Measurement of the Sixth-Order Cumulant of Net-Particle Multiplicity Distributions

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Outline

✓ **Introduction**

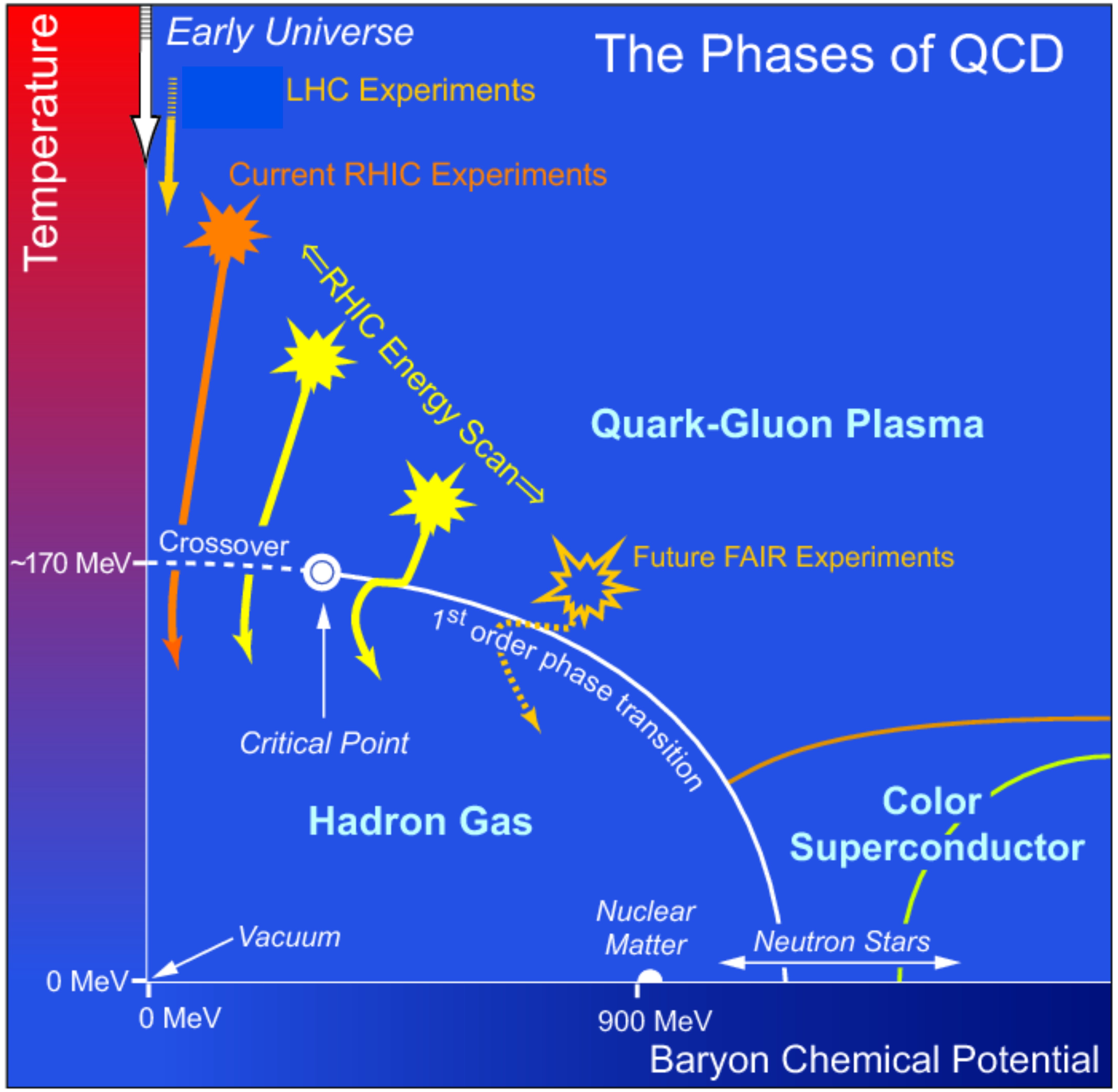
- Observables
- Analysis methods

✓ **Experimental results**

- Net-charge C_6/C_2
- Net-proton C_6/C_2

✓ **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?**

Fluctuations of conserved quantities

PRL 112, 032302 (2014) : STAR Collaboration

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

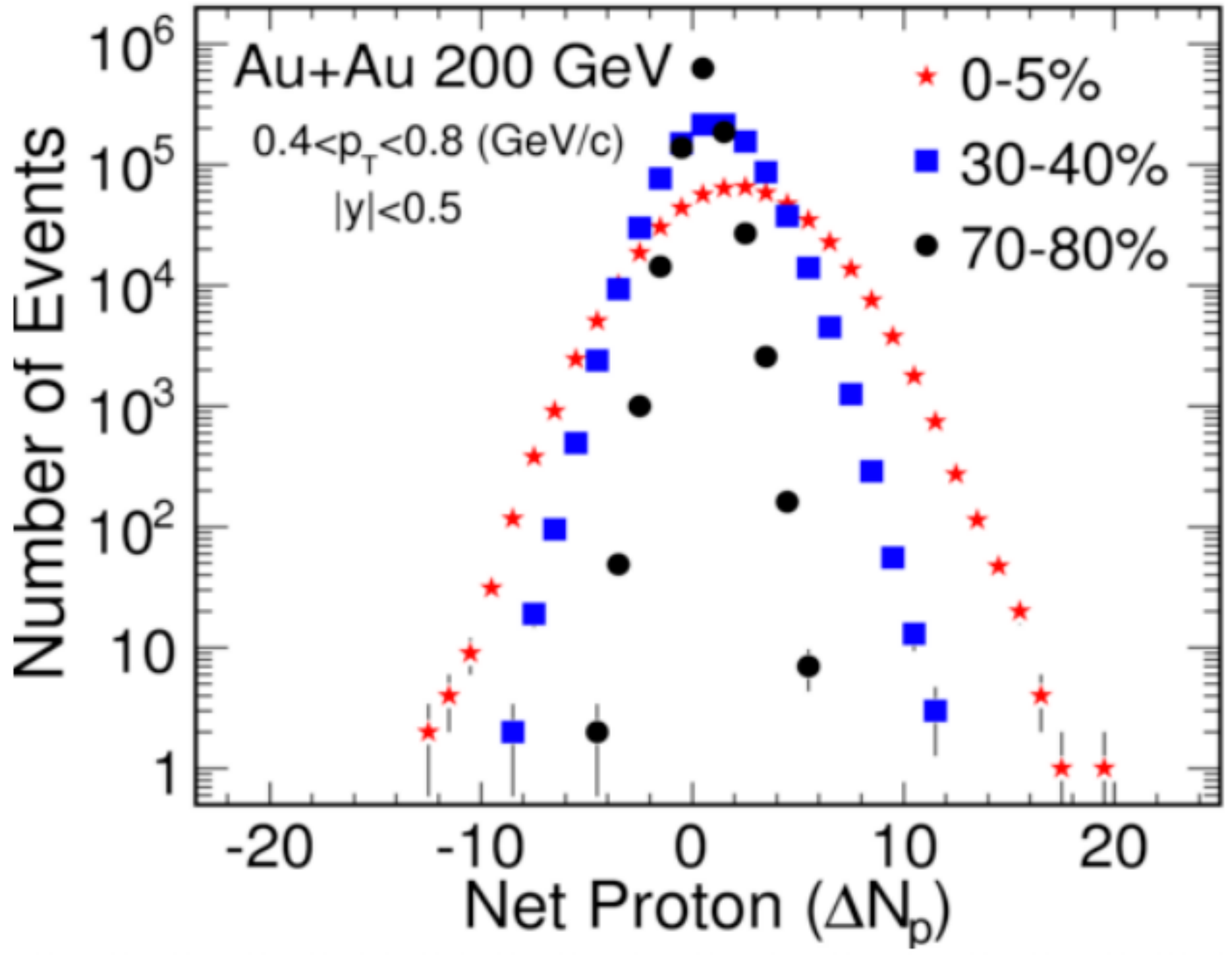
"Net" : positive - negative

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

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

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

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

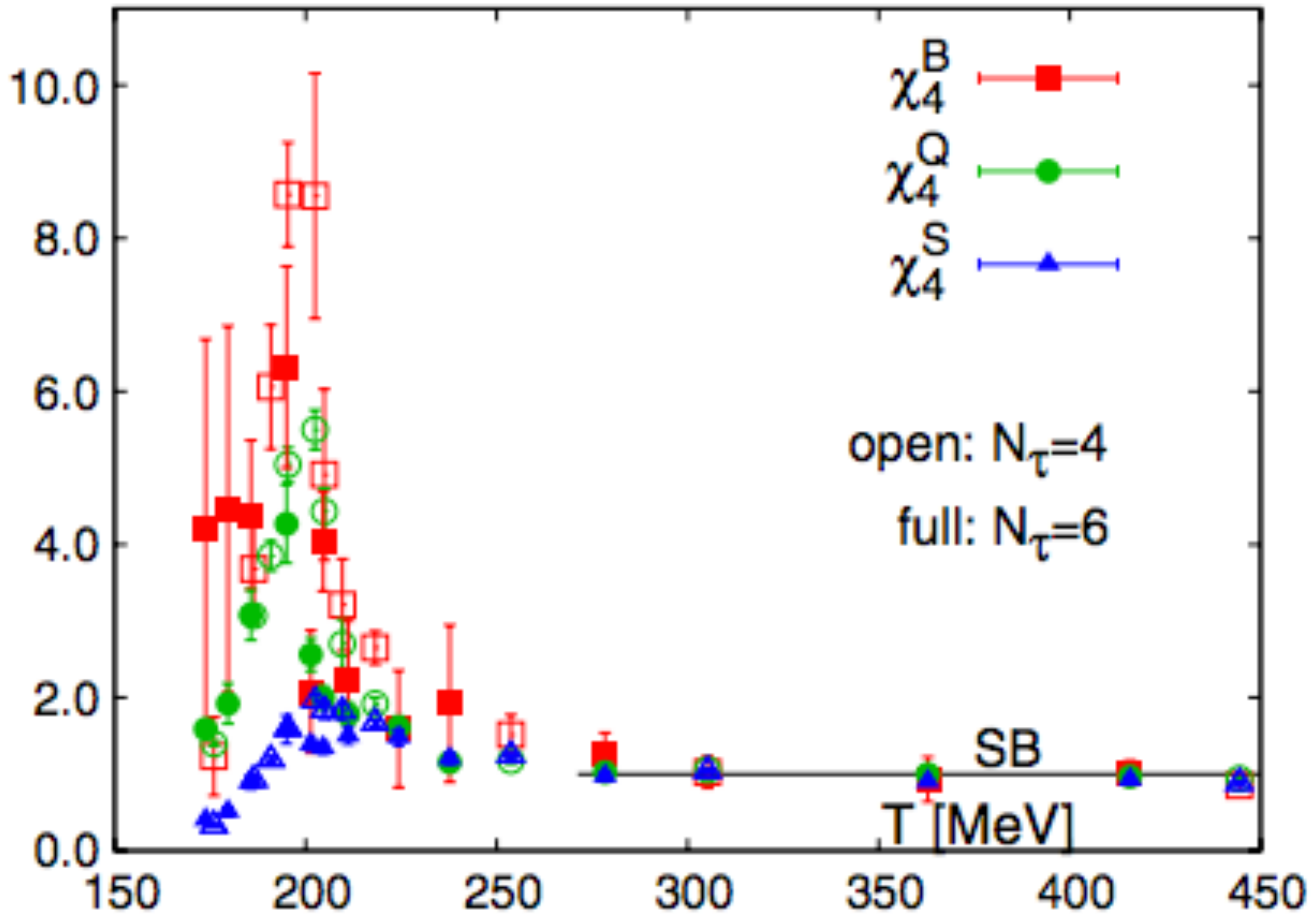
$$C_4 = <(\delta N)^4>_c \approx \xi^7$$

(2) Direct comparison with susceptibilities.

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

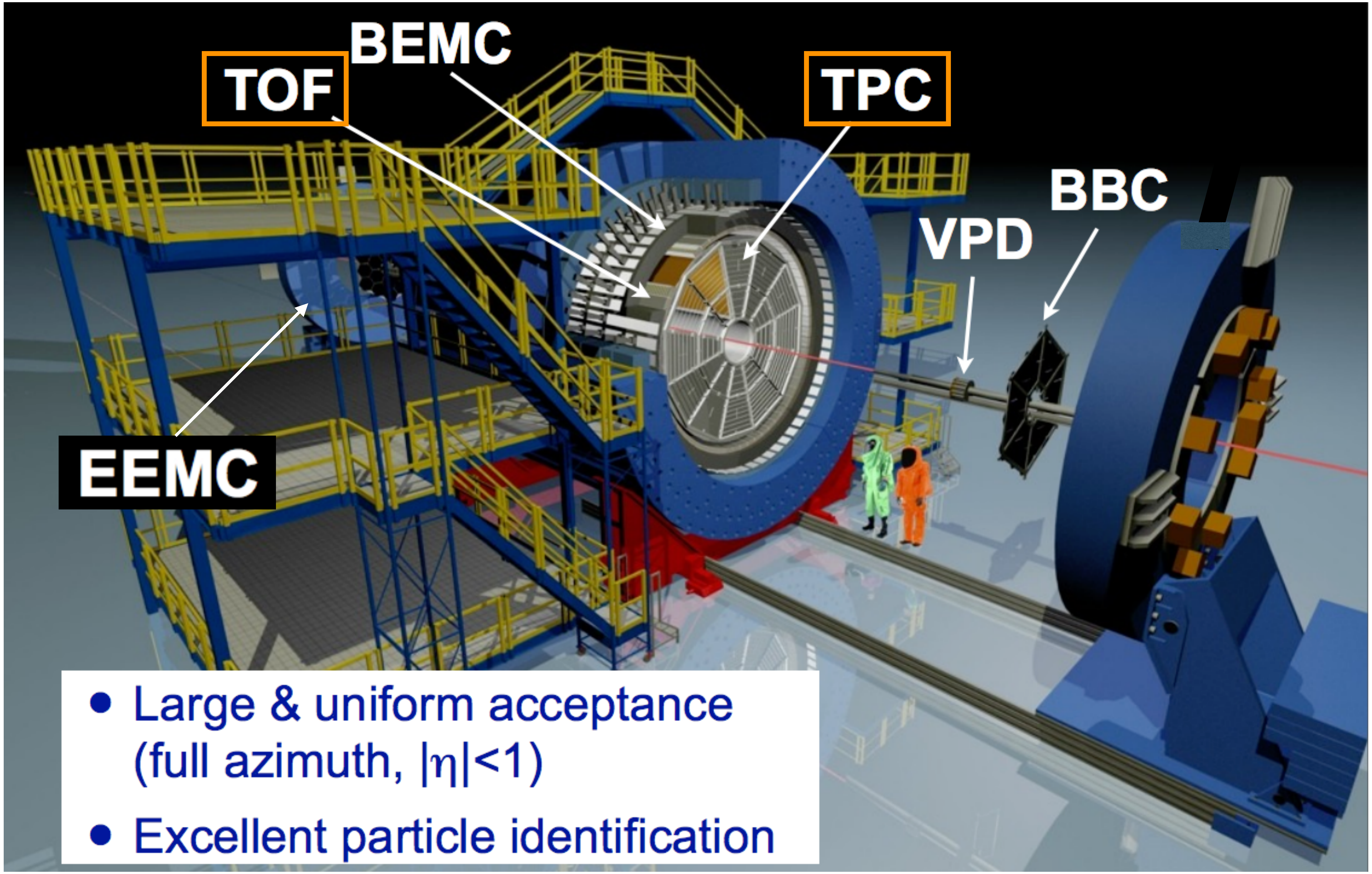
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

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



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

The STAR detector

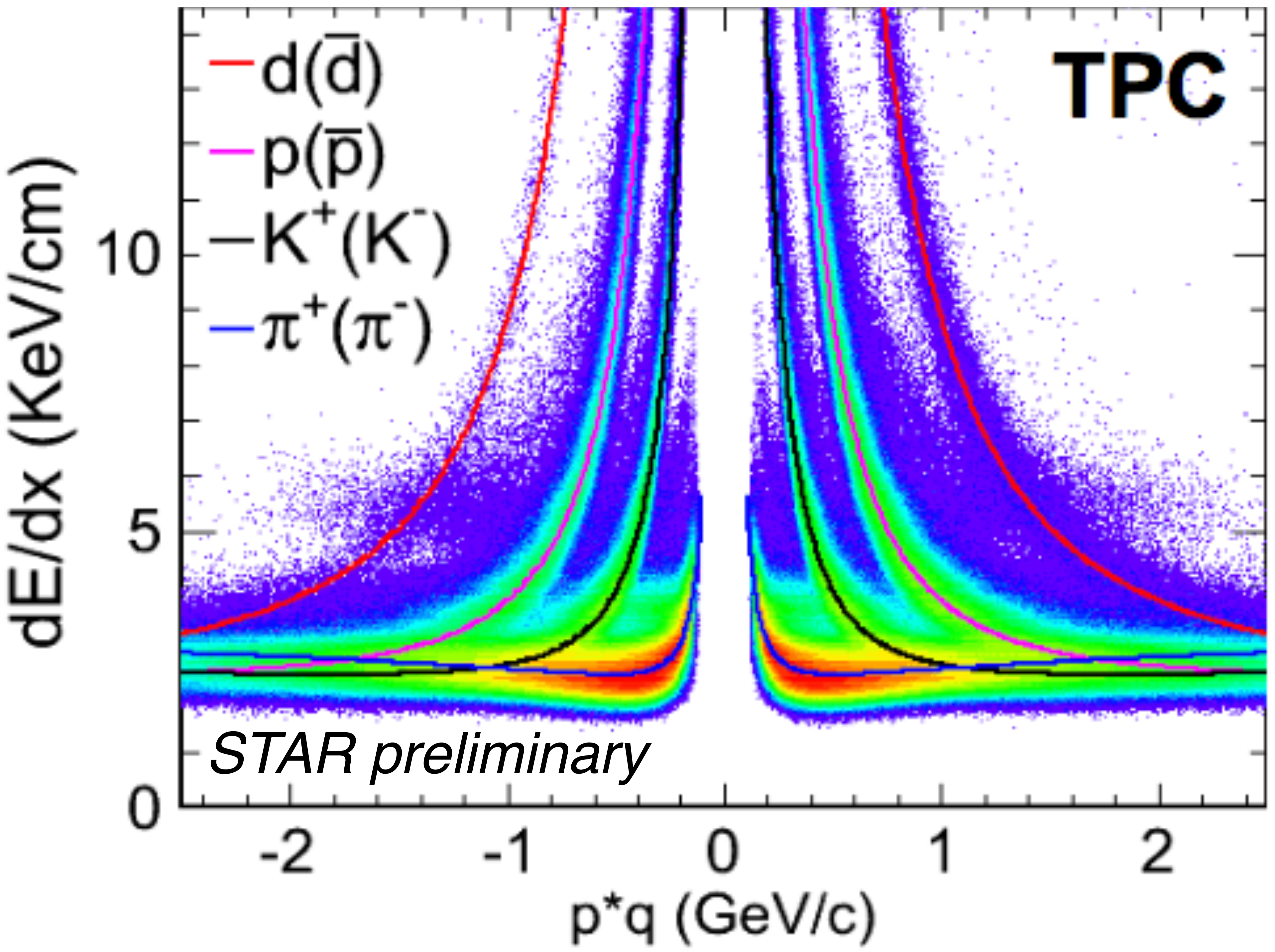


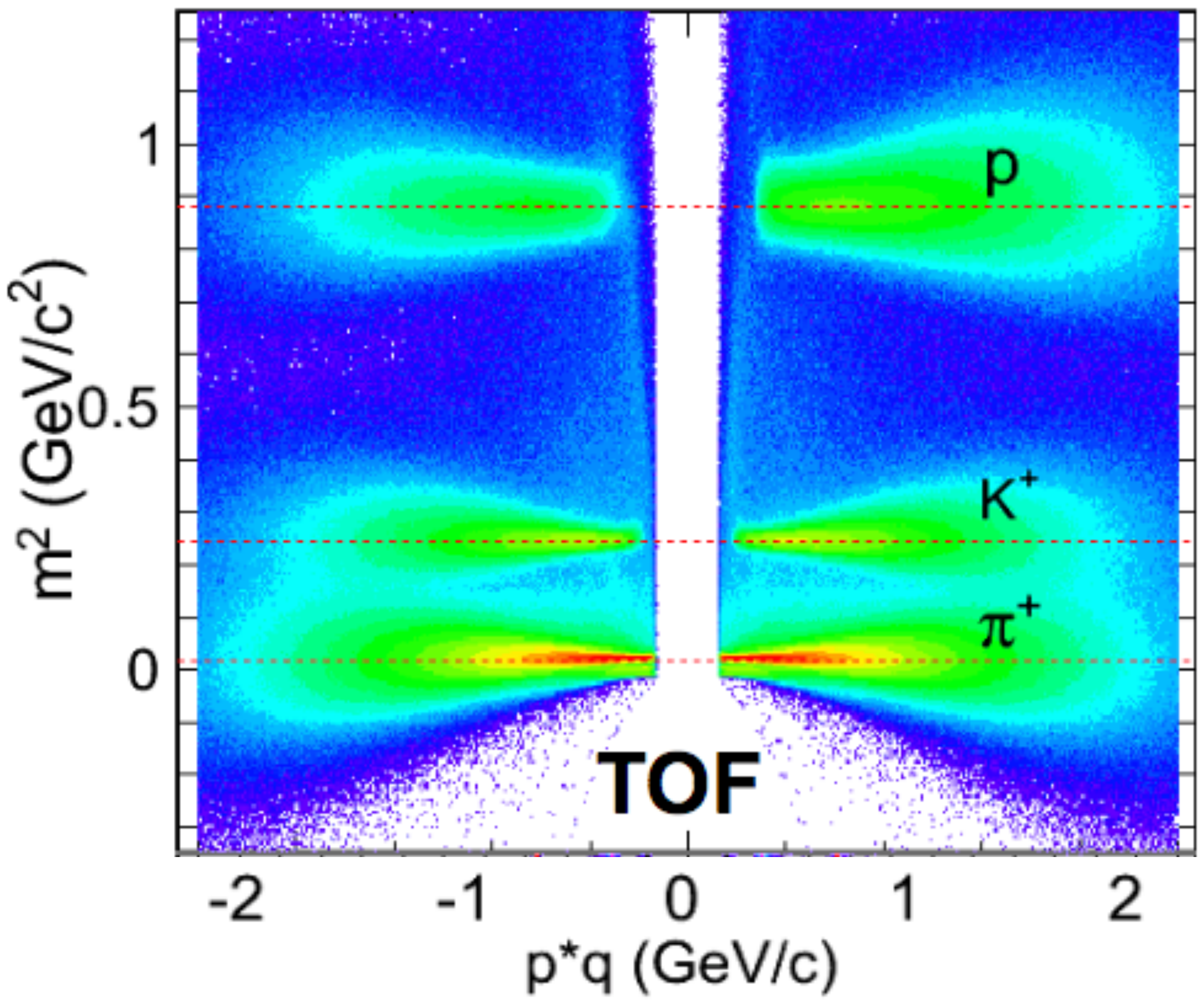
- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

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.

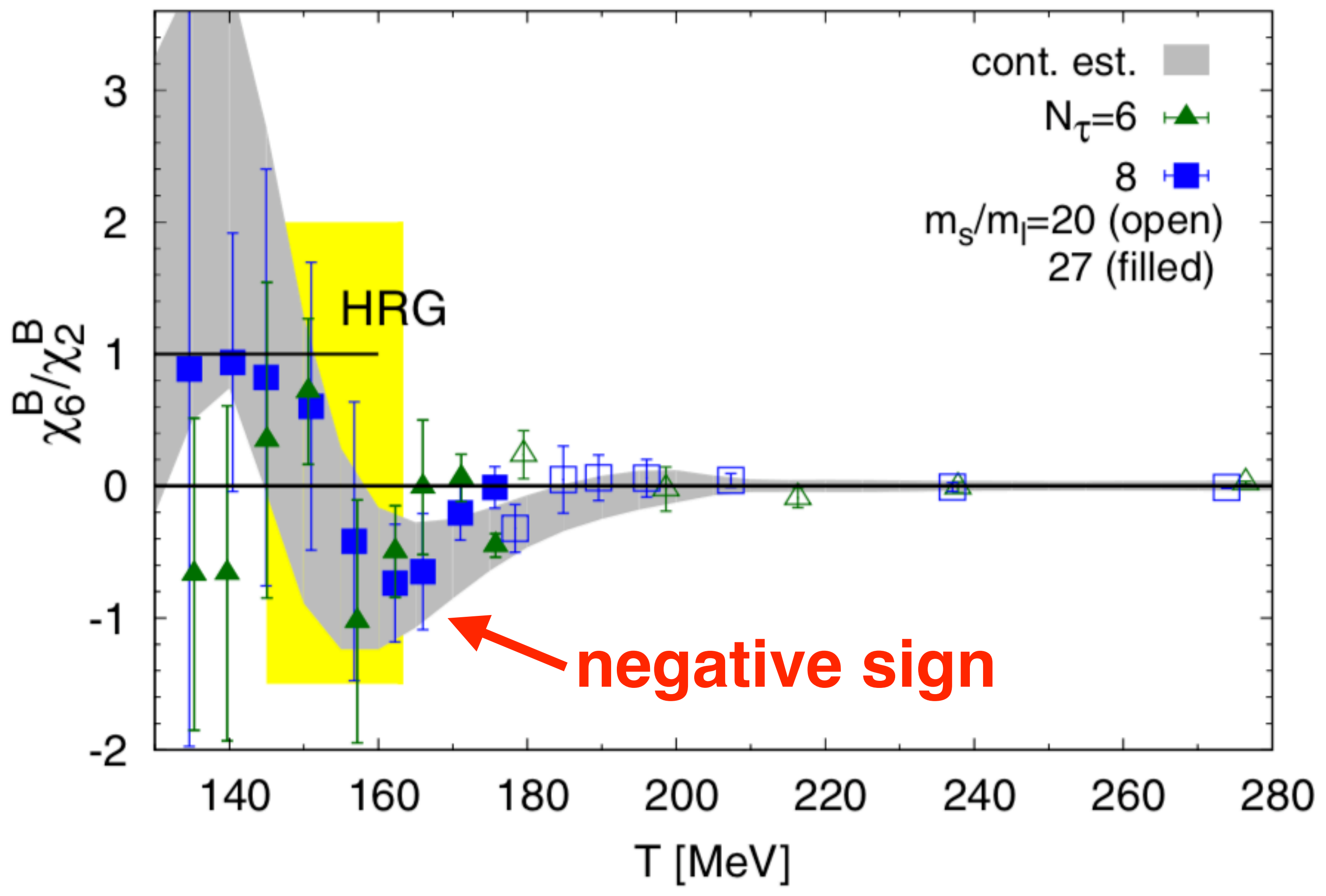




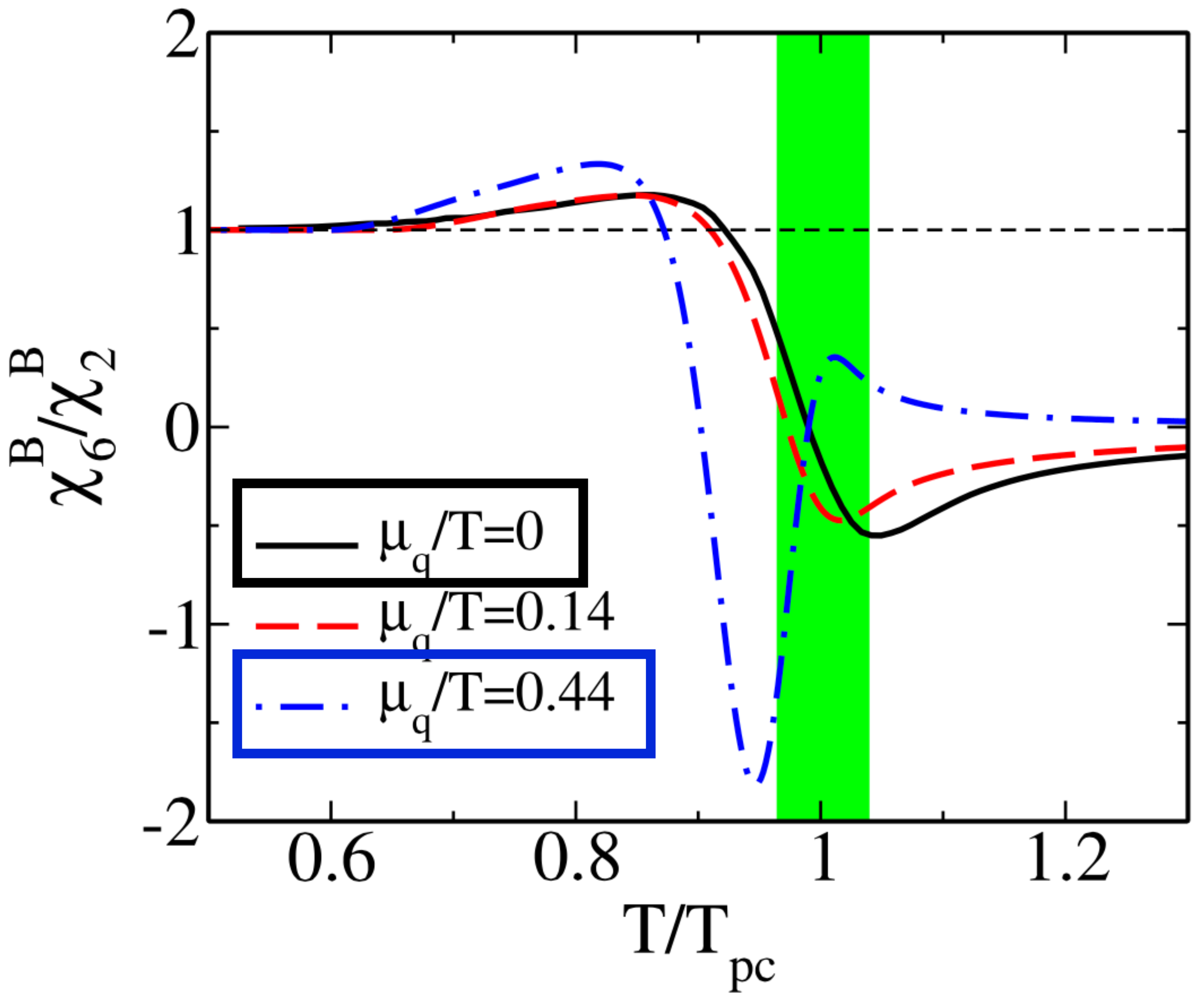
The sixth-order cumulant

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

Predicted scenario for this measurement

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

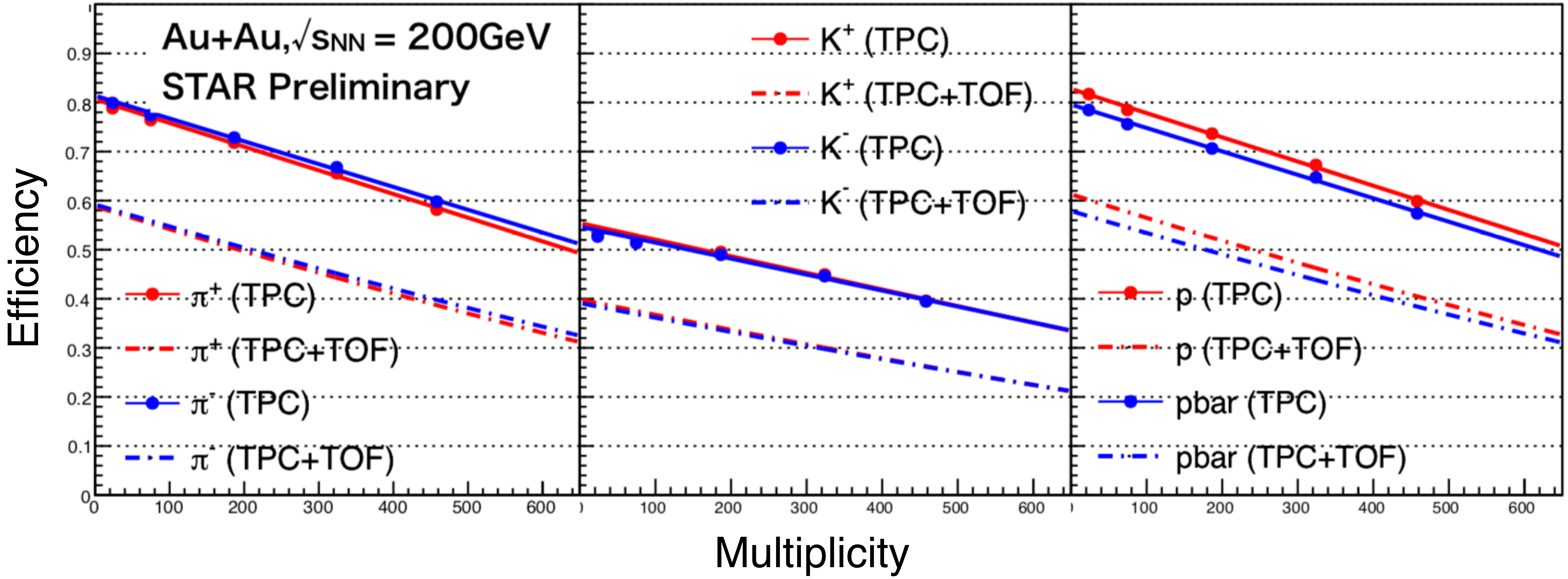
✓ Efficiency correction on cumulants have been done assuming the binomial efficiencies.

- *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*

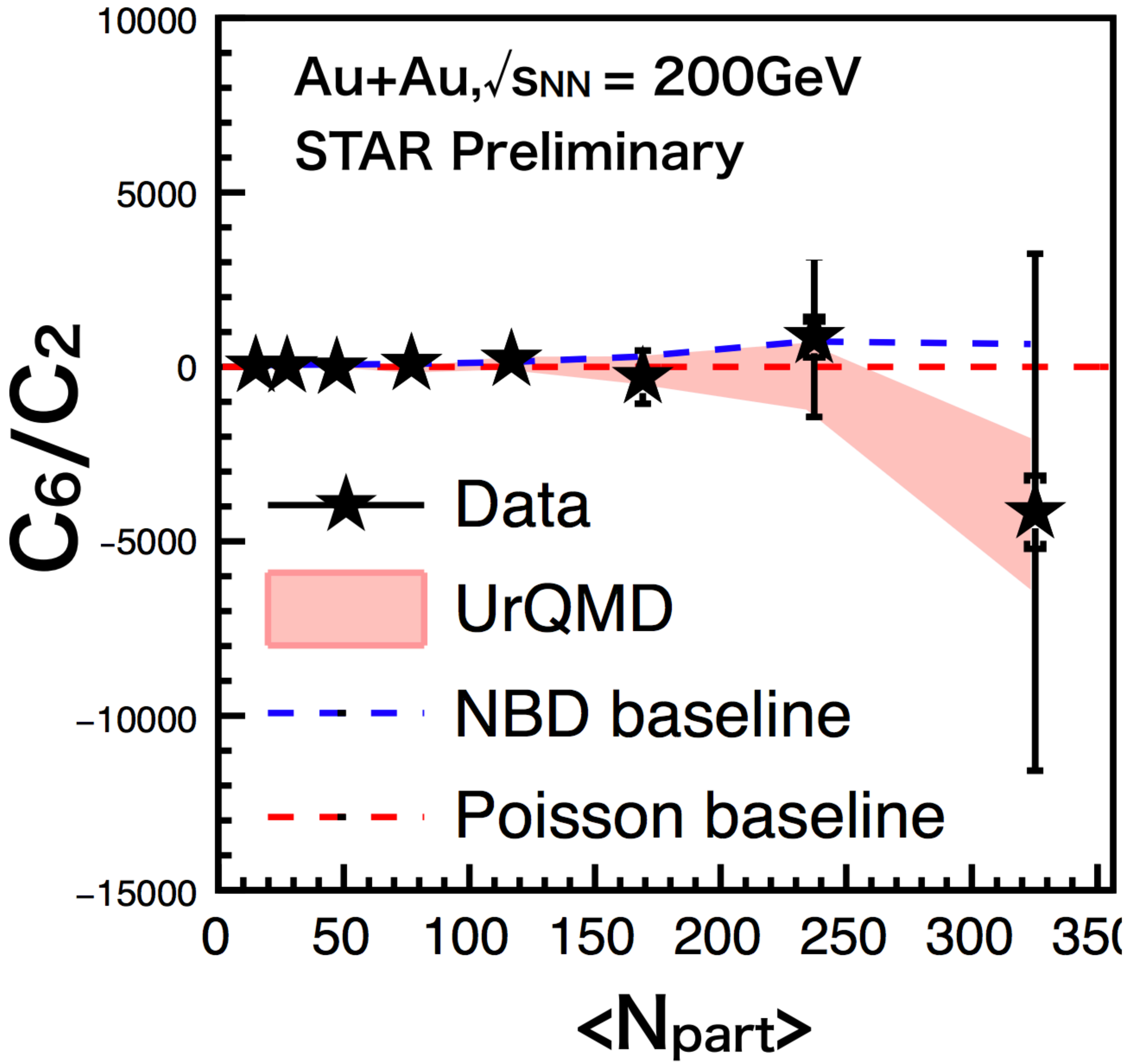
$$B_{p,N}(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^n$$

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



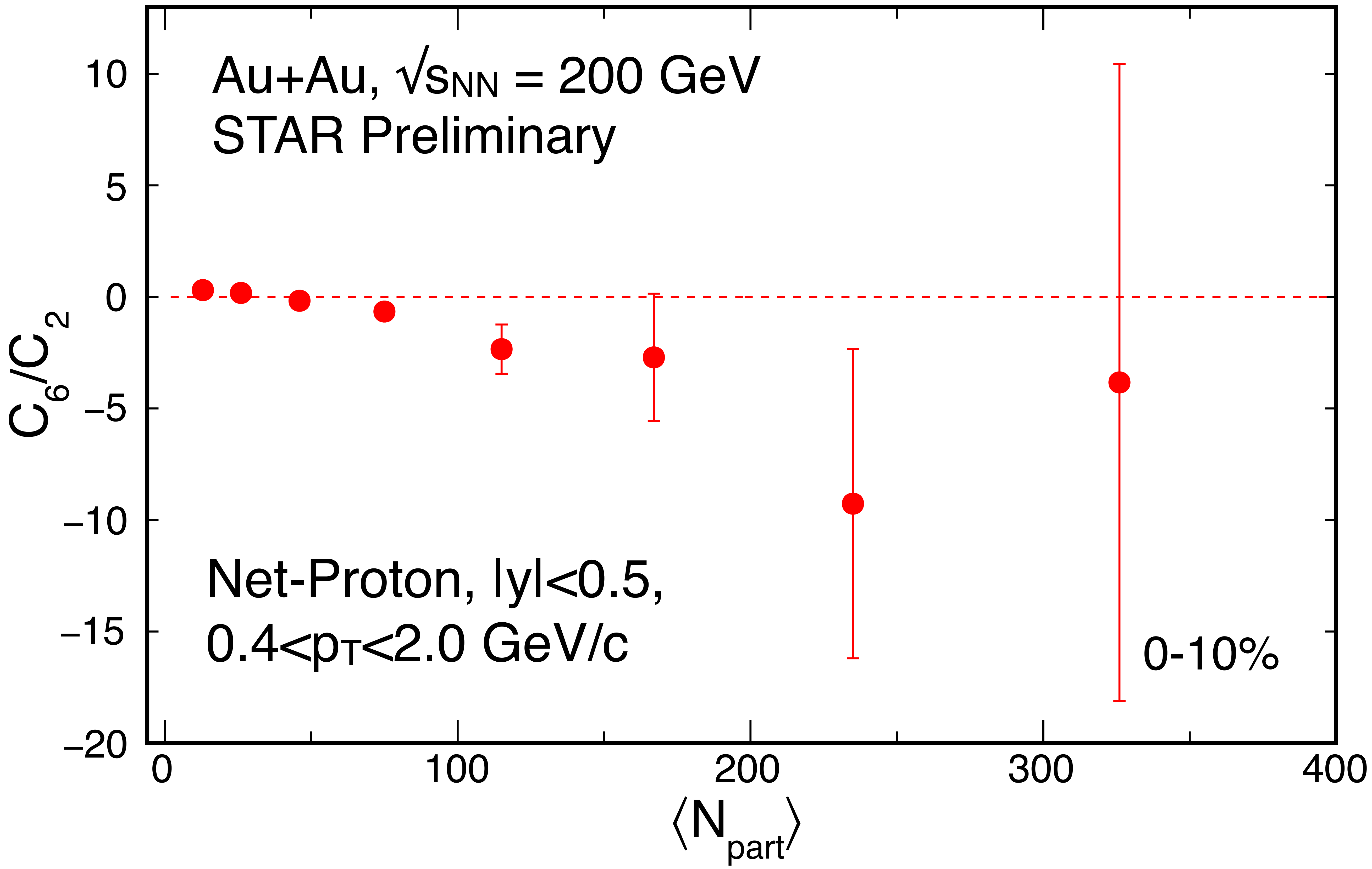
✓ **Results of net-charge C_6/C_2 are consistent with zero within large statistical uncertainties.**

T. Sugiura, QM2018

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

✓ **Much better precision compared to net-charge.**

✓ **Negative values are observed systematically from mid-central to central collisions, which seems consistent with theoretical prediction.**



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

Used statistics

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

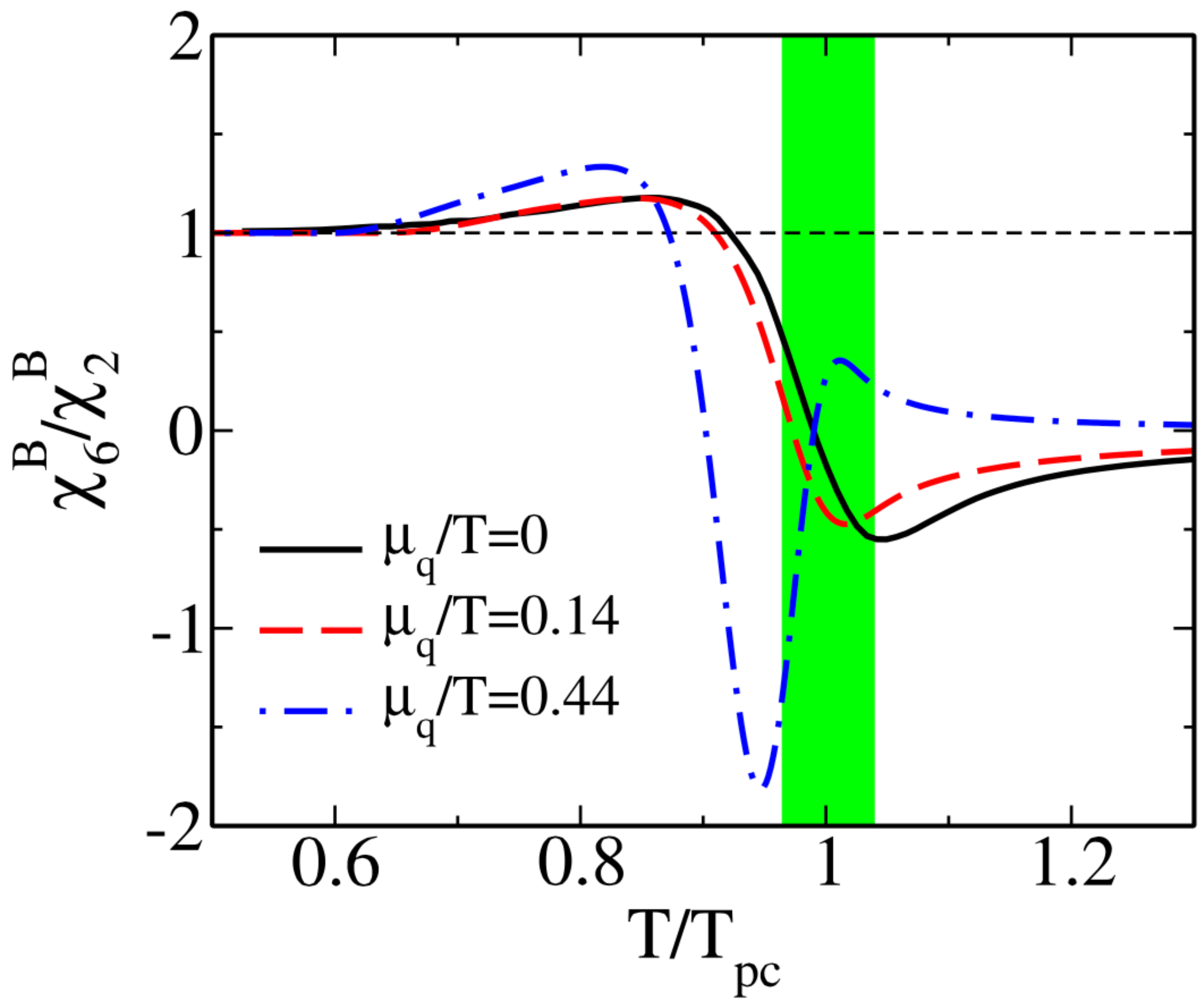
T. Nonaka, QM2017

Lower beam energy?

- ✓ Positive C_6 is predicted in $\sqrt{s_{NN}}$<60 GeV (μ_B/T<0.5).
- ✓ STAR collected ~1B minimum bias events (500M good events) at $\sqrt{s_{NN}}$ = 54.4 GeV in 2017.

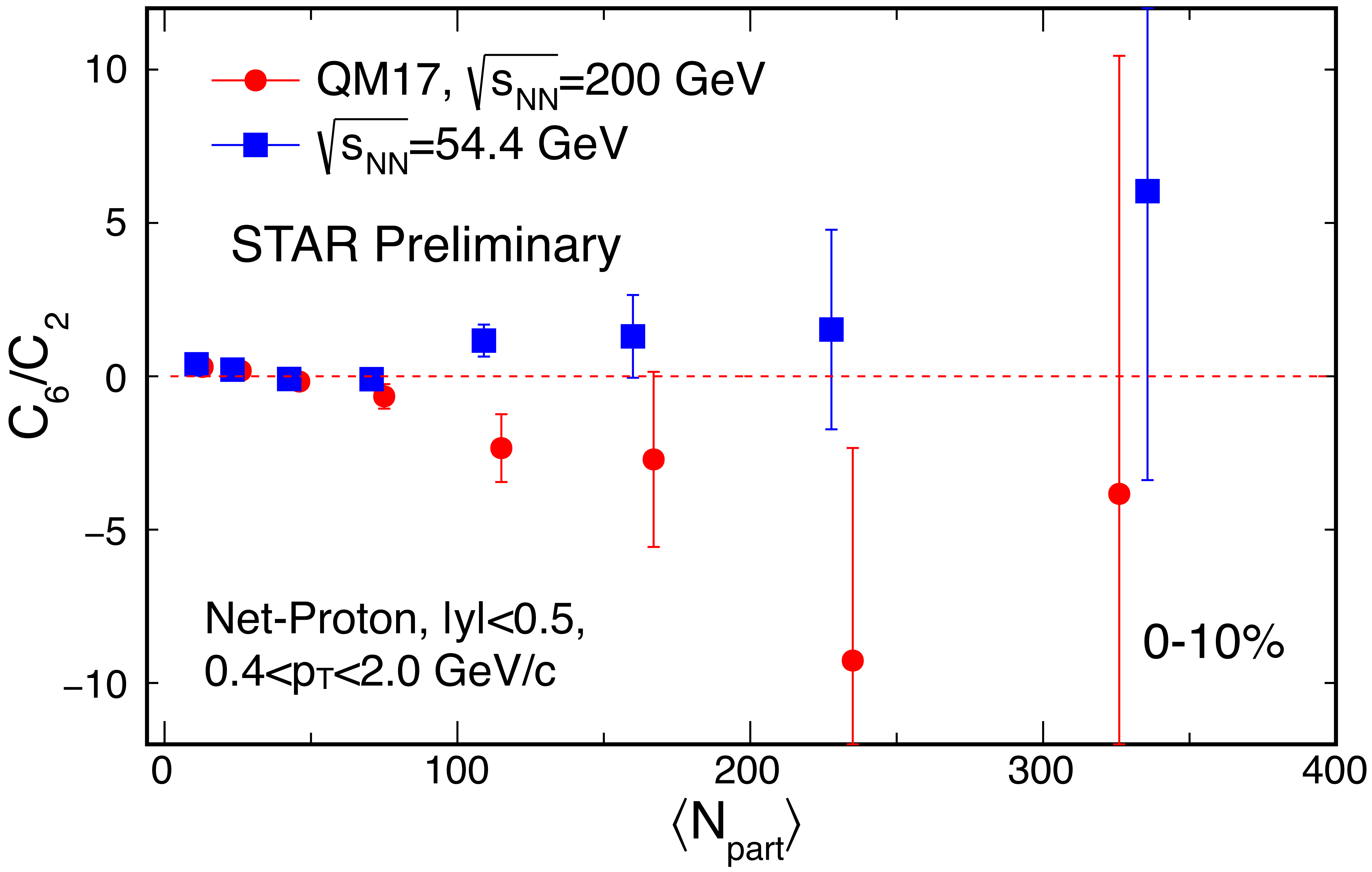
Friman et al, Eur. Phys. J. C (2011) 71:1694

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 at $\sqrt{s_{NN}}$ = 54.4 GeV

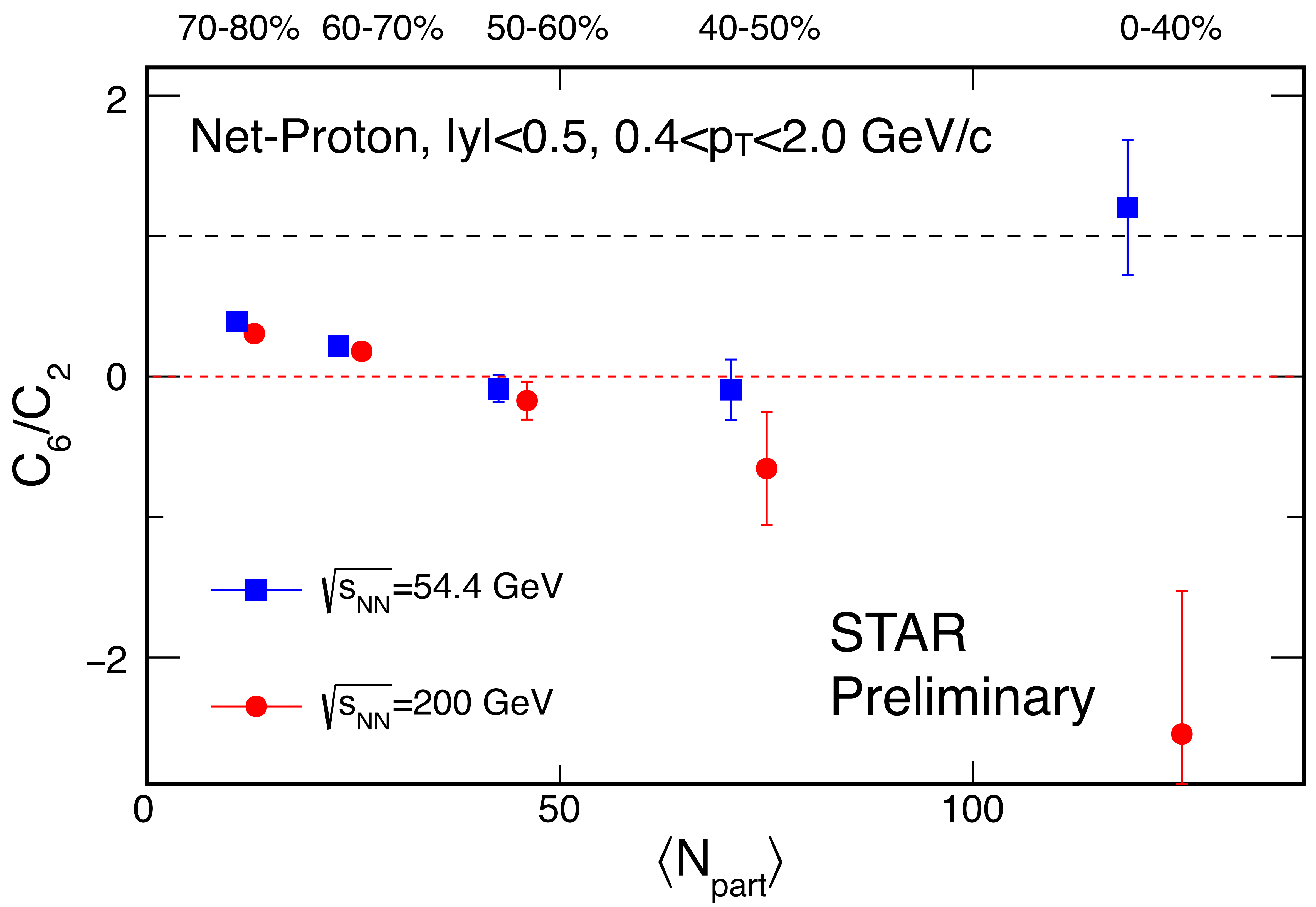
✓ Positive values are observed systematically from peripheral to central collisions.



T. Nonaka, ATHIC2018

0-40% centrality

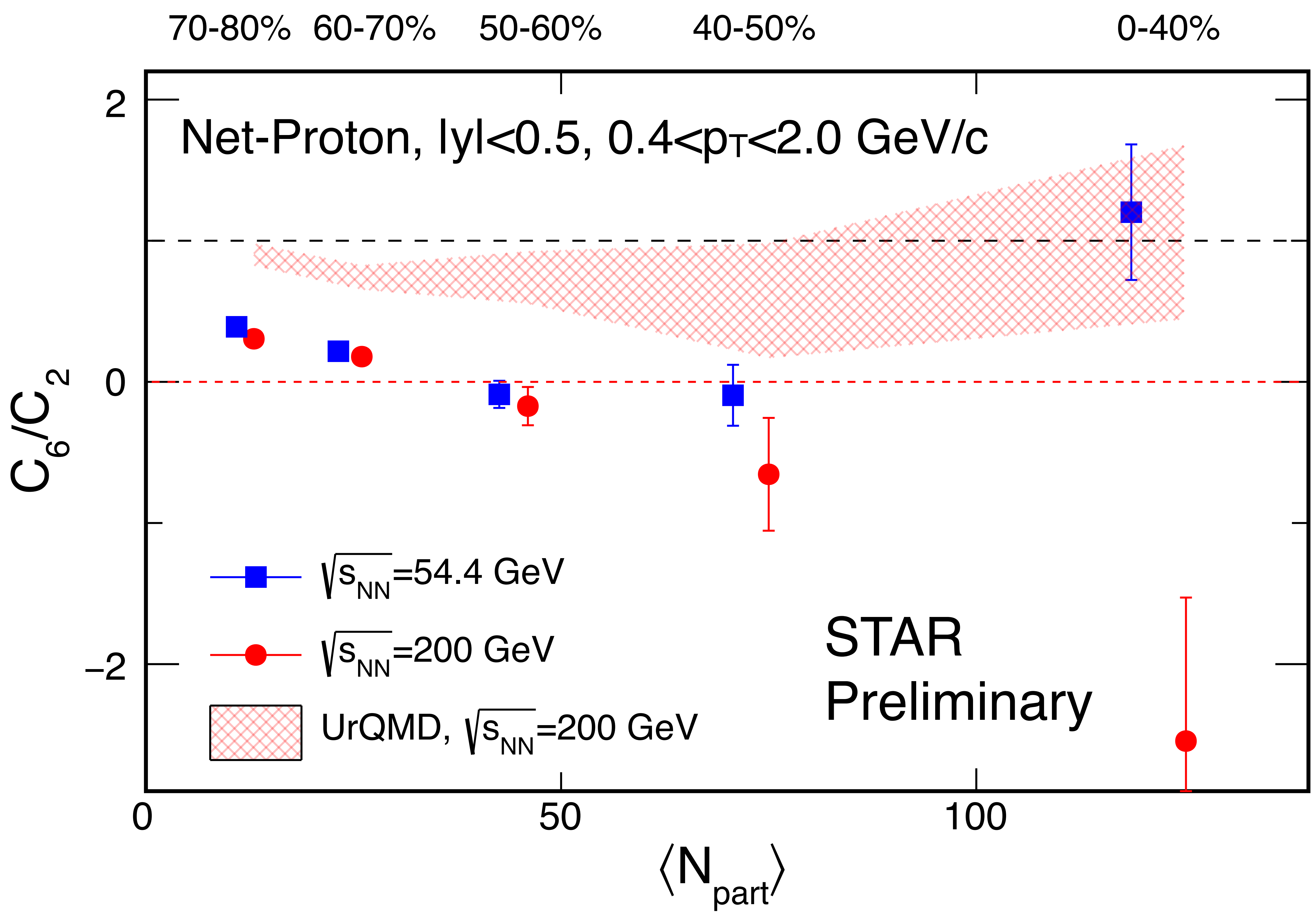
✓ Clear separation and opposite signs between two energies in 0-40%.



T. Nonaka, ATHIC2018

UrQMD

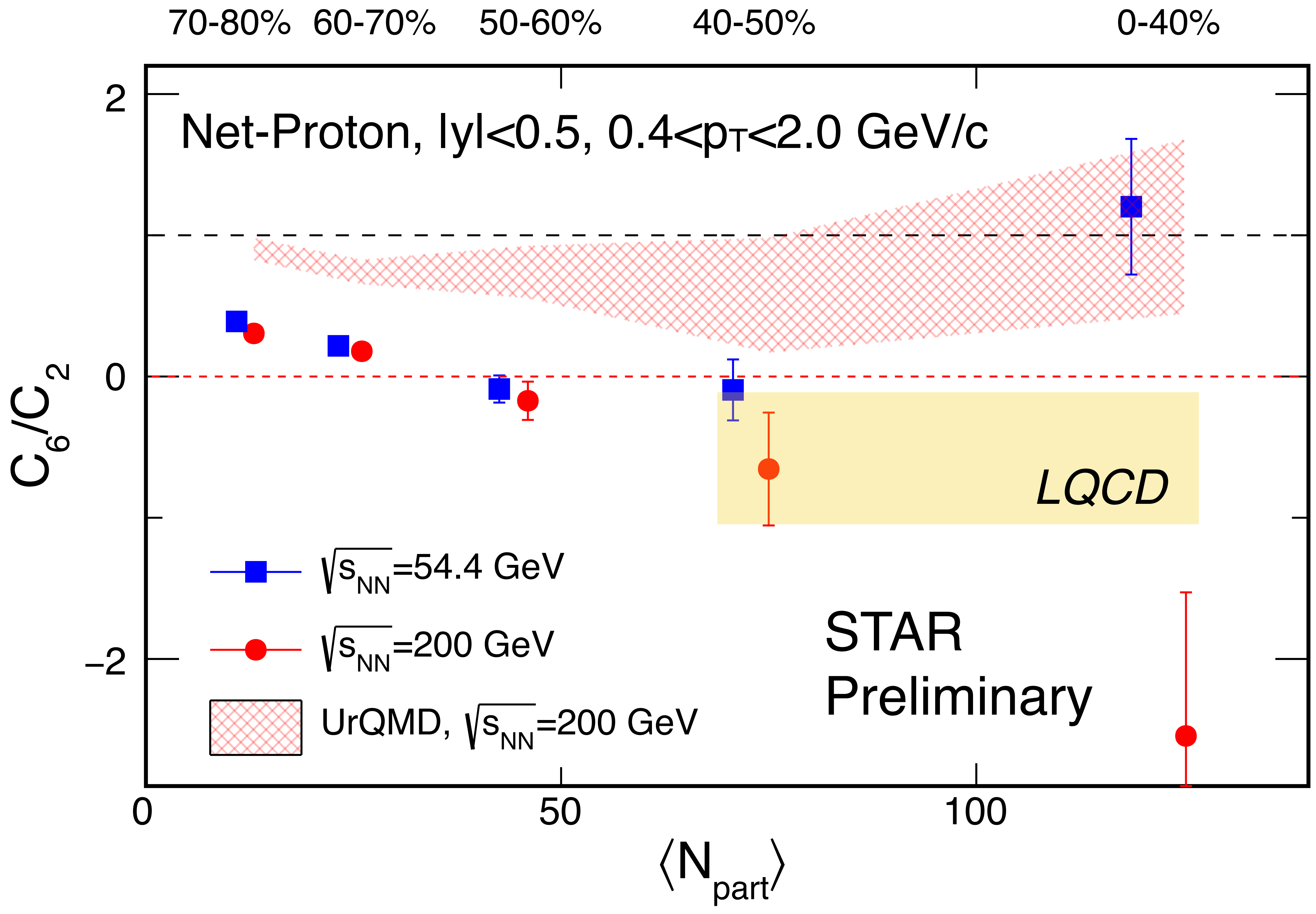
- ✓ Clear separation and opposite signs between two energies in 0-40%.
- ✓ UrQMD result shows positive signs for all centralities at $\sqrt{s_{NN}}$ = 200 GeV.



T. Nonaka, ATHIC2018

0-40% centrality

- ✓ 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.



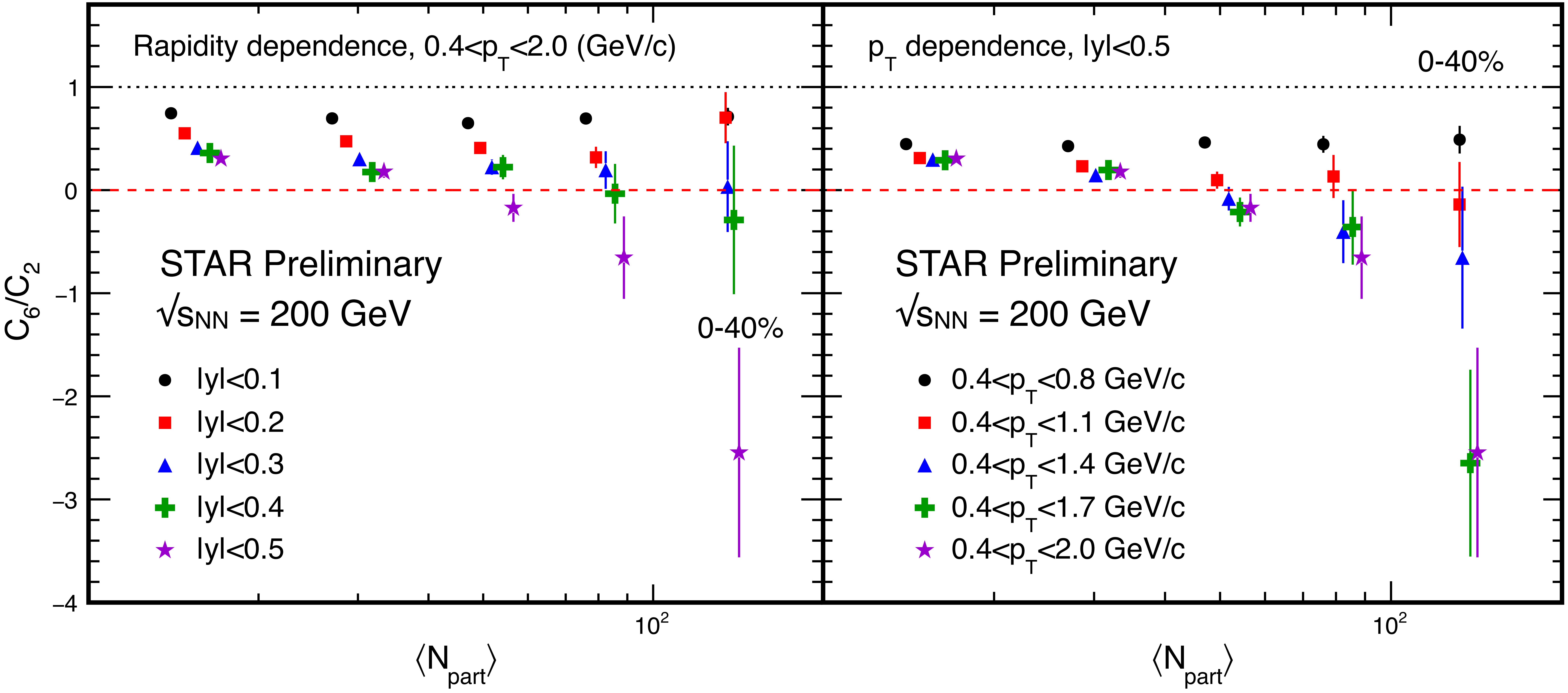
LQCD : A. Bazavov et al, PhysRevD.95.054504

T. Nonaka, ATHIC2018

Acceptance dependence

✓ Monotonic decrease with enlarging the acceptance.

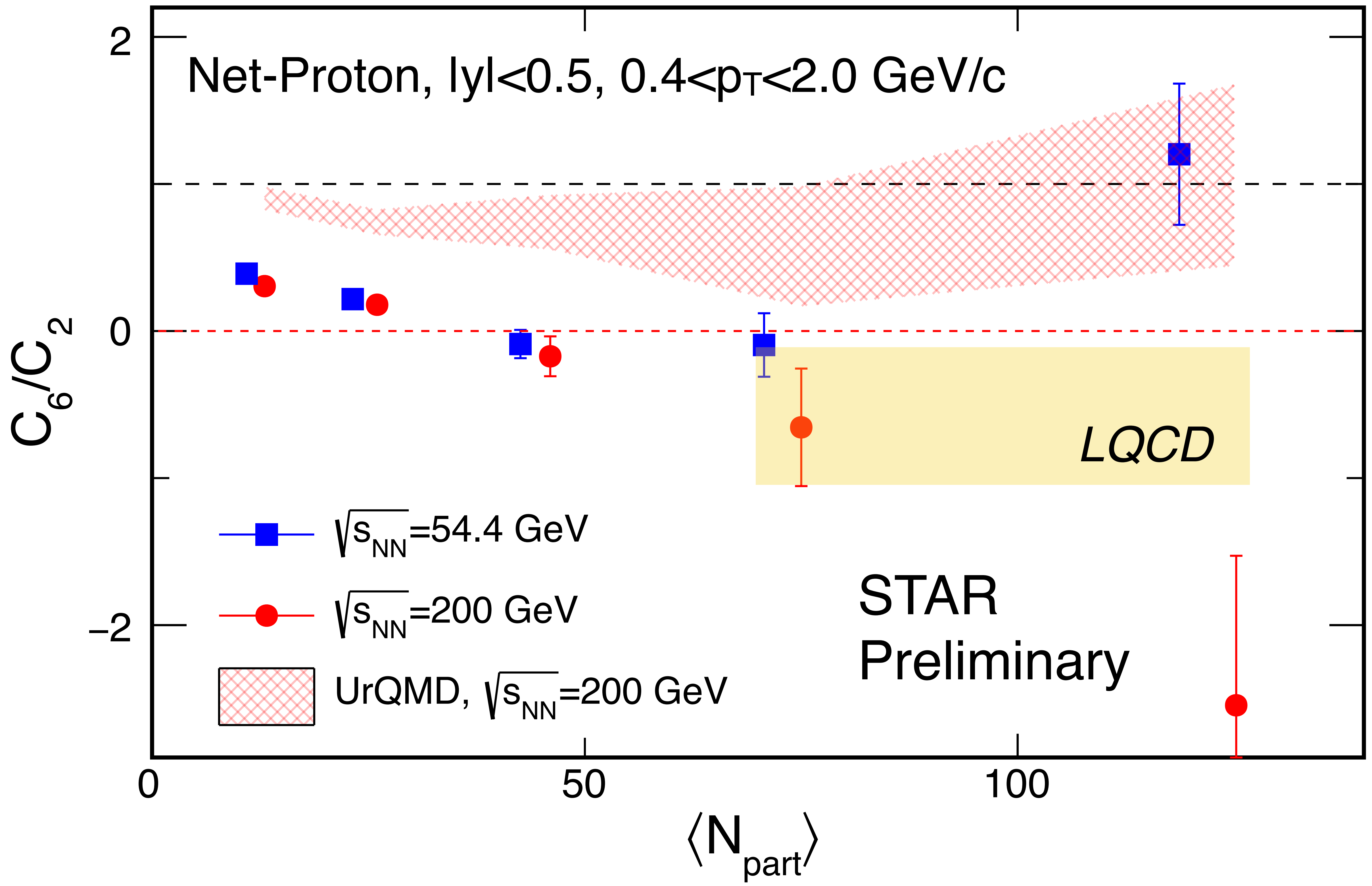
✓ p_T dependence seems to be saturated at $0.4<p_T<1.7$ GeV/c.



T. Nonaka, ATHIC2018

Summary

- ✓ C_6/C_2 of net-charge multiplicity distributions show zero within large uncertainties.
- ✓ 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.



Thank you for your attention

Back up