisions.
- BES-II will shrink the statistical uncertainties at 7.7—19.6 GeV region.

Thank you for your attention

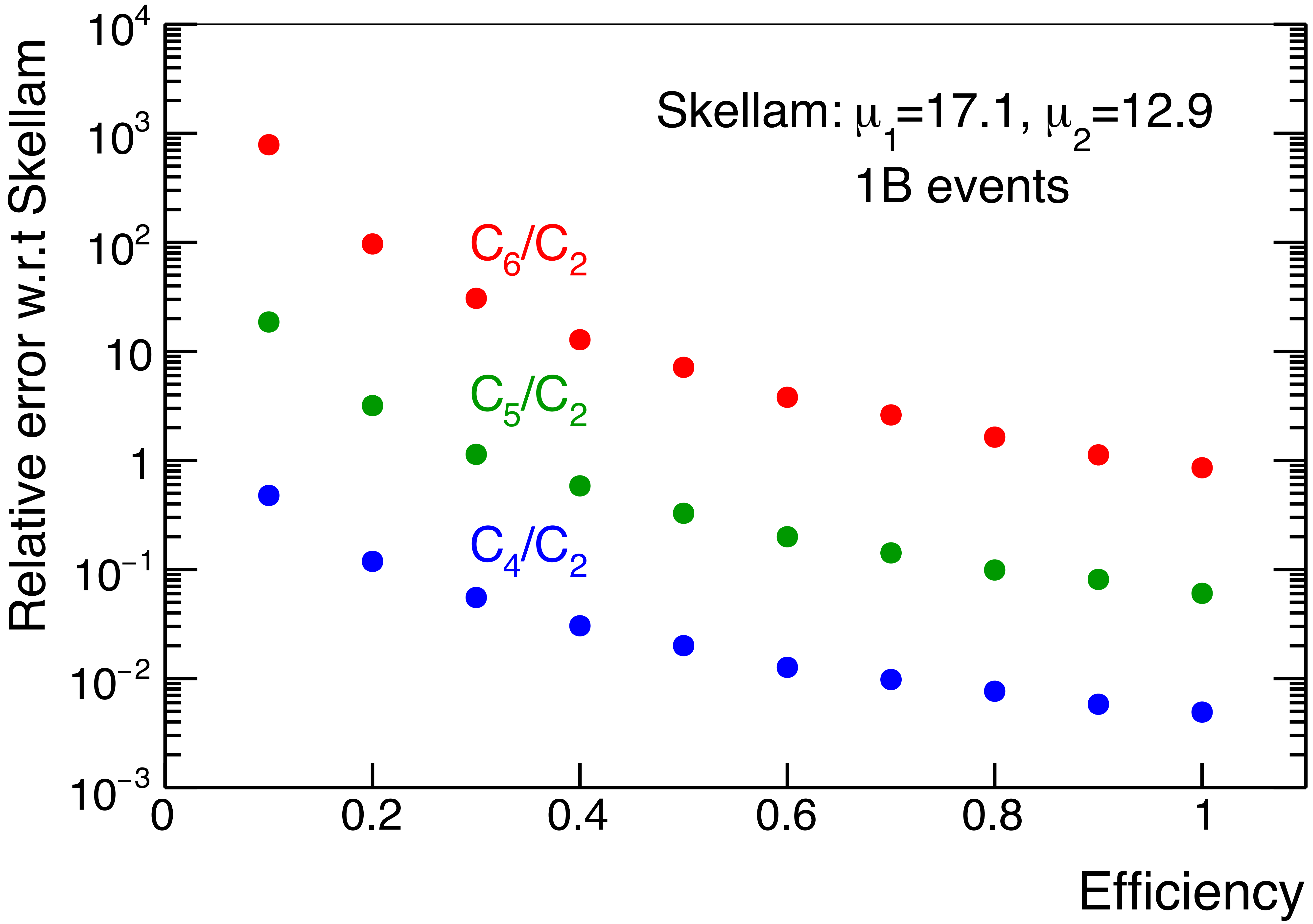
Back up

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



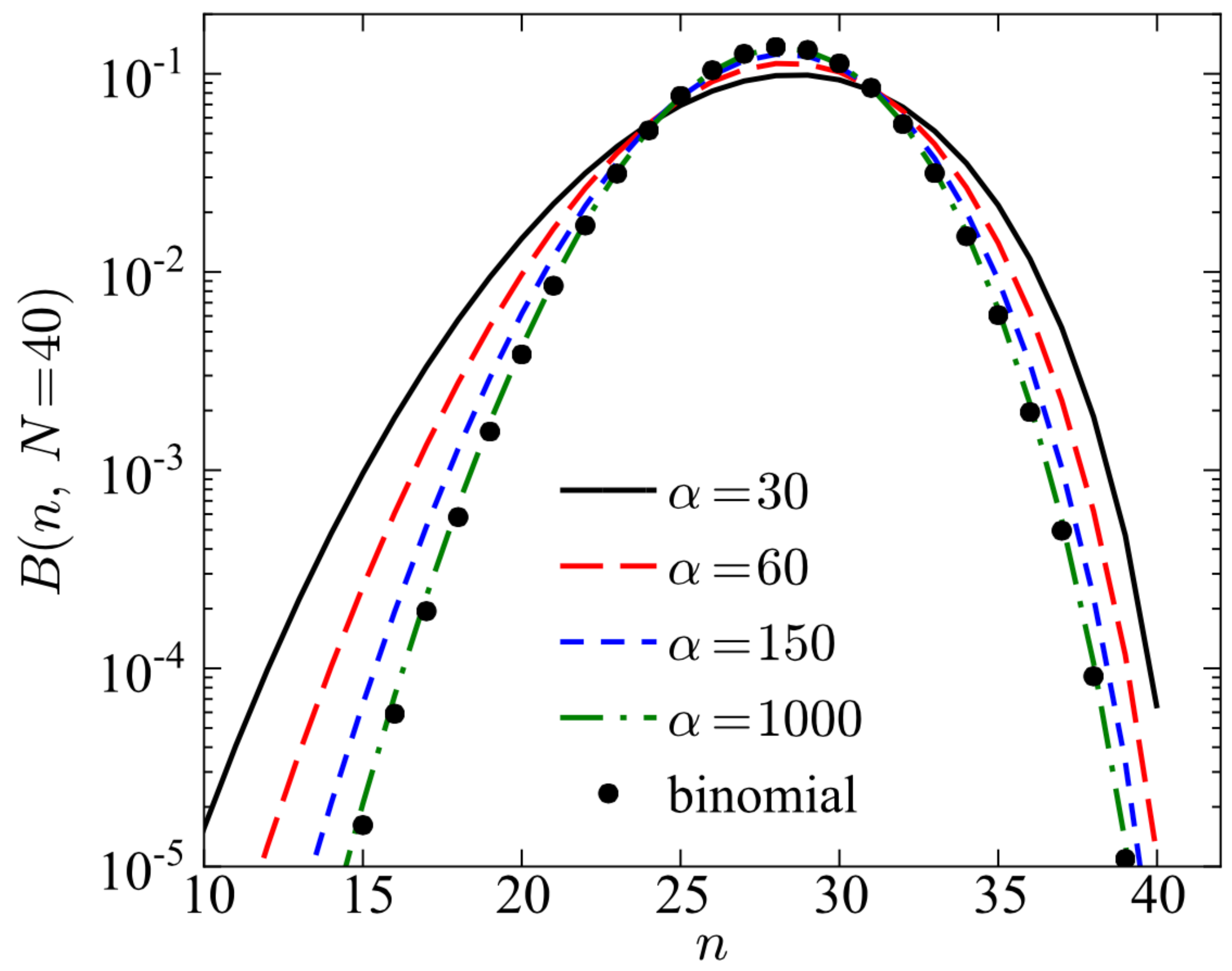
- ✓ **Error estimation using a simple toy model with Skellam distributions.**
- ✓ **One order of cumulant increases, statistical errors becomes x10. ($C_4 \rightarrow C_6$: x100 err)**
- ✓ **C_6 measurement is more challenging than C_4.**

Non-binomial efficiencies

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

1. Experimental effects

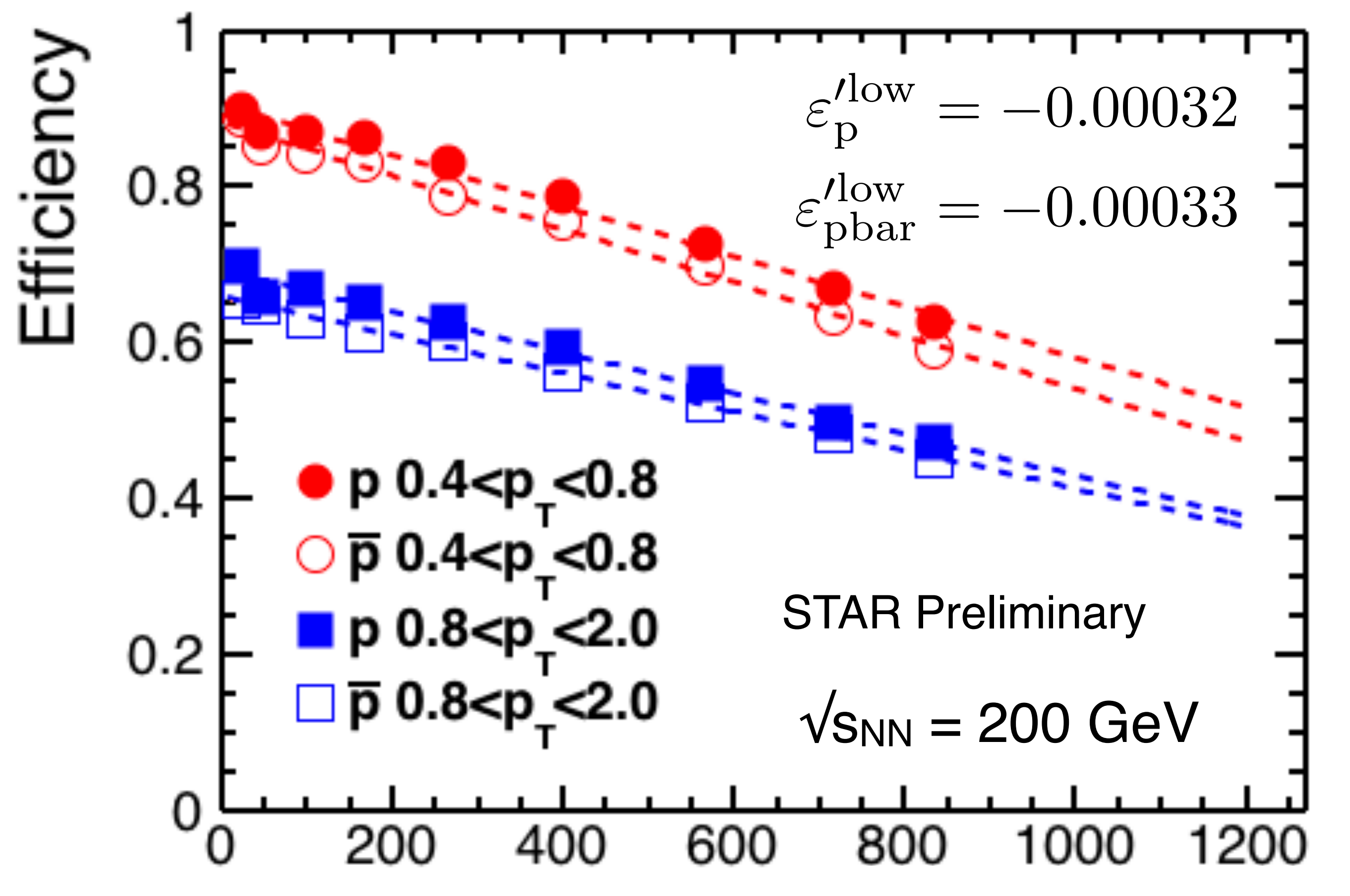
✓ The detector efficiency may not be binomial, which would be due to the particle mis-identification, track splitting/merging effects, and many other reasons.



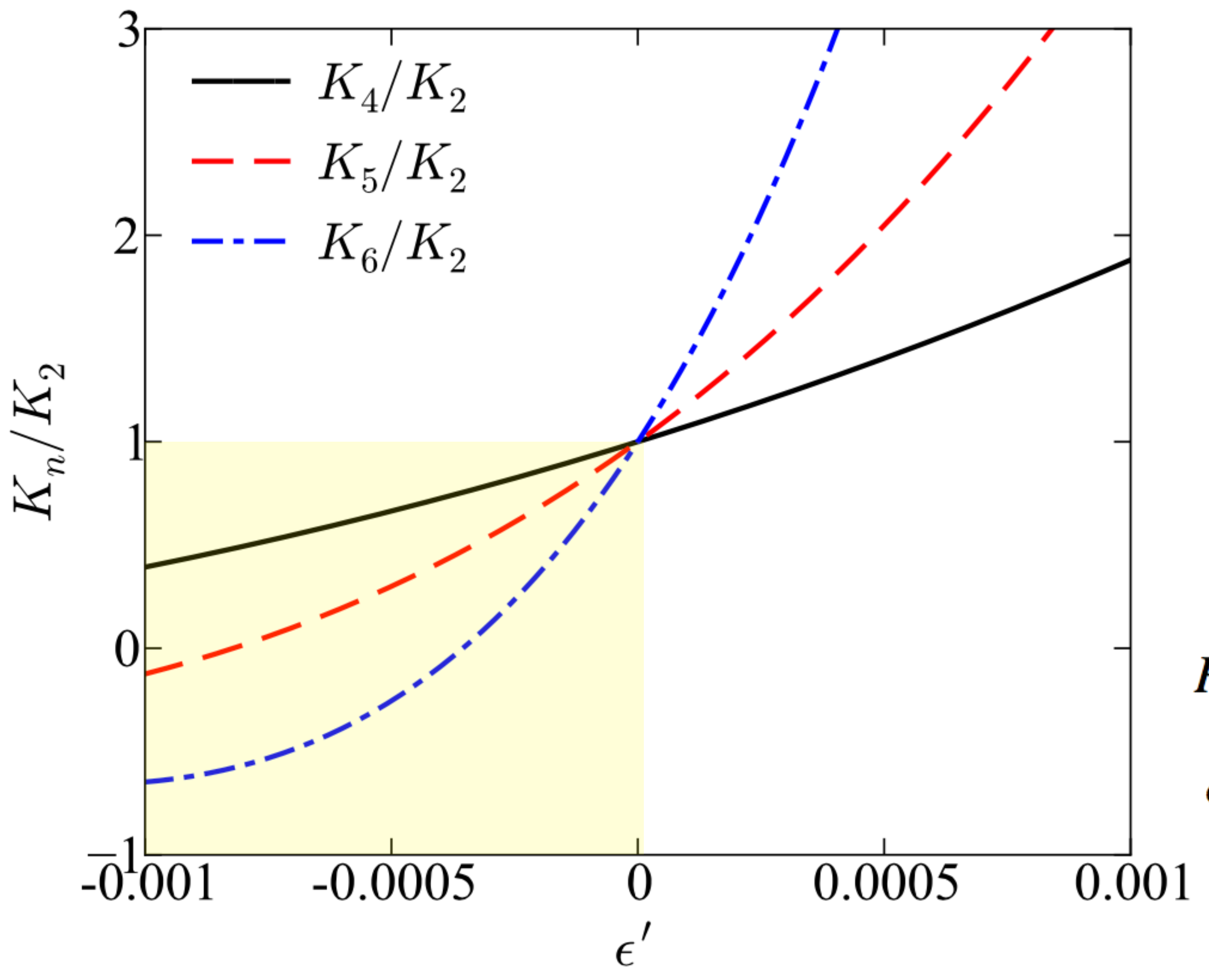
➡ *One example of non-binomial distribution, Beta-binomial, is wider distribution than binomial*

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
$N_w = \alpha N_p \quad \varepsilon = N_w/(N_w + N_b)$