Strangeness enhancement with effective energy in pp collisions at the LHC with ALICE

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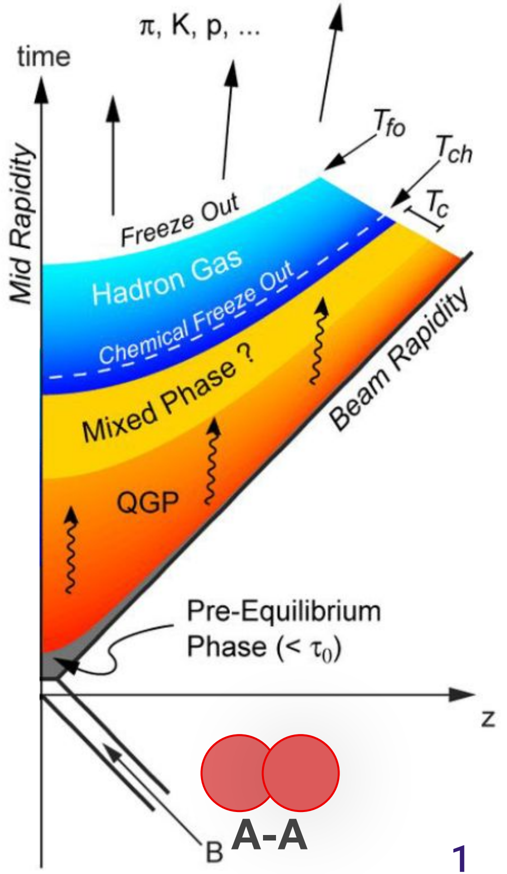
EPS HEP2025 MARSEILLE

High-energy heavy-ion collisions

From QCD a phase transition is expected 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 to study the properties of the medium



High-energy heavy-ion/pp collisions

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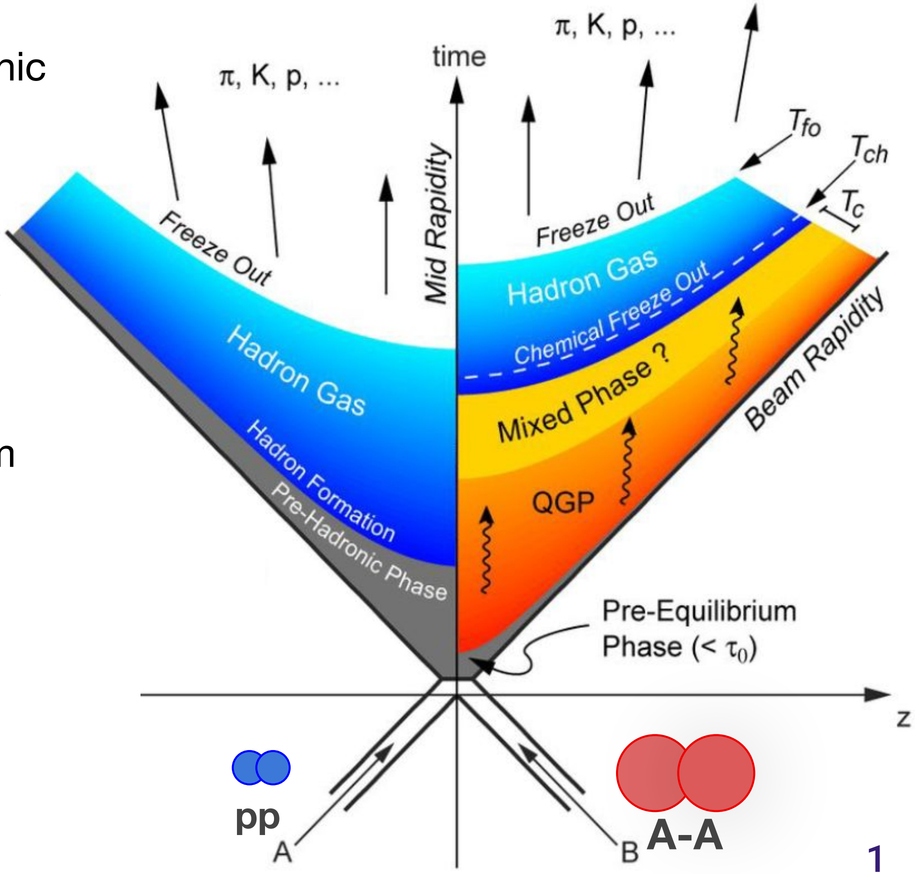
Light flavor quarks (*u*, *d*, *s*) are thermally produced in the QGP → key to study the properties of the medium

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



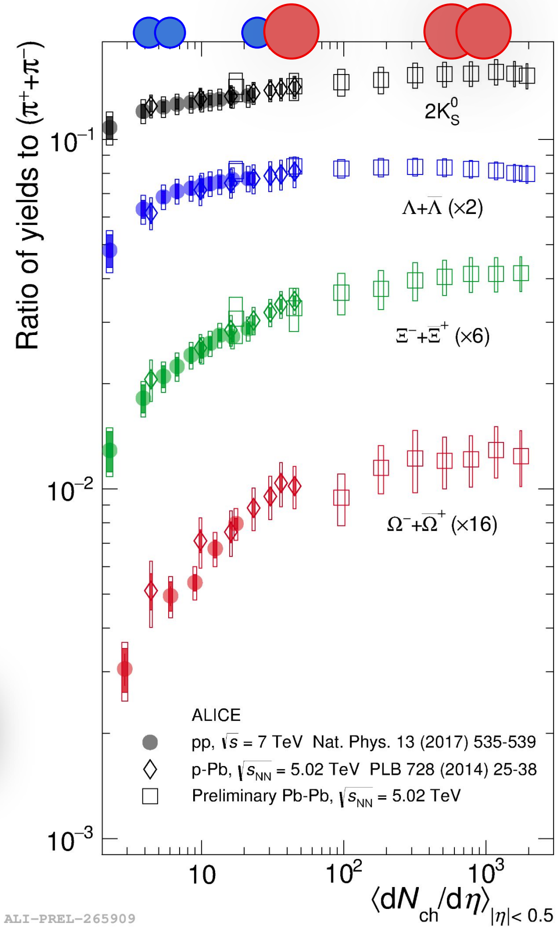
Strangeness evolution with multiplicity

Strangeness enhancement (S) in heavy-ion / suppression in small systems due to local strangeness conservation [1,2]

Strange-hadron-to-pion yields in pp, p–Pb and Pb–Pb as a function of the charged-particle multiplicity:

- h/π increases from low multiplicity pp collisions, saturating for central Pb–Pb
- Continuous evolution smoothly connecting different systems
- Strange content hierarchy: $|S_{\Omega^\pm}| > |S_{\Xi^\pm}| > |S_\Lambda| \approx |S_{K^0_S}|$

Strangeness vs multiplicity: what about the **available energy**?



ALICE Collaboration, Nature Phys 13, 535-539 (2017)

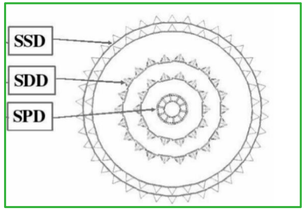
[1] J. Rafelski and B. Müller PRL, 48, 106-1069 (1982)
[2] V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

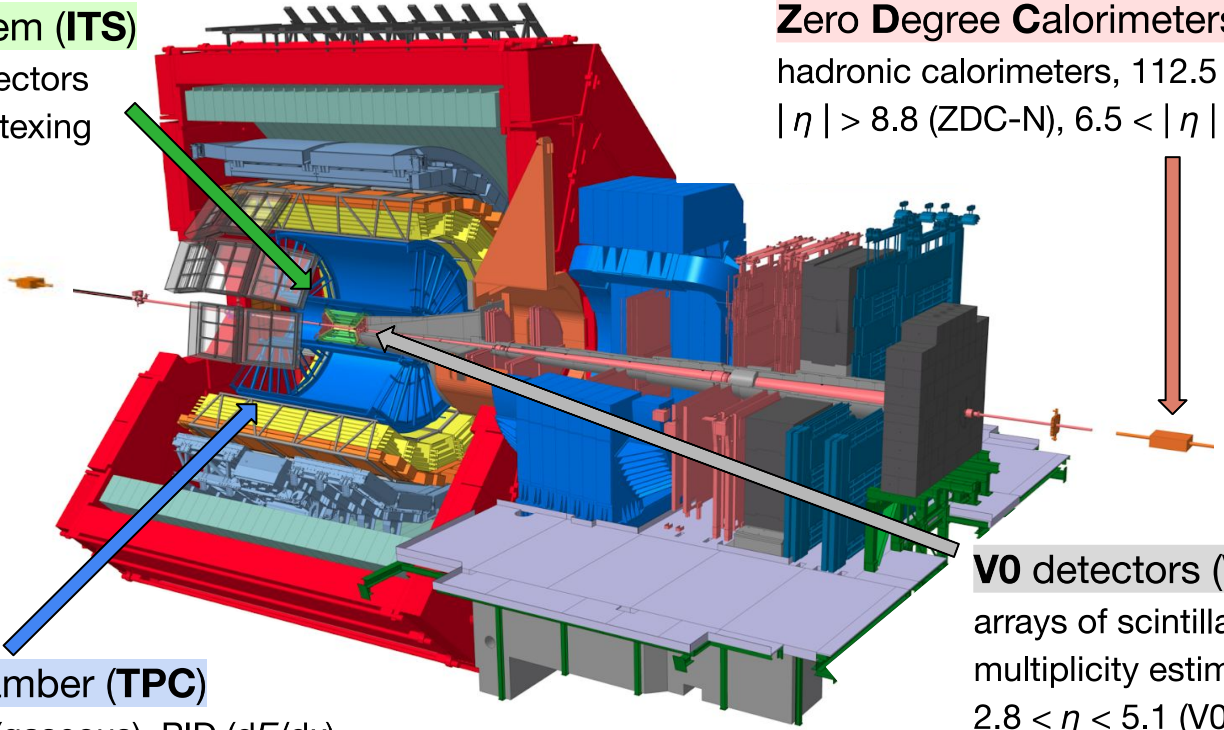
ALICE in Run 2

Inner **T**racking **S**ystem (**ITS**)

six layers of silicon detectors

tracking, triggering, vertexing





Zero **D**egree **C**alorimeters (**ZDC**)

hadronic calorimeters, 112.5 m from the IP

$|\eta| > 8.8$ (ZDC-N), $6.5 < |\eta| < 7.4$ (ZDC-P*)

Time **P**rojection **C**hamber (**TPC**)

main tracking detector (gaseous), PID (dE/dx)

V0 detectors (**V0A, V0C**)

arrays of scintillators, triggering,

multiplicity estimators

$2.8 < \eta < 5.1$ (V0A),

$-3.7 < \eta < -1.7$ (V0C)

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

The concept of effective energy

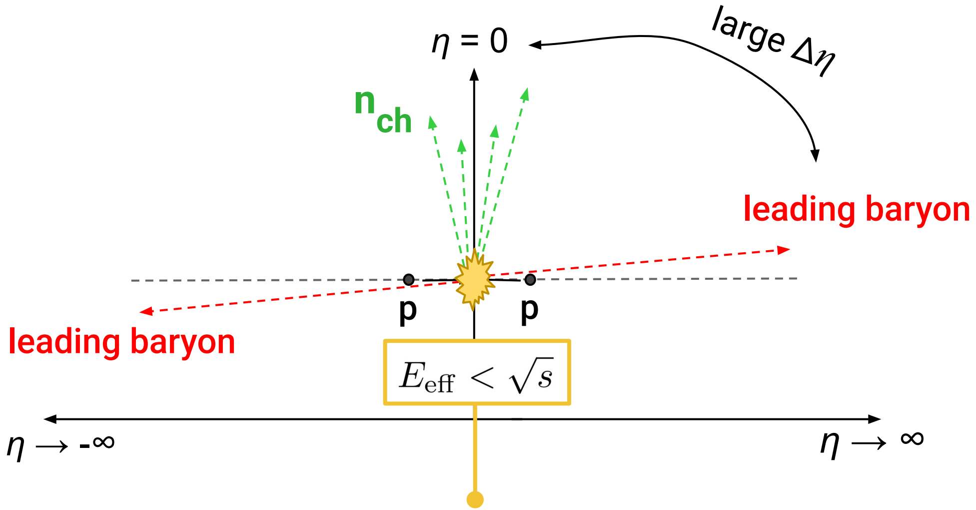
- Charged-multiplicity at midrapidity
  proxy for **local effects**, e.g.
  jet production at midrapidity

- Leading energy at forward rapidity
  proxy for **global effects**, e.g. the
  effective energy in the collision,
  the number of MPI

Independent proxies: large η separation

First studied at the CERN ISR in the 80's [1,2]

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



EFFECTIVE ENERGY

energy available for particle production in the **initial stages** of the pp collision

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

Analysis Strategy

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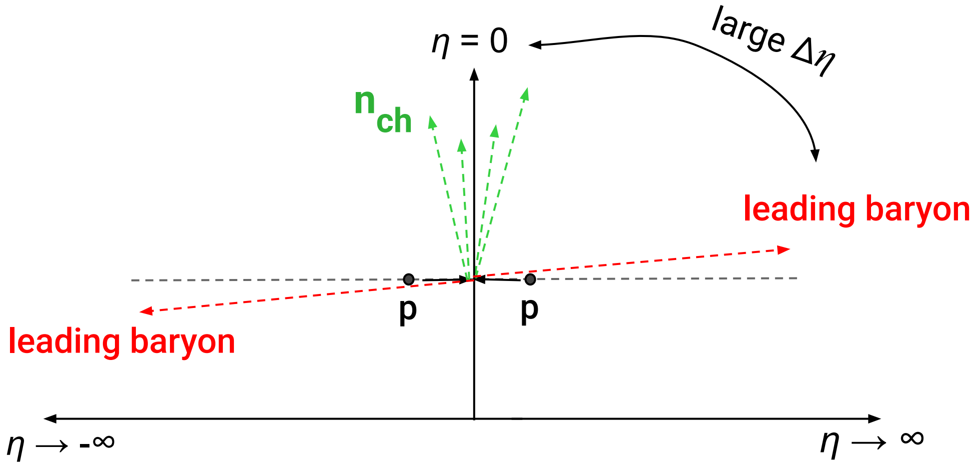

ALICE can measure:

ALICE Collaboration, JHEP 2025, 29 (2025)

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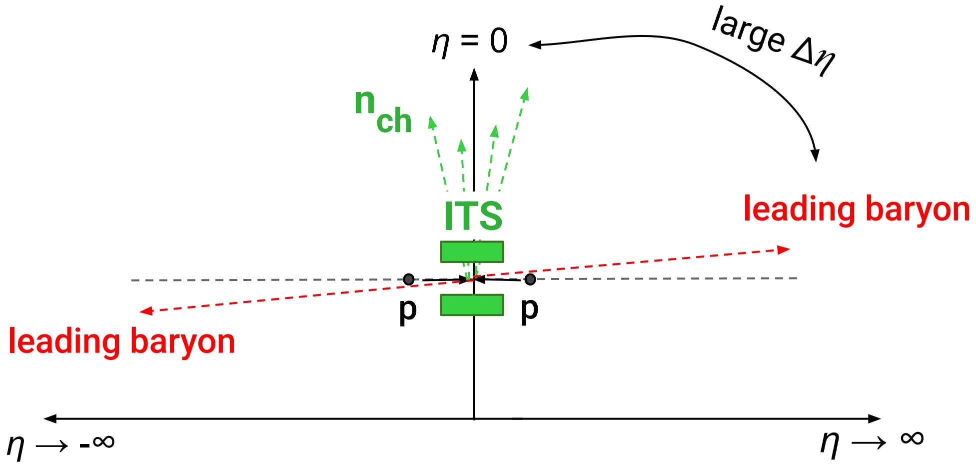

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- midrapidity multiplicity (**ITS**)

ALICE Collaboration, JHEP 2025, 29 (2025)

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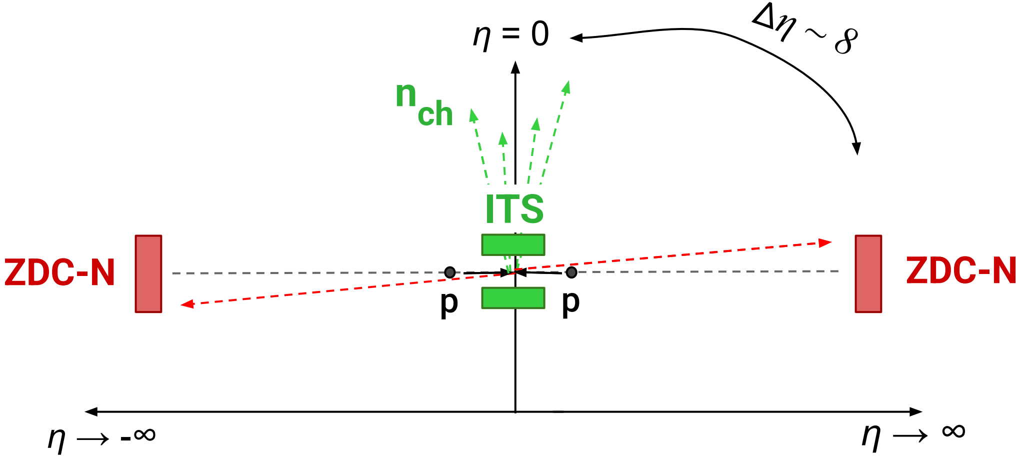


ALICE can measure:

- midrapidity multiplicity (**ITS**)
- leading energy (**ZDC-N** $|\eta| > 8.8$)

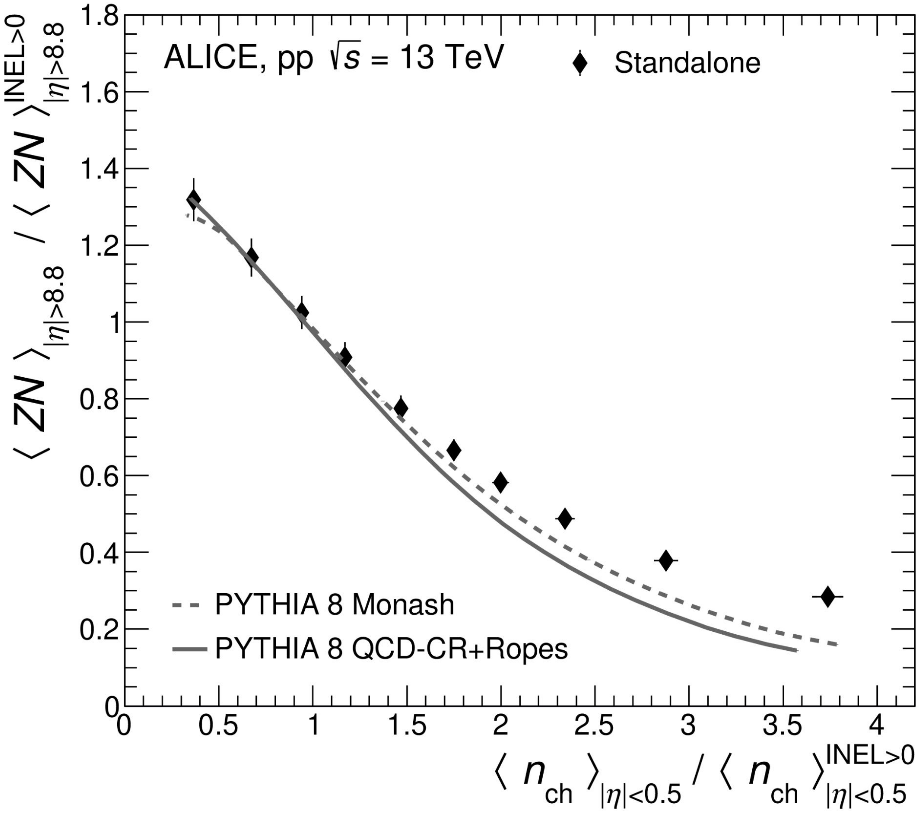
$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}} \approx \sqrt{s} - E_{\text{forward}}$$

ALICE Collaboration, JHEP 2025, 29 (2025)

Double-differential event engineering

$\langle n_{ch} \rangle_{|\eta|<0.5}$ midrapidity (local) multiplicity → average charged-particle pseudorapidity density $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

$\langle ZN \rangle_{|\eta|>8.8}$ forward energy, proxy for the leading energy → average signal in the ZDC-N



ALI-DER-608457

[1] ALICE Collaboration, JHEP 08 (2022) 086
[2] ALICE Collaboration, JHEP 2025, 29 (2025)

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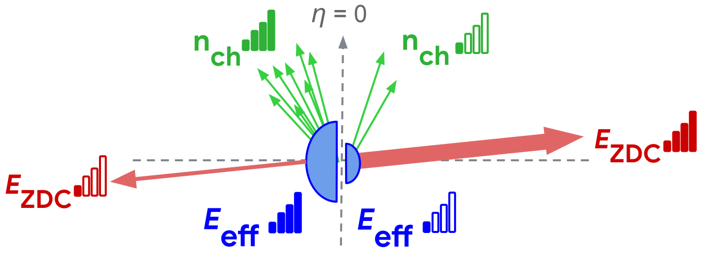
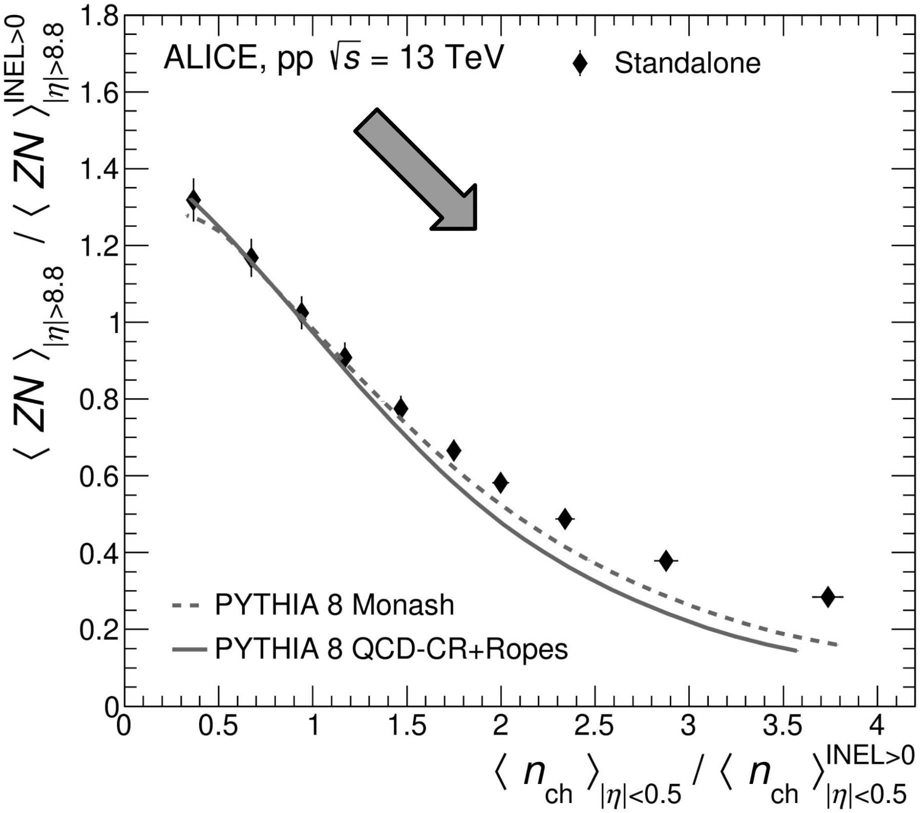
  - Increasing $\langle n_{ch} \rangle$ for decreasing $\langle ZN \rangle$





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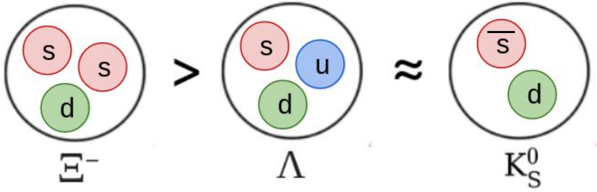
[2] ALICE Collaboration, JHEP 2025, 29 (2025)

Strange to non-strange vs leading energy

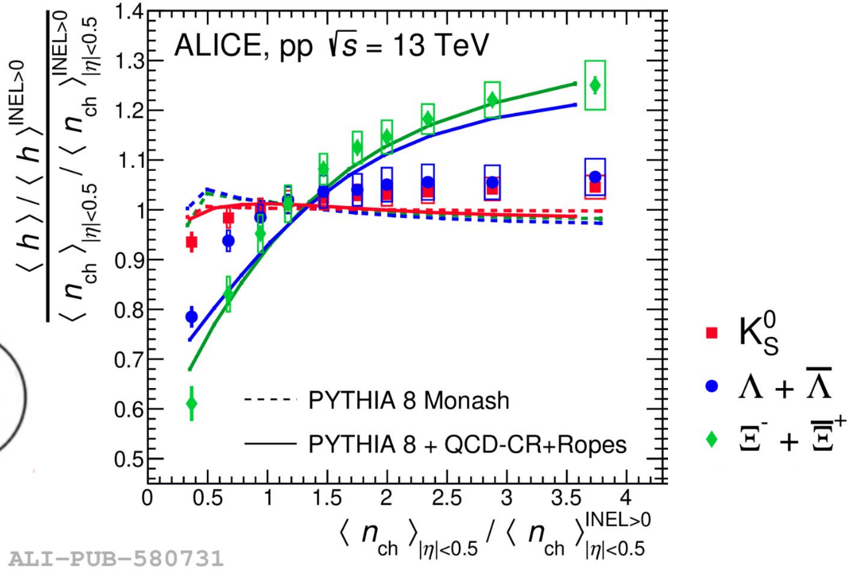
$$\frac{\langle h \rangle / \langle h \rangle_{\mathrm{INEL}>0}}{\langle n_{\mathrm{ch}} \rangle / \langle n_{\mathrm{ch}} \rangle_{\mathrm{INEL}>0}}$$

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



Strangeness production per charged particle:

Increases with midrapidity multiplicity



Midrapidity multiplicity

ALICE Collaboration, JHEP 2025, 29 (2025)

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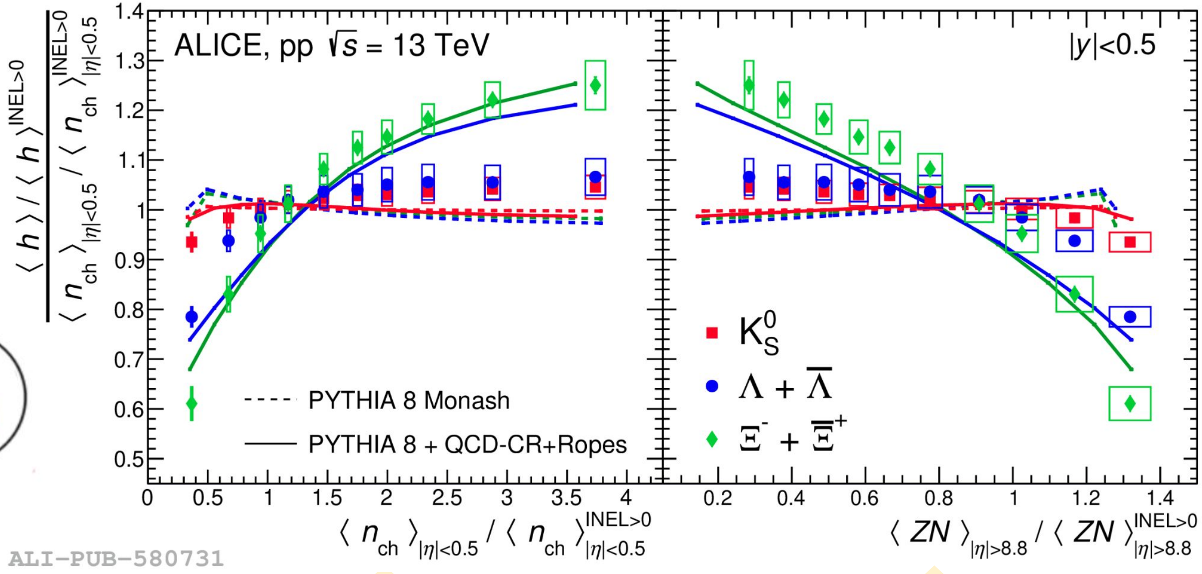
"Self-normalised yield ratios" proxy for h/π

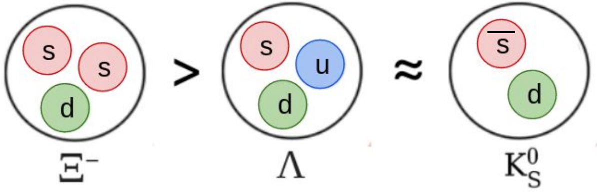
Strangeness production per charged particle: NEW!

Increases with midrapidity multiplicity	Anticorrelated with the *ZN* energy



Midrapidity multiplicity

Forward energy



ALICE Collaboration, JHEP 2025, 29 (2025)

Strange to non-strange vs leading energy

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

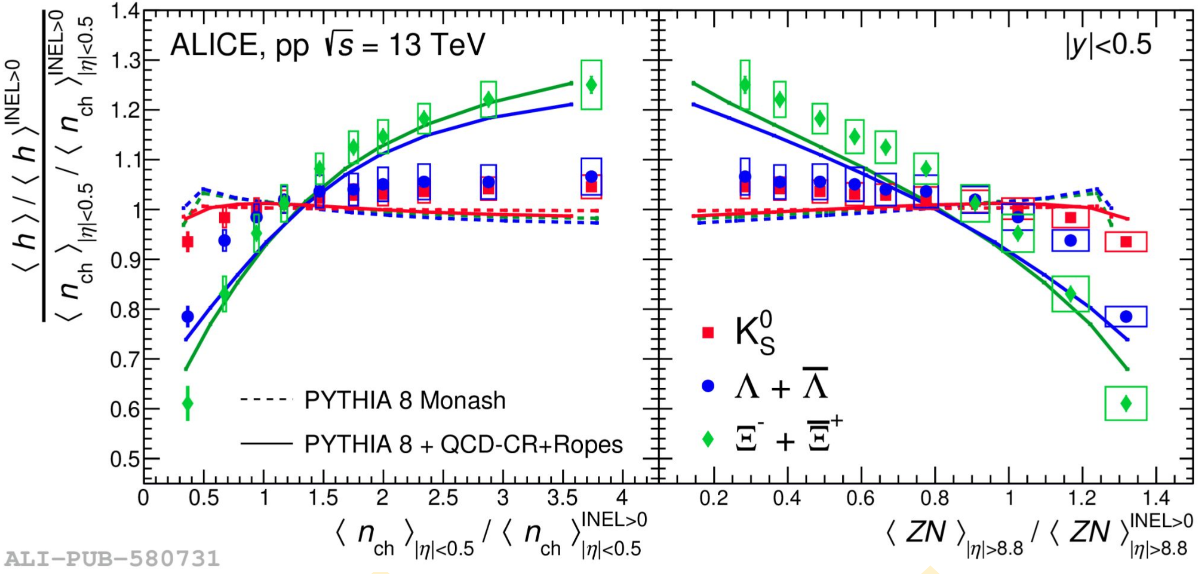
"Self-normalised yield ratios" proxy for h/π

No enhancement in PYTHIA8 Monash (Lund String Model)

Strange-baryon enhancement predicted when QCD-CR + Color Ropes are included

Strangeness production per charged particle: NEW!

Increases with midrapidity multiplicity	Anticorrelated with the *ZN* energy



Midrapidity multiplicity

Forward energy

ALICE Collaboration, JHEP 2025, 29 (2025)

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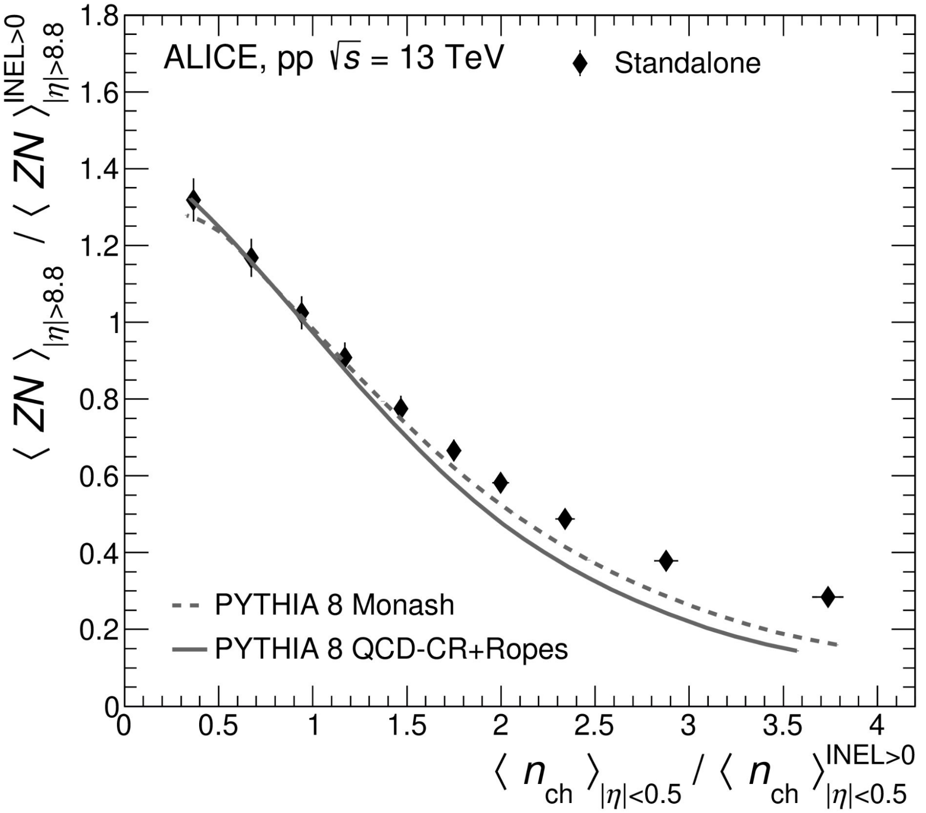

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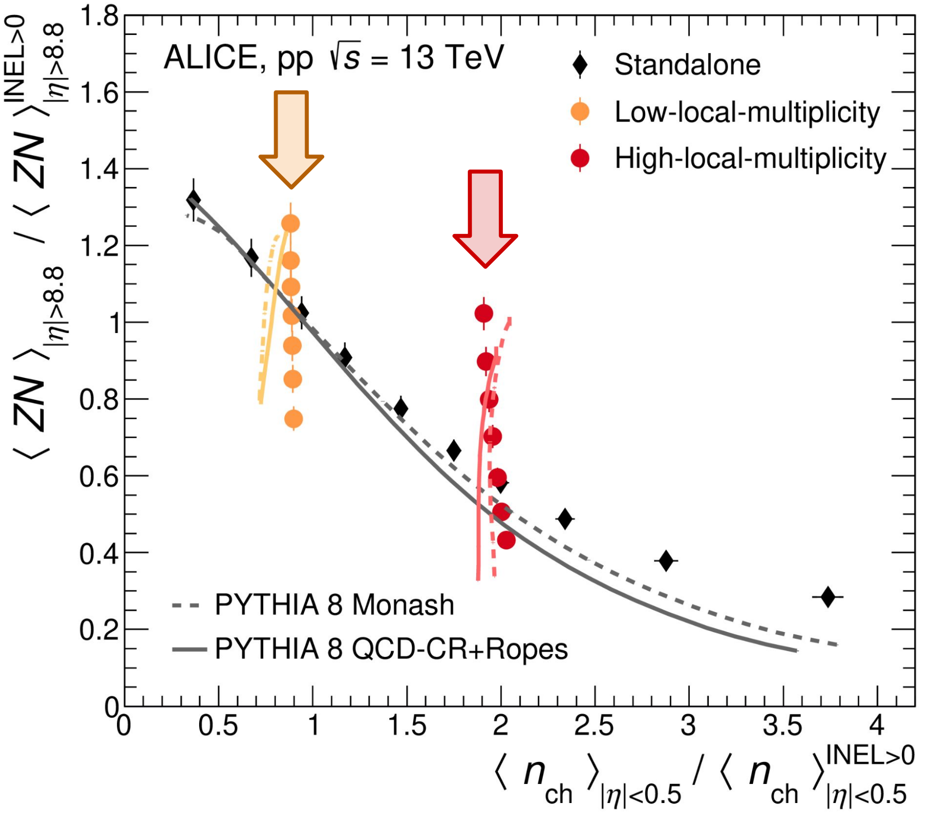
- **Standalone**
  - Increasing $\langle n_{ch} \rangle$ for decreasing $\langle ZN \rangle$
- **High/Low-local-multiplicity**
  - Fixed $\langle n_{ch} \rangle$ and decreasing $\langle ZN \rangle$



ALI-DER-608464

ALICE Collaboration, JHEP 2025, 29 (2025)

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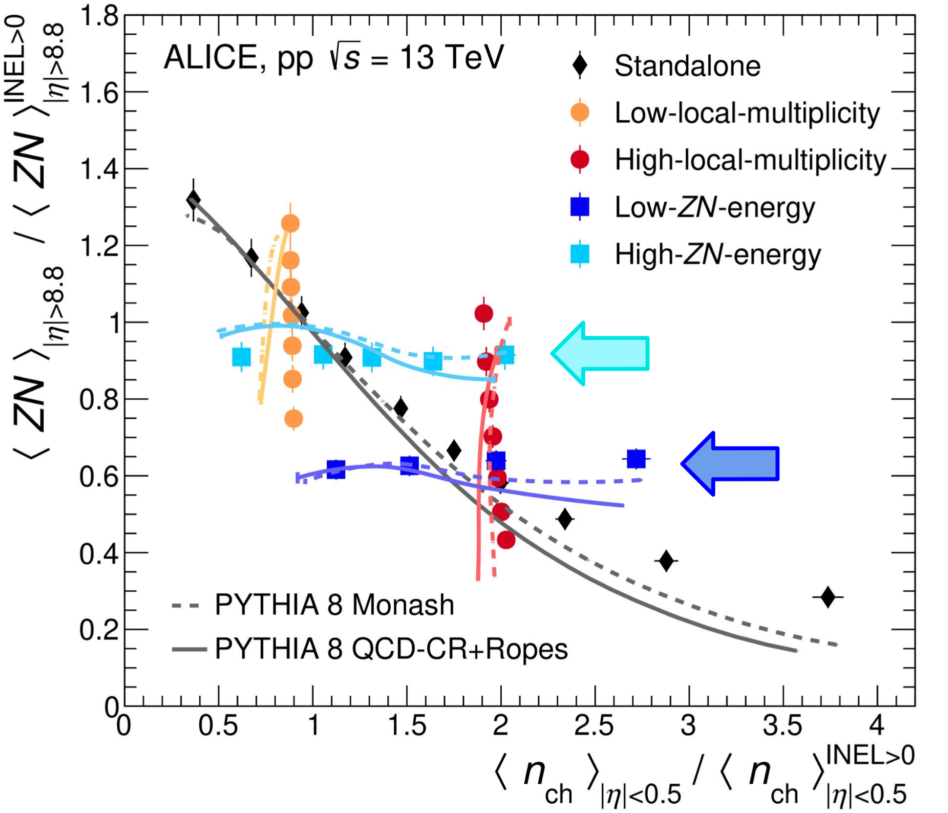
- ● ● **High/Low-local-multiplicity**
  - Fixed $\langle n_{ch} \rangle$ and decreasing $\langle ZN \rangle$
- ■ ■ **High/Low-*ZN*-energy**
  - Fixed $\langle ZN \rangle$ and increasing $\langle n_{ch} \rangle$

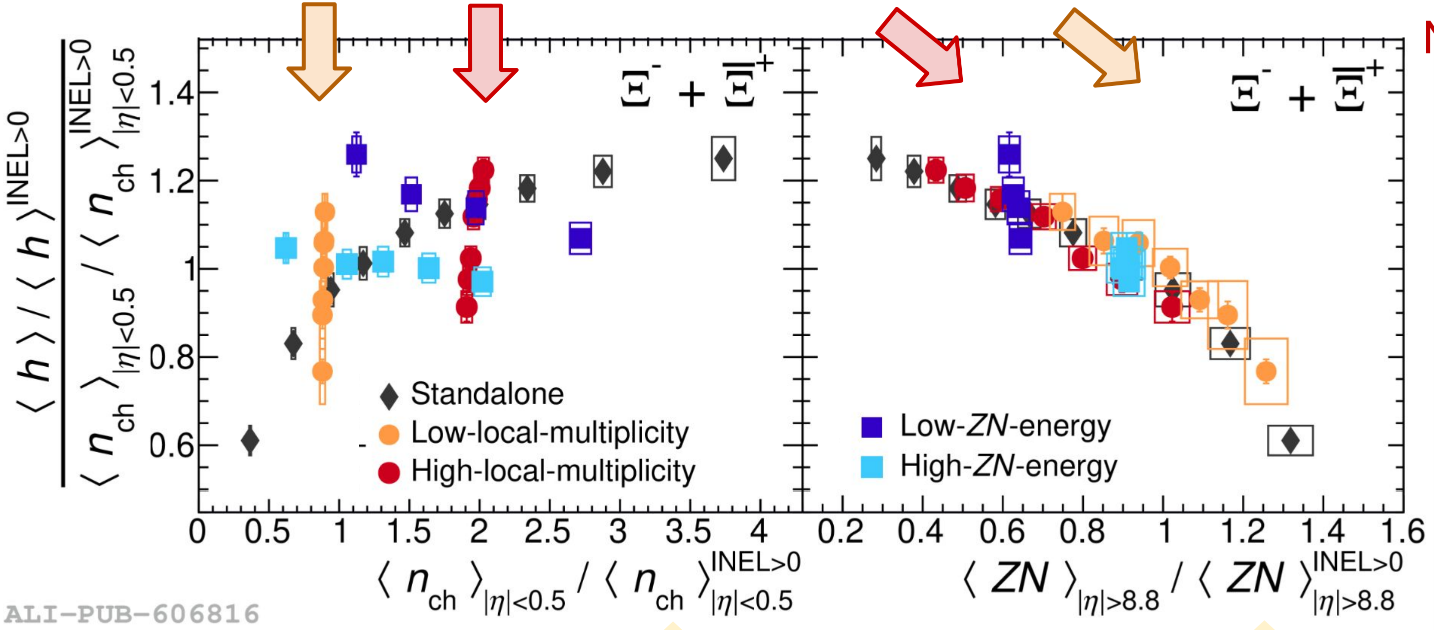


ALI-PUB-580691

ALICE Collaboration, JHEP 2025, 29 (2025)

Results for multi-strange baryons

- **Fixed local multiplicity**: Ξ/n_{ch} increases at fixed multiplicity with decreasing *ZN* energy

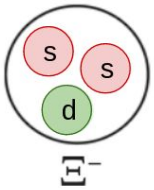


Midrapidity multiplicity

Forward energy

NEW!

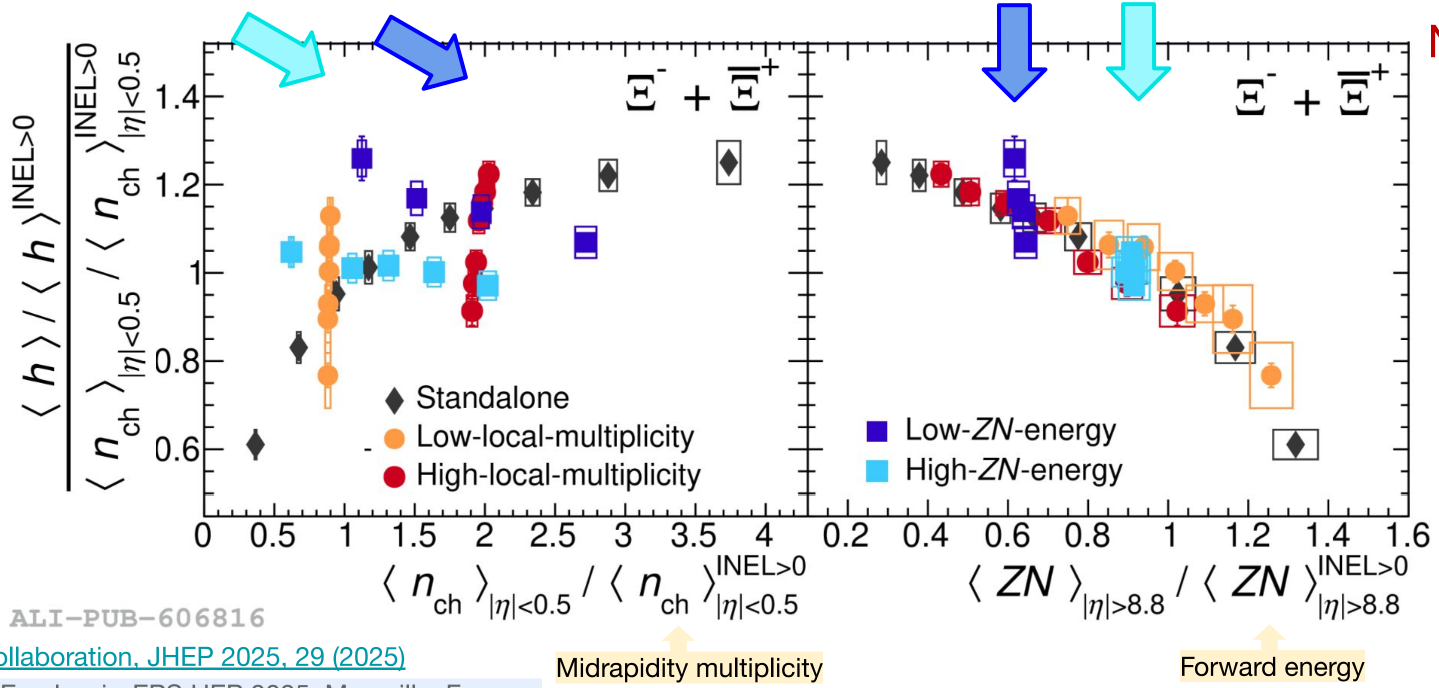
S = 2



ALICE Collaboration, JHEP 2025, 29 (2025)

Results for multi-strange baryons

- ● ● **Fixed local multiplicity**: Ξ/n_{ch} increases at fixed multiplicity with decreasing *ZN* energy
- ■ ■ **Fixed *ZN* energy:** No enhancement with multiplicity, anticorrelation at fixed *ZN* energy



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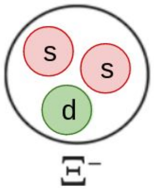
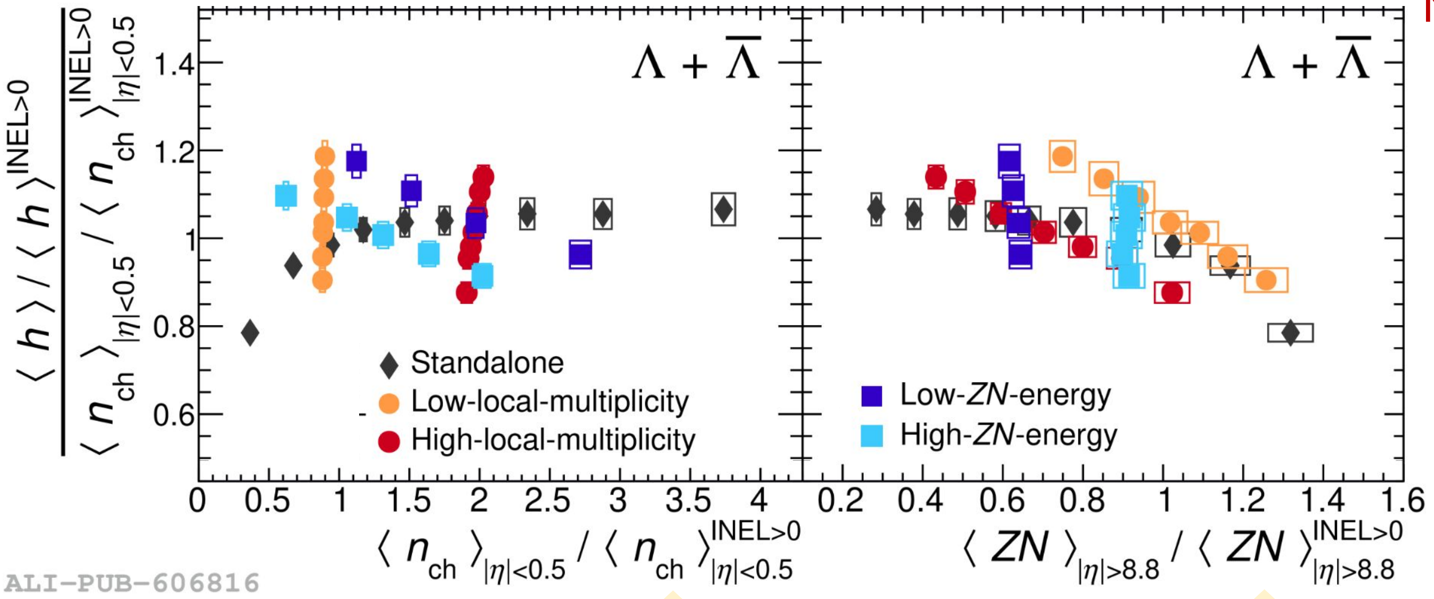


[ALICE Collaboration, JHEP 2025, 29 (2025)](#)

Results for strange baryons

Similar behaviour observed for Λ/n_{ch}

- increases at fixed multiplicity
- anticorrelation with n_{ch} at fixed ZN energy



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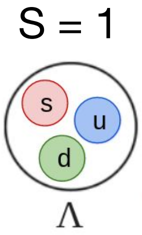


ALICE Collaboration, JHEP 2025, 29 (2025)

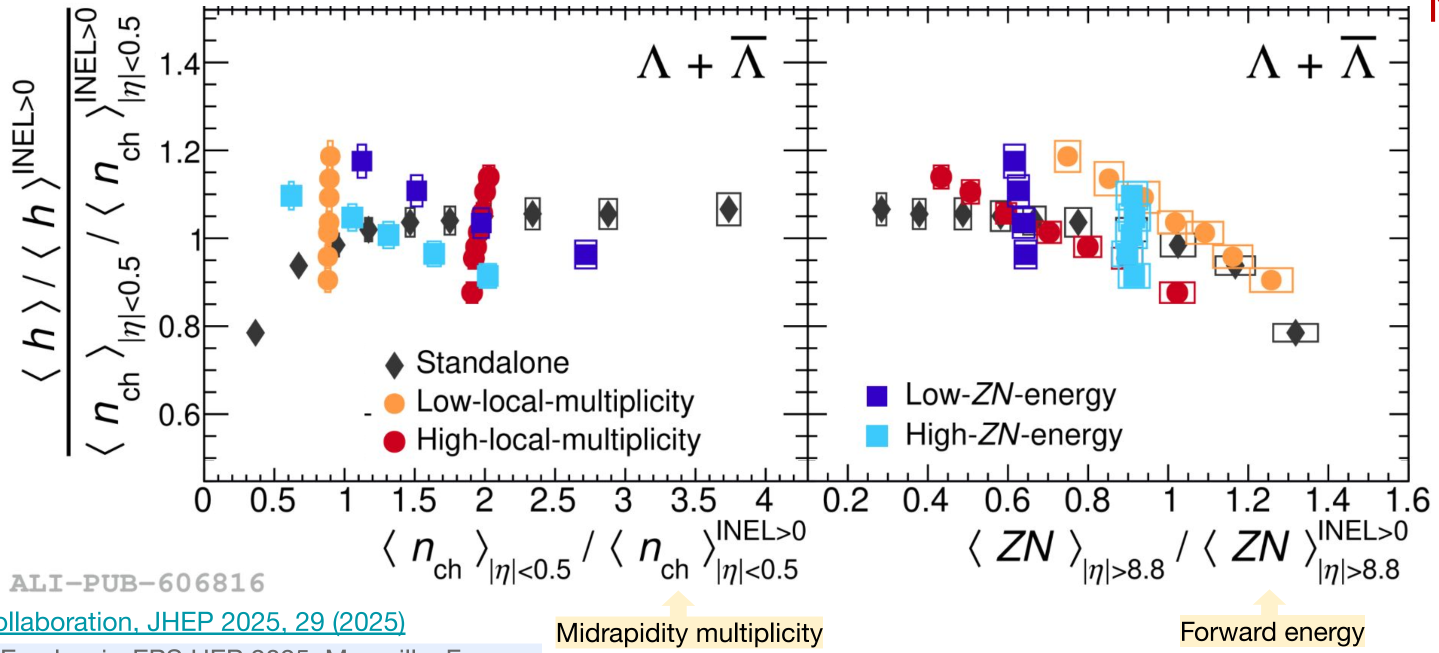
Results for strange baryons

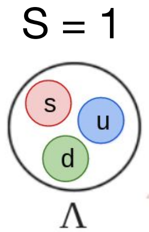
Similar behaviour observed for Λ/n_{ch}

- ● ● increases at fixed multiplicity
- ■ ■ anticorrelation with n_{ch} at fixed *ZN* energy

Strong correlation of strange-baryon enhancement with the effective energy

NEW!

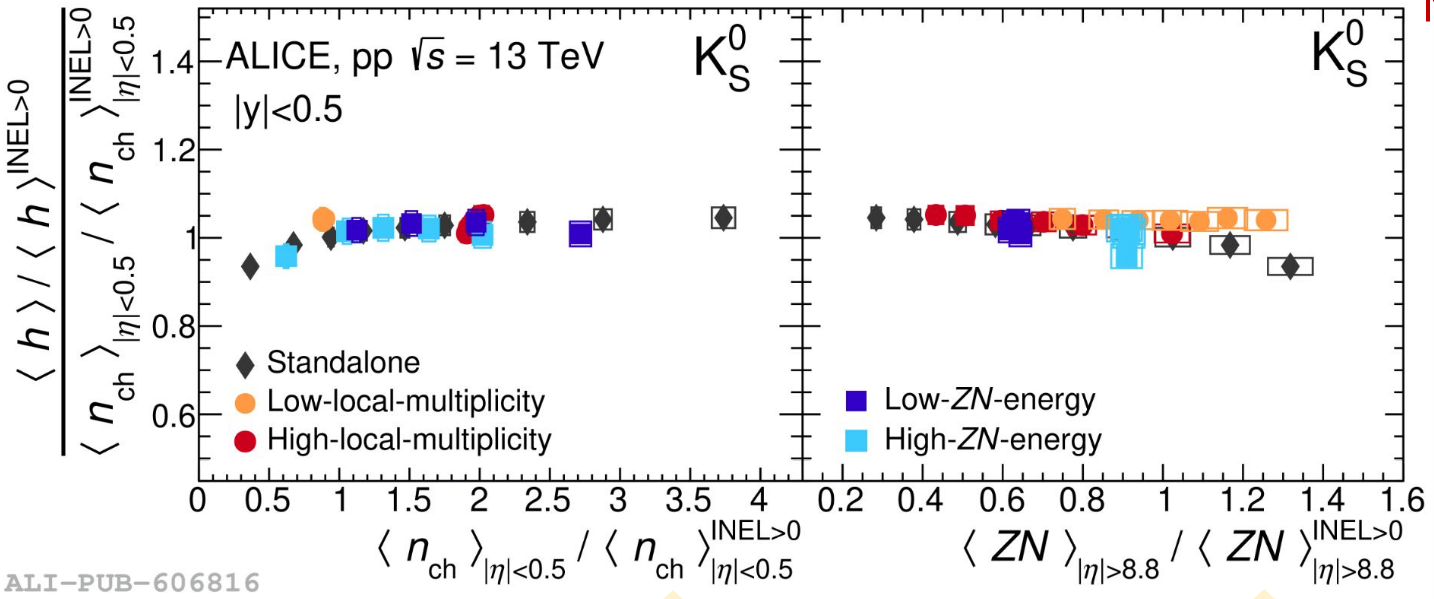




[ALICE Collaboration, JHEP 2025, 29 (2025)](#)

Results for strange mesons

Strange meson (K^0_S) ratios show mild-to-no dependence with multiplicity or leading energy

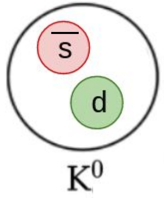


Midrapidity multiplicity

Forward energy

NEW!

S = 1



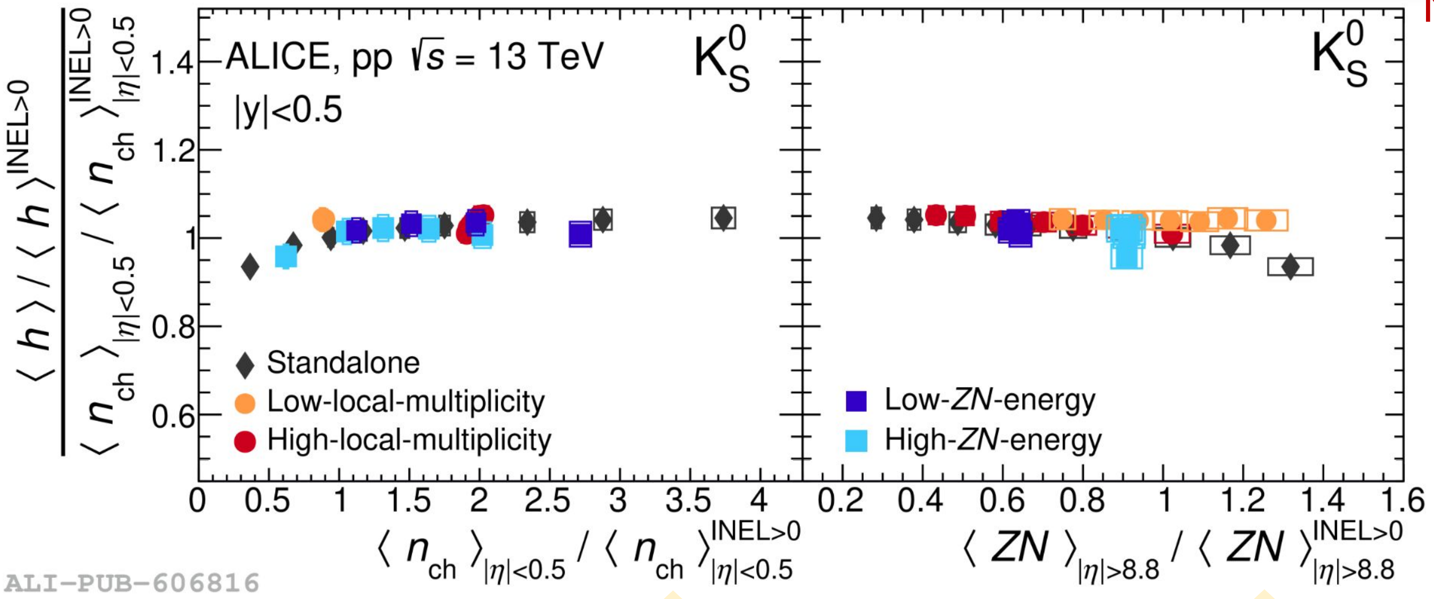
ALICE Collaboration, JHEP 2025, 29 (2025)

Results for strange mesons

Strange meson (K^0_S) ratios show mild-to-no dependence with multiplicity or leading energy

Suggests different production mechanisms at play for strange mesons and baryons

NEW!



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Forward energy

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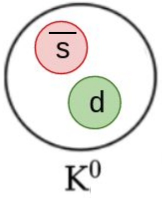


ALICE Collaboration, JHEP 2025, 29 (2025)

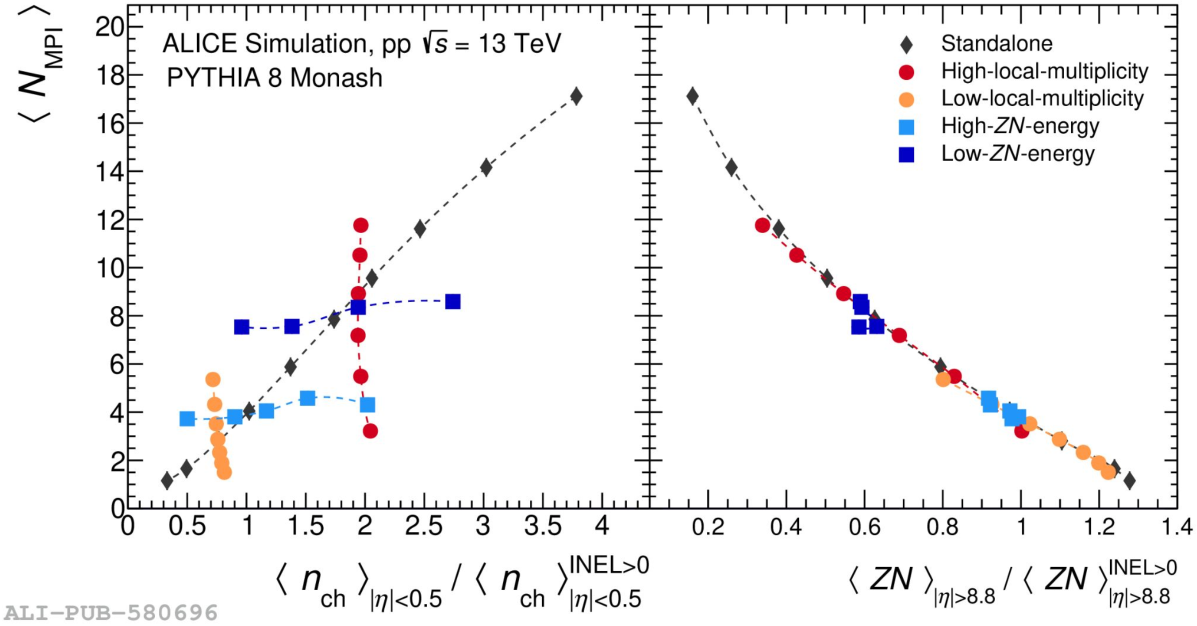
Predictions from PYTHIA8: MPI

In PYTHIA, the number of **Multiple Parton Interactions (MPI)** influences the strangeness formation via string hadronization

NEW!

No evolution with multiplicity once the leading energy is fixed

Number of MPI increases at fixed midrapidity activity



Midrapidity multiplicity

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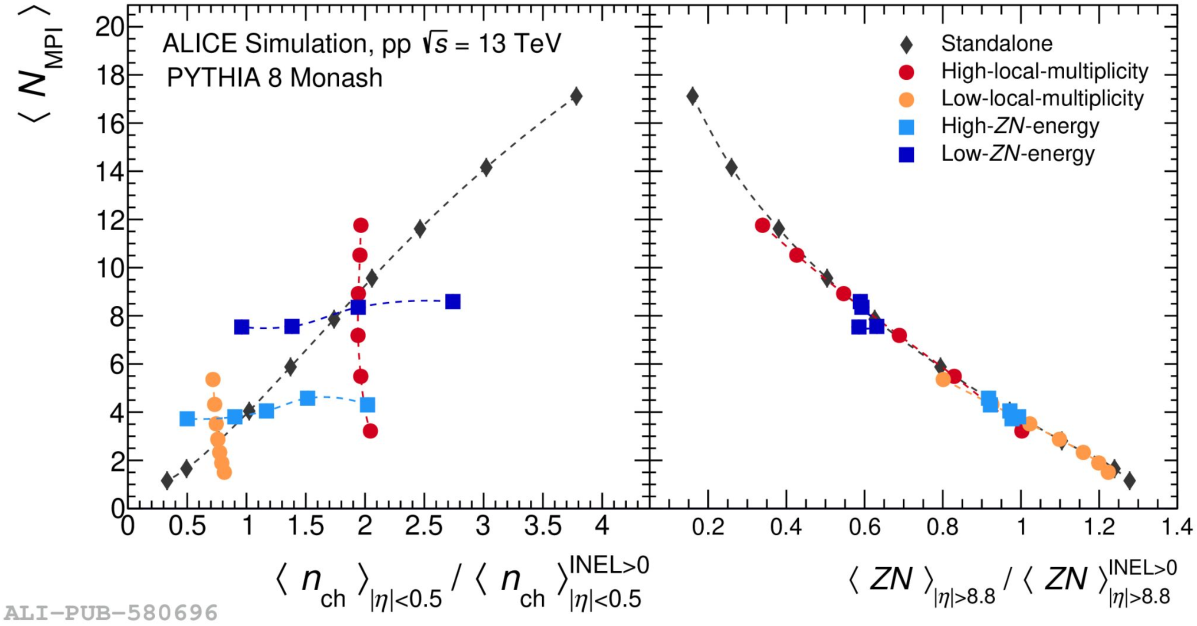
Clear connection between leading energy and MPI in PYTHIA



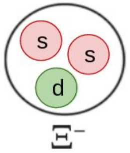
Midrapidity multiplicity

Forward energy

ALICE Collaboration, JHEP 2025, 29 (2025)

Predictions from PYTHIA8: baryons

S = 2



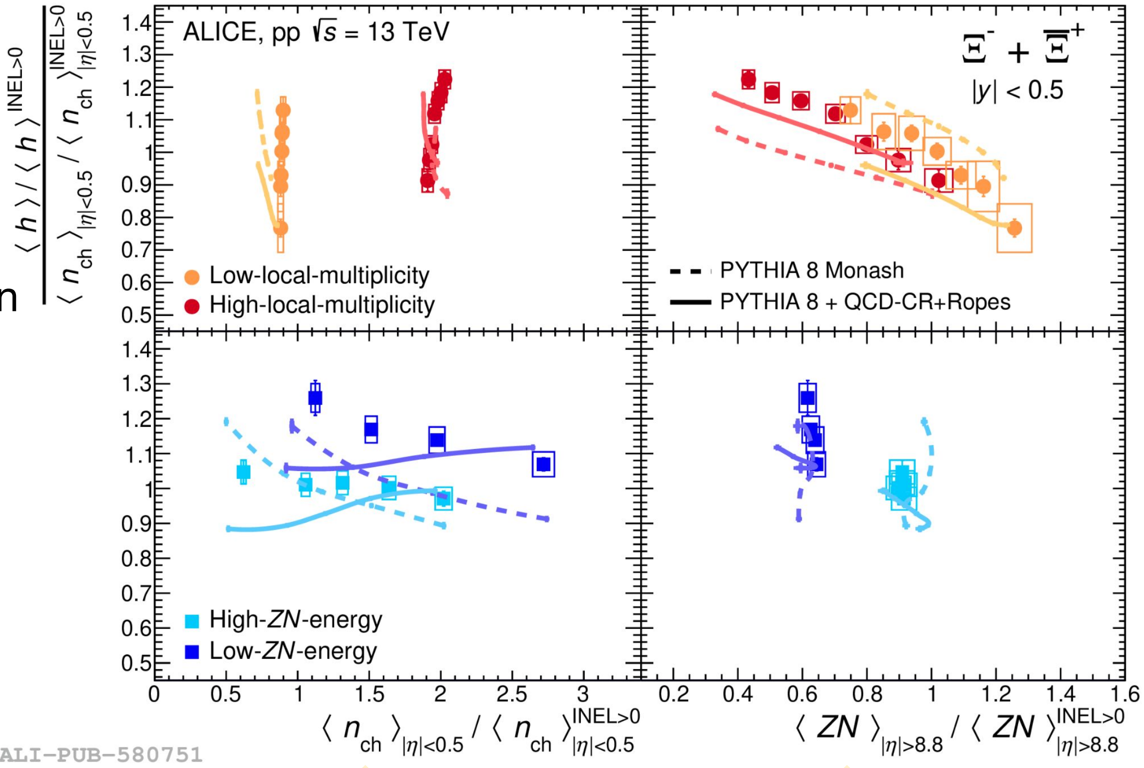
Fixed midrapidity multiplicity

- PYTHIA8 predicts an increase of strange-baryon production with MPI
- Regardless of the hadronization mechanism (Monash or QCD-CR+Ropes)

Fixed *ZN* energy

- Anticorrelation / mild evolution with multiplicity predicted

NEW!

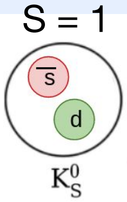


Midrapidity multiplicity

Forward energy

ALICE Collaboration, JHEP 2025, 29 (2025)

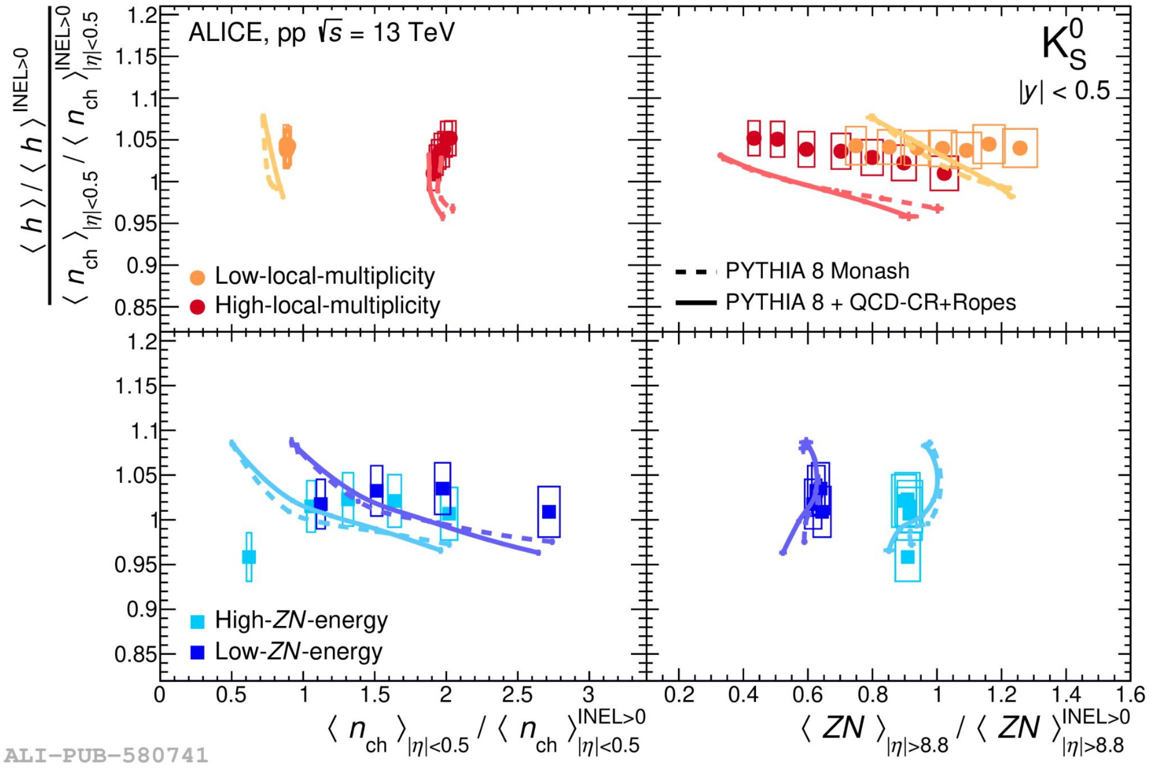
Predictions from PYTHIA8: mesons



NEW!

PYTHIA8 predicts mild-to-no dynamics for the K^0_S meson

Regardless of the hadronization mechanism at play (Monash or QCD-CR+ Ropes)



Midrapidity multiplicity

Forward energy

ALICE Collaboration, JHEP 2025, 29 (2025)

Summary

ALICE Collaboration, JHEP 2025, 29 (2025): "*First observation of strange baryon enhancement with effective energy in pp collisions at the LHC*"

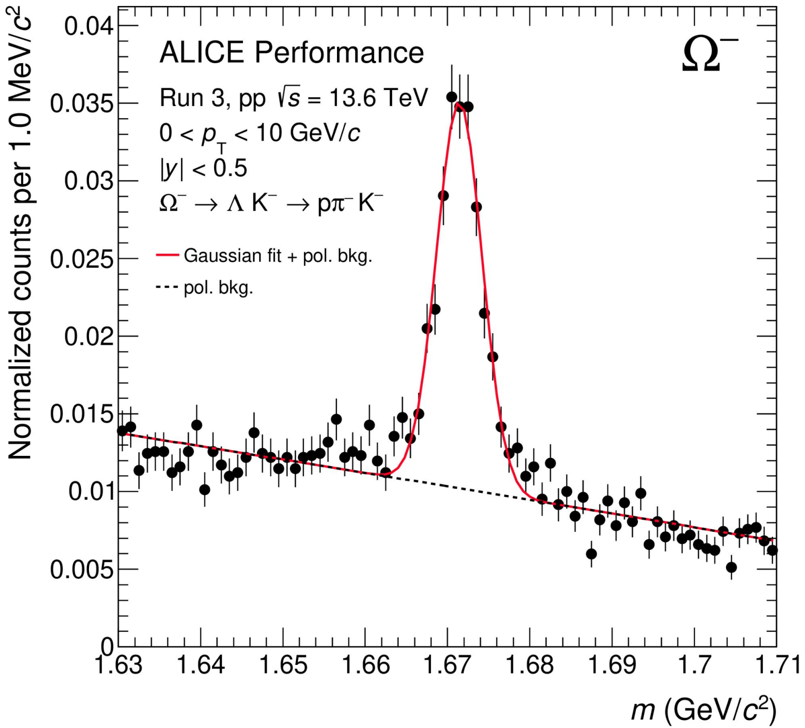
- new approach to study strangeness production in small systems → test the interplay between multiplicity and effective energy
- Observation of strange-baryon enhancement (Λ, Ξ) with effective energy in pp collisions → connected to global properties of the event
- Strange mesons (K^0_S) seems to be less influenced by the effective energy, suggesting different hadronization mechanisms at play for baryons and mesons
- The leading energy is strongly correlated to the number of MPIs in PYTHIA → intriguing input to tune strange-baryon production mechanisms in the models

Perspectives

For Run 3 light flavour results see Romain Schotter's talk next!

- Run 3 will provide an overall increase in statistics of a factor x3000 wrt Run 2
- In addition, dedicated software triggers to select events with Ω candidates
- Subset of pp runs including ZDC recorded by ALICE in Run 3

→ Extend this study to the Ω baryon to access the highest strangeness content



ALI-PERF-542947

Backup

Strange hadron reconstruction

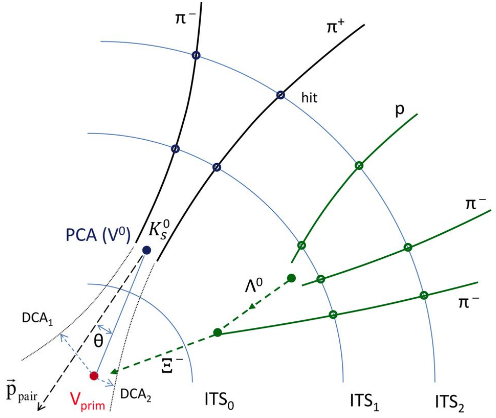
Kinematical and geometrical criteria are used to reconstruct candidates for strange hadrons: K^0_S, Λ, Ξ

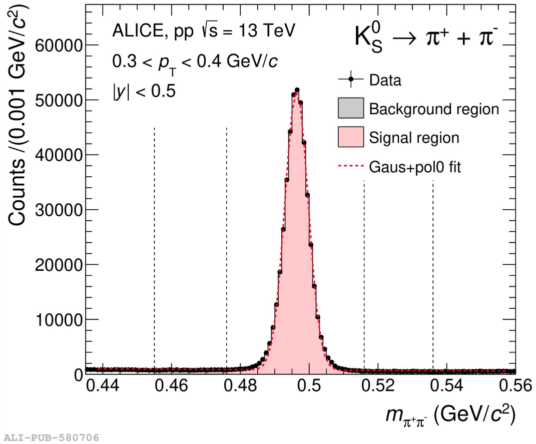
V^0 → neutral with V-shaped decay

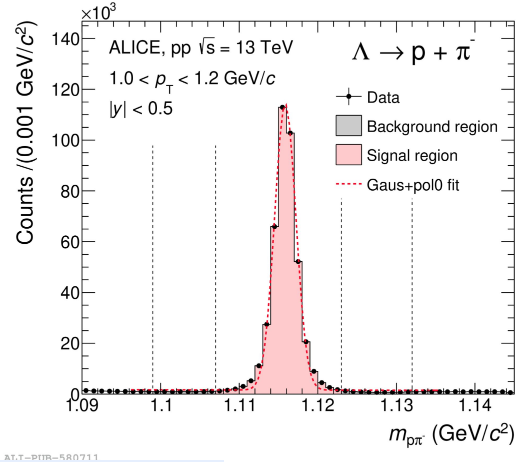
$$\begin{cases} K^0_S \rightarrow \pi^+ + \pi^- \ (69.20 \pm 0.05)\% \\ \Lambda \rightarrow p + \pi^- \ (63.9 \pm 0.5)\% \end{cases}$$

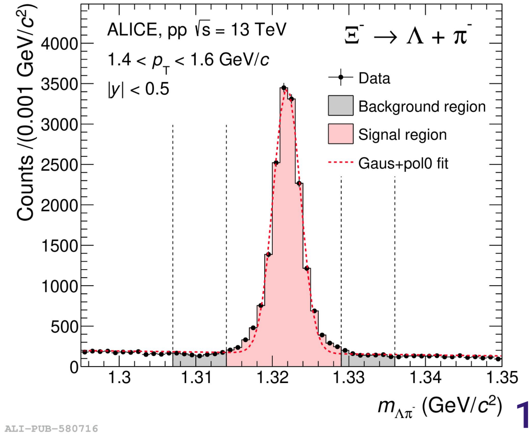
Cascade → V^0 decay + bachelor

$$\Xi^- \rightarrow \Lambda + \pi^- \ (99.887 \pm 0.035)\%$$









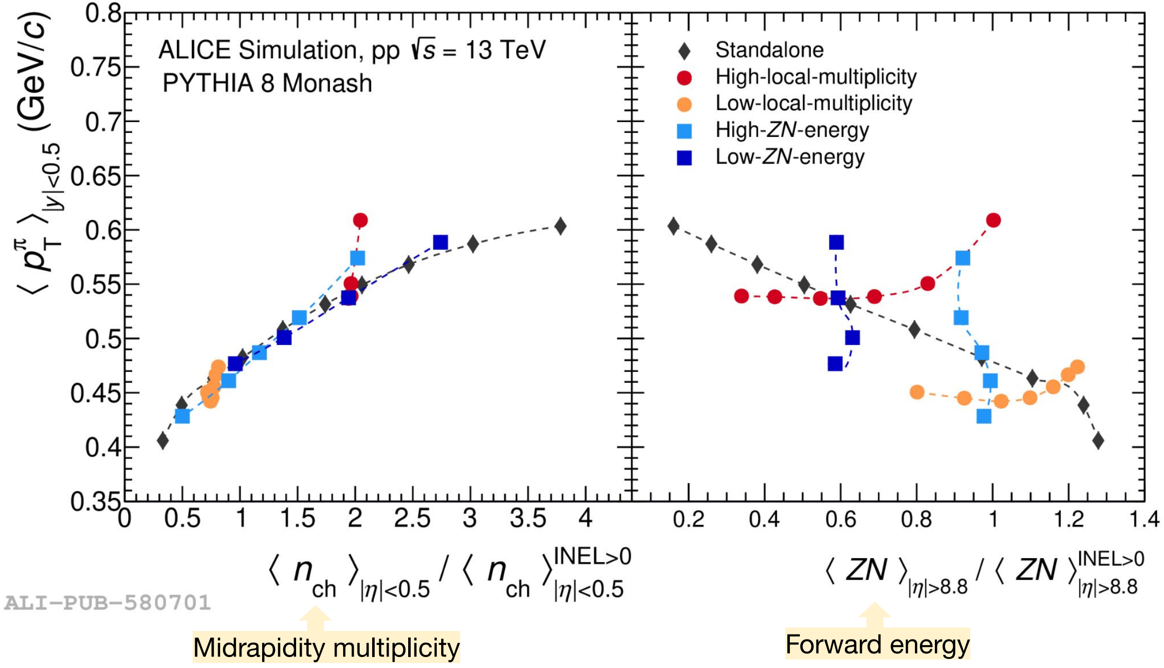
Predictions from PYTHIA8: $\langle p_T \rangle$

The $\langle p_T^\pi \rangle_{|y|<0.5}$, ~ proxy for the p_T of the hard parton scattering process, can be used to study local effects, such as jets at midrapidity

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

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

In PYTHIA, sensitive to local/global collision properties



ALICE Collaboration, JHEP 2025, 29 (2025)