Investigating strangeness production in pp collisions using multi-differential analyses with ALICE at the LHC

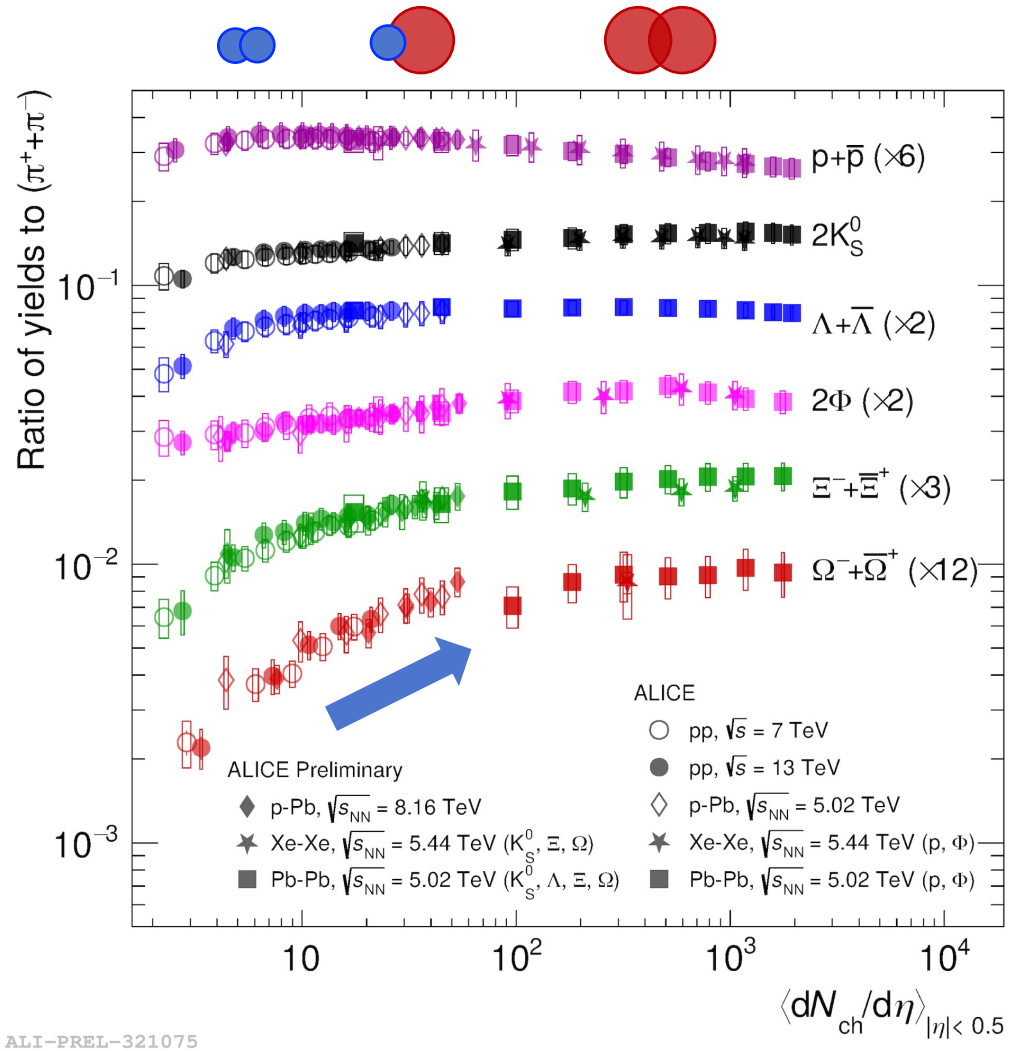
Chiara De Martin on behalf of the ALICE Collaboration

University and INFN - Trieste

XVth Quark Confinement and the Hadron Spectrum Conference

2022 - University of Stavanger

Physics motivation



Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- 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
- The enhancement is larger for particles with larger strangeness content ($\Omega > \Xi > \Lambda \sim K^0_S$)

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

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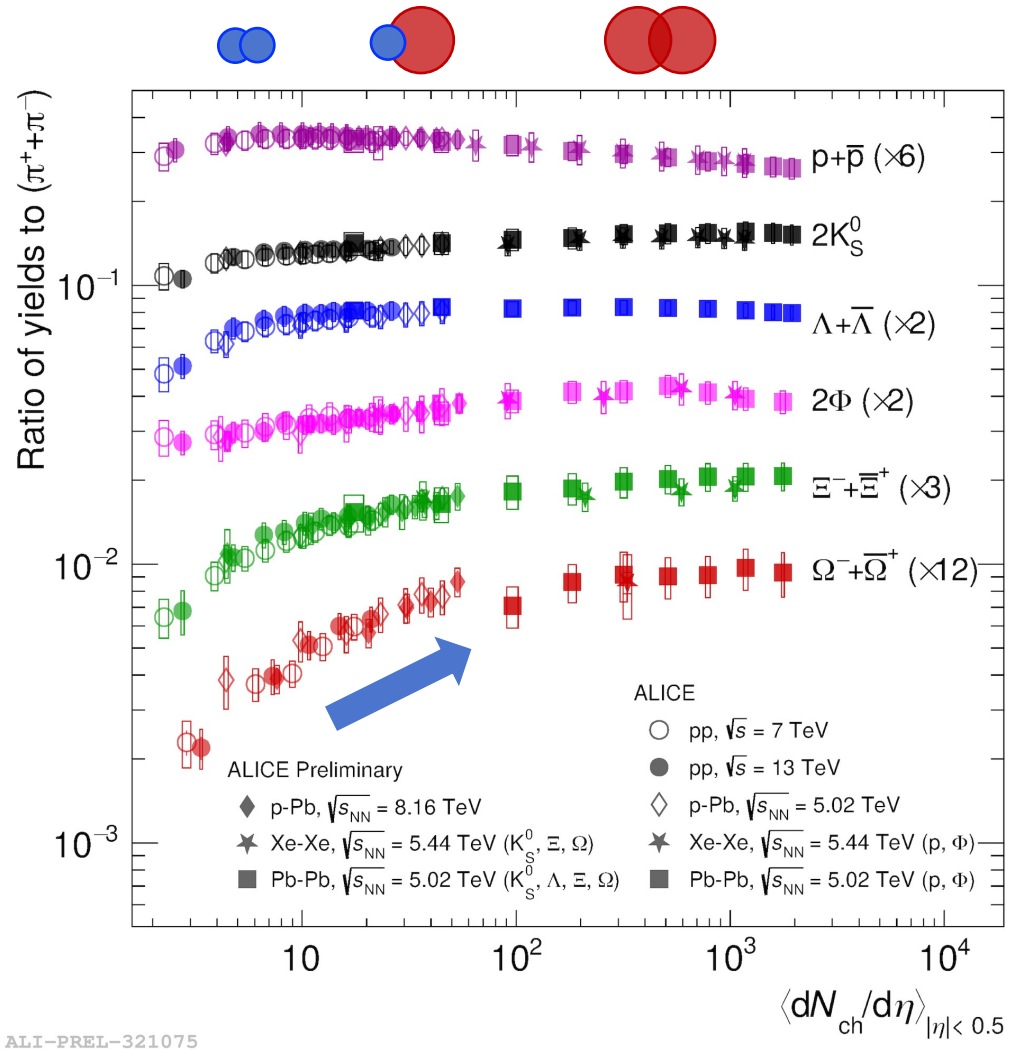

Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- Is strangeness enhancement in pp collisions correlated only with final state particle multiplicity, or do initial stage effects play a role?
- Is strangeness enhancement in pp collisions related to hard processes, such as jets, to out-of-jet processes, or to both?

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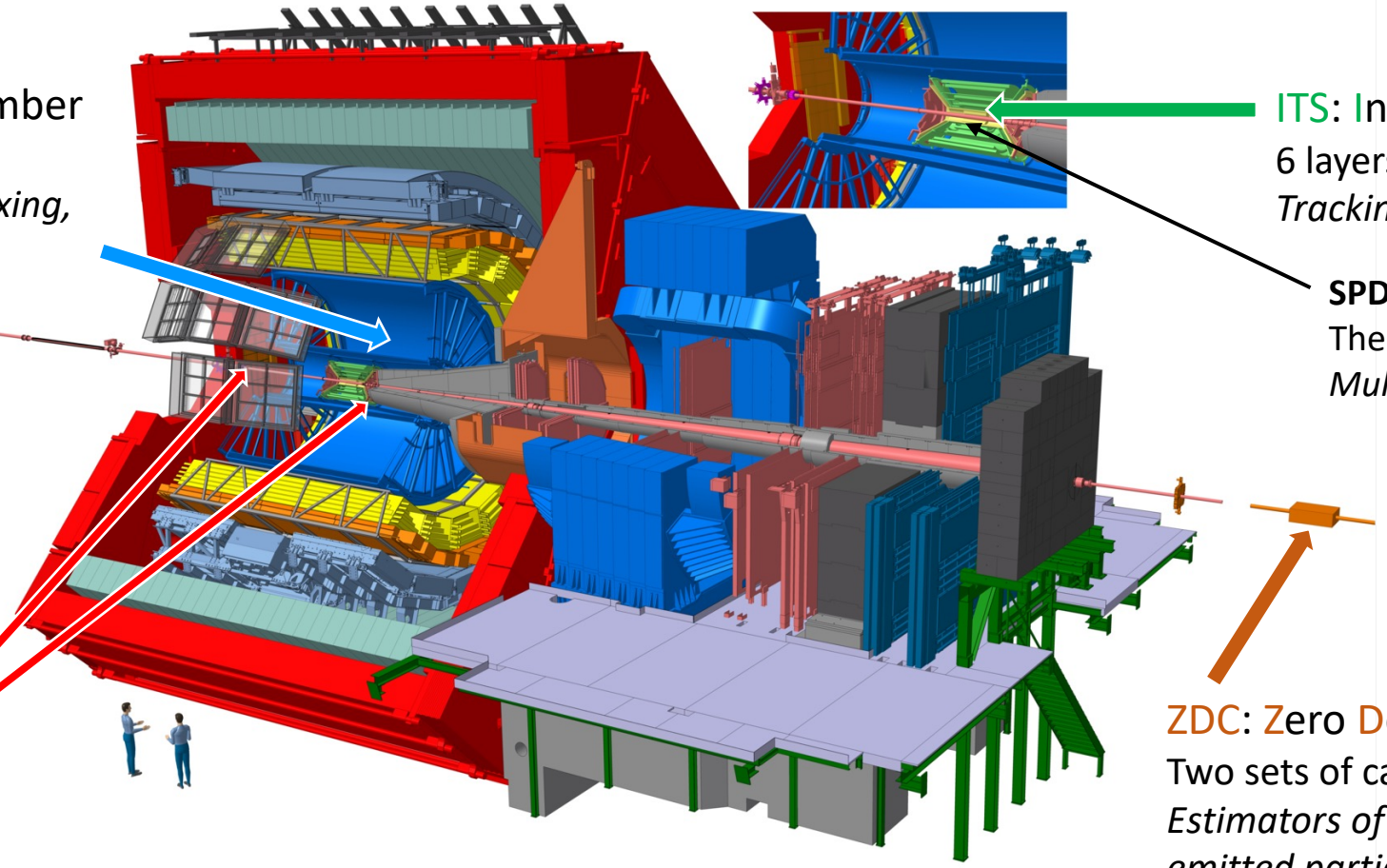
ALICE at the LHC



TPC: Time Projection Chamber
Gas-filled detector
Main tracking detector, vertexing, PID (dE/dx)

ITS: Inner Tracking System
6 layers of silicon detectors
Tracking, triggering, vertexing

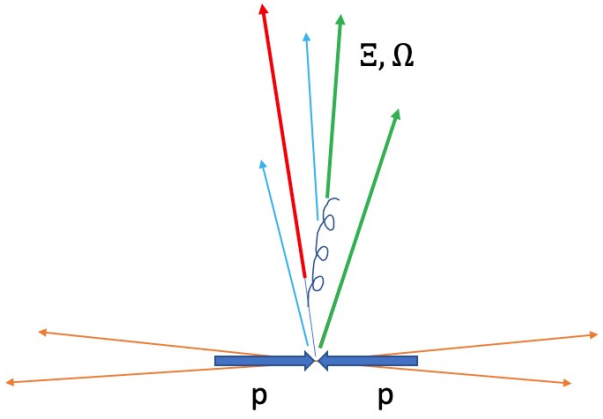
SPD: **S**ilicon **P**ixel **D**etector
The first 2 layers of the ITS
Multiplicity estimators

ZDC:
Zero Degree Calorimeters

ZDC: Zero Degree Calorimeters
Two sets of calorimeters at forward rapidity
Estimators of energy deposits of forward emitted particles

V0A and V0C
Arrays of scintillators at forward rapidity
Triggering, multiplicity estimators

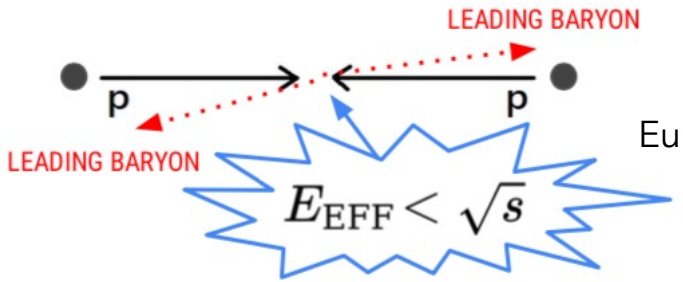
Strangeness production as a function of effective energy



The concept of effective energy in pp collisions

- The energy available in an event for particle production is only a fraction of the centre-of-mass energy, because of the leading baryon effect

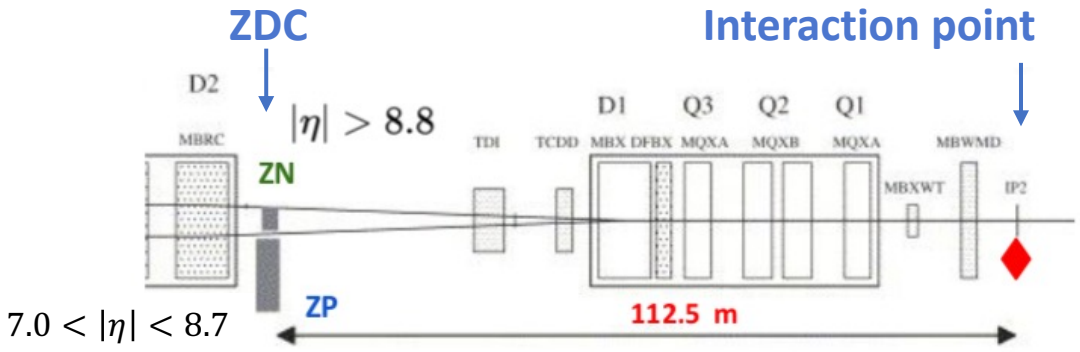
Leading baryon effect:
high probability of emitting baryons with high longitudinal momentum in the forward direction



Eur.Phys.J.C 50, 341-352 (2007)

- ALICE estimates the event effective energy from the measurement of the energy deposited in the forward calorimeters (ZDCs):

$$E_{\mathrm{EFF}} \simeq \sqrt{s} - \langle \text{ZDC energy sum} \rangle$$



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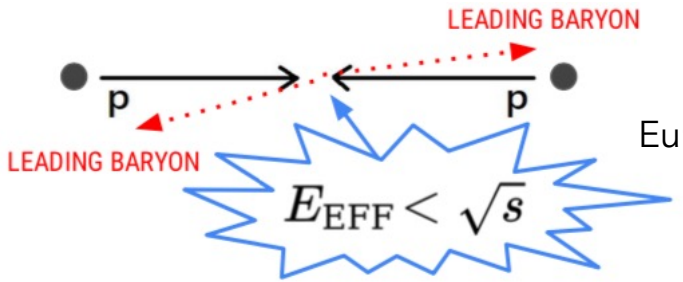

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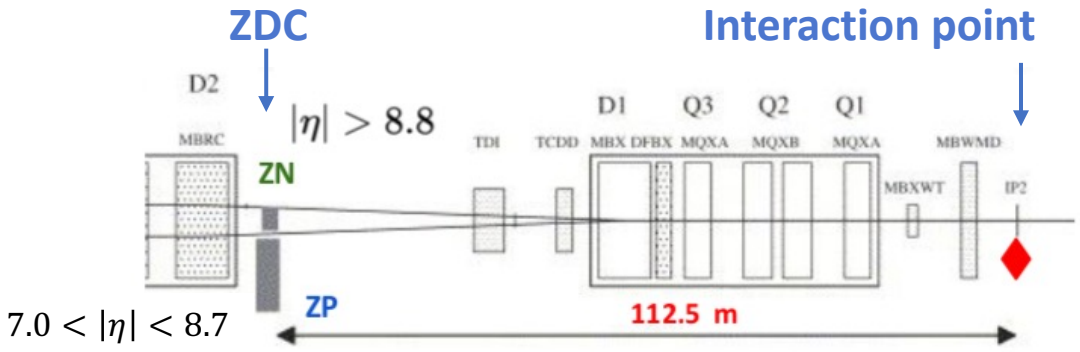
Is strangeness production correlated with the effective energy, which is connected with the initial stage of the collision?



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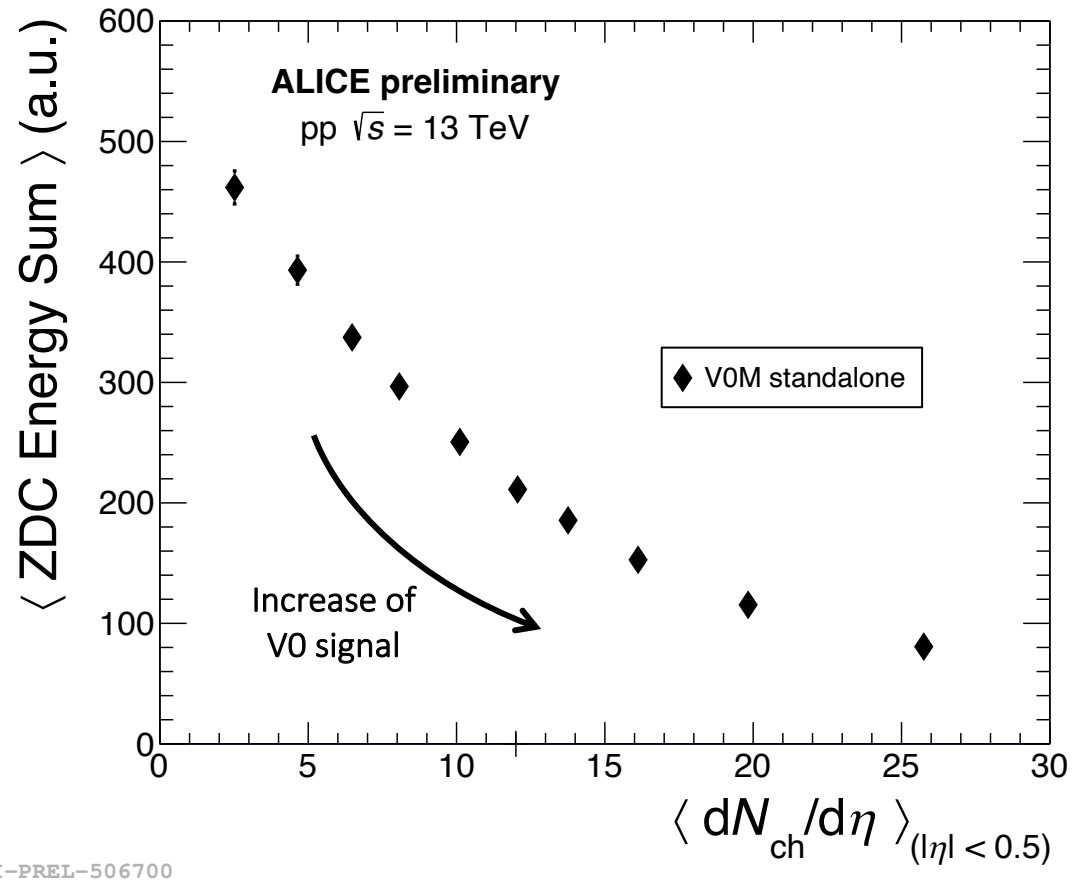
Multiplicity and effective energy are correlated



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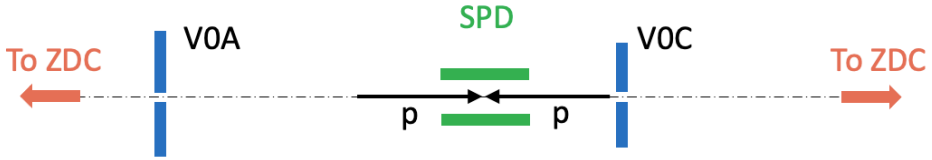

♦ V0M standalone classes:

- Percentile classes based on signal amplitude in V0 detectors
- Show a strong **correlation** between **effective energy** and **multiplicity at midrapidity**

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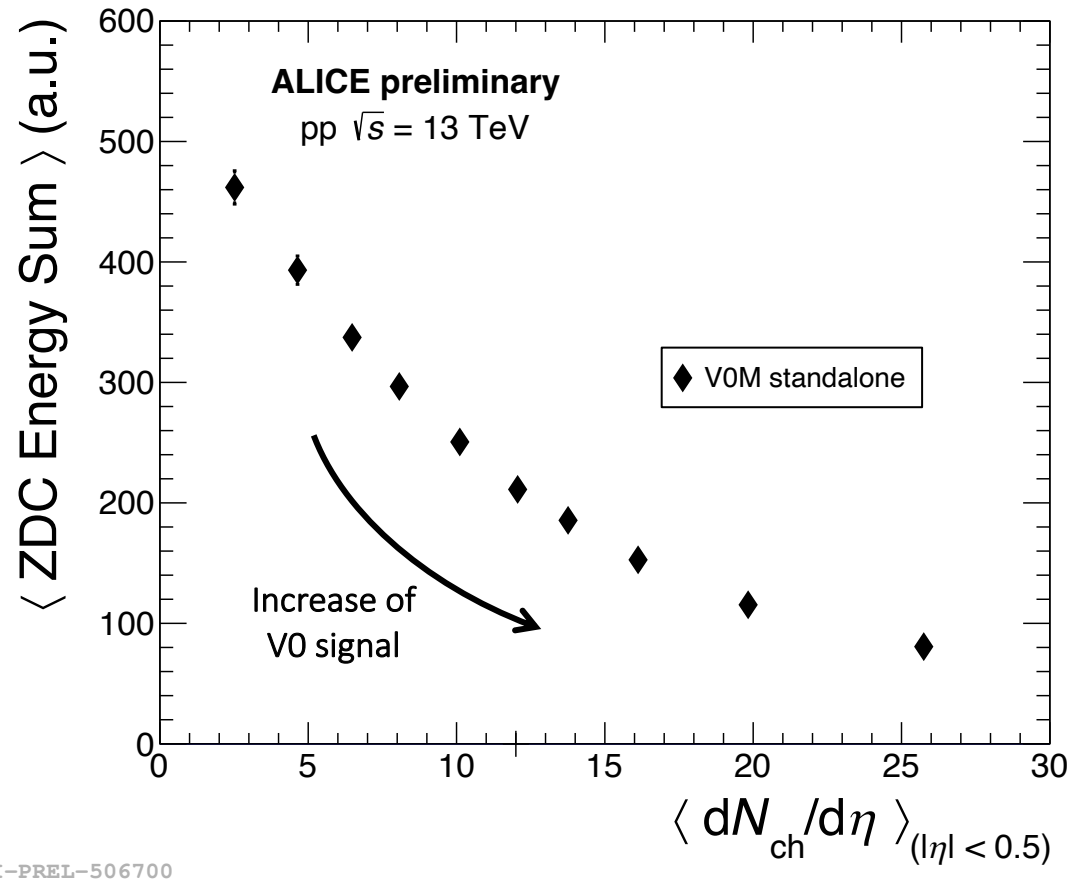
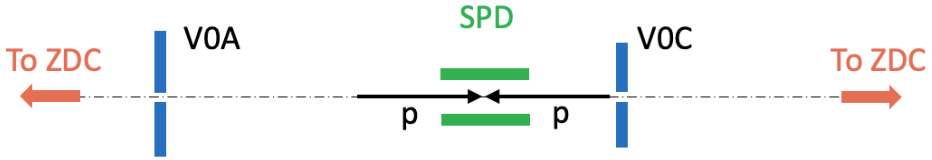




♦ V0M standalone classes:

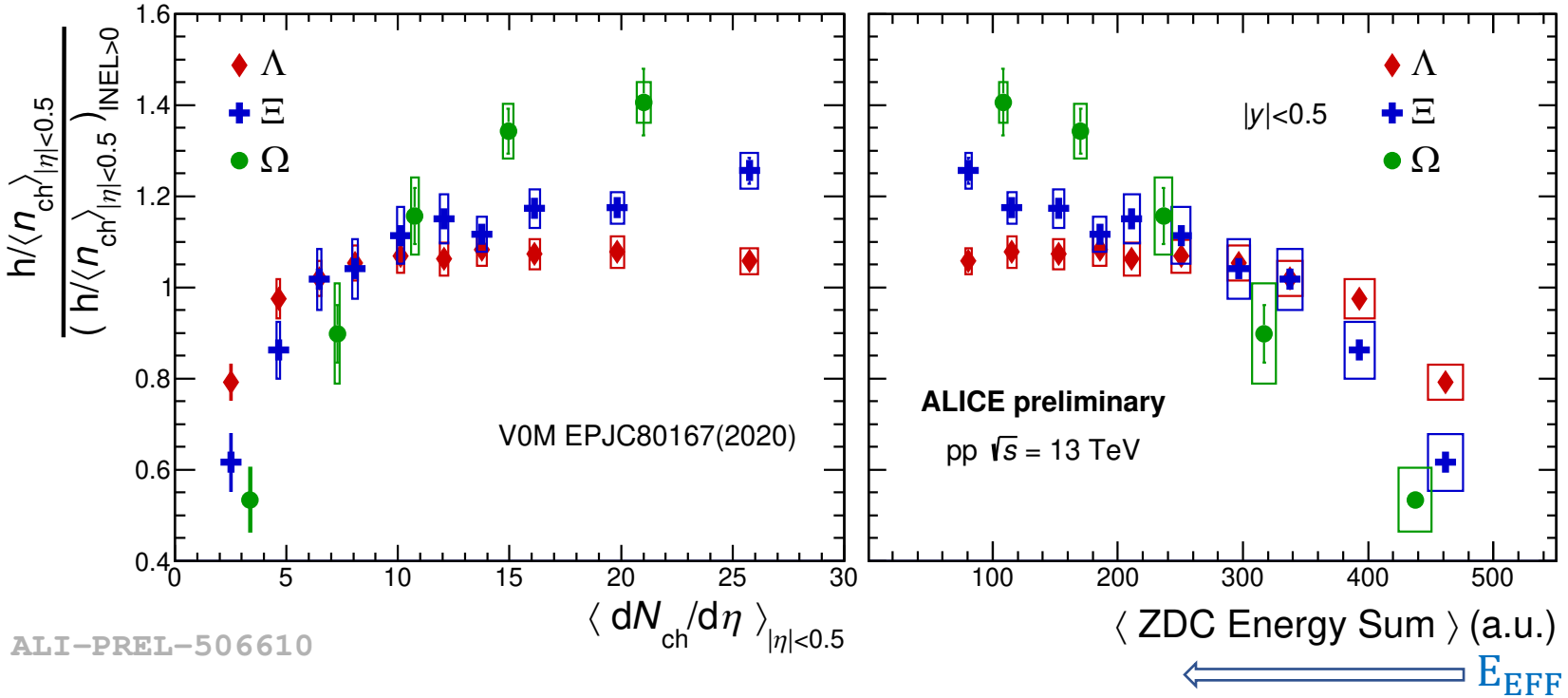
- Percentile classes based on signal amplitude in V0 detectors
- Show a strong **correlation** between **effective energy** and **multiplicity at midrapidity**

The analysis of **strangeness production in V0M classes does not allow to disentangle** the multiplicity dependence from the effective energy dependence

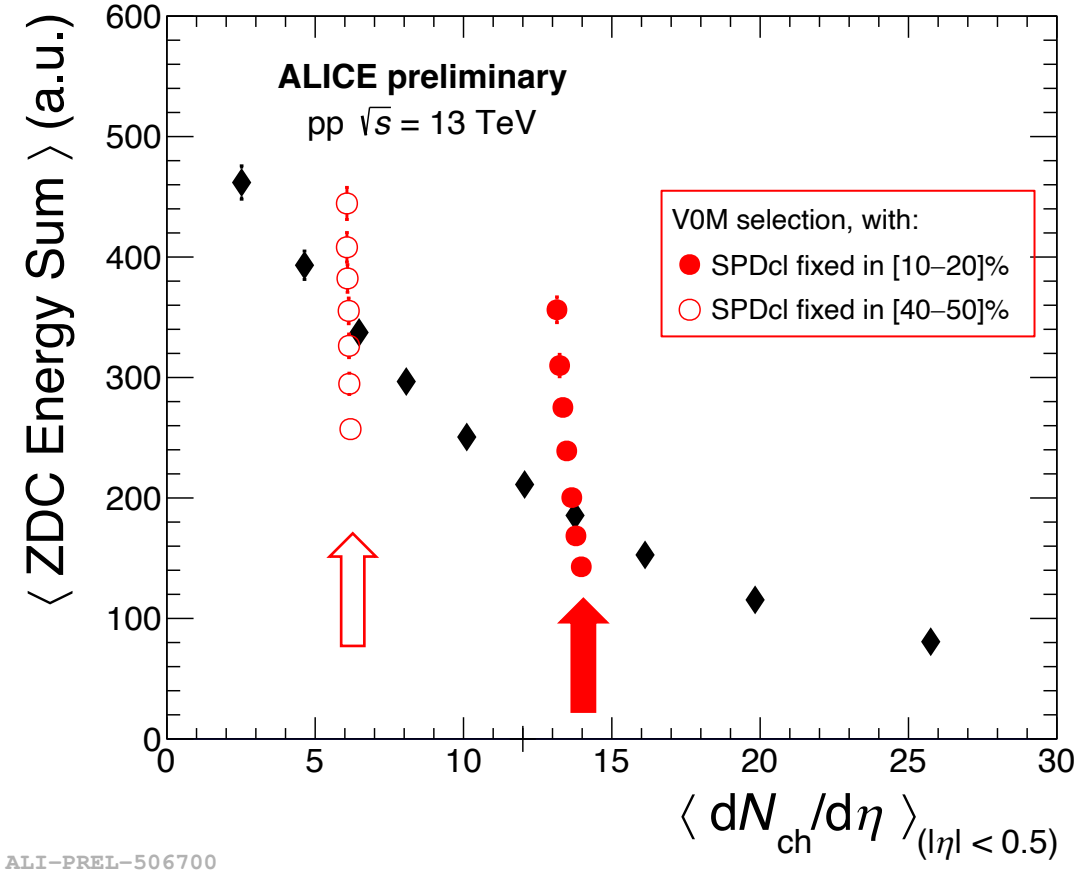
Strangeness production in V0M classes

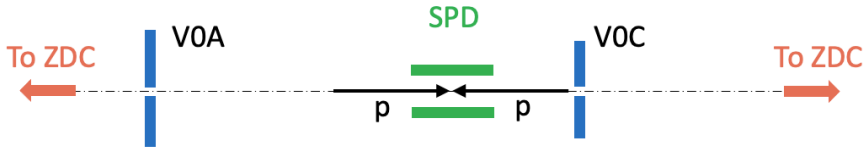
- The yields of strange hadrons normalised to the charged particle multiplicity:
  - **increase** with the **multiplicity at midrapidity** (the well known strangeness enhancement!)
  - **decrease** with the **ZDC energy sum**

→ Multi-differential analysis needed to disentangle effective energy from multiplicity dependence



Disentangle multiplicity and effective energy



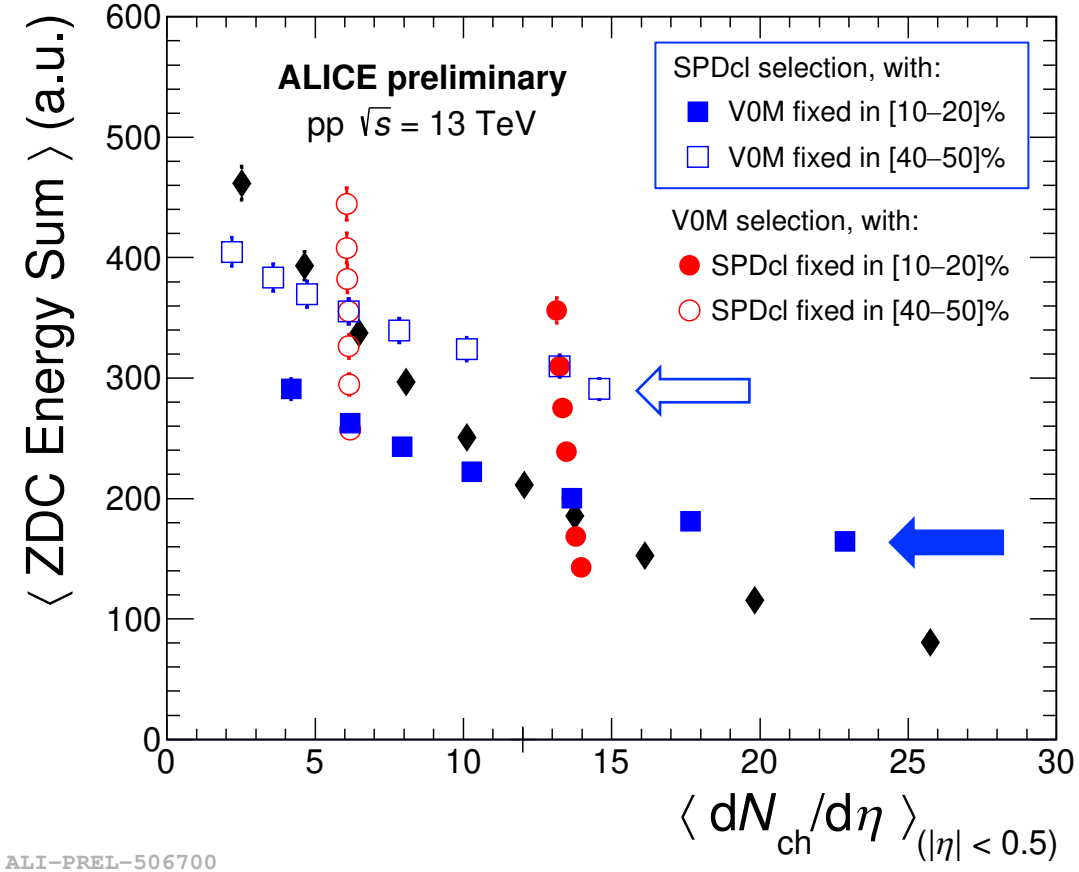


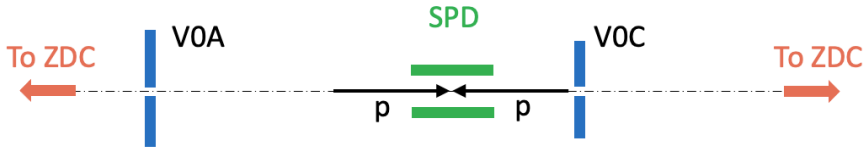
SPD classes:
Percentile classes based on the number of clusters in the SPD ($|\eta| < 0.8$)

○ ● SPD class fixed + V0M selections:

Fix the multiplicity at midrapidity and vary the effective energy

Disentangle multiplicity and effective energy





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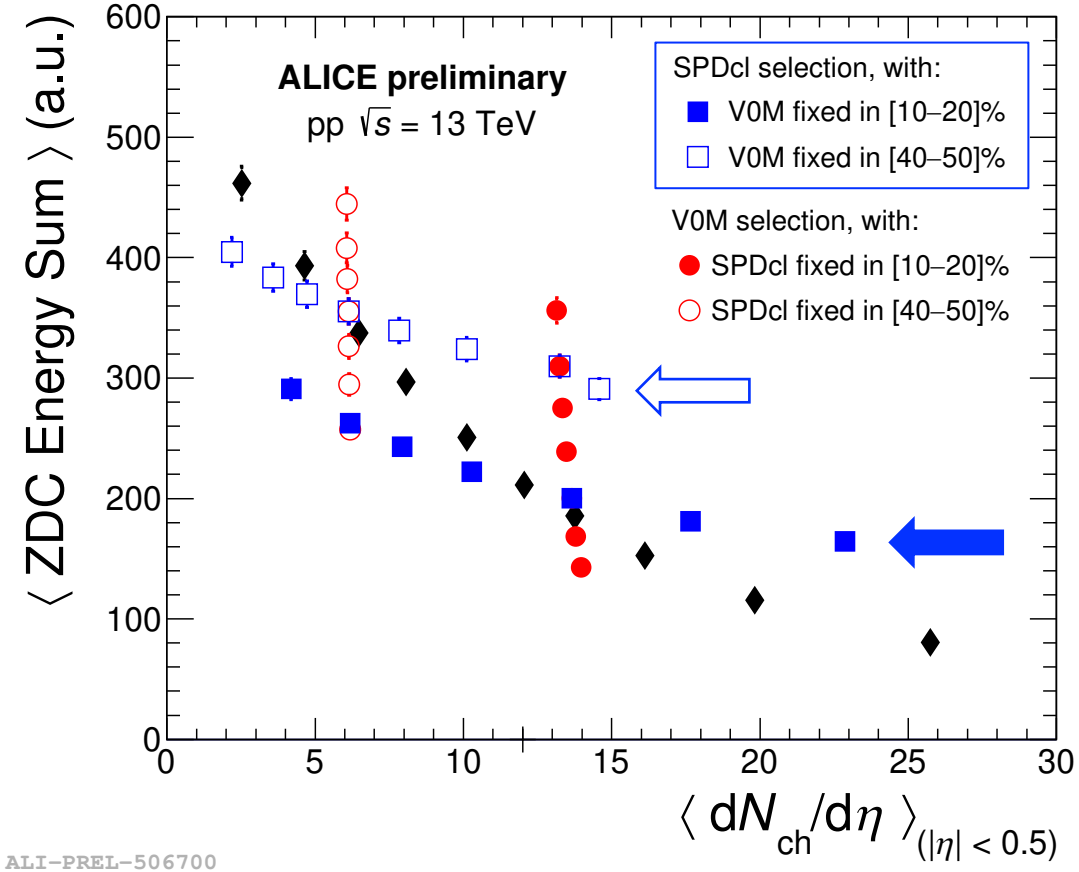
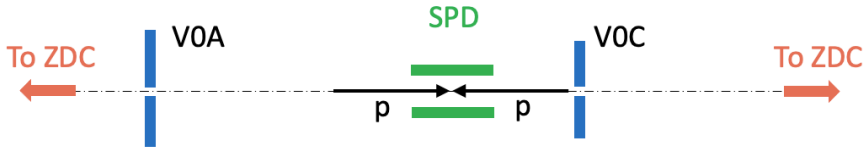
Fix the multiplicity at midrapidity and vary the effective energy

□ ■ V0M class fixed + SPD selections:

Reduce the span of the effective energy and vary the multiplicity at midrapidity

Disentangle multiplicity and effective energy





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○ ● SPD class fixed + V0M selections:

Fix the multiplicity at midrapidity and vary the effective energy

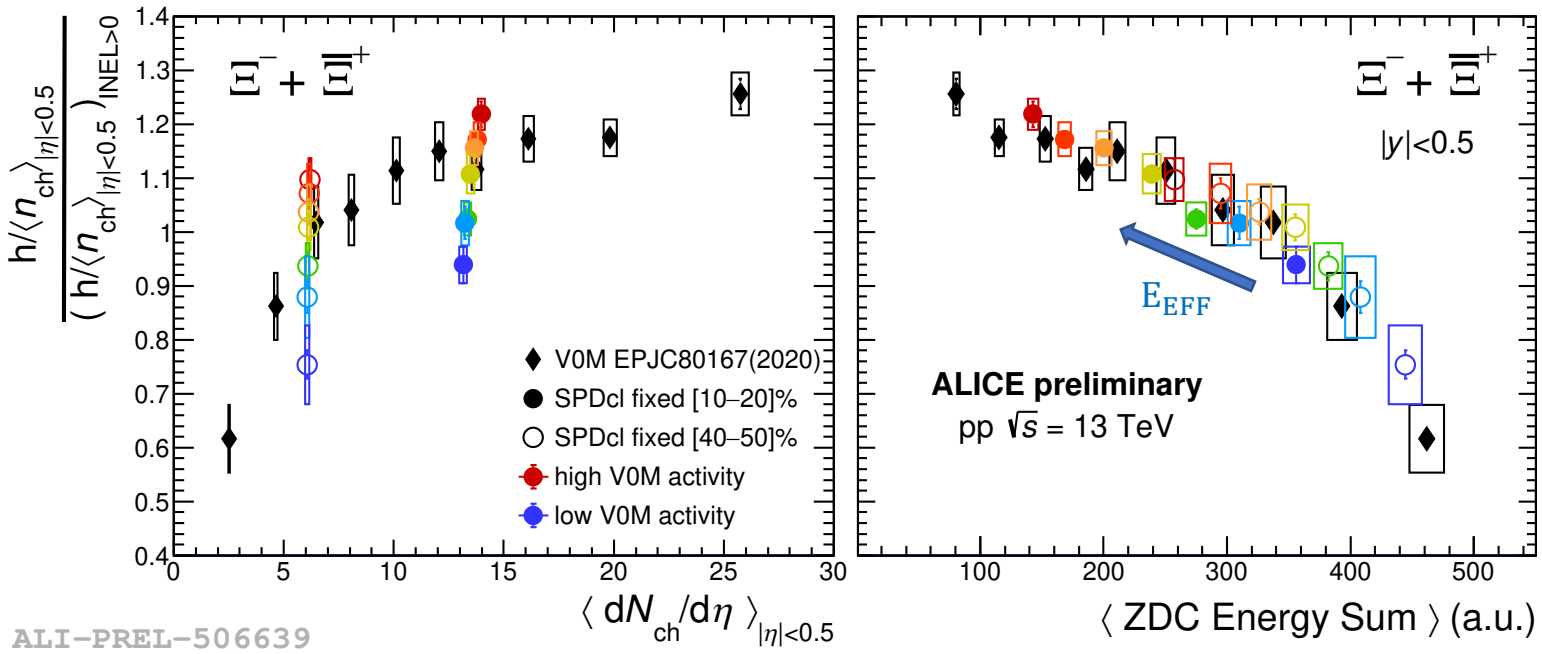
□ ■ V0M class fixed + SPD selections:

Reduce the span of the effective energy and vary the multiplicity at midrapidity

A **multi-differential analysis in combined V0M and SPD classes** allows to disentangle the effective energy and the multiplicity at midrapidity

Disentangle multiplicity and effective energy

$\Xi^{\pm}$ yield normalised to the charged-particle multiplicity, fixing the multiplicity at midrapidity:



- Strangeness enhancement with effective energy is observed also when the multiplicity at midrapidity is fixed
- Compatible trends with effective energy between the V0M standalone and the double differential analysis

→ Effective energy plays an important role in determining the production of strange hadrons

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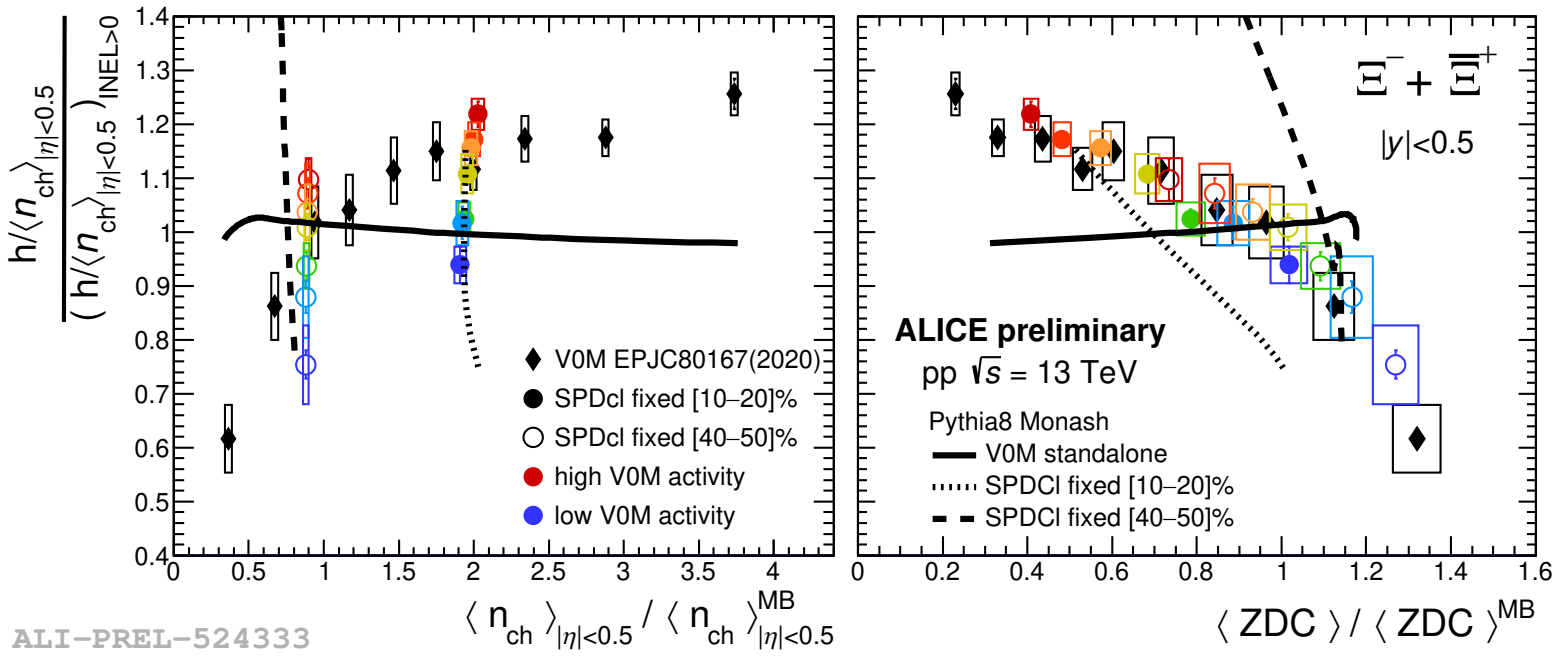

Comparison with Monte Carlo predicitions:

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

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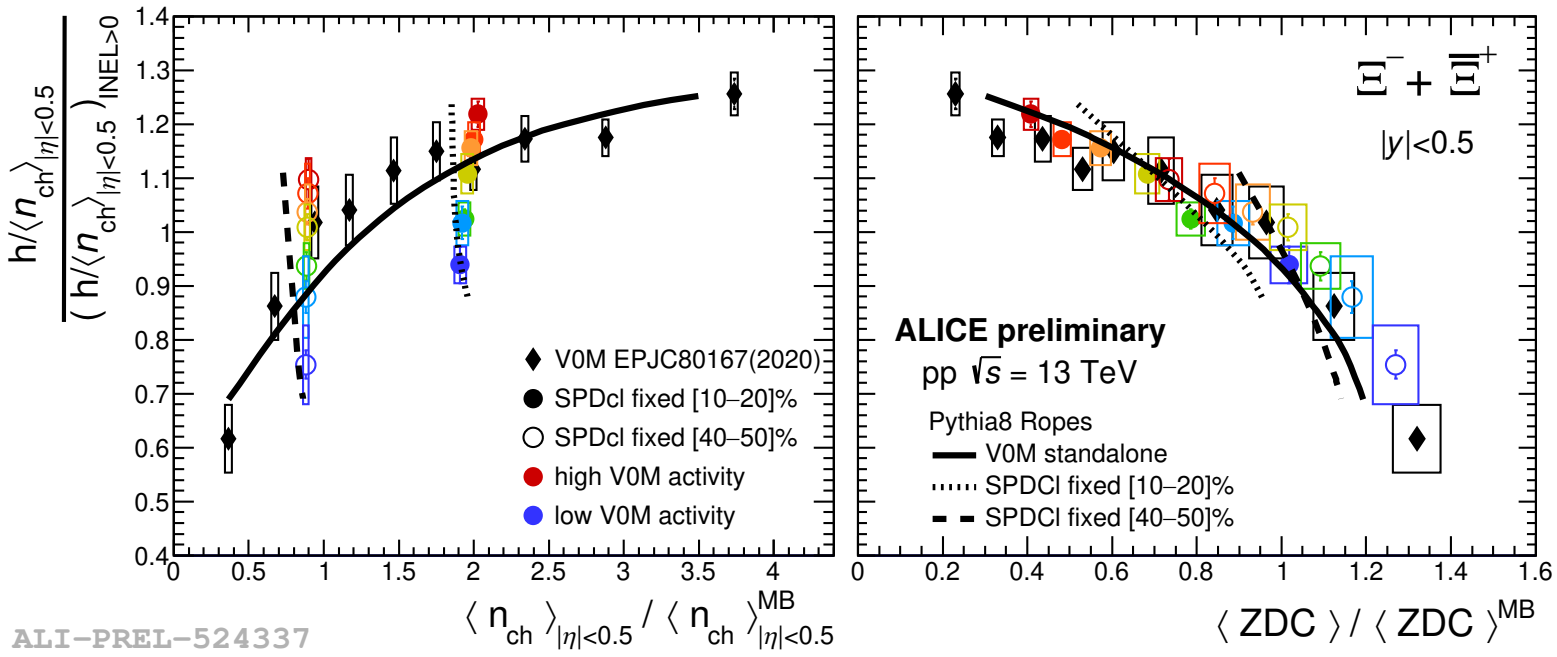

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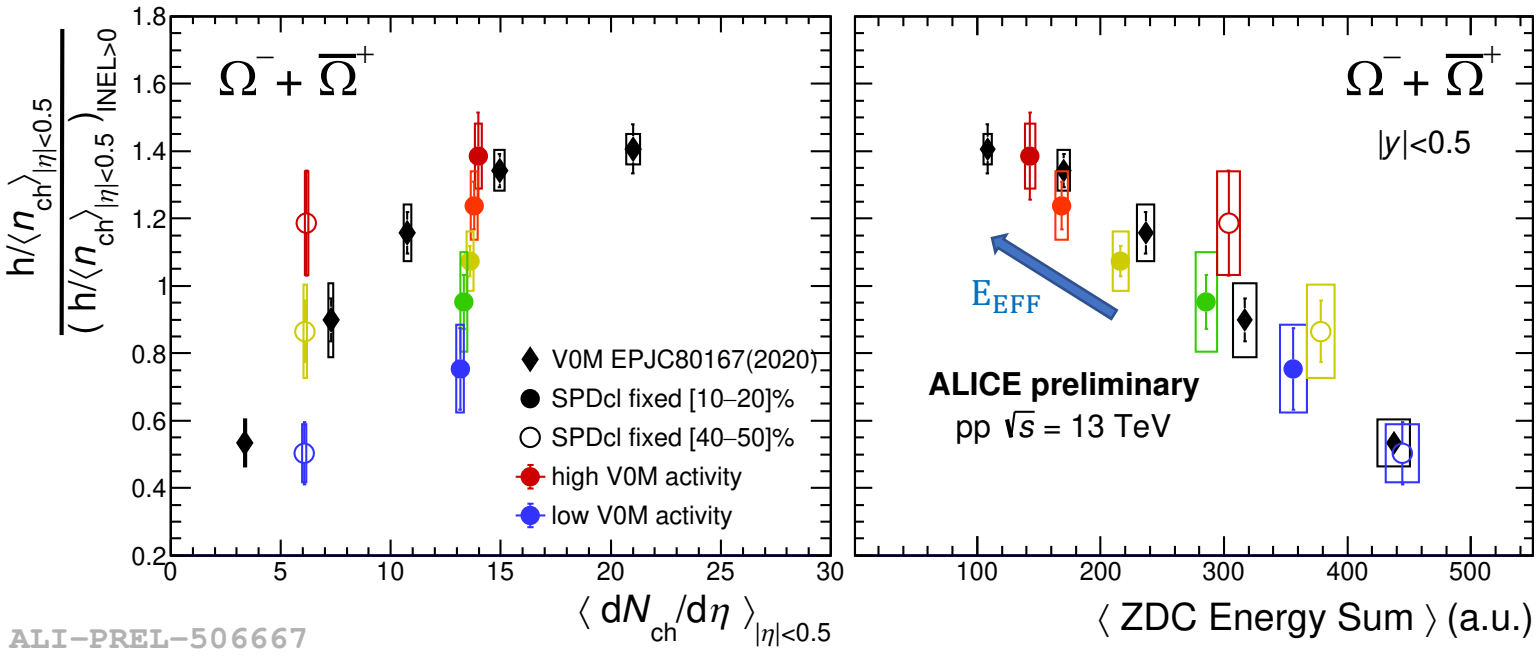
$\Omega^{\pm}$ yield normalised to the charged-particle multiplicity, fixing the multiplicity at midrapidity:



- Similar results obtained for the triple strange baryon $\Omega^{\pm}$

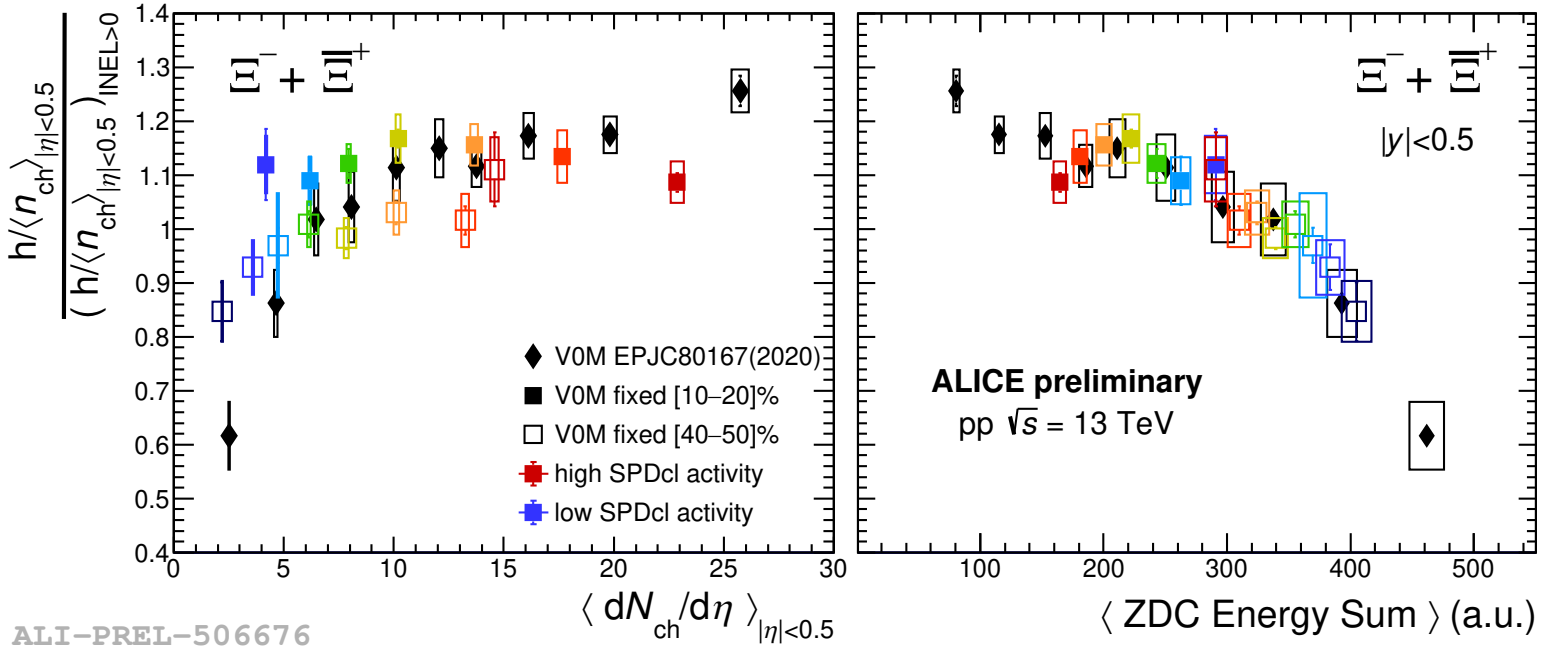
→ Effective energy plays an important role in determining the production of strange hadrons

Disentangle multiplicity and effective energy

$\Xi^{\pm}$ yield normalised to the charged-particle multiplicity, reducing the effective energy span:

Larger E_{EFF}

Smaller E_{EFF}



- When the effective energy is constrained, the strangeness enhancement with multiplicity is reduced

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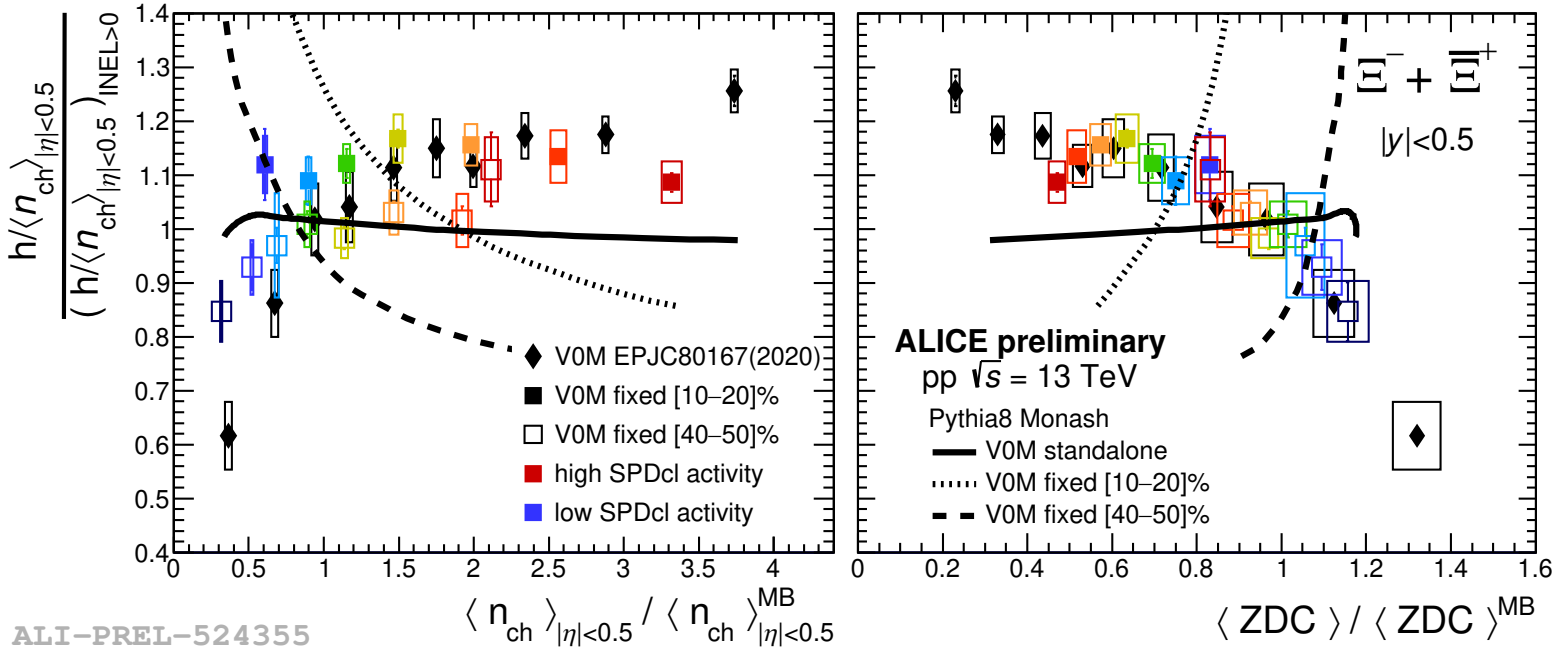

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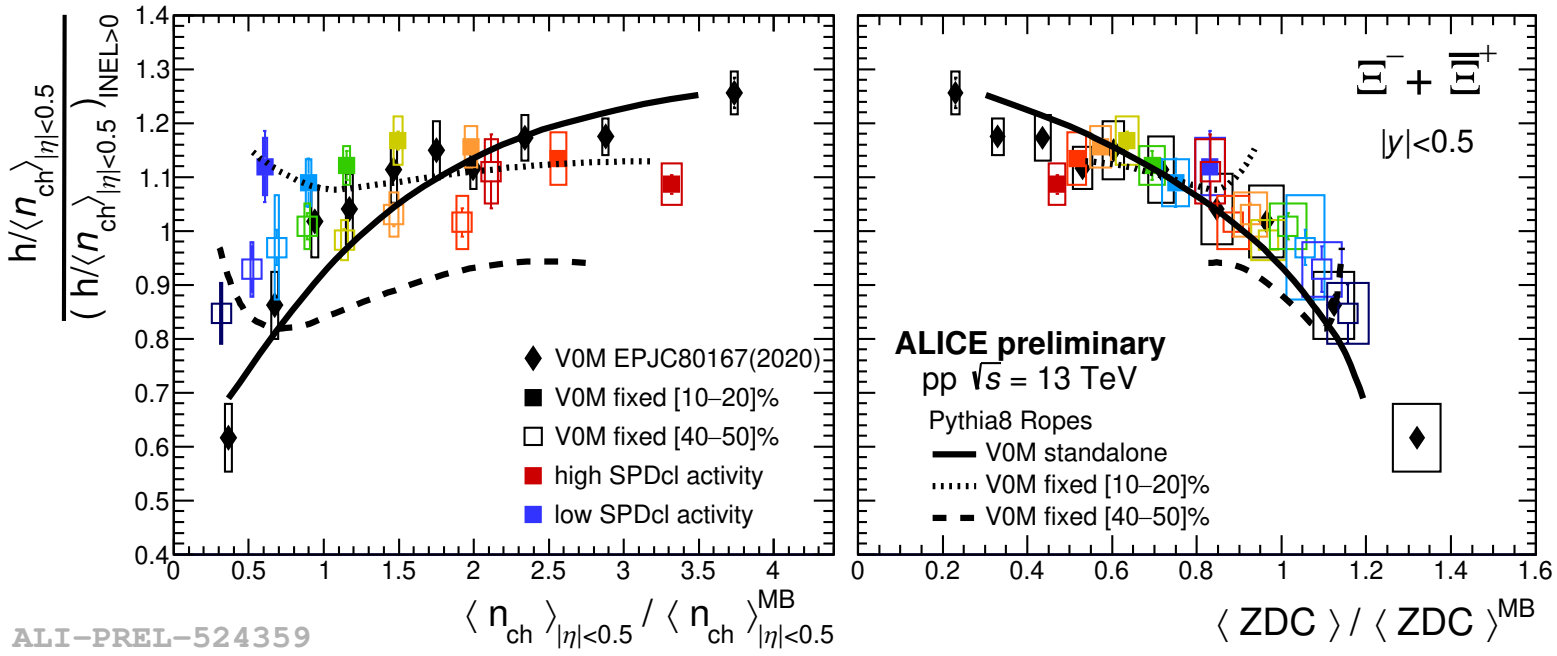

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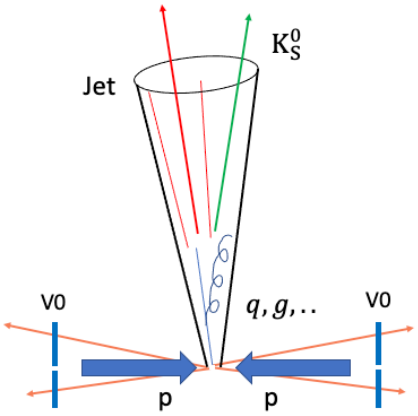
Angular correlations for in-jet and out-of-jet studies of strange hadron production



Correlations of high-p_T charged hadrons with strange particles

The angular correlation method:

1. Selection of the trigger particle (~jet axis): the charged primary particle with the highest p_T and $p_T > 3$ GeV/c

2. Identification of strange hadrons (associated particles)

3. Angular correlation between trigger and associated particles is calculated

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

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

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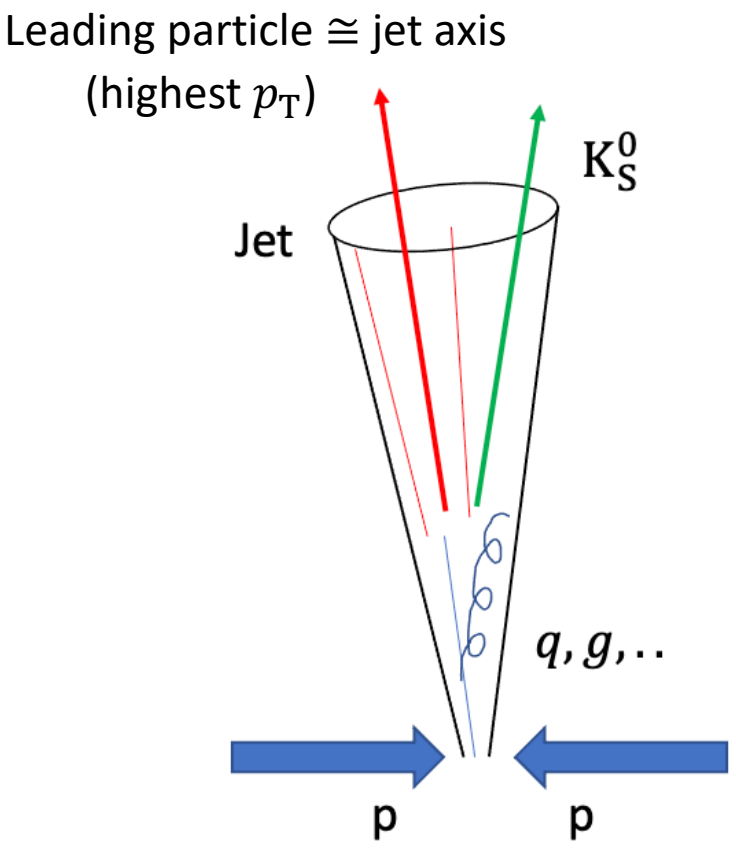

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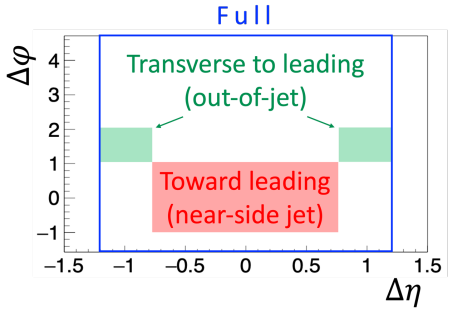
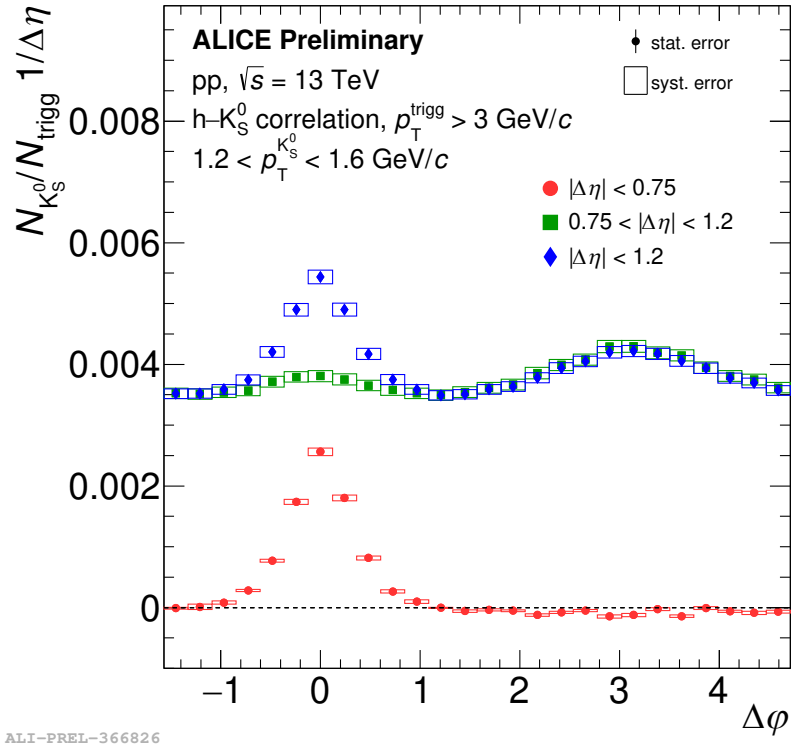
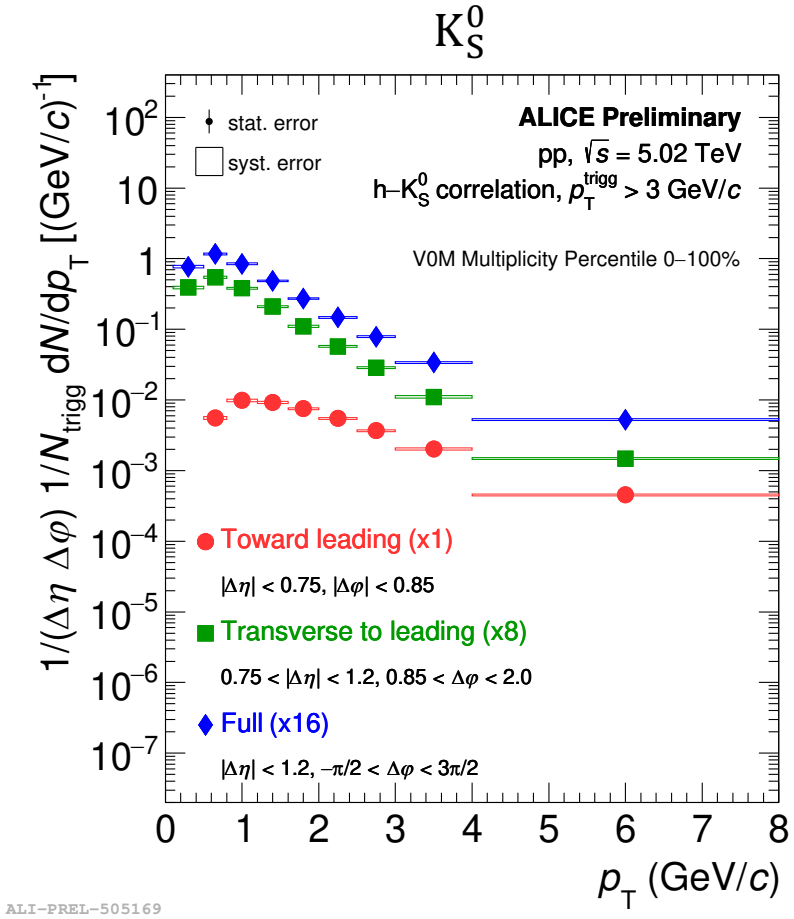
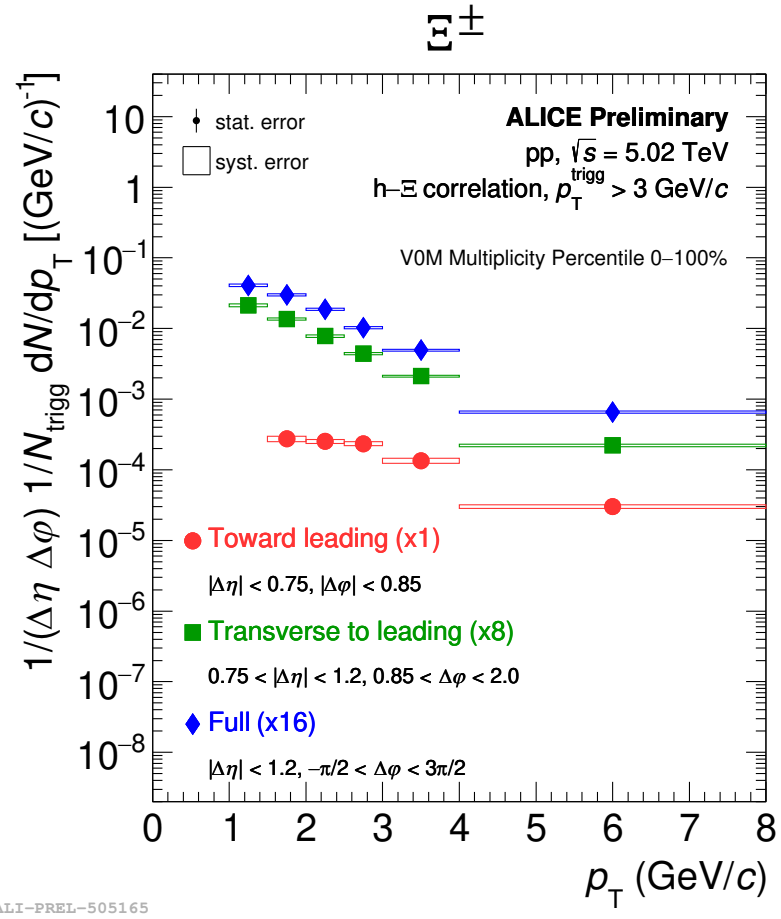




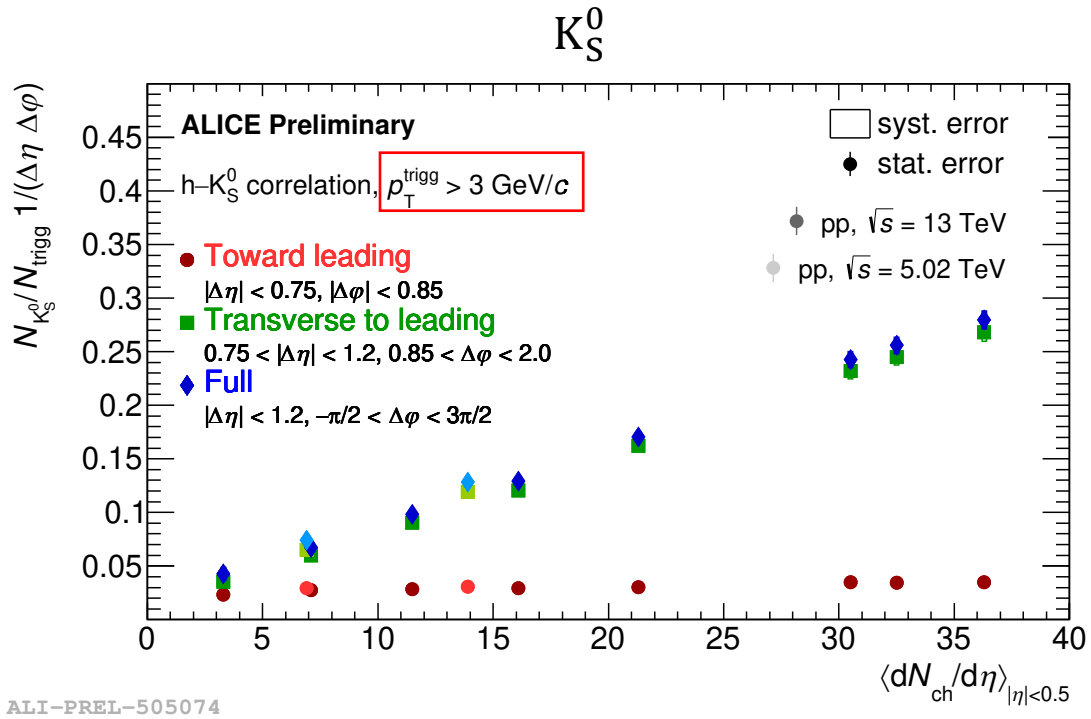
Toward, transverse-to-leading and full p_T spectra of K^0_S and $\Xi^{\pm}$

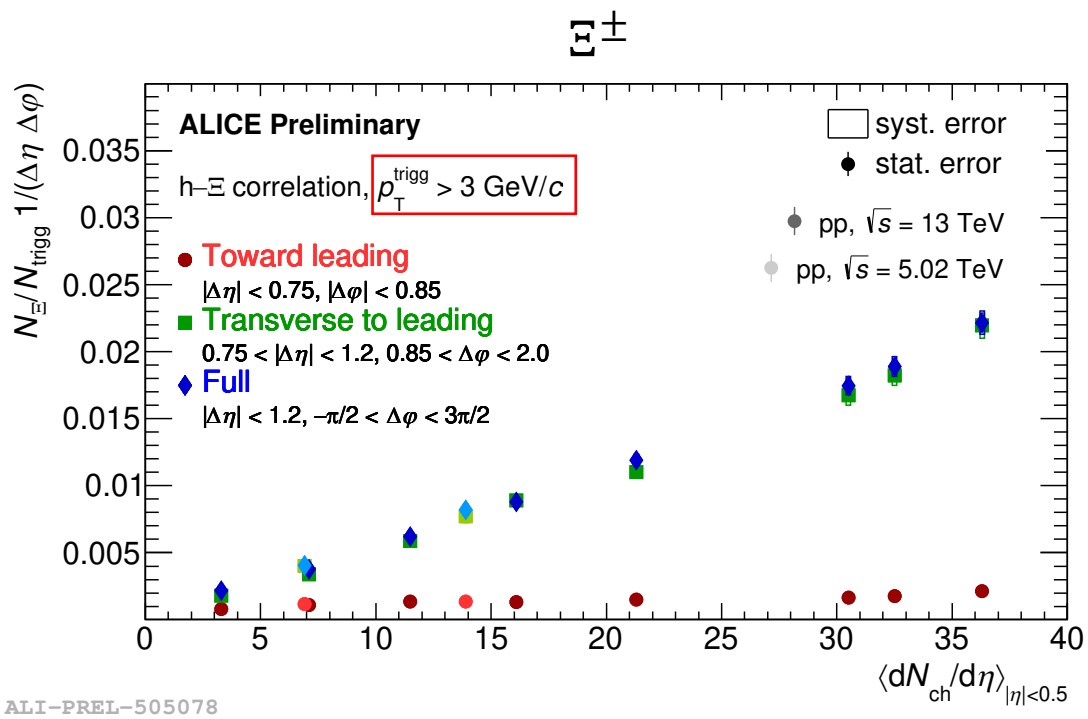




- Toward-leading spectra of K^0_S ($\Xi^{\pm}$) are harder than transverse-to-leading spectra of K^0_S ($\Xi^{\pm}$)
- Same feature observed in different V0M multiplicity classes and different centre-of-mass energies

Toward, transverse-to-leading and full yields of strange hadrons vs multiplicity

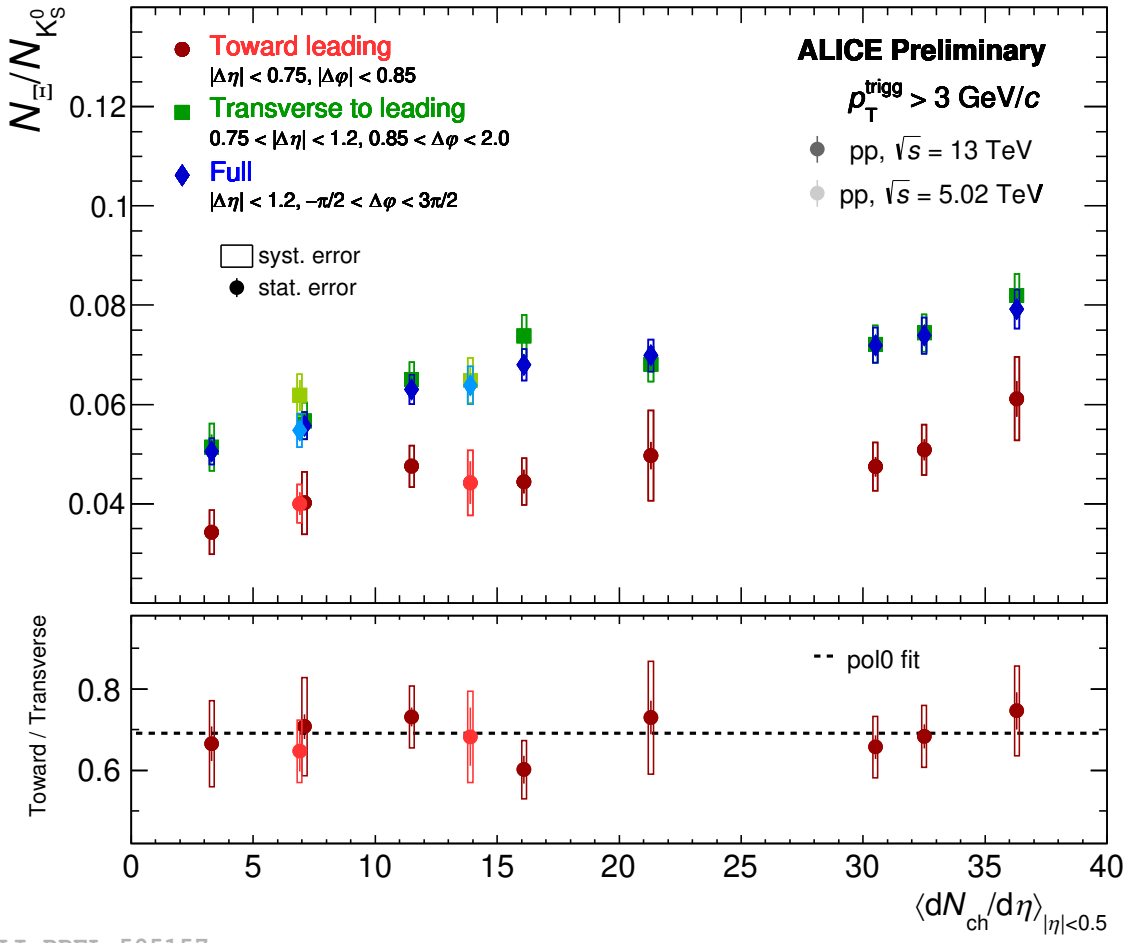




- Both the full yield and the transverse-to-leading yield increase with the multiplicity
- Very mild to no evolution with multiplicity of the toward-leading yield
- The yields show no dependence on the centre-of-mass energy

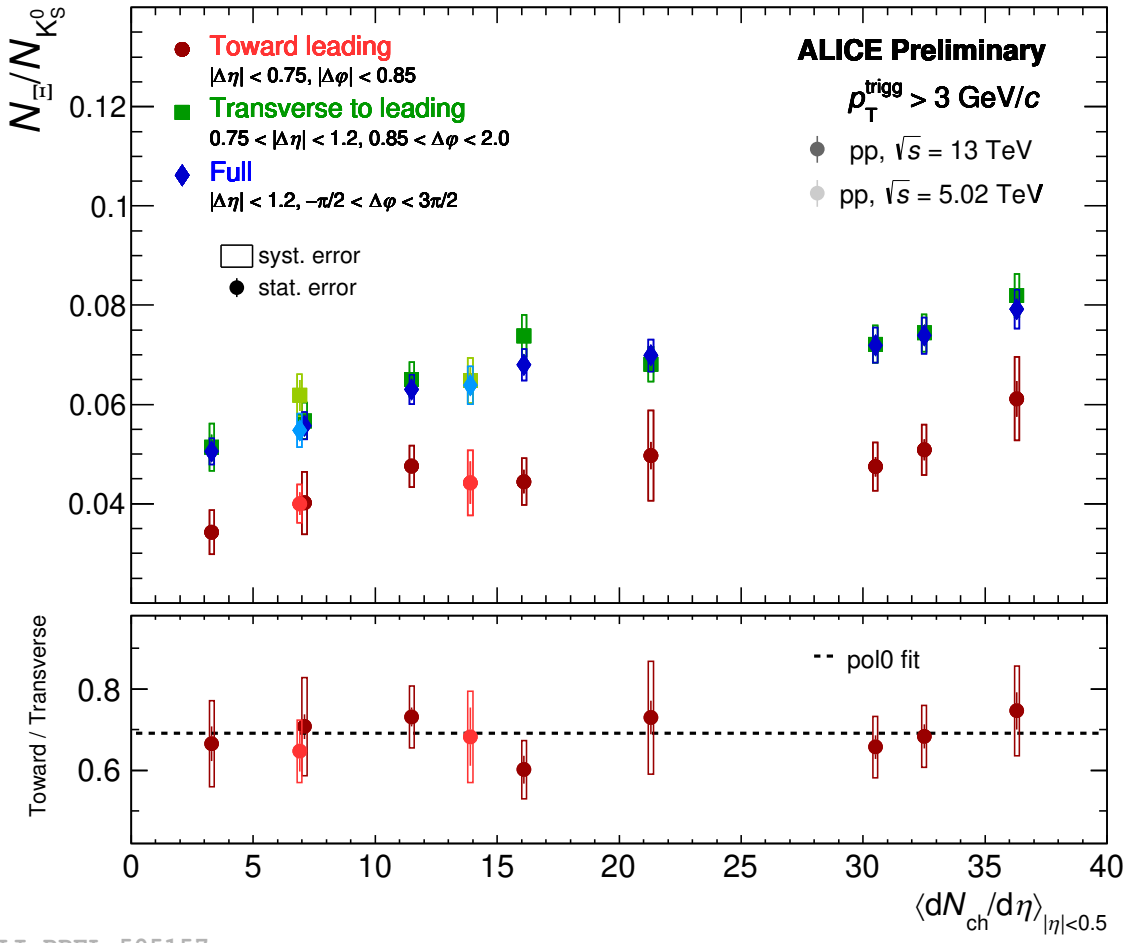
→ The contribution of transverse-to-leading wrt toward-leading production increases with multiplicity

Strangeness enhancement in jets and out of jets



- The strangeness enhancement in the ratio of full yields is attributed to the larger strangeness content of Ξ ($|S| = 2$) with respect to K^0_S ($|S| = 1$)
- The transverse-to-leading Ξ/K^0_S yield ratio **increases with the multiplicity** and is compatible with the ratio of full yields
- The toward-leading ratio is **smaller** than the transverse-to-leading one
- The toward-leading and transverse-to-leading Ξ/K^0_S yield ratios show **compatible increase** with multiplicity

Strangeness enhancement in jets and out of jets



→ Transverse-to-leading processes give the **dominant contribution** to the $\Xi/\mathrm{K}^0_\mathrm{S}$ full yield ratio in pp collisions

→ The $\Xi/\mathrm{K}^0_\mathrm{S}$ production is favoured in transverse-to-leading processes wrt toward-leading processes

→ The toward-leading and transverse-to-leading $\Xi/\mathrm{K}^0_\mathrm{S}$ yield ratios show **compatible increase with multiplicity**

Summary

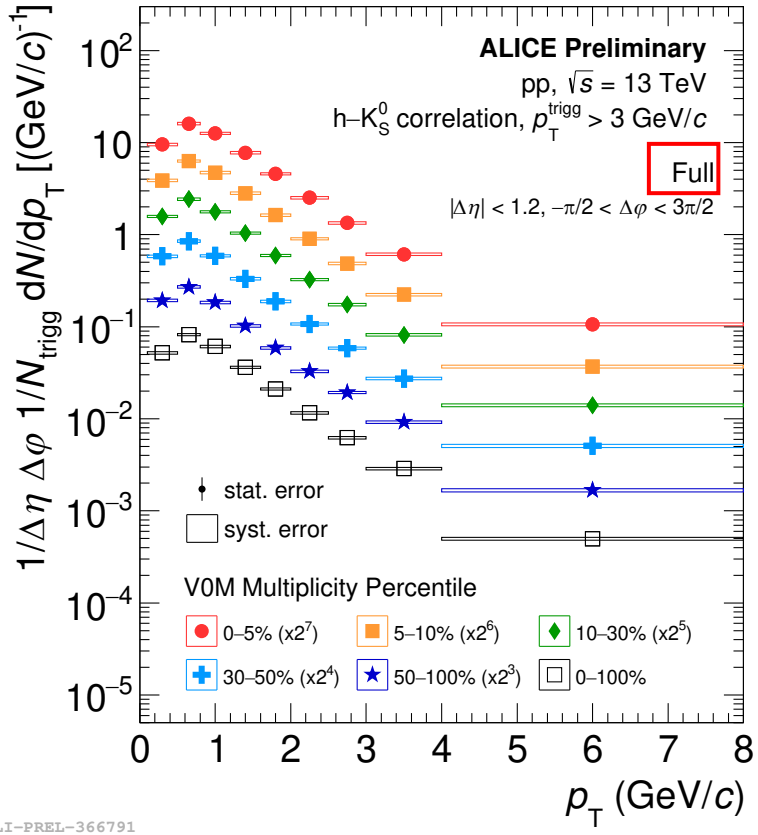
- **Strangeness enhancement** in pp collisions **is strongly correlated** with the **effective energy**
- **Out-of-jet processes** give the **dominant contribution to strange particle production** in pp collisions
- **Strangeness enhancement** with multiplicity is observed in **out-of-jet processes**

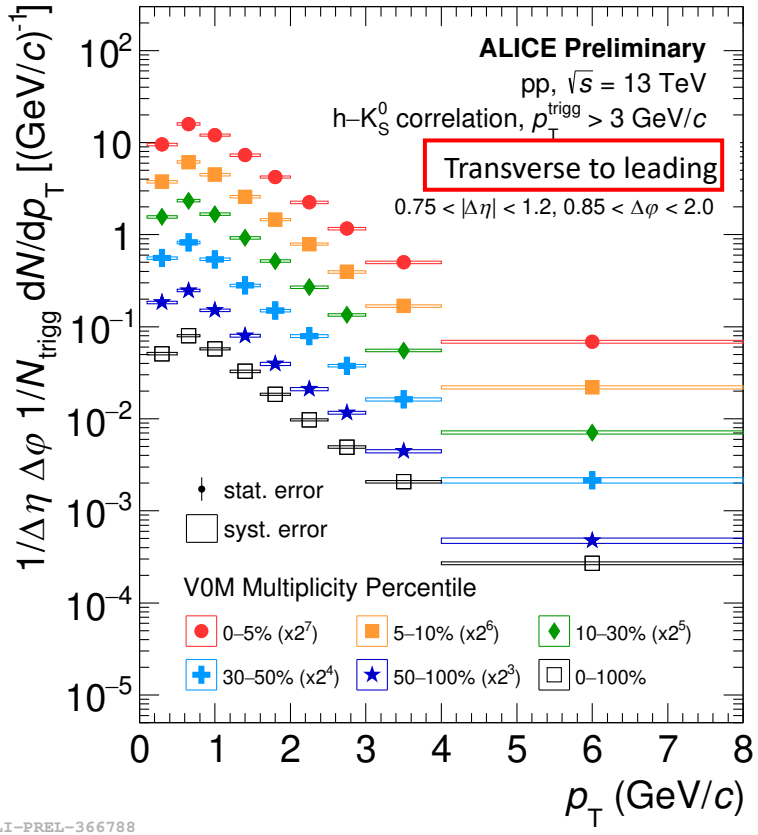
Studies of strangeness production in pp collisions will profit from the large amount of data which will be collected during Run 3

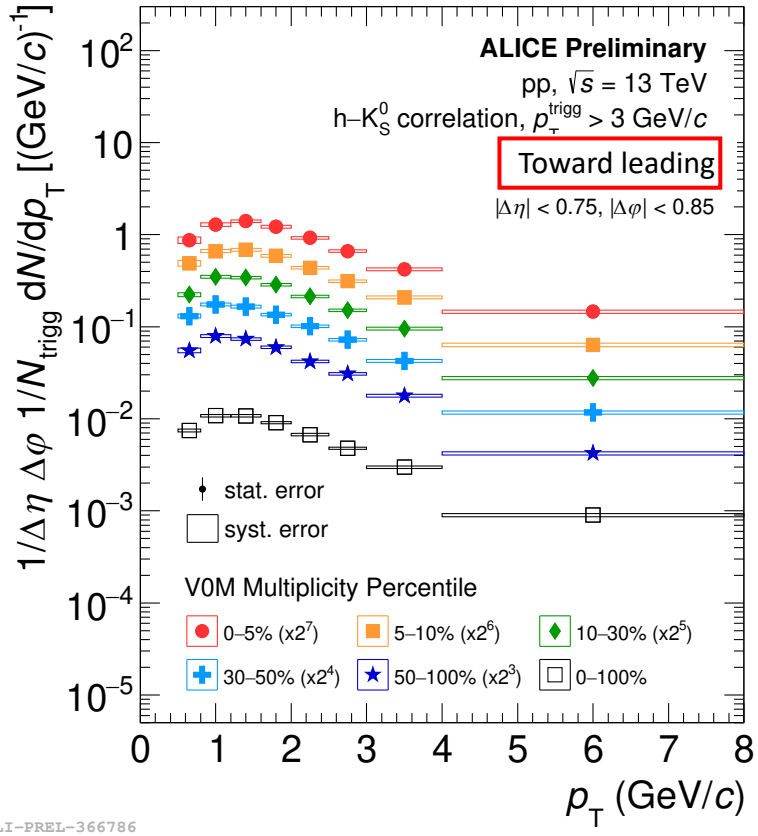
→ e.g. x3000 increase of $\Omega^{\pm}$ for in- and out-of-jet analysis

Backup

Toward, transverse-to-leading and full p_T spectra of K^0_S

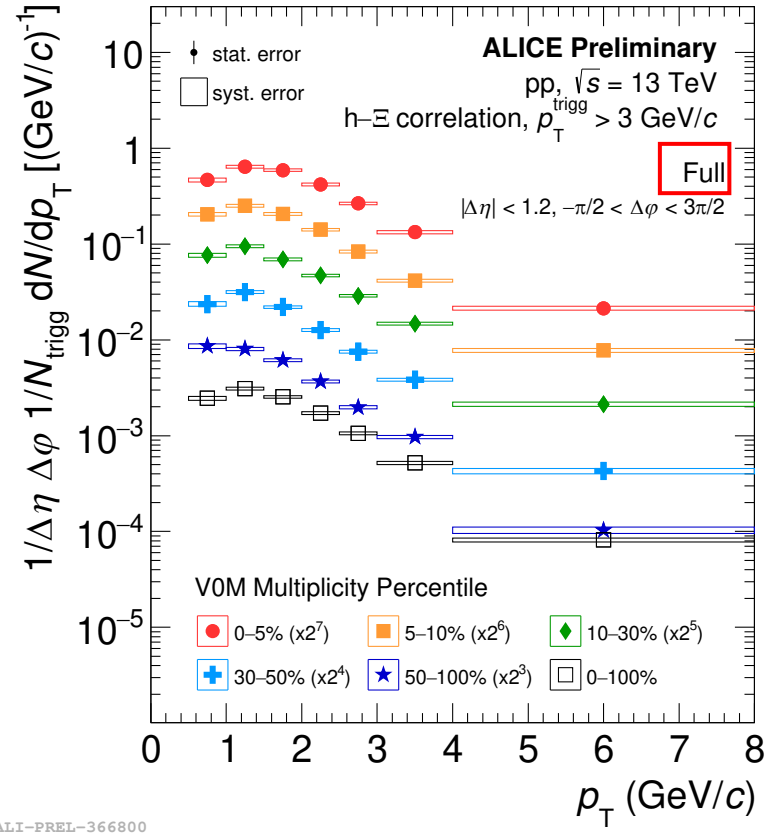


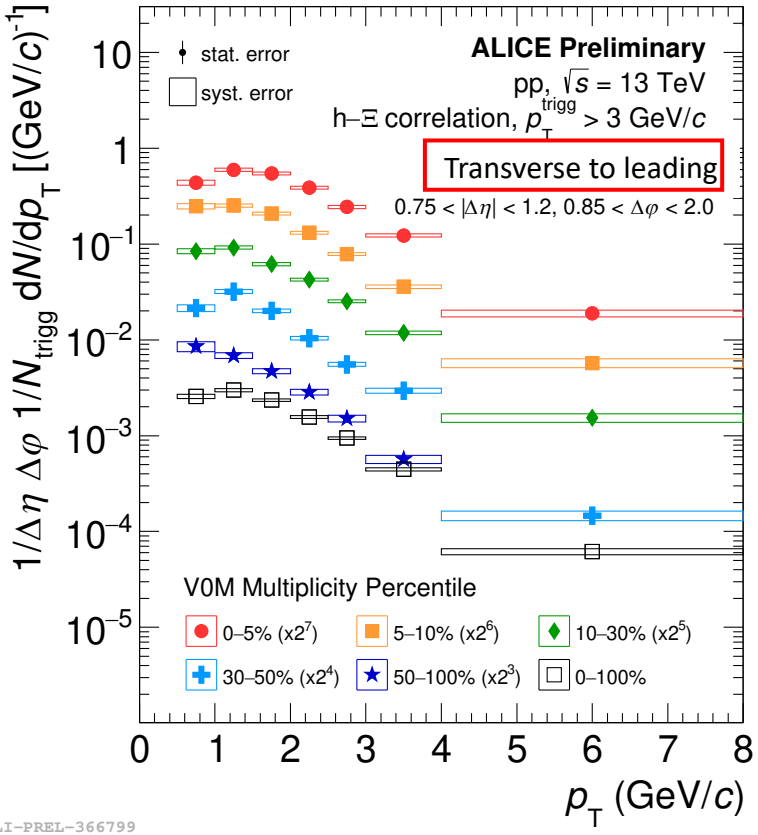


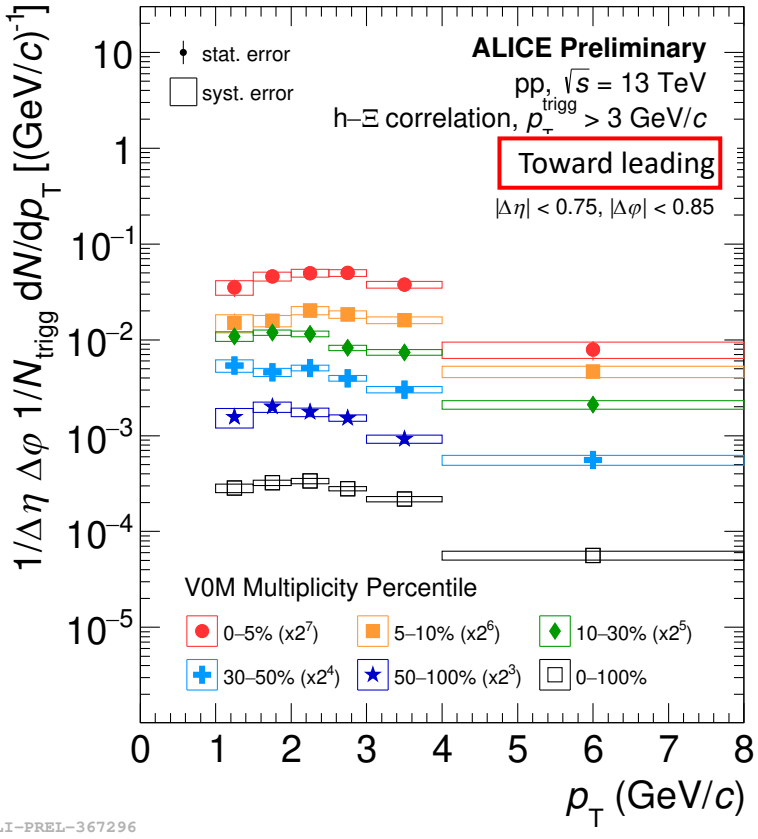


Toward-leading spectra of K^0_S are harder than transverse-to-leading spectra of K^0_S

Toward, transverse-to-leading and full p_T spectra of $\Xi^{\pm}$

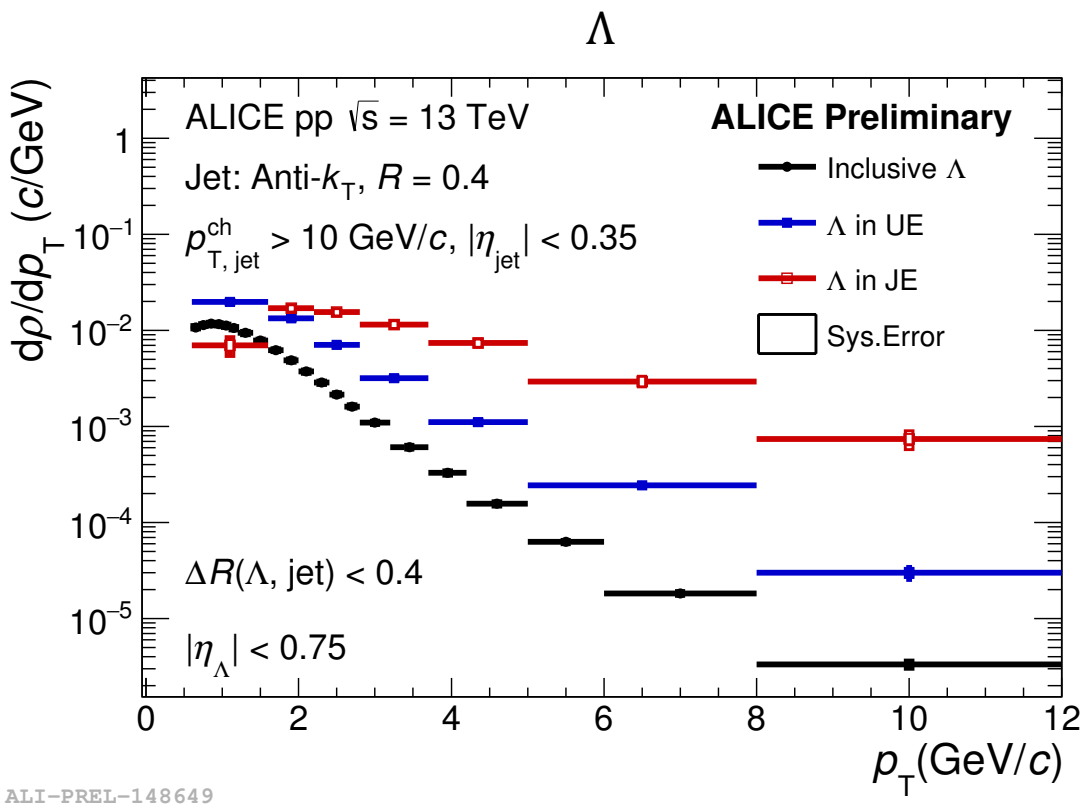


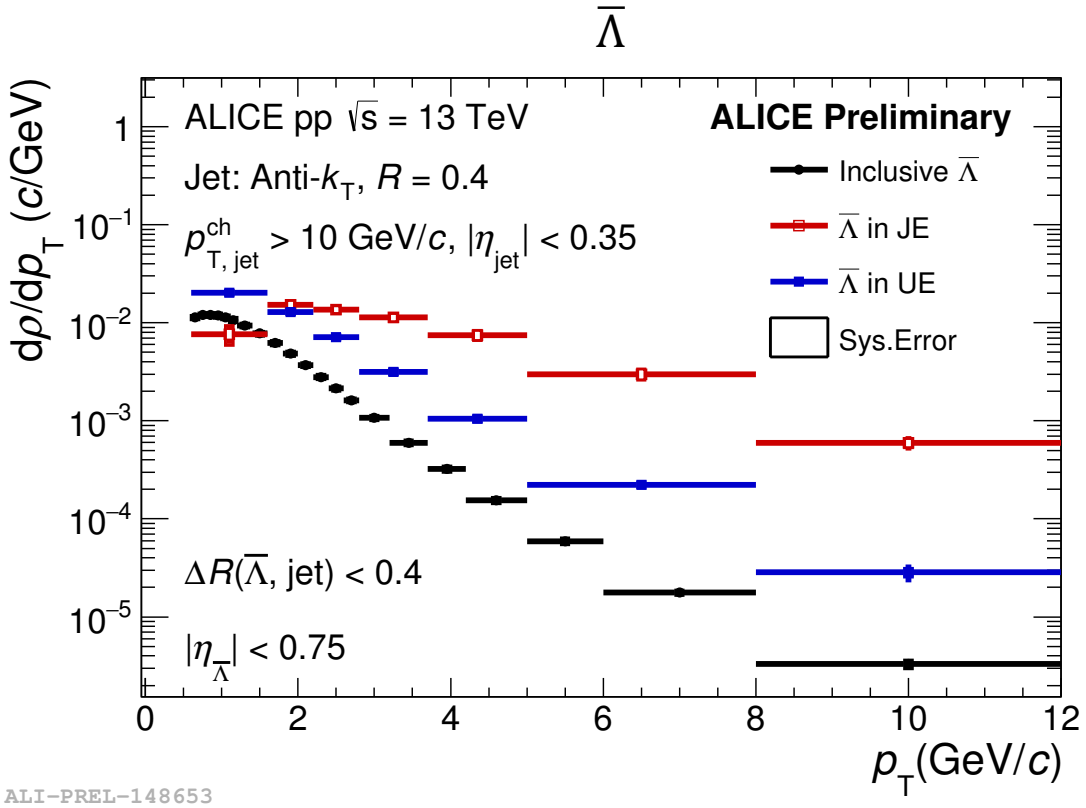




Toward-leading spectra of $\Xi^{\pm}$ are harder than transverse-to-leading spectra of $\Xi^{\pm}$

Strange particle production in and out of jets

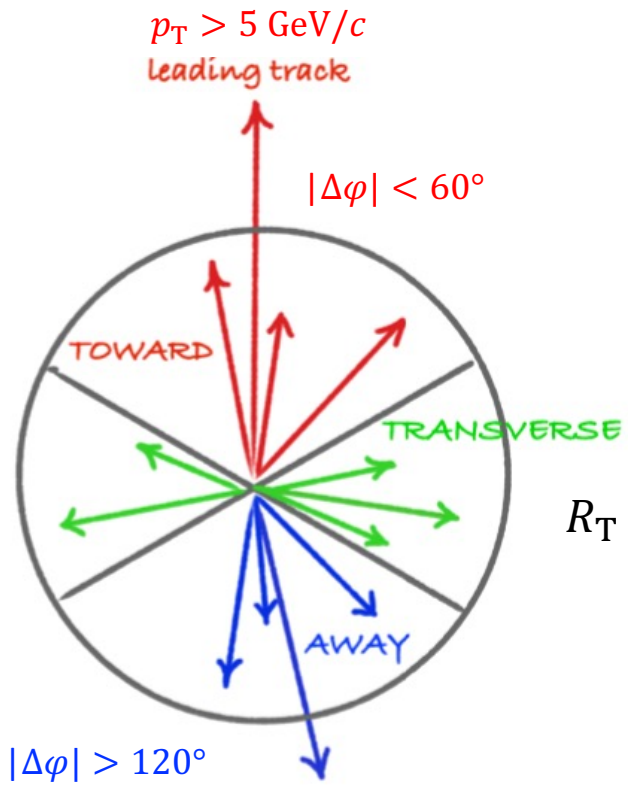




- The spectra of Λ and $\bar{\Lambda}$ in jets are harder than in the UE

R_{T} : particle production in the Underlying Event

R_{T} measures the multiplicity of tracks in a transverse region with respect to the leading track
i.e. the multiplicity related to the underlying event (UE)



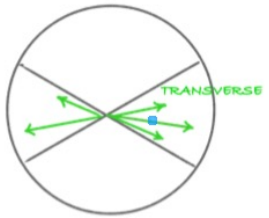
$$R_{\mathrm{T}} = \frac{N_T}{\langle N_T \rangle}$$

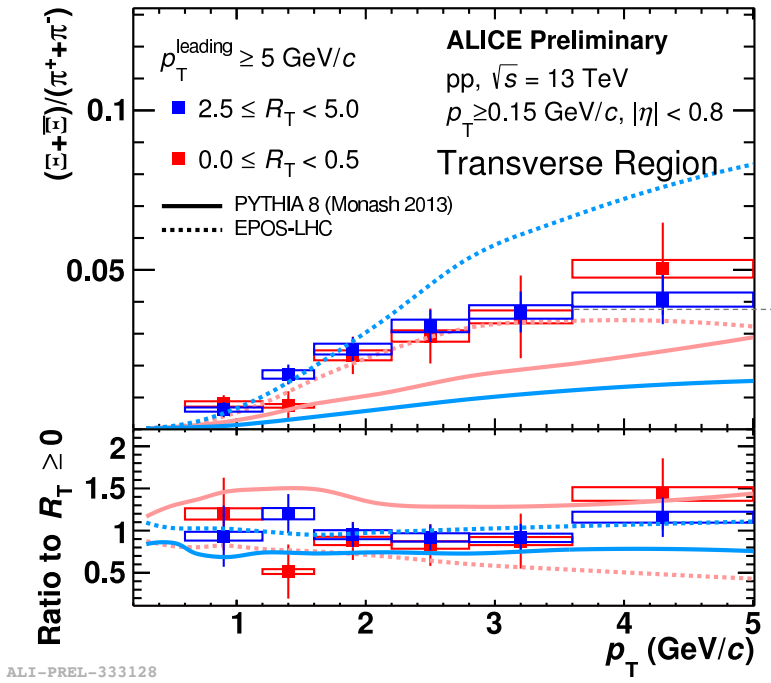
Topological classification of pp events:
Toward region (jet + UE)
Transverse region (UE)
Away region (recoiling jet + UE)

Studies of strange hadron production vs R_{T} in the different regions provide insight into strangeness enhancement

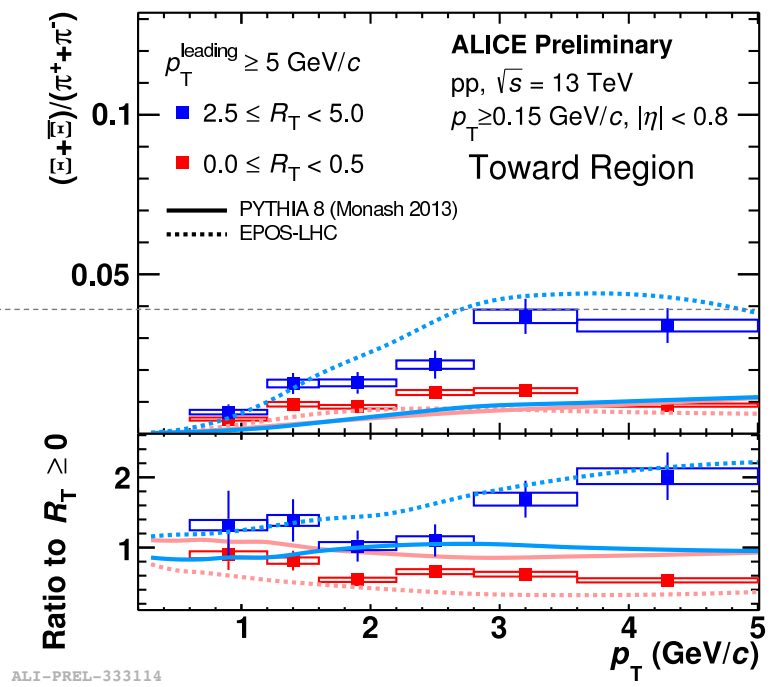
$\Xi^{\pm}$ production vs R_T

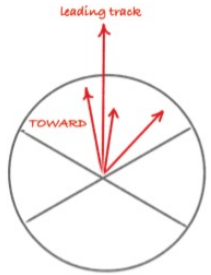
UE





Jet + UE



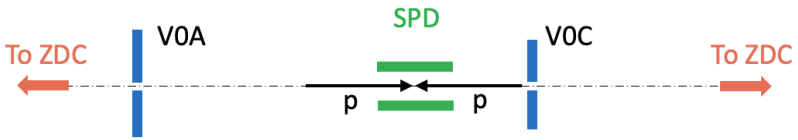


Ξ/π does not depend on R_T in the Transverse Region (UE)

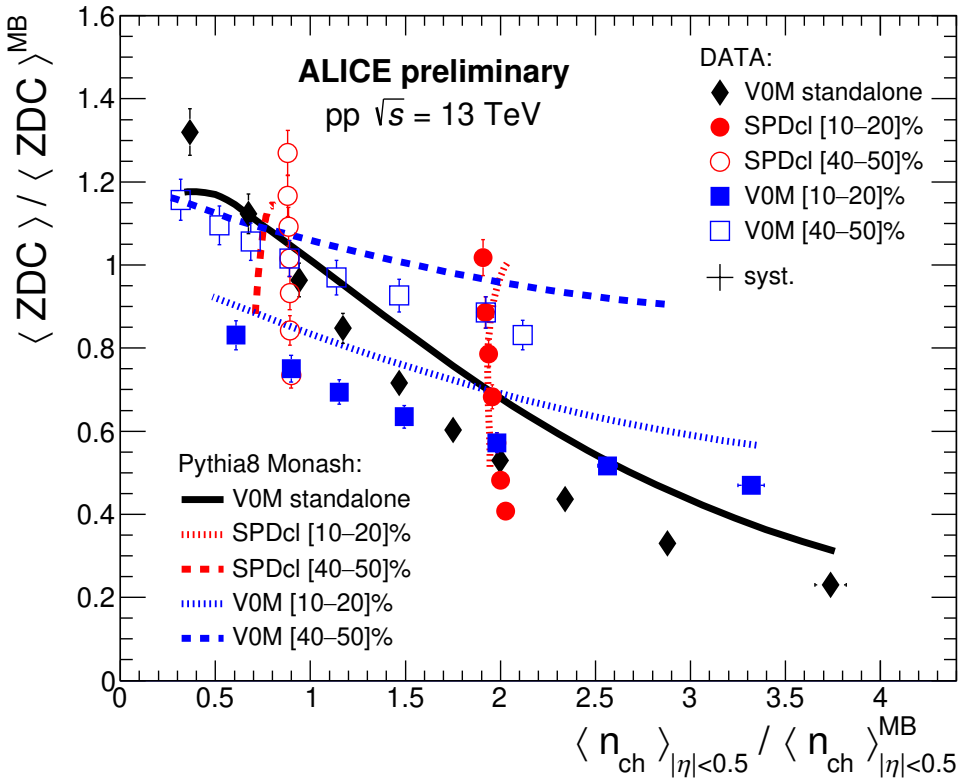
Ξ/π increases with R_T in the Toward Region (Jet + UE), approaching the values of the Transverse Region

$\rightarrow$ Ξ/π higher in the UE than in the jet

Disentangle multiplicity and effective energy



PYTHIA8 Monash



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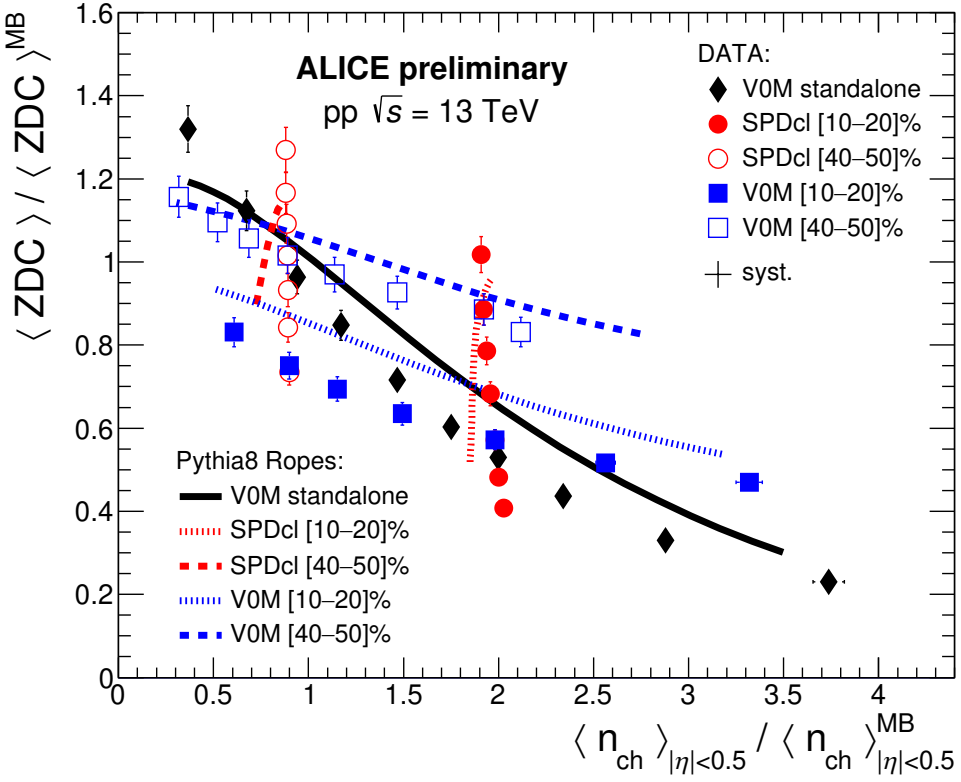
PYTHIA8 Ropes



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