Soft QCD (experiment)

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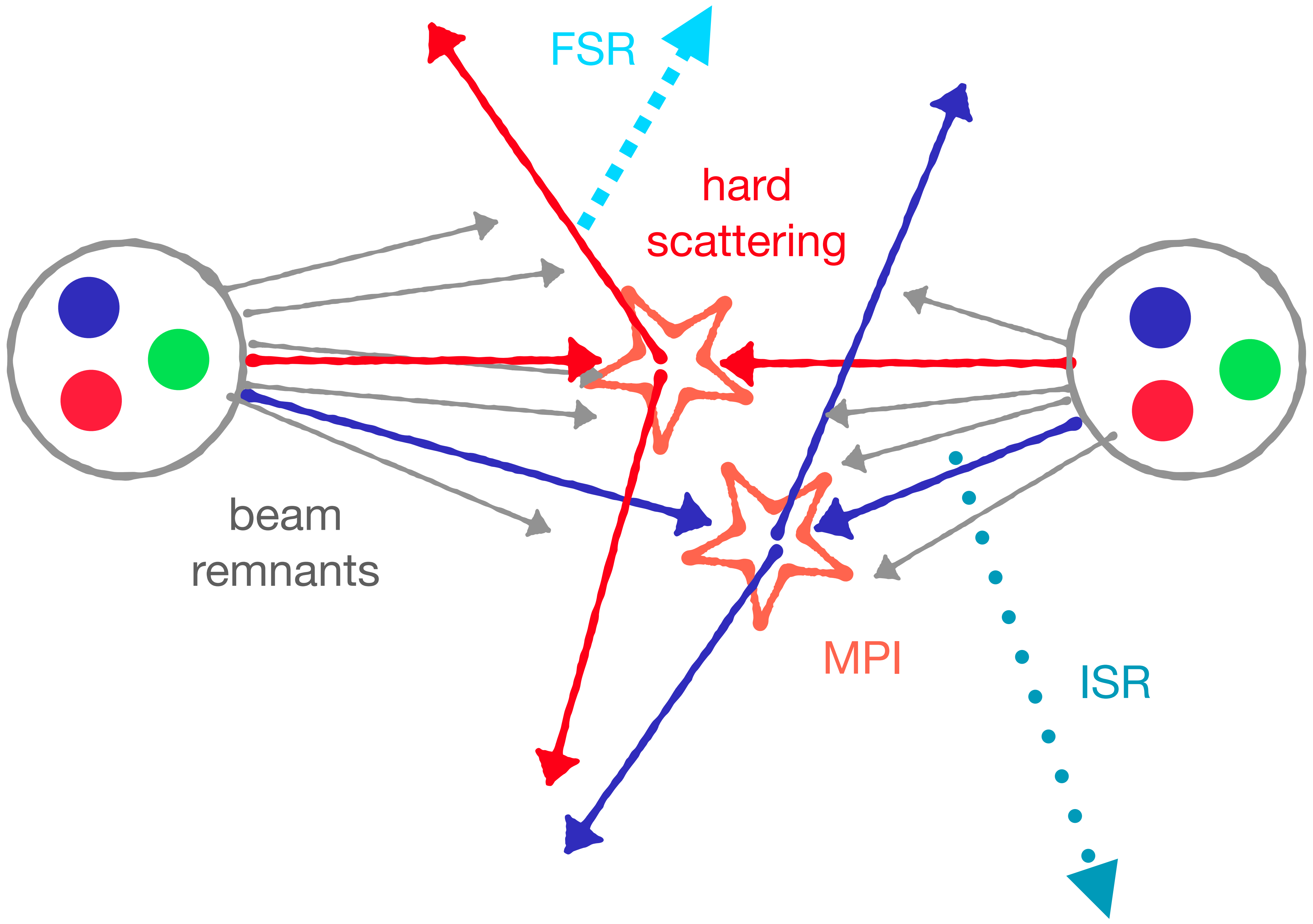
ALICE ATLAS EXPERIMENT CMS LHCb

2022 LHCP TAIPEI

Soft QCD at LHC



Soft interactions ➧ low momentum transfer
➧ effective theories, phenomenological models

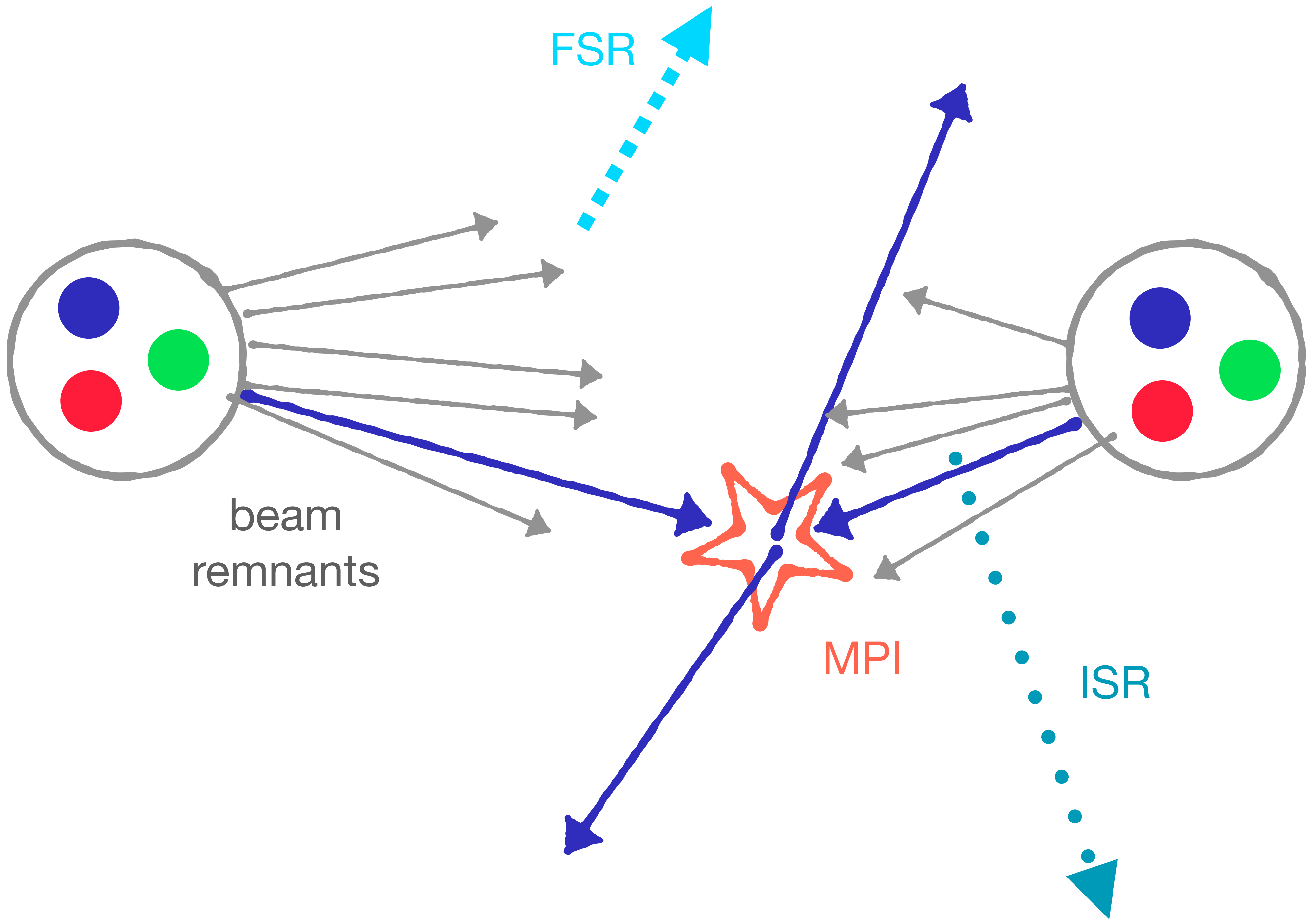
EXPERIMENTAL OBSERVABLES

Diffraction (large y gap),
Multi Parton Interactions (MPI),
MB event and Underlying Event (UE),
Double Parton Scattering (DPS),
strangeness production and enhancement

DATA AND MODELS

➧ input/constraint on models: diffraction, parton showering, nPDF, hadronization, MPI modelling, beam remnants
➧ discriminating power between different assumptions
➧ relevance for simulation of extensive cosmic air showers

Soft QCD at LHC



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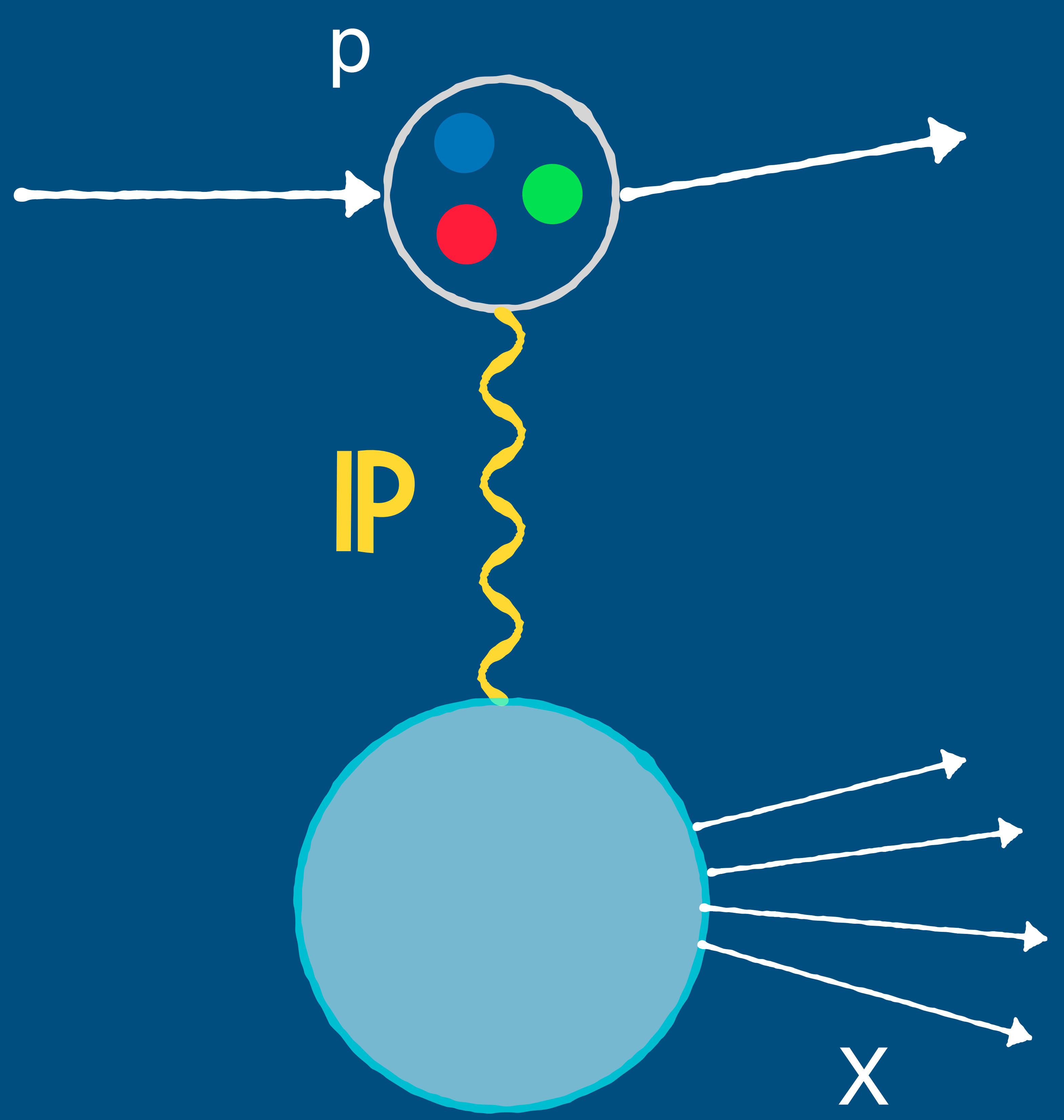


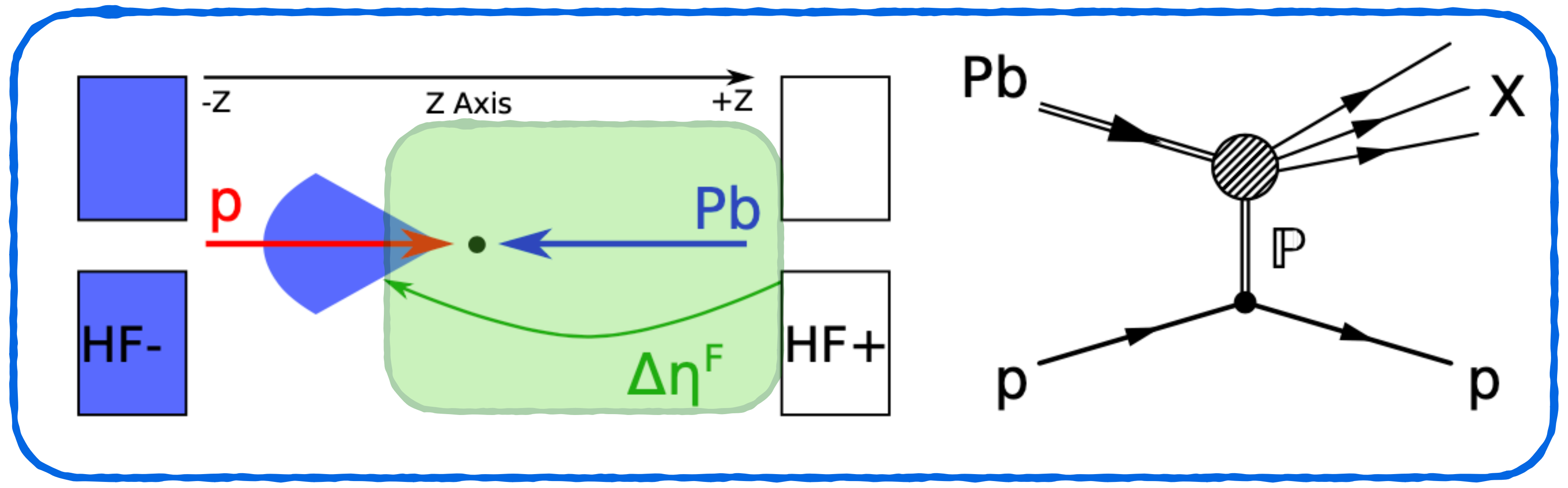
Diffractive events

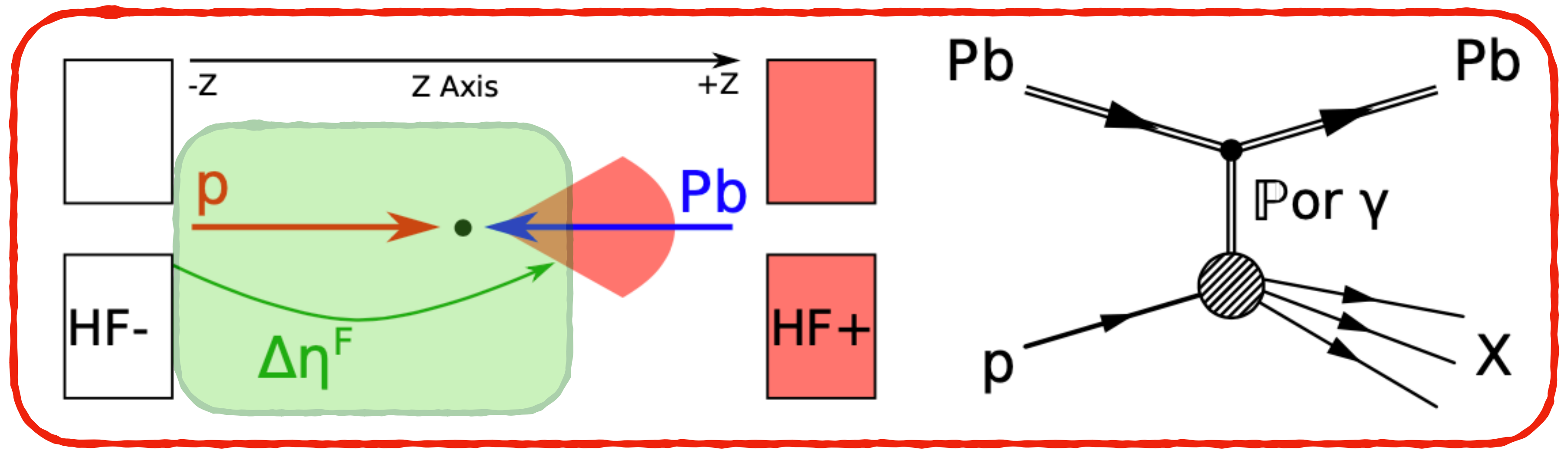
Pomeron interactions

Diffraction in p-Pb collisions

CMS, PAS-HIN-18-019

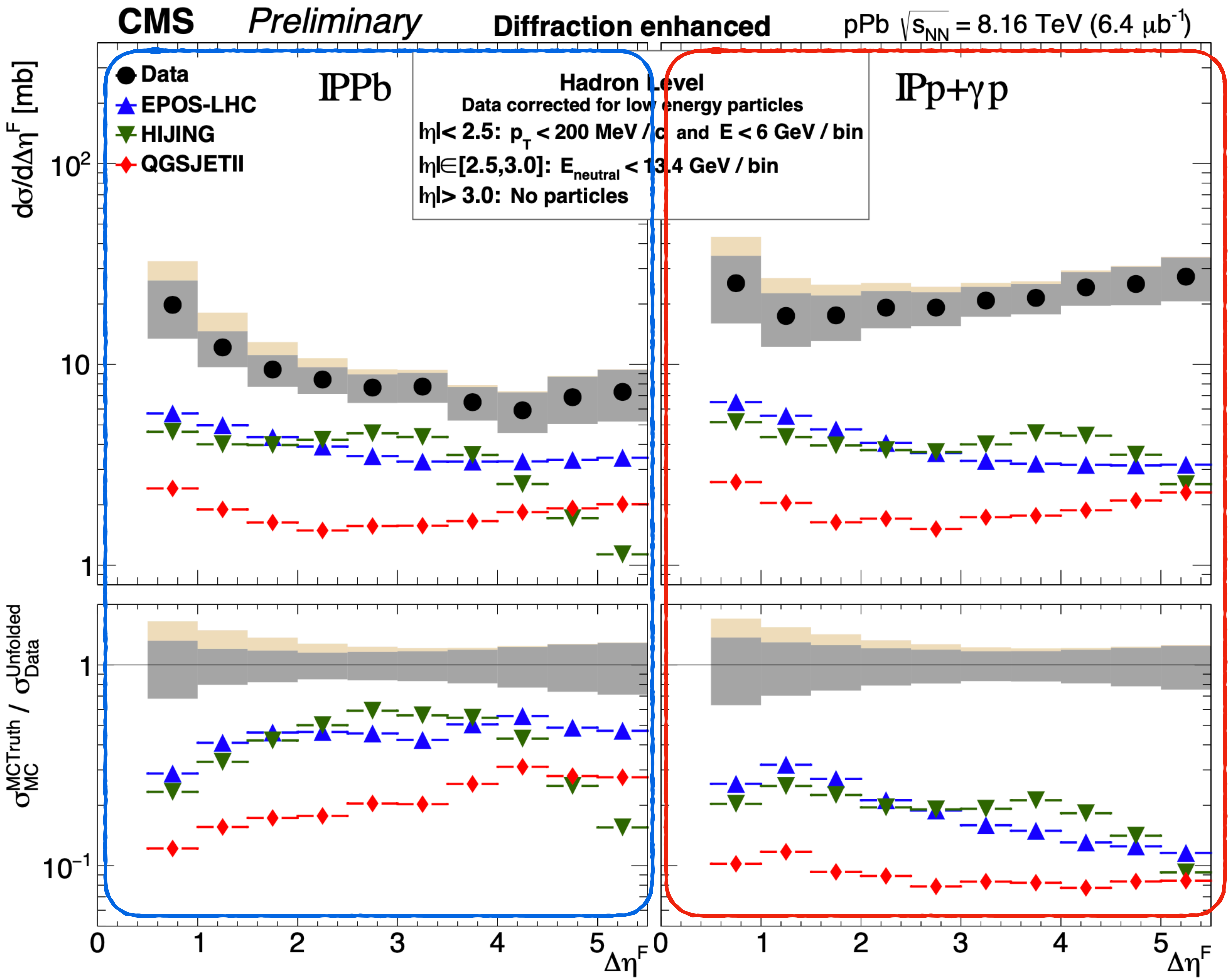
First measurement of forward rapidity gap distribution in p-Pb collisions for IPPb and IPp (+γp) topologies

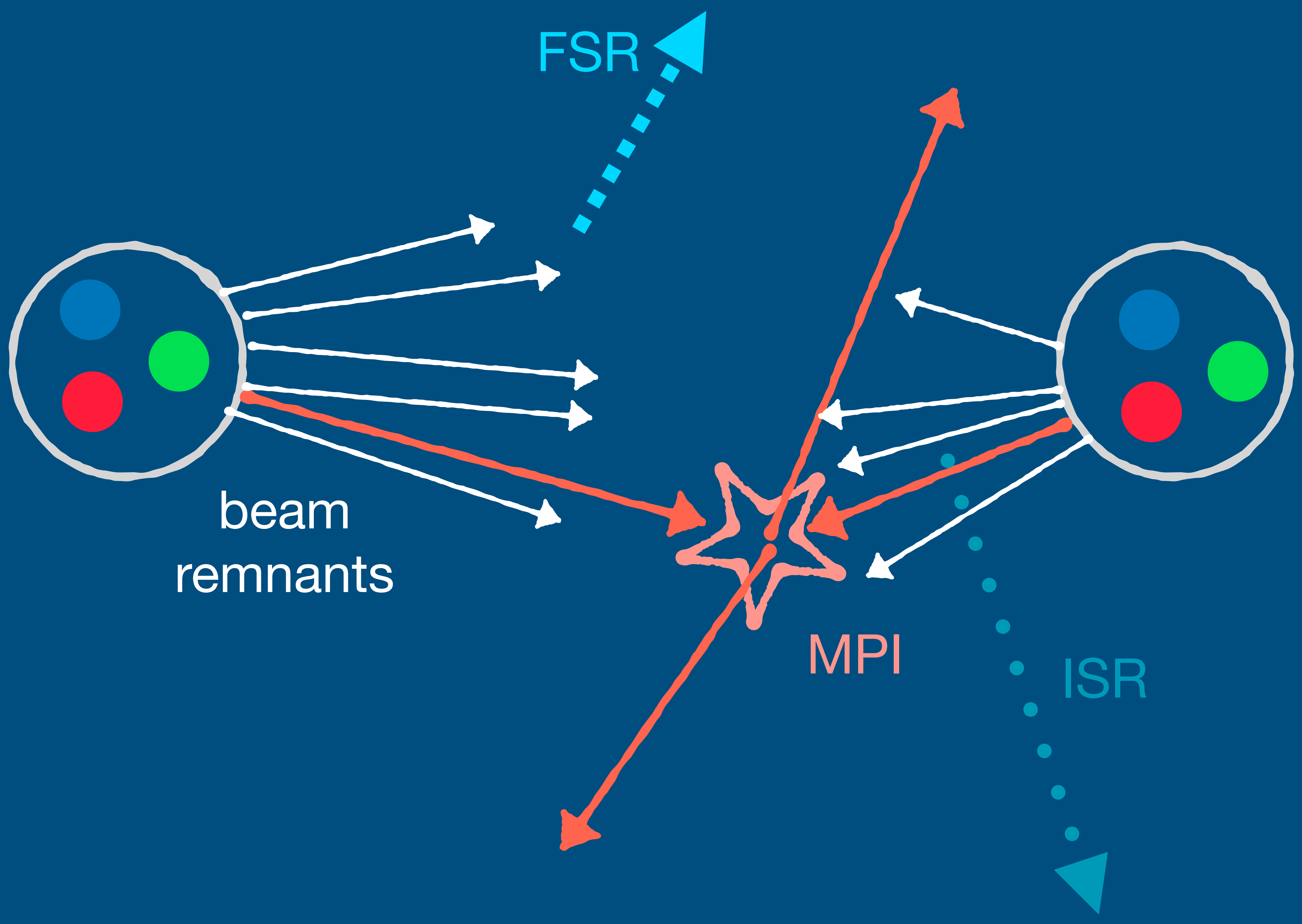




- IPPb: all generators underestimate data
- IPp + γp: large discrepancy at large $\Delta\eta^F$, (γp processes not included in generators)

- input for inelastic diffraction tuning of event generators, relevance for cosmic ray physics





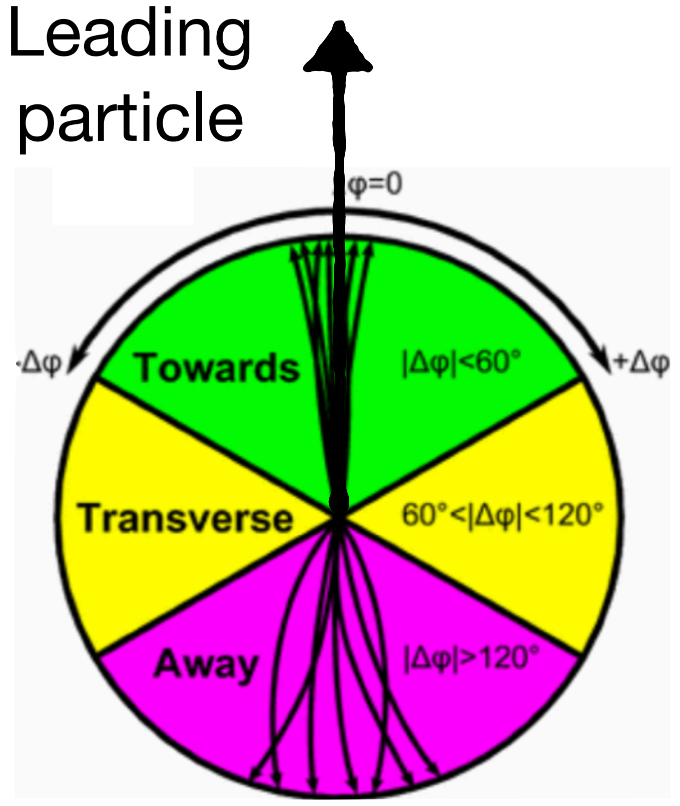
Underlying Event

MPI + beam remnants +
Initial State radiation (ISR) +
Final State radiation (FSR)

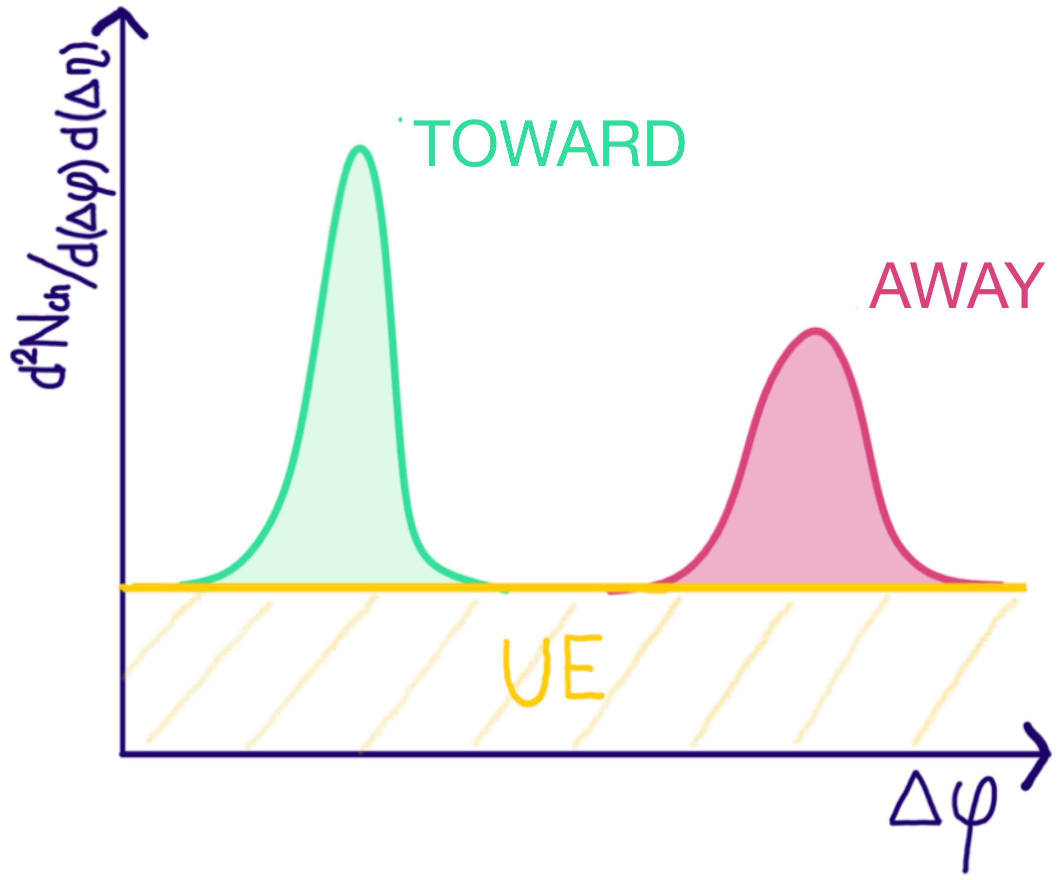
UE in pp and p-Pb collisions

ALICE, arxiv 2204.10389

Transverse region activity dominated by UE
➧ challenge for models to describe UE observables in all collision systems



Azimuthal distributions



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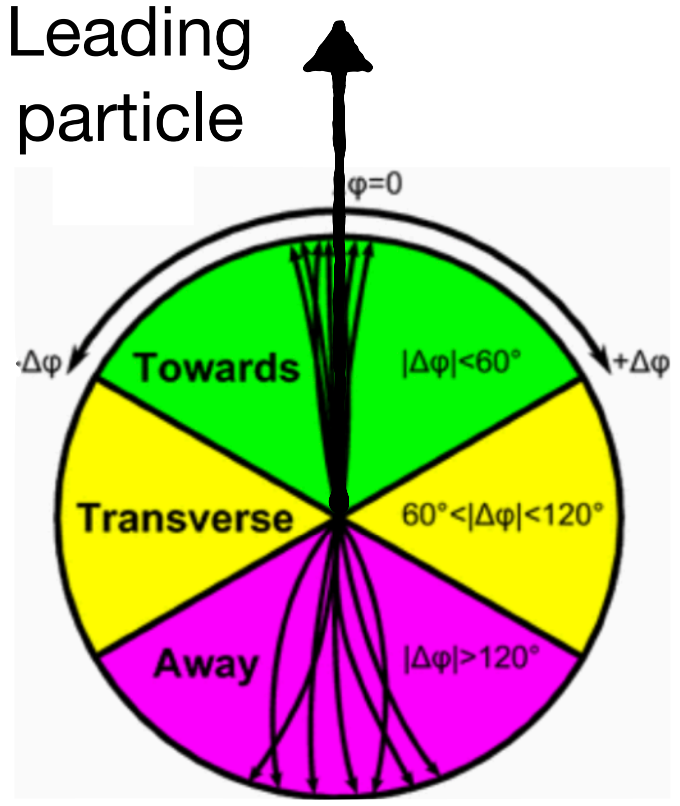

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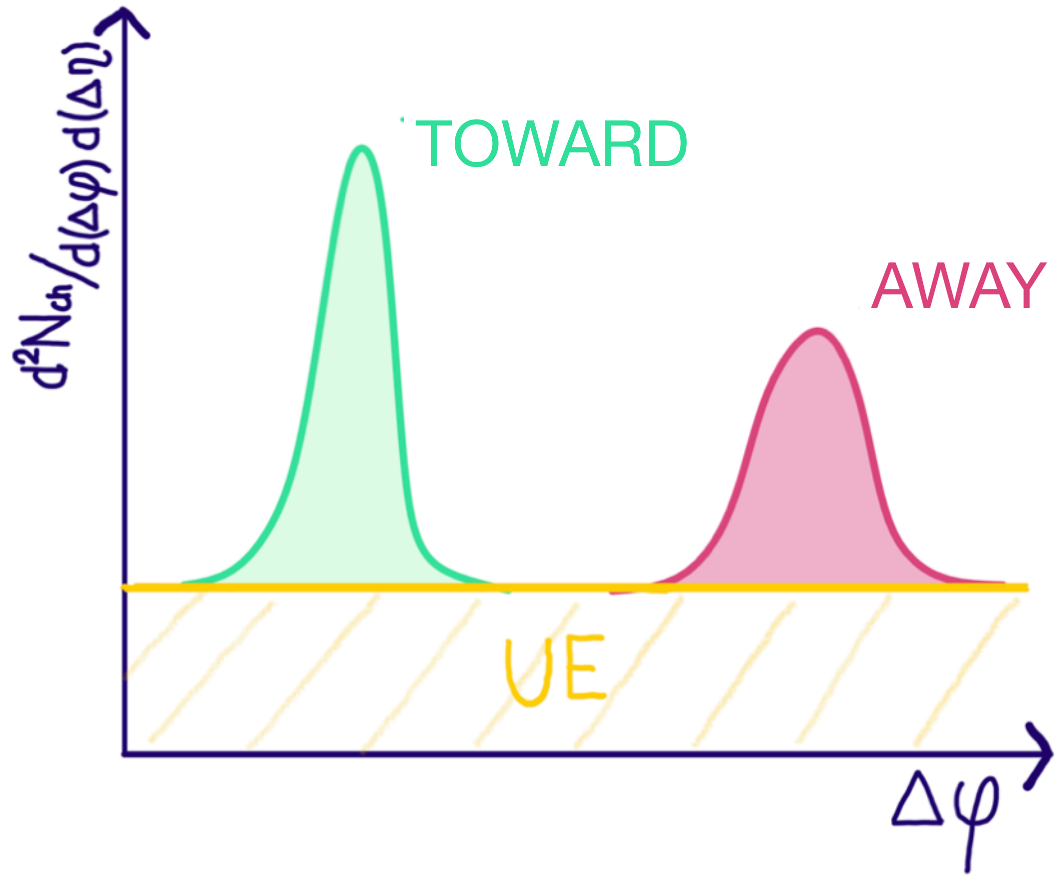
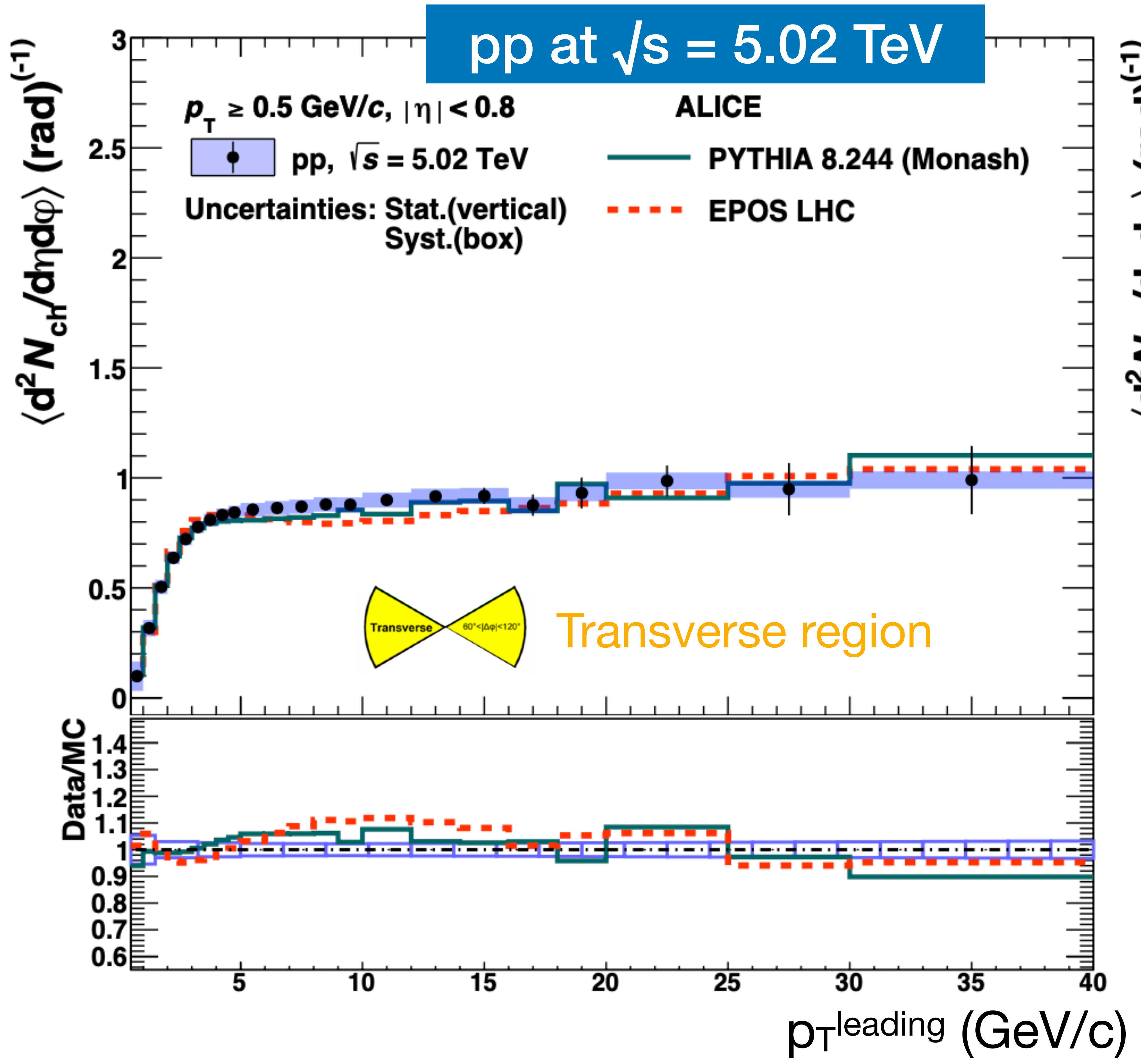
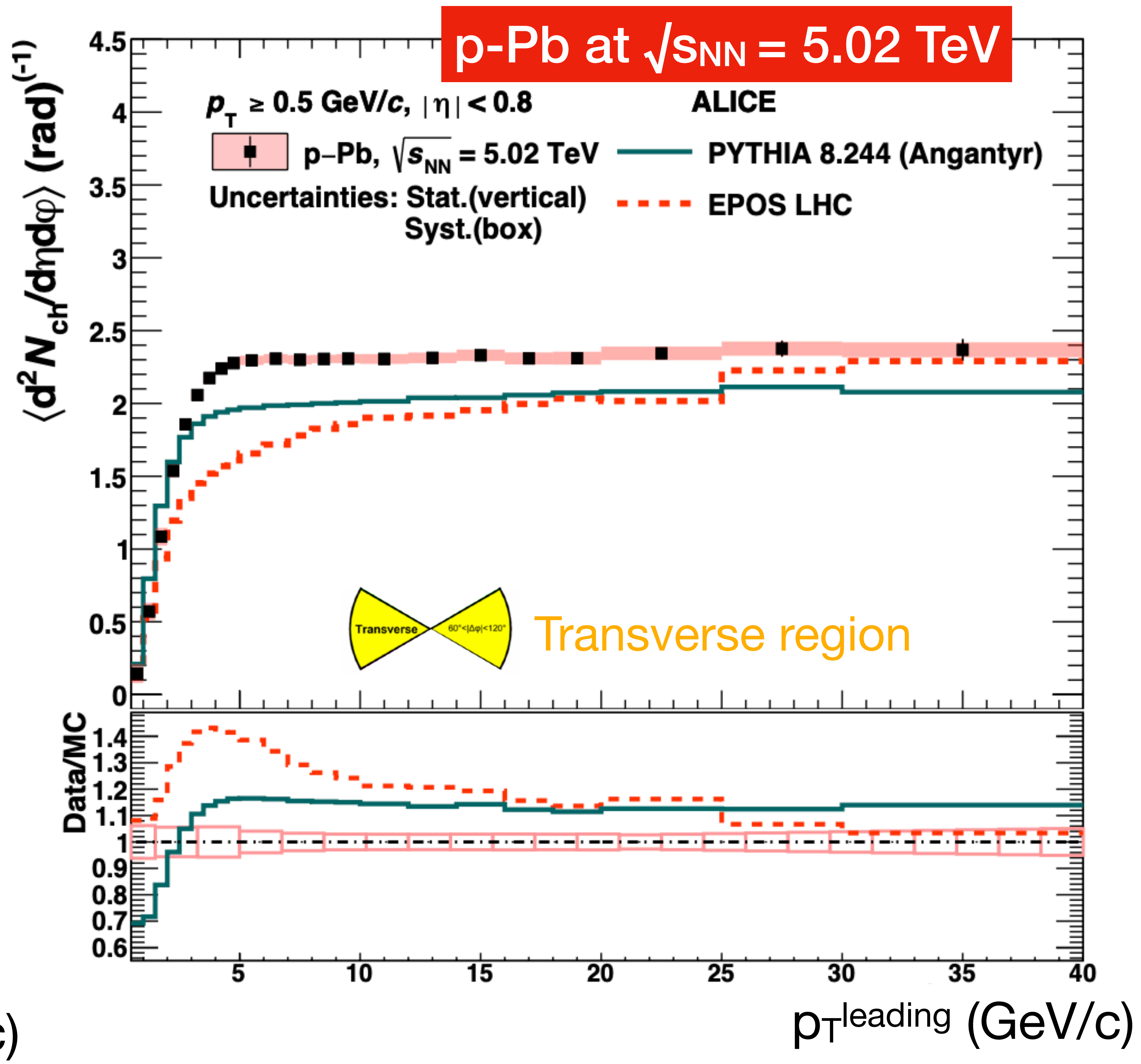




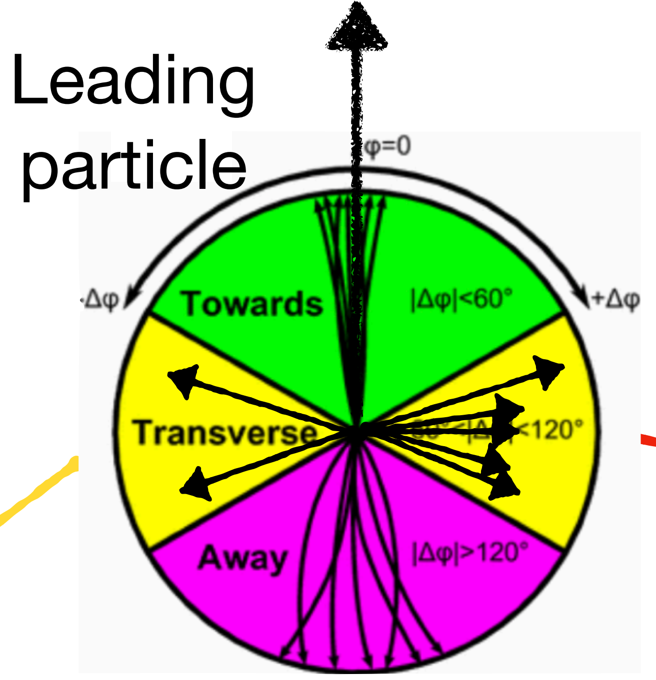


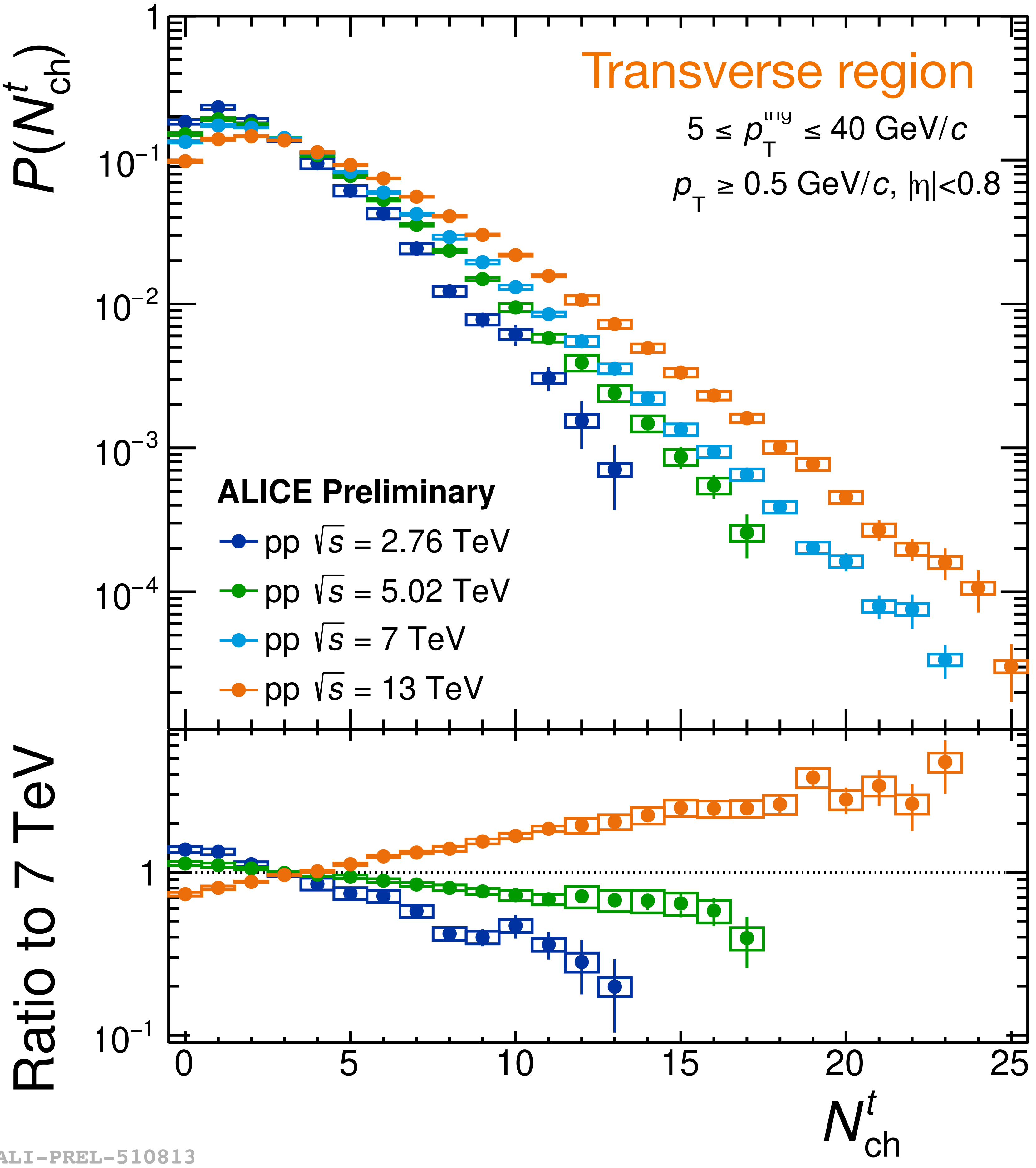
➧ models that reproduce UE in pp collisions are not able to describe p-Pb results

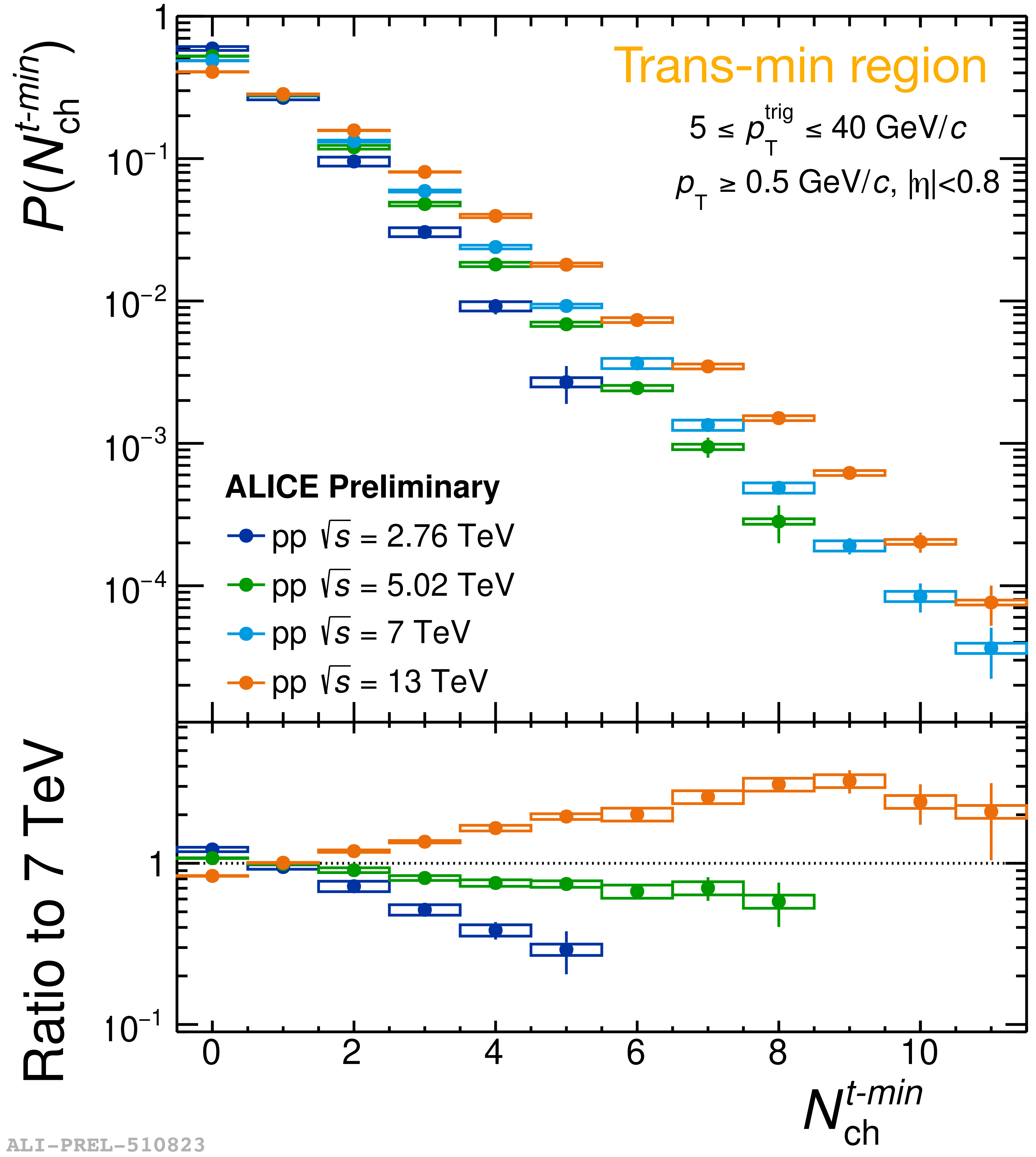
Energy dependence of UE

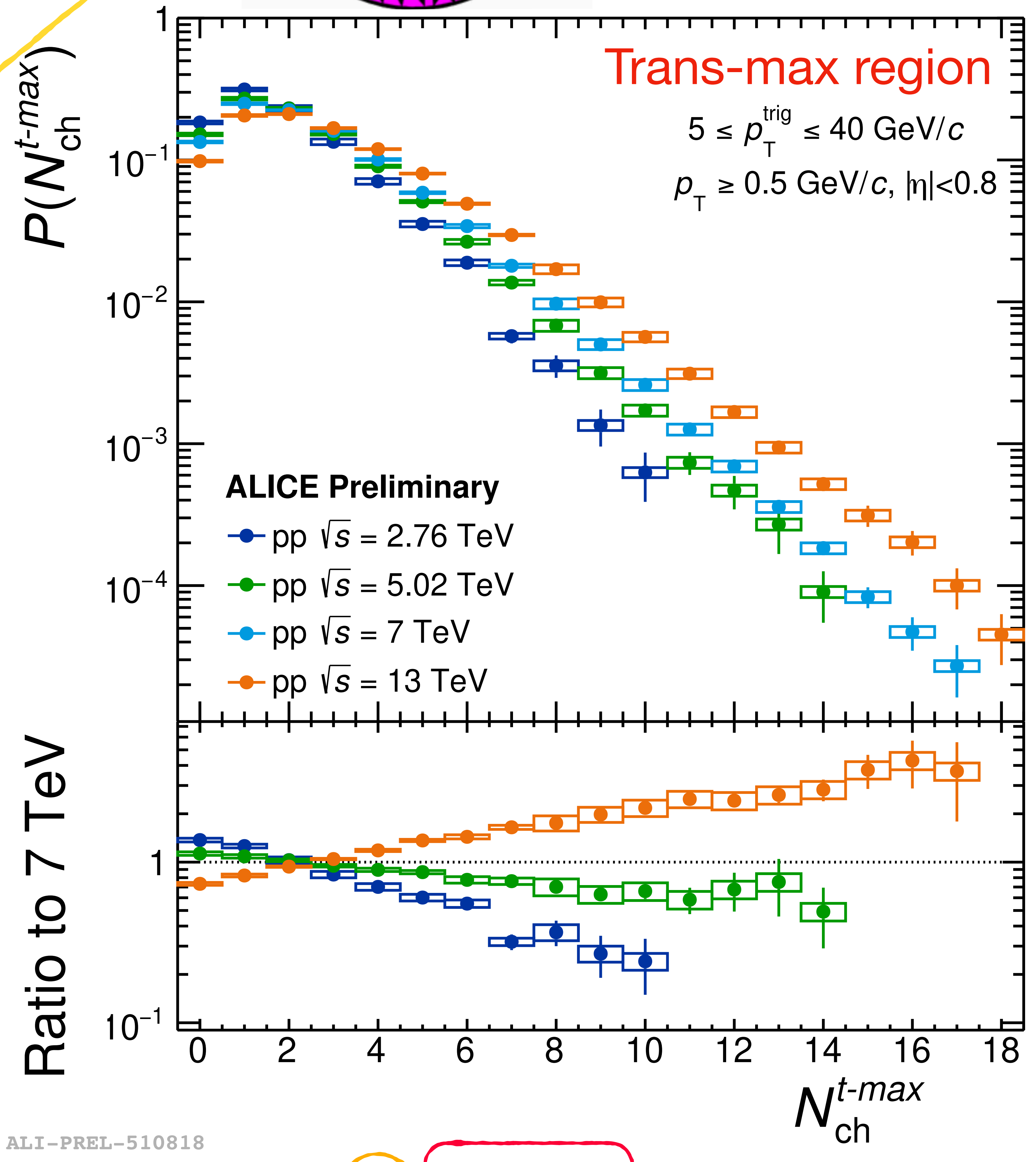
Split transverse region by maximum and minimum activity

- trans-max region is dominated by ISR-FSR, trans-min is more sensitive to MPI









- $\langle N_{ch} \rangle$ can be described by a parametrisation: $s^{\alpha} + k \log(s)$

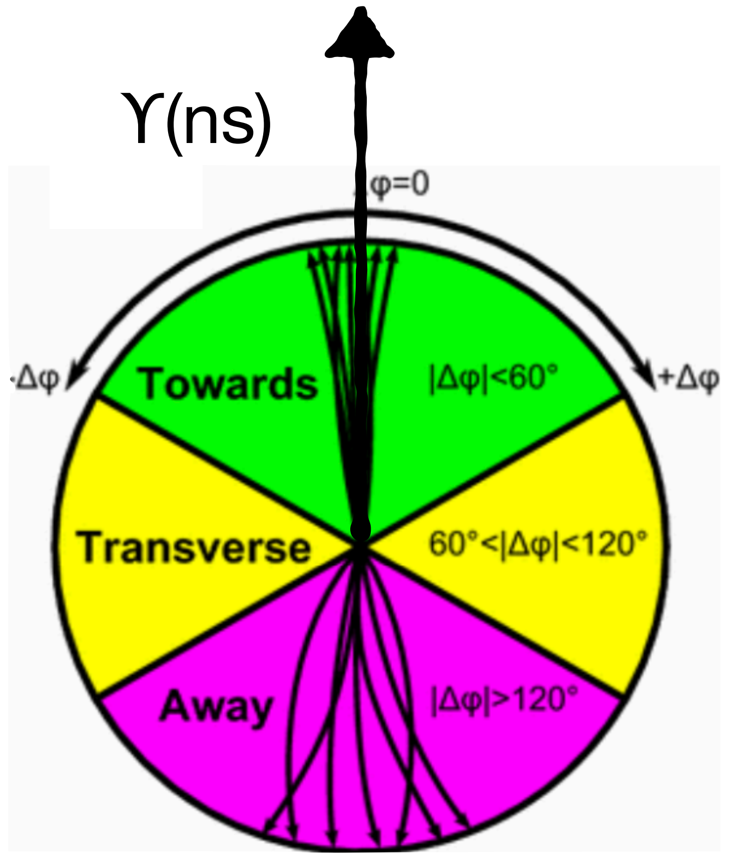
MPI-sensitive region

ISF-FSR sensitive region

Υ meson production vs. UE in pp collisions

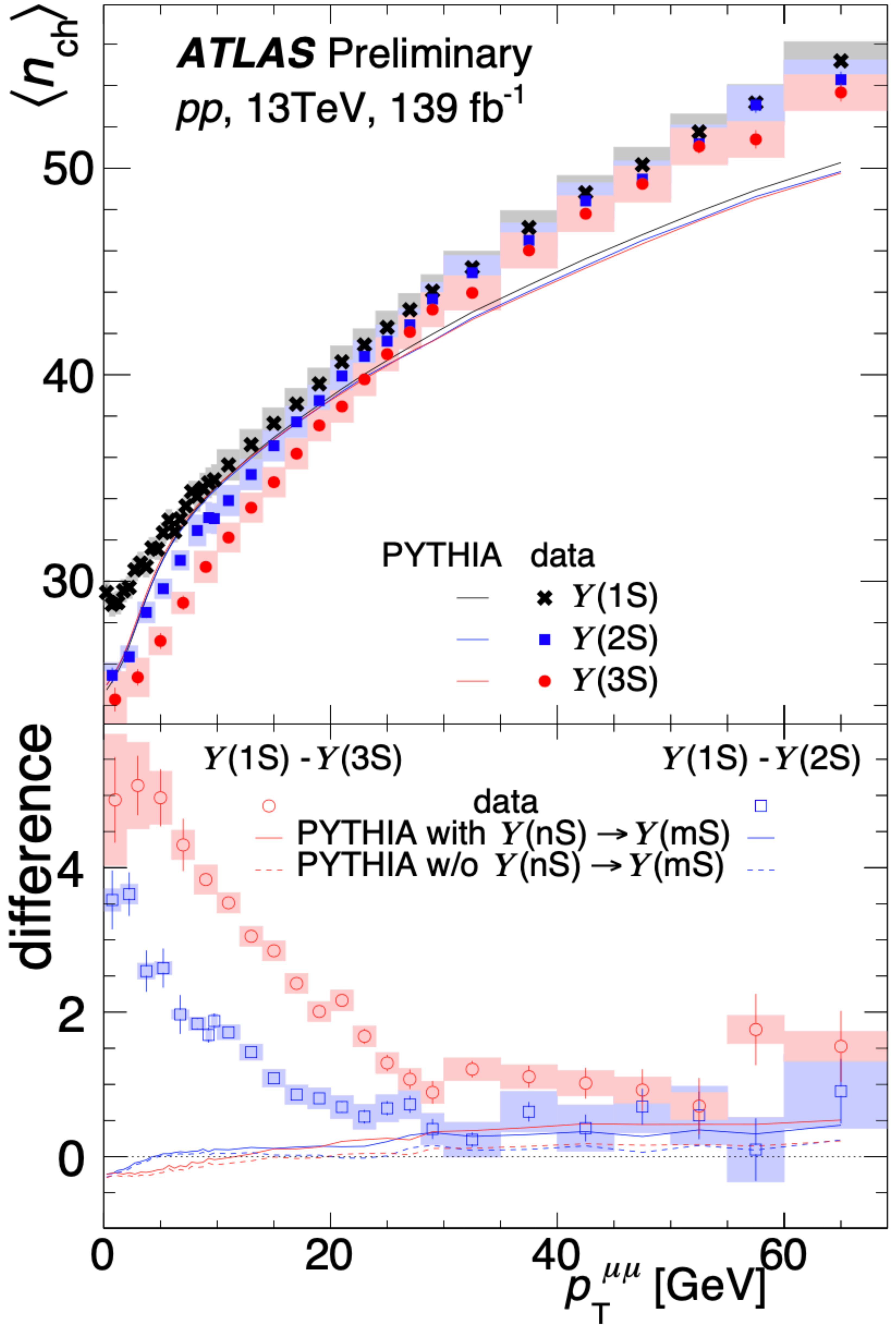
ATLAS-CONF-2022-023

Characterization of multiplicity in UE in events where a heavy flavour meson (ϒ) is produced ➧ role of MPI



➧ significantly different UE multiplicity, <n_{ch}>, produced in association with different ϒ(ns) states at low $p_T^{\mu\mu}$ values

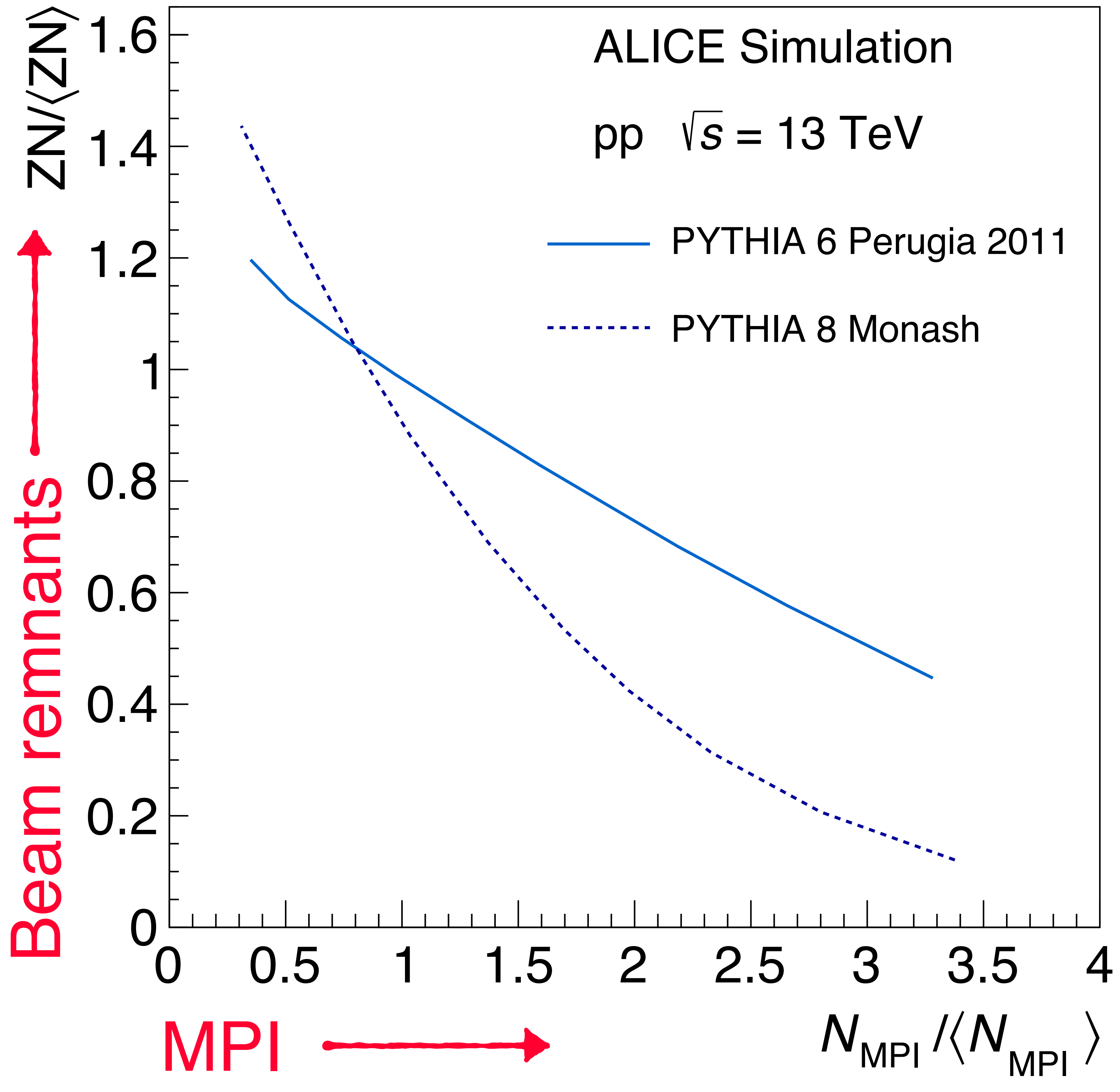
➧ PYTHIA predicts very similar distributions for the three ϒ(ns) states, even including Color Reconnection



Very forward energy in pp collisions

ALICE, arxiv 2107.10757

Midrapidity multiplicity vs. very forward energy measured in neutron ZDC (ZN)



➧ ZN energy expected to decrease with increasing N_{MPI}

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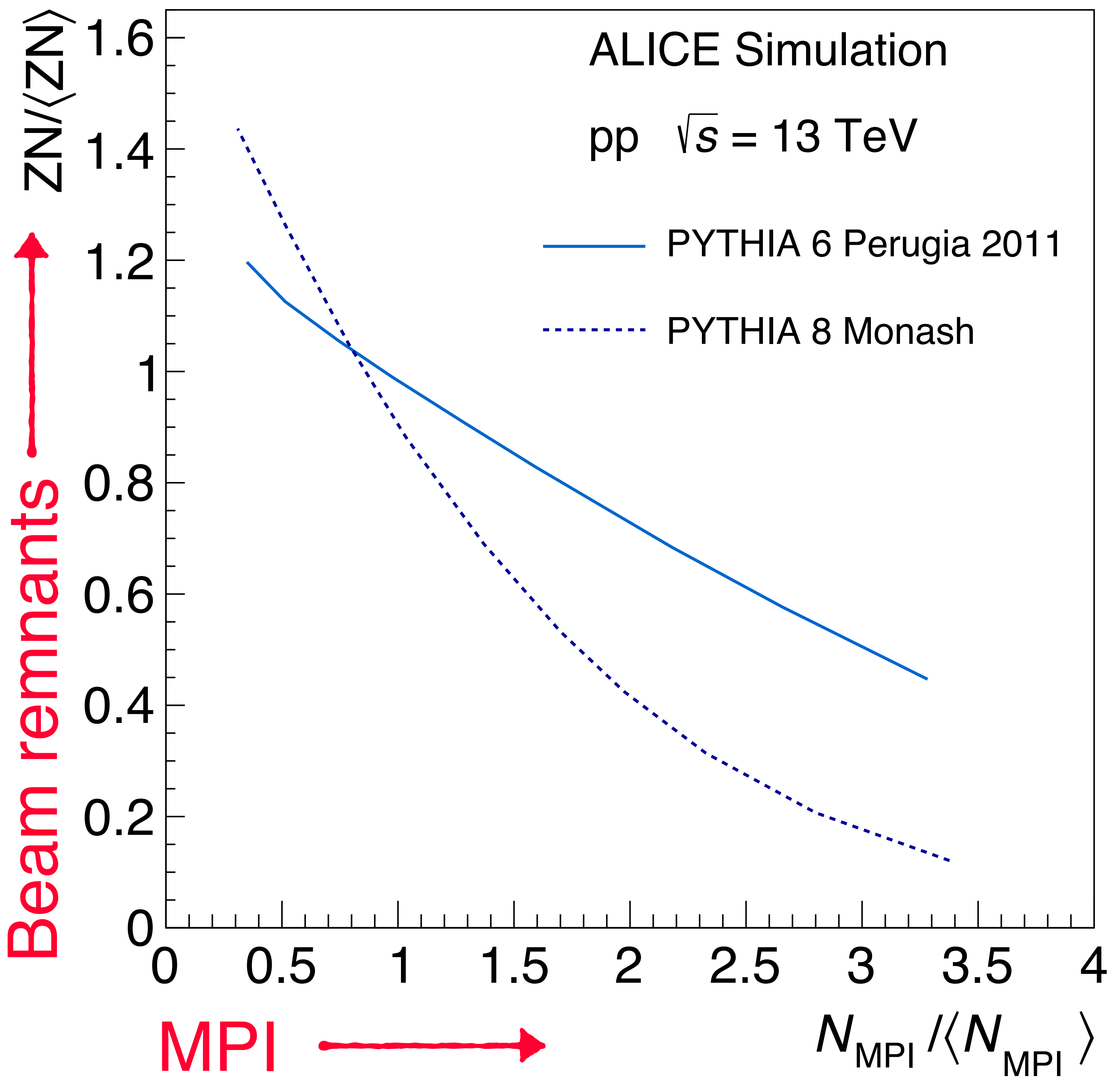

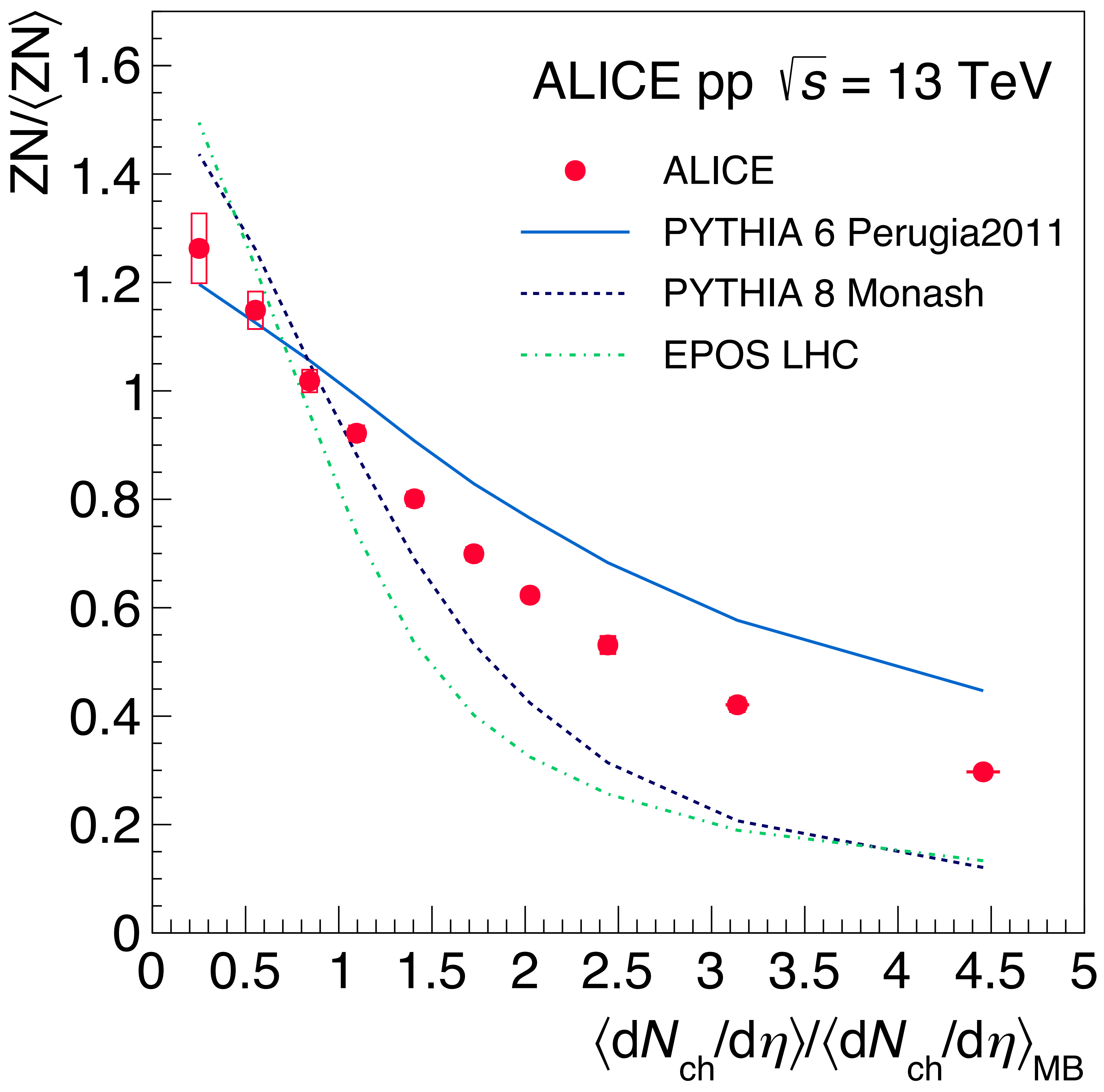

- ZN energy expected to decrease with increasing N_{MPI}
- Forward energy decreases with increasing multiplicity at midrapidity

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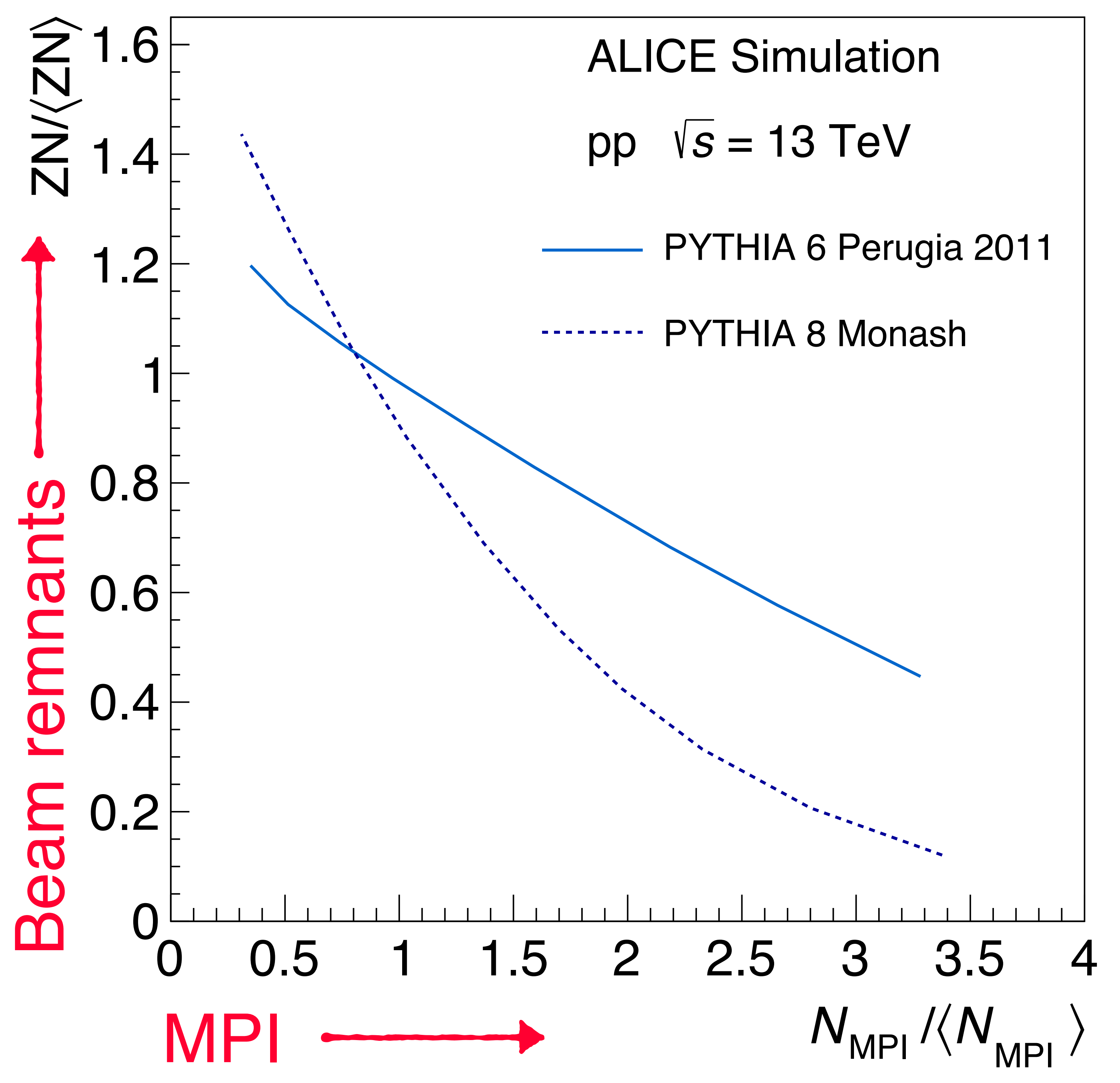
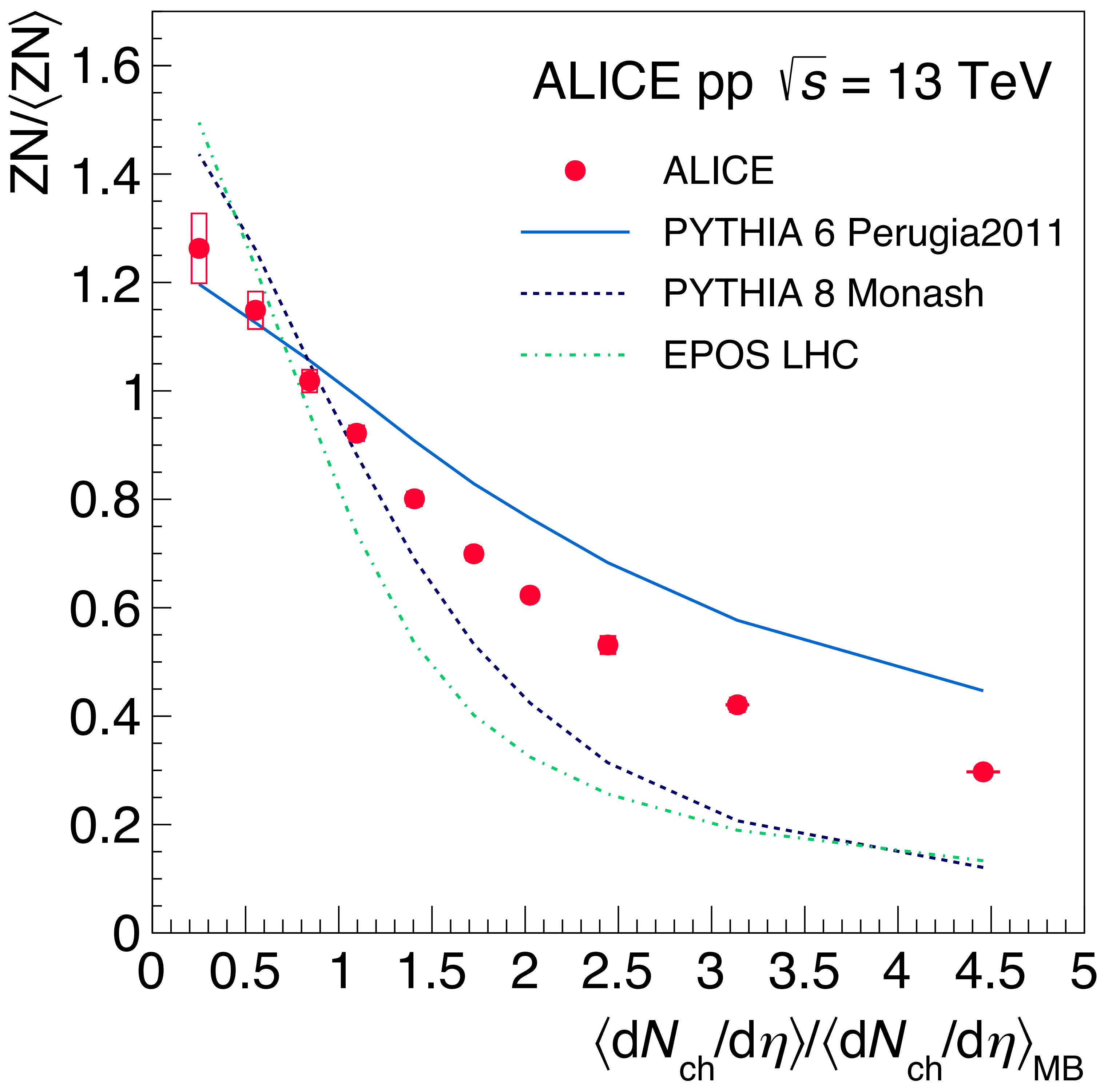
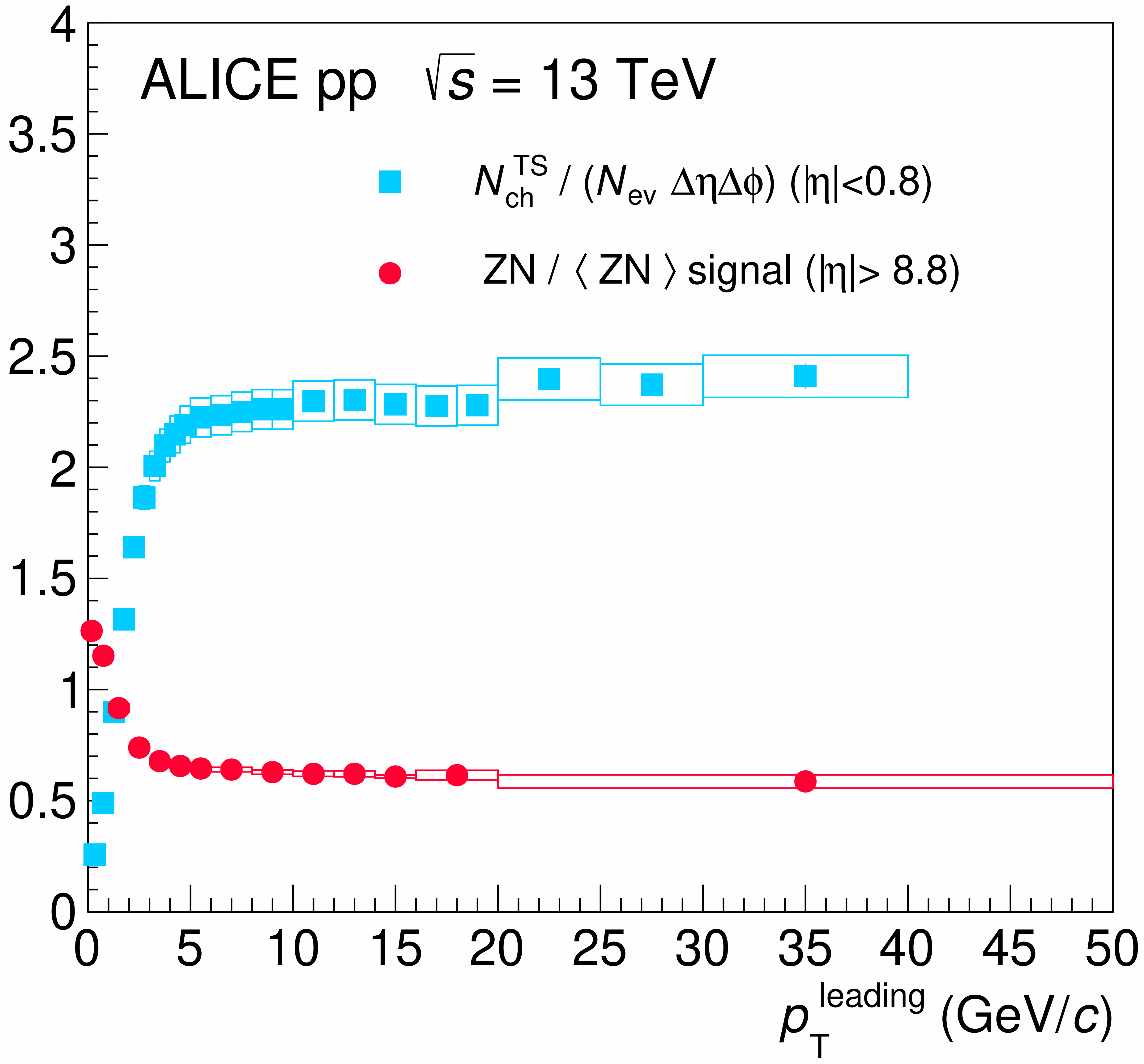
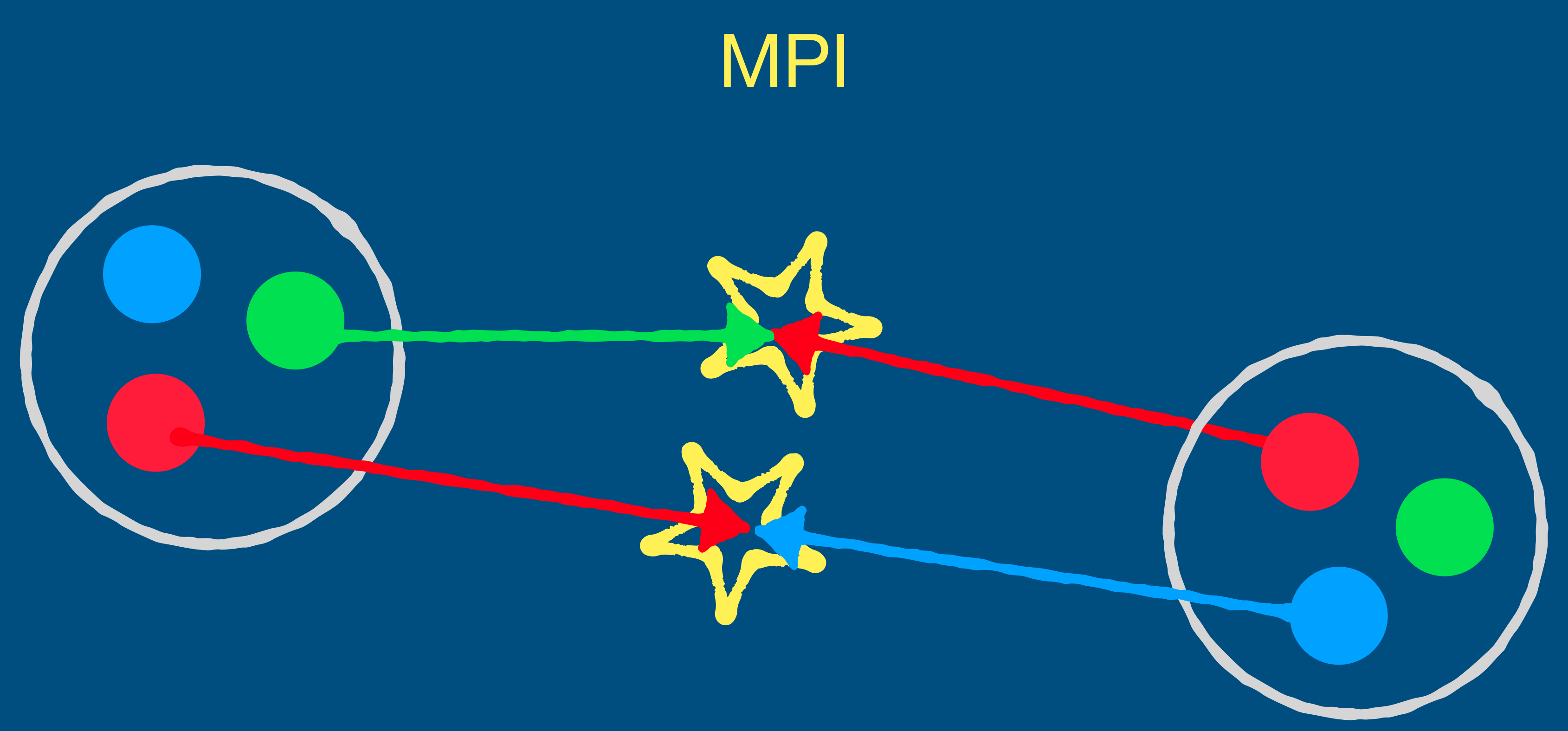






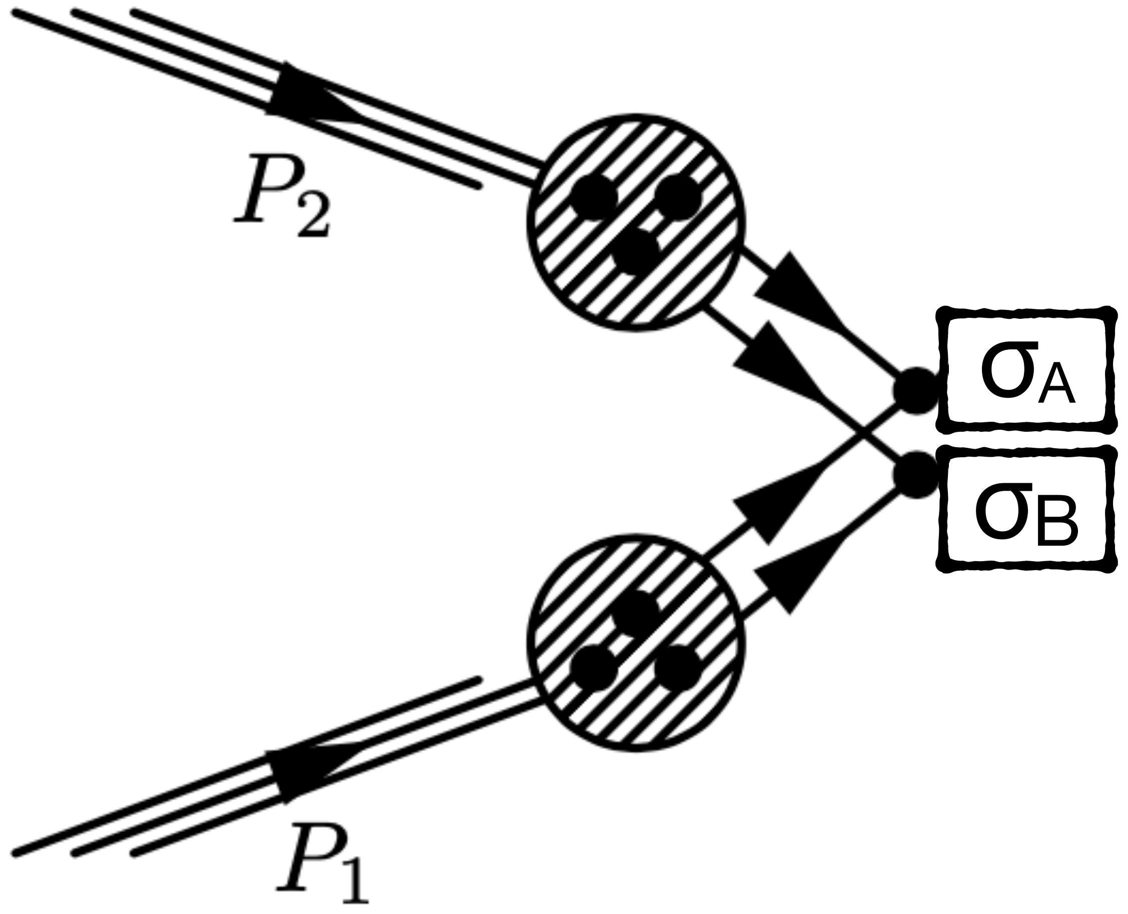
- ZN energy expected to decrease with increasing N_{MPI}
- Forward energy decreases with increasing multiplicity at midrapidity
- ZN energy and UE saturation occur at the same leading p_T scale (~5 GeV/c)
- built in the initial stages of the collision



Double Parton Scattering

MPI, UE

Double Parton Scattering (DPS)



2 hard parton-parton interactions in the same collision
➧ simplest case of MPI

Assuming that the 2 partonic scatterings are uncorrelated
➧ fully factorised cross section

$$\sigma^{DPS}_{A,B} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

m = { 1 for identical processes; 2 for non identical processes

σ_{eff} ➧ effective cross section, measures the transverse distribution of partons inside the colliding hadrons and their overlap in the collision

In models, DPS is quantified through σ_{eff} parameter
Parameters relative to transverse parton density are extracted from fit to UE data
➧ data can test the accuracy of predictions form different MPI implementations and UE description

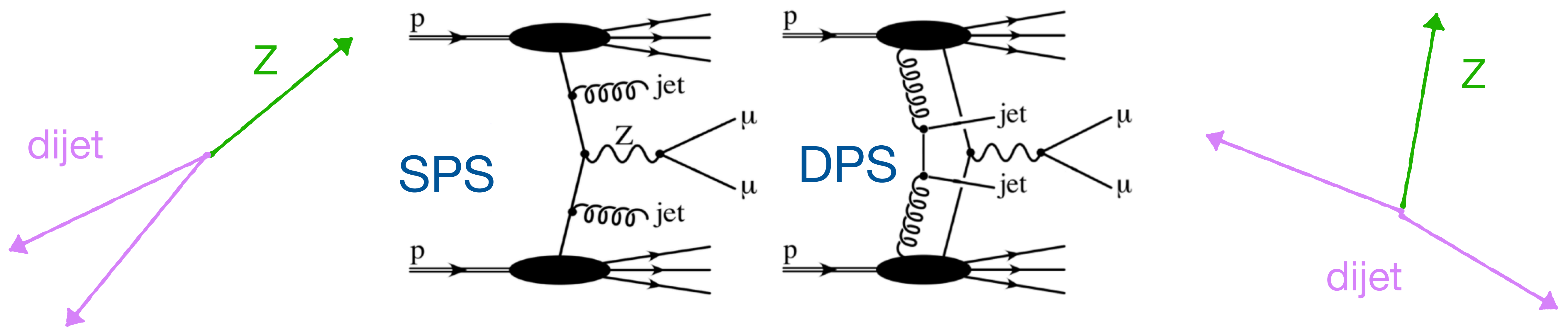
Study of observables sensitive to DPS (showing different distributions relative to SPS) in different channels

DPS in Z boson + jets events

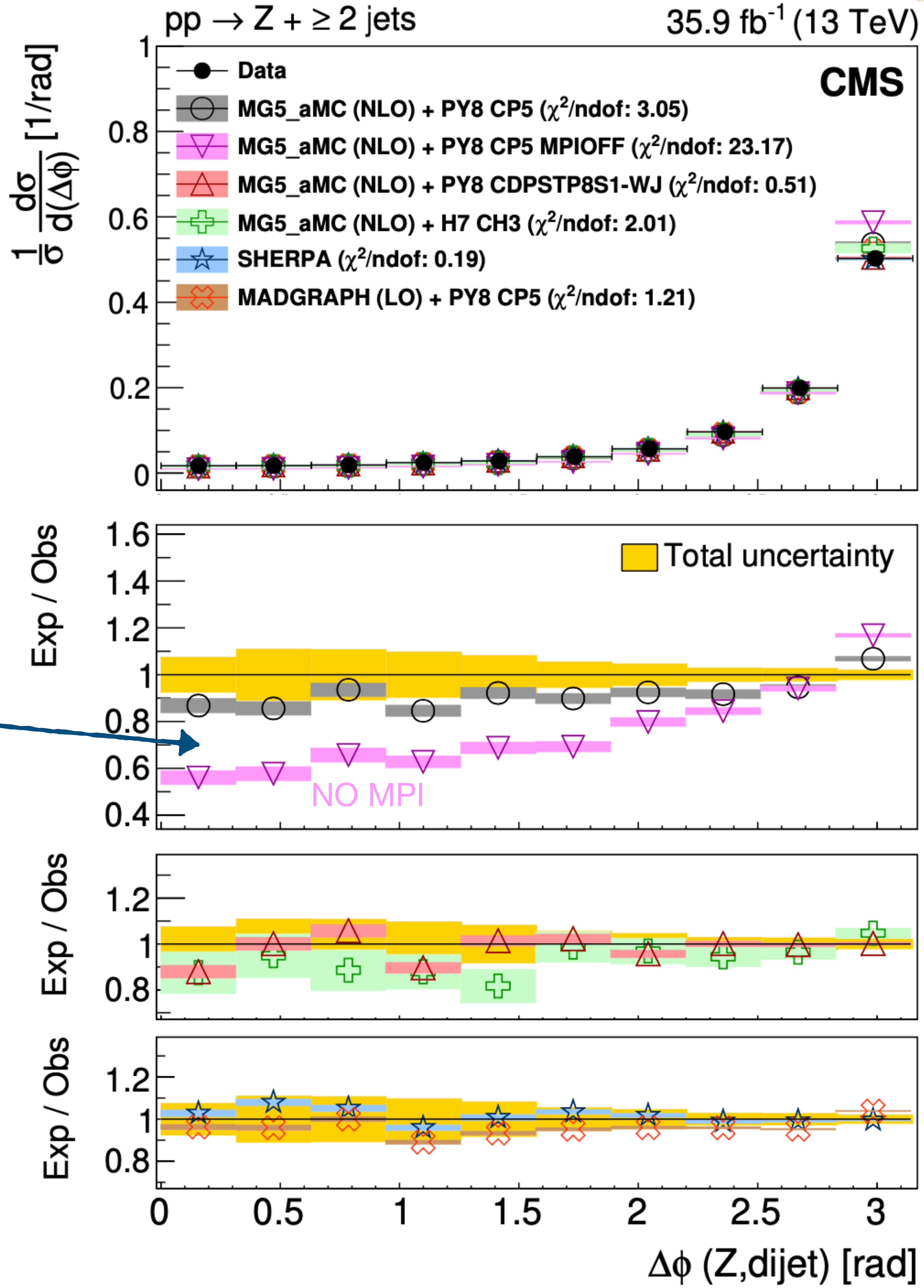
CMS, JEHP 10 (2021) 176

First DPS measurement with Z+jets at 13 TeV

Differential cross section vs. azimuthal angle between Z and dijet, ΔΦ(Z, dijet) (peak at π for SPS, flat for DPS)

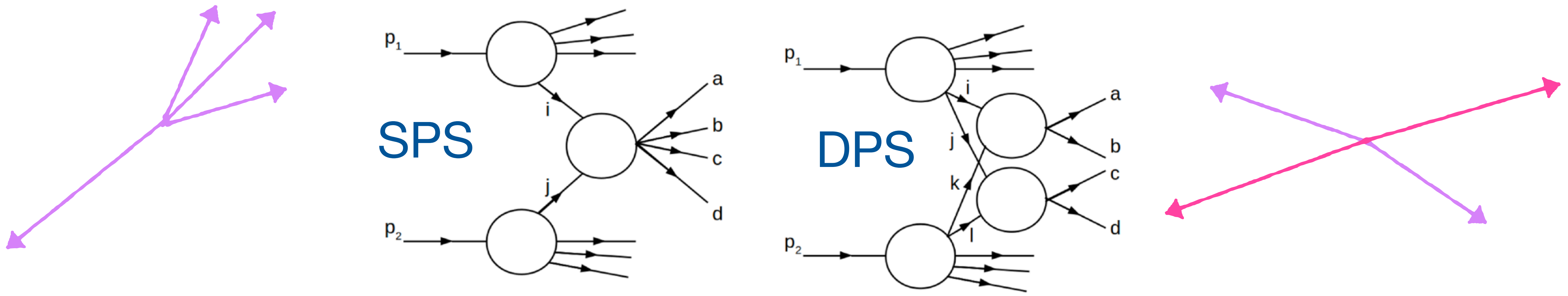


- MPI are needed to describe the observed shapes!
- different MPI implementations (SHERPA [☆] and MG5_aMC + HERWIG7 [✚]) reasonably describe data
- DPS specific tune CDPDTP8S1-WJ [Δ] (tuned on 7 TeV data) gives a good description of 13 TeV data
- MPI modelling crucial to describe the measurements



DPS in 4-jets at low p_T

CMS, JHEP 01 (2022) 177



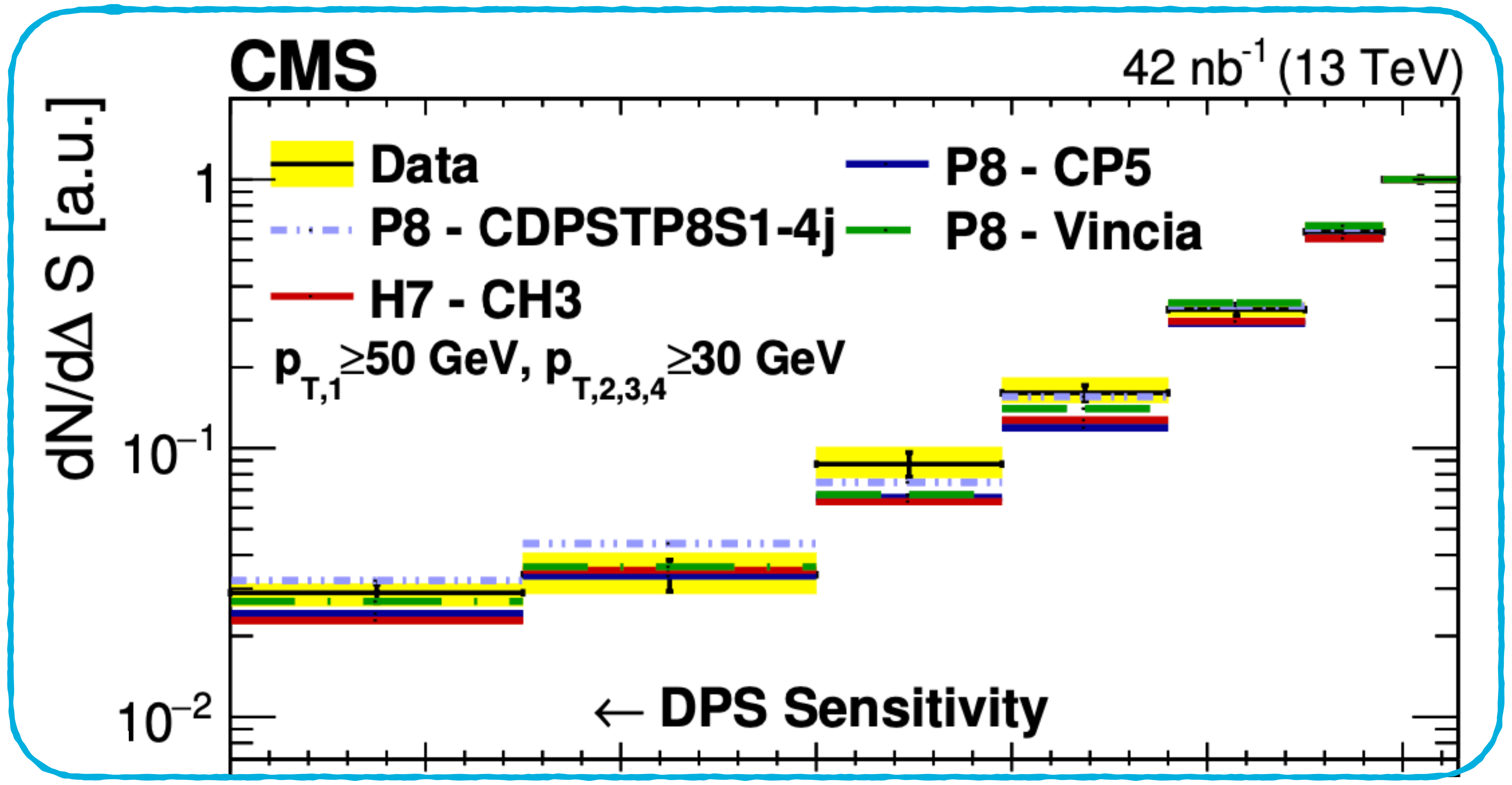
Classes of models compared:

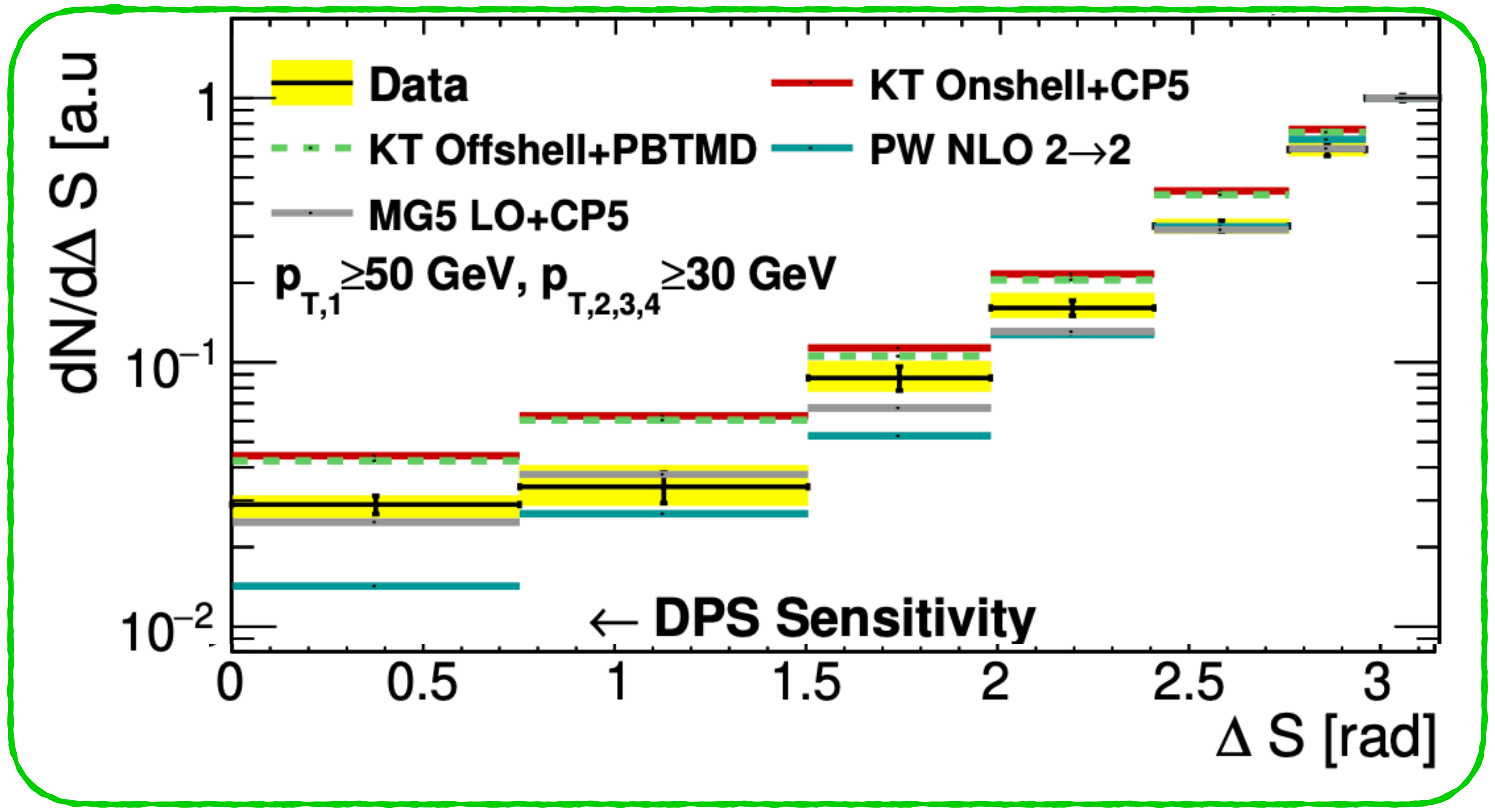
- 2→2 LO matrix elements: overestimate cross sections
- NLO multijet models: closer to measured cross sections

ΔS ➧ azimuth angular difference between harder and softer jet pairs (peaks at π for SPS balanced jets, small values for DPS)

$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}|\ |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right)$$

ΔS is not sensitive to parton shower implementation





DPS in 4-jets at low p_T

CMS, JHEP 01 (2022) 177

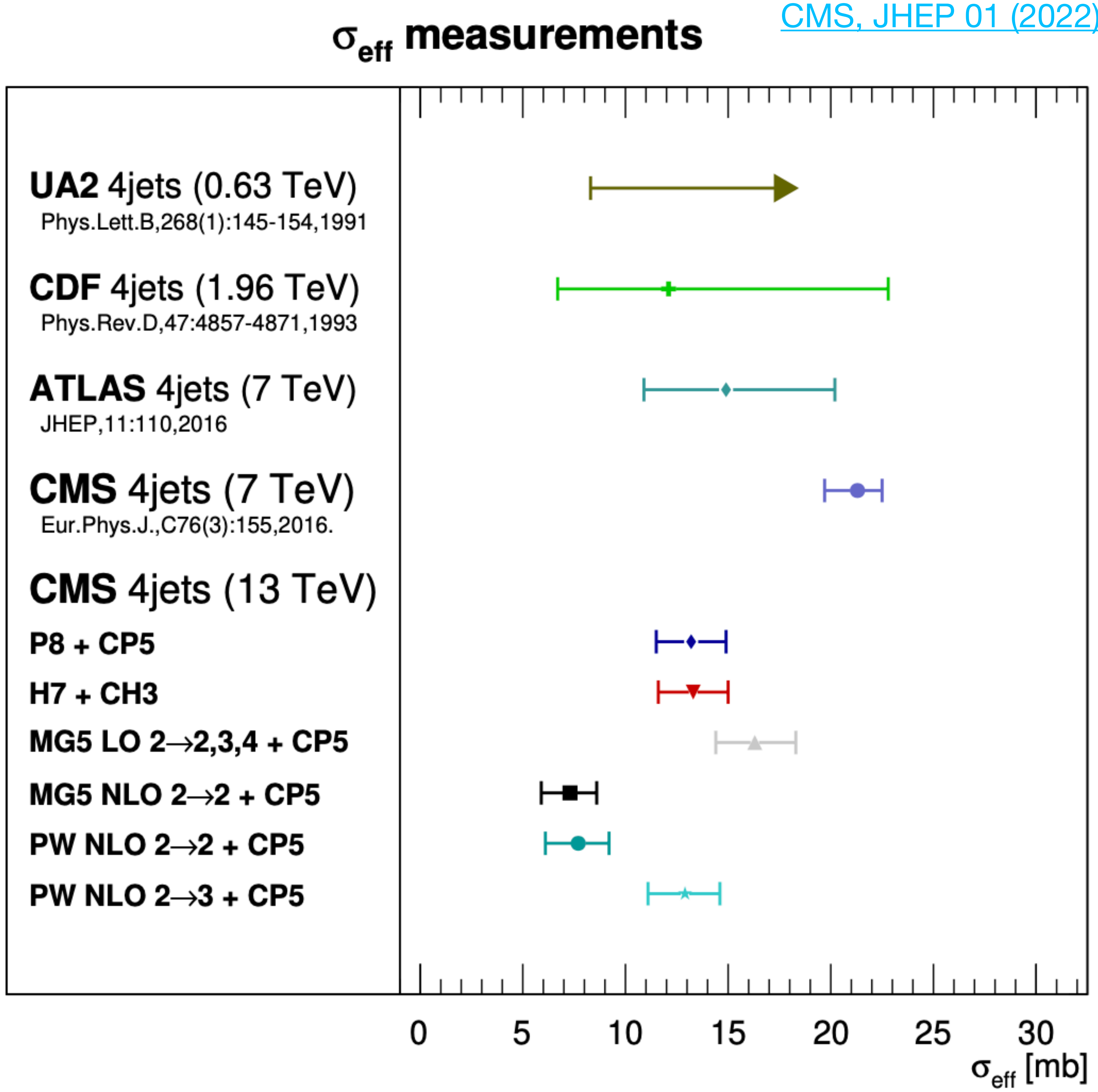
Extraction of effective cross section
➧ large model dependence

σ_{eff} = 7.7 - 34.8 mb

higher order   LO 2→2

➧ models based on NLO matrix elements give the smallest σ_{eff} values ➧ larger DPS contribution

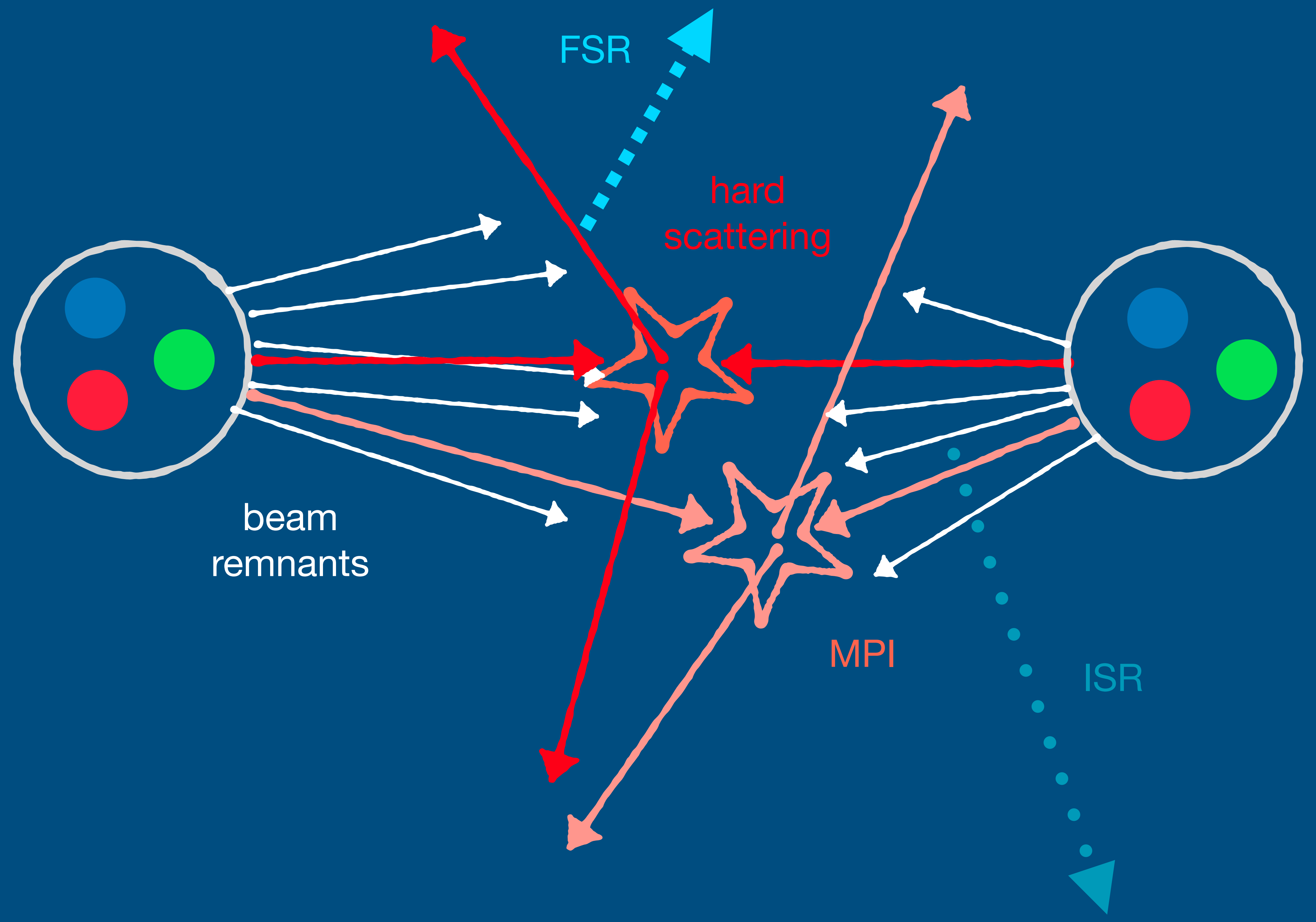
➧ further model development needed



Other DPS measurements at $\sqrt{s}$ = 13 TeV:

$\sigma_{eff} = 12.7^{+5.0}_{-2.9}$ mb from same sign WW   CMS, Eur. Phys. J. C 80, 41 (2020)   A. Metha, Plenary IV

σ_{eff} = 7.3 ± 0.5 (stat) ± 1.0 (syst) mb from J/ψ pair   LHCb, JHEP 2017, 47 (2017)



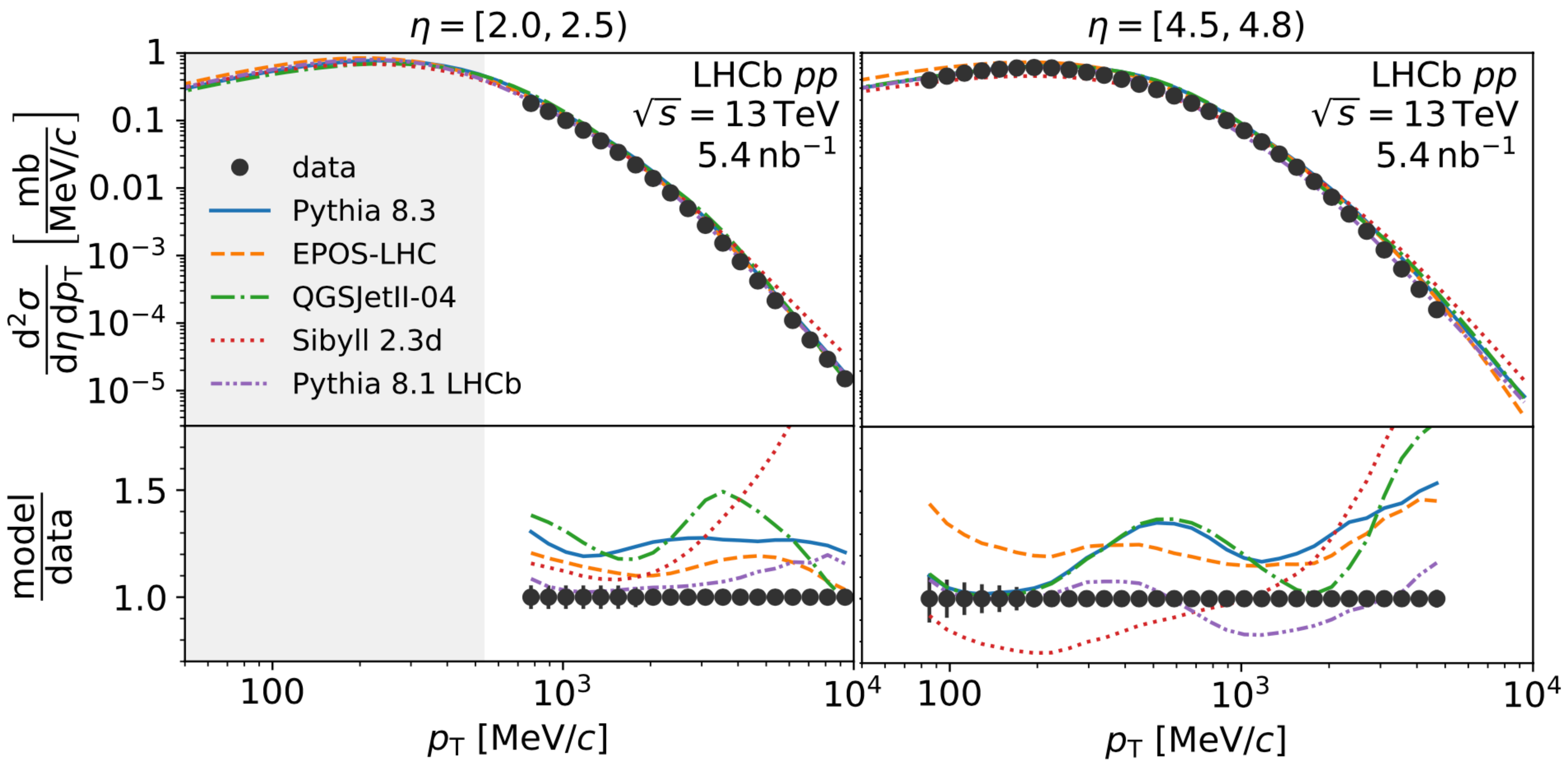
MB event

Bulk particle production

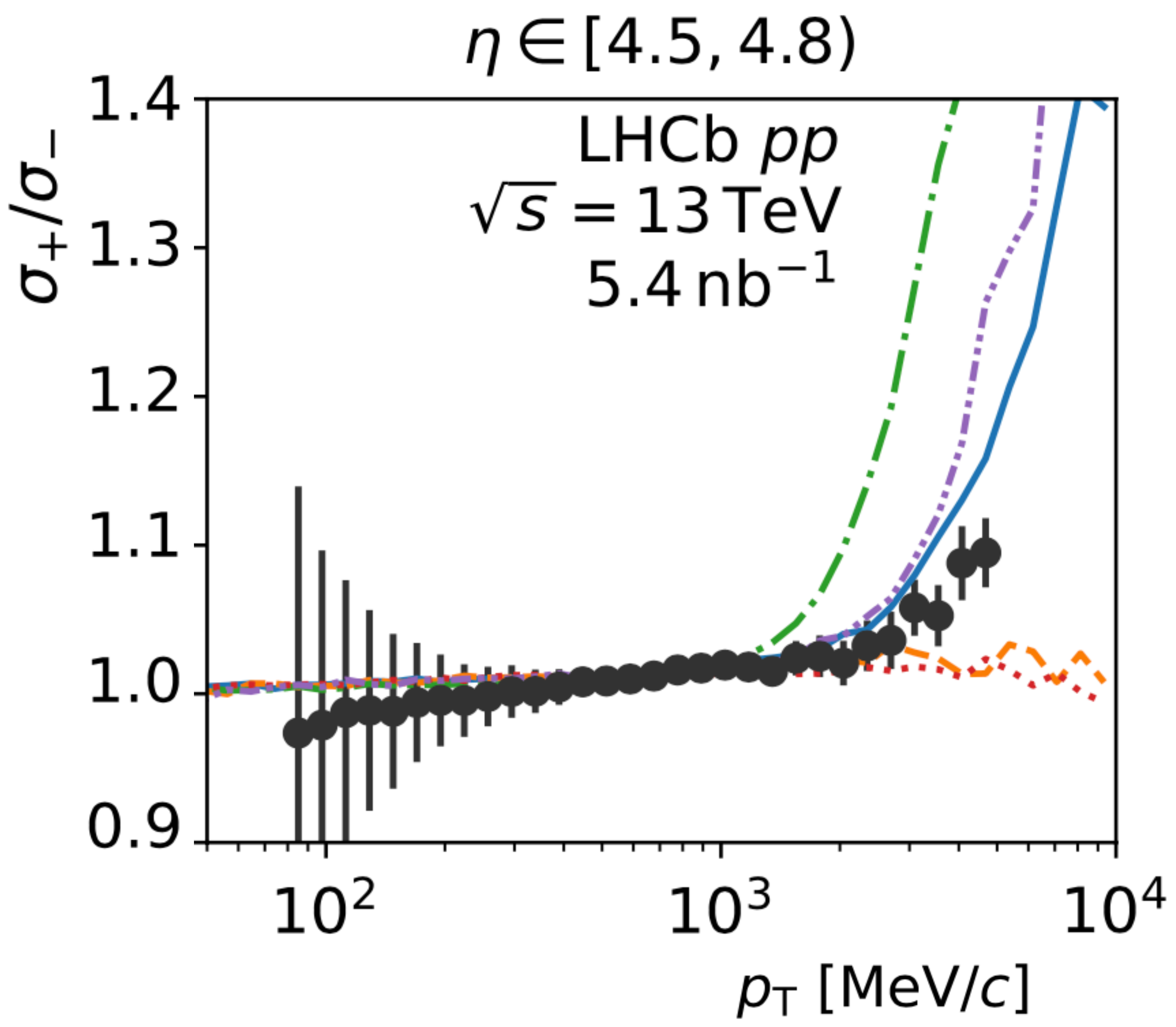
Particle production in pp collisions

LHCb, JHEP 01 (2022) 166

Double differential cross section of inclusive production of prompt charged particles



Ratio positive to negative



Models mostly overestimate the differential cross sections at forward η

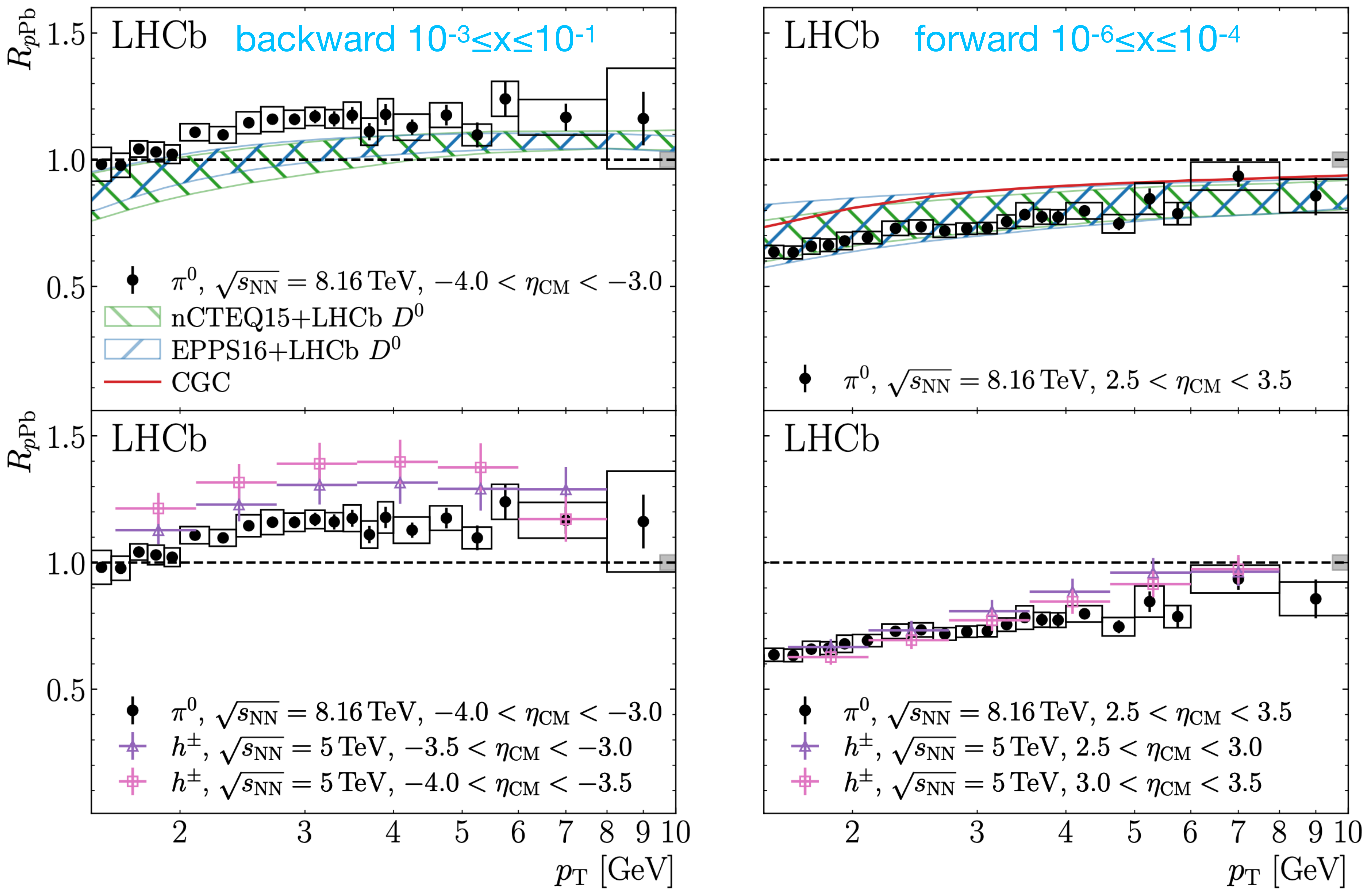
Ratio increase at large η and high p_T not described by models

High precision measurement ➧ valuable input for simulation of UE and cosmic air showers

Nuclear modifications in p-Pb collisions

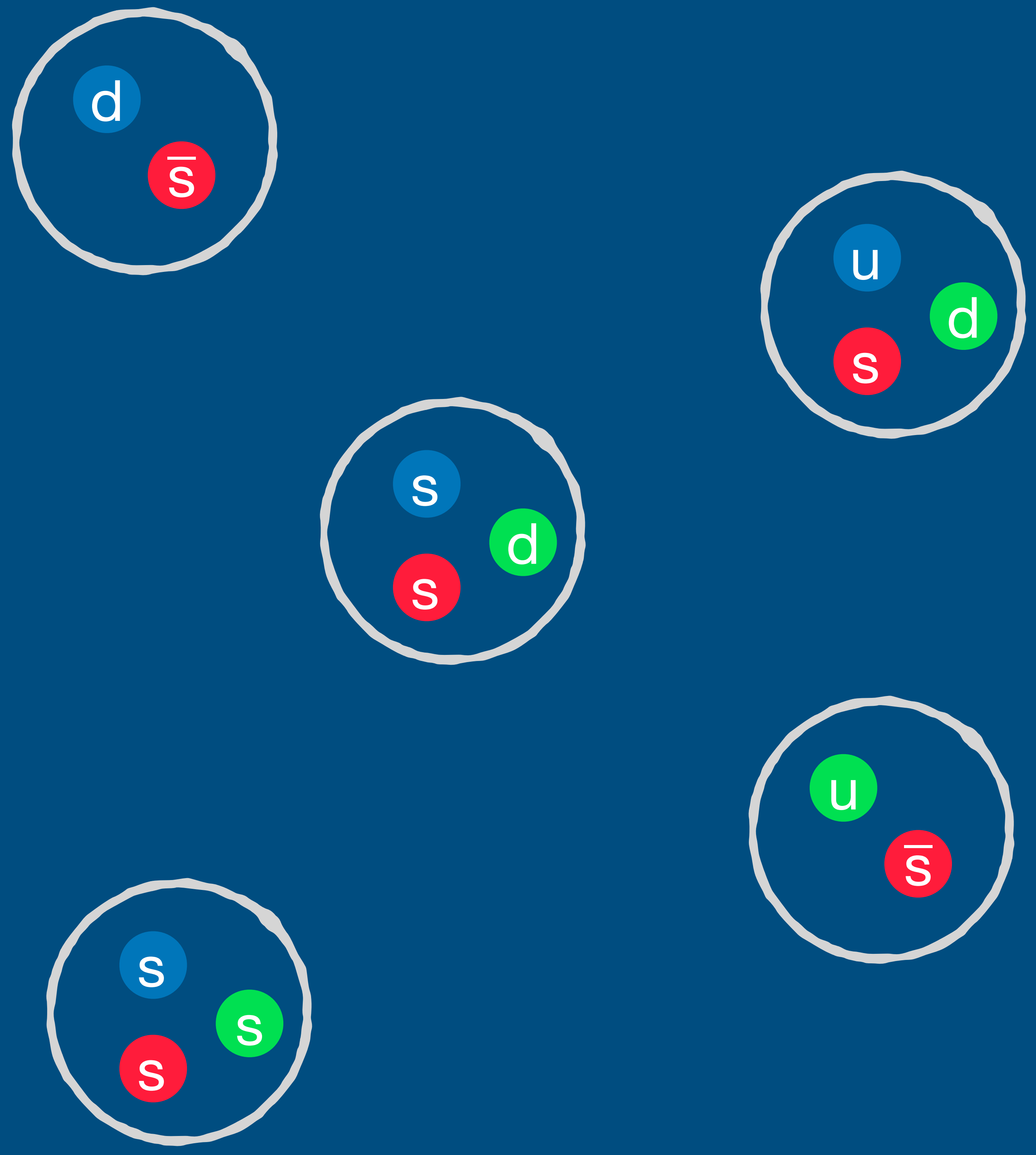
LHCb, arXiv:2108.13115

Nuclear modification factor R_{pPb} for π^0 is sensitive to nPDF and parton saturation in the initial state



$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \cdot d\sigma_{pp}/dp_T}$$

- suppression of π^0 production in forward region is consistent with nPDF, but larger than CGC calculations
- enhancement in backward region larger than nPDF predictions
- constraints for nPDFs and saturation models in low-x region



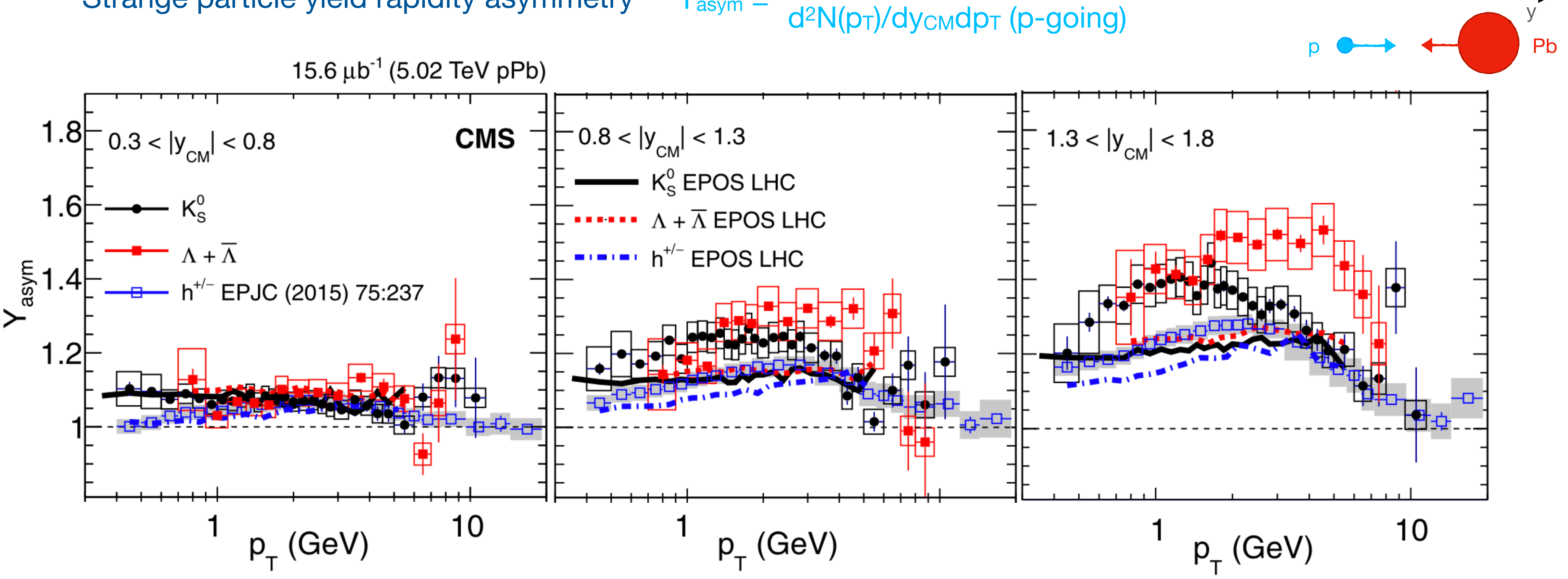
Strangeness production

Strangeness enhancement in high multiplicity pp collisions

Strange hadron production in p-Pb collisions

CMS, Phys. Rev. C 101, 064906

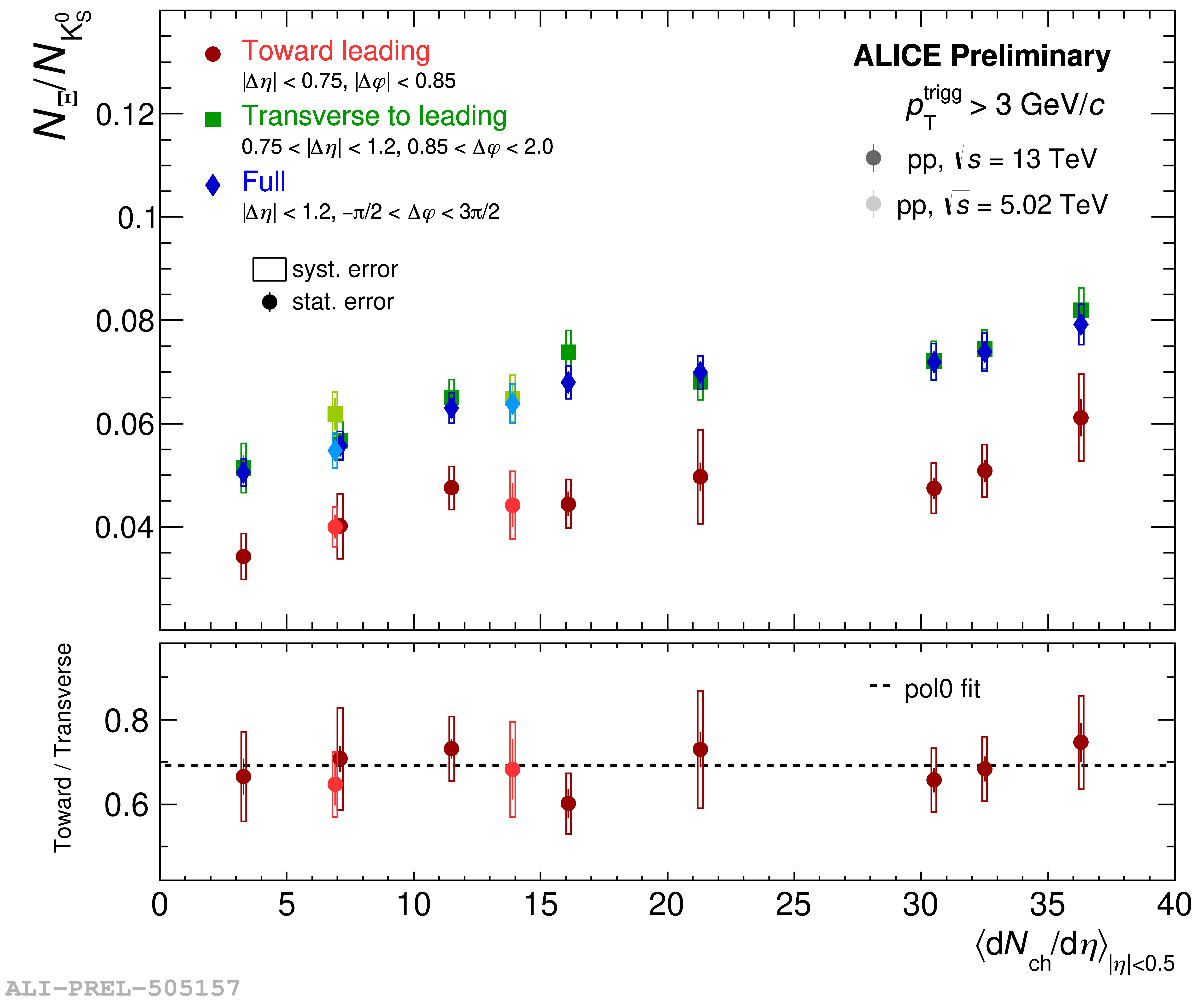
Strange particle yield rapidity asymmetry $Y_{asym} = \frac{d^2N(p_T)/dy_{CM}dp_T \text{ (Pb-going)}}{d^2N(p_T)/dy_{CM}dp_T \text{ (p-going)}}$

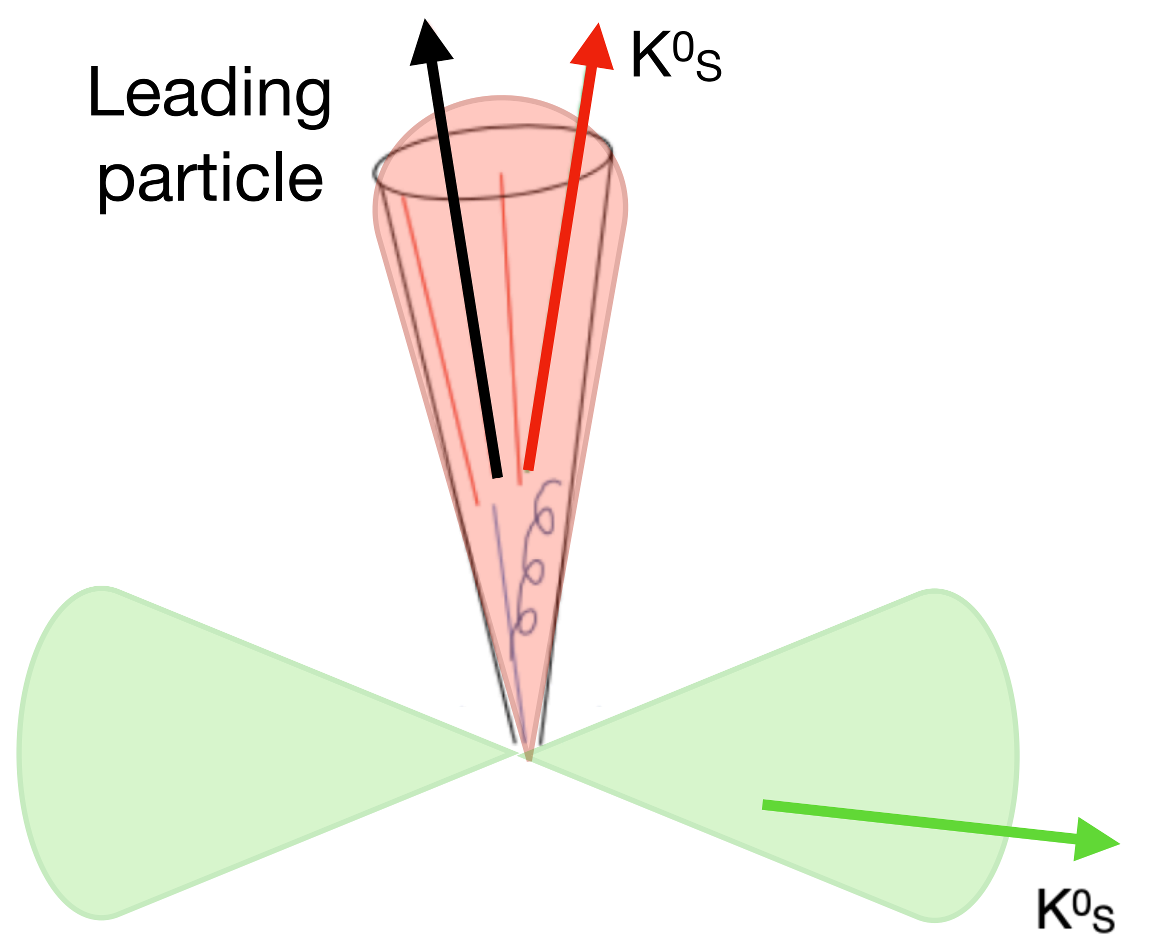


- strange hadrons show larger asymmetry values than charged particles at forward rapidities
- not reproduced by EPOS LHC model

Angular correlation of strangeness production

Strangeness production in regions toward and transverse to leading particle could provide insight into production mechanism ➧ soft vs. hard production





➧ strangeness production mainly comes from transverse to high p_T particle (soft production)

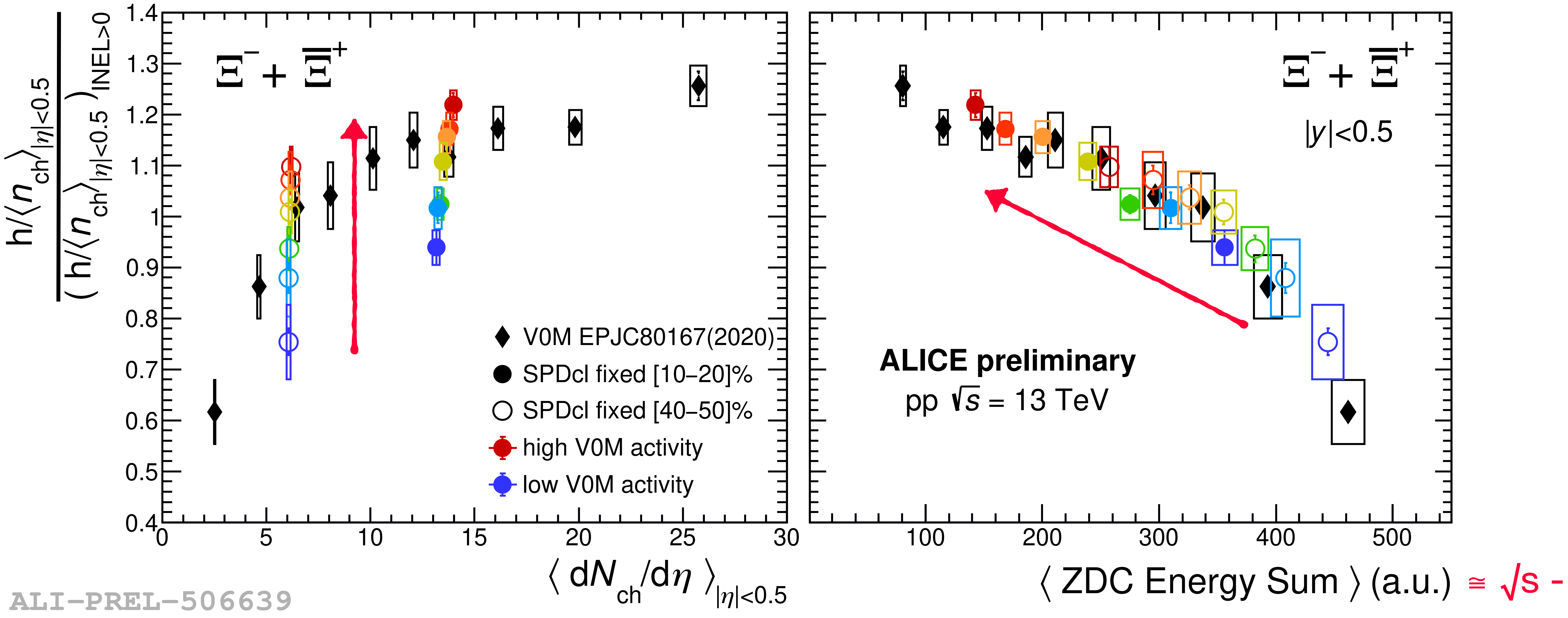
➧ BUT toward/transverse yield is flat as a function of multiplicity

➧ no different evolution vs. multiplicity in the 2 regions

Strangeness production vs. effective energy

Origin of strangeness enhancement in small systems

➧ study of (multi) strange baryon production vs. multiplicity and effective energy $E_{eff} \cong \sqrt{s} - E_{ZDC}$

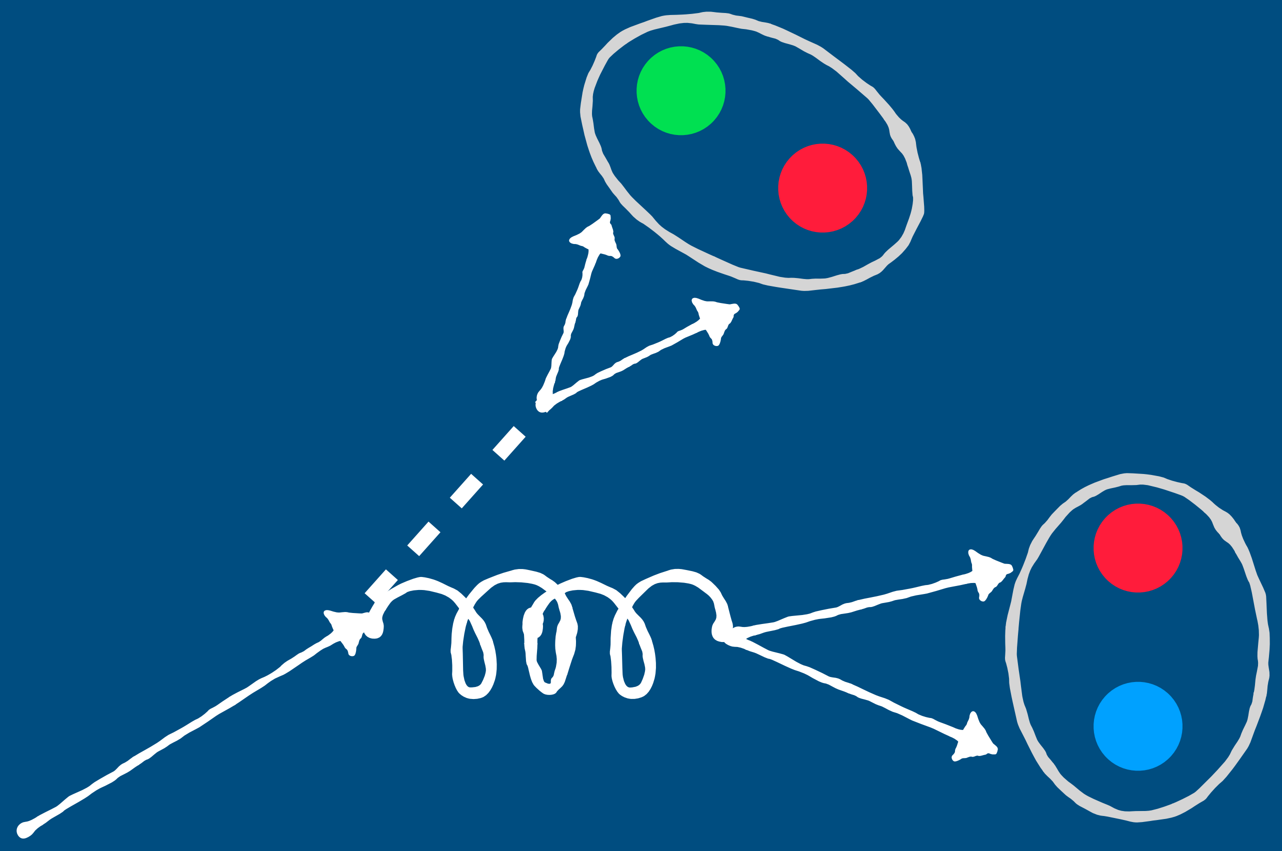


$\cong \sqrt{s} - E_{eff}$

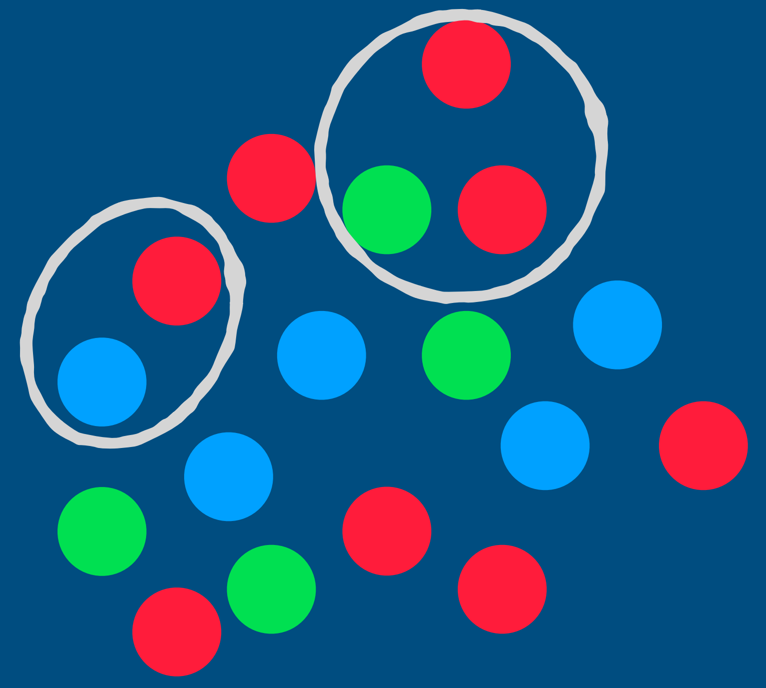
= Increasing effective energy

➧ strange over charged particles baryon production increases with forward event activity at fixed multiplicity but also with increasing effective energy

➧ initial stages play a role in strangeness enhancement



Hadronization

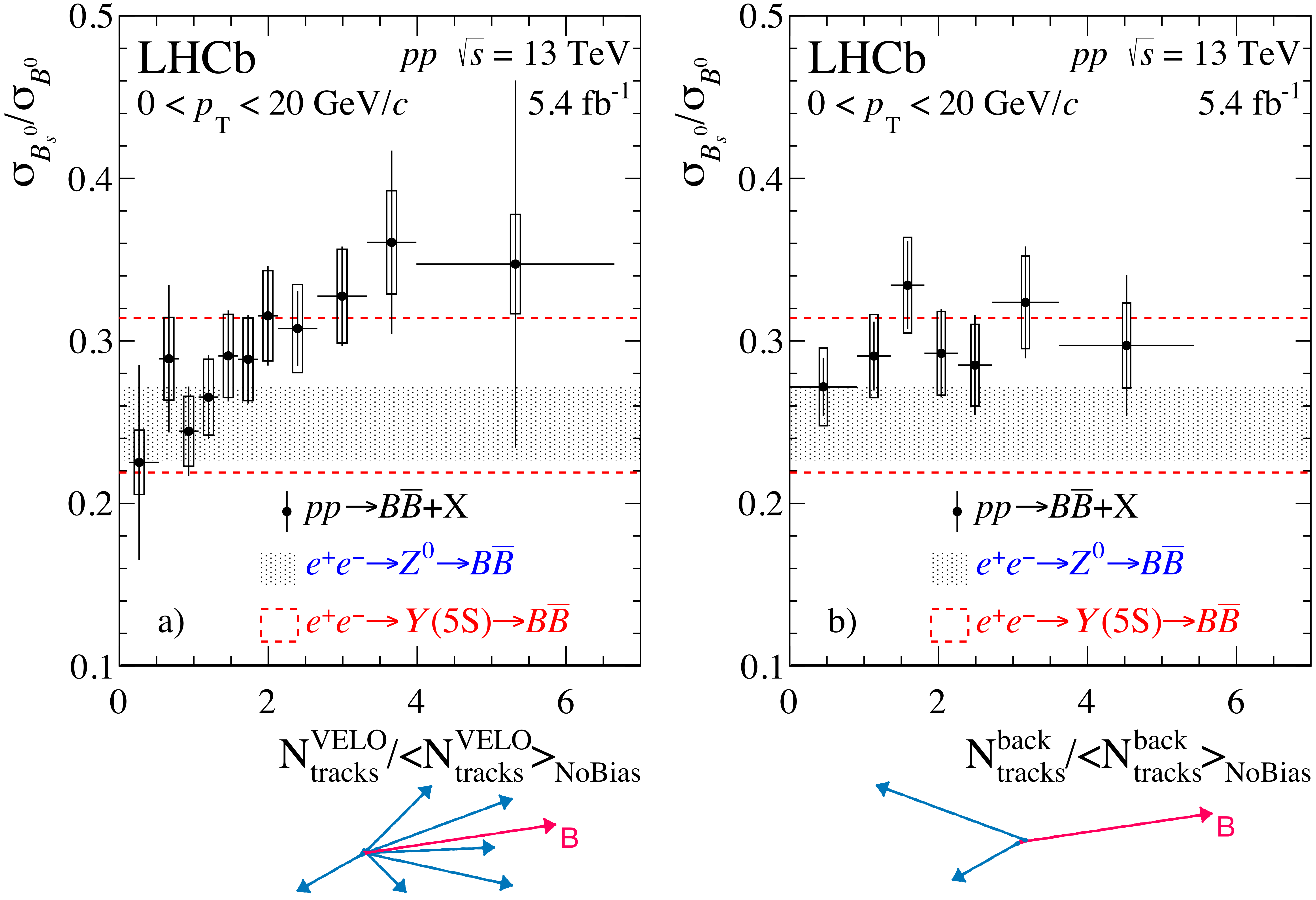


Universality of fragmentation,
quark coalescence

b quark hadronization

LHCb, arxiv: 2204.13042

B_s^0/B^0 meson production to address hadronization (fragmentation vs. coalescence) and b quark paring with strange or light quarks



➧ increase at high multiplicity and low p_T, in qualitative agreement with expectations from coalescence as additional hadronization mechanism

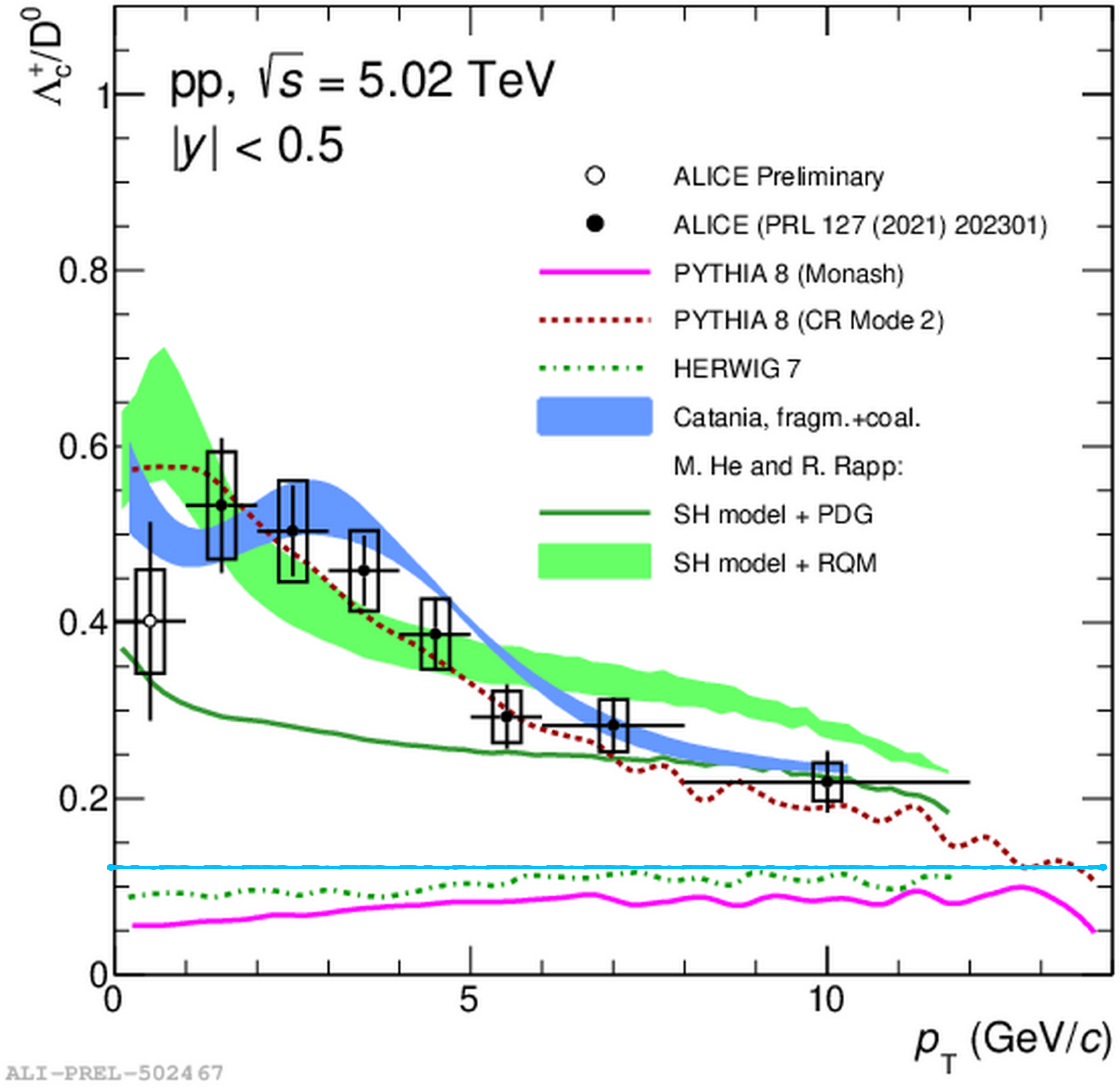
➧ BUT no enhancement as a function of backward N_{tracks} ➧ dependence on local particle density

➧ indication of a possible breaking of b quark factorisation between e^+e^- and hadronic collisions

c quark hadronization

ALICE, PRL 127 202301

Λ_c^+/D^0 production to investigate hadronization and test universality of fragmentation functions



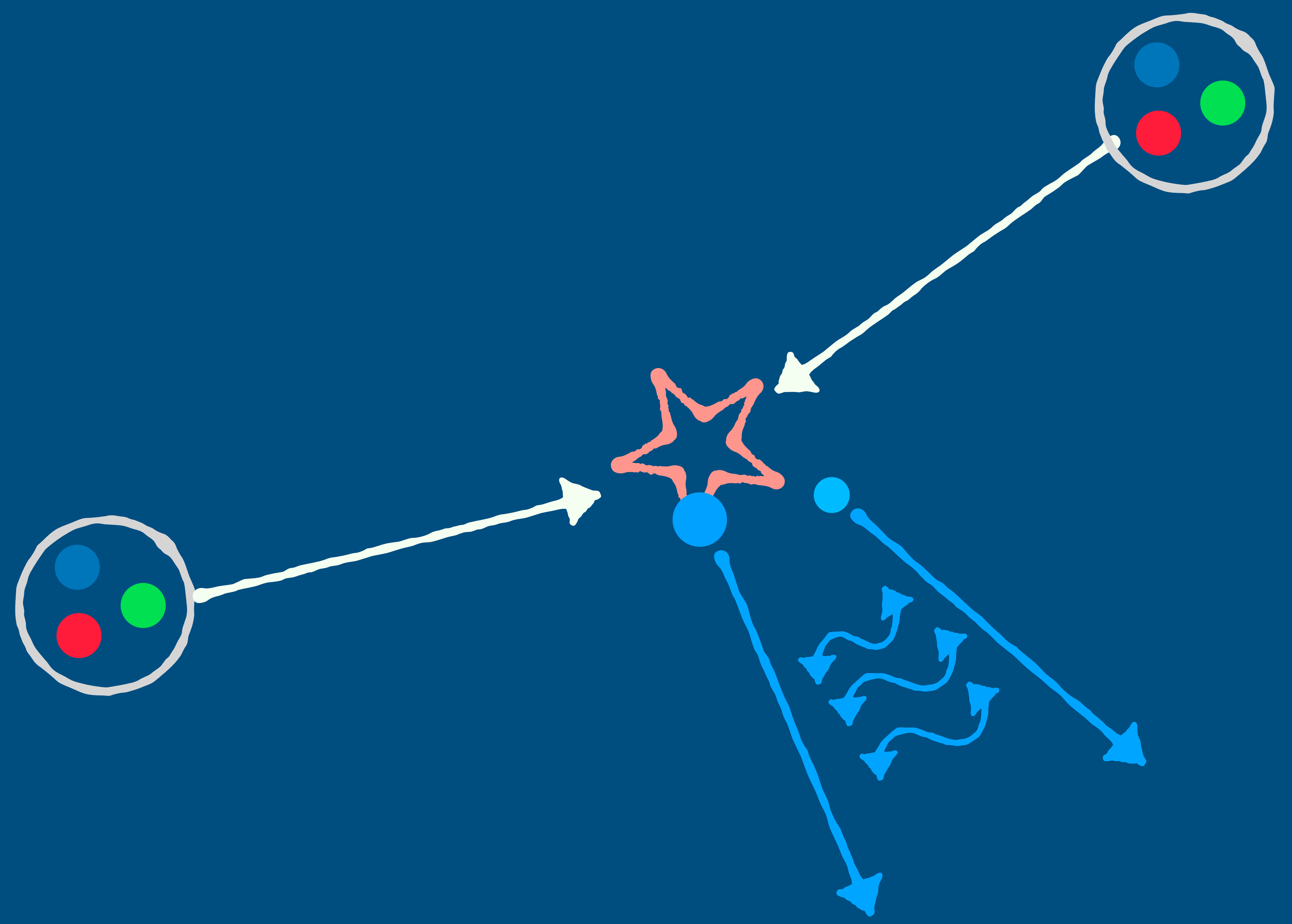
- models incorporating fragmentation parameters from e^+e^- collisions significantly underestimate the ratio and do not reproduce the observed p_T dependence

- Models able to describe the results:
  - PYTHIA including enhanced colour reconnection beyond leading order
  - Statistical Hadronization model with augmented set of high mass charm-baryon states
  - hadronization via coalescence and fragmentation

- strong indication of very different hadronization in pp relative to e^+e^-

LEP average e^+e^- [EPJC 75 (2015) 19]
➧ 0.113 ± 0.013 ± 0.006

F. Prino, Heavy ions & QCD



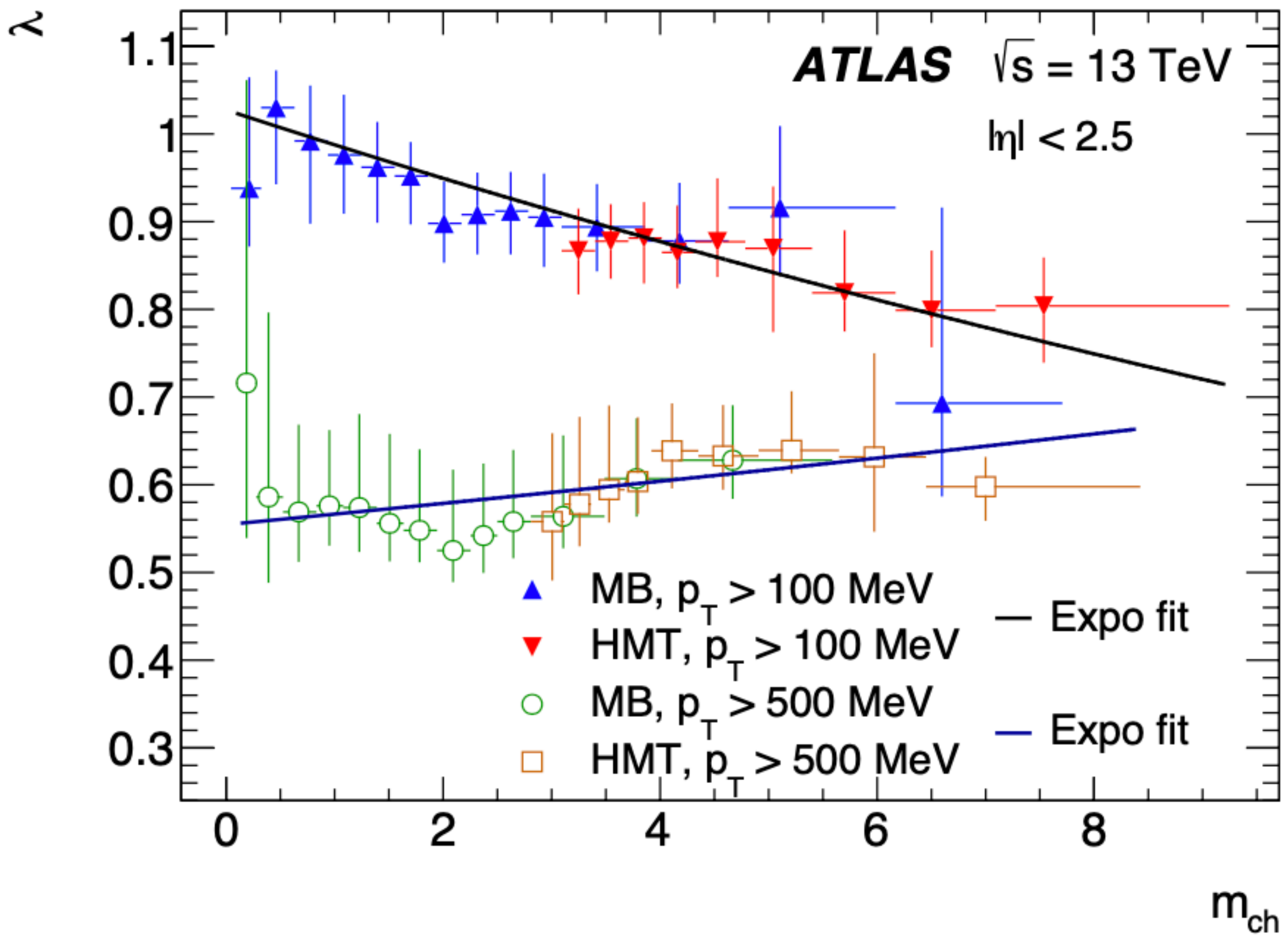
Final state interactions

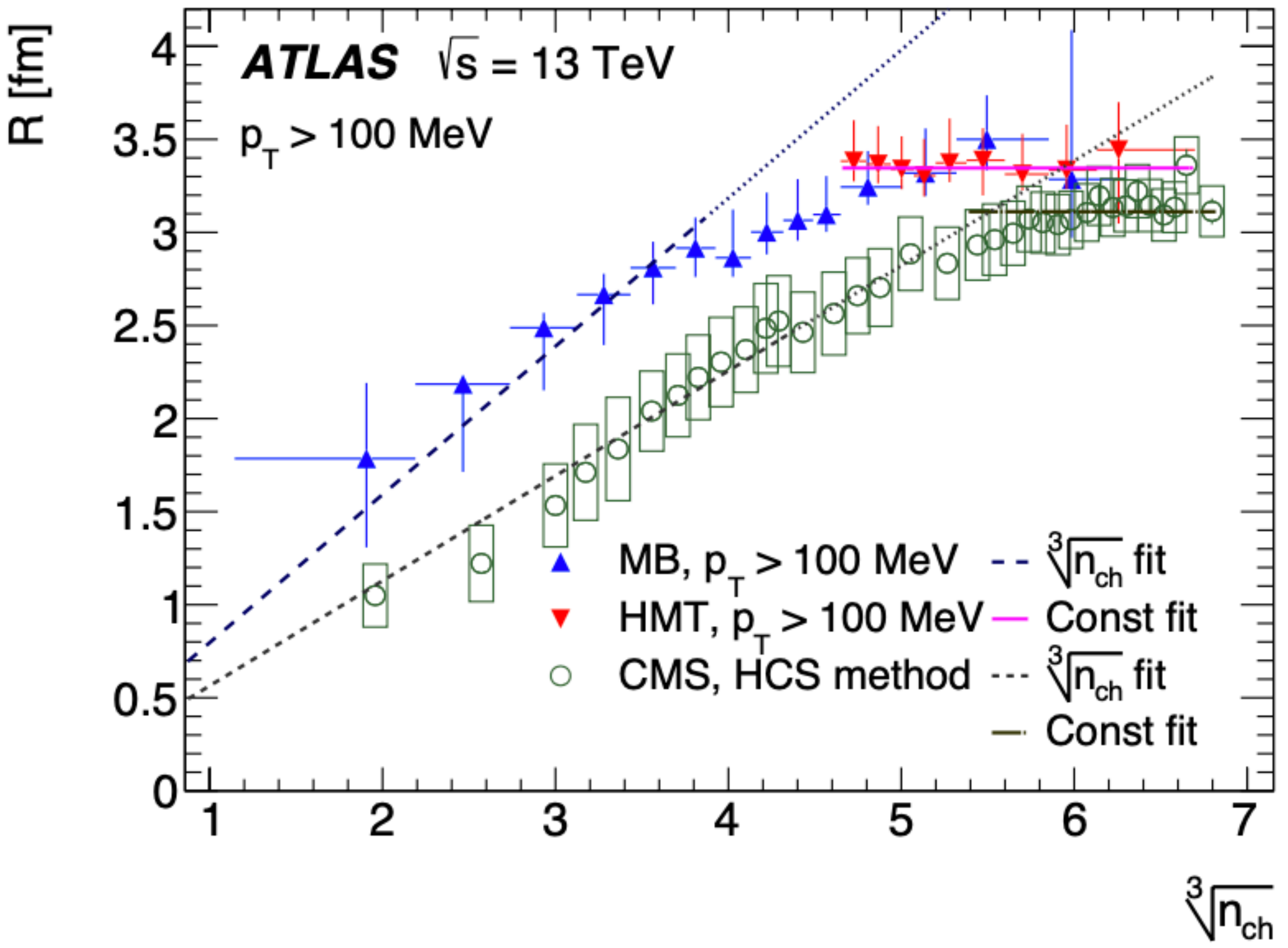
Interferometry,
correlation functions

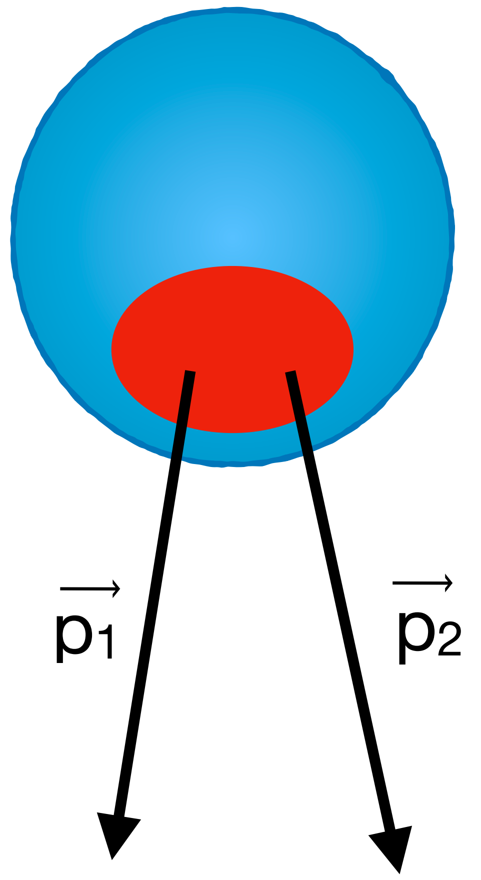
Bose-Einstein Correlations in pp collisions

ATLAS, arXiv: 2202.02218

Study final hadronic state ➧ characterisation of source emitting radius and particle correlation strength through correlation strength λ and effective radius R







λ decreases with self-normalised multiplicity for p_T>100 MeV, weak dependence for p_T>500 MeV

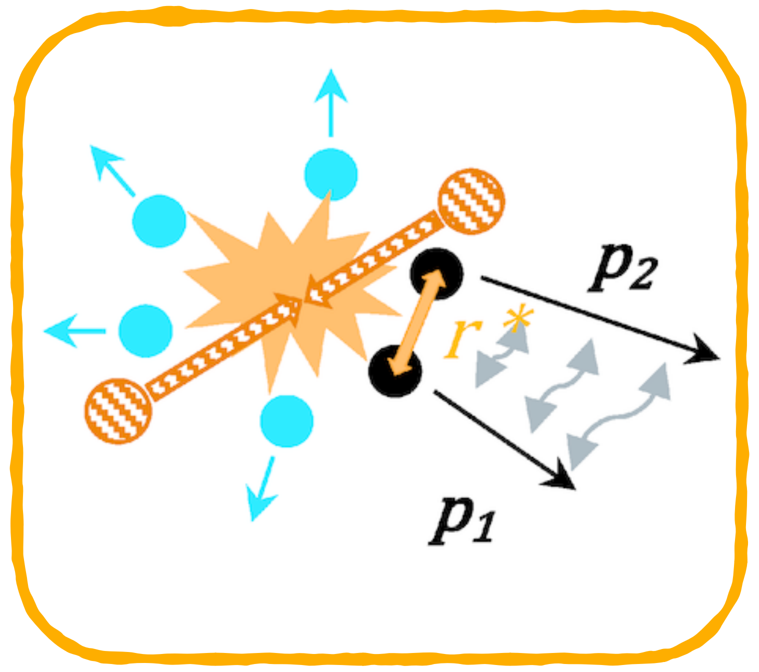
R increases with system volume (~$N_{ch}^{1/3}$) and saturates at large N_{ch}

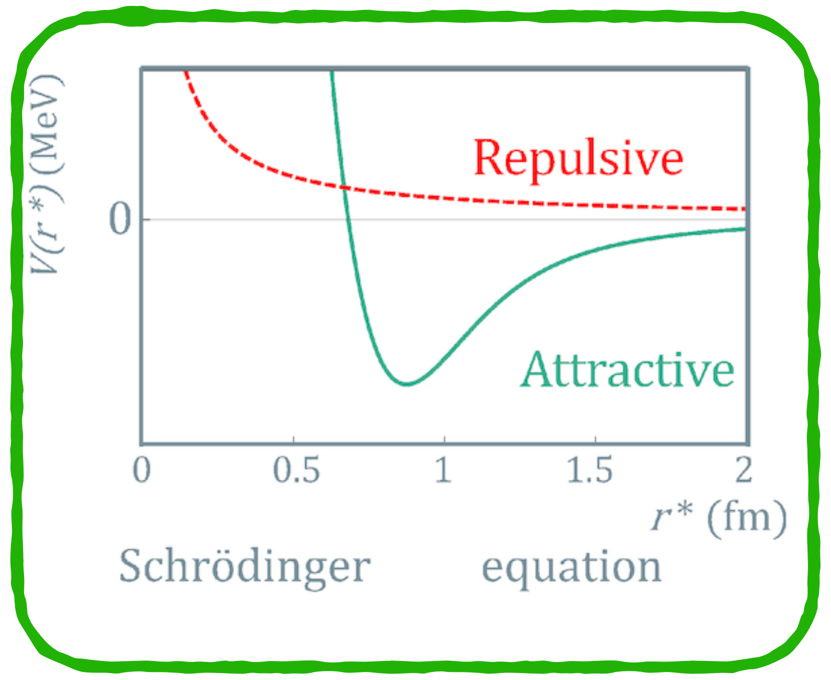
➧ indication of BE correlation at low Q^2, saturation of the emitting source radius at high multiplicity

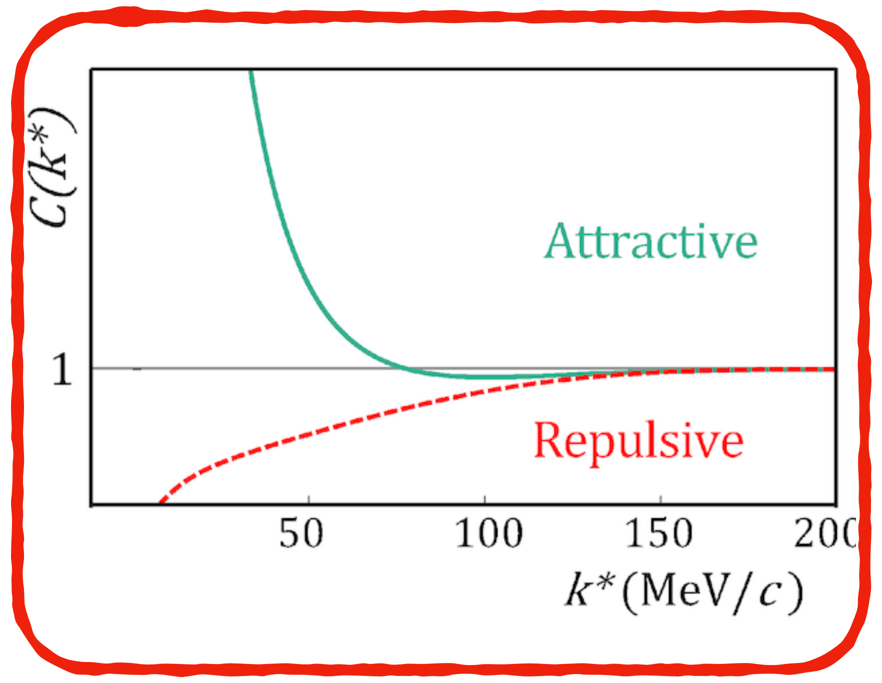
p-ϕ interaction

ALICE, PRL 127 172301

First measurement of p-ϕ interaction in pp collisions



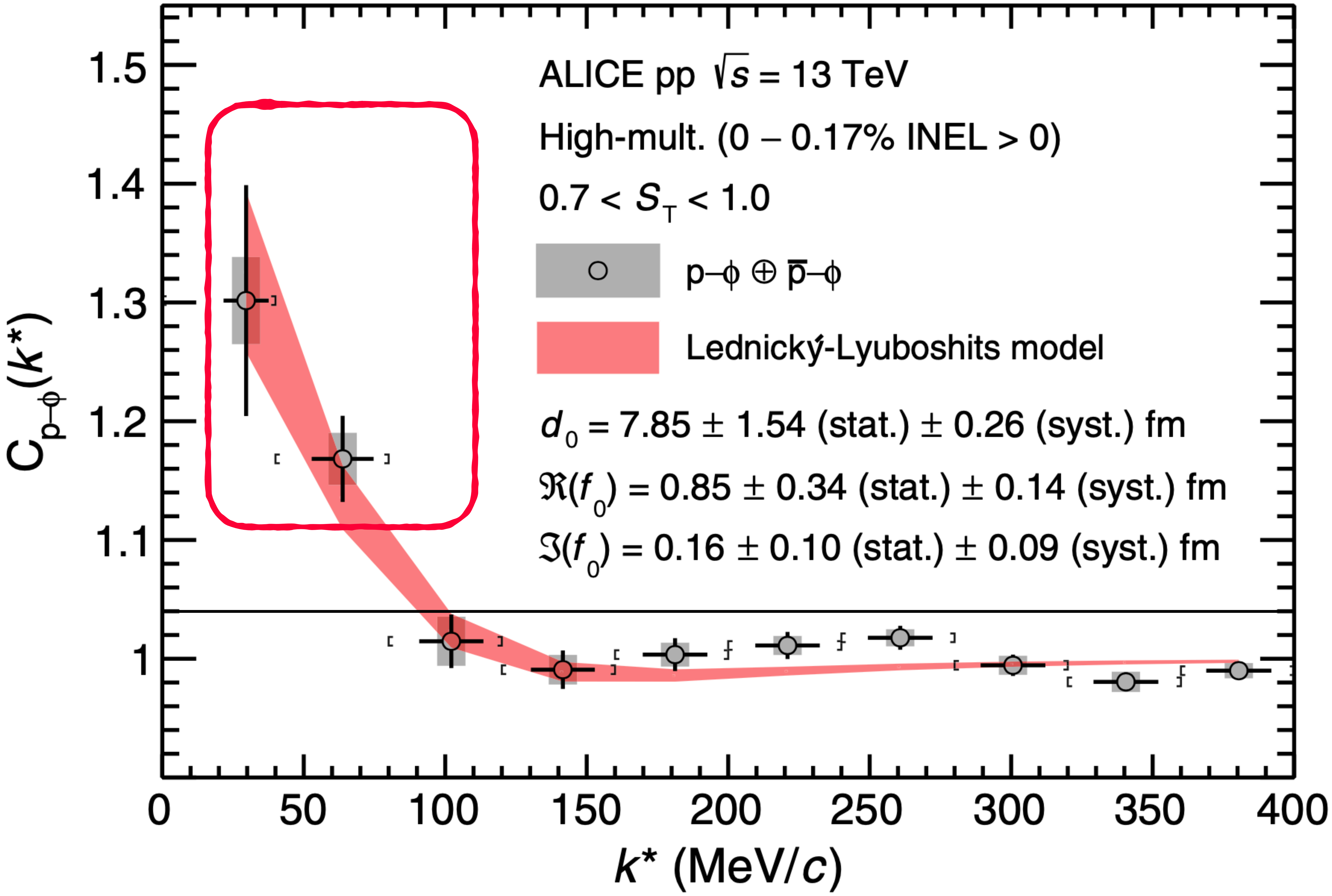




Emitting source   Interaction potential   Correlation function C(k*)

$$C(k^*) = \int S(r^*) \, |\Psi(k^*, r^*)|^2 d^3 r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

$$\vec{k}^* = \frac{\vec{p}_1 - \vec{p}_2}{2}$$



➧ The extraction of scattering parameters indicates that the p–ϕ interaction in vacuum is dominated by elastic scattering

➧ attractive nature of p-ϕ interaction

Wrap up

Many differential and precise measurement at LHC:

- shed light on soft particle production
- provide input and constraints for theoretical models
- need for further improvement of existing modelling
  (charged particle production, UE, MPI, DPS, hadronization mechanisms)

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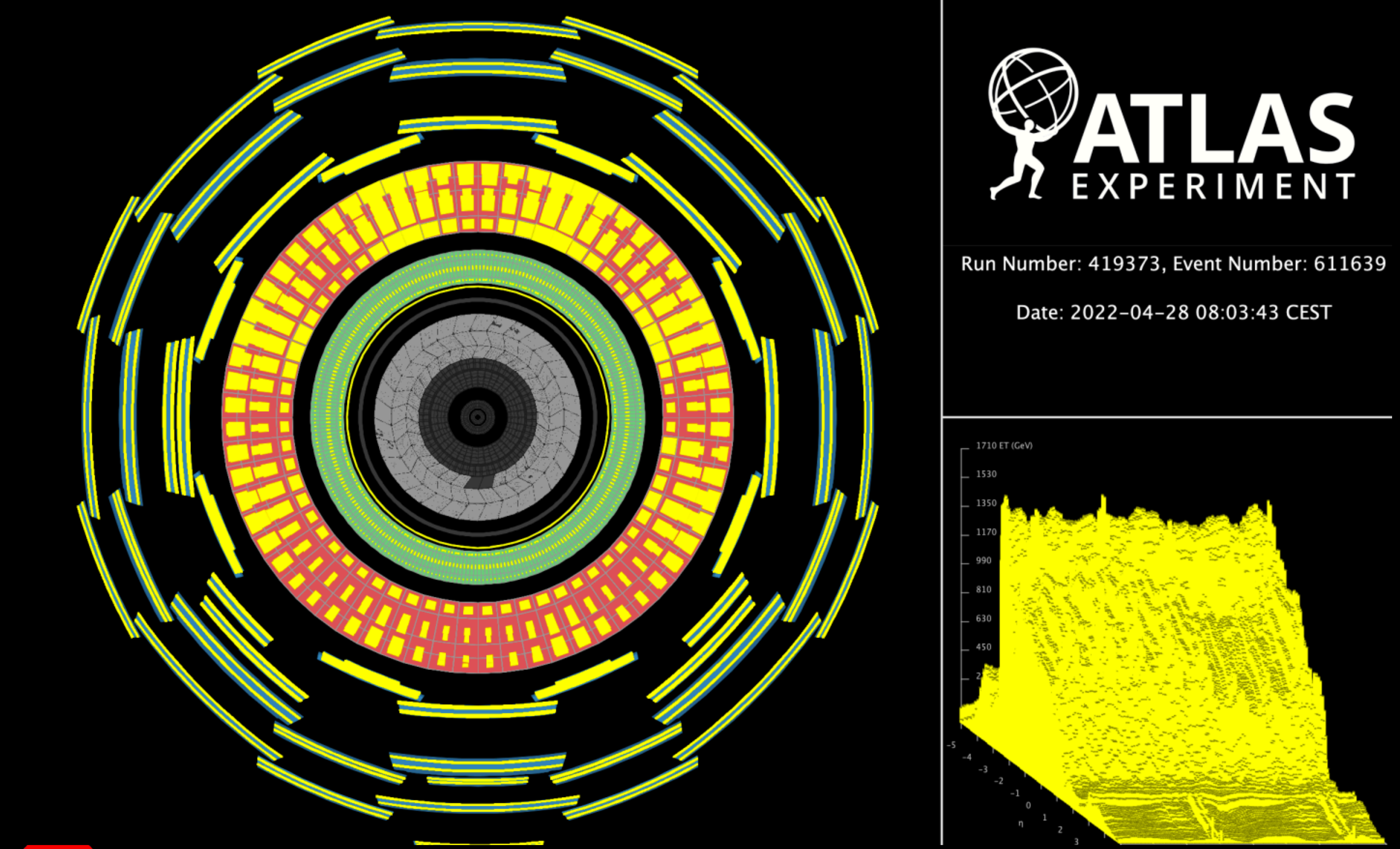
Still many intriguing open questions…

Ready for new data!



ATLAS
EXPERIMENT
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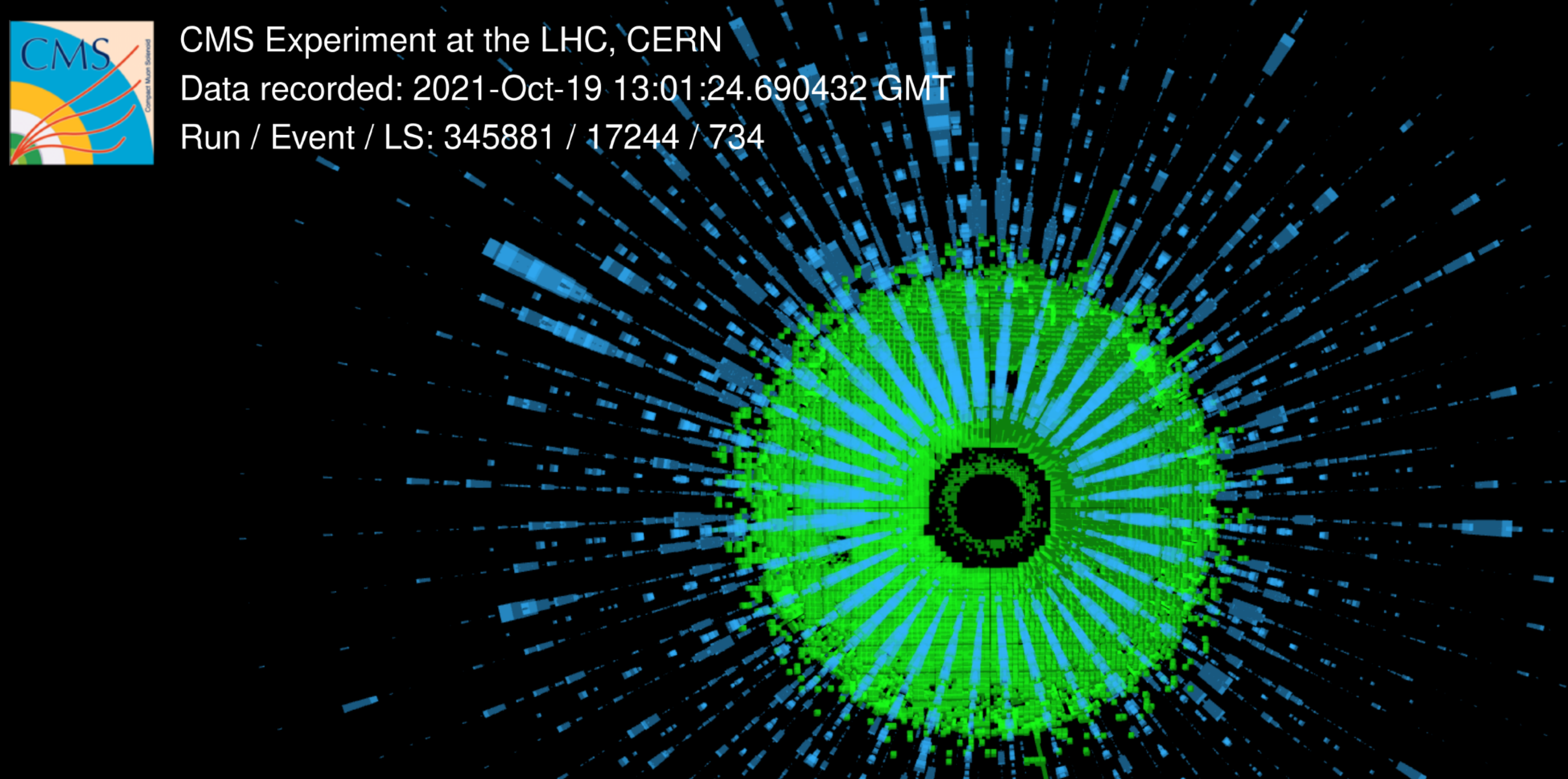
Date: 2022-04-28 08:03:43 CEST



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CMS Experiment at the LHC, CERN
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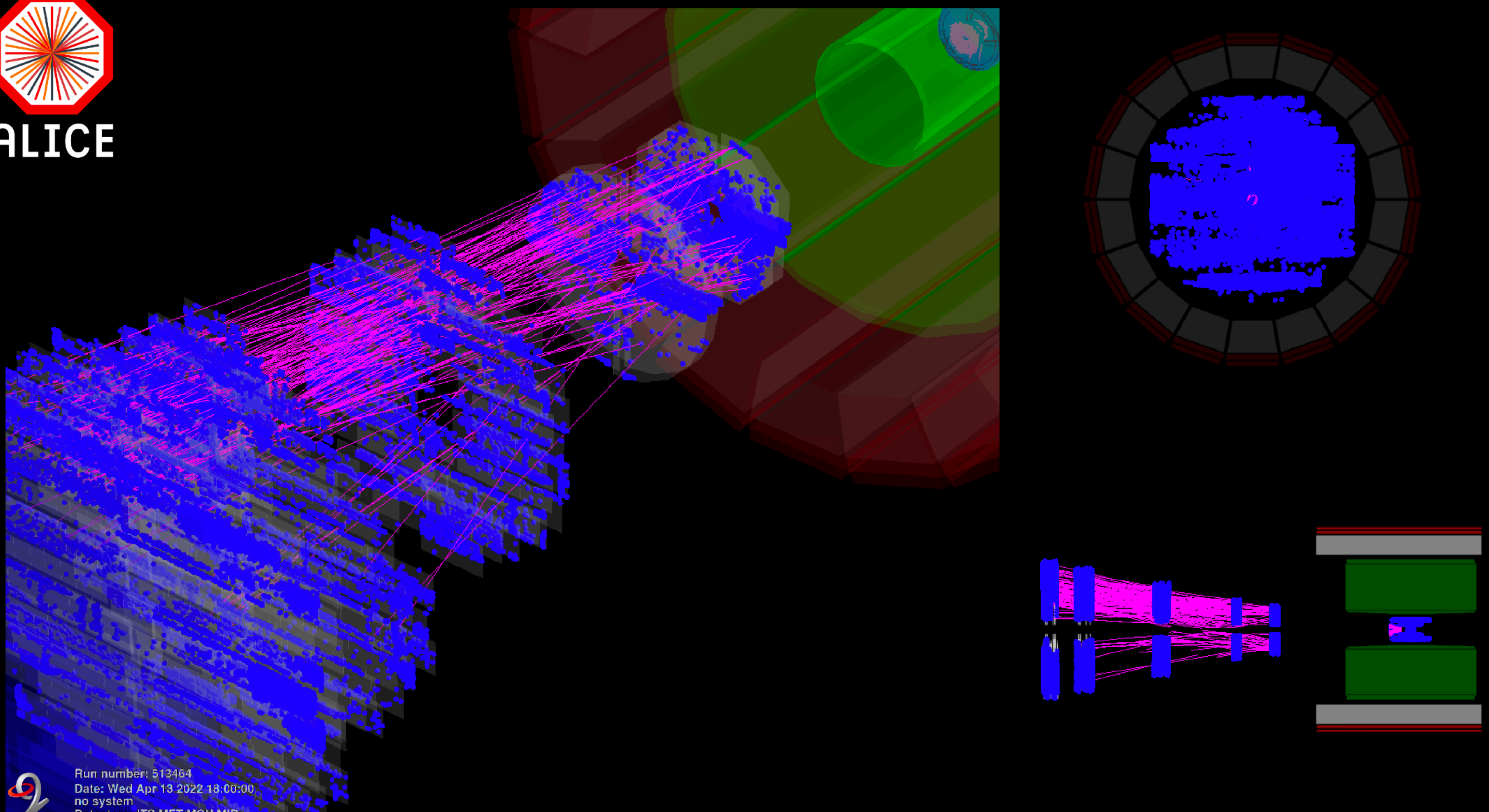
Run / Event / LS: 345881 / 17244 / 734



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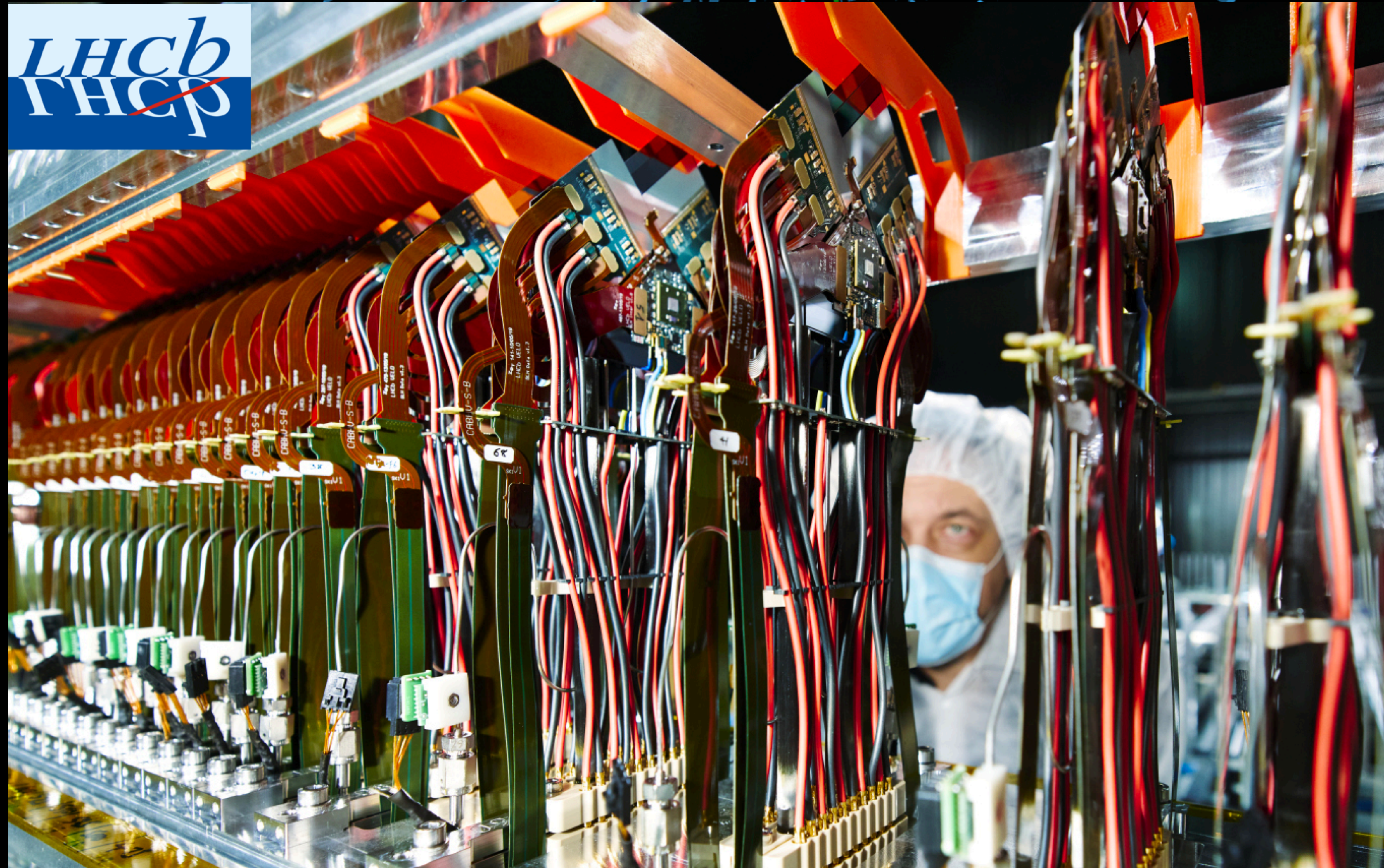

LHCb