Studies on system-size dependence of particle production with ALICE

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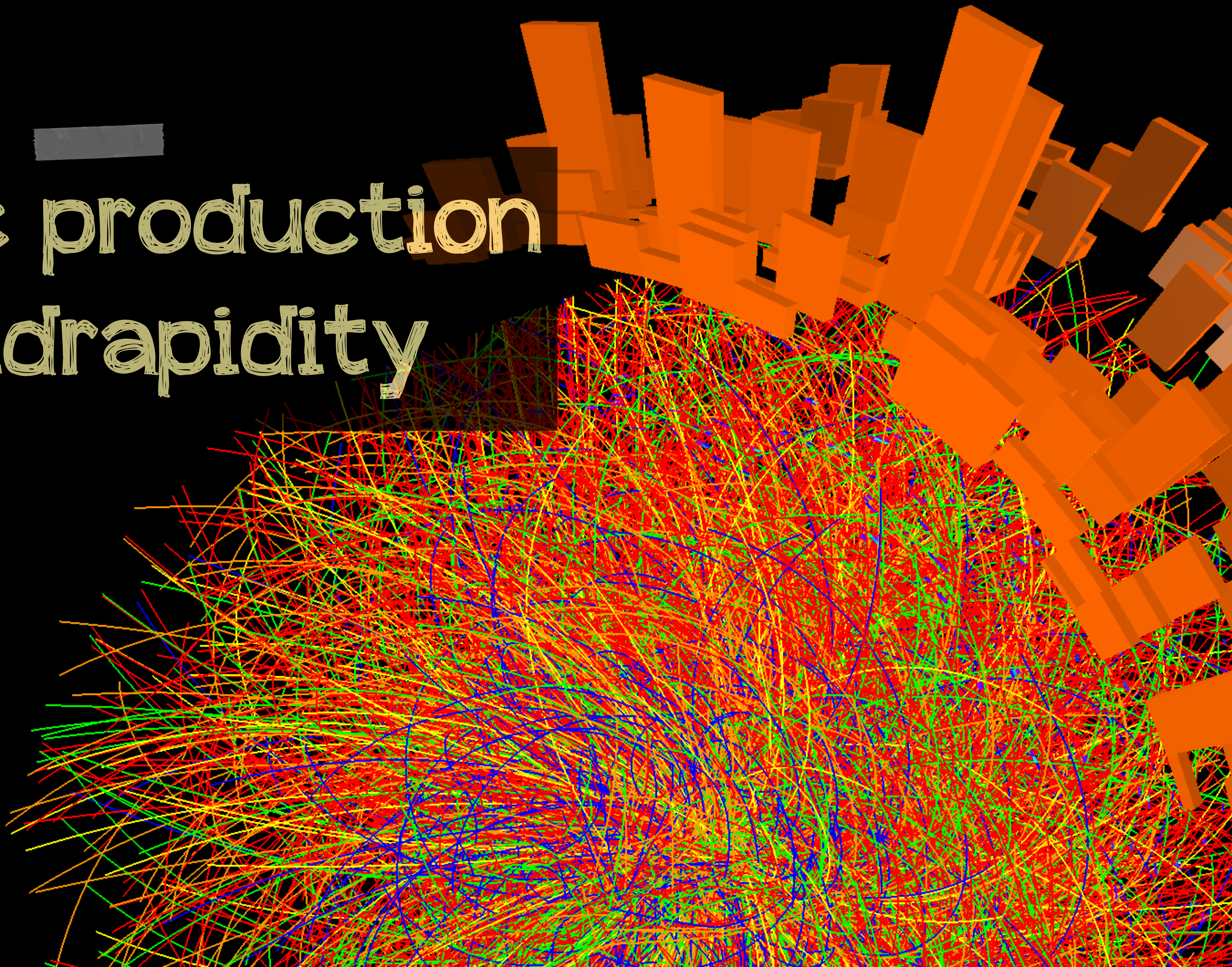
on behalf of the ALICE Collaboration

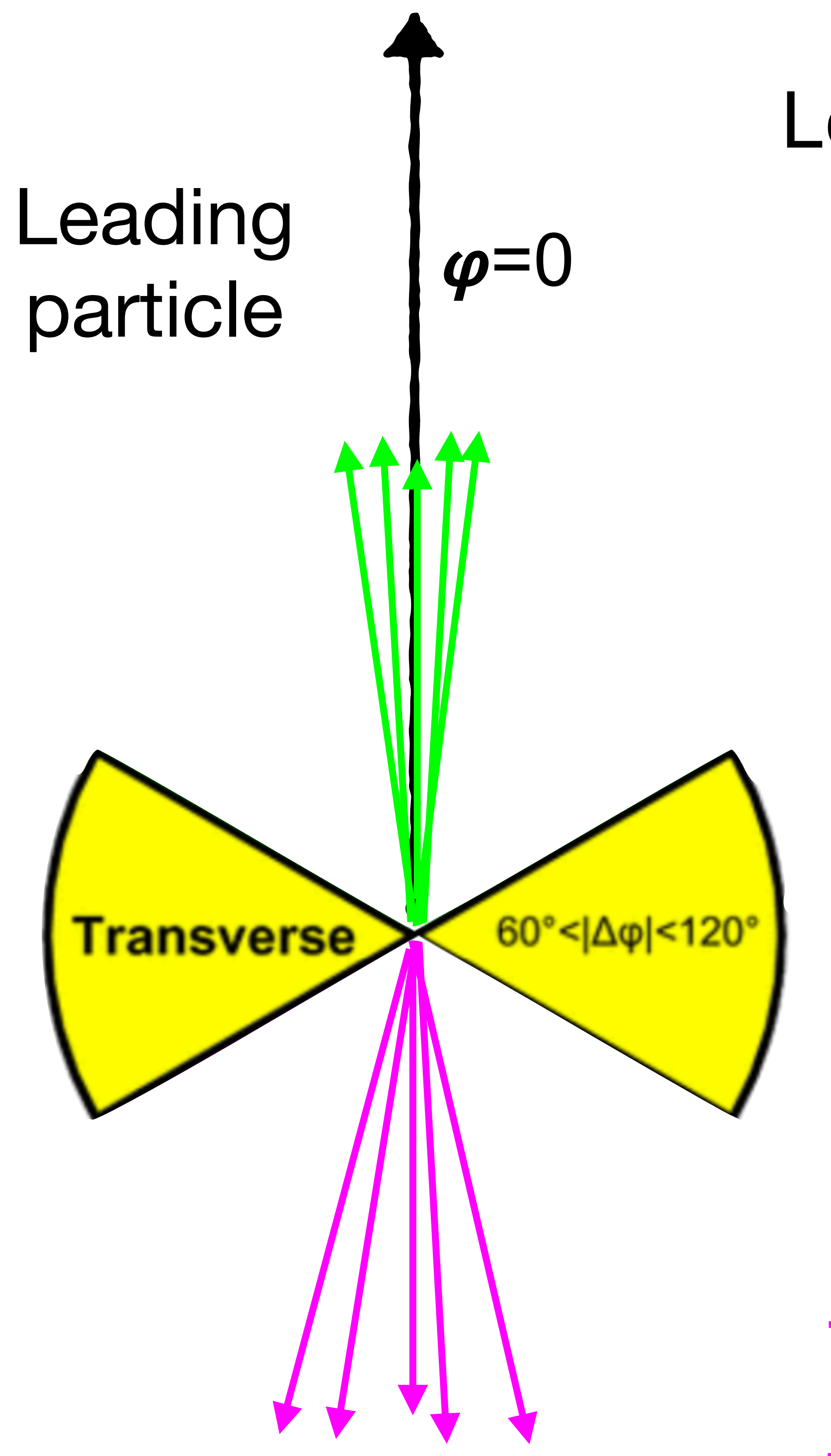
QCD @ LHC 2023
4-8 September, Durham, UK

ALICE in Run2

Particle production at midrapidity



The underlying event



Leading particle ➧ hard scattering

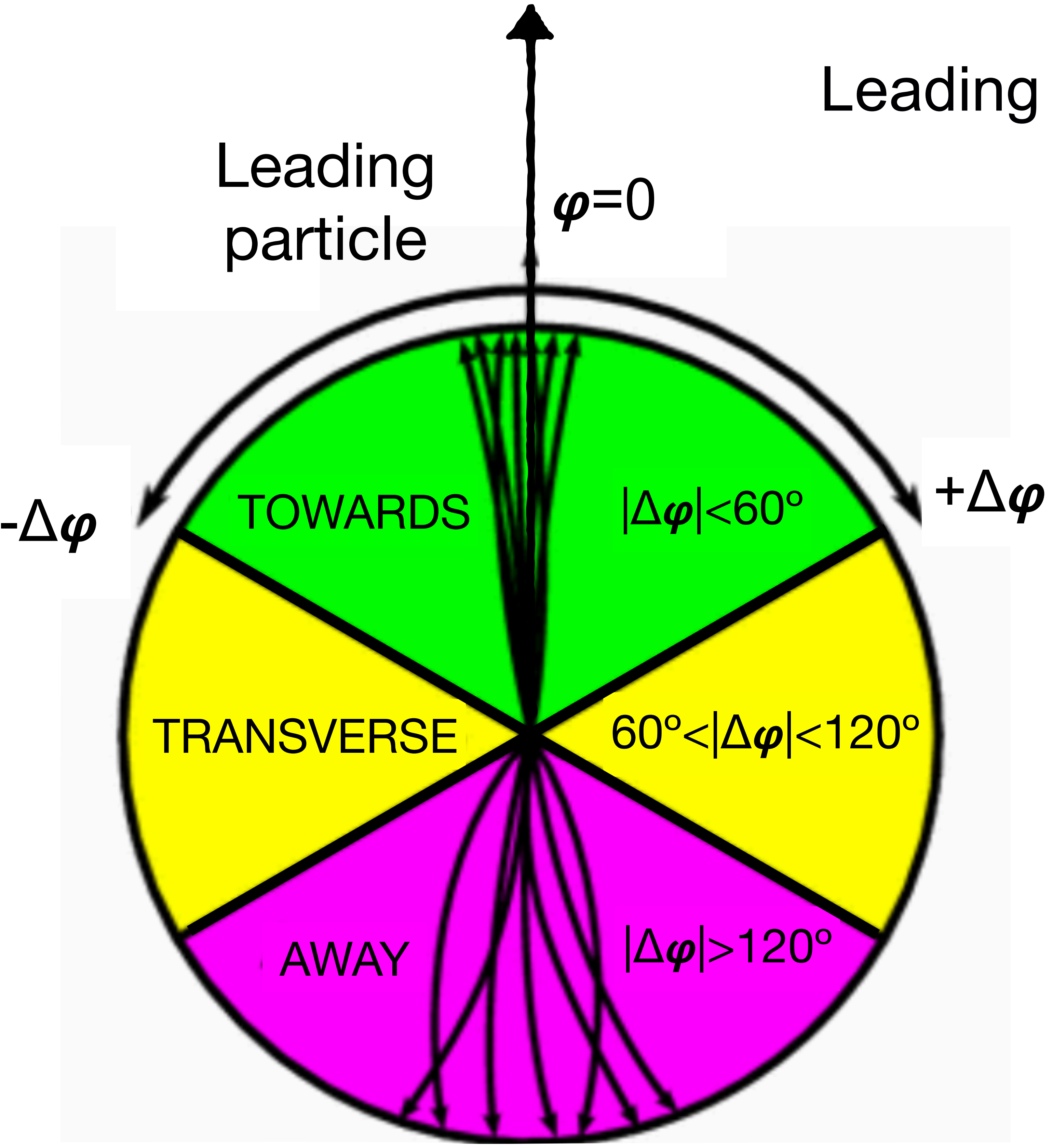
REGION TOWARDS the leading particle contains fragmentation from hard scattering

The TRANSVERSE REGION contains:

- ❑ (mostly) particles NOT originating from primary hard scattering
  - ➧ beam remnants, MPI ➧ UNDERLYING EVENT (UE)
- ❑ Residual of the hard fragmentation ➧ Initial and Final State Radiation (ISR/FSR)

The AWAY region contains the fragmentation from the back-to-back jet

The underlying event

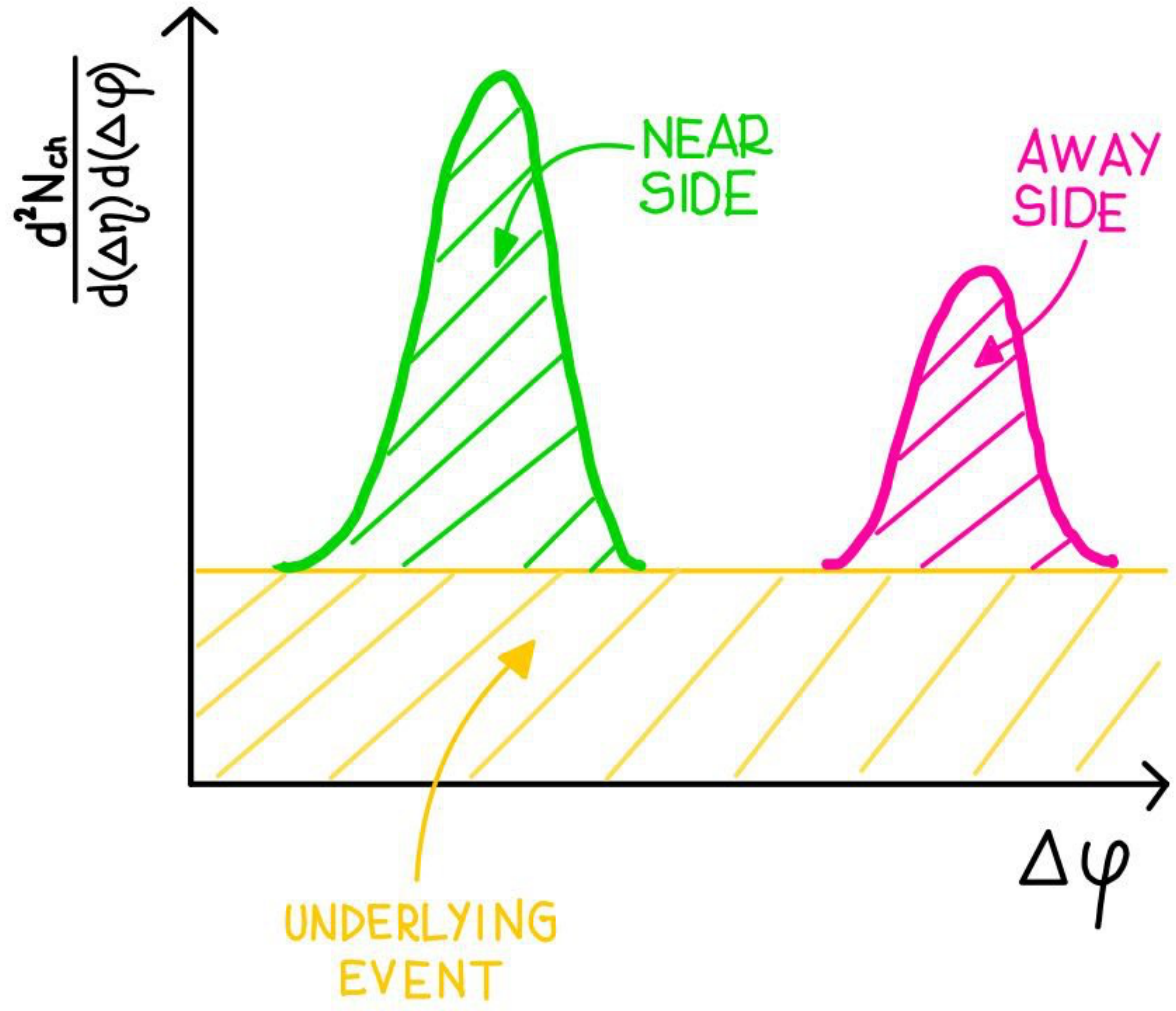


Leading particle ➧ hard scattering

TOWARDS REGION ($|\Delta\varphi|<60^\circ$)

TRANSVERSE REGION ($60^\circ<|\Delta\varphi|<120^\circ$)

AWAY REGION ($|\Delta\varphi|>120^\circ$)

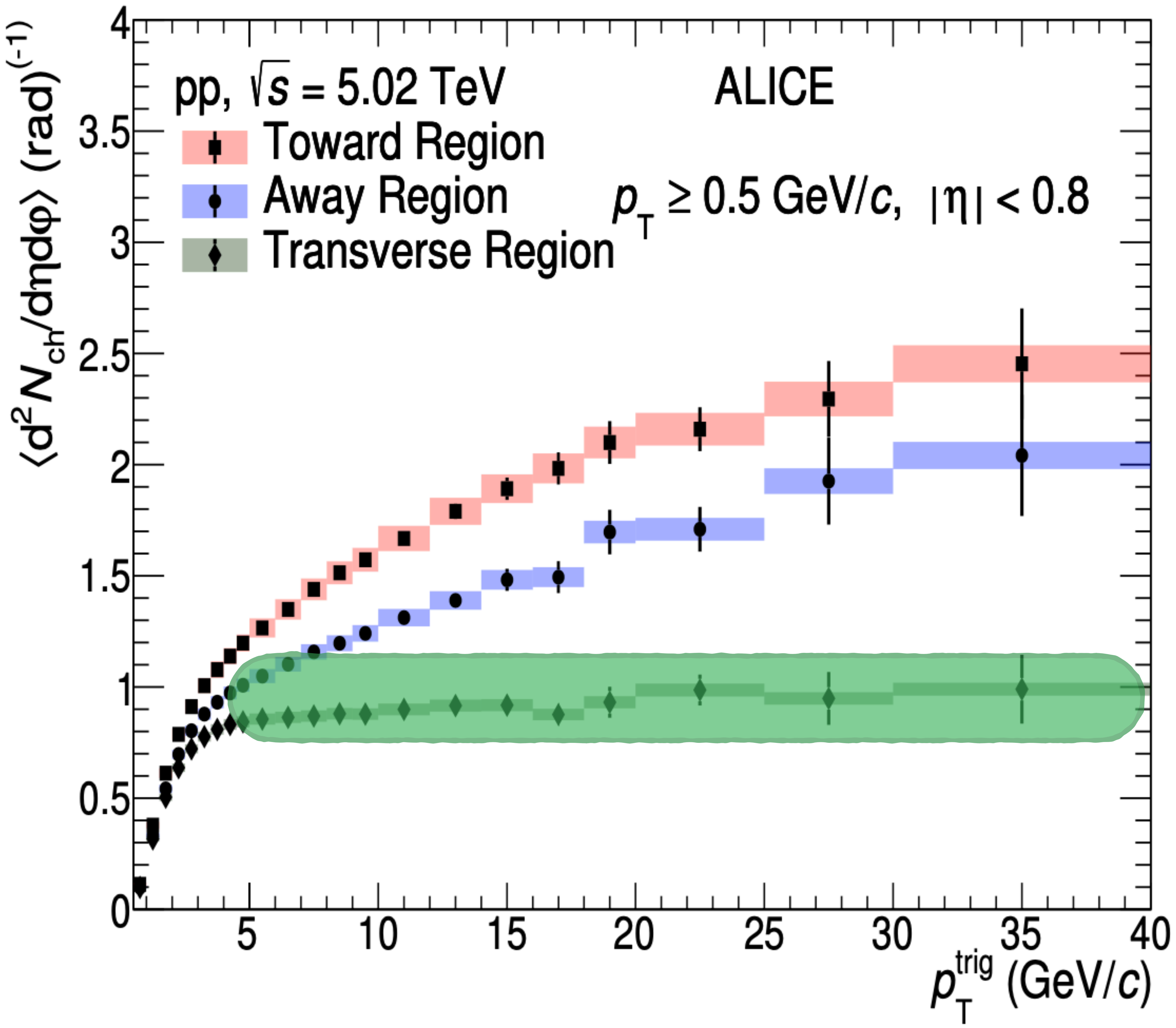


➧ Disentangle HARD from SOFT particle production mechanisms

TOWARDS and AWAY regions | TRANSVERSE region

The underlying event

ALICE Coll., JHEP 06 (2023) 023



TOWARDS and AWAY regions

- Charged-particle density scales with the hardness of the process

TRANSVERSE region

- Models implementing MPI with impact-parameter dependence: small impact parameter ➧ larger N_{MPI} ➧ larger matter overlap
- Saturation for $p_T^{leading}$ >5 GeV/c ➧ multiplicity in the TRANSVERSE region is largely independent on leading particle p_T when the trigger particle originates from a hard partonic scattering

➧ the TRANSVERSE region is the ideal place to study SOFT particle production mechanisms, “outside” the jet

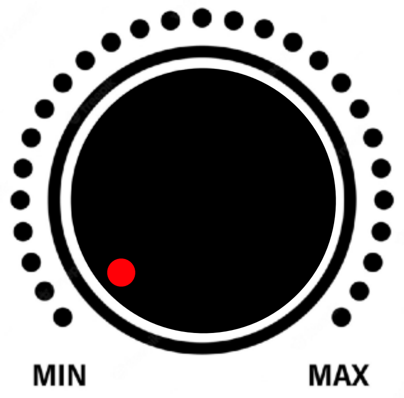
R_T variable

T. Martin et al., Eur. Phys. J. C76 5, (2016) 299

- Define a "KNO-like" variable for $p_T^{leading}$ >5 GeV/c based on multiplicity in the transverse region, N_{ch}^T, used to classify events as function of event-by-event UE level

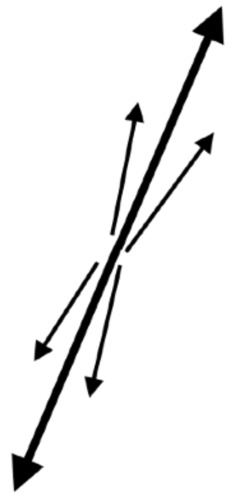
$$R_T = N_{ch}^T / \langle N_{ch}^T \rangle$$

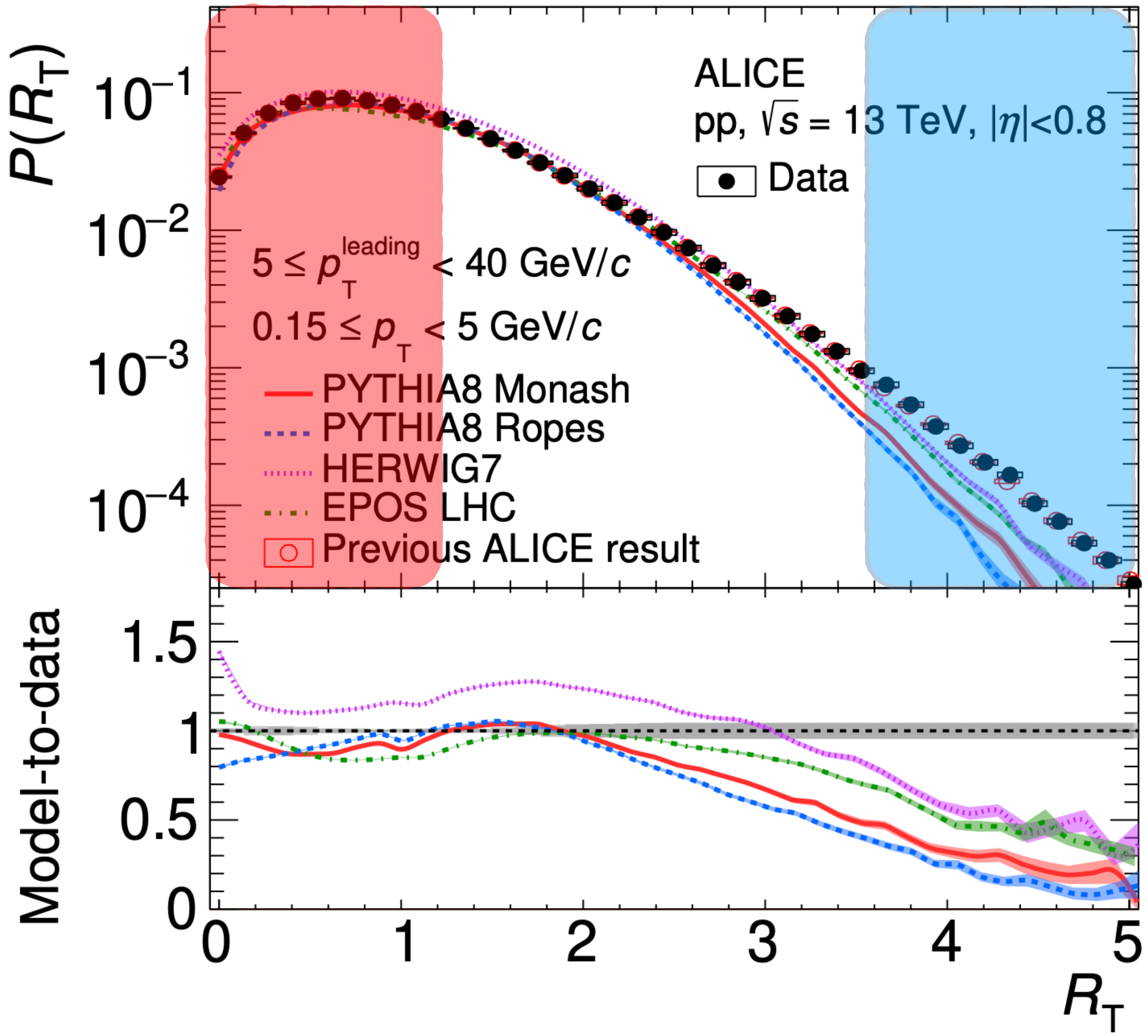
ALICE Coll., JHEP 06 (2023) 027

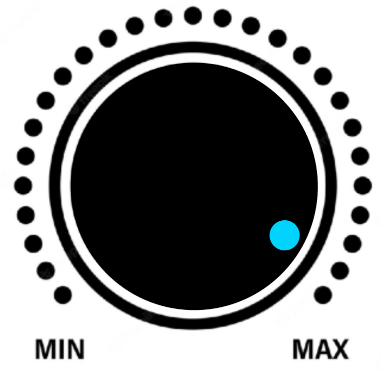


Small R_T

- e^+e^--like
- event dominated by jet
- low-UE, low N_{MPI}

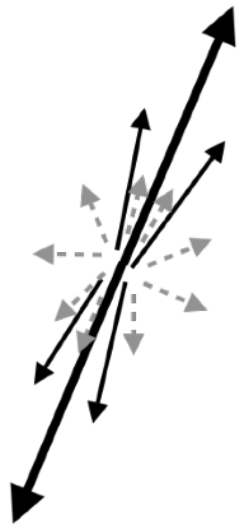






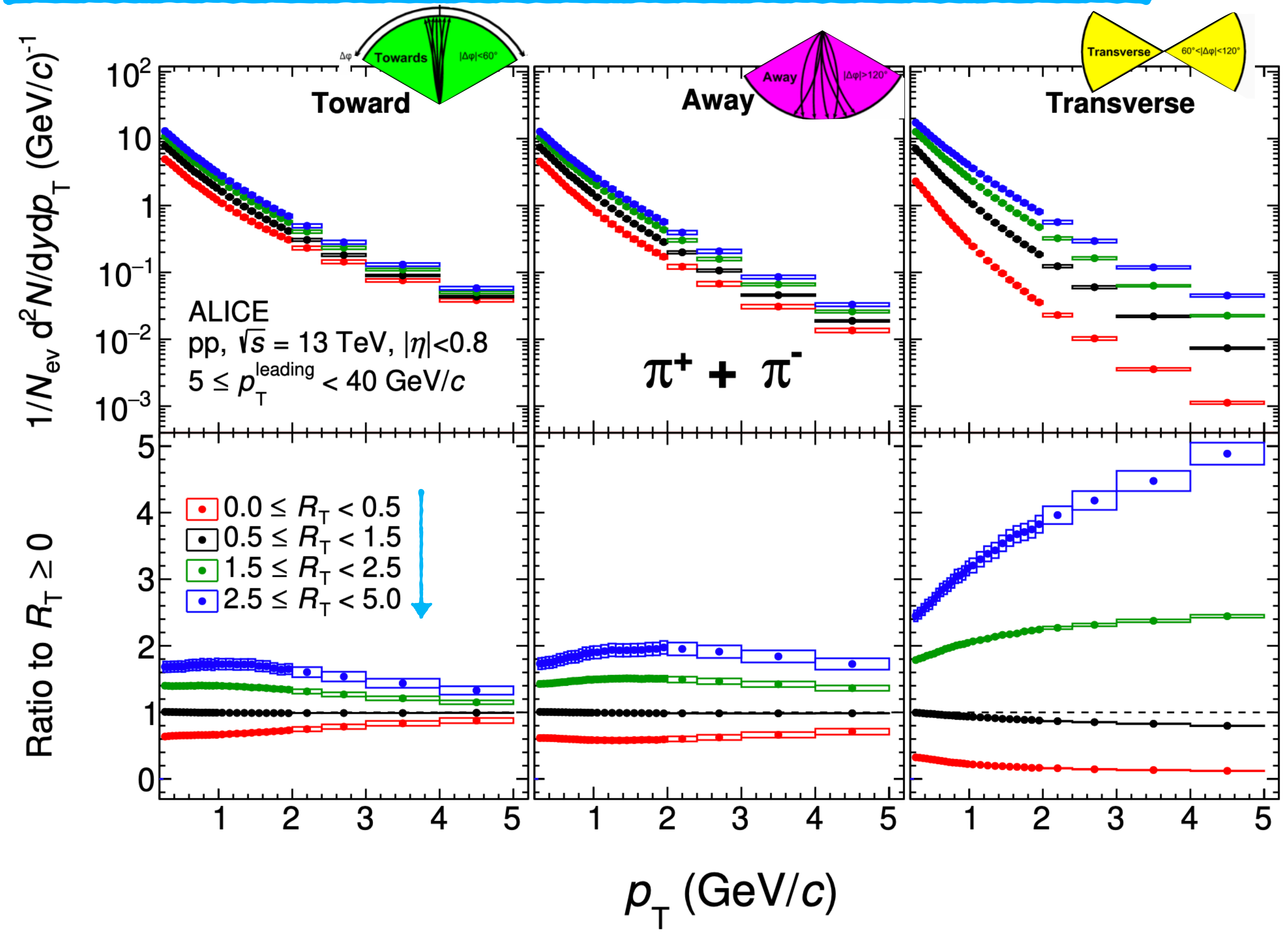
Large R_T

- high-UE
- event characterised by large N_{MPI}



Pion spectra vs. R_T

ALICE Coll., JHEP 06 (2023) 027



TOWARDS and AWAY regions

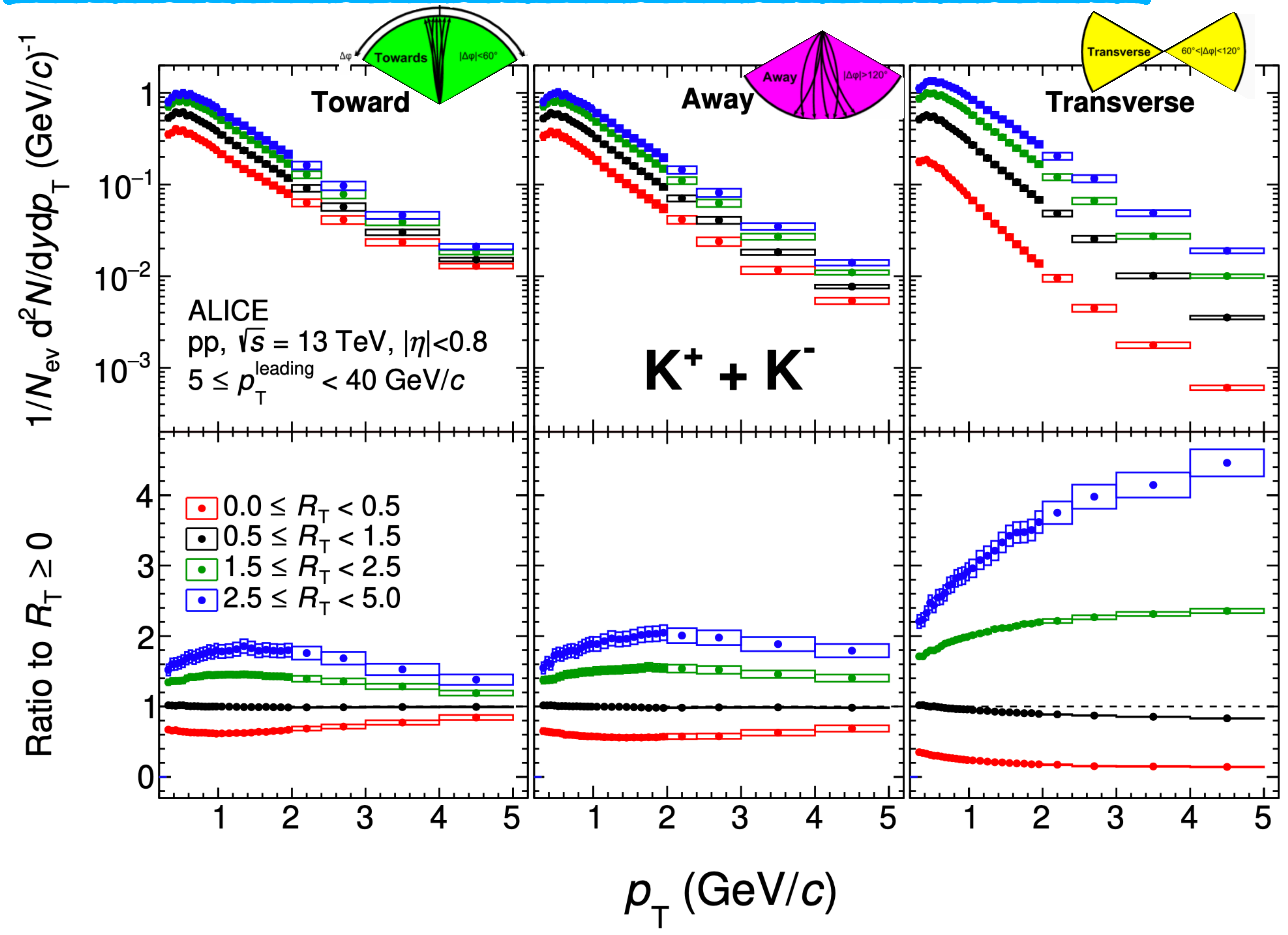
- Depletion of low p_T particle with increasing R_T
- Softening of the spectra with increasing R_T for $p_T \geq 2$ GeV/c

TRANSVERSE region

- Hardening of the spectra with increasing UE activity

Kaon spectra vs. R_T

ALICE Coll., JHEP 06 (2023) 027



TOWARDS and AWAY regions

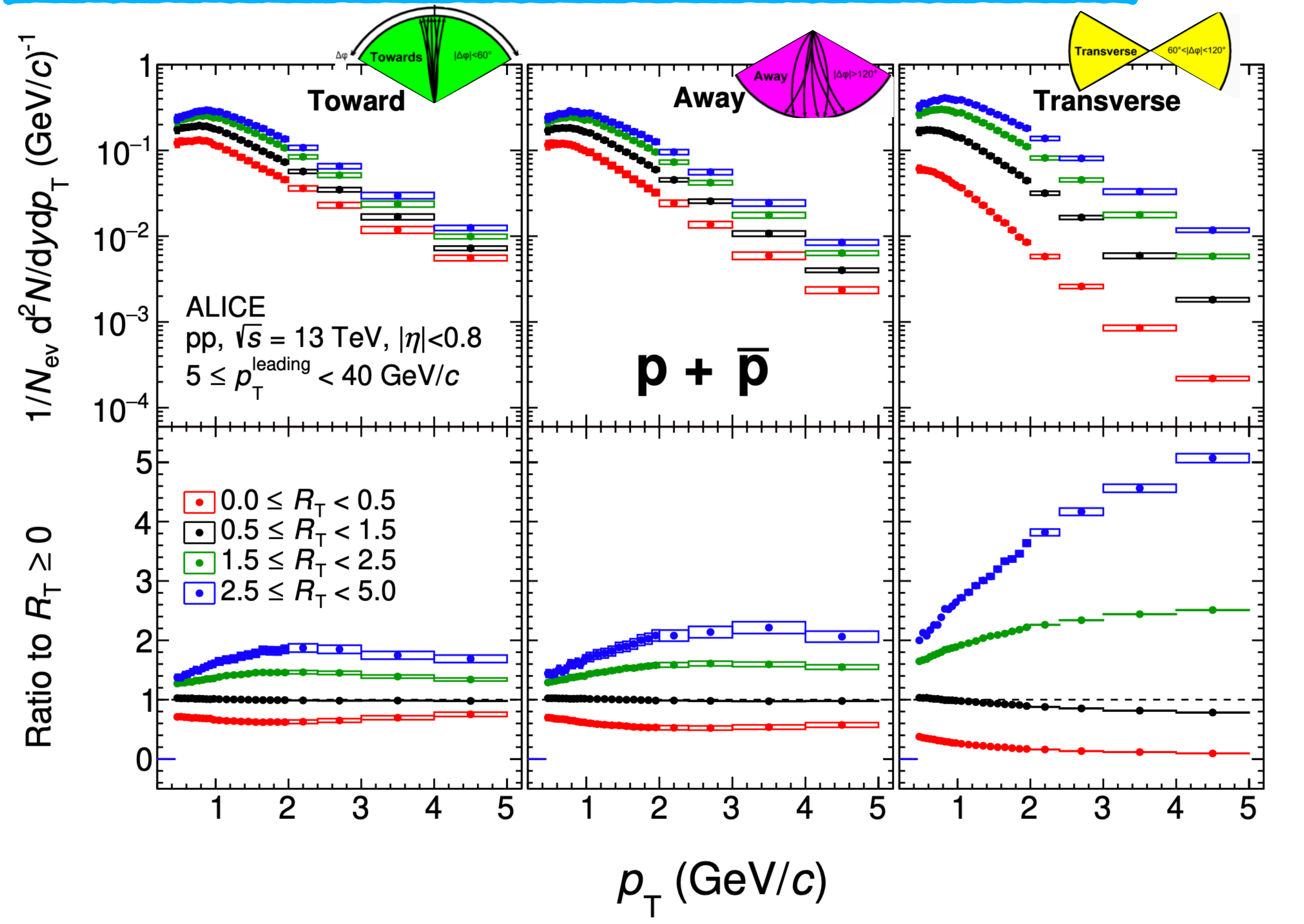
- Depletion of low p_T particle with increasing R_T
- Softening of the spectra with increasing R_T for $p_T \geq 2$ GeV/c

TRANSVERSE region

- Hardening of the spectra with increasing UE activity

Proton spectra vs. R_T

ALICE Coll., JHEP 06 (2023) 027



TOWARDS and AWAY regions

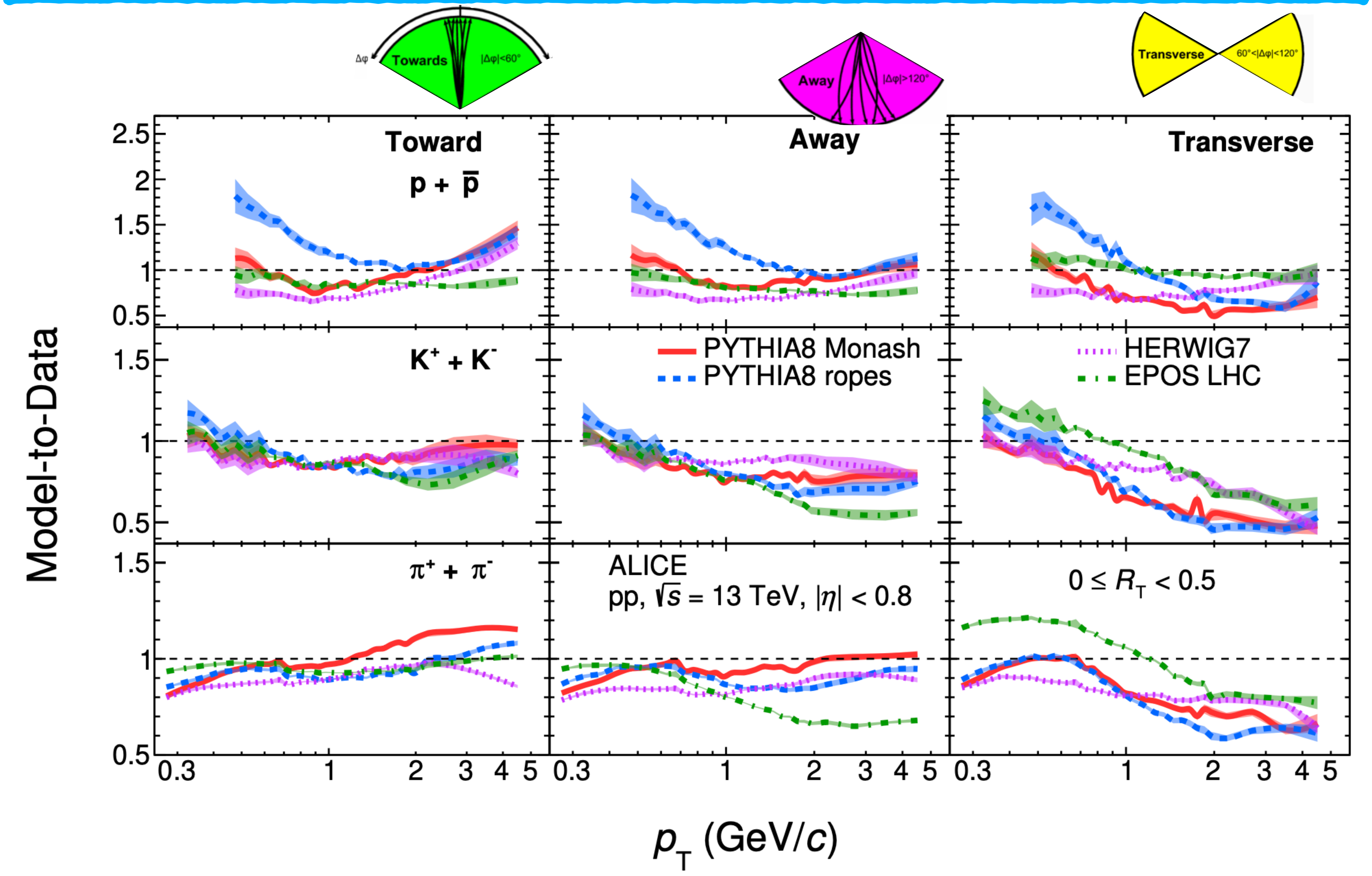
- Depletion of low p_T particle with increasing R_T
  - reminiscent of radial flow (m ordering)
- Softening of the spectra with increasing R_T for $p_T \geq 2$ GeV/c
  - "dilution" of the jet with increasing UE activity

TRANSVERSE region

- Hardening of the spectra with increasing UE activity
  - jet hardening

Model vs. data for small R_T

ALICE Coll., JHEP 06 (2023) 027



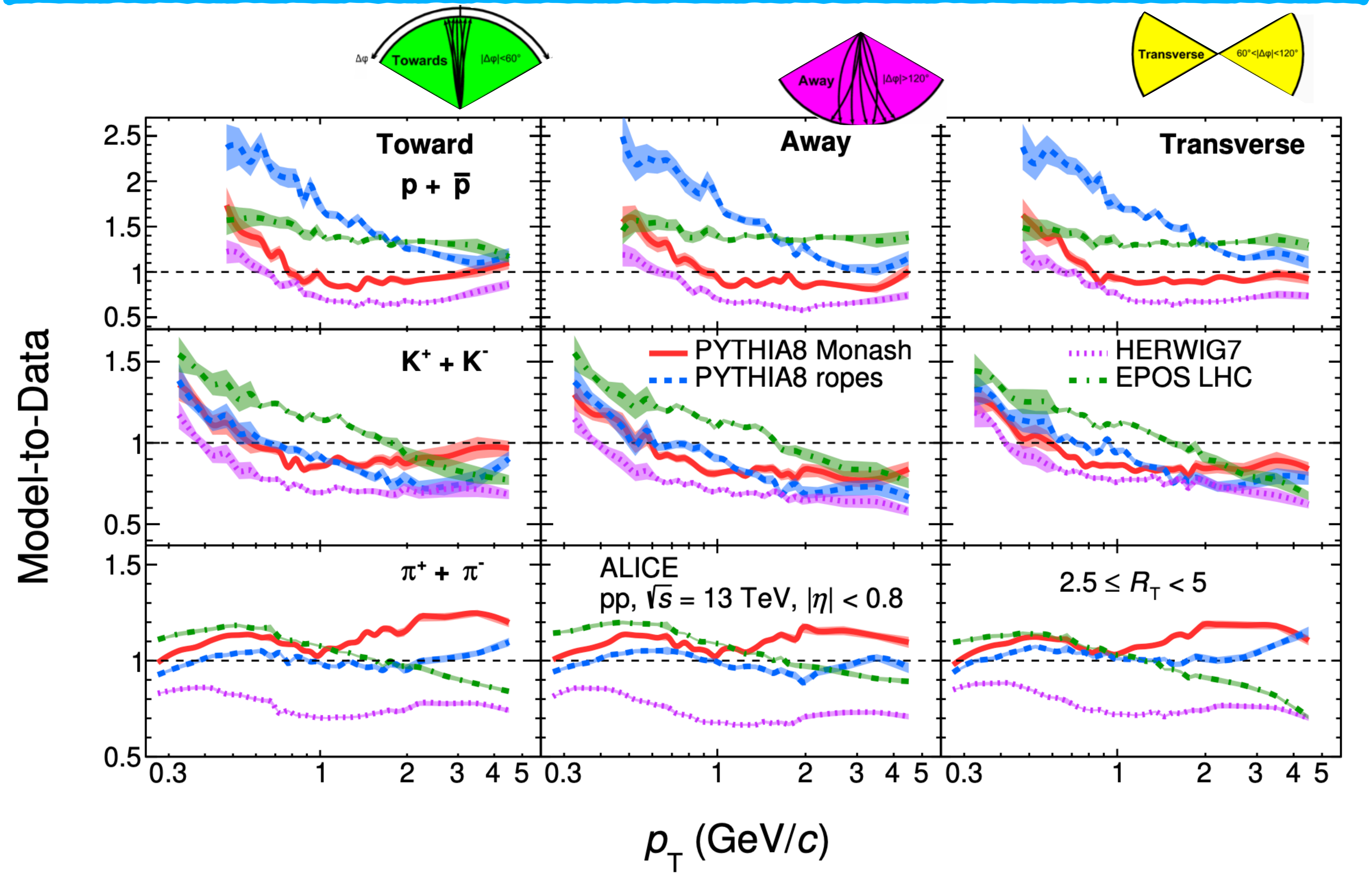
Models are able to qualitatively describe spectra for $p_T > 2$ GeV/c in TOWARDS and AWAY regions

- expected since small R_T events are dominated by jet fragmentation products, and models are tuned to e^+e^- data

Models fail to reproduce soft particle production in the TRANSVERSE region for $p_T > 1$ GeV/c

Model vs. data for large R_T

ALICE Coll., JHEP 06 (2023) 027

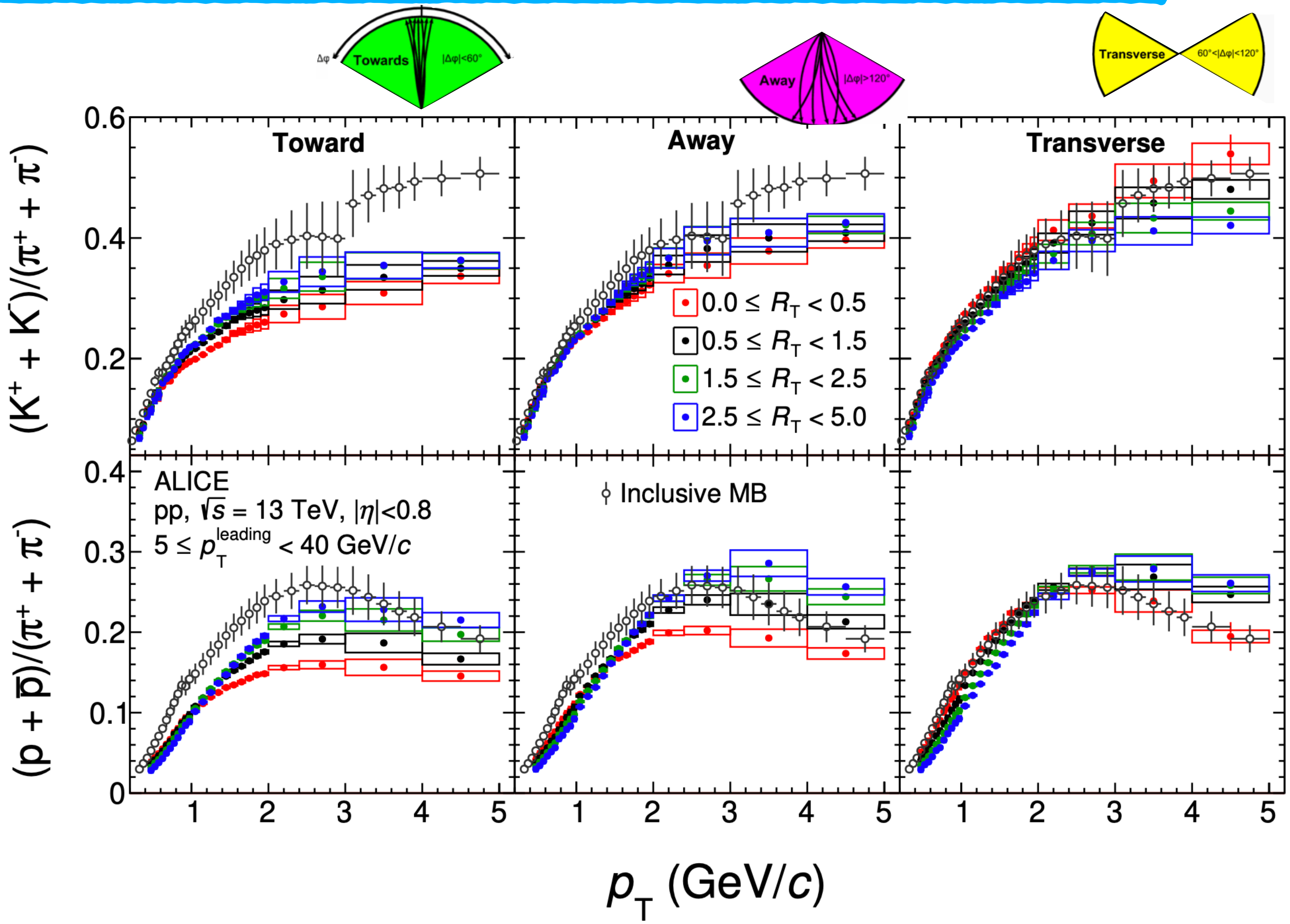


Models fail to describe data in all topological regions when UE activity is higher

➧ ALICE measurements provide valuable input to models

Particle ratios vs. R_T

ALICE Coll., JHEP 06 (2023) 027



TOWARDS and AWAY regions

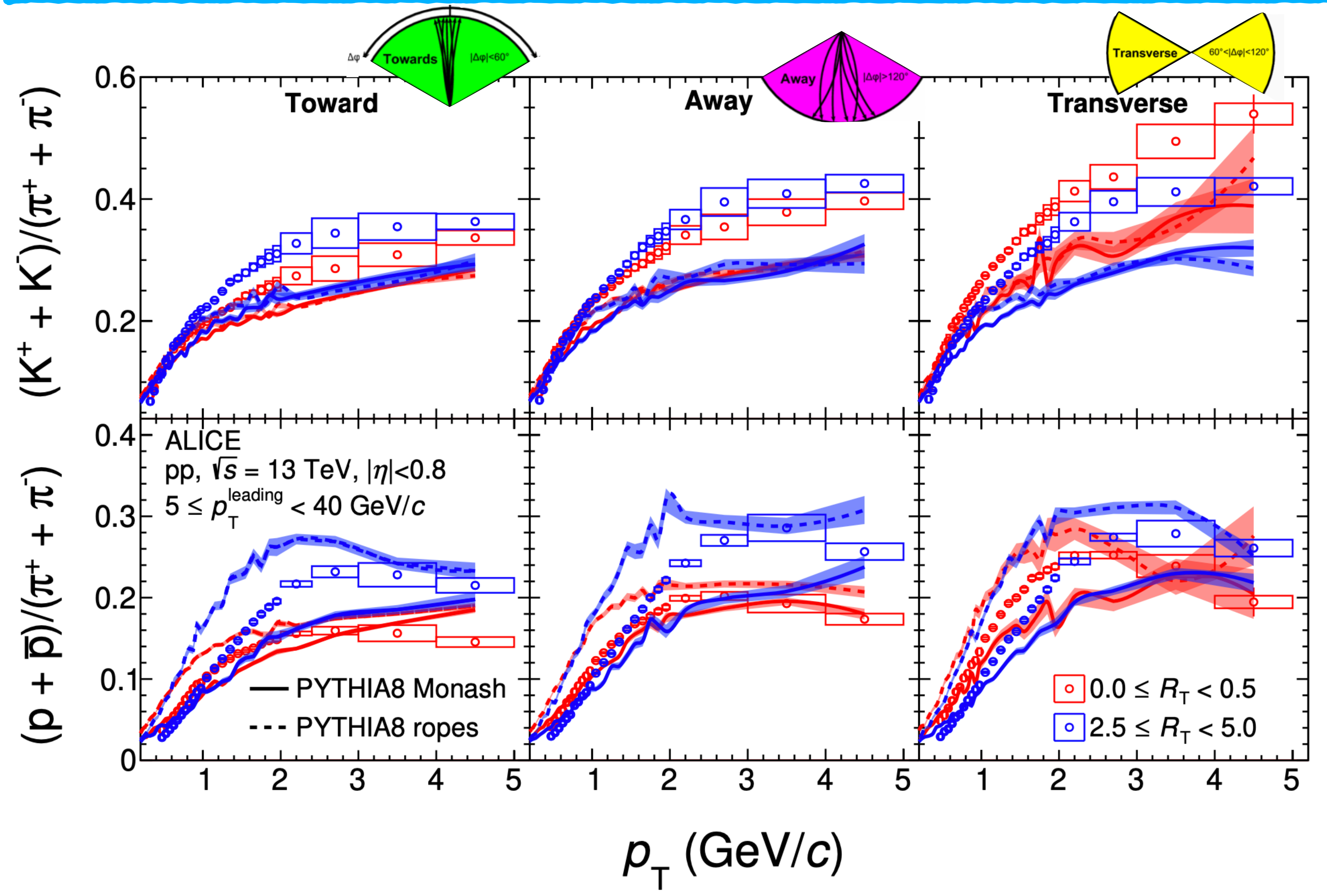
- K/p and π/p ratios: increase with increasing R_T

TRANSVERSE region

- More similar to MB (small increase of π/p ratio with increasing UE activity)

Particle ratios: model vs. data

ALICE Coll., JHEP 06 (2023) 027



PYTHIA8 Monash

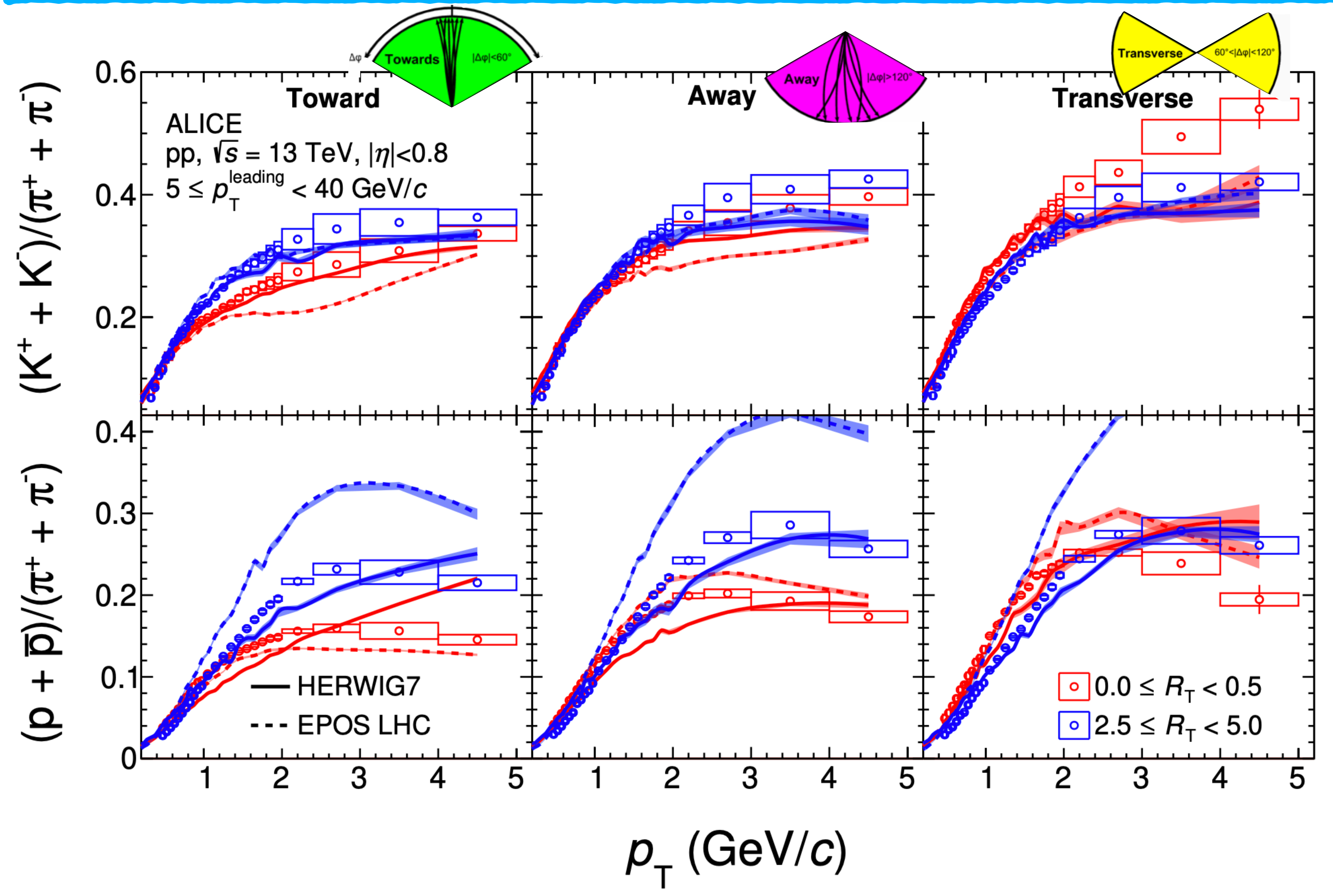
- no evolution with increasing UE activity in jet fragmentation regions

PYTHIA8 ropes

- evolution with increasing UE activity, but overestimates data for large R_T

Particle ratios: model vs. data

ALICE Coll., JHEP 06 (2023) 027



HERWIG7

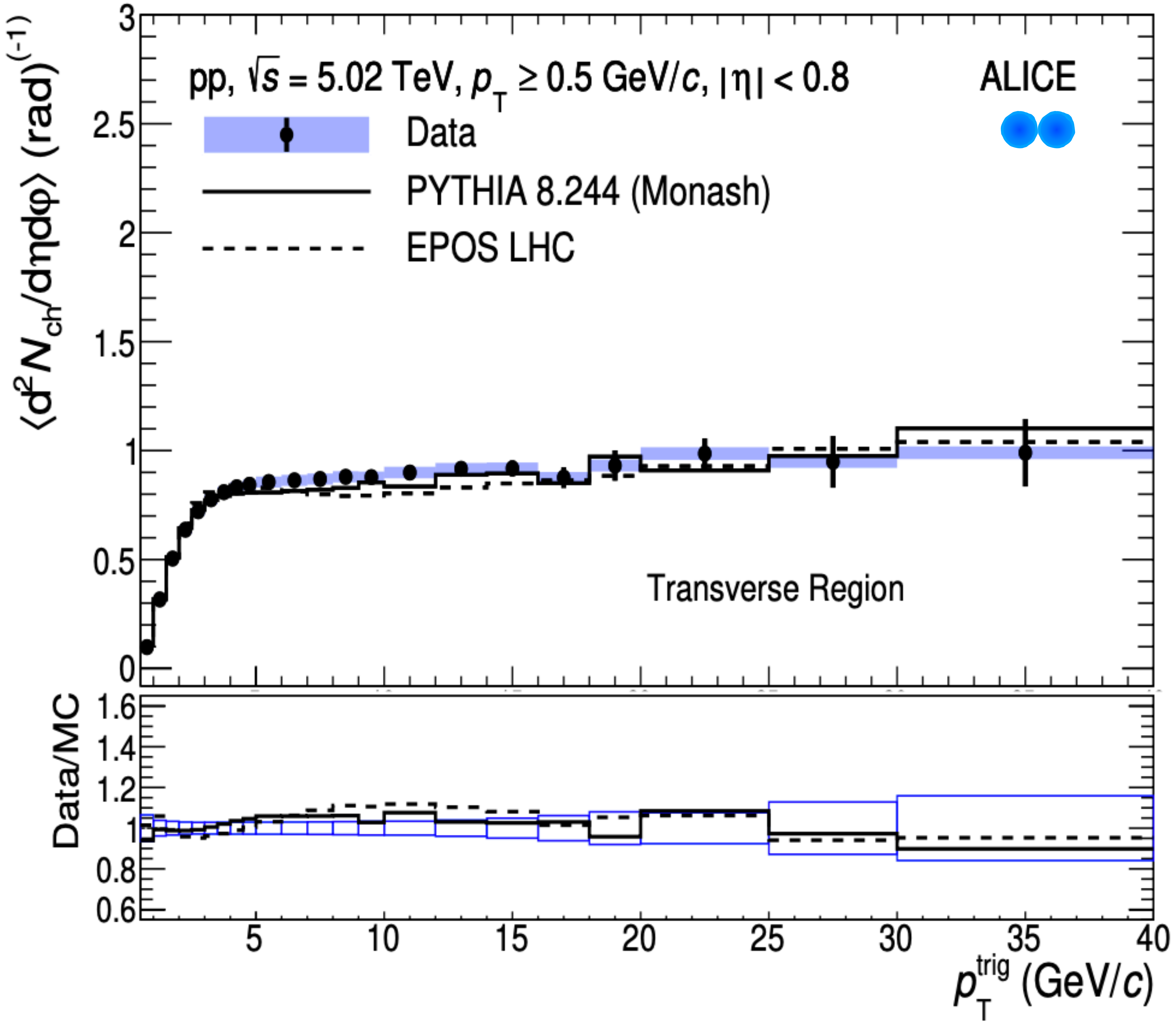
- evolution with increasing R_T, but misses the p_T trend of p/π ratio

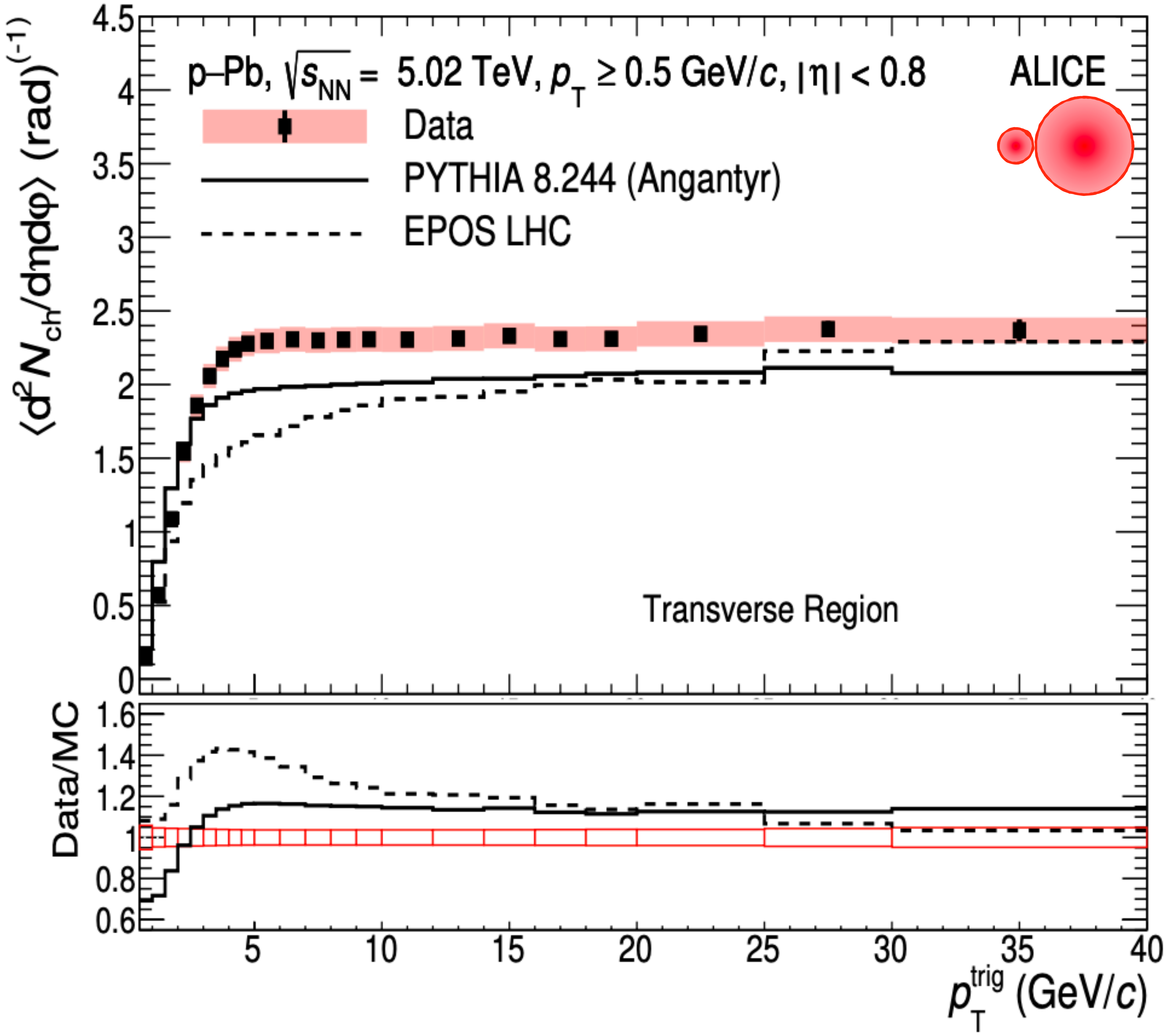
EPOS LHC

- evolution with increasing R_T, but overshoots π/p ratio for large R_T

UE in larger system collisions

ALICE Coll., JHEP 06 (2023) 023



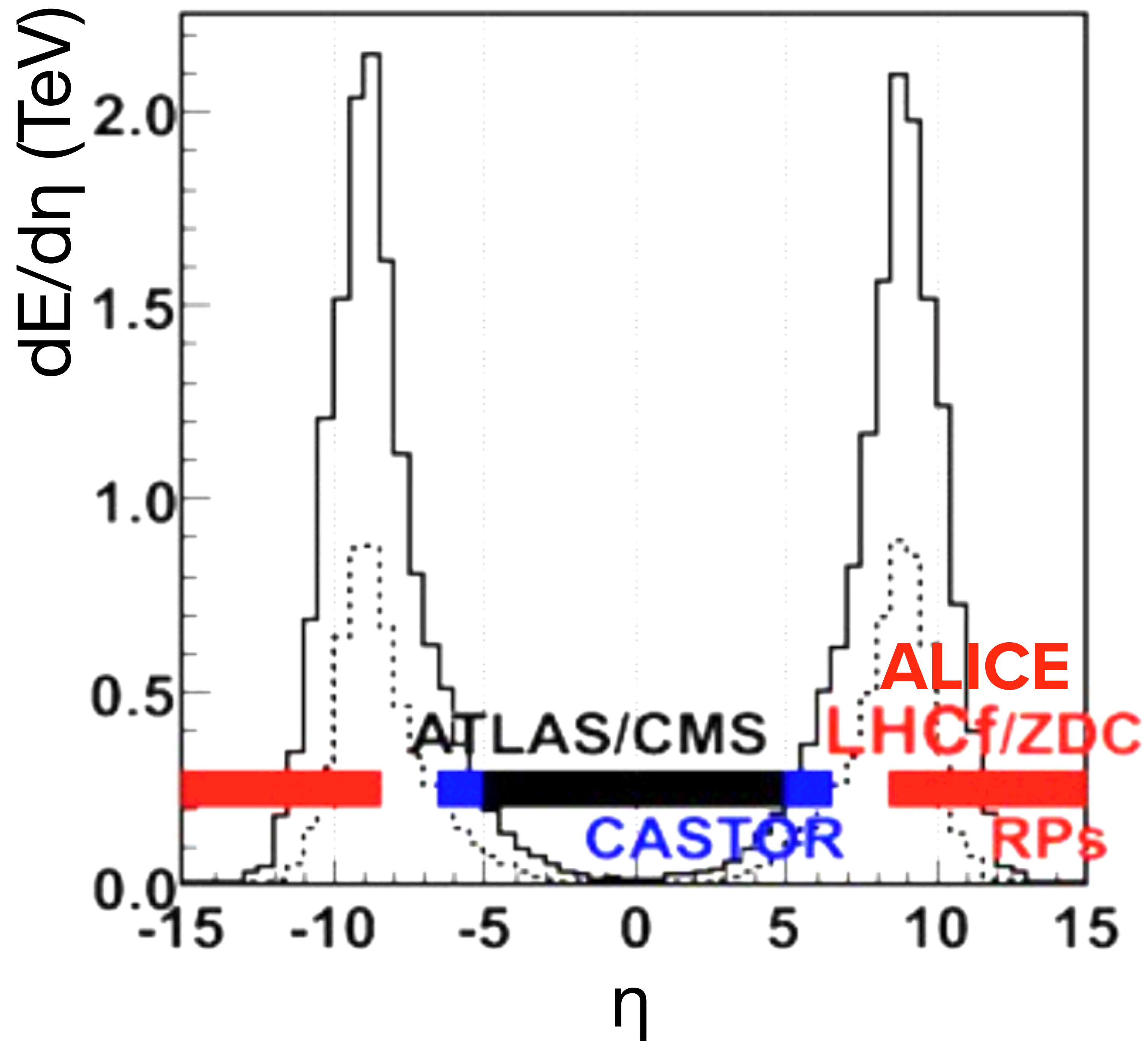


- larger UE magnitude in p-Pb collisions
- saturation in the transverse region also in p-Pb collisions, occurring nearly at the same leading particle p_T scale ($p_T^{leading}$ ~ 5 GeV/c) as in pp collisions
- models are able to describe the UE in pp collisions are not reproducing p-Pb results


Particle production vs.
very forward energy

Why forward?

▸ most of the energy flows very forward!



EPJ Web of Conferences 49, 11001 (2013)

QCD physics

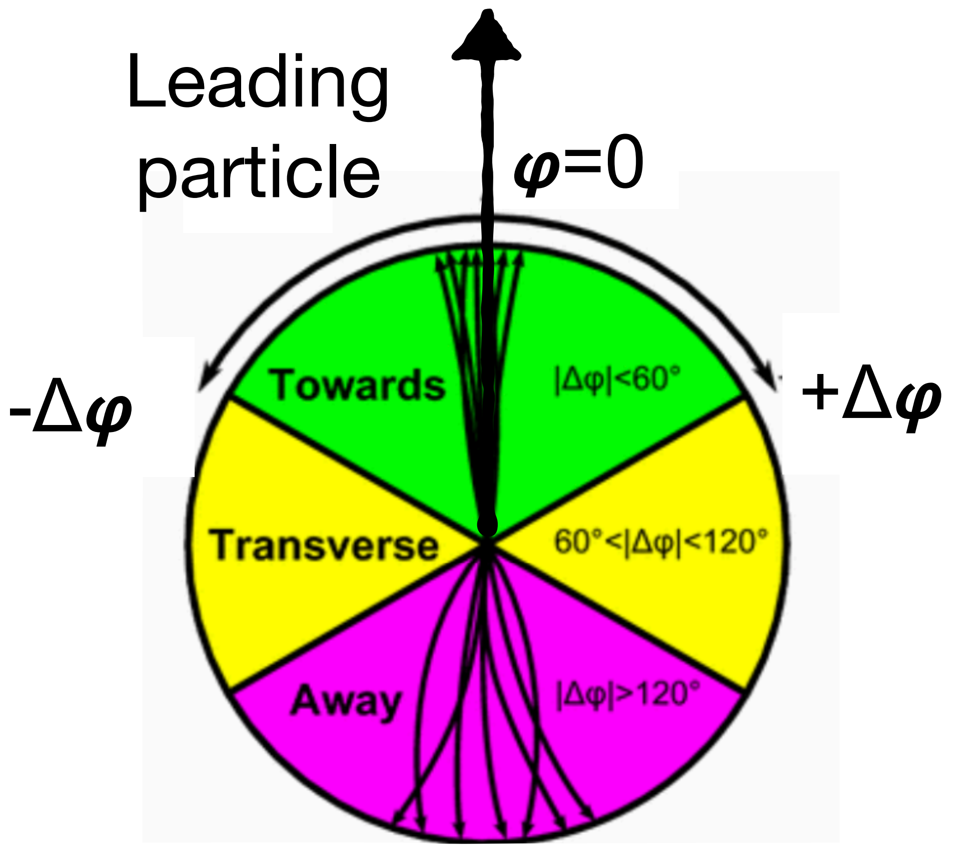
- elastic cross-section, diffractive events, central exclusive processes
- low Bjorken-*x* range, low-*x* parton structure and dynamics
- photon-induced reactions
- validate hadronic models for ultra-high energy cosmic rays

ALICE measures very forward energy using two sets of Zero Degree Calorimeters (ZDC) placed at 112.5 m from the IP on each side (A and C)

- one for neutrons ZN covering $|\eta| < 8.7$
- one for protons ZP covering $7.8 < |\eta| < 12.9$

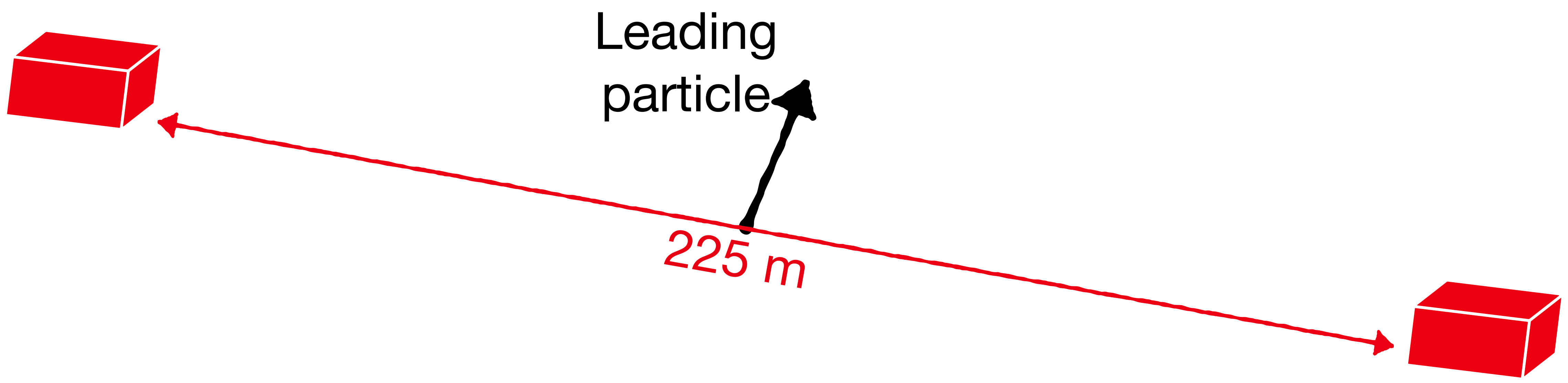
Mid- and very forward

Midrapidity



Transverse region ➧ study particle emission in a region largely separated in azimuth from the hard scattering fragmentation

Very forward rapidity



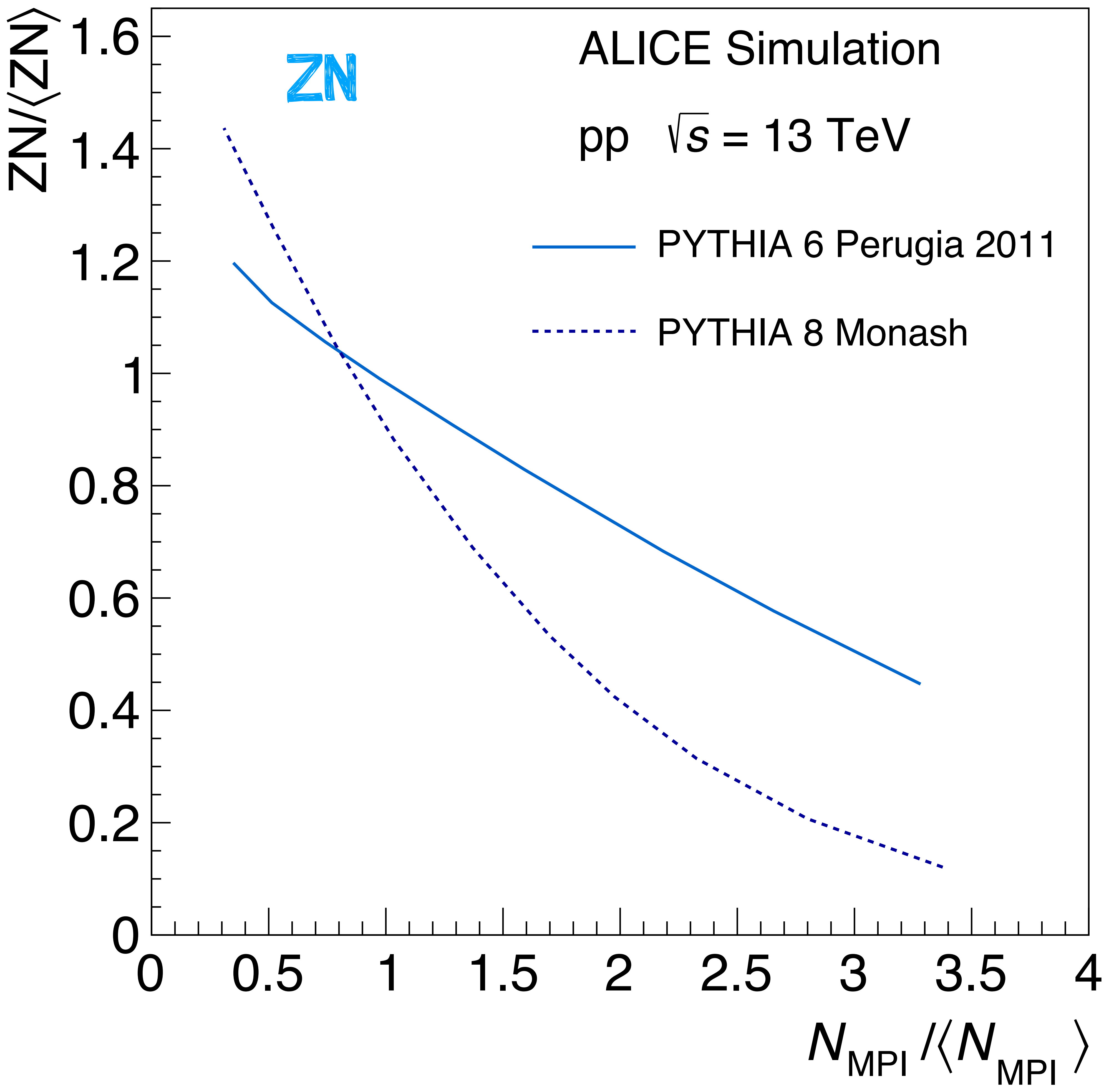
ZDC energy ➧ study beam remnants in a region separated in pseudorapidity from the hard scattering fragmentation

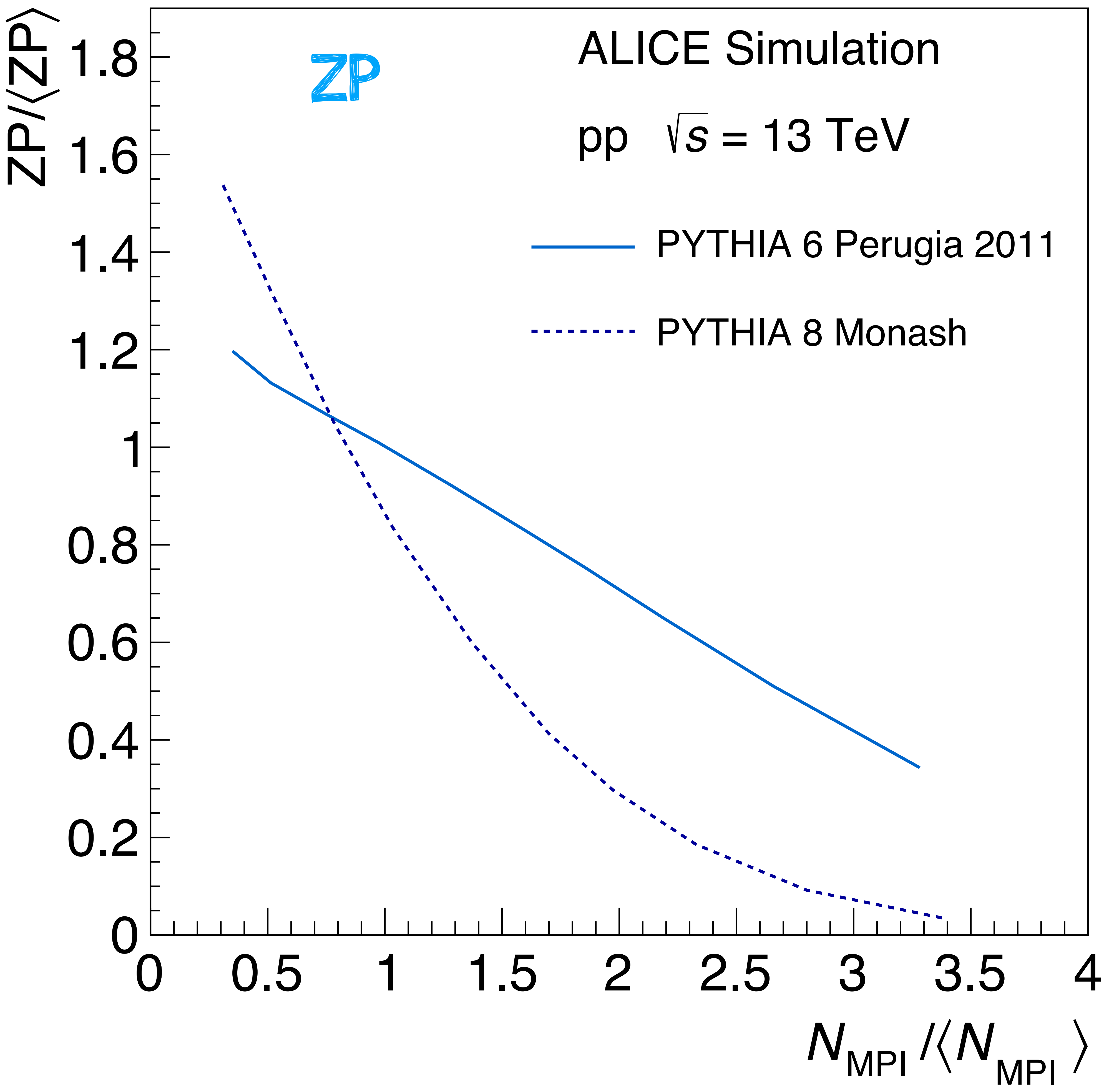
Midrapidity and very forward rapidity observables are causally disconnected after the collision
➧ any correlation in the final state must have been built during the initial stages of the collision

Forward energy and MPI

ALICE Coll., JHEP08 (2022) 086

- models implementing MPI with impact parameter dependence (PYTHIA) predict a decrease of very forward energy with increasing number of MPIs

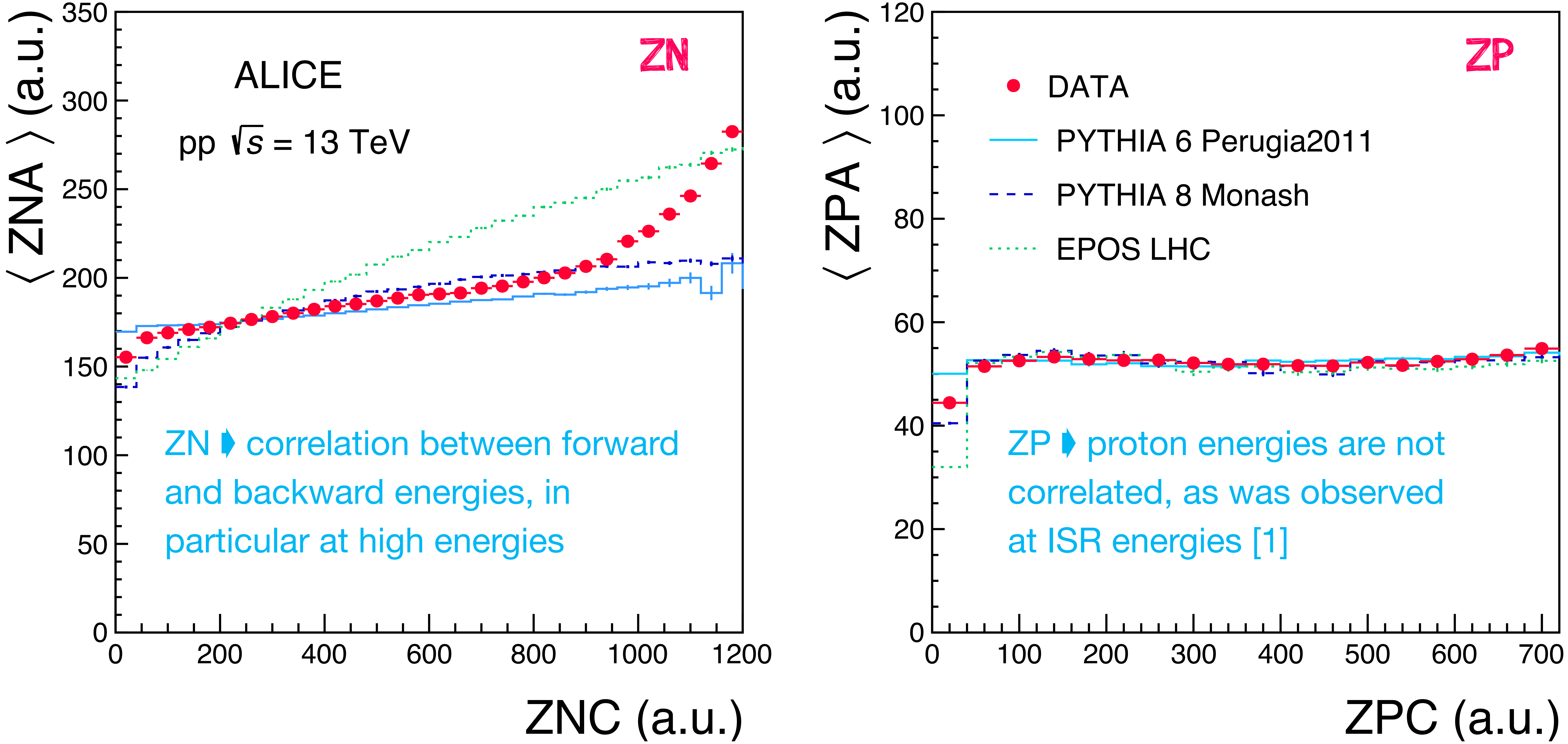




Forward-backward correlation

ALICE Coll., JHEP08 (2022) 086

Average signal on one side (A) as a function of the signal on the other side (C)



Models predict a flat behaviour for ZP in agreement with data, but are not able to reproduce quantitatively the measured ZN dependence over the whole range

[1] M. Basile et al., Nuovo Cim. 353 A 73 (1983) 329

Forward energy vs. midrapidity multiplicity

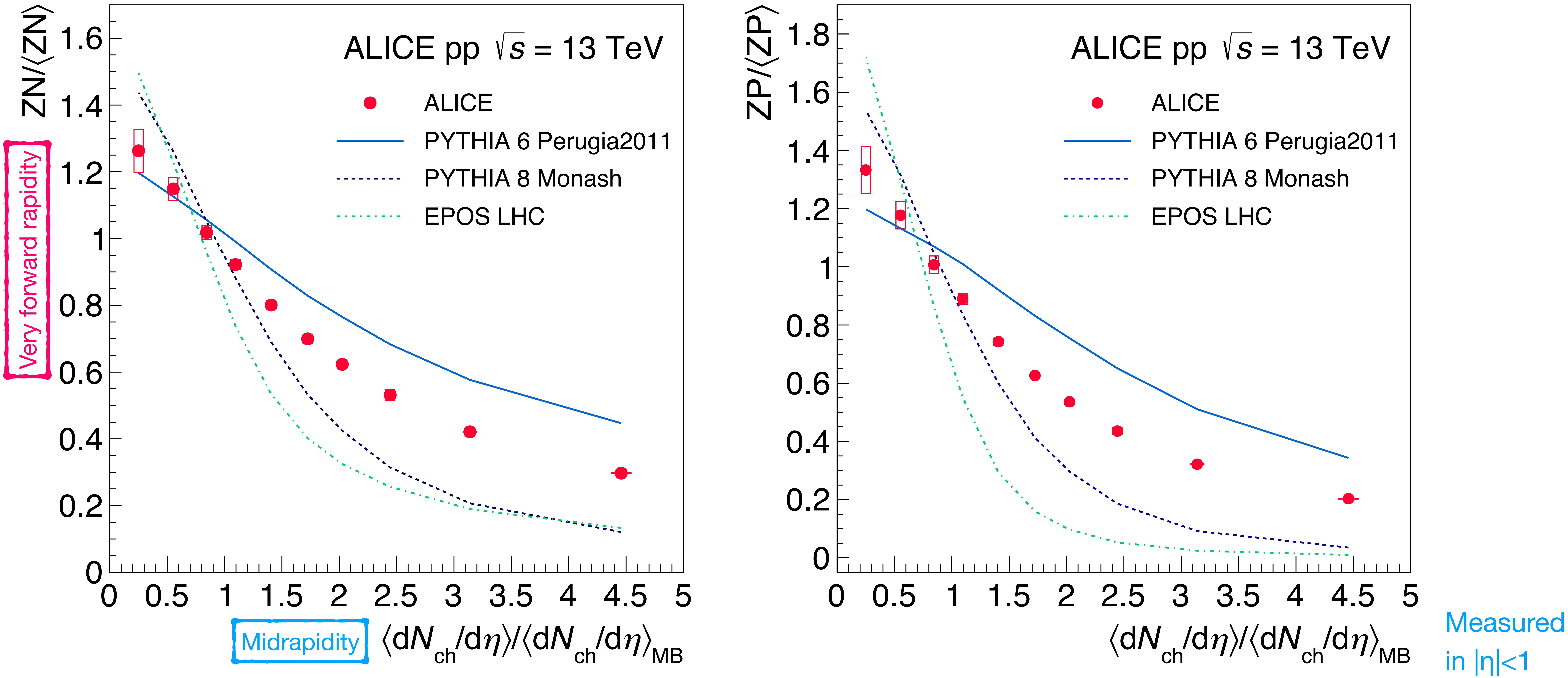
ALICE Coll., JHEP08 (2022) 086

➧ very forward energy decreases with increasing multiplicity produced at midrapidity in |η|<0.5

Similar features in pp and in the p-fragmentation region in p-Pb collisions for self-normalized values

Forward energy vs. midrapidity multiplicity

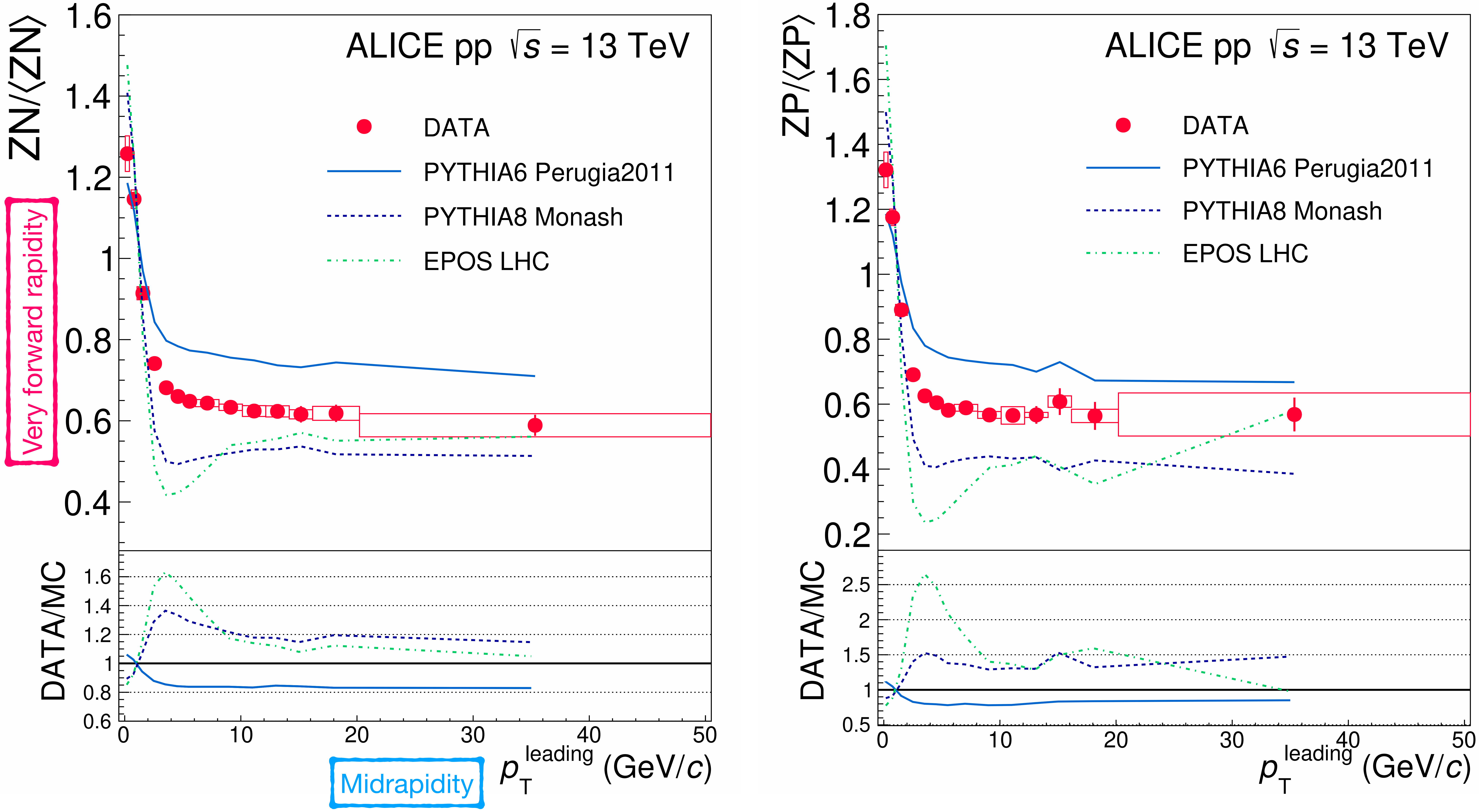
ALICE Coll., JHEP08 (2022) 086



➧ the models used for comparison do not reproduce very forward vs. midrapidity measurements

Forward energy vs. leading particle p_T

ALICE Coll., JHEP08 (2022) 086

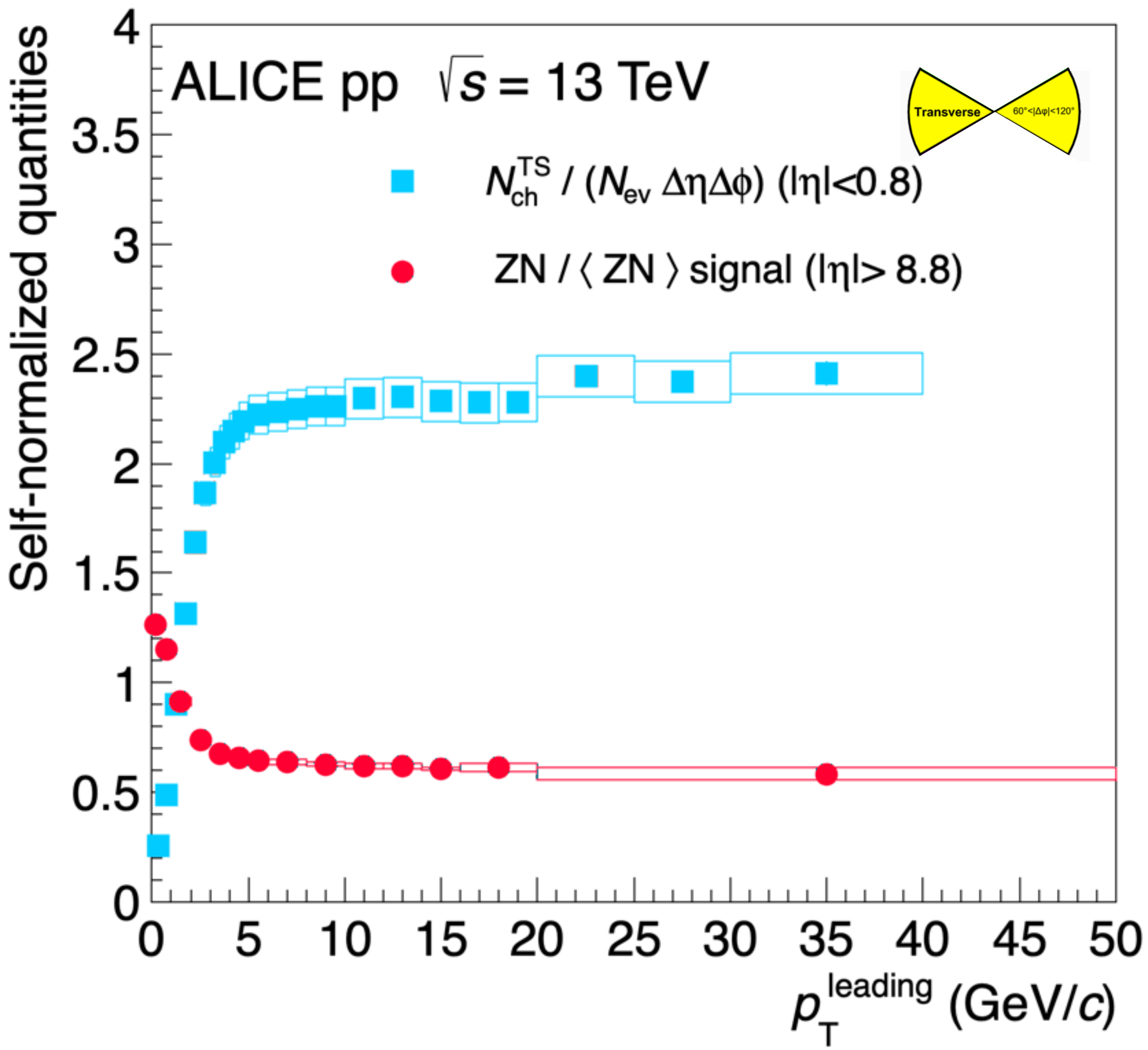


Measured in |η|<0.8

➧ very forward energy saturates with increasing hardness of the collision at midrapidity

UE and very forward energy

ALICE Coll., JHEP08 (2022) 086



Very forward energy ➧ shows saturation with increasing $p_T^{leading}$ in a complementary way to UE

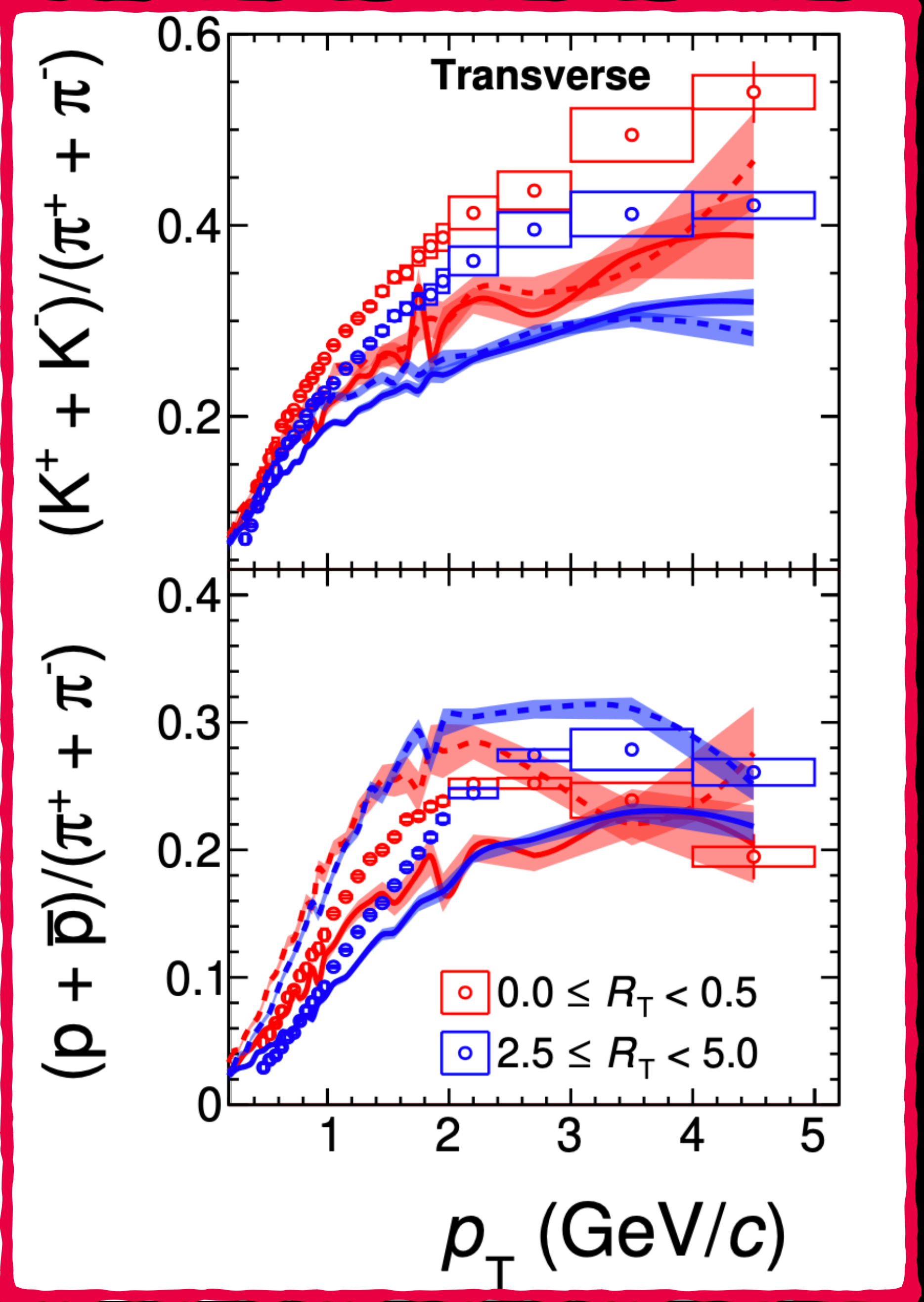
UE ➧ multiplicity in the transverse region at midrapidity is constant in events characterized by a larger than average number of MPIs

➧ saturation occurs at the same scale: $p_T^{leading} > 5$ GeV/c

➧ saturation observed in transverse region at midrapidity and in very forward energy must be built in the initial stages of the collision

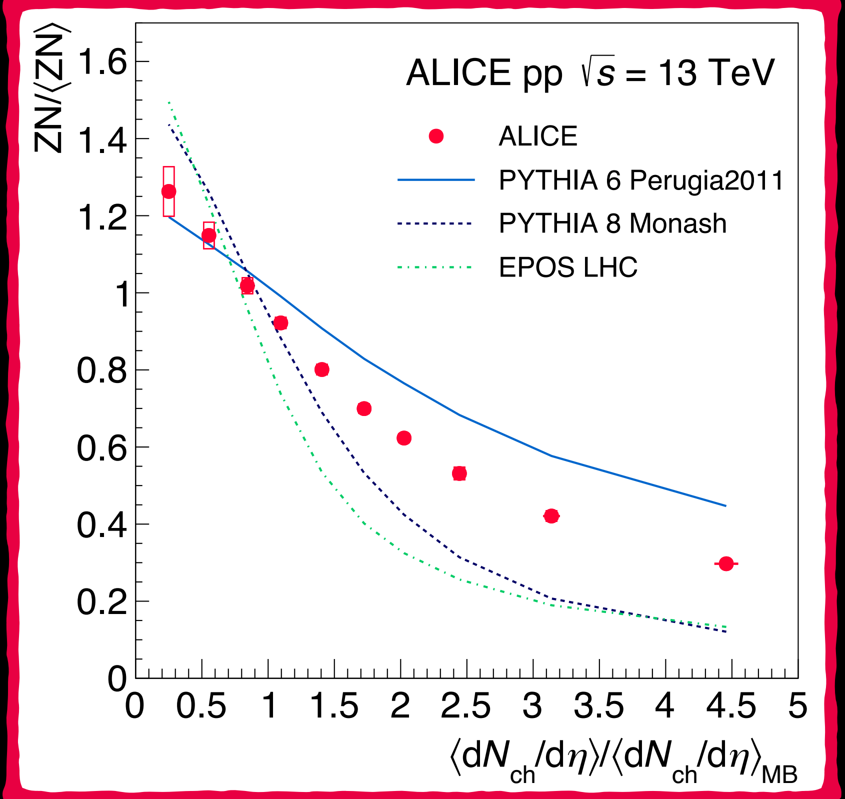
Wrap-up

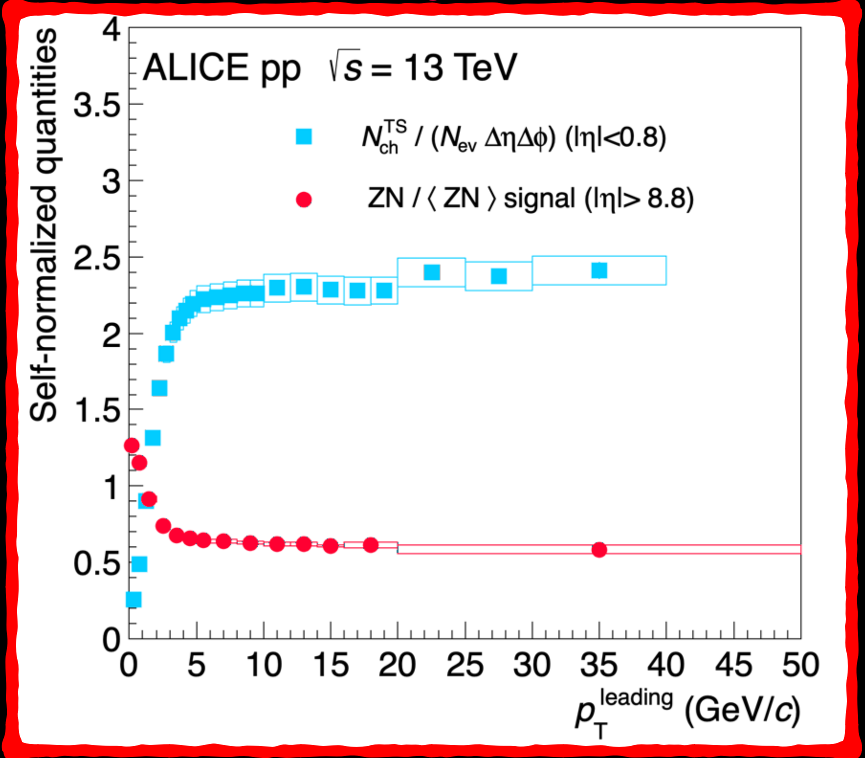
Midrapidity



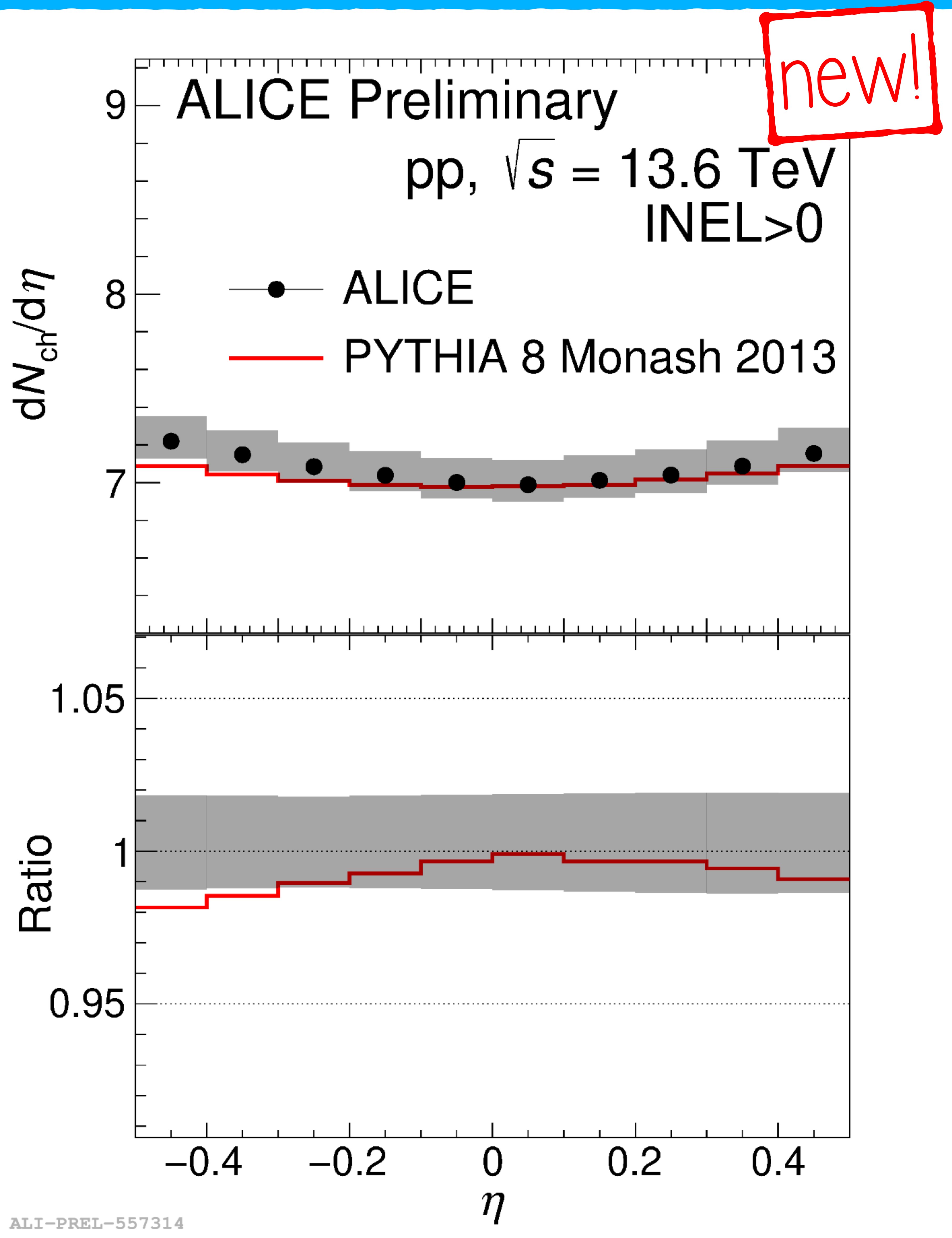
- Many measurements (many not included in this presentation!) done by ALICE in Run2 to characterize particle production mechanisms in pp and p-Pb collisions at LHC energies
- Results provide inputs and challenges for existing models
- More precise results expected with Run3 data, where ALICE is running in continuous mode with an upgraded apparatus

Very forward rapidity

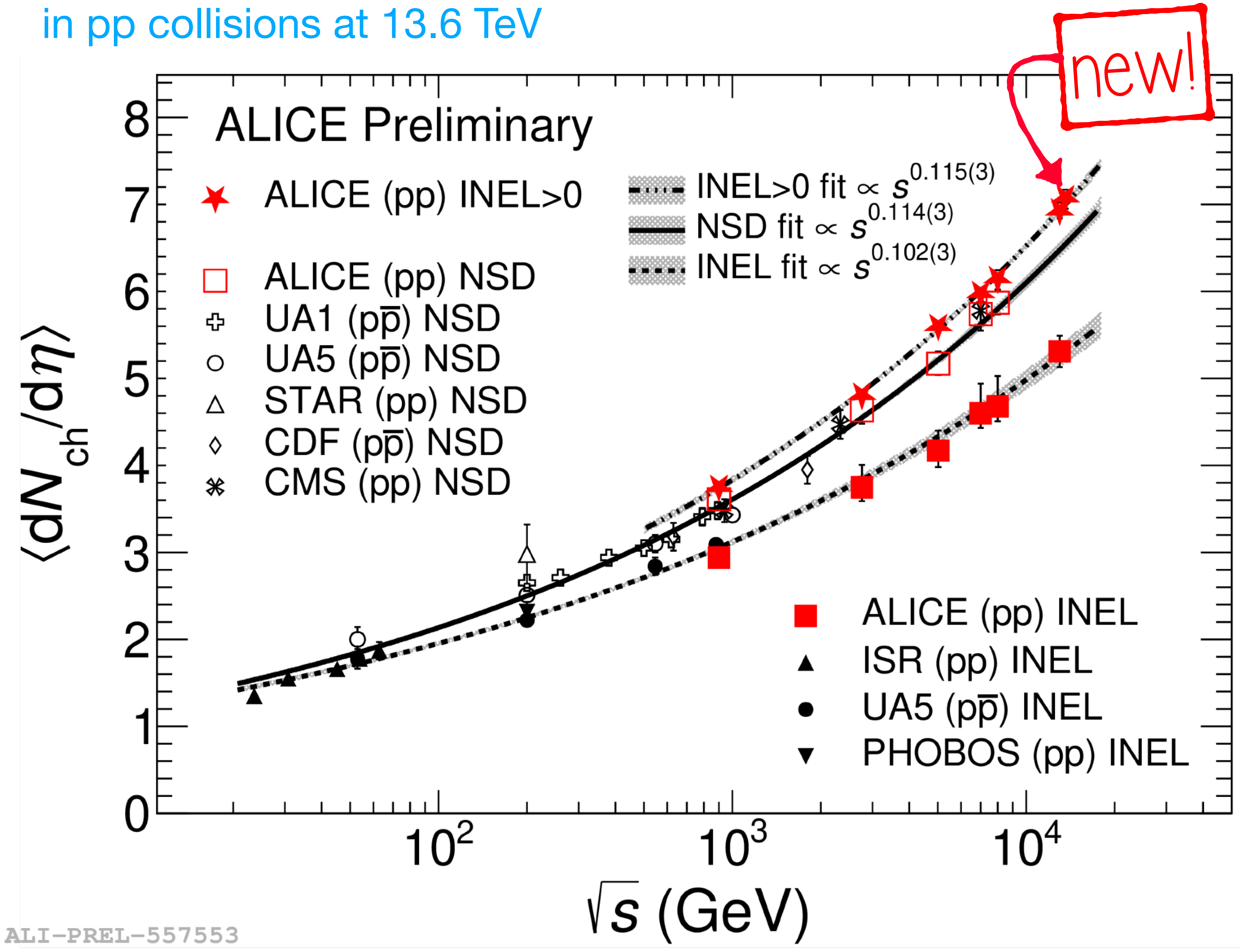




Latest updates from Run3



Multiplicity: pseudorapidity distribution and $\sqrt{s}$ dependence in pp collisions at 13.6 TeV

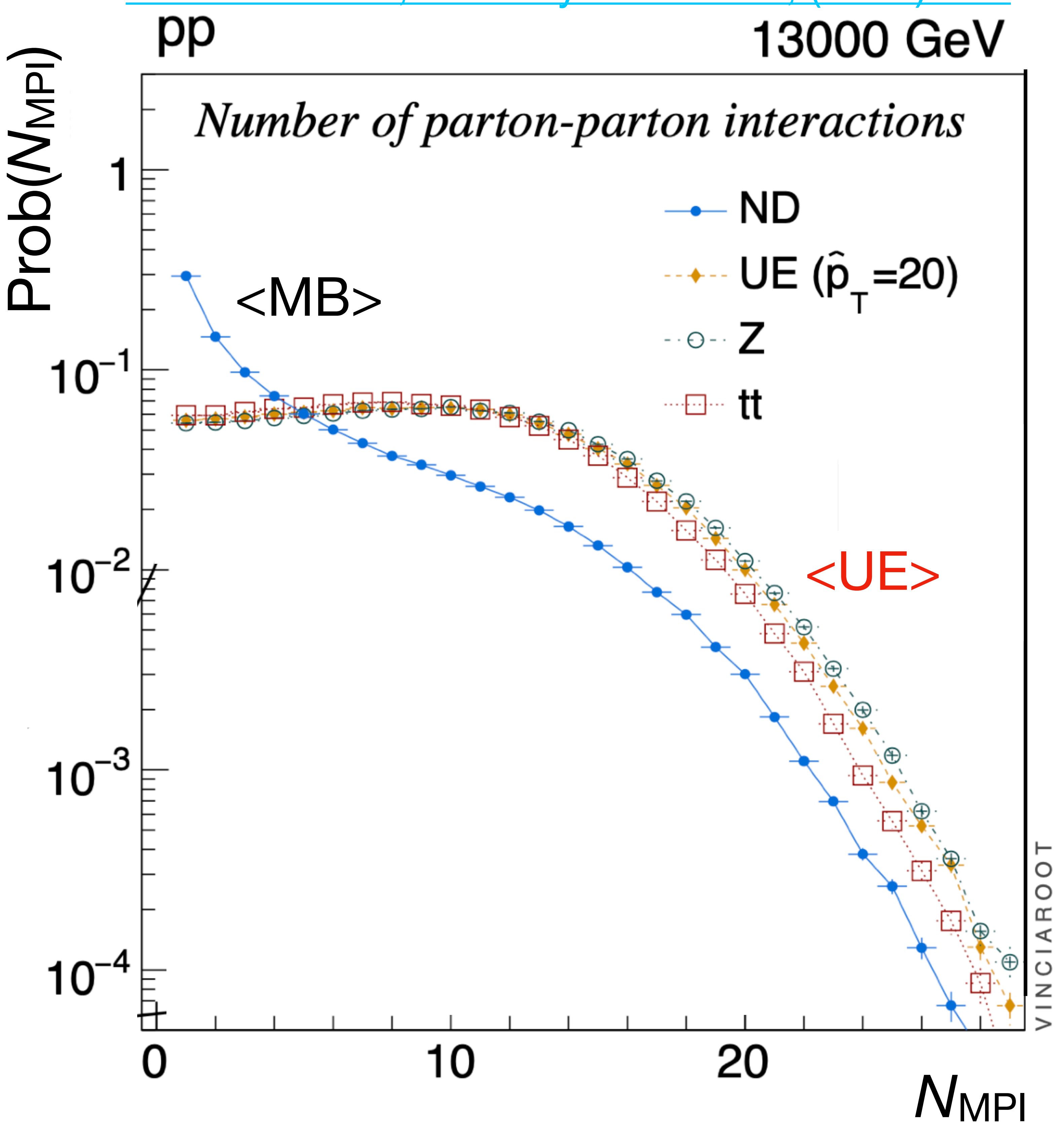


Additional material

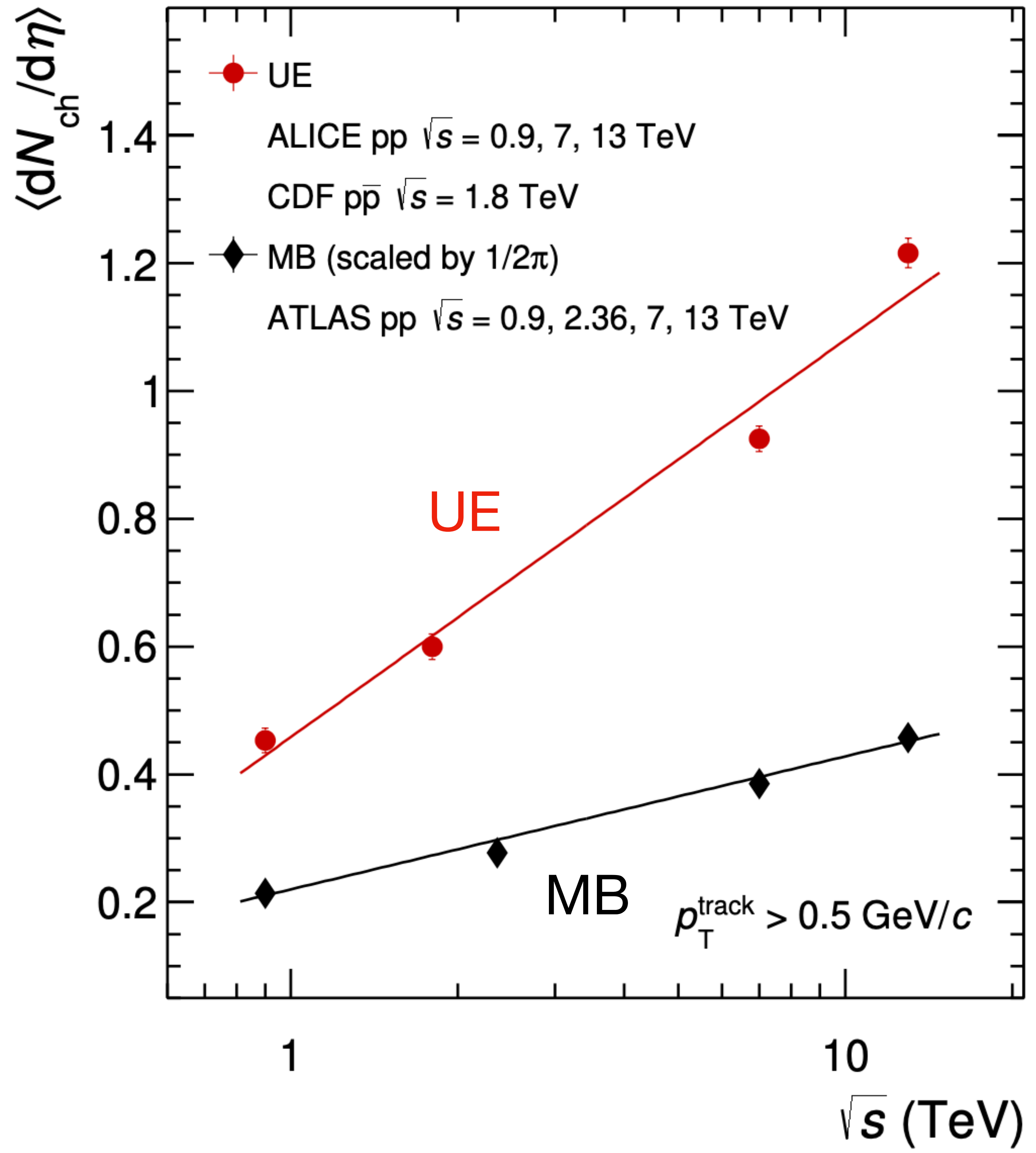
UE vs. MB

- requesting a high p_T particle at midrapidity biases the event towards a larger activity than in MB collisions
- in models including MPIs with an impact parameter dependence, this is explained as a bias towards events with smaller b and larger number of MPI than in MB

T. Martin et al., Eur. Phys. J. C76 5, (2016) 299

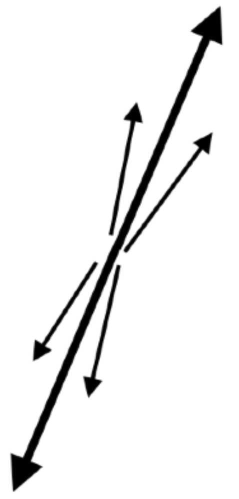


ALICE Coll., JHEP 04 (2020) 192

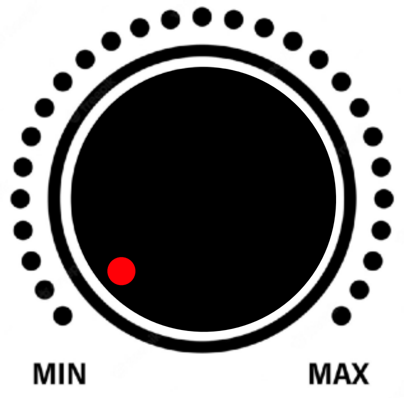


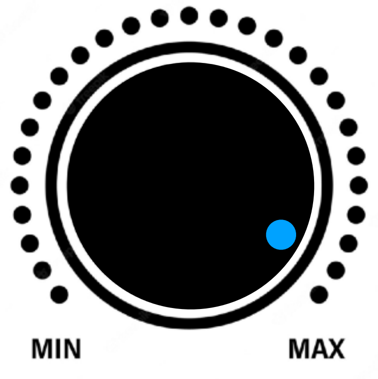
UE ➧ phase-space region exhibiting high-multiplicity MB-like features ➧ larger number of MPI, higher multiplicity

R_T estimator

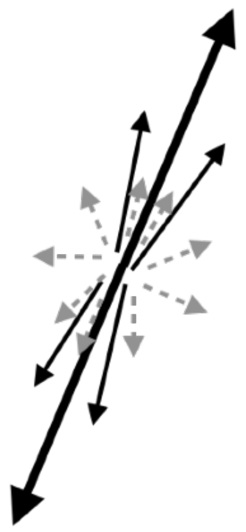


Small R_T ➧ e+e--like
➧ low-UE, low N_{MPI}

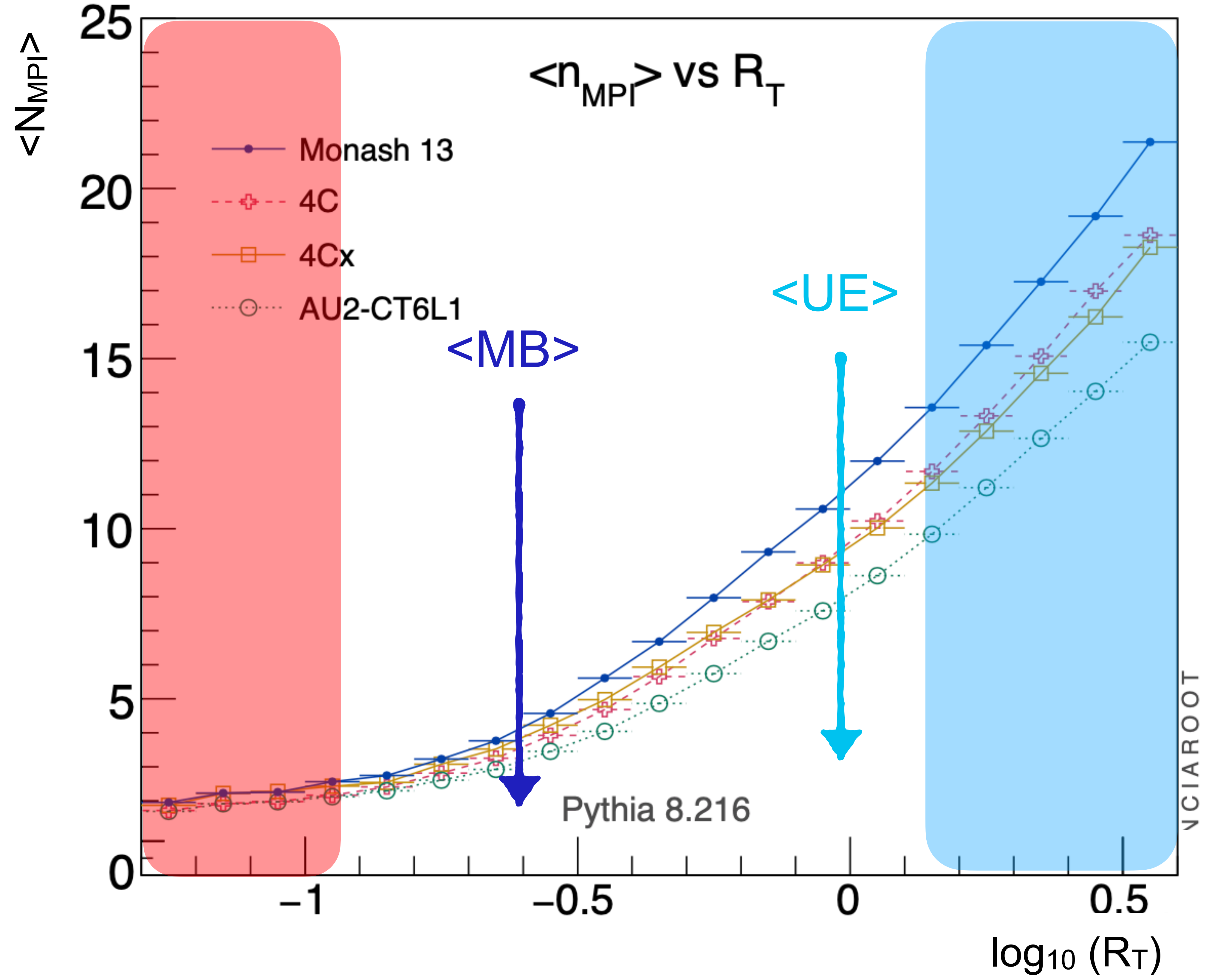




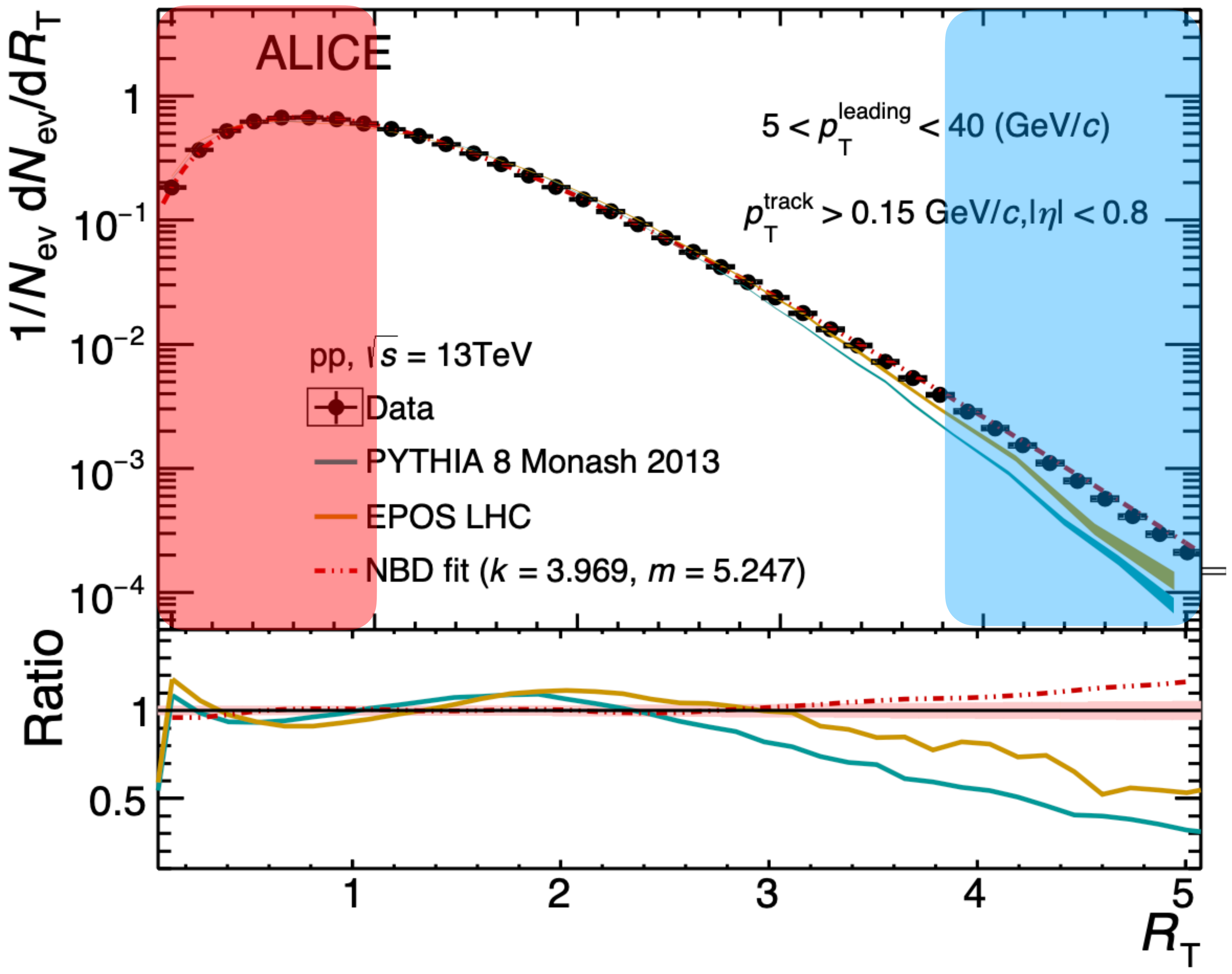
large R_T
➧ high-UE, high N_{MPI}



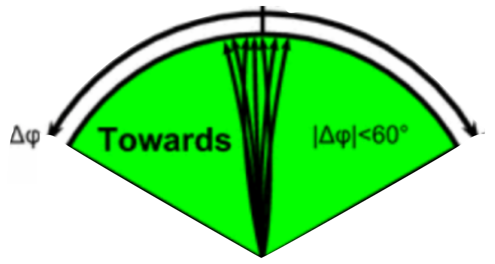
T. Martin et al., Eur. Phys. J. C76 5, (2016) 299



ALICE Coll., JHEP 04 (2020) 192



Spectra in towards region

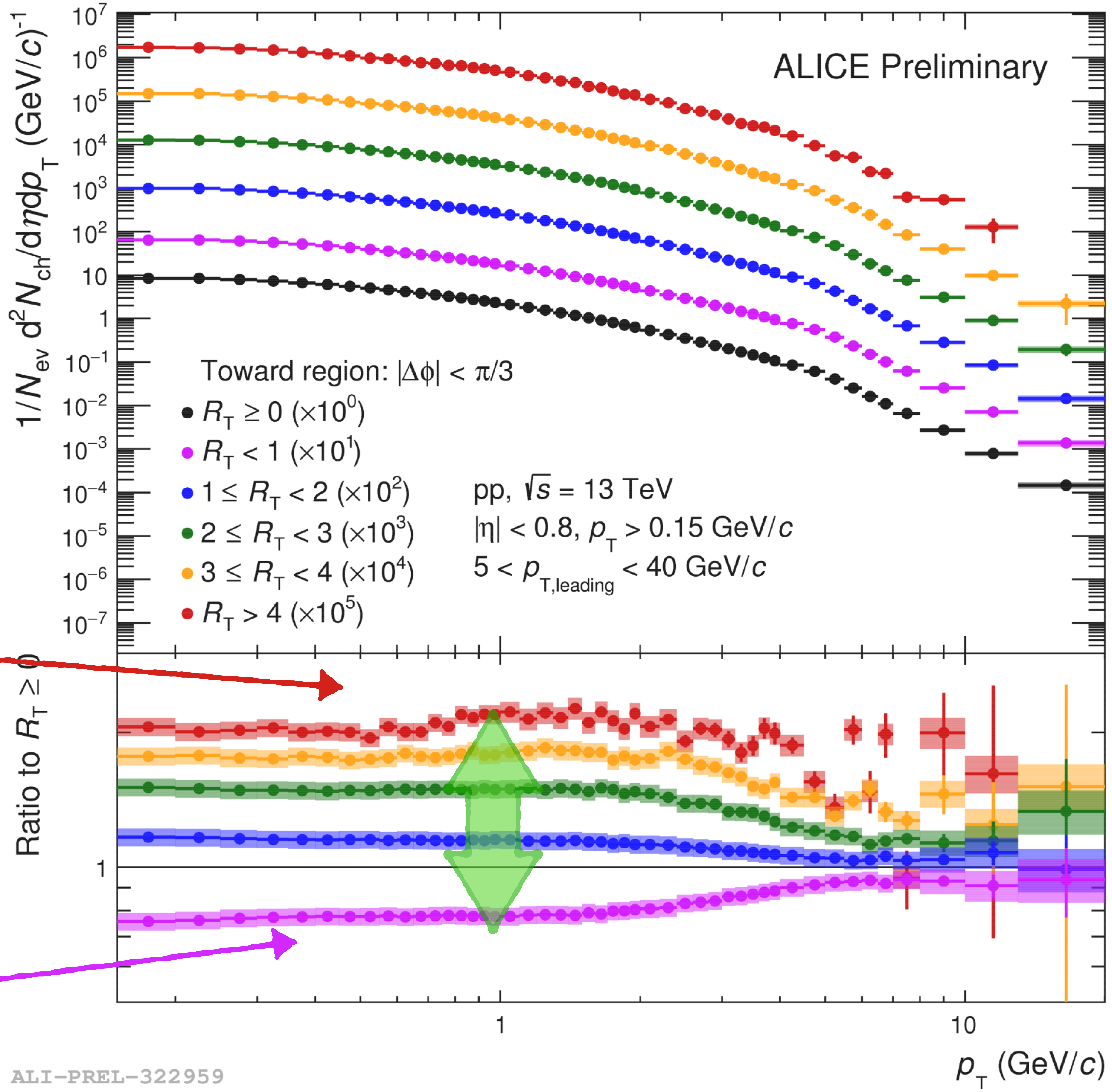


TOWARDS REGION

- soft "jet pedestal" from UE whose relevance varies with R_T
- UE does not affect the hard part of the jet

High UE ➧ UE dominate the yields ("polluted" jets)

Small UE ➧ UE not contributing ("clean" jets)



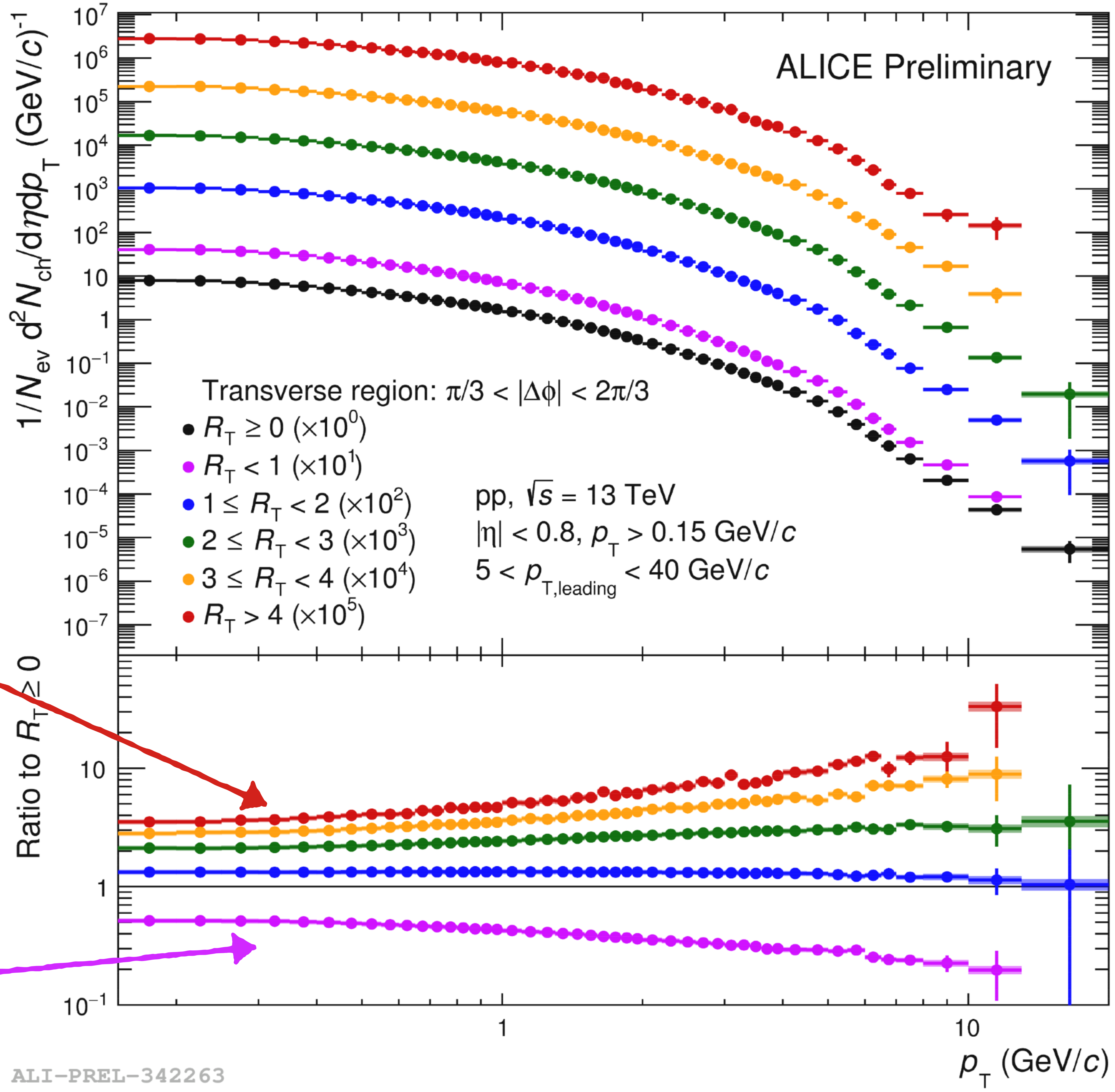
Spectra in transverse region

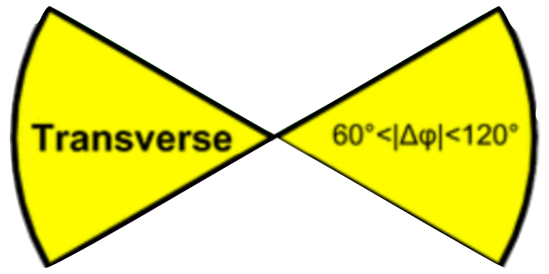
TRANSVERSE REGION

- $\langle p_T \rangle$ increases with UE (as in MB)

High UE ➧ harder spectra

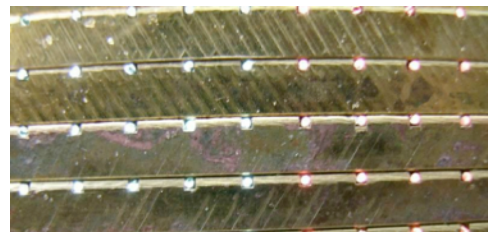
High UE ➧ softer spectra

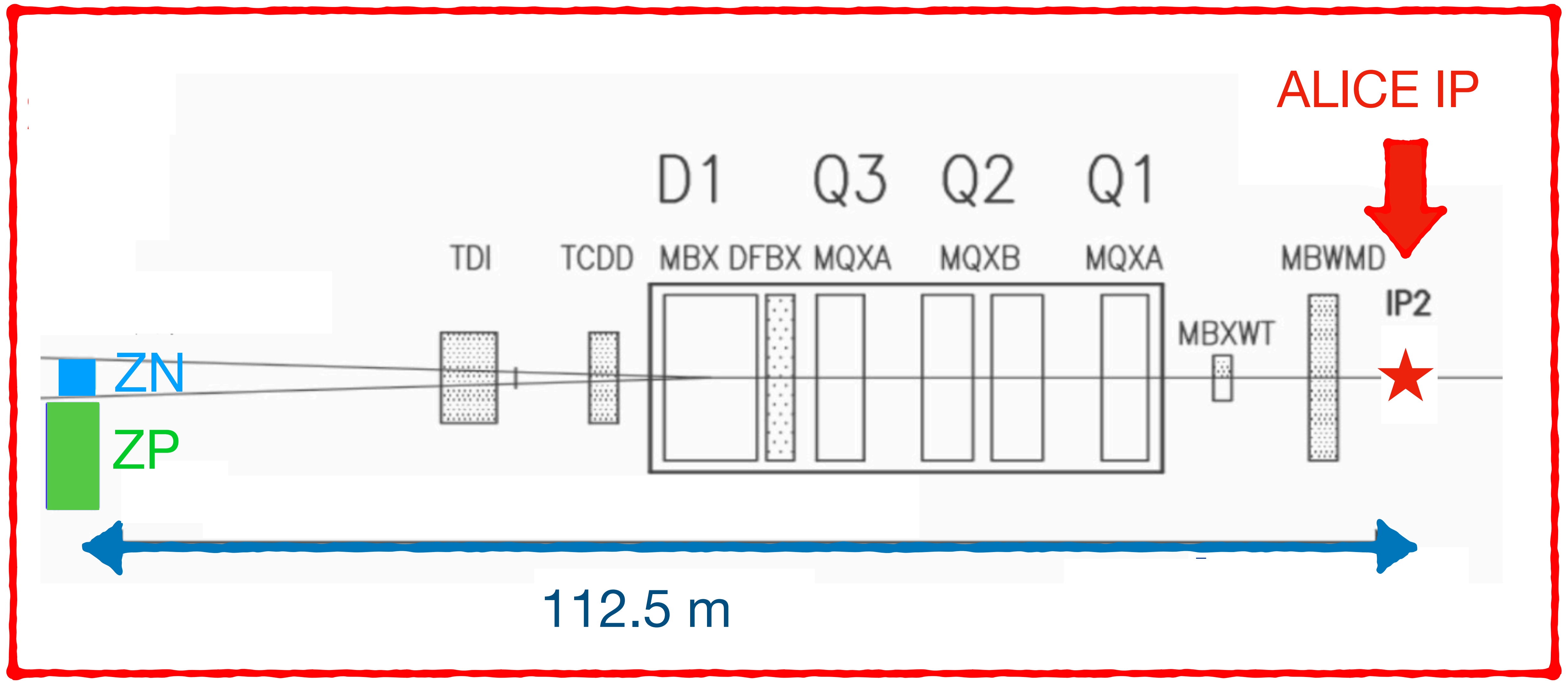


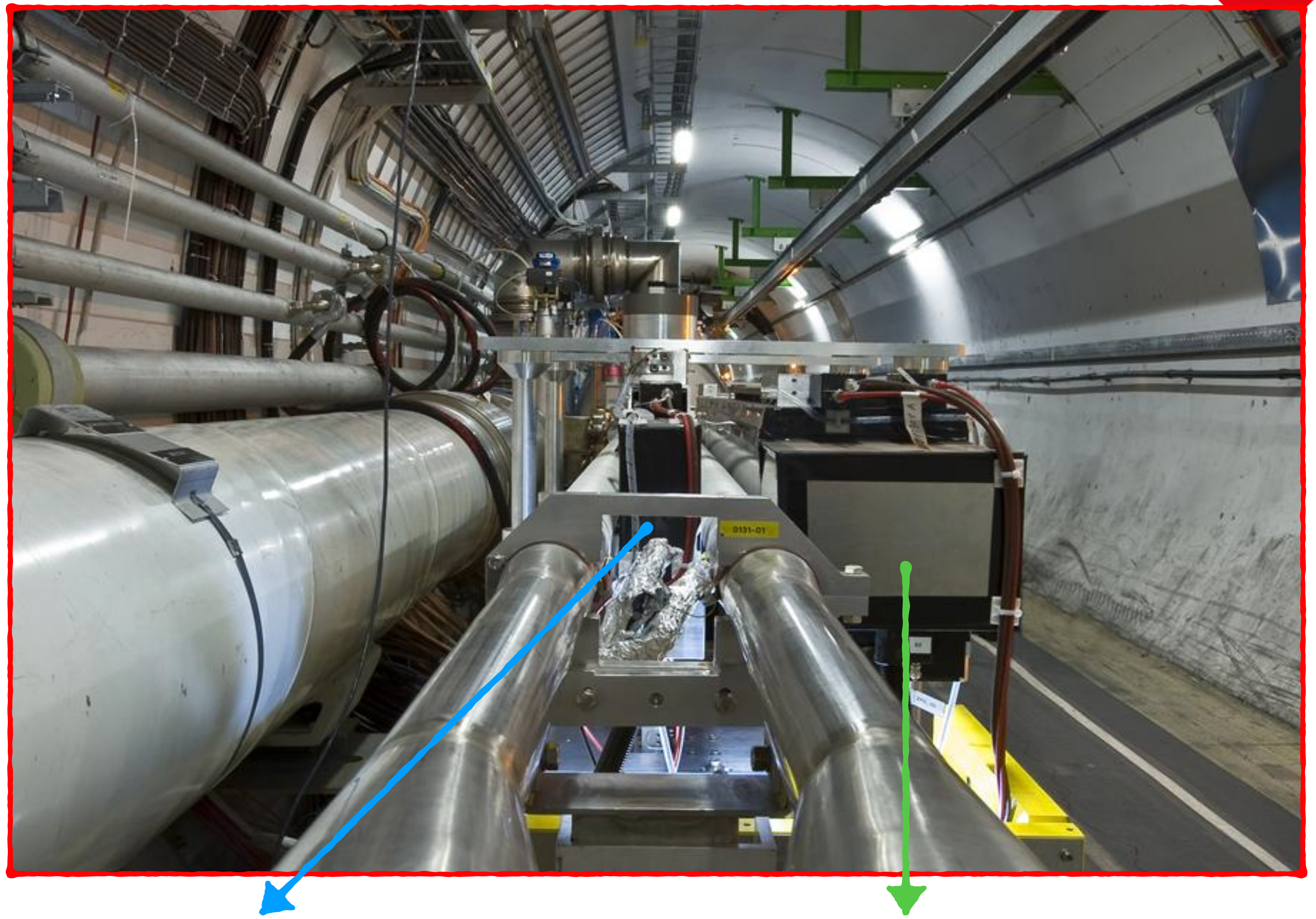


ALICE ZDC

Quartz fibre spaghetti calorimeters
Cerenkov light produced of shower particles

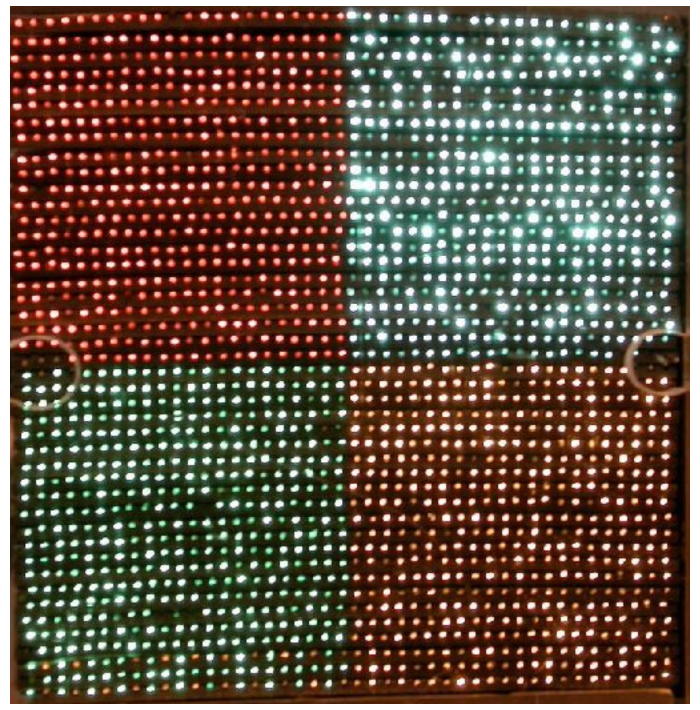




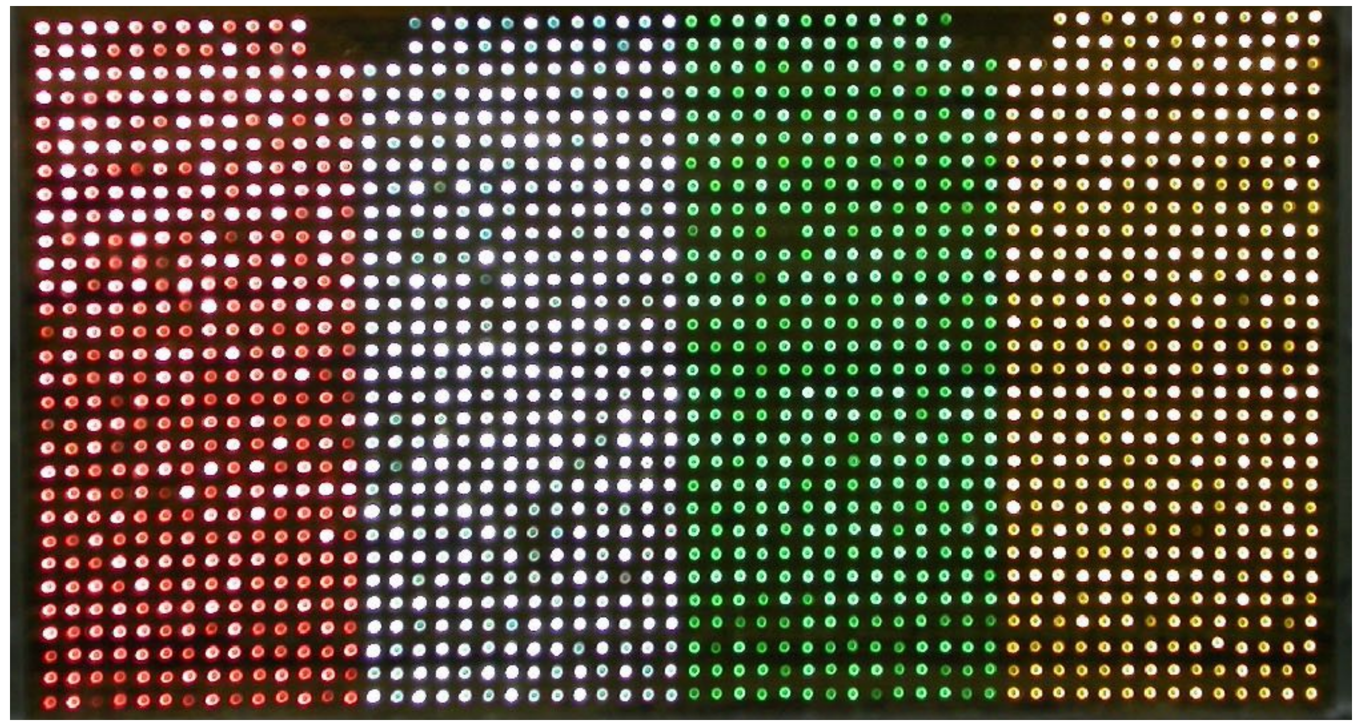


Two identical systems on both sides relative to IP, each made by:

- a neutron ZDC (ZN) at 0° w.r.t LHC axis, 7x7x100 cm^3 that detects neutral forward energy in |η|>8.7
- a proton ZDC (ZP) external to the beam pipe, 22.4x11.2x150 cm^3, detecting positively charged particles (mainly protons) in a pseudo rapidity range defined by the LHC magnetic beam settings



ZN



ZP

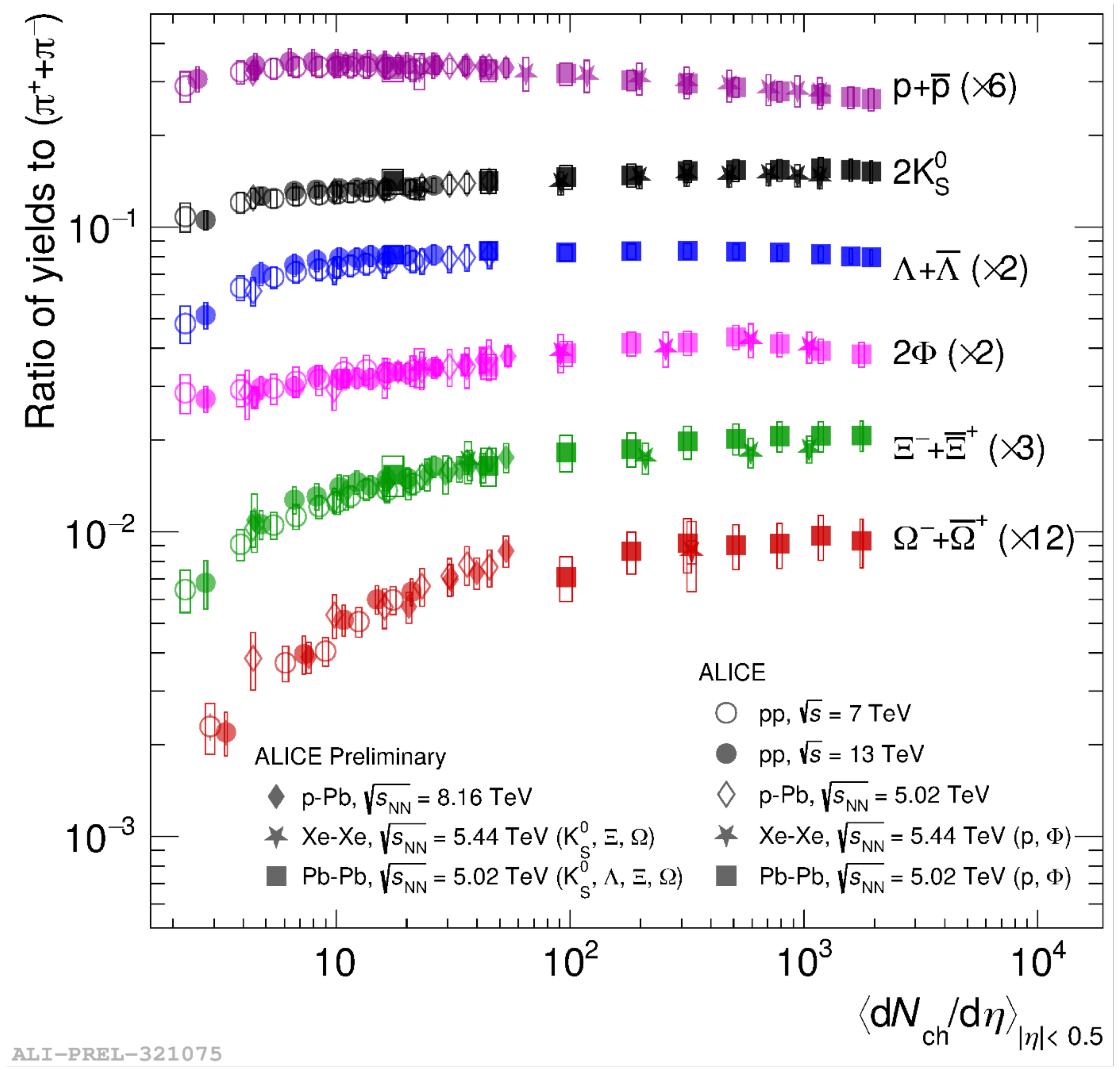
Strangeness enhancement vs. forward energy

What is the origin of strangeness enhancement observed in small systems?

Effective energy = energy in the initial phase available for particle production. Reduced relative to centre-of-mass energy due to leading baryon production.

$$E_{eff} = \sqrt{s} - E_{leading\ baryons} \sim \sqrt{s} - E_{ZDC}$$

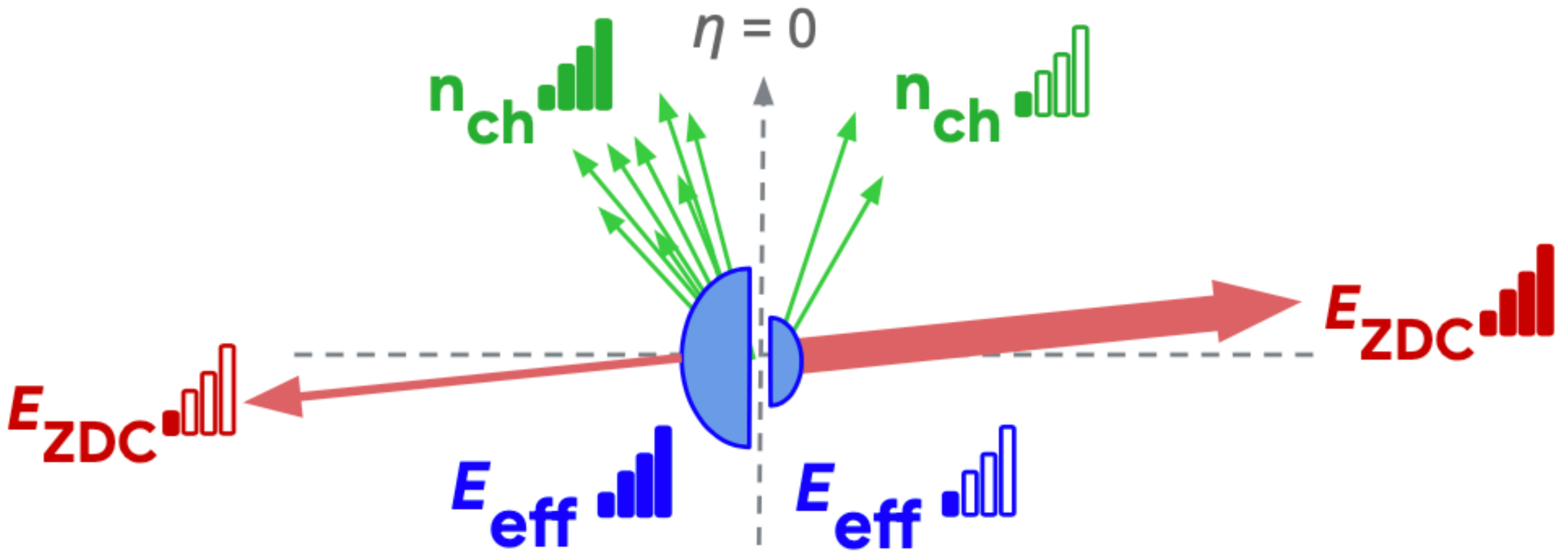
➧ study of strange baryon production vs. multiplicity and effective energy



Ratio of strange to non-strange hadron yields increases with charged-particle multiplicity.

The multiplicity distribution of charged particles is:

- characteristic of the final state of the collision
- strongly correlated to the initial effective energy



Strangeness enhancement vs. forward energy

- strange baryon over charged particle production increases with forward event activity (V0M) at fixed midrapidity multiplicity but also with increasing effective energy

- initial stages play a role in strangeness enhancement