Measurement of the Sixth-Order Cumulant of Net-Proton Multiplicity Distributions in Au+Au Collisions $\sqrt{s_{NN}}$ = 54.4 and 200 GeV at RHIC

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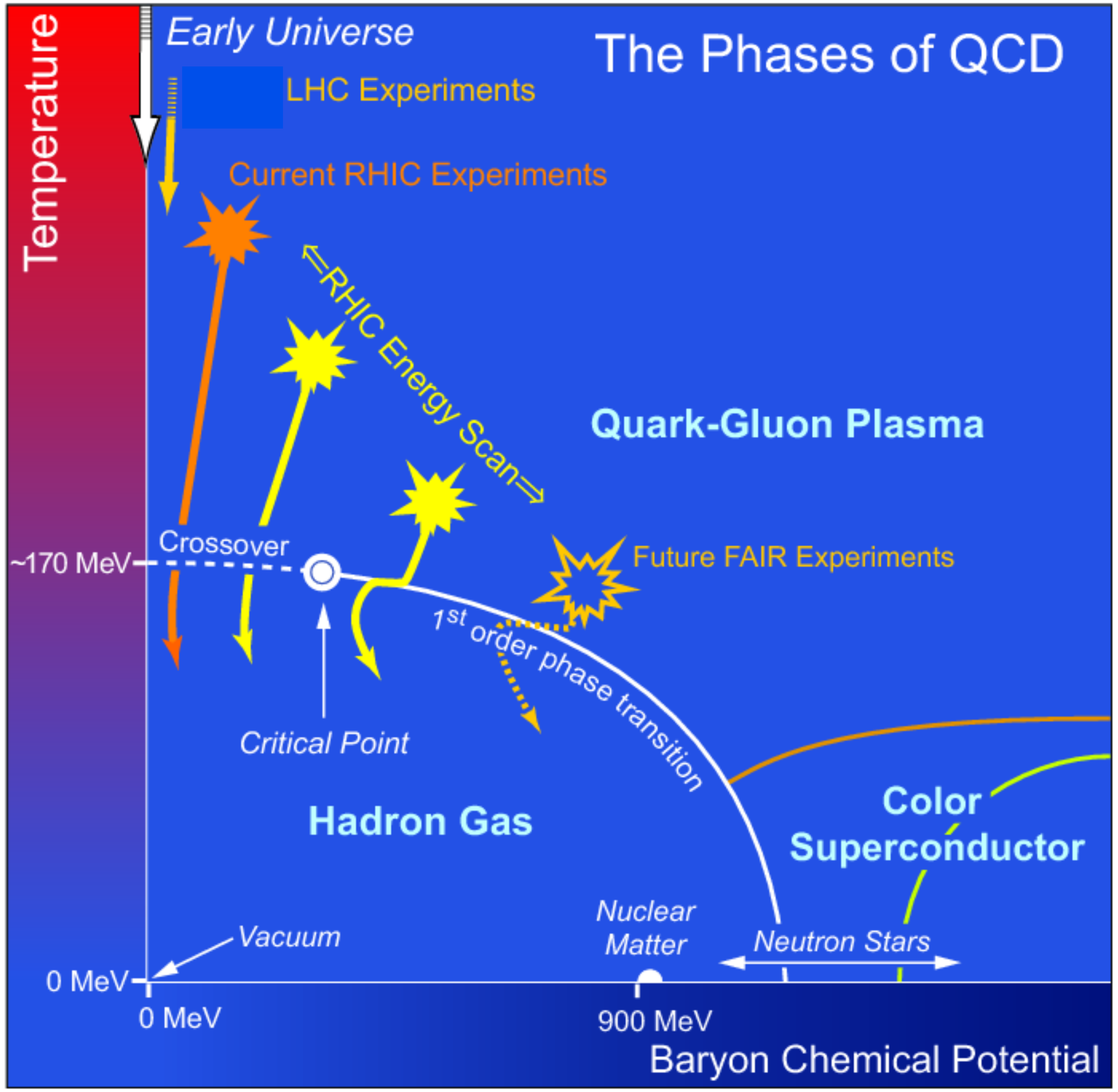
Outline

- ✓ **Introduction**
  - **Motivation**
  - **Analysis methods**
- ✓ **Experimental results**
  - **Centrality dependence**
  - **Acceptance dependence**
- ✓ **Summary**

QCD phase diagram

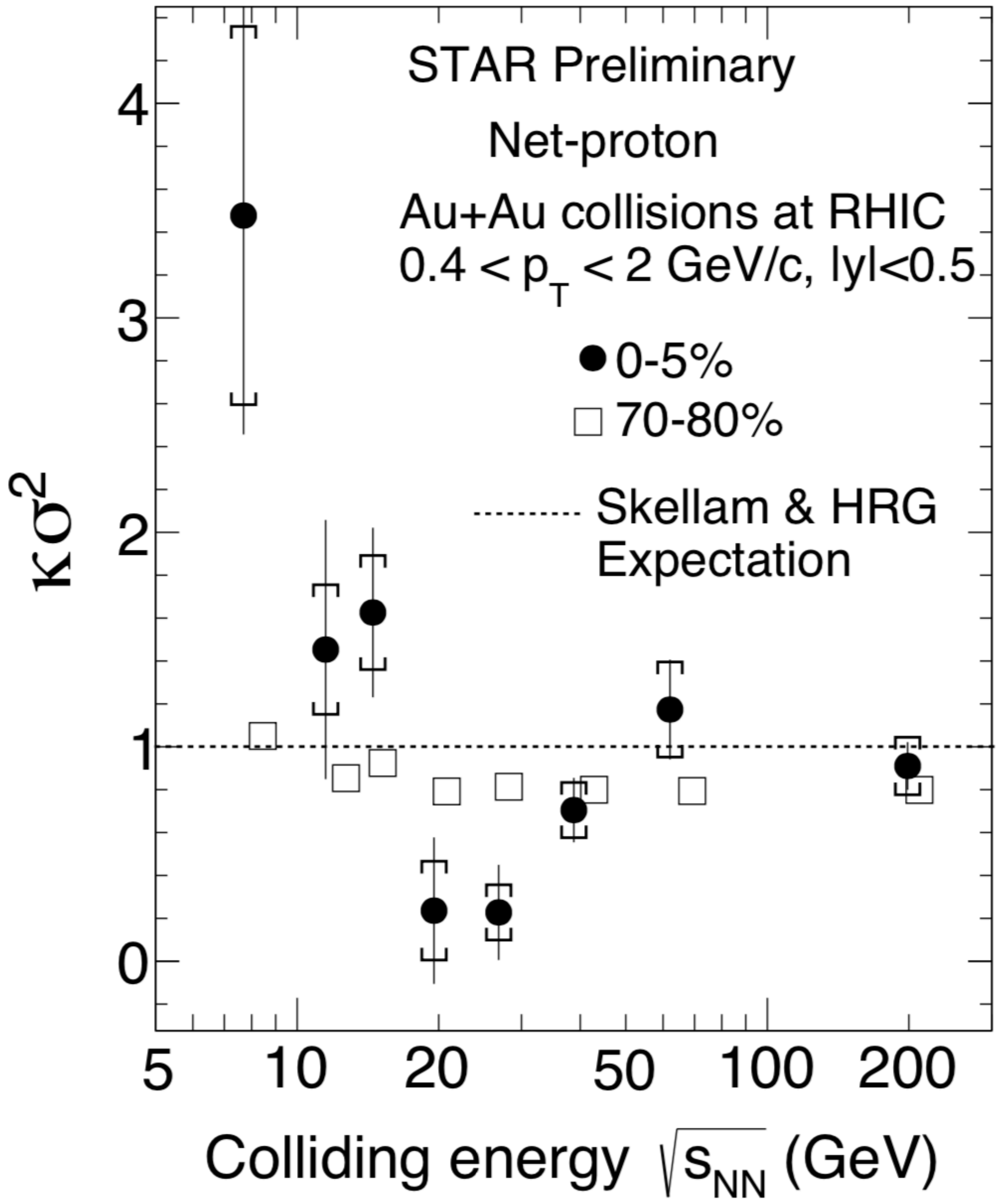


✓ **Higher-order fluctuations of net-particle distributions.**

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

QCD phase diagram

STAR, PoS CPOD2014 (2015)019



✓ **Higher-order fluctuations of net-particle distributions.**

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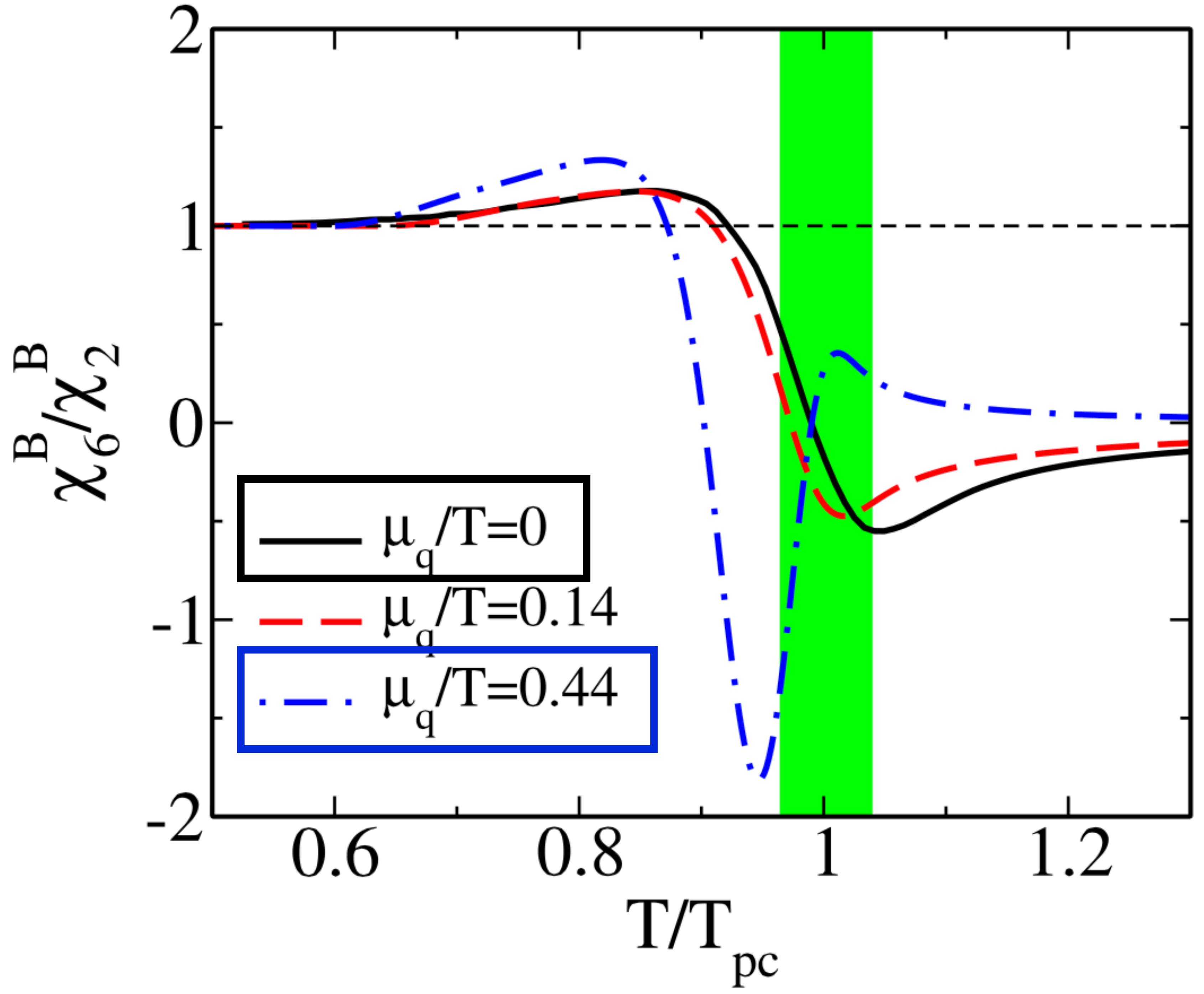
- **1st-order phase transition at large μ_B?**
- **Critical point?**

✓ **Non-monotonic energy dependence of $\kappa\sigma^2 = C_4/C_2$ could be a signature of critical point.**

Motivation

- ✓ There isn't yet direct 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.

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

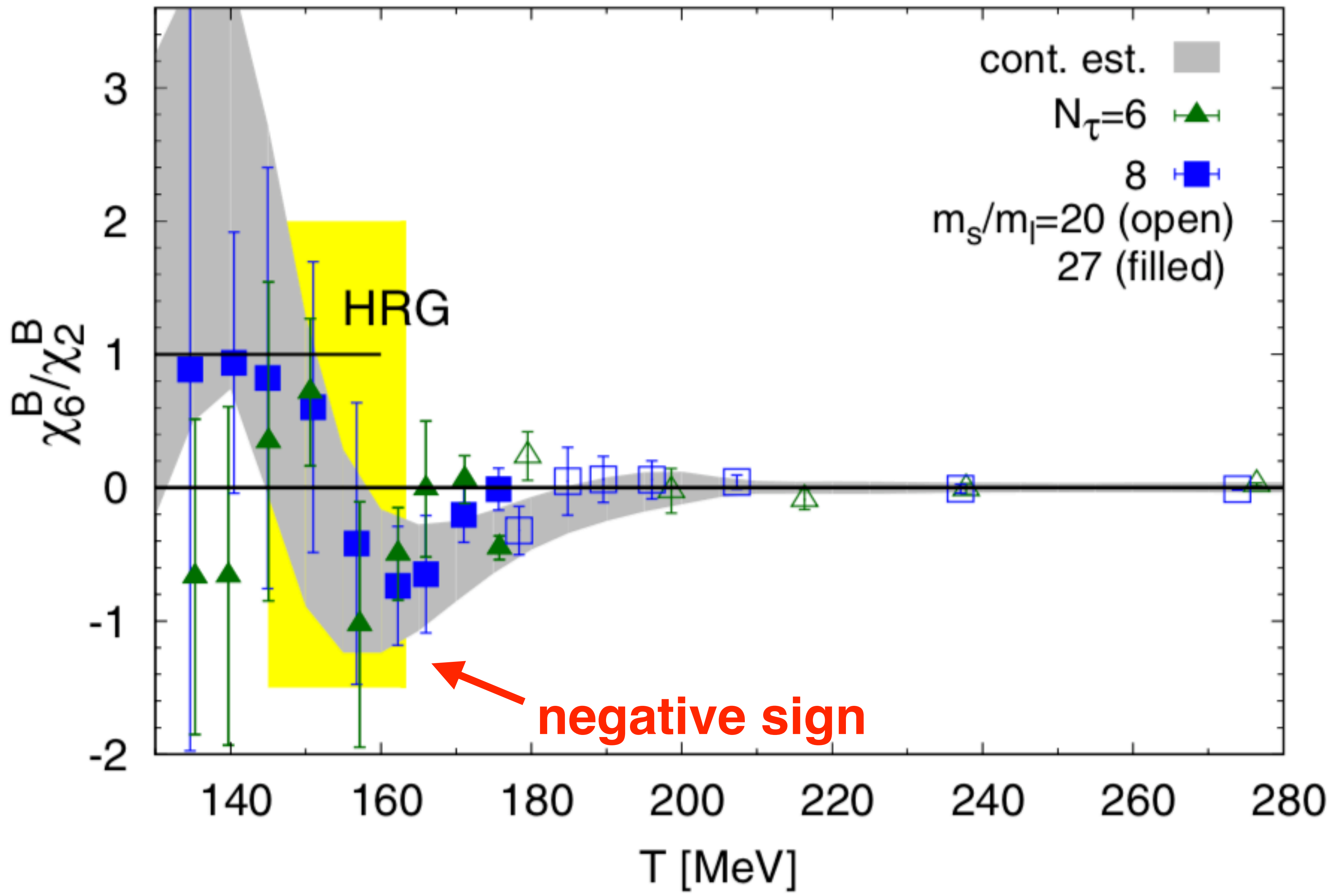
Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{\text{freeze}}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{\text{freeze}}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

Predicted scenario for this measurement

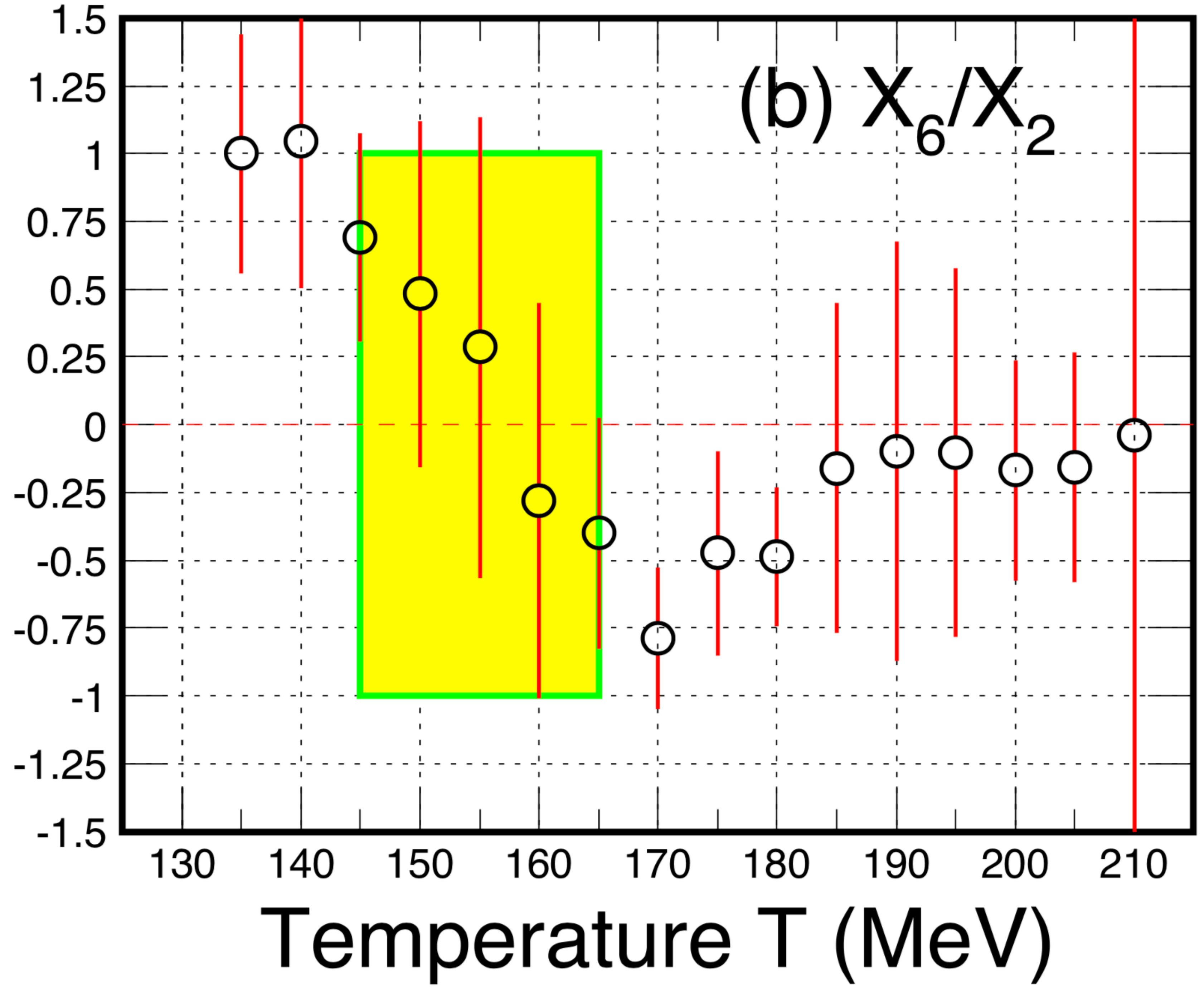
Motivation

- ✓ There isn't yet direct 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.
- ✓ LQCD also predicts negative sign around transition temperature.

A. Bazavov et al, PhysRevD.95.054504(2017)



S. Borsanyi et al, JHEP.10.205(2018)



Fluctuations of conserved quantities

PRL 105, 022302 (2010) : STAR Collaboration

✦ Net-baryon, net-charge and net-strangeness

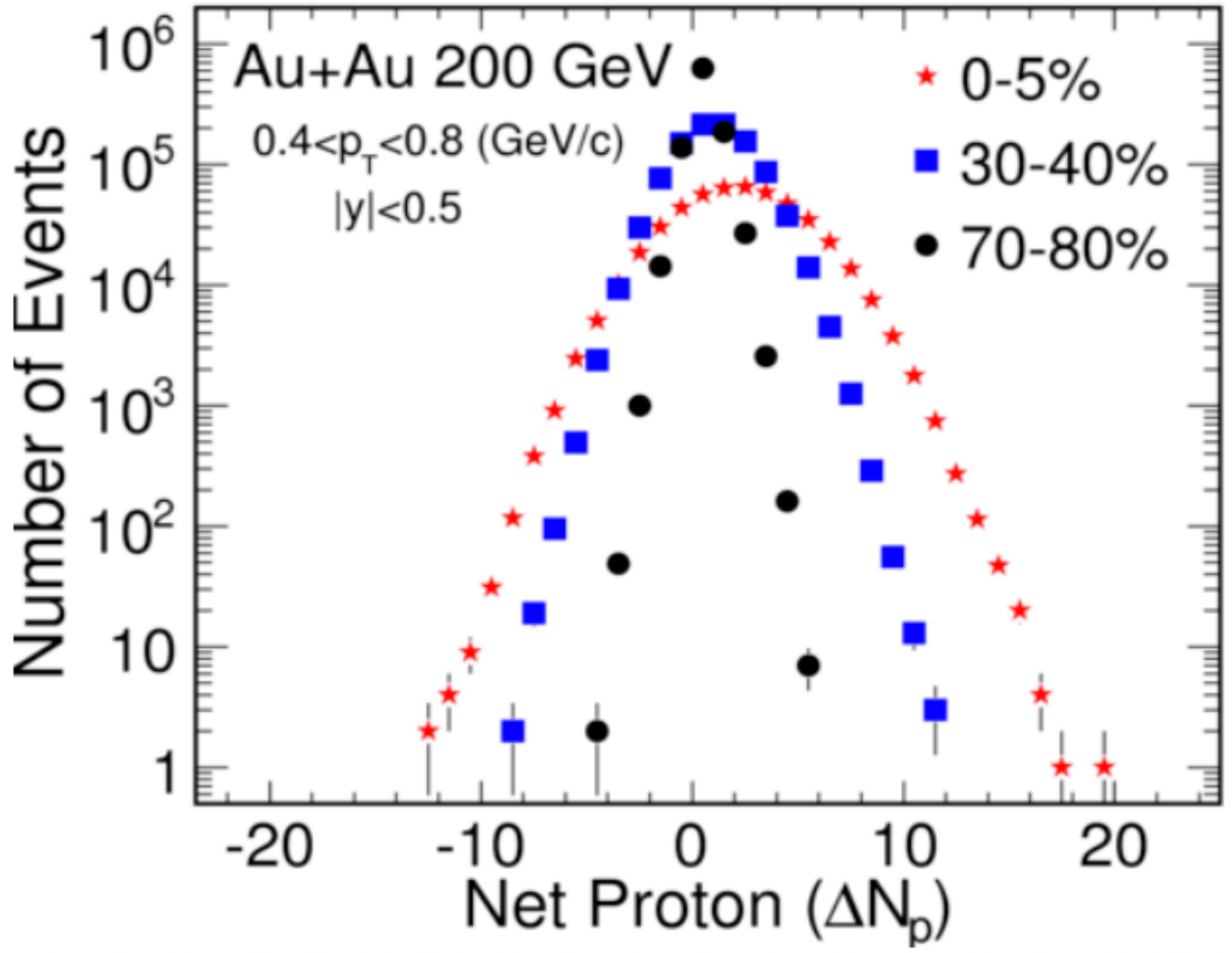
"Net" : positive - negative

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

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

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

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

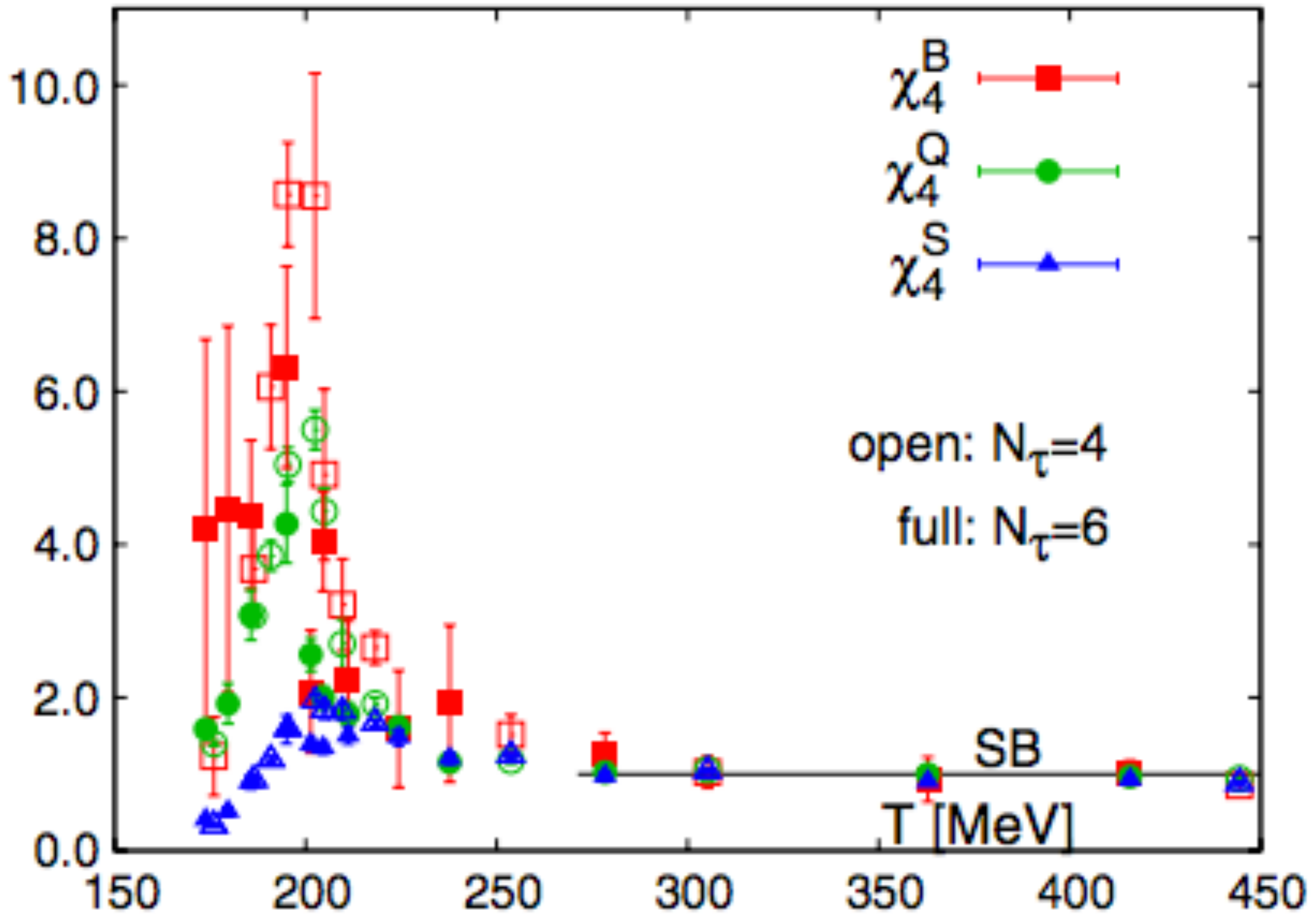
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

(2) Direct comparison with susceptibilities.

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2} \qquad \frac{C_6}{C_2} = \frac{\chi_6}{\chi_2}$$

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

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

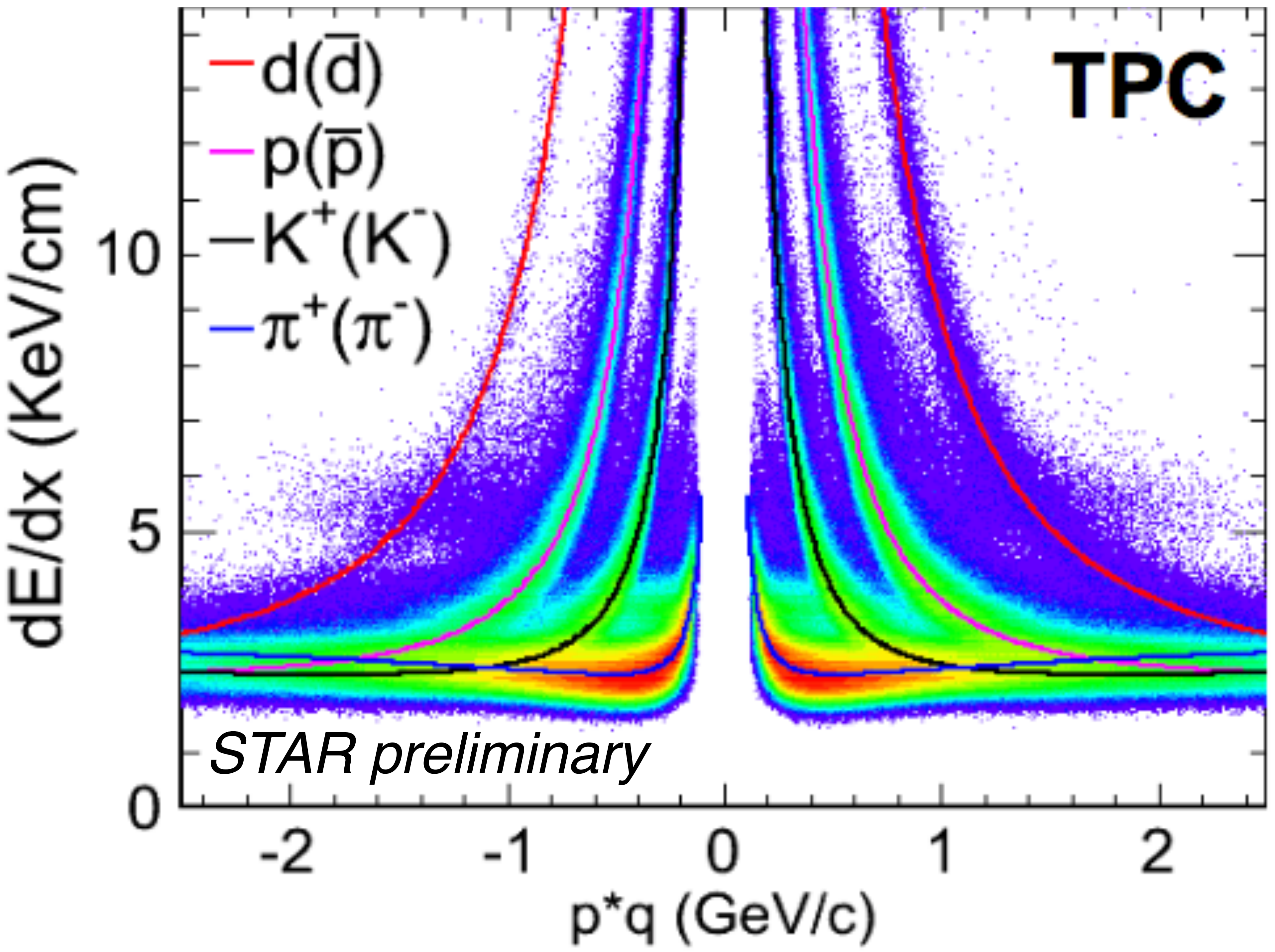


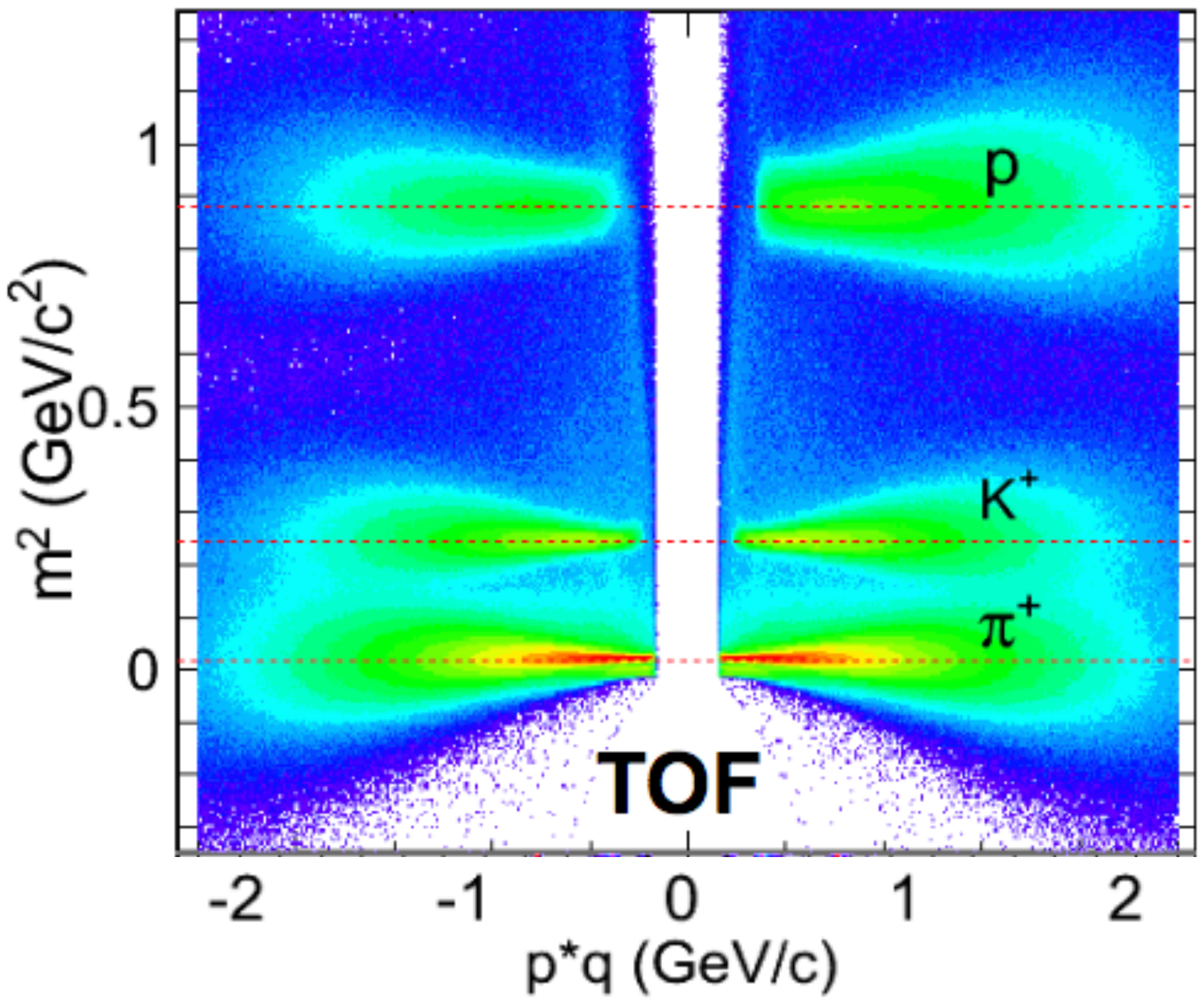
M. Cheng et al, PRD 79, 074505 (2009)

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.





Analysis methods

✓ Centrality bin width averaging is done for the reduction of the initial volume fluctuation.

✓ Calculate the cumulants at each value of the multiplicity used for centrality, then weighted-average these in each centrality bin.

- *X.Luo, J. Xu, B. Mohanty and N. Xu. J. Phys. G40,105104(2013)*

$$C_n = \frac{\sum_{r=N_1}^{N_2} n_r C_n^r}{\sum_{r=N_1}^{N_2} n_r} = \sum_{r=N_1}^{N_2} \omega_r C_n^r \qquad \omega_r = n_r / \sum_{r=N_1}^{N_2} n_r$$

N_1, N_2 : lowest and highest multiplicity bin in the centrality
n_r : # of events in rth multiplicity bin

✓ Efficiency correction on cumulants have been done assuming the binomial efficiencies.

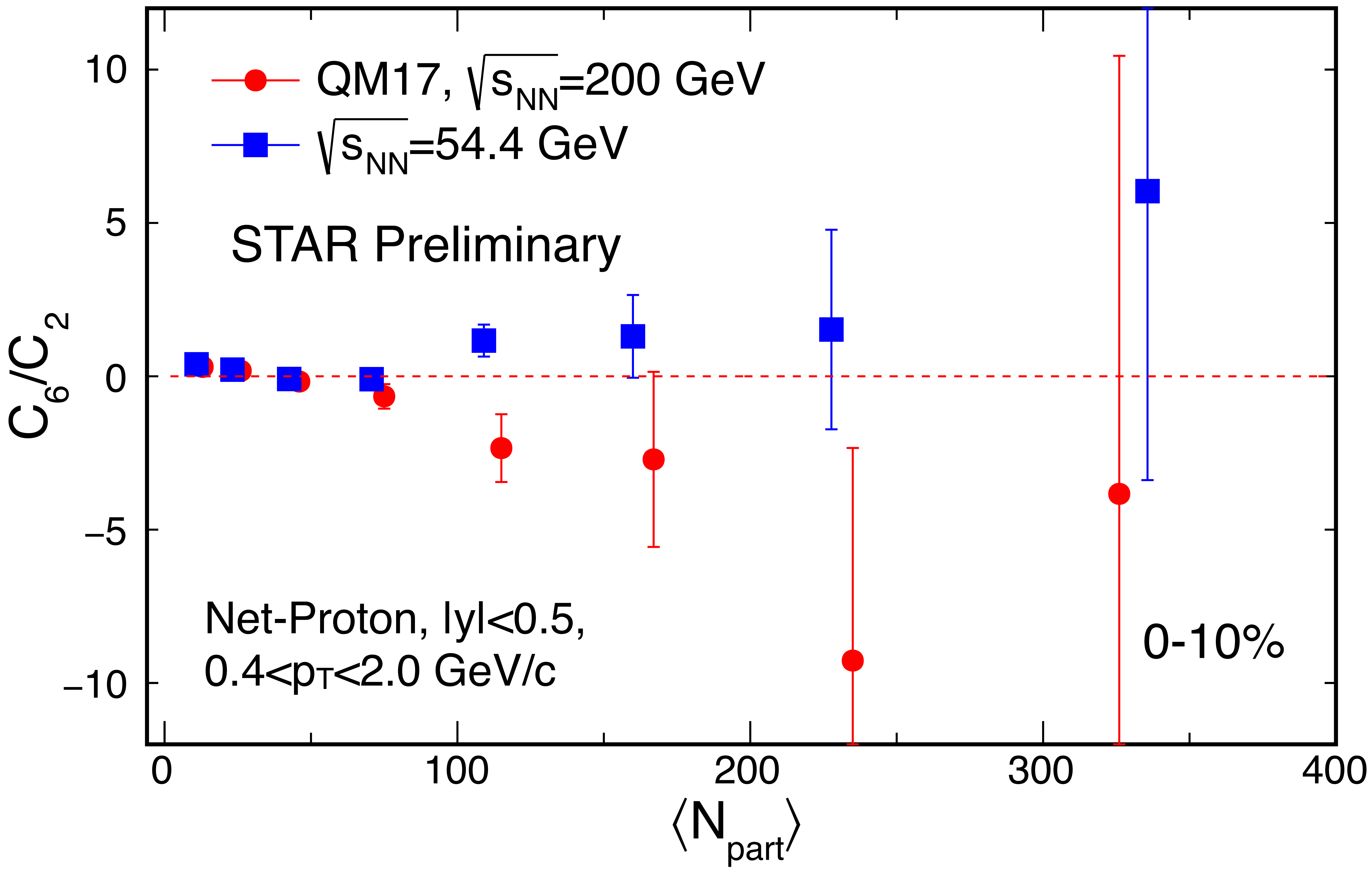
- *M. Kitazawa : PRC.86.024904, M. Kitazawa and M. Asakawa : PRC.86.024904*
- *A. Bzdak and V. Koch : PRC.86.044904, PRC.91.027901, X. Luo : PRC.91.034907*
- *T. Nonaka, M. Kitazawa, S. Esumi : PRC.95.064912*
- *X. Luo, T. Nonaka : PRC.99.044917*

$$B_{p,N}(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^n$$

Net-proton C_6/C_2

✓ $C_6/C_2>0$ at 54.4 GeV and $C_6/C_2<0$ at 200 GeV

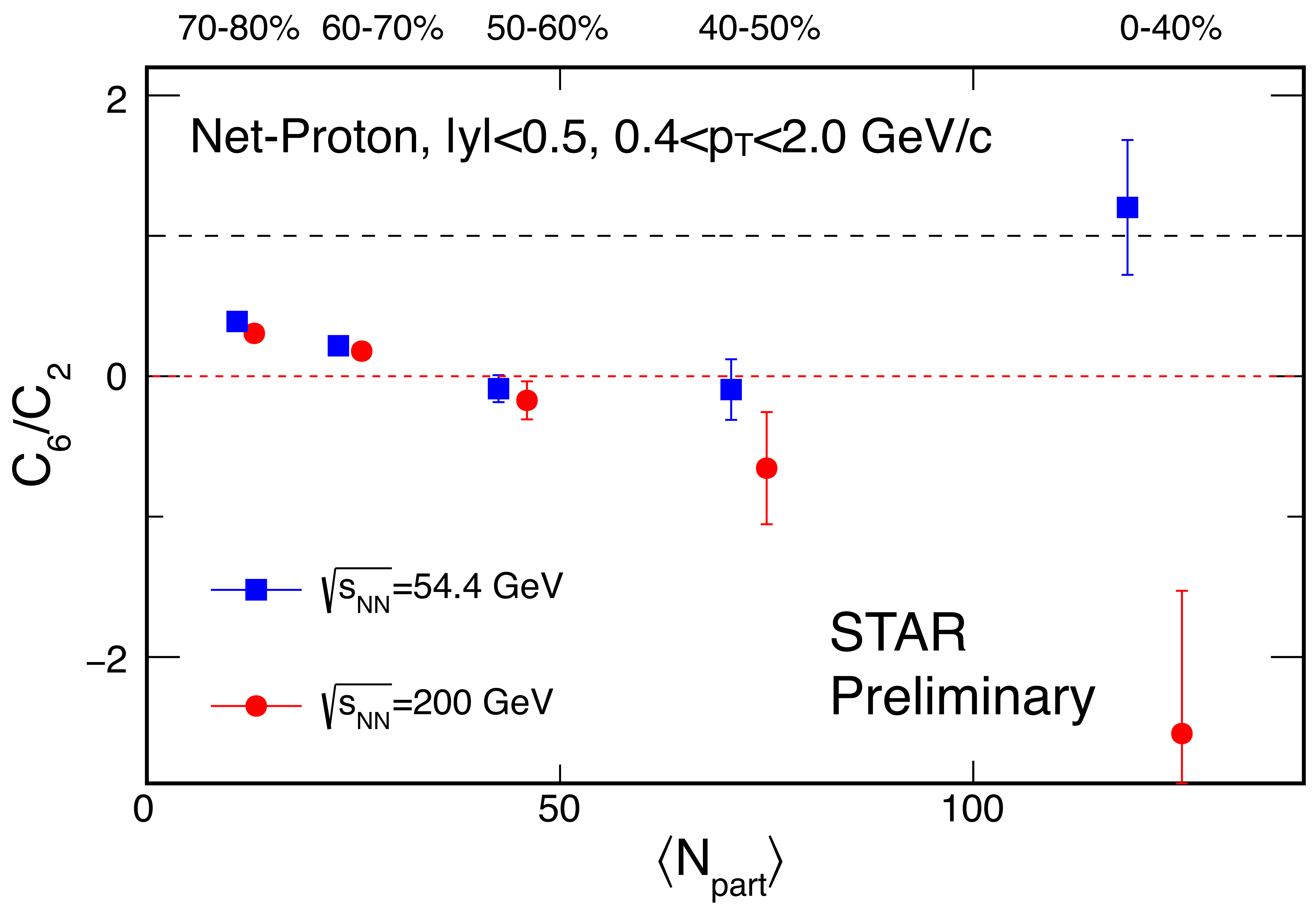
✓ Qualitatively consistent with PQM model prediction



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

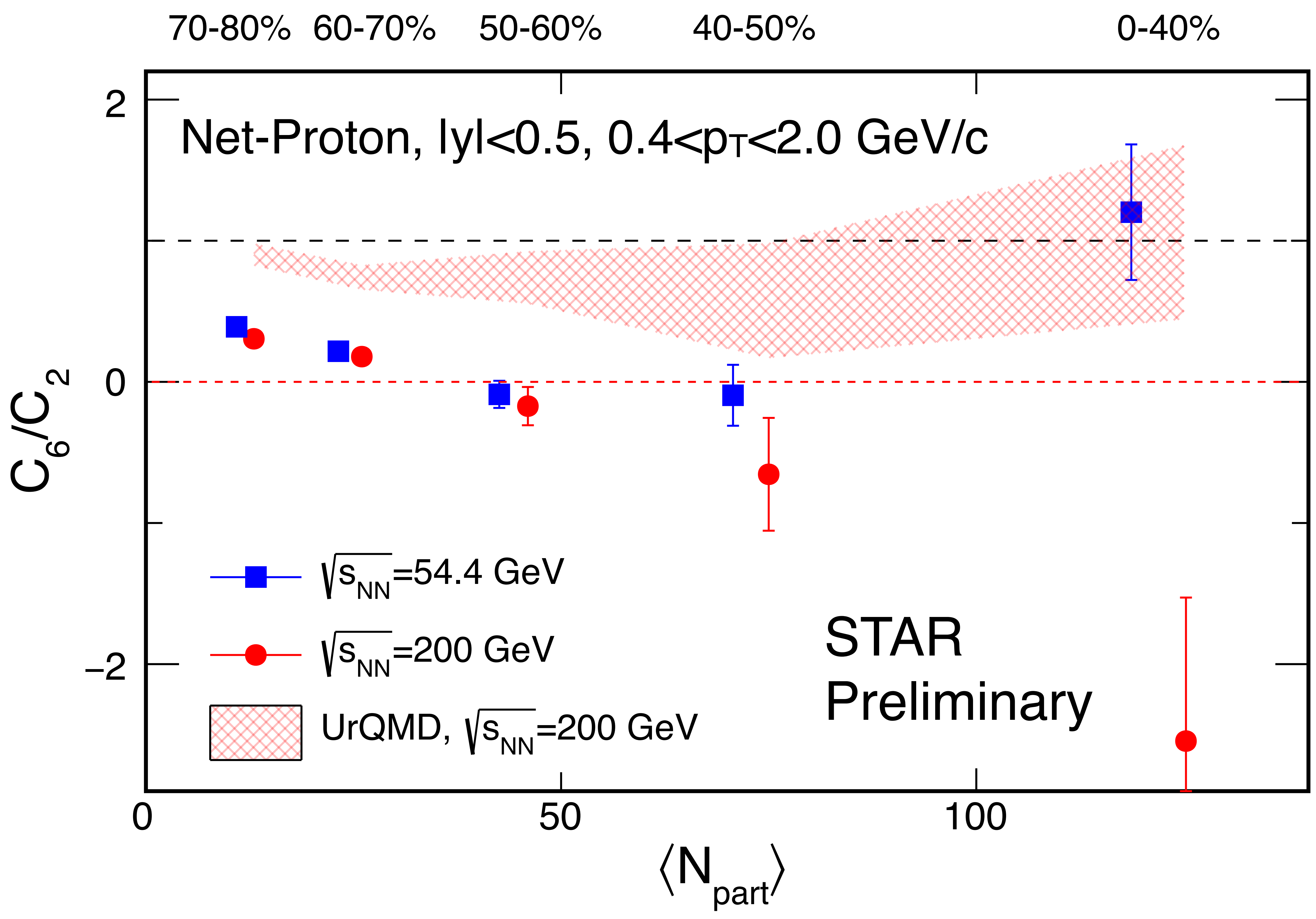
Net-proton C_6/C_2

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



UrQMD at 200 GeV

- ✓ 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.

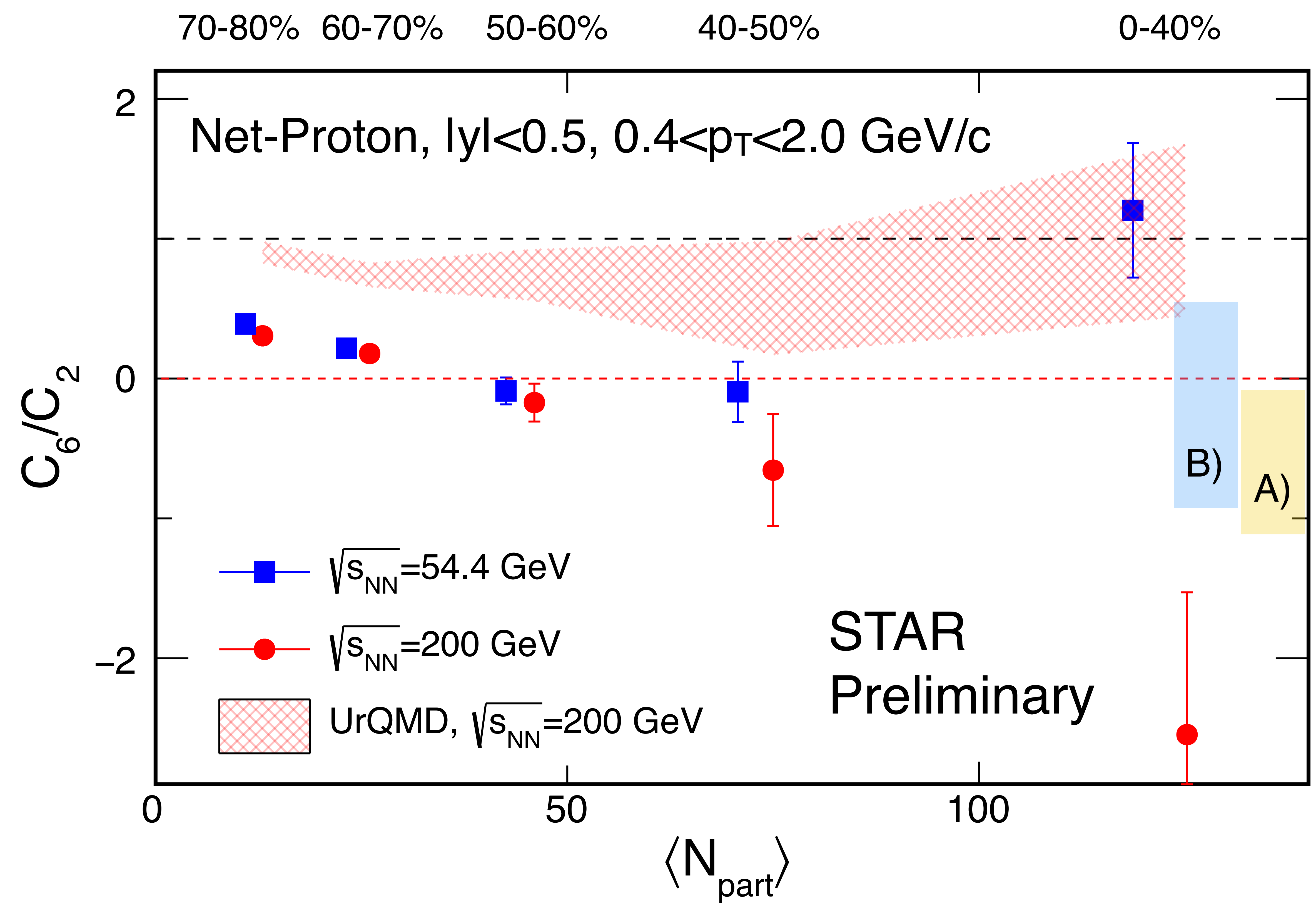


Comparison with LQCD

✓ 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.

✓ 200 GeV results are consistent with the LQCD results.



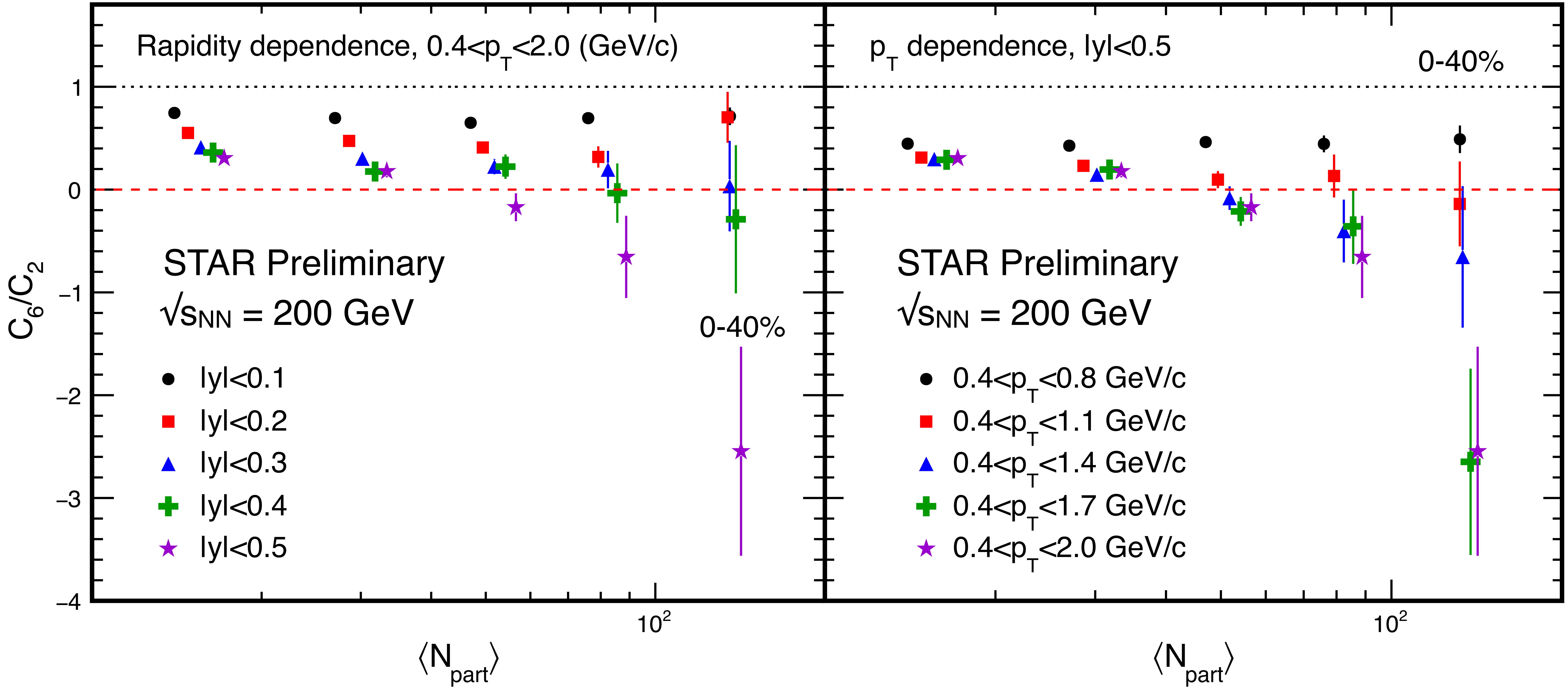
LQCD (T=160 MeV, μ_B=0 MeV) :

A) A. Bazavov et al, PhysRevD.95.054504

B) Z. Borsanyi et al, JHEP.10.205

Acceptance dependence

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



Summary

✓ C_6/C_2 of net-proton multiplicity distributions show

- negative value in 0-40% centrality at $\sqrt{s_{NN}}$ = 200 GeV
- positive value in 0-40% centrality at $\sqrt{s_{NN}}$ = 54.4 GeV
- linear decrease with respect to p_T and rapidity coverage.

LQCD (T=160 MeV, μ_B=0 MeV) :

A) A. Bazavov et al, PhysRevD.95.054504

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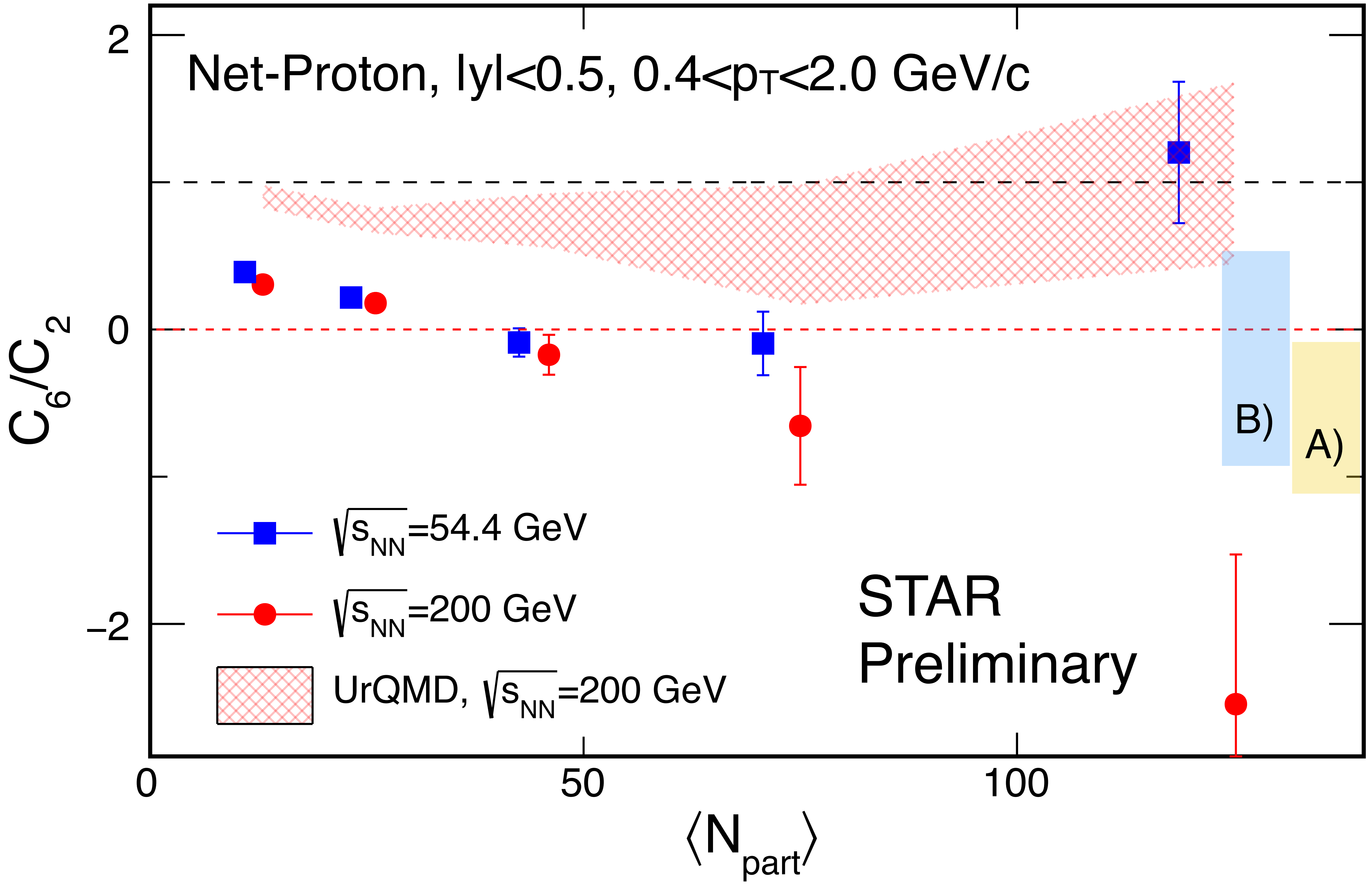


Thank you for your attention

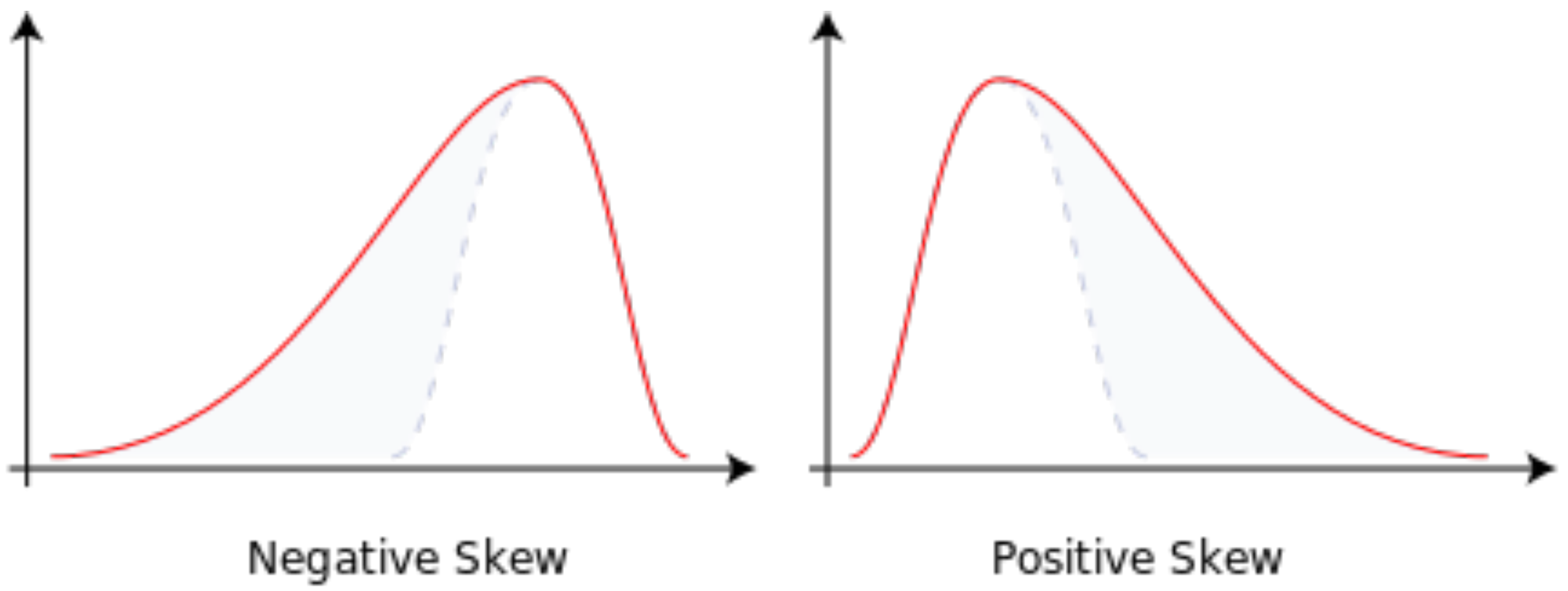
Back up

Higher-order fluctuation

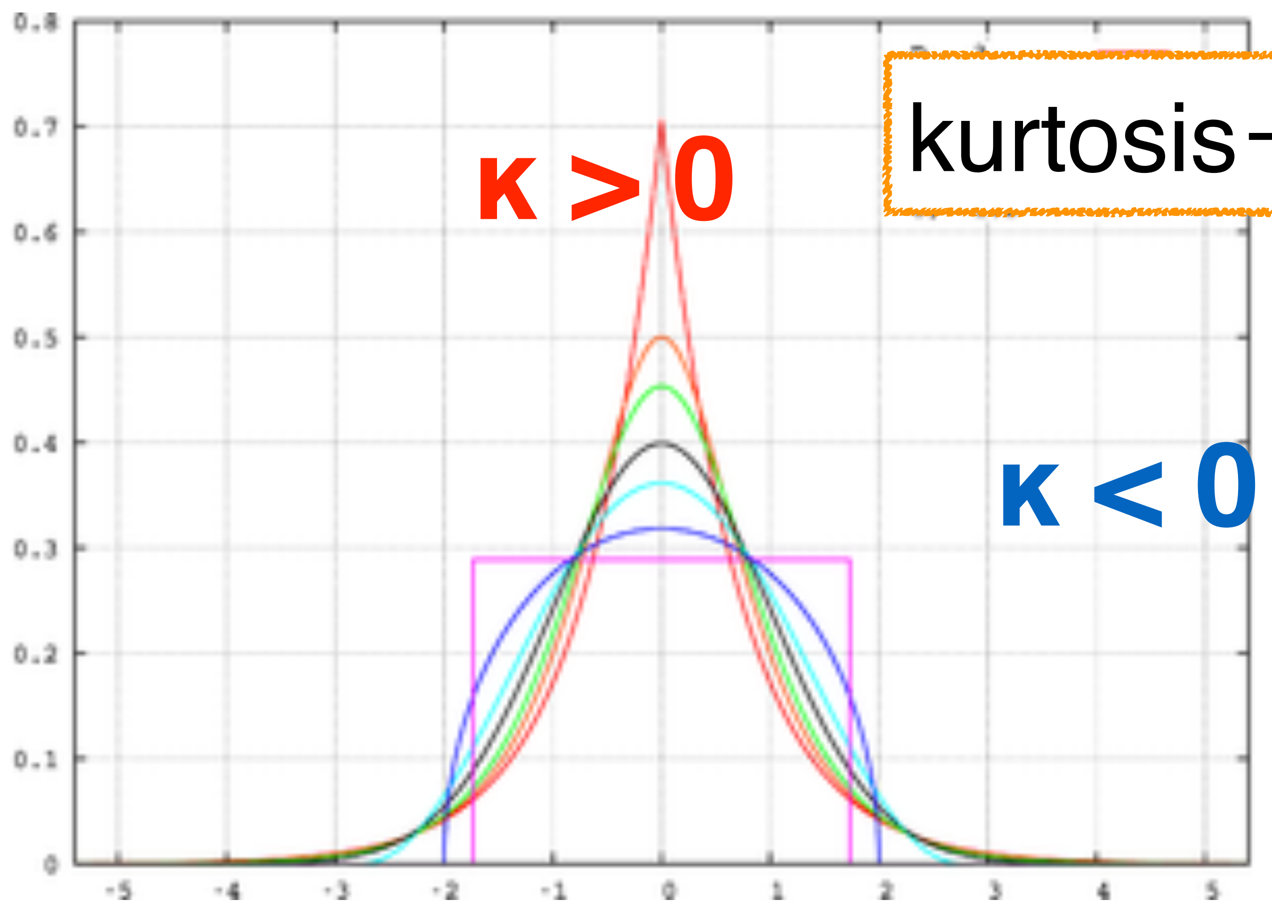
✦ **Moments and cumulants are mathematical measures of “shape” of a distribution which probe the fluctuation of observables.**

- ✓ **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**

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

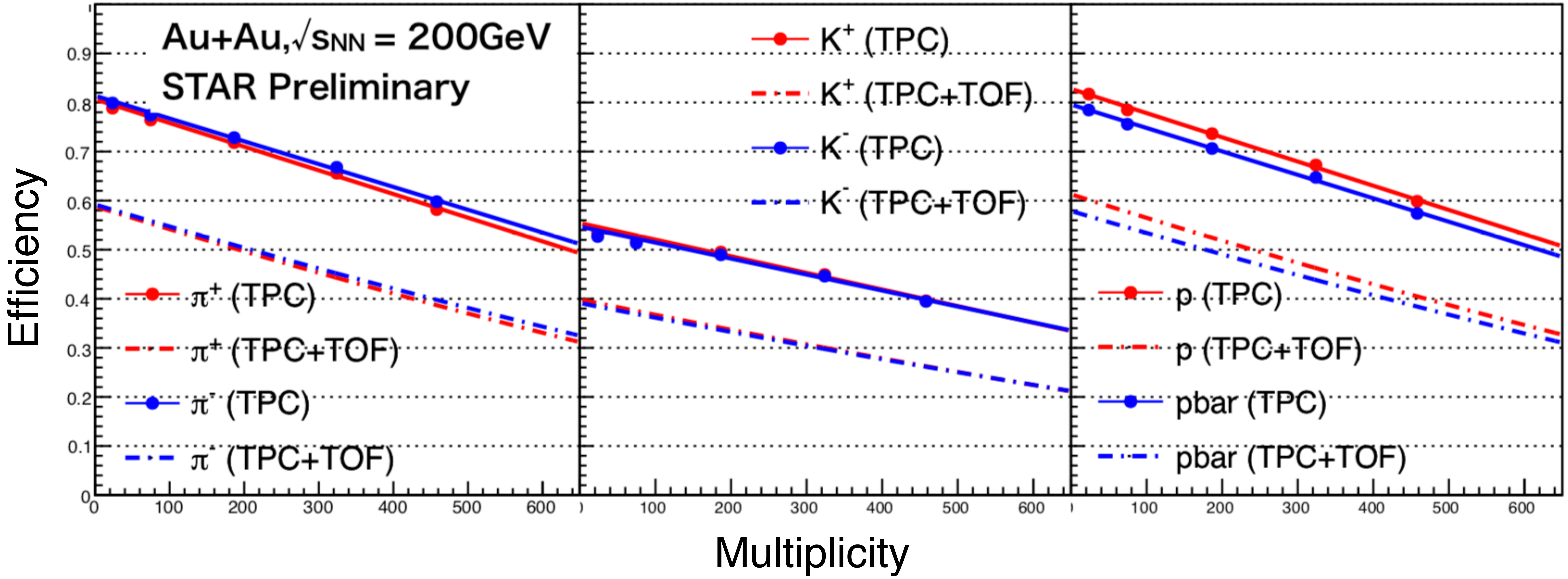
✓ **Cumulant : additivity**

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

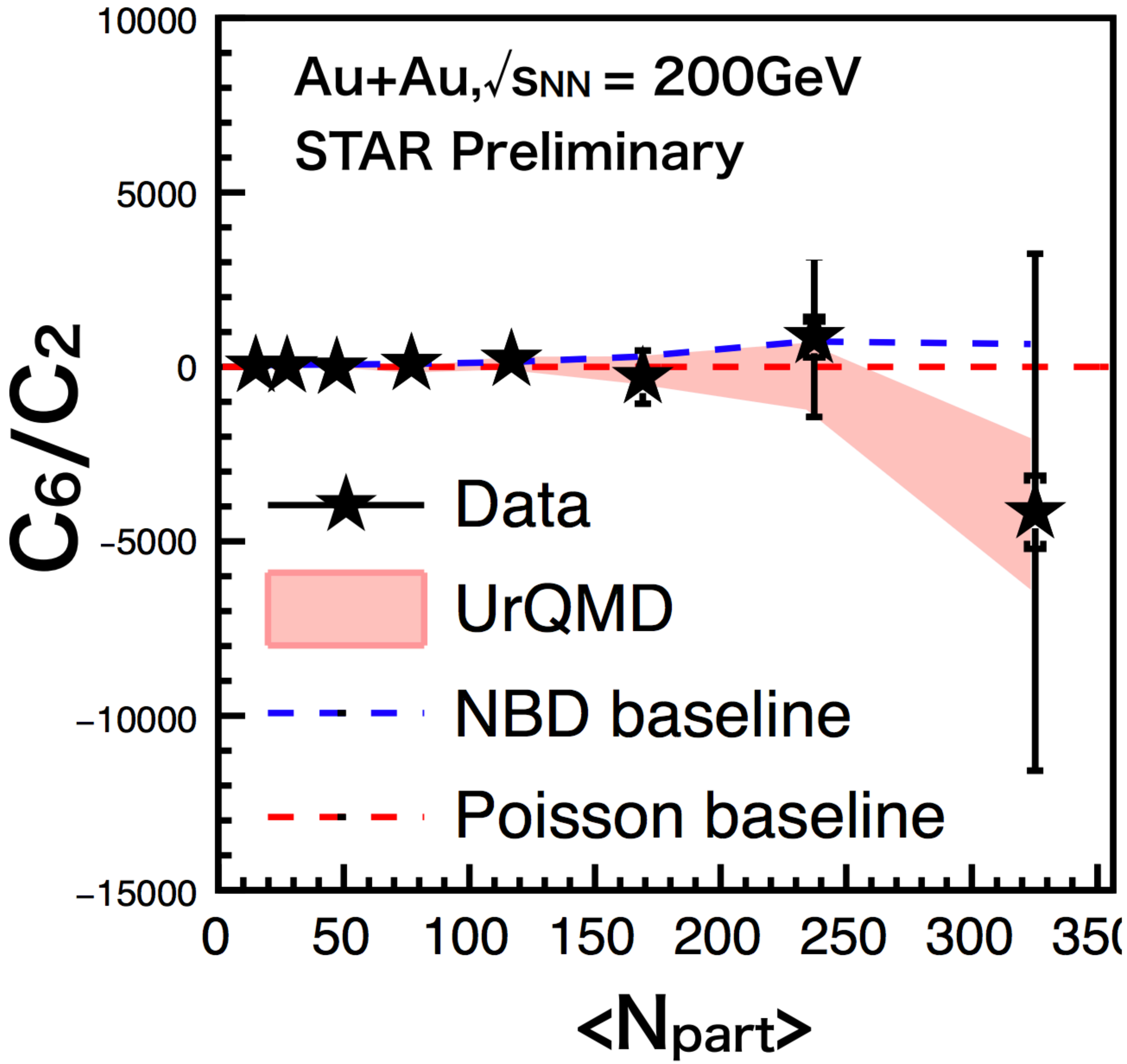
➡ **proportional to volume**

Efficiency

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



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



T. Sugiura, QM2018

✓**Results of net-charge C_6/C_2 are consistent with zero within large statistical uncertainties.**