CFNS Ad-hoc Workshop
Target fragmentation and diffraction physics with novel processes
Ultraperipheral, electron-ion, and hadron collisions

Leading protons and neutrons in pA collisions at LHC energies

C. Oppedisano

INFN Torino

CFNS Ad-hoc Workshop

Target fragmentation and diffraction physics with novel processes

Ultraperipheral, electron-ion, and hadron collisions

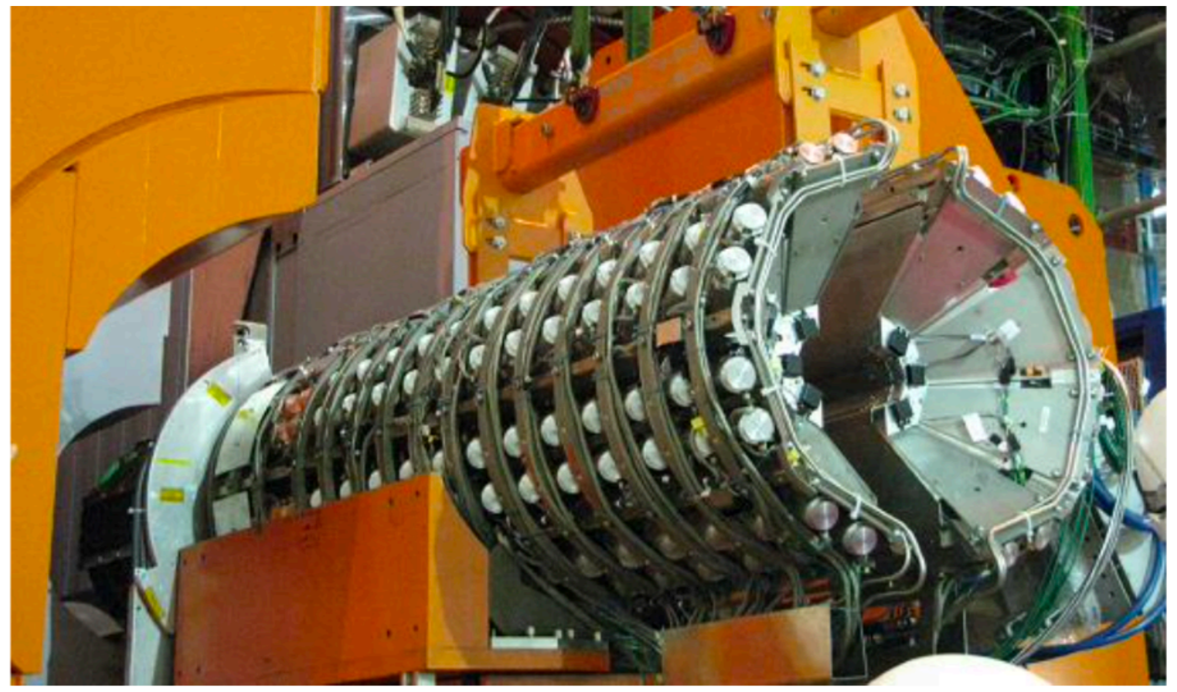
Leading protons and neutrons in pA collisions at LHC energies

pp

C. Oppedisano

INFN Torino

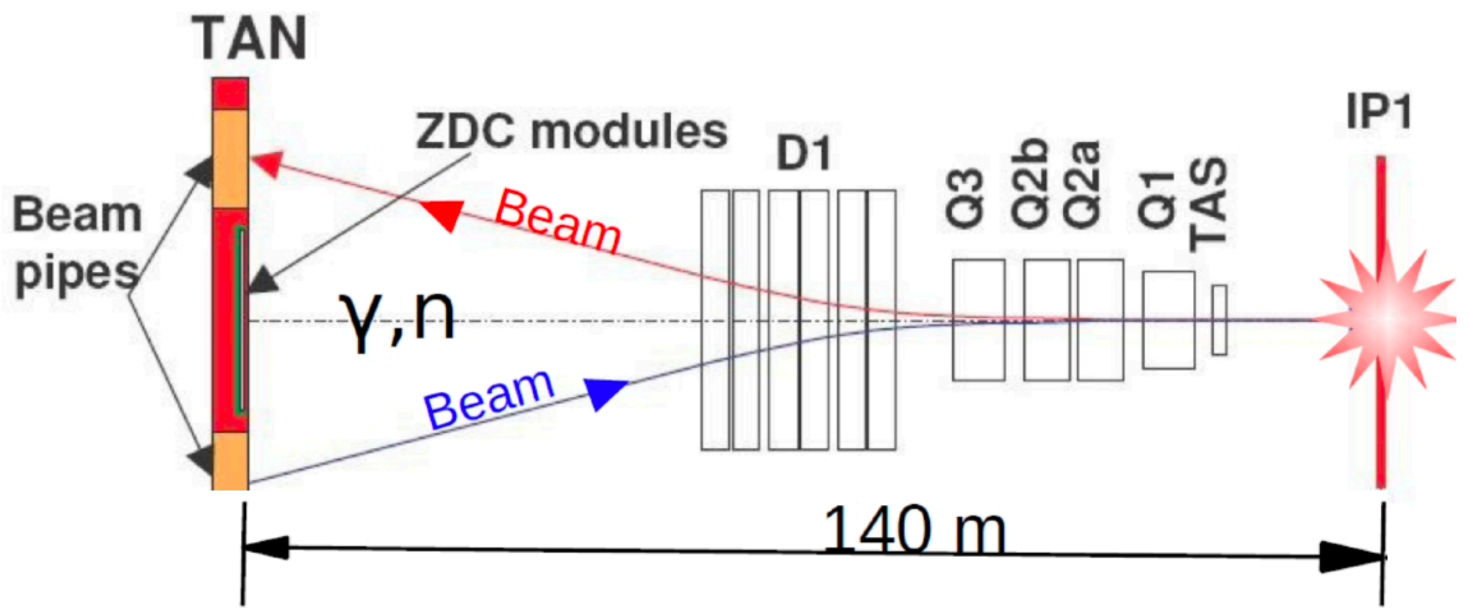
Forward detectors at LHC



CASTOR -6.6 < η < -5.2
ZDC |η| > 8.3

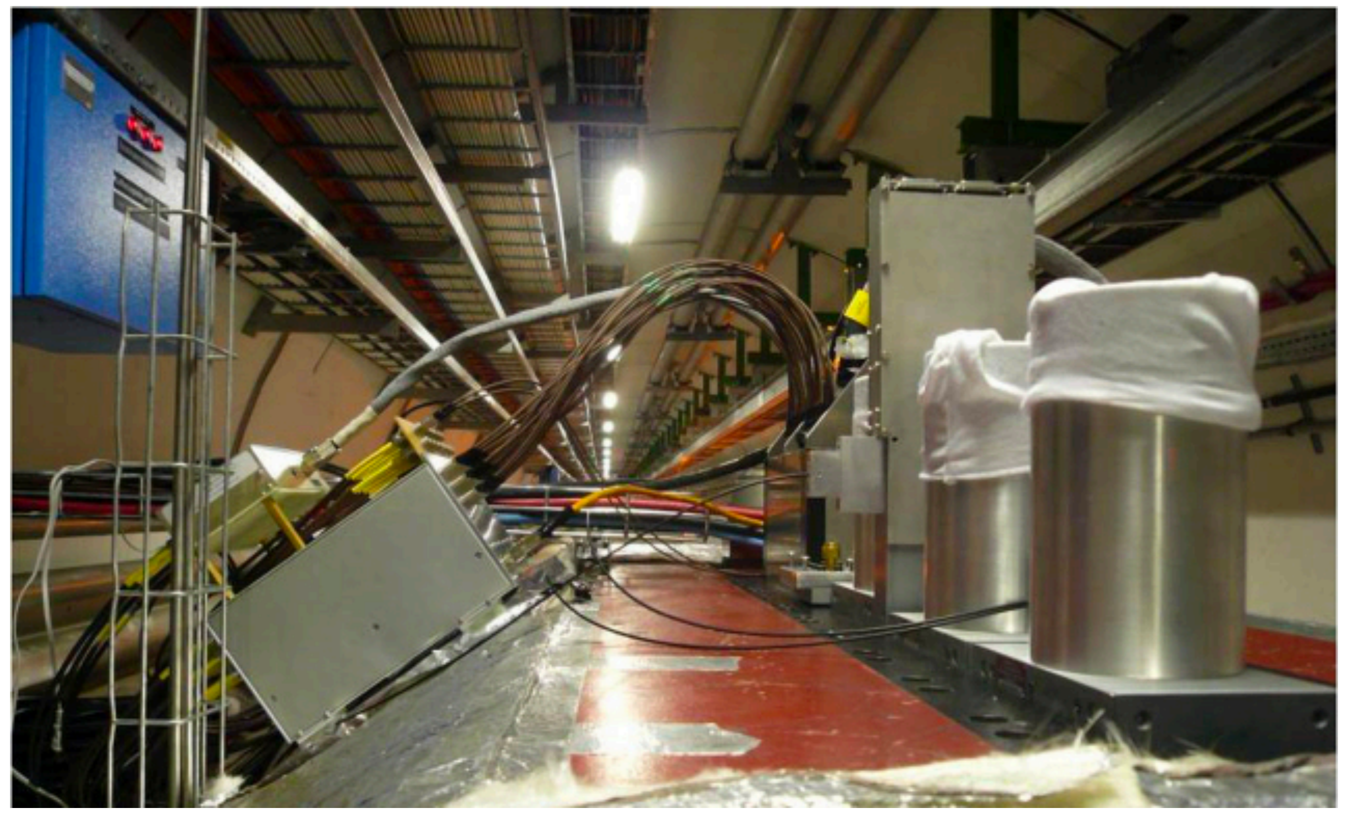
ATLAS EXPERIMENT

AFP Forward Proton Roman Pots 10.6 < |η| < 13.5
ZDC |η| > 8.3



LHCf

ZDC |η| > 8.4



ALICE

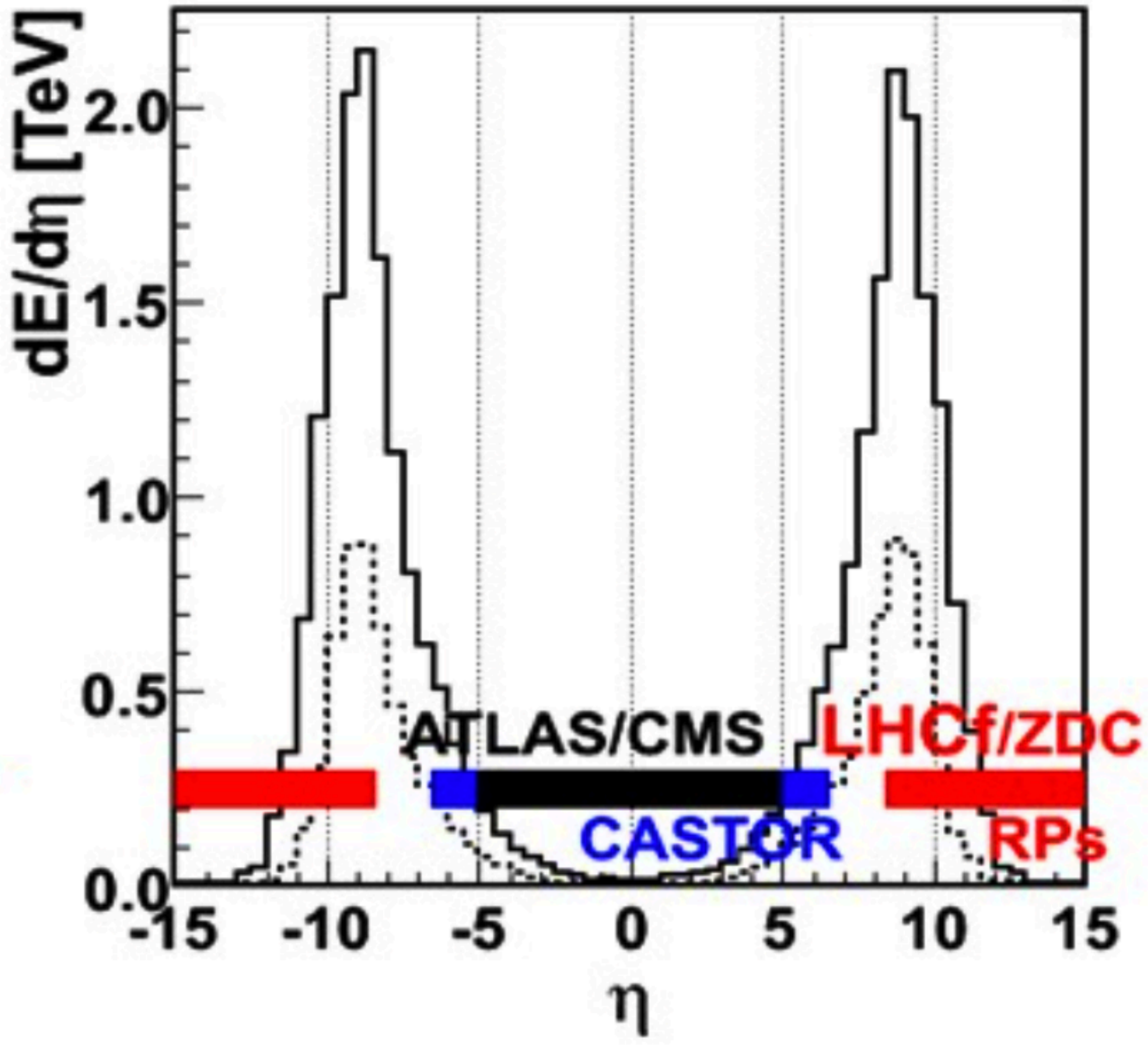
neutron ZDC |η| > 8.7
proton ZDC |η| > 6.5(*)

(*) strongly dependent on magnetic field settings

Why go forward?

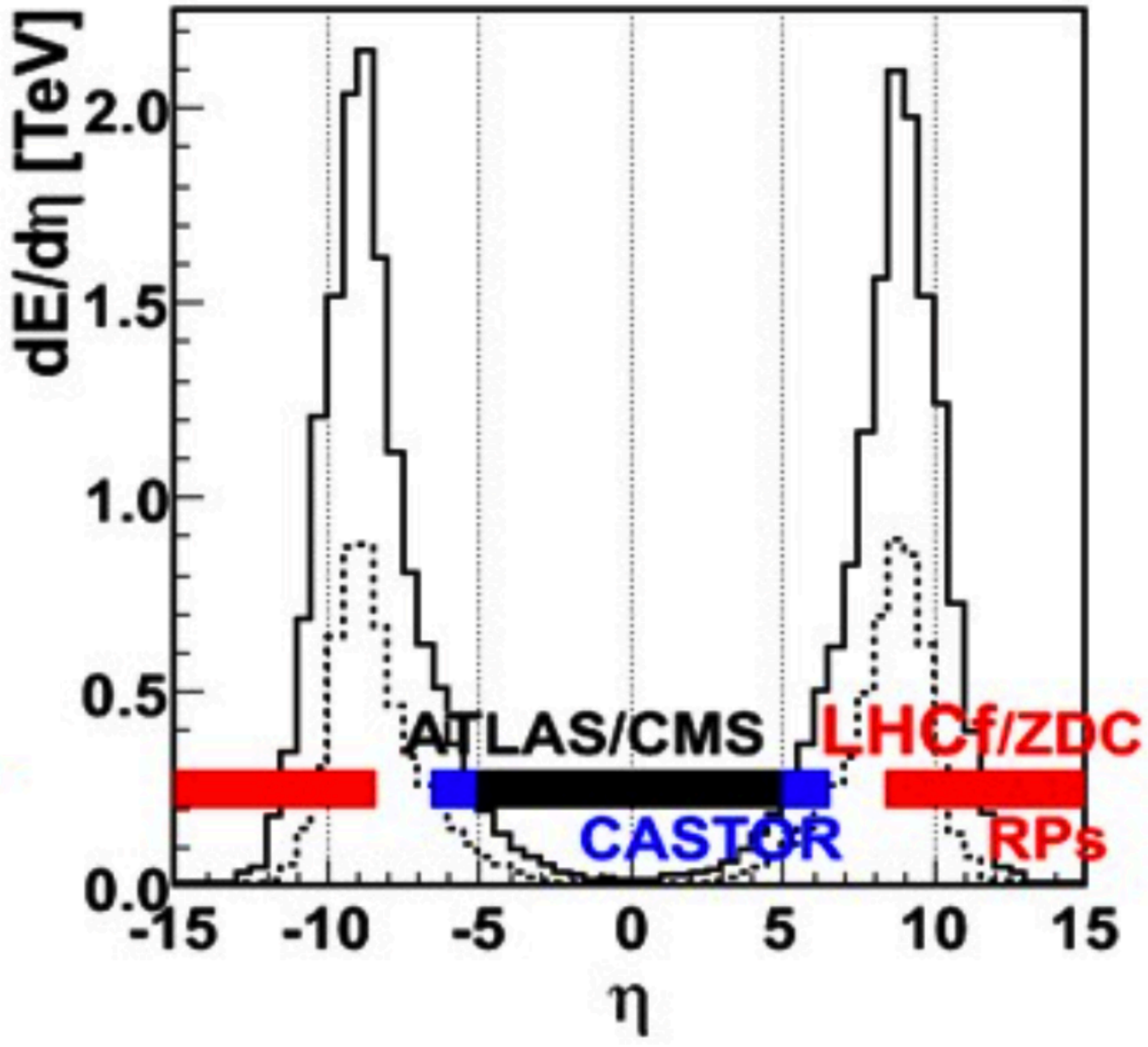
Why go forward?

- where the energy goes!!!



Why go forward?

◗ where the energy goes!!!



QCD physics

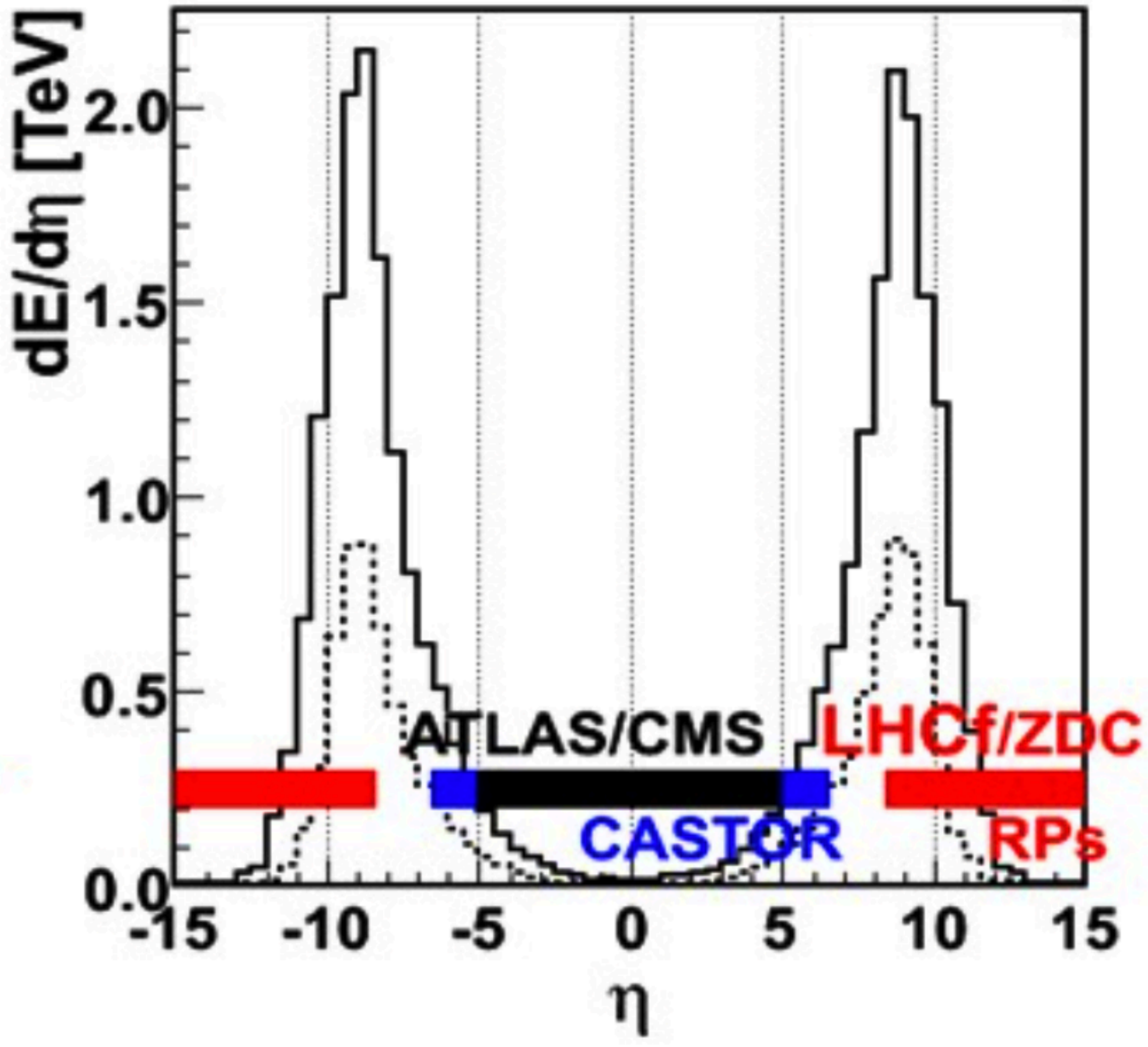
- elastic cross-section, soft/hard diffractive events, central exclusive processes in pp collisions
- explore low Bjorken-x range, low-x parton structure and dynamics
- underlying event (UE), multi parton interactions (MPI)
- photon-induced reactions
- validate hadronic models for ultra-high energy cosmic rays

QED physics:

- photo-production processes
- Light-by-light scattering

Why go forward?

➧ where the energy goes!!!



QCD physics

- elastic cross-section, soft/hard diffractive events, central exclusive processes in pp collisions
- explore low Bjorken-x range, low-x parton structure and dynamics
- underlying event (UE), multi parton interactions (MPI)
- photon-induced reactions
- validate hadronic models for ultra-high energy cosmic rays

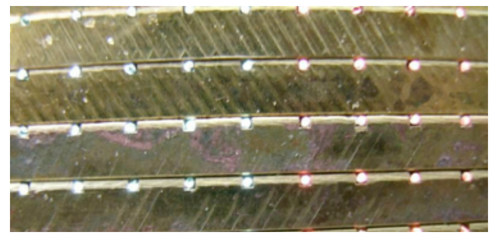
QED physics:

- photo-production processes
- Light-by-light scattering

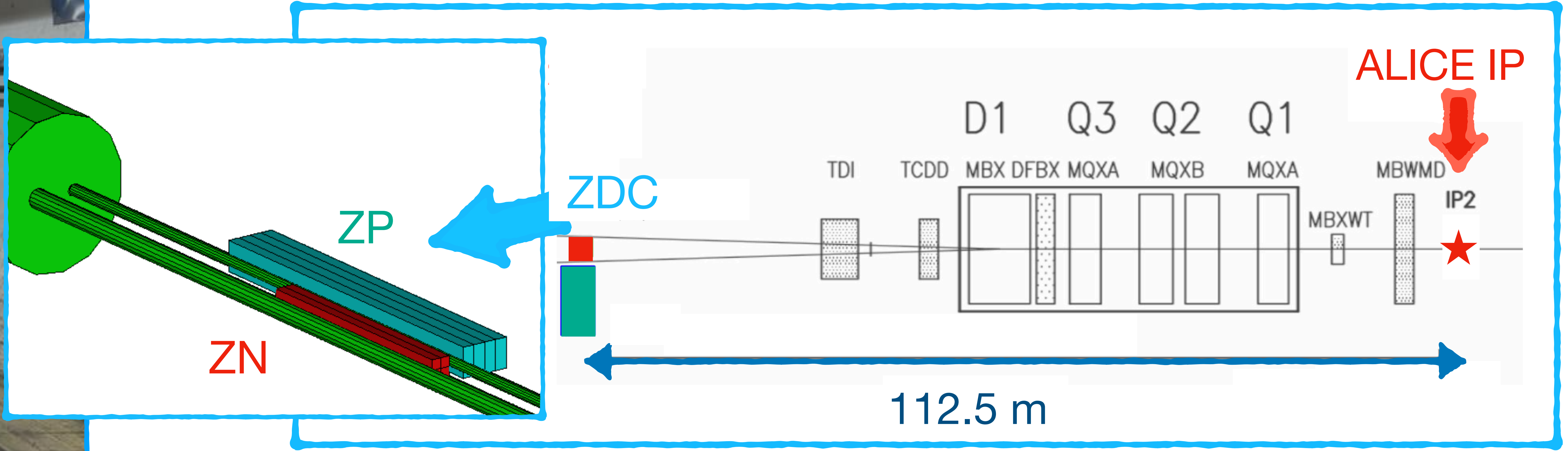
- target/projectile fragmentation
- measurement highly correlated to the geometry of the collision
- unbiased centrality estimator in pA collisions, avoid auto-correlations
- effective energy available at mid rapidity

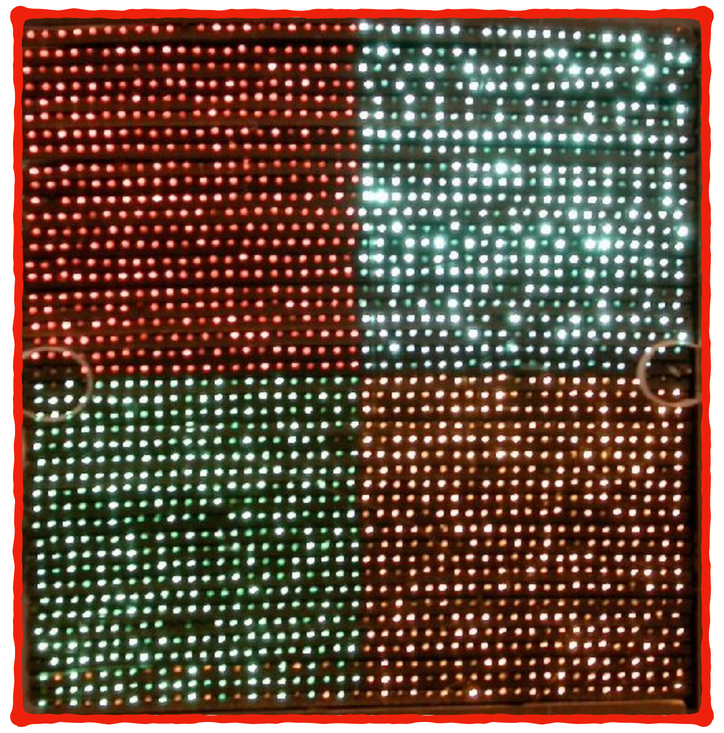
ALICE ZDCs

Quartz fibre spaghetti calorimeters

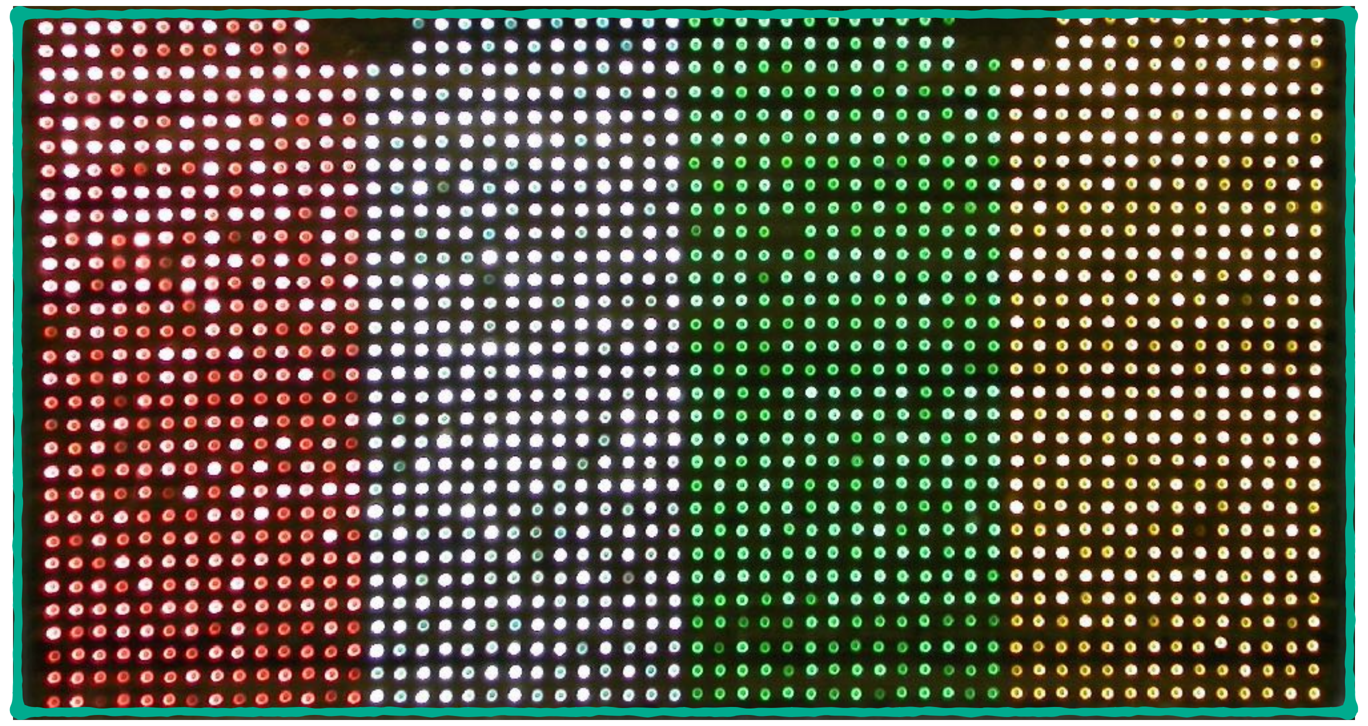


Cerenkov light produced of shower particles





ZN

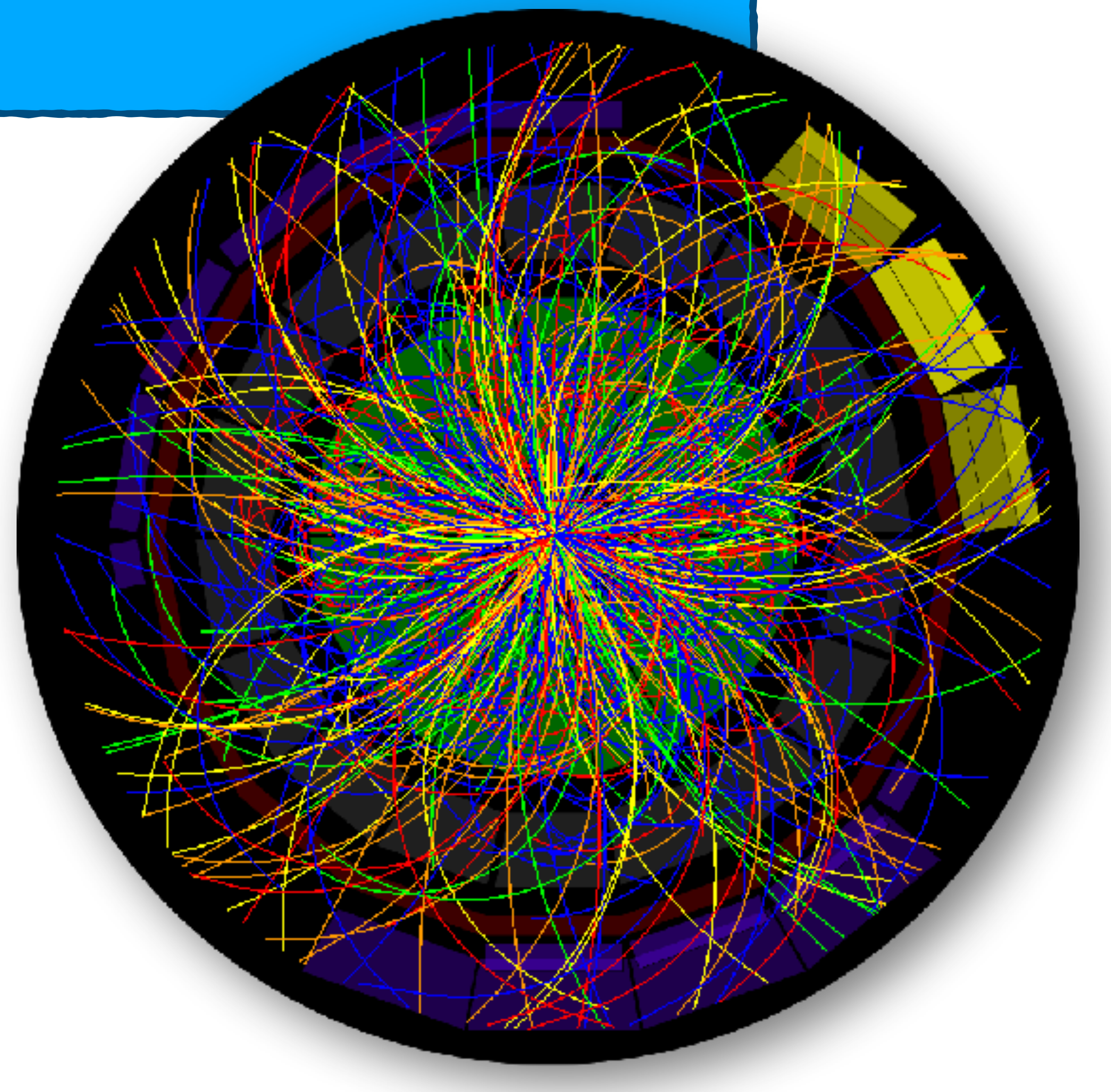


ZP

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 $|\eta|>8.7$
- 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

ZDC in p-Pb collisions

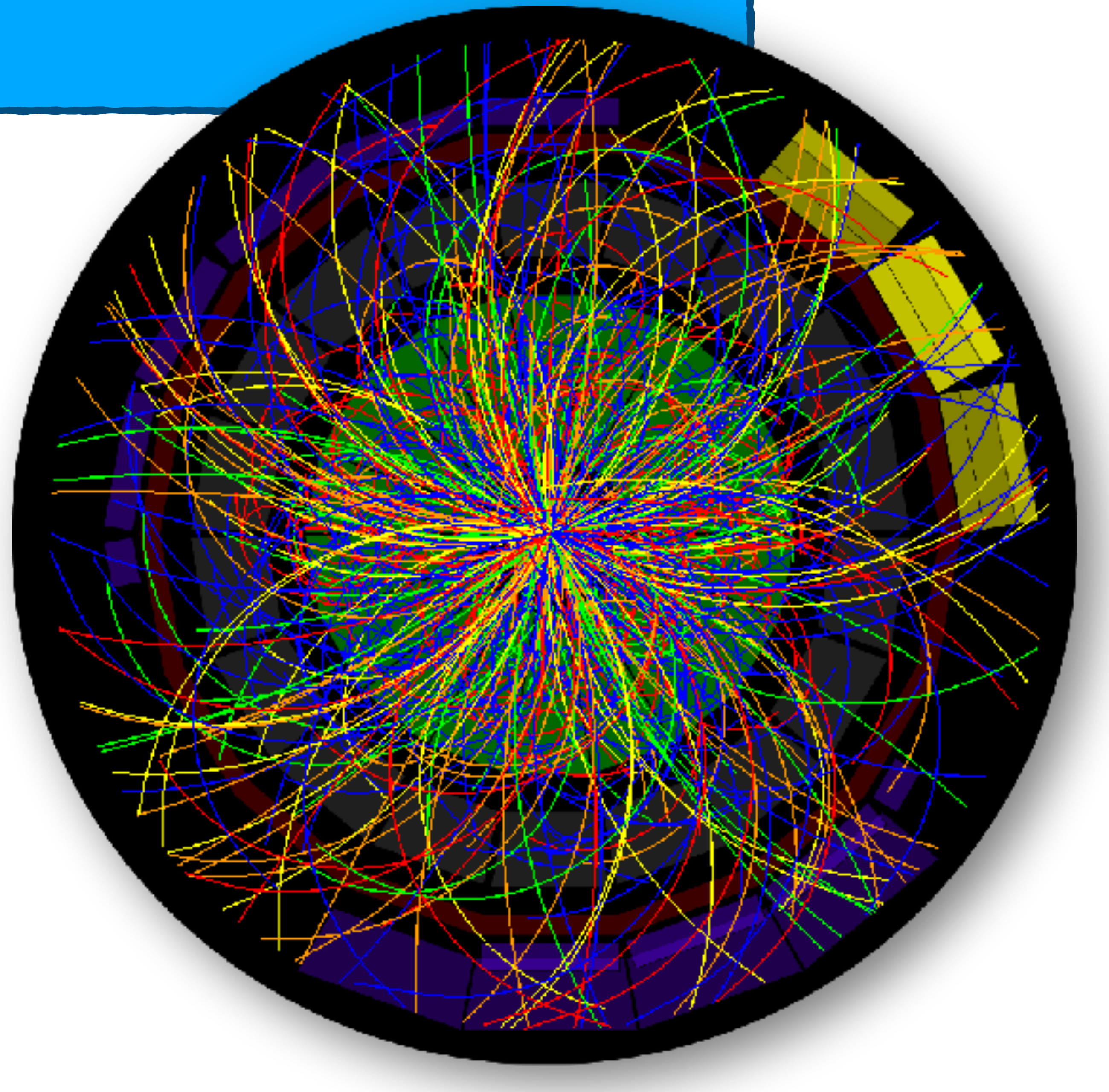


p-Pb collisions at $\sqrt{s}$ = 5.02 TeV and 8.16 TeV

$\sqrt{s}$ = 5.02 TeV ➧ proton beam at 4 TeV + Pb ions at 1.57 TeV per nucleon

$\sqrt{s}$ = 8.16 TeV ➧ proton beam at 6.5 TeV + Pb ions at 2.56 TeV per nucleon

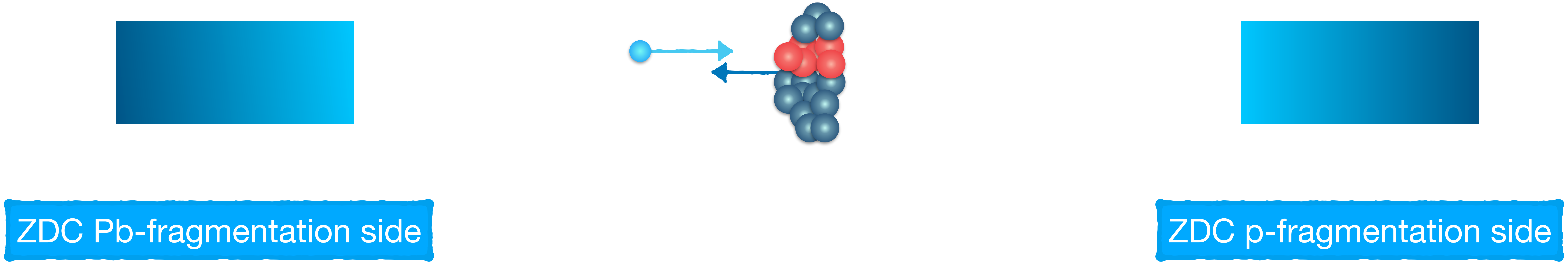
ZDC in p-Pb collisions



p-Pb collisions at $\sqrt{s}$ = 5.02 TeV and 8.16 TeV

$\sqrt{s}$ = 5.02 TeV ➧ proton beam at 4 TeV + Pb ions at 1.57 TeV per nucleon

$\sqrt{s}$ = 8.16 TeV ➧ proton beam at 6.5 TeV + Pb ions at 2.56 TeV per nucleon



p-Pb collisions @ 5 TeV

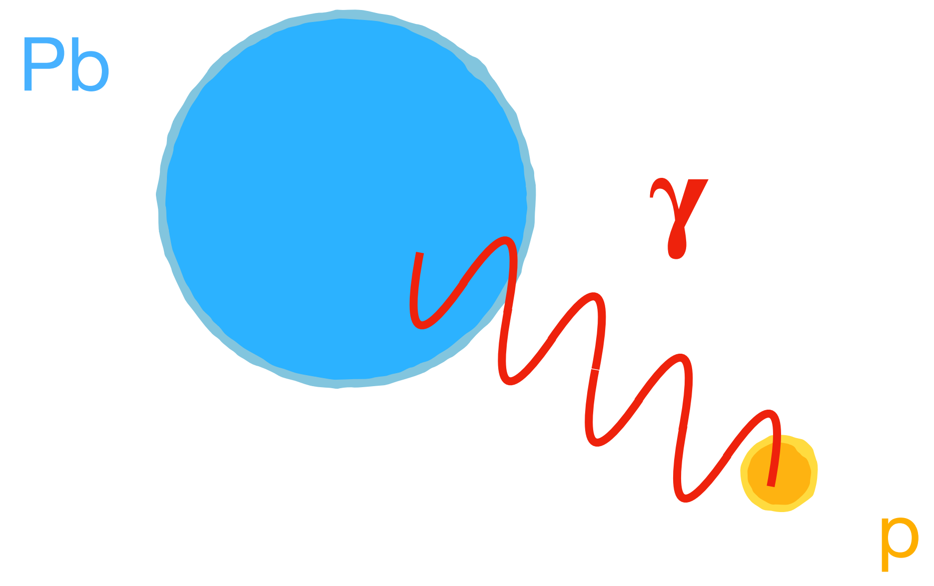
ALICE “visible” cross section of 2.09 ± 0.07 b measured in a van der Meer scan

Monte Carlo simulations ➧ the measured cross section consists mainly of non-single-diffractive (NSD) collisions and a negligible contribution of single-diffractive (SD) and electromagnetic events

Electromagnetic contribution evaluated using RELDIS model [1,2] for 4 TeV protons interacting with Pb nuclei of 1.57*A TeV

EM fragmentation of Pb nucleus
➧ cross section = 33.9 ± 2.0 mb (16.3 mb in neutron emission)

Excitation of proton by virtual photons from Pb nucleus
➧ cross section ~ 392 ± 118 mb (~200 mb in neutron emission)
(<1/5 of the visible cross section ➧ much less relevant than in Pb-Pb collisions!)

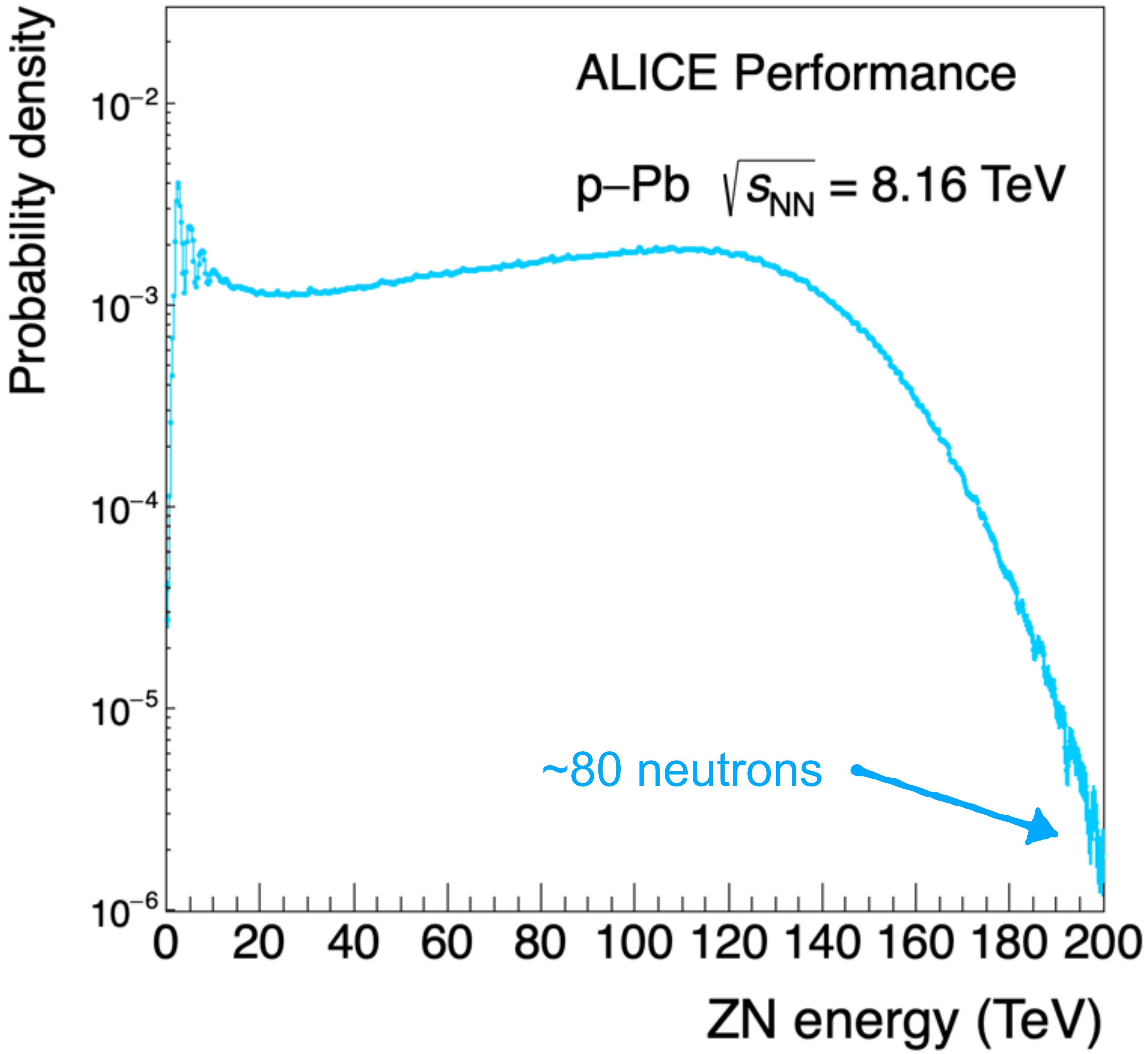


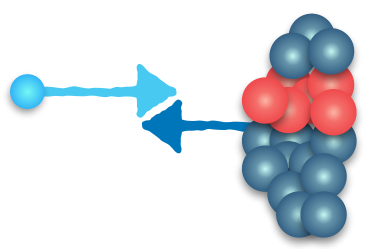
[1] I.A.Pshenichnov et al., Phys.Rev. C 60 044901 (1999)
[2] I.A.Pshenichnov, Phys. Part. Nuclei 42 215 (2011)

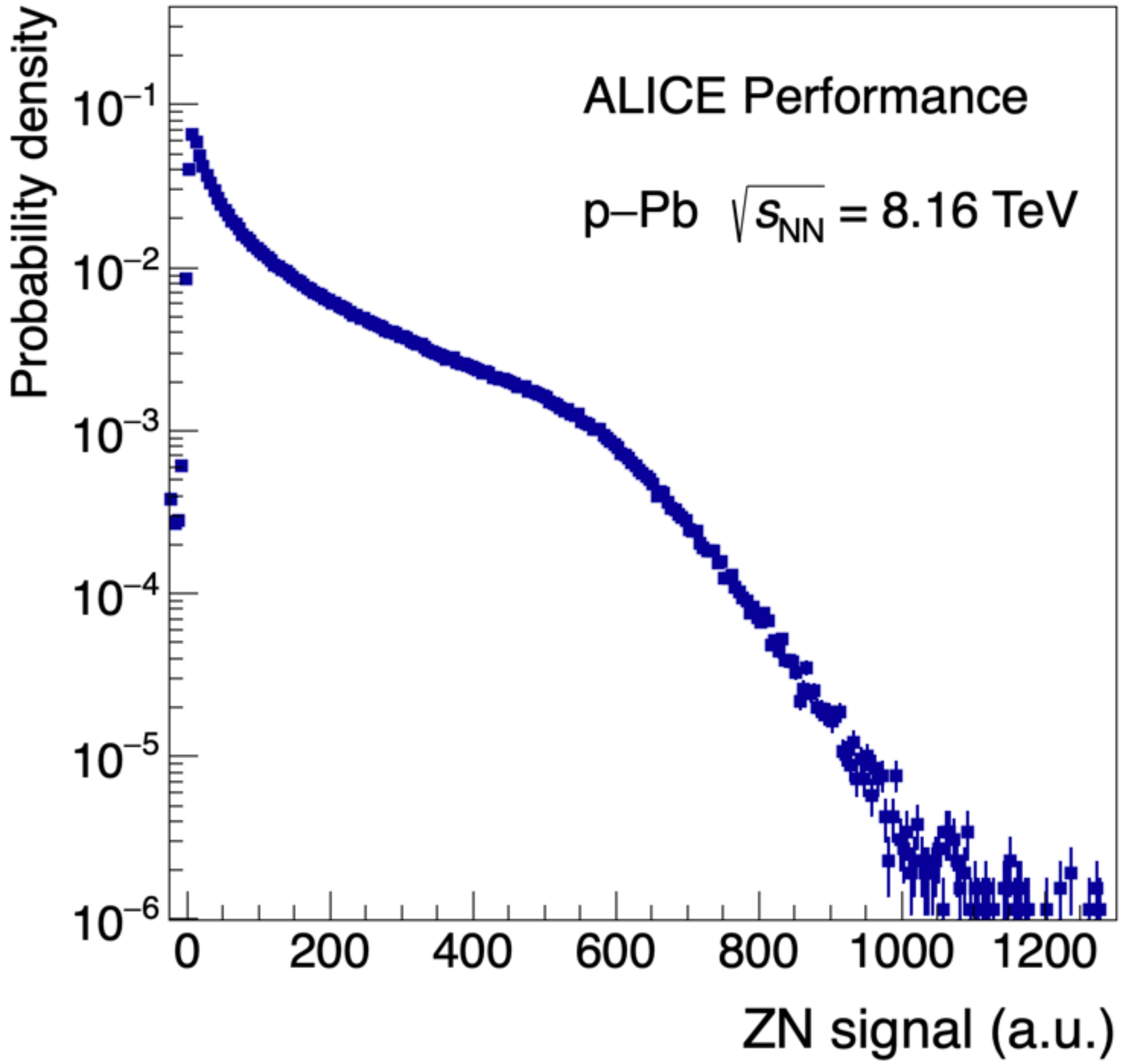
ZN spectra in p-Pb collisions

Pb fragmentation side ZDC

p fragmentation side ZDC





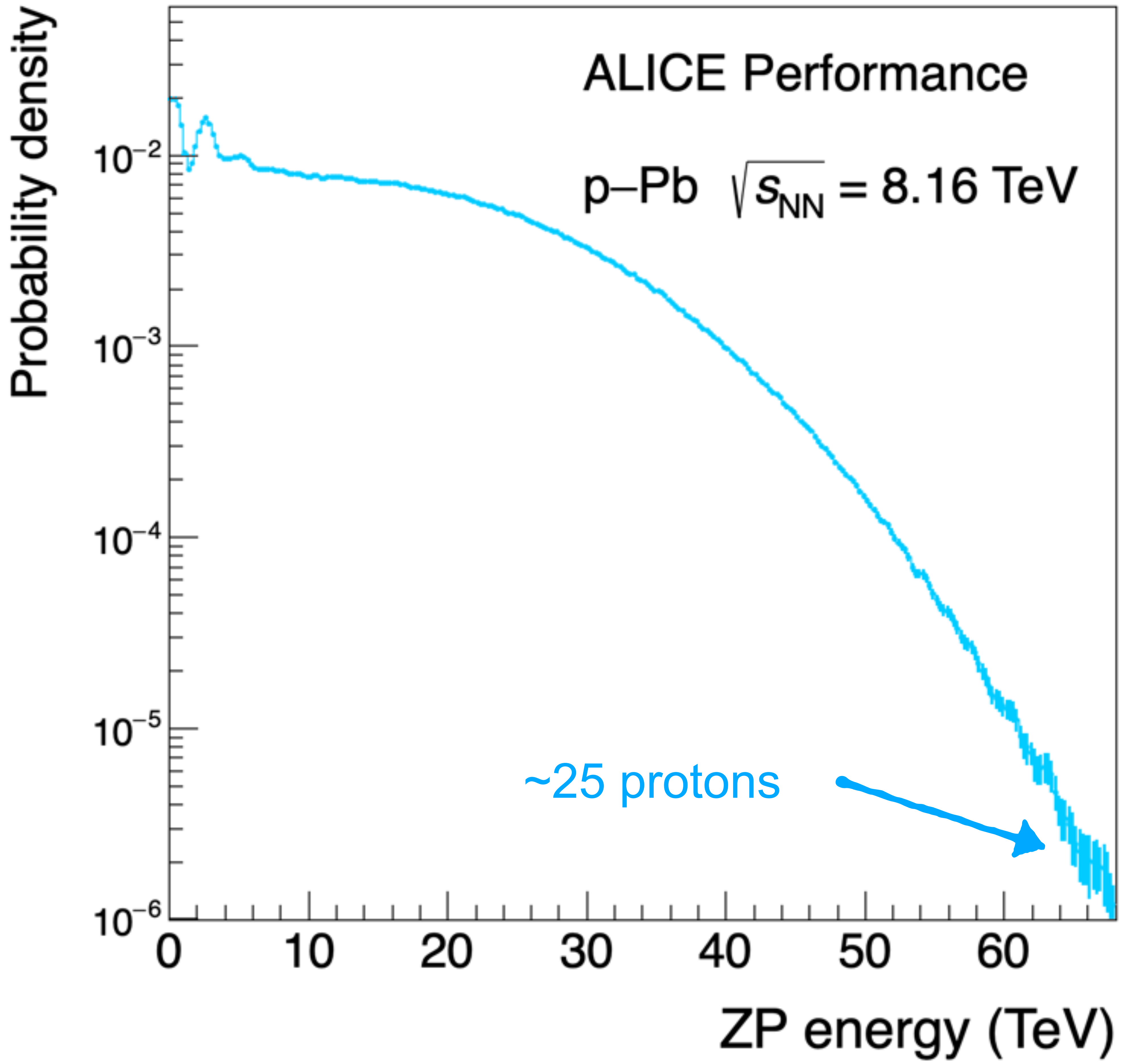


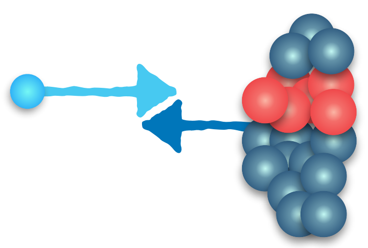
Pb fragmentation signal due to “slow” neutrons

p fragmentation signal mainly due to neutrons

ZP spectra in p-Pb collisions

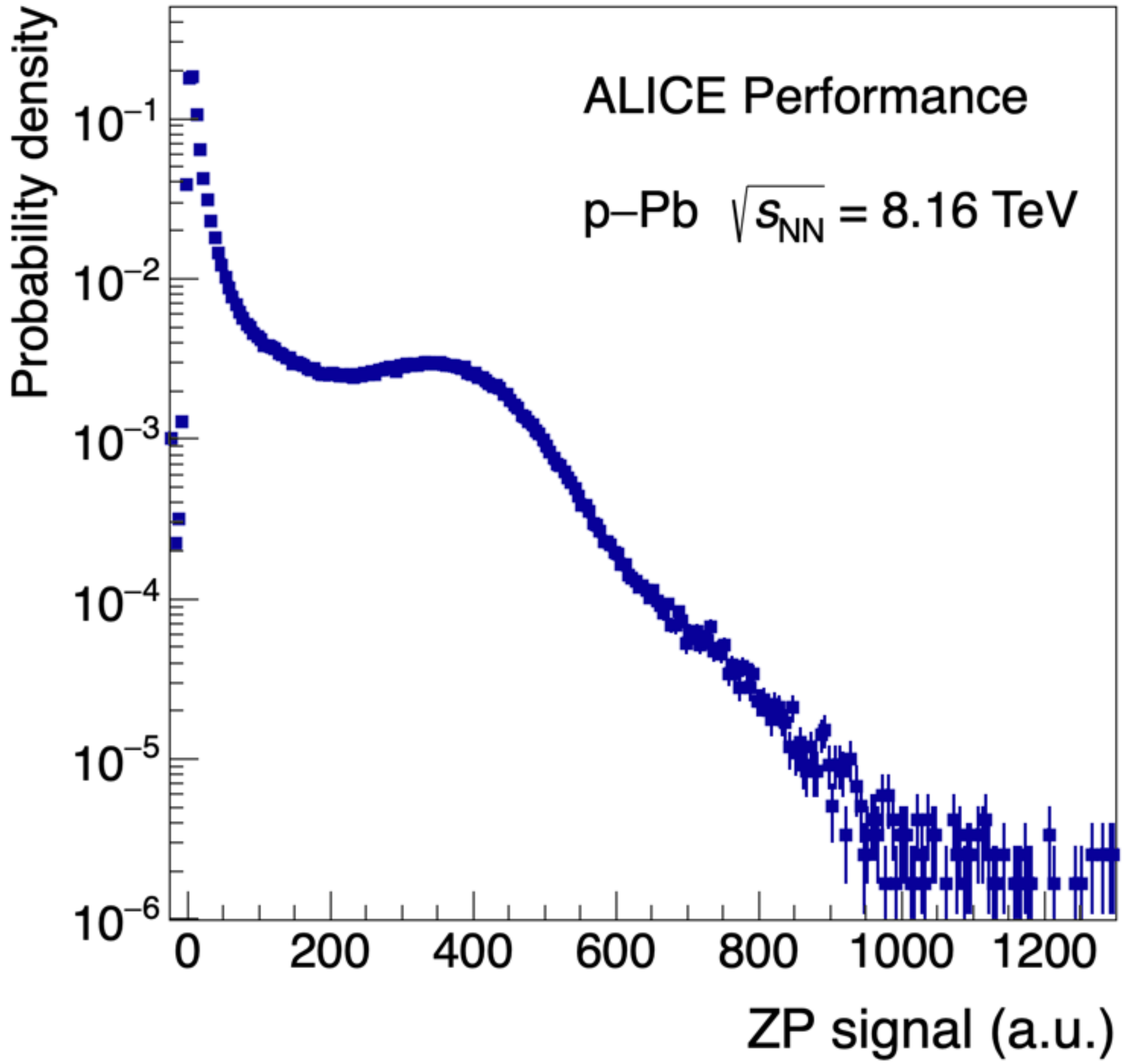
Pb fragmentation side ZDC





ZP

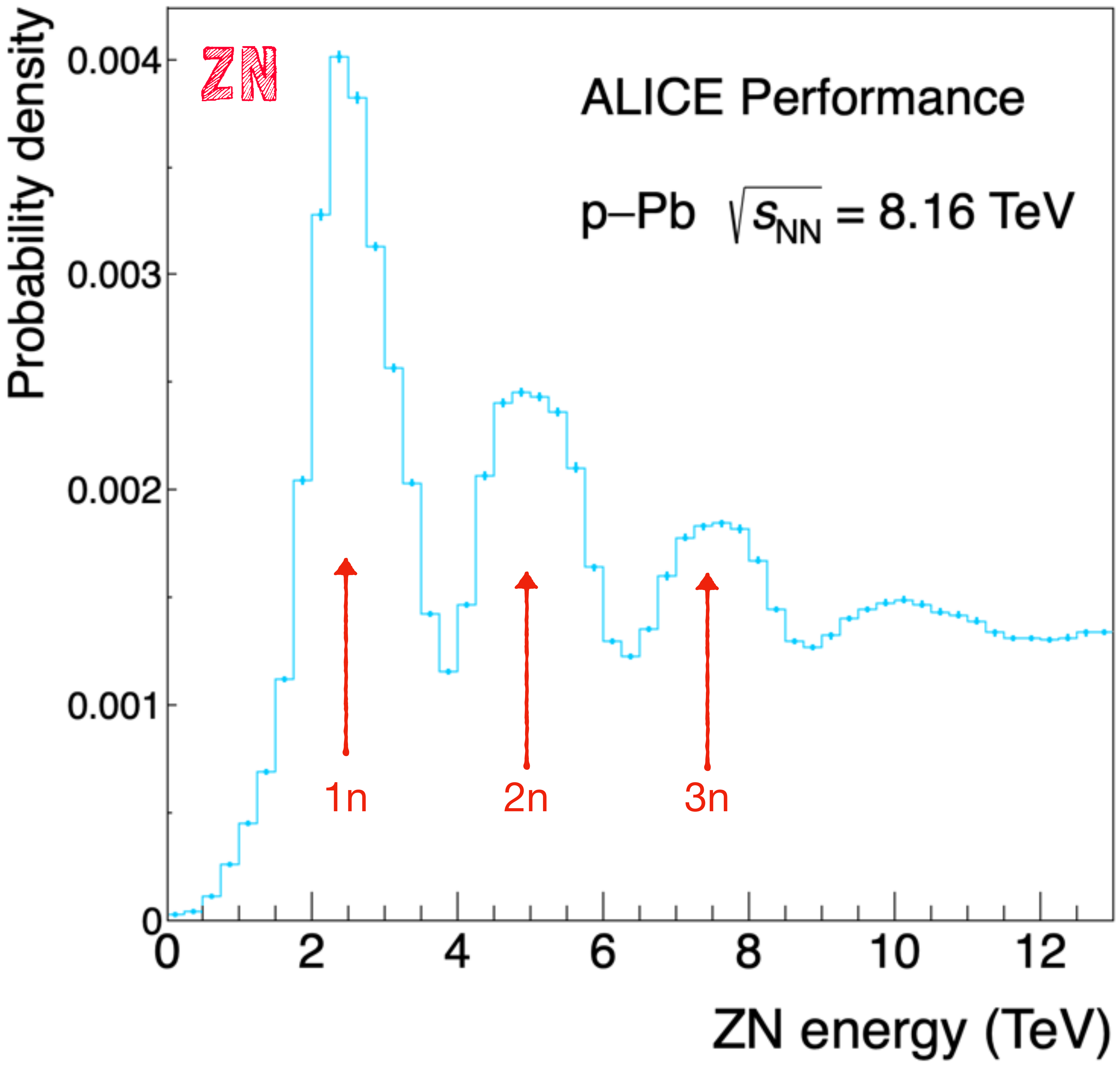
p fragmentation side ZDC

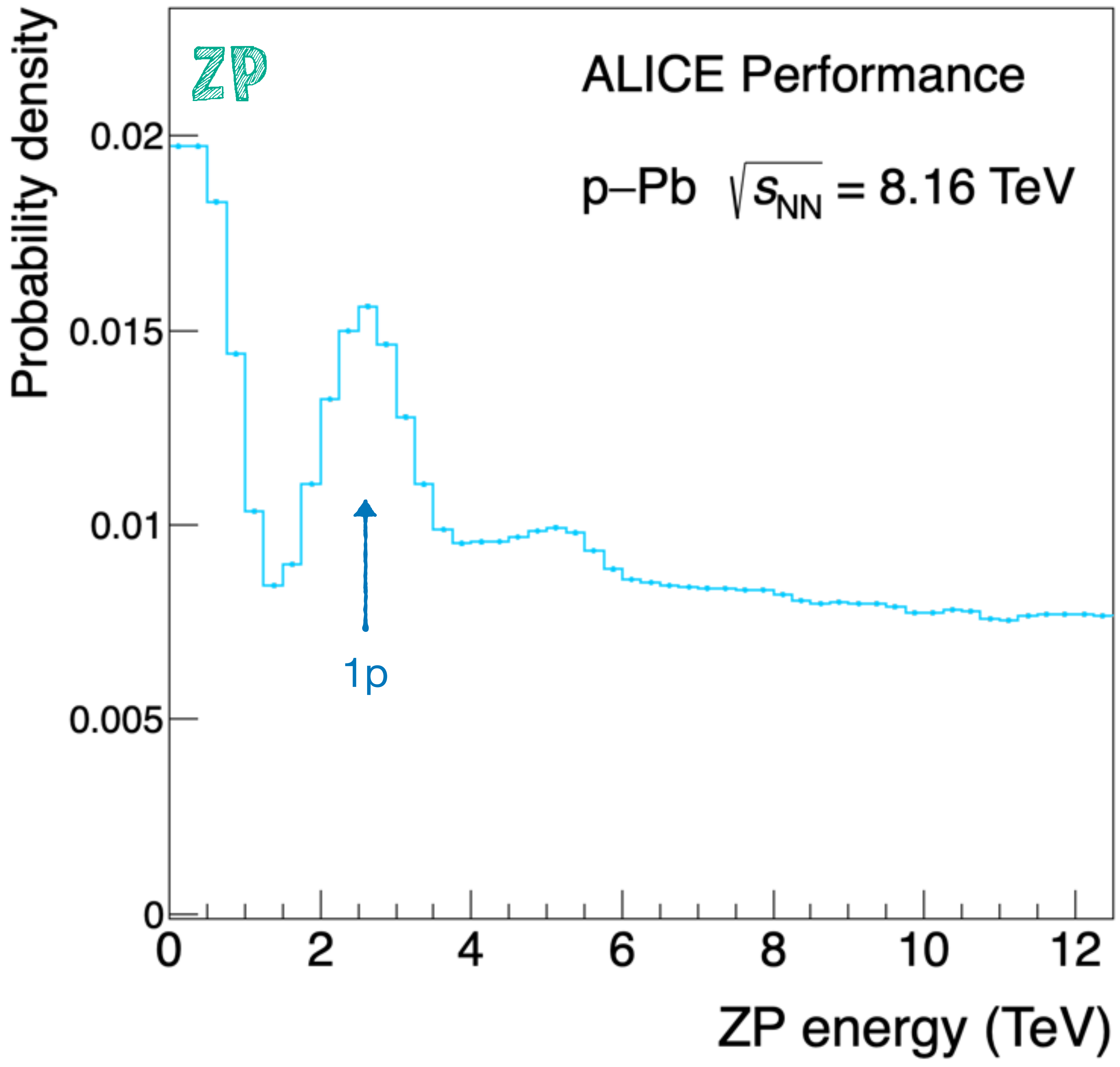


Pb fragmentation signal due to "slow" protons

p fragmentation signal mainly due to protons

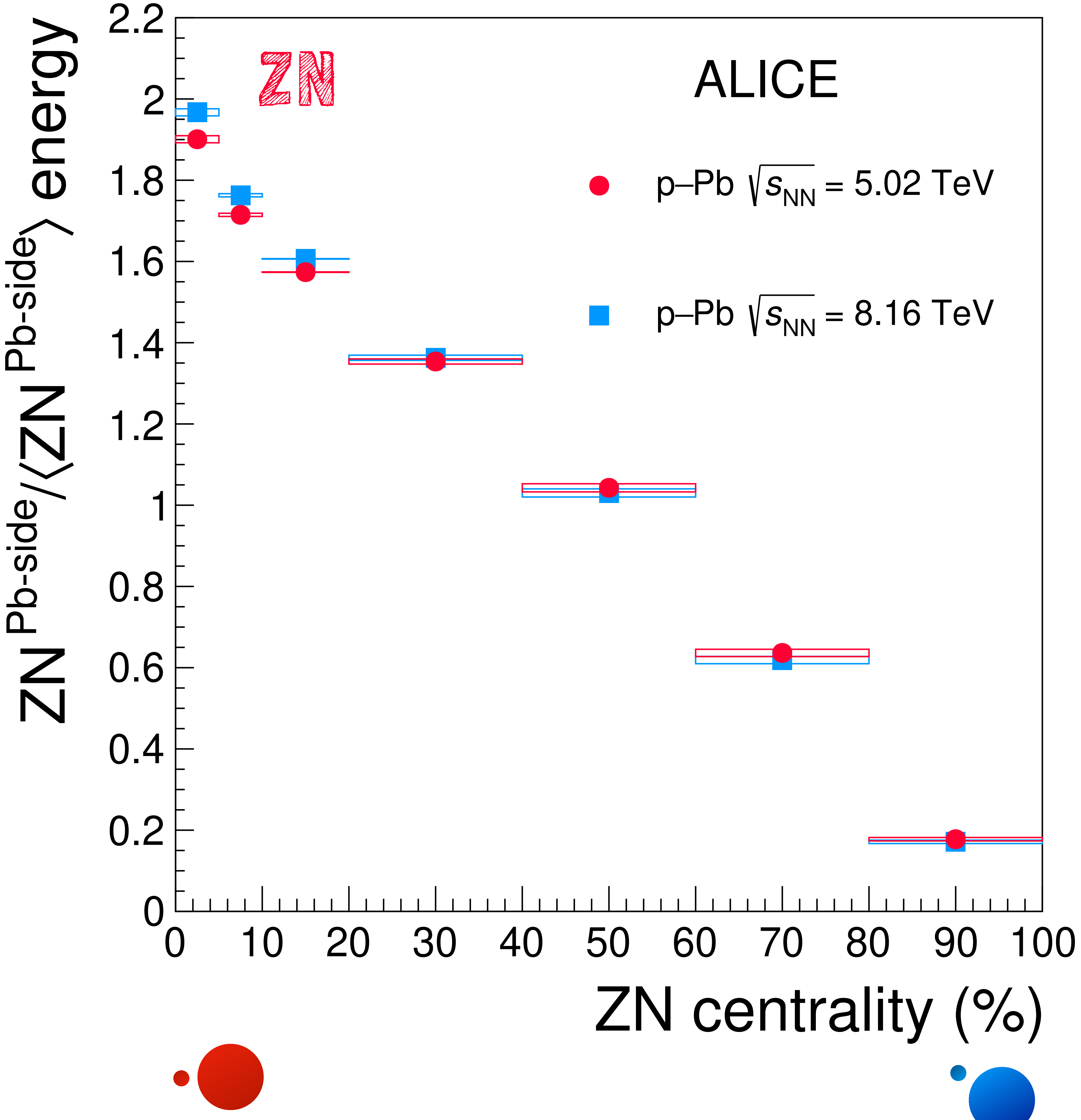
Energy calibration





- Single nucleon peaks are used to calibrate in energy the ZN and ZP spectra on the Pb-fragmentation side

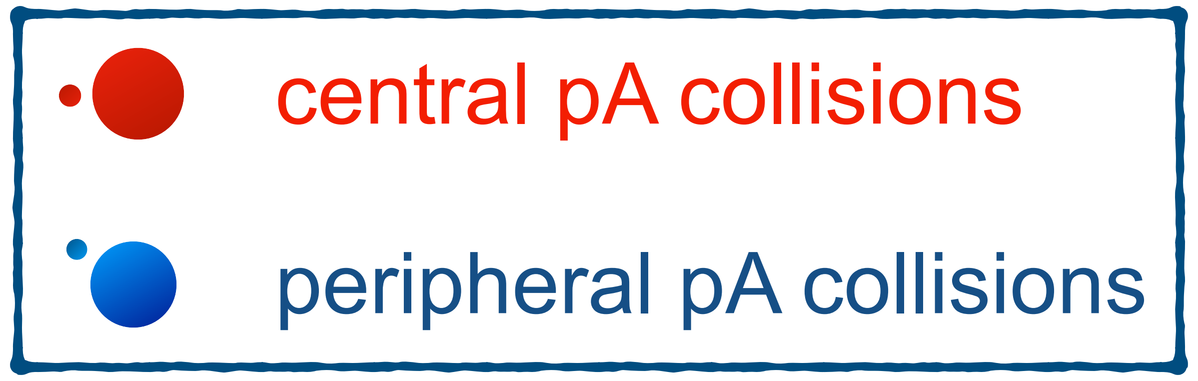
Pb fragmentation region



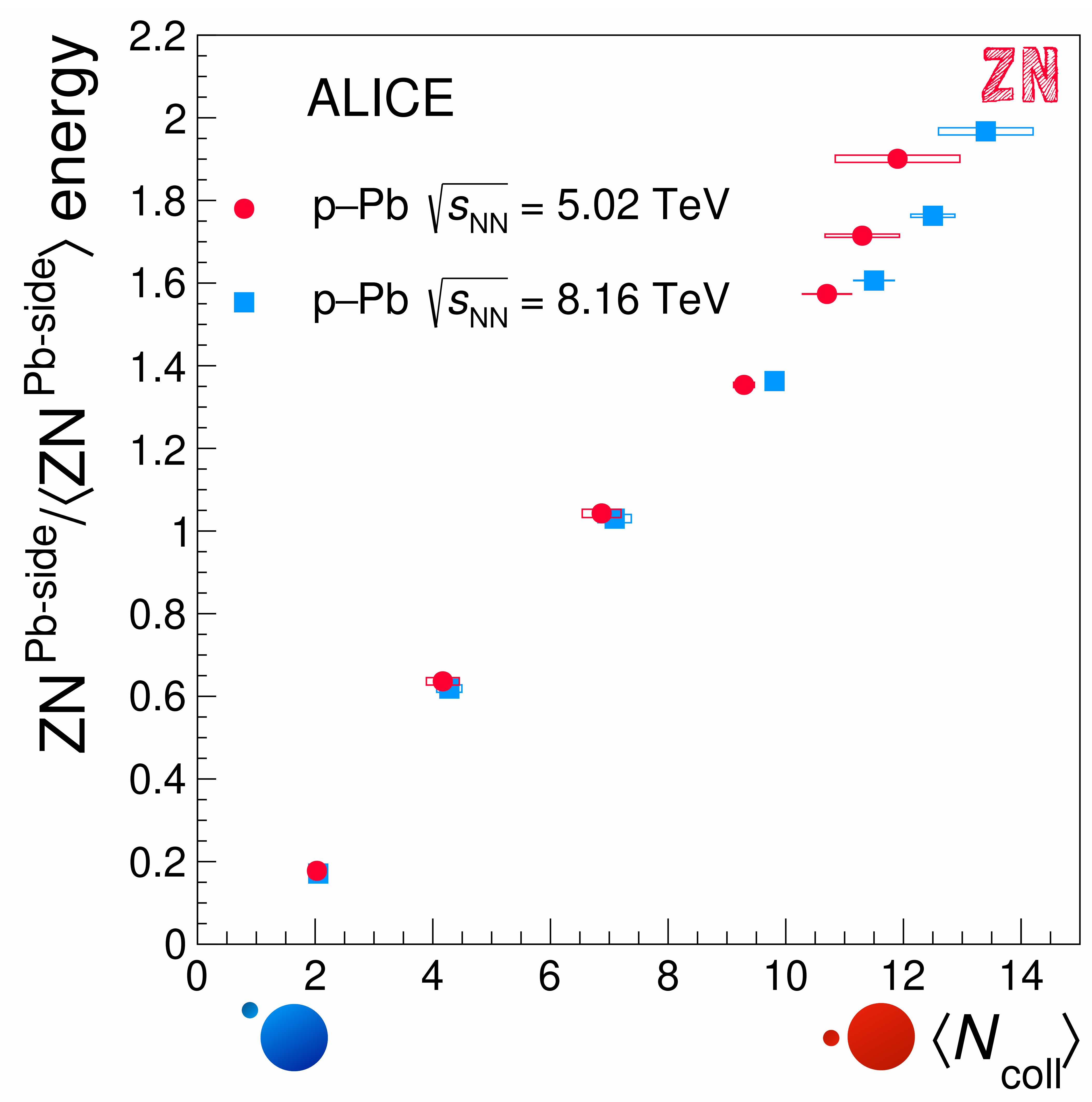
ALICE coll., arXiv 2107.10757

Self-normalized energies to compare different center-of-mass energies: ZN/<ZN^{MB}>

The energy carried by neutrons emitted from the Pb nucleus (slow neutrons) measured in ZN:
- increases with the centrality of the collisions
- once divided by the respective minimum bias value (self-normalisation), 5.02 and 8.16 TeV data show similar slopes



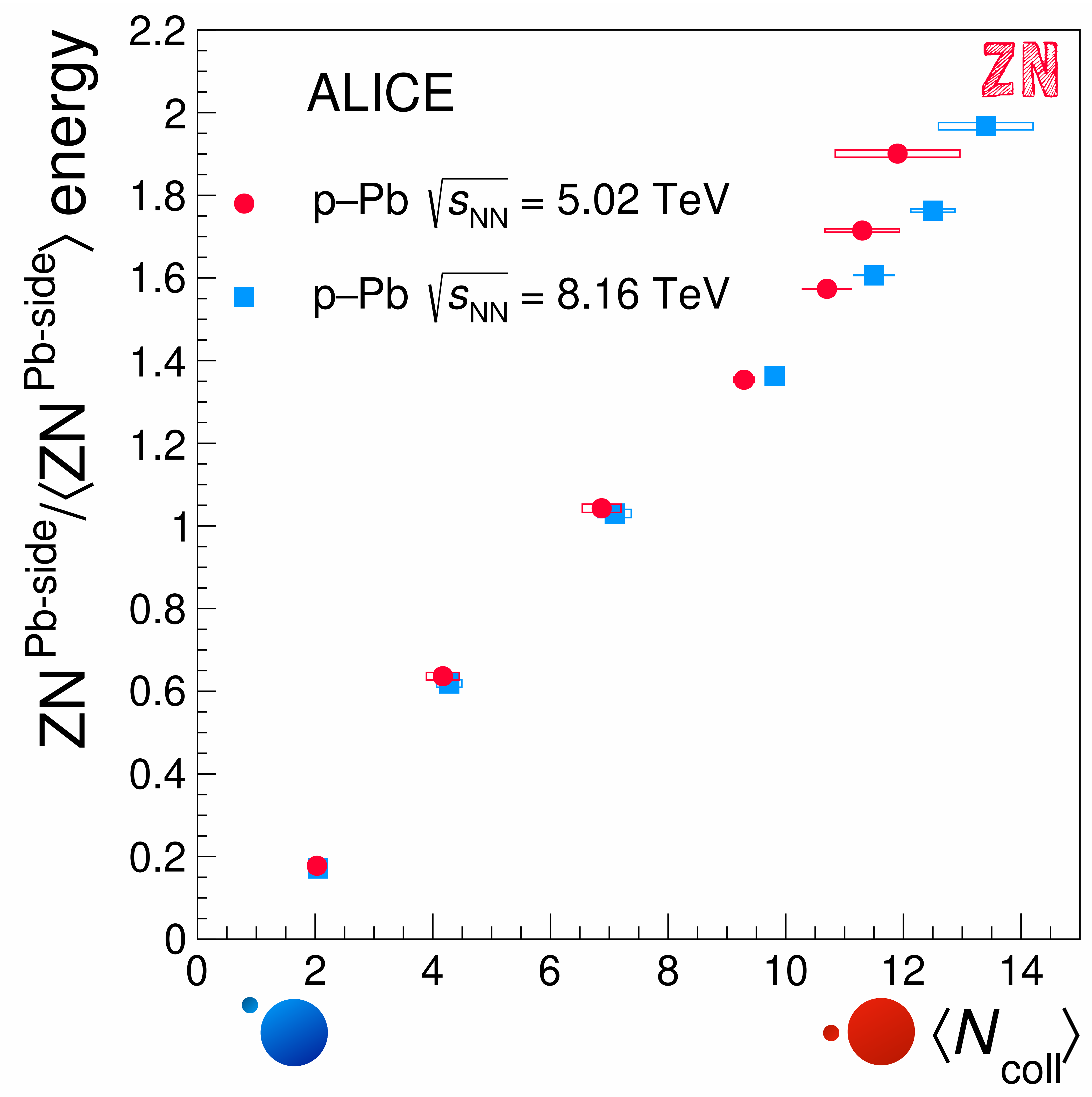
Pb fragmentation vs. collision geometry



ALICE coll., arXiv 2107.10757

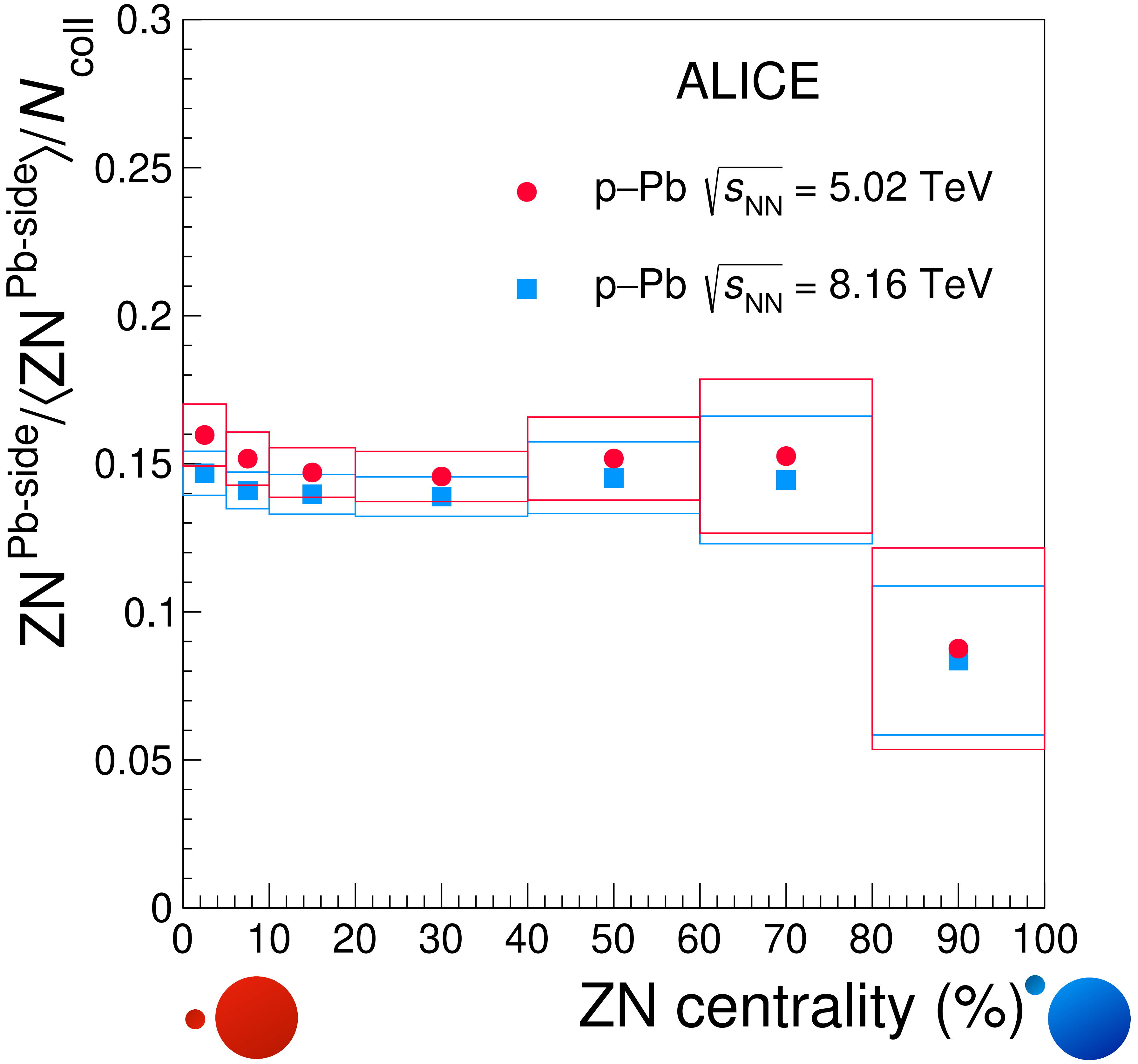
Energy carried by neutrons emitted from the Pb nucleus (slow neutrons) increases linearly with the number of binary N-N collisions (as already observed at smaller energies)

Pb fragmentation vs. collision geometry



ALICE coll., arXiv 2107.10757

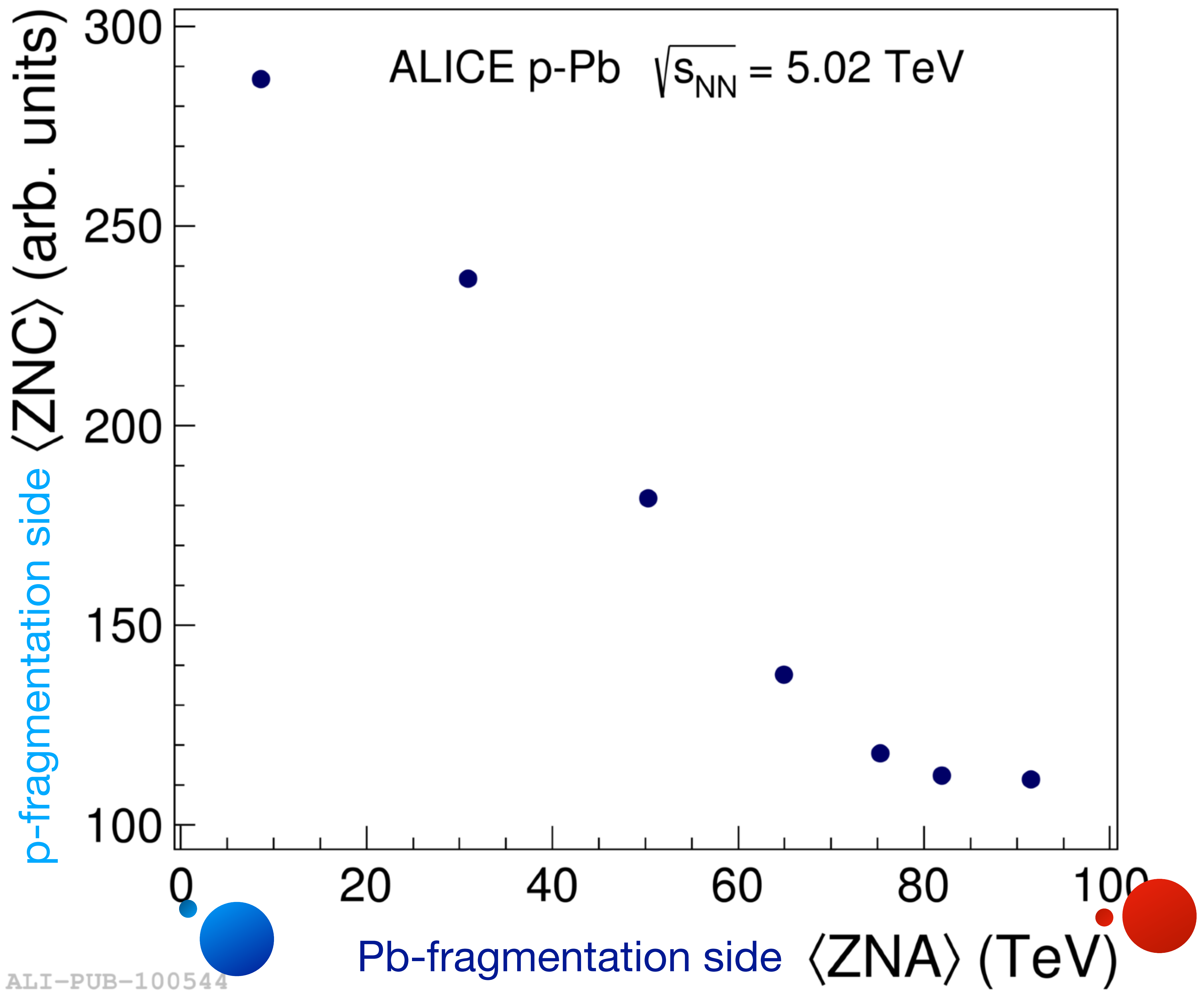
Energy carried by neutrons emitted from the Pb nucleus (slow neutrons) increases linearly with the number of binary N-N collisions (as already observed at smaller energies)



N_{coll} scaling valid up to most peripheral collisions

p fragmentation region

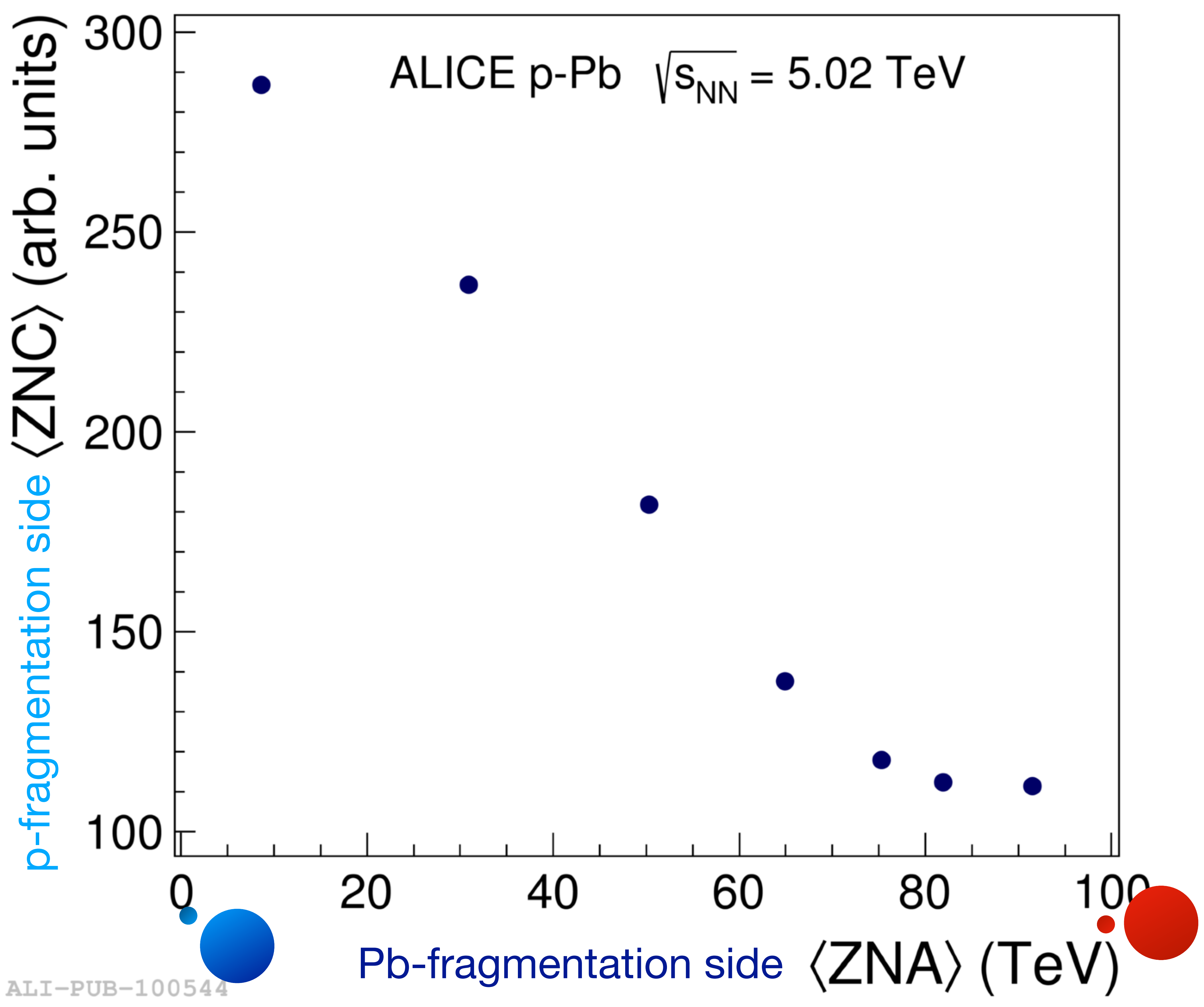
ALICE coll., Phys. Rev. C 91 (2015) 064905



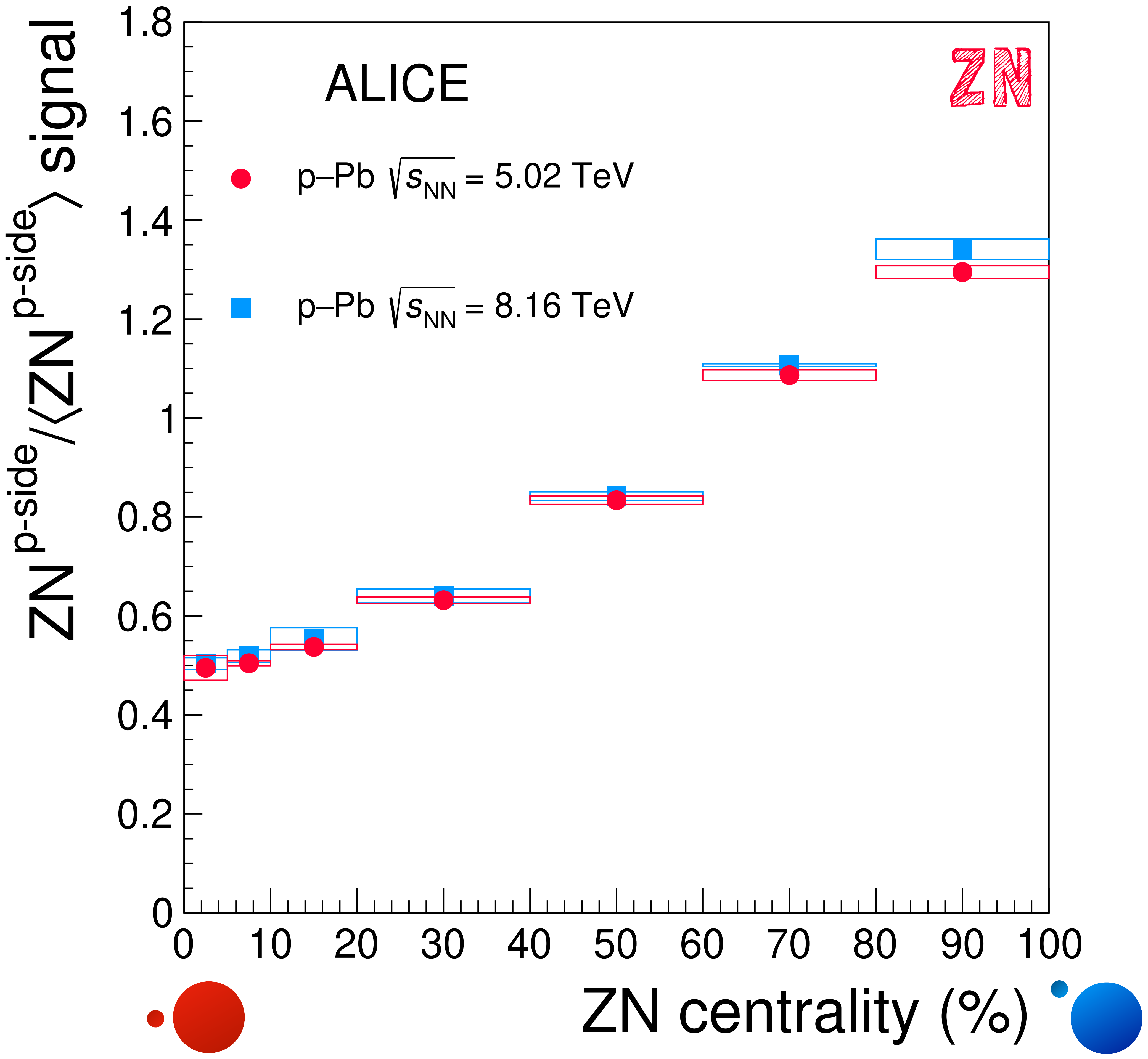
p-fragmentation side ZN signal is anti-correlated with ZN energy detected on the Pb-fragmentation side

p fragmentation region

ALICE coll., Phys. Rev. C 91 (2015) 064905



ALICE coll., arXiv 2107.10757

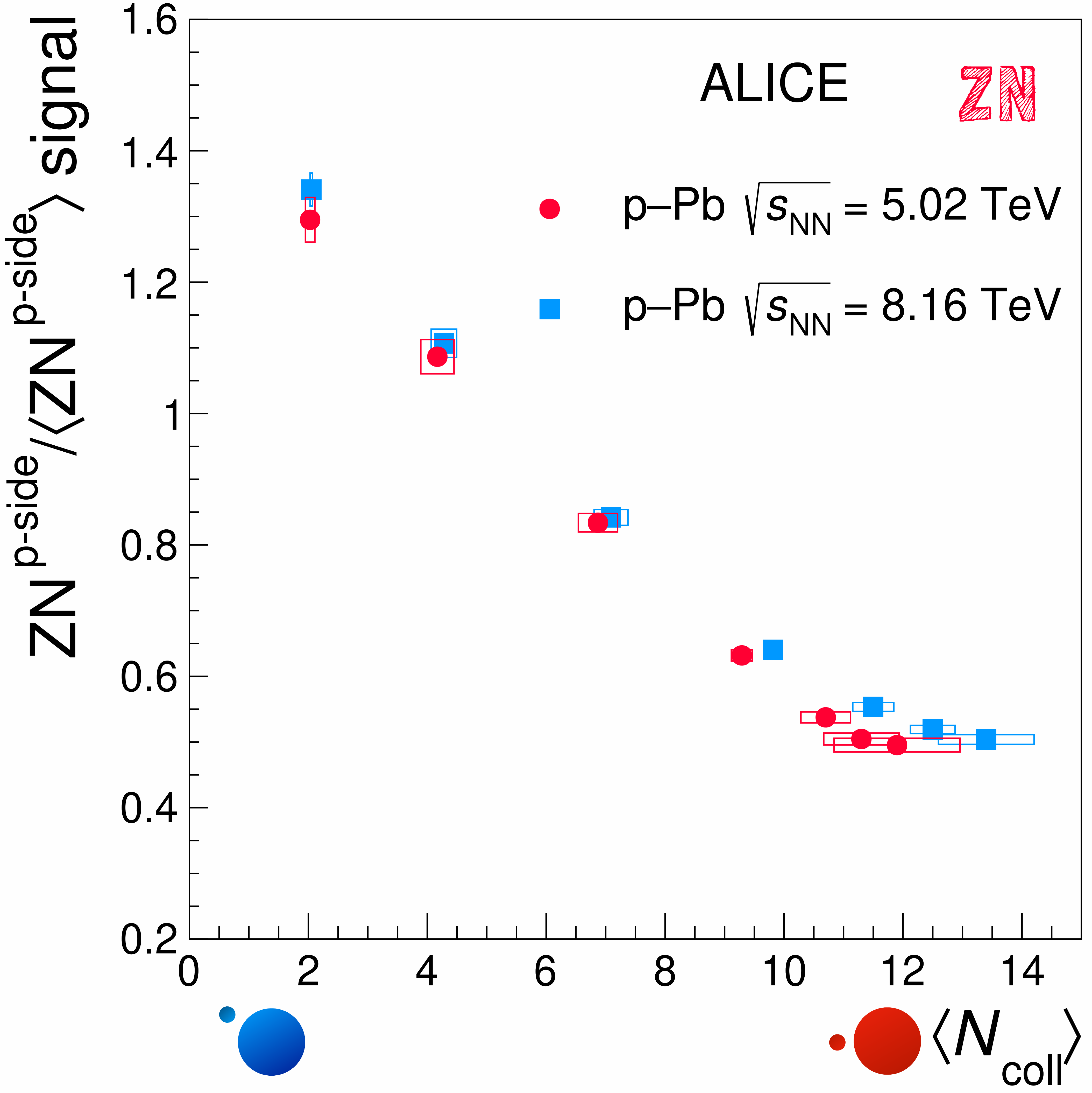


p-fragmentation side ZN signal is anti-correlated with ZN energy detected on the Pb-fragmentation side

The energy measured in ZN from the p fragmentation:

- decreases with the centrality of the collisions
- 5.05 and 8.16 TeV data show very similar dependence

p fragmentation vs. collision geometry

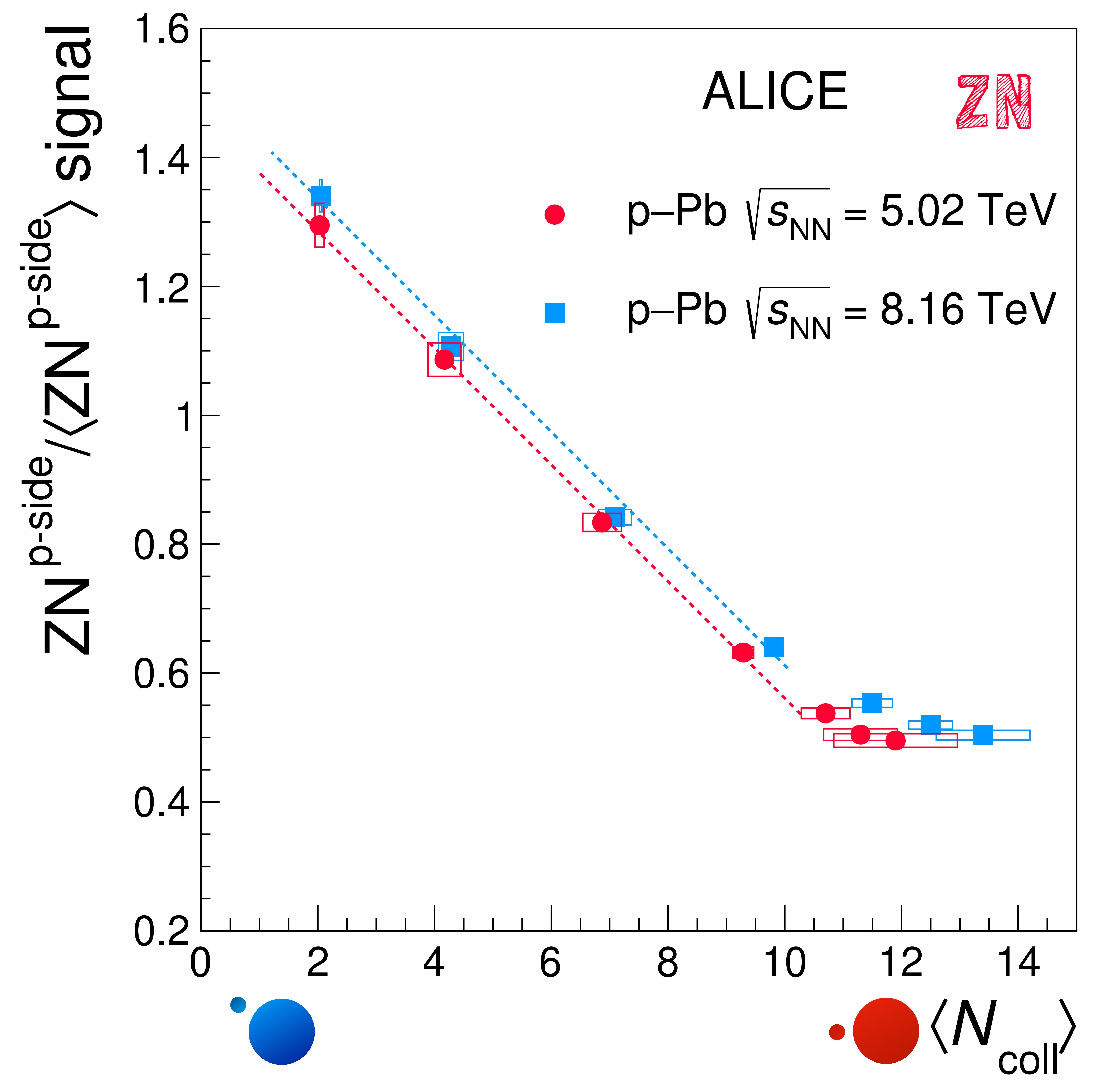


ALICE coll., arXiv 2107.10757

p-fragmentation side ZN energy vs. <N_{coll}>

- linear anti-correlation over a wide centrality range
- consistent with a energy transfer from the proton proportional to N_{coll}
- same slope for different center-of-mass energies

p fragmentation vs. collision geometry



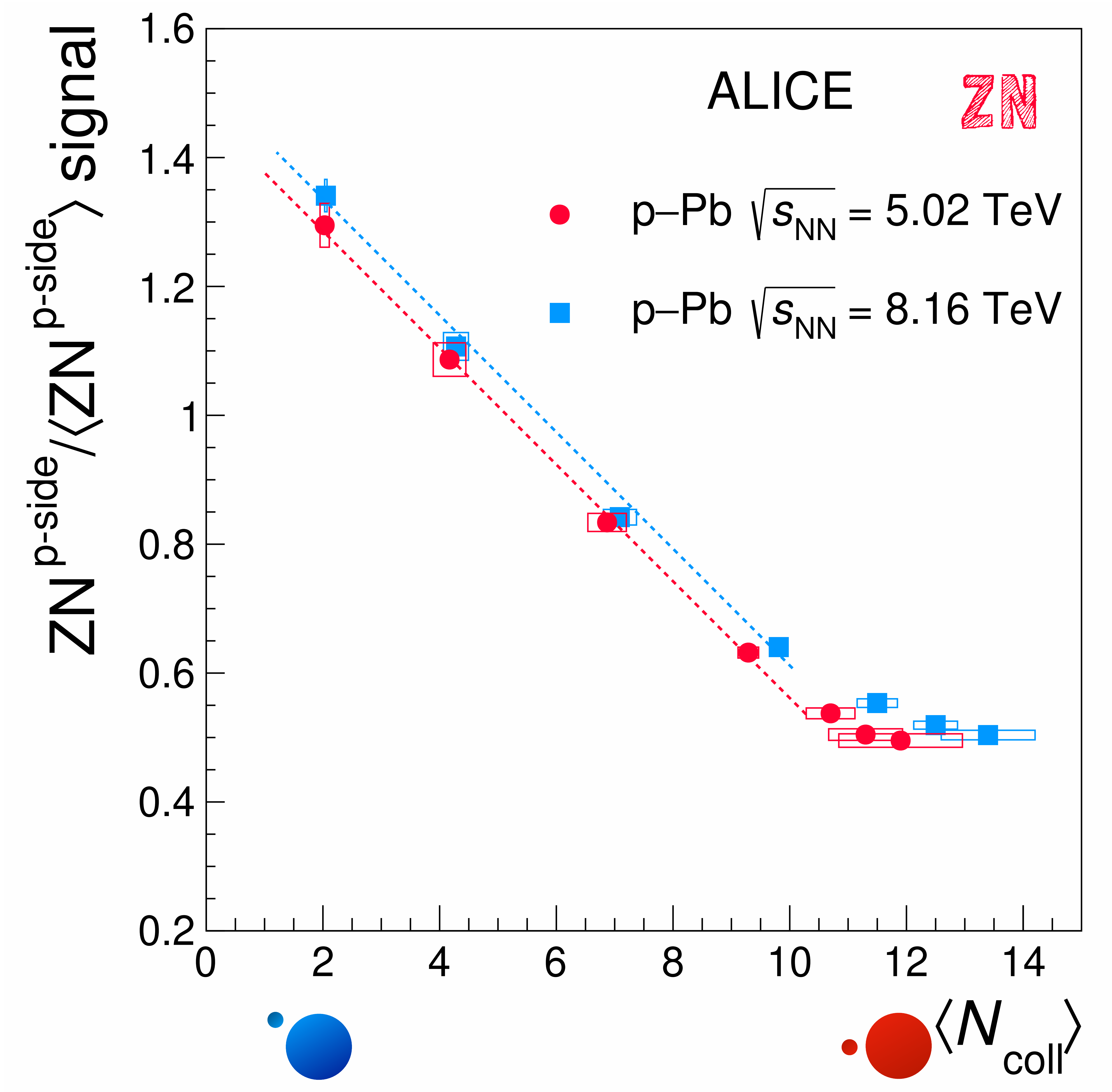
ALICE coll., arXiv 2107.10757

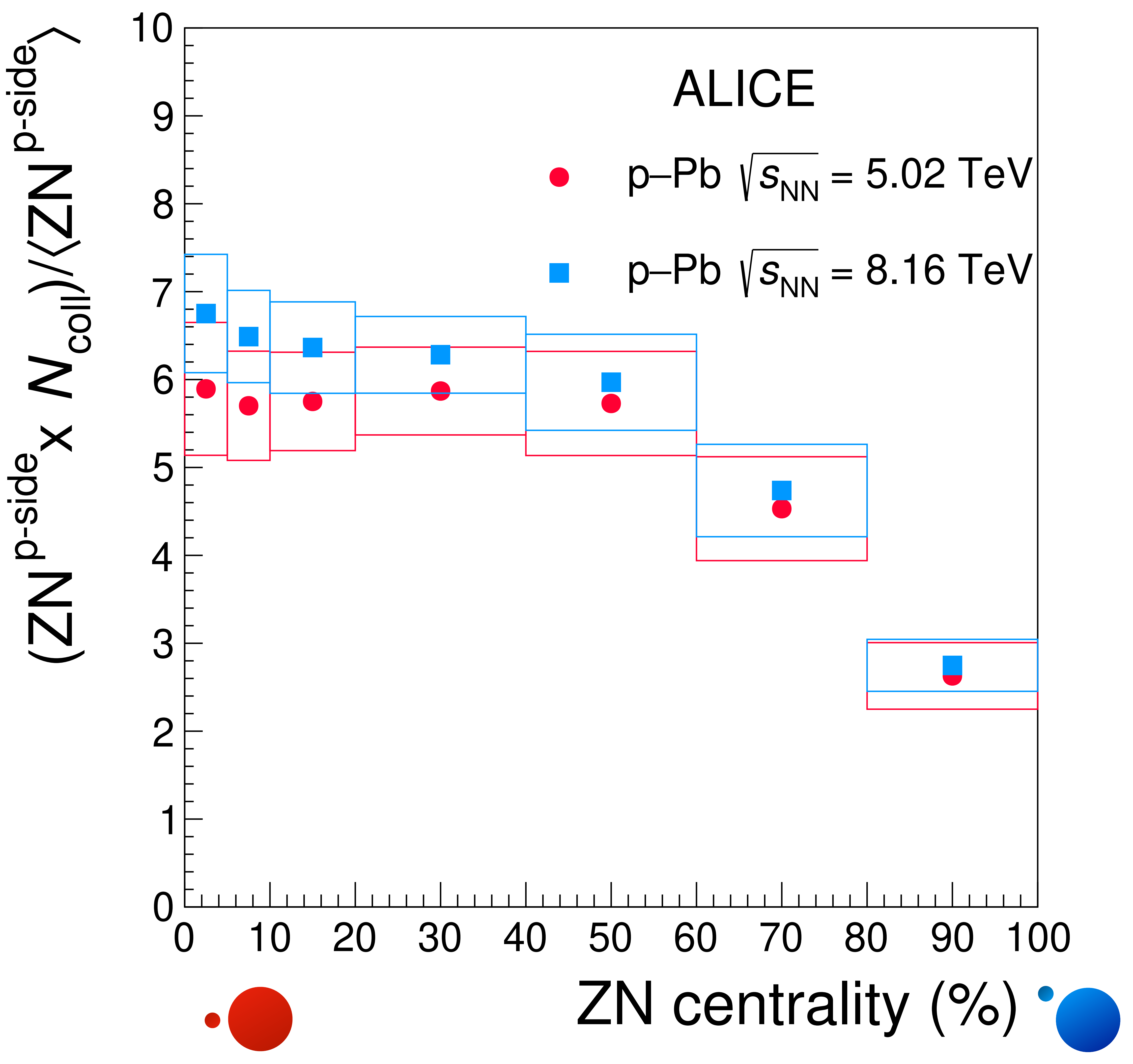
p-fragmentation side ZN energy vs. $\langle N_{coll}\rangle$

- linear anti-correlation over a wide centrality range
- consistent with a energy transfer from the proton proportional to N_{coll}
- same slope for different center-of-mass energies

Lines to guide the eye

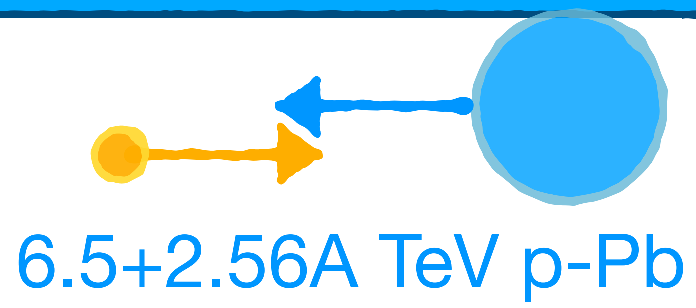
ZN scaling in p-fragmentation region





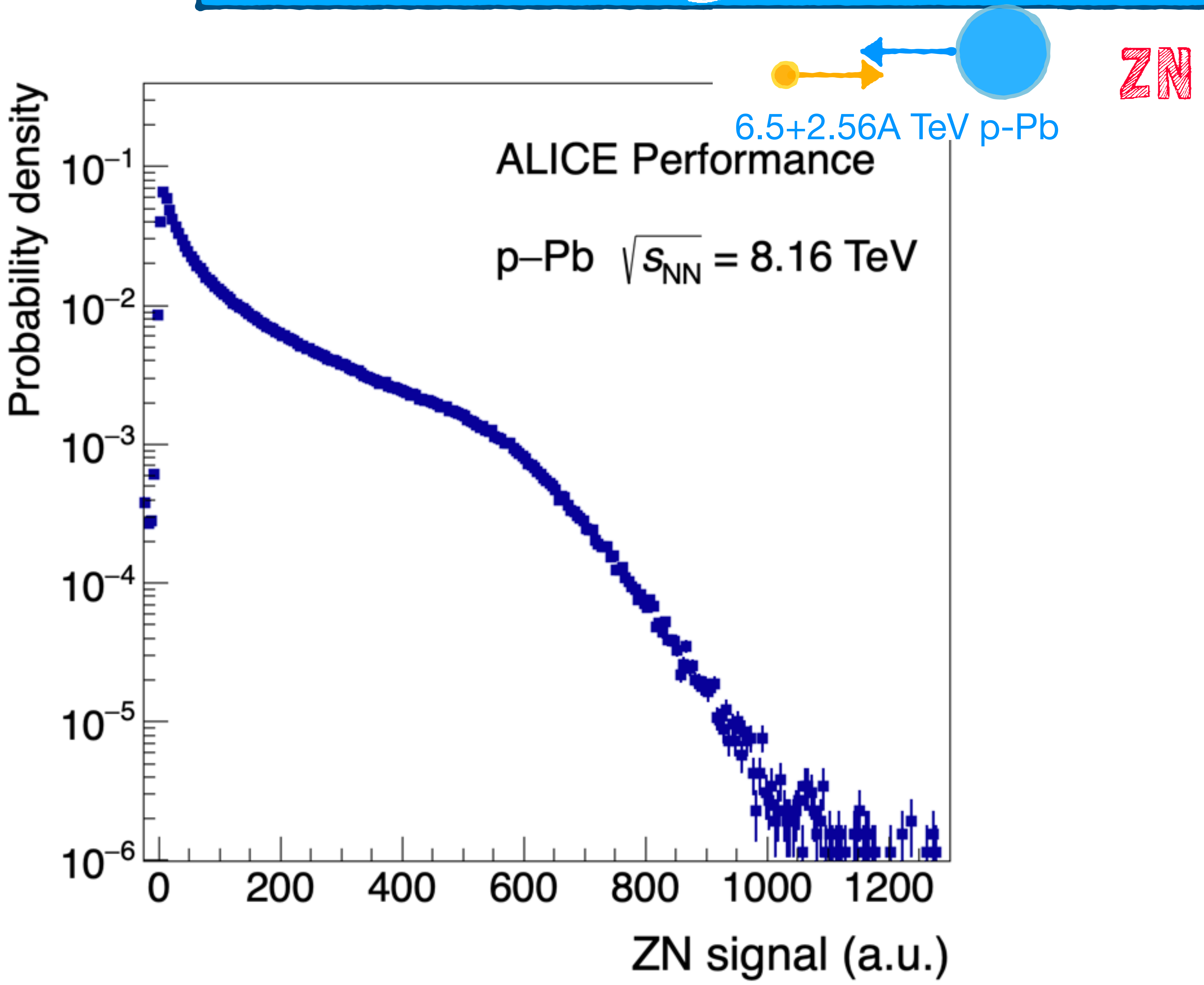
$1/N_{coll}$ scaling valid up to peripheral collisions

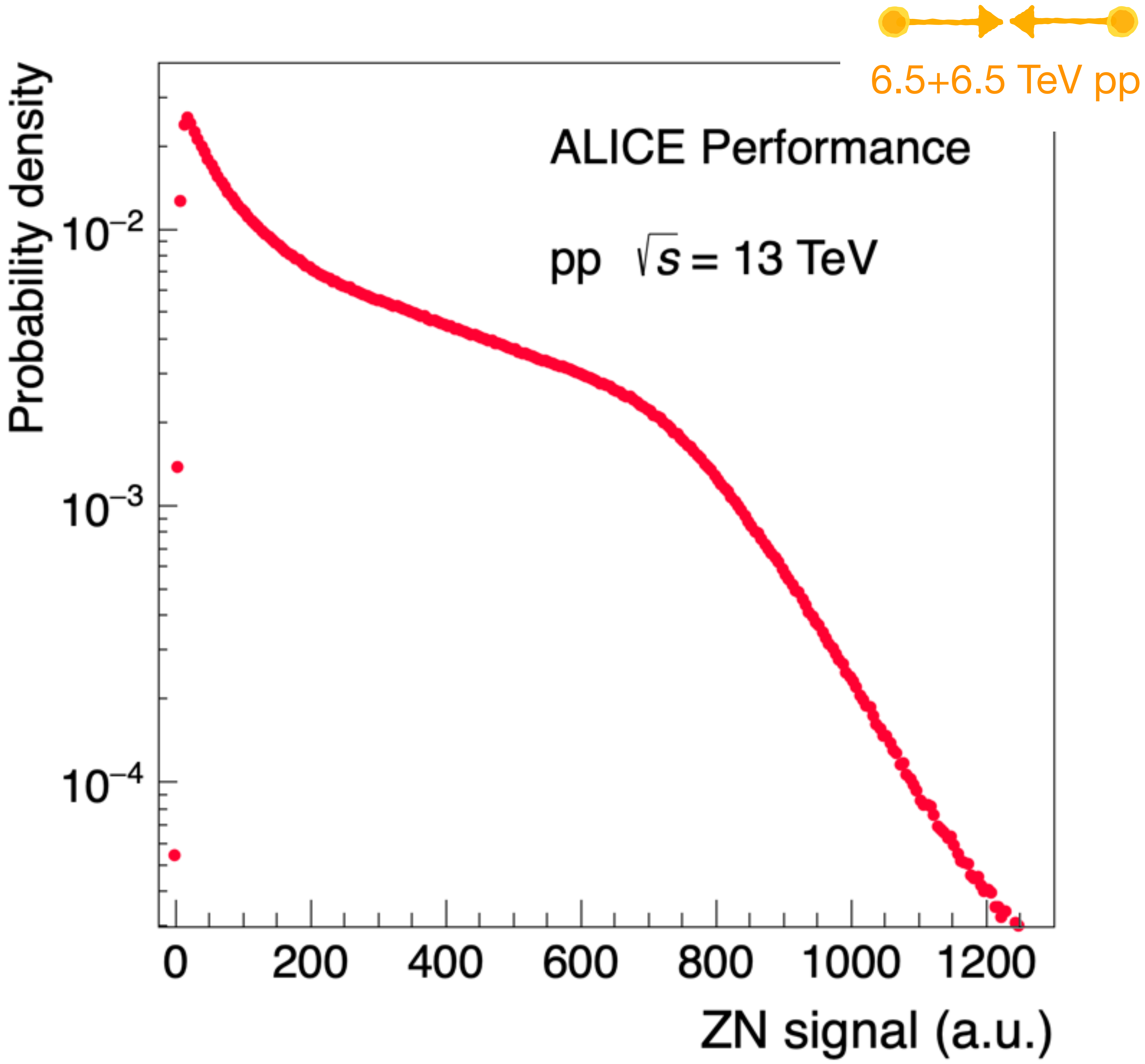
p fragmentation: p-Pb vs. pp



ZN

p fragmentation: p-Pb vs. pp

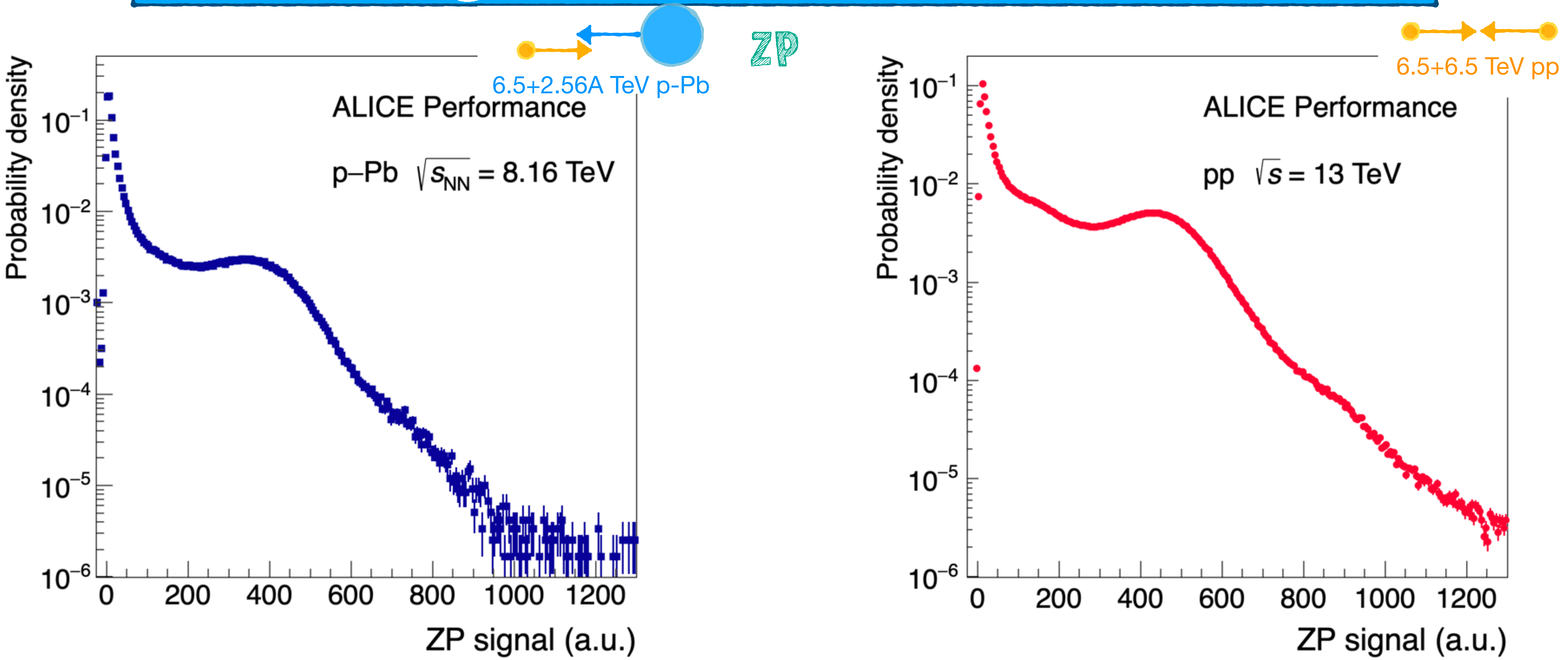




Very similar features in spectra from the p-fragmentation region

Different fraction of events with a signal in ZN over number of MB events triggers: 43% in p-Pb 61% in pp

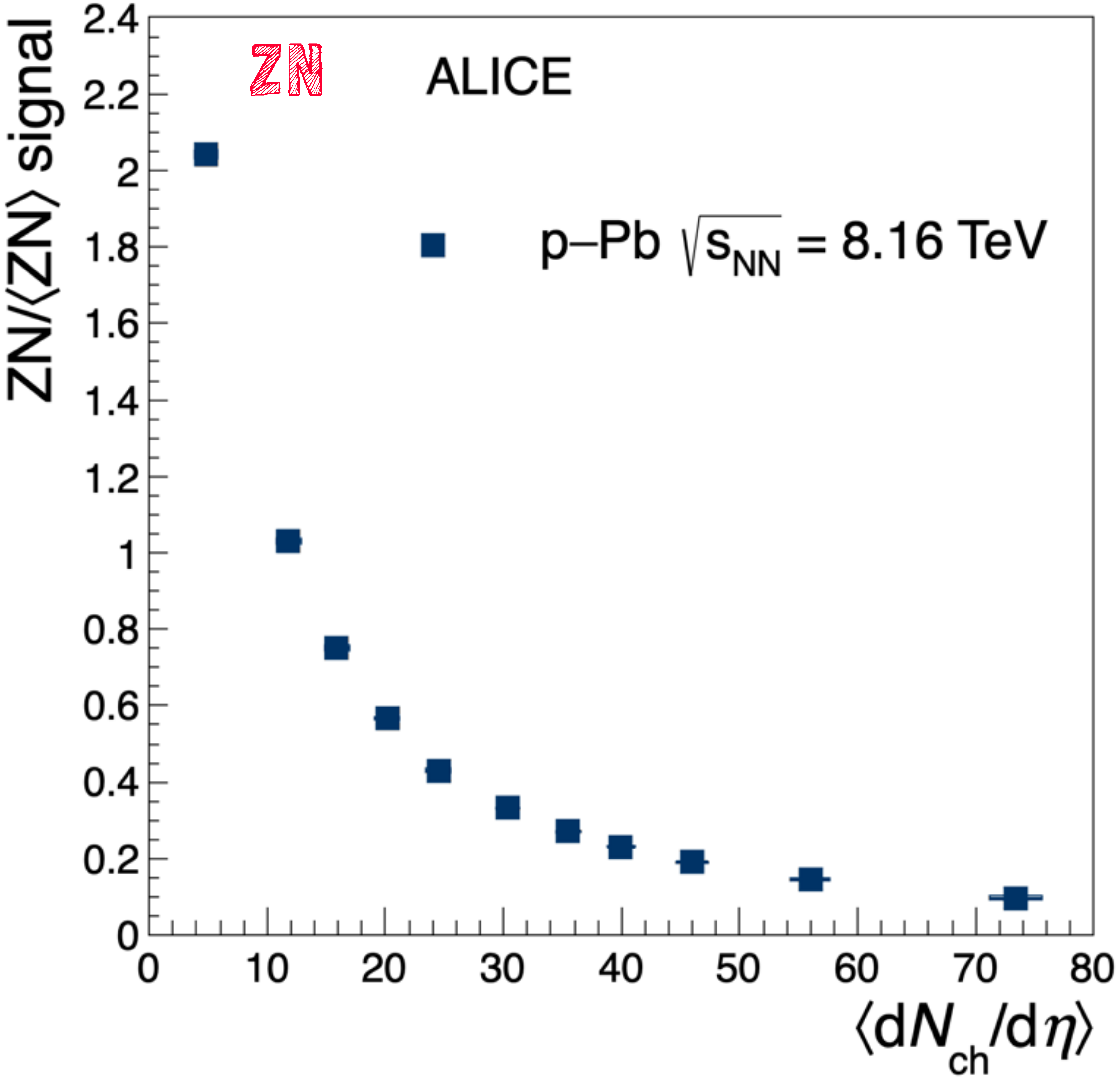
p fragmentation: p-Pb vs. pp

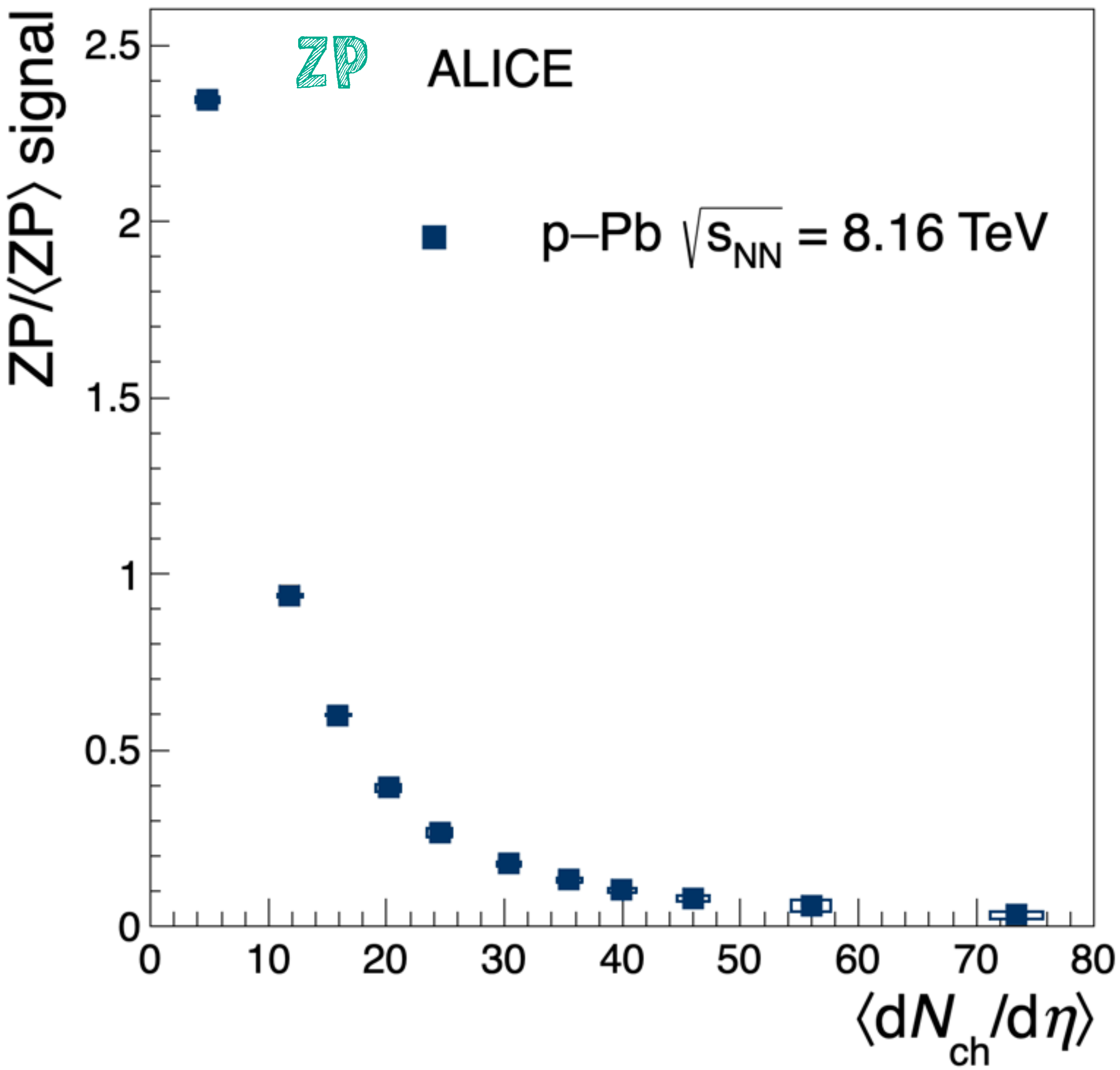


Very similar features in spectra from the p-fragmentation region

Different fraction of events with a signal in ZN over number of MB events triggers: 15% in p-Pb 23% in pp

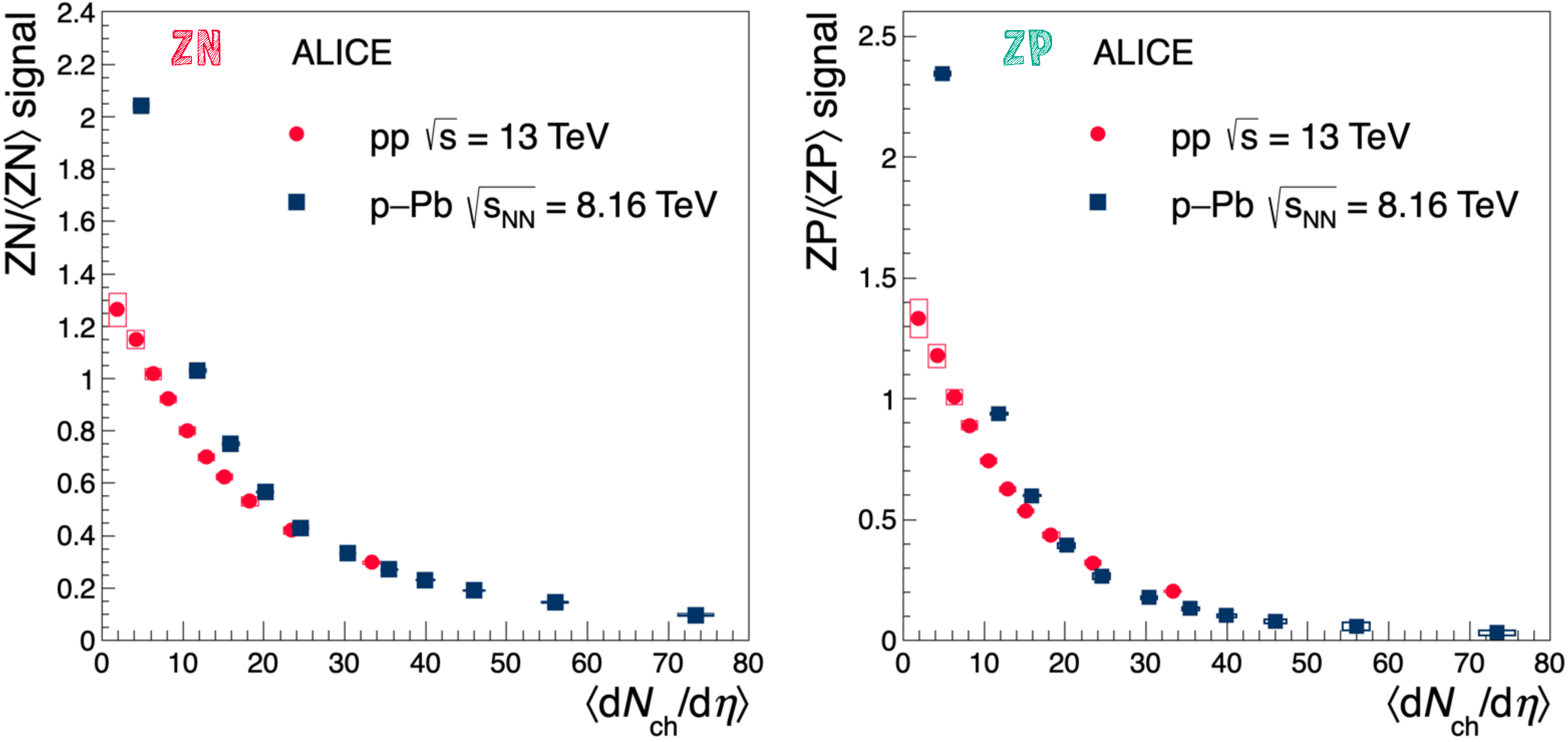
p fragmentation





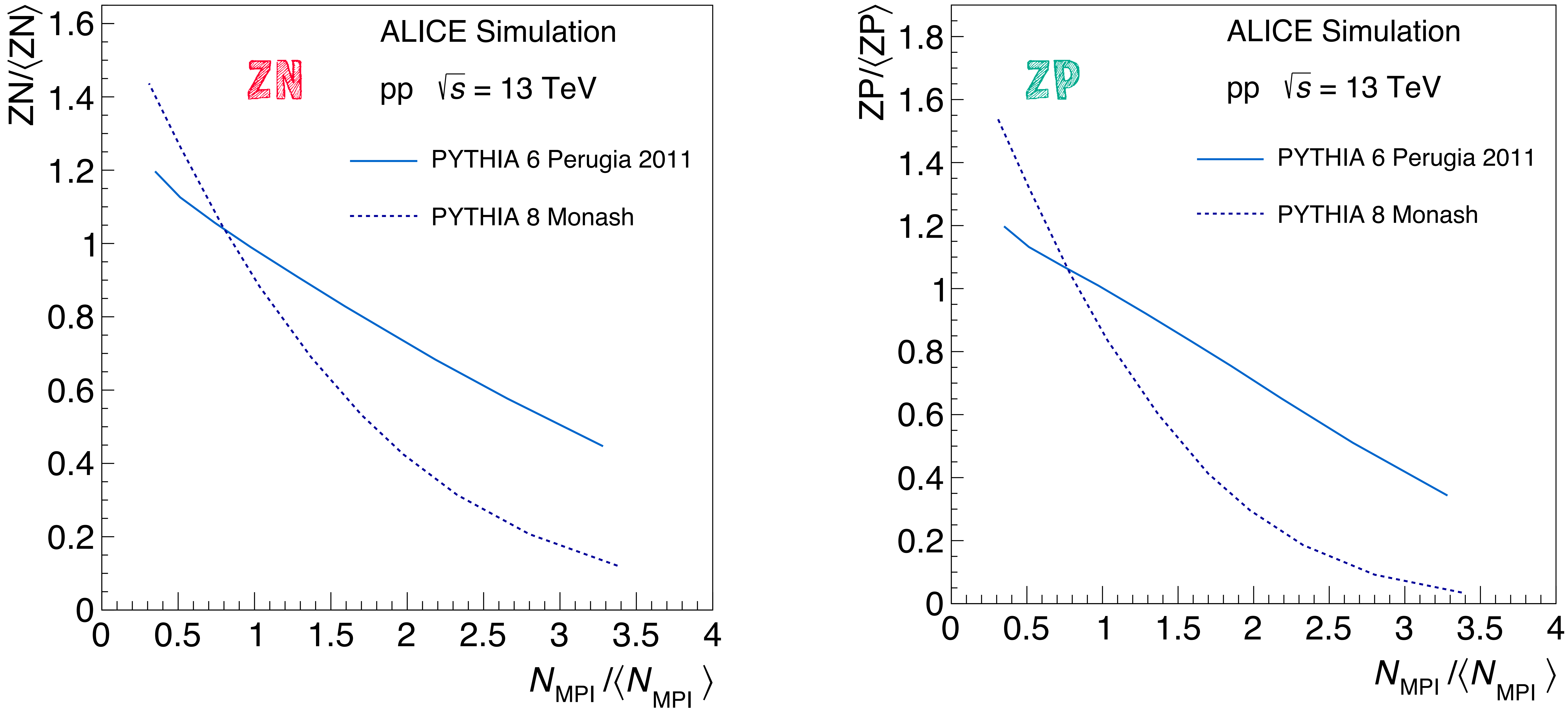
- ZN and ZP energies decrease with increasing multiplicity at midrapidity

p fragmentation



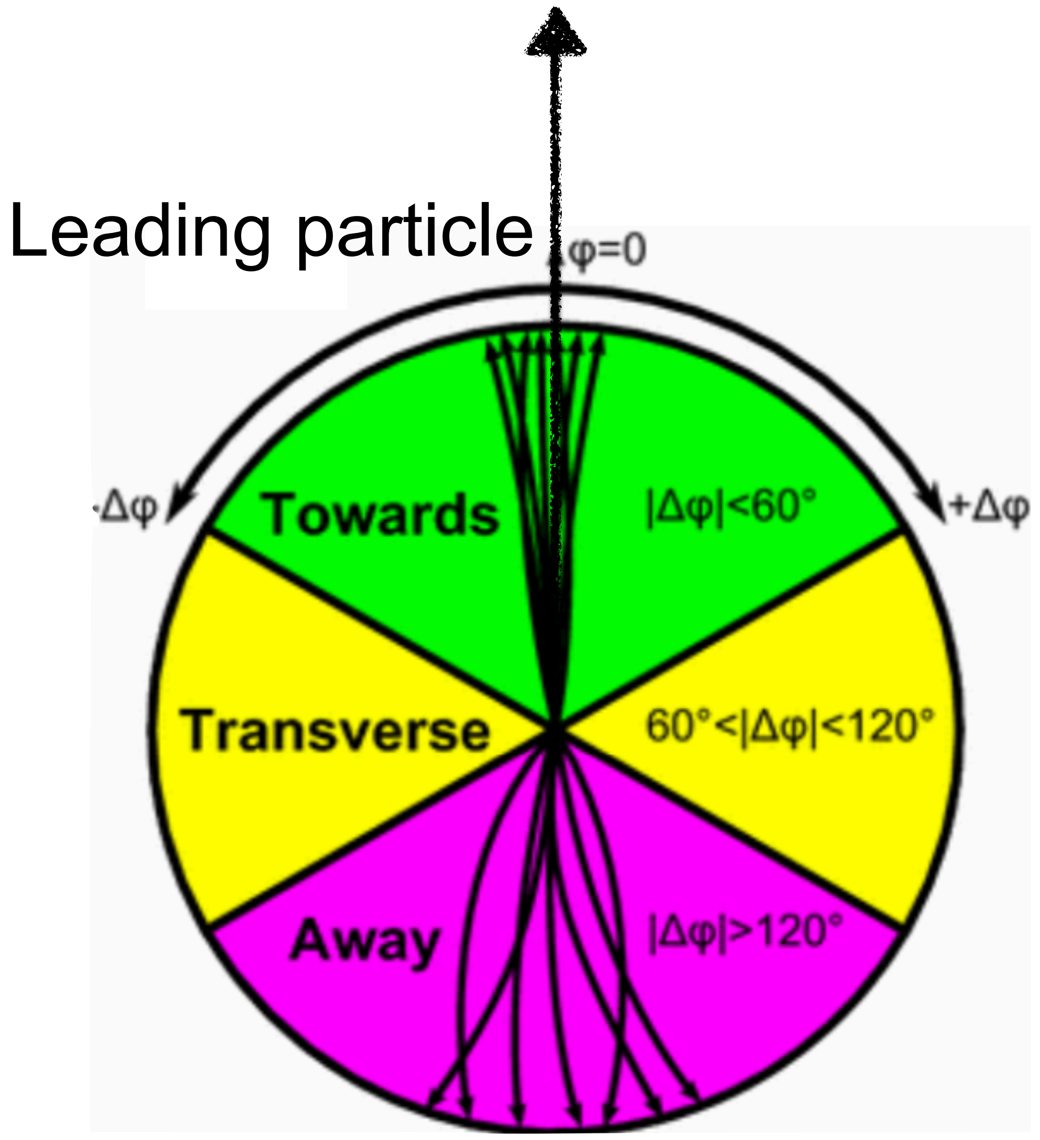
- similar pattern for self-normalized ZN and ZP energies vs. multiplicity at midrapidity between p-Pb and pp collisions

MPIs and ZDC energy



- PYTHIA models predict a decrease of very forward energy for an increasing number of MPIs
- the pattern resembles the observed dependence on charged-particle multiplicity, as expected in an impact-parameter dependent MPI picture

Underlying Event



Particle production in presence of a leading particle (hard scattering) in 3 different regions:

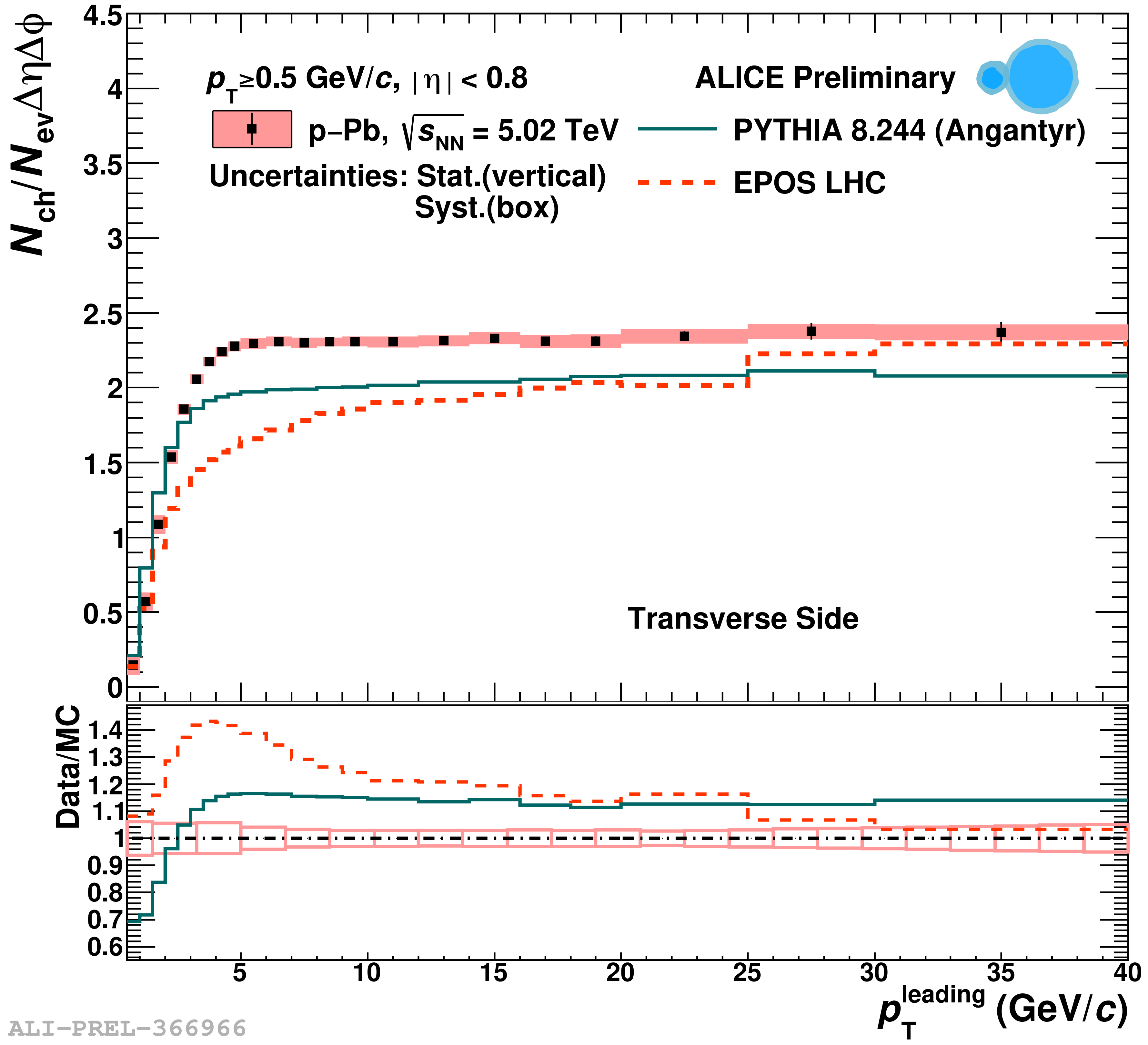
- TOWARDS ($|\Delta\varphi|<60°$)
- AWAY ($|\Delta\varphi|>120°$)

→ Fragmentation products from hard scatterings

- TRANSVERSE ($60°<|\Delta\varphi|<120°$) → Underlying Event (UE), MultiParton Interactions (MPI), ISR/FSR, beam remnants

TRANSVERSE REGION:

- MPI with impact-parameter dependence: smaller impact parameter ➧ larger matter overlap ➧ larger N_{MPI} ➧ higher probability of a hard interaction
- for $p_T^{leading}$ >5 GeV/c: saturation in particle production (pedestal effect, UE) ➧ particle density dominated by MPI



Underlying Event and ZDC energy

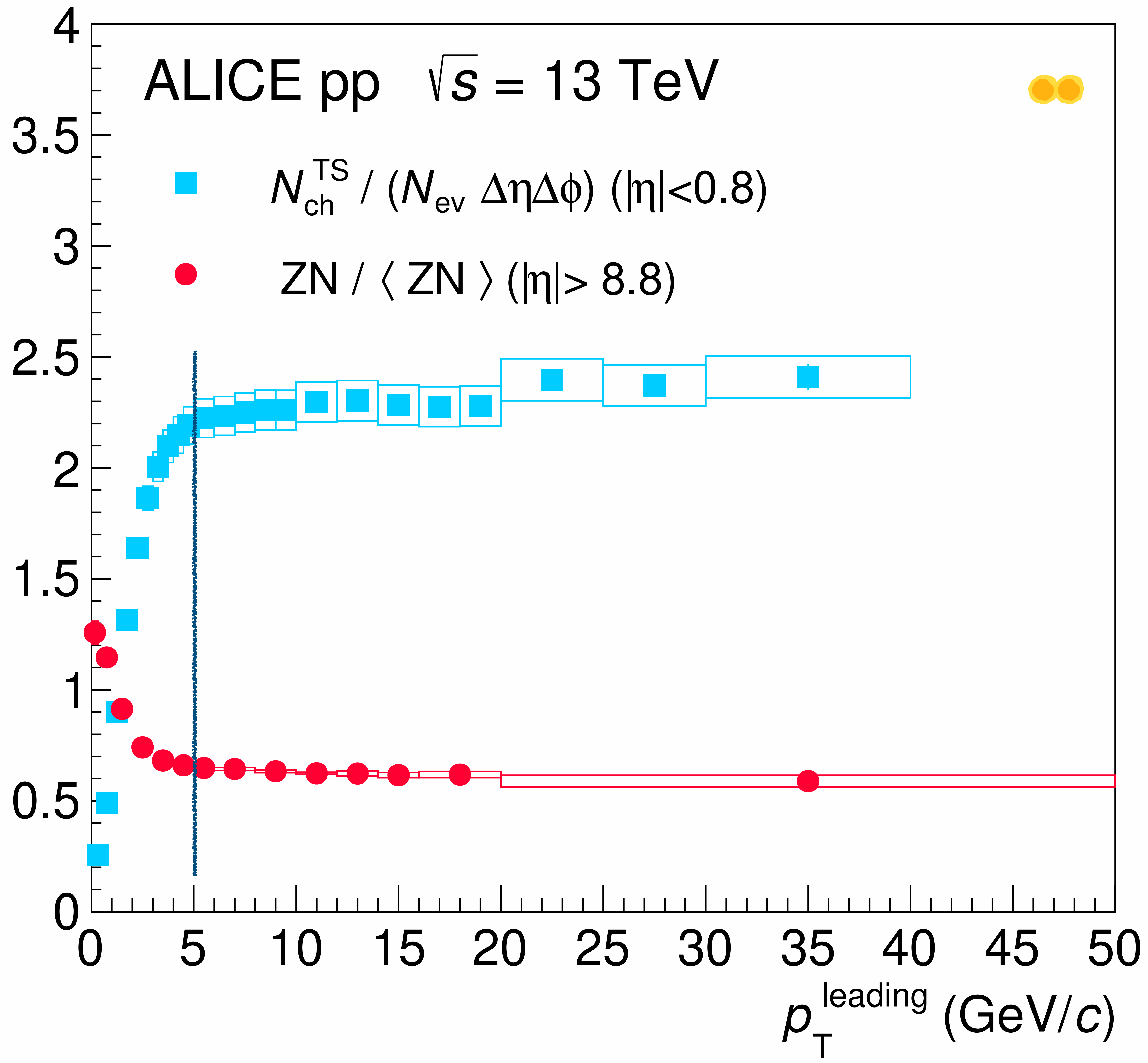
ALICE Coll., arXiv 2107.10757

UE measurements ➧ multiplicity in transverse region constant in events with a larger than average number of MPIs (separation in azimuthal angle from high p_T particle)

ZDC energy ➧ shows saturation in a complementary way to UE (separation in rapidity)

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

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



Underlying Event and ZDC energy

ALICE Coll., arXiv 2107.10757

UE measurements ➧ multiplicity in transverse region constant in events with a larger than average number of MPIs (separation in azimuthal angle from high p_T particle)

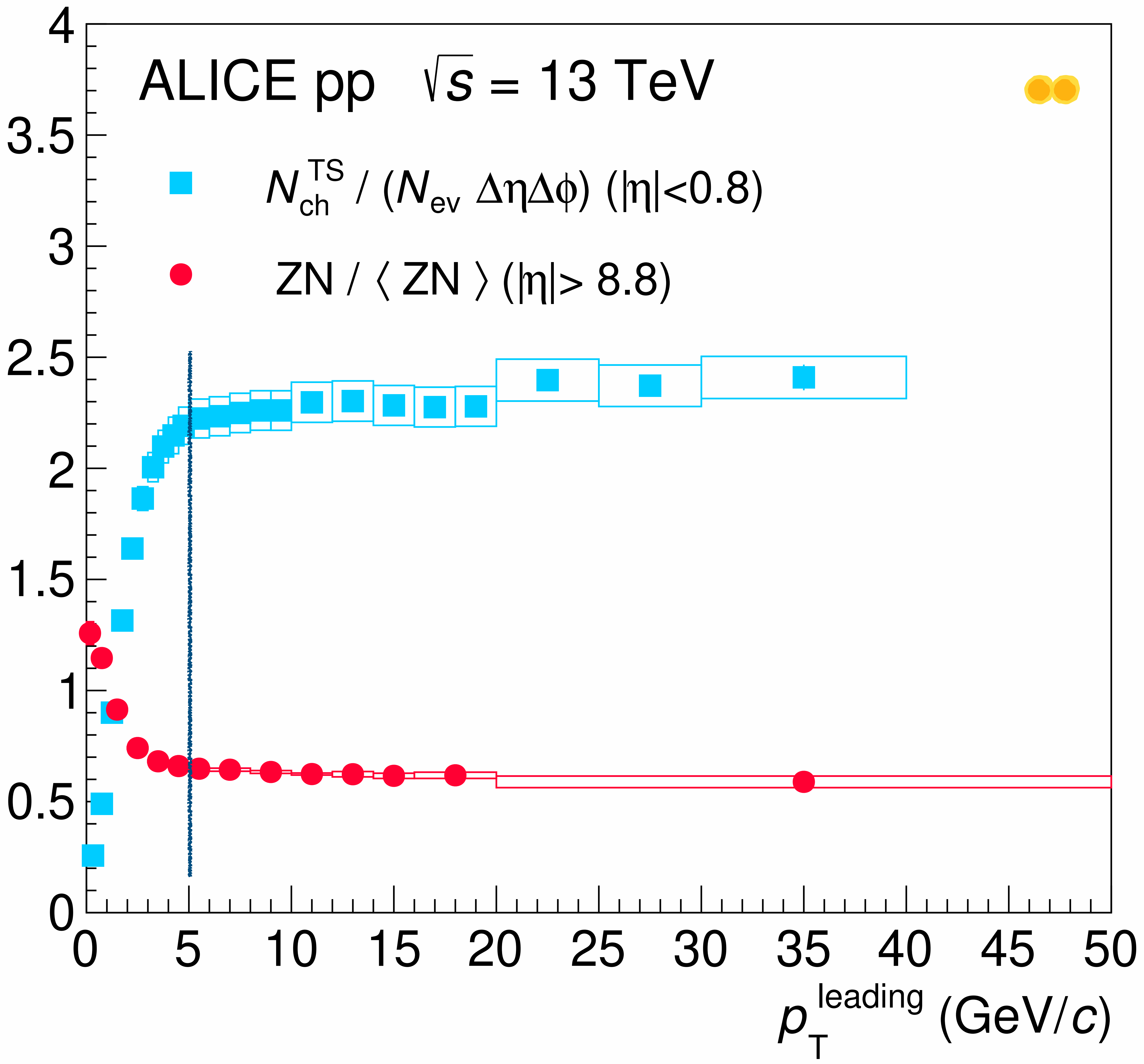
ZDC energy ➧ shows saturation in a complementary way to UE (separation in rapidity)

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

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

Small energy values measured in p-fragmentation region select:

- ➧ larger than average N_{MPI}
- ➧ higher than average multiplicity
- ➧ high-p_T particle production at midrapidity

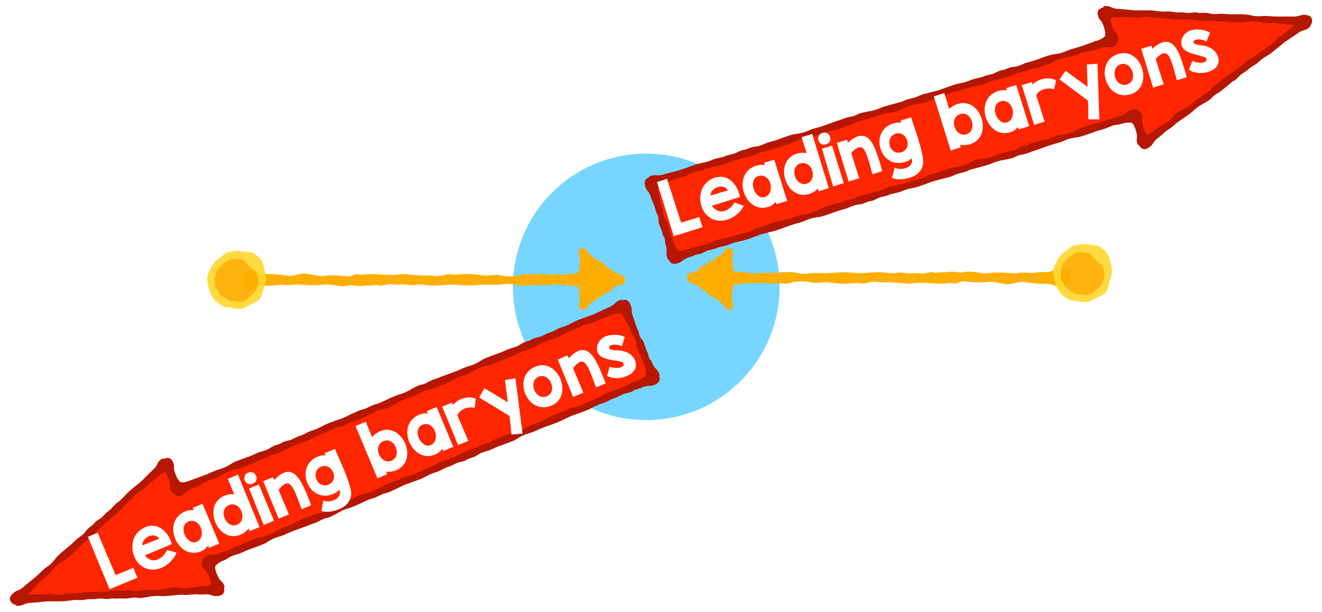


Effective energy

Effective energy = energy available for particle production in pp collisions

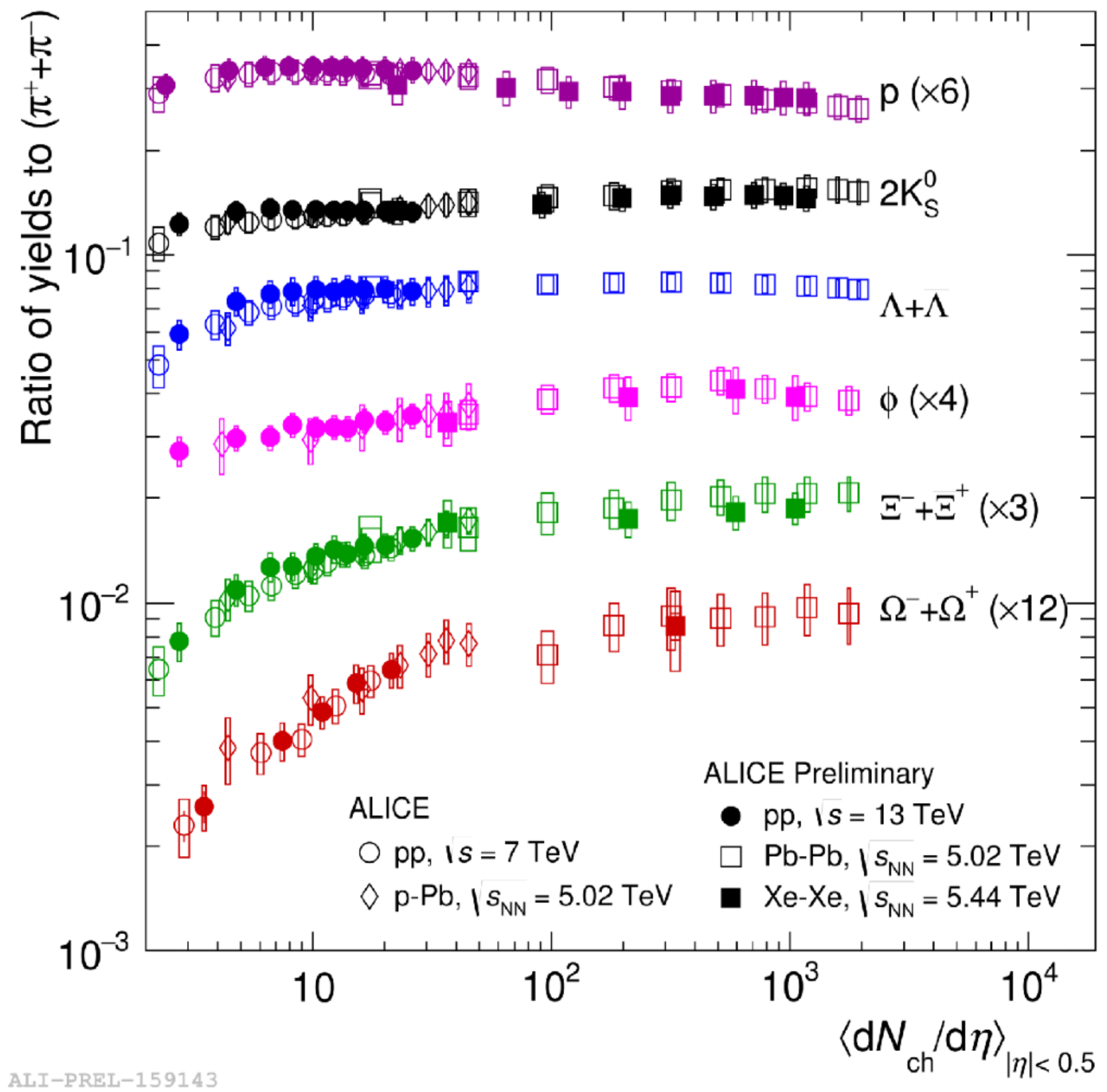
$$E_{EFF} = \sqrt{s} - E_{ZDC}$$

- reduced relative to the center of mass energy due to the high probability to emit leading baryons in the forward region (leading effect)
- can be estimated measuring ZDC energy

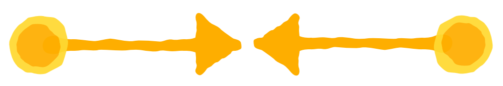


Effective energy is correlated to the initial state

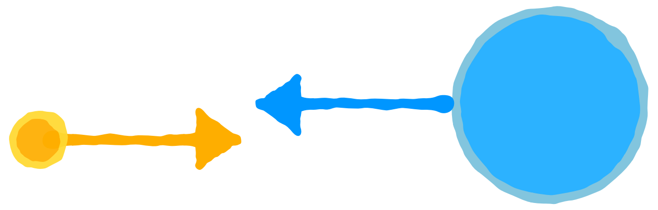
- study dependence of observables on initial state (energy carried by leading baryons in ZDCs) and on final state (charged particle multiplicity) to disentangle the driving variable
- ongoing analysis in ALICE (strangeness production in pp collisions)



Wrap up



6.5+6.5 TeV pp

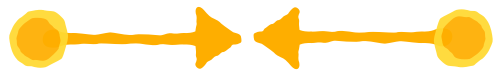


6.5+2.56A TeV p-Pb

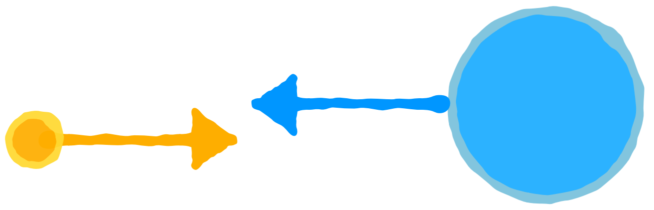
Similar features shown in p-fragmentation region for pp and p-Pb collisions

Same proton beam energy
➧ study proton fragmentation with two different targets (p and Pb)

Wrap up



6.5+6.5 TeV pp

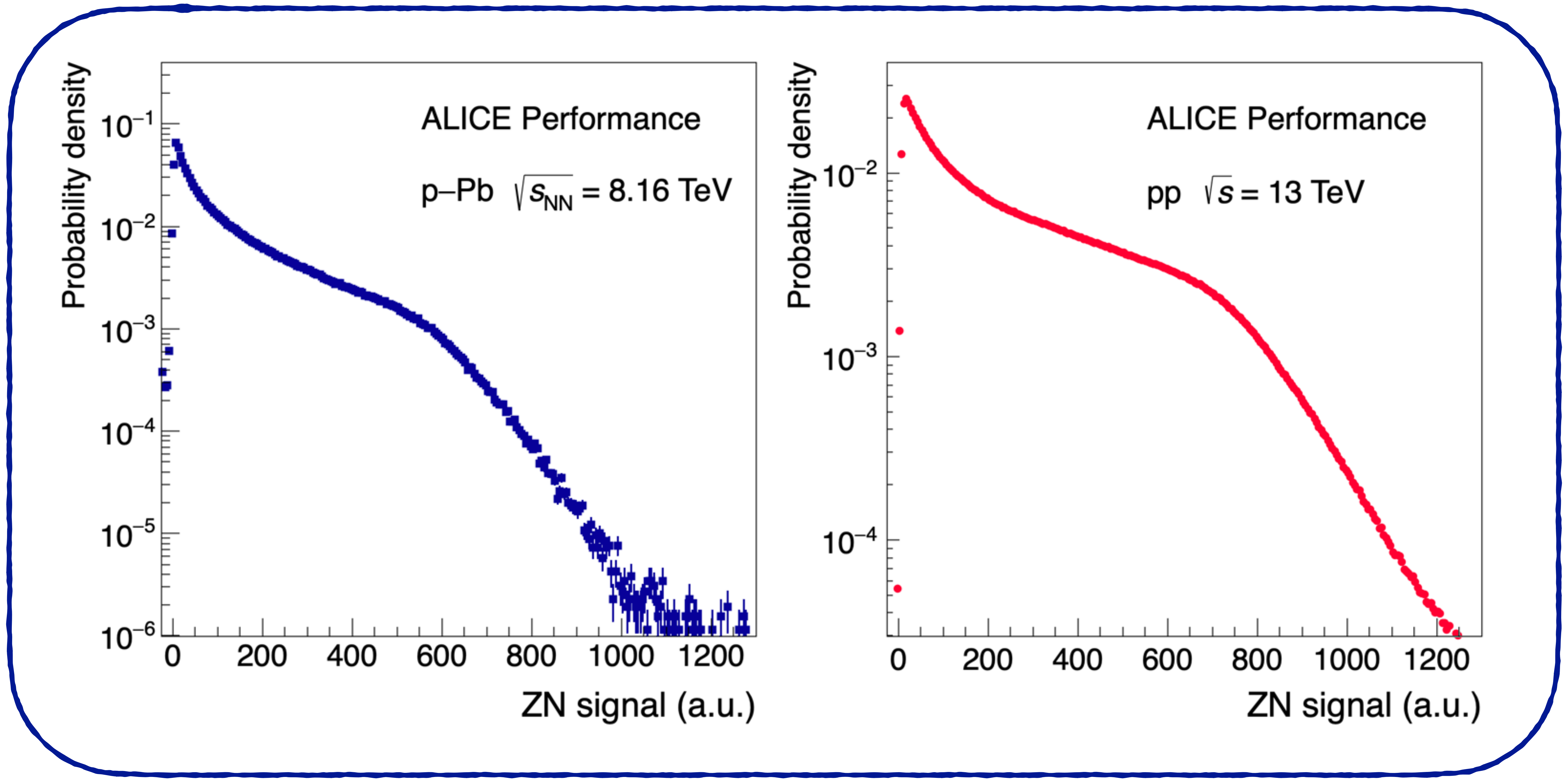


6.5+2.56A TeV p-Pb

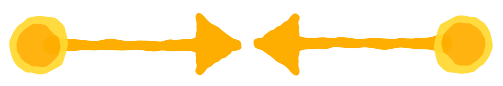
Same proton beam energy
➧ study proton fragmentation with two different targets (p and Pb)

Similar features shown in p-fragmentation region for pp and p-Pb collisions

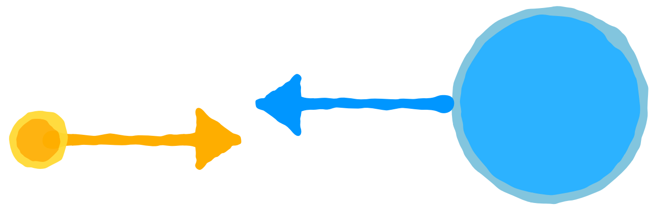
Spectra



Wrap up



6.5+6.5 TeV pp

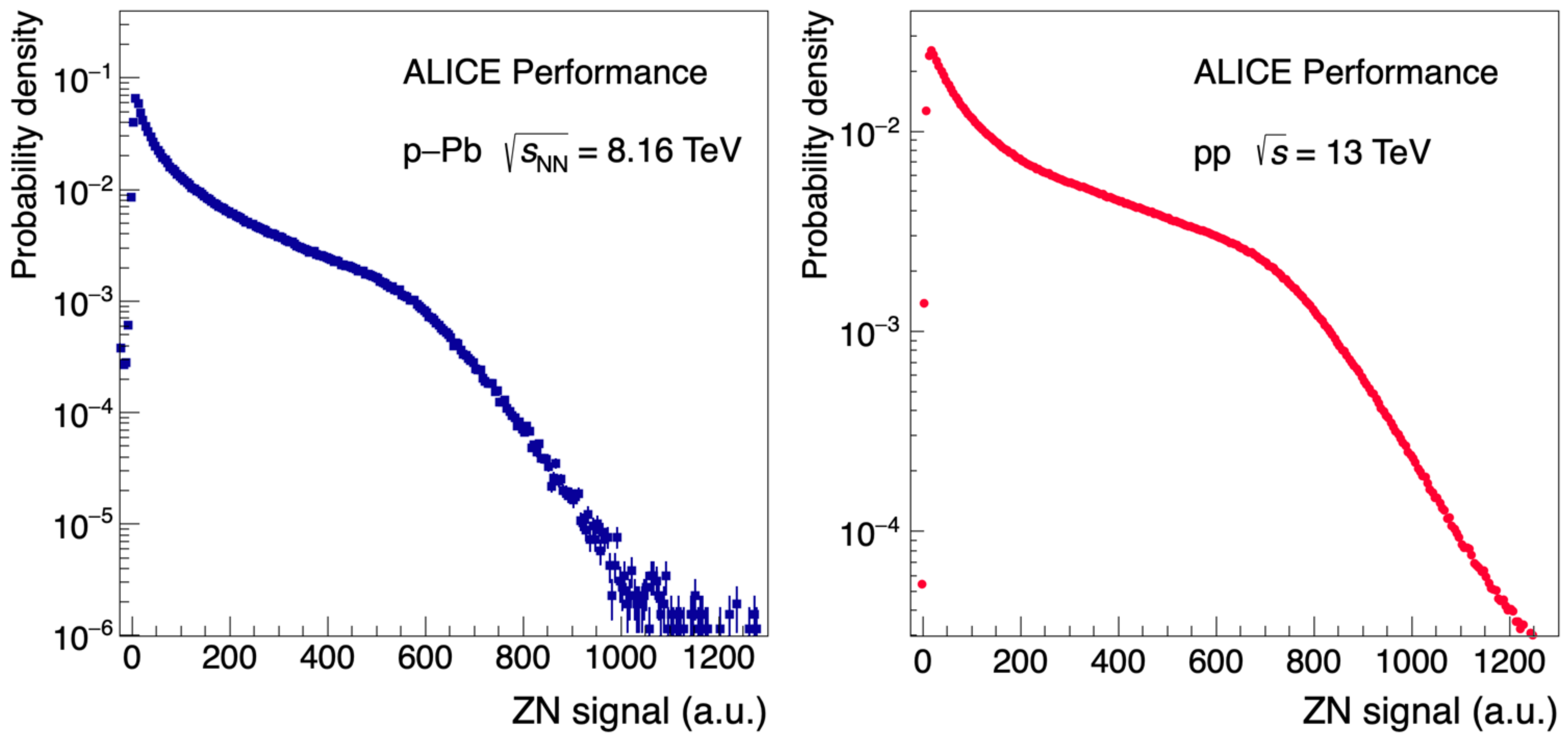


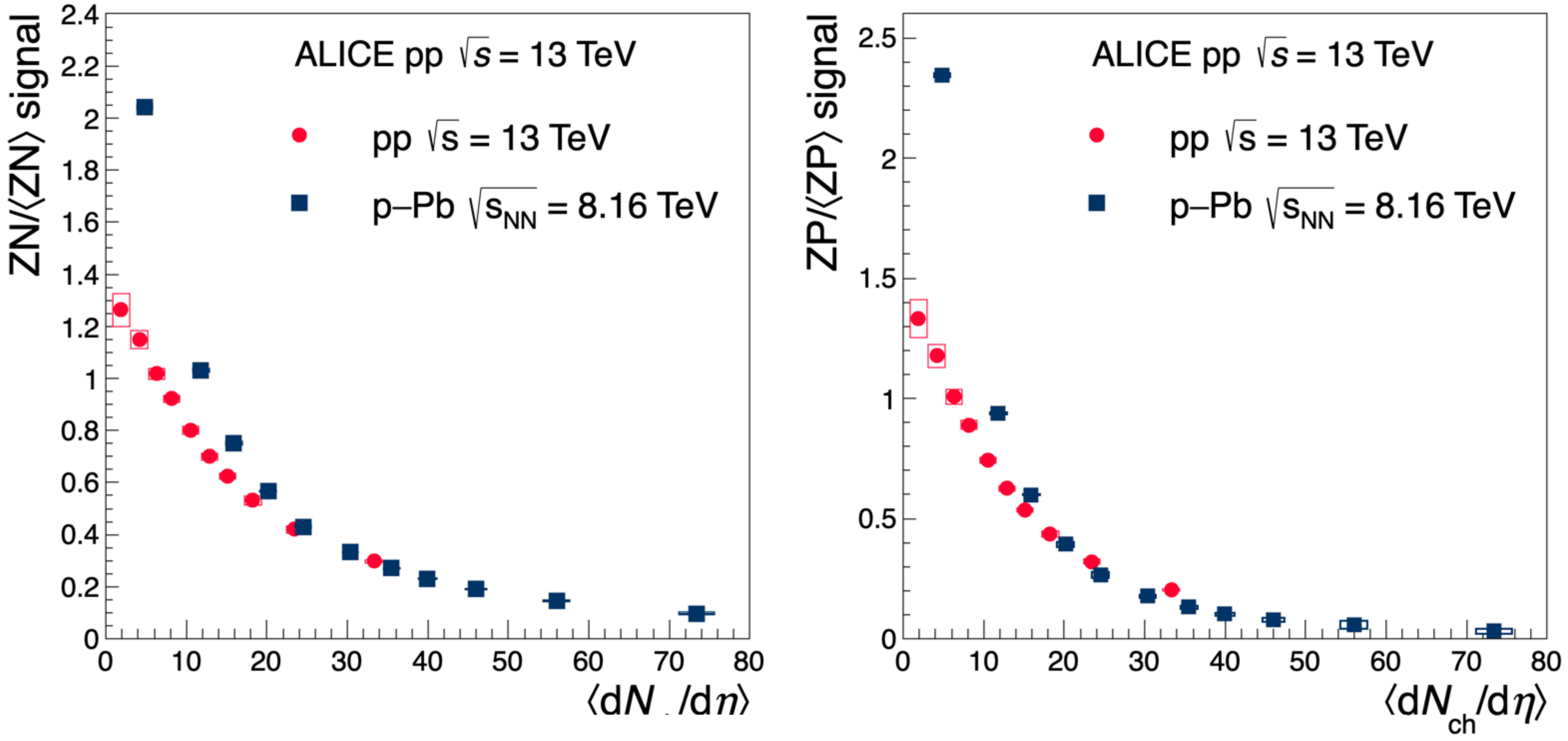
6.5+2.56A TeV p-Pb

Similar features shown in p-fragmentation region for pp and p-Pb collisions

Same proton beam energy
➧ study proton fragmentation with two different targets (p and Pb)

Spectra





Self-normalized ZDC energy vs. mid rapidity multiplicity

Wrap up

p-Pb collisions energy at 2 different center-of-mass energies:

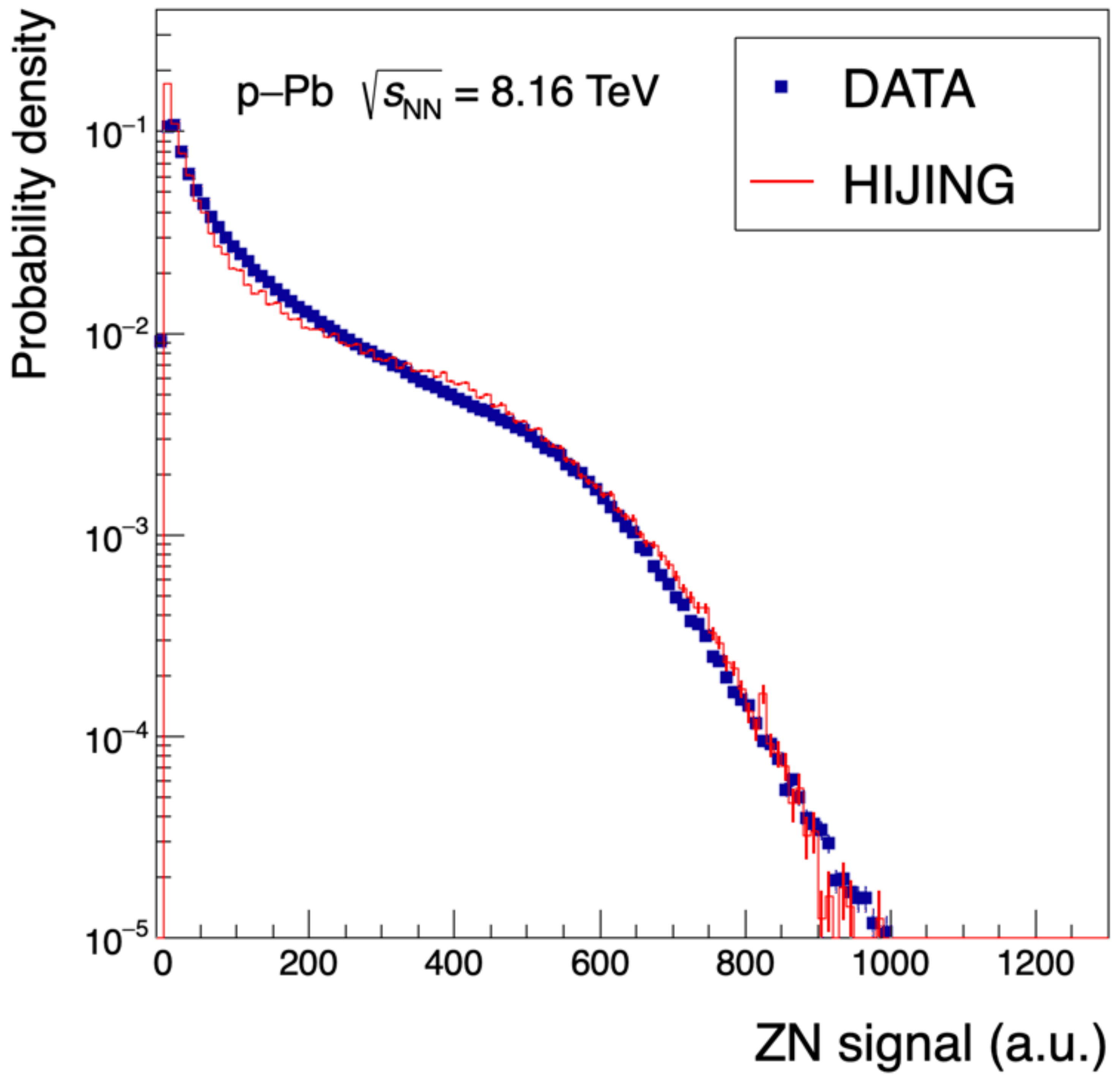
- neutral forward energy in p-fragmentation region decreases with centrality ~1/N_{coll} for central collisions
- neutral forward energy in Pb-fragmentation region increases with centrality ~N_{coll} over a wide centrality range

Wrap up

p-Pb collisions energy at 2 different center-of-mass energies:

- neutral forward energy in p-fragmentation region decreases with centrality ~$1/N_{coll}$ for central collisions
- neutral forward energy in Pb-fragmentation region increases with centrality ~N_{coll} over a wide centrality range

HIJING describes quite well the ZN spectrum in the p-fragmentation region (full simulation through the ALICE setup)

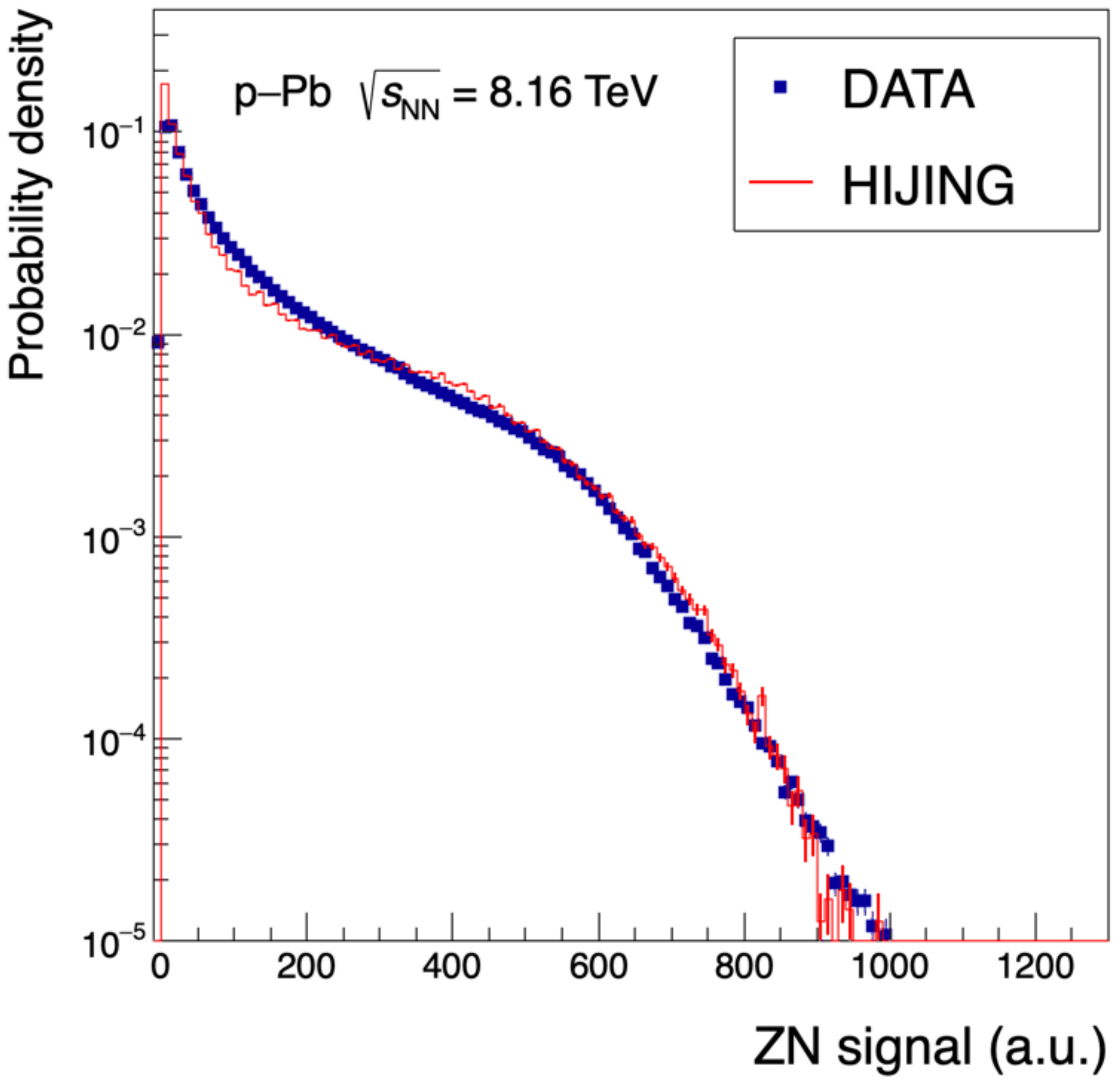


Wrap up

p-Pb collisions energy at 2 different center-of-mass energies:

- neutral forward energy in p-fragmentation region decreases with centrality ~$1/N_{coll}$ for central collisions
- neutral forward energy in Pb-fragmentation region increases with centrality ~N_{coll} over a wide centrality range

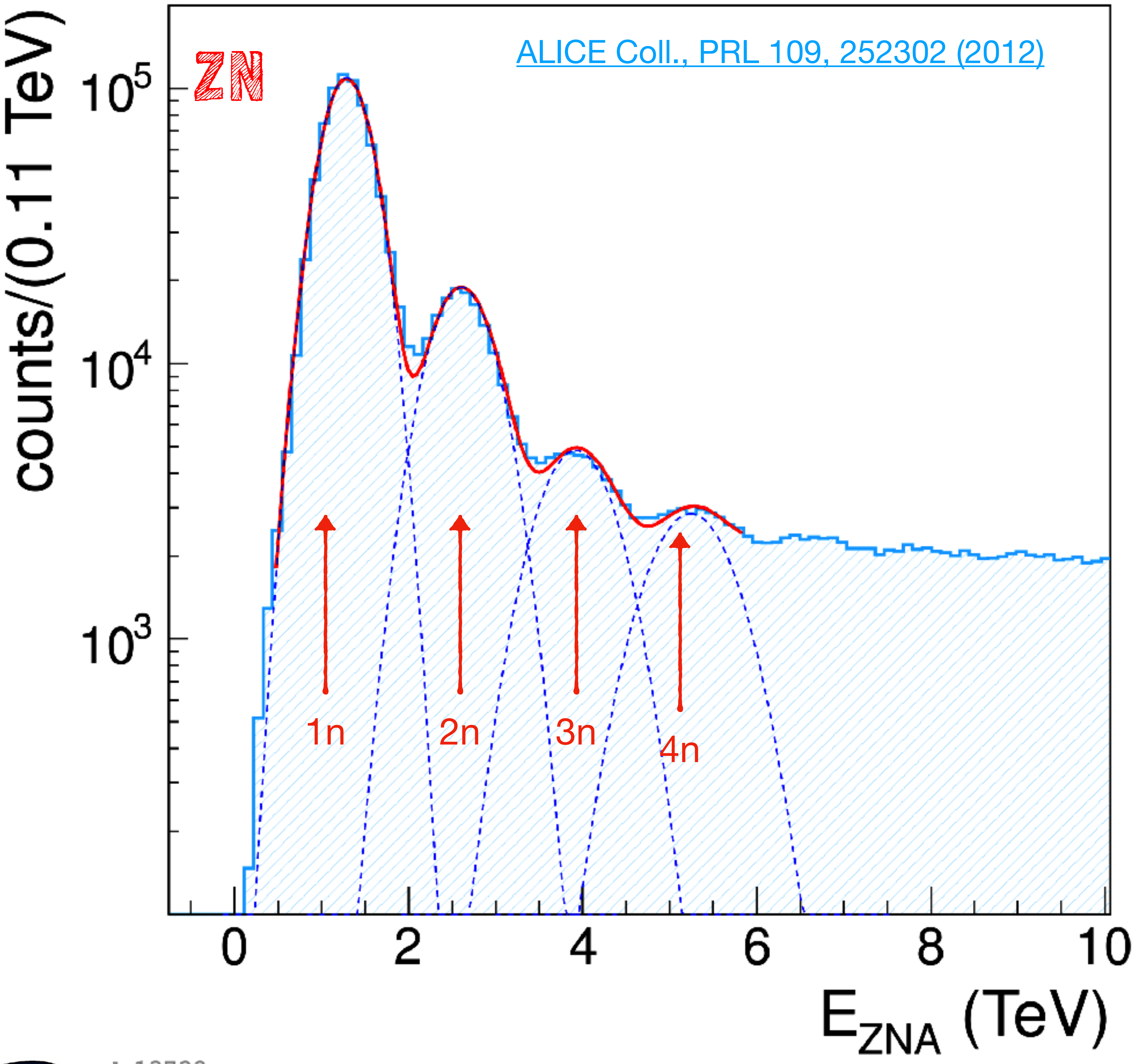
HIJING describes quite well the ZN spectrum in the p-fragmentation region (full simulation through the ALICE setup)



More results in p-A and pp collision can be extracted from LHC data to relate very forward (ZDC) energy to UE, MPIs or effective energy...

More material...

ZN spectra in Pb-Pb



Selecting signal only one side ZN (requesting no signal on the other side ZN) the events selected comes from single EMD processes

Symmetric events (from hadronic and mutual EMD processes) are removed

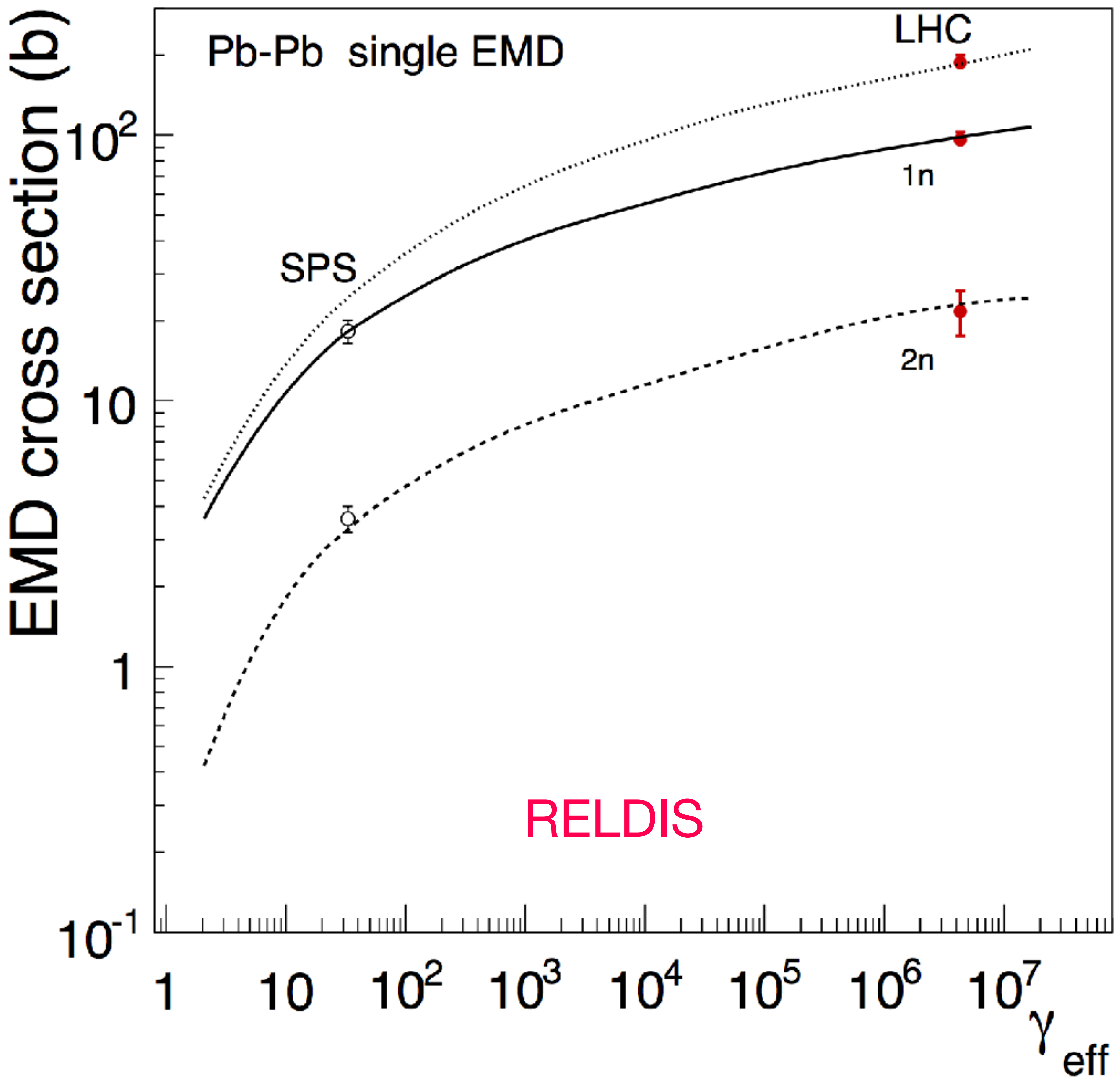
Fitting the single, double…neutron peaks allows the energy calibration of the ZN spectra.

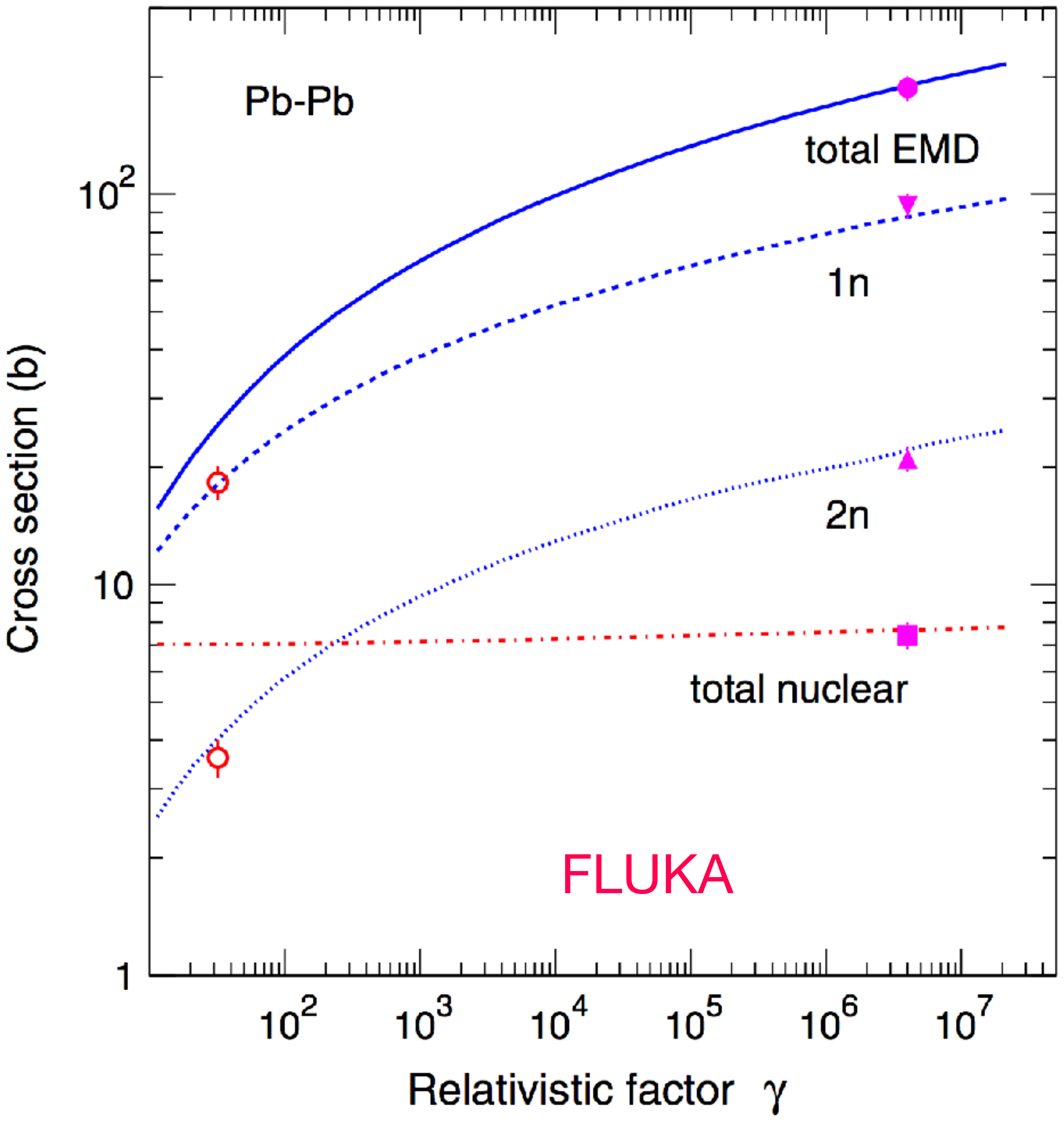
Similar approach is used to calibrate ZP

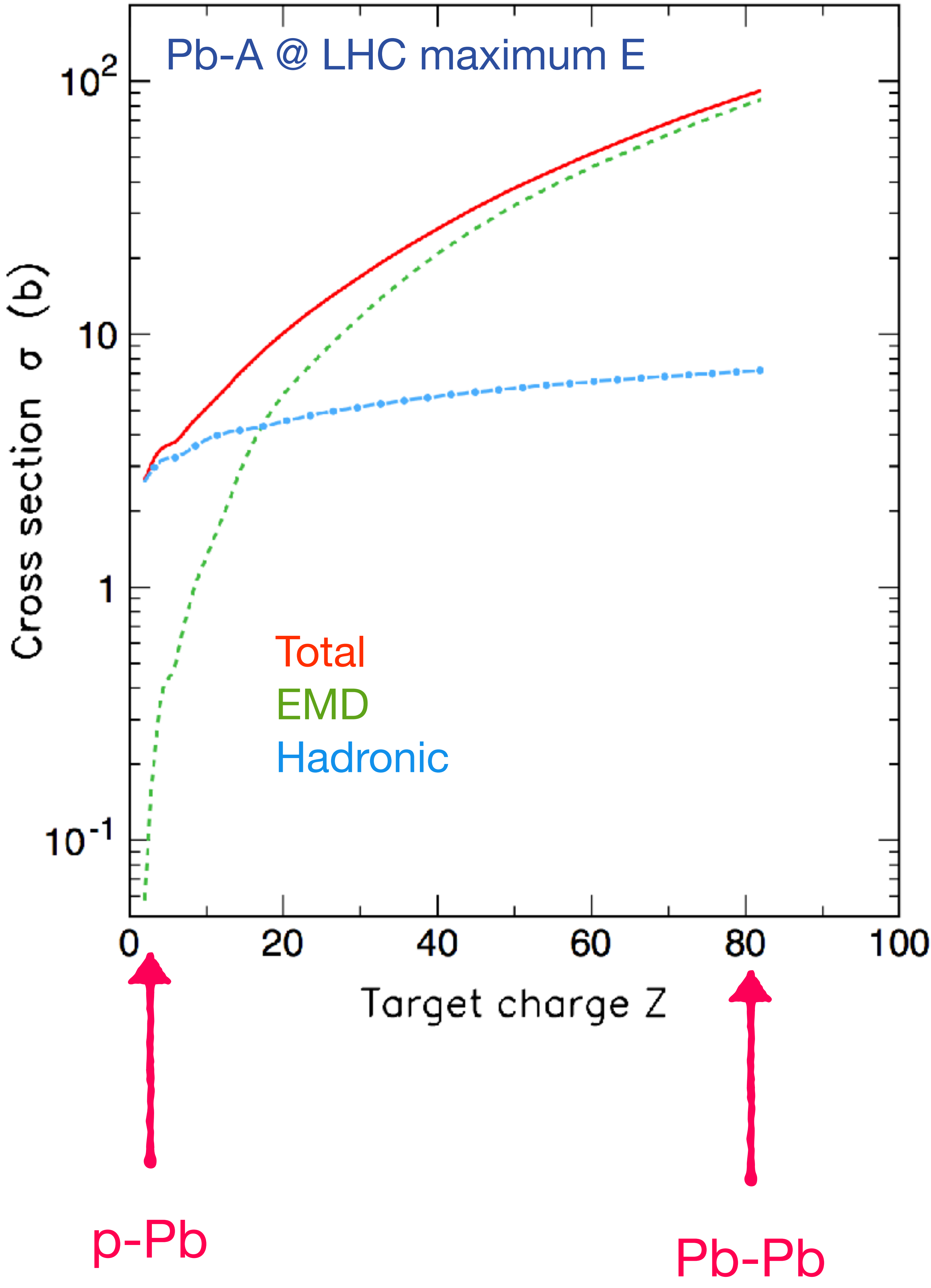
Models for EMD processes

ALICE Coll., PRL 109, 252302 (2012)

Braun et al., Phys.Rev. ST Accel. Beams 17, 021006 (2014)







EMD in Pb-Pb collisions

ALICE Coll., PRL 109, 252302 (2012)

- Single EMD cross section is more than 20 times larger than the hadronic cross-section at $\sqrt{s_{NN}}$ = 2.76 TeV

Process	Cross-section (b)	RELDIS
Mutual EMD	5.7 ± 0.1 stat ± 0.4 syst	192.9 ± 9.2
Hadronic	7.7 ± 0.1 stat $^{+0.6}_{-0.5}$ syst	179.7 ± 9.2
Single EMD	187.4 ± 0.2 stat $^{+13.2}_{-11.2}$ syst	5.5 ± 0.6

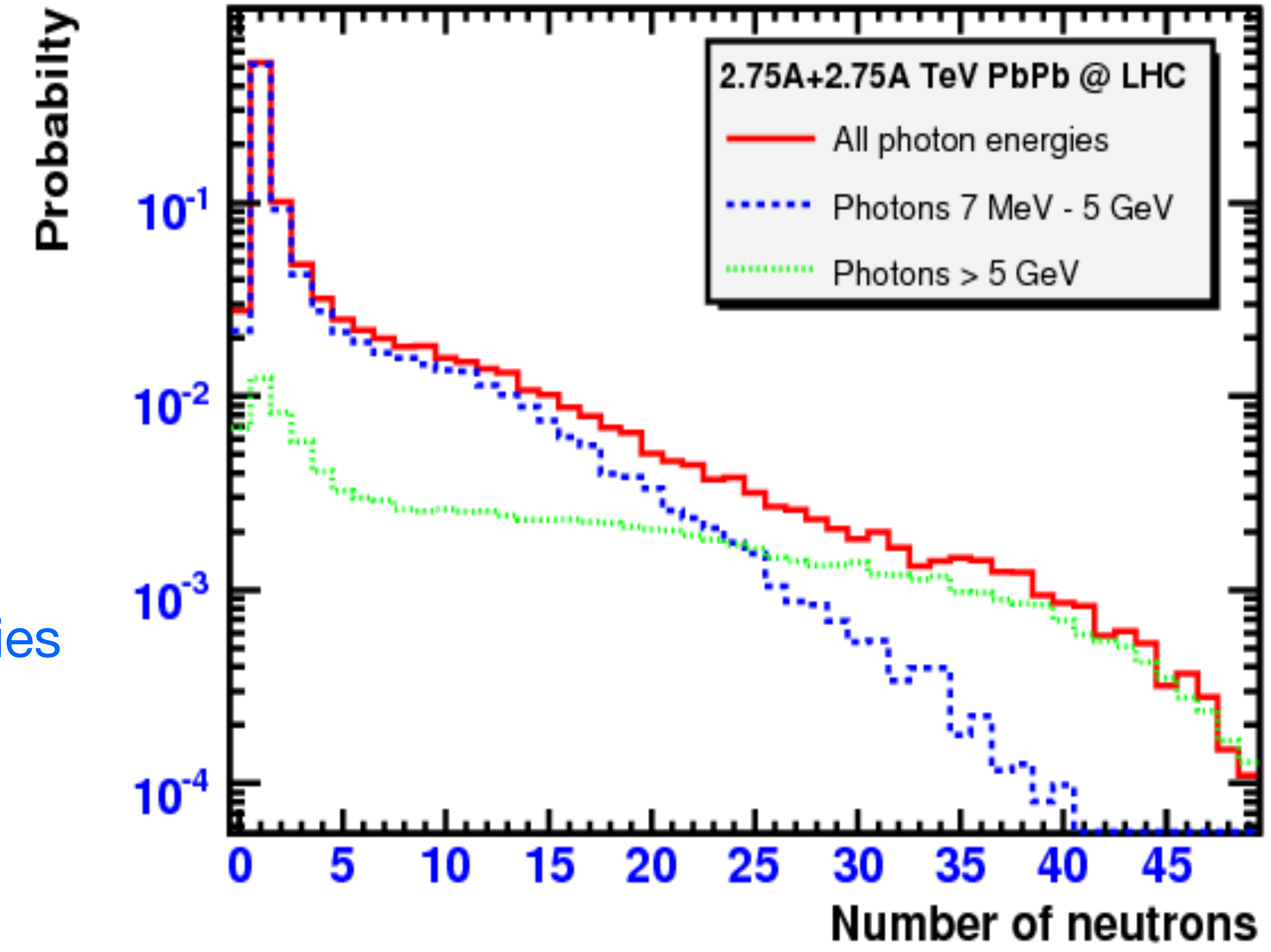
- More than 60% of neutron emission in single EMD processes occur via 1n, 2n channels

Ratio	Data (%)	RELDIS
$1n/N_{TOT}$	51.5 ± 0.4 stat ± 0.2 syst	54.2 ± 2.4
$2n/N_{TOT}$	11.6 ± 0.3 stat ± 0.5 syst	12.7 ± 0.8
$3n/N_{TOT}$	3.6 ± 0.2 stat ± 0.2 syst	5.4 ± 0.7
2n/1n	22.5 ± 0.5 stat ± 0.9 syst	23.5 ± 2.5

Models for EM processes

RELDIS

- treatment of photonuclear interactions at very high energies
- designed to study excitation and fragmentation in UPC
- equivalent photons from n emission threshold (E_γ<7 MeV)
- may be less accurate for E_γ>10 GeV photons
- validated for photon-induced reactions below 10 GeV and for EM fragmentation of various nuclei at AGS, SPS, RHIC and LHC energies

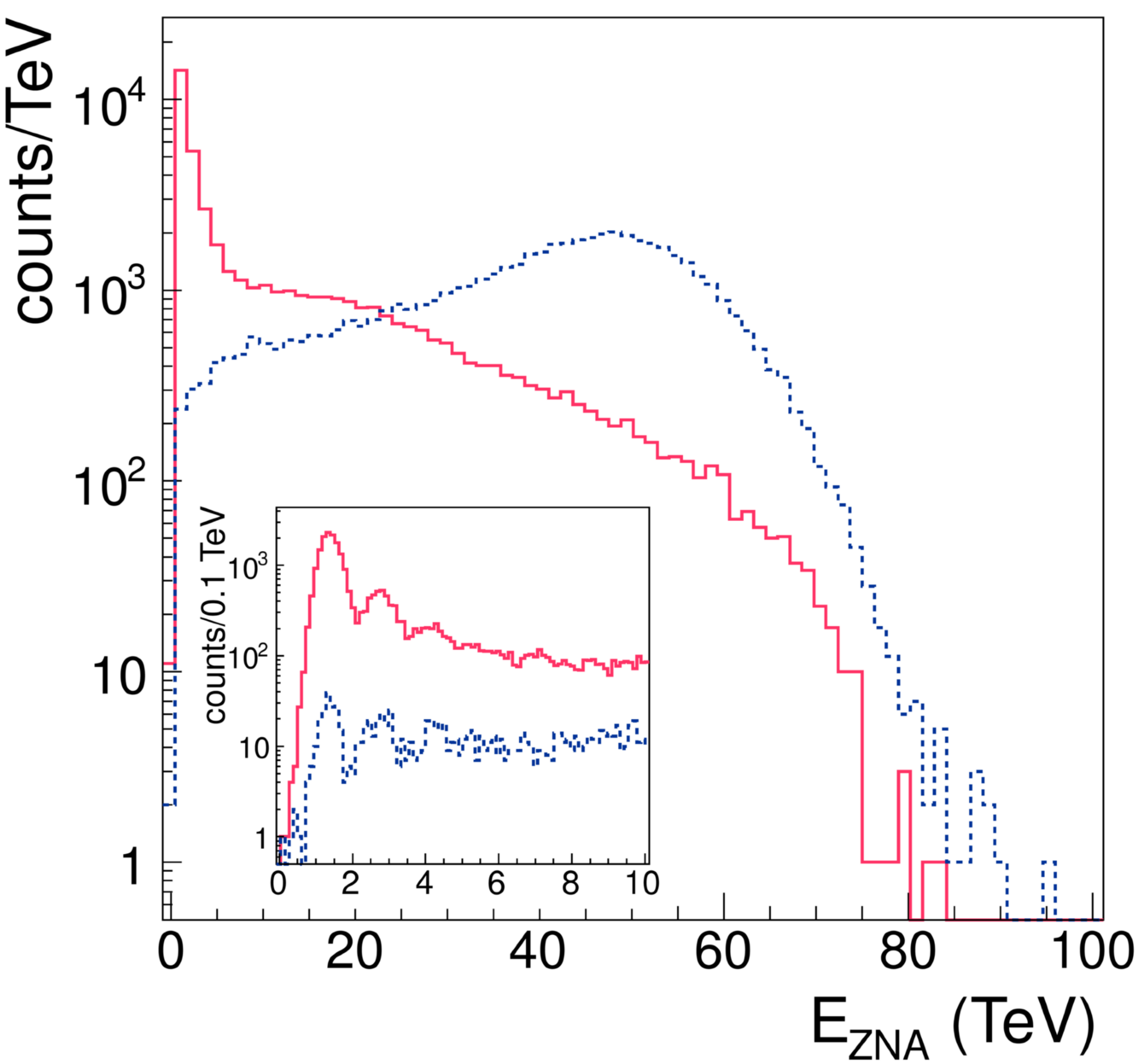


STARLIGHT

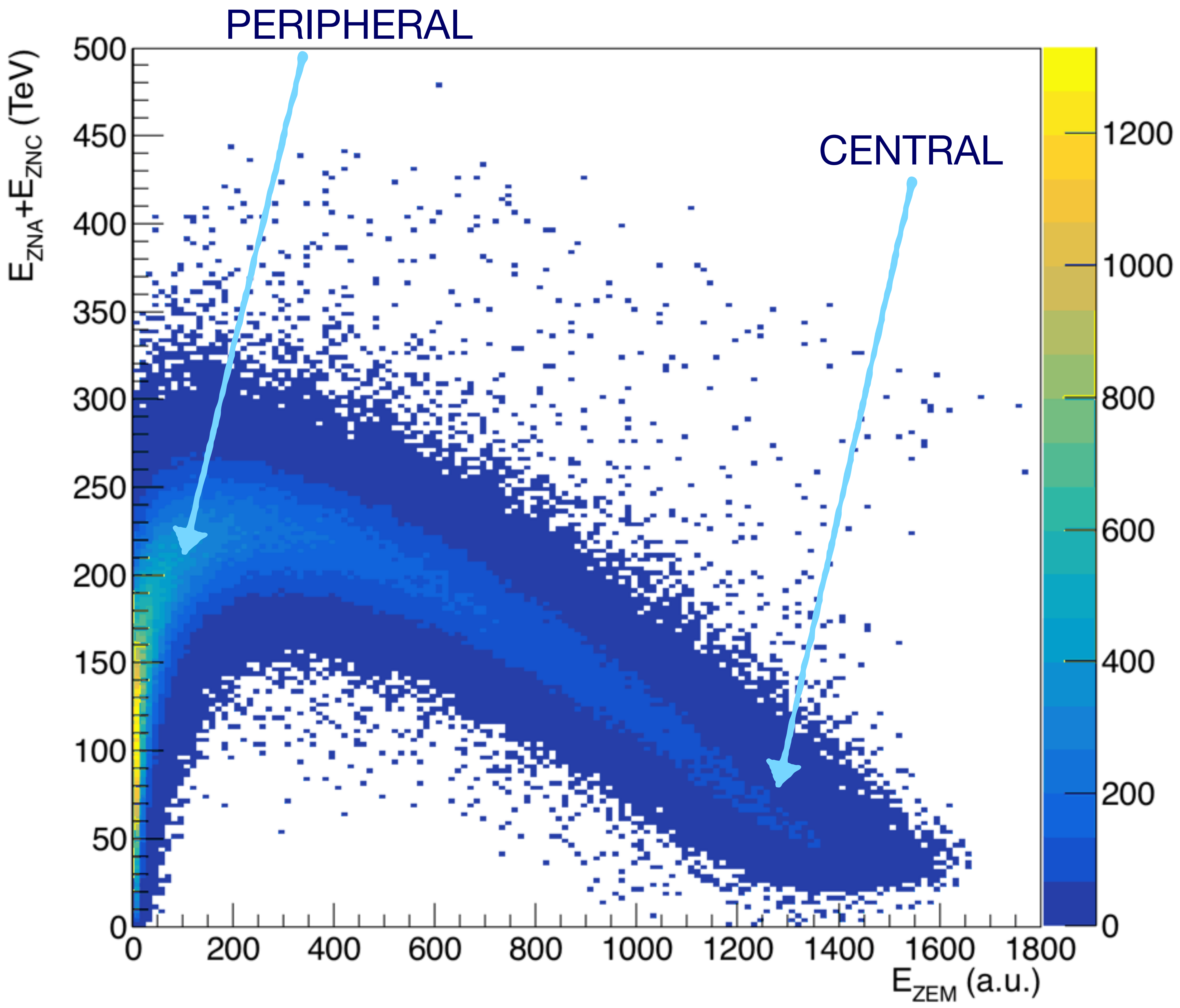
- based on DPMJET extended to photonuclear reactions
- only interaction of energetic (E_γ >6 GeV) photons
- does not include the nucleus break-up

Hadronic and mutual EMD processes

[ALICE Coll., PRL 109, 252302 (2012)](#)

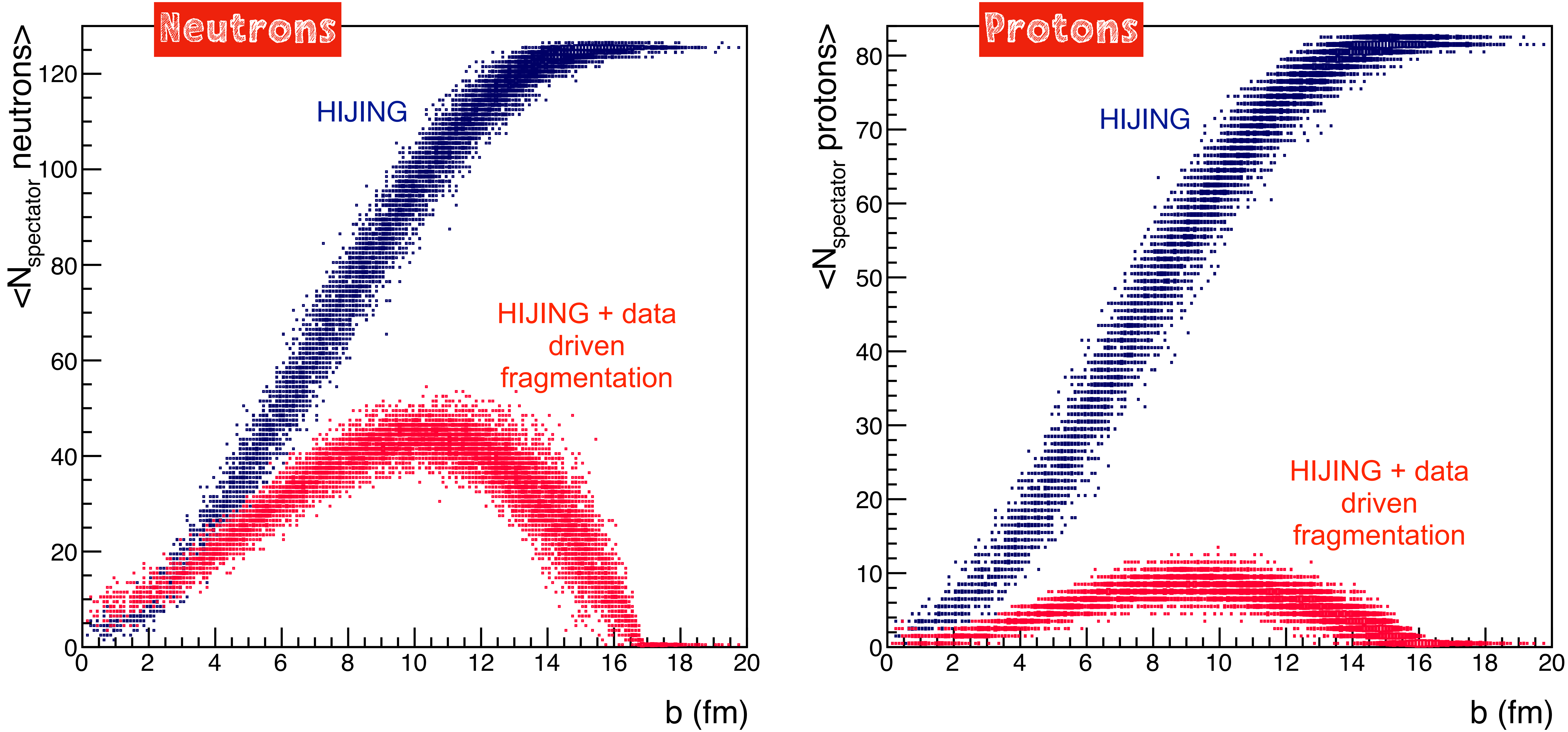


ALI-PERF-13737



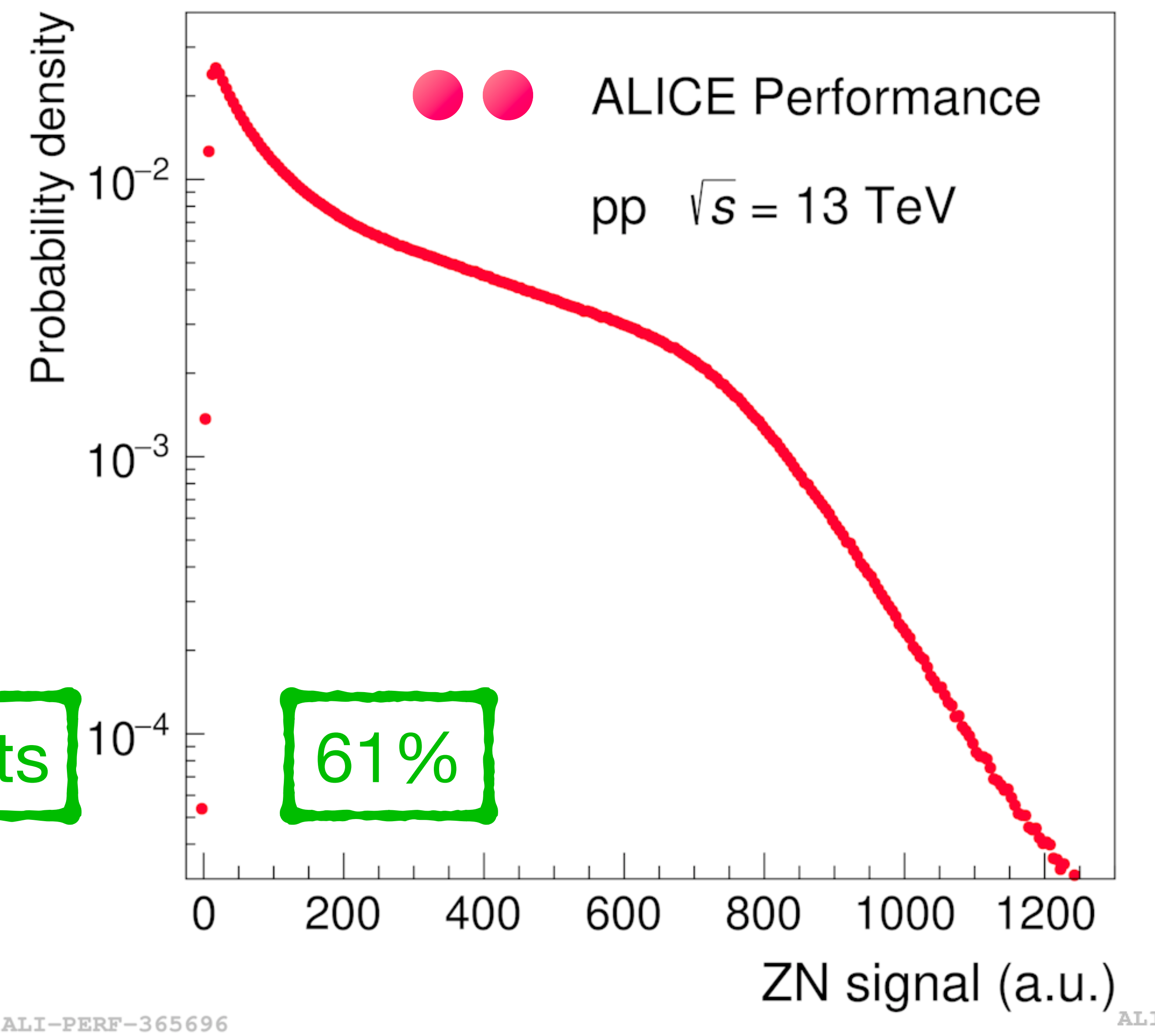
Data driven model for nuclear fragmentation

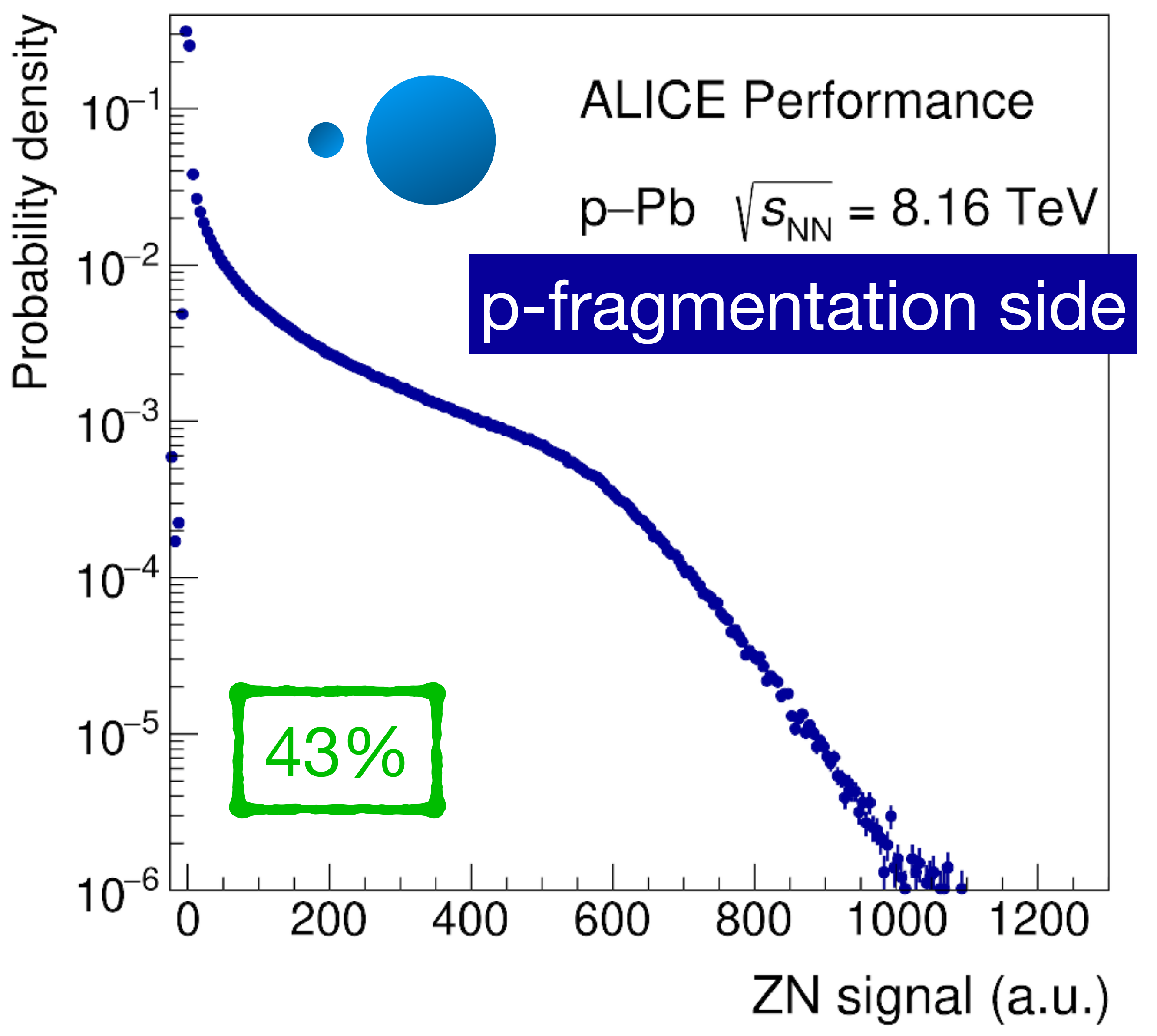
ALICE-PUBLIC-2020-001

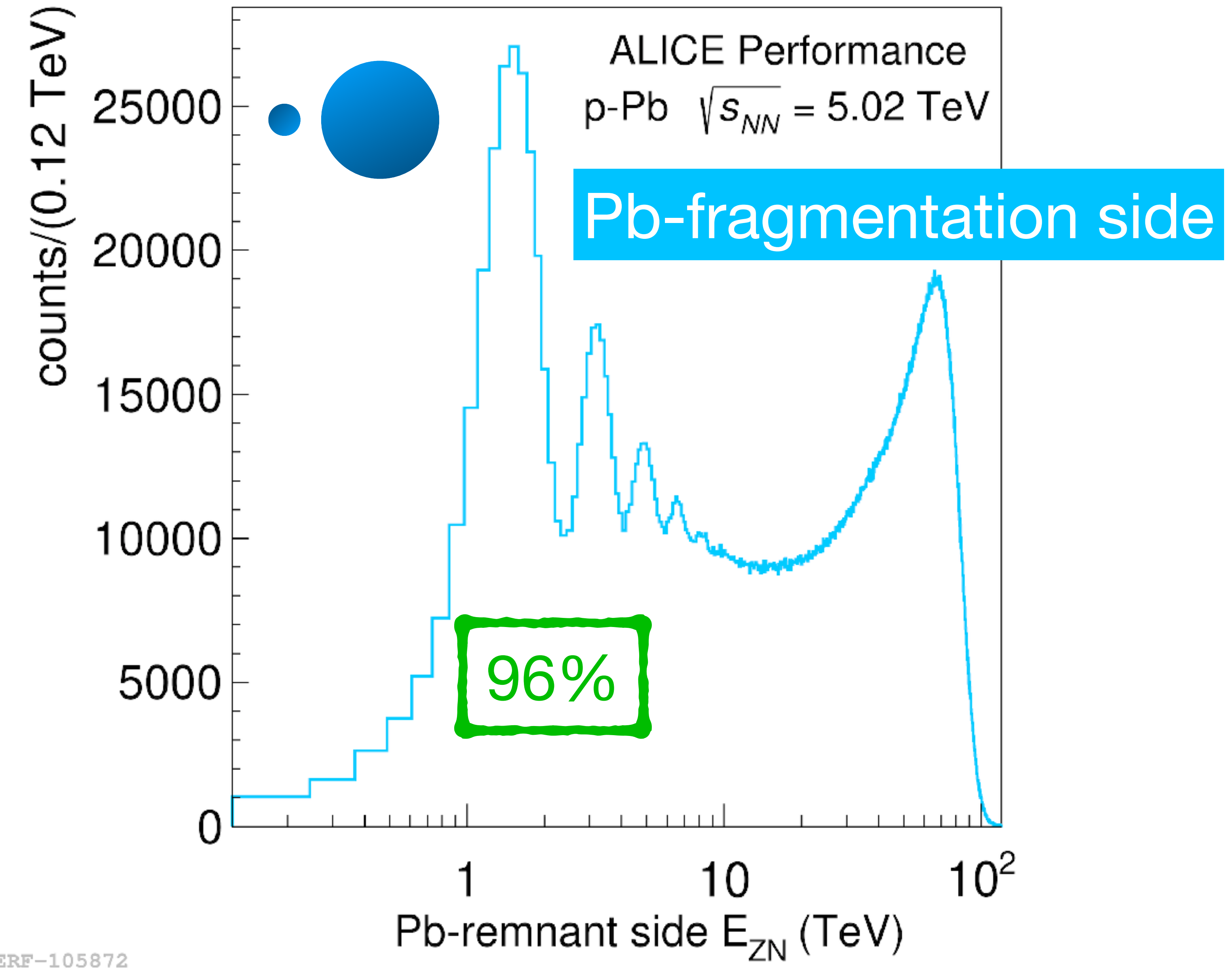


Colliding systems and ZDC spectra

ZN

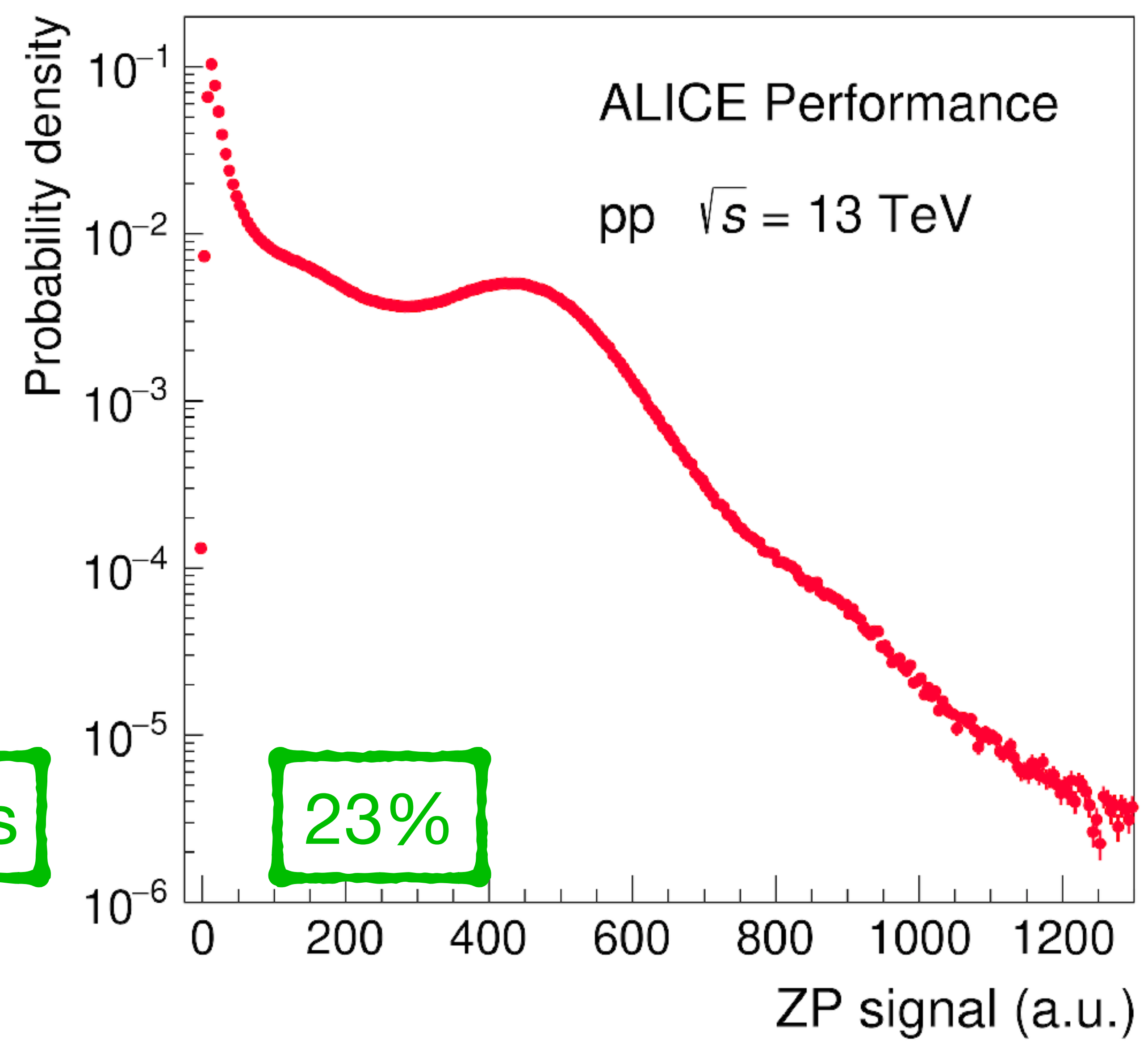


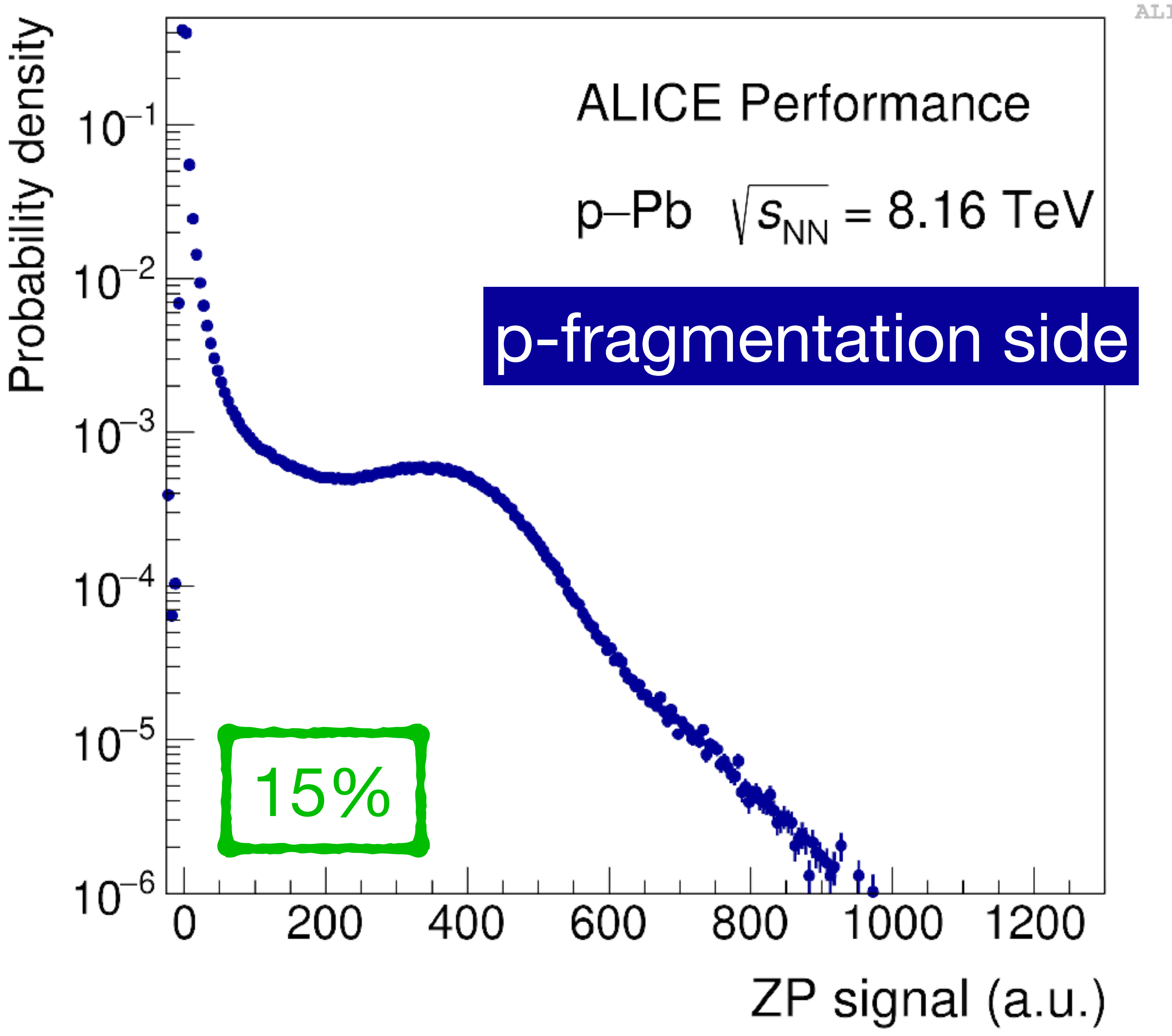


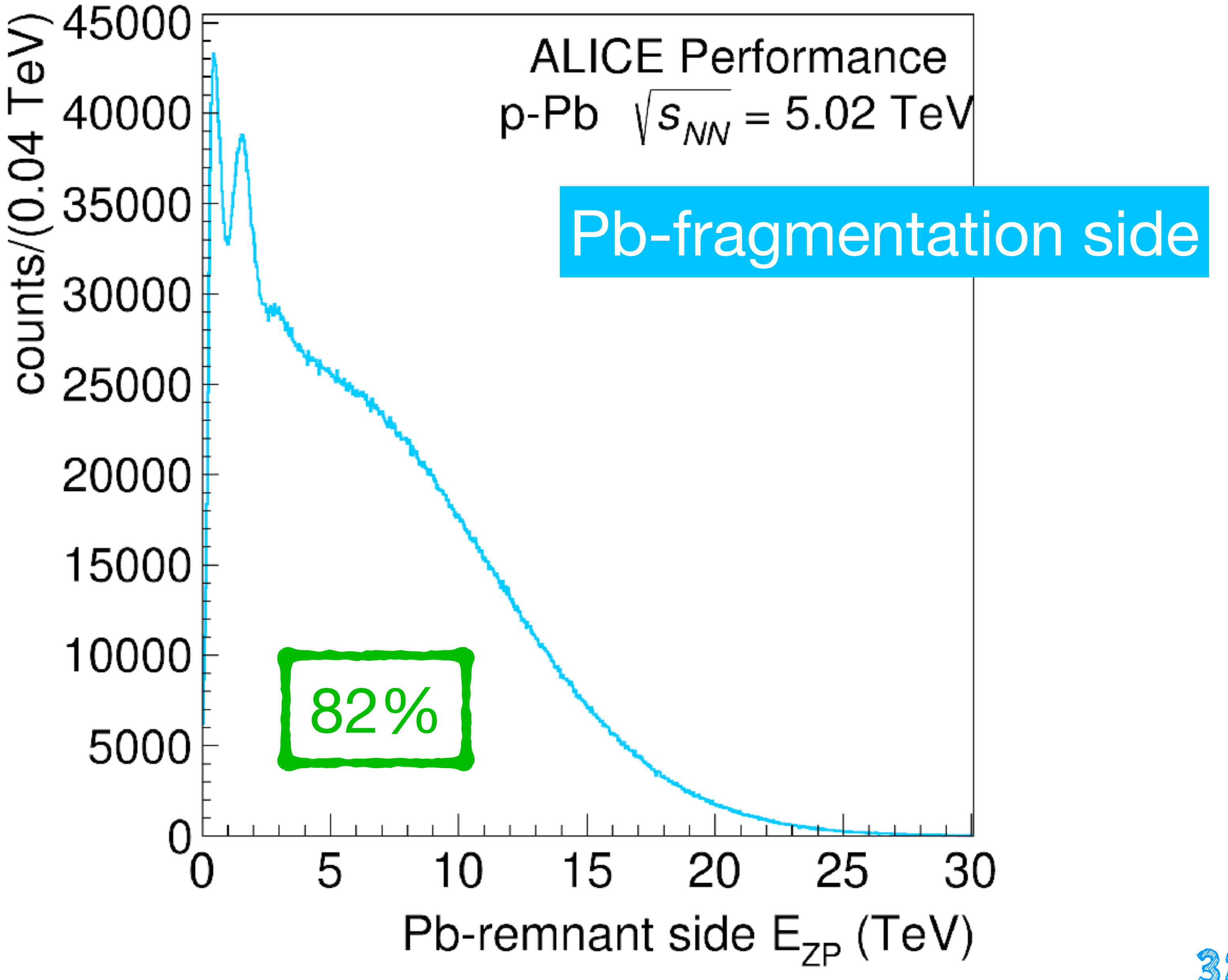


Fraction of events

ZP







Fraction of events

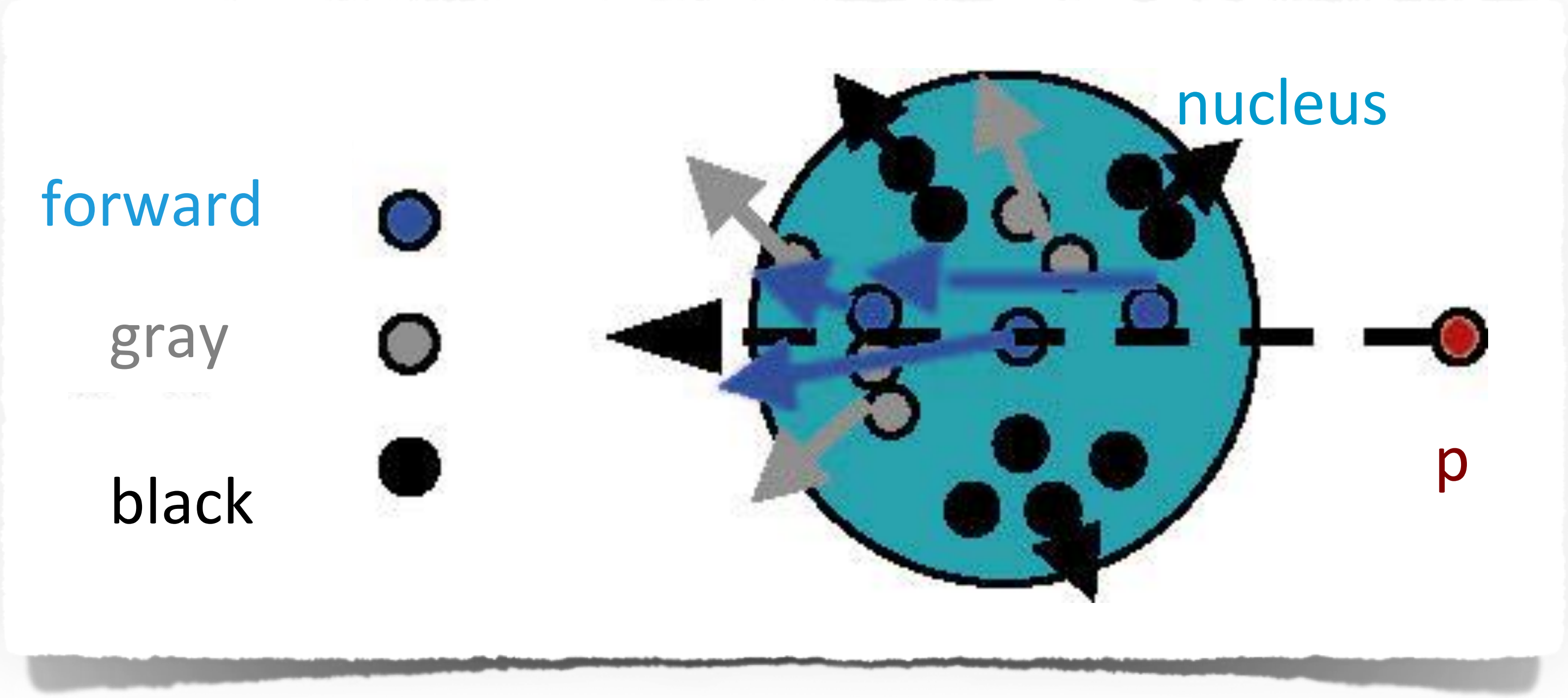
Slow nucleons

Hadron-nucleus collisions ➧ “slow” nucleon emission

F. Sikler, hep-ph/0304065

“Black” and “gray” components (terminology coming from emulsions experiments)

	β	p (MeV/c²)
Black	0 ÷ 0.25	0 ÷ 250
Gray	0.25 ÷ 0.7	250 ÷ 1000



Black ➧ nucleons + low-energy target fragments from nuclear evaporation processes
Gray ➧ nucleons and light fragments emitted in the intra-nuclear cascade processes

Features of slow nuclear emission weakly depend on hadron beam energy in a wide range (1 GeV - 1 TeV)
➧ slow particle emission mainly dictated by nuclear geometry

- ➡ kinematical distributions described by independent statistical emission from a moving frame
- ➡ isotropic emission from a source moving with velocity β
- ➡ number distribution of black/gray nucleons follows binomial distributions

Slow nucleon model

[ALICE coll., Phys. Rev. C 91 (2015) 064905]

Model based on lower energy data

Average no. of grey protons ➧ $\langle N_{grey,\,p}\rangle = c_0 + c_1 {}^* N_{coll} + c_2 {}^* N_{coll}$
the linear term is the dominant contribution (c_2~0)

[E910 Coll., Phys. Rev. C 60 024902 (1999)]

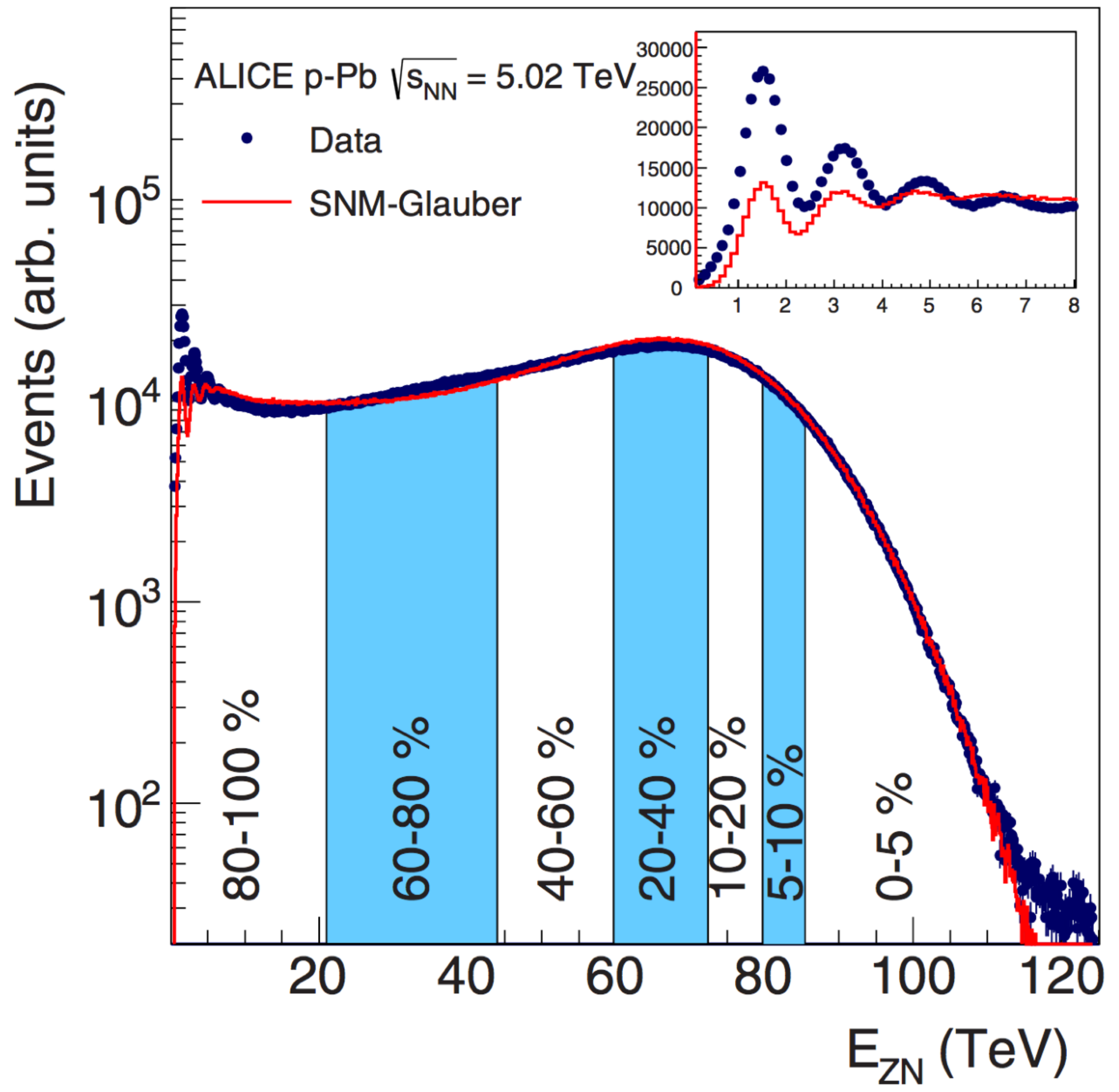
Average no. of black protons ➧ $\langle N_{black,\,p}\rangle = 0.65{}^*\langle N_{grey,\,p}\rangle$

[A. Letourneau, Nucl. Phys. A 712 133 (2002)]

Average number of slow neutrons ➧

$$\langle N_{slow n}\rangle = \alpha N_{LCF} + \left(a - \frac{b}{c + N_{LCF}}\right)$$

with:
- N_{LCF} = no. of Light Charge fragments (Z<8) = $\gamma^*\langle N_{slow,\,p}\rangle$ (γ = 1.75)
  ➧ ~ linear in N_{coll}
- a = 50, b = 230, c = 4.2 (from a minimization procedure on LHC data)
  ➧ saturation term
- α = 0.48 ➧ term linearly increasing in N_{coll}

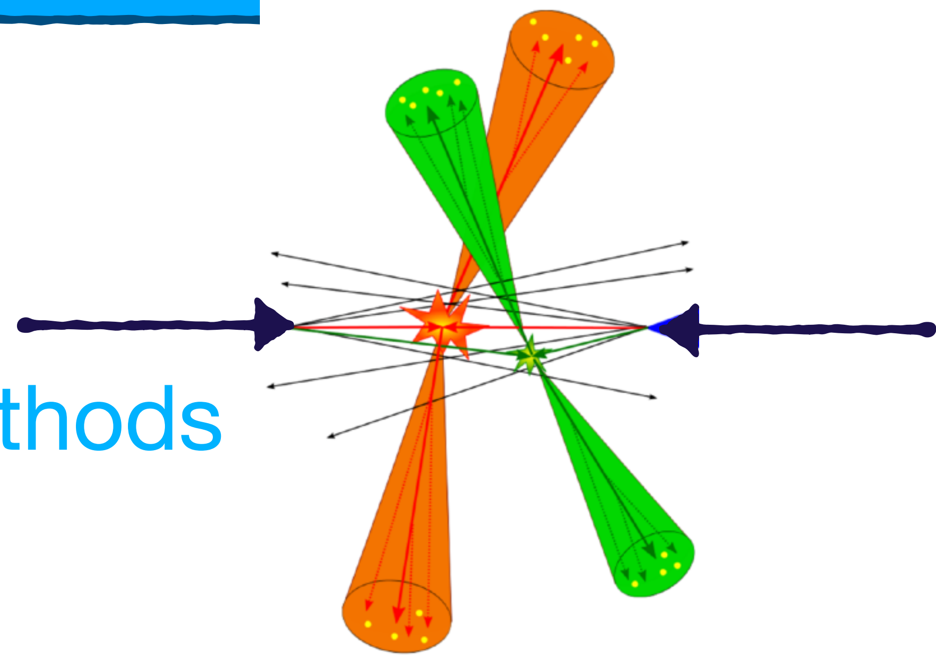


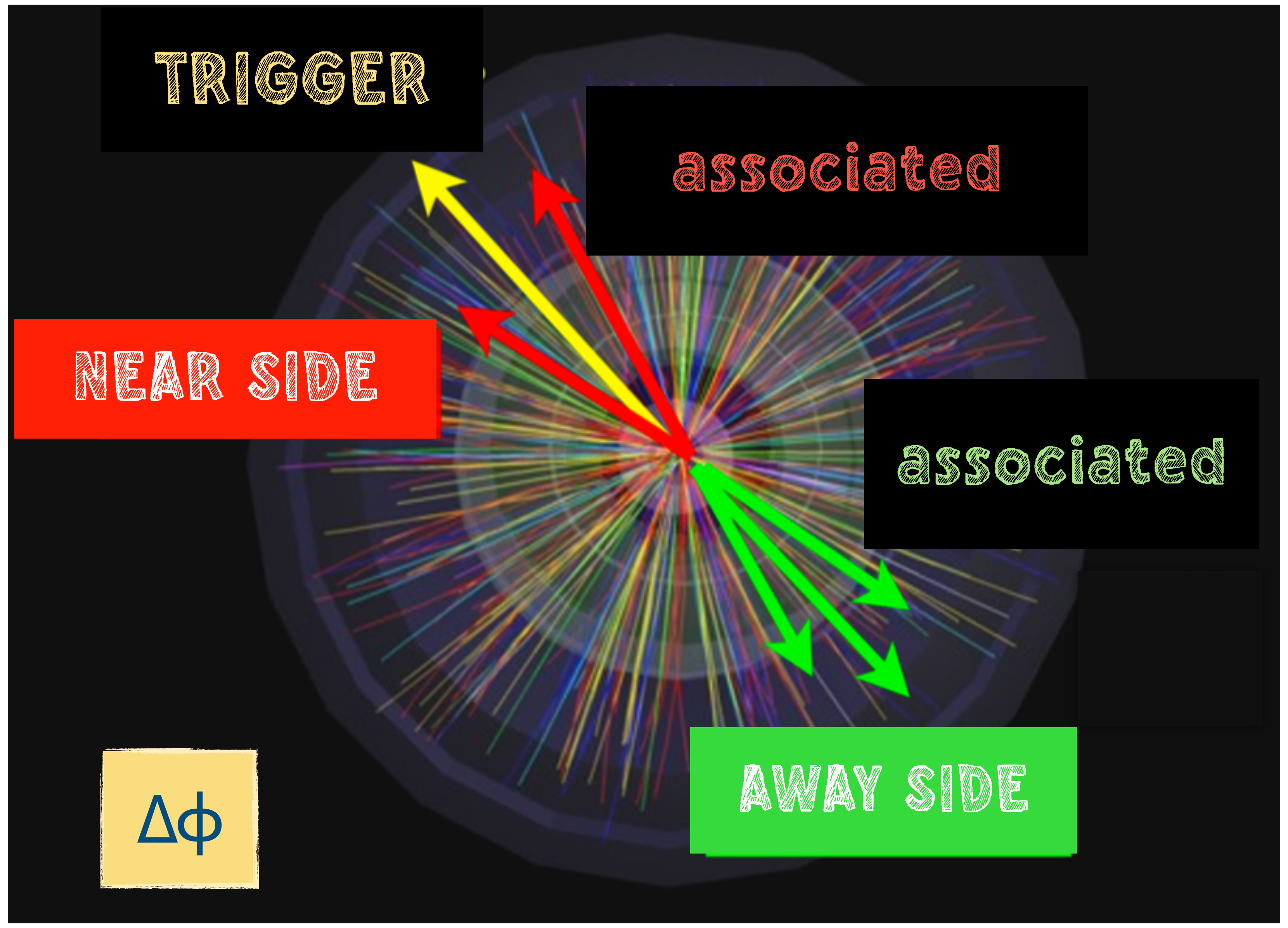
Multi Parton Interactions (MPI)

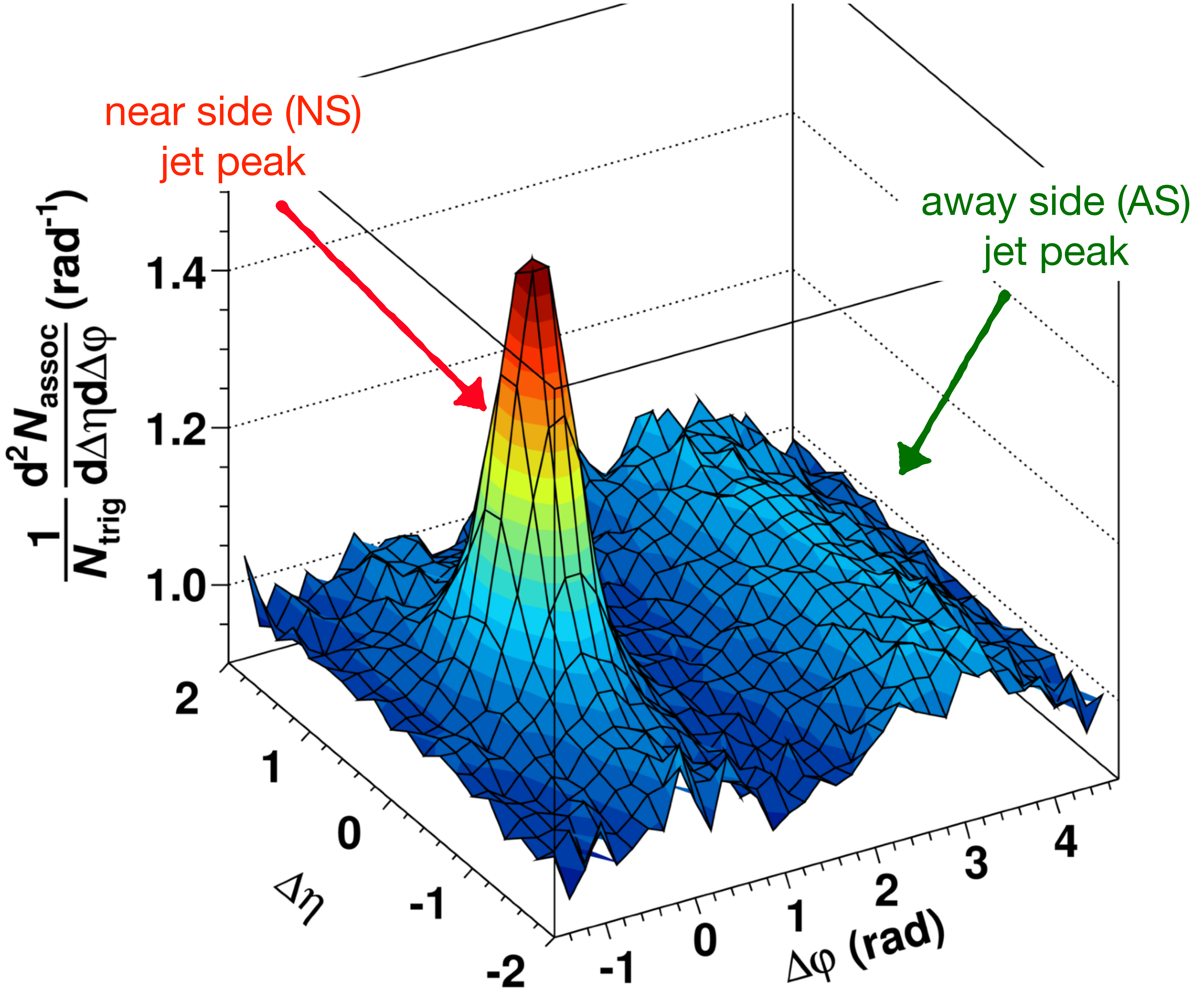
Average N_{MPI} becomes large at perturbative scales

Measurement of semi-hard MPI in p-Pb collisions ➧ study mini-jets (jets at low p_T)

Mini-jets overlap in high multiplicity collisions ➧ reconstructed with 2-particle correlation methods







p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

0-20%

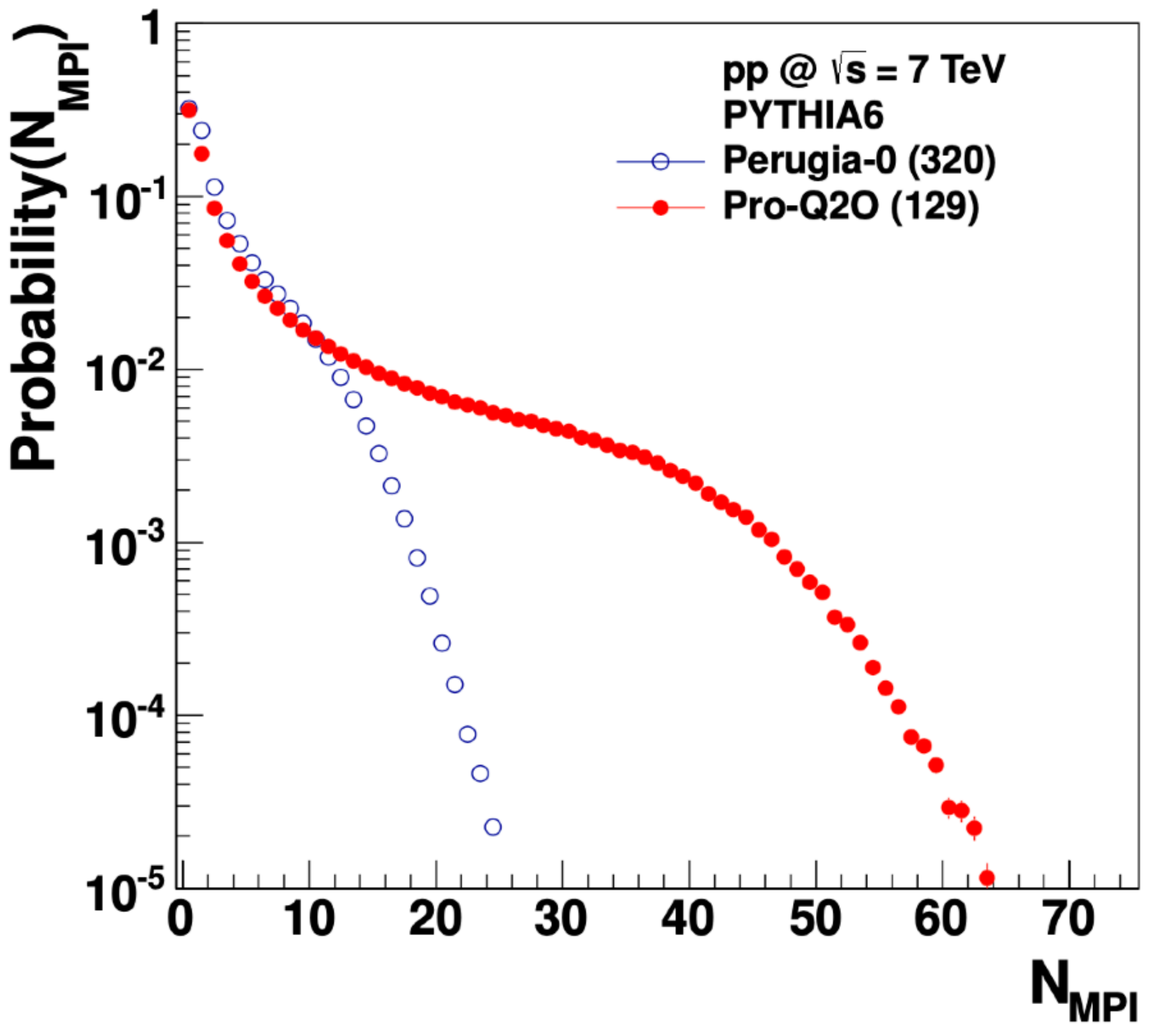
$2 < p_{T,trig} < 4$ GeV/c

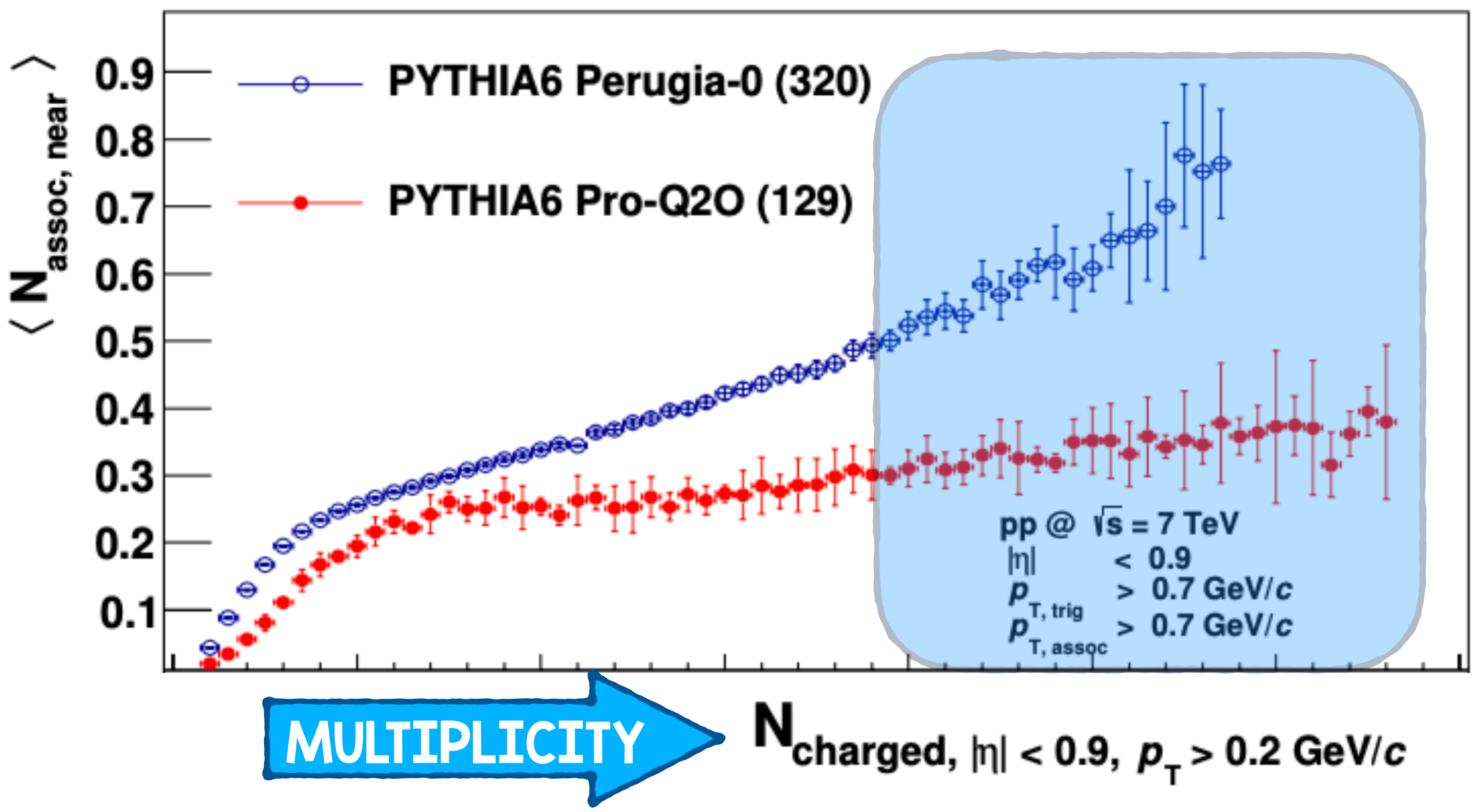
$1 < p_{T,assoc} < 2$ GeV/c

➧ subtracting long range correlations, jet-like short range correlations can be studied

Observables

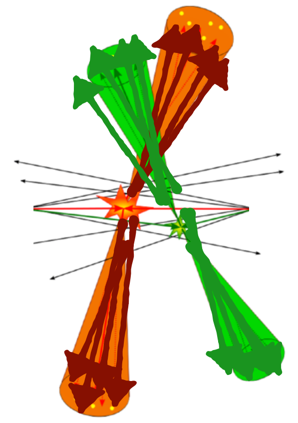
Associated particle production ➧ sensitive to number of MPIs



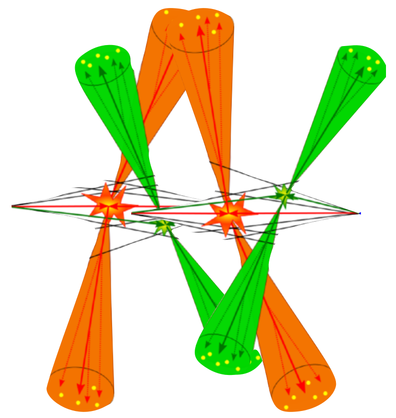


High multiplicity:

low <N_{MPI}> ➧ few mini-jets with higher associated particle production



high <N_{MPI}> ➧ more mini-jets with the same associated production



Mini-jets ➧ parsonic hard scattering ⊕ fragmentation

Observable with reduced dependence on fragmentation

$$\boxed{\langle N_{\text{uncorrelated seeds}} \rangle = \frac{\langle N_{\text{trig}} \rangle}{\langle N_{\text{correlated triggers}} \rangle}}$$

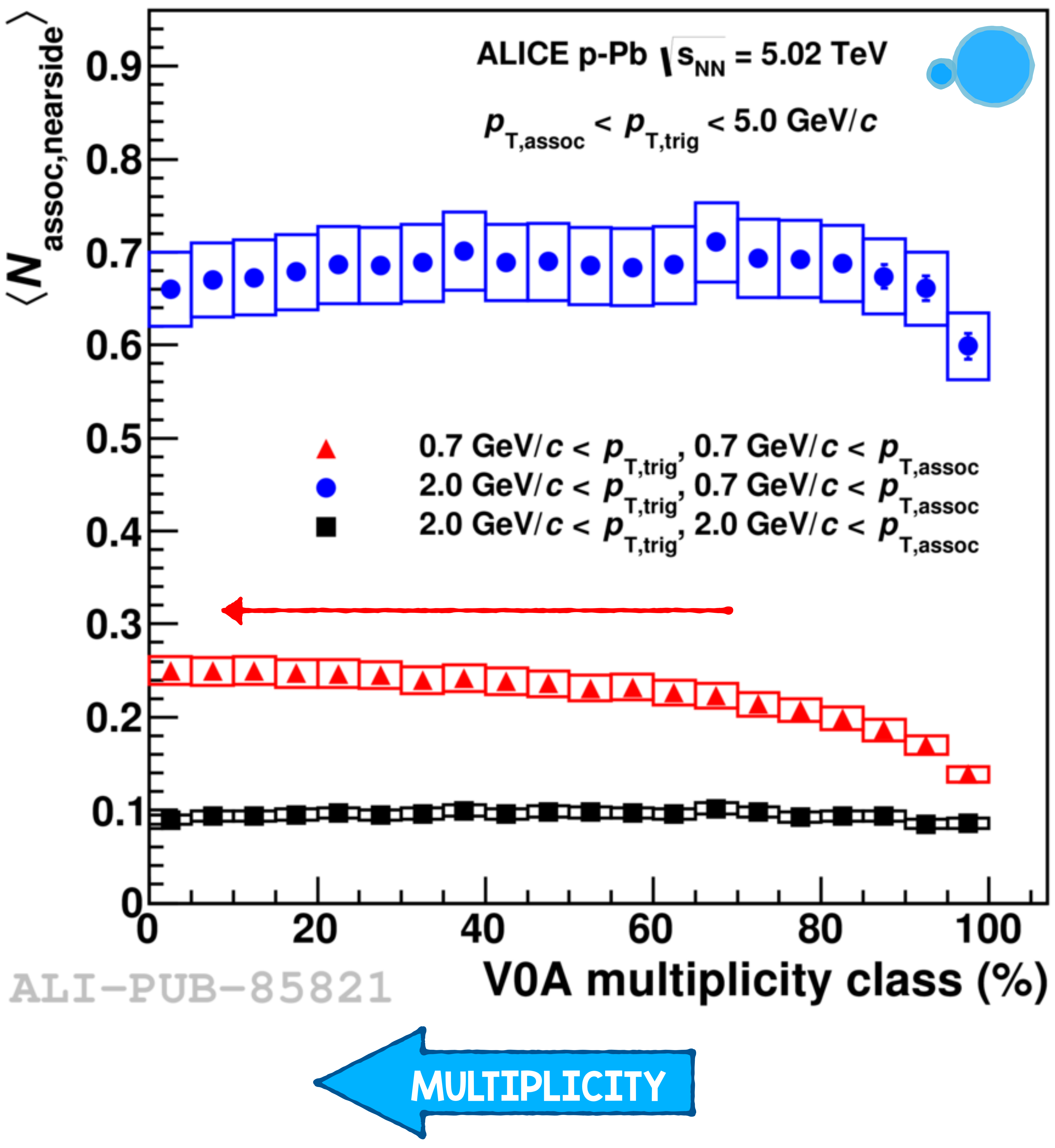
➧ number of independent sources in particle production

➧ $N_{\text{uncorrelated seeds}} \propto N_{MPI}$ in MPI-based models (PYTHIA)

Fragmentation region

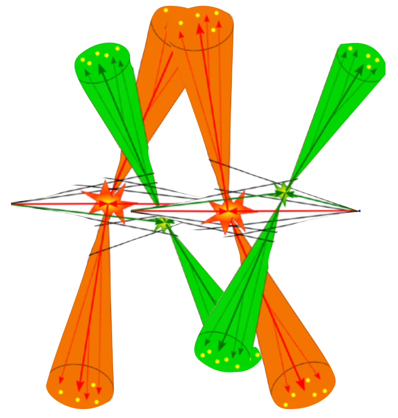
ALICE, Phys. Lett. B 741 (2015) 38

◗ sensitive to jet fragmentation properties



High multiplicity events in p-Pb collisions have the same number of associated yield per trigger particle in jet peak

◗ consistently with an increase of <N_{MPI}> and following incoherent fragmentation of multiple-parton scatterings

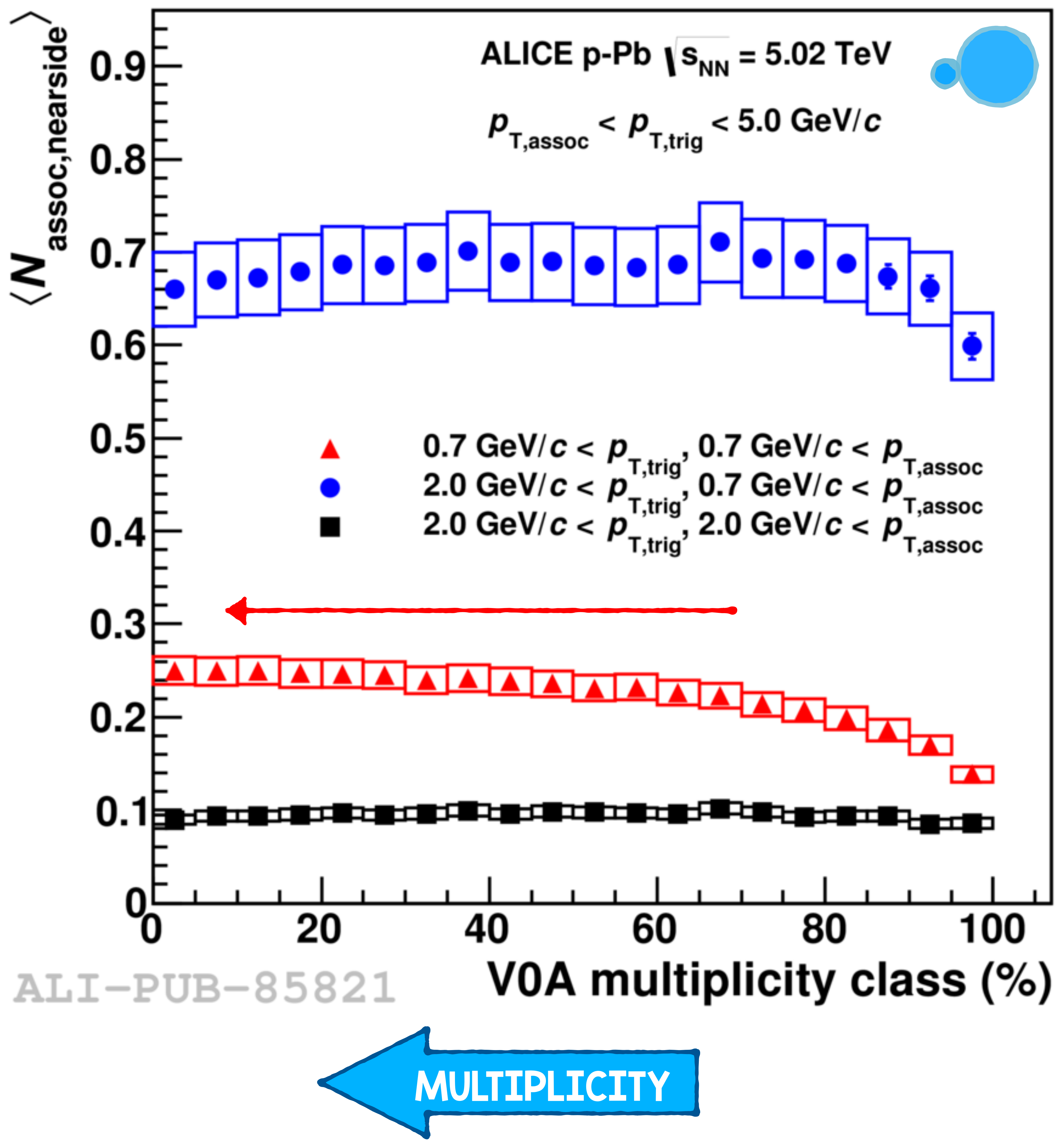


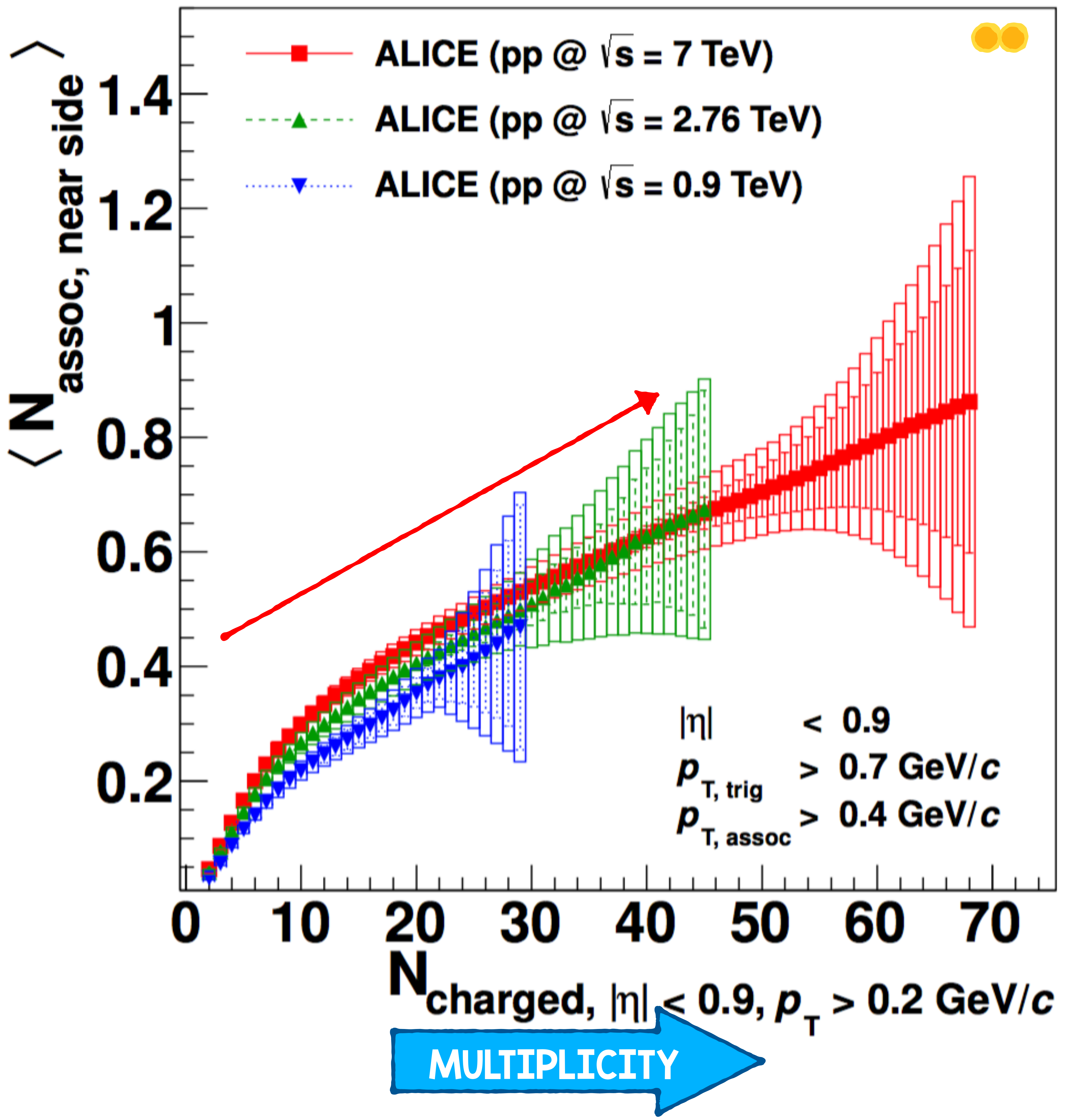
Fragmentation region (NS)

➧ sensitive to jet fragmentation properties

ALICE, Phys. Lett. B 741 (2015) 38

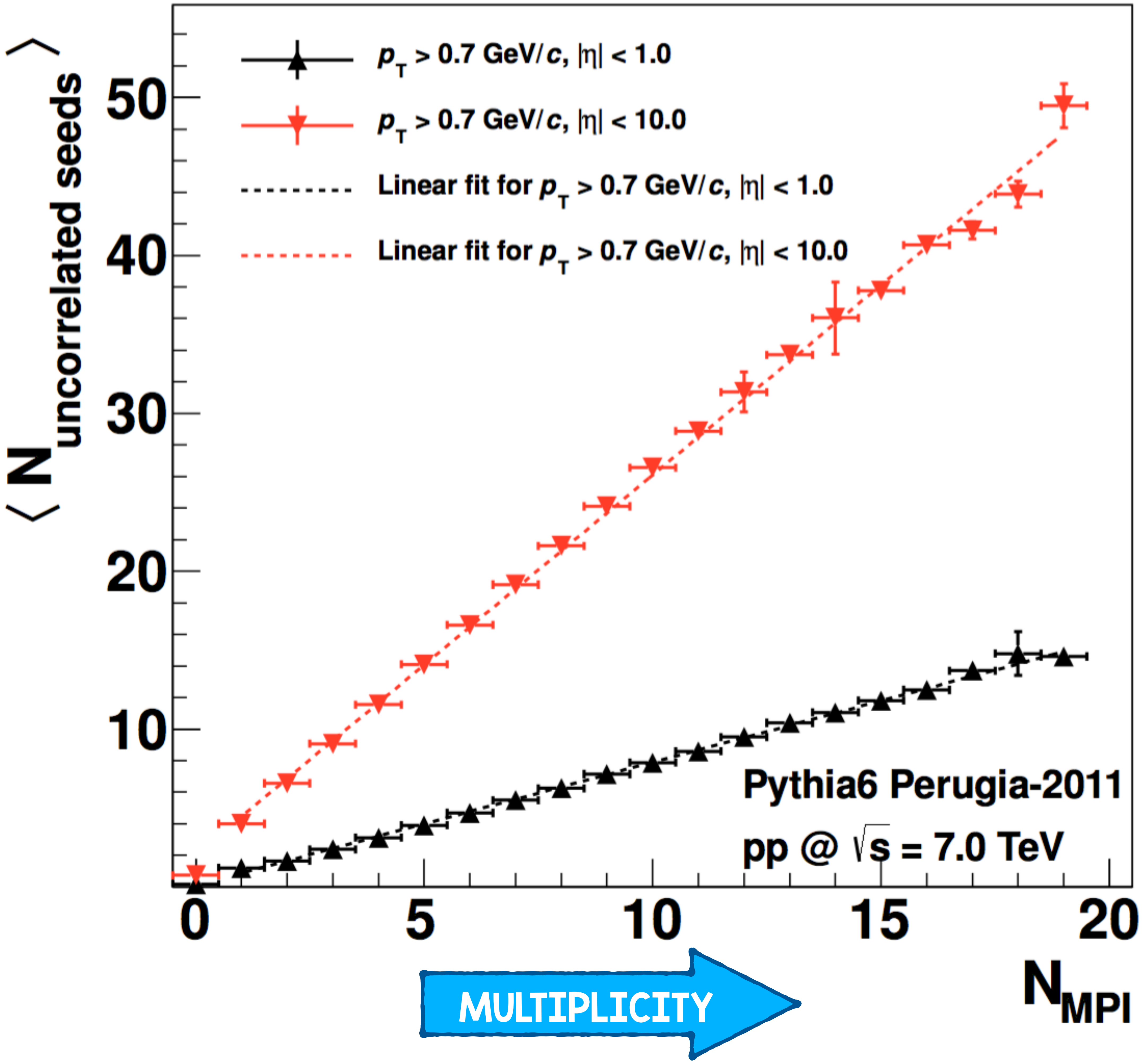
ALICE, JHEP 1309 (2013) 049





MPI

Uncorrelated seeds to probe the number of semi-hard scatterings ◗ proxy for N_{MPI}

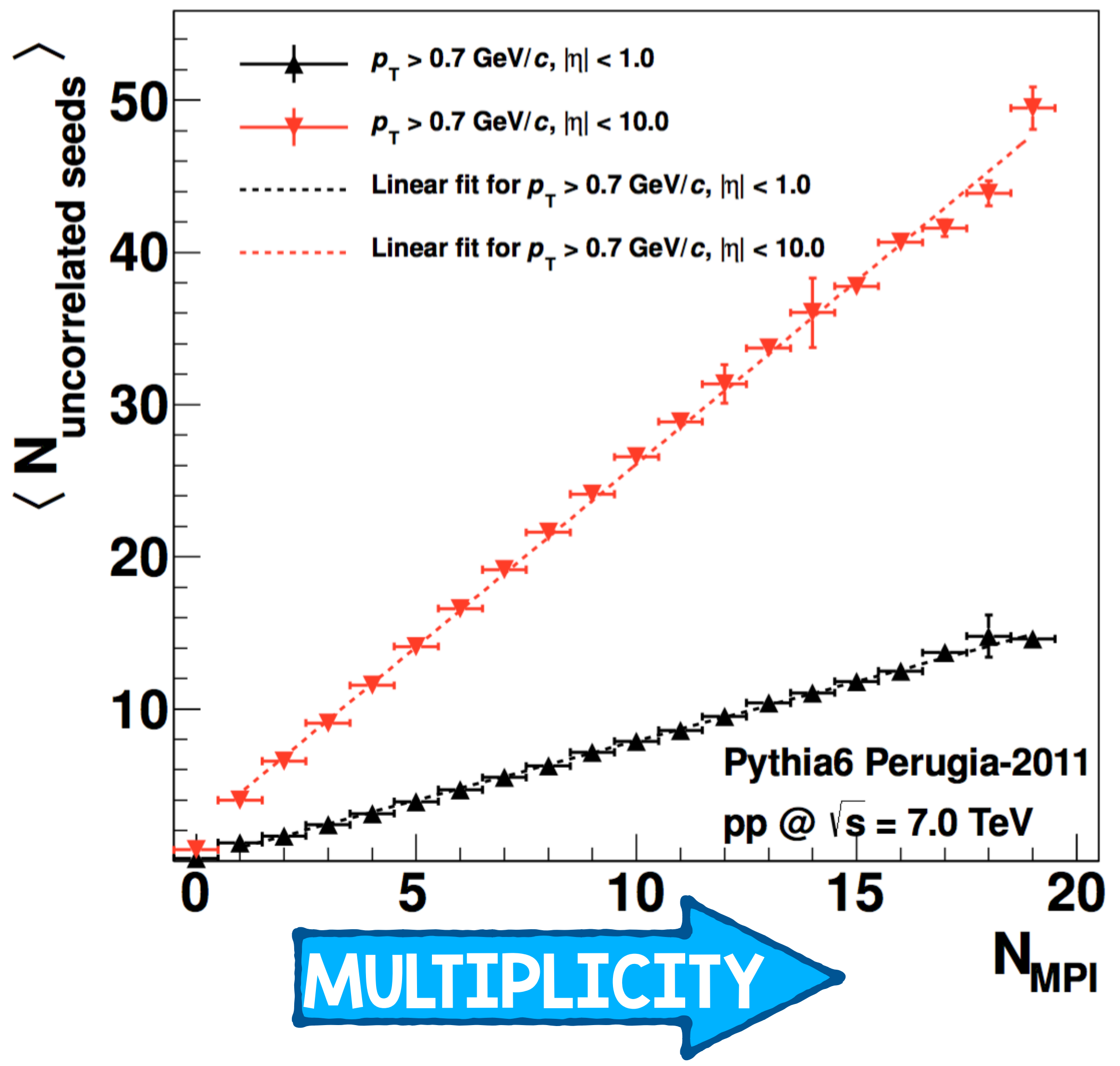


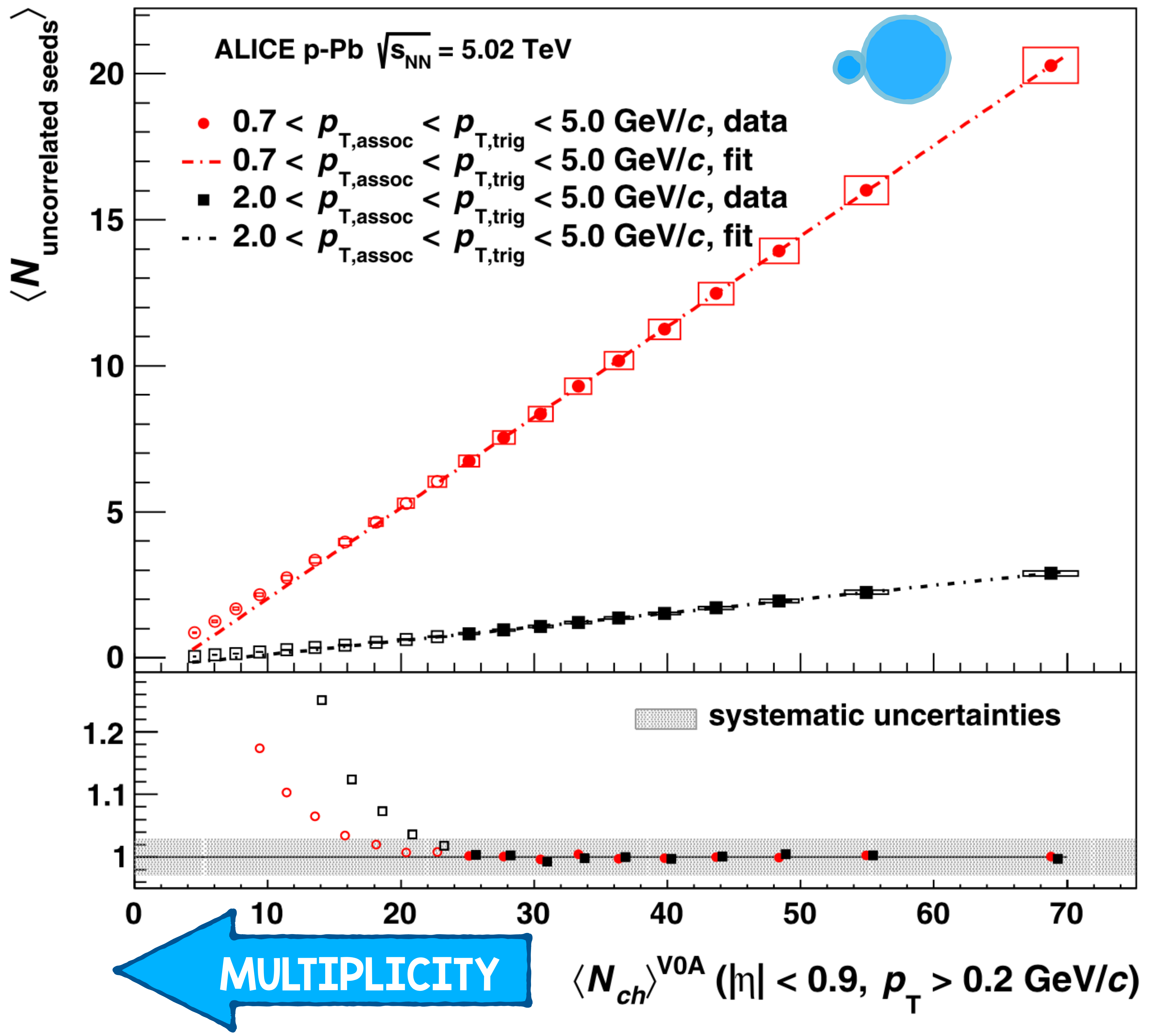
MPI

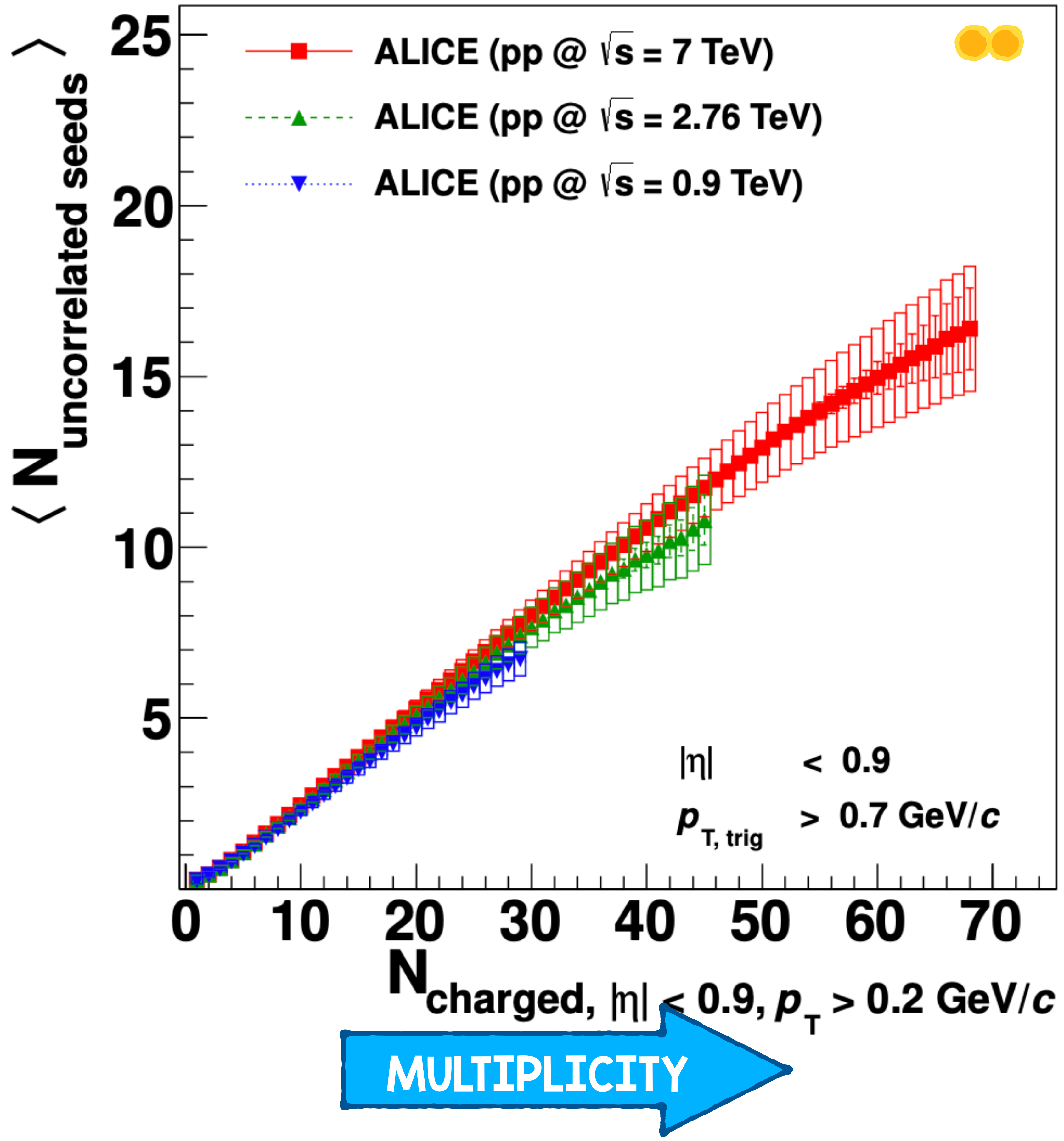
Uncorrelated seeds to probe the number of semi-hard scatterings ➧ proxy for N_{MPI}

ALICE, Phys. Lett. B 741 (2015) 38

ALICE, JHEP 1309 (2013) 049







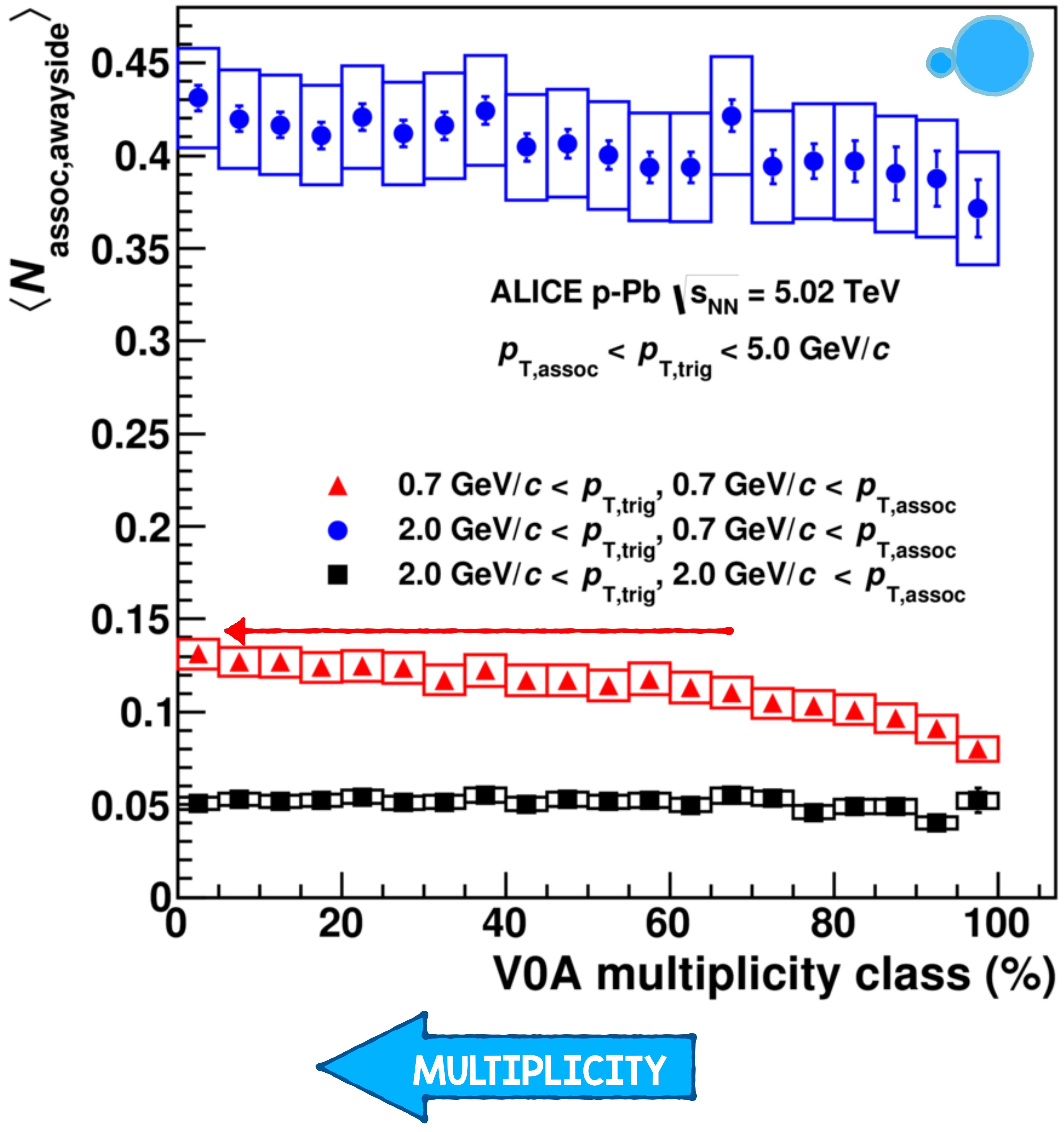
➧ In p-Pb N_{MPI} scales linearly with particle multiplicity, while in pp there is an indication of saturation in N_{MPI}

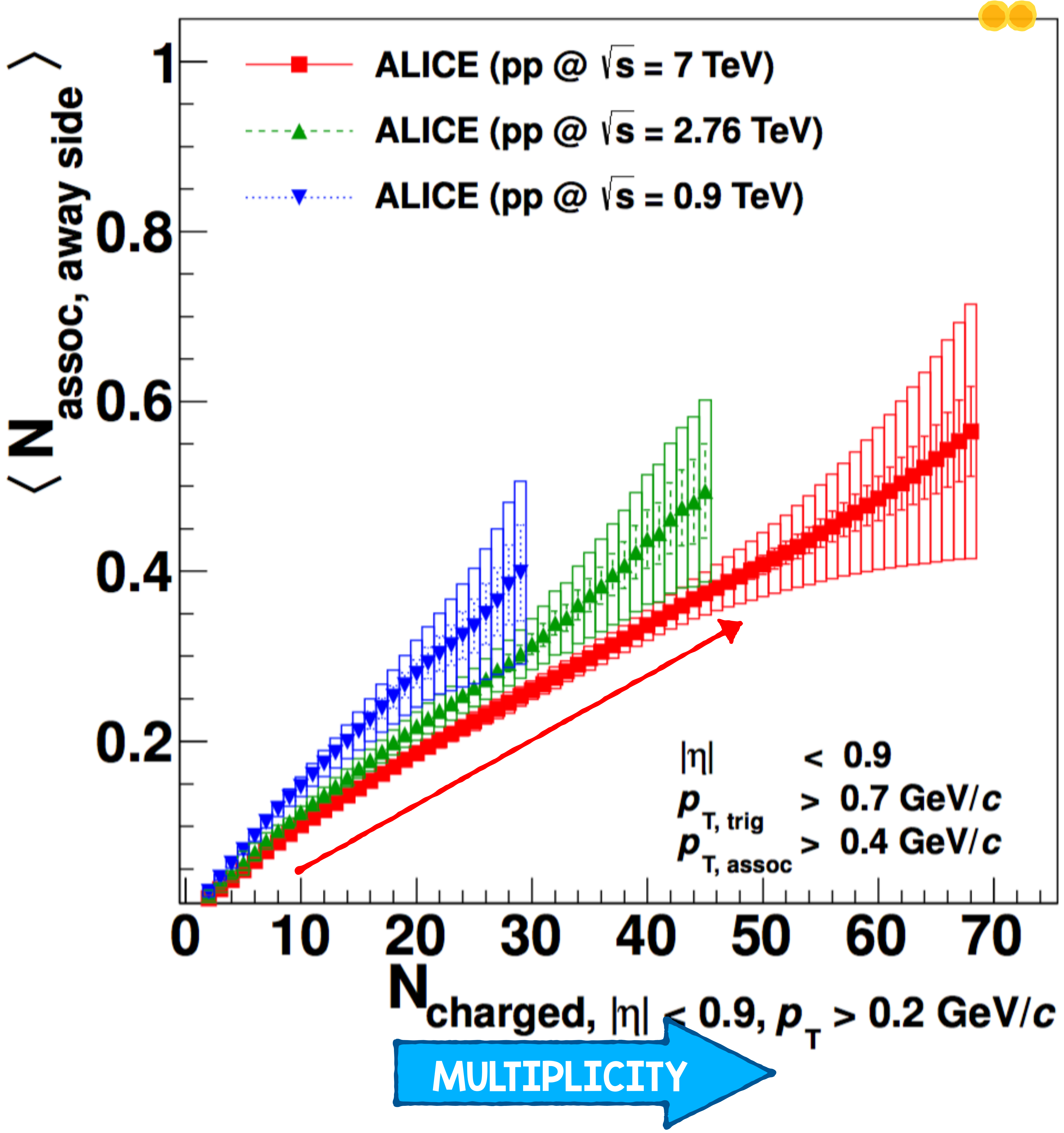
Fragmentation region (AS)

➧ sensitive to jet fragmentation properties

ALICE, Phys. Lett. B 741 (2015) 38

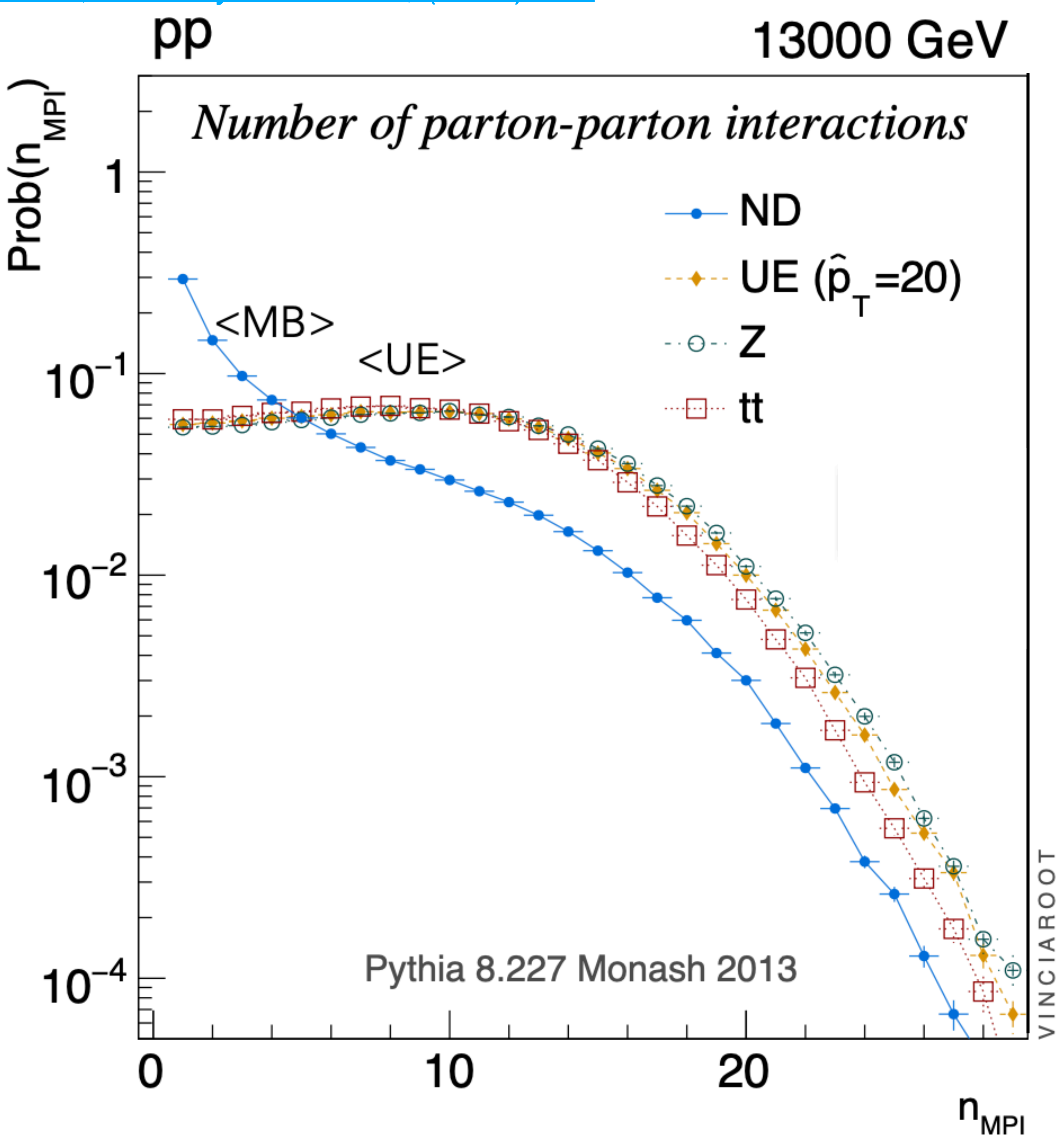
ALICE, JHEP 1309 (2013) 049





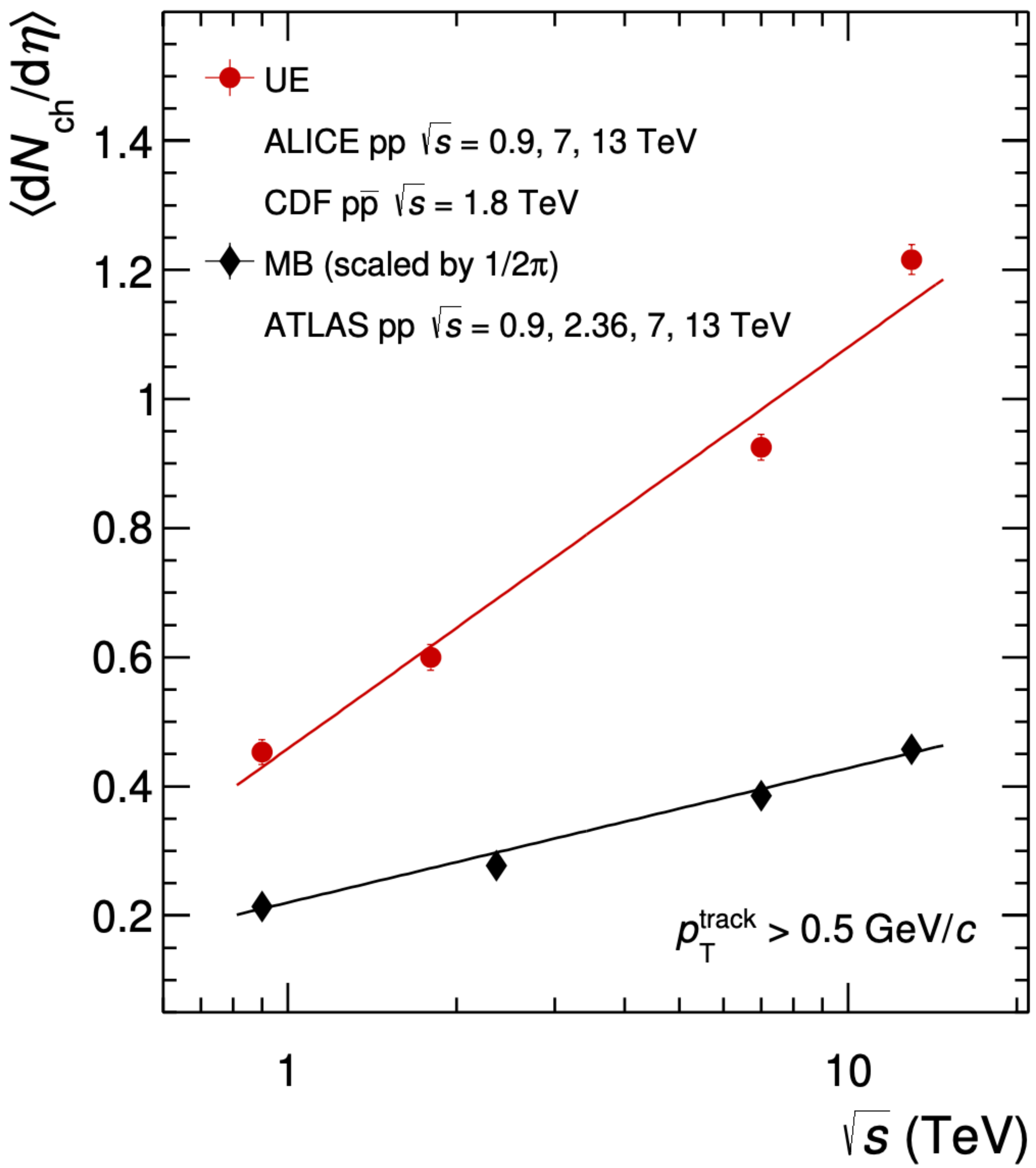
MPIs and multiplicity in MB and UE

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



➧ UE is expected to show larger <N_{MPI}> than MB

ALICE Coll., JHEP 04 (2020) 192



➧ multiplicity increases faster in UE than in MB