Critical fluctuations at STAR BES & FXT

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University of Tsukuba

3rd workshop on Physics performance studies at FAIR and NICA

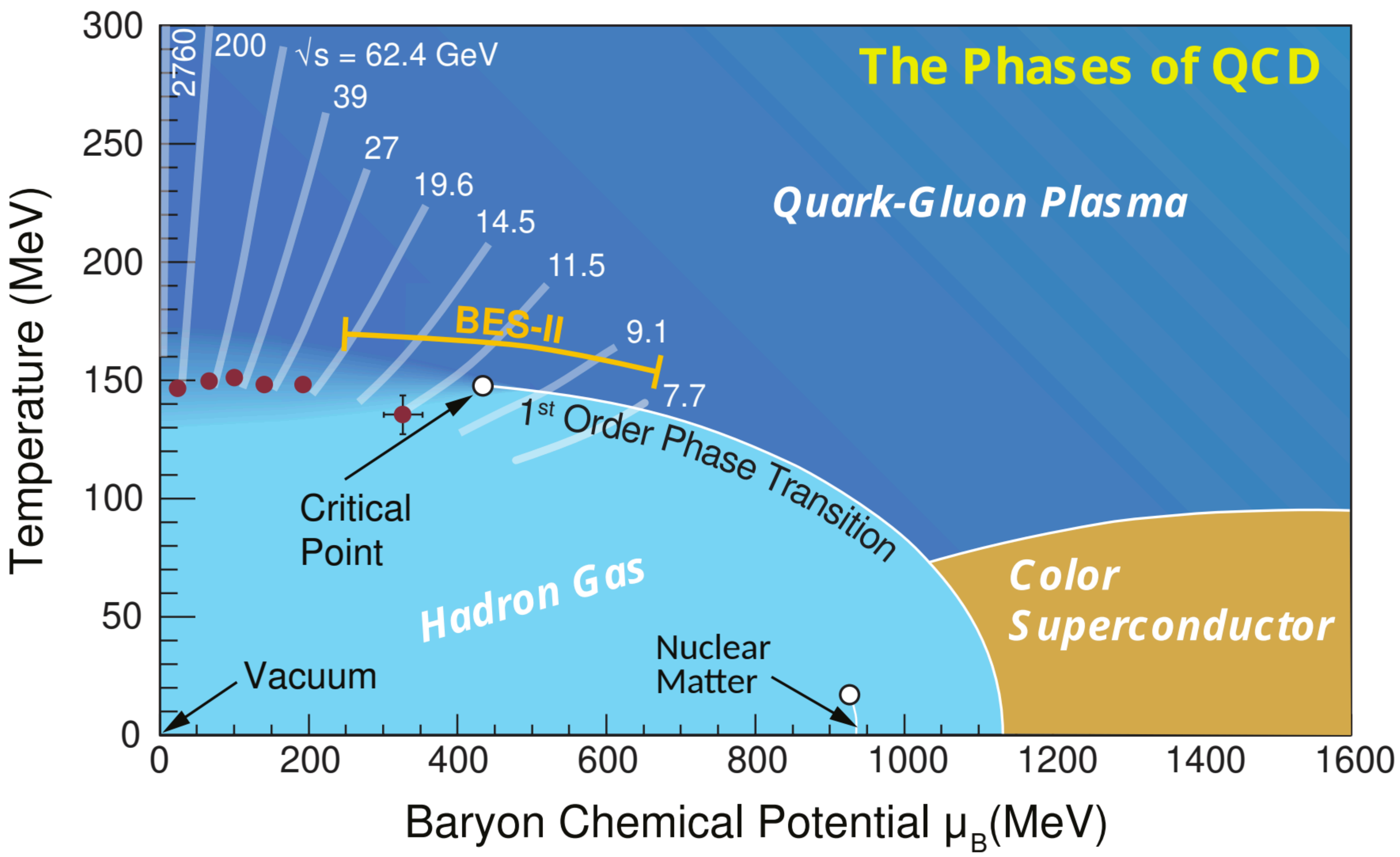
Supported in part by

Outline

- Introduction
- Analysis techniques
- C_4/C_2 for critical point search
- C_5/C_1 and C_6/C_2 for crossover search
- Future perspective
- Summary

QCD phase diagram

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



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

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

Beam Energy Scan

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

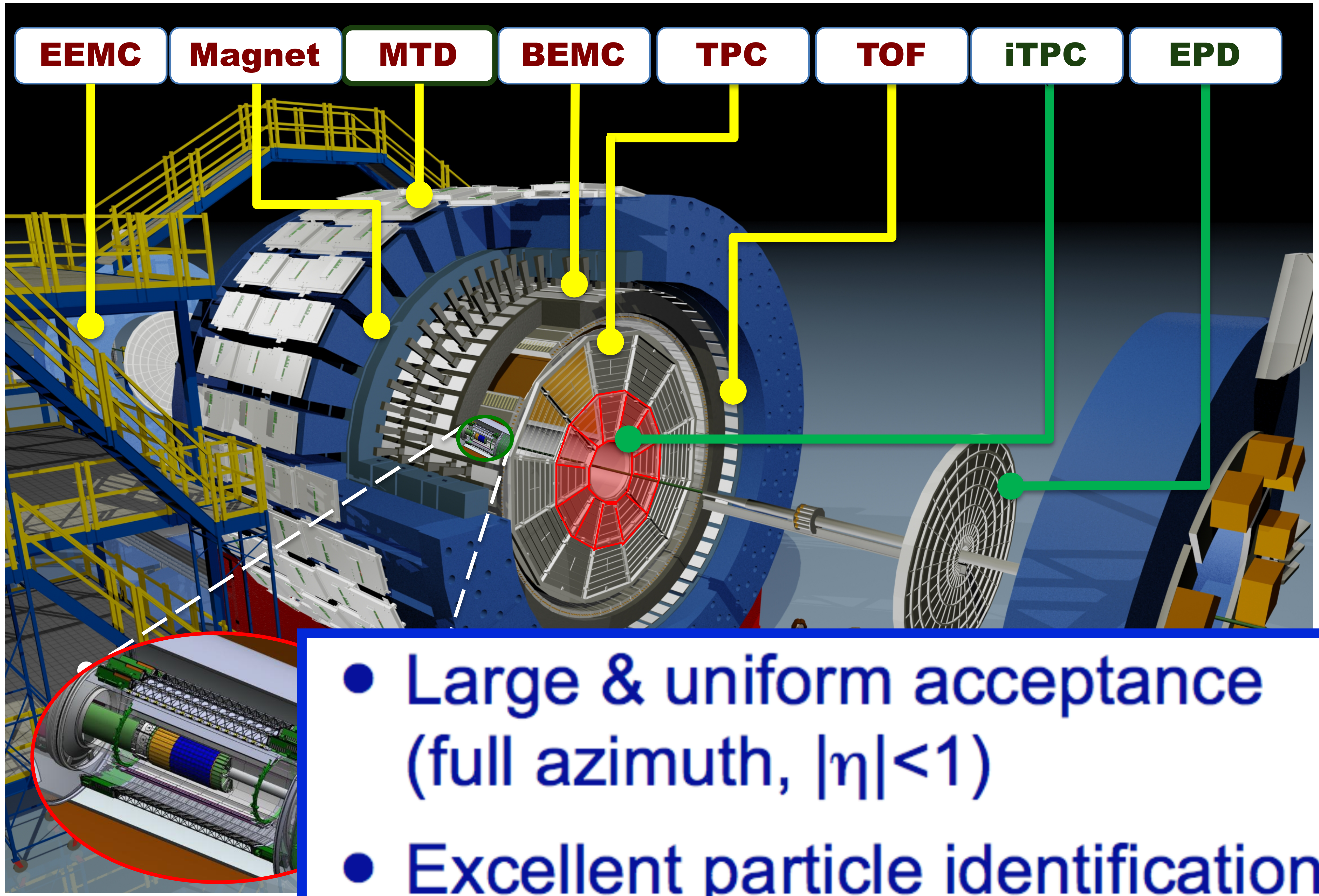
$\sqrt{s_{NN}}$ (GeV)	No. of events (million)	T_{ch} (MeV)	μ_B (MeV)
200	238	164.3	28
62.4	47	160.3	70
54.4	550	160.0	83
39	86	156.4	160
27	30	155.0	144
19.6	15	153.9	188
14.5	20	151.6	264
11.5	6.6	149.4	287
7.7	3	144.3	398

2010-2017

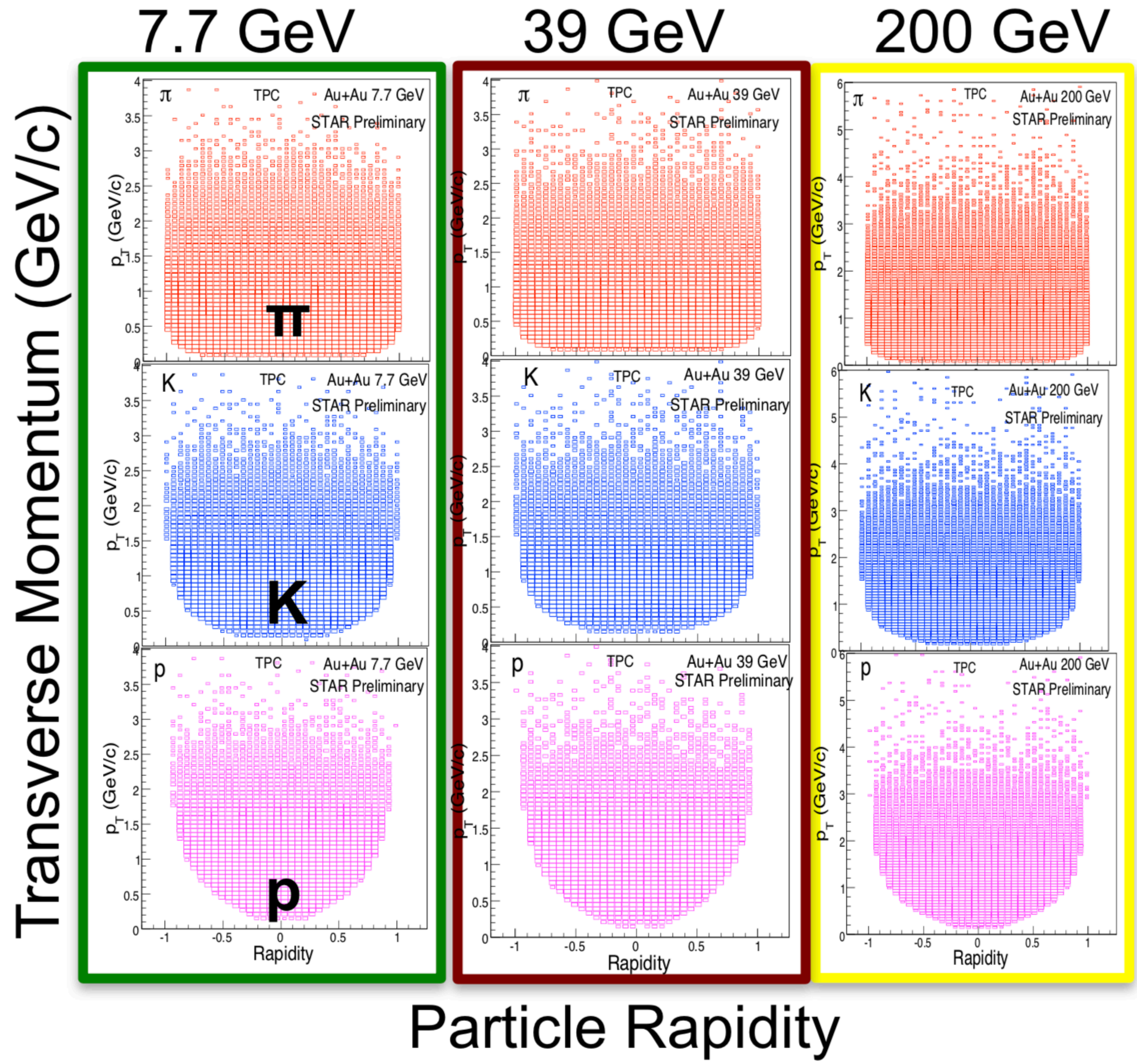
- **Crossover at μ_B = 0 MeV**
  Y. Aoki et al, Nature 443, 675(2006)
- **1st-order phase transition at large μ_B?**
- **Critical point?**

STAR detector

✓ TPC and TOF are used for fluctuation analysis.



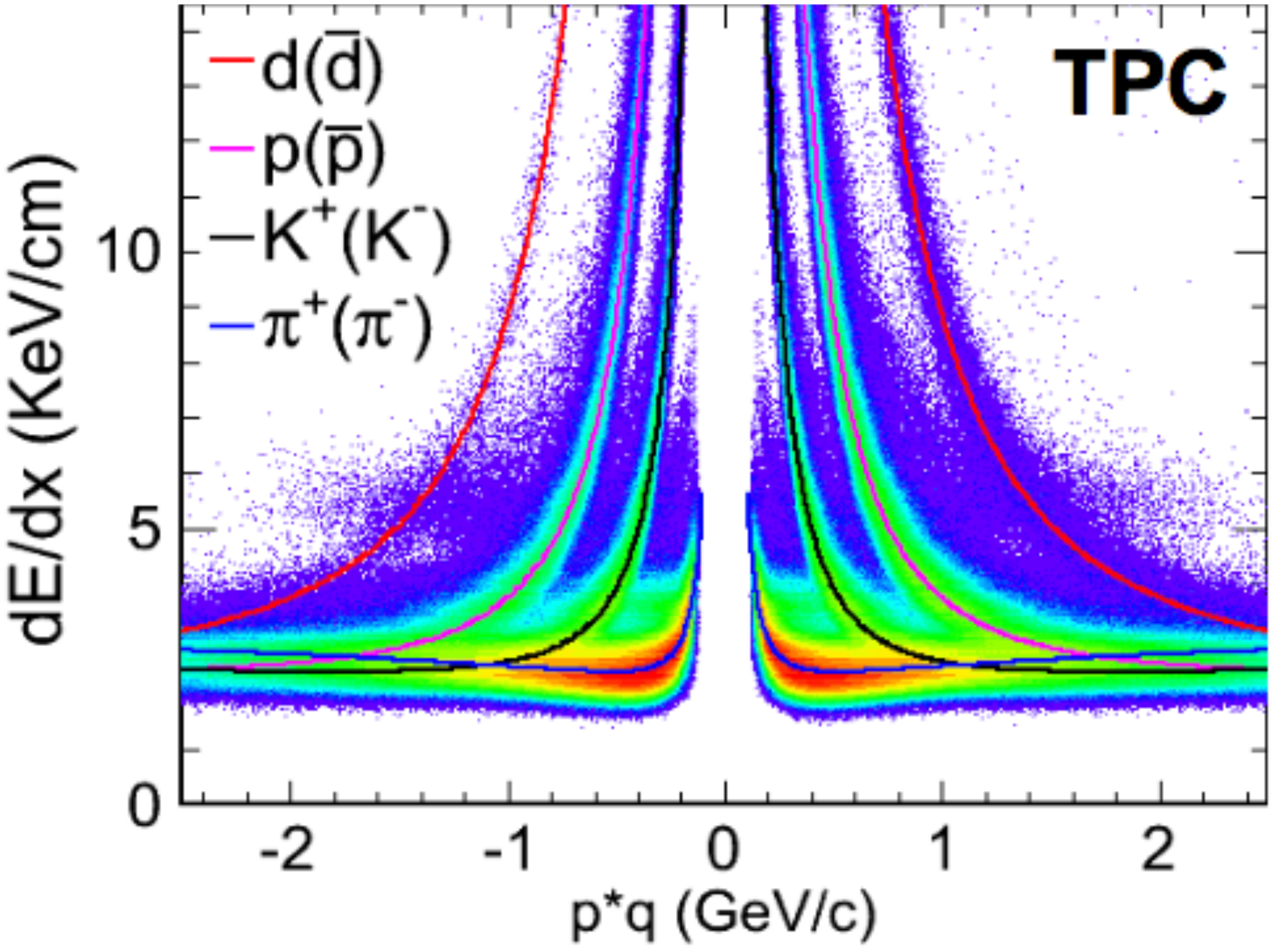
- Large & uniform acceptance (full azimuth, $|\eta|<1$)
- Excellent particle identification

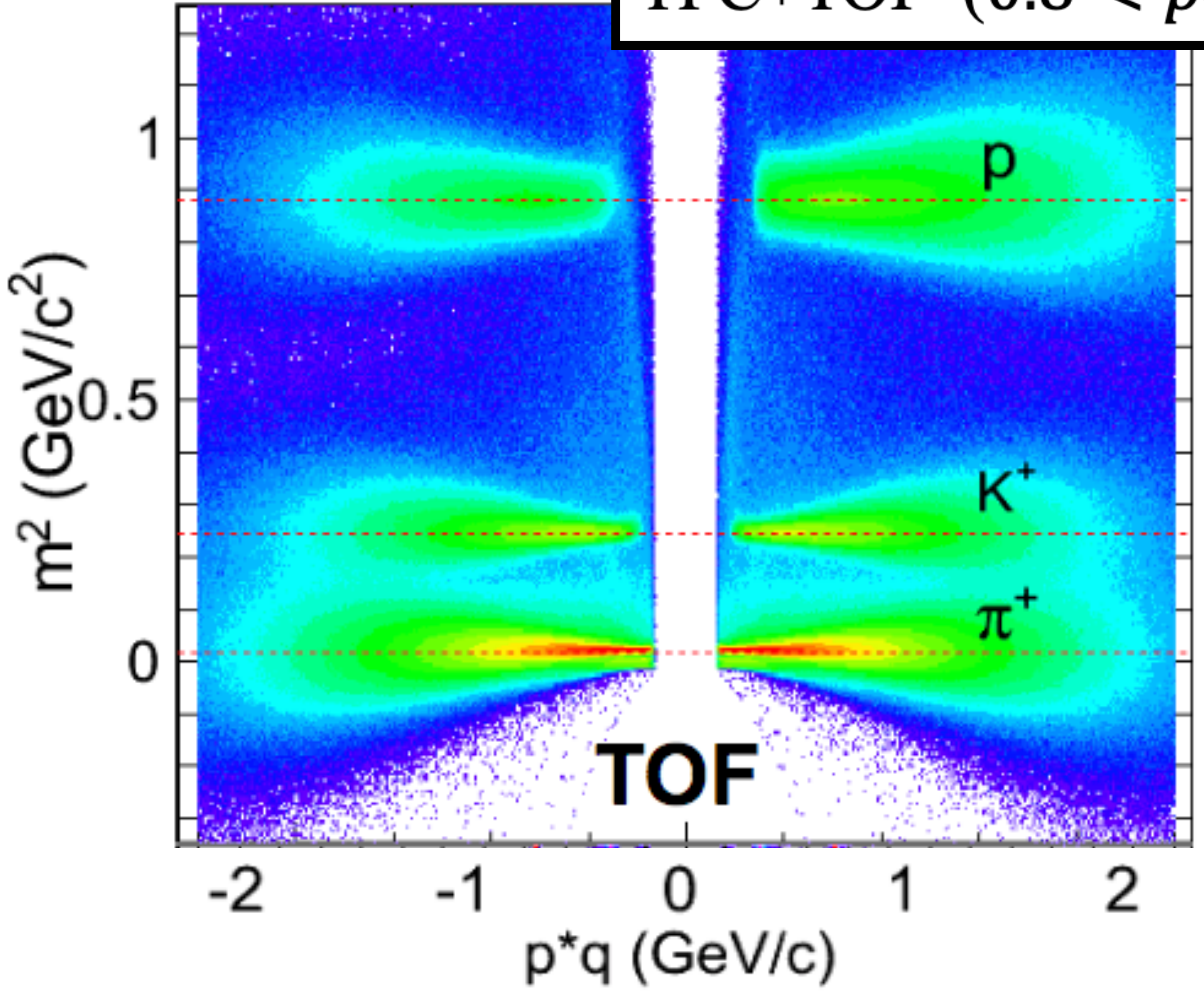


Particle identification

- ✓ dE/dx measured with TPC is used for particle identification at low p_T region.
  - ✓ < 2σ on dE/dx distribution
  - ✓ Track quality is assured based on # of hits in TPC
- ✓ The combined PID with m^2 from TOF is used at high p_T region.

Analysis window:
$0.4 < p_T < 2.0$ GeV/c, $|y| < 0.5$
Proton identification:
TPC $(0.4 < p_T < 0.8$ GeV/c$)$
TPC+TOF $(0.8 < p_T < 2.0$ GeV/c$)$

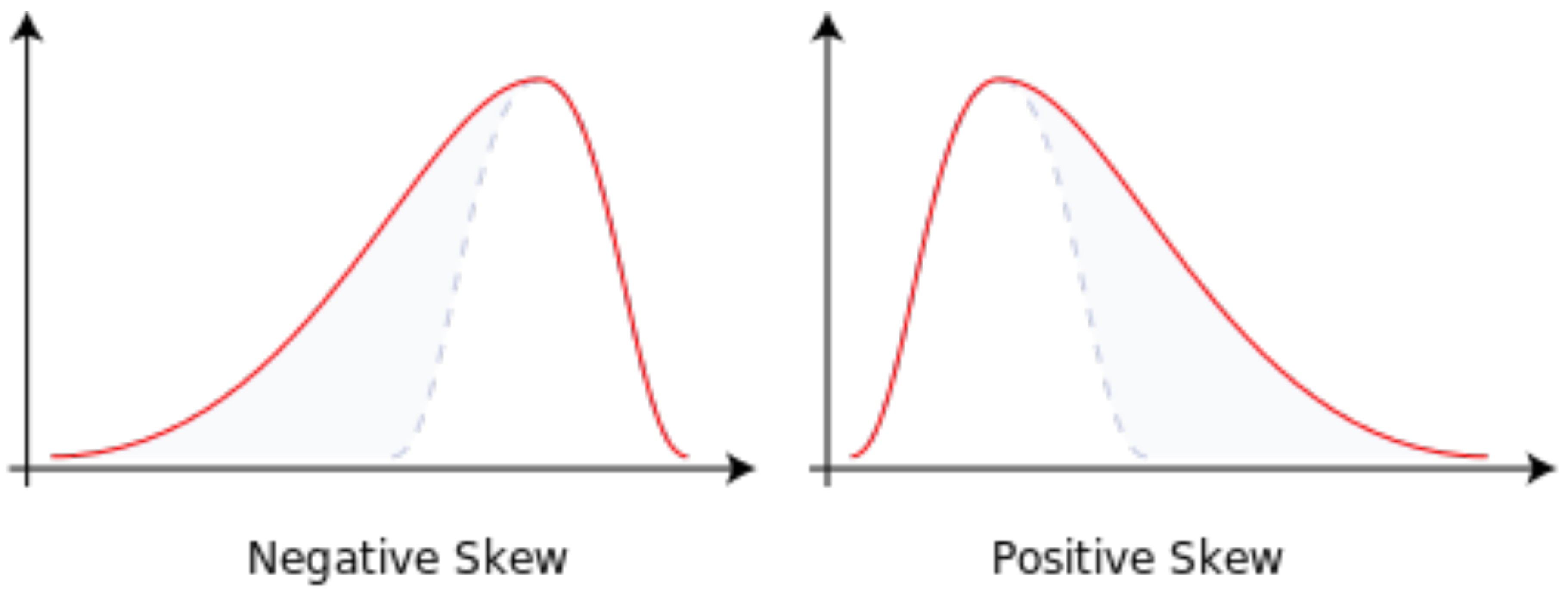




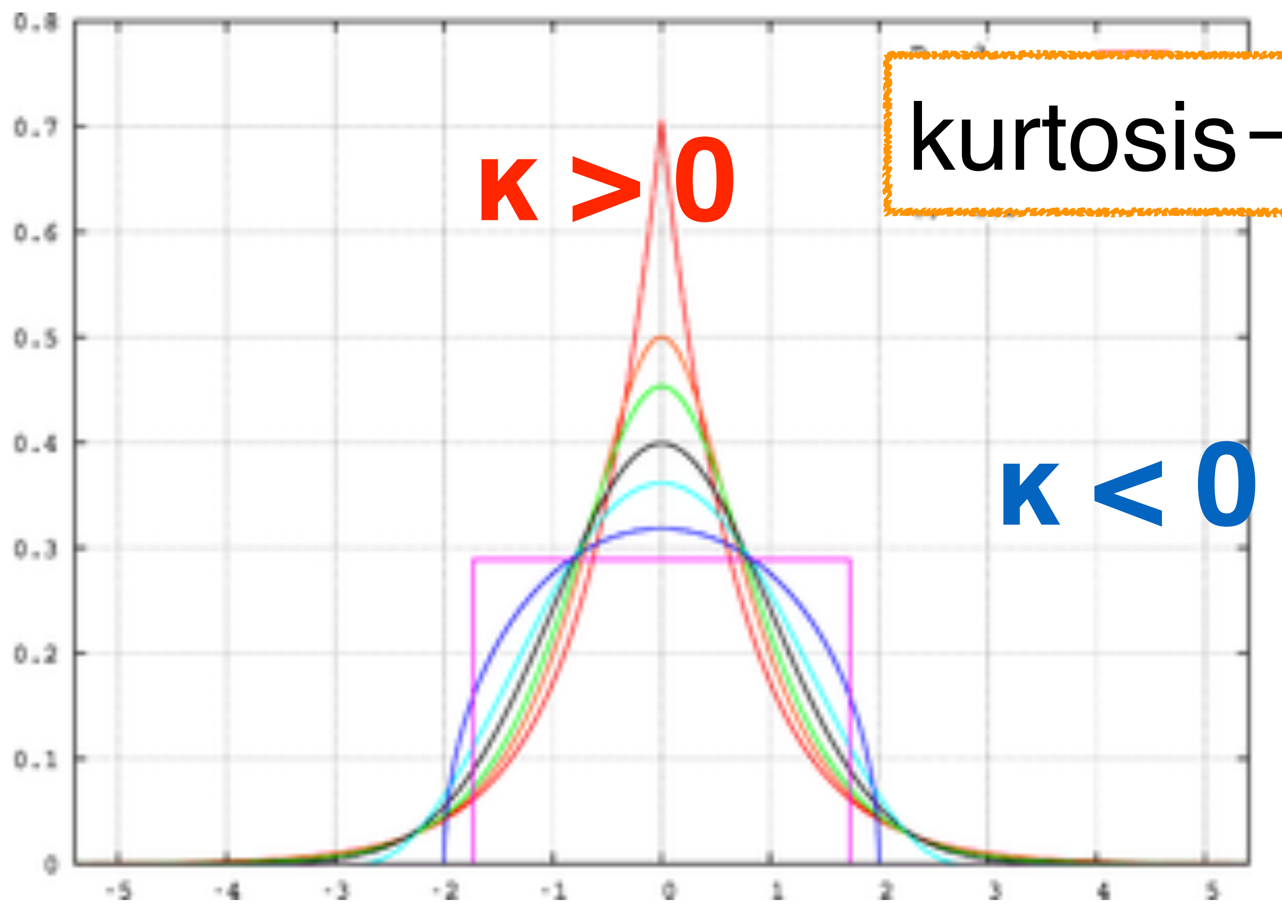
Higher-order fluctuations

- ✦ 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

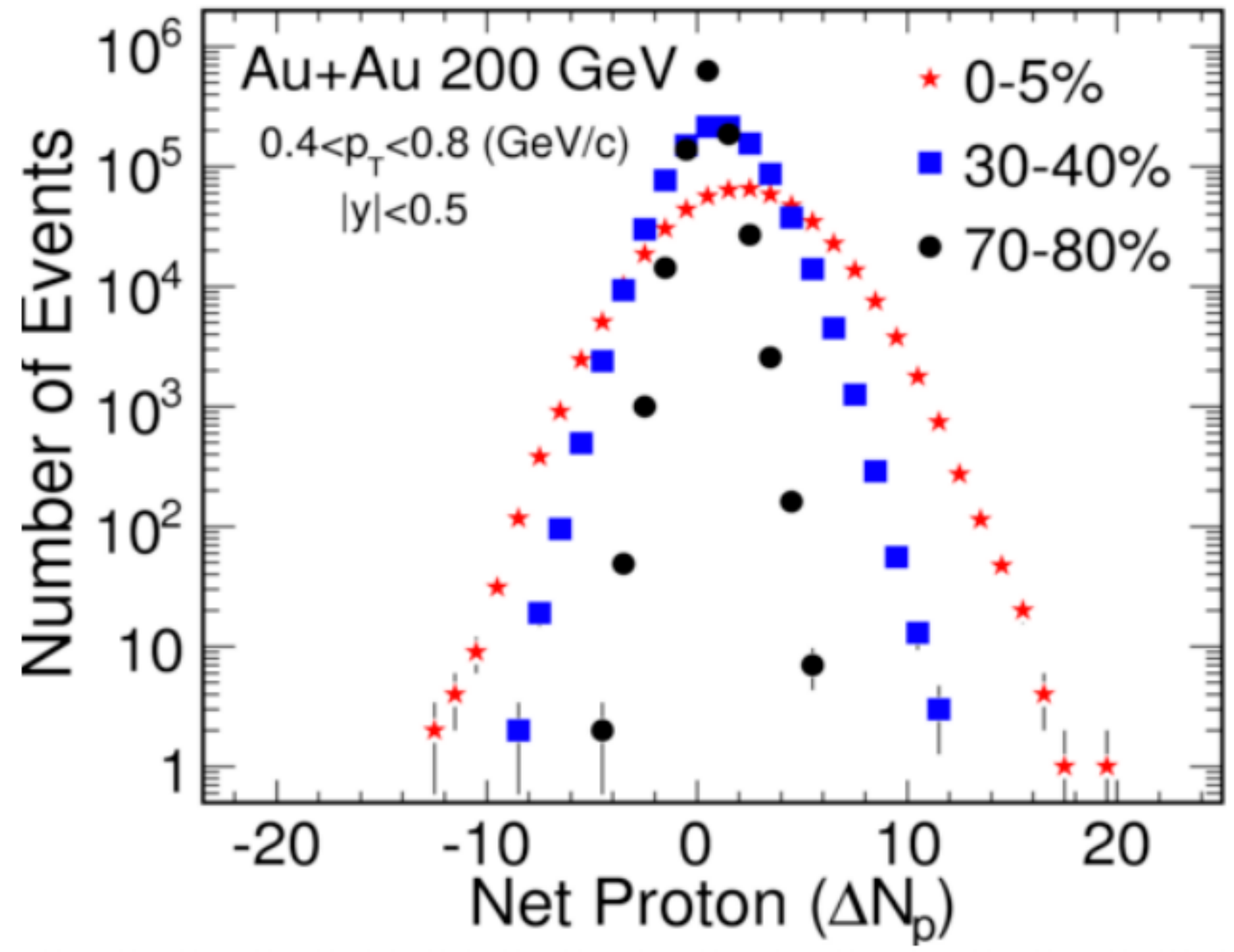
✦ Net baryon, net charge and net strangeness

"Net" : positive - negative

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

No. of positively charged particles in one collision	No. of negatively charged particles in one collision

Fill in histograms over many collisions →



→neutrons cannot be measured

(1) Sensitive to correlation length

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

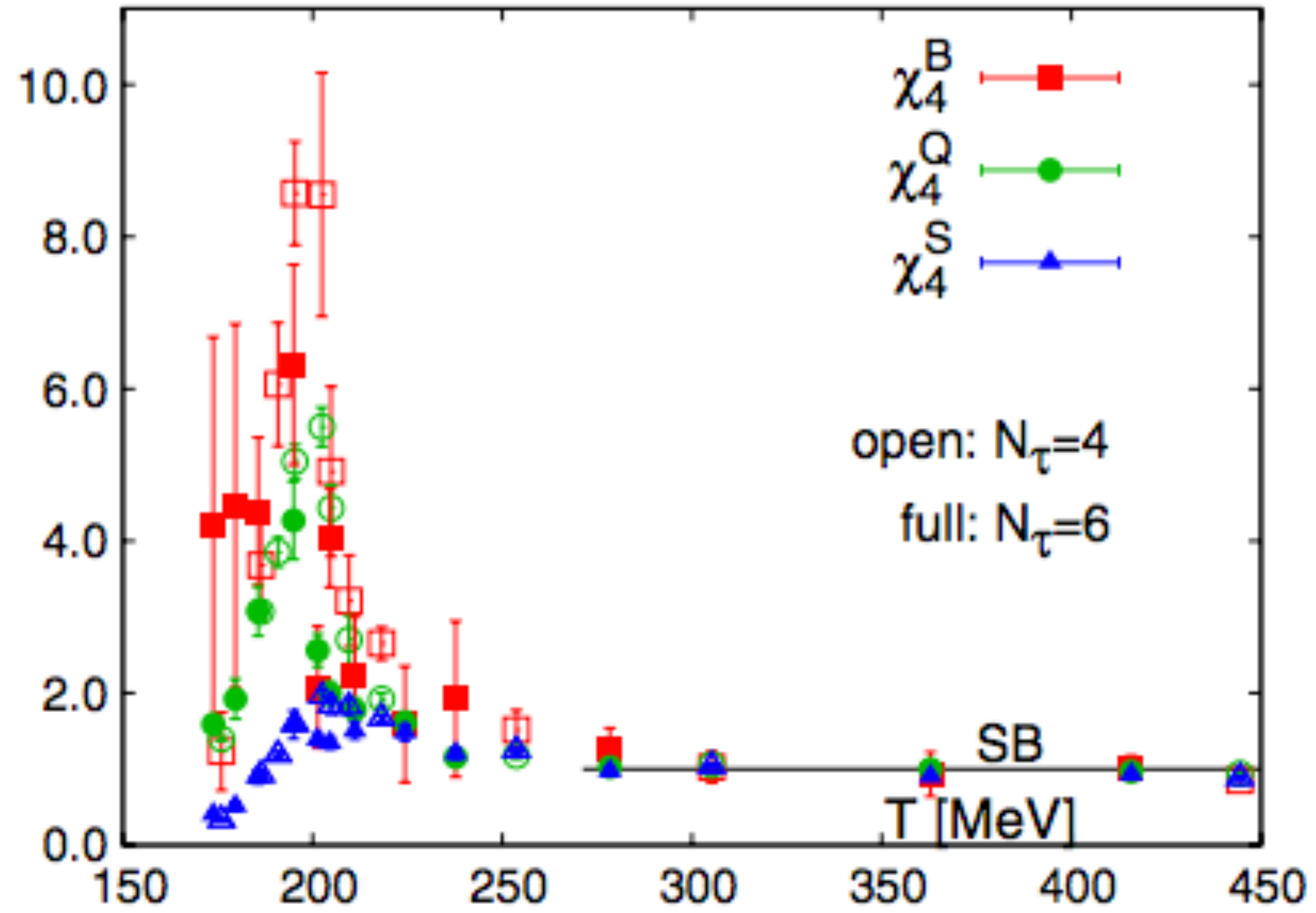
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

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

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

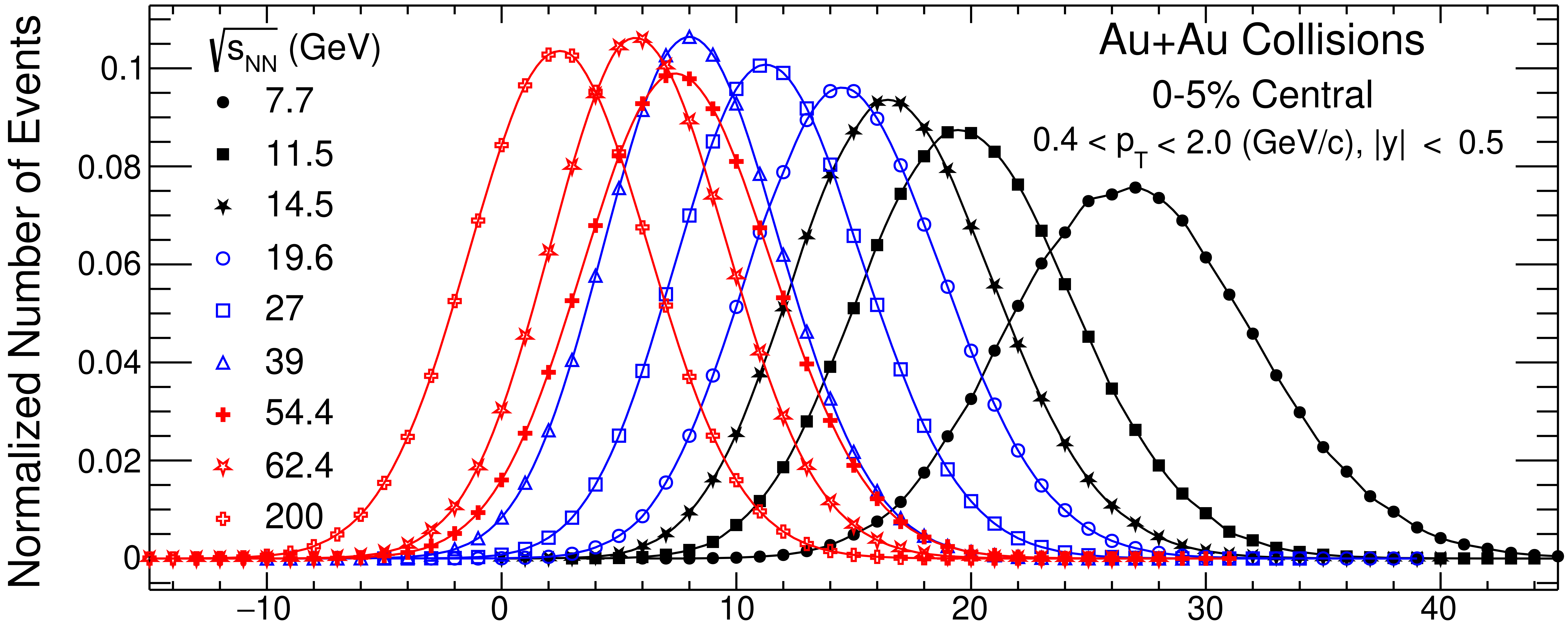
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$



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

Raw net-proton distribution

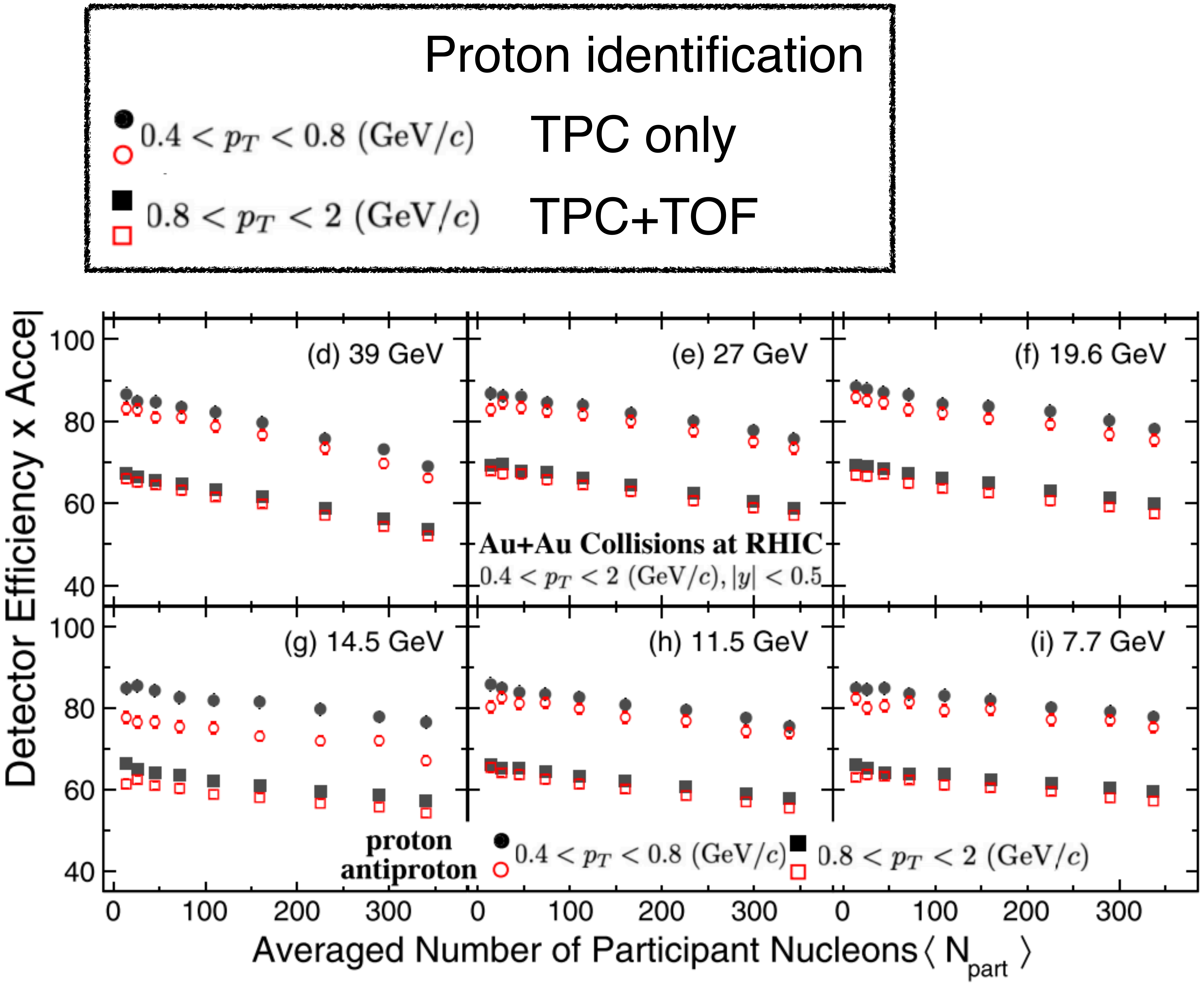
- ✓ Avoid auto-correlation effects : New centrality definition
- ✓ Suppress initial volume fluctuation : Centrality bin width correction
- ✓ Detector efficiency correction : Binomial model



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)

Efficiency correction



STAR Collaboration, PRC.104.024902(2021)

- ✓ Efficiencies are assumed to follow binomial distributions.

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

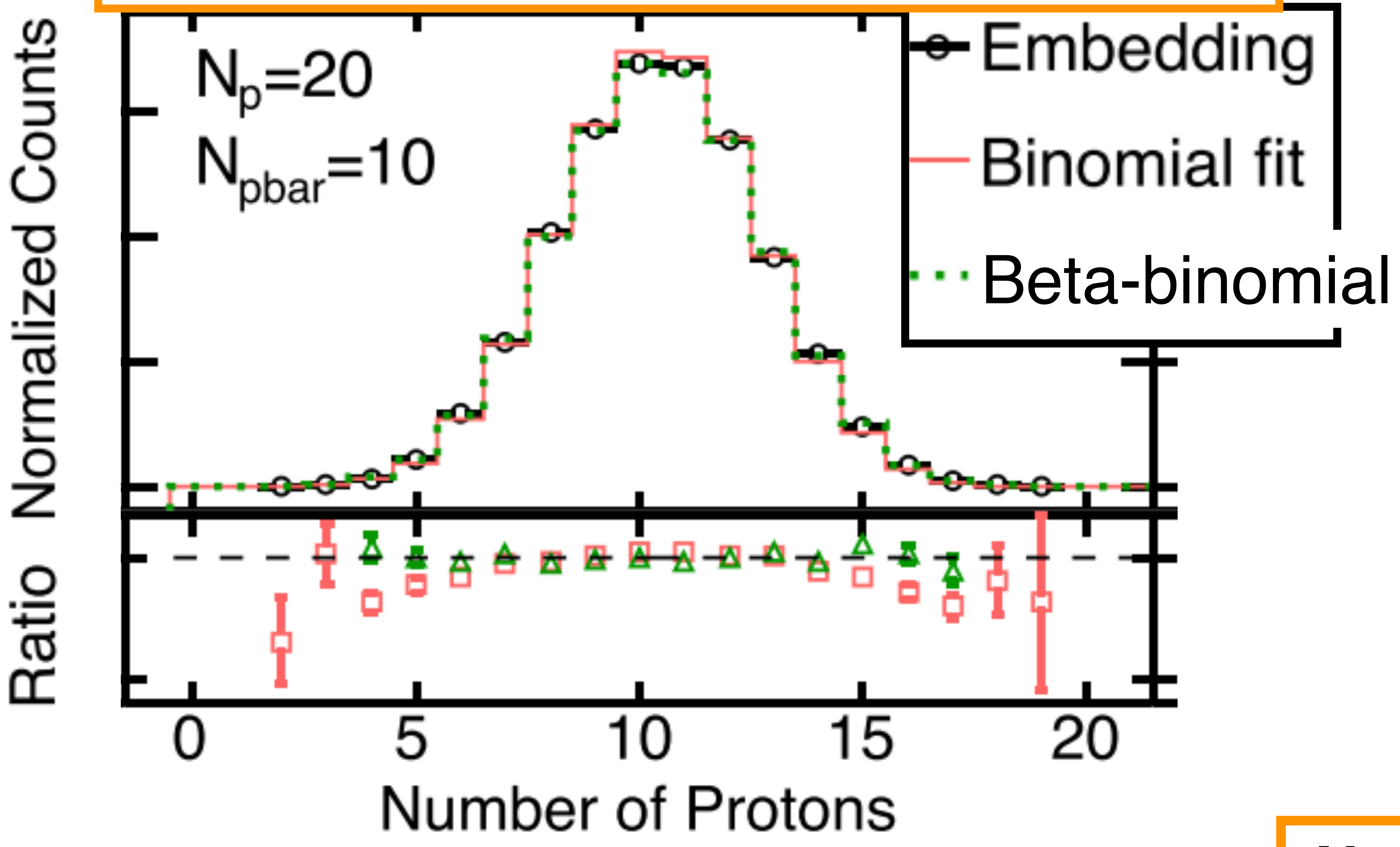
- ✓ Multiplicity and p_T dependence are taken into account.

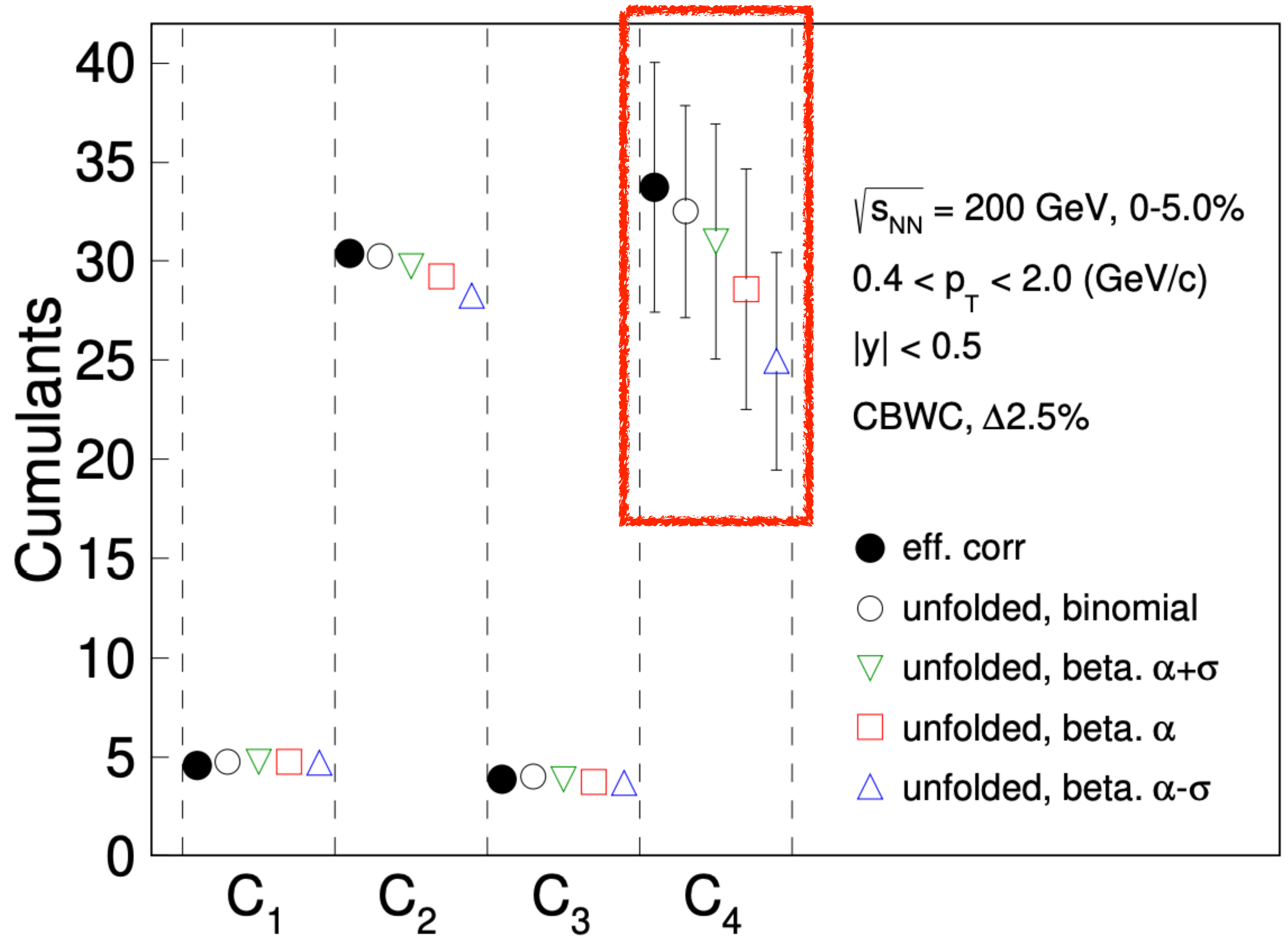
M. Kitazawa : PRC.86.024904(2012)
A. Bzdak and V. Koch : PRC.86.044904(2012)
X. Luo : PRC.91.034907(2016)
T. Nonaka, M. Kitazawa, S. Esumi : PRC.95.064912(2017)
X. Luo, T. Nonaka : PRC.99.044917(2019)

Non-binomial efficiency correction

- ✓ Efficiency distributions need to be carefully studied through simulations.
- ✓ **Higher-order cumulants from non-binomial efficiency corrections are consistent with binomial corrections.**

Slightly deviates from binomial distribution



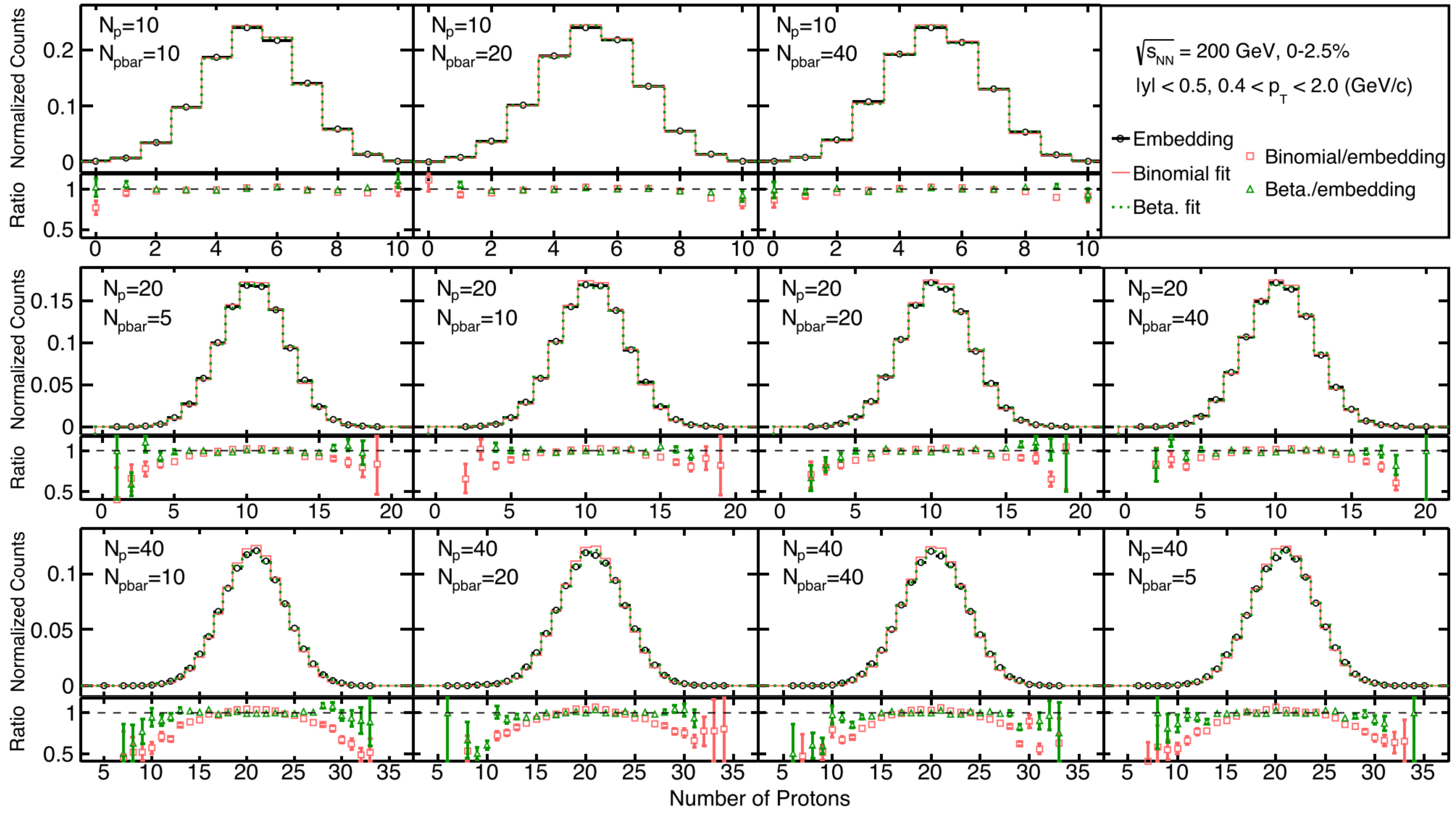


STAR Collaboration, PRC.104.024902(2021)
STAR Collaboration, PRL.126.092301(2021)

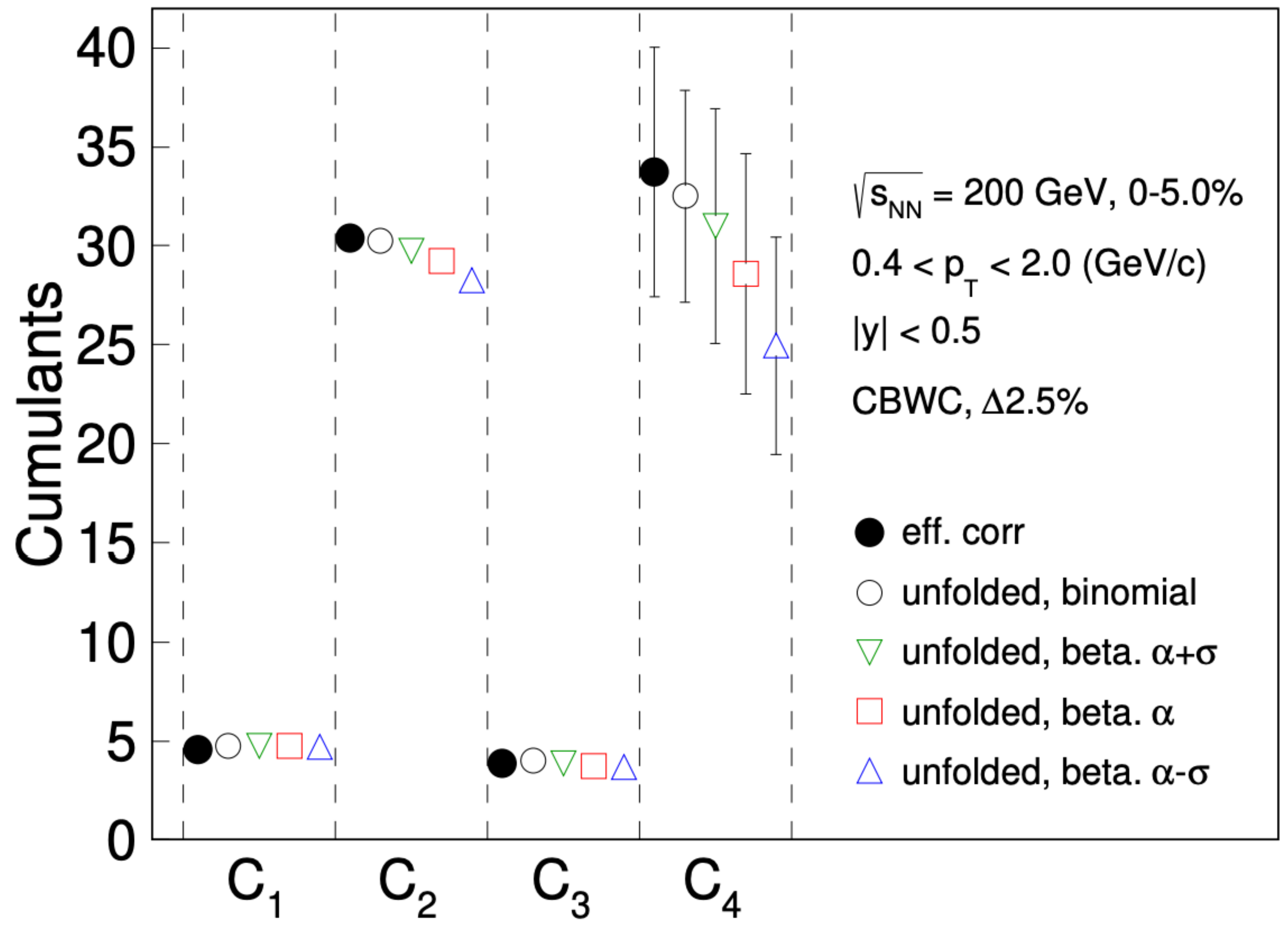
Non-binomial efficiency correction
Unfolding: Esumi, Nakagawa, Nonaka, NIMA.987.164802(2021)
Moment expansion: Nonaka, Kitazawa, Esumi, NIMA906 10-17 (2018)

Non-binomial efficiency correction

- ✓ Efficiency distributions are studied via simulations to check the binomial assumption.
- ✓ Results of non-binomial efficiency corrections are consistent with those from conventional binomial corrections.



STAR Collaboration, PRC.104.024902(2021)

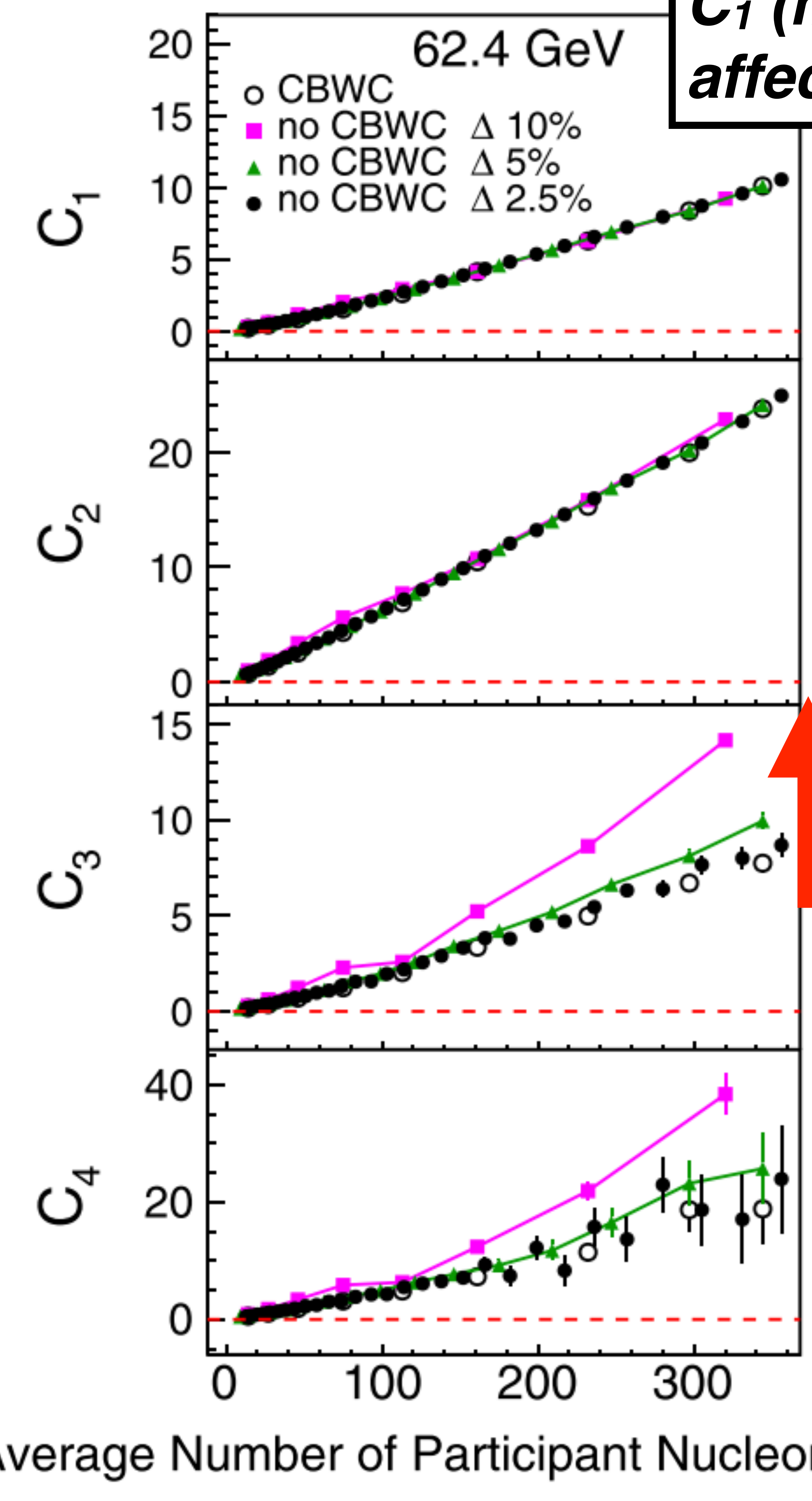


STAR Collaboration, PRL.126.092301(2021)

Unfolding: Esumi, Nakagawa, Nonaka, NIMA.987.164802(2021)

Moment expansion: Nonaka, Kitazawa, Esumi, NIMA906 10-17 (2018)

Centrality bin width correction



STAR Collaboration, PRC.104.024902(2021)

C_1 (mean) is not affected by definition

- ✓ Final state multiplicity and initial geometry are not one-to-one corresponding → volume fluctuation
- ✓ **Higher-order cumulants are artificially enhanced by volume fluctuations.**
- ✓ Data driven approach (CBWC) is applied.

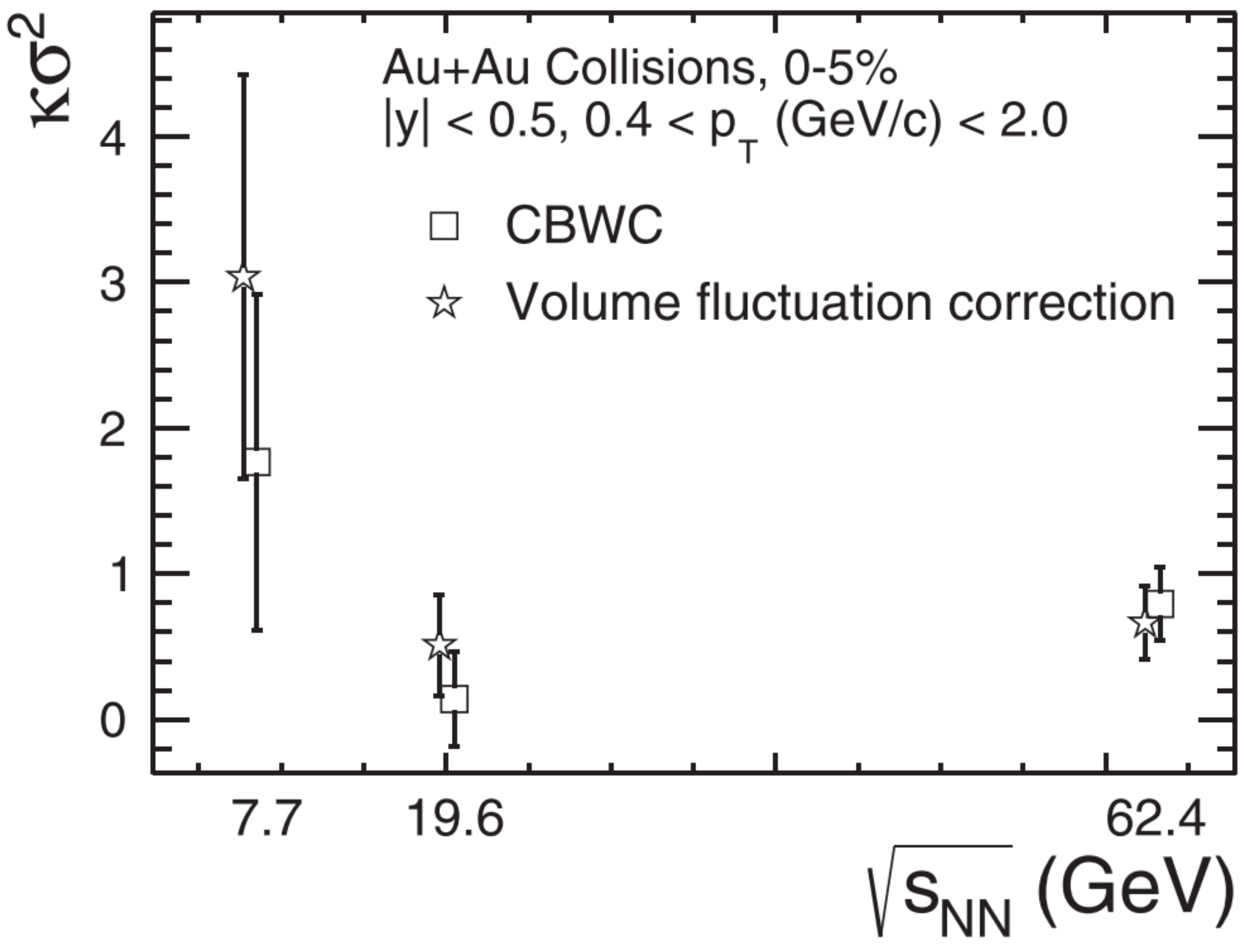
X.Luo et al, J. Phys. G40,105104(2013)

no CBWC Δ 10%
no CBWC Δ 5%
no CBWC Δ 2.5%

Wider centrality bin: larger value of higher-order cumulants

Volume fluctuation correction

✓ Data driven approach (CBWC) and model dependent method (VFC) are consistent with each other in BES-I data.



STAR Collaboration, PRC.104.024902(2021)

Measured cumulant | True cumulant

Additional terms appear from the event by event participant fluctuation

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

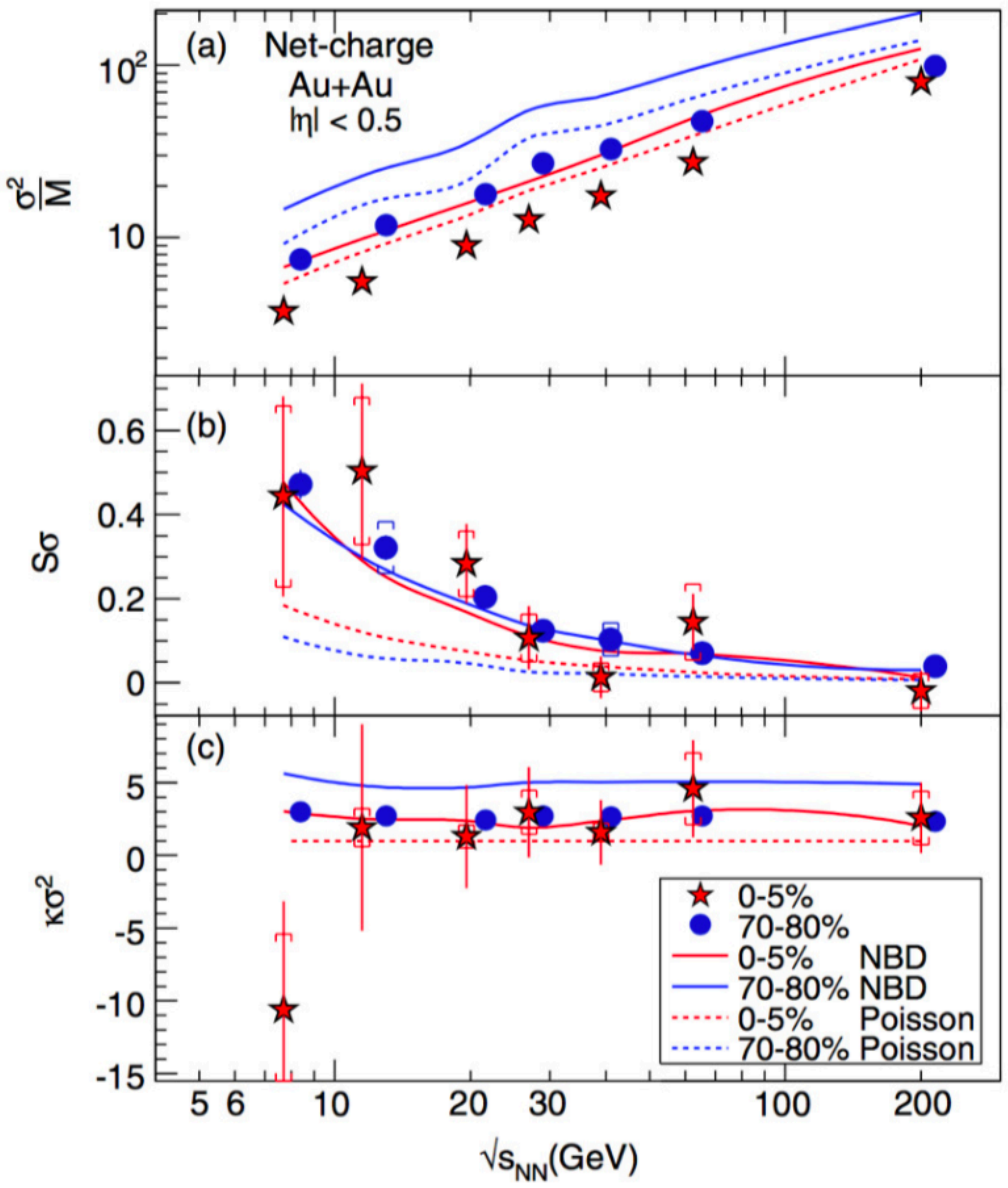
P. Braun-Munzinger, A. Rustamov, J. Stachel: *NPA.2017.01.011*

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

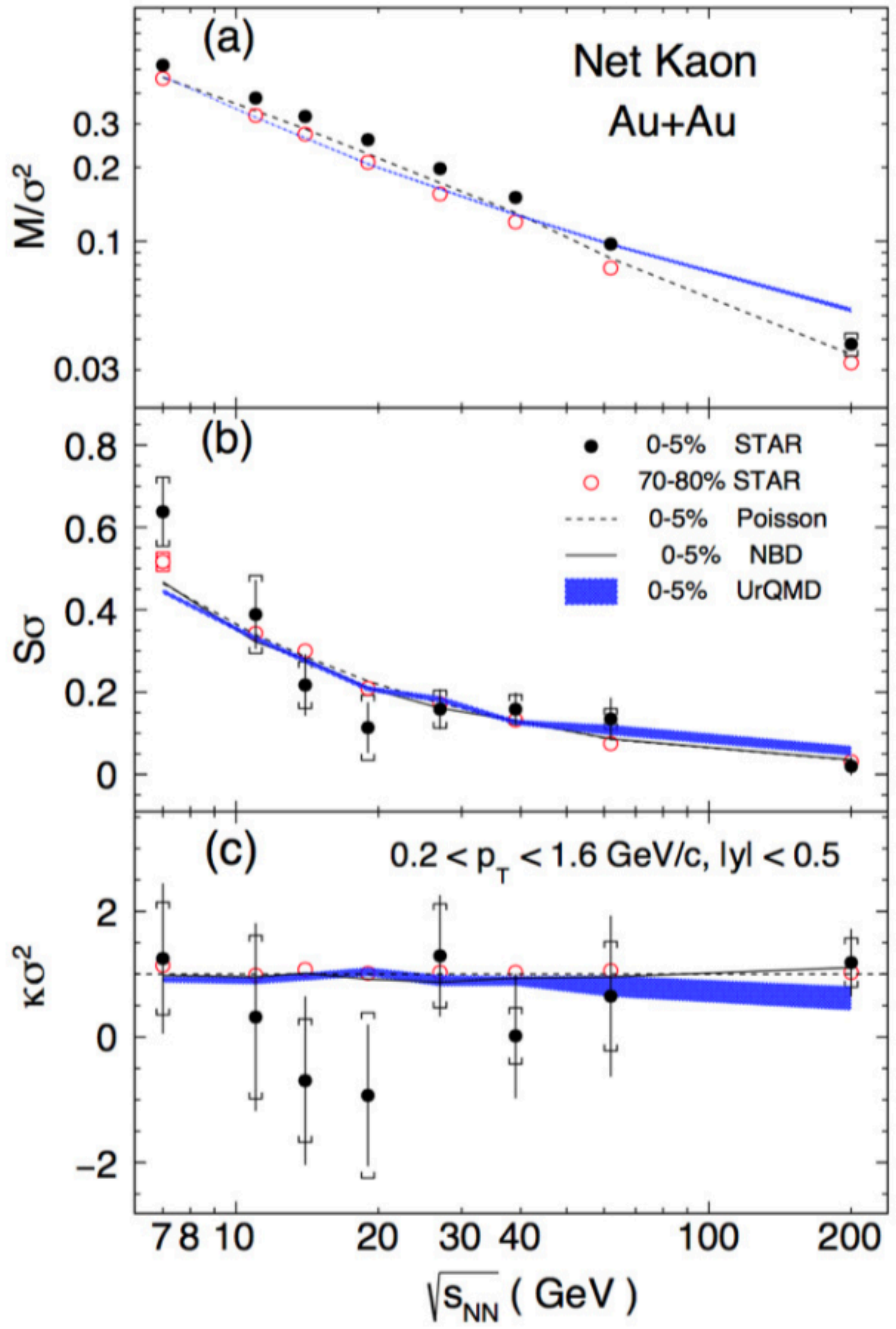
Taylor expansion around the mean volume employed in HADES: Phys.Rev.C 102 (2020) 2, 024914

Net-charge and net-kaon

STAR: PRL113, 092301(2014)



STAR: PLB, 785, 551(2018)

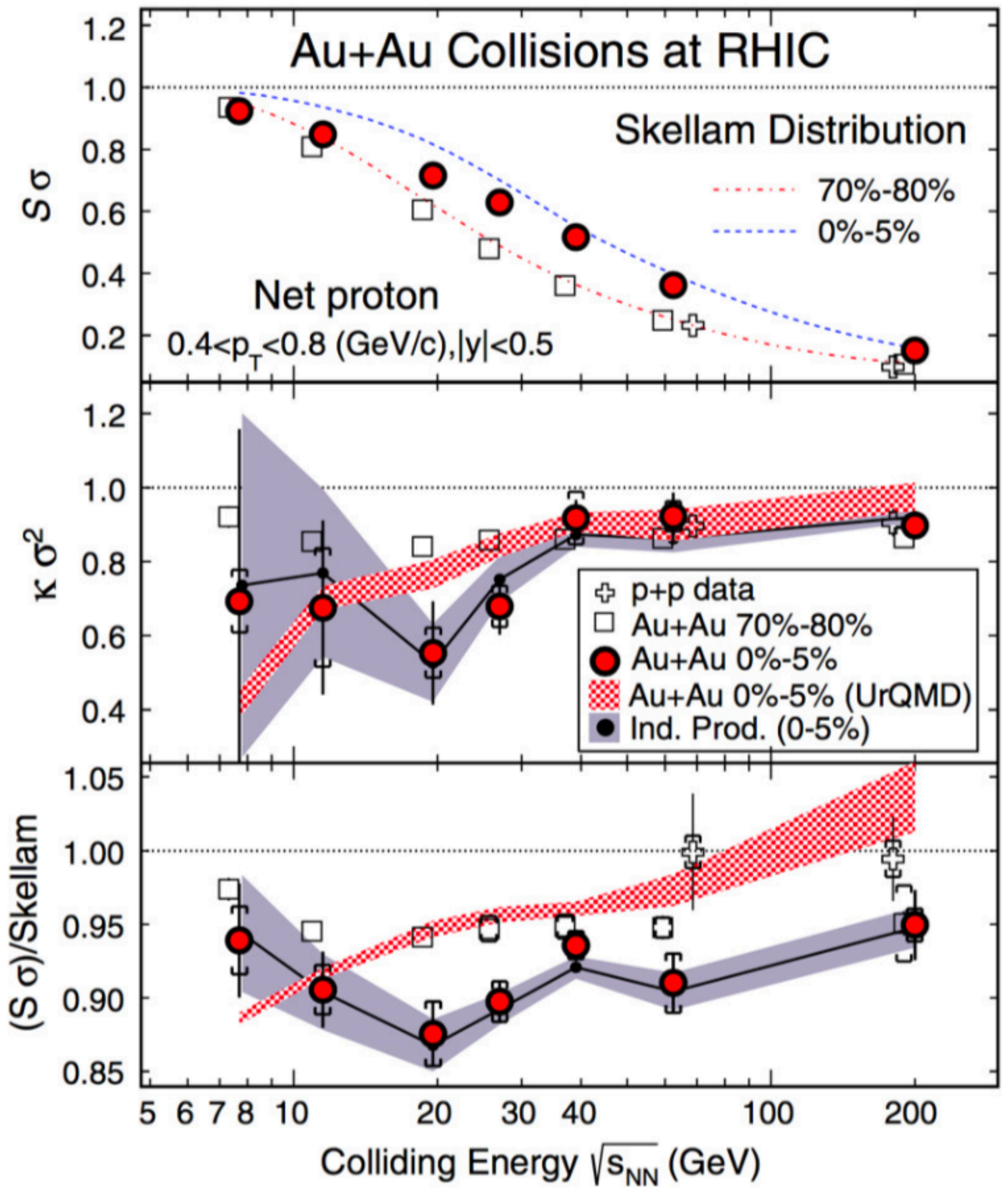


- ✓ **Statistical errors depend on width of the distribution and detector efficiencies.**

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

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

Net-proton

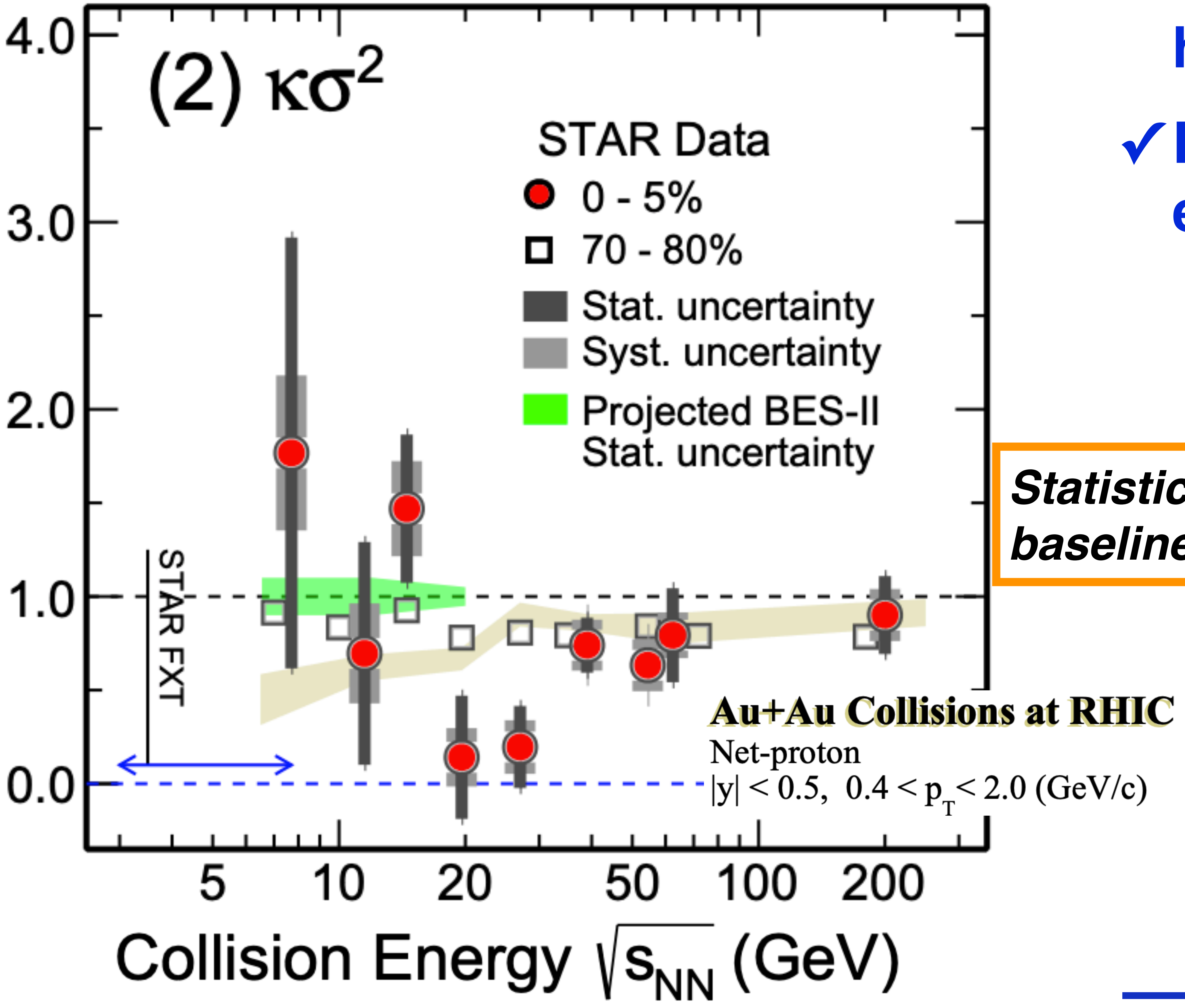


- ✓ **Deviation below Poisson baseline (unity).**
- ✓ **Both 3rd- and 4th-order fluctuations have their minima at $\sqrt{s_{NN}}$ = 19.6 GeV.**

PRL112, 032302(2014): STAR Collaboration

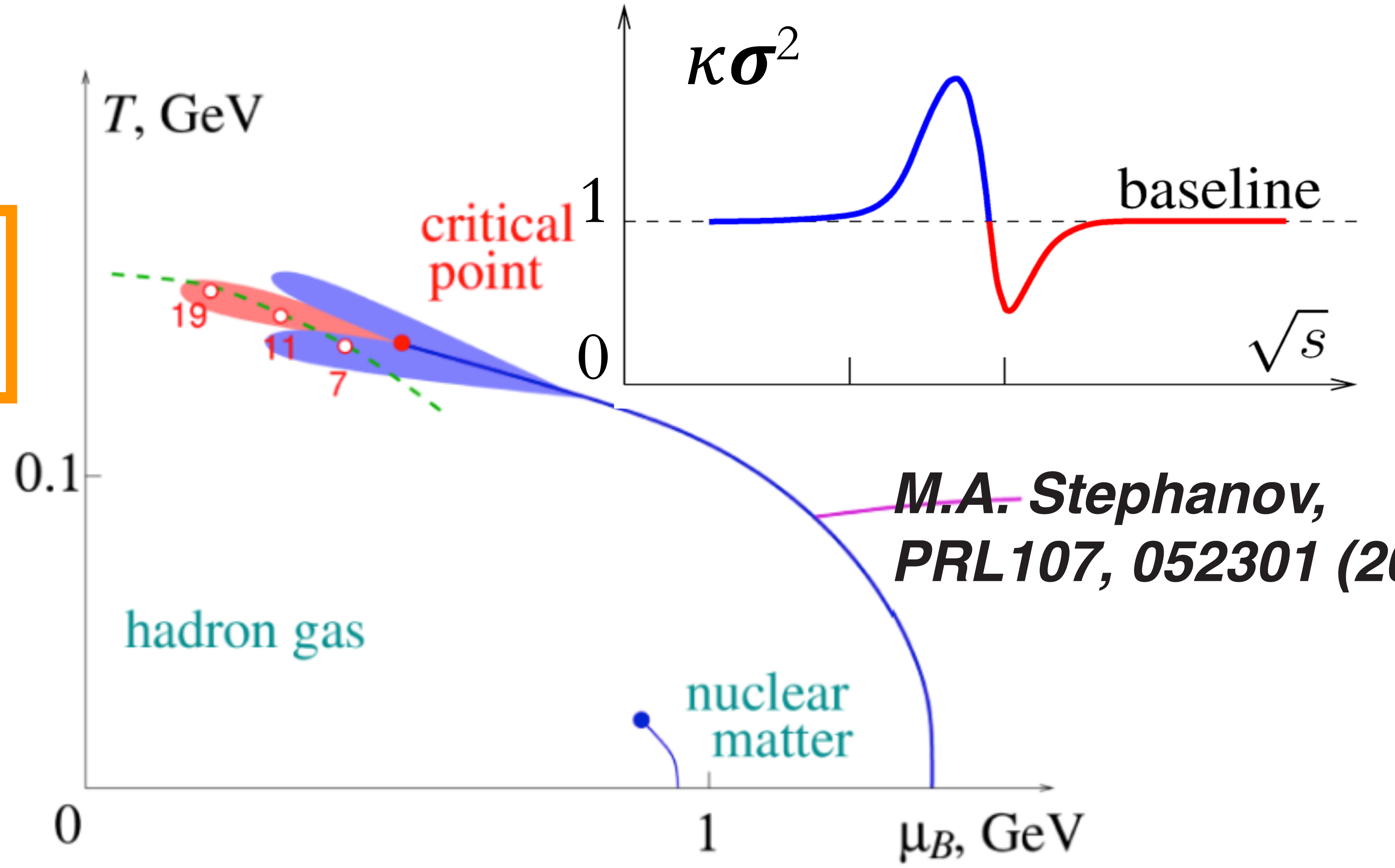
Net-proton C_4/C_2 with extended p_T coverage

STAR Collaboration, PRL.126.092301(2021)



Statistical baseline: C_4/C_2=1

- ✓ 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.

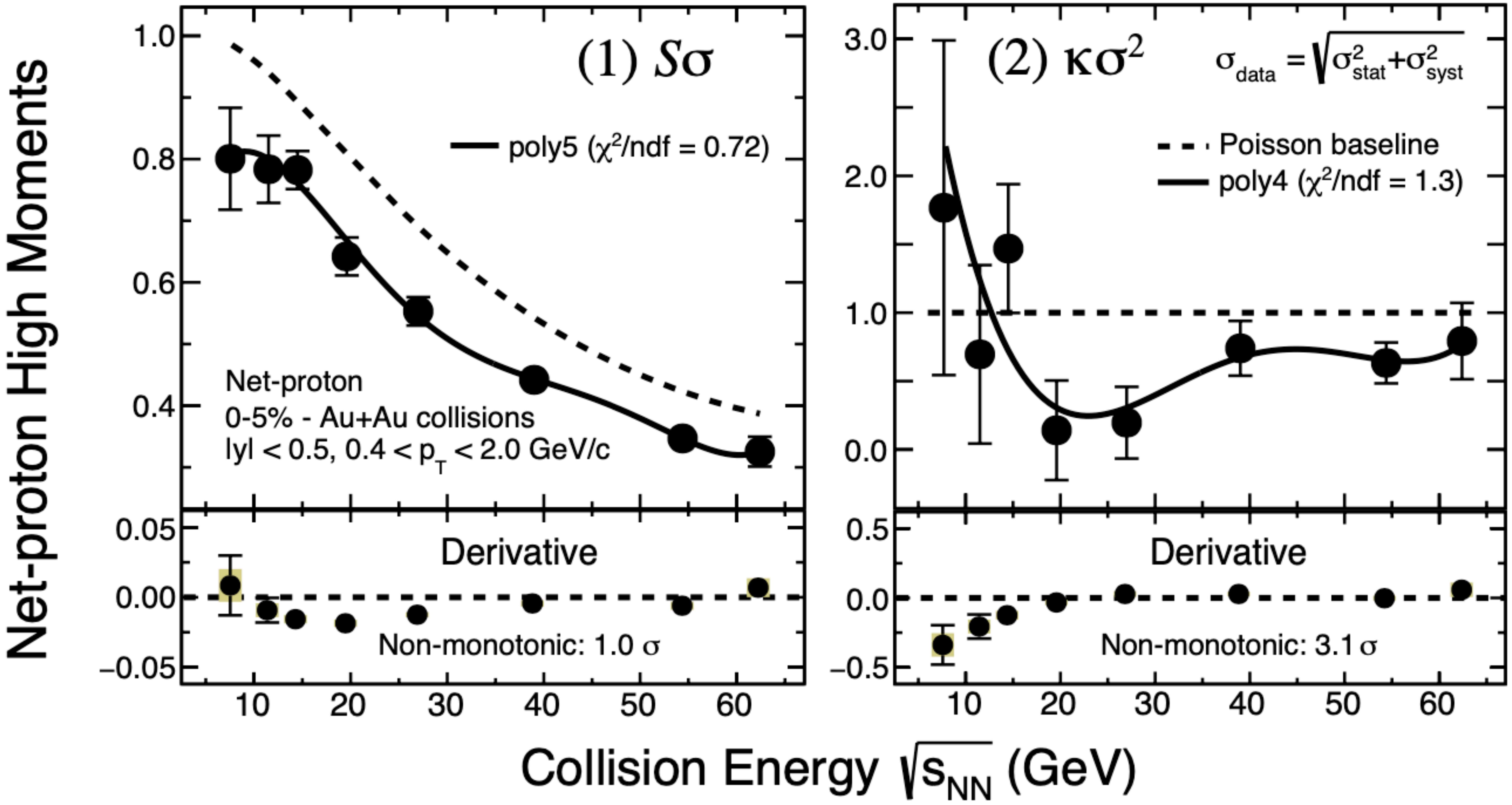


M.A. Stephanov, PRL107, 052301 (2011)

Non-monotonicity

✓ Polynomial fits are done varying the data point within uncertainties.

✓ Check the probability that at least one point of derivatives at 8 energies has different sign from others → **3.1σ significance of non-monotonicity for $\kappa\sigma^2$**

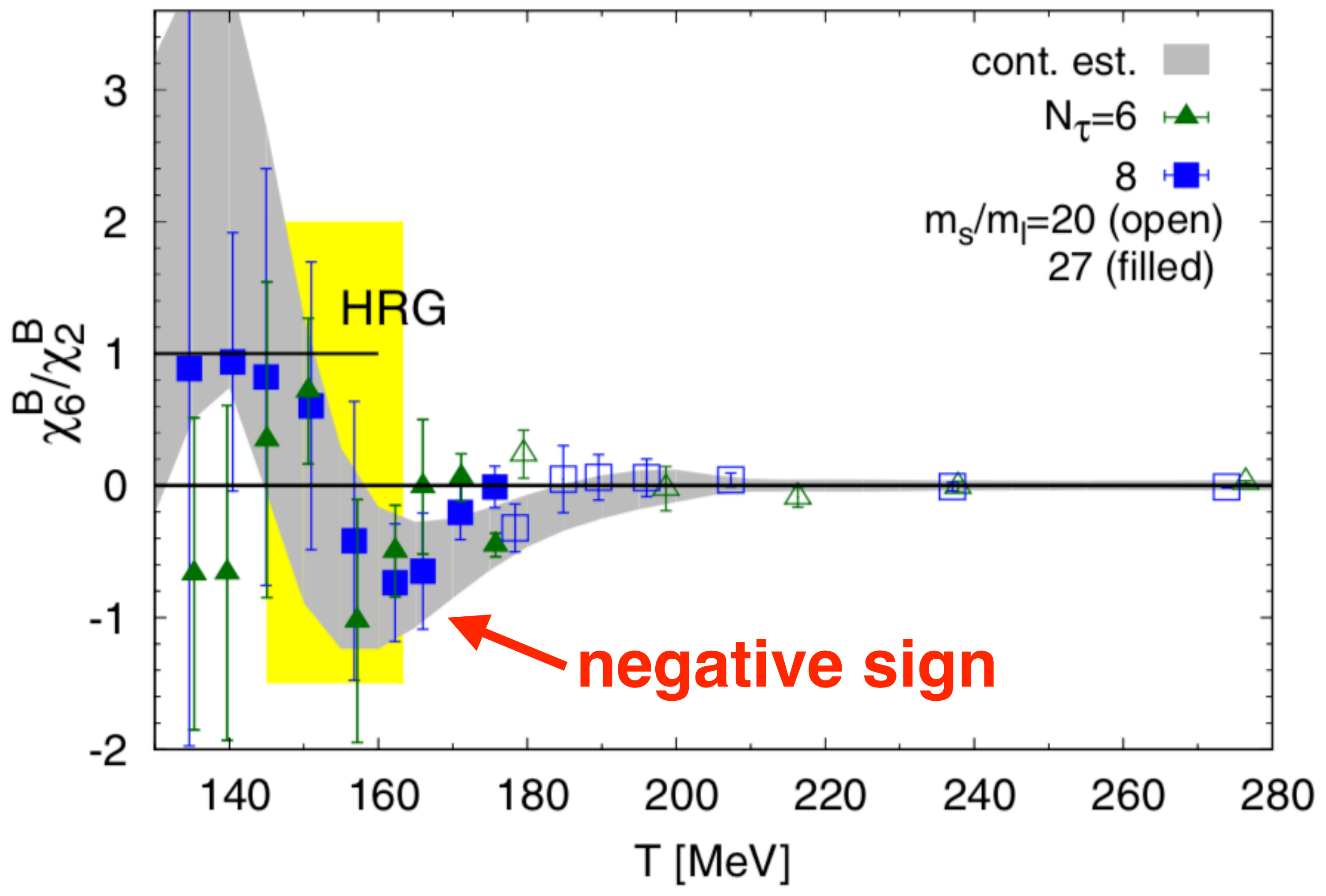


STAR Collaboration, PRL.126.092301(2021)

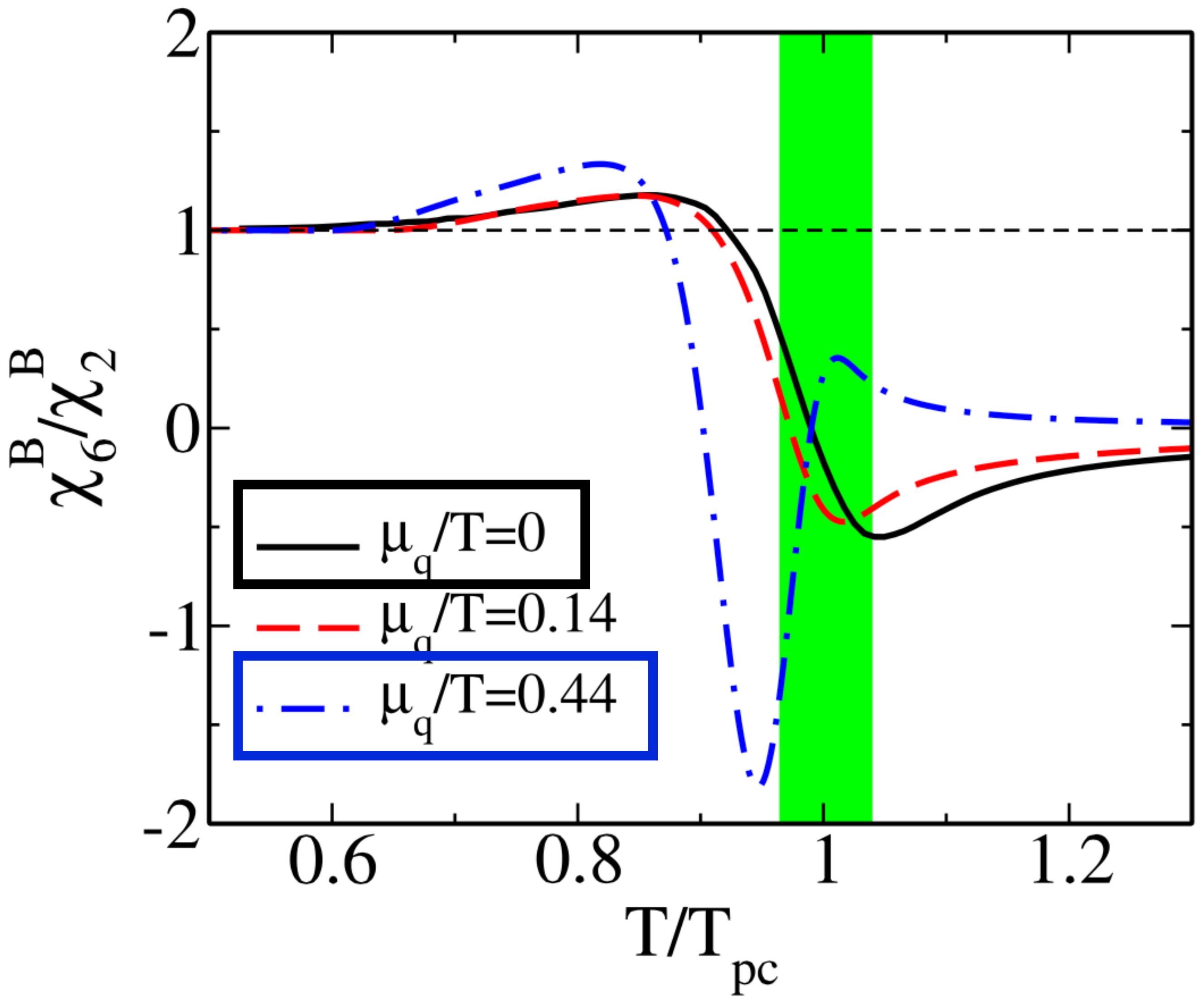
C_6/C_2 for crossover search

- ✓ There isn't yet any direct experimental evidence for the smooth crossover at μ_B~0.
- ✓ **C_6/C_2 < 0** is predicted 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

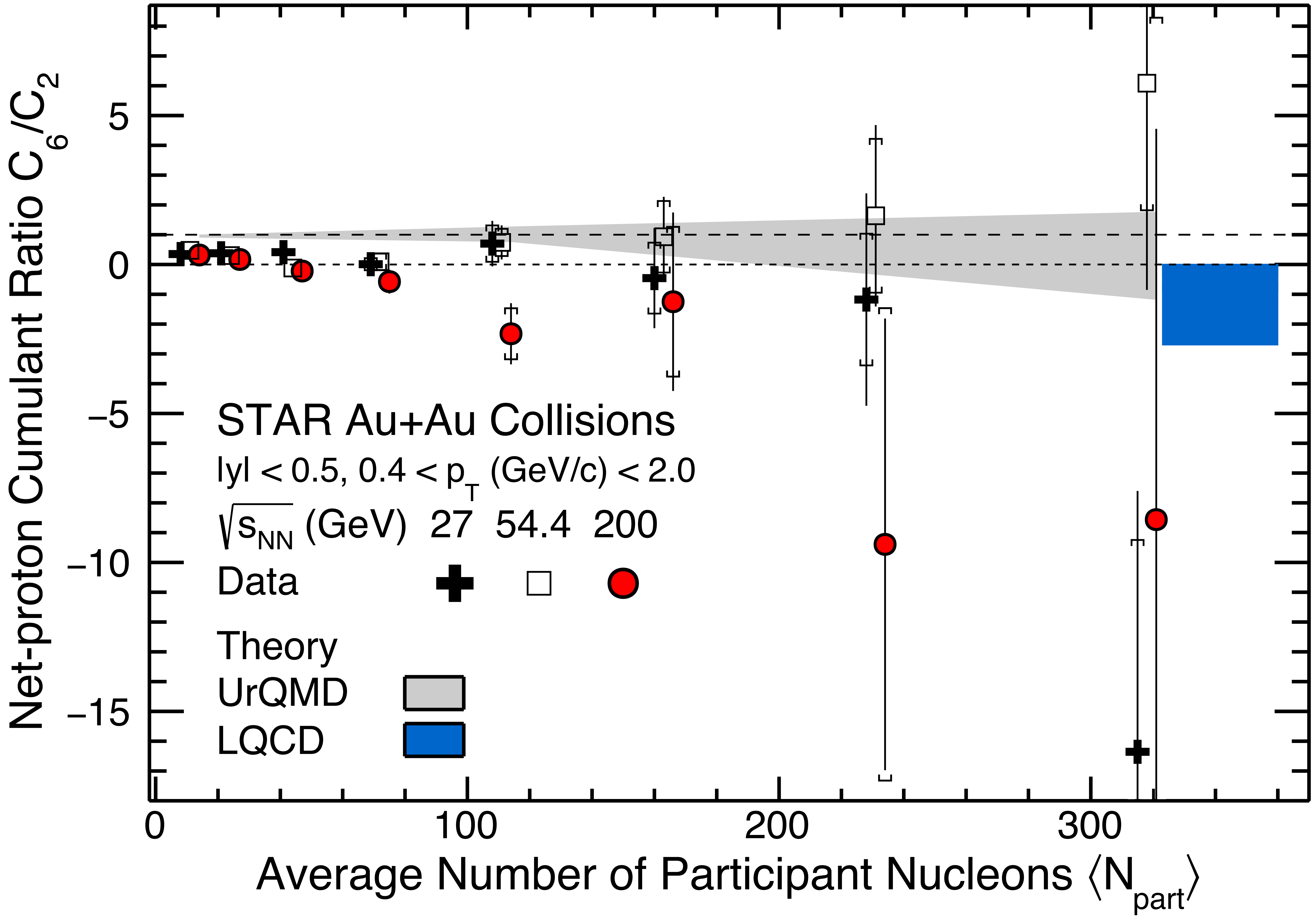


C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

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	~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

Centrality dependence

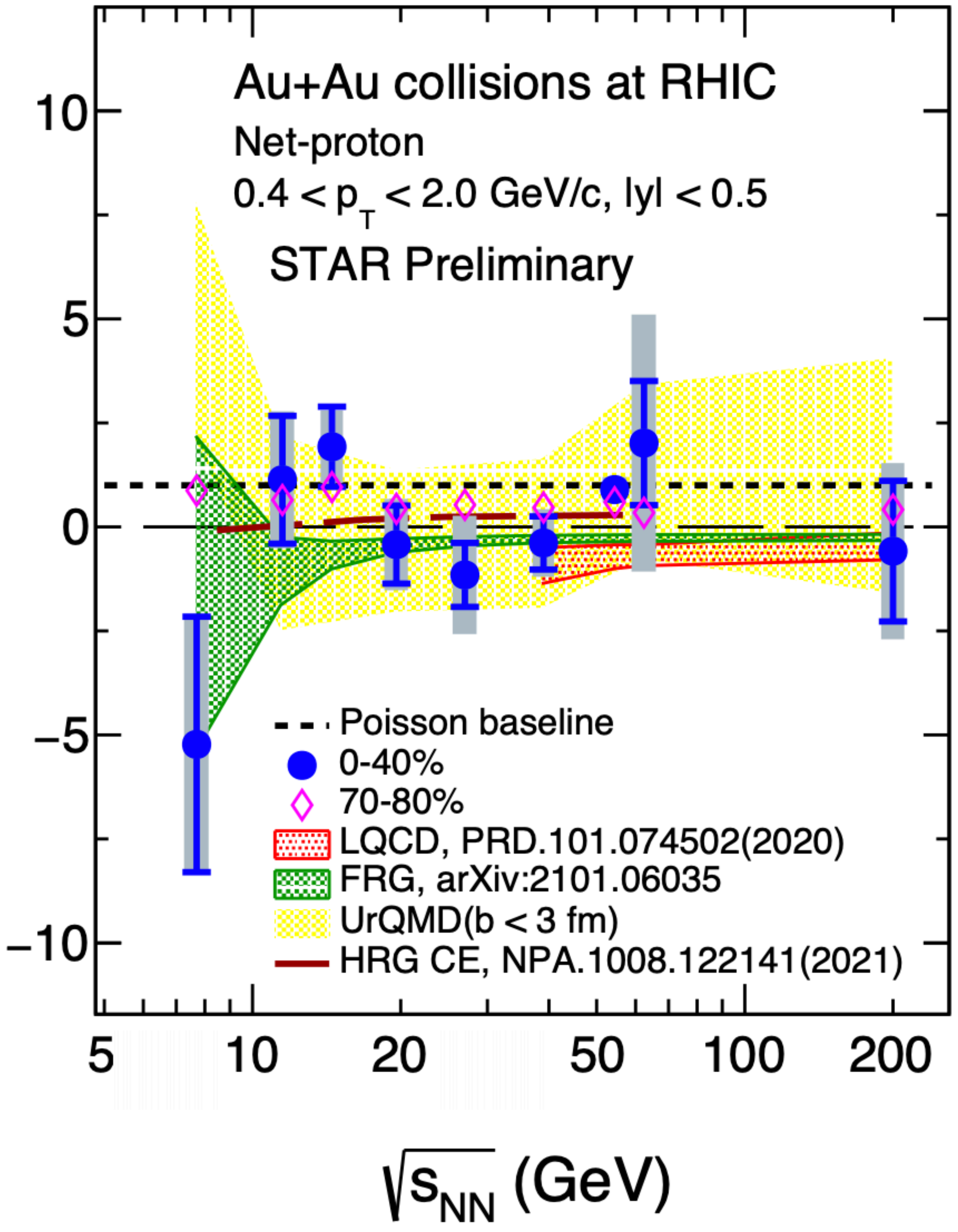


- ✓ C_6/C_2 values are progressively negative from peripheral to central collisions at 200 GeV, which is consistent with LQCD calculations.
- ✓ Could suggest a smooth crossover transition at top RHIC energy.

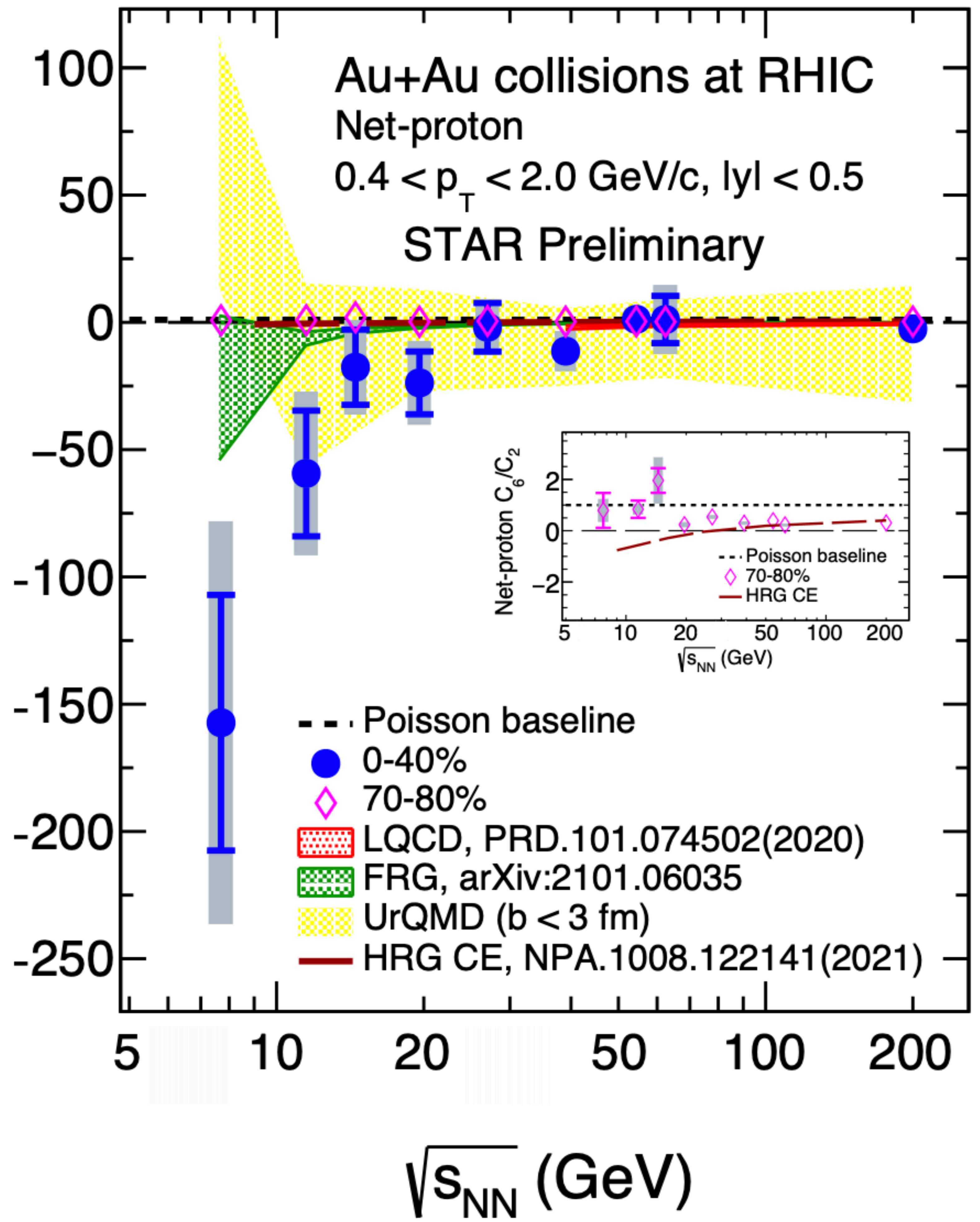
STAR, arXiv:2105.14698 (accepted by PRL)

Energy dependence of C_5/C_1 and C_6/C_2

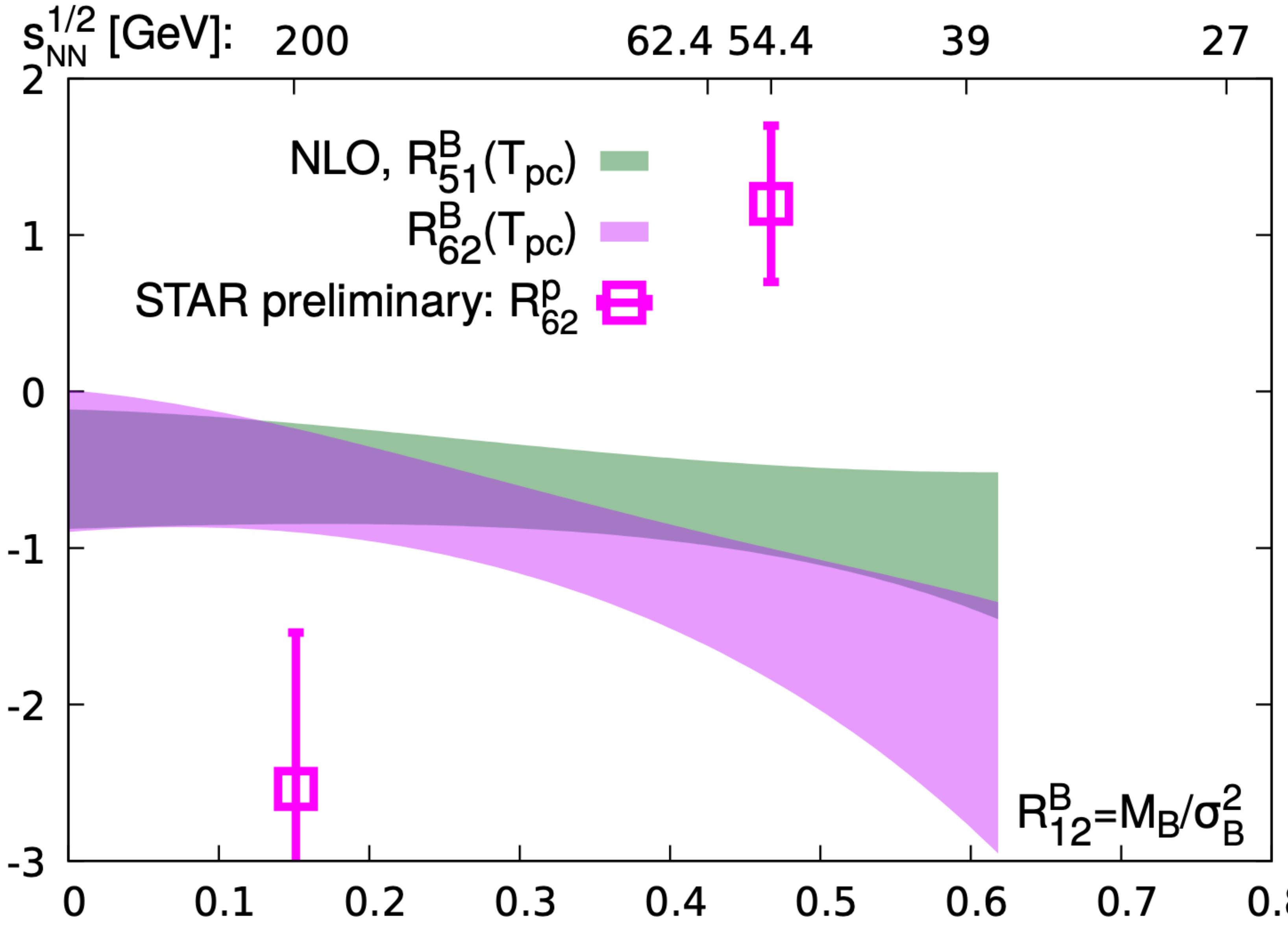
C_5/C_1



C_6/C_2



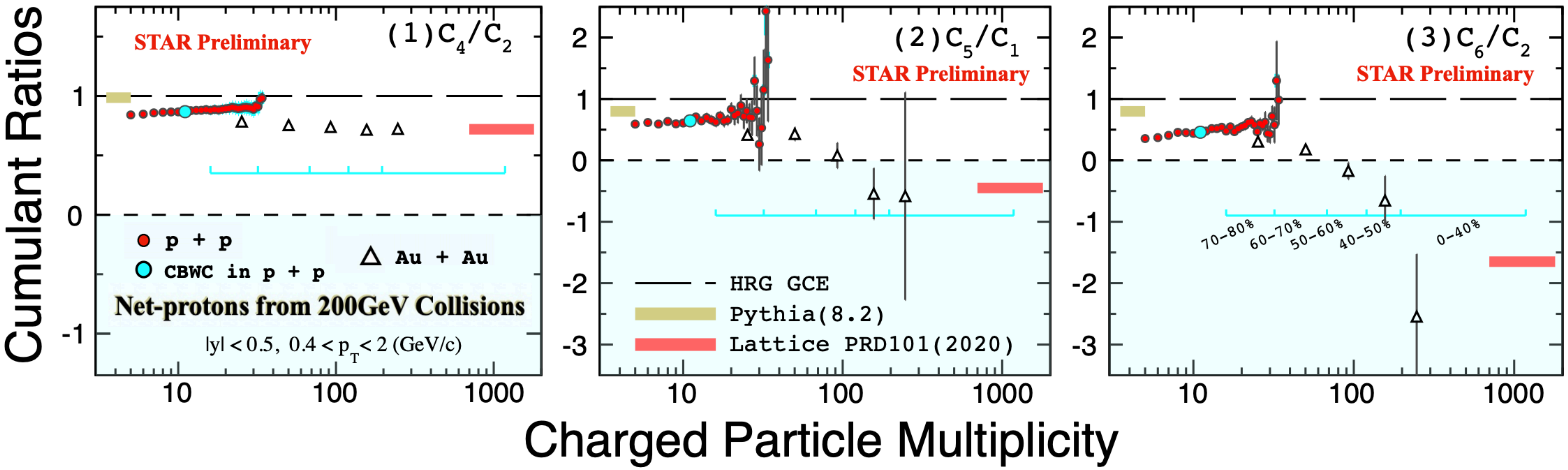
- ✓ Weak collision energy dependence observed for 0-40% centrality.
- ✓ Deviations from zero at a level of < 2σ observed for 0-40% centrality.



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

System size 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

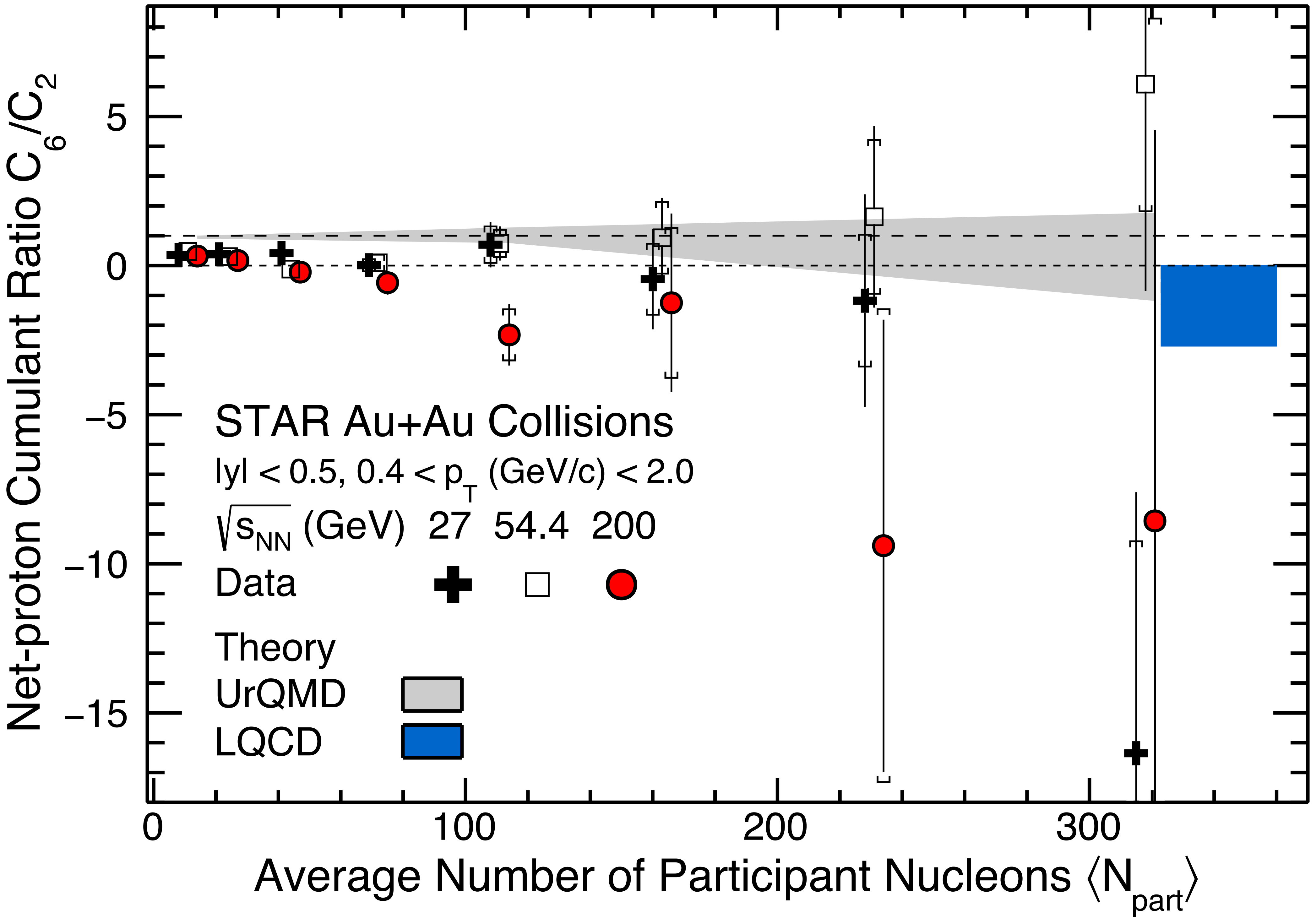
STAR Collaboration, PRC.104.024902(2021)

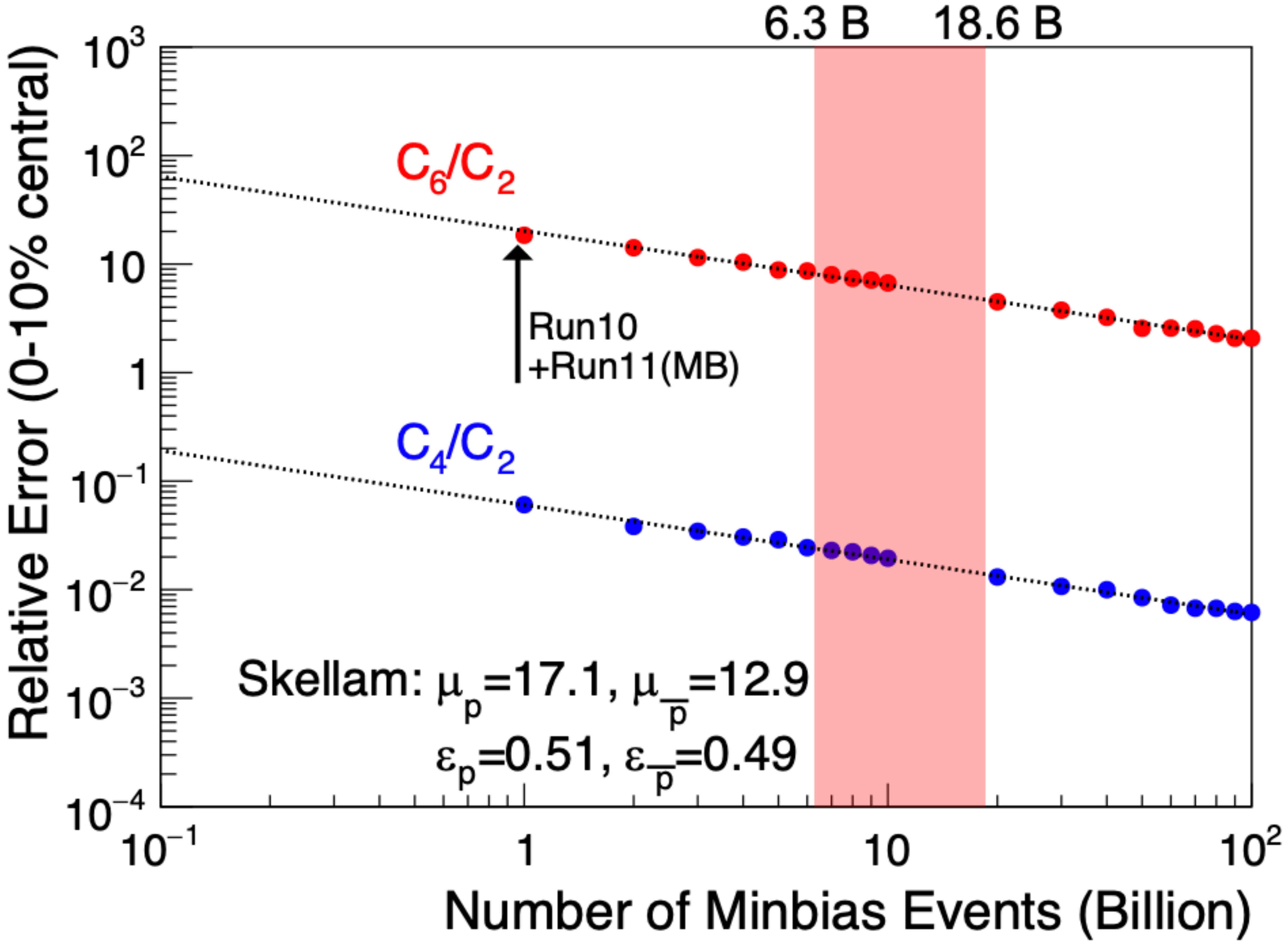
LQCD : Phys. Rev. D 101, 074502 (2020)

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

Future perspective @small μ_B

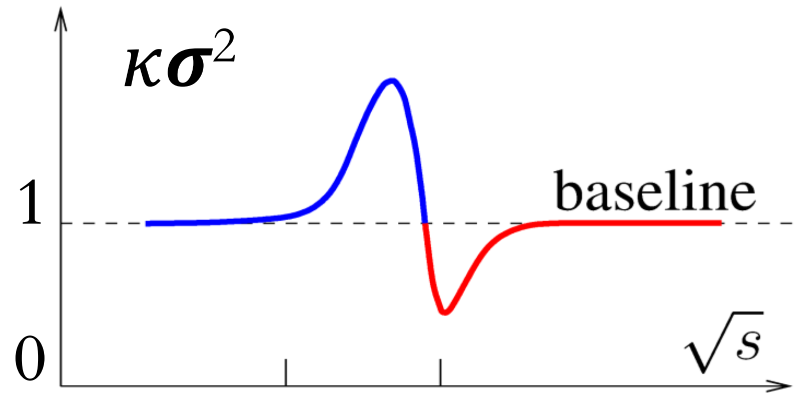
- ✓ ~18 times event statistics in Au+Au collisions at 200 GeV for 2023-2025.
- ✓ More definitive signature of smooth crossover at μ_B~20 MeV.



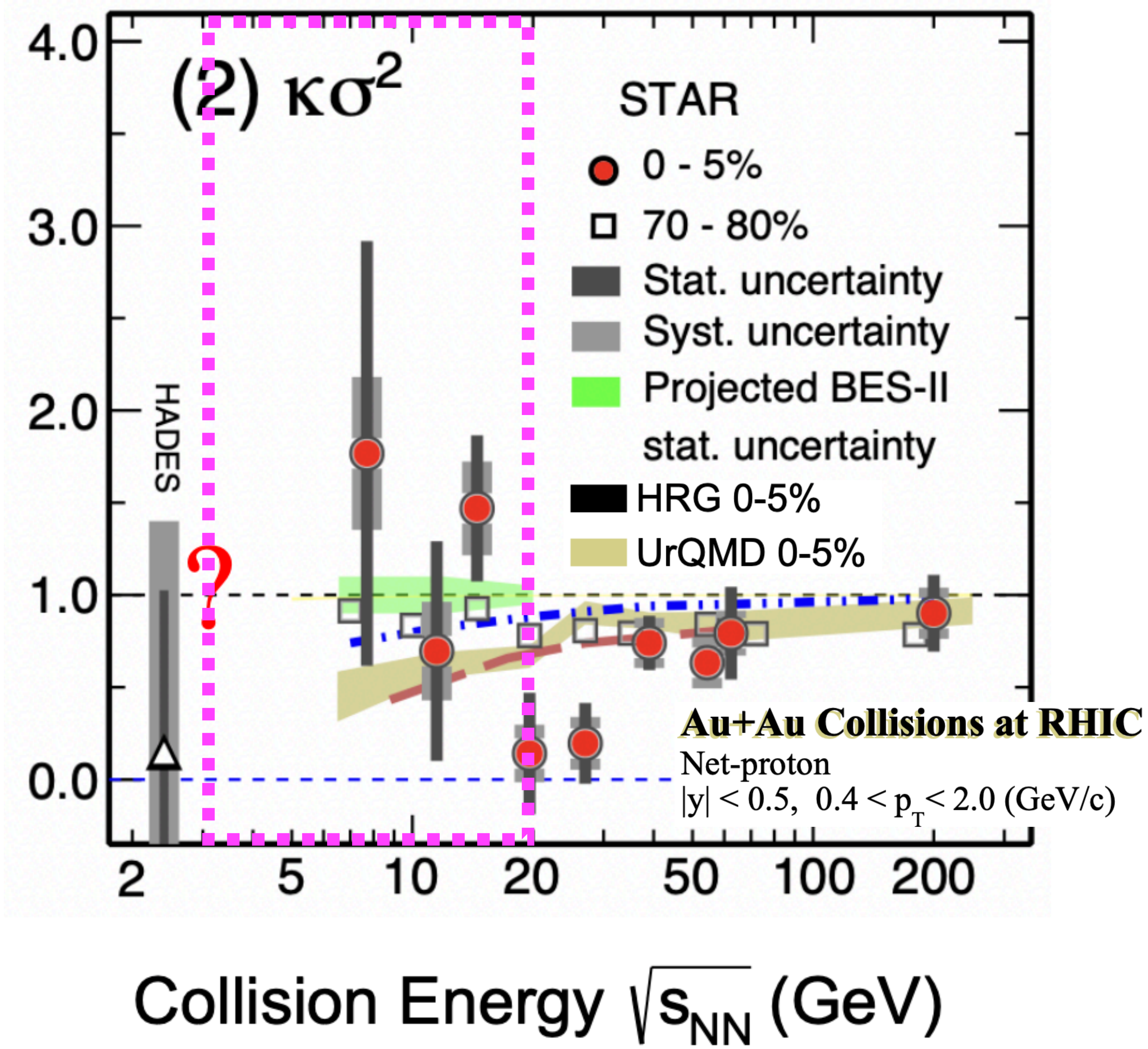


SN0773, "The STAR Beam Use Request for Run-22 and data taking in 2023-2025"

Future perspective



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



STAR Collaboration, PRL.126.092301(2021)

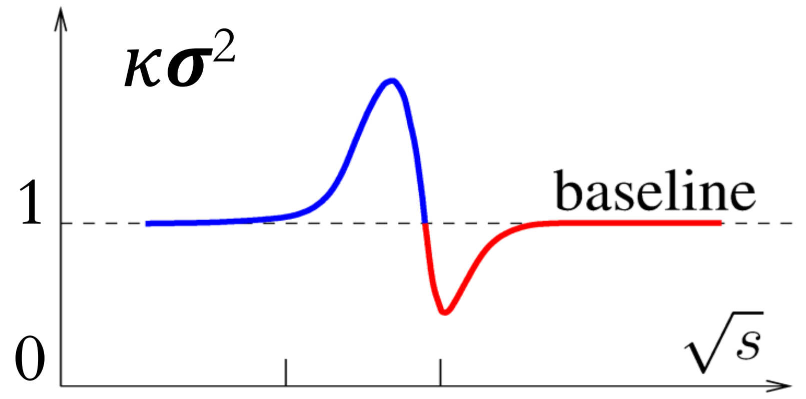
HADES Collaboration, PRC.102.024914(2020)

BESII 7.7 < $\sqrt{s_{NN}}$ GeV < 19.6:
10-20 times larger statistics than BES-I have been successfully collected.

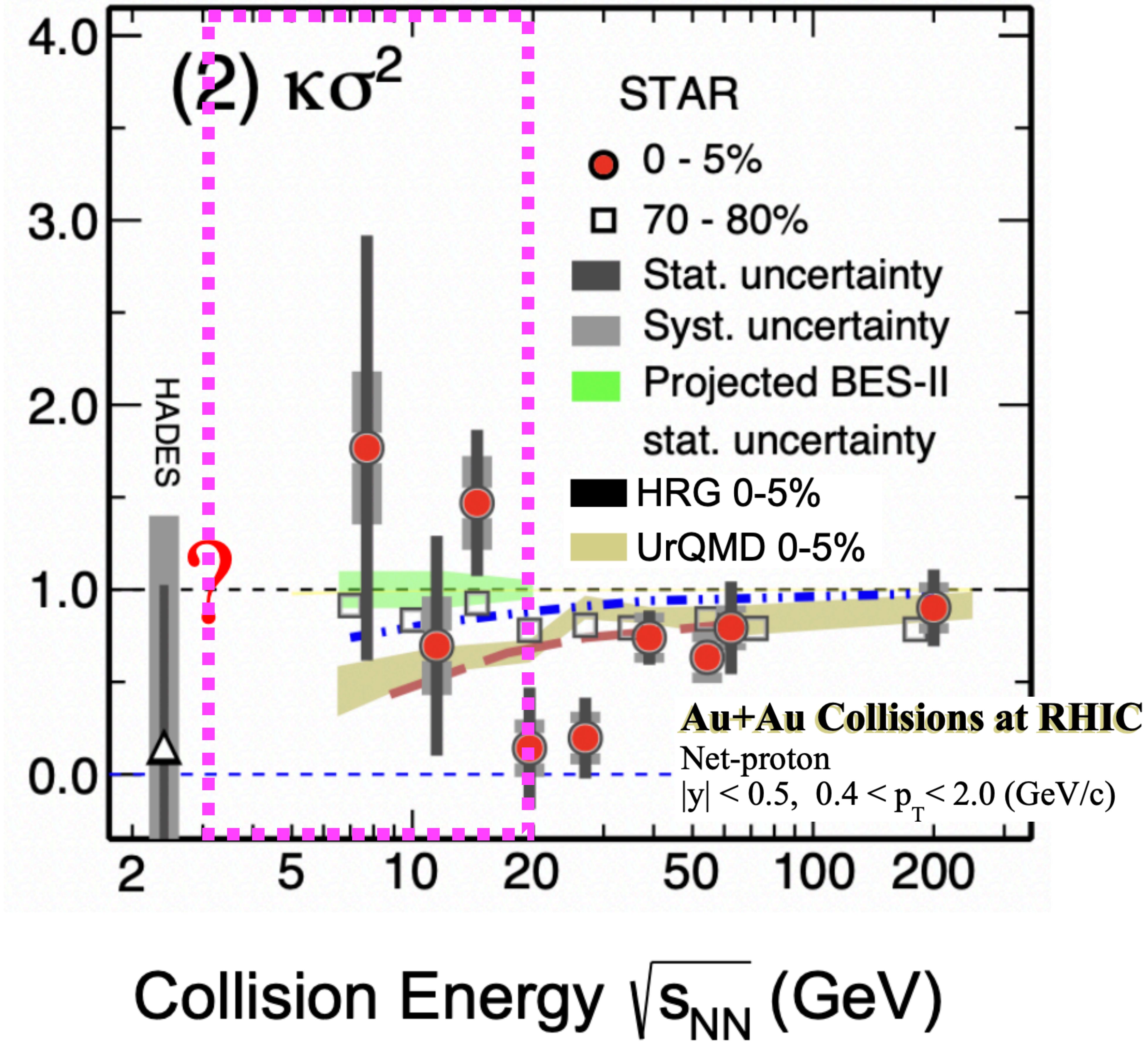
HADES $\sqrt{s_{NN}}$ = 2.4 GeV:
Consistent with zero, drop from STAR 7.7 GeV. *HADES, Phys.Rev.C 102 (2020) 2, 024914*

FXT 3.0 < $\sqrt{s_{NN}}$ GeV < 13.7:
Bridging the gap between BES-II and HADES

Future perspective



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



STAR Collaboration, PRL.126.092301(2021)

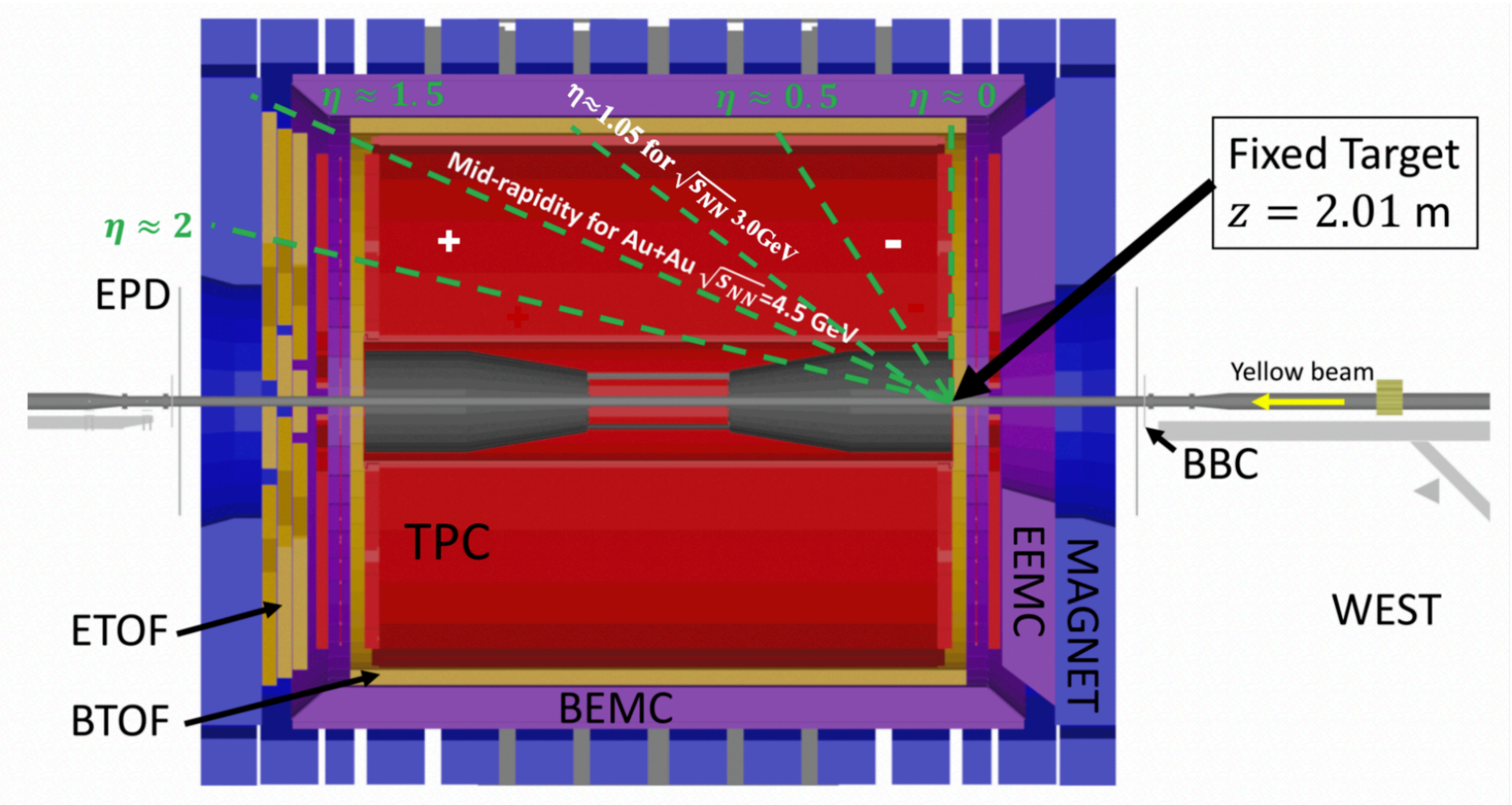
HADES Collaboration, PRC.102.024914(2020)

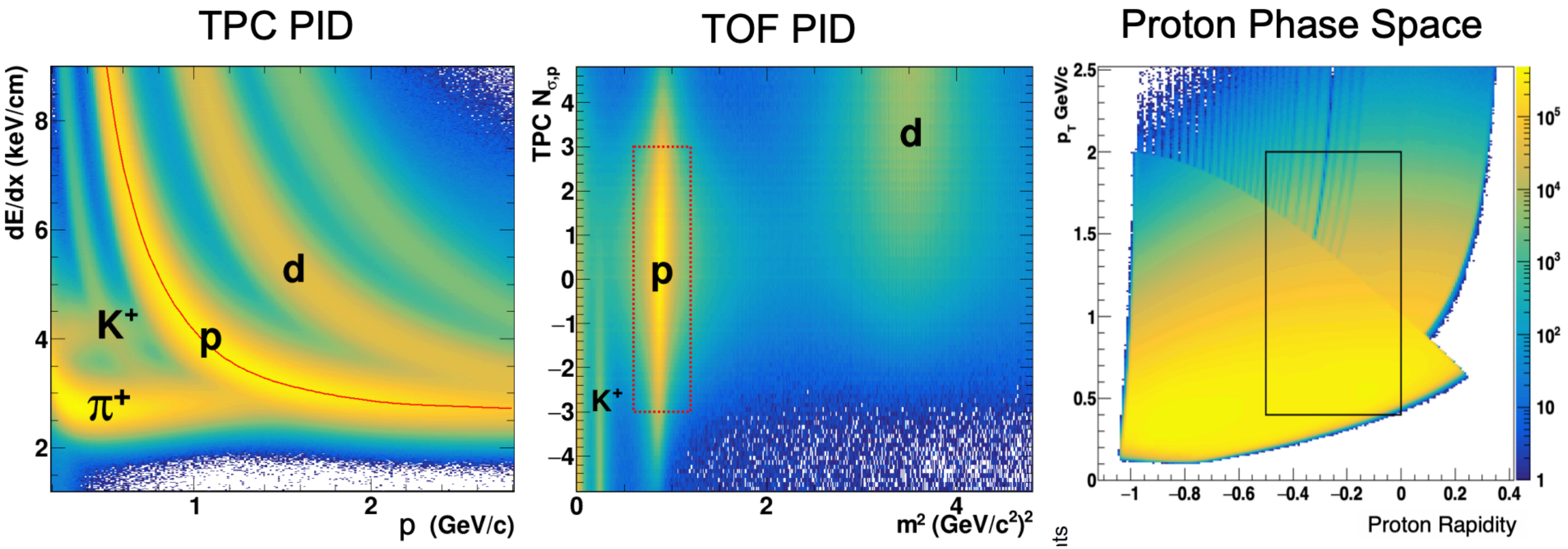
✓ 10-20 times larger statistics than BES-I have been successfully collected.

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

Fixed-target setup

✓ Baryon chemical potential has been extended up to 720 MeV.

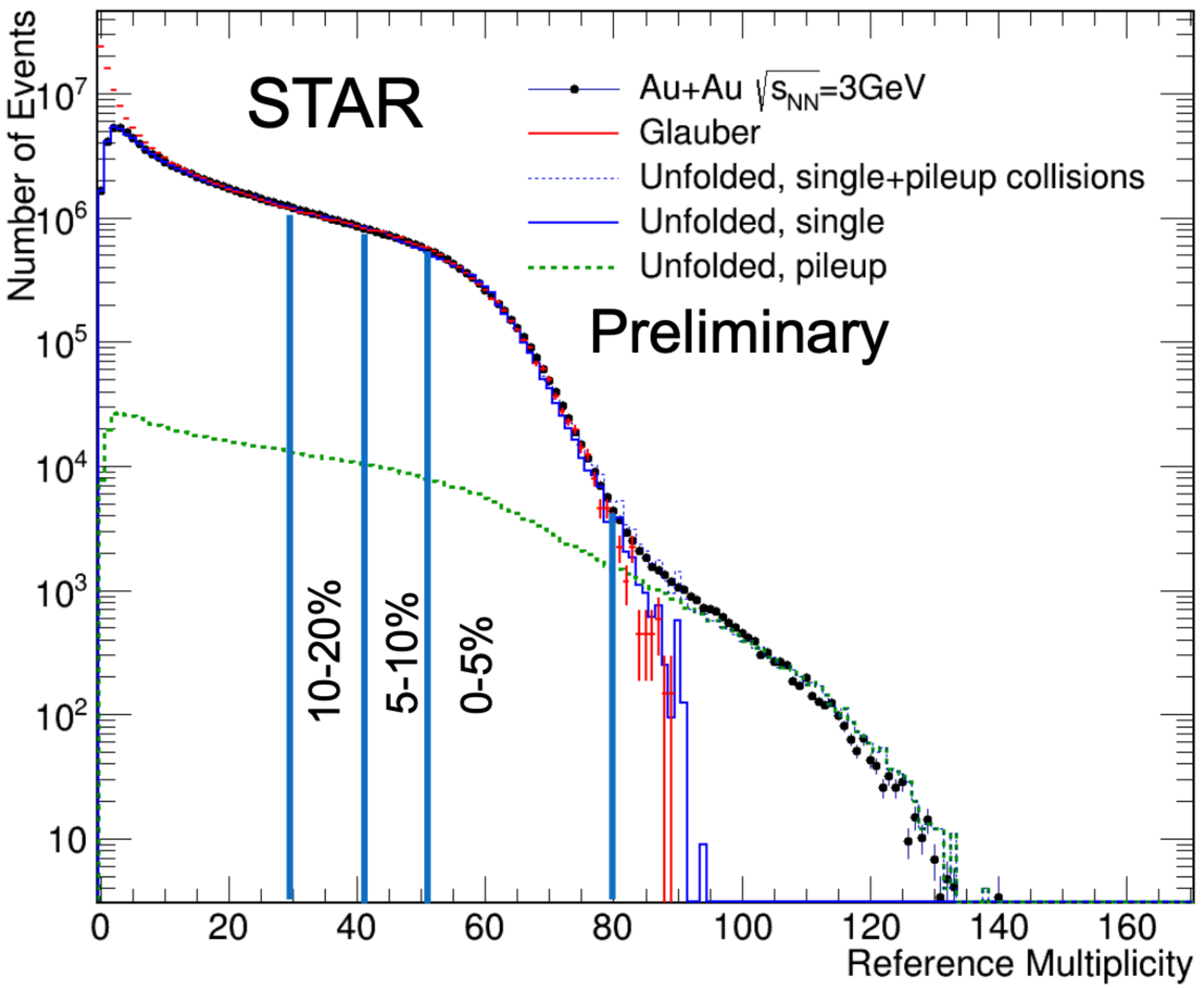




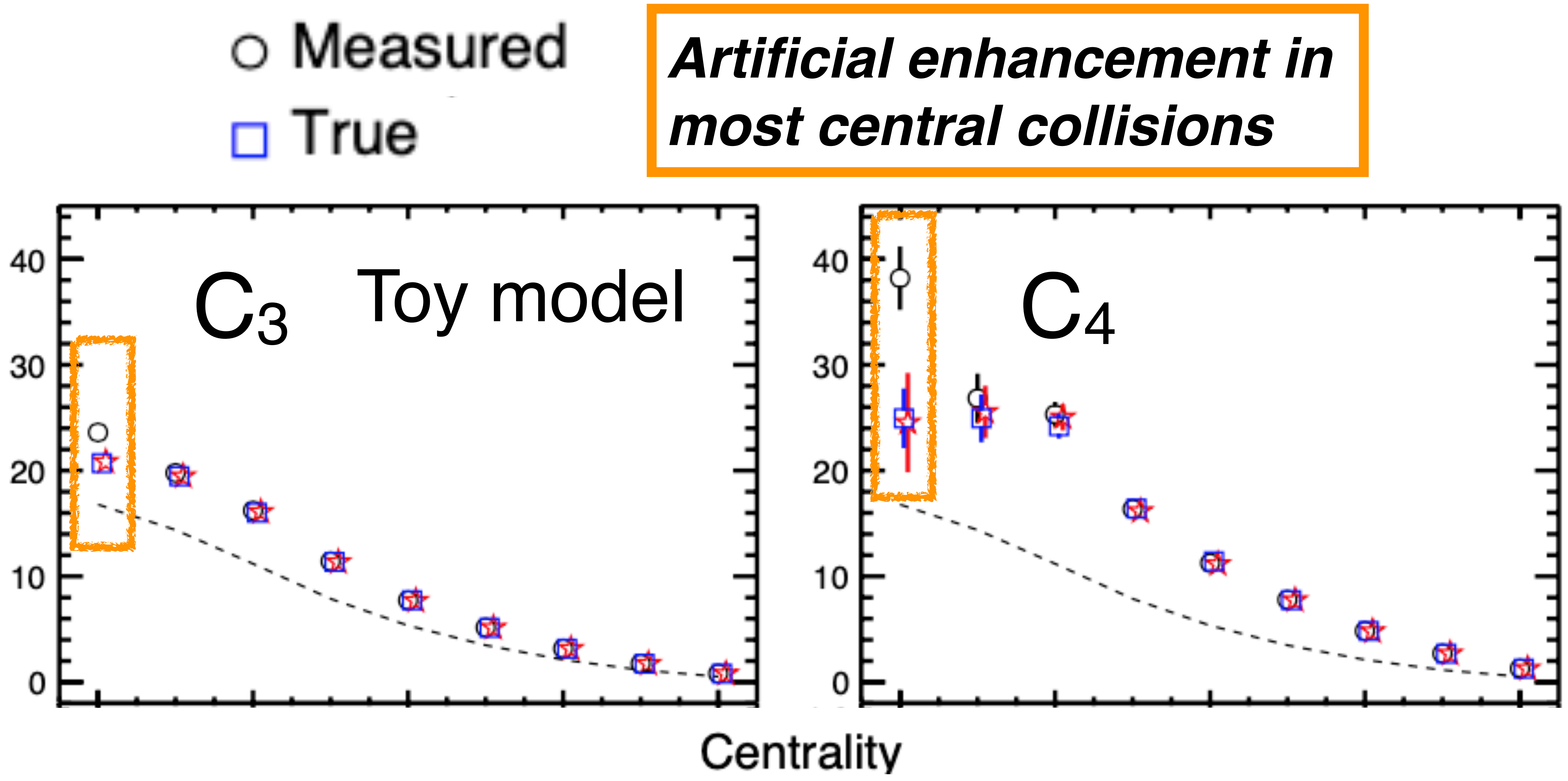
Analysis window:
$0.4 < p_T < 2.0$ GeV/c, $-0.5 < y < 0$
Proton identification:
TPC when $p < 2.0$ GeV/c
TPC+TOF when $p > 2.0$ GeV/c

Pileup events

✓ Visible tail in multiplicity distribution due to pileup events, which is known to enhance the value of cumulants.



Y. Zhang, APS April meeting 2021

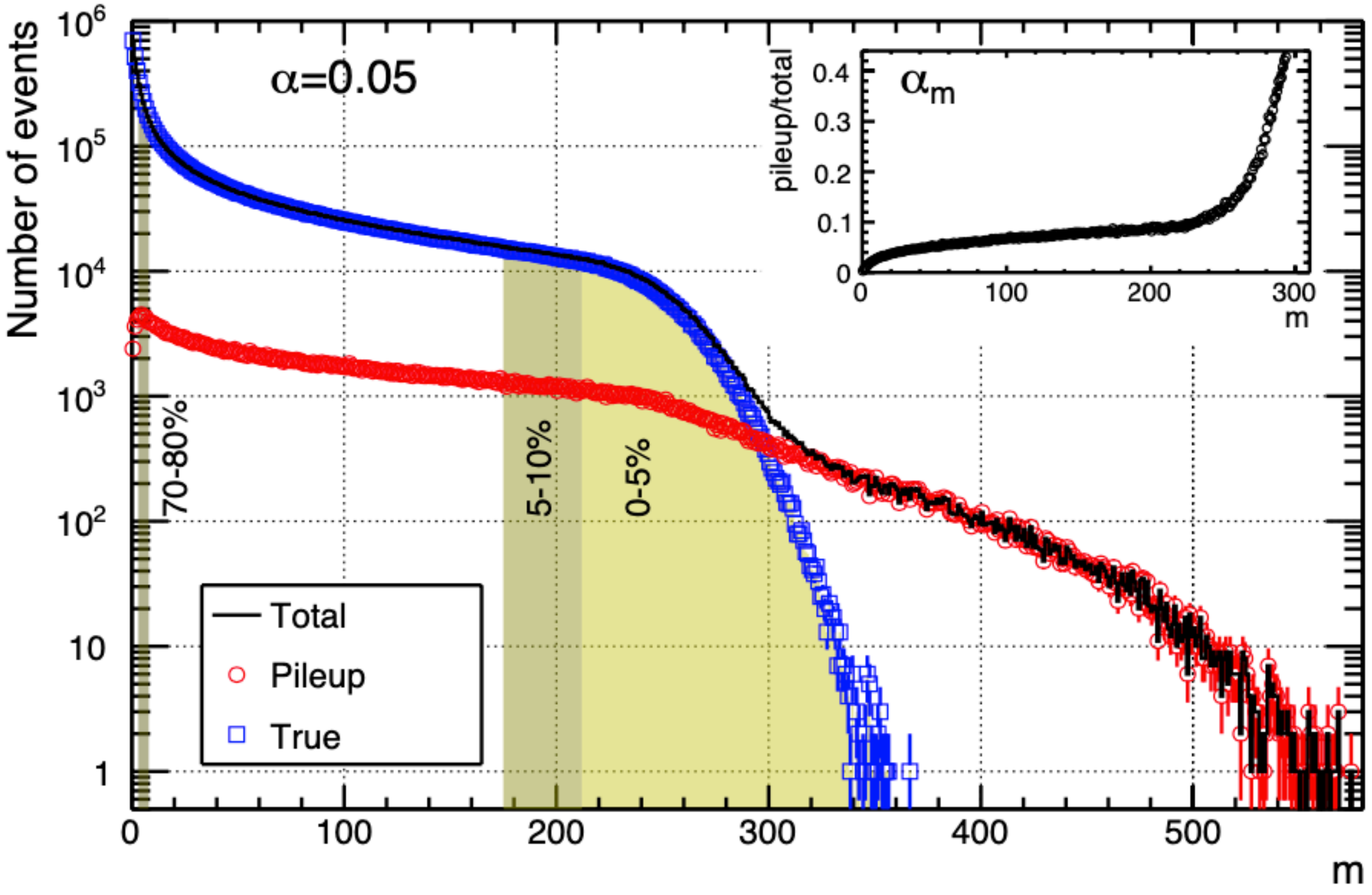


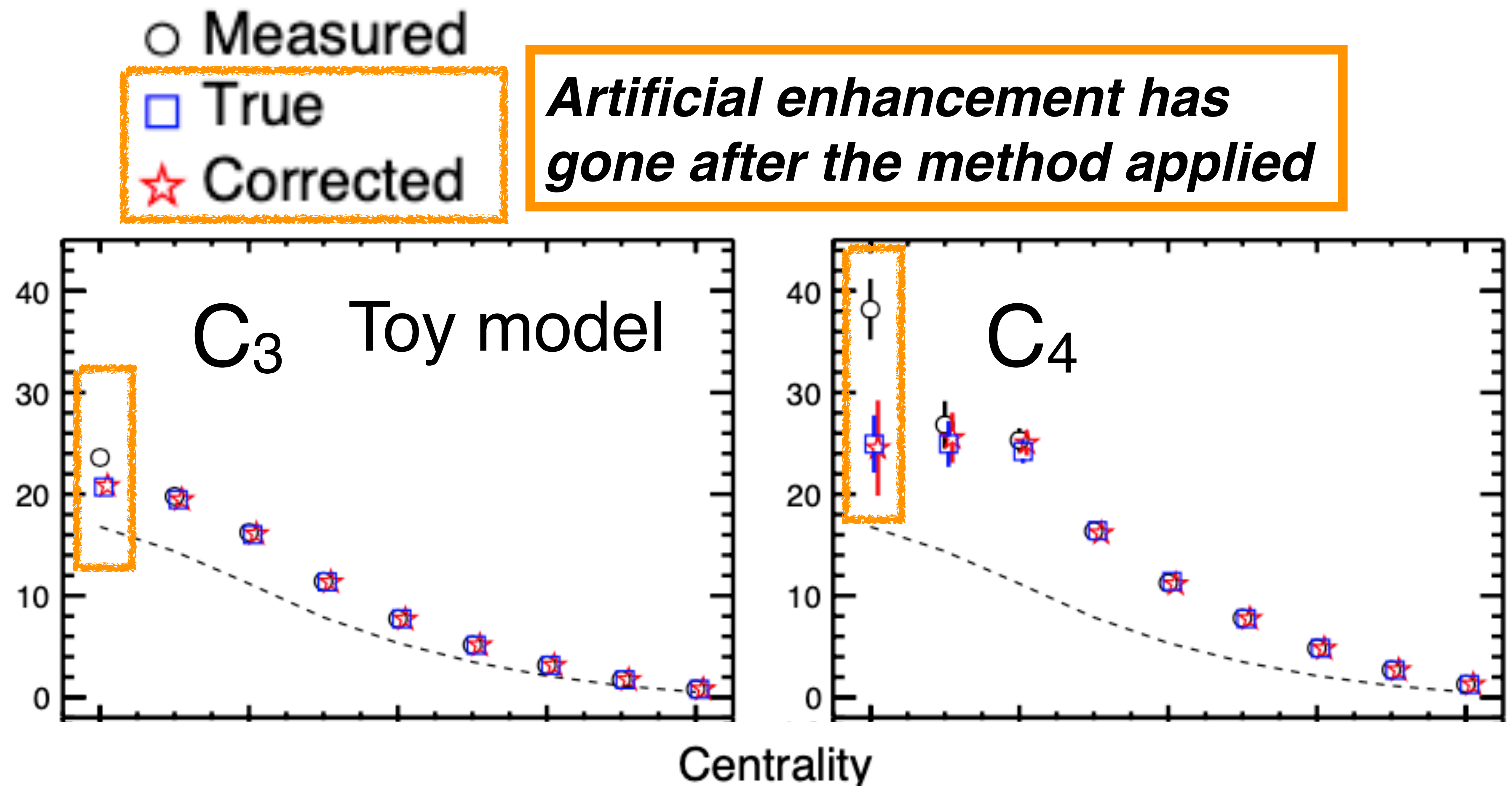
T. Nonaka, M. Kitazawa, S. Esumi, NIMA.984.164632(2020)

Pileup correction

✓ Data-driven approach of the pileup correction is available once true and pileup multiplicity distributions are determined by simulations.

✓ Necessary information: True multiplicity distribution from single-collision





Artificial enhancement has gone after the method applied

T. Nonaka, M. Kitazawa, S. Esumi, NIMA.984.164632(2020)
Yu Zhang et al., arXiv: 2108.10134

Summary

- ✓ Non-monotonic beam energy dependence of net-p C_4/C_2 has been observed in BES-I: ***Critical point at $\sqrt{s_{NN}}$<=7.7GeV?***
- ✓ Negative value of net-p C_6/C_2 at $\sqrt{s_{NN}}$ = 200 GeV central collisions: ***Crossover at μ_B~20MeV?***
- ✓ Stay tuned for precise measurement from ***BES-II and FXT energies (3.0-19.6 GeV)*** to have more definitive messages.

Thank you for your attention

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