QCD相図探索のための高次ゆらぎ測定と体積ゆらぎについて

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QCD相転移やQGP生成のモデル化による重イオン衝突の時空発展の理解に向けた理論・実験共同研究会(Zoom)

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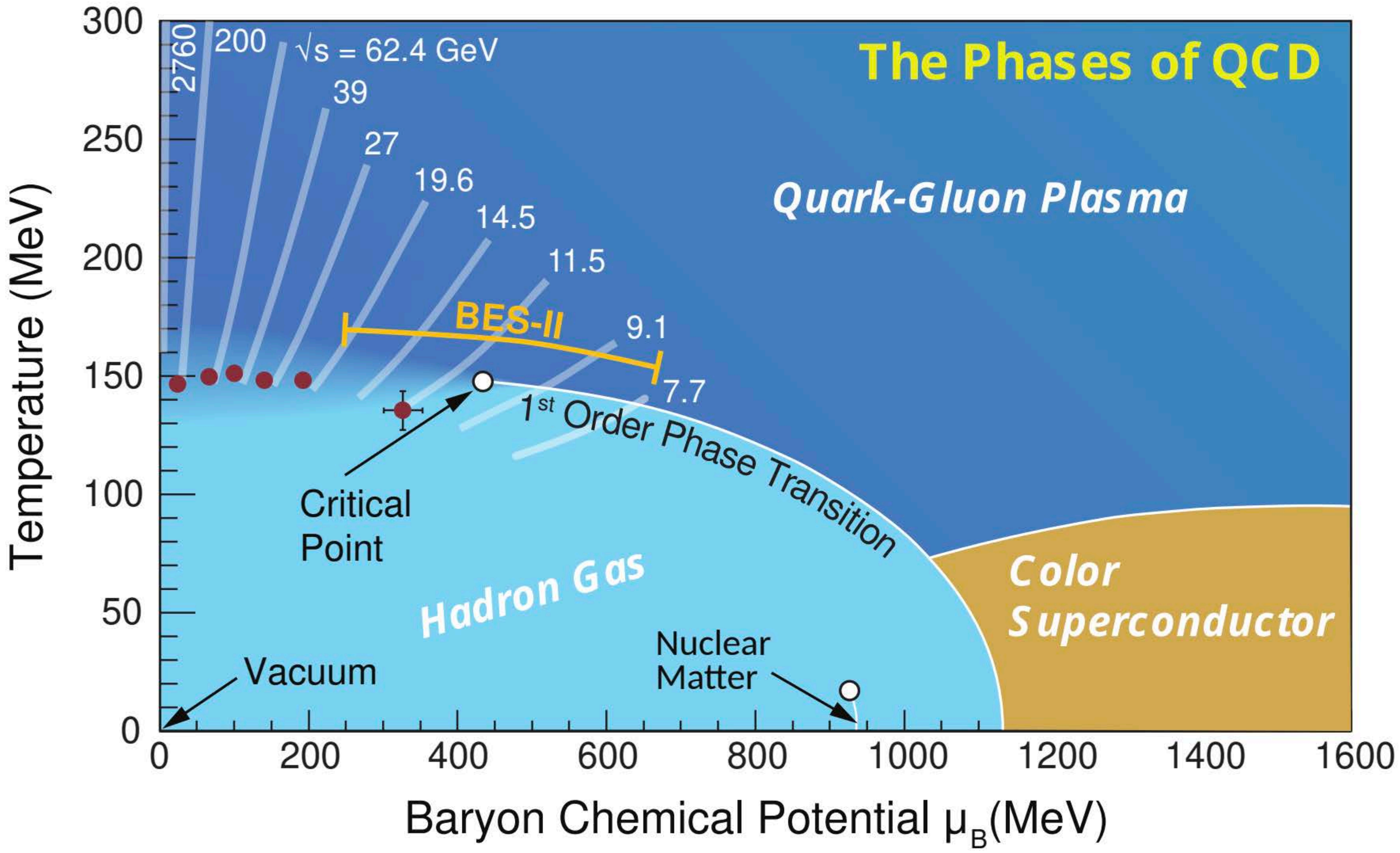
Tomonaga Center for the History of the Universe

Outline

- 導入
- 実験結果
- 体積ゆらぎ

QCD phase diagram

✓ QCD phase structure in wide (μ_B,T) region.



A. Bzdak et al, Phys. Rep. 853 pp 1-87 (2020)

- **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

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

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)	T_{ch} (MeV)	μ_B (MeV)
200	238	164.3	28
62.4	47	160.3	70
54.4	550	160.0	83
39	86	156.4	160
27	30	155.0	144
19.6	15	153.9	188
14.5	20	151.6	264
11.5	6.6	149.4	287
7.7	3	144.3	398

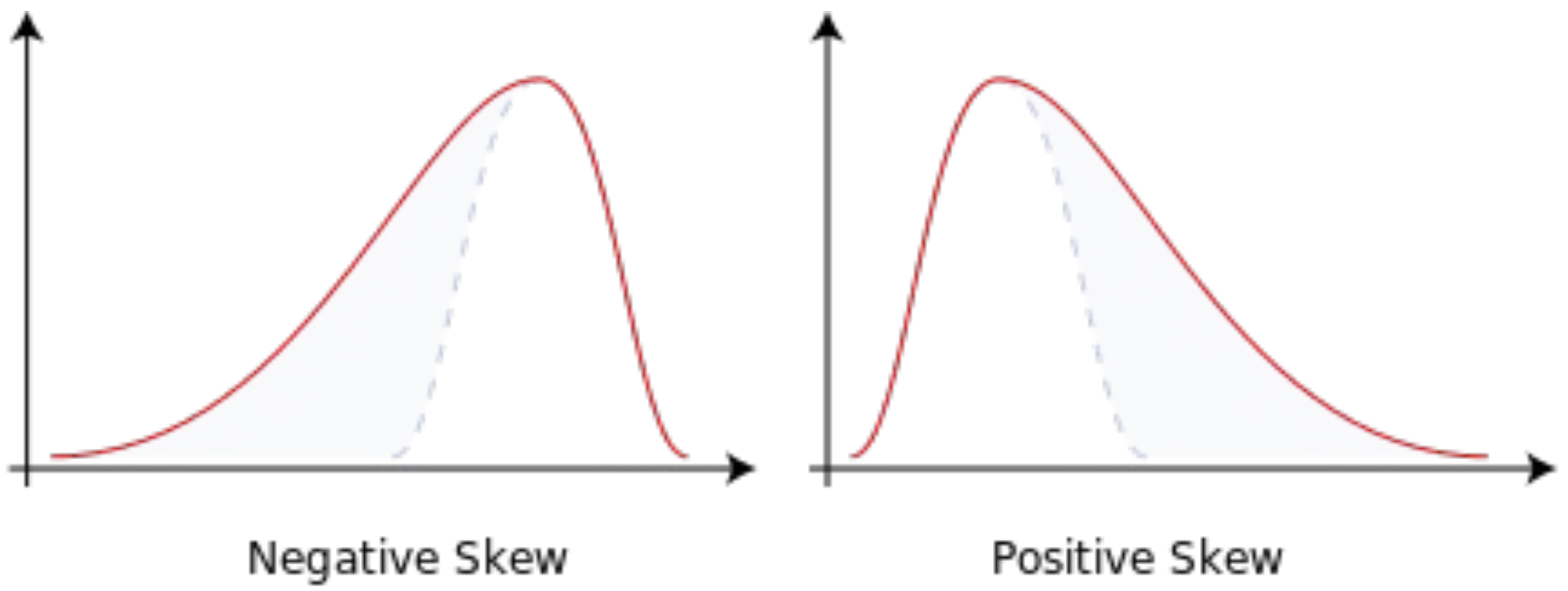
2010-2017

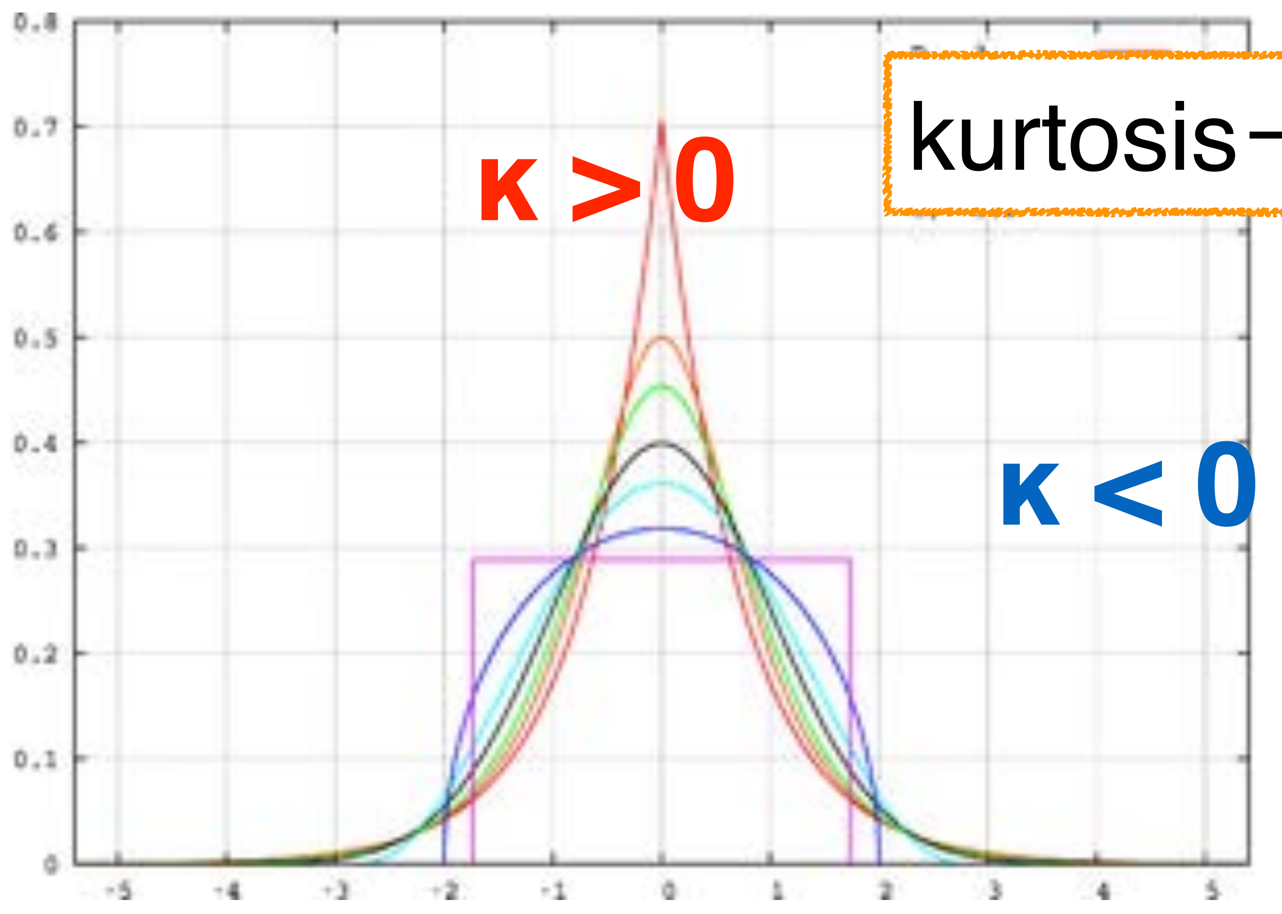
- **Crossover at μ_B = 0 MeV**
  Y. Aoki et al, Nature 443, 675(2006)
- **1st-order phase transition at large μ_B?**
- **Critical point?**

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 sensitive to non-gaussian* fluctuations.**

skewness→asymmetry





kurtosis→sharpness

from wikipedia

✓ **Cumulant ⇄ Central 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 105, 022302 (2010) : STAR Collaboration

✦ Net baryon, net charge and net strangeness

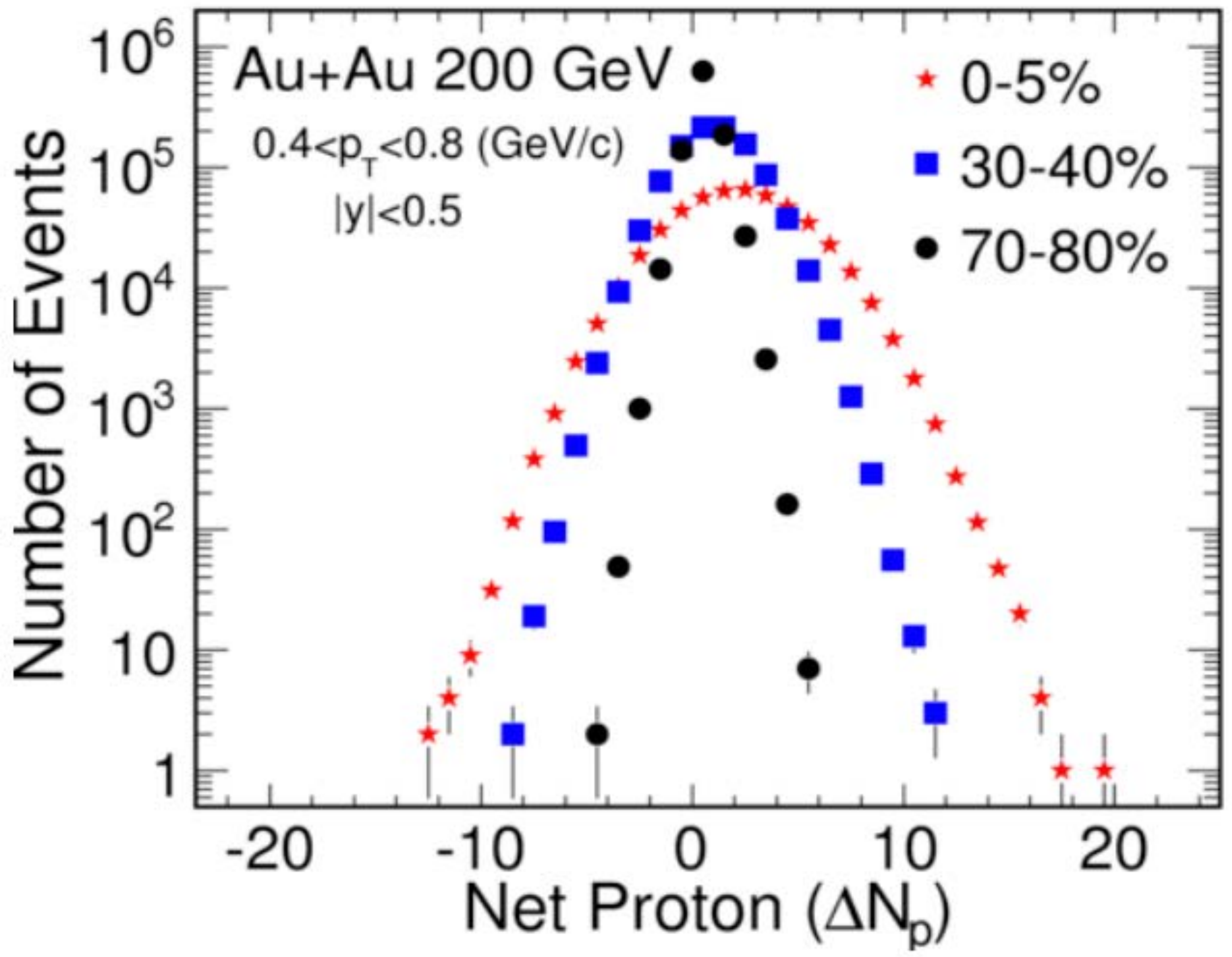
"Net" : positive - negative

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

No. of positively charged particles in one collision (N_q)

No. of negatively charged particles in one collision ($N_{\bar{q}}$)

Fill in histograms over many collisions →



→neutrons cannot be measured

(1) Sensitive to correlation length

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

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

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

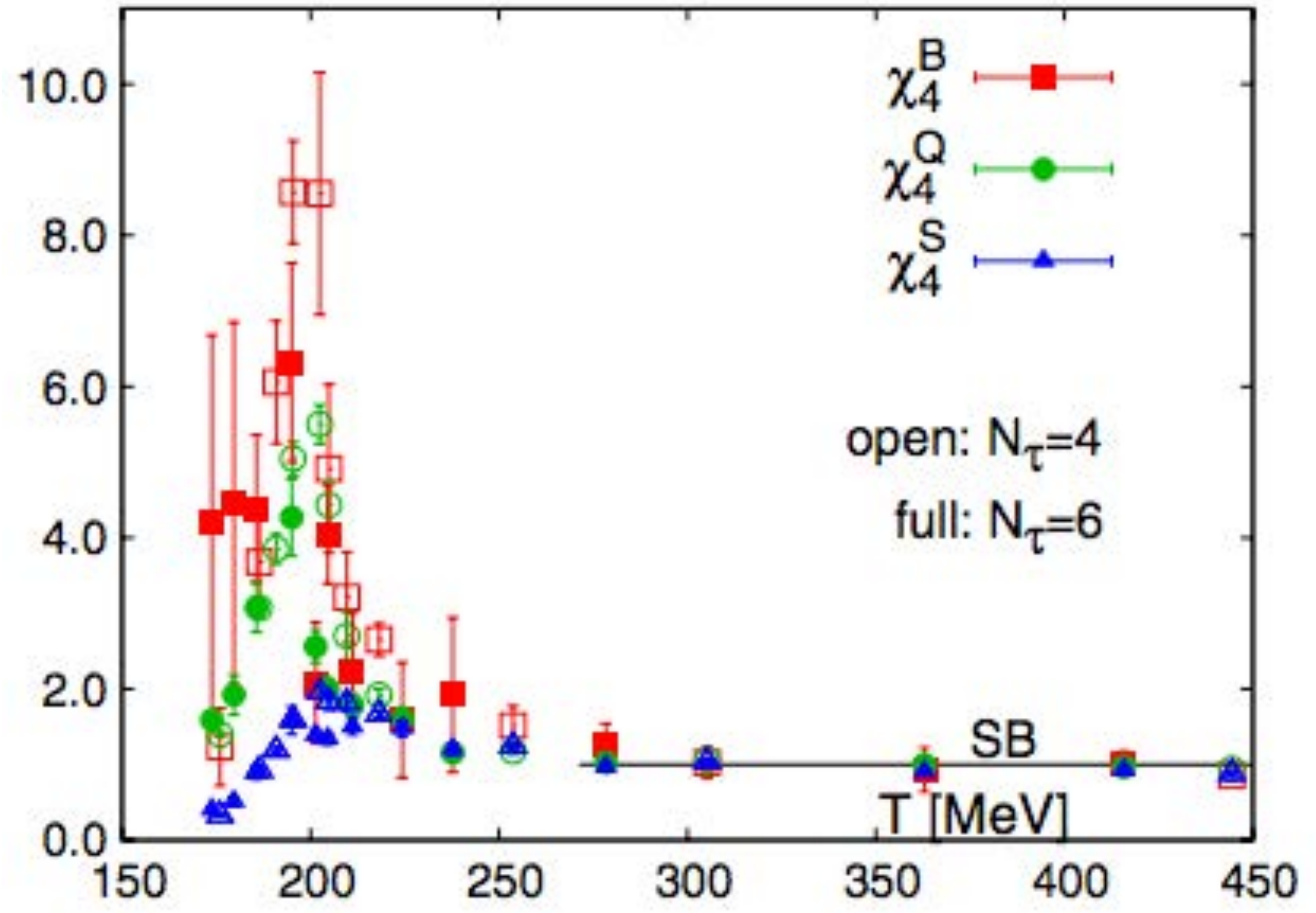
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
MAsakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

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

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

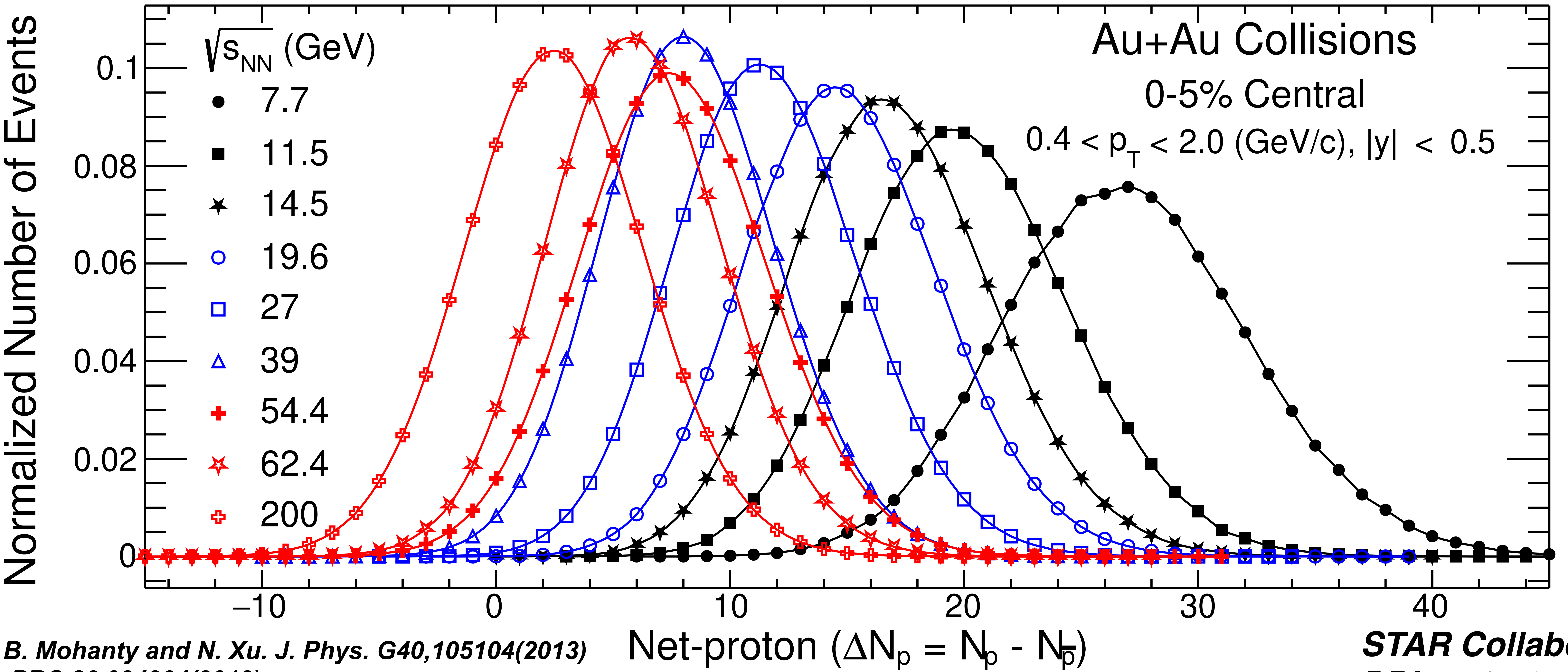
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$



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

Raw net-proton distribution

✓ Avoid auto-correlation effects : New centrality definition
✓ Suppress initial volume fluctuation : Centrality bin width correction
✓ Detector efficiency correction : Binomial model

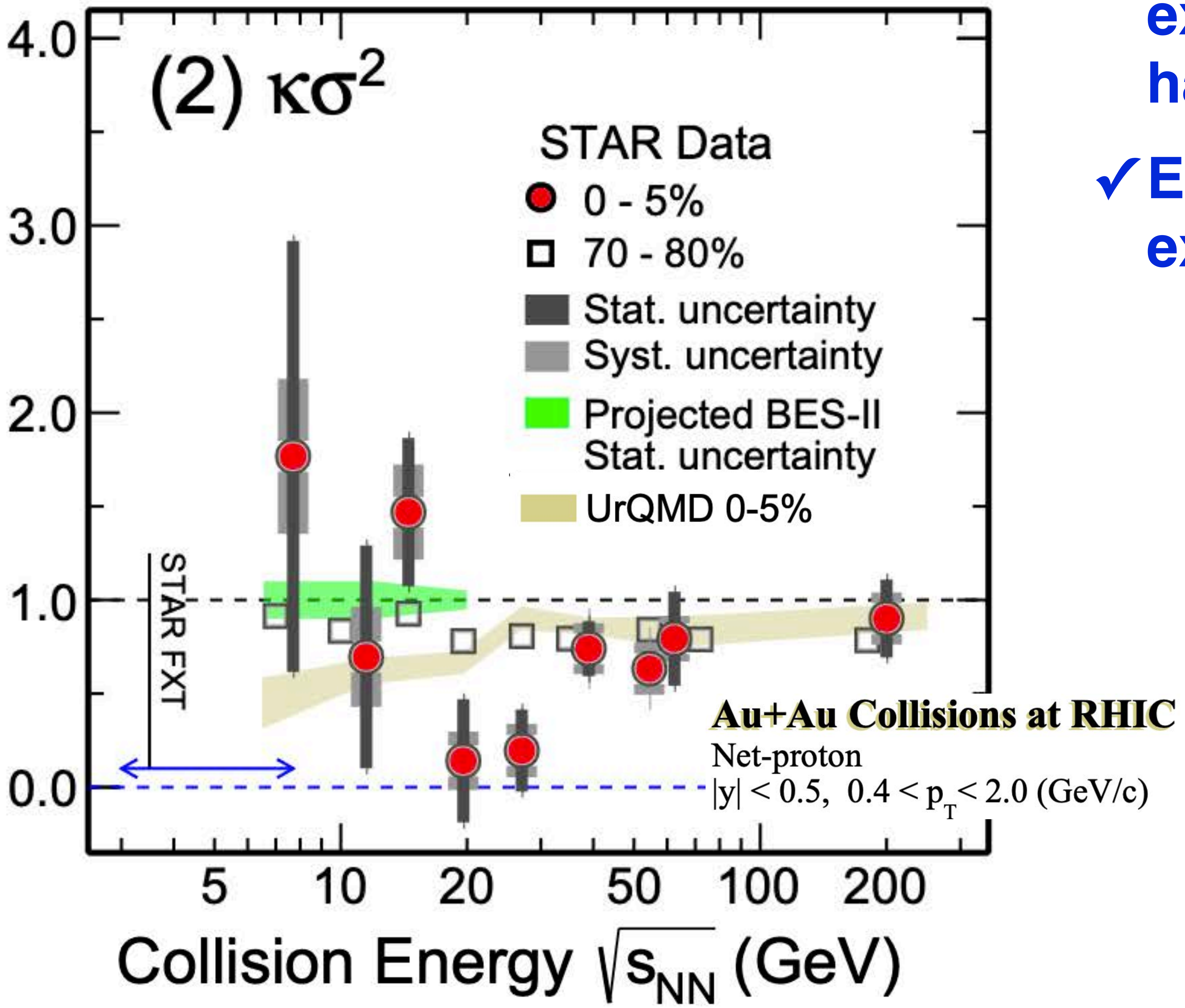


X.Luo, J. Xu, B. Mohanty and N. Xu. J. Phys. G40,105104(2013)
M. Kitazawa : PRC.86.024904(2012)
A. Bzdak and V. Koch : PRC.86.044904(2012), X. Luo : PRC.91.034907(2016)
T. Nonaka, M. Kitazawa, S. Esumi : PRC.95.064912(2017), NIMA906 10-17 (2018), NIMA984(2020)164632
X. Luo, T. Nonaka : PRC.99.044917(2019)

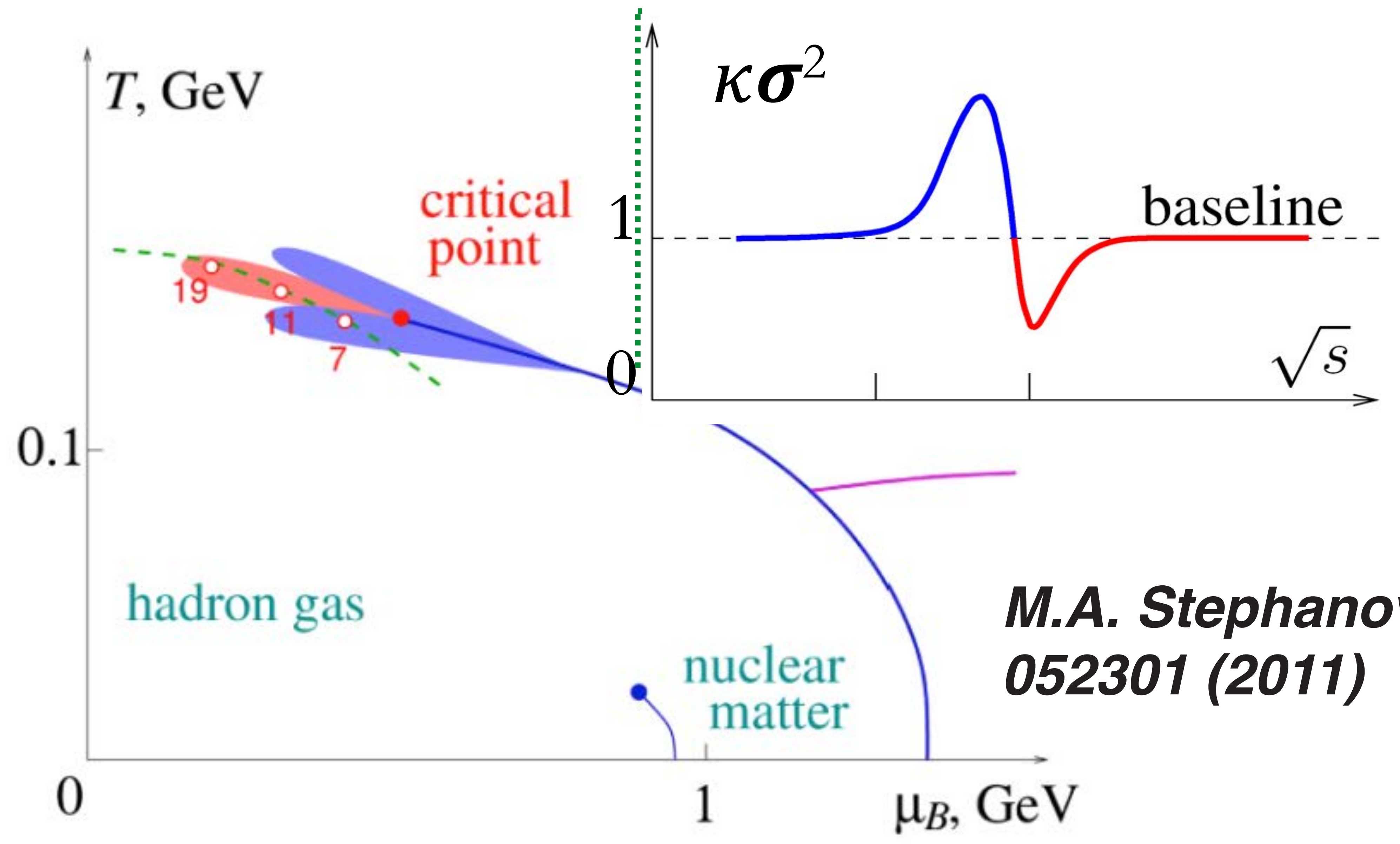
STAR Collaboration, PRL.126.092301(2021) PRC.104.024902(2021)

C_4/C_2 for critical point search

STAR Collaboration, PRL.126.092301(2021)



- ✓Net-proton $\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the expectation from theoretical calculations having a critical point.
- ✓Enhancement at low beam energies cannot be explained by baryon number conservation.

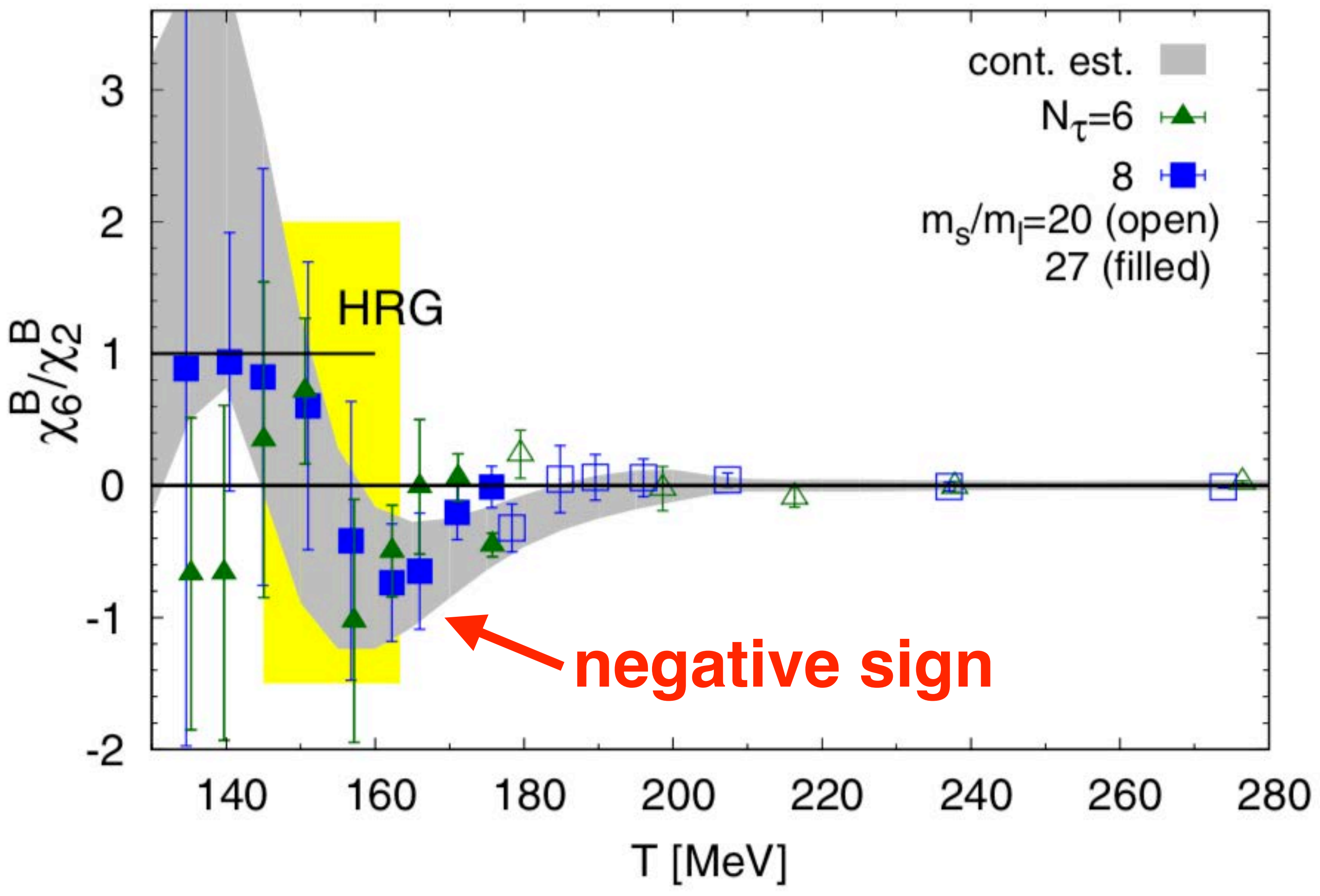


M.A. Stephanov, PRL107, 052301 (2011)

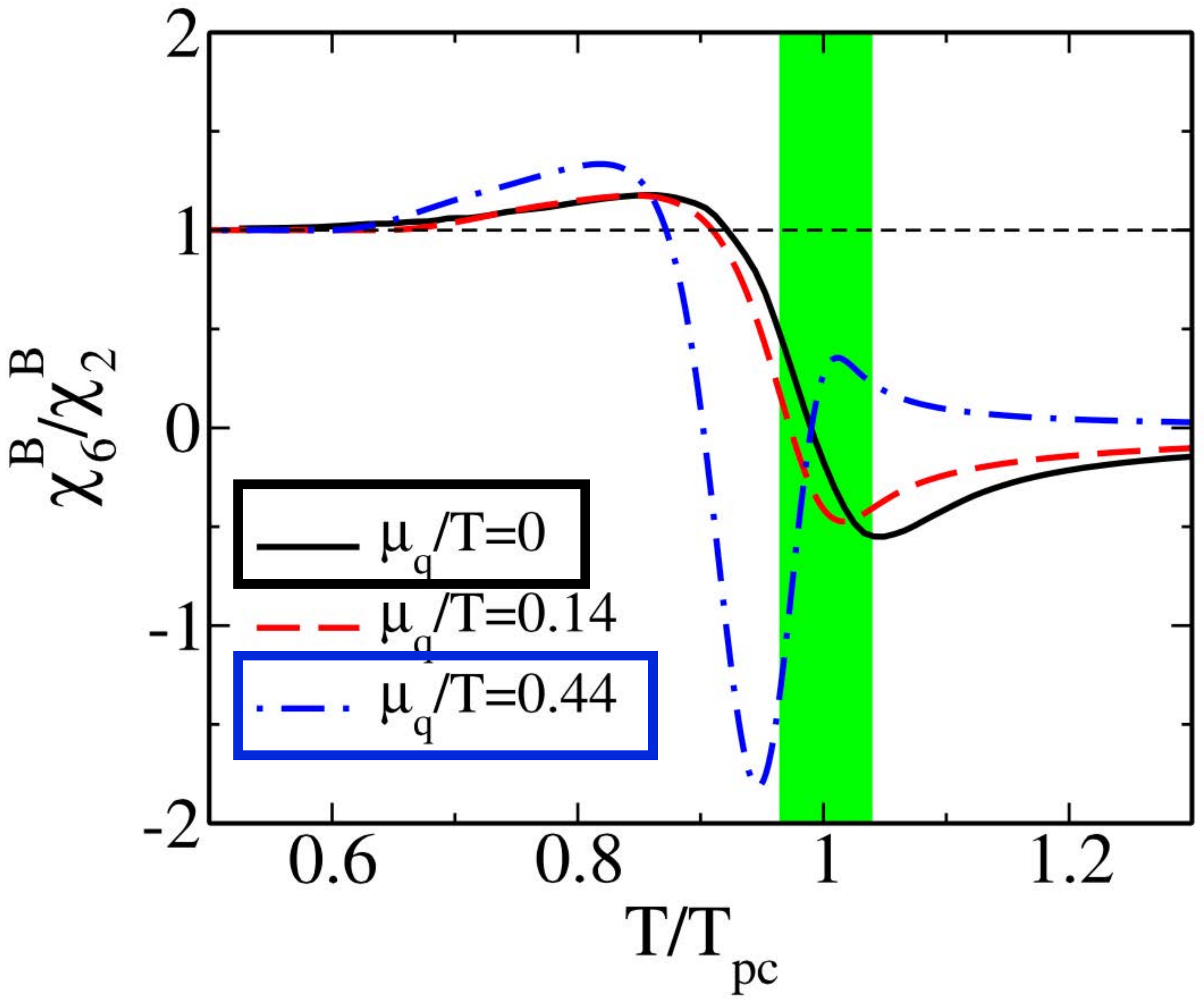
C_6/C_2 for crossover search

- ✓ There isn't yet any direct experimental evidence for the smooth crossover at $\mu_B \sim 0$.
- ✓ **$C_6/C_2 < 0$** is predicted as a signature of crossover transition.
- ✓ High-statistics data sets at **$\sqrt{s_{NN}}$ = 27, 54.4, and 200 GeV** are analyzed to look for the **experimental signature of crossover transition**.

A. Bazavov et al, PhysRevD.95.054504 : LQCD



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

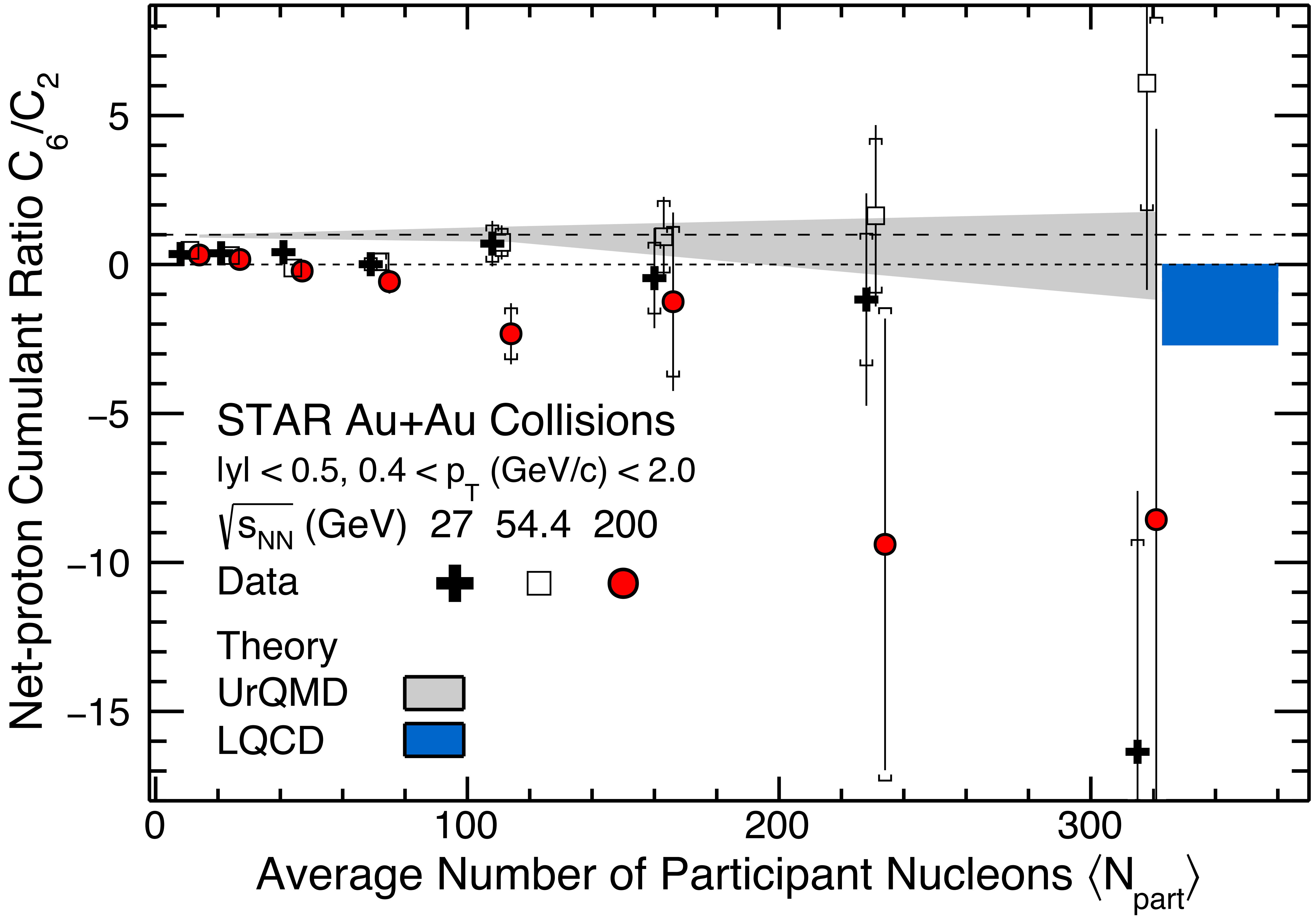


C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

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

Predicted scenario for this measurement

Centrality dependence of C_6/C_2



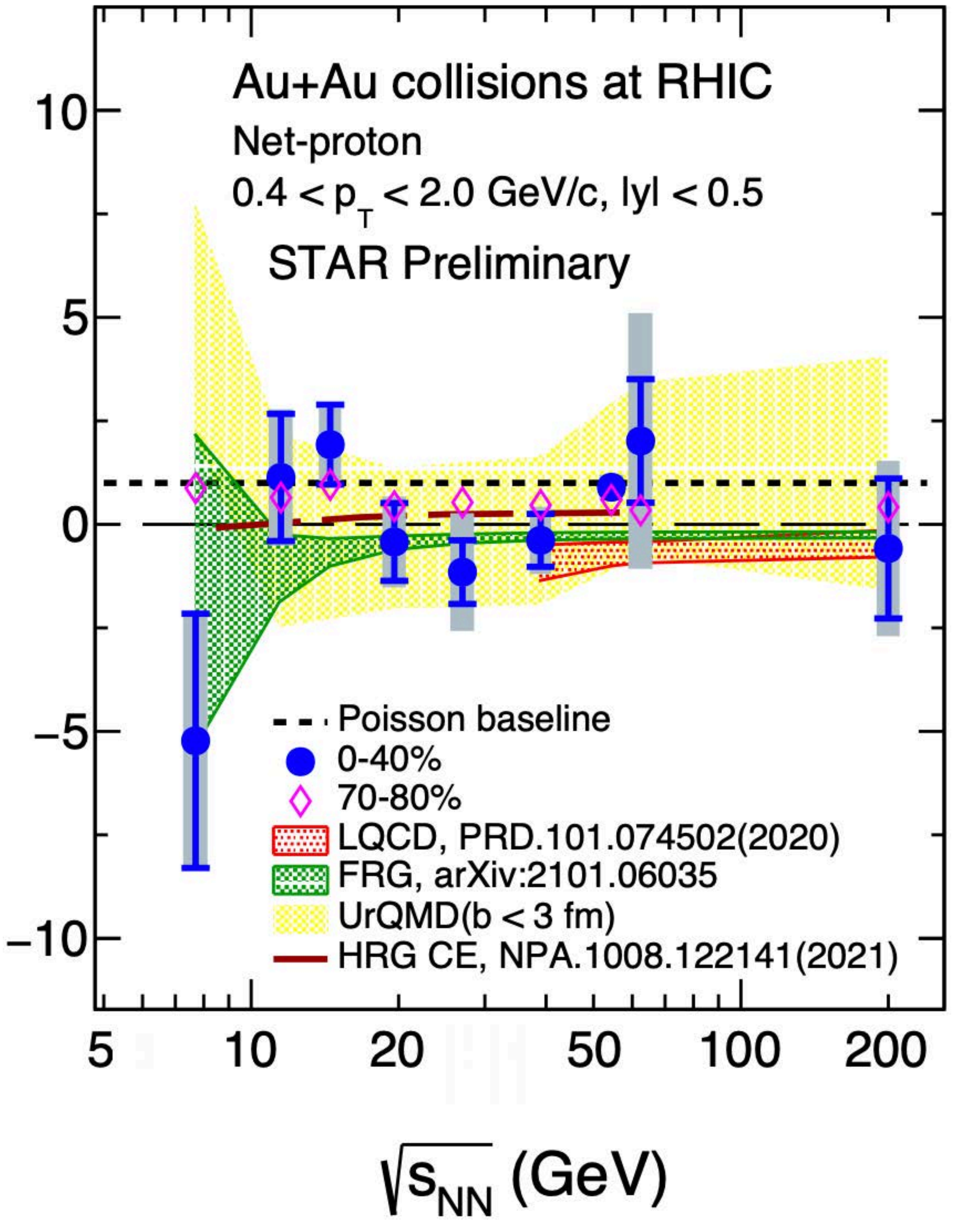
✓ C_6/C_2 values are progressively negative from peripheral to central collisions at 200 GeV, which is consistent with LQCD calculations.

✓ Could suggest a smooth crossover transition at top RHIC energy.

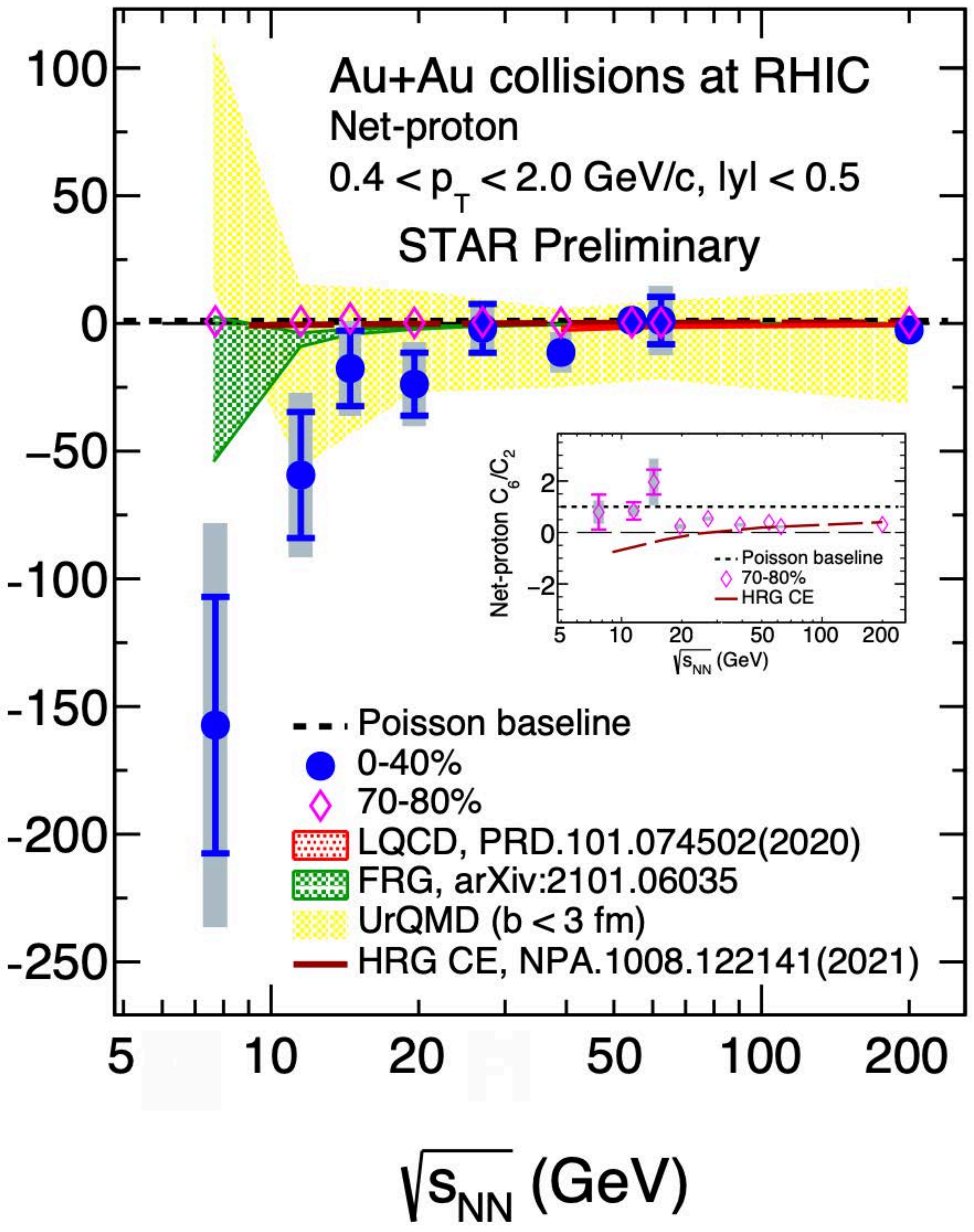
STAR, arXiv:2105.14698

Energy dependence of C_5/C_1 and C_6/C_2

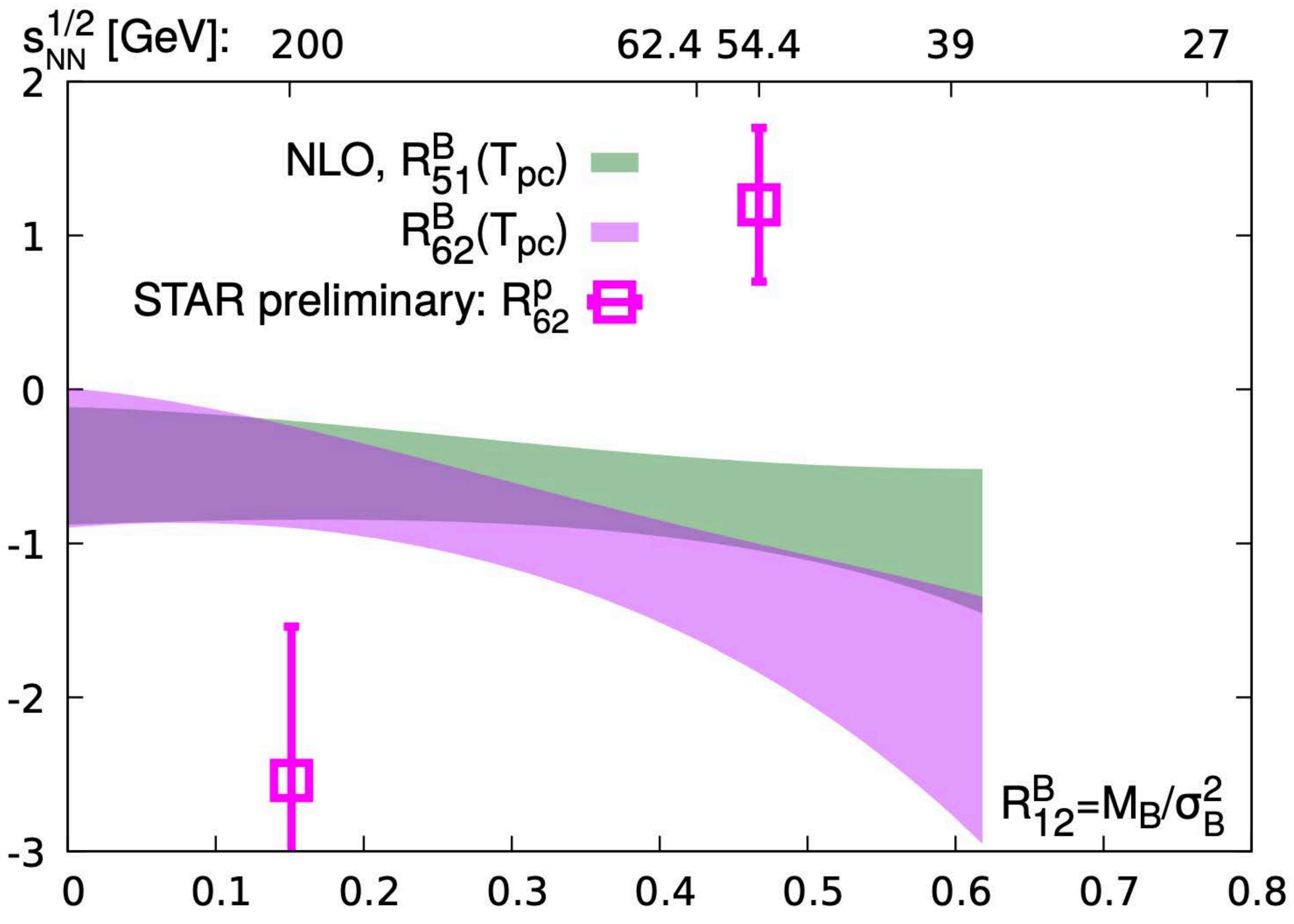
C_5/C_1



C_6/C_2



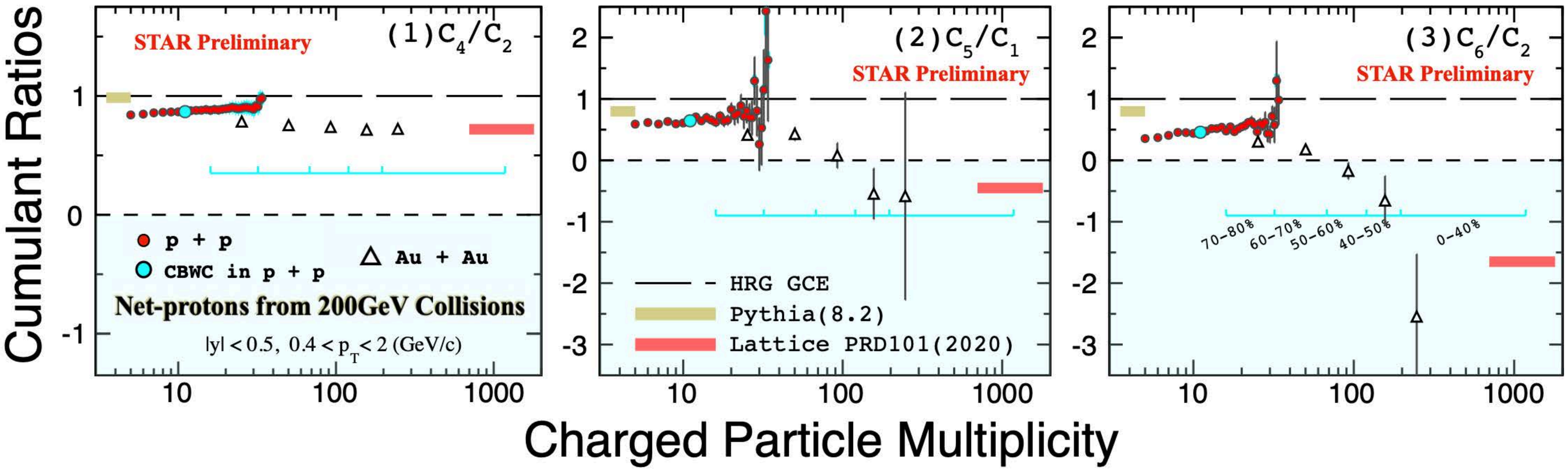
- ✓ Weak collision energy dependence observed for 0-40% centrality.
- ✓ Deviations from zero at a level of < 2σ observed for 0-40% centrality.



Bazavov et al., Phys.Rev.D101,074502 (2020)

Multiplicity dependence

- ✓ C_5/C_1 and C_6/C_2 are positive for p+p collisions, while negative for central Au+Au collisions.
- ✓ Lattice calculations imply chiral phase transition in the thermalized QCD matter, which is not the case in 200 GeV p+p collisions.



- Only statistical errors are shown for Au+Au results
- Efficiency is not corrected for x-axis

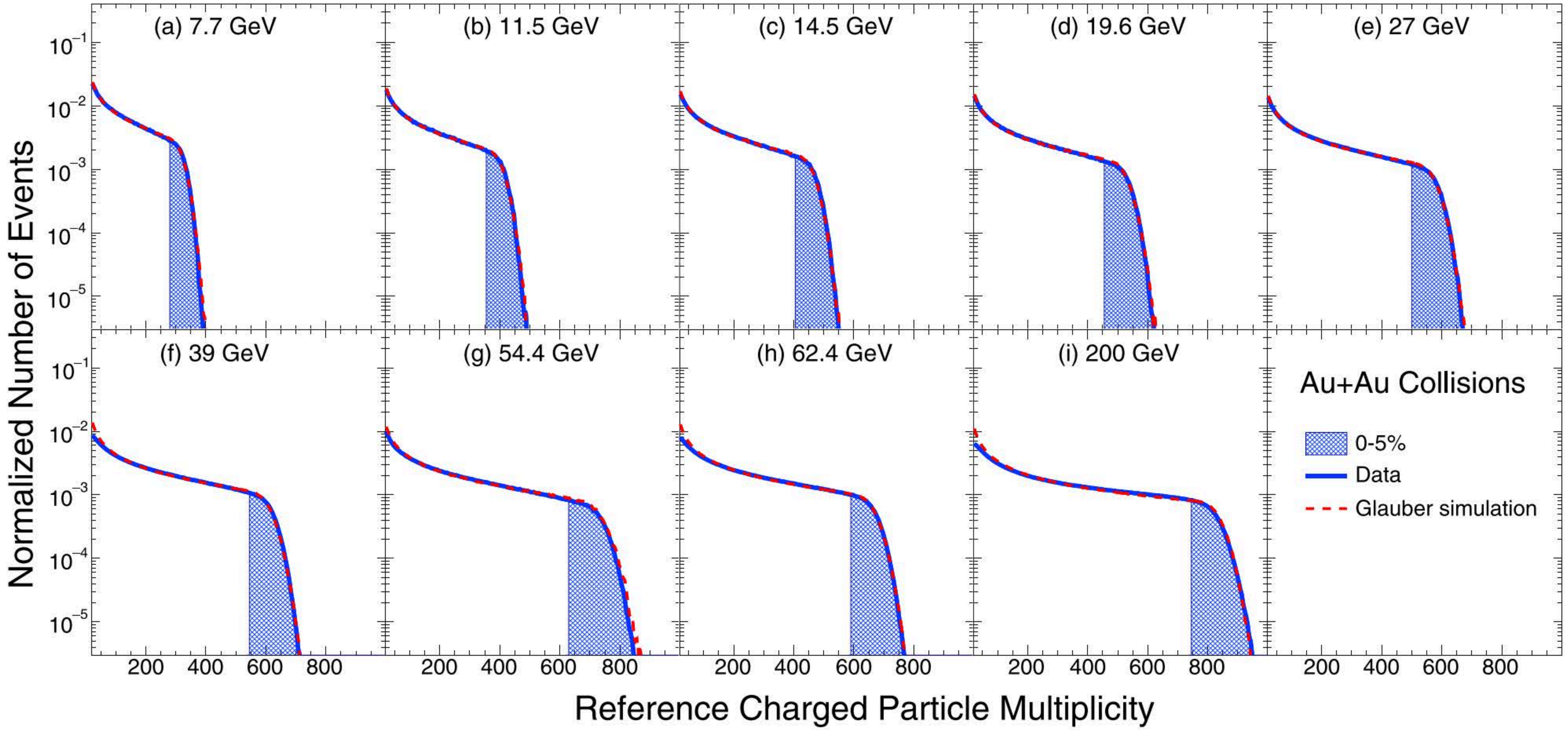
STAR Collaboration, PRC.104.024902(2021)

LQCD : Phys. Rev. D 101, 074502 (2020)

STAR Collaboration, Nuclear Physics A, 1005, 121882 (2021)

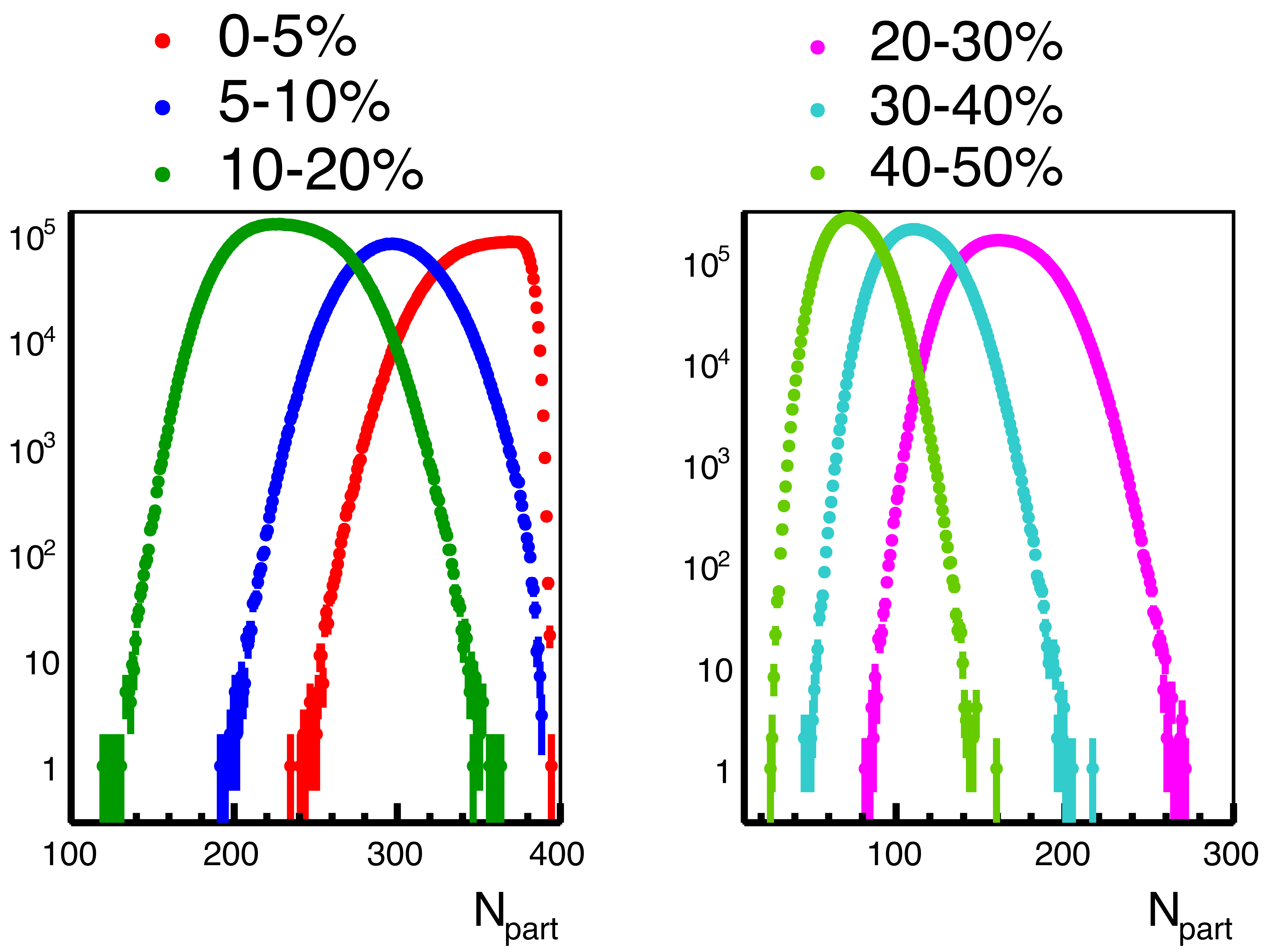
Centrality

✓ インパクトパラメータを測定できないので、粒子数分布（をモデルでフィットした分布）を等分割してCentralityを定義。



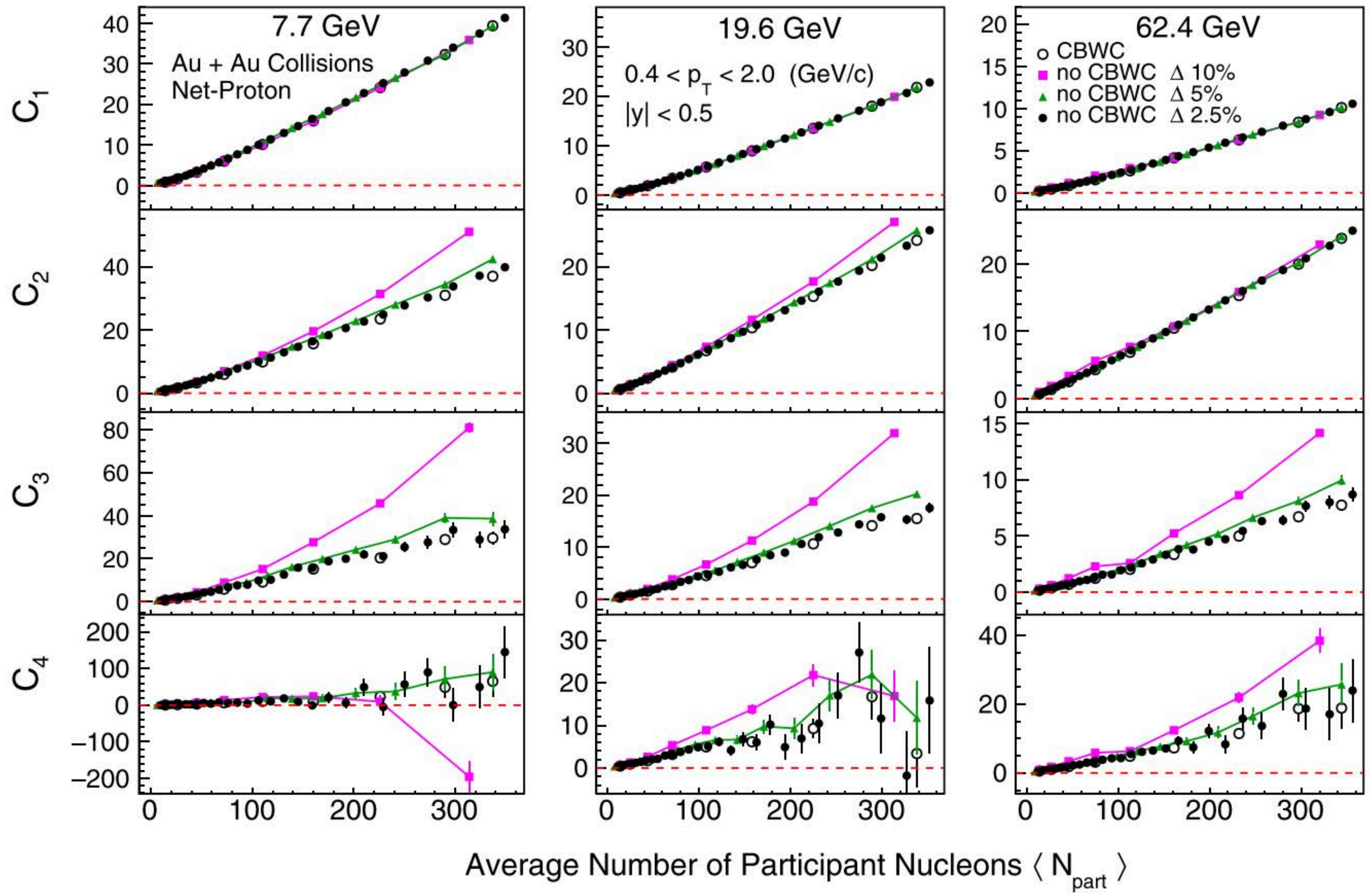
STAR Collaboration, PRC.104.024902(2021)

Npart ゆらぎ

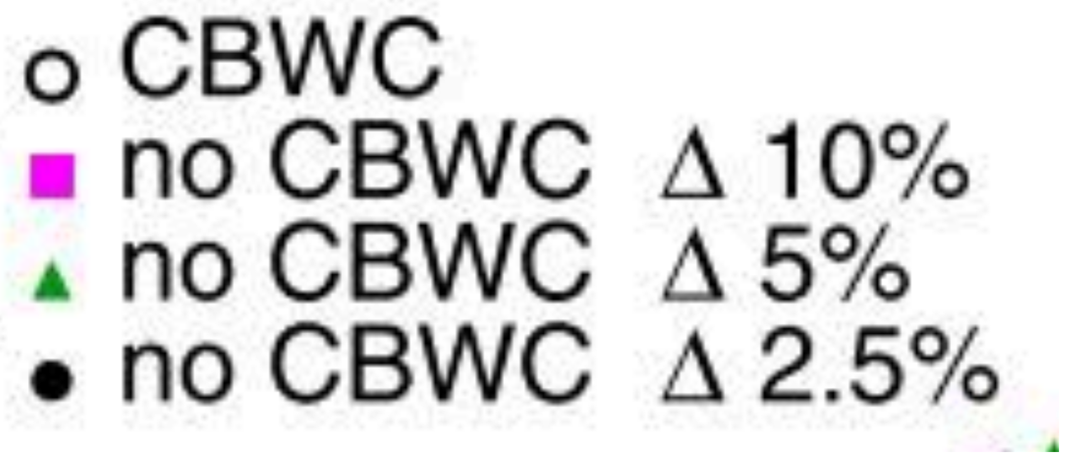


✓ 生成粒子数分布を分割して
Centarlityを定義しているため、
Npart (or b)分布は大きく揺らぐ
→体積ゆらぎ

補正手法１：*Centrality bin width correction*



STAR Collaboration, PRC.104.024902(2021)



- ✓ Centrality幅を狭くすると、ある値に収束→体積ゆらぎの抑制
- ✓ 平均値の解析には影響なし。
- ✓ Reference multiplicity １ビンごとにキュムラントを計算し、Centrality内で平均を取る。

補正手法２：*Volume fluctuation correction*

- ✓ Npartごとの独立な粒子生成を仮定すると、測定キュムラントは（真のゆらぎ）と（Npart高次ゆらぎ）の組み合わせで表される。
- ✓ Data-drivenな手法と統計誤差の範囲内で一致。

Measured cumulant | True cumulant

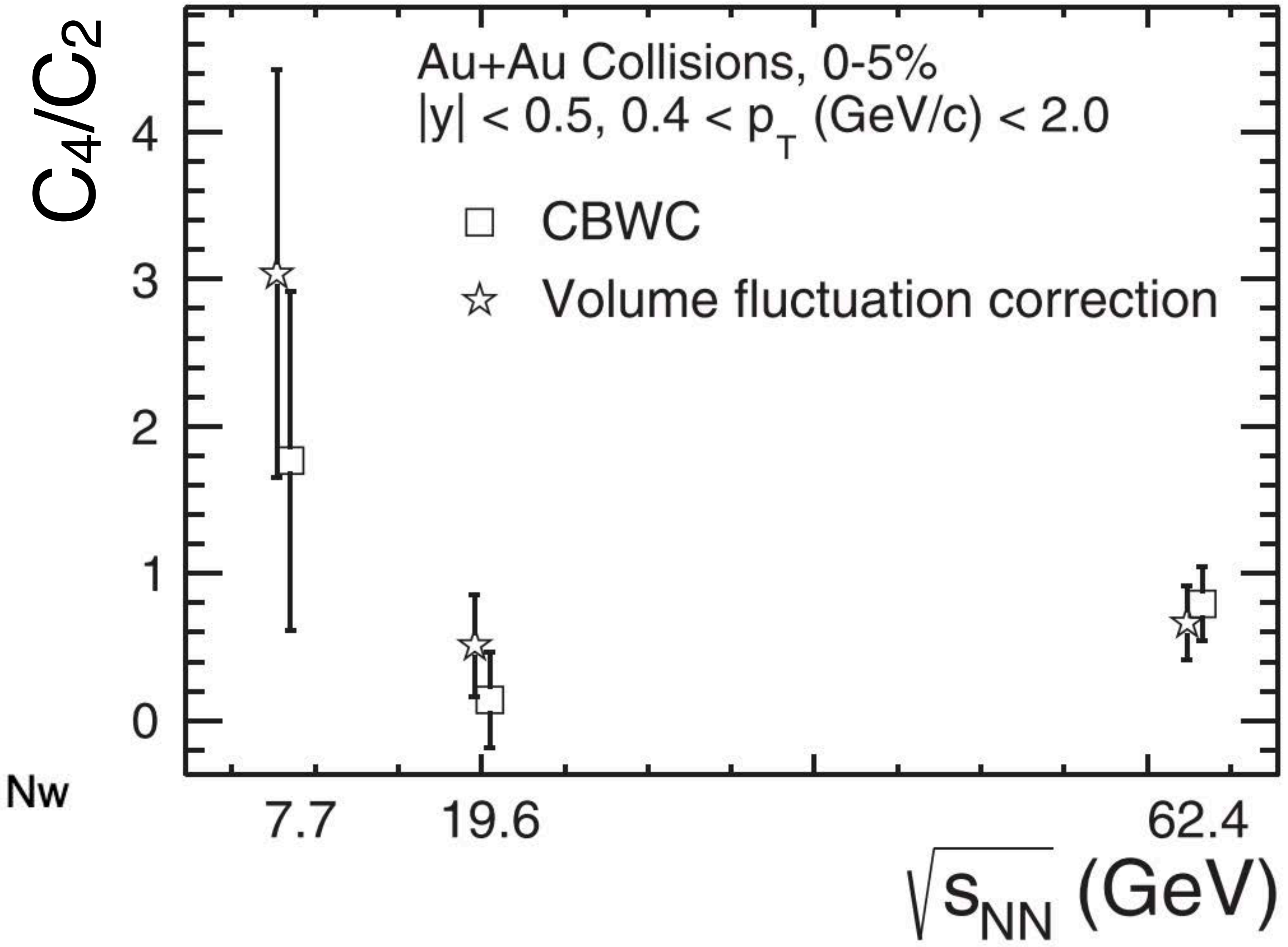
Additional terms appear from the event by event participant fluctuation

$$\kappa_1(\Delta N) = \langle N_W \rangle \kappa_1(\Delta n)$$
$$\kappa_2(\Delta N) = \langle N_W \rangle \kappa_2(\Delta n) + \langle \Delta n \rangle^2 \kappa_2(N_W),$$
$$\kappa_3(\Delta N) = \langle N_W \rangle \kappa_3(\Delta n) + 3\langle \Delta n \rangle \kappa_2(\Delta n)\kappa_2(N_W) + \langle \Delta n \rangle^3 \kappa_3(N_W),$$
$$\kappa_4(\Delta N) = \langle N_W \rangle \kappa_4(\Delta n) + 4\langle \Delta n \rangle \kappa_3(\Delta n)\kappa_2(N_W) + 3\kappa_2^2(\Delta n)\kappa_2(N_W) + 6\langle \Delta n \rangle^2 \kappa_2(\Delta n)\kappa_3(N_W) + \langle \Delta n \rangle^4 \kappa_4(N_W).$$

P. Braun-Munzinger, A. Rustamov, J. Stachel: *NPA.2017.01.011*

Δn : net-proton per Nw
ΔN : net-proton

STAR Collaboration, PRC.104.024902(2021)



手法比較

Centrality bin width correction

- モデルに依存しない。
- Multiplicity 1ビンの分解能で補正が頭打ちになる。
- 補正が衝突エネルギーに依存する。

Volume fluctuation correction

- 独立な粒子生成モデル。
- 初期ゆらぎ＋粒子生成ゆらぎの２段階で仮定が必要。
- これらの仮定のもと、体積ゆらぎを完全に除去できる。

問題点

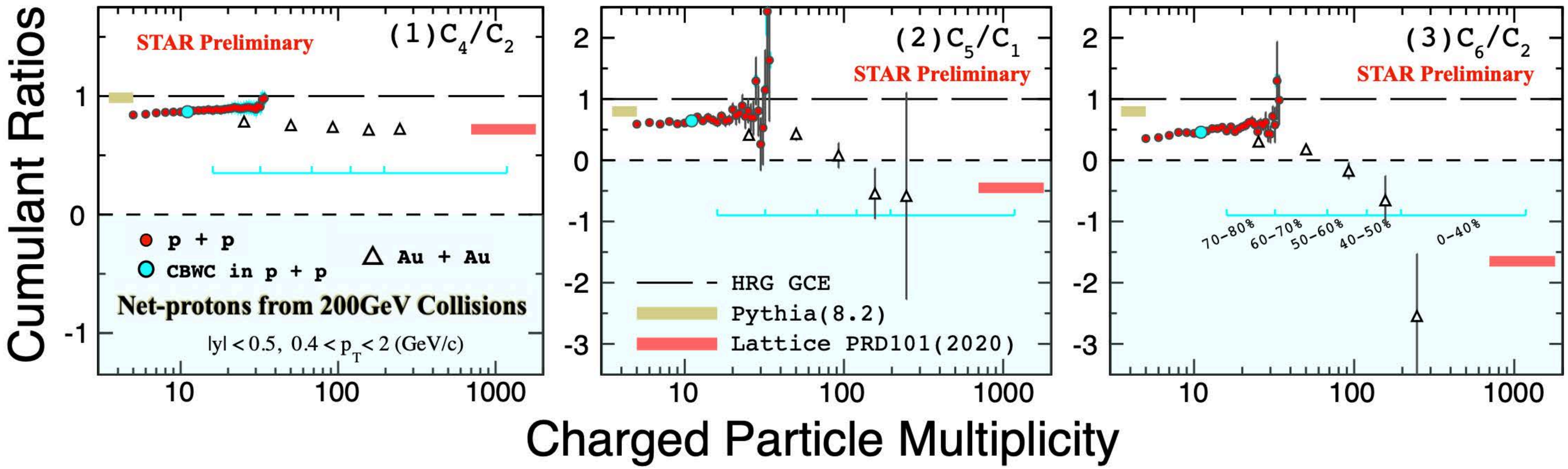
- たとえインパクトパラメータを直接測定できたとしても、解決する問題では無い。→ そもそも「初期体積」とは？

- 現状では、（体積ゆらぎ）＝（初期ゆらぎ）＋（粒子生成ゆらぎ）であり、これらを切り分けられないのが問題をさらに複雑にしている。

- p+pとの比較で何かできないか？

p+p vs A+A ?

✓ p+pとAu+Auの差が体積ゆらぎだと仮定して、何か調べられないか？



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STAR Collaboration,
PRC.104.024902(2021)

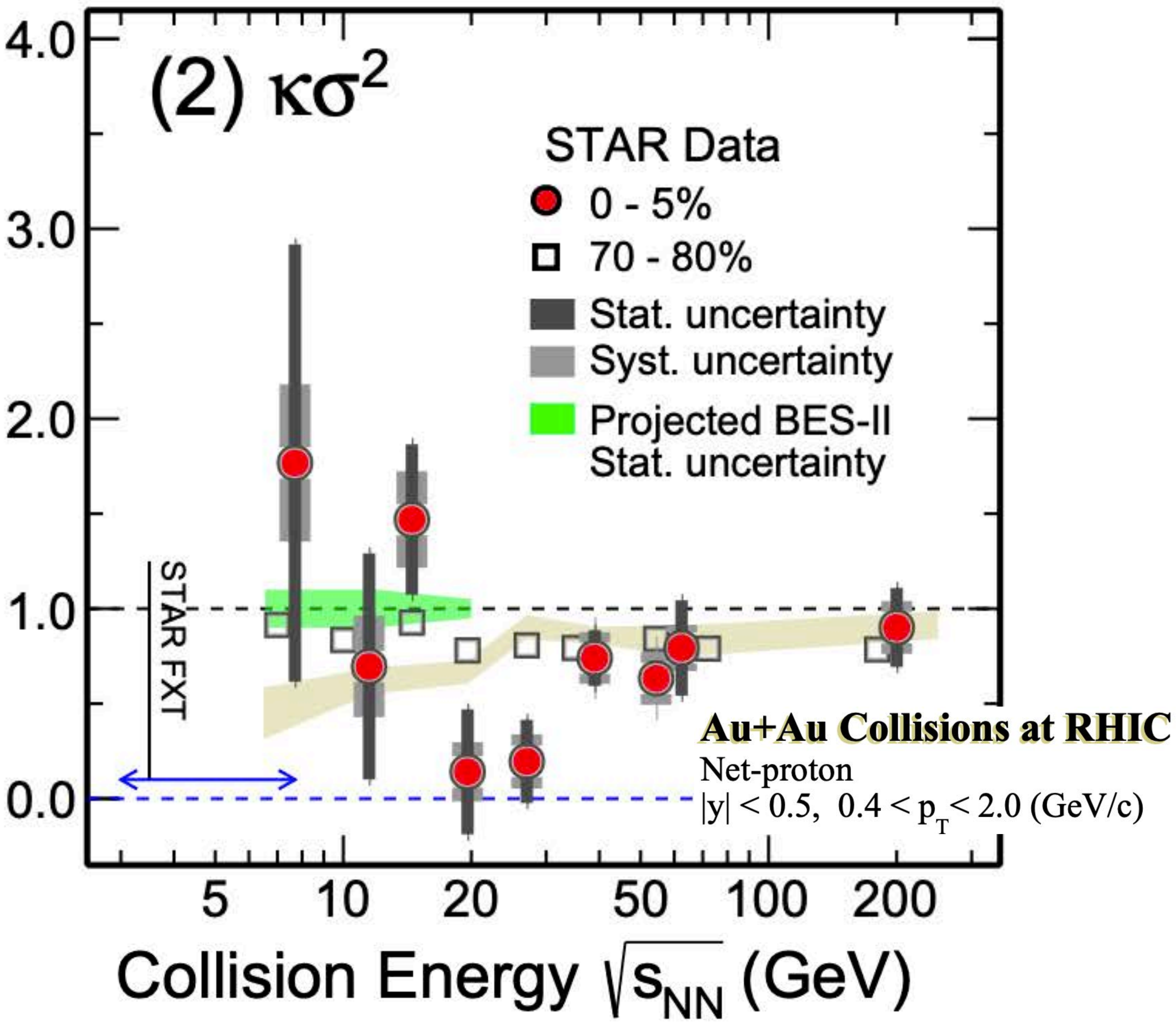
LQCD : Phys. Rev. D 101, 074502 (2020)

STAR Collaboration,
Nuclear Physics A, 1005,
121882 (2021)

まとめ

- RHIC-STARにおける高次ゆらぎ測定で臨界点やクロスオーバーの兆候
- 今後（おそらく）3-4年でBES-II / FXTの結論が出る。
- 非単調な振る舞いが再確認された場合、その解釈は？
- 実験と比較ができる（体積ゆらぎを含む）動的モデルが必要。

STAR Collaboration, PRL.126.092301(2021)



Thank you for your attention