Multi-differential studies to explore strangeness enhancement in pp collisions with ALICE at the LHC

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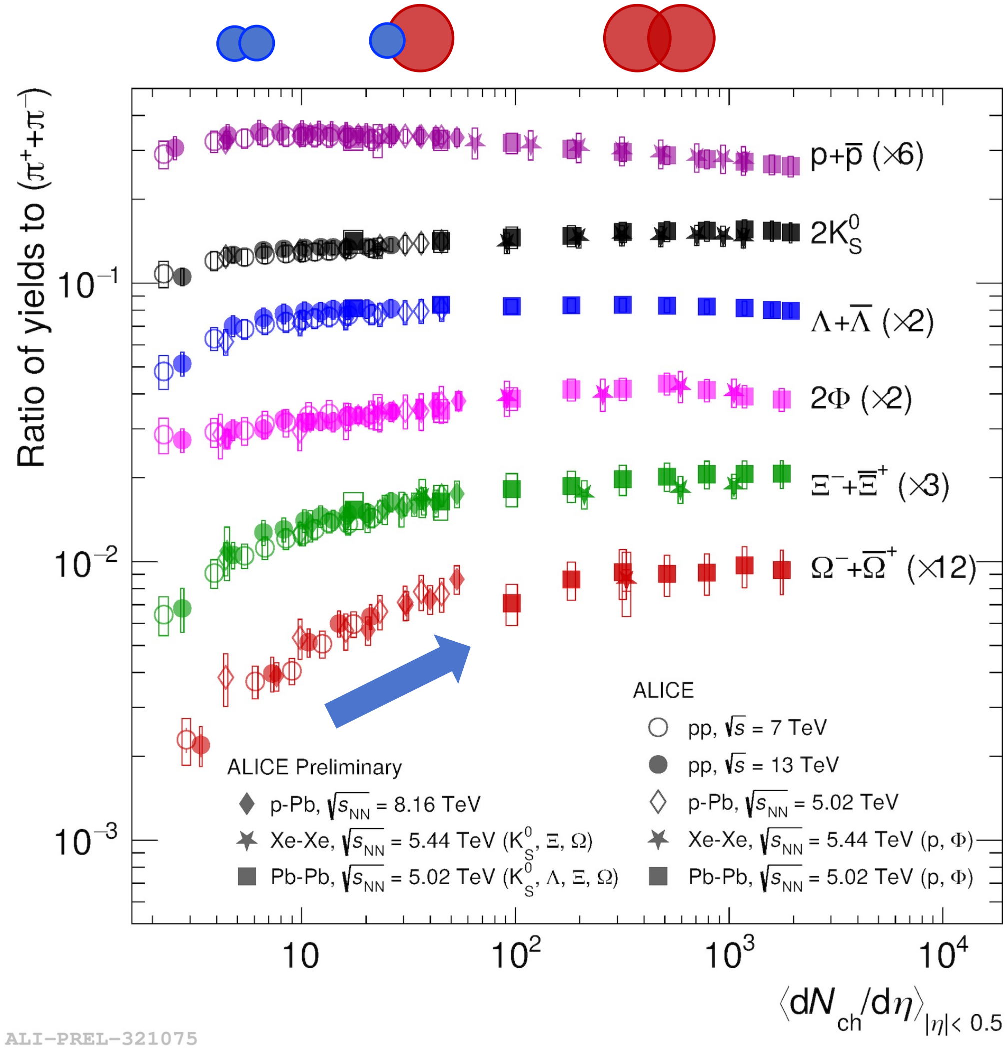
University and INFN - Trieste

Physics motivation

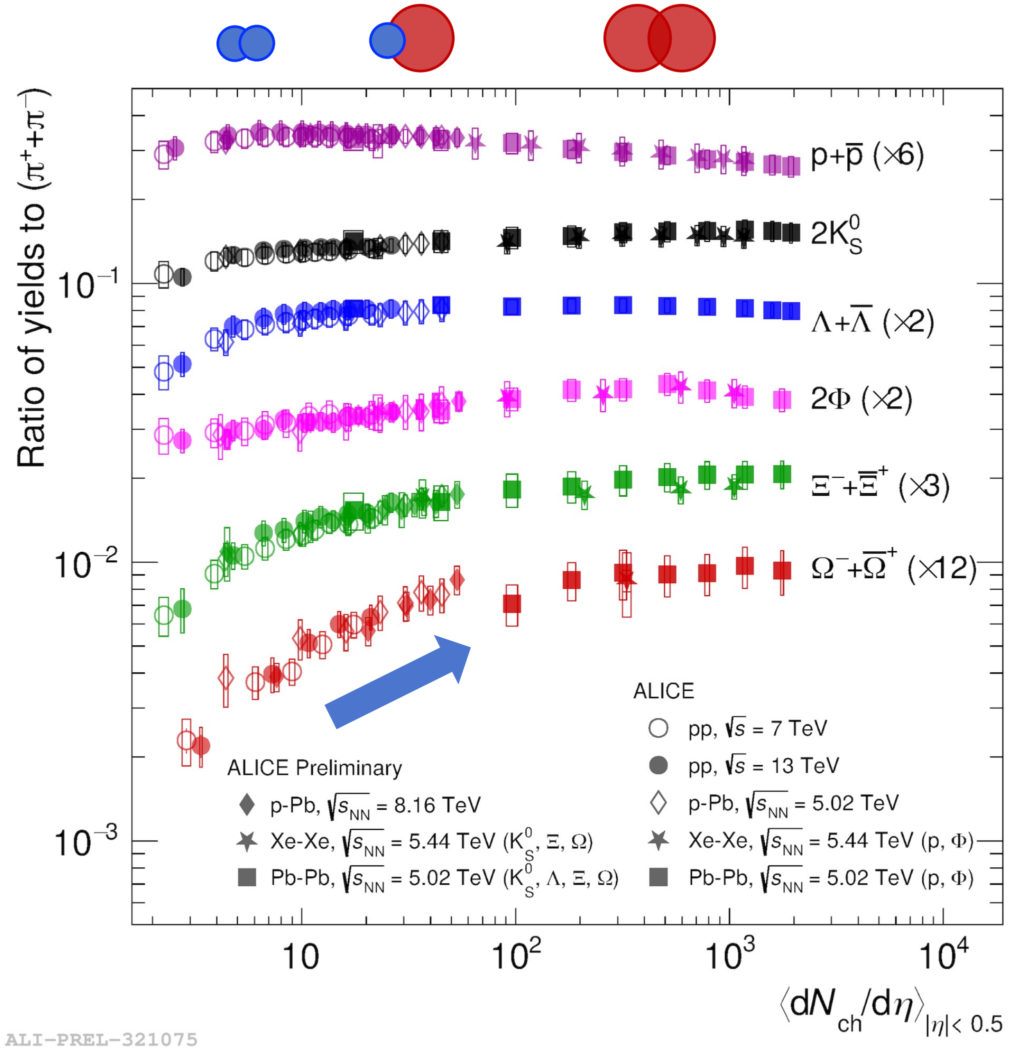


Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- 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 ($\Omega > \Xi > K_S^0$)

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

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

- Is strangeness enhancement driven only by final state effects, such as particle multiplicity, or do initial state effects play a role?

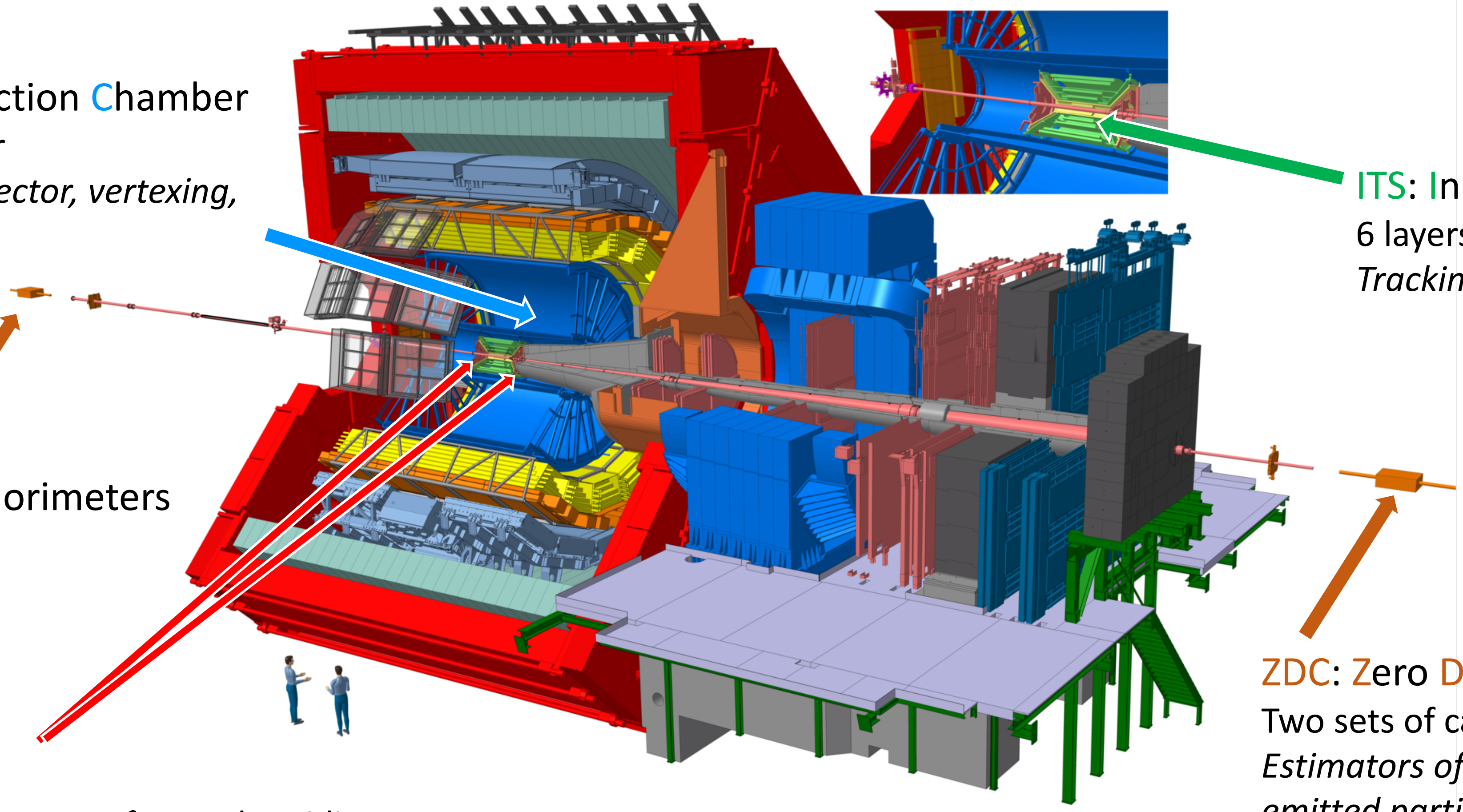
- Is strangeness enhancement related to soft particle production or to hard processes, such as jets?

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

ALICE at the LHC

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

ZDC:
Zero Degree Calorimeters



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

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

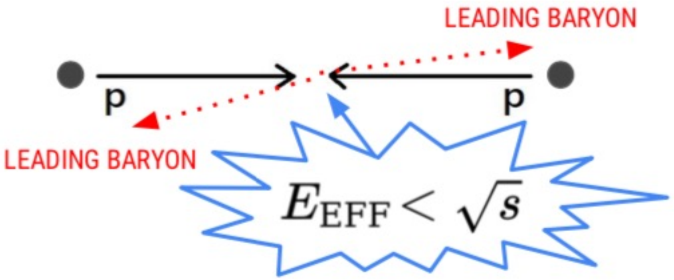
ZDC: Zero Degree Calorimeters
Two sets of calorimeters at forward rapidity
Estimators of energy deposits of forward emitted particles

Initial and final state effects on strangeness production in pp collisions

The concept of effective energy in pp collisions

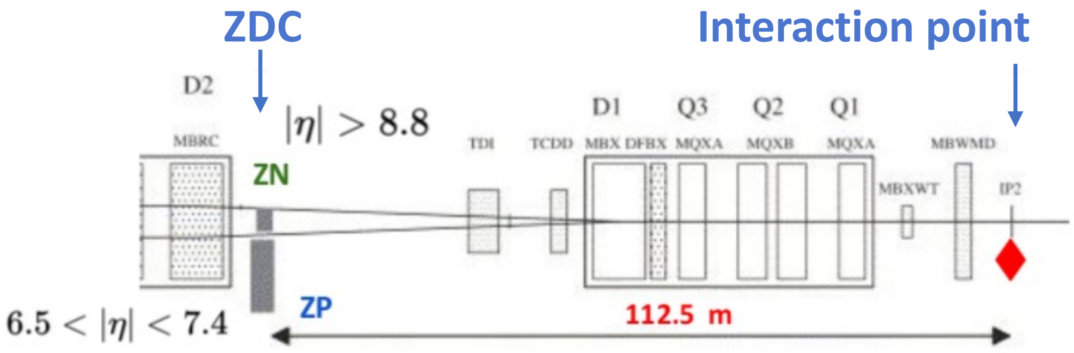
- The energy available for particle production is only a fraction of the centre-of-mass energy, because of the leading baryon effect

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



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

$$E_{\mathrm{EFF}} = \sqrt{s} - E_{|\eta|>8}$$



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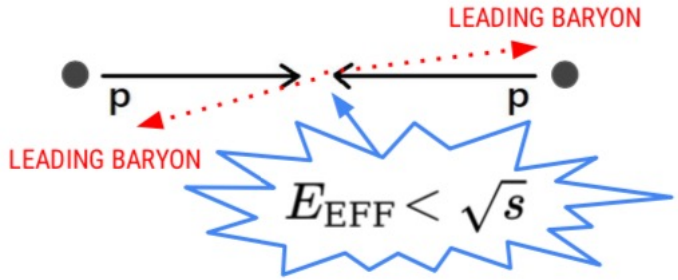

- ALICE estimates the effective energy from the measurement of the energy deposited in the forward calorimeters (ZDCs):

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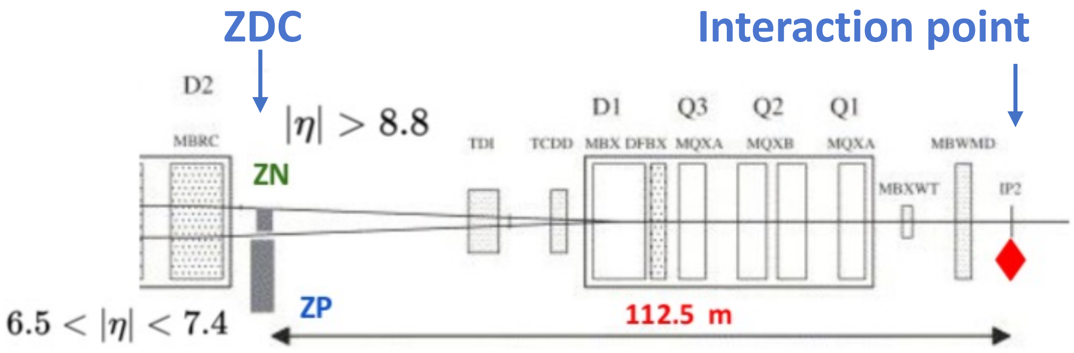
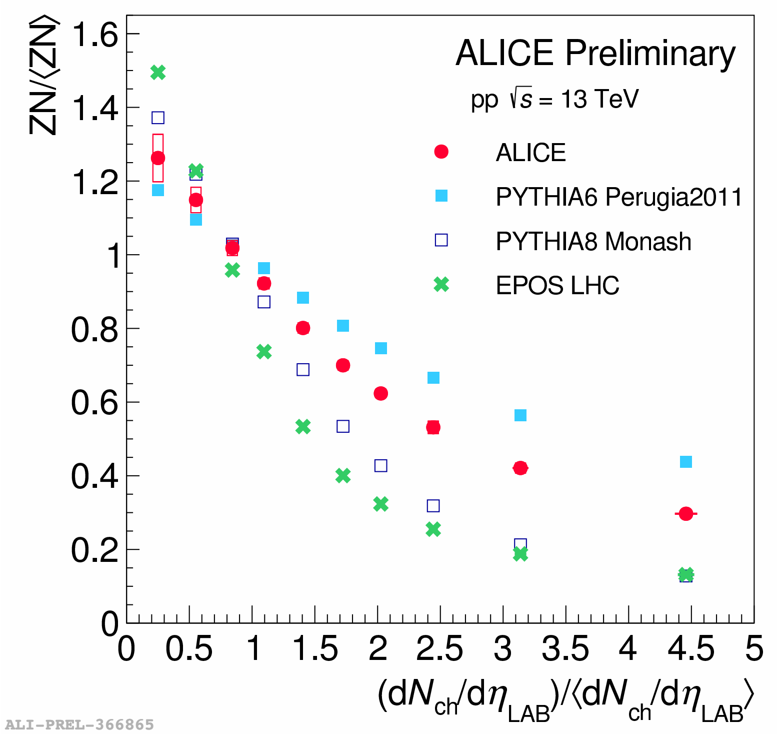
Studying strangeness production as a function of the effective energy might give insight into the role of initial state effects



Effective energy and multiplicity are correlated

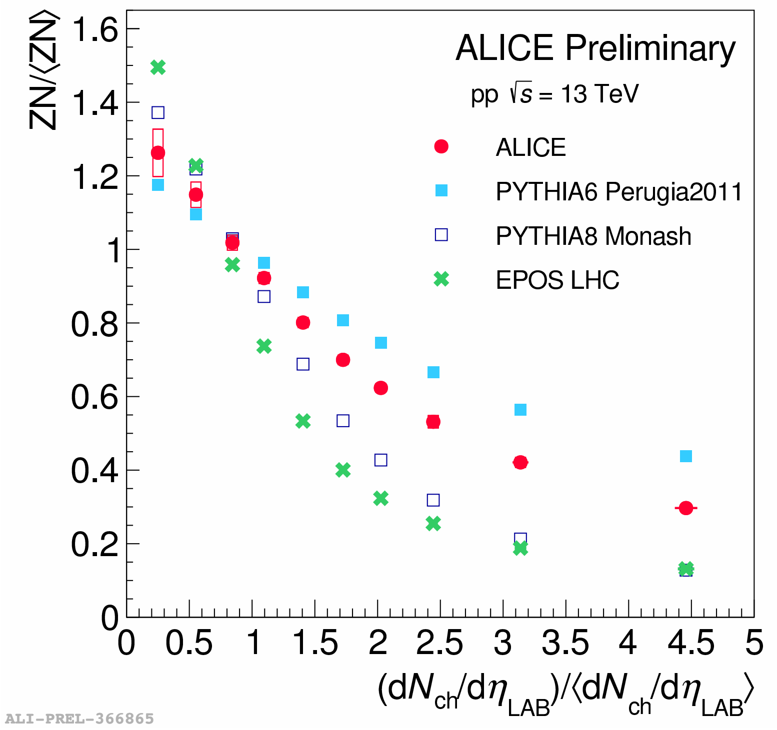
- The **effective energy** is correlated with the **multiplicity** of charged particles produced at midrapidity
- The correlation is observed in the data and is qualitatively predicted by Monte Carlo simulations

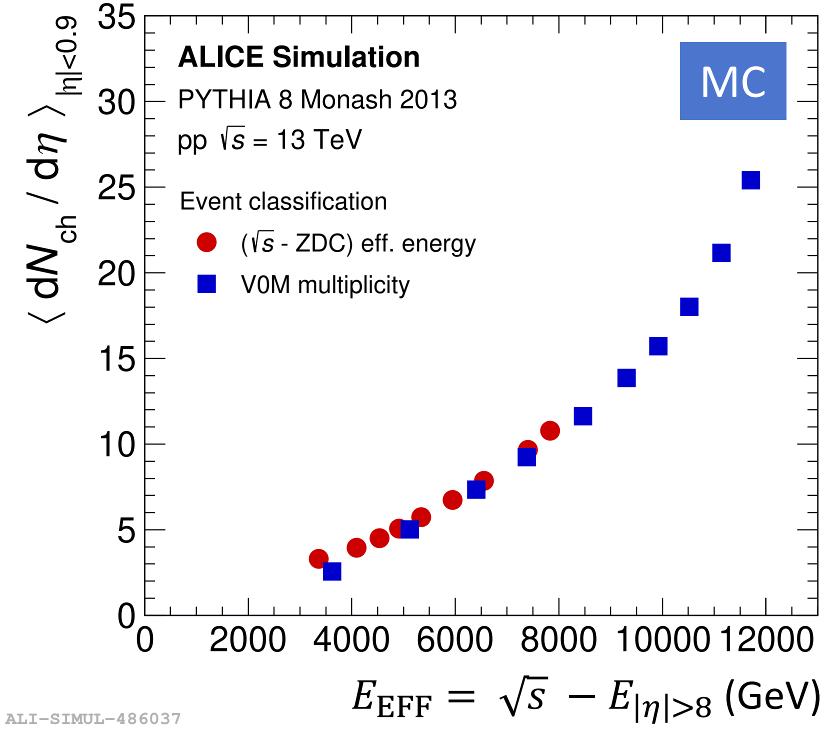


$ZN/\langle ZN\rangle$:
self-normalised energy measured in the neutron calorimeters of the ZDC

Effective energy and multiplicity are correlated

- The **effective energy** is correlated with the **multiplicity** of charged particles produced at midrapidity
- The correlation is observed in the data and is qualitatively predicted by Monte Carlo simulations
- V0M and ZDC based event classes are sensitive to both **multiplicity** and **effective energy**





ZN/⟨ZN⟩:
self-normalised energy measured in the neutron calorimeters of the ZDC

● $(\sqrt{s} - \text{ZDC})$ effective energy:
Energy percentile classes based on energy deposited in ZDCs

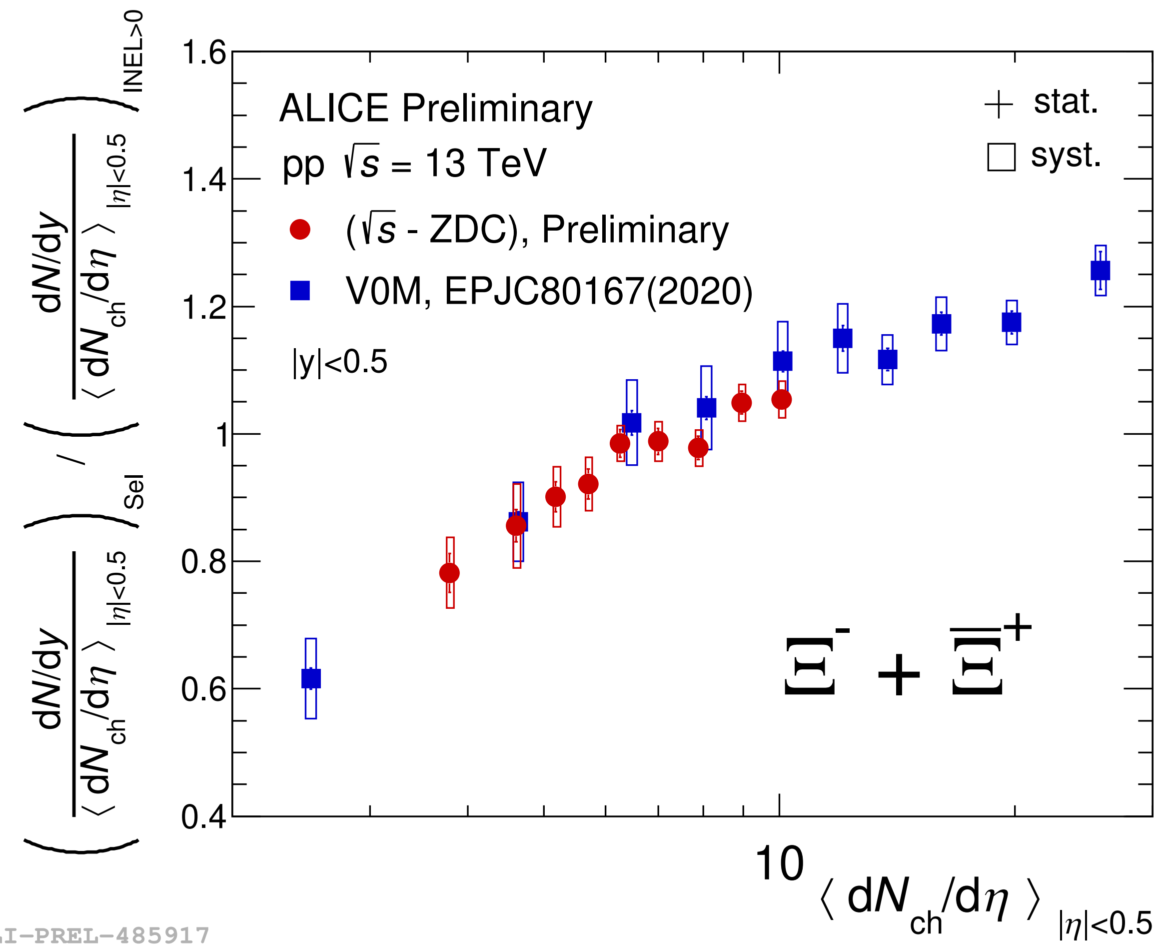
■ V0M multiplicity classes:
Multiplicity percentile classes based on V0 amplitude

Strangeness production in multiplicity and effective energy classes

The $\Xi^{\pm}$ yield normalised to the charged particle multiplicity is studied in V0M and ZDC based classes

- The increase with the multiplicity is the well known **strangeness enhancement** effect
- The analysis in V0M classes gives compatible results to the analysis in ZDC classes

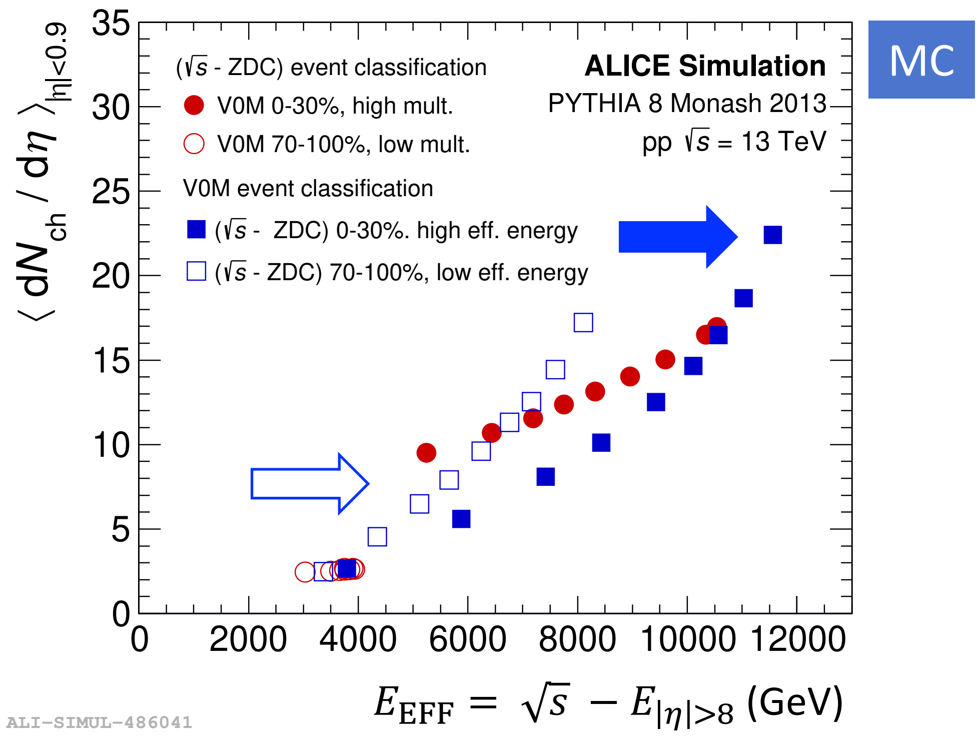
A multi-differential analysis in combined V0M and ZDC classes is needed in order to disentangle initial state and final state effects



Disentangle initial and final state effects

$\Xi^{\pm}$ yield normalised to the charged particle multiplicity in multiplicity classes, fixing the effective energy to:

- ■ High effective energy ($\sqrt{s} - \mathrm{ZDC}$) 0-30%
- □ Low effective energy ($\sqrt{s} - \mathrm{ZDC}$) 70-100%



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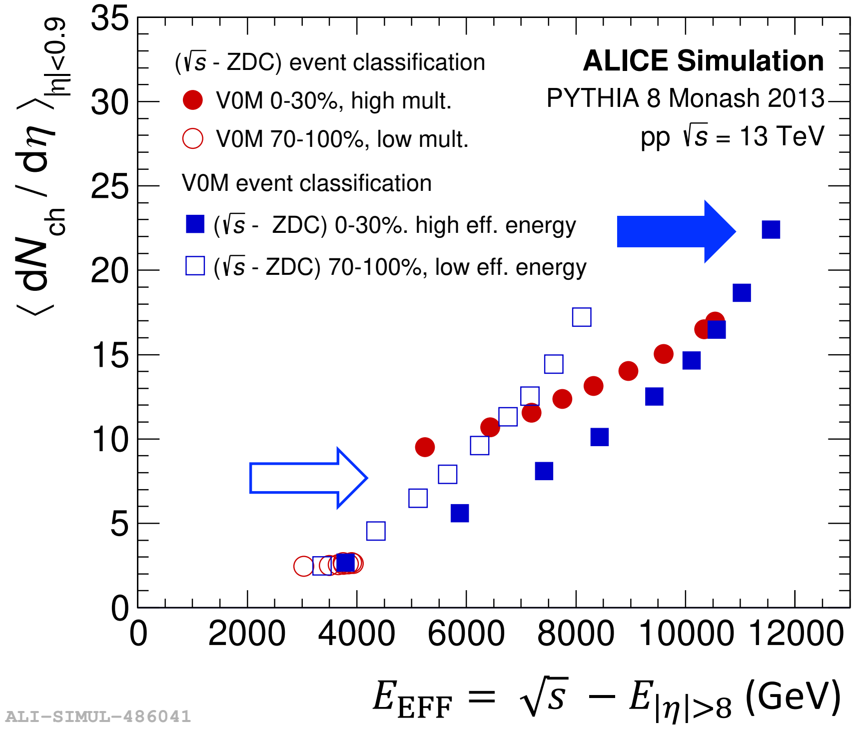
Strangeness enhancement with multiplicity does not depend on the effective energy selection

MC



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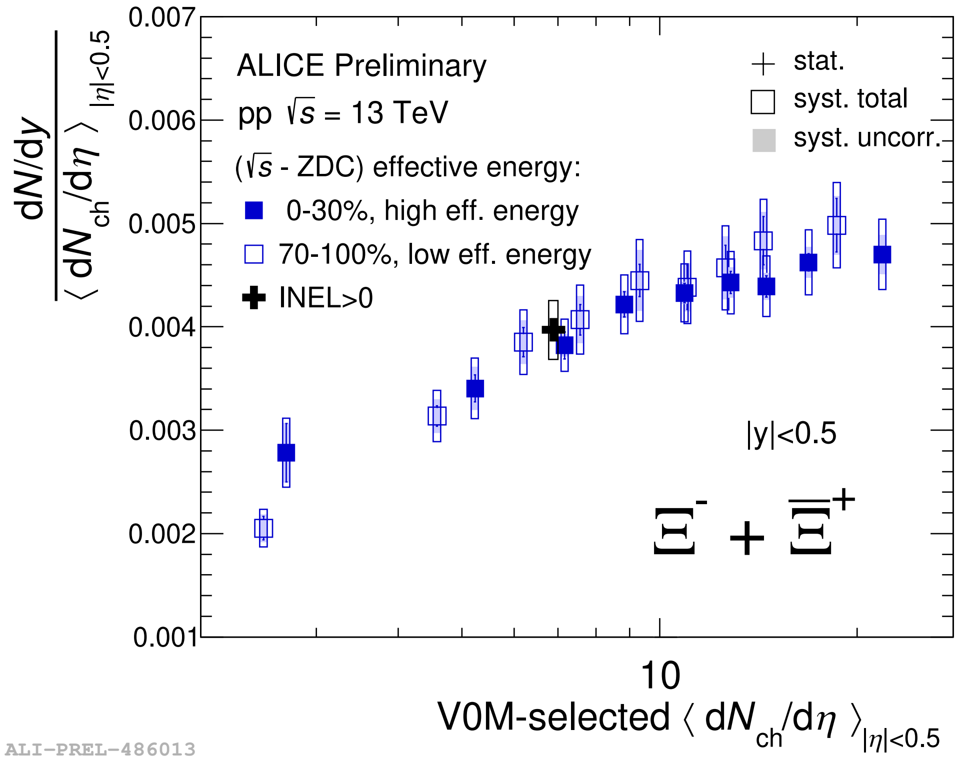

Disentangle initial and final state effects

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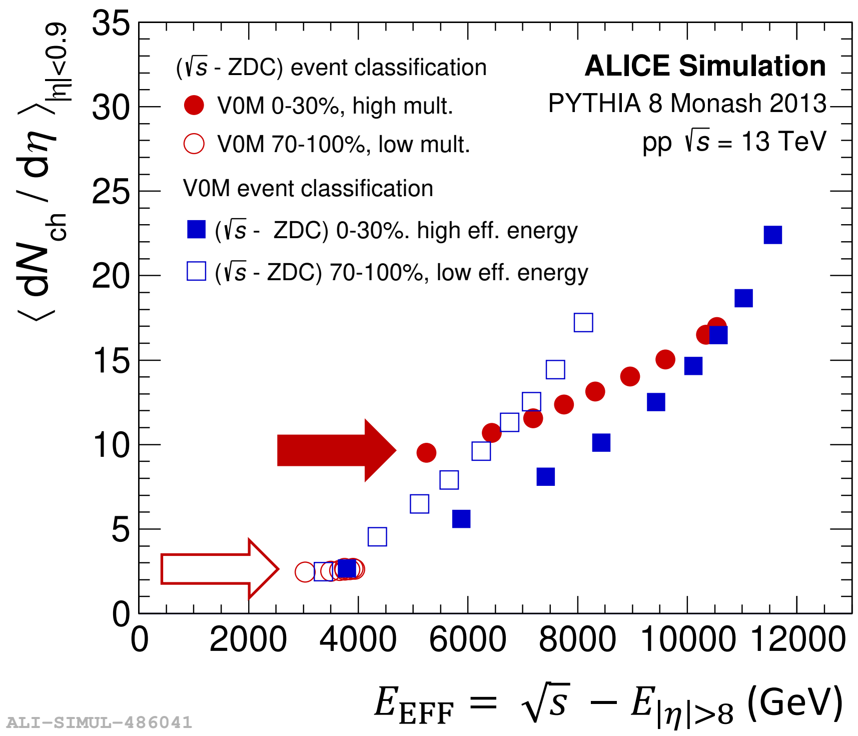

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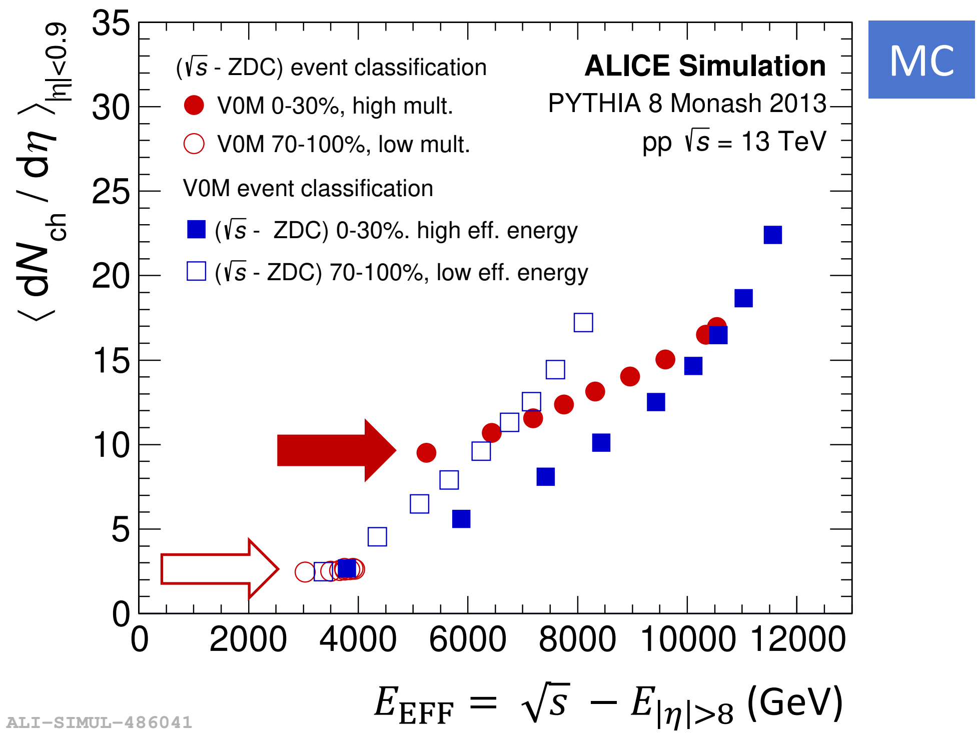

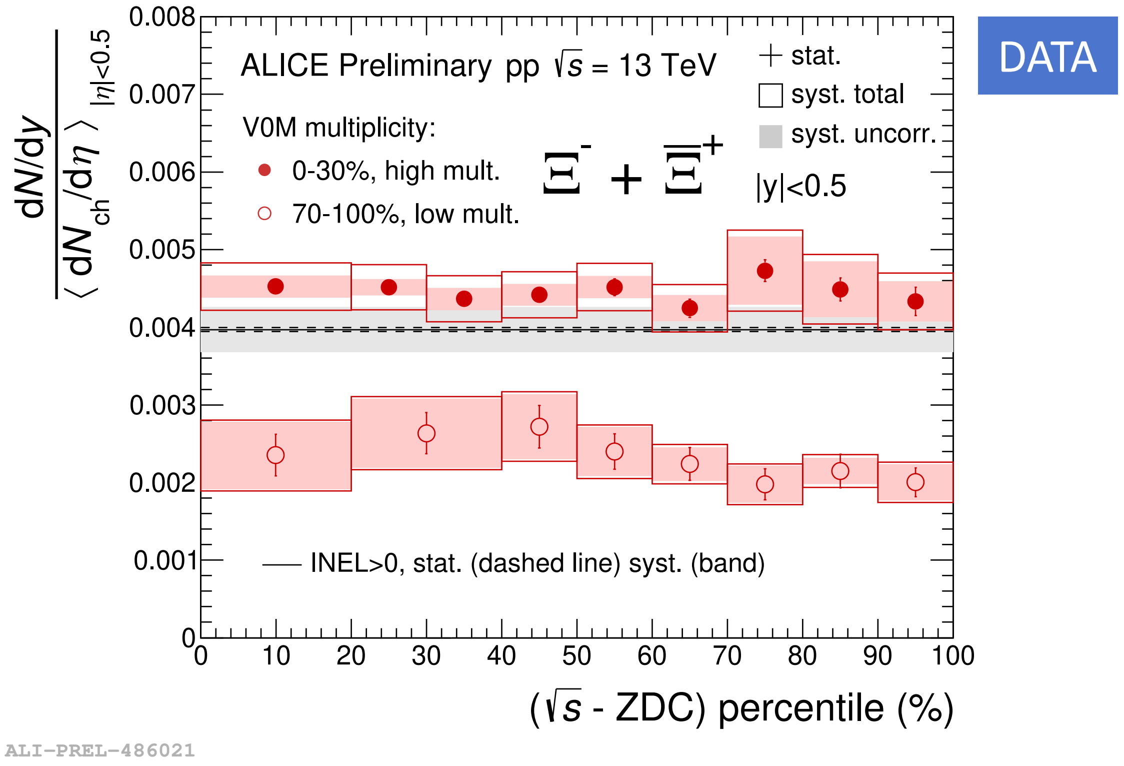

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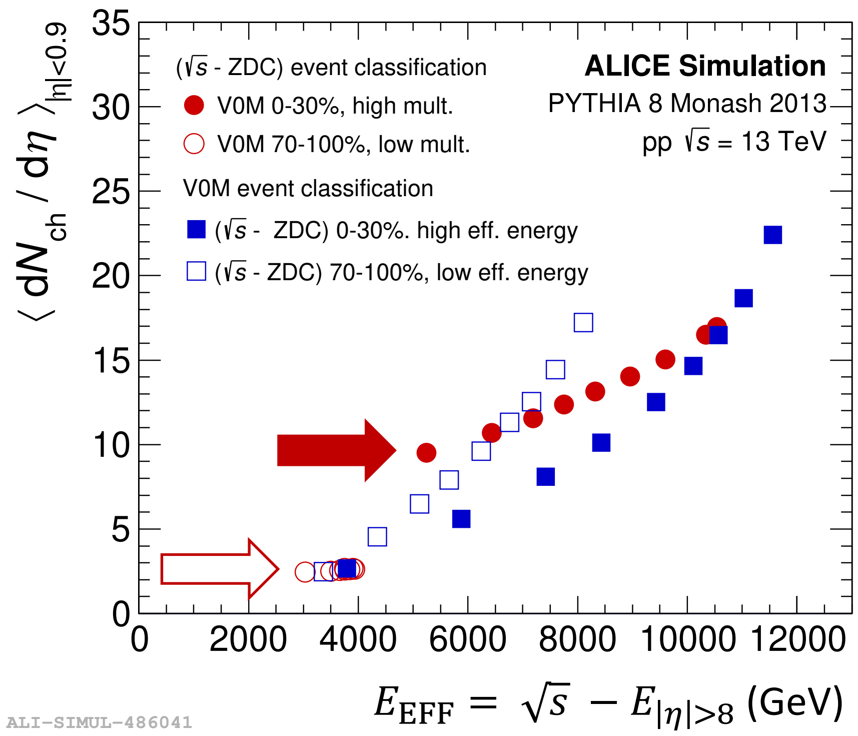
→ Strangeness enhancement is mainly driven by the final-state multiplicity

MC



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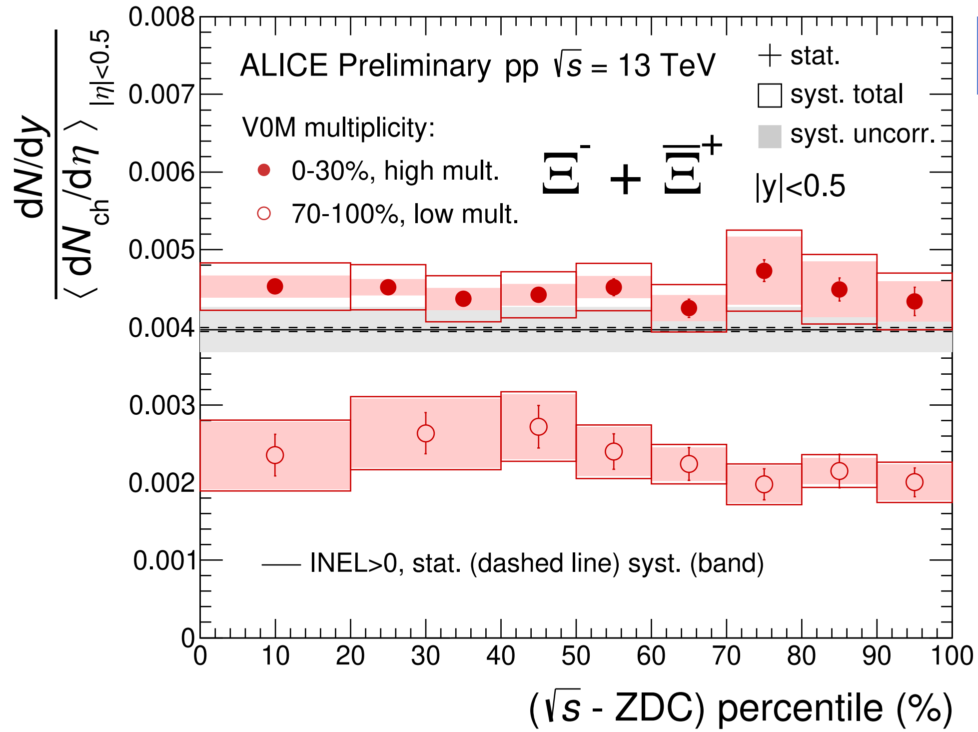

Angular correlations for in-jet and out-of-jet studies of strange hadron production

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 $p_{\mathrm{T}} > 3$ GeV/c

2. Identification of strange hadrons (associated particles)

3. Angular correlation between trigger and associated particles is calculated

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

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

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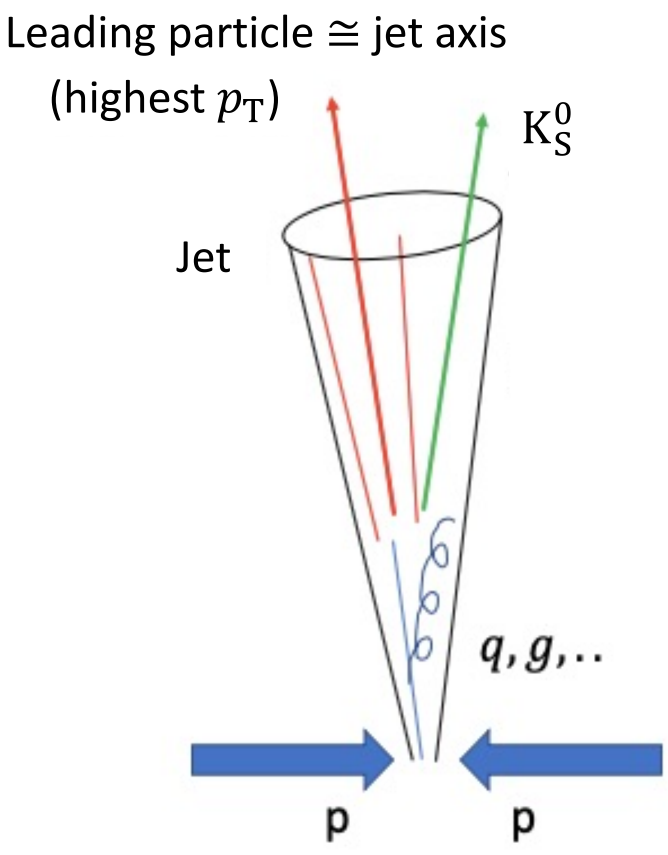

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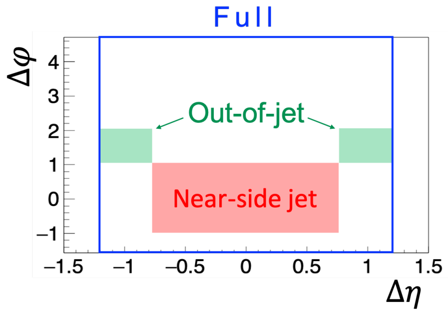
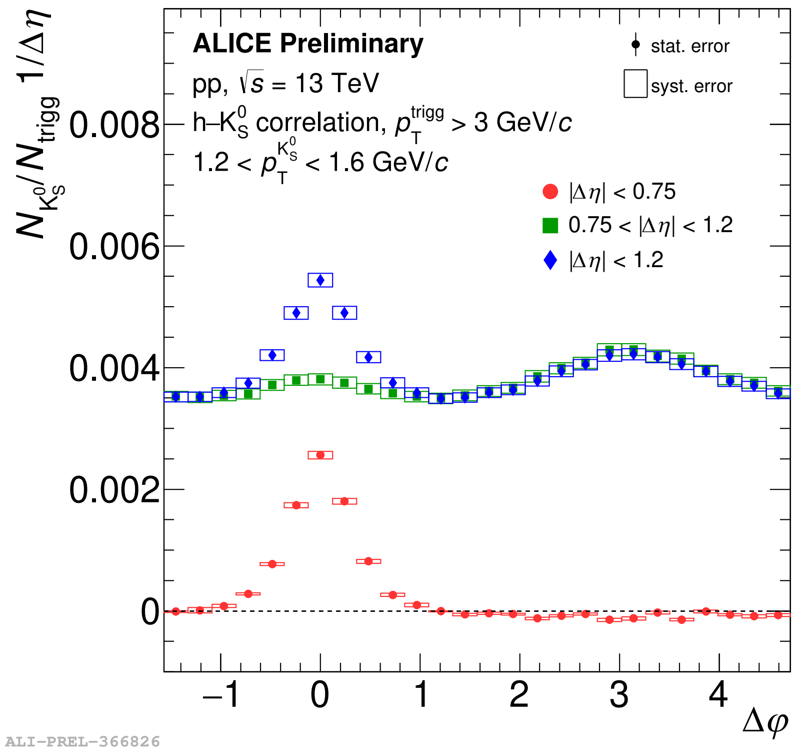
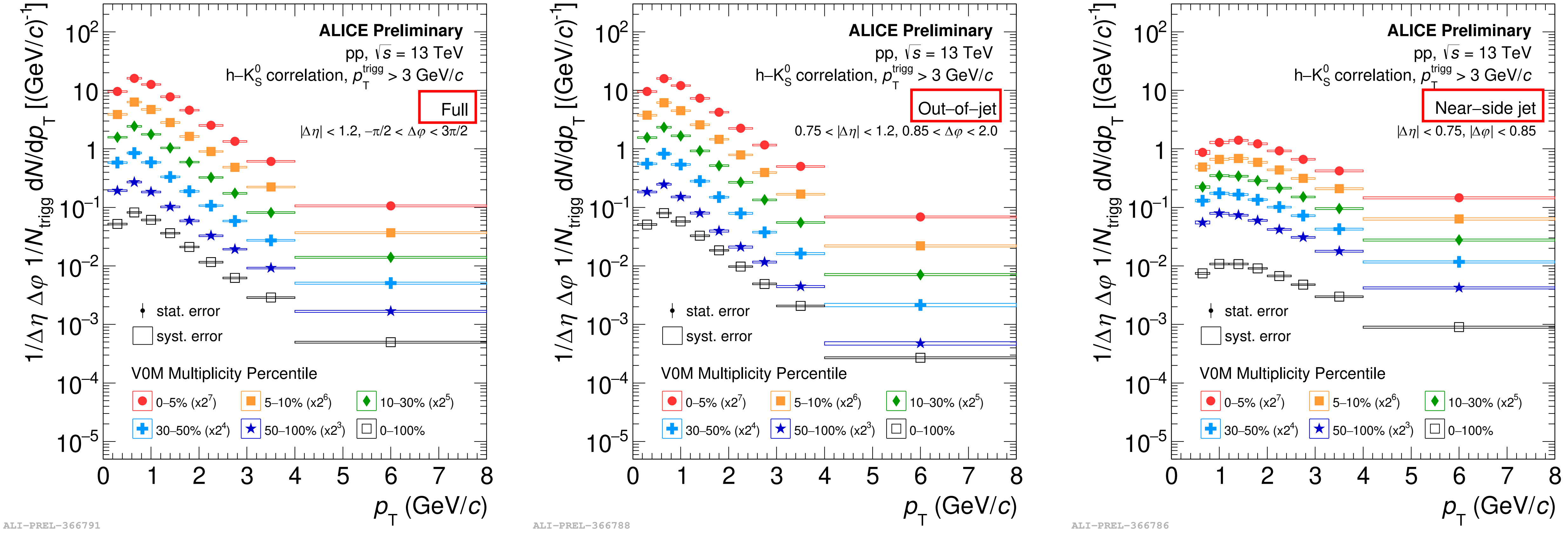




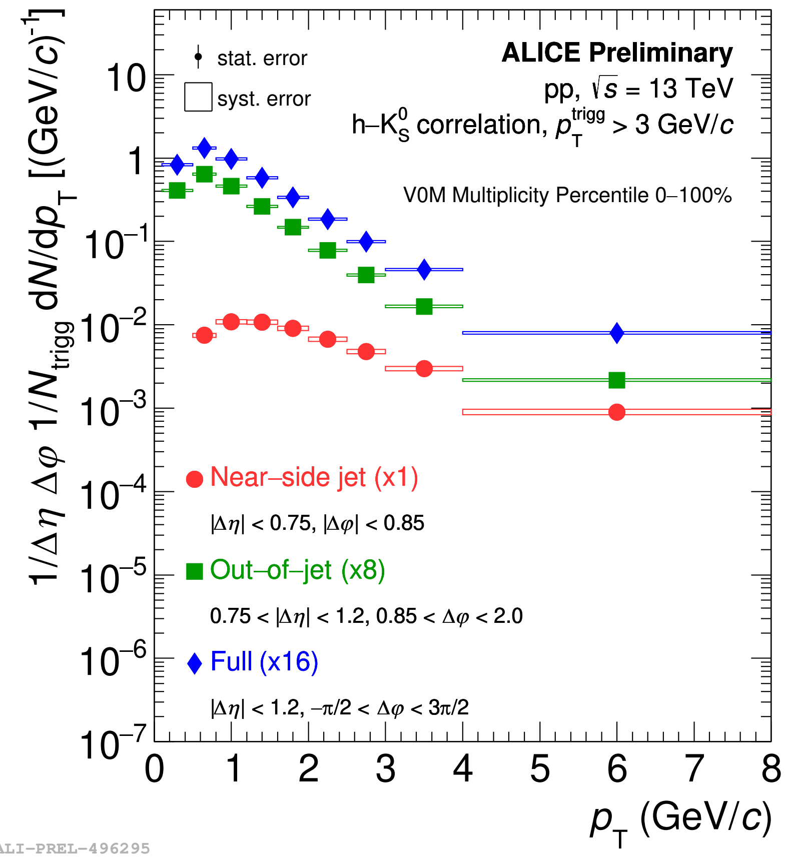
Near-side jet, out-of-jet and full p_T spectra of K^0_S



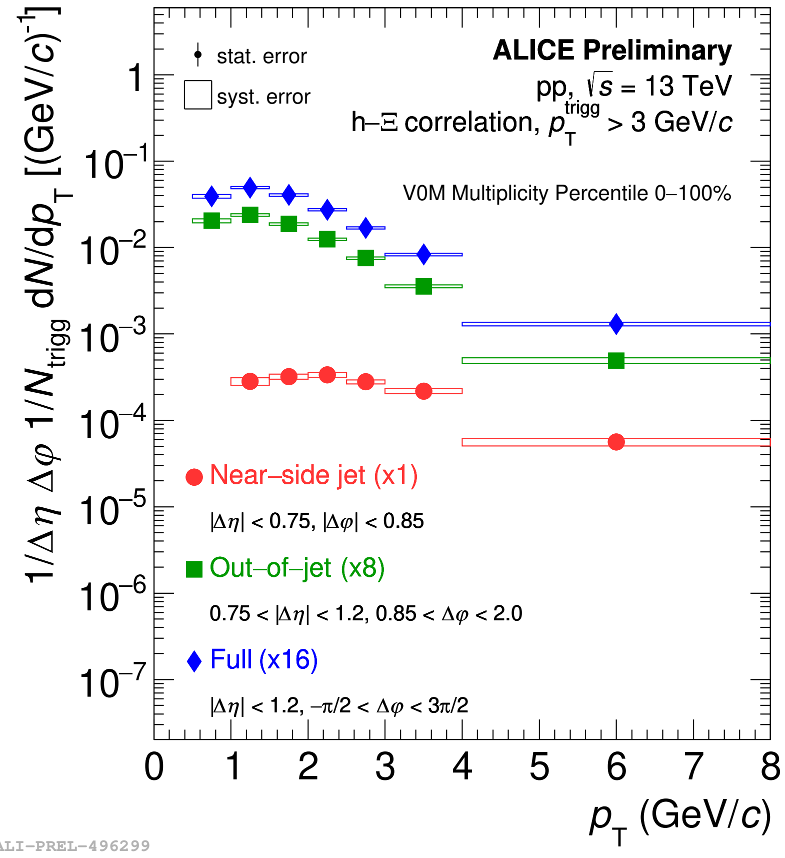
Spectra of K^0_S produced in jets are harder than spectra of K^0_S produced out of jets

Near-side jet, out-of-jet and full p_T spectra of K^0_S and $\Xi^{\pm}$

K^0_S

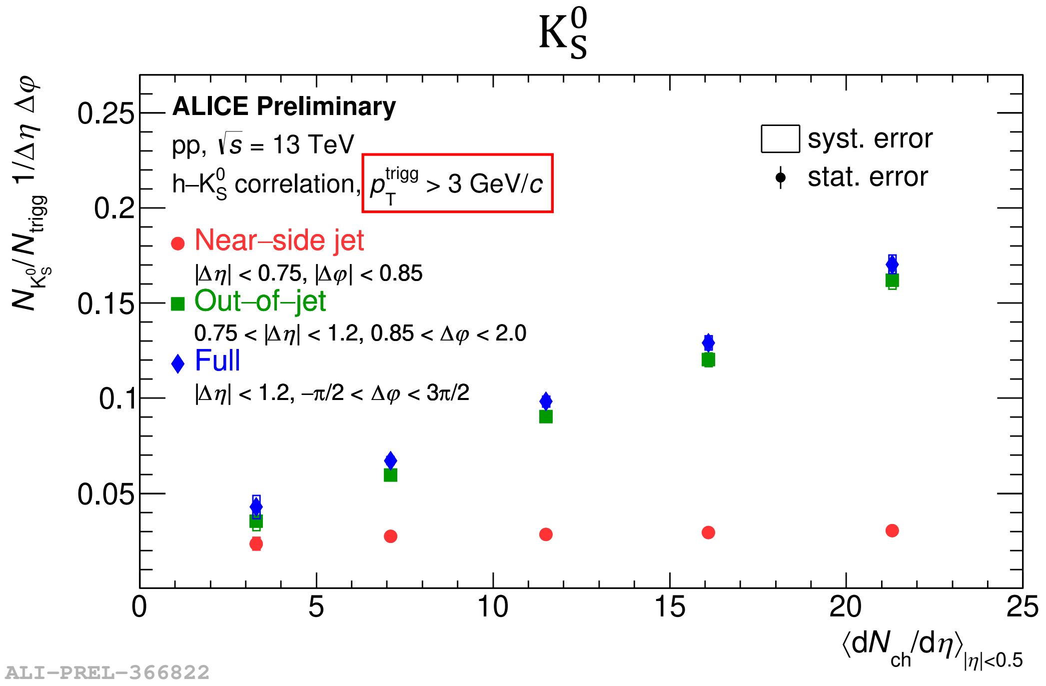


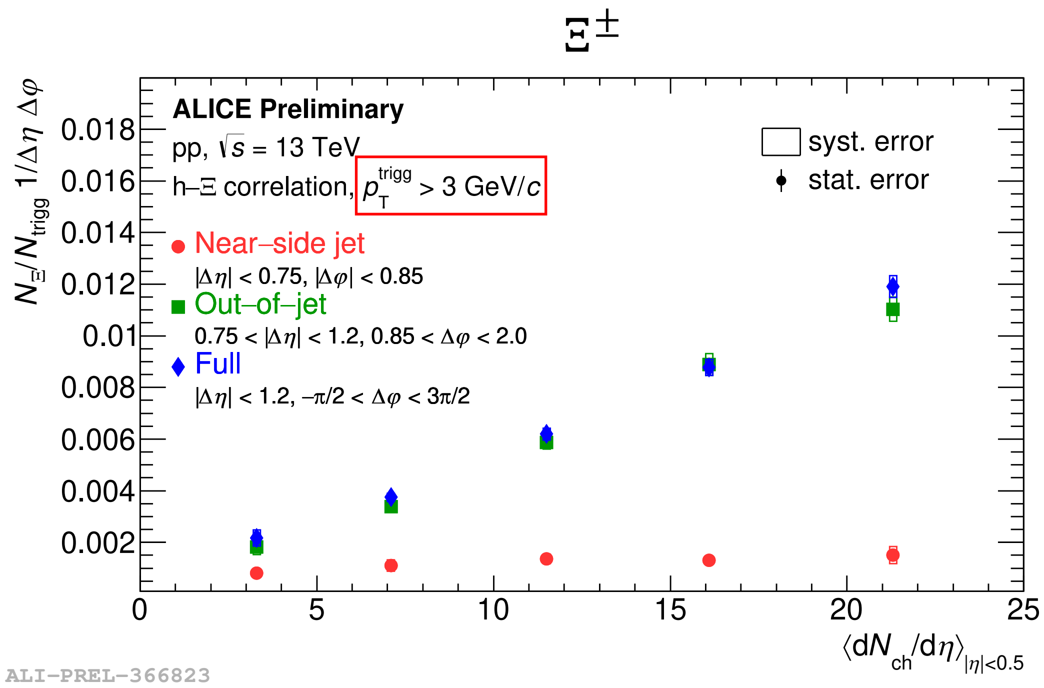
$\Xi^{\pm}$



Spectra of K^0_S ($\Xi^{\pm}$) produced in jets are harder than spectra of K^0_S ($\Xi^{\pm}$) produced out of jets

Near-side jet, out-of-jet and full yields of strange hadrons vs multiplicity

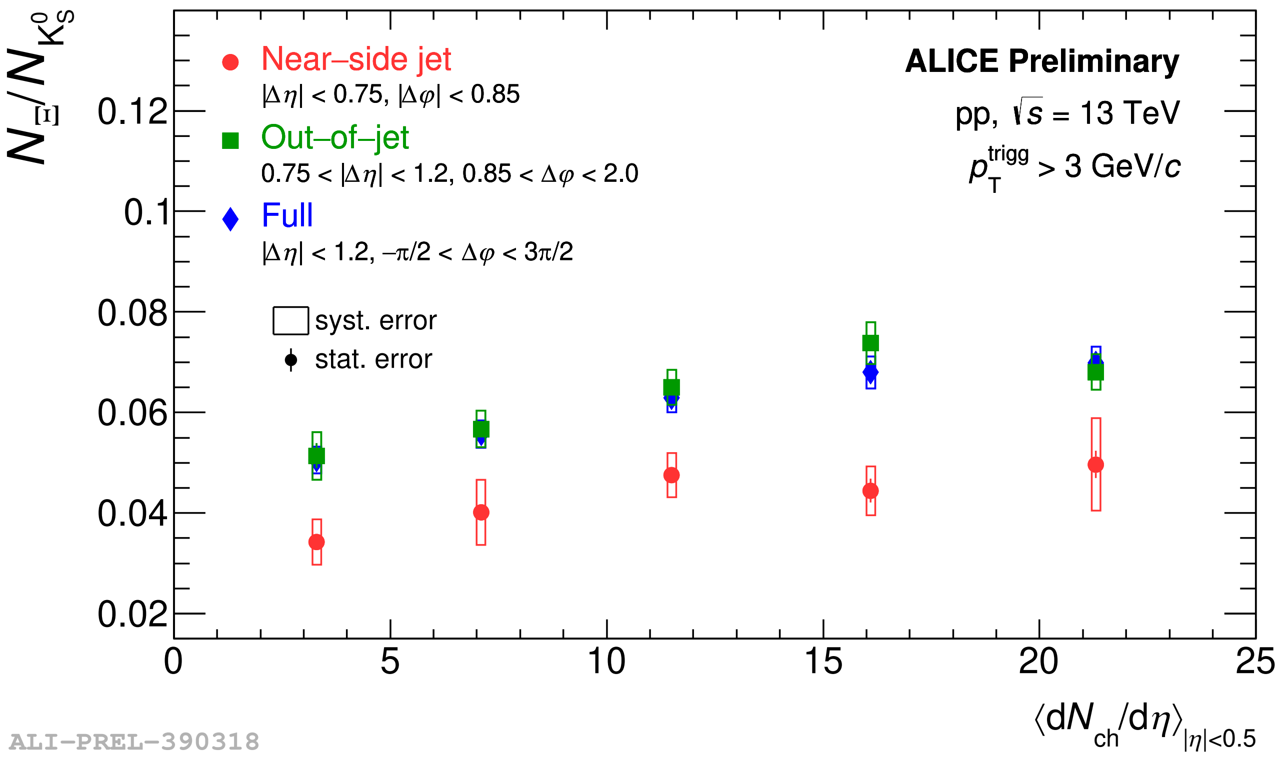




- Both the full yield and the out-of-jet yield increase with the multiplicity
- Very mild to no evolution with multiplicity of the near-side-jet yield

→ The contribution of out-of-jet production relative to near-side jet 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 out-of-jet Ξ/K^0_S yield ratio increases with the multiplicity
- Firm conclusions on the multiplicity dependence of the near-side jet Ξ/K^0_S yield ratio cannot be drawn due to large uncertainties

→ Soft (out of jet) processes are the dominant contribution to the Ξ/K^0_S full yield ratio

Summary

Do initial state effects play a role in the strangeness enhancement observed in pp collisions?

- The increase with multiplicity of the $\Xi^{\pm}$ yield normalised to the charged particle multiplicity does not depend on the effective energy selection

→ No significant role of effective energy in strangeness enhancement

→ Strangeness enhancement is mainly driven by final state particle multiplicity

Is strange hadron production dominated by soft interactions or by hard processes?

- The $\Xi/\mathrm{K}^0_\mathrm{S}$ ratio measured out of jets increases with multiplicity
- The out-of-jet $\Xi/\mathrm{K}^0_\mathrm{S}$ ratio represents the dominant contribution to the full yield ratio

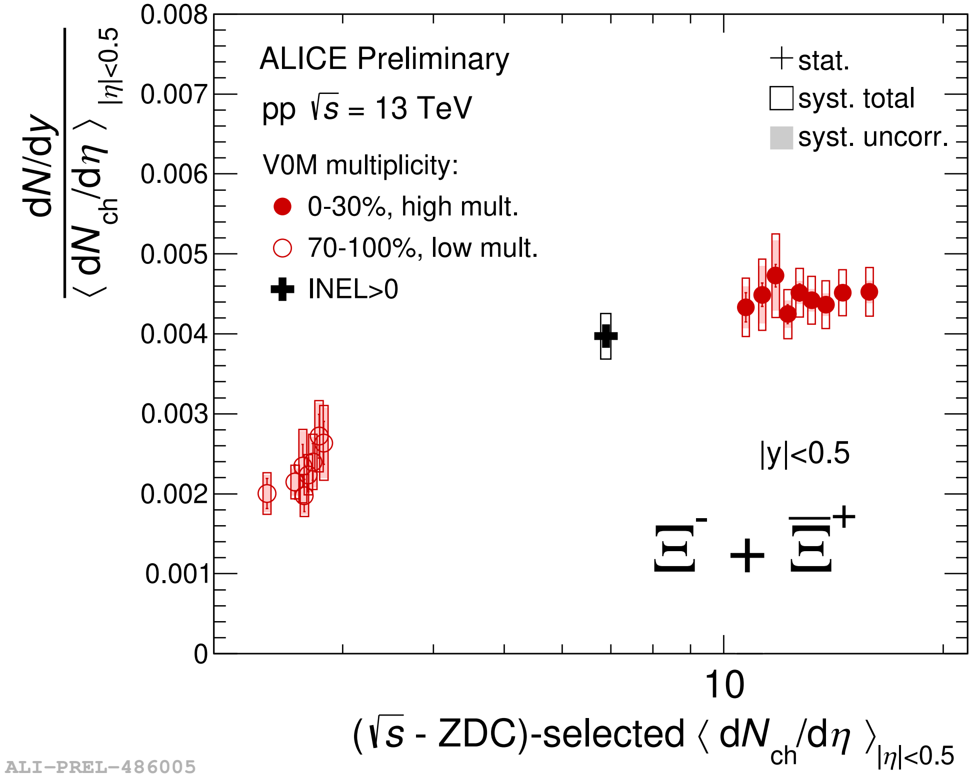
→ Soft (out of jet) processes are the dominant contribution to strange particle production

Backup

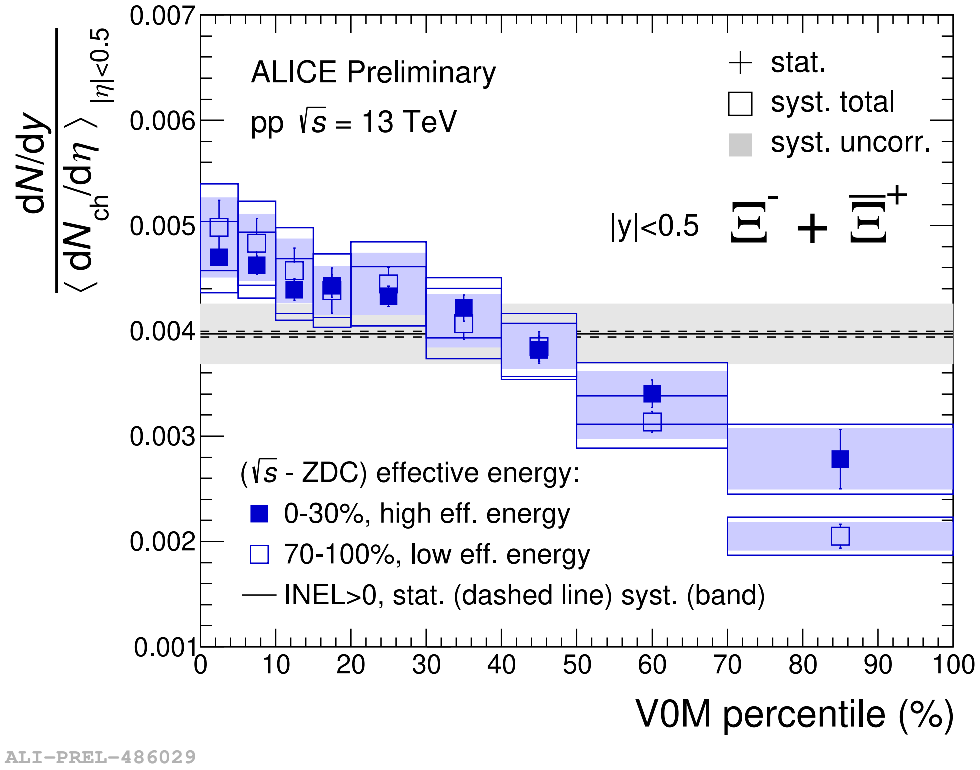
Disentangle initial and final state effects

$\Xi^{\pm}$ yield normalised to the charged particle multiplicity

In effective energy classes, fixing the multiplicity:



In multiplicity classes, fixing the effective energy:



Correlations of high-p_T charged hadrons with strange particles

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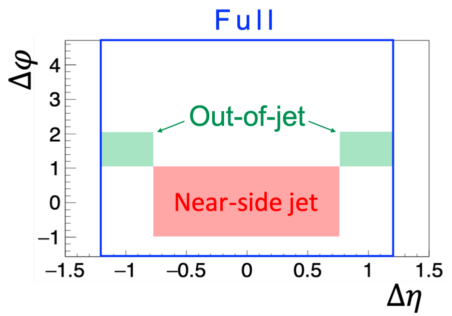
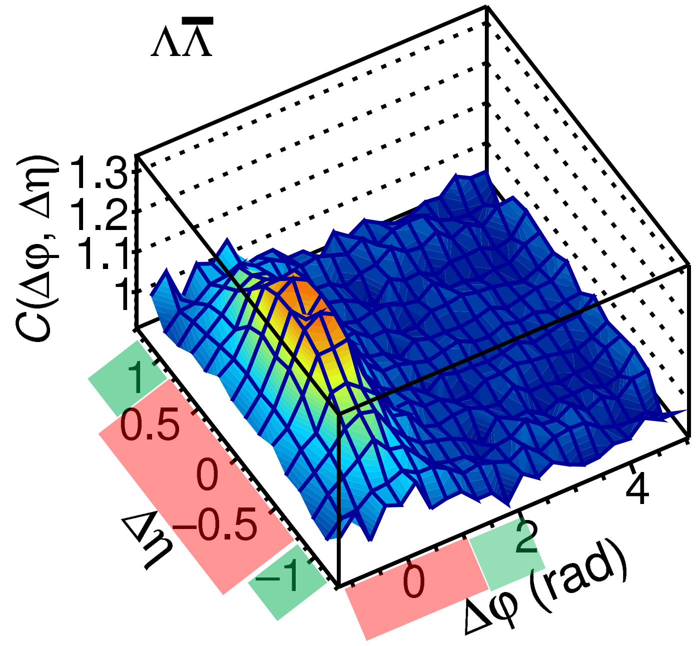
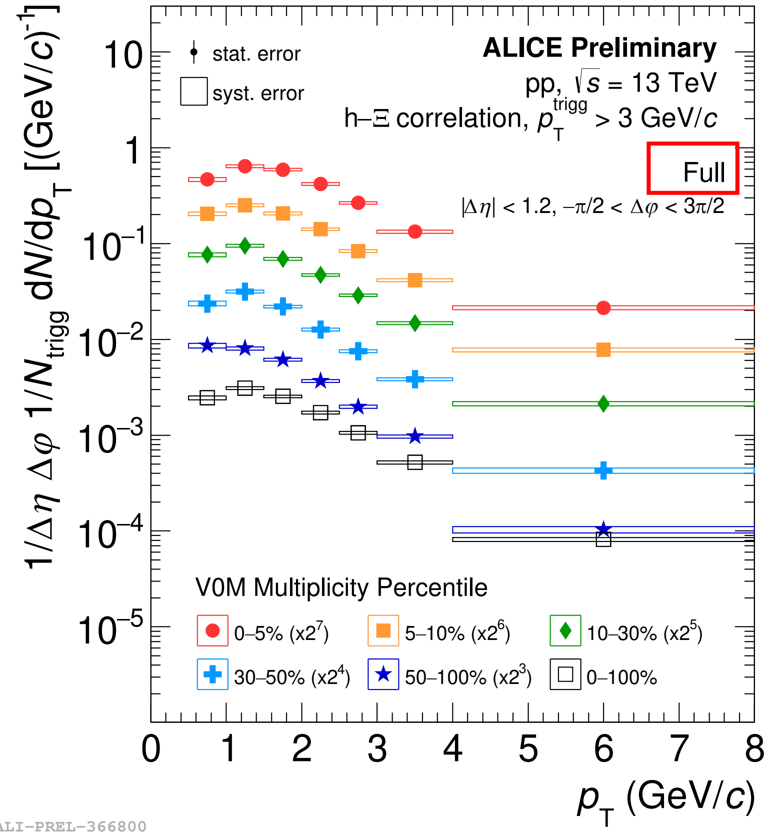
Example of angular correlation distribution

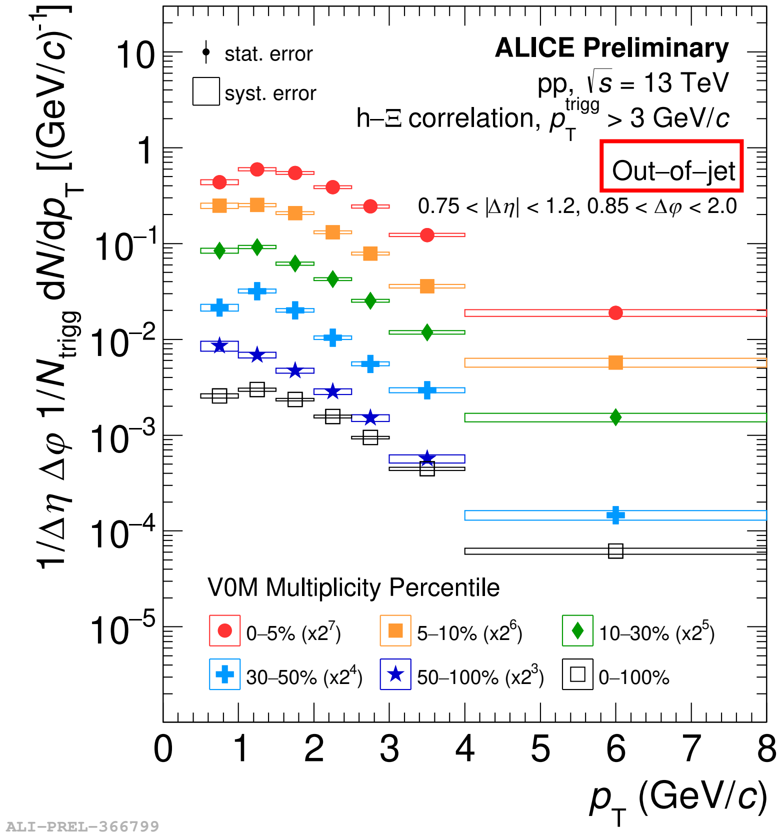


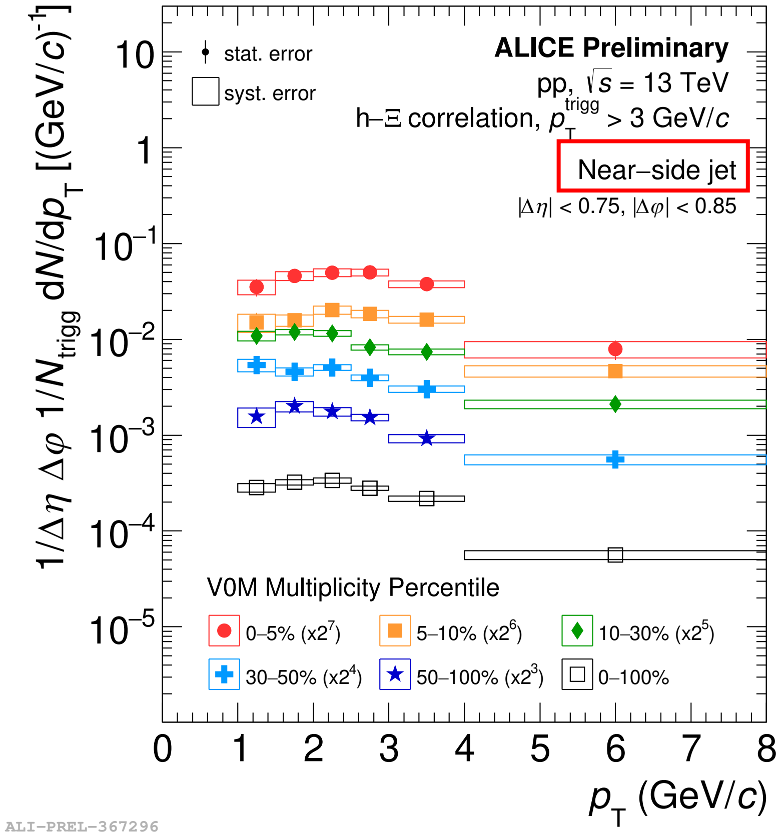


ALICE Preliminary, High-Mult. (0-0.072% INEL) pp $\sqrt{s}$ = 13 TeV

Near-side jet, out-of-jet and full p_T spectra of $\Xi^{\pm}$

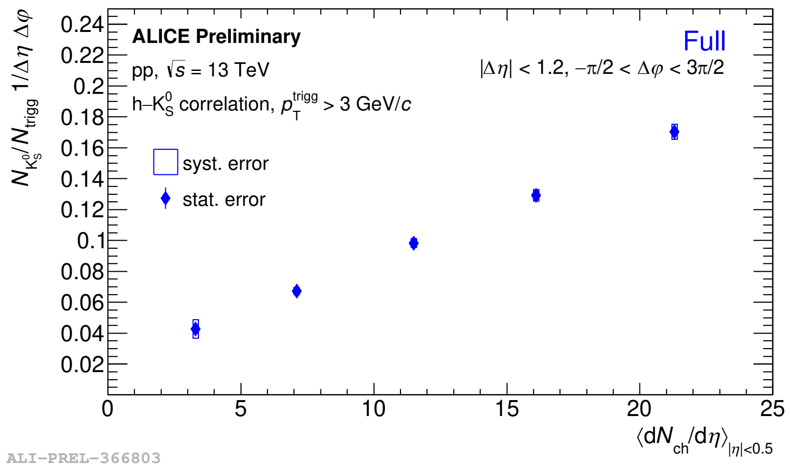


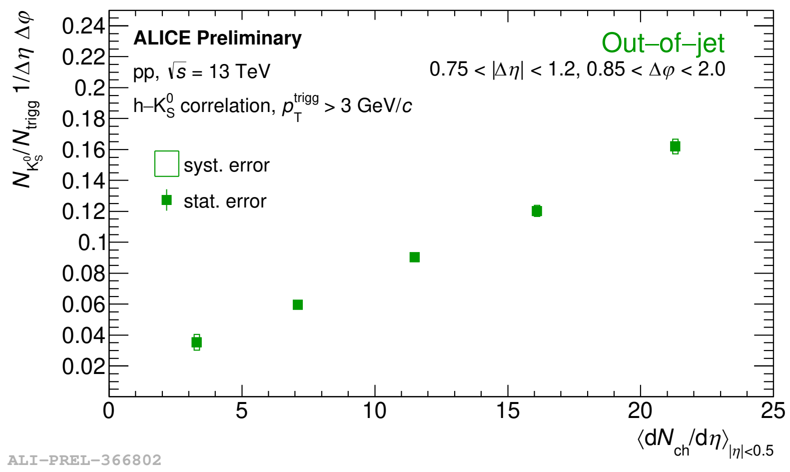


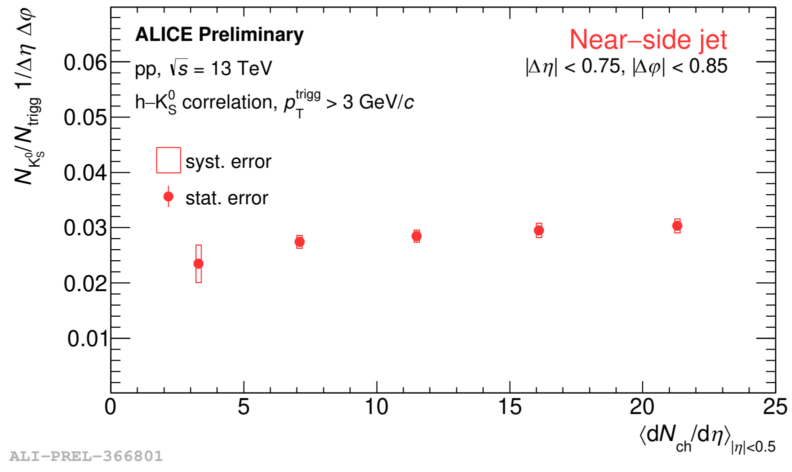


Spectra of $\Xi^{\pm}$ produced in jets are harder than spectra of $\Xi^{\pm}$ produced out of jets

Near-side jet, out-of-jet and full yields of K^0_S vs multiplicity







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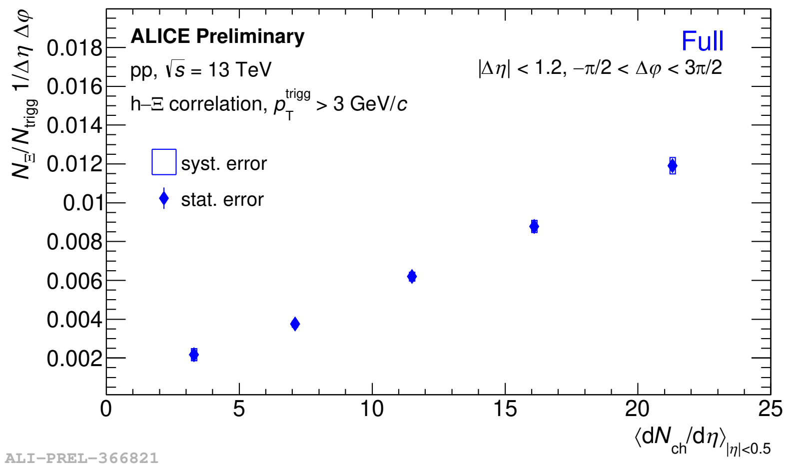
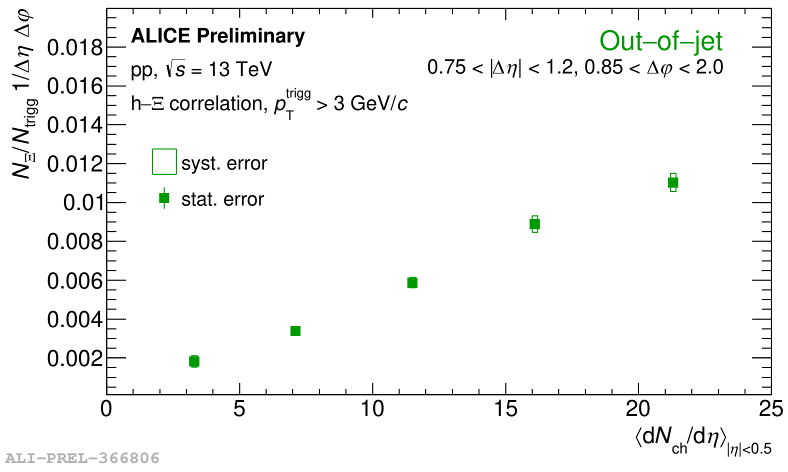
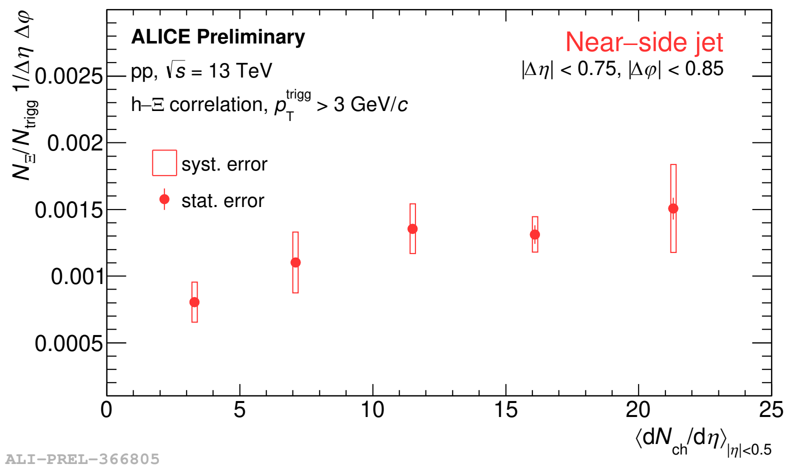
Near-side jet, out-of-jet and full yields of Ξ vs multiplicity







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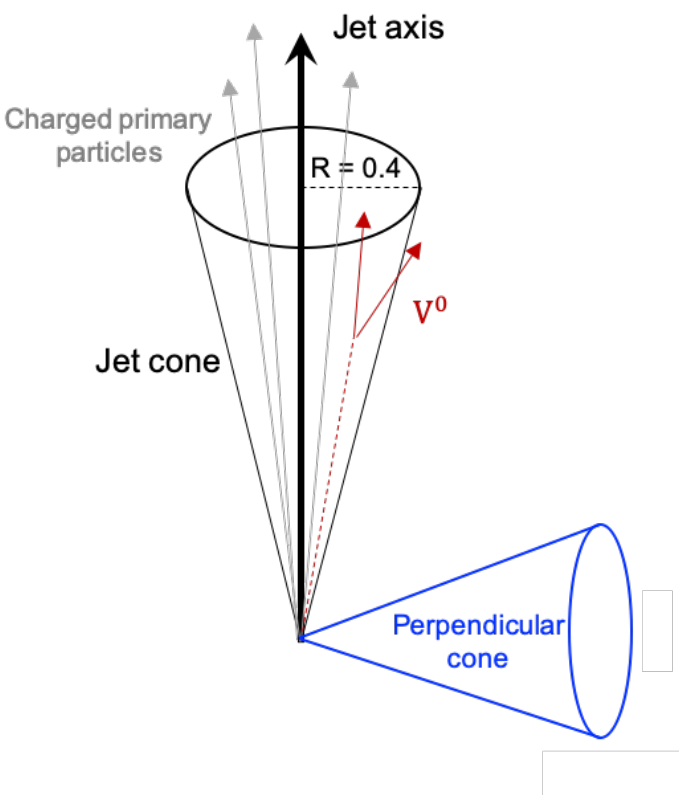
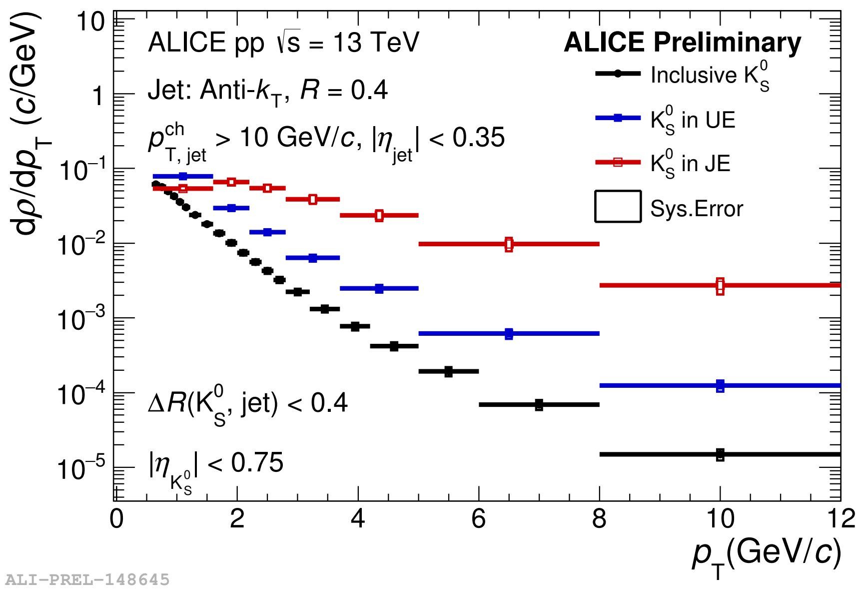
Strange particle production in and out of jets using jet finder algorithm

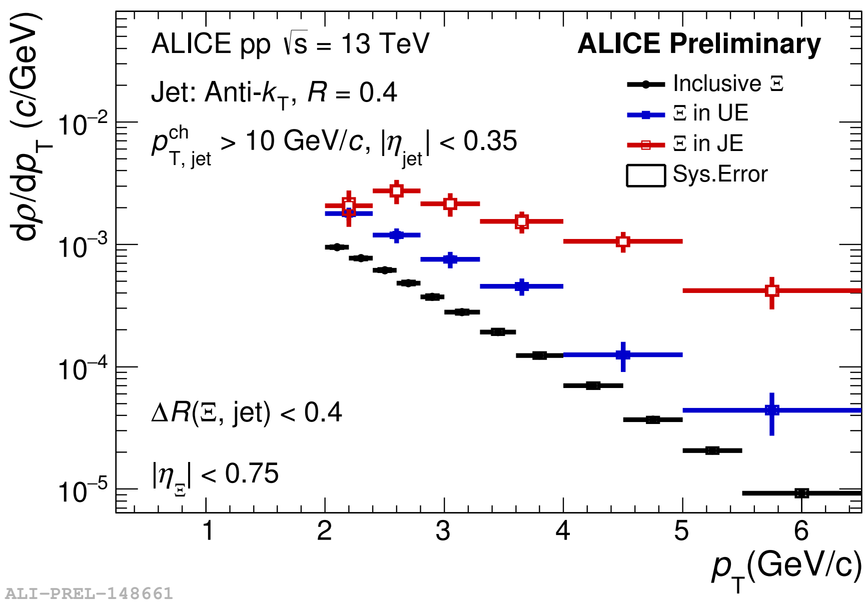
Jet finder algorithm: anti-k_T



K^0_S



Ξ

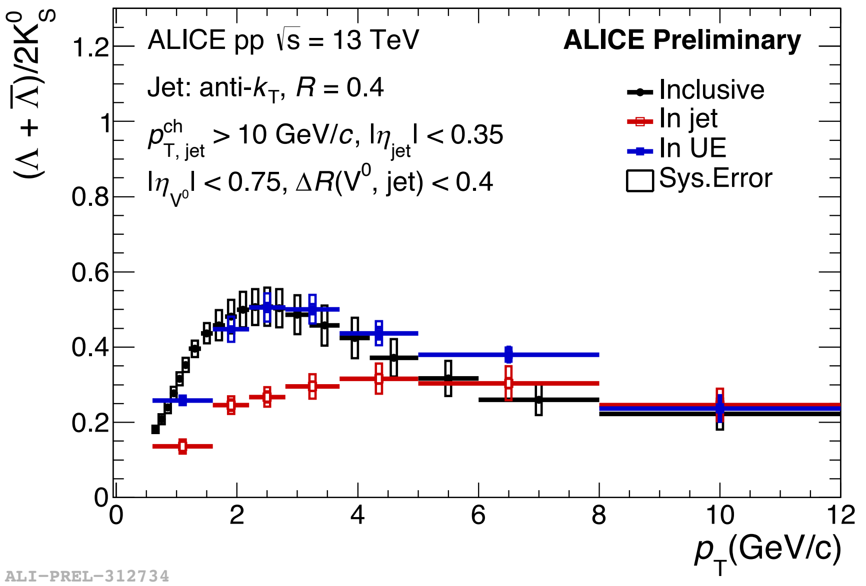


- Jet cone (JC) : R(strange hadron, jet) < 0.4
- Underlying Event (UE):
  strange hadrons in perpendicular cone
- In jet production (JE) = JC - UE

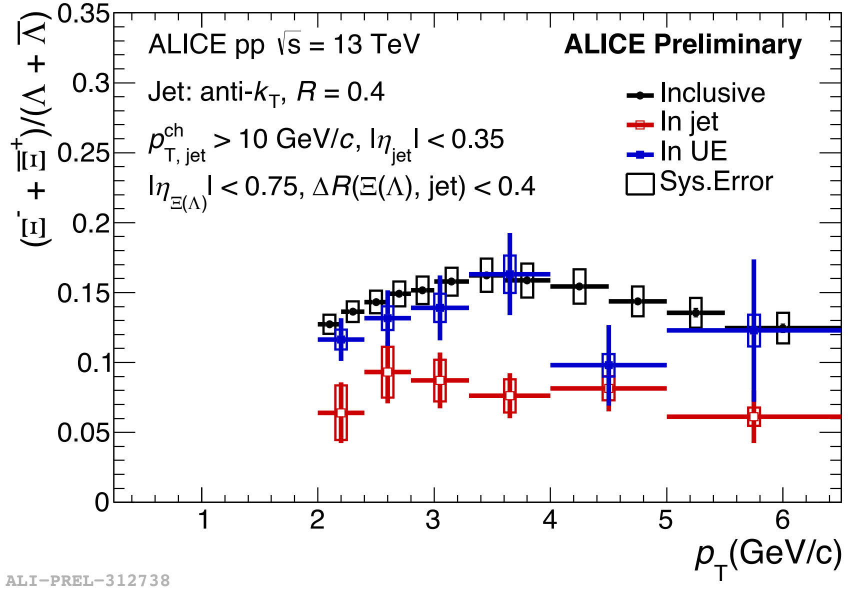
- The spectra of K^0_S and Ξ in jets are harder than in the UE
- The same is observed for Λ and $\overline{\Lambda}$

Λ/K^0_S and Ξ/Λ ratios in and out of jets

Λ/K^0_S



Ξ/Λ



Λ/K^0_S (baryon/meson) $|S|$=1

- The inclusive and UE ratios show a peak at $p_T \sim 3$ GeV/c
  - The effect is much suppressed within the jets

Ξ/Λ (baryons with different strangeness content: $|S|$=2/$|S|$=1)

- The UE ratio is consistent with the inclusive, the ratio in jets is rather flat with p_T