Particle production in small systems using event shapes with ALICE

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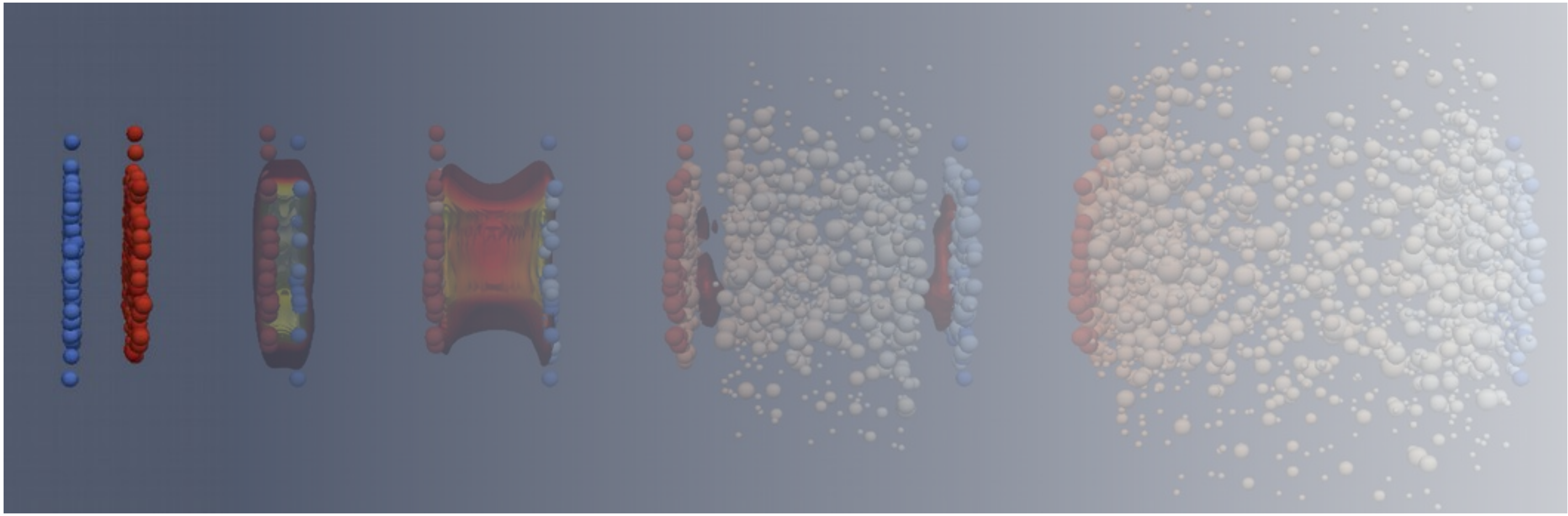
ALICE

U.S. DEPARTMENT OF ENERGY

The ALICE's experiment aim



Ultrarelativistic AA collisions allow studying QCD matter under extremely hot and dense conditions.

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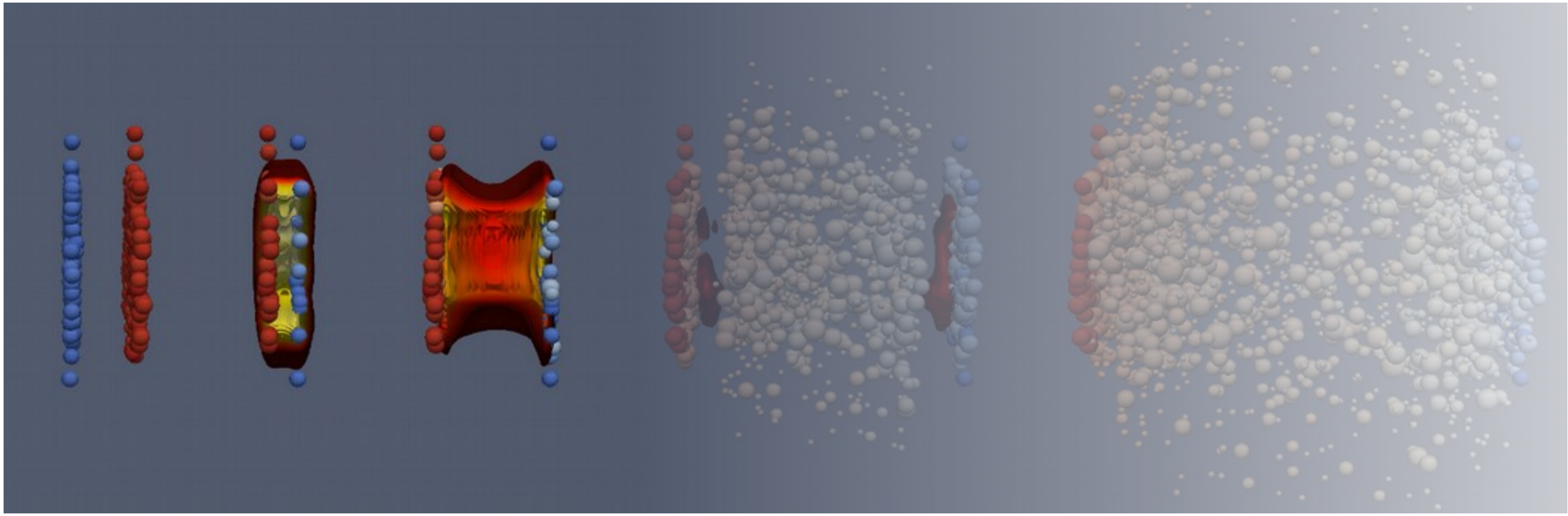

Ultrarelativistic AA collisions allow studying QCD matter under extremely hot and dense conditions.

Ann.Rev.Nucl.Part.Sci. 68 (2018) 339-376

Right after the collision, the energy density is about 12 GeV fm^{-3}.

The quark-gluon plasma (QGP) is formed: quarks and gluons are strongly coupled to one another that they form a collective medium that expands and flows.

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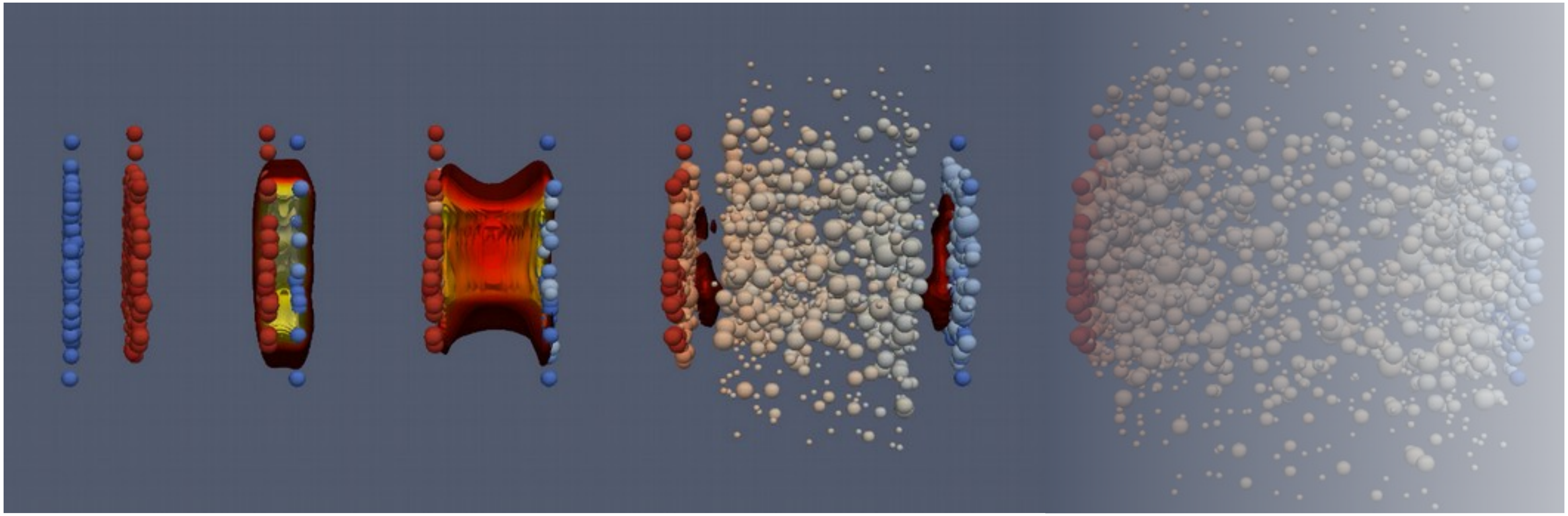

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At $\epsilon \approx 1$ GeV fm^{-3} hadrons are formed.

Chemical freeze-out: hadrons interact inelastically and the yields are fixed.

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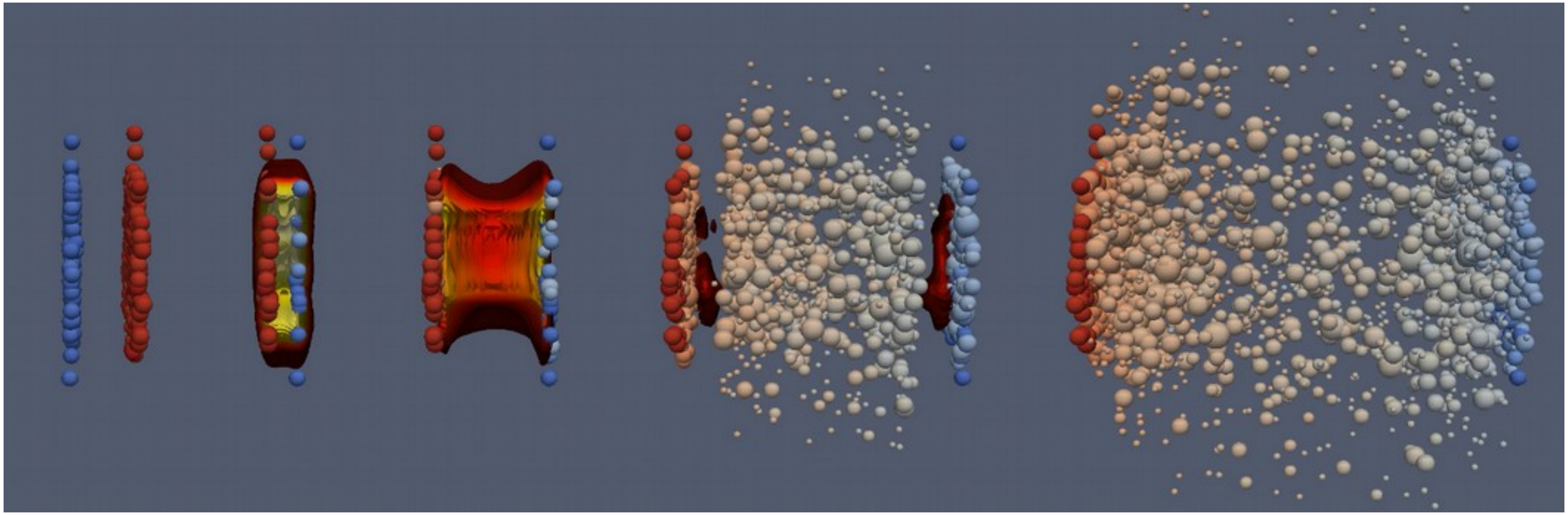

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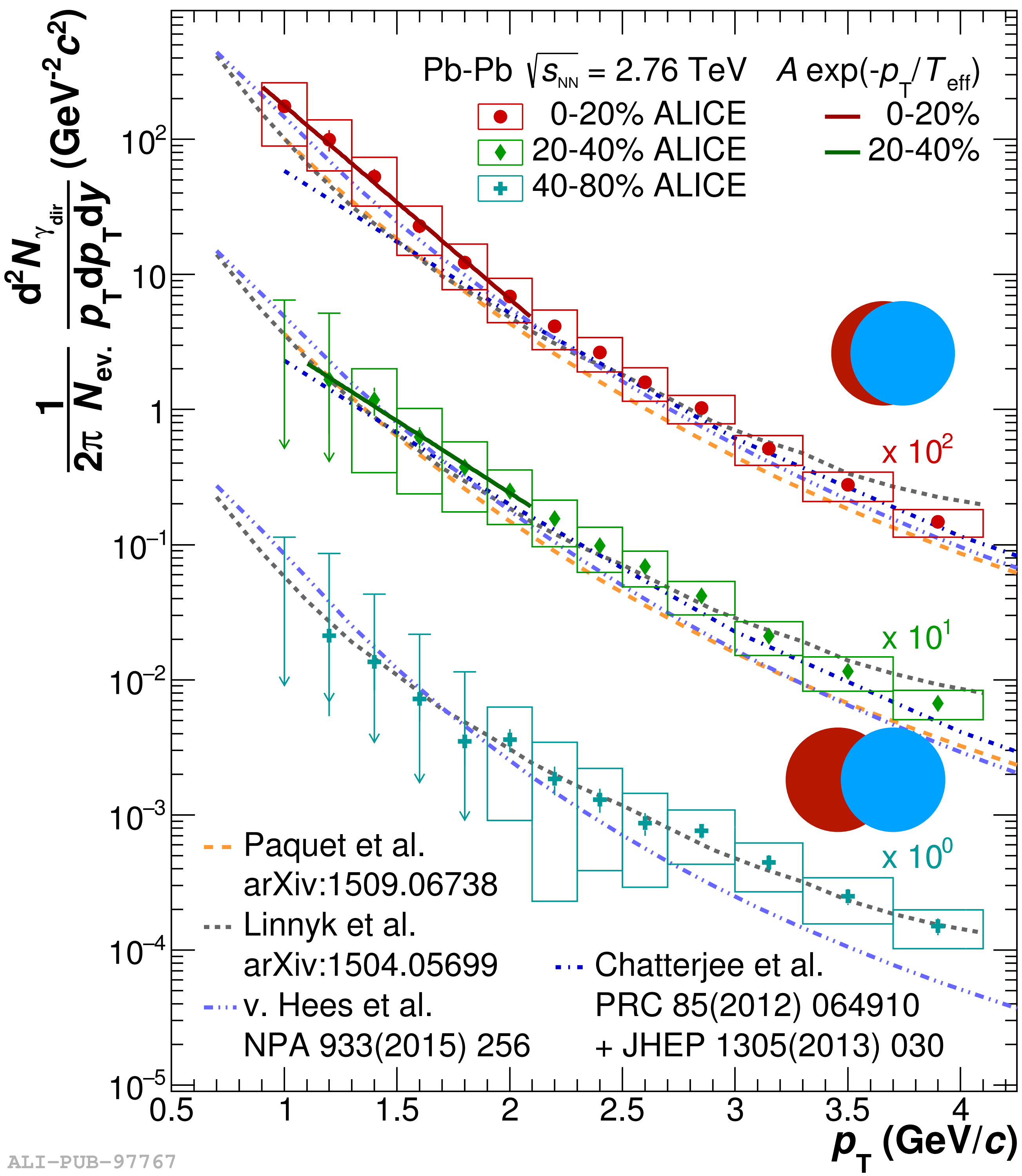
At $\epsilon \approx 1$ GeV fm^{-3} hadrons are formed.

Chemical freeze-out: hadrons interact inelastically and the yields are fixed.

Kinetic freeze-out: elastic interactions cease.

The hottest system ever produced in the lab

Phys. Lett. B 754 (2016) 235-248



The QGP's temperature can be accessed by measuring the spectra of thermal photons.

Thermal photons are created throughout the evolution of the QGP.

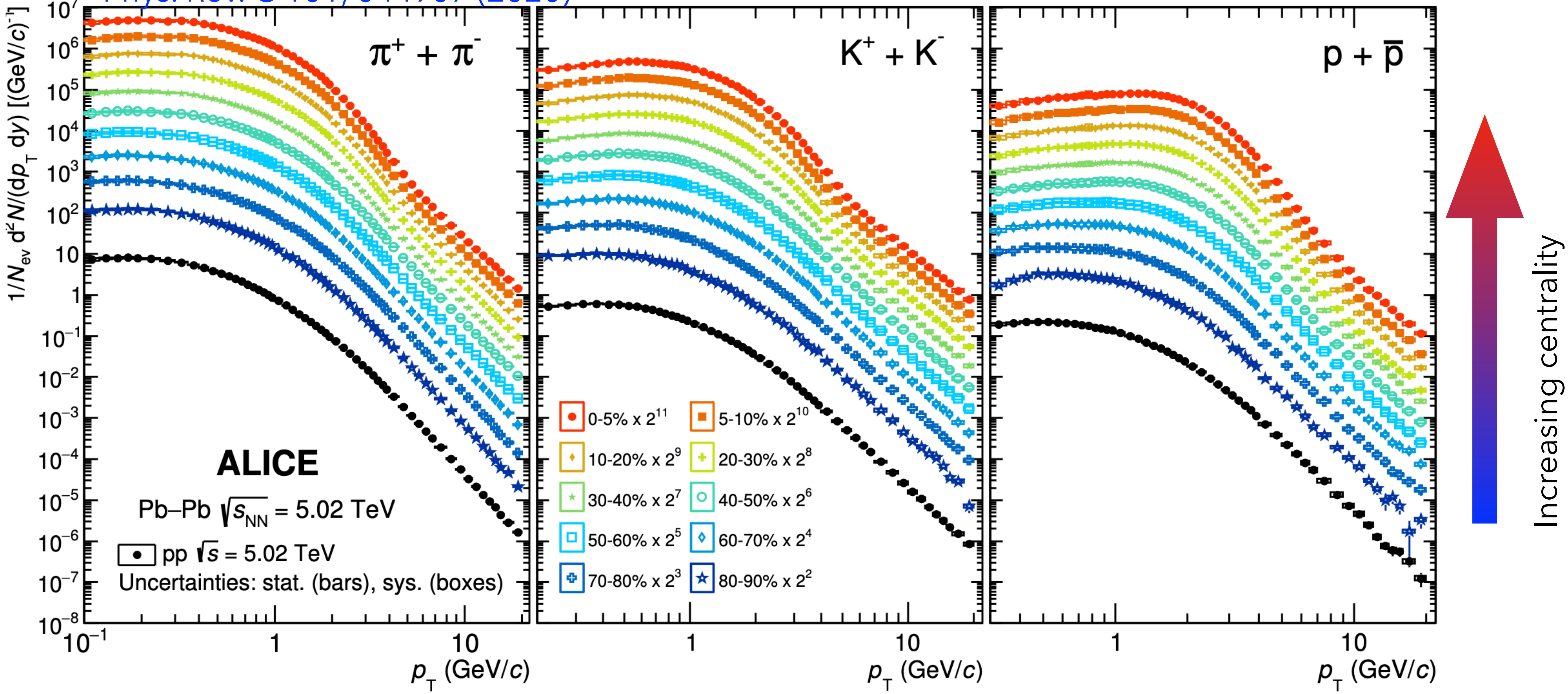
This measurement provides an estimate of the effective temperature (T_{eff}) of the system.

In central Pb-Pb collisions at 2.76 TeV, the measured $T_{eff} \approx 300$ MeV (3×10^{12} K).

This is about 100,000 times hotter than the sun's center.

QGP signatures in AA: radial flow

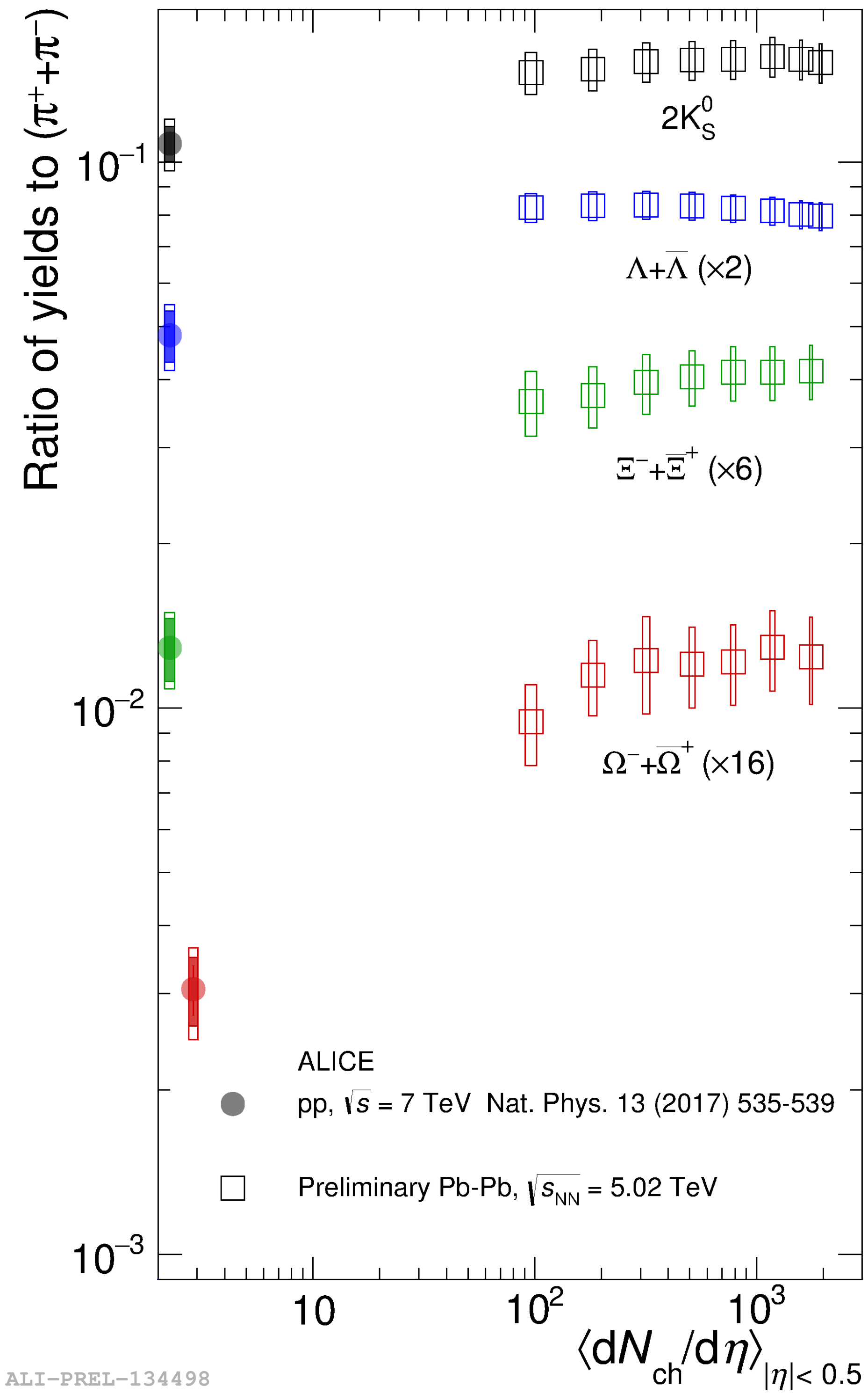
Phys. Rev. C 101, 044907 (2020)



The produced hadrons have radial and anisotropic velocities inherited from the flow of the expanding liquid that came before.

Radial flow pushes low-p_T particles toward higher values.

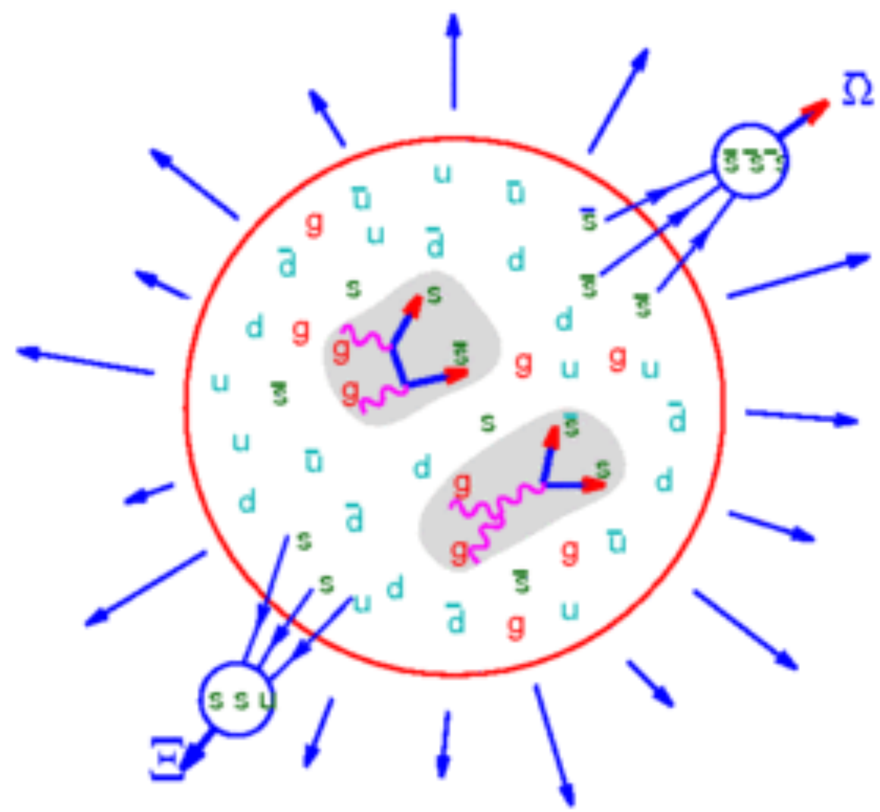
QGP signatures in AA: strangeness production



Nature Physics 13, 535-539 (2017)

One key signature of the formation of the QGP is the thermal production of strange hadrons.

The yield of K^0_s, $\Lambda(1s)$, $\Xi(2s)$ and $\Omega(3s)$ in PbPb collisions at 5.02 TeV are enhanced wrt to the yield of pions.



The paradigm of pp collisions (small systems)

Old paradigm: reference systems to isolate QGP effects in heavy-ion collisions.

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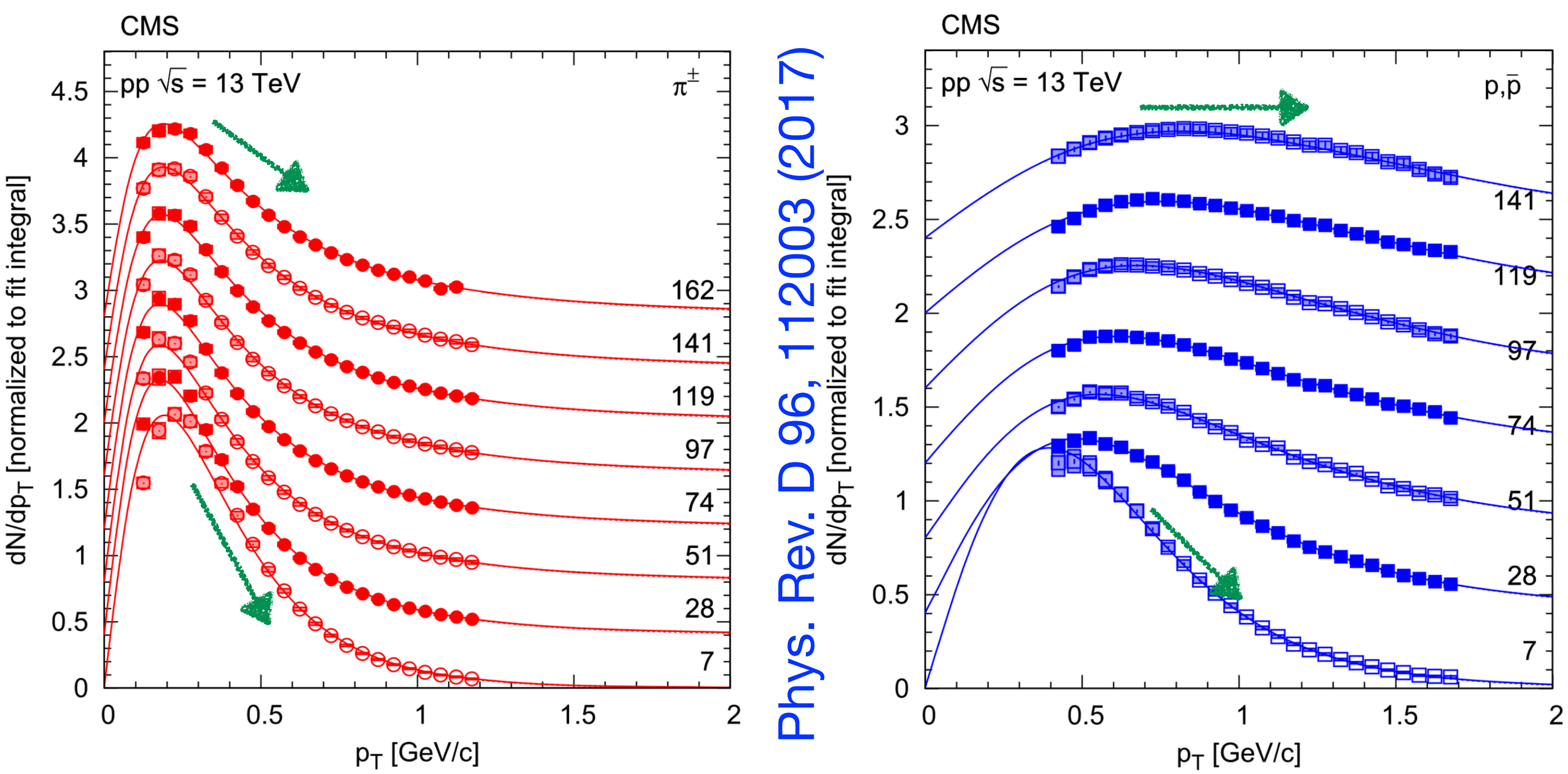
Very different reality, QGP signatures are also observed in pp collisions: radial flow,



Modification of the p_T spectral shapes with increasing event multiplicity.

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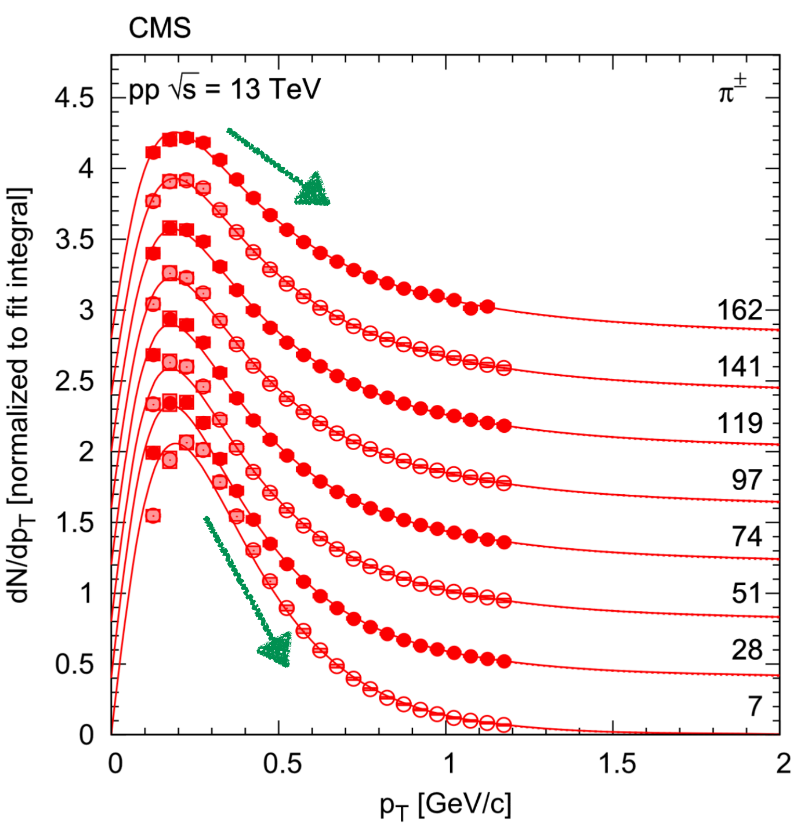
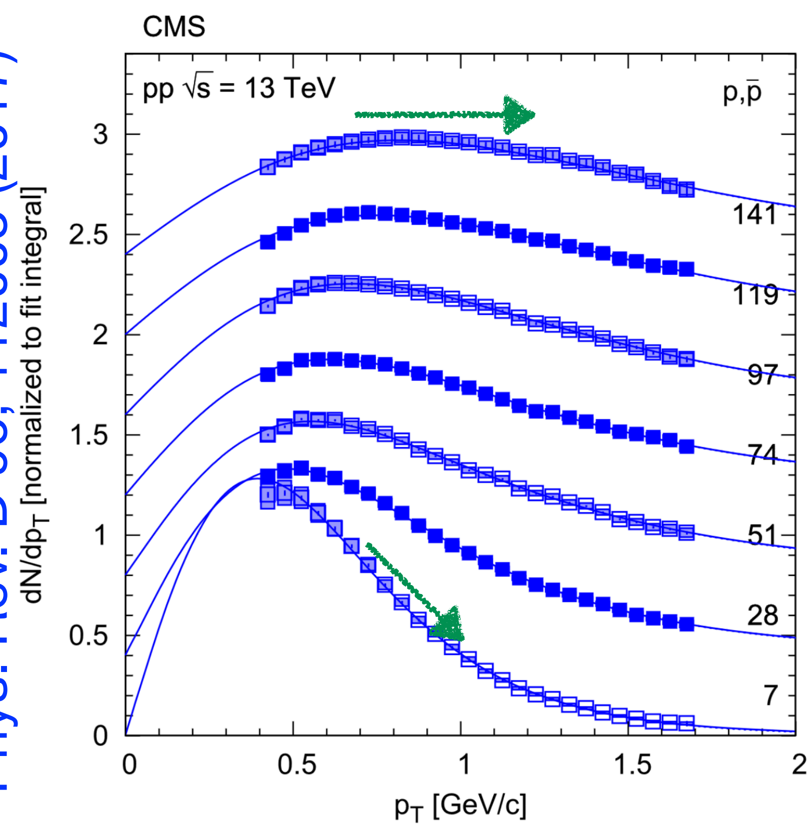
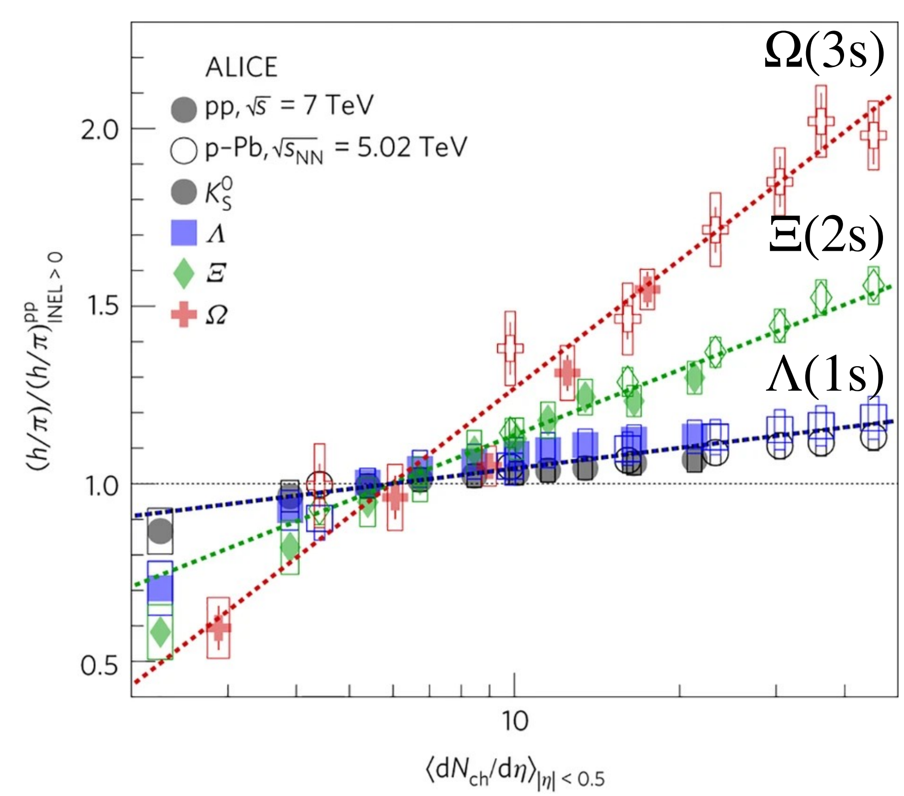


Phys. Rev. D 96, 112003 (2017)





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Modification of the p_T spectral shapes with increasing event multiplicity.

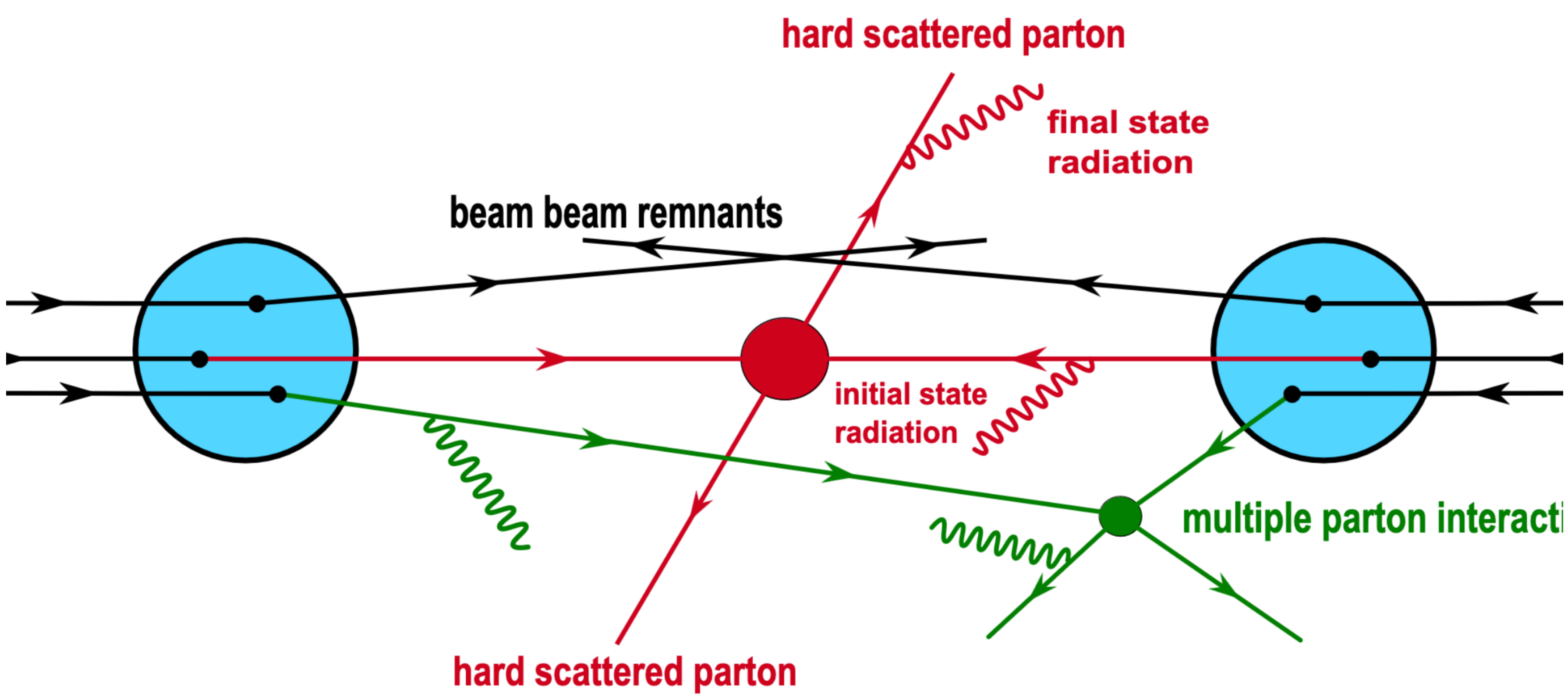
Enhanced production of strange hadrons in high-multiplicity events. Is the charged-particle particle density a driving quantity for the enhanced production of strange hadrons?

The paradigm of pp collisions (small systems)

Very complex systems: pp collisions are the sum of several sub-interactions at different energy scales according to the energy of the incoming partons.

Hard processes: interactions between hard scattered partons.

Underlying event: multiple parton interactions (MPI), beam remnants interactions + initial- and final-state radiations (ISR/FSR).



CERN-THESIS-2010-187

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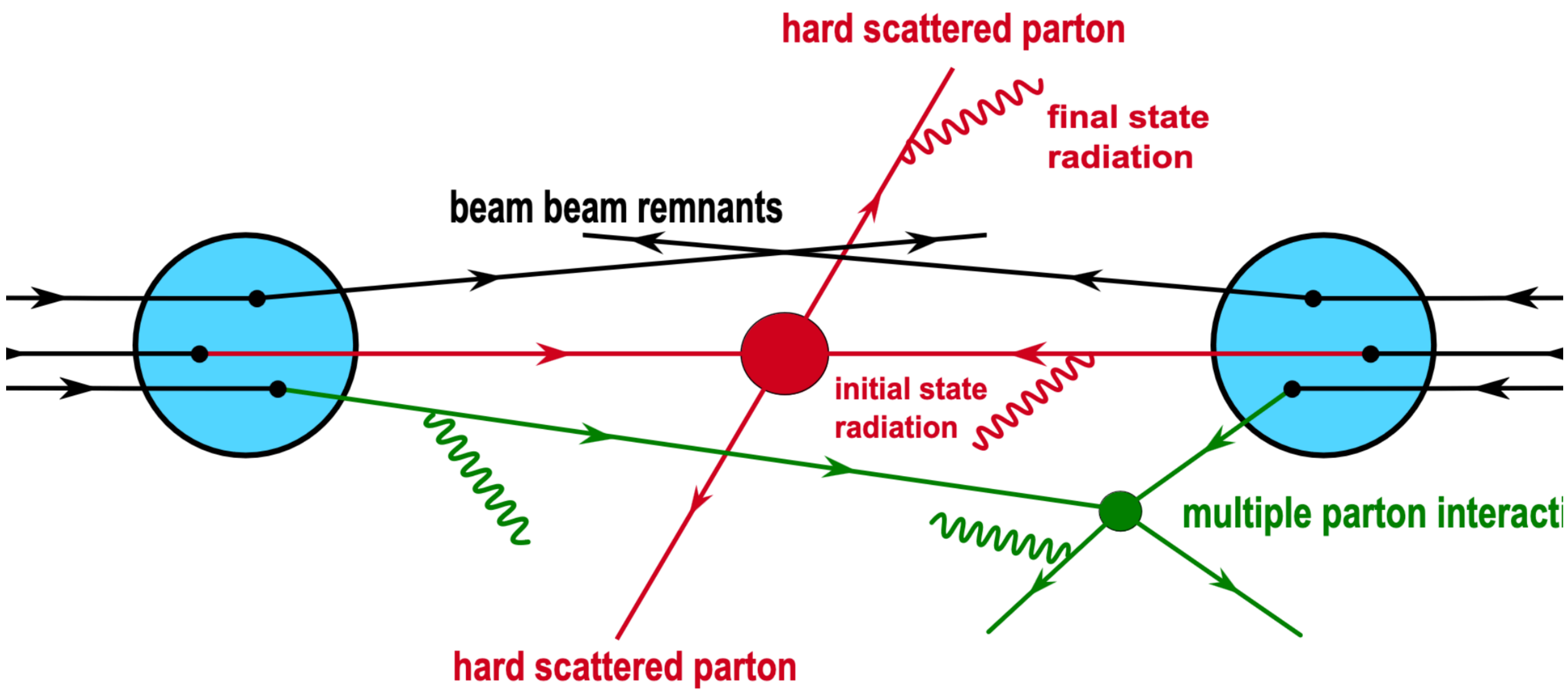
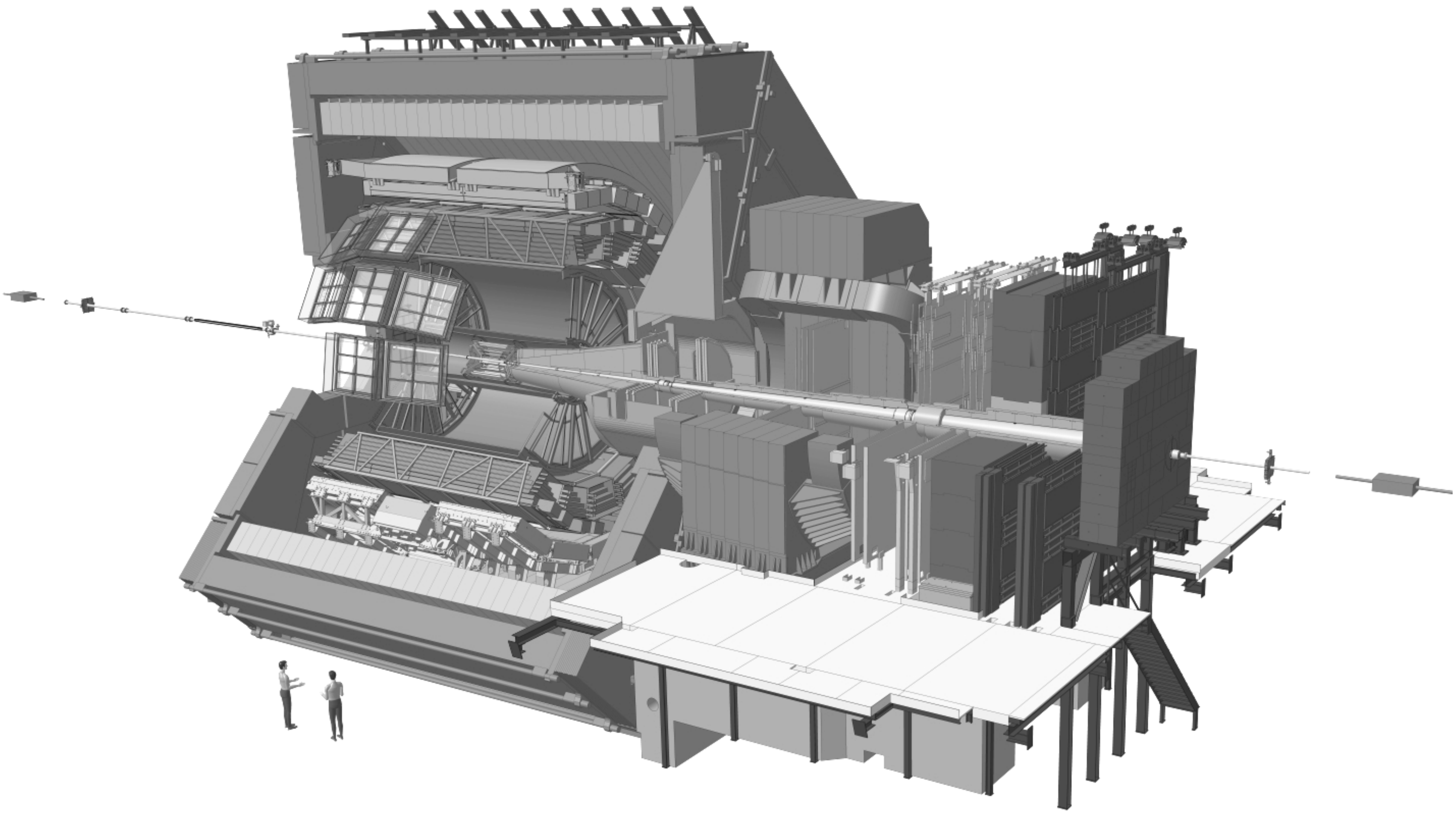
Here I will present recent results from using event shape observables to gain further insight into the underlaying mechanisms for QGP-like effects in small systems.



CERN-THESIS-2010-187

The ALICE experiment (Run 2)



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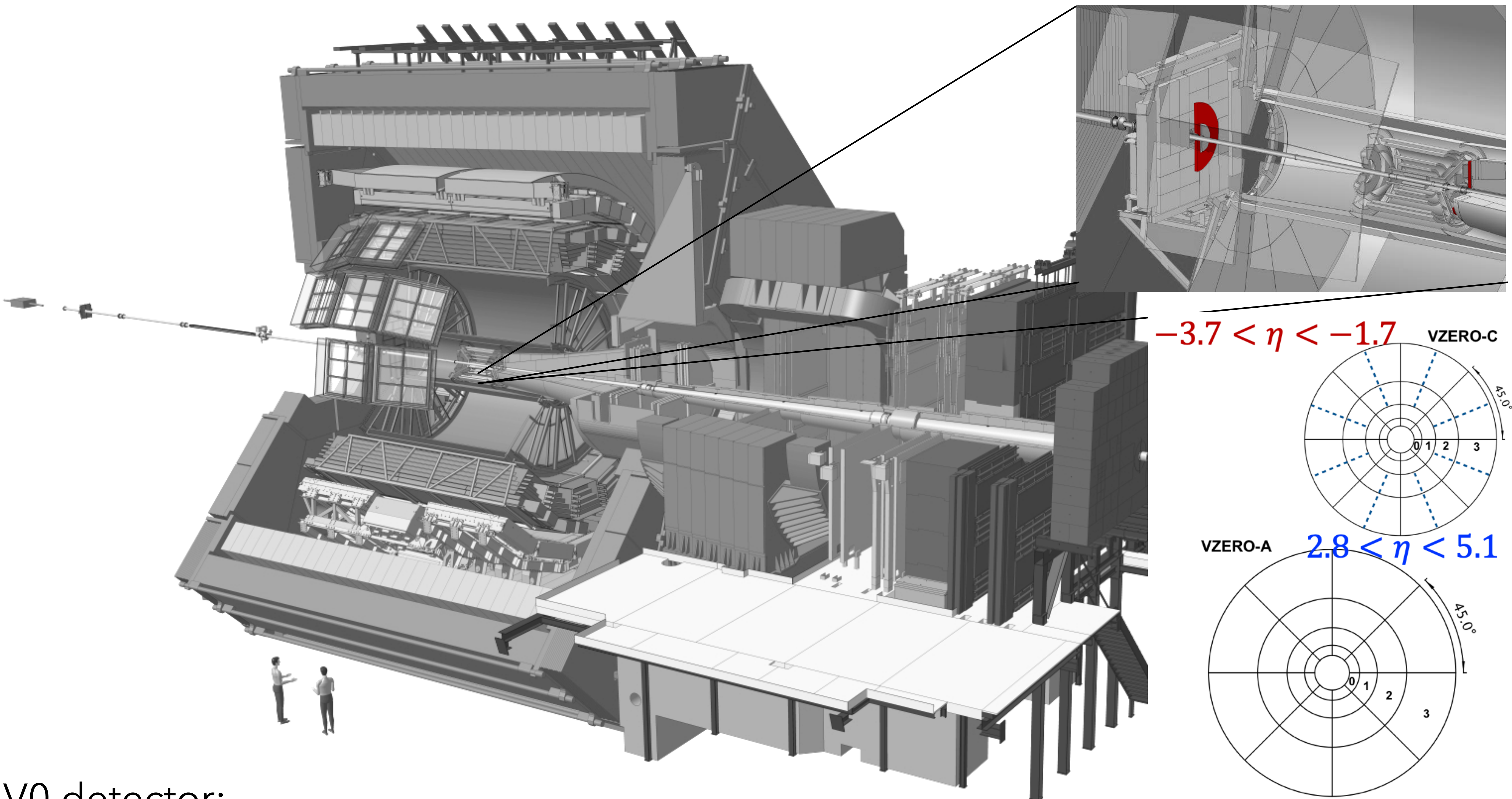
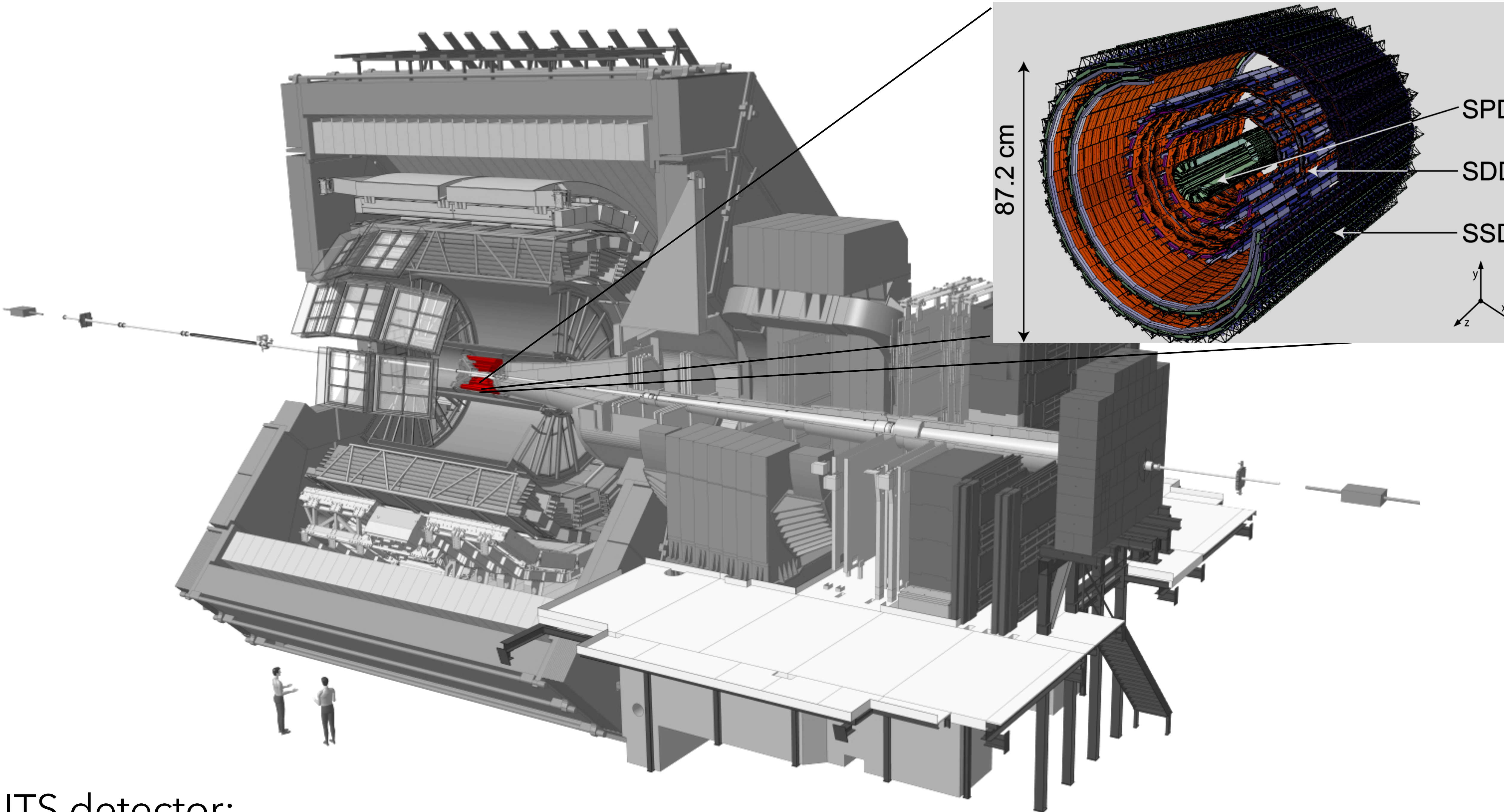


The V0 detector:

Forward scintillator hodoscopes, V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$).

Used for triggering, background suppression, and multiplicity estimation.

The ALICE experiment (Run 2)

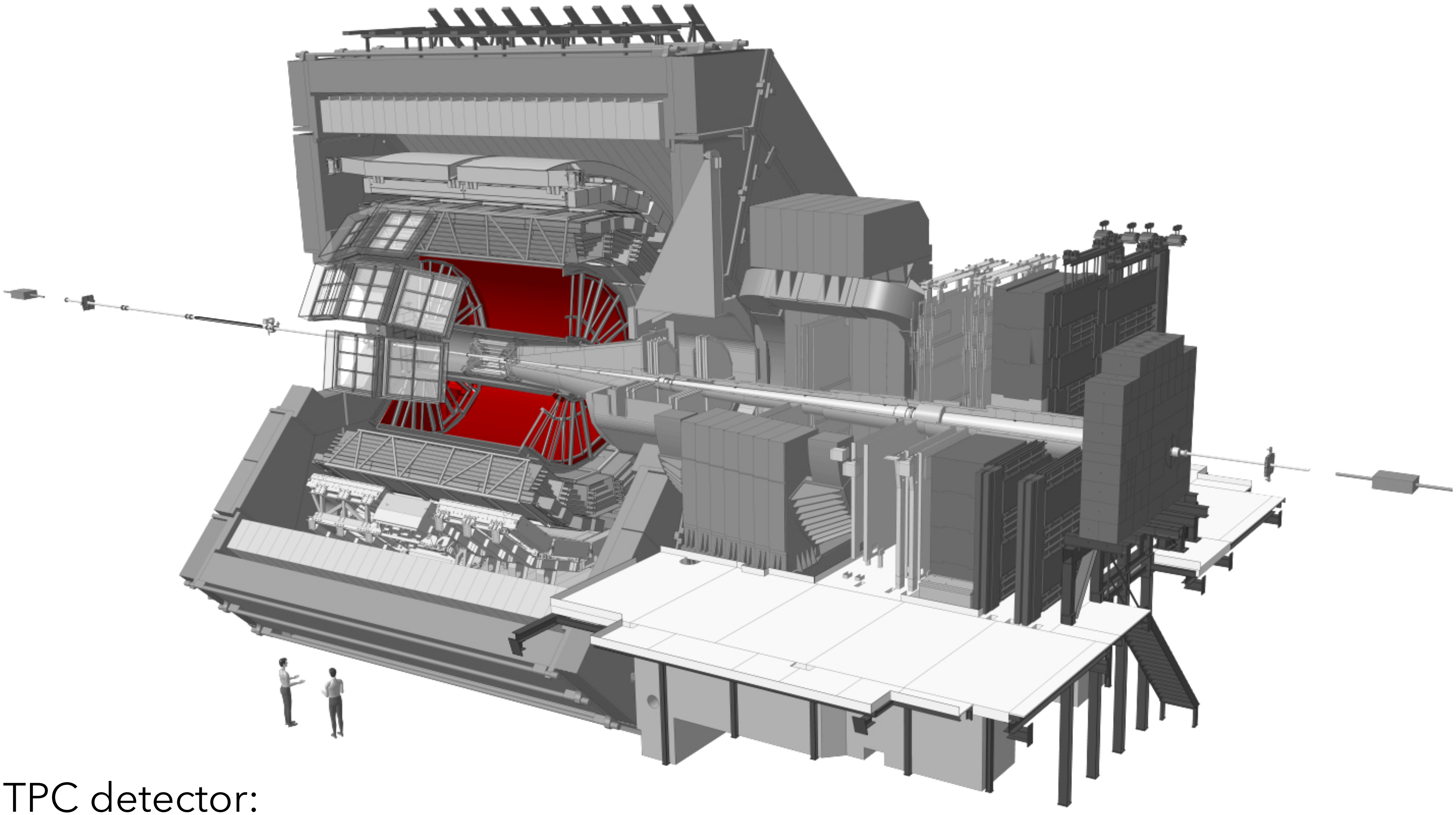


The ITS detector:

Six-layer silicon detector.

Used for vertex selection and multiplicity estimation.

The ALICE experiment (Run 2)

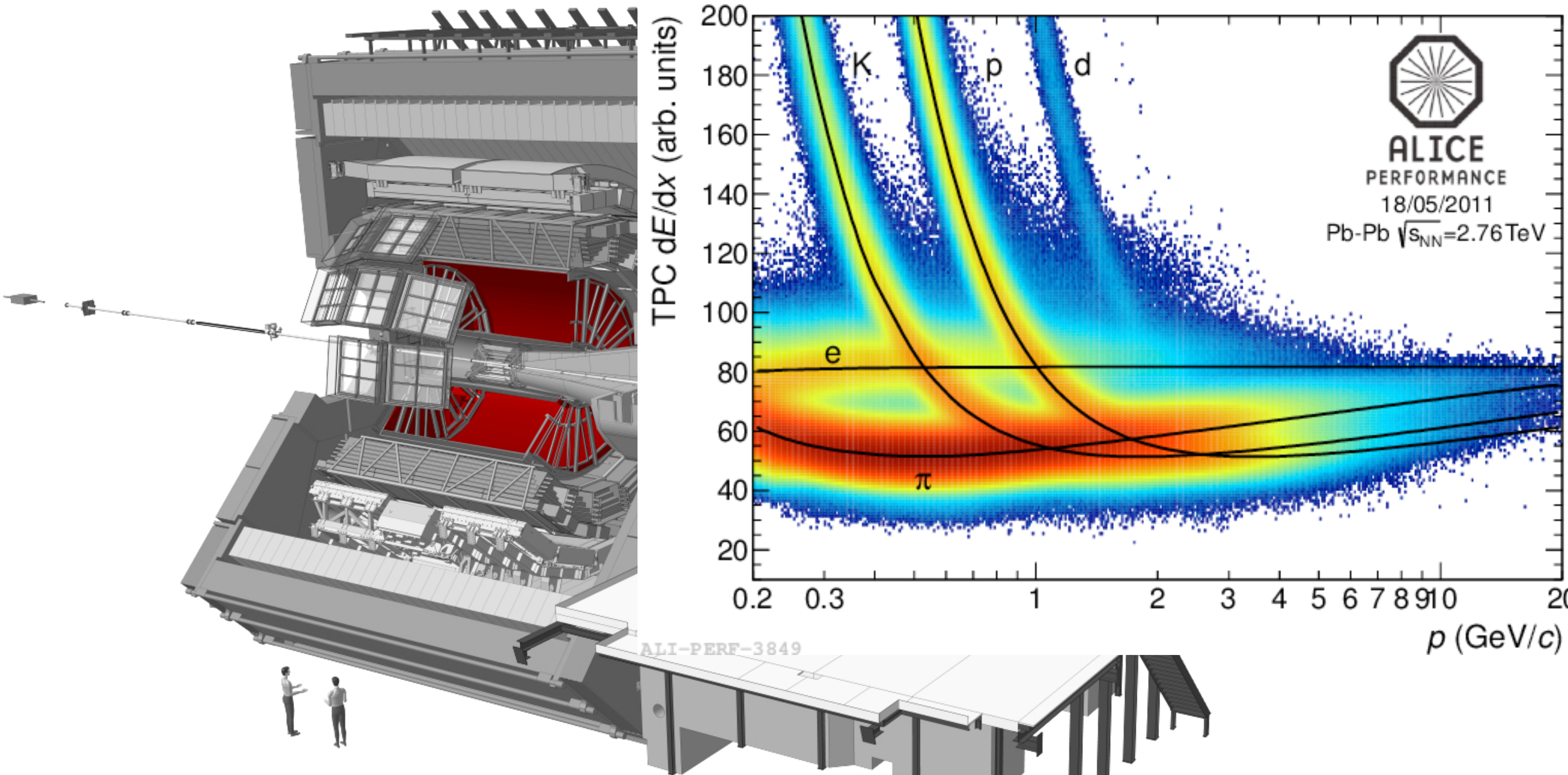


The TPC detector:

Drift chamber covering the central region and full azimuthal angle coverage.

Main tracking detector used for vertex reconstruction and PID.

The ALICE experiment (Run 2)



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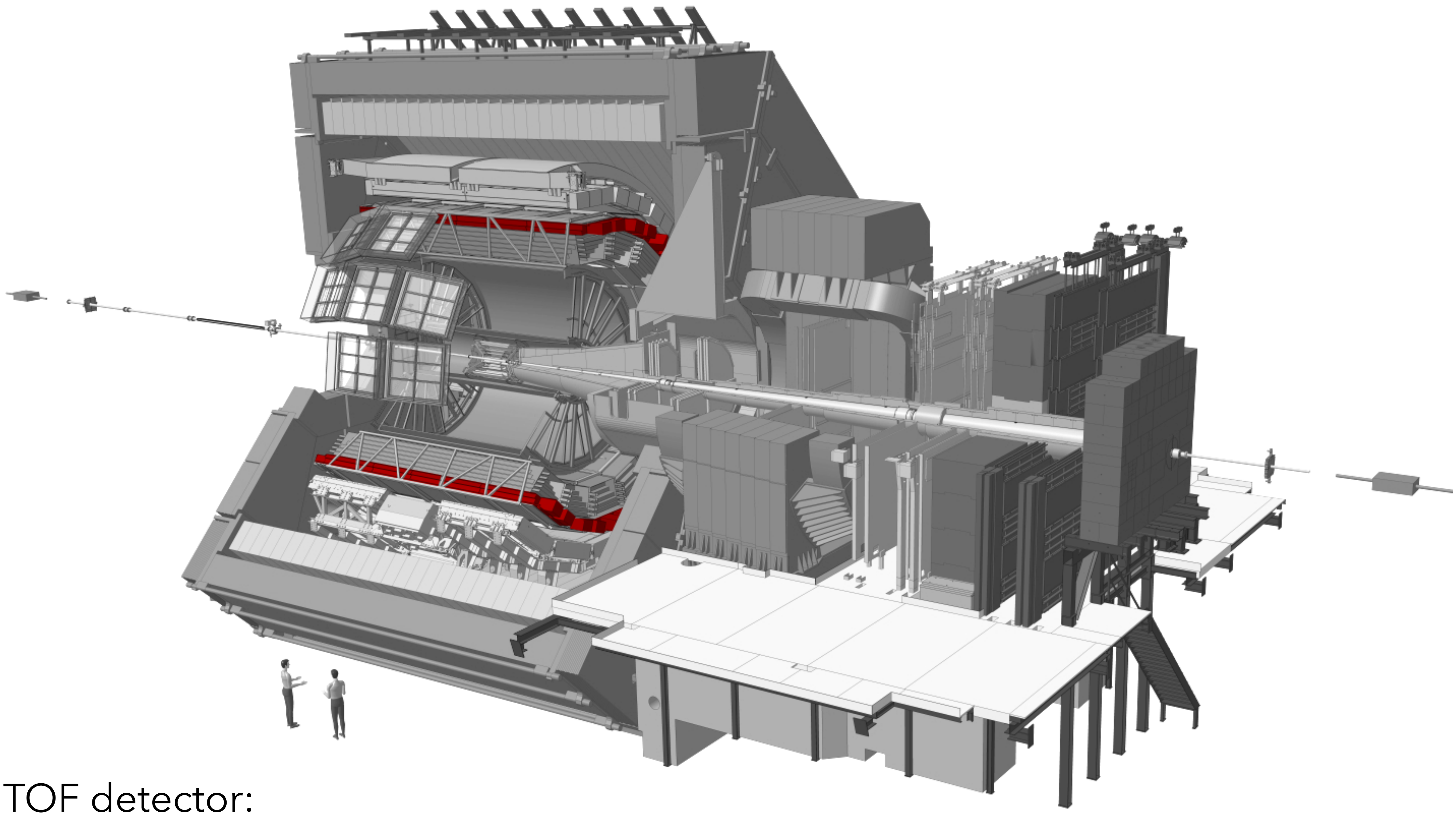

The TOF detector:

Covers the central region and has full azimuthal angle coverage.

Mainly used for PID.

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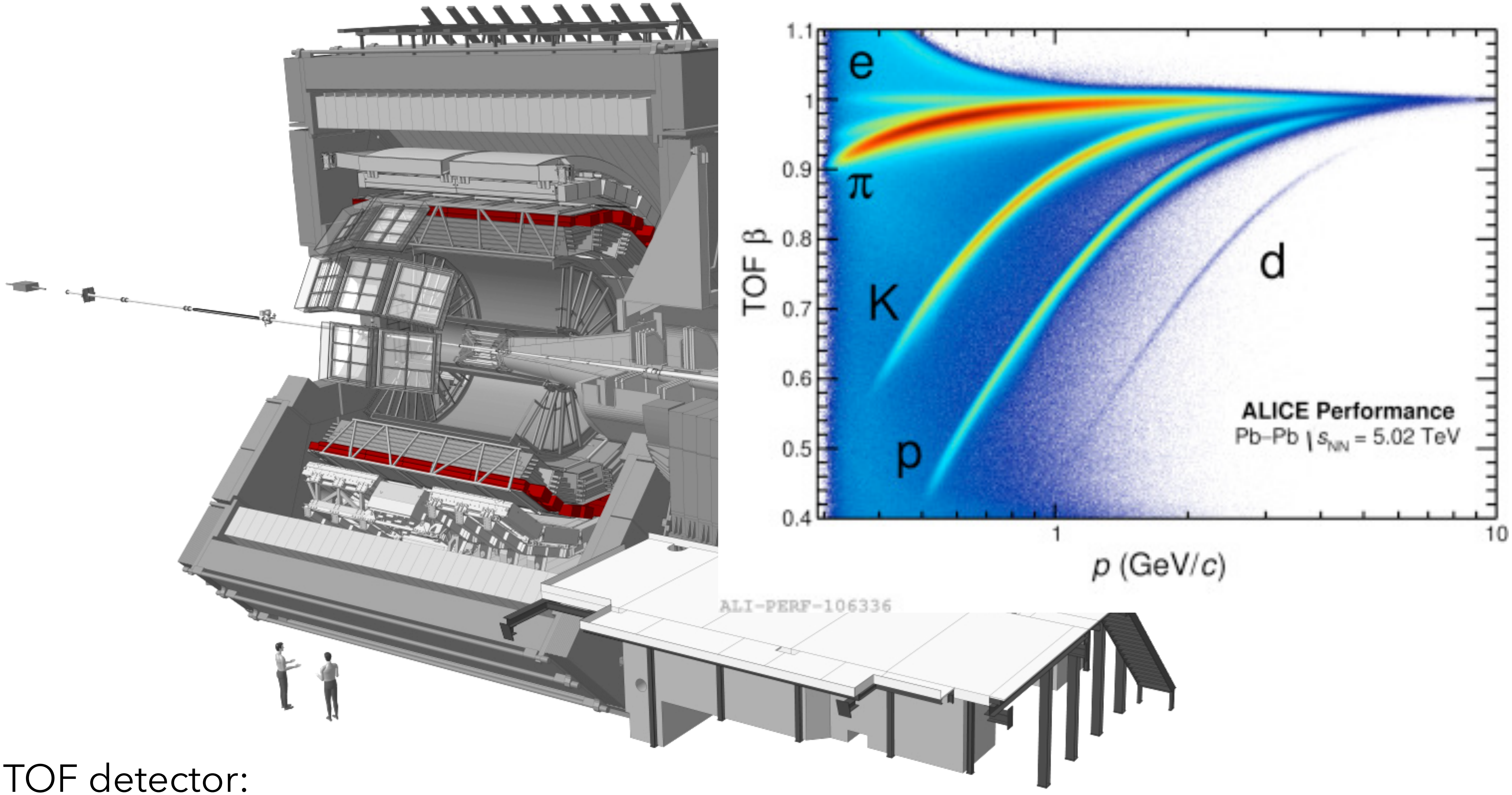


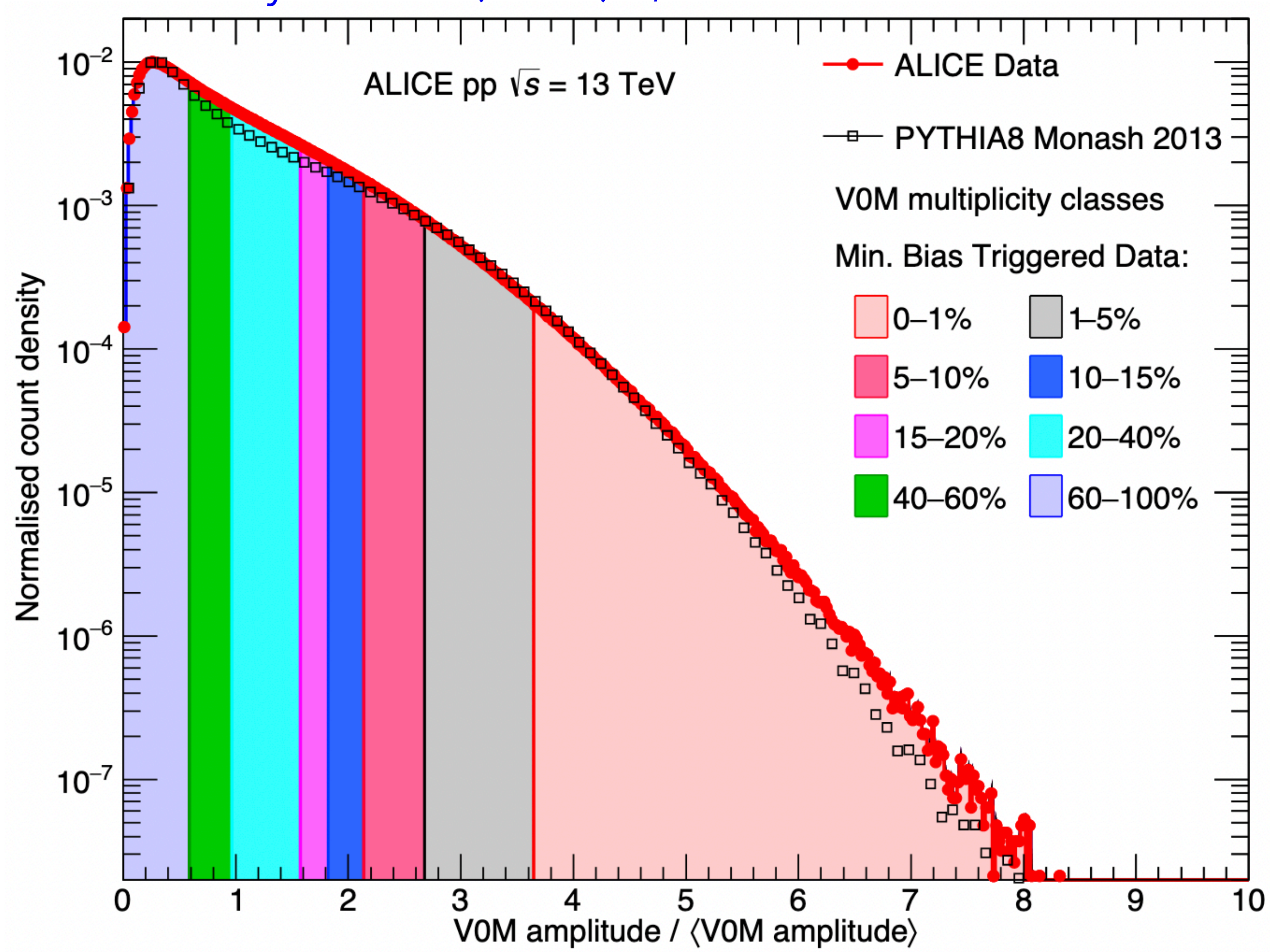
The TOF detector:

Covers the central region and has full azimuthal angle coverage.

Mainly used for PID.

Event classification: Multiplicity based

Eur.Phys.J.C 82 (2022) 6, 514

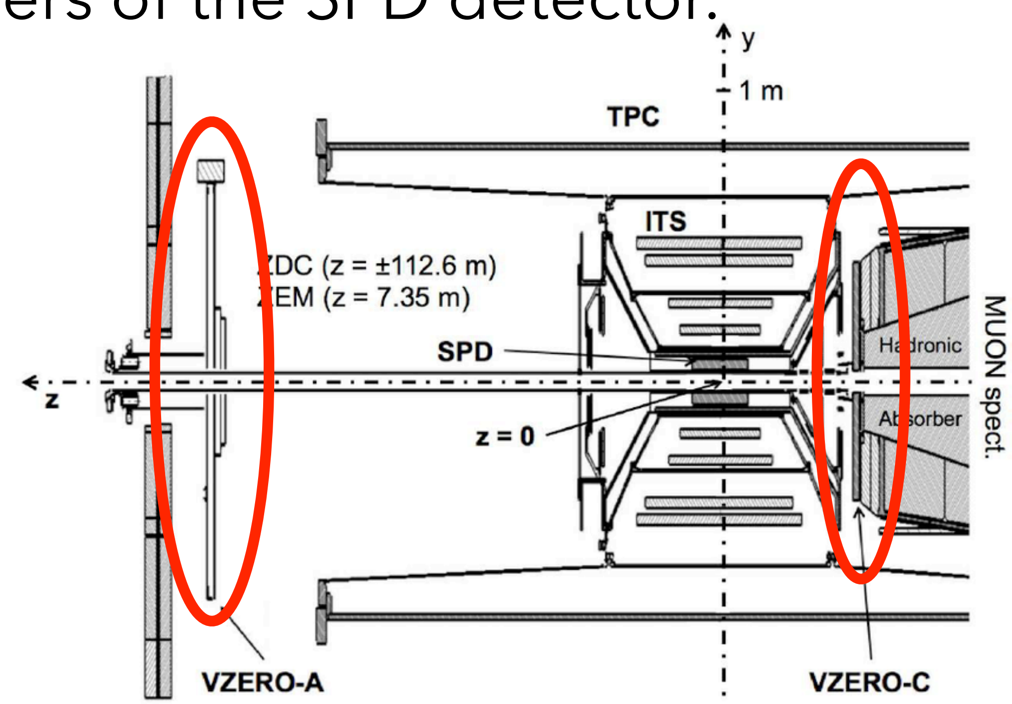


V0M estimator (V0M)

Event classification based on the summed amplitude between the V0A and V0C detectors.

SPD estimator $(N_{\text{tracklets}}^{|\eta|<0.8})$

Uses the number of reconstructed tracklets $(|\eta| < 0.8)$ between the two layers of the SPD detector.



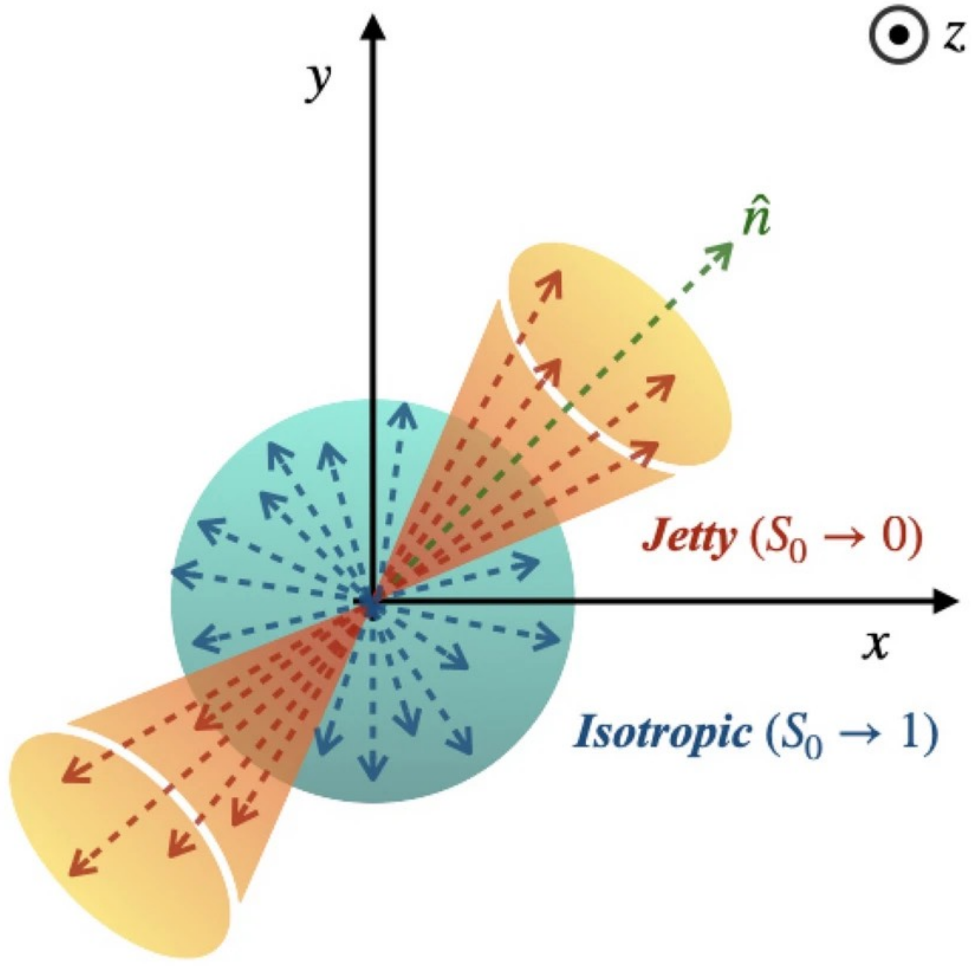
V0A $2.8 < \eta < 5.1$

V0C $-3.7 < \eta < -1.7$

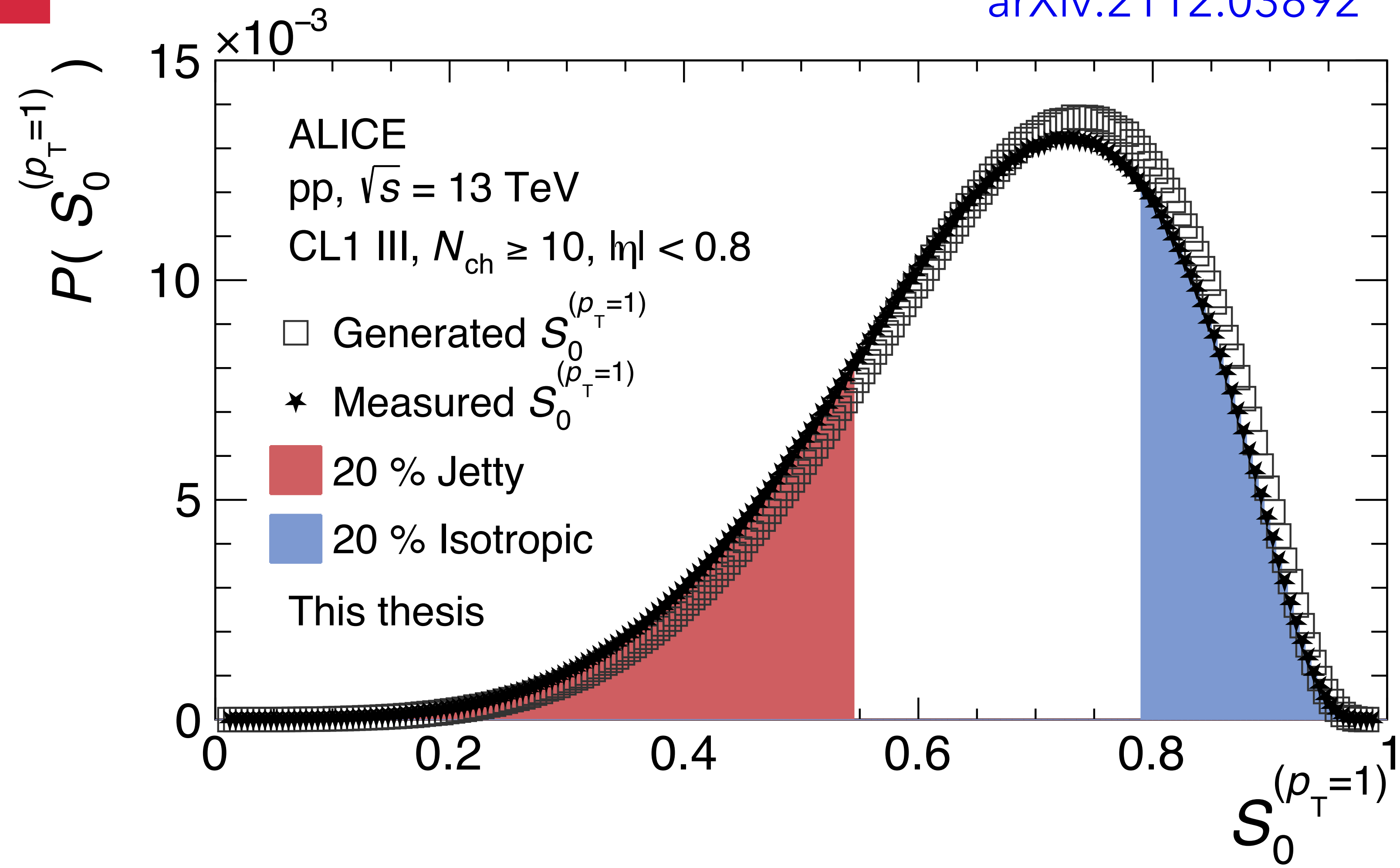
Event shapes: Spherocity

Spherocity tells us about the shape of the event in the transverse plane.

$$S_0^{p_\mathrm{T}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{\mathrm{T},i}} \times \hat{n}|}{N_\mathrm{tracks}} \right)^2$$

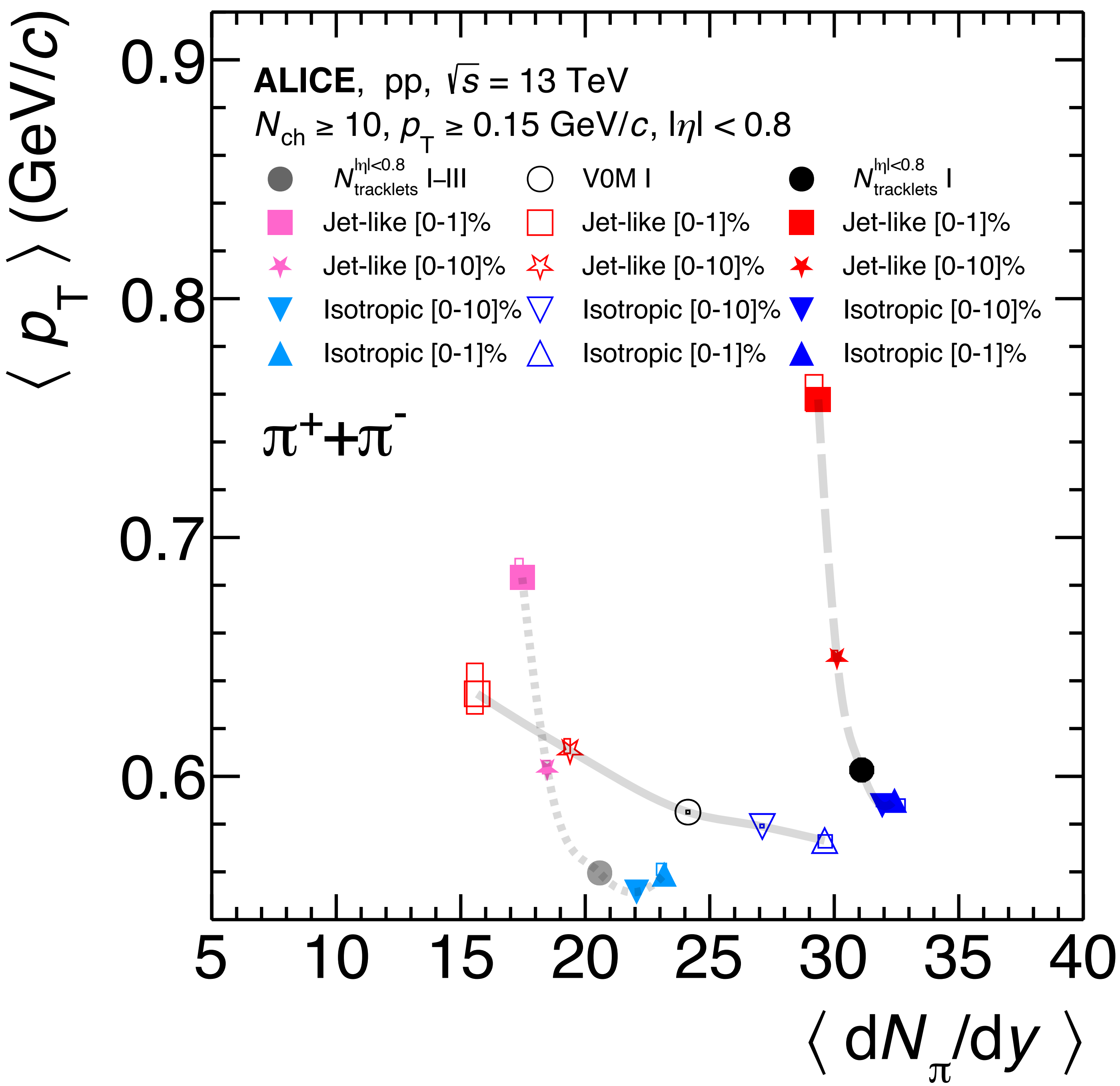


arXiv:2112.03892



Event shapes: Spherocity

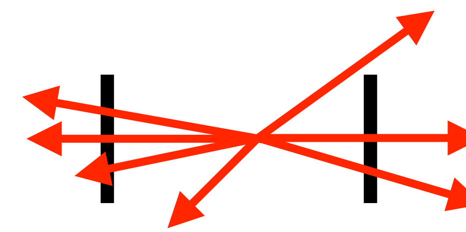
ALICE, arXiv:2310.10236



This study uses only the HM sample:

$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.8}$ (V0M) ≥ 27.

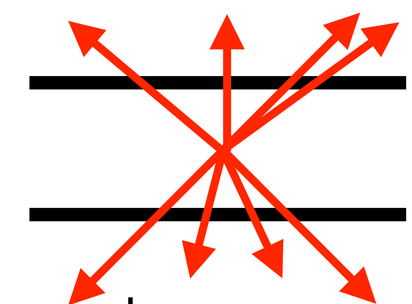
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.8}$ (SPD) ≥ 54.



V0M estimator (V0M)

Similar $\langle p_T \rangle$ across the Spherocity classes.

Large variations in $\langle dN/dy \rangle$.

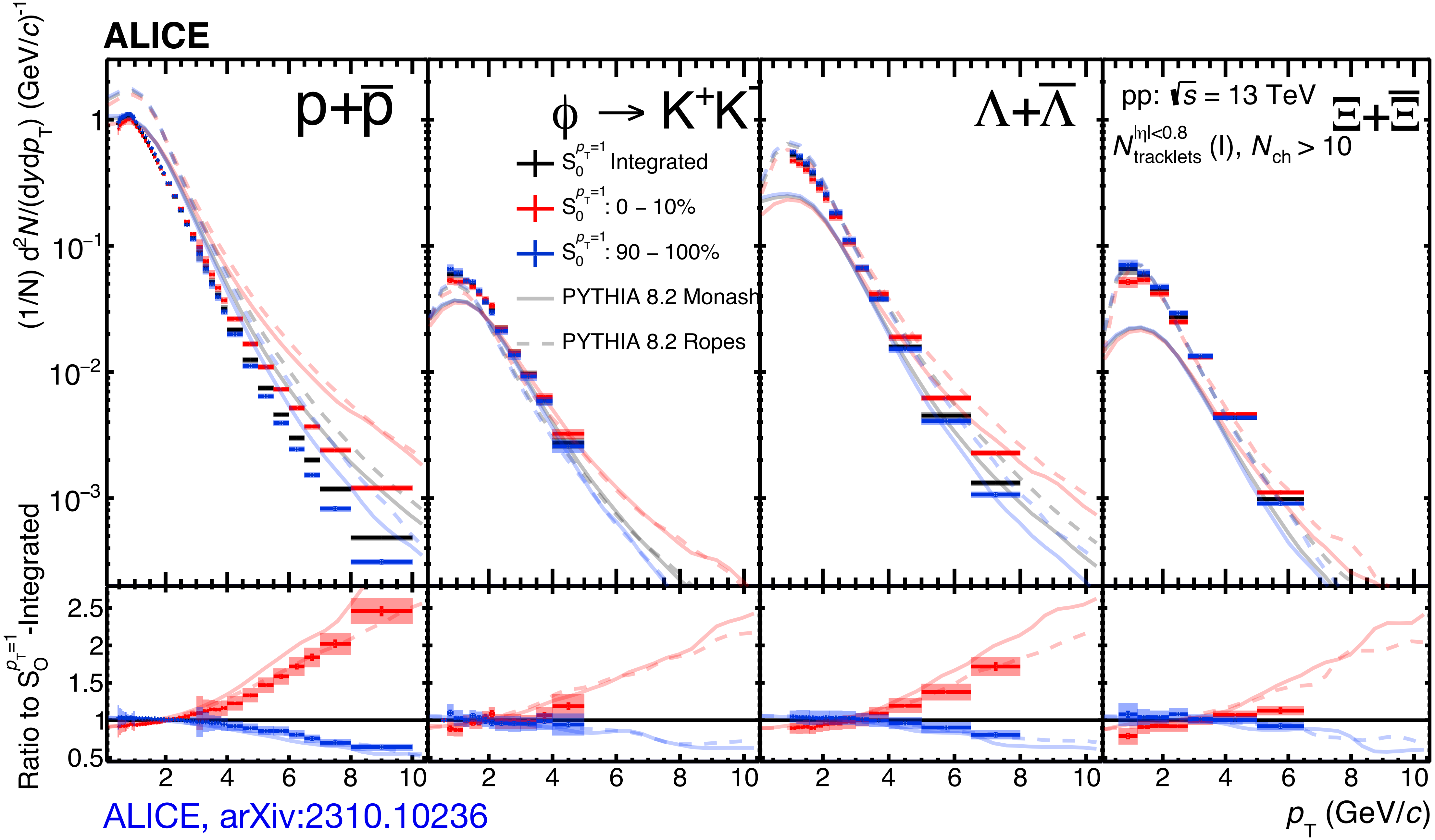


SPD estimator $(N_{\text{tracklets}}^{|\eta|<0.8})$

Large variations in $\langle p_T \rangle$ among the Spherocity classes.

Constrained $\langle dN/dy \rangle$.

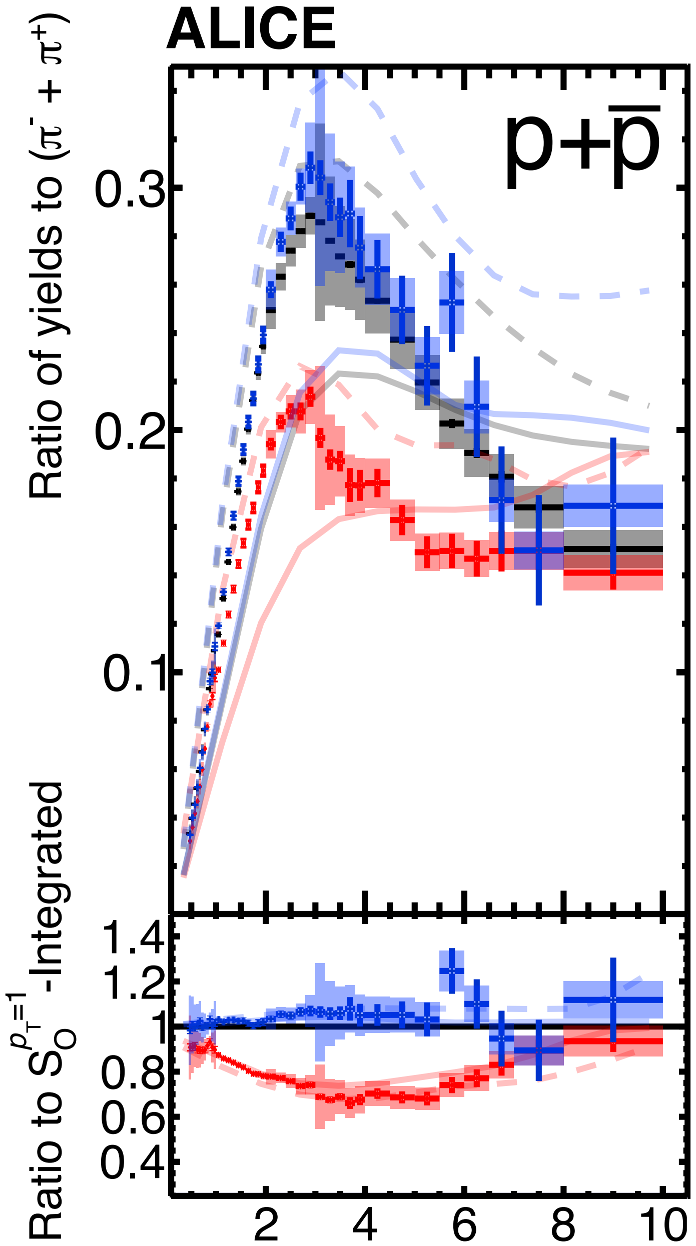
Identified particle p_T spectra



Significant hardening (softening) of the spectra in the low (high) Spherocity events.

PYTHIA model describes well the relative trend w.r.t. the Spherocity-integrated spectrum.

p_T-differential particle ratios



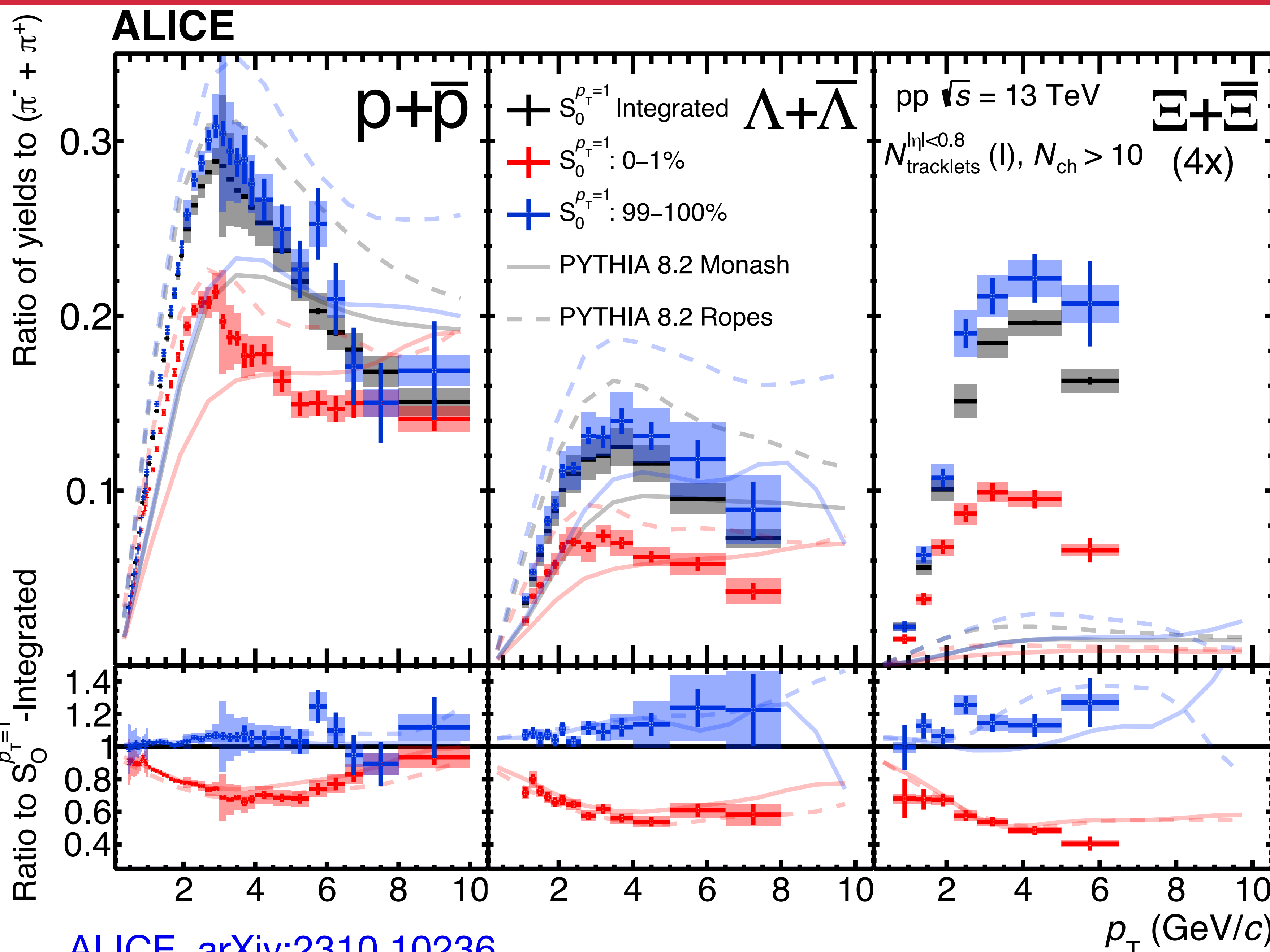
ALICE, arXiv:2310.10236

The double ratio (DR):

$$\left(\frac{dN/dp_T}{dN_\pi/dp_T}\right)_{S_0^{p_T=1}} \Big/ \left(\frac{dN/dPT}{dN_\pi/dpT}\right)_{S_0^{p_T=1}-\text{int.}}$$

Radial flow effects are stronger in isotropic events than in jet-like topologies.

p_T-differential particle ratios



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The double ratio (DR):

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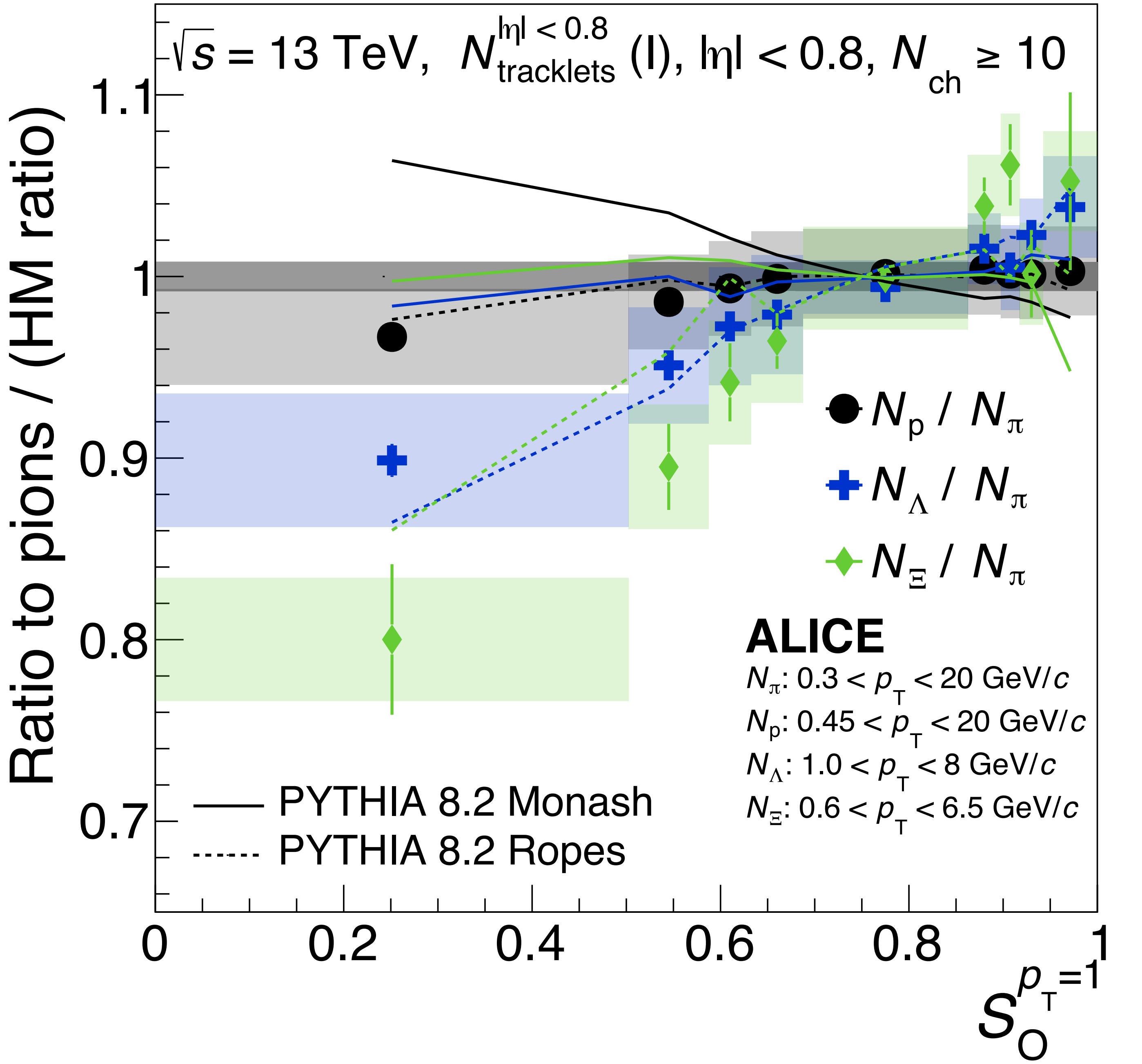
Radial flow effects are stronger in isotropic events than in jet-like topologies.

Strange particle production is favored in isotropic topologies.

The DR for all particle ratios decrease significantly for jet-like events.

p_T-integrated particle ratios

ALICE, arXiv:2310.10236



Jet-like events

Isotropic events

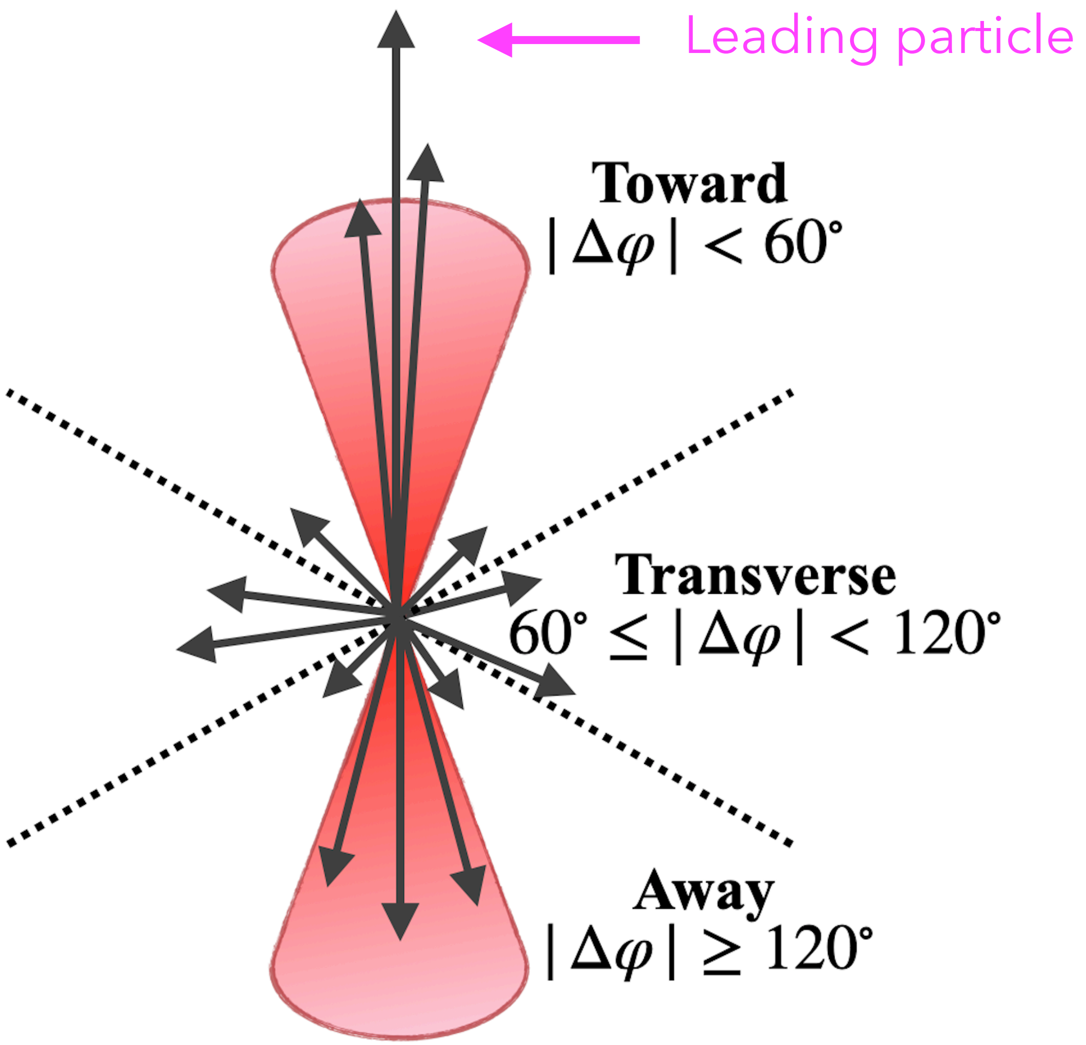
The strange-hadron yield increases as a function of Spherocity.

- ~20% increase between the extremes of Spherocity.
- The increase is ordered with strangeness content.

PYTHIA Ropes predicts qualitative trends but misses the ordering with increasing strangeness content.

Event shapes: Relative transverse activity

Uses events with leading charged particles in the central region.



Event shapes: Relative transverse activity

Uses events with leading charged particles in the central region.

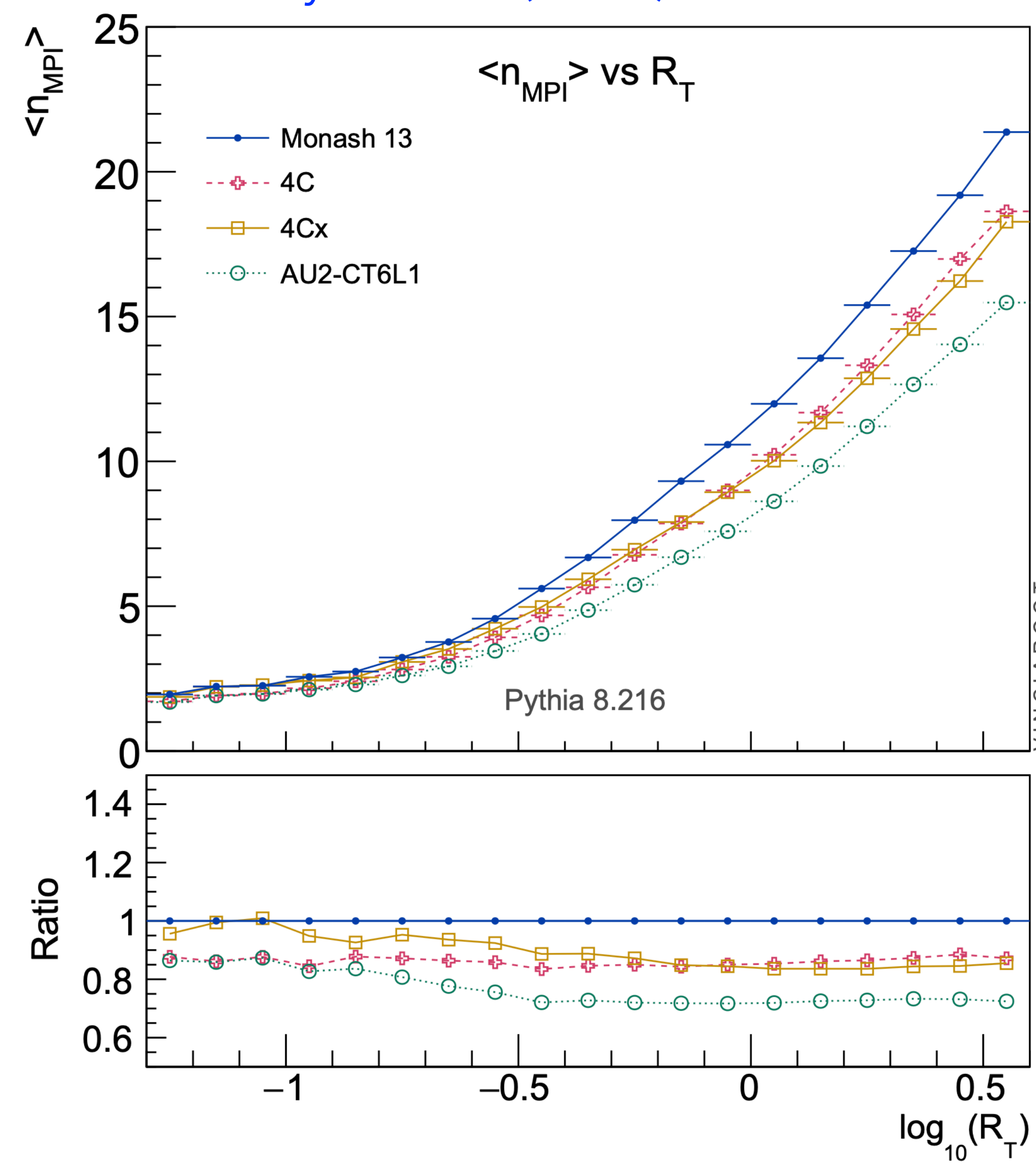
The relative transverse activity classifier:

$R_T = N_T / \langle N_T \rangle$

Separates events with ``higher-than-average" UE from ``lower-than-average" ones.

R_T is sensitive to the UE.

Eur.Phys.J. C76 (2016) 299



N_T is the particle multiplicity in the transverse region.

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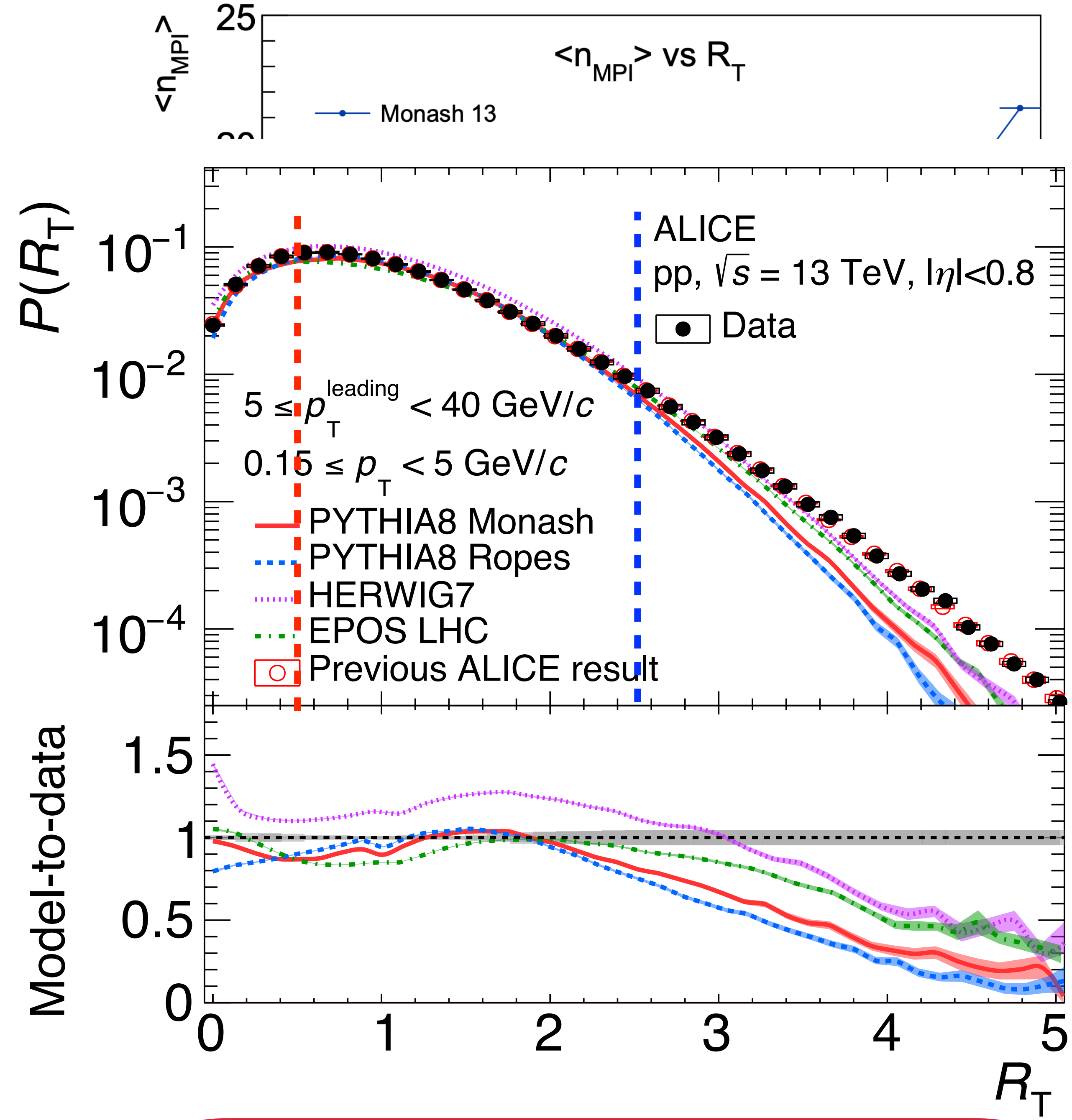
Measure the particle production in intervals of R_T:

Low UE activity: $0 < R_T < 0.5$

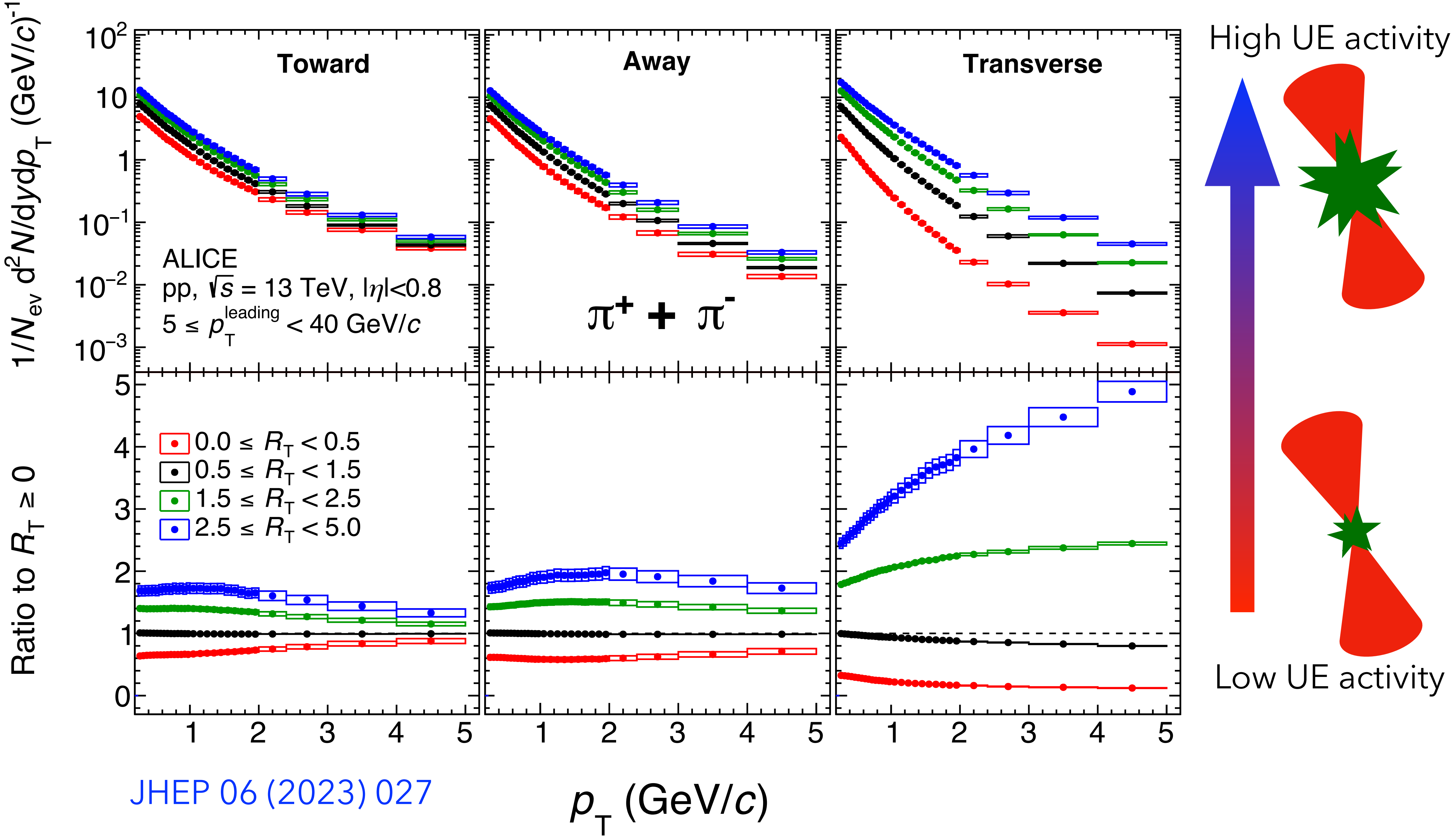
High-UE activity: $2.5 < R_T < 5$

JHEP 06 (2023) 027



N_T is the particle multiplicity in the transverse region.

Identified particle p_T spectra: pions



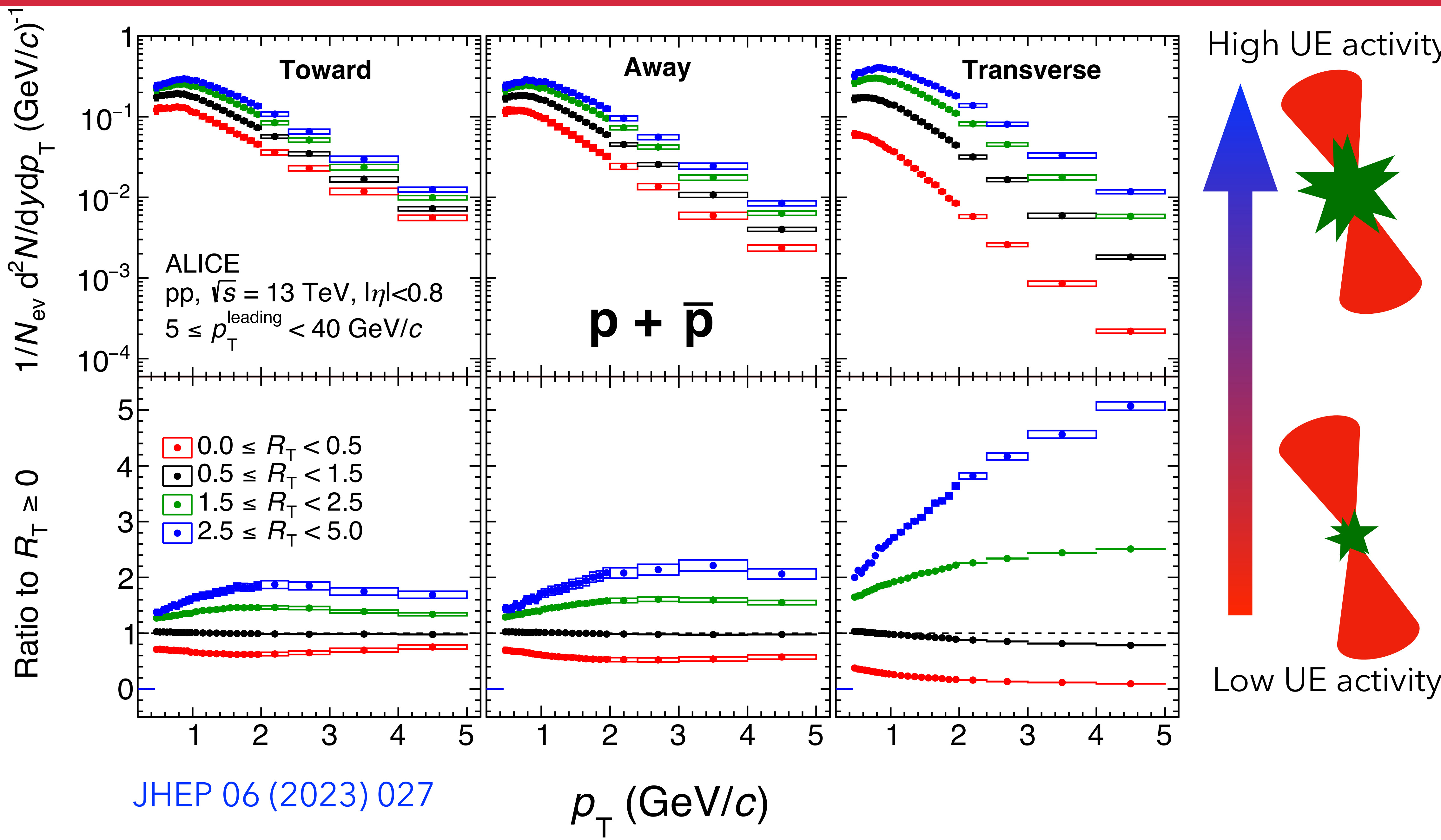
JHEP 06 (2023) 027

Toward & Away: Radial flow signatures emerge with increasing UE activity.

There is a mass-dependent effect in the proton spectra.

Transverse: The p_T spectra get harder with increasing UE activity (autocorrelation effect).

Identified particle p_T spectra: protons



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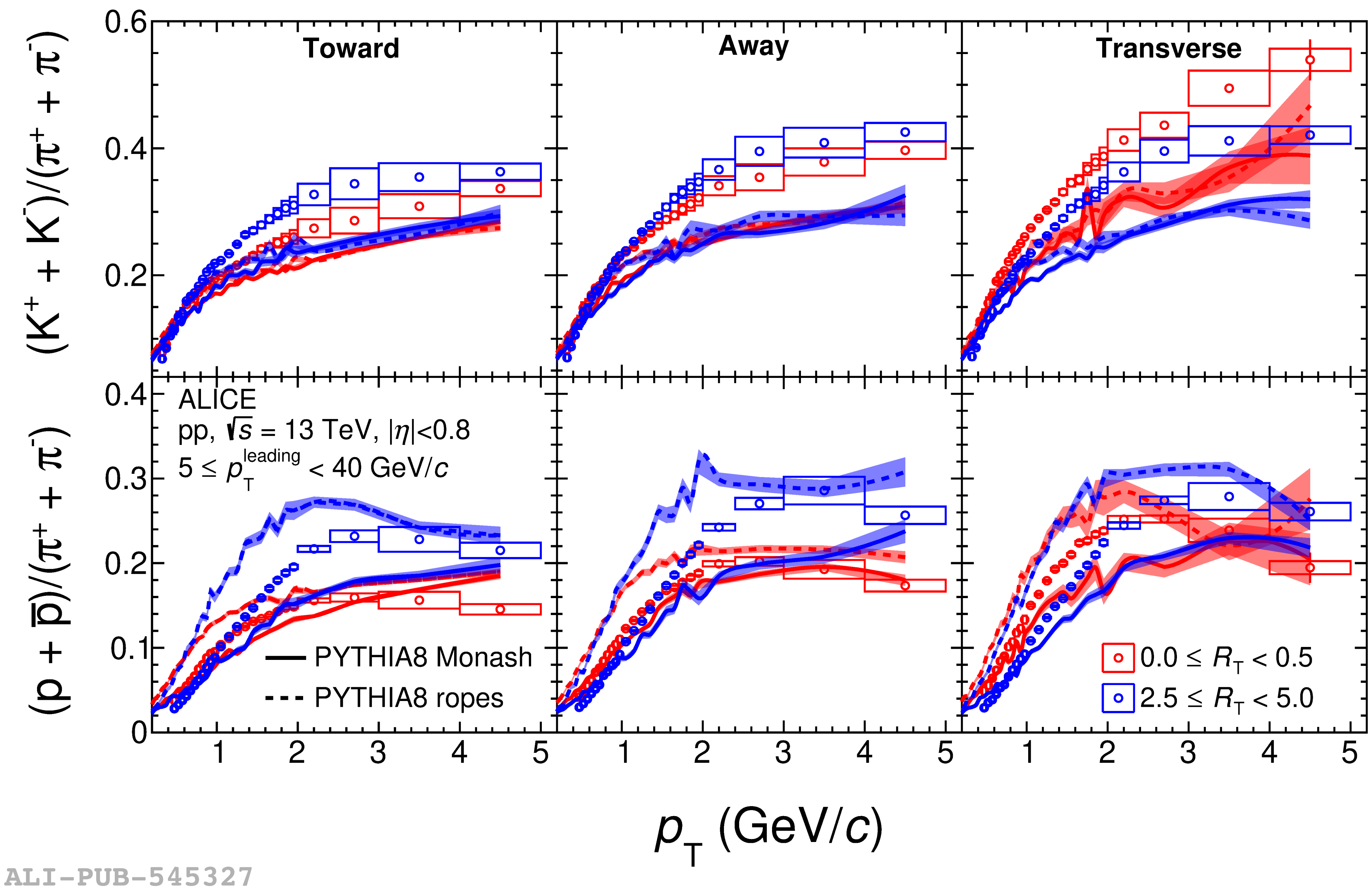
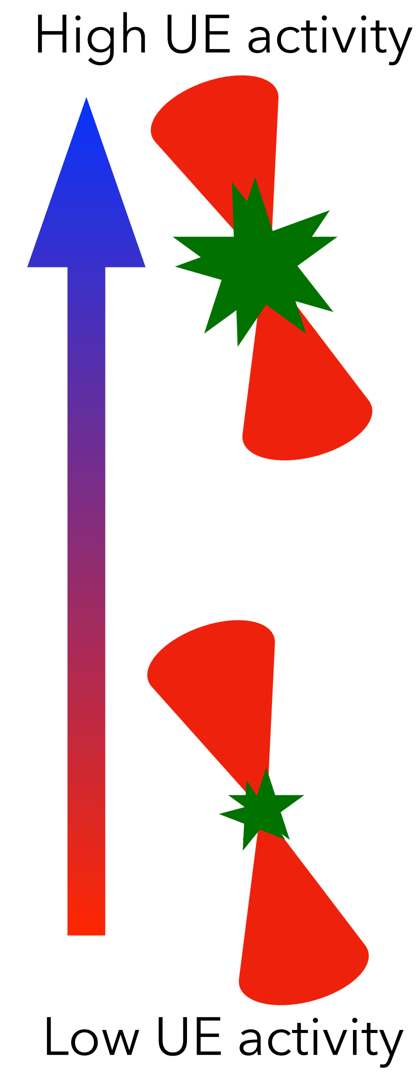
p_T-differential particle ratios





Clear evolution of the proton-to-pion ratio with R_T (radial flow) in the toward and away regions.

PYTHIA 8 Monash tune describes only qualitatively the particle ratios in the toward and away regions for $0 < R_T < 0.5$.

Summary (1/2)

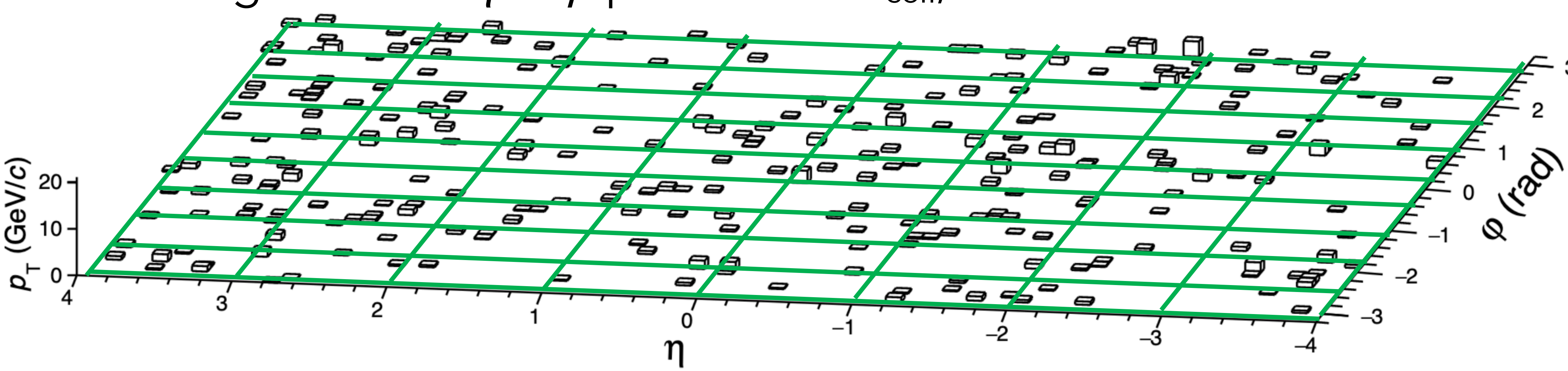
- Small systems show signatures of the formation of a QGP droplet (radial and anisotropic flow, strangeness enhancement…).
- Event shape observables can select pp collisions driven by soft QCD processes.
- Isotropic events showcase stronger signatures of radial flow and favor the production of strange hadrons compared with jet-like events.
- Autocorrelation biases can completely obscure the effects from soft QCD physics.

Event classification: Charged particle flattenicity

Motivation: Propose an observable with high sensitivity to the UE activity and color reconnection effects, but without introducing biases towards hard physics processes.

Flattenicity definition: Phys.Rev.D 107 (2023) 7

Define a grid in the $\eta - \varphi$ plane with N_{cell}, number of cells.



$$\rho = \frac{\sqrt{\sum_i \left(N_{\text{ch}}^{\text{cell},i} - \langle N_{\text{ch}}^{\text{cell}} \rangle\right)^2 / N_{\text{cell}}^2}}{\langle N_{\text{ch}}^{\text{cell}} \rangle}$$

ρ is measured per event.

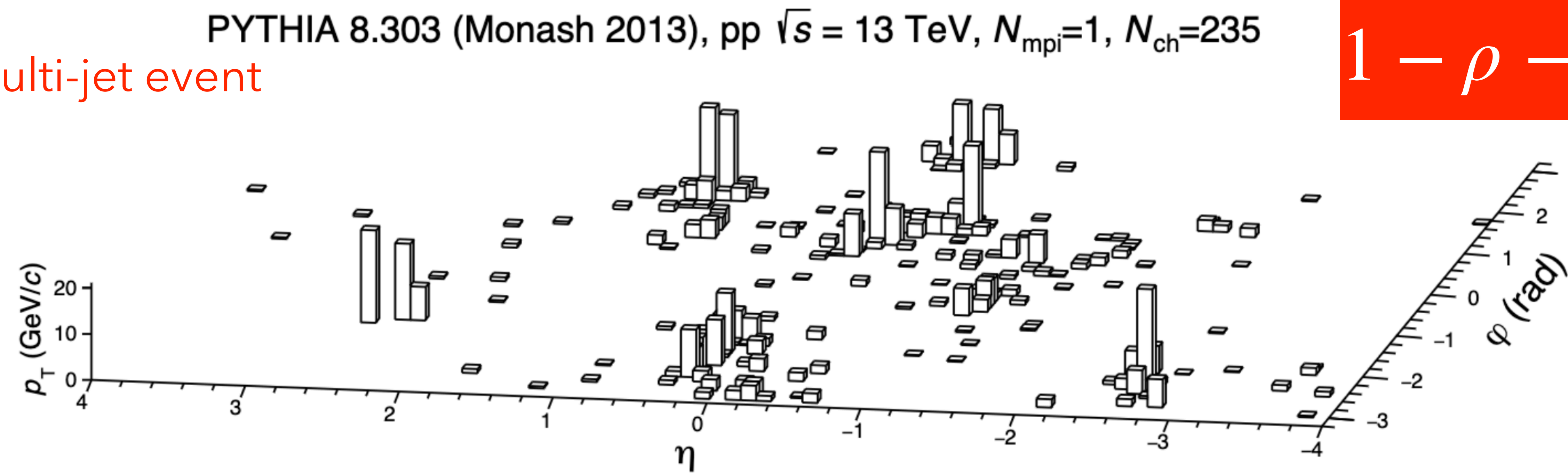
$N_{\text{ch}}^{\text{cell},i}$: particle multiplicity per cell.

$\langle N_{\text{ch}}^{\text{cell}} \rangle$: average over the number of cells.

Event classification: Charged particle flattenicity

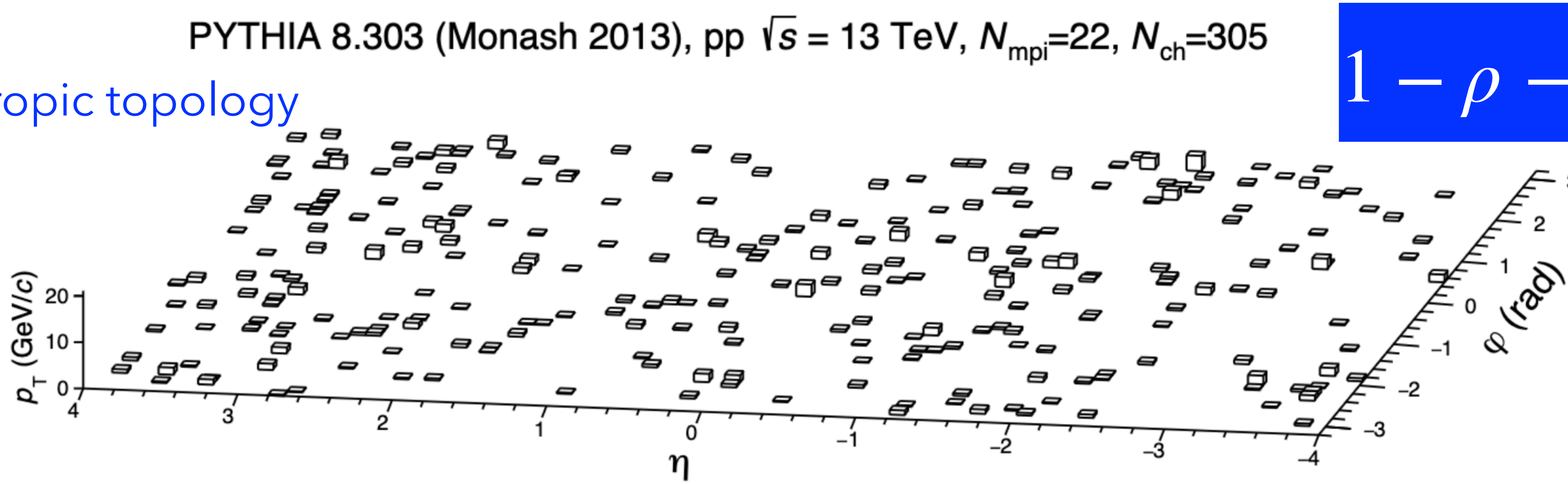
Multi-jet event

$1 - \rho \to 0$



Isotropic topology

$1 - \rho \to 1$



Phys.Rev.D 107 (2023) 7

Flattenicity with the V0 detector

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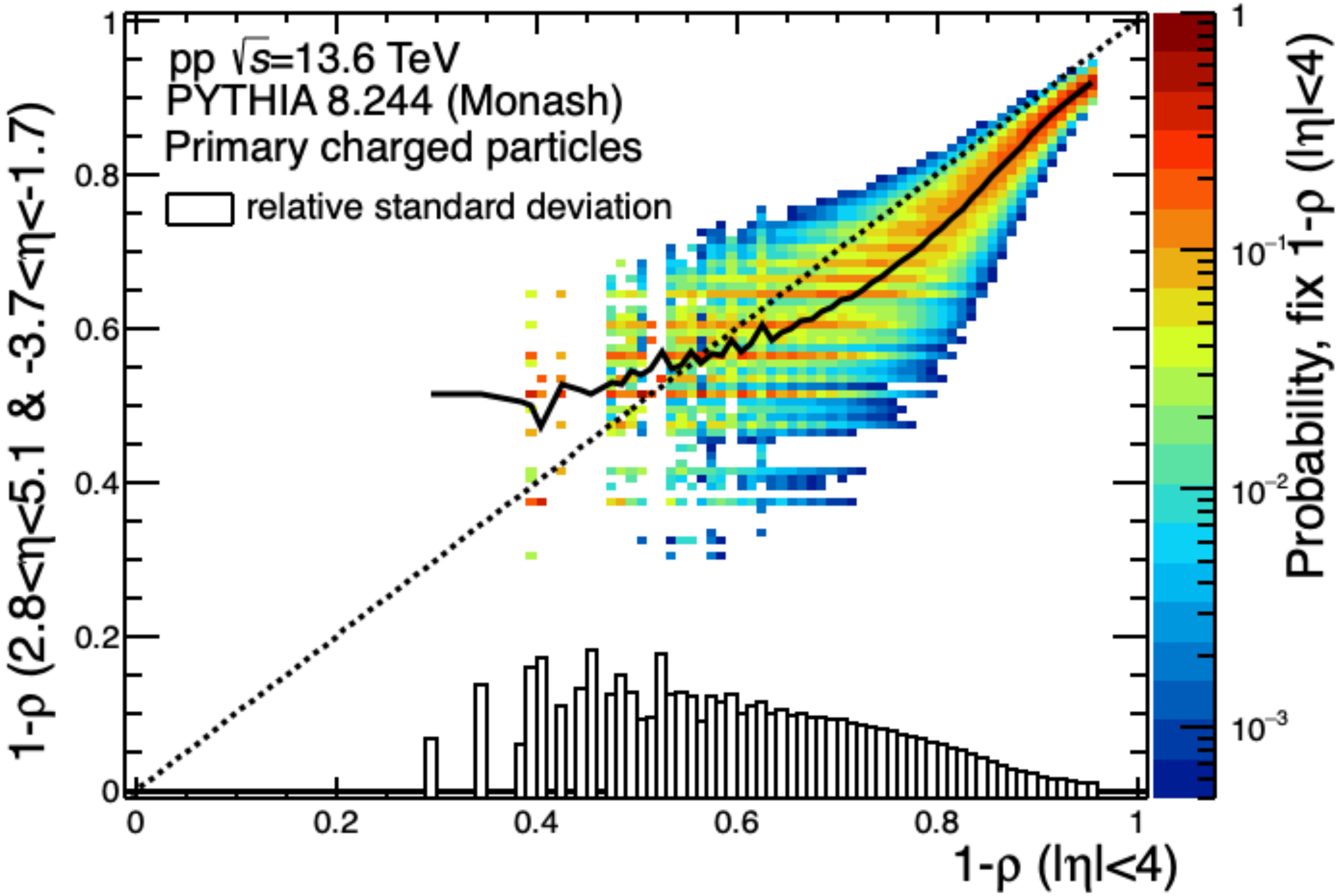
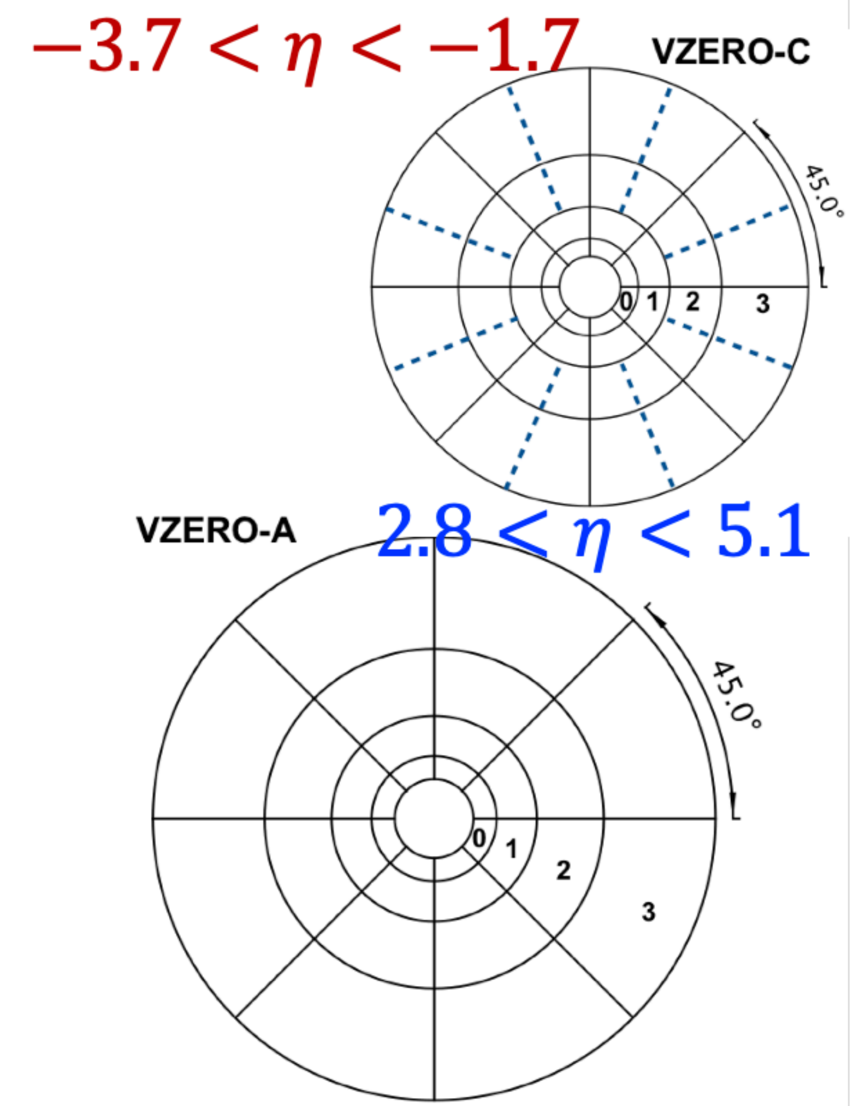
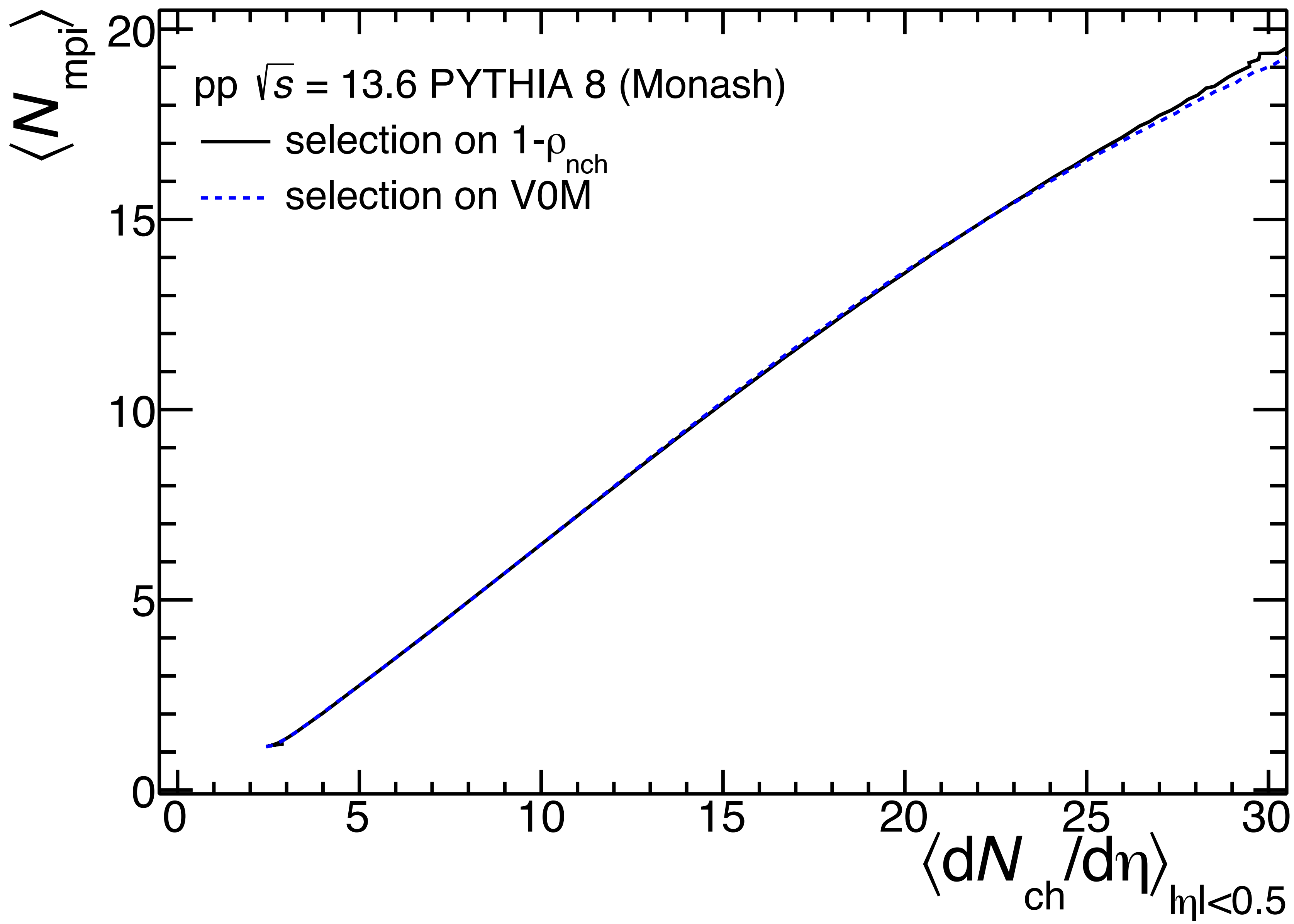




Flattenicity measured with the V0 → sensitive to the global shape

Sensitivity of flattenicity to MPIs



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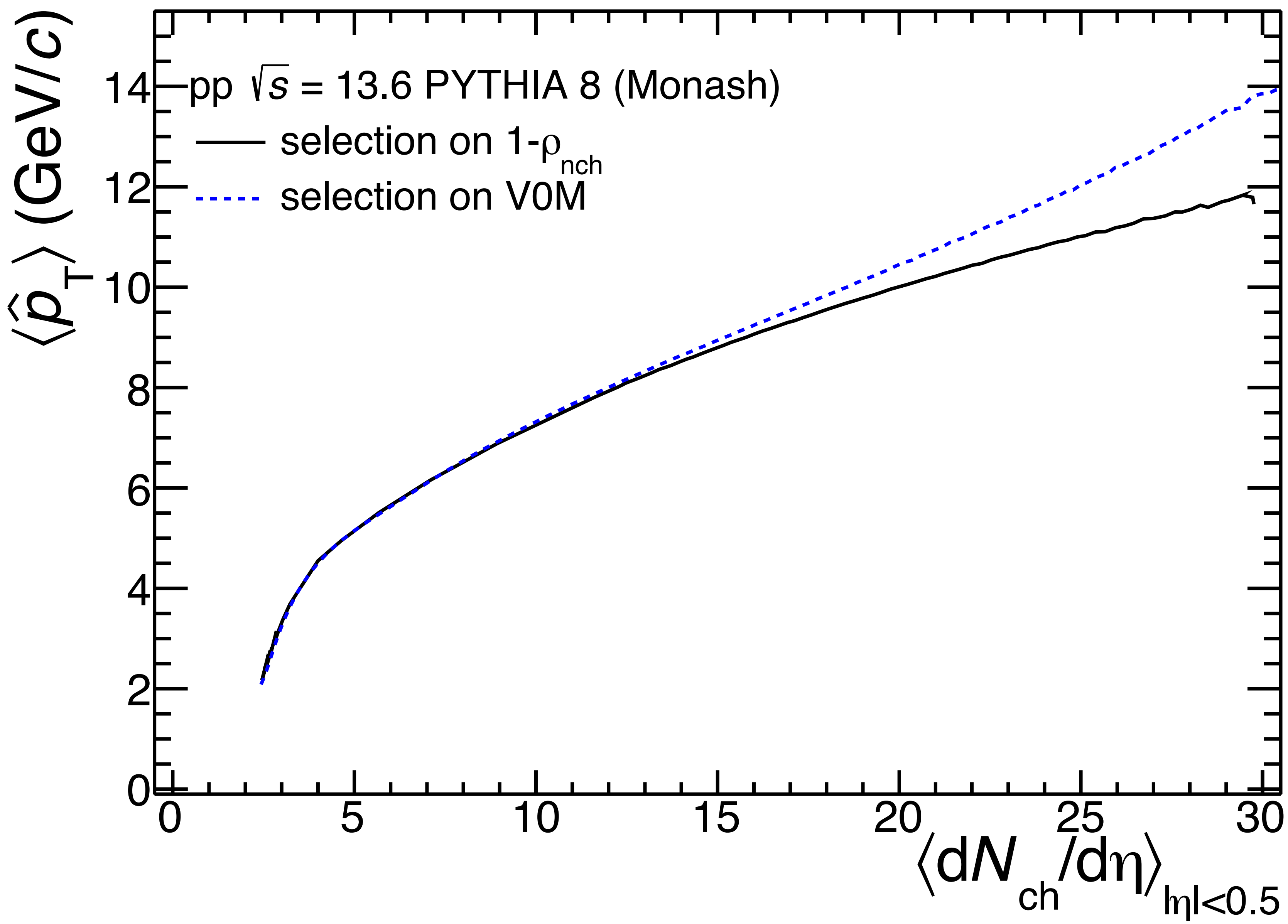
Flattenicity and the V0M estimator yield similar sensitivity to MPIs

Sensitivity of flattenicity to MPIs

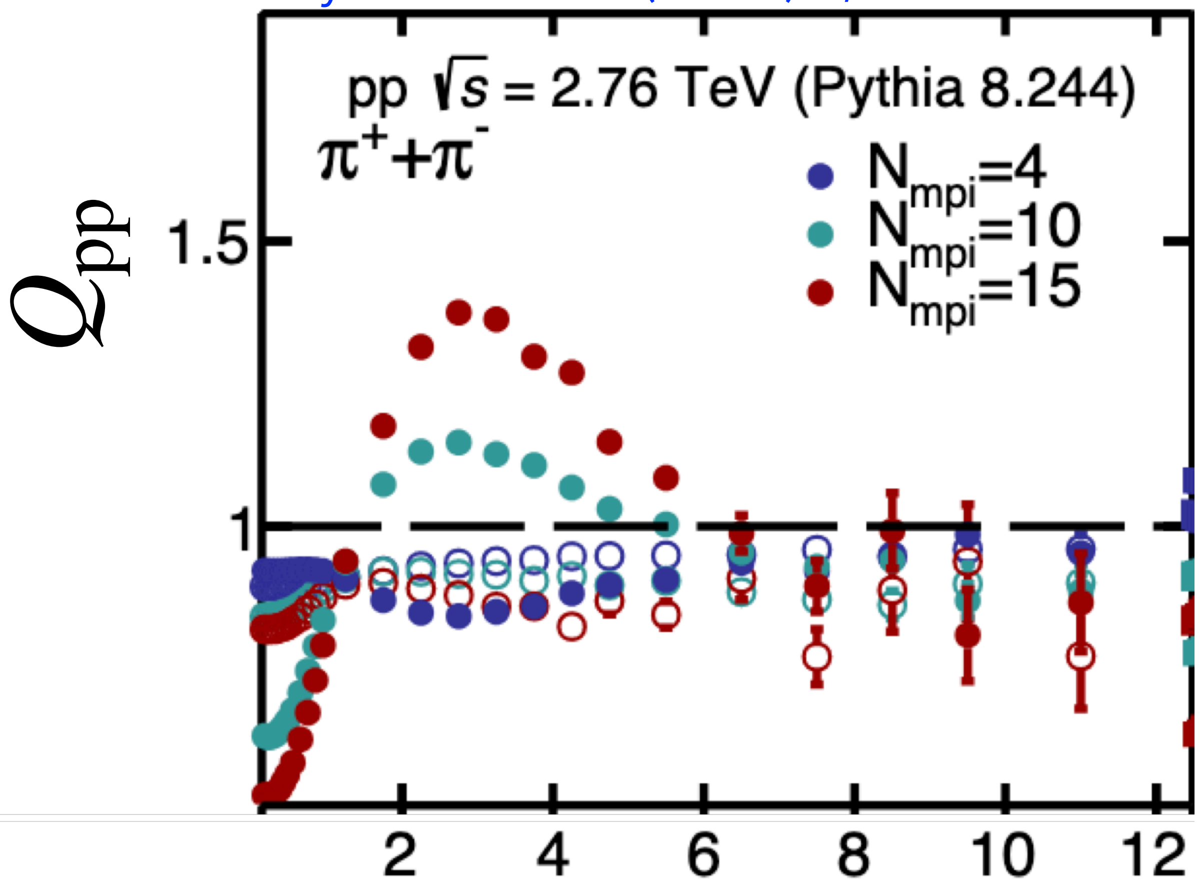


Phys.Rev.D 107 (2023) 7

Flattenicity and the V0M estimator yield similar sensitivity to MPIs

Expected effects from MPIs

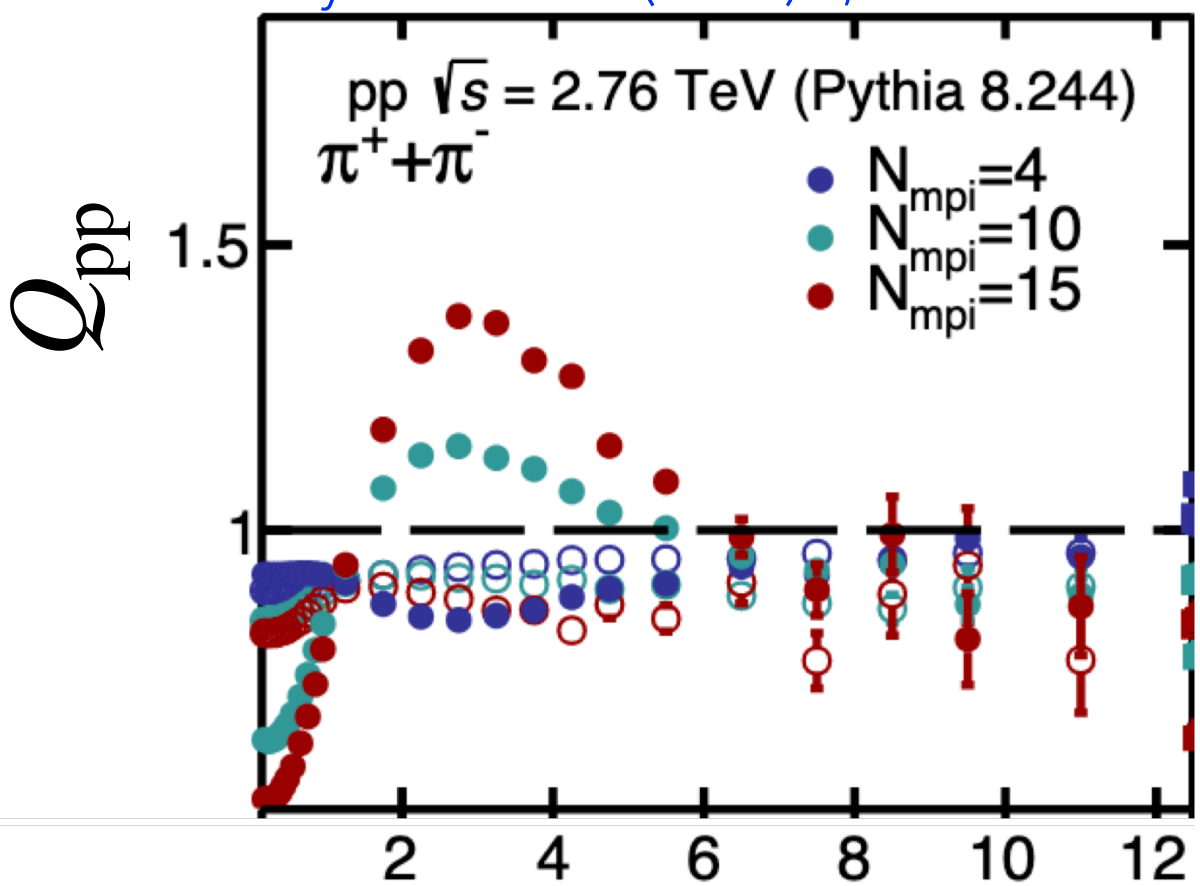
Phys.Rev.D 102 (2020) 7, 076014



$$Q_{\mathrm{pp}} = \frac{\mathrm{d}N_{\mathrm{ch}}^{N_{\mathrm{mpi}}} / \langle N_{\mathrm{mpi}} \rangle \mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{ch}}^{\mathrm{MB}} / \langle N_{\mathrm{mpi}}^{\mathrm{MB}} \rangle \mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$$

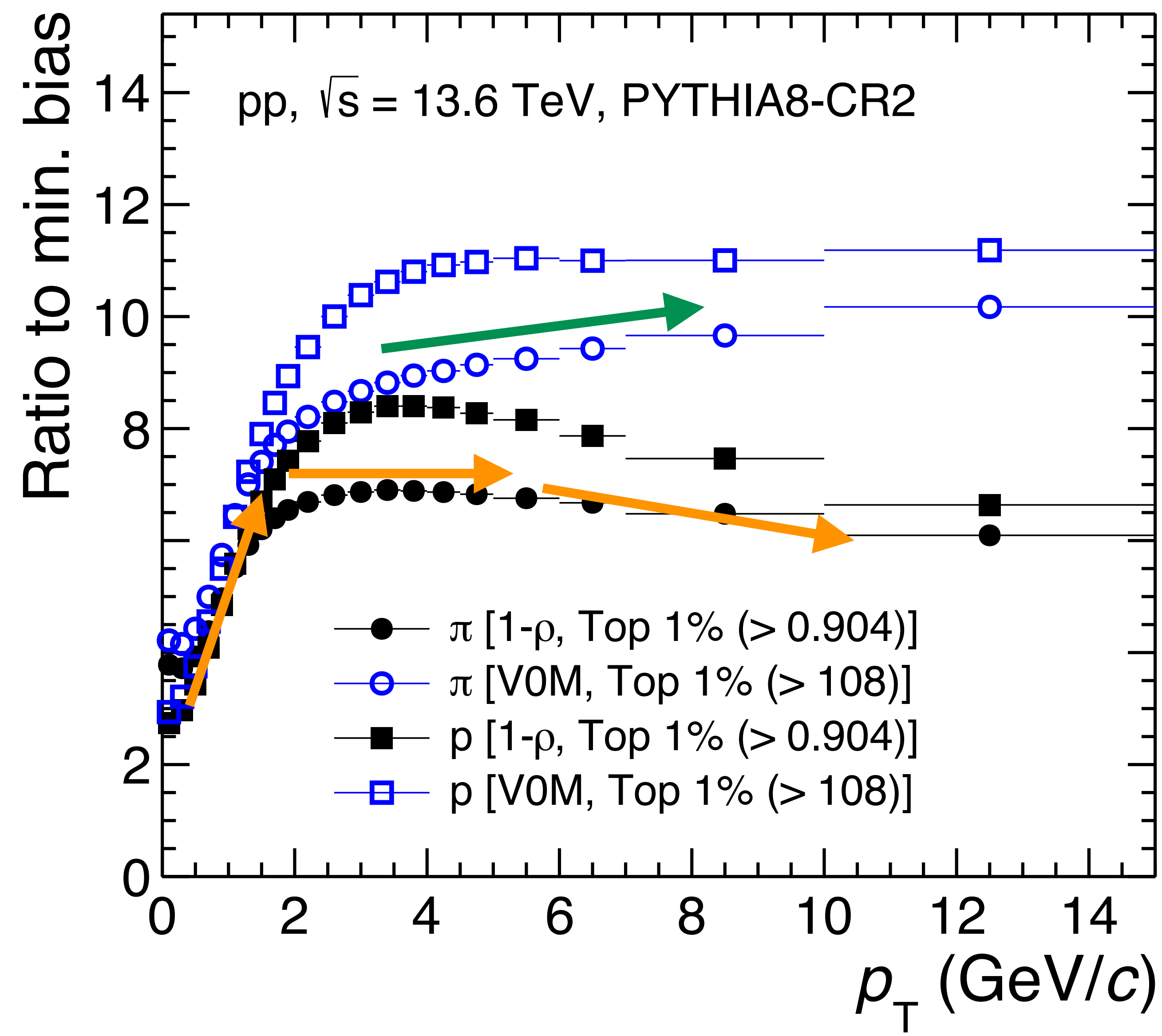
Expected effects from MPIs with PYTHIA

Phys.Rev.D 102 (2020) 7, 076014



$$Q_{pp} = \frac{dN_{ch}^{N_{mpi}}/\langle N_{mpi}\rangle d\eta dp_T}{dN_{ch}^{MB}/\langle N_{mpi}^{MB}\rangle d\eta dp_T}$$

Phys.Rev.D 107 (2023) 7



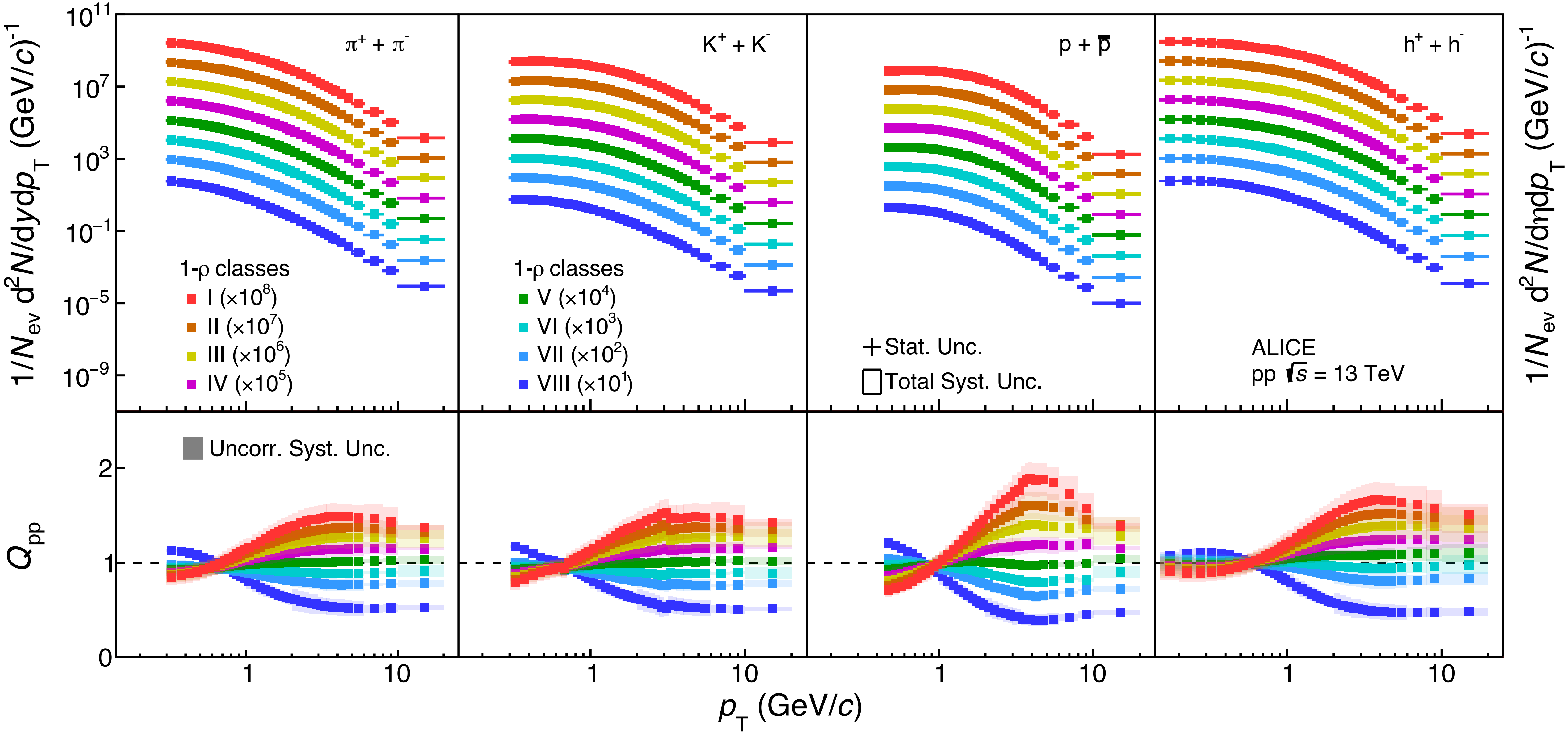
V0M: HM events are bias towards hard pp collisions.

Flattenicity: A bump is observed in the p_T interval 1-8 GeV/c.

The high-p_T yield decreases instead.

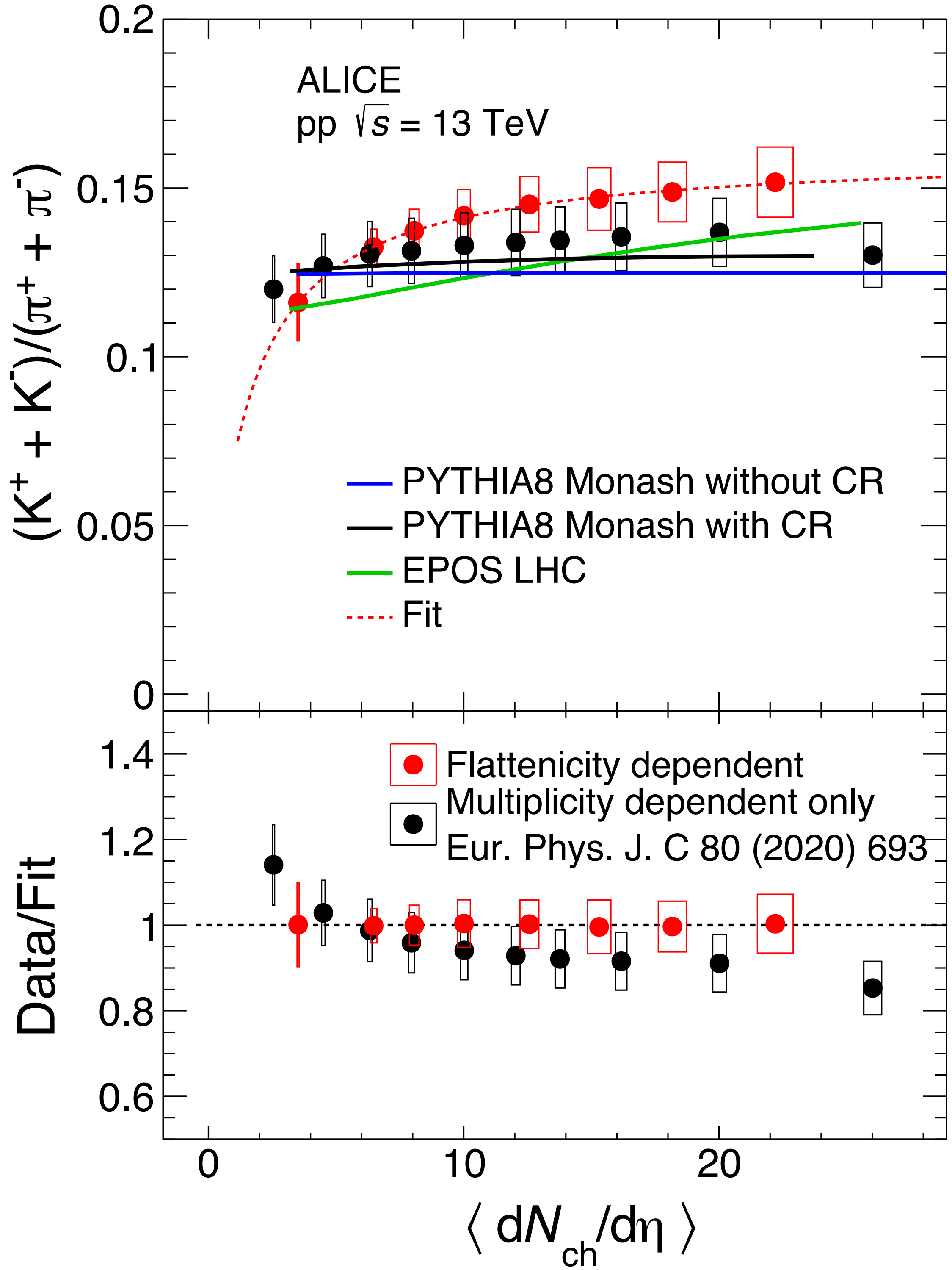
Particle production vs. flattenicity

$$Q_{pp} = \frac{dN_{ch}^{1-\rho}/\langle dN_{ch}/d\eta\rangle^{1-\rho} d\eta dp_T}{dN_{ch}^{MB}/\langle dN_{ch}/d\eta\rangle^{MB} d\eta dp_T}$$



Bump structure in the Q_{pp}, similar to the selection based on MPIs.

p_T-integrated particle ratios

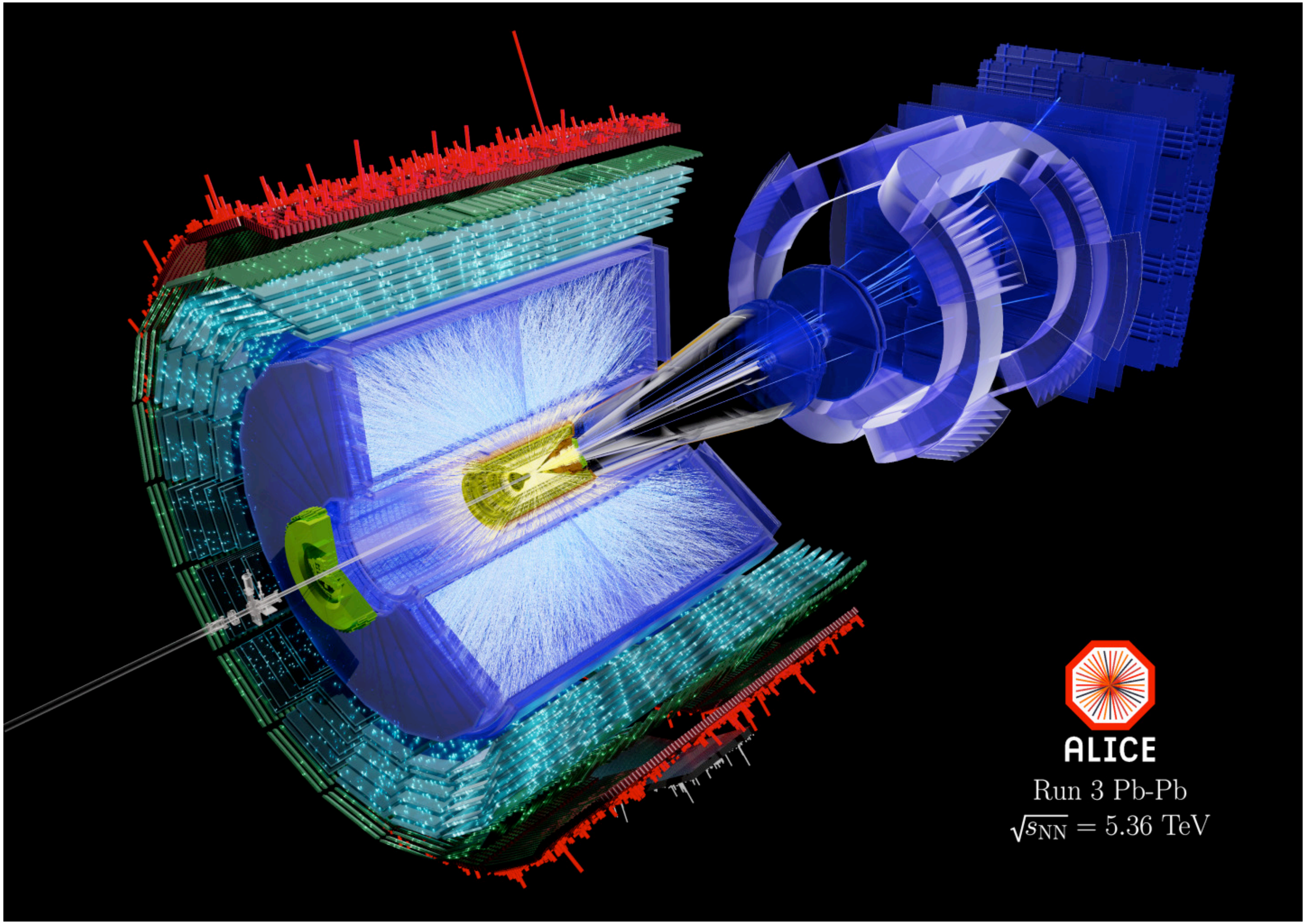


Is flattenicity sensitive to strangeness enhancement?

Summary (2/2)

- A selection based on flattenicity selects events with a large number of MPIs.
- Flattenicity seems to be more robust against selection biases.

This ain’t over yet…

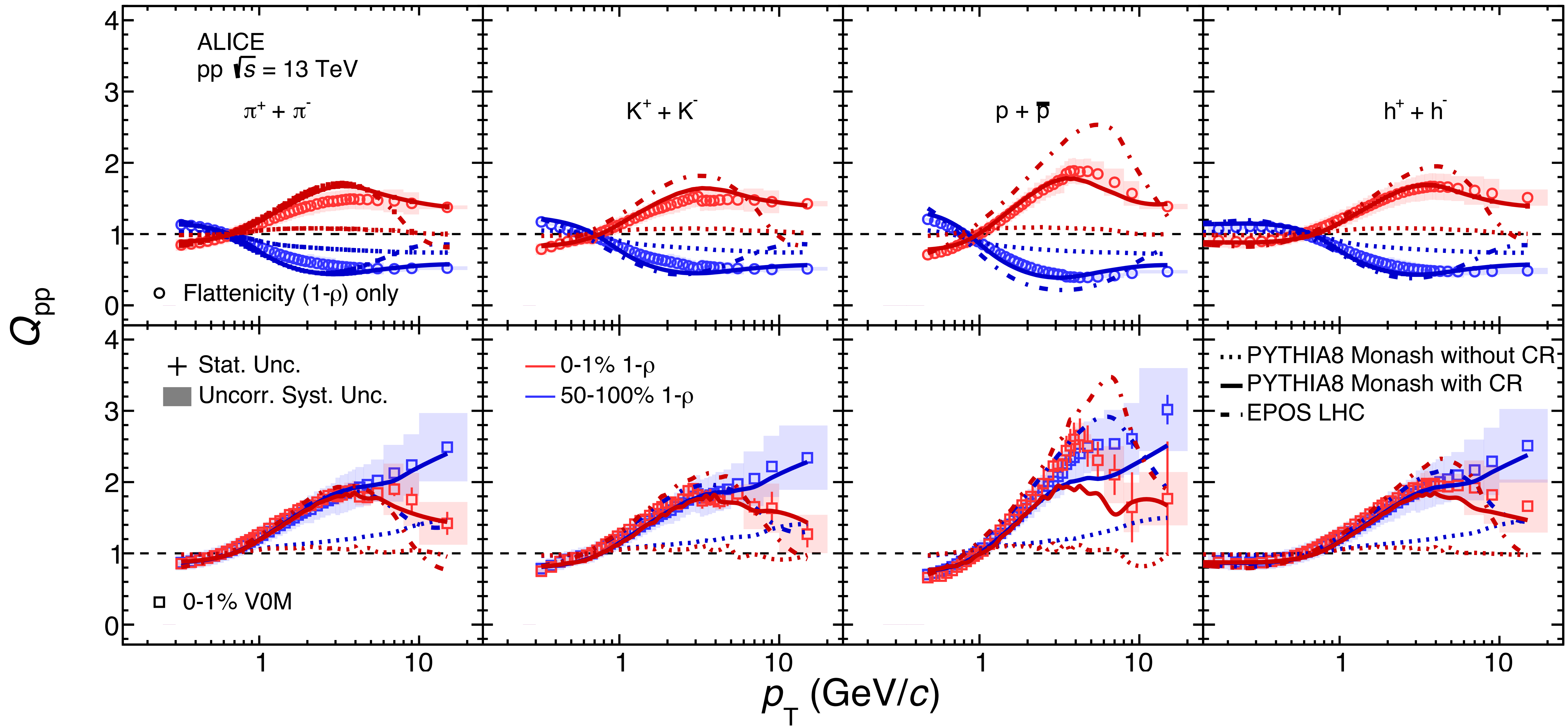


During the Run 3, ALICE recorded about 12 billion PbPb collisions – 40 times more collisions than the total recorded by ALICE between 2010 to 2018.

Backup

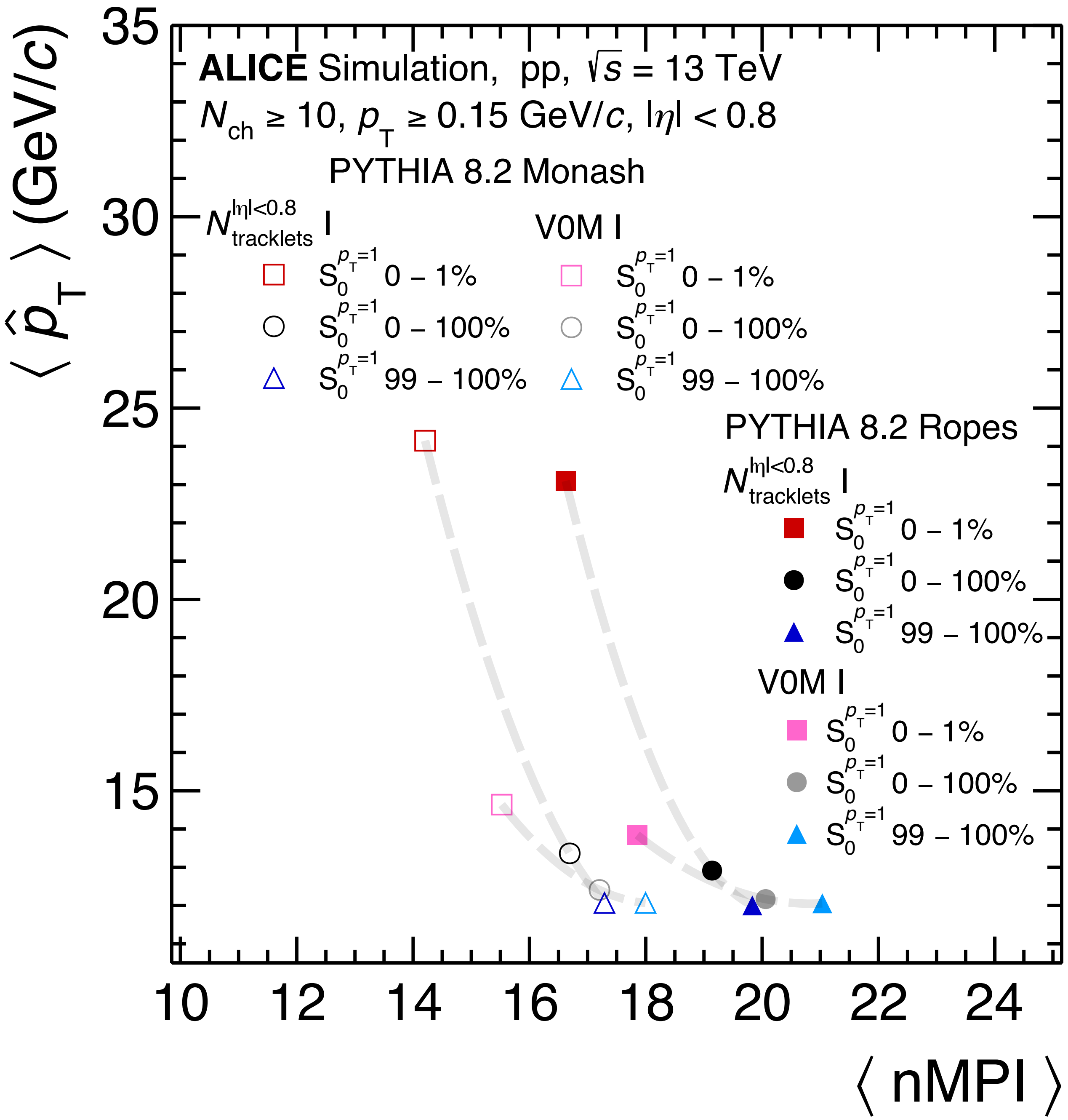
Particle production vs. flattenicity

$$Q_{pp} = \frac{dN_{ch}^{1-\rho}/\langle dN_{ch}/d\eta \rangle^{1-\rho} d\eta dp_T}{dN_{ch}^{MB}/\langle dN_{ch}/d\eta \rangle^{MB} d\eta dp_T}$$



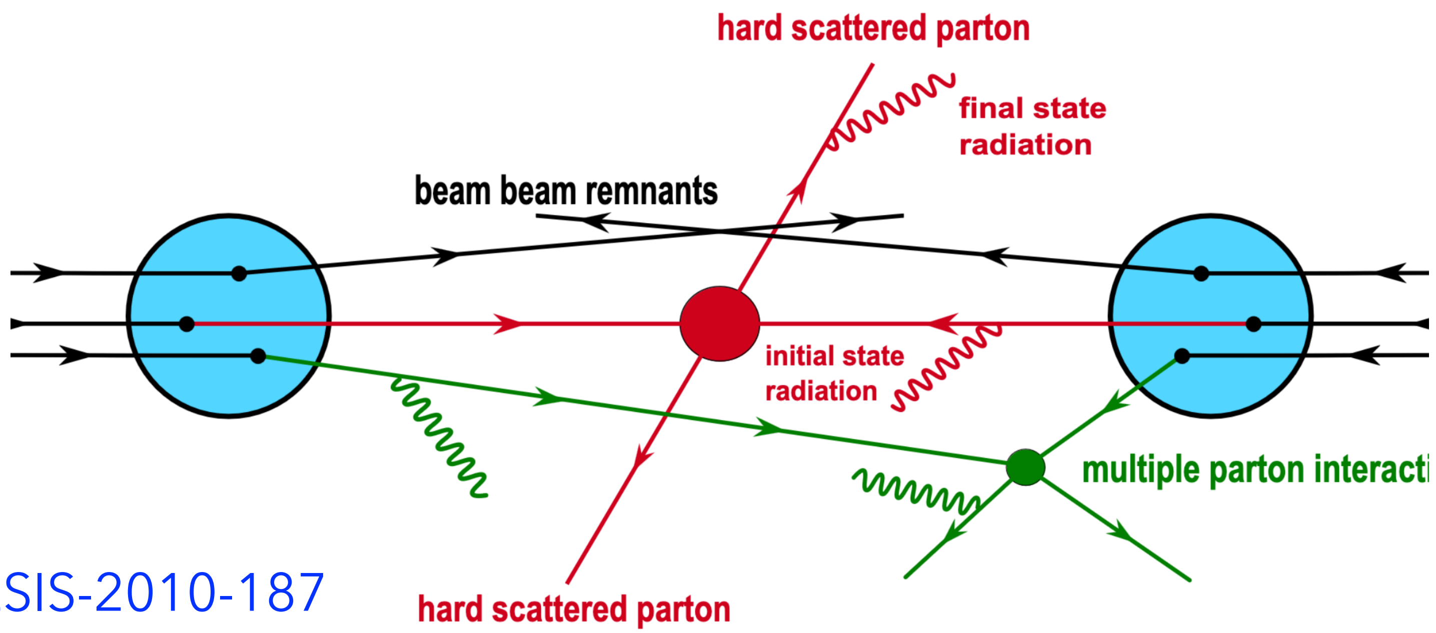
PYTHIA 8 Monash with MPI and CR effects describe well the data.

Event shapes: Spherocity



The paradigm of pp collisions (small systems)

- Old paradigm: reference systems to isolate QGP effects in heavy-ion collisions (for example R_{AA}).
- Very different reality: pp collisions are already very complex systems.
  - QGP signatures are observed in these systems: collective-like effects, strangeness enhancement…
- pp collisions are the sum of several sub-interactions at different energy scales according to the energy of the incoming partons.
  - Hard processes: interactions between hard scattered partons.
  - Underlying event: multiple parton interactions (MPI), beam remnants interactions + initial- and final-state radiation (ISR/FSR).
- The basic idea of this study is the separation between interactions at a high energy scale and soft partonic sub-interactions.



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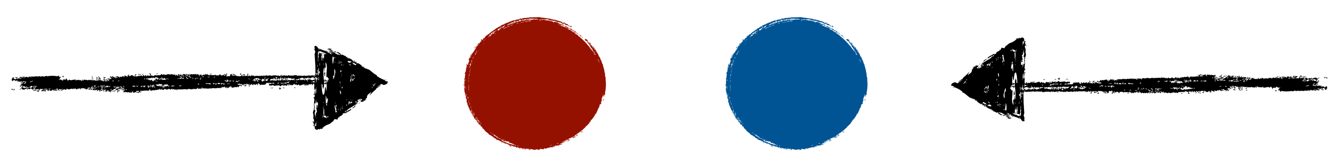
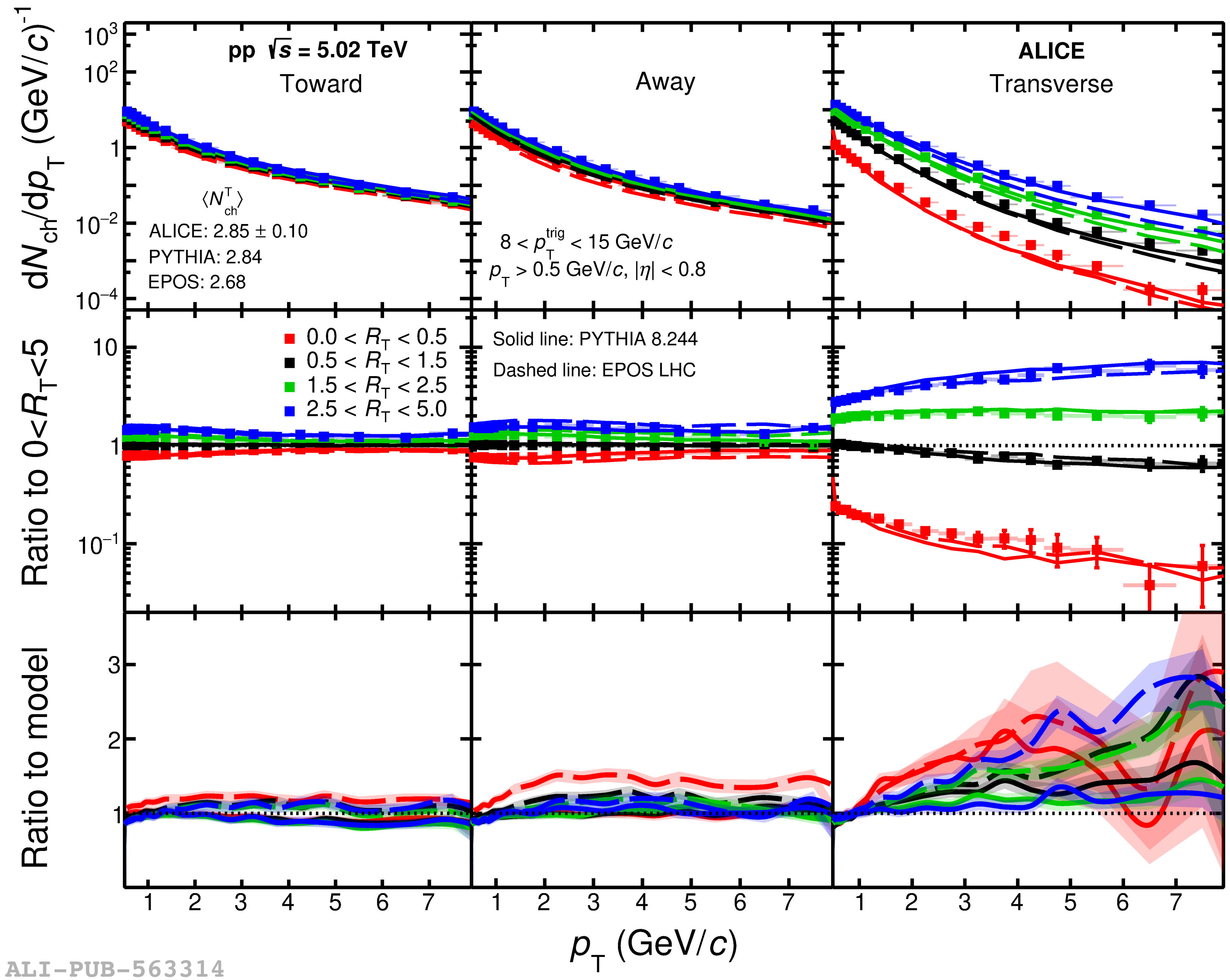
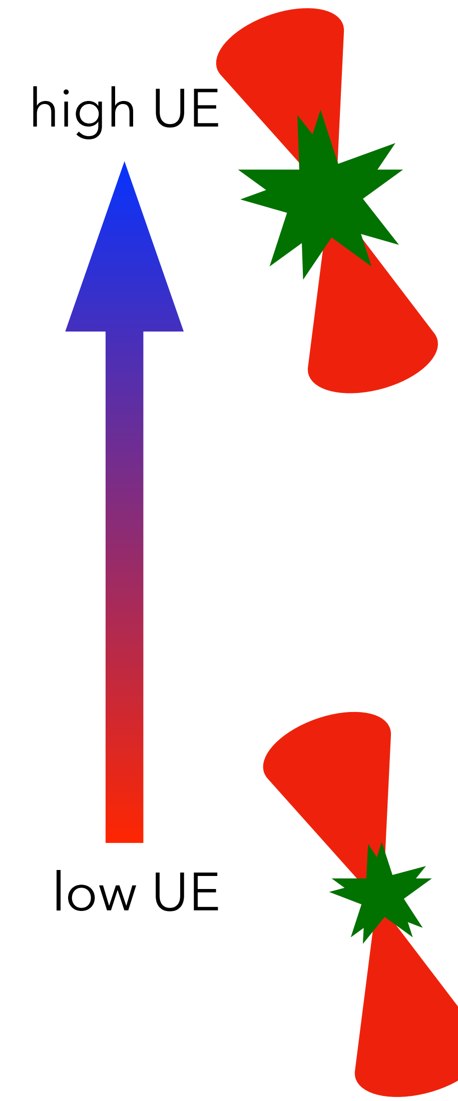
Charged particle production v.s. R_T

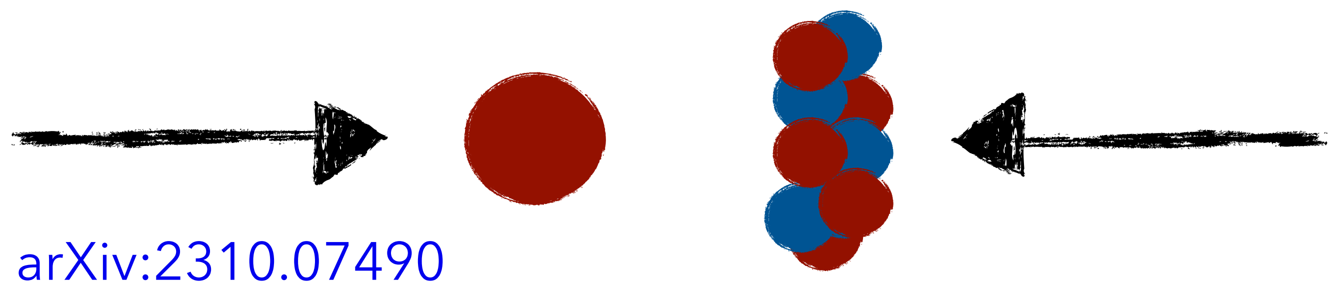


arXiv:2310.07490

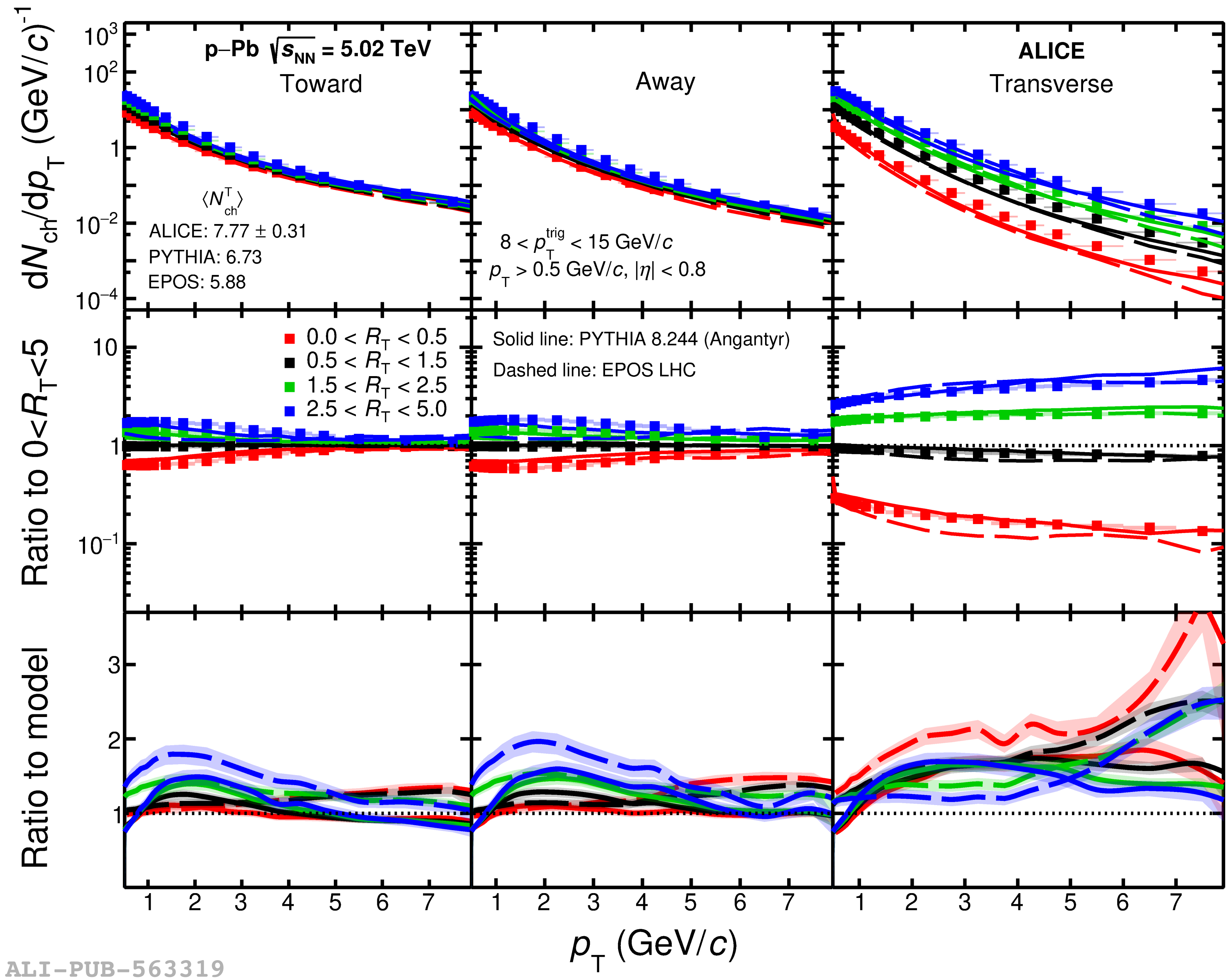


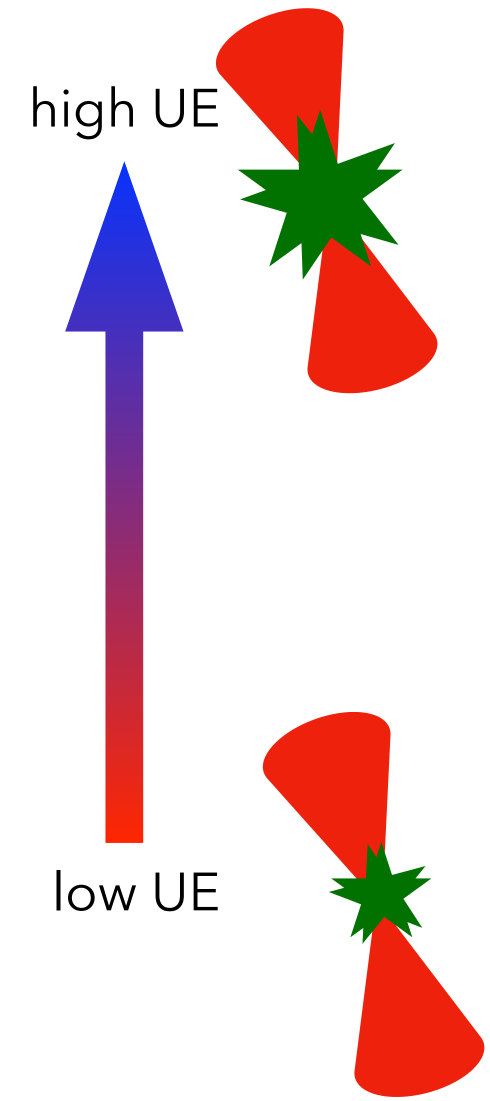


Charged particle production v.s. R_T

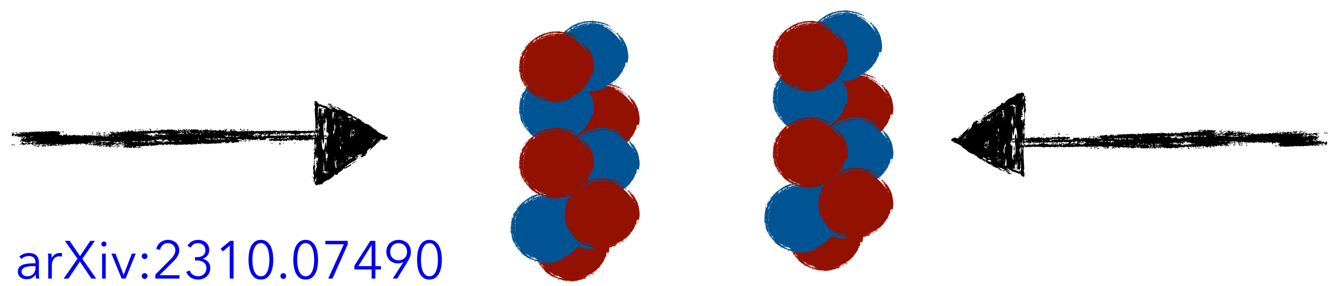


arXiv:2310.07490





Charged particle production v.s. R_T



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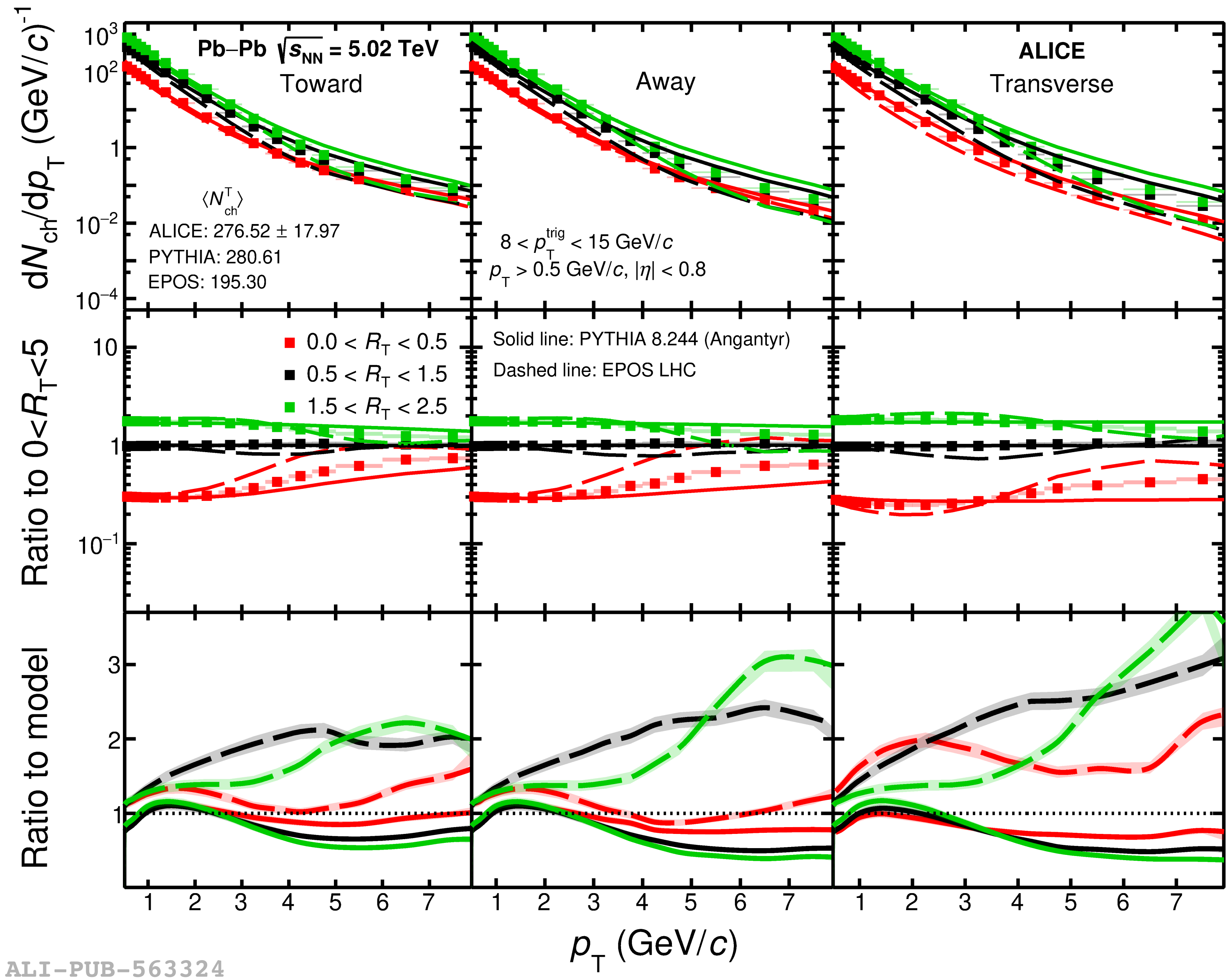
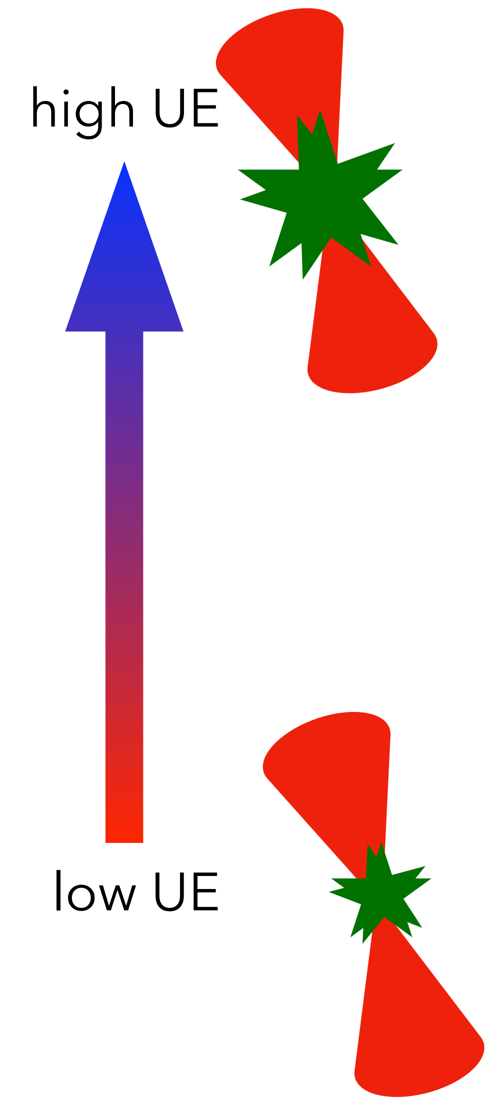
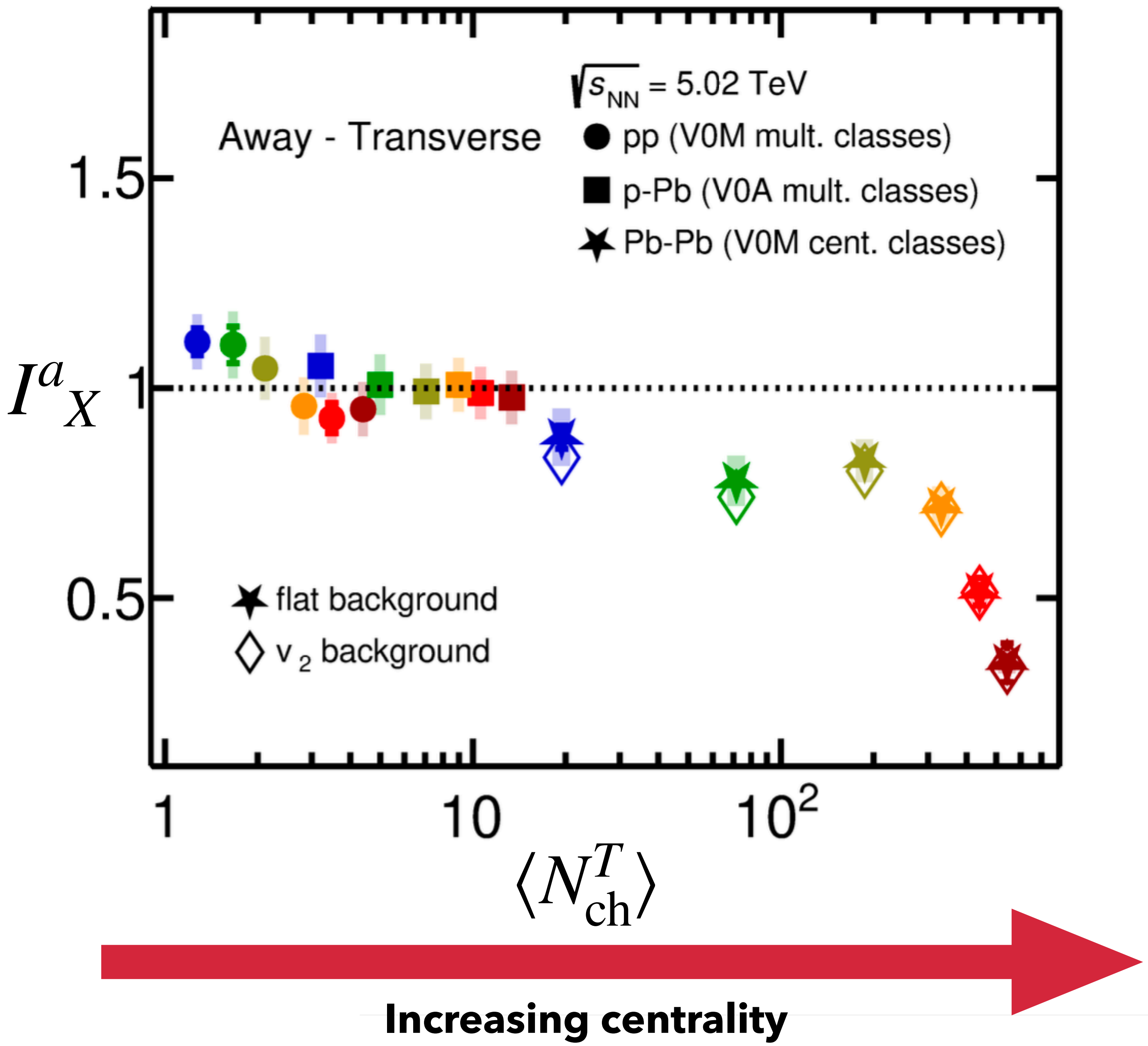




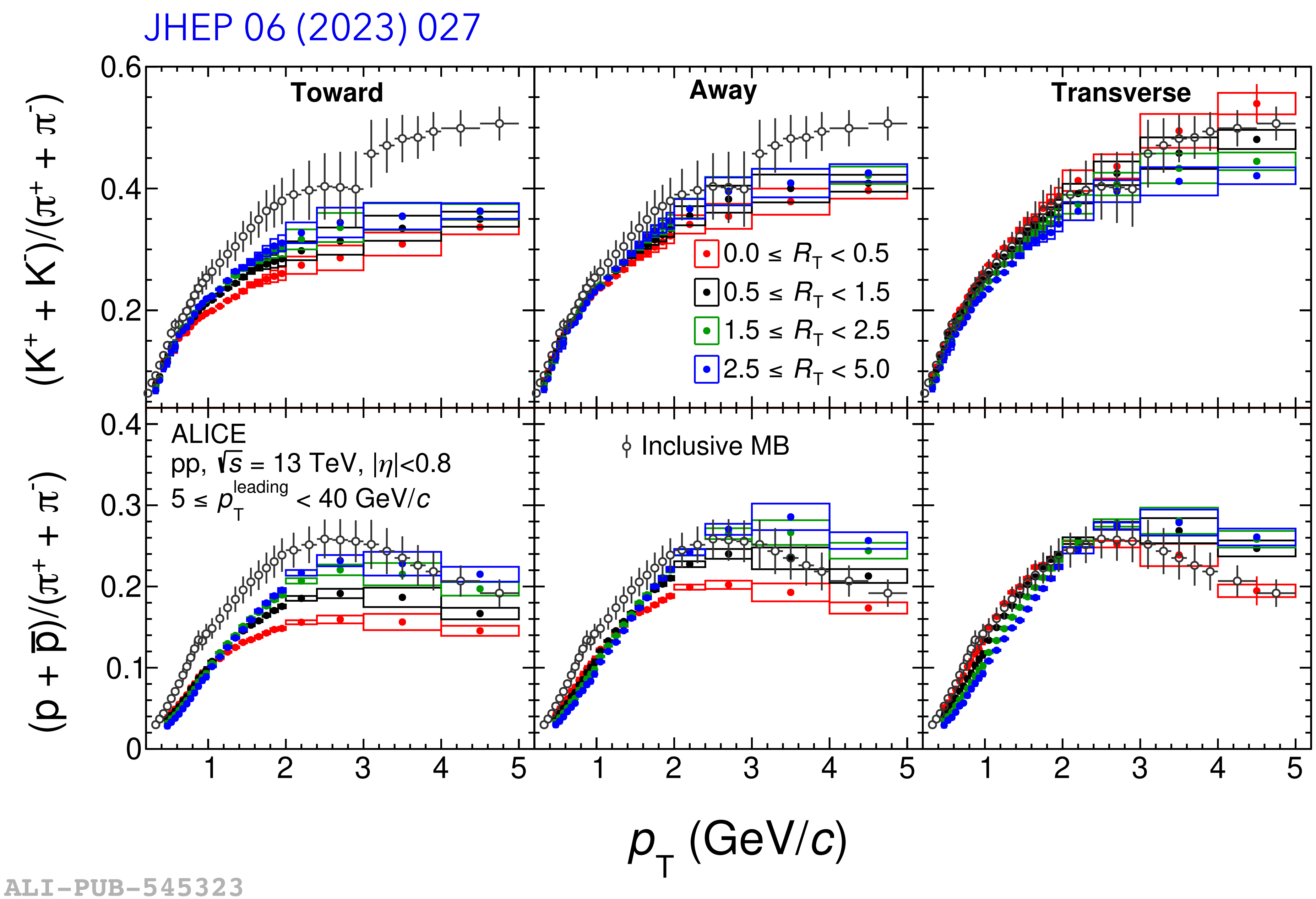
I_X as a function of $\langle N_T \rangle$ (away region)

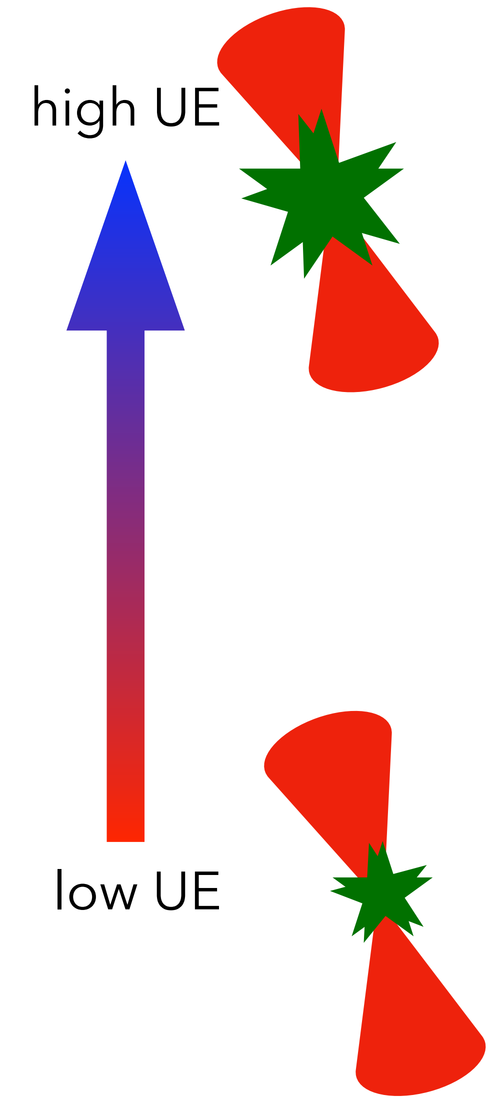
Phys. Lett. B 843 (2022) 137649



- Strong suppression of the jet-like yields with increasing centrality in Pb–Pb.
  - Medium effects: jet-quenching.
- The jet-like yields are consistent with unity in pp and p–Pb collisions.
  - No indication of jet-like modifications in small systems.

Particle ratios as a function of R_T

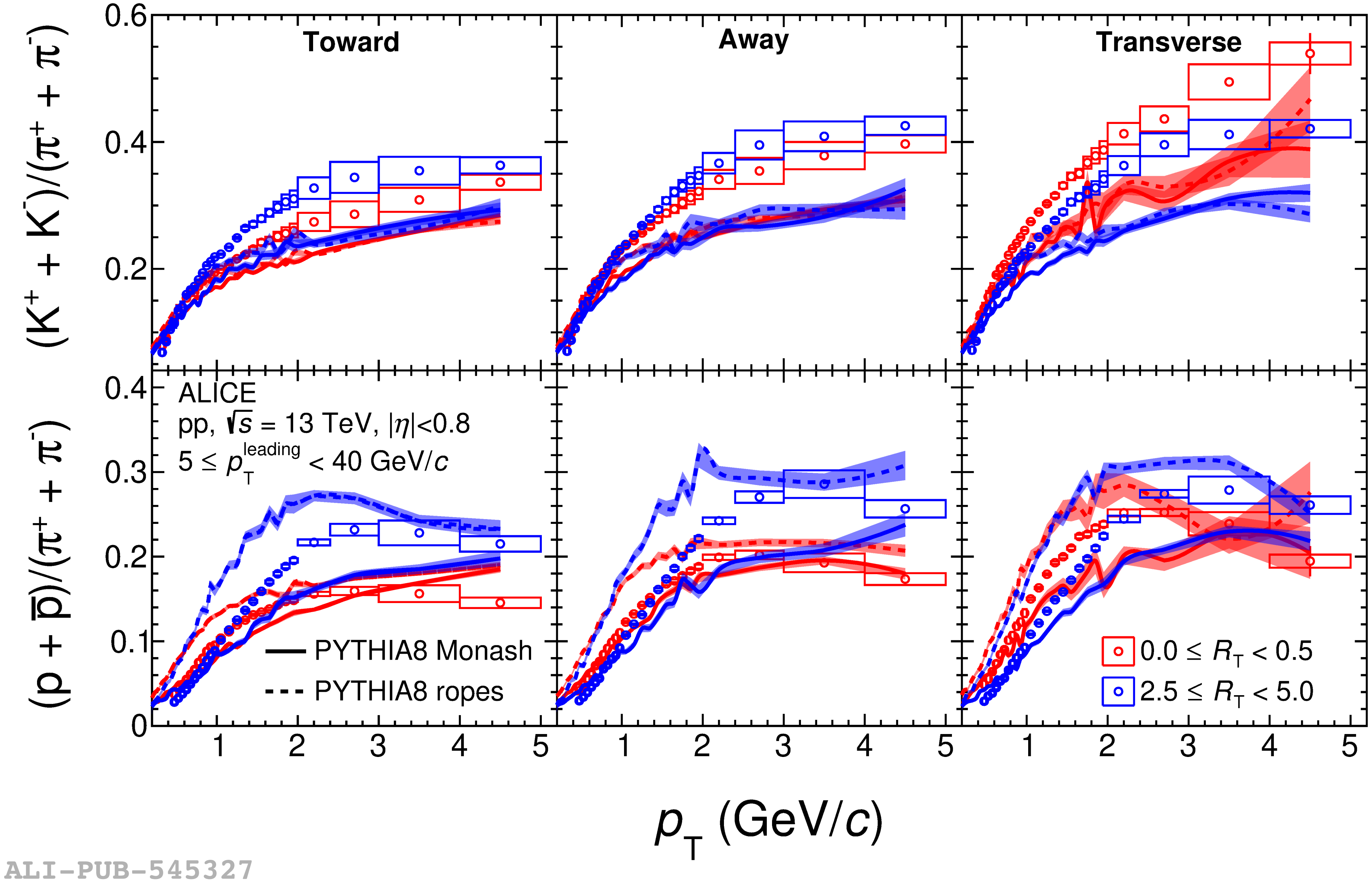


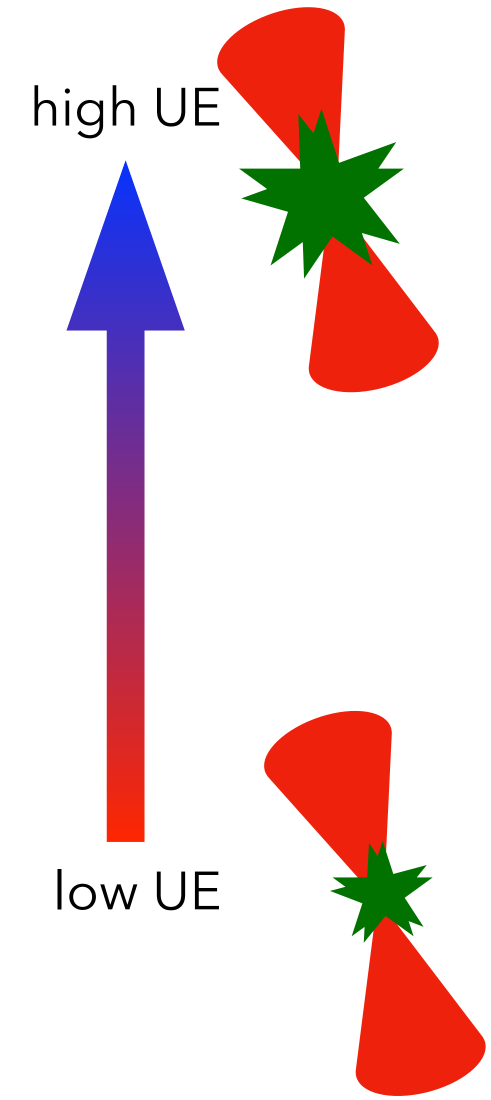


- Clear evolution of the p/π ratios with increasing R_T in the toward region.
- The enhanced baryon-to-meson ratios can be attributed to radial flow effects.
- The p/π and K/π varies little as a function of R_T in the transverse region.

Particle ratios as a function of R_T

JHEP 06 (2023) 027





- PYTHIA 8 Monash tune can only describe qualitatively the particle ratios in the toward and away regions for $0 \leq R_T < 0.5$. This is expected since it is tuned to reproduce jet-like e^+e^- measurements.
- PYTHIA 8 with ropes predicts an increasing p/π with increasing UE activity.