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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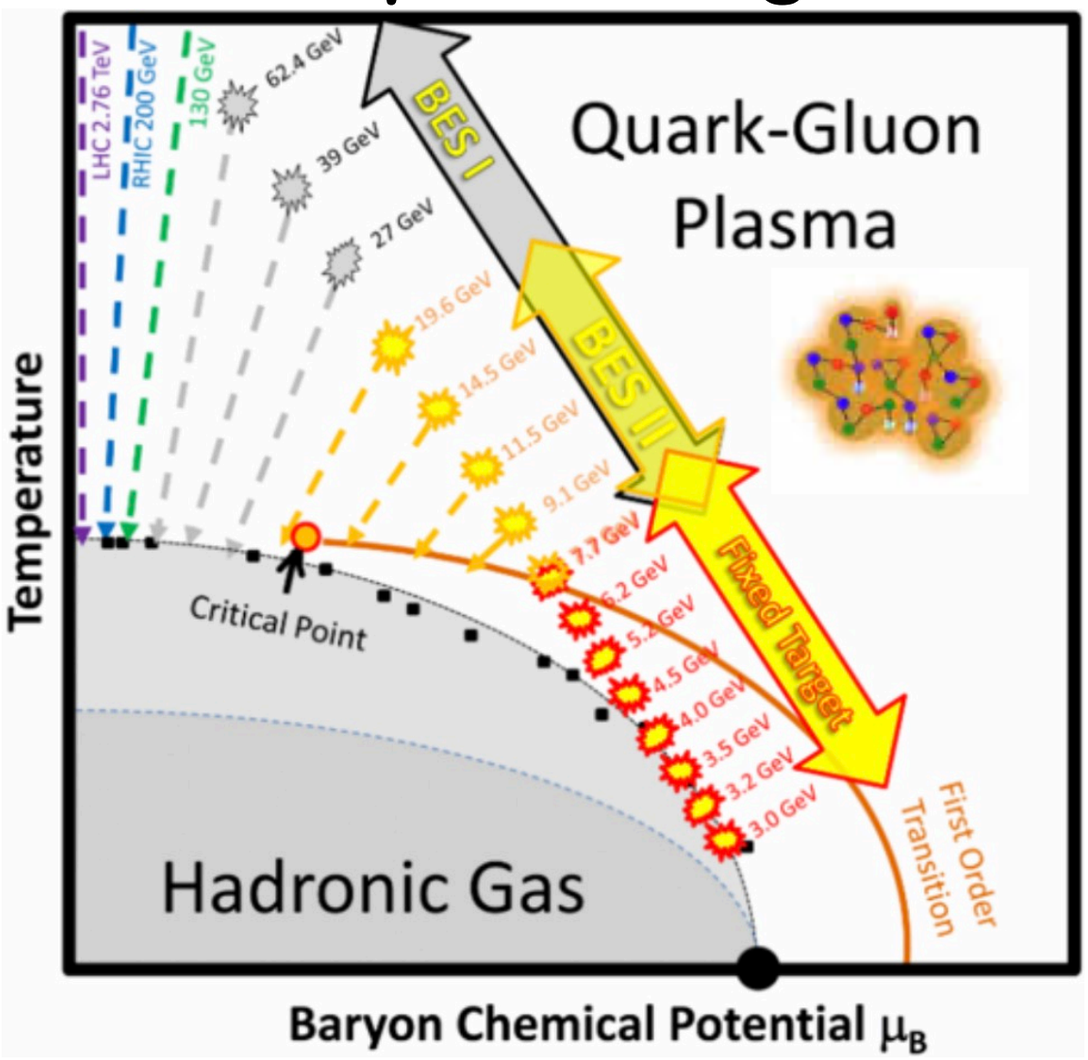
Introduction

QCD phase diagram



STAR Collaboration, Nuclear Physics A 982, 899-902 (2019)

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

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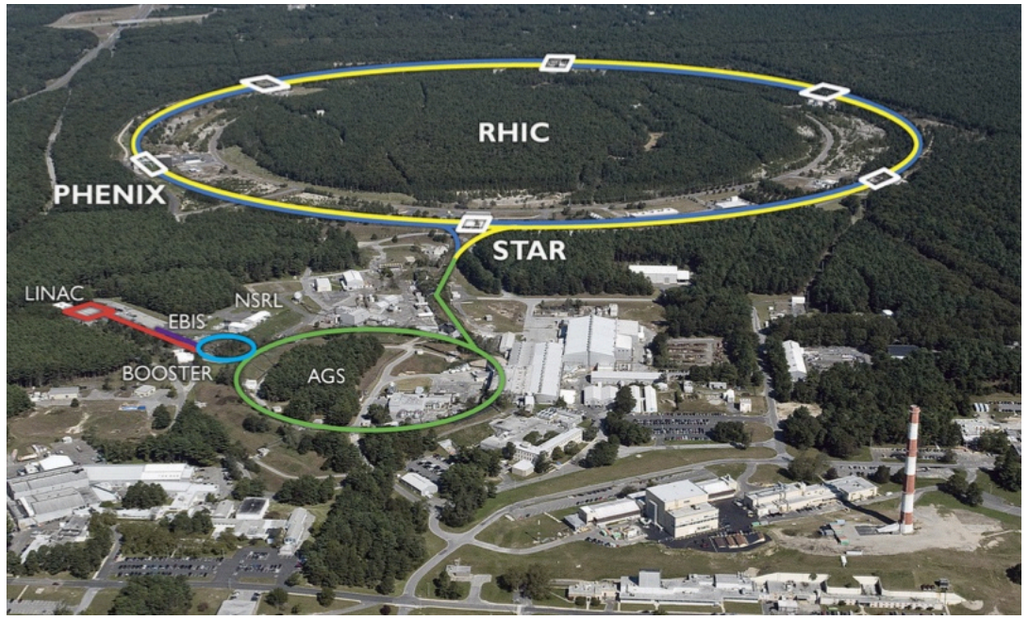
Experimental search by Beam Energy Scan (BES) at RHIC-STAR



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**

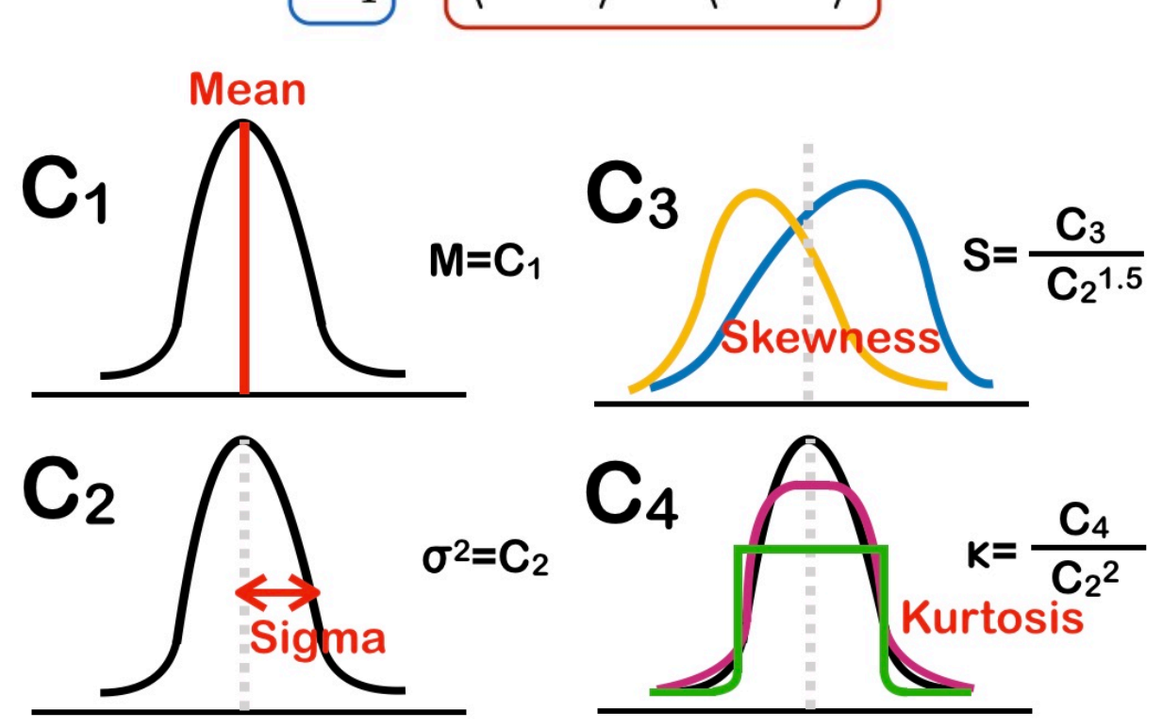
Skellam = Poisson - Poisson'

Skellam : Difference between two independent Possion distributions

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

Cumulant **Moment**

$$C_1 = \langle m \rangle$$
$$C_2 = \langle \delta m^2 \rangle$$
$$C_3 = \langle \delta m^3 \rangle$$
$$C_4 = \langle \delta m^4 \rangle - \langle \delta m^3 \rangle$$



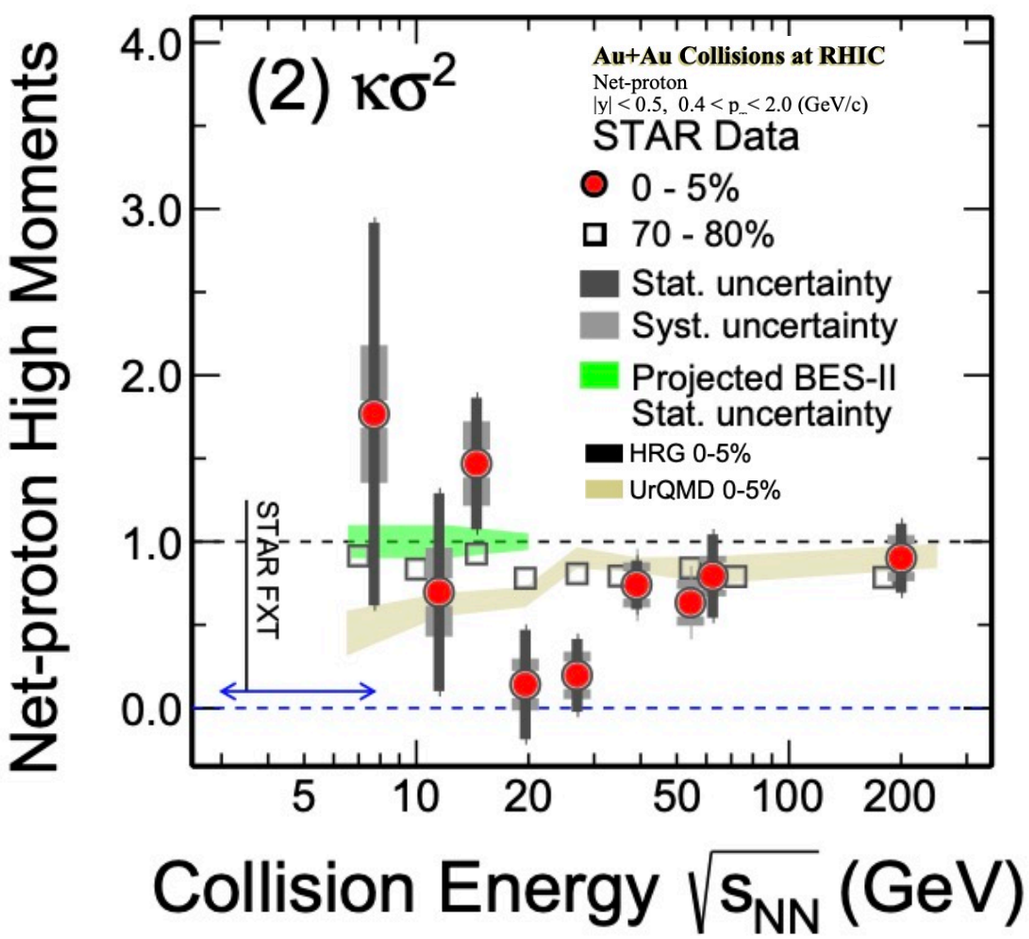
The 4th-order fluctuation for critical point search

- **Conserved quantity is sensitive to correlation length ξ**

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

ξ diverges near the C.P.

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)
STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)
STAR Collaboration, arXiv, 2101. 12413 (2021)



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

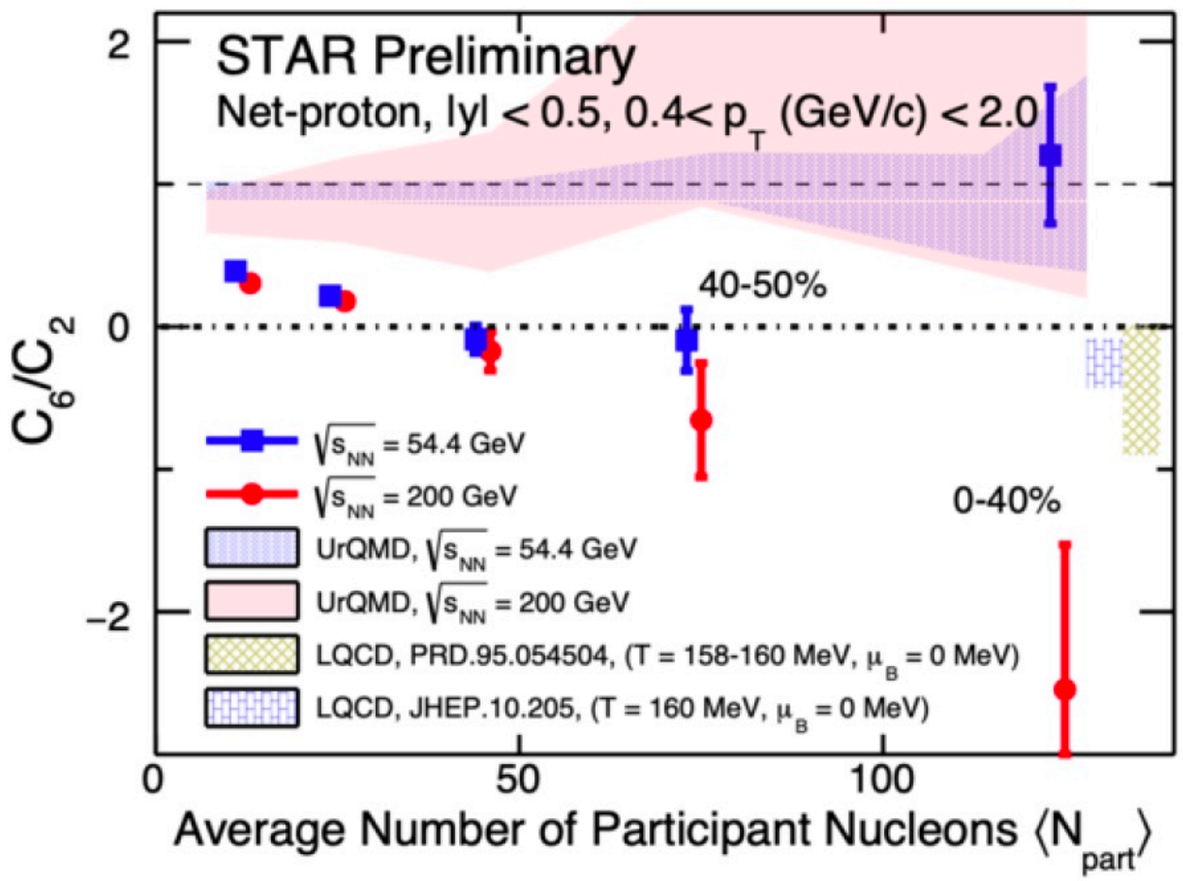
↓

Possible signature of critical point

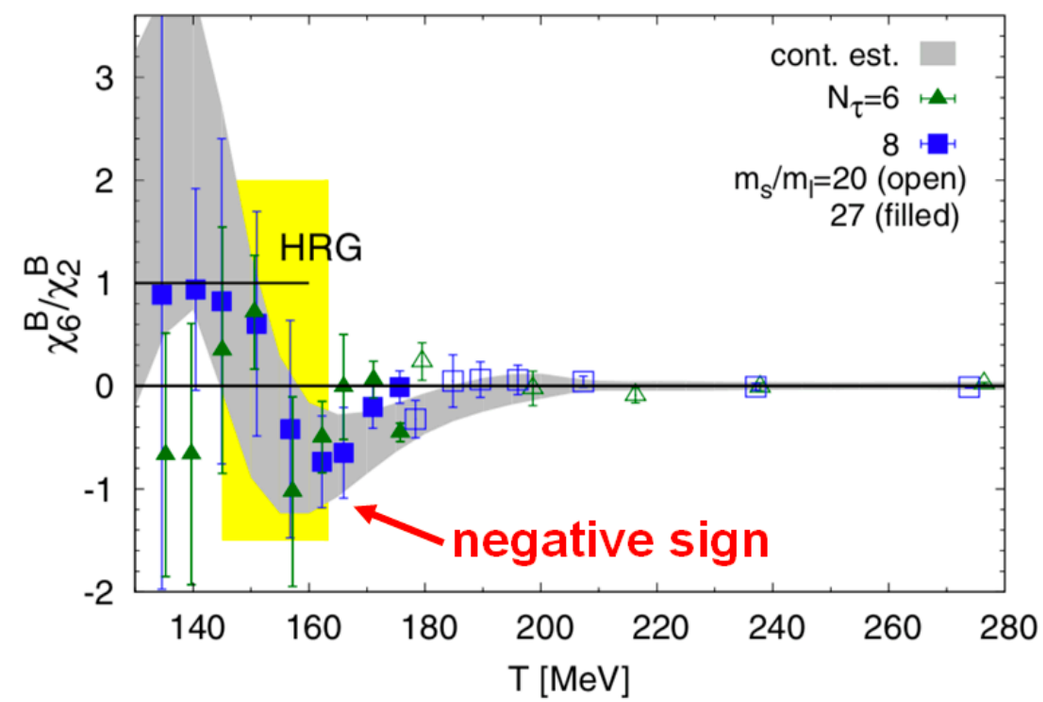
STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)
STAR Collaboration, arXiv, 2101.12413 (2021)

Sixth-order fluctuation and 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)

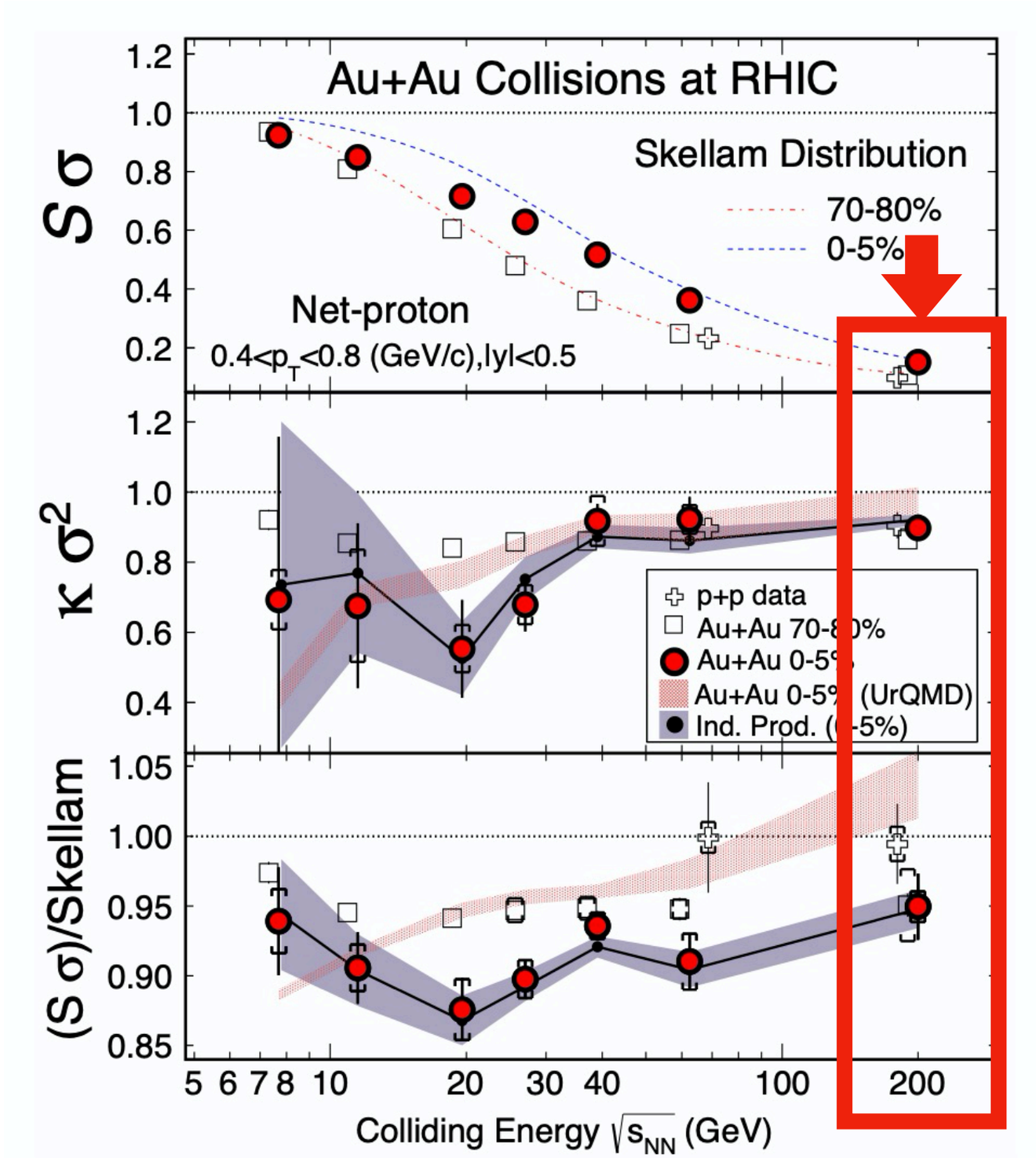


- **From peripheral to central collisions, the values of C_6/C_2 change from positive to negative**
- **Lattice QCD calculations at $\mu_B = 0$ show negative C_6/C_2**

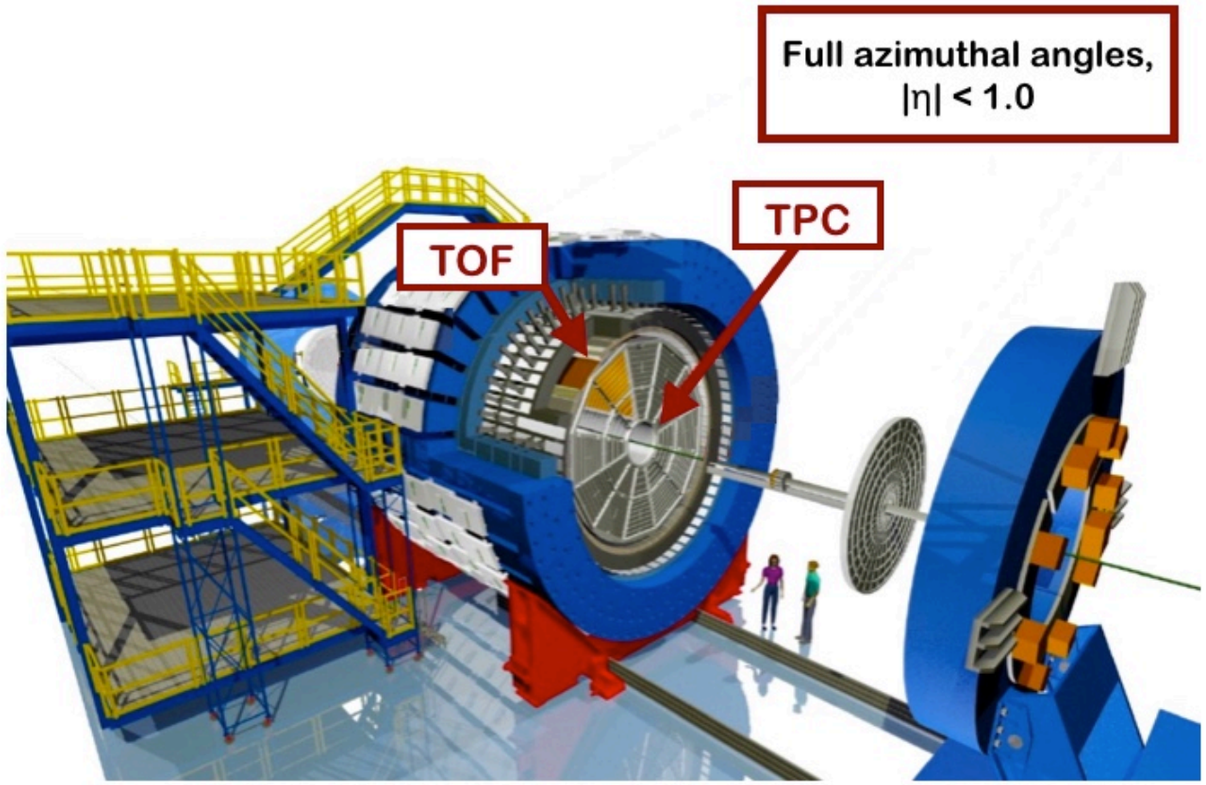
Why p+p ?

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

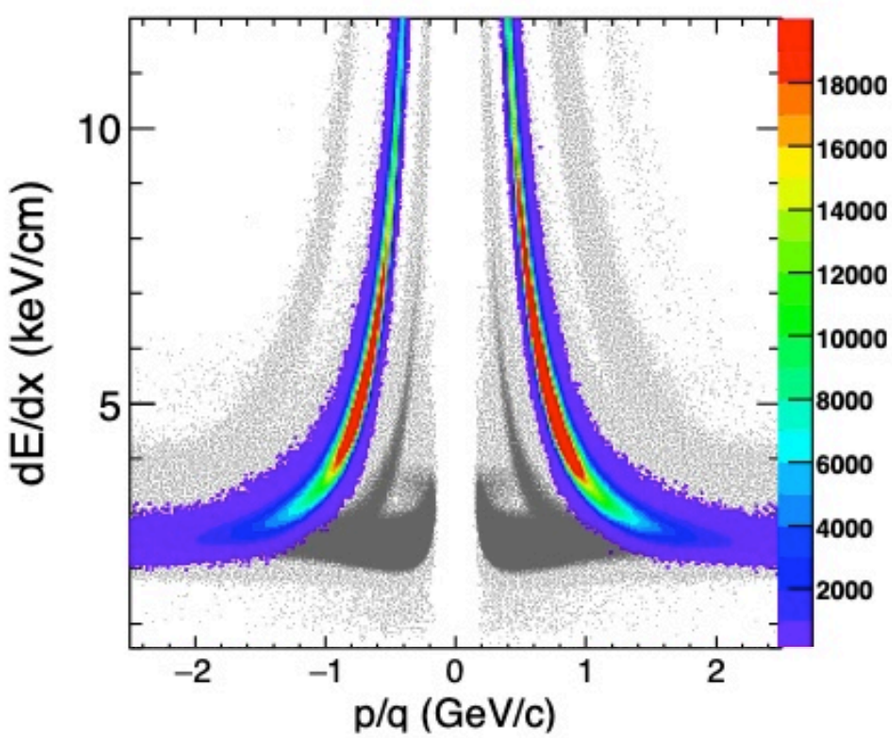


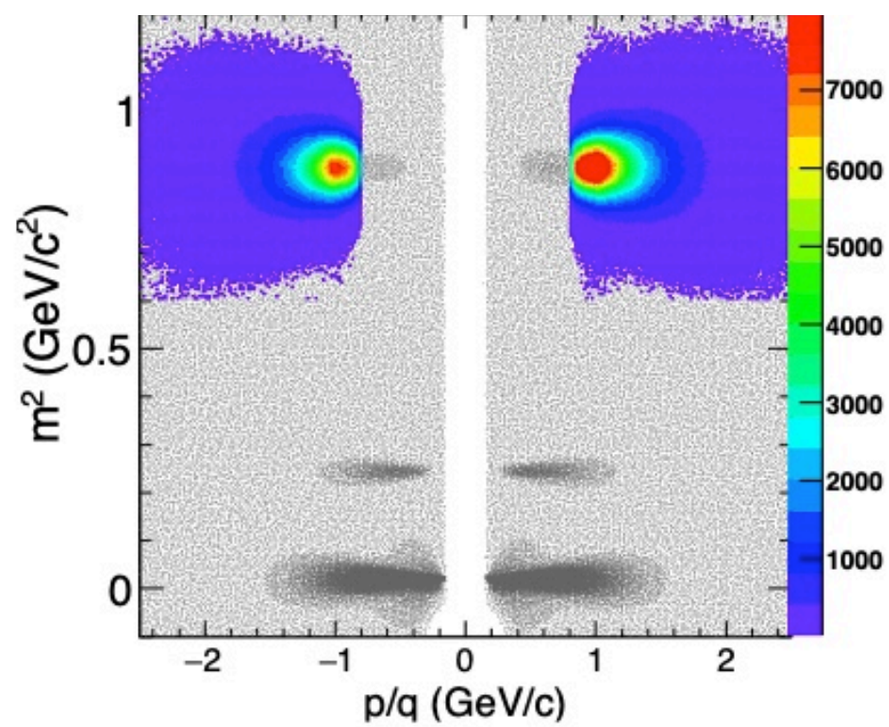
STAR Detector



- Time Projection Chamber (TPC) : PID, Vertex
- Time Of Flight (TOF) : Additional PID

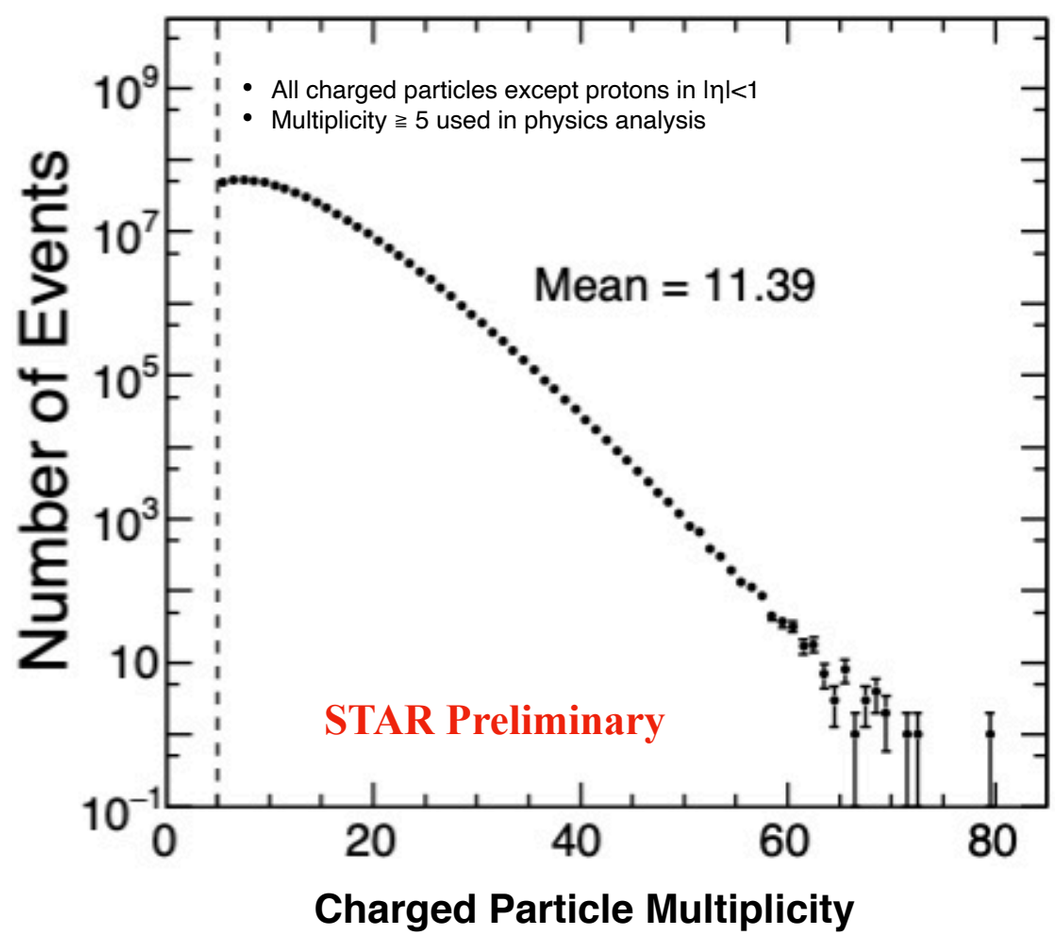
$|y| < 0.5$,
$0.4 < p_T$ (GeV/c) < 2.0

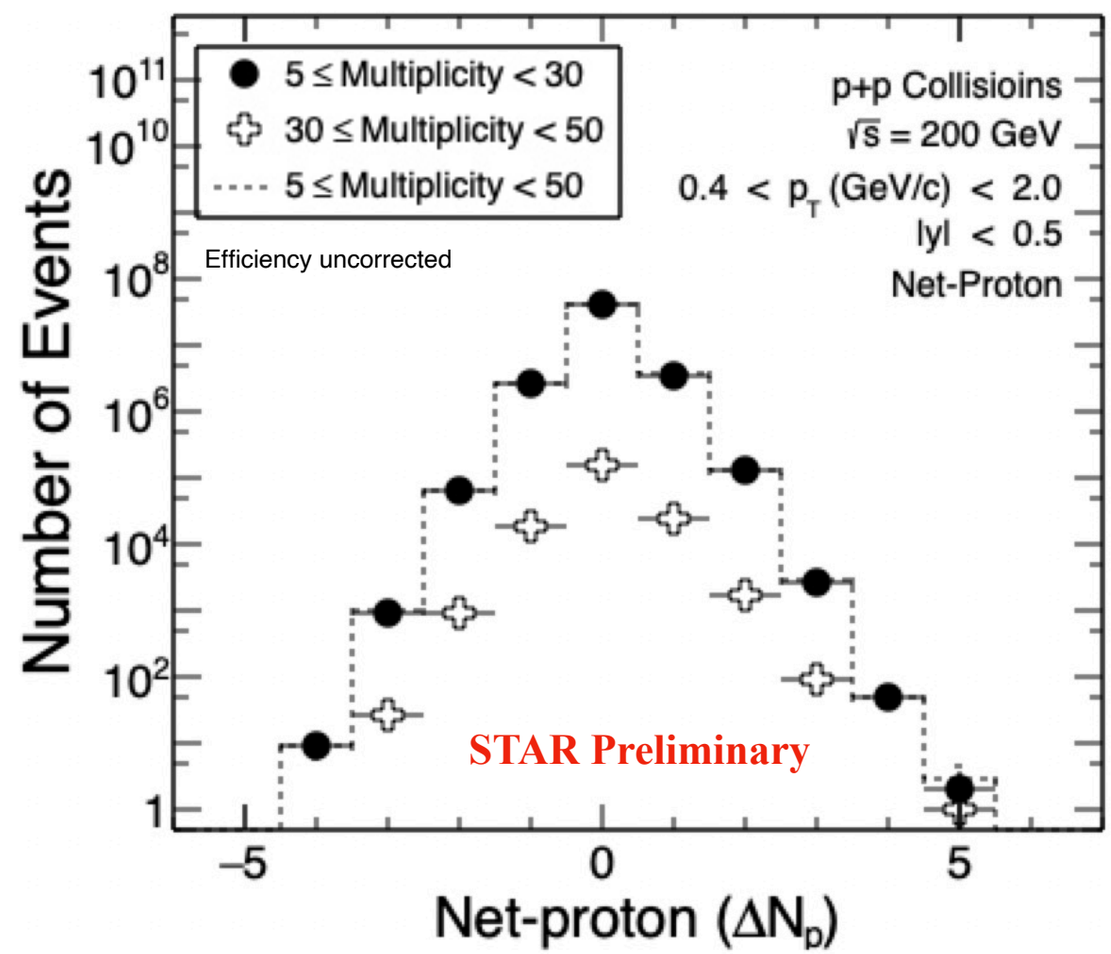




Multiplicity distributions

- **Reference multiplicity is defined in |η|<1.0 excluding (anti)protons.**
- **Event-by-event net-proton distributions are measured at mid-rapidity.**





Analysis method

Efficiency Correction

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

a: charge, ε: efficiency

T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C95 064912 (2017)
X. Luo, T. Nonaka : Phys. Rev. C99, 044917 (2019)

$$\begin{aligned}
\langle Q\rangle_{\rm c} &= \langle q_{(1,1)}\rangle_{\rm c},\\
\langle Q^2\rangle_{\rm c} &= \langle q_{(1,1)}^2\rangle_{\rm c} + \langle q_{(2,1)}\rangle_{\rm c} - \langle q_{(2,2)}\rangle_{\rm c},\\
\langle Q^3\rangle_{\rm c} &= \langle q_{(1,1)}^3\rangle_{\rm c} + 3\langle q_{(1,1)}q_{(2,1)}\rangle_{\rm c} - 3\langle q_{(1,1)}q_{(2,2)}\rangle_{\rm c} + \langle q_{(3,1)}\rangle_{\rm c} - 3\langle q_{(3,2)}\rangle_{\rm c} + 2\langle q_{(3,3)}\rangle_{\rm c},\\
\langle Q^4\rangle_{\rm c} &= \langle q_{(1,1)}^4\rangle_{\rm c} + 6\langle q_{(1,1)}^2 q_{(2,1)}\rangle_{\rm c} - 6\langle q_{(1,1)}^2 q_{(2,2)}\rangle_{\rm c} + 4\langle q_{(1,1)}q_{(3,1)}\rangle_{\rm c} + 3\langle q_{(2,1)}^2\rangle_{\rm c} + 3\langle q_{(2,2)}^2\rangle_{\rm c} - 12\langle q_{(1,1)}q_{(3,2)}\rangle_{\rm c}\\
&\quad + 8\langle q_{(1,1)}q_{(3,3)}\rangle_{\rm c} - 6\langle q_{(2,1)}q_{(2,2)}\rangle_{\rm c} + \langle q_{(4,1)}\rangle_{\rm c} - 7\langle q_{(4,2)}\rangle_{\rm c} + 12\langle q_{(4,3)}\rangle_{\rm c} - 6\langle q_{(4,4)}\rangle_{\rm c},
\end{aligned}$$

Centrality Bin Width Correction (CBWC)

- **Event averaging for each multiplicity bin**

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

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

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)

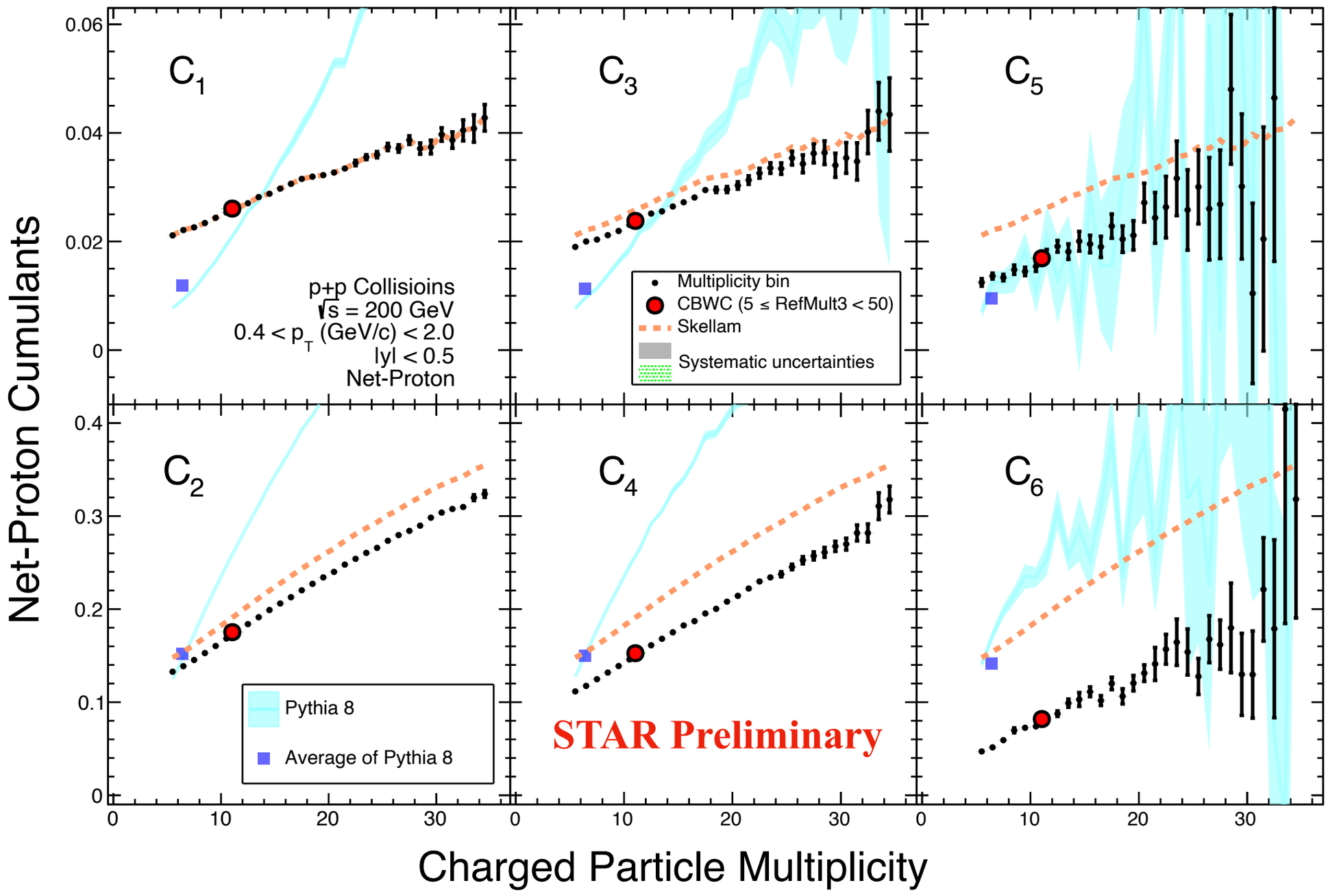
Error estimation

- **Bootstrap method**

Multiplicity Dependence of Net-Proton Cumulants

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

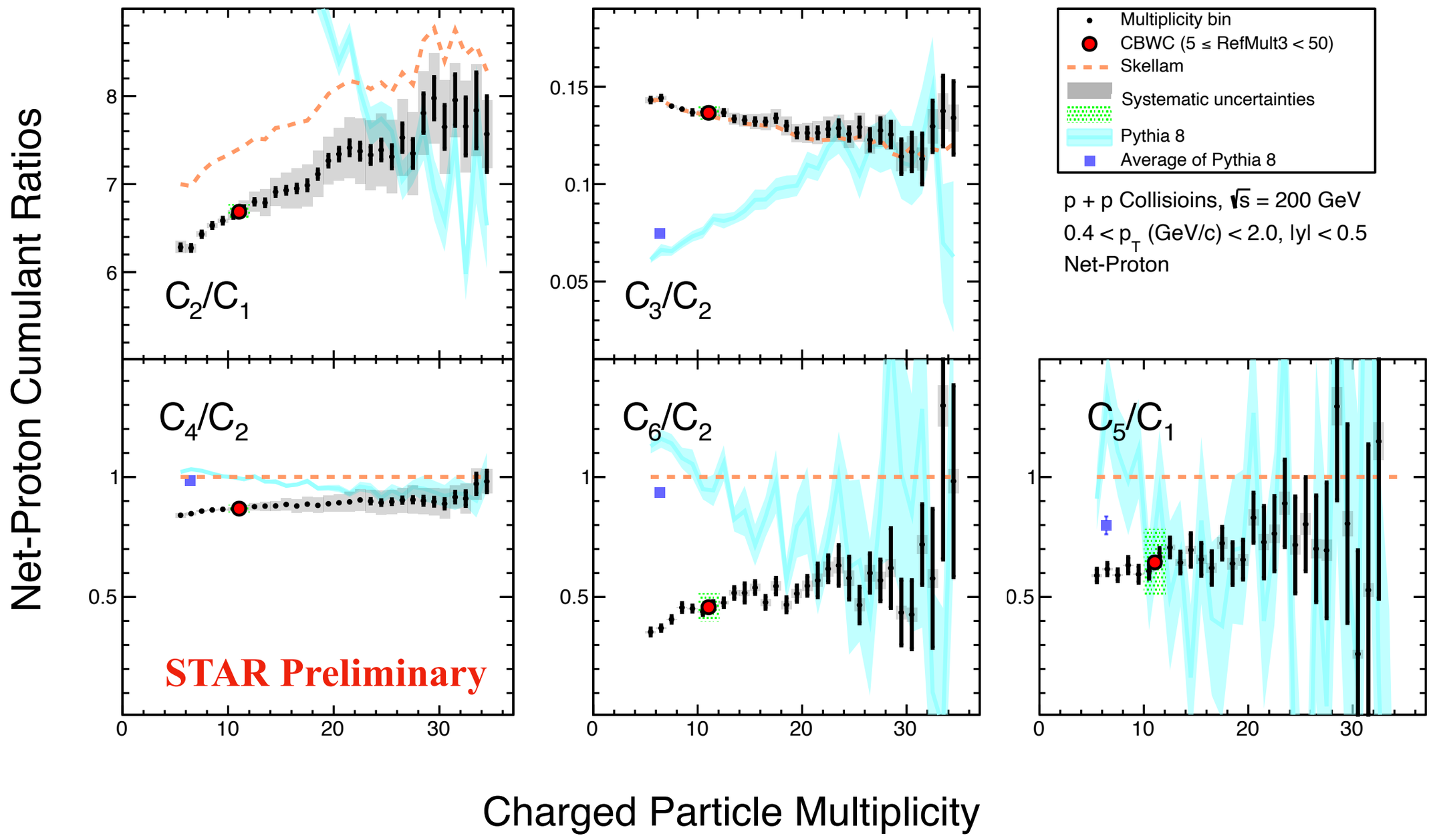
※ Skellam = Poisson - Poisson'



Multiplicity Dependence of Net-Proton Cumulant Ratios

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

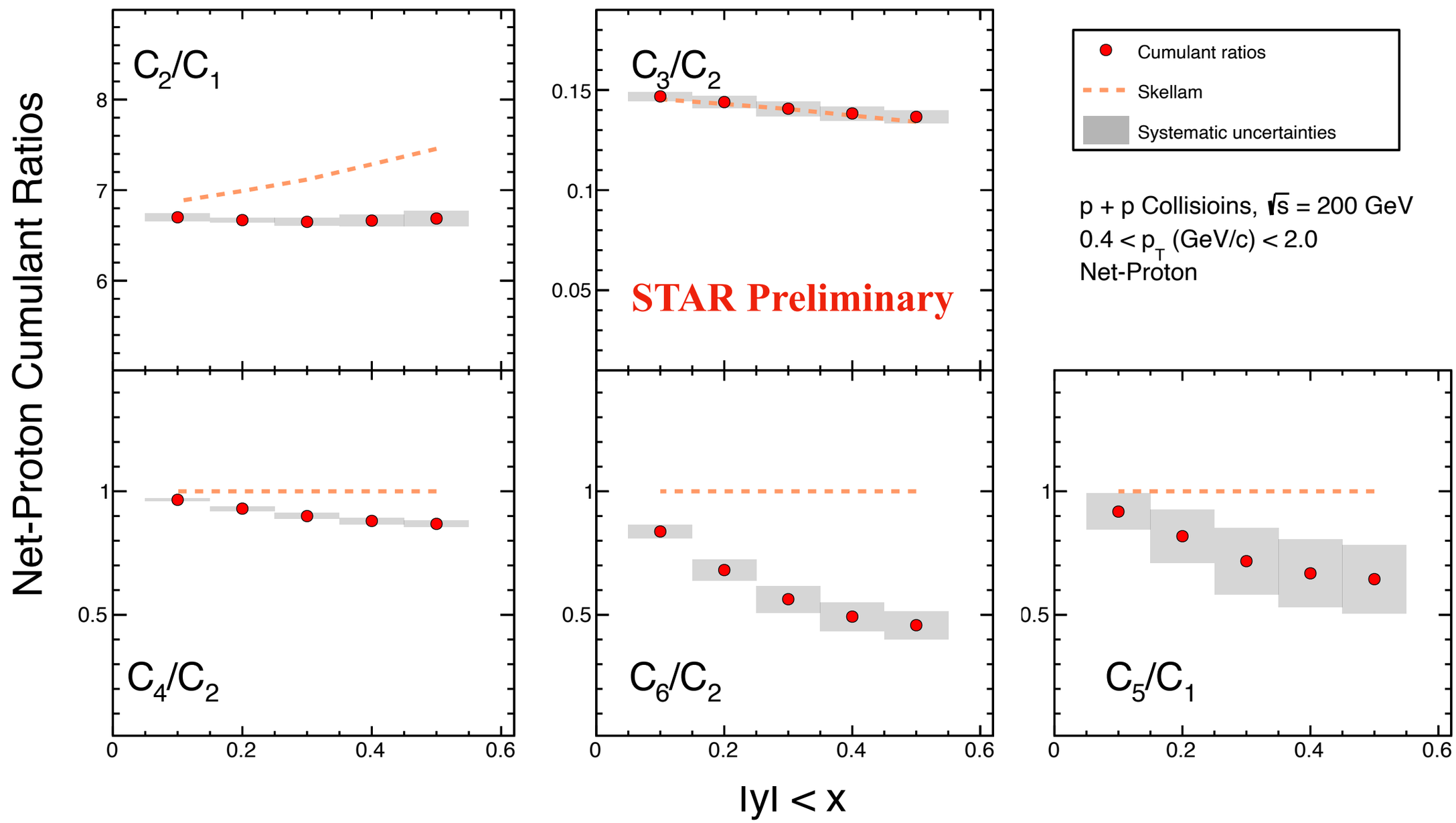
※ Skellam = Poisson - Poisson'



Acceptance Dependence of Net-Proton Cumulant Ratios

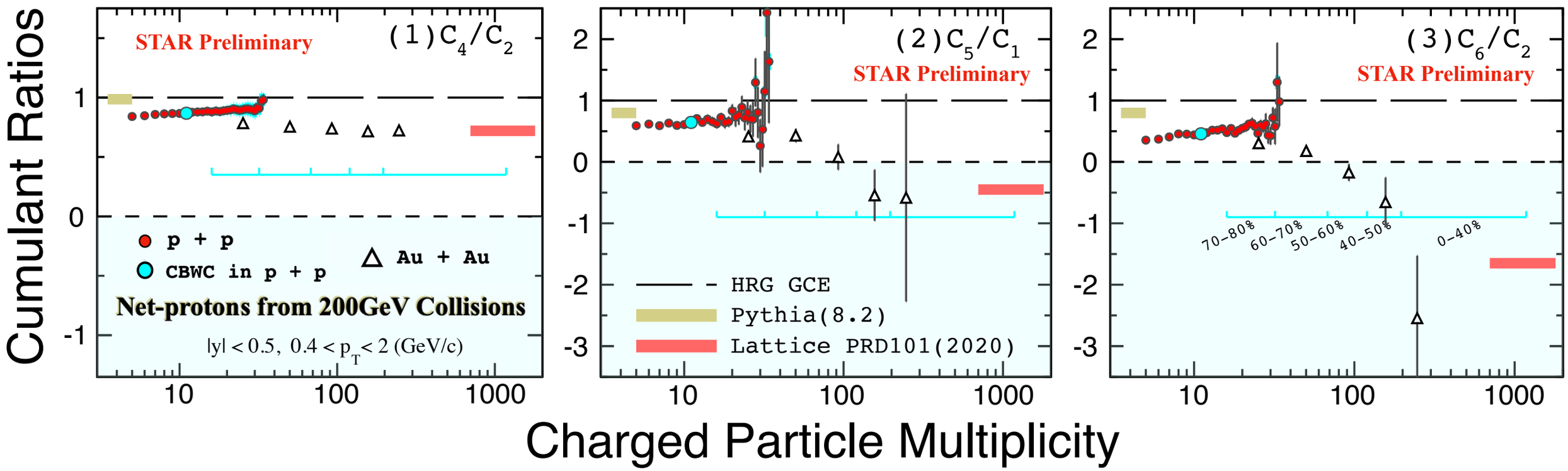
|Δy| dependence

- Deviations from Skellam baseline become large with increasing |Δy| 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
- $C_6/C_2 > 0$ for p+p collisions, while $C_6/C_2 < 0$ for Au+Au central collisions



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

Au+Au data taken from STAR Collaboration, arXiv, 2101.12413 (2021)

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

Au+Au data taken from STAR Collaboration, Nuclear Physics A, 1005, 121882 (2021)

Summary

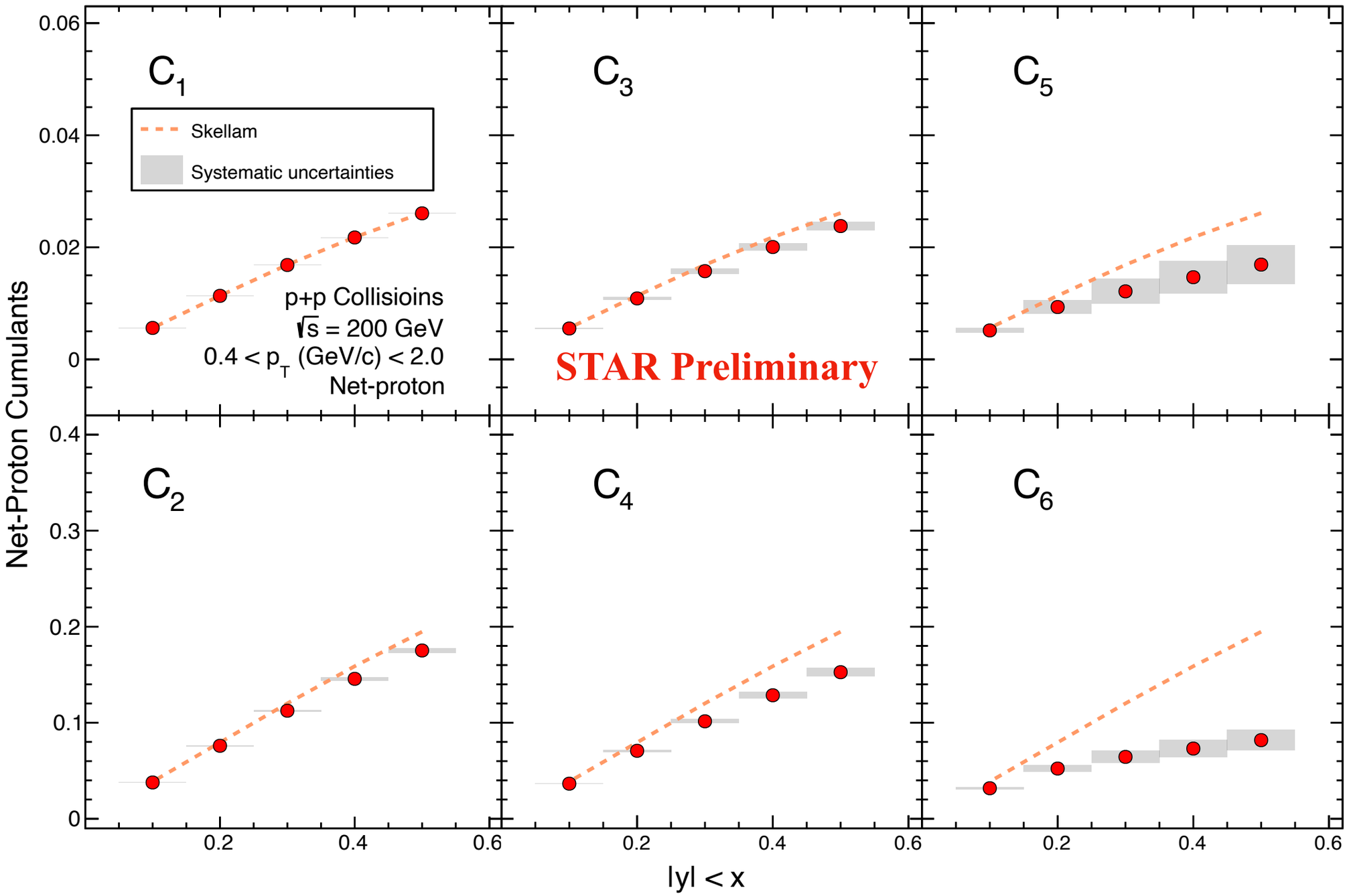
- Multiplicity dependence of net-proton cumulant has been measured in p+p collisions at $\sqrt{s}$ = 200 GeV
- Larger deviations from Skellam / Pythia expectations are observed for higher-order cumulants
- Larger deviations from Skellam expectations are observed for rapidity acceptance dependence of cumulant ratios
- $C_6/C_2 > 0$ for p+p collisions, while $C_6/C_2 < 0$ 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

Acceptance Dependence of Net-Proton Cumulants

|Δy| dependence

- **Cumulants become large with increasing |Δy| 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_{def}: default cuts results**
- **$Y_{i,j}$: ith change of the cut on jth variable**

	|y|<0.5, 0.4<pT<2.0	|y|<0.4, 0.4<pT<2.0	|y|<0.3, 0.4<pT<2.0	|y|<0.2, 0.4<pT<2.0	|y|<0.1, 0.4<pT<2.0	|y|<0.5, 0.4<pT<1.7	|y|<0.5, 0.4<pT<14	|y|<0.5, 0.4<pT<1.1	|y|<0.5, 0.4<pT<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%