Experimental Search for QCD Phase Diagram

STAR

Toshihiro Nonaka

TCHoU member meeting 2020

Based on : arXiv:2001.02852 (STAR Collaboration), submitted to Nature Physics

Net-proton number fluctuations and the Quantum Chromodynamics critical point

Observations from collisions of heavy-ion at relativistic energies have established the formation of a new phase of matter, Quark Gluon Plasma (QGP), a deconfined state of quarks and gluons [1] in a specific region of the temperature versus baryonic chemical potential phase diagram of strong interactions. A program to study the features of the phase diagram, such as a possible critical point, by varying the collision energy ($\sqrt{s_{\rm NN}}$), is performed at the Relativistic Heavy-Ion Collider (RHIC) facility. Non-monotonic variation with $\sqrt{s_{\rm NN}}$ of moments of the net-baryon number distribution, related to the correlation length and the susceptibilities of the system, is suggested as a signature for a critical point [2,3]. We report the first evidence of a non-monotonic variation in kurtosis $\times$ variance of the net-proton number (proxy for net-baryon number) distribution as a function of $\sqrt{s_{\rm NN}}$ with 3.0σ significance, for head-on (central) gold-on-gold (Au+Au) collisions measured using the STAR detector [4] at RHIC. Non-central Au+Au collisions and models of heavy-ion collisions without a critical point show a monotonic variation as a function of $\sqrt{s_{\rm NN}}$.

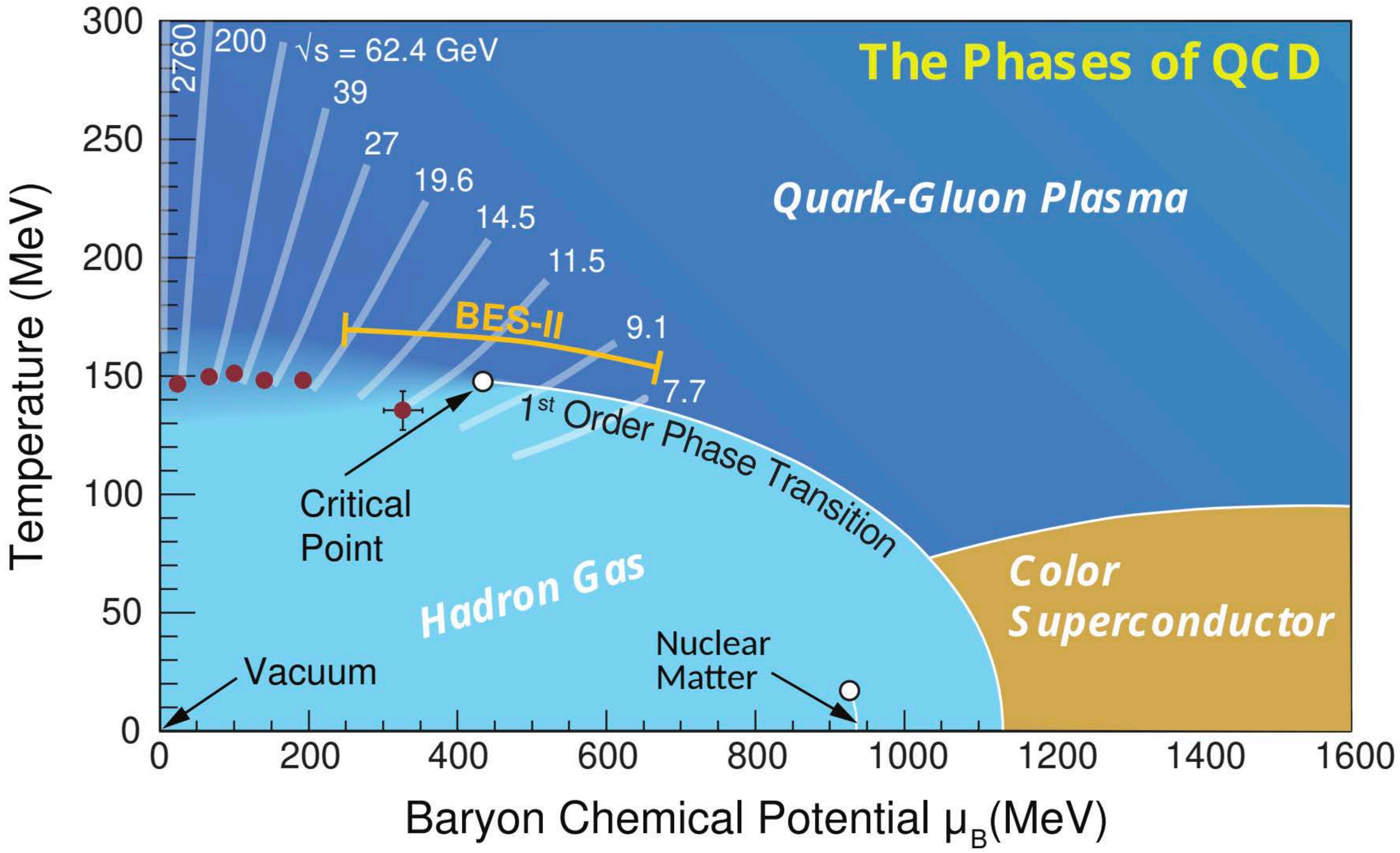
One of the fundamental goals in physics is to understand the properties of matter when sub-

Outline

- Introduction
- C_4 measurement for critical point search
- C_6 measurement for crossover search
- Future plan

QCD phase diagram

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

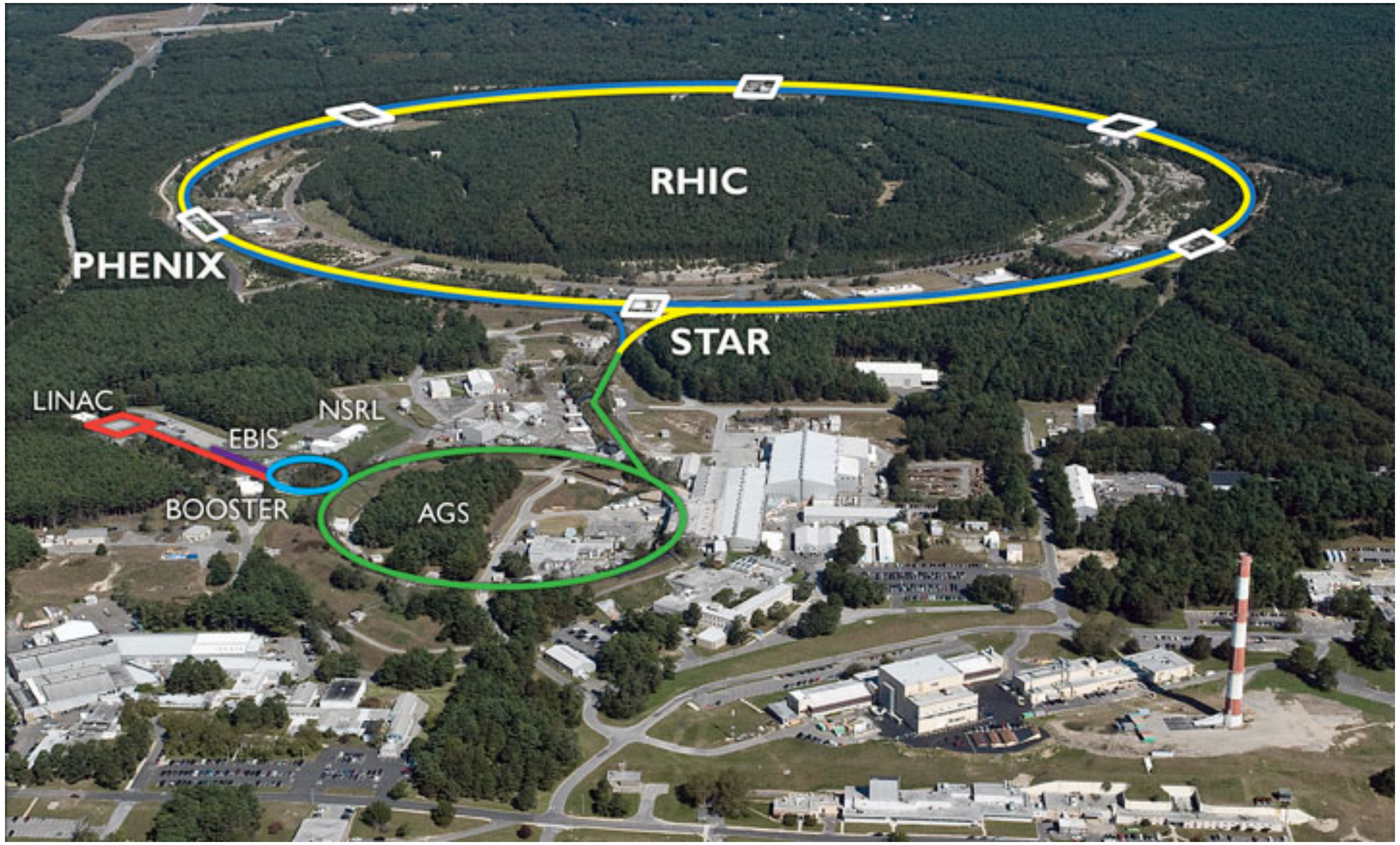


A. Bzdak et al, 1906.00936

- **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

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



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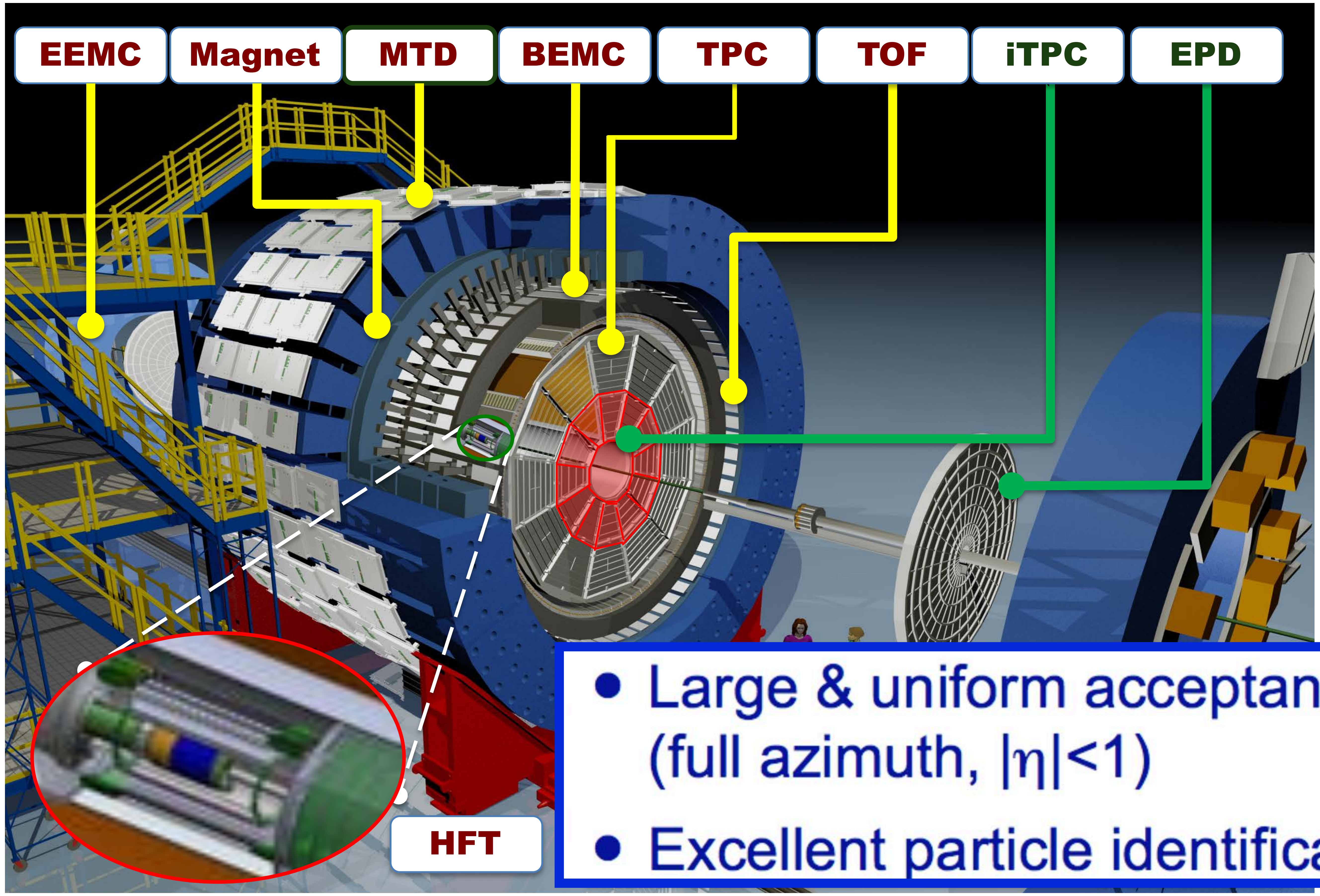


- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

- **Crossover at $\mu_B = 0$ 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)	$T_{\rm ch}$ (MeV)	$\mu_{\rm B}$ (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

2010-2014

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

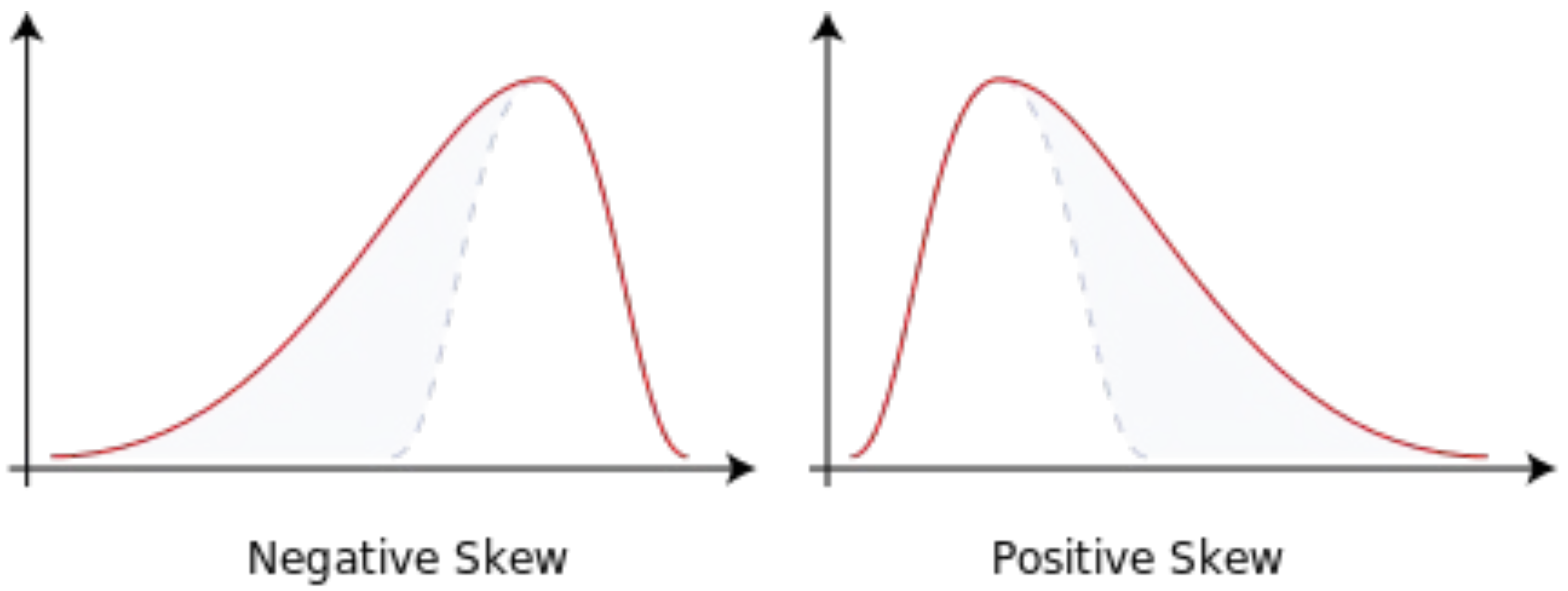
Higher-order fluctuations

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

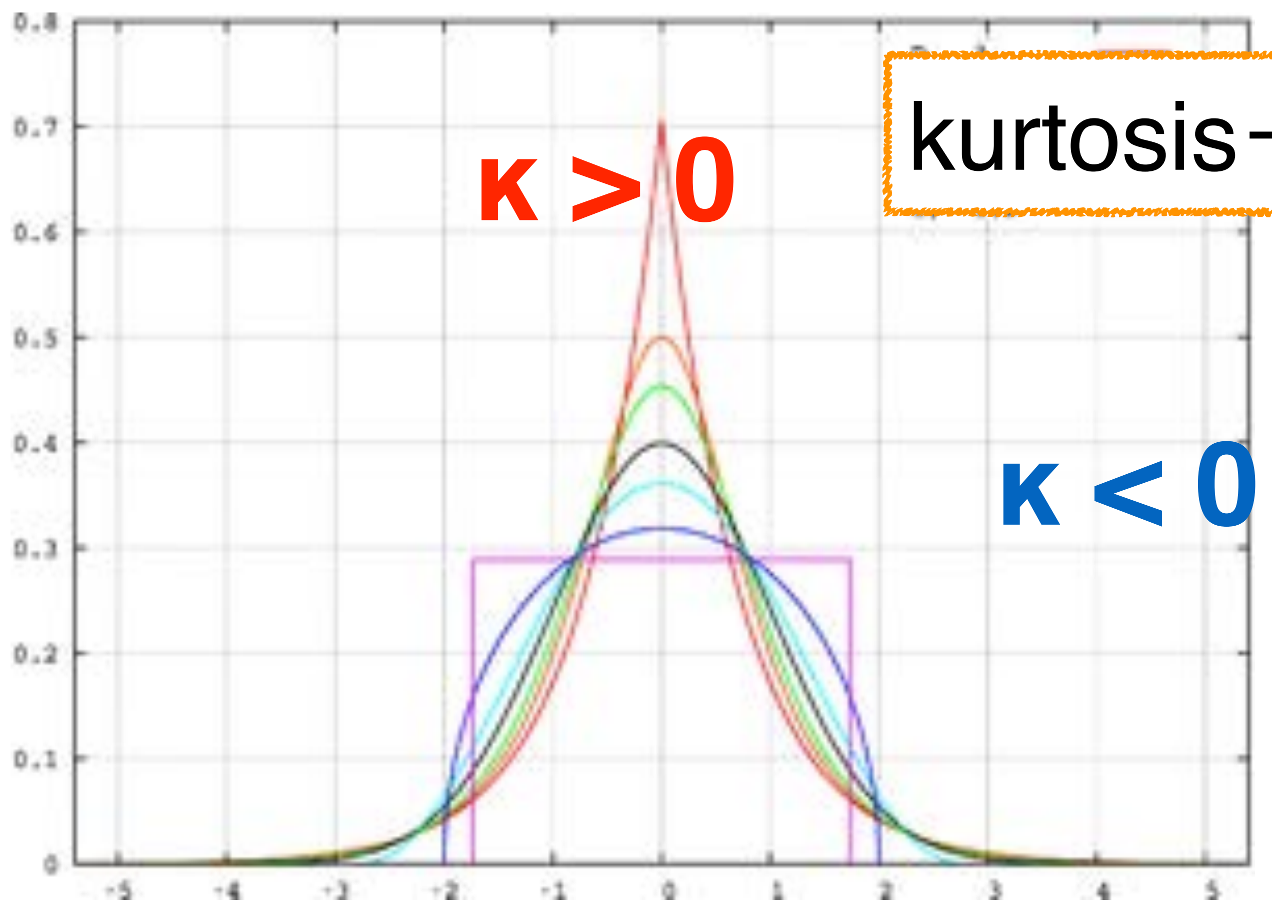
✓ **Moments: mean (*M*), standard deviation (*σ*), skewness (*S*) and kurtosis (κ).**

✓ ***S and κ are 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 105, 022302 (2010) : STAR Collaboration

✦ Net baryon, net charge and net strangeness

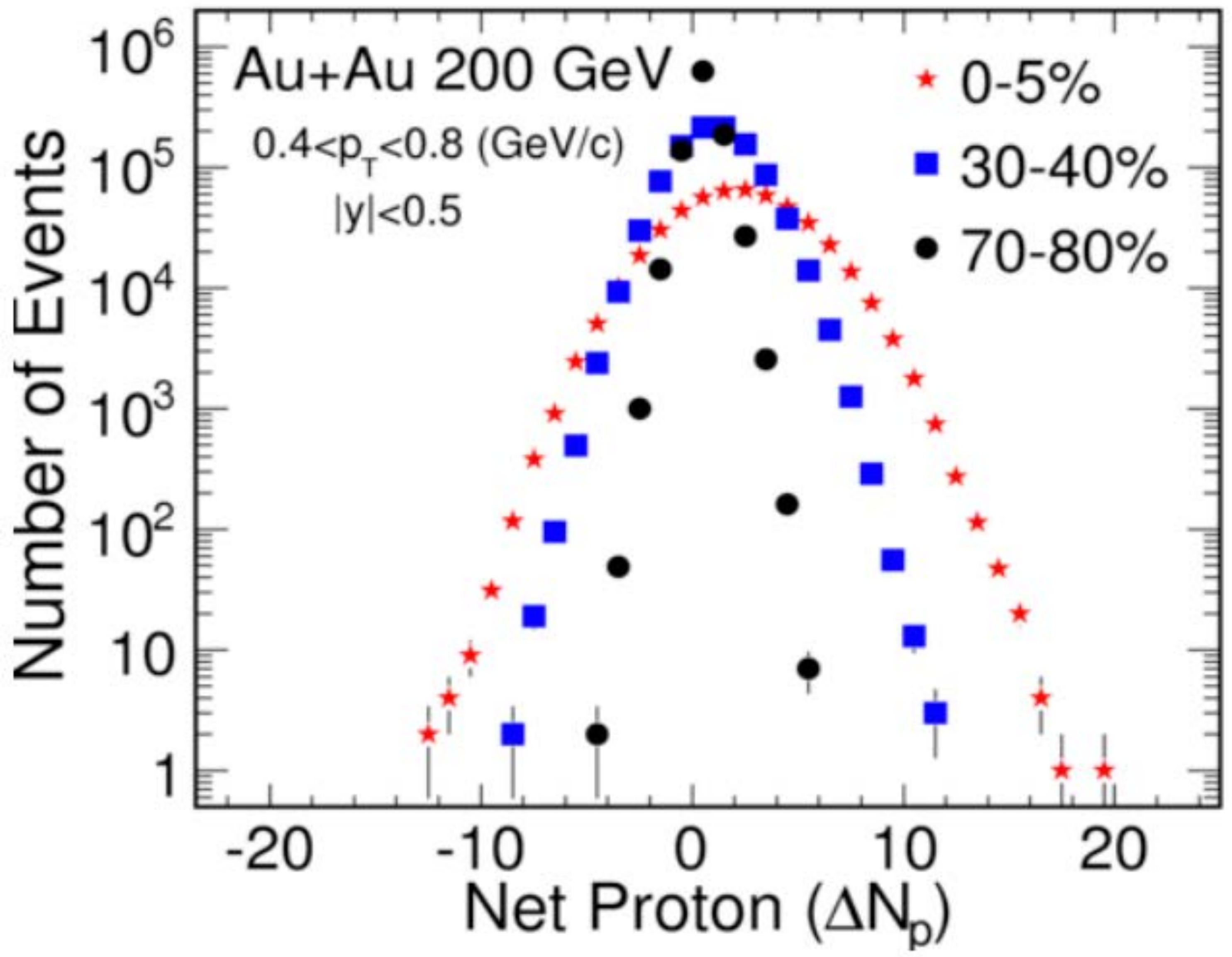
"Net" : positive - negative

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

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

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

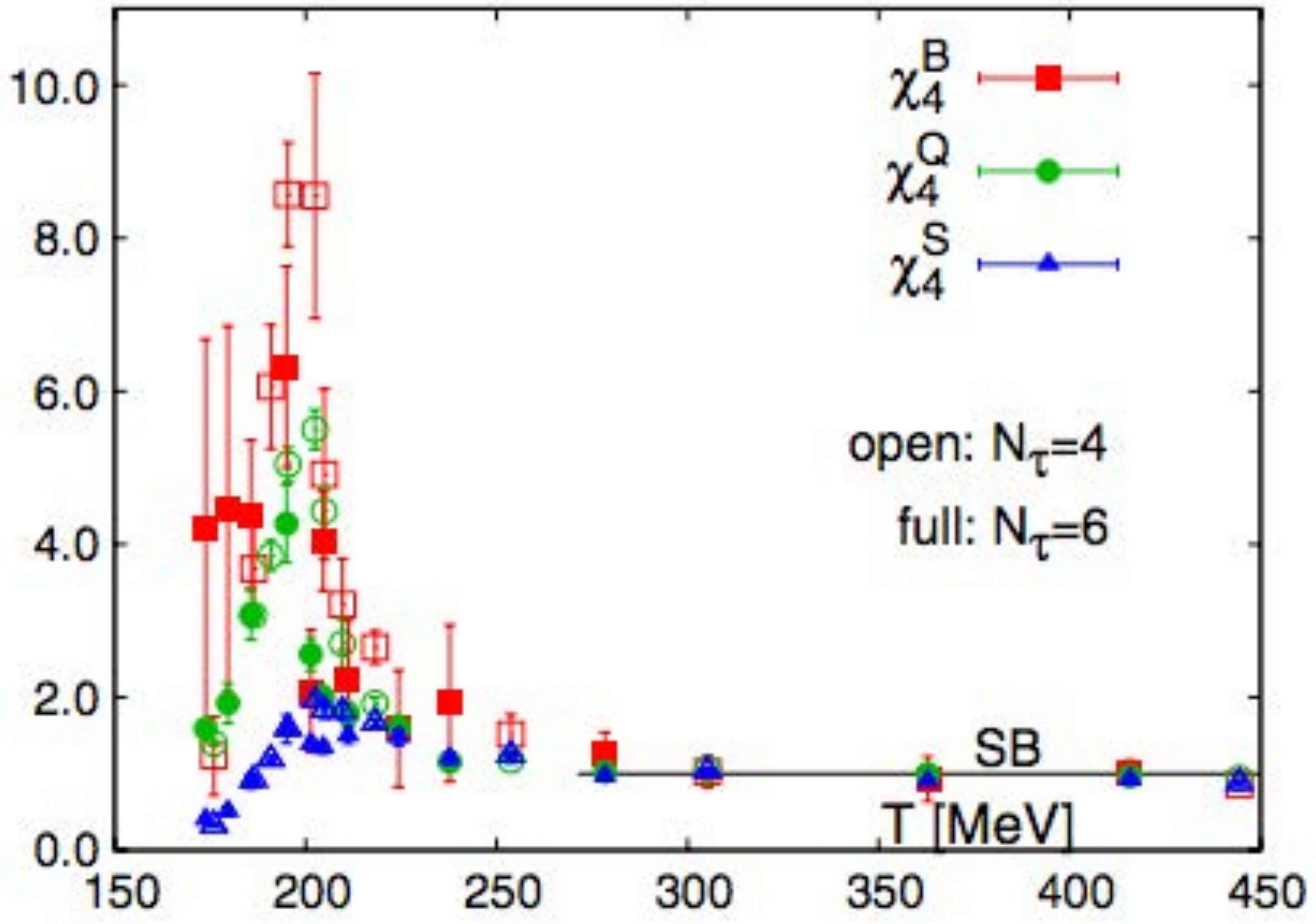
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
MAsakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

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

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

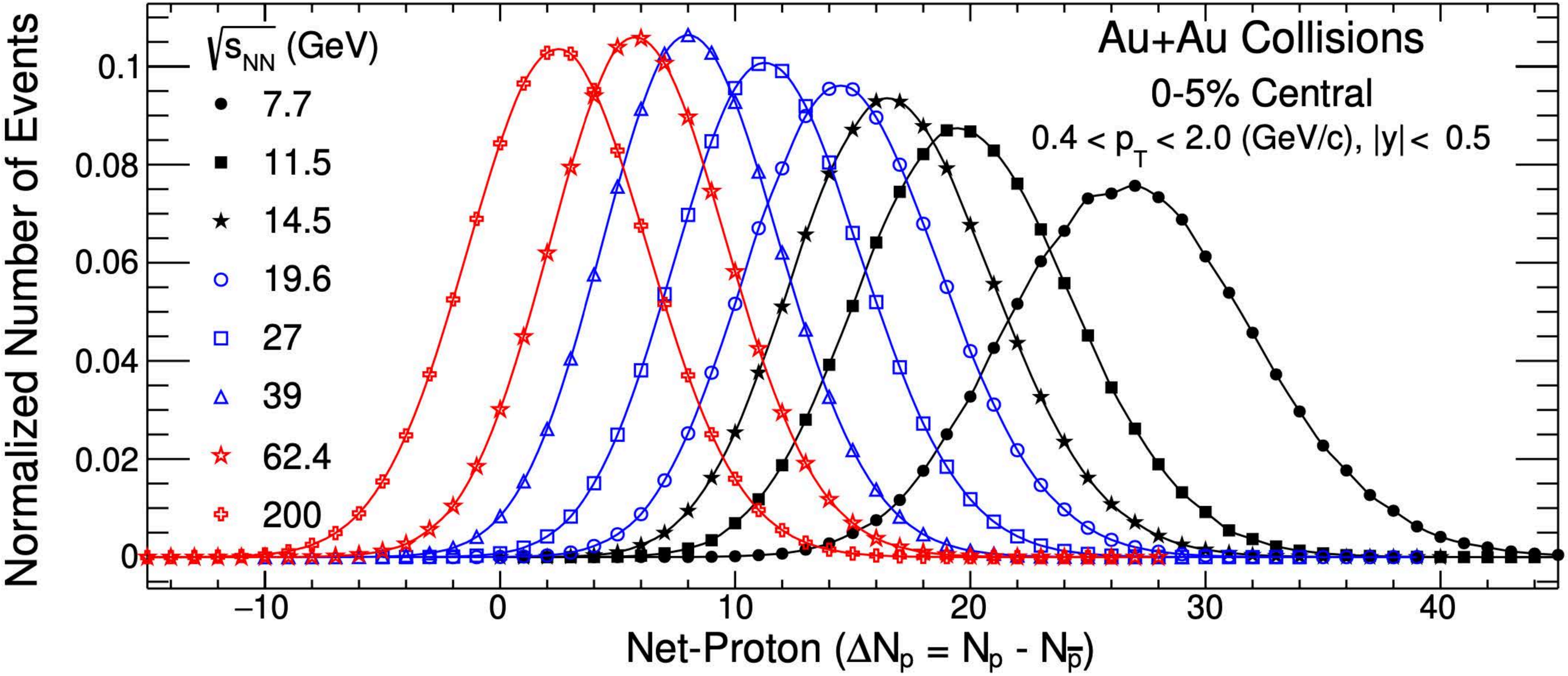
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$



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

Net-proton multiplicity distributions

✓ ***RAW distribution!***



STAR Collaboration, arXiv:2001.02852, submitted to NP

Efficiency correction

- ✦ **Efficiency follows binomial distribution.**
- ✦ **Factorial moments can be easily corrected.**
  - M. Kitazawa and M. Asakawa : PRC.86.069902 (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)

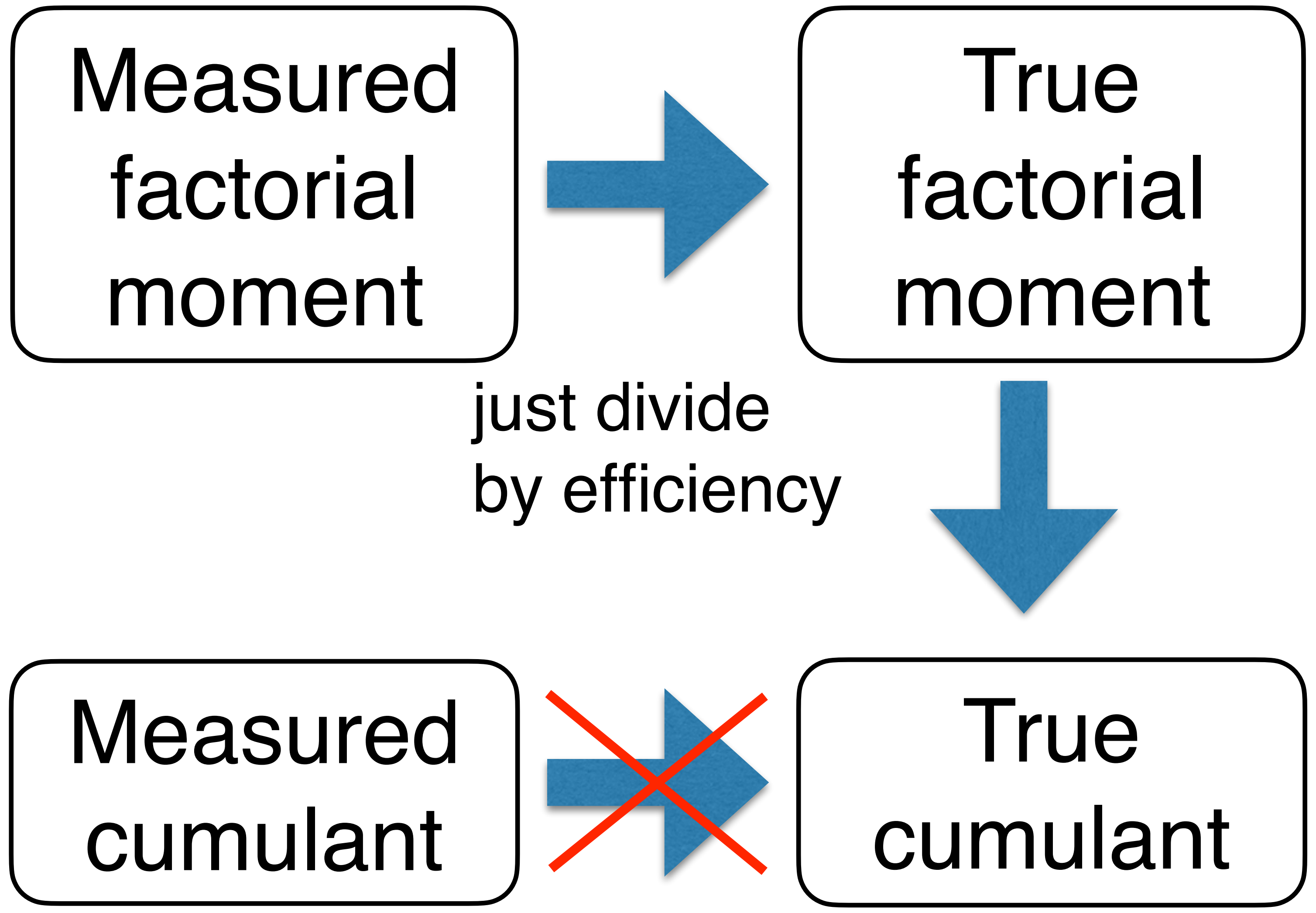
$$B(n,N;\varepsilon) = \frac{N!}{n!(N-n)!}\varepsilon^n(1-\varepsilon)^{N-n} \qquad f_{ik} = \varepsilon_p^i \varepsilon_{pbar}^k F_{ik}$$

$$F_{ik} \equiv \left\langle \frac{N_1!}{(N_1-i)!}\frac{N_2!}{(N_2-k)!} \right\rangle$$

$$f_{ik} \equiv \left\langle \frac{n_1!}{(n_1-i)!}\frac{n_2!}{(n_2-k)!} \right\rangle$$

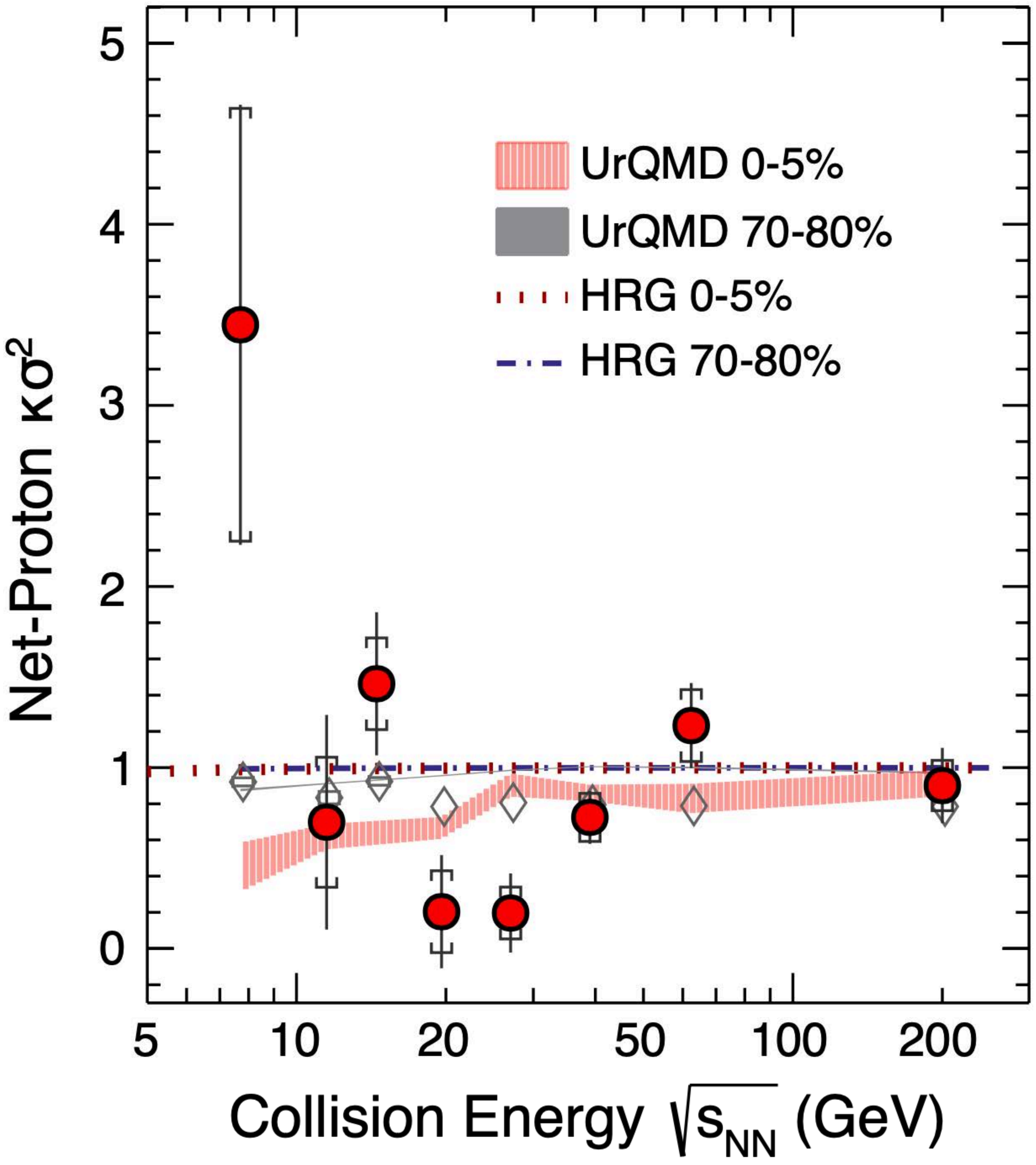
- ✦ **Corrected cumulants are expressed in terms of measured factorial moments and efficiency.**

$$\begin{aligned}
\kappa_4(\Delta N) = {} & (((f_{10}/\varepsilon_1) + 7(f_{20}/\varepsilon_1^2) + 6(f_{30}/\varepsilon_1^3) + (f_{40}/\varepsilon_1^4) - 4(f_{10}/\varepsilon_1)^2 - \\
& 12(f_{20}/\varepsilon_1^2)(f_{10}/\varepsilon_1) - 4(f_{30}/\varepsilon_1^3)(f_{10}/\varepsilon_1) + 6(f_{10}/\varepsilon_1)^3 + 6(f_{20}/\varepsilon_1^2)(f_{10}/\varepsilon_1)^2 - 3(f_{10}/\varepsilon_1)^4) - \\
& 4((f_{11}/\varepsilon_1/\varepsilon_2) - (f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2) + 3(f_{21}/\varepsilon_1^2/\varepsilon_2) - 3(f_{20}/\varepsilon_1^2)(f_{01}/\varepsilon_2) + (f_{31}/\varepsilon_1^3/\varepsilon_2) - \\
& (f_{30}/\varepsilon_1^3)(f_{01}/\varepsilon_2) - 3(f_{11}/\varepsilon_1/\varepsilon_2)(f_{10}/\varepsilon_1) + 3(f_{10}/\varepsilon_1)^2(f_{01}/\varepsilon_2) - 3(f_{21}/\varepsilon_1^2/\varepsilon_2)(f_{10}/\varepsilon_1) + \\
& 3(f_{20}/\varepsilon_1^2)(f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2) + 3(f_{11}/\varepsilon_1/\varepsilon_2)(f_{10}/\varepsilon_1)^2 - 3(f_{10}/\varepsilon_1)^3(f_{01}/\varepsilon_2)) + 6((f_{11}/\varepsilon_1/\varepsilon_2) + \\
& (f_{12}/\varepsilon_1/\varepsilon_2^2) - 2(f_{11}/\varepsilon_1/\varepsilon_2)(f_{01}/\varepsilon_2) + (f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2)^2 + (f_{21}/\varepsilon_1^2/\varepsilon_2) + (f_{22}/\varepsilon_1^2/\varepsilon_2^2) - \\
& 2(f_{21}/\varepsilon_1^2/\varepsilon_2)(f_{01}/\varepsilon_2) + (f_{20}/\varepsilon_1^2)(f_{01}/\varepsilon_2)^2 - 2(f_{11}/\varepsilon_1/\varepsilon_2)(f_{10}/\varepsilon_1) - 2(f_{12}/\varepsilon_1/\varepsilon_2^2)(f_{10}/\varepsilon_1) + \\
& 4(f_{11}/\varepsilon_1/\varepsilon_2)(f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2) - 3(f_{10}/\varepsilon_1)^2(f_{01}/\varepsilon_2)^2 + (f_{10}/\varepsilon_1)^2(f_{01}/\varepsilon_2) + (f_{02}/\varepsilon_2^2)(f_{10}/\varepsilon_1)^2) - \\
& 4((f_{11}/\varepsilon_1/\varepsilon_2) + 3(f_{12}/\varepsilon_1/\varepsilon_2^2) + (f_{13}/\varepsilon_1/\varepsilon_2^3) - 3(f_{11}/\varepsilon_1/\varepsilon_2)(f_{01}/\varepsilon_2) - 3(f_{12}/\varepsilon_1/\varepsilon_2^2)(f_{01}/\varepsilon_2) + \\
& 3(f_{11}/\varepsilon_1/\varepsilon_2)(f_{01}/\varepsilon_2)^2 - 3(f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2)^3 - (f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2) - 3(f_{02}/\varepsilon_2^2)(f_{10}/\varepsilon_1) - \\
& (f_{03}/\varepsilon_2^3)(f_{10}/\varepsilon_1) + 3(f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2)^2 + 3(f_{02}/\varepsilon_2^2)(f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2)) + ((f_{01}/\varepsilon_2) + \\
& 7(f_{02}/\varepsilon_2^2) + 6(f_{03}/\varepsilon_2^3) + (f_{04}/\varepsilon_2^4) - 4(f_{01}/\varepsilon_2)^2 - 12(f_{02}/\varepsilon_2^2)(f_{01}/\varepsilon_2) - 4(f_{03}/\varepsilon_2^3)(f_{01}/\varepsilon_2) + \\
& 6(f_{01}/\varepsilon_2)^3 + 6(f_{02}/\varepsilon_2^2)(f_{01}/\varepsilon_2)^2 - 3(f_{01}/\varepsilon_2)^4)) - 3(((f_{10}/\varepsilon_1) + (f_{20}/\varepsilon_1^2) - (f_{10}/\varepsilon_1)^2) - \\
& 2((f_{11}/\varepsilon_1/\varepsilon_2) - (f_{10}/\varepsilon_1)(f_{01}/\varepsilon_2)) + ((f_{01}/\varepsilon_2) + (f_{02}/\varepsilon_2^2) - (f_{01}/\varepsilon_2)^2))^2
\end{aligned}$$

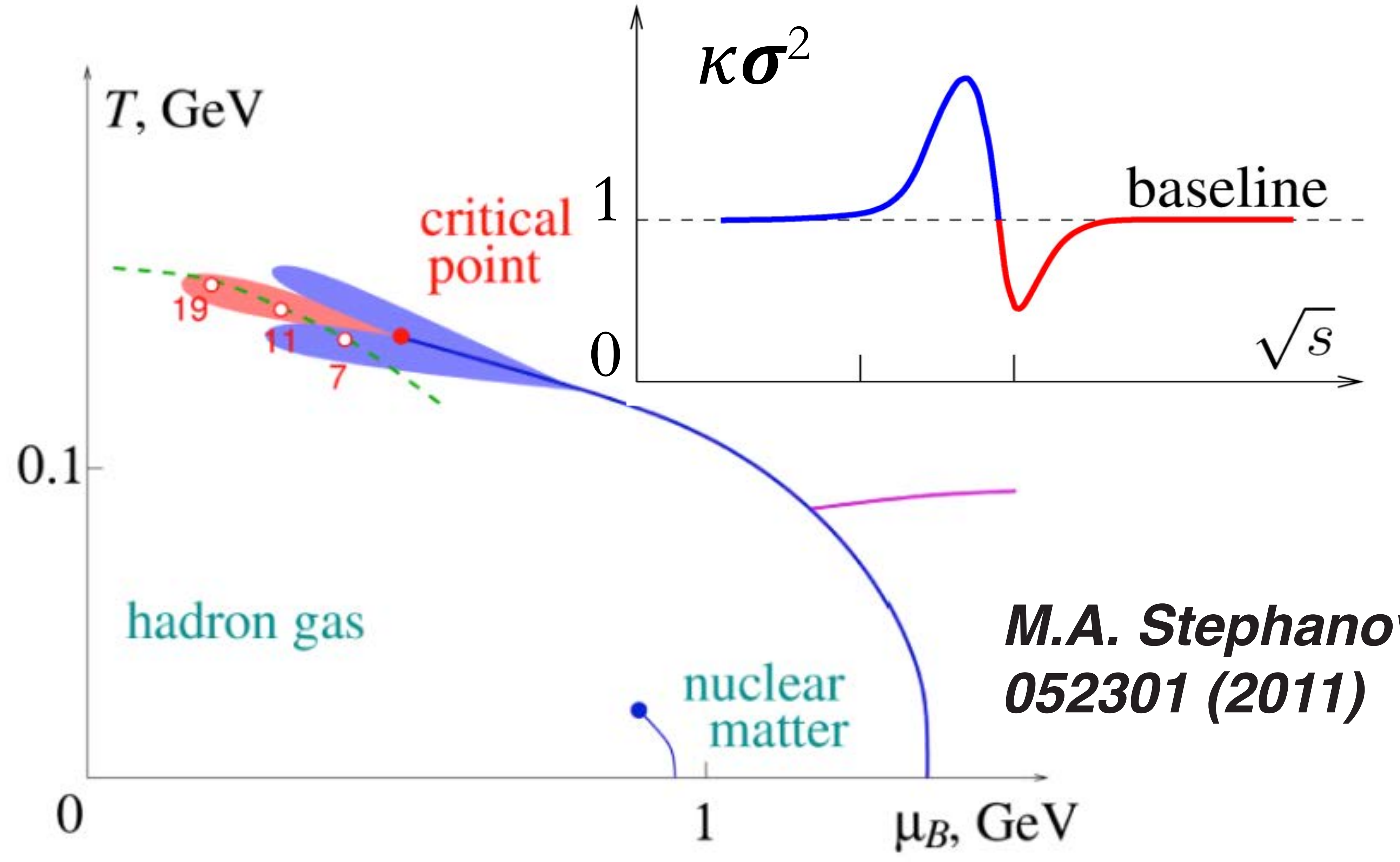


C_4/C_2 for critical point search

STAR Collaboration, arXiv:2001.02852, submitted to NP

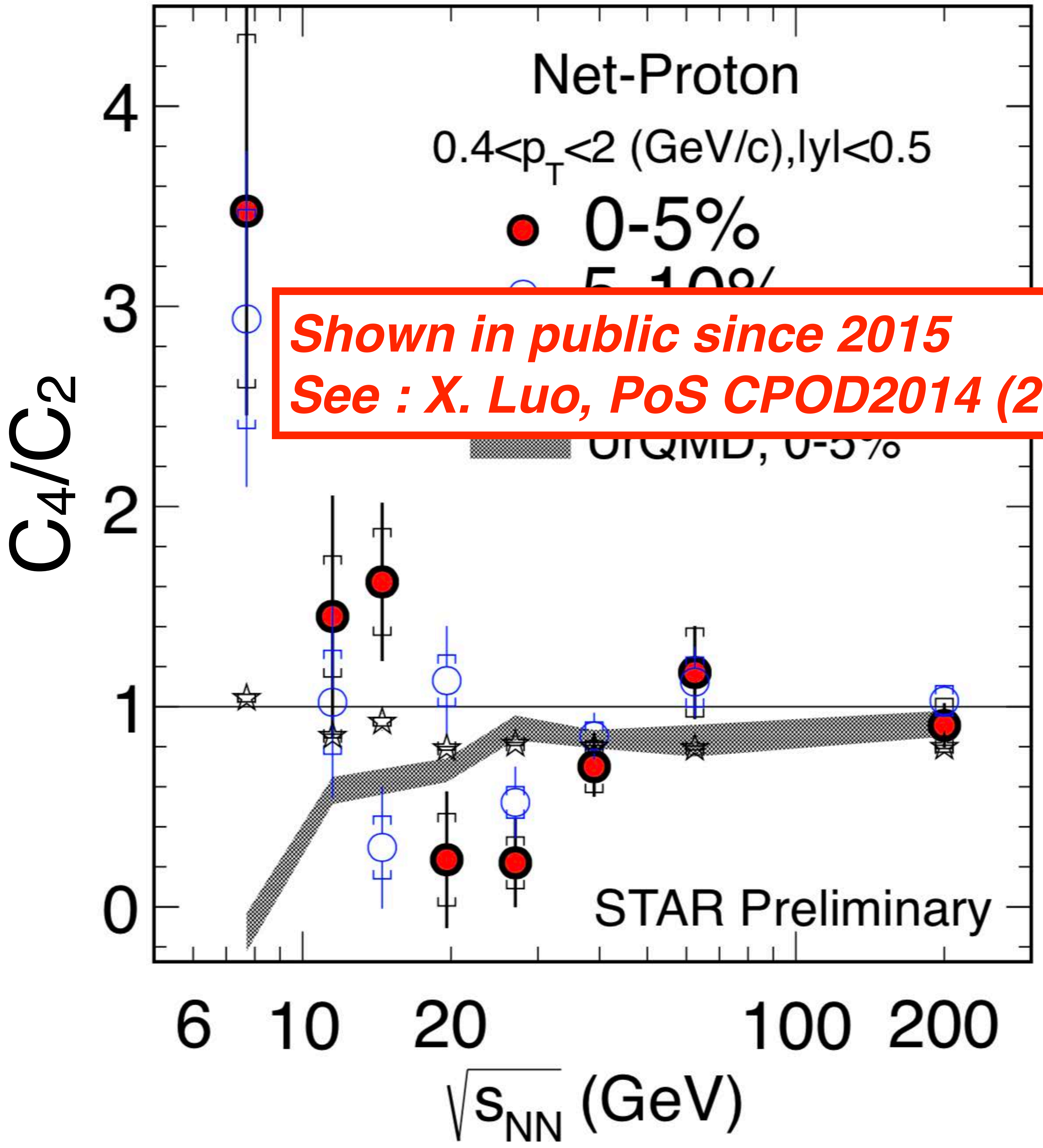


- ✓ $\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the theoretical calculation.
- ✓ Enhancement at low beam energies cannot be explained by baryon number conservation.



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

C_4/C_2 for critical point search



Shown in public since 2015
See : X. Luo, PoS CPOD2014 (2015) 019

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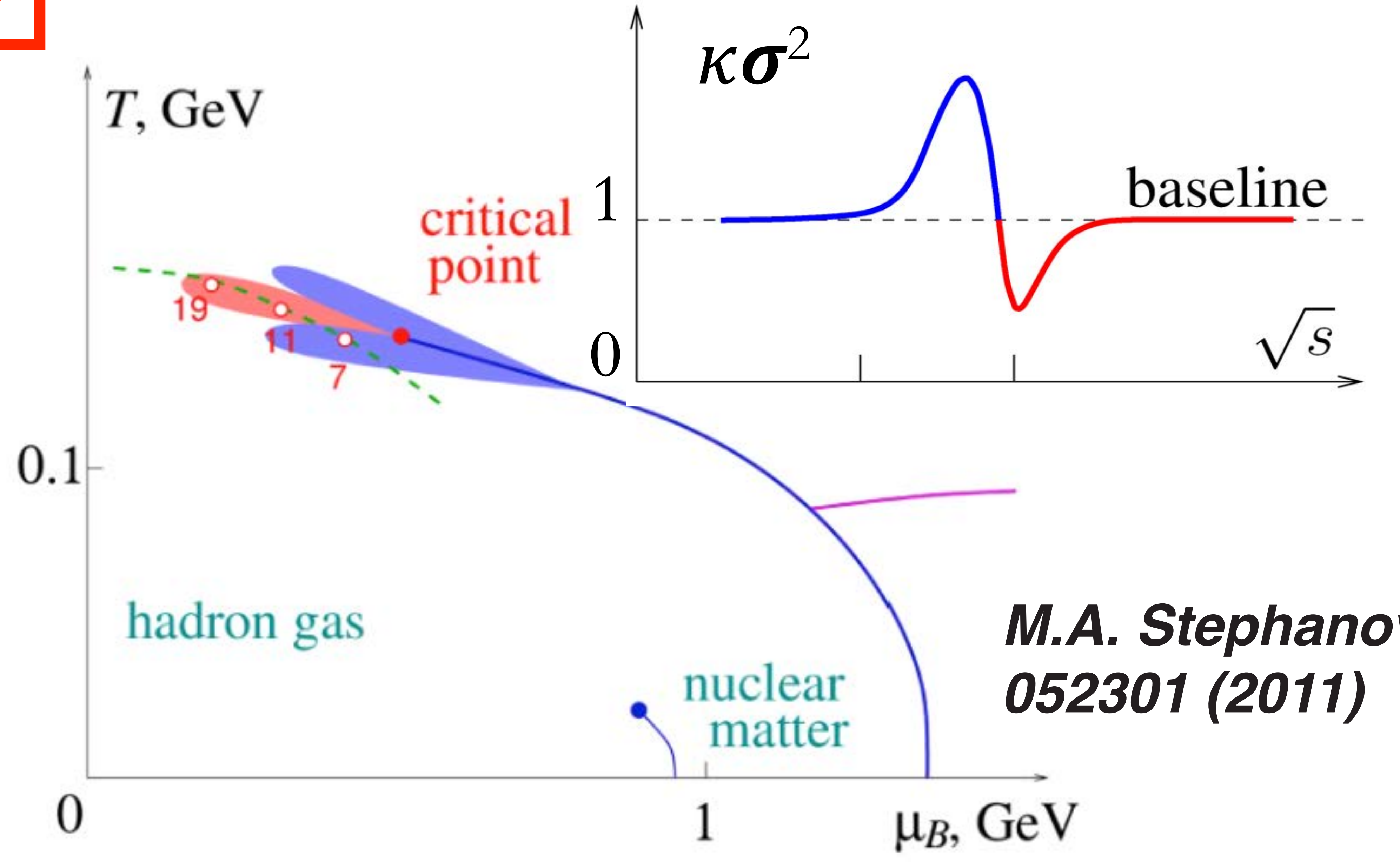

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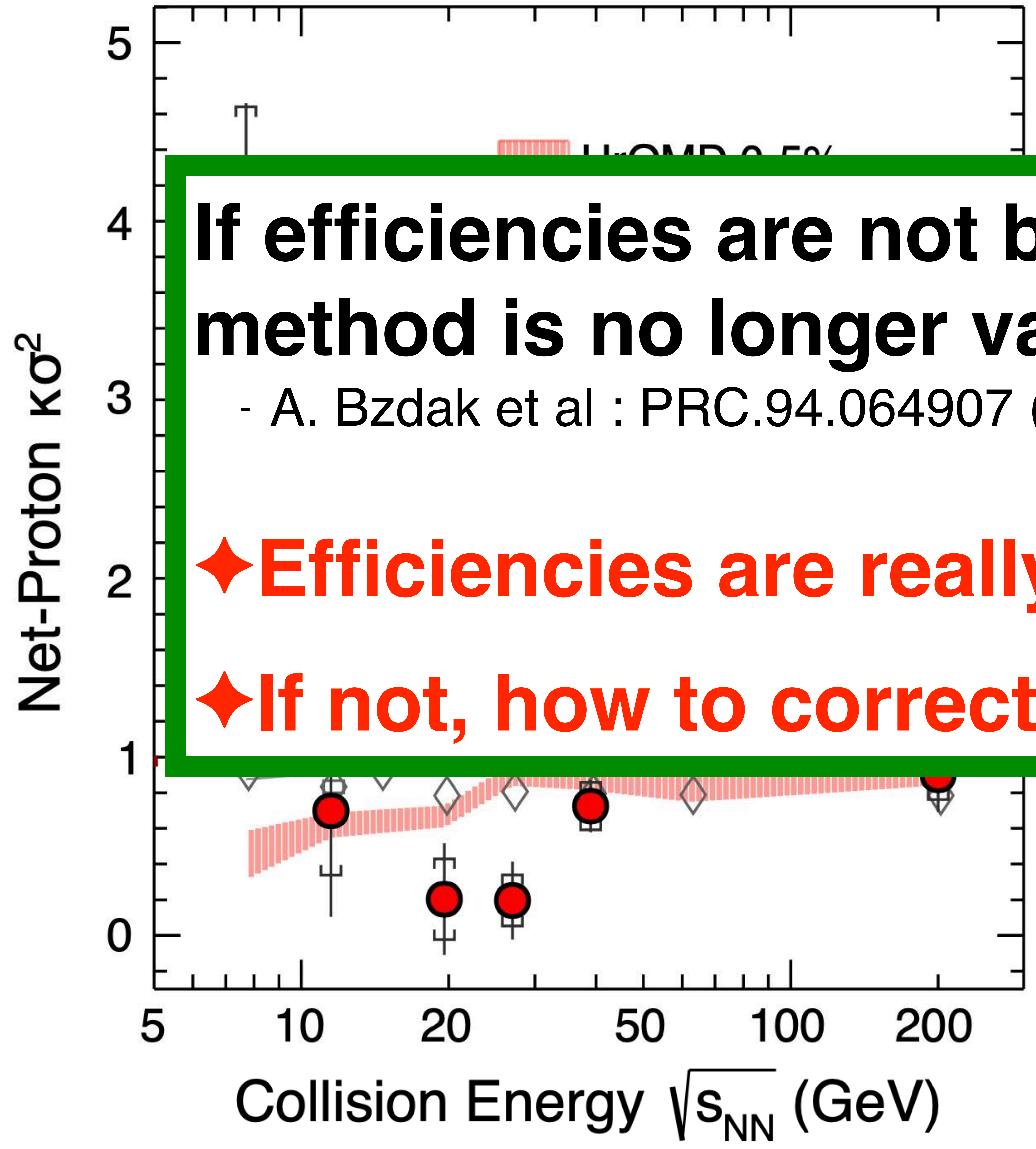


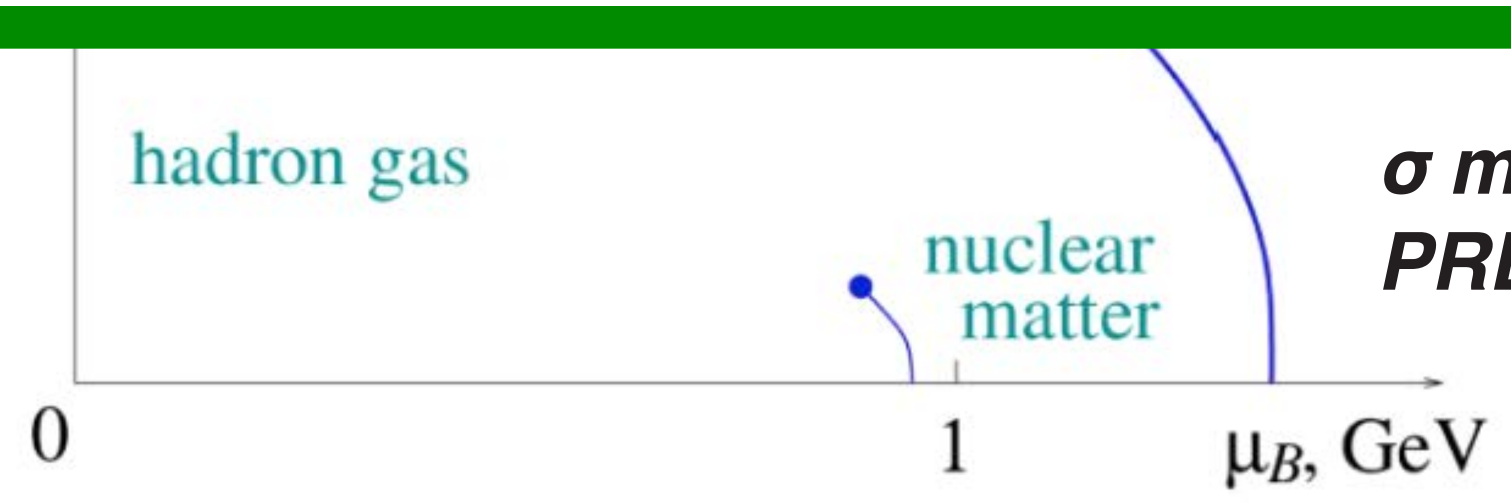
✓ $\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the theoretical calculation.

If efficiencies are not binomial, the efficiency correction method is no longer valid.

- A. Bzdak et al : PRC.94.064907 (2016)

✦Efficiencies are really binomial?

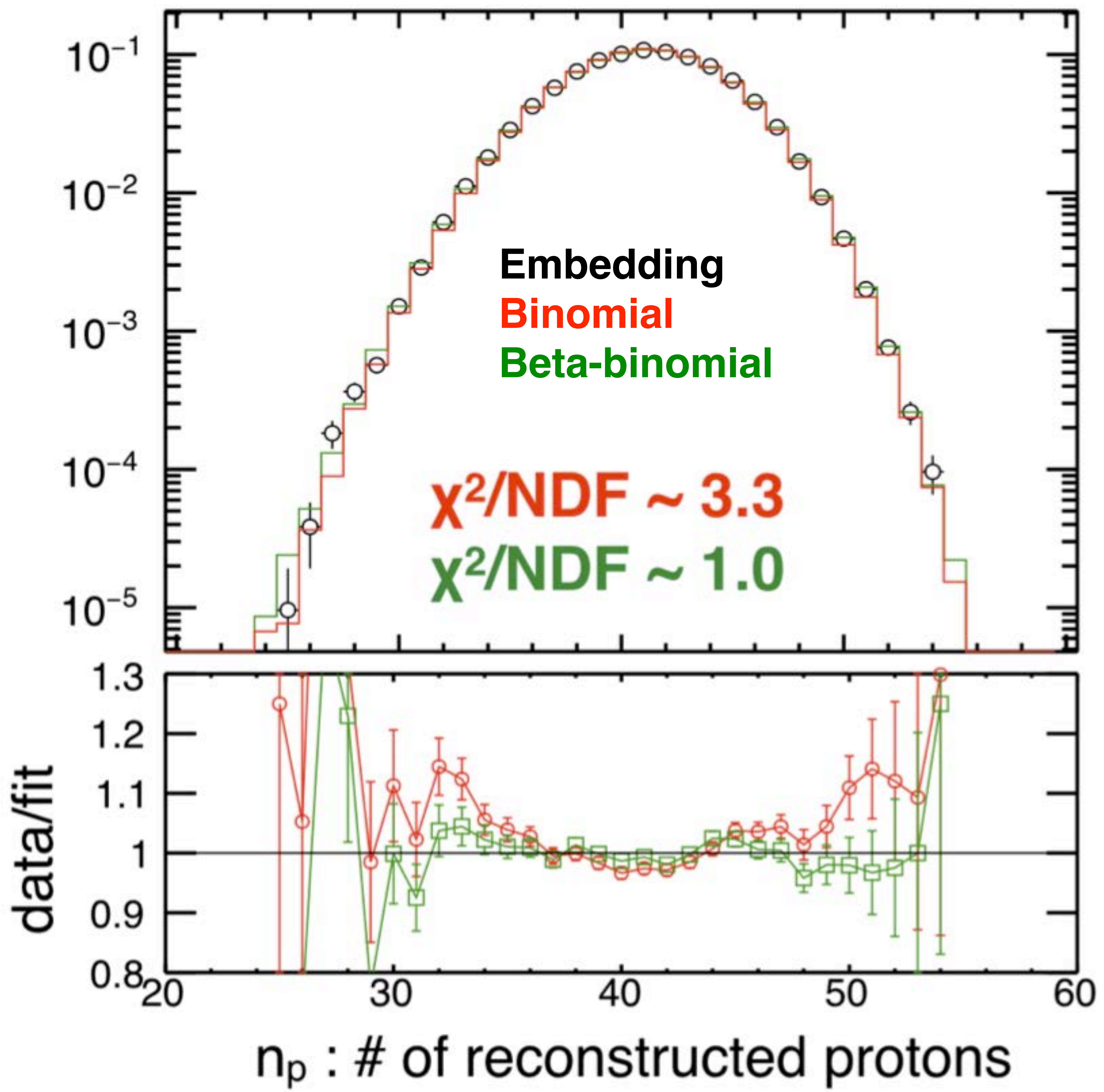
✦If not, how to correct?



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

Embedding simulation

T. Nonaka, NPA982 863-866 (2019)



✓ First results on detector efficiency distributions, reported in QM2018.

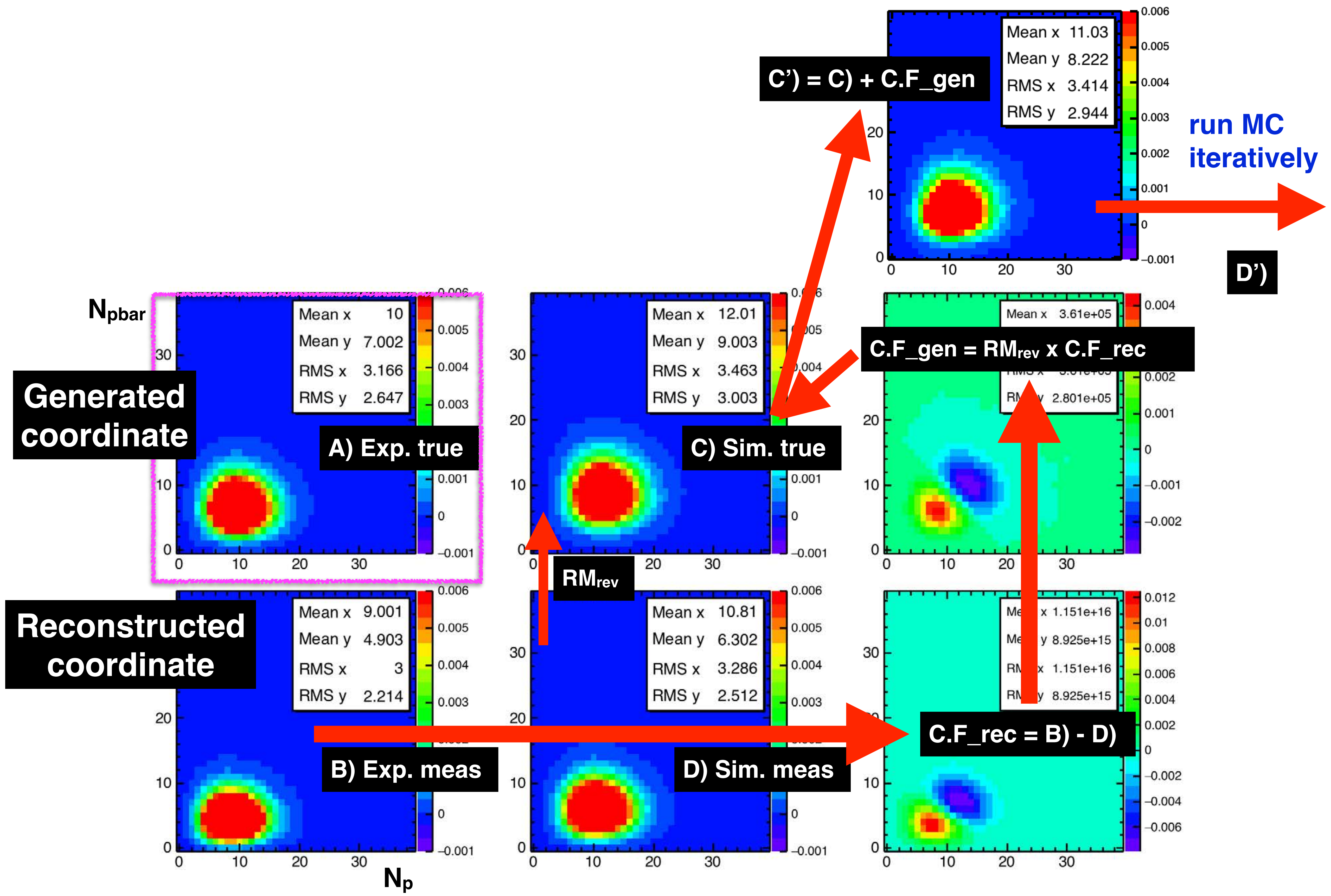
✓ Efficiencies follow beta-binomial distribution.

✓ How much are final results affected?

Correction methods

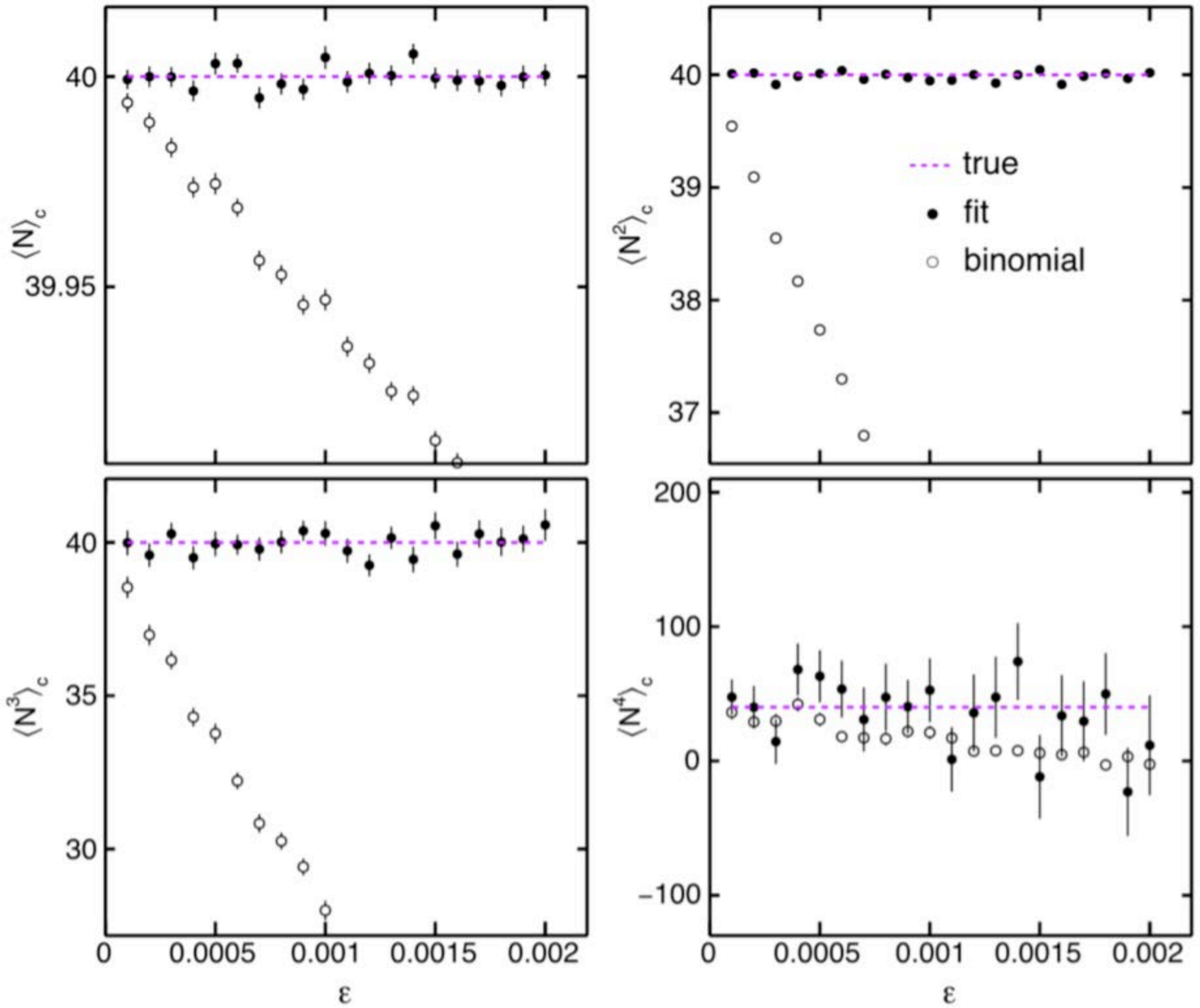
✓ Unfolding

S. Esumi and T. Nonaka, arXiv:2002.11253 (submitted to NIM)



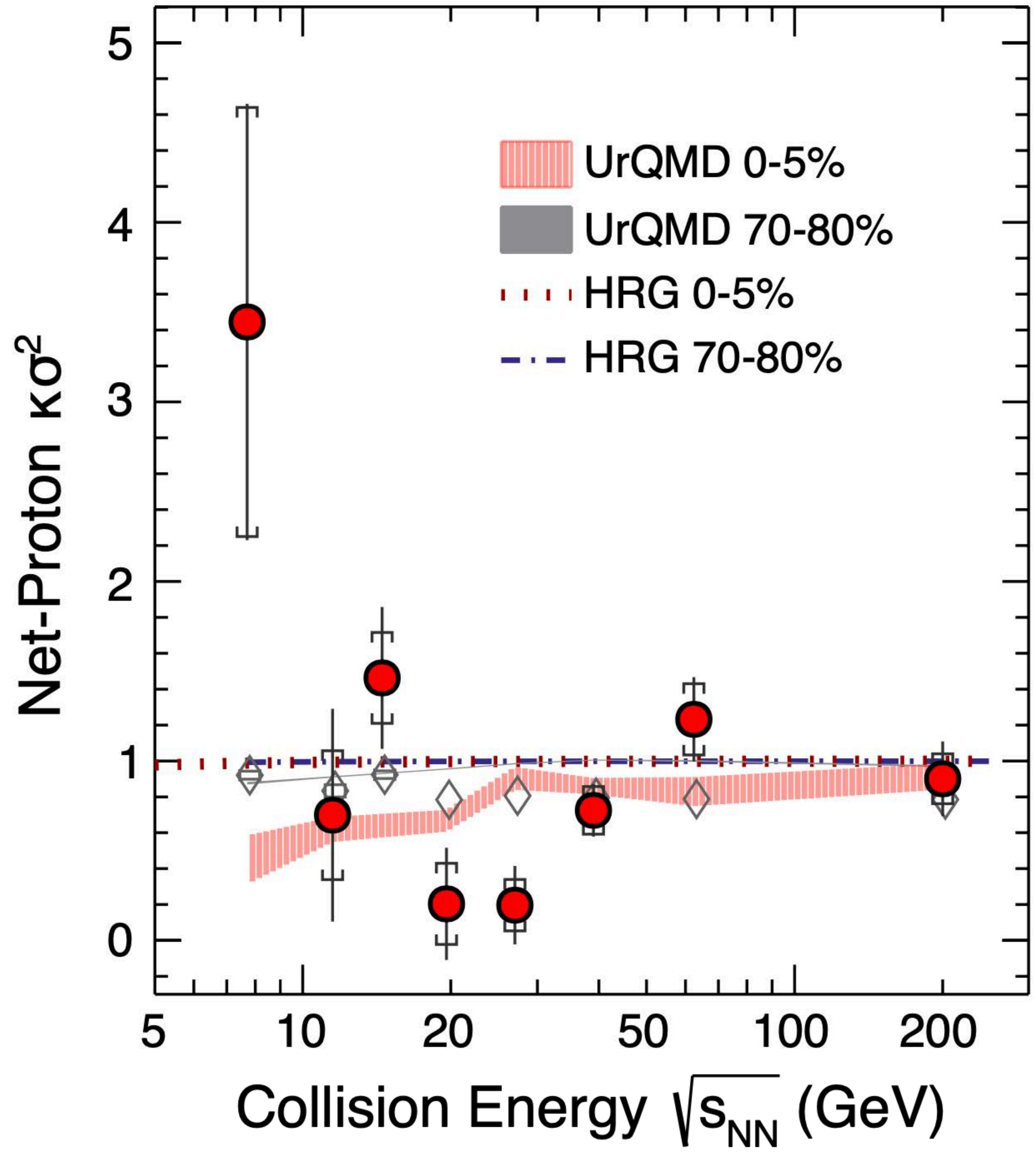
✓ Moment expansion method

T. Nonaka, M. Kitazawa, S. Esumi, NIM A906 10-17 (2018)



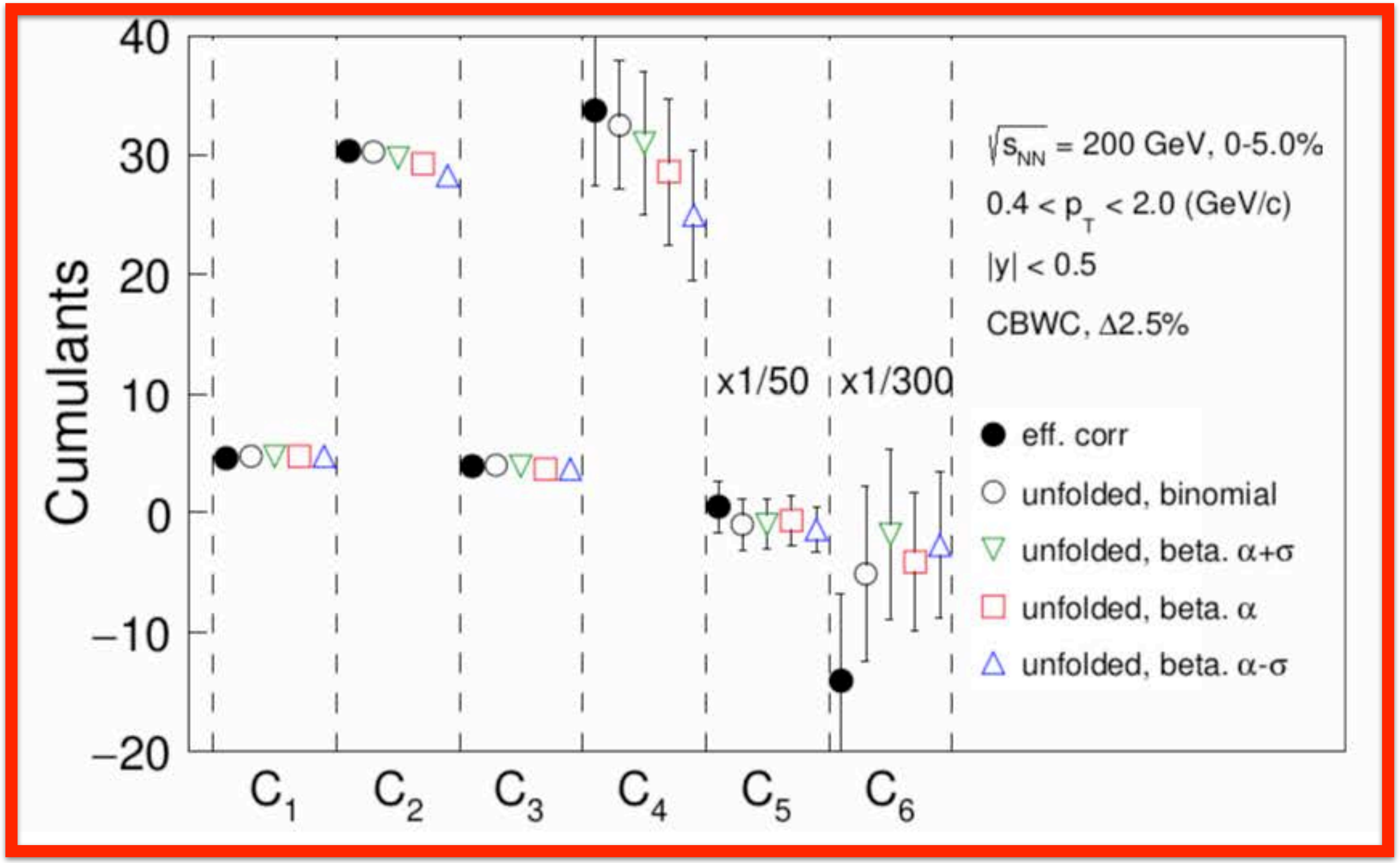
Results

STAR Collaboration, arXiv:2001.02852, submitted to NP



✓ **Results are consistent with those from binomial efficiency correction!**

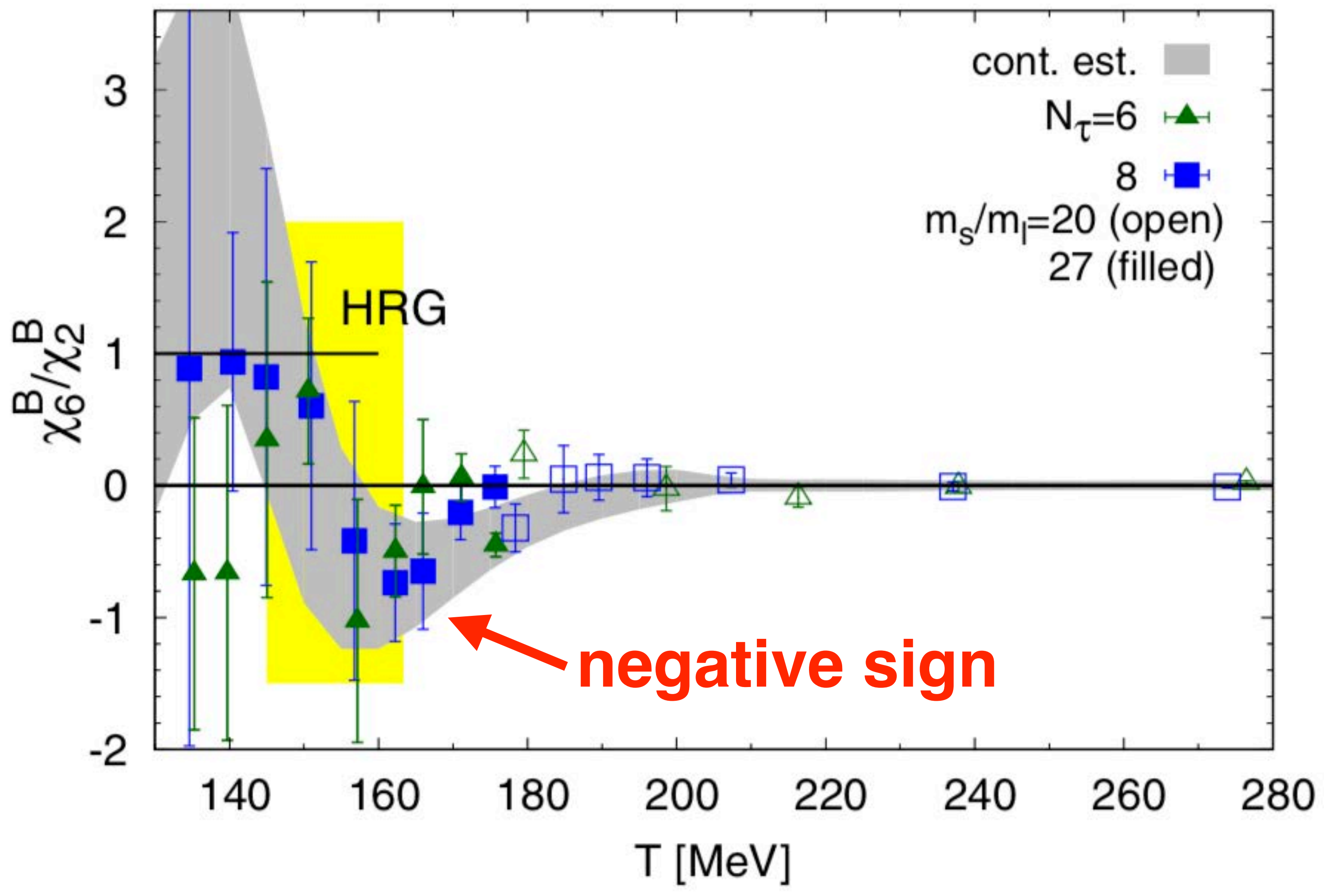
✓ **STAR paper is in collaboration review.. Will be submitted to Nature Physics soon.**



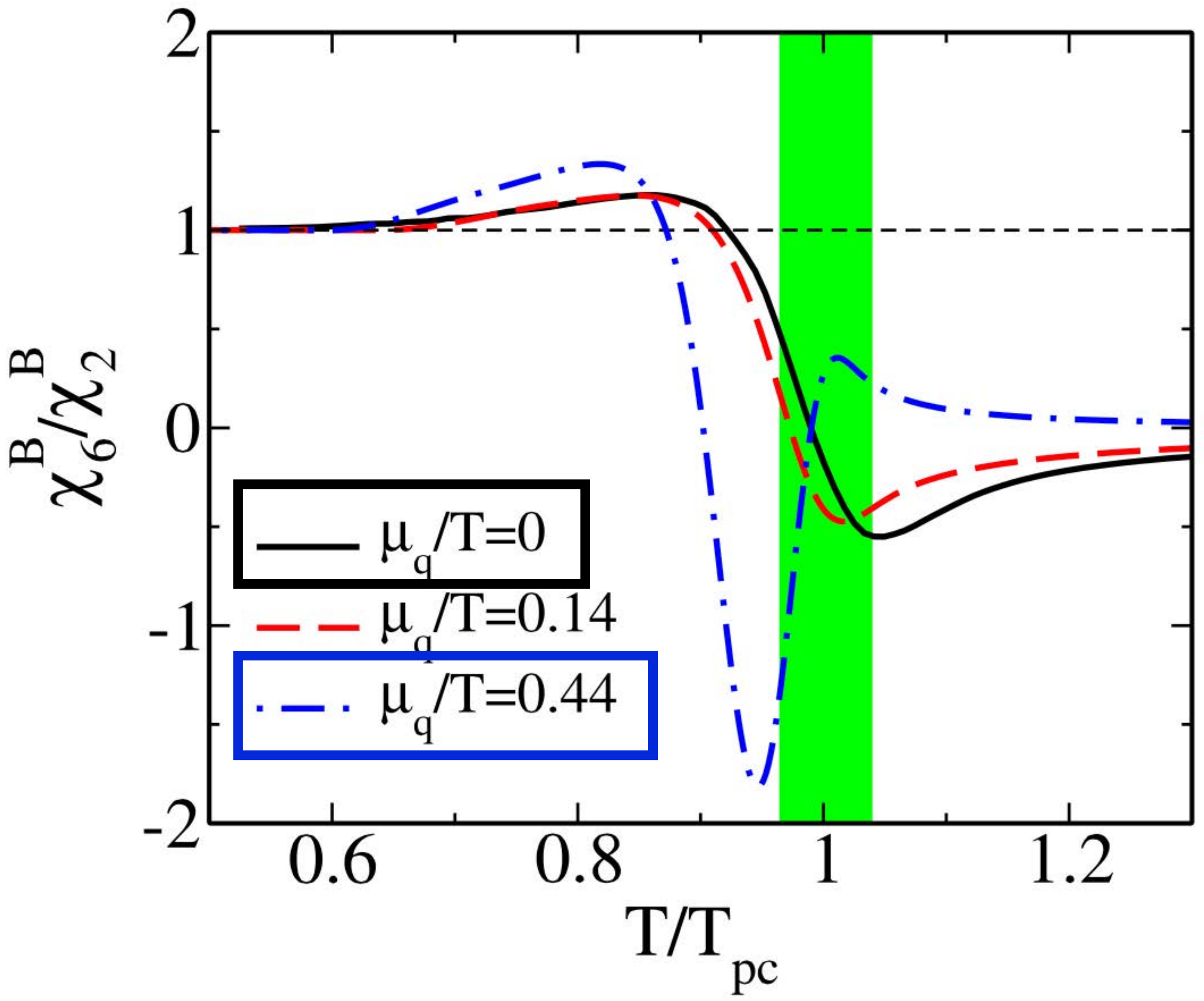
C_6/C_2 for crossover search

- ✓ There isn't yet any direct experimental evidence for the smooth crossover at μ_B~0.
- ✓ **$C_6/C_2 < 0$** is predicted at $\sqrt{s_{NN}} > 60$ GeV.
- ✓ High-statistics data sets at **$\sqrt{s_{NN}}$ = 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



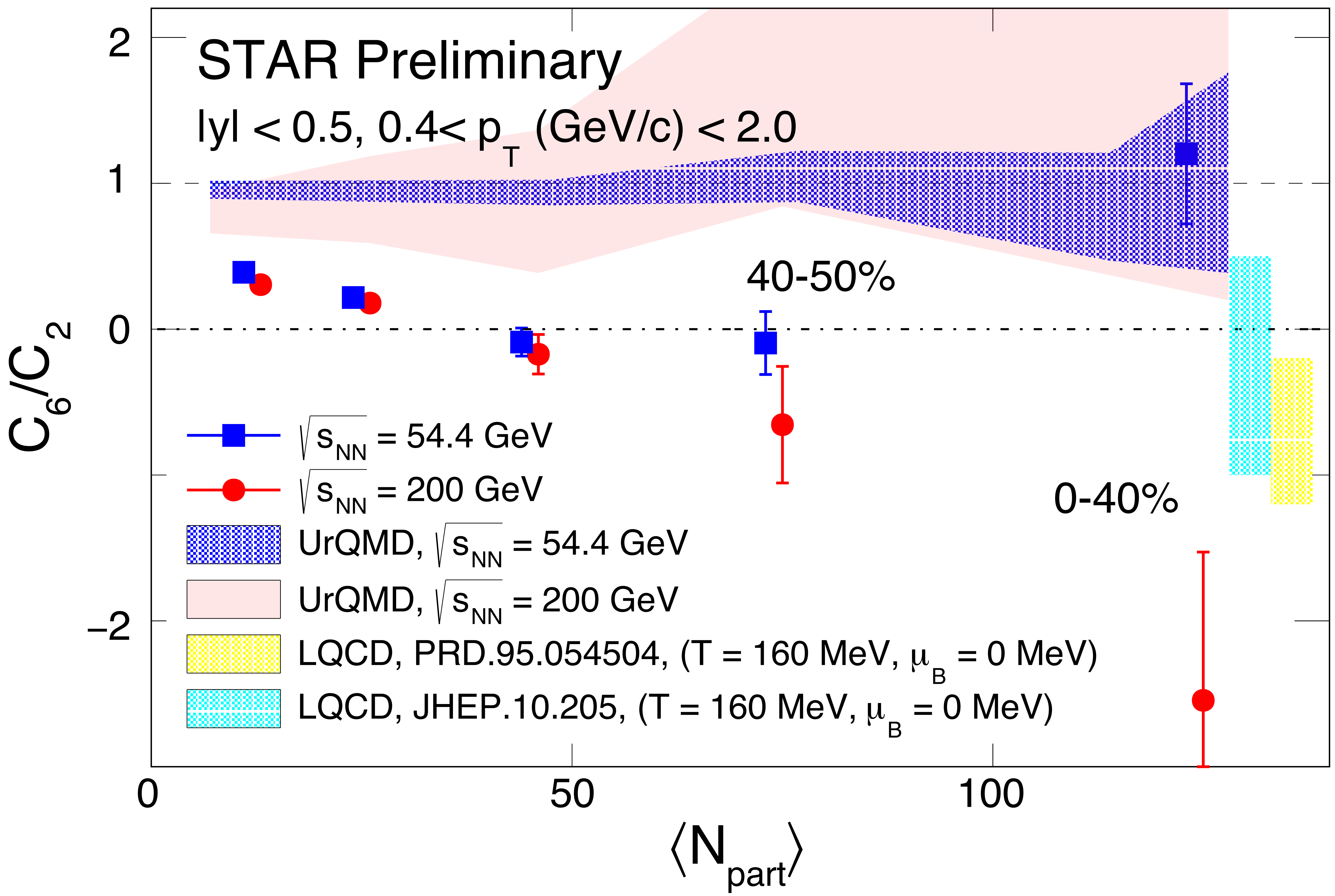
Positive sign is predicted in $\sqrt{s_{NN}}$<60 GeV

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	$\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

Results



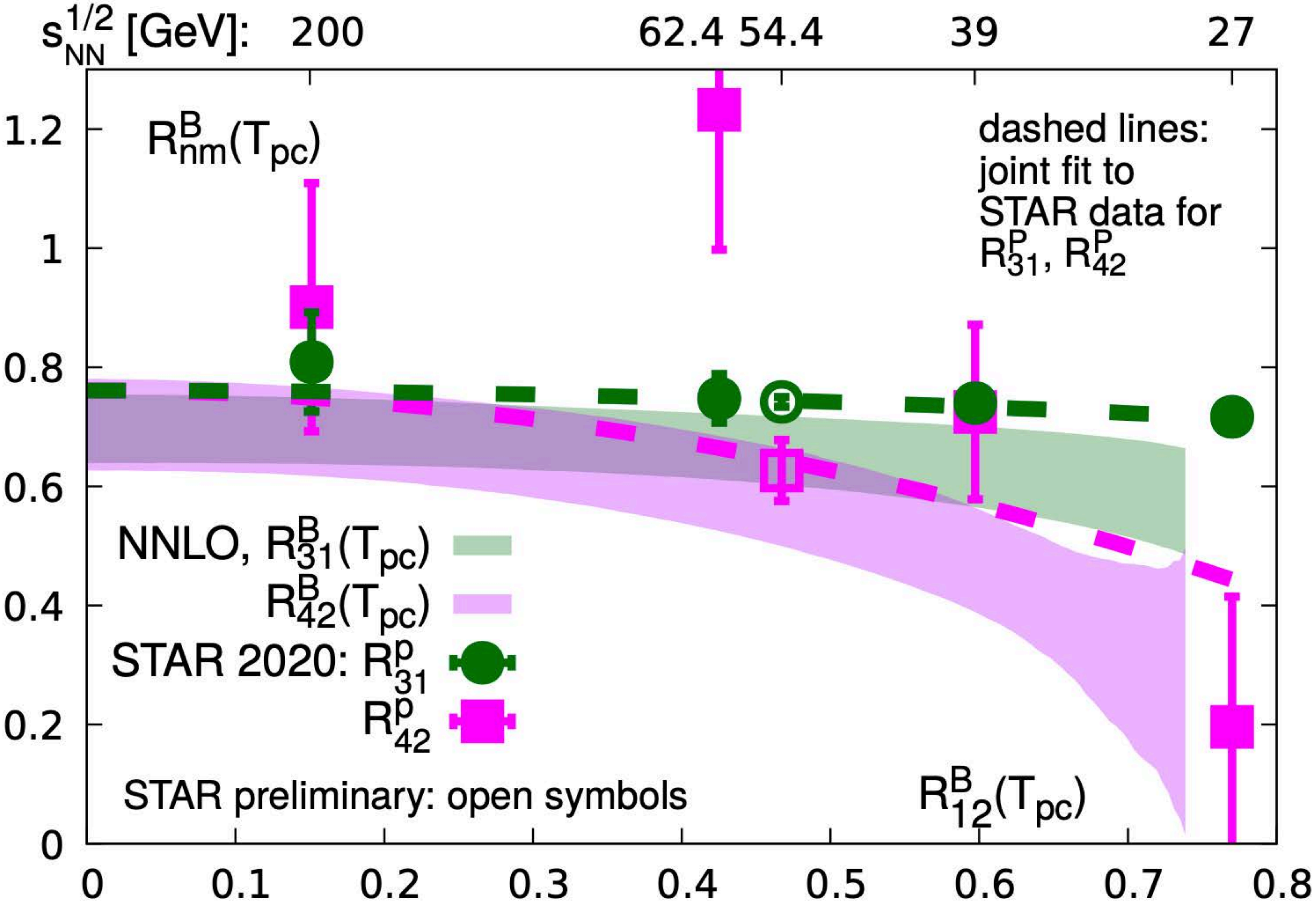
200 GeV data taken in 2010 and 2011

54.4 GeV data taken in 2017

C_6/C_2<0 at 200 GeV central collisions could be an experimental indication of smooth crossover at small μ_B.

T. Nonaka, QM2019

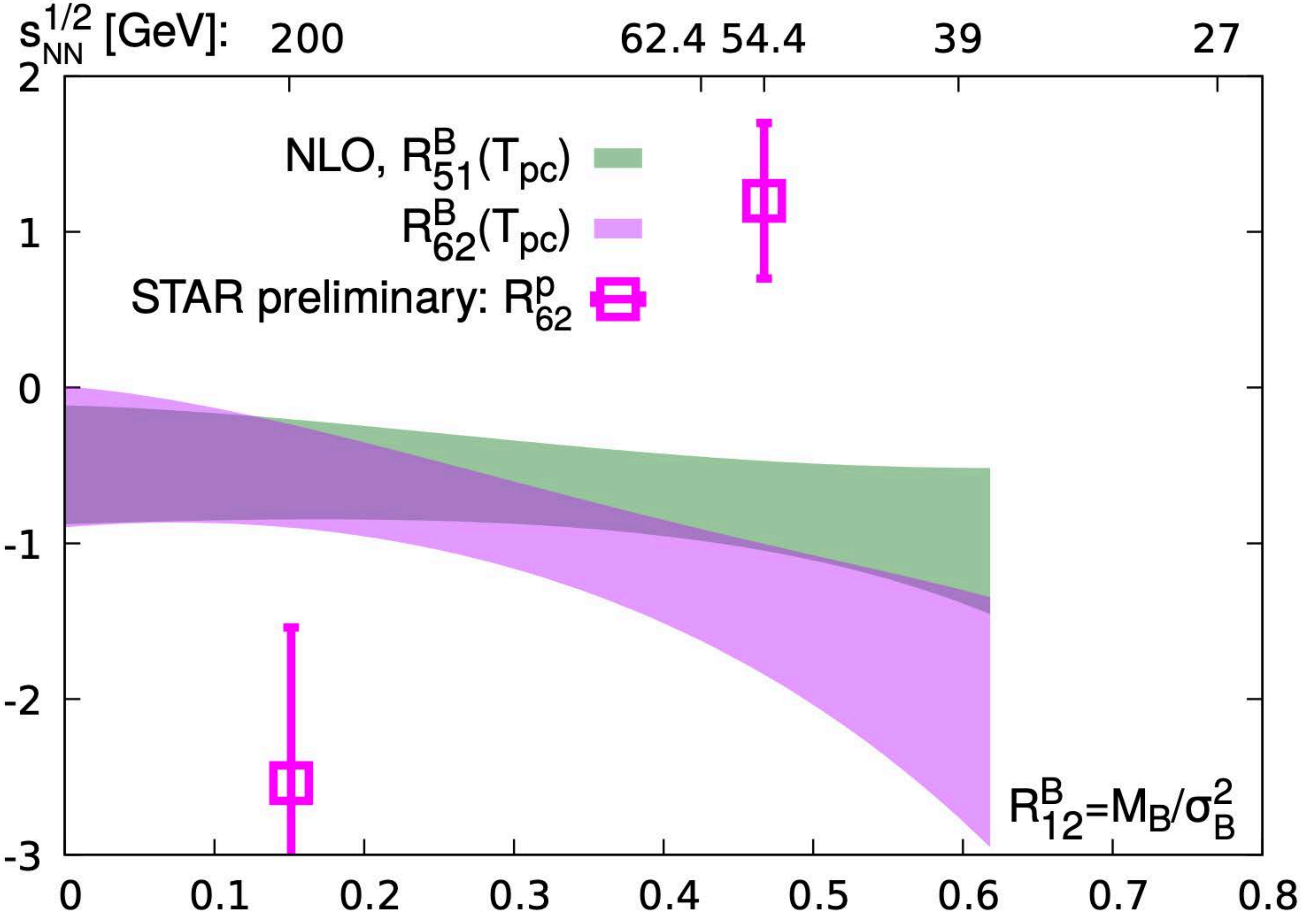
Comparison with LQCD



✓ Consistent with LQCD for 3rd and 4th net-proton(baryon) fluctuations

Bazavov et al., Phys. Rev. D 101,074502 (2020)

Comparison with LQCD



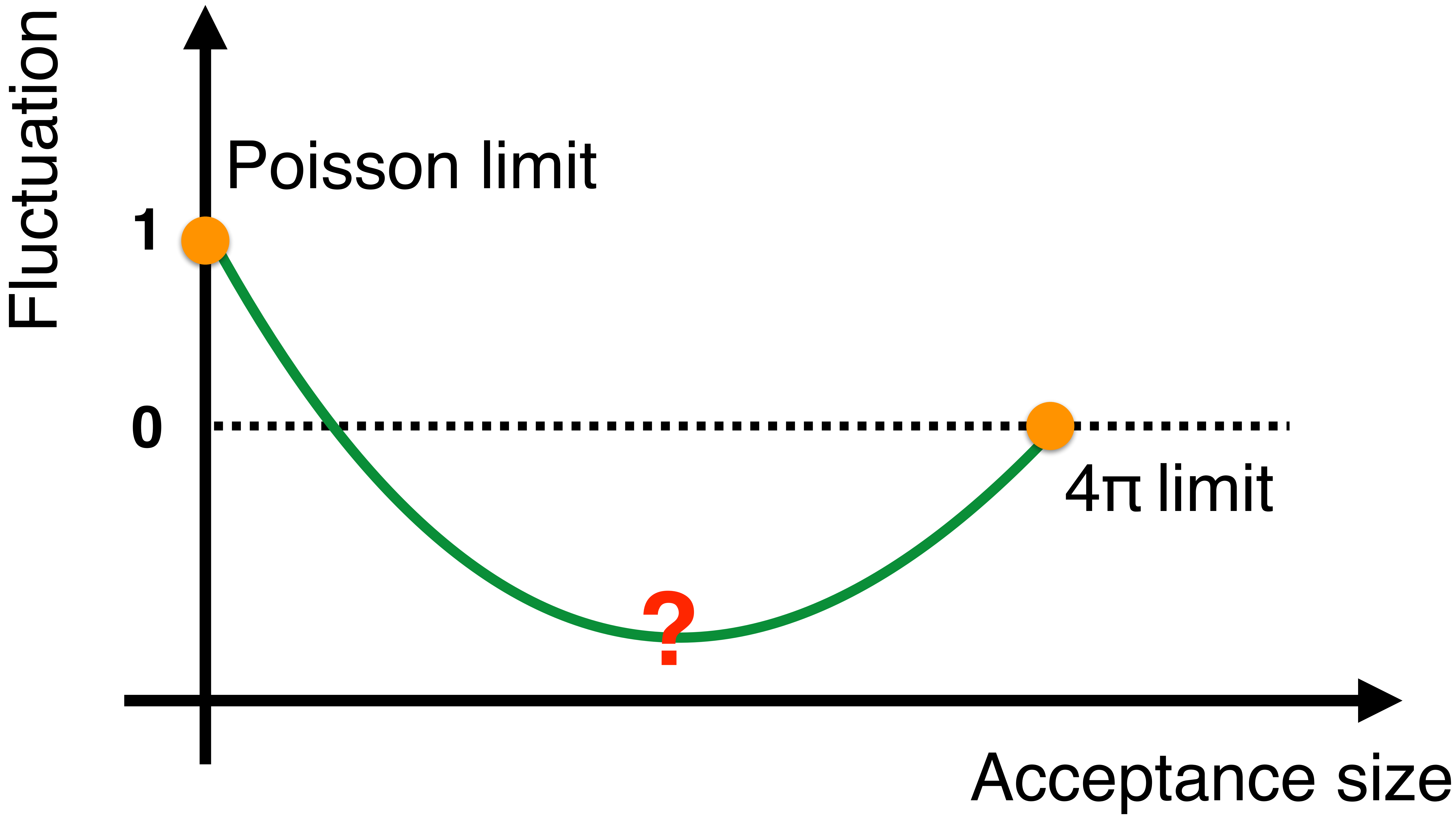
✓ $C_6/C_2 < 0$ is predicted for $\sqrt{s_{NN}} > 39$ GeV

Bazavov et al., Phys. Rev. D 101,074502 (2020)

Acceptance dependence

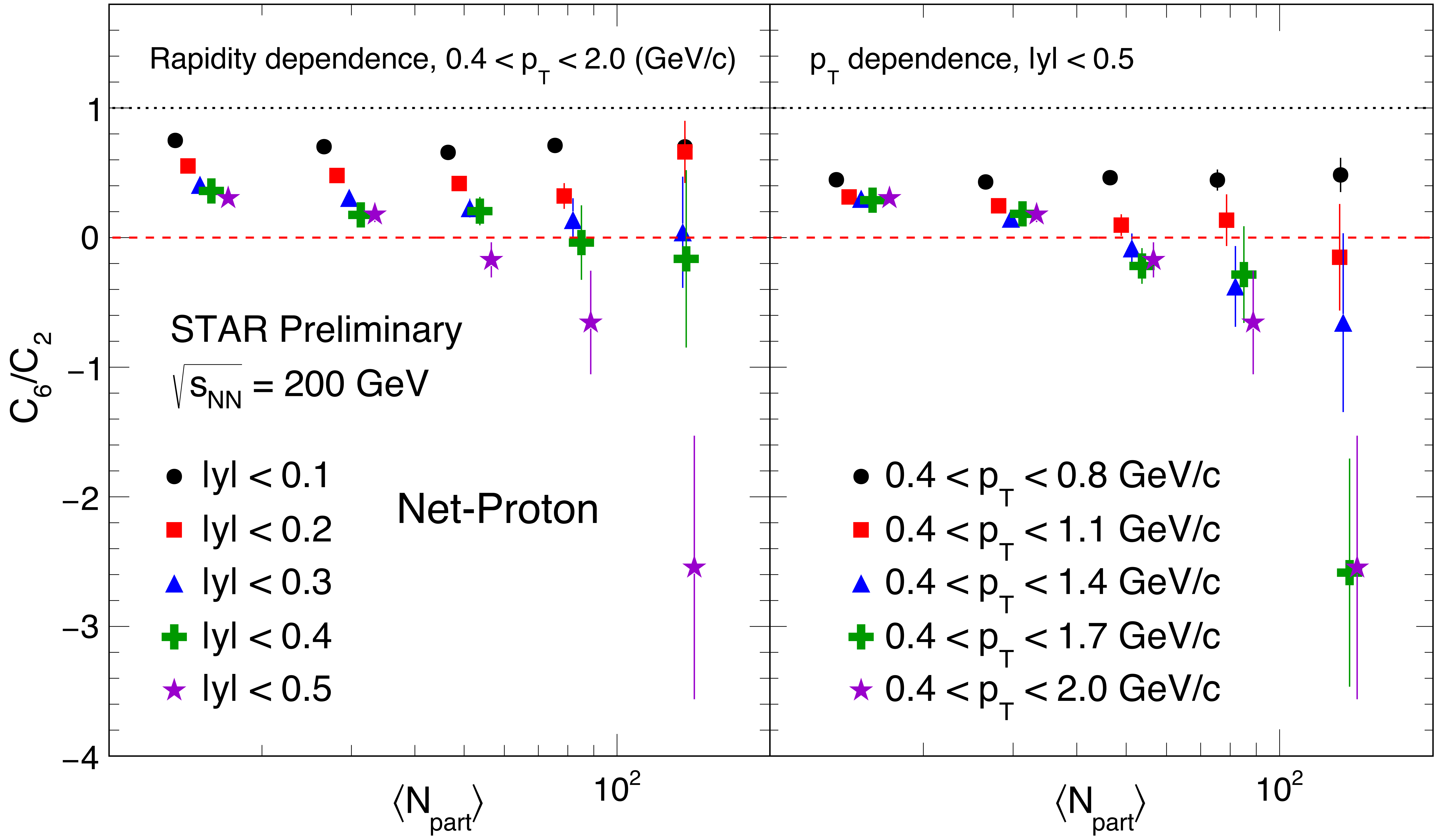
✓ Which acceptance should be compared with LQCD calculations?

✓ Fluctuations should have minimum/maximum somewhere in acceptance size.



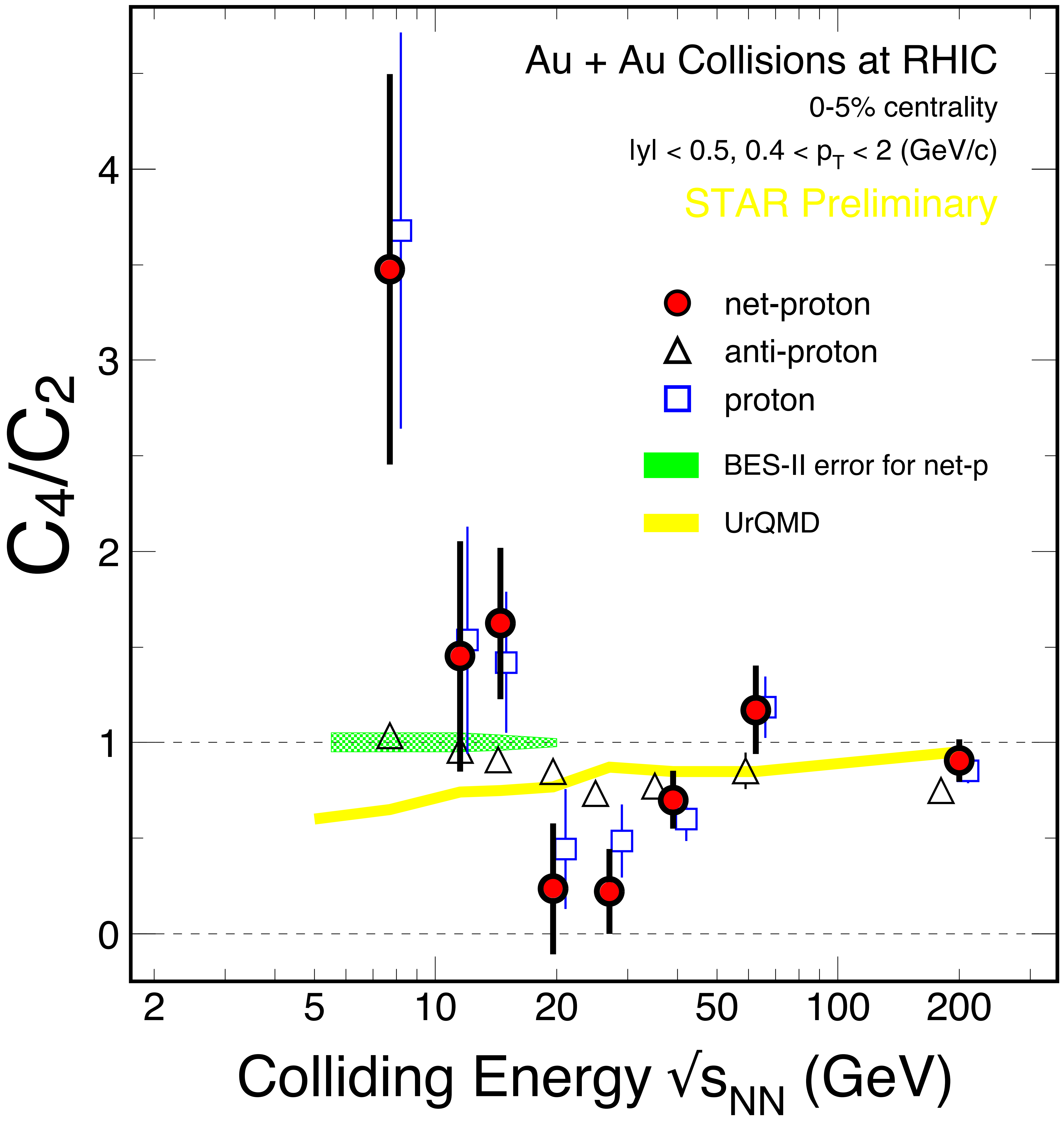
Acceptance dependence at 200 GeV

✓ Wide acceptance is crucial for fluctuation measurements!



Future Plan

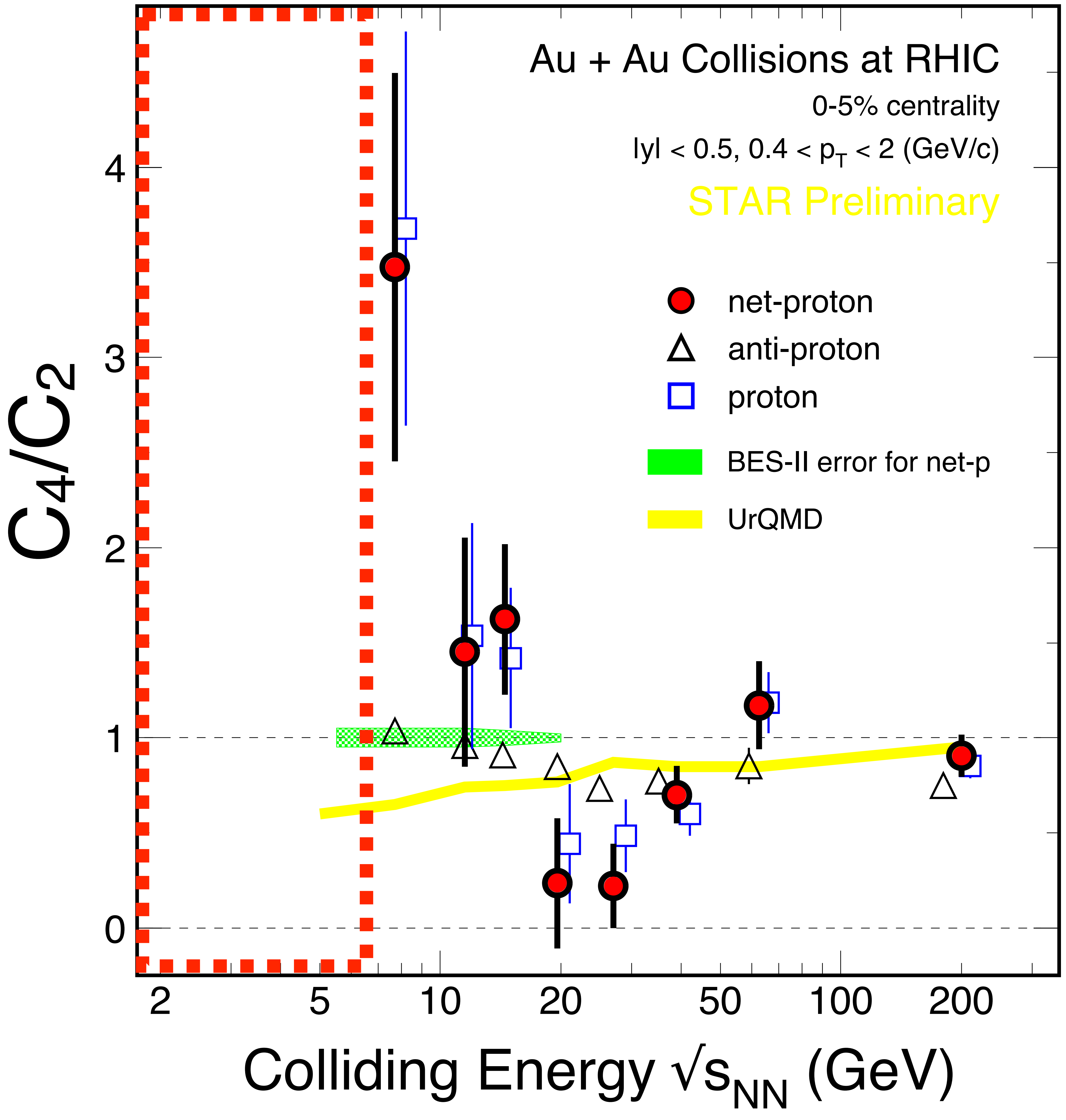
2019-2021 : BES-II at RHIC



- ✓ **Need to shrink the errors at low energies.**
- ✓ **BES-II has started this year.**
- ✓ **Map the QCD phase diagram 200 < μ_B < 420 MeV**

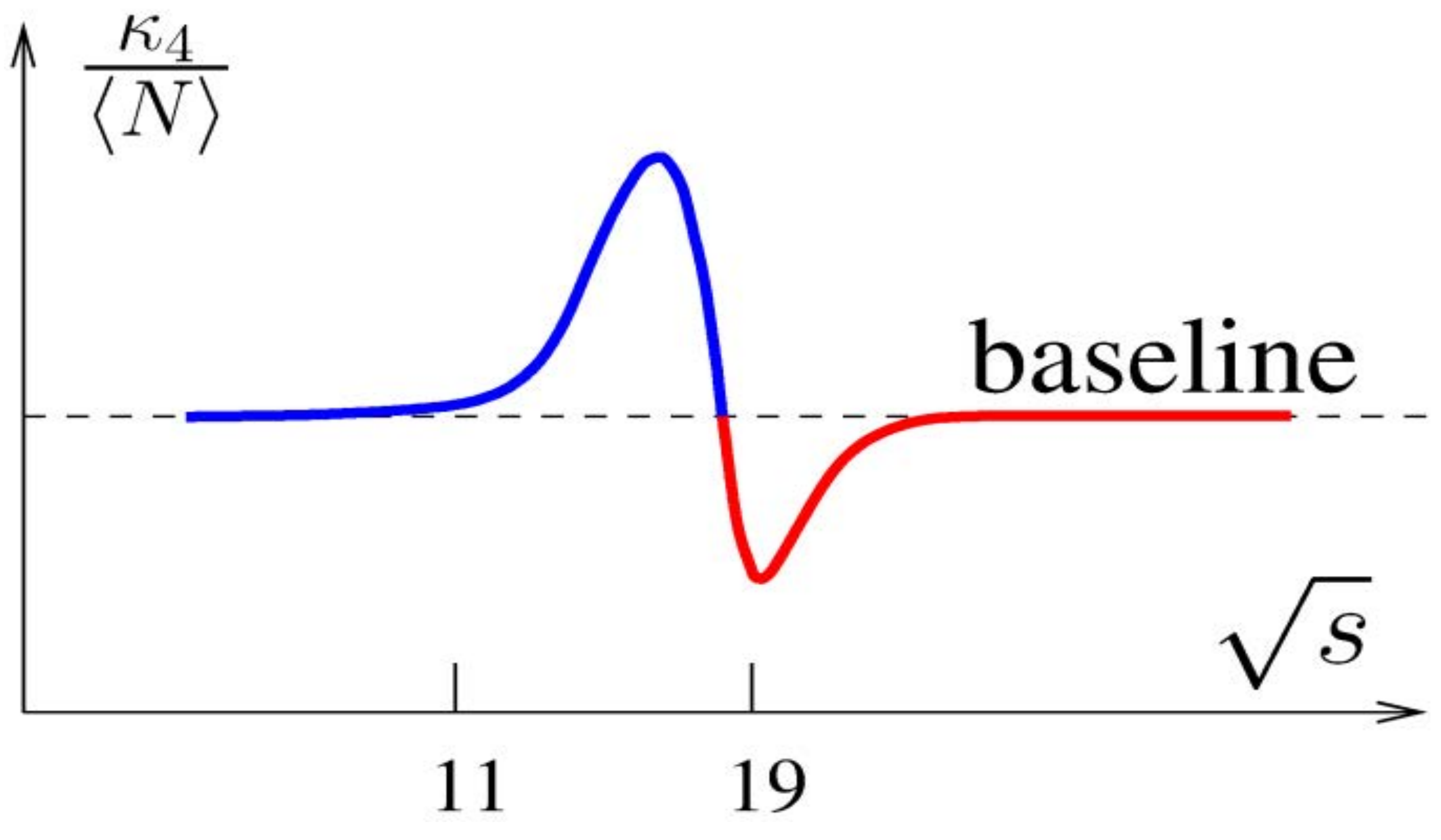
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES-II / BES-I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1200	2017			
39	39	2010		112	164
27	70	2011		156	162
19.6	400 / 36	2019-21 / 2011	3	206	160
14.5	300 / 20	2019-21 / 2014	2.5	264	156
11.5	230 / 12	2019-21 / 2010	5	315	152
9.2	160 / 0.3	2019-21 / 2008	9.5	355	140
7.7	100 / 4	2019-21 / 2010	14	420	140

Beyond BES-II

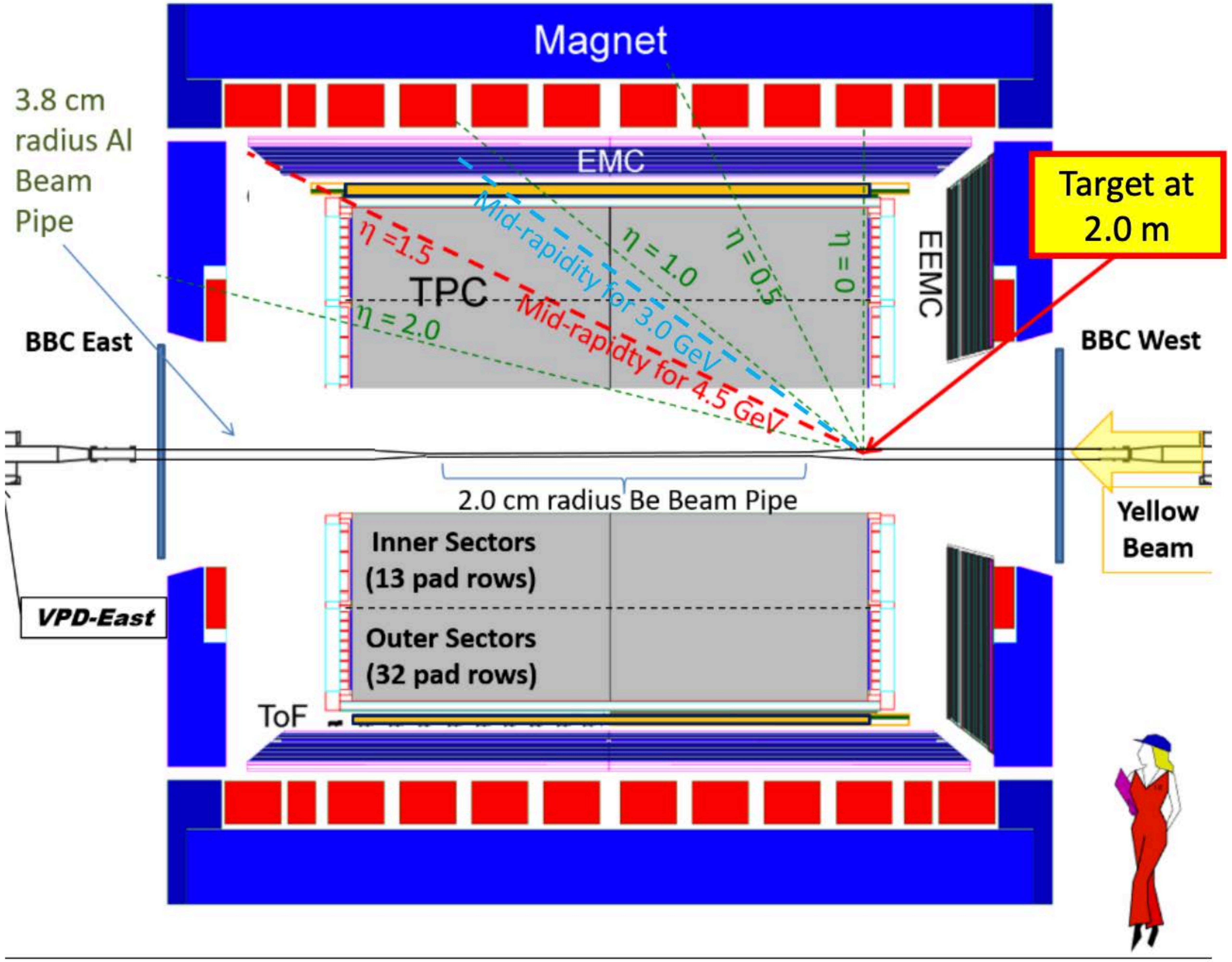


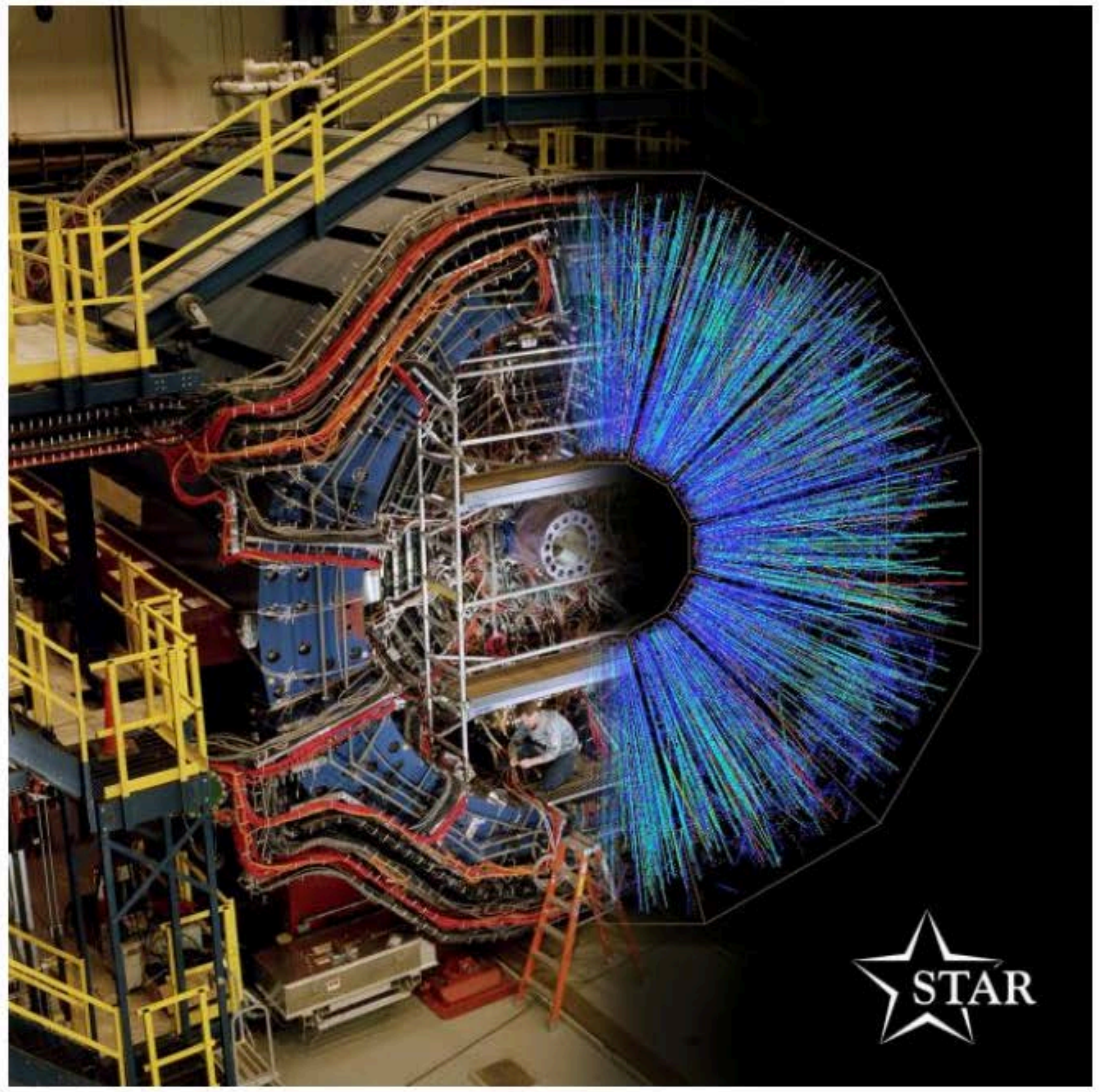
- ✓ **Statistical uncertainties will be dramatically reduced.**
- ✓ **Can we measure a possible "peak" structure?**

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



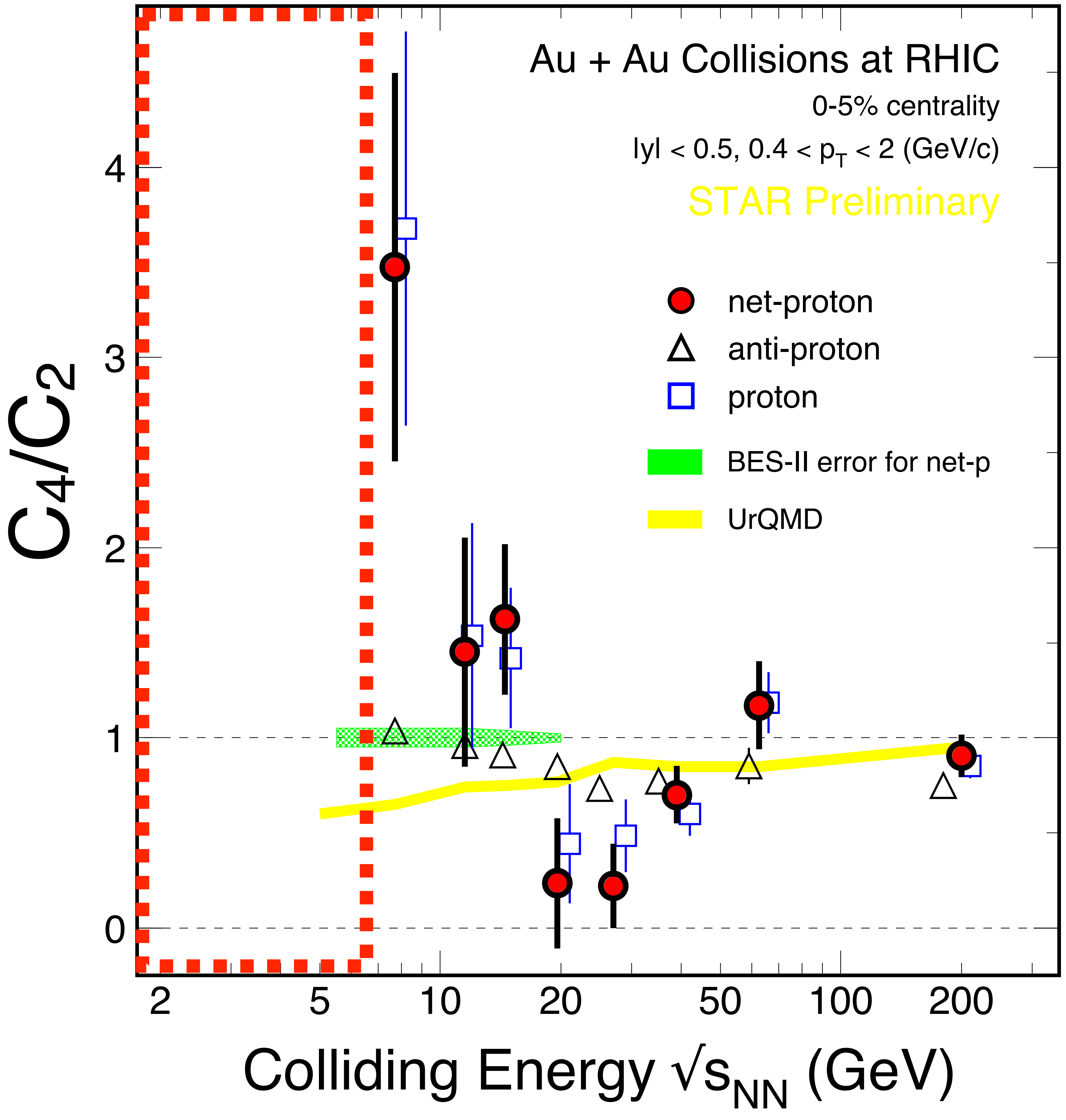
FXT@STAR





Target design:
Gold foil
1/4 mm Thick (1%)
~1 cm High
~4 cm Wide
~2 cm below beam axis
200 cm from IR

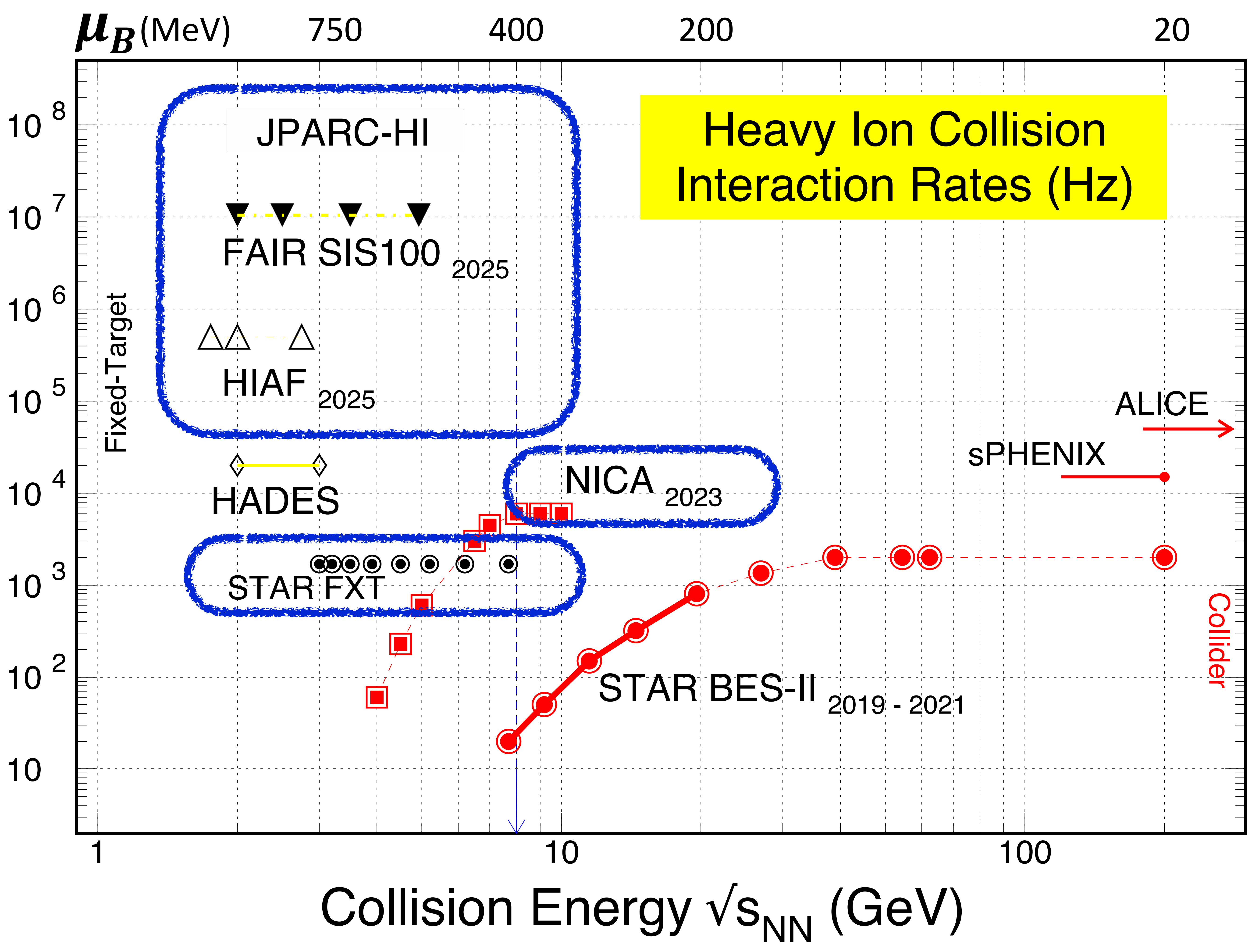
Beyond BES-II



✓ **Fixed-target experiment is also ongoing.**

	Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number "Good" Events requested / collected	
	9.8	19.6	205	4.5 weeks	400M	582M
	7.3	14.5	260	5.5 weeks	300M	324M
Run20	5.75	11.5	315	9.5 weeks	230M	
	4.55	9.1	370	9.5 weeks	160M	
	3.85	7.7	420	12 weeks	100M	
Run20	31.2	7.7 (FXT)	420	2 days	100M	51M
	19.5	6.2 (FXT)	487	2 days	100M	
	13.5	5.2 (FXT)	541	2 days	100M	
	9.8	4.5 (FXT)	589	2 days	100M	
	7.3	3.9 (FXT)	633	2 days	100M	53M
	5.75	3.5 (FXT)	666	2 days	100M	
	4.55	3.2 (FXT)	699	2 days	100M	201M
	3.85	3.0 (FXT)	721	2 days	100M	3.7M+300M (run18

Beyond BES-II



- ✓ **High beam intensity facilities coming in 5~10 years**
  - **CBM @FAIR (Germany)**
  - **MPD @NICA (Russia)**
  - **HIAF (China)**
  - **JPARC-HI (Japan)**
- ✓ **Huge statistics for critical point search using higher order fluctuations.**

Summary

- Higher-order fluctuations of net-particle distributions to search for the QCD phase structure
- Non-monotonic beam energy dependence of C_4/C_2
- Negative value of C_6/C_2 at $\sqrt{s_{NN}}$ = 200 GeV central collisions
- Future FXT experiments at $\sqrt{s_{NN}} < 10$ GeV with higher beam intensity

Thank you for your attention