Measurements of Higher-Order Cumulants of Net-Proton Distributions in 200 GeV p+p Collisions at RHIC-STAR

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STAR

Tomonaga Center for the History of the Universe

Outline

Introduction

- QCD phase diagram
- Higher-order cumulants
- STAR Au+Au results
- Physics motivation in p+p collisions

Data analysis

- Particle identification
- Efficiency correction
- Statistical uncertainties
- Effects of pileup
- Pileup model
- Systematic uncertainties

Results

- Acceptance dependence
- Multiplicity dependencies of cumulants

Discussion

- Baryon number conservation effect
- Comparison between p+p and Au+Au

Summary

Oral Presentations

- STAR Collaboration meeting (March 4, 2021)
- JPS (March 14, 2021)
- CPOD2021 - the International conference on Critical Point and Onset of Deconfinement (March 15-19, 2021)
- TCHoU workshops (March 30, 2021)
- RHIC & AGS Annual Users' Meeting 2021 (June 8-11, 2021)

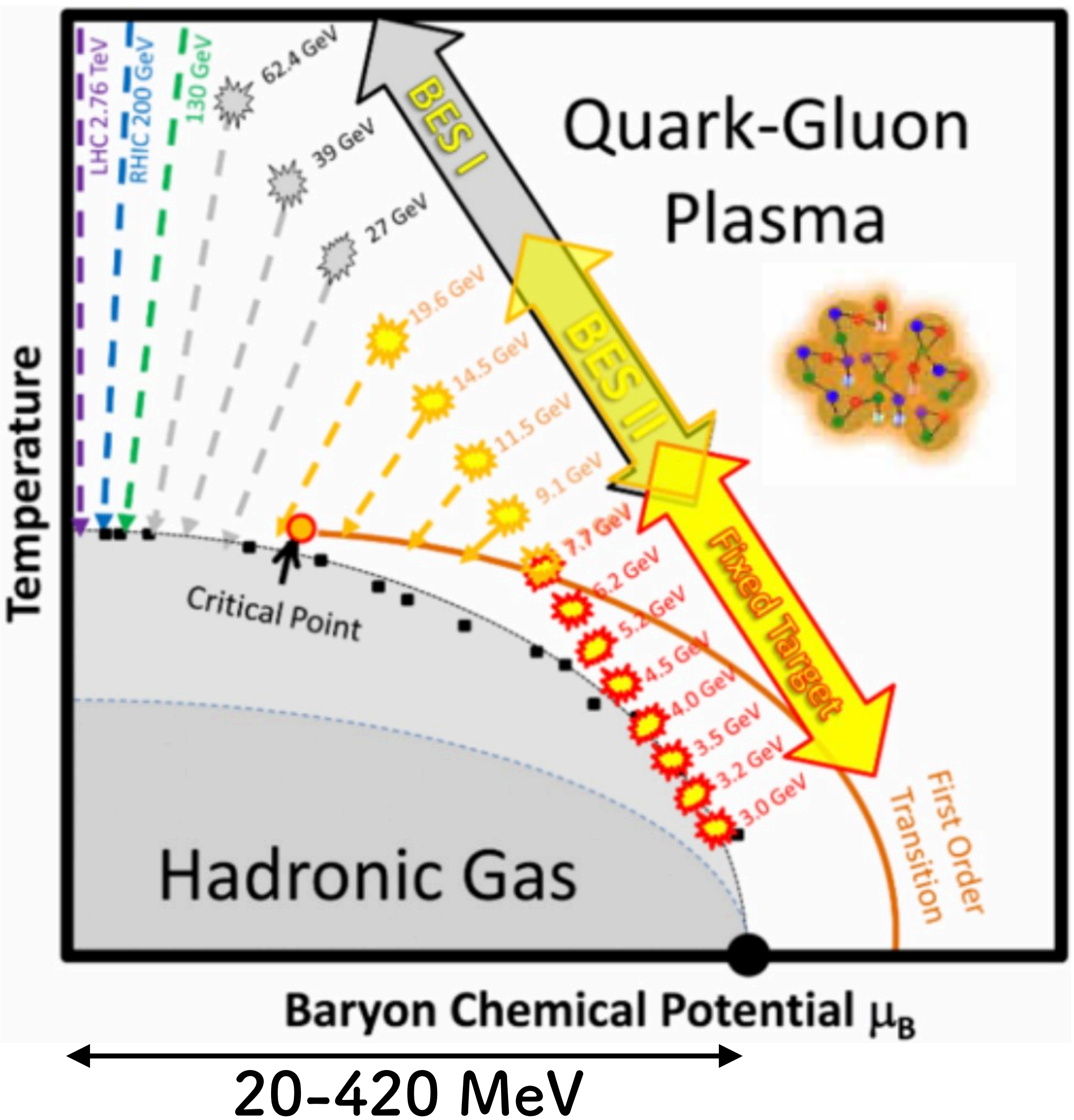
Activities

- STAR Shift (2019, 2020)
- Workshop in Wayne State University (2020)
- Physics Working Group Meeting at the STAR experiment
- v_1 (flow) meeting
- Fluctuation Focus Meeting

Introduction

- QCD phase diagram
- Higher-order fluctuations
- C_4/C_2 for critical point search
- C_5/C_1 and C_6/C_2 for crossover search
- Phase transition in p+p?
- Fluctuations in p+p collisions

QCD phase diagram

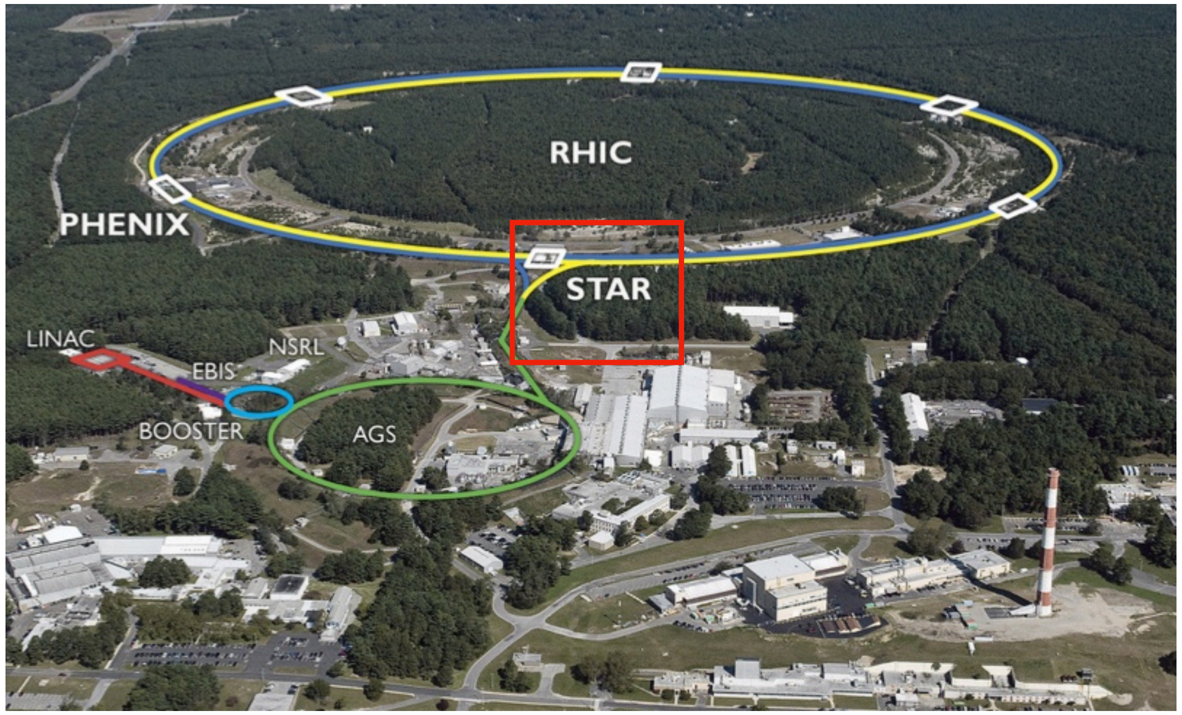


STAR Collaboration, Nuclear Physics A 982, 899-902 (2019)
STAR public note, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

- □ 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



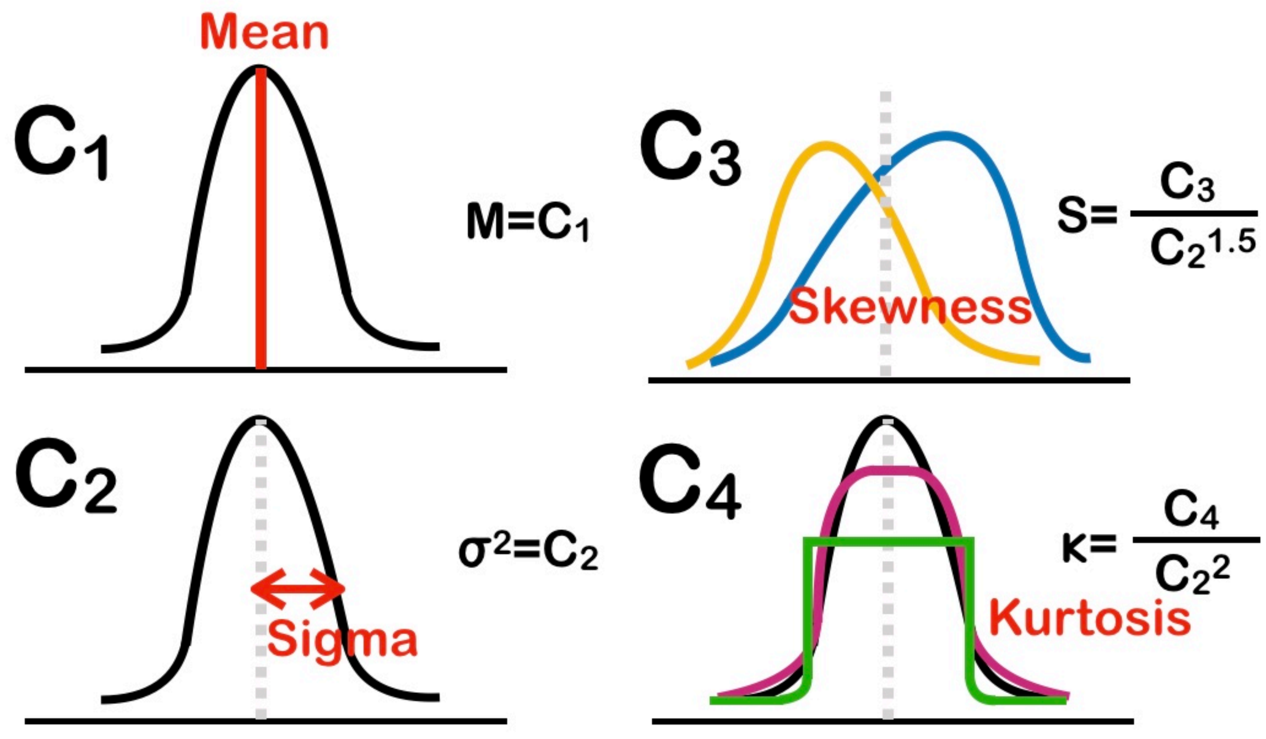
Goal : Study the phase diagram of QCD matter

Fluctuation = Cumulant, Moment

Cumulant $\rightleftarrows$ **Moment**

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

$$\begin{aligned} C_1 &= < N > \\ C_2 &= < (\delta N)^2 > \\ C_3 &= < (\delta N)^3 > \\ C_4 &= < (\delta N)^4 > -3 < (\delta N)^2 >^2 \end{aligned}$$



Fluctuations of conserved quantities

- 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. Asakawa, et.al., Phys, Rev, Lett. 103, 262301 (2009)
M. A. Stephanov, Phys, Rev, Lett. 107, 052301 (2011)

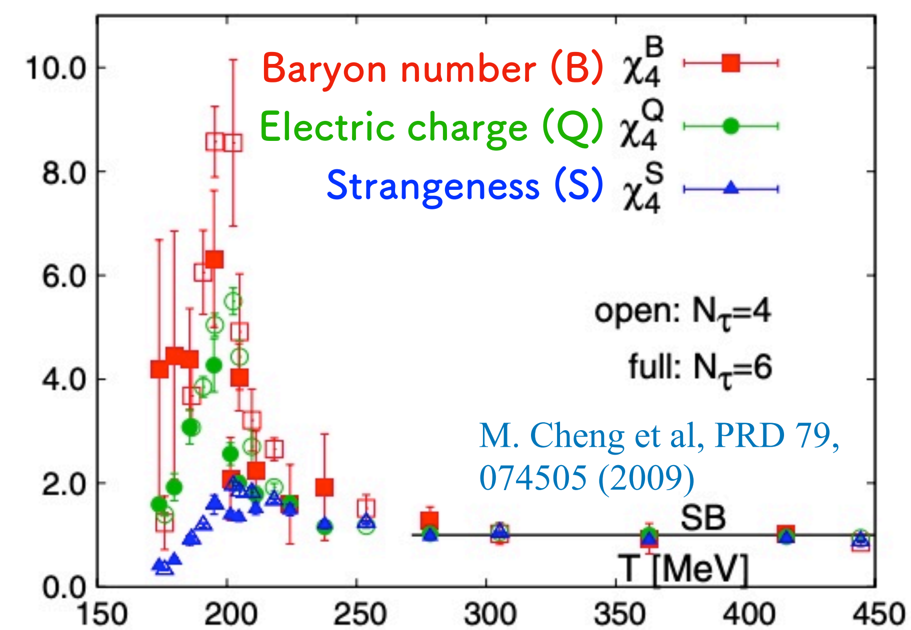
- Volume terms are cancelled by taking ratio to connect to baryon number susceptibility

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

$$\chi = \frac{1}{VT^3} \times C_n^B$$

- Higher-order cumulants and their ratios of conserved charges are sensitive to phase structure ▶

$$\Delta N_q = N_q - N_{\bar{q}}$$



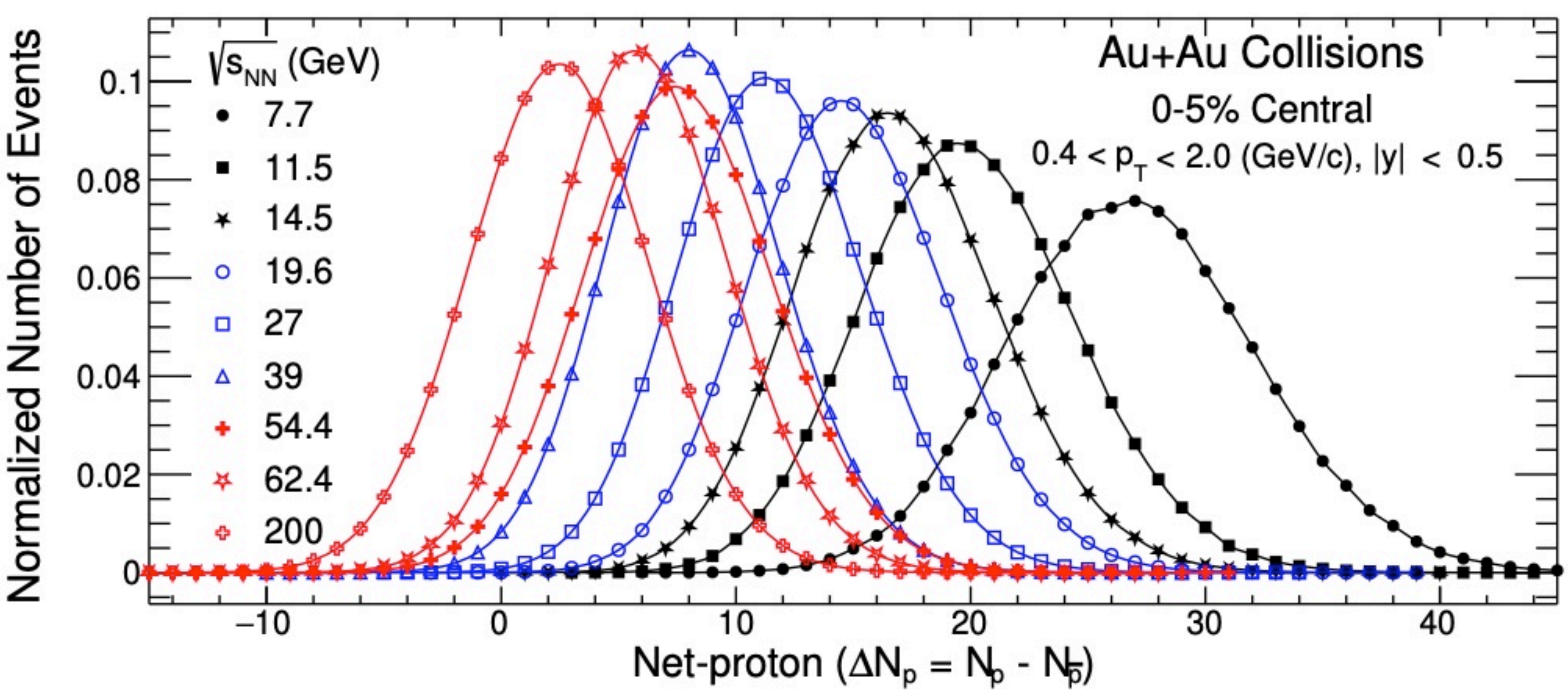
- Statistical baseline ：“Skellam” = Poisson - Poisson’

$$C_4/C_2 = C_5/C_1 = C_6/C_2 = 1$$

Difference between two independent Possion distributions

Net-proton distributions

Energy dependence of net-proton distributions

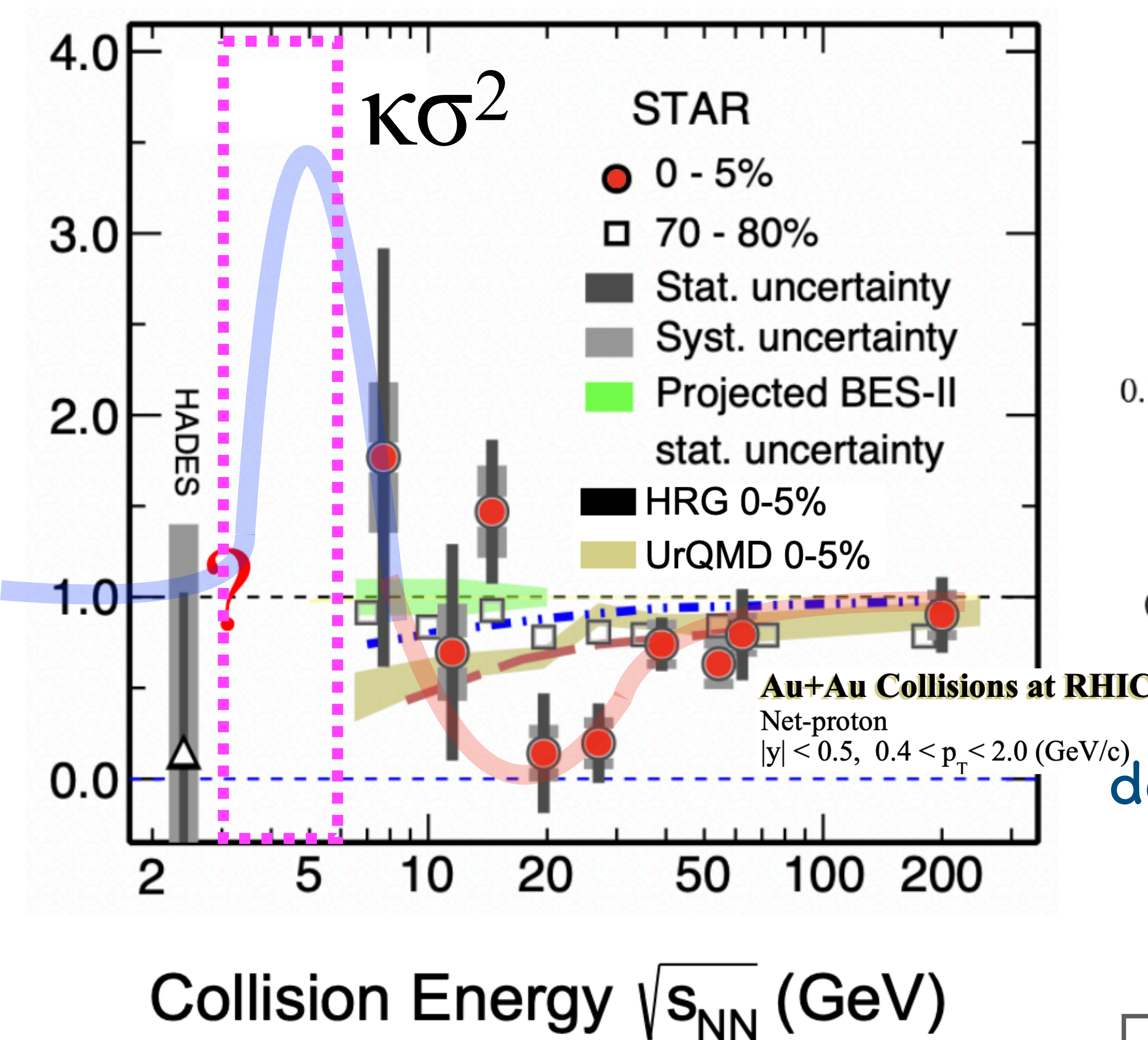


STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)
STAR Collaboration, arXiv, 2101.12413 (2021)

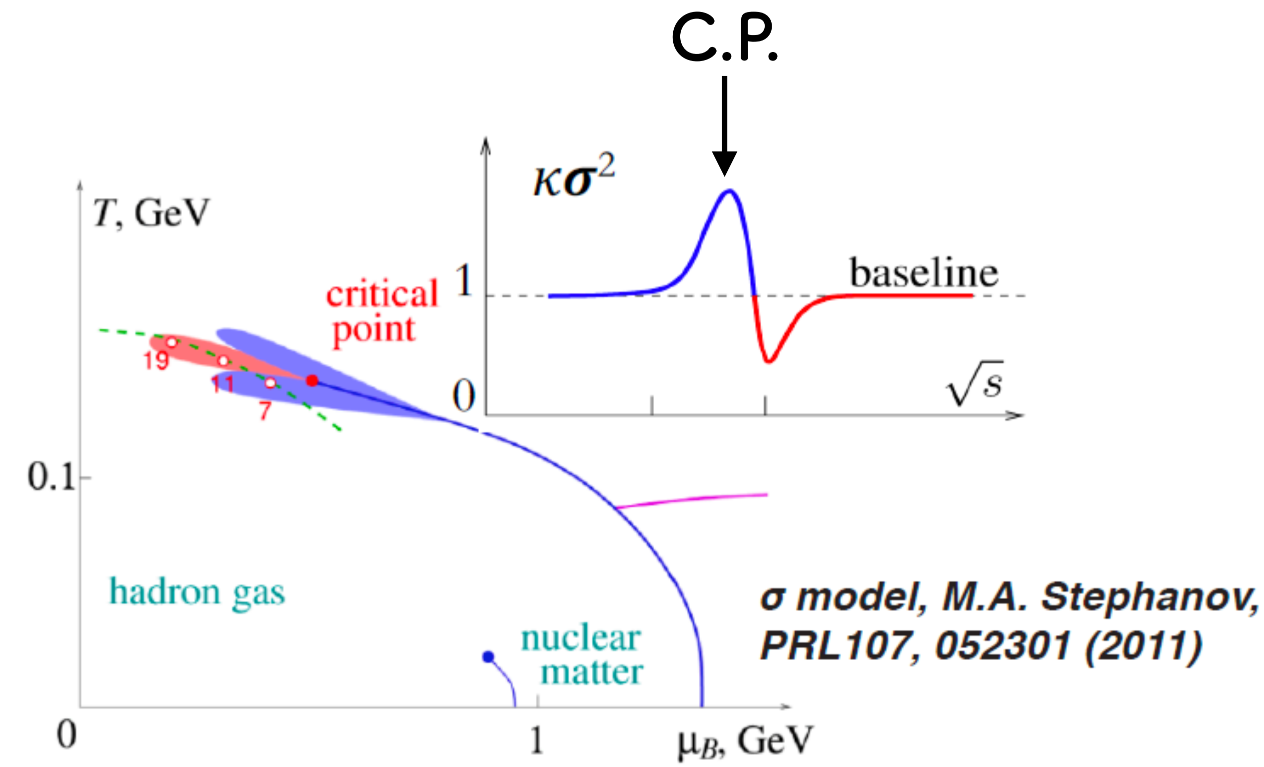
Net-baryon cumulants can be reconstructed from net-proton cumulants

Asakawa, Kitazawa *Phys.Rev.C* 86 (2012) 024904

Fourth-order fluctuations for critical point search



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

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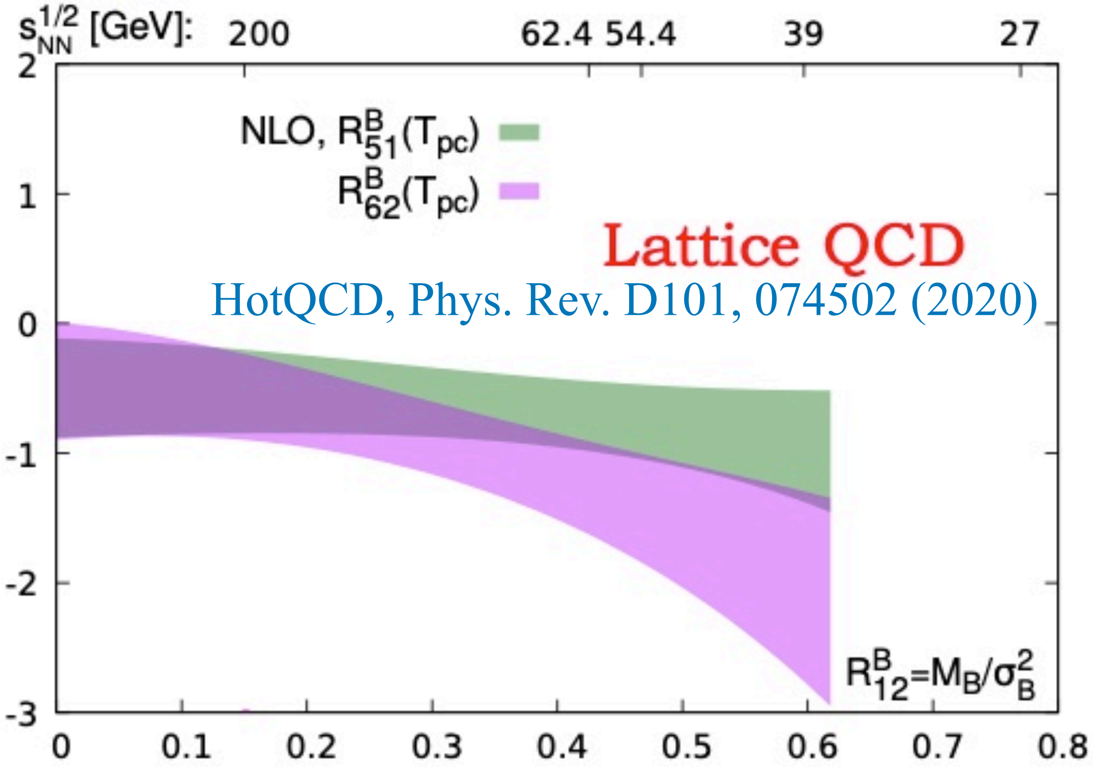
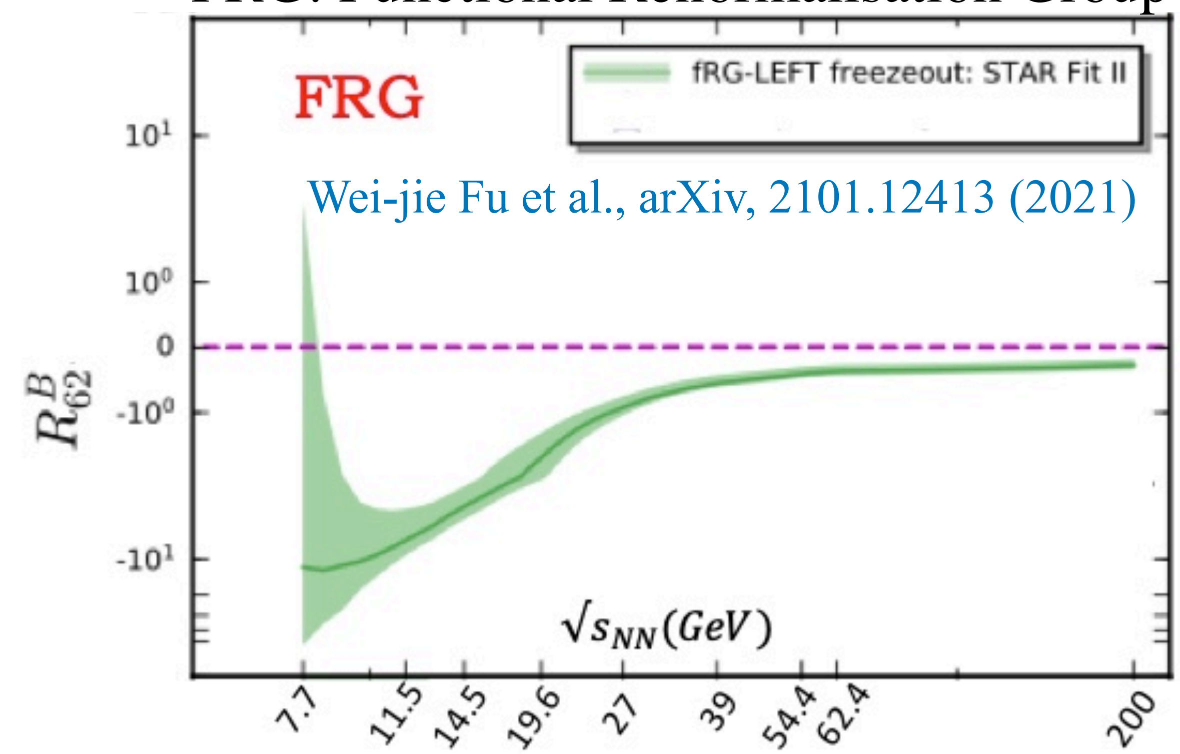
Possible signature of critical point at 2.4-7.7 GeV

Crossover

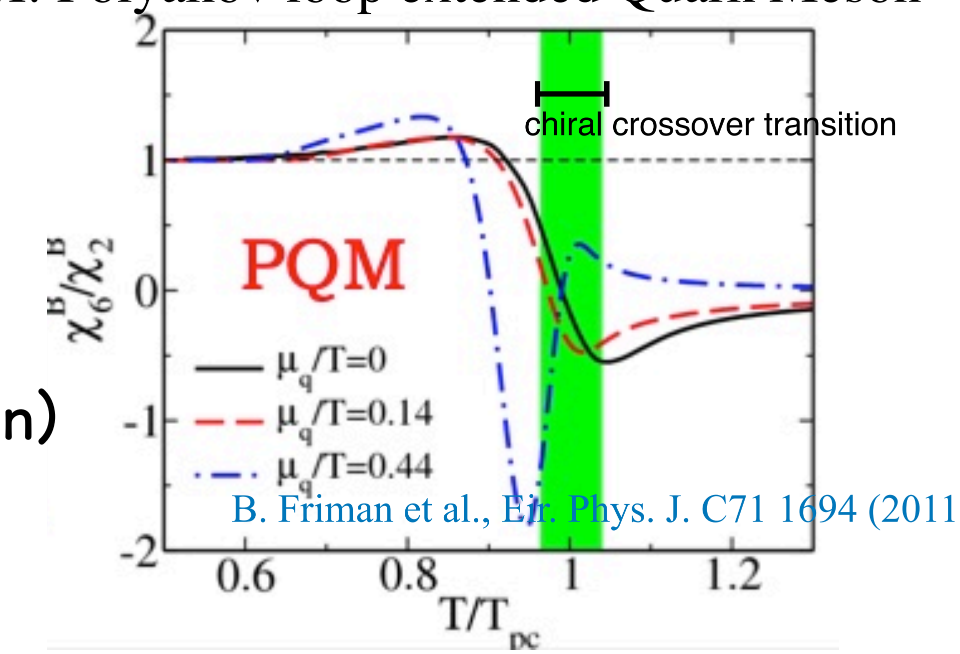
Goal : Identification of O(4) chiral criticality on the phase boundary



FRG: Functional Renormalisation Group



PQM: Polyakov loop extended Quark Meson

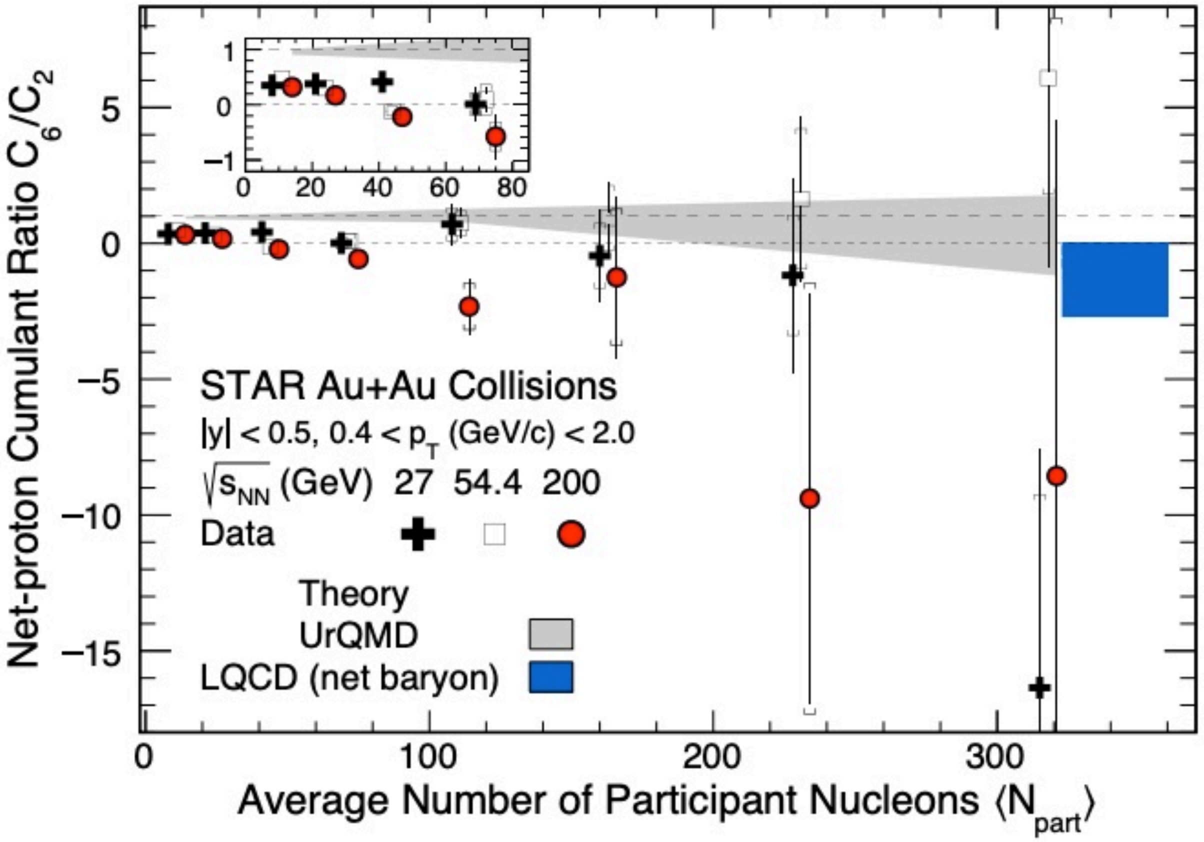


C_5, C_6 :

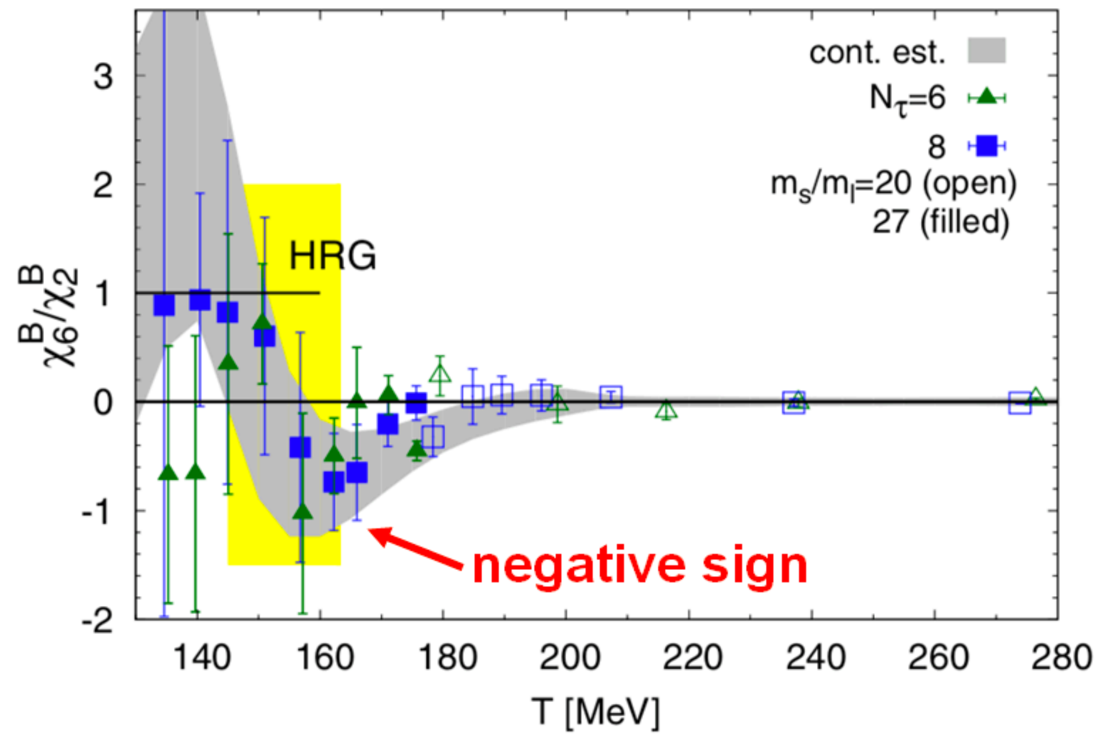
- Negative for LQCD, FRG, PQM - crossover
- Positive for HRG and UrQMD (no QCD transition)

Sixth-order fluctuations for crossover search

M. S. Abdallah, et.al., Phys. Rev. Lett. 127, 262301 (**2021**)



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

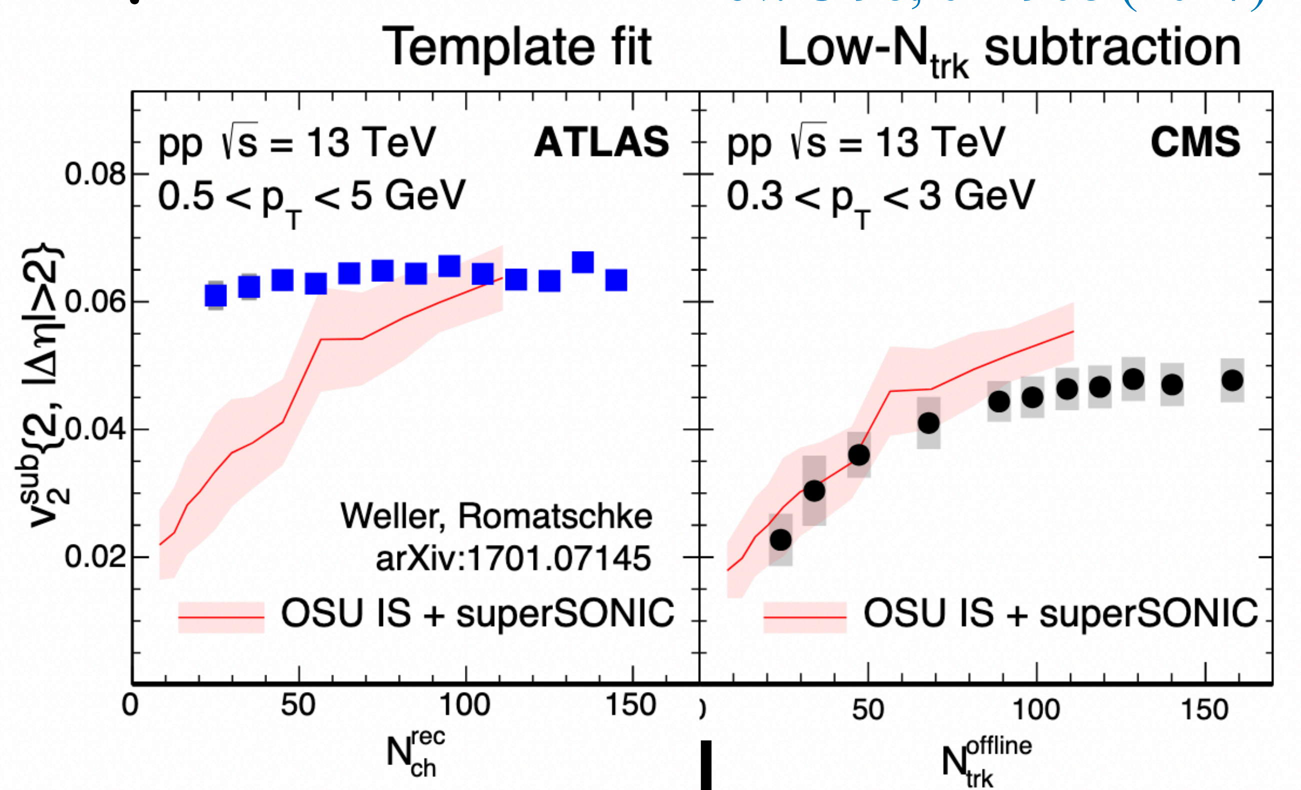


- From peripheral to central collisions, the values of C_6/C_2 change from positive to negative at 200 GeV
- Lattice QCD calculations at $\mu_B = 0$ show negative C_6/C_2

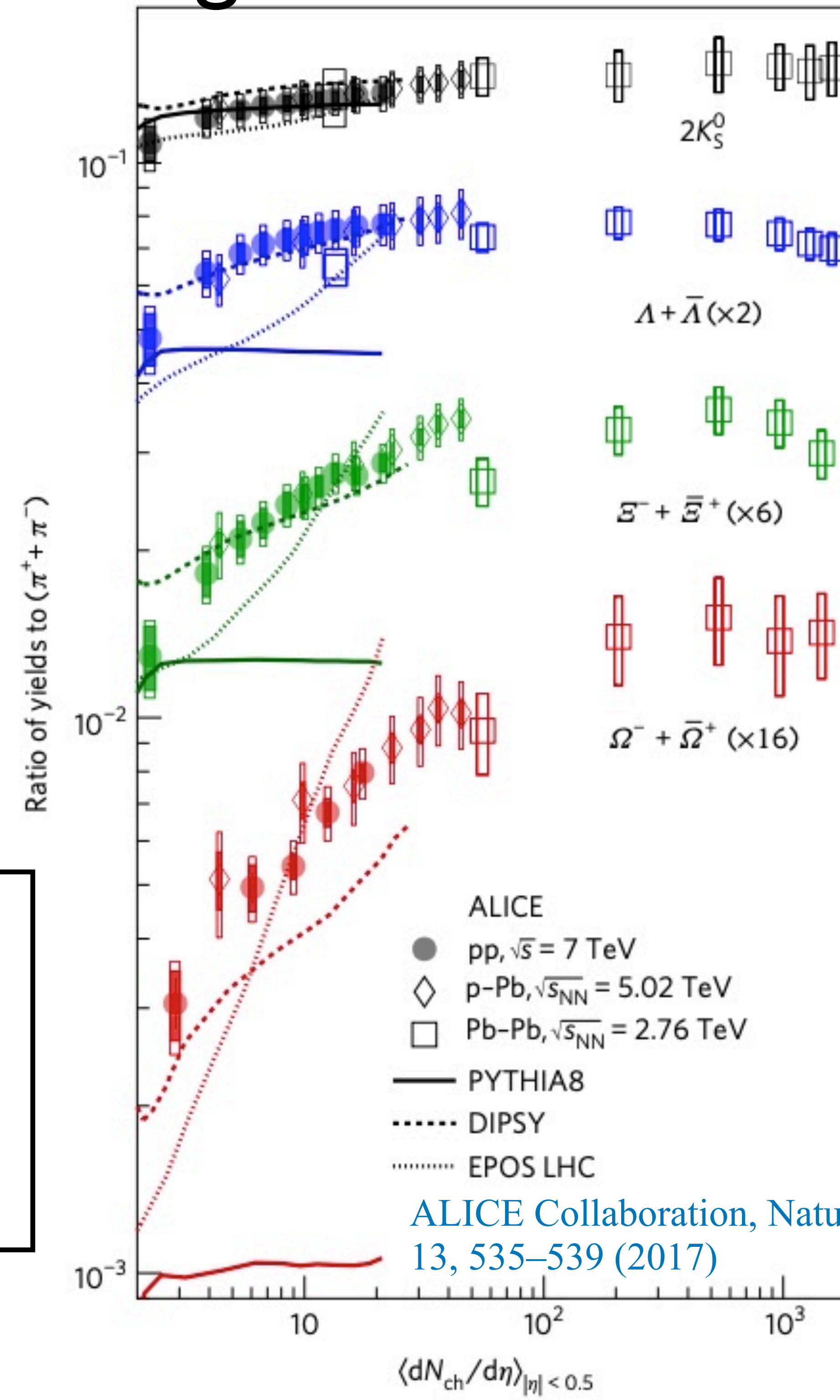
QGP in p+p at high multiplicity?

- Elliptic flow (v_2)

ATLAS Collaboration, Phys. Rev. C 96, 024908 (2017)



- Strangeness enhancement

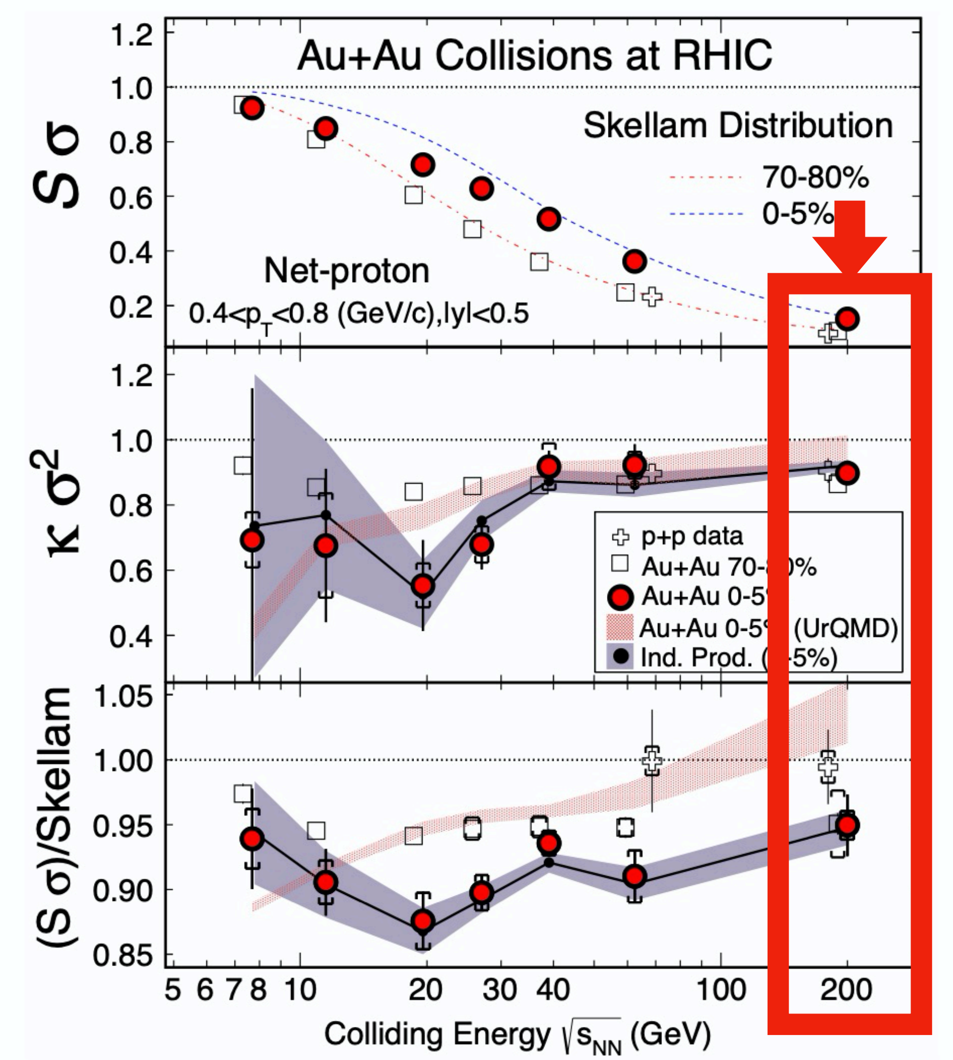


ALICE Collaboration, Nature Physics, 13, 535–539 (2017)

Indication of QGP signals
in p+p collisions at LHC energies
but still not established

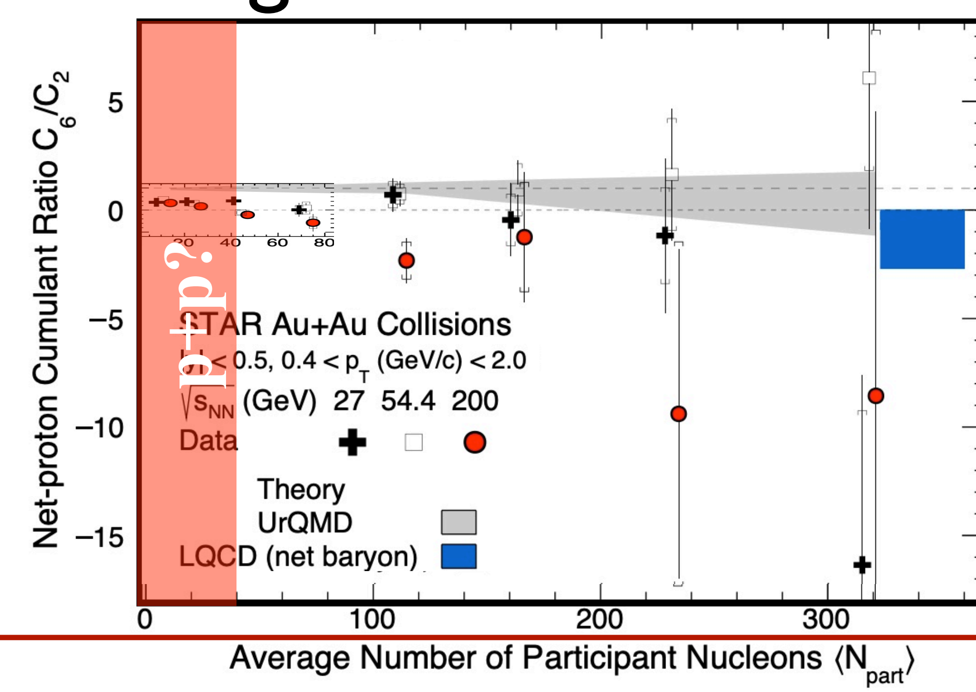
Previous study

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



This study

- Statistics is 70 times larger than previous results
- Multiplicity / acceptance dependence would be available with high statistics dataset



Goal of this study:

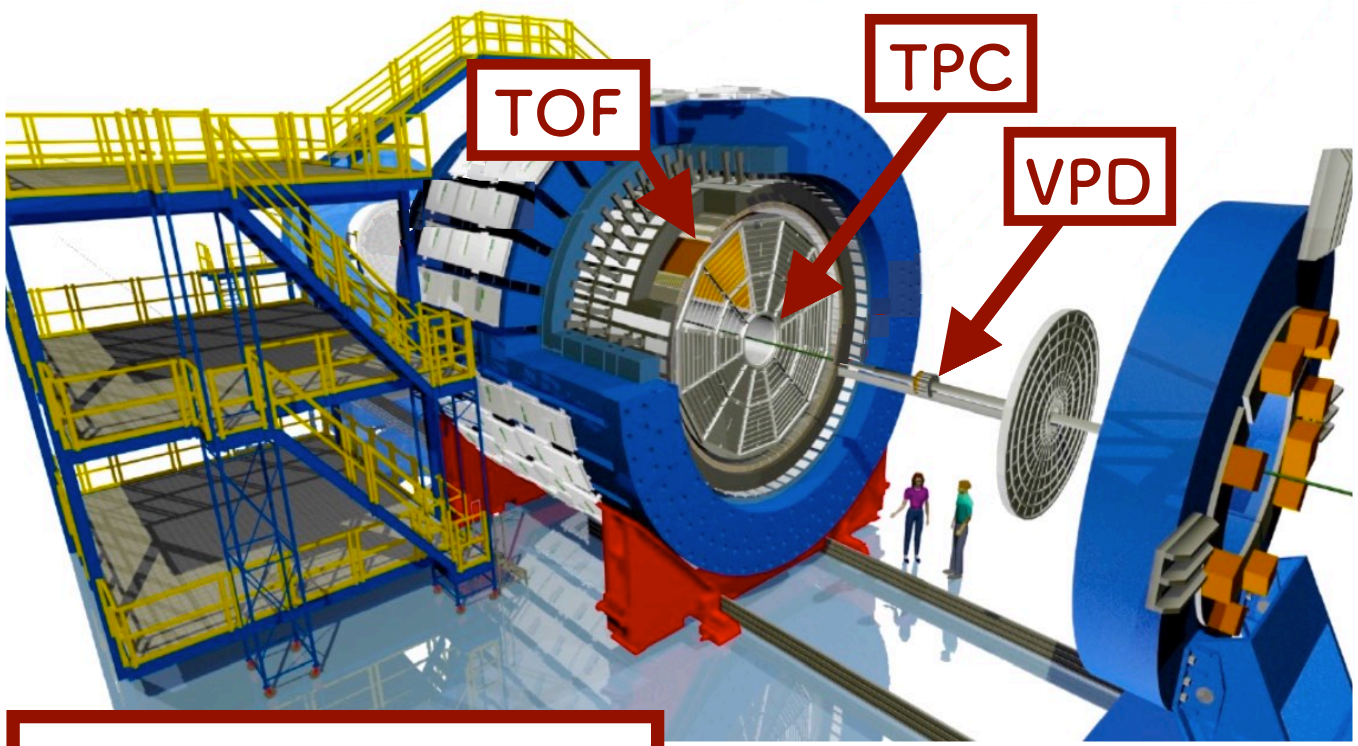
Precise determination the physics baseline
+ Check the possibility of phase transition in high multiplicity events in p+p collisions through the measurements of higher-order cumulants

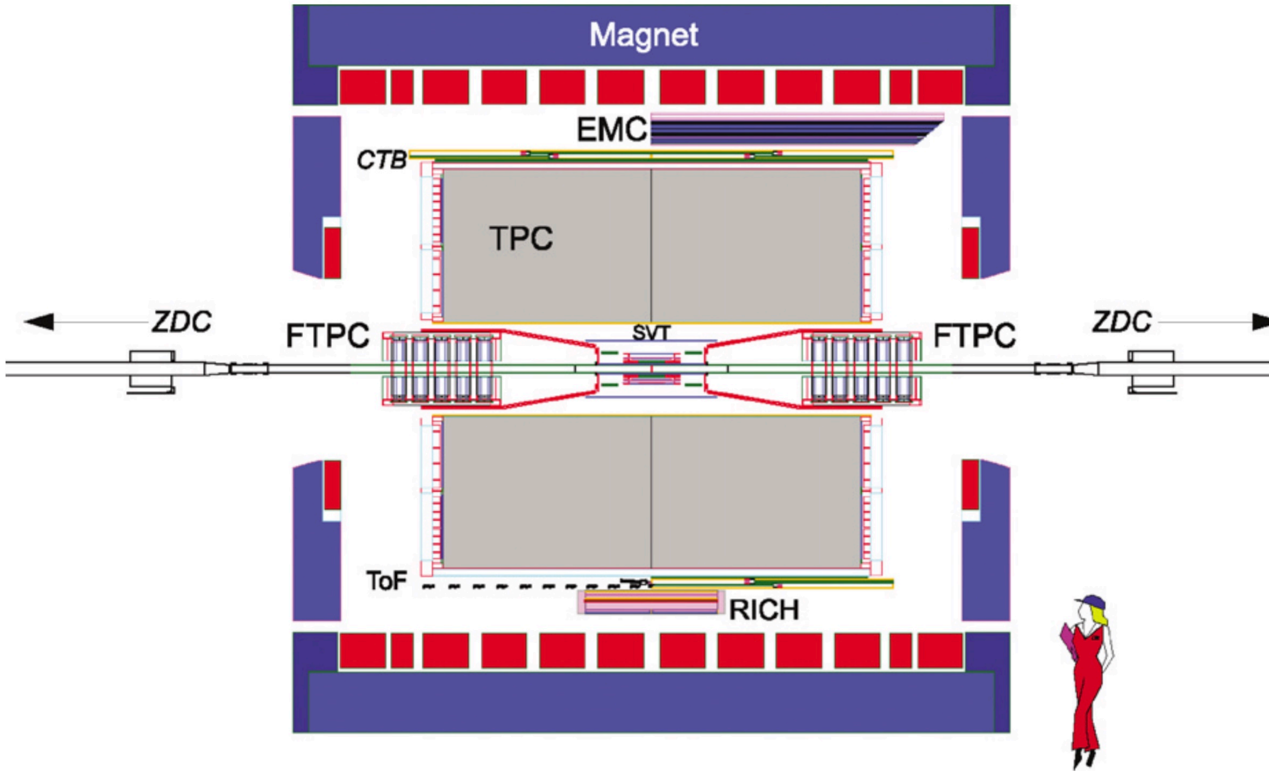
Data Analysis

- Particle identification
- Efficiency correction
- Statistical uncertainties
- Effects of pileup
- Systematic uncertainties

STAR detector

- Time Projection Chamber (TPC) : Tracking, PID, Vertex
- Time Of Flight (TOF) : Extend proton PID up to p_T = 2 GeV/c
  - Start timing from Vertex Position Detector (VPD)
- Electro-Magnetic Calorimeter (EMC)
- Zero Degree Calorimeter (ZDC)





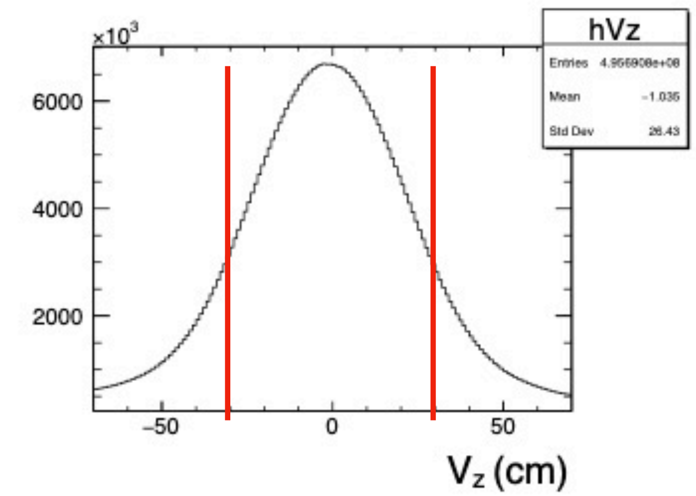
Full azimuthal angles,
$|\eta| < 1.0$

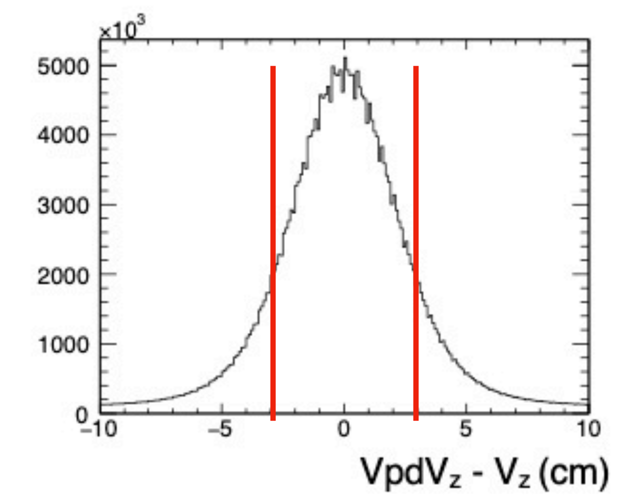
STAR, Nucl.Instrum.Meth.A 499 624-632, (2003)

Event & Track cuts

Event

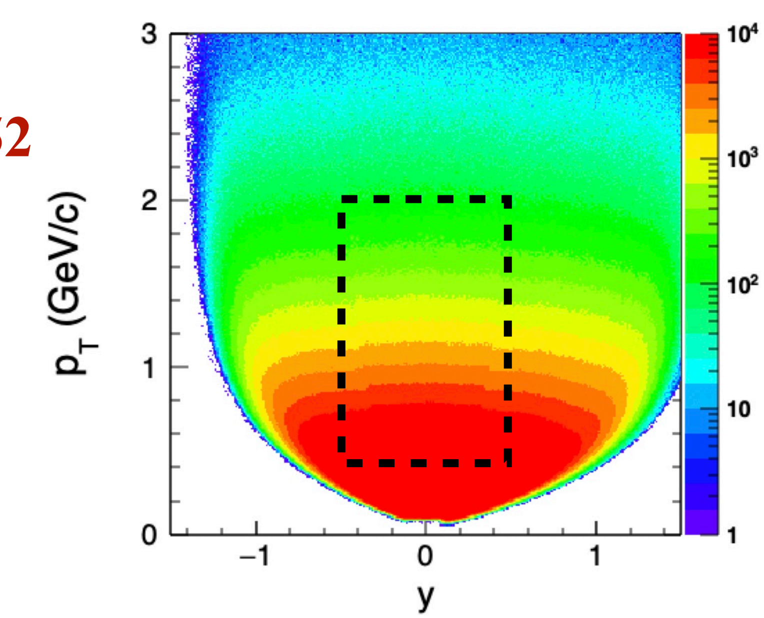
- Collision vertex is required
  - along the beam line : $|V_Z^{TPC}| < 30\mathrm{cm}$
  - in transverse direction : $|V_r^{TPC}| < 2\mathrm{cm}$
- Collision pileups are suppressed by : $|V_Z^{VPD} - V_Z^{TPC}| < 3\mathrm{cm}$





Track cut

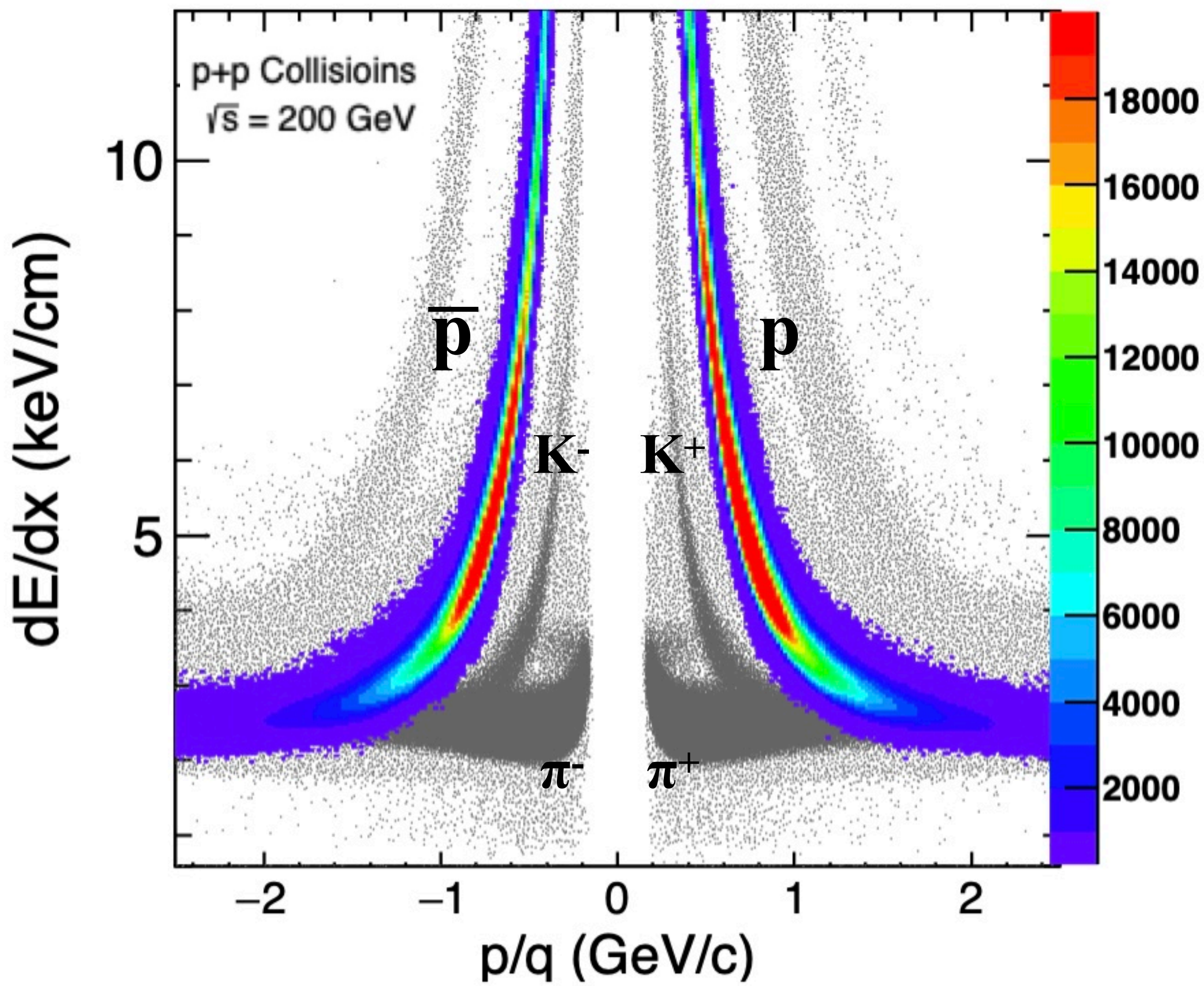
- Distance of Closest Approach : DCA < 1cm
- Number of TPC hit : nHitsFit > 20
  - For long distance of tracks : nHitsFit/nHitsMax <0.52
- Rapidity : $|y|<0.5$
- Transverse momentum : $0.4 < p_T\ (\mathrm{GeV}/c) < 2.0$



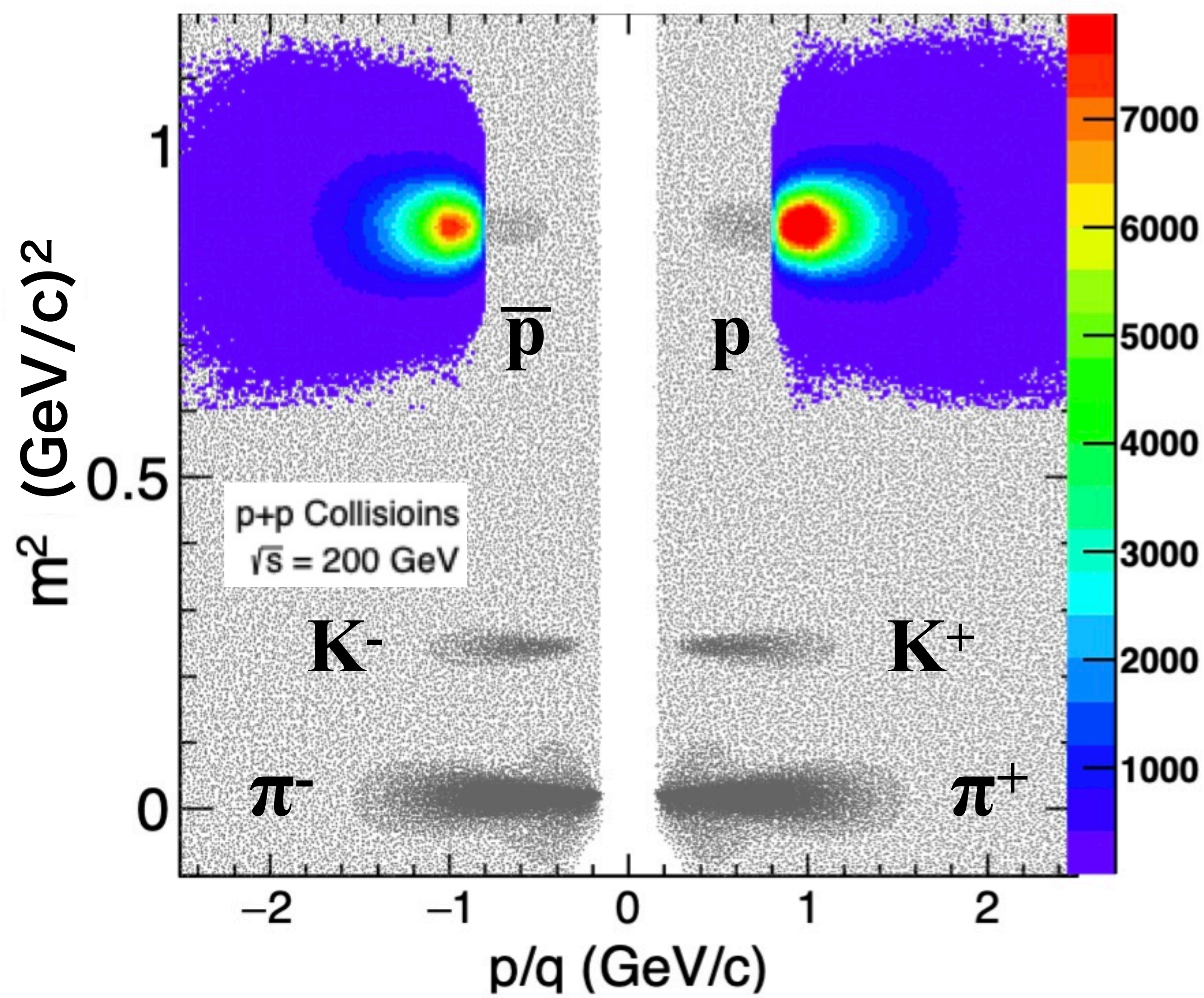
Particle identification

Protons and antiprotons can be identified by TPC and/or TOF depending on p_T region

- Proton identification in dE/dx : $|n\sigma_P|<2$

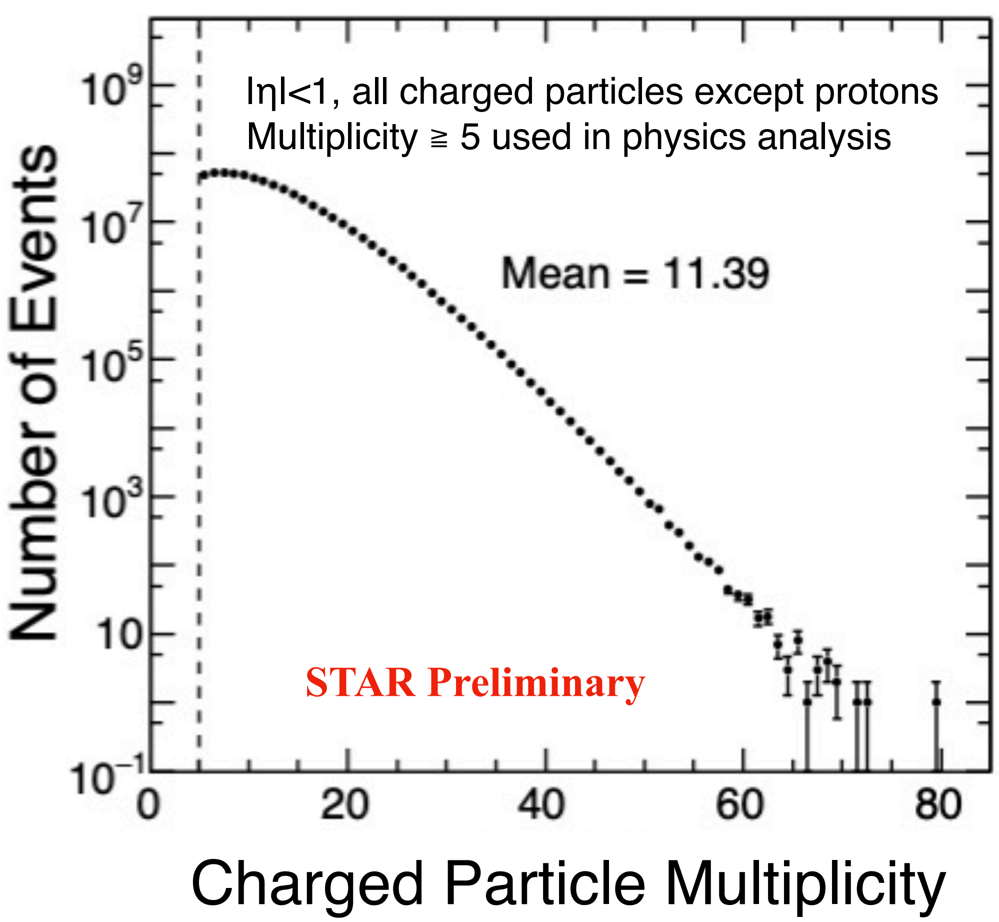


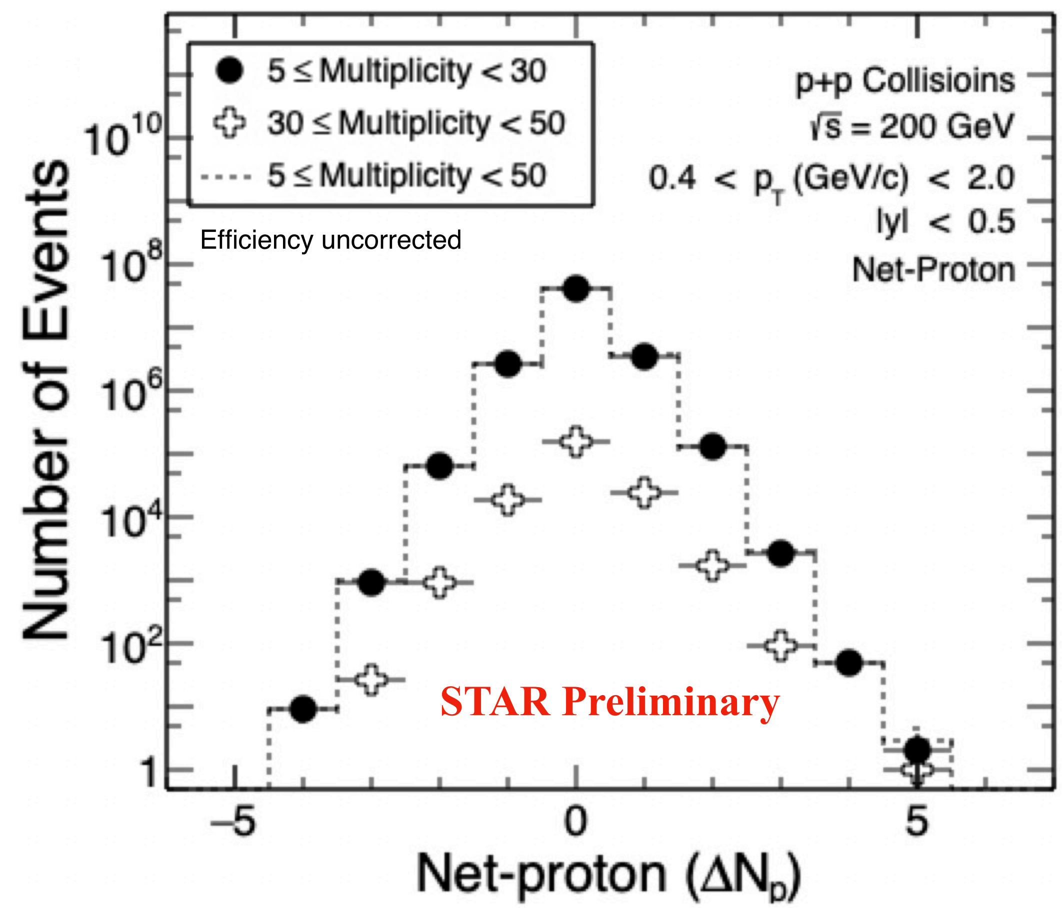
- Mass square : $0.6<m^2\ (GeV/c)^2<1.2$



Precise measurements in p+p 200 GeV

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





Cumulants

X-axis of the results

Y-axis of the results

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),
A. Bzdak, R. Holzmann, V. Koch, PRC.94.064907 (2016)
X. Luo, T. Nonaka, Phys. Rev. C99, 044917 (2019)
T. Nonaka, M. Kitazawa, S. Esumi, PRC.95.064912 (2017)

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

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

a: charge, ε: efficiency

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

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

Efficiency

Particle species	p_T(GeV/c) range	Detector
Proton	$0.4 < p_T < 0.8$	TPC
	$0.8 < p_T < 2.0$	TPC×TOF
Anti-Proton	$0.4 < p_T < 0.8$	TPC
	$0.8 < p_T < 2.0$	TPC×TOF

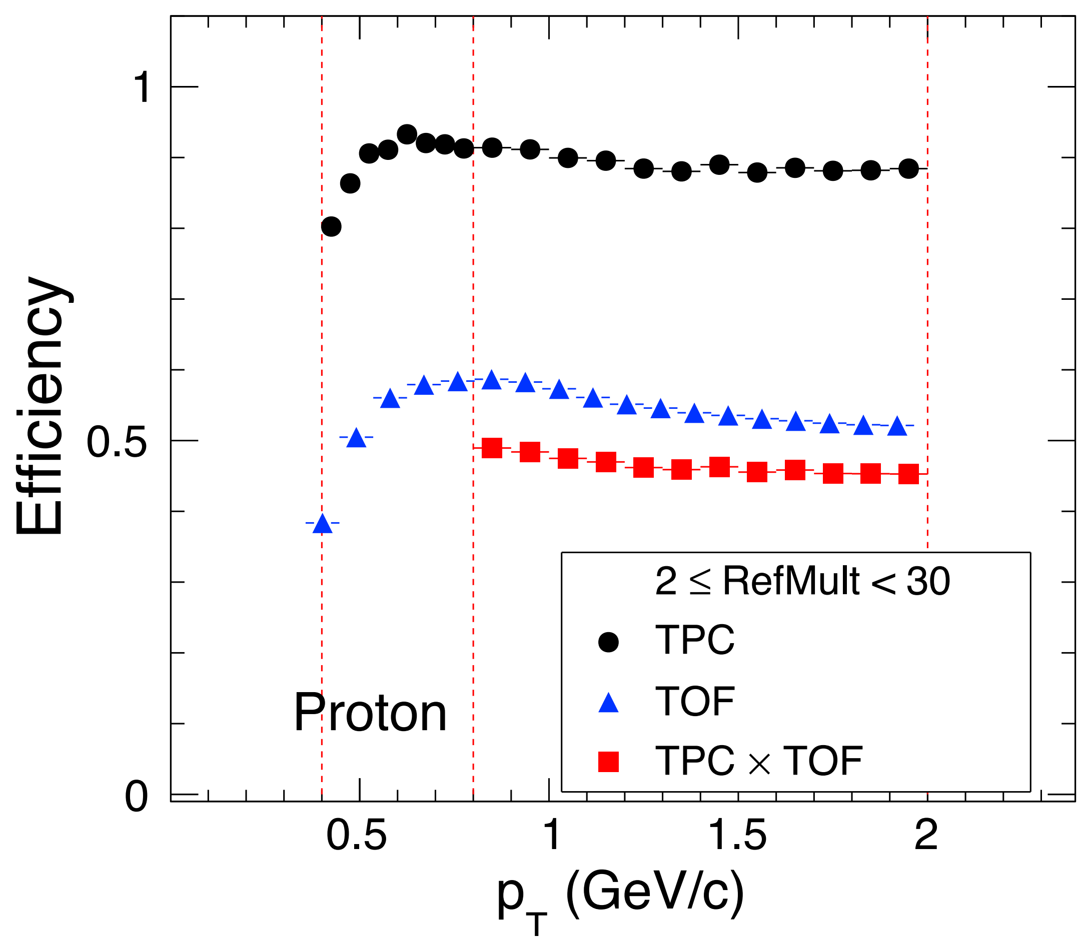
TPC efficiency

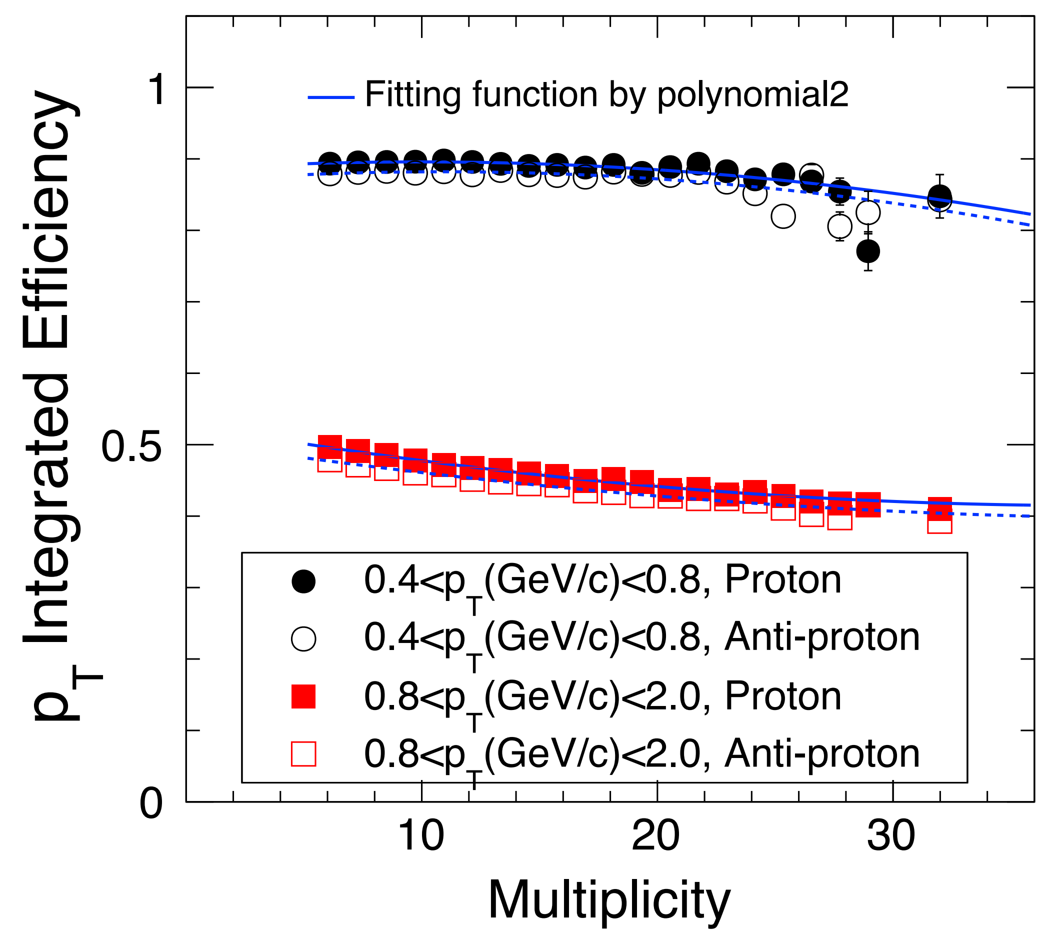
from "Embedding simulation" with GEANT
: using MC tracks embedded
into experimental data

TOF matching efficiency

$$\varepsilon = \frac{|n\sigma_P|<2 \cap \text{TOF-hit}}{|n\sigma_P|<2}$$

= TPC tracking protons



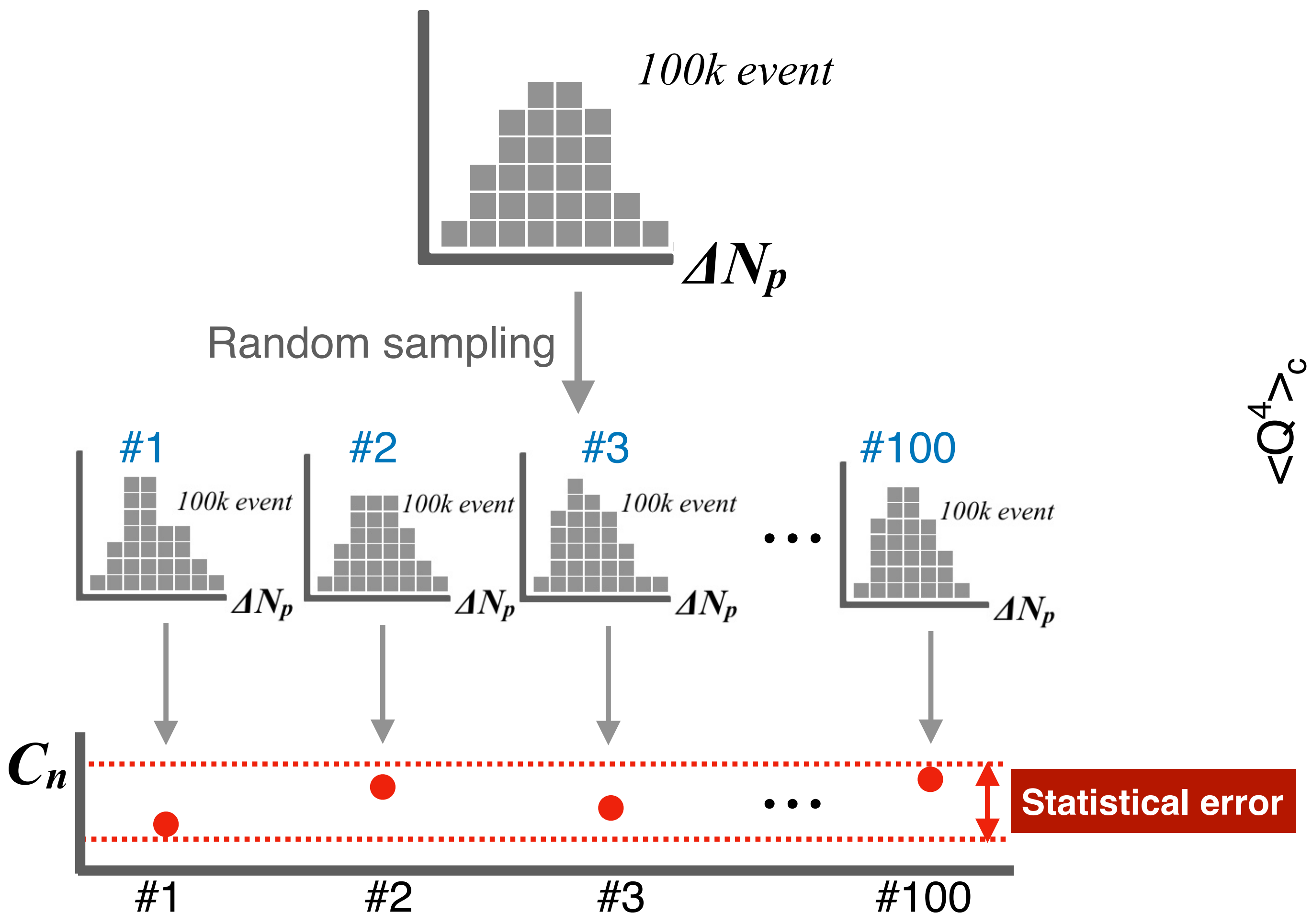


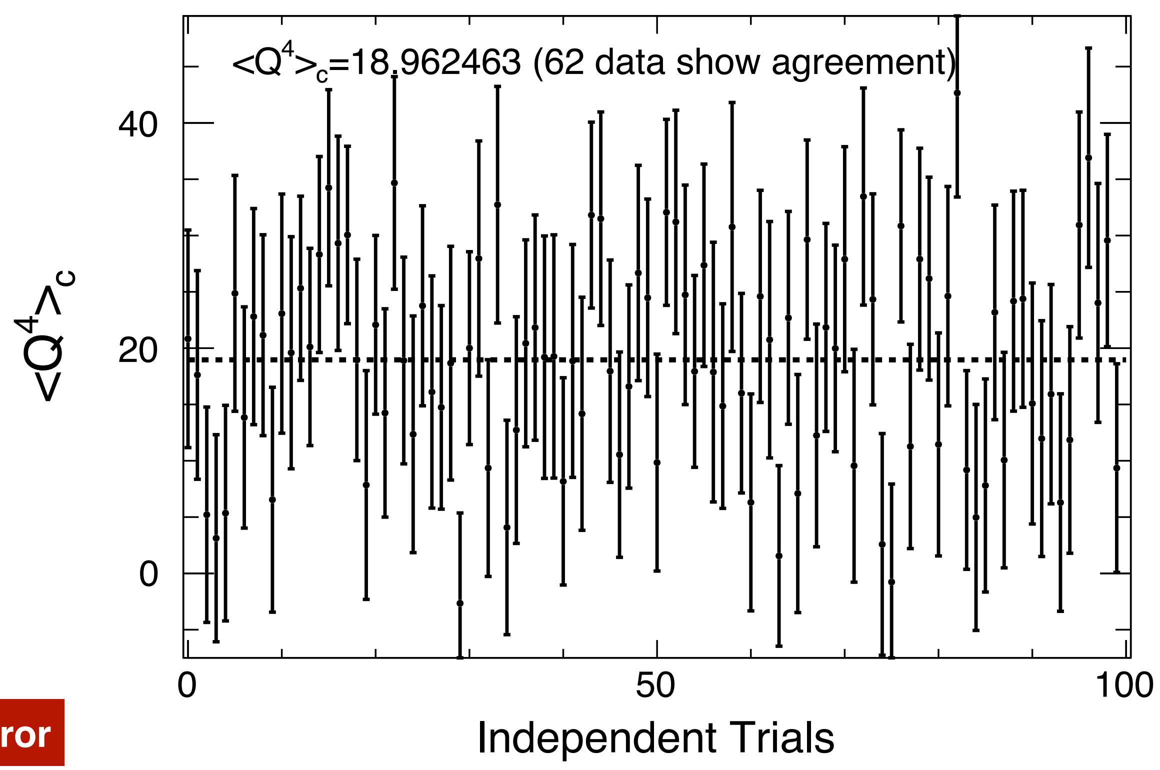
Statistical uncertainties

General method which can be applied to complicated procedures in cumulant calculations are needed

Bootstrap method

X. Luo., X. Nu, Nucl. Sci. Tech., 28, 112 (2017)
X. Luo., T. Nonaka, PRC 99, 044917 (2019)





~1 σ of total show agreement with mean

Pileup events in p+p collisions

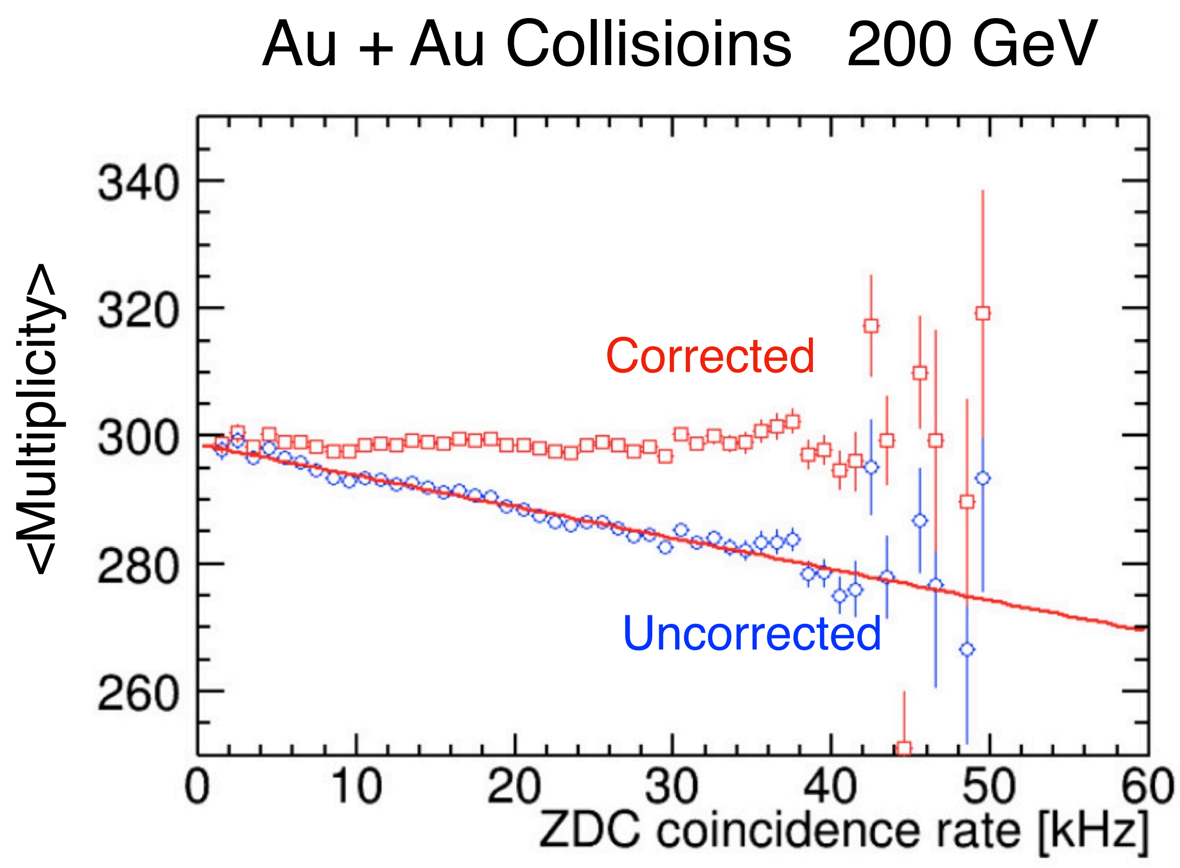
- Effects of pileups
- Effects on TOF matching efficiency
- Effects on Multiplicity distributions
- Necessary number of bins in net-proton distribution

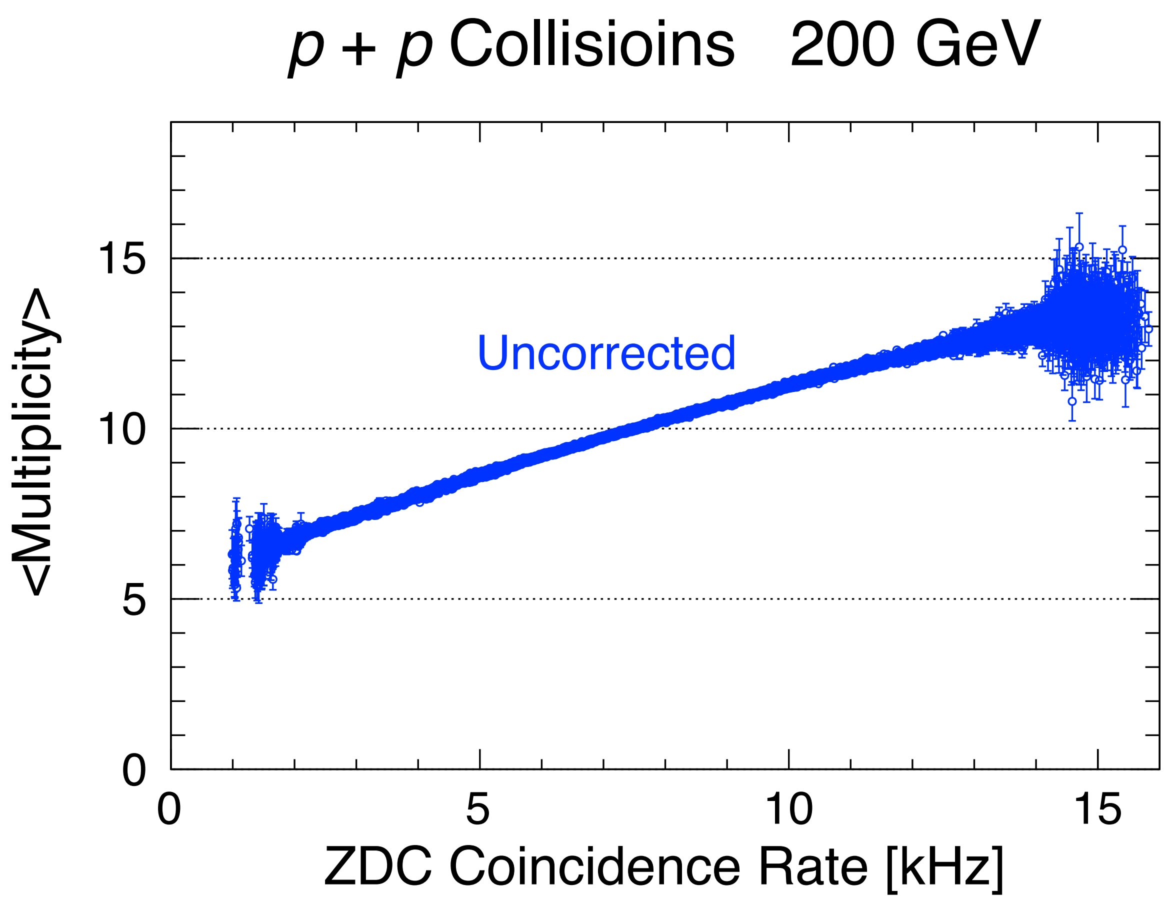
Effects of pileups

Two effects are contained at high luminosity events:

(1) Increasing of pileup backgrounds.

(2) Decreasing of efficiency due to higher track density





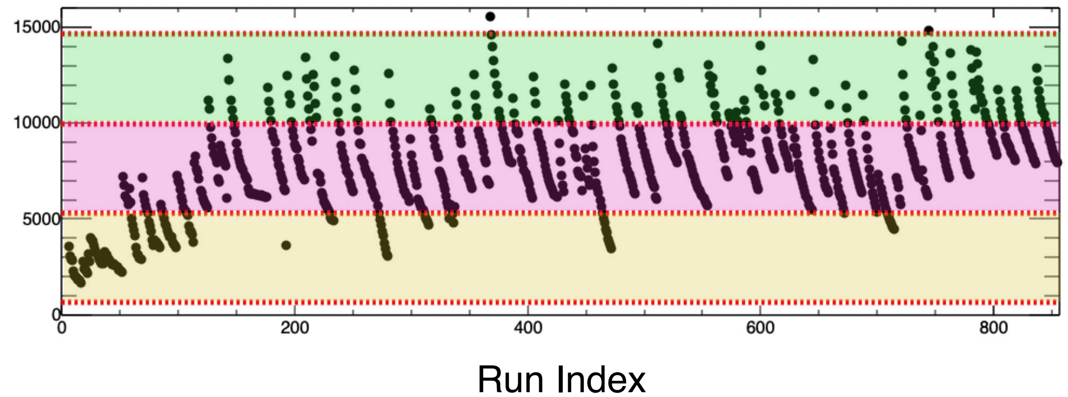
(1) < (2)

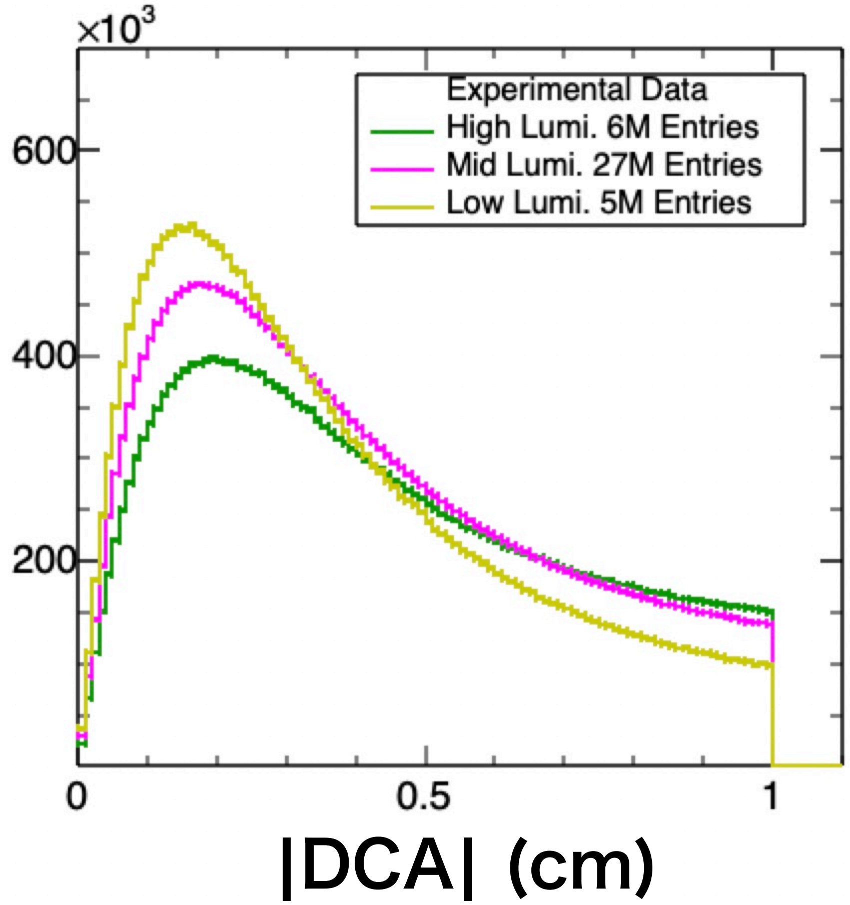
(1) > (2)

Effects of pileups

Luminosity
High
Middle
Low

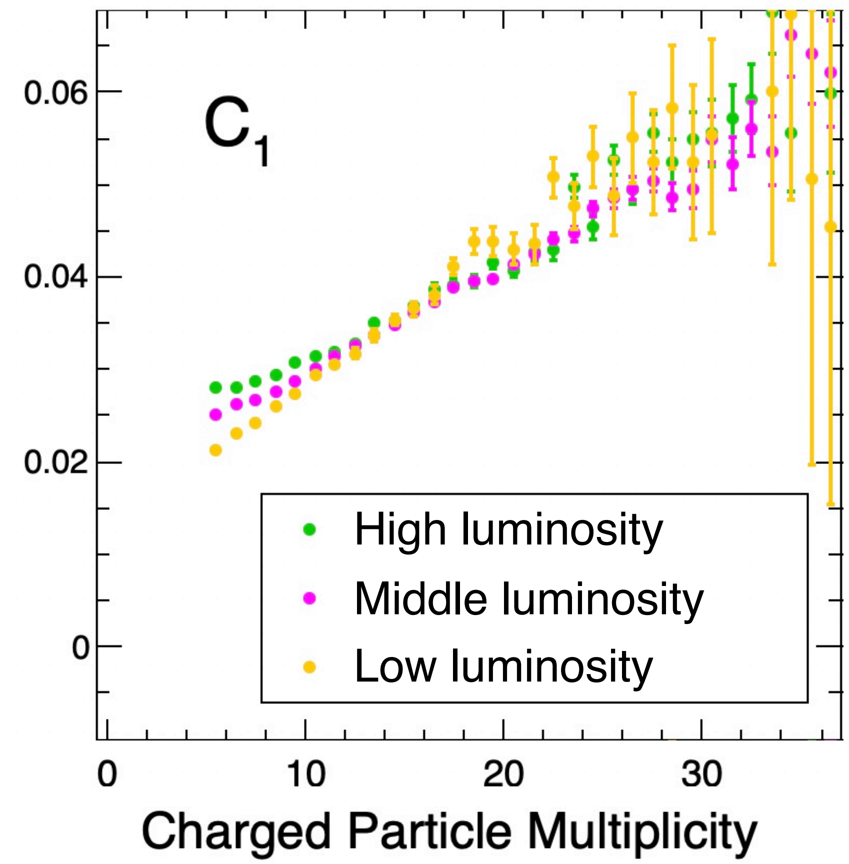
<ZDC concidence rate (Hz)>





- Large tail in high luminosity

→ B.G. : High lumi. > Low lumi.



C_1 are different in 3 luminosity groups

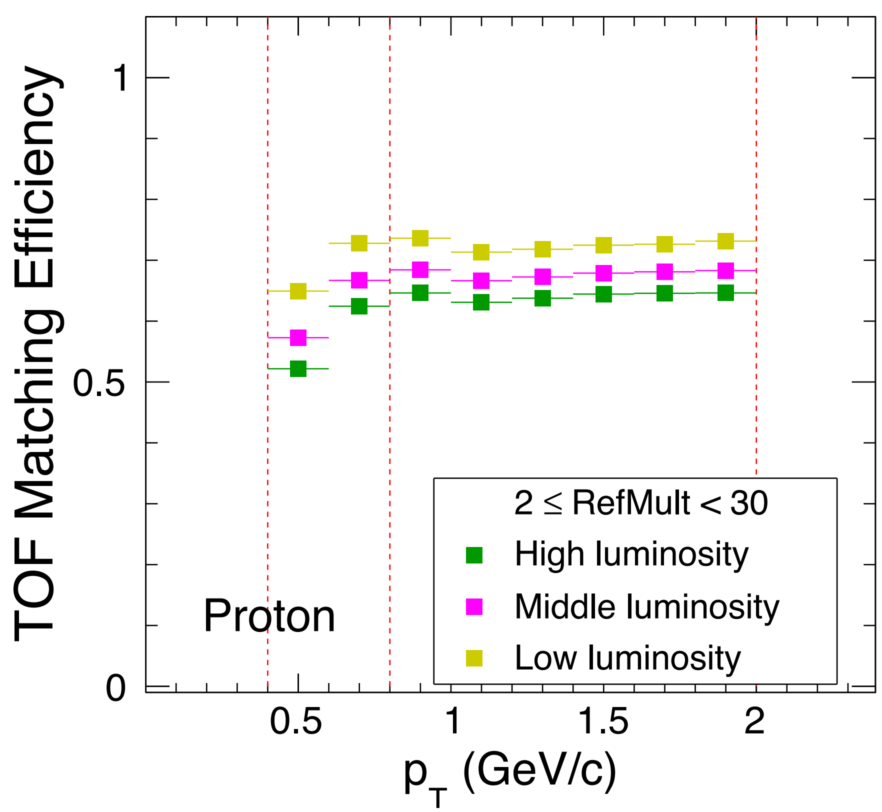
Effects on TOF matching efficiency

TOF matching efficiency

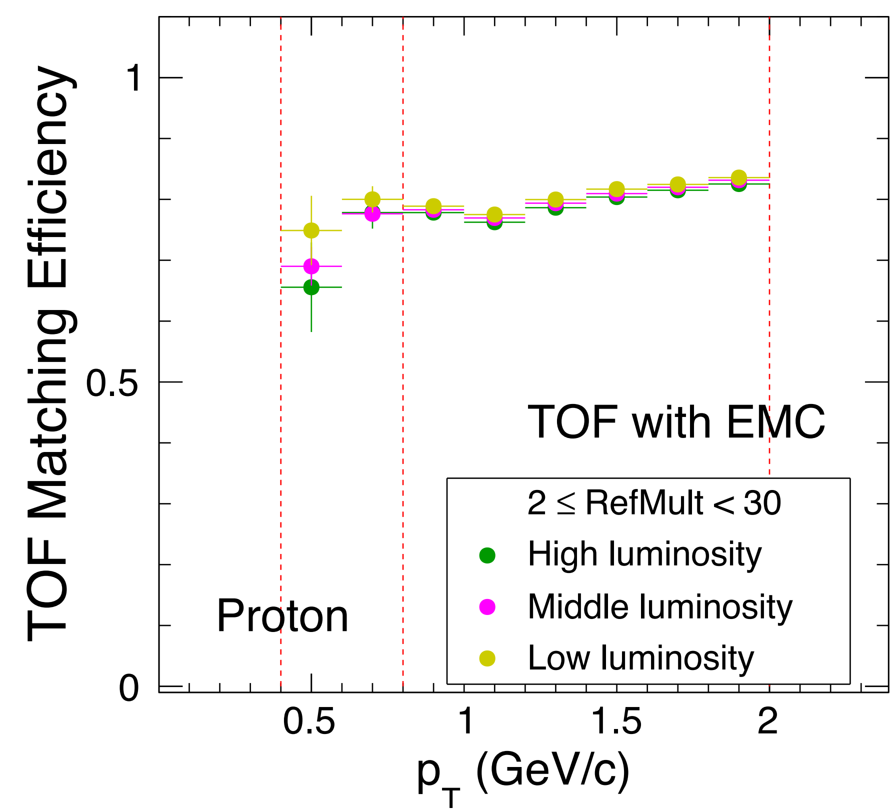
$$\varepsilon = \frac{|n\sigma_P|<2 \cap \text{TOF-hit}}{|n\sigma_P|<2}$$

= TPC tracking protons

$$\varepsilon' = \frac{|n\sigma_P|<2 \cap \text{TOF-hit} \cap \text{EMC-hit}}{|n\sigma_P|<2 \cap \text{EMC-hit}}$$

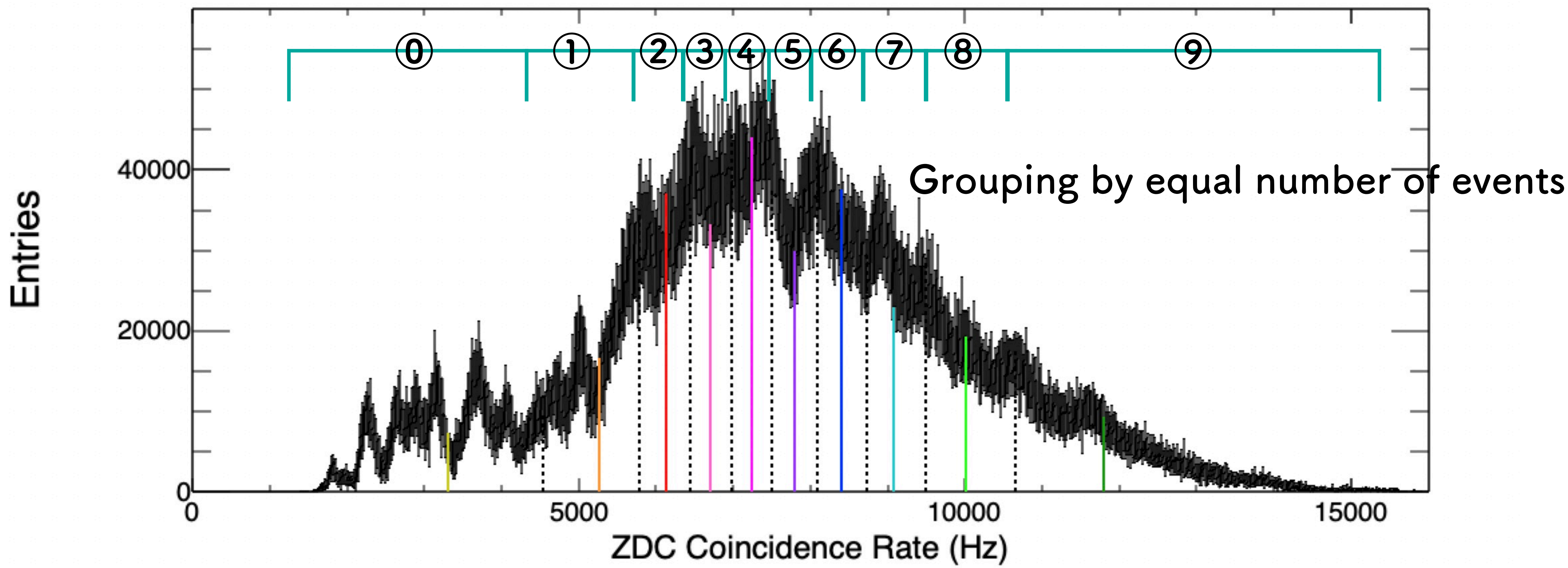


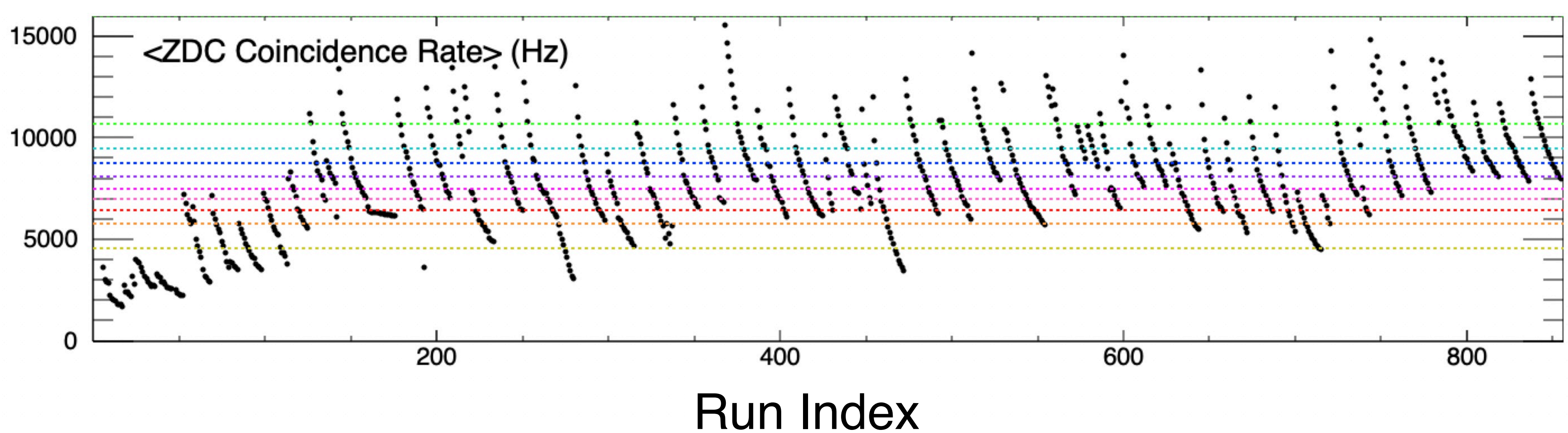
+EMC



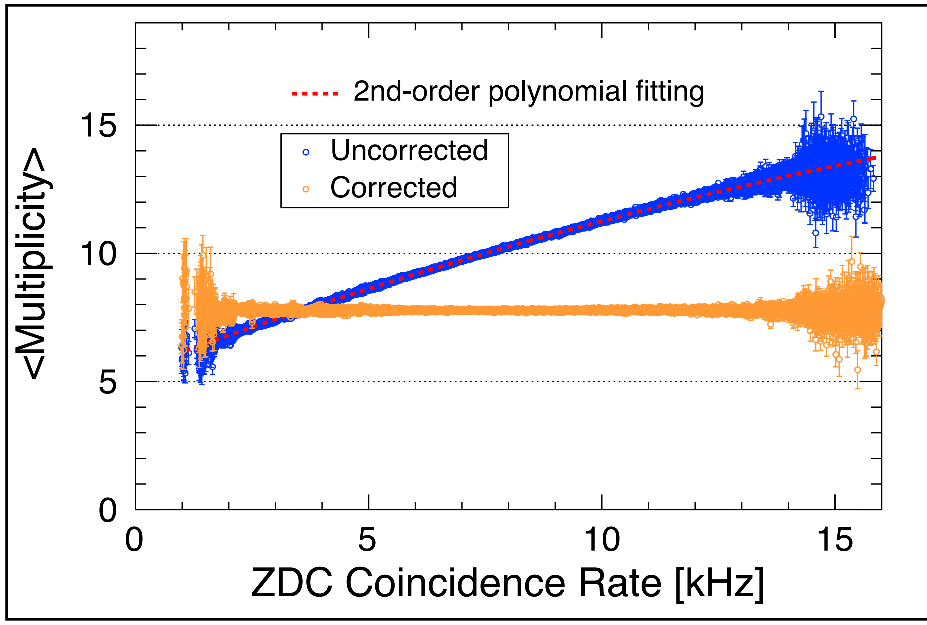
- TOF match efficiency change ~10% depending on luminosity
- Increasing of backgrounds with luminosity in TPC detected tracks
- Deviations between different luminosity results are clearly reduced even in the low p_T
- TOF with EMC are required for entire p_T

More systematic grouping of luminosity

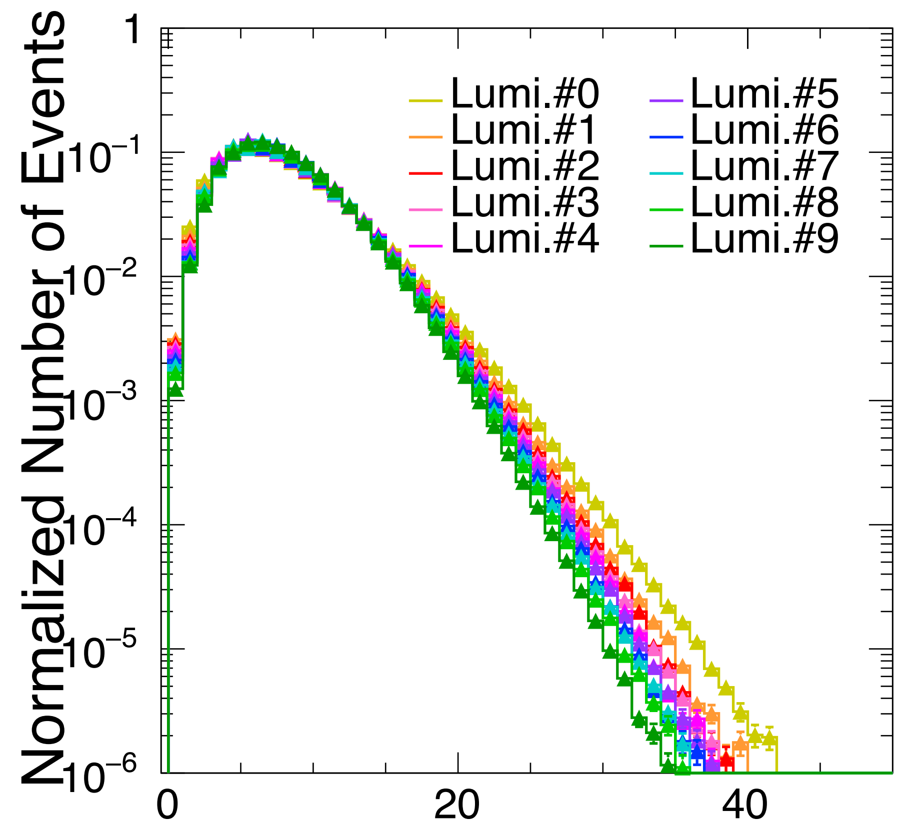


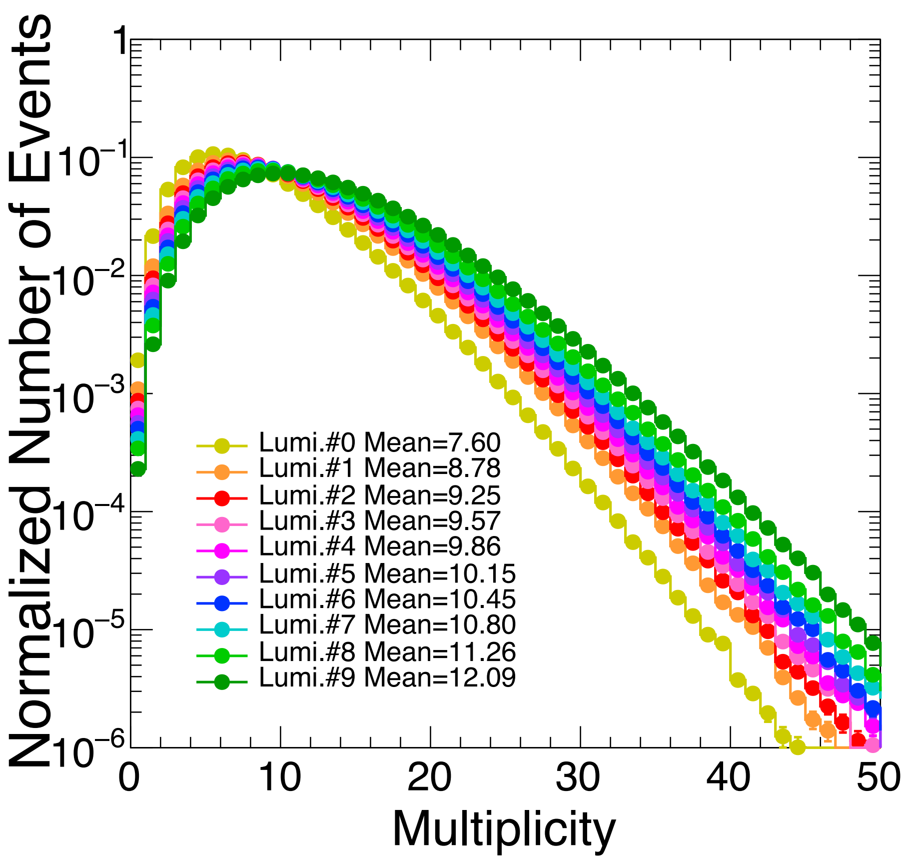


Effects on Multiplicity distributions

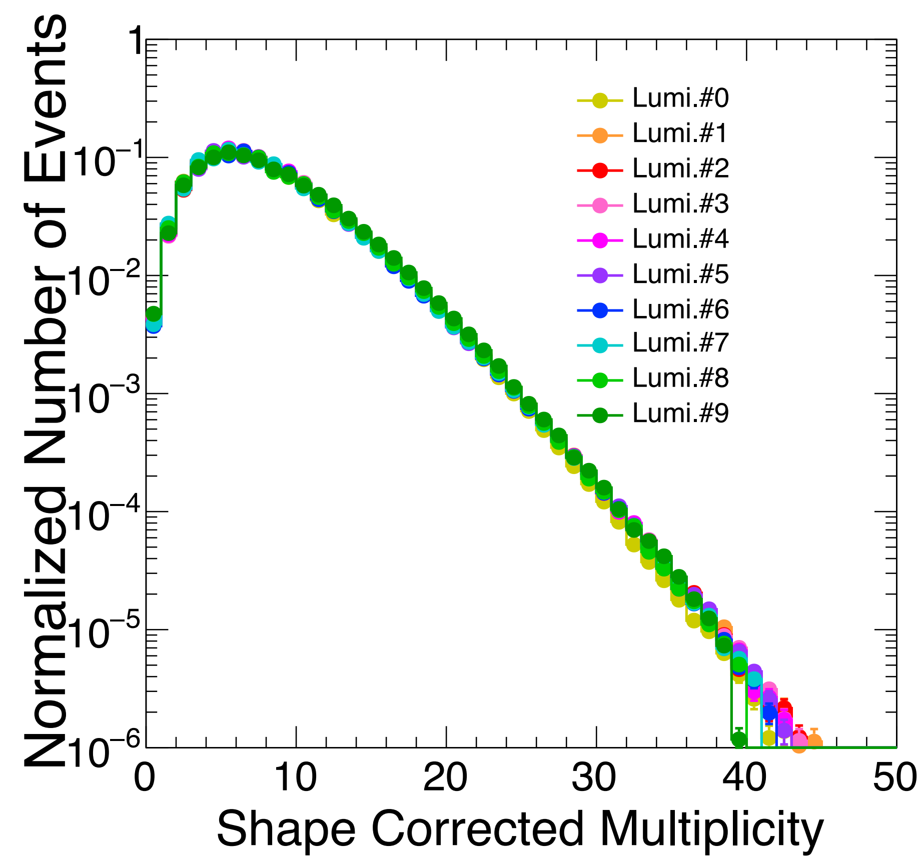


Mean correction





Shape correction

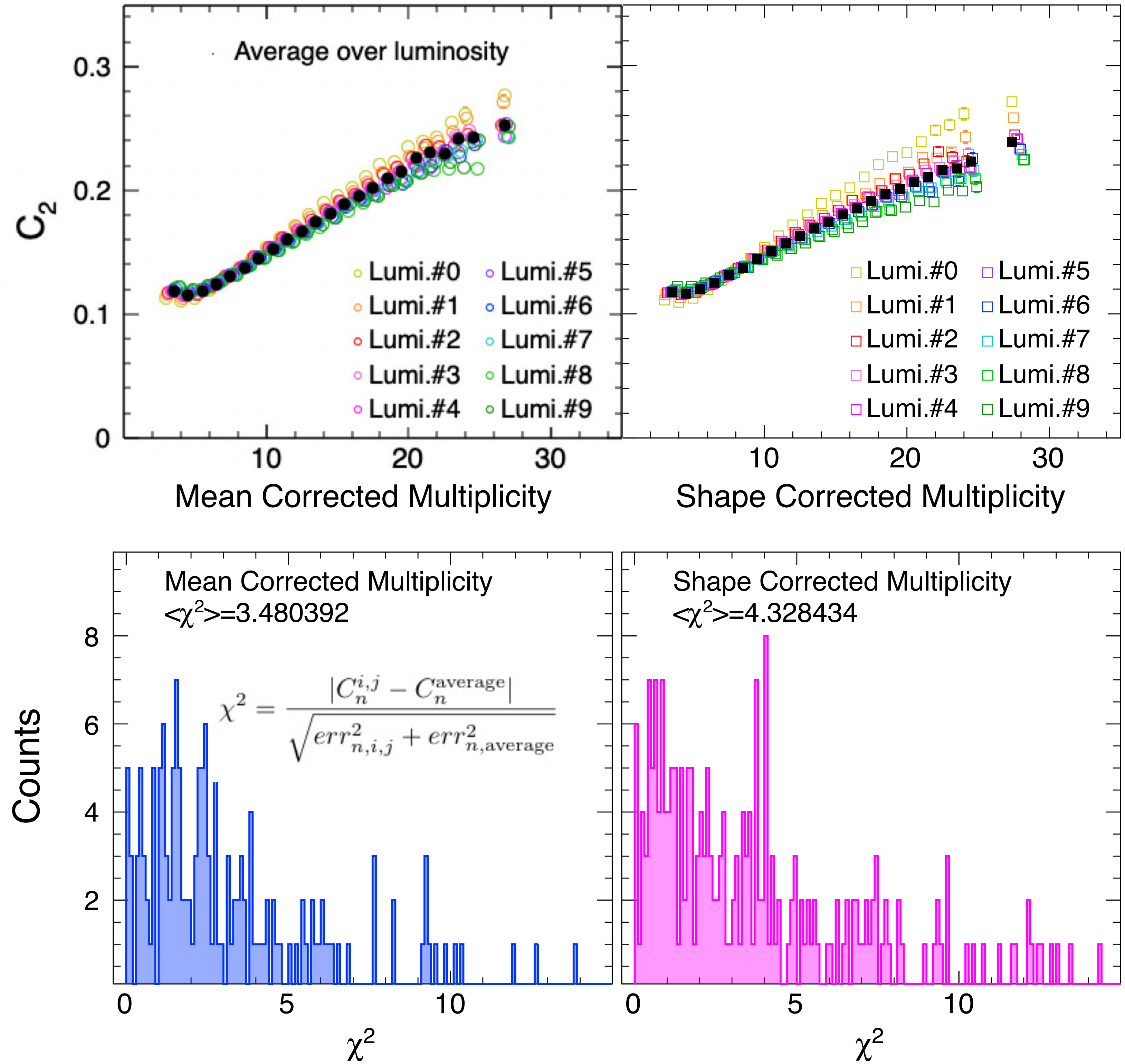


Effects on Multiplicity distributions

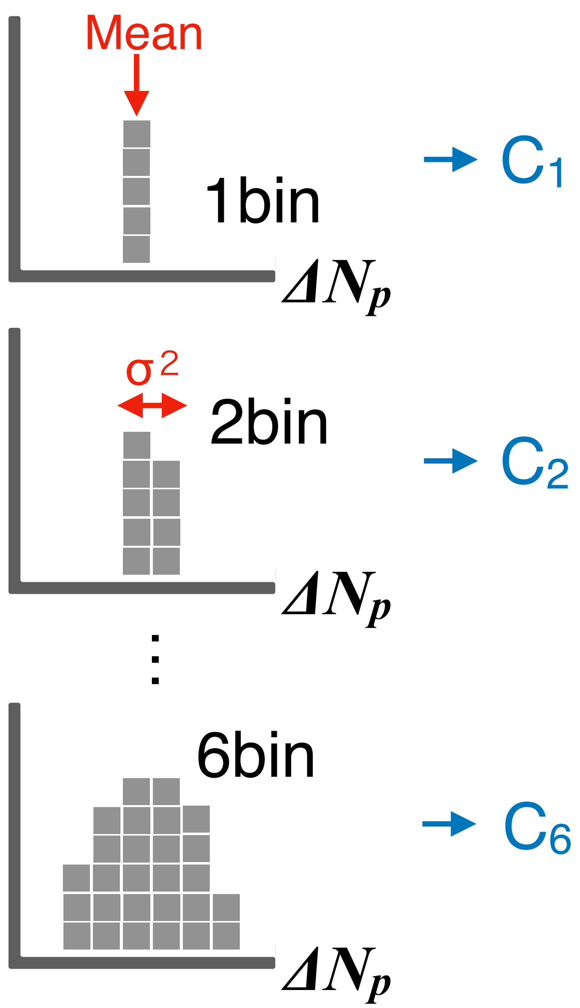
- Correction method is determined by better agreement of results from different luminosity groups
- $<\chi^2>$ of C_2 in mean corrected multiplicity is smaller than in shape correction
- Same results are shown for most order of cumulants

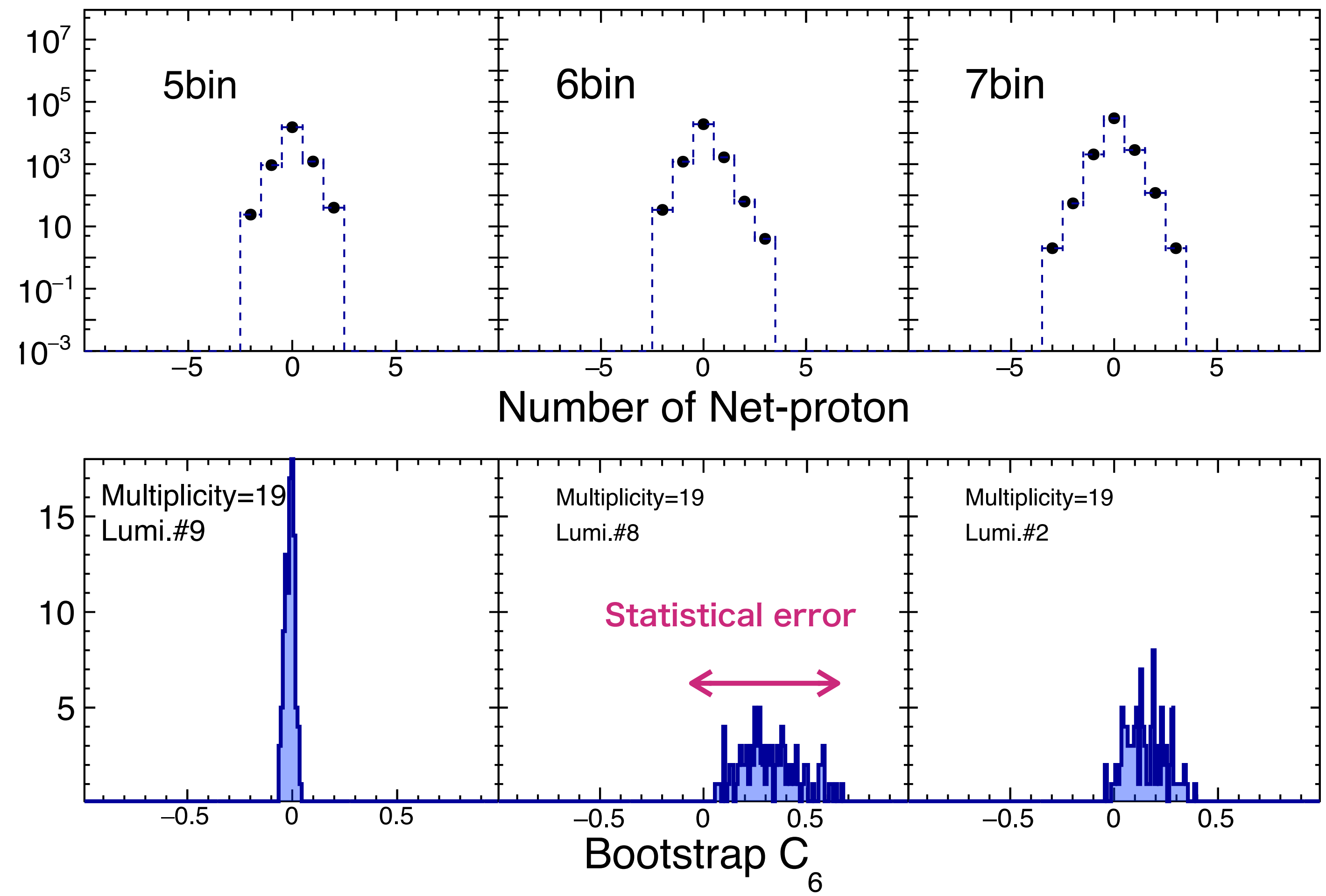
↓

Mean corrections are employed



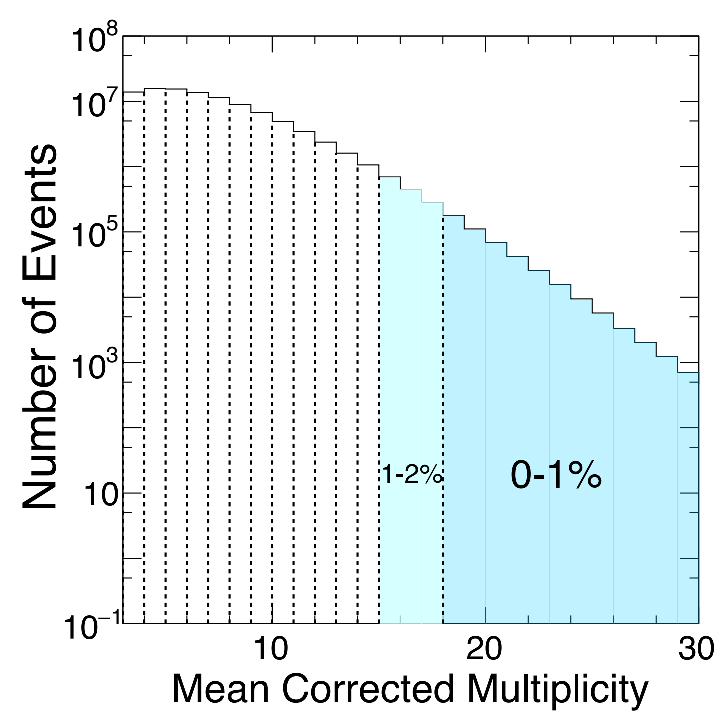
Necessary number of bins in net-proton distribution





Statistical errors for each luminosity groups at high multiplicity bins cannot be properly estimated due to small number of bins (<6) in net-proton distributions

Luminosity categorizations so that net-proton distributions have enough number of bins



Multiplicity	Number of events
3	14 (M)
4	16
5	15
6	14
7	11
8	9
9	7
10	5
11	3
12	2
13	2
14	1
$15 \leq m_{ch} < 18$	1.4
$18 \leq m_{ch} < 30$	0.5

Summary of systematic study

$$\sigma_{sys} = Y_{def}\sqrt{\sum_j R_j^2} \times 100$$

C_1	4.16 %
C_2	3.63 %
C_3	3.91 %
C_4	3.12 %
C_5	8.18 %
C_6	6.99 %

C_2/C_1	1.35 %
C_3/C_2	1.58 %
C_4/C_2	0.65 %
C_5/C_1	7.97 %
C_6/C_2	8.75 %

Large uncertainties in C_5, C_6/C_2

Contribution (R_j) for each variables

$$R_j = \sqrt{\frac{1}{n}\sum_i \left[\frac{Y_{i,j} - Y_{def}}{Y_{def}}\right]^2} \times 100$$

	$\lvert n\sigma_p \rvert$	DCA[cm]	nHitsFit	m^2	Efficiency	ZDC coincidence rate(Hz)
C_1	0.04 %	2.47 %	0.23 %	0.07 %	2.79 %	1.81 %
C_2	0.02 %	1.23 %	0.31 %	0.04 %	2.46 %	2.33 %
C_3	0.18 %	2.57 %	0.23 %	0.07 %	2.38 %	1.70 %
C_4	0.07 %	1.13 %	0.20 %	0.06 %	2.00 %	2.10 %
C_5	2.98 %	4.63 %	0.87 %	0.57 %	0.56 %	5.92 %
C_6	1.09 %	1.21 %	0.91 %	0.37 %	2.66 %	6.17 %
C_2/C_1	0.06 %	1.22 %	0.23 %	0.09 %	0.33 %	0.37 %
C_3/C_2	0.14 %	1.37 %	0.36 %	0.09 %	0.12 %	0.66 %
C_4/C_2	0.04 %	0.12 %	0.13 %	0.02 %	0.53 %	0.31 %
C_5/C_1	2.34 %	1.53 %	1.10 %	0.60 %	3.48 %	6.48 %
C_6/C_2	0.98 %	1.49 %	1.47 %	0.28 %	4.56 %	7.10 %

DCA is dominant for most ratios

Results & Discussion

- Acceptance dependence
- Multiplicity dependence
    - Mean corrected multiplicity dependence
    - Luminosity independent variable dependence

Discussion① :

Study of baryon number conservation effect

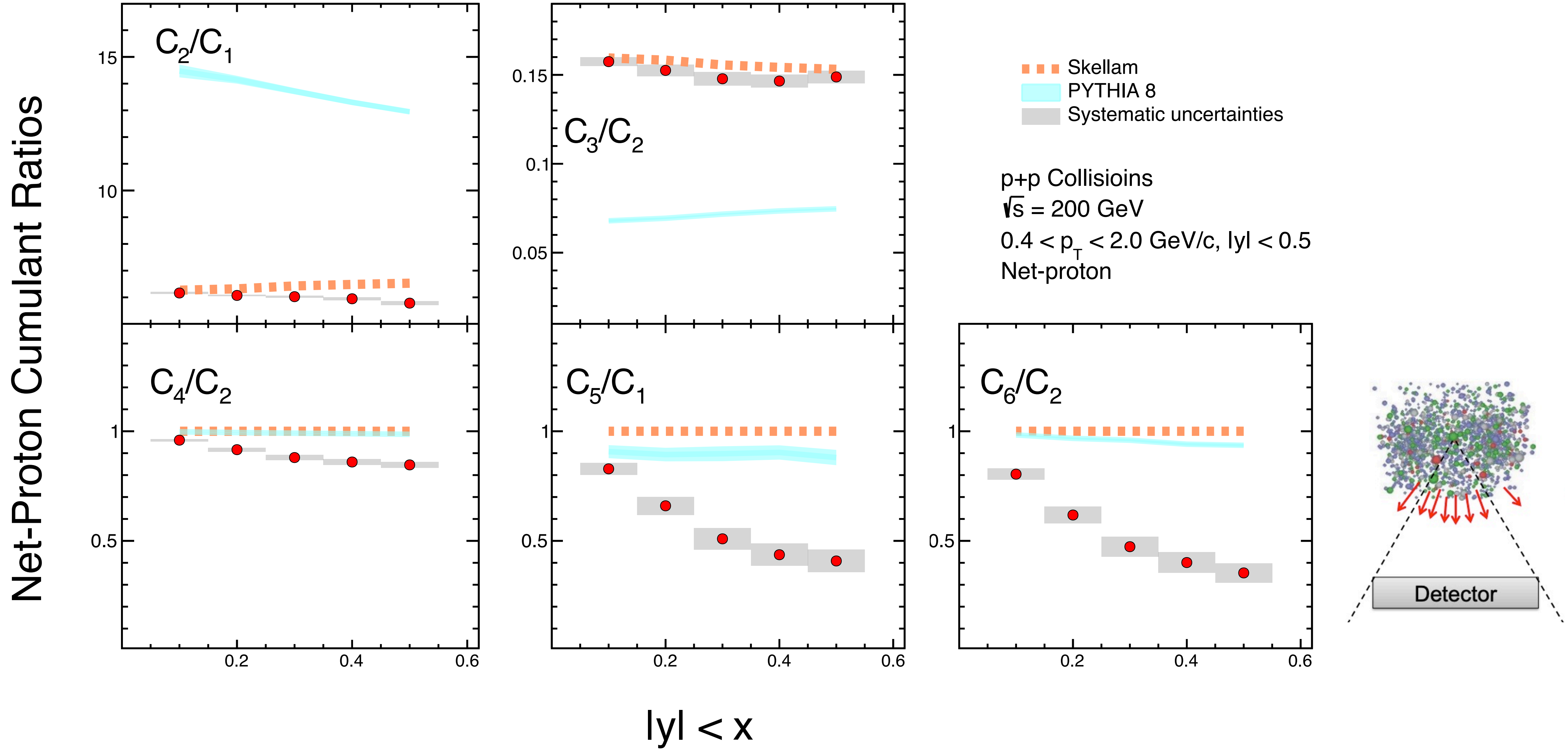
Discussion② :

Comparison between p+p and Au+Au

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
- PYTHIA calculations do not reproduce the observed deviations



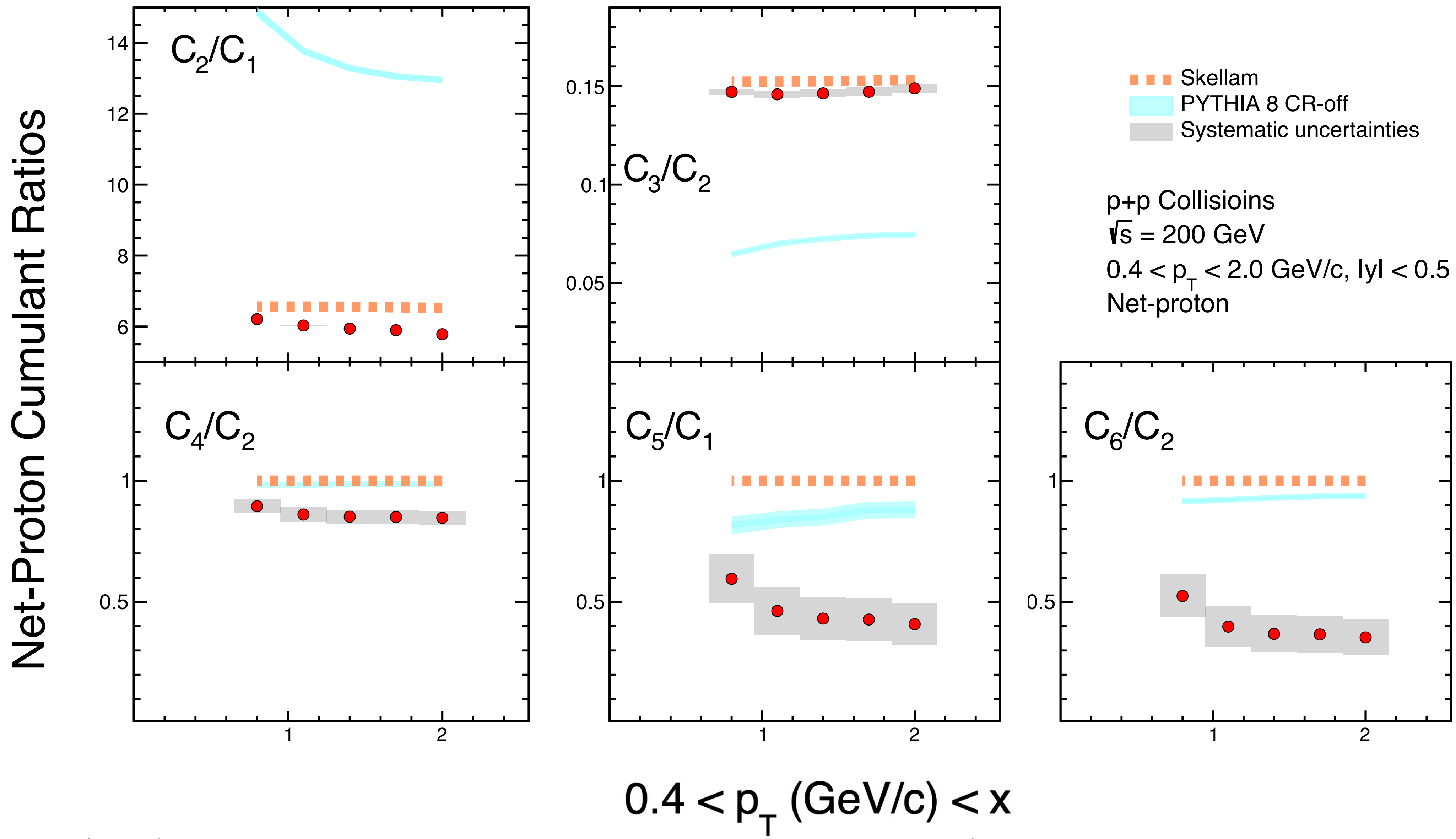
- The baseline is suppressed by baryon number conservation

P. Braun-Munzinger et. al., Nucl. Phys. A 961 (2016)

Acceptance dependence of net-proton cumulant ratios

Δ p_T dependence

- Deviations from Skellam baseline become large with increase of p_T acceptance except for C_3/C_2
- PYTHIA calculations do not reproduce the observed deviations

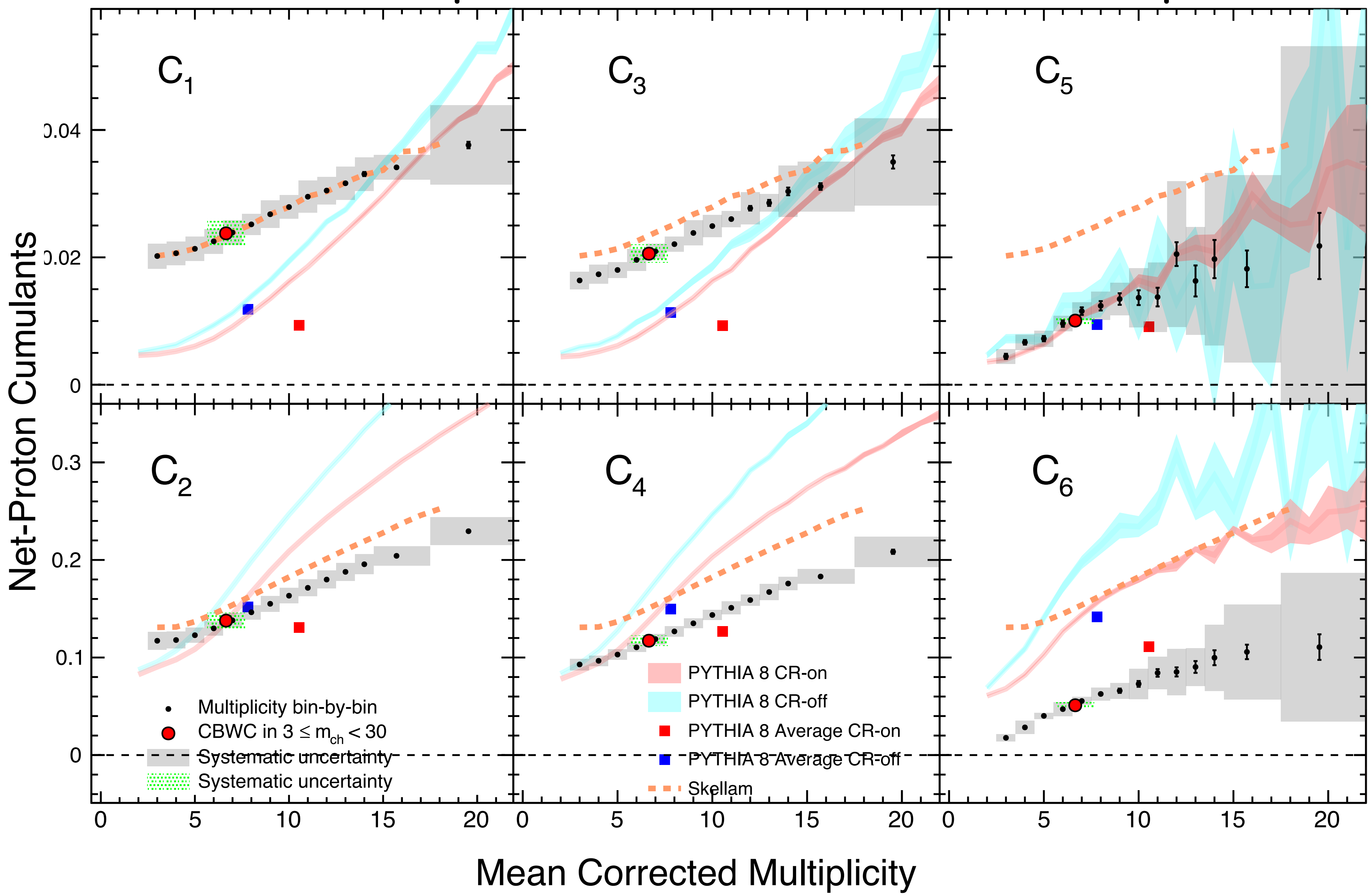


- The baseline is suppressed by baryon number conservation

P. Braun-Munzinger et. al., Nucl. Phys. A 961 (2016)

Multiplicity dependence of net-proton cumulants

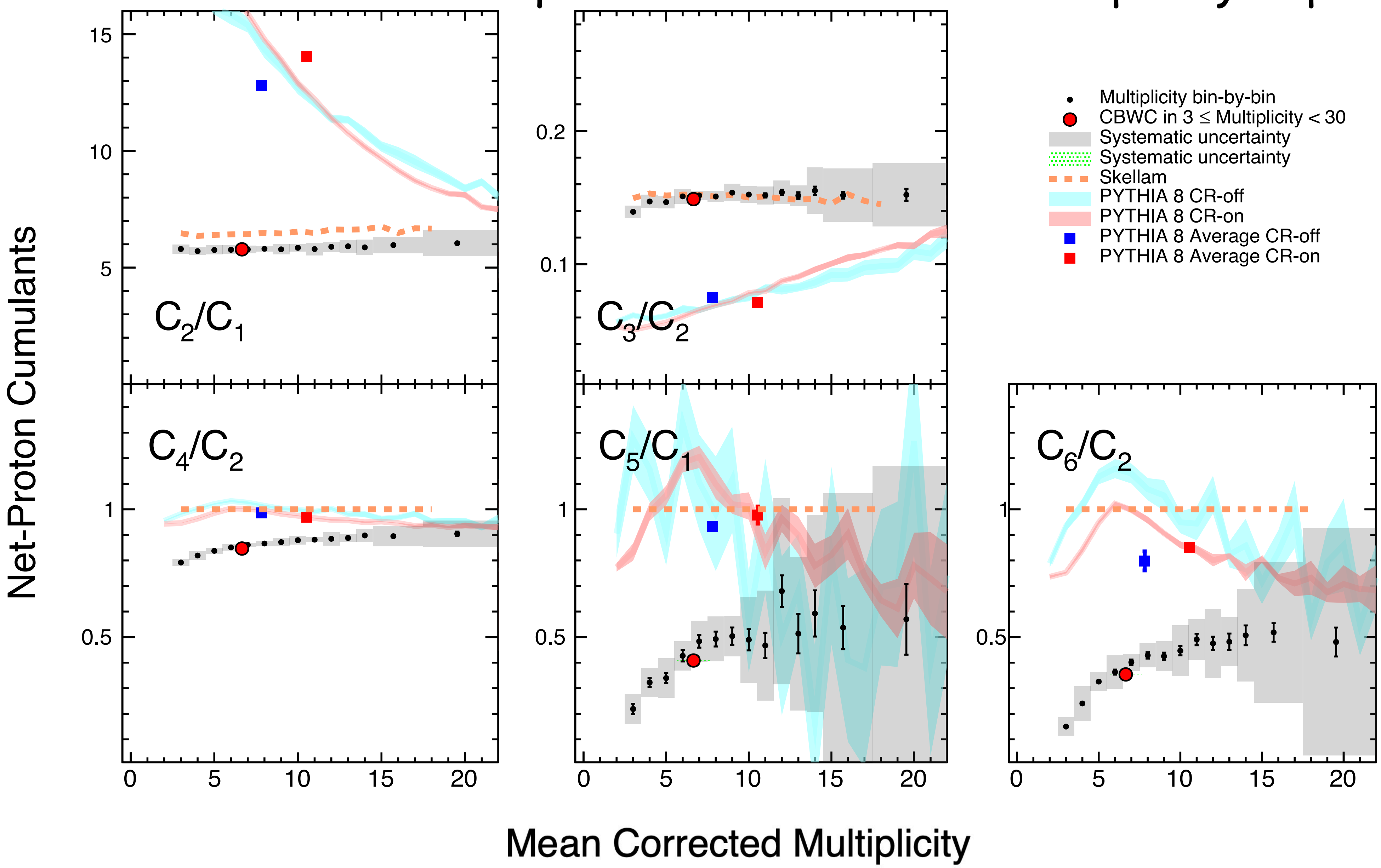
- Cumulants increase with increasing multiplicity
- Deviations from Skellam※ become larger for higher-order ※ Skellam = $(\text{Poisson})_{\text{proton}} - (\text{Poisson})_{\text{antiproton}}$
- PYTHIA calculations do not reproduce the observed values except for C_5



- The baseline is suppressed by baryon number conservation P. Braun-Munzinger et. al., Nucl. Phys. A 961 (2016)

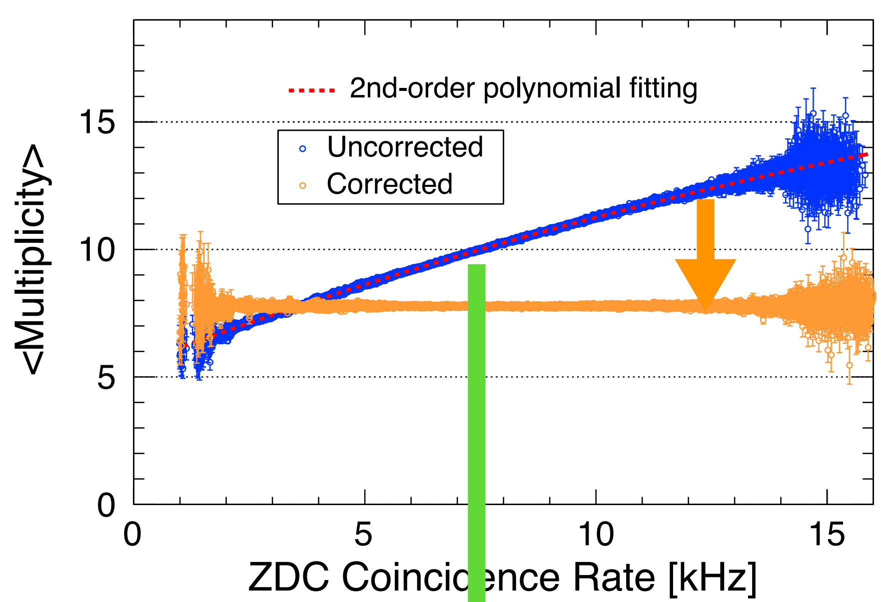
Multiplicity dependence of net-proton cumulant ratios

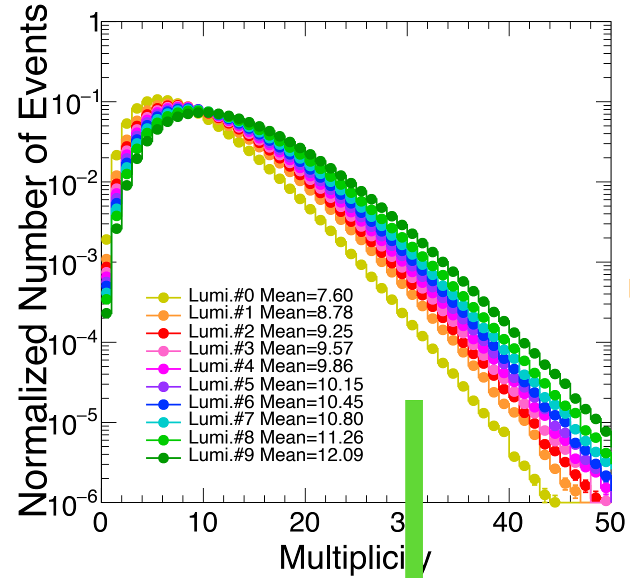
- C_3/C_2 is consistent with the Skellam expectations
- Deviations from Skellam become larger for higher-order
- PYTHIA calculations do not reproduce the observed multiplicity dependence

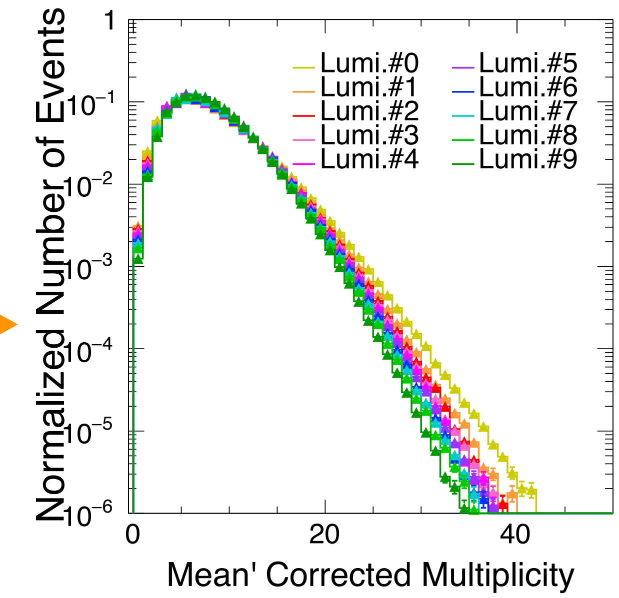


- The baseline is suppressed by baryon number conservation P. Braun-Munzinger et. al., Nucl. Phys. A 961 (2016)

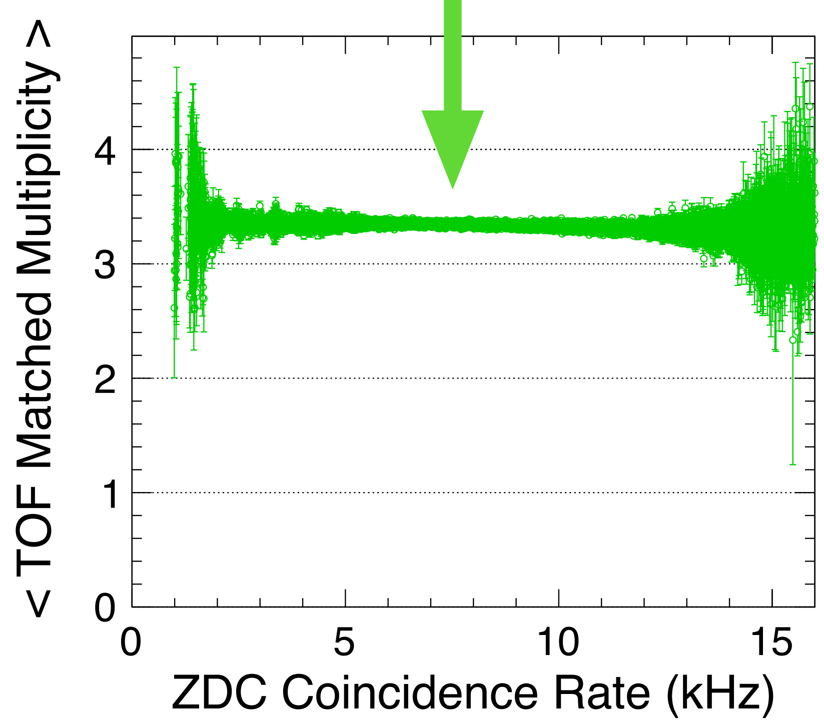
Mean corrected multiplicity

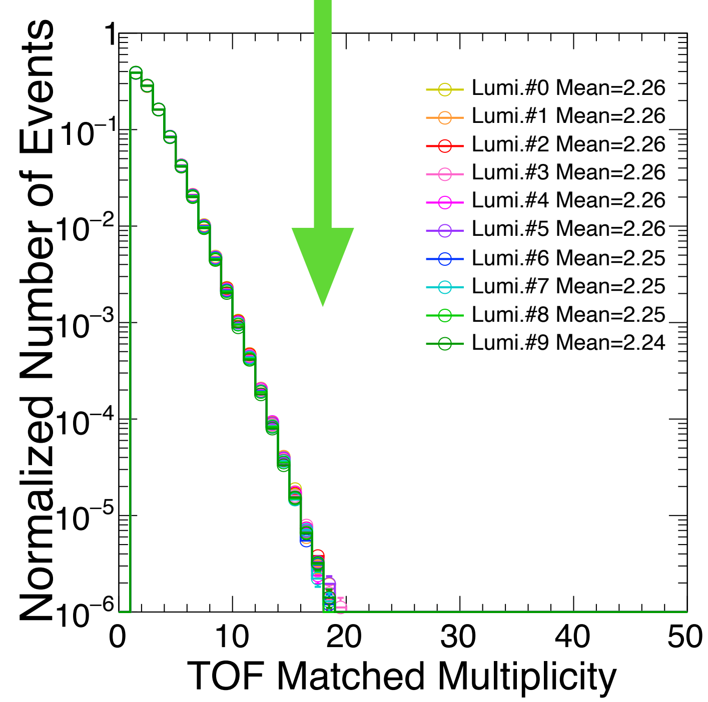






TOF matched multiplicity

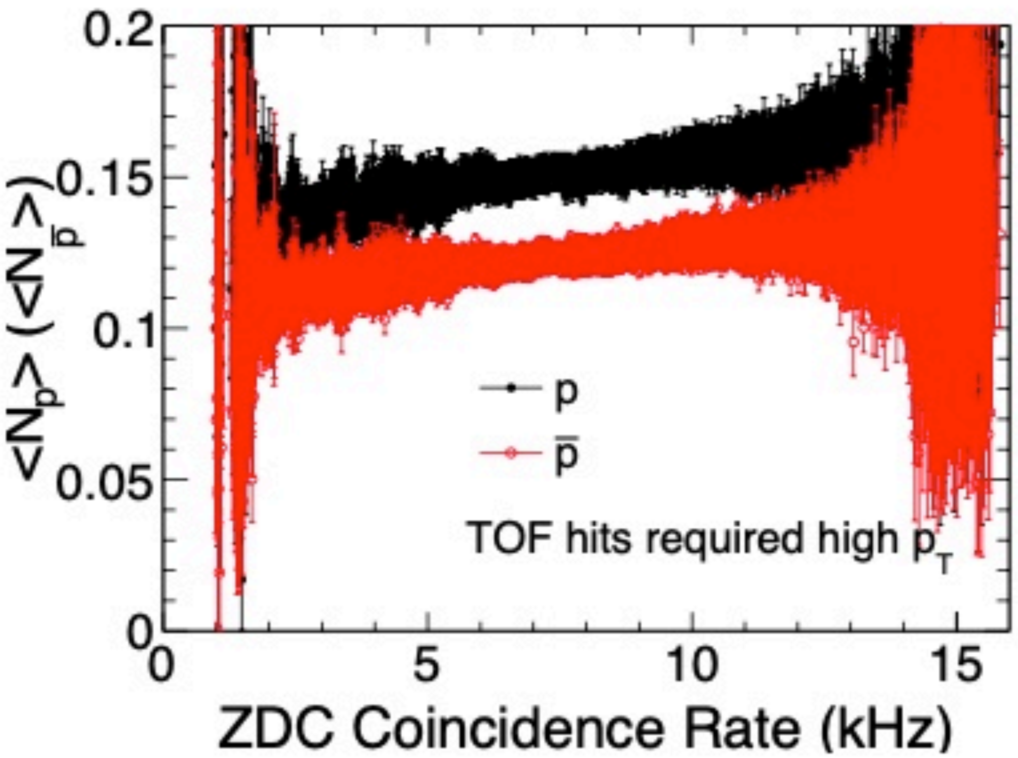




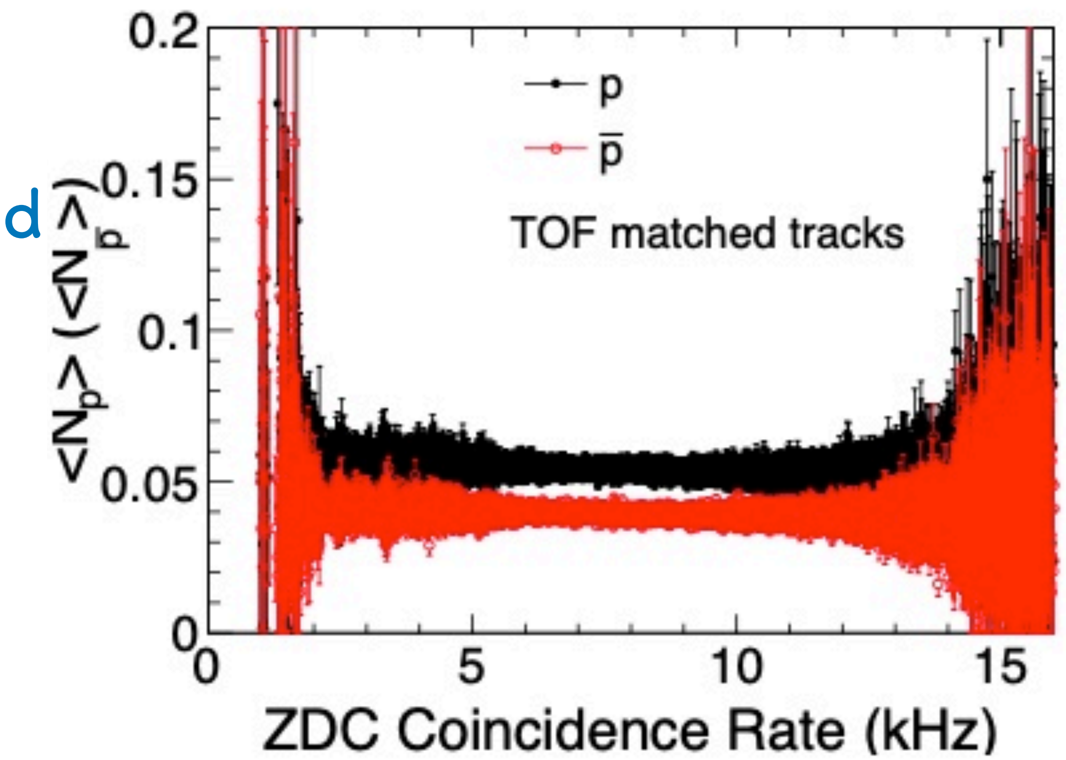
TOF matced multiplicity distributions become consistent among different luminsosity group

- ZDC coincidence rate dependence of TOF matced multiplicity become flat

TOF matched average number of (anti)protons



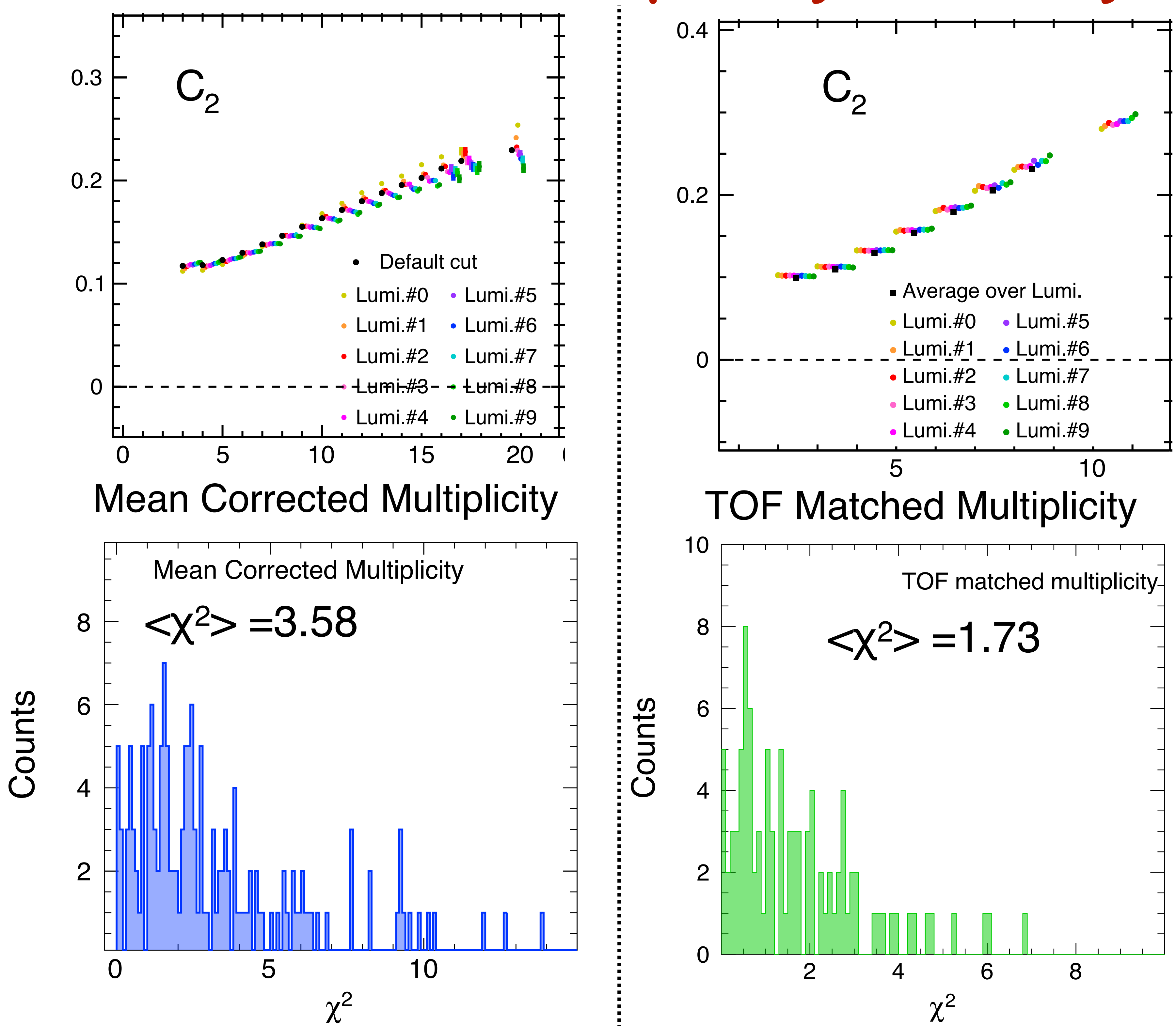
TOF matched tracks



Average number of (anti)proton becomes flat as a function of ZDC coincidence rate by requiring the TOF matching

-> TOF matching can reduce background tracks from pileup events

C_2 as a function of multiplicity in 2 way



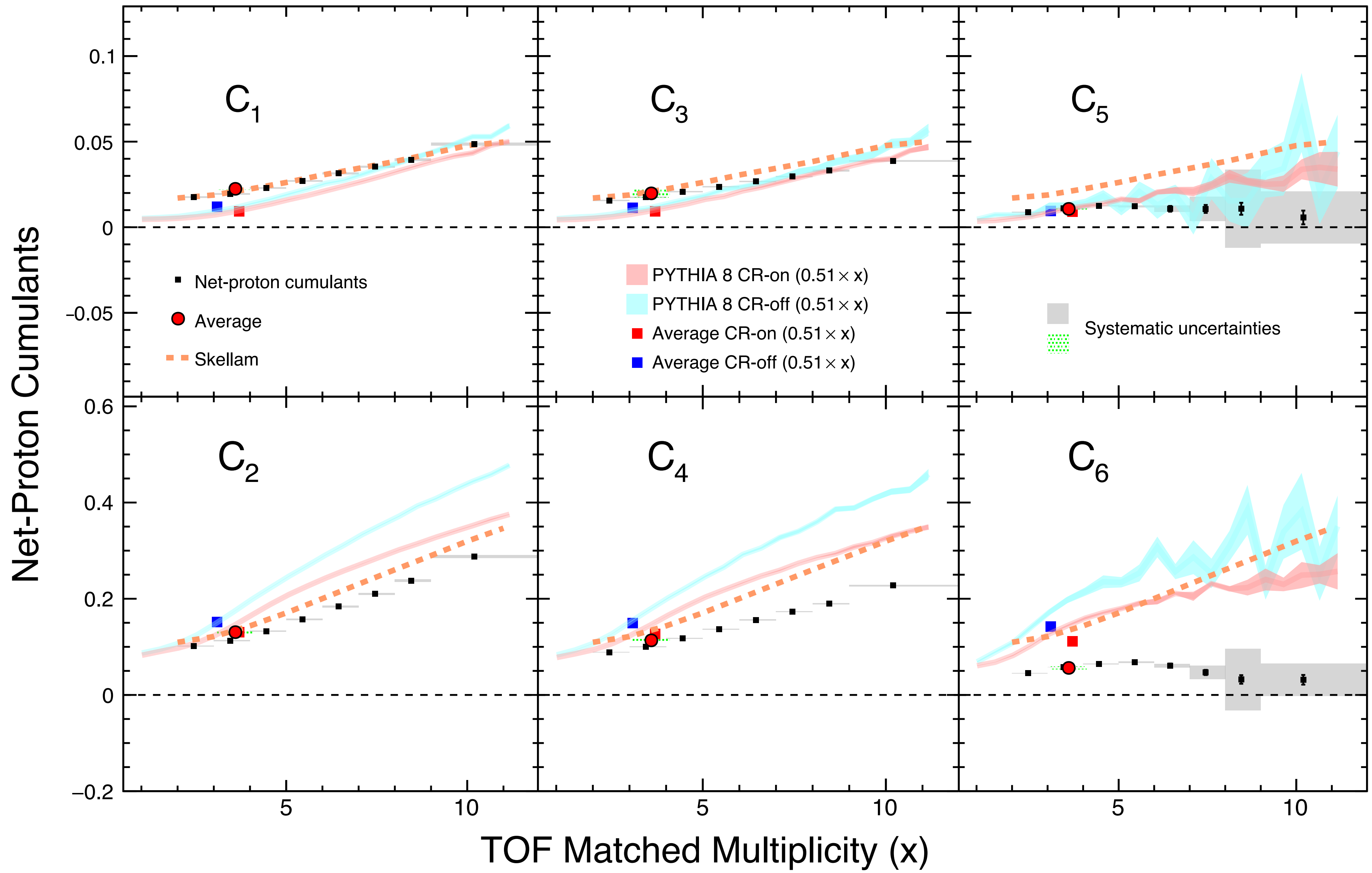
Deviations of C_2 among different luminosity groups are small in TOF matched mutiplicity

-> TOF matching multiplicity are employed

TOF matched Multiplicity dependence of net-proton cumulants

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

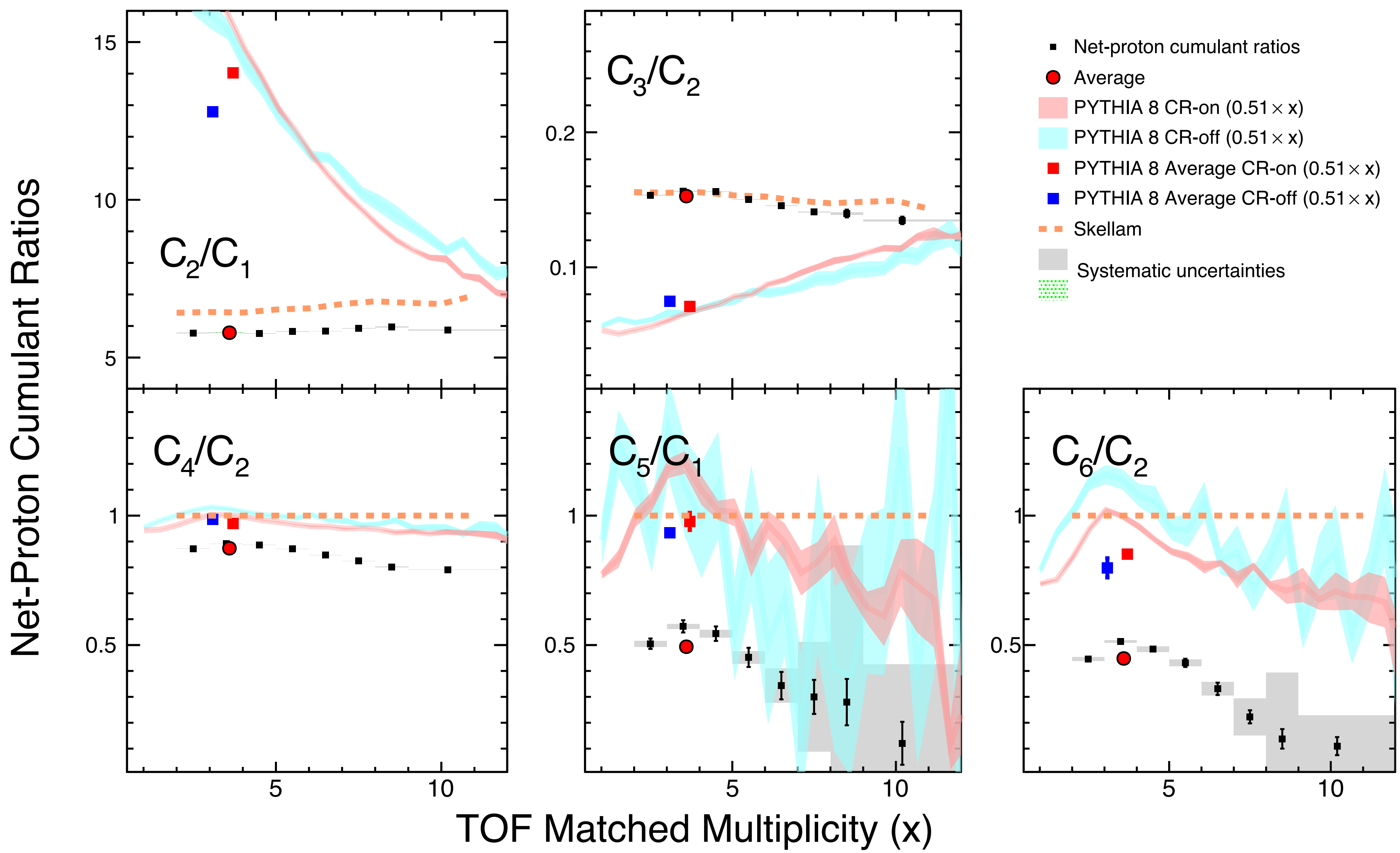
※ Skellam = $(\mathrm{Poisson})_{\mathrm{proton}}$ - $(\mathrm{Poisson})_{\mathrm{antiproton}}$



- The baseline is suppressed by baryon number conservation

TOF matched multiplicity dependence of net-proton cumulant ratios

- Decreasing trends are shown in C_4/C_2, C_5/C_1, C_6/C_2 for data & PYTHIA 8
- Deviations from Skellam become larger for higher-order



- C_4/C_2, C_5/C_1, and C_6/C_2 decrease with increasing the multiplicity
- Multiplicity dependence of PYTHIA 8 qualitatively reproduce observed C_4/C_2, C_5/C_1, C_6/C_2

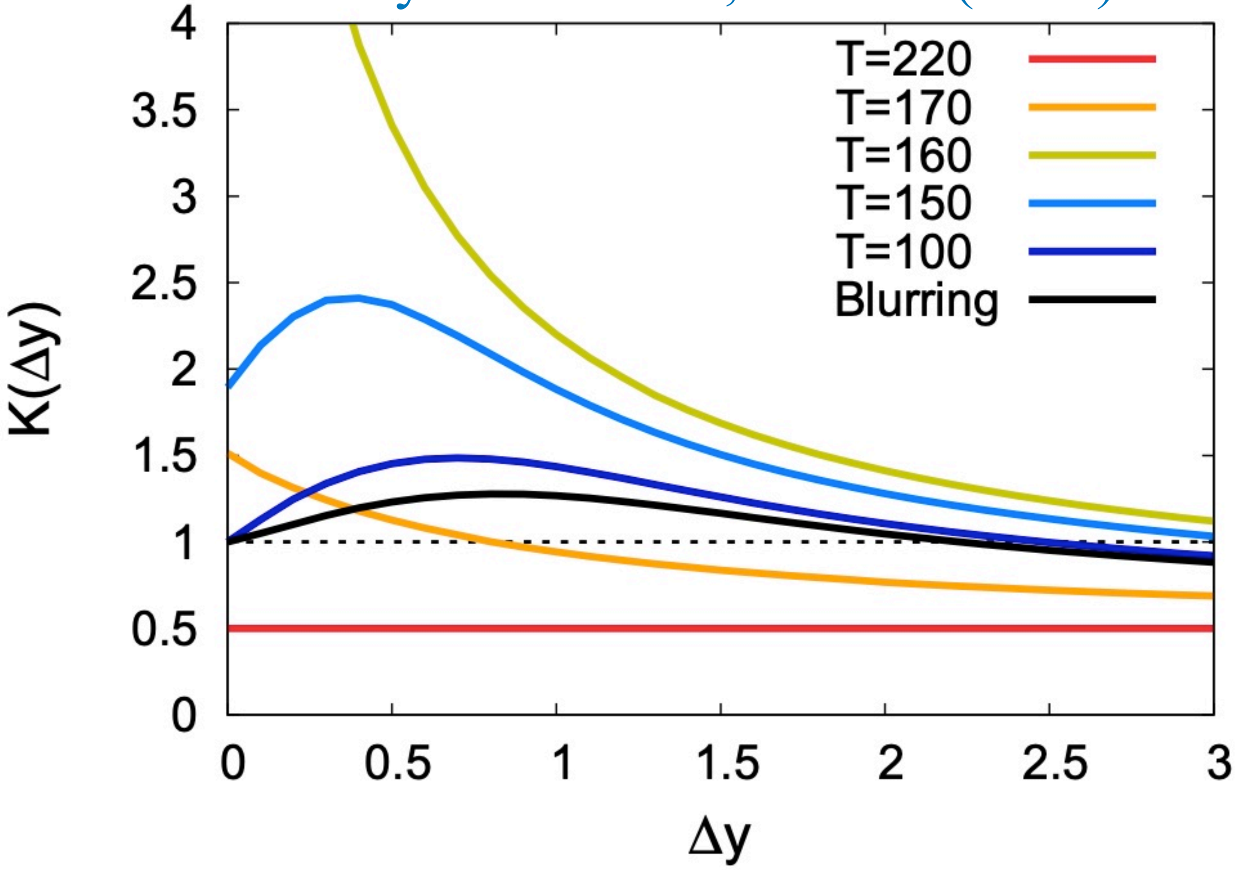
Discussion ①

Baryon number conservation effect

Rapidity acceptance dependence of cumulants

Acceptance dependence of cumulants are important to understand the time revolution of critical fluctuations near the QCD critical point in heavy ion collisions.

M. Sakaida, M. Asakawa, M. Kitazawa, Phys. Rev. C 95, 064905 (2017)



- A possibility of probing the early time fluctuations are obtained through the rapidity dependence of the second-order cumulant
- Their non-monotonic behaviors as a function of rapidity show experimental signals for the existence of the critical enhancement around the QCD critical point

Baryon number conservation effects

- The baseline is suppressed by baryon number conservation

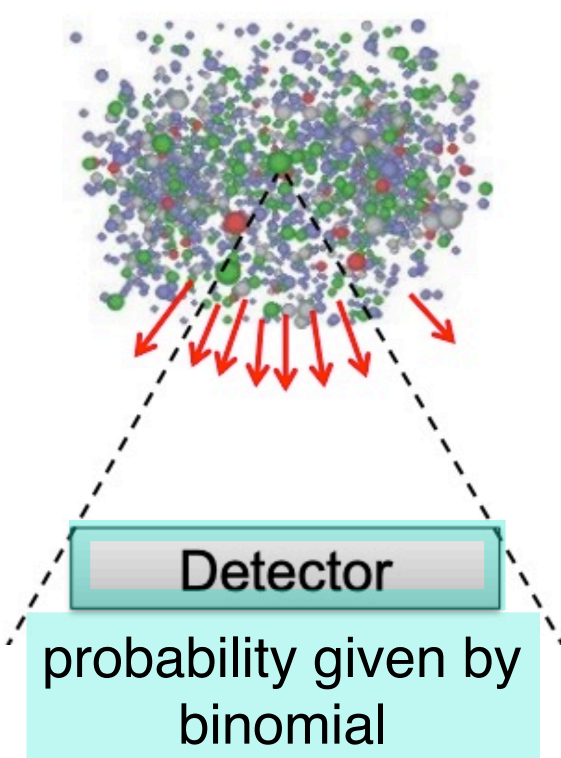
P. Braun-Munzinger et. al., Nucl. Phys. A 961 (2016)

Mean number of proton measured in small acceptance

$$p = \frac{\boxed{\langle N_p \rangle}}{\boxed{\langle N_B^{4\pi} \rangle}}$$

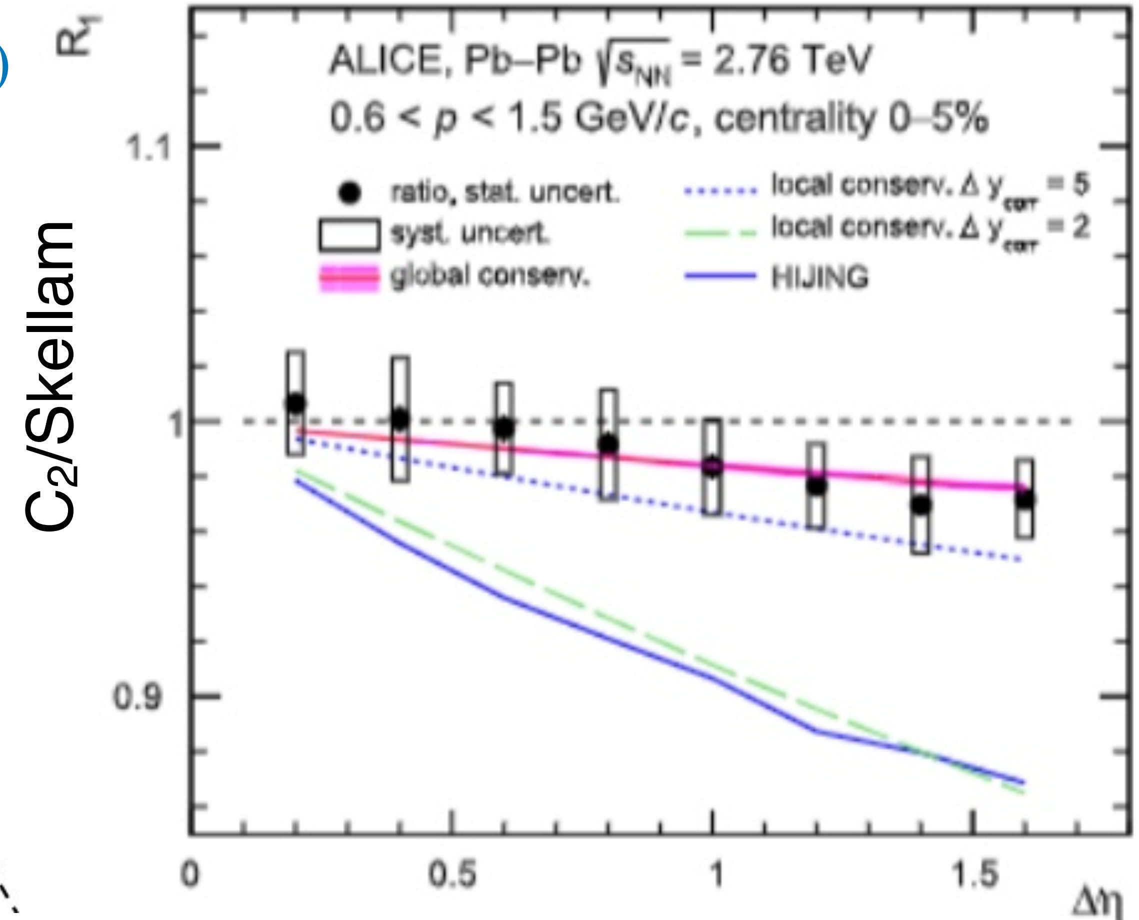
Mean number of baryon measured in full phase space

$$\frac{C_2}{\mathrm{Skellam}} = 1 - p$$



- Mean baryon number is given by PYTHIA 8

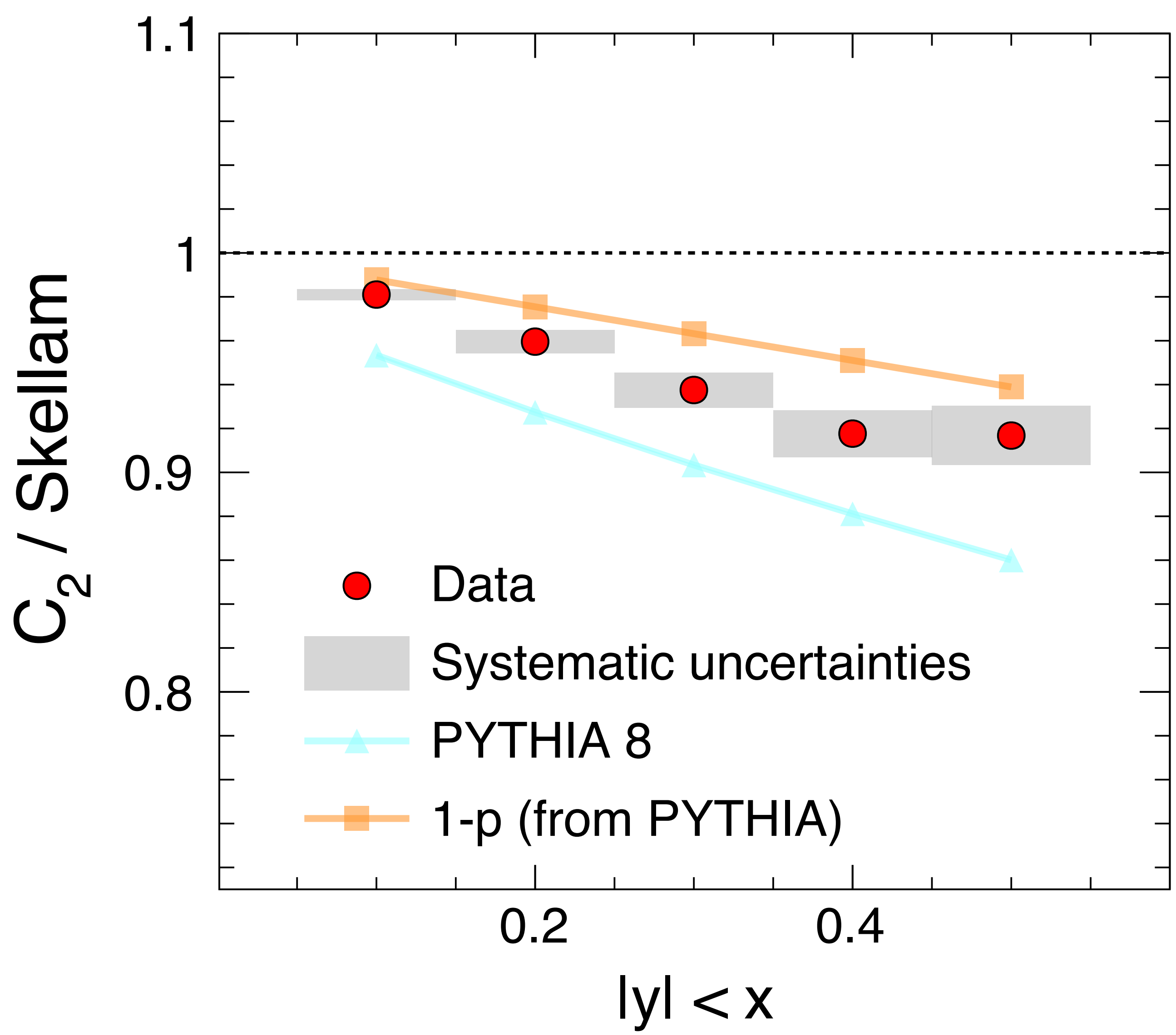
ALICE Collaboration, Phys. Lett. B 807, 10 (2020), 135564



In the ALICE experiment, measured $\Delta\eta$ dependence of C_2/Skellam for Pb+Pb are purely explained by global baryon number conservation

Baryon number conservation effects

- Rapidity acceptance dependence of C_2/Skellam



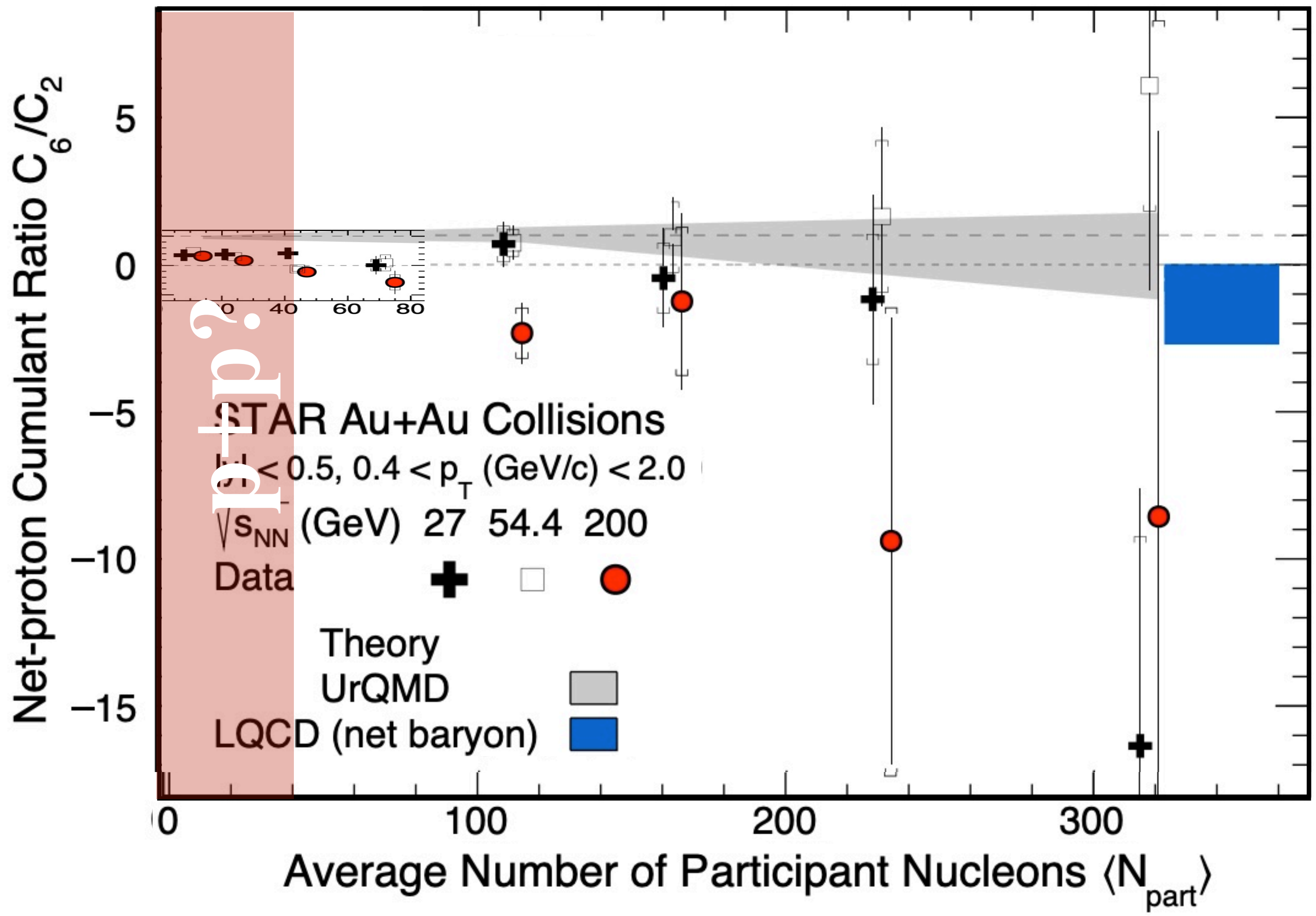
- C_2/Skellam are below 1-p at |y|>0.1
- PYTHIA 8 do not reproduce measured results
- Observed deviation can not be explained only by baryon number conservation effect

Discussion ②

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

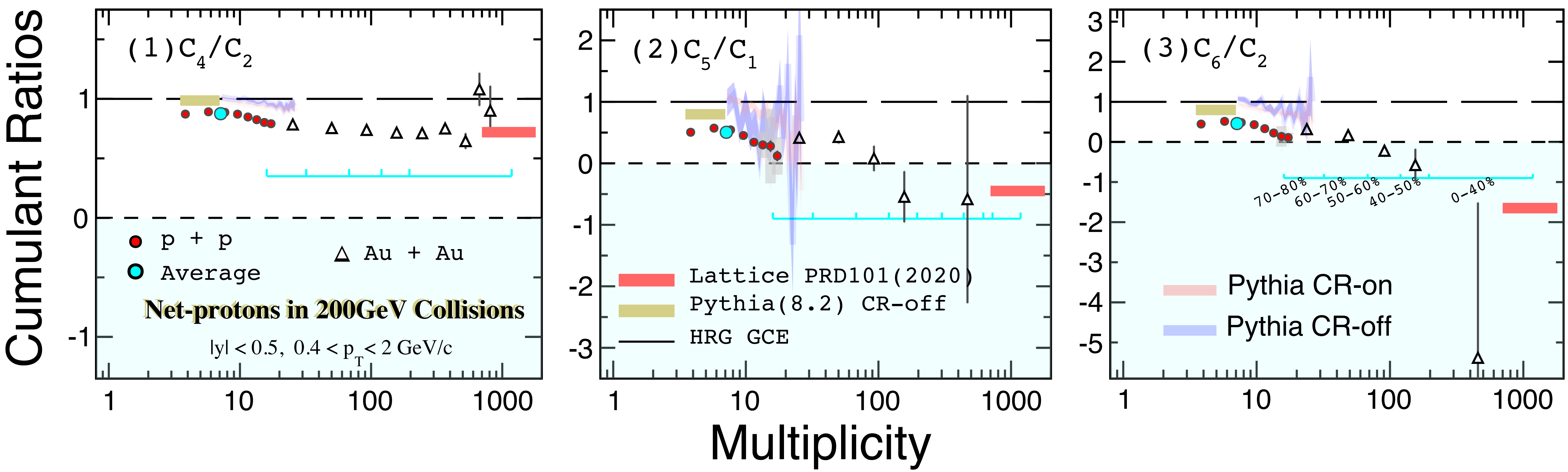
Comparison between p+p and Au+Au collisions at 200 GeV

Check the possibility of phase transition in high multiplicity events in p+p collisions through the measurements of higher-order cumulants



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

- The trends from p+p collisions fit into the centrality dependence of Au+Au collisions
- C_5/C_1 and C_6/C_2 < 0 for Au+Au central collisions
- C_5/C_1 and C_6/C_2 > 0 for p+p collisions, while they decrease and show small value at high multiplicity



- Only statistical errors are shown for Au+Au results

Au+Au: STAR, Phys.Rev.C 104, 024902 (2021),
C_6/C_2: M. S. Abdallah, et.al., Phys. Rev. Lett. 127, 262301 (2021)

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

Summary

Goal of this study:

Precise determination the physics baseline
+ Check the possibility of phase transition in high multiplicity events
in p+p collisions through the measurements of higher-order cumulants

p+p 200GeV -> $C_6/C_2 > 0$

Au+Au 200GeV -> $C_6/C_2 < 0$
Lattice QCD -> $C_6/C_2 < 0$

Signal of the QCD phase transition <u>was not observed</u>
for p+p 200GeV collisions.
However, the decreasing trend in high multiplicity events
hints the negative C6/C2.

The measurements at higher collision energies
or larger colliding system will be important

Backup

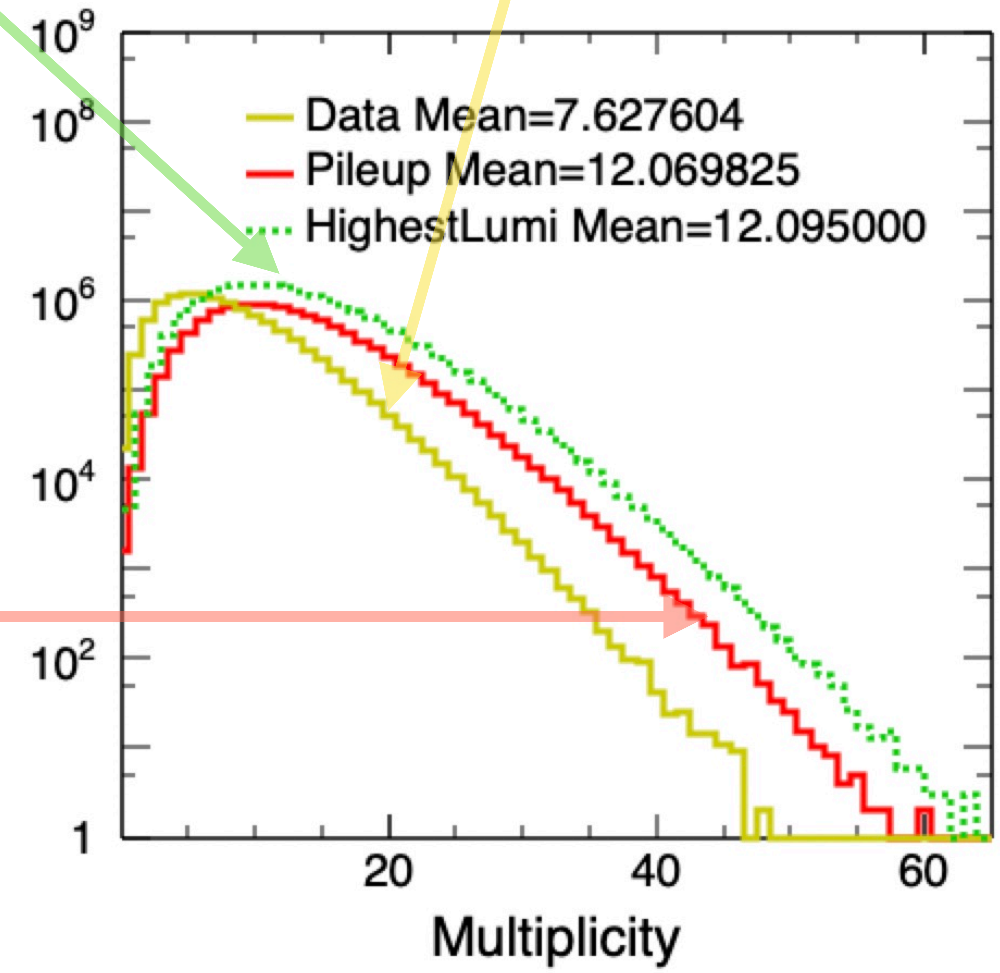
- Effect of pileup events

The pileup events are included in the cumulant calculations.
In this study, we tried to understand the effect of pileup events by modeling a "pileup-filter" based on the data

Explain the multiplicity distributions with pileup model

We have tried to model a pileup filter to describe the multiplicity distributions for the highest luminosity based on the lowest luminosity

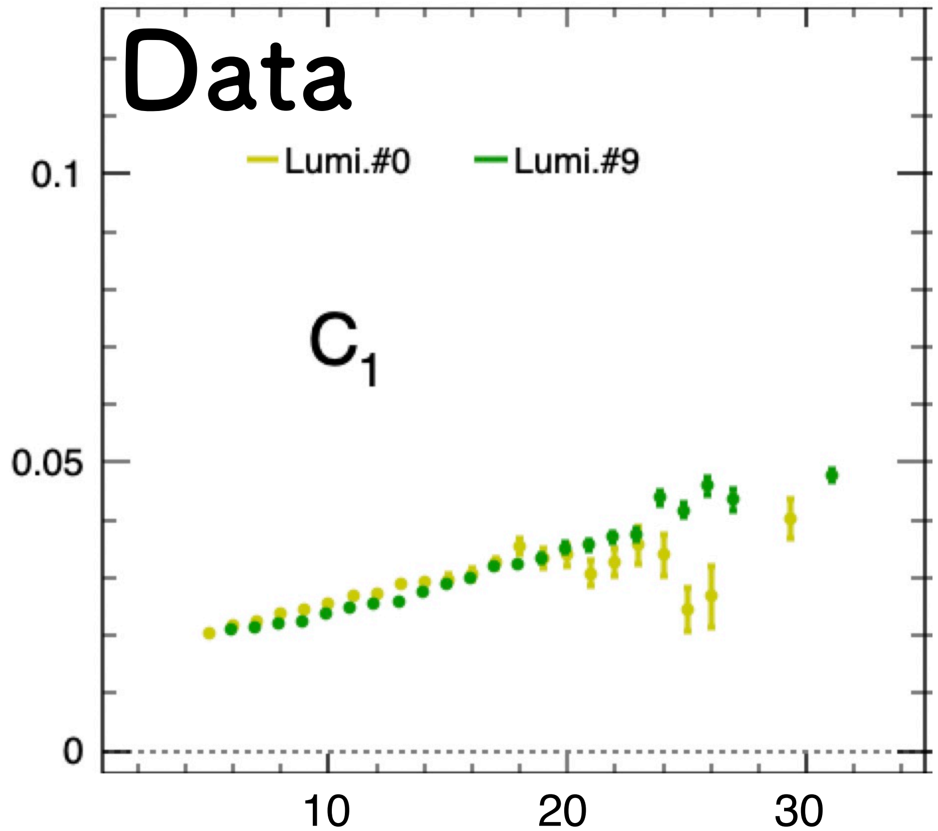
- Lowest luminosity events are divided into two sub-groups
- Two(three) events are randomly picked up from each sub-group with the probability α (β), and they are superimposed
- Parameters α=0.89, β=0.11 can explain the highest luminosity

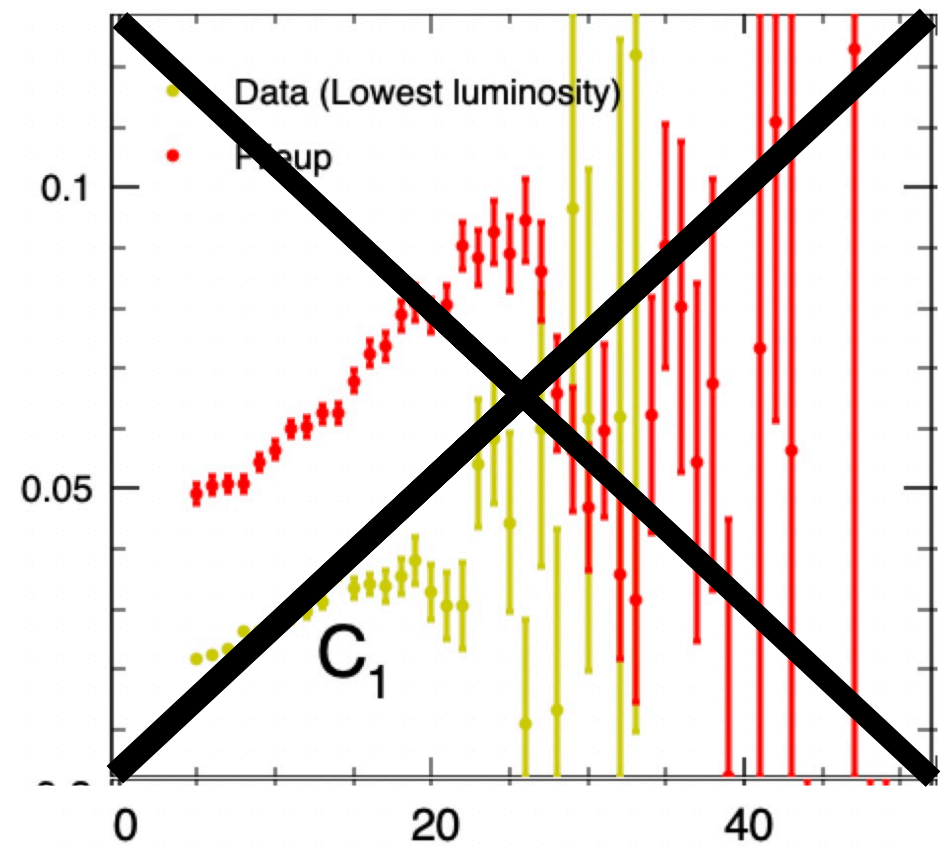


The effect of pileup events on cumulants can be studied by using the pileup filter

Filter on p/pbar

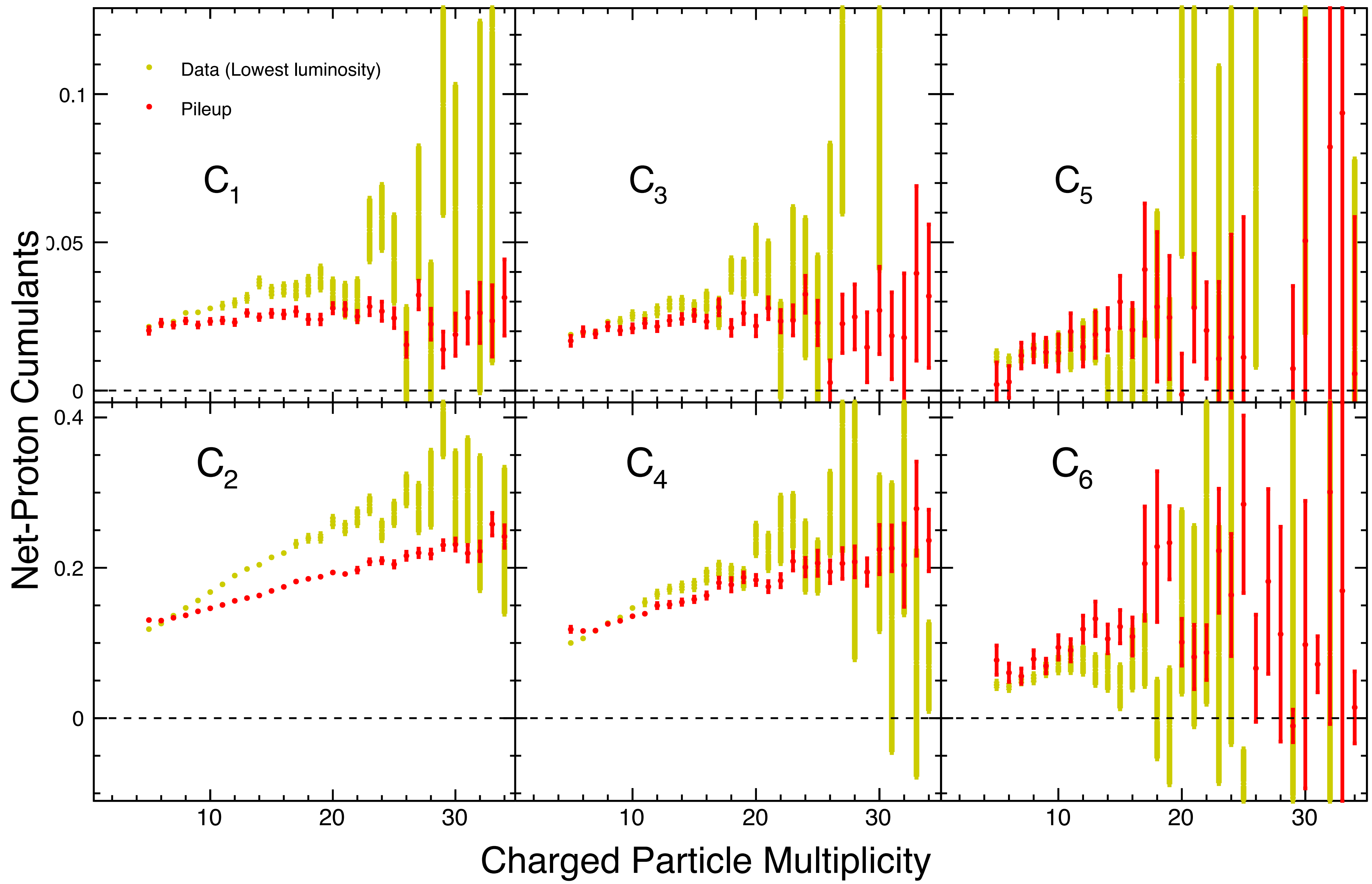
- Once the pileup filter is applied to the number of p/pbar as done for the multiplicity, the value of C_1 is doubled by construction
- On the other hand, such a significant difference is not observed in the data





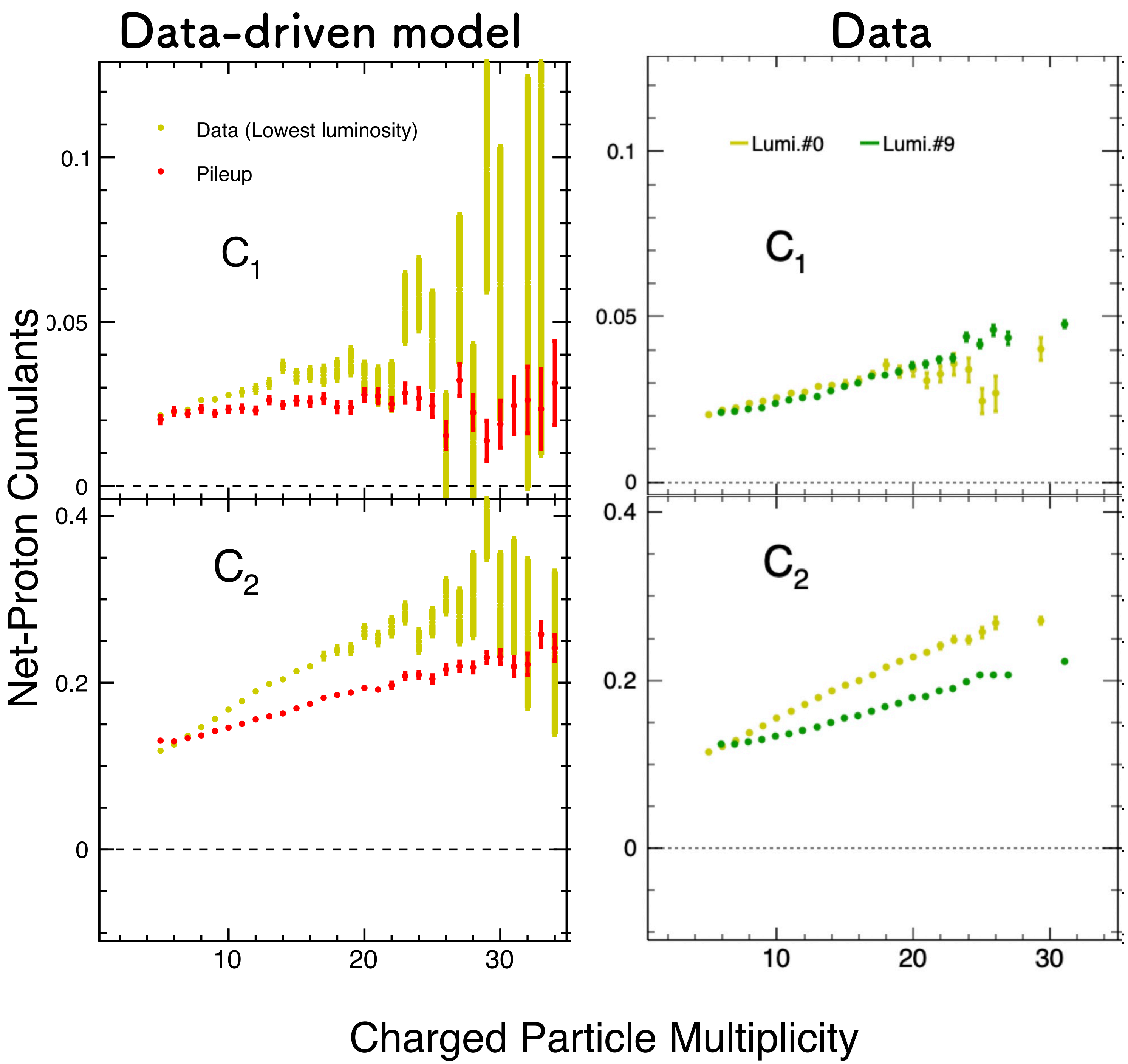
- The pileup filter is NOT applied to p/pbar.

Data-driven model



- C_1 : the “pileup-filtered” data show smaller value than the lowest luminosity’s data
- C_2 : Two datas cross and they show the larger deviations than the other orders of cumulants

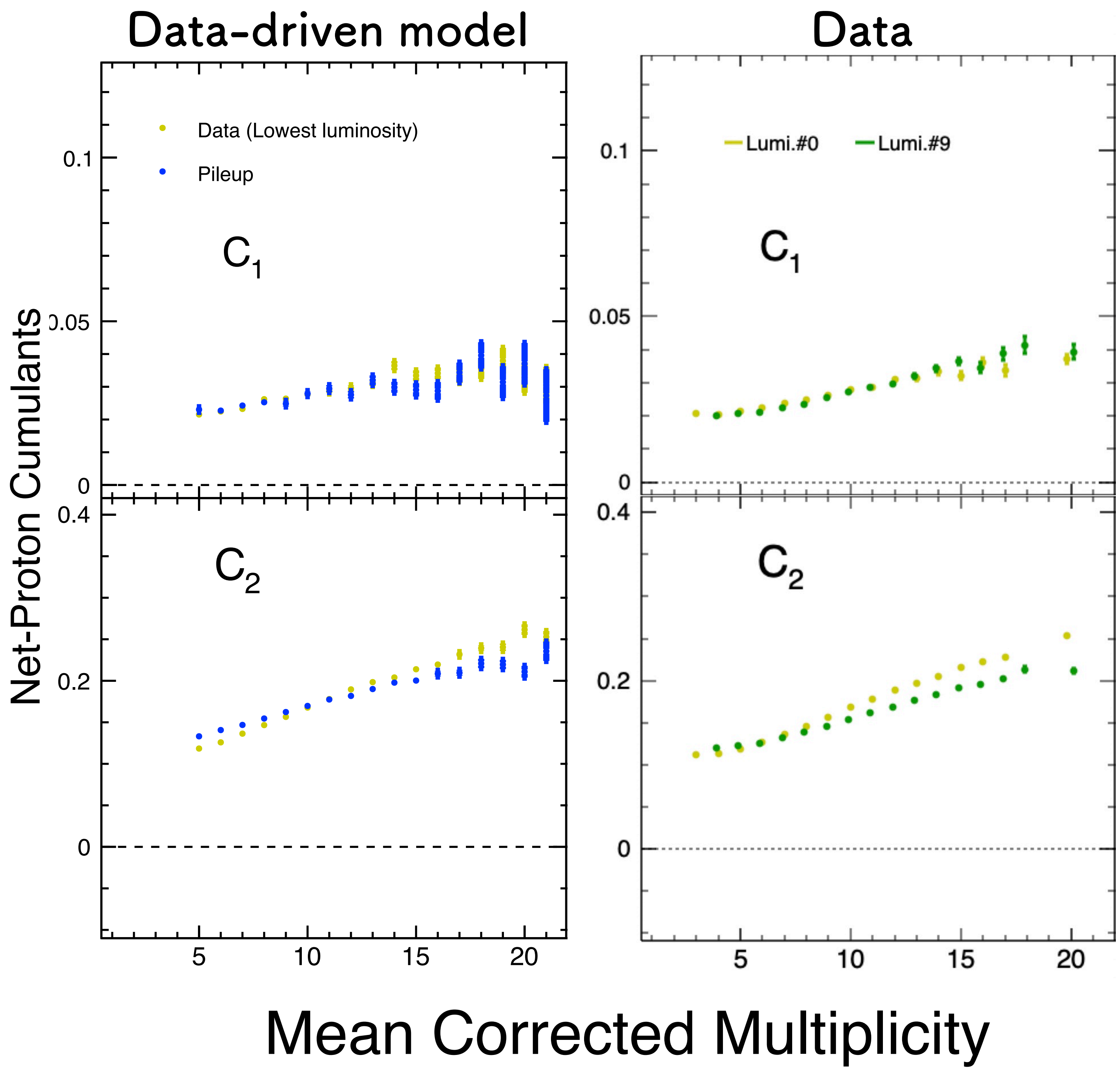
Data vs Data-driven model



Data and data-driven model are qualitatively consistent in terms of:

- crossing point
- high lumi. < low lumi.
- largest deviation in C_2

Data vs Data-driven model



Data and data-driven model are qualitatively consistent in terms of:

- crossing point
- high lumi. < low lumi.
- largest deviation in C_2

↓

For the results up to C_2,

Results are consistent between low lumi. and high lumi. after the mean correction for both data & model

The pileup effect can be reasonably suppressed by the mean correction even if the pileup events cannot be excluded