First observation of strange baryon enhancement with effective energy in pp collisions at the LHC

https://arxiv.org/pdf/2409.12702

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ALICE

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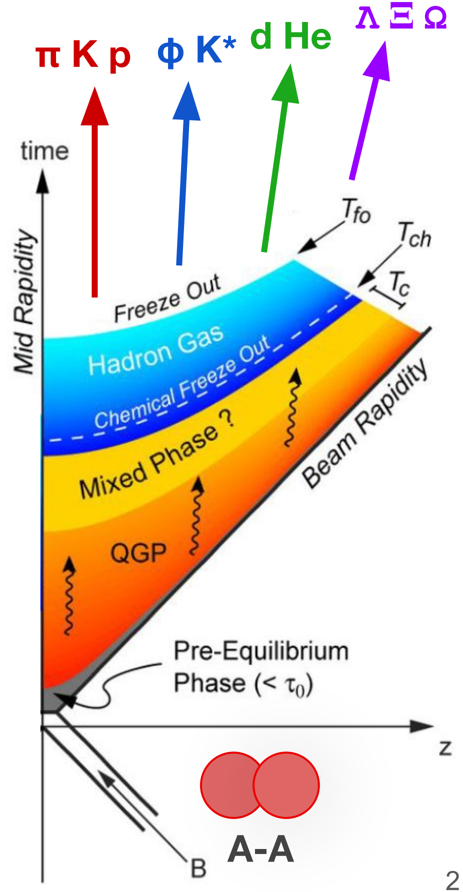
High energy hadronic collisions

QCD phase transition from hadronic matter to a deconfined state of quarks and gluons: **Quark Gluon Plasma** (QGP)

Studied in the **laboratory** with **collisions of heavy ions**

Light flavor quarks (u,d,s) are **thermally produced in the QGP** → key probes to study the properties of the medium



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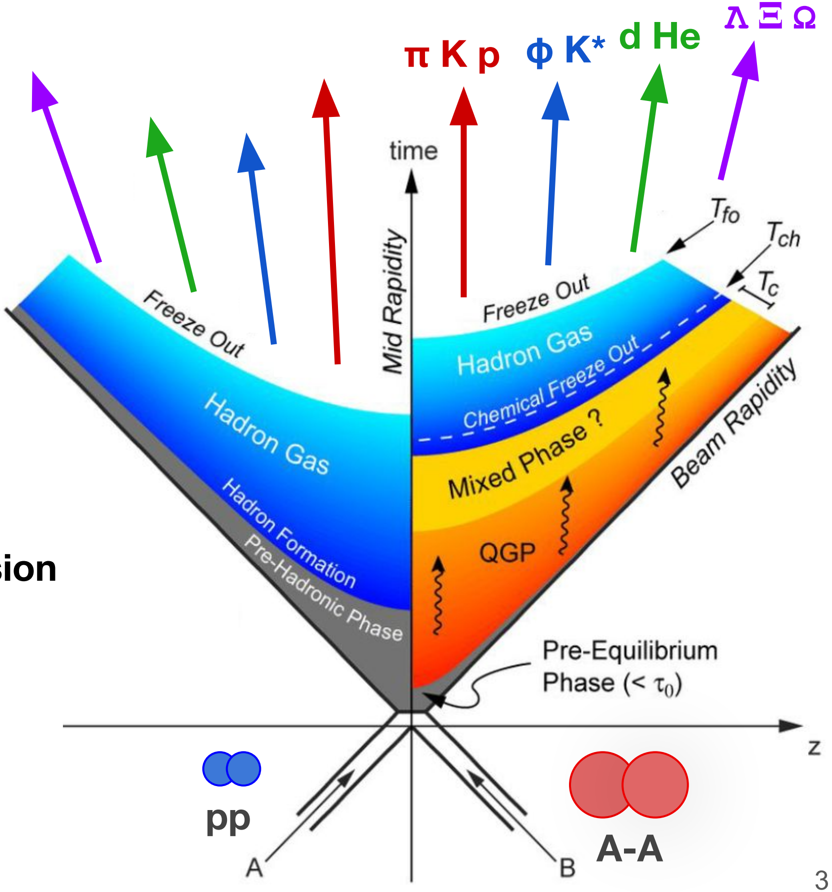
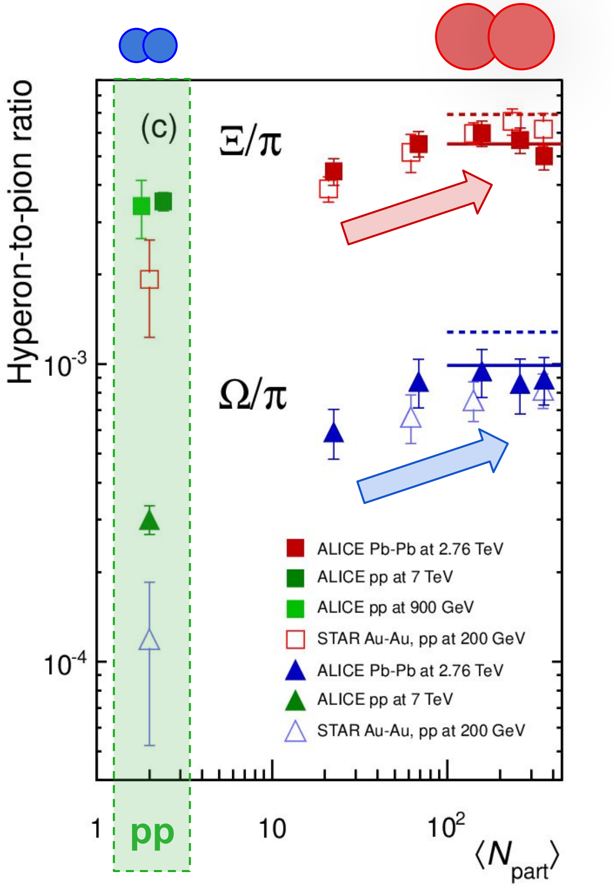
Identified particle production is **compared** with **small collision systems**, i.e. pp, where no QGP is expected (Hadron Gas)

Is there a way to **coherently describe** particle production across collision systems?



Strangeness enhancement: then



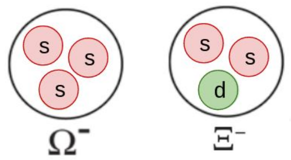
Strangeness enhancement is historically one of the first proposed signatures of QGP formation in heavy-ion collisions [1]

Increase of (multi-)strange hadron production in **heavy-ion** with respect to **minimum-bias pp** collisions

Saturation for central AA → grand-canonical SHM predictions [2]

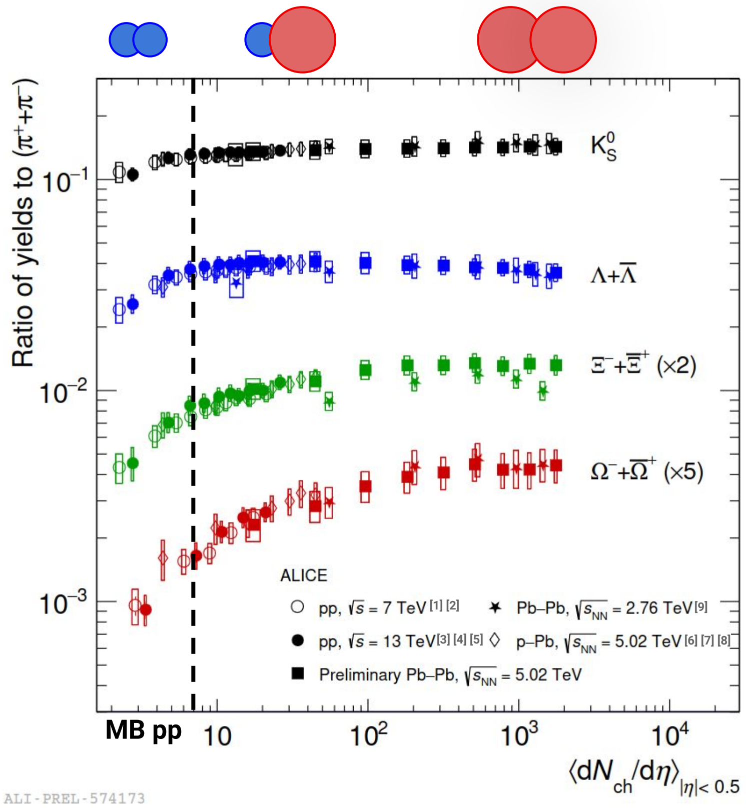
Expected **strangeness suppression in small systems** → finite system with hadronic degrees of freedom

GSI-Heidelberg: T_{ch} = 164 MeV [Andronic et al, PLB 673 (2009) 142]
THERMUS: T_{ch} = 170 MeV [Cleymans et al, PRC 74 (2006) 034903]



[1] P. Koch, B. Müller, and J. Rafelski. Physics Reports, 142(4):167–262, 1986
[2] ALICE, PLB 728 (2014) 216-227

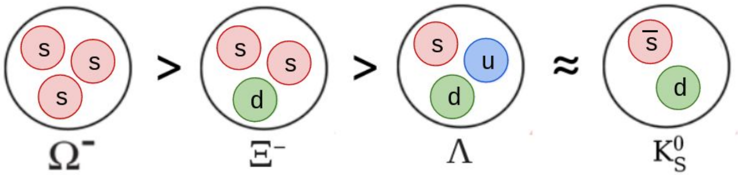
Strangeness enhancement: now



Continuous evolution of strange hadron yield ratios to pions **with the charged-particle multiplicity** observed at the LHC, smoothly connecting different systems and energies

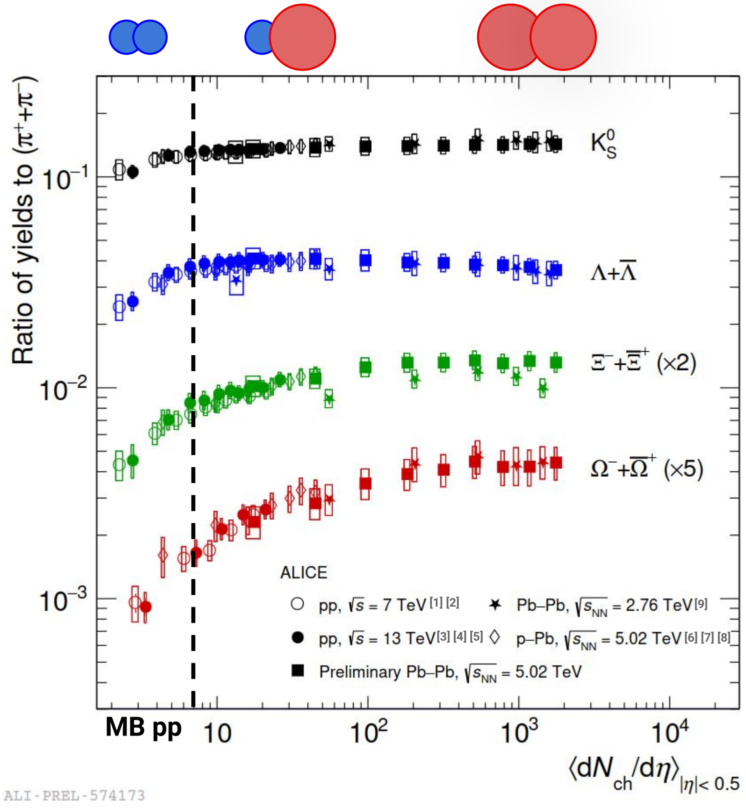
Strangeness production **increases with** particle **multiplicity**, saturating for central Pb–Pb

Strange content **hierarchy**: $|S_{\Omega^\pm}| > |S_{\Xi^\pm}| > |S_{\Lambda}| \approx |S_{K^0_S}|$



[1] Nature Phys. 13, 535-539 (2017)
[2] PRC 99, 02490 (2019)
[3] EPJC 80, 167 (2020)
[4] EPJC 80, 693 (2020)
[5] PLB 807, 135501 (2020)
[6] PLB 728, 25-38 (2014)
[7] PLB 758, 389-401 (2016)
[8] EPJC 76, 245 (2016)
[9] PRC 101, 044907 (2020)

Strangeness enhancement: now



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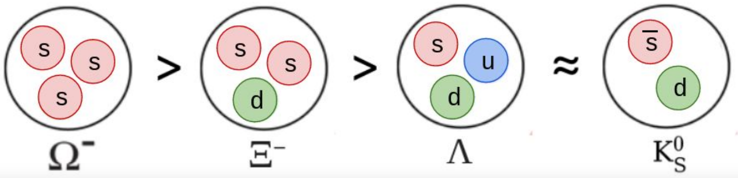

Is the charged-particle multiplicity the driving factor in this effect?

[1] Nature Phys. 13, 535-539 (2017)
[2] PRC 99, 02490 (2019)
[3] EPJC 80, 167 (2020)
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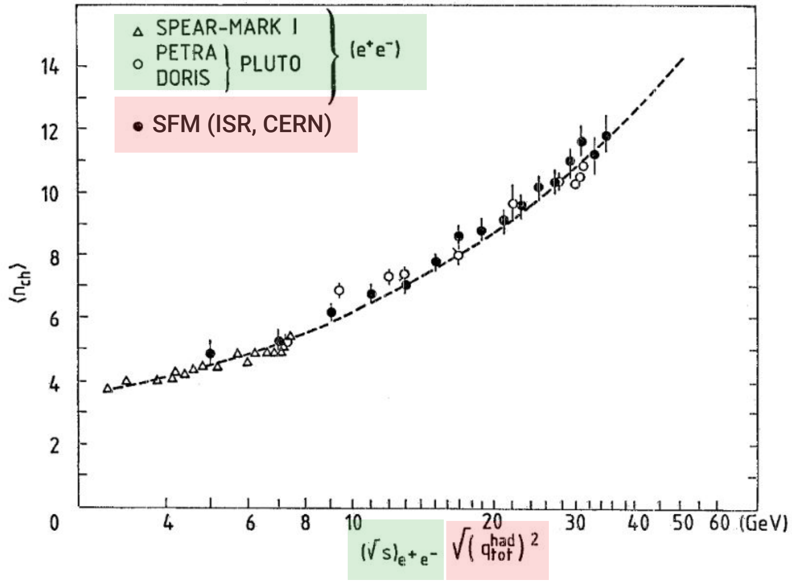
The concept of effective energy



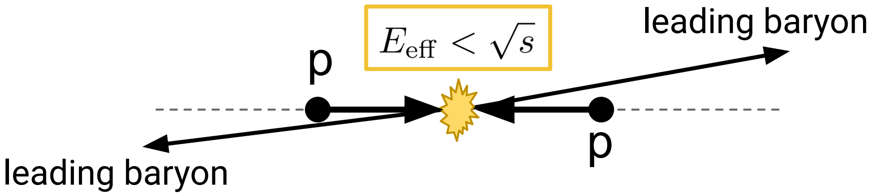
$$E_{\text{effective}} \equiv \sqrt{(\boldsymbol{q}_{\text{tot}}^{\text{had}})^2} = \sqrt{(\boldsymbol{q}_{\text{tot}}^{\text{inc}} - \boldsymbol{q}_{\text{tot}}^{\text{lead}})^2}$$

A new point of view: consider other observables correlated with the charged particle multiplicity

Effective energy: energy available for particle production in the initial stages of the collision

In **pp** reduced due to leading baryon emission at very forward rapidity (**leading effect**)

First studies at the CERN ISR in the 80's lead by the Bologna group of Professor Zichichi



M. Basile et al., Phys. Lett. B 95 (1980) 311
A. Akindinov et al., EPJ C 50 (2007) 341–352

Analysis strategy

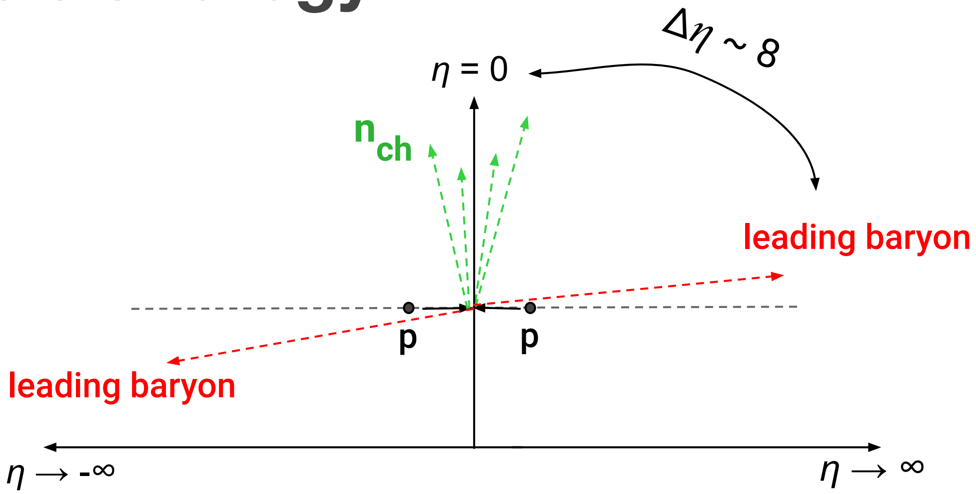
Two-dimensional analysis as a function of**:**

- **Charged-multiplicity at midrapidity**
  proxy for local effects,
  e.g. jet production

- **Leading energy**
  proxy for global effects, e.g. the
  initial effective energy in the collision

$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}}$$

Independent proxies given the large η separation

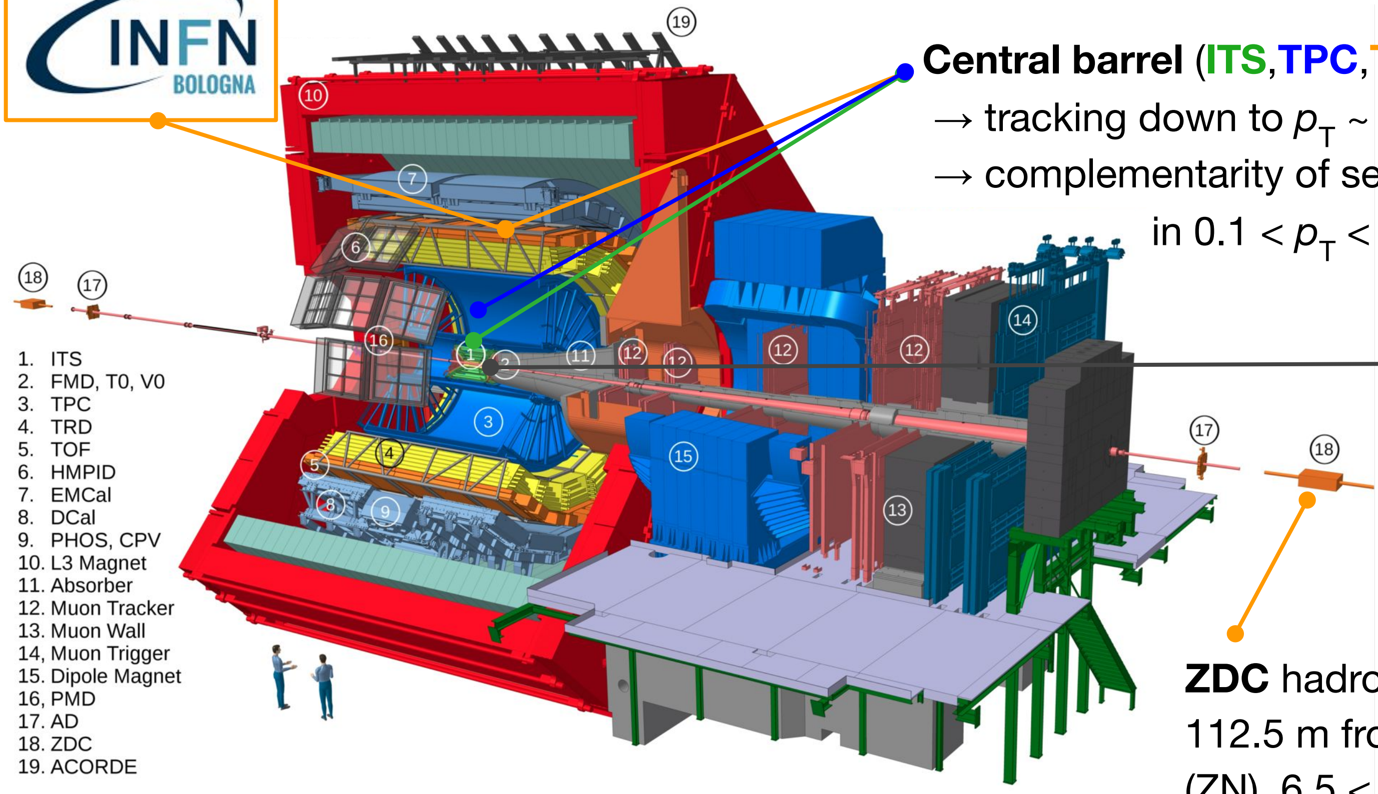


Key point:

What is the interplay of multiplicity and leading energy on strange hadron production?

The ALICE detector in Run 1 and 2

ALICE-TOF



1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

Central barrel (ITS,TPC,TOF): $|\eta| < 0.9$, B = 0.5 T
→ tracking down to p_T ~ 100 MeV/c
→ complementarity of several PID techniques in $0.1 < p_T < 30$ GeV/c

V0 detectors: triggering, multiplicity
$2.8 < \eta < 5.1$ (V0A)
$-3.7 < \eta < -1.7$ (V0C)

ZDC hadronic calorimeters, 112.5 m from the IP $|\eta| > 8.8$ (ZN), $6.5 < |\eta| < 7.4$ (ZP*)

*considering LHC beam optics ZP acceptance for protons is $7.0 < |\eta| < 8.7$

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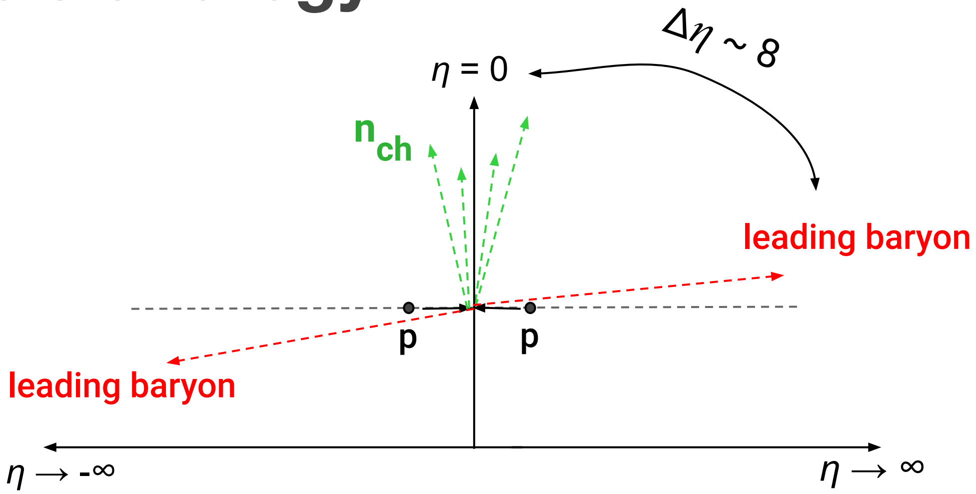

Independent proxies given the large η separation

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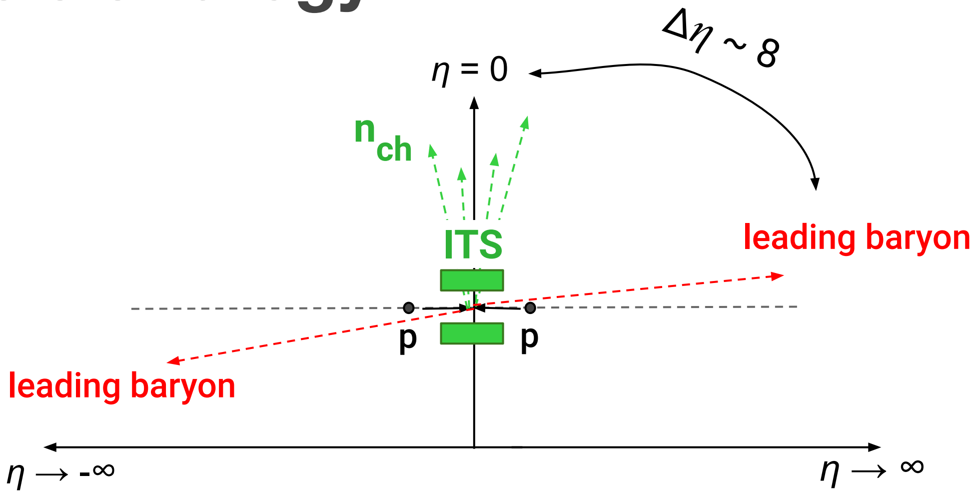

ALICE can measure:

- midrapidity multiplicity (**SPD**)

Independent proxies given the large η separation

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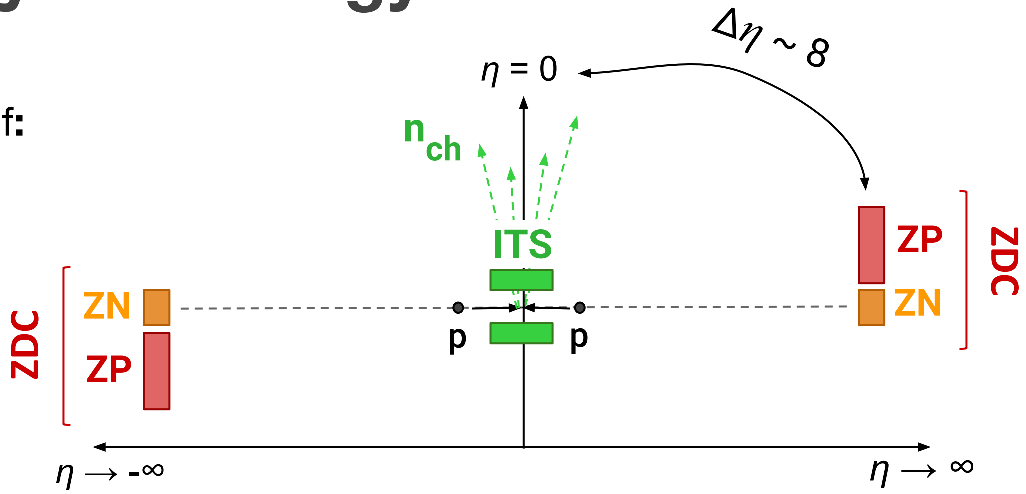
Independent proxies given the large η separation



ALICE can measure:

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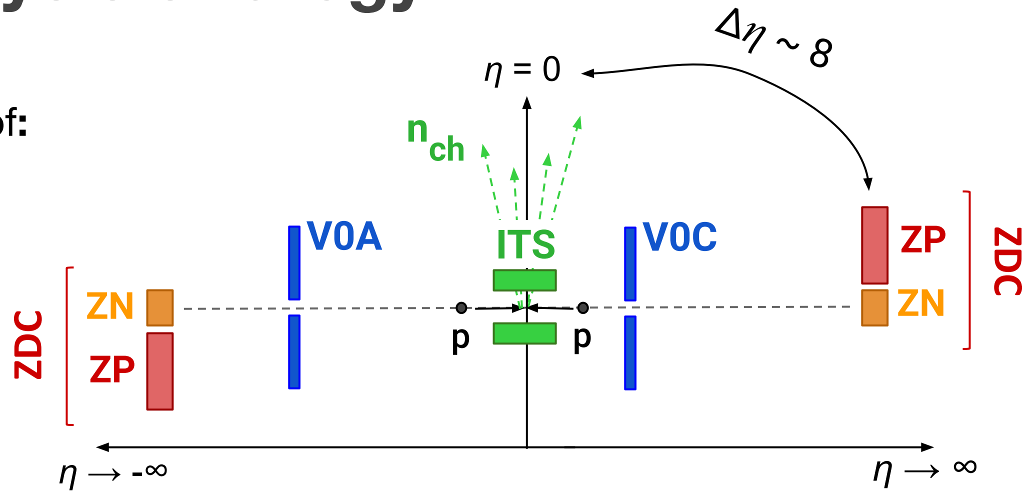


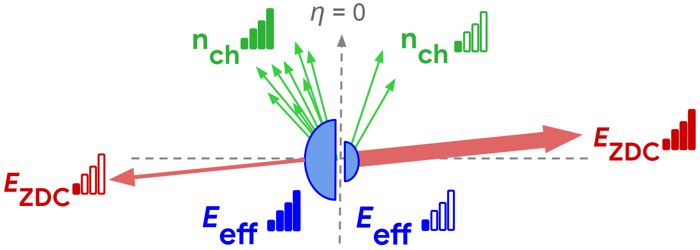
ALICE can measure:

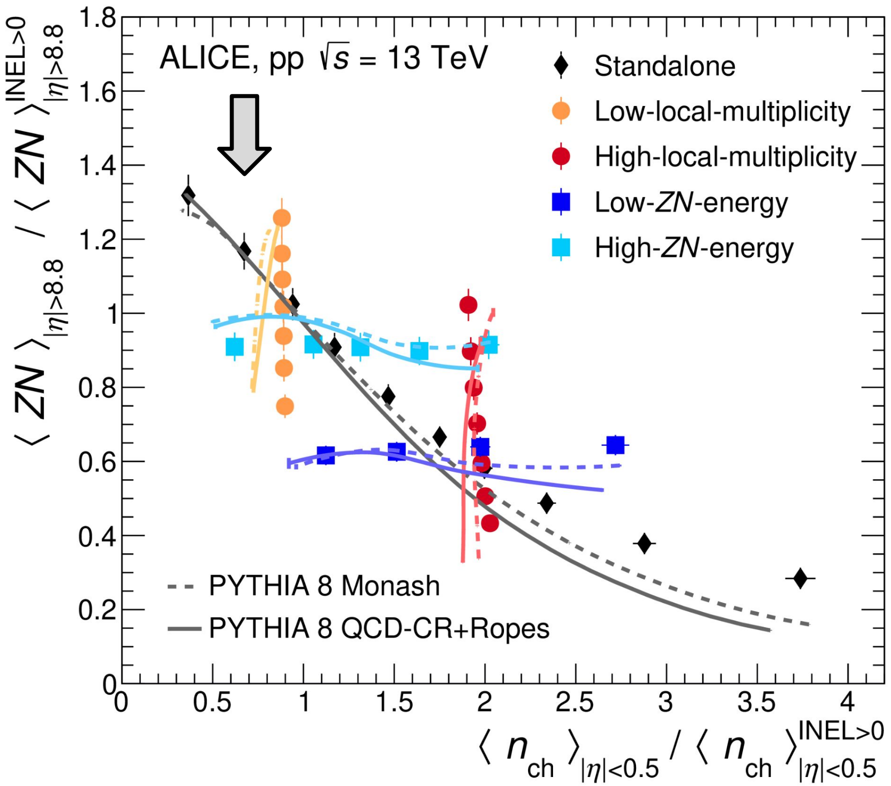
- midrapidity multiplicity (**SPD**)
- leading energy (**ZDC**)
- forward multiplicity (**V0M** = V0A+V0C)

Event classification

♦ **Standalone:**
event classes defined by increasing n_{ch} and decreasing ZN energy

The forward energy decreases with increasing particle multiplicity produced at midrapidity [1]





[1] ALICE, JHEP 08 (2022) 086

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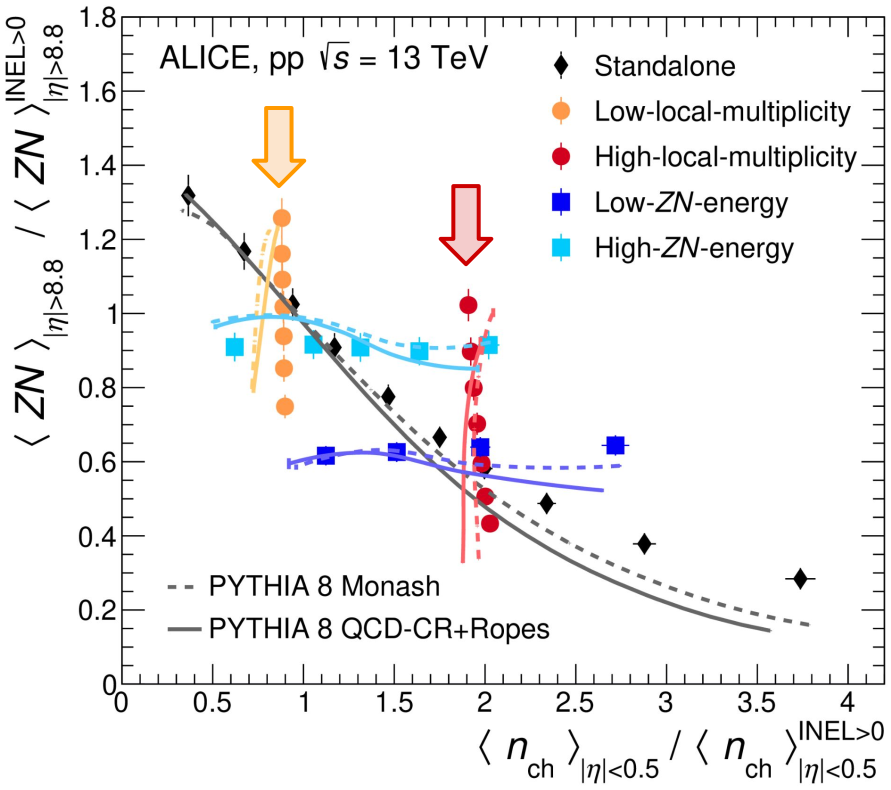
● **Low-local-multiplicity**
event classes with similar average values of n_{ch} but different ZN energies



ALI-PUB-580691

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■ **High-ZN-energy**
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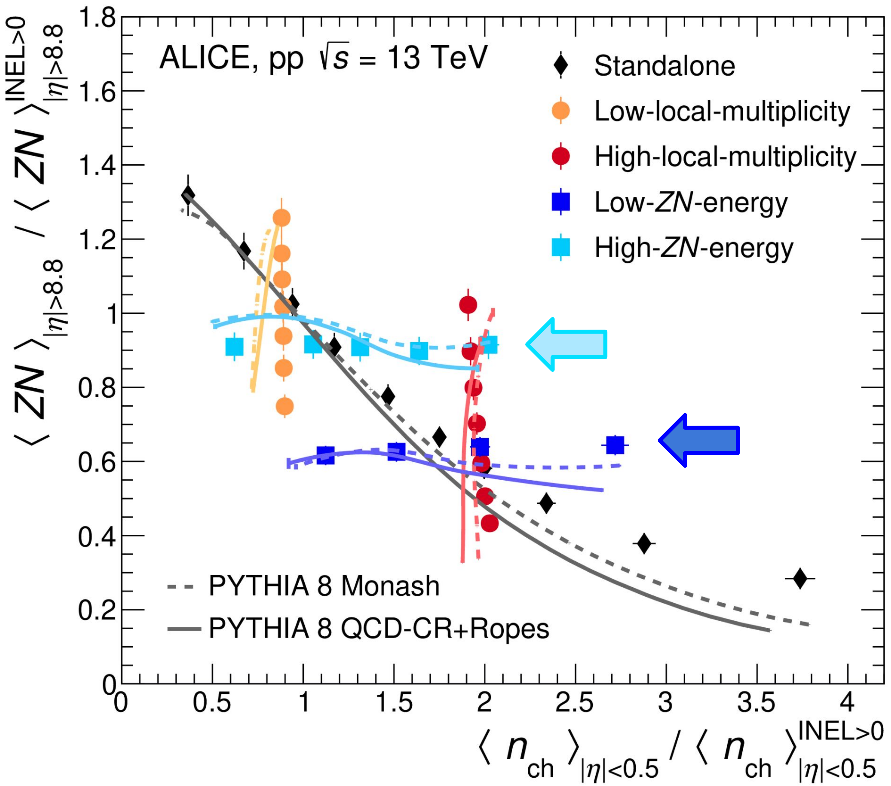

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Strange hadron reconstruction

Kinematical and geometrical criteria are used to reconstruct candidates for strange hadrons

Identification of (multi-)strange baryons is based on two topologies:

V^0 → neutral particle decaying weakly into a pair of charged particles (V-shaped decay)

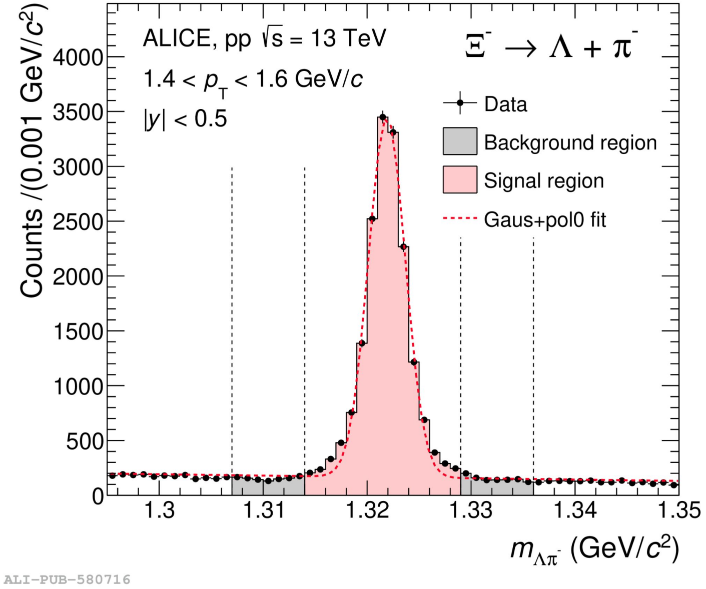
$$K^0_S \rightarrow \pi^+ + \pi^-$$

$$\Lambda \rightarrow p + \pi^-$$

Cascade → charged particle decaying weakly into a V^0 + charged particle

$$\Xi^- \rightarrow \Lambda + \pi^-$$

$$\bar{\Xi}^+ \rightarrow \bar{\Lambda} + \pi^+$$



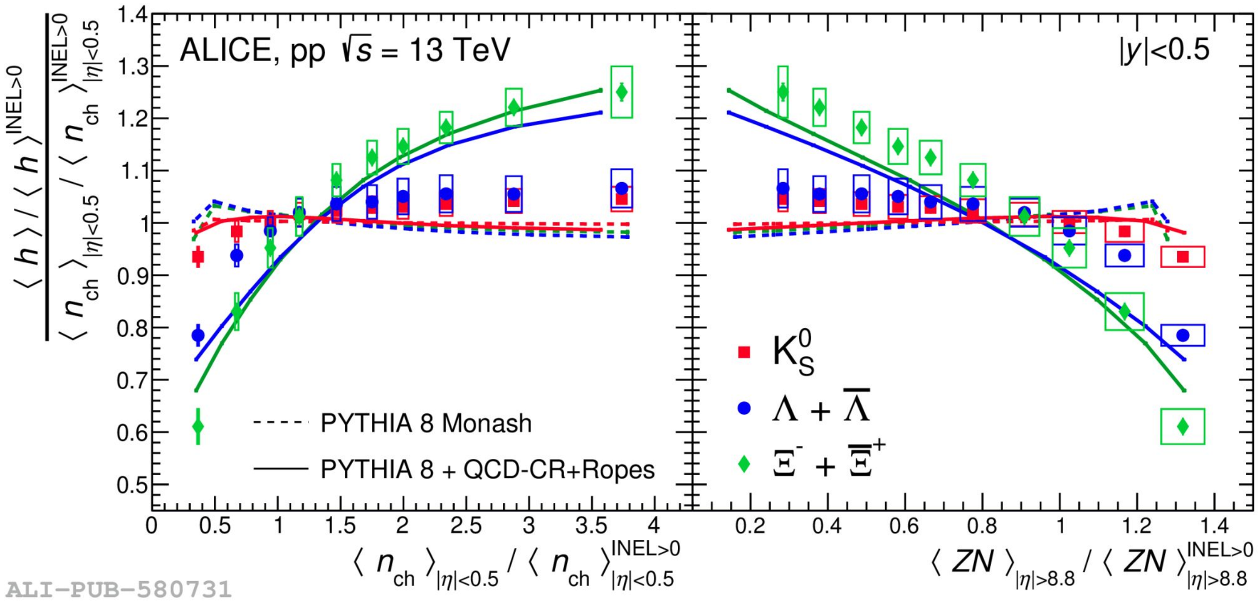
Results: standalone classification

$$\frac{\langle h \rangle / \langle h \rangle_{\mathrm{INEL}>0}}{\langle n_{\mathrm{ch}} \rangle / \langle n_{\mathrm{ch}} \rangle_{\mathrm{INEL}>0}}$$

"Self-normalised yield ratios" proxy for h/π

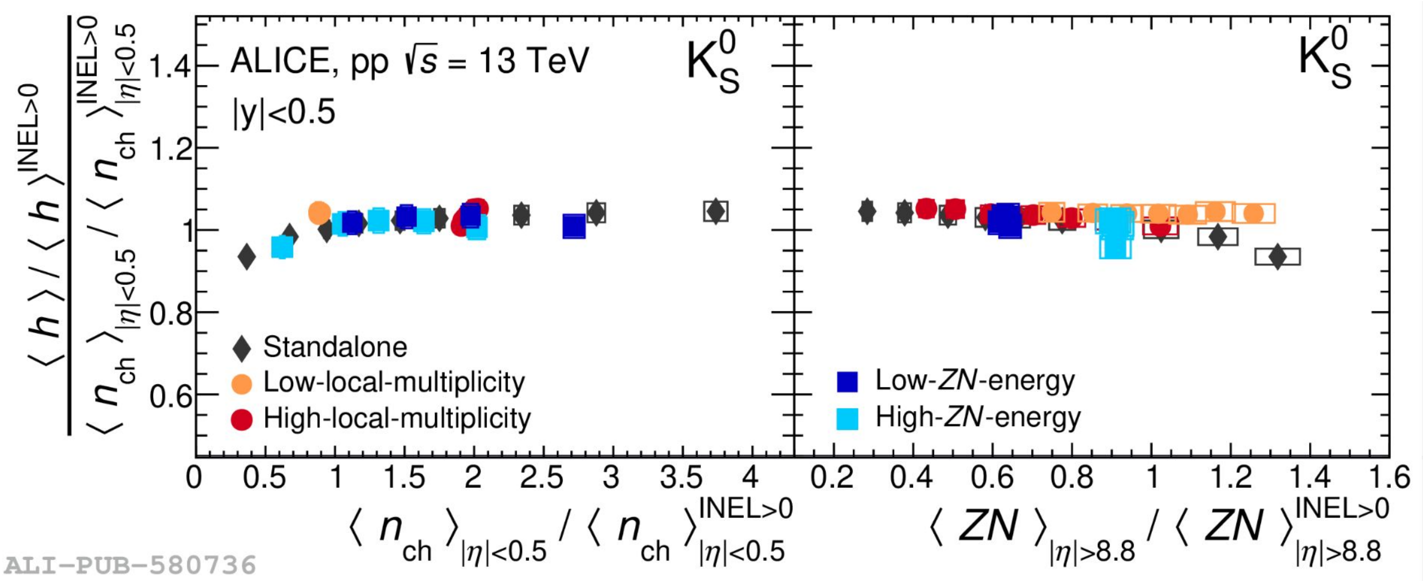
Strangeness production per charged particle:

- increases with midrapidity multiplicity (left)
- is **anticorrelated with the ZN energy** (right)



Results for strange mesons

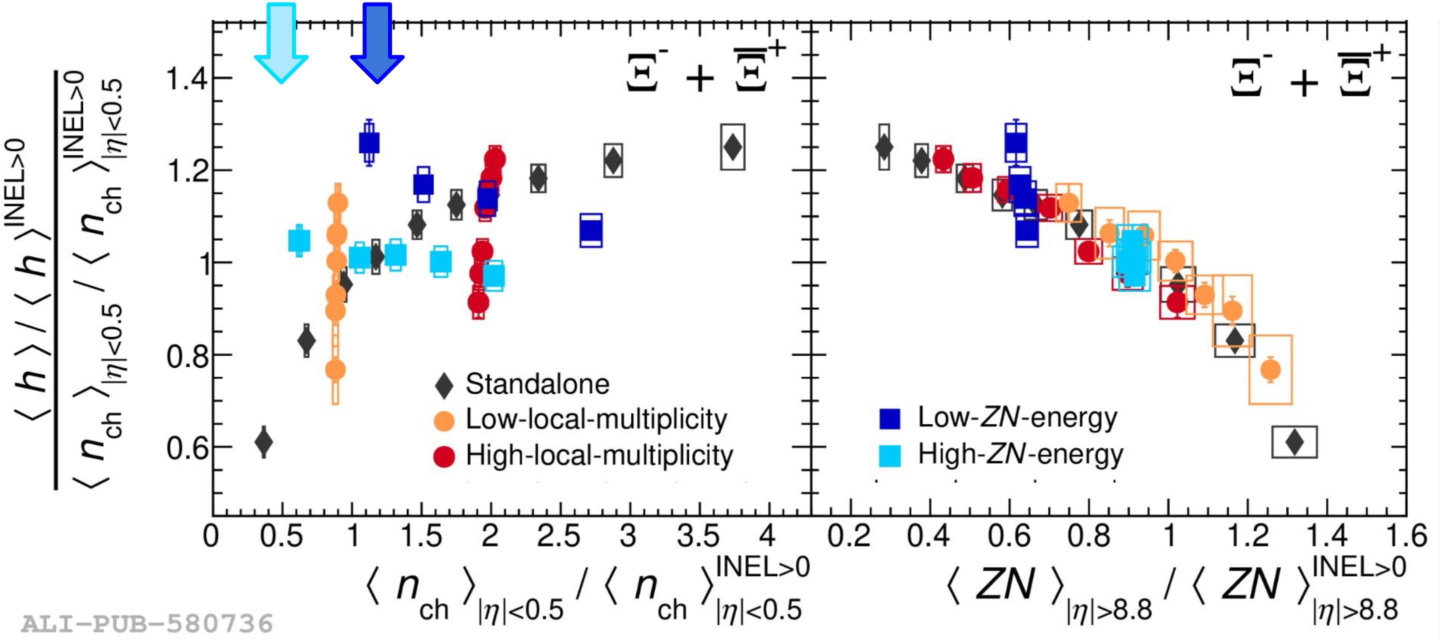
At fixed leading energy and at fixed multiplicity, **small-to-no dynamics** observed for strange mesons (K^0_S) as a function of both observables



Results for strange baryons

At fixed leading energy:
- High-ZN-energy
- Low-ZN-energy

No strangeness enhancement observed with midrapidity multiplicity → anti-correlation of strange baryon ratios with n_{ch}

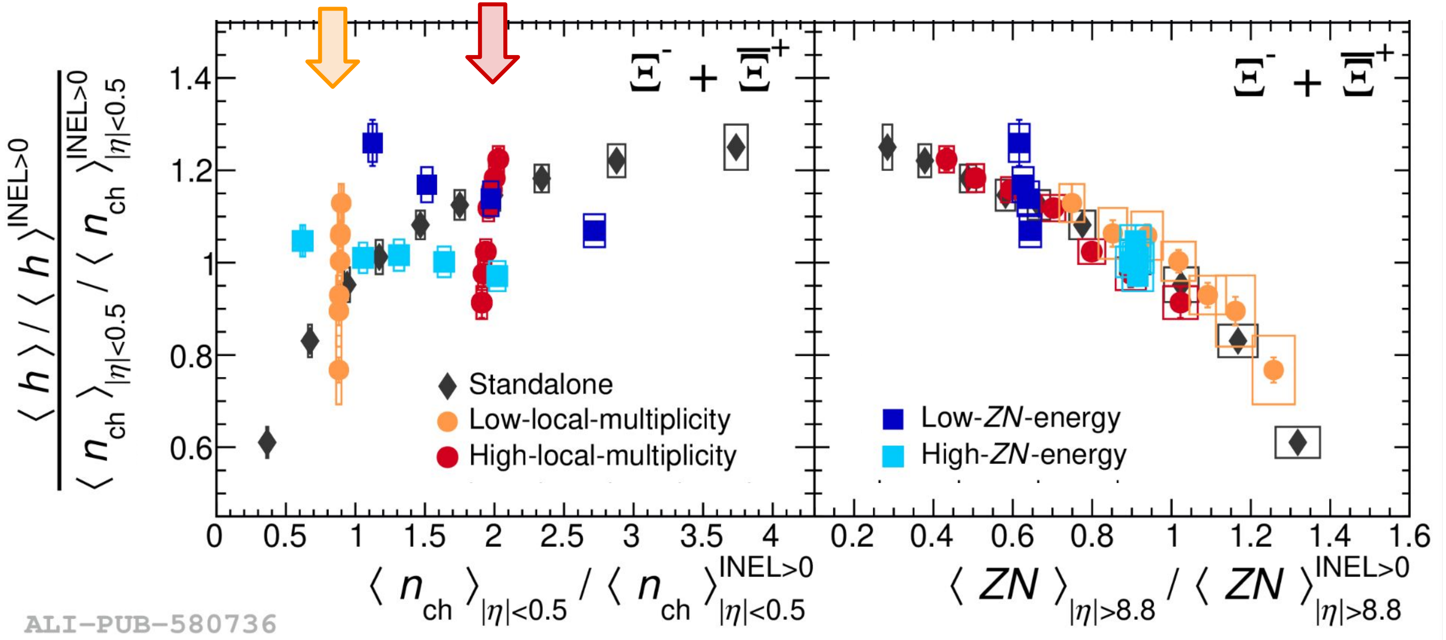


Results for strange baryons

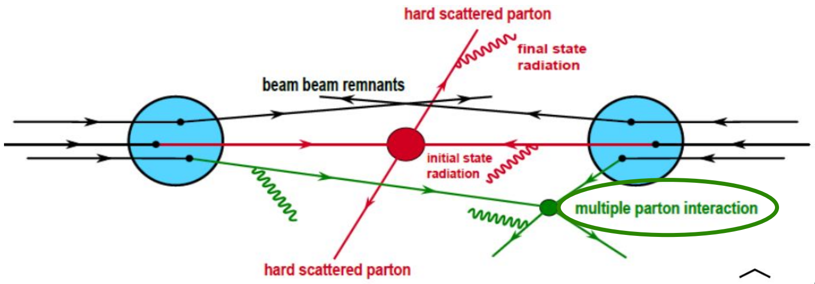
At fixed midrapidity multiplicity:

- High-local-multiplicity
- Low-local-multiplicity

Strange baryon **enhancement** observed with **decreasing leading energy** following a **universal** trend



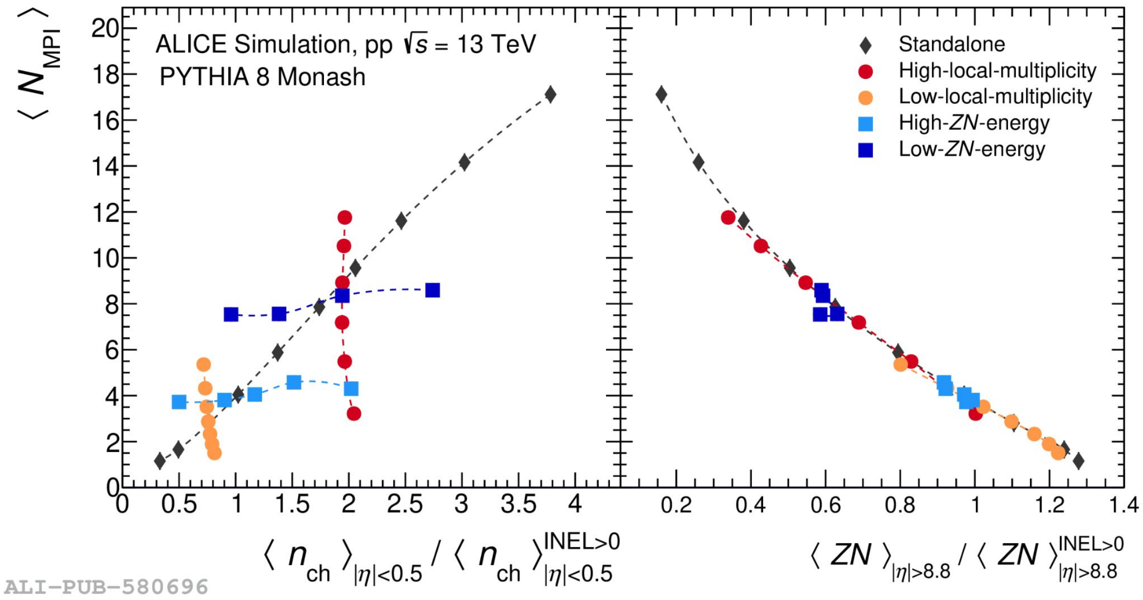
Connection to the MPIs in PYTHIA



In PYTHIA, the number of **Multiple Parton Interactions** strongly **influence** the **string hadronization processes** responsible for strange hadron production

MPIs increase at fixed local multiplicity with decreasing leading energies

Universal dependence with the leading energy, i.e. common for all selections



Summary

Novel approach to study strangeness production in small systems → focus on the interplay between multiplicity and effective energy on particle production

- Strange baryon enhancement in pp collisions is **connected to global** properties of the event, e.g. the **effective energy** → the **local multiplicity is <u>not</u> the key observable** in this phenomenon (NEW!)

- Strange mesons (K^0_S) seems to be less influenced by the effective energy, suggesting different hadronization mechanisms at play for baryons and mesons → **strange baryon enhancement**

- The leading energy is predicted to be strongly **correlated to the number of MPIs** → intriguing input to tune strange baryon production mechanisms in the models

Outlook

The results presented today are included in the paper: https://arxiv.org/abs/2409.12702
Currently on arxiv and recently accepted by JHEP

The work is based on my PhD thesis:
Title: "*The interplay of multiplicity and effective energy for (multi) strange hadron production in pp collisions at the LHC*"
Supervisors: Prof.ssa Luisa Cifarelli, Dott. Francesco Noferini
Link: http://amsdottorato.unibo.it/11341/

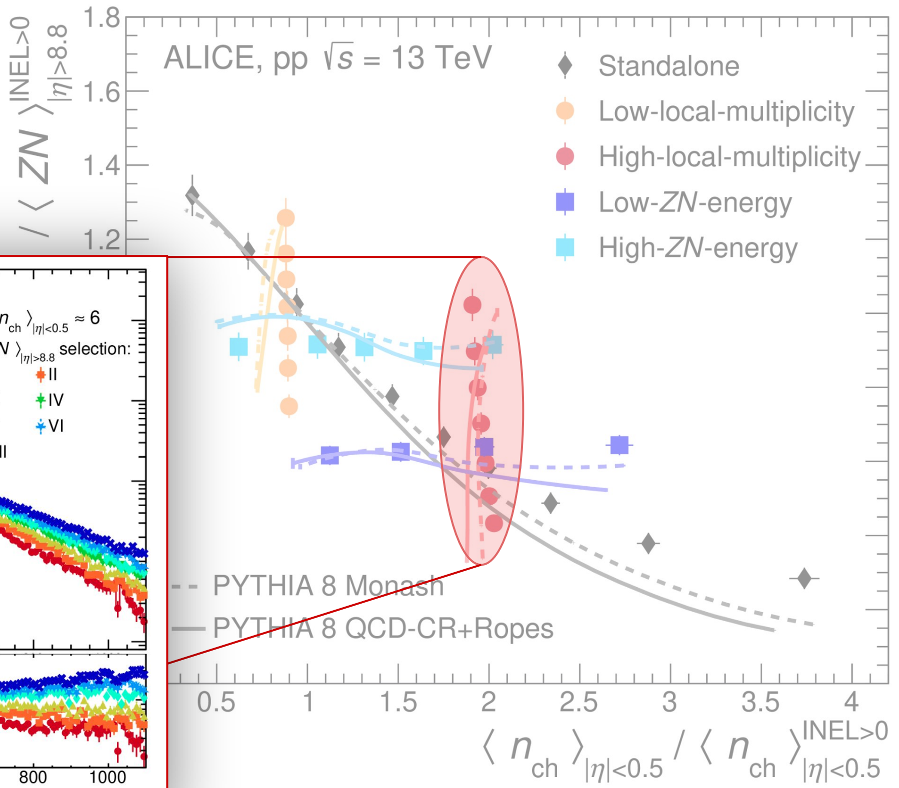
The thesis was awarded with the ALICE Thesis Award 2024

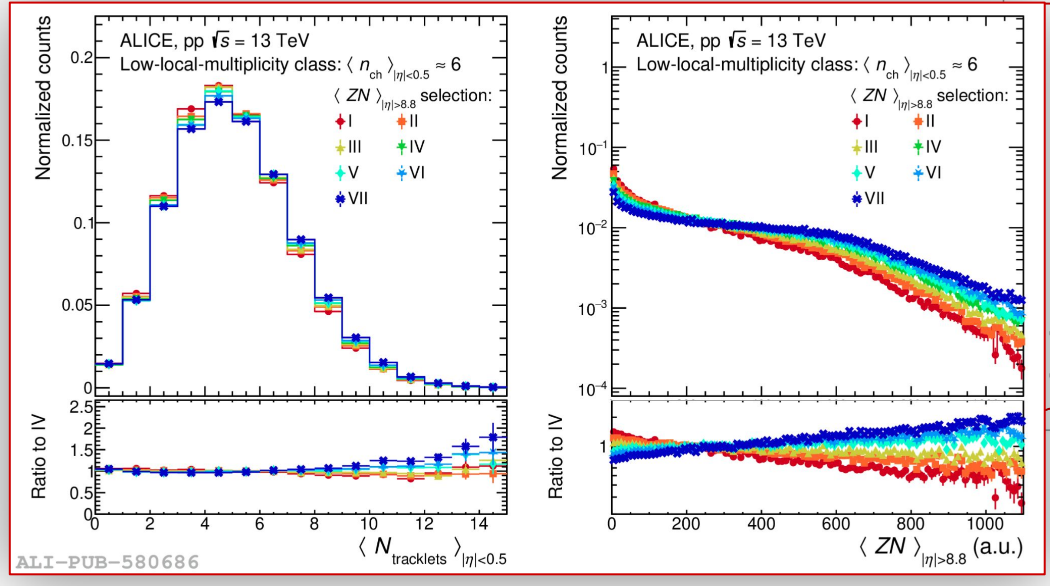
Backup

Event engineering

- **High-local-multiplicity**
- **Low-local-multiplicity**

event classes with similar average values of n_{ch} but different ZN energies

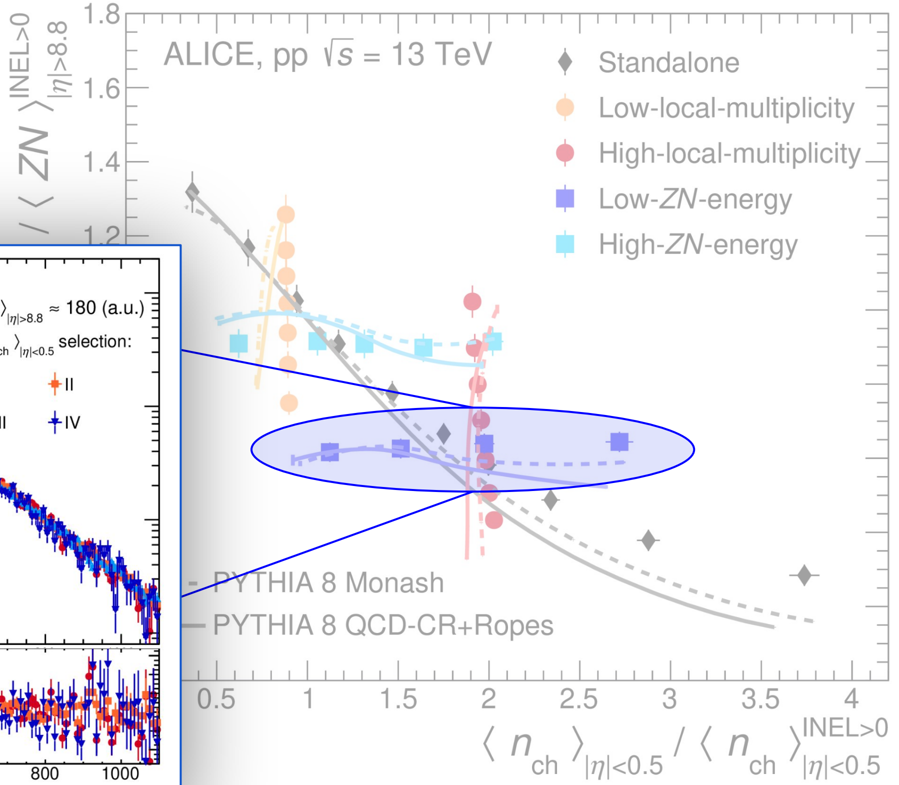


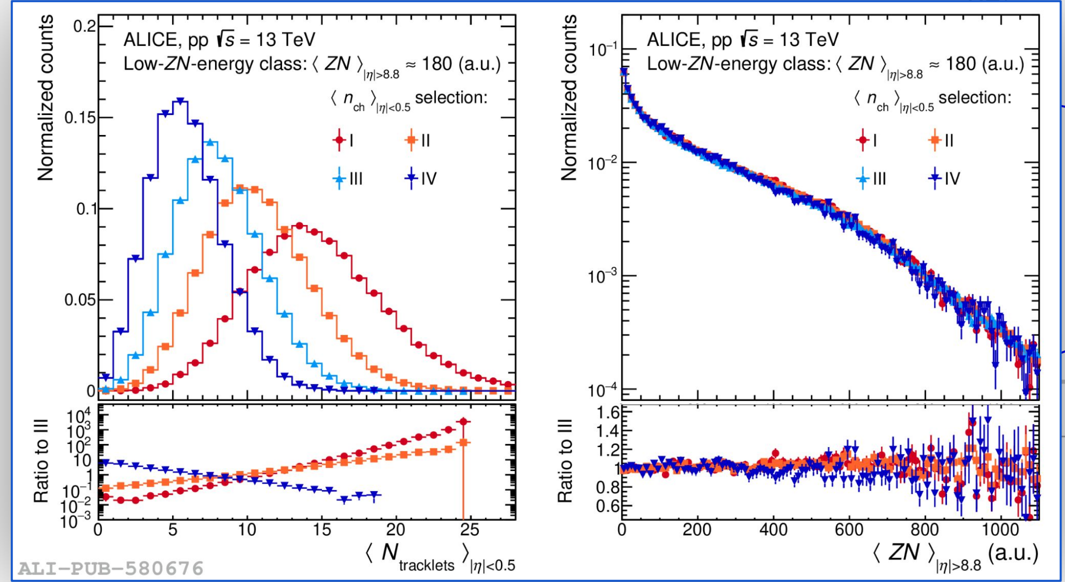


Event engineering

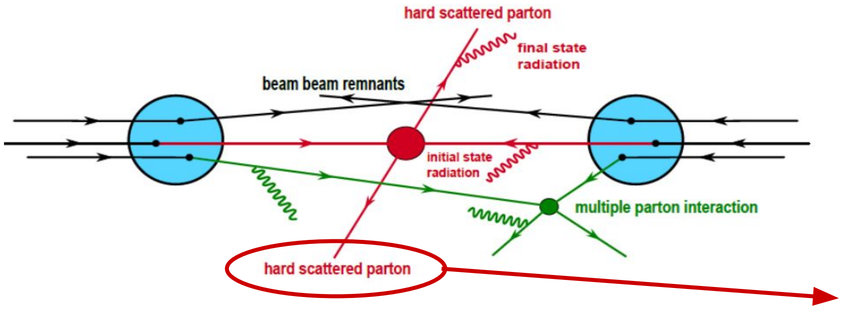
- **High-ZN-energy**
- **Low-ZN-energy**

event classes with similar average values of ZN energies but different n_{ch}





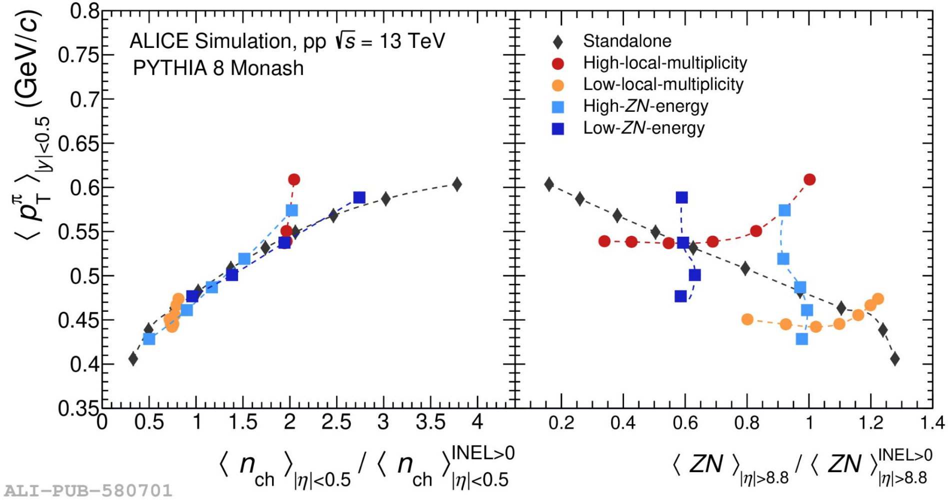
Connection to hard-scattering processes in PYTHIA



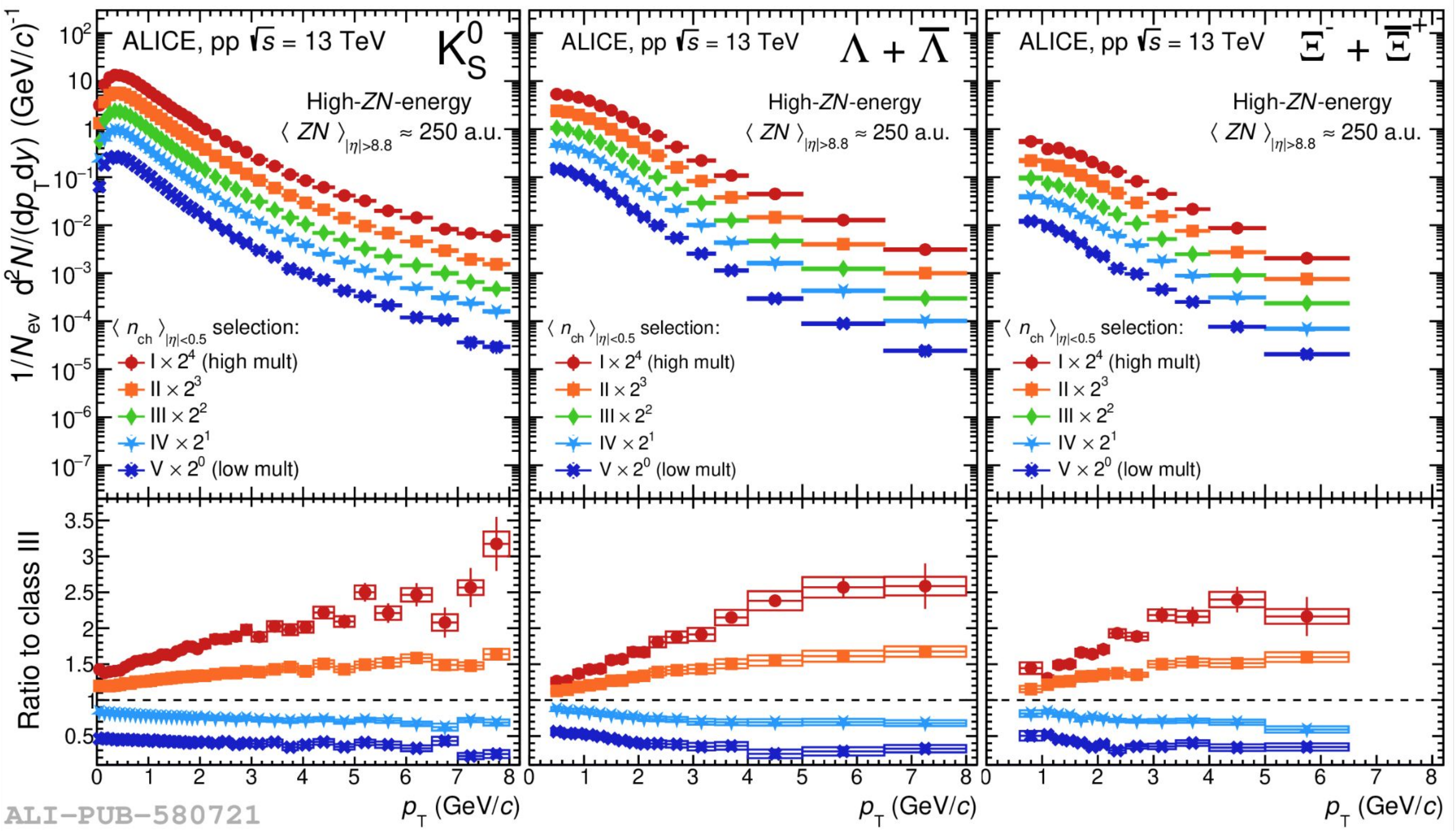
The presence of jets at midrapidity is studied in PYTHIA considering the $\langle p_{\mathrm{T}}^{\pi} \rangle_{|y|<0.5}$, proxy for the **$p_{\mathrm{T}}$ of the hard parton scattering process**

Very **mild dependence** of $\langle p_{\mathrm{T}}^{\pi} \rangle_{|y|<0.5}$ with the **leading energy**

Local phenomena, such as jets at midrapidity, are correlated with local observables, such as the charged-multiplicity



p_T spectra



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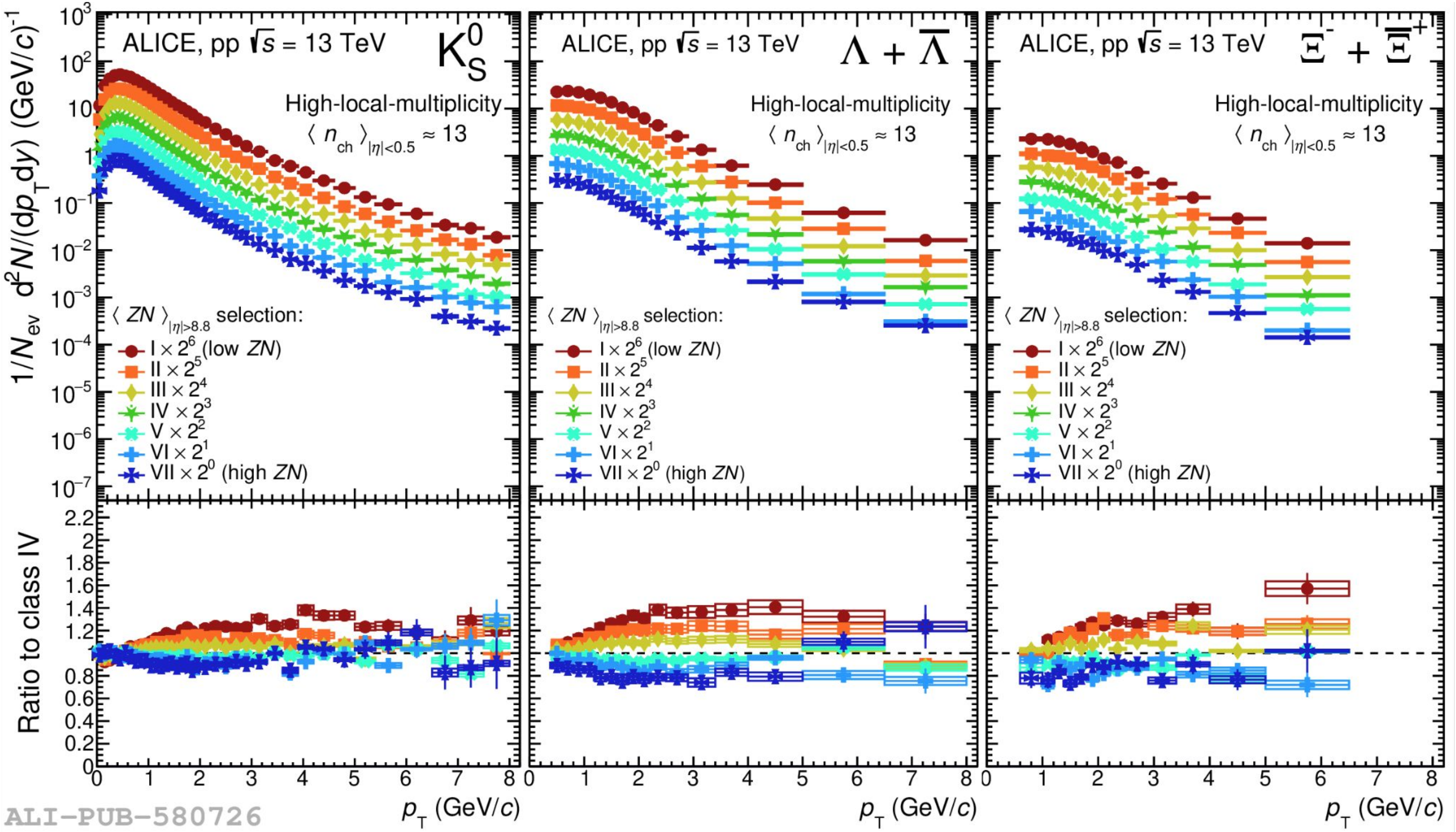
p_T spectra



ALICE, pp √s = 13 TeV
K^0_S
$\Lambda + \overline{\Lambda}$
$\Xi^- + \overline{\Xi}^+$
High-local-multiplicity
⟨ n_{ch} ⟩$_{|\eta|<0.5}$ ≈ 13
⟨ ZN ⟩$_{|\eta|>8.8}$ selection:
I × 2^6 (low ZN)
II × 2^5
III × 2^4
IV × 2^3
V × 2^2
VI × 2^1
VII × 2^0 (high ZN)
$1/N_{ev}$ $d^2N/(dp_T dy)$ (GeV/c)$^{-1}$
Ratio to class IV
p_T (GeV/c)
ALI-PUB-580726