India+ lectures on Heavy Ion Collision experiments

Measurement of global observables with ALICE at the LHC

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INFN Bologna, Italy
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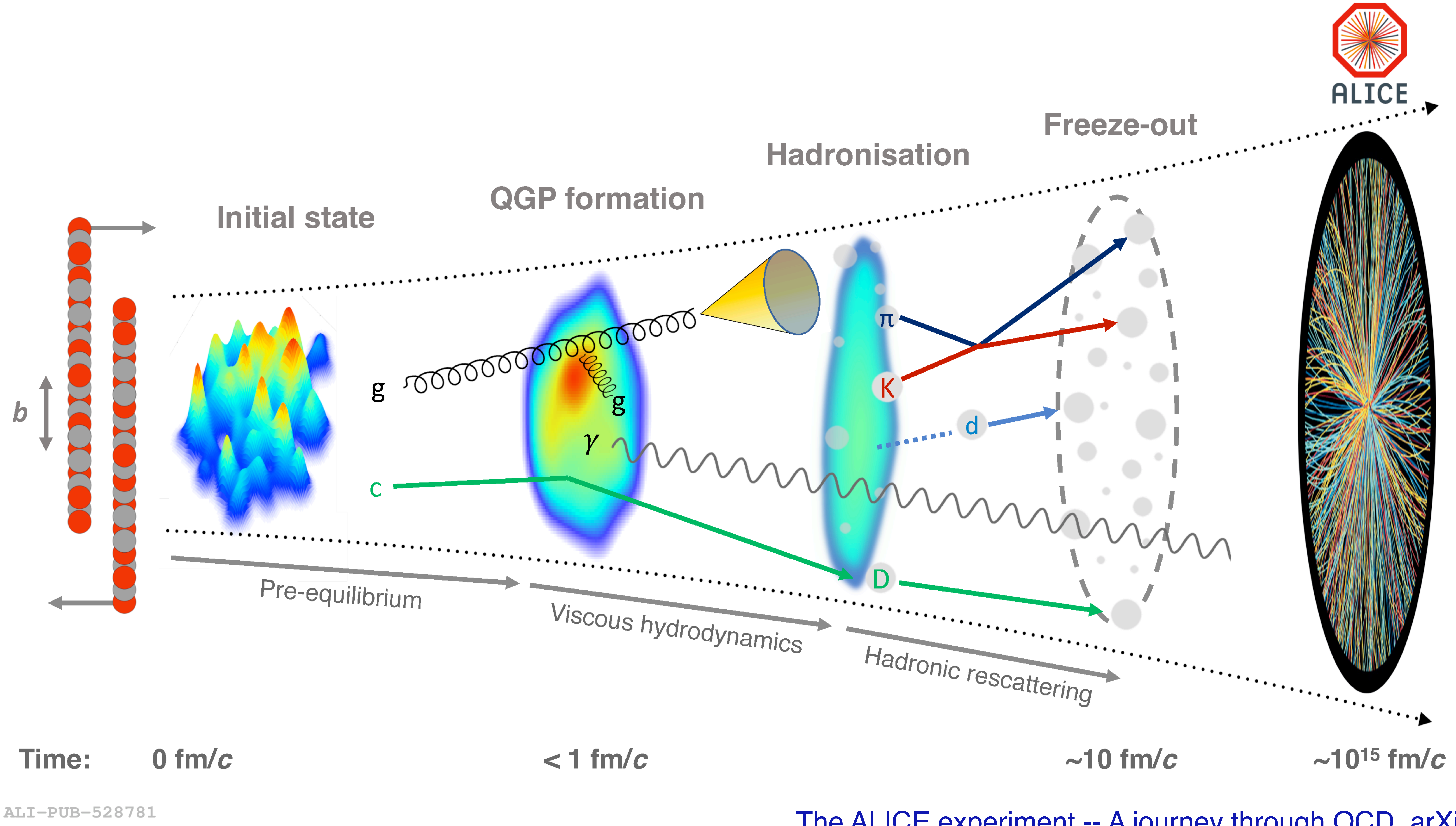
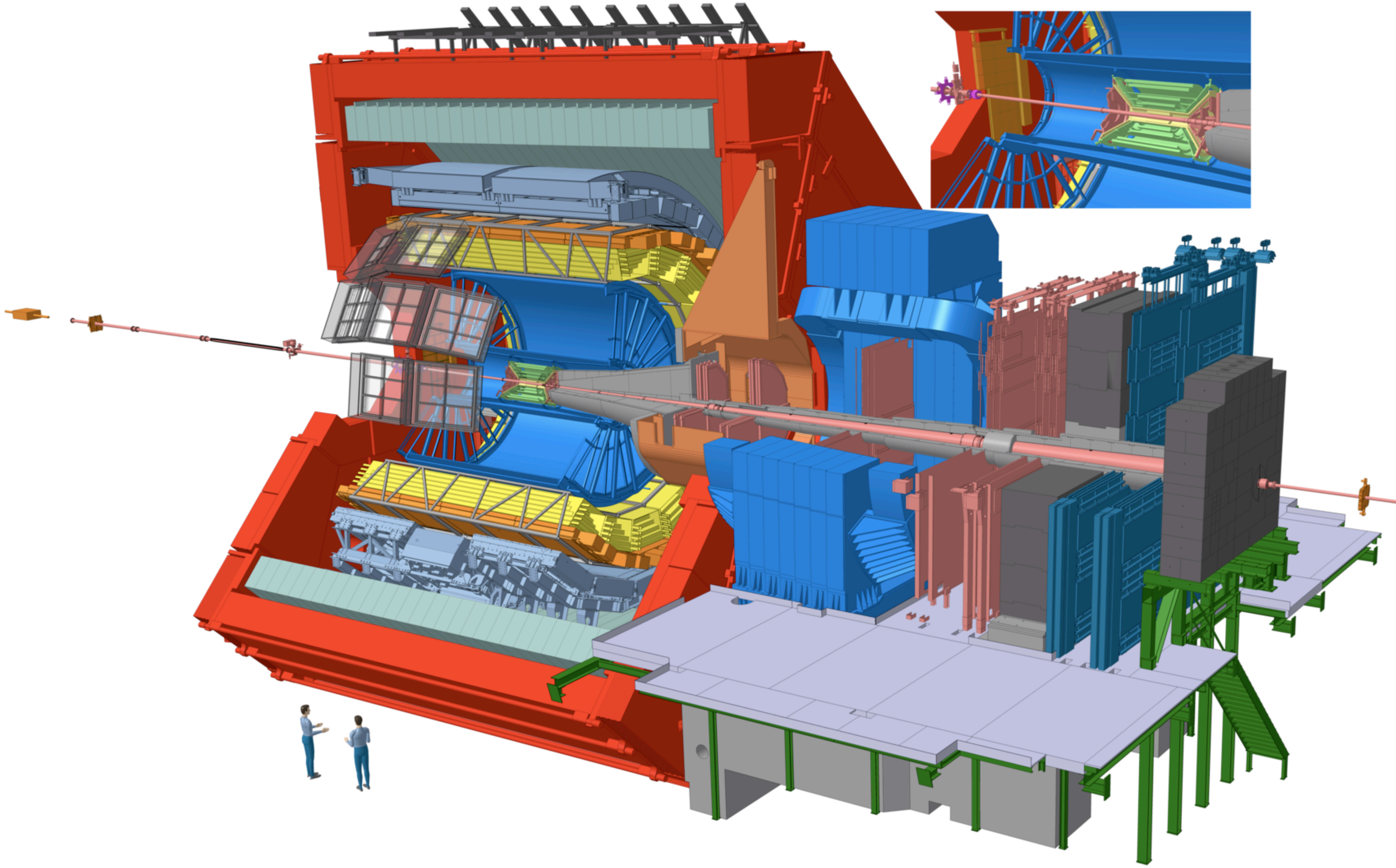
Relativistic Heavy-ion collisions



The ALICE experiment -- A journey through QCD, arXiv:2211.04384

A Large Ion Collider Experiment



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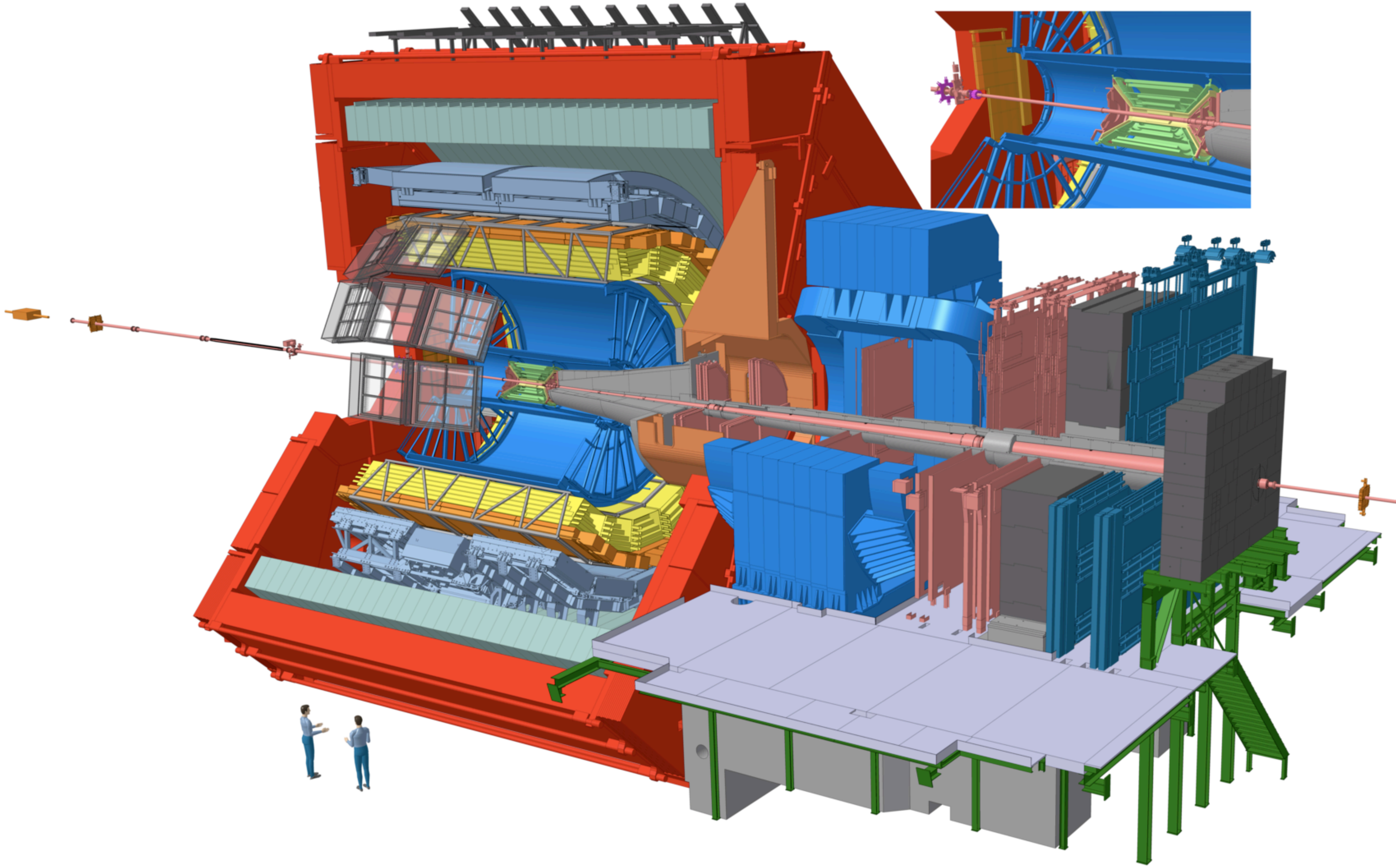

System	Years Run 1 I Run 2	$\sqrt{s_{NN}}$ (TeV)
Pb—Pb	2010, 2011 2015, 2018	2.76 5.02
Xe—Xe	2017	5.44
p—Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13

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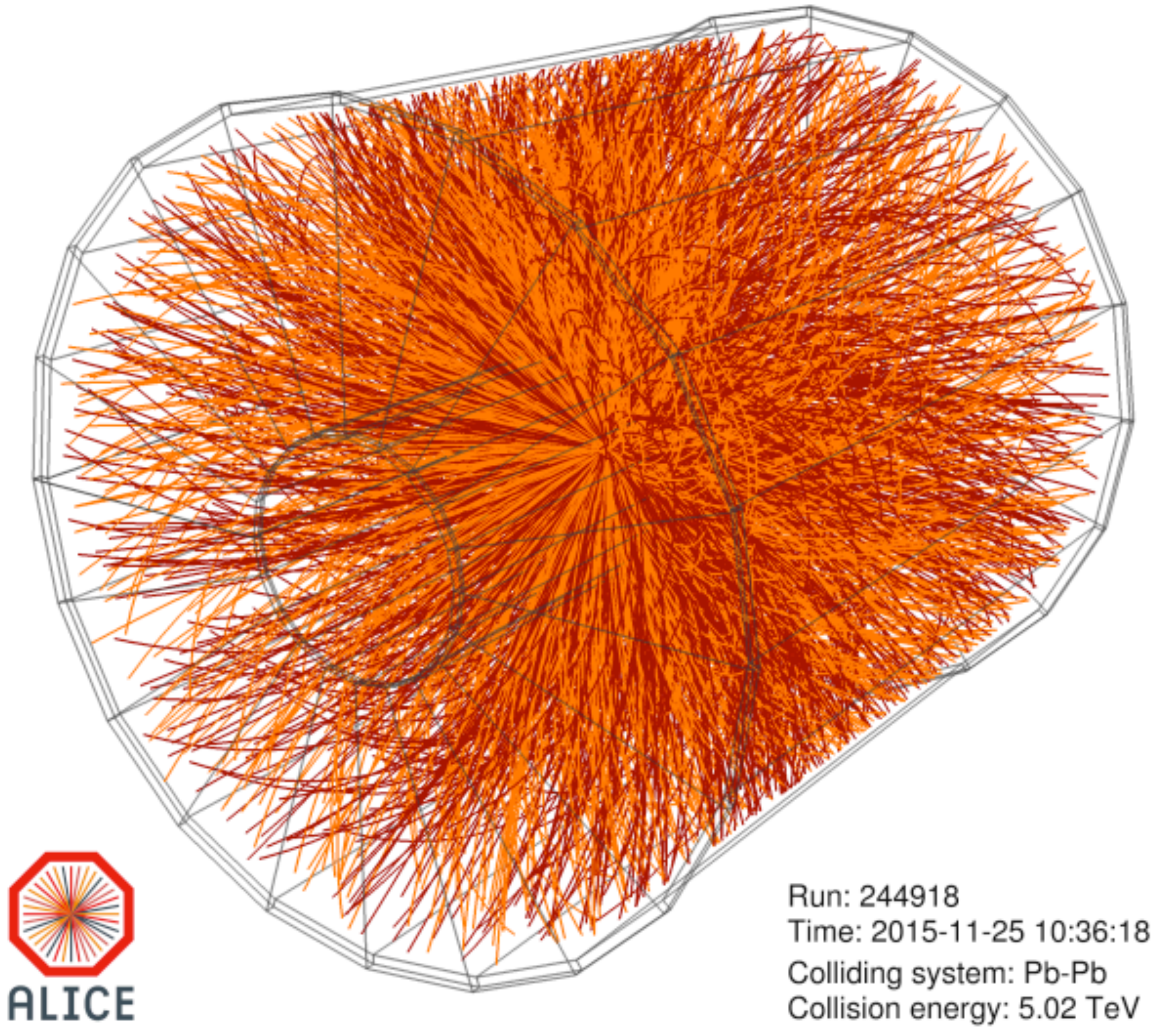

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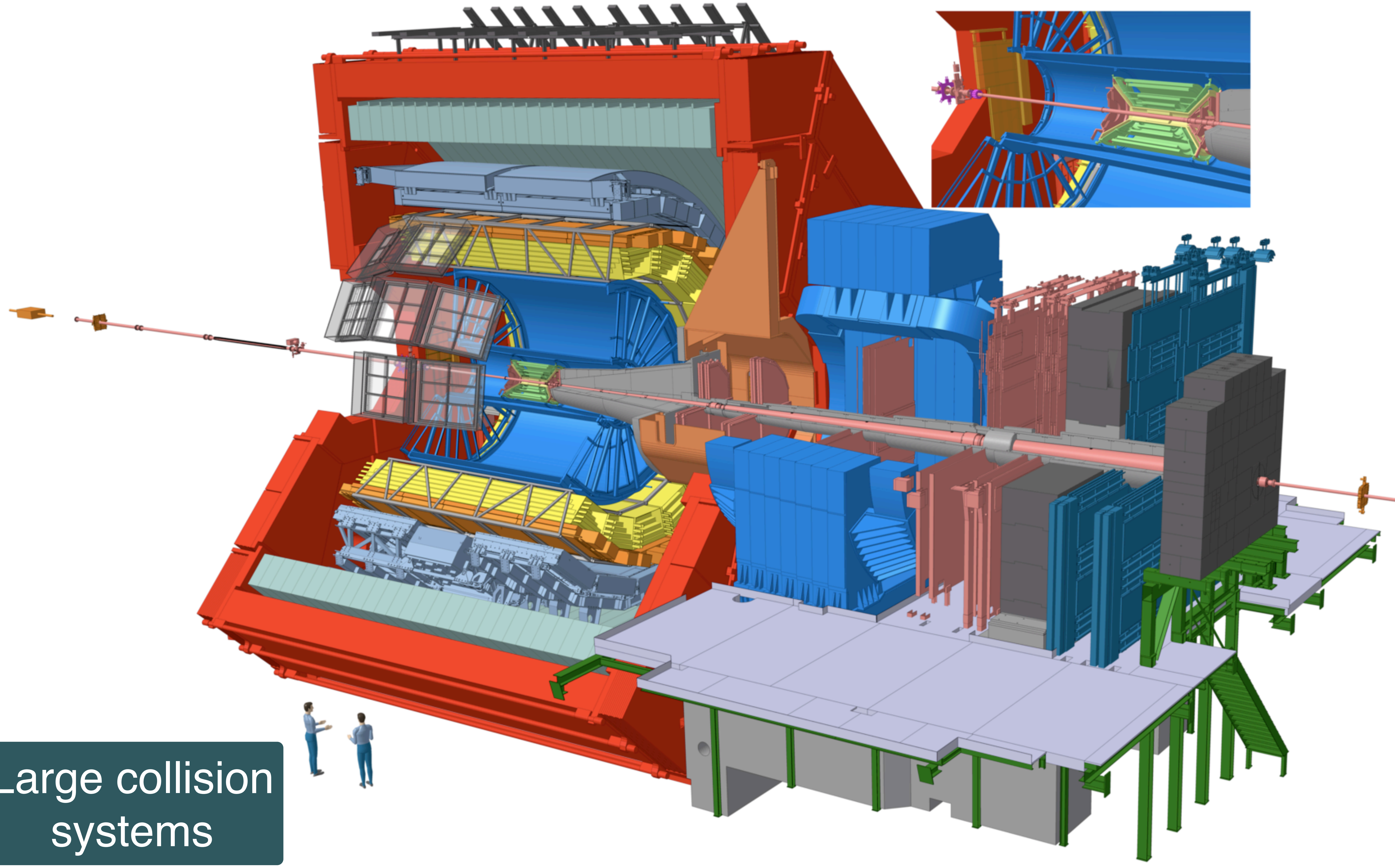
Large collision systems



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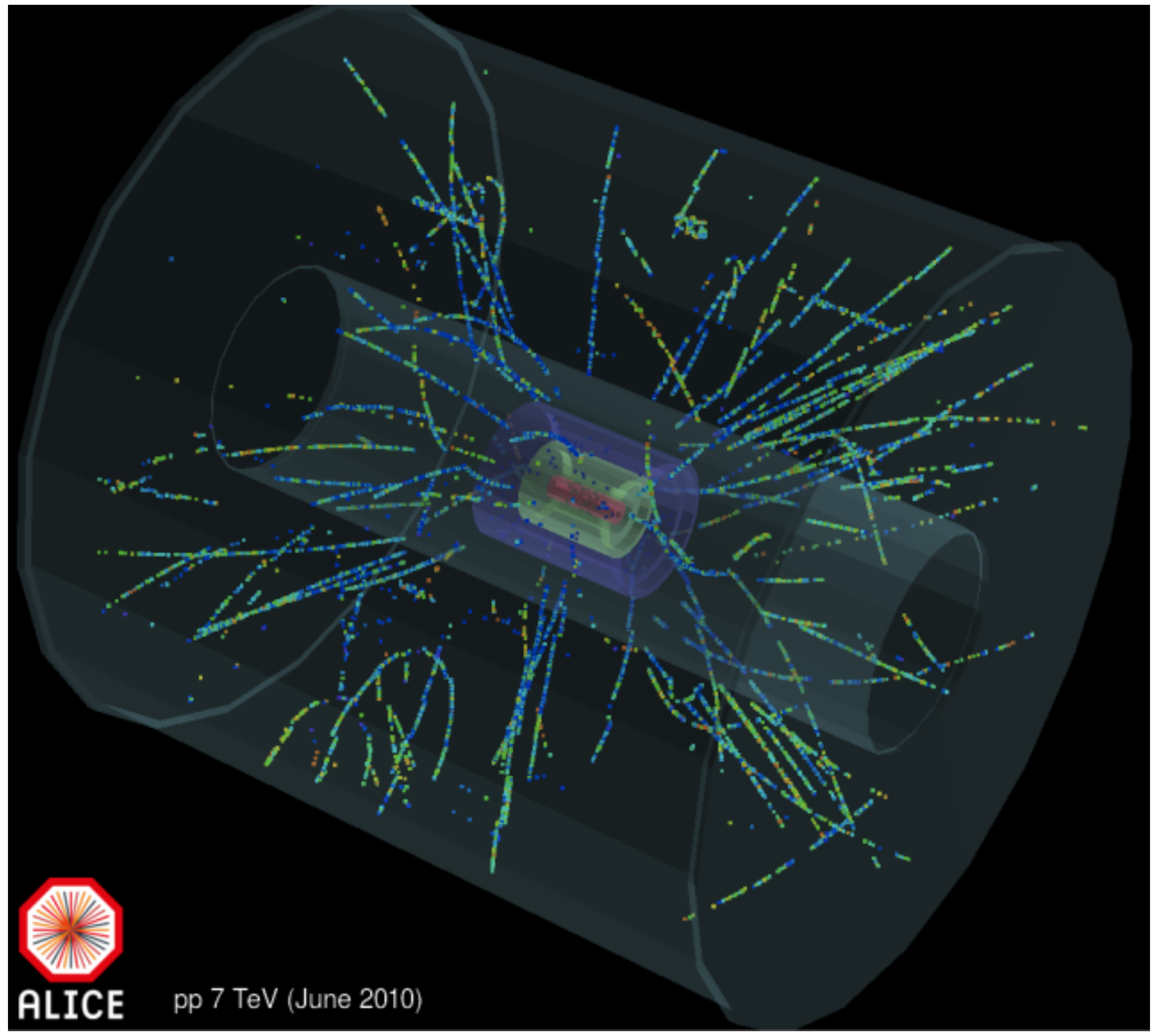

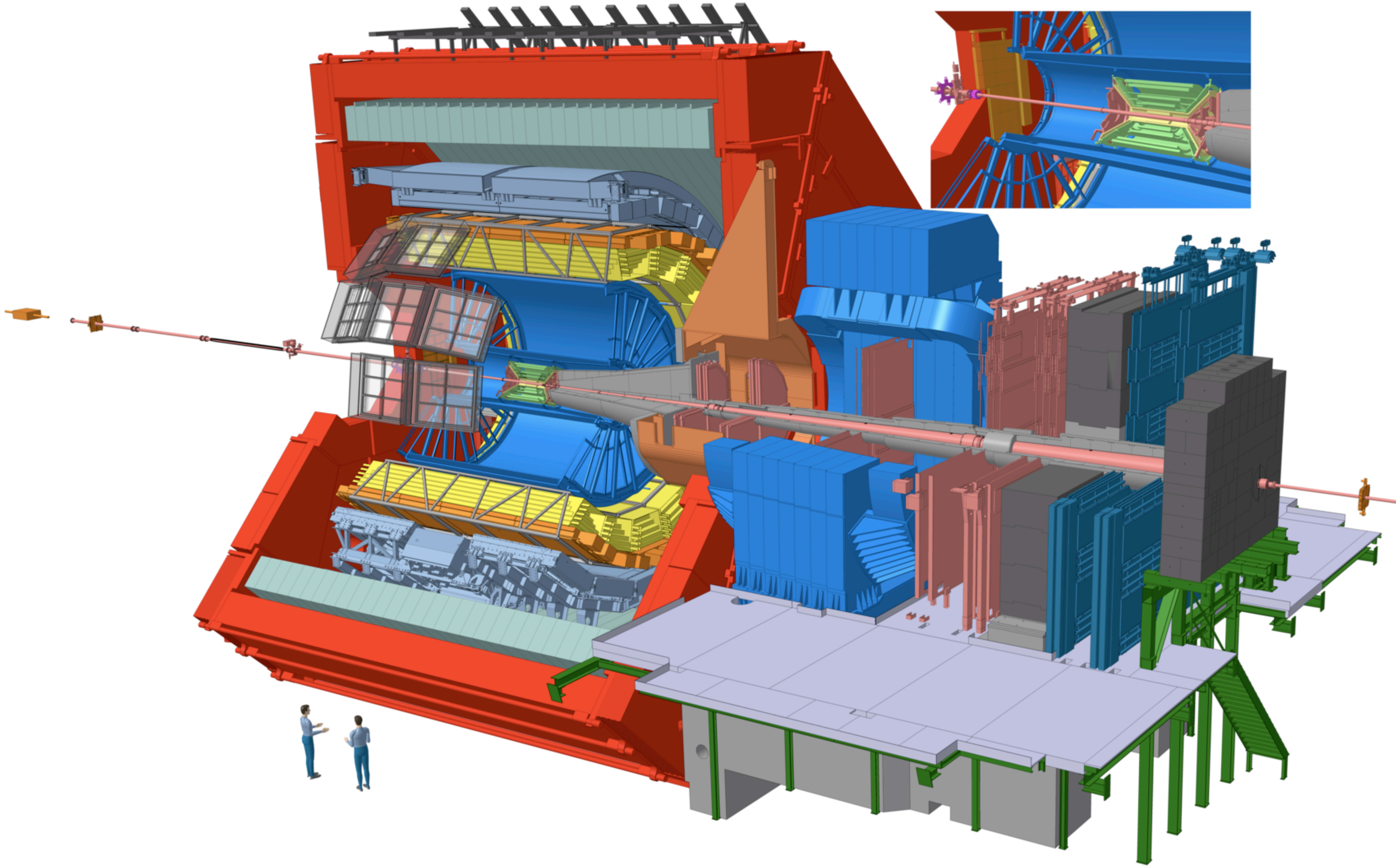

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Small collision systems

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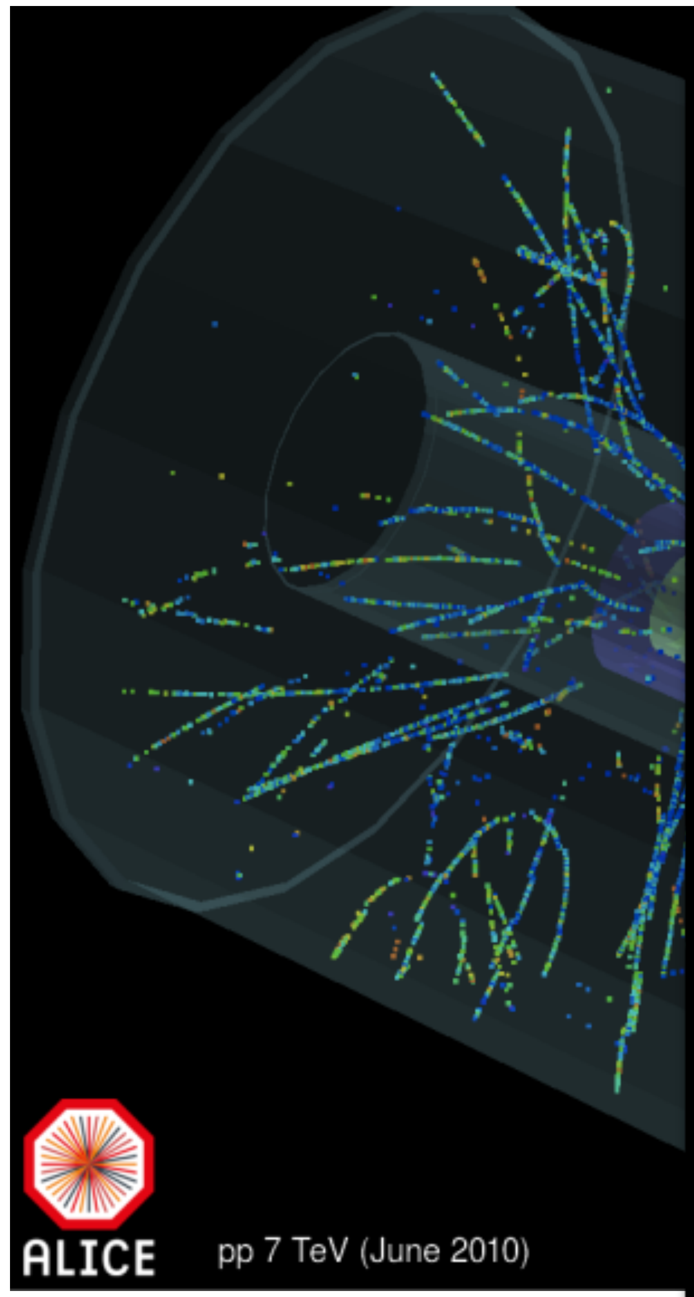

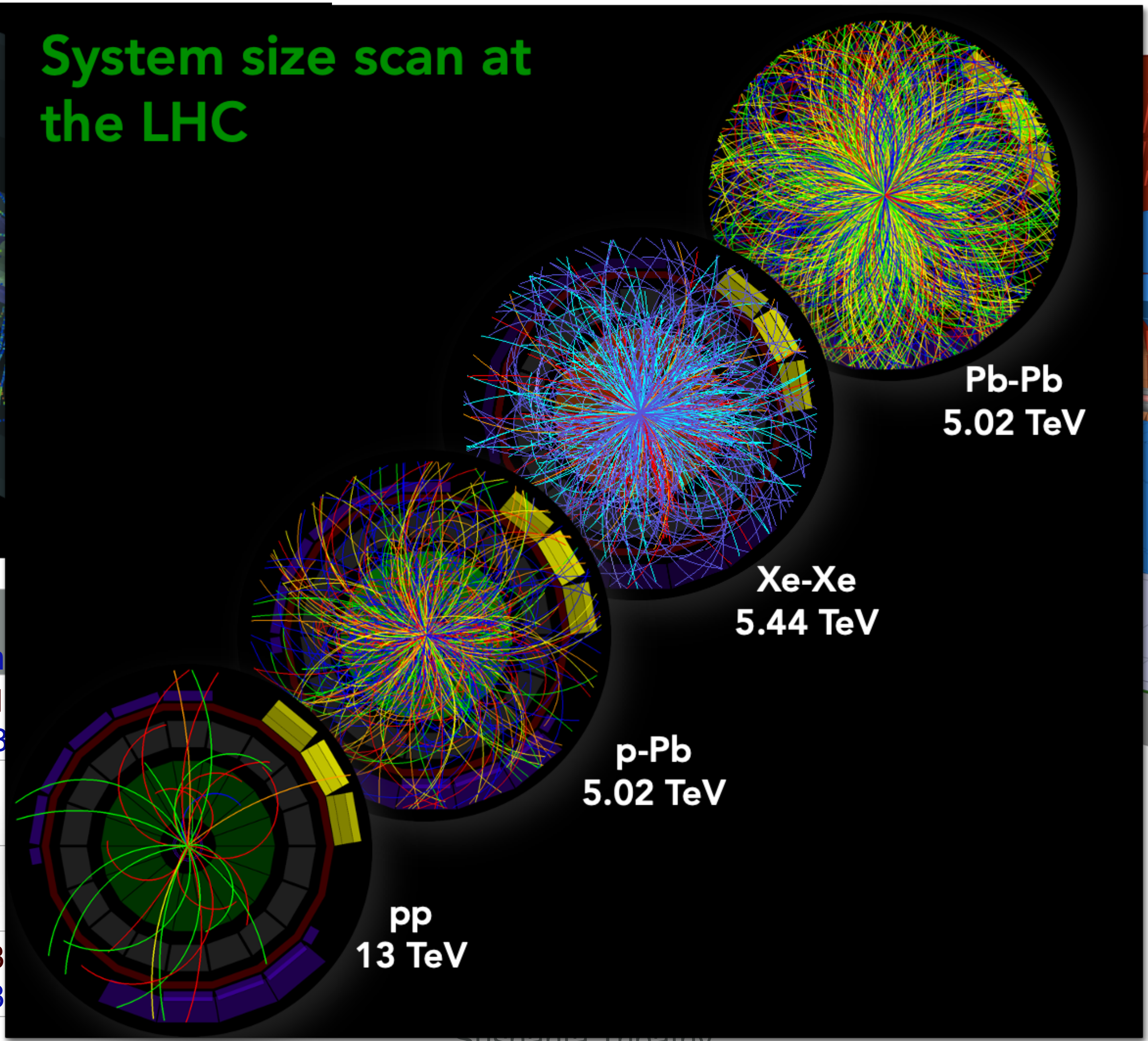

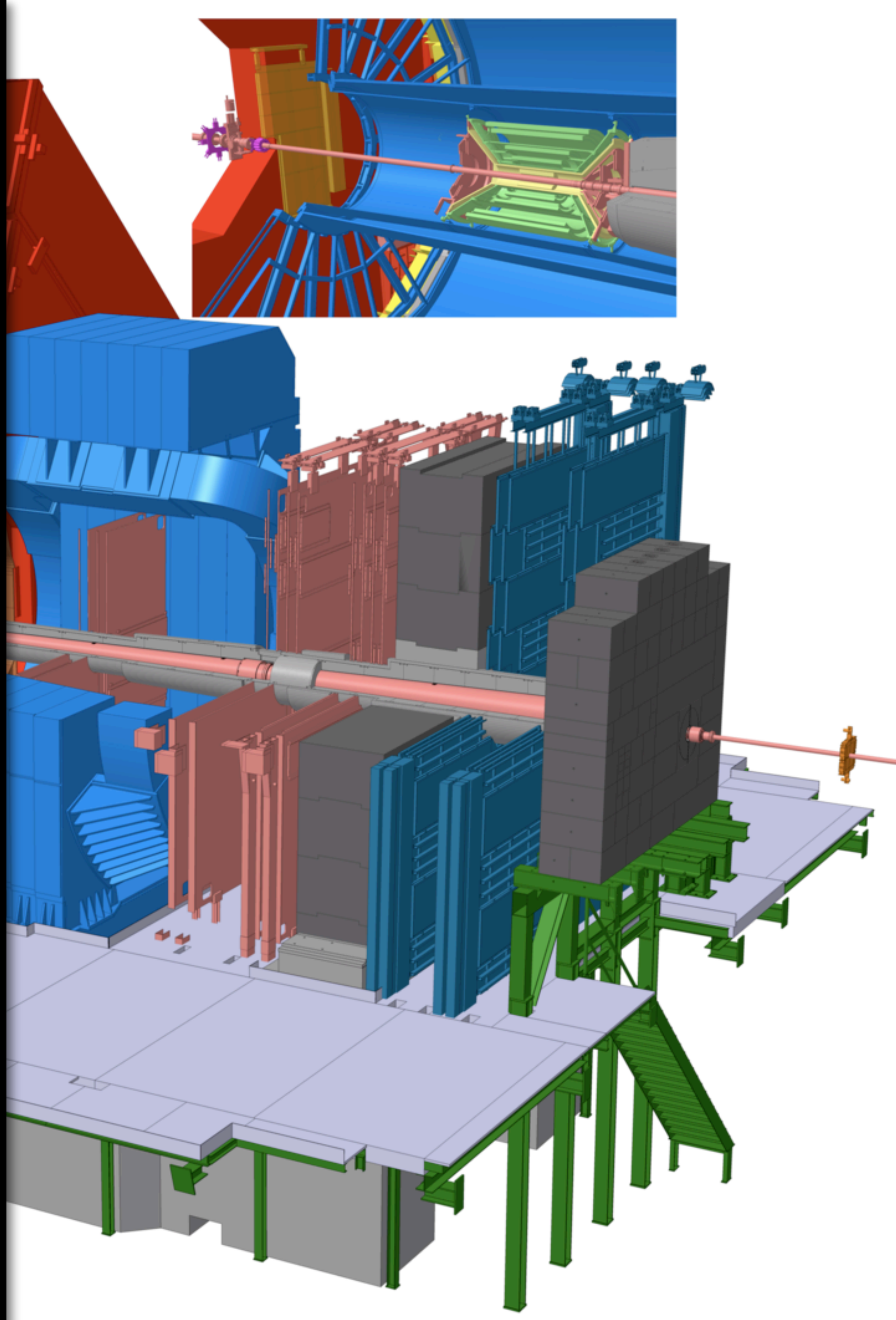

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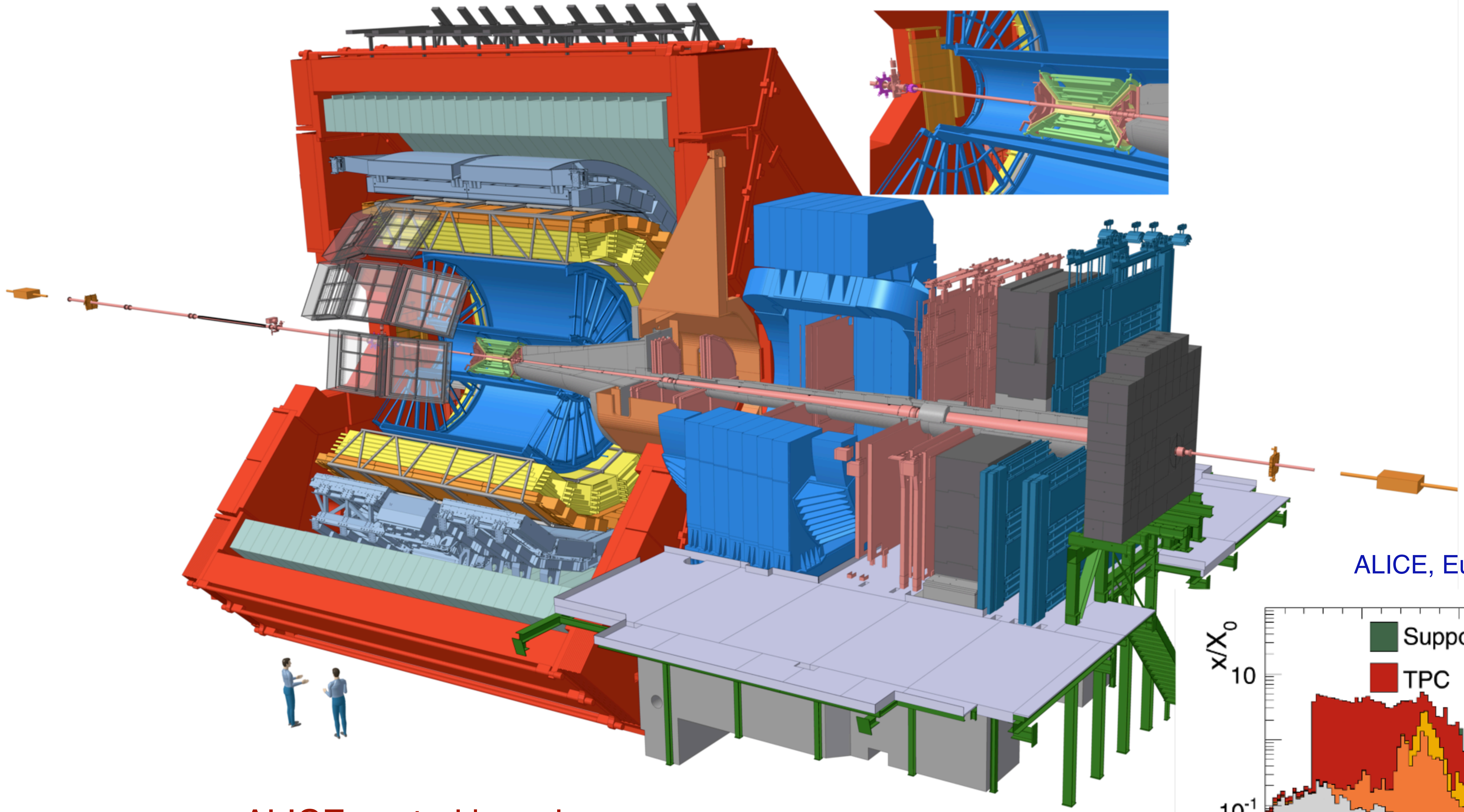
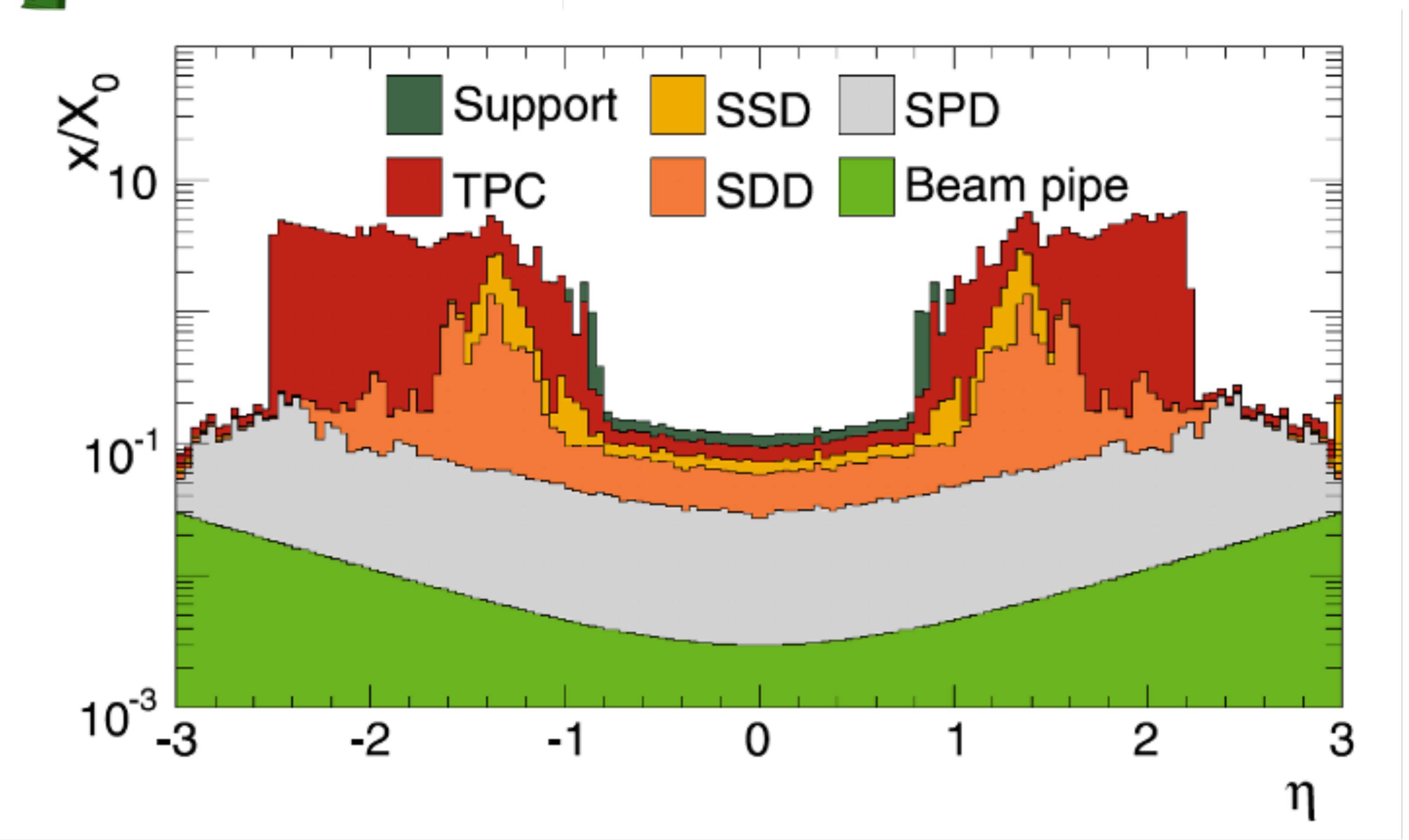


ALICE central barrel

- $B = 0.5$ T solenoid, $|\eta| < 0.9$
- 2π tracking and PID
- Lowest material budget in central rapidity region at the LHC

ALICE, Eur. Phys. J. C (2009) 62: 237



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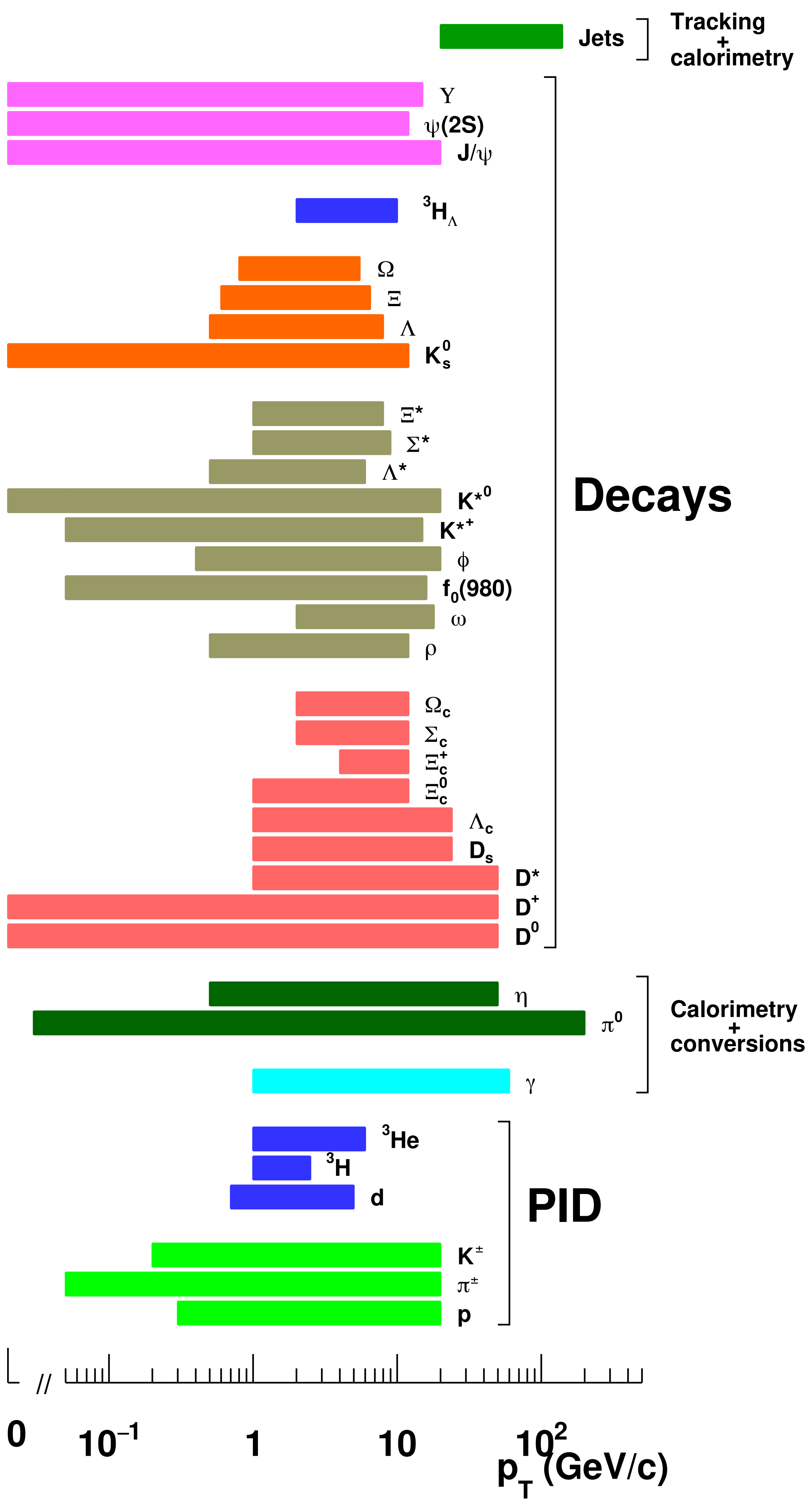
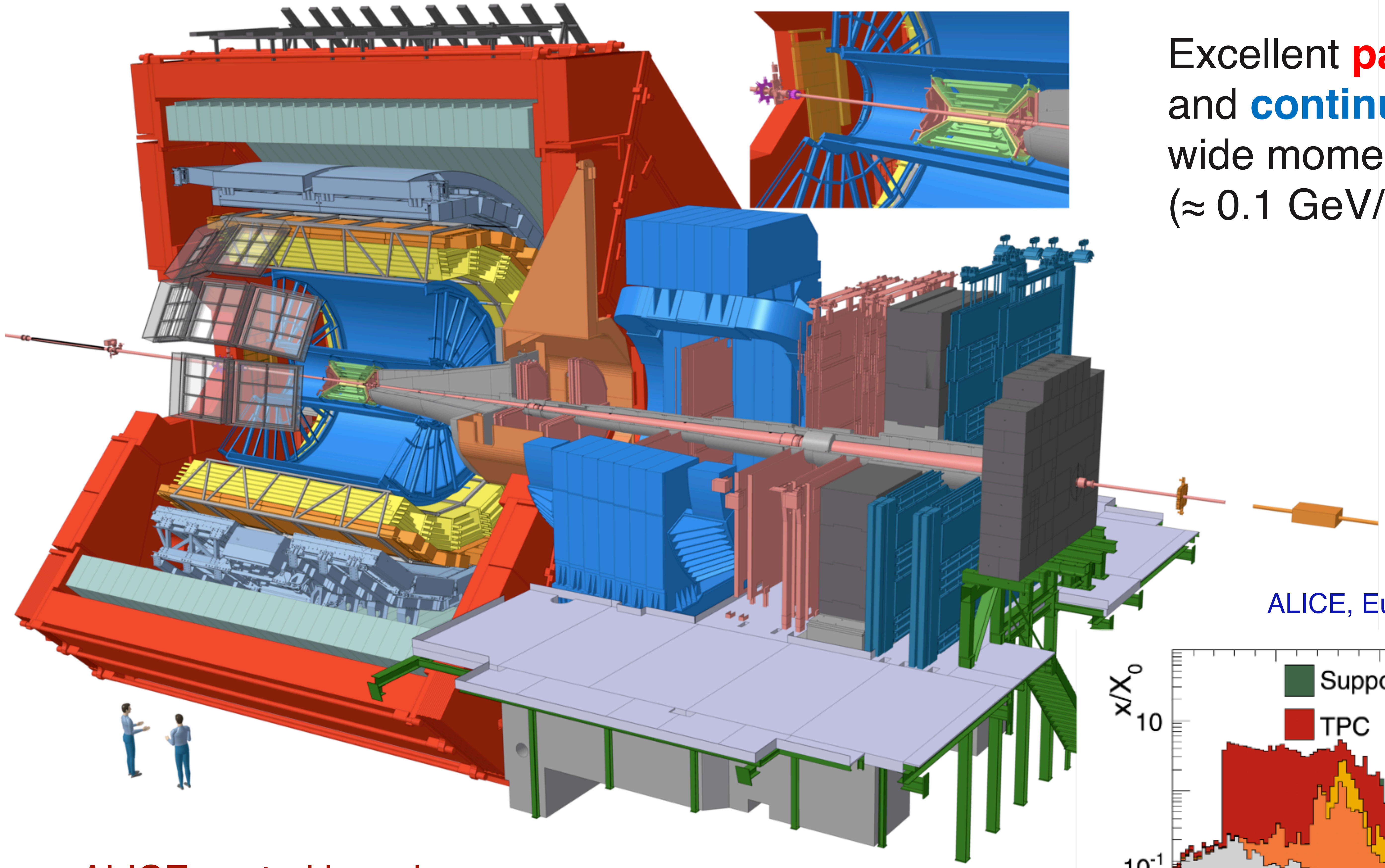


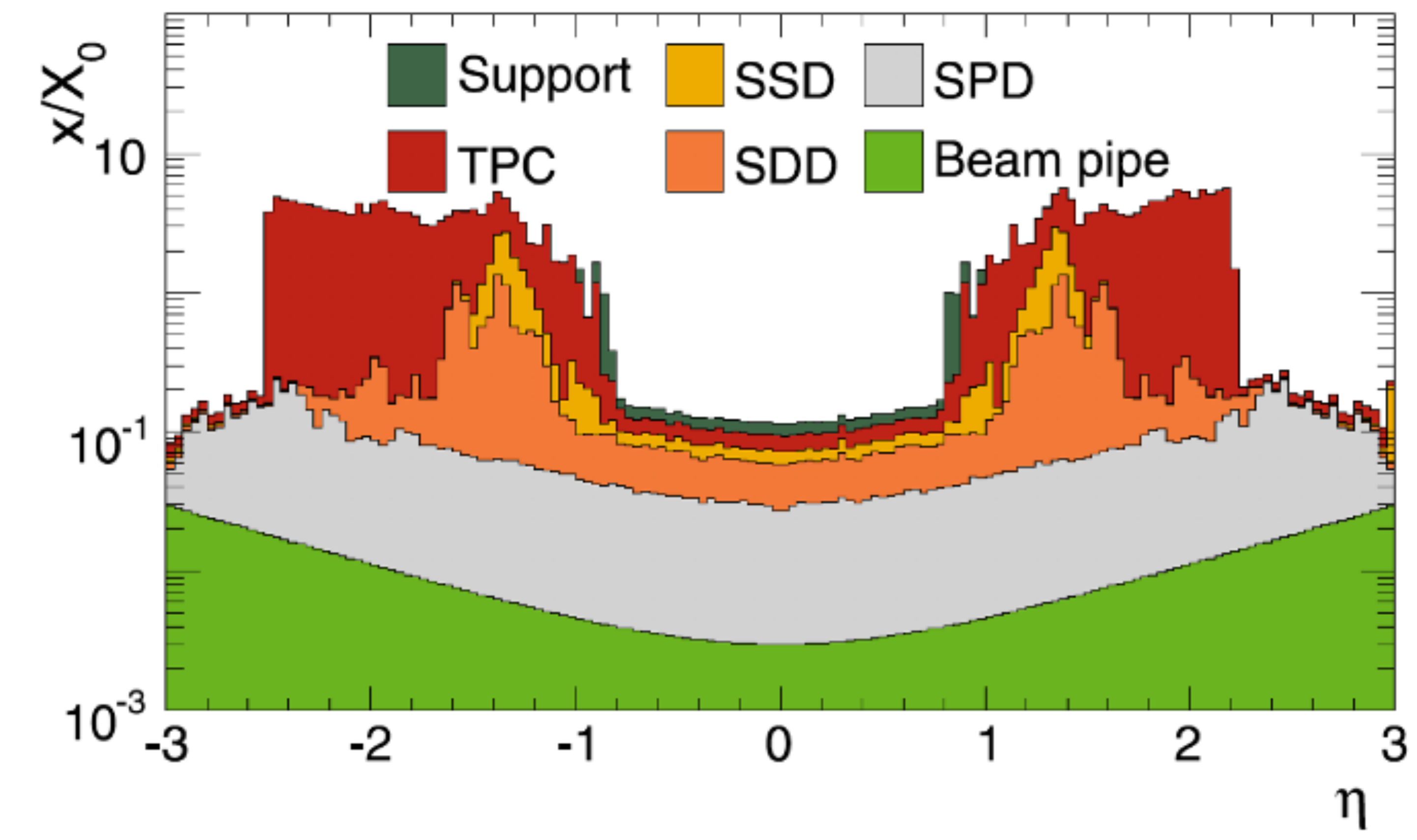
ALICE, arXiv:2211.04384

ALI-PUB-528808



Excellent **particle identification** and **continuous tracking** over a wide momentum range (≈ 0.1 GeV/c to ≈ 30 GeV/c)

ALICE, Eur. Phys. J. C (2009) 62: 237



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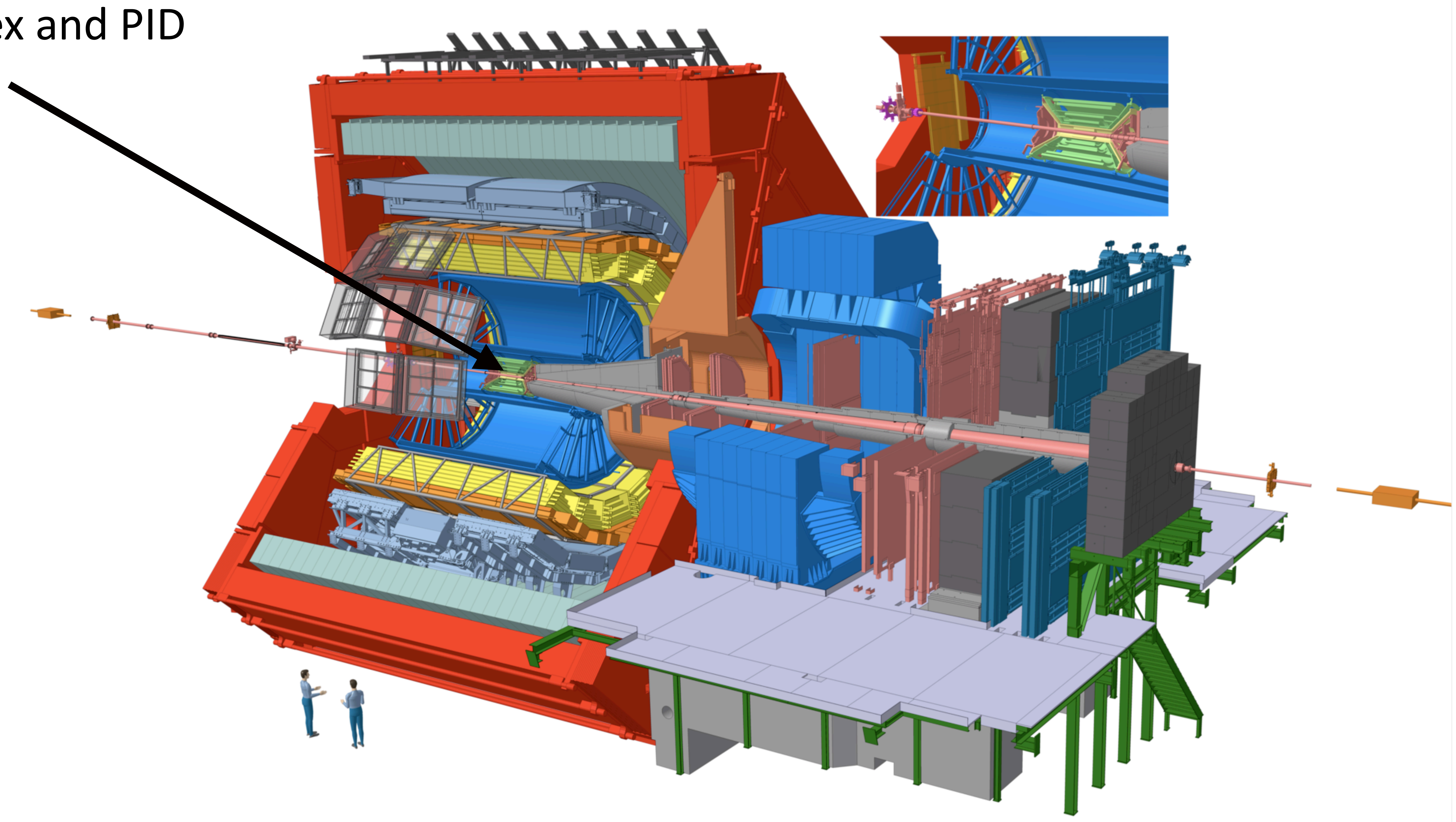
A Large Ion Collider Experiment

Inner Tracking System (ITS)

Tracking, vertex and PID



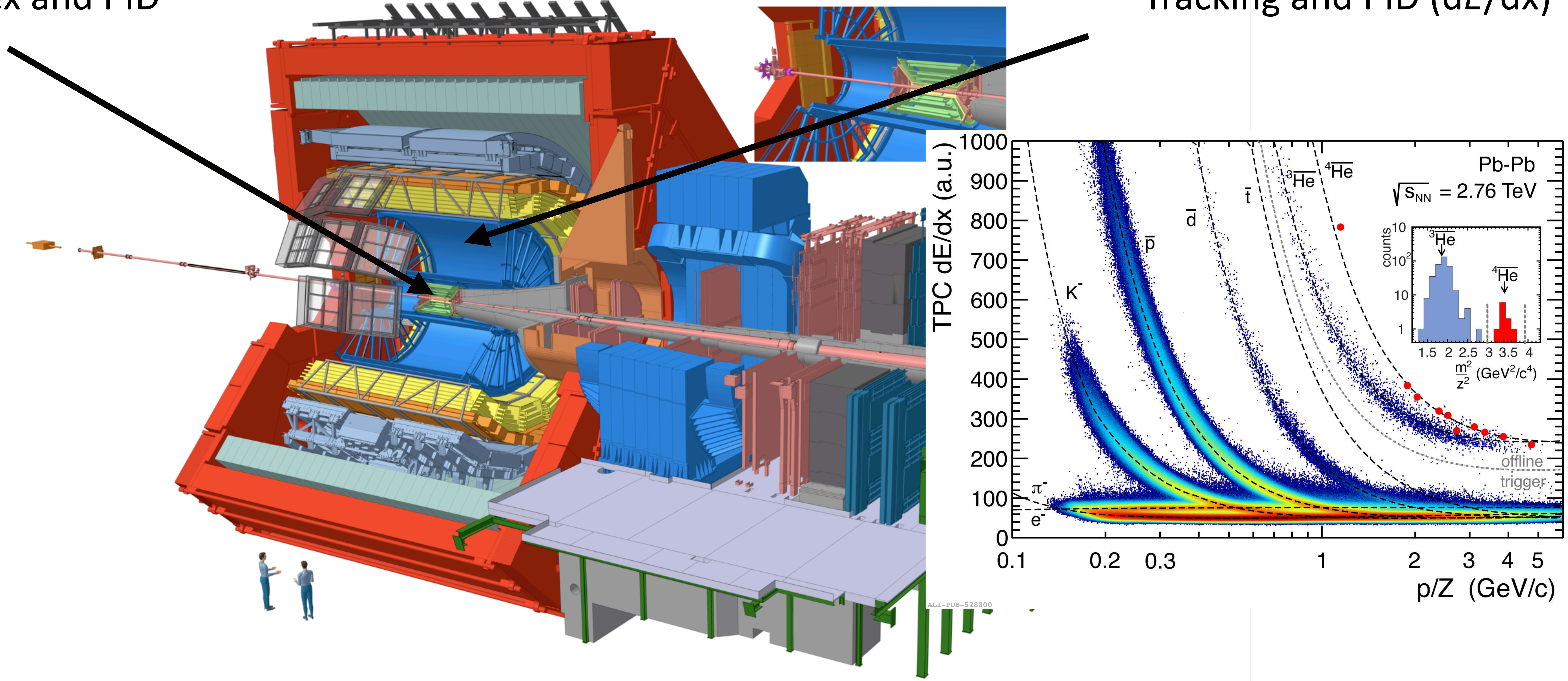
A Large Ion Collider Experiment

Inner Tracking System (ITS)

Tracking, vertex and PID

Time Projection Chamber (TPC)

Tracking and PID (dE/dx)

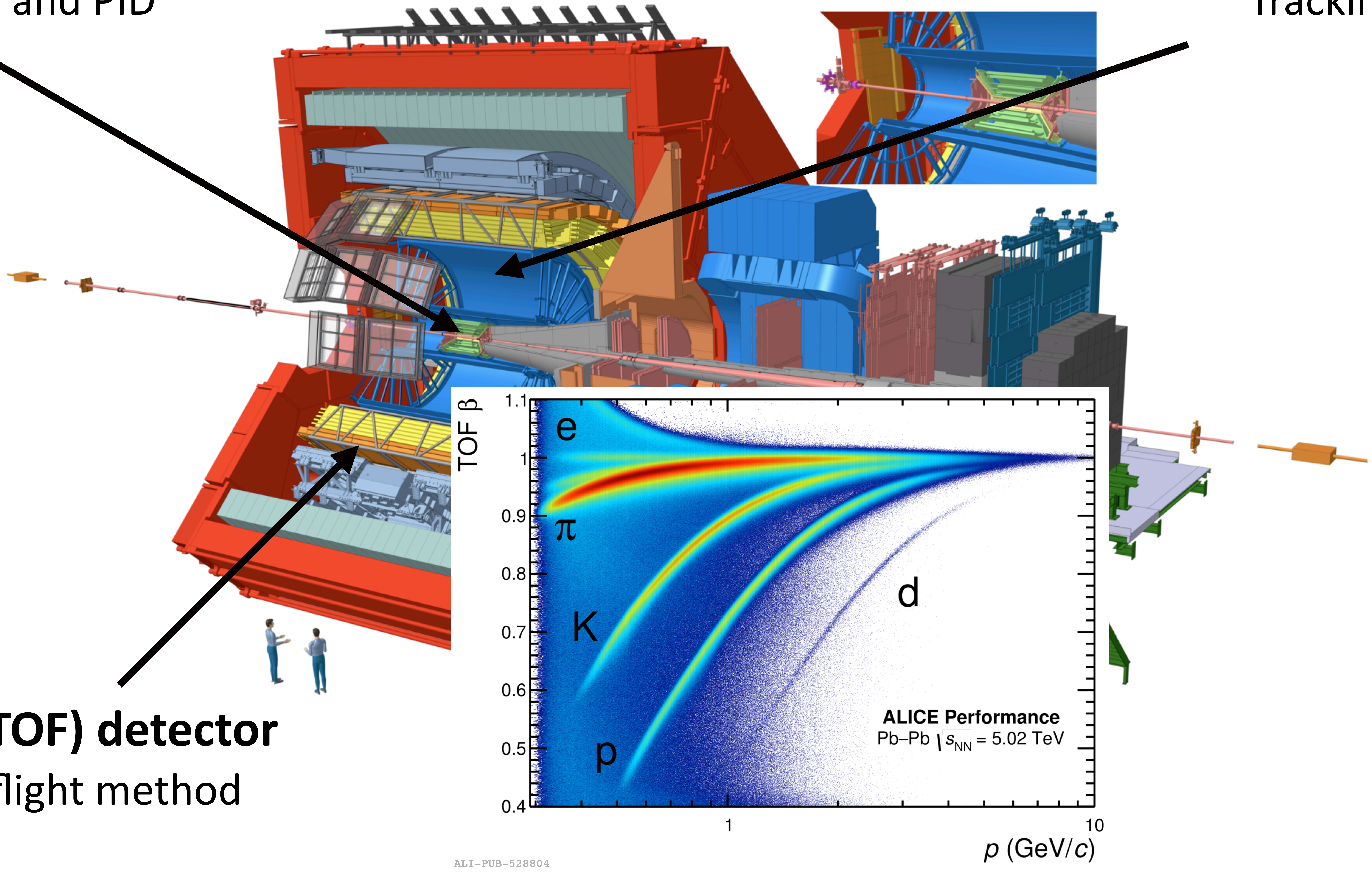


A Large Ion Collider Experiment

Inner Tracking System (ITS)
Tracking, vertex and PID

Time Projection Chamber (TPC)
Tracking and PID (dE/dx)

Time of Flight (TOF) detector
PID via time-of-flight method



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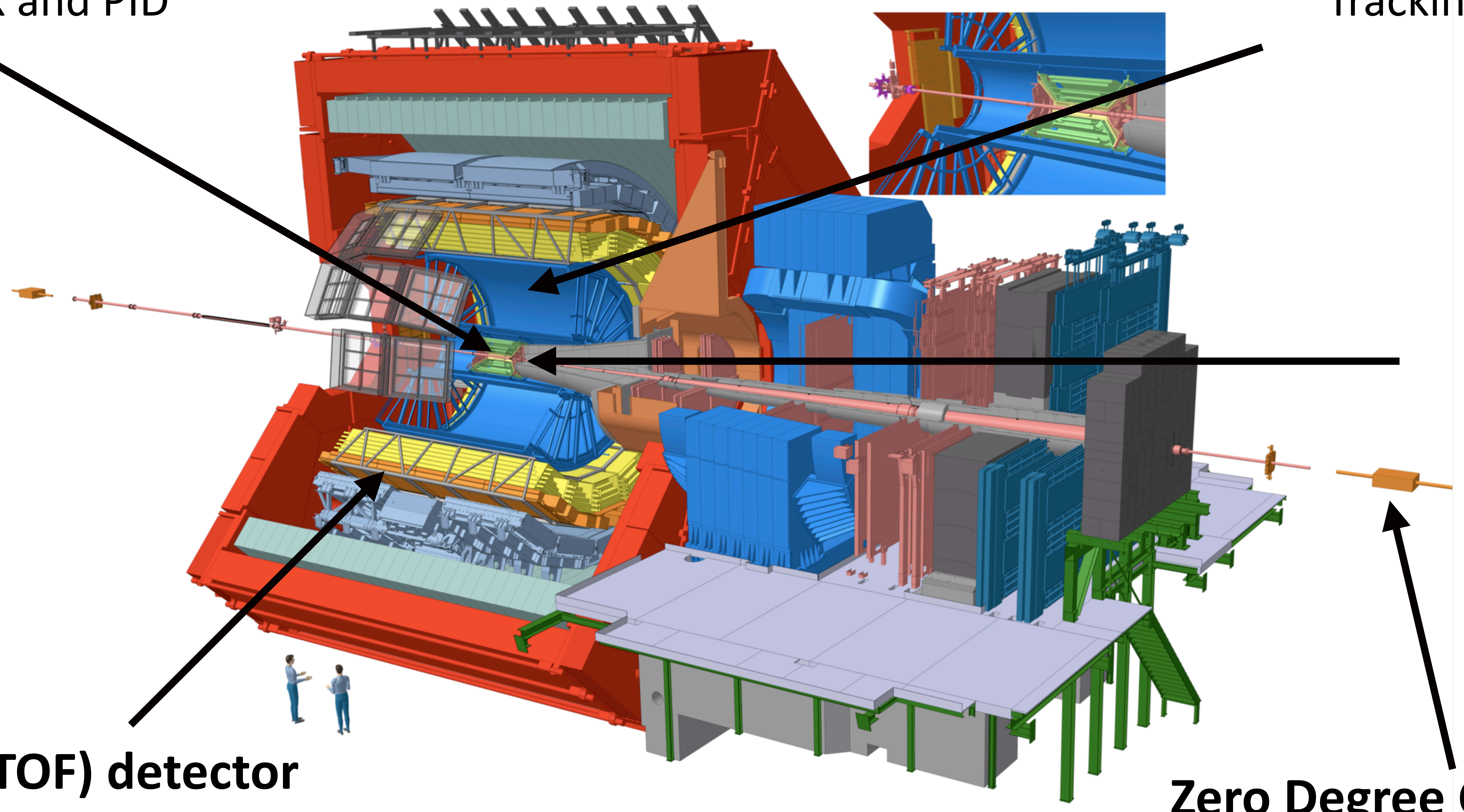

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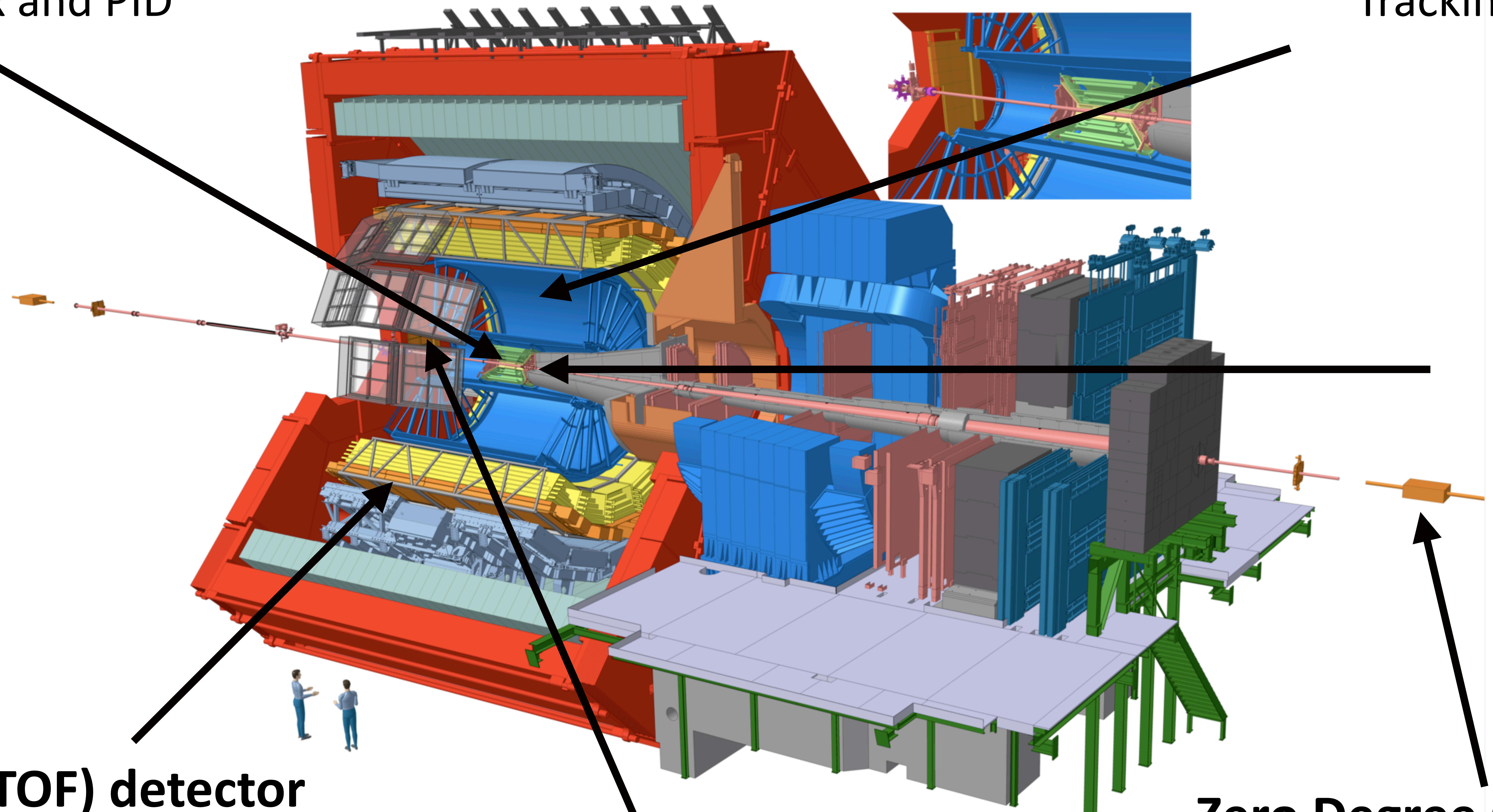


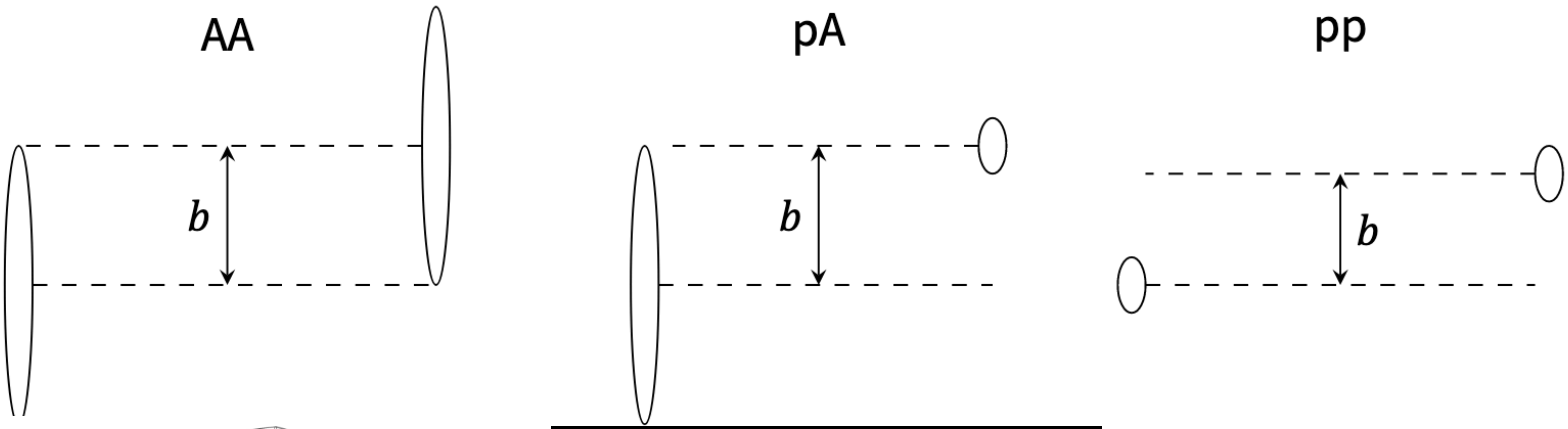
V0
Trigger, multiplicity estimator

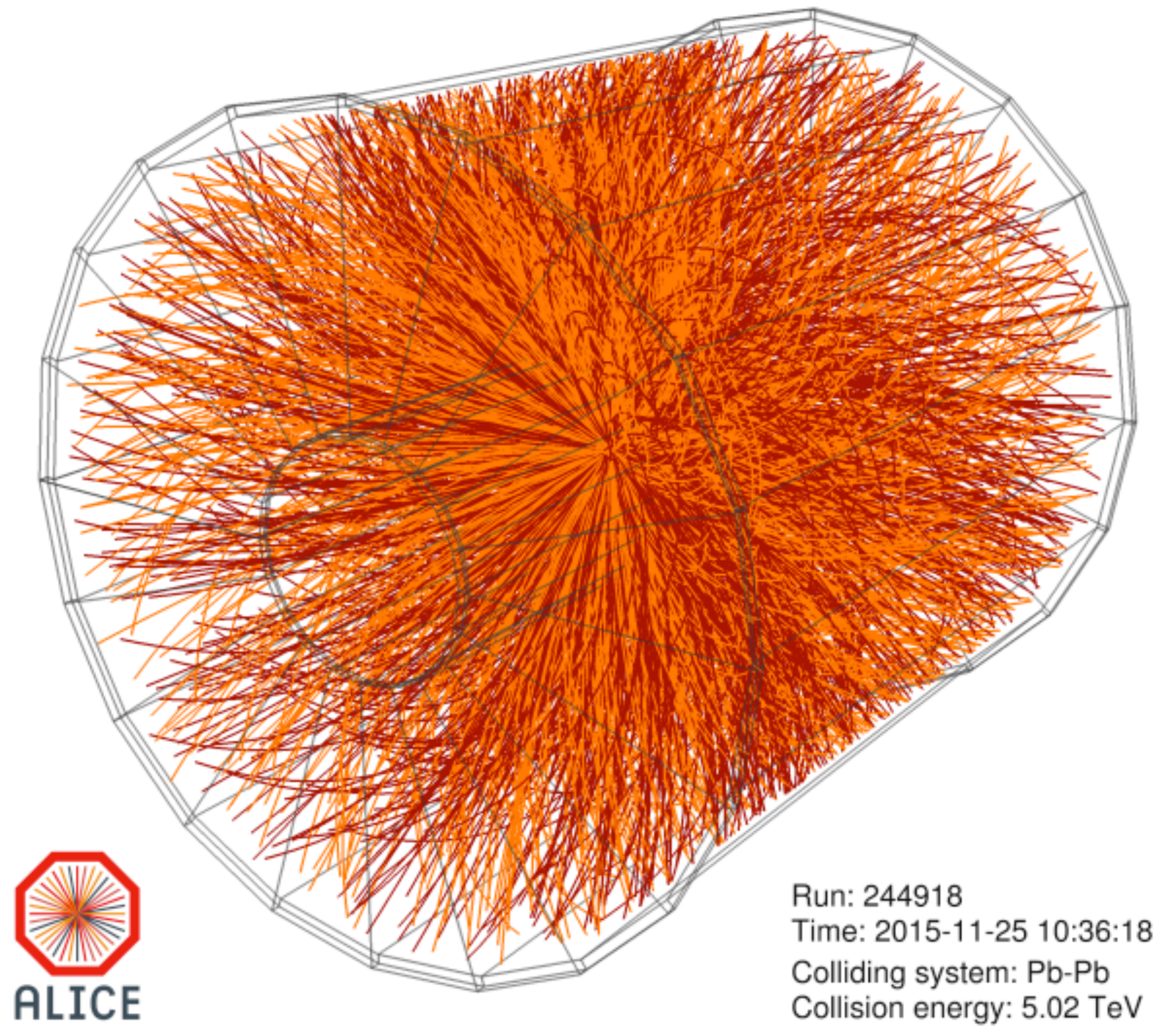
Time of Flight (TOF) detector
PID via time-of-flight method

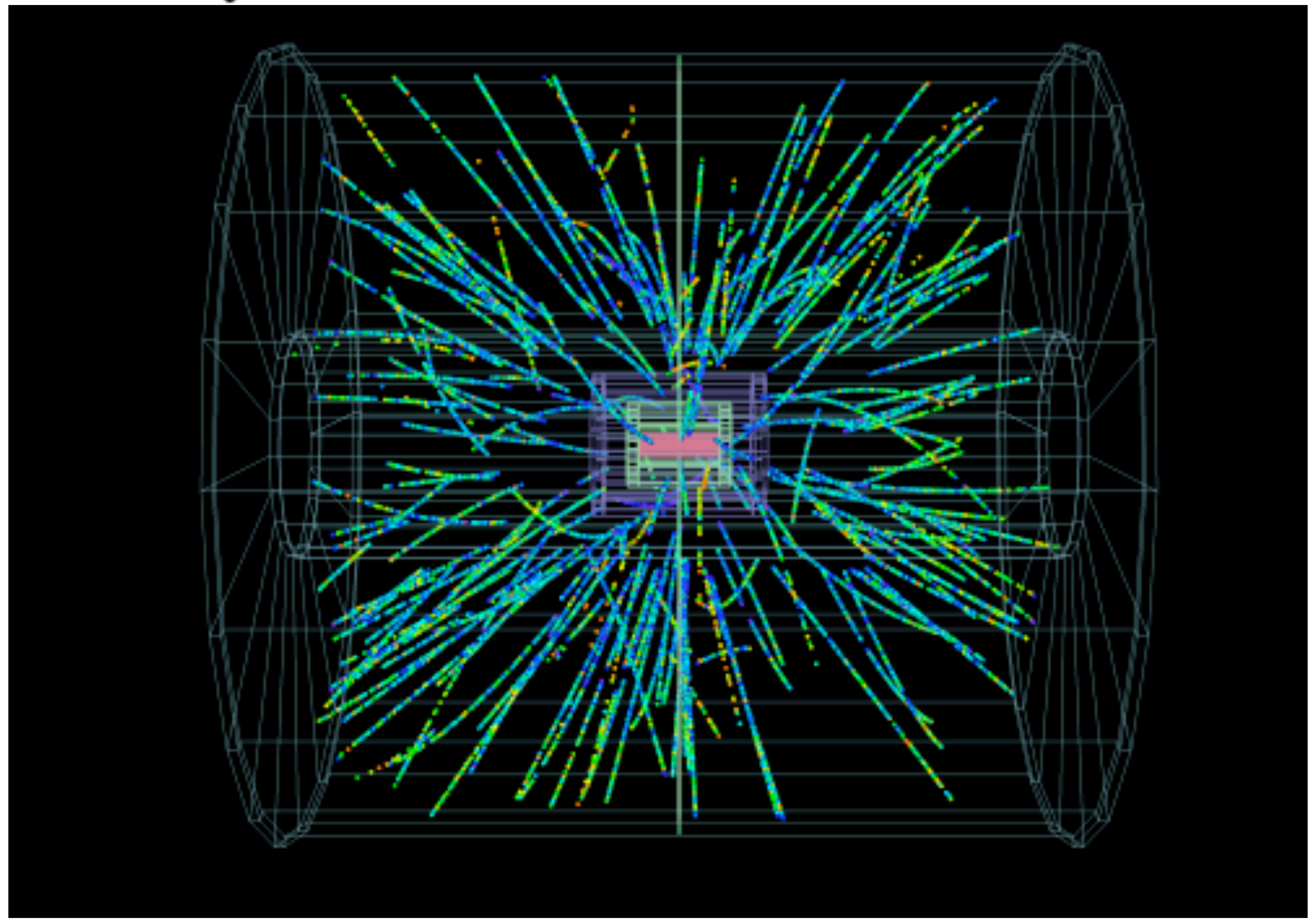
Photon Multiplicity Detector (PMD)
Photon detection

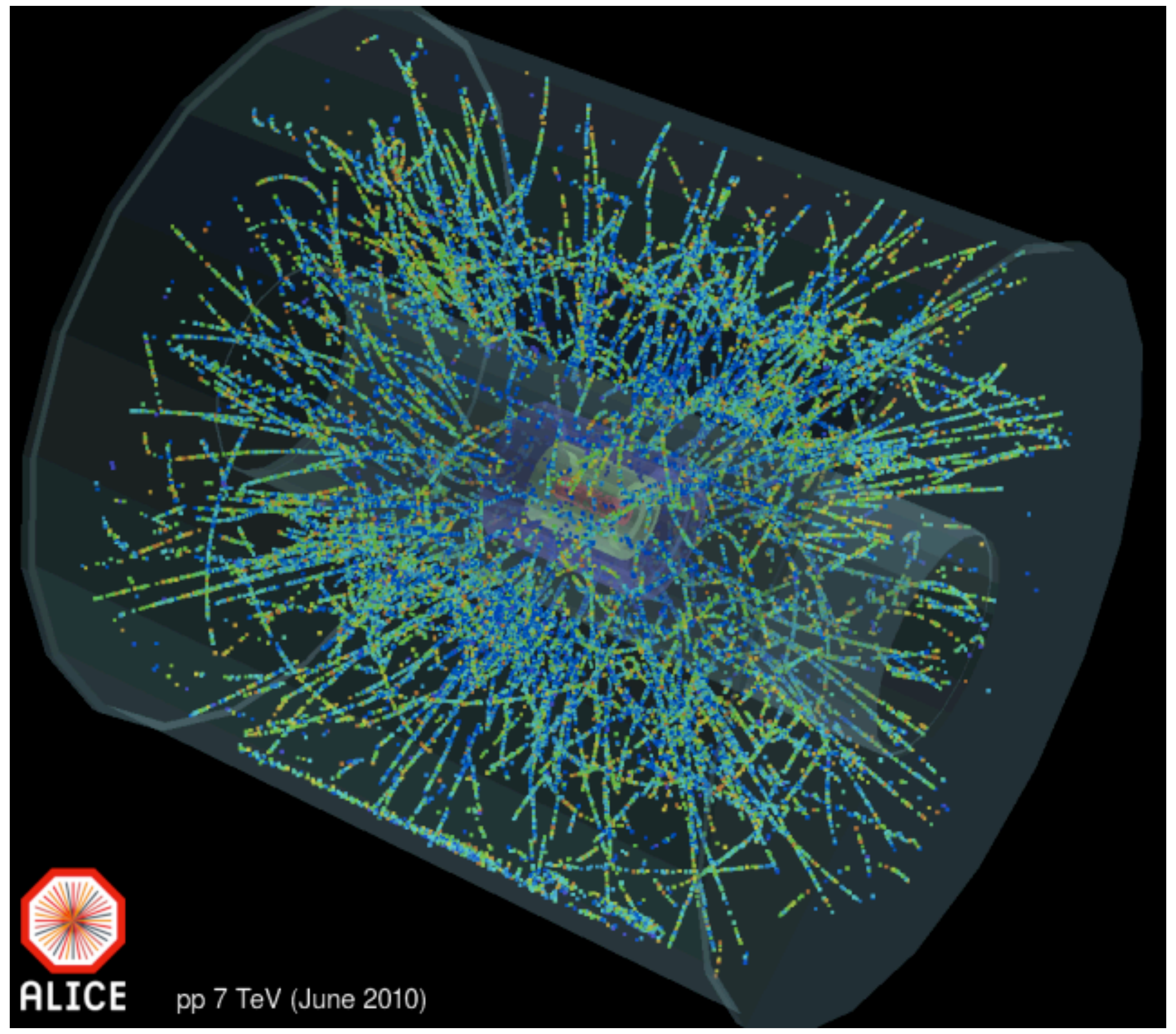
Zero Degree Calorimeter (ZDC)
112.5 m from IP2, energy percentiles based on energy deposition, measurement of beam remnants

Schematic picture of pp, p-ion and ion-ion collisions





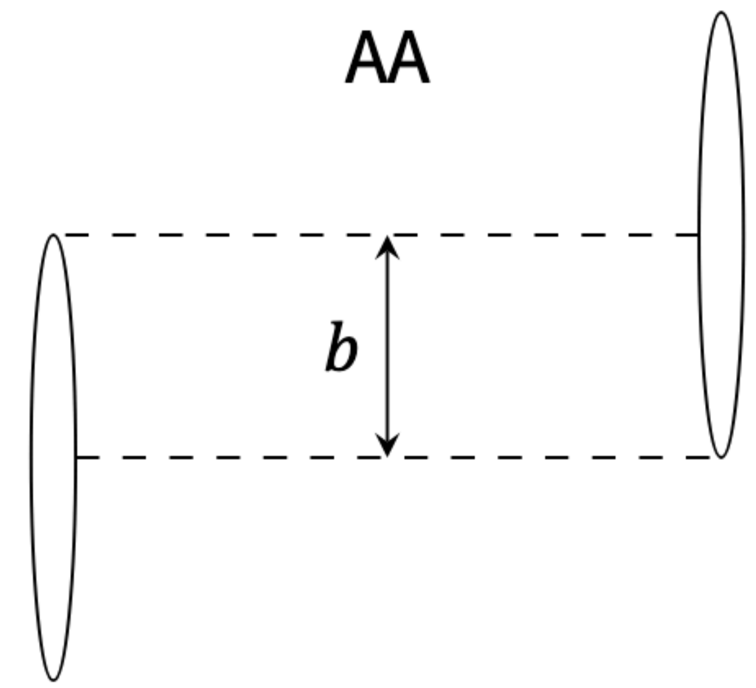




Centrality/multiplicity estimation

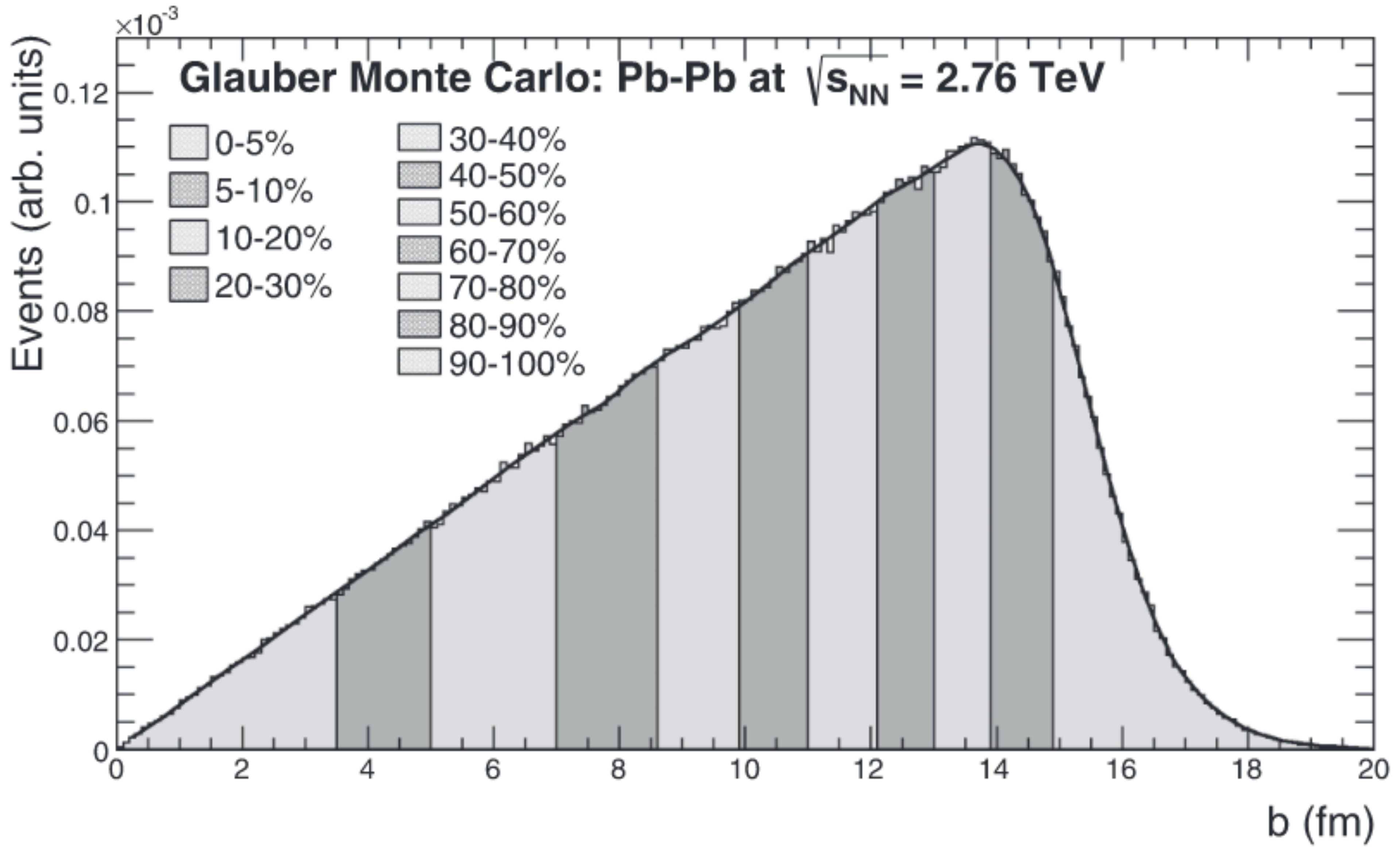
Centrality estimation in Pb—Pb

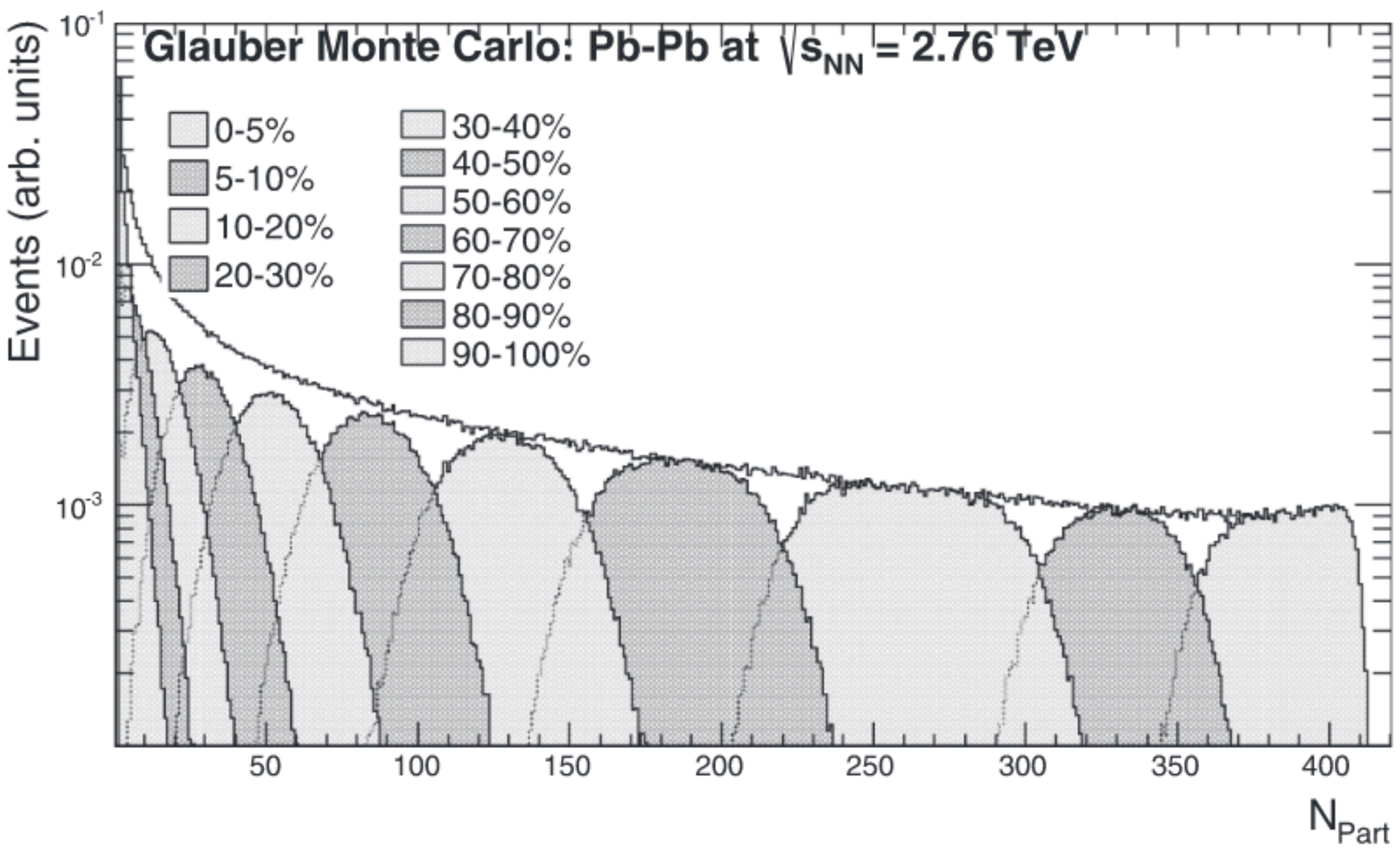
Centrality(c) is defined as: $c = \frac{\int_0^b d\sigma/db'\, db'}{\int_0^\infty d\sigma/db'\, db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db'$



It can be estimated in ALICE as $c \approx \frac{1}{\sigma_{AA}} \int_{N_{ch}^{THR}}^{\infty} \frac{d\sigma}{dN'_{ch}} dN'_{ch} \approx \frac{1}{\sigma_{AA}} \int_0^{E_{ZDC}^{THR}} \frac{d\sigma}{dE'_{ZDC}} dE'_{ZDC}$

Using the Monte-Carlo based on the Glauber model we then relate these centrality estimates to geometrical quantities such as N_{part}, N_{coll}, b

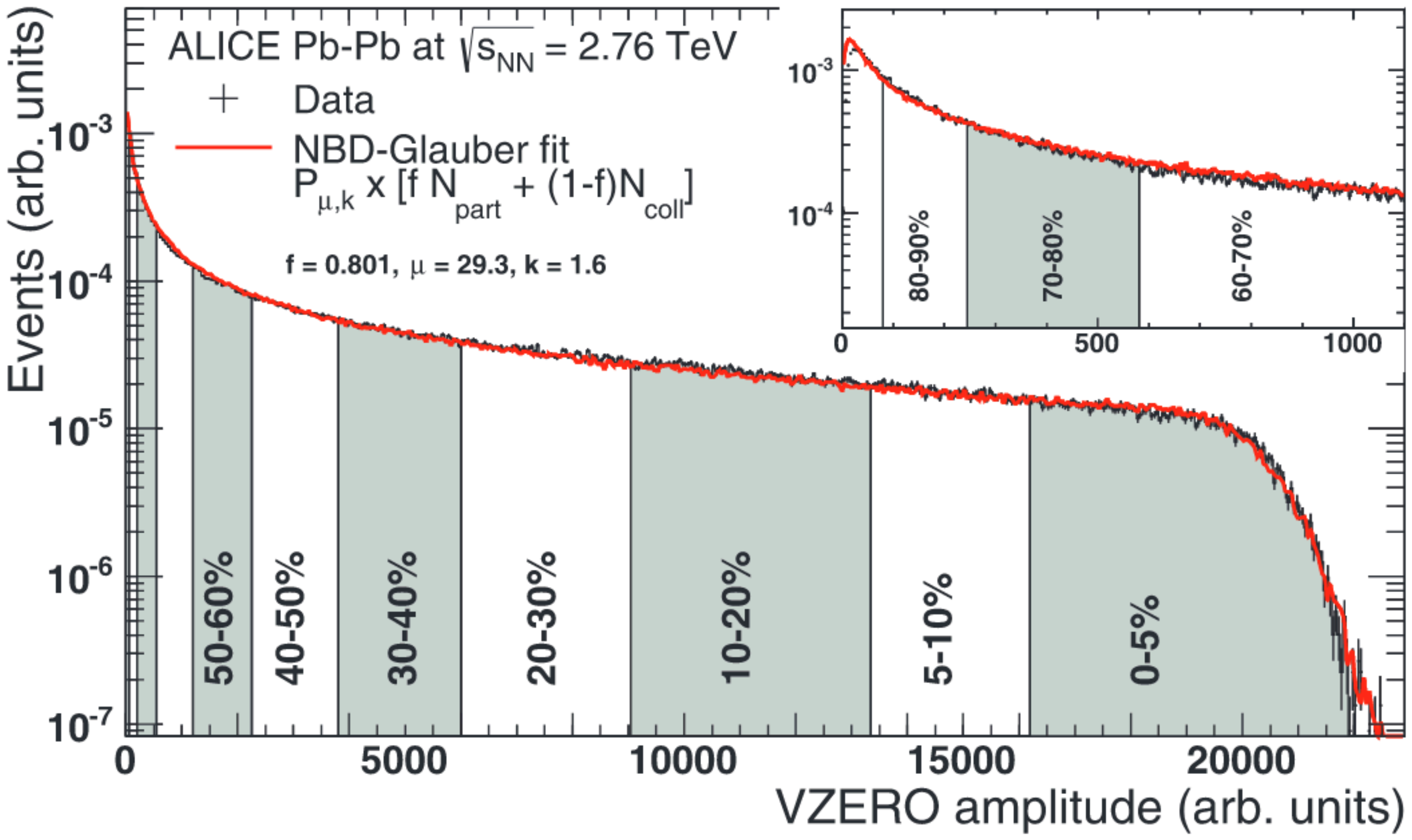


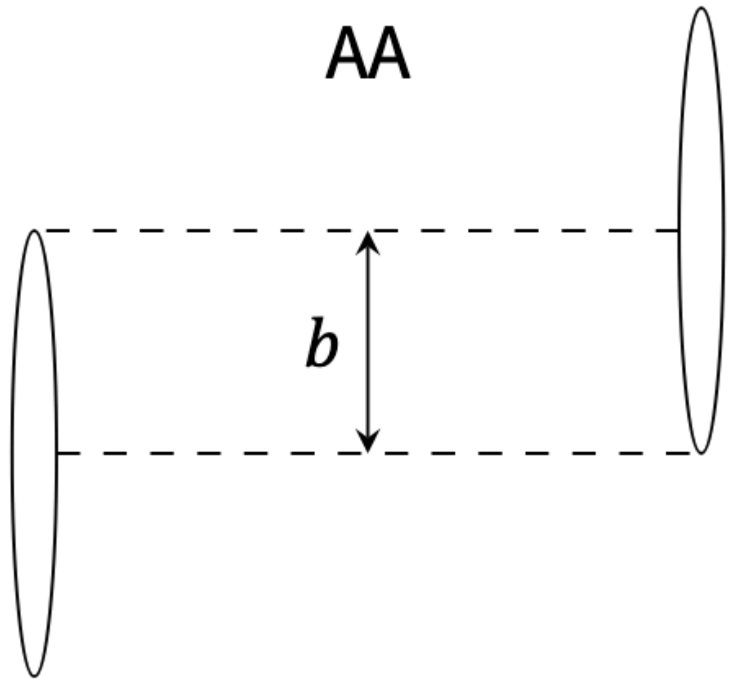


ALICE, Phys. Rev. C**88**, 044909 (2013)

Centrality estimation in Pb—Pb (with V0 amplitude)

Distribution of the sum of amplitudes in the VZERO scintillators





The distribution is fitted with the MC NBD-Glauber fit

$$N_{\text{ancestors}} = f N_{\text{part}} + (1 - f) N_{\text{coll}}$$

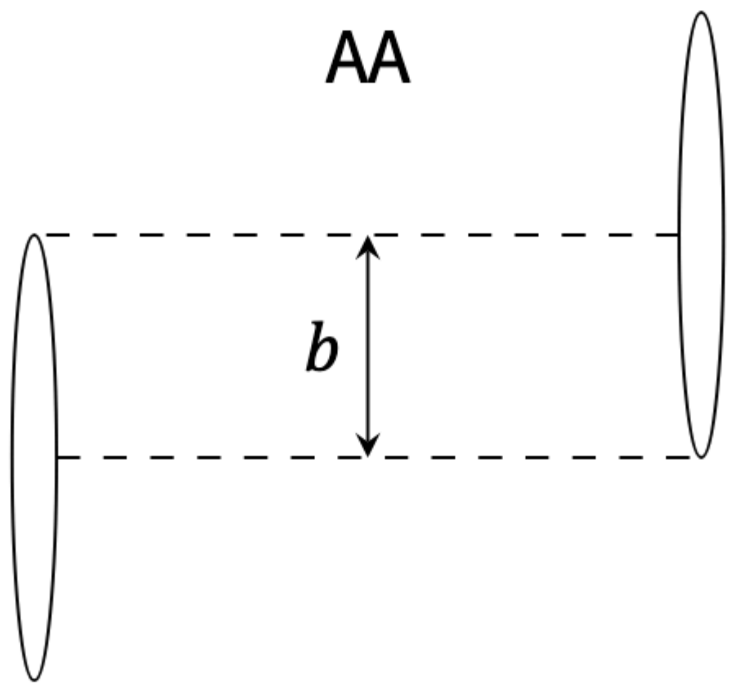
$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}},$$

ALICE, Phys. Rev. C**88**, 044909 (2013)

Centrality estimation in Pb—Pb (using ZDC)

$$N_{\text{part}} = 2\text{A} - E_{\text{ZDC}}/E_{\text{A}}$$

A = Mass number of Pb
E_{A} = beam energy per nucleon



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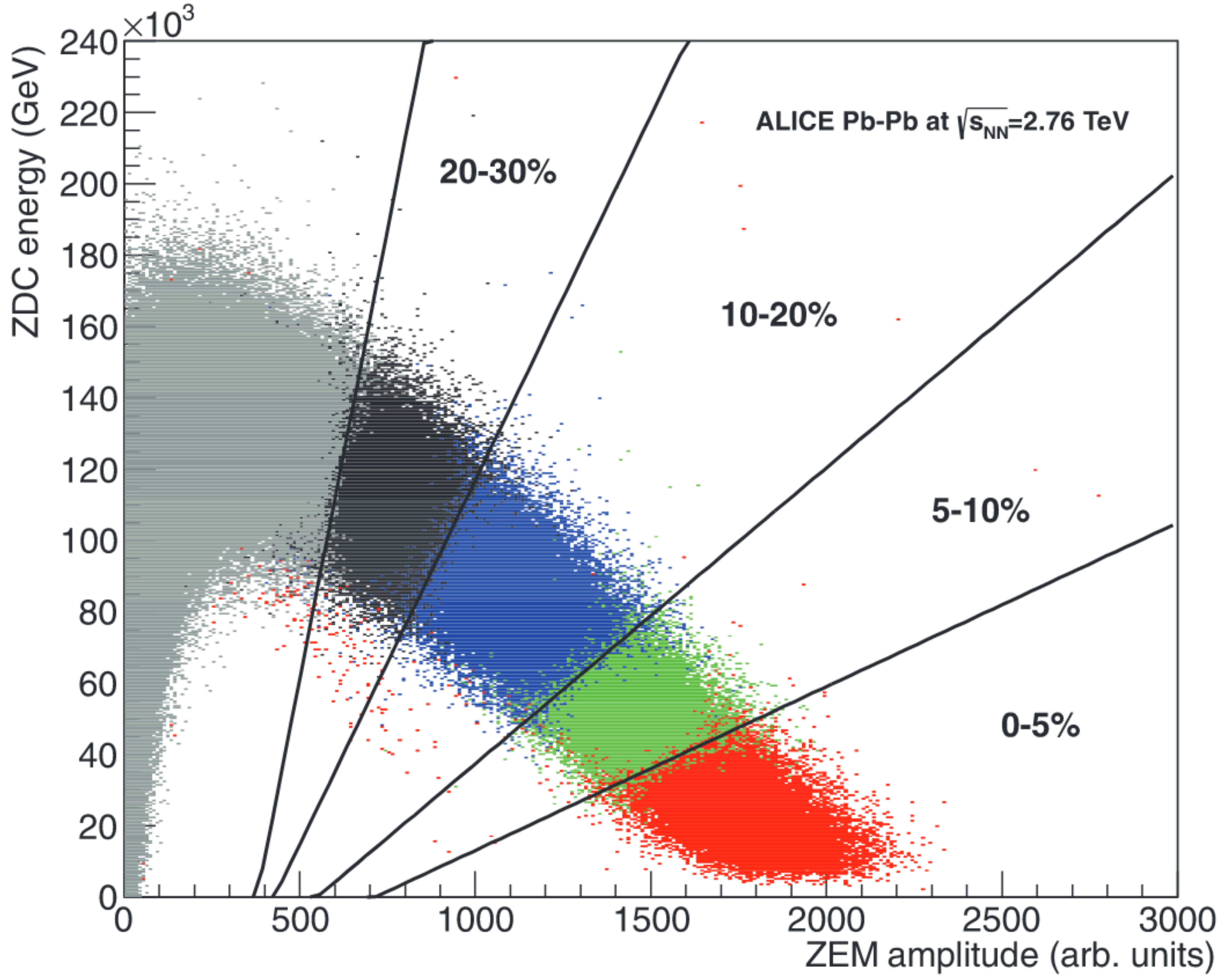
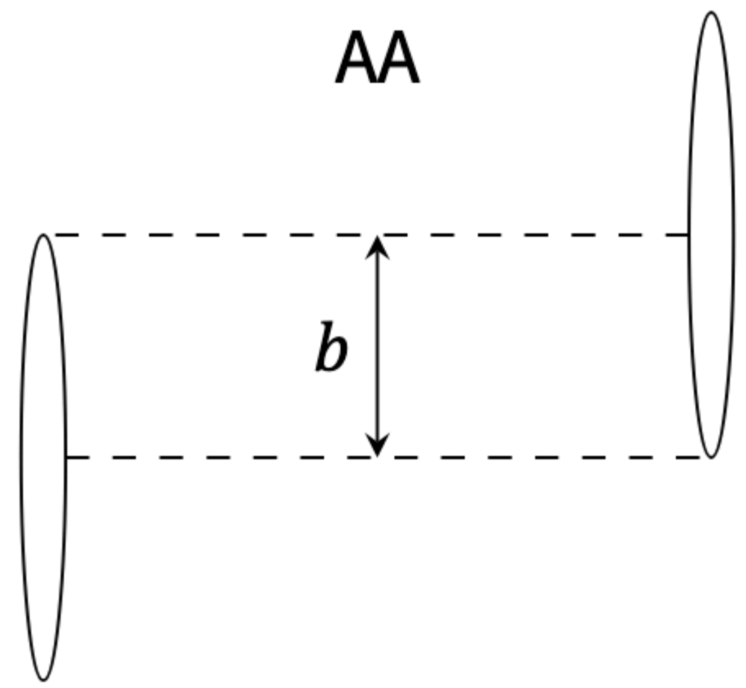


Spectator energy deposited in the ZDC calorimeters as a function of ZEM amplitude



Nuclear fragments typically have Z/A similar to beam —> fragments remain in the beam pipe and are not detected by ZDC

—> not easy to model centrality determination where fragments production is important (use ZDC for centrality values up to ~30-40%)

ALICE, Phys. Rev. C**88**, 044909 (2013)

Centrality estimation in Pb—Pb (using ZDC)

$$N_{\text{part}} = 2A - E_{\text{ZDC}}/E_A$$

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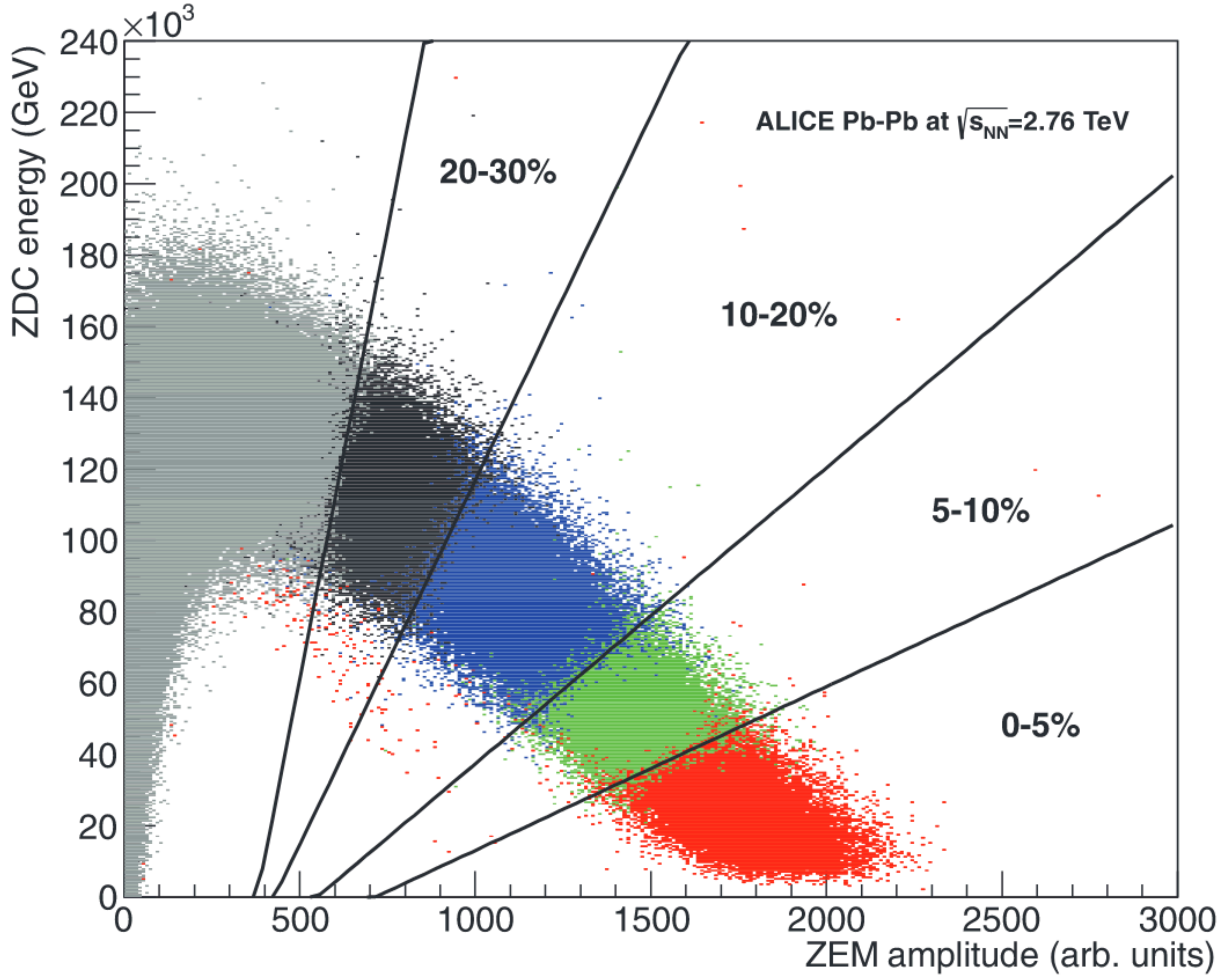

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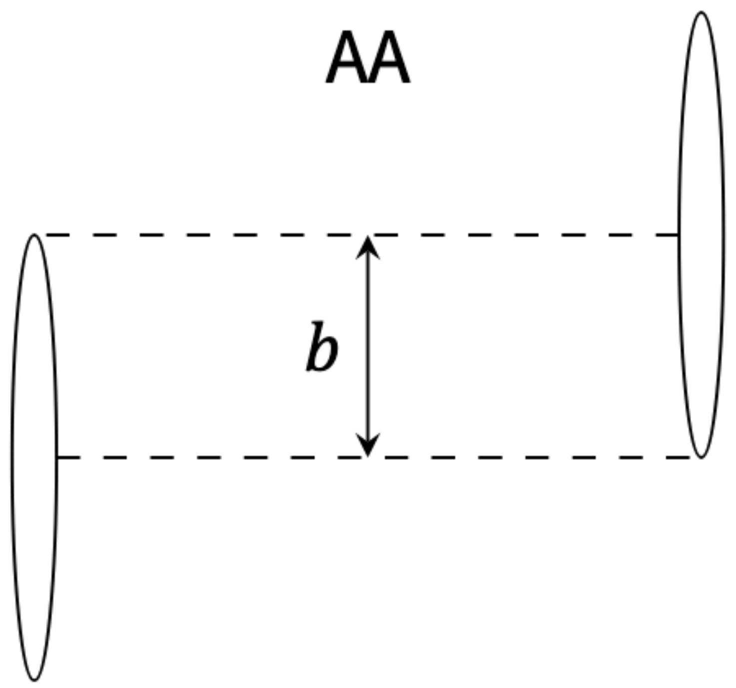
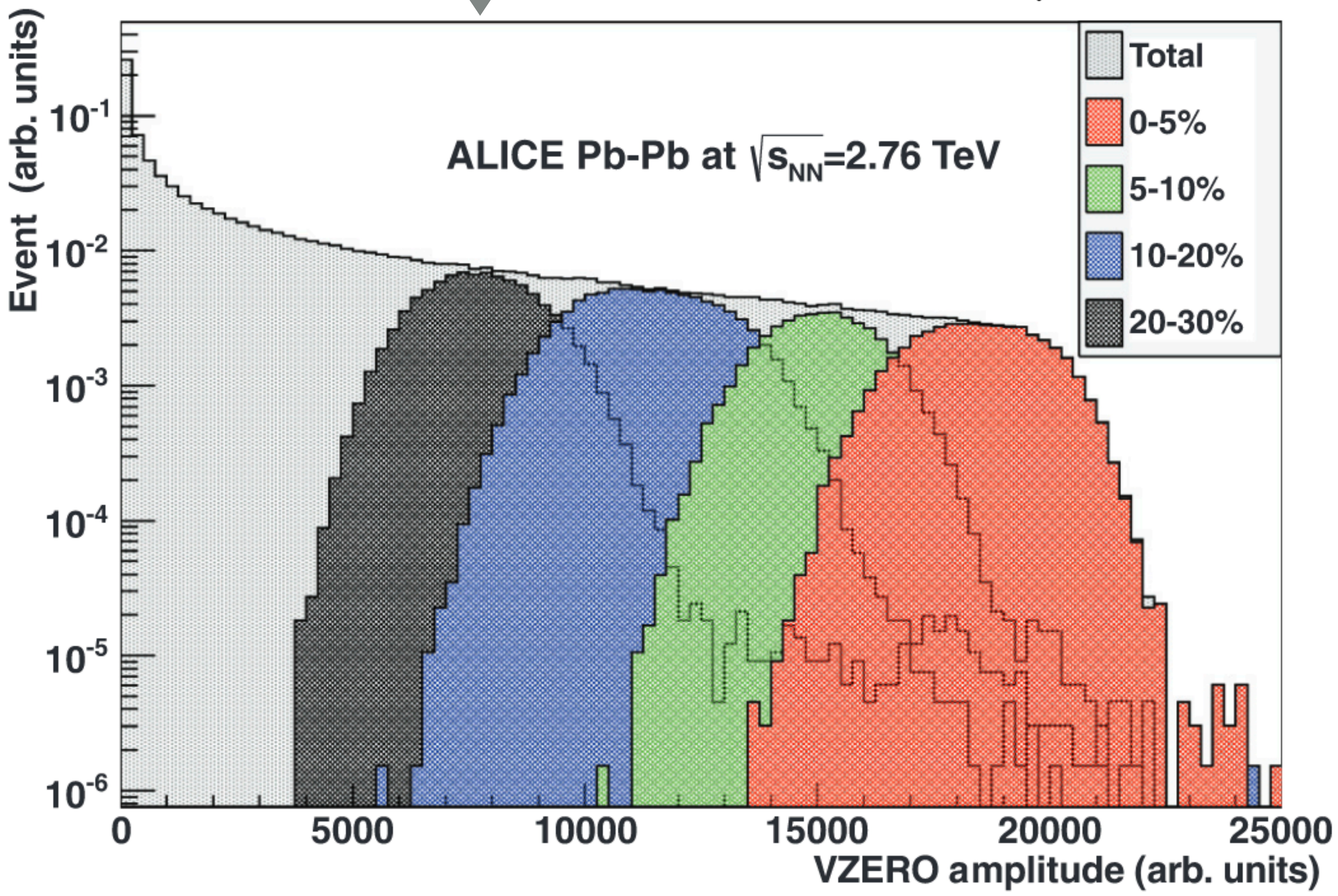


V0 amplitude selected from the correlation between ZDC and ZEM amplitudes



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Multiplicity estimation in pp

- No direct analogue of centrality for pp collisions
- Multiplicity serves to roughly separate soft and hard processes
- Using simulation from competing models one can define better observables and event class separation criteria

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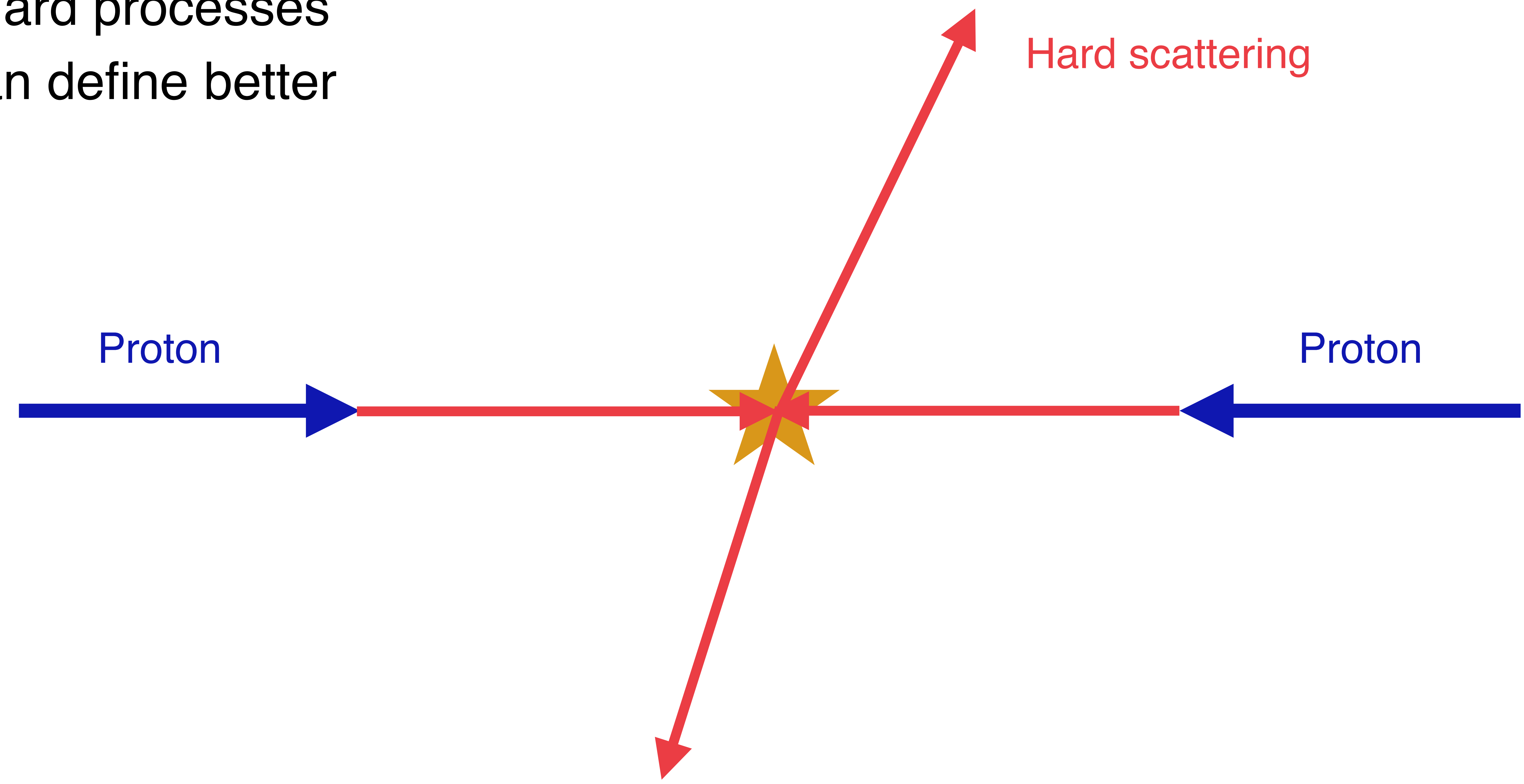
Hard scattering: perturbative QCD



A hypothetical picture of pp (with Pythia event generator)

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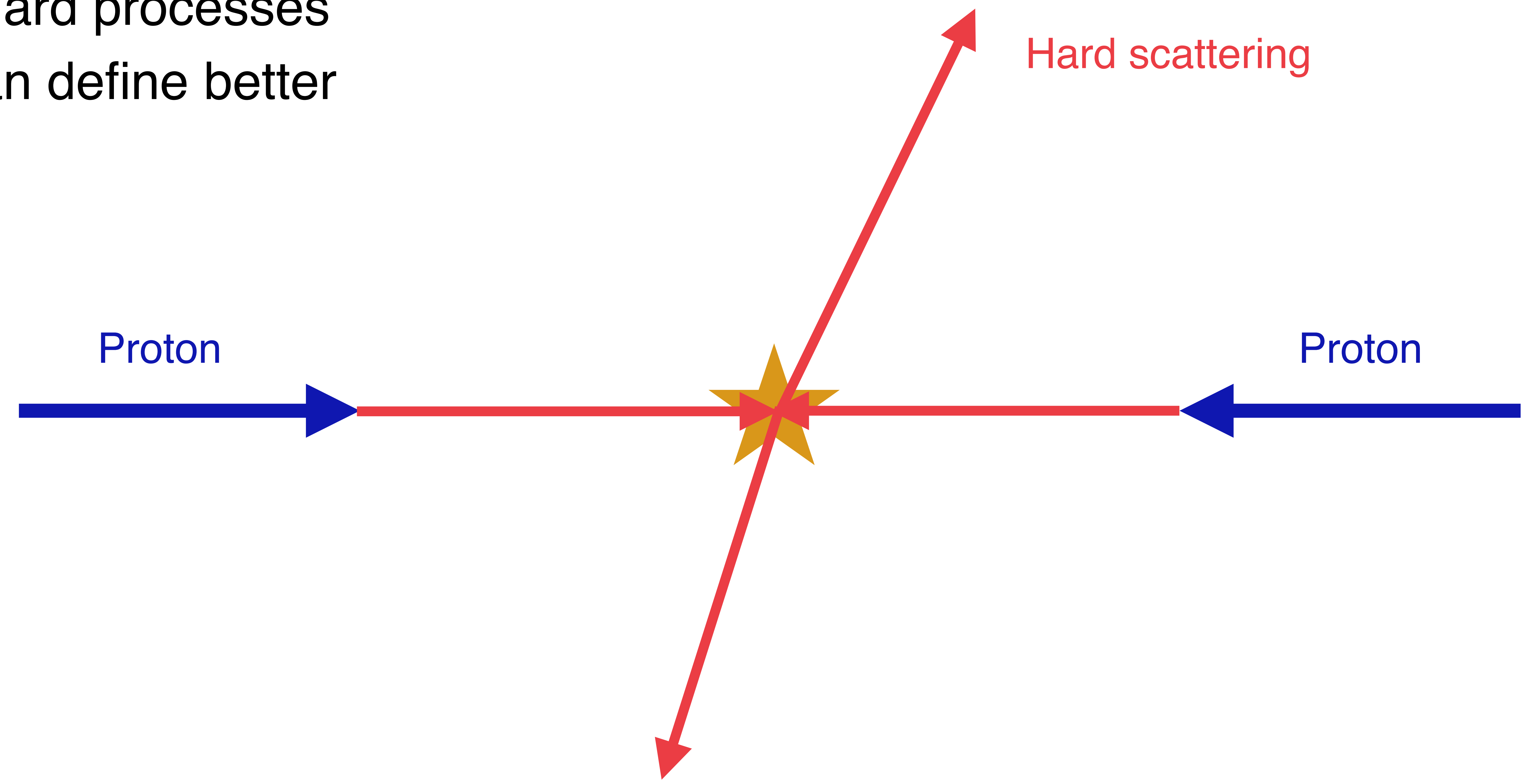
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

- Underlying Event (UE)



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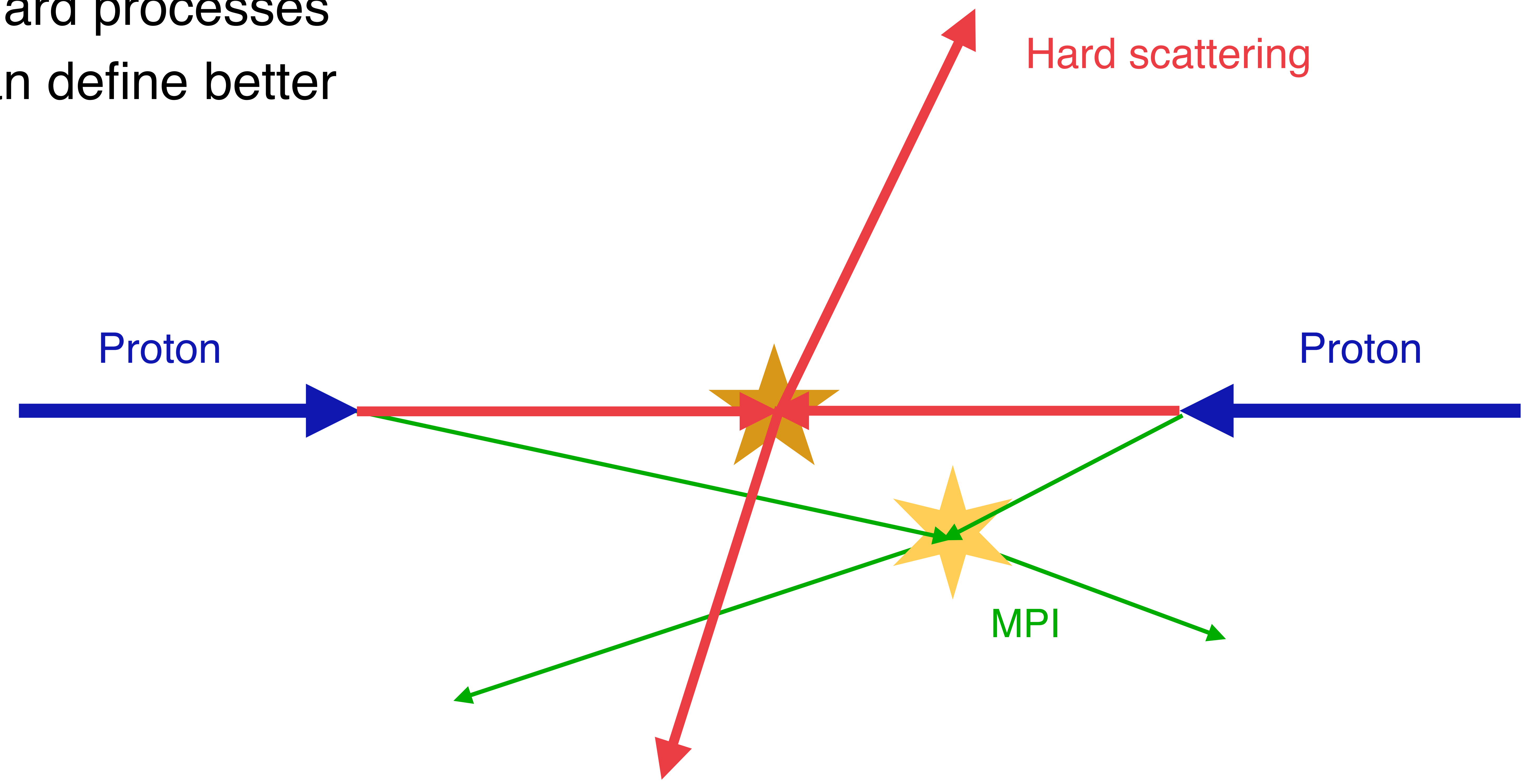

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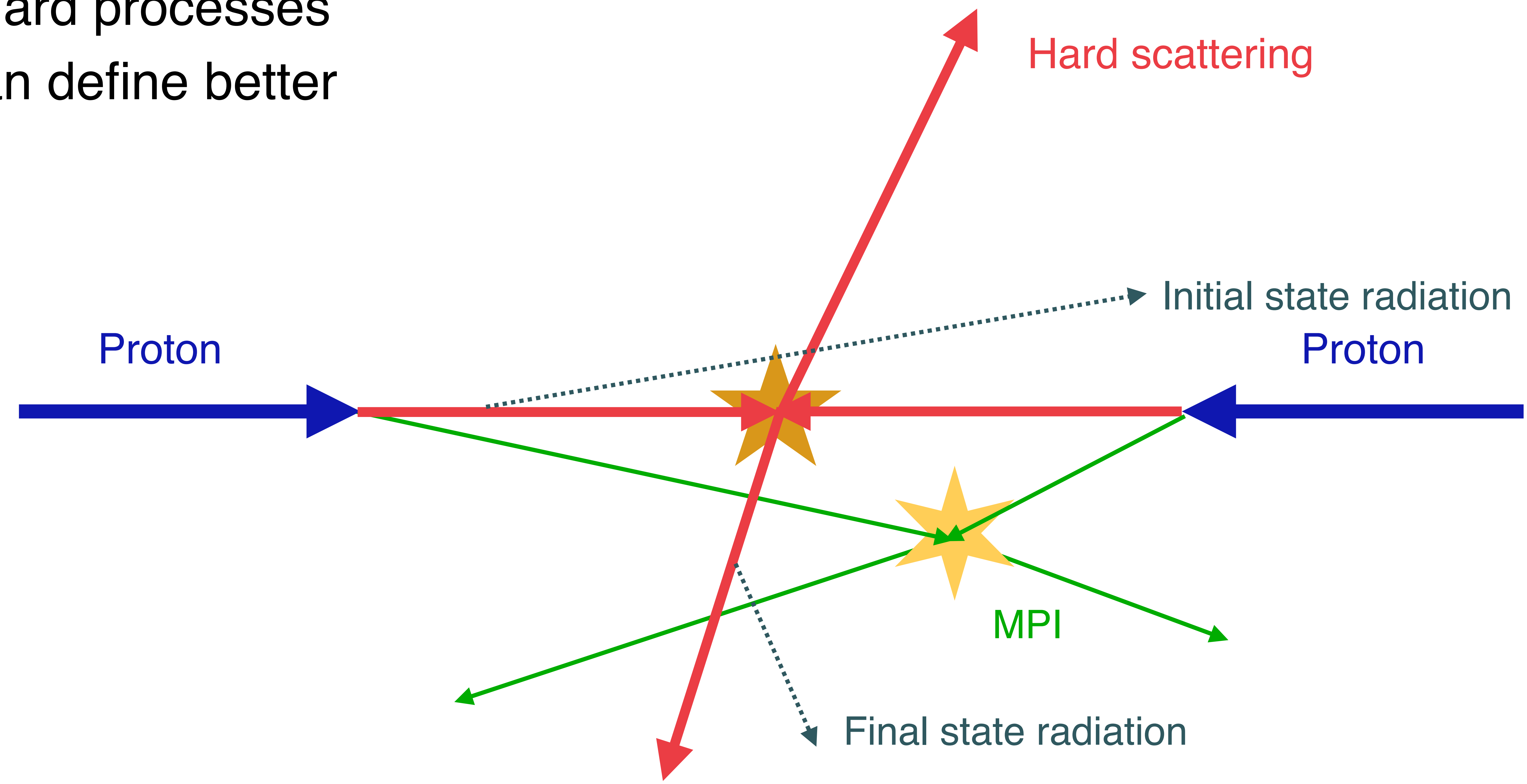

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Includes:

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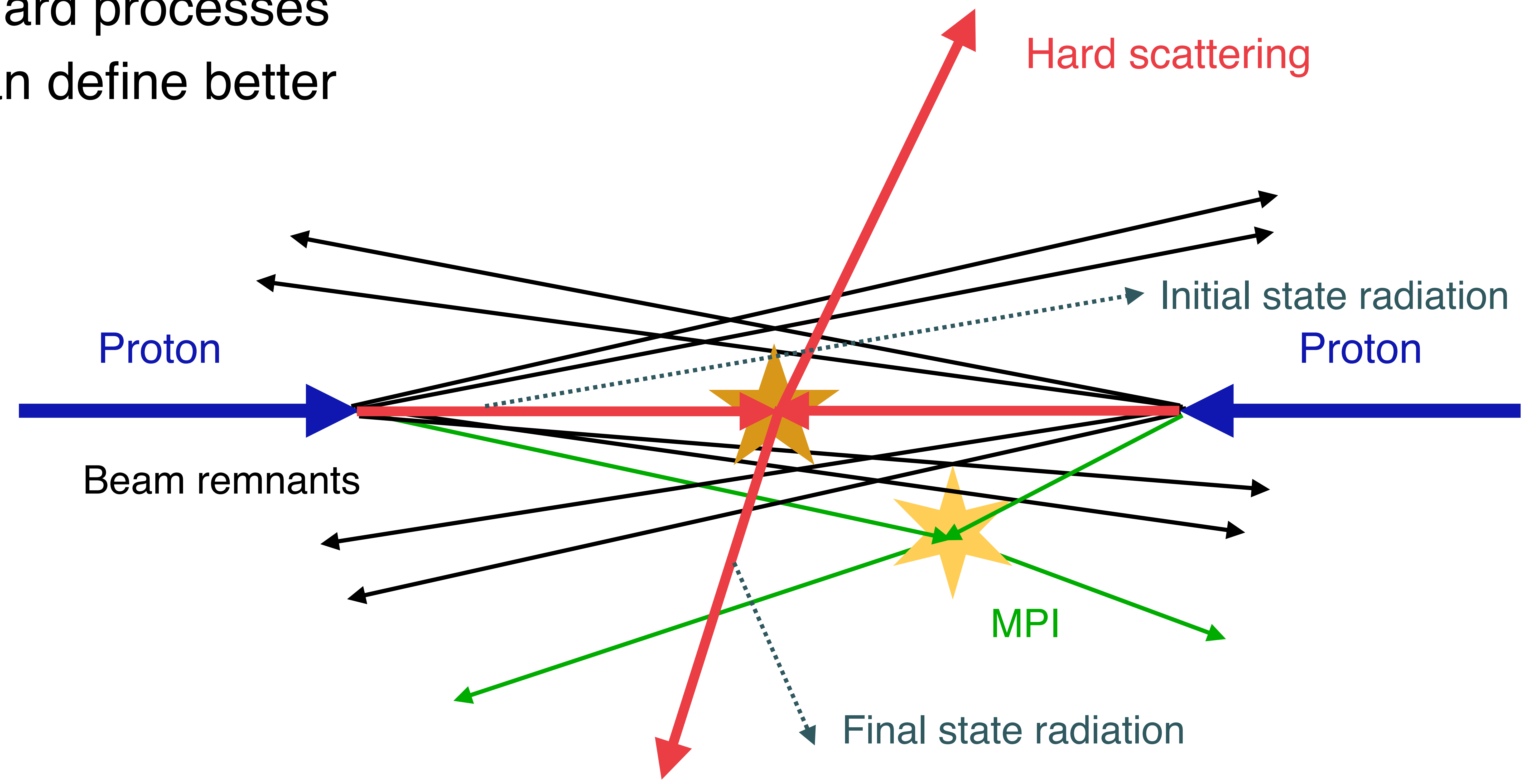
  - Initial- and final-state radiation
  - Beam remnants



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Includes:

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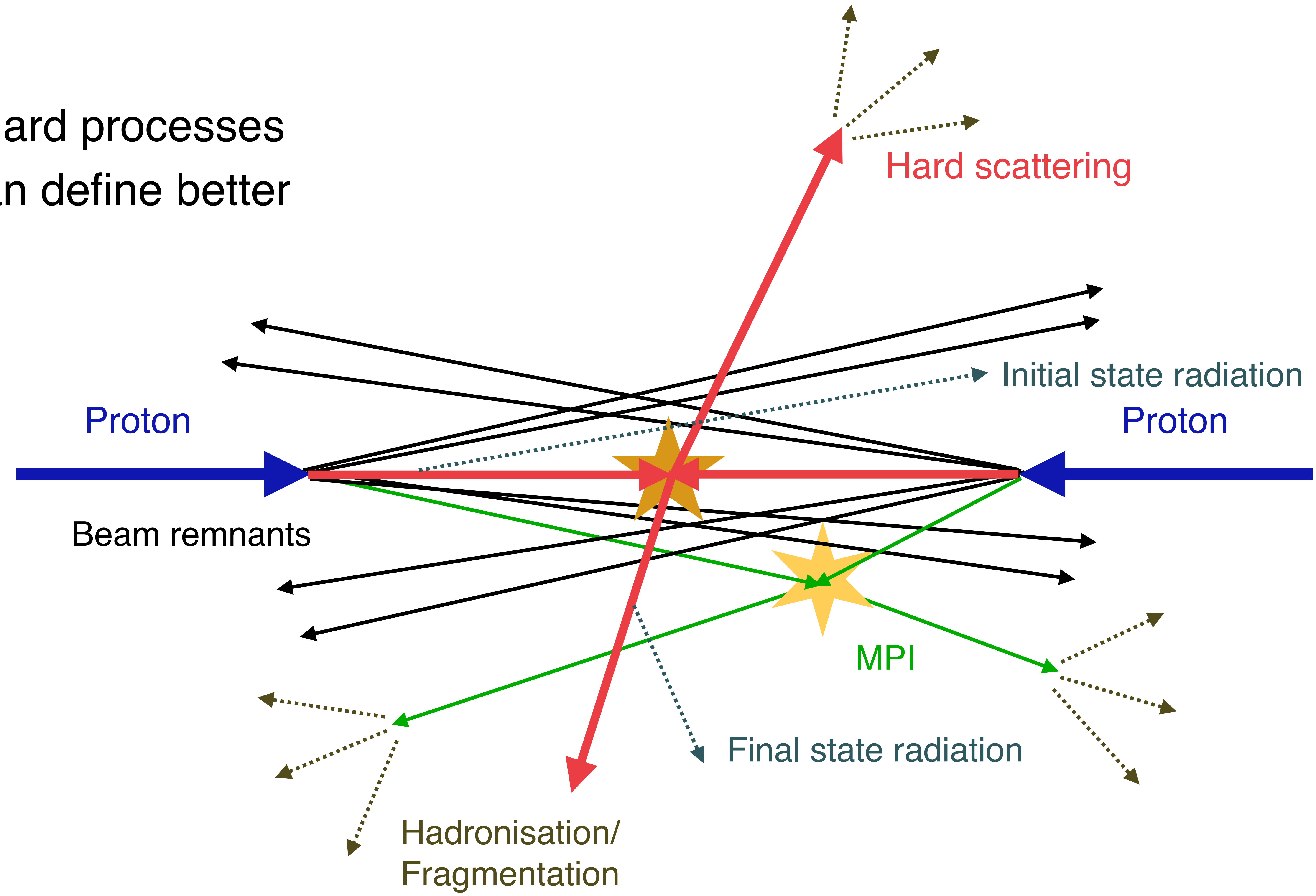
  - Multiparton interactions (MPI)
  - Initial- and final-state radiation
  - Beam remnants
- Hadronisation products
- Collective effects



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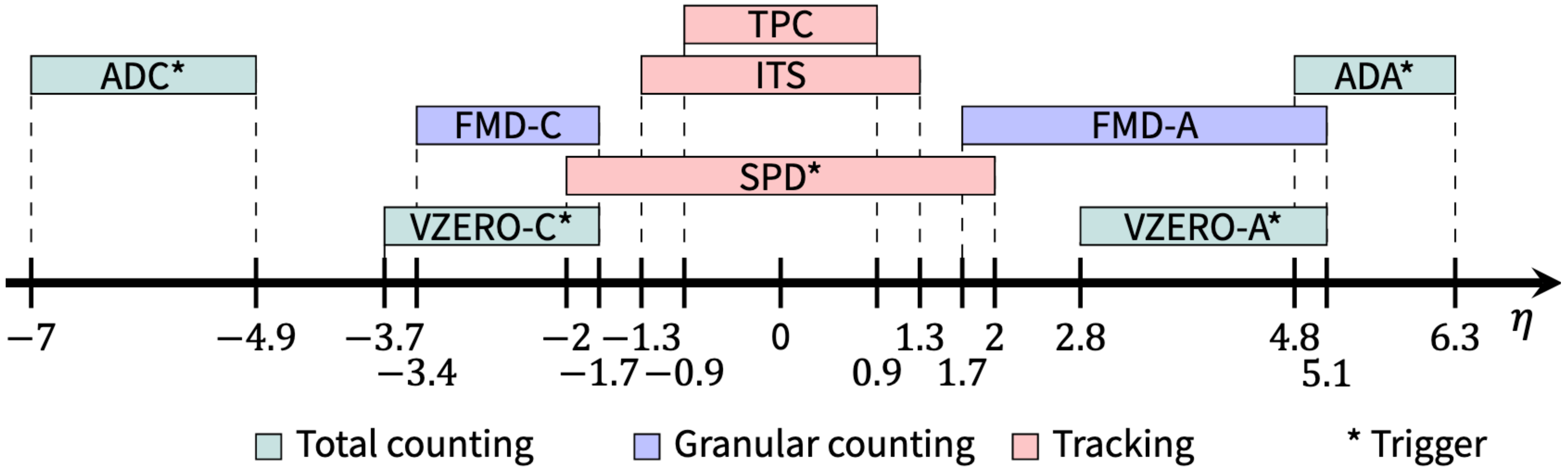
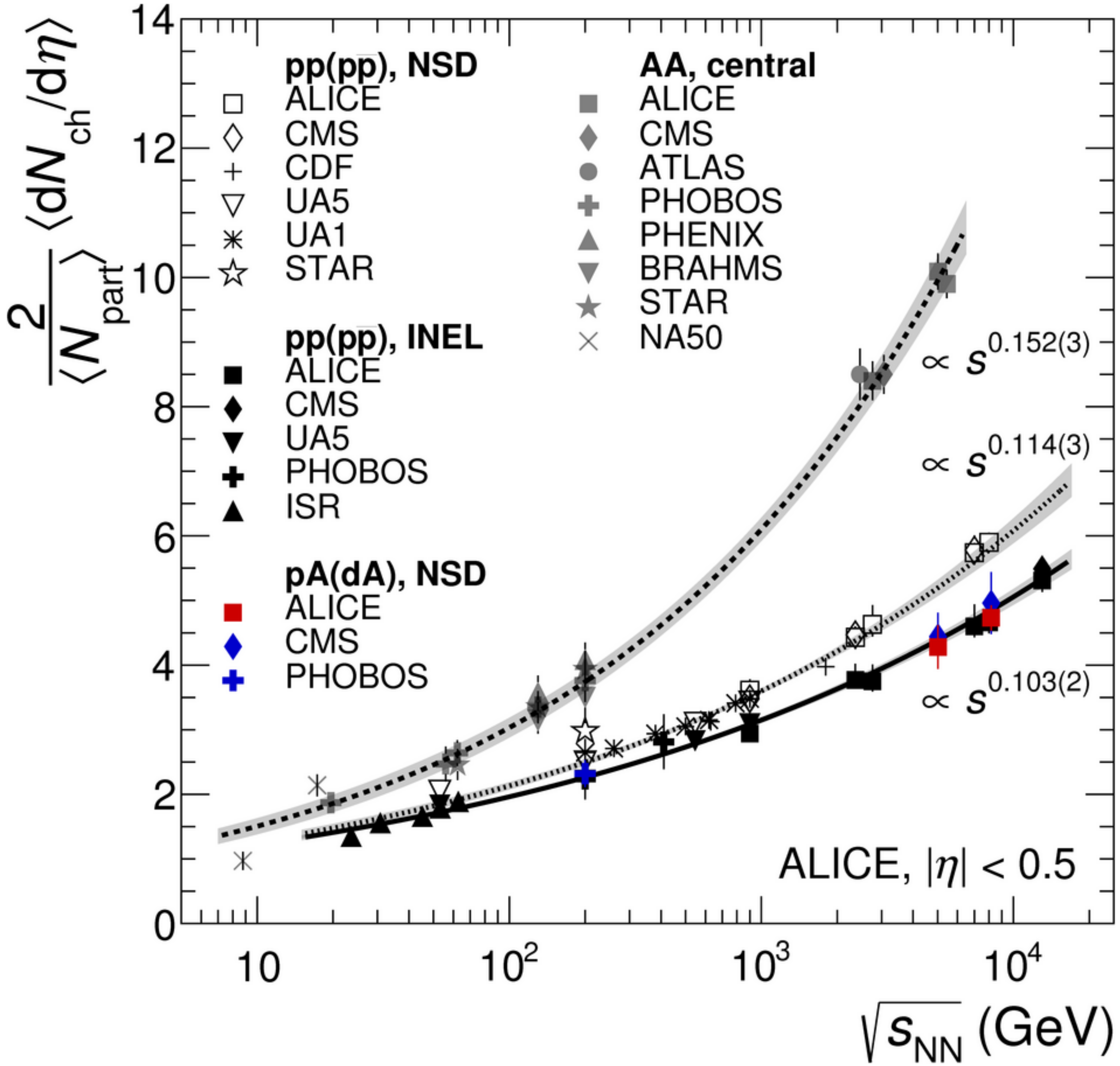
Multiplicity estimators

Reference central:	SPD+ITS+TPC; SPD+ITS; SPD; SPD layer1
Reference forward:	V0A; V0C; V0M = V0A + V0C
Rapidity granular:	Reference central, FMD



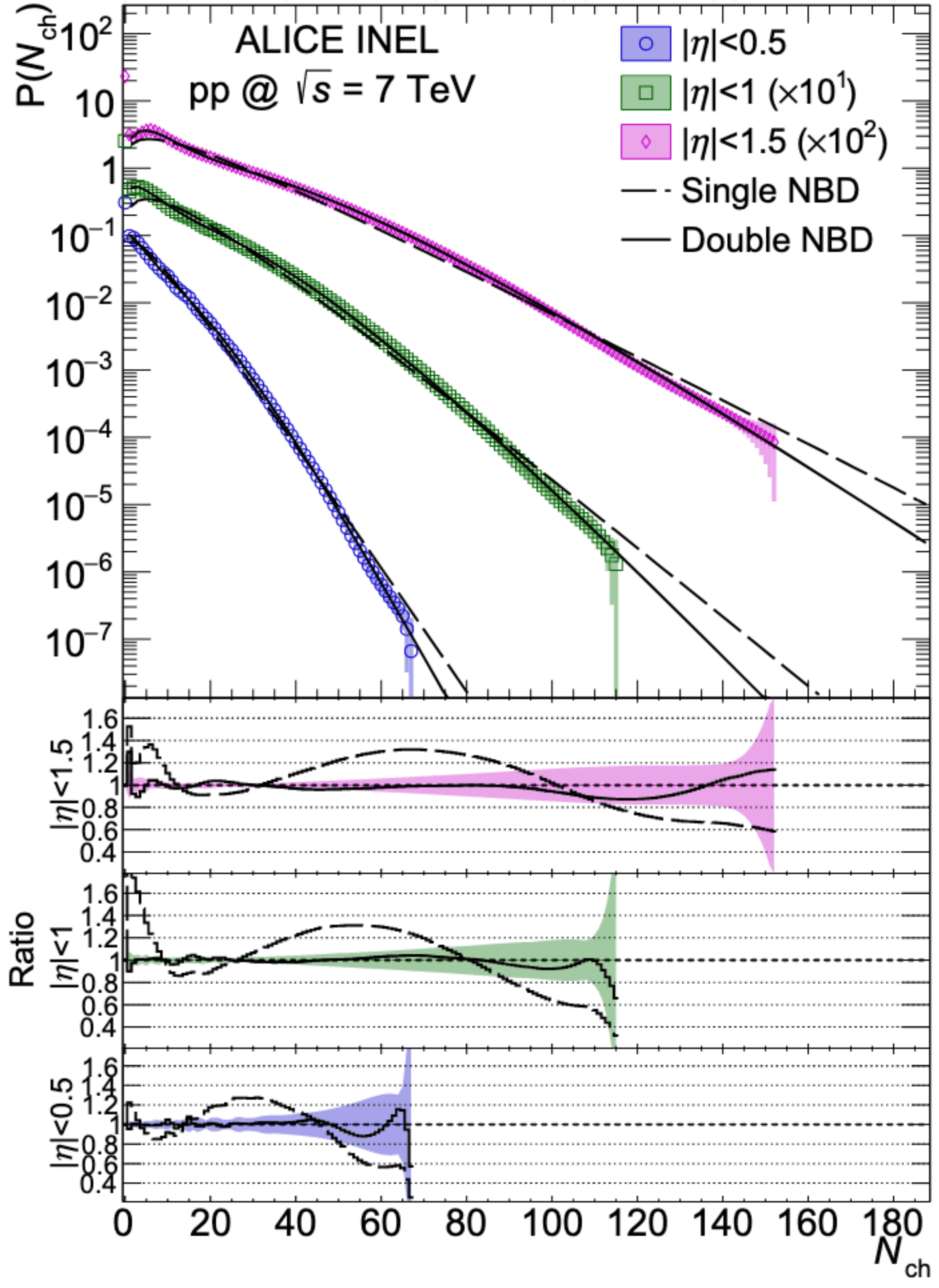
Multiplicity at midrapidity

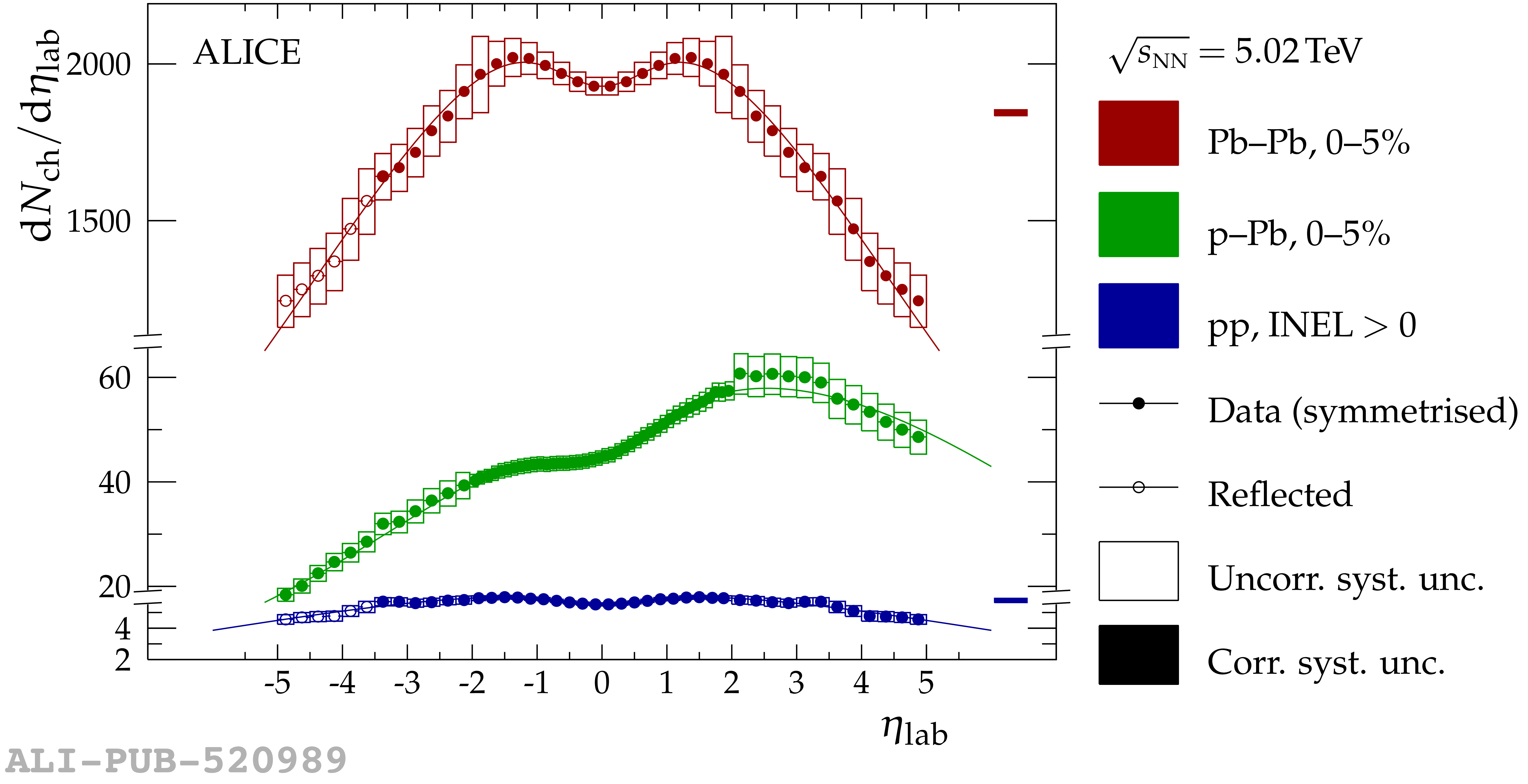


- Steeper rise with system energy for AA than for small systems
- p—Pb and dA results overlap with INEL pp, which indicates that the strong rise in AA is not solely related to multiple collisions undergone by the participating nucleons

ALICE, Eur. Phys. J. C (2019) 79: 307

Multiplicity distributions at midrapidity

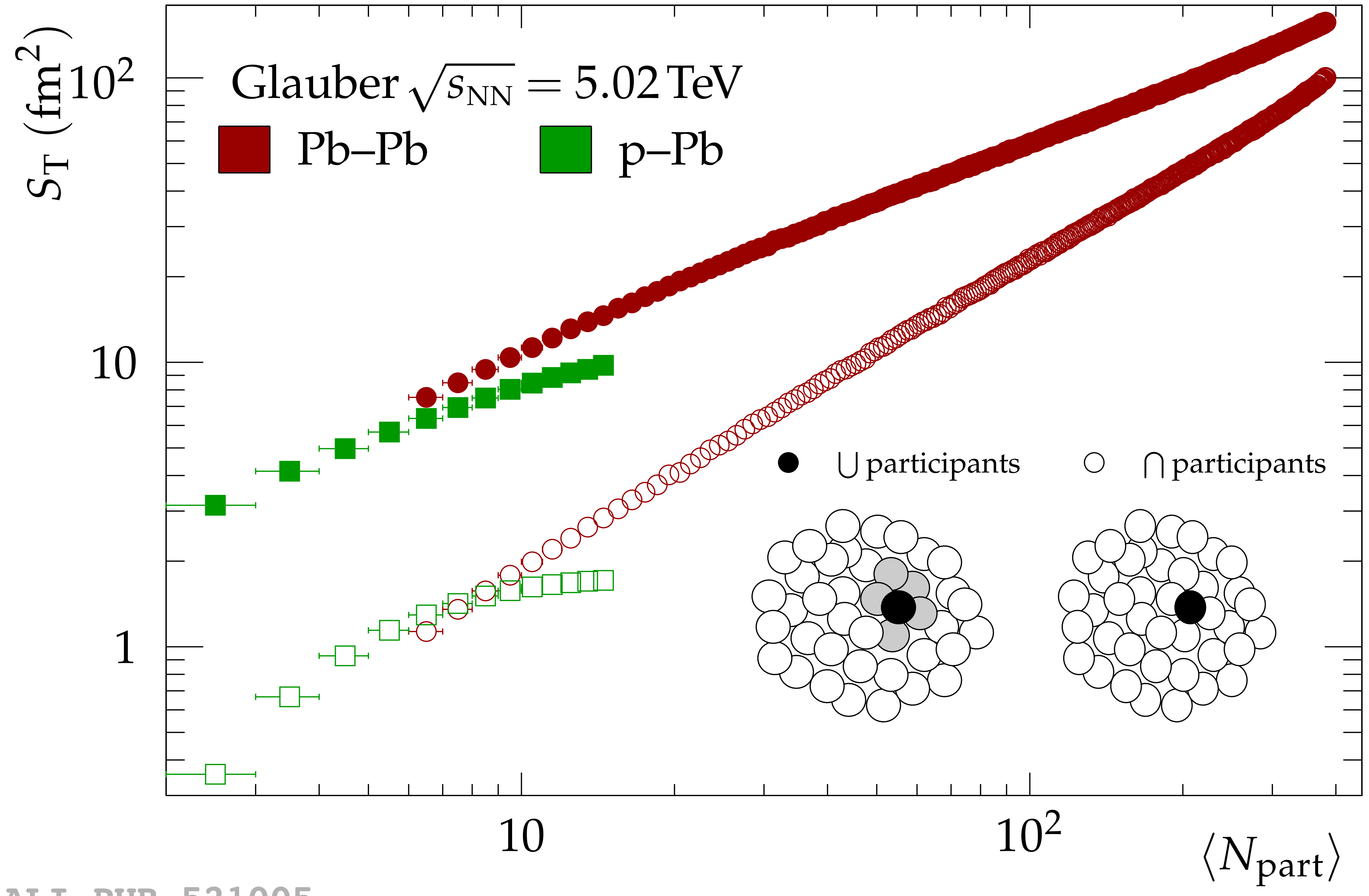




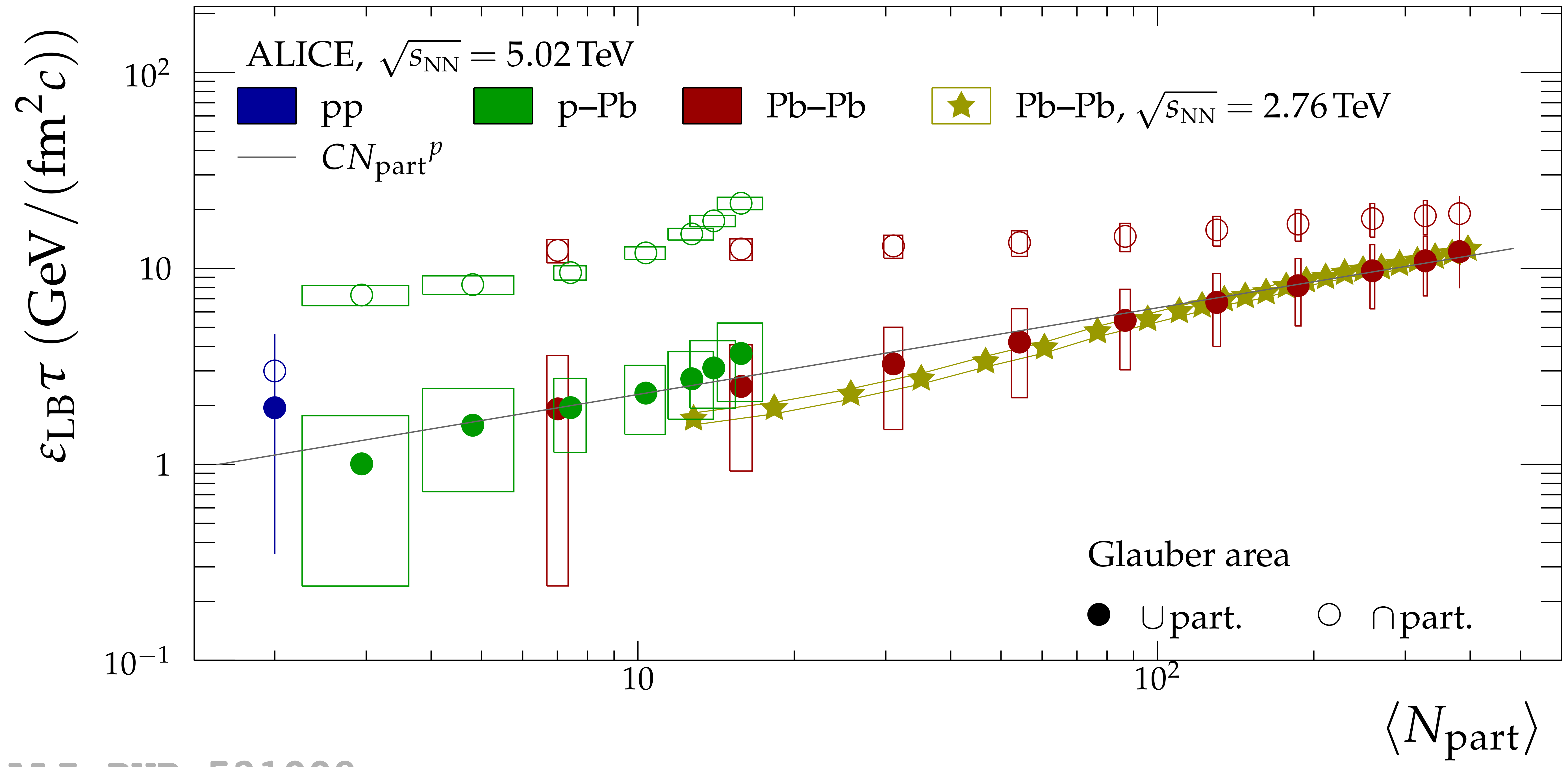
ALICE, Eur. Phys. J. C (2017) 77, 33

ALICE, arXiv:2204.10210

Lower bound of Bjorken transverse energy density



ALI-PUB-521005



ALI-PUB-521009

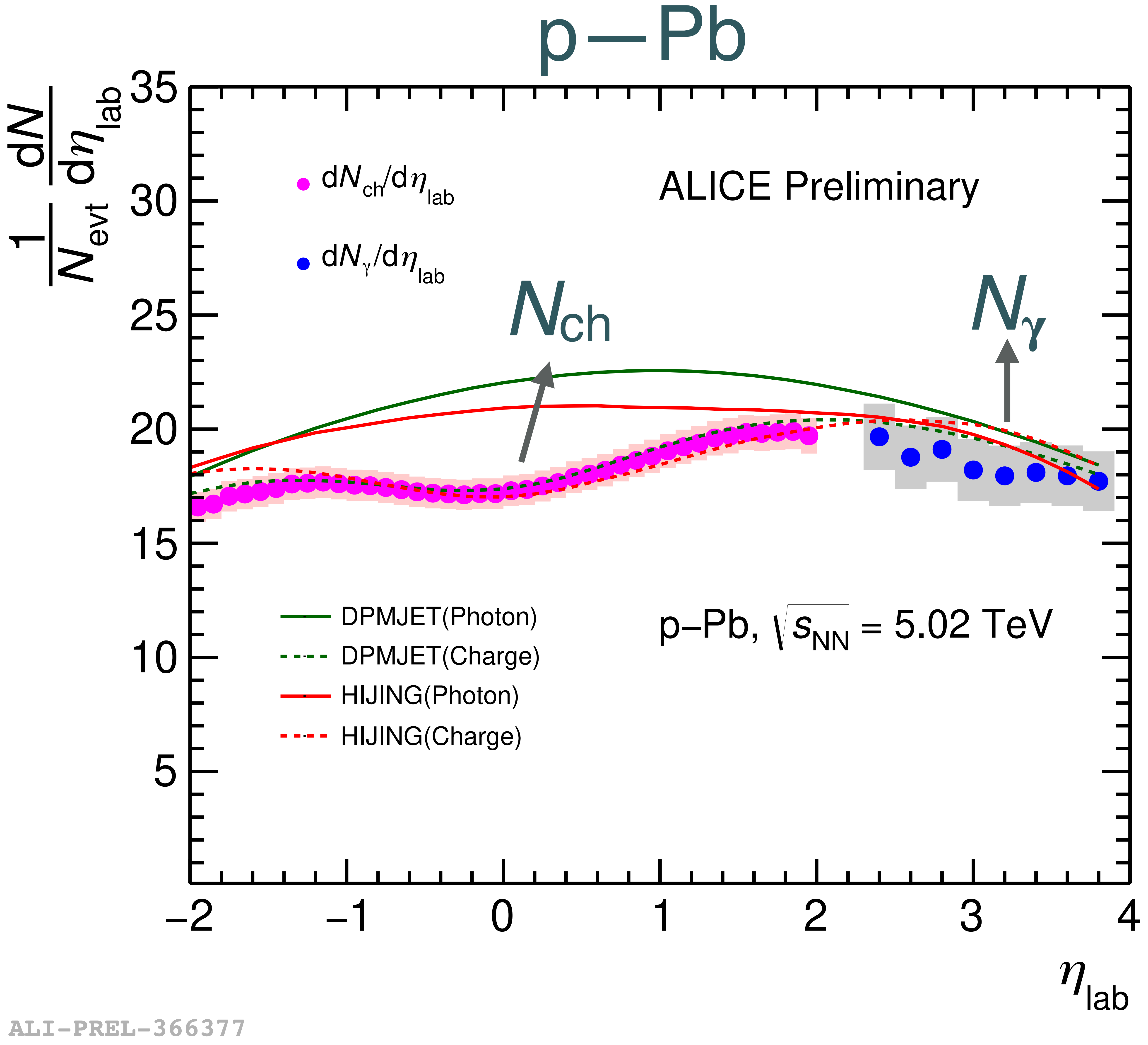
$$\varepsilon_{Bj} = \frac{1}{c\tau}\frac{1}{S_T}\left\langle \frac{dE_T}{dy} \right\rangle$$

$$S_T \approx \pi R^2 \approx \pi N_{part}^{2/3}$$

$$\left\langle \frac{dE_T}{dy} \right\rangle \approx \langle m_T \rangle \frac{1}{f_{total}}\frac{dN_{ch}}{dy} = \langle m \rangle \sqrt{1+\left(\frac{\langle p_T \rangle}{\langle m \rangle}\right)^2}\frac{1}{f_{total}}\frac{dN_{ch}}{dy}$$

$f_{total} = 0.55 \pm 0.01$, the ratio of charged particles to all particles

Inclusive photon production at forward rapidity



- Both inclusive photon and charged-particle production are described fairly well both by HIJING and DPMJET models within uncertainties

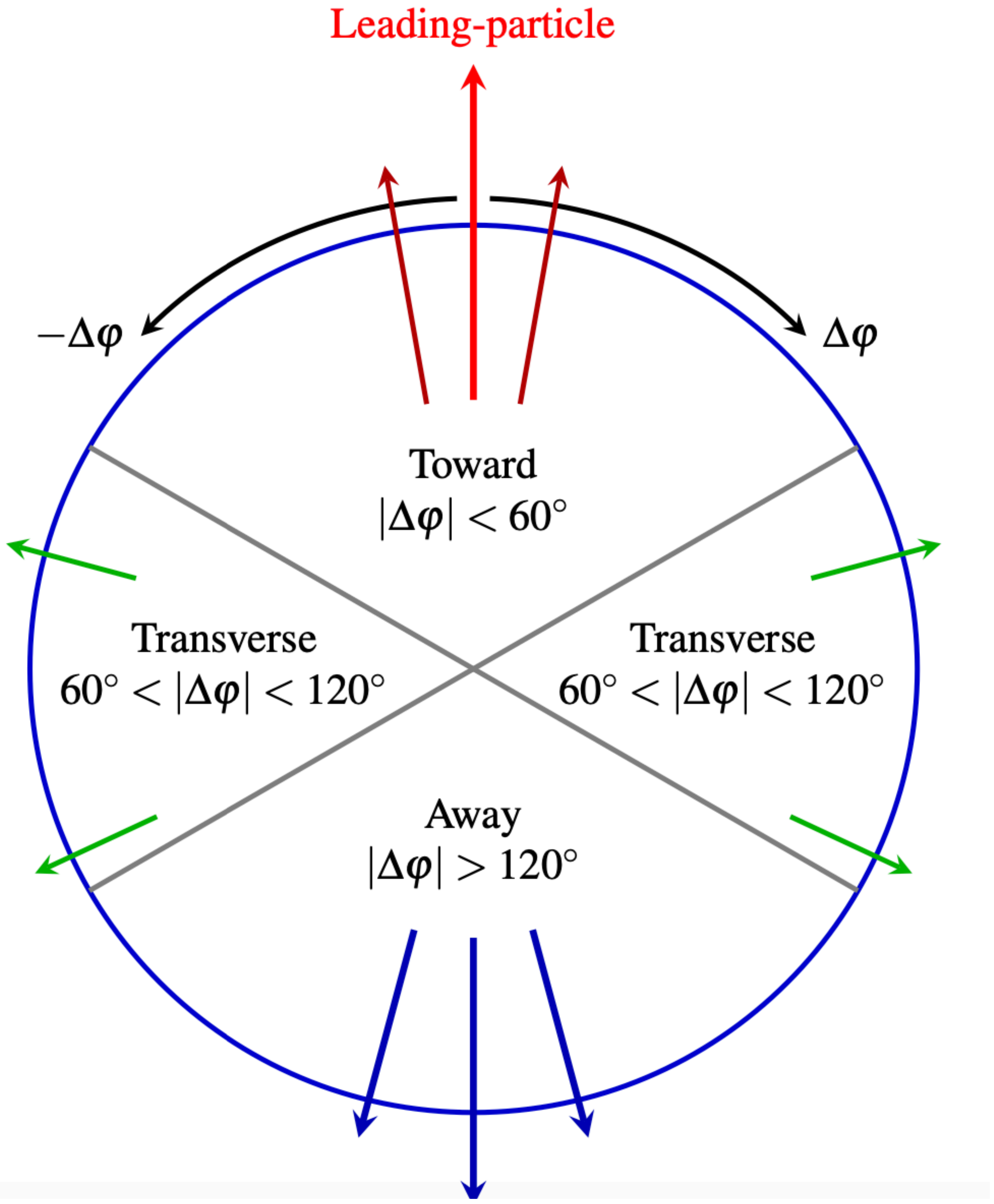
Underlying event

Underlying event

Underlying event (UE): collection of particles which do not originate from the primary hard parton-parton scattering or the related fragmentation (Includes MPI, ISR/FSR, beam remnants)

Conventional UE analyses

- Particle production in three topological regions w.r.t. leading particle
- Main UE observables: particle density, summed-p_T density



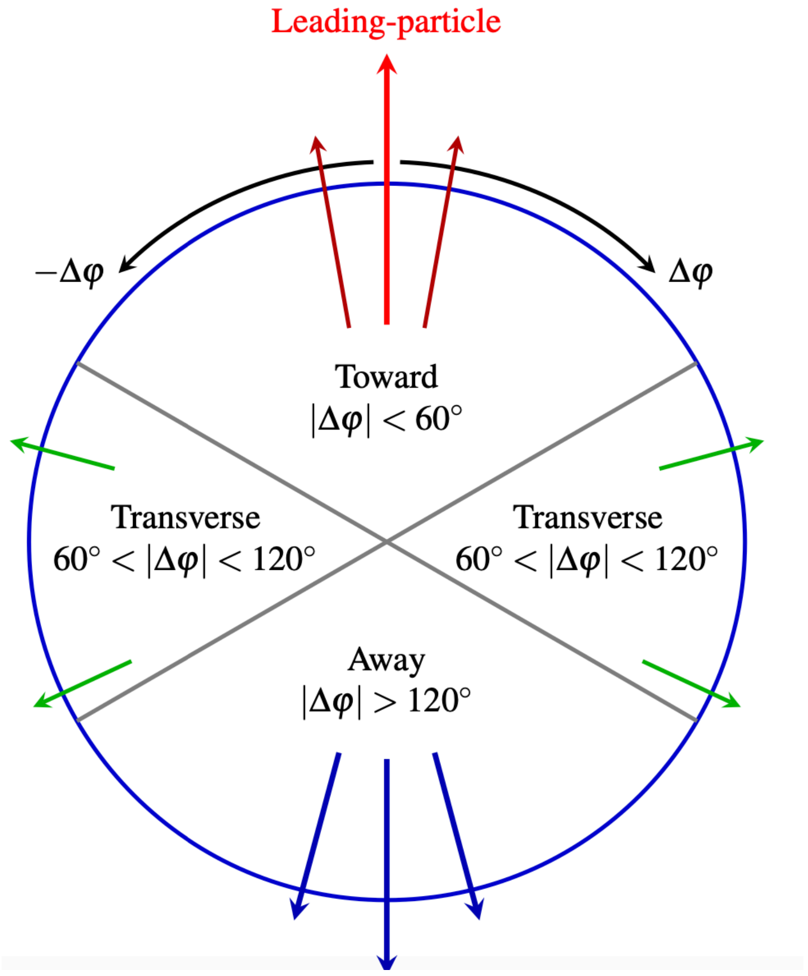
ALICE, JHEP04 (2020) 192

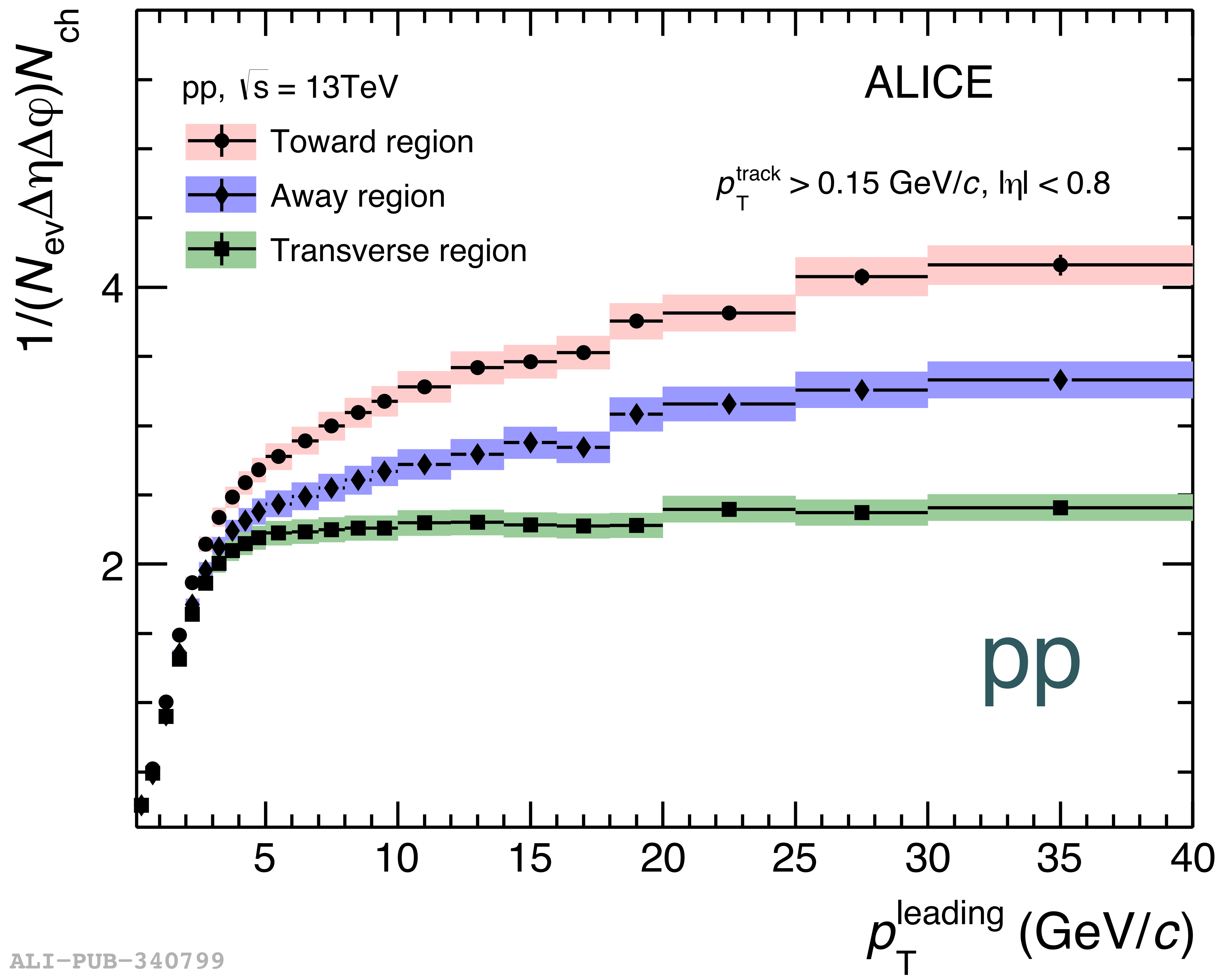
Underlying event

Underlying event (UE): collection of particles which do not originate from the primary hard parton-parton scattering or the related fragmentation (Includes MPI, ISR/FSR, beam remnants)

Conventional UE analyses

- Particle production in three topological regions w.r.t. leading particle
- Main UE observables: particle density, summed-p_T density

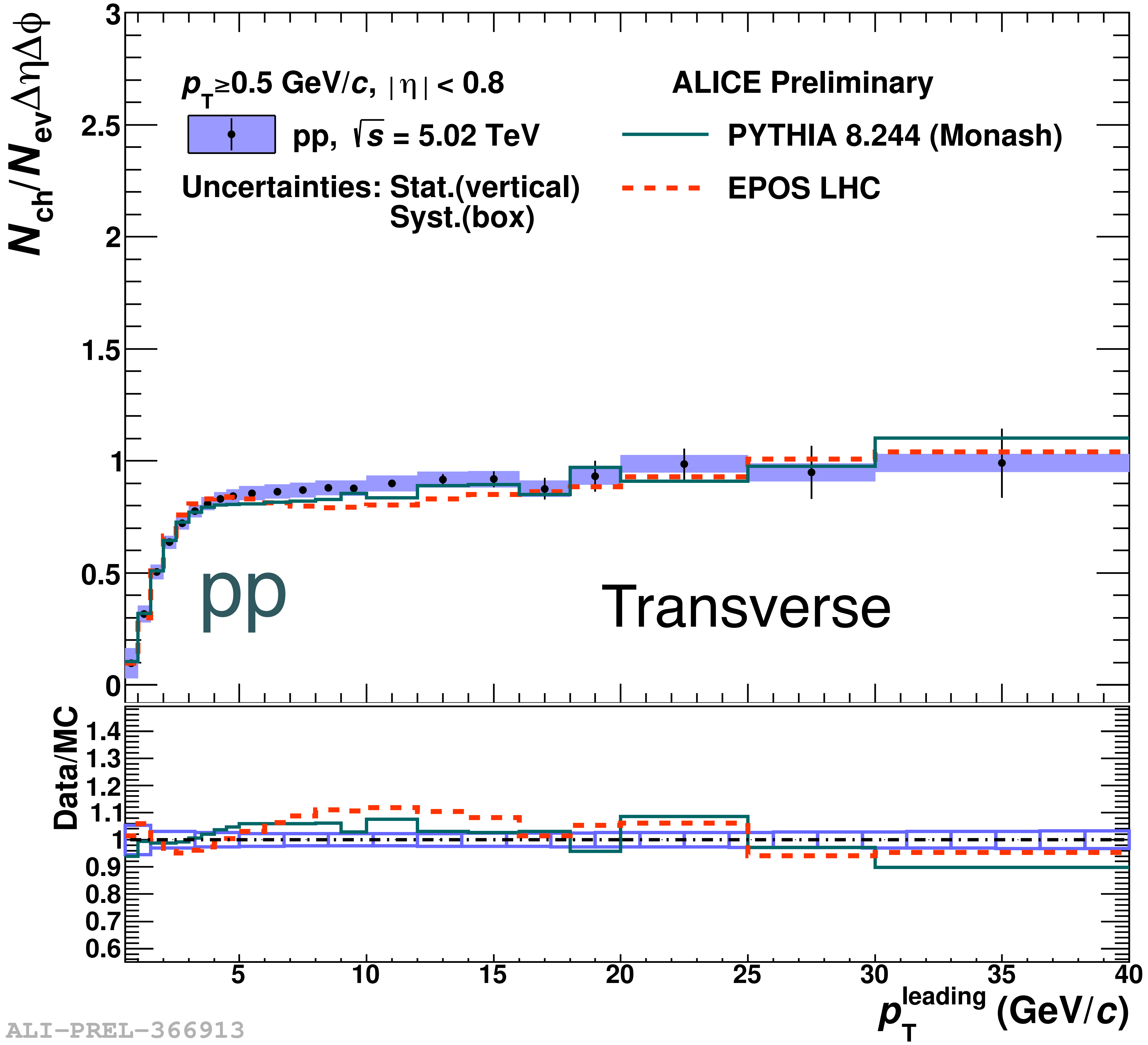


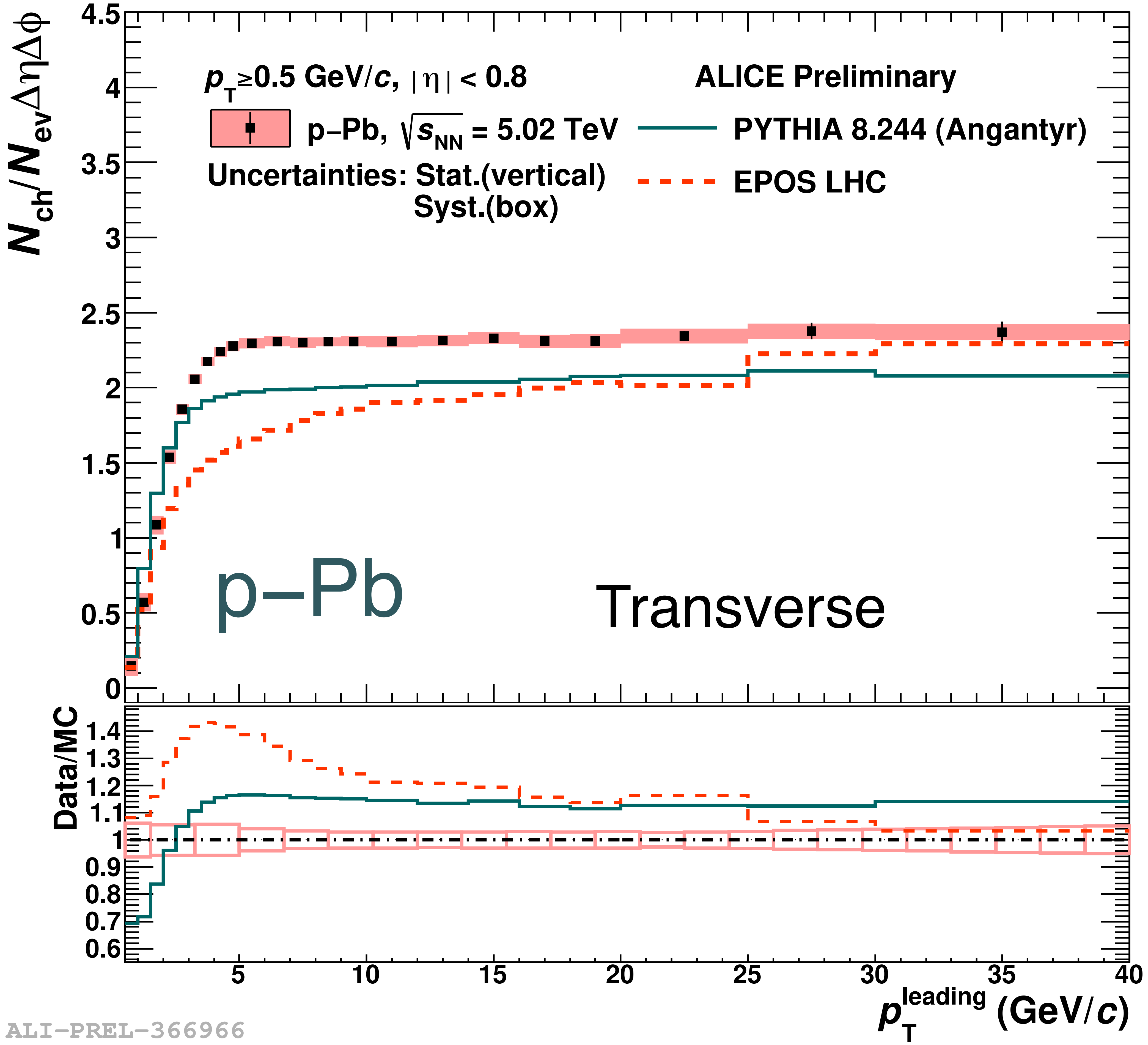


- Steep rise in the event activity at low $p_T^{leading}$ for all topological regions
- After $p_T^{leading} > 5$ GeV/c charged particle density in Transverse region is insensitive to hard component
- In Toward/Near and Away regions, charged particle density scales with hardness

ALICE, JHEP04 (2020) 192

Charged particle density

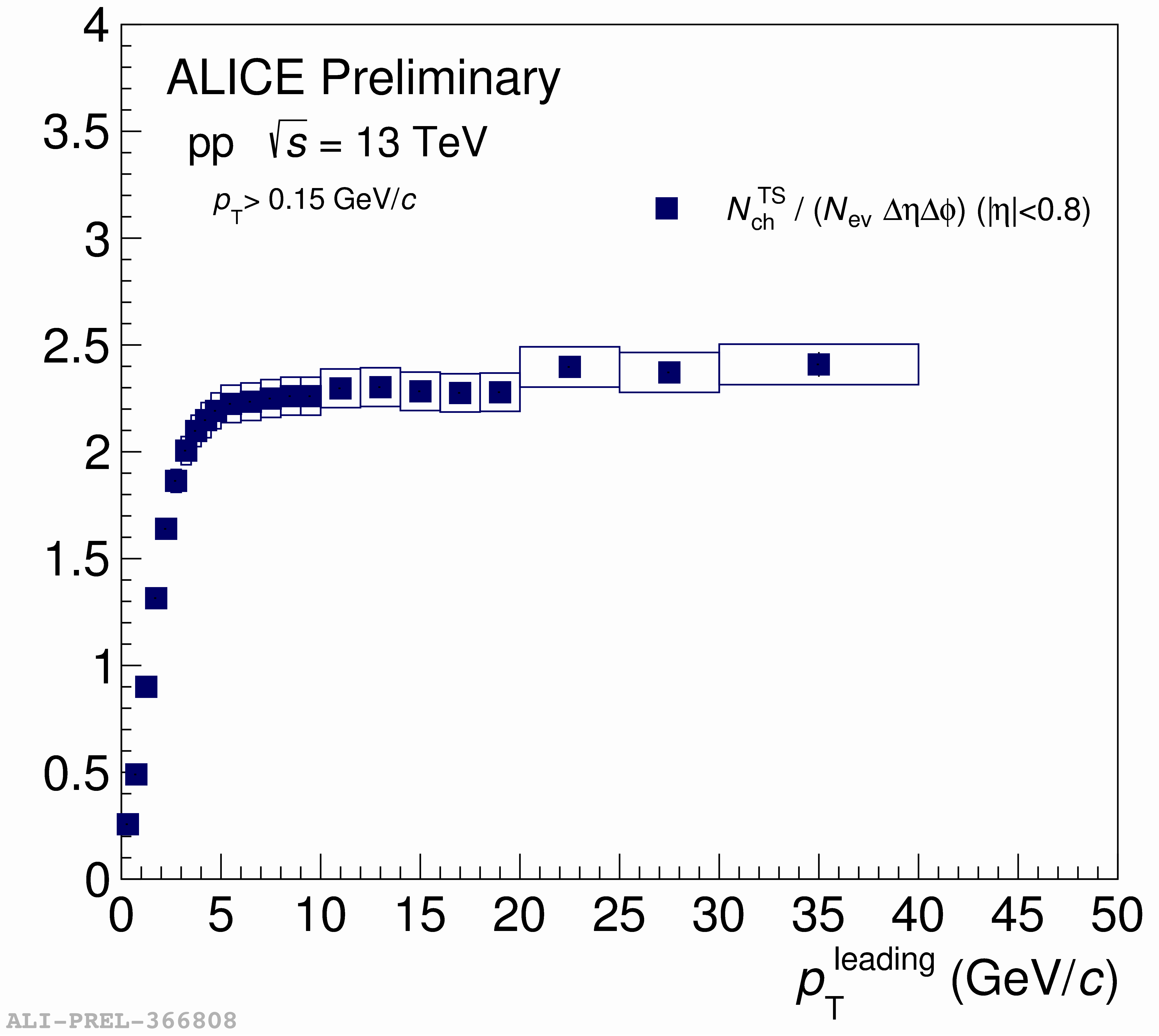




- Larger UE magnitude in p–Pb collisions
- Both PYTHIA8 (Angantyr) and EPOS-LHC fail to describe the UE activity for p–Pb

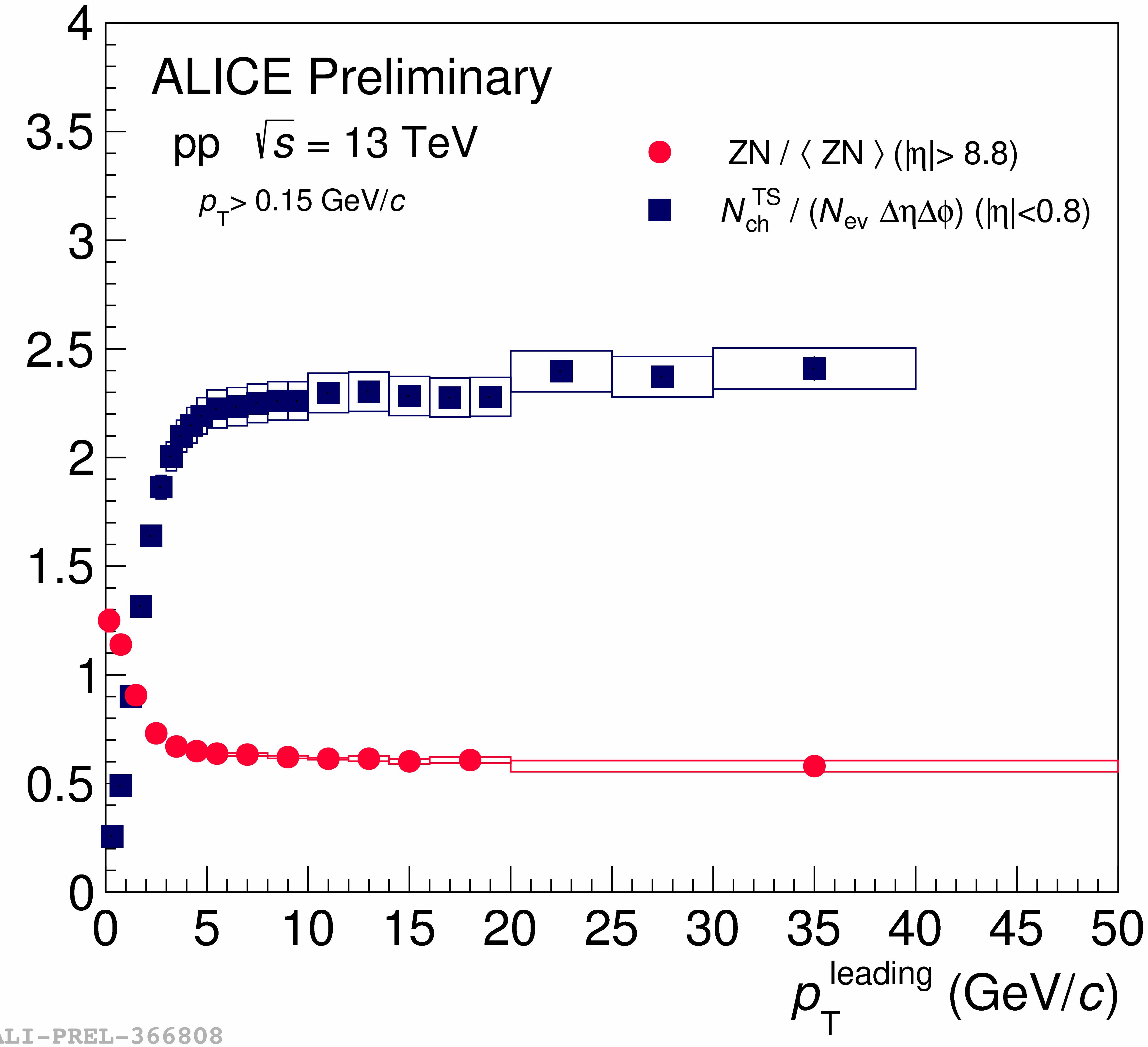
Forward energy vs. UE activity

- The forward energy measured by ALICE ZDC gives a complementary measurement to conventional UE analyses



Forward energy vs. UE activity

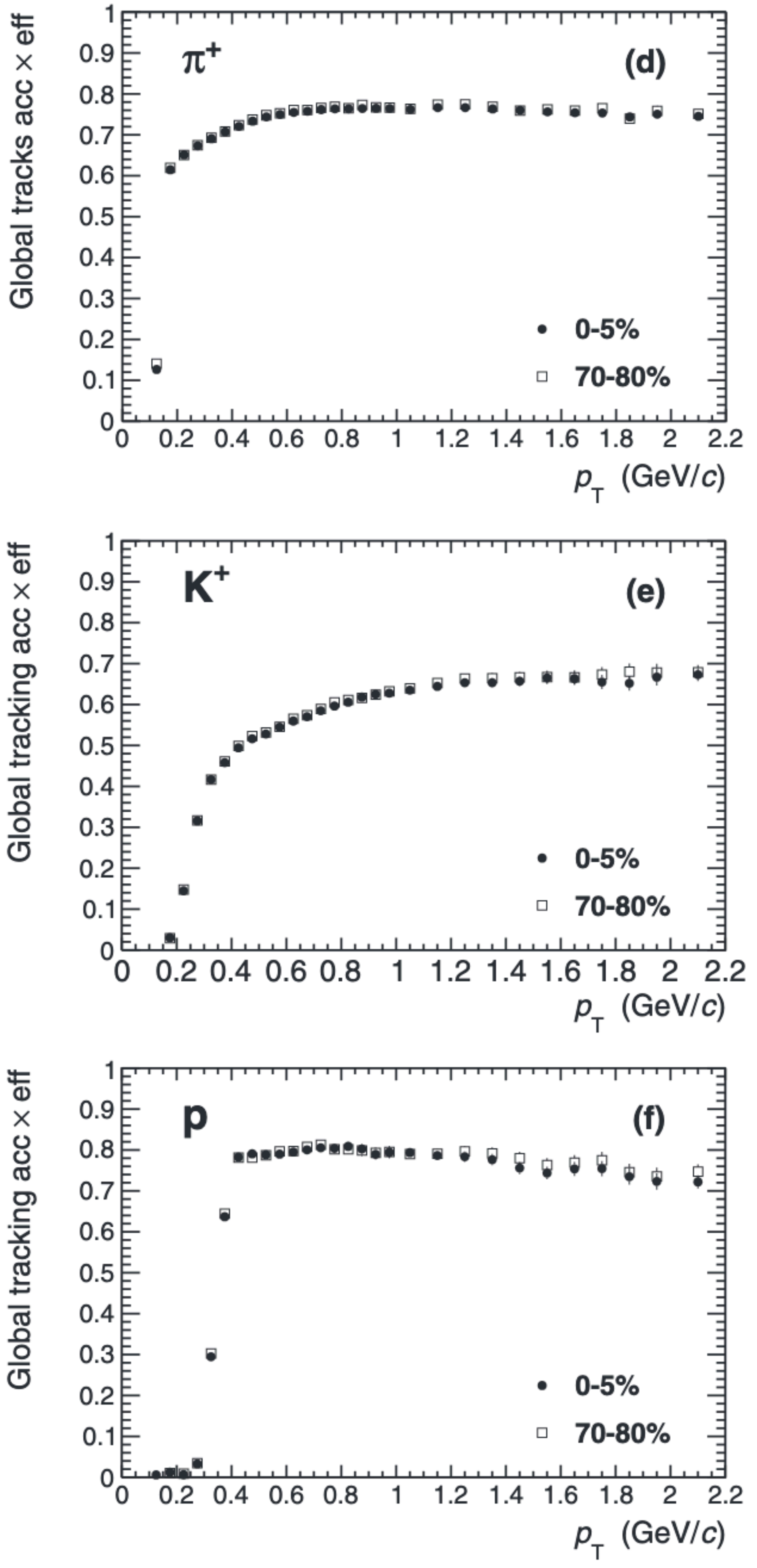
- The forward energy measured by ALICE ZDC gives a complementary measurement to conventional UE analyses
- Both observables saturate for $p_T^{leading} > 5$ GeV/c
- Forward energy is anticorrelated to midrapidity UE activity
- Small forward energy detection selects high multiplicity and high $p_T^{leading}$ particle at midrapidity



ALI-PREL-366808

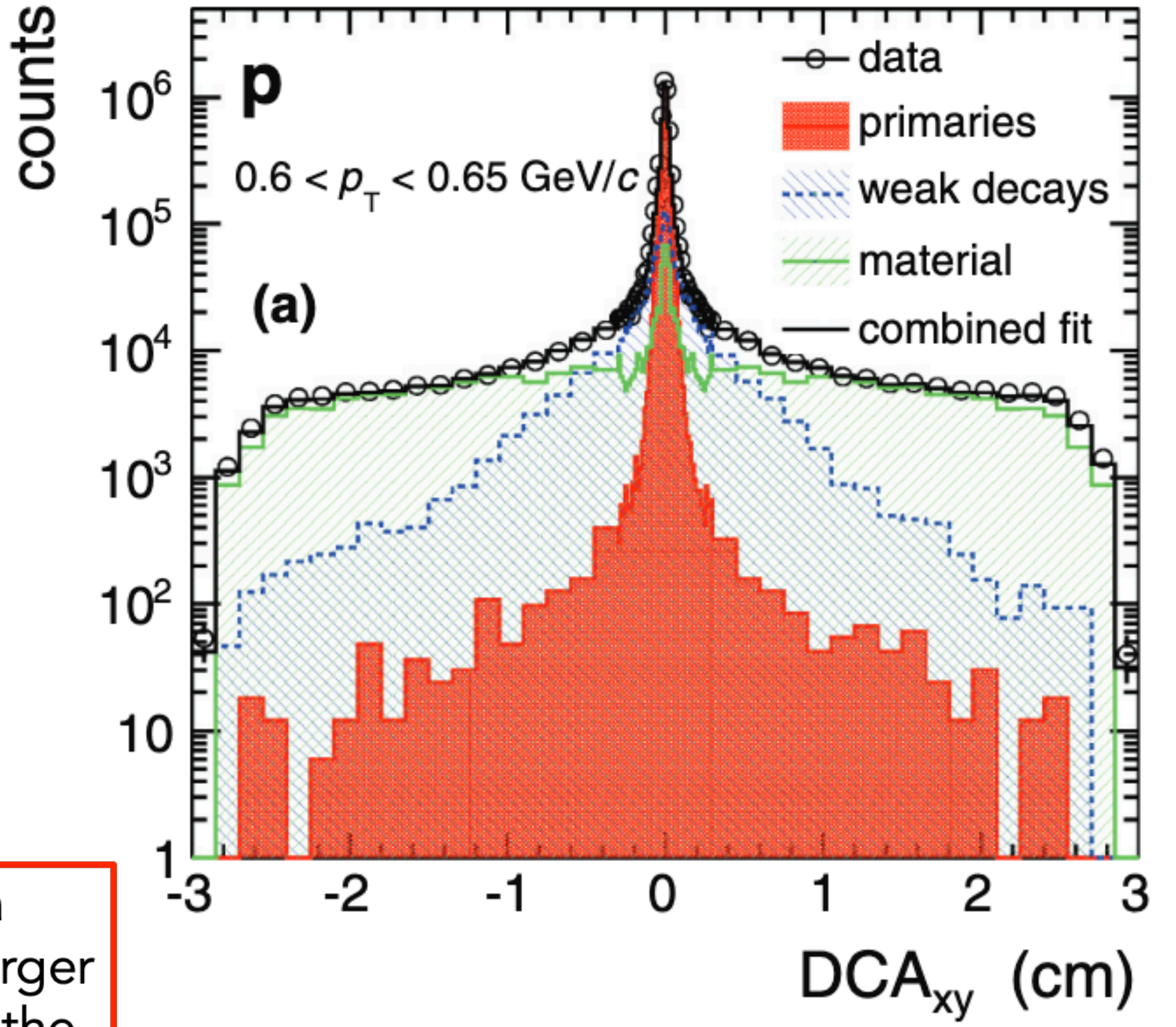
Evolution of hadron-chemistry with multiplicity/centrality

Efficiency and Feed-down correction



Global tracks: information from ITS and TPC

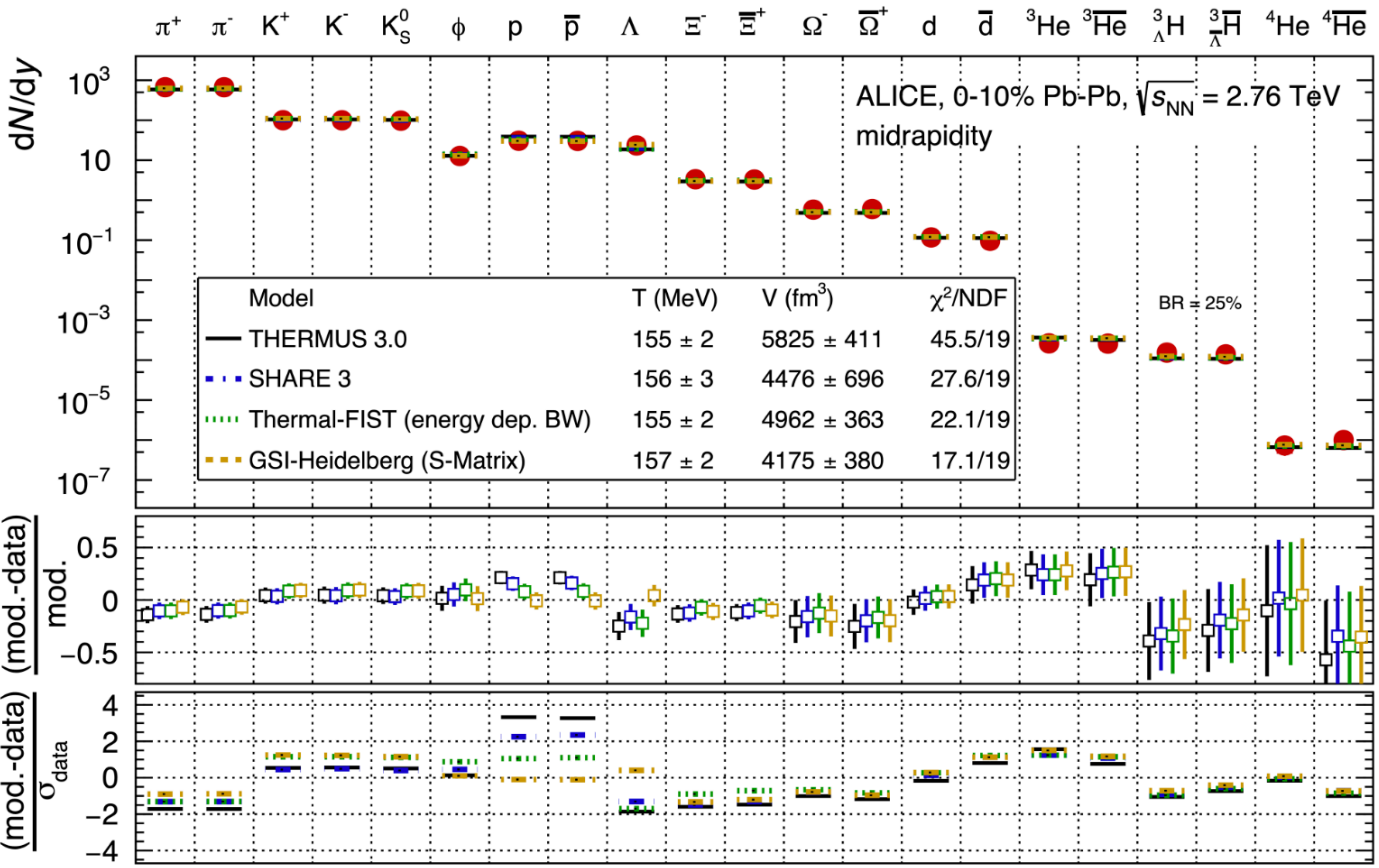
- Good resolution in the transverse distance of closest approach (DCA) to the vertex
- Hence, good separation of primary and secondary particle
- Careful subtraction based on the DCA.



ALICE, Phys. Rev. C**88**, 044910 (2013)

A primary charged particle is defined to be a charged particle with a mean proper lifetime τ larger than 1 cm/*c* which is either produced directly in the interaction or from decays of particles with τ smaller than 1 cm/*c*, excluding particles produced in interactions with the detector material.

Hadron formation from QGP



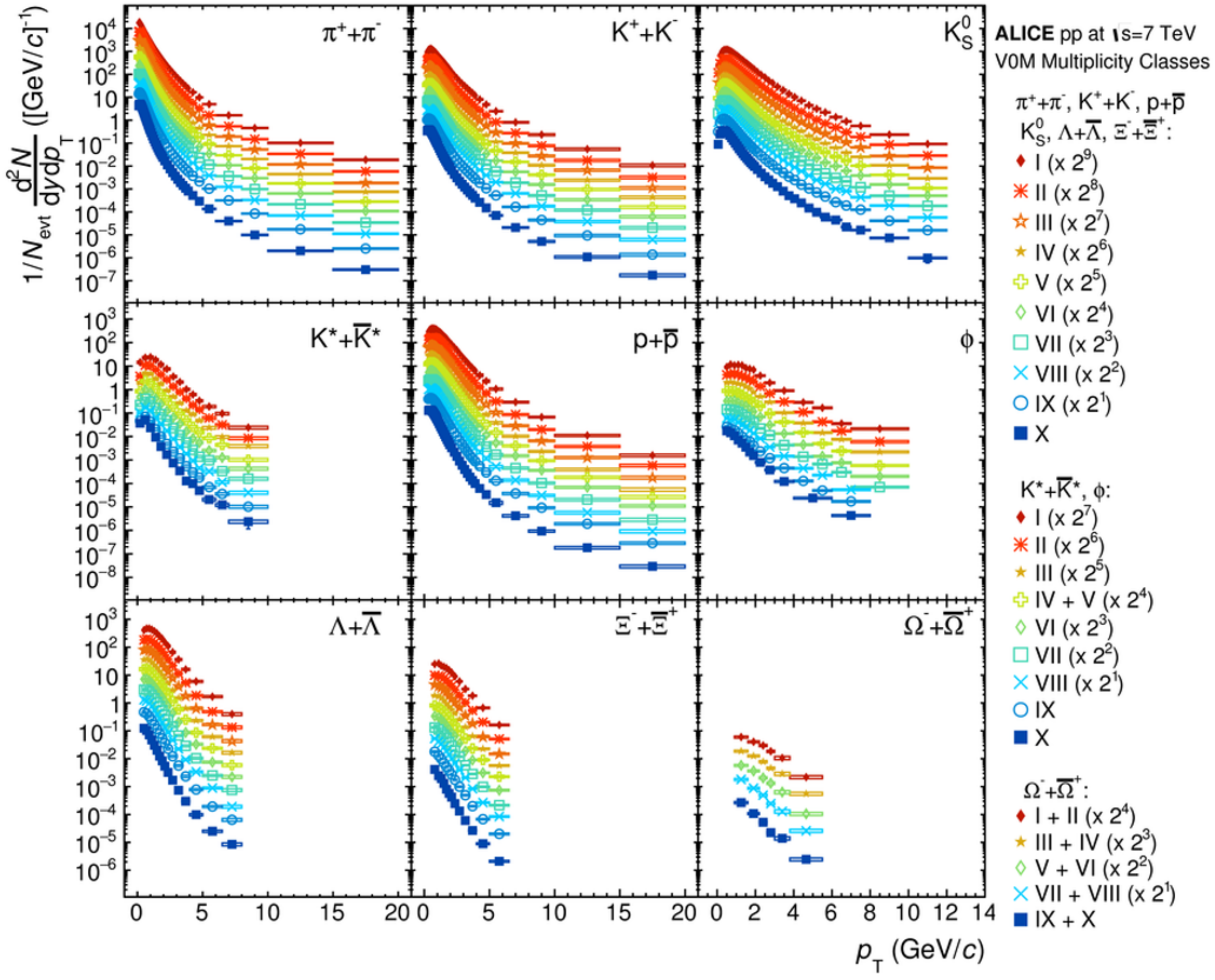
Hadron and light nuclei yield described by statistical hadronisation models over many orders of magnitude

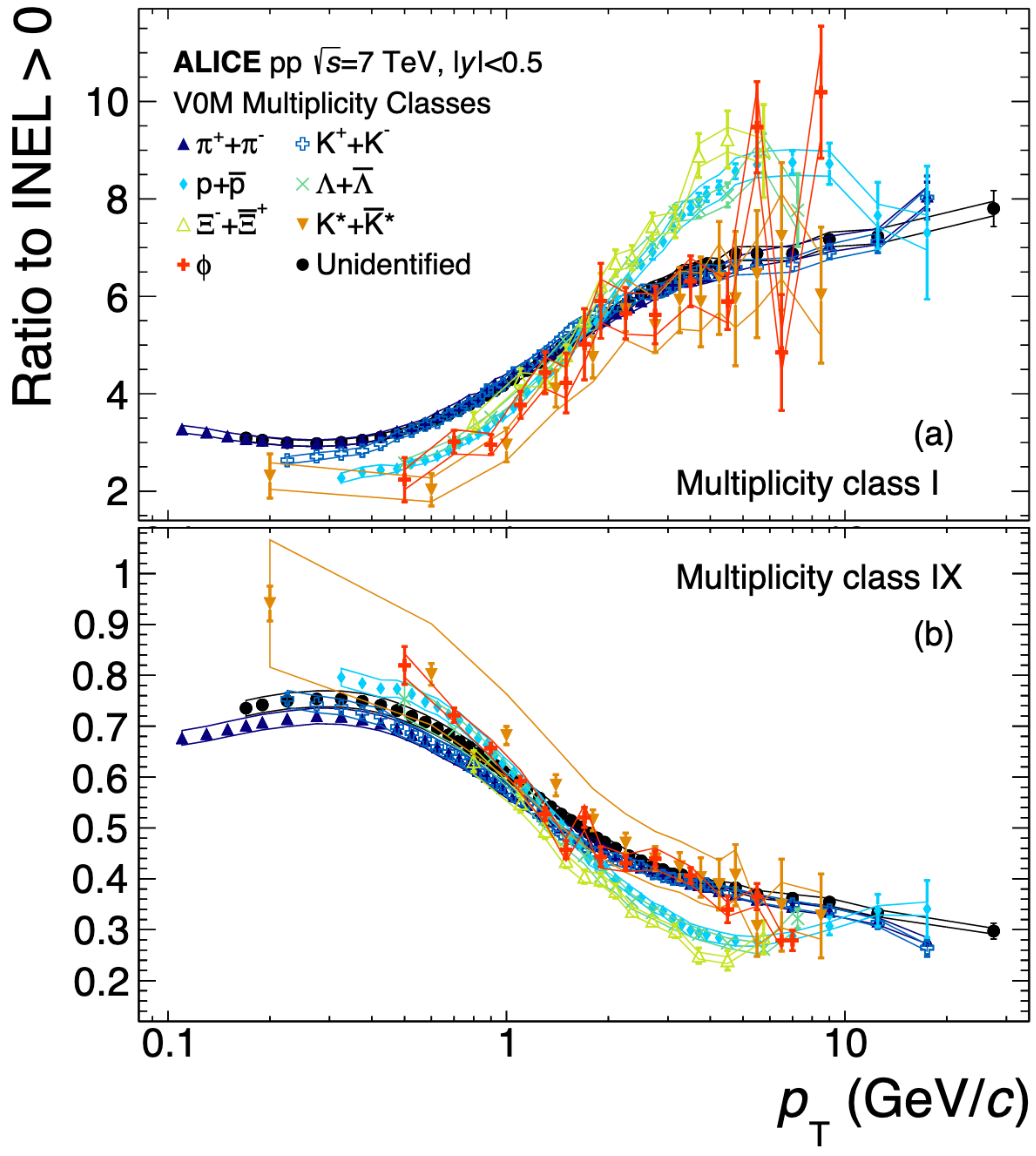
—> Implies hadrons subject to chemical equilibrium close to the QGP transition temperature

$T_{chem} \approx T_c \approx 156$ MeV

ALICE, arXiv:2211.04384

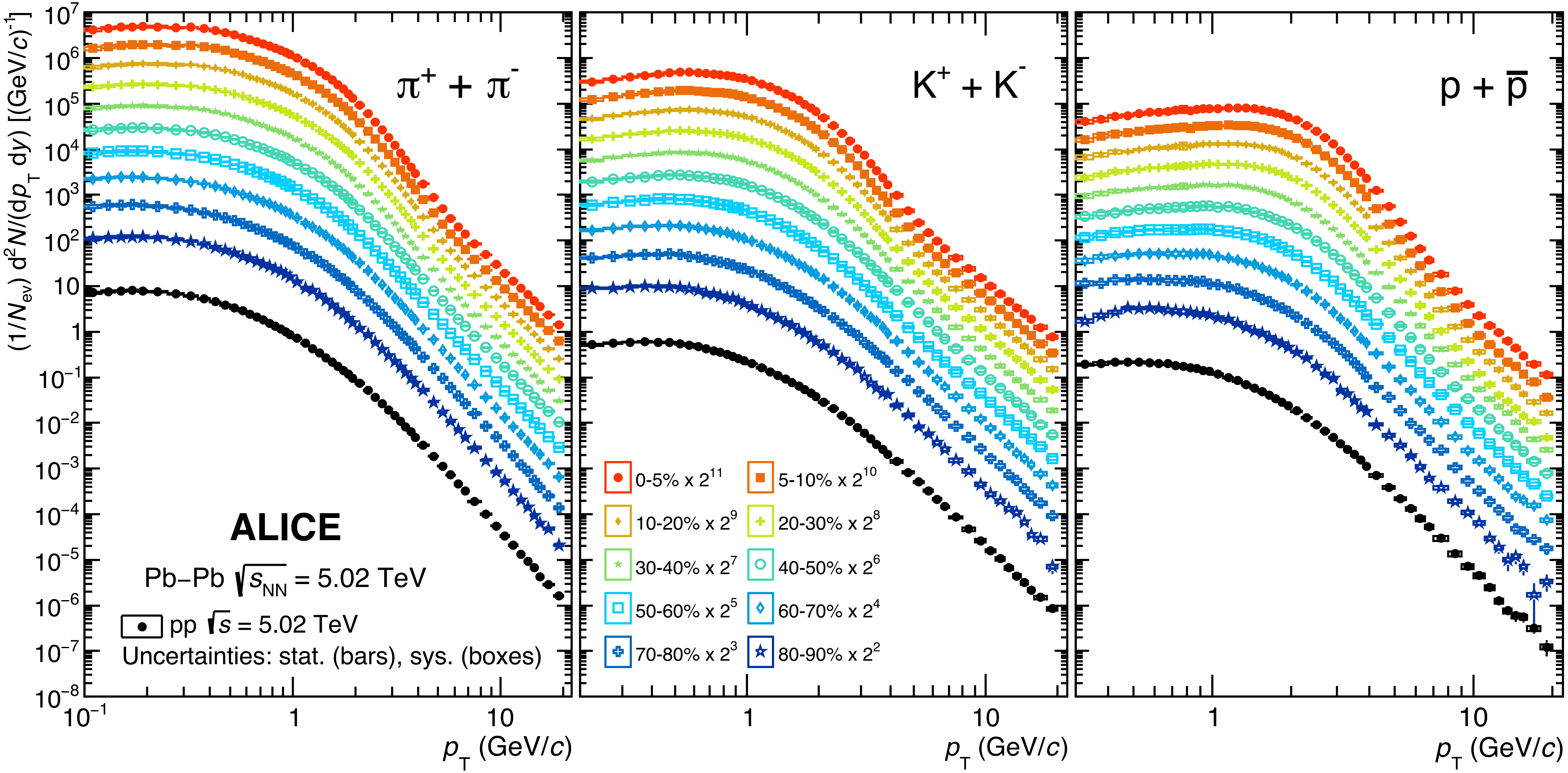
Transverse momentum spectra (pp)





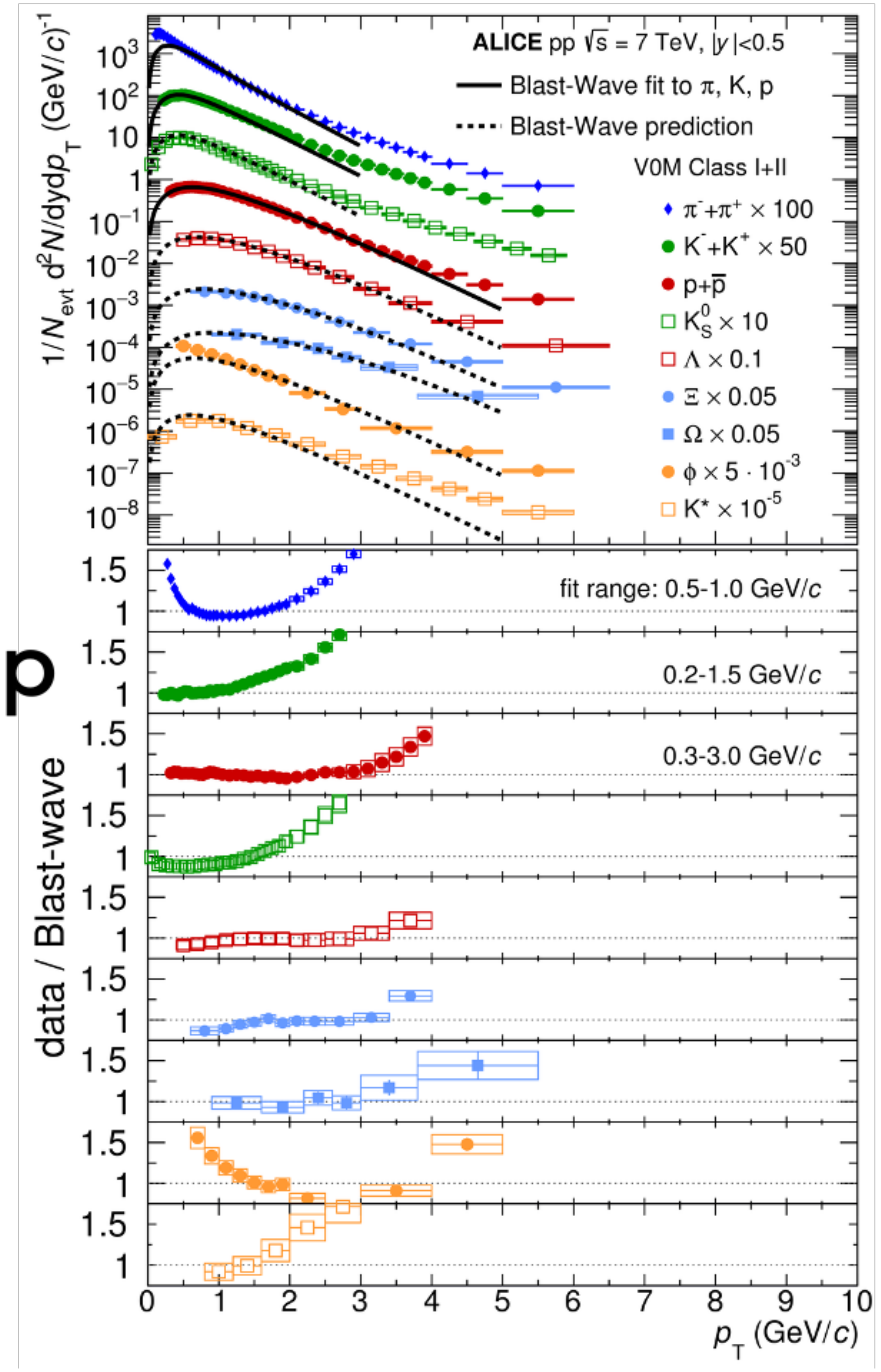
ALICE, Phys. Rev. C99 (2018) 024906

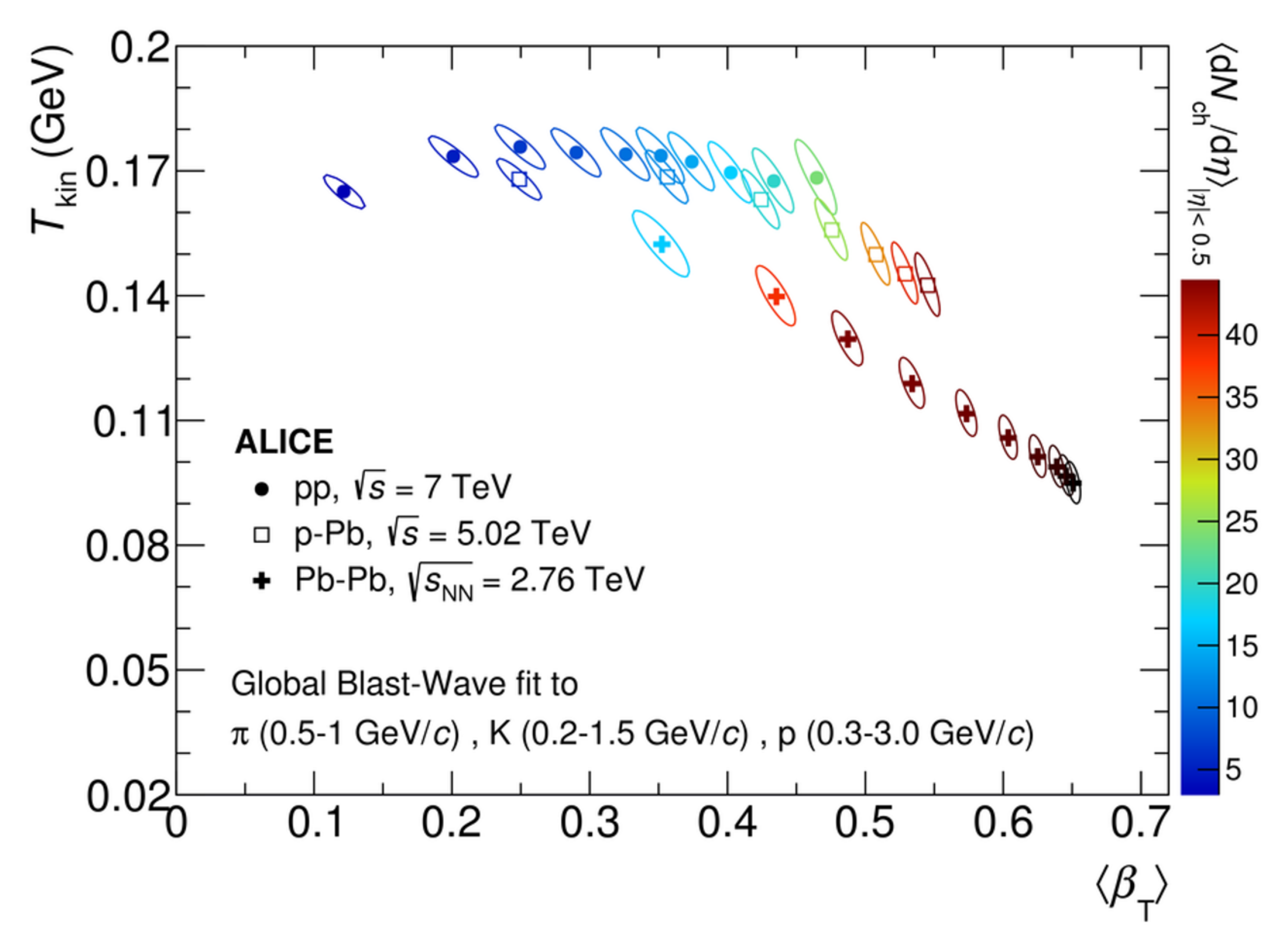
Transverse momentum spectra (Pb—Pb)



ALICE, Phys. Rev. C 101, 044907 (2020)

Spectral shapes vs multiplicity



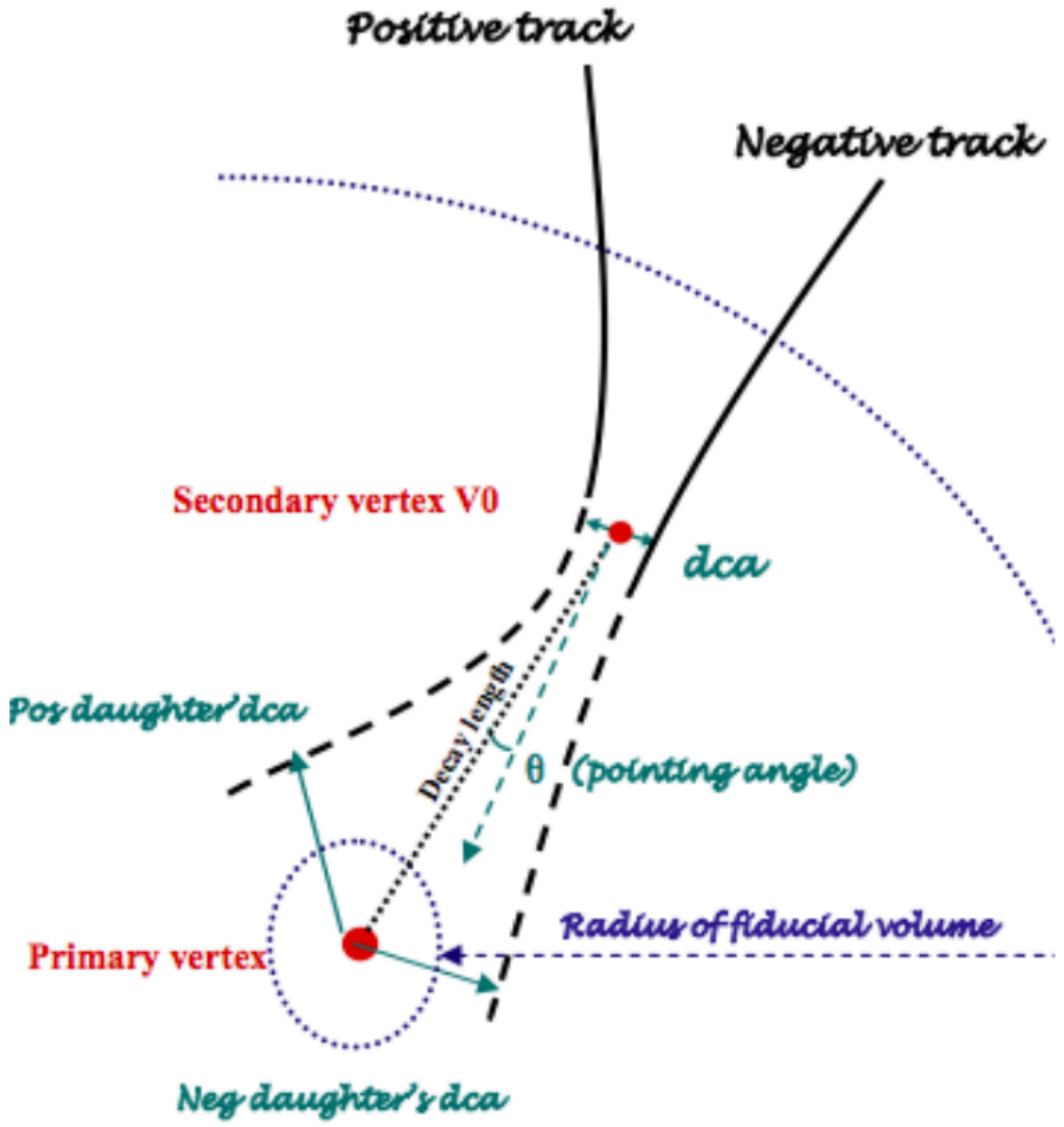


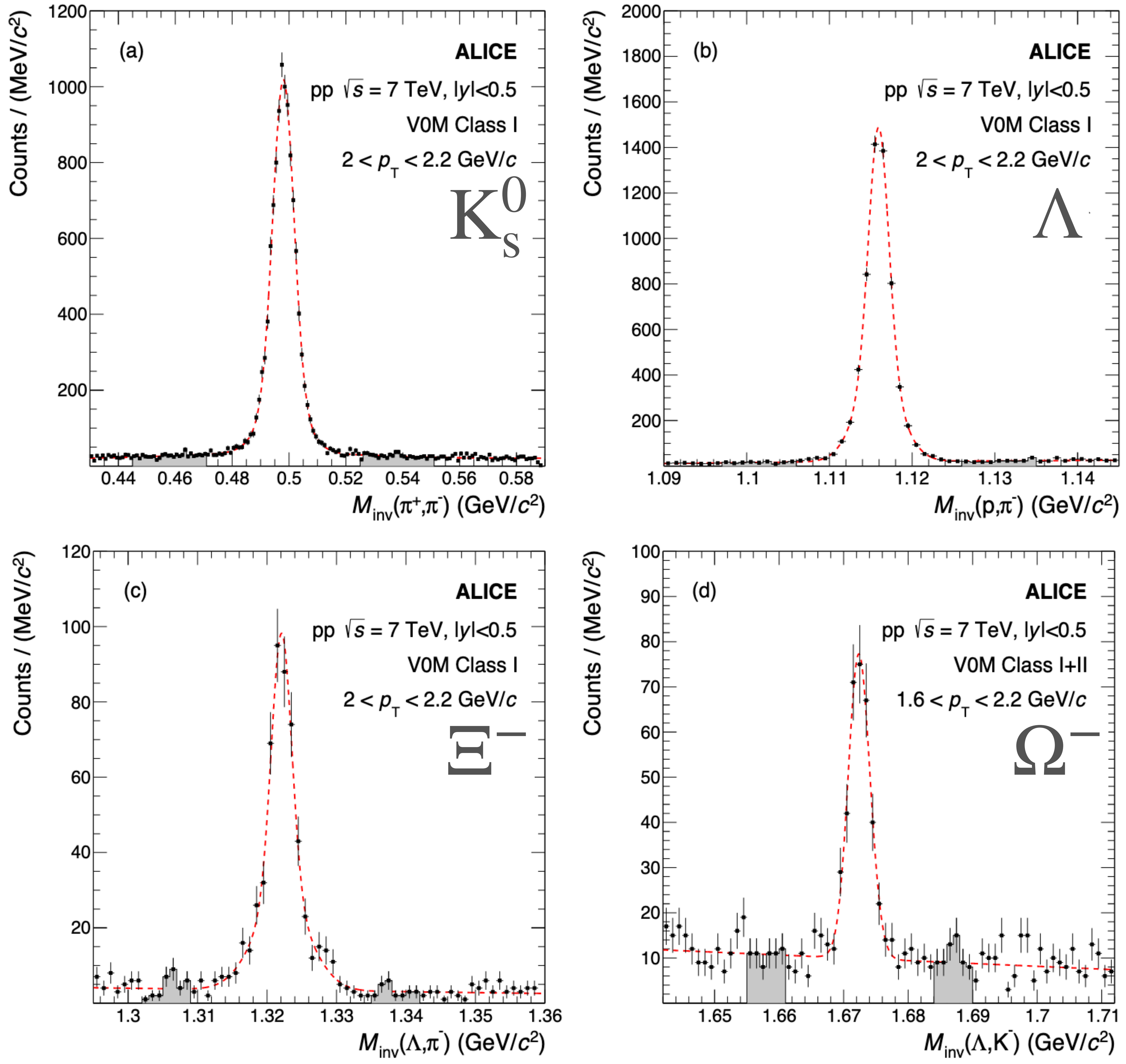
- Spectral shapes can be quantified based on the blast-wave model (simplified hydro model) which describes π/K/p data in pp, p-Pb and Pb-Pb collisions (consistent with a common radial expansion of all particles).
- At similar multiplicities, smaller collision systems' spectra seem harder (larger average expansion velocity).

ALICE, Phys. Rev. C99 (2018) 024906

Strangeness production

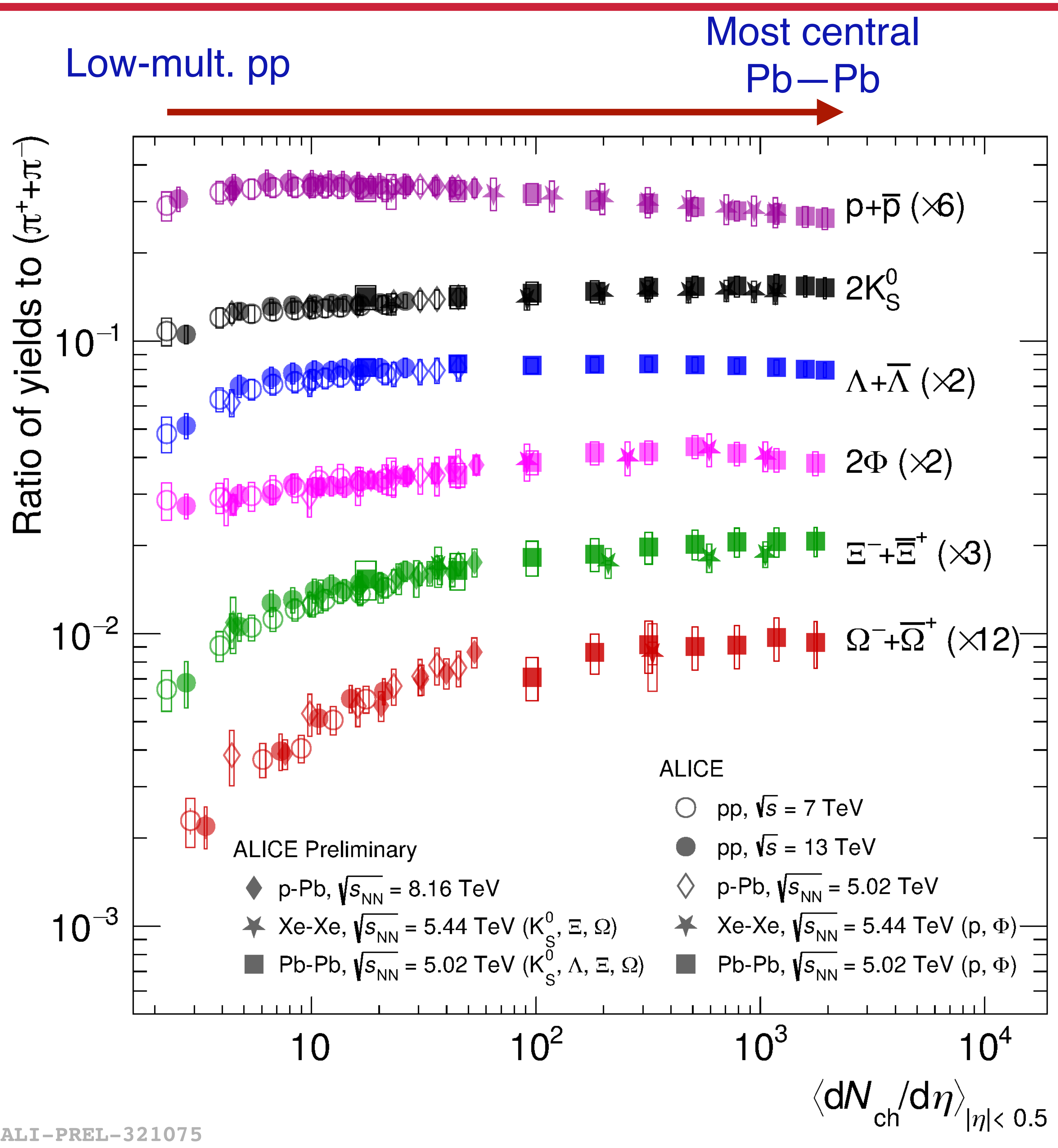
K^0_S	$\rightarrow$	$\pi^+ + \pi^-$	B.R. = (69.20 ± 0.05) %
$\Lambda(\overline{\Lambda})$	$\rightarrow$	$p\ (\overline{p}) + \pi^-\ (\pi^+)$	B.R. = (63.9 ± 0.5) %
$\Xi^-\ (\overline{\Xi}^+)$	$\rightarrow$	$\Lambda\ (\overline{\Lambda}) + \pi^-\ (\pi^+)$	B.R. = (99.887 ± 0.035) %
$\Omega^-\ (\overline{\Omega}^+)$	$\rightarrow$	$\Lambda\ (\overline{\Lambda}) + K^-\ (K^+)$	B.R. = (67.8 ± 0.7) %





ALICE, Phys. Rev. C99 (2018) 024906

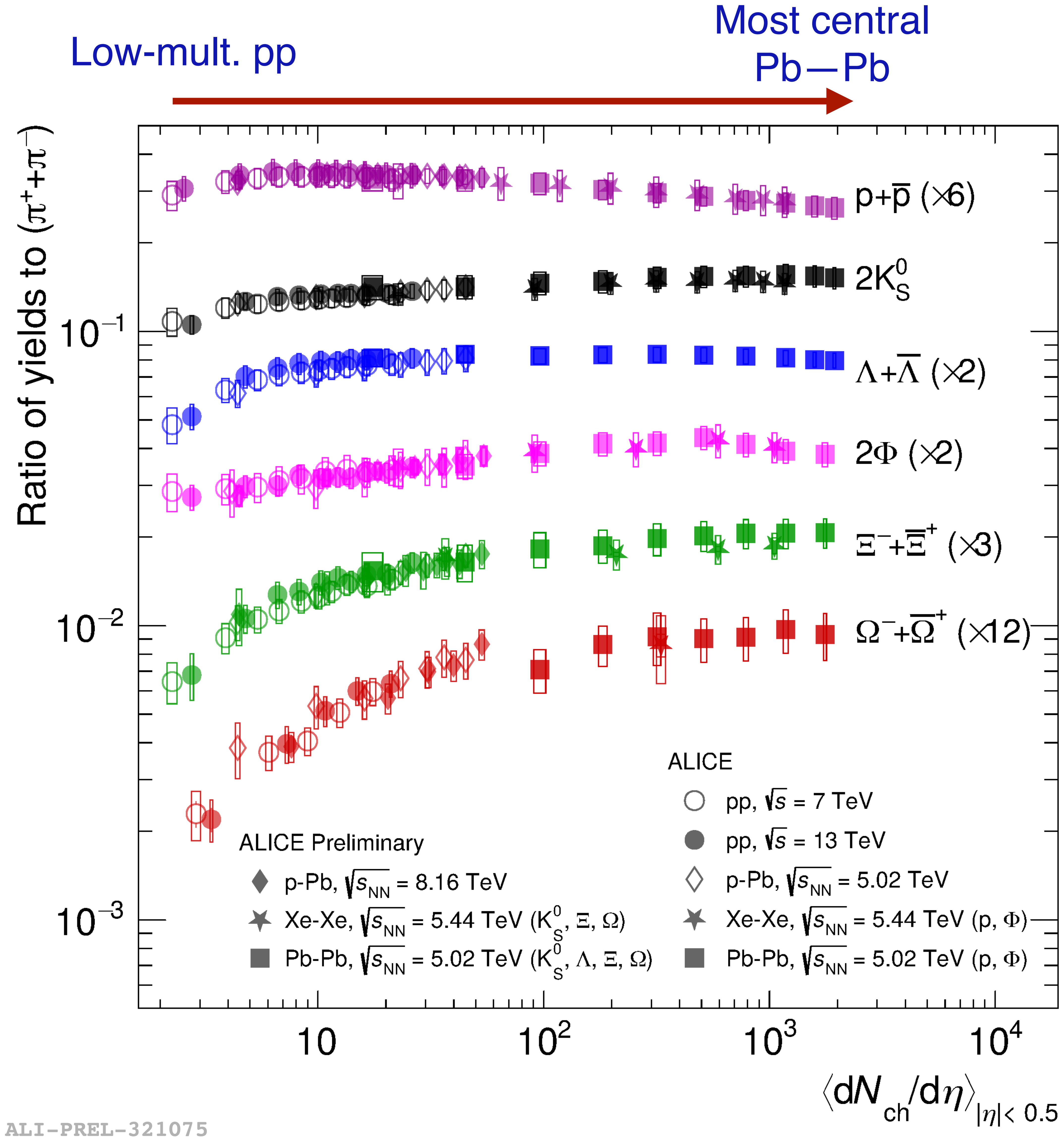
Strangeness production



ALICE, Nature Phys 13, 535 (2017)
ALICE, Eur. Phys. J. C80, 167 (2020)

Strangeness production

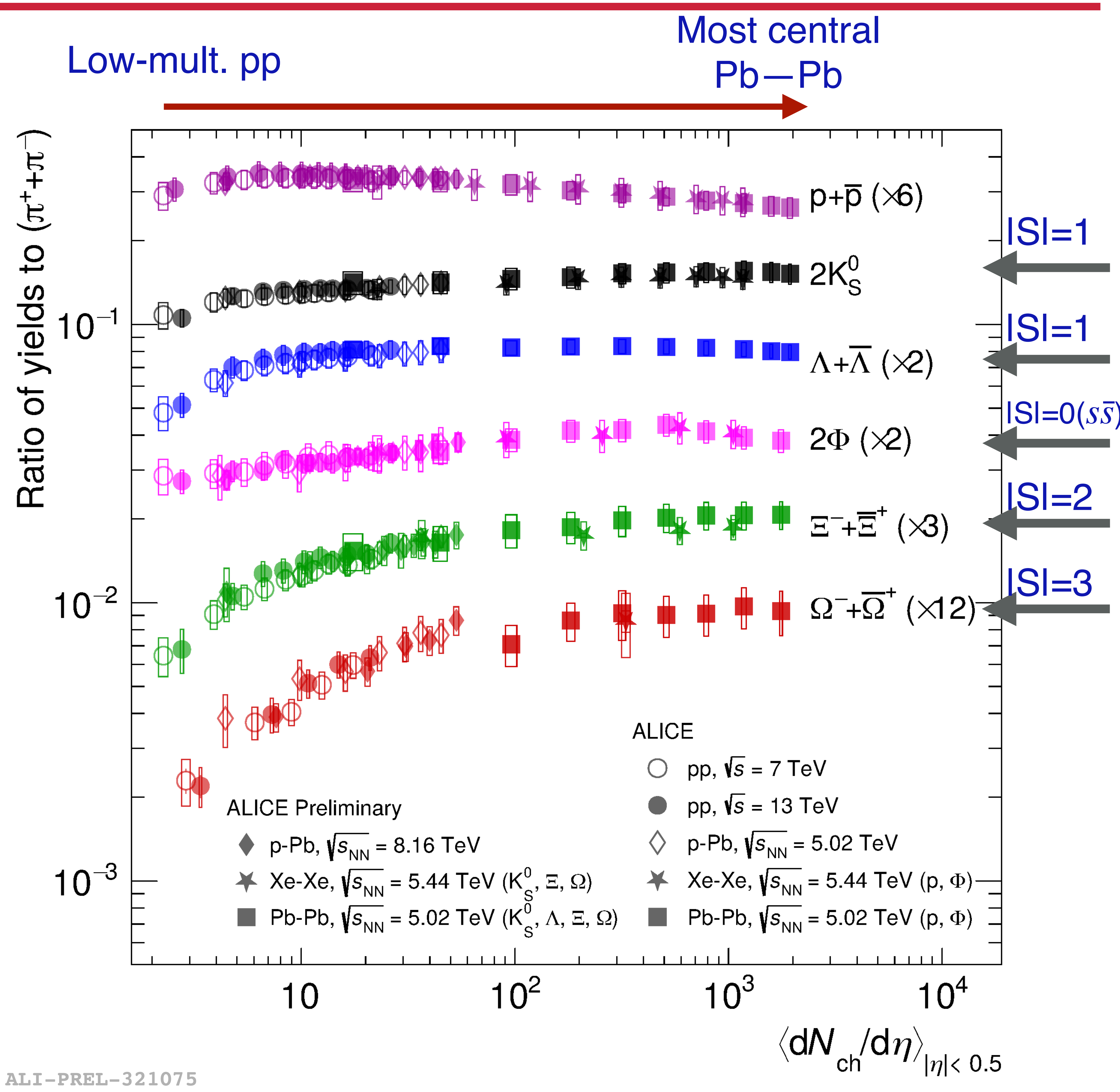
- Smooth evolution of hadron to pion ratios across multiplicity: Independent of collision energy and system



ALICE, Nature Phys 13, 535 (2017)
ALICE, Eur. Phys. J. C80, 167 (2020)

Strangeness production

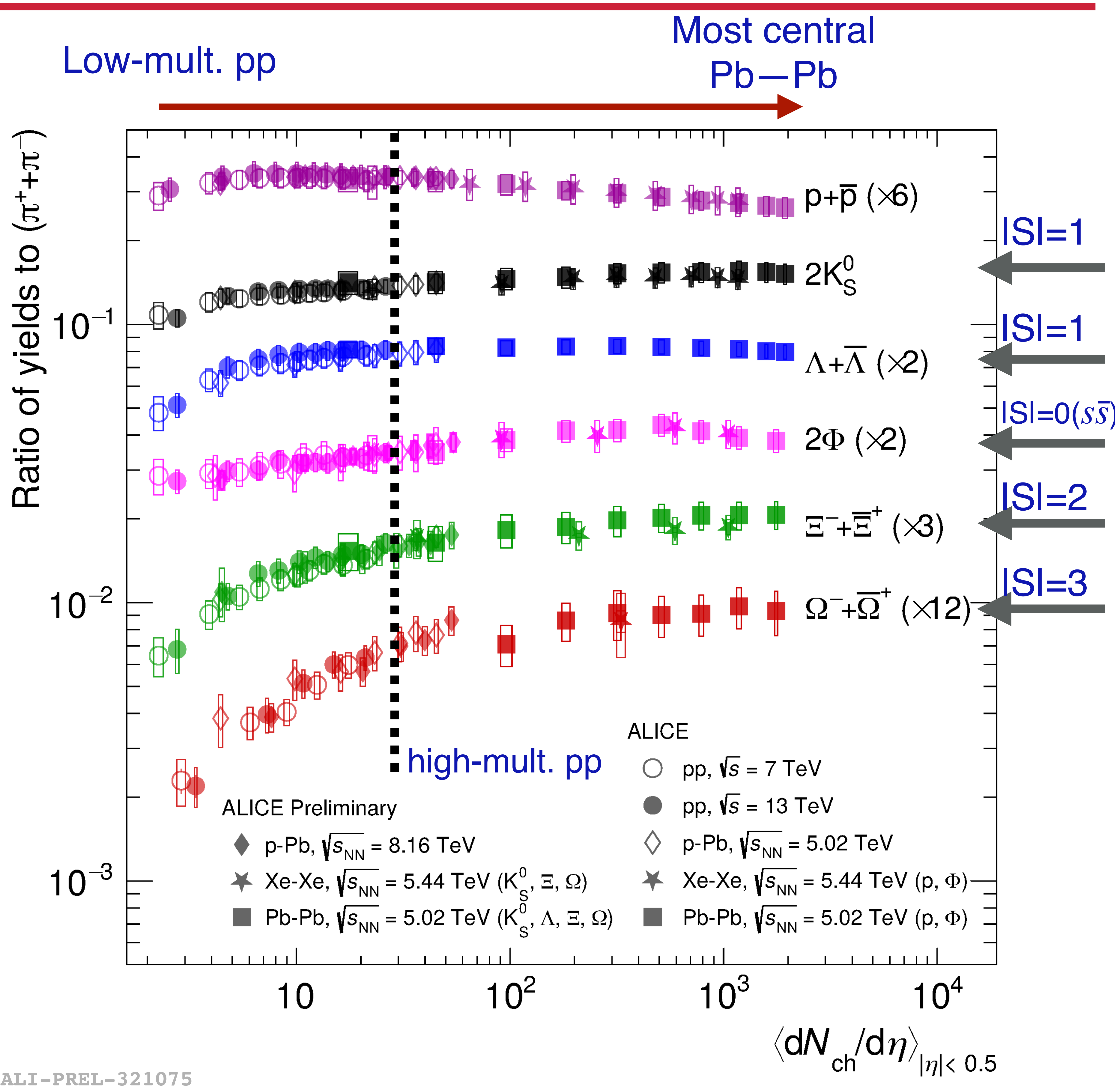
- Smooth evolution of hadron to pion ratios across multiplicity: Independent of collision energy and system
- Strangeness enhancement increases with the strangeness content of the particle



ALICE, Nature Phys 13, 535 (2017)
ALICE, Eur. Phys. J. C80, 167 (2020)

Strangeness production

- Smooth evolution of hadron to pion ratios across multiplicity: Independent of collision energy and system
- Strangeness enhancement increases with the strangeness content of the particle
- Enhancement in high multiplicity pp is similar to that of central Pb-Pb collisions



ALICE, Nature Phys 13, 535 (2017)
ALICE, Eur. Phys. J. C80, 167 (2020)

Resonances production

$$K^{*0} \rightarrow \pi^{\pm} + K^{\mp} \qquad \text{B.R.} = (\sim 66.6)\ \%$$

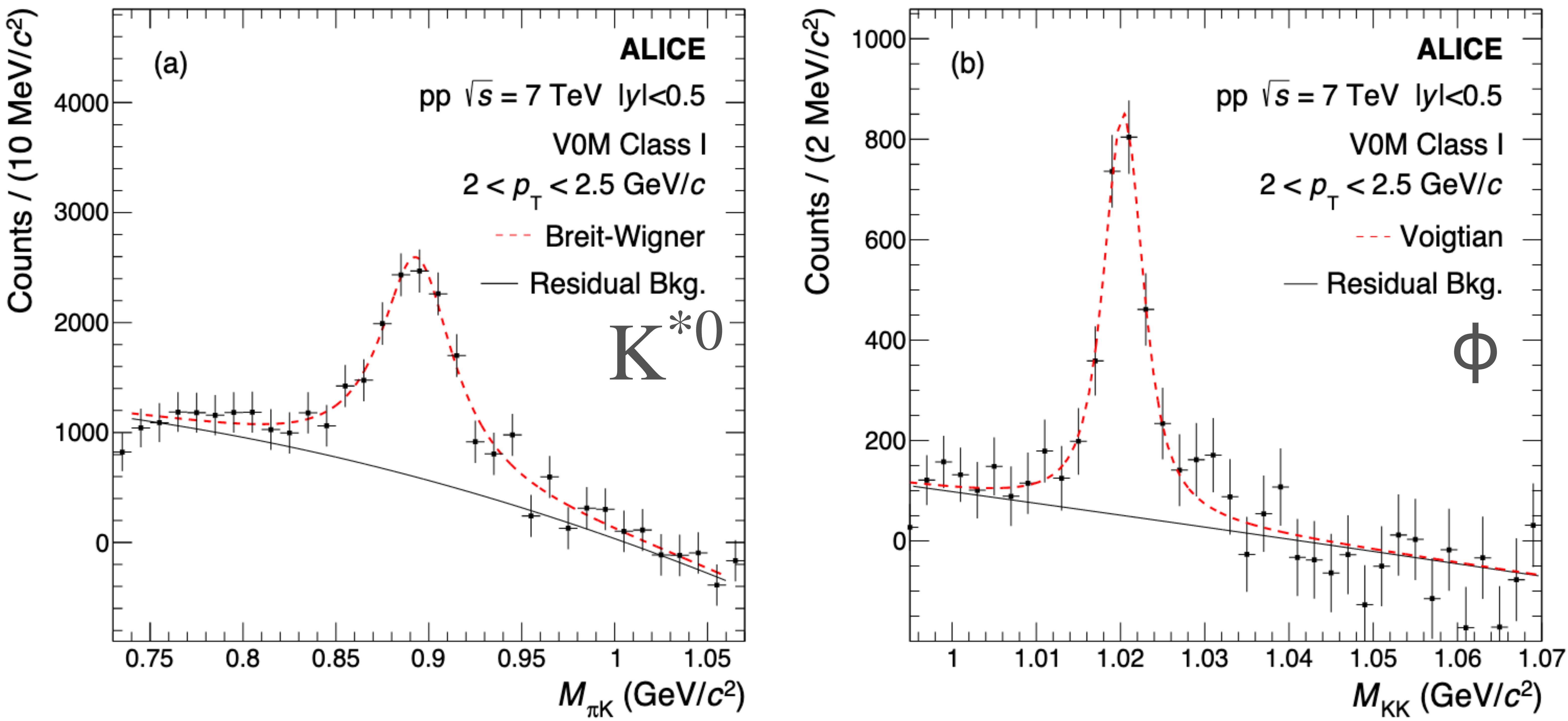
$$\phi \rightarrow K^{+} + K^{-} \qquad \text{B.R.} = (48.9 \pm 0.5)\ \%$$

$$\frac{dN}{dM_{\pi K}} = \frac{Y}{2\pi} \times \frac{\Gamma}{(M_{\pi K} - M_0)^2 + \frac{\Gamma^2}{4}}$$

$$\frac{dN}{dM_{KK}} = \frac{Y}{2\pi} \int \frac{\Gamma}{(M_{KK} - m')^2 + \Gamma^2/4} \times \frac{e^{-(m'-M_0)^2/2\sigma^2}}{\sqrt{2\pi}\sigma} dm'$$

M_0, Γ and Y are the mass, width and raw yield of the resonances, respectively.

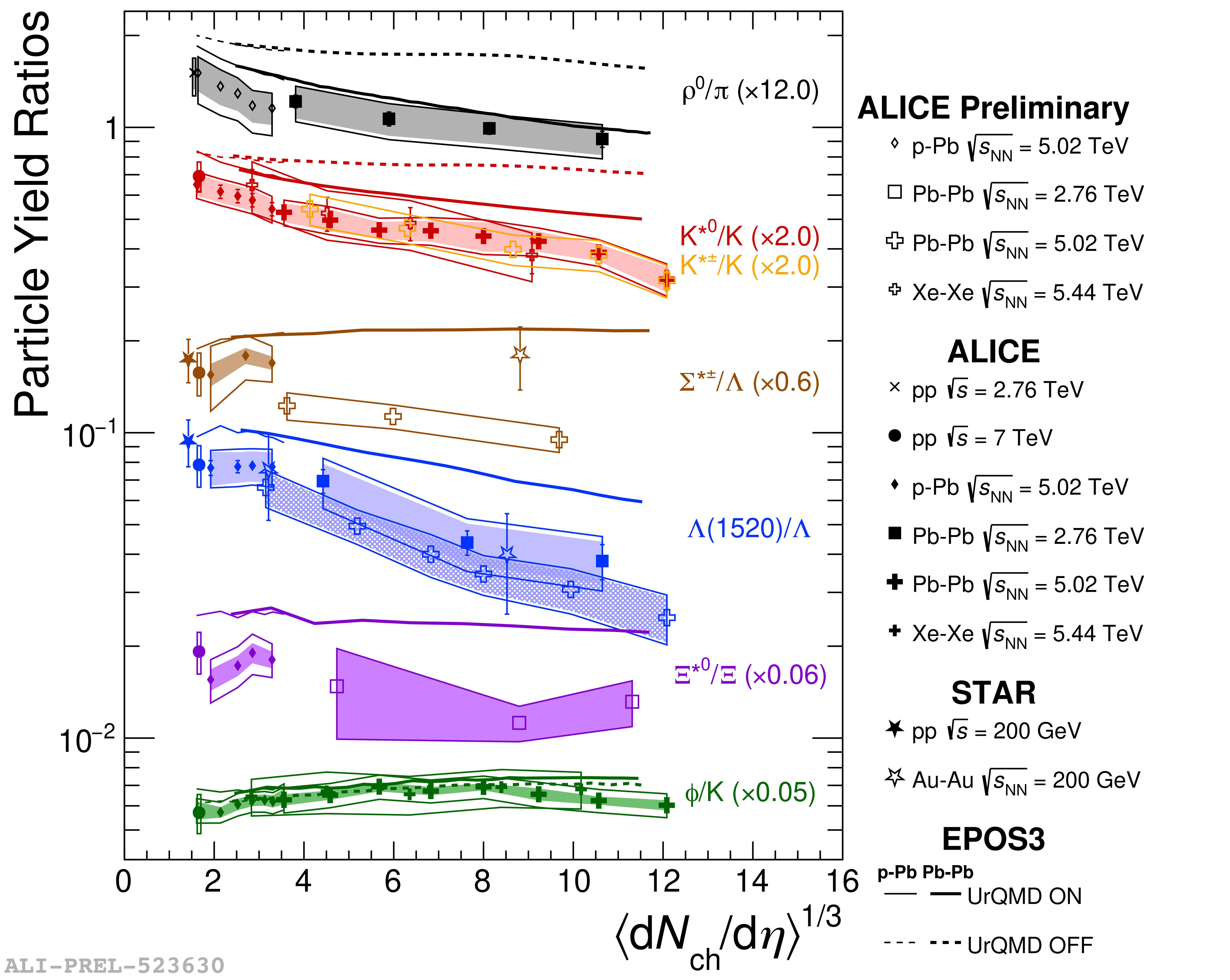
The parameter σ represents the mass resolution.



ALICE, Phys. Rev. C99 (2018) 024906

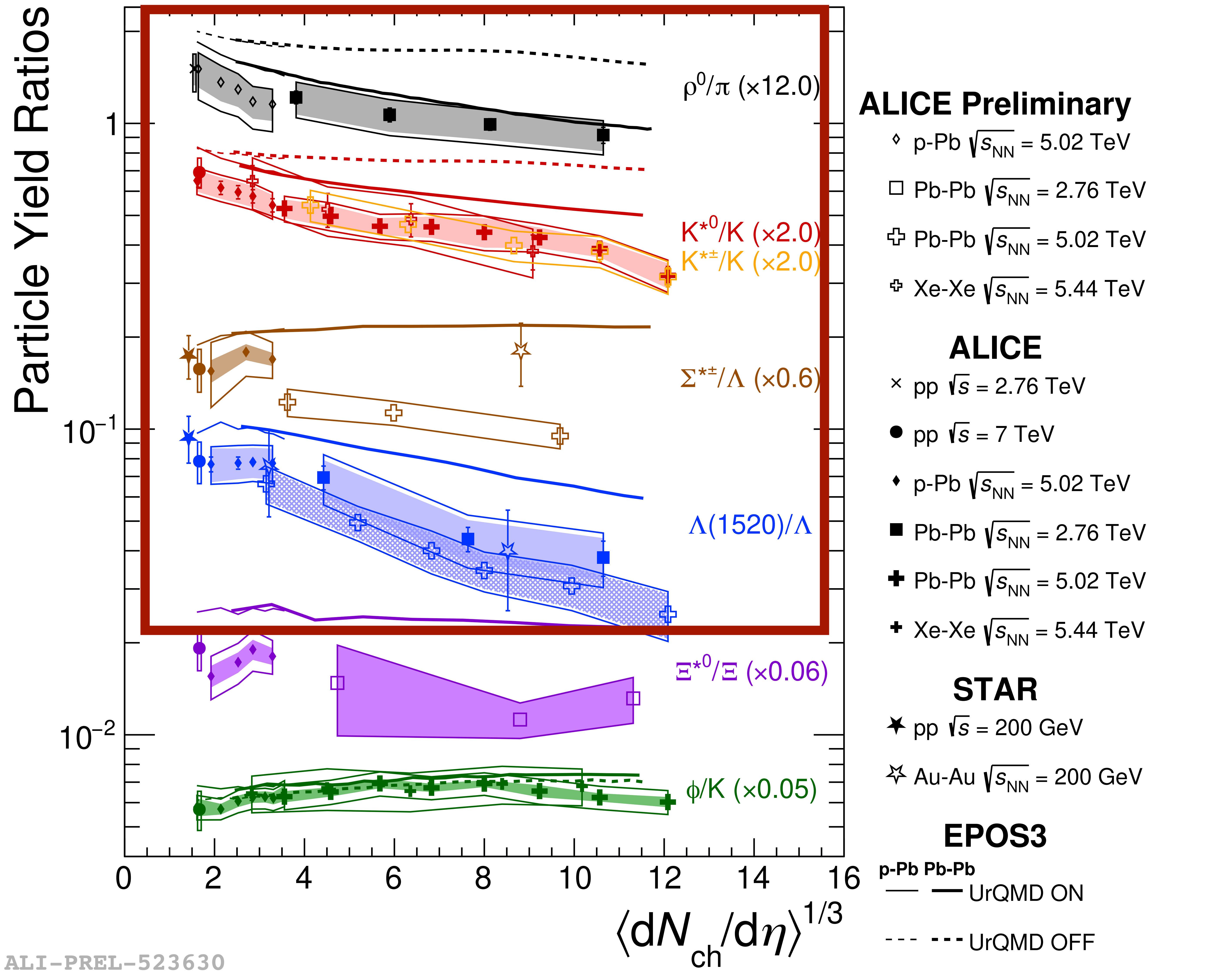
Resonances production

- ALICE has measured several resonances with varying lifetimes



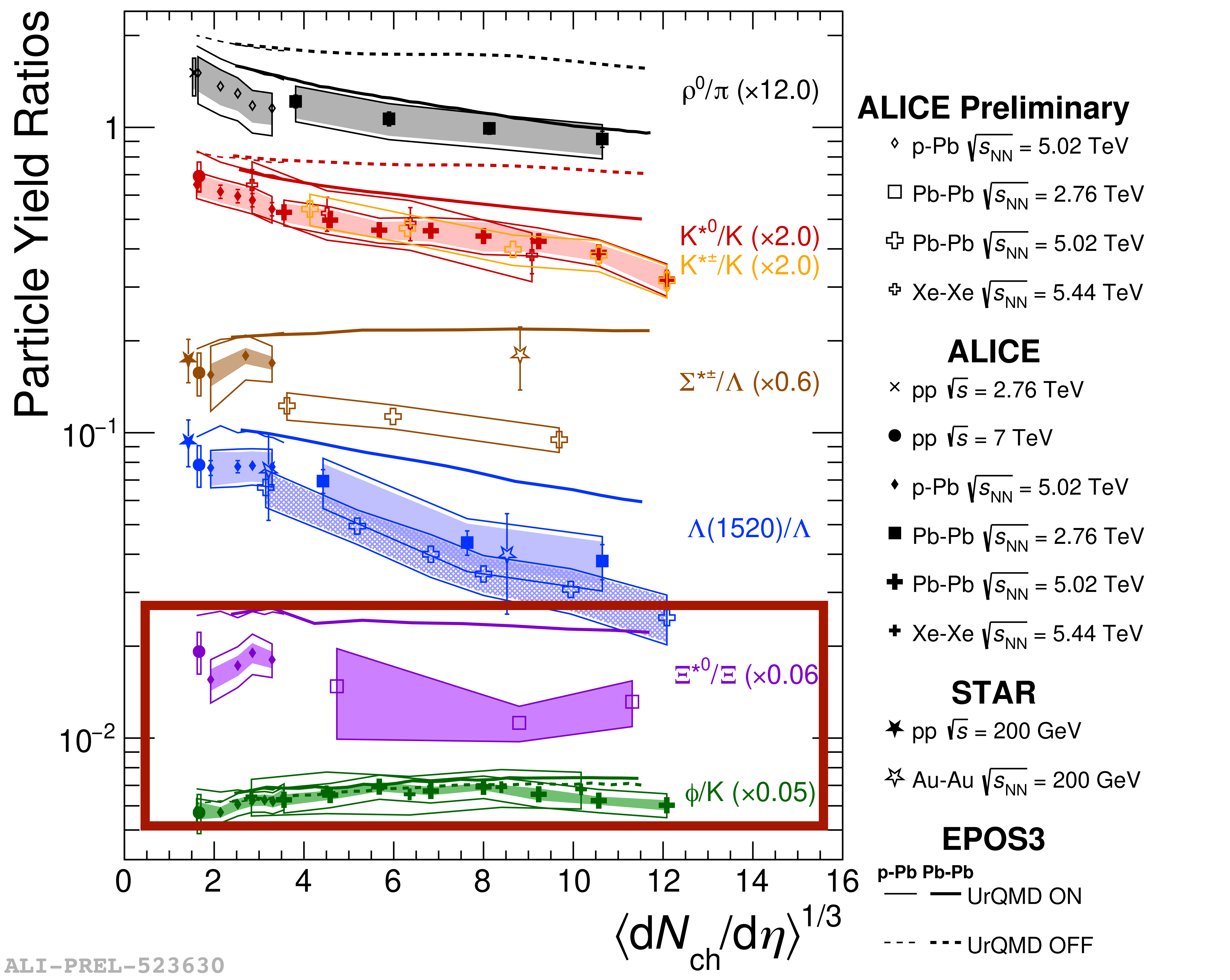
Resonances production

- ALICE has measured several resonances with varying lifetimes
- Suppression of short-lived resonances in larger collision systems: attributed to hadronic rescattering
- EPOS with UrQMD seems to describe data qualitatively

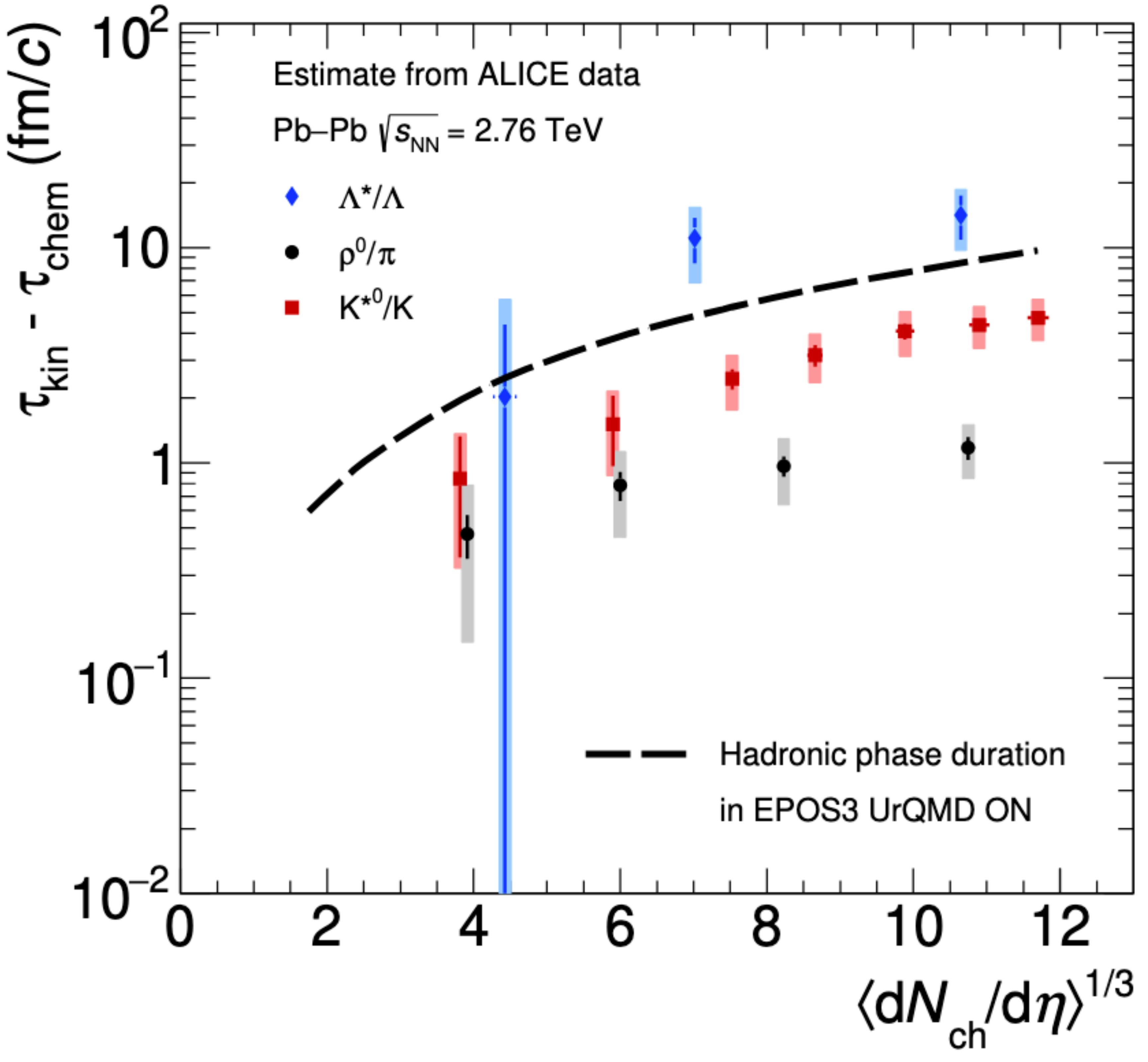


Resonances production

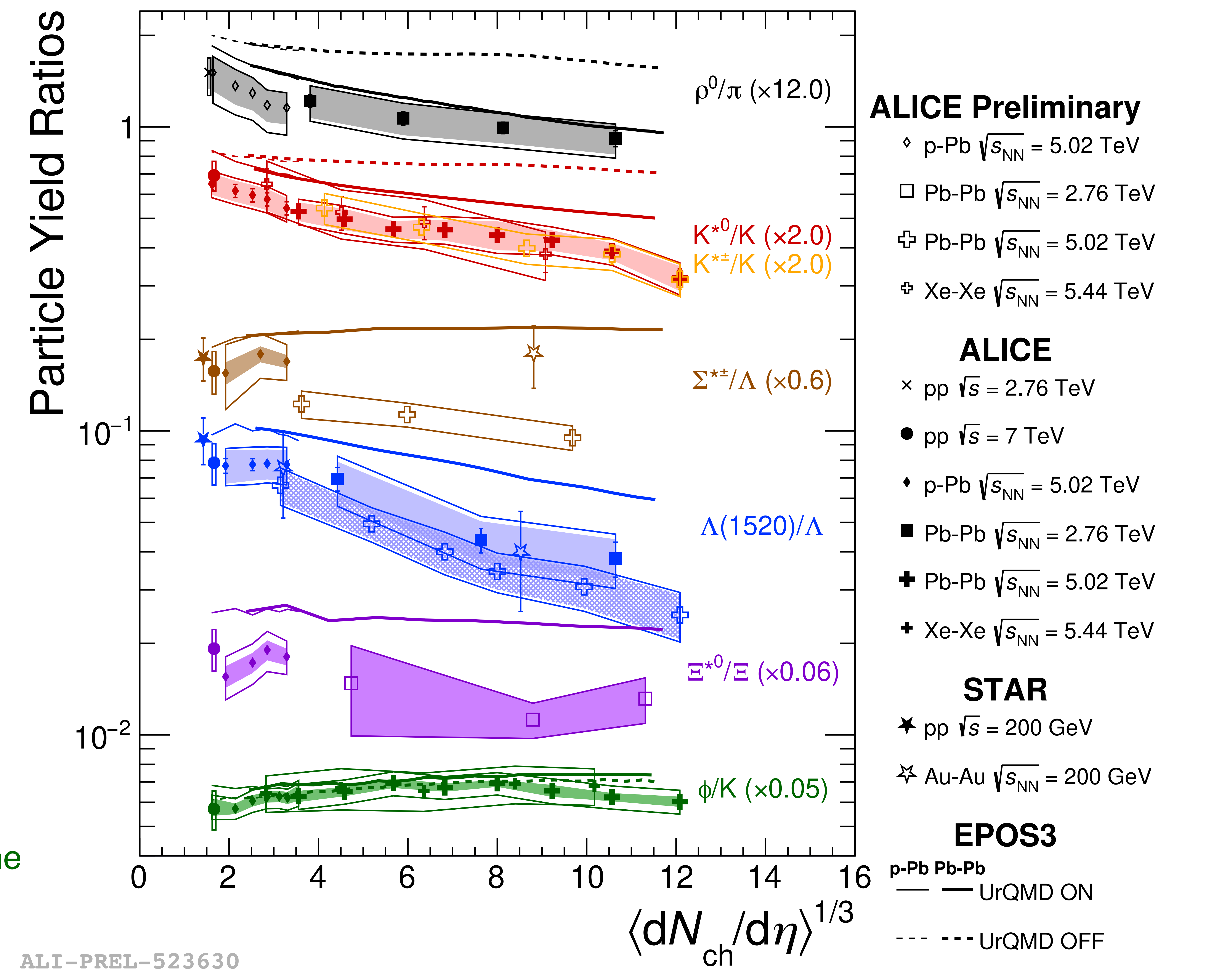
- ALICE has measured several resonances with varying lifetimes
- Suppression of short-lived resonances in larger collision systems: attributed to hadronic rescattering
- EPOS with UrQMD seems to describe data qualitatively
- Weak/no suppression for long-lived resonances



Resonances production



ALICE, arXiv:2211.04384



For K^{*0}:

$$[K^{*0}/K^-]_{kinetic} = [K^{*0}/K^-]_{chemical} \times e^{-\tau/\tau_{K^{*0}}}$$

Pb-Pb — pp — Lifetime of K^{*0}

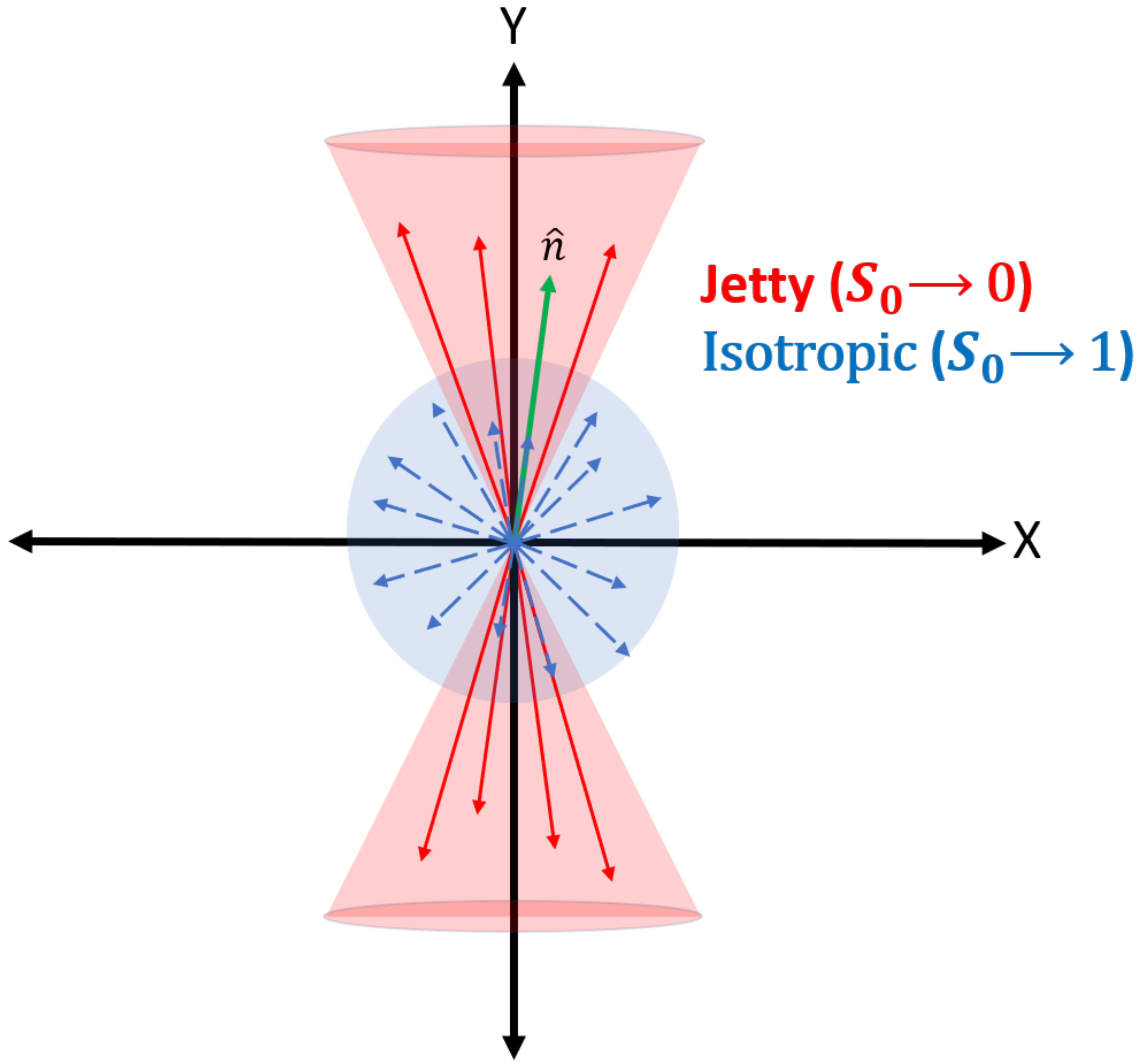
Lower limit of the hadronic phase lifetime

Multi-differential studies with event shape observables

Event shape observables: Transverse spherocity

Transverse Spherocity may discriminate between hard and soft processes.

- Jetty: Back-to-back structure, indication of hard QCD ($S_0 \to 0$)
- Isotropic: enhances underlying events, soft QCD ($S_0 \to 1$)

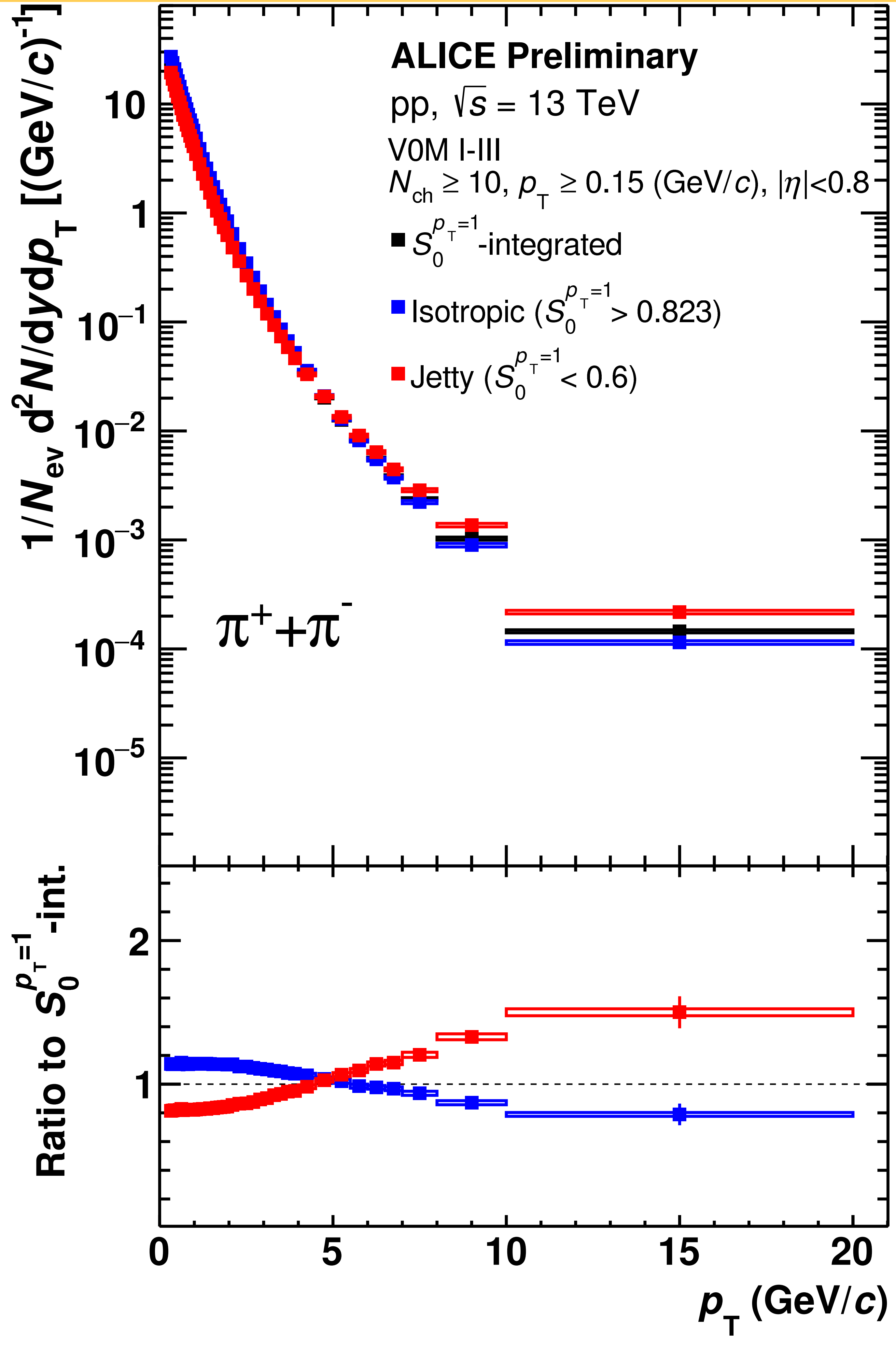


$$S_0^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{Ti}} \times \hat{n}|}{N_{trk}} \right)^2$$

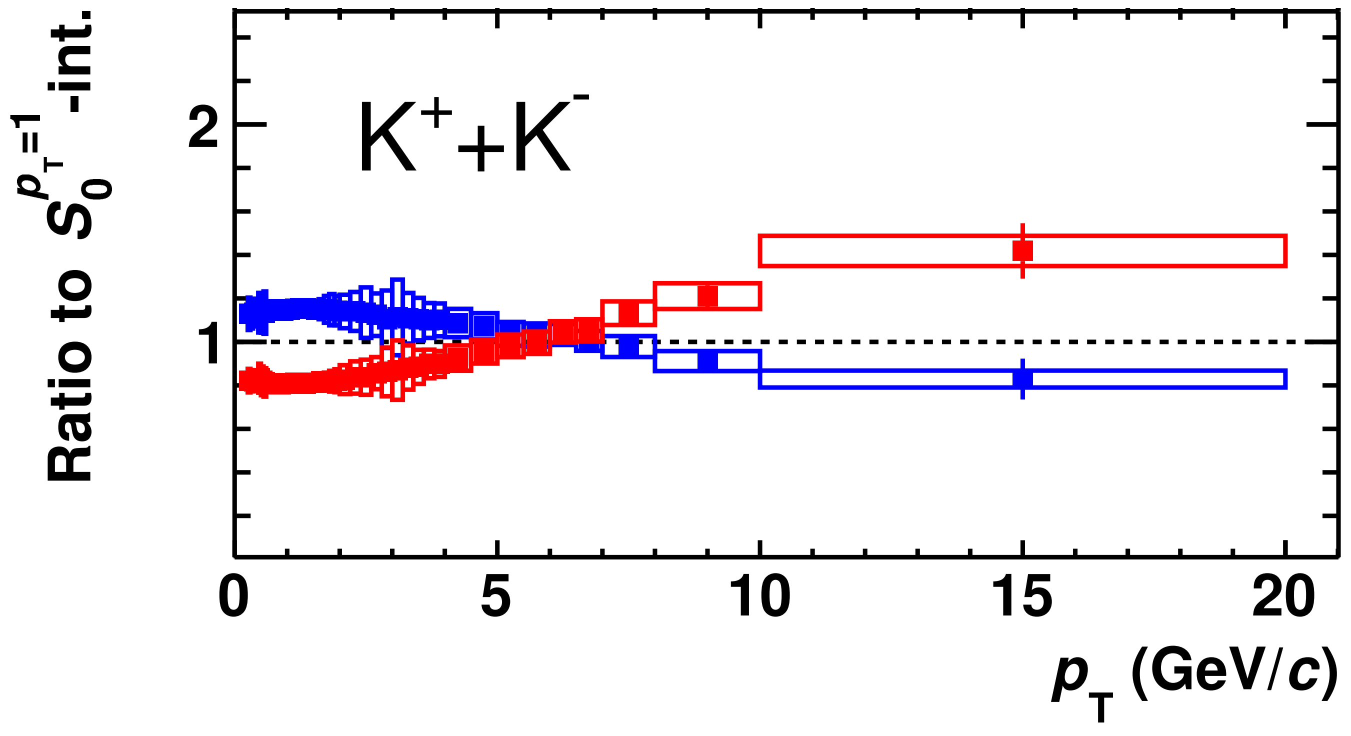
A. Ortiz, Adv.Ser.Direct.High Energy Phys. 29 (2018) 343.
A. Banfi, G. P. Salam and G. Zanderighi, JHEP 06 (2010) 038.
S. Tripathy [ALICE], *PoS* ICHEP2020 (2021) 512.

Identified particle production as a function of spherocity

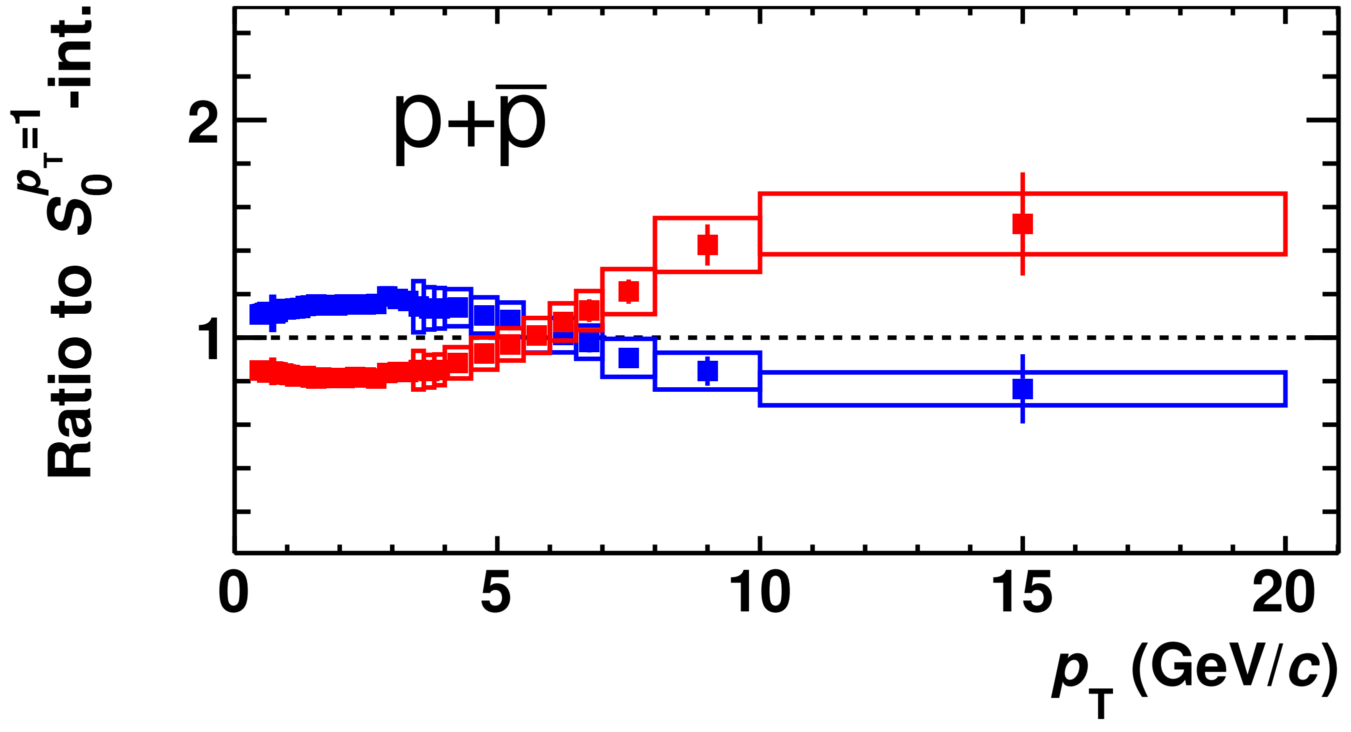
VOM forward-rapidity estimator



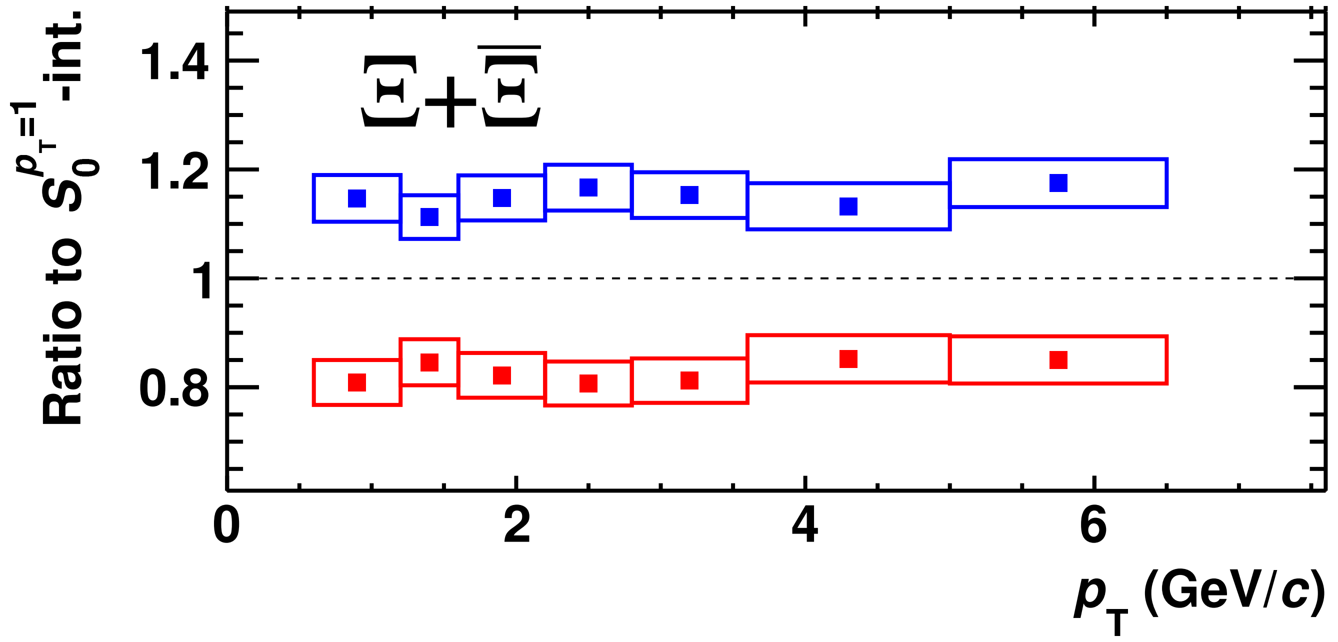
ALI-PREL-334853



ALI-PREL-334858



ALI-PREL-334877

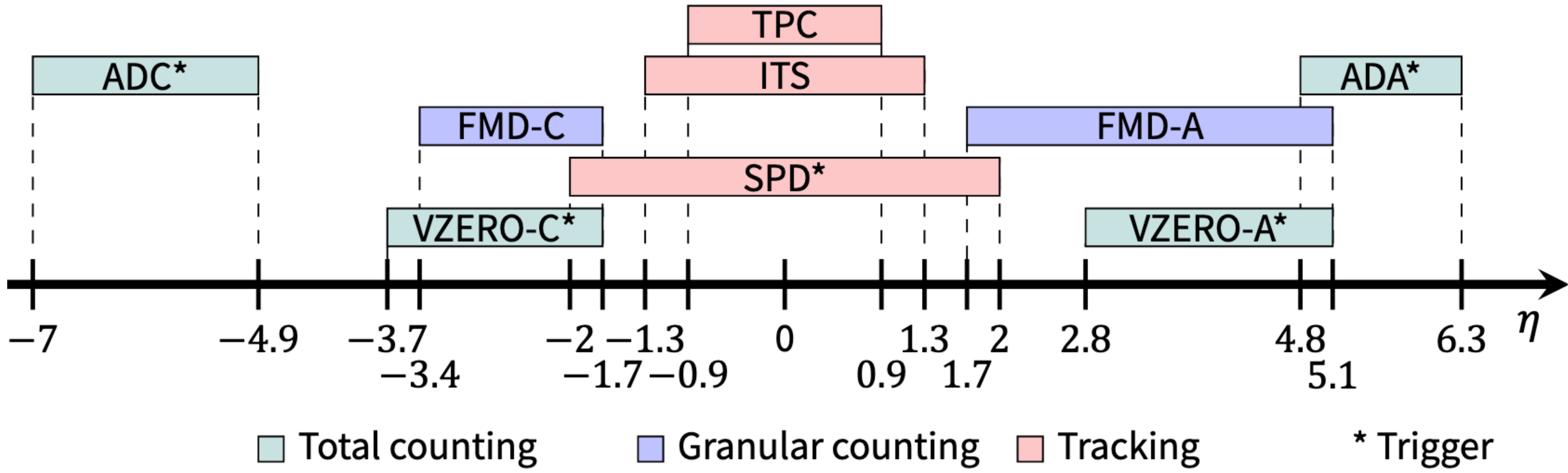


ALI-PREL-335032

- A clear dependence of p_T spectra on $S_0^{p_T=1}$.

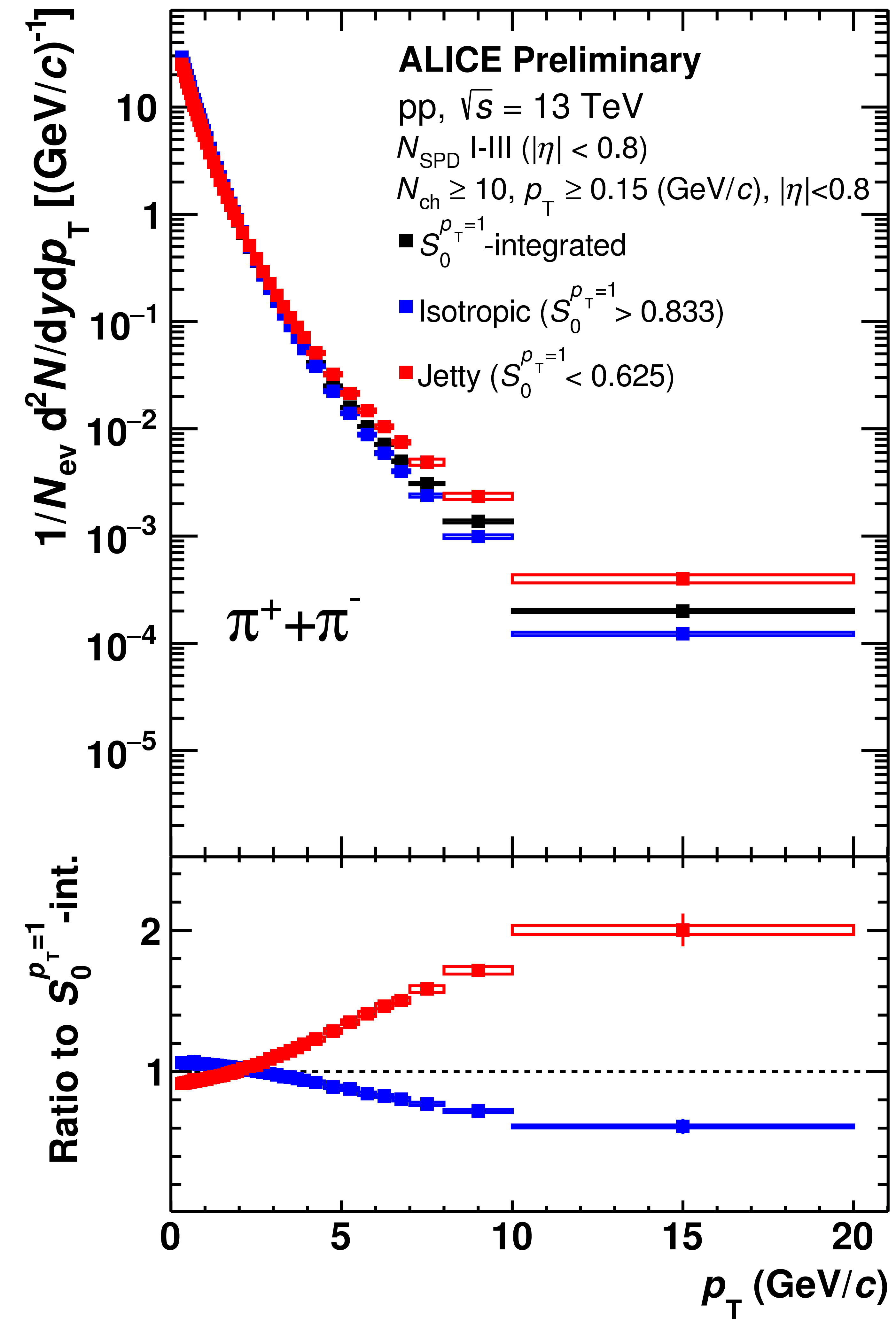
  The ratio of the $S_0^{p_T=1}$-integrated spectra, to the isotropic and jetty events spectra have distinct crossing points at low-p_T for pions, kaons and protons

- The ratios for Ξ look flatter wrt other identified particles (but notice the different p_T range!) and no crossing points are observed in the measured momentum range.

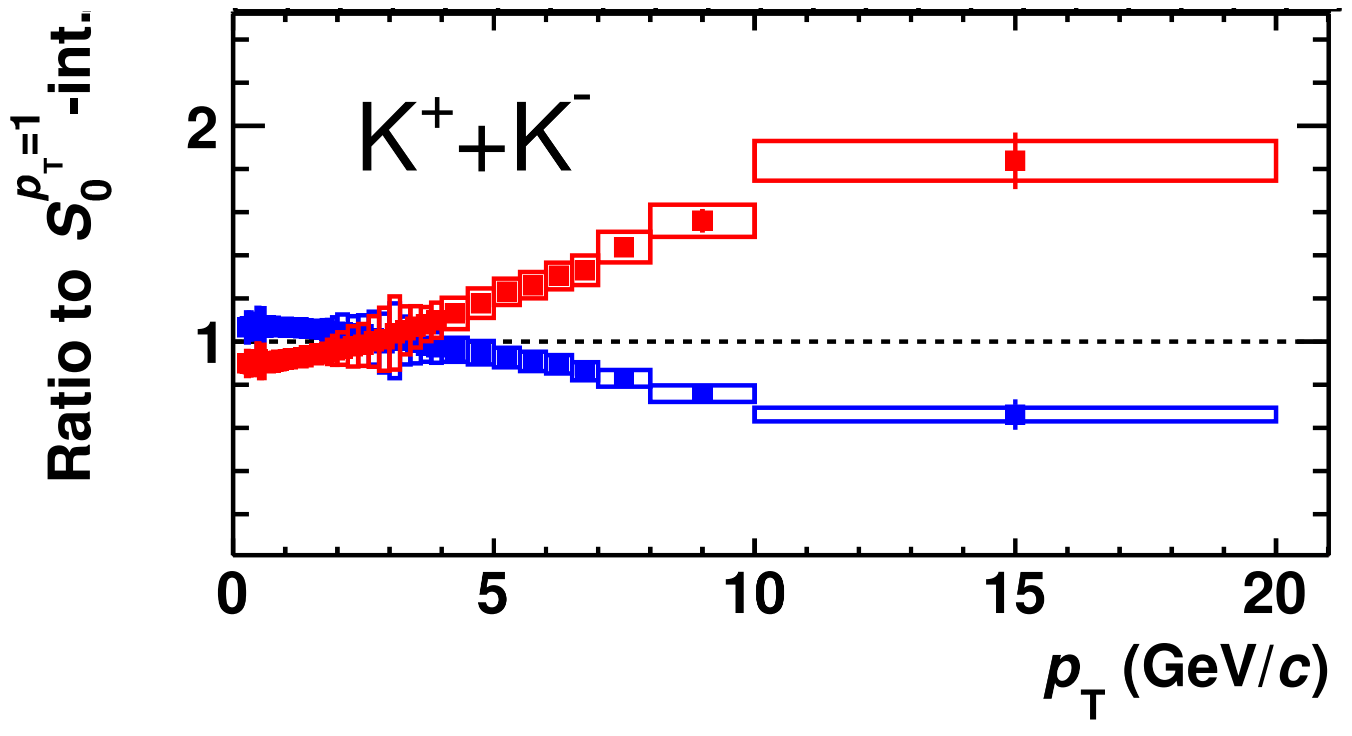


Identified particle production as a function of spherocity

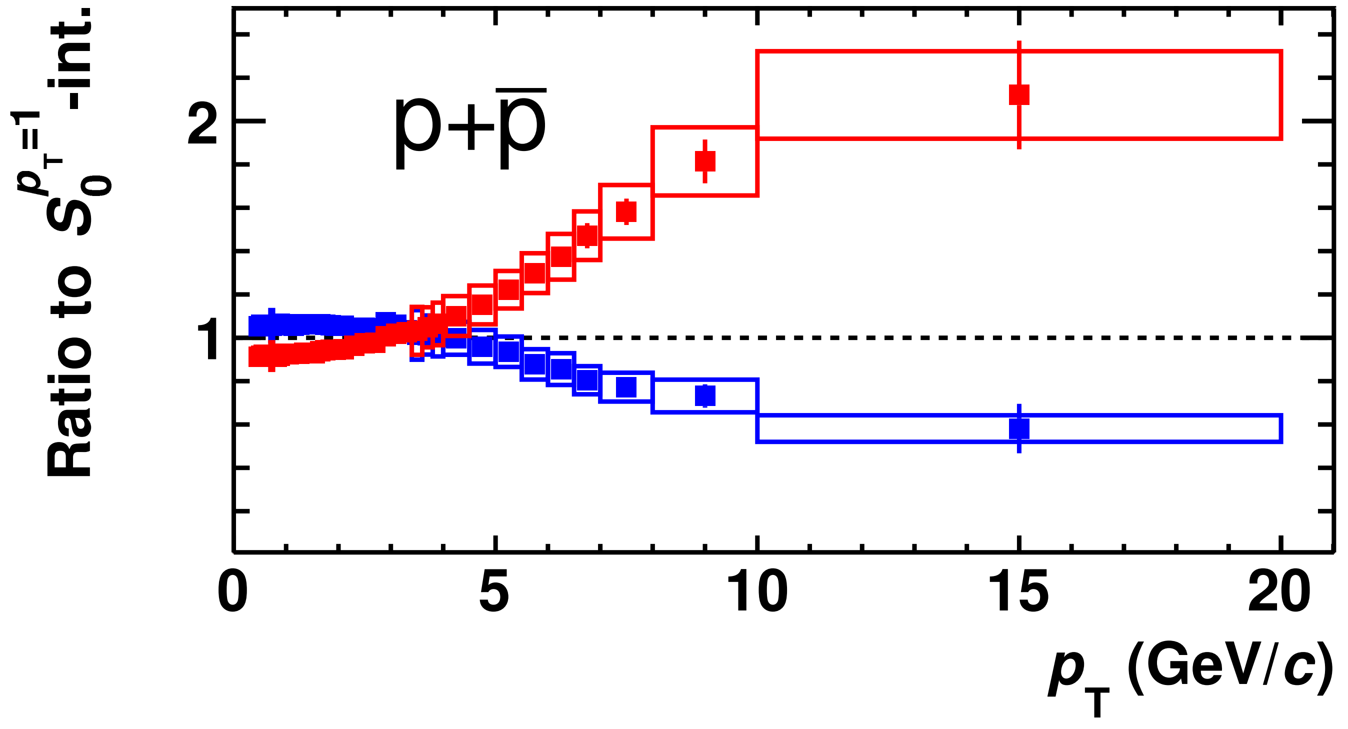
NSPD mid-rapidity estimator



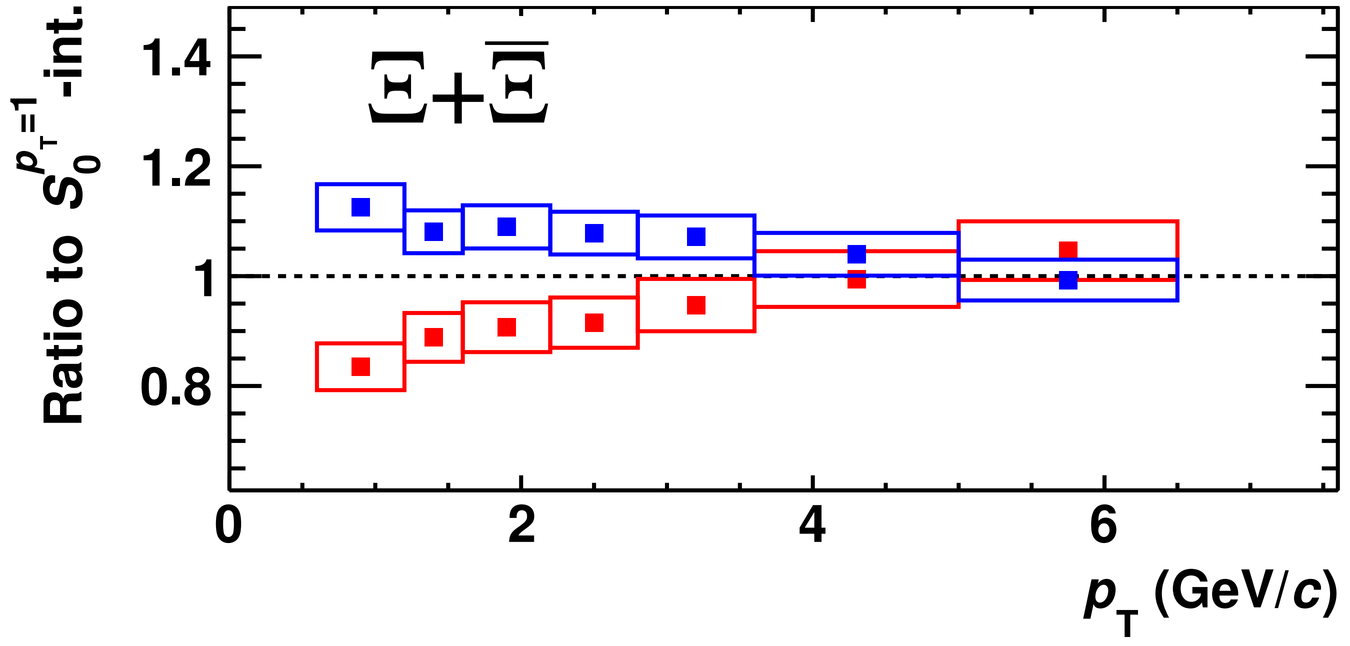
ALI-PREL-334909



ALI-PREL-334914



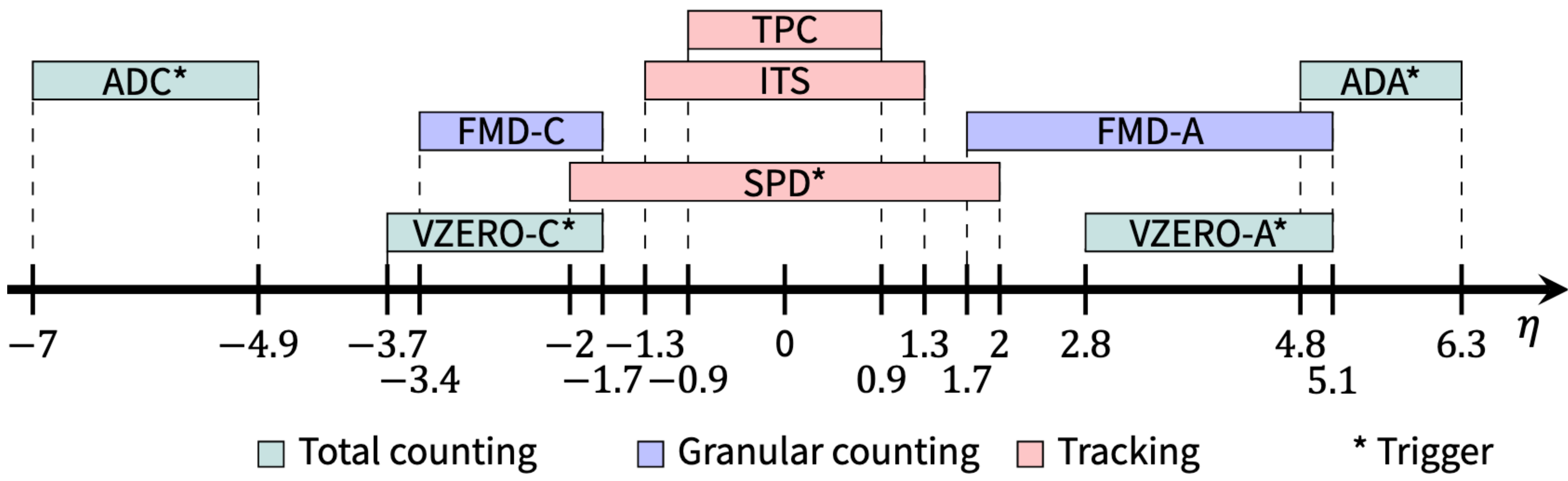
ALI-PREL-334919



ALI-PREL-335104

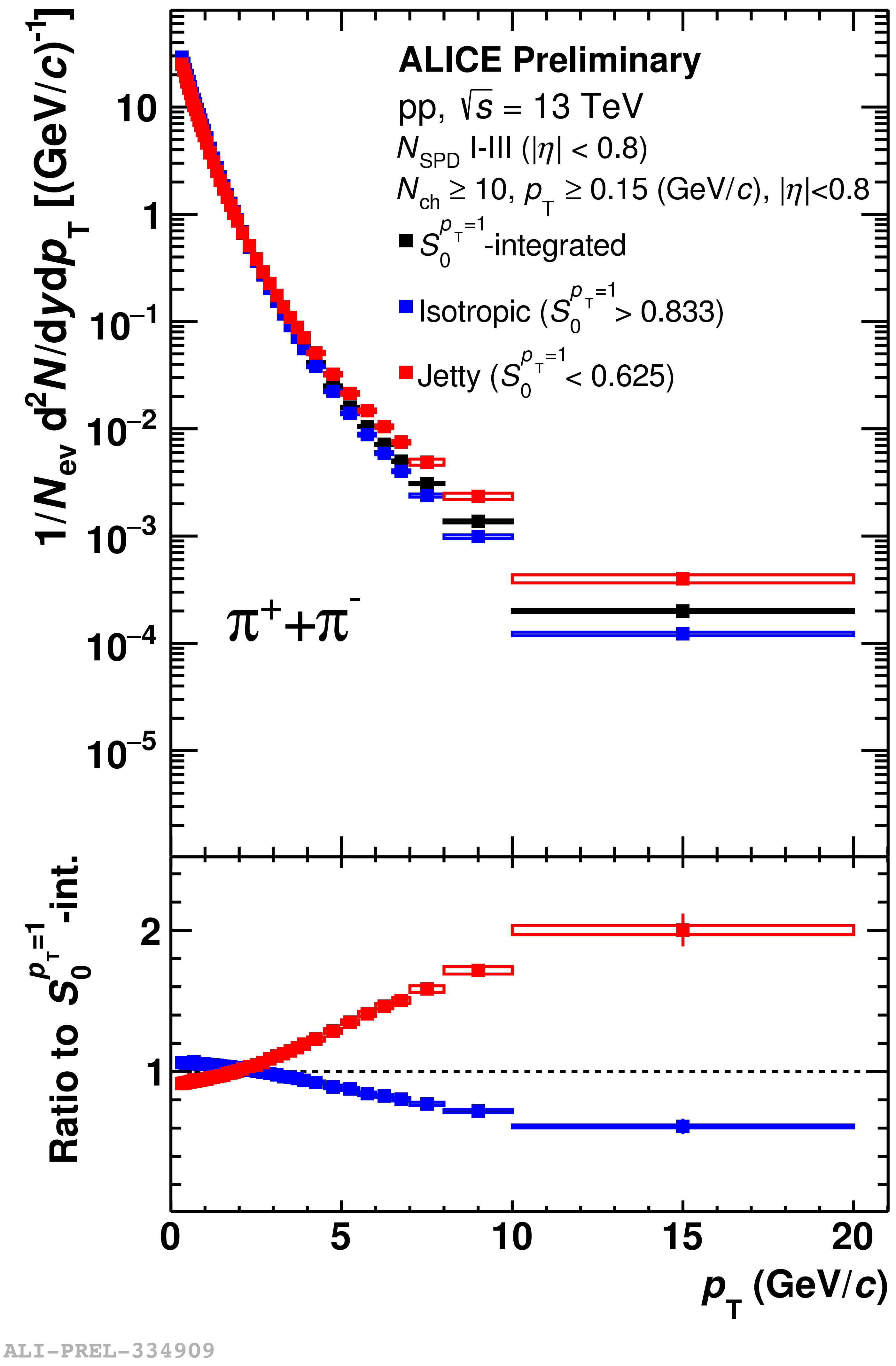
- For pions, kaons and protons, the particle production from jetty events dominates from a lower-p_T bin when compared to the V0M estimator

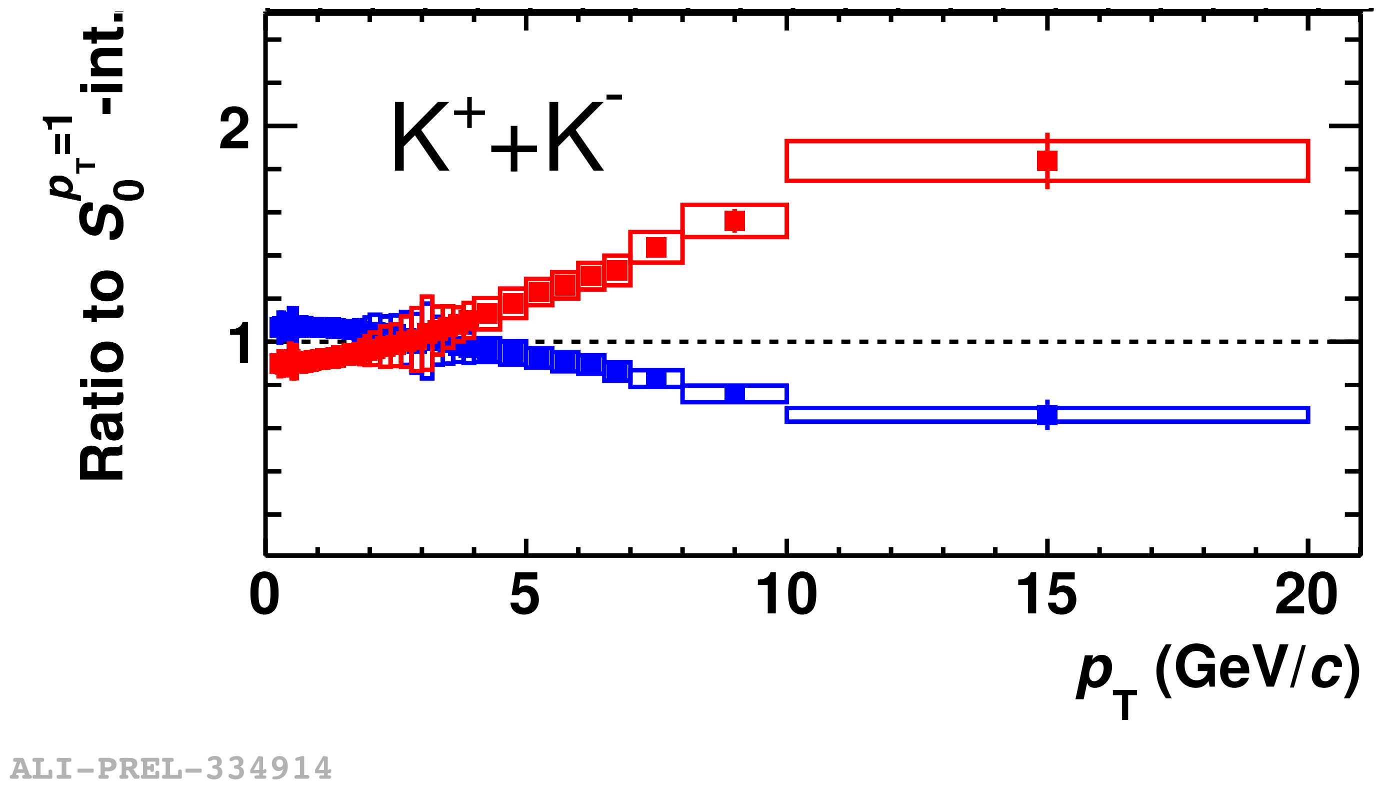
- The ratios for Ξ converge towards unity beyond p_T ~3 GeV/c

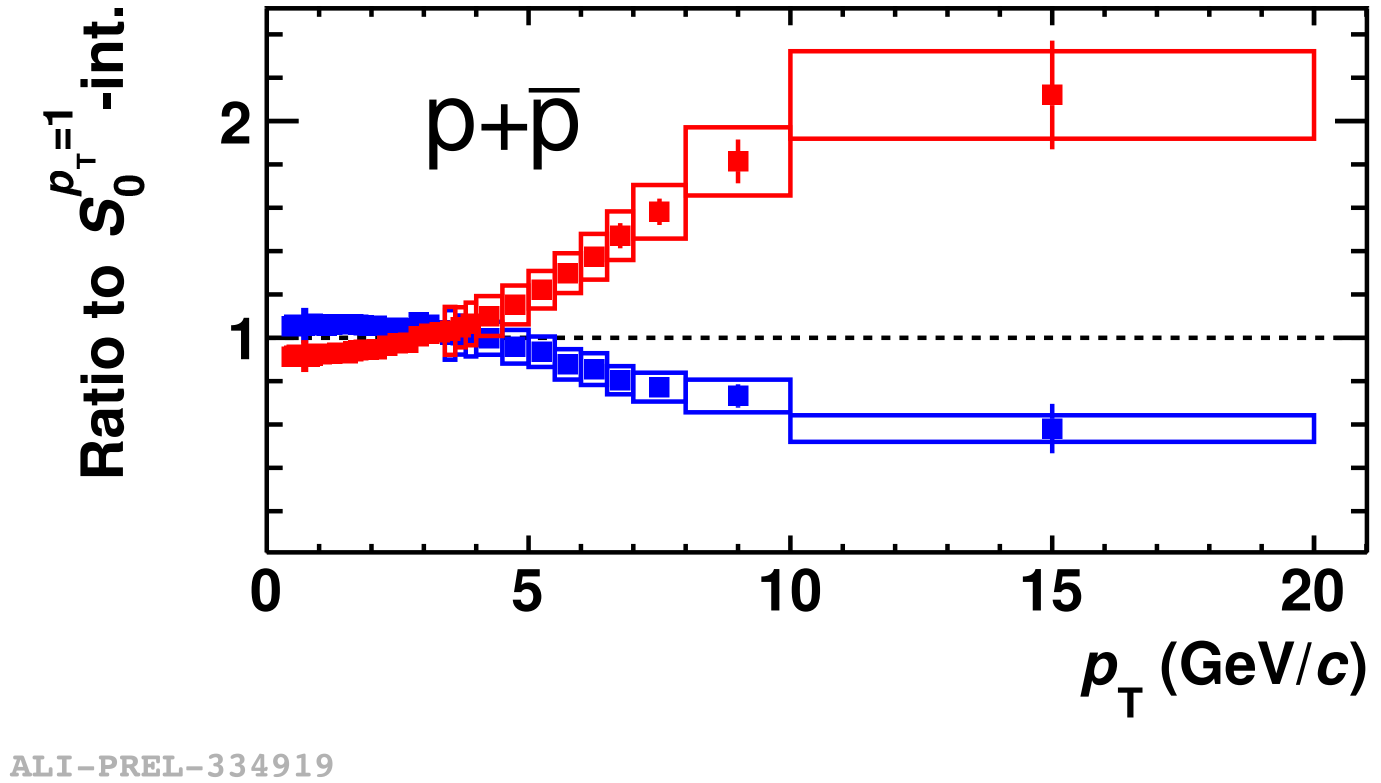


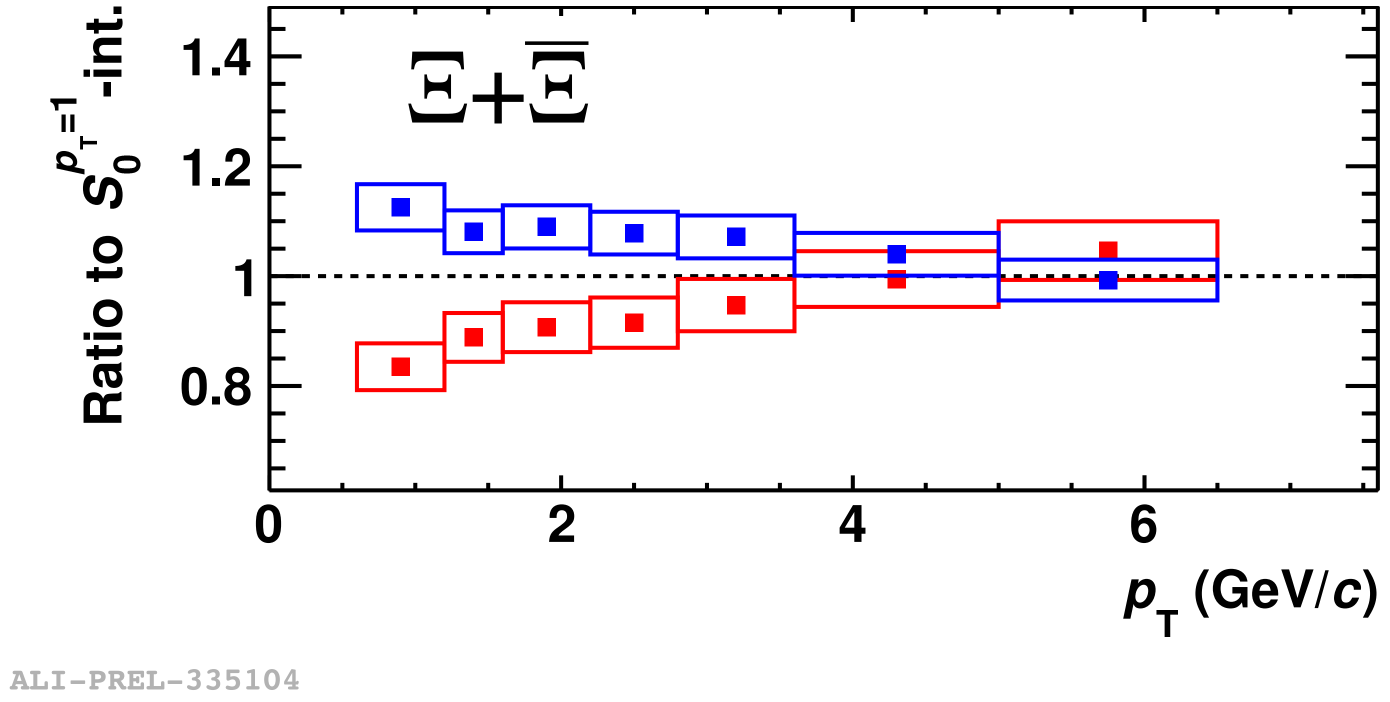
Identified particle production as a function of spherocity

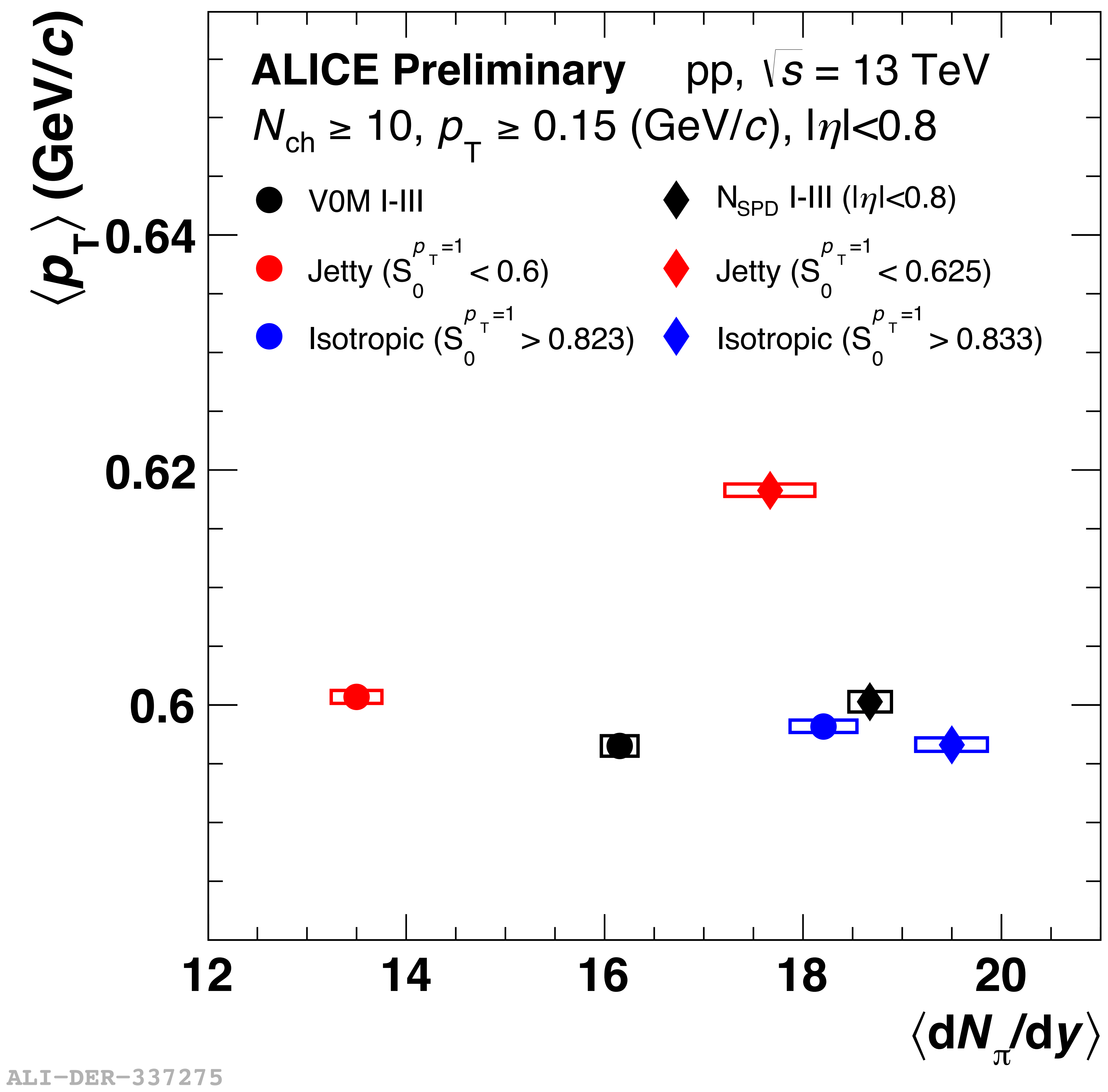
NSPD mid-rapidity estimator





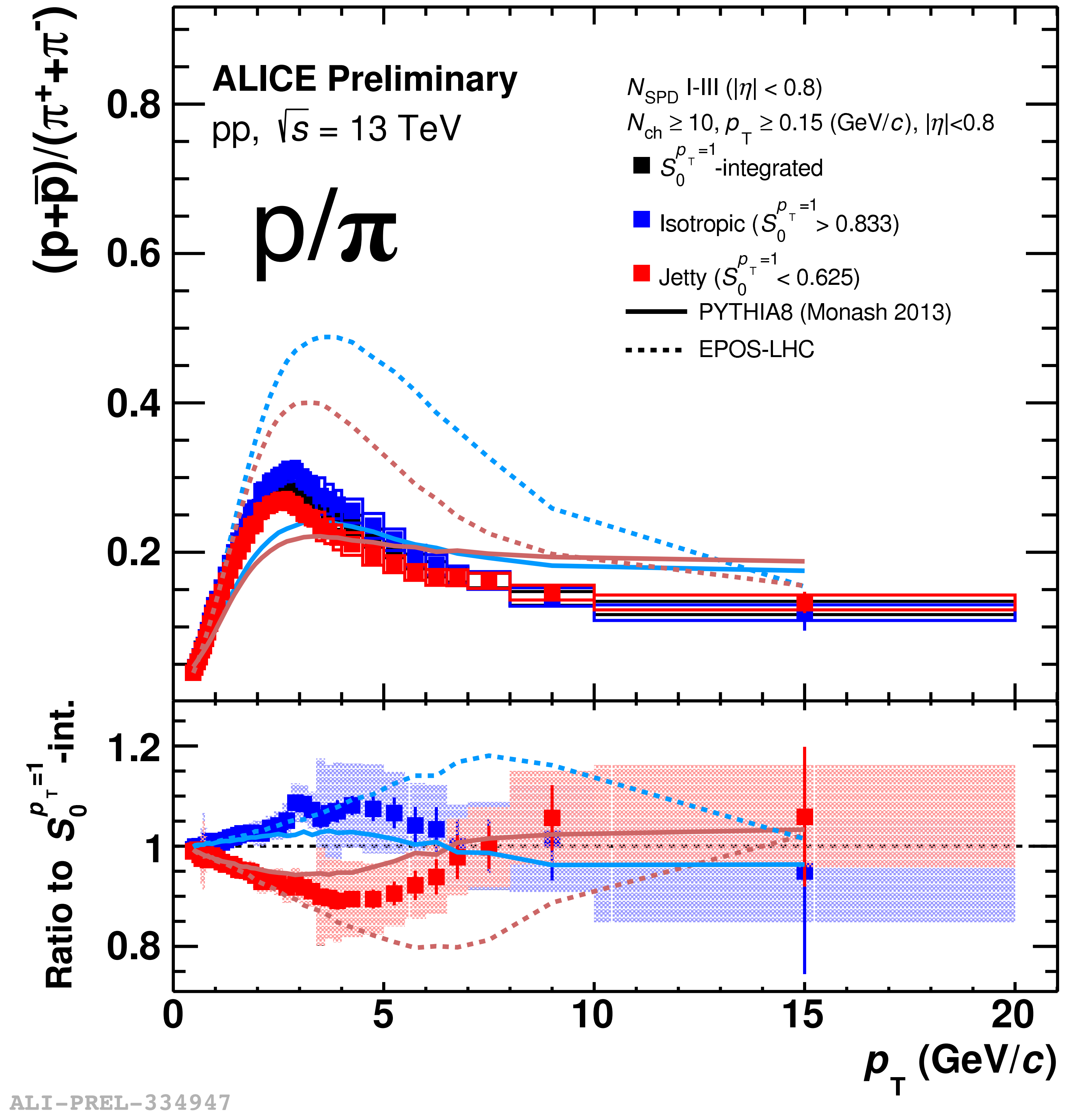






NSPD-triggered events disentangle soft and hard events more accurately in small multiplicity gap.

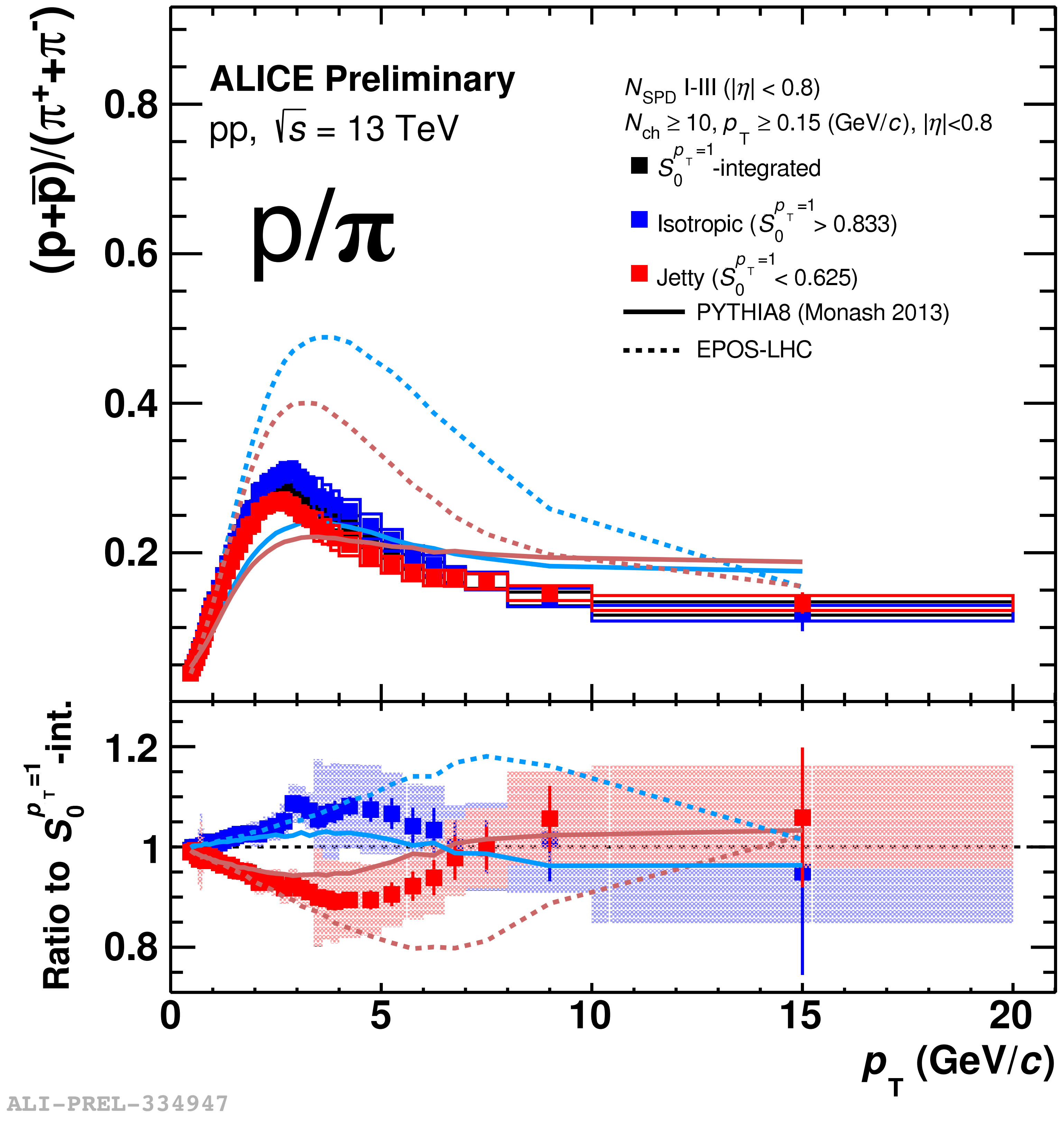
Identified particle production as a function of spherocity

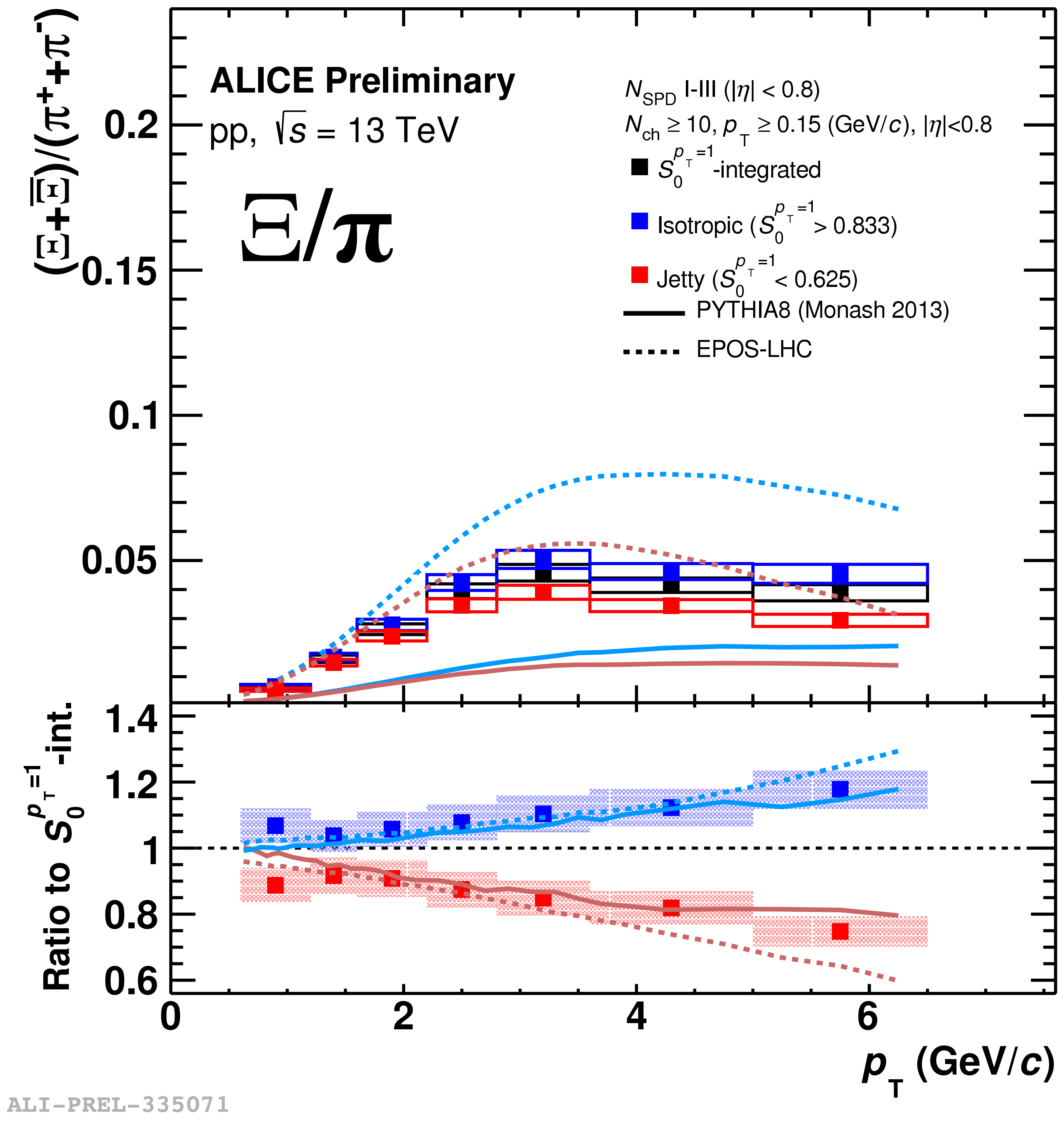


- p/π ratio enhanced at intermediate p_T in isotropic events, reminiscent of similar effect in Pb-Pb collisions

N_{SPD} (CL1) mid-rapidity estimator

Identified particle production as a function of spherocity





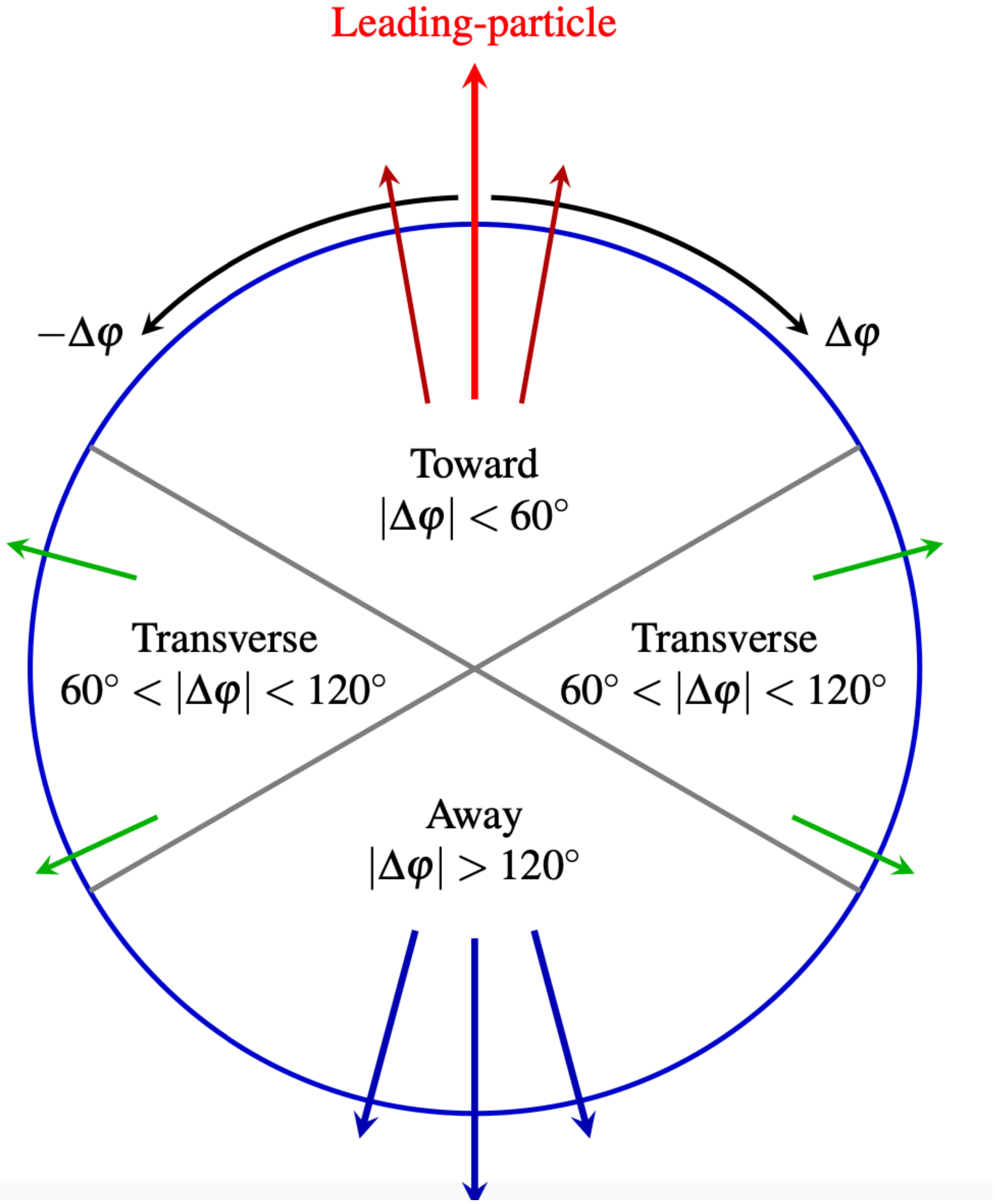
- p/π ratio enhanced at intermediate p_T in isotropic events, reminiscent of similar effect in Pb-Pb collisions
- In the measured p_T interval Ξ/π ratio suggests that strange particle production is higher in isotropic than in jetty events

N_{SPD} (CL1) mid-rapidity estimator

Relative transverse activity classifier, R_T

Relative transverse activity classifier, $R_T = N_{ch}^{Transverse} / \langle N_{ch}^{Transverse} \rangle$

(Introduced in P. Skands et. al., Eur. Phys. J. C **76,** 299 (2016))



ALICE, JHEP04 (2020) 192

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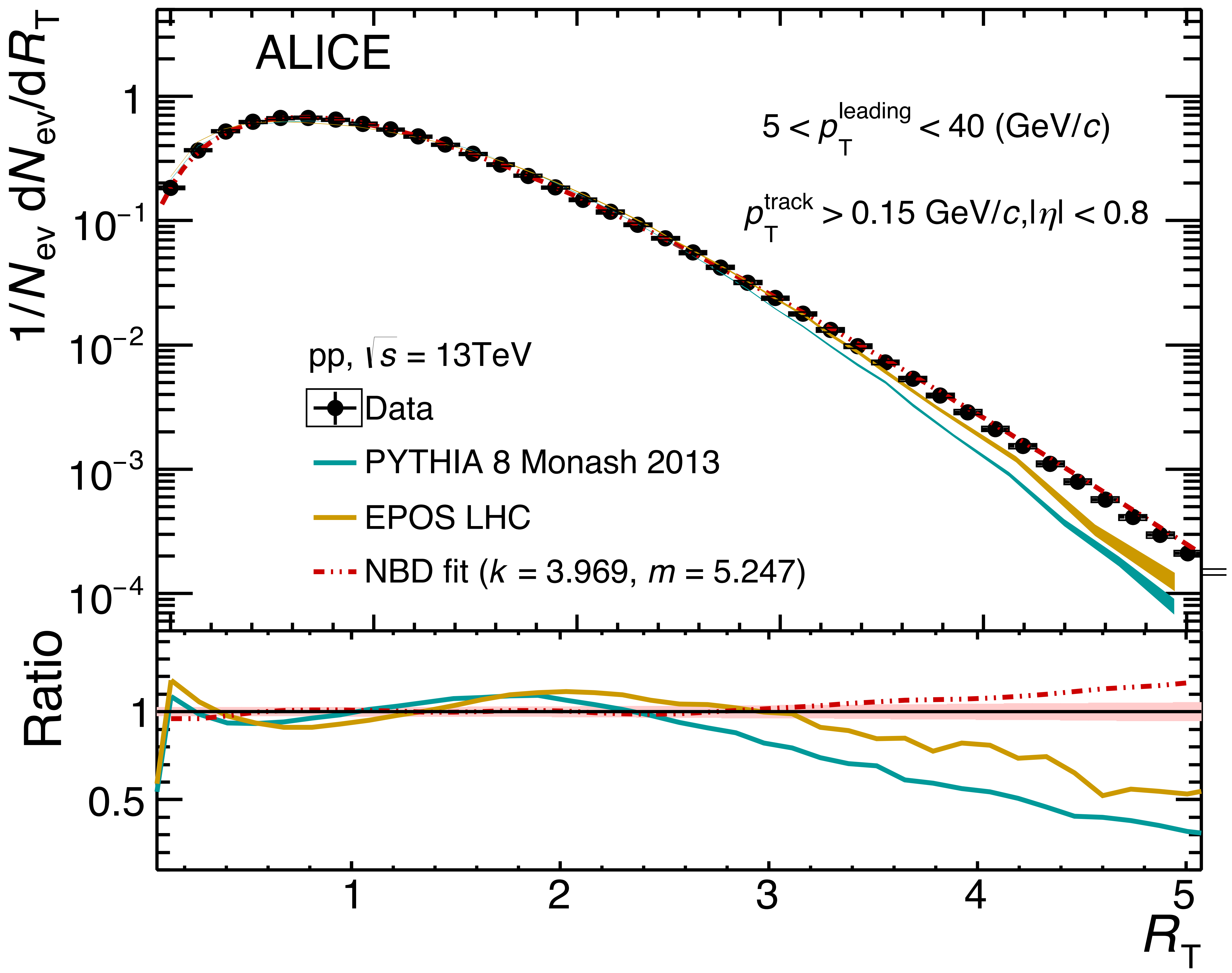
(Introduced in P. Skands et. al., Eur. Phys. J. C **76,** 299 (2016))

- Using R_T, one can vary the magnitude of the underlying event (UE) and study the particle production



ALICE, JHEP04 (2020) 192

Relative transverse activity classifier, R_T

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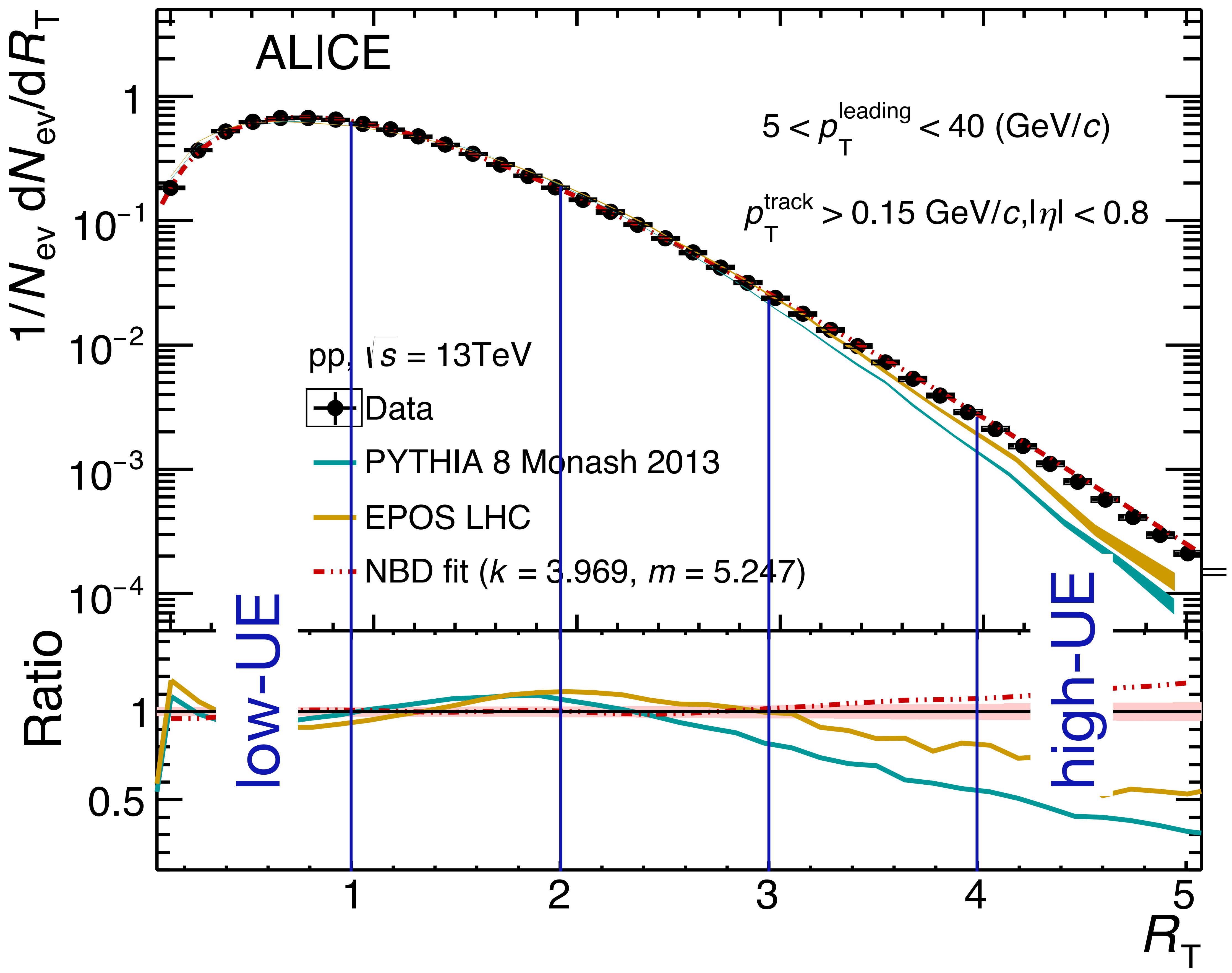
(Introduced in P. Skands et. al., Eur. Phys. J. C **76,** 299 (2016))

- Using R_T, one can vary the magnitude of the underlying event (UE) and study the particle production
- $R_T \rightarrow 0$: Events with less UE (dominated by jets)
- Higher R_T → Higher UE contribution



ALICE, JHEP04 (2020) 192

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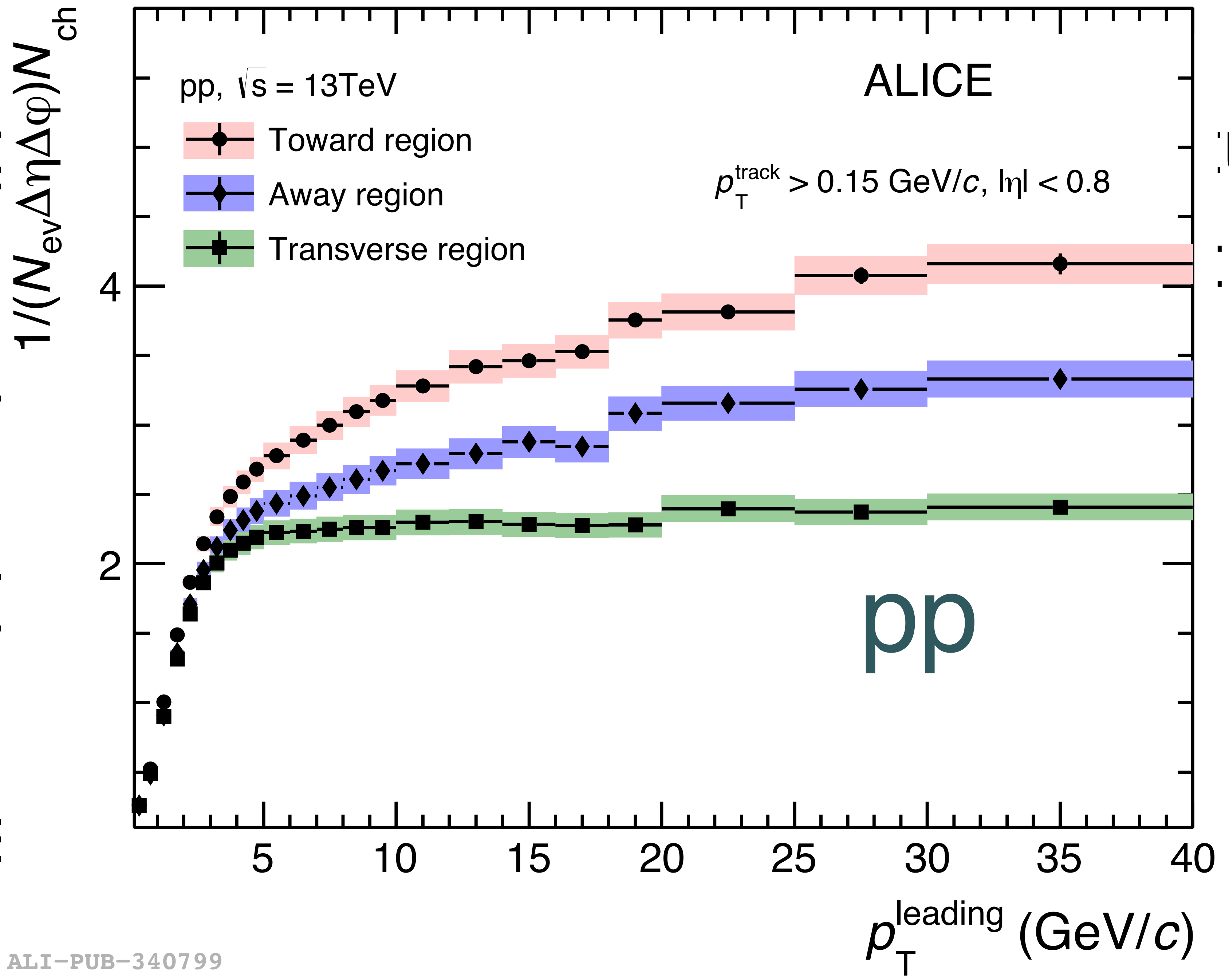
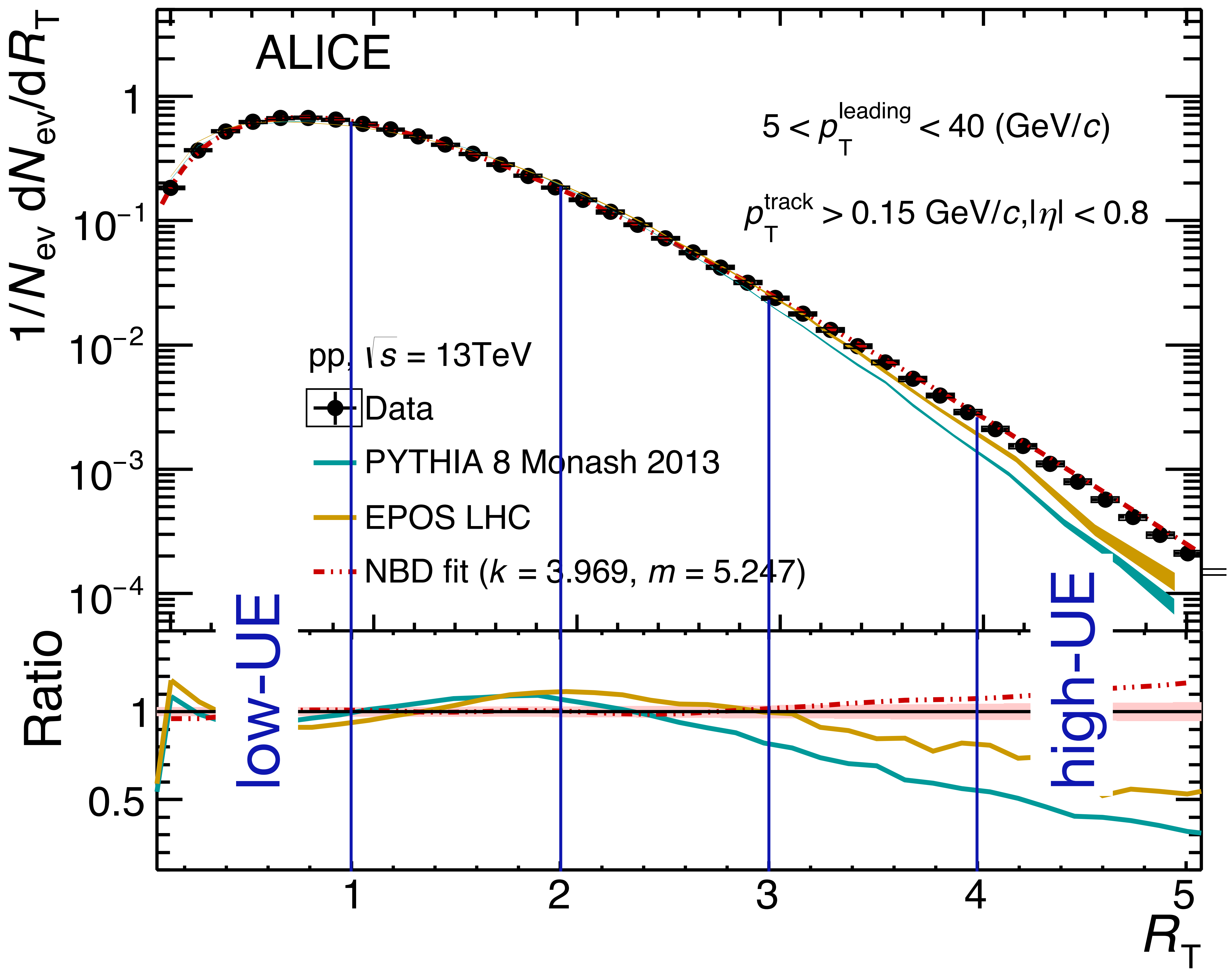
- Using ... ude of the unde ... he particle produ



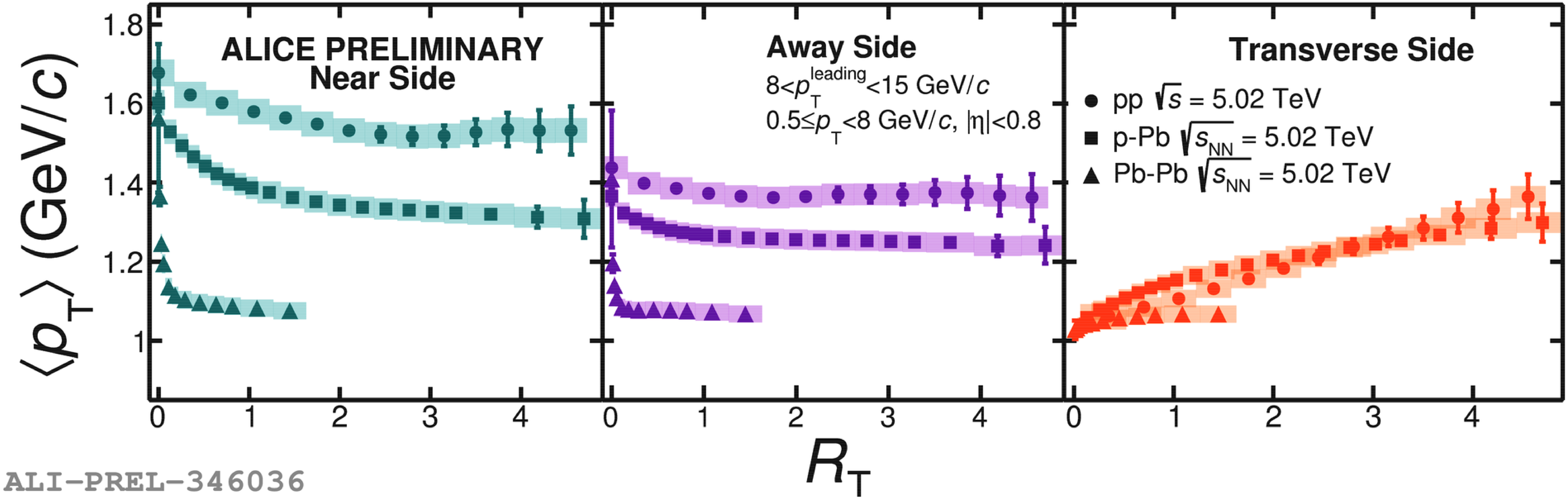
- $R_T \rightarrow$ (... by jets)
- Highe
- A p_T cut for the leading particle is required to ensure a hard process: $p_T^{leading} > 5$ GeV/c, where the charged particle density in transverse region remains nearly constant



ALICE, JHEP04 (2020) 192

Charged particle production vs. R_T

Relative Transverse activity classifier, $R_T = N_{ch}^{Transverse} / \langle N_{ch}^{Transverse} \rangle$



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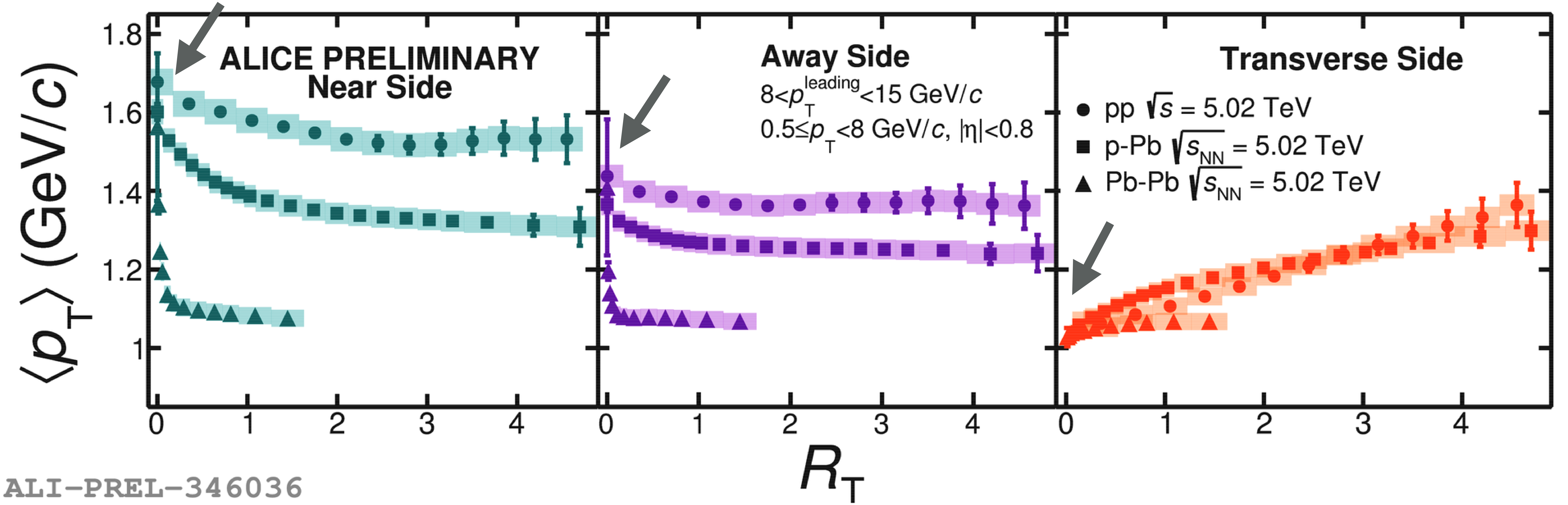

- The contribution from the jets dominate at low R_T and the values are similar for all systems, as one would naively expect for $R_T \rightarrow 0$

Charged particle production vs. R_T

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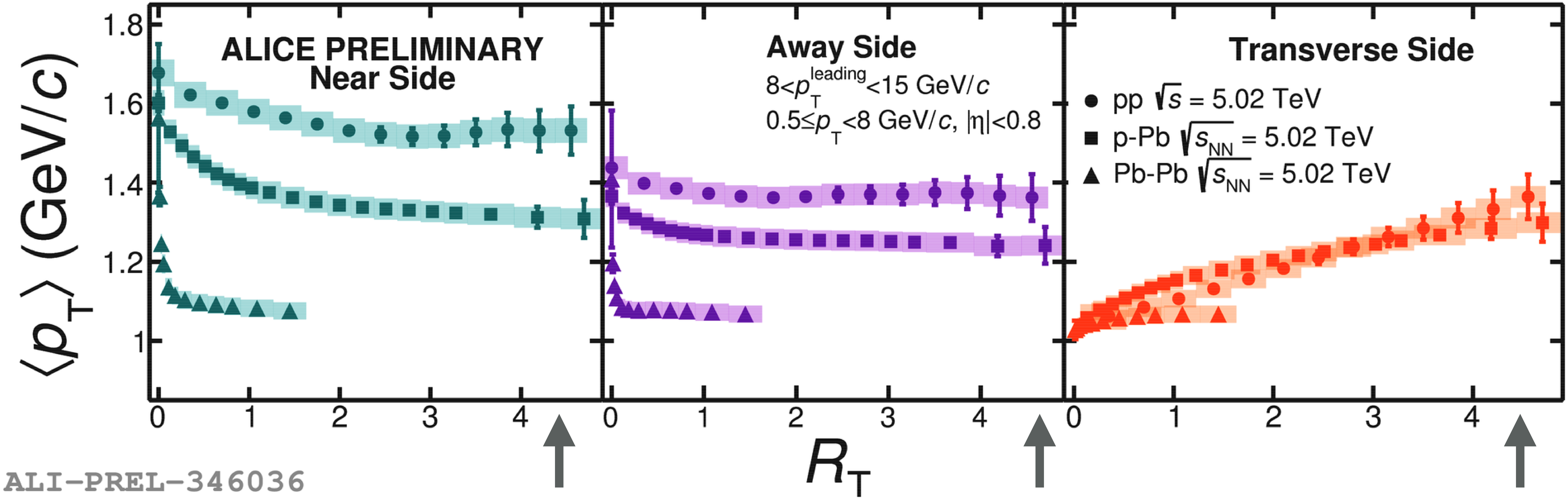
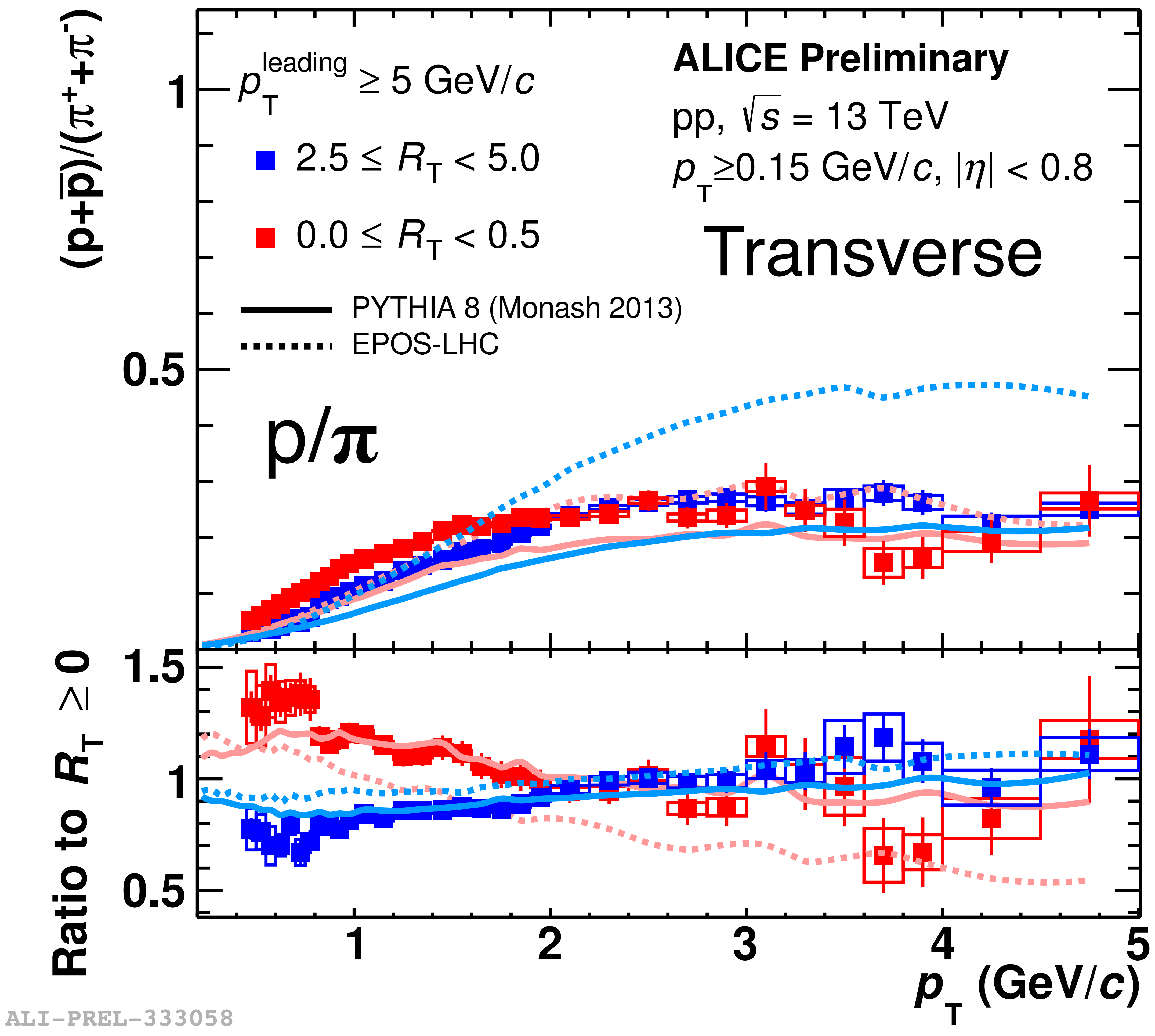


- For large R_T, the $\langle p_T \rangle$ approaches similar values in all three topological regions for a given system: dominant UE contribution

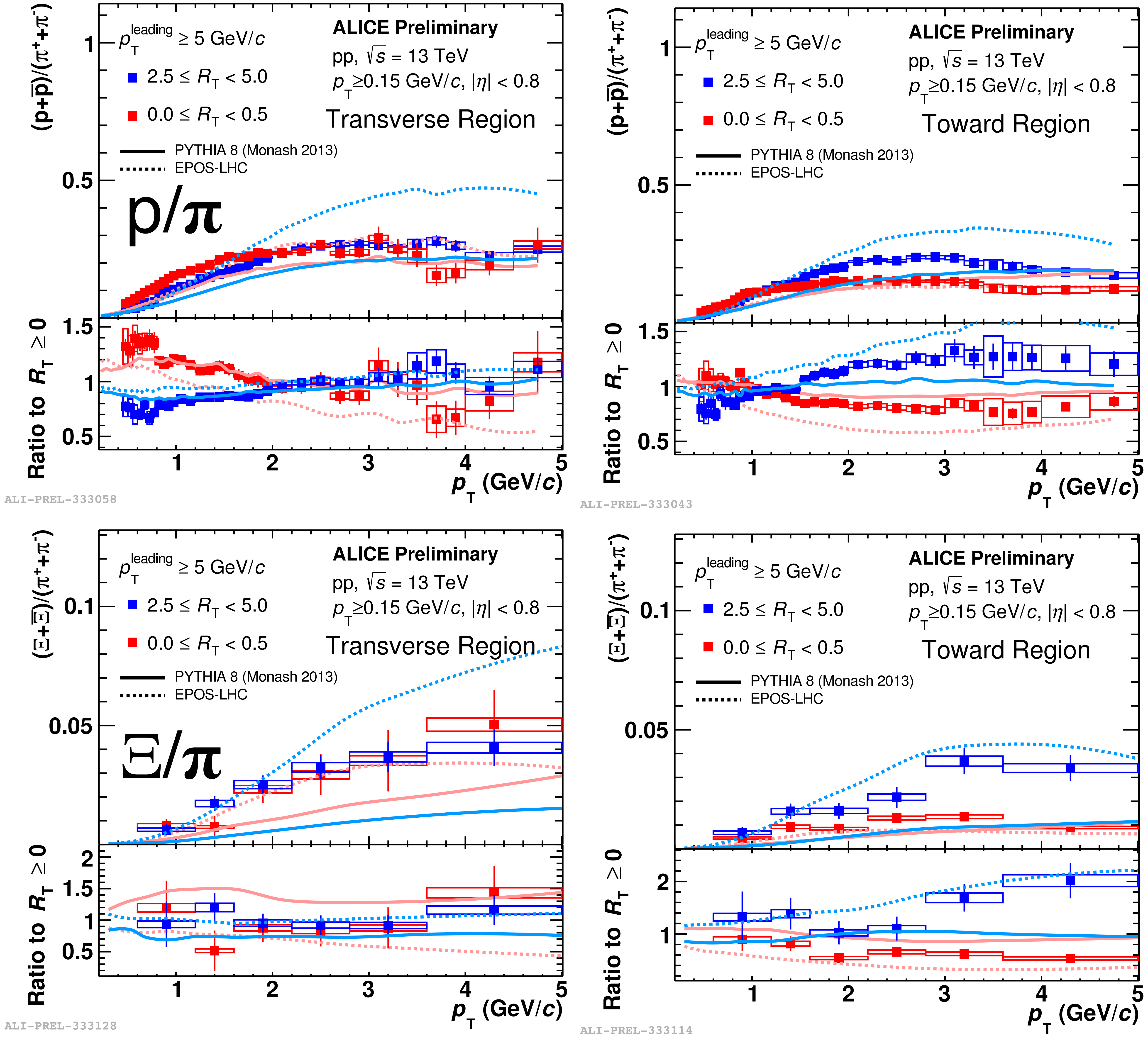
Identified particle production vs. R_T



- p/π ratio:
  - Radial flow-like features
  - Model predictions do not describe particle ratios quantitatively

Identified particle production vs. R_T

Transverse | Toward

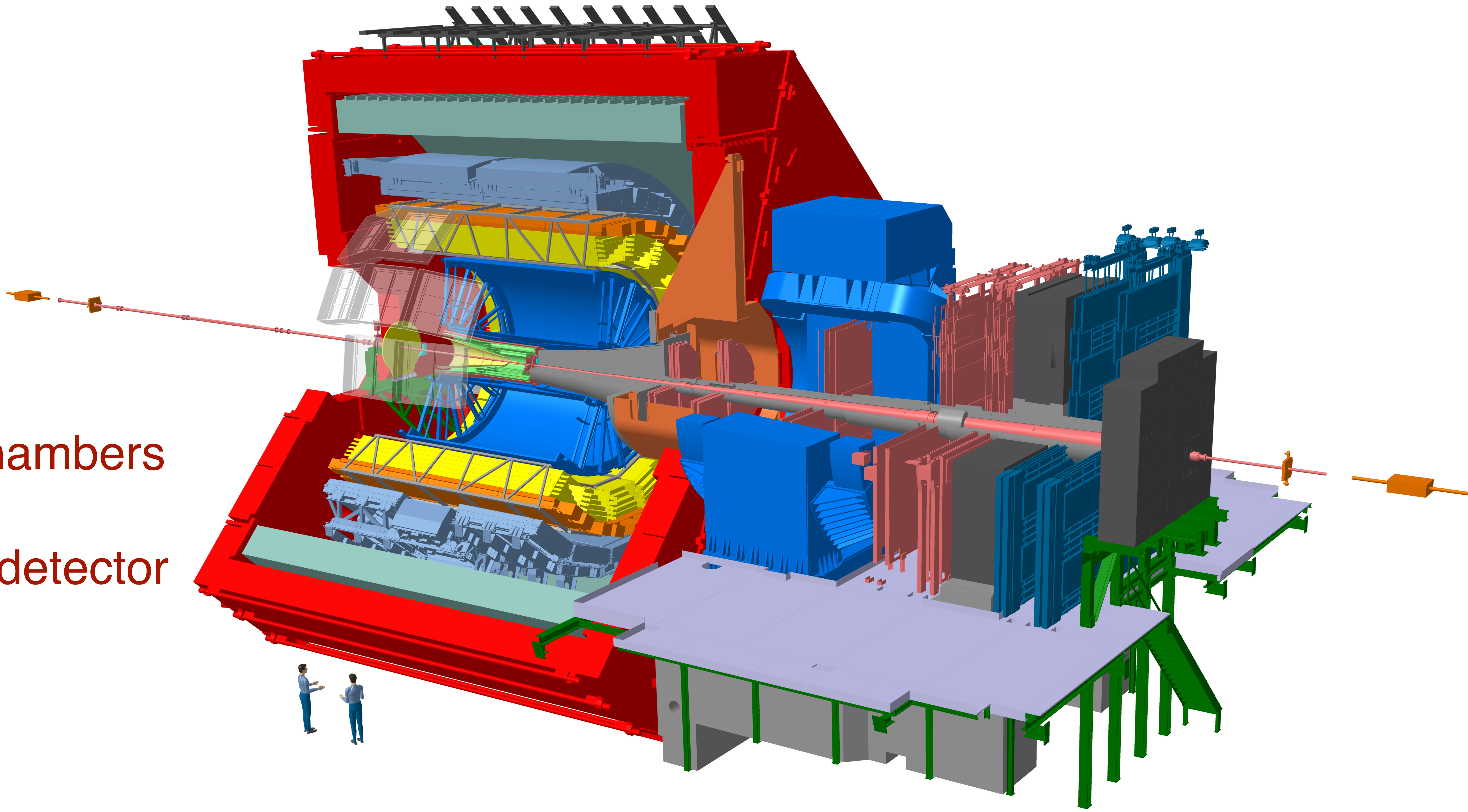


- p/π ratio:
  - Radial flow-like features in both regions.
  - Model predictions do not describe particle ratios quantitatively
- Ξ/π ratio:
  - show a similar trend to the p/π ratio.
  - high-R_T toward-region approaches the results in transverse-region.

The results indicate the interplay between UE and jet-like components

ALICE upgrades for LHC Run 3 (2022-2024)

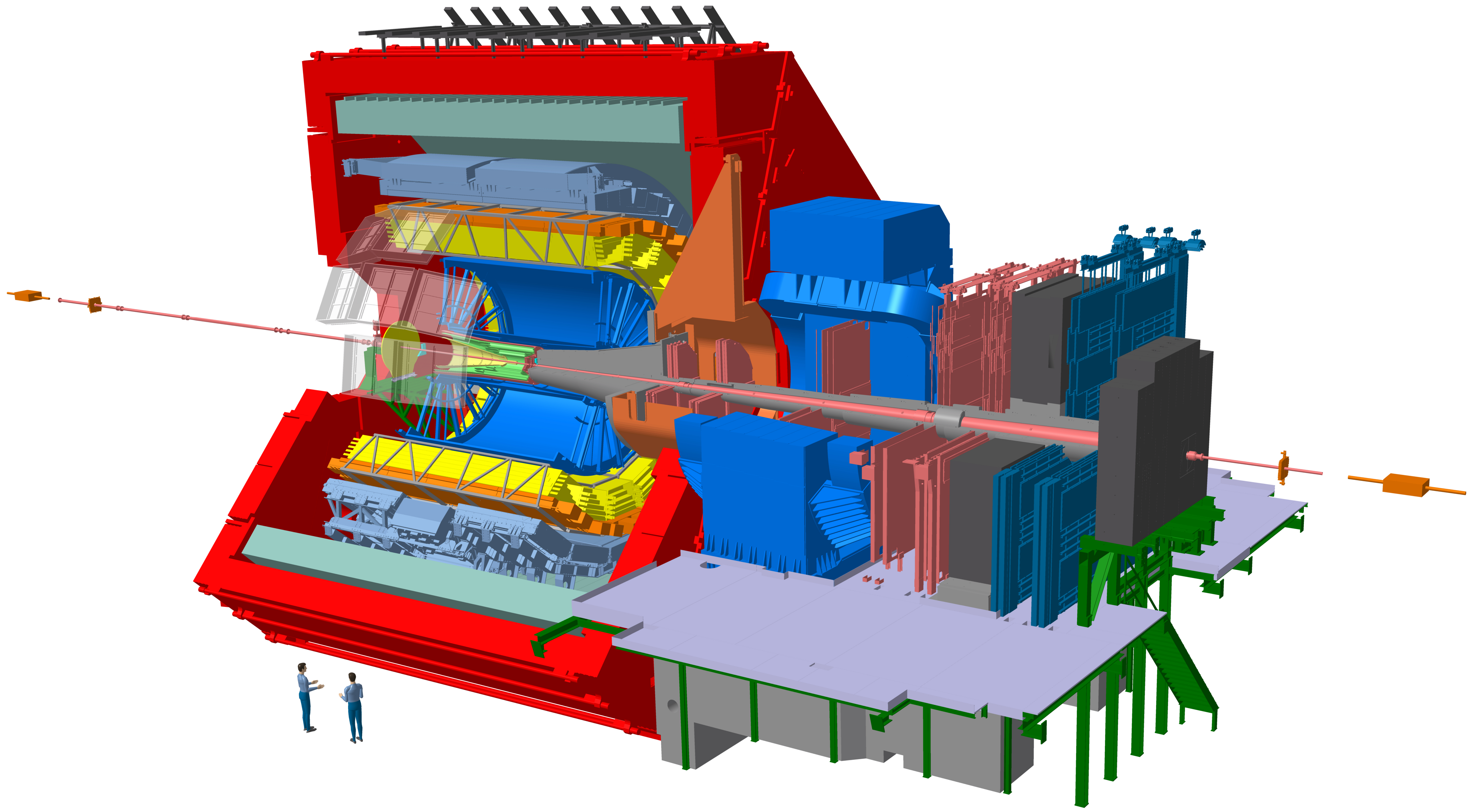
- New silicon trackers
  - ITS2:
    - Innermost layer closer to IP
    - Reduced material thickness
  - MFT (muon forward tracker):
    - Improved muon tracking
- New TPC GEM based readout chambers
- New fast interaction trigger (FIT) detector
- New readout for all the detectors
- New online-offline system (O^2)

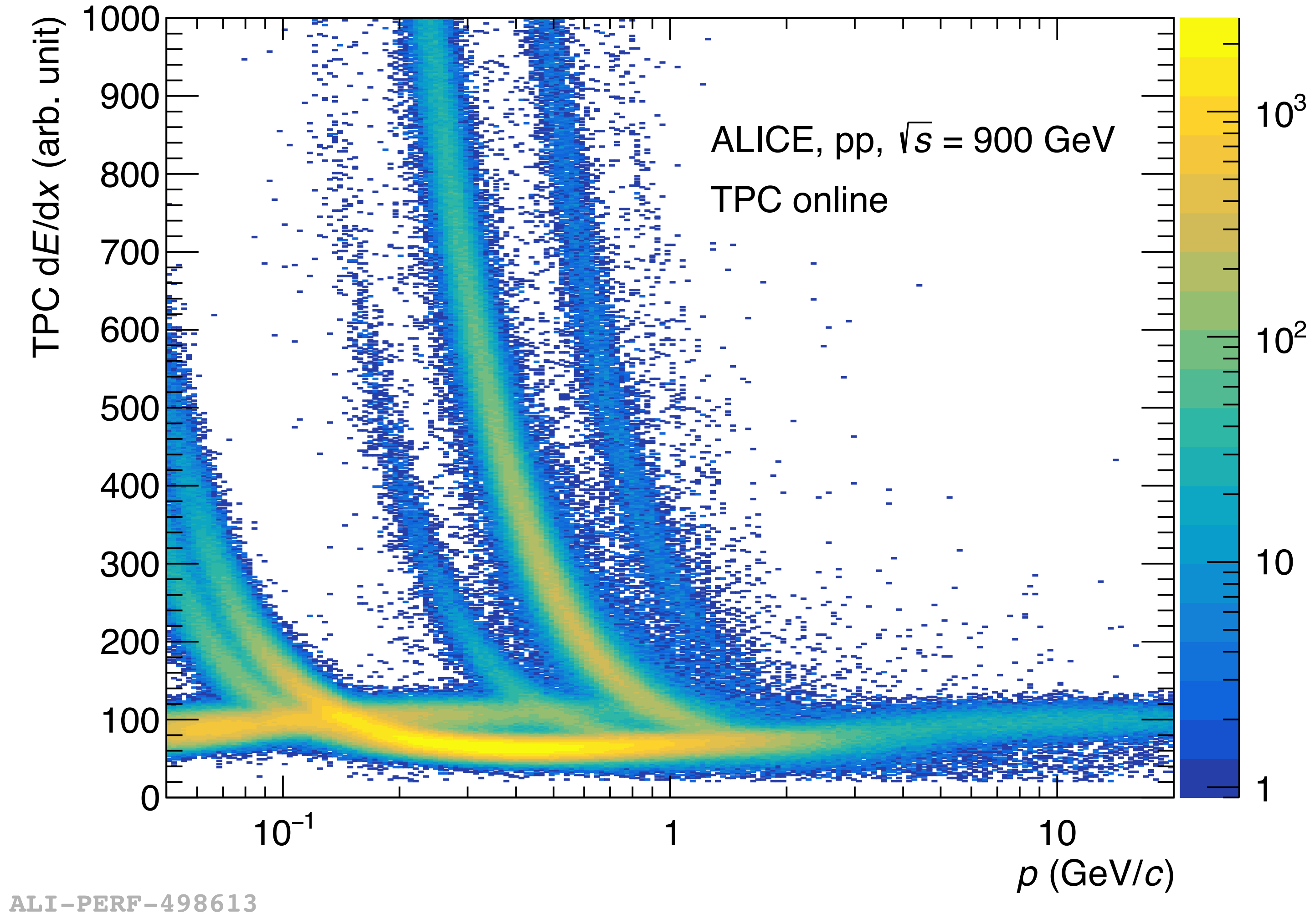


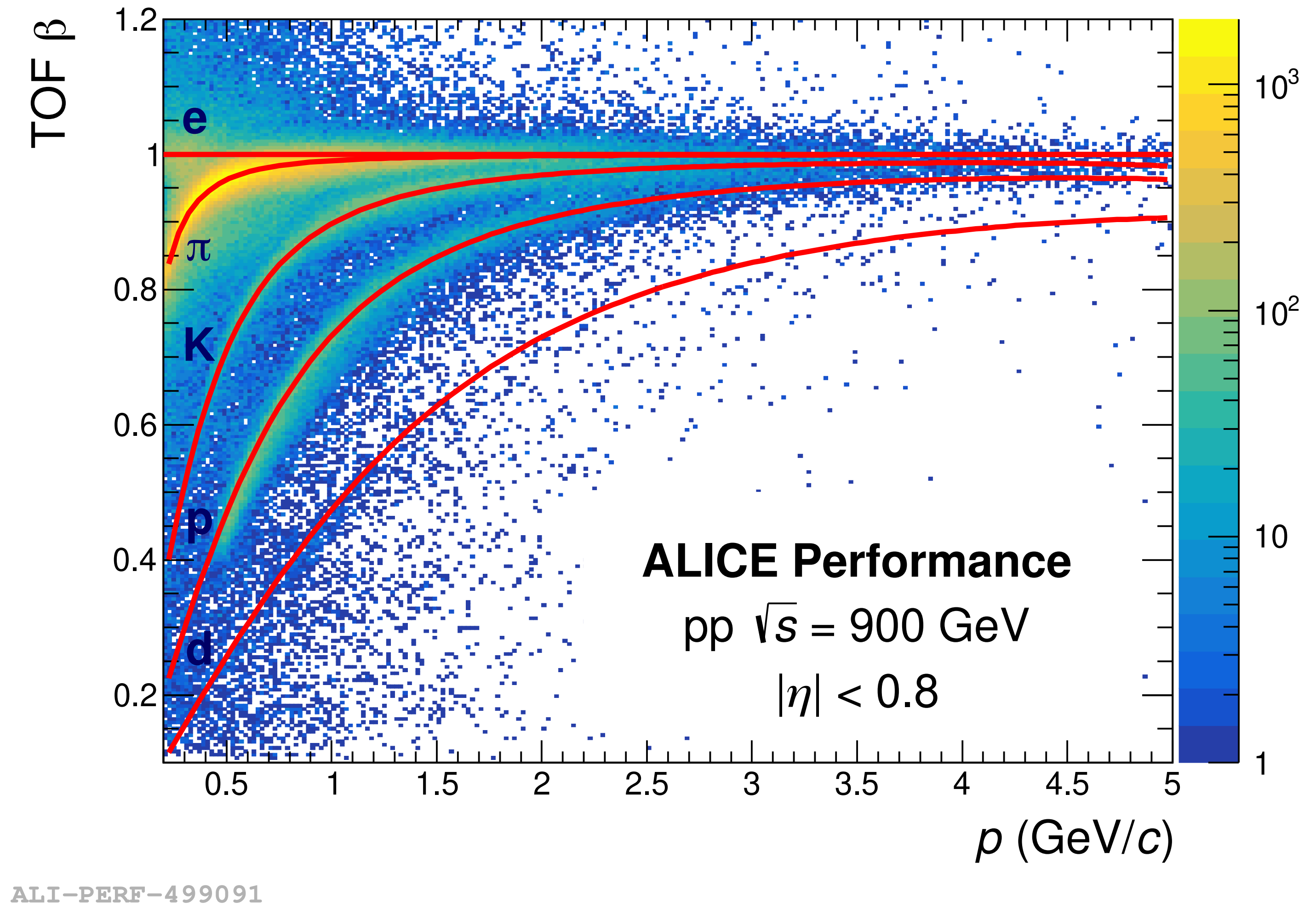
ALICE upgrades for LHC Run 3 (2022-2024)

Largest pixel detector ever built…

CERNCourier, Jul-Aug, 2021







TPC and TOF performance from pp, √s = 900 GeV pilot beam in October, 2021

Pilot beam 2021 pseudorapidity density measurement

- Results obtained with ITS2 are consistent with previous ALICE published results
- This performance provides a benchmark for the tracking and reconstruction, as well as for the new analysis framework

Summary and outlook

- A comprehensive set of measurements on global observables is available from ALICE Collaboration
- An enormous amount of data on pp, pA and AA collisions has been recorded and can be used to compare strong-interacting systems of different sizes
- Strangeness enhancement and collective-like effects are seen for high multiplicity pp and p—Pb which are reminiscent of effects observed in heavy-ion collisions —> Small collision systems: much more than just a reference!
- Resonances are instrumental in probing the hadronic phase lifetime
- Multi-differential studies with event shape observables help to distinguish soft and hard events
- Stay tuned for many new and high-precision results from ALICE as Run 3 of the LHC is currently ongoing

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Thank you very much for your attention!

Back-up