ALICE insights into strangeness production in pp collisions

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University and INFN Bologna

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BLOIS

PARTICLE PHYSICS AND COSMOLOGY

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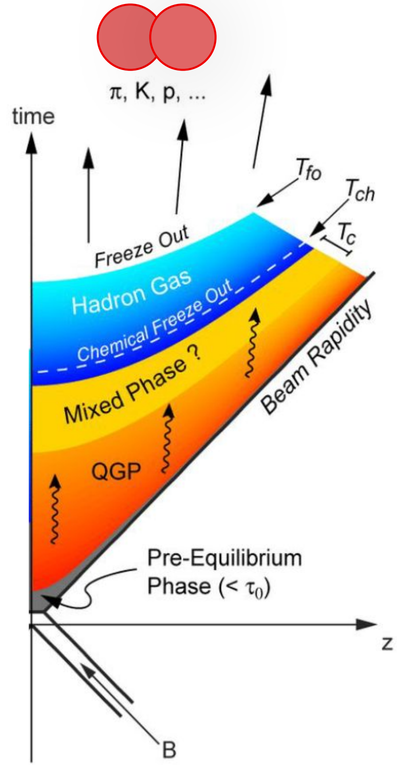
From large to small collision systems

Large systems:

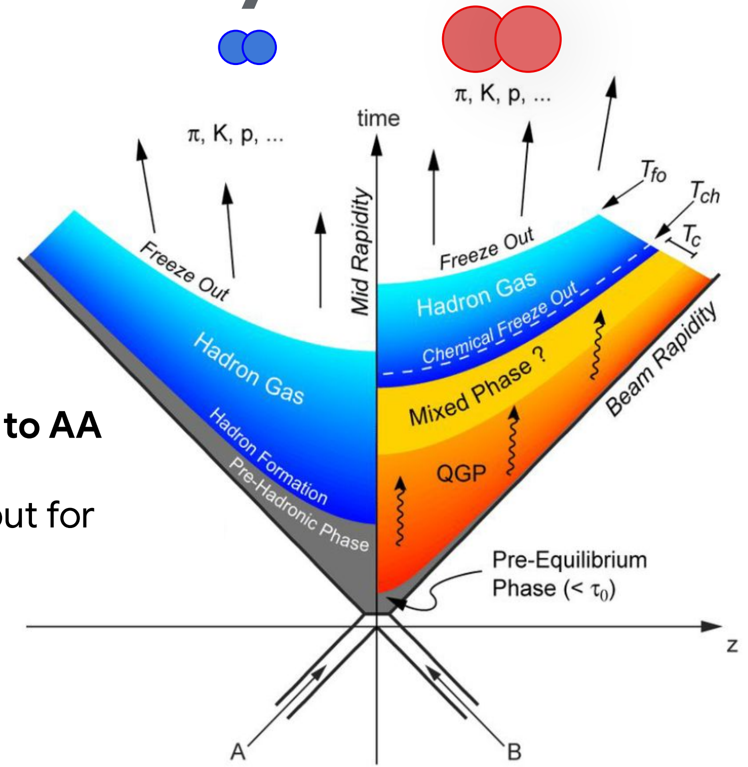
- Many partonic collisions → **collective partonic motion**
- **Statistical approach** to describe light flavour particle production
- ***s* quark can be thermally produced in the QGP** (dominantly by fusion of thermalized gluons)
- After hadronization, the abundance of (multi)strange hadrons reflects that of strangeness in the partonic phase
- **Strangeness enhancement in AA relative to pp** was historically proposed as a signature of QGP formation



From large to small collision systems

Small systems:

- High-energy hadronic interactions are not *elementary*: **multiparton interactions (MPI)**
- **Strangeness canonical suppression** + **energy threshold problem** in a hadron gas at high temperature
- Observations in small systems show striking **similarities to AA**
- Measurements of strange hadron production used as input for **tuning Monte Carlo generators** (PYTHIA, EPOS, ...)



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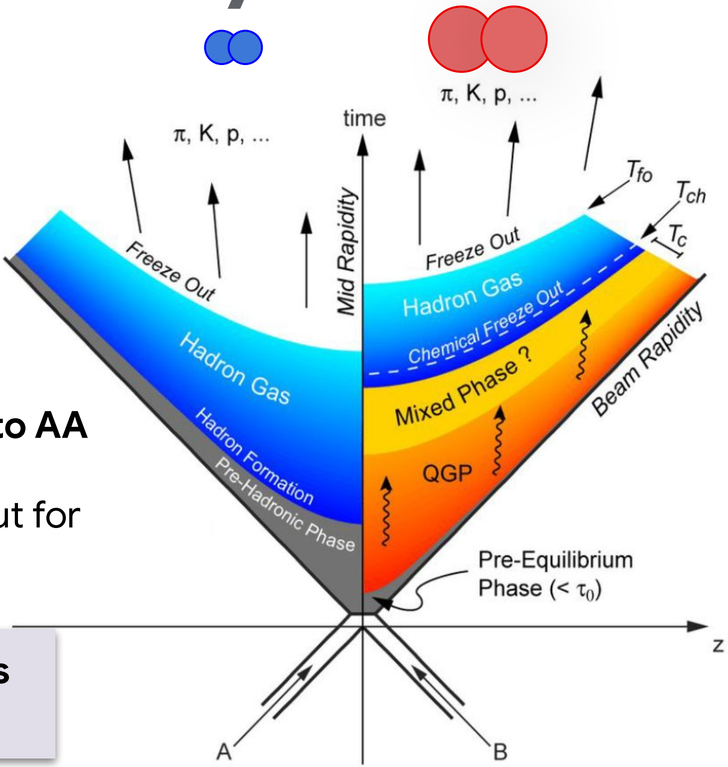
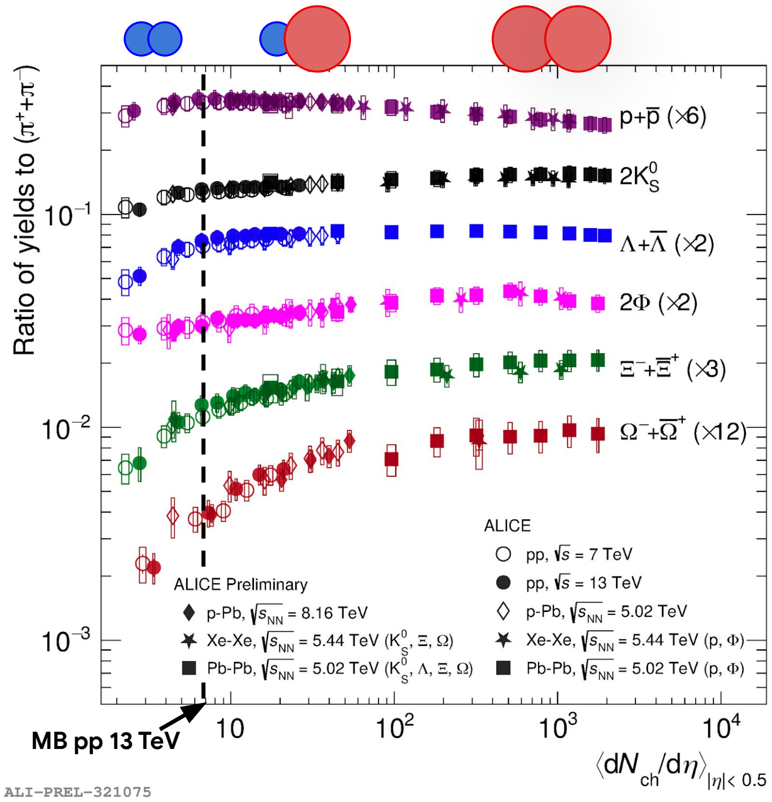
How can we **explain the observations in small collisions** systems (no QGP formation there)?



Strangeness production across systems



ALICE observed that the ratio of strange to non-strange hadron yields (h/π):

- **increases with** midrapidity **multiplicity**
- **smoothly evolves across** different collision **systems**
- shows a **larger enhancement** for particles with larger **strangeness content**

Models traditionally applied in pp fail to quantitatively reproduce the data

Nature Phys 13, 535-539 (2017)
Eur. Phys. J. C 80, 167 (2020)

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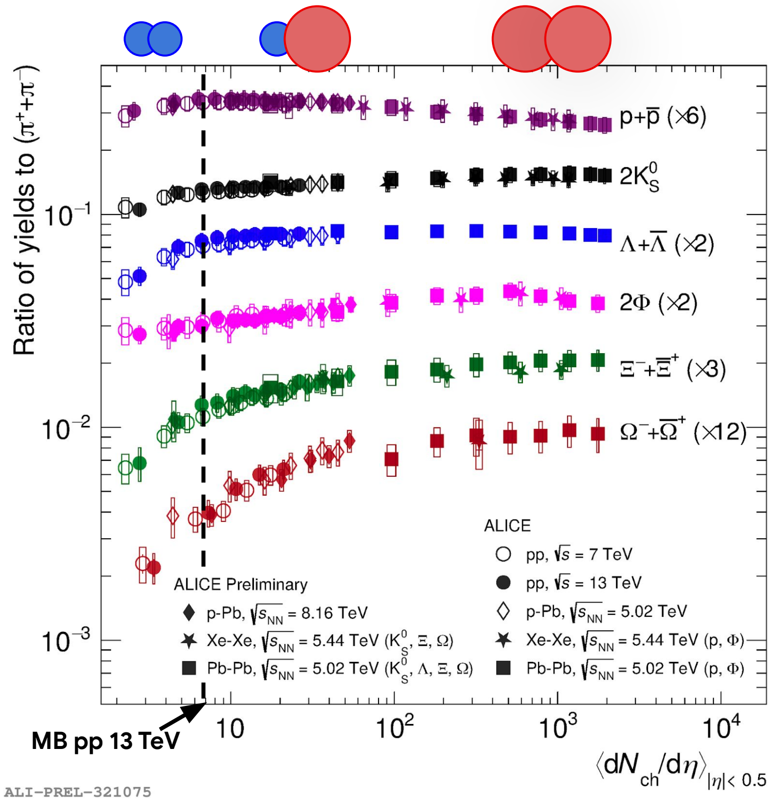

Recent ALICE results contribute to understanding:

- the connection of strangeness production to **hard** processes and soft **out-of-jet processes**
- the relation to specific **event topologies** (pencil-like, isotropic)
- the correlation of strangeness production to **global event properties** w.r.t. local particle multiplicity, possibly also giving insights into **earlier collision phase** mechanisms

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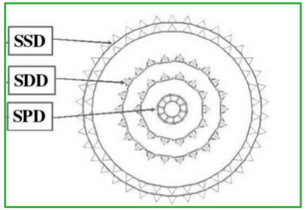
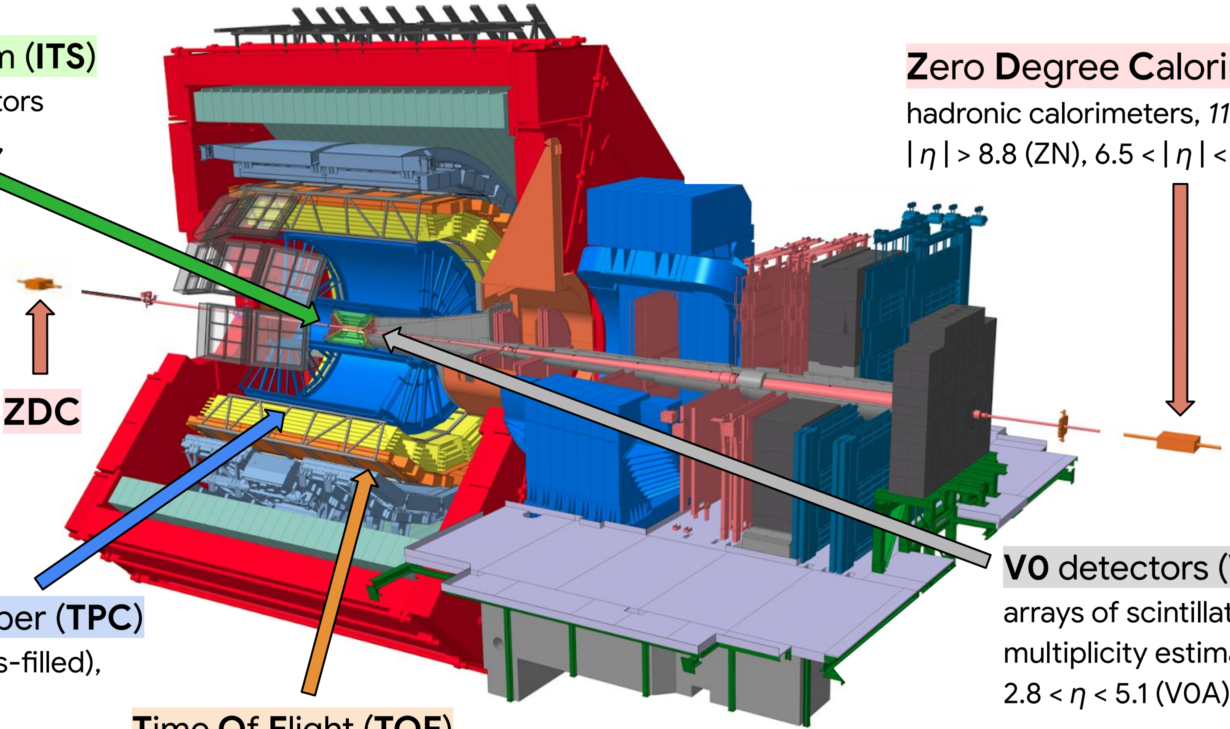
ALICE: A Large Ion Collider Experiment

Inner **T**racking **S**ystem (**ITS**)
six layers of silicon detectors (SPD, SDD, SSD), tracking, triggering, vertexing





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

Time **P**rojection **C**hamber (**TPC**)
main tracking detector (gas-filled), vertexing, PID (d*E*/dx)

Time **O**f **F**light (**TOF**)
PID via Time-Of-Flight technique

V0 detectors (**V0A** and **V0C**)
arrays of scintillators, triggering, multiplicity estimators
$2.8 < \eta < 5.1$ (V0A), $-3.7 < \eta < -1.7$ (V0C)

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

ALICE strangeness 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)

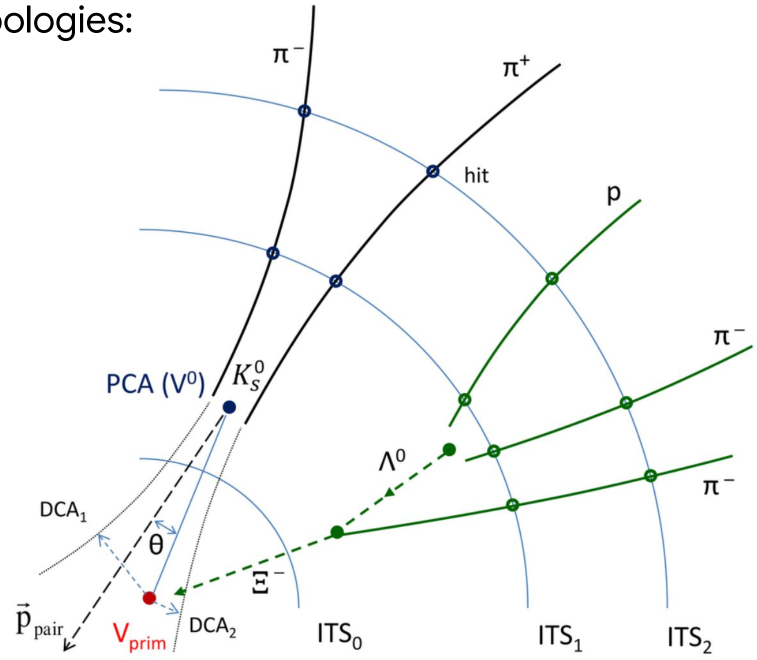
$$K^0_S \rightarrow \pi^+ + \pi^-$$

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

- **Cascade ⟶** charged particle decaying weakly into a V^0 + charged particle

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

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



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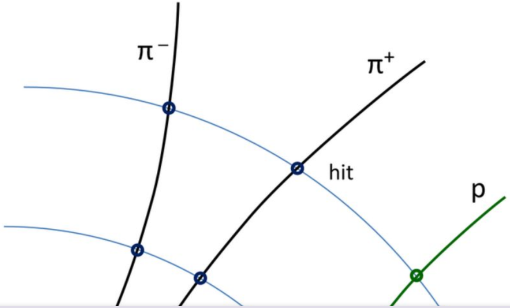

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Brand new technique for strange hadron reconstruction is under development: the ***strangeness tracking***

⟶ finds signatures of weakly decaying hyperons / hypertritons before decay using the upgraded ITS2
⟶ will allow for unprecedented precision in measuring these particles during Run 3 of the LHC and beyond

D.D.Chinellato, "Strangeness tracking" LHCP 2022

Strangeness-hadron correlation

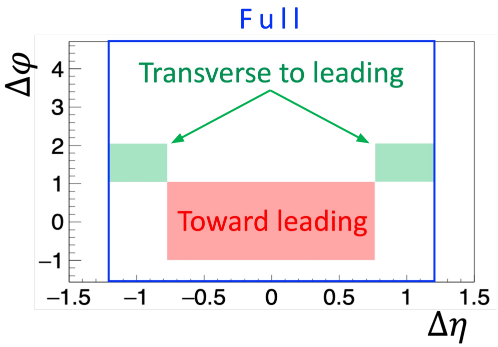
ANGULAR CORRELATION METHOD

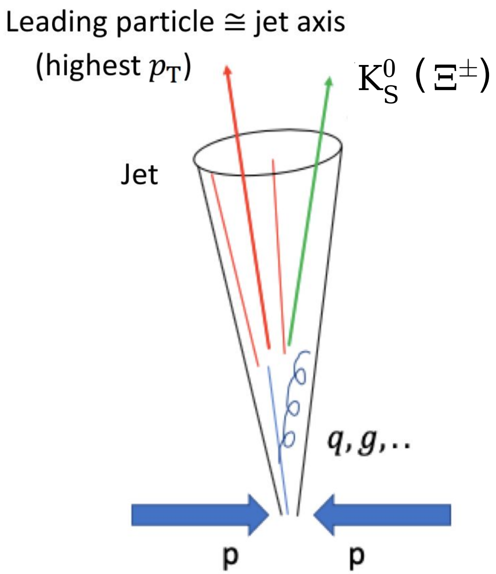
1) **Trigger particle** as a proxy for the **jet axis** ($p_T > 3$ GeV/c)
2) Identification of **associated particles** (strange hadrons)
3) **Angular correlation** between trigger and associated particles

$$\Delta\varphi = \varphi_{Trigg} - \varphi_{Assoc}$$

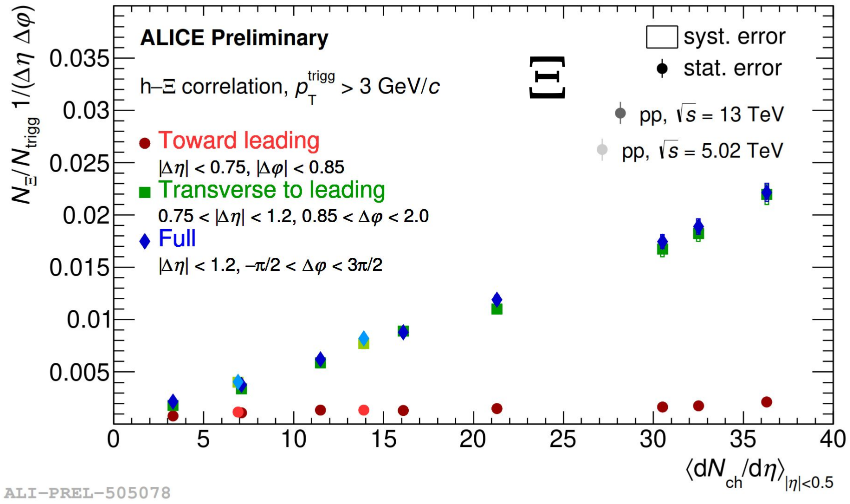
$$\Delta\eta = \eta_{Trigg} - \eta_{Assoc}$$

φ: azimuthal angle
η = - ln (tan(θ/2))
θ: polar angle





Strangeness in and out-of-jet



(Multi-)strange hadrons are mostly produced in the **transverse to leading** region

The **toward leading yield** shows a weak multiplicity dependence

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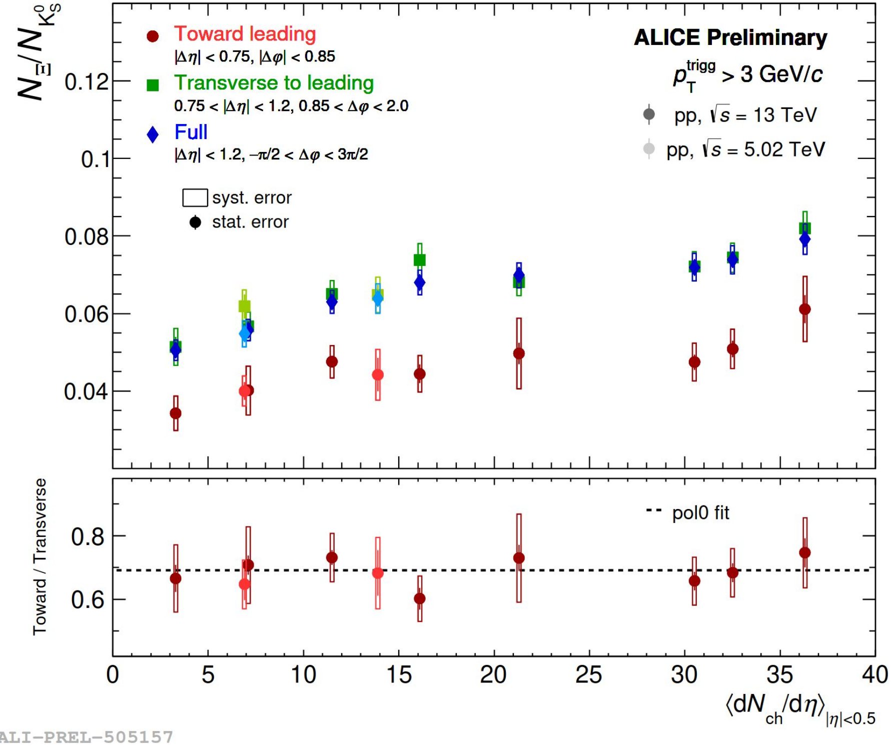

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$\Xi^{\pm}/K^0_S$ **full yield ratio increases with multiplicity**
→ larger strangeness content of $\Xi^{\pm}$ w.r.t. K^0_S

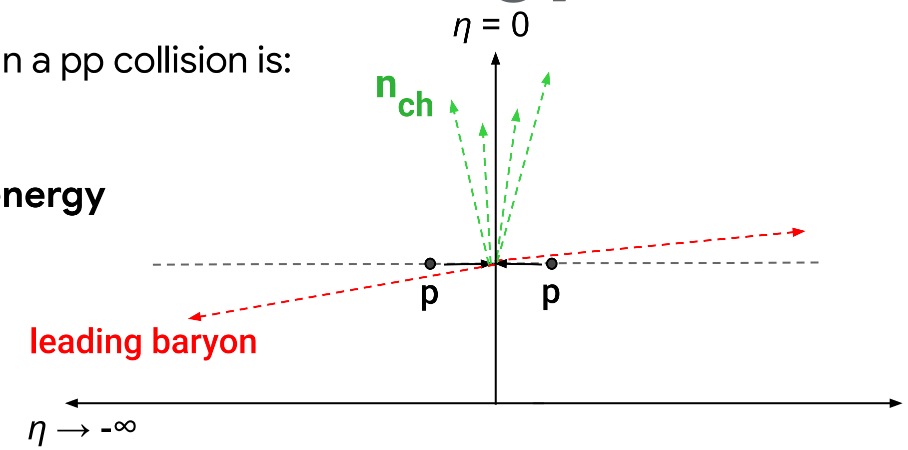
The **toward leading** ratio is **lower w.r.t. transverse to leading** and **full yield ratio**

Compatible increase with multiplicity is observed **in** and **out-of-jet** within uncertainties

The concept of effective energy

The **charged-particle multiplicity** produced in a pp collision is:

- characteristic of the **hadronic final state**
- strongly correlated to the **initial effective energy**



EFFECTIVE ENERGY

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

$E_{\mathrm{EFF}} < \sqrt{s}$ due to **leading baryon emission** at forward rapidity

A. Akindinov et al., Eur. Phys. J. C 50, 341-352 (2007)

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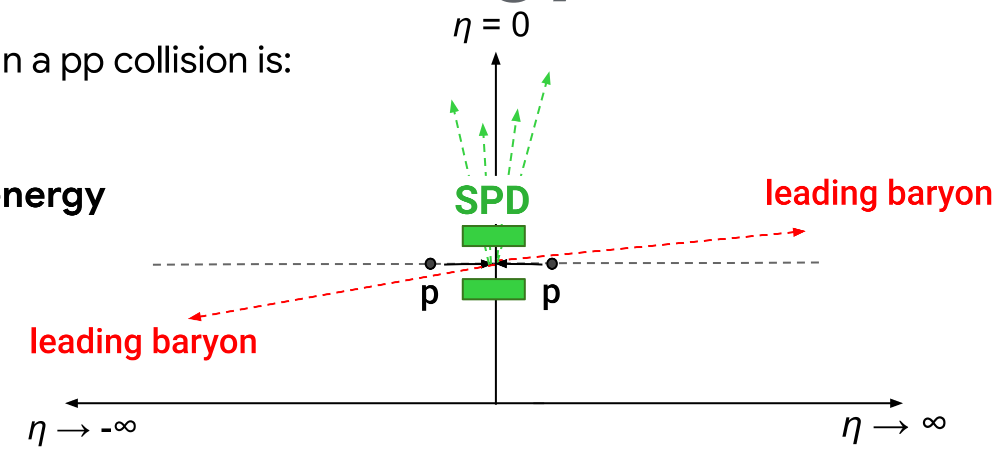

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ALICE can measure:

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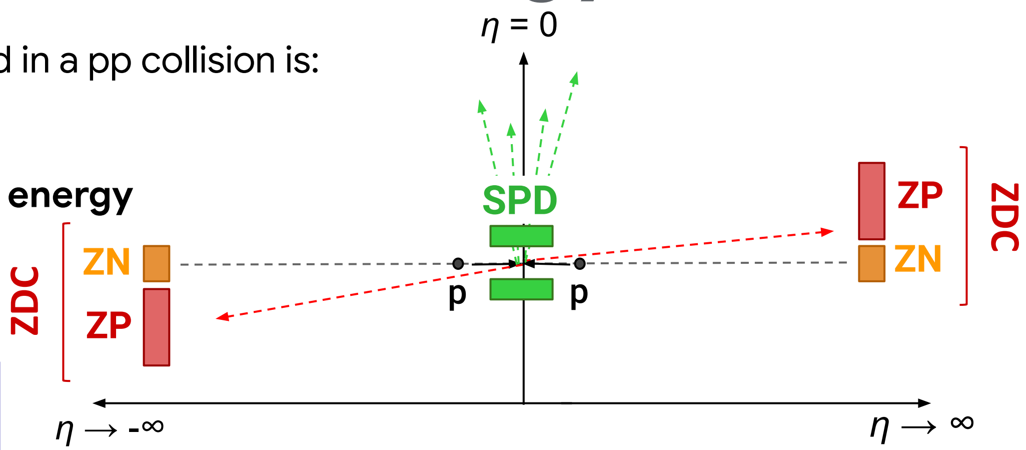

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energy available for particle production in the **initial stages** of the pp collision

ALICE can measure:

- midrapidity multiplicity (**SPD**)
- leading energy (**ZDC**)

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

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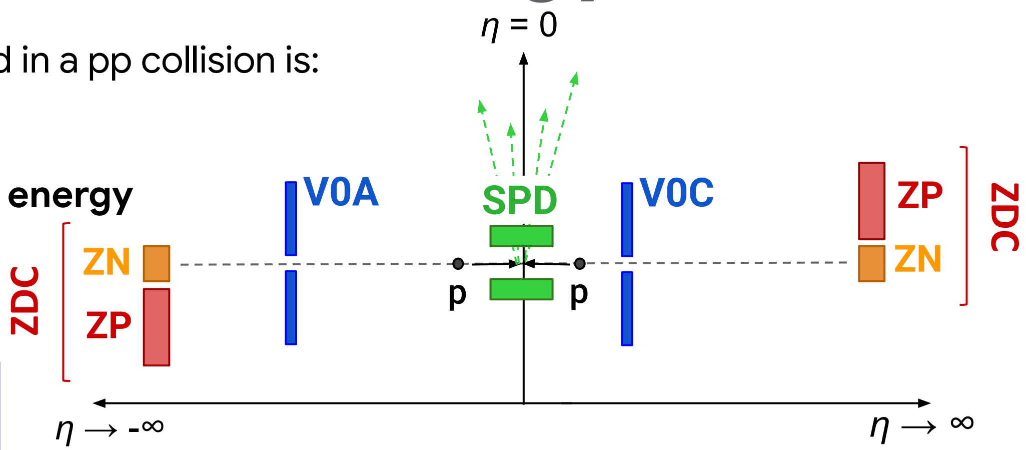

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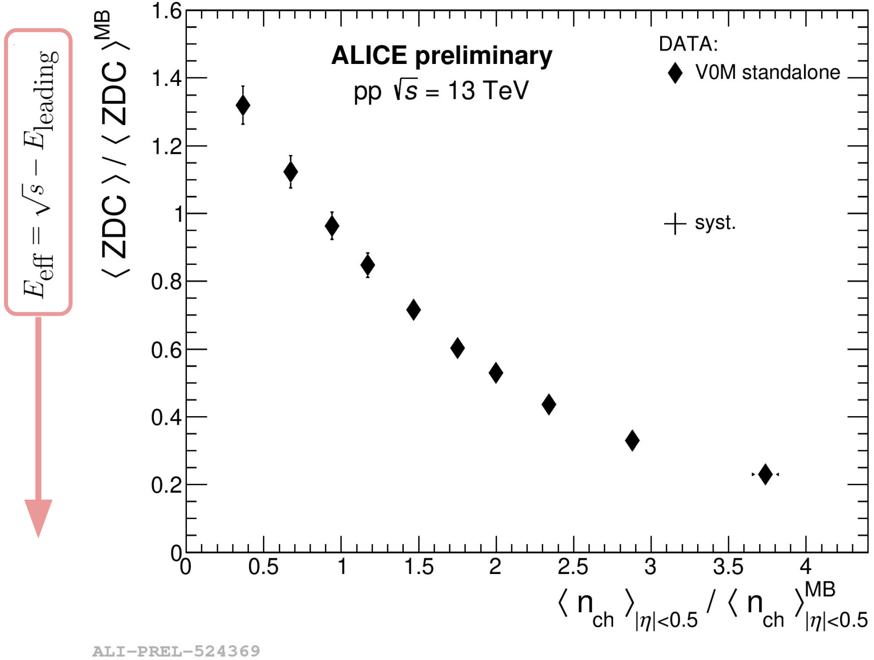
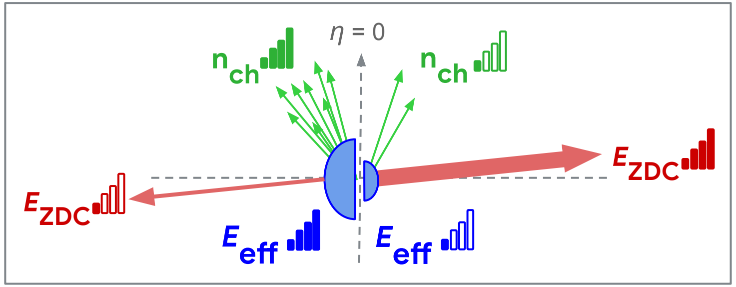
  $E_{\mathrm{eff}} = \sqrt{s} - E_{\mathrm{leading}} \simeq \sqrt{s} - E_{\mathrm{ZDC}}$
- multiplicity (**V0M** = V0A+V0C)

Single-differential event classes

The **forward energy decreases with** increasing particle **multiplicity** produced at **midrapidity**



♦ **Standalone** V0 event classes



ALICE Collaboration arxiv.org/2107.10757

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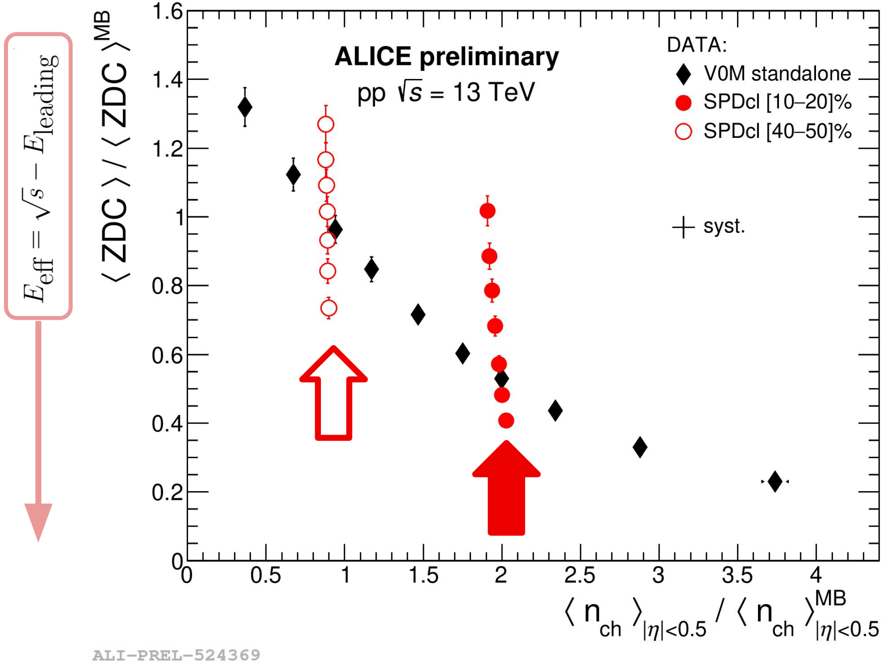

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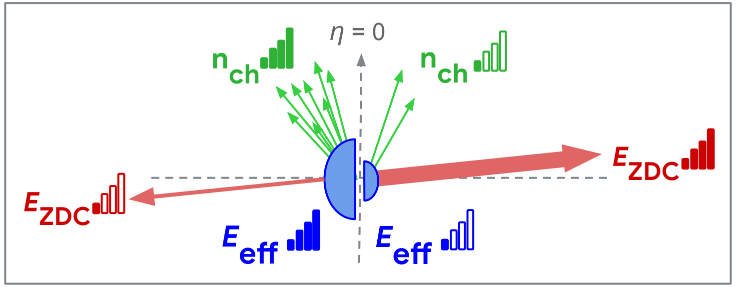
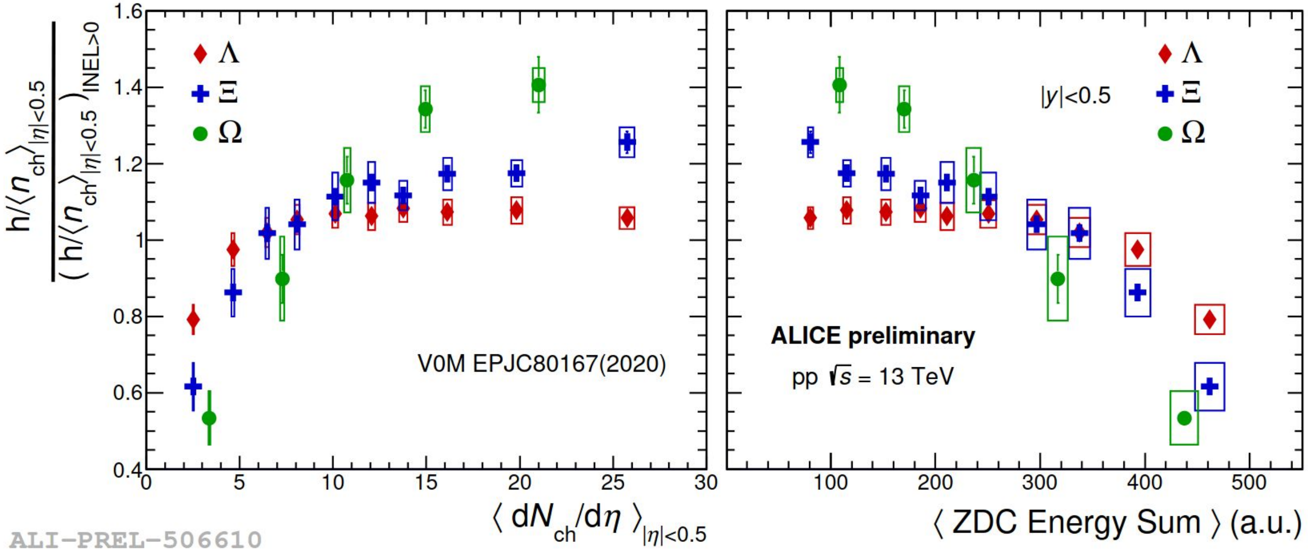


Strangeness vs multiplicity and energy

Strangeness production per charged particle:

- **increases** with **midrapidity multiplicity** (left)
- is **anticorrelated** with the **ZDC energy** (right)
- shows **hierarchy** with strangeness content **vs multiplicity and forward energy**

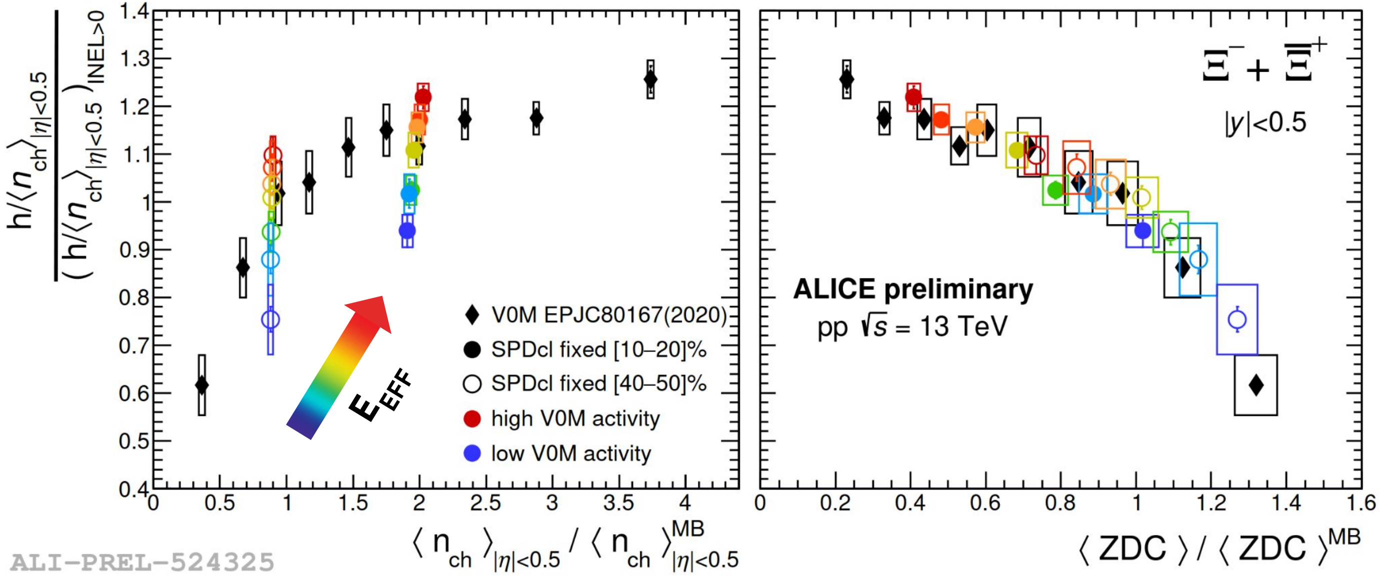
Can we **disentangle** the dependence on leading energy and multiplicity?



Strangeness at fixed multiplicity

In events with the same particle multiplicity produced:

- **increase** in Ξ production per charged particle is observed for **decreasing forward energy** (ZDC)
- scaling trends with ZDC energy are **compatible within uncertainties**



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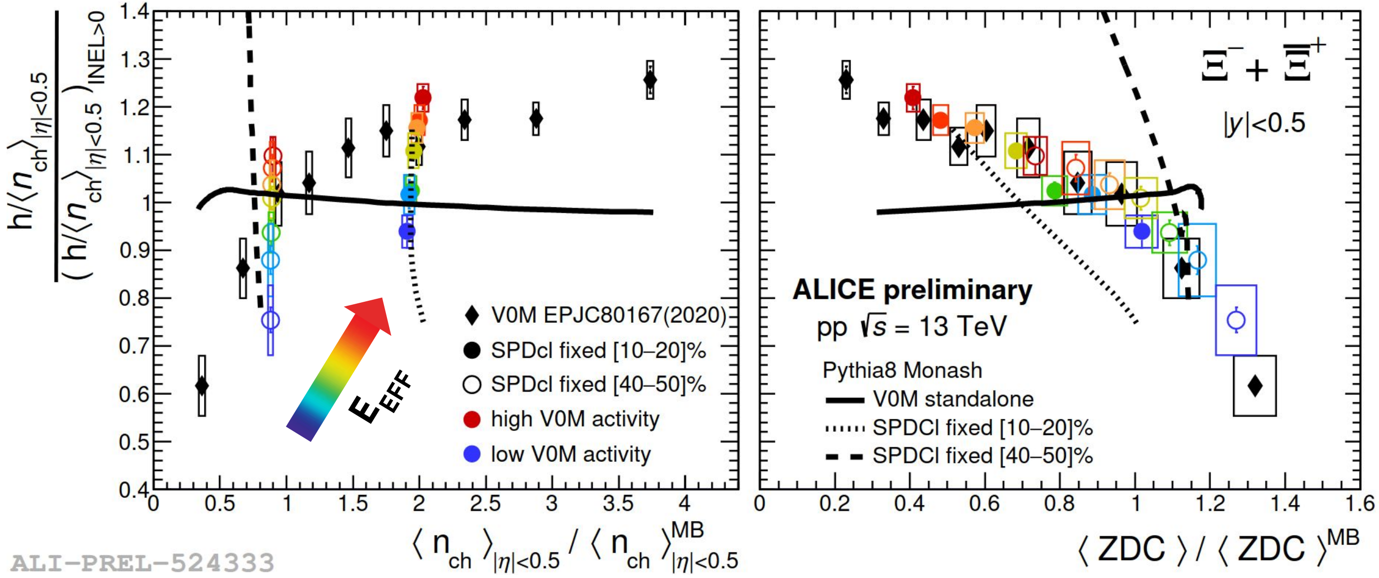

The **Pythia Monash 2013** tune **fails to reproduce** the results

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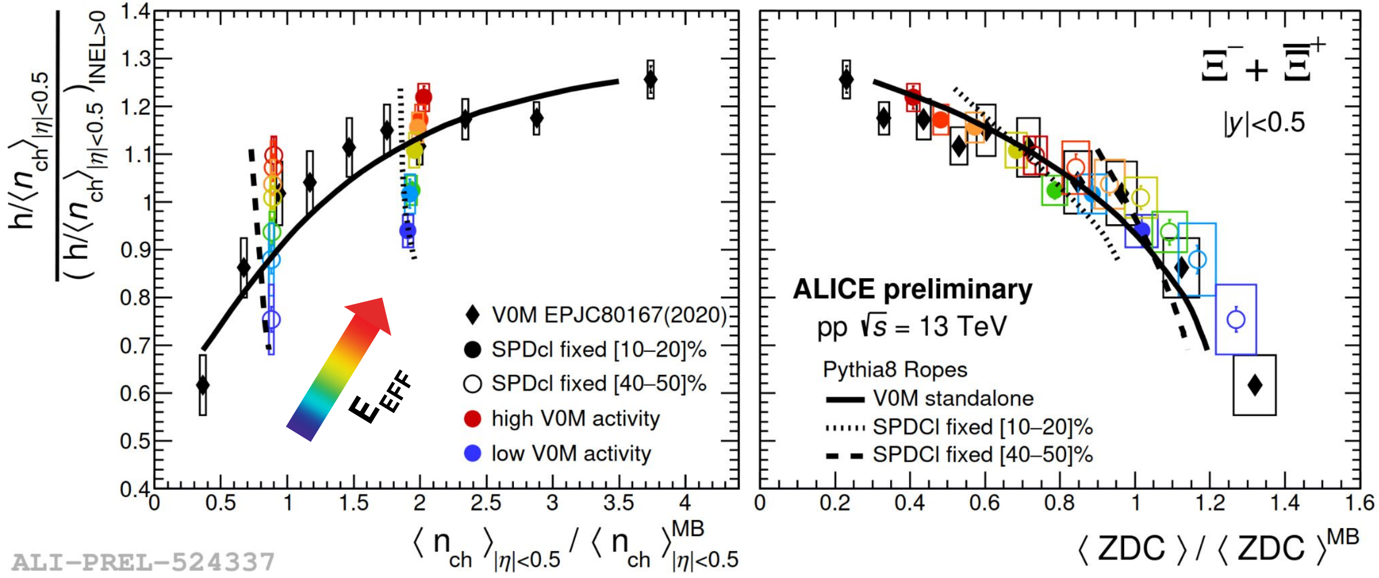


Including **Color Ropes** in the model **improves the agreement** with data

Strangeness studies using spherocity

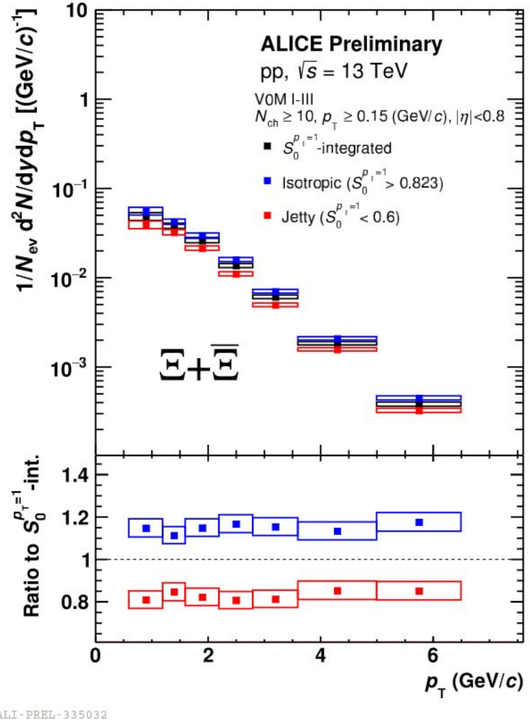
$$S_{\mathrm{O}}^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |p\hat{_{\mathrm{T},i}} \times \hat{n}|}{N_{\mathrm{trks}}} \right)$$

- S = 0 "pencil-like" limit (hard events)
- S = 1 "isotropic" limit (soft events)

Fixed V0 multiplicity (forward):
S_{O} selects different yields but similar p_{T} shapes

Fixed mid-rapidity multiplicity:
S_{O} selects harder spectra

Fixed V0 multiplicity (forward)



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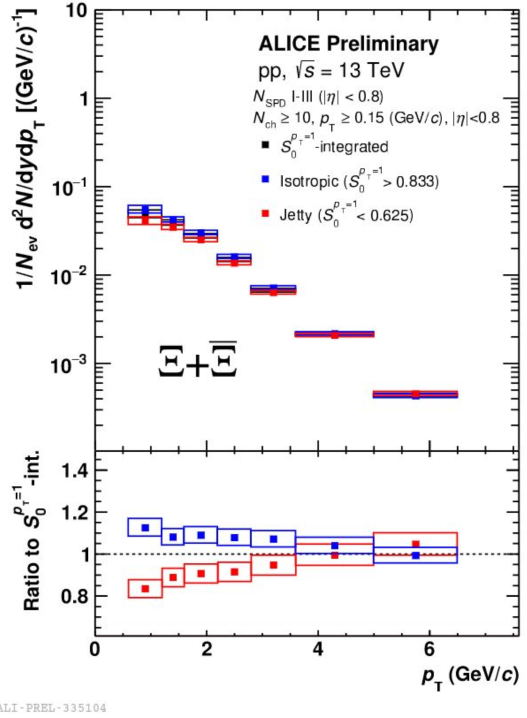

Summary

Striking observations at the LHC: strangeness enhancement vs multiplicity from small to large systems

Big theoretical effort in order to reproduce ALICE data, but we are still far from a complete understanding

Recent ALICE results help to understand:

- (Multi-)strange hadrons are **mostly produced in out-of-jet processes**, but strangeness **enhancement** with multiplicity is **observed in both toward and transverse to leading** processes
- Strangeness enhancement in pp collisions is **observed** at **fixed midrapidity multiplicity**, showing **correlation with leading energy** at forward rapidity
- S_O is a powerful tool to **select** events with specific **event topologies** and study strangeness enhancement at fixed mid-rapidity/forward multiplicity

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- Str … y, showing **co** …
- S_O … eness en …

The study of strangeness production in pp collisions will benefit from the **large statistics** ALICE is collecting during **Run 3**

The extended Run 3 pp programme will provide a **sample larger by more than three orders of magnitude** than that of Run 2 for specific signals of interest, i.e. events with a reconstructed Ω baryon

Backup

Strangeness-hadron correlation

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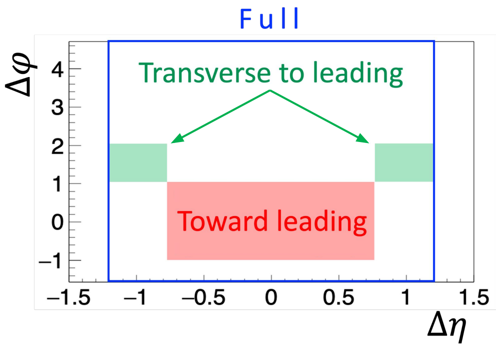
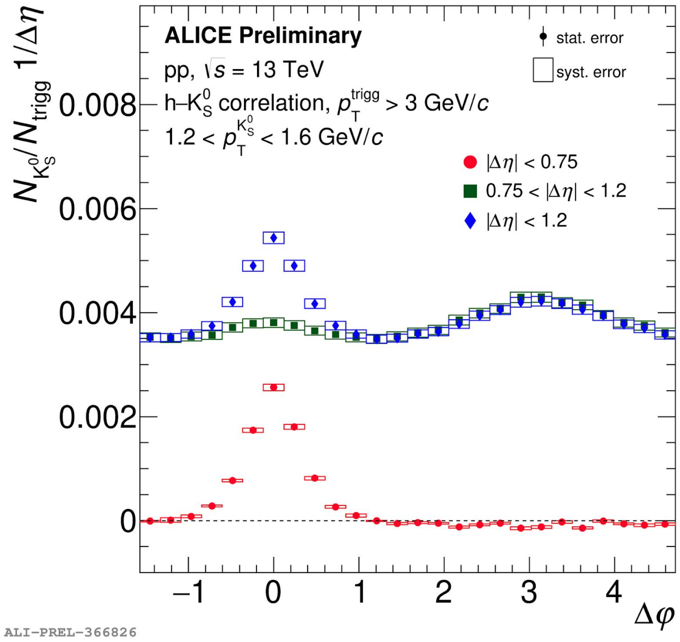
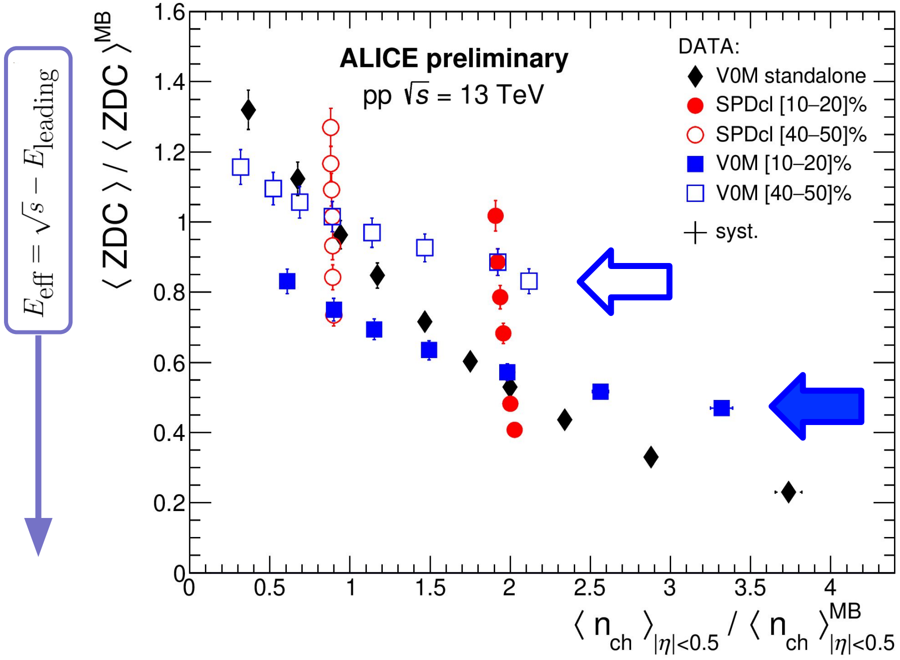




Toward leading = Full − Transverse to leading

Multi-differential event classes

The **forward energy decreases with** increasing particle **multiplicity** produced at **midrapidity**



♦ **Standalone** V0 event classes

Event classes defined using V0 and SPD (clusters):

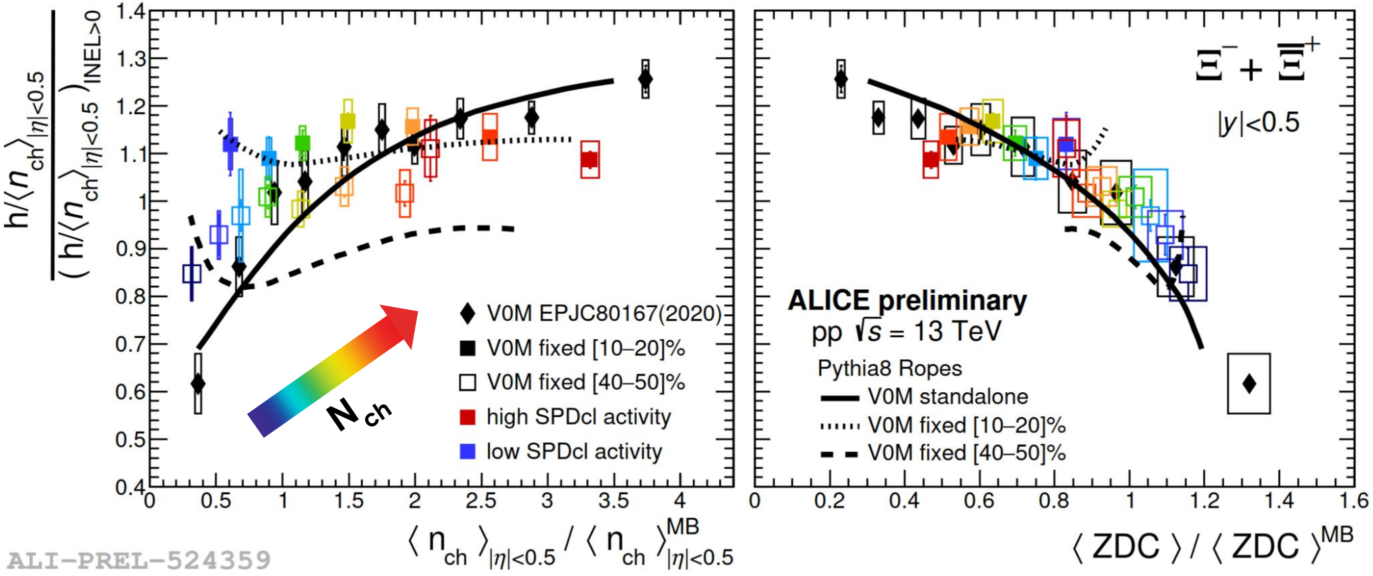
● ○ **Fixed multiplicity** at midrapidity + different forward energy deposits in the ZDC

■ □ **ZDC energy fixed in a small range** + different multiplicity produced in the event

Strangeness at constrained ZDC energy

In events with ZDC energy deposits fixed in a small range:

- strangeness **enhancement with multiplicity is reduced** (left)
- within the small ZDC energy range, scaling **trends** are **compatible** within uncertainties (right)



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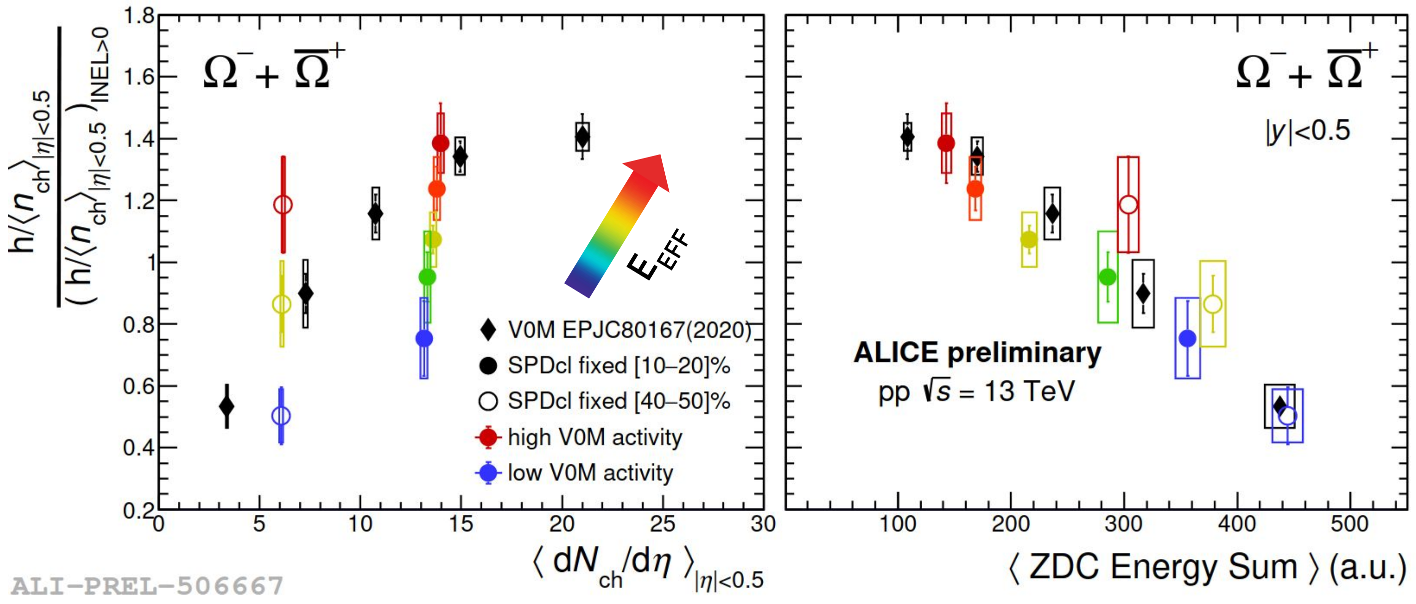
Strangeness at fixed multiplicity

Similar results are obtained for the Ω baryon (higher strangeness content)



Forward energy vs MPI

Inverse dependence of very forward energy as a function of the number of MPIs observed in Pythia