MCnet-CTEQ Summer School 2021 VIRTUAL

Organised by:

New event classifiers for the analysis of pp data

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MPI and HI-like effects

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Striking similarities between numerous observables have been observed across different collision systems at both RHIC and LHC energies, when compared at similar multiplicity

Besides hydrodynamic description, calculations from transport models, hadronic re-scattering, as well as initial state effects have been investigated. Others like Multi-Parton Interactions (MPI), string rope and shoving can also explain some features of data

- Radial flow-like effects emerge in QCD-inspired event generators like Pythia due to color reconnection and MPI, PRL 111 (2013) 042001
- In a model based on the QCD theory of MPI, QCD interference is shown to give rise to values for $v_n\{2\}, v_n\{4\}, n$ even, that persists in high N_{mpi} events: B. Block, C. D. Jäkel, M. Strikman, U. A. Wiedemann, JHEP 12 (2017) 074

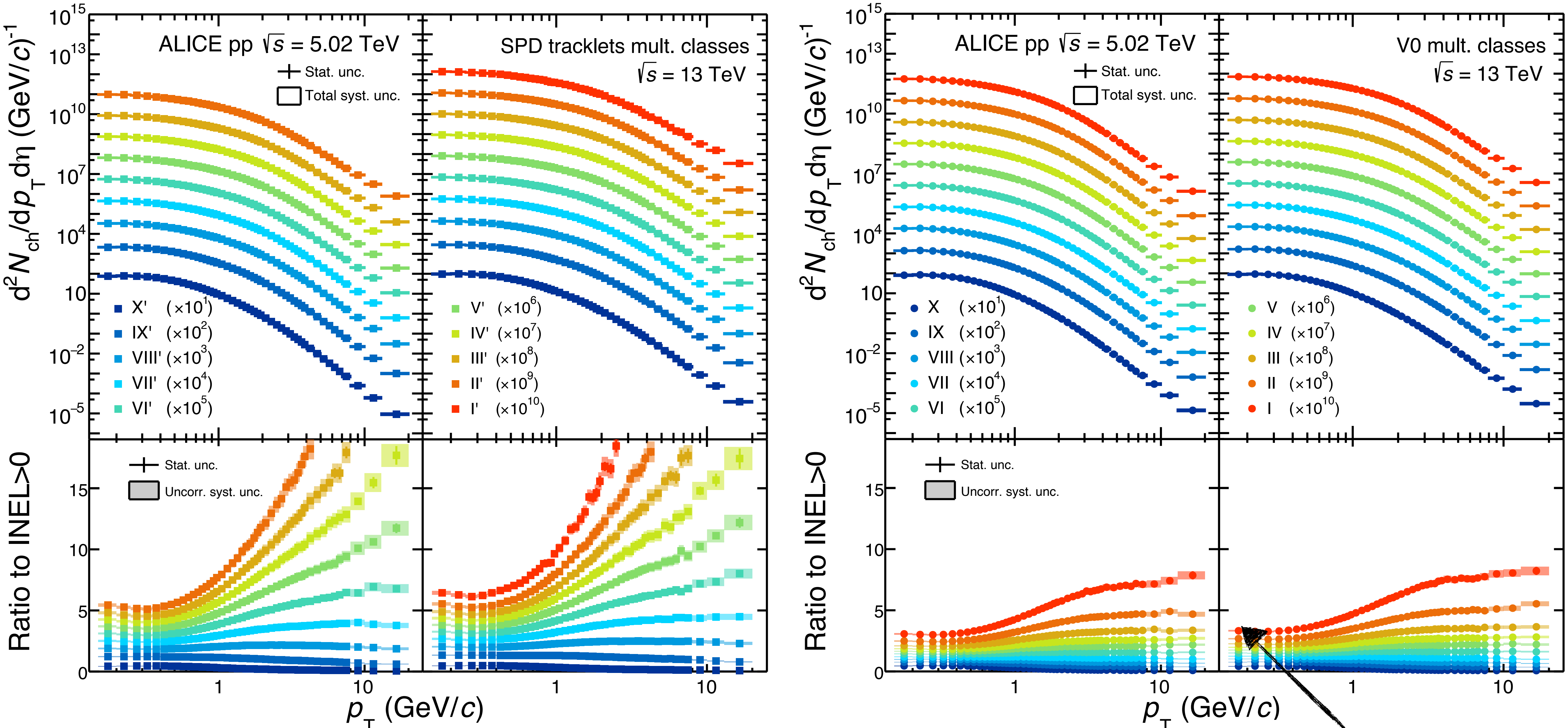
Selection biases

Particle production vs N_{ch}

ALICE, arXiv:1905.07208

Multiplicity selection at mid-pseudorapidity

Multiplicity selection at forward rapidity

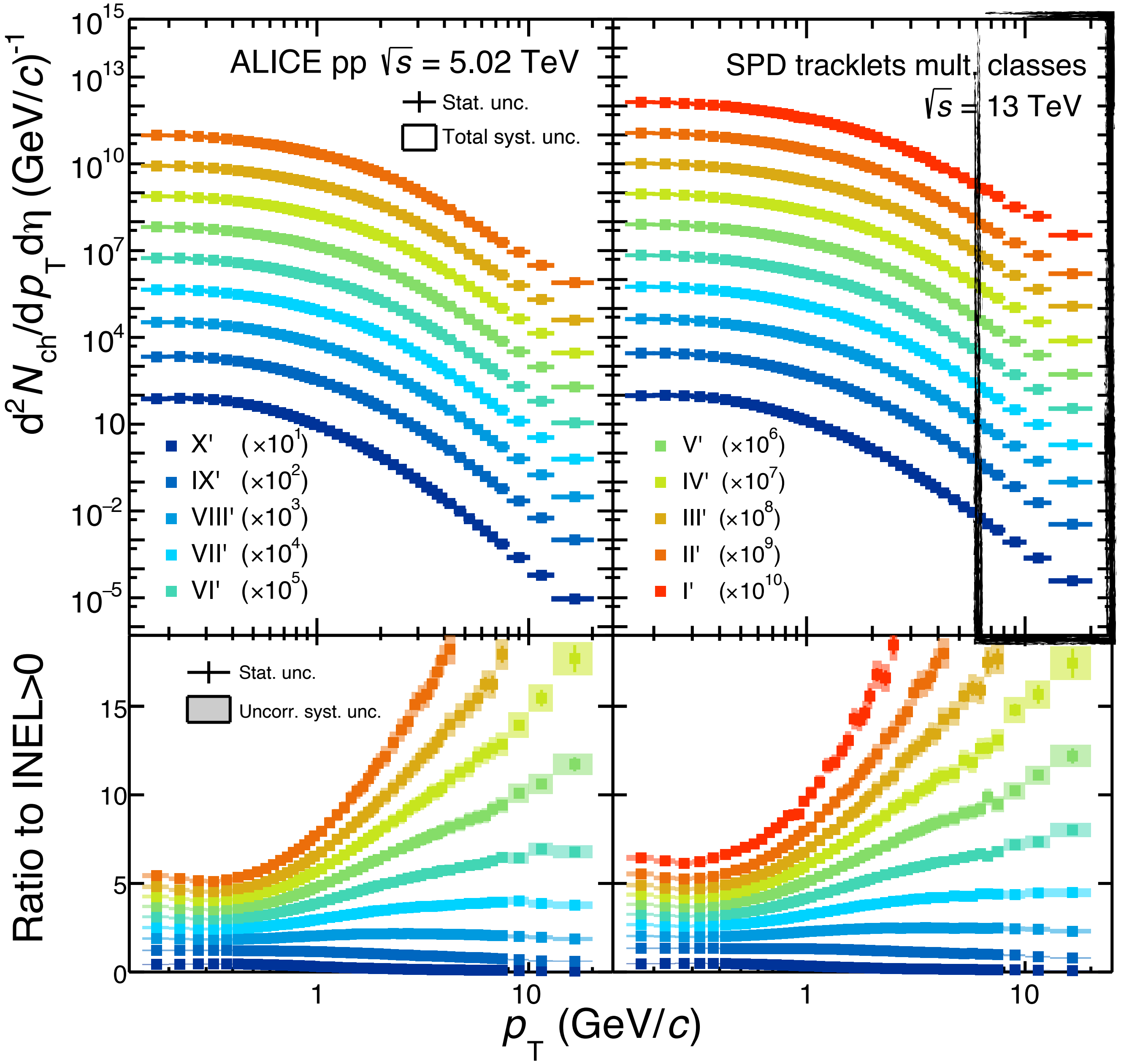


Correlation between inclusive multiplicity (low p_T) and high-p_T particle production

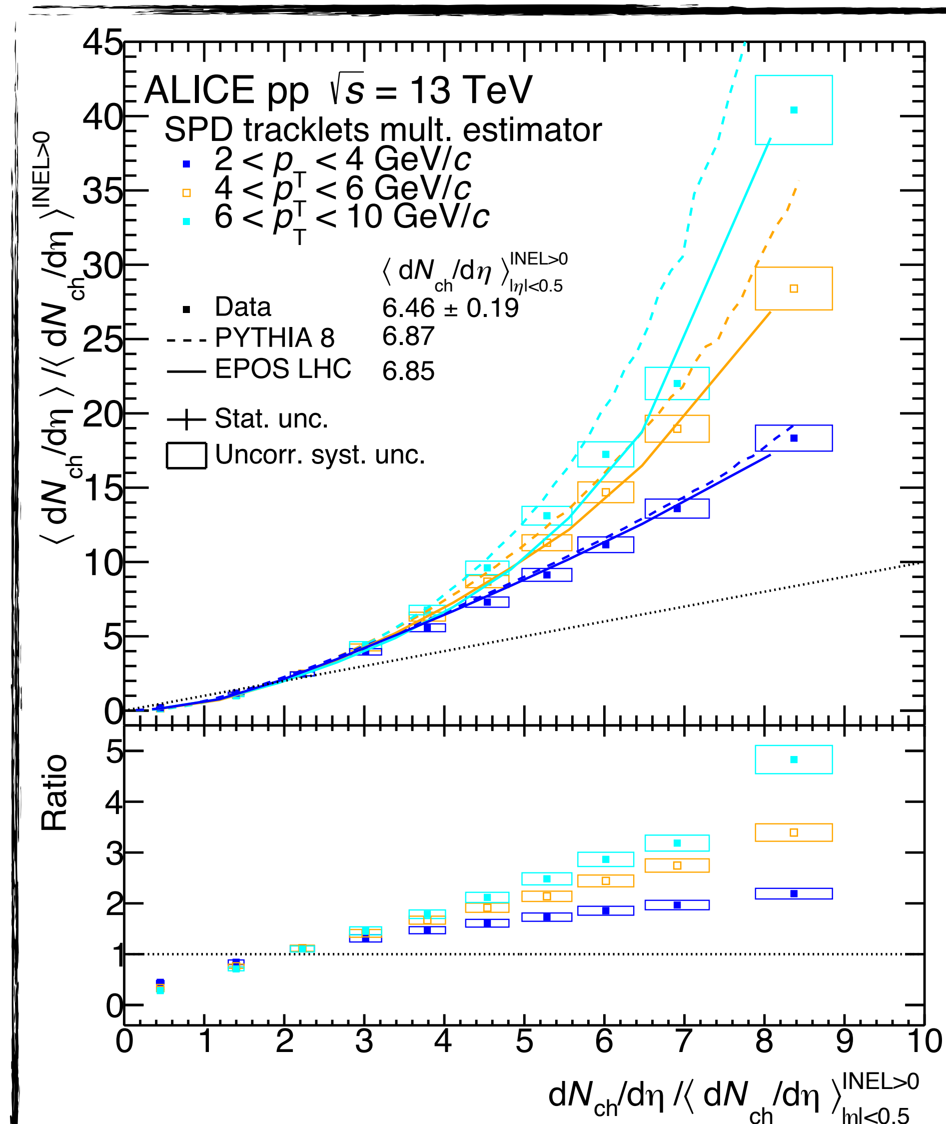
Lower multiplicity reach for the highest V0M multiplicity class than that for the highest SPDtracklets multiplicity class

Particle production vs N_{ch}

Multiplicity selection at mid-pseudorapidity



ALICE, arXiv:1905.07208

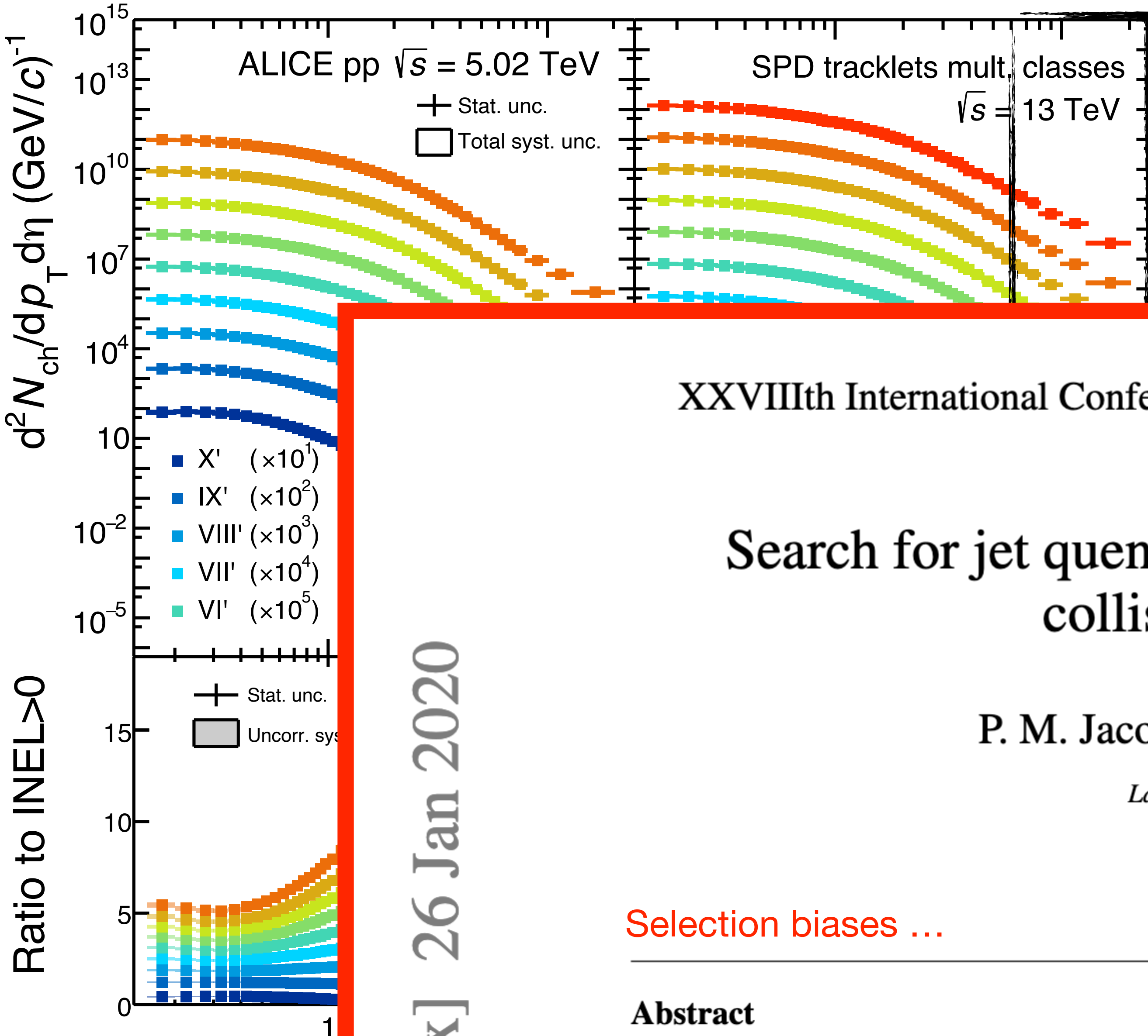


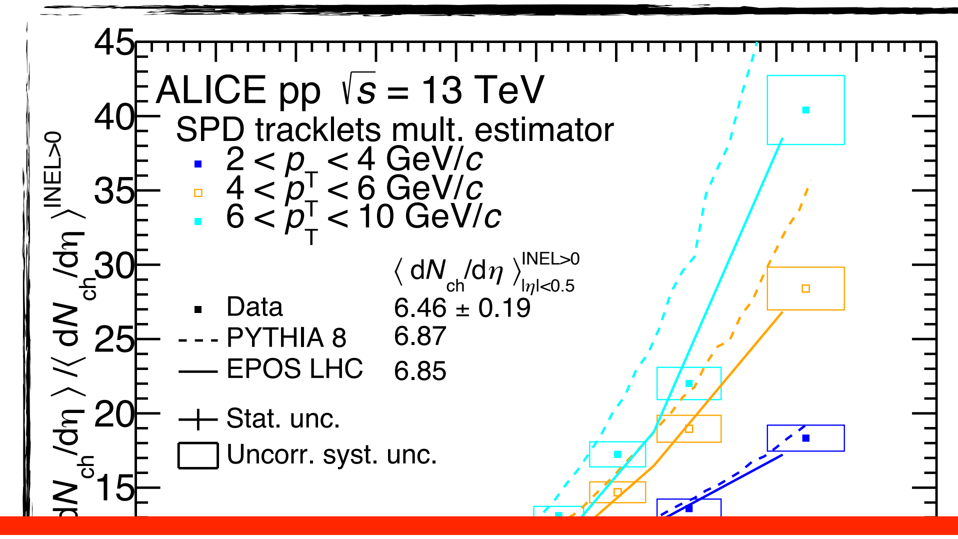
The results illustrate the role of hard physics in high multiplicity events

Non-linear increase of the high-p_T particle production as a function of multiplicity. EPOS LHC describes the relative yields better than PYTHIA, but it fails in describing the spectral shapes at high p_T

Particle production vs N_{ch}

Multiplicity selection at mid-pseudiorapidity





[nucl-ex] 26 Jan 2020

XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2019)

Search for jet quenching effects in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV

P. M. Jacobs for the ALICE Collaboration

Lawrence Berkeley National Laboratory

Selection biases ...

Abstract

The ALICE Collaboration reports a search for jet quenching effects in pp collisions at $\sqrt{s} = 13$ TeV, in events selected on high multiplicity compared to the minimum bias population. The measurement is based on the semi-inclusive acoplanarity distribution of jets recoiling from a high-p_T trigger hadron. Significant broadening of the recoil jet acoplanarity distribution is observed in high multiplicity pp collisions, in both data and in simulations based on the PYTHIA model. Analysis is ongoing to elucidate the origin of this effect.

The result
physics in

Event shapes

Transverse spherocity

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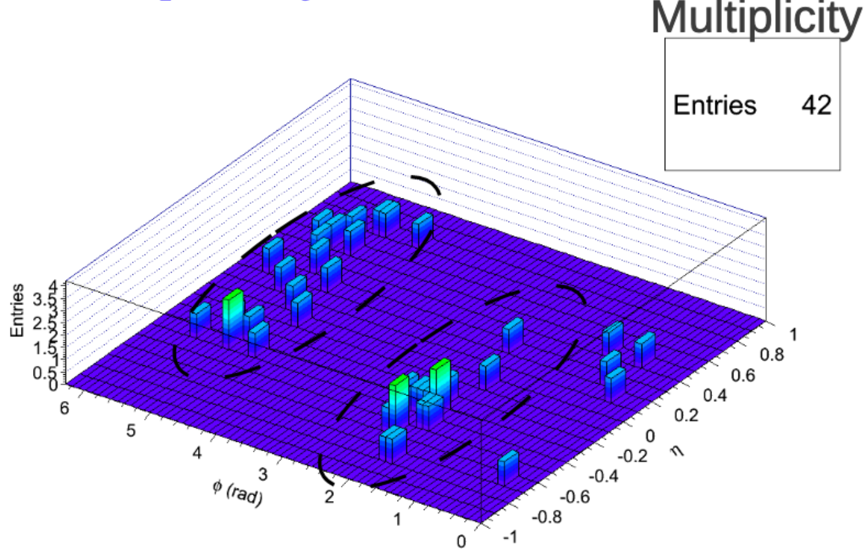
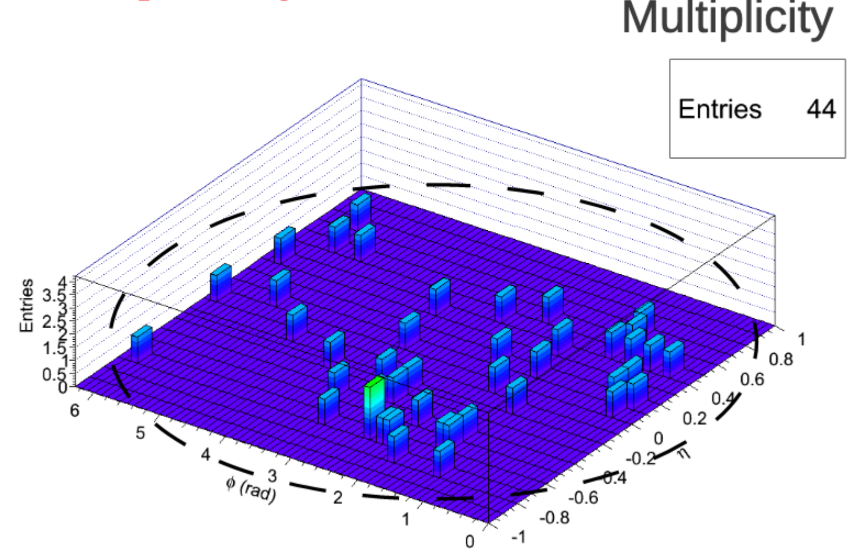
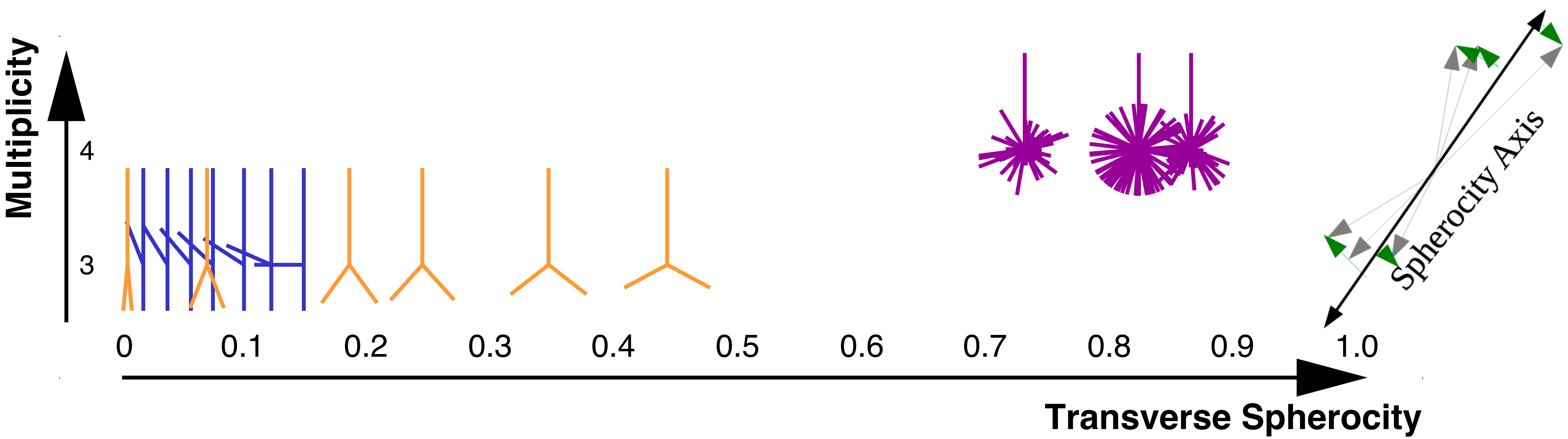
Spherocity=0.09
Sphericity=0.14



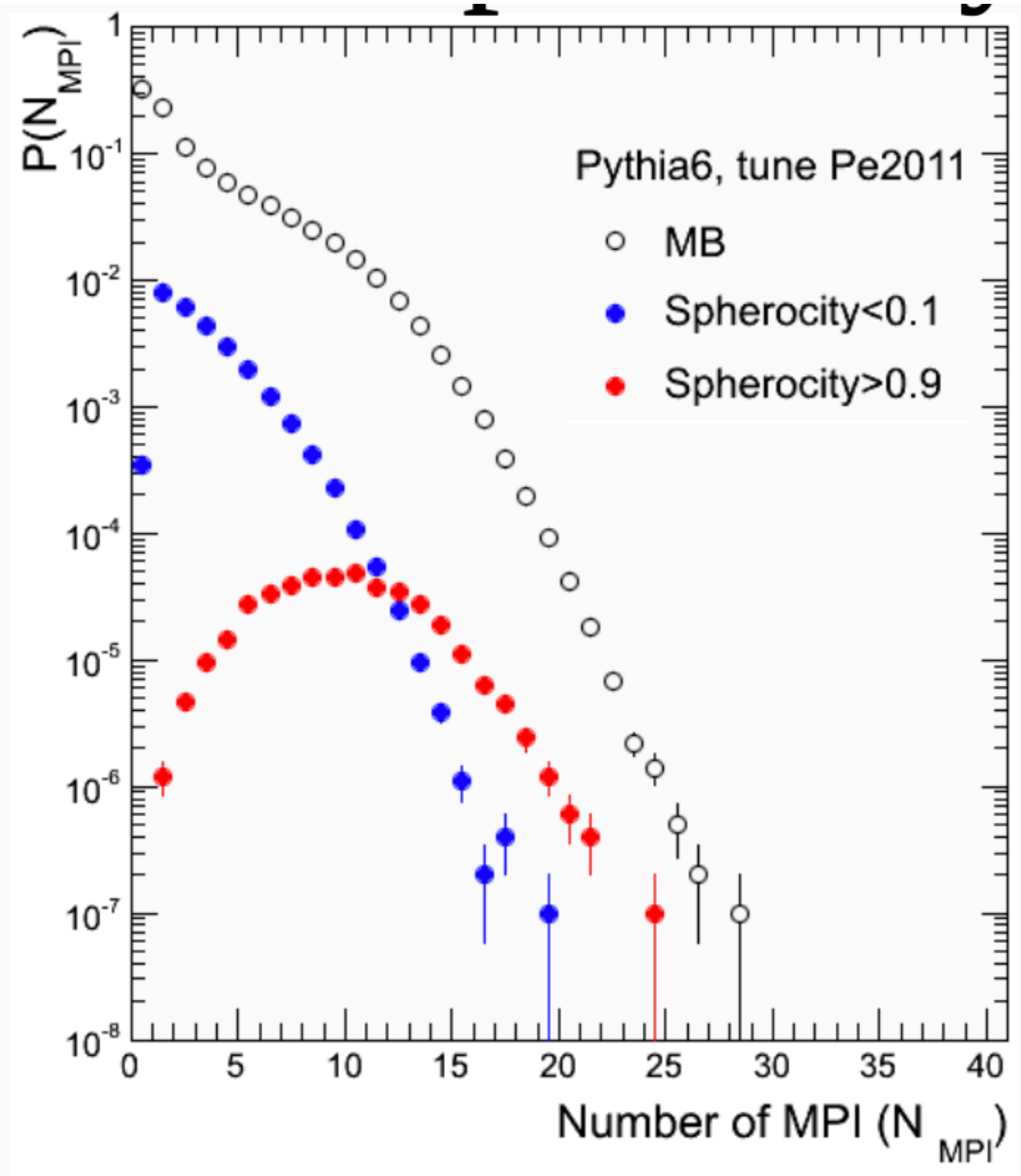
Spherocity=0.96
Sphericity=0.99

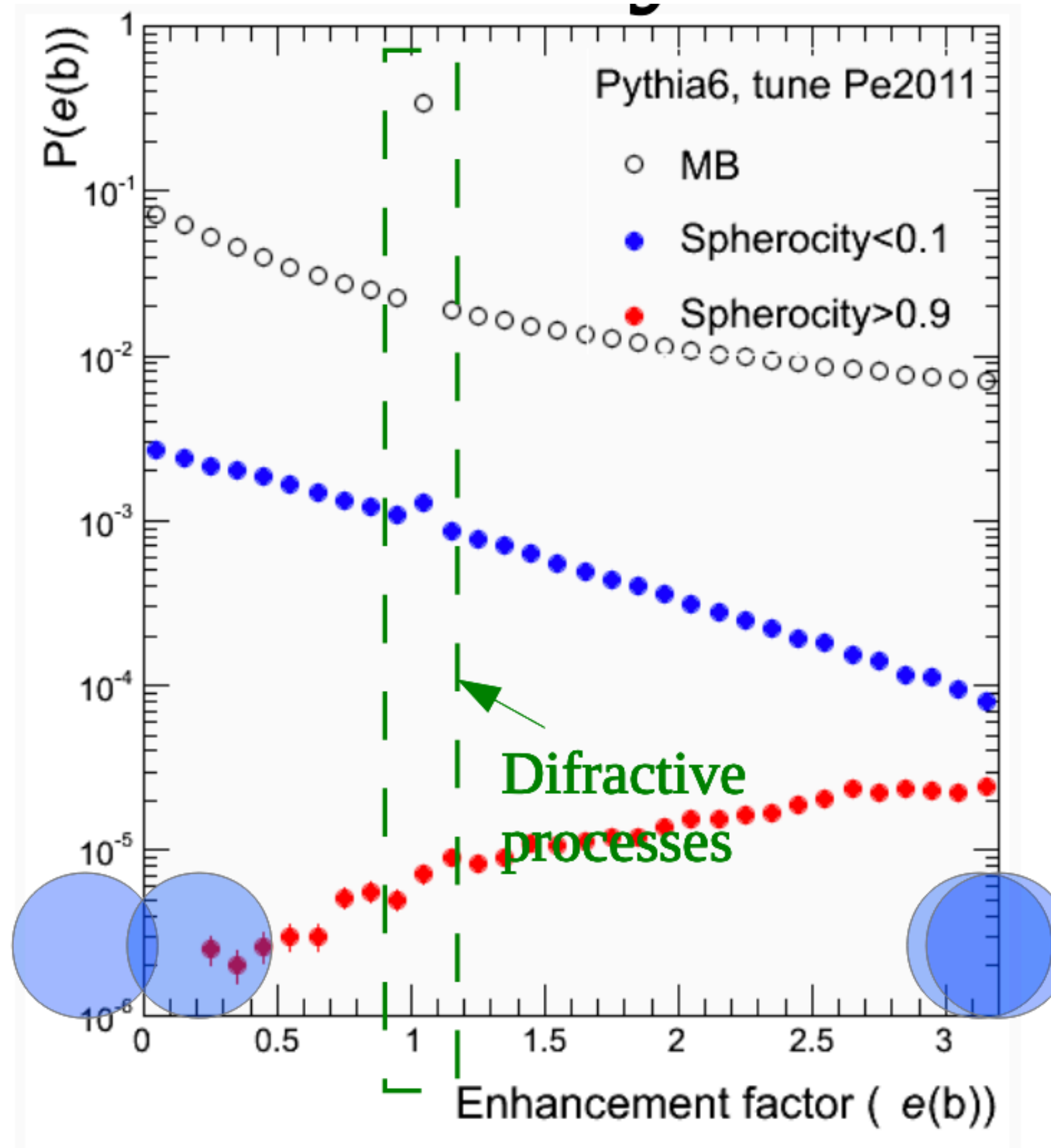


$$S_0 = \min \frac{\pi^2}{4} \left(\frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{\mathrm{n}}|}{\sum_i p_{\mathrm{T},i}} \right)^2$$



Transverse spherocity





First scientific publication

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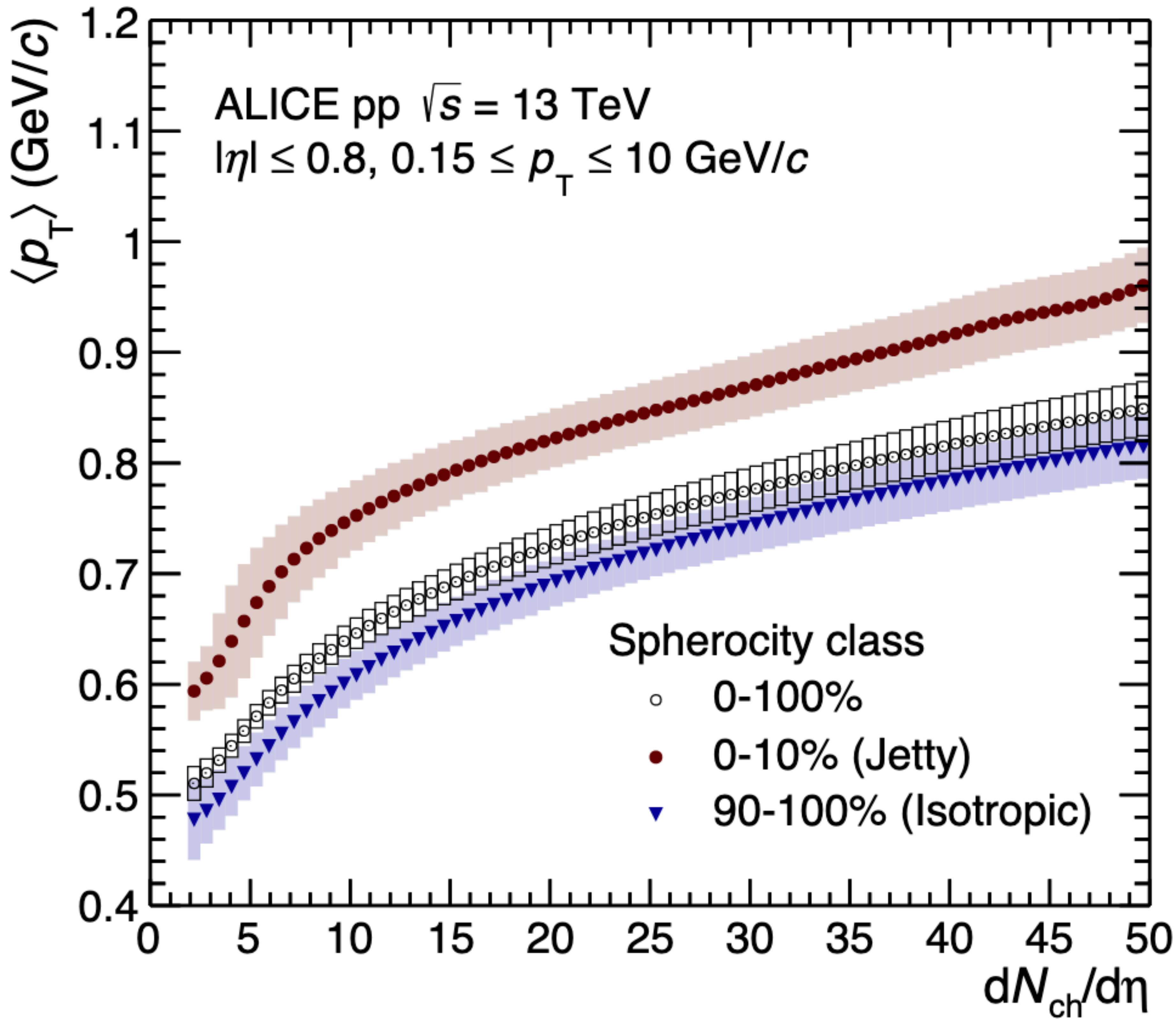
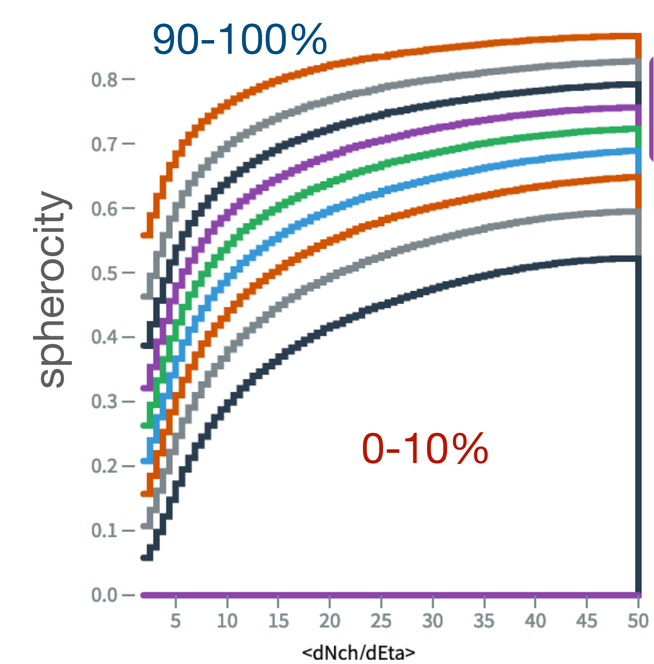
ALICE, EPJC 79, 857 (2019)



Jet-like events:
Higher $<p_T>$ than in MB: expected given the selection of hard pp collisions

Isotropic-like events:
Lower $<p_T>$ than in MB: expected given the selection of soft pp collisions



Importance of data for MC tuning

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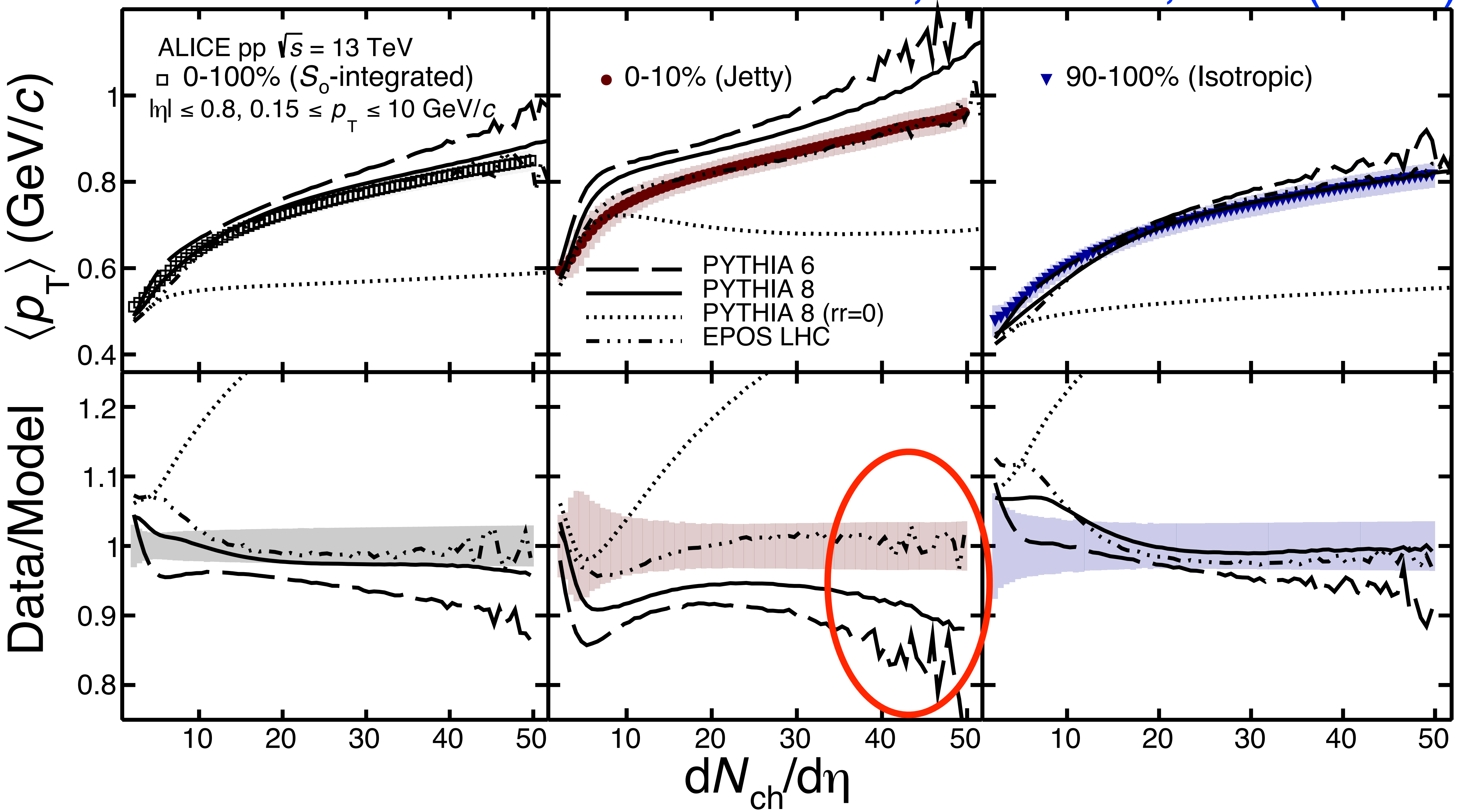
ALICE, EPJC 79, 857 (2019)



PYTHIA predicts a different behaviour for high multiplicity jetty-like events: a third rise of $\langle p_T \rangle$ at $dN_{ch}/d\eta > 30$. This is a surprise because we know that PYTHIA describes better hard physics than EPOS, e.g. ALICE, PRD 99 (2019) no.1, 012016 and PLB 753 (2016) 319-329

The origin of the effect in Pythia

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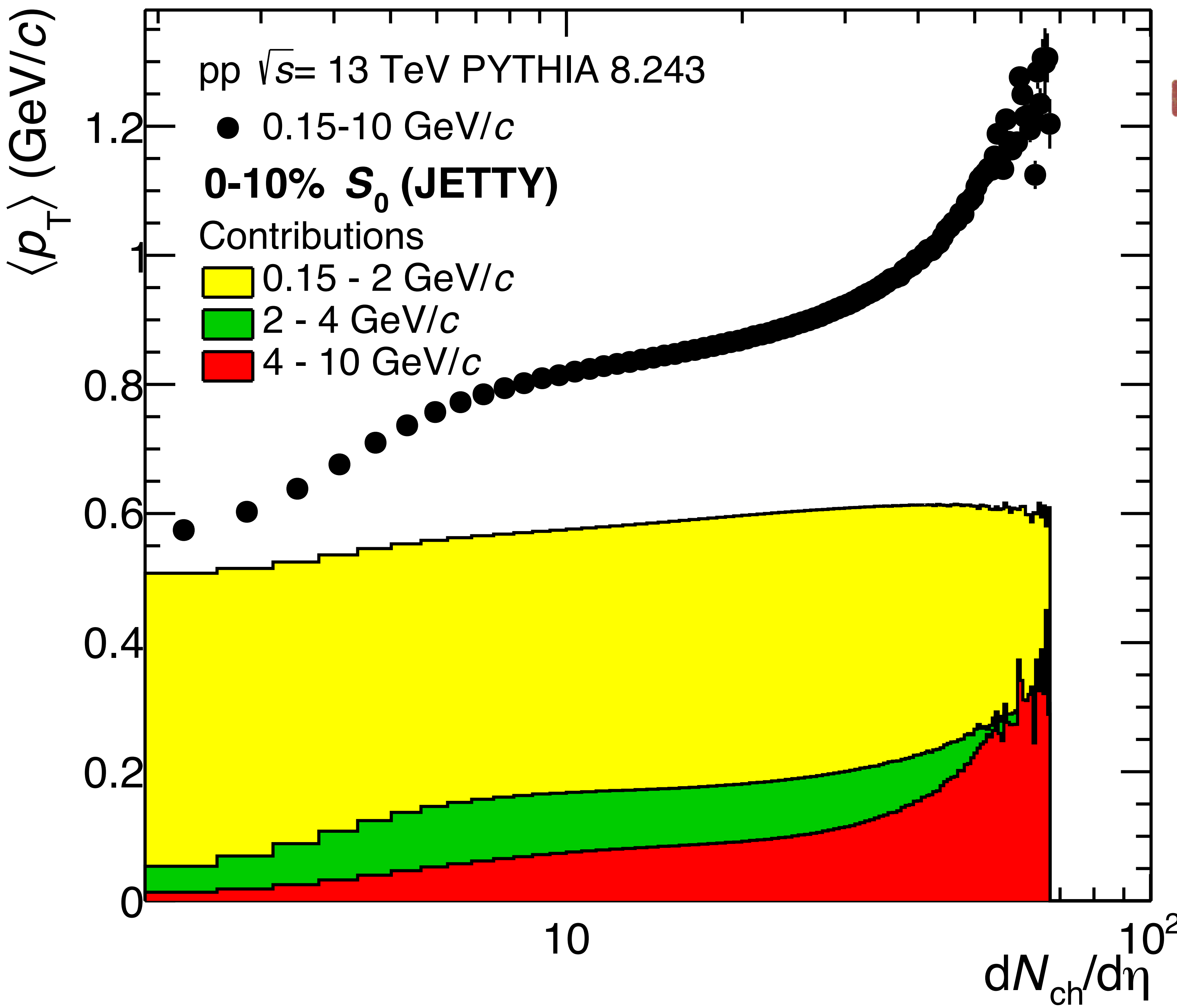
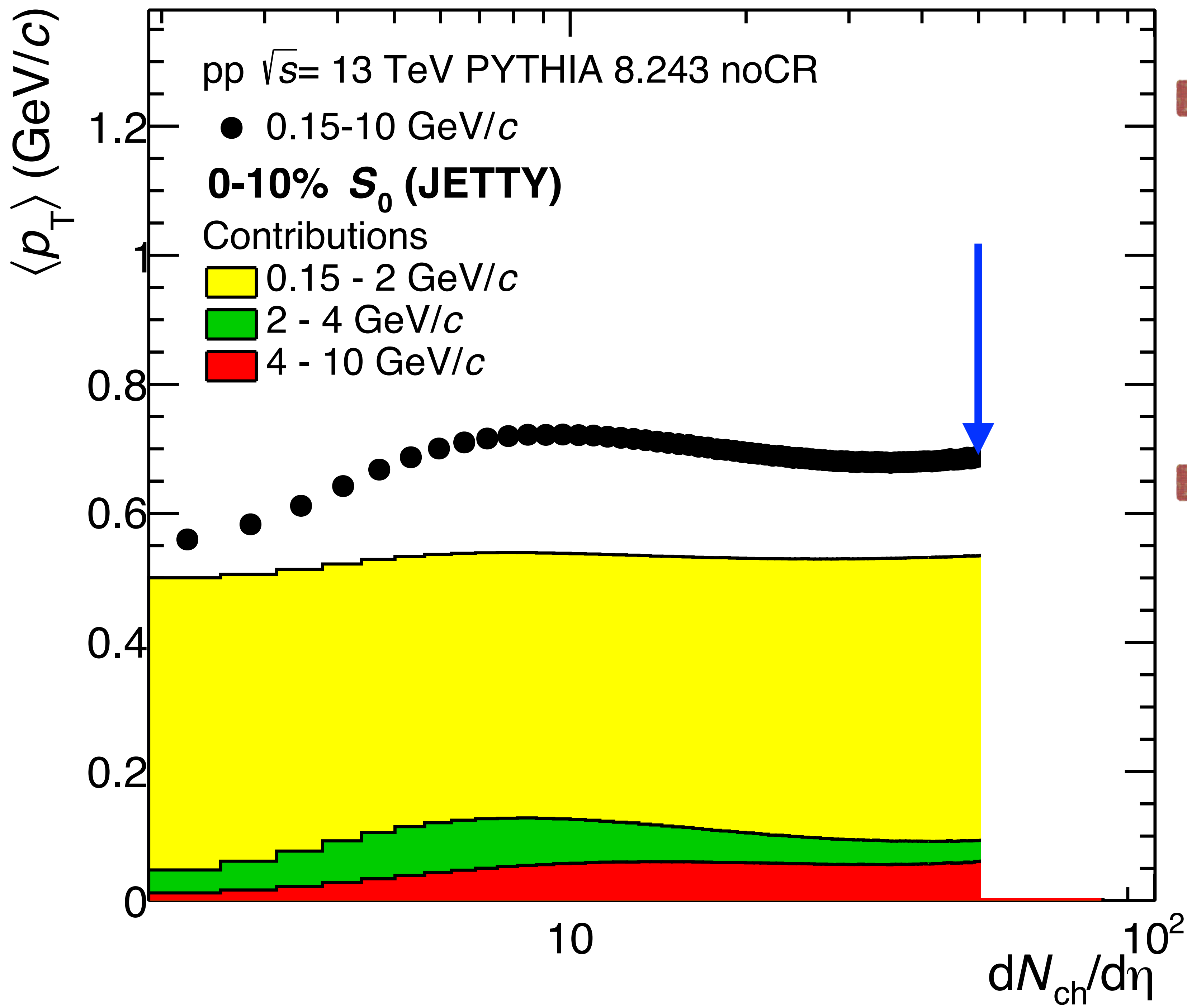
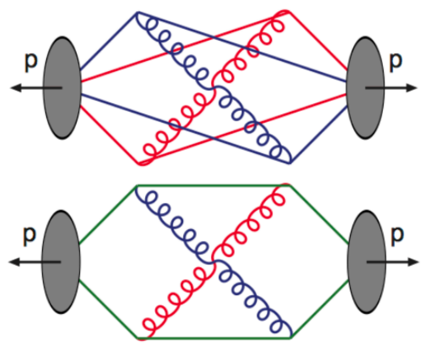


- The effect is produced by high-p_T particles [this agrees with the picture: low S_0->hard events]

The origin of the effect in Pythia

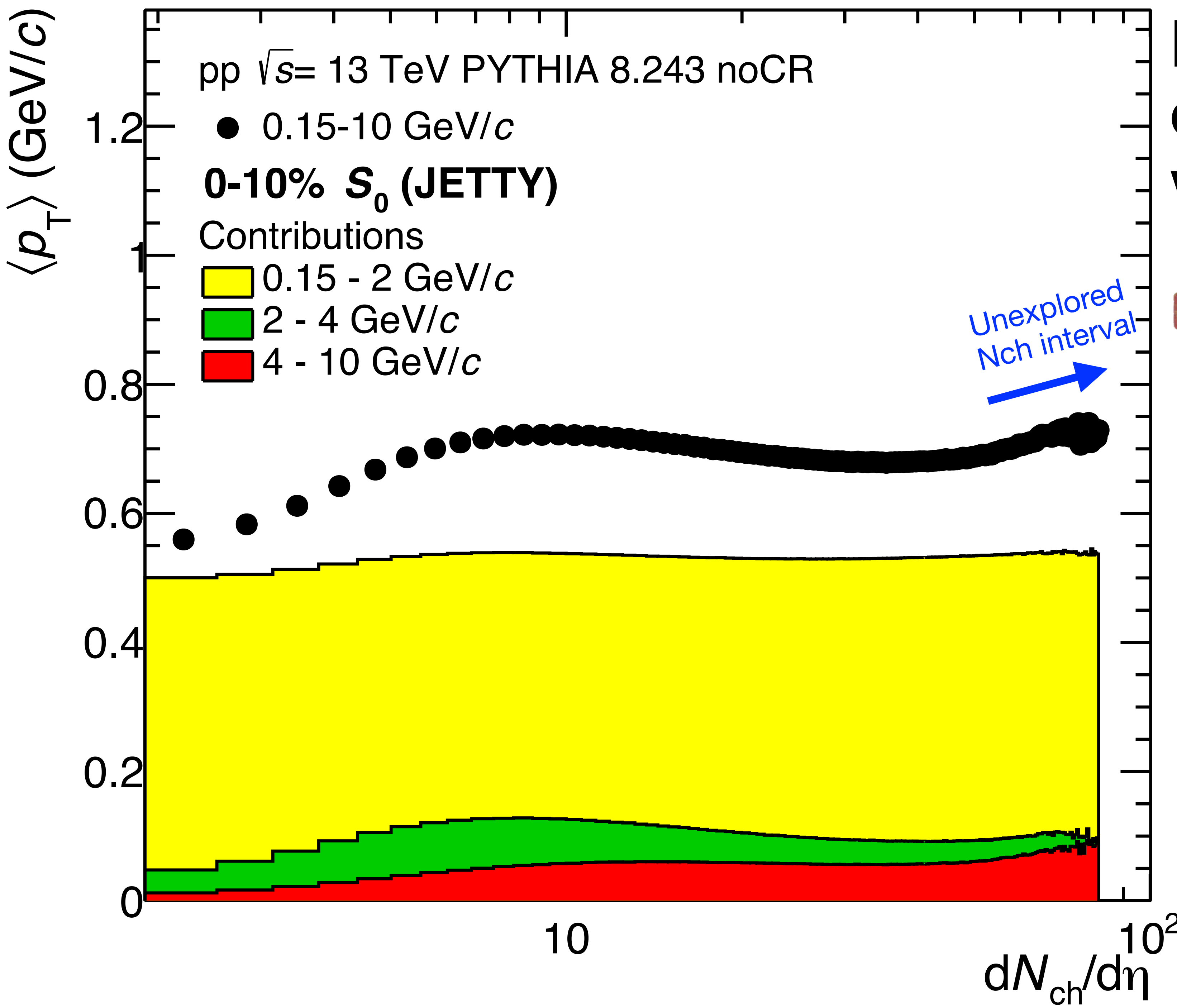


- The effect is produced by high-p_T particles [this agrees with the picture: low S_0->hard events]
- A significant amount of the effect is attributed to strong correlations between the Underlying Event (UE) and jets produced by Color Reconnection (CR)



CR enhances the particle production from intermediate to high-p_T. A. Ortiz, L. Valencia, PRD 99 (2019) 3, 034027

The origin of the effect in Pythia



Even w/o CR we still observe a small effect which is not seen in data:

- Can PYTHIA improve the description of jetty-like events ?

Measurements of p_T spectra in very high multiplicity events would help to clarify this

Hadrochemistry vs spherocity

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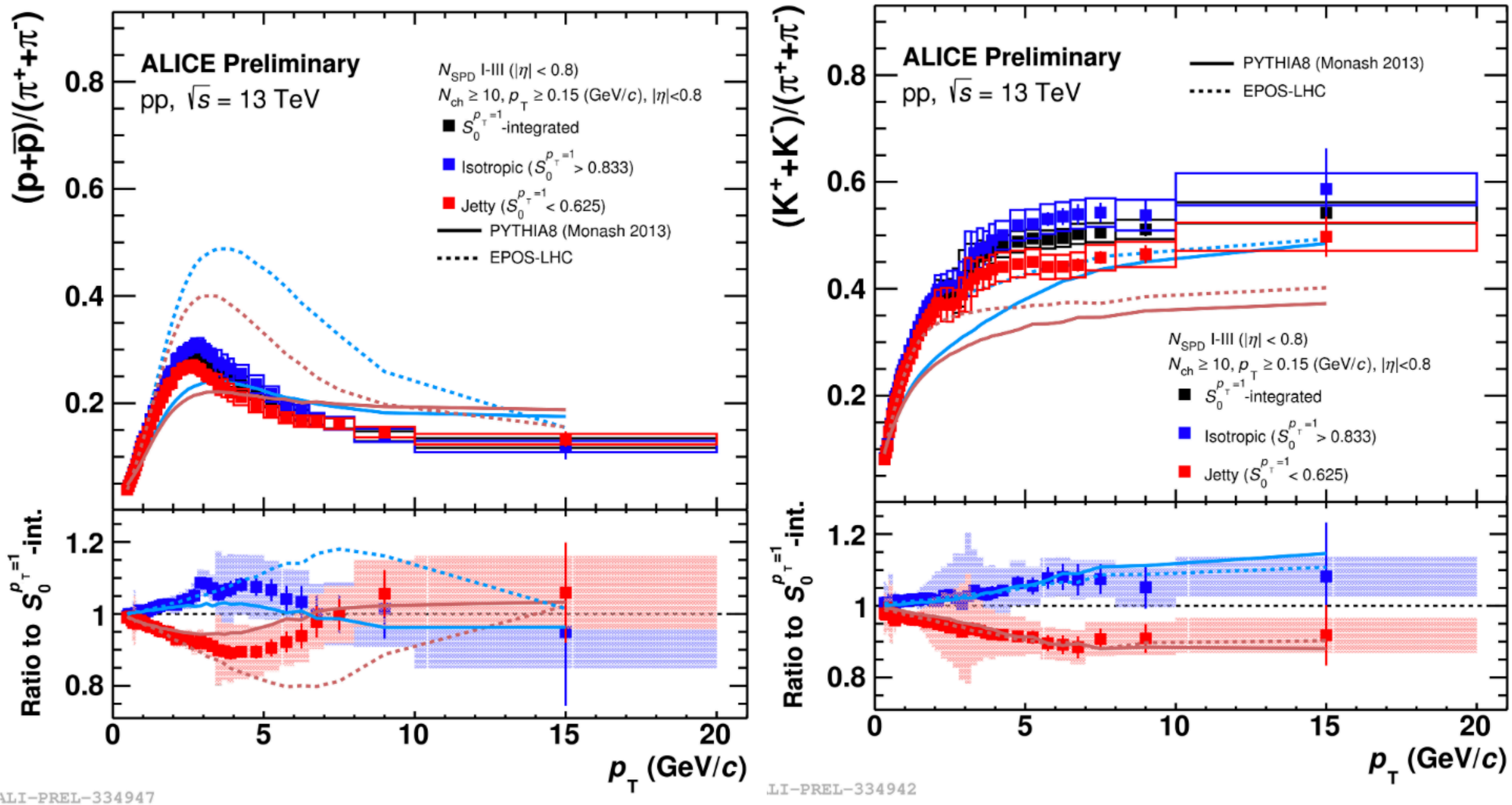
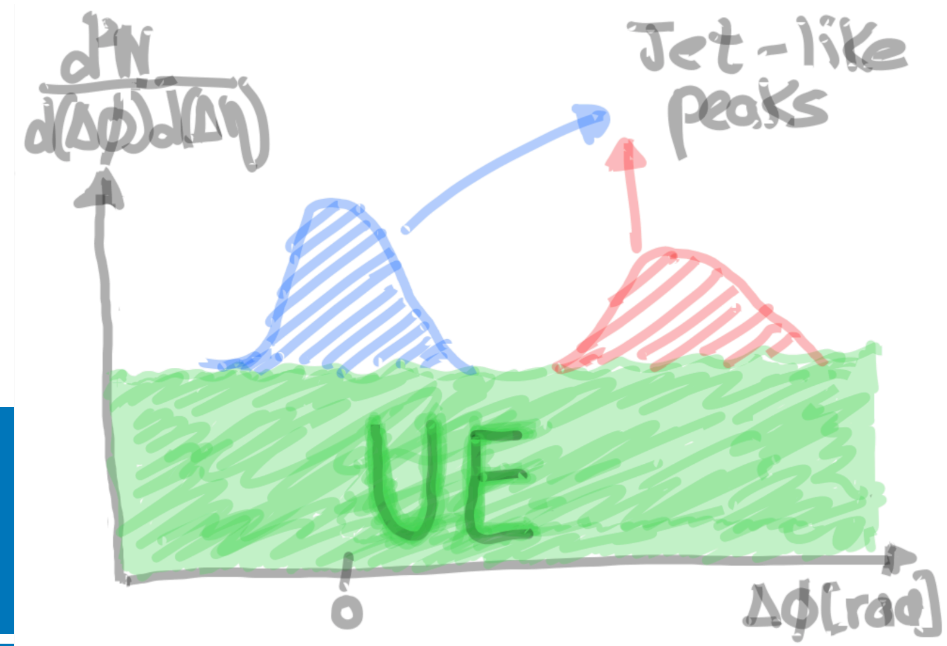


Adrian Nassirpour (The ALICE Collaboration), J. Phys.: Conf. Ser. 1602 (2020) 012007



Underlying event

Underlying-event observables

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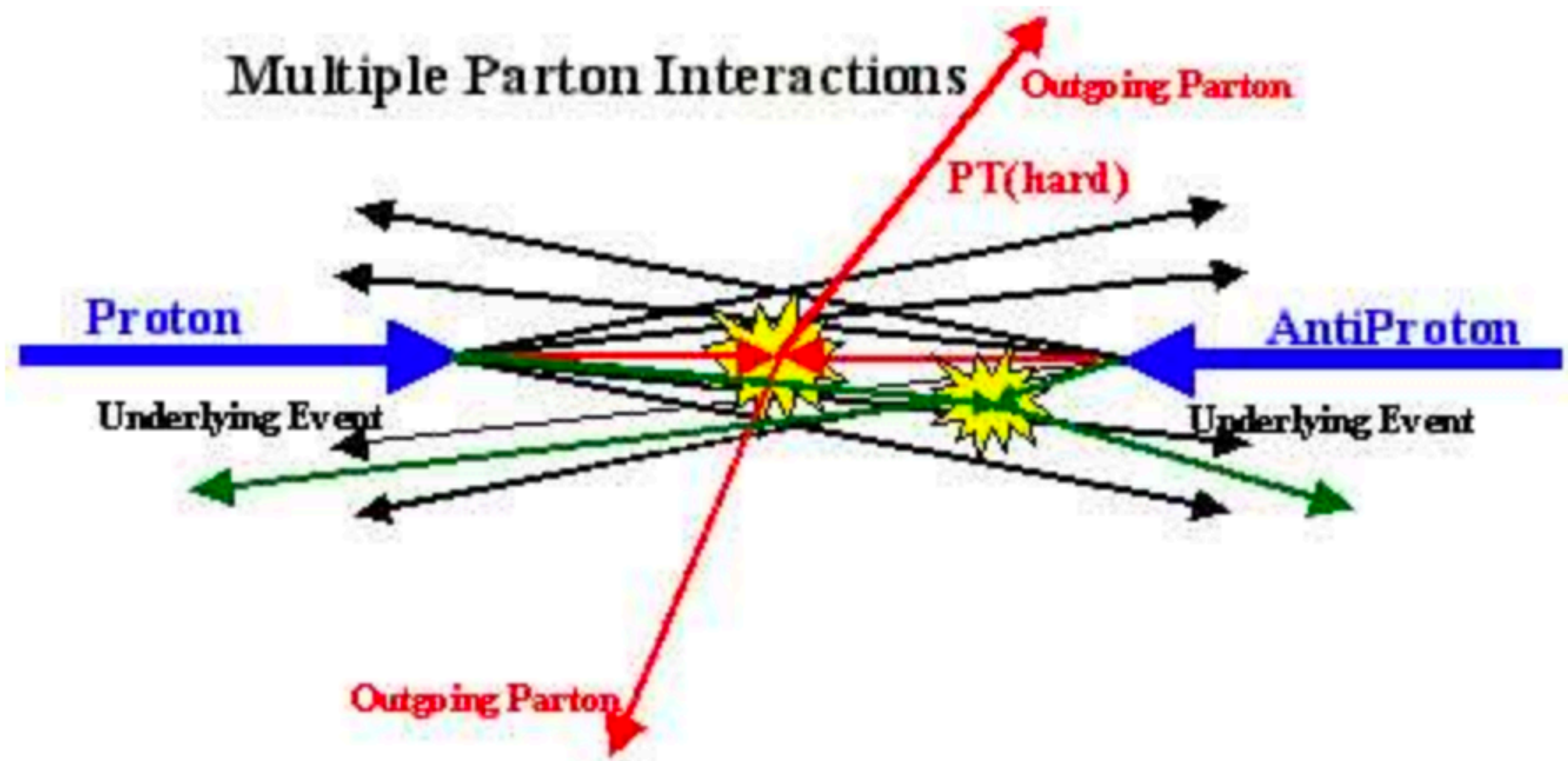
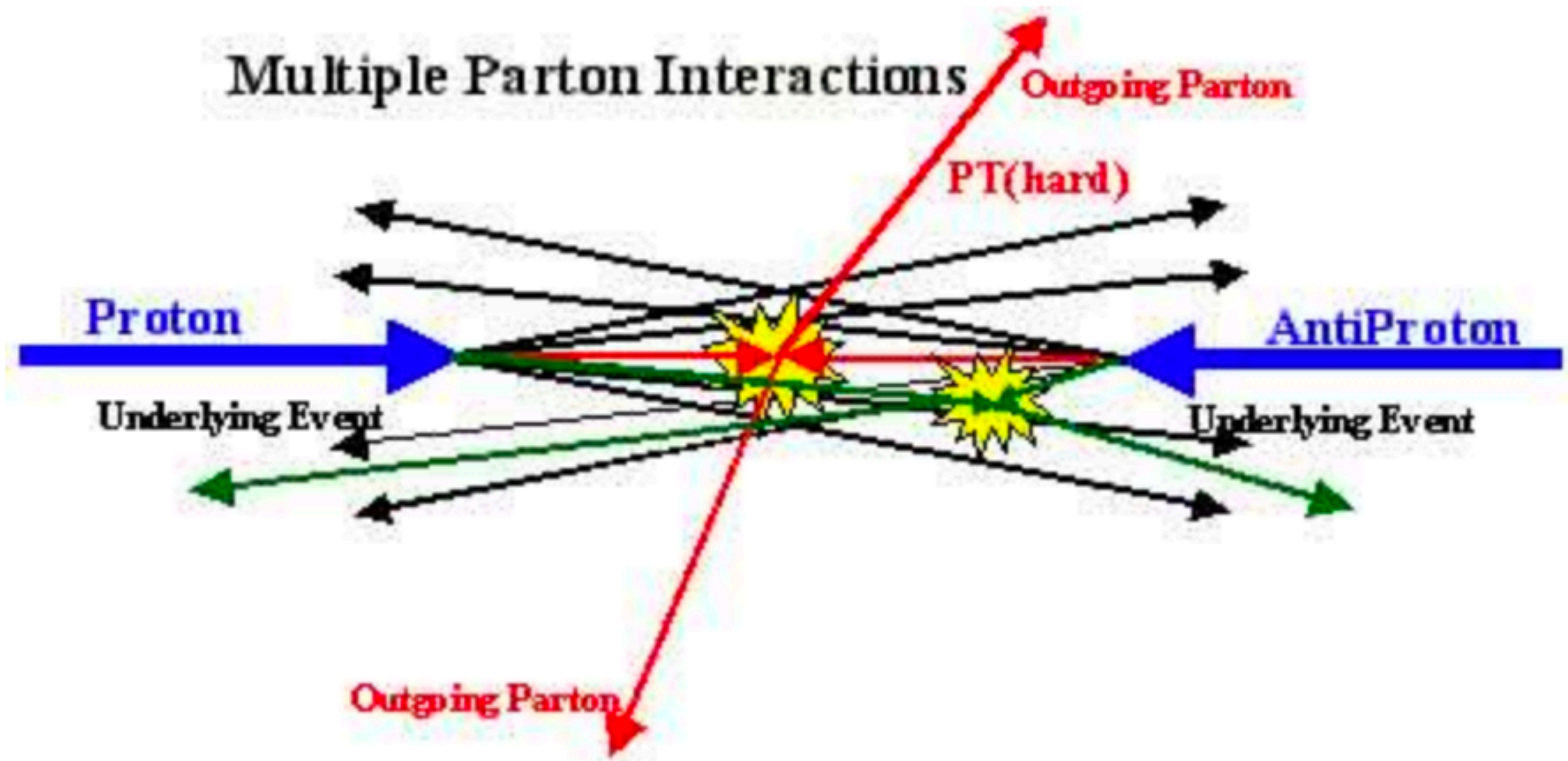
Figure taken from: https://www-cdf.fnal.gov/physics/new/qcd/ue_escan/



In high-energy pp interactions more than one parton-parton scattering can occur within the same collision (MPI)

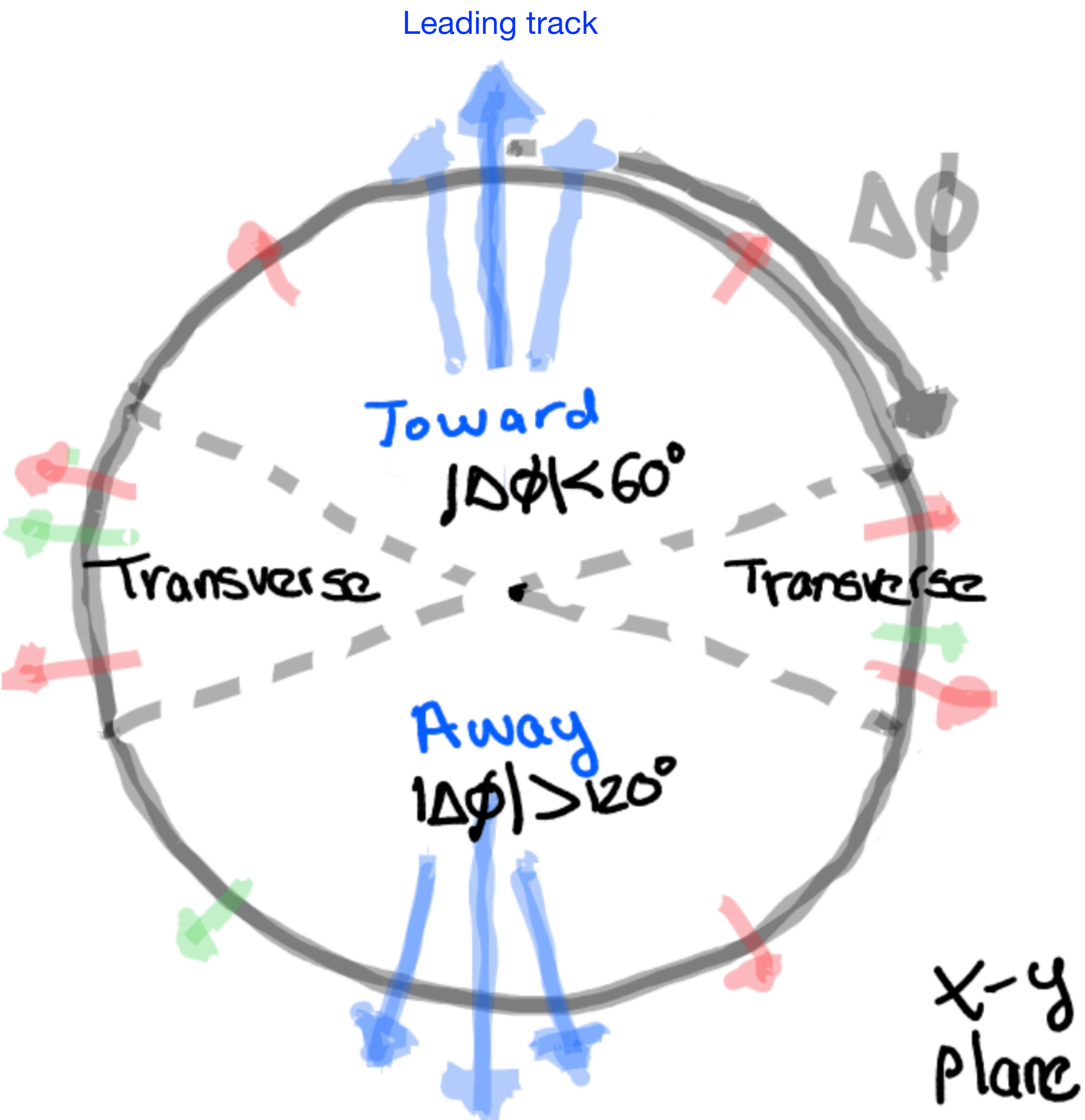
Underlying-event observables

Figure taken from: https://www-cdf.fnal.gov/physics/new/qcd/ue_escan/



Everything which does not belong the main partonic scattering conforms the Underlying Event (UE)

Underlying-event observables



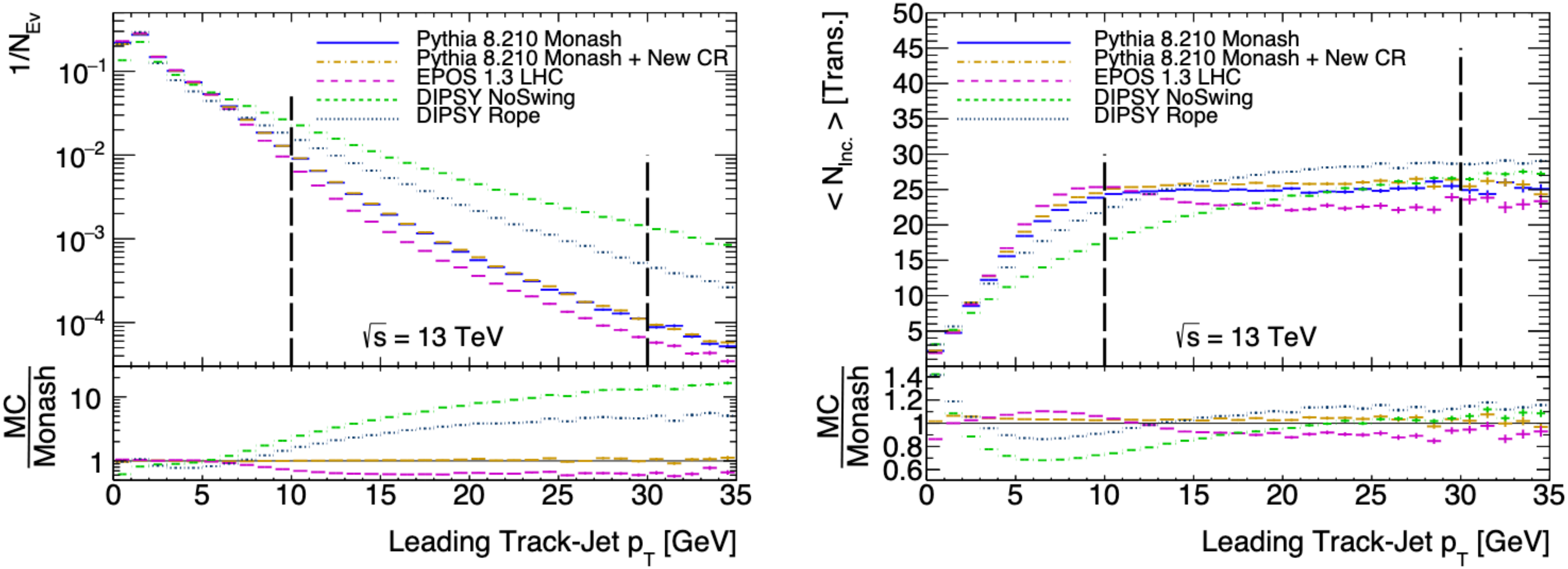
The transverse side is the most sensitive to UE (MPI and beam remnants) but is also has contributions from initial- and final-state radiation (ISR & FSR)

New developments R_T

We can define R_T as follows: $$R_{\mathrm{T}} = \frac{N_{\mathrm{ch}}^{\mathrm{Transv.Side}}}{\langle N_{\mathrm{ch}}^{\mathrm{Transv.Side}} \rangle}$$

R_T allows the selection of events as a function of UE

$||\eta| < 2.5, p_{\mathrm{T}} > 0.2$ GeV/c



T. Martin, P. Skands, S. Farrington, EPJC 76 (2016) 299

New developments R_T

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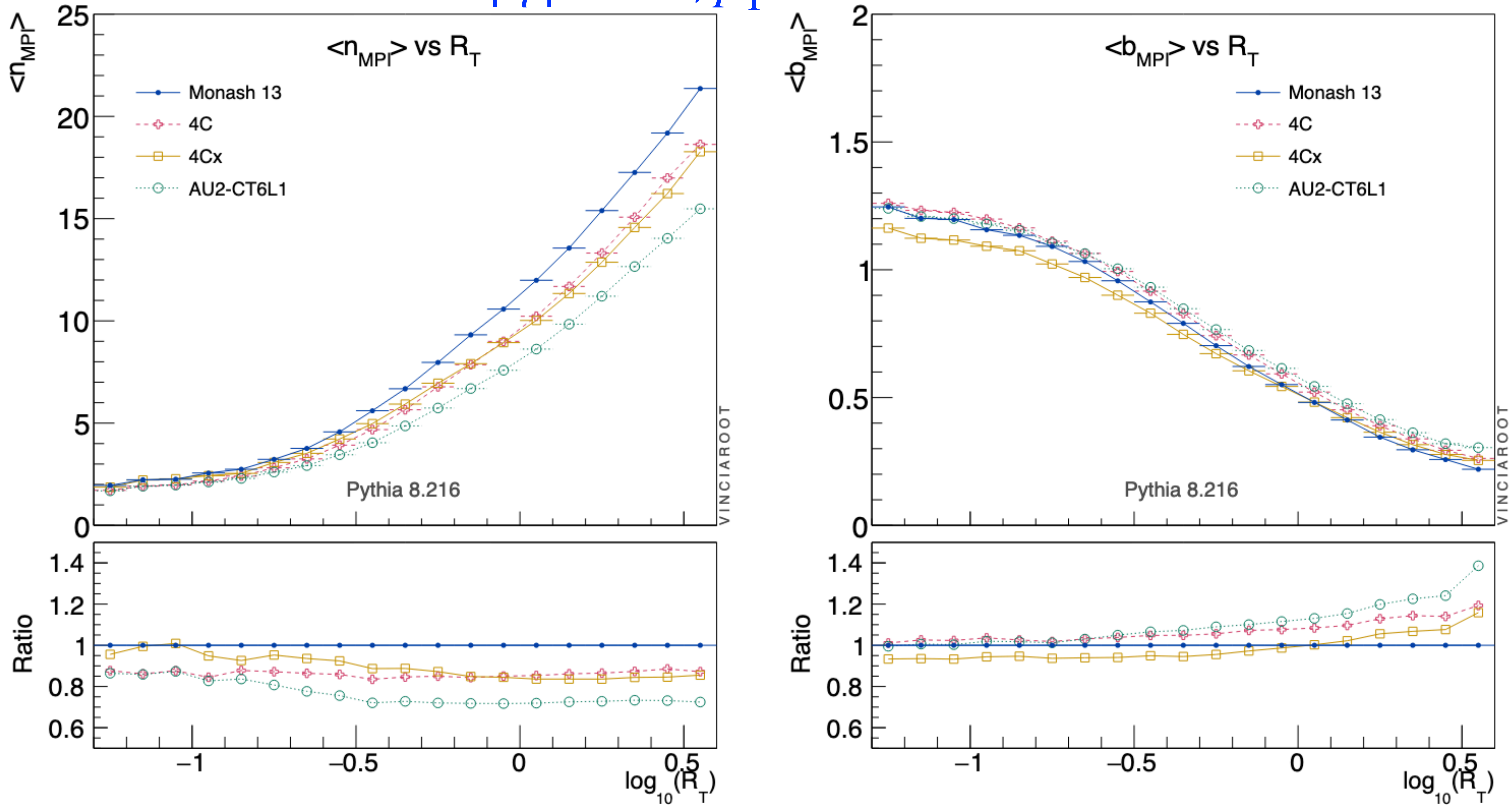
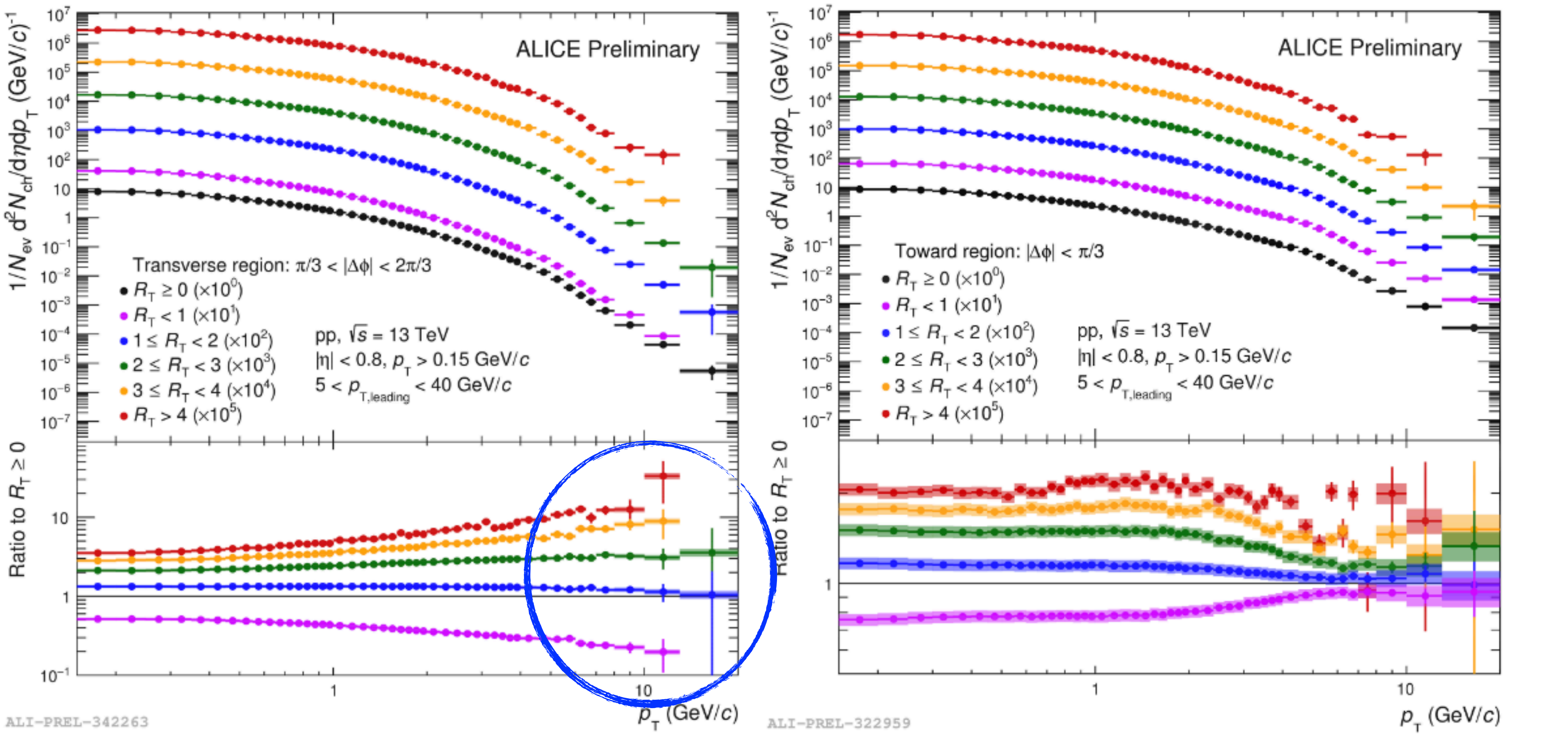


T. Martin, P. Skands, S. Farrington, EPJC 76 (2016) 299

Preliminary ALICE results



V. Zaccolo (for the ALICE Collaboration), Springer Proc.Phys. 250 (2020) 245-248

Preliminary ALICE results

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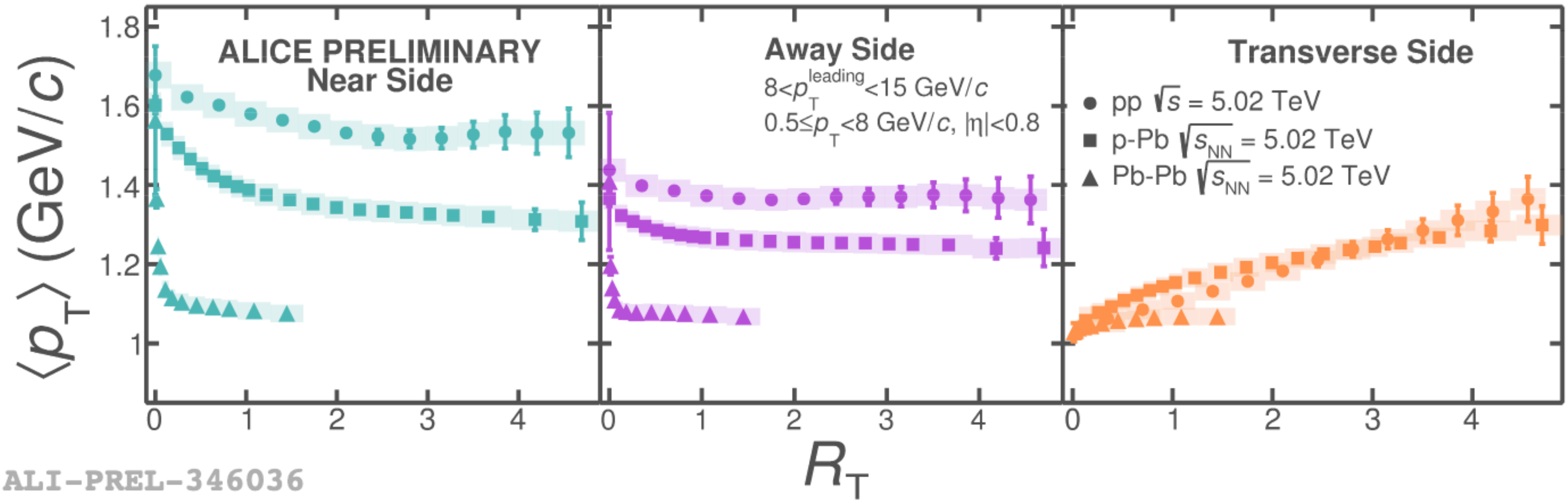

S. Tripathy (for the ALICE Collaboration), J. Phys.: Conf. Ser. 1690, 012126 (2020)

Multi-Parton Interactions from Machine Learnig-based regression

MPI and HI-like effects

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Can we infer N_{mpi} (target variable) from a given a set of input variables? → Regression problem

We use a multivariate regression technique based on Boosted Decision Trees (BDT) with gradient boosting training, which is implemented in TMVA (arXiv:physics/0703039)

We use the existing data on p_{T} spectra as a function of multiplicity [OK for MPI studies in minimum-bias pp collisions]

- **Input variables:** Event-by-event average p_{T} of charged particles / Multiplicity

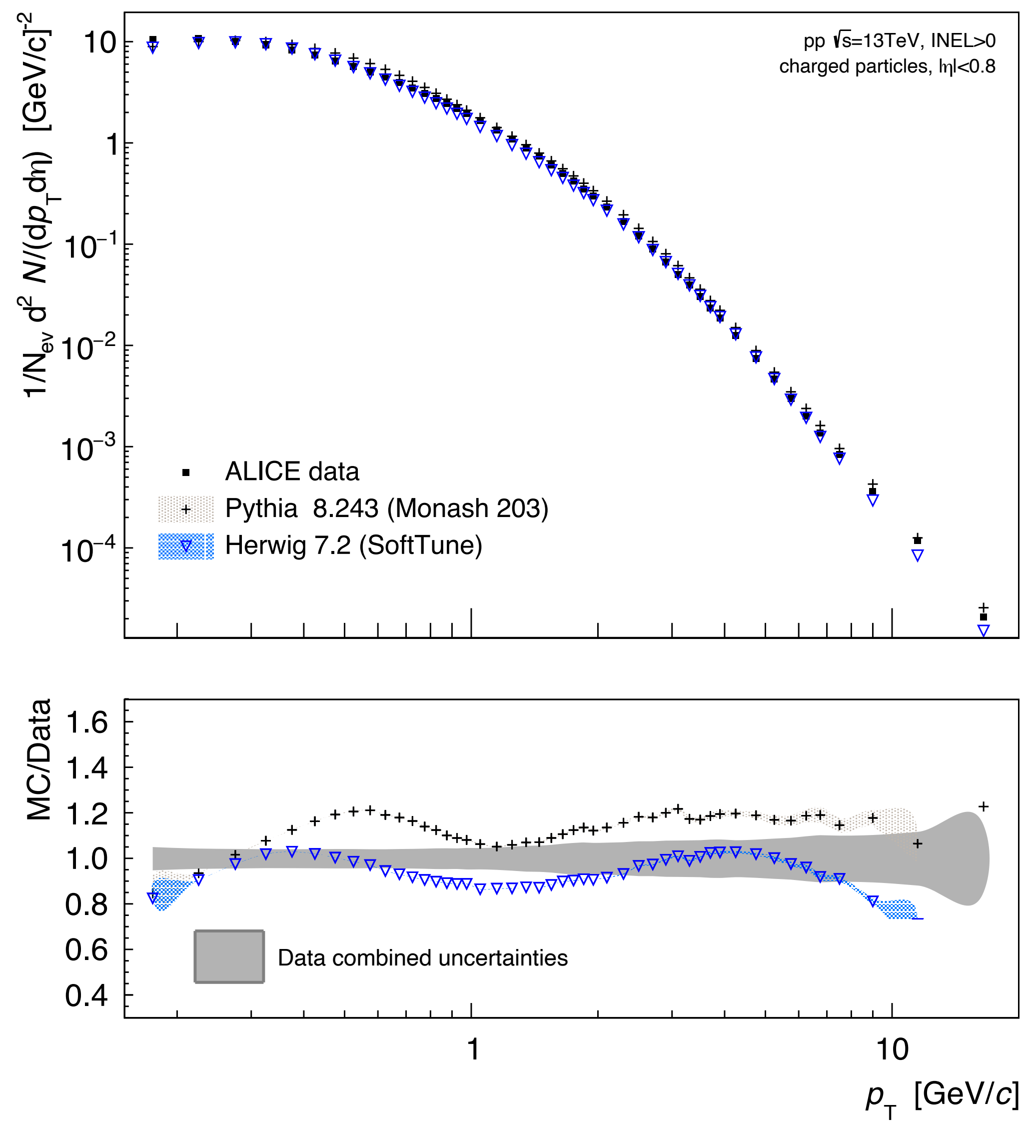
For systematic uncertainties other set of input variables was considered: Charged particle multiplicity in the pseudorapidity region covered by VZERO detector / Transverse spherocity

MC validation

MC validation

In order to investigate the model dependence (MPI and hadronization models), we use pp collisions simulated with **Herwig 7.2** (soft tune): S. Gieseke, C. Rohr and A. Siodmok, EPJC 72 (2012) 2225

Pythia 8.2: T. Sjöstrand et al., Comput. Phys. Commun. 191 (2015) 159-177



MPI vs $\sqrt{s}$ (Pythia 8.244)

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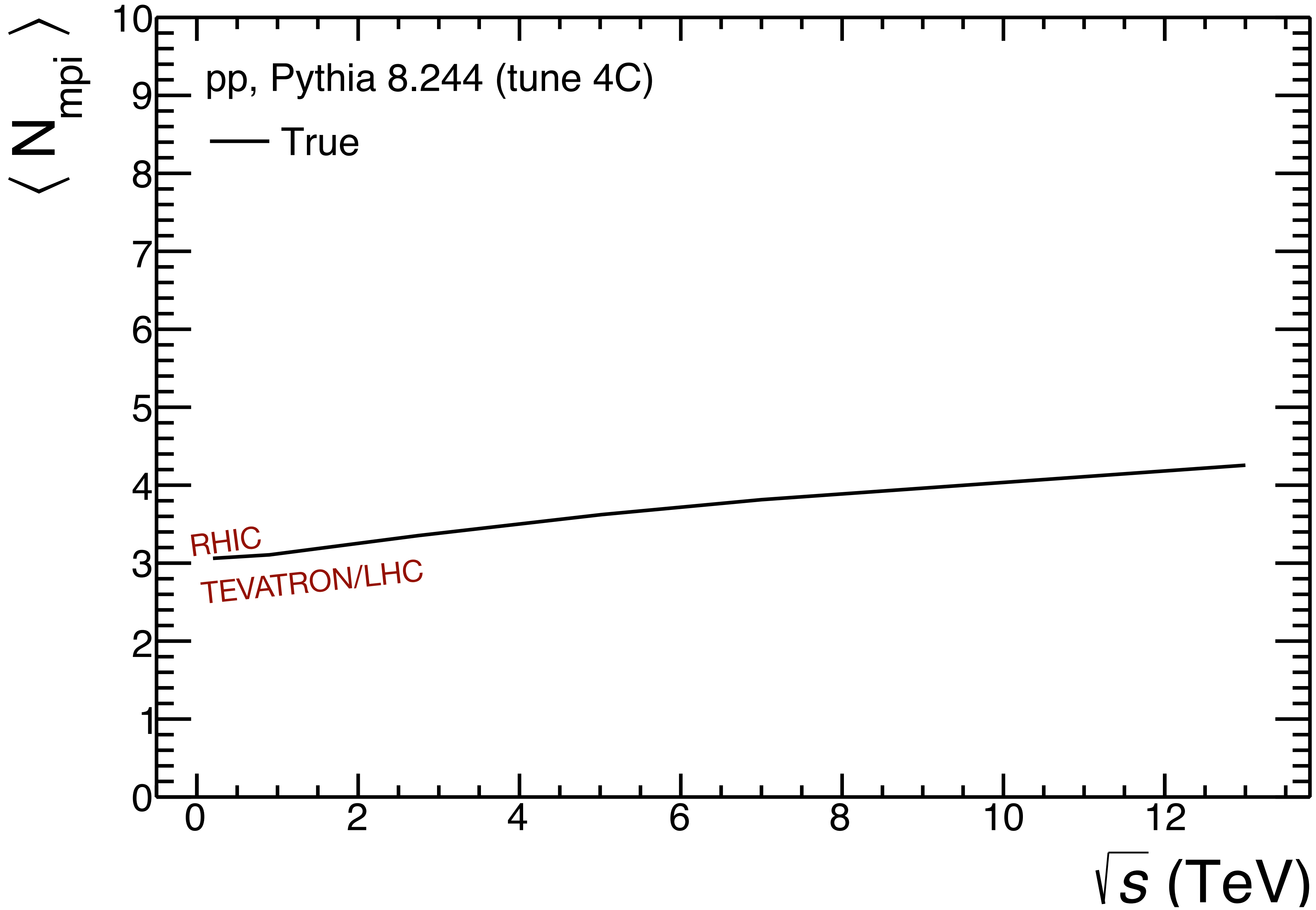
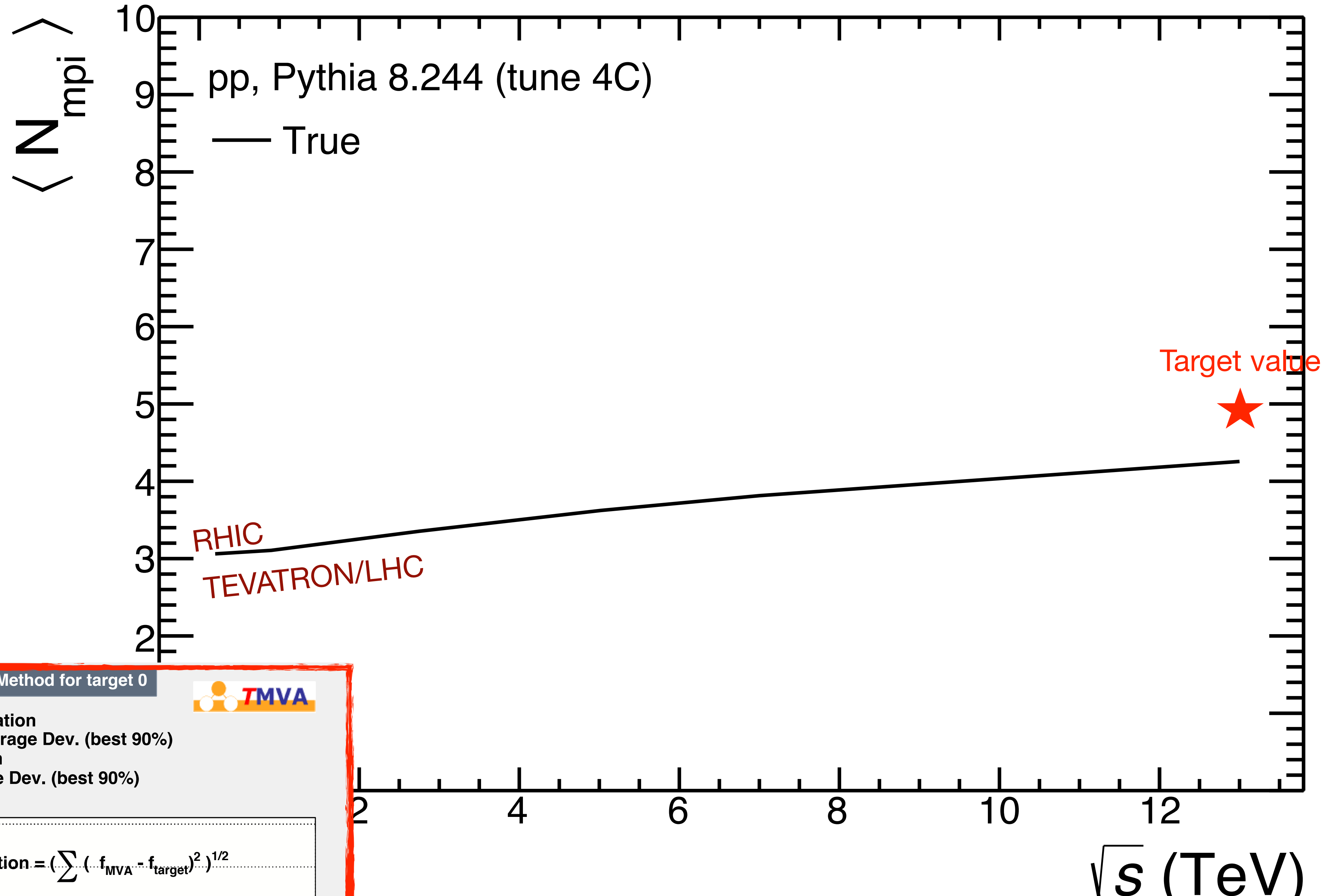
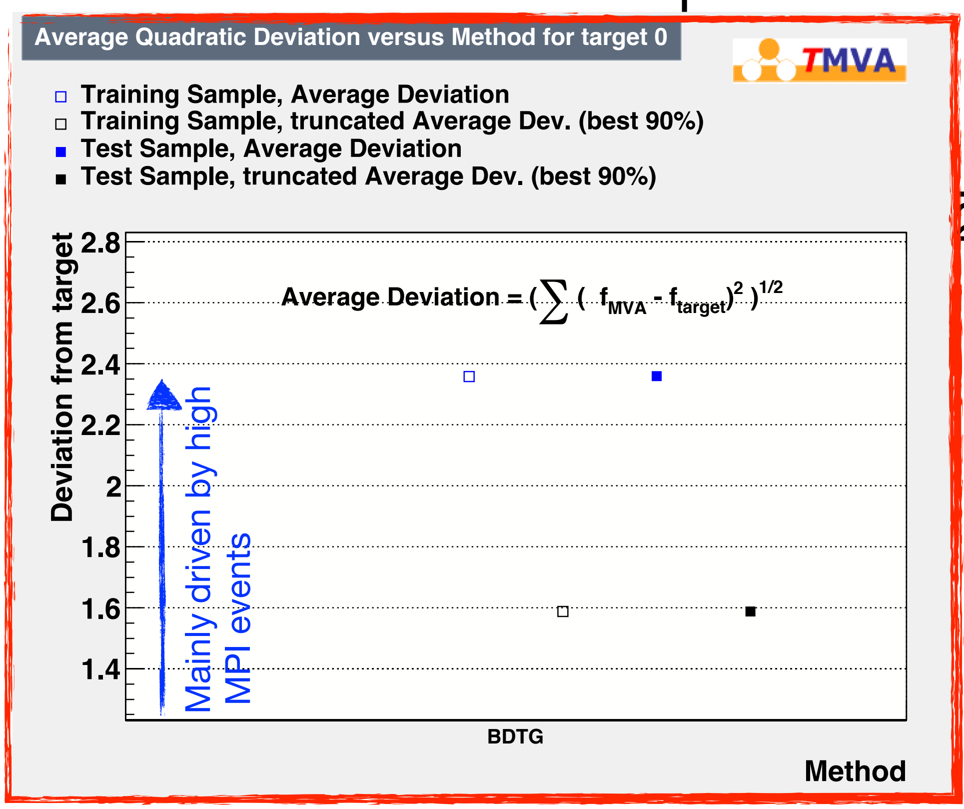


MPI from BDT





TRAINING (MB pp collisions at 13 TeV, Pythia tune 4C)

Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_{\mathrm{T}} \geq 0.15$ GeV/c)
- multiplicity

TEST (MB pp collisions at $\sqrt{s} = 13$ TeV, Pythia tune 4C)

MPI from BDT

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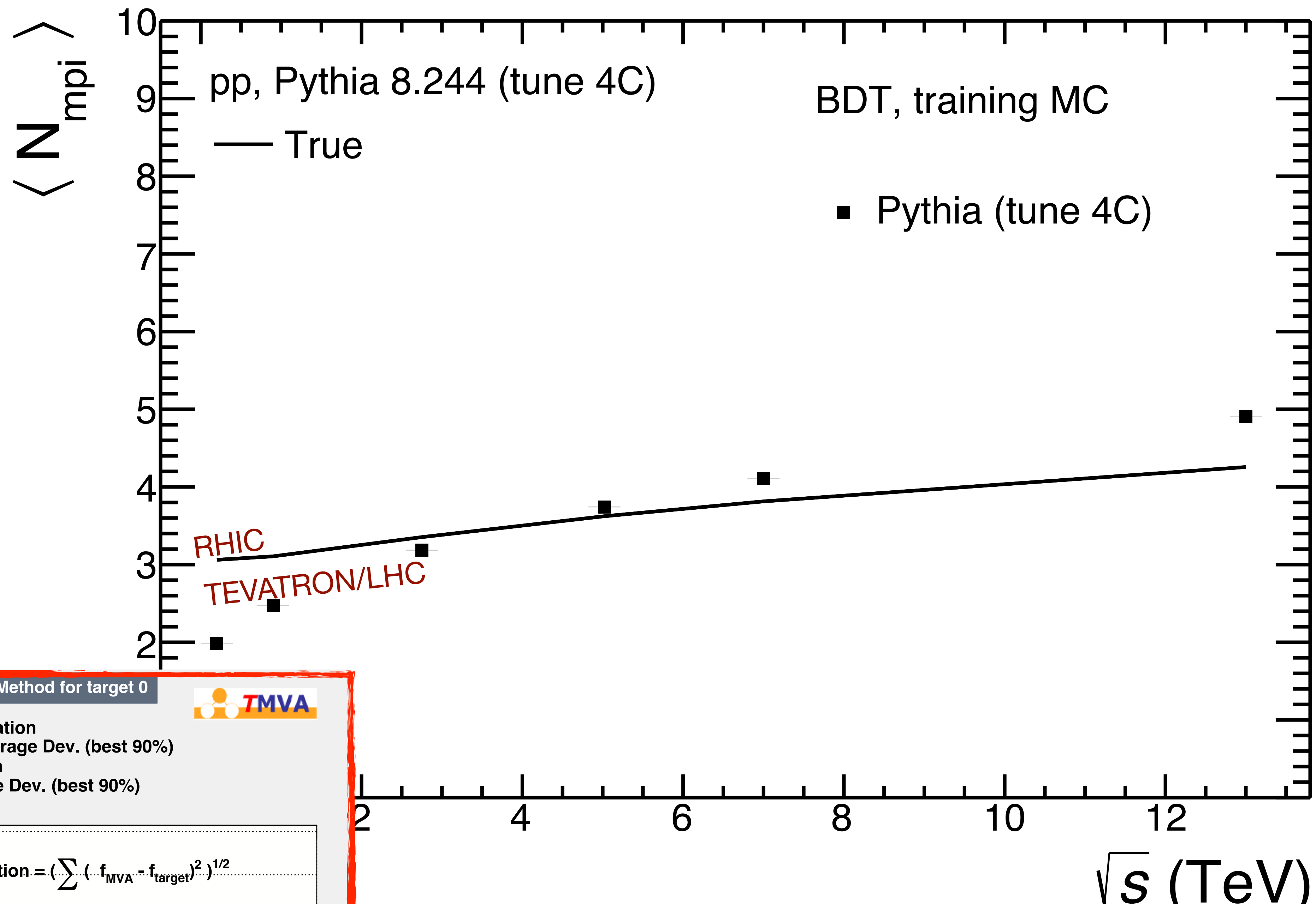
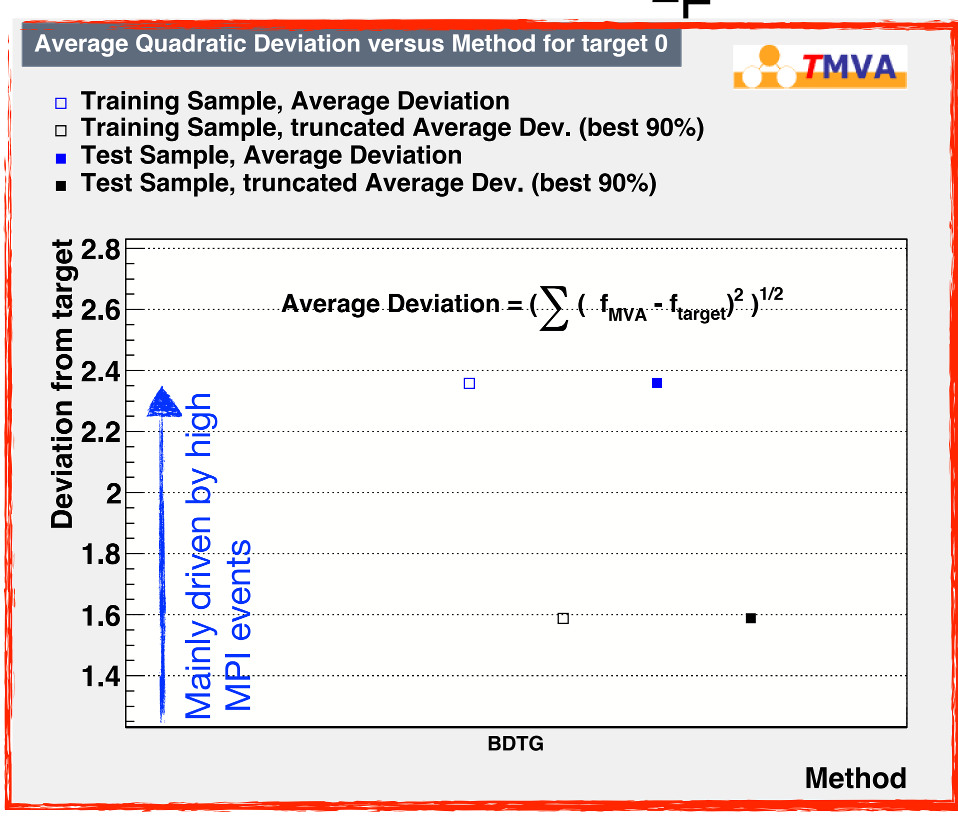




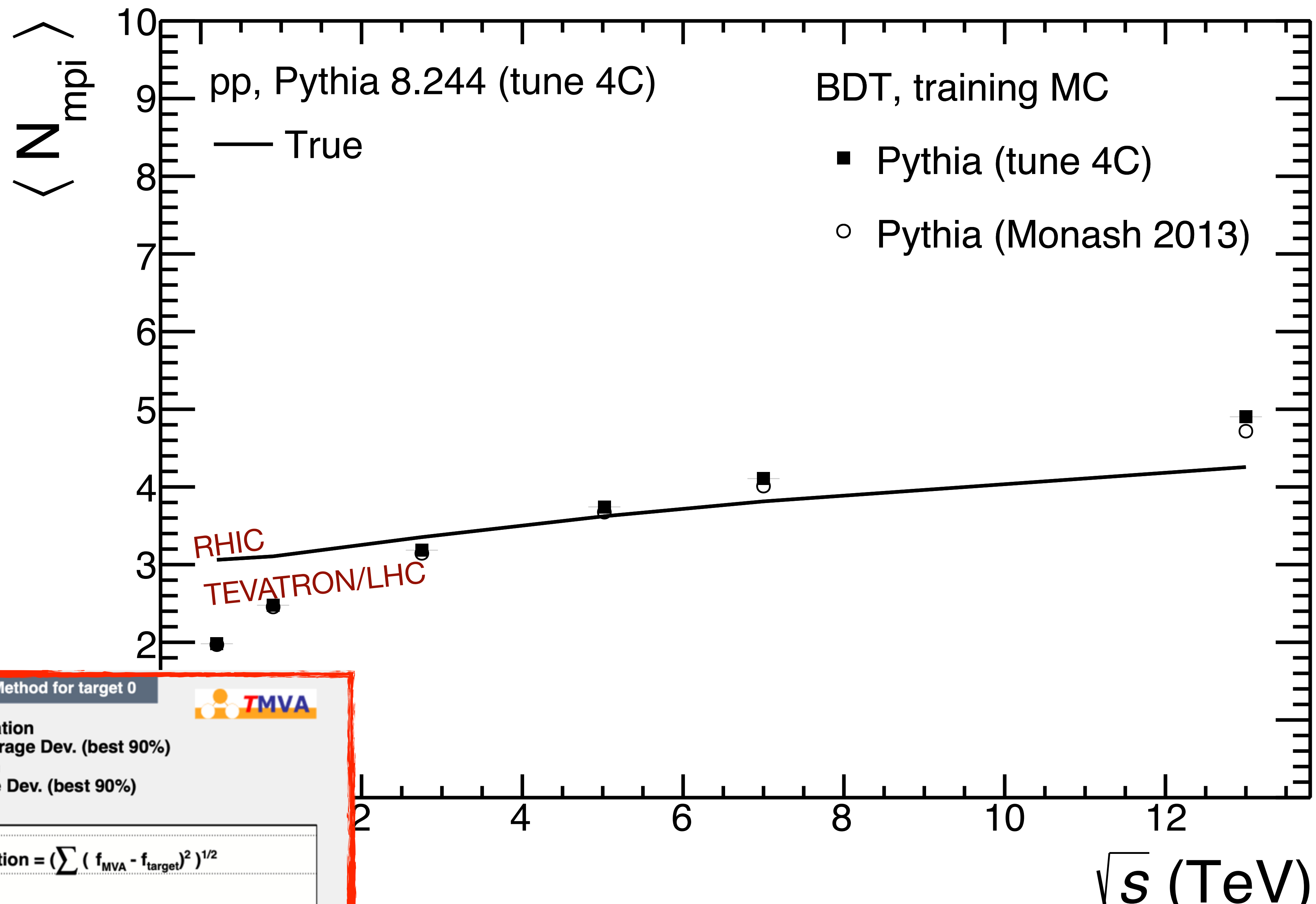
TRAINING (MB pp collisions at 13 TeV, Pythia tune 4C)

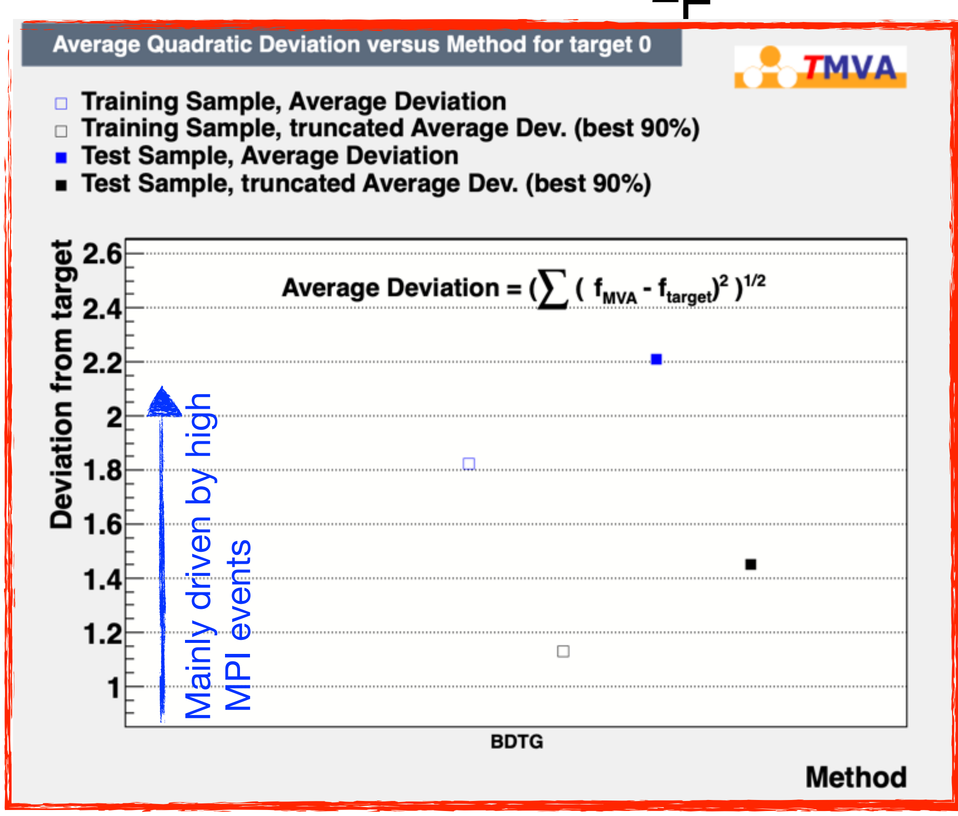
Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_{\rm T} \geq 0.15$ GeV/c)
- multiplicity

TEST (MB pp collisions at different $\sqrt{s}$, Pythia tune 4C)

MPI from BDT (model dependence)





TRAINING (MB pp collisions at 13 TeV, Pythia Monash)

Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_{\mathrm{T}} \geq 0.15$ GeV/c)
- multiplicity

TEST (MB pp collisions at different $\sqrt{s}$, Pythia tune 4C)

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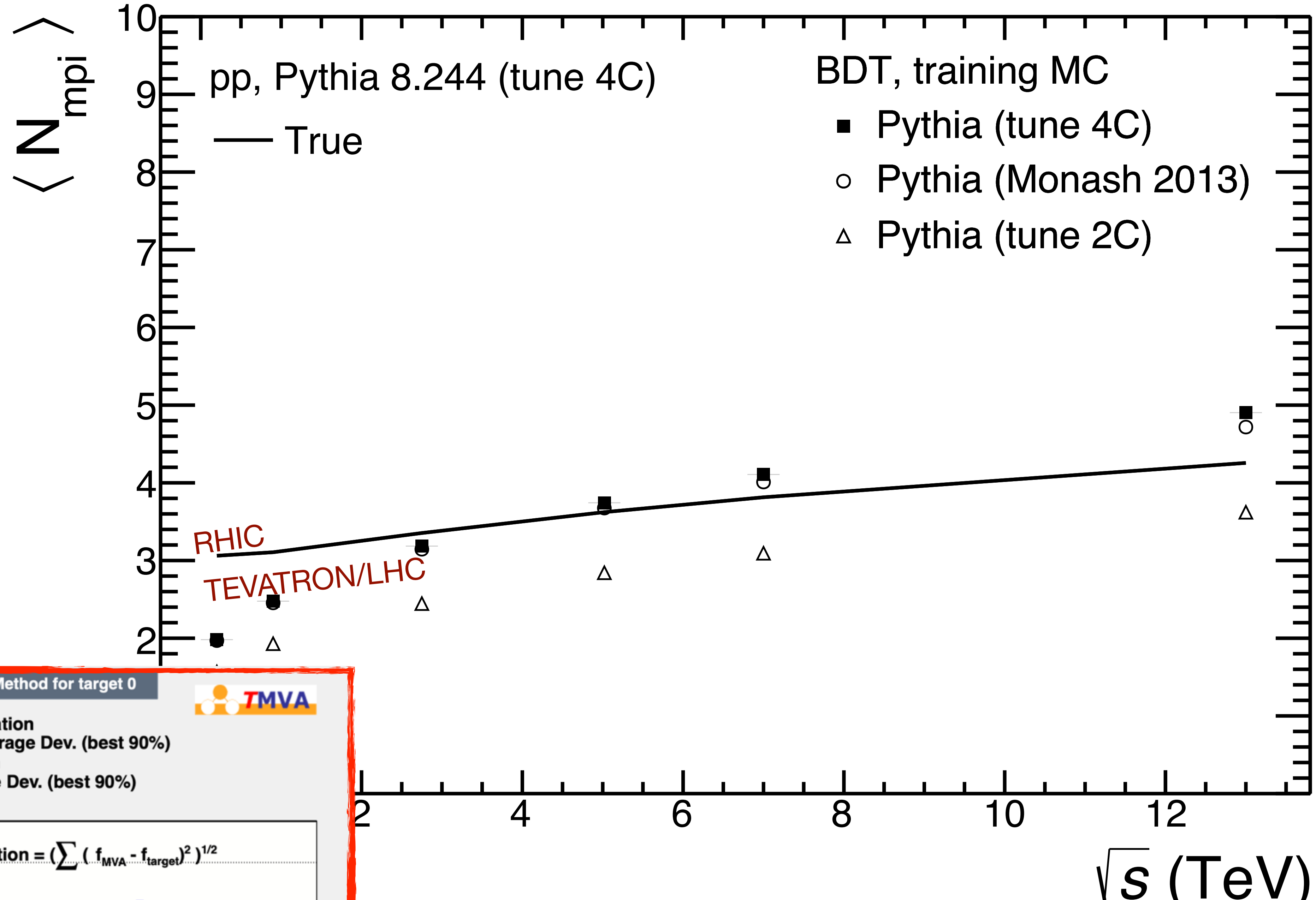
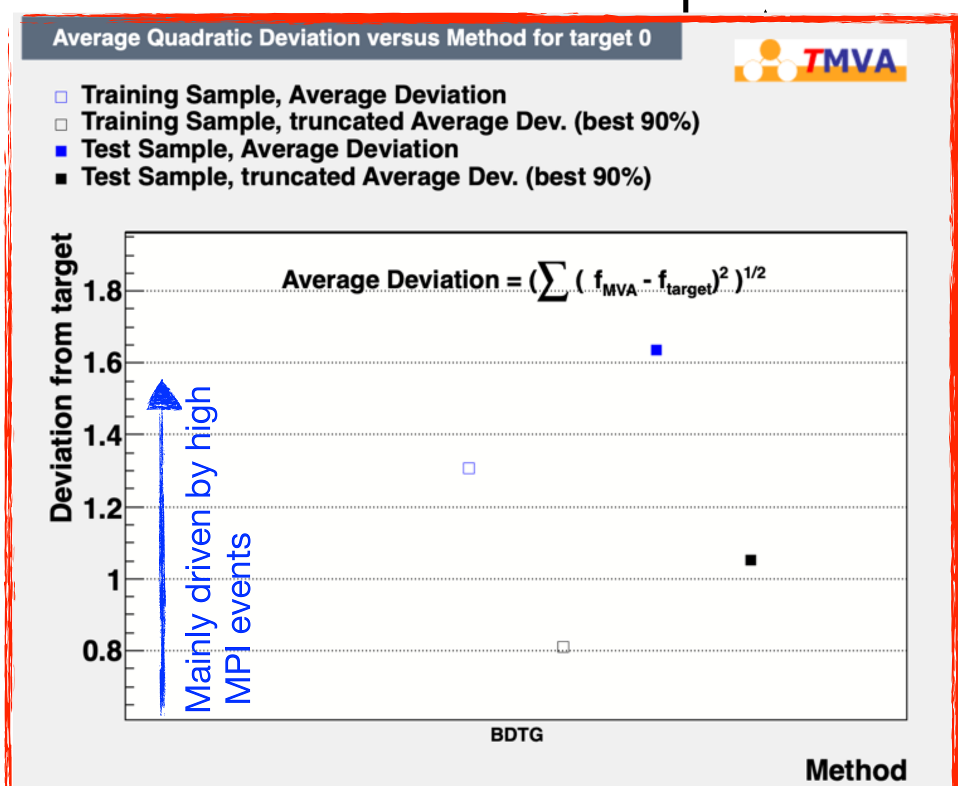




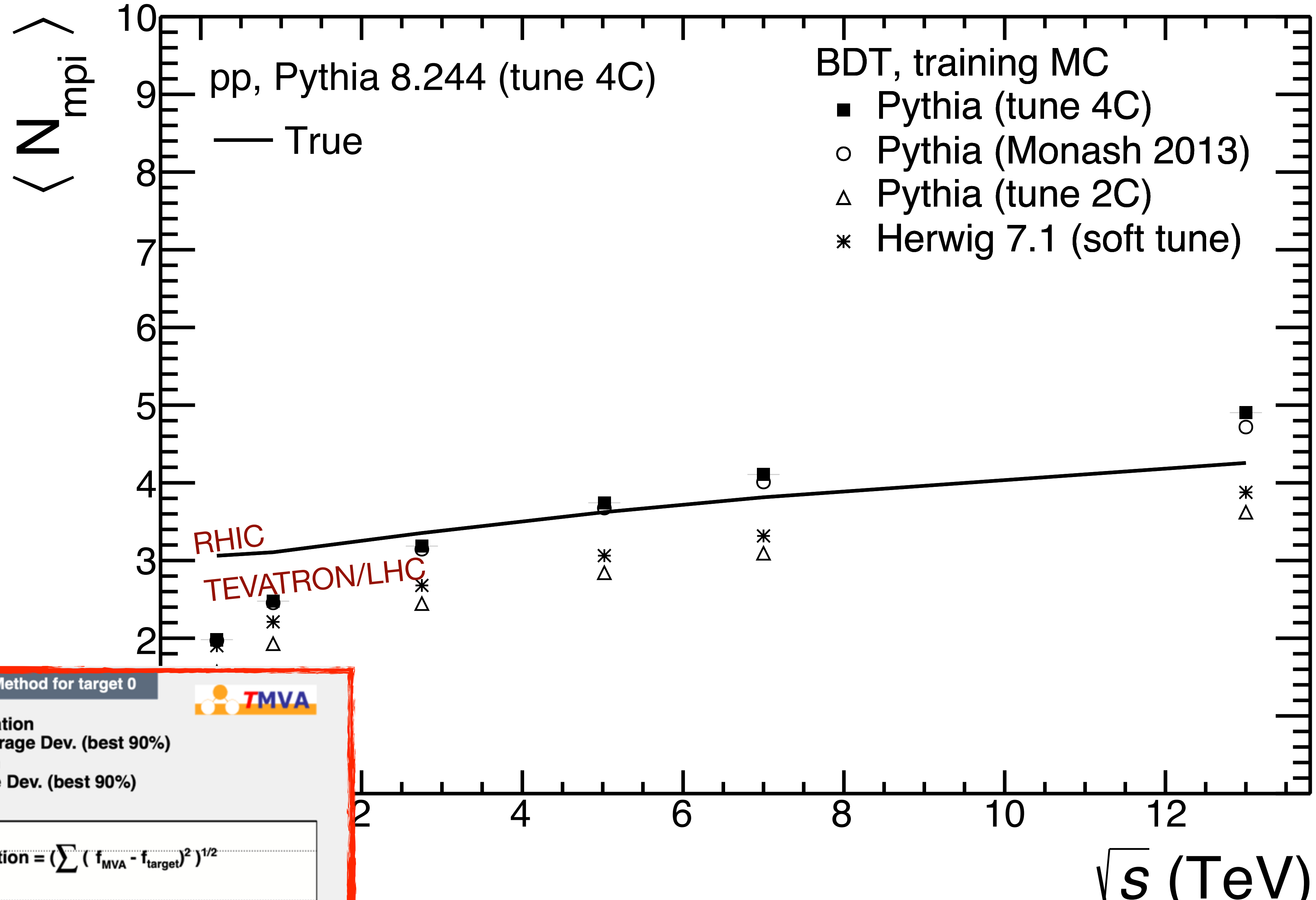
TRAINING (MB pp collisions at 13 TeV, Pythia tune 2C)

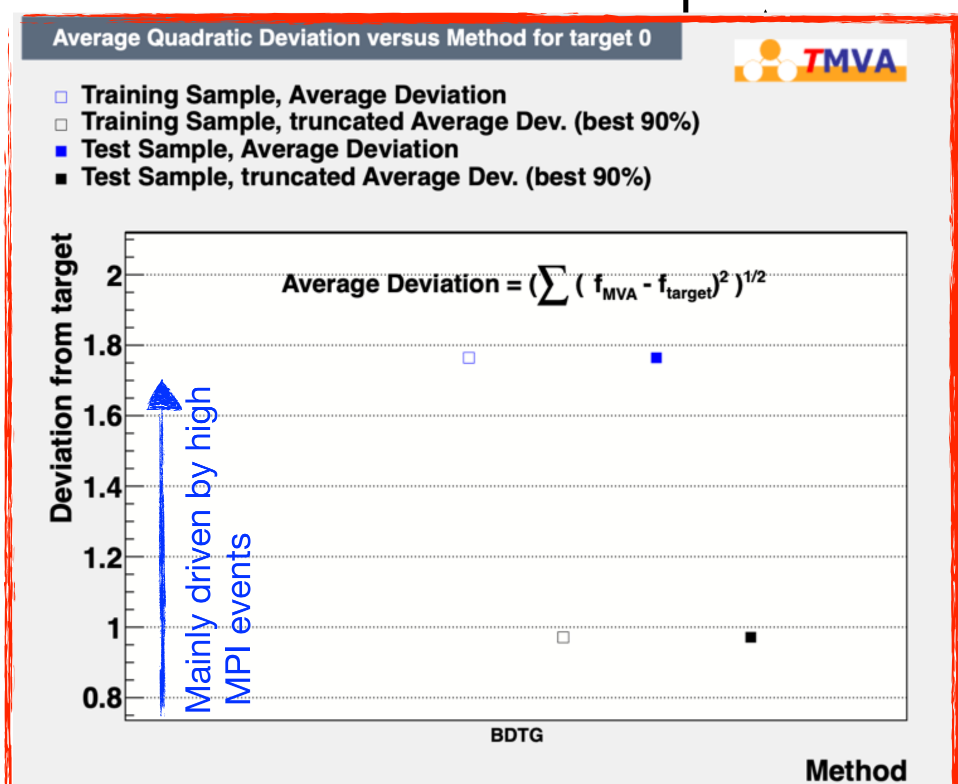
Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_{\rm T} \geq 0.15$ GeV/c)
- multiplicity

TEST (MB pp collisions at different $\sqrt{s}$, Pythia tune 4C)

Effect of hadronization model I





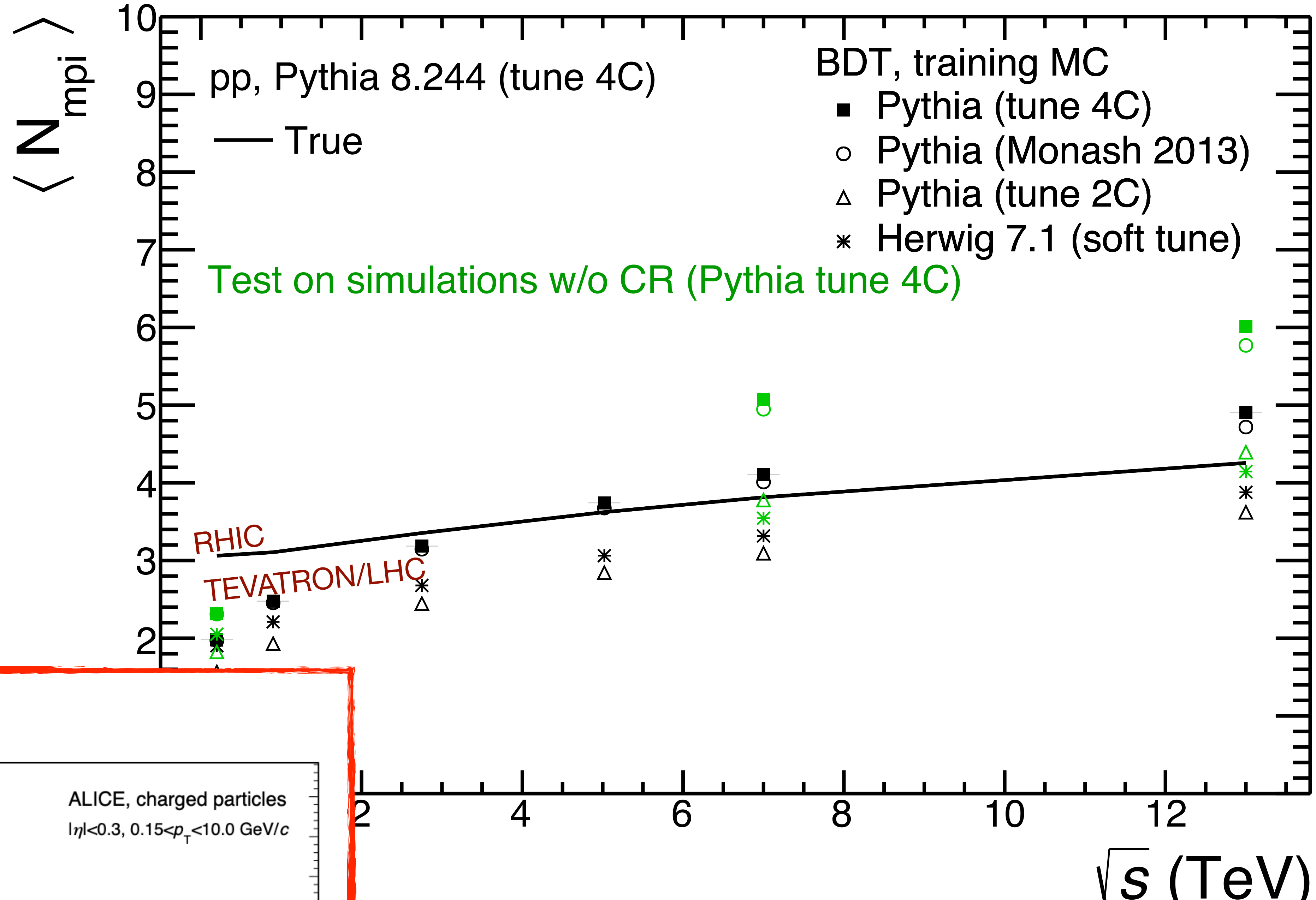
TRAINING (MB pp collisions at 13 TeV, Herwig soft tune)

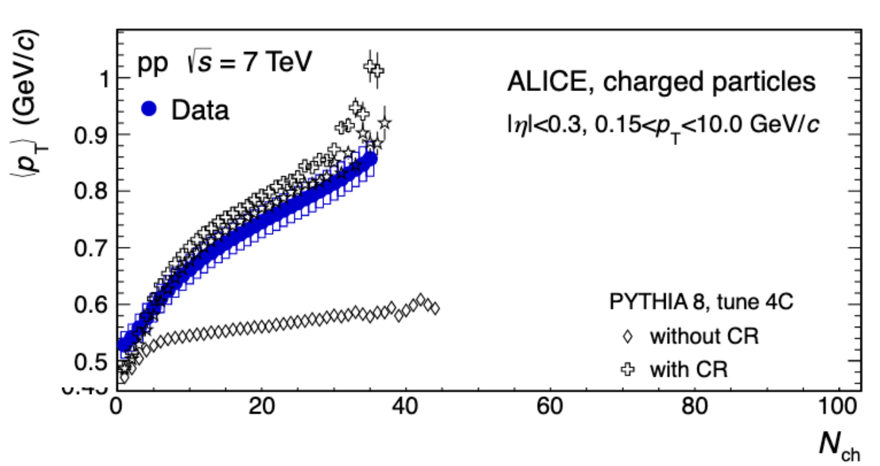
Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_{\rm T} \geq 0.15$ GeV/c)
- multiplicity

TEST (MB pp collisions at different $\sqrt{s}$, Pythia tune 4C)

Effect of hadronization model II





Simulations w/o CR can not describe the data

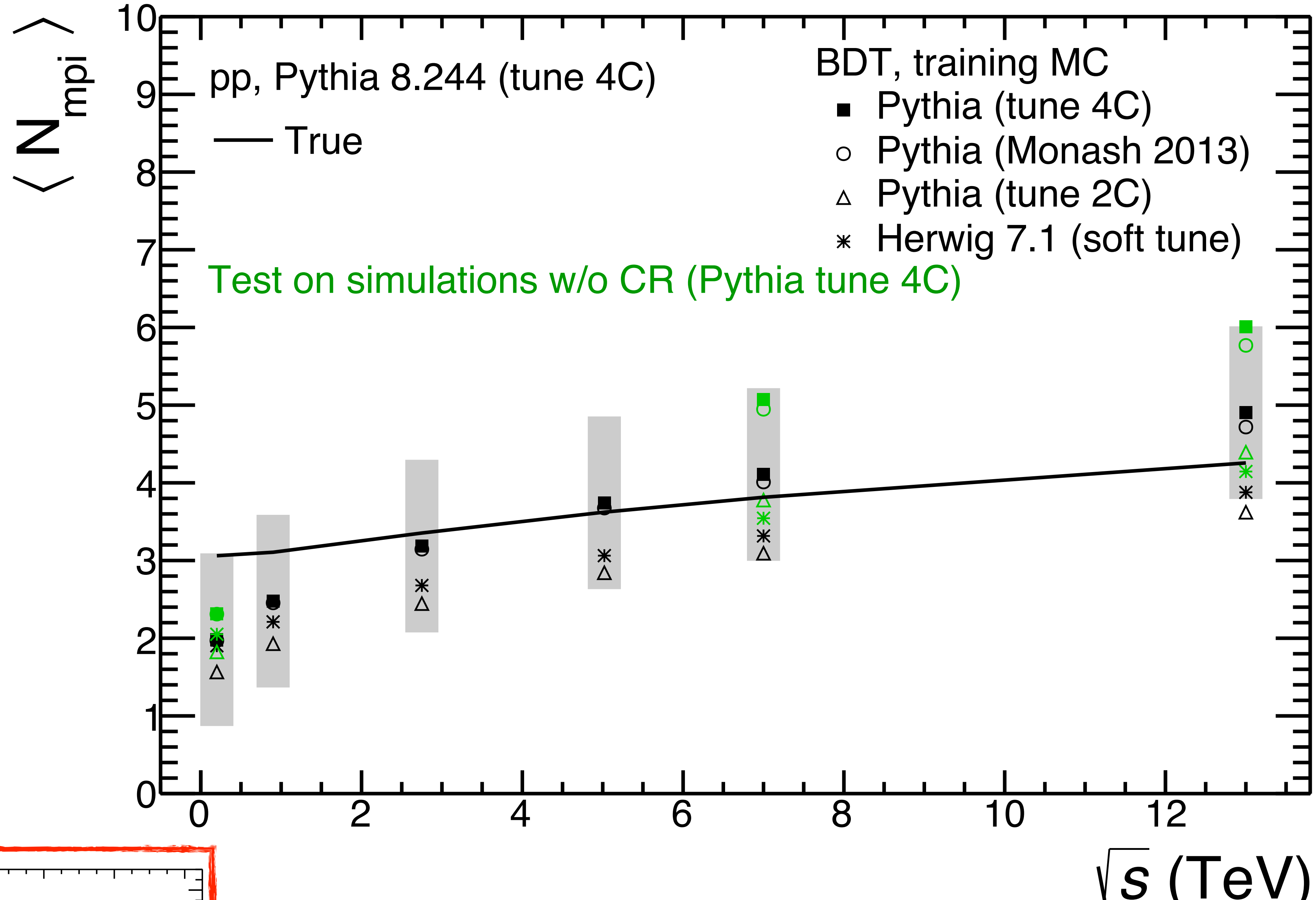
TRAINING (MB pp collisions at 13 TeV, Pythia tune 4C)

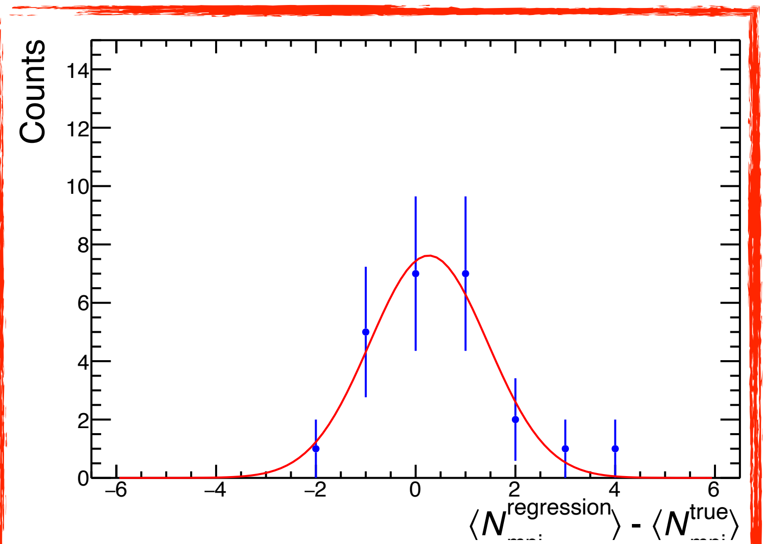
Input variables (primary charged particles $|\eta| < 0.8$):

- EbE average transverse momentum ($p_T \geq 0.15$ GeV/c)
- multiplicity

TEST (Pythia, tune 4C w/o Color Reconnection)

Systematic uncertainties

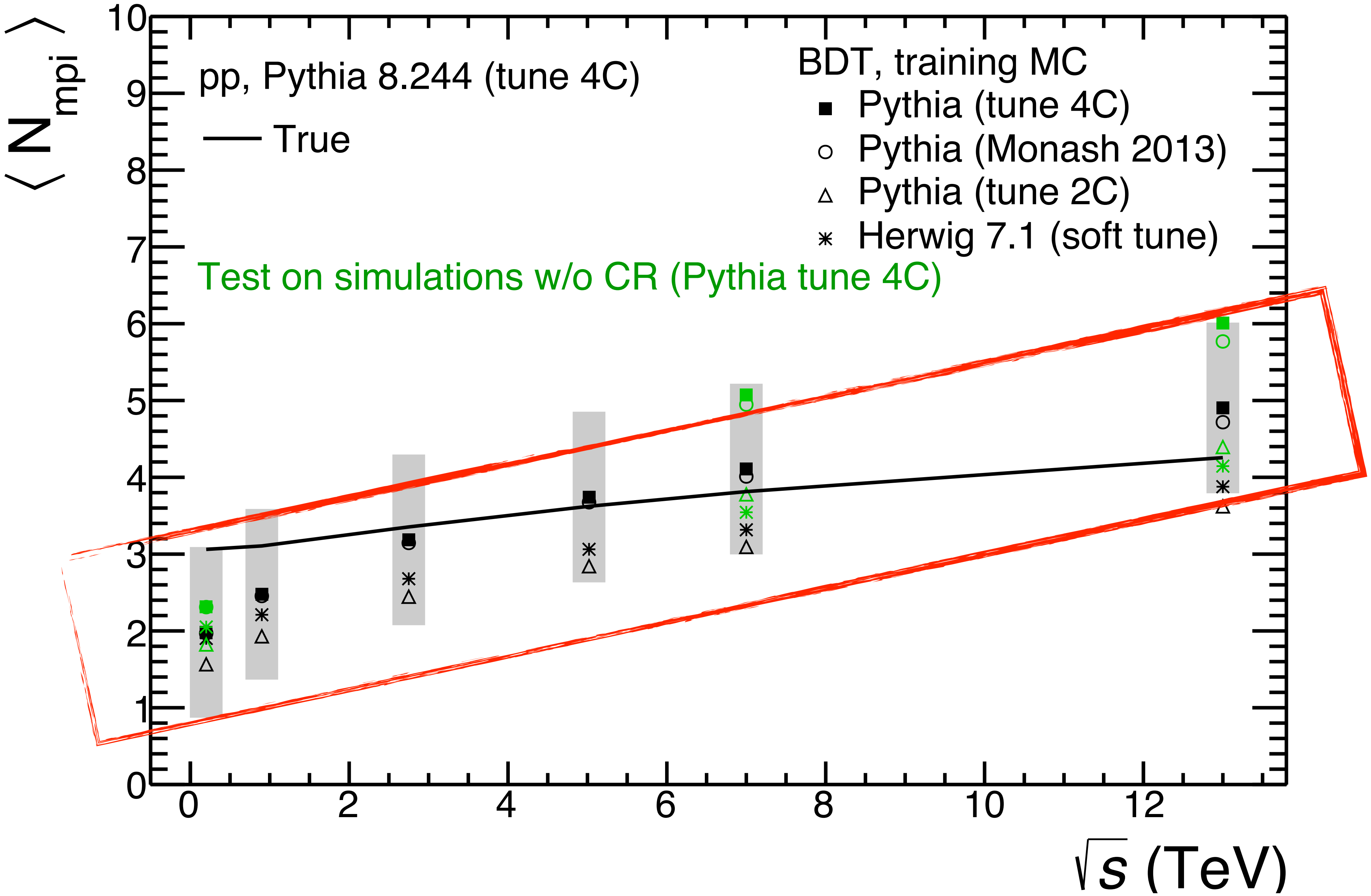




The analysis was repeated considering the following variations:

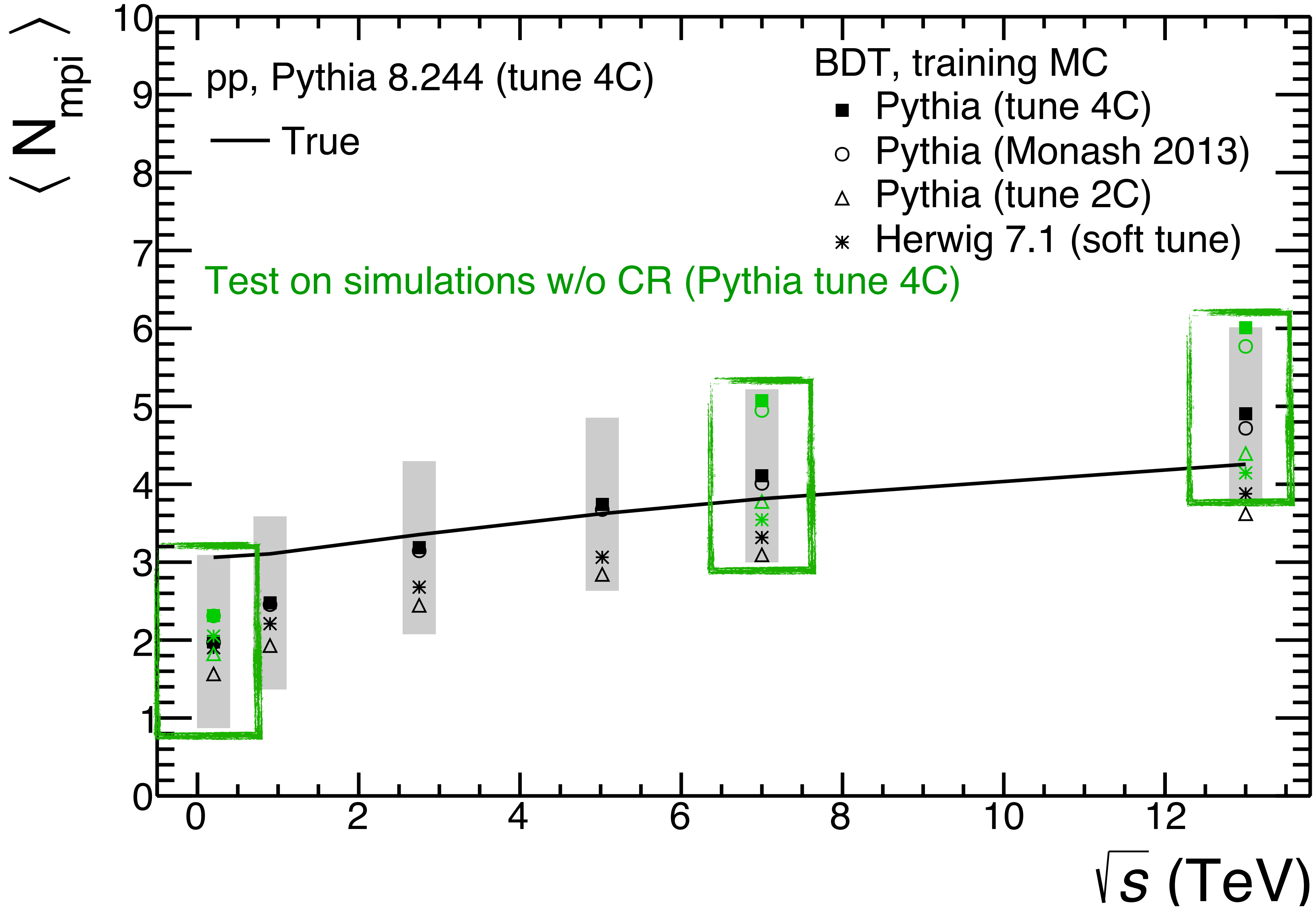
- A different set of input variables was used (spherocity, EbE average transverse momentum and multiplicity in the pseudorapidity region covered by the ALICE VZERO detector)
- Assuming a different MPI distribution (flat)
- All center-of-mass energies were considered

Systematic uncertainties



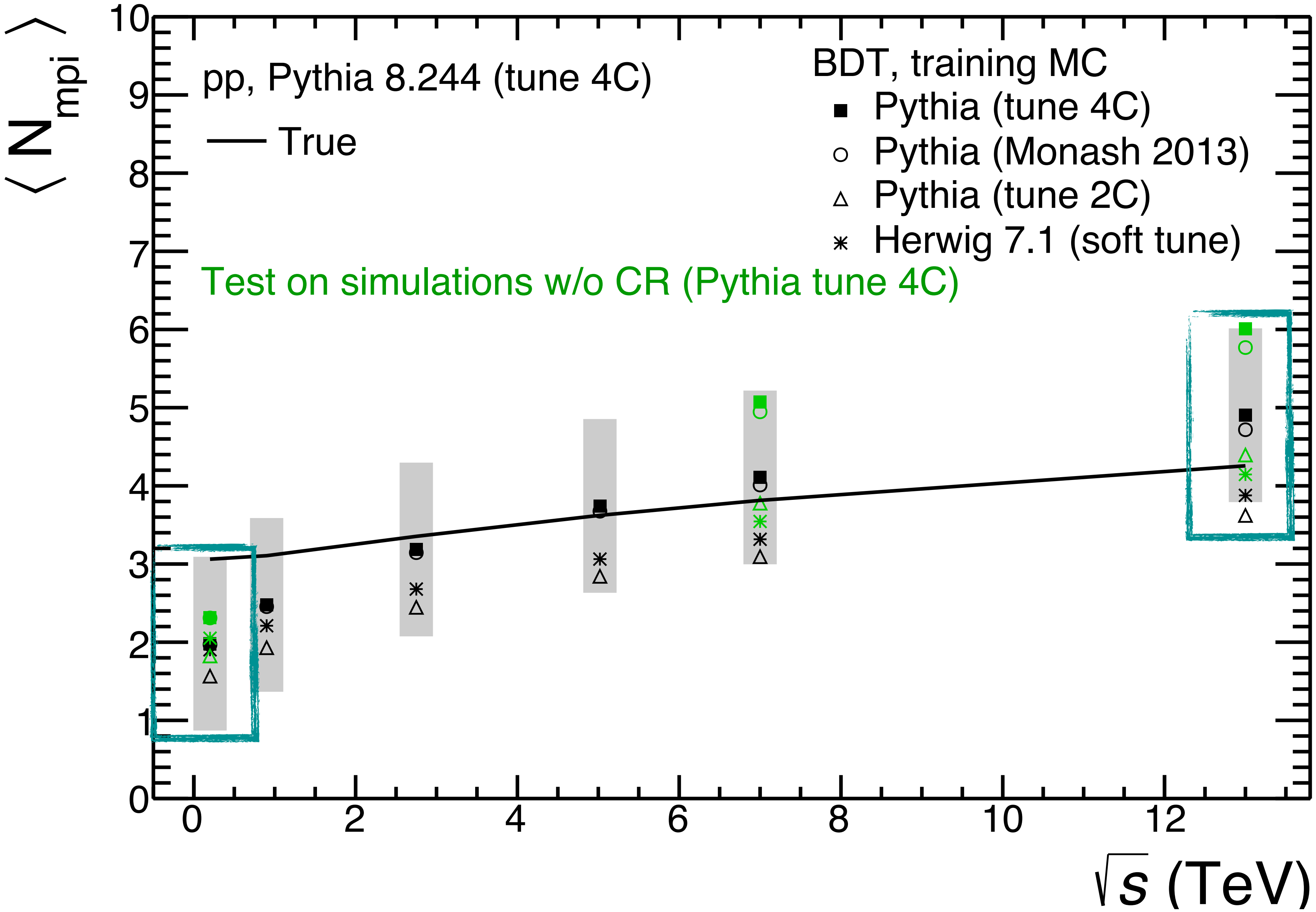
- Within uncertainties, we recover the modest center-of-mass energy dependence of $\langle N_{\mathrm{mpi}} \rangle$

Systematic uncertainties



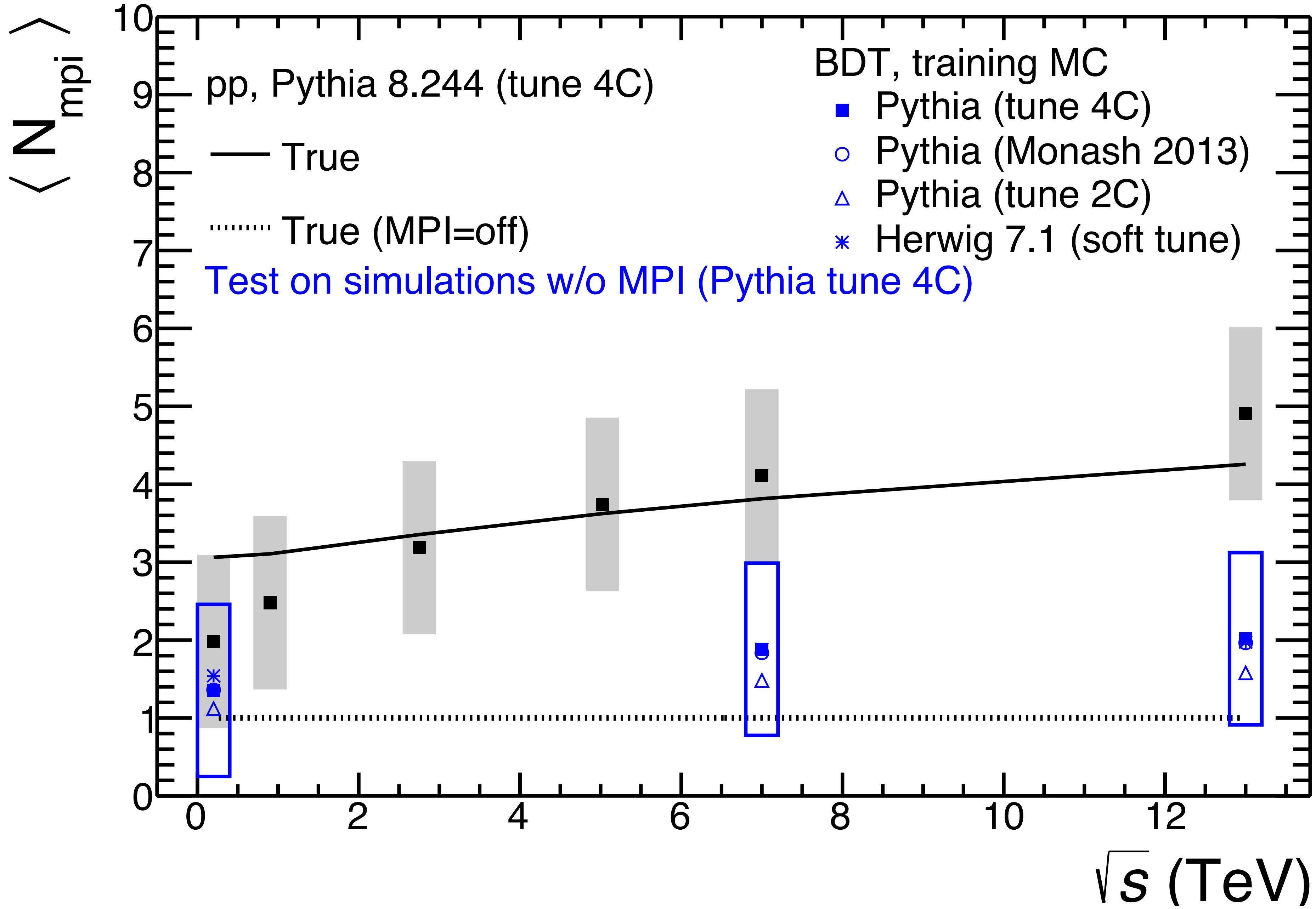
- Within uncertainties, we recover the modest center-of-mass energy dependence of $\langle N_{\rm mpi}\rangle$
- Within uncertainties, $\langle N_{\rm mpi}\rangle$ is found to be independent of CR (expected behaviour)

Systematic uncertainties



- Within uncertainties, we recover the modest center-of-mass energy dependence of $\langle N_{\mathrm{mpi}} \rangle$
- Within uncertainties, $\langle N_{\mathrm{mpi}} \rangle$ is found to be independent of CR (expected behaviour)
- The model dependence is well covered by the systematic uncertainties

Systematic uncertainties



- Within uncertainties, we recover the modest center-of-mass energy dependence of $\langle N_{\rm mpi} \rangle$
- Within uncertainties, $\langle N_{\rm mpi} \rangle$ is found to be independent of CR (expected behaviour)
- The model dependence is well covered by the systematic uncertainties
- In simulations with MPI=off, within uncertainties, the regression value is consistent with one

Systematic uncertainties

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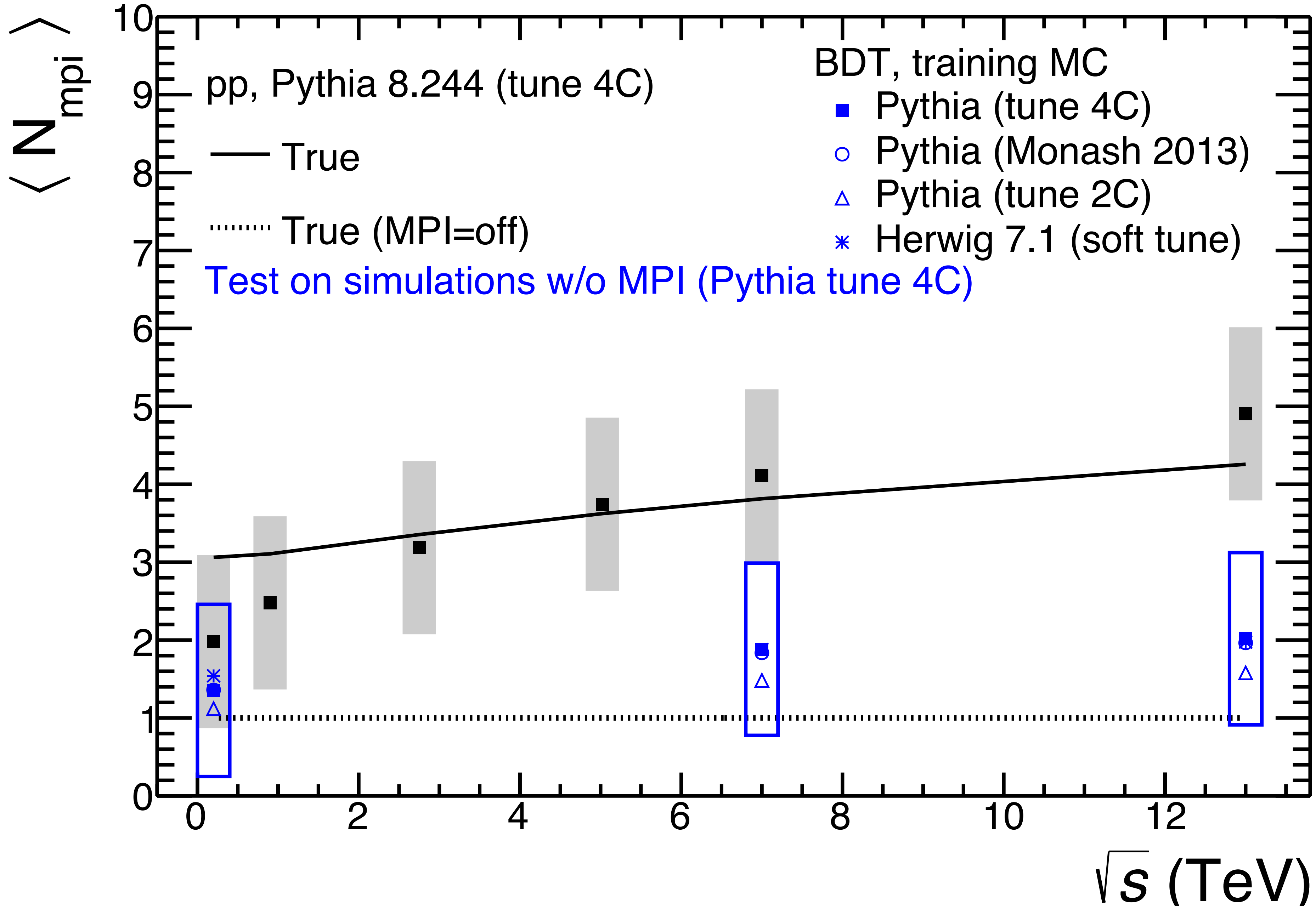
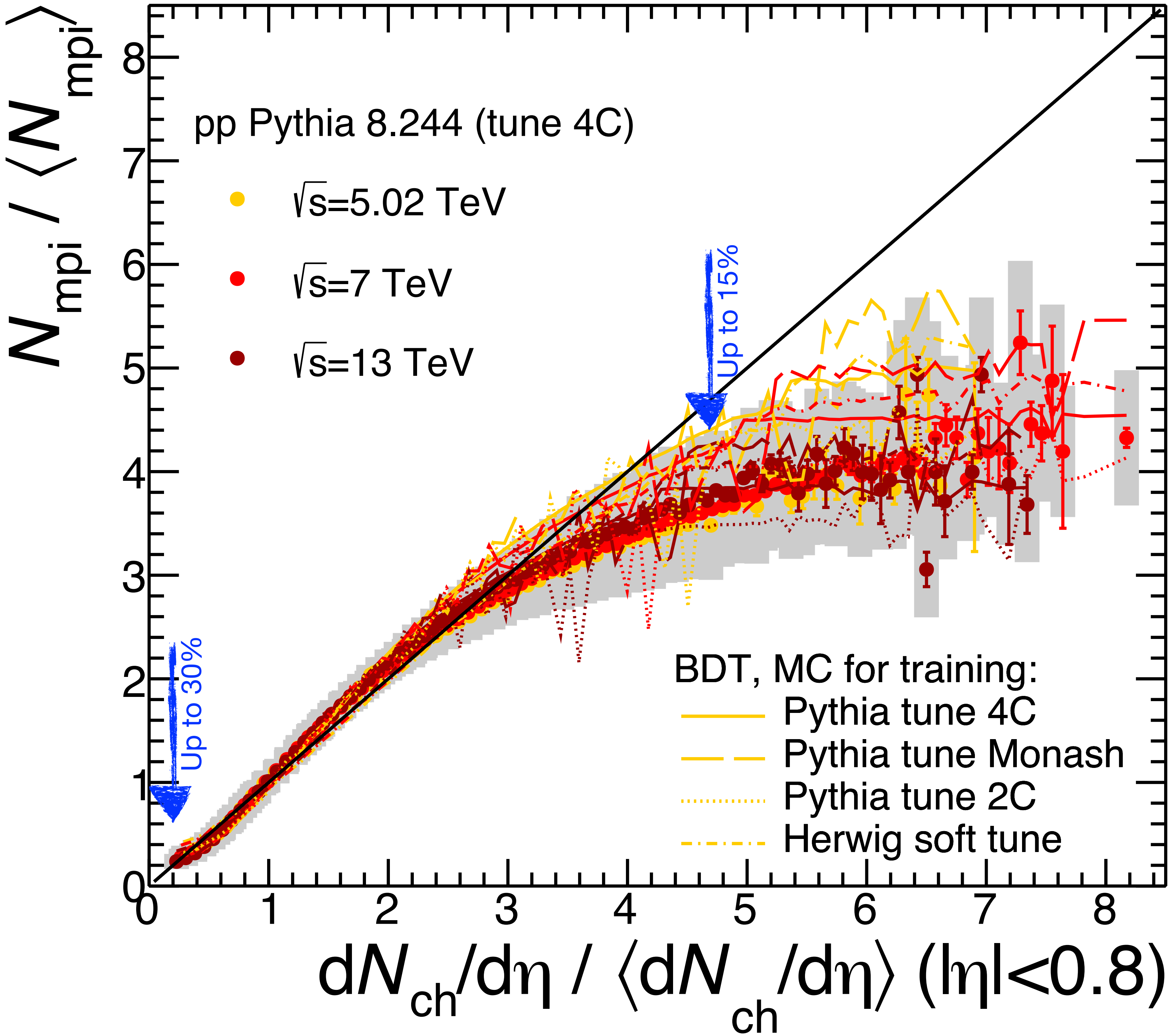


The method has been validated using minimum-bias pp collisions simulated with Pythia and Herwig, the systematic uncertainties cover the model dependence

MC closure test + Syst. Unc.

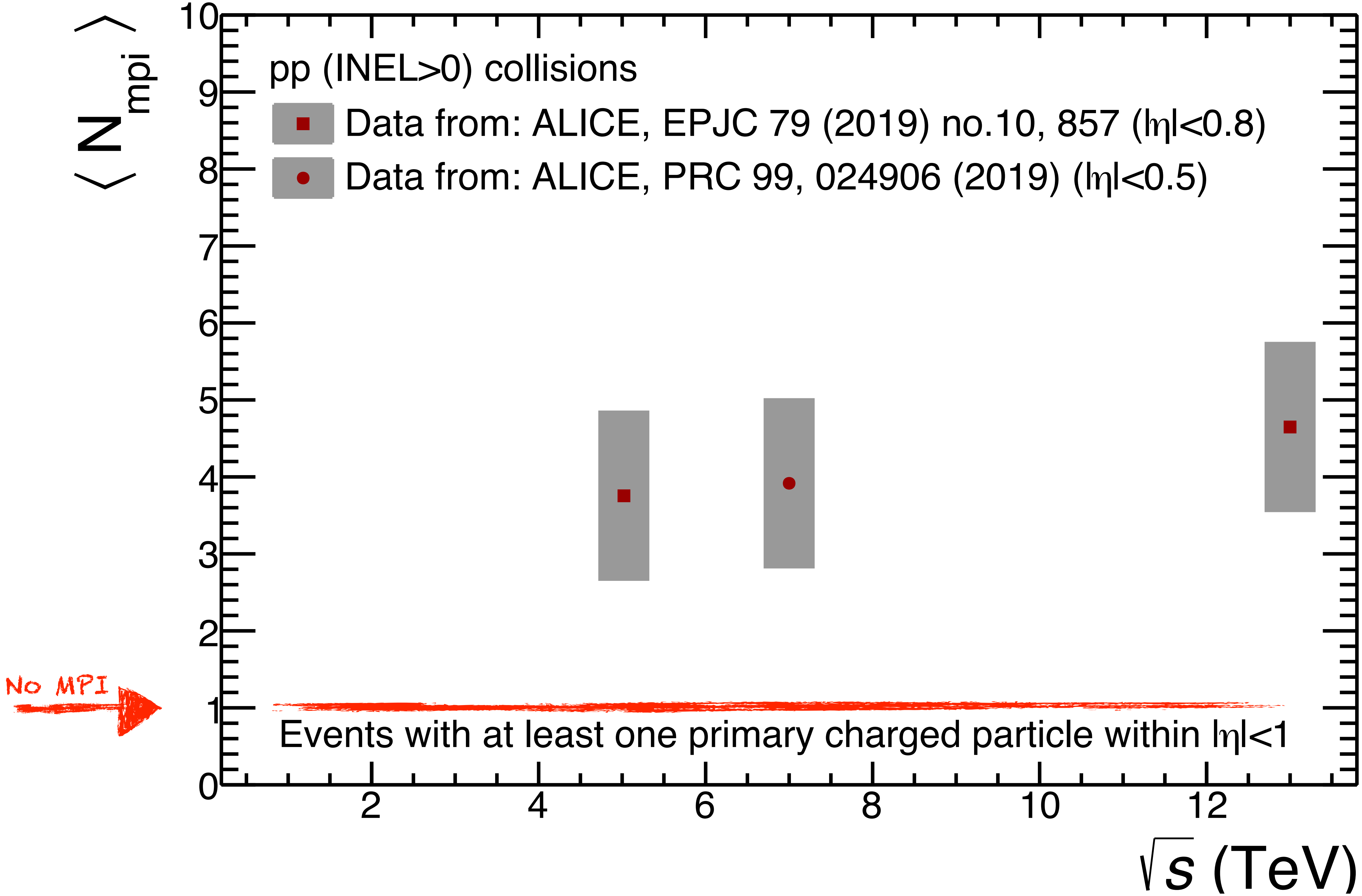


The systematic uncertainties cover the model dependence

Extraction of N_{mpi} from existing LHC data

MPI from ALICE data

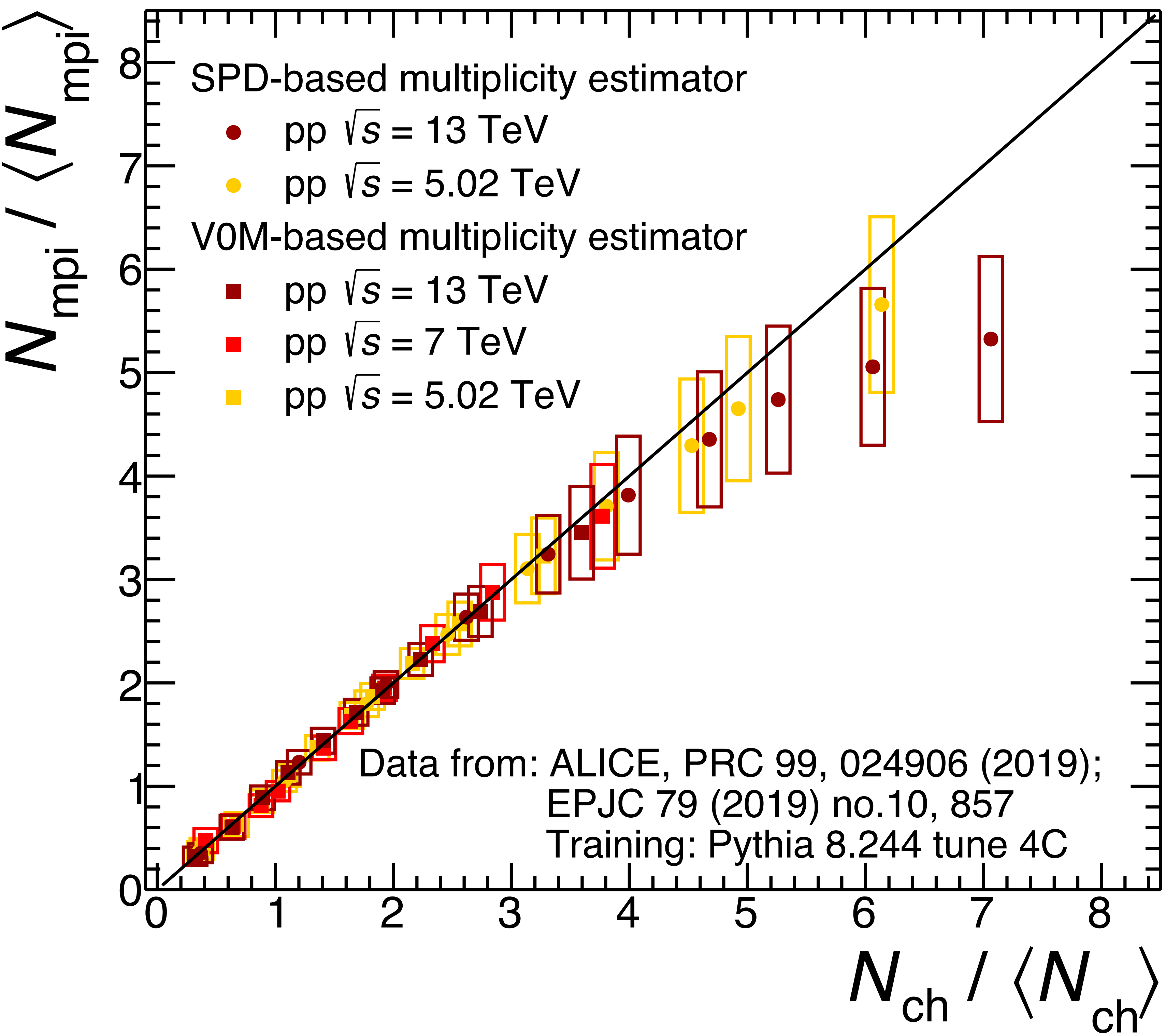
Instituto de Ciencias Nucleares UNAM



Data support the presence of MPI, regression value above 1!

MPI from ALICE data

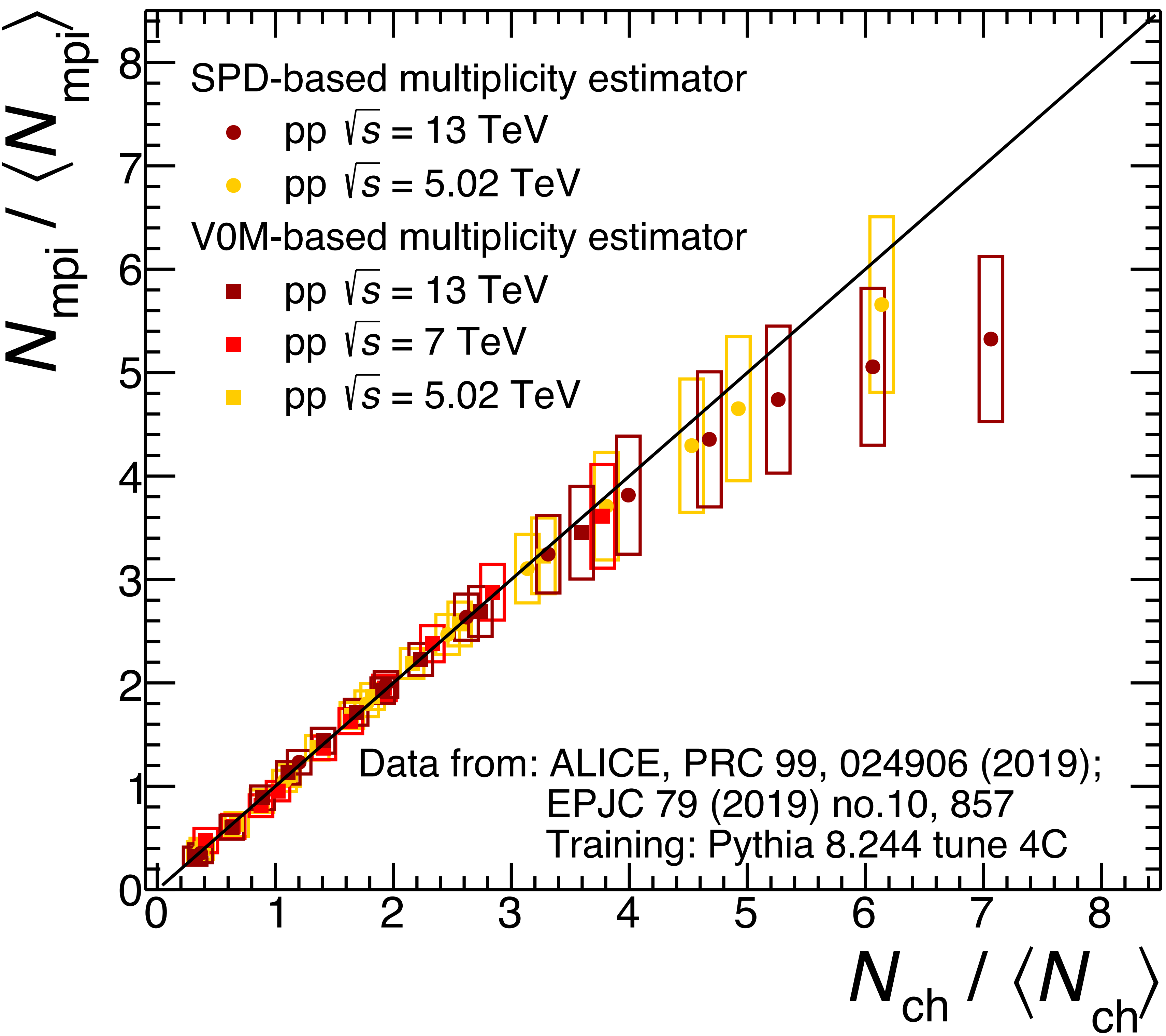
Instituto de Ciencias Nucleares UNAM

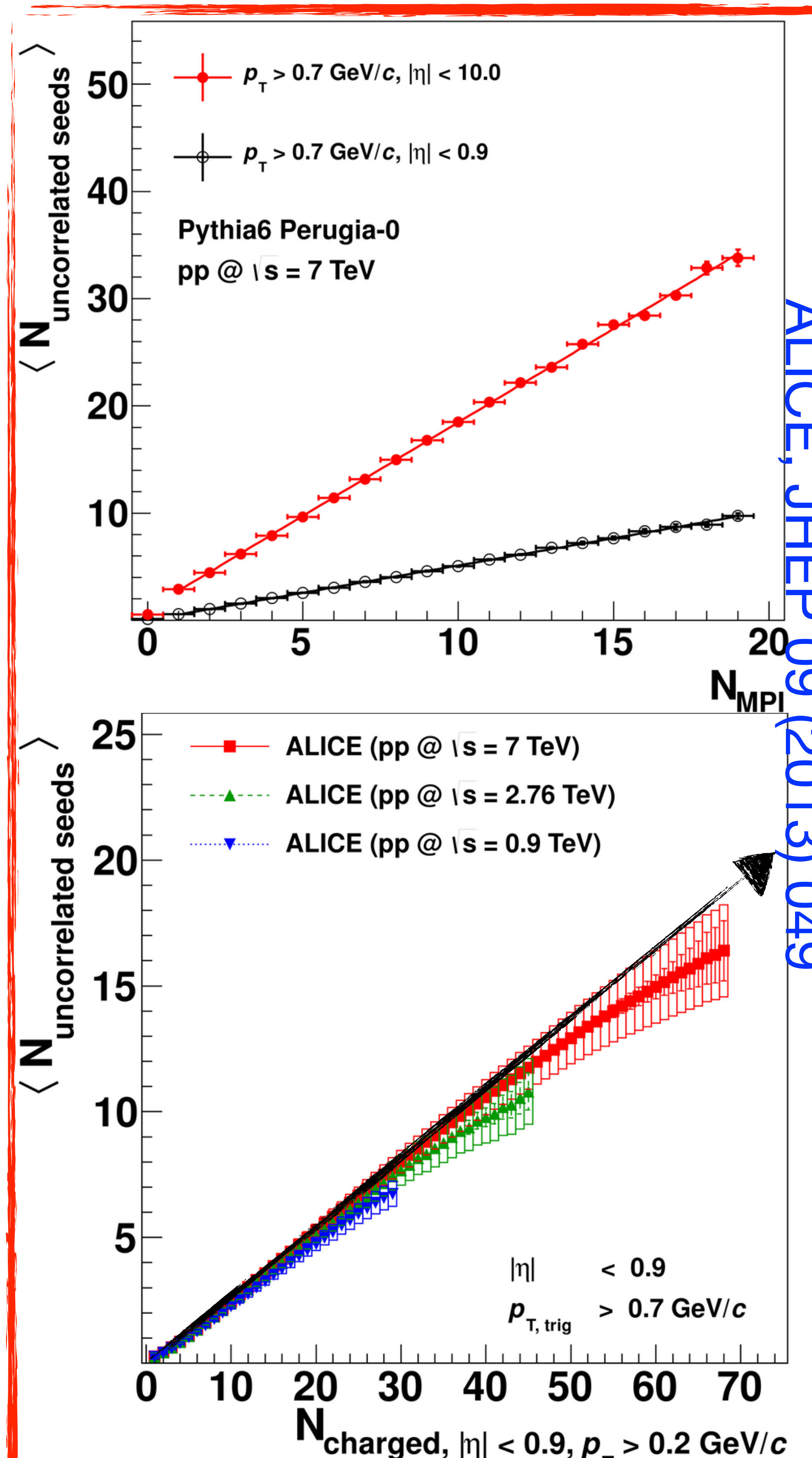


- N_{mpi} as a function of N_{ch} does not show a $\sqrt{s}$ dependence
- $N_{\mathrm{ch}} < 3 \times \langle N_{\mathrm{ch}} \rangle$: N_{ch} increases linearly with N_{mpi}
- $N_{\mathrm{ch}} > 3 \times \langle N_{\mathrm{ch}} \rangle$ can only be reached by selecting events with many high-multiplicity jets

MPI from ALICE data

Instituto de Ciencias Nucleares UNAM





ALICE, JHEP 09 (2013) 049

Our result is qualitatively consistent with the MPI-dedicated analysis

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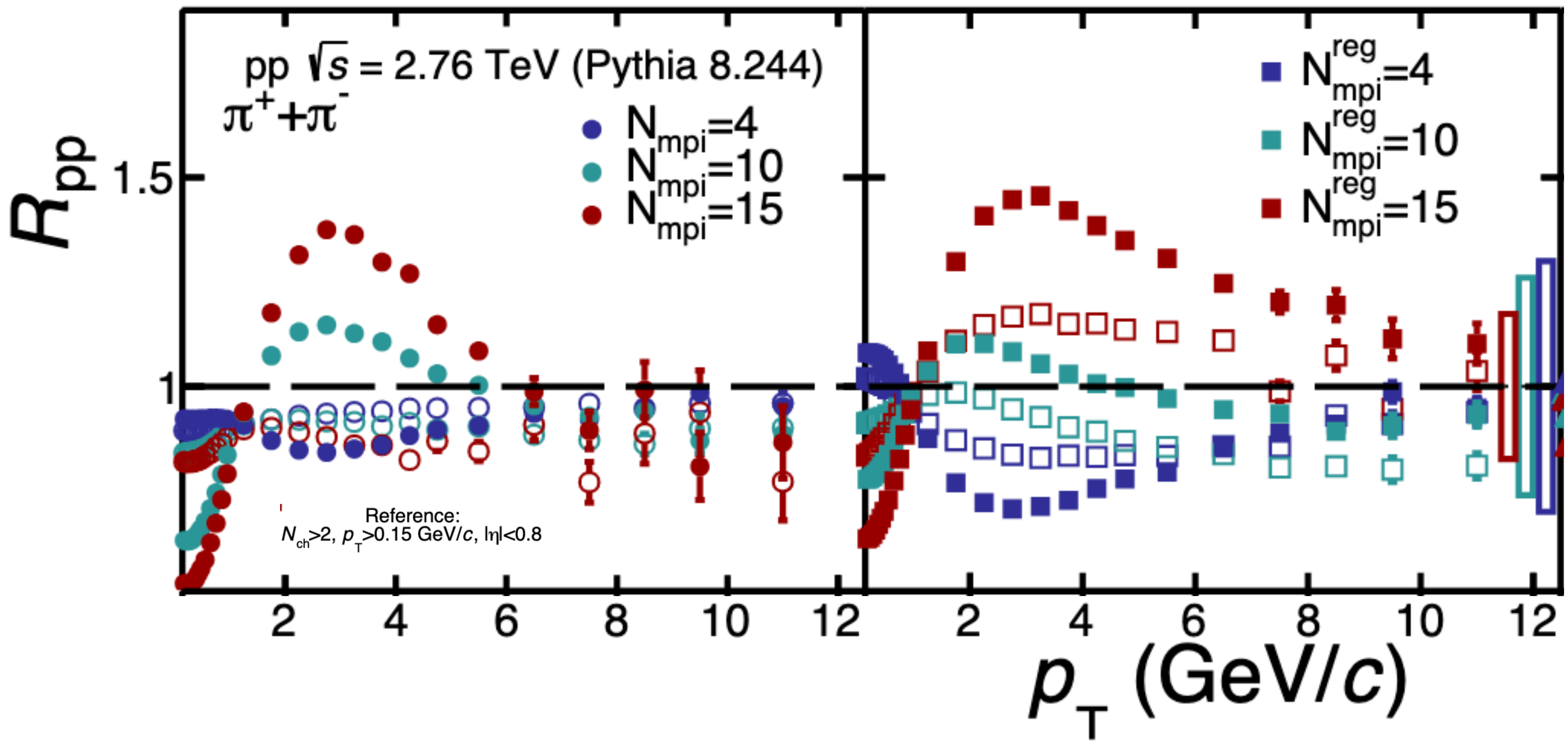
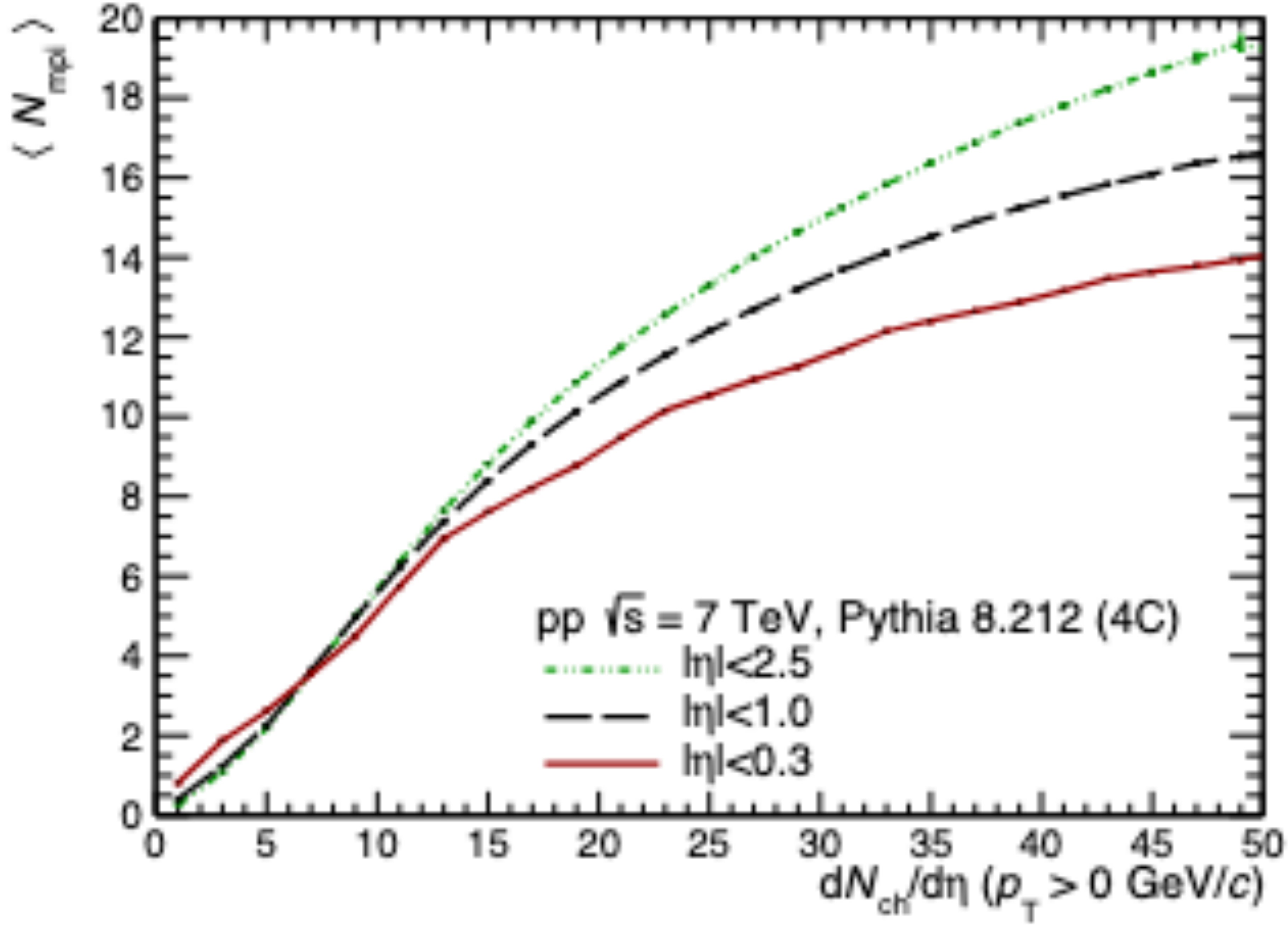
Event-by-event determination of N_{mpi}



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

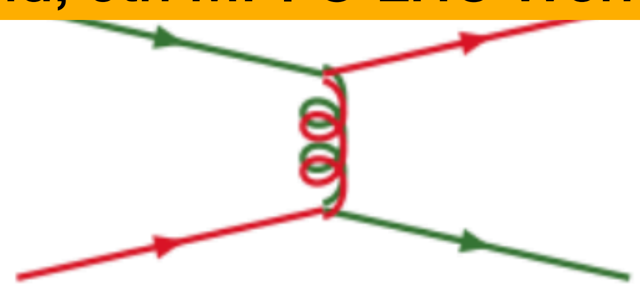
Backup



⟨ N_{mpi} ⟩
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
50
$dN_{ch}/d\eta$ (p_T > 0 GeV/c)
pp $\sqrt{s}$ = 7 TeV, Pythia 8.212 (4C)
|η|<2.5
|η|<1.0
|η|<0.3

- 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 $2 \to 2$

$qq' \to qq'$

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

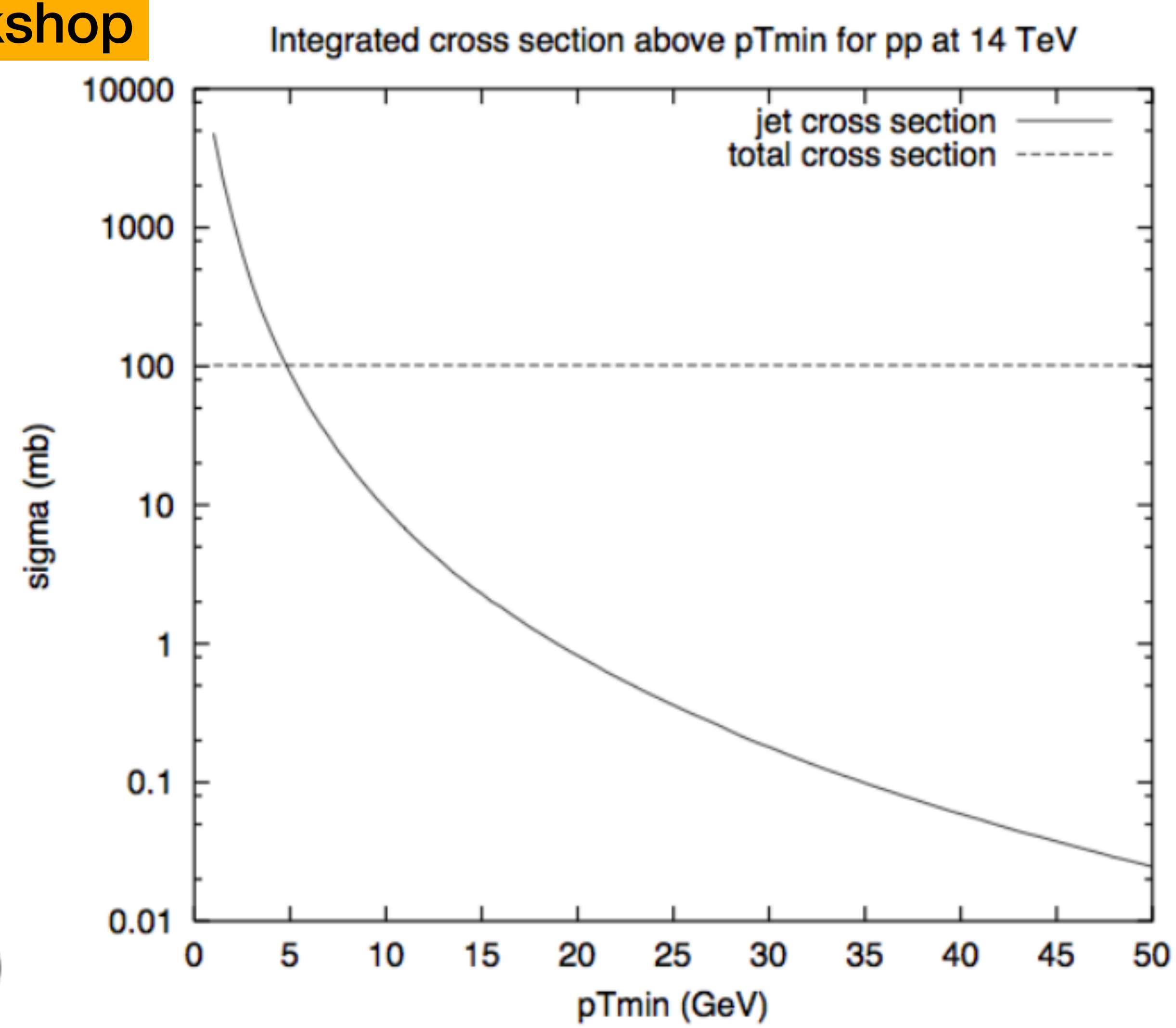
$q\bar{q} \to gg$

$qg \to qg$

$gg \to gg$

$gg \to q\bar{q}$

(with CTEQ 5L PDF's)



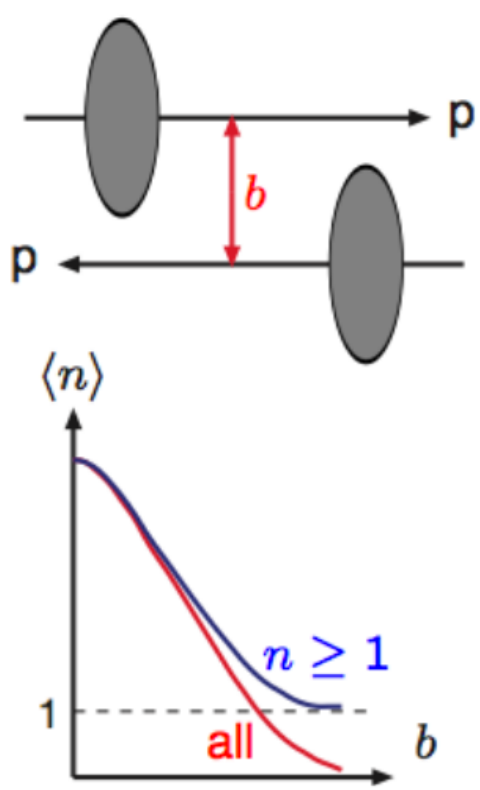
MPI in HEP

Instituto de Ciencias Nucleares UNAM

- At high energies, the leading order cross-section for $2 \to 2$ p… e… w… [

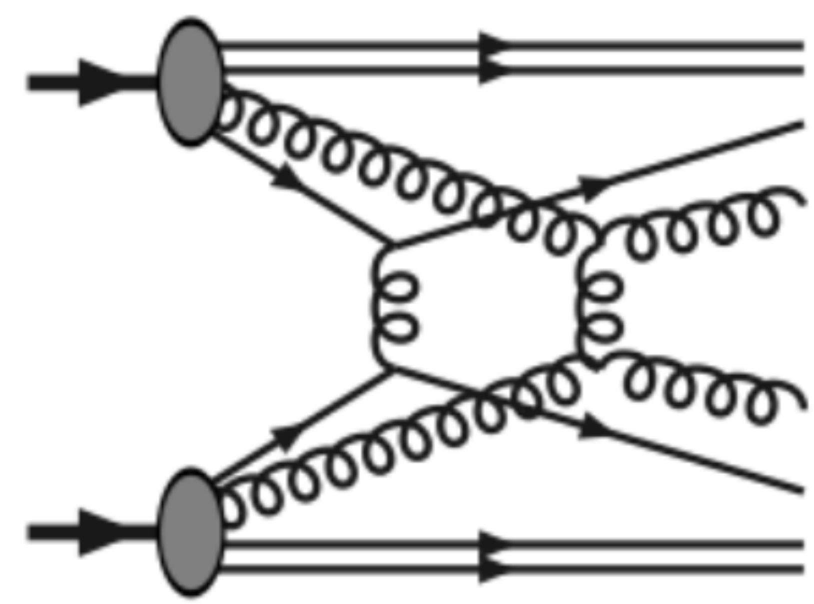
Interpretation: Many partonic scatterings per event: (MPI)

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



T. Sjöstrand, ISAPP 2018

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

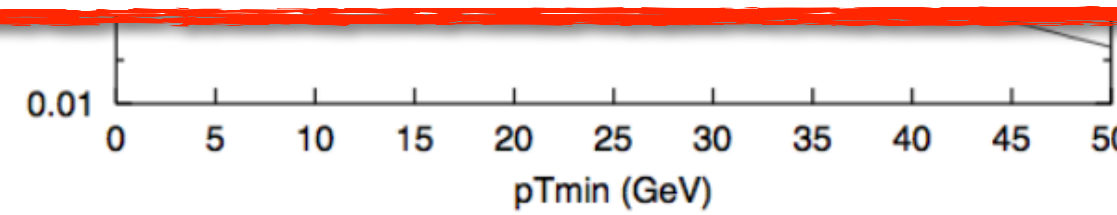


Overlap of protons during encounter is

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

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

$gg \to q\bar{q}$
(with CTEQ 5L PDF's)



MPI in HEP

Instituto de Ciencias Nucleares UNAM

- At high energies, the leading order cross-section for $2 \rightarrow 2$

Interpretation: Many partonic scatterings per event: (MPI)

MPI help to describe particle multiplicities in MB events

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

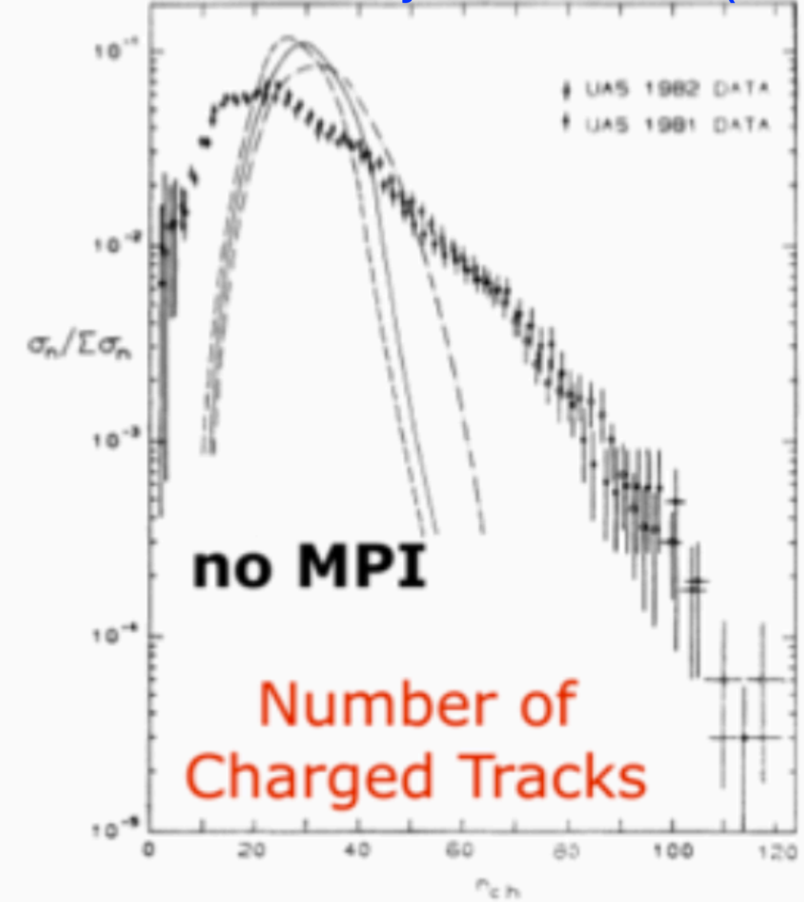


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

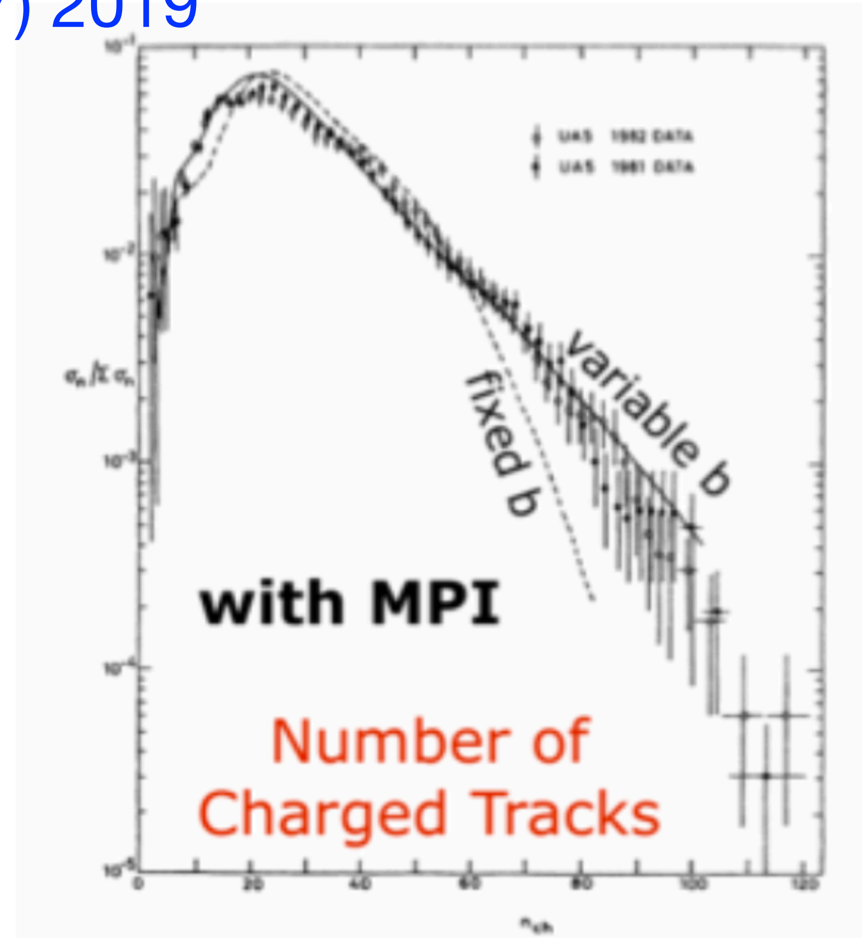


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

(with CTEQ 5L PDF's)