A Large Ion Collider Experiment

A multi-differential investigation of strangeness production in pp collisions with ALICE

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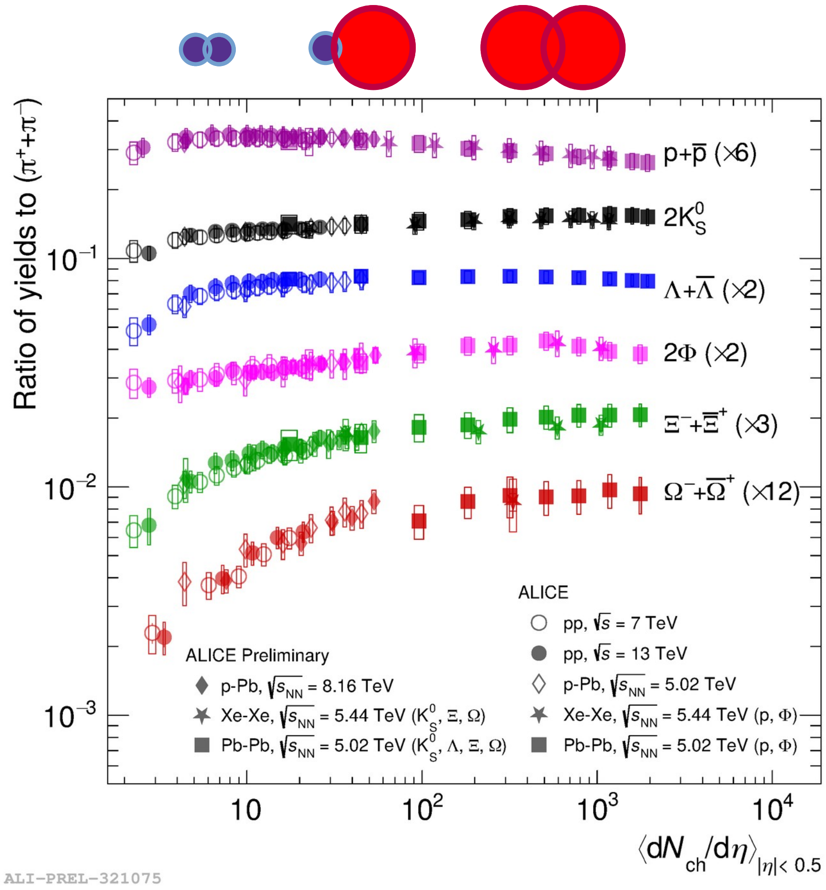
Motivations

ALICE



One of the key signatures of QGP is **strangeness enhancement**

Increase of the ratio of (multi-)strange to non-strange hadron yields with the multiplicity of charged particles produced in the collision

Strangeness enhancement in ALICE :

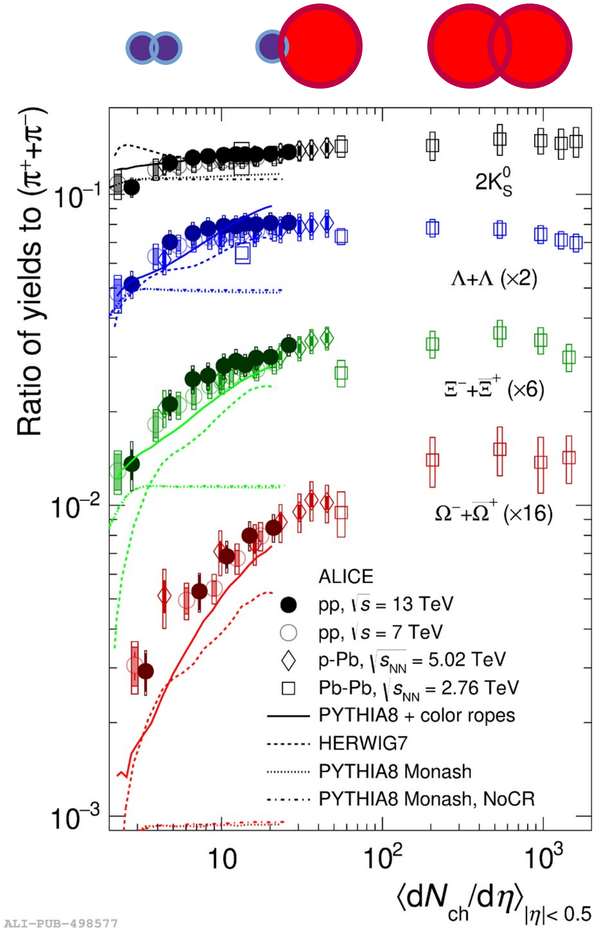
- **Smooth evolution** with the multiplicity of charged particles across different collision systems (**pp**, p-Pb, Pb-Pb)
- No dependence on the collision energy at the LHC
- **More pronounced** for hadrons **with larger strangeness content**

$$E(\Omega) > E(\Xi) > E(\Lambda) \simeq E(\mathrm{K^0_S})$$

with E = the observed enhancement with respect to $(\pi^+ + \pi^-)$

Nature Physics 13, 535-539 (2017)

Motivations



Eur. Phys. J. C 80 (2020) 693

One of the key signatures of QGP is **strangeness enhancement**

Increase of the ratio of (multi-)strange to non-strange hadron yields with the multiplicity of charged particles produced in the collision

Several phenomenological models qualitatively reproduce these measurements, but **no unambiguous explanation yet**

In order to improve our understanding :

- Is strangeness enhancement in pp collisions correlated only with **final state particle multiplicities**, or does the **initial stage of the collision** play a role?
- What are the relative contributions of **hard processes** (such as jets) and **out-of-jet processes** to the strangeness enhancement?

The ALICE set-up

ALICE is composed of 19 detection systems (during LHC Runs 1 & 2)

Inner Tracking System (ITS), six layers of silicon detector (SPD, SDD, SSD)

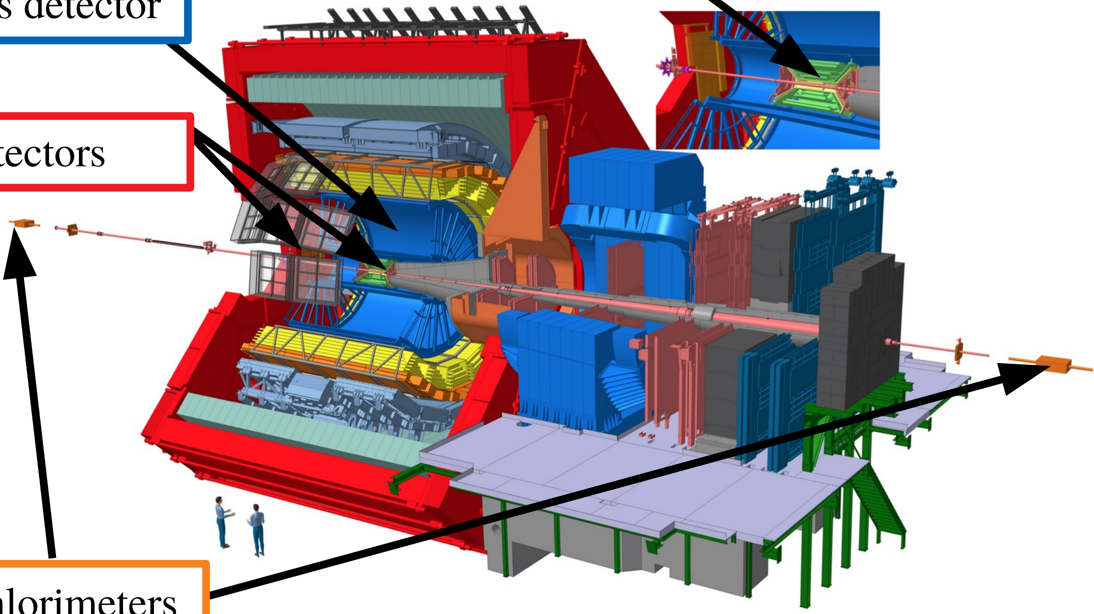
→ Reconstruct tracks and vertices + trigger + multiplicity estimation (SPD)

Time Projection Chamber (TPC), gaseous detector

→ Reconstruct tracks + PID (dE/dx)

V0 : V0A and **V0C**, two arrays of scintillator detectors

→ Trigger, multiplicity estimation at forward rapidity



Zero Degree Calorimeters (ZDC), two sets of calorimeters

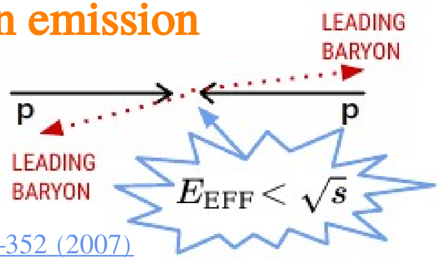
→ Energy deposit of particles at **very** forward rapidity

Dependence of strange particle production on multiplicity and effective energy

Is strangeness enhancement in pp collisions correlated only with **final state particle multiplicities**, or does the **initial stage of the collision** play a role?

The concept of effective energy

- The **effective energy** is the energy effectively available for particle production in the **initial stages** of the pp collision, reduced due to **forward leading baryon emission**



Forward leading baryon emission :

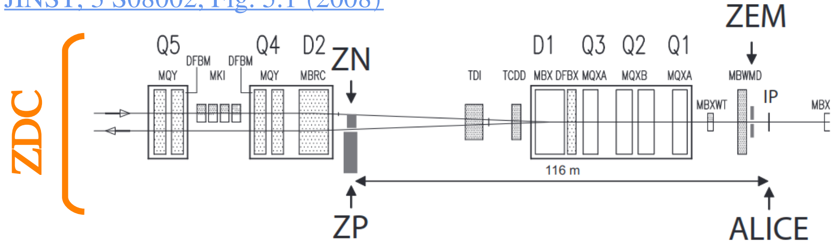
Emission of baryons at forward rapidity
(i.e. with large longitudinal momentum)

Eur. Phys J. C 50, 341–352 (2007)

- In ALICE, the energy of leading baryons can be measured from their energy deposited in the very forward calorimeters (**ZDCs**)

$$\mathbf{E_{eff} \simeq \sqrt{s} - \langle ZDC\ energy\ sum \rangle}$$

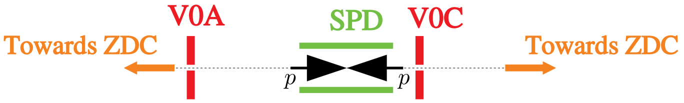
JINST, 3 S08002, Fig. 5.1 (2008)



Is strangeness enhancement correlated with **effective energy**,
or is it correlated only with final state particle **multiplicity (at midrapidity)**?

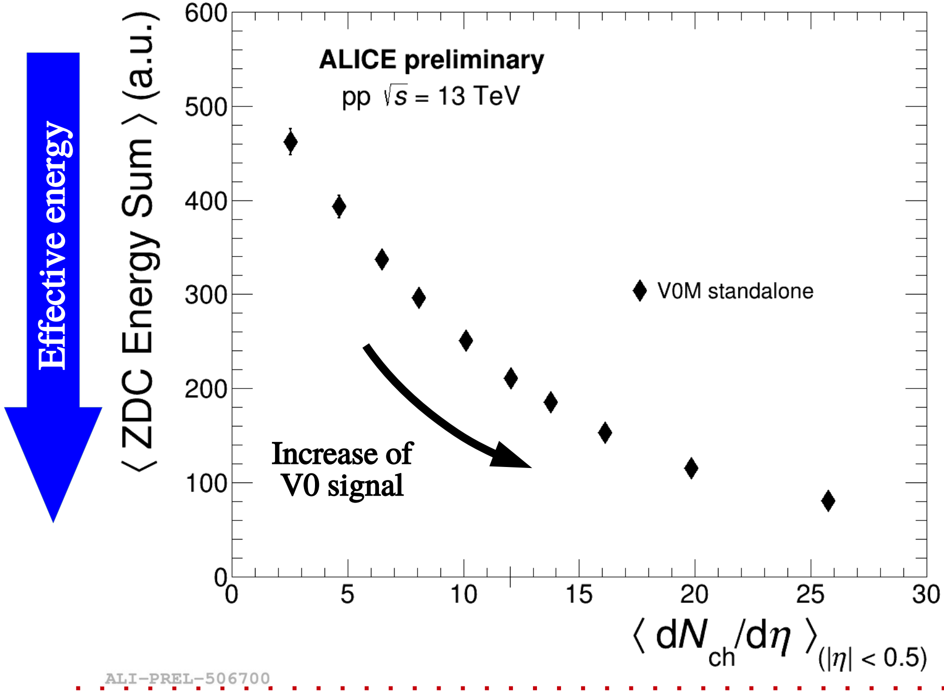
Correlation ZDC energy sum Vs charged particle multiplicity, arXiv:2107.10757

Multiplicity & effective energy correlation



♦ : **V0M standalone** = multiplicity percentile classes based on the sum of signal amplitudes in the V0A and V0C

→ **Anticorrelation** between the **multiplicity at midrapidity** and the **energy deposited in the ZDC**

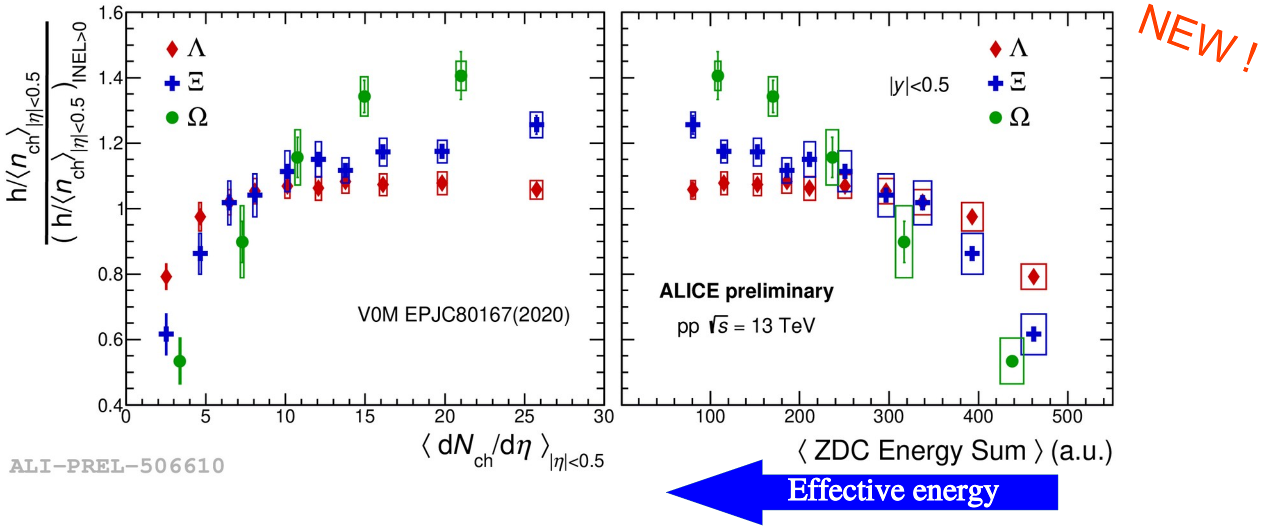


NEW !

The analysis in V0M classes **alone** is not able to disentangle initial and final state effects

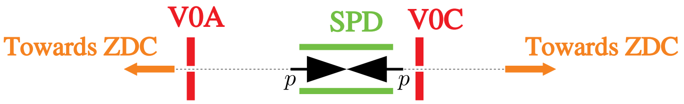
Strangeness production in V0M classes

- The yield of strange hadrons normalized to the charged particle multiplicity
  - **Increases** with the **multiplicity at midrapidity** (the strangeness enhancement)
  - **Decreases** with the **energy deposited at forward rapidity** in the ZDCs



- Need multi-differential analysis to disentangle effective energy from the multiplicity dependence → Use SPDclusters classes in addition to V0M selections (double event class selections)

Disentangling initial and final state effects



SPDclusters = multiplicity percentile classes based on the number of clusters in the SPD

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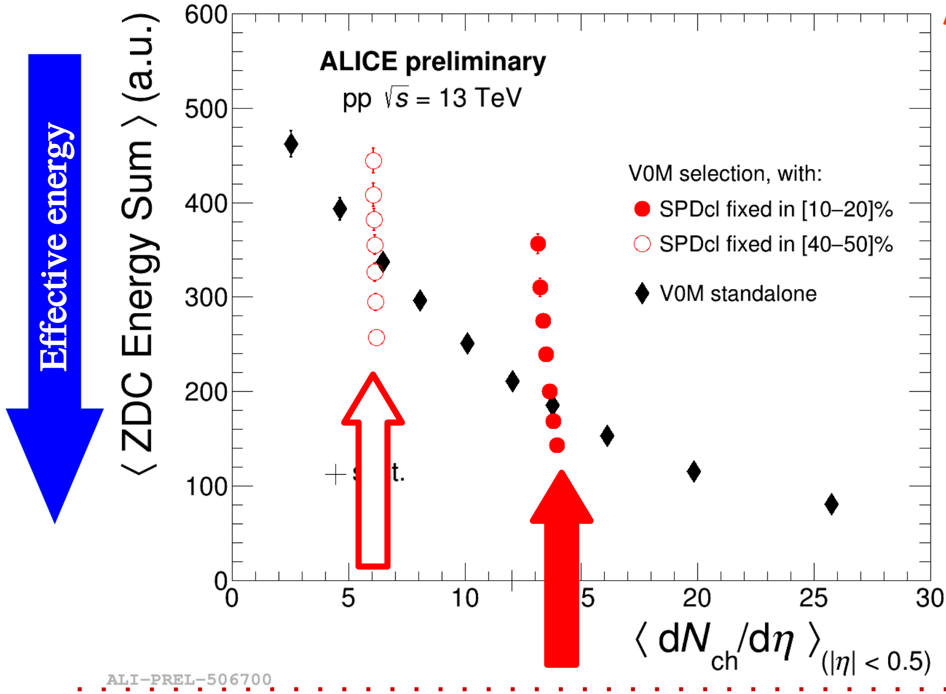
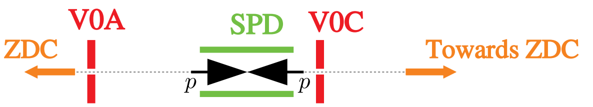


NEW !

○● : SPDclusters class fixed + V0M selection

→ Fix the multiplicity at midrapidity and vary the effective energy

Disentangling initial and final state effects



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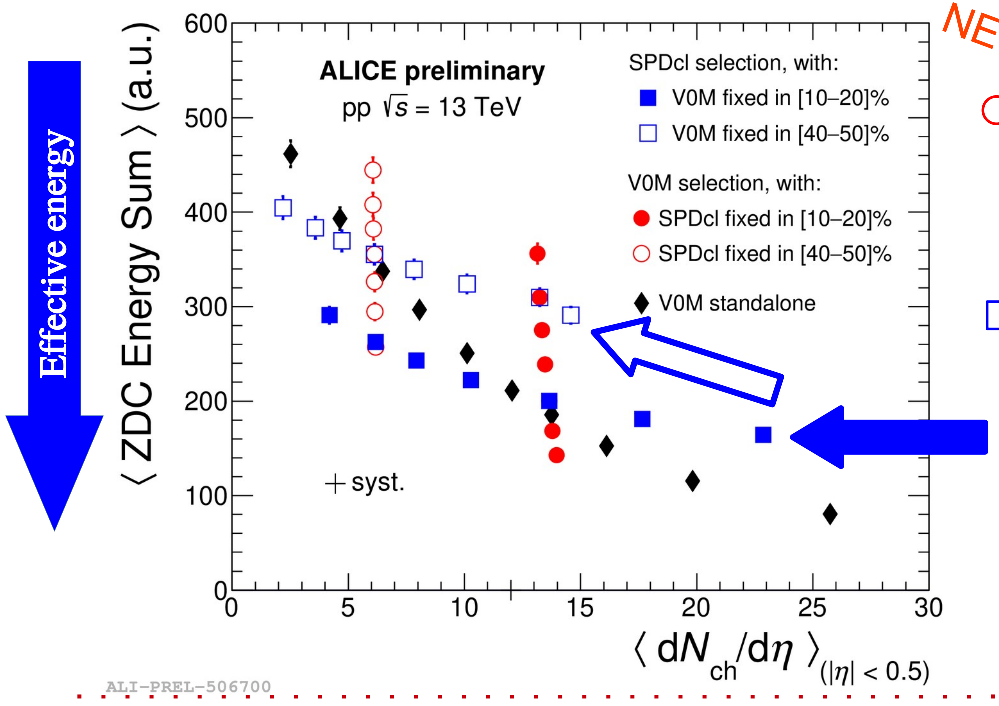

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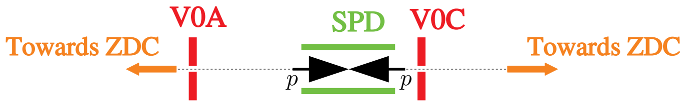
→ Fix the multiplicity at midrapidity and vary the effective energy

□■: V0M class fixed + SPDclusters selection

→ Reduce the effective energy window and vary the multiplicity at midrapidity

Disentangling initial and final state effects



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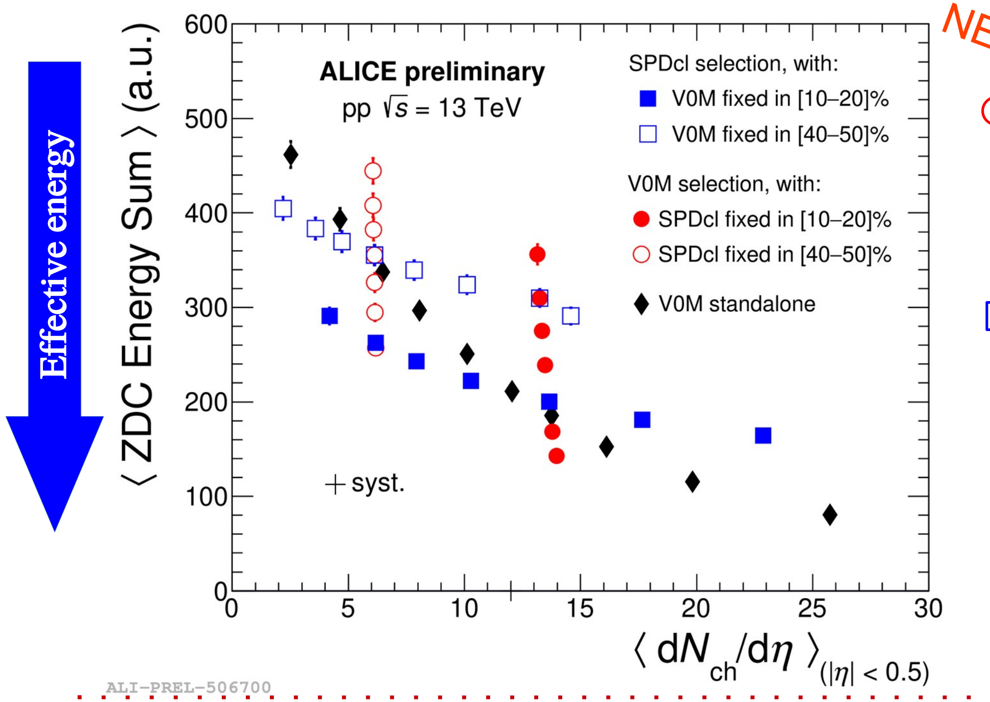

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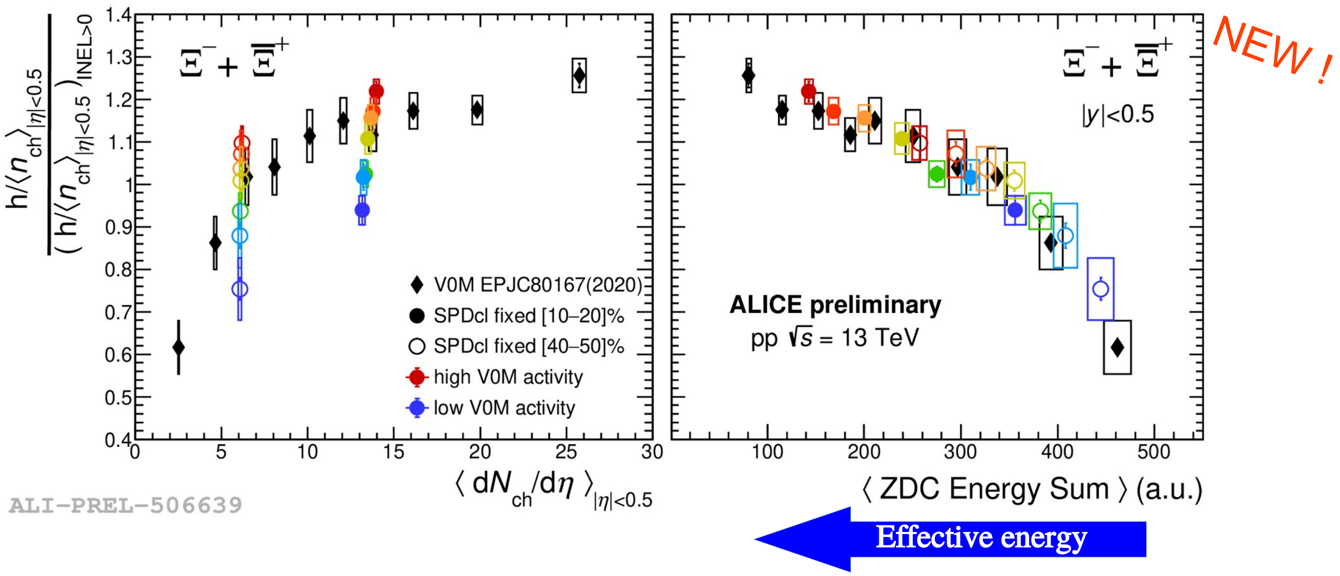
Combination of V0M and SPDclusters classes allows to disentangle initial and final state effects

Ξ production at fixed multiplicity

- Ξ yield normalized to the charged particle multiplicity at **fixed multiplicity** :

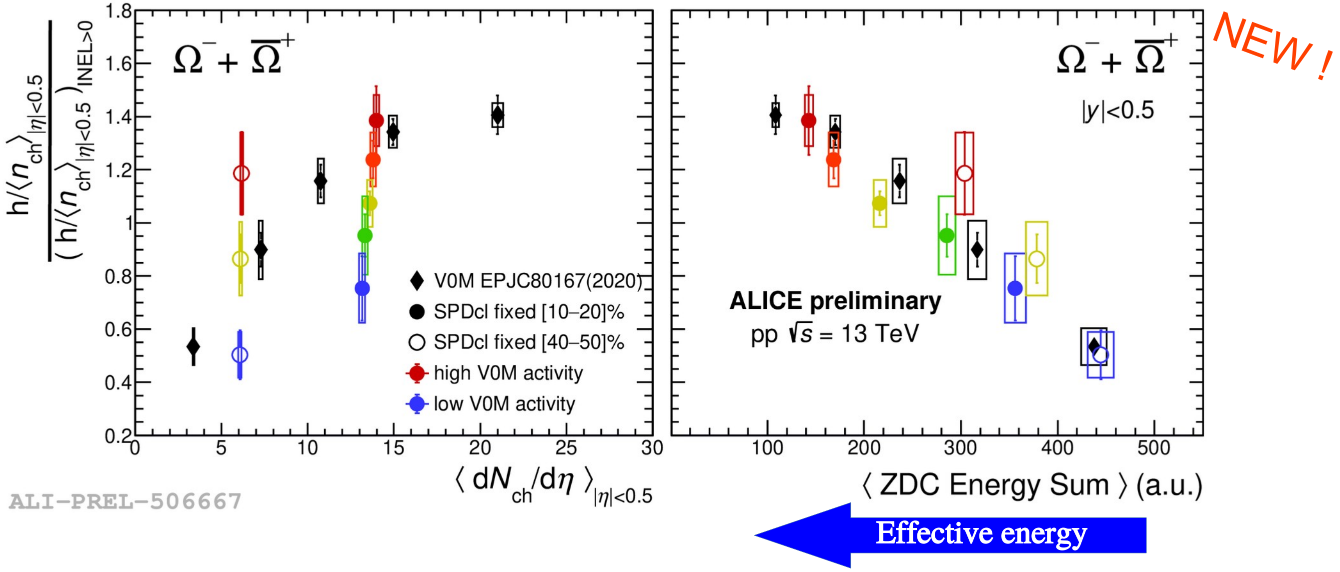


- There is a strangeness enhancement with the effective energy, when multiplicity is **fixed**
- Compatible trends with effective energy between **V0M standalone** and the **double event selection**

→ Effective energy plays an important role in the strangeness enhancement

Ω production at fixed multiplicity

- Ω yield normalized to the charged particle multiplicity at **fixed multiplicity** :

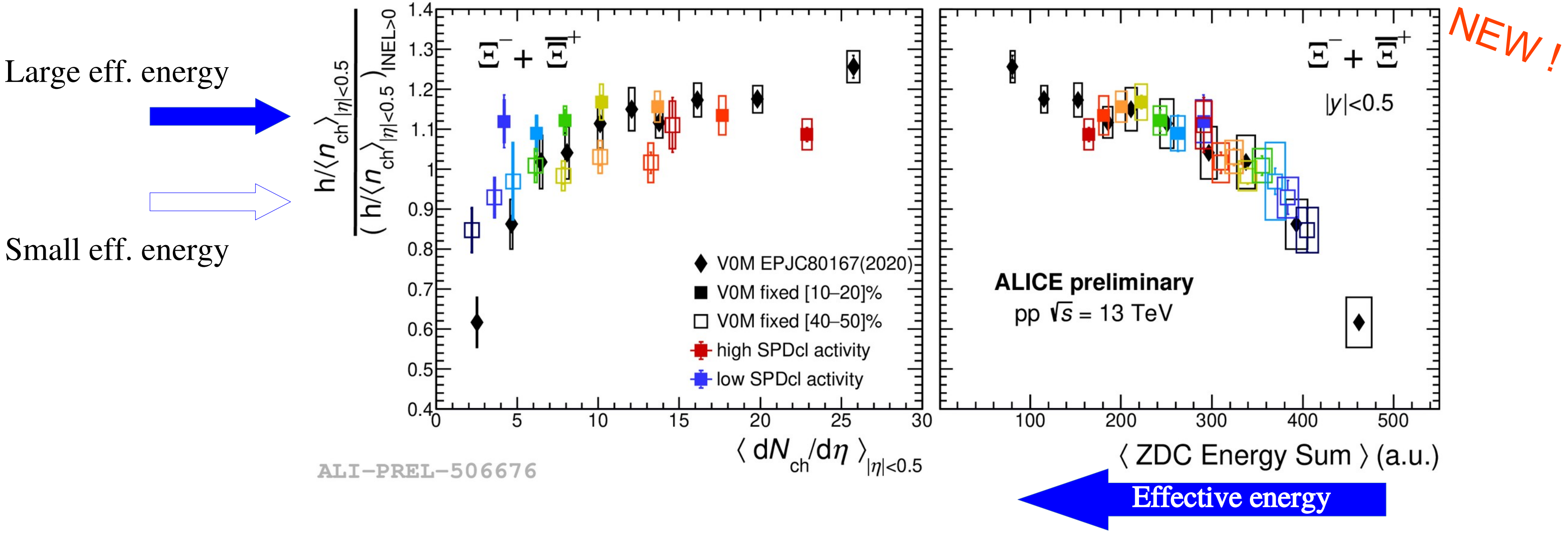


- There is a strangeness enhancement with the effective energy, when multiplicity is **fixed**
- Compatible trends with effective energy between **V0M standalone** and the **double event selection**

→ Effective energy plays an important role in the strangeness enhancement

Ξ production with reduced effective energy

- Ξ yield normalized to the charged particle multiplicity with **reduced effective energy :**



- **With constrained effective energy,** the strangeness enhancement with multiplicity is strongly affected

→ **Effective energy plays an important role in the strangeness enhancement**

Study of the in-jet and out-of-jets production of strange hadrons

What are the relative contributions of **hard processes** (such as jets) and **out-of-jet processes** to the strangeness enhancement?

Angular correlation method

- The angular correlation method :

1) Selection of the **trigger particle** (leading particle): the charged particle with the highest p_{T} and $p_{\mathrm{T}} > 3$ GeV/c

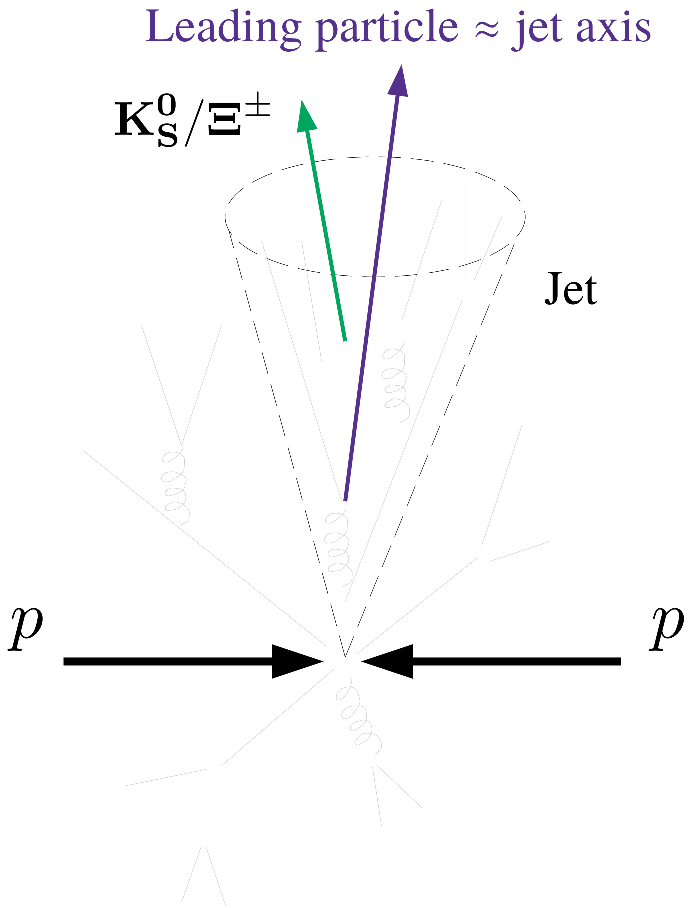
2) Identification of all strange hadrons (**associated particles**)

3) **Angular correlation** between the trigger particle and the associated particles

$$\Delta\eta = \eta_{\mathrm{Trig.}} - \eta_{\mathrm{Assoc.}}$$

$$\Delta\varphi = \varphi_{\mathrm{Trig.}} - \varphi_{\mathrm{Assoc.}}$$

η = pseudorapidity
φ = azimuthal angle



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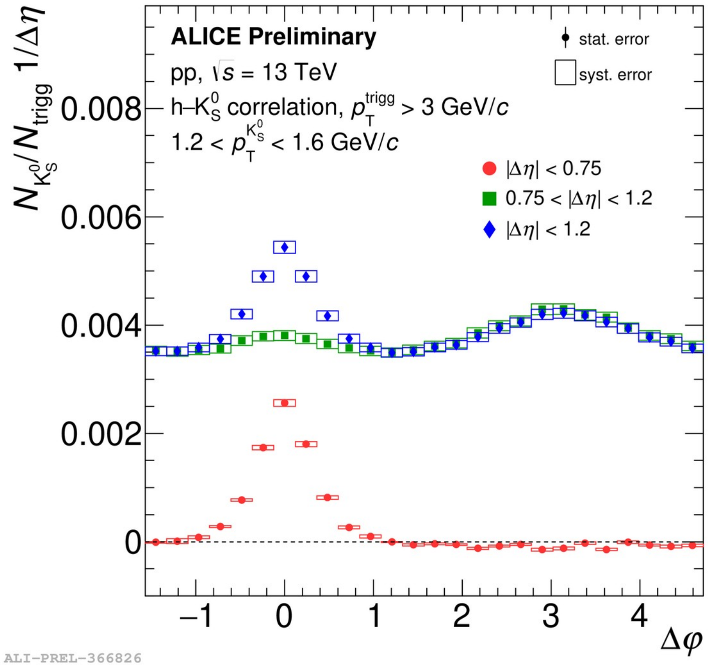

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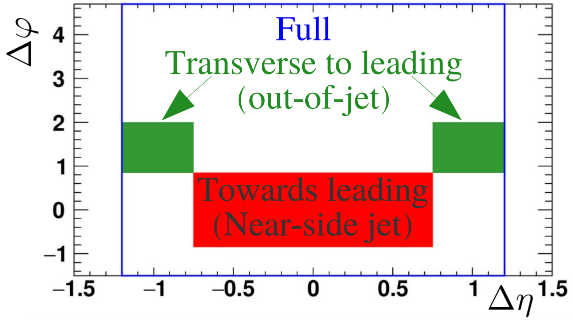
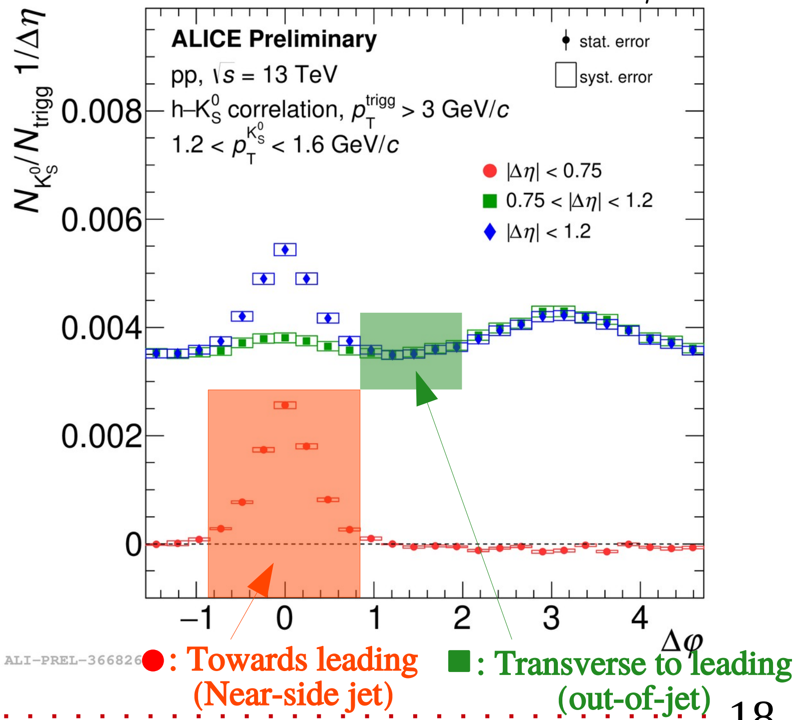
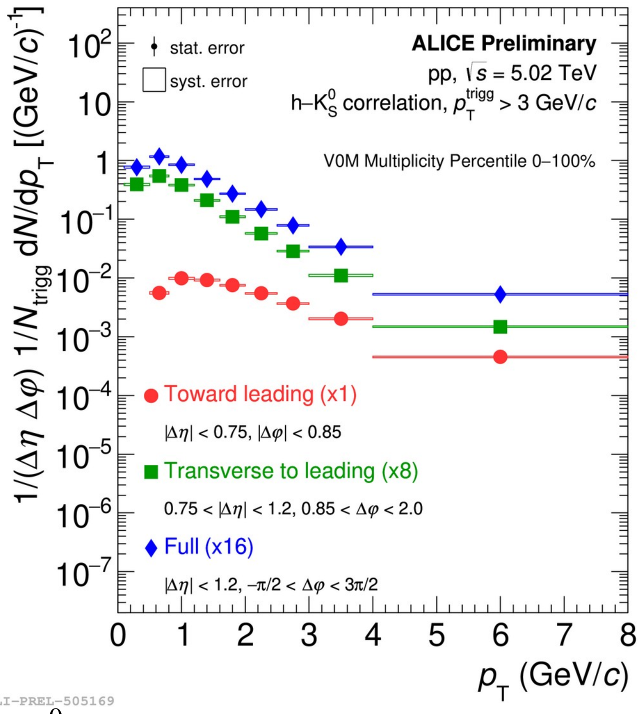




Full, in-jet, and trans. to leading jet p_T spectra

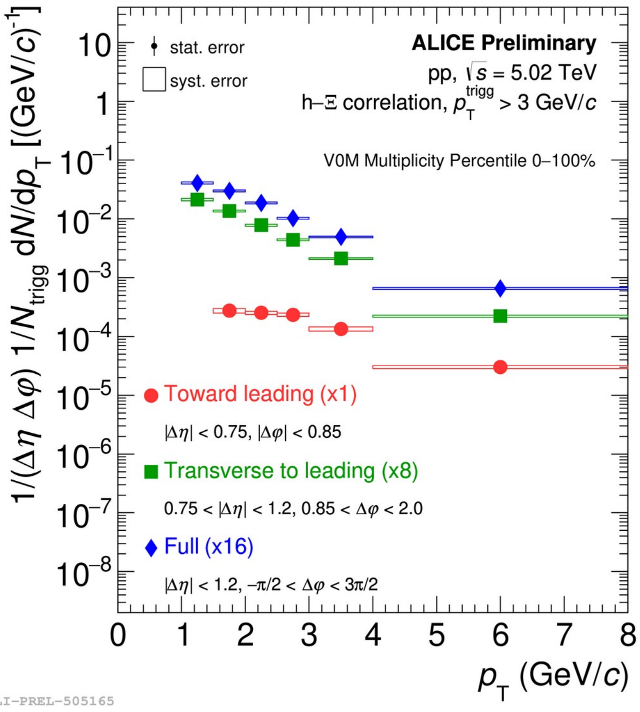
K^0_S

NEW !



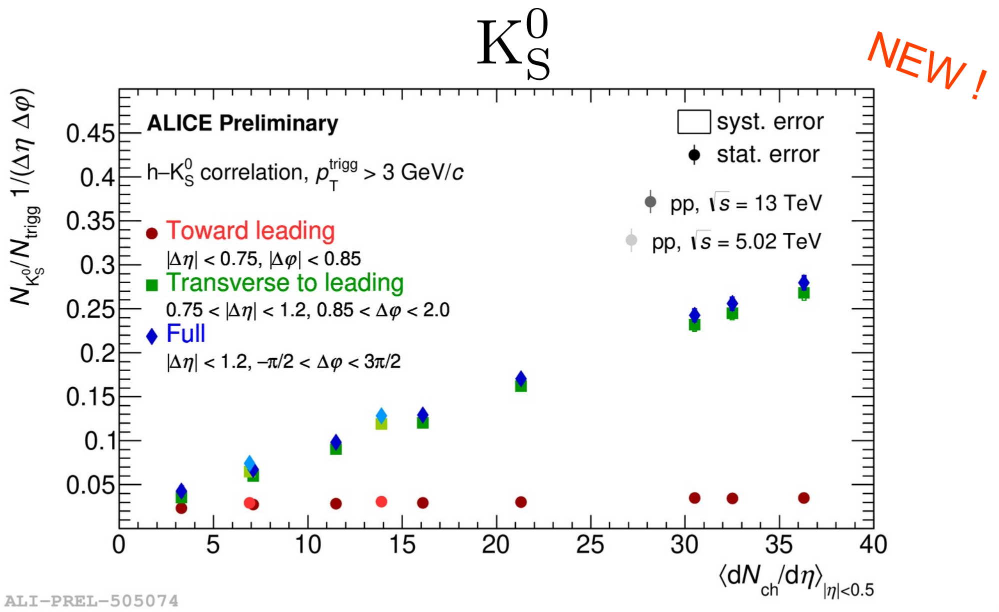
$\Xi^\pm$

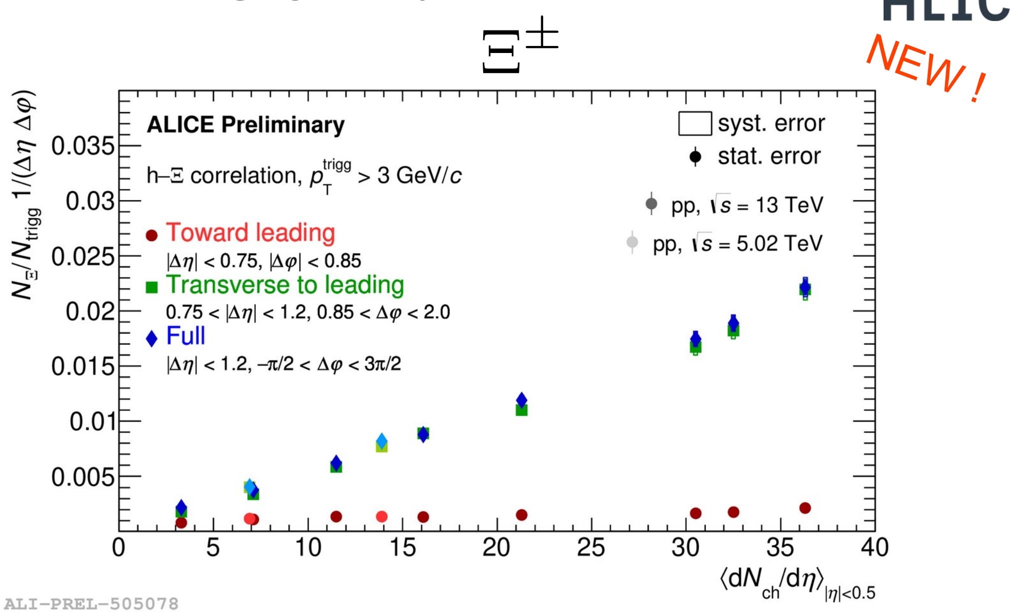
NEW !



- Both K^0_S and Ξ spectra are **harder** toward the leading jet than transverse to it
- This feature is also observed at different center-of-mass energies

Full, in-jet, and trans. to leading jet yields



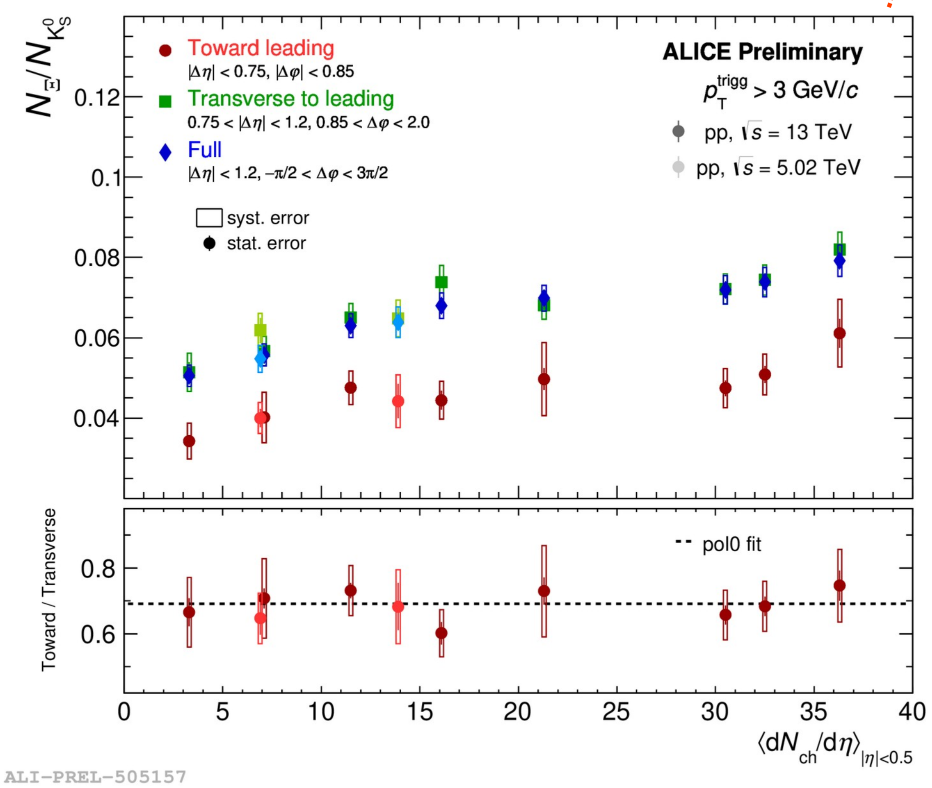


- Both **full** and **transverse to leading jet** yields **increase with multiplicity** at midrapidity
- **Toward leading jet** yield shows an almost **flat dependence** with multiplicity
- No dependence on the center-of-mass energy is observed

→ **Strange hadrons in pp collisions are dominantly produced in the transverse region to the leading jet**

Ξ / K^0_S yield ratio

NEW !



Strangeness enhancement can be observed by looking at the ratio of Ξ to K^0_S yields

→ The **full yield** ratio increases with multiplicity

- The yield ratio in the **transverse region to the leading jet increases** with multiplicity and is **compatible** with the **full yield** ratio.
- The **toward leading jet yield** ratio is **smaller** than the one in the **transverse region**

→ The **Ξ to K^0_S yield ratio** in pp collisions is **dominated by transverse to leading jet processes**

→ The yield ratio **toward** and **transverse to the leading jet** show **compatible trend with multiplicity**

Conclusion

- Initial questions :
  - Is strangeness enhancement in pp collisions correlated only with **final state particle multiplicities**, or do the **initial stage of the collision** play a role?

    → At fixed multiplicity, strangeness enhancement is strongly correlated with effective energy, and thus with the **initial stage of the collision**

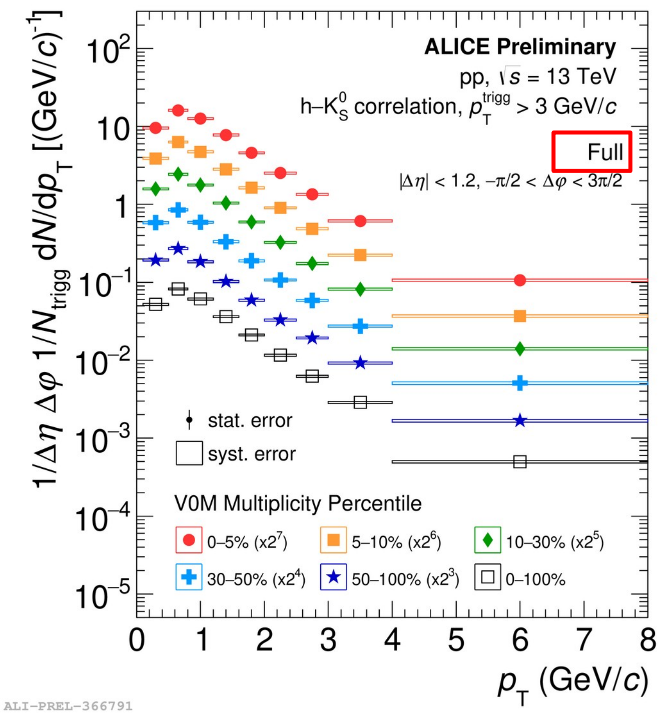
  - What are the relative contributions of **hard processes** (such as jets) and **out-of-jet processes** to the strangeness enhancement?

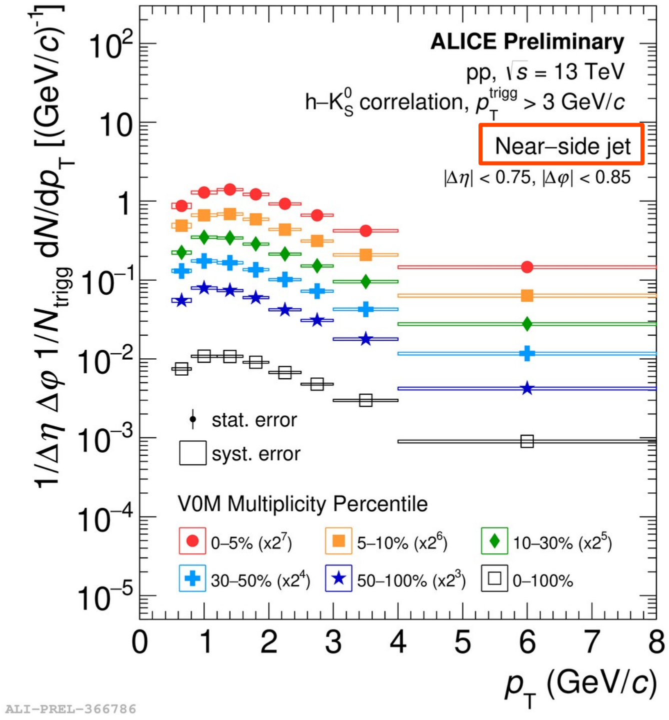
    → **Transverse to leading jet processes** are the dominant contribution to strangeness enhancement

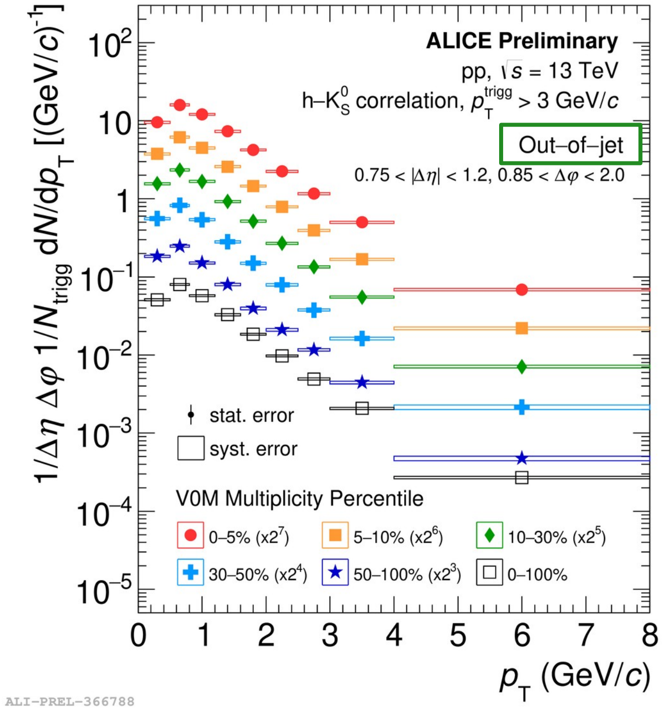
- Studies of the **correlation between effective energy and transverse to leading jet processes** are needed to shed light on the origin of strangeness enhancement in pp collisions
- Such studies will profit from the **large amount of data**, that will be collected during the **Run 3**

Backup slides

Full, in-jet, and out-of-jet spectra of K^0_S

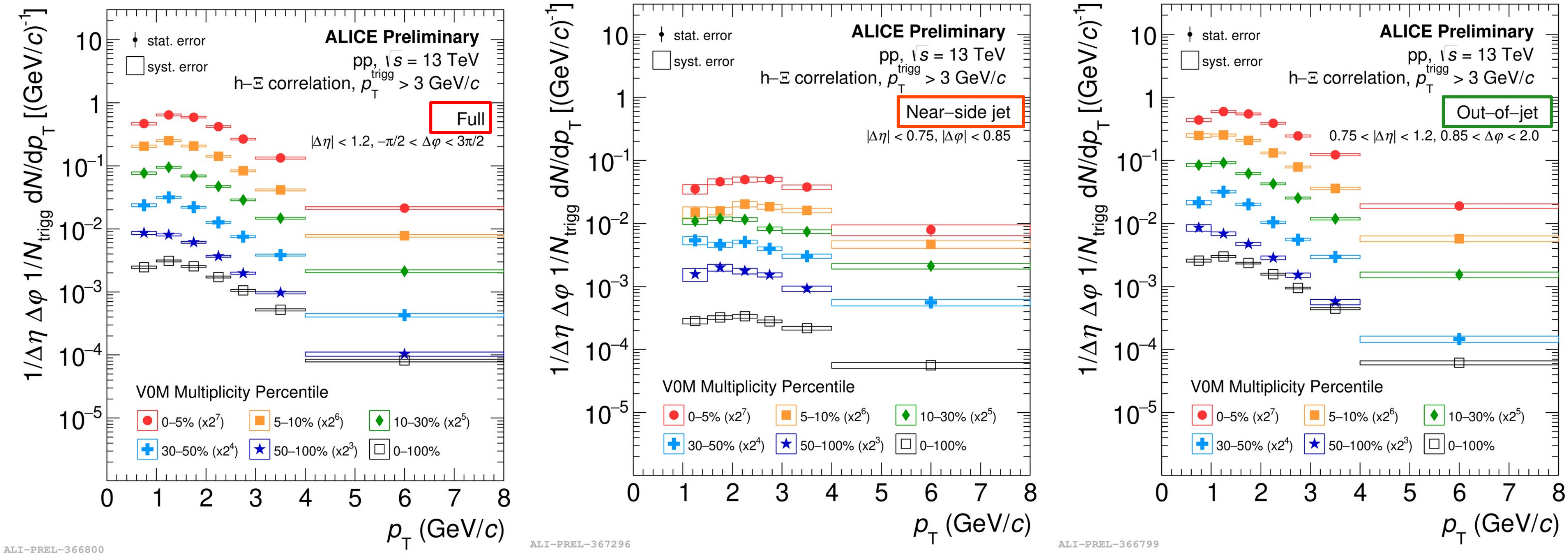






- K^0_S spectra is **harder** toward the leading jet than transverse to it

Full, in-jet, and out-of-jet spectra of Ξ



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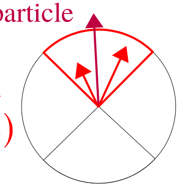
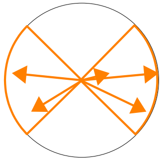
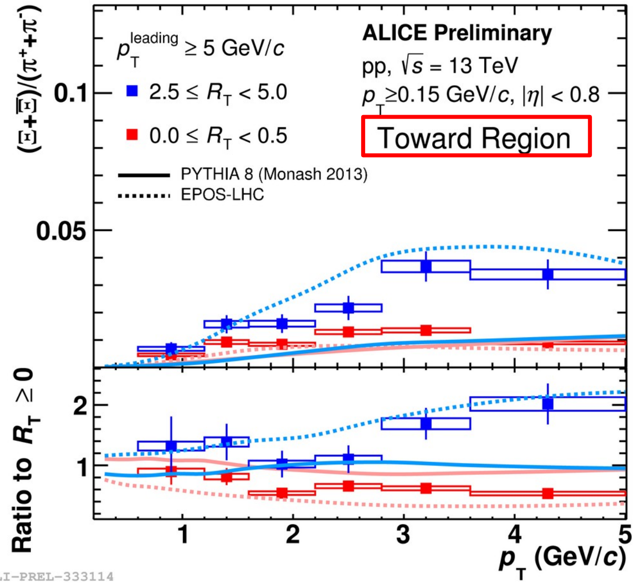
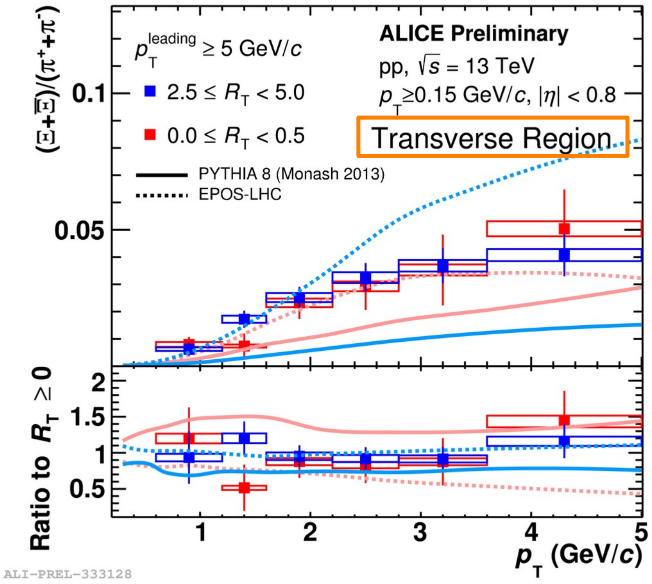
Ξ production vs R_T









- The Ξ/π yield ratio show no dependence on R_T in the **transverse region.**
- The Ξ/π yield ratio increases with R_T in the **toward region**, approaching the value in the **UE region**