Beam Energy Scan (BES) の最新結果

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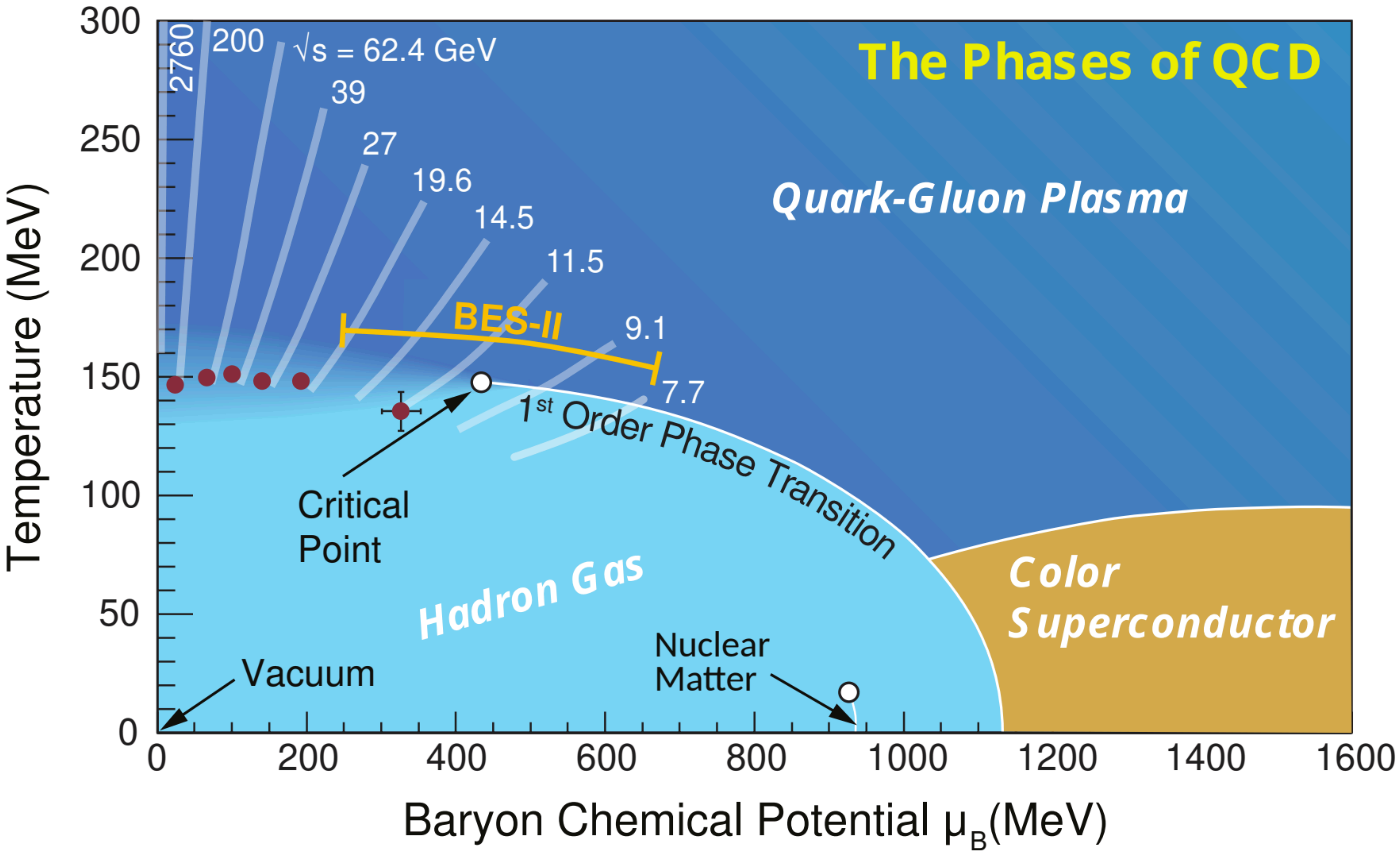
チュートリアル研究会　「高エネルギー重イオン衝突の物理：基礎・最先端・課題・展望」

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?**

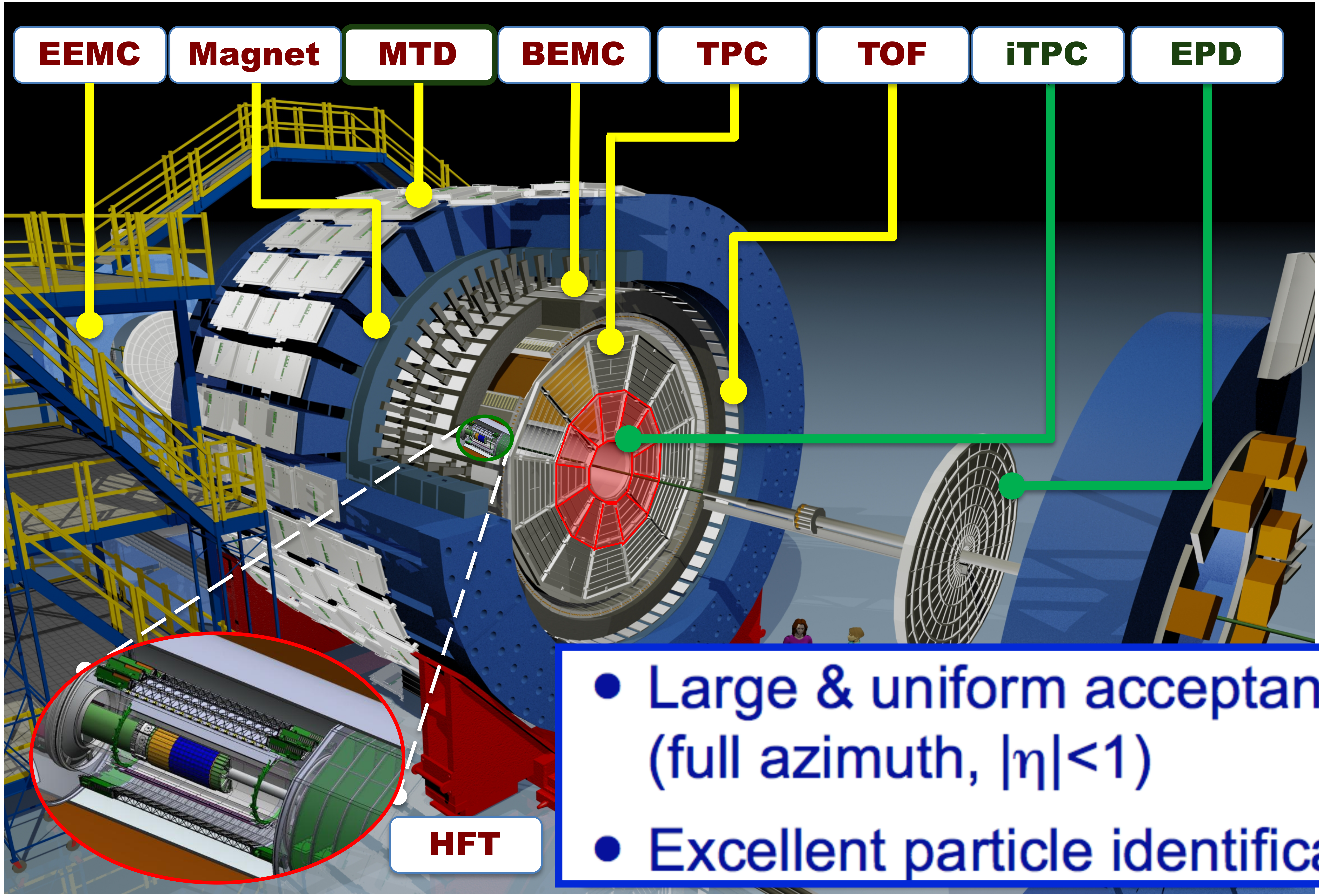
QCD phase diagram

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

√s (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)
7.7	~4	2010	420	140
11.5	~12	2010	315	152
14.5	~ 20	2014	266	156
19.6	~36	2011	205	160
27	~70	2011	155	163
39	~130	2010	115	164
62.4	~67	2010	70	165
200	~350	2010	20	166

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

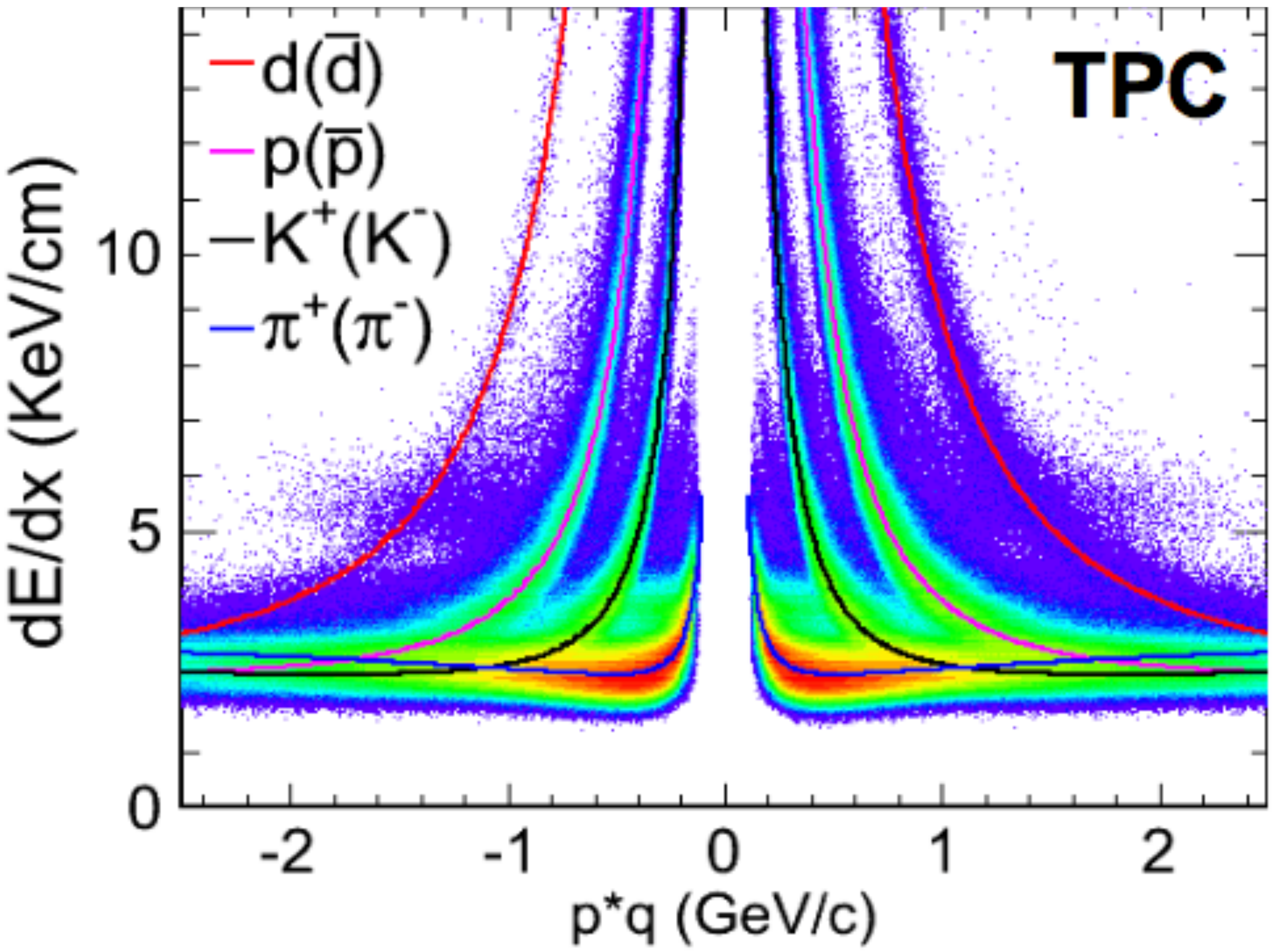
The STAR detector

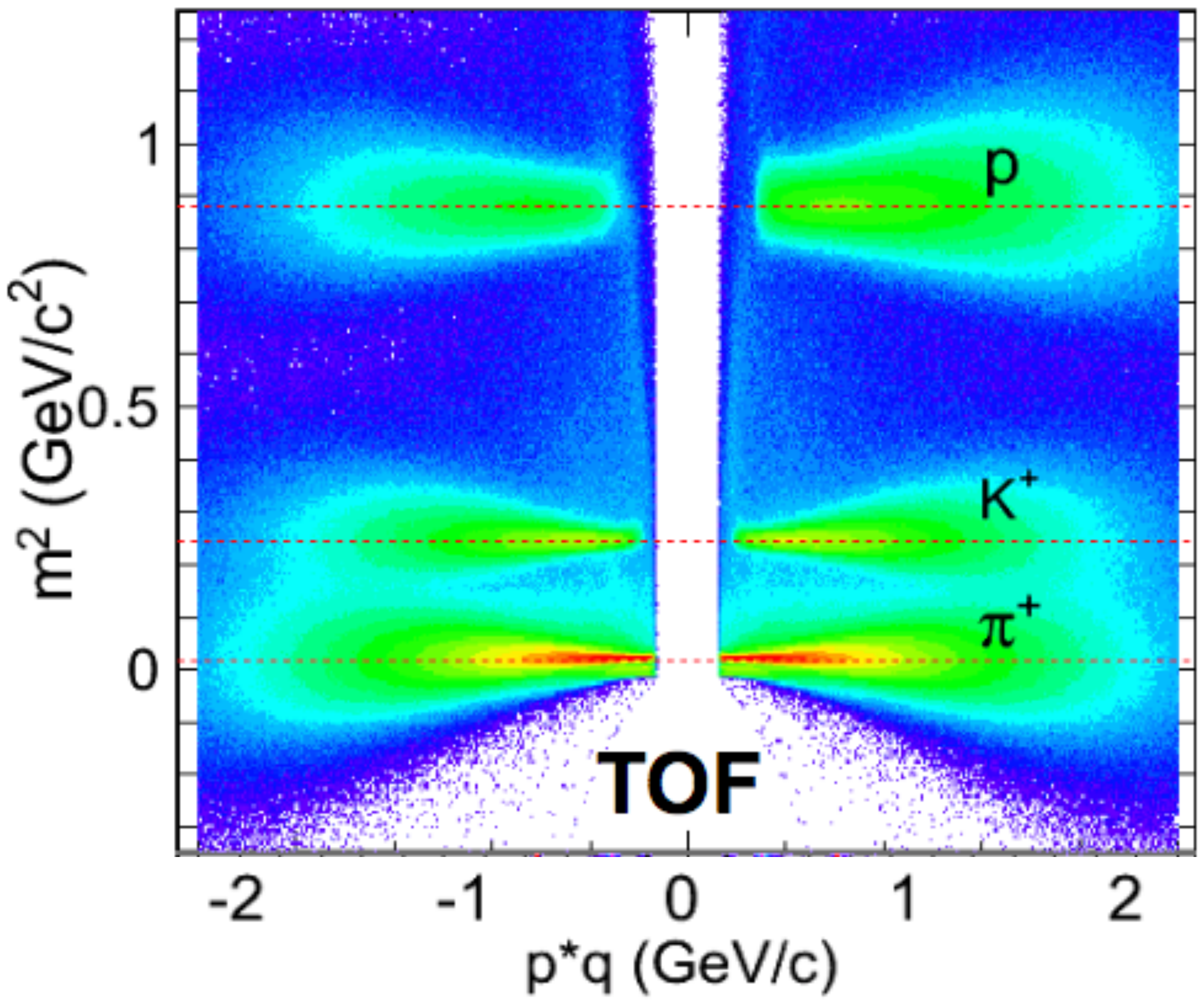


- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

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.





Outline

- ✓ **Experimental results**
  - Freeze-out conditions
  - The 1st-order phase transition
  - Critical point
- ✓ **BES-II**
- ✓ **Summary**

Questions related to this talk

✓ These questions will be addressed.

6. QCDの相図について何を議論することができるのか。

7. 重イオン衝突実験において、どのような測定によって高温・高密度ができたとするのか？

70. QCD臨界点、相転移について現在どこまでわかっているのか？

95. なぜ衝突実験では金原子核や鉛原子核をぶつけるのですか？小さい系を測るためにより小さな原子核同士はぶつけられないのですか？

Freeze-out conditions

Freeze-out dynamics

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

√s (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)
7.7	~4	2010	420	140
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200	~350	2010	20	166

✓ **Chemical freeze-out**

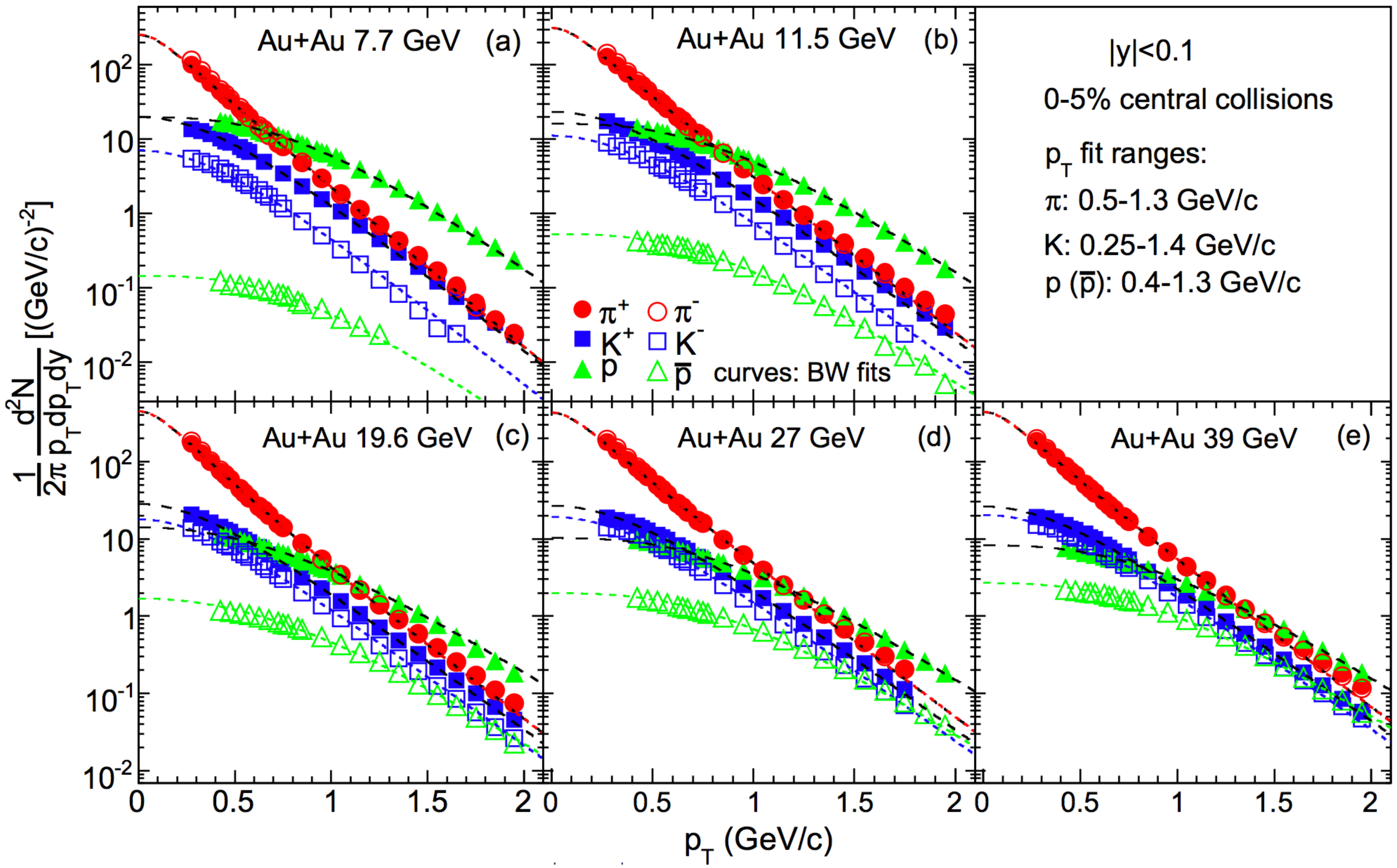
- **Inelastic collisions cease**
- **Yield ratios get fixed**

✓ **Kinetic freeze-out**

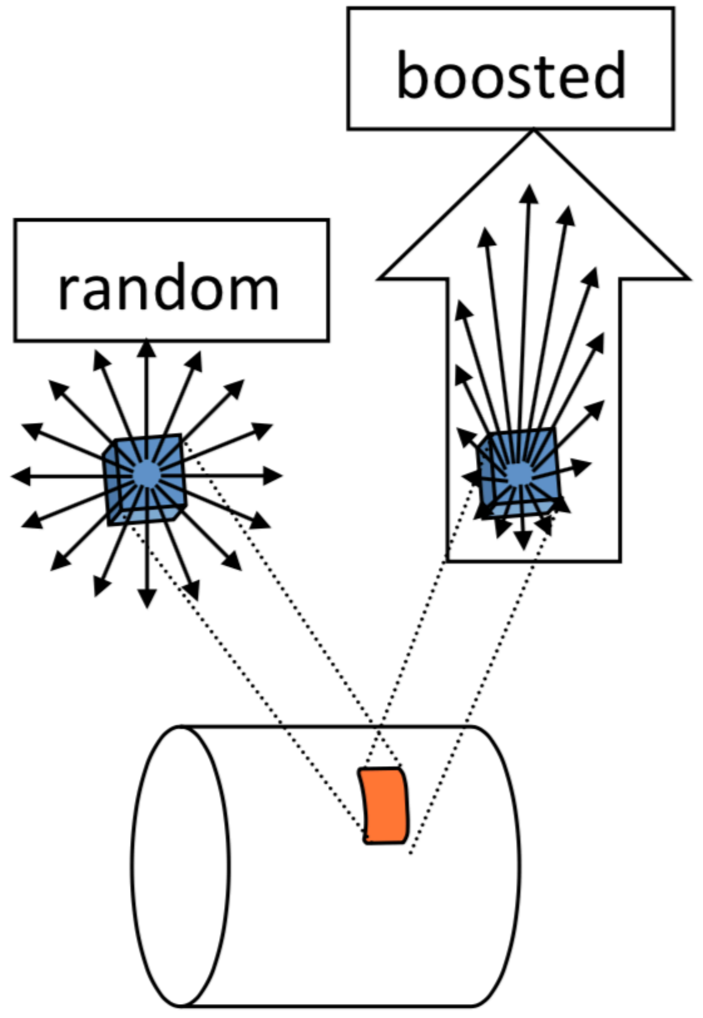
- **Elastic collisions cease**
- **Momentum distribution gets fixed**

Kinetic freeze-out

- ✓ **Fitted by BW model to extract kinetic freeze-out temperature and collective velocity.**

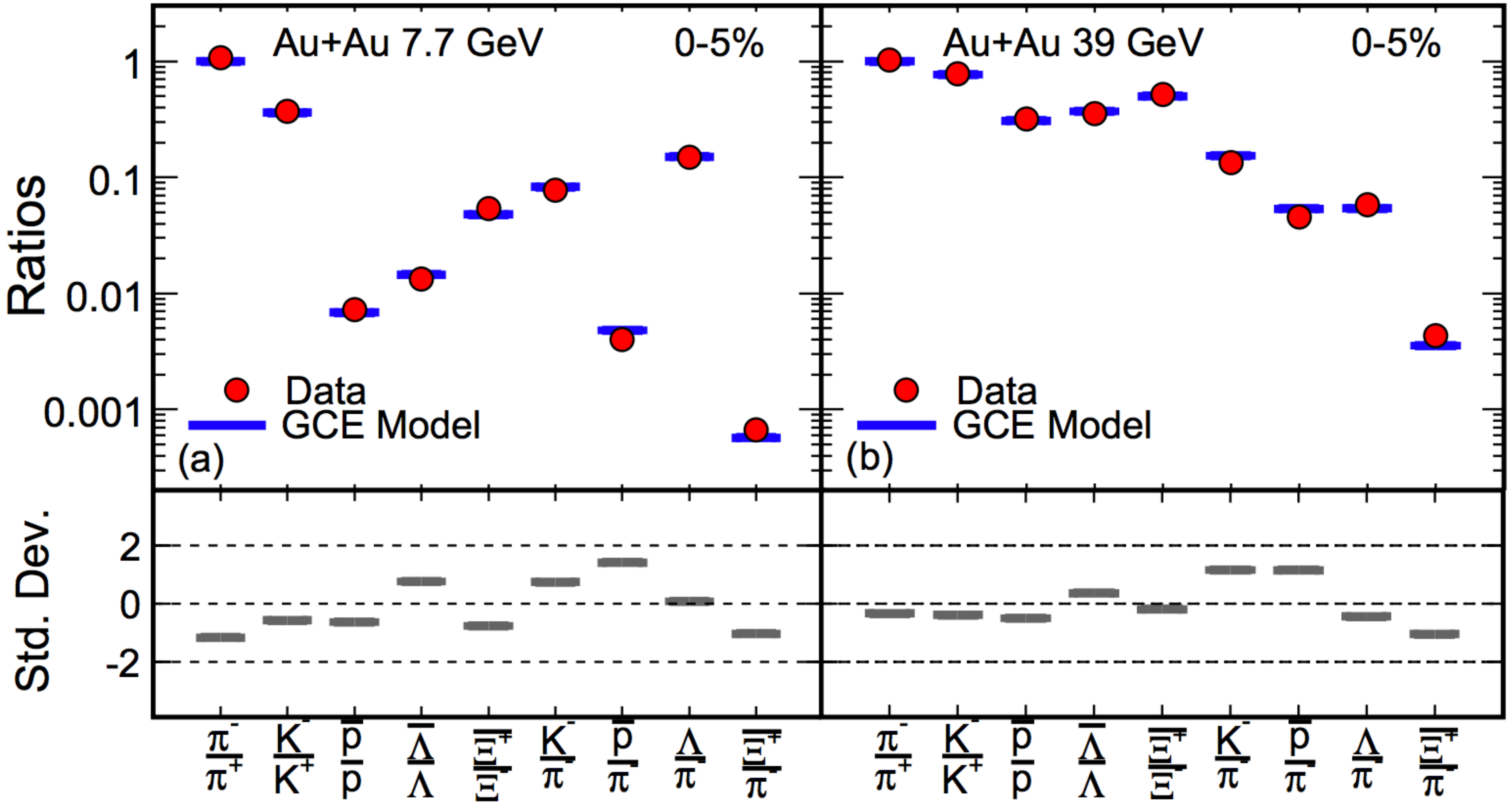


Source is assumed to be locally thermal equilibrated, and boosted in radial direction : T_{kin}, $<\beta>$



PRC96, 44904(2017) 1906.03732 : STAR Collaboration

Chemical freeze-out



- ✓ **Inelastic collisions cease. Particle ratios get fixed.**
- ✓ **Compare with HRG to extract chemical freeze-out temperature (T_{ch}) and baryon chemical potential (μ_B).**

PRC96, 44904(2017) 1906.03732 : STAR Collaboration

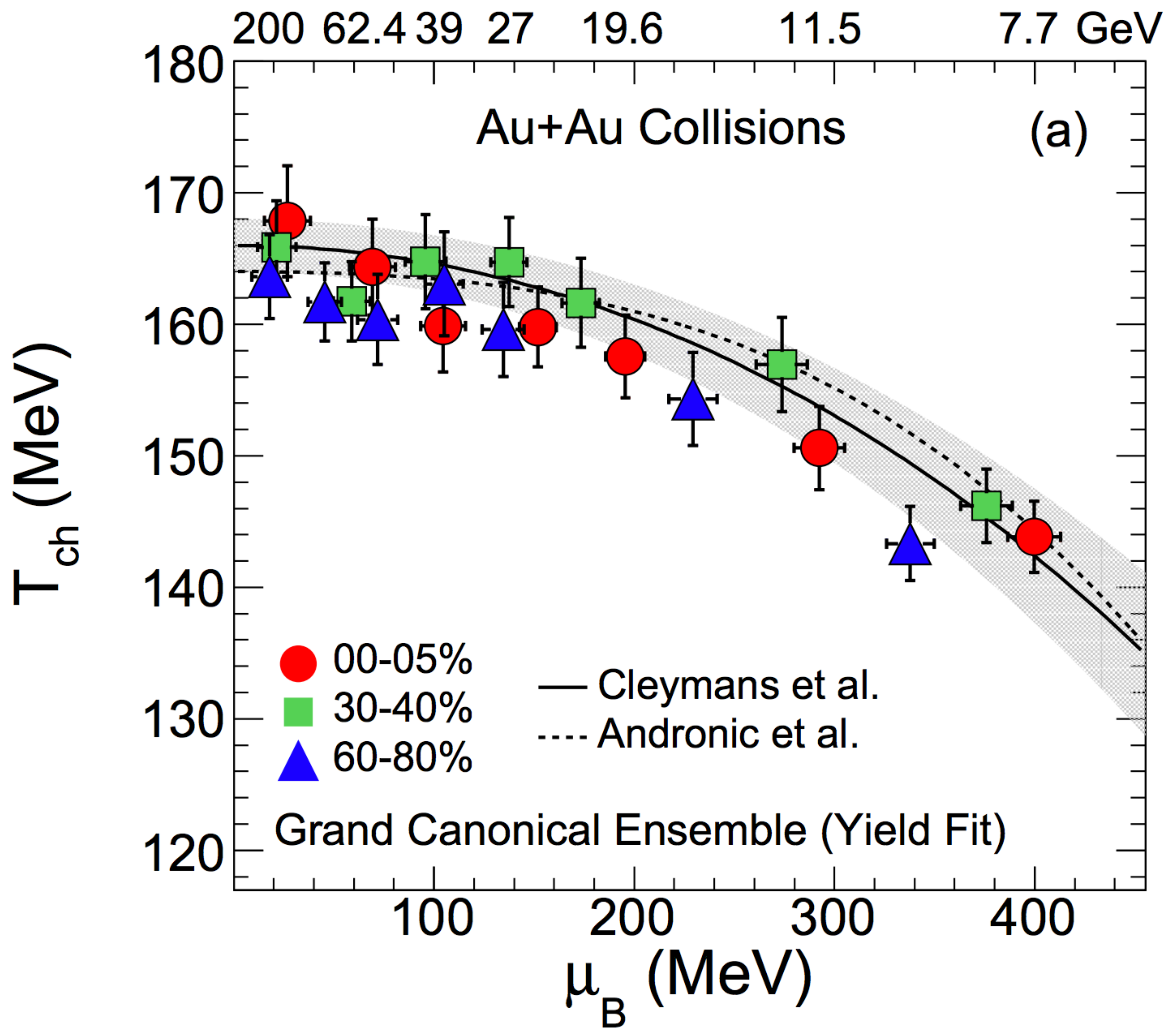
Freeze-out conditions

✓ ***Chemical freeze-out***

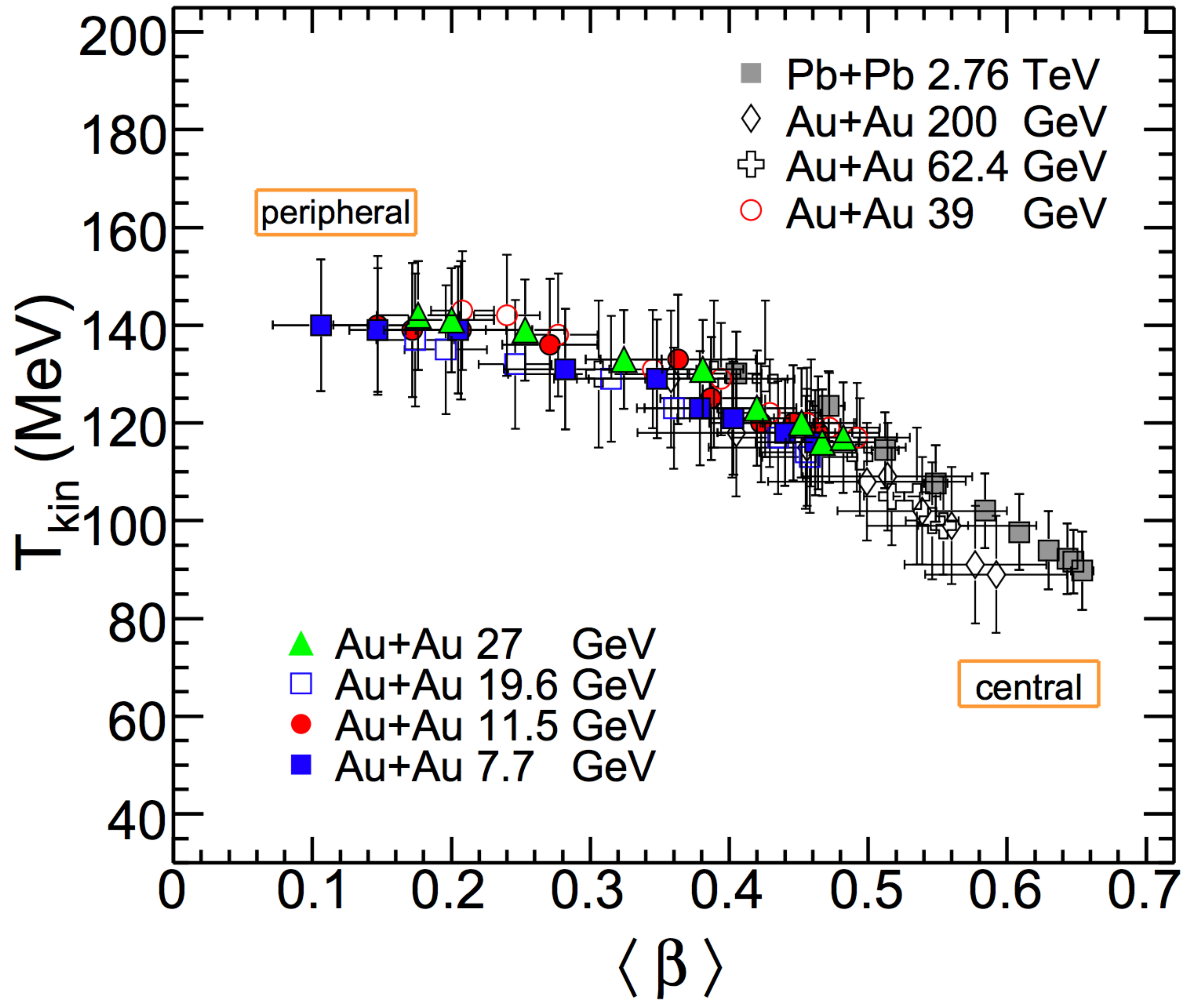
- Weak temperature dependence
- Centrality dependence of μ_B

✓ ***Kinetic freeze-out***

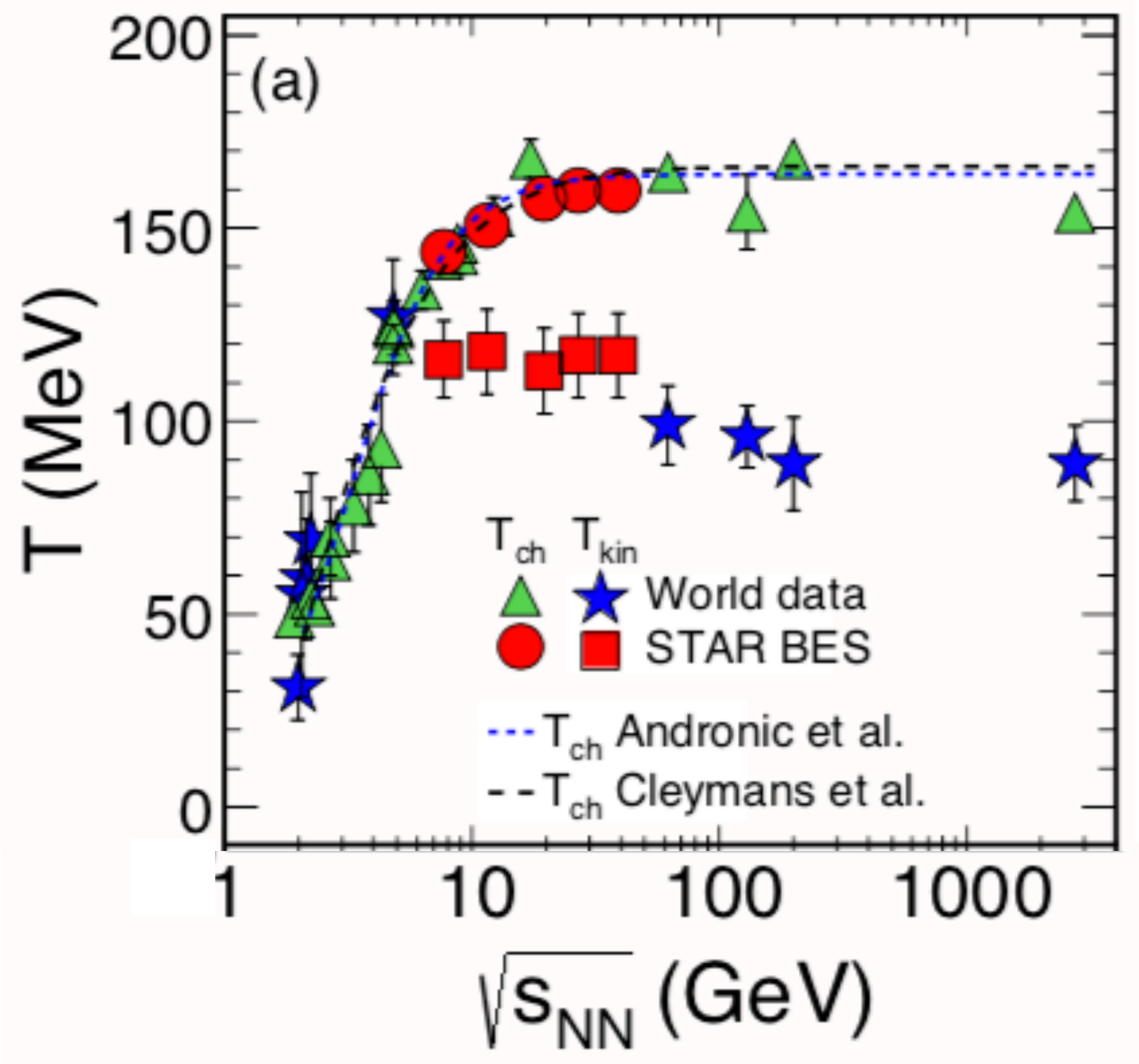
- Central collisions→lower value of T_{kin} and larger collectivity $\langle\beta\rangle$
- Stronger collectivity at higher energy, even for peripheral collisions.



PRC96, 44904(2017) : STAR Collaboration



Freeze-out conditions

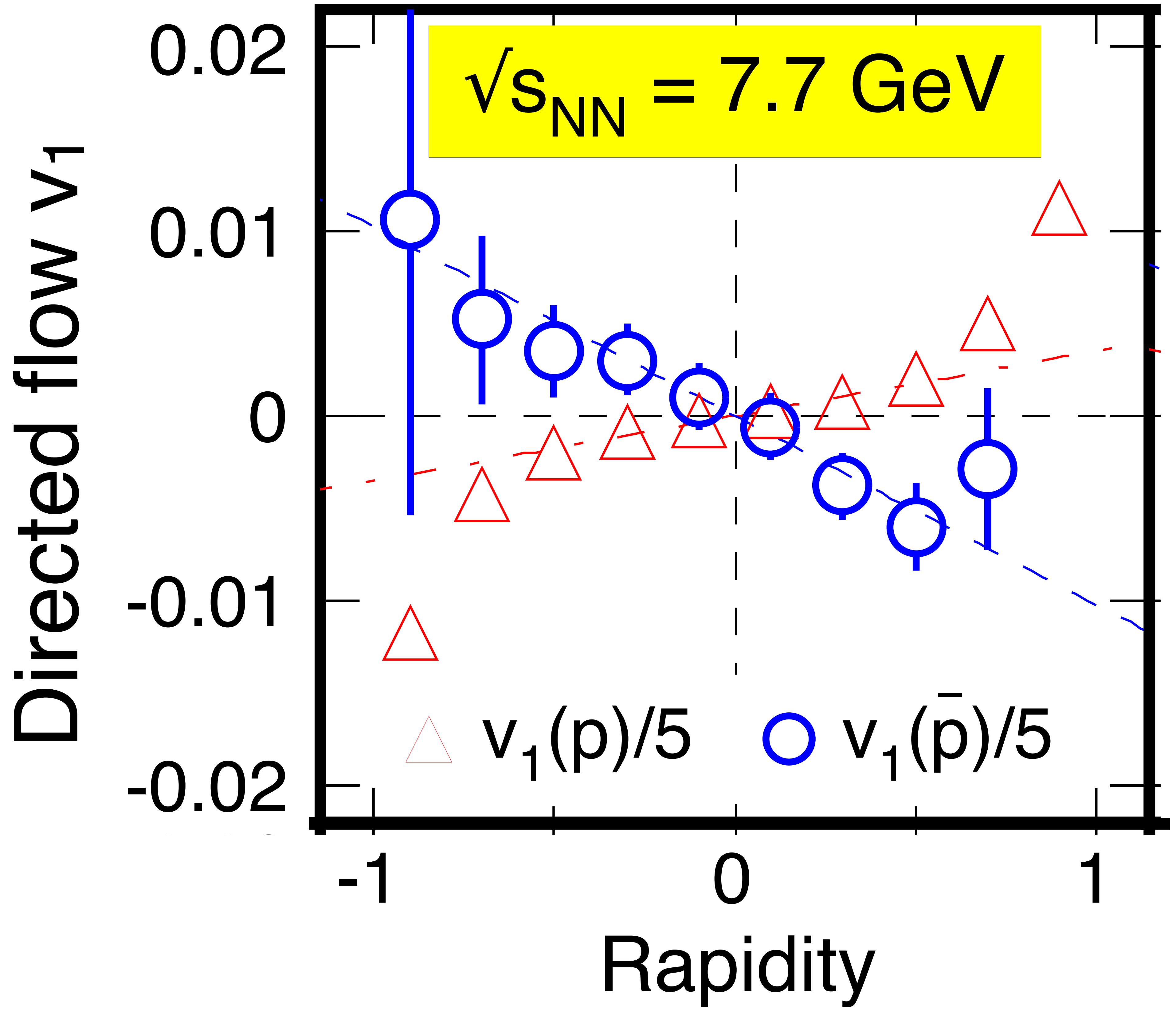


- ✓ **Both the larger separation of the freeze-out temperature (T_{ch}-T_{kin}) and stronger collectivity imply a longer hadronic interactions at higher collision energies.**

PRC96, 44904(2017) : STAR Collaboration

1st-order phase transition

Directed flow vs rapidity



PRL120, 62301(2018) : STAR Collaboration

✓ **Directed flow : collected sidewards deflection of the particles**

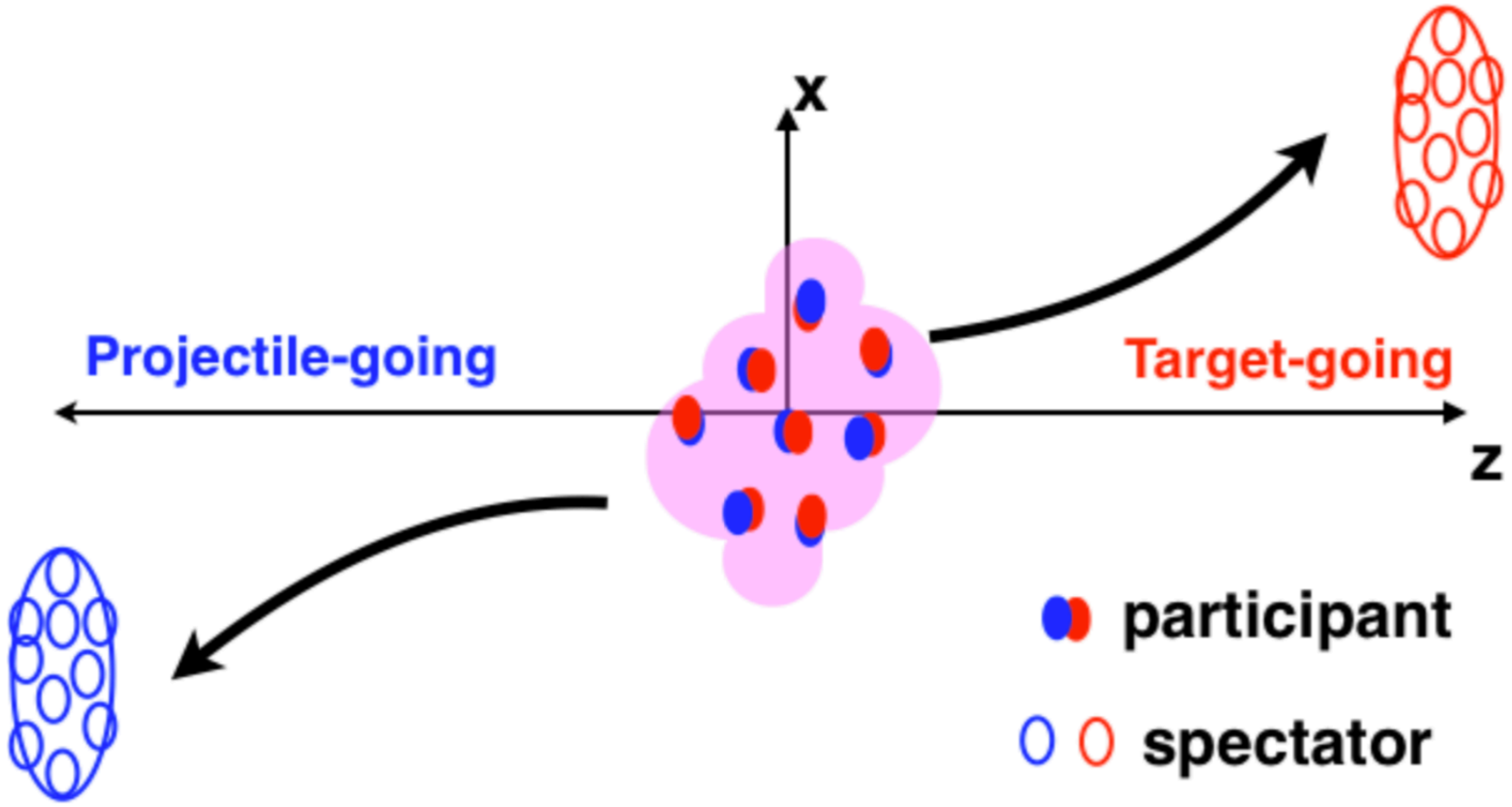
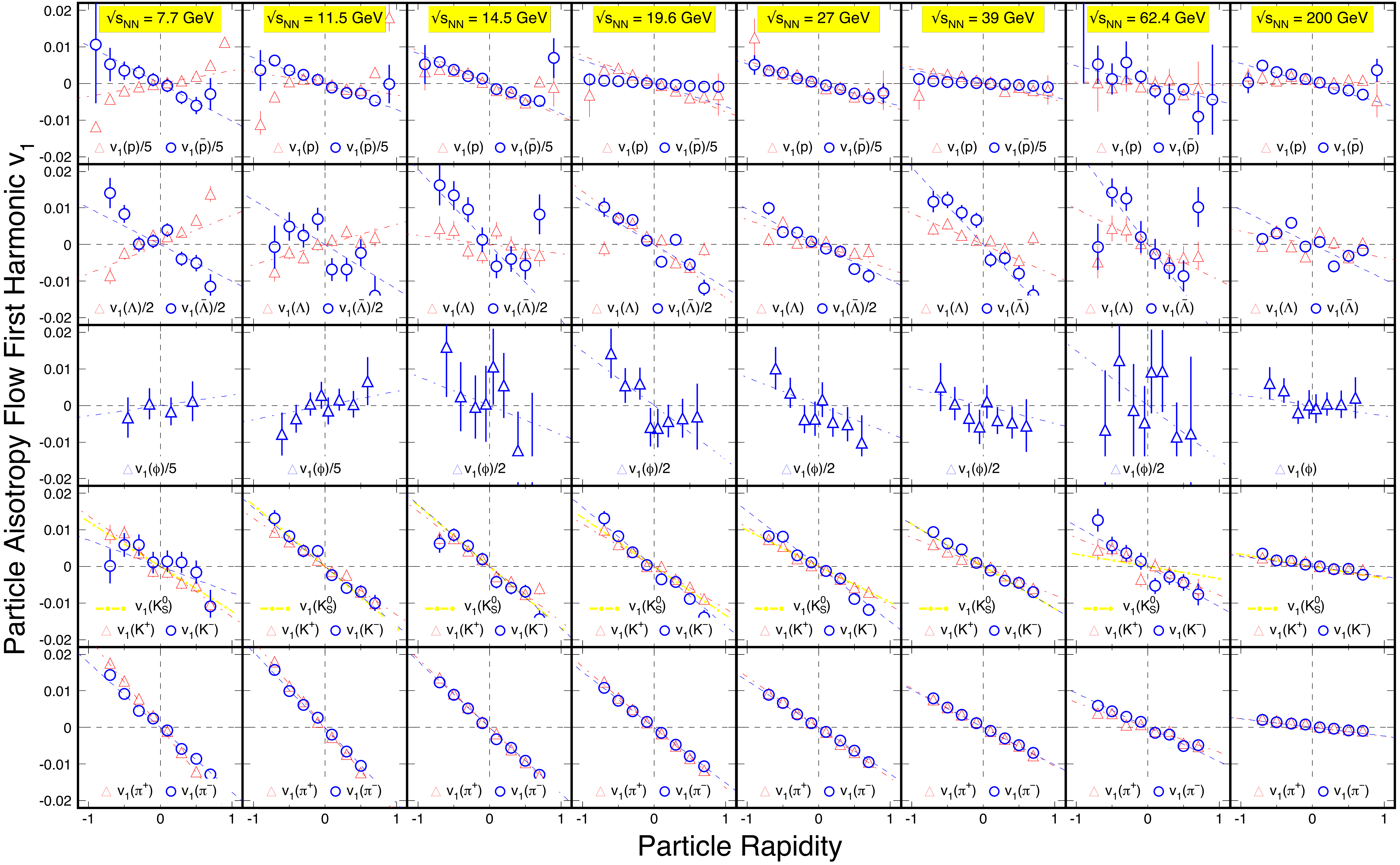


Figure by H. Kato

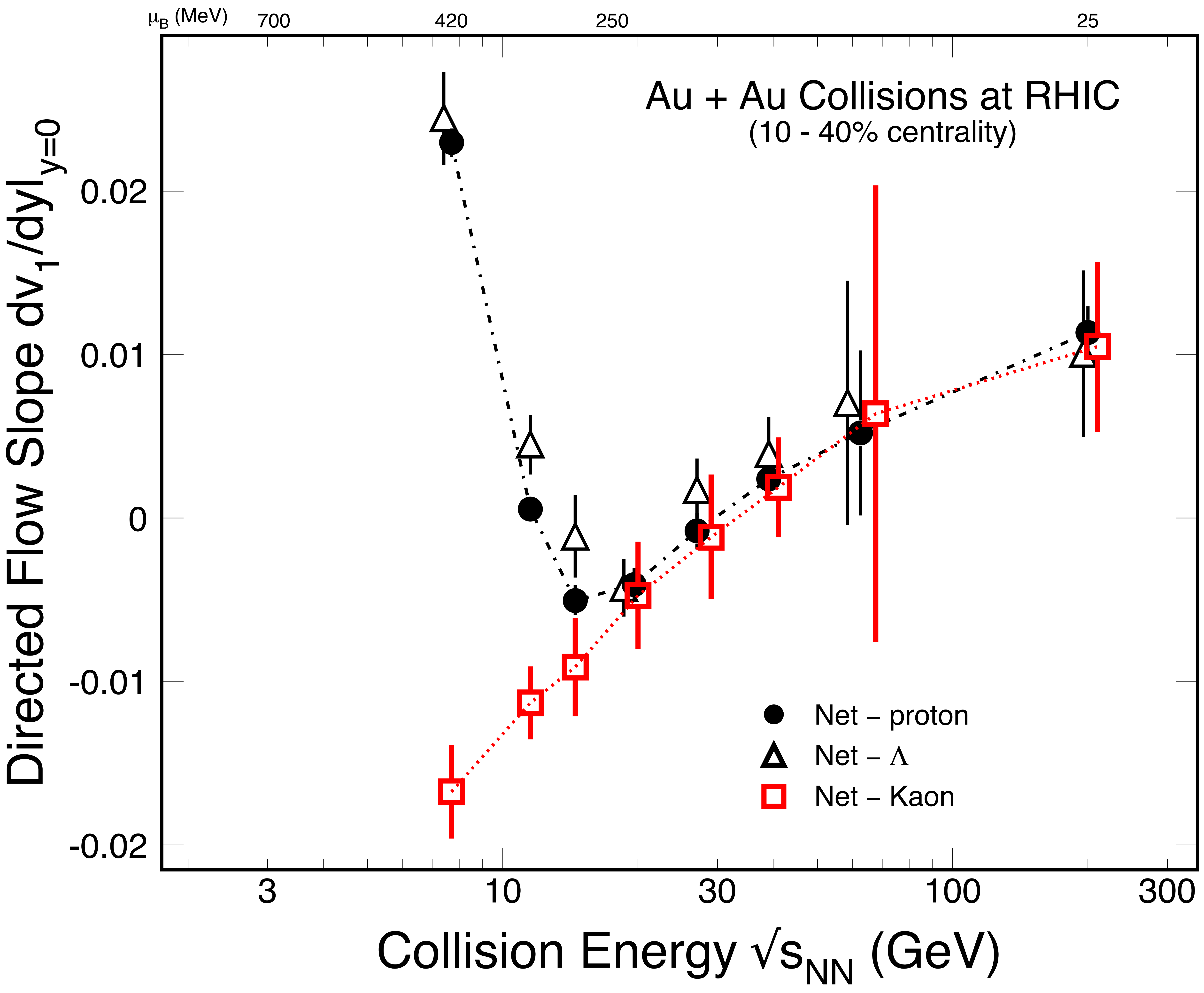
v_1 versus collision energy

10-40% Au+Au Collisions at RHIC (STAR 1708.07132)



PRL120, 62301(2018) : STAR Collaboration

v_1 slope versus collision energy



● STAR: PRL**112**, 162301(2014)

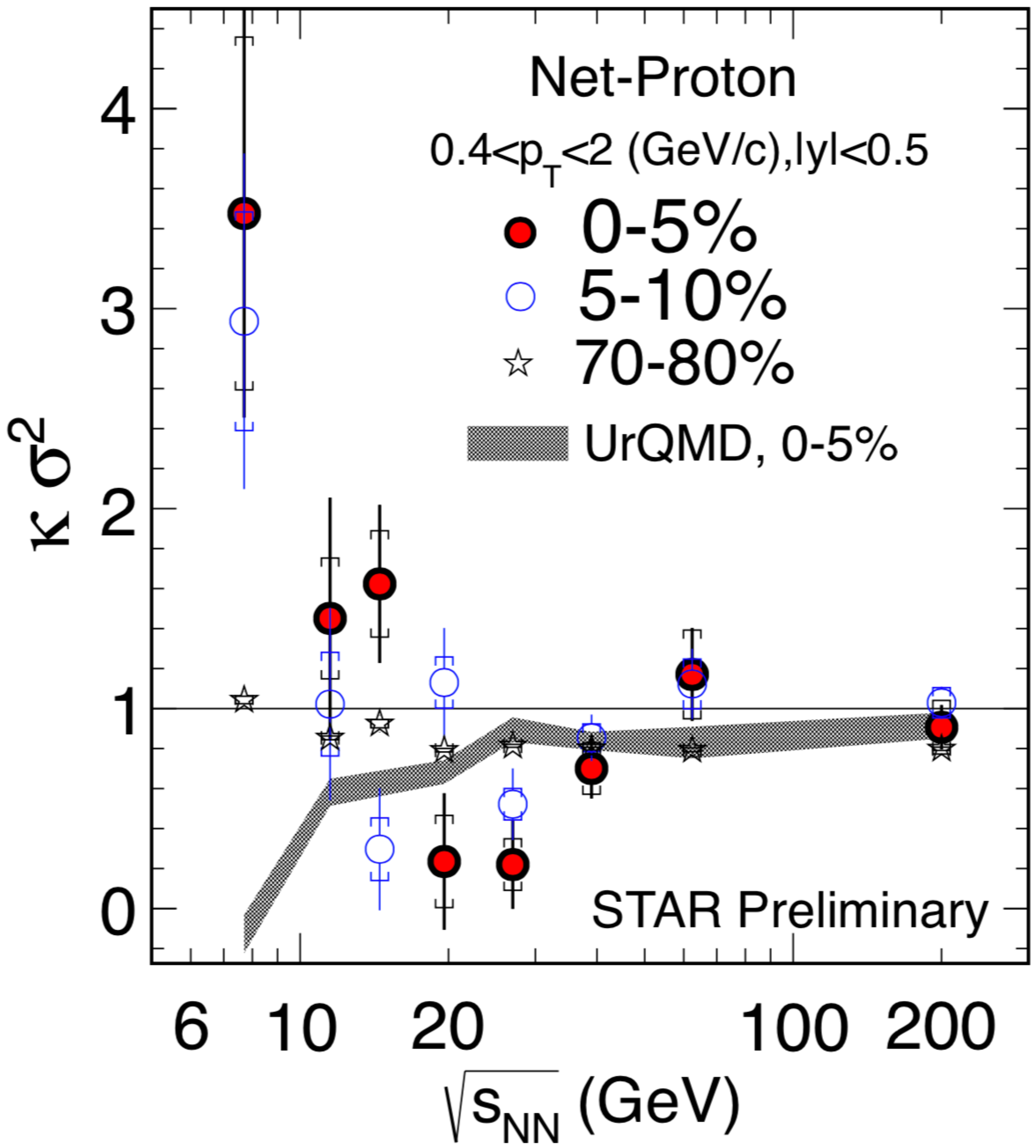
□ △ STAR: 1708.07132; **PRL120**, 62301(2018)

- ✓ 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.
- ✓ Model calculations show minimum slope at $\sqrt{s_{NN}}$~4 GeV
- ✓ 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)

Critical point search : Higher-order fluctuation

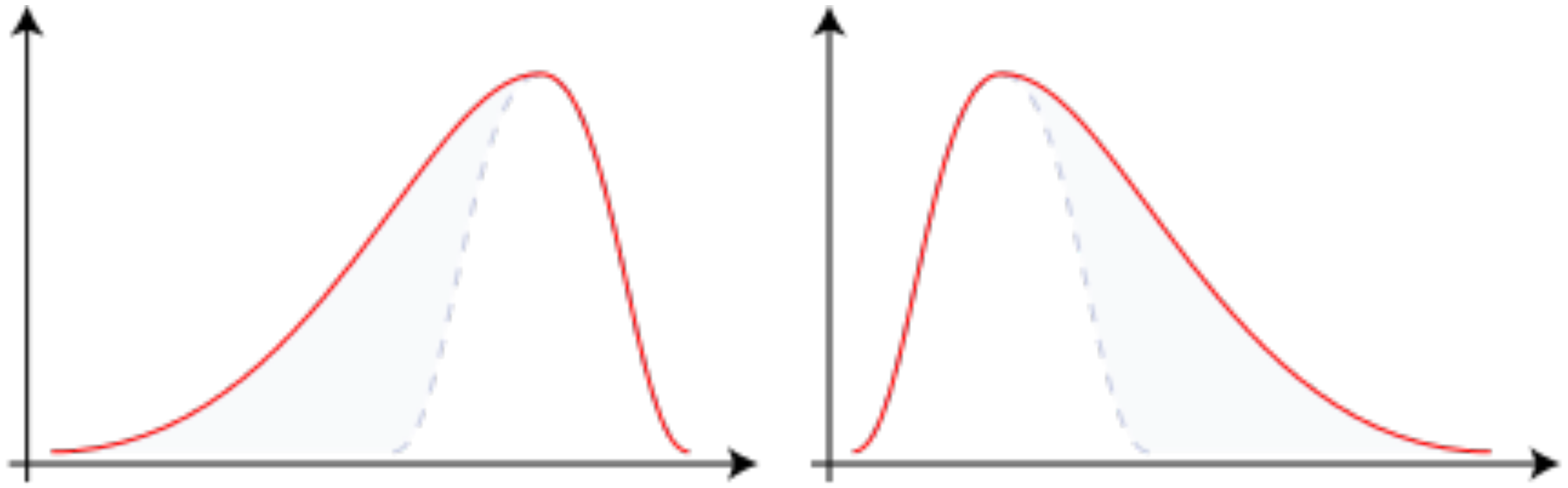
STAR, PoS CPOD2014 (2015)019



Higher-order fluctuations

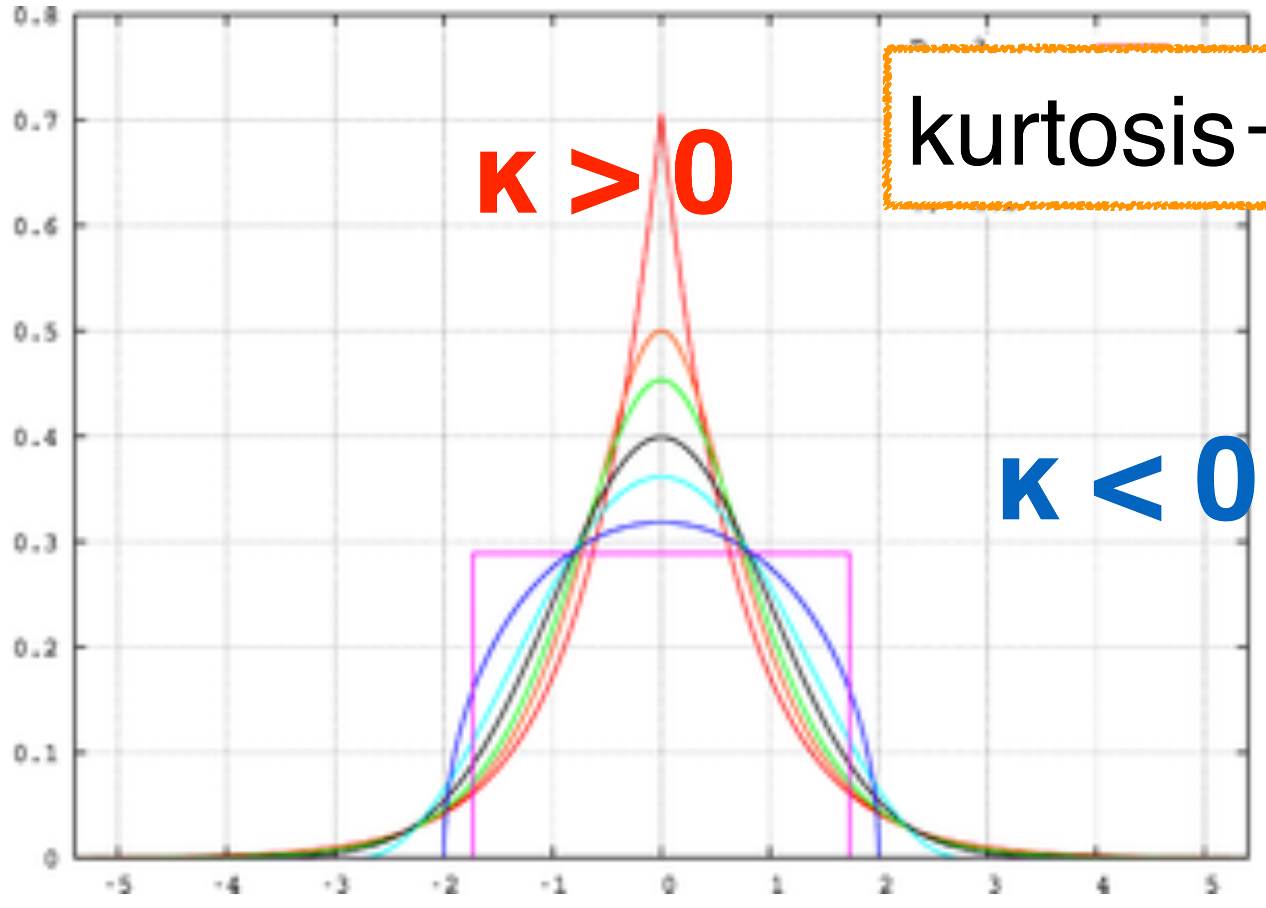
- **Moments and cumulants are mathematical measures of “shape” of a distribution which probe the fluctuation of observables.**
  - ✓ **Moments: mean (*M*), standard deviation (*σ*), skewness (*S*) and kurtosis (κ).**
  - ✓ ***S and κ are non-gaussian* fluctuations.**

skewness→asymmetry



Negative Skew

Positive Skew



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**

Higher-order fluctuations

- ✦ **Moments and cumulants are mathematical measures of “shape” of a distribution which probe the fluctuation of observables.**
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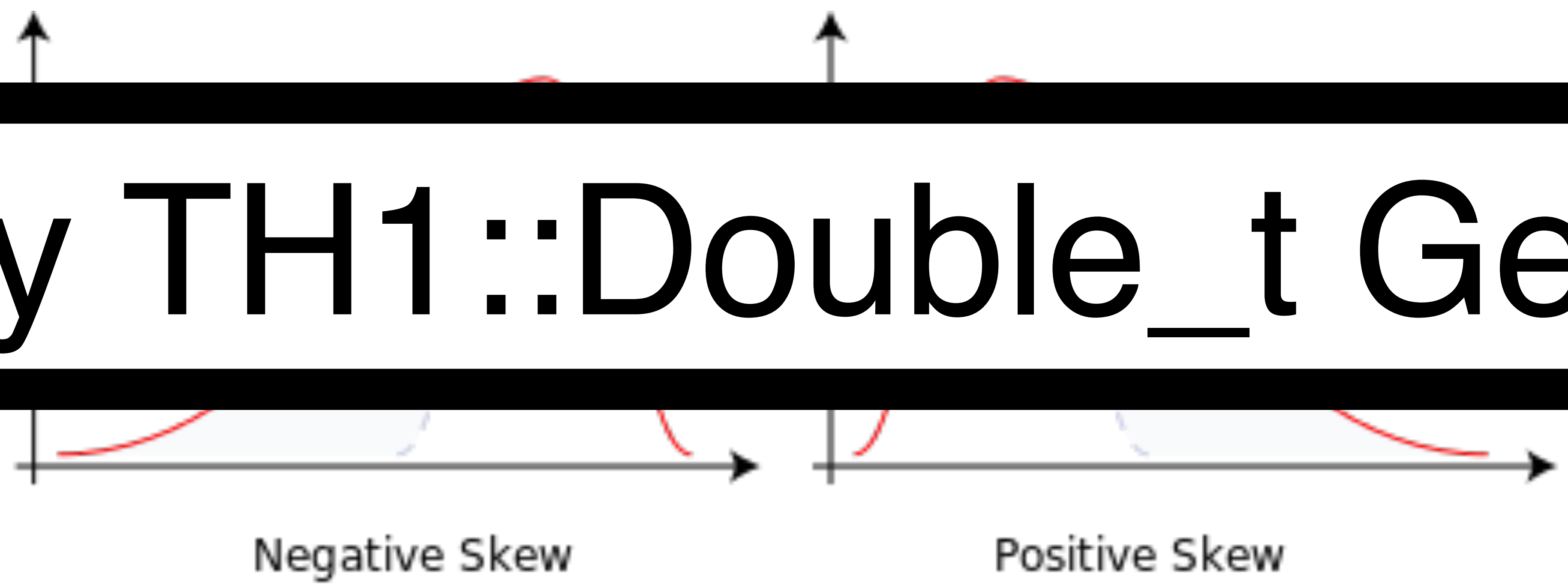
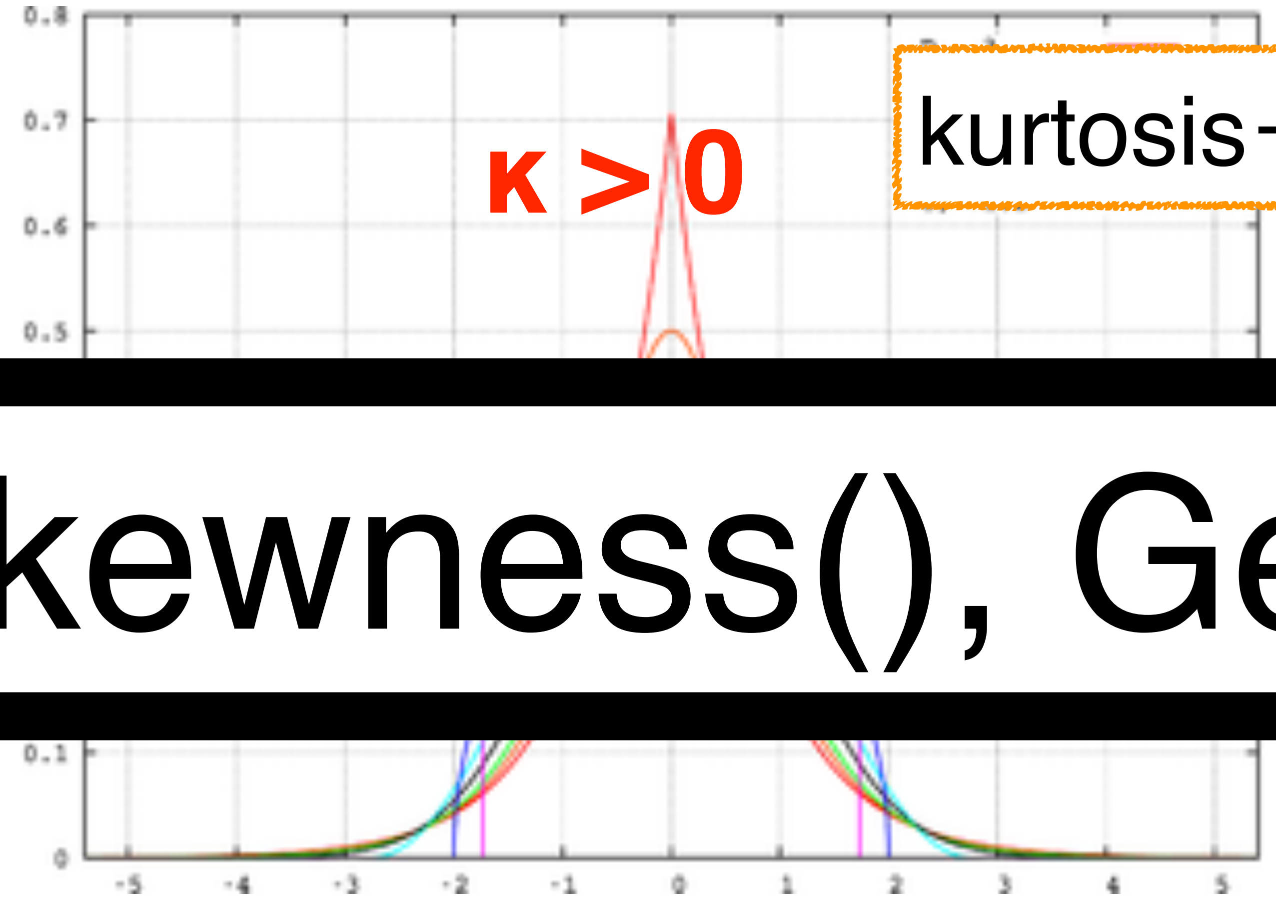
skewness→asymmetry



kurtosis→sharpness



Try TH1::Double_t GetSkewness(), GetKurtosis()

from wikipedia

- ✓ **Cumulant ⇄ Moment**

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- ✓ **Cumulant : additivity**

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

➞ **proportional to volume**

Fluctuations of conserved quantities

✦ Net baryon, net charge and net strangeness

"Net" : positive - negative

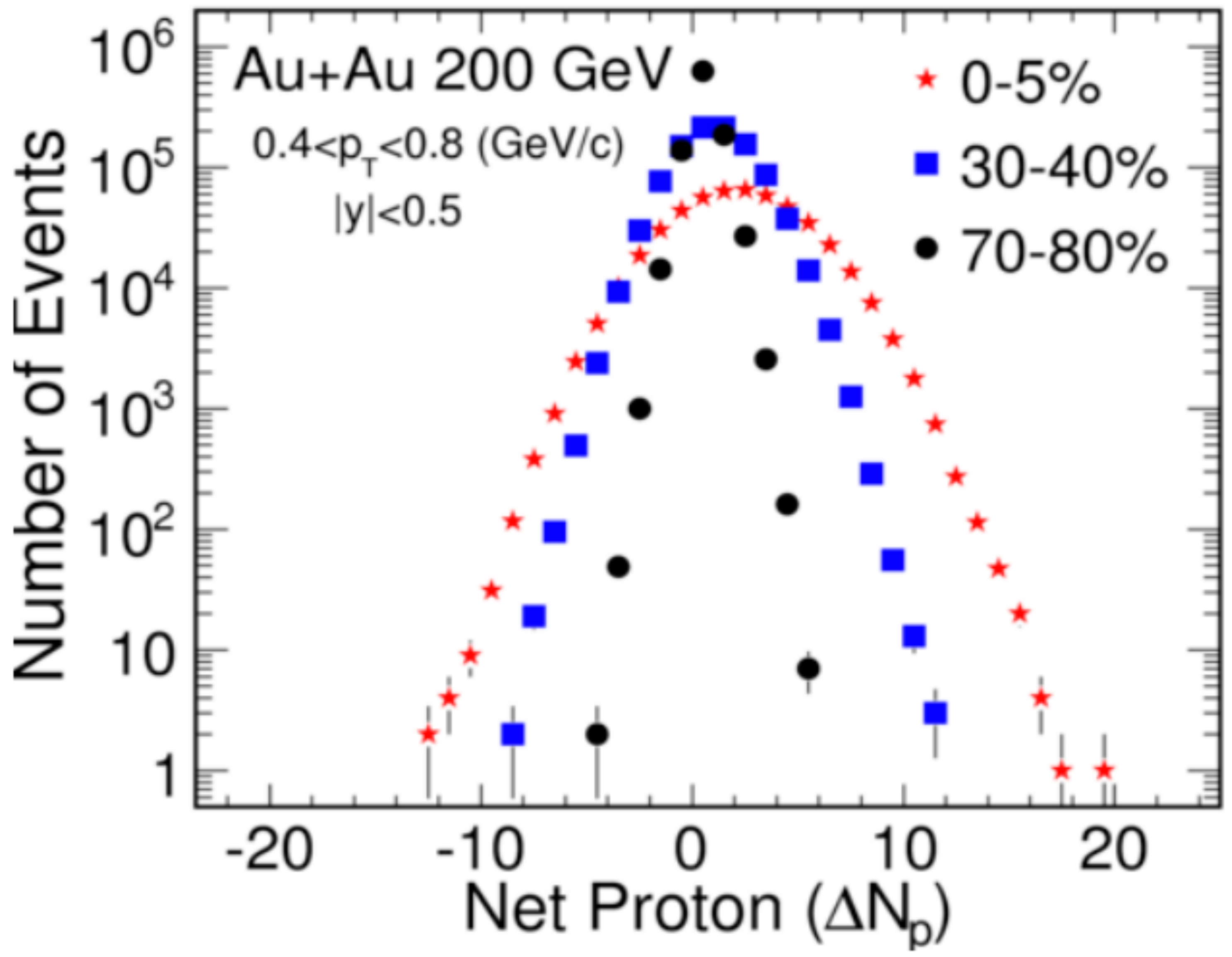
$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

No. of positively charged particles in one collision

No. of negatively charged particles in one collision

Fill in histograms over many collisions

PRL 105, 022302 (2010) : STAR Collaboration



→neutrons cannot be measured

(1) Sensitive to correlation length

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

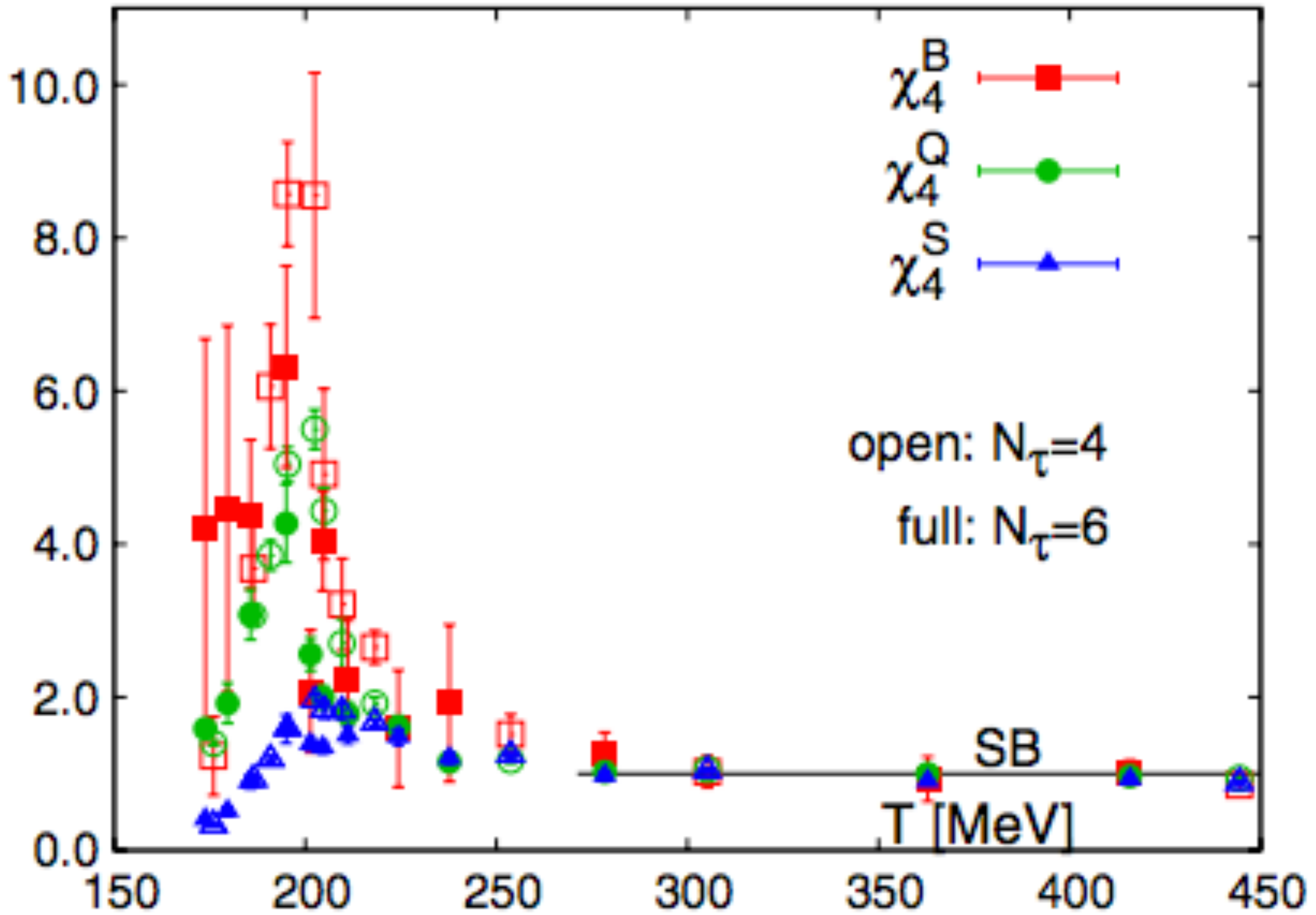
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
MAsakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

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

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

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

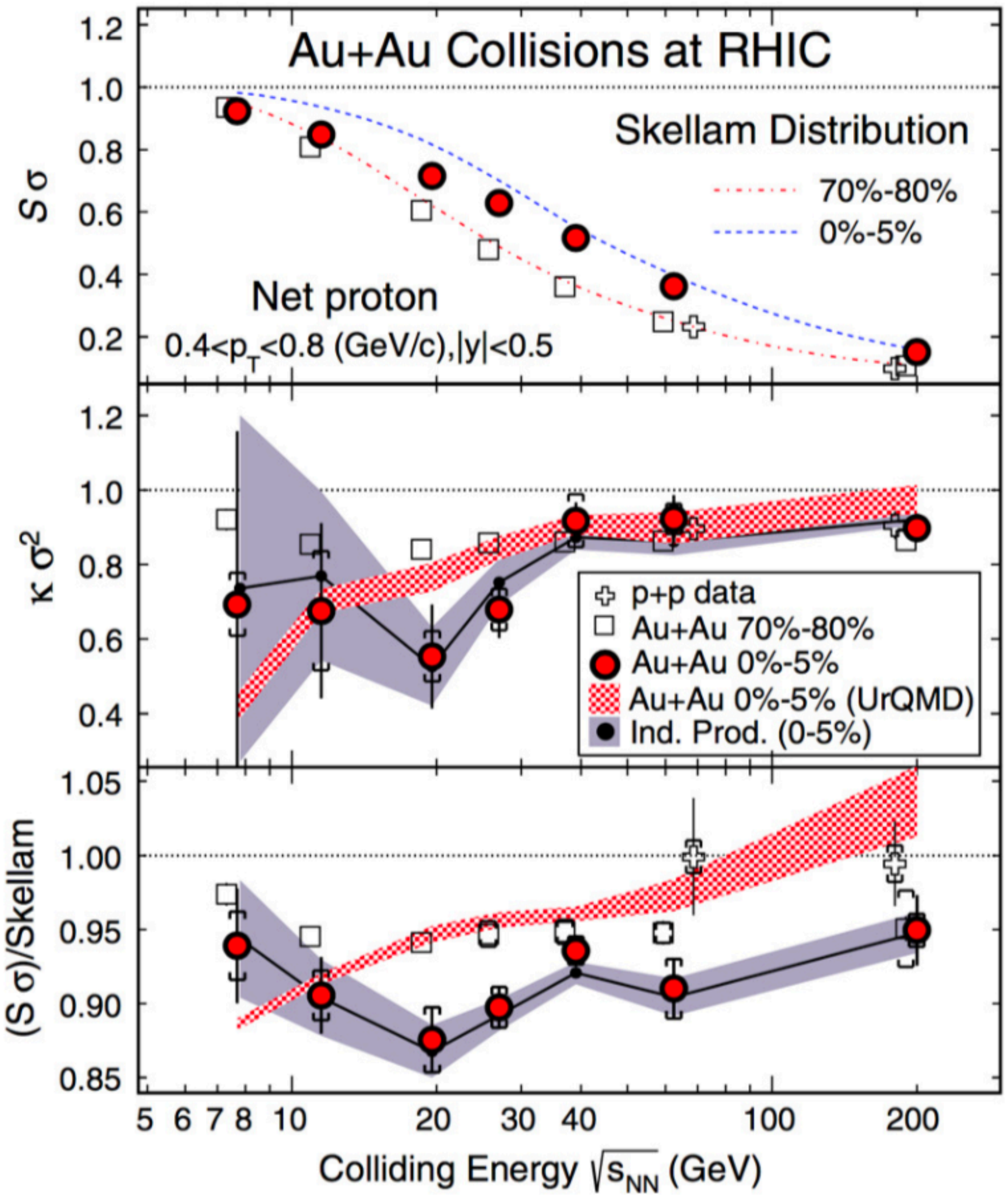


M. Cheng et al, PRD 79, 074505 (2009)

Net-proton from BES-I

C_3/C_2

C_4/C_2

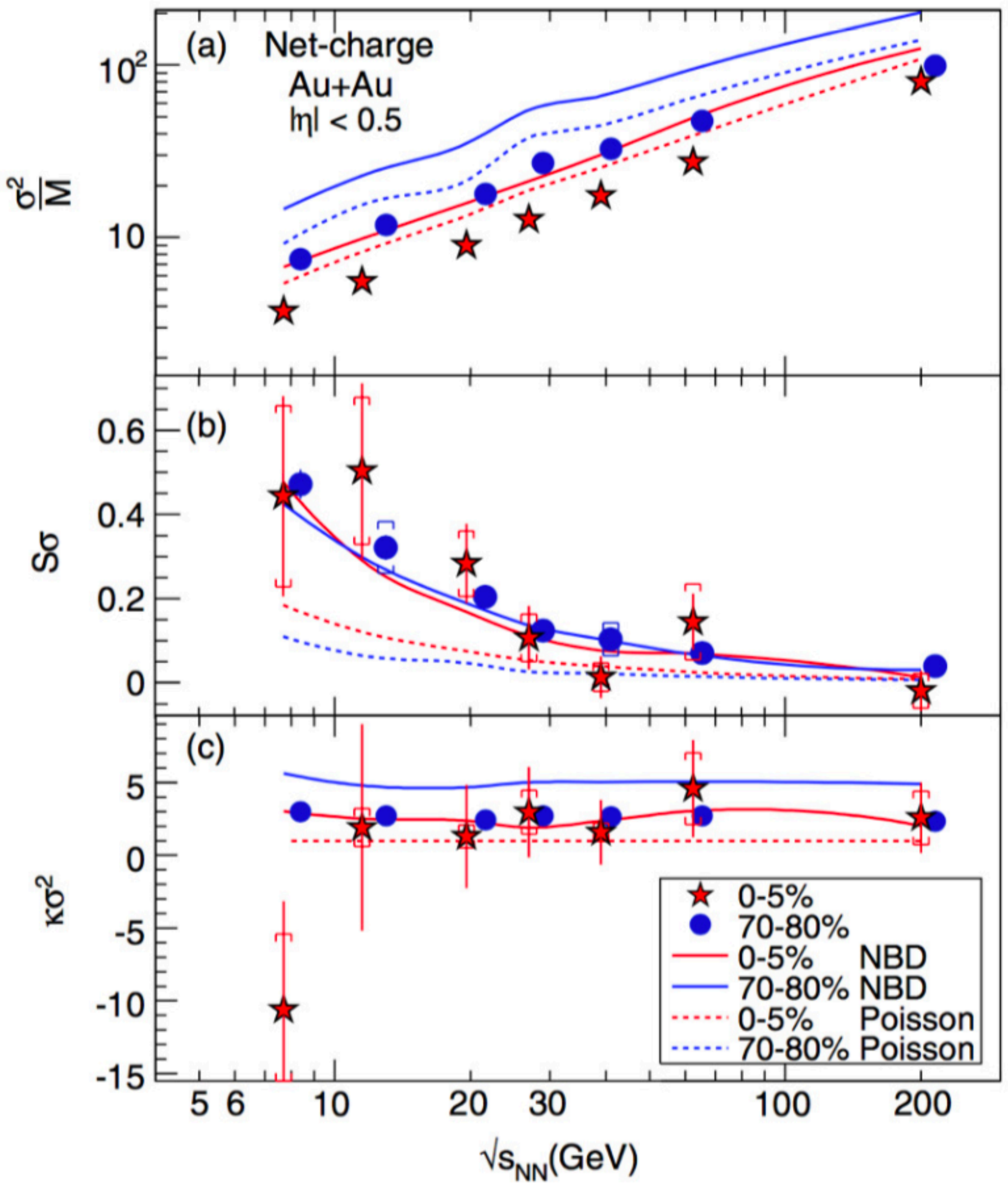


- ✓ **Statistical fluctuation : Poisson distribution ($C_n=C_1$)**
- ✓ **Poisson - Poisson = Skellam**
  - $C_{odd}=\mu_p-\mu_{pbar}$, $C_{even}=\mu_p+\mu_{pbar}$
- ✓ **Deviation below Poisson baseline (unity).**
- ✓ **Both 3rd- and 4th-order fluctuations have their minima at $\sqrt{s_{NN}}$ = 19.6 GeV.**

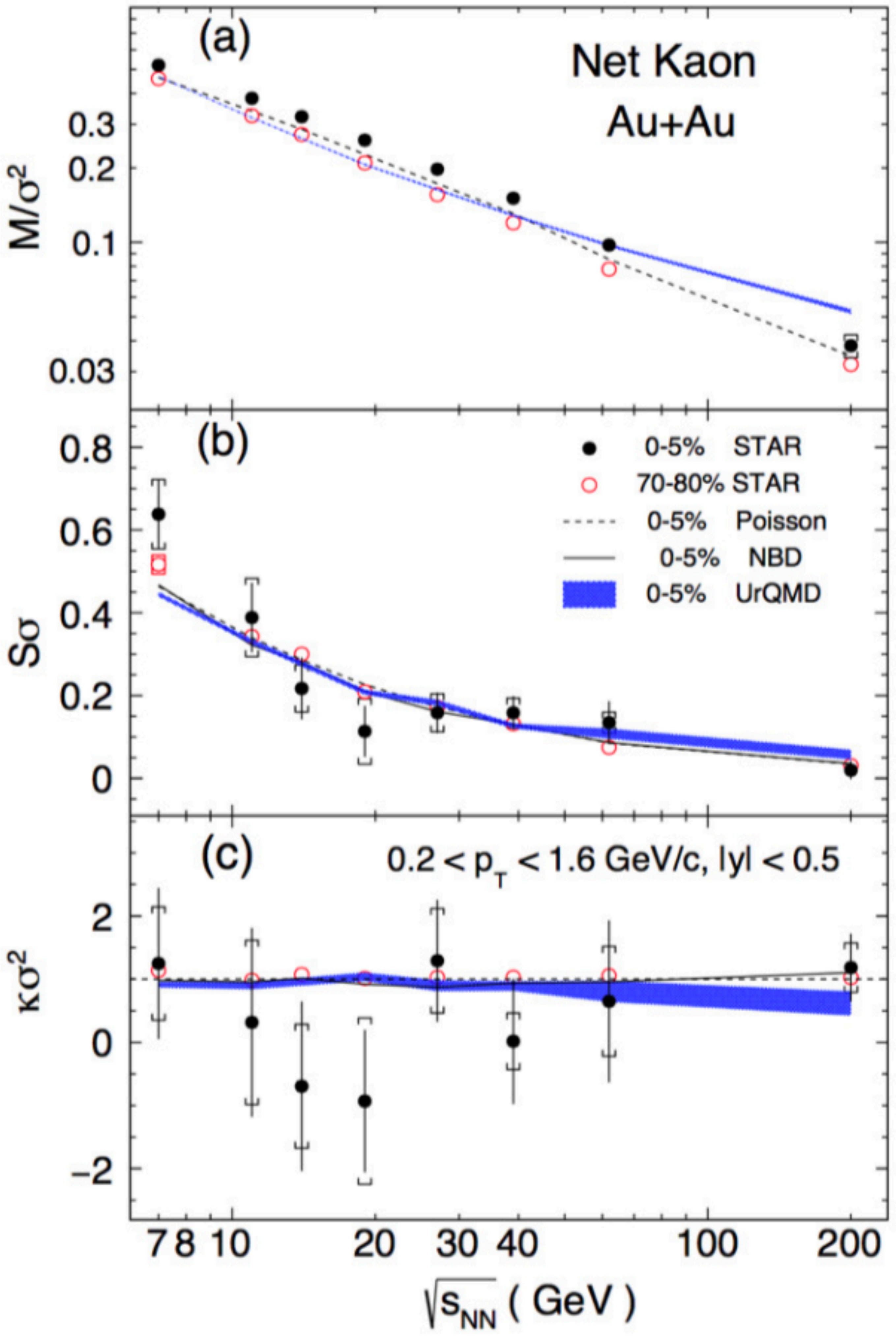
PRL112, 032302(2014): STAR Collaboration

Net-charge and net-kaon

PRL113, 092301(2014): STAR



PLB, 785, 551(2018): STAR



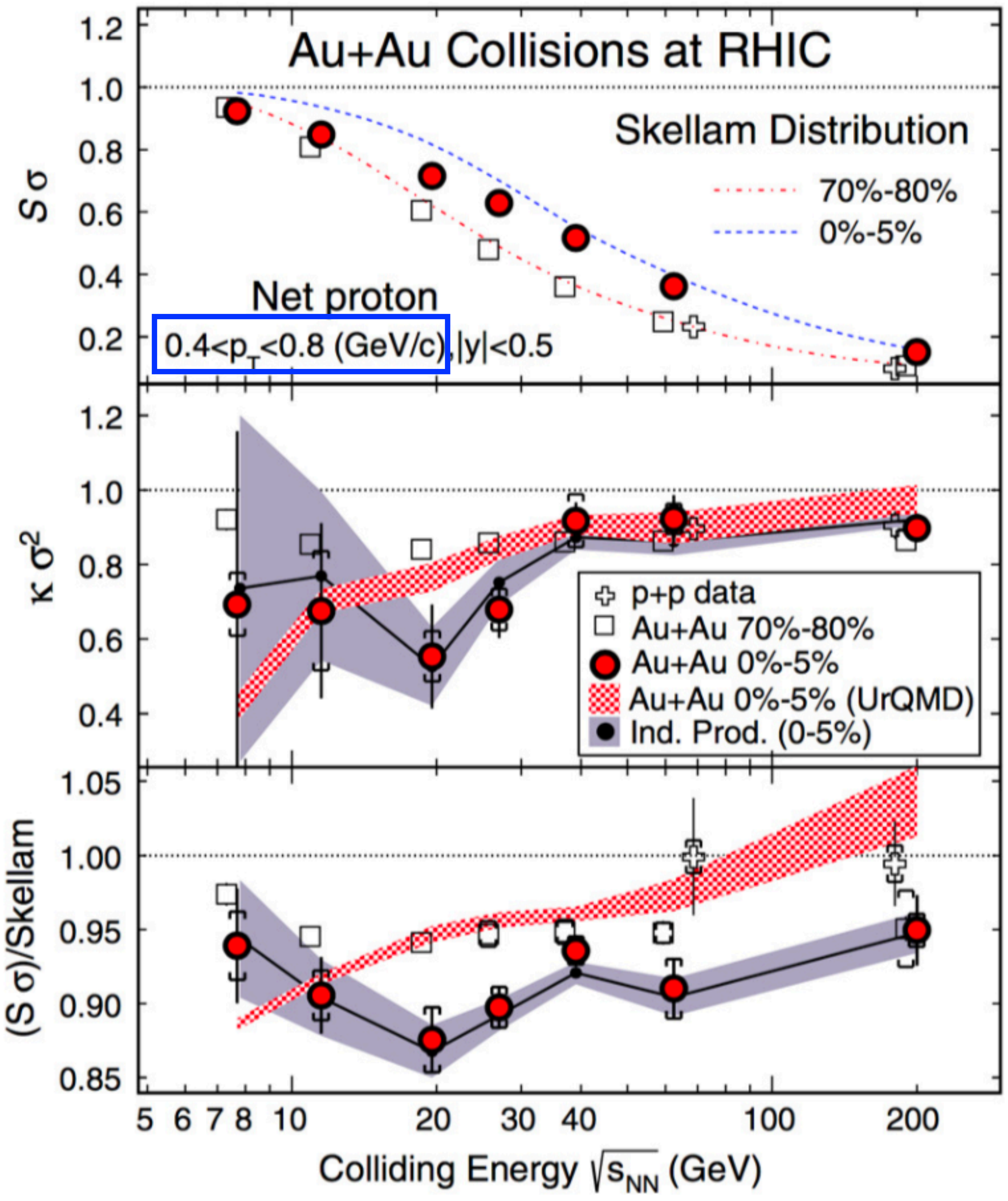
$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}\frac{1}{\sqrt{N_{evts}}}$$

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

Net-proton from BES-I

C_3/C_2

C_4/C_2

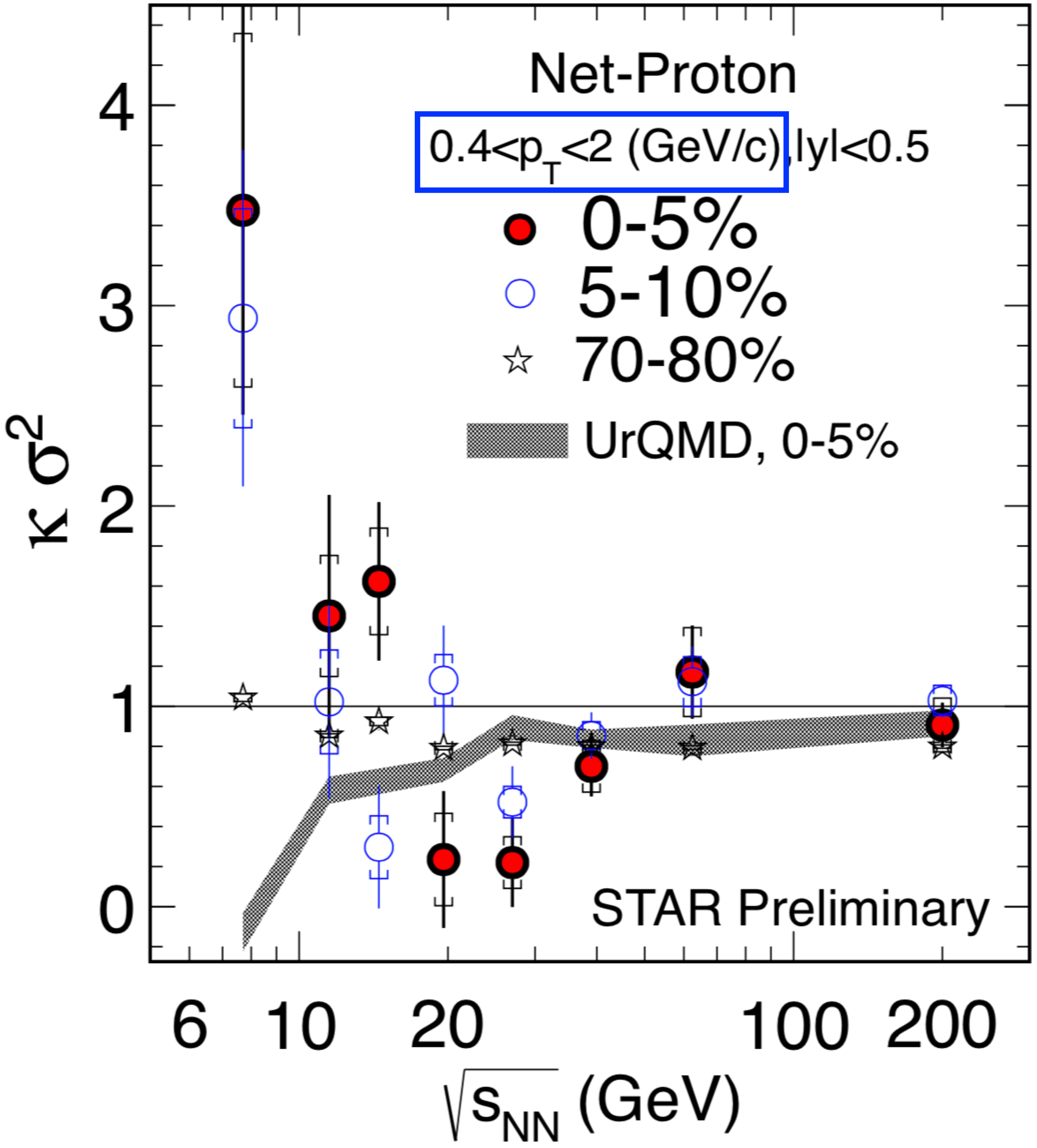


- ✓ **Mean p_T of proton is ~1 GeV/c.**
- ✓ **Proton statistics are doubled by measuring p_T acceptance up to 2.0 GeV/c.**

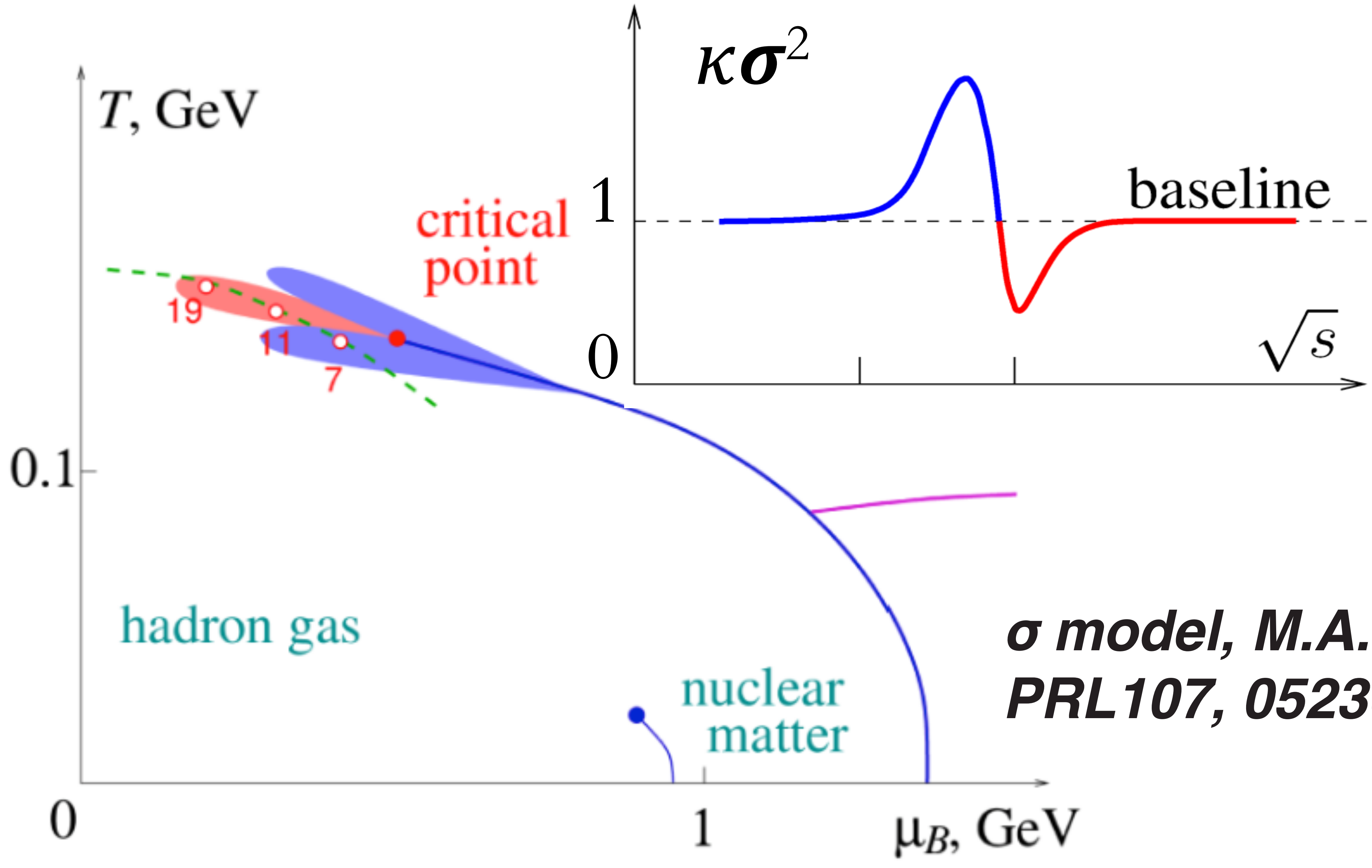
PRL112, 032302(2014): STAR Collaboration

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.**
- ✓ **Enhancement at low beam energies cannot be explained by baryon number conservation.**



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

Beam Energy Scan Phase II

Beam Energy Scan Phase II

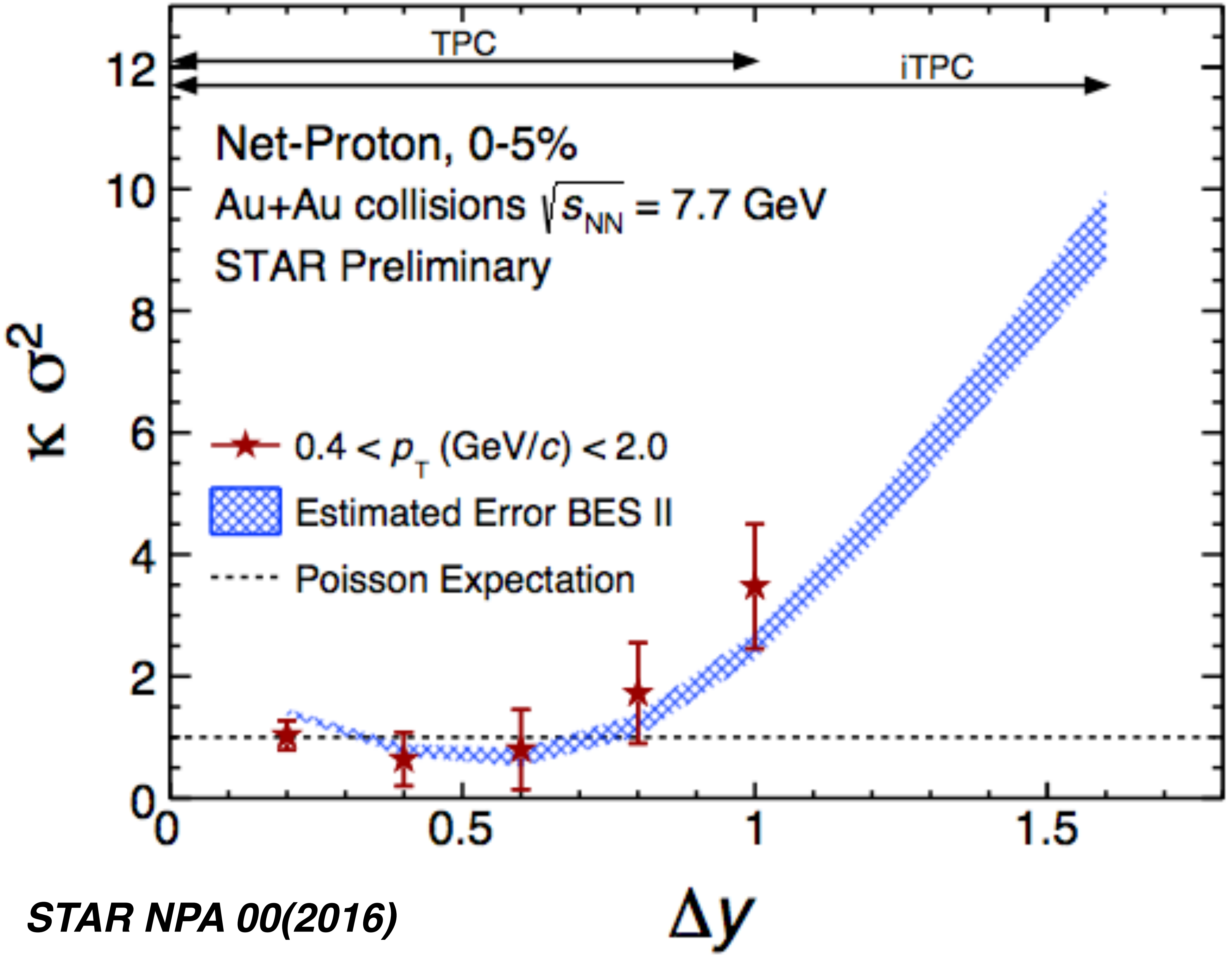
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES-II / BES-I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	**1200**	**2017**			
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-21** / 2011	**3**	206	160
14.5	**300** / 20	**2019-21** / 2014	**2.5**	264	156
11.5	**230** / 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.**

Beam Energy Scan Phase II

Non-monotonic rapidity dependence as a signal for critical point
Sakaida et al, Phys. Rev. C 95, 064905

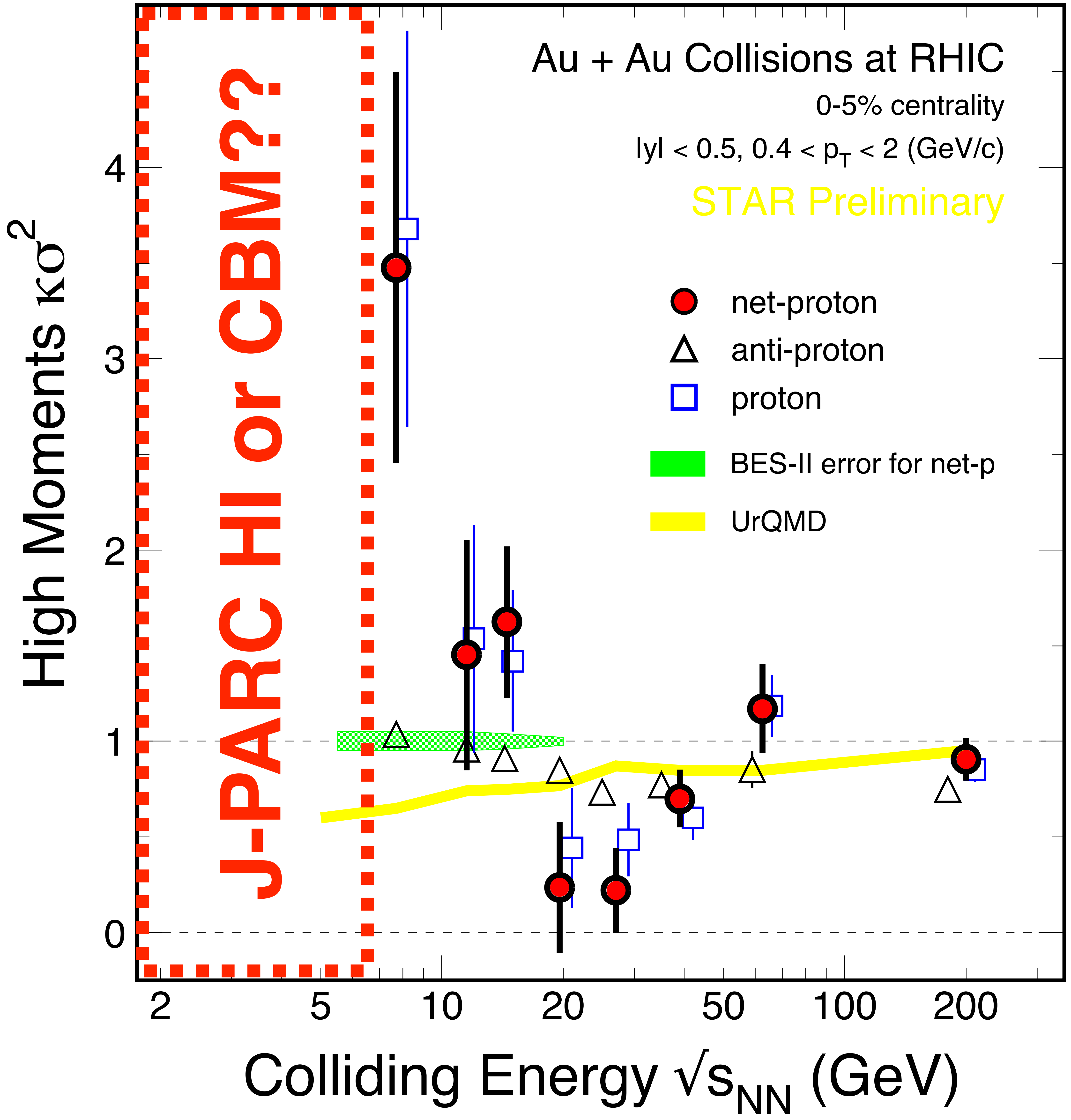


STAR NPA 00(2016)

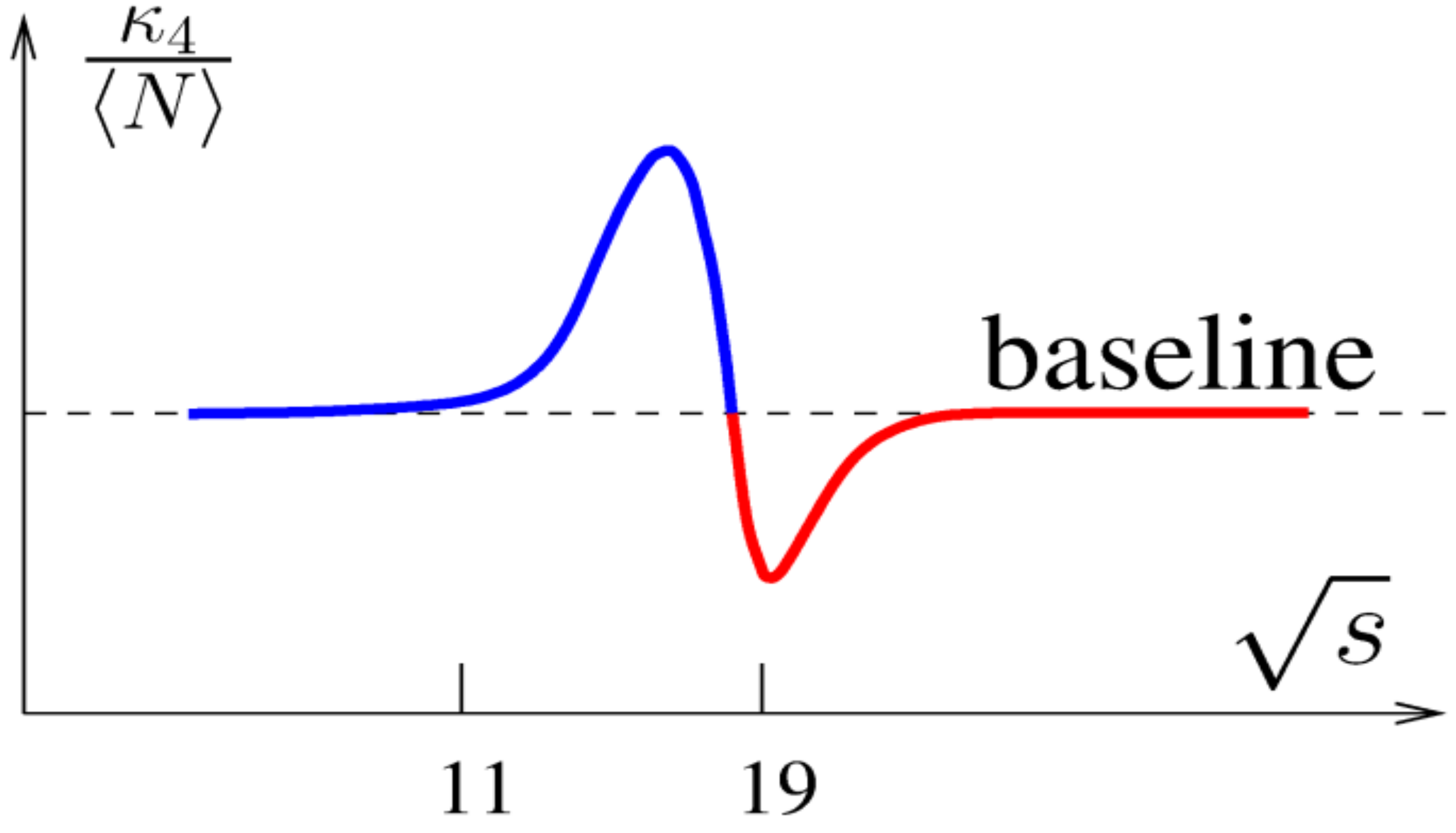
- ✓ **BES-II has started this year.**
- ✓ **Luminosity has been improved with the electron cooling system.**
- ✓ **Inner TPC has been fully integrated, which extends the pseudorapidity coverage from 1.0 to 1.5**
- ✓ **Higher-order fluctuation measurement with small errors and large acceptance.**

Critical point search in BES-II

STAR Data : PoS CPOD2014 (2015)019

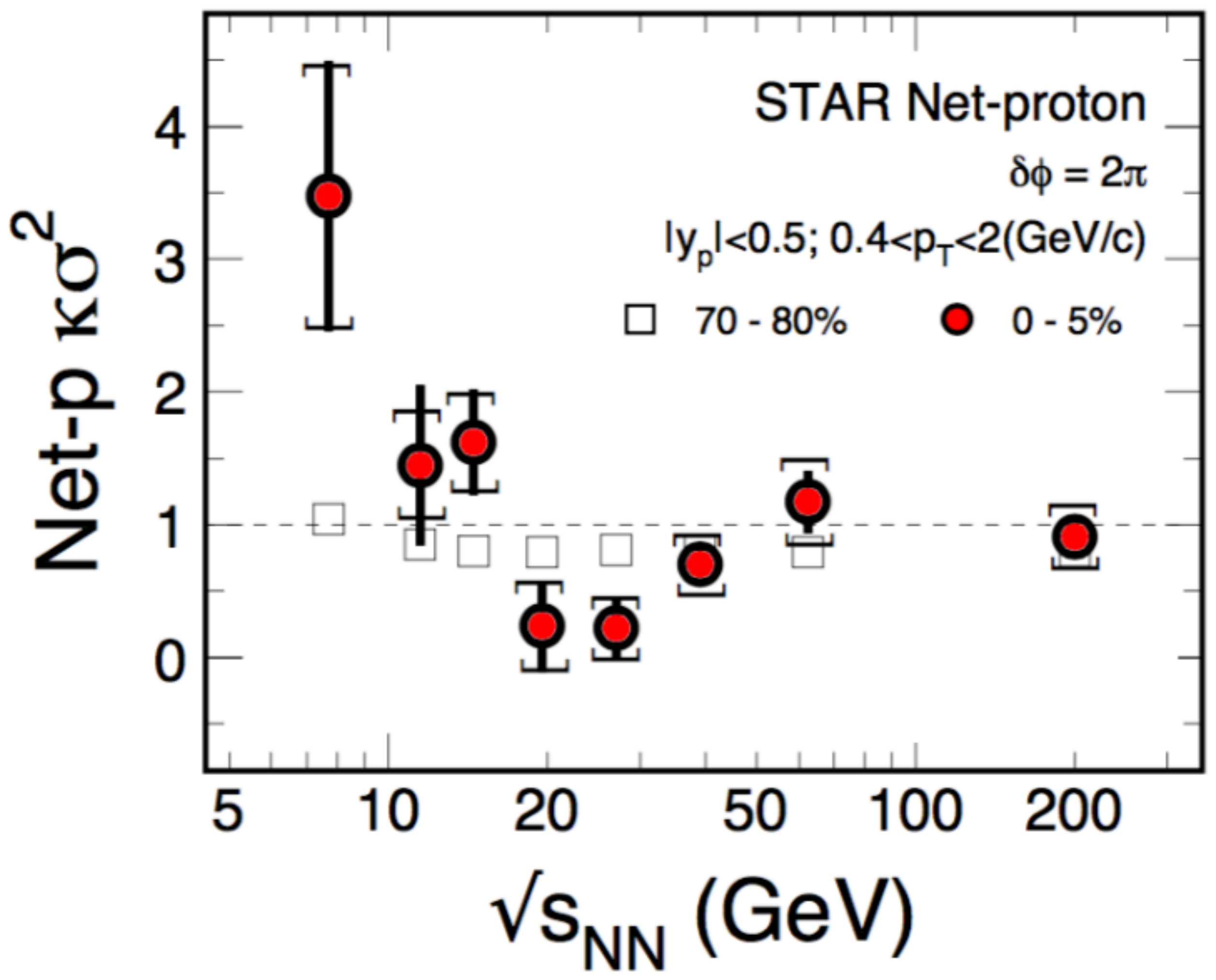


- ✓ **Statistical uncertainties will be dramatically reduced.**
- ✓ **Can we measure a possible "peak" structure?**

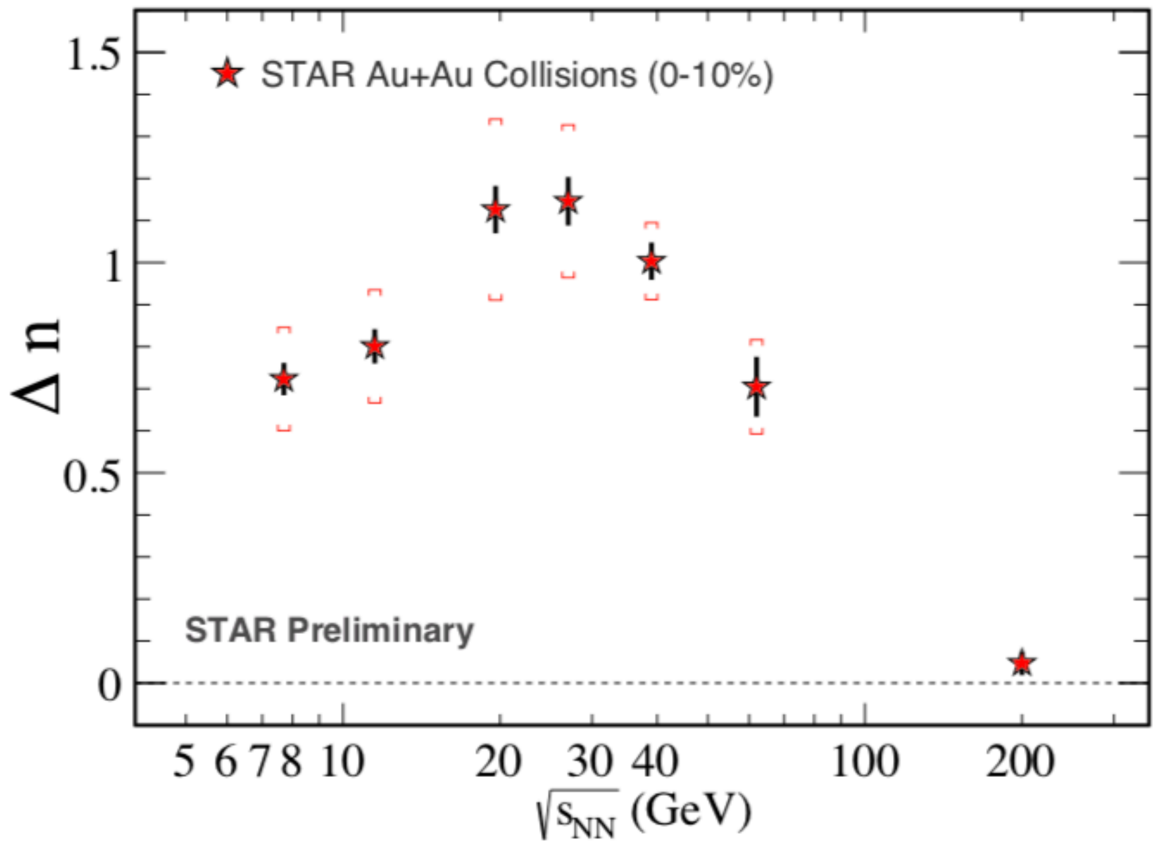


Summary

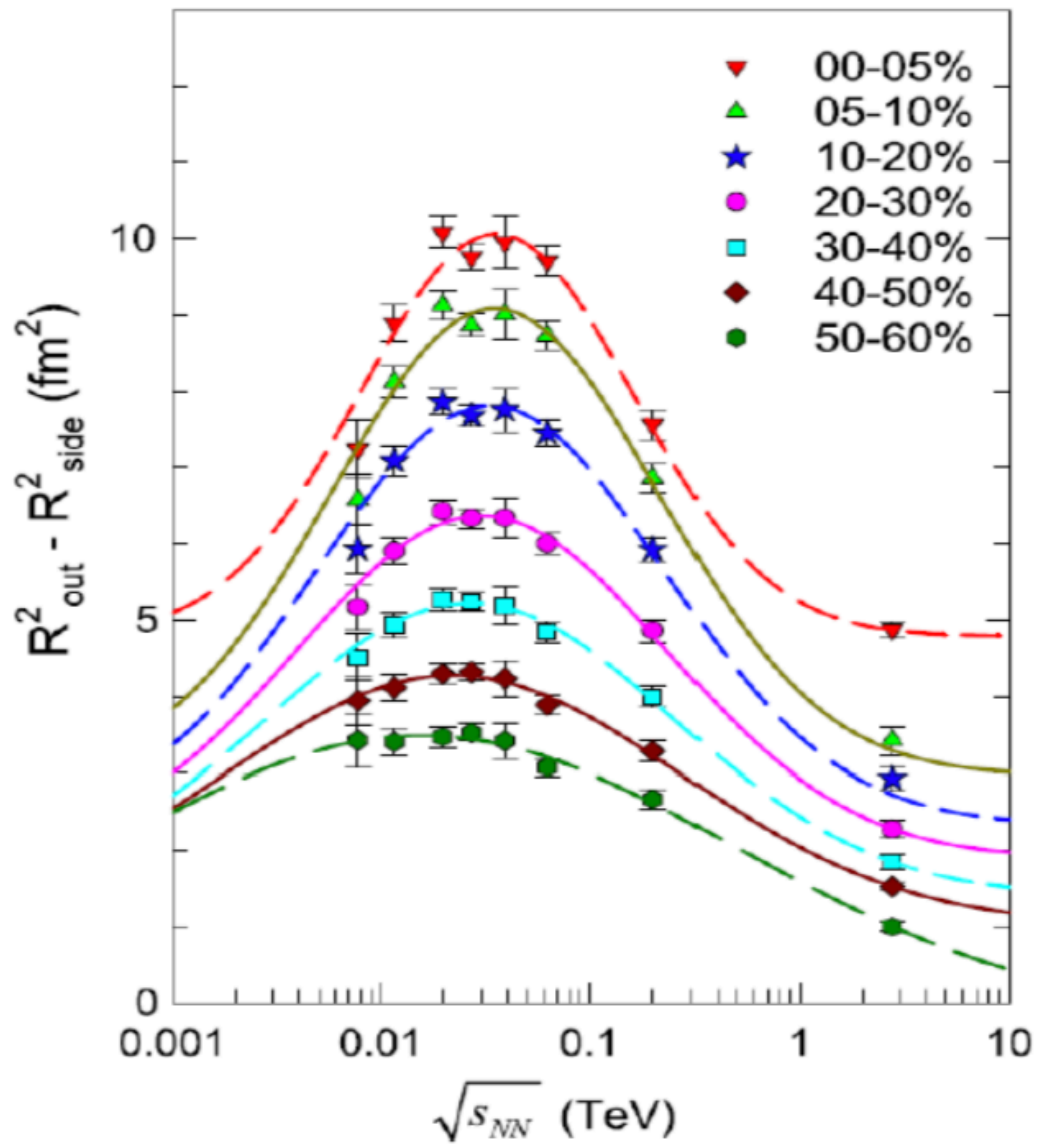
Net-p flu.



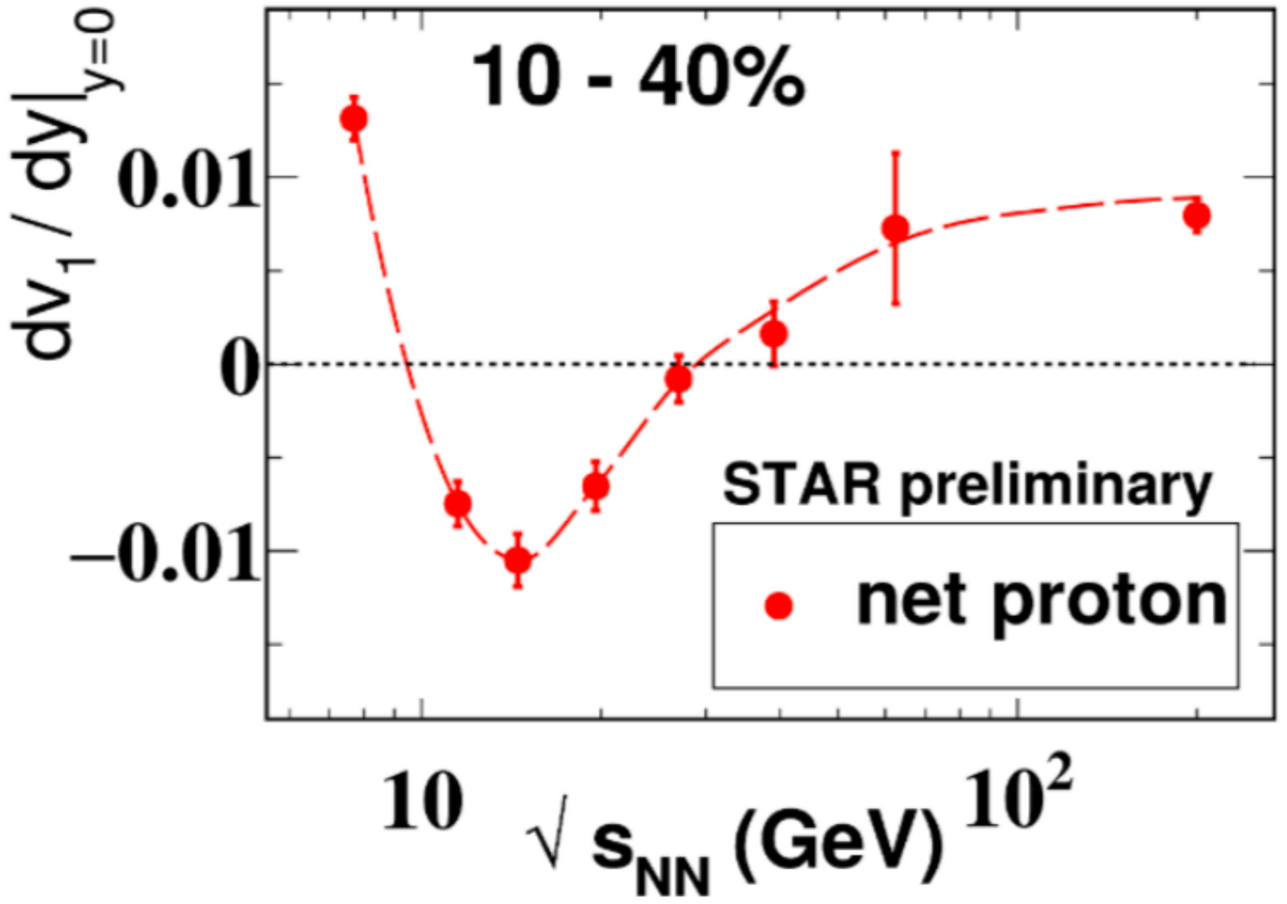
Neutron density flu.



HBT radii



Slope of Directed flow vs y.



Peak and/or dip structures observed
at common energy ranges : 20-30 GeV !!

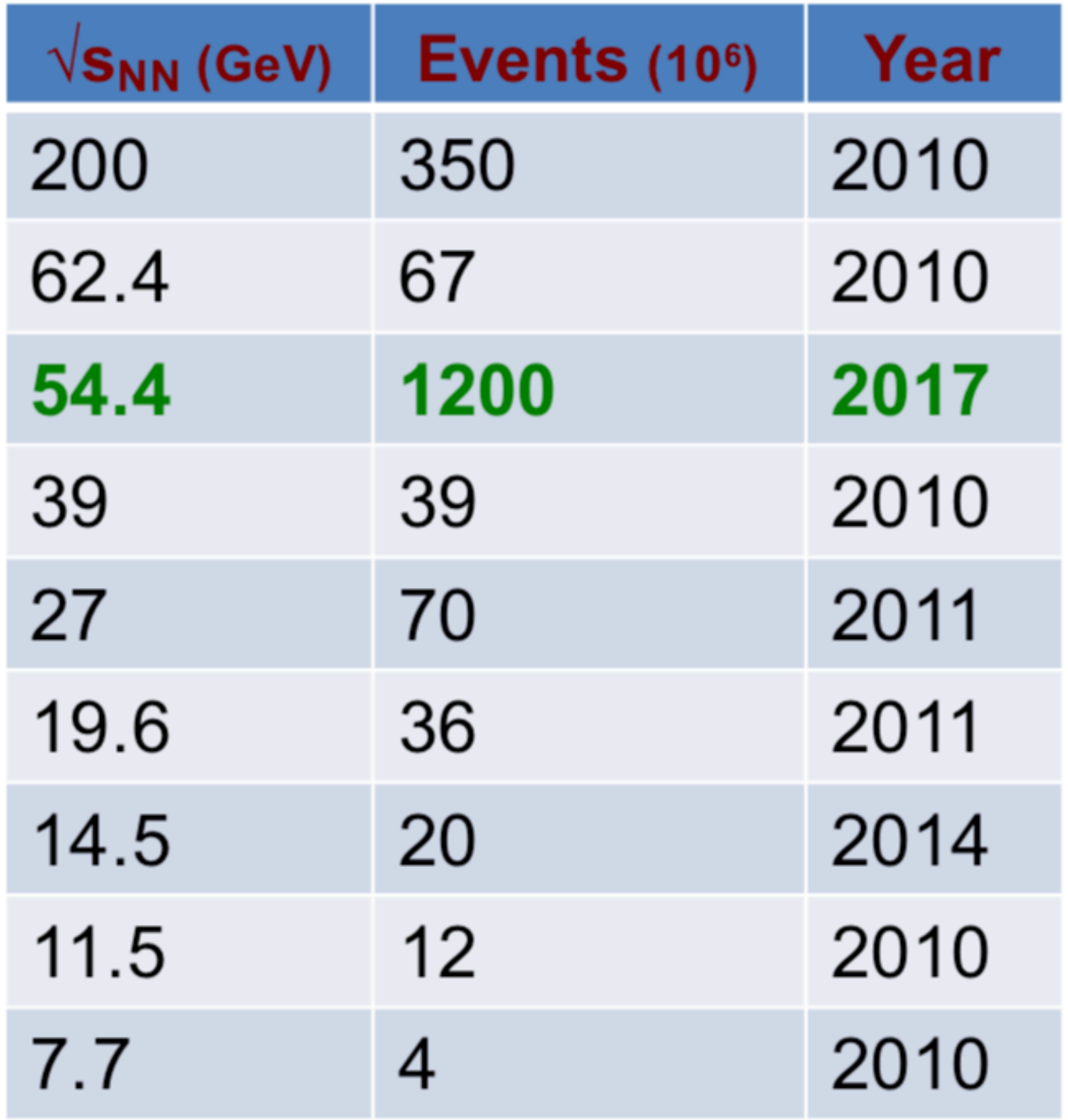
Hard to believe those are driven by different physics.

Thank you for your attention

Back up

Beam Energy Scan

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



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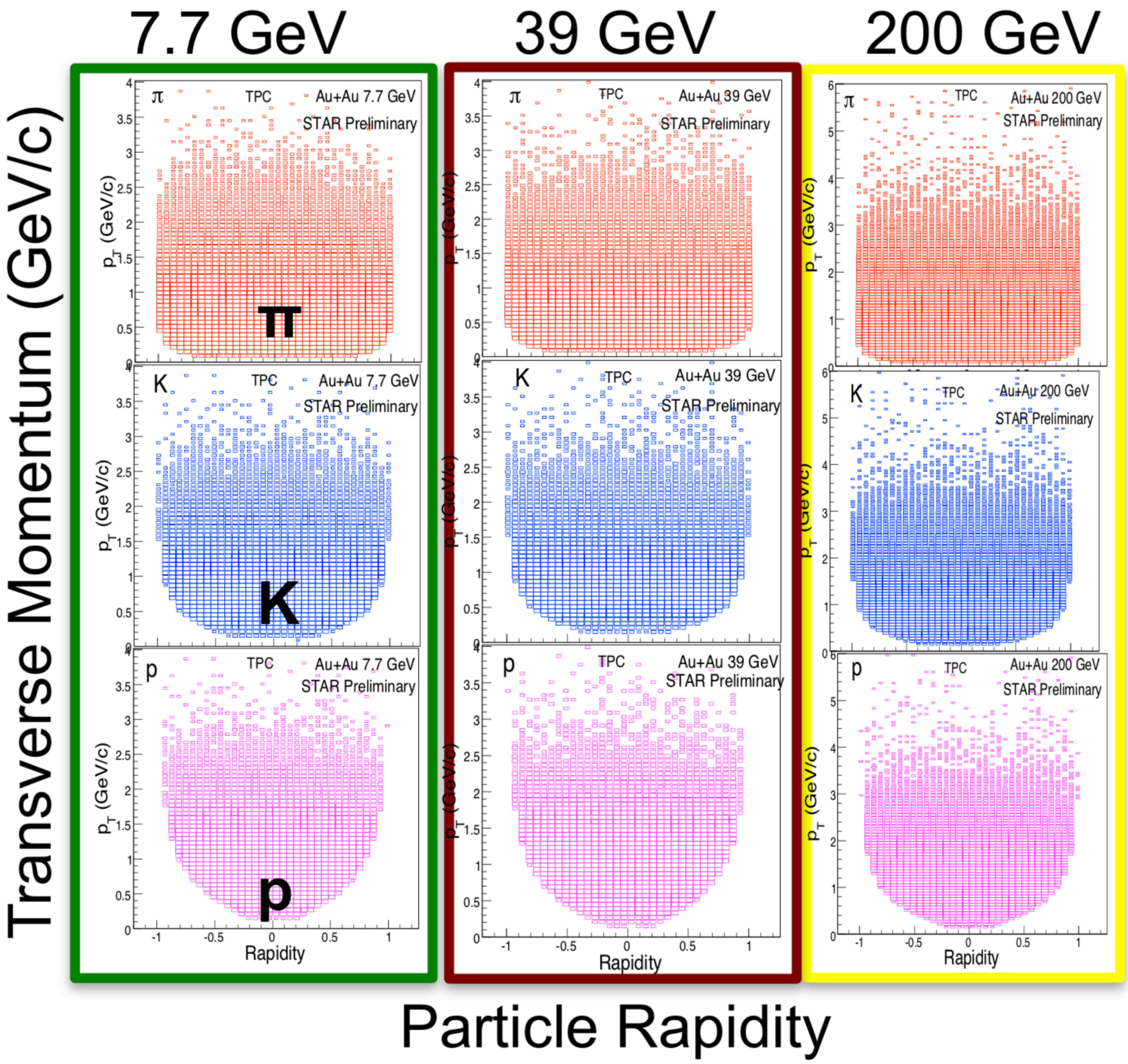
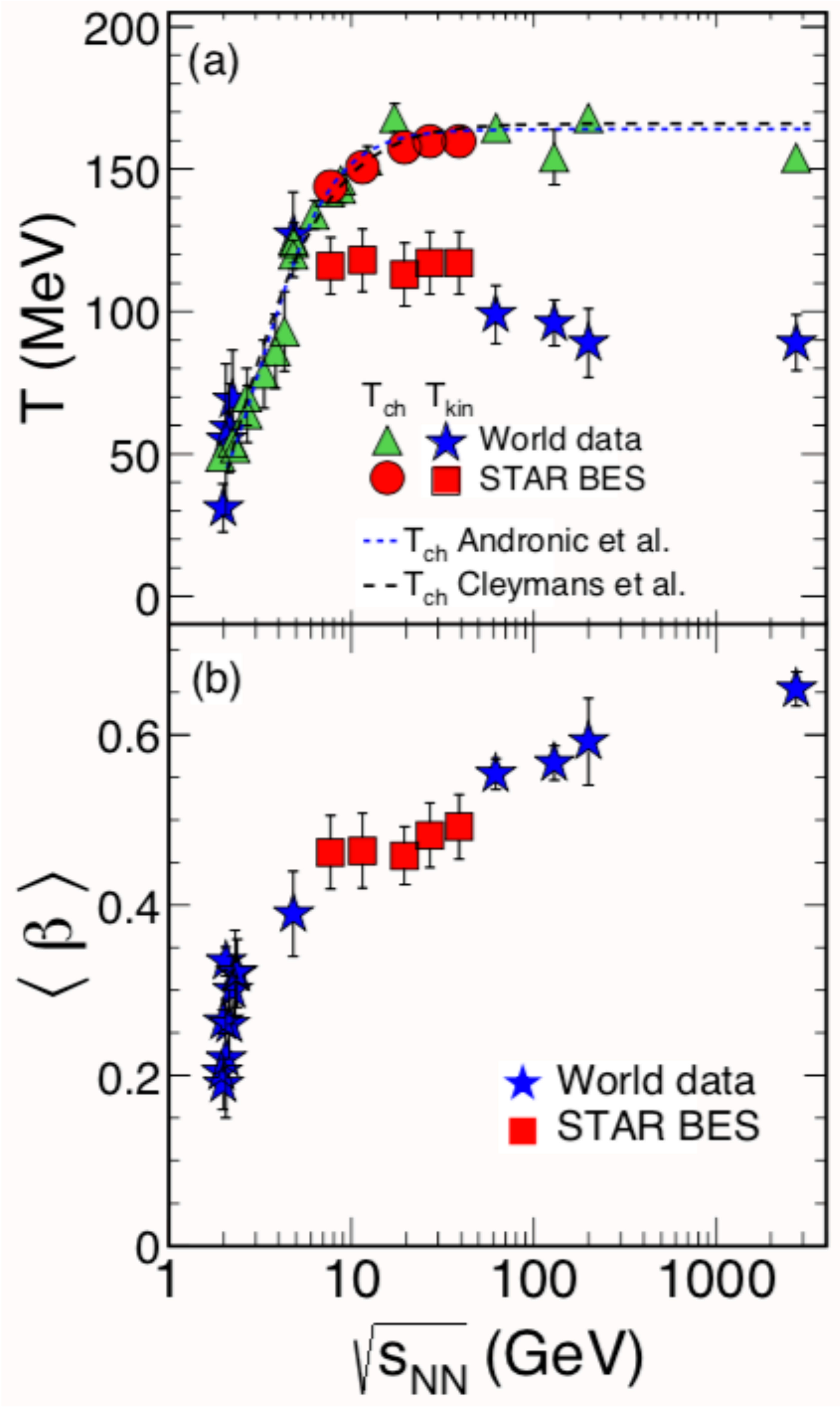
7.7	4	2010



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

Skellam baseline

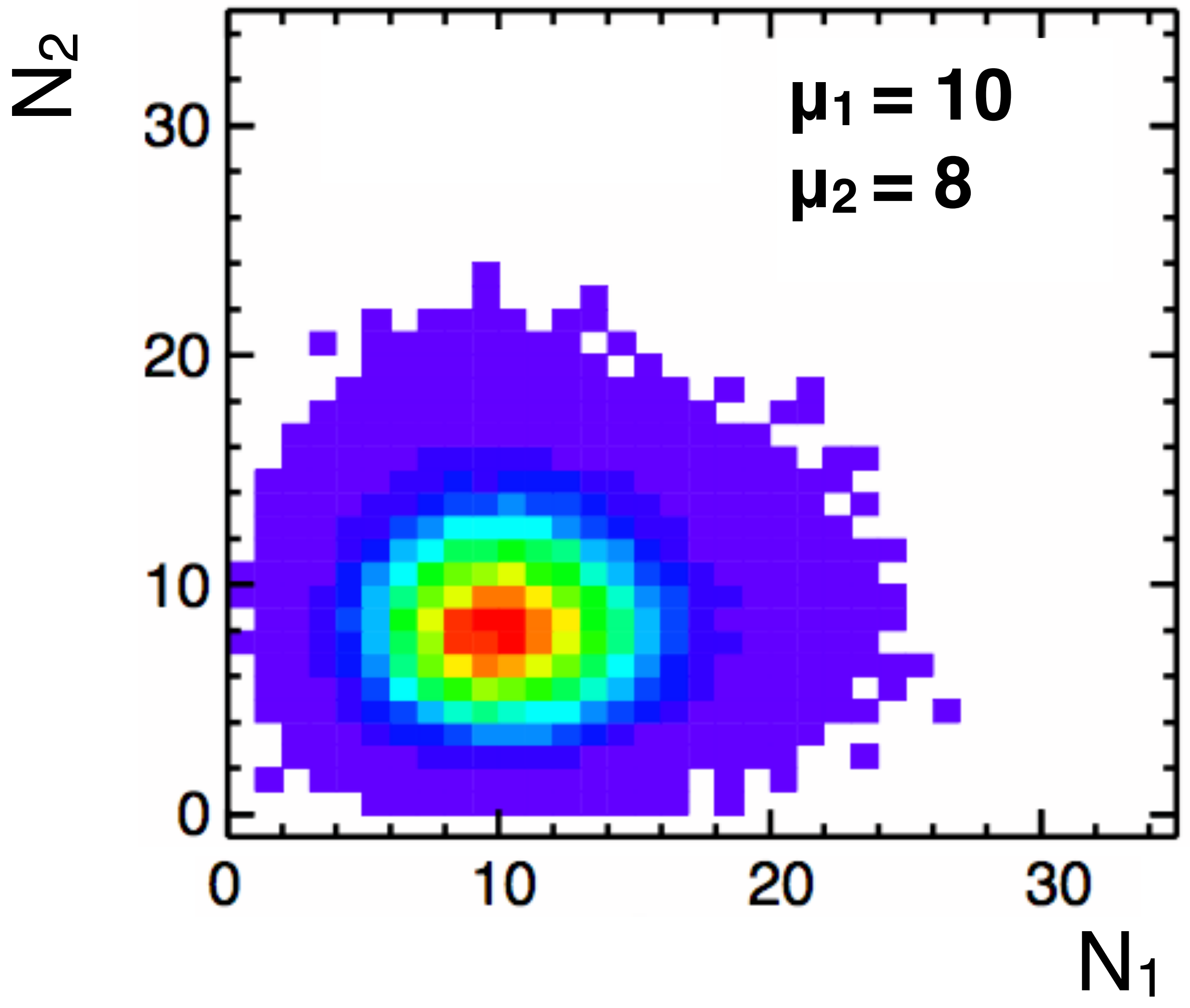
- ✓ **Assuming protons and antiprotons follow Poisson distribution.**
- ✓ **Poisson - Poisson = Skellam**

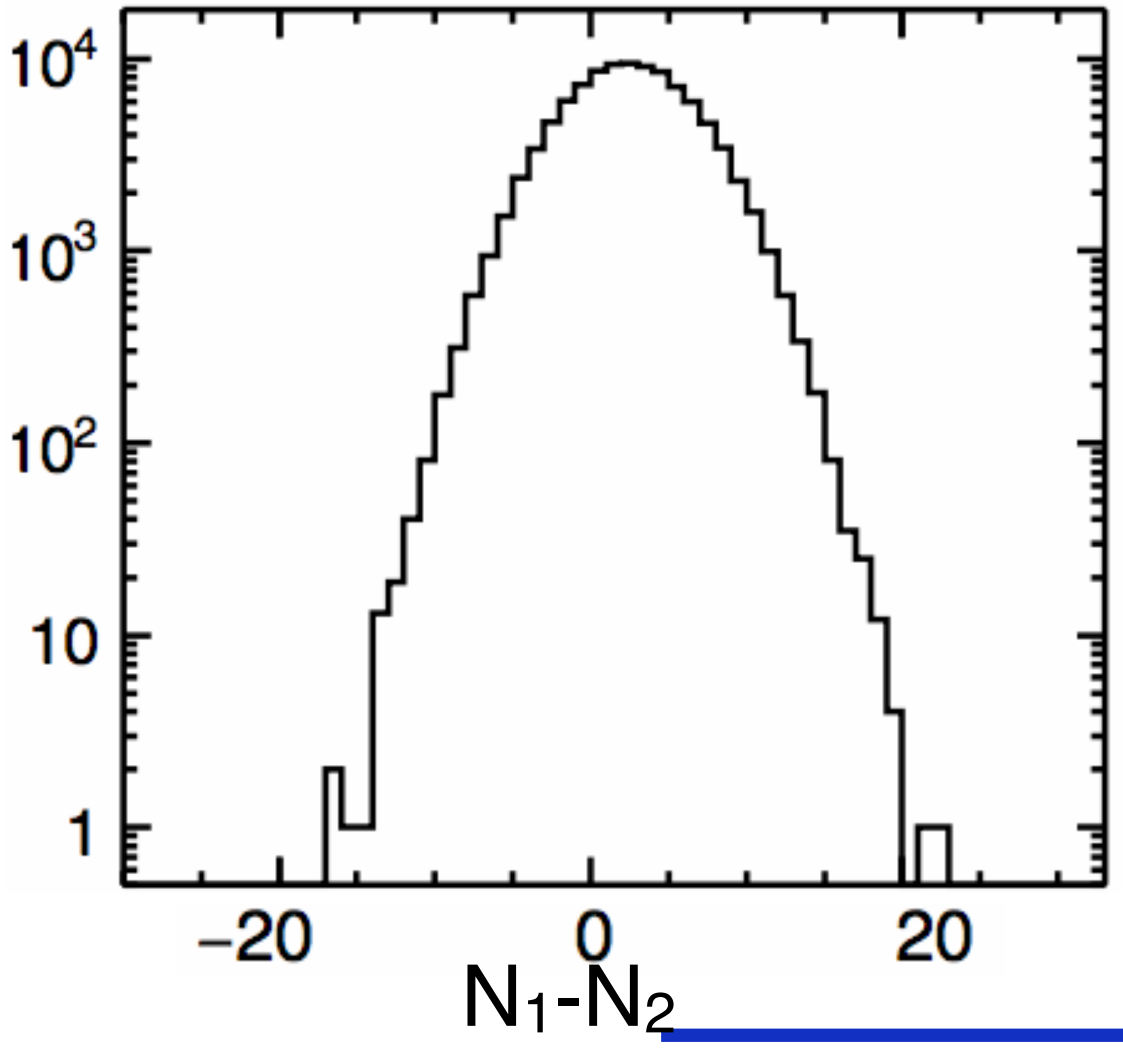
$$p(k;\mu_1,\mu_2) = \Pr\{K=k\} = e^{-(\mu_1+\mu_2)}\left(\frac{\mu_1}{\mu_2}\right)^{k/2} I_k(2\sqrt{\mu_1\mu_2})$$

- ✓ **Odd(even) order cumulant of Skellam distribution is difference(sum) between means of two Poissons.**

μ_1, μ_2 : mean parameter of Poisson

$$C_{odd} = \mu_1 - \mu_2 \qquad S\sigma = \frac{C_3}{C_2} = \frac{\mu_1-\mu_2}{\mu_1+\mu_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = 1$$
$$C_{even} = \mu_1 + \mu_2$$





Skellam baseline

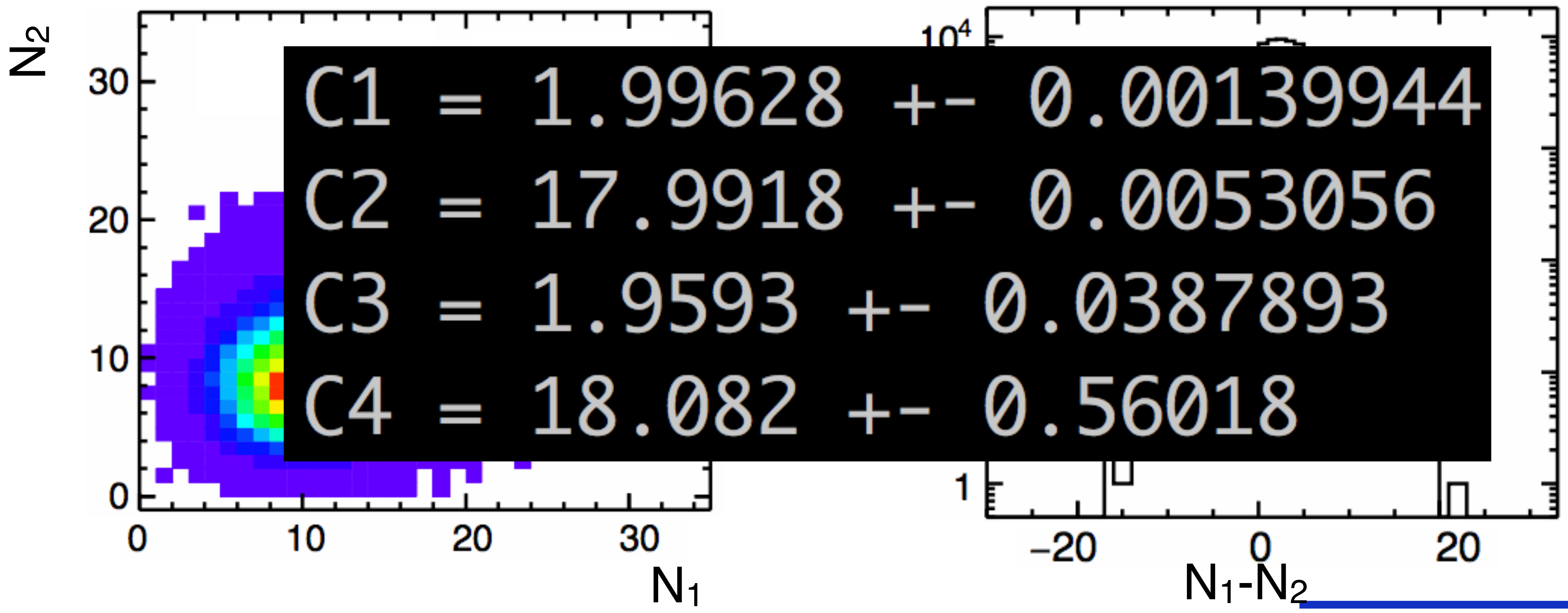
- ✓ **Assuming protons and antiprotons follow Poisson distribution.**
- ✓ **Poisson - Poisson = Skellam**

$$p(k;\mu_1,\mu_2) = \Pr\{K=k\} = e^{-(\mu_1+\mu_2)}\left(\frac{\mu_1}{\mu_2}\right)^{k/2} I_k(2\sqrt{\mu_1\mu_2})$$

- ✓ **Odd(even) order cumulant of Skellam distribution is difference(sum) between means of two Poissons.**

μ_1, μ_2 : mean parameter of Poisson

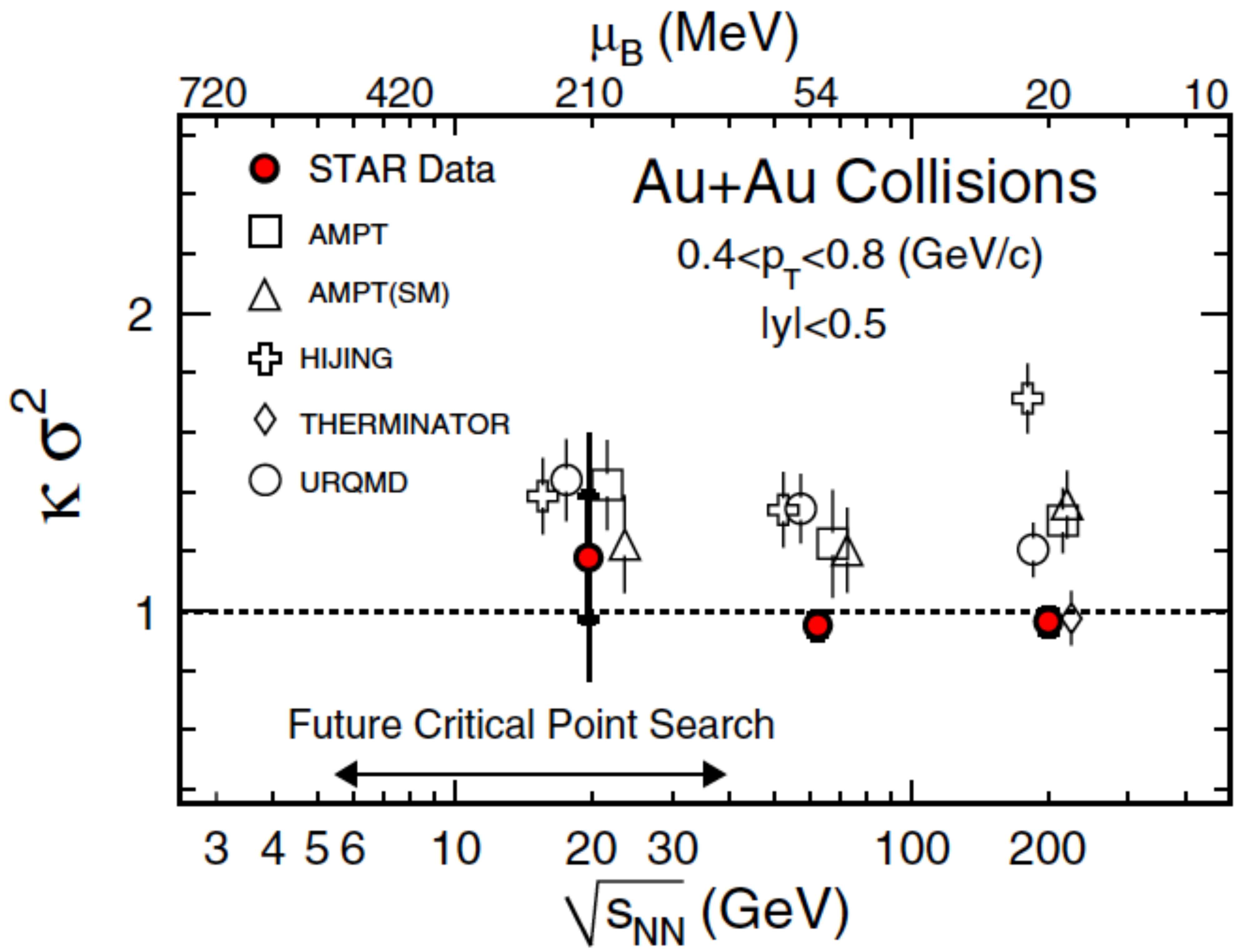
$$C_{odd} = \mu_1 - \mu_2 \qquad S\sigma = \frac{C_3}{C_2} = \frac{\mu_1-\mu_2}{\mu_1+\mu_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = 1$$
$$C_{even} = \mu_1 + \mu_2$$

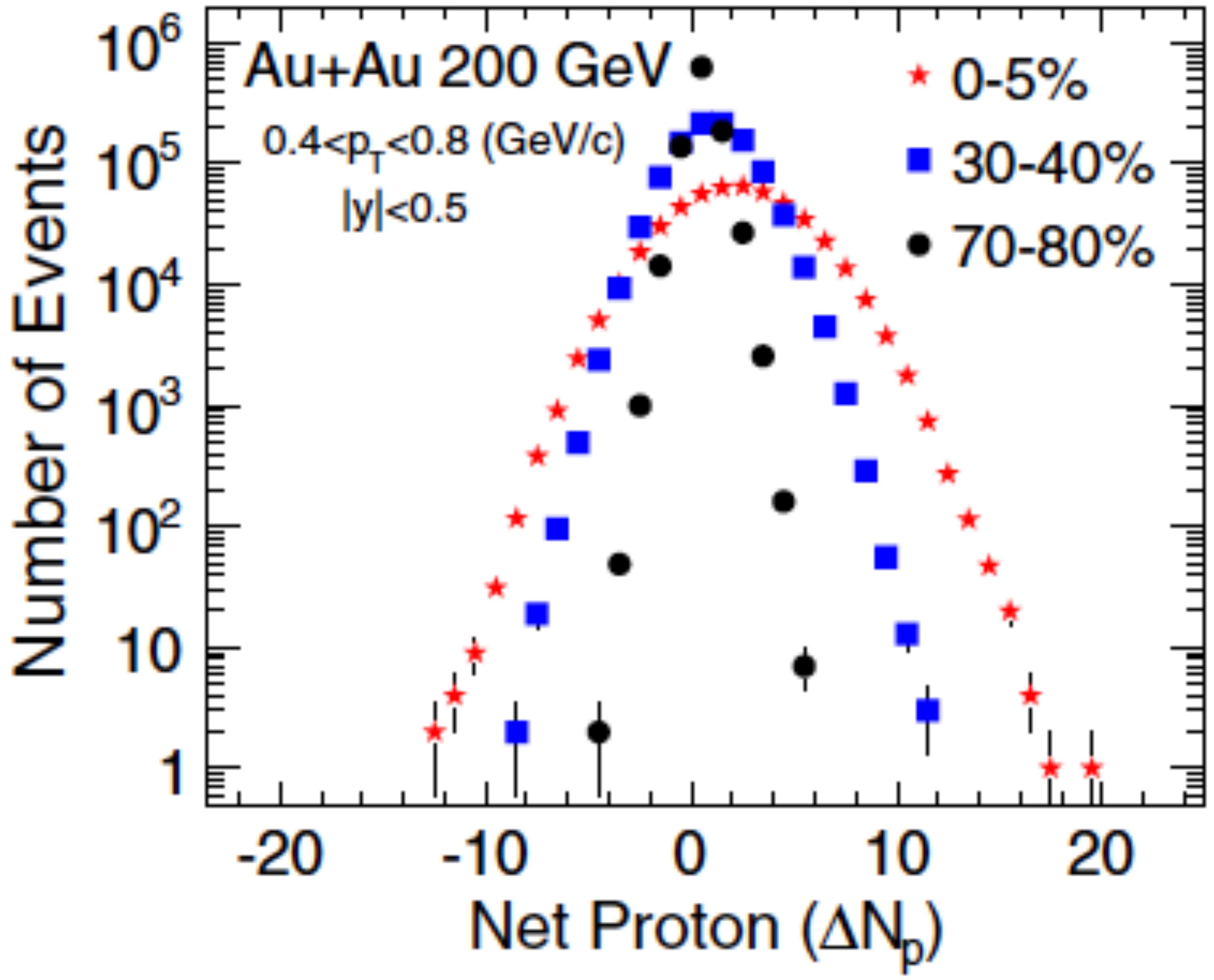


```
C1 = 1.99628 +- 0.00139944
C2 = 17.9918 +- 0.0053056
C3 = 1.9593 +- 0.0387893
C4 = 18.082 +- 0.56018
```

First measurement of net proton

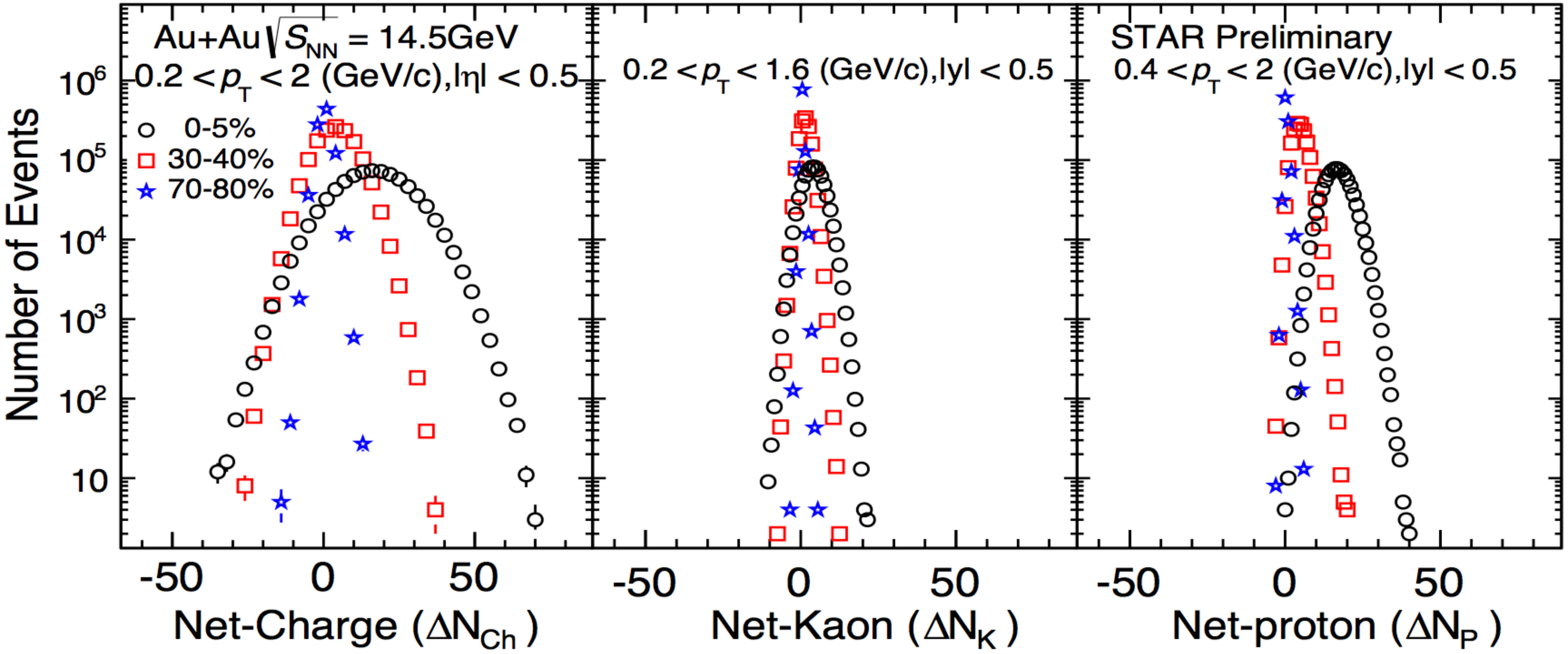
- ✓ At $\mu_B < 210$ MeV, the 4th-order fluctuation is found to be flat as a function of collision energy.





PRL105, 022302(2010): STAR Collaboration

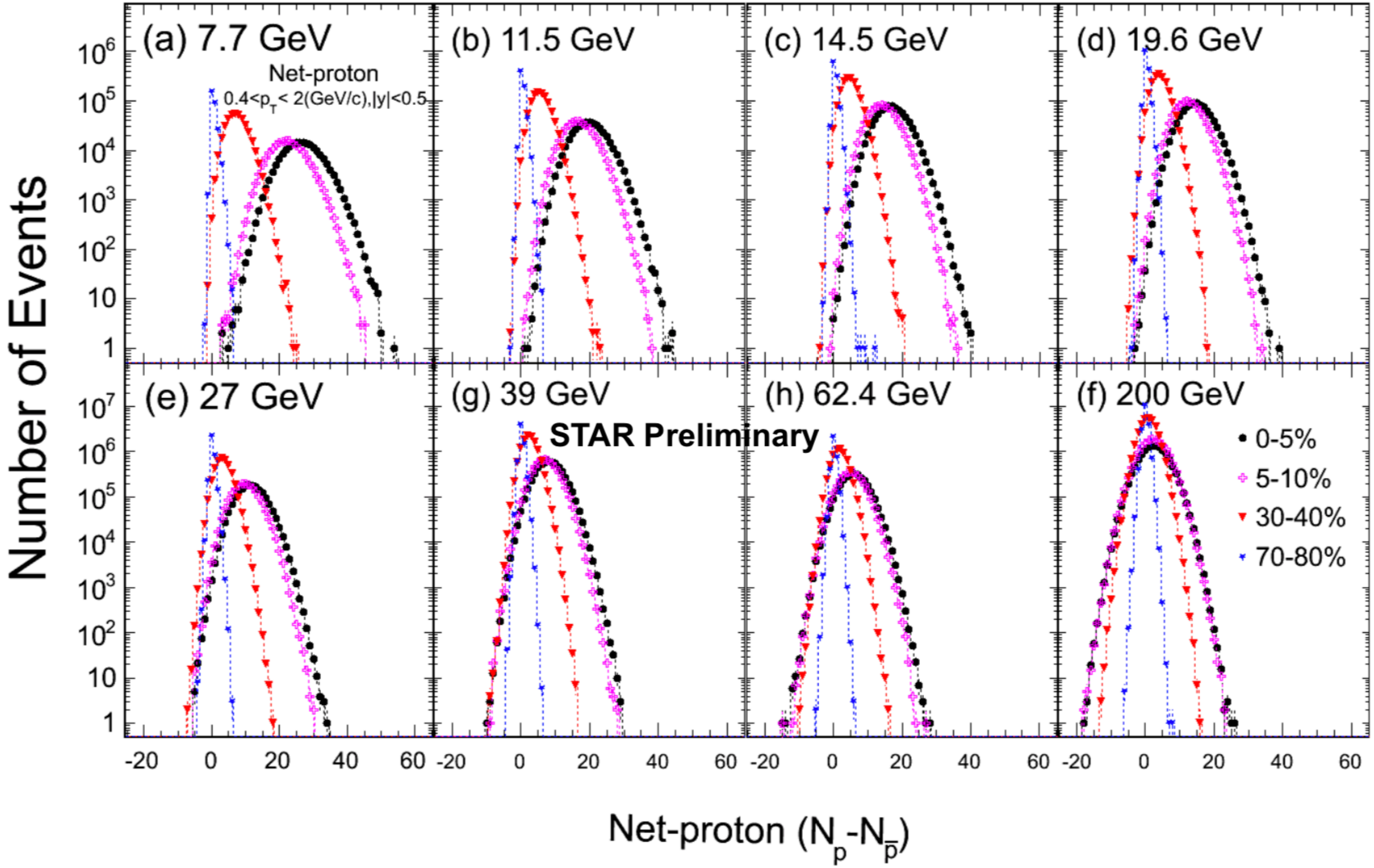
Data analysis method



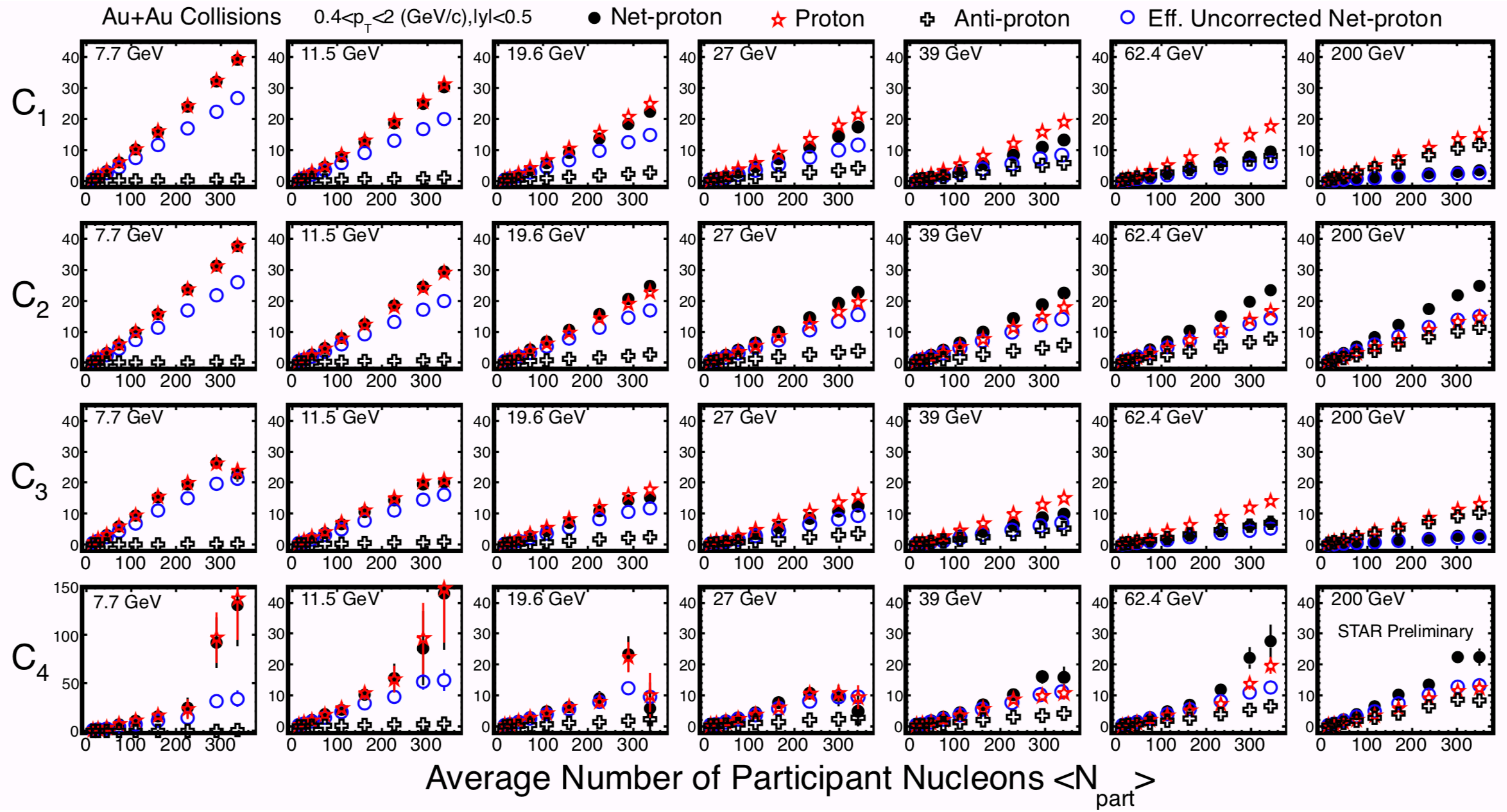
- ✓ **Statistical error estimation : Delta theorem or bootstrap**
- ✓ **Avoid auto-correlation effects : New centrality definition**
- ✓ **Suppress initial volume fluctuation : Centrality bin width correction**
- ✓ **Detector efficiency correction : Binomial model**

- ***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***

Net-proton multiplicity distribution



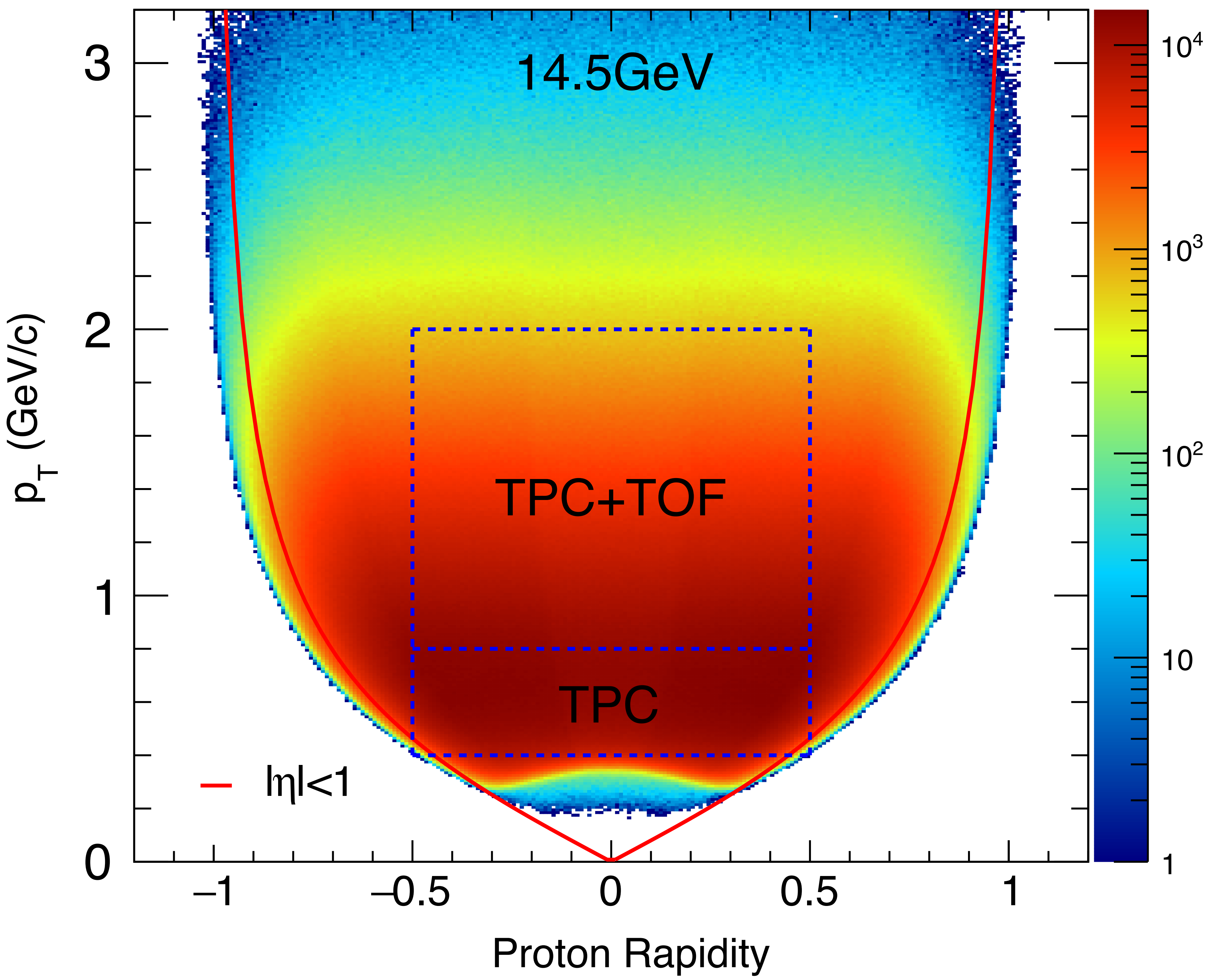
Cumulants in BES-I energies

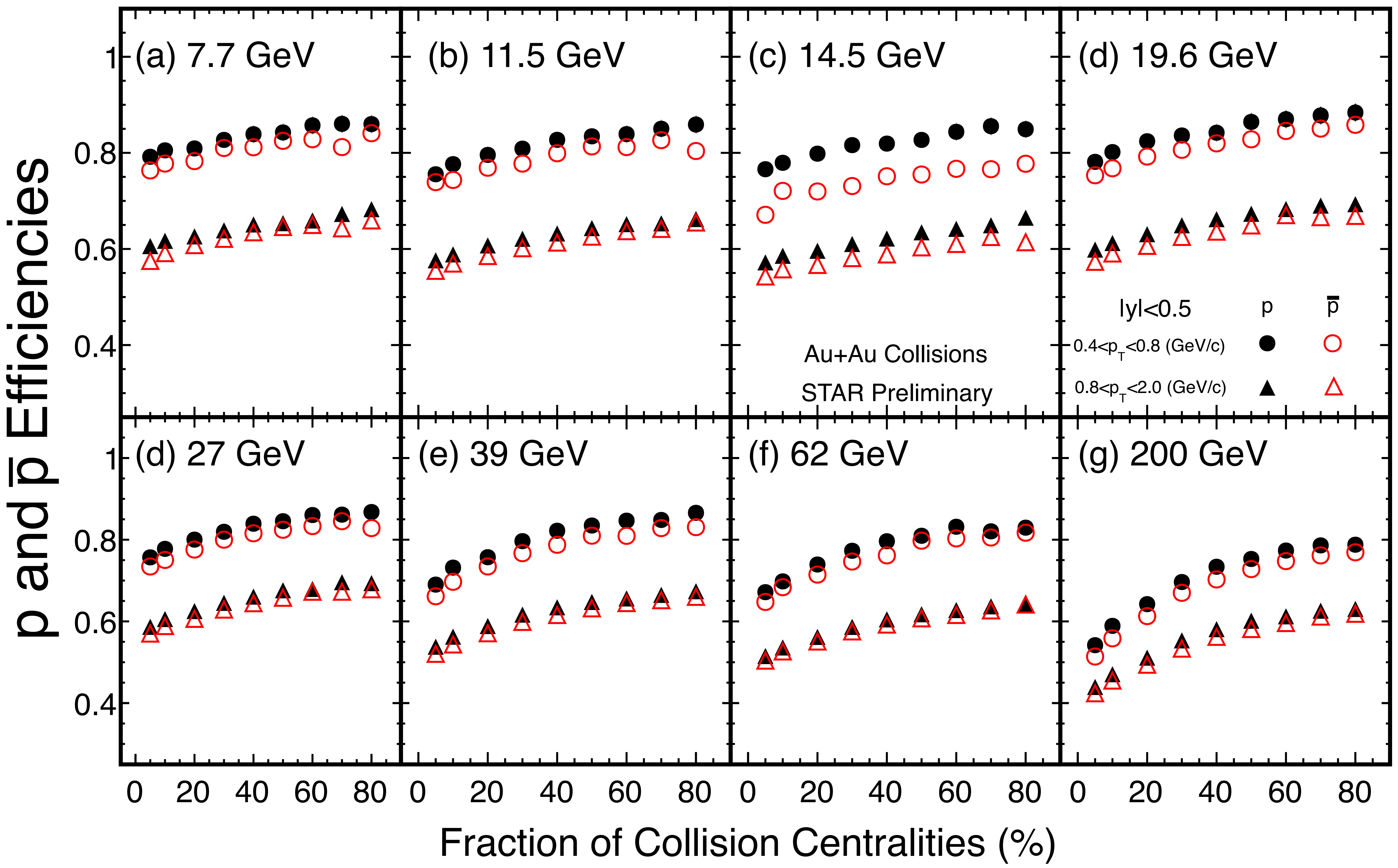


STAR, PoS CPOD2014 (2015)019

Extend p_T coverage

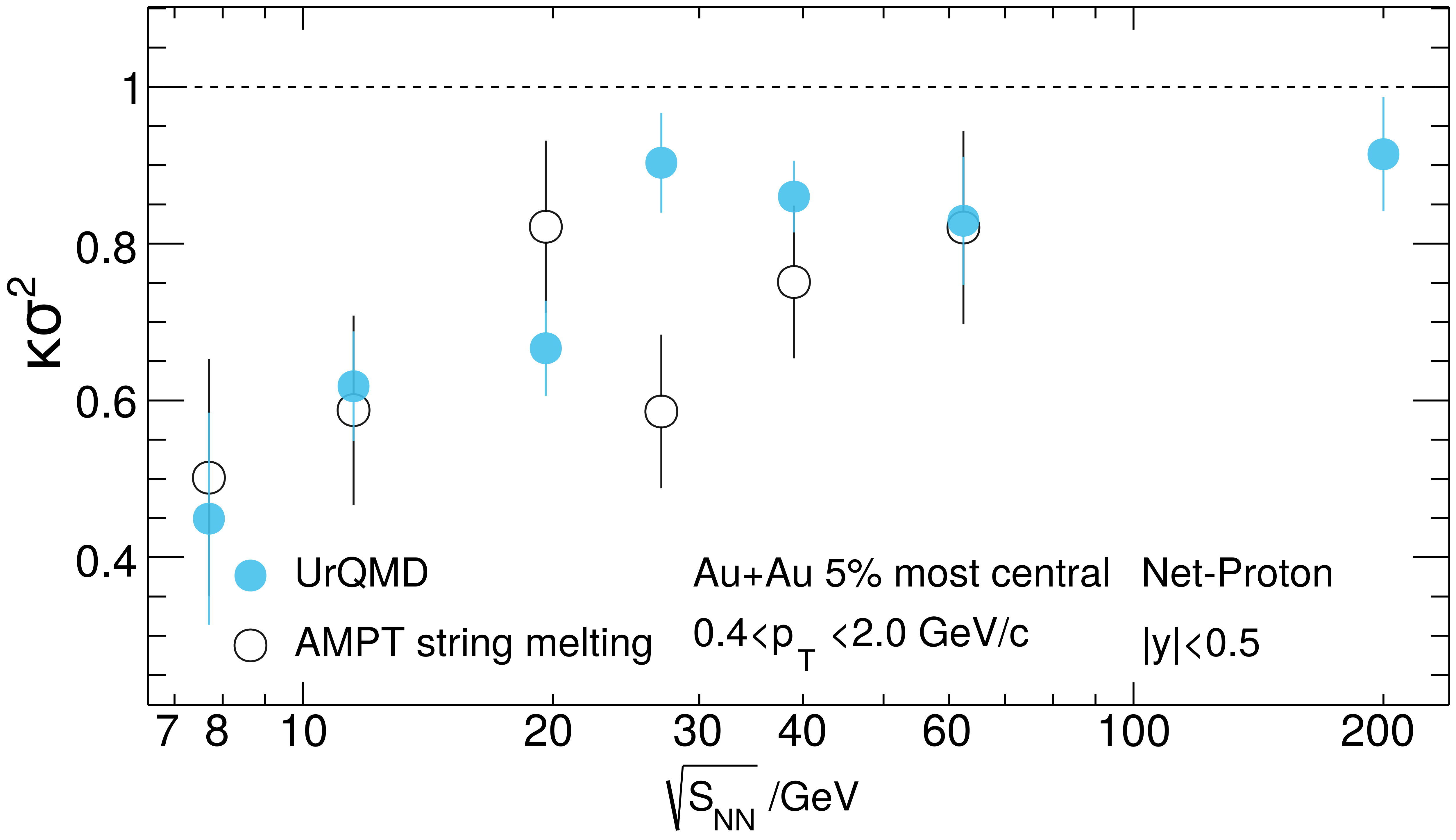
- ✓ p_T region can be extended up to 2.0 GeV by using TOF as well as TPC.
- ✓ (Anti)proton statistics is doubled with respect to the published results.

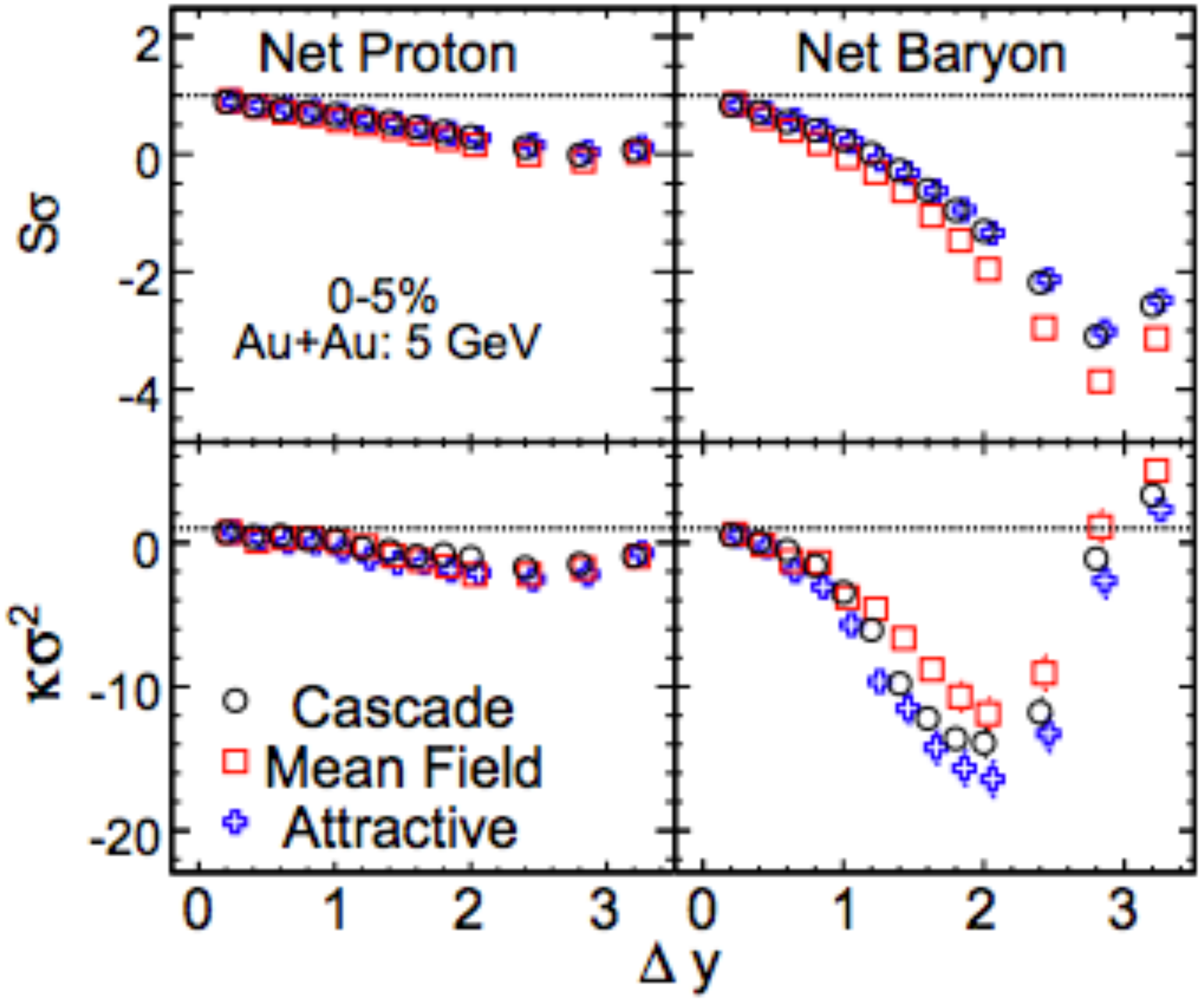




Non-critical contributions

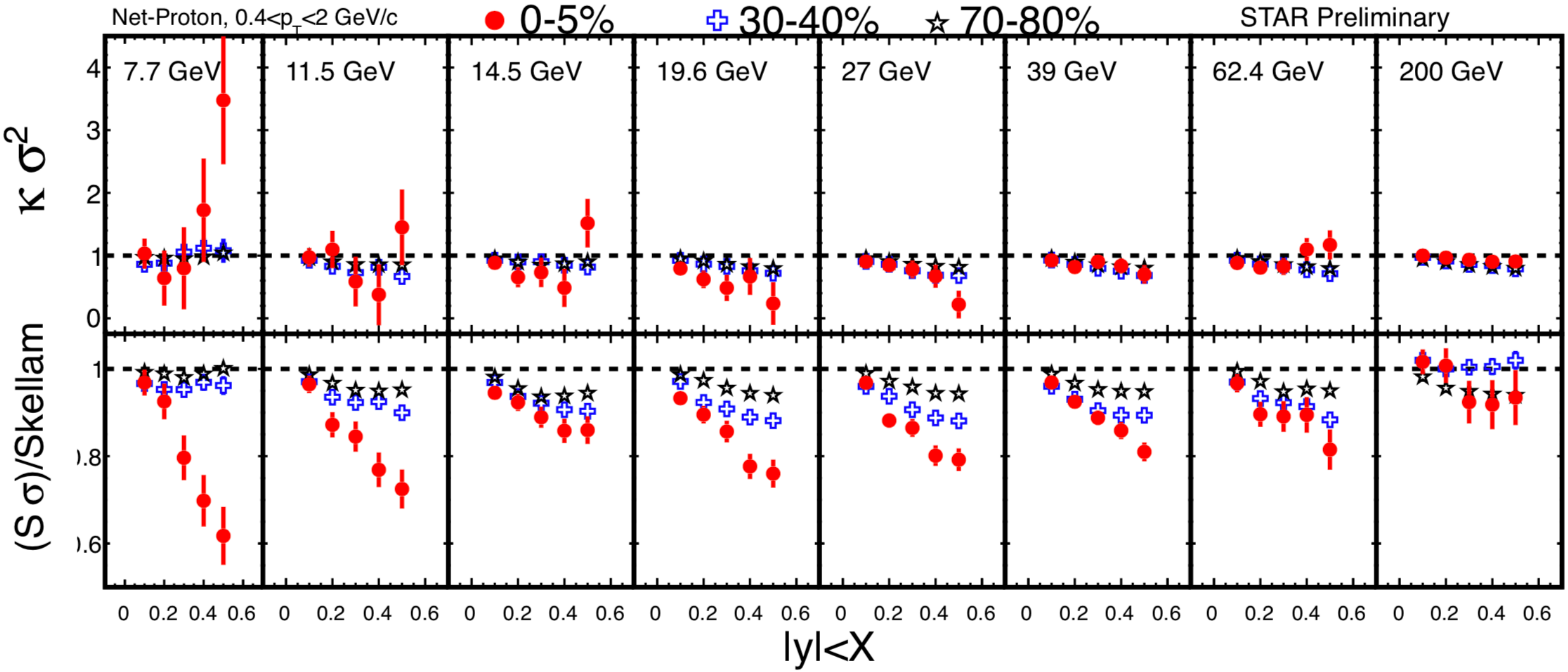
- ✓ At $\sqrt{s_{NN}}$<10 GeV, data shows $\kappa\sigma^2>1$, while model shows $\kappa\sigma^2<1$
- ✓ No model simulations can explain the enhancement at low beam energies.





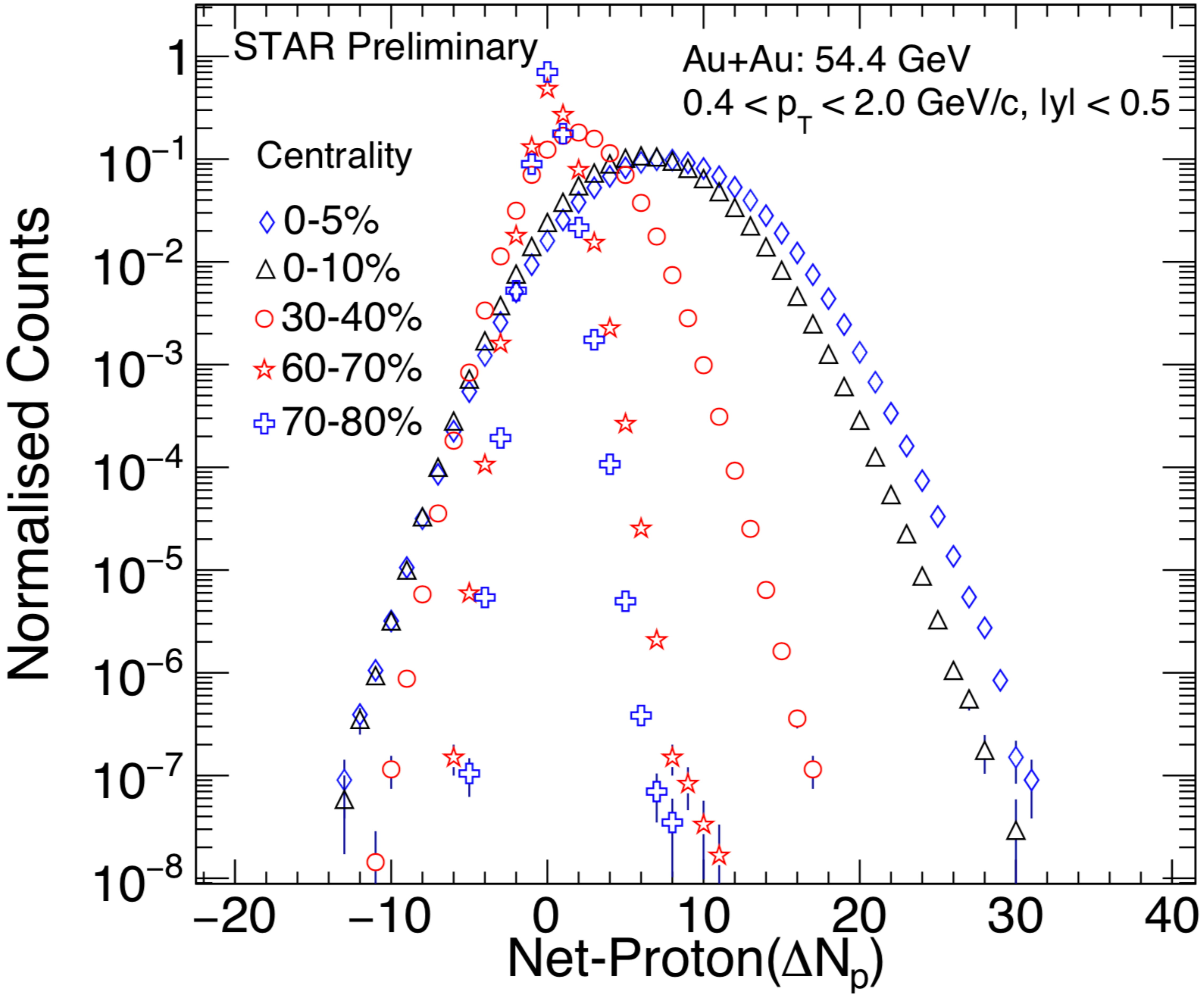
Z. Feckova, et al., PRC92, 064908(2015). J. Xu, et. al., PRC94, 024901(2016). X. Luo et al., NPA931, 808(14), P.K. Netrakanti et al. 1405.4617, NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016). S. He, X. Luo, PLB 774, 623 (2017).

Rapidity acceptance dependence



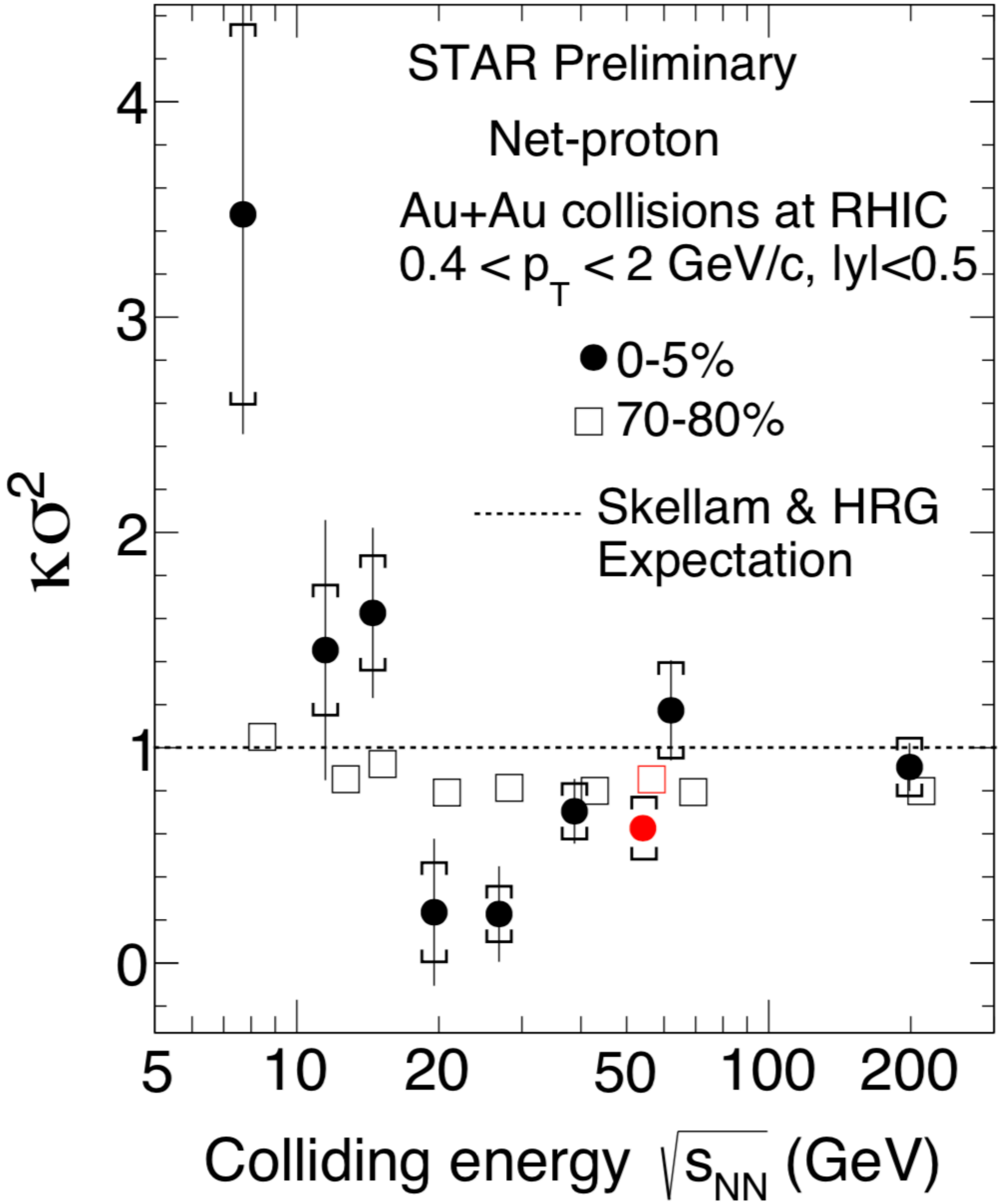
New data set : 54.4 GeV

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	$\|\eta\| < 1$; 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

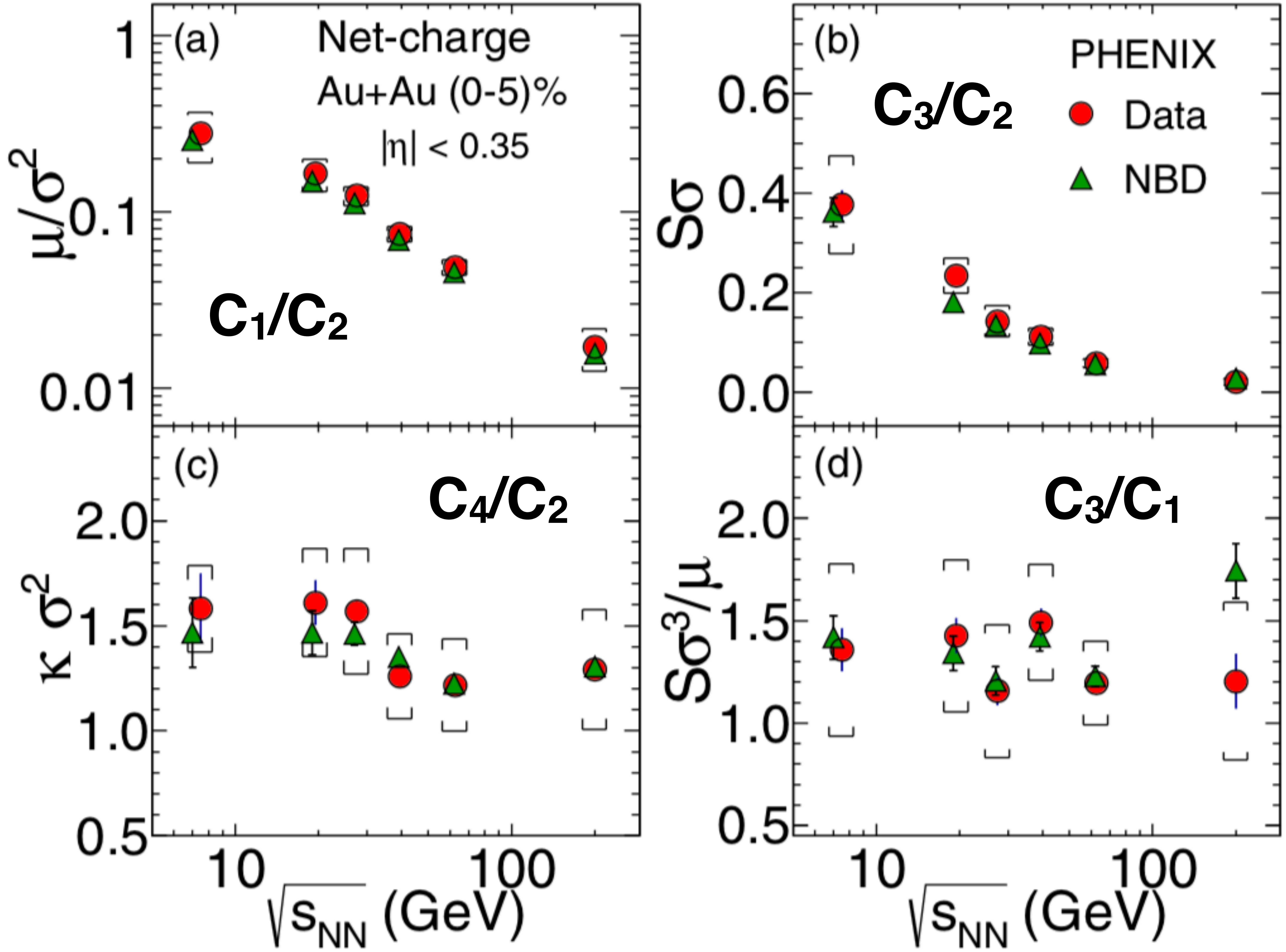
STAR, PoS CPOD2014 (2015)019



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

Net charge from PHENIX

PRC93,011901(2016): PHENIX

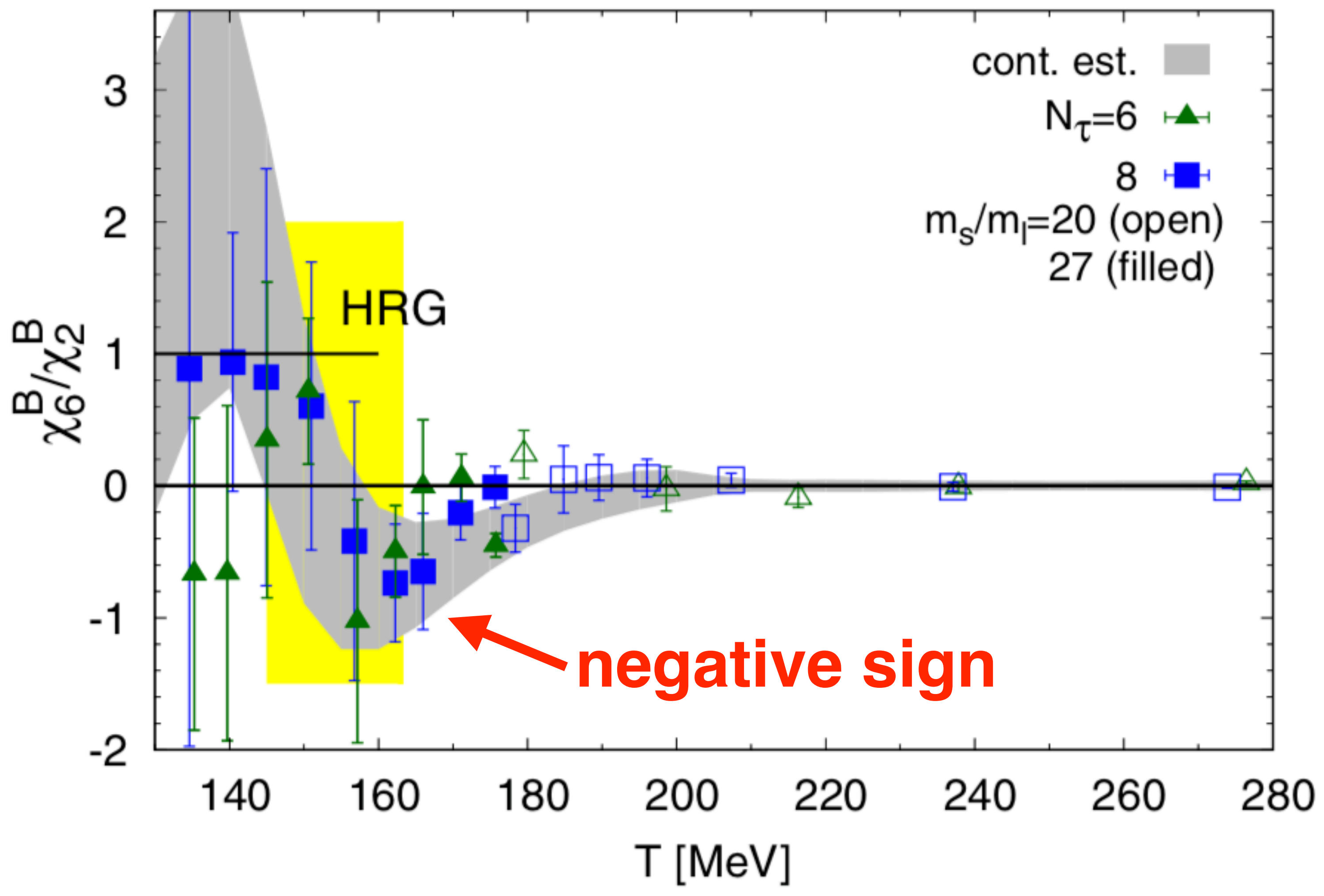


- ✓ **No non-monotonic behavior was observed.**
- ✓ **Acceptance is important.**

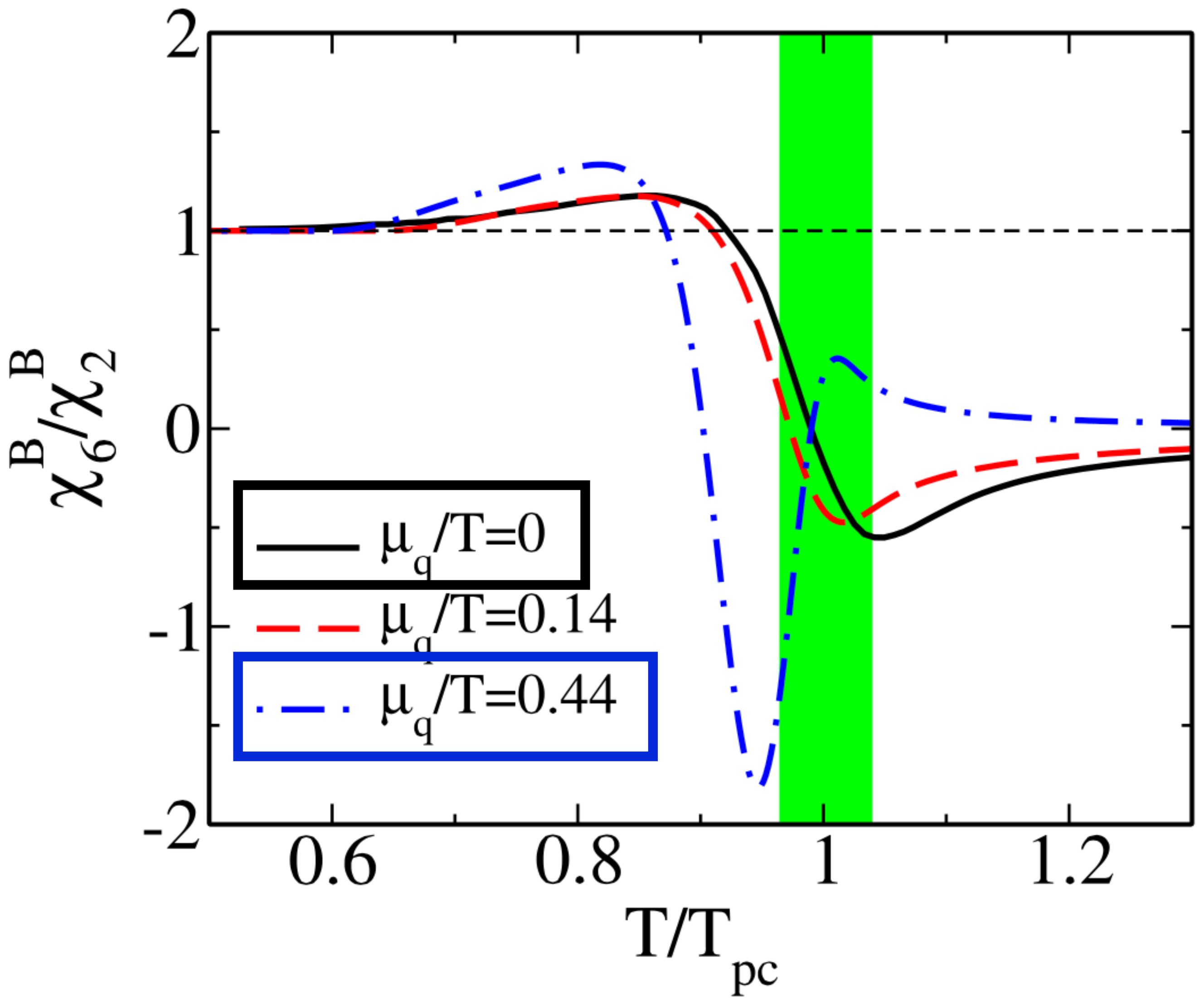
Sixth-order cumulants

- ✓ **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 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

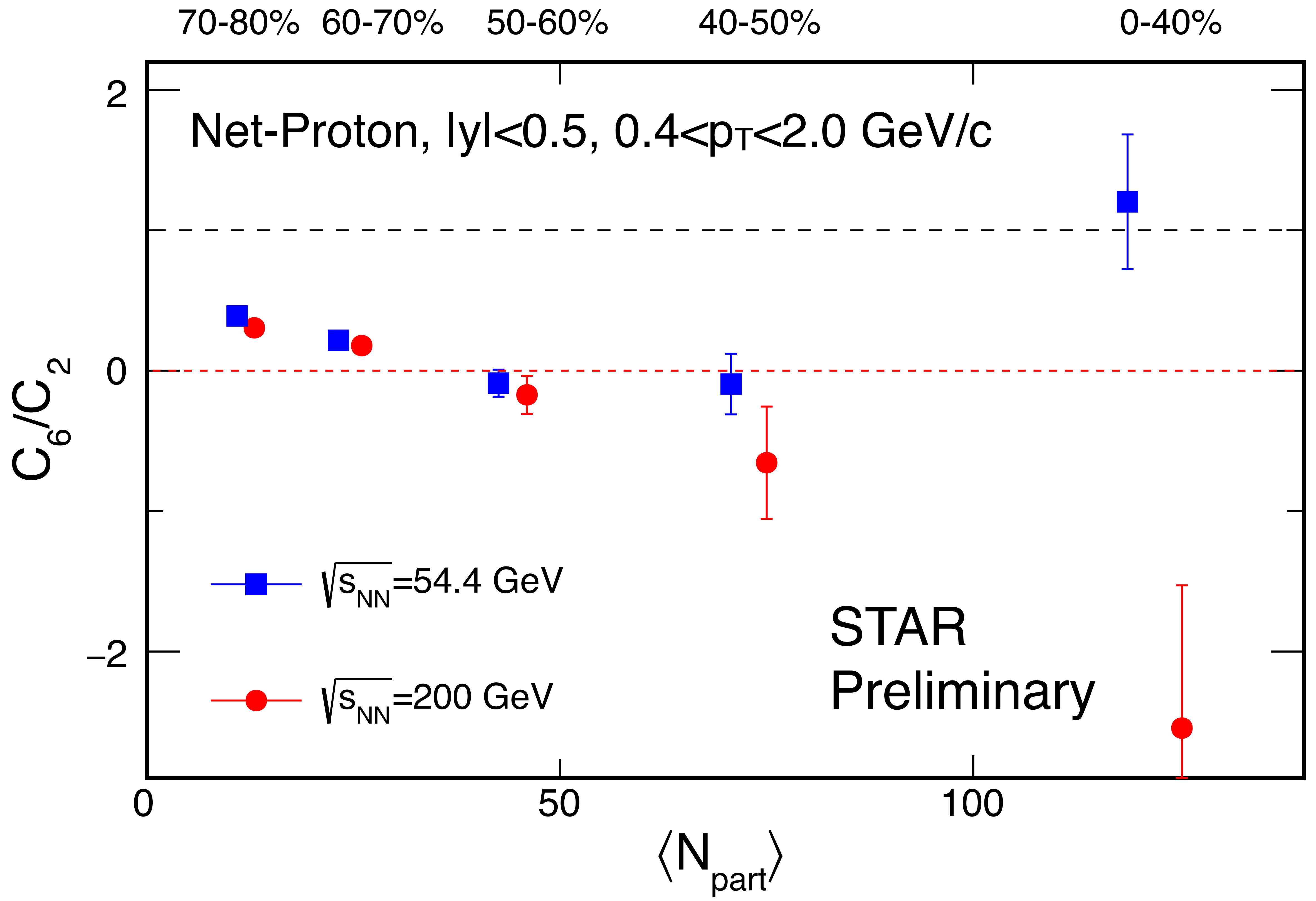
C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

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: $T^{\text{freeze}}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{\text{freeze}}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

Predicted scenario for this measurement

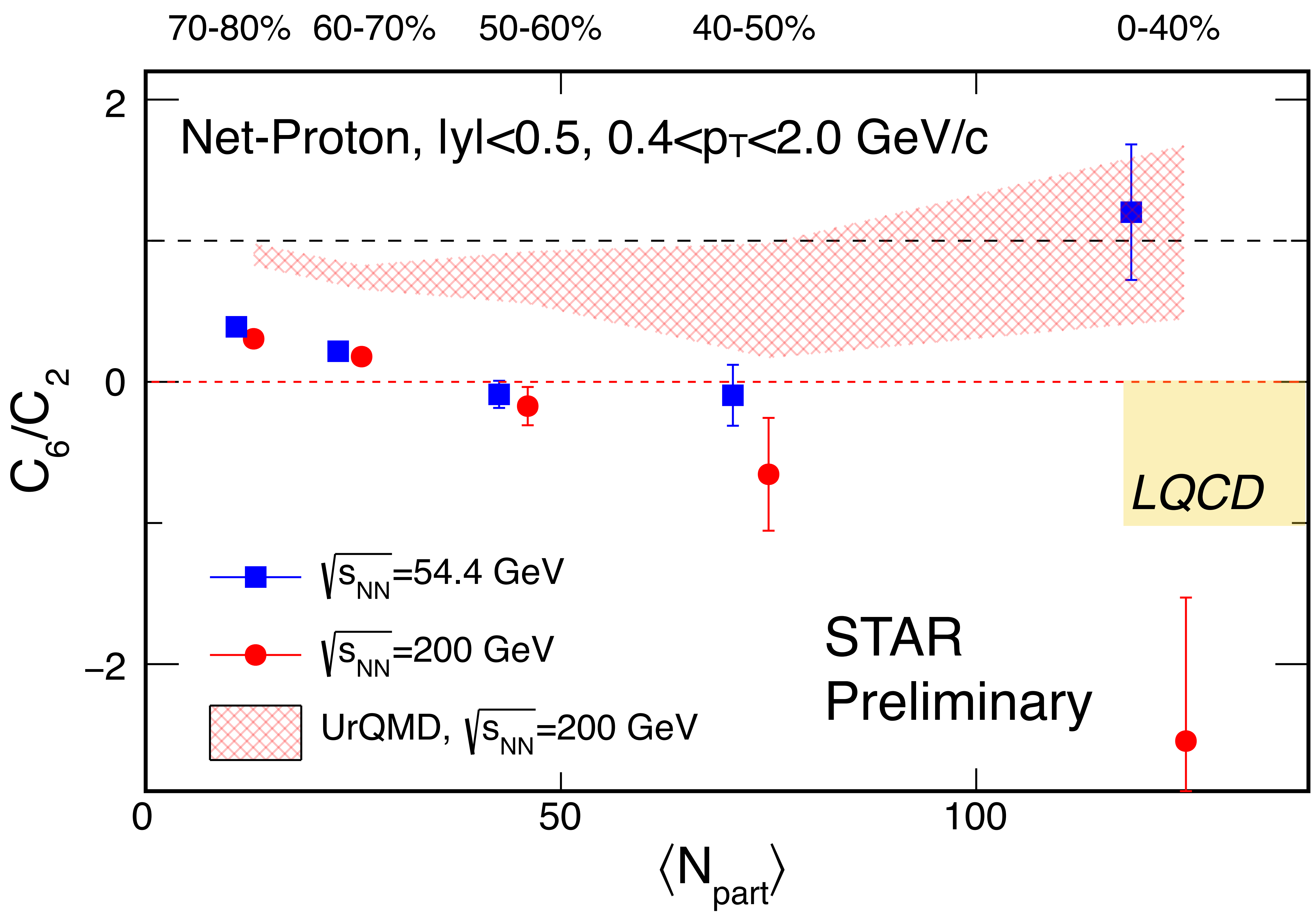
0-40% centrality

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



0-40% centrality

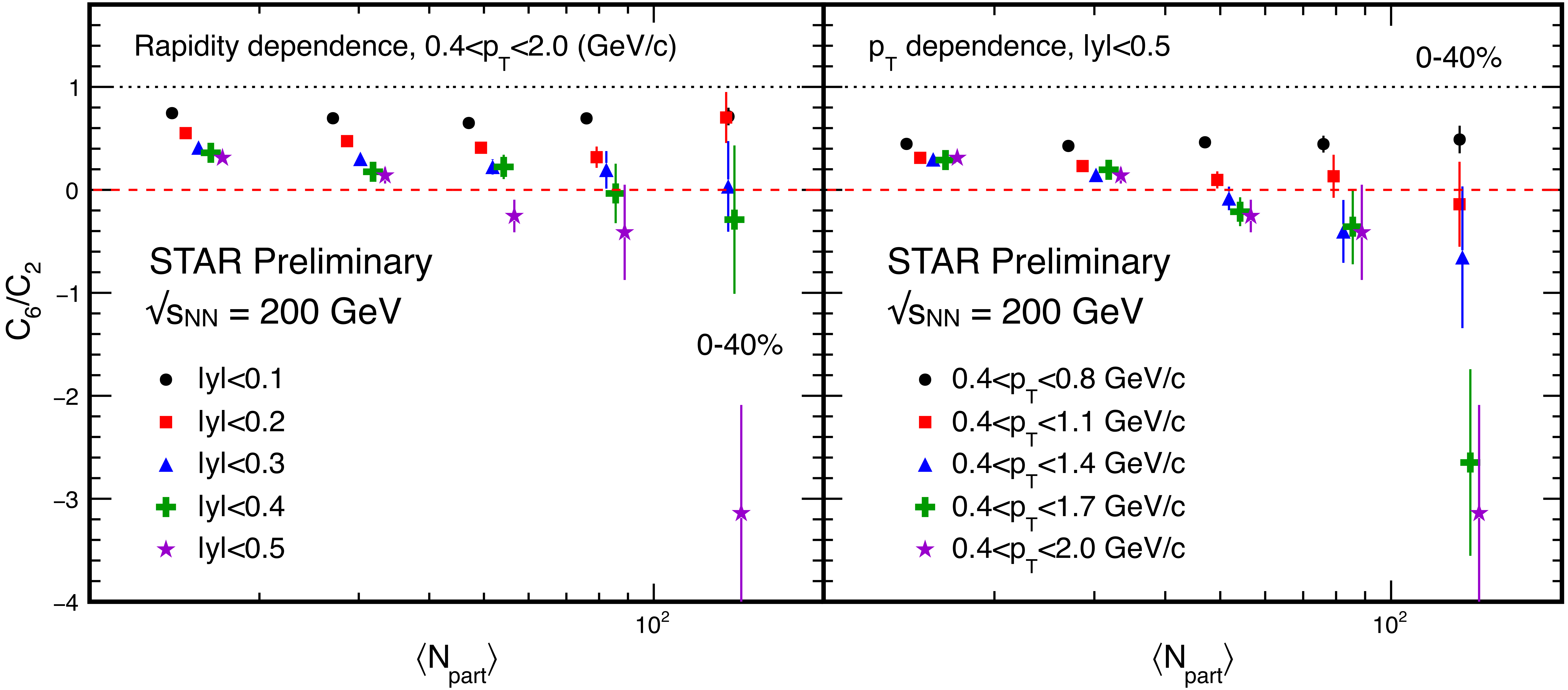
✓ Results from the central bin of 200 GeV Au+Au collisions are consistent with the LQCD prediction → remittance of chiral phase transition?



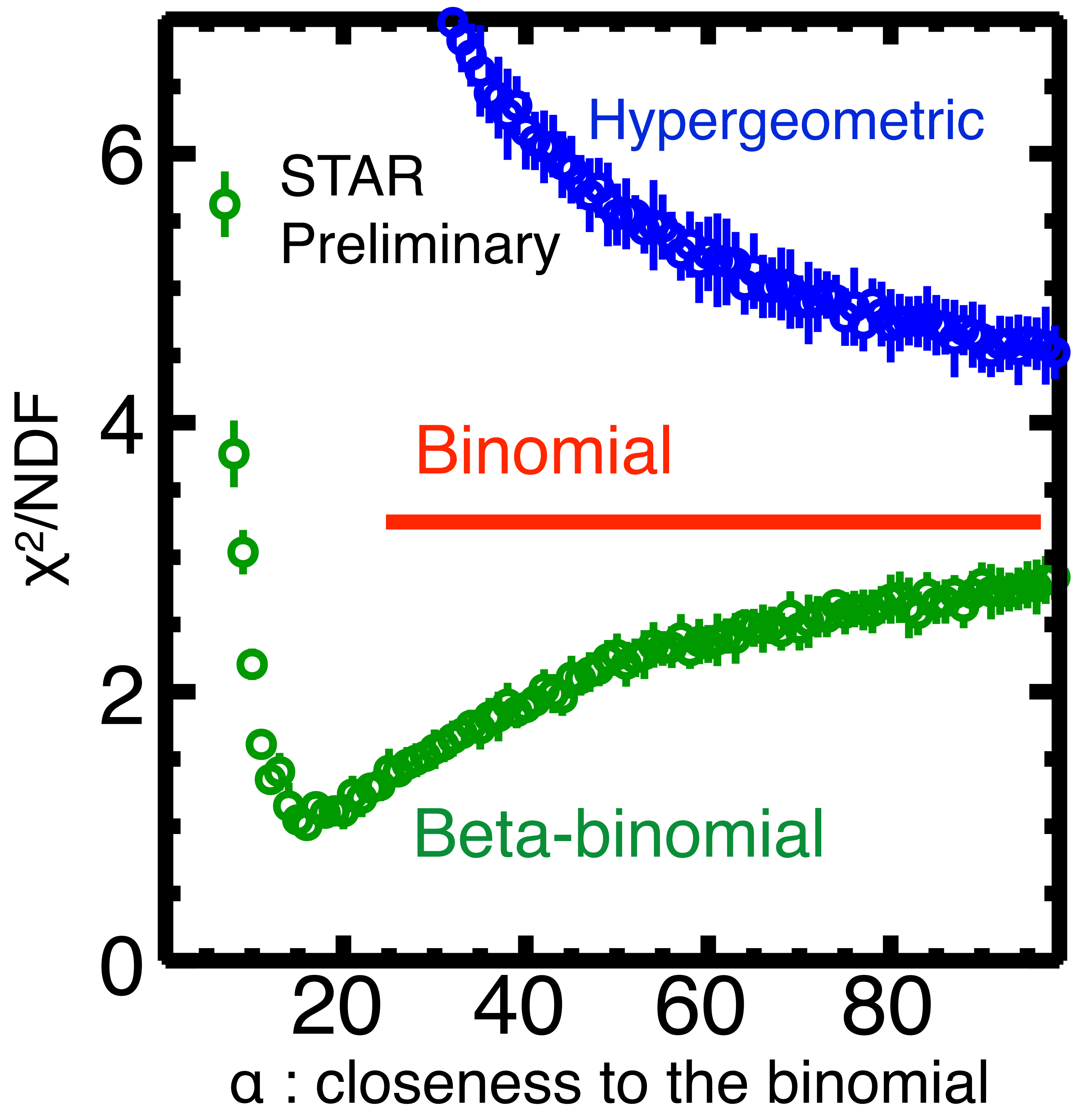
LQCD : A. Bazavov et al, PhysRevD.95.054504

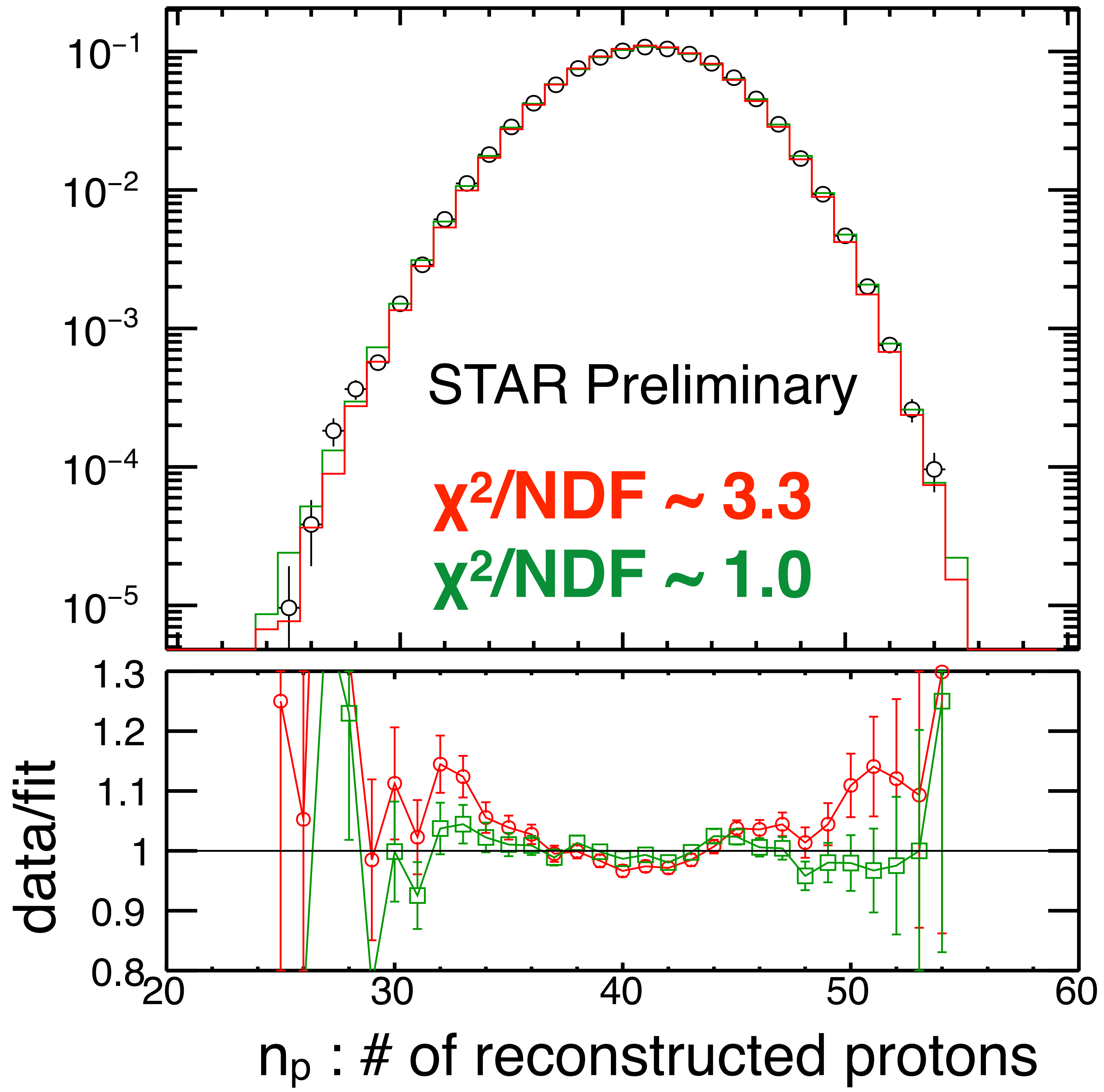
Acceptance dependence

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



Efficiency distribution





$\sqrt{s_{NN}}$ = 19.6 GeV, 0-2.5% centrality,
60 protons and 15 antiprotons are embedded

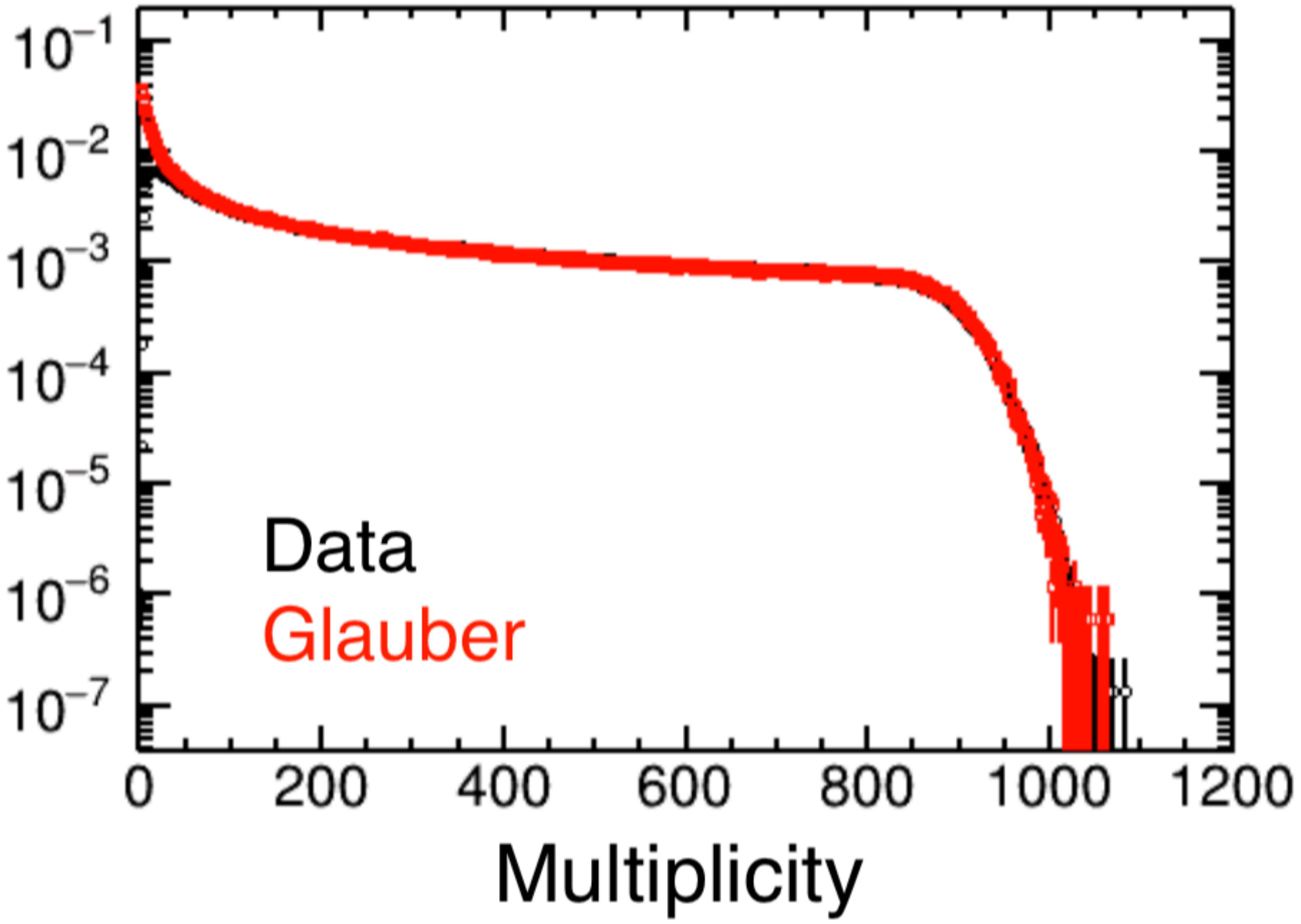
Volume fluctuation

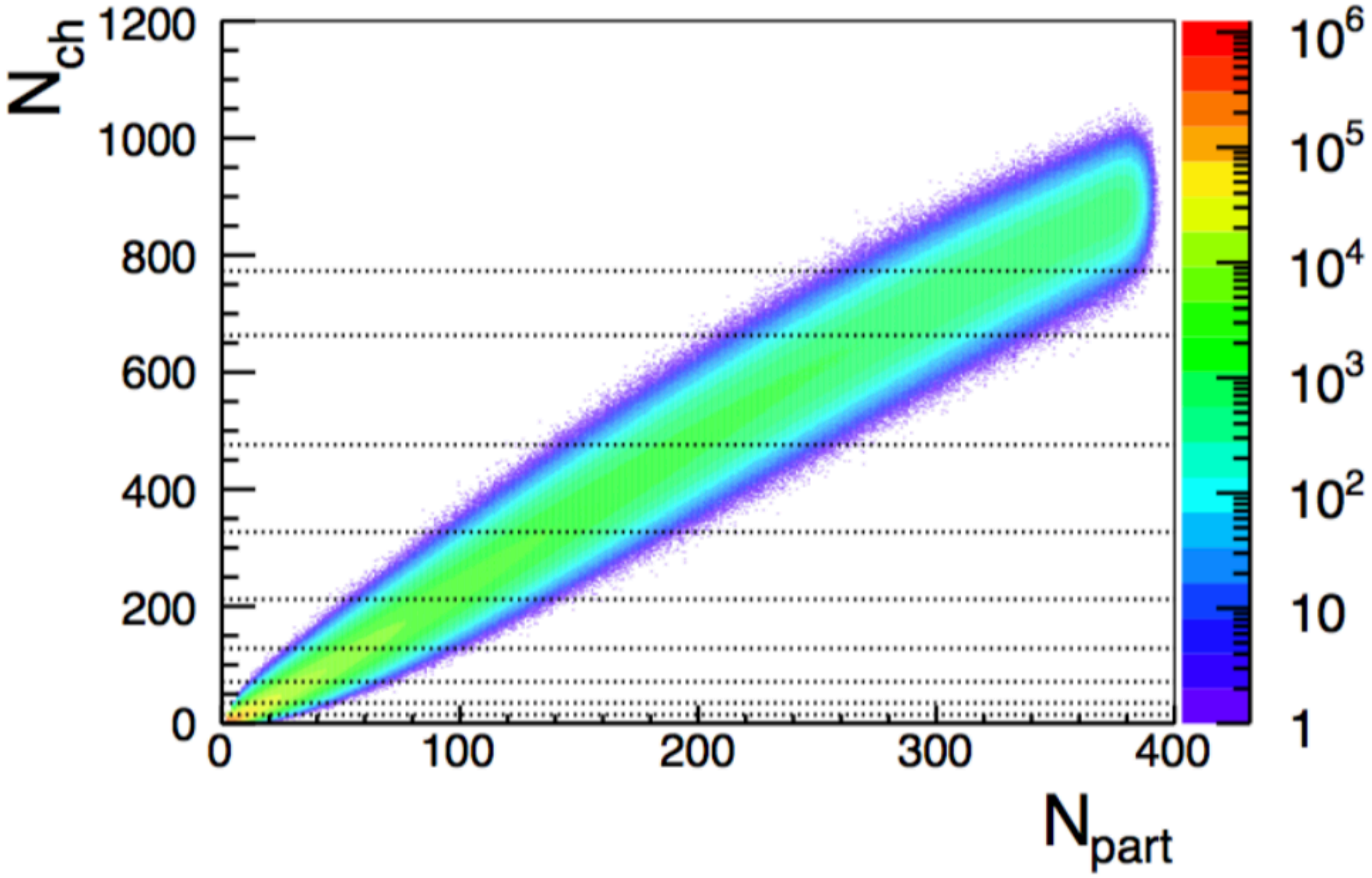
- ✓ **Calculate cumulants in each multiplicity bin, and average them in one centrality.**
- ✓ **Strongly depend on the centrality resolution.**

$$
\begin{aligned}
C_r &= \sum_i \omega_i K_r^i, \\
\omega_i &= \frac{n_i}{\sum_i n_i},
\end{aligned}
$$

K_r^i : r-th order cumulant in i-th multiplicity bin

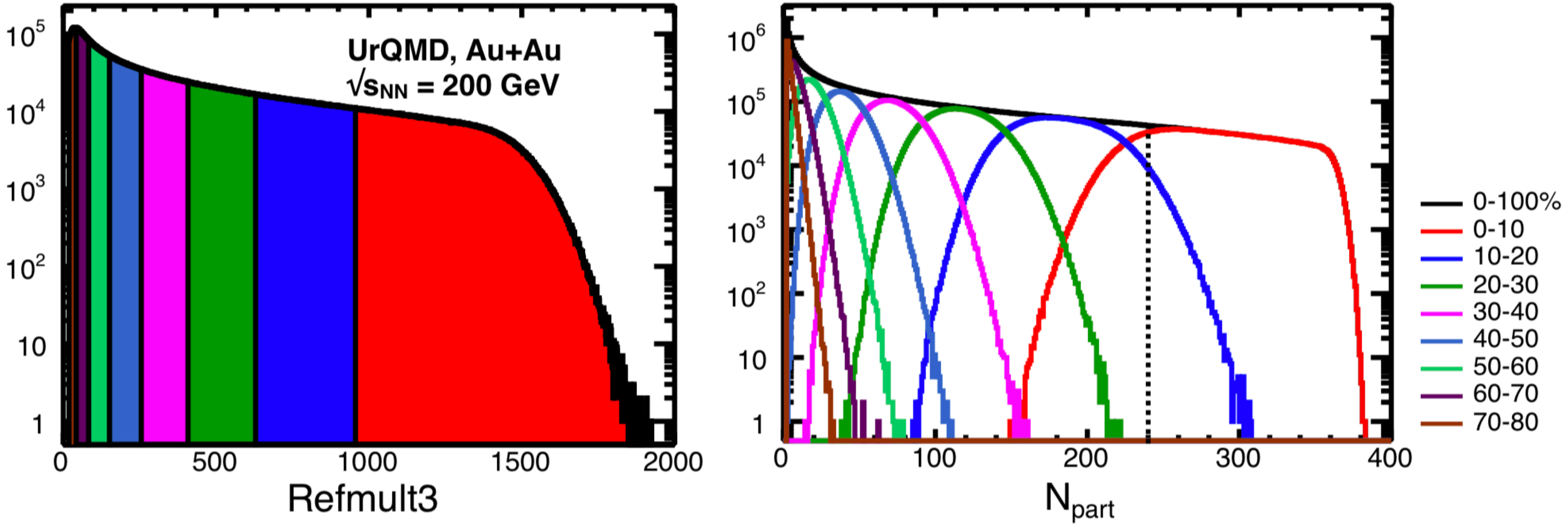
n^i : # of events in i-th multiplicity bin





Volume fluctuation

- ✓ Centrality is determined by using pions and kaons as is done in the expreiment.
- ✓ True cumulants can be defined by using the event by event N_{part} given by UrQMD.
- ✓ Calculate cumulants at each N_{part}, then averaged them in one centrality.



Volume fluctuation

- ✓ **Derived based on the assumption of independent particle production from source of N_{part}.**
- ✓ **Volume fluctuations can be completely eliminated with some model inputs.**

Measured cumulant

True cumulant

Additional terms appears from the event by event participant fluctuation

$$
\begin{aligned}
\kappa_1(\Delta N) &= \langle N_W \rangle \, \kappa_1(\Delta n) \\
\kappa_2(\Delta N) &= \langle N_W \rangle \, \kappa_2(\Delta n) + \langle \Delta n \rangle^2 \kappa_2(N_W), \\
\kappa_3(\Delta N) &= \langle N_W \rangle \, \kappa_3(\Delta n) + 3 \langle \Delta n \rangle \, \kappa_2(\Delta n) \kappa_2(N_W) + \langle \Delta n \rangle^3 \kappa_3(N_W), \\
\kappa_4(\Delta N) &= \langle N_W \rangle \, \kappa_4(\Delta n) + 4 \langle \Delta n \rangle \, \kappa_3(\Delta n) \kappa_2(N_W) \\
&\quad + 3\kappa_2^2(\Delta n) \kappa_2(N_W) + 6 \langle \Delta n \rangle^2 \kappa_2(\Delta n) \kappa_3(N_W) + \langle \Delta n \rangle^4 \kappa_4(N_W).
\end{aligned}
$$

P. Braun-Munzinger, A. Rustamov, J. Stachel: *arXiv:1612.00702*

Δn : net-proton per Nw

ΔN : net-proton