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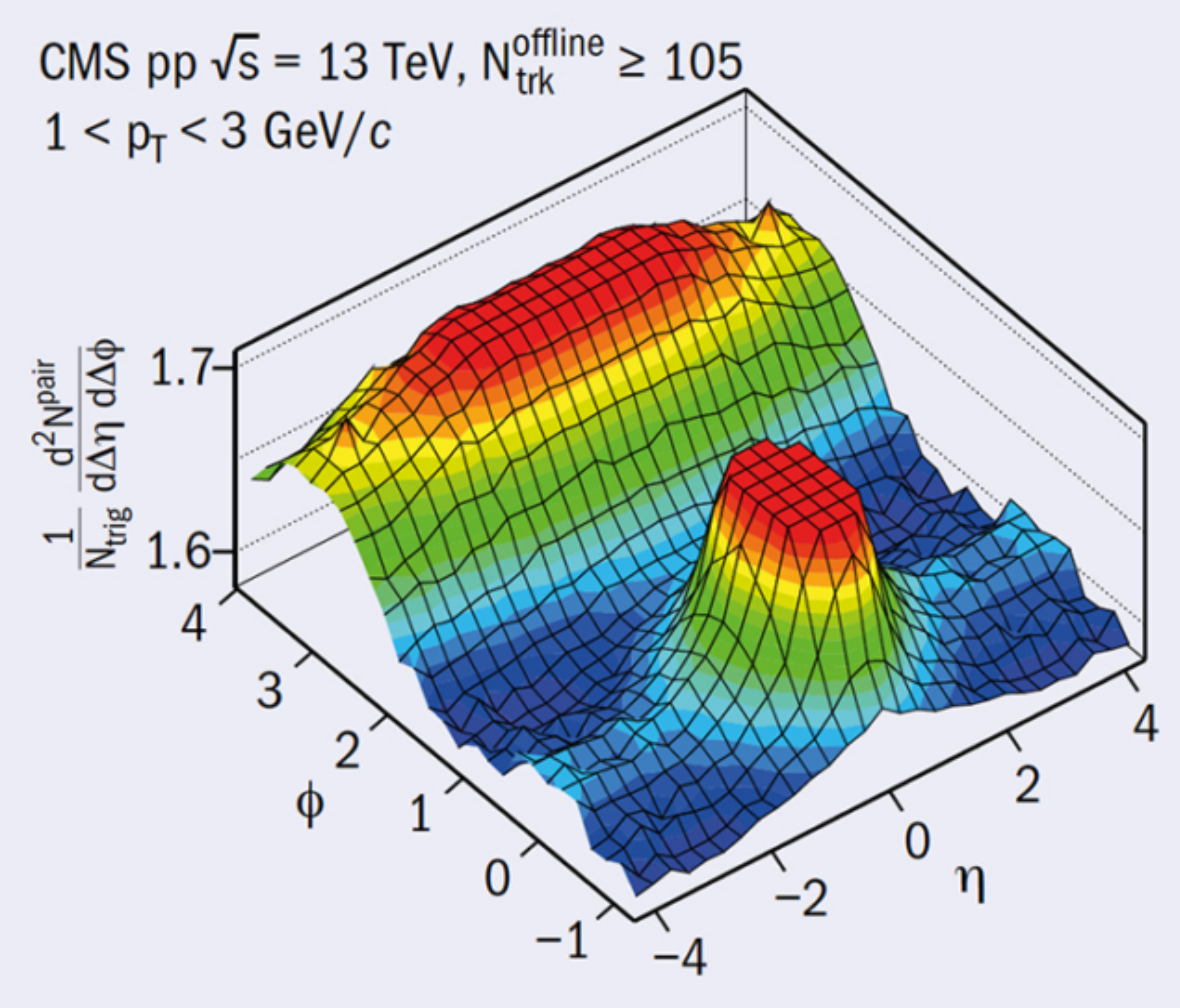
Multi-parton interactions in the LHC Run 3 and beyond

Antonio Ortiz

A. Khuntia, S. Tripathy, S. Prasad, O. Vázquez, F. Fan, P. Vargas, A. Paz, G. Bencédi

Introduction

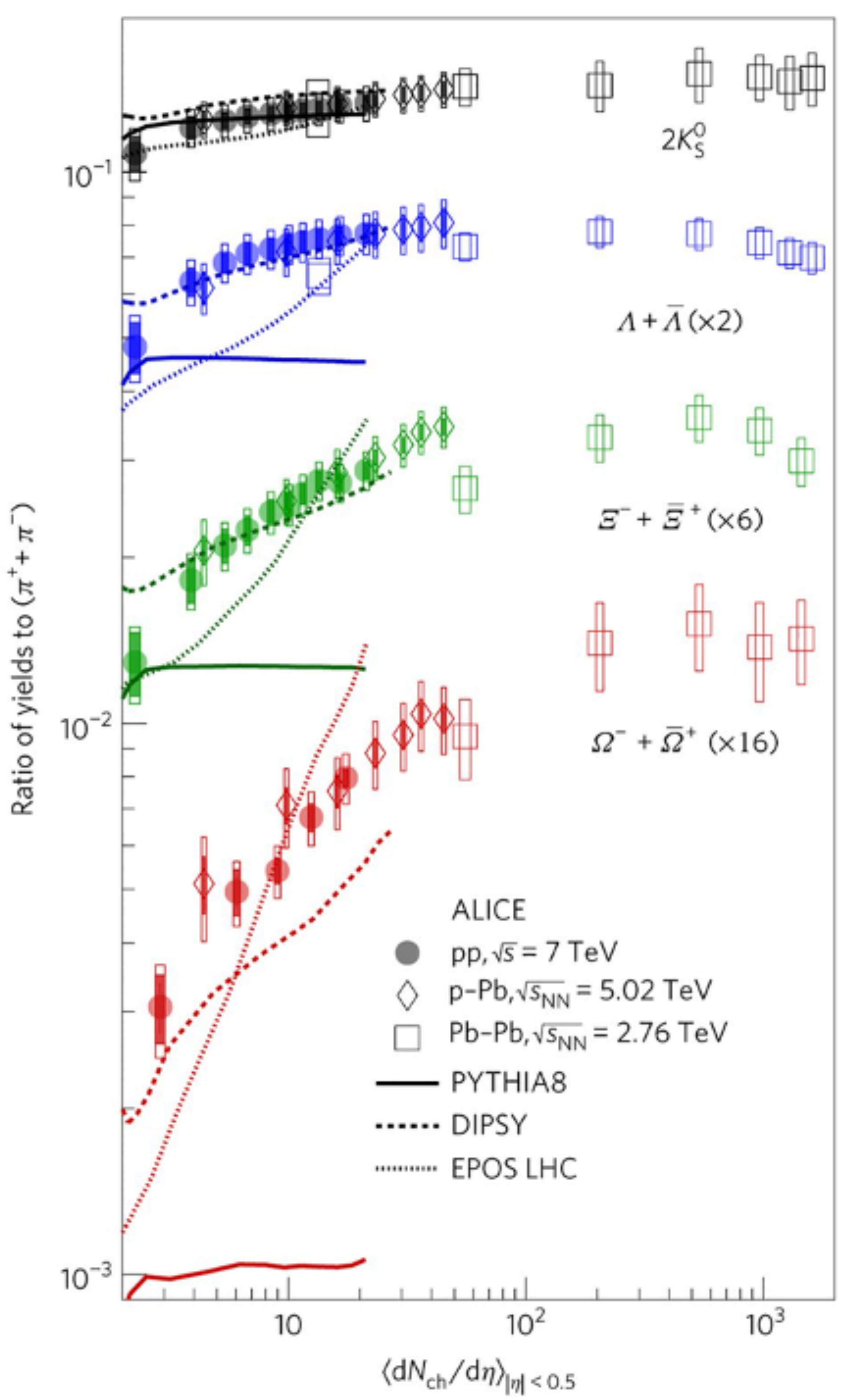
Small collision systems



Long range correlations in high-multiplicity pp collisions

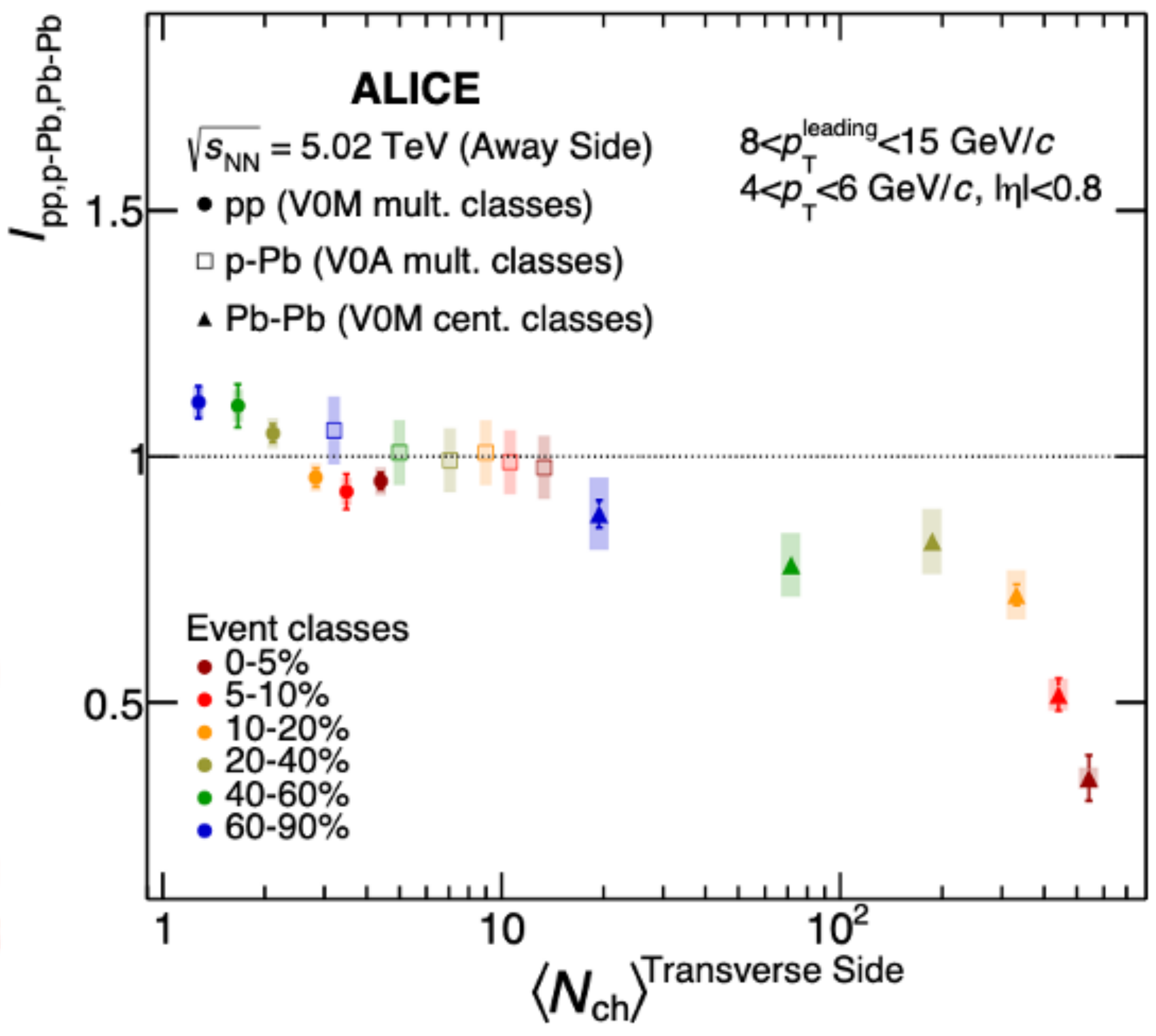
This result led to a variety of theoretical models aiming for an explanation

ALICE, Nat. Phys. 13, 535-539 (2017)



Strangeness enhancement

Effects at high p_T



Within the limited multiplicity reach, no jet quenching effects are seen in small systems

ALICE, arXiv:2204.10157

Physics opportunities: high-multiplicity pp collisions

Example: ALICE plans for the LHC runs 3 and 4:

- Study pp collisions with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \approx 100$ (estimated energy density ϵ≈50 GeV/fm³ as found in central Pb–Pb collisions)
- Search for jet quenching effects
- Check whether the Ω/π ratio reaches or exceeds the thermal limit

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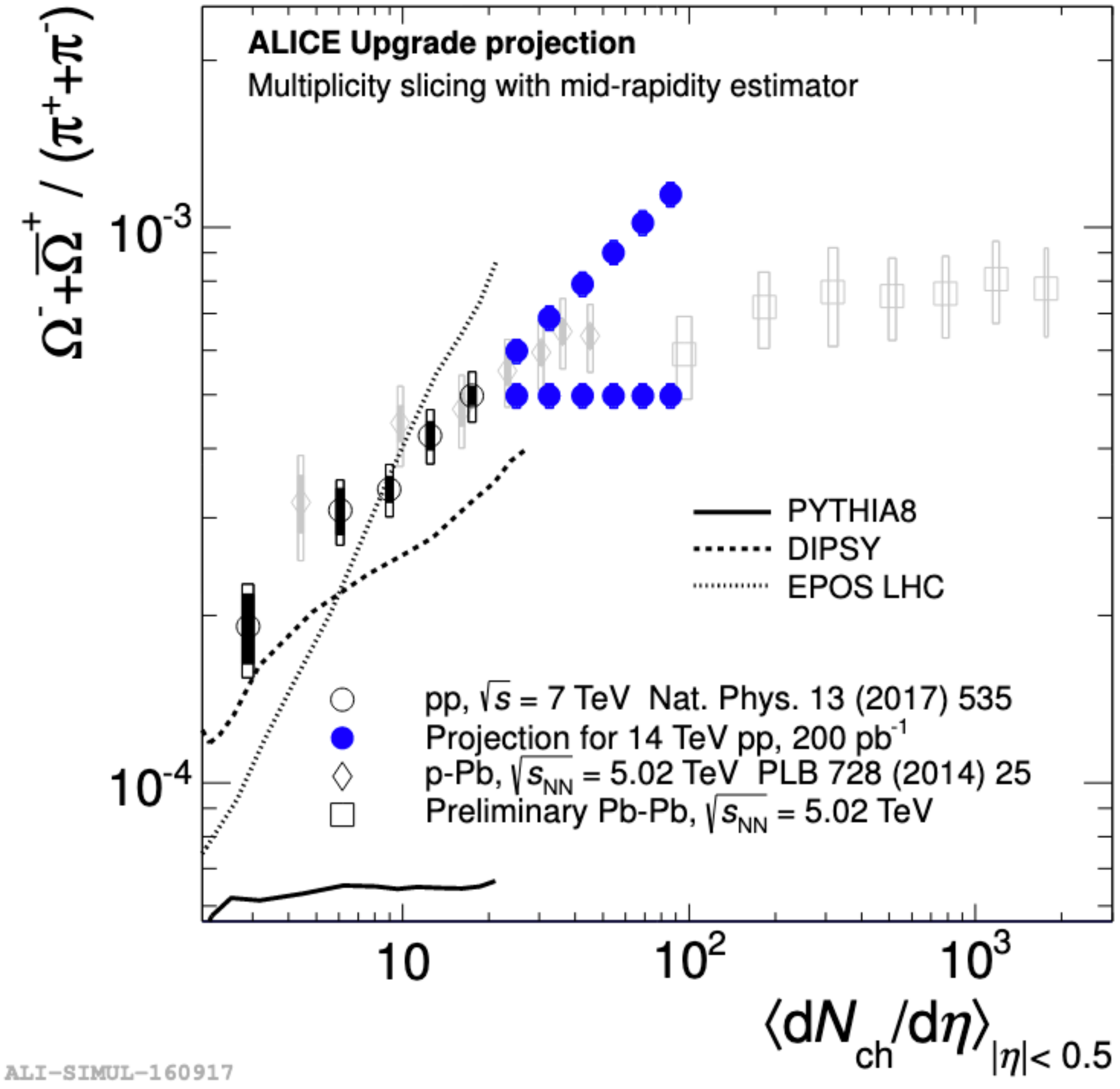

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To reach high particle multiplicities one has to use the particle density at mid-pseudorapidity

This talk: issues with this selection and a proposal to reduce the biases (flattenicity)
To illustrate the proposed methodology I will consider the MPI model implemented in PYTHIA

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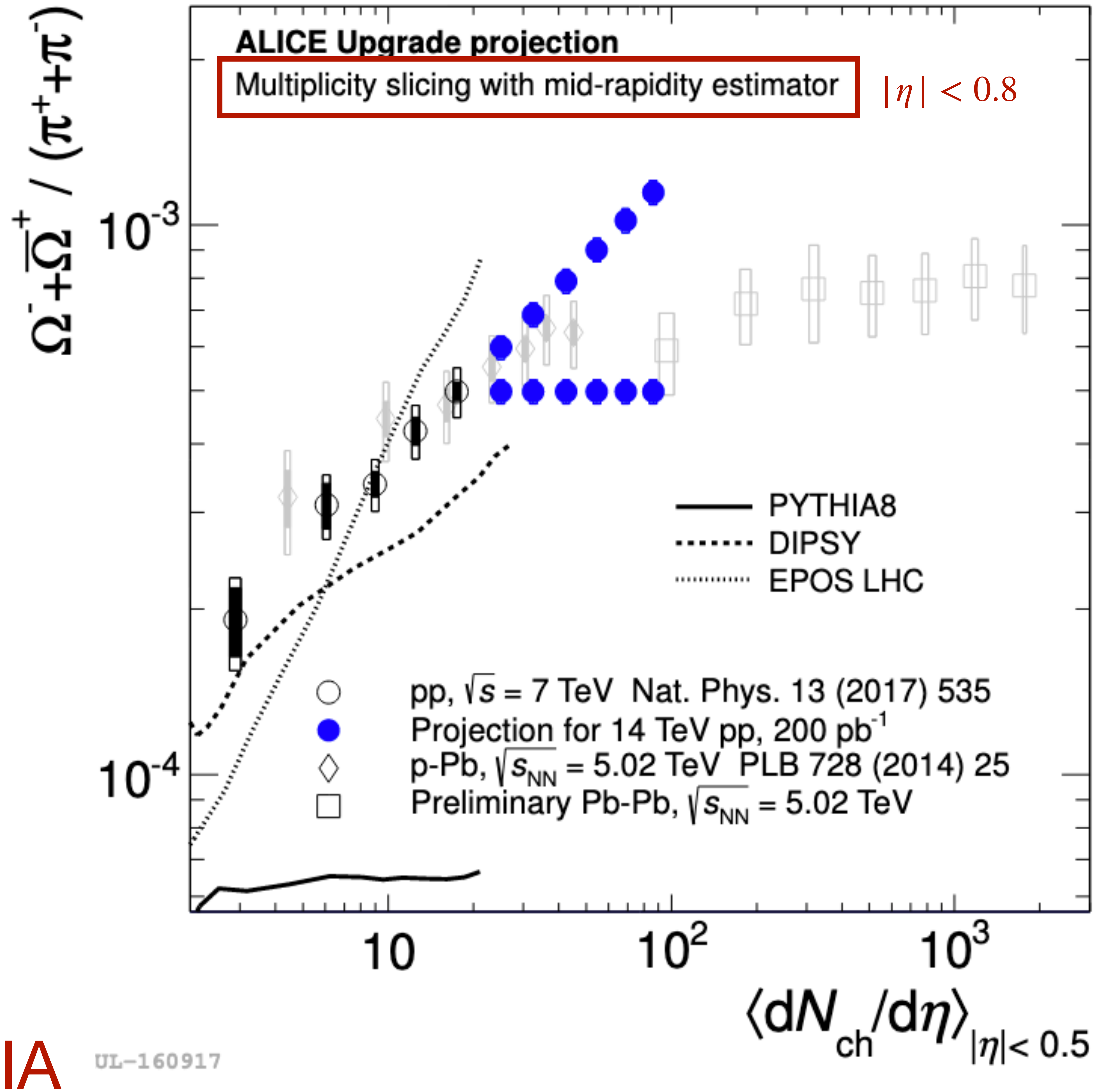
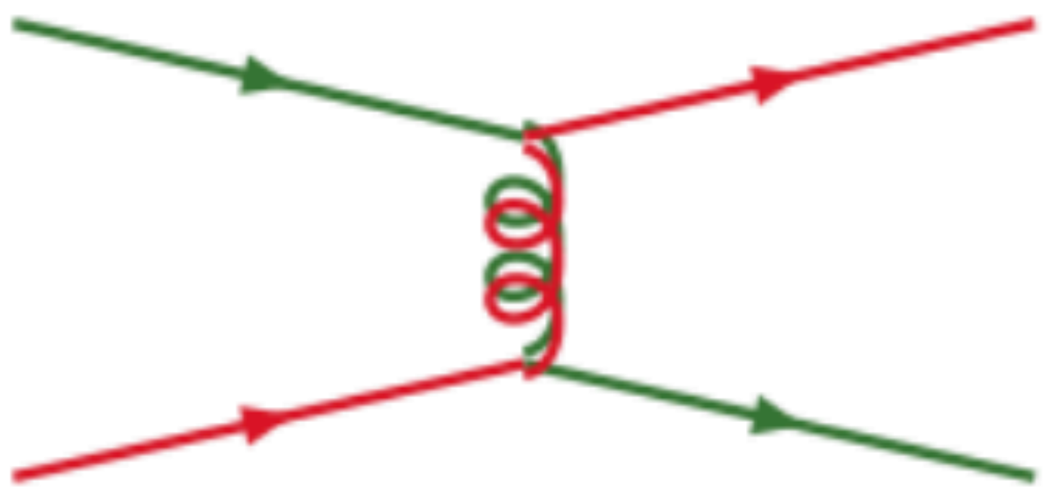


Multiparton interactions (MPI)

At high energies, the leading order cross-section for $2 \to 2$ parton scatterings with momentum transfer $Q > Q_{\text{min}} \gg \Lambda_{\text{QCD}}$ exceeds the total pp cross-section at a range of Q_{min}-values where perturbative QCD is applicable (at LHC, $Q_{\text{min}} \approx 4$ GeV/*c*) [T. Sjöstrand and M. Zijil Phys. Rev. D36 (1987)]

T. Sjöstrand, 6th MPI @ LHC Workshop



Integrate QCD $2 \to 2$

$qq' \to qq'$

$q\bar{q} \to q'\bar{q}'$

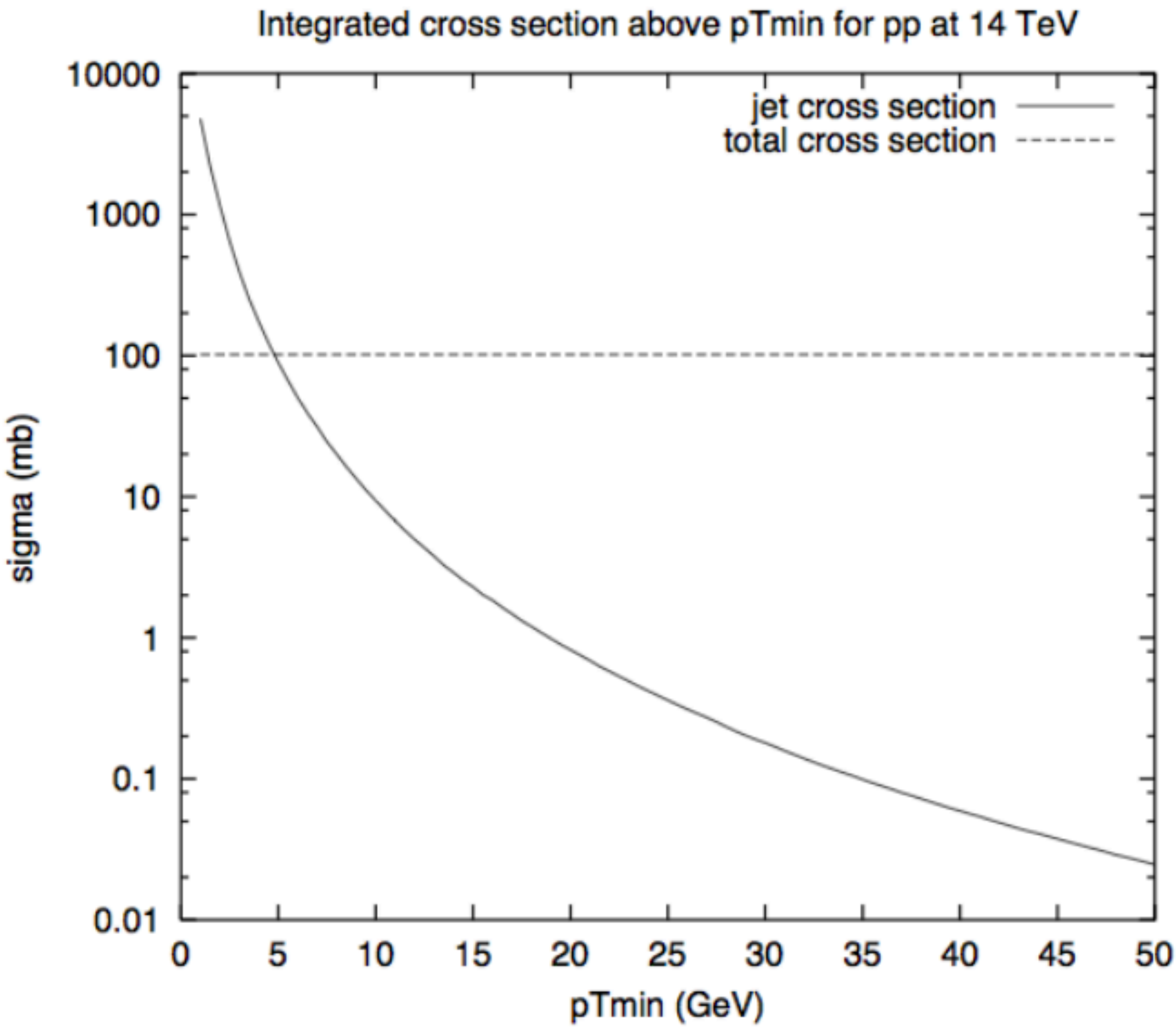
$q\bar{q} \to gg$

$qg \to qg$

$gg \to gg$

$gg \to q\bar{q}$

(with CTEQ 5L PDF's)

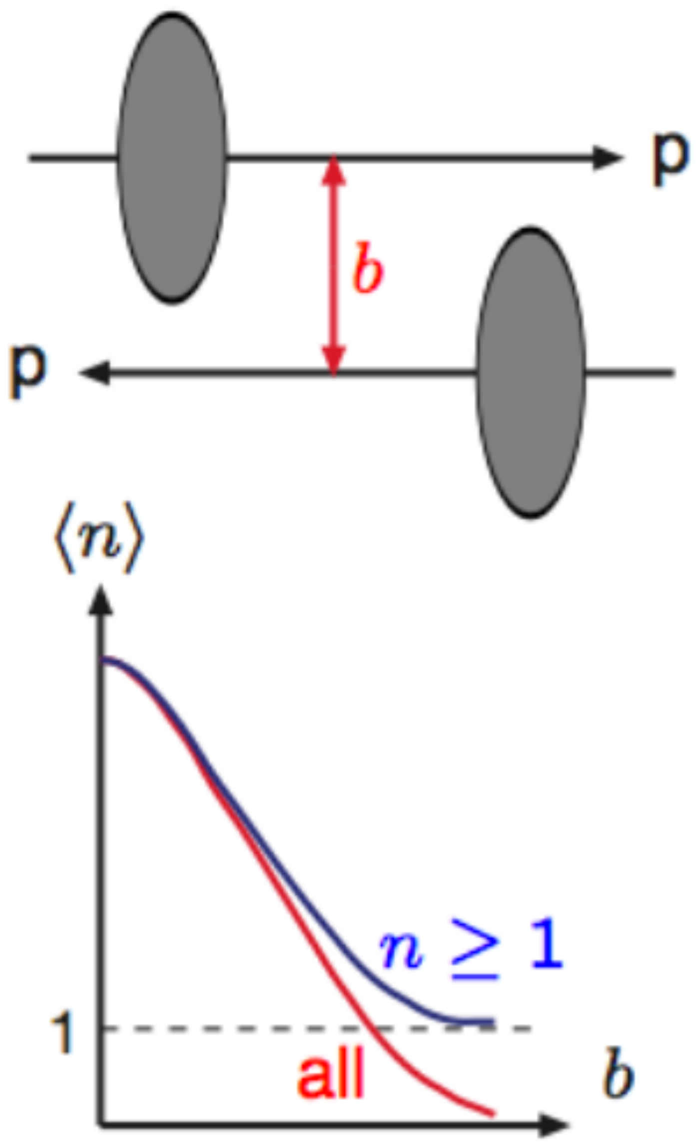


MPI

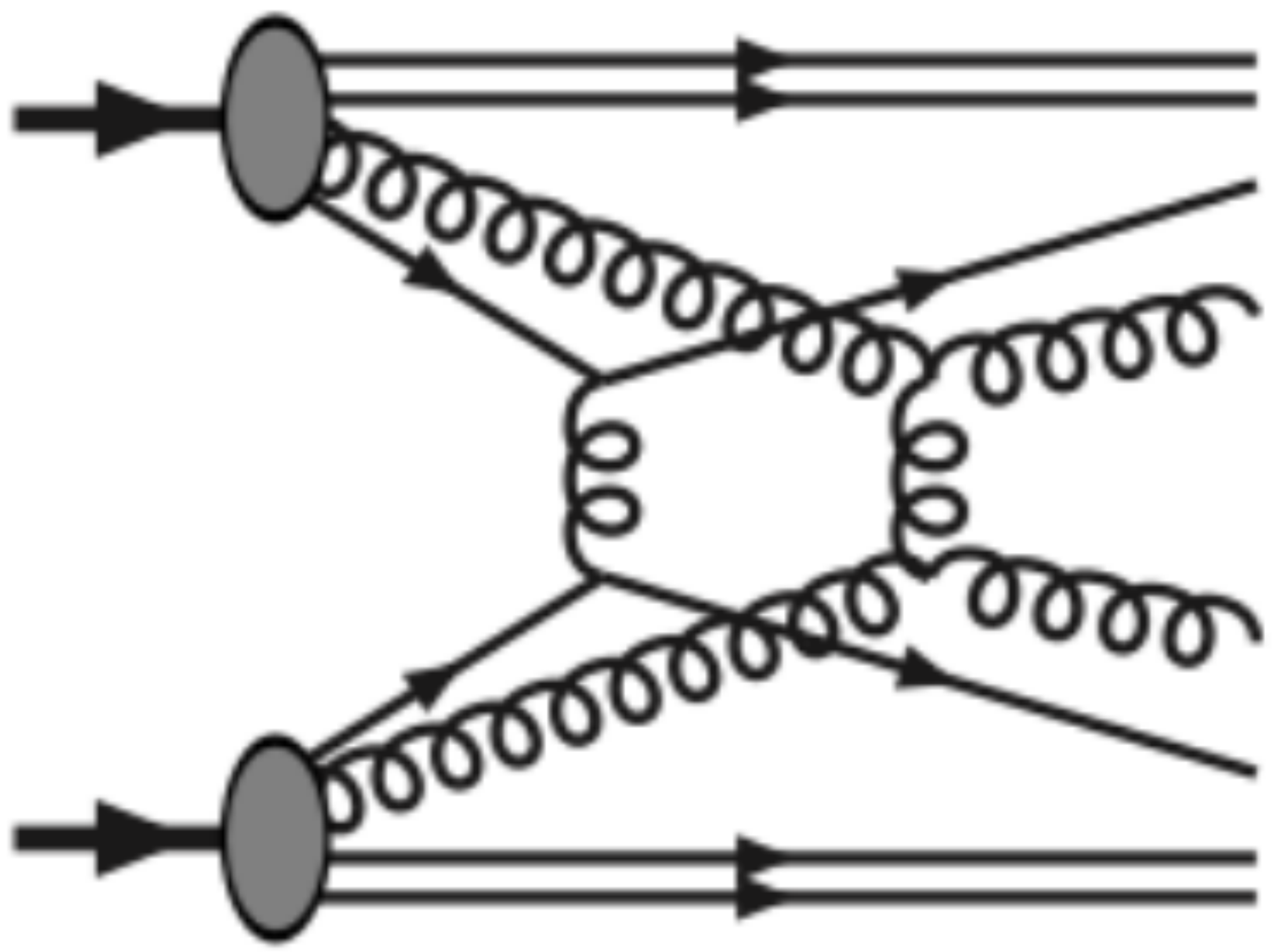
At high ene
order cross
$2 \to 2$ part
with mome
$Q > Q_{\min}$
the total pp
range of Q_{r}
perturbative
applicable (
GeV/c) [T. S
Zijil Phys. R

Interpretation: Many partonic scatterings per event: (MPI)

- MPI is a logical consequence of the composite nature of protons



- In event generators like Pythia, an impact parameter dependence is considered

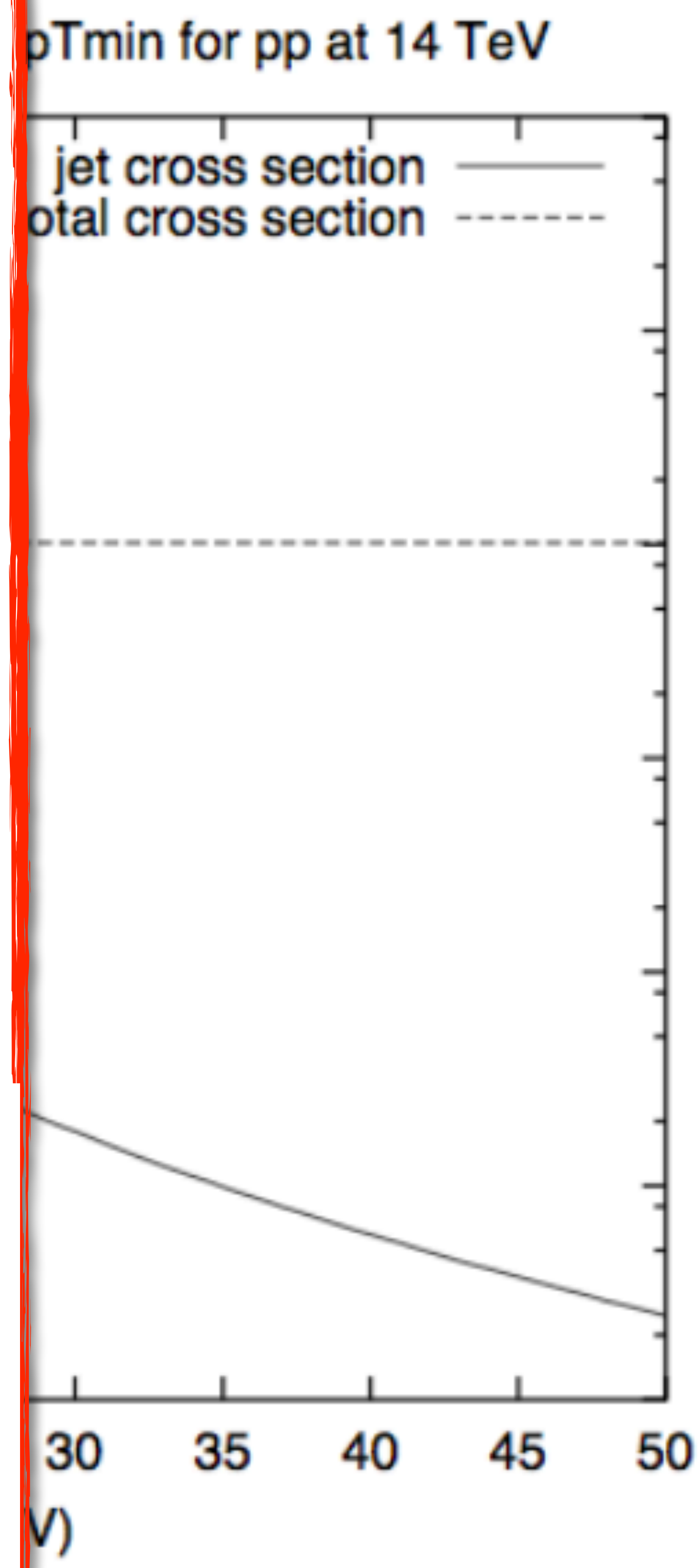


Overlap of protons during encounter is

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\, \mathrm{d}t\, \rho_1(\mathbf{x}, t)\, \rho_2(\mathbf{x}, t)$$

where ρ is (boosted) matter distribution in p, e.g. Gaussian or more narrow peak.

T. Sjöstrand, ISAPP 2018



MPI

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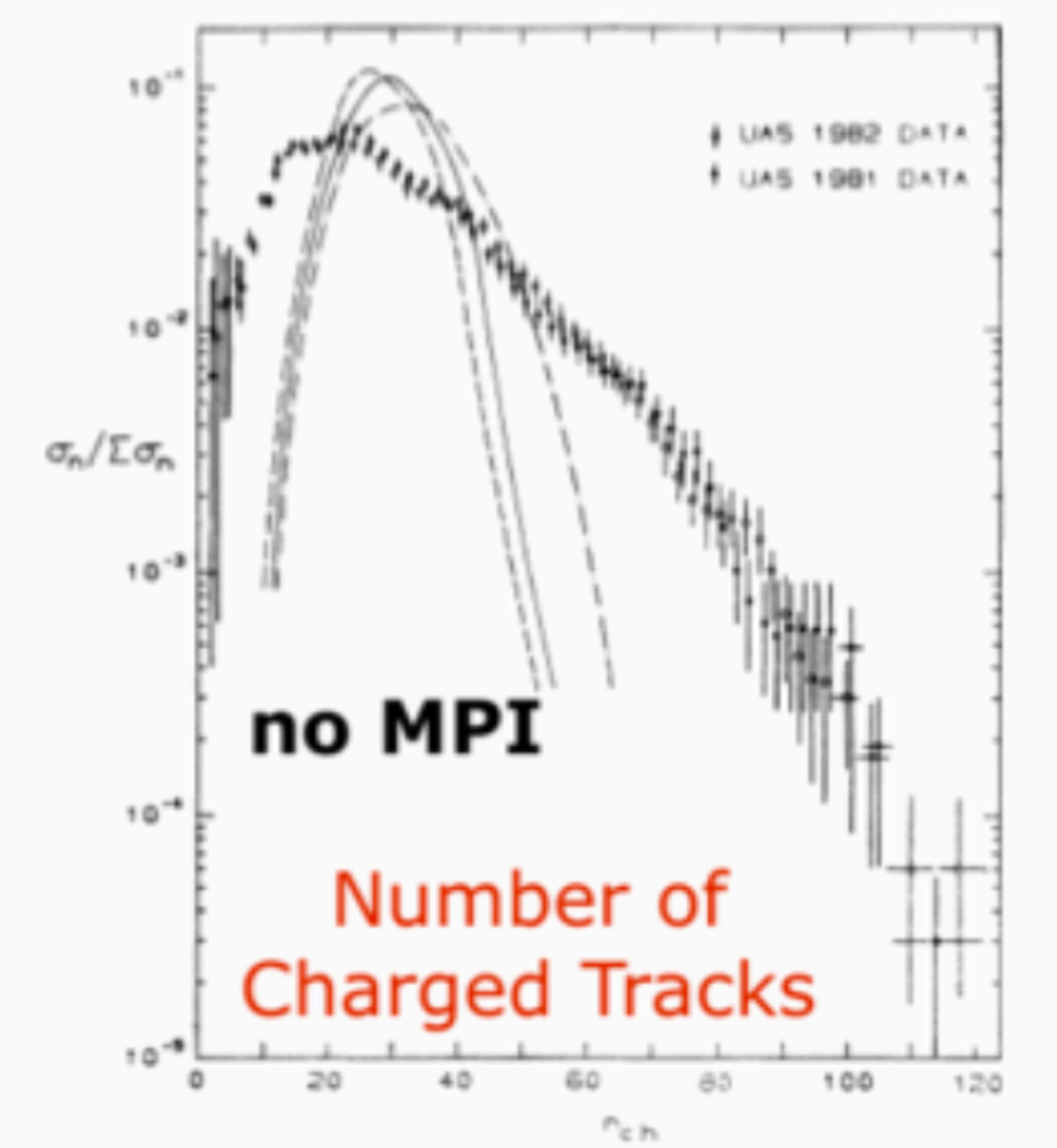


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

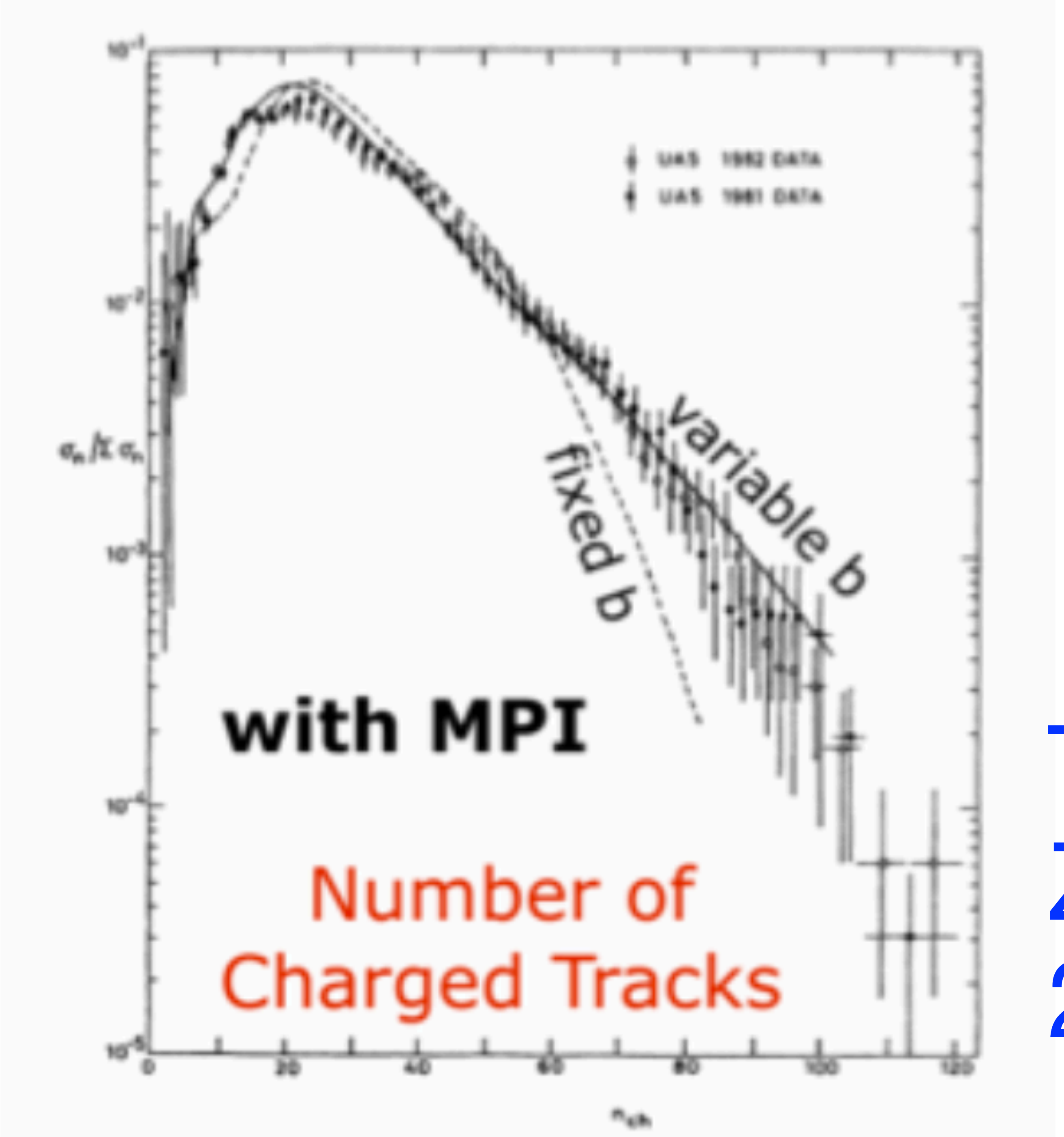


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

MPI help to describe particle multiplicities in MB events

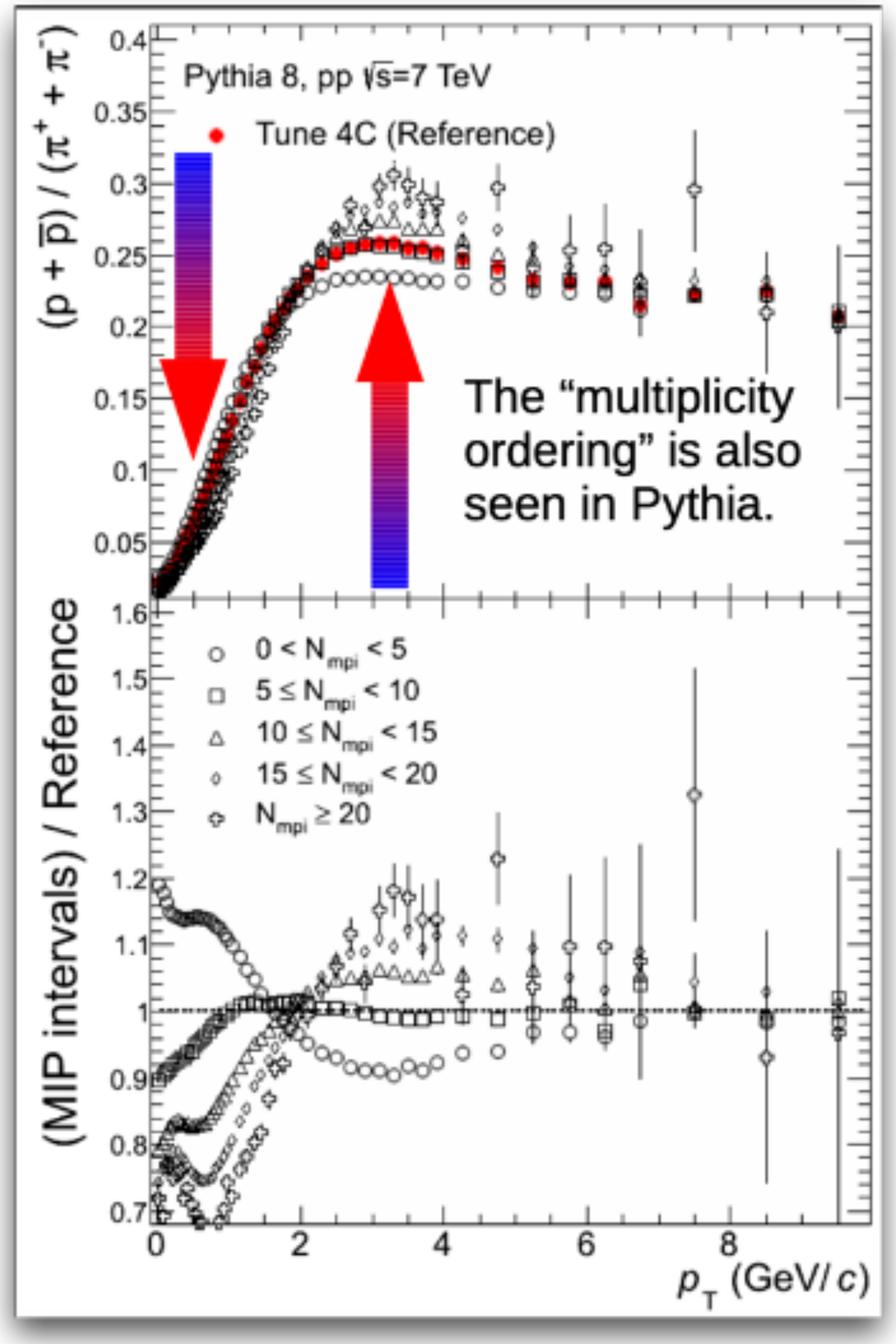
T. Sjöstrand and M. v. Zijl, PRD 36 (1987) 2019

Charged particle multiplicity is expected to be sensitive to MPI

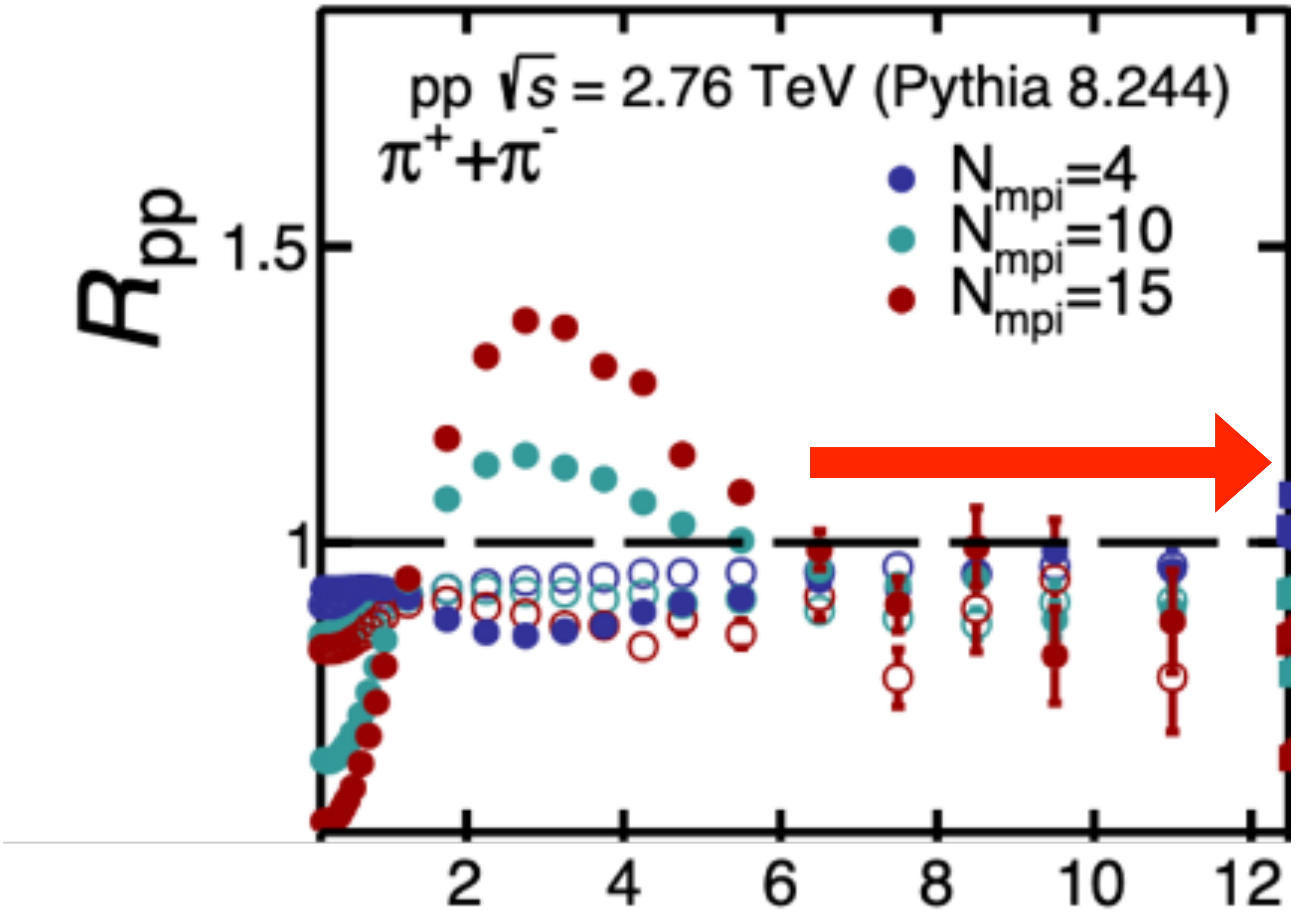
Data support the presence of MPI in high energy pp collisions, see e.g. these recent studies using ML: PRD 102 (2020) 7,076014, J. Phys. G: Nucl. Part. Phys. 48 (2021) 8, 085014

MPI and heavy-ion-like features

Phys. Rev. Lett. 111, 042001 (2013)



Radial flow-like behaviour

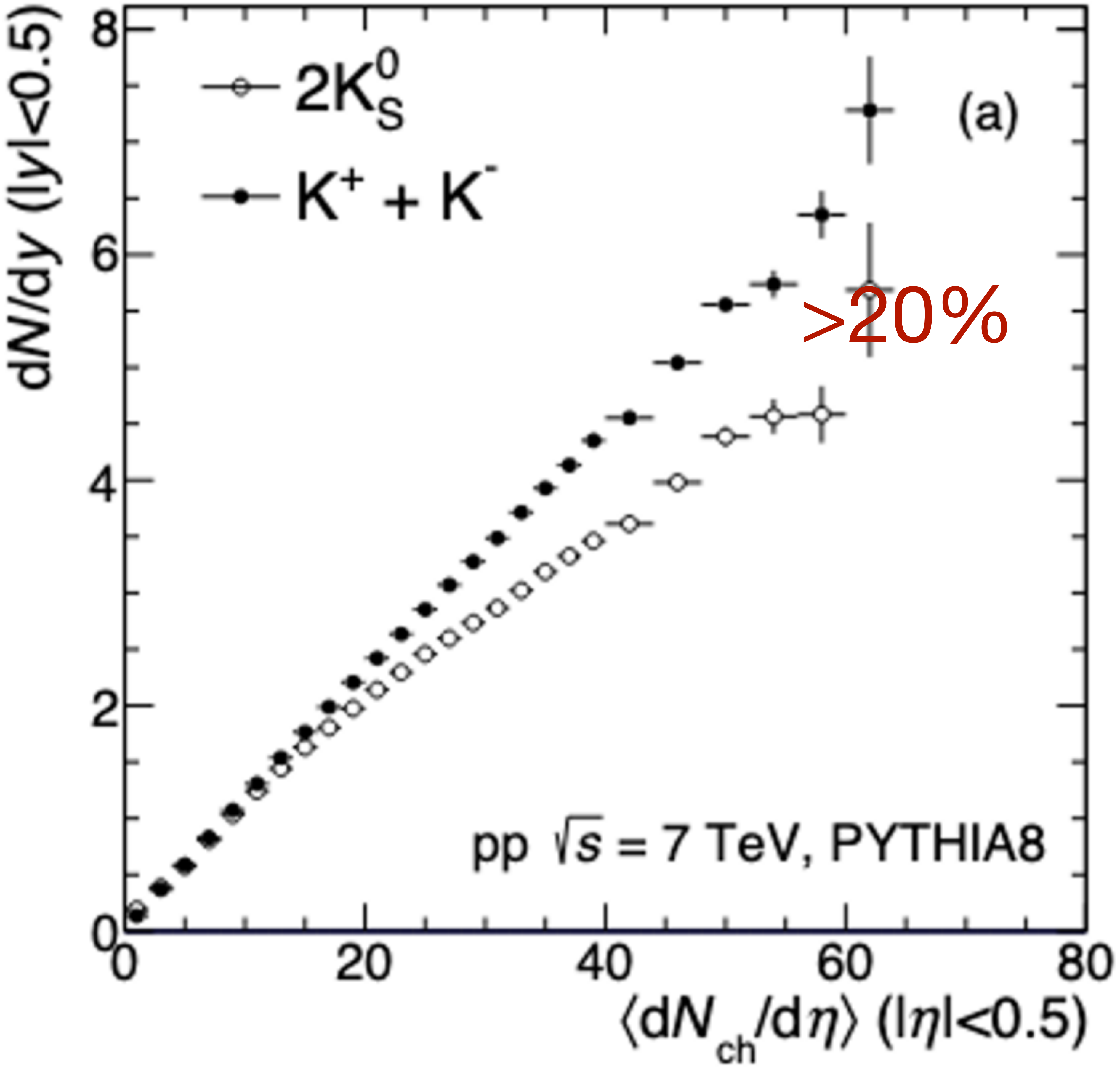


$$R_{\mathrm{pp}} = \frac{\mathrm{d}^2 N_{\mathrm{ch}}^{\mathrm{mpi}}/(\langle N_{\mathrm{mpi}}\rangle \mathrm{d}\eta \mathrm{d}p_{\mathrm{T}})}{\mathrm{d}^2 N_{\mathrm{ch}}^{\mathrm{MB}}/(\langle N_{\mathrm{mpi}}^{\mathrm{MB}}\rangle \mathrm{d}\eta \mathrm{d}p_{\mathrm{T}})}$$

Phys. Rev.D 102 (2020) 7, 076014

Scaling with number of parton-parton interactions at high p_{T}

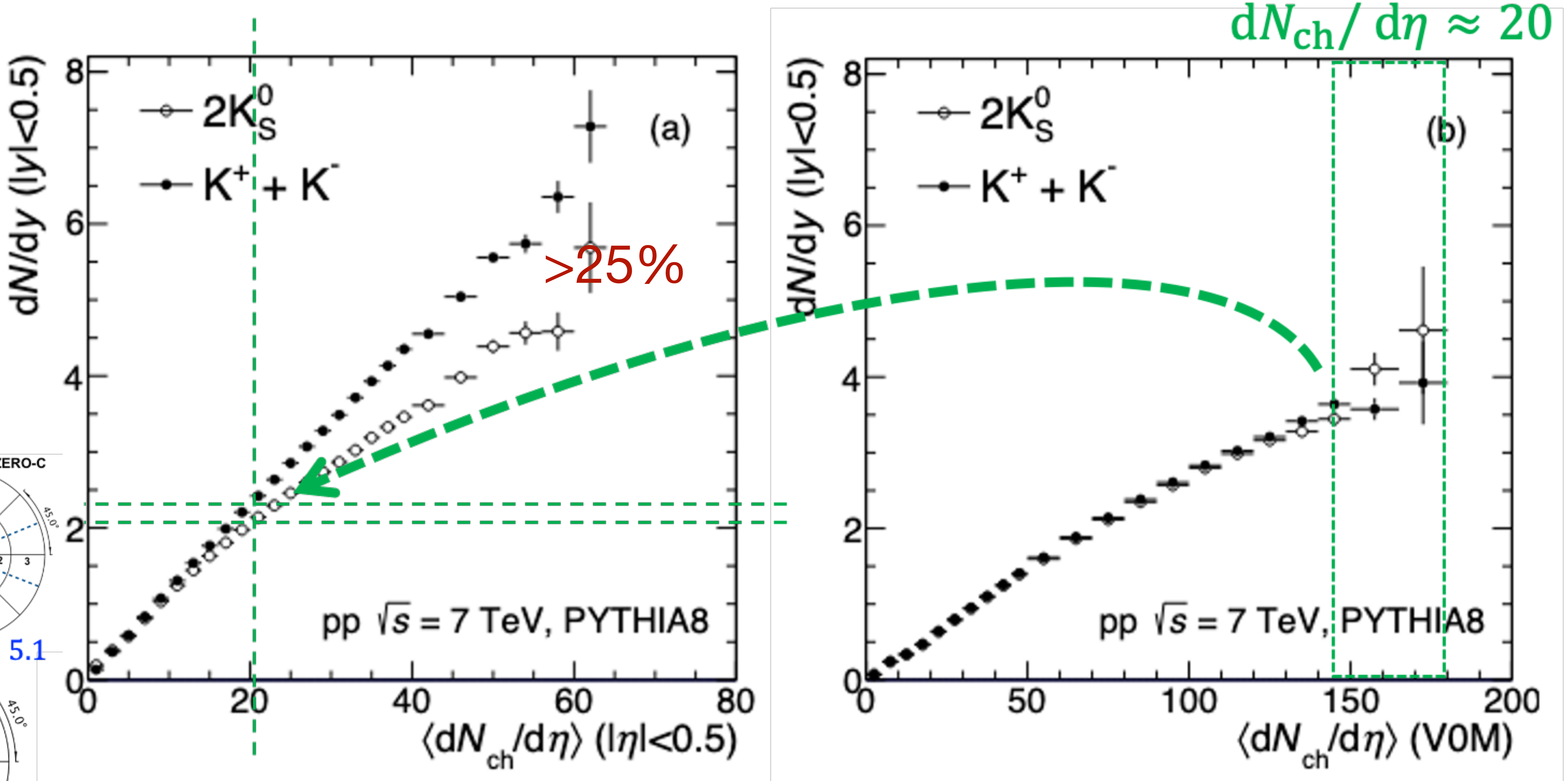
Selection biases (I)

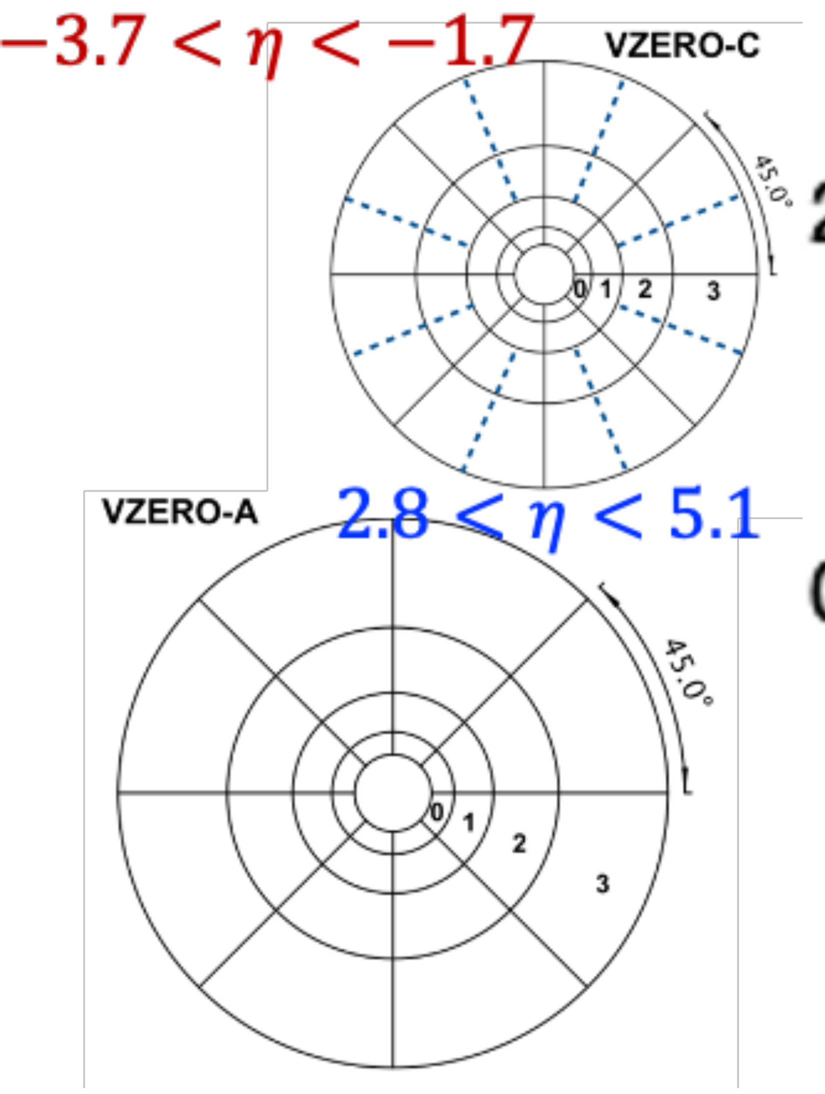


- Multiplicity selection within $|\eta| < 0.8$: imbalance between neutral and charged particle yields

Selection biases (I)

- The effect is reduced if the activity is determined in the forward region



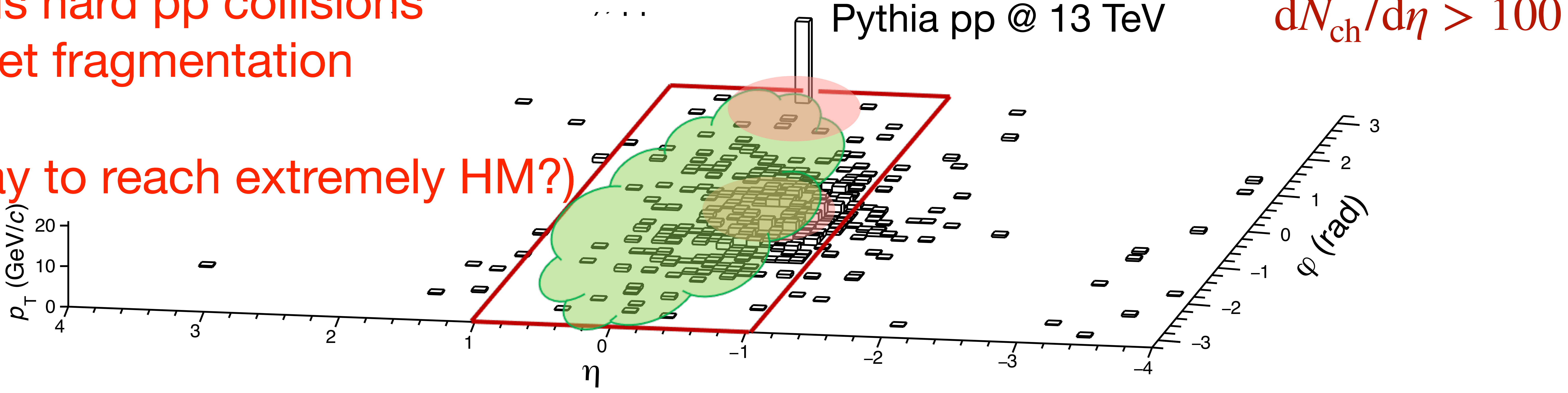


V0M estimator: the multiplicity reach at mid-pseudorapidity is smaller

Selection biases (II)

Bias towards hard pp collisions
Bias in the jet fragmentation

(the only way to reach extremely HM?)



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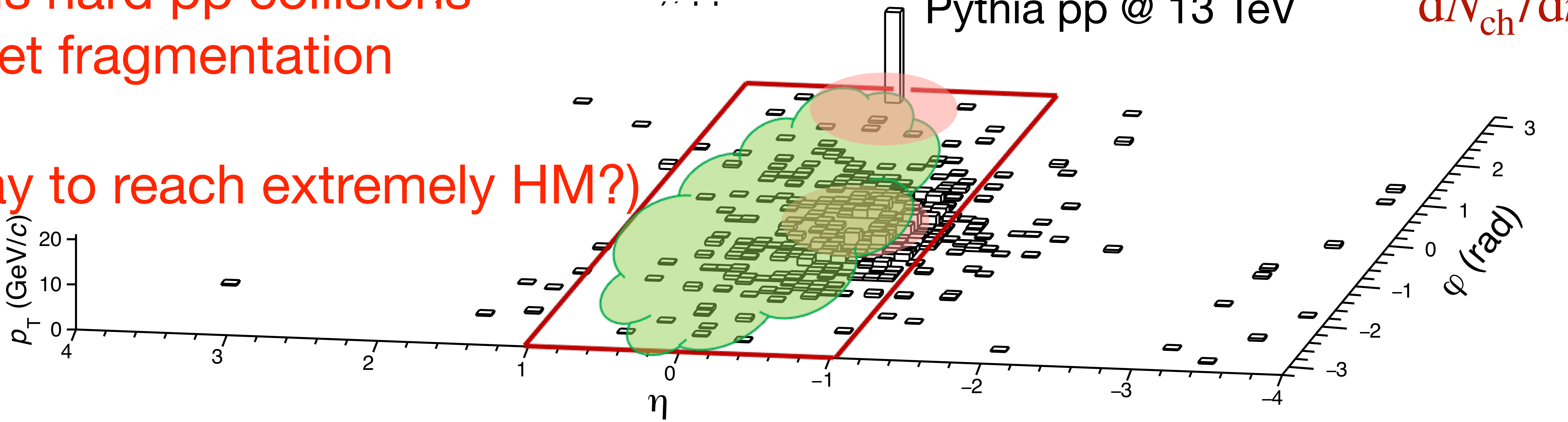
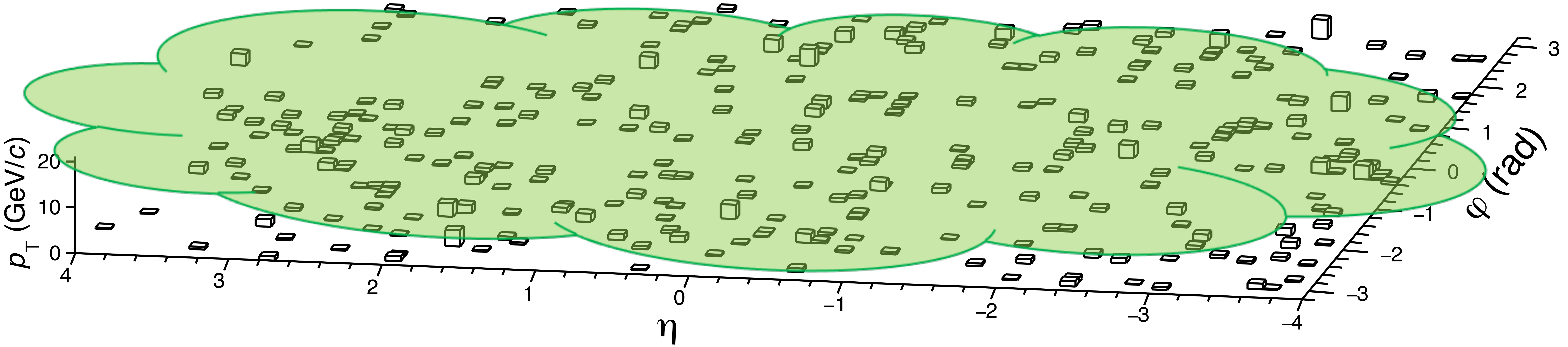
Pythia pp @ 13 TeV

$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta > 100$



$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \approx 50$ within $|\eta| < 1$ Modest multiplicity (several minijets)



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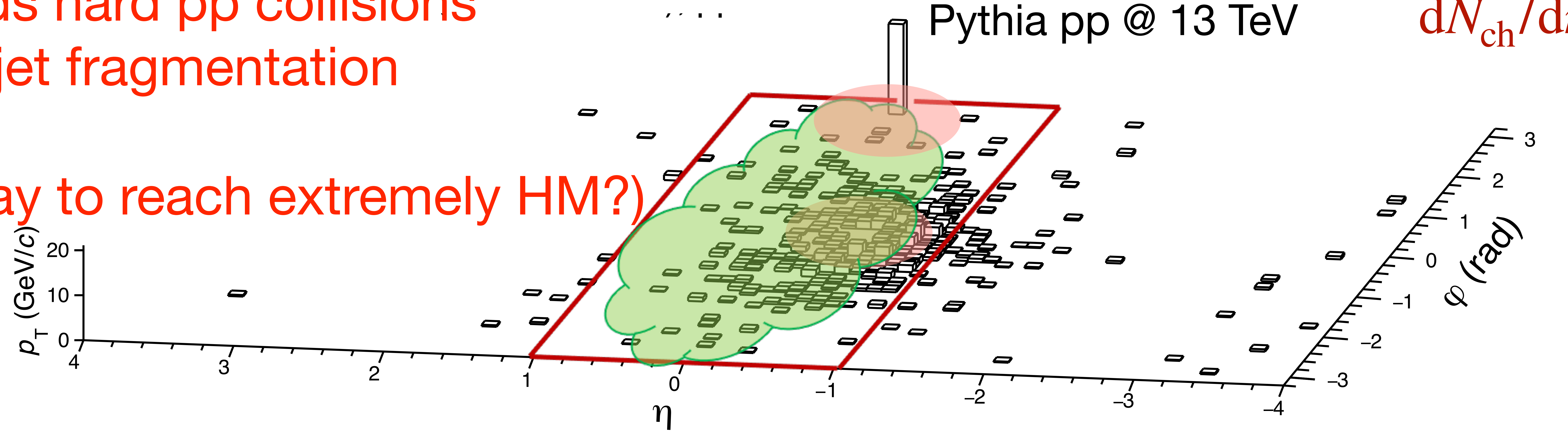
$dN_{ch}/d\eta > 100$



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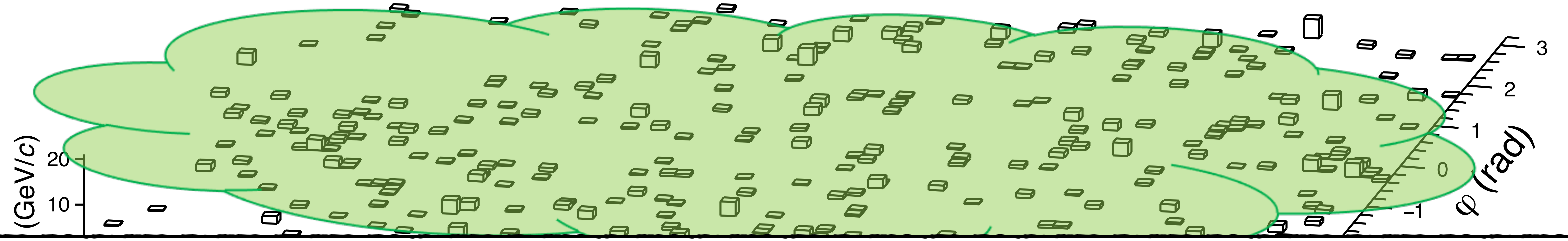
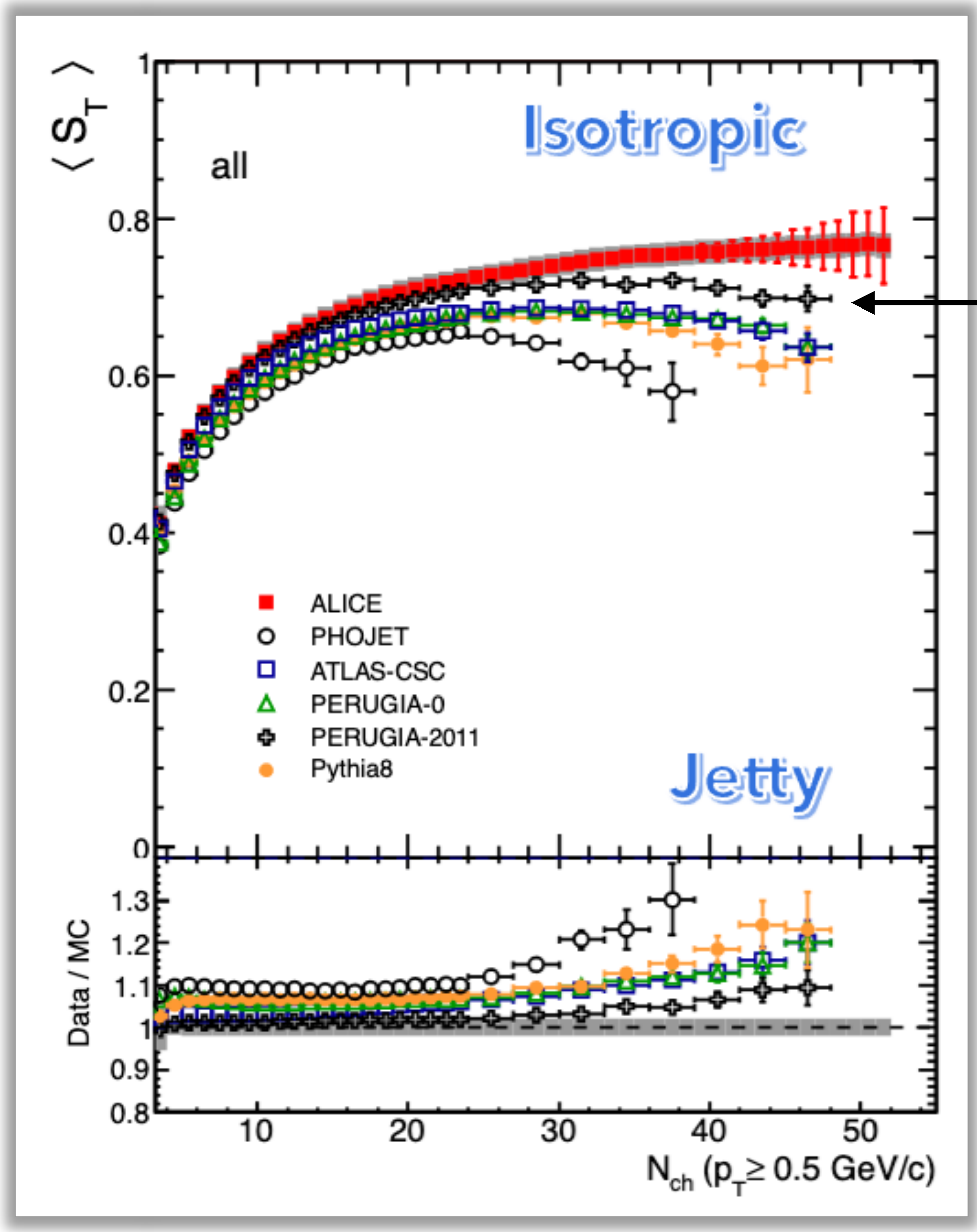


Several semi-hard scatterings within the same pp collisions, UE-dominated pp collisions. Goal: tag these events and study their properties

First attempts to classify the events as a function of MPI

Using sphericity we found that the system created in pp collisions are more isotropic than predicted by models. The minijet analysis supports the picture of MPI in pp collisions



More active MPI than Perugia 0

$$S^{L}_{xy} = \frac{1}{\sum_i p_{T i}} \sum_i \frac{1}{p_{T i}} \begin{pmatrix} p_{x i}^2 & p_{x i} p_{y i} \\ p_{y i} p_{x i} & p_{y i}^2 \end{pmatrix}$$

$$S_T \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

ALICE, EPJC 72 (2012) 2124 / JHEP 09 (2013) 049

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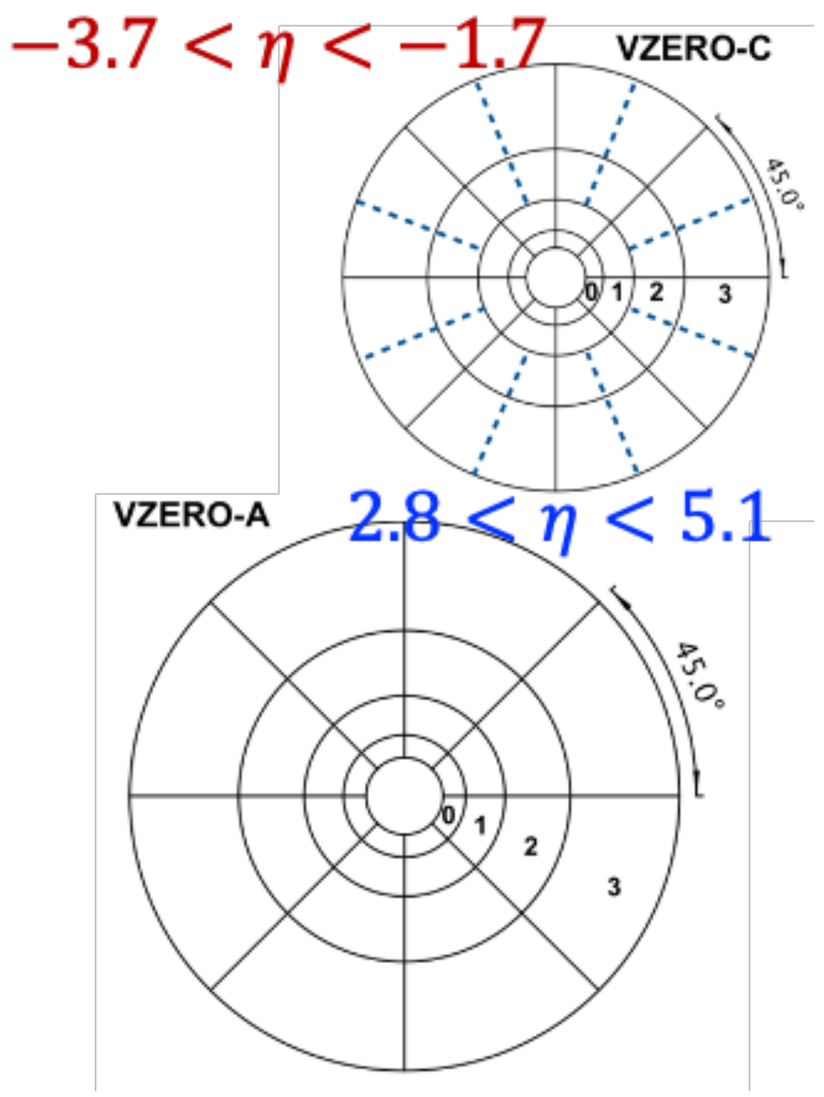
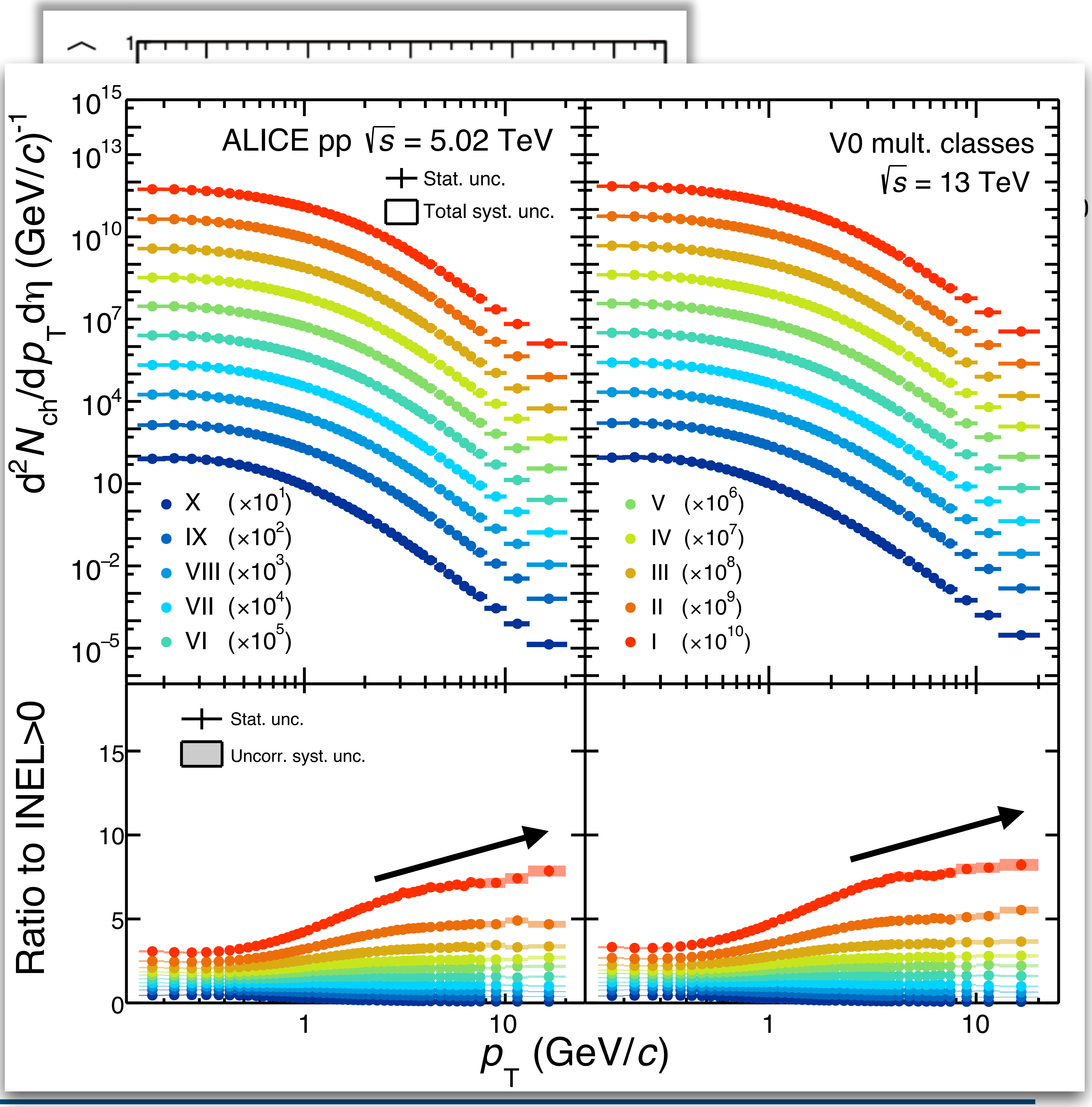


To reduce the bias towards hard pp collisions, the event activity has been measured in the forward V0 detector

[ALICE, EPJC 79 (2019) no.10, 857](#)

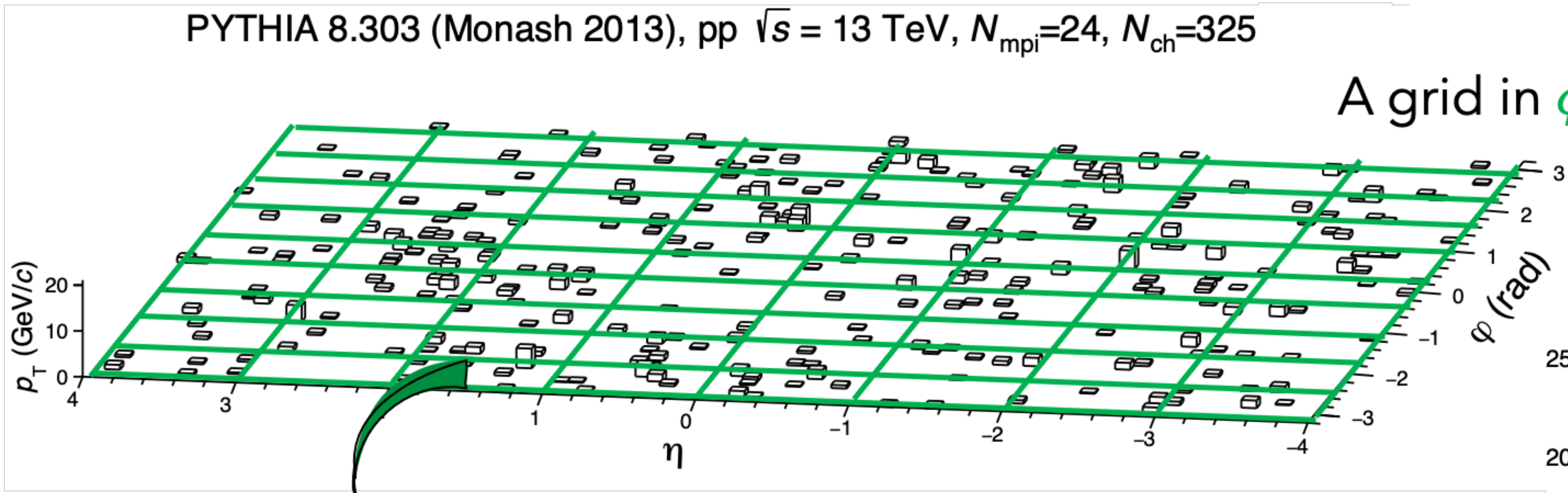


For LHC runs 3 and 4 we should explore new directions

->

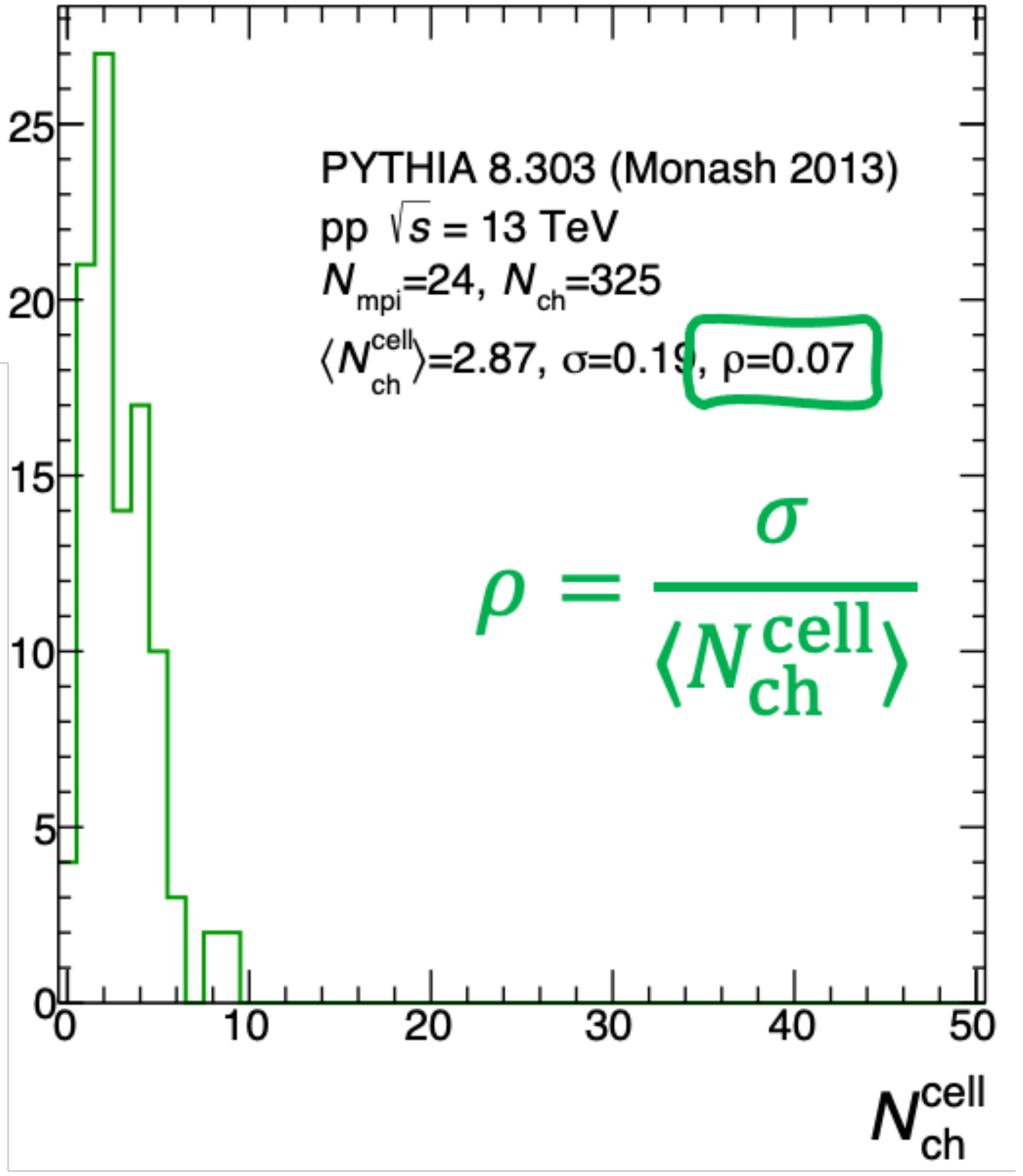
Flattenicity

Flattenicity



A grid in $\varphi - \eta$ is built: 10×8

In each cell, the charged particle multiplicity is computed: N_{ch}^{cell}

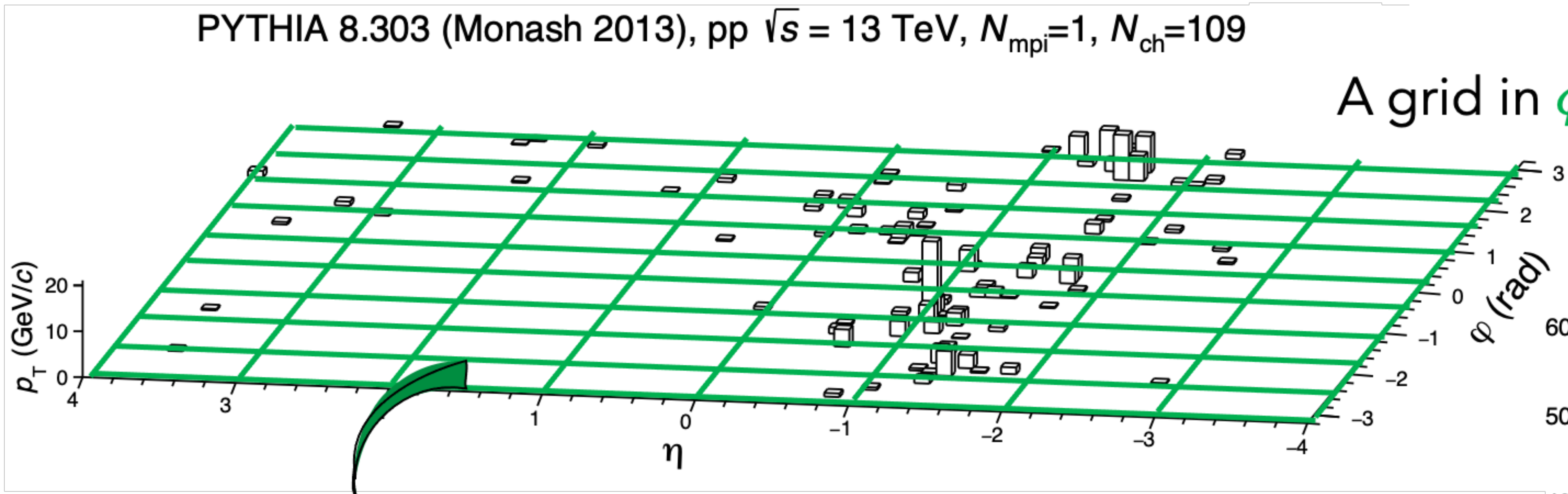


$$\rho = \frac{\sigma}{\langle N_{ch}^{cell} \rangle}$$

EbE the N_{ch}^{cell} distribution is obtained

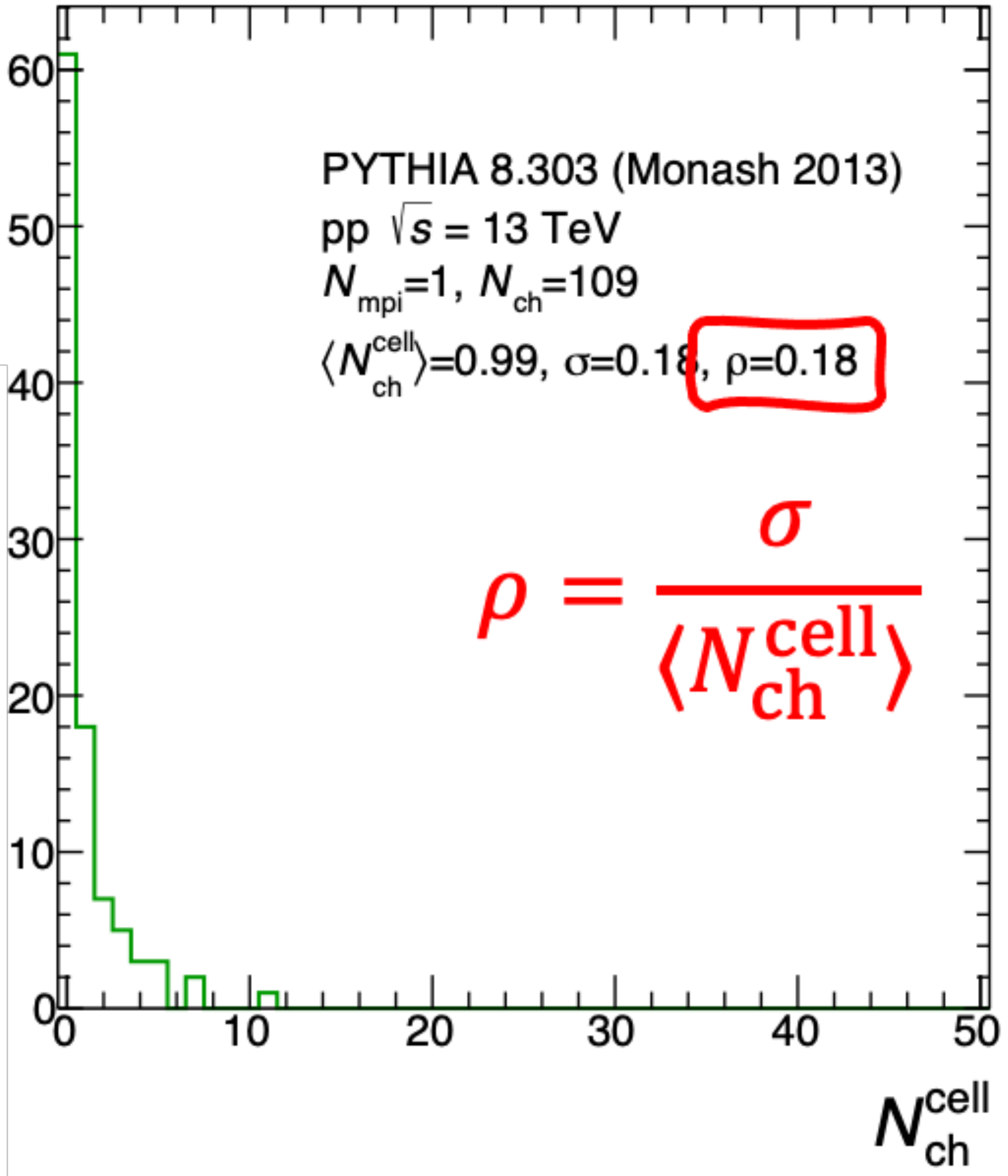
Events with isotropic distribution of particles (very active MPI) are expected to have small ρ values

Flattenicity



A grid in $\varphi - \eta$ is built: 10×8

In each cell, the charged particle multiplicity is computed: $N_{\rm ch}^{\rm cell}$



$$\rho = \frac{\sigma}{\langle N_{\rm ch}^{\rm cell}\rangle}$$

EbE the $N_{\rm ch}^{\rm cell}$ distribution is obtained

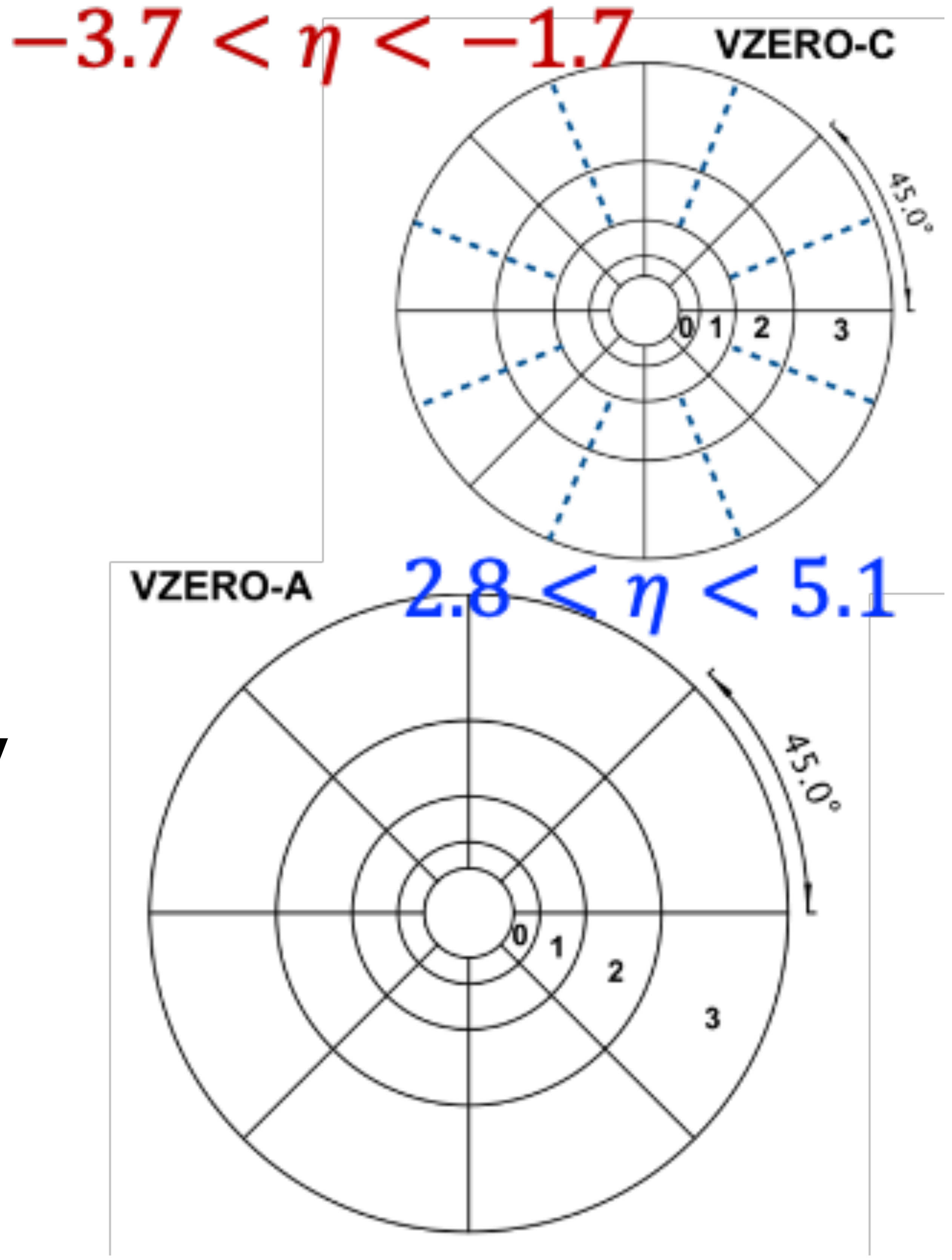
Events with jet structures are expected to have large ρ values

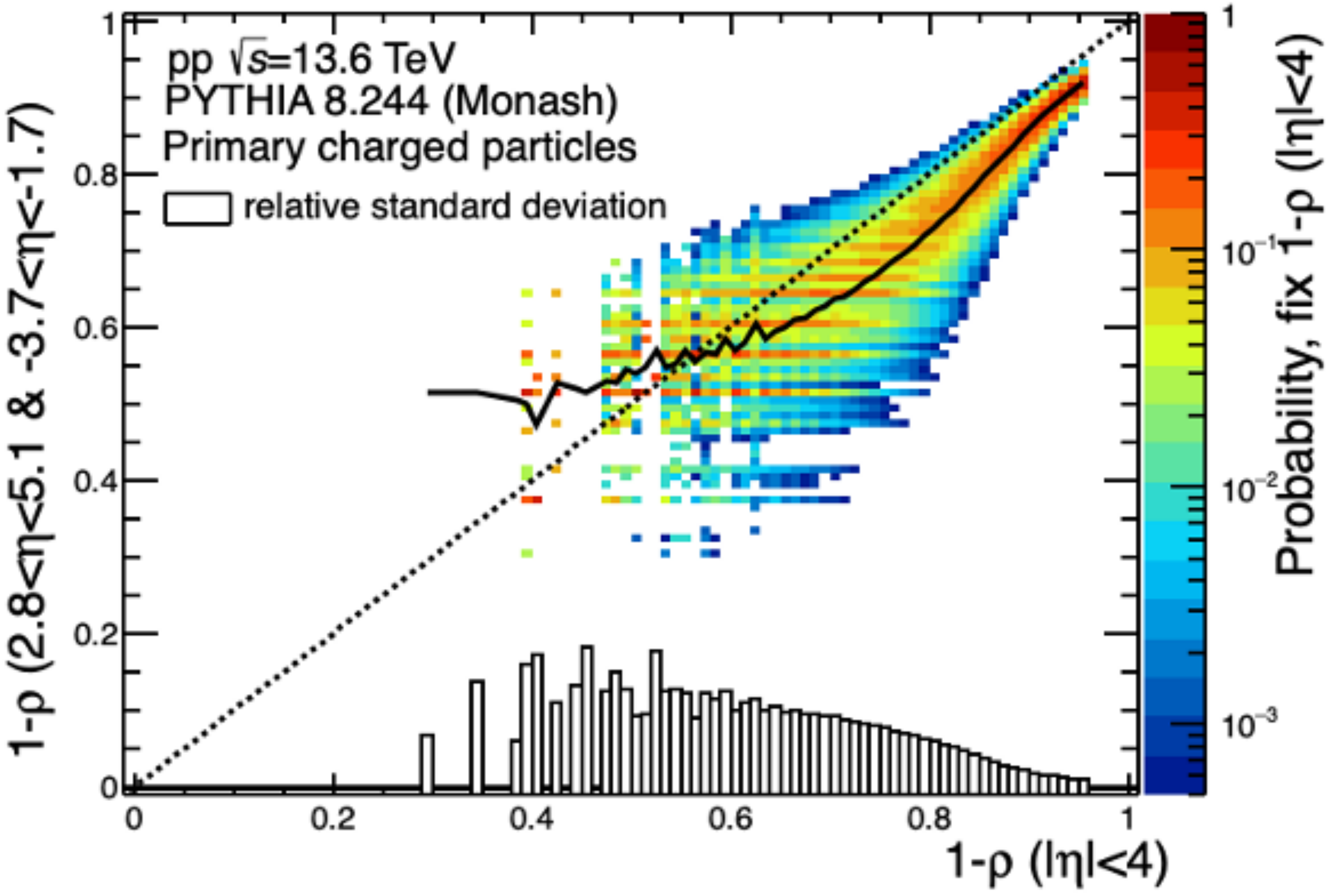
Flattenicity

- Flattenicity was defined in a way that its values stay between 0 and 1

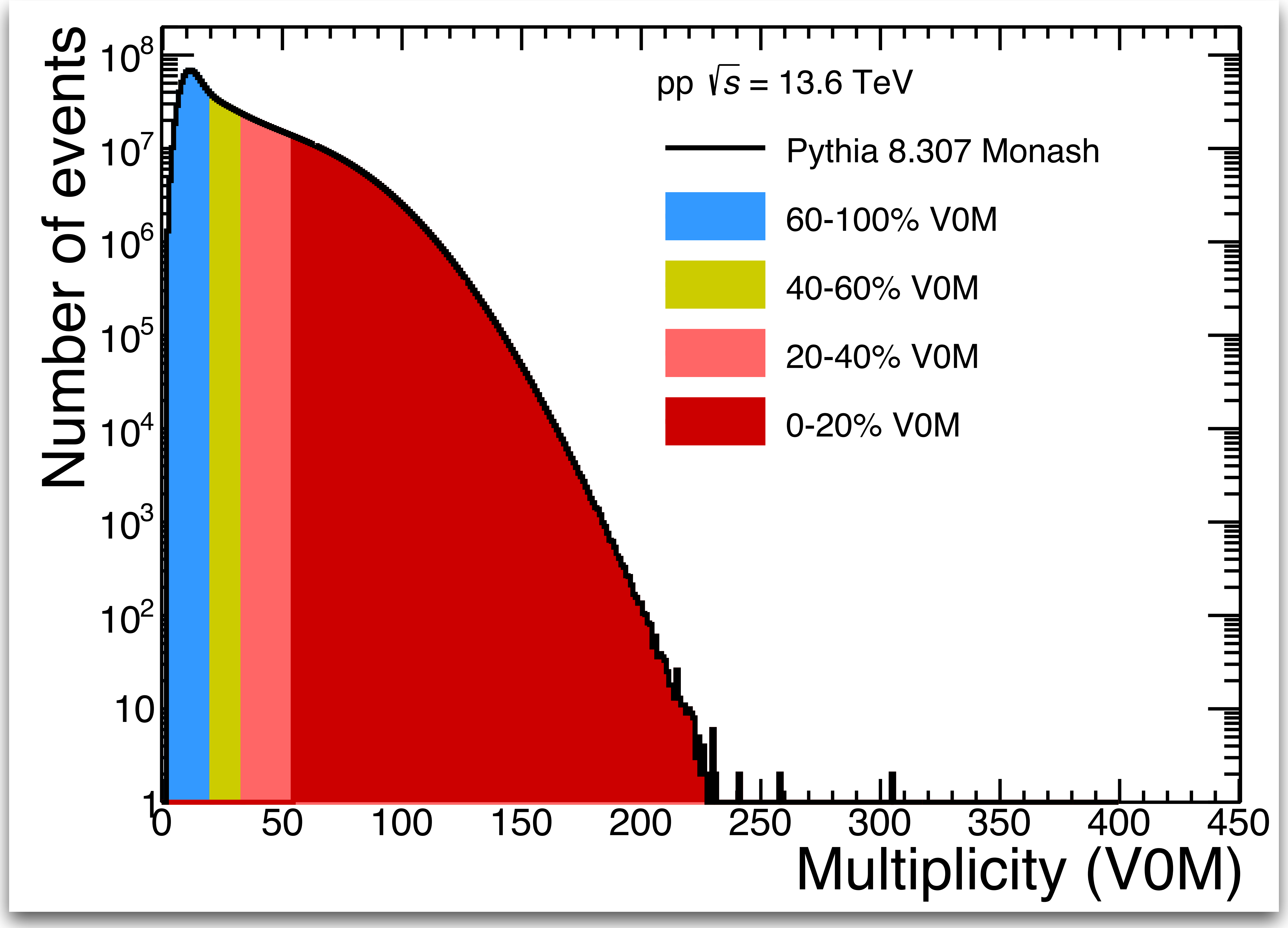
$$\rho = \frac{\sqrt{\sum_i^{N_{\rm cell}} \left(N_{\rm ch}^i - \langle N_{\rm ch}\rangle\right)^2 / N_{\rm cell}^2}}{\langle N_{\rm ch}\rangle}$$

- Based on MC simulations, flattenicity in the pseudorapidity interval covered by ALICE V0A and V0C detectors is strongly correlated with the global shape of the event





Event classification (example)



In this case mult. V0M is the number of charged particles registered in $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

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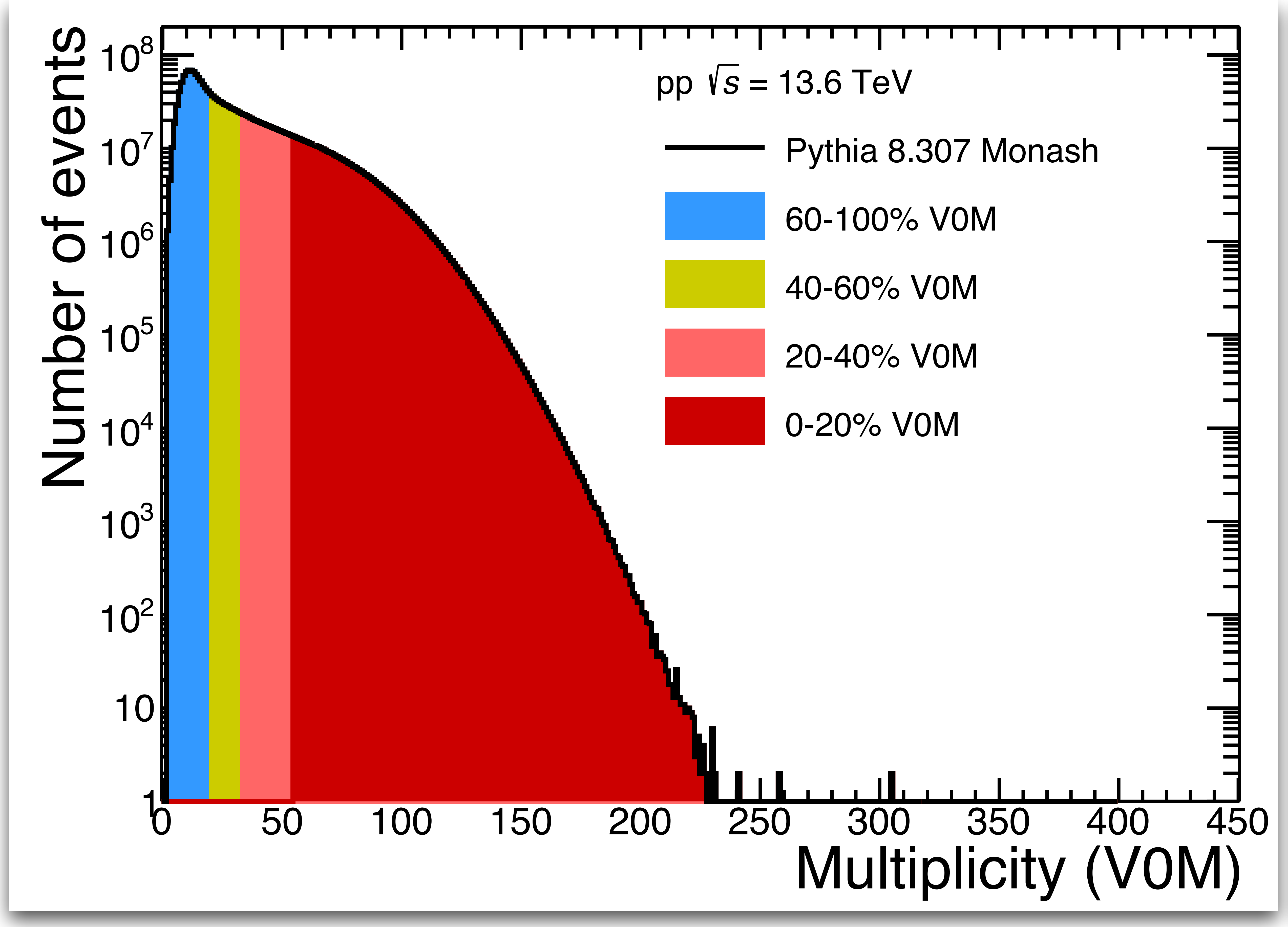
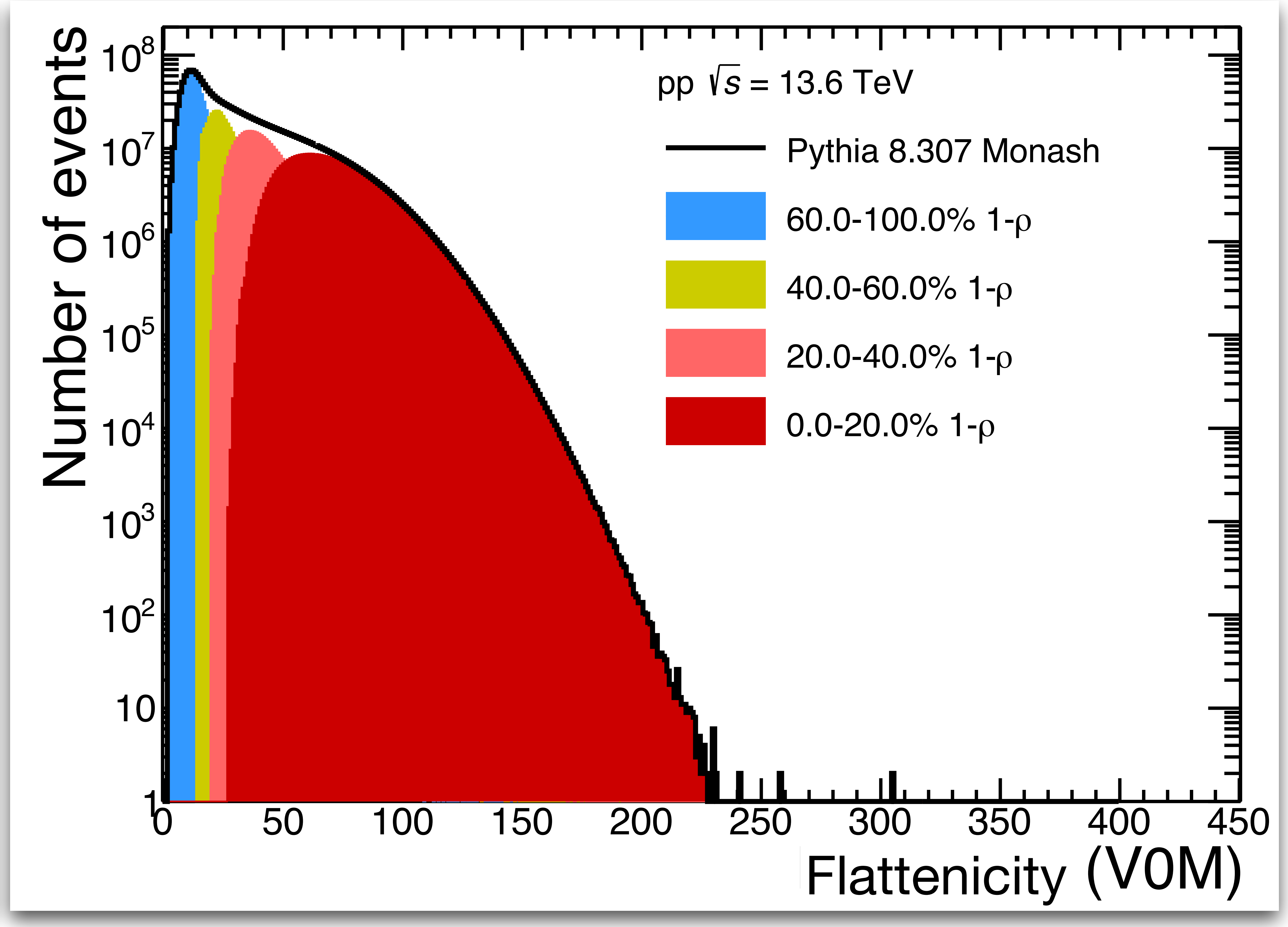


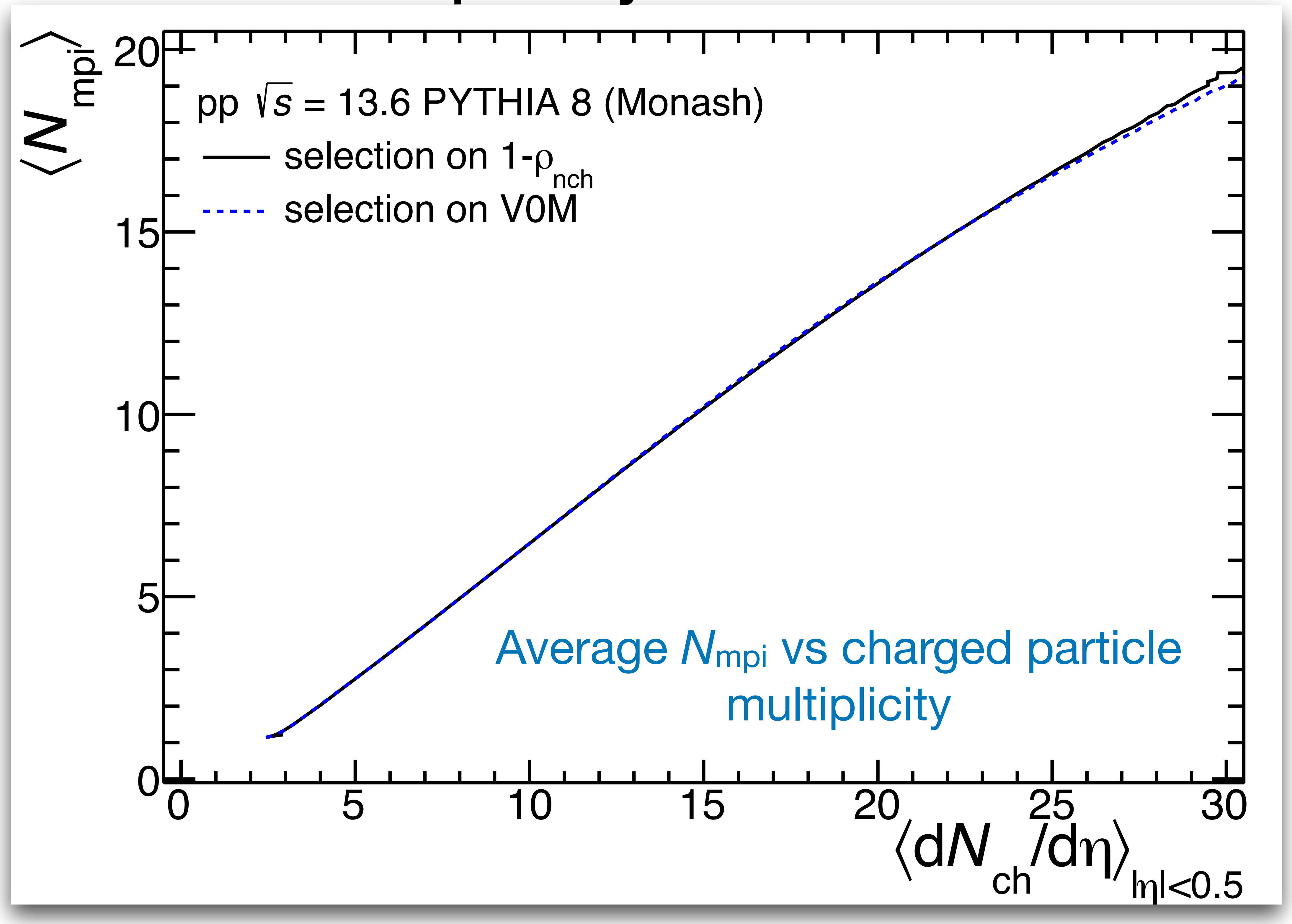


In this case mult. V0M is the number of charged particles registered in $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

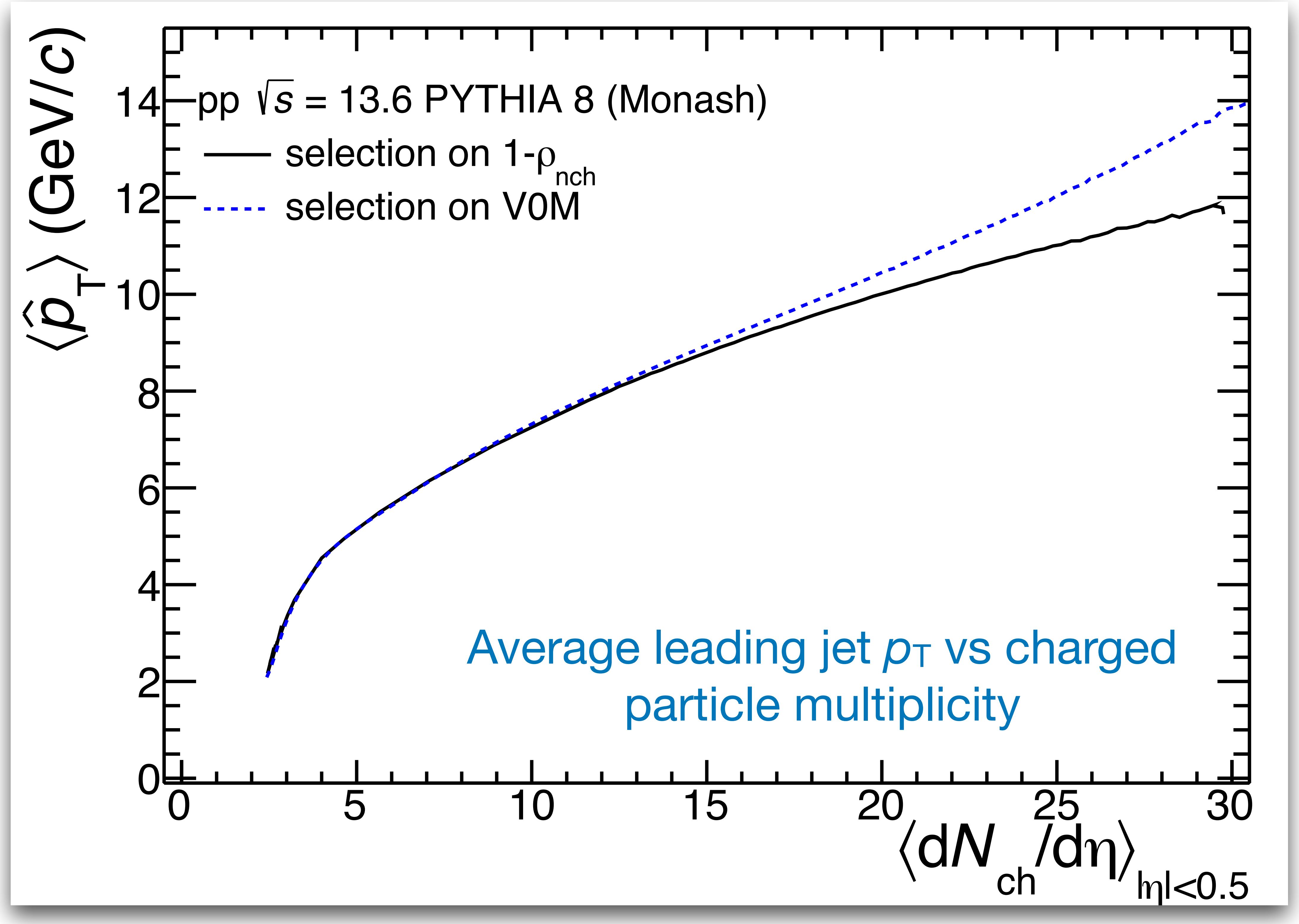
In this case $1-\rho$ is calculated using the charged particles registered in $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

Sensitivity of flattenicity to MPI

- Same sensitivity to MPI as the V0M multiplicity estimator



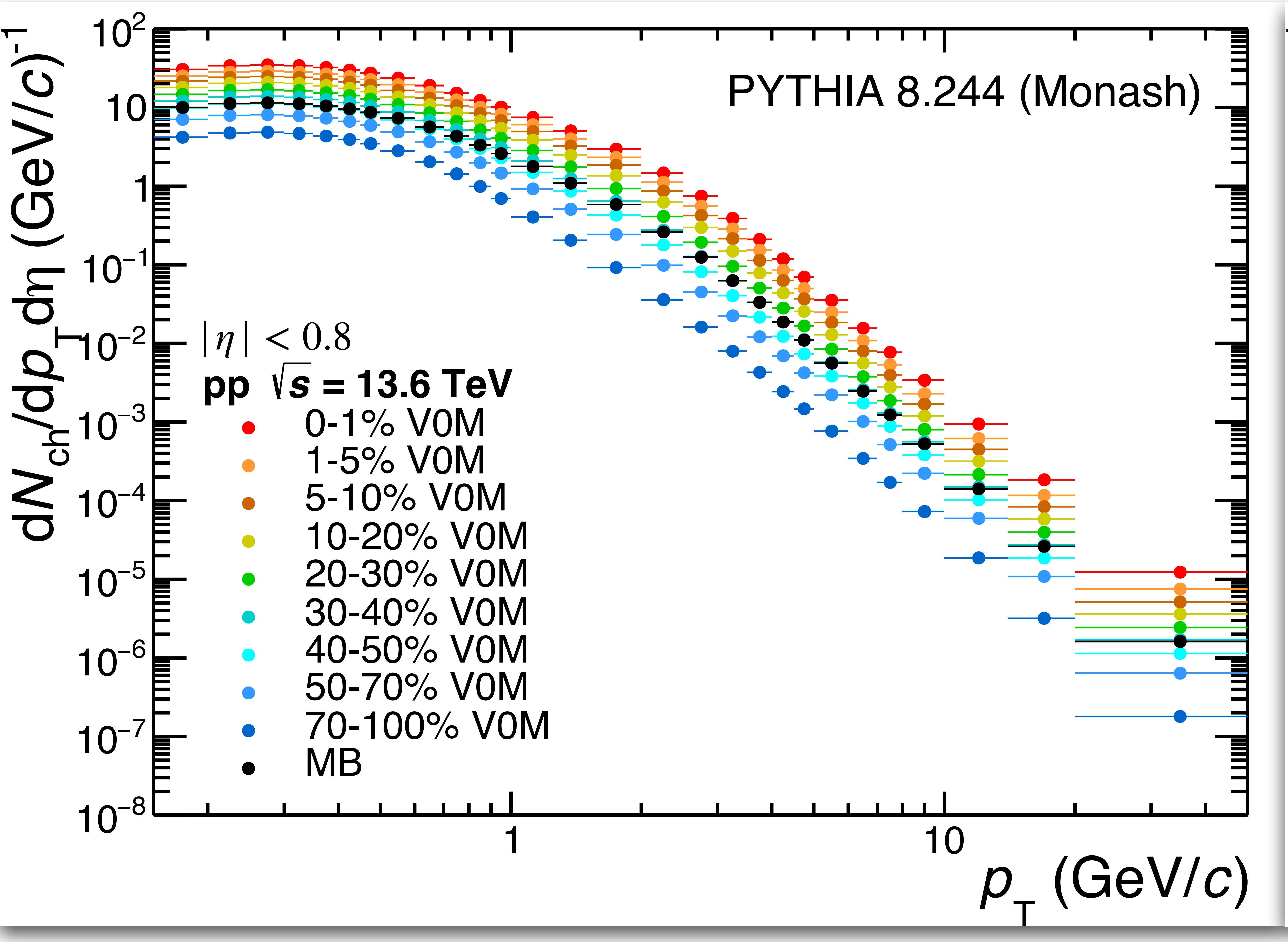
- Flattenicity selects "softer" pp collisions than the V0M estimator



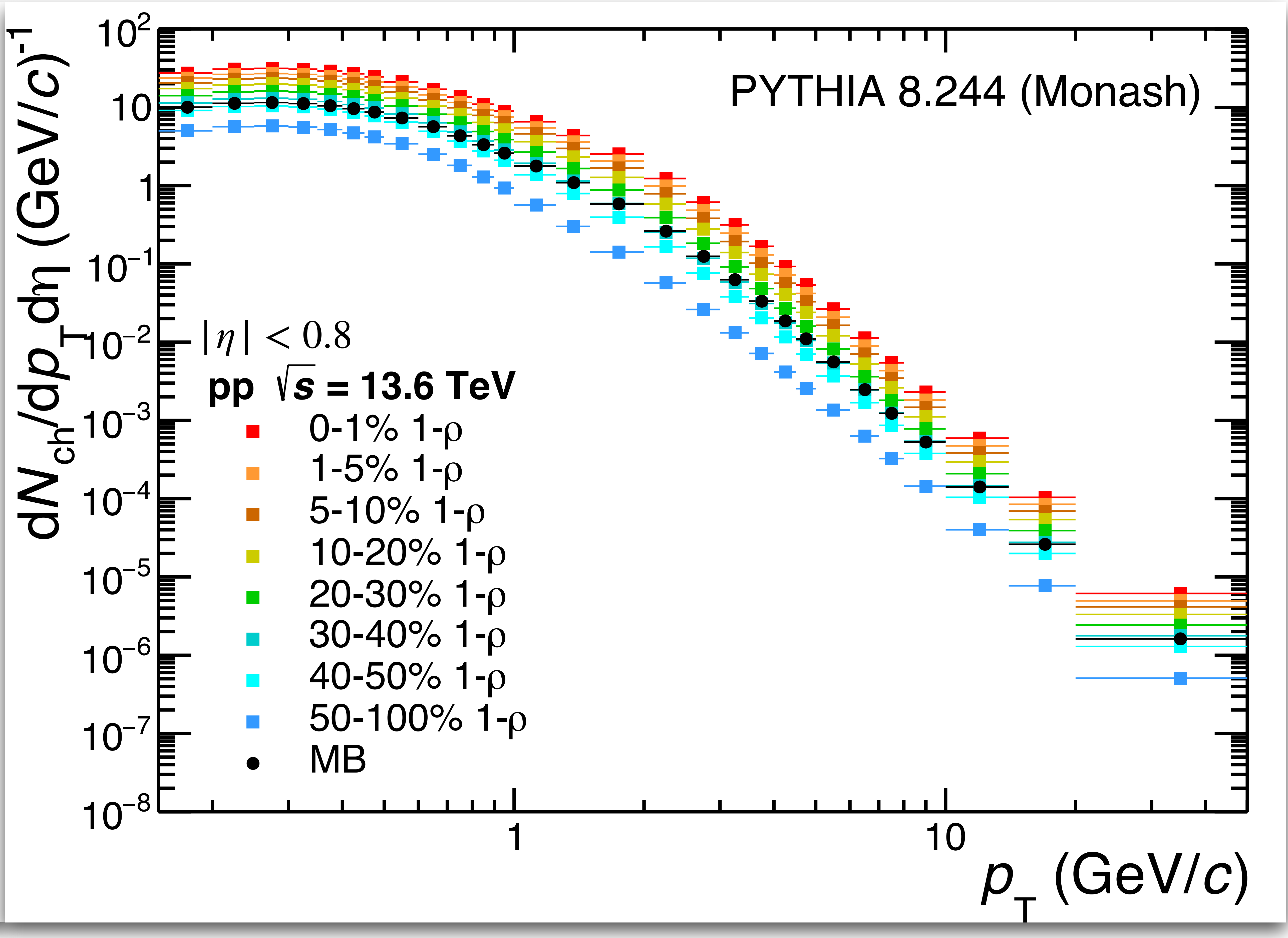
More details here: arXiv:2211.06093, A. Ortiz, A. Khuntia, O. Vázquez, S. Tripathy, G. Bencédi, S. Prasad, F. Fan

Effects in transverse momentum spectra

Selection based on V0M



Selection based on flattenicity



Effects in transverse momentum spectra

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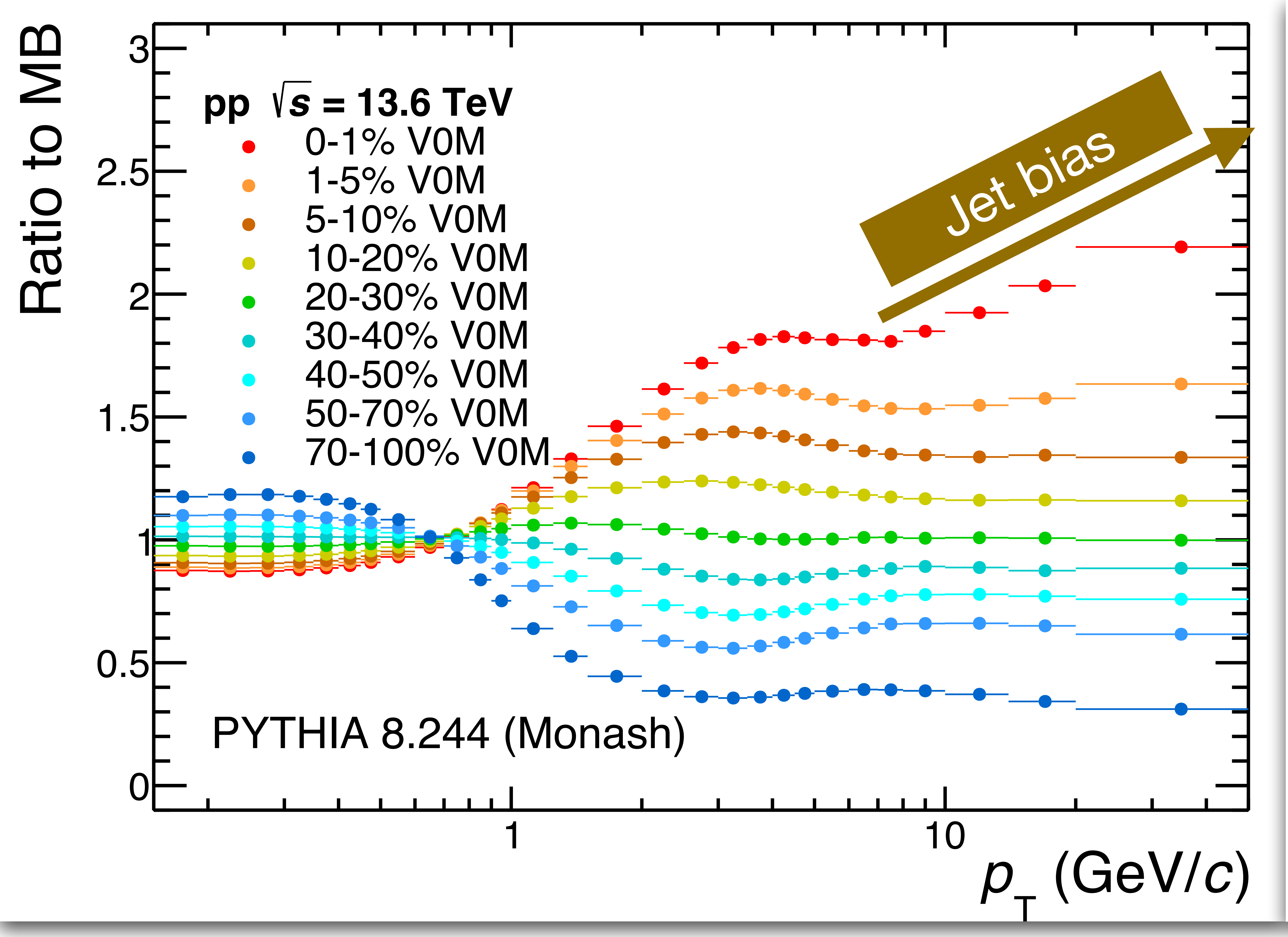
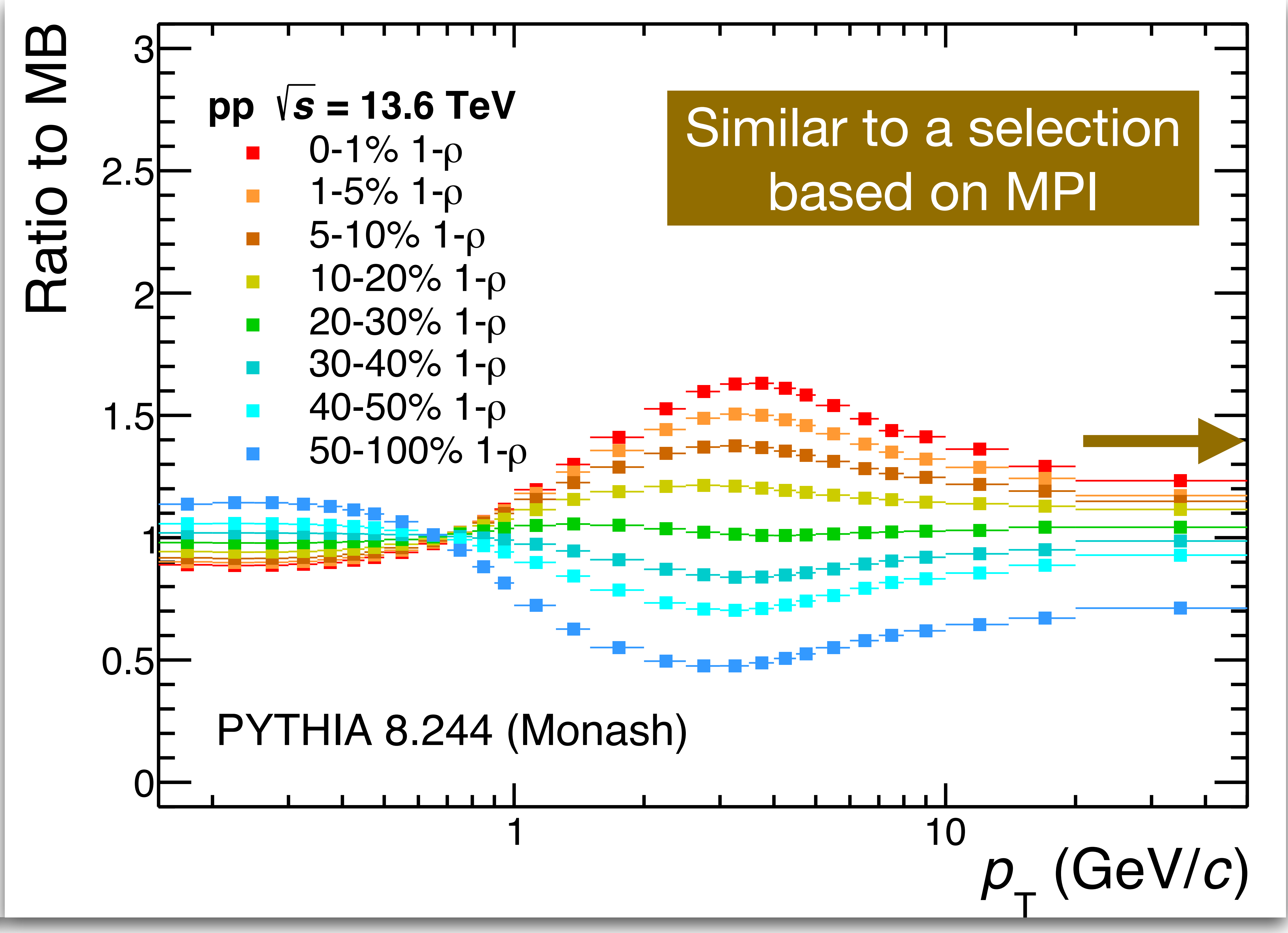


Selection based on flattenicity

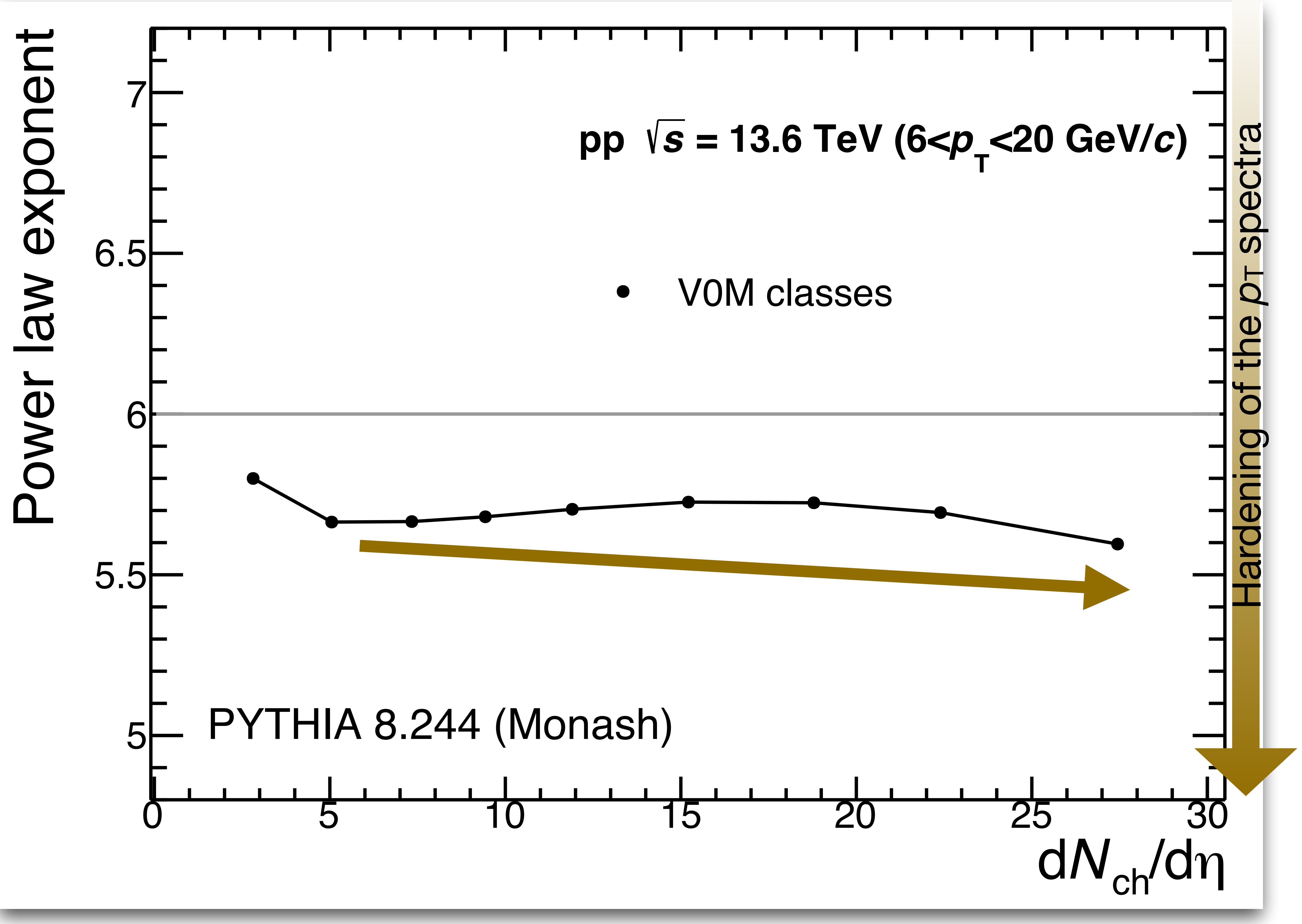


For this ratio each p_{T} spectra was normalised to the average multiplicity

Quantification of the bias towards hard physics

Quantification of the bias towards hard physics

Selection based on V0M



Quantification of the bias towards hard physics

Softer interactions are selected using flattenicity than V0M multiplicity

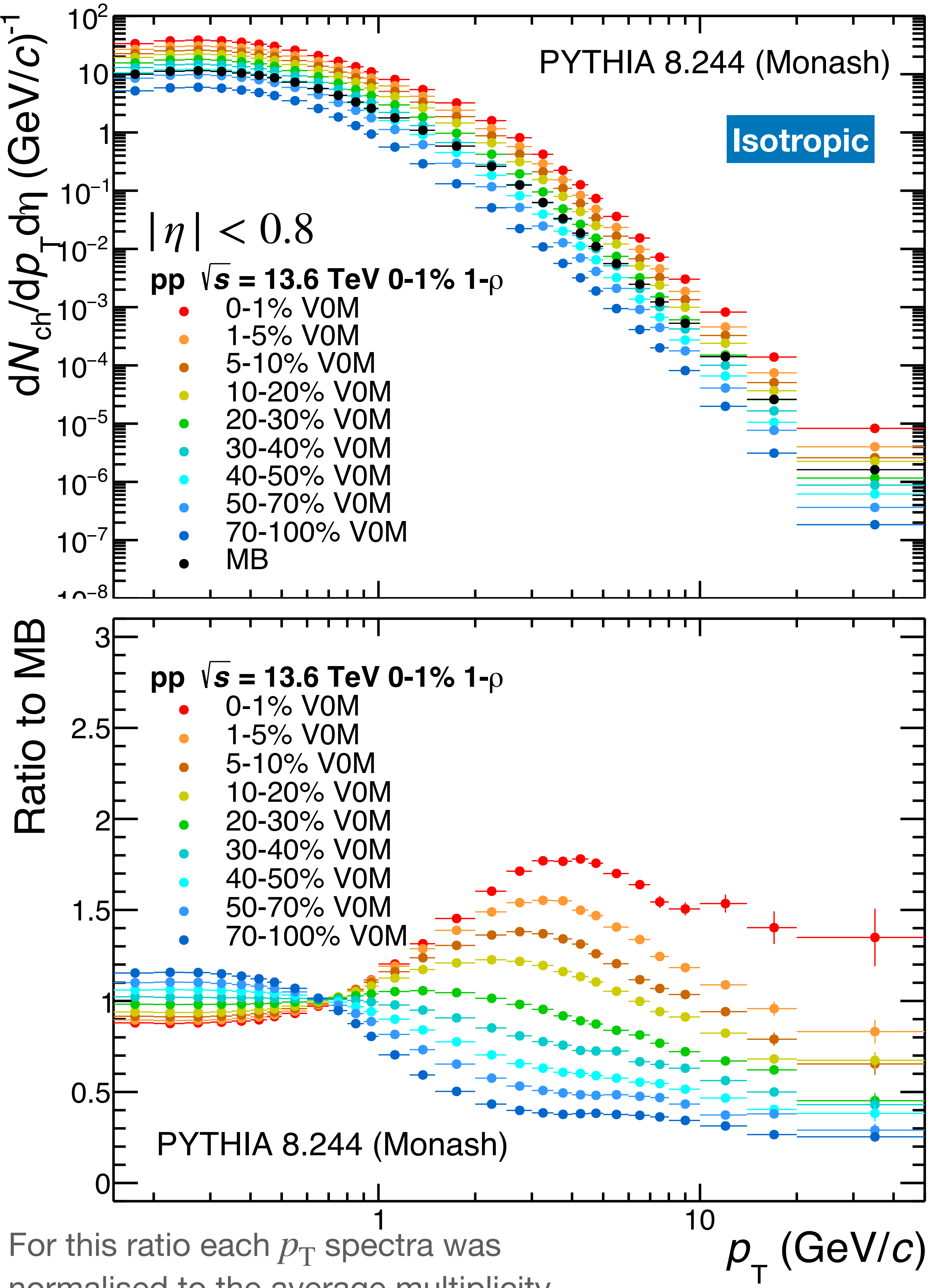
Double differential study

Flattenicity as a function of V0M multiplicity

Multiplicity increase

Isotropic limit at forward rapidity

p_T spectra as a function of flattenicity (I)

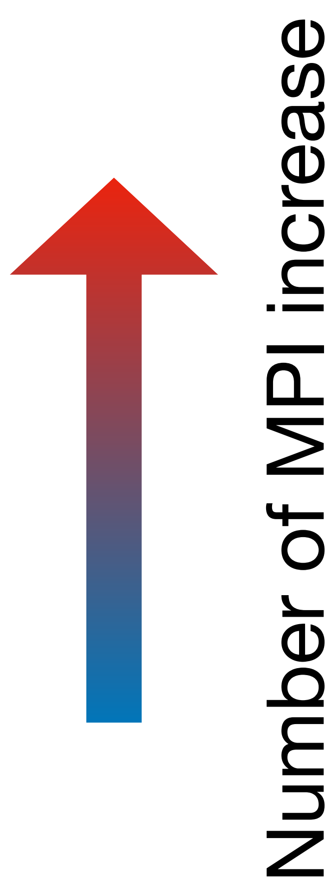


For this ratio each p_{T} spectra was normalised to the average multiplicity

$0-1\,\%\ 1-\rho$: particles are isotropically distributed in pseudorapidity and azimuthal angle

These events are dominated by soft parton-parton scatterings

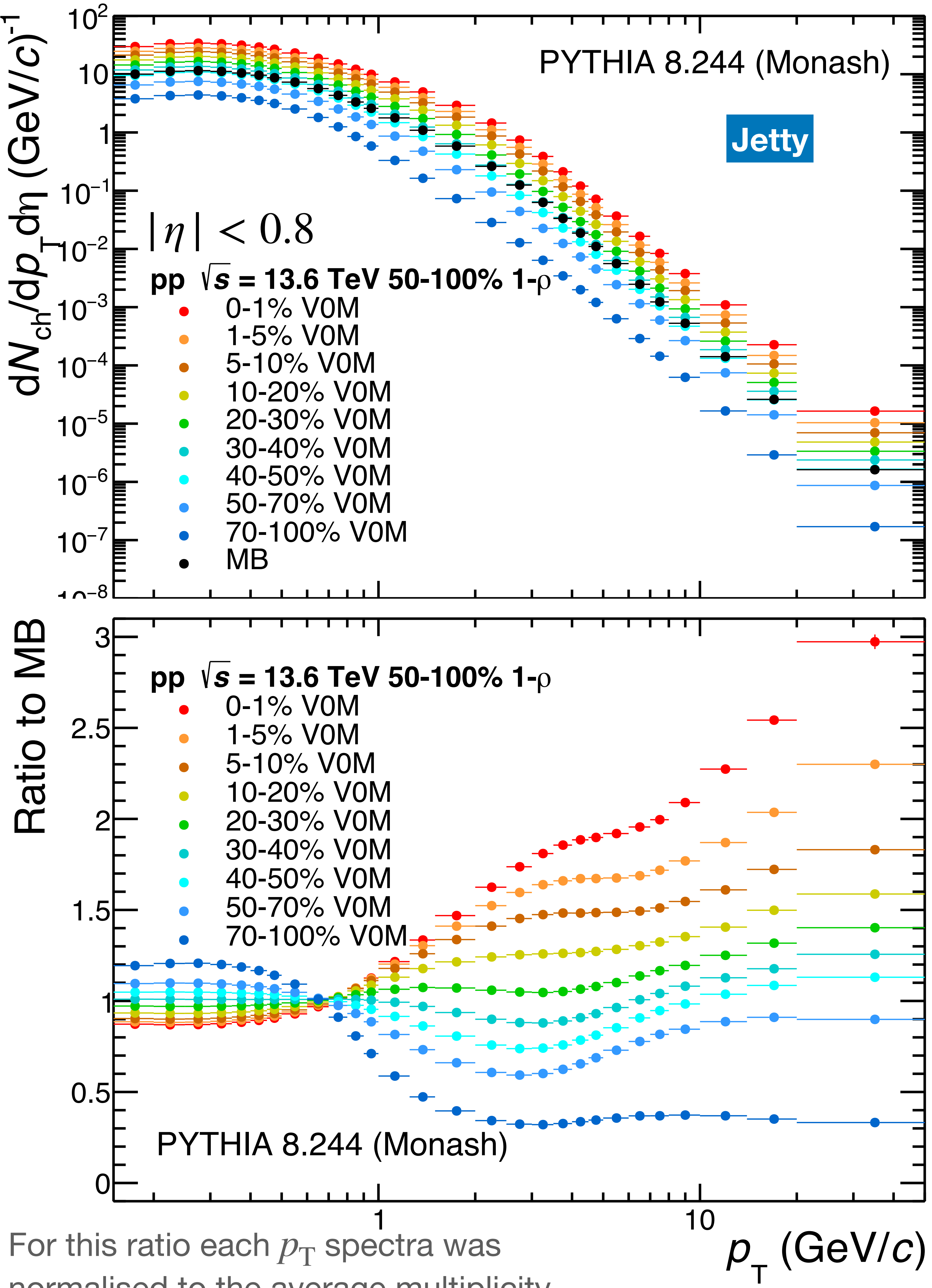
The study as a function of V0M multiplicity helps to control the number of “soft” parton-parton scatterings



Relative to MB a bump structure is built going from low to high multiplicity ($\propto N_{\mathrm{mpi}}$)

- Similar structure is observed in $R_{\mathrm{p-Pb}}$

p_T spectra as a function of flattenicity (II)



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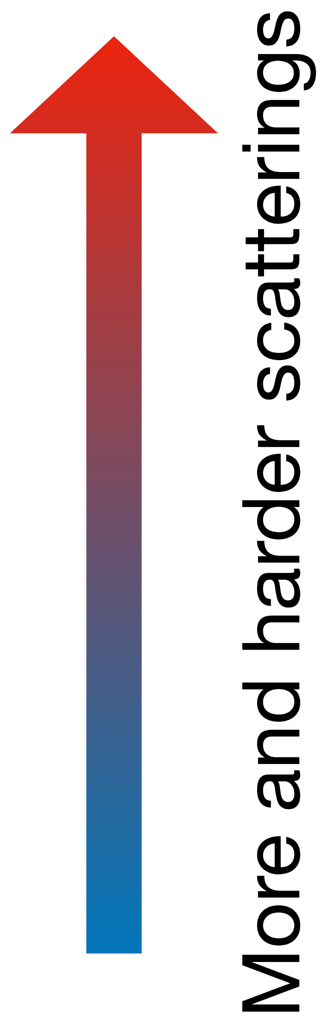


$50-100\,\%\ 1-\rho$: hard events

These events are due to jets (relatively high p_T) + UE

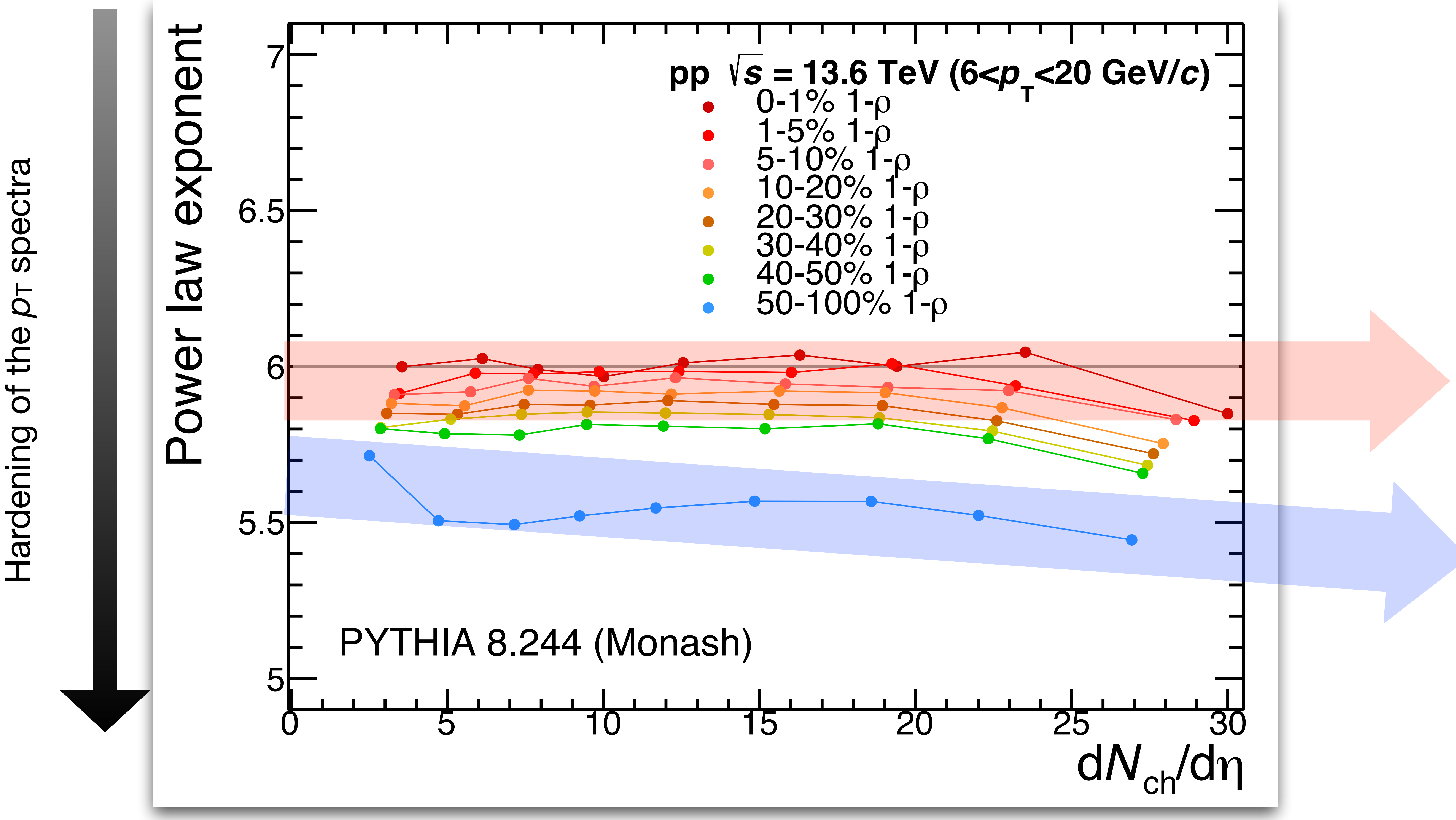
Relative to MB going from low to high multiplicity ($\propto N_{\rm mpi}$) the p_T spectra get harder

Similar behaviour like in Pythia

Hard vs soft particle production (III)

Characterisation of the soft particle production:

the charged particle multiplicity is derived from the spectra (integration)



Isotropic events: modest multiplicity dependence

Jetty events: small reduction of the exponent with multiplicity increase

Summary and outlook

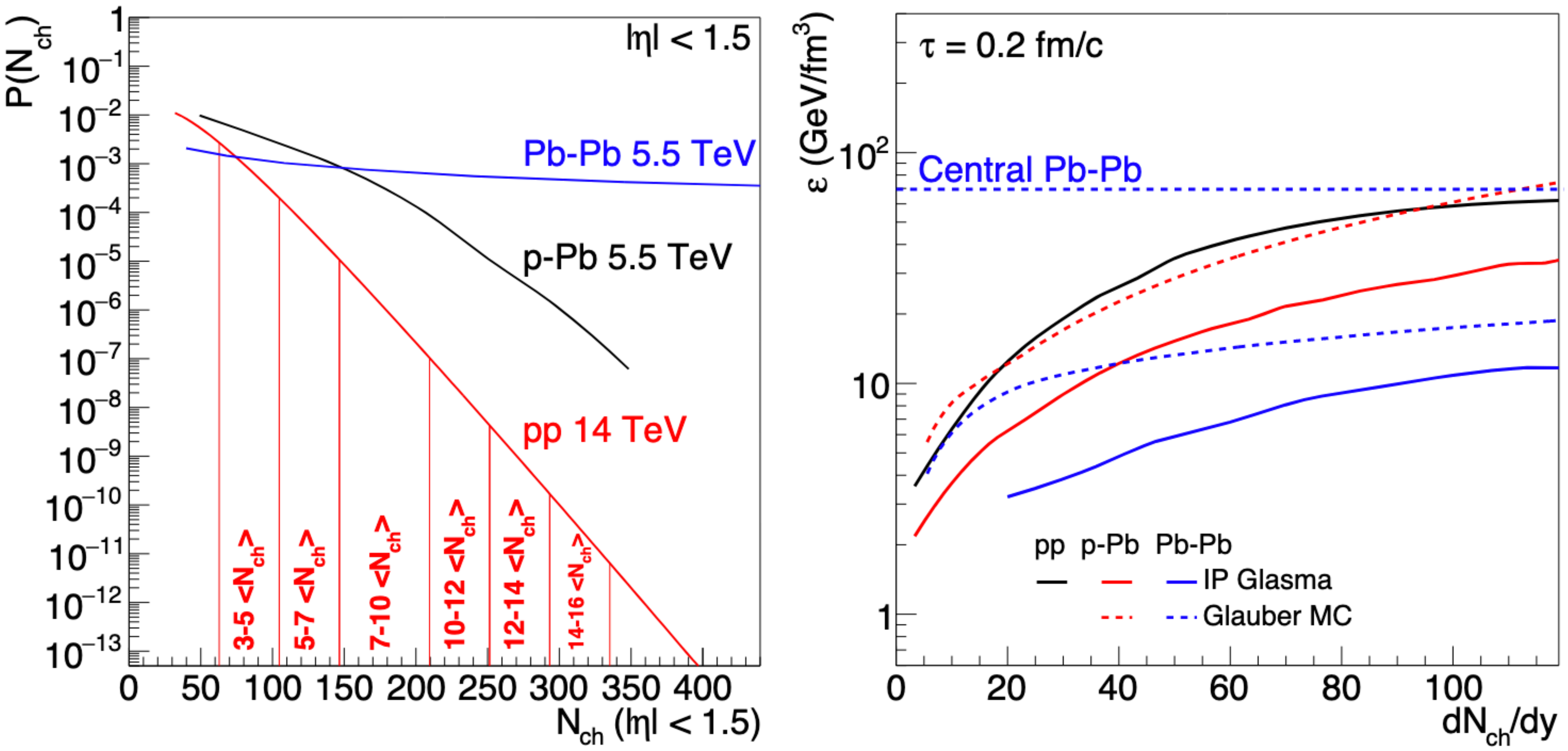
Experiments have produced several good results in pp collisions using different event classifiers based on multiplicity and/or event shapes, in run 3 and beyond we could refine our studies by reducing the unwanted biases introduced by the event activity estimators used so far

Flattenicity is a new event classifier that can help to reduce the unwanted biases, it is very sensitive to MPI

Proton-proton collisions dominated by “soft” physics (several semi-hard scatering within the same pp collision) look like a good laboratory to improve our understanding of the heavy-ion-like effects observed in small collision systems

Backup

Energy density in hm pp collisions



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