Net-Particle Cumulant Measurement from the STAR Experiment

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STAR

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Outline

Introduction

- Higher-order fluctuations

Data analysis

- Particle identification
- Efficiency correction
- Centrality bin width correction

Results

- C_4/C_2 for critical point search
- C_5/C_1 and C_6/C_2 for crossover search
- Higher order fluctuations in p+p

Summary

Introduction

- □ Hadronic gas →QGP
- □ Crossover @ μ_B=0
  Y. Aoki, et al., Nature 443, 675 (2006)
- □ **Critical point ?**

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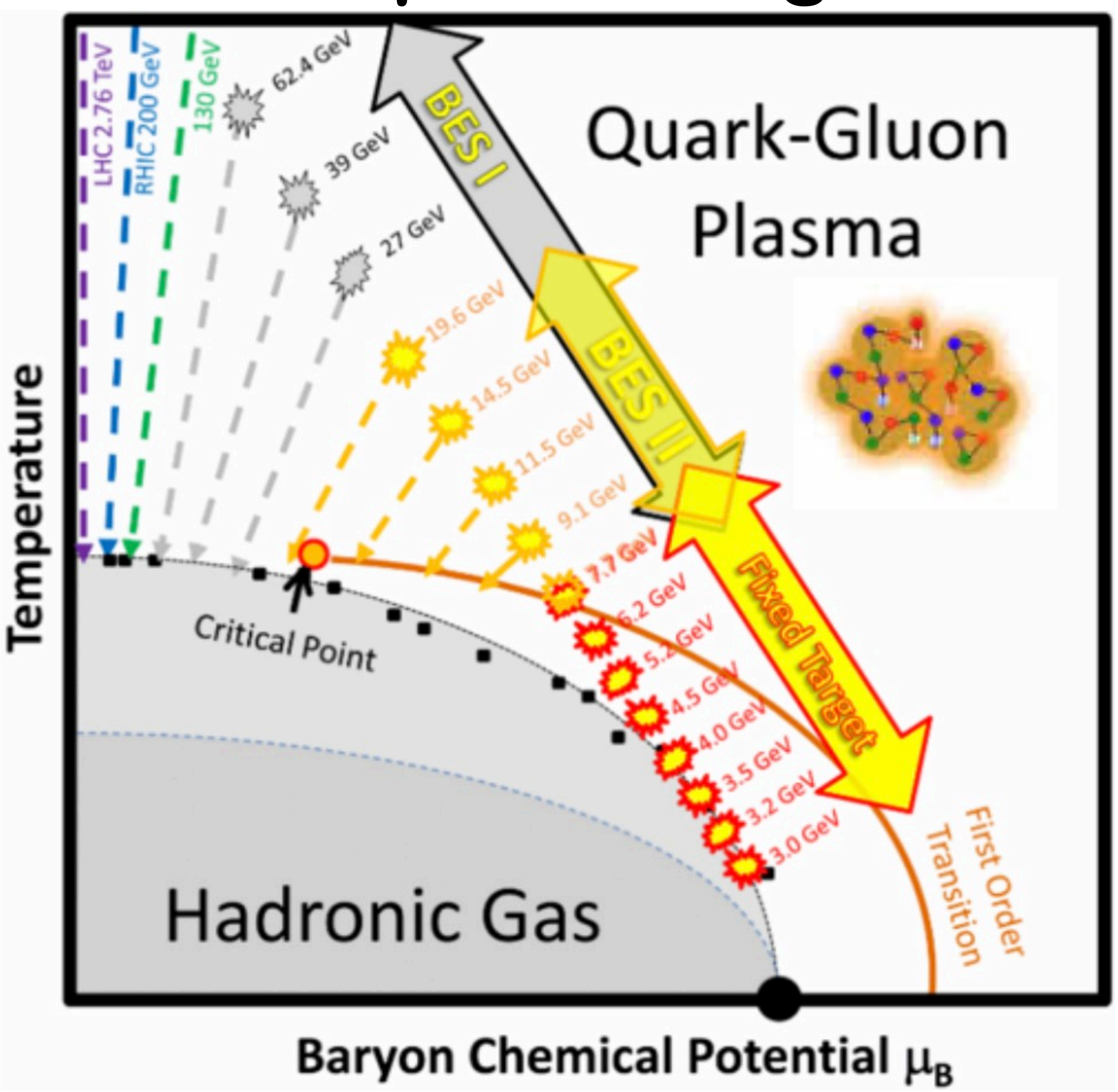
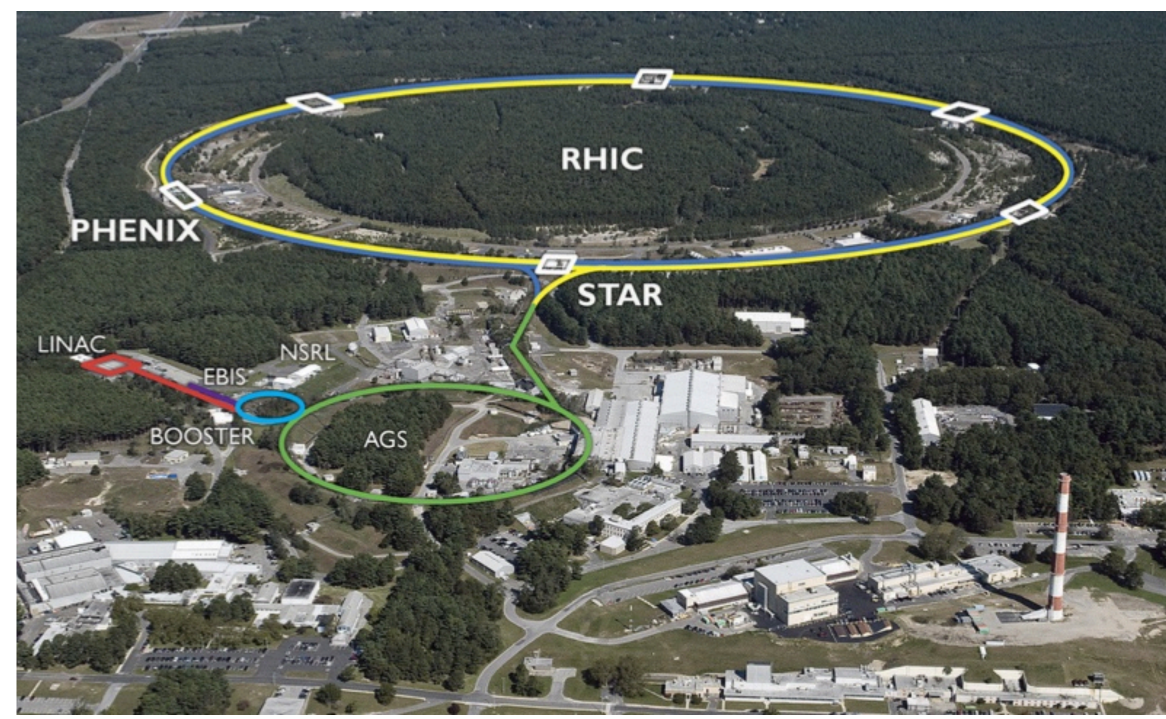
Experimental search
by Beam Energy Scan (BES)
at RHIC-STAR

QCD phase diagram





STAR Collaboration, Nuclear Physics A 982, 899-902 (2019)
STAR public note, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

Goal : Study the phase diagram of QCD

BES-I Data at STAR

Au+Au

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B(MeV)
200	238	2010	25
62.4	43	2010	73
54.4	550	2017	83
39	92	2010	112
27	31	2011	156
19.6	14	2011	206
14.5	14	2014	264
11.5	7	2010	315
7.7	2.2	2010	420

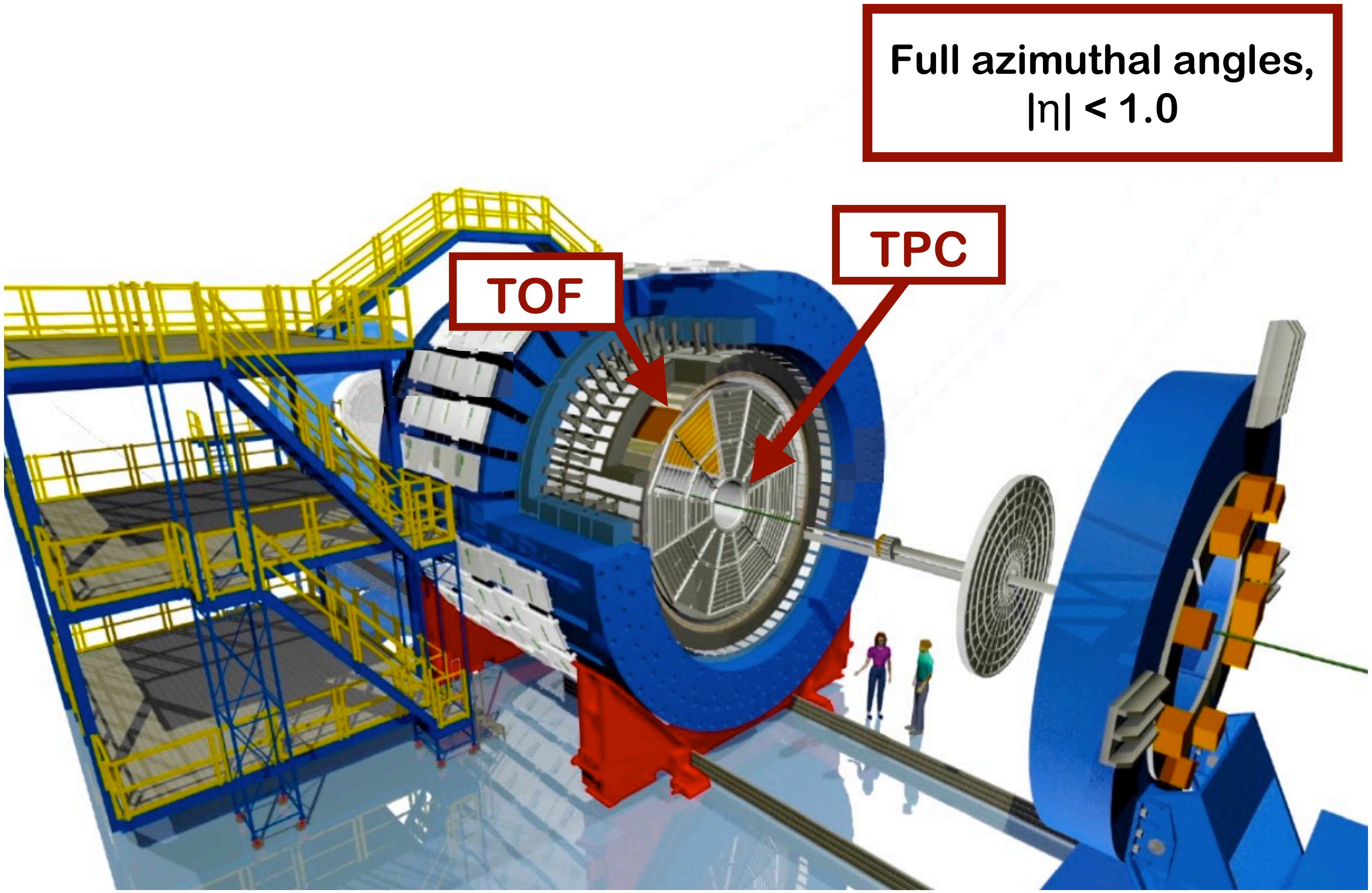
p+p

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	220	2012

Goal : to map the QCD phase diagram $25 < \mu_B$(MeV) < 420

STAR detector

- Time Projection Chamber (TPC) : PID, Vertex
- Time Of Flight (TOF) : Extend proton PID up to p_T = 2 GeV/c

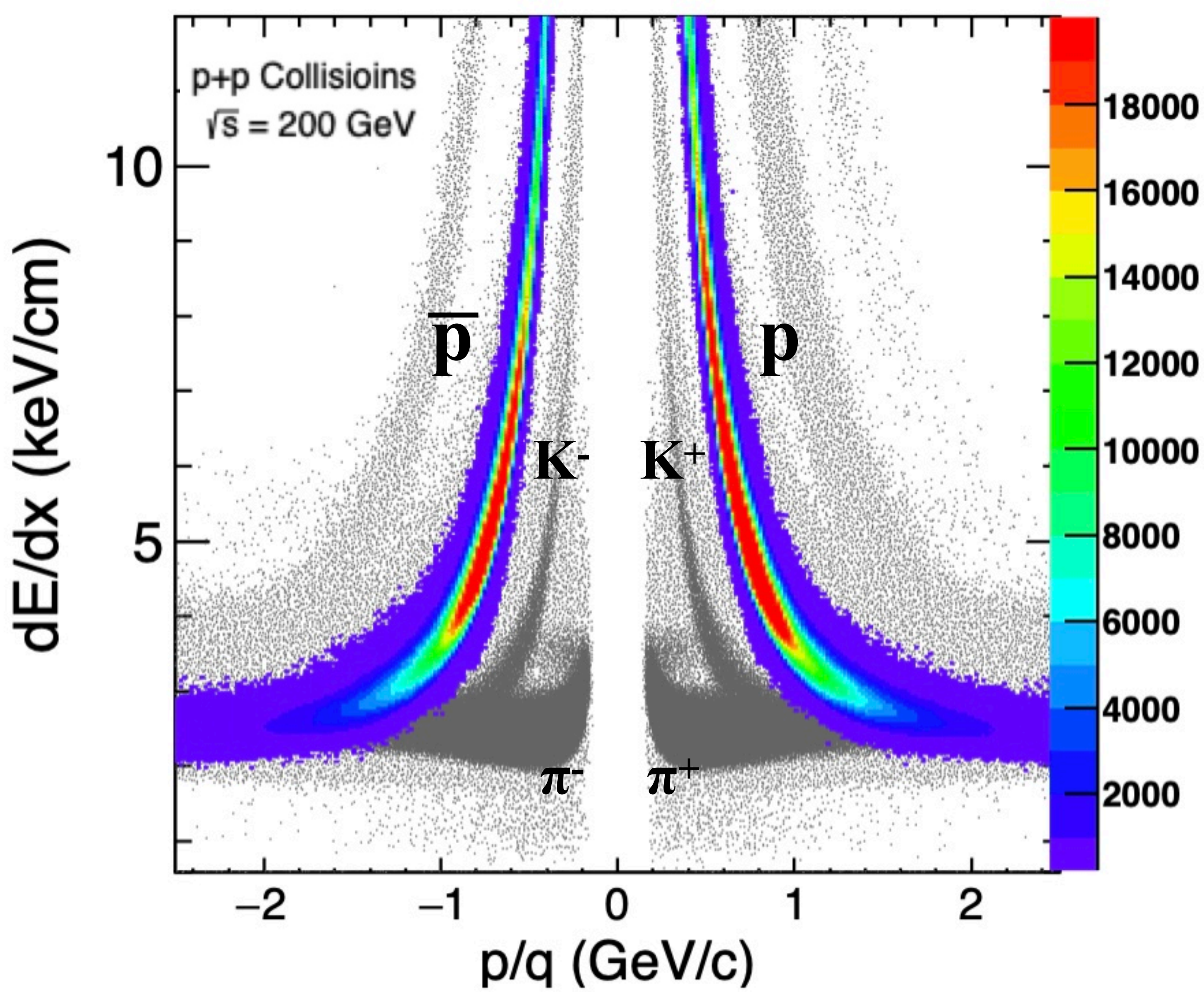


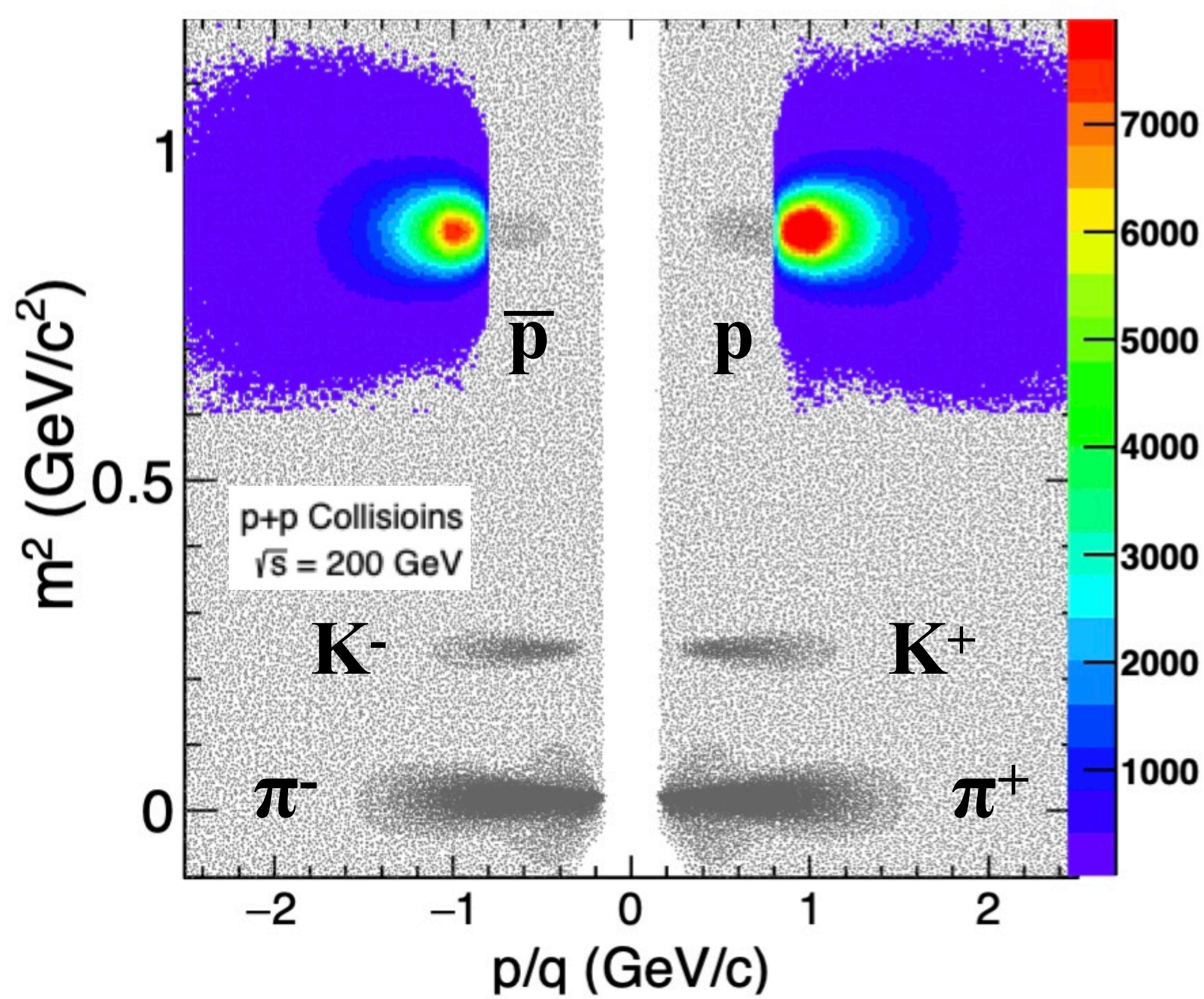
STAR, Nucl.Instrum.Meth.A 499 624-632, (2003)

Particle identification

Protons and Antiprotons are identified by

- **TPC for 0.4 < p_T (GeV/c)< 0.8**
- **TPC and TOF for 0.8< p_T (GeV/c)< 2.0**





Fluctuation = Cumulant, Moment

- **n-th order moment is defined by**

$$\langle m^n \rangle = \sum_m m^n P(m) \,, \quad \langle \delta m^n \rangle = \langle (m - \langle m \rangle)^n \rangle$$

- **Cumulants are extensive variables**

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

X and Y are independent each other

- **Volume terms are cancelled by taking ratio to connect to baryon number susceptibility** χ

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2}$$

$$\kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

- **$C_6/C_2 = C_4/C_2 = 1$ … Skellam baseline**

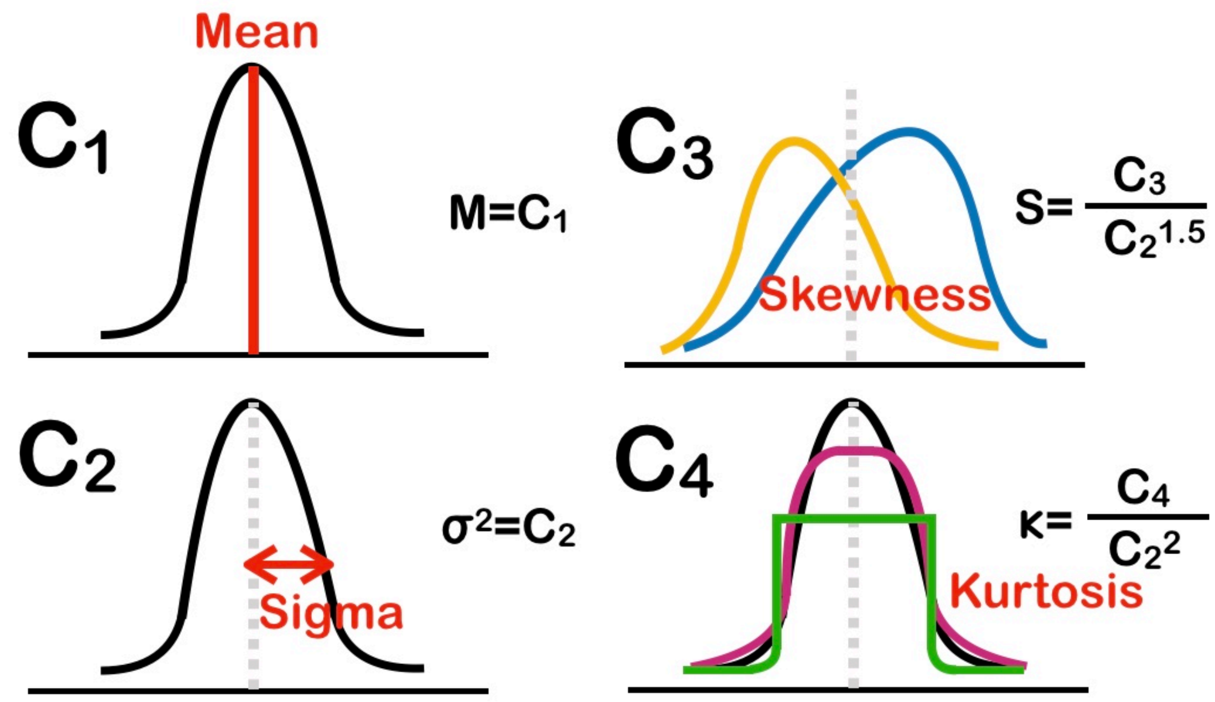
Skellam = Poisson - Poisson'

Skellam : Difference between two independent Possion distributions

Cumulant $\rightleftarrows$ Moment

$$< \delta N >= N - < N >$$

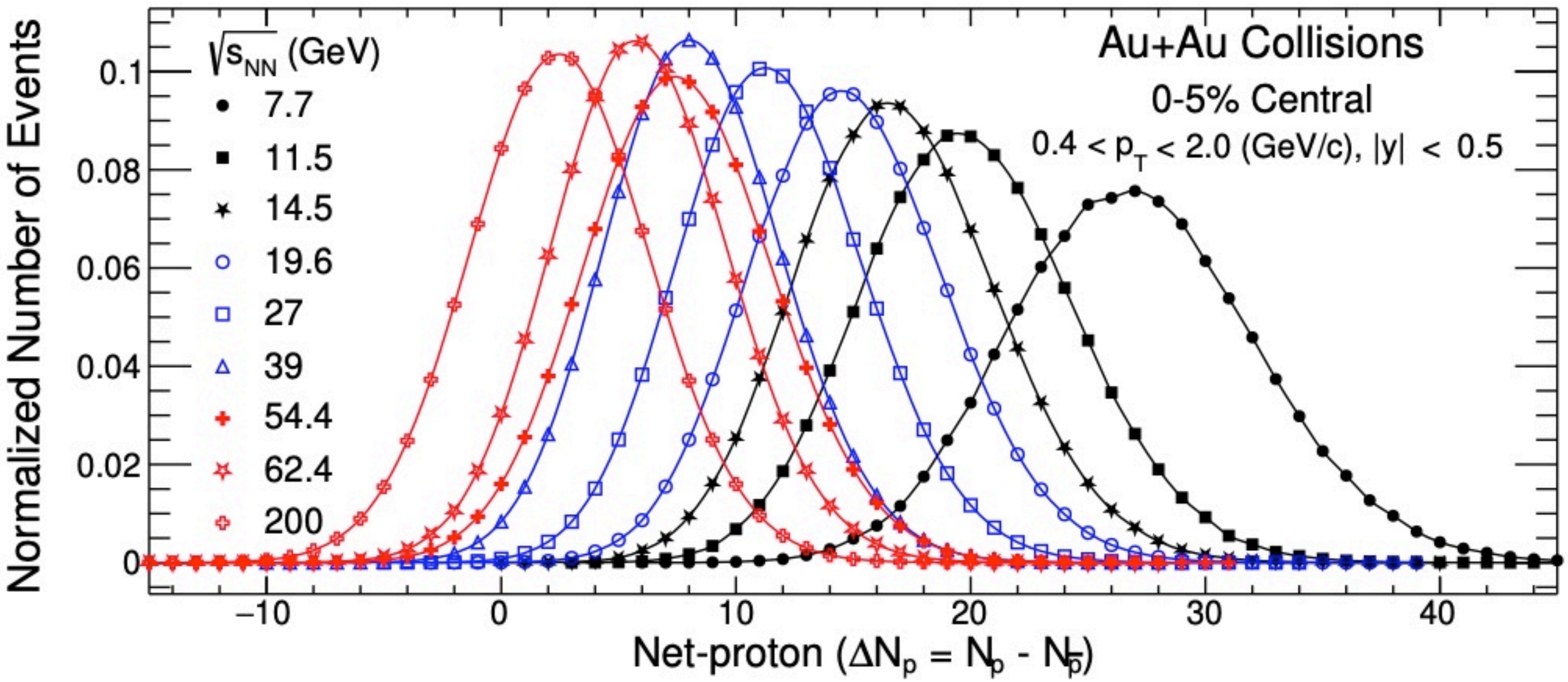
$$C_1 = < N >$$
$$C_2 = < (\delta N)^2 >$$
$$C_3 = < (\delta N)^3 >$$
$$C_4 = < (\delta N)^4 > -3 < (\delta N)^2 >^2$$



- **Higher-order cumulants and ratios are sensitive to phase structure**

Net-proton distributions

Energy dependence of net-proton distributions



STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)
STAR Collaboration, arXiv, 2101.12413 (2021)

Efficiency correction

- **Cumulants are corrected for detector efficiencies by assuming they follow the binomial distribution.**

M. Kitazawa, PRC.86.024904 (2012),
M. Kitazawa and M. Asakawa, PRC.86.024904 (2012)
A. Bzdak and V. Koch, PRC.86.044904 (2012), PRC.91.027901 (2015),
X. Luo, PRC.91.034907 (2015)
T. Nonaka et al, PRC.94.034909 (2016), T. Nonaka, M. Kitazawa, S. Esumi, PRC.95.064912 (2017)
A. Bzdak, R. Holzmann, V. Koch, PRC.94.064907 (2016)
X. Luo, T. Nonaka, Phys. Rev. C99, 044917 (2019)

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

- **Efficiency variations on acceptance and multiplicity are taken into account.**

$$q_{(r,s)} = \sum_{j=1}^{n_{\mathrm{tot}}} \frac{a_j^r}{\varepsilon_j^s}$$ a: charge, ε: efficiency

$$\begin{aligned}
C_1 &= \langle Q\rangle_c = \langle q_{(1,1)}\rangle_c,\\
C_2 &= \langle Q^2\rangle_c = \langle q_{(1,1)}^2\rangle_c + \langle q_{(2,1)}\rangle_c - \langle q_{(2,2)}\rangle_c,\\
C_3 &= \langle Q^3\rangle_c = \langle q_{(1,1)}^3\rangle_c + 3\langle q_{(1,1)}q_{(2,1)}\rangle_c - 3\langle q_{(1,1)}q_{(2,2)}\rangle_c + \langle q_{(3,1)}\rangle_c - 3\langle q_{(3,2)}\rangle_c + 2\langle q_{(3,3)}\rangle_c,\\
C_4 &= \langle Q^4\rangle_c = \langle q_{(1,1)}^4\rangle_c + 6\langle q_{(1,1)}^2 q_{(2,1)}\rangle_c - 6\langle q_{(1,1)}^2 q_{(2,2)}\rangle_c + 4\langle q_{(1,1)}q_{(3,1)}\rangle_c + 3\langle q_{(2,1)}^2\rangle_c + 3\langle q_{(2,2)}^2\rangle_c - 12\langle q_{(1,1)}q_{(3,2)}\rangle_c\\
&\quad + 8\langle q_{(1,1)}q_{(3,3)}\rangle_c - 6\langle q_{(2,1)}q_{(2,2)}\rangle_c + \langle q_{(4,1)}\rangle_c - 7\langle q_{(4,2)}\rangle_c + 12\langle q_{(4,3)}\rangle_c - 6\langle q_{(4,4)}\rangle_c,
\end{aligned}$$

Centrality bin width correction

- **Cumulants are calculated for each multiplicity bin, and averaged for each centrality class.**

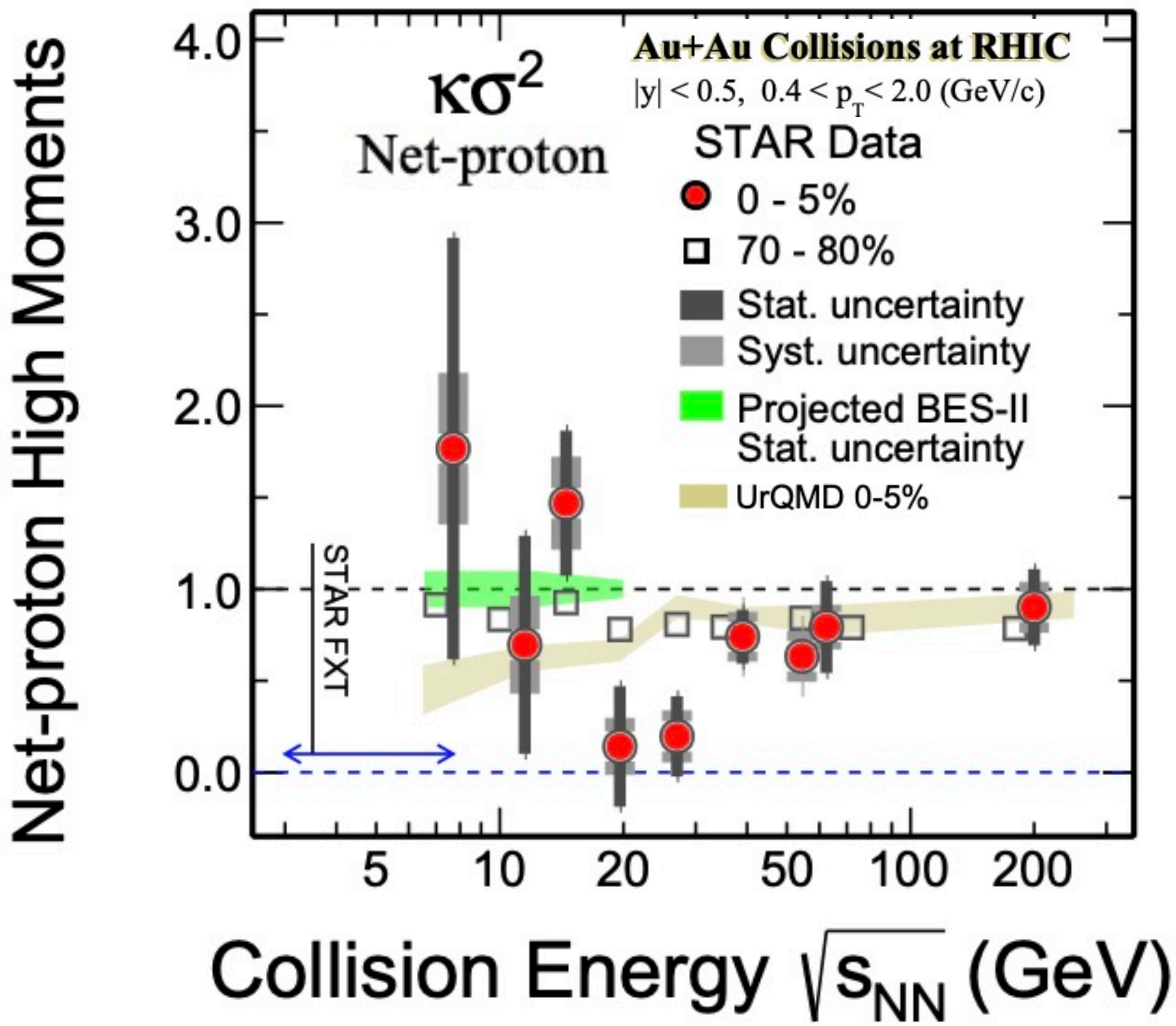
X. Luo et al, J. Phys. G40, 105104 (2013),
A. Chatterjee et al., PRC 101, 034902 (2020)

$$C_n' = \frac{\sum_i w_i C_{(n,i)}}{\sum_i w_i}$$

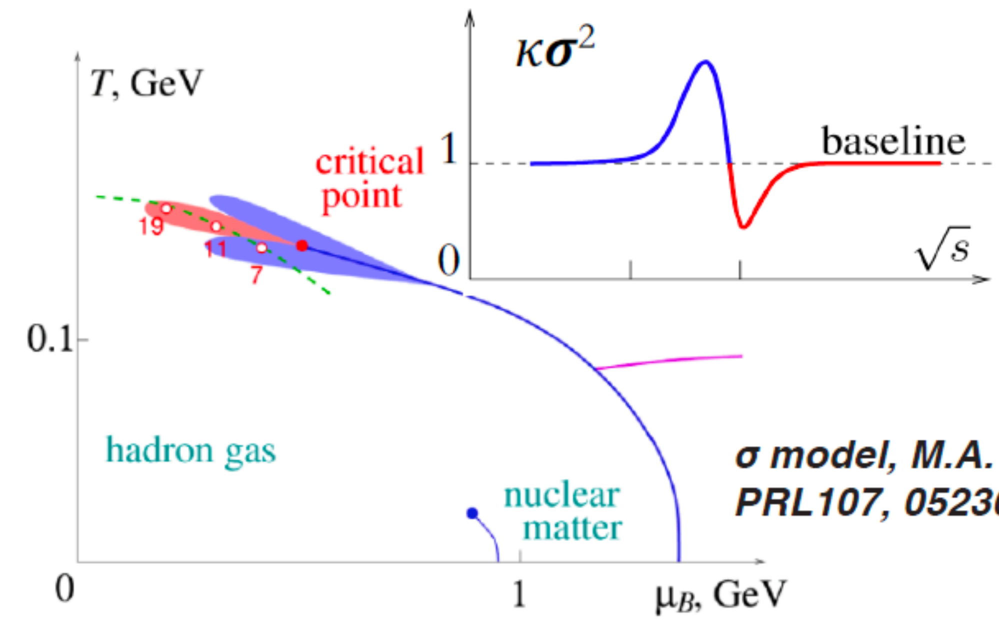
i **: Multiplicity bin**
w_i **: Number of event**

Effects of initial volume fluctuations are suppressed in a data-driven way.

Fourth-order fluctuations for critical point search



STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)
STAR Collaboration, arXiv, 2101.12413 (2021)



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

Non-monotonic beam energy dependence of κσ² has been observed for net-proton fluctuations

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Possible signature of critical point

BES-II Data at STAR

Au+Au

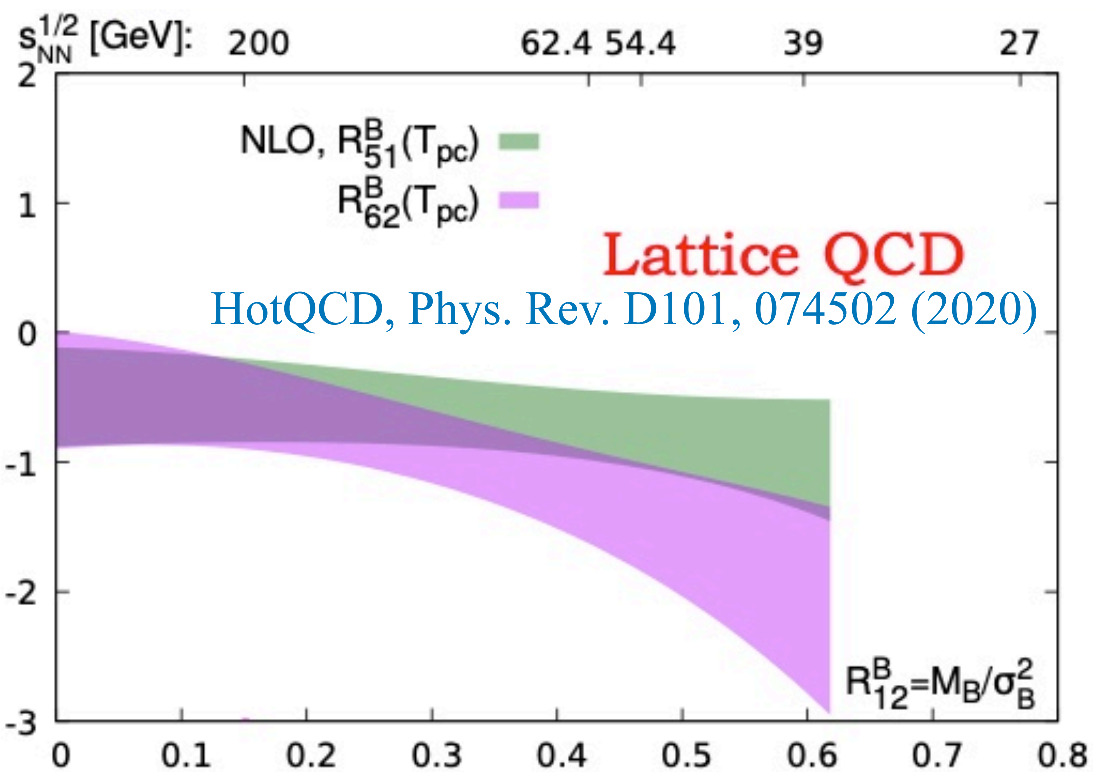
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B(MeV)
27	560	2018	156
19.6	582	2019	206
14.6	324	2019	262
11.5	235	2020	316
9.2	162	2020	373
7.7	101	2021	420
3 (FXT)	565+	2018	721

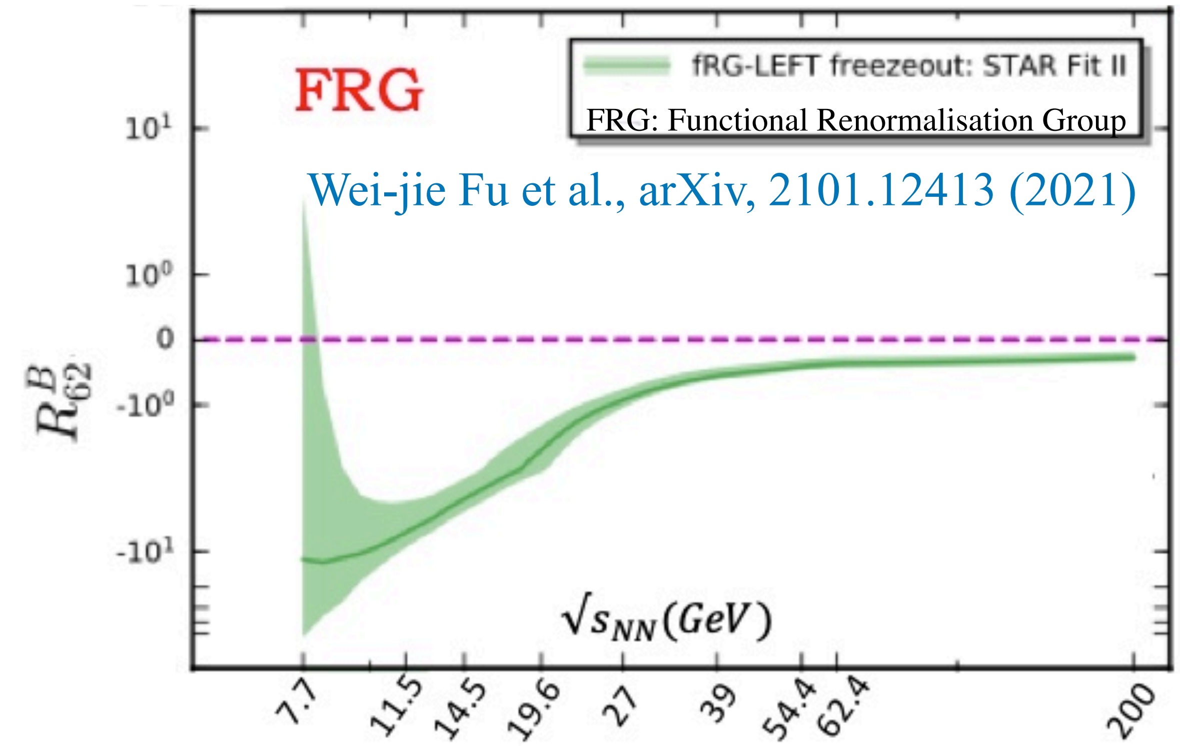
+FXT data at 9.2, 11.5, 13.7 GeV, ~50M for each

- 10 - 20 times larger statistics than BES-I
- Collision energies : 3 - 20 GeV
- μ_B : 20 - 720 MeV

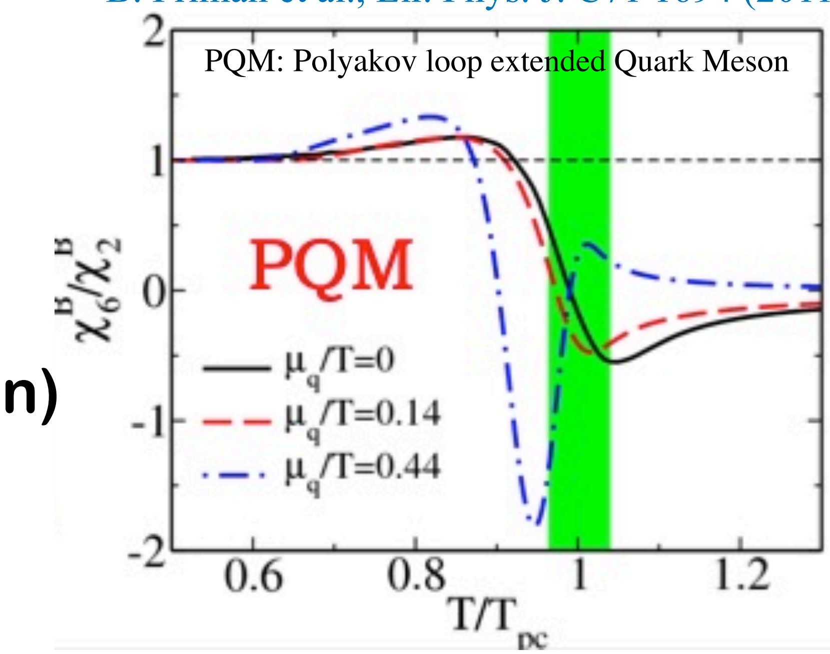
Crossover

Goal : **Identification of O(4) chiral criticality on the phase boundary**





B. Friman et al., Eir. Phys. J. C71 1694 (2011)

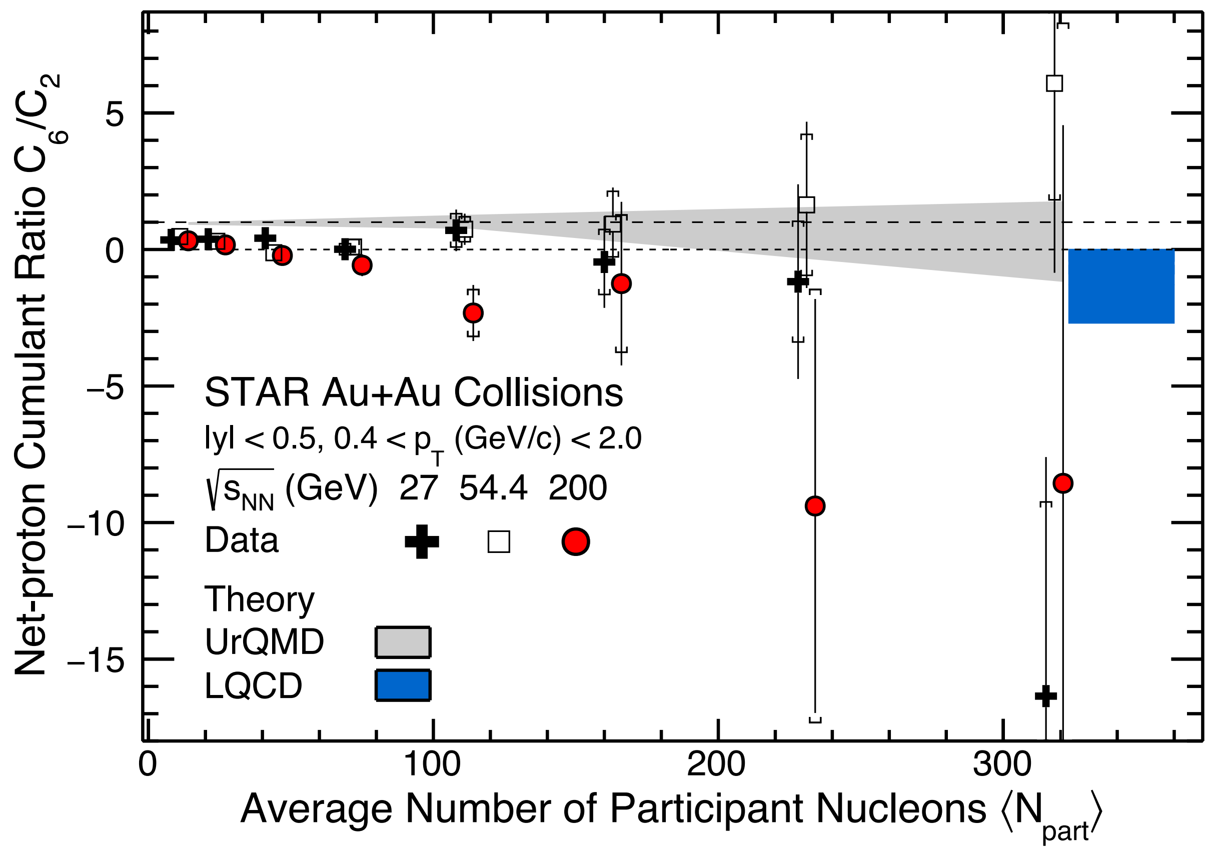


C_5, C_6 :

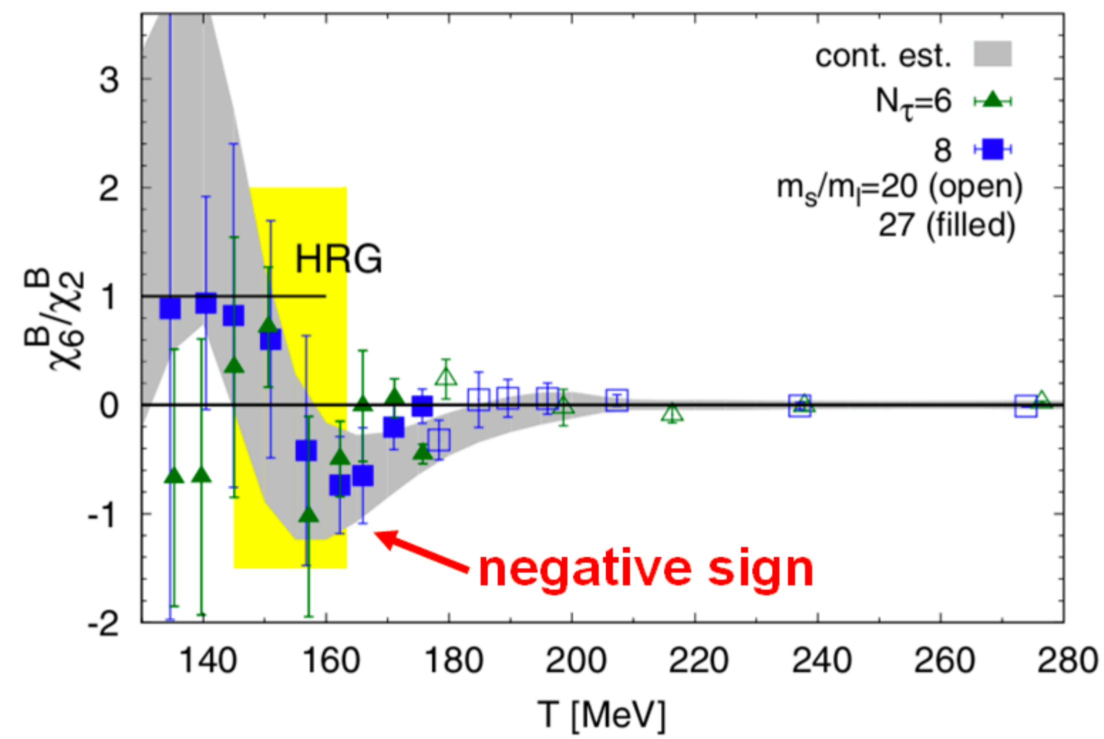
- **Negative for LQCD, FRG, PQM - crossover**
- **Positive for HRG and UrQMD (no QCD transition)**

Sixth-order fluctuations for crossover search

STAR, arXiv : 2105.14698

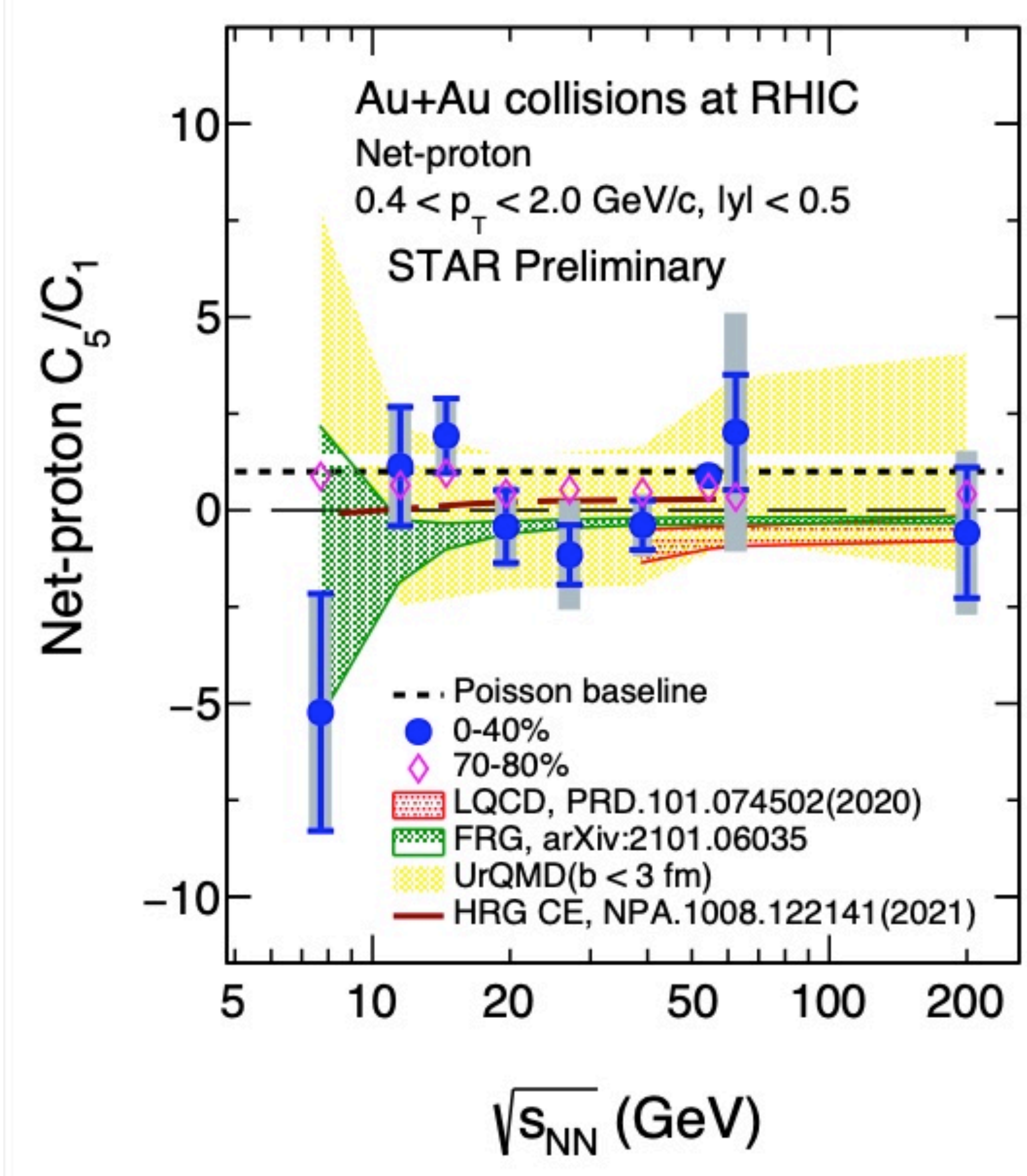


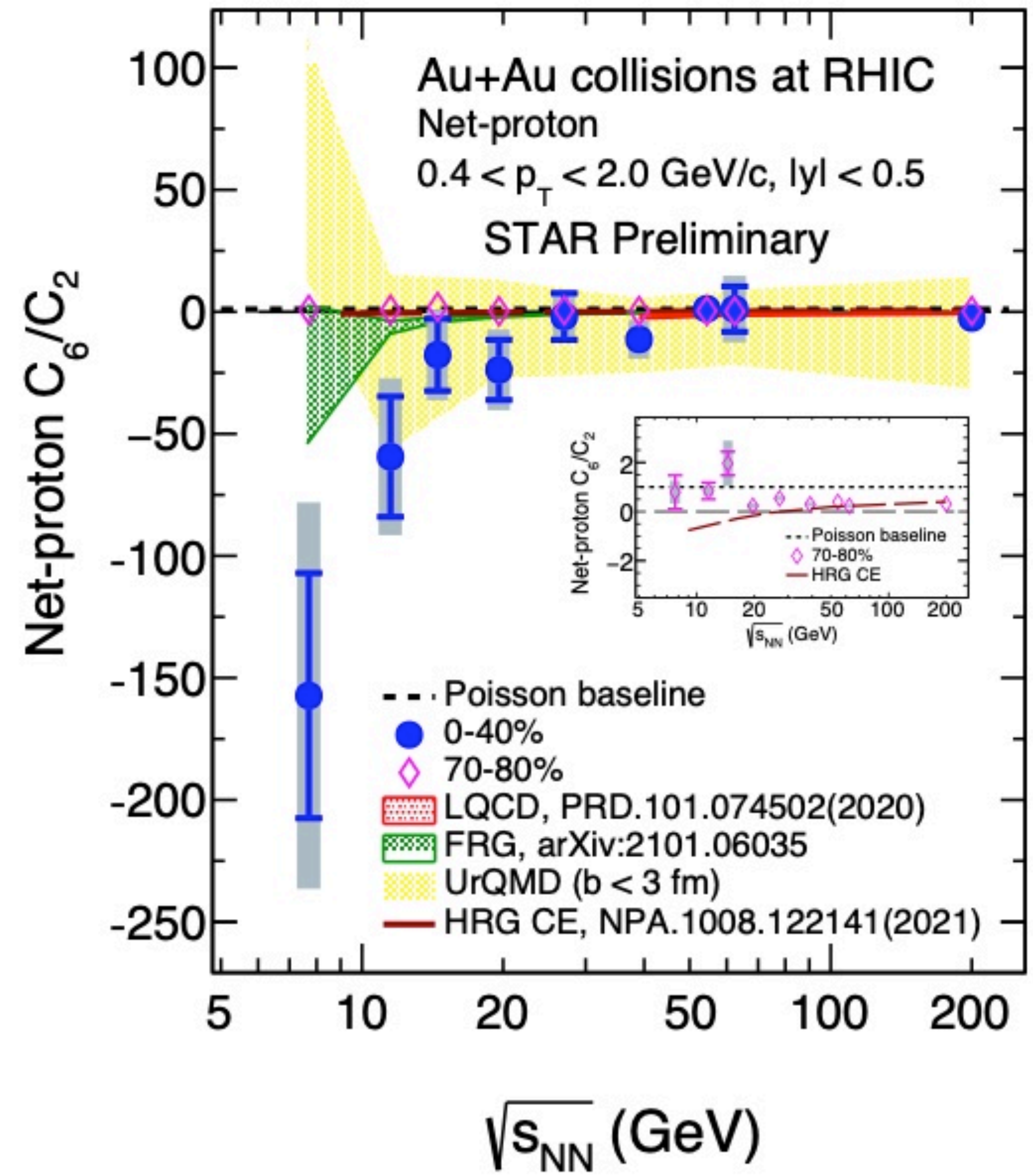
A. Bazavov et al, Phys. Rev. D 95, 054504 (2017)
HotQCD Collaboration, Phys. Rev. D 101, 074502 (2020)



- **From peripheral to central collisions, the values of C_6/C_2 change from positive to negative at 200 GeV**
- **Lattice QCD calculations at μ_B = 0 show negative C_6/C_2**

Collision energy dependence of C_5 and C_6 in Au+Au

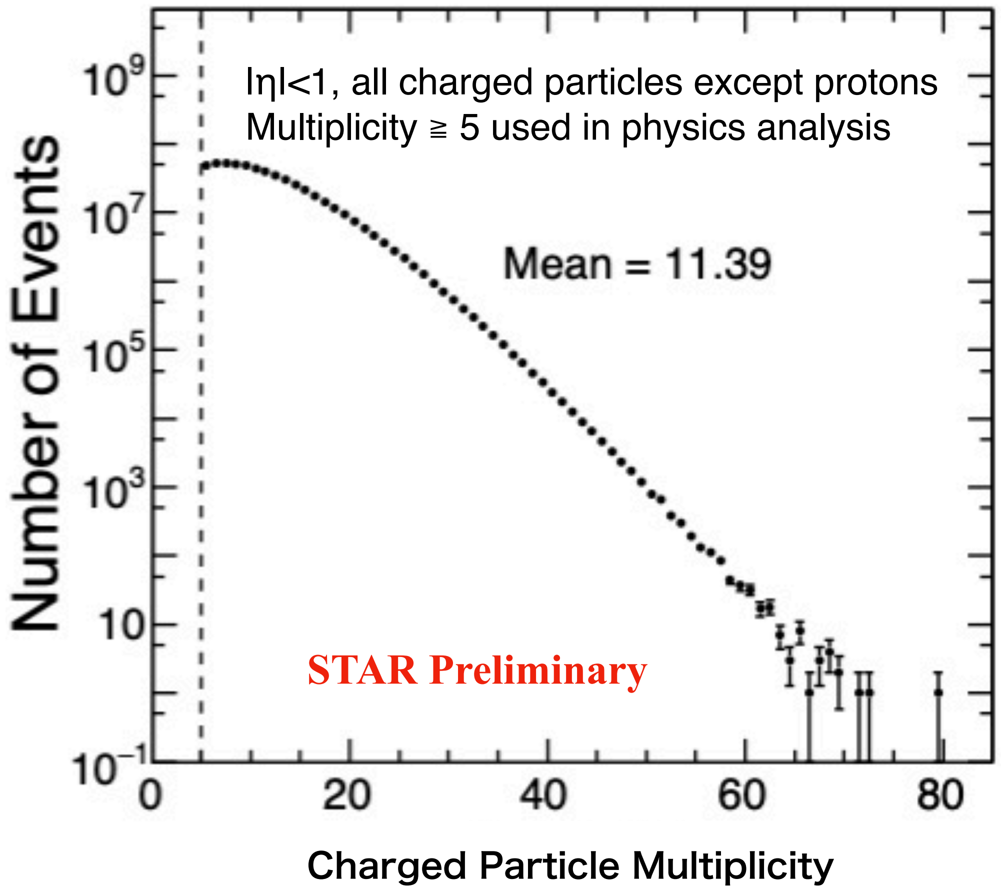


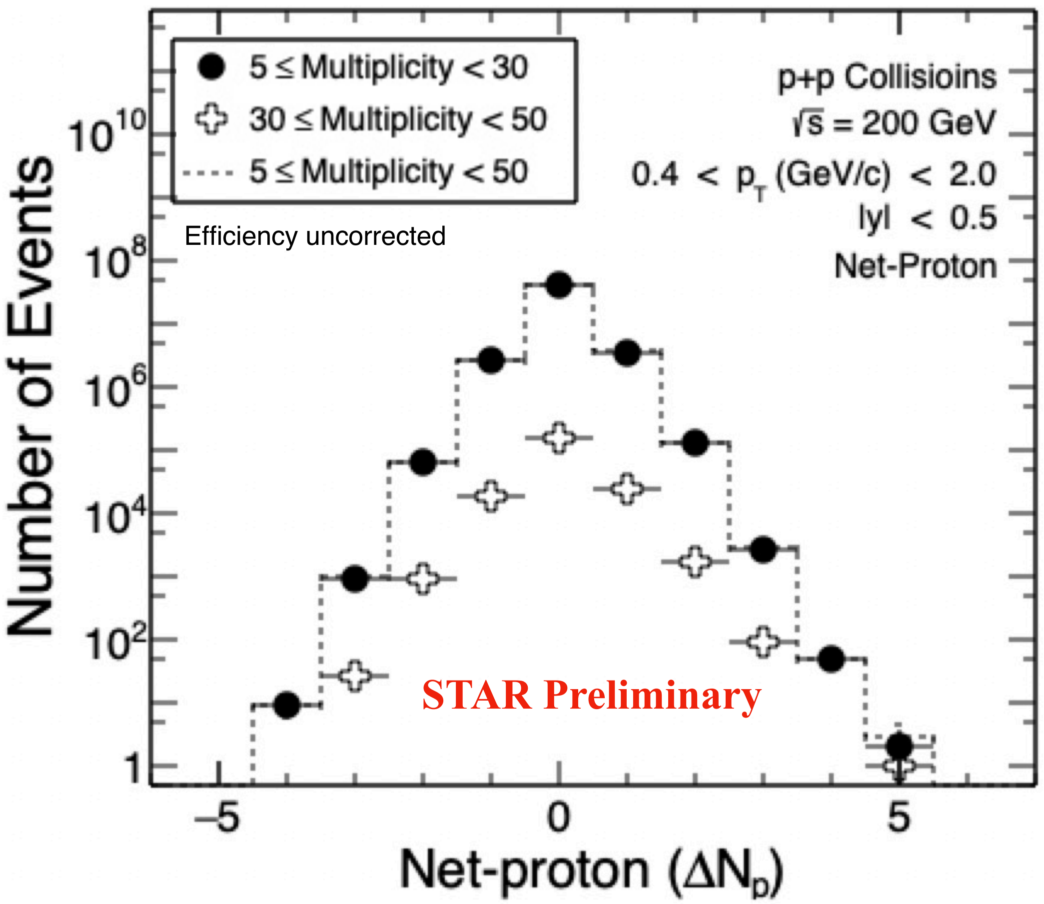


- **Weak collision energy dependence for C_5/C_1 (0-40%)**
- **Deviation from 0 at a level of <2σ**
- **C_5/C_1, C_6/C_2 (70-80%) > 0 for all energies**

Precise measurements in p+p 200 GeV

- **Multiplicity / acceptance dependence would be available with high statistics dataset**
- **There is no initial volume fluctuations by construction, thus CBWC is just to take averaging.**

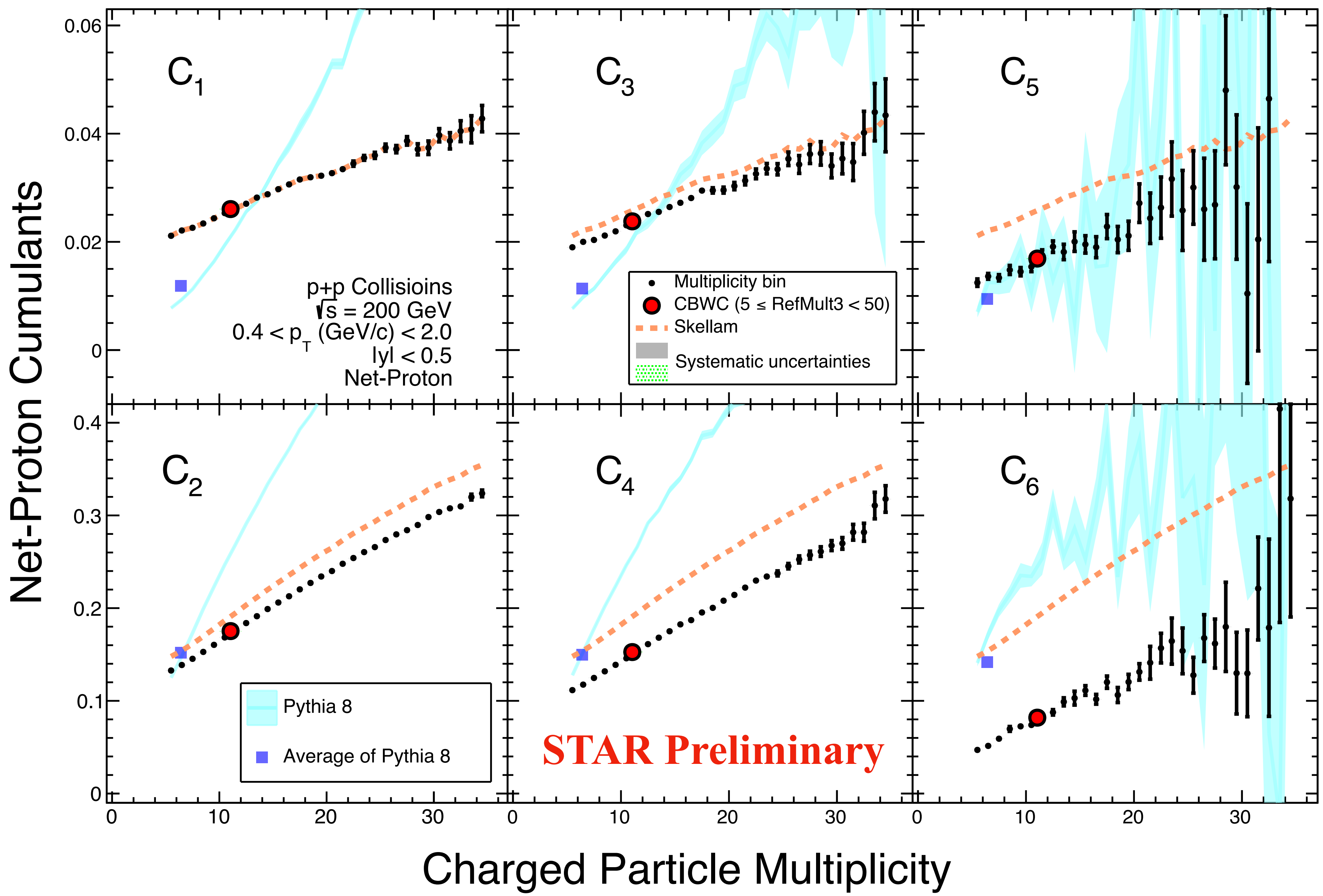




Multiplicity dependence of net-proton cumulants

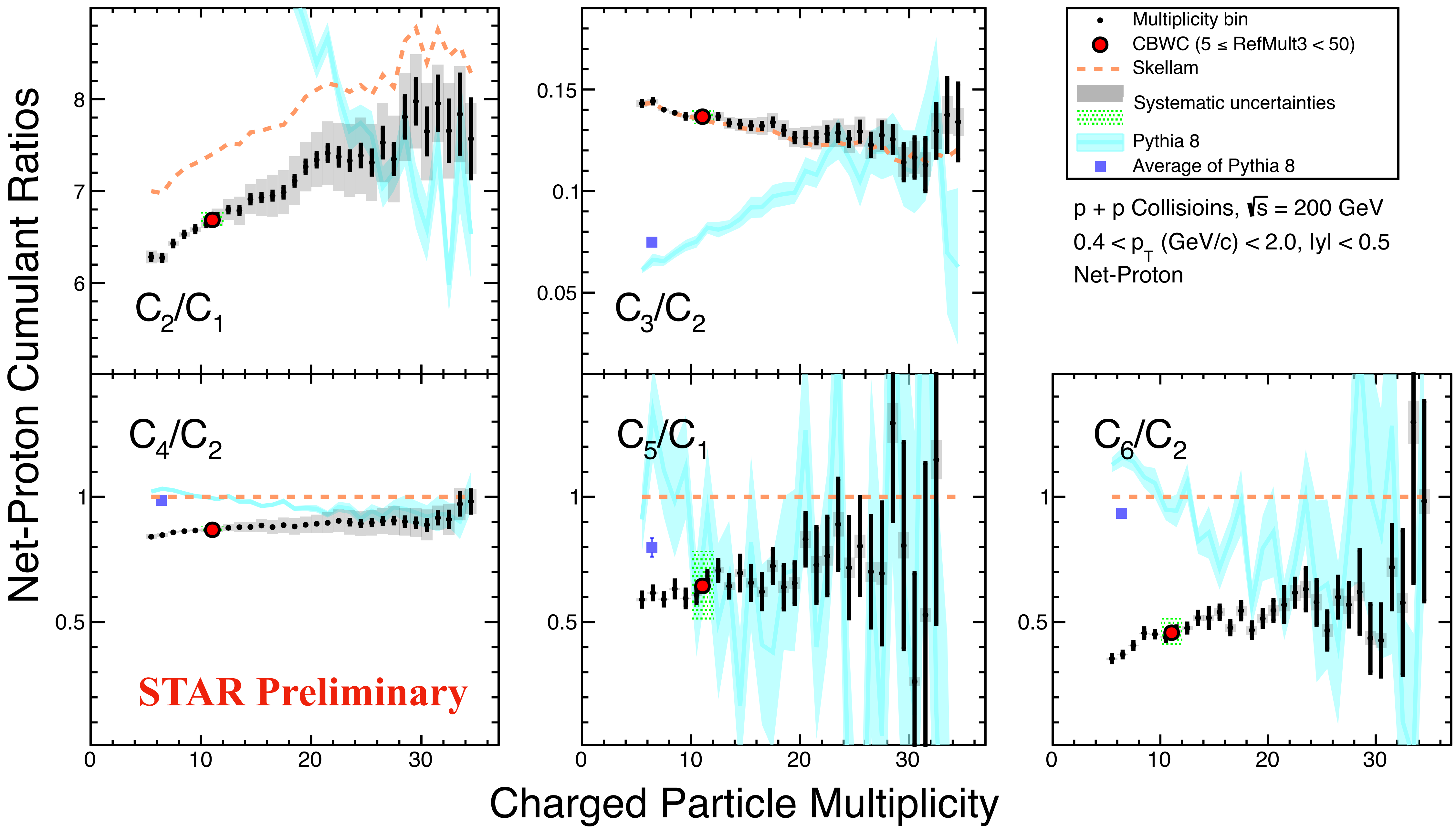
- **Cumulants increase with increasing multiplicity**
- **Deviations from Skellam※ and Pythia become larger for higher-order**

※ Skellam = $(\text{Poisson})_{\text{proton}} - (\text{Poisson})_{\text{antiproton}}$



Multiplicity dependence of net-proton cumulant ratios

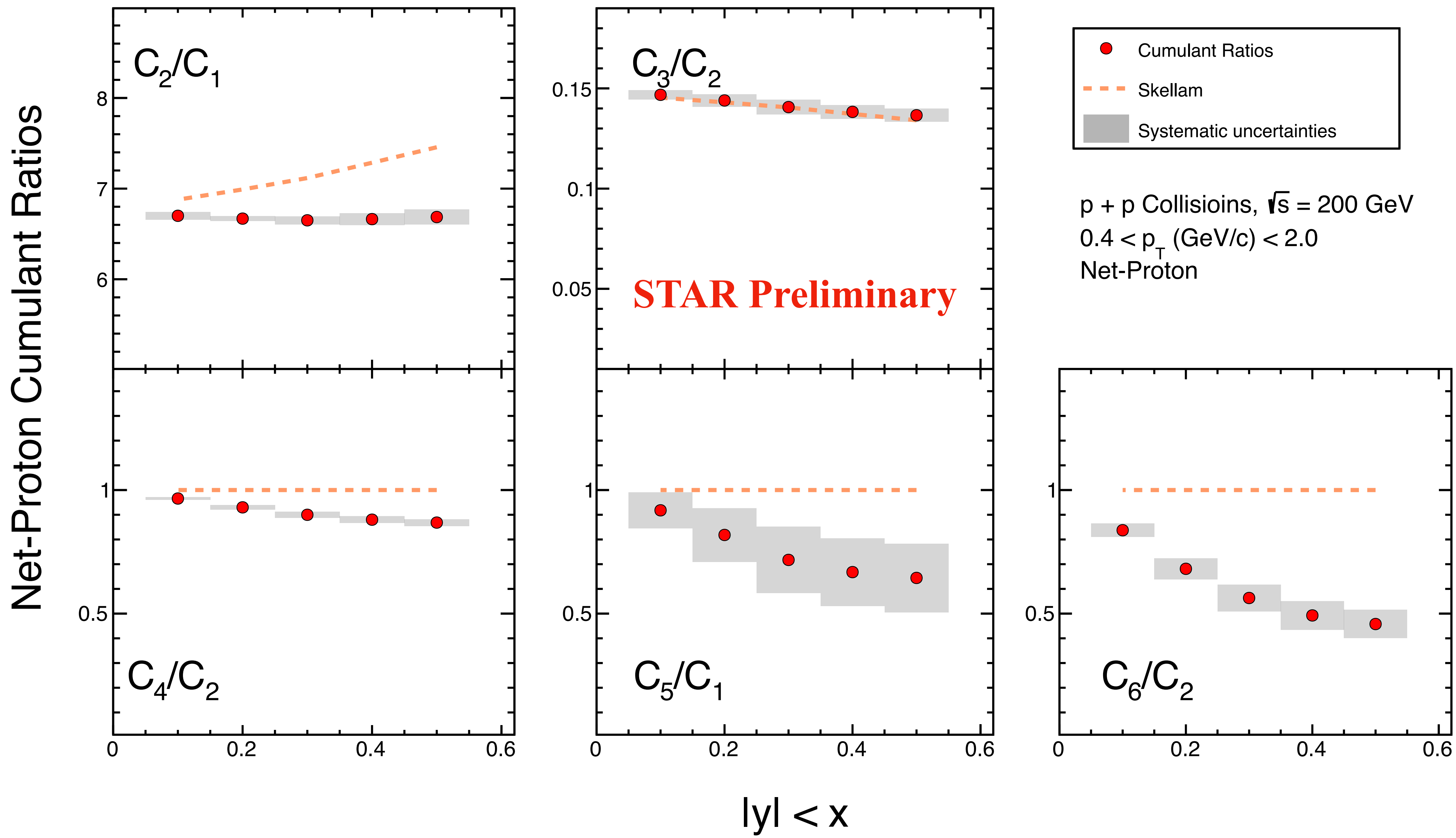
- C_3/C_2 is consistent with the Skellam expectations
- Deviations from Skellam and Pythia become larger for higher-order



Acceptance dependence of net-proton cumulant ratios

Δy dependence

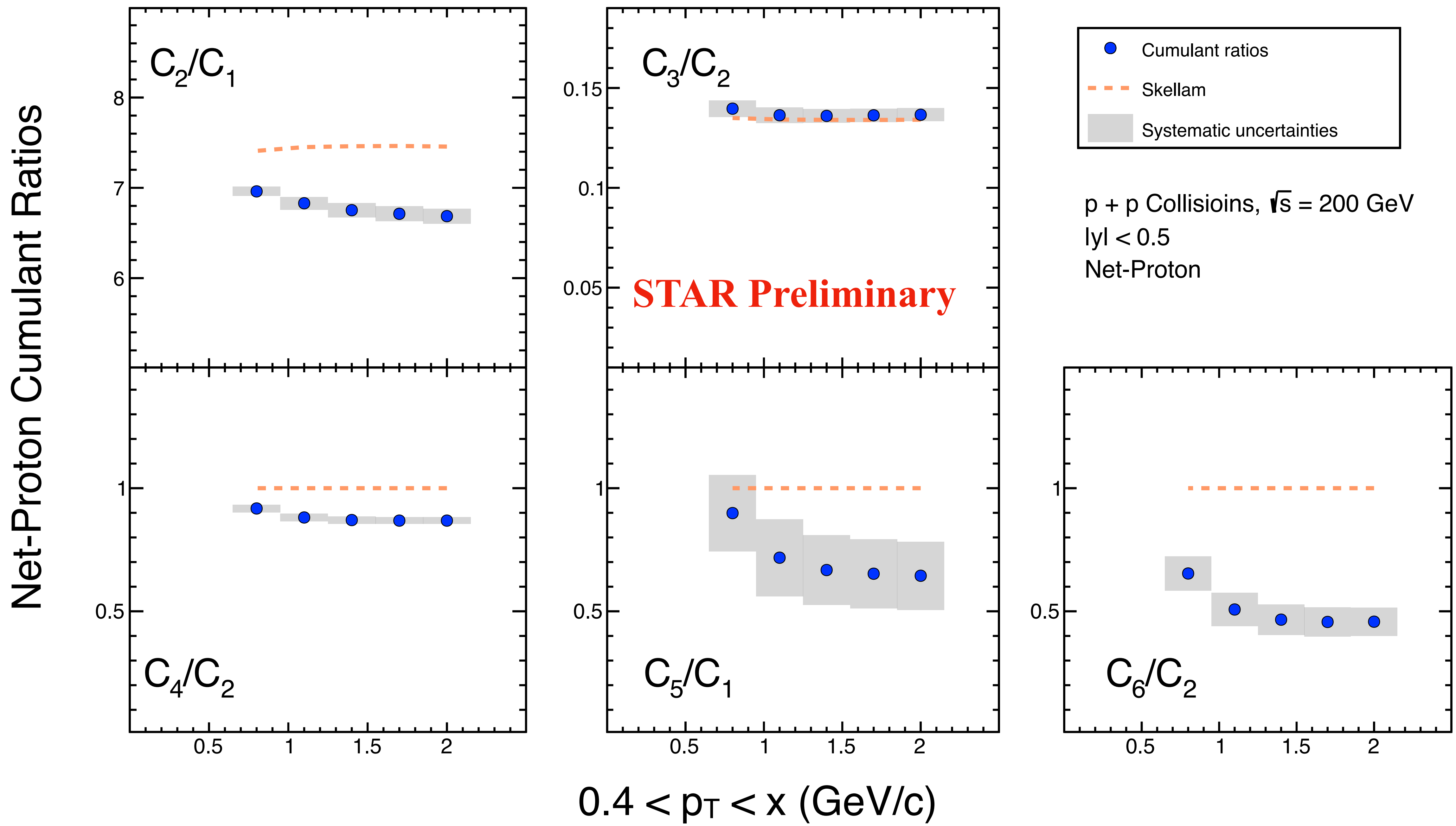
- **Deviations from Skellam baseline become large with increase of |Δy| acceptance except for C_3/C_2**
- **C_3/C_2 is consistent with Skellam**



Acceptance dependence of net-proton cumulant ratios

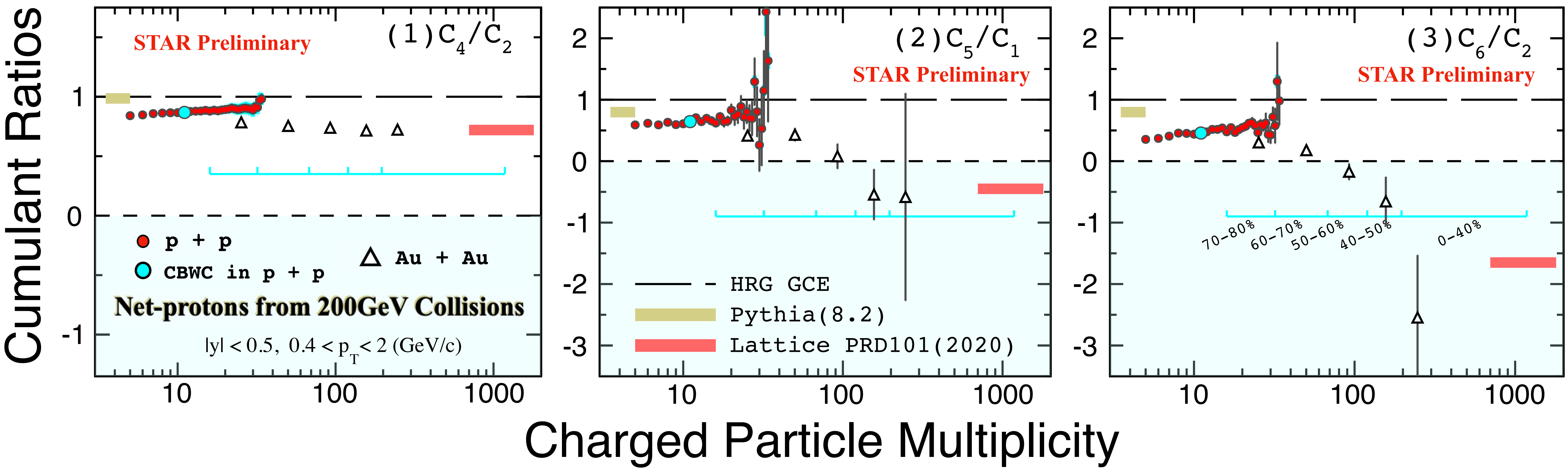
Δp_T dependence

- **Deviations from Skellam baseline become large with increase of p_T acceptance except for C_3/C_2**
- **C_3/C_2 is consistent with Skellam**



Comparison between p+p and Au+Au collisions at 200 GeV

- The results from p+p collisions fit into the centrality dependence of Au+Au collisions
- C_5/C_1 and C_6/C_2 > 0 for p+p collisions, while C_5/C_1 and C_6/C_2 < 0 for Au+Au central collisions



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

Au+Au: STAR, arXiv:2103.12413 (2021), arXiv:2105.14698 (2021)

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

Summary

Au+Au

- Net-proton C_4/C_2 shows non-monotonic beam energy dependence, which could be a signal from the critical point
- Net-proton C_5/C_1 and C_6/C_2 show negative values within large uncertainties at $\sqrt{s_{NN}}$ = 200 GeV

p+p

- Multiplicity dependence of net-proton cumulant has been measured in p+p collisions at $\sqrt{s}$ = 200 GeV
- The ratios from higher order cumulants are all positive

While the results of the ratios of C_5/C_1 and C_6/C_2 are all positive in 200 GeV p+p collisions, these ratios are progressively towards negative in more central Au+Au collisions at the same energy.

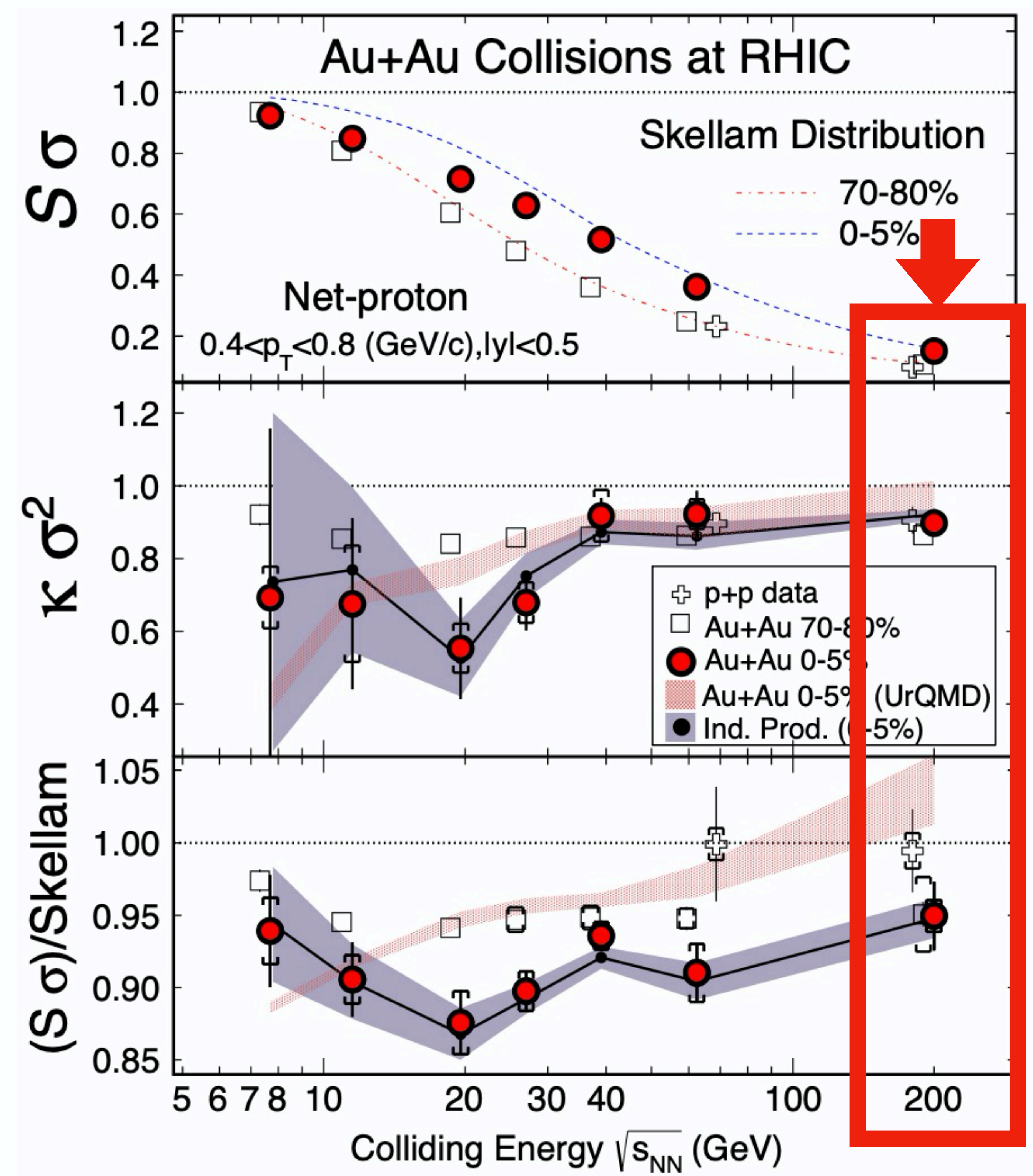
The observations are consistent with the chiral crossover transition predicted by model calculations at vanishing μ_B.

Backup

Why p+p ?

STAR Collaboration, Phys. Rev. Lett. 112, 32302 (2014)

- As a baseline to be compared with Au+Au collisions
- Statistics is 70 times larger than previous results
- Multiplicity / acceptance dependence would be available with high statistics dataset



Acceptance Dependence of Net-Proton Cumulants

|Δy| dependence

- **Cumulants become large with increasing |Δy| acceptance**