Cumulants of net-proton number in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE

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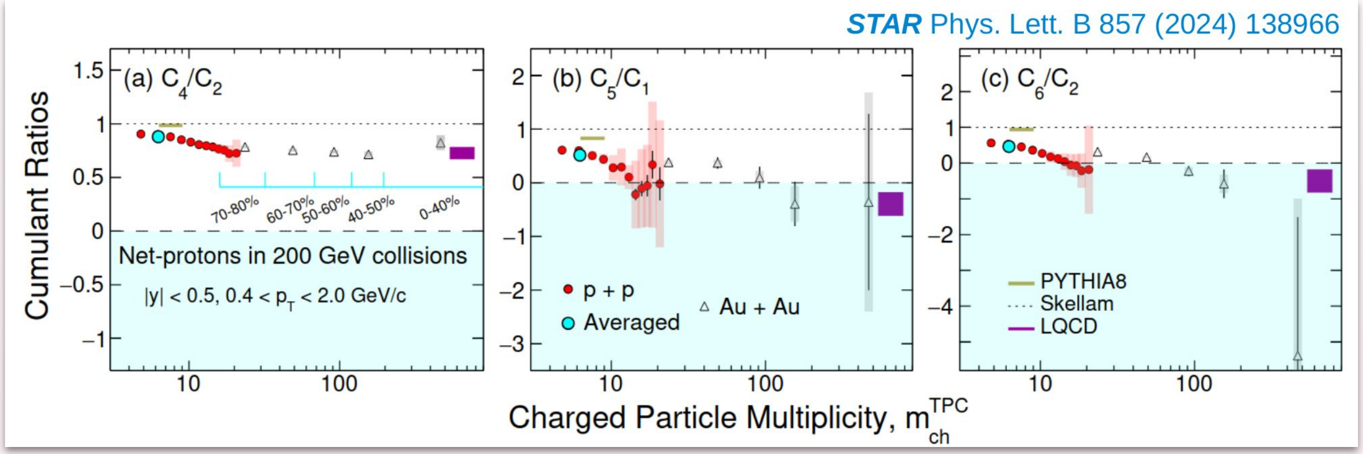
INDIA - ALICE - STAR collaboration meeting: July 1-4, 2025

Variable Energy Cyclotron Centre (VECC), Kolkata

Analysis note: https://alice-notes.web.cern.ch/node/1625

Motivation

- High-multiplicity pp collisions exhibit QGP-like features similar to those observed in heavy-ion collisions.
- Net-proton cumulant ratios for high multiplicity pp at RHIC → approaching lattice QCD (LQCD) predictions.



Net-proton cumulants are experimental proxies of net-baryon number susceptibilities in LQCD

$$\chi_B^n \equiv \frac{\partial^n (p/T^4)}{\partial(\mu_B/T)^n} = \frac{\kappa_B^n}{VT^3}$$

We aim to explore these cumulants in pp collisions at the LHC for possible signs of QCD medium effects.

Observable

❖ Cumulants (C or κ) of the distribution of *N* are:

$$\kappa_1 = \langle \delta N \rangle,$$
$$\kappa_2 = \langle (\delta N)^2 \rangle,$$
$$\kappa_3 = \langle (\delta N)^3 \rangle,$$
$$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2,$$
$$\kappa_5 = \langle (\delta N)^5 \rangle - 10\langle (\delta N)^3 \rangle \langle (\delta N)^2 \rangle,$$
$$\kappa_6 = \langle (\delta N)^6 \rangle - 15\langle (\delta N)^4 \rangle \langle (\delta N)^2 \rangle - 10\langle (\delta N)^3 \rangle^2 + 30\langle (\delta N)^2 \rangle^3.$$

$$\delta N = N - \langle N \rangle$$

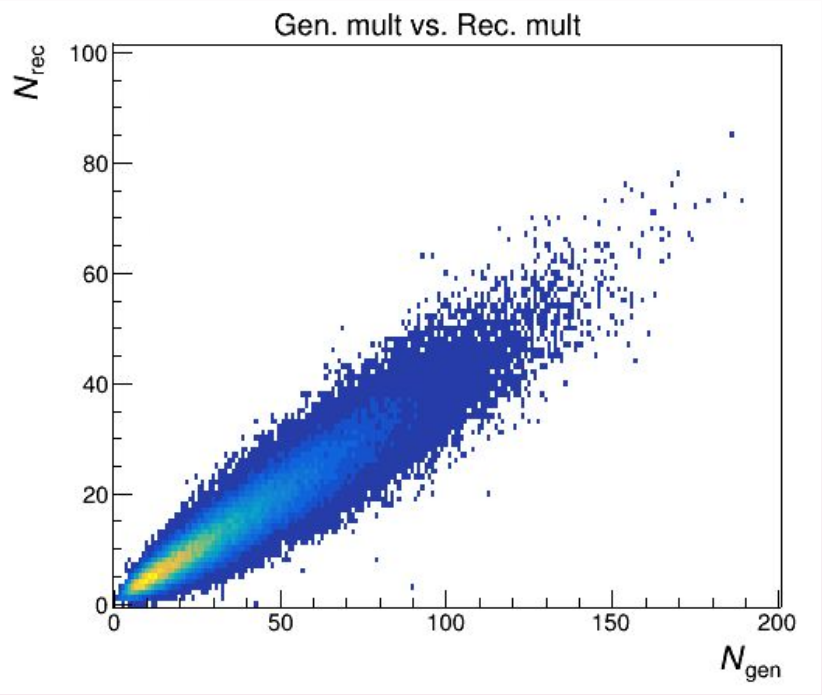
N is the difference between proton and antiproton number in an event

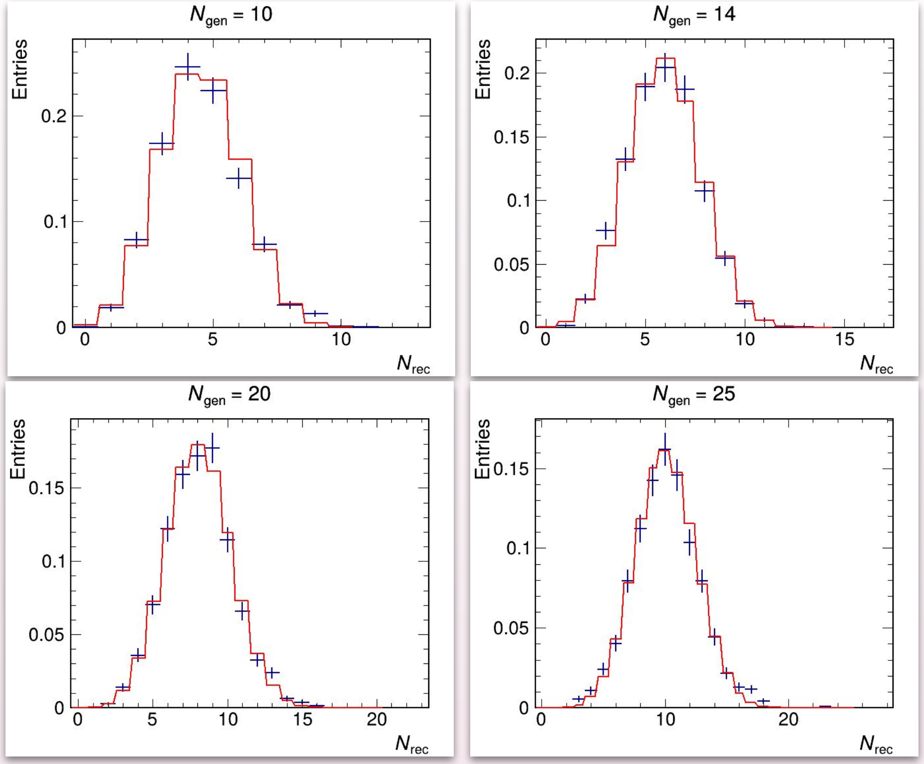
<..> → event-average

❖ Cumulants are corrected for efficiencies considering Binomial model of detector response.

T. Nonaka et al., *Phys. Rev. C* 95, 064912 (2017)
X. Luo et al., *Phys. Rev. C* 99, 044917 (2019)

Binomial response of detector





- The distribution of the number of reconstructed particles for fixed number of generated particles are obtained in MC.
- Fit with Binomial distribution function ⇒ good agreement ensures **binomiality of detector response**

Dataset and analysis cuts

- **System: pp collisions at $\sqrt{s}$ = 13.6 TeV (Run3)**
  - Data: LHC22o_pass7_minBias
    - – (~5.6 B events after event selection)
  - MC: LHC24f3c (Pythia)
    - – (~58 M events after event selection)

- **Event selection:**
  - $|V_z| < 10$ cm
  - Minimum bias
  - Multiplicity percentile estimator: FT0M

- **Track selection:**
  - kGlobalTrack
  - One hit on all the 7 ITS layers
  - $|DCA_{xy}| < 0.0105 + 0.035 / p_T^{1.1}$
  - $|DCA_z| < 0.2$ cm
  - No. of TPC cluster > 80
  - No. of ITS cluster > 5
  - $0.4 < p_T$ (GeV/c) < 1.0
  - $|\eta| < 0.8$

PARTICLE IDENTIFICATION

$0.4 < p_T$ (GeV/c) < 0.8

If no TOF information for the track, track is selected if

➔ $|n\sigma_{TPC}(\text{proton})| < 2$

If TOF information available for the track, track is selected if

➔ $|n\sigma_{TPC}(\text{proton})| < 2$ && $|n\sigma_{TOF}(\text{proton})| < 2$

p_T (GeV/c) > 0.8

If track has TOF information, track is selected if

➔ $n\sigma_{combined}(\text{proton}) < 1$ &&

➔ $n\sigma_{combined}(\text{proton}) < n\sigma_{combined}(\text{pion})$ &&

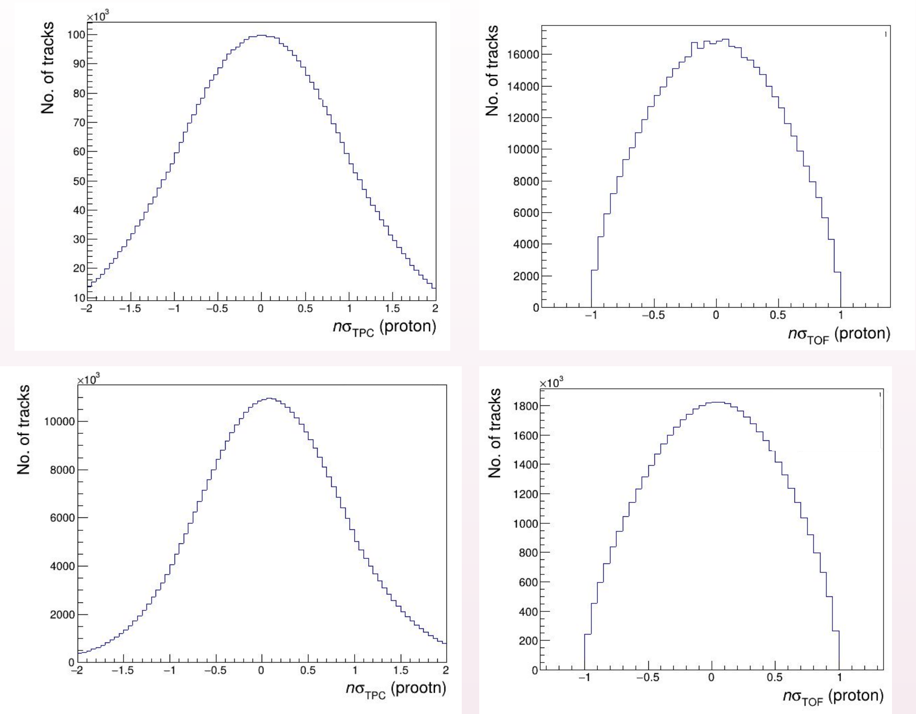
➔ $n\sigma_{combined}(\text{proton}) < n\sigma_{combined}(\text{kaon})$

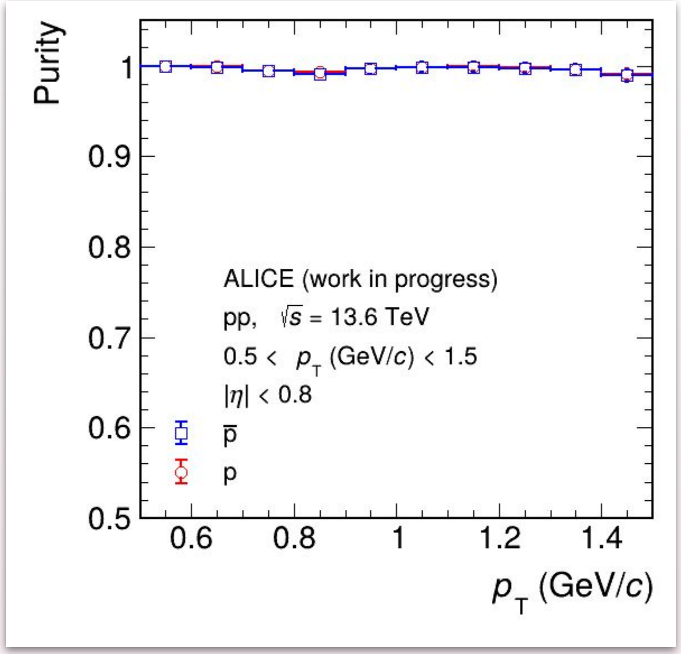
$$n\sigma_{combined} = \sqrt{(n\sigma_{TPC}^2 + n\sigma_{TOF}^2)}$$

Purity of protons and antiprotons

MC

Data



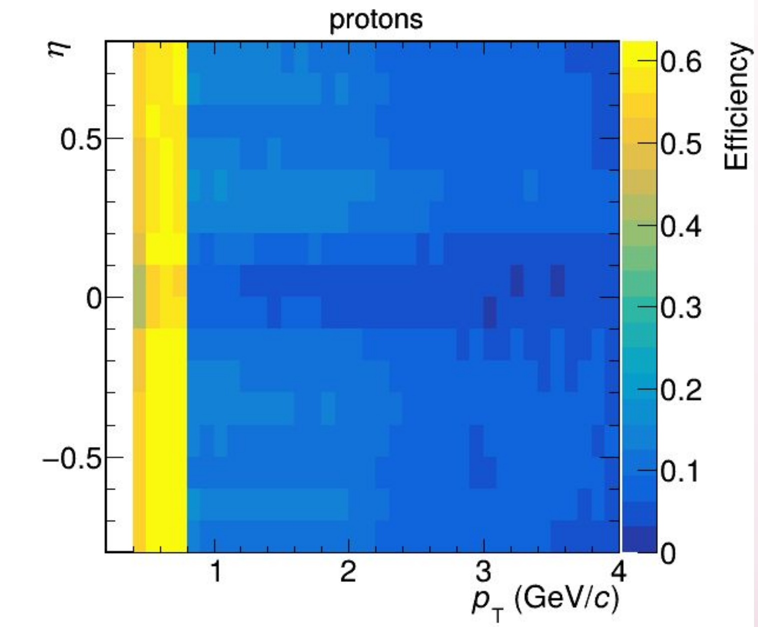


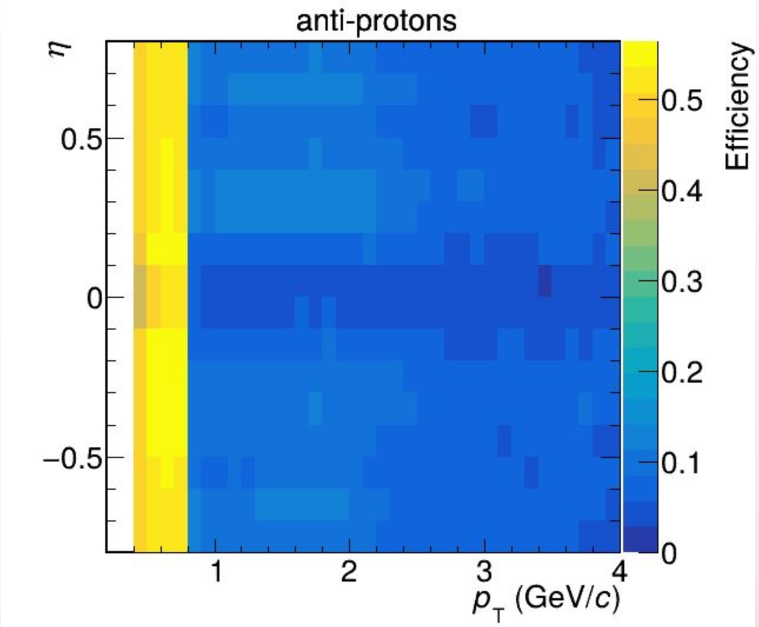
❖ Purity of protons and antiprotons across all p_T bins is > 99%

Efficiency of protons and antiprotons

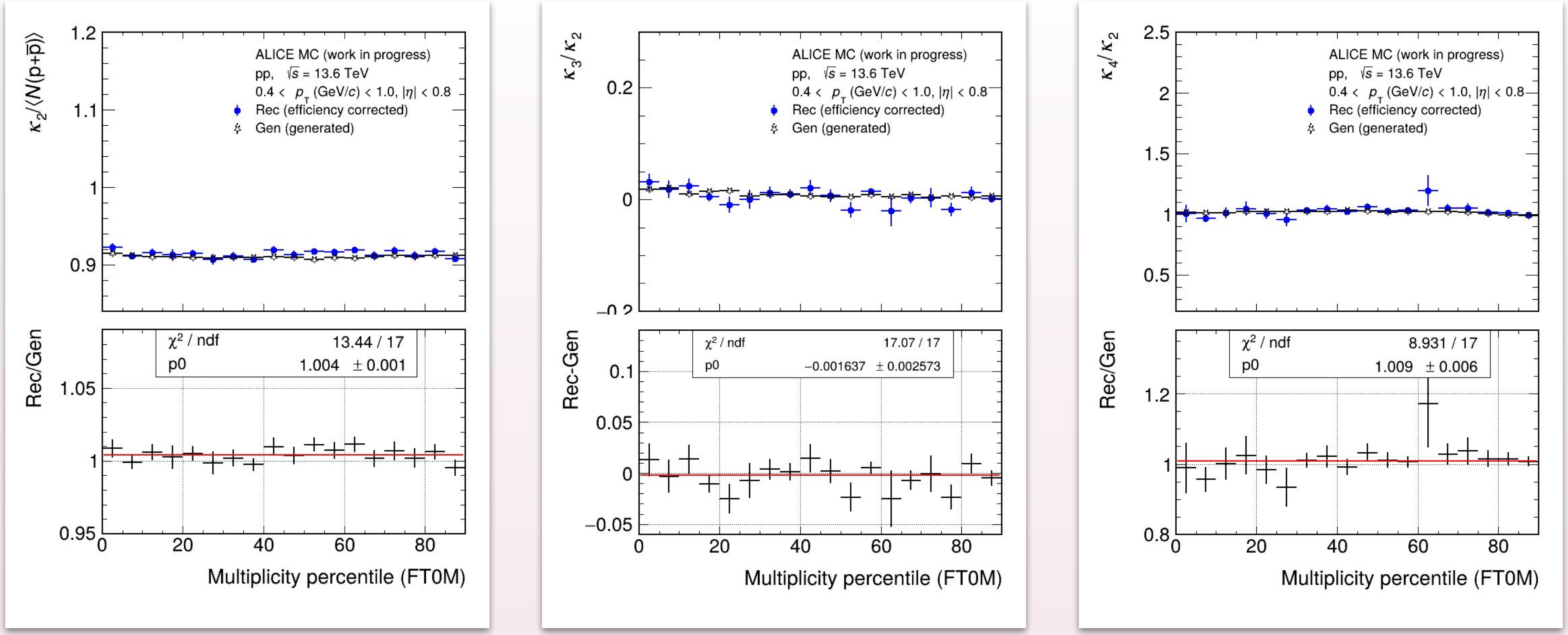
★ Two-dimensional efficiency maps are obtained as functions of p_T and η, for protons and antiprotons to correct the cumulants.

$$\epsilon(p_T, \eta) = \frac{N_{\text{reconstructed}}(p_T, \eta)}{N_{\text{generated}}(p_T, \eta)}$$





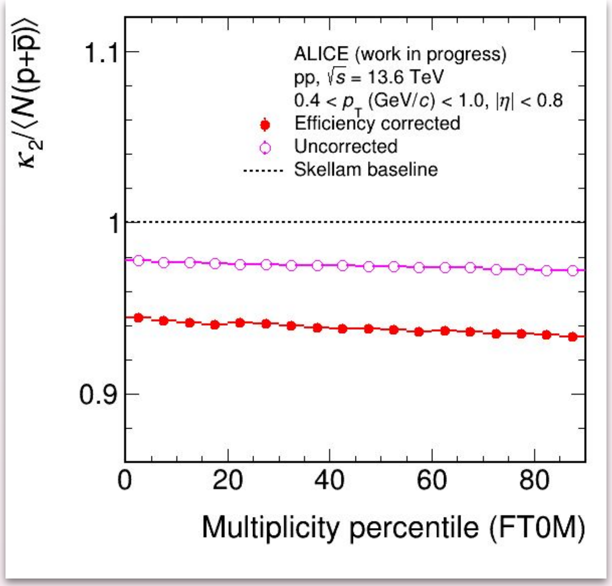
MC Closure of cumulant ratios

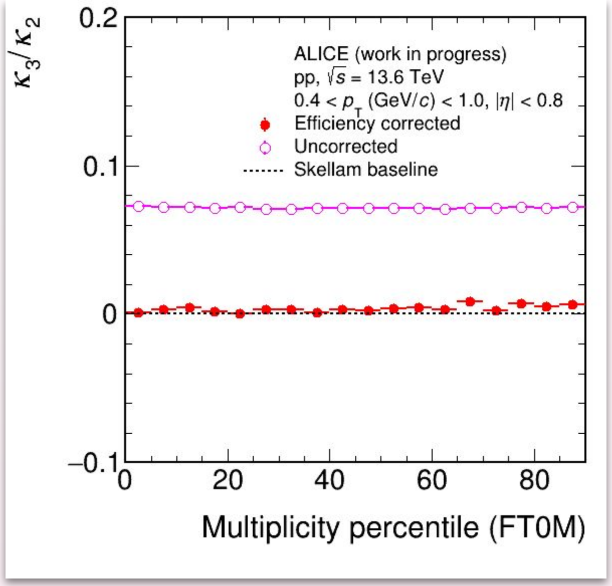


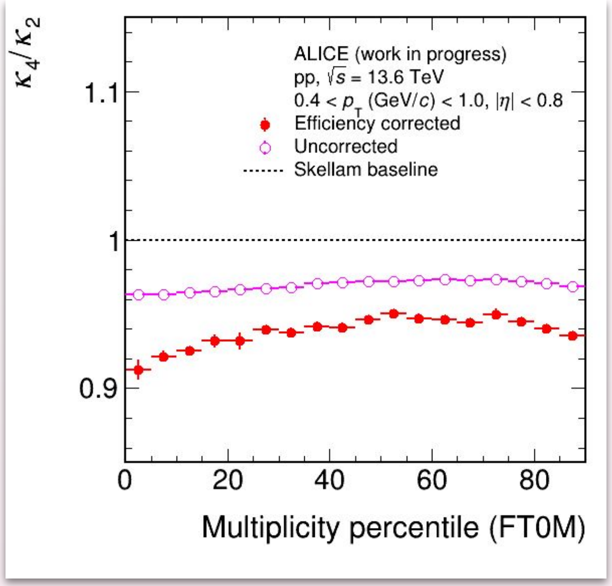
- ❖ Generated and efficiency corrected results of cumulant ratios in MC are consistent within uncertainties.

Net-proton cumulants ratios vs. FT0M percentile

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$
net-proton (proxy of net-baryon)





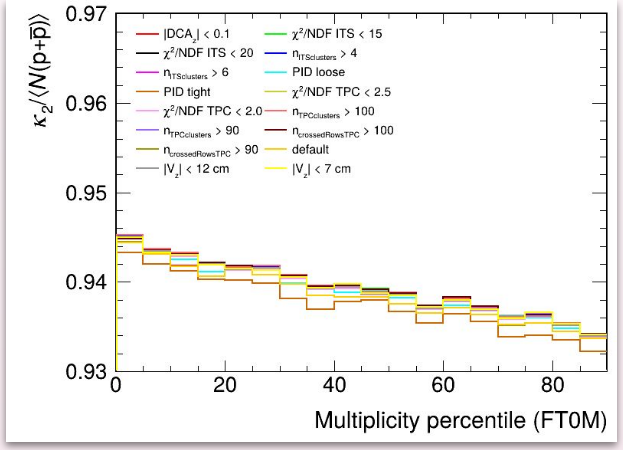


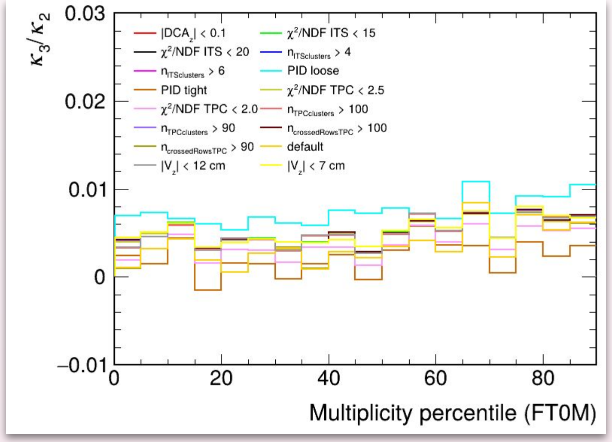
- ❖ Raw and efficiency corrected cumulants as a function of FT0M multiplicity (%) in data.
- ❖ Only statistical uncertainties are shown (Subsampling method, no of samples =10)

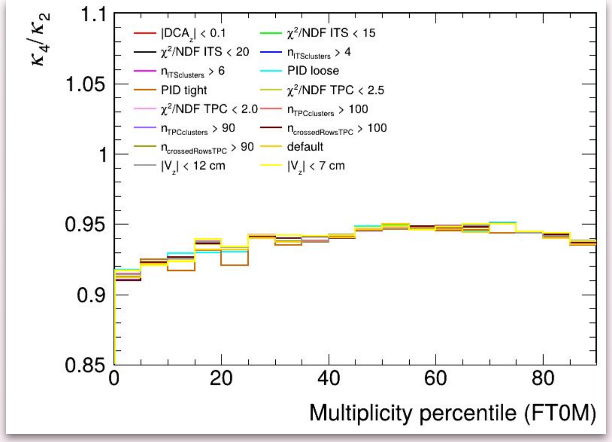
Systematic variations

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$
net-proton (proxy of net-baryon)

Analysis selection	DCA_z (cm)	χ^2/NDF ITS	χ^2/NDF TPC	No. of ITS clusters	No. of TPC clusters	VertexZ (cm)	PID ($n\sigma$) (TPC, TOF, combined)	No. of TPC crossed-rows
Default	0.2	36	4	5	80	10	(2.0, 2.0, 1.0)	70
Variations	0.5, 0.1	20, 15	2, 2.5	4, 6	100, 90	7, 12	(2.5, 2.5, 1.5), (1.5, 1.5, 0.8)	90, 100



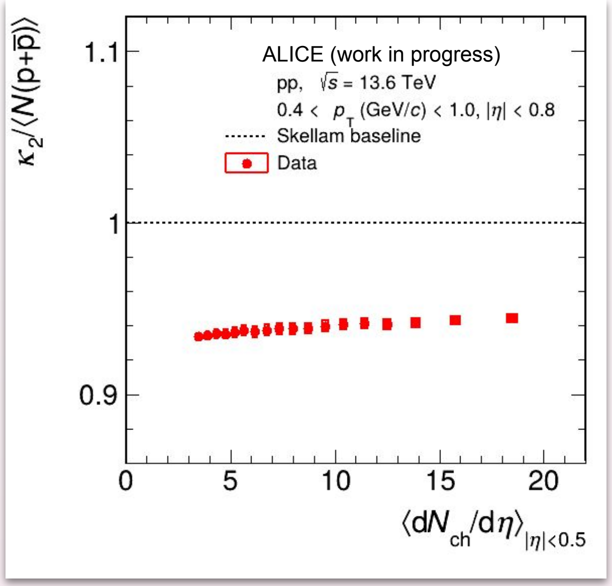


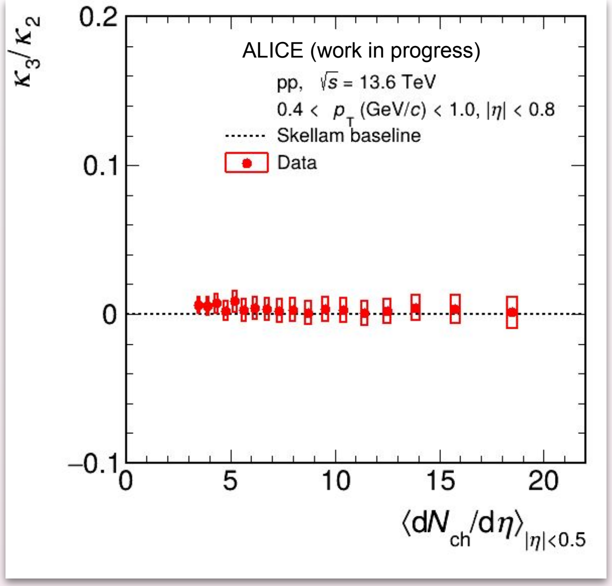


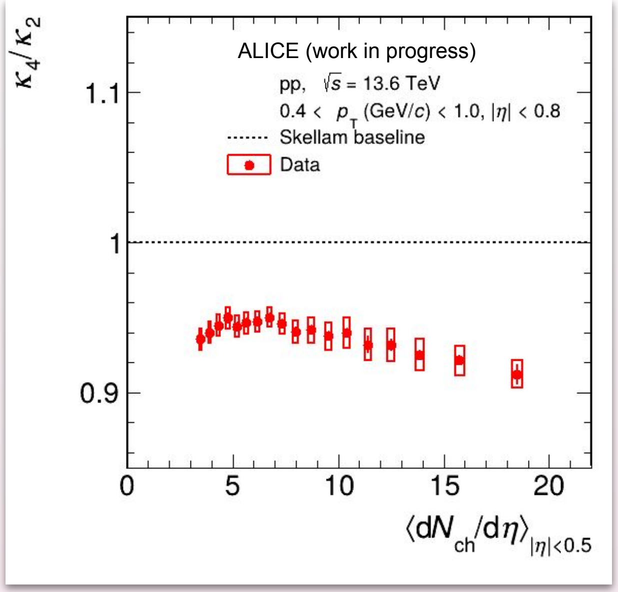
❖ The default selections are varied systematically and the cumulant ratios are calculated for each case.

Results as a function of multiplicity

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$
net-proton (proxy of net-baryon)



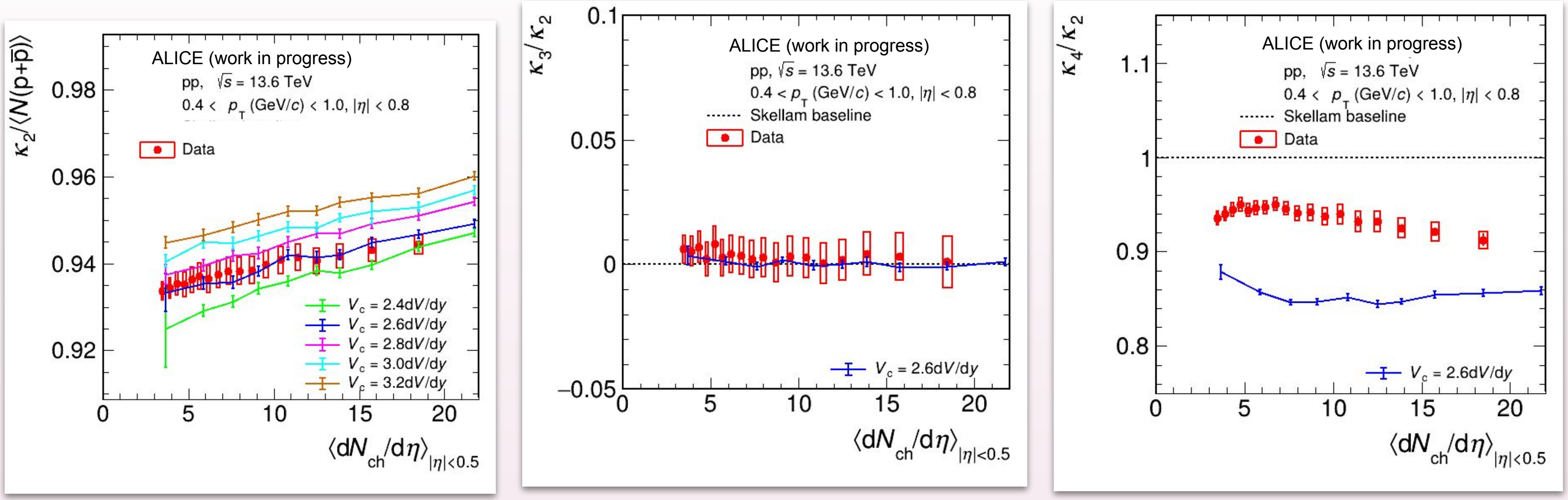




- The cumulants are shown as a function of <dNch/dη>, taken from https://alice-publications.web.cern.ch/node/10934.
- Second- and fourth-order cumulant ratios show deviation from the Skellam baseline, while the third-order ratio remains consistent.

Comparison with thermal model

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$
net-proton (proxy of net-baryon)



- Compared to Thermal-FIST predictions using BW parameters of pp 13 TeV, https://arxiv.org/pdf/2003.02394.
- Second and third order cumulants agree with ThermalFIST predictions with V_c = 2.6dV/dy.
- Fourth-order shows deviation from ThermalFIST model.

Summary

- We presented the efficiency corrected net-proton cumulant ratios upto 4th order as a function of FT0M in pp collisions at $\sqrt{s}$ = 13.6 TeV.
- Current results are limited to $0.4 < p_T < 1.0$ GeV/c based on PID using TPC and TOF only.
- $\kappa_2/\kappa_{2,\mathrm{skellam}}$ and κ_4/κ_2 are positive and shows deviation from Skellam expectations, while κ_3/κ_2 is consistent with Skellam within uncertainties.
- Thermal-FIST model describes second and third order cumulant ratios with a correlation volume of $V_c = 2.6 \mathrm{d}V/\mathrm{d}y$, while deviations exist in fourth order.

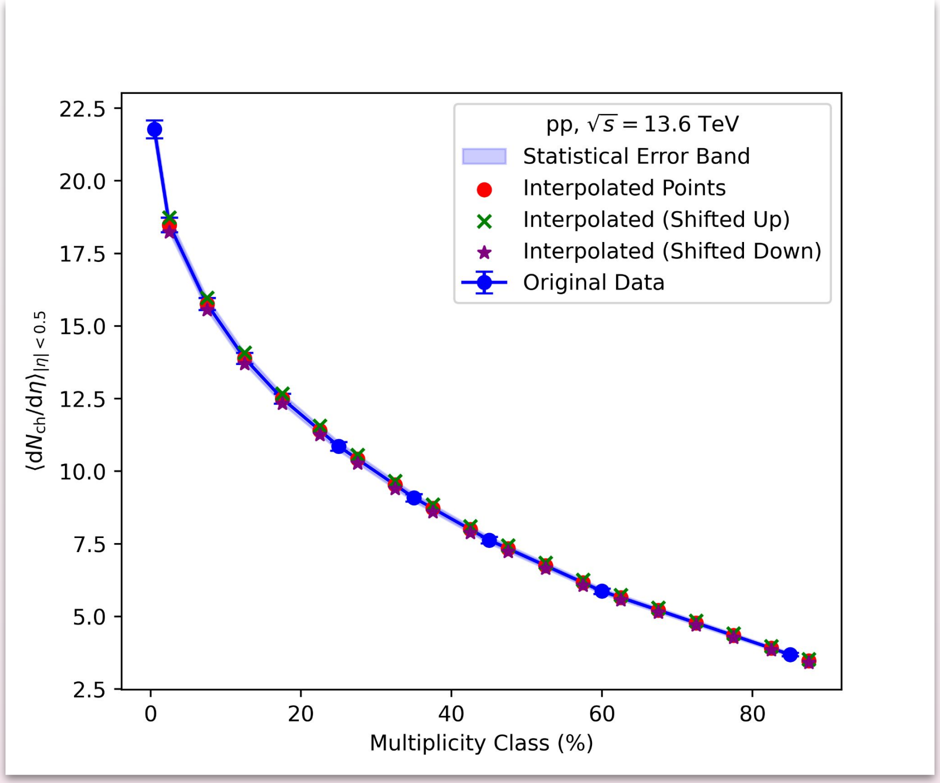
Outlook

- Look into the predictions of ThermalFIST with volume-fluctuations for fourth-order.
- Extend the p_T acceptance of the analysis, and calculate 5th and 6th order as well.

Thank you for listening

Backup slides next

Extracting multiplicity



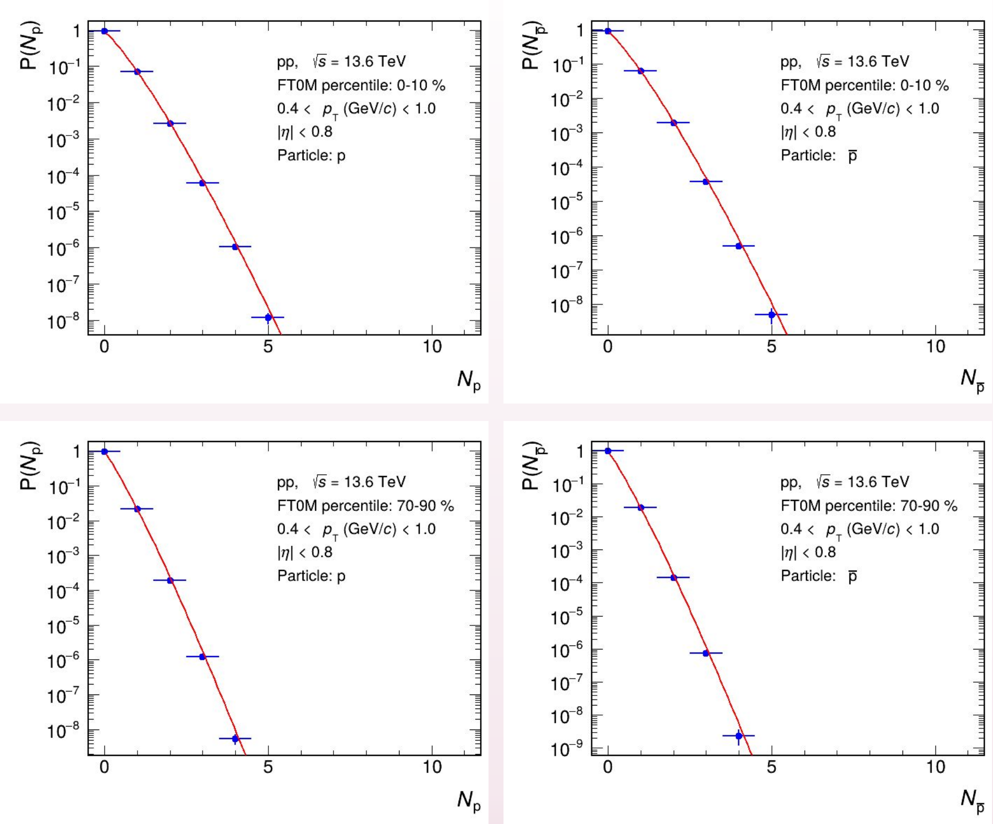

```
V0M: 2.5, dNch/dEta: 18.48, err: 0.25
V0M: 7.5, dNch/dEta: 15.76, err: 0.21
V0M: 12.5, dNch/dEta: 13.89, err: 0.19
V0M: 17.5, dNch/dEta: 12.50, err: 0.17
V0M: 22.5, dNch/dEta: 11.41, err: 0.16
V0M: 27.5, dNch/dEta: 10.42, err: 0.15
V0M: 32.5, dNch/dEta: 9.53, err: 0.14
V0M: 37.5, dNch/dEta: 8.72, err: 0.13
V0M: 42.5, dNch/dEta: 8.00, err: 0.12
V0M: 47.5, dNch/dEta: 7.34, err: 0.11
V0M: 52.5, dNch/dEta: 6.75, err: 0.10
V0M: 57.5, dNch/dEta: 6.16, err: 0.09
V0M: 62.5, dNch/dEta: 5.65, err: 0.09
V0M: 67.5, dNch/dEta: 5.22, err: 0.08
V0M: 72.5, dNch/dEta: 4.78, err: 0.08
V0M: 77.5, dNch/dEta: 4.34, err: 0.07
V0M: 82.5, dNch/dEta: 3.91, err: 0.06
V0M: 87.5, dNch/dEta: 3.47, err: 0.06
```

❖ https://alice-publications.web.cern.ch/node/10934.

Uncorrected net-proton distributions

High multiplicity

Low multiplicity



❖ Efficiency uncorrected proton and antiproton number distributions are shown

❖ Fitted with Poisson distribution functions