Measurements of Net-Proton Fluctuation for p+p Collisions at $\sqrt{s}$ = 200 GeV from the STAR Experiment

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STAR

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Outline

Introduction

- Higher-order fluctuations
- Recent STAR results

Data analysis

- Particle identification
- Efficiency correction
- Centrality bin width correction

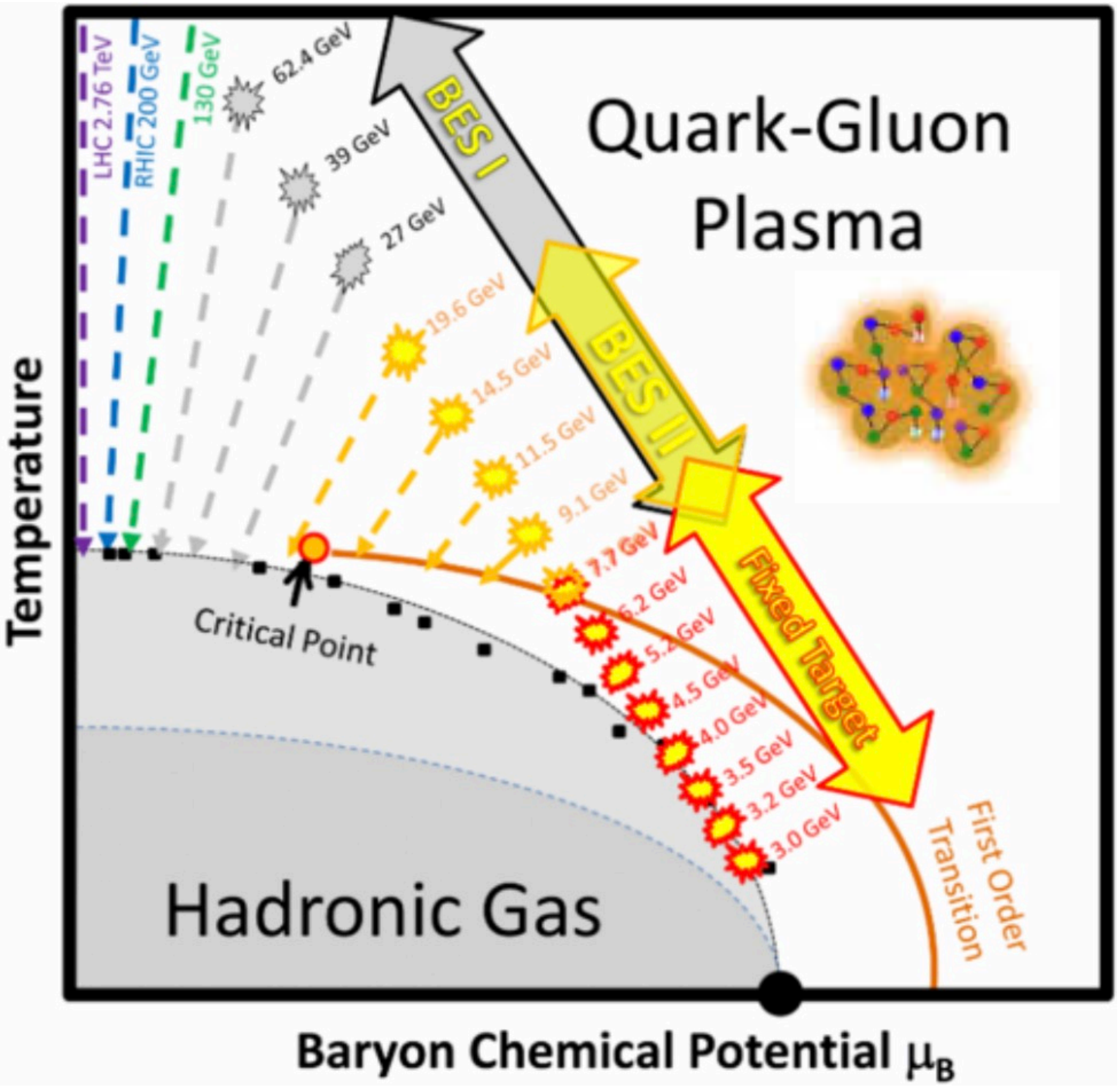
Results

- Multiplicity dependence
- Acceptance dependence
- Comparison with Au+Au collisions

Summary

Introduction

QCD phase diagram

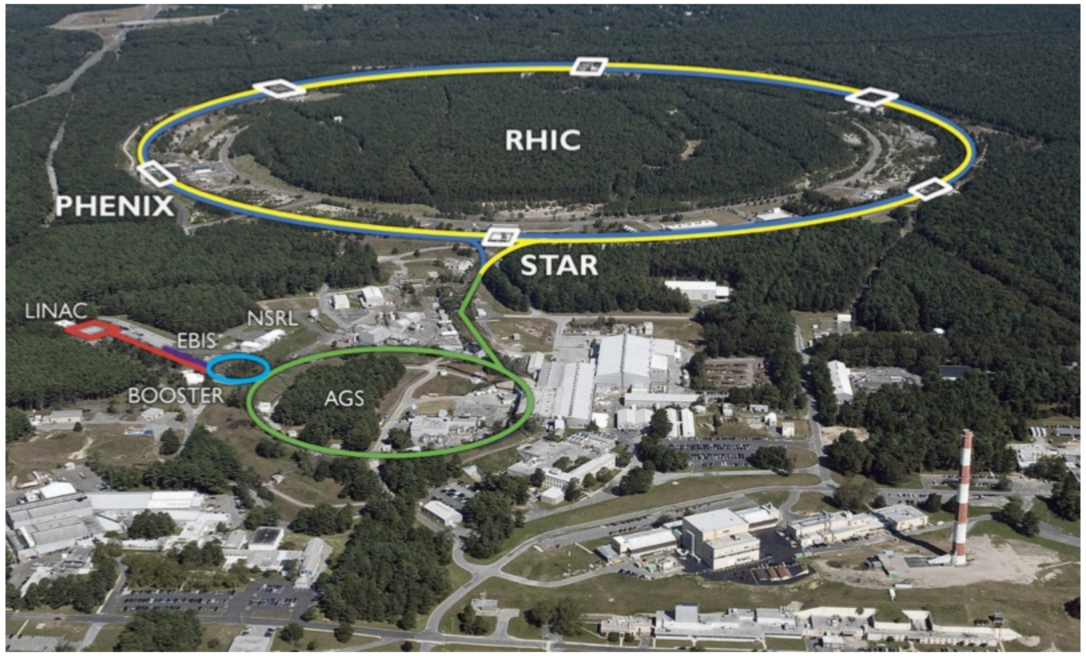


STAR Collaboration, Nuclear Physics A 982, 899-902 (2019)
STAR public note, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
STAR public note, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

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

↓

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



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**

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

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

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

Skellam = Poisson - Poisson'

Skellam : Difference between two independent Possion distributions

Cumulant ⇄ Moment

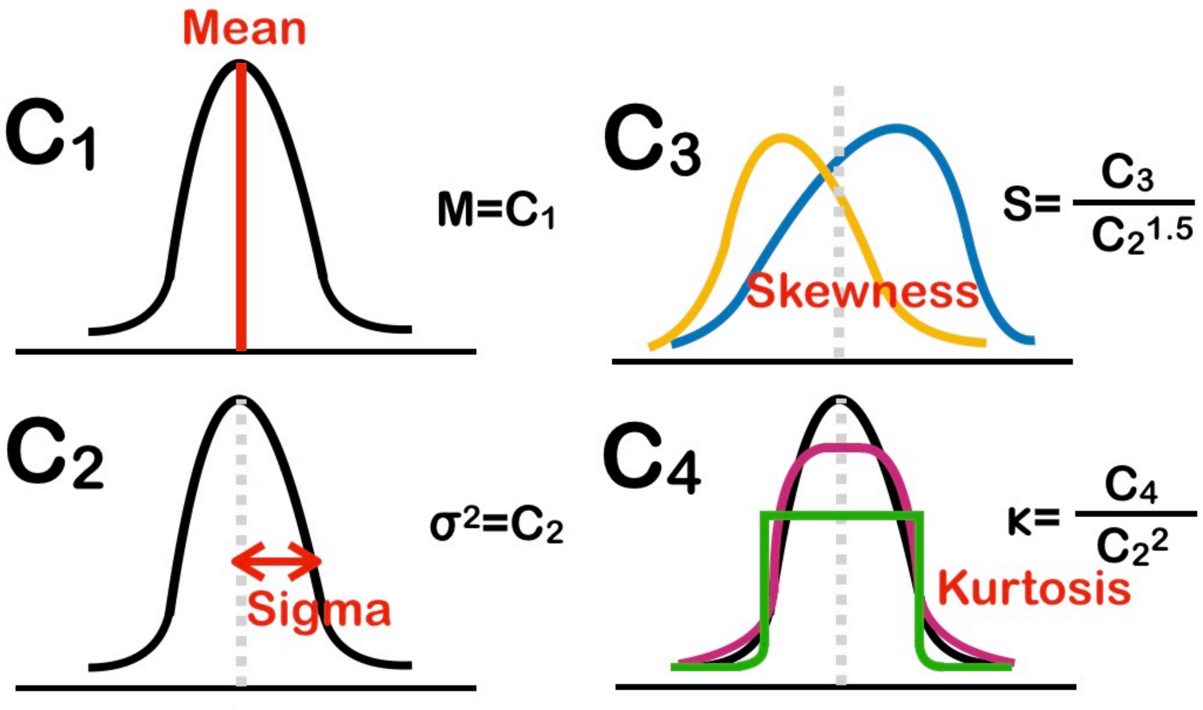
$$< \delta N >= N - < N >$$

$$C_1 = < N >$$

$$C_2 = < (\delta N)^2 >$$

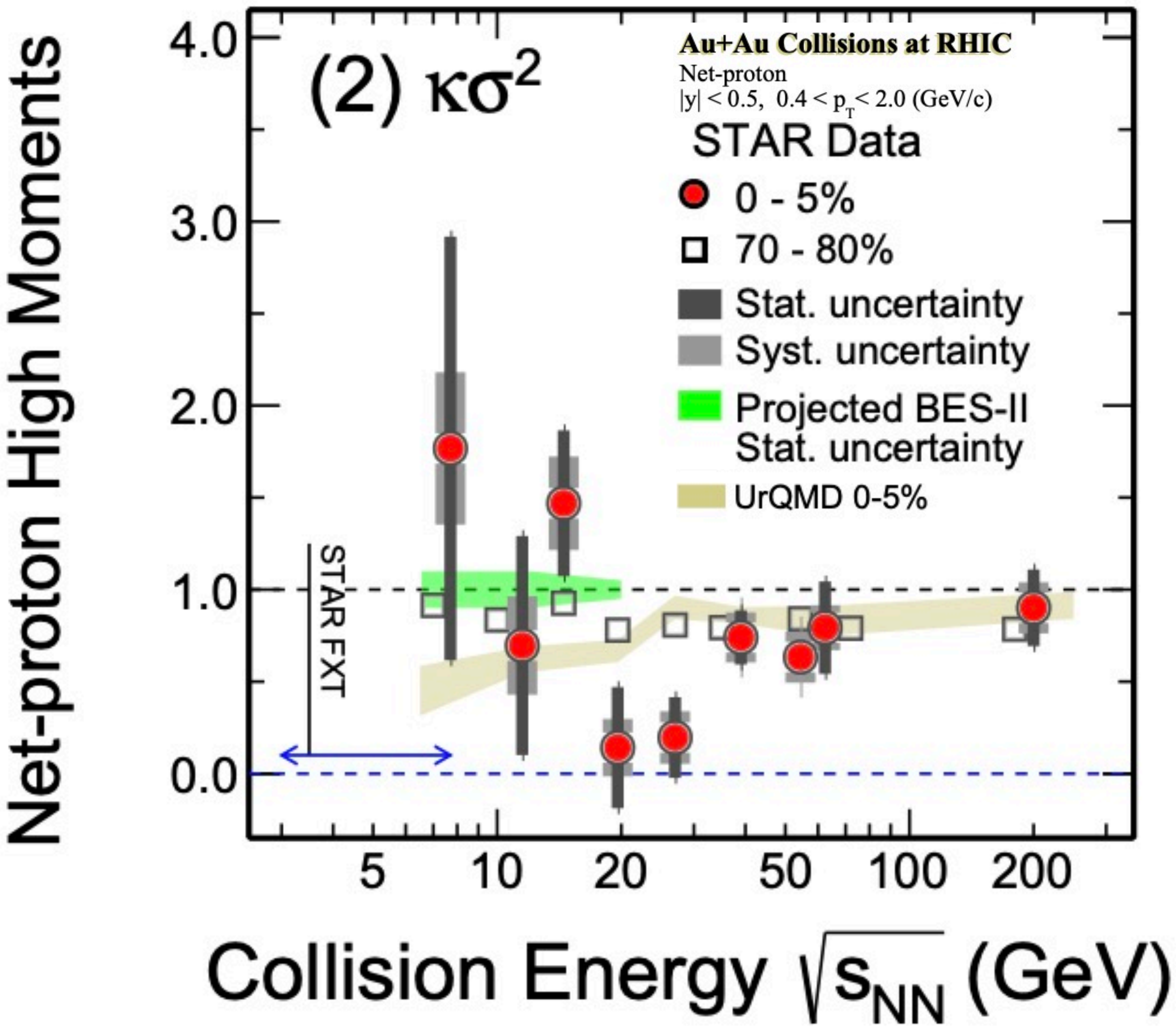
$$C_3 = < (\delta N)^3 >$$

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

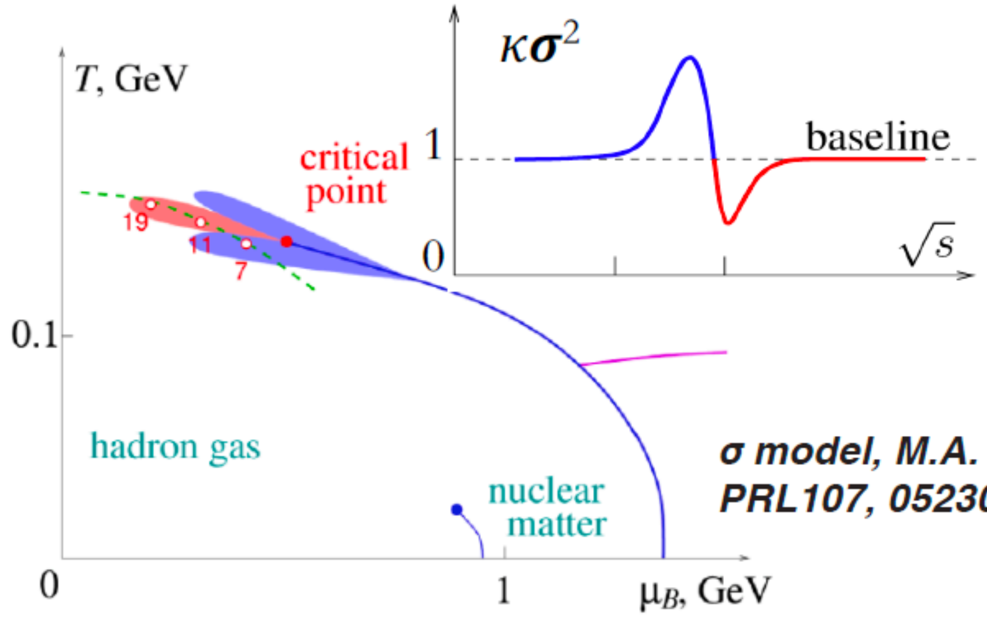


- **Higher-order cumulants and ratios are sensitive to phase structure**

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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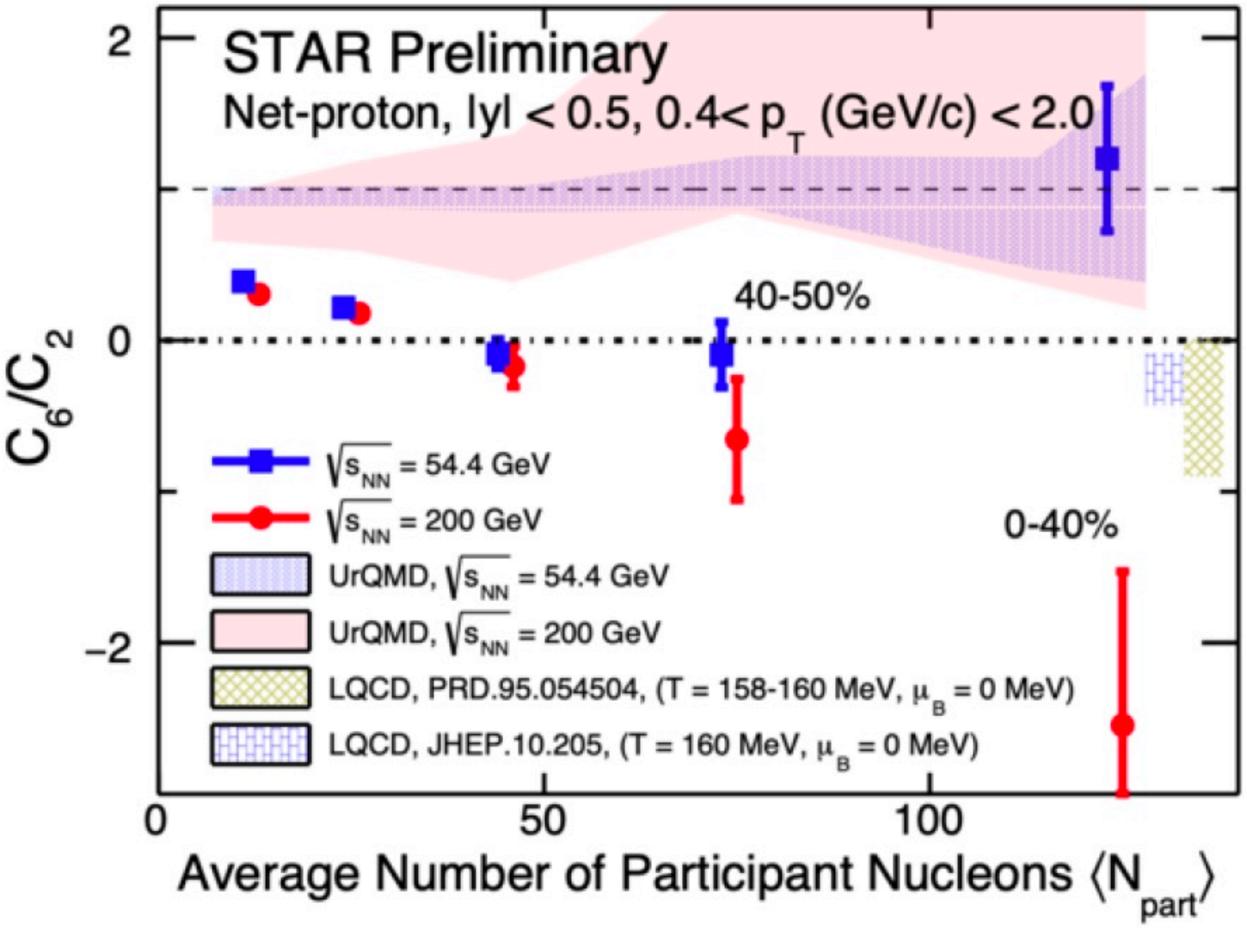
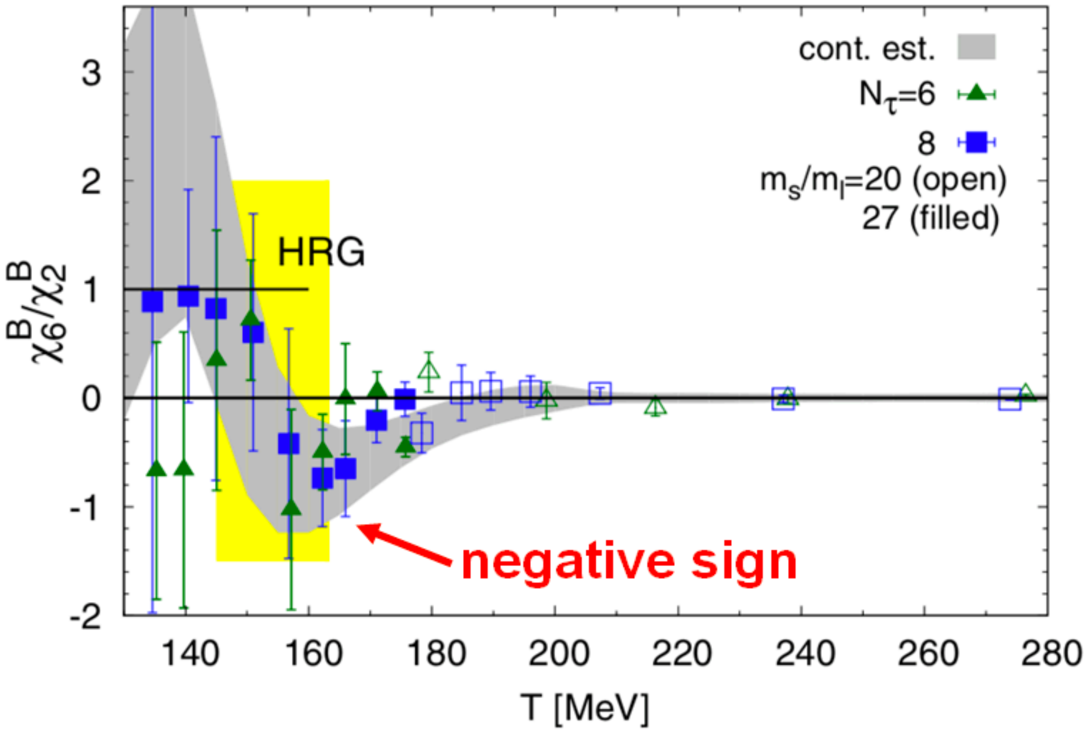
Possible signature of critical point

Sixth-order fluctuations for crossover search

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



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

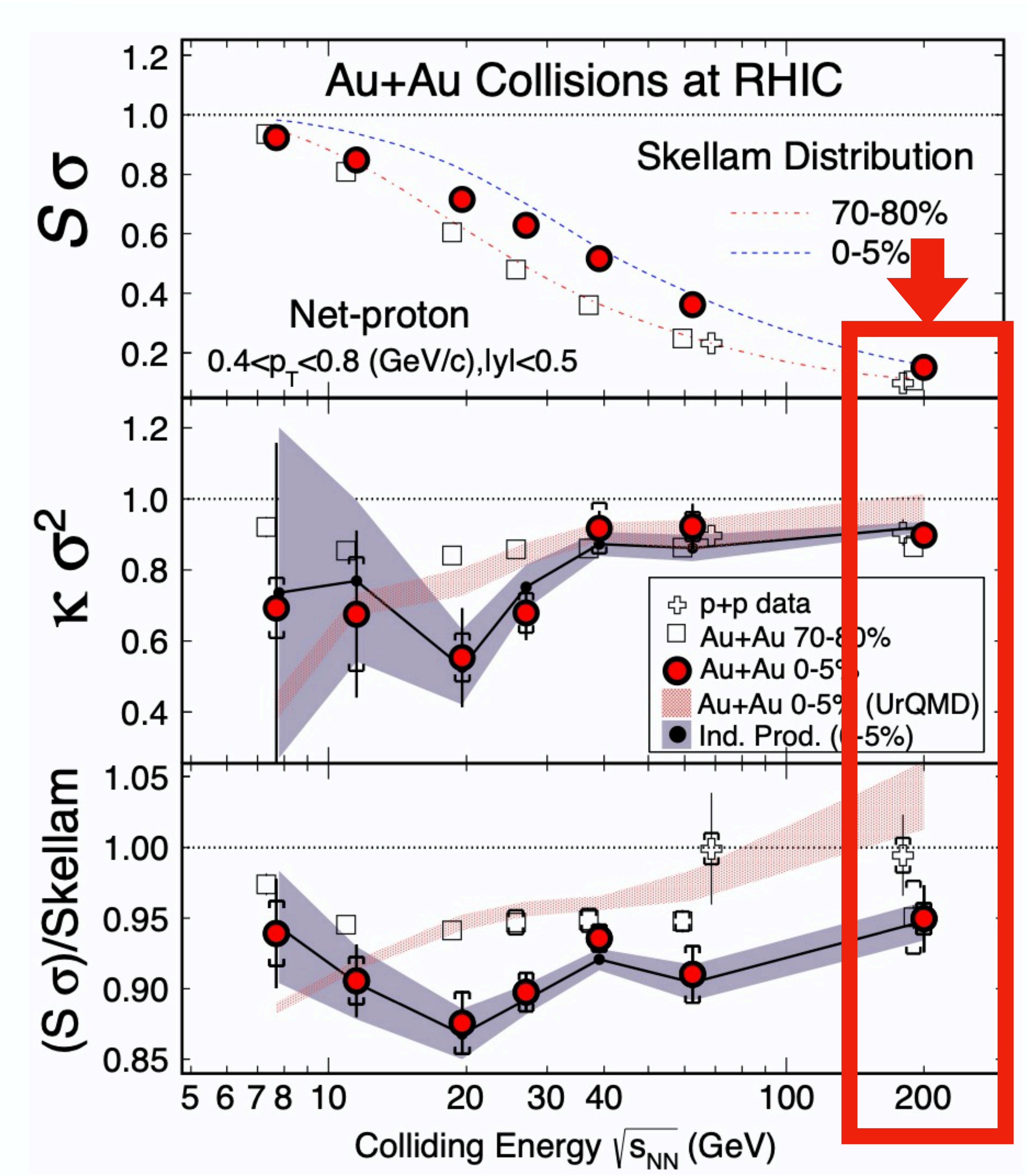


- From peripheral to central collisions, the values of C_6/C_2 change from positive to negative
- Lattice QCD calculations at μ_B = 0 show negative C_6/C_2

Why p+p ?

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

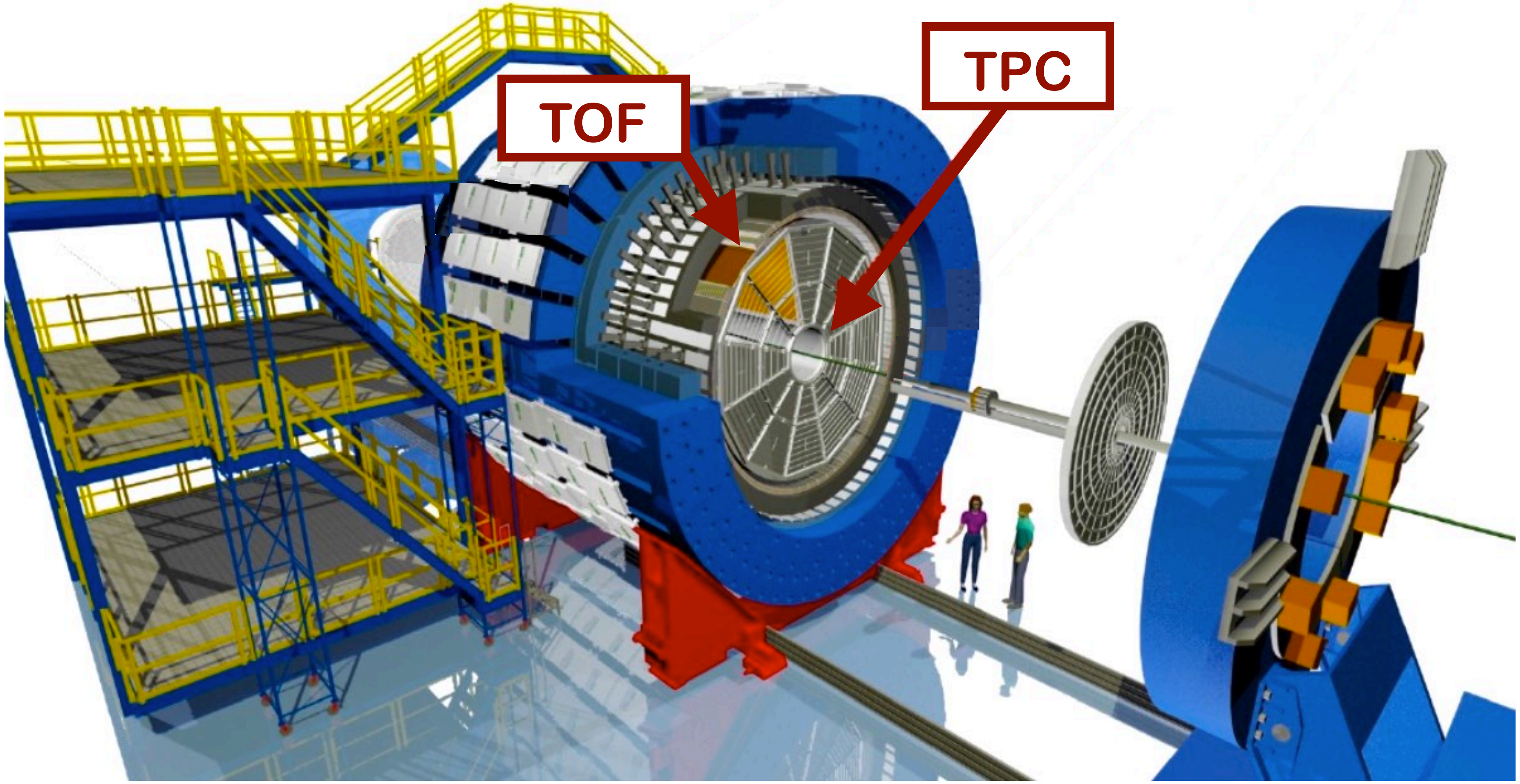
- As a baseline to be compared with Au+Au collisions
- Statistics is 70 times larger than previous results
- Multiplicity / acceptance dependence would be available with high statistics dataset



STAR detector

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

Full azimuthal angles, $|\eta| < 1.0$

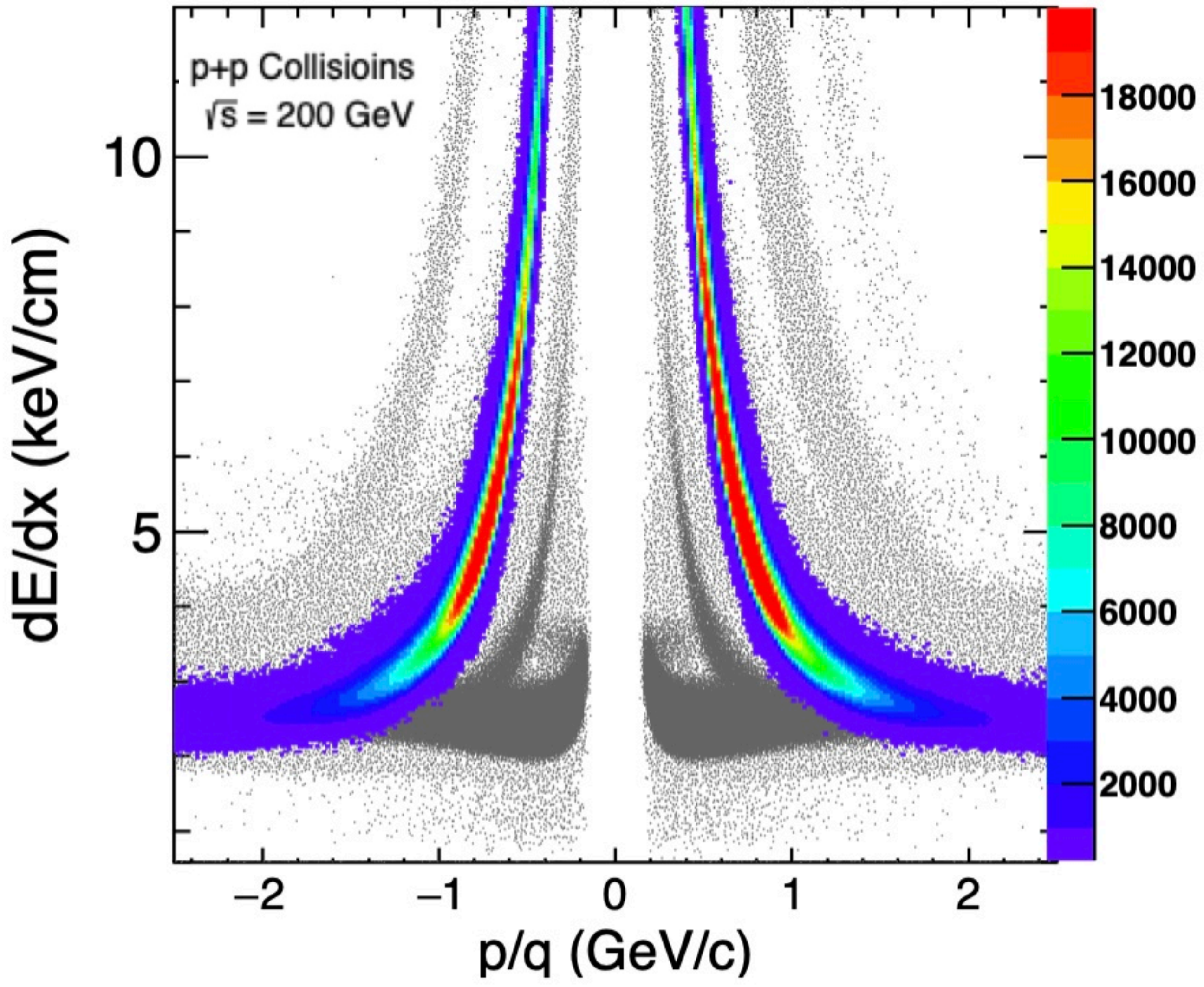


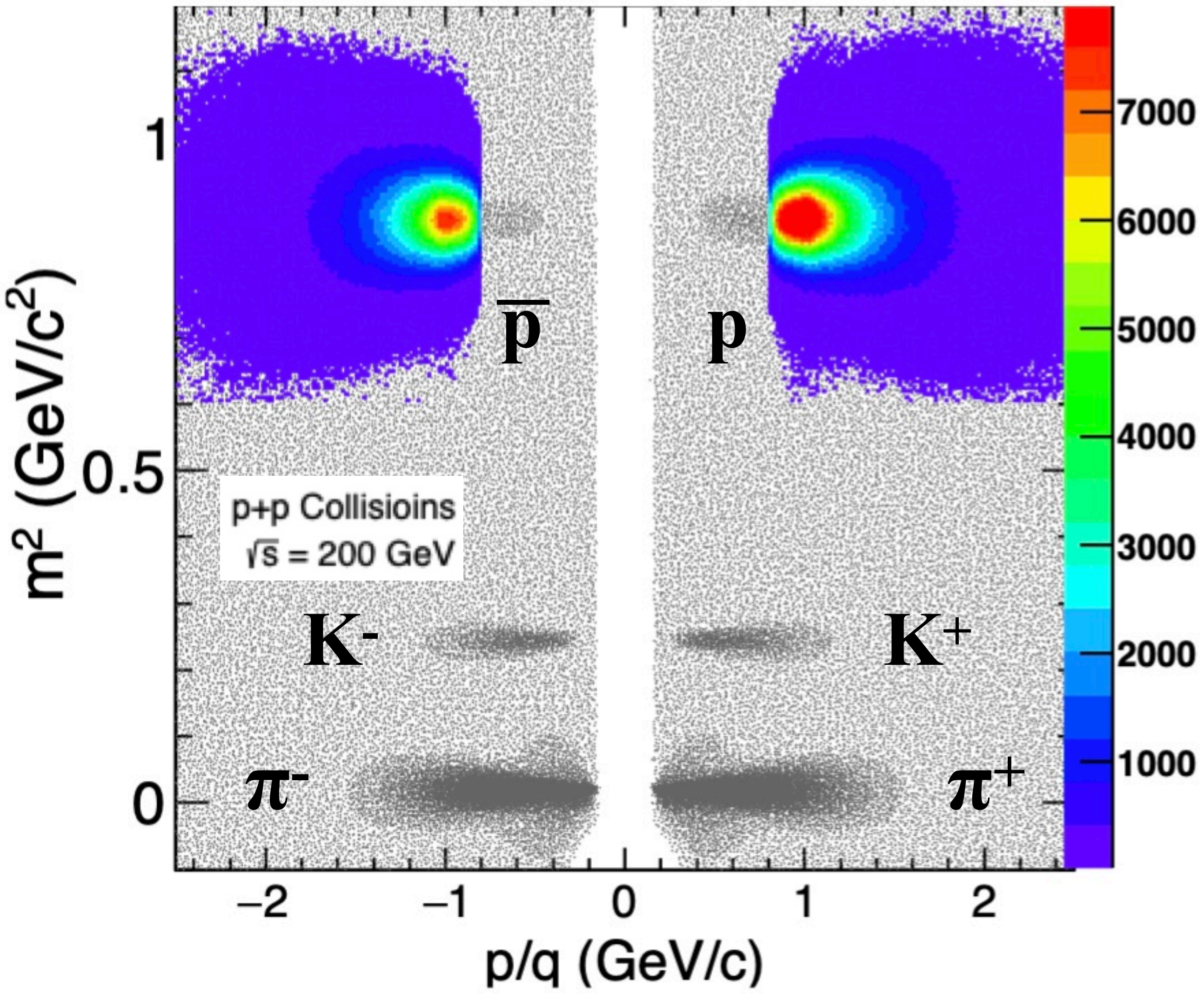
STAR, Nucl.Instrum.Meth.A 499 624-632, (2003)

Particle identification

Protons and Antiprotons are identified by

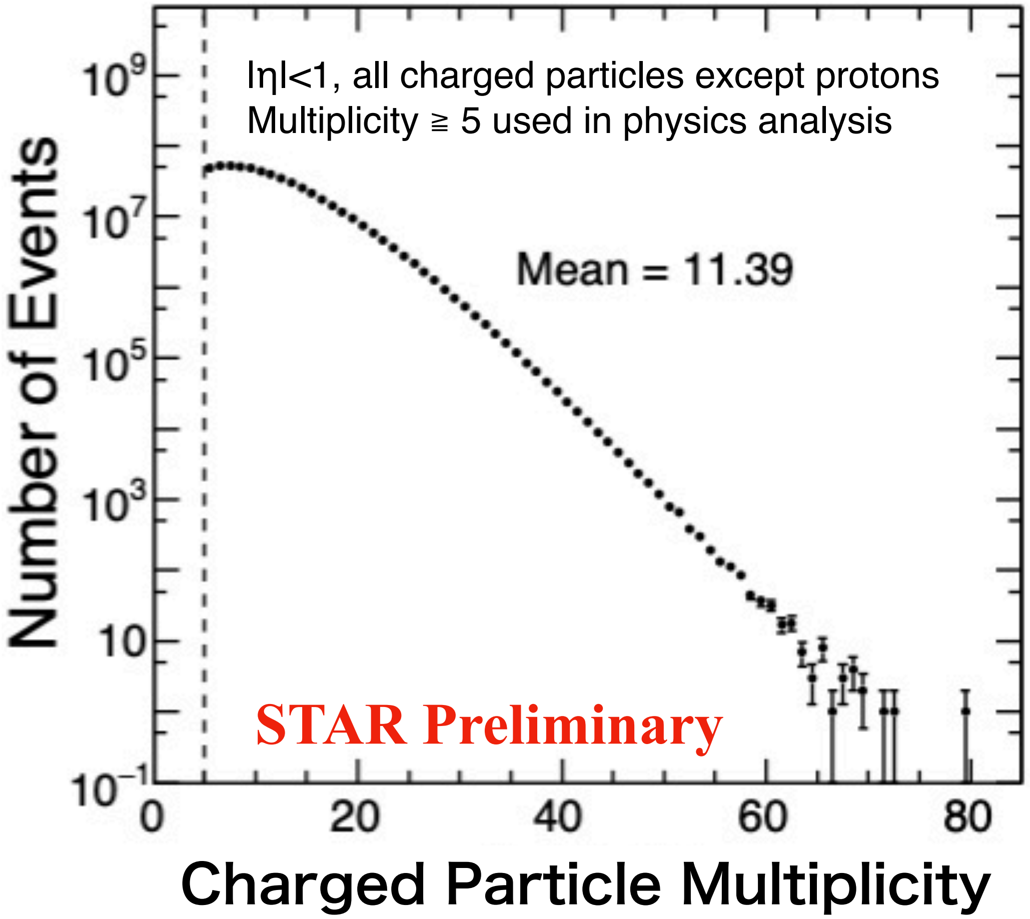
- **TPC for 0.4 < p_T (GeV/c)< 0.8**
- **TPC and TOF for 0.8< p_T (GeV/c)< 2.0**

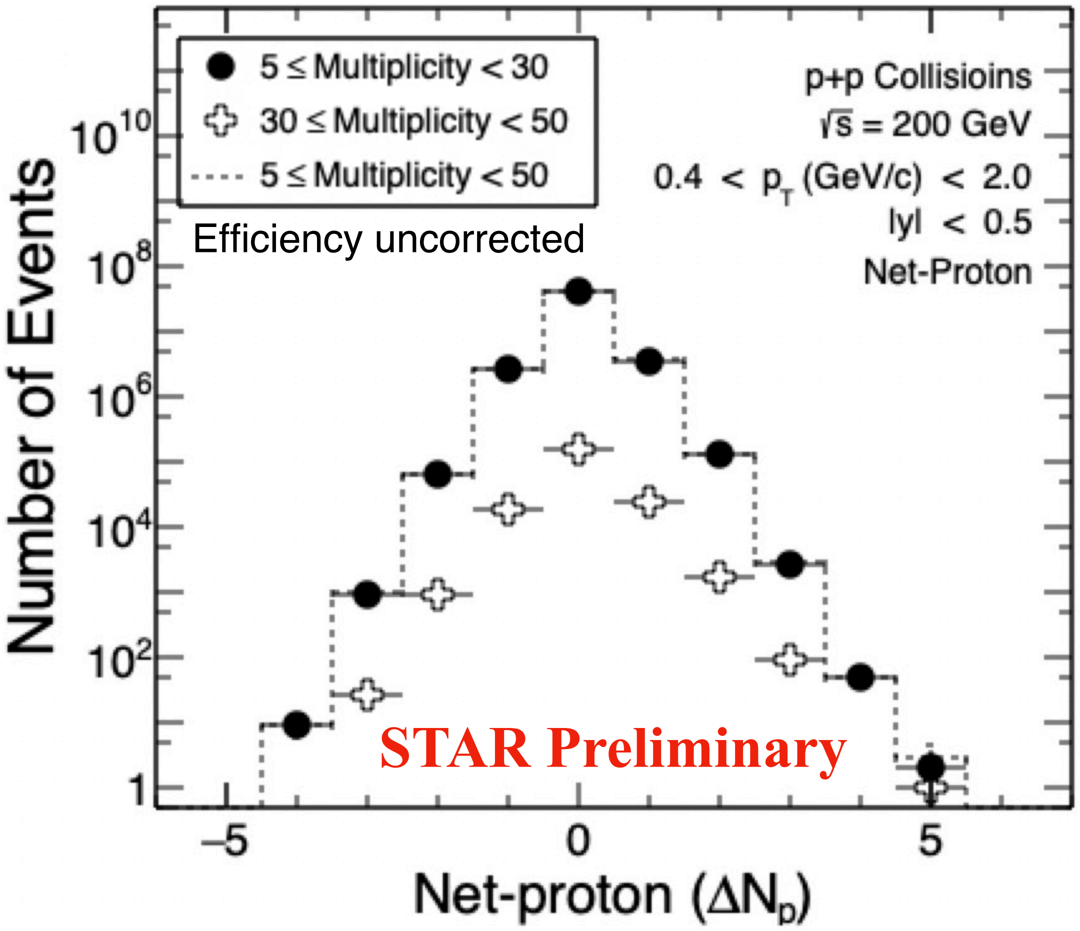




Multiplicity distributions

- **Charged particle multiplicity is defined in $|\eta|<1.0$ excluding (anti)protons.**
- **Event-by-event net-proton distributions are measured at mid-rapidity.**





Efficiency correction

- **Cumulants are corrected for detector efficiencies by assuming they follow the binomial distrbiution.**
- **Efficiency variations on acceptance and multiplicity are taken into account.**

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

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)

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

a: charge, ε: efficiency

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 = $\langle Q^4 \rangle_c = \langle q_{(1,1)}^4 \rangle_c + 6\langle q_{(1,1)}^2 q_{(2,1)} \rangle_c - 6\langle q_{(1,1)}^2 q_{(2,2)} \rangle_c + 4\langle q_{(1,1)} q_{(3,1)} \rangle_c + 3\langle q_{(2,1)}^2 \rangle_c + 3\langle q_{(2,2)}^2 \rangle_c - 12\langle q_{(1,1)} q_{(3,2)} \rangle_c$
$+ 8\langle q_{(1,1)} q_{(3,3)} \rangle_c - 6\langle q_{(2,1)} q_{(2,2)} \rangle_c + \langle q_{(4,1)} \rangle_c - 7\langle q_{(4,2)} \rangle_c + 12\langle q_{(4,3)} \rangle_c - 6\langle q_{(4,4)} \rangle_c$

Centrality bin width correction

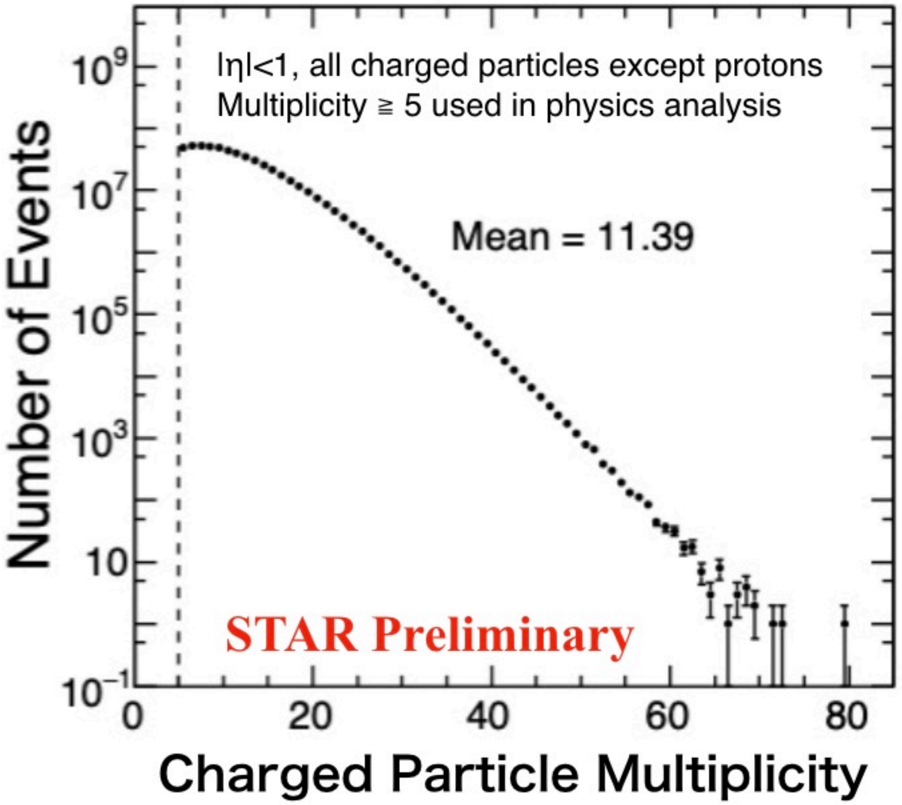
- **Cumulants are calculated for each multiplicity bin, and averaged for each centrality class in AuAu collisions.**
- **Effects of initial volume fluctuations are suppressed in a data-driven way.**

X. Luo, J. Xu, B. Mohanty and N. Xu, J. Phys. G40, 105104 (2013),
A. Chatterjee, Y. Zhang , J. Zeng, N. R. Sahoo, X. Luo, 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**

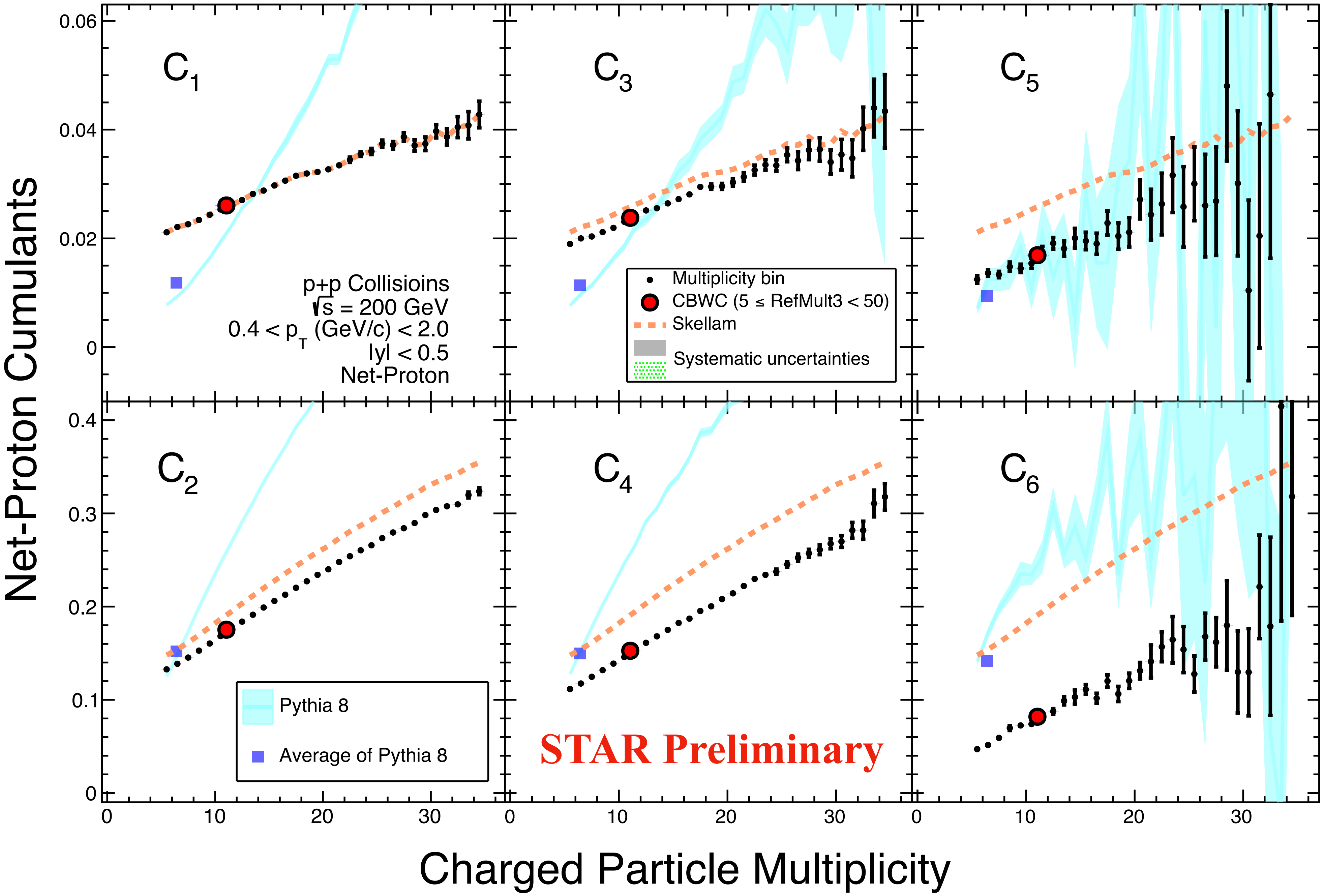


- **There is no initial volume fluctuations by construction, thus CBWC is just to take averaging.**

Multiplicity dependence of net-proton cumulants

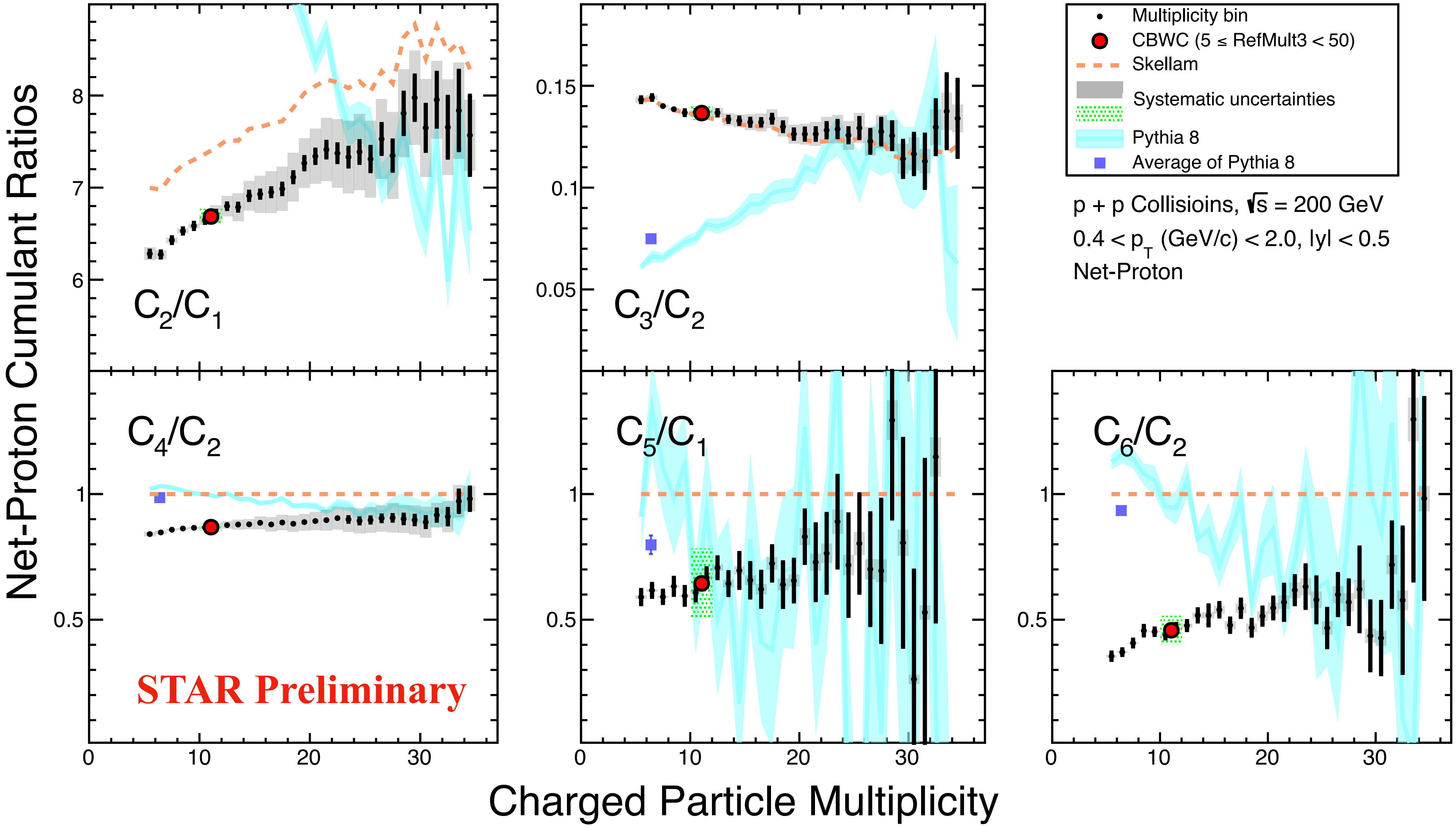
- **Cumulants increase with increasing multiplicity**
- **Deviations from Skellam※ and Pythia become larger for higher-order**

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



Multiplicity dependence of net-proton cumulant ratios

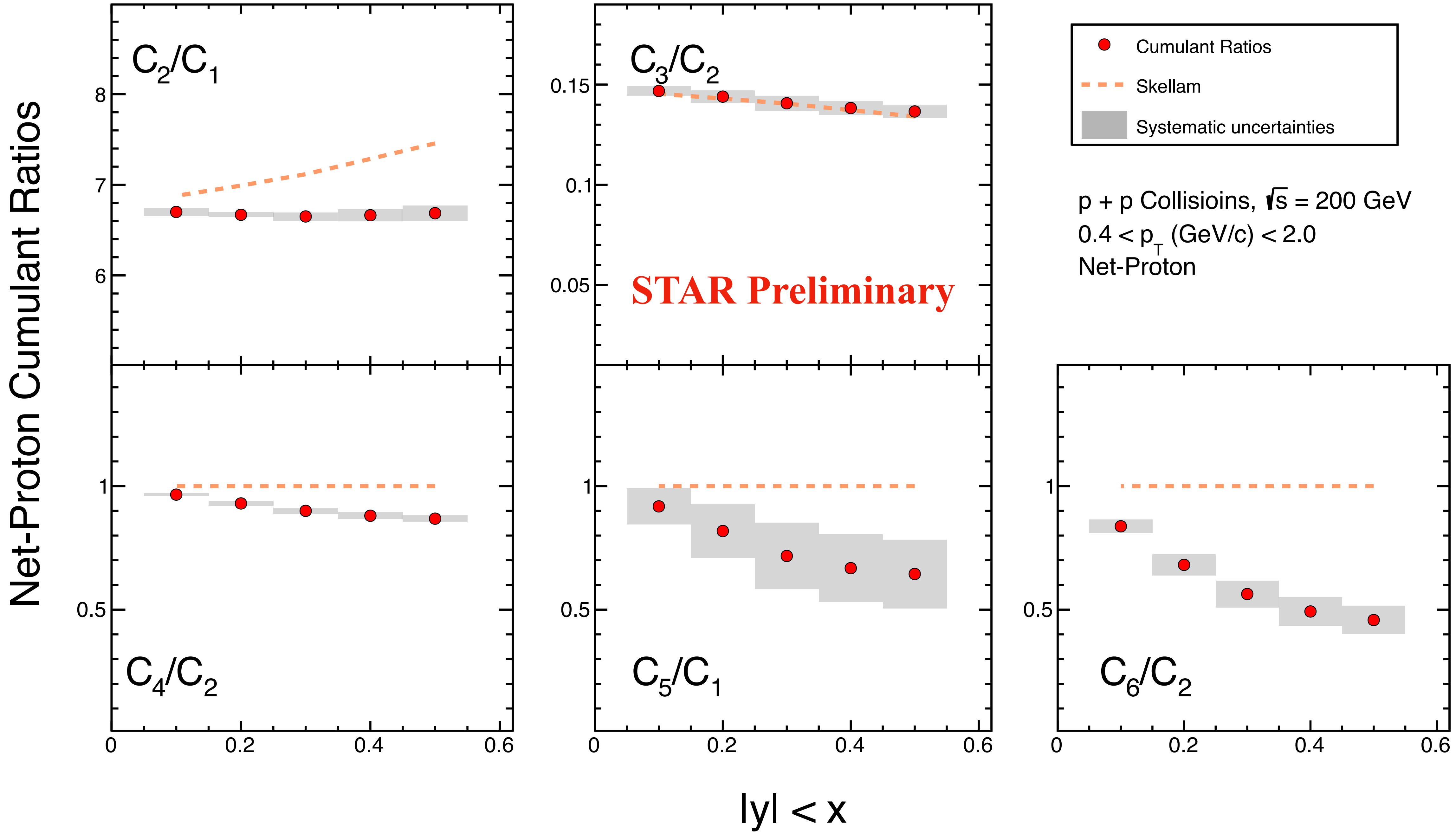
- C_3/C_2 is consistent with the Skellam expectations
- Deviations from Skellam and Pythia become larger for higher-order



Acceptance dependence of net-proton cumulant ratios

$|\Delta y|$ dependence

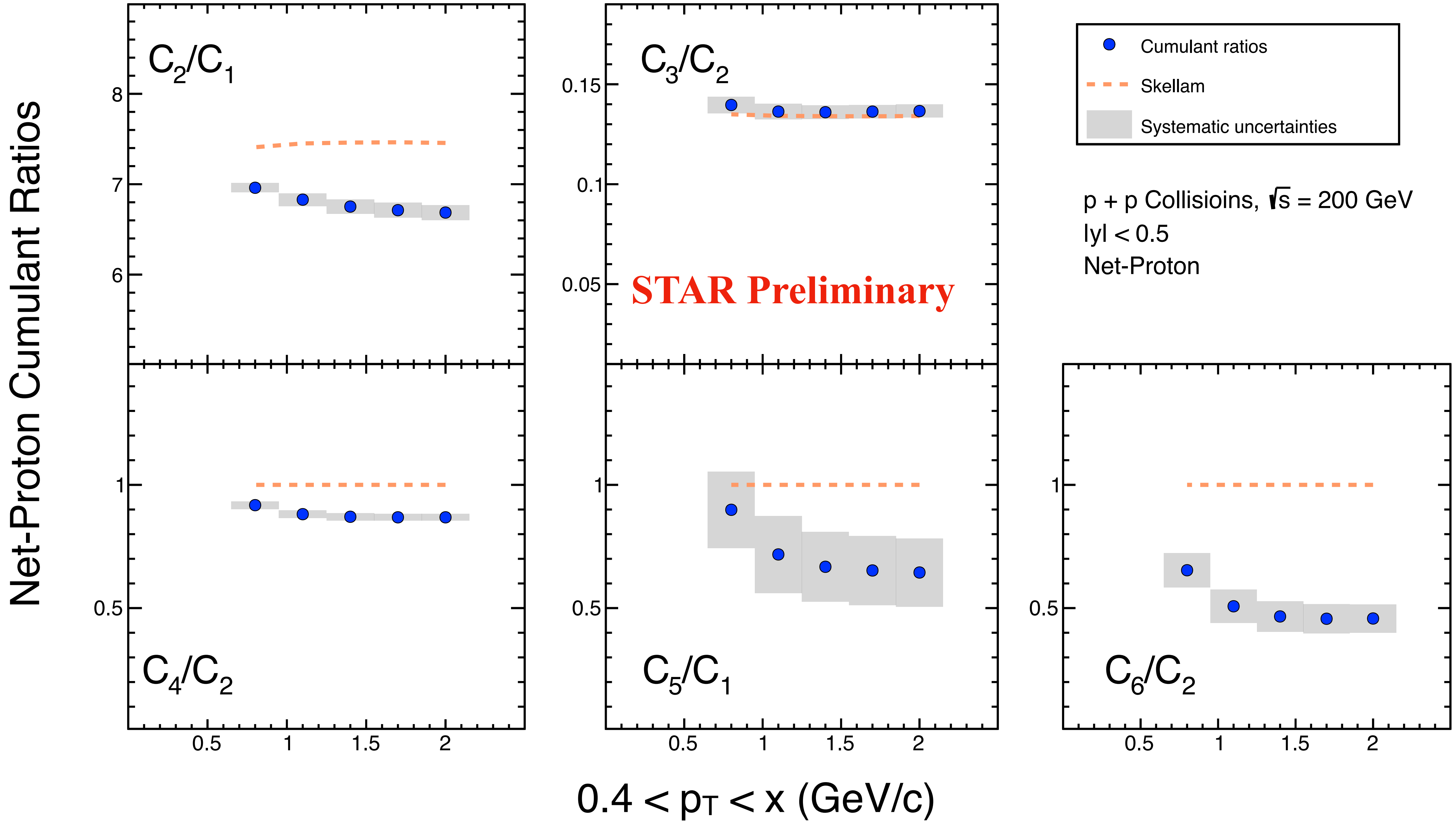
- **Deviations from Skellam baseline become large with increasing $|\Delta y|$ acceptance except for C_3/C_2**
- **C_3/C_2 is consistent with Skellam**



Acceptance dependence of net-proton cumulant ratios

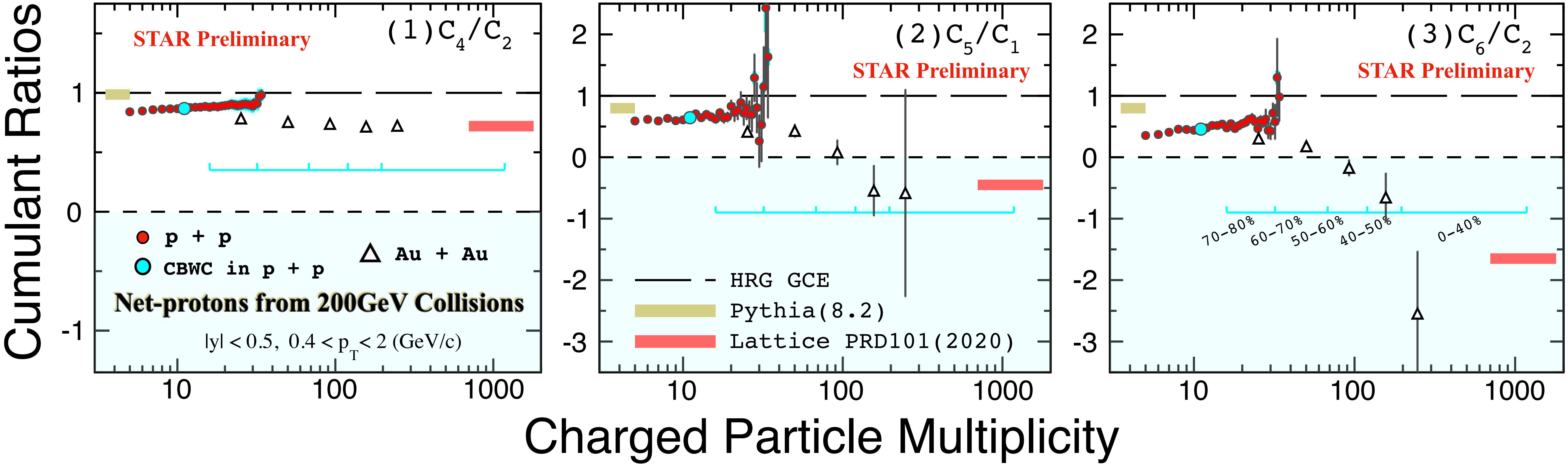
Δp_T dependence

- **Deviations from Skellam baseline become large with increasing 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

- 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

STAR Collaboration, arXiv, 2101.12413 (2021)

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

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

Summary

- **Multiplicity dependence of net-proton cumulant has been measured in p+p collisions at $\sqrt{s}$ = 200 GeV**

- **Larger deviations from Skellam / Pythia expectations are observed for higher-order cumulants**

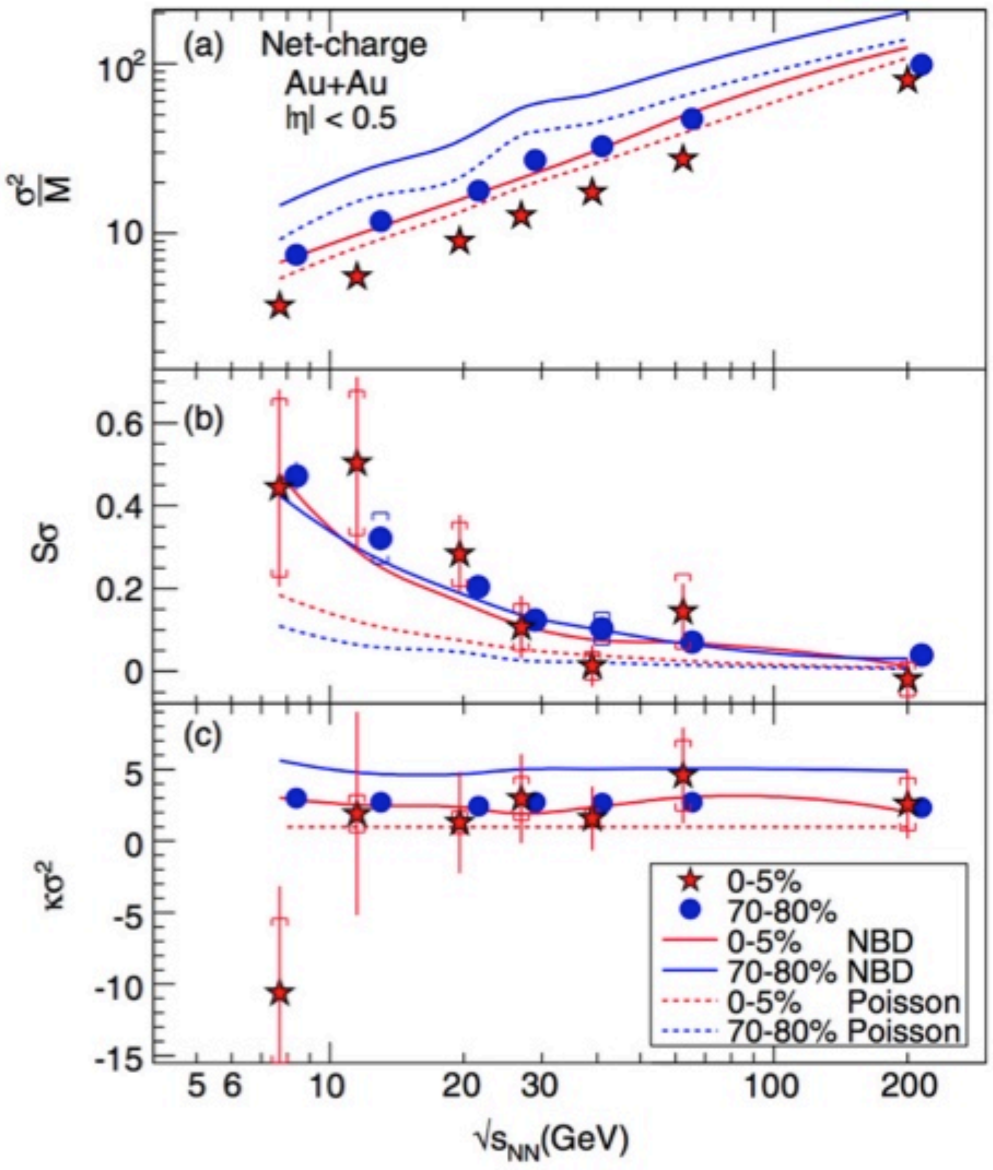
- **Cumulant ratios decrease with increasing rapidity acceptance**

- **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**

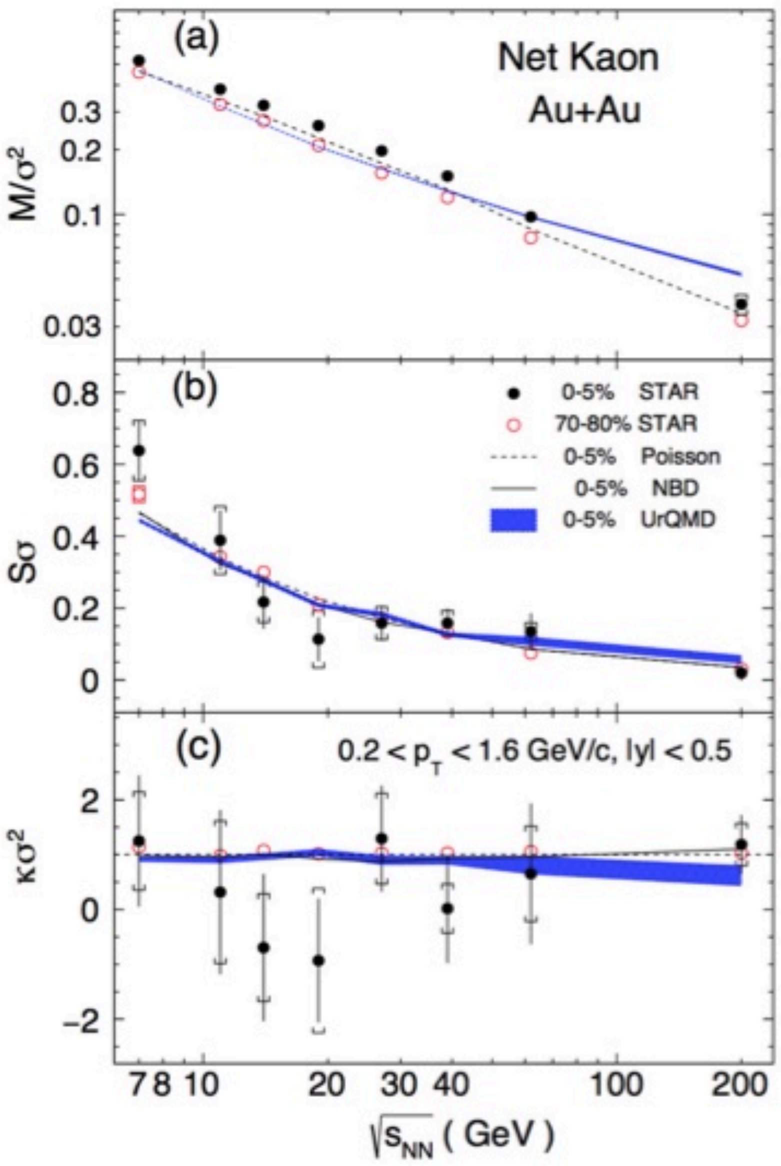
- **The results from p+p collisions fit into the centrality dependence of Au+Au collisions at the same energy. Lattice calculations imply chiral phase transition in the thermalized QCD matter. This is not the case in 200 GeV p+p collisions.**

Backup

STAR results for net-charge and net-kaon



STAR Collaboration, Phys. Rev. Lett, 113 092301 (2014)



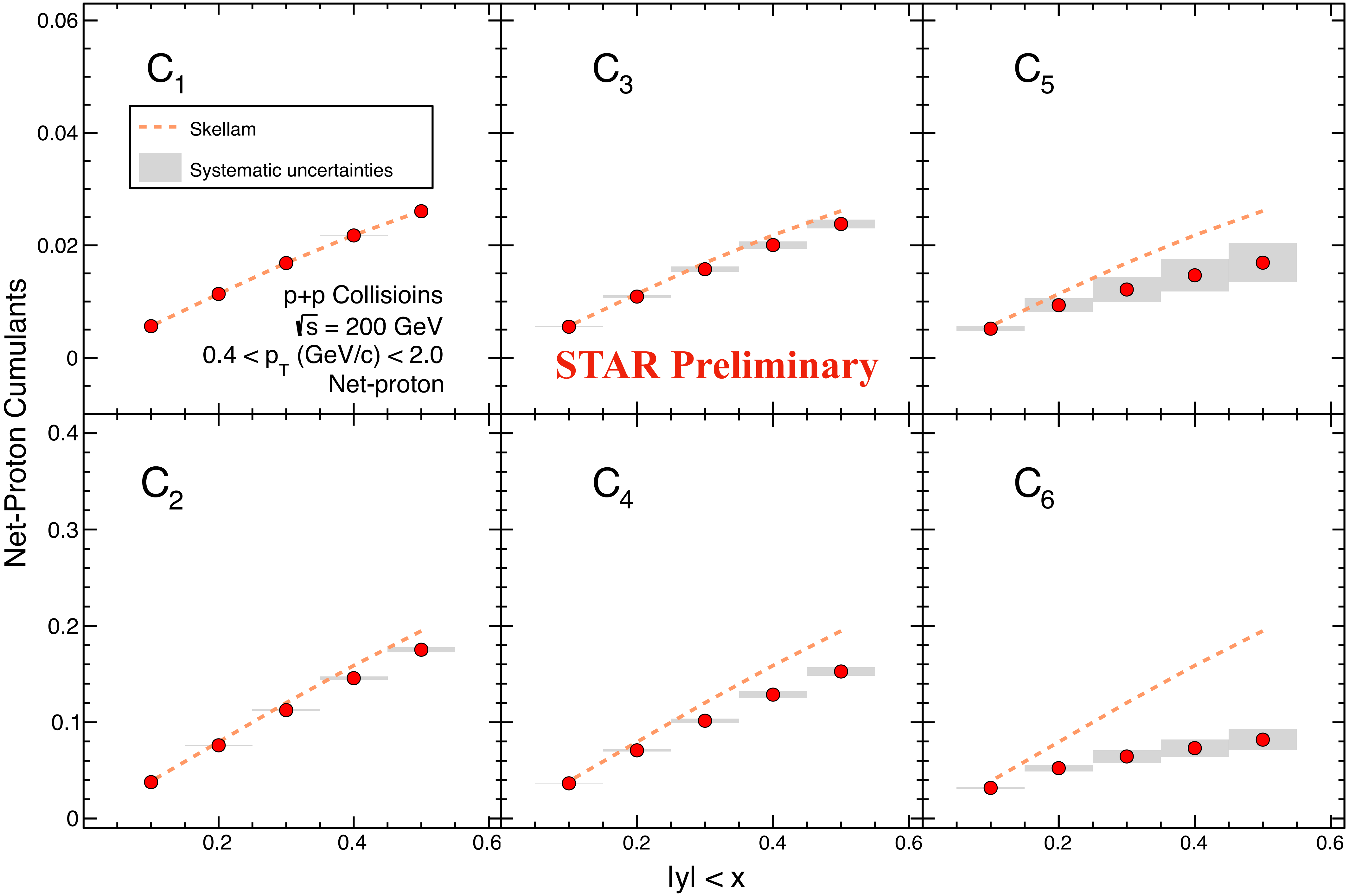
STAR Collaboration, 1709.00773 (2017)

Monotonic beam energy dependence

Acceptance Dependence of Net-Proton Cumulants

|Δy| dependence

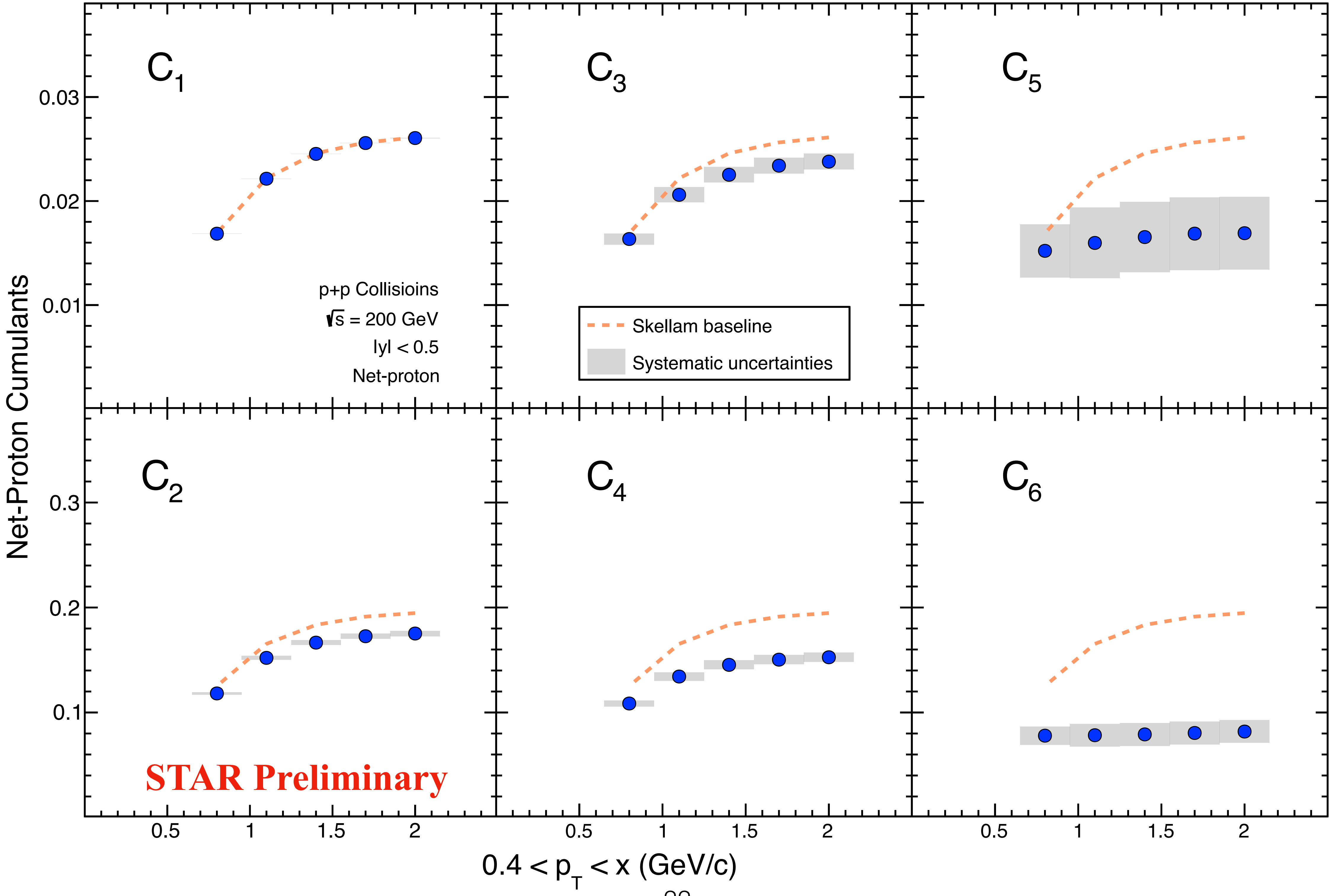
- **Cumulants become large with increasing |Δy| acceptance**



Acceptance Dependence of Net-Proton Cumulant

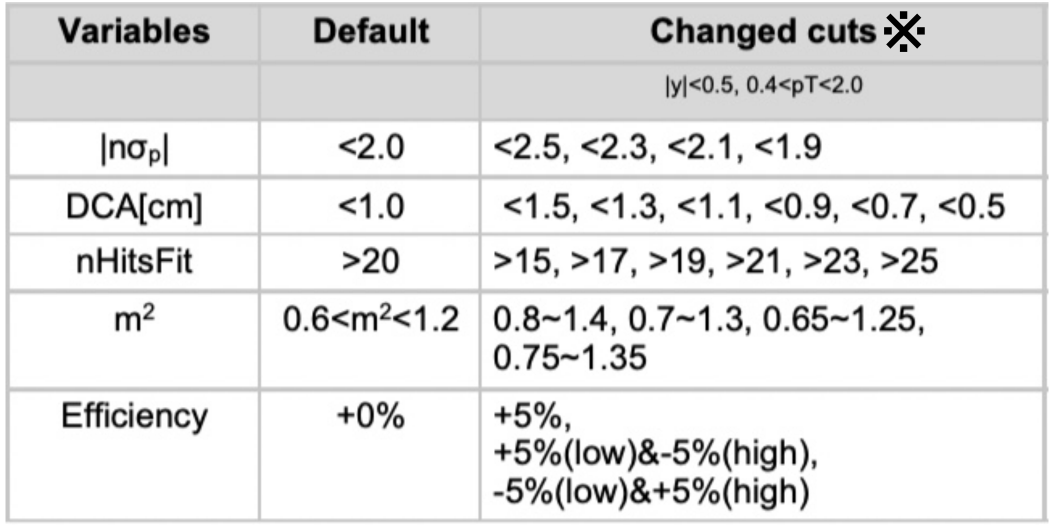
Δp_T dependence

- Cumulants become large with increasing p_T acceptance



Systematic uncertainties

Cuts on PID, track quality, and efficiencies were checked



Variables	Default	Changed cuts ※
		|y|<0.5, 0.4<pT<2.0
$\|n\sigma_p\|$	<2.0	<2.5, <2.3, <2.1, <1.9
DCA[cm]	<1.0	<1.5, <1.3, <1.1, <0.9, <0.7, <0.5
nHitsFit	>20	>15, >17, >19, >21, >23, >25
m^2	$0.6<m^2<1.2$	0.8~1.4, 0.7~1.3, 0.65~1.25, 0.75~1.35
Efficiency	+0%	+5%, +5%(low)&-5%(high), -5%(low)&+5%(high)

※ The range has been determined based on the ±5% change of C_1

- Efficiencies are modified so that the corrected C_1 values become identical for each systematic cuts
- This will be checked again once we have large data of embedding (now producing)
- Barlow check has been done to remove statistical effects → Only a few cuts condition has passed

$$\sigma_{sys} = Y_{\rm def}\sqrt{\sum_j R_j^2}, \quad R_j = \sqrt{\frac{1}{n}\sum_i\left[\frac{Y_{i,j}-Y_{\rm def}}{Y_{\rm def}}\right]^2}$$

- **$Y_{\rm def}$: default cuts results**
- **$Y_{i,j}$: ith change of the cut on jth variable**

	|y|<0.5, 0.4<p_T<2.0	|y|<0.4, 0.4<p_T<2.0	|y|<0.3, 0.4<p_T<2.0	|y|<0.2, 0.4<p_T<2.0	|y|<0.1, 0.4<p_T<2.0	|y|<0.5, 0.4<p_T<1.7	|y|<0.5, 0.4<p_T<14	|y|<0.5, 0.4<p_T<1.1	|y|<0.5, 0.4<p_T<0.8
C_1	0.067%	0.048%	0.086%	0.082%	0.144%	0.046%	0.060%	0.060%	0.046%
C_2	1.466%	1.165%	0.851%	0.550%	0.255%	1.437%	1.272%	1.272%	1.020%
C_3	3.202%	3.133%	3.001%	2.329%	1.490%	3.255%	3.556%	3.556%	3.264%
C_4	2.889%	2.615%	2.142%	1.485%	0.812%	2.930%	2.979%	2.979%	2.674%
C_5	20.646%	19.743%	18.317%	12.996%	7.696%	20.710%	21.282%	21.282%	16.808%
C_6	13.121%	12.193%	9.979%	6.490%	3.435%	13.506%	13.826%	13.826%	11.059%
C_2/C_1	1.253%	0.976%	0.678%	0.415%	0.646%	1.236%	1.171%	1.035%	0.752%
C_3/C_2	2.391%	2.511%	2.607%	2.176%	1.595%	2.463%	2.554%	2.884%	2.976%
C_4/C_2	1.566%	1.549%	1.362%	0.987%	0.577%	1.627%	1.706%	1.810%	1.741%
C_6/C_2	12.545%	11.726%	9.664%	6.247%	3.271%	12.949%	13.357%	13.343%	10.642%
C_5/C_1	21.531%	20.522%	18.728%	13.272%	7.948%	21.508%	21.188%	21.779%	17.305%