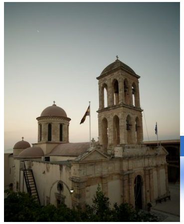


Recent results on strangeness enhancement in small collision systems with ALICE

Sara Pucillo[1,2] on behalf of the ALICE Collaboration

ICNFP 2024 - Kolymbari

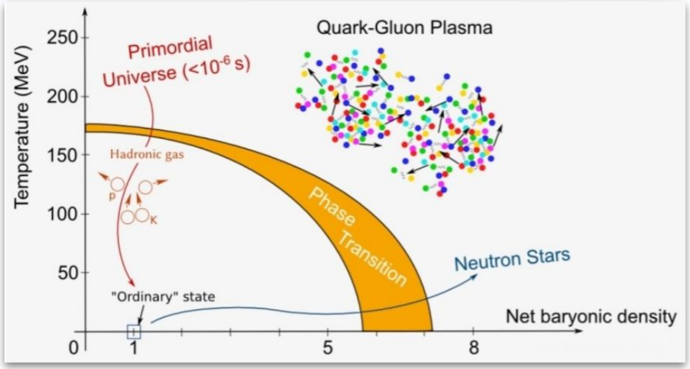
1. Università degli Studi di Torino

2. INFN Torino

QCD: theory that describes strong interactions among quarks and gluons → confinement.

T ~ 160 MeV [1], ε~ 1 GeV/fm^3: phase transition: quark–gluon plasma (**QGP**) → state of matter where **quarks and gluons are deconfined.**

Experimentally → ultrarelativistic heavy-ion collisions: **ALICE** (A Large Ion Collider Experiment).



[1] *C.Gale, S.Jeon, B.Schenke, arxiv.org/1301.5893*

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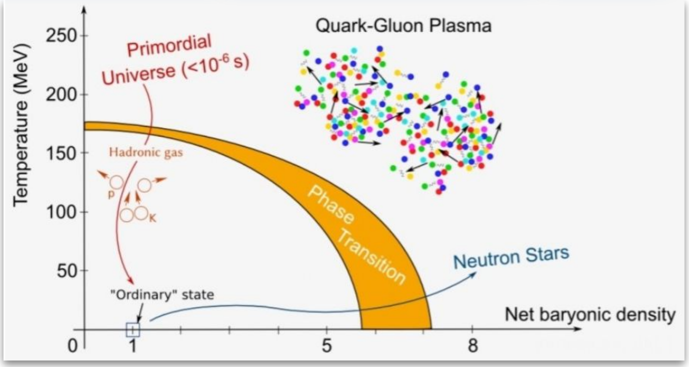

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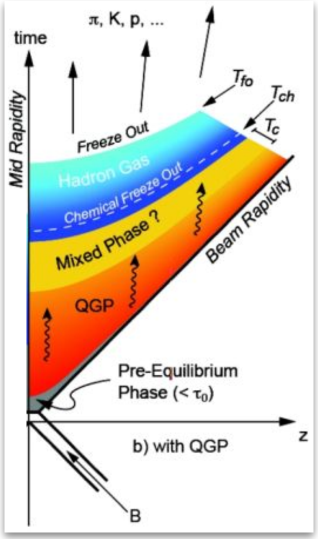

- "Fireball" in local thermal equilibrium that expands hydrodynamically: partonic degrees of freedom
- chemical freeze-out: hadrons are formed
- kinetical freeze-out: all particles cease to interact

Short lifetime ($\tau \sim 10^{-23}$ s) of the QGP: **no direct detection** → characterization from the determination of the properties and modifications of final-state observables.

Historical QGP signatures include **strangeness enhancement** (topic of this talk).

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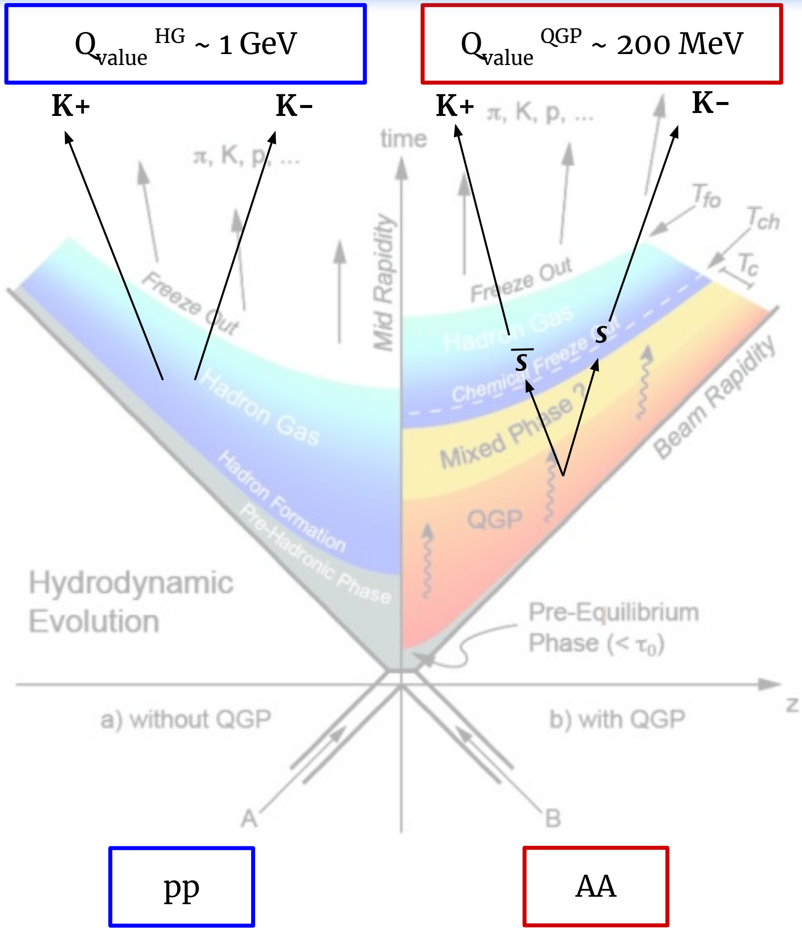
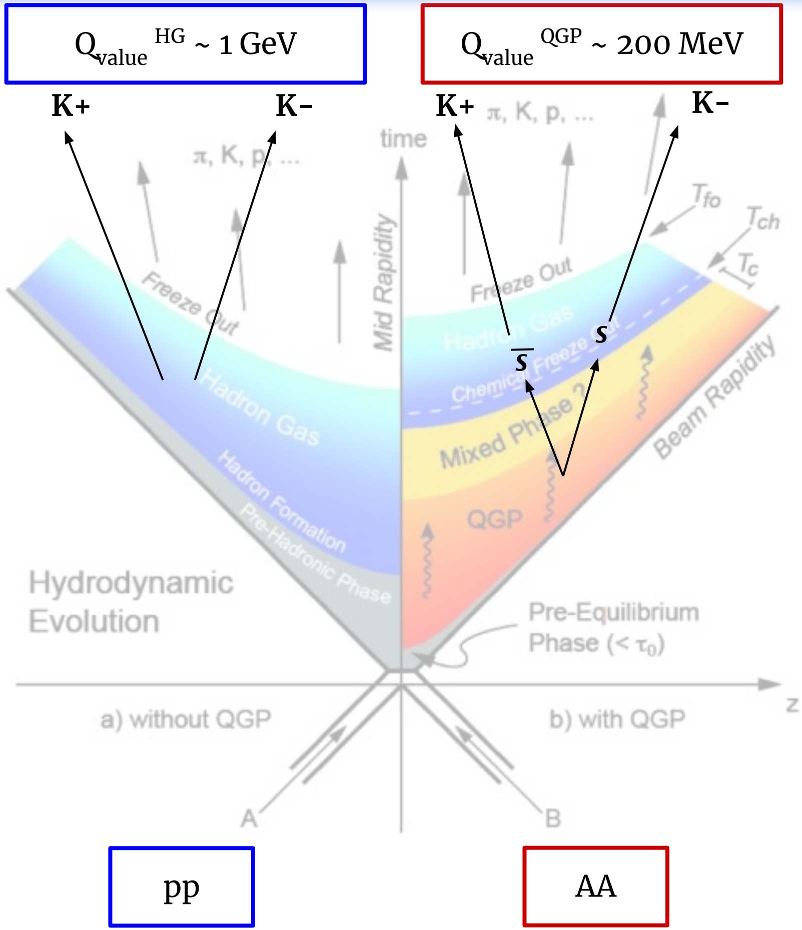


Proposed signature for QGP formation: relative abundance of particles containing strange quarks is expected to be higher in AA collisions than in pp interactions.
([Rafelski J., Phys.Rev.Lett. 48, 1066 (1982)])

Energy needed to produce pairs of strange particles (e.g. K^+K^-) in a partonic medium (degrees of freedom: quark and gluons → gluon fusion processes) < in a gas of hadrons (degrees of freedom: hadrons → direct production).



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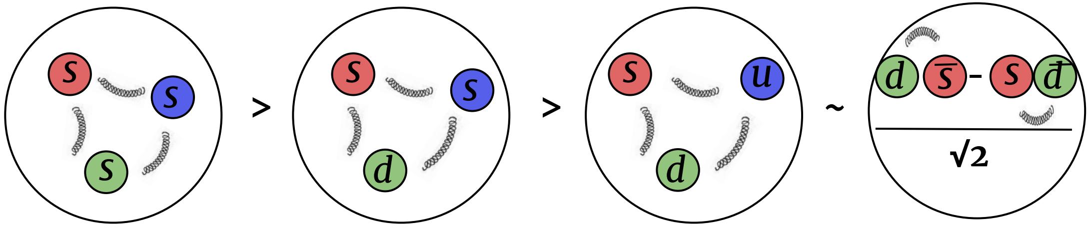
Recently, **statistical models** (e.g [arxiv.org/1610.03001]) have been effective in replicating strangeness production in heavy-ion collisions without the need to assume the formation of the QGP.

QGP ⟹ (foreseen) altered chemical composition

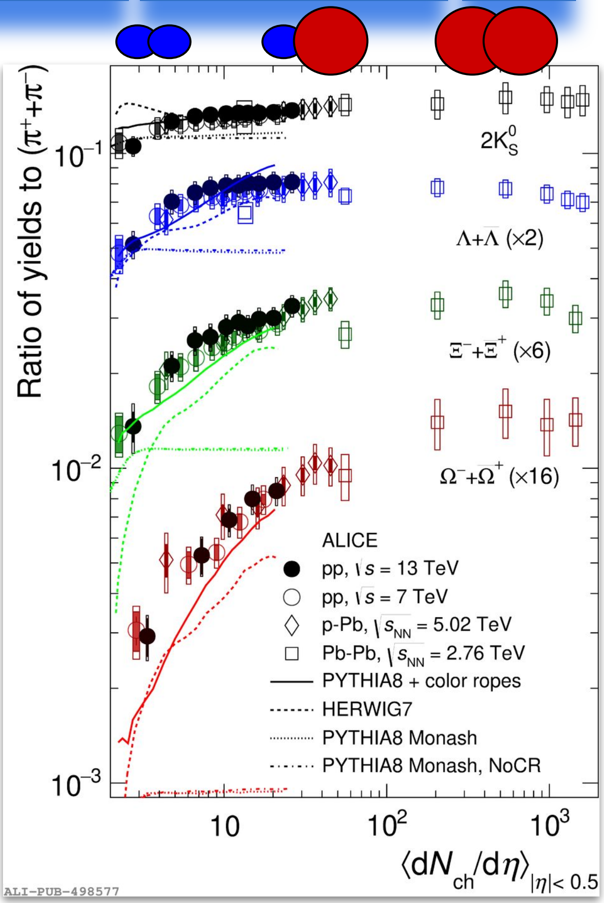
QGP ⟸̸ altered chemical composition

ALICE observed that the ratio of strange to non-strange hadron yields (h/π): [2,3]

- **increases with** midrapidity **multiplicity**
- **evolves independently on the** different **energies and collision systems** (the origin of this effect is unexpected and unclear in smaller systems)
- shows a **hierarchy with** the hadron **strangeness content**



Ω^- Ξ^- Λ K^0_S



ALICE Coll., Eur. Phys. J. C 80 (2020) 2, 167

[2] ALICE Coll., *Nature Physics 13 (2017) 535–539*
[3] ALICE Coll., *Eur. Phys. J. C 80 (2020) 2, 167*

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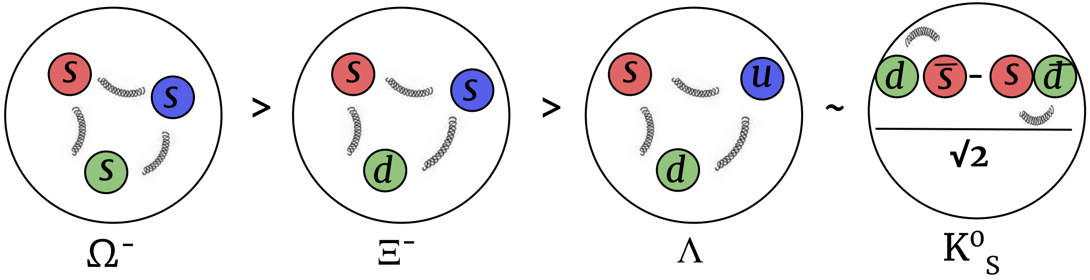
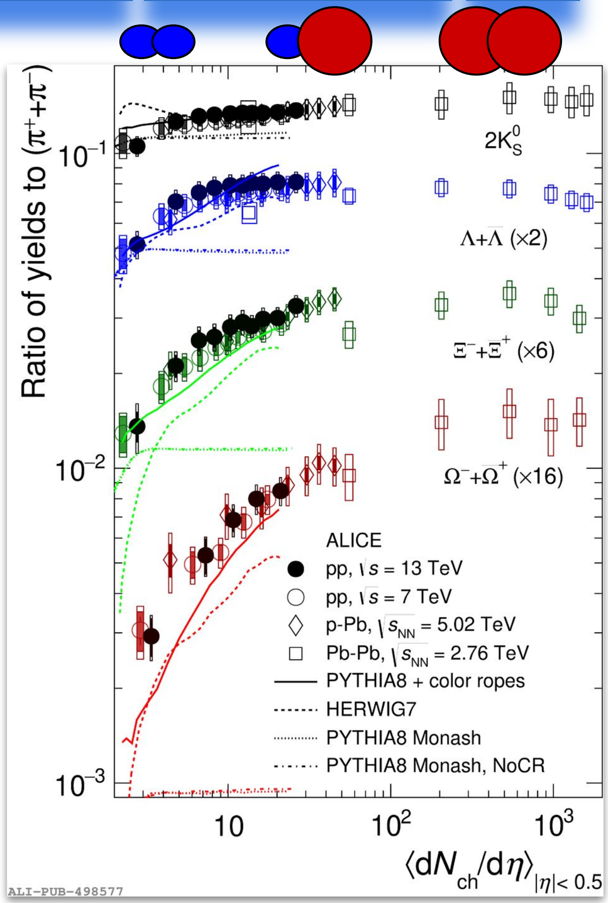




ALICE Coll., Eur. Phys. J. C 80 (2020) 2, 167

Model comparison:

- in-vacuum hadronization (e.g. Pythia8 Monash, Pythia8 + color ropes, HERWIG7 ...)
- two-component models (e.g. EPOS LHC ...)

[2] ALICE Coll., Nature Physics 13 (2017) 535–539
[3] ALICE Coll., Eur. Phys. J. C 80 (2020) 2, 167

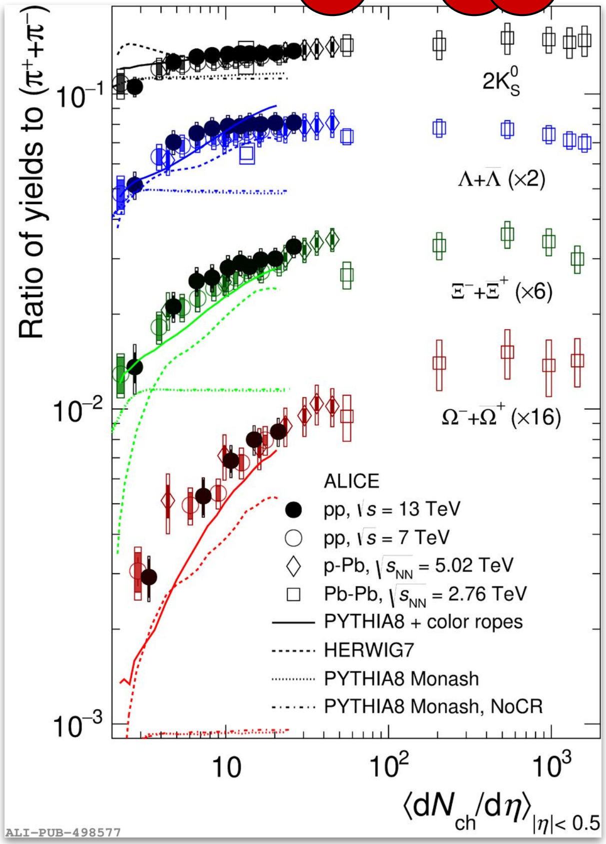
ALICE observed that the ratio of strange to non-strange hadron yields (h/π): [2,3]

How can we improve our understanding of strangeness production mechanisms in pp collisions?

- Can this behaviour be characterized by other properties than a difference in $<dN_{ch}/d\eta>$?
  - **classify high-multiplicity (HM) events based on event topology (transverse spherocity)**
  - **decouple global properties and local effects (effective energy)**
- Are models able to describe multiple strange hadron production probability?
  - **measure the (multi-)strange particle multiplicity distribution**

HERWIG ...)

- two-component models (e.g. EPOS LHC ...)



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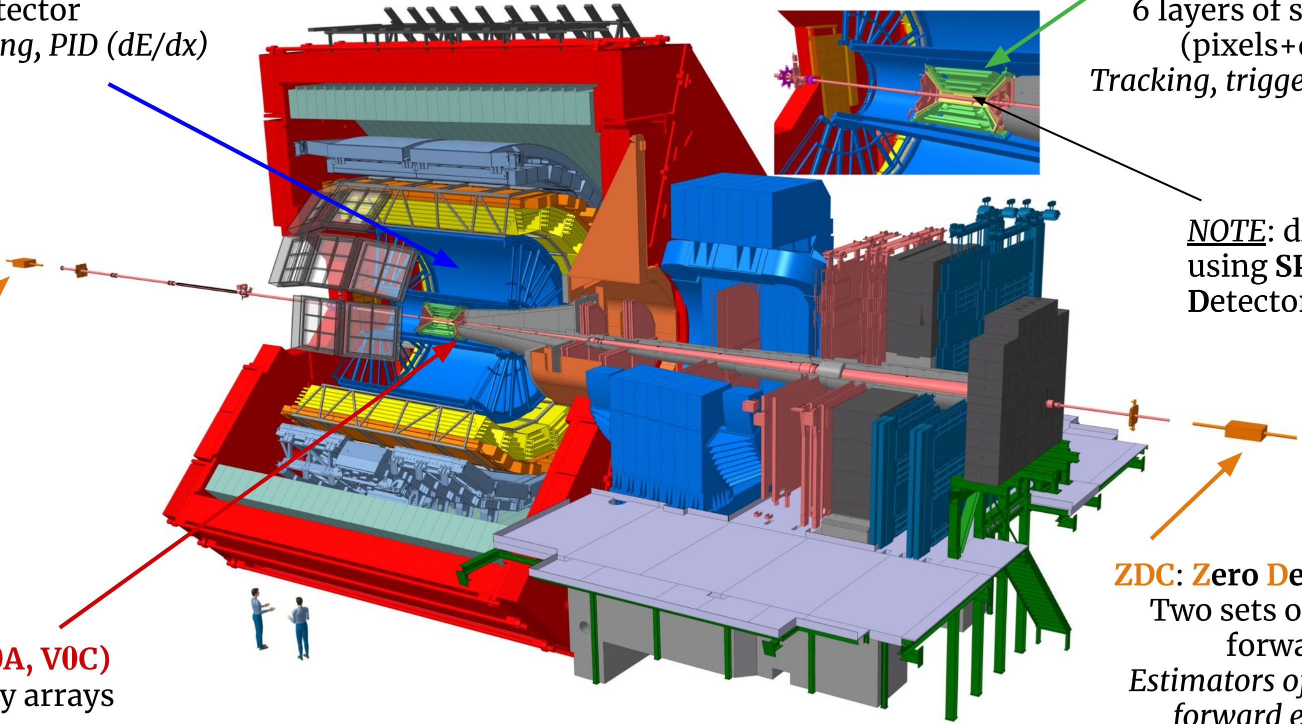
[3] ALICE Coll., Eur. Phys. J. C 80 (2020) 2, 167

TPC: Time Projection Chamber
Gas detector
Tracking, vertexing, PID (dE/dx)

ITS: Inner Tracking System
6 layers of silicon detectors
(pixels+drift+strips)
Tracking, triggering, vertexing, PID



NOTE: $dN_{ch}/d\eta$ is measured using **SPD** (**S**ilicon **P**ixel **D**etectors) at midrapidity

V0 detectors (V0A, V0C)
Forward-rapidity arrays of scintillators
Triggering, multiplicity estimators

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

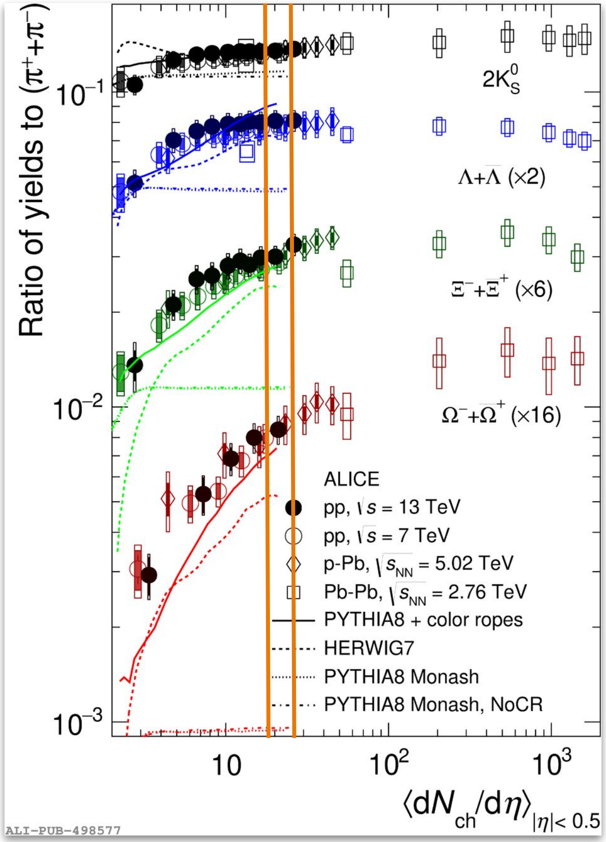
- Can this behaviour be characterized by other properties than a difference in $\langle dN_{ch}/d\eta \rangle$?
  - **classify HM events* based on event topology**

TRANSVERSE SPHEROCITY estimation

$$S_0^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \sum_i \left(\frac{|\hat{p}_{T,i} \times \hat{n}|}{N_{trk}} \right)$$

→ categorize events by their azimuthal topology

*top 1% multiplicity pp events



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The concept of transverse spherocity

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*top 1% multiplicity pp events

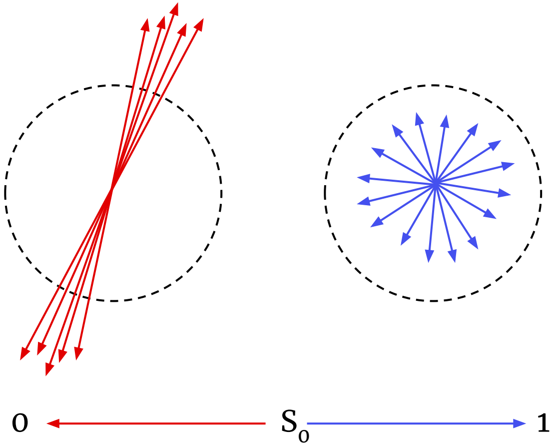
- Can this behaviour be characterized by other properties than a difference in <dN_{ch}/dη>?
  - **classify HM events* based on event topology**

TRANSVERSE SPHEROCITY estimation $$S_0^{p_{\rm T}=1} = \frac{\pi^2}{4}\min_{\hat{n}} \sum_i \left(\frac{|\hat{p}_{{\rm T},i}\times \hat{n}|}{N_{\rm trk}}\right)$$

→ categorize events by their azimuthal topology

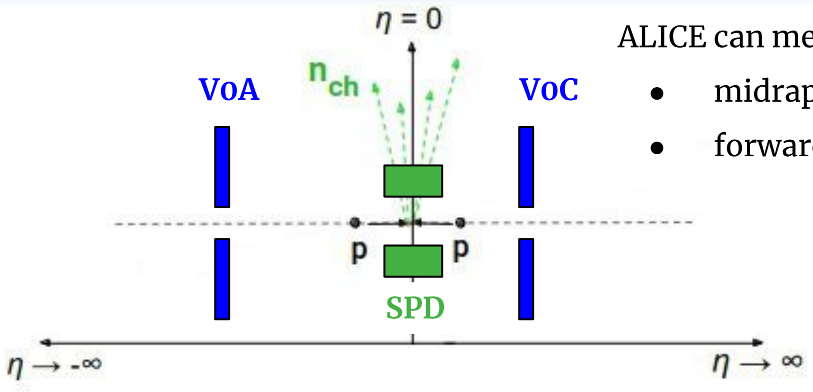
Jet-like events

- topology similar to a pair of back-to-back jets
- all tracks are parallel in the azimuthal plane
- particle production mainly driven by **hard processes** (in-vacuum hadonization)



Isotropic events

- symmetric azimuthal topology
- all tracks are uniformly distributed in the azimuthal plane
- particle production mainly driven by **multiple softer collisions** (hadronization in a medium – QGP)



ALICE can measure:

- midrapidity multiplicity (SPD)
- forward multiplicity (V0 detectors)

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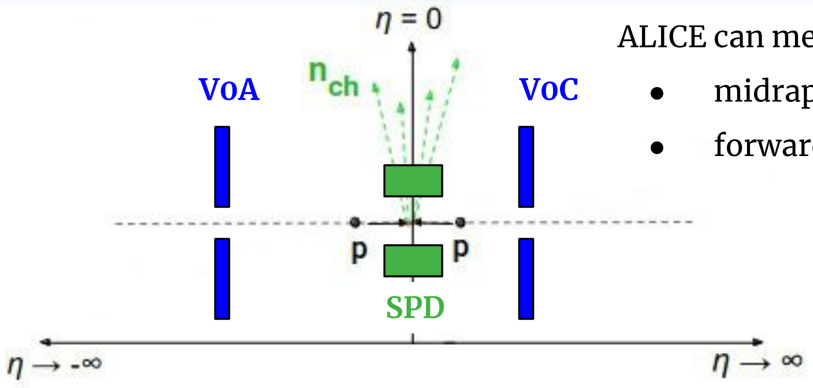

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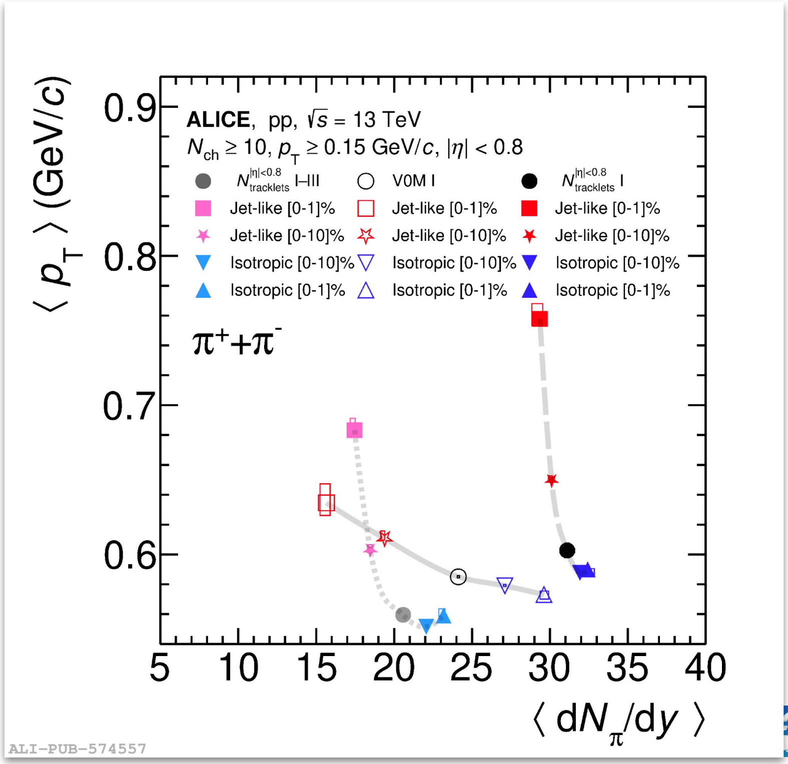
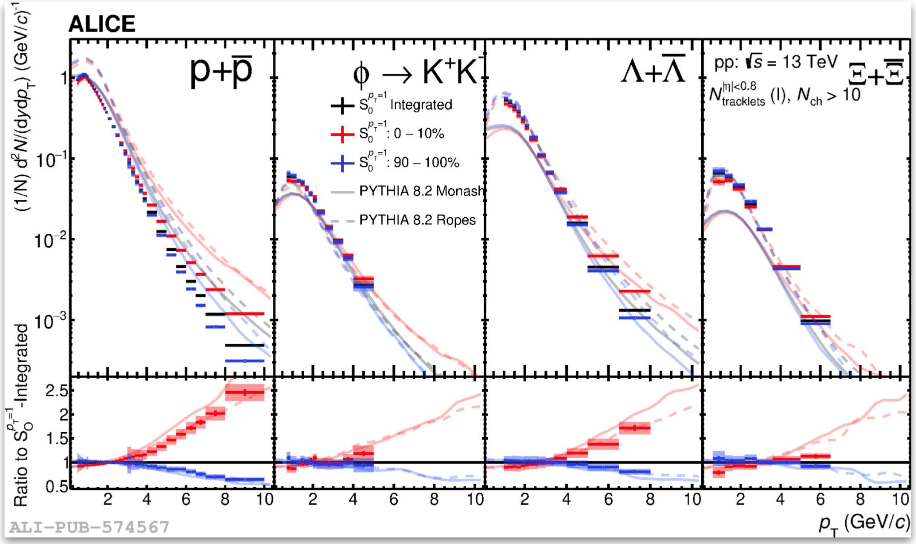
ALICE Coll., JHEP 05 (2024) 184

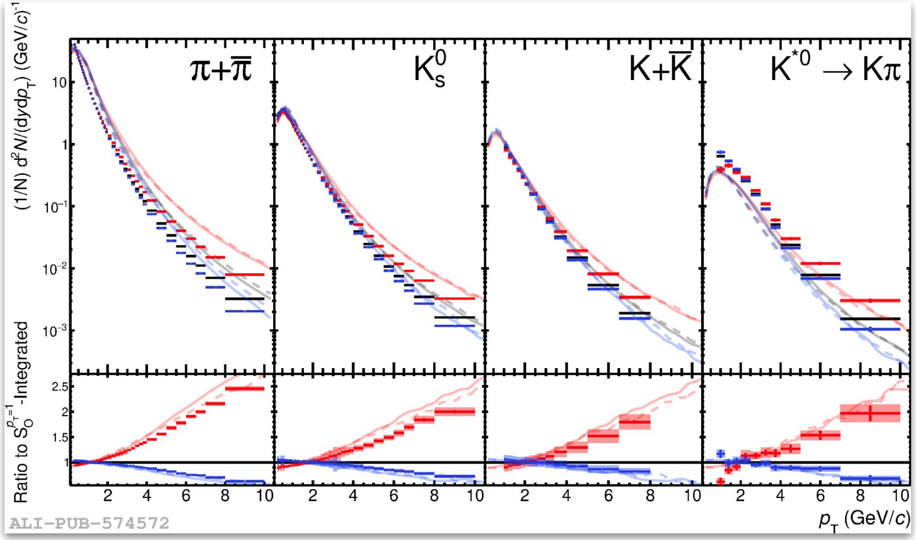


- Selecting the high multiplicity at midrapidity in conjunction with spherocity selection:
  - large differences in $<p_T>$ among the event classes
  - small shift in yields

  → **best at separating events based on their hardness**
- Selecting the high multiplicity at forward in conjunction with spherocity selection:
  - similar $<p_T>$ among the event classes
  - large variations in yields

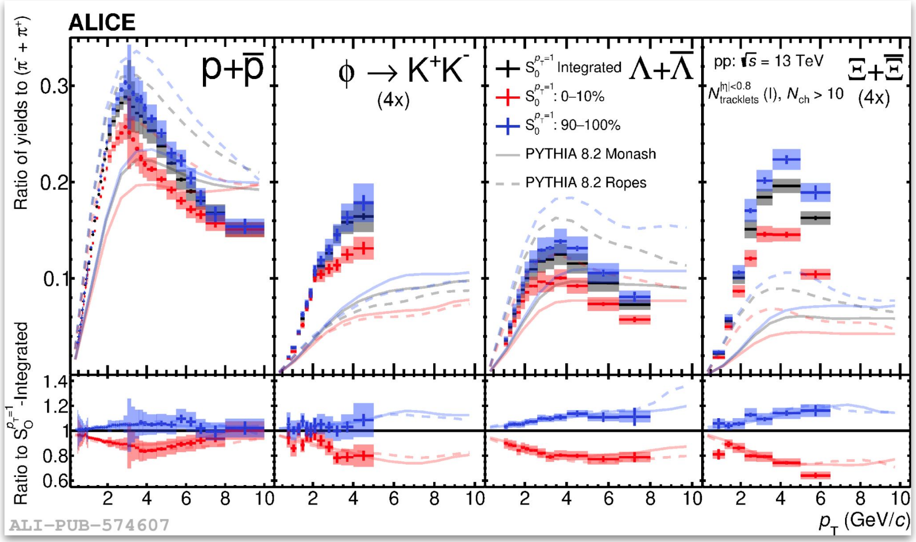
Baryons | Mesons | *ALICE Coll.*, JHEP 05 (2024) 184





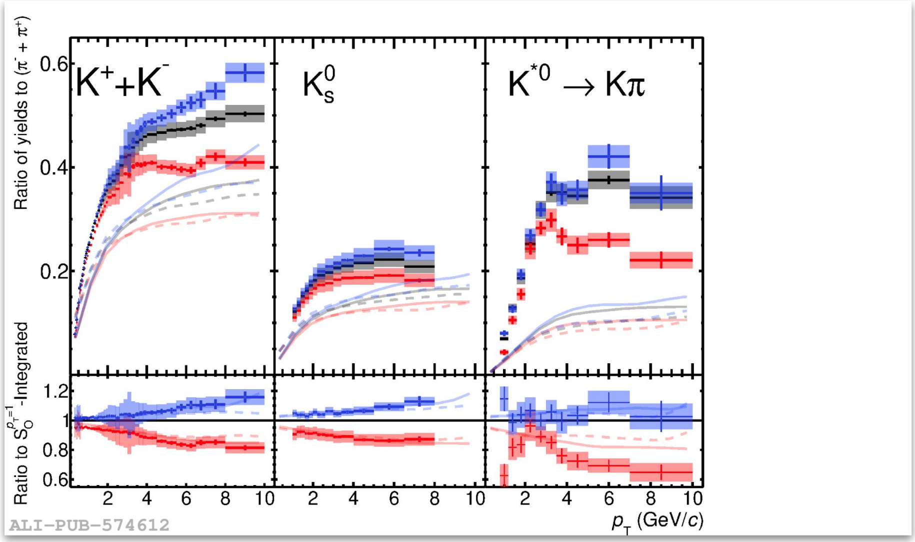
- Trends are consistent between all observed particle species:
  - for **jet-like events**: suppression at low-p_T, but enhancement at high-p_T (viceversa for **isotropic events**)
- Model comparison:
  - none of the available models (see slide 27 for EPOS LHC and Herwing 7.2 predictions) is able to reproduce the absolute trends

Baryons



Mesons

ALICE Coll., [JHEP 05 (2024) 184]



- Enhancement of strangeness yield in isotropic events, suppression in jet-like events → **strange particle production is driven by isotropic topologies**
- selecting top 1% of $N_{tracklets}^{|\eta|<0.8}$, 1% $S_0^{pT=1}$ classes (see slide 29): more pronounced suppression in jet-like events
- Model comparison:
  - none of the available models (see slide 28 for EPOS LHC and Herwing 7.2 predictions) is able to reproduce the absolute trends

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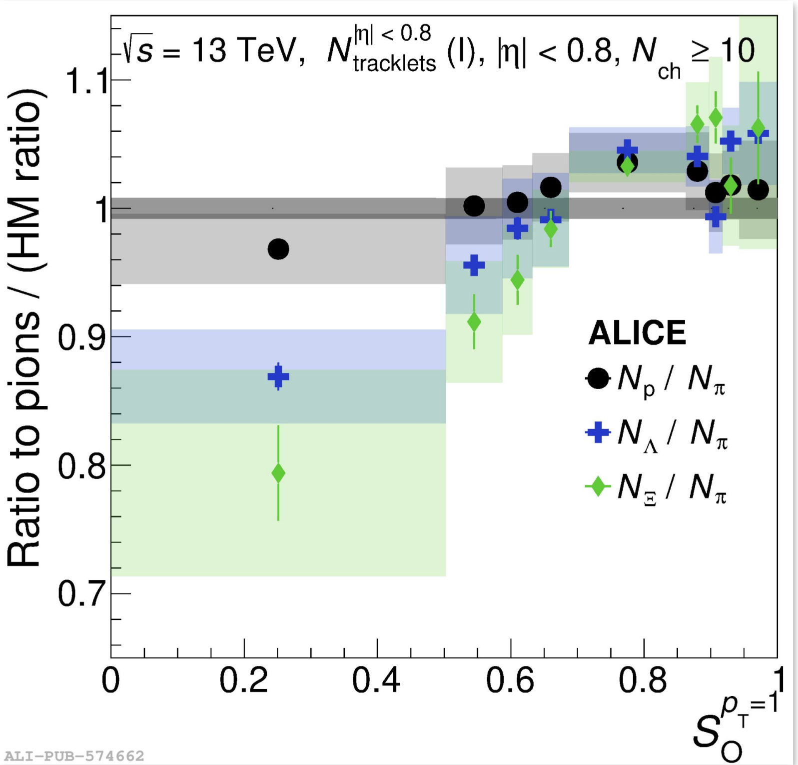
- Strangeness production is suppressed in **jet-like events** ($S_0^{pT=1} \to 0$), slightly enhanced in softer, **isotropic events** ($S_0^{pT=1} \to 1$)
- **increase** as a function of $S_0^{pT=1}$ with indications of an **ordering with strangeness content**
  - Proton is mostly unmodified



ALICE Coll., JHEP 05 (2024) 184

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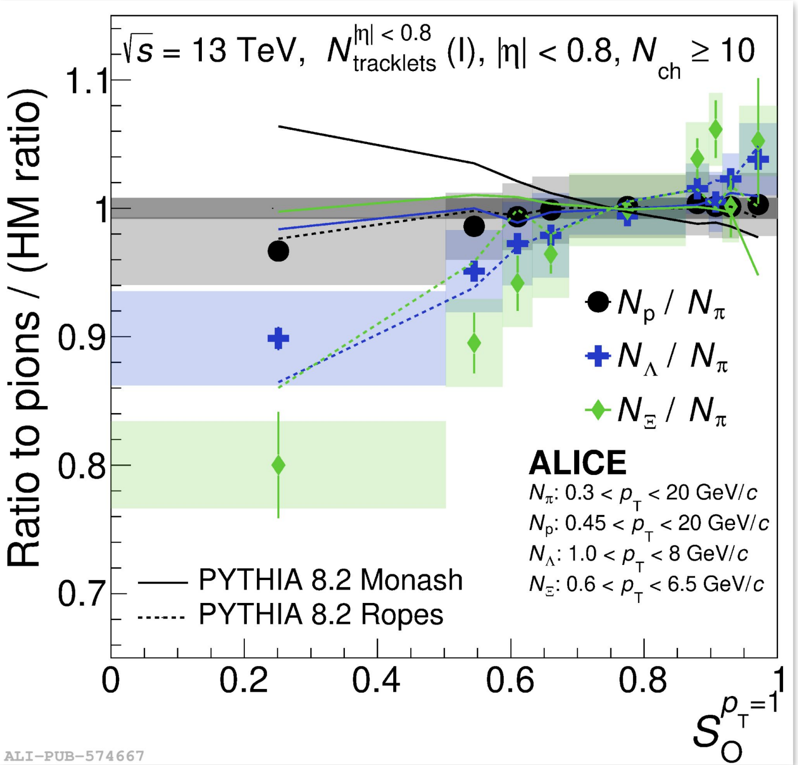

ALICE Coll., JHEP 05 (2024) 184

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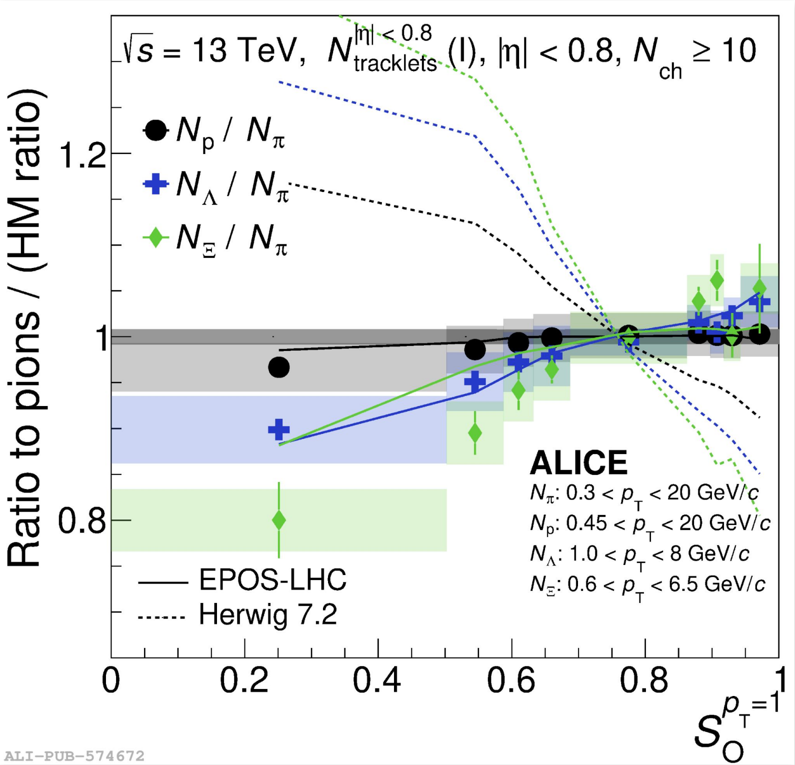

ALICE Coll., JHEP 05 (2024) 184

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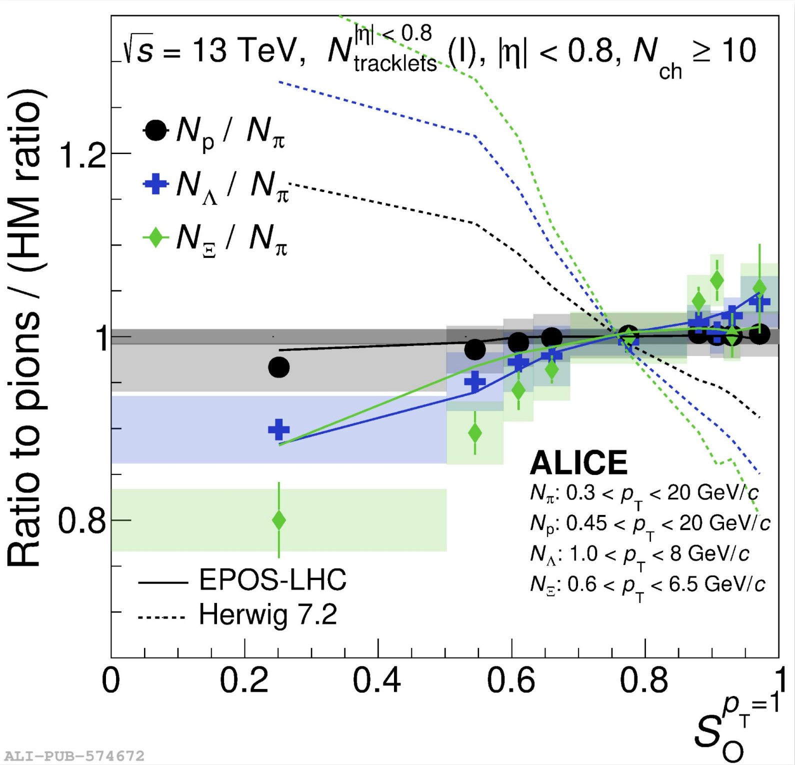
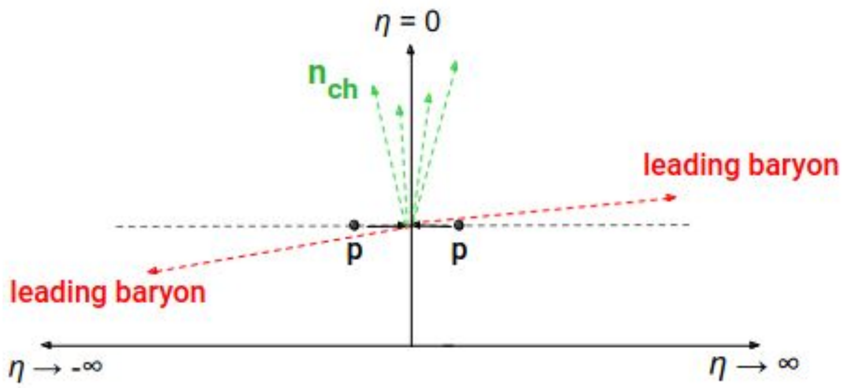


MESSAGE #1

One is able to **control the degree of QGP-like effects in small systems** by categorizing events based on the **azimuthal topology. $S_0^{p_T=1}$ integrated HM events are dominated by isotropic processes**

- Can this behaviour be characterized by other properties than a difference in $\langle dN_{ch}/d\eta \rangle$?
  - **decouple global properties and local effects**

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



The charged-particle multiplicity produced in pp collisions is:

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

EFFECTIVE ENERGY: energy available for particle production in the initial stages of the collision

$E_{eff} < \sqrt{s}$ due to the **emission of leading baryons** at very forward rapidity

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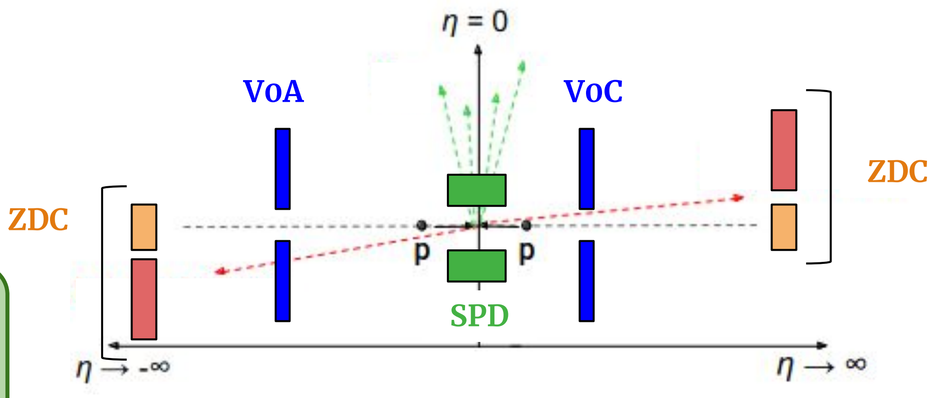

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$E_{eff} < \sqrt{s}$ due to the **emission of leading baryons** at very forward rapidity

Is strangeness production correlated with E_{eff}, which is connected with the initial stage of the collision?

ALICE can measure:

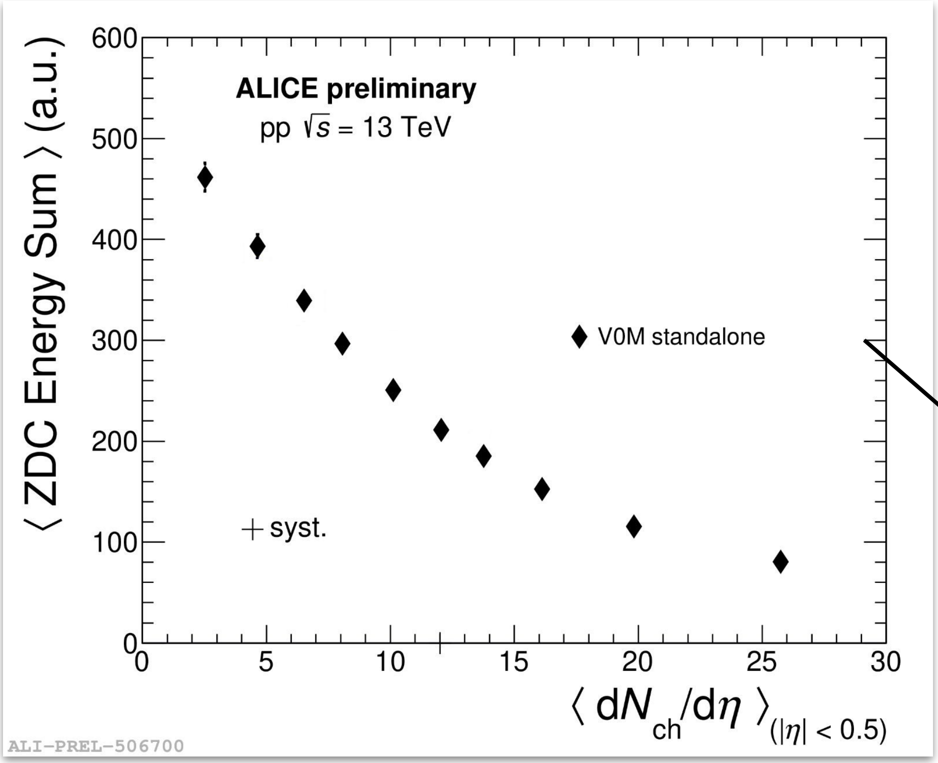
- midrapidity multiplicity (**SPD**)
- forward multiplicity (**V0 detectors**)
- leading energy (**ZDC**)

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

ALICE measured that the **forward** energy **decreases with increasing particle** multiplicity produced at **midrapidity**

Multiplicity and effective energy are anti-correlated → **multi-differential analysis is needed to decouple effective energy from multiplicity dependence**

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



Percentile classes based on signal amplitude in V0 detectors

ALICE Coll., arxiv.org/2107.10757

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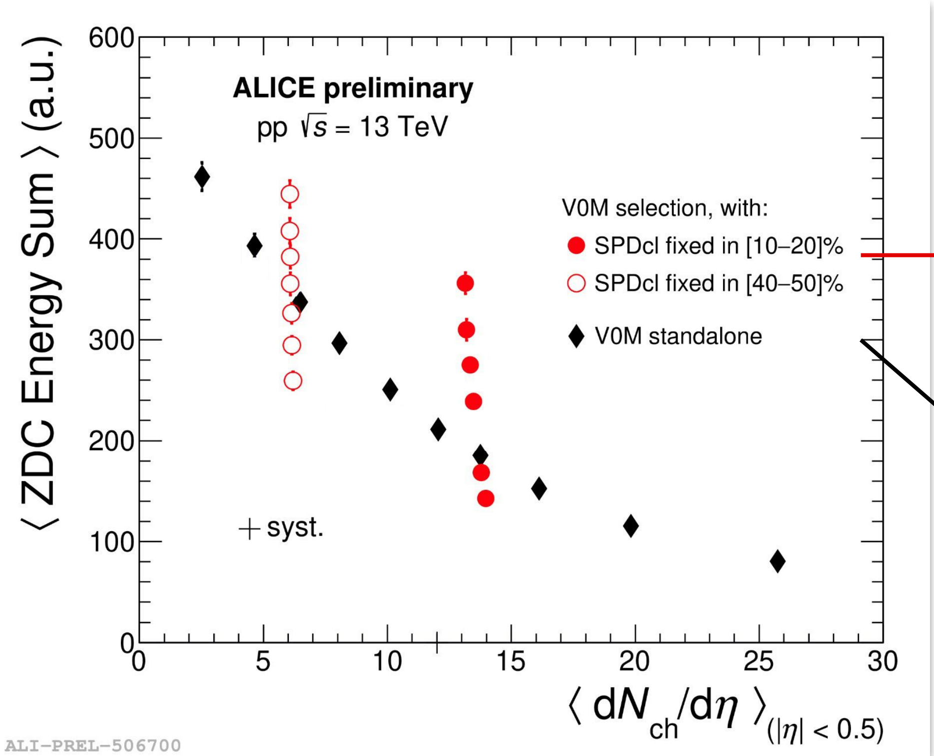

Fixed SPD class + V0M selections:
Fixed multiplicity at midrapidity +
different forward energy deposits in the ZDC

Percentile classes based on signal amplitude in V0 detectors

NOTE: SPD classes based on the number of clusters in the SPD

ALICE measured that the **forward** energy **decreases with increasing particle** multiplicity produced at **midrapidity**

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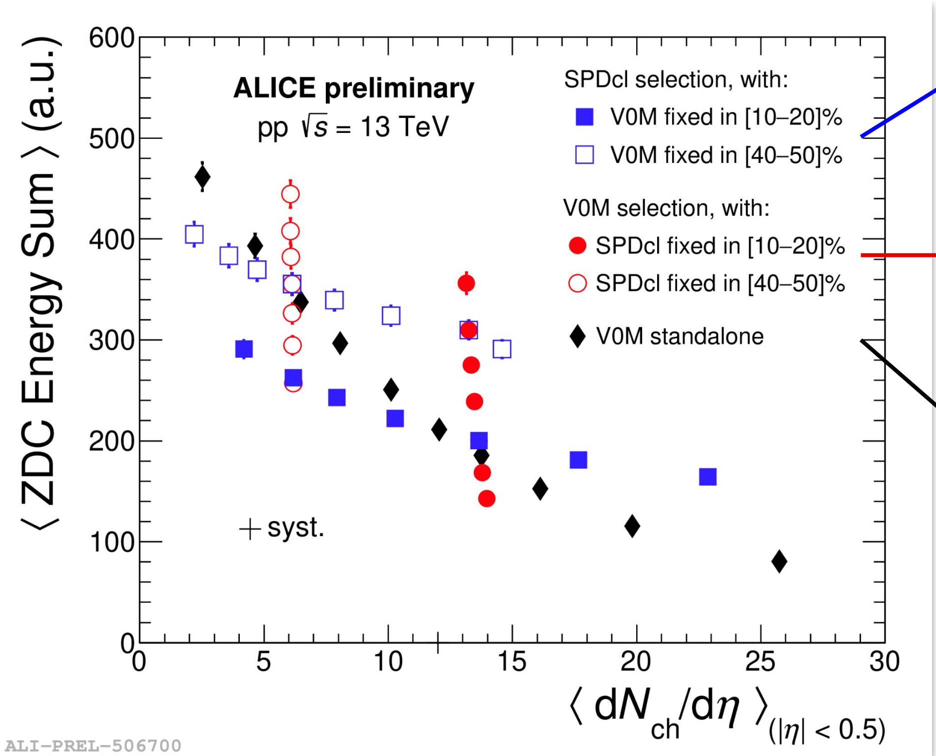


Fixed V0M class + SPD selections:
ZDC energy constrained in a small range + different multiplicity produced in the event

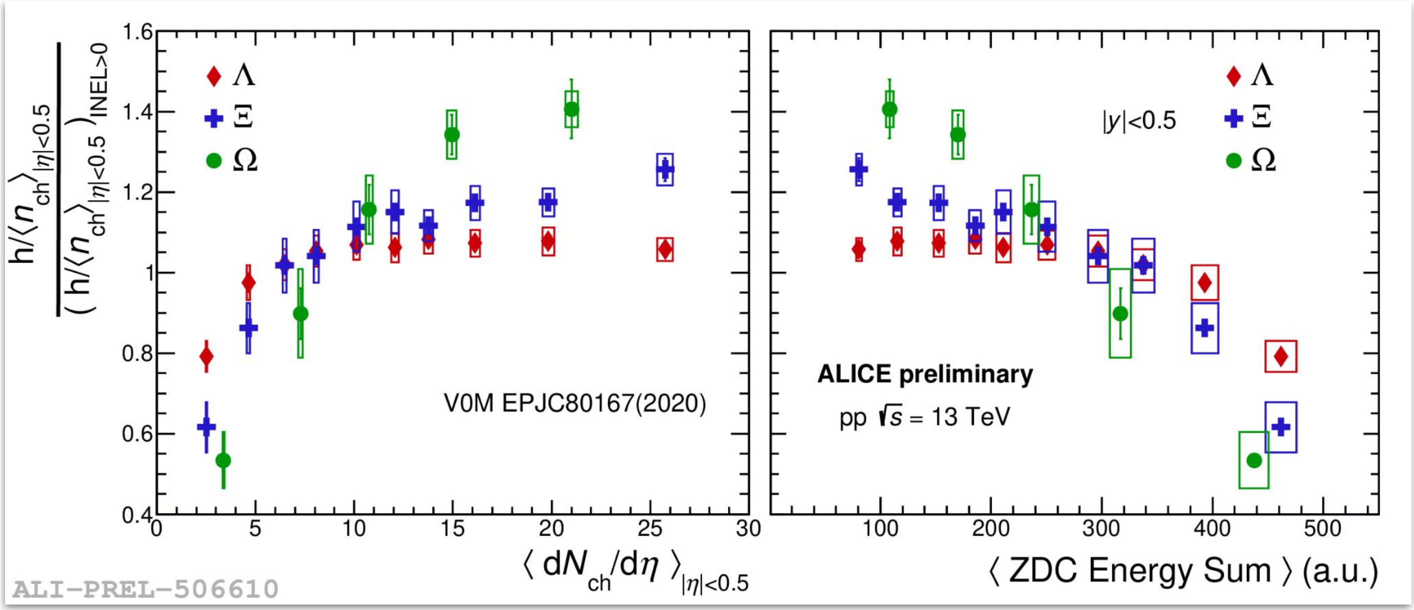
Fixed SPD class + V0M selections:
Fixed multiplicity at midrapidity + different forward energy deposits in the ZDC

Percentile classes based on signal amplitude in V0 detectors

NOTE: SPD classes based on the number of clusters in the SPD

Yields of strange hadrons normalised to the charged particle multiplicity (proxy for pions):

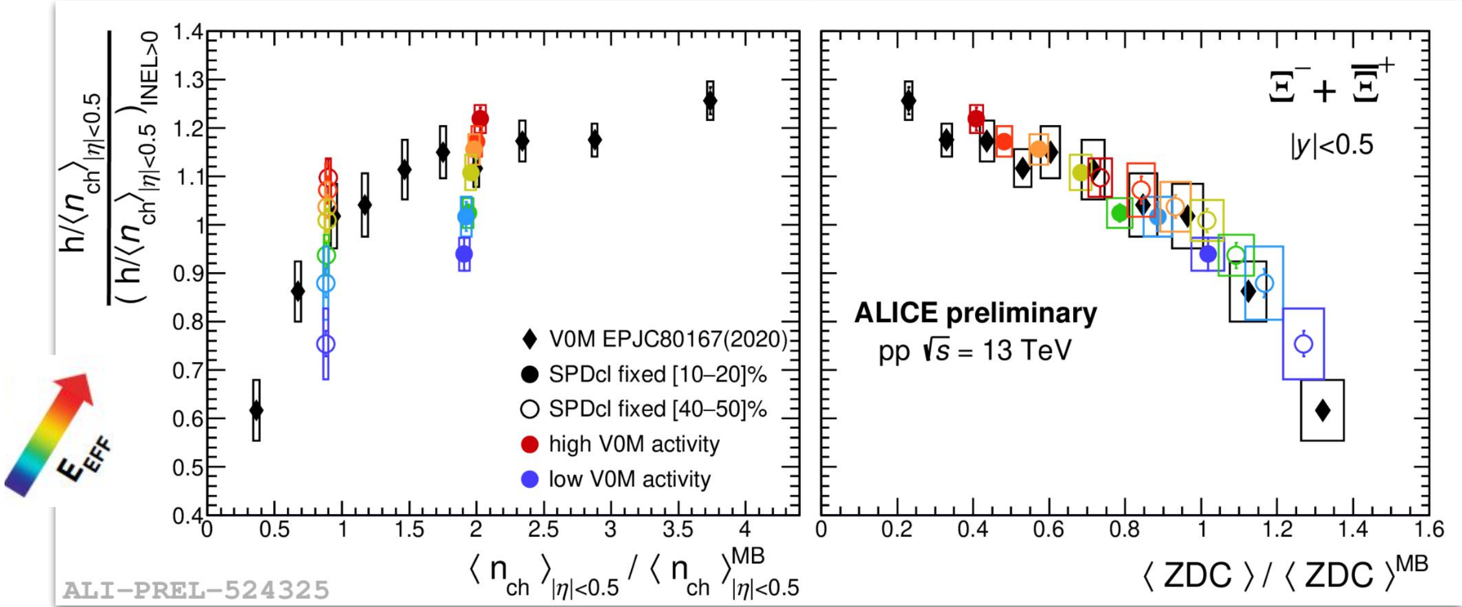
- **increase** with the **multiplicity at midrapidity** (the well known strangeness enhancement!) – left
- are **anticorrelated** with the **ZDC energy** – right



There is a **hierarchy**: increase/decrease with strangeness content

Ξ yields normalised to the charged particle multiplicity, **fixing the multiplicity at midrapidity**:

- **increase** for **decreasing forward energy (increasing E_{eff})** – left
- scaling trends with ZDC energy are **compatible with standalone classes**– right



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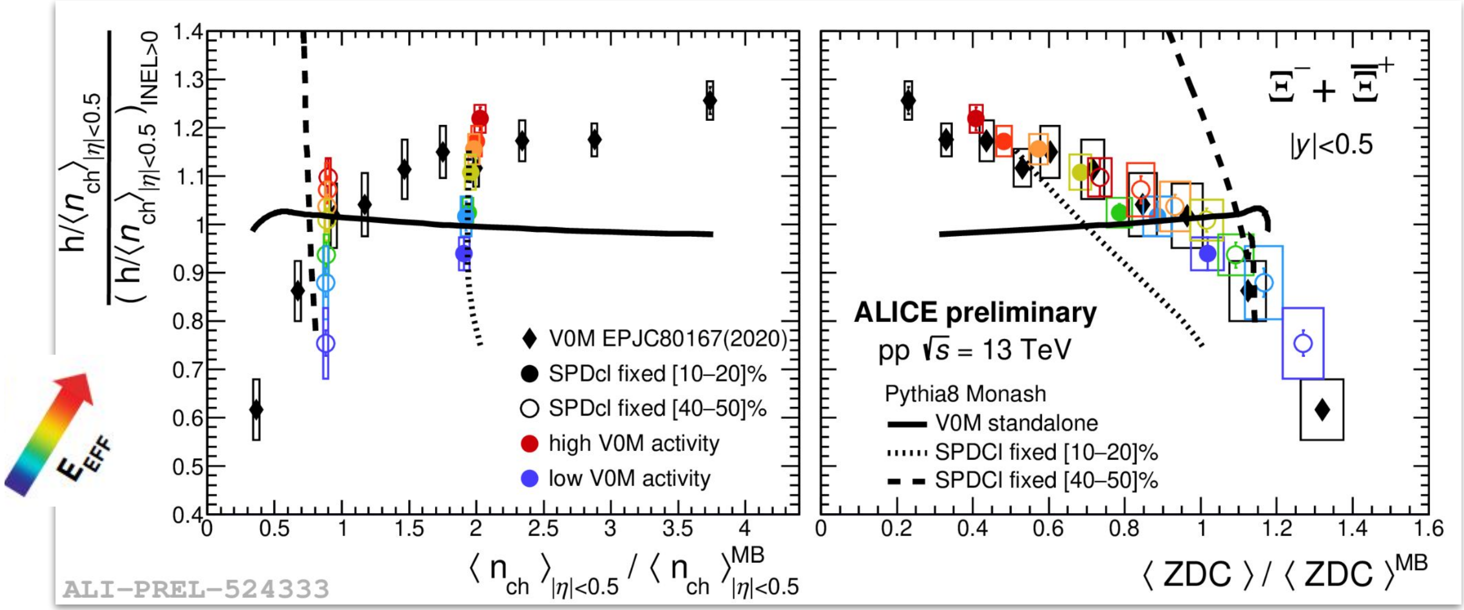

Model comparison:

- Pythia8 Monash tune fails to reproduce the results

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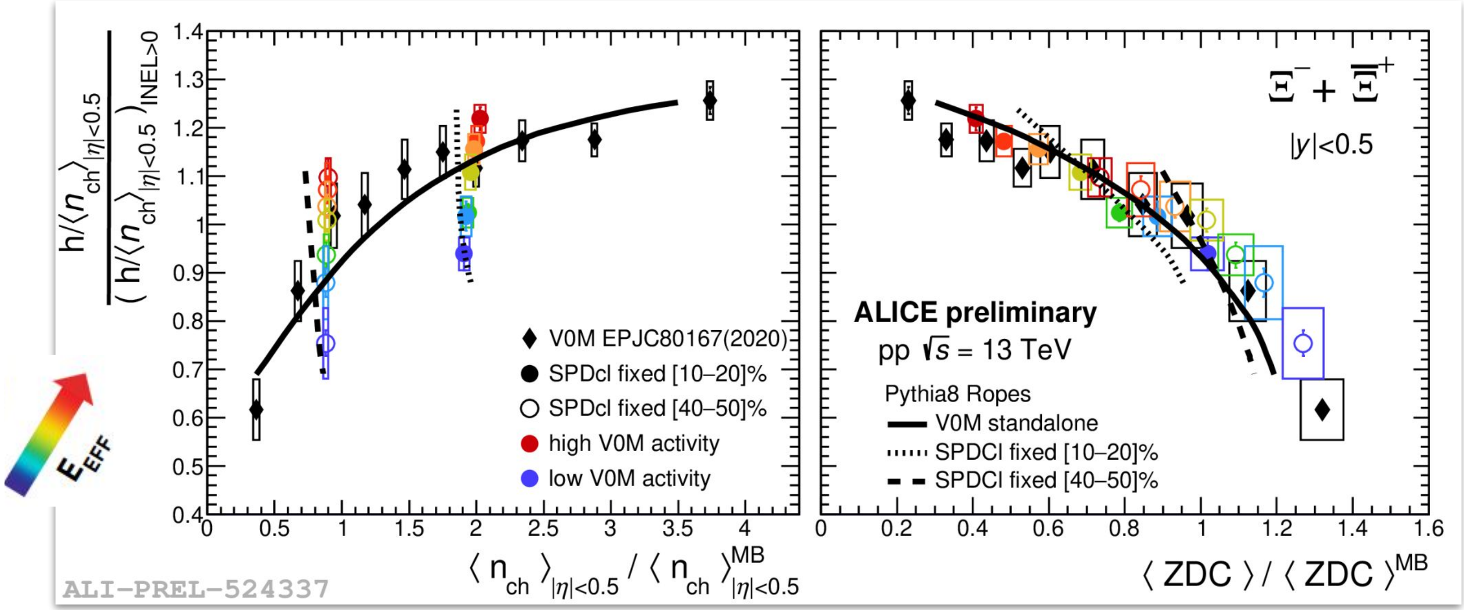

Model comparison:

- Pythia8 Monash tune fails to reproduce the results
- including QCD-CR + ropes (Pythia8 Ropes) in the model improves the agreement with data

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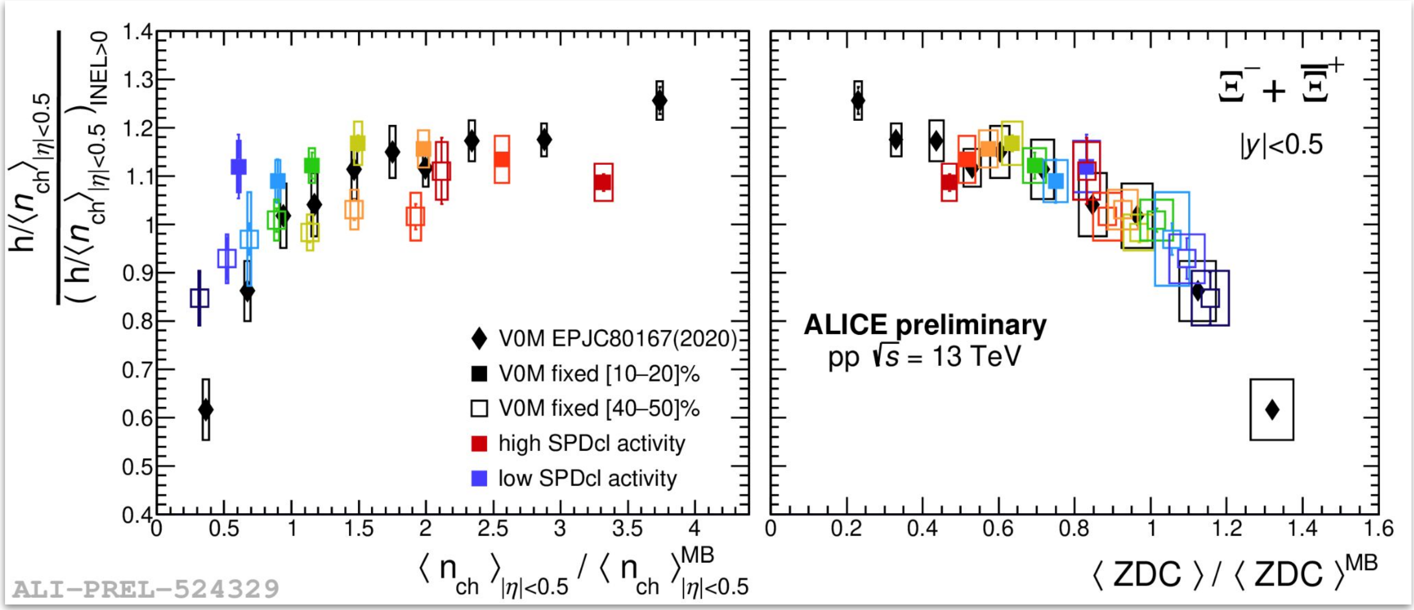
Ξ yields normalised to the charged particle multiplicity, **reducing the effective energy span**:

- **increase with multiplicity is reduced** – left
- within the small ZDC energy range, scaling trends are **compatible with standalone classes**– right



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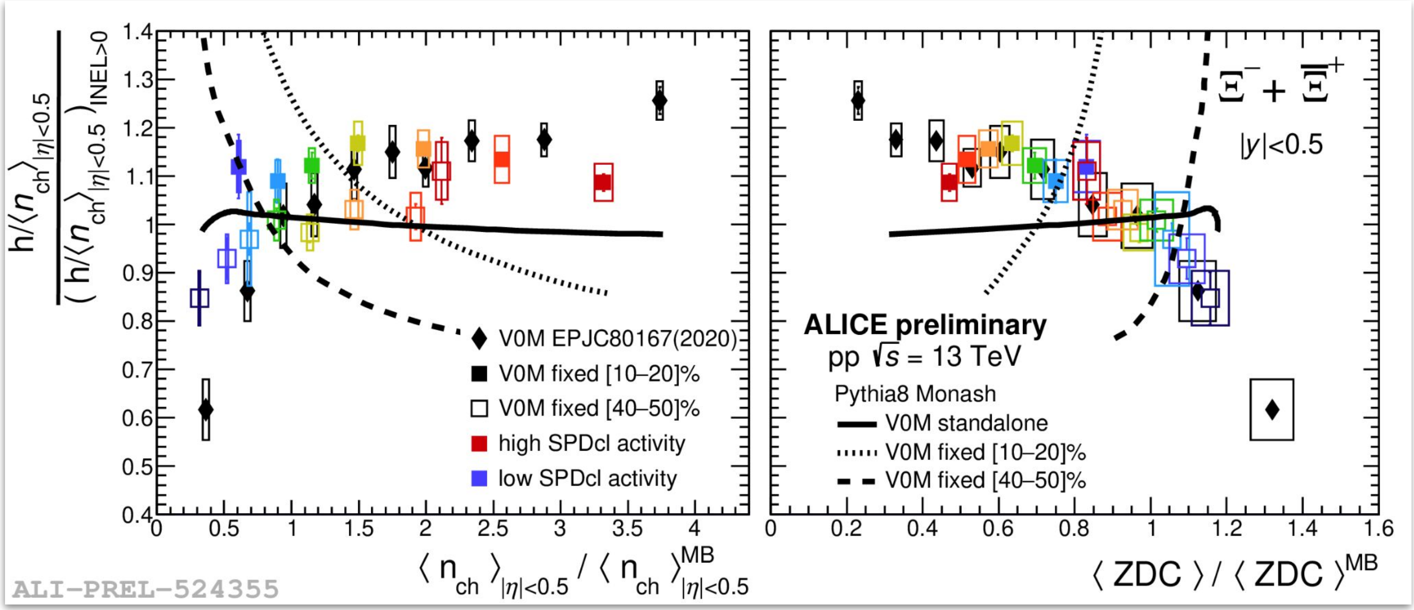

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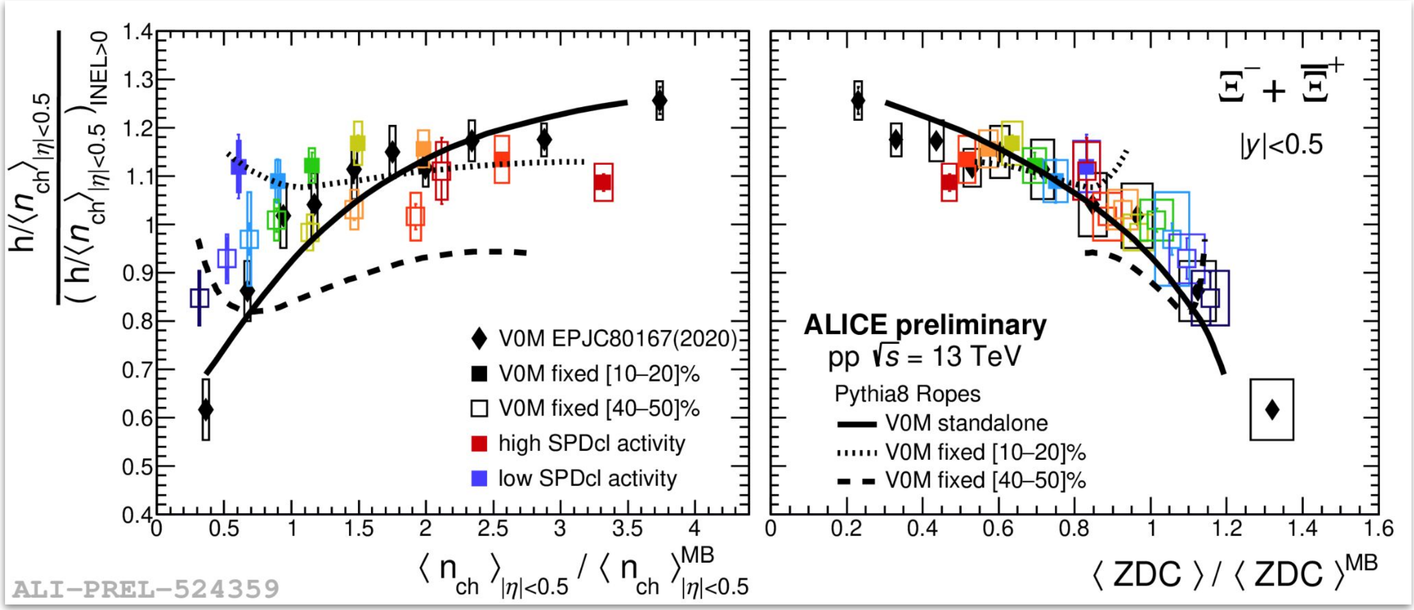

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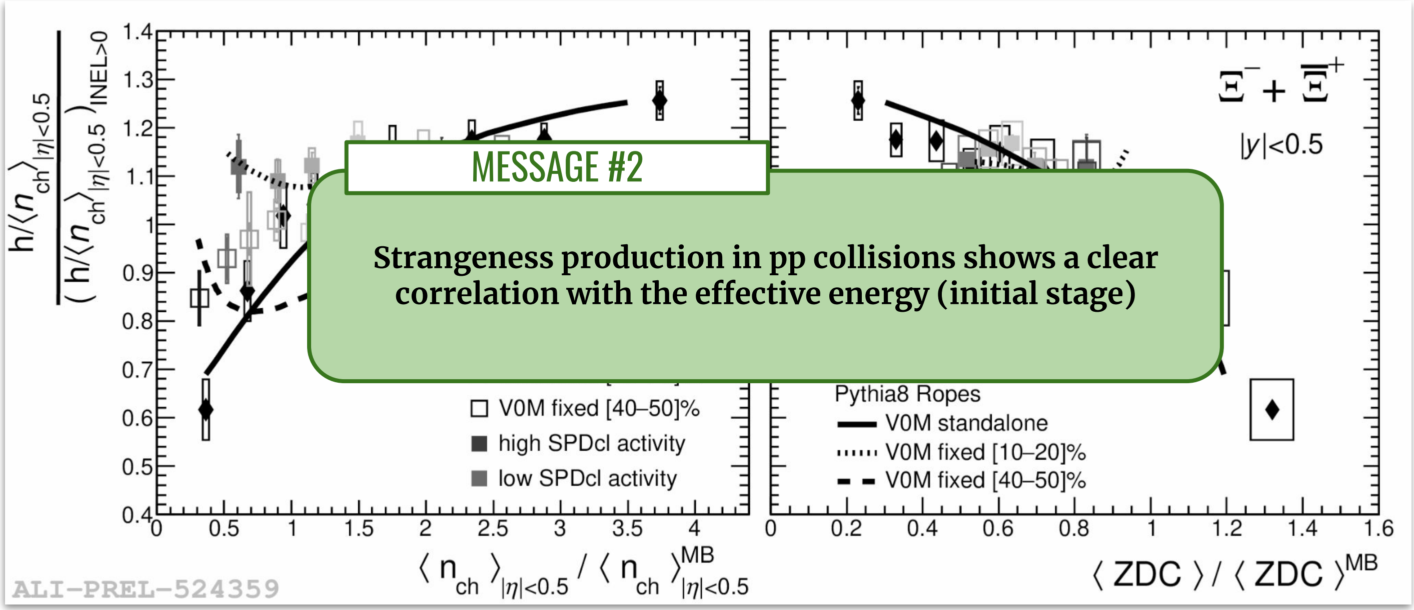
- Pythia8 Ropes improves the agreement with data

Ξ yields normalised to the charged particle multiplicity, **reducing the effective energy span**:

- **increase with multiplicity is reduced** – left
- within the small ZDC energy range, scaling trends are **compatible with standalone classes**– right

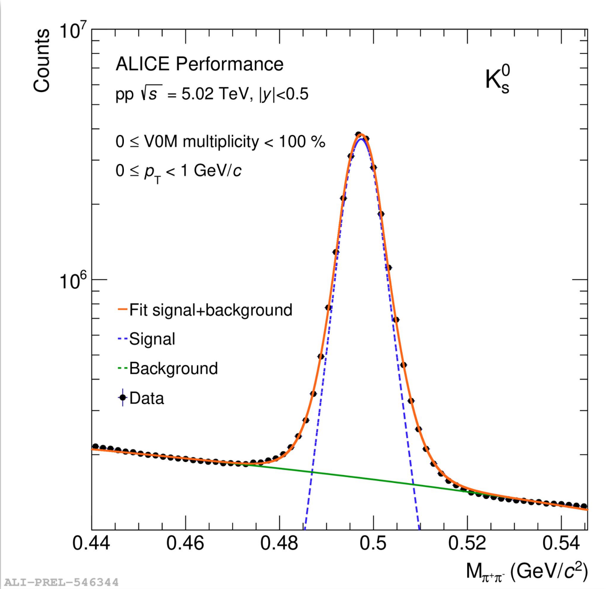


Model comparison:

- Pythia8 Monash tune fails to reproduce the results
- Pythia8 Ropes improves the agreement with data

- Are models able to describe multiple strange hadron production probability?
    - **measure the (multi-)strange particle multiplicity distribution** (extending beyond the average value of the production rate – previous results –) counting the number of strange particles event-by-event in pp collisions

Each candidate **weighted by *P*(sig)** or *P*(bkg) estimated by **1D** invariant mass **fit** in p_T/multiplicity bins



$P(\mathrm{Sig}) = \mathrm{fsignal}(m_i, p_T) / \mathrm{fsum}(m_i, p_T)$

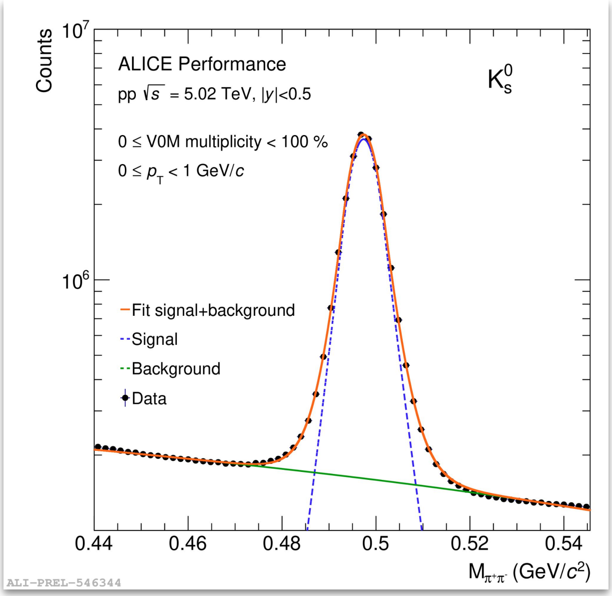
$P(\mathrm{Bkg}) = \mathrm{fbkg}(m_i, p_T) / \mathrm{fsum}(m_i, p_T)$

- Are models able to describe multiple strange hadron production probability?
    - **measure the (multi-)strange particle multiplicity distribution** (extending beyond the average value of the production rate – previous results –) counting the number of strange particles event-by-event in pp collisions

Each candidate **weighted by *P*(sig)** or *P*(bkg) estimated by **1D** invariant mass **fit** in p_T/multiplicity bins

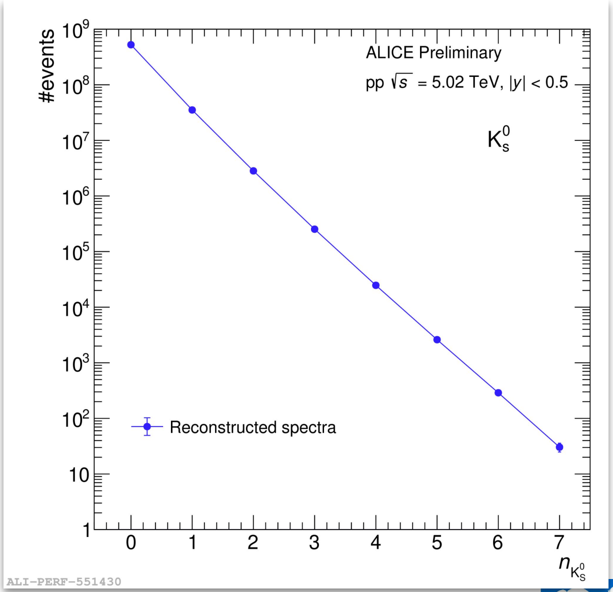
$$P(Sig) = fsignal(m_i, p_T) / fsum(m_i, p_T)$$

$$P(Bkg) = fbkg(m_i, p_T) / fsum(m_i, p_T)$$



Weights associated to each of the N candidates **combined** to obtain: P(all-sig), ... , P(all-bkg)

For each event: full probability spectrum spanning from 0 to N



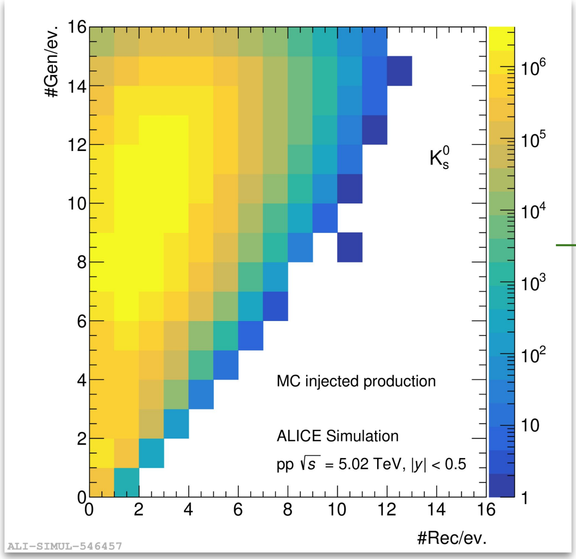
Correction for the detector response (Monte Carlo simulation featuring realistic p_T distribution)

$$\begin{bmatrix} R0 \\ R1 \\ R2 \\ \dots \\ \dots \\ Rn \end{bmatrix} = \begin{bmatrix} P(R0|G0) & P(R0|G1) & P(R0|G2) & \dots & \dots & P(R0|Gn) \\ P(R1|G0) & P(R1|G1) & P(R1|G2) & \dots & \dots & \dots \\ P(R2|G0) & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ P(Rn|G0) & \dots & \dots & \dots & \dots & P(Rn|Gn) \end{bmatrix} \cdot \begin{bmatrix} G0 \\ G1 \\ G2 \\ \dots \\ \dots \\ Gn \end{bmatrix}$$

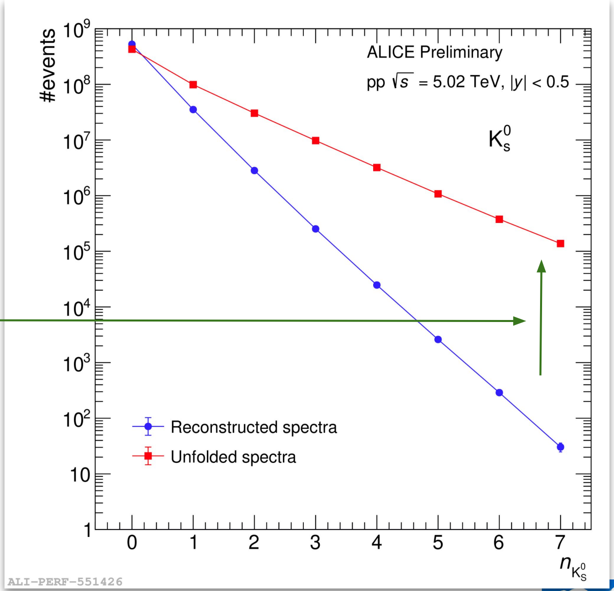
Reco. yields | Response matrix | Corr. distr.

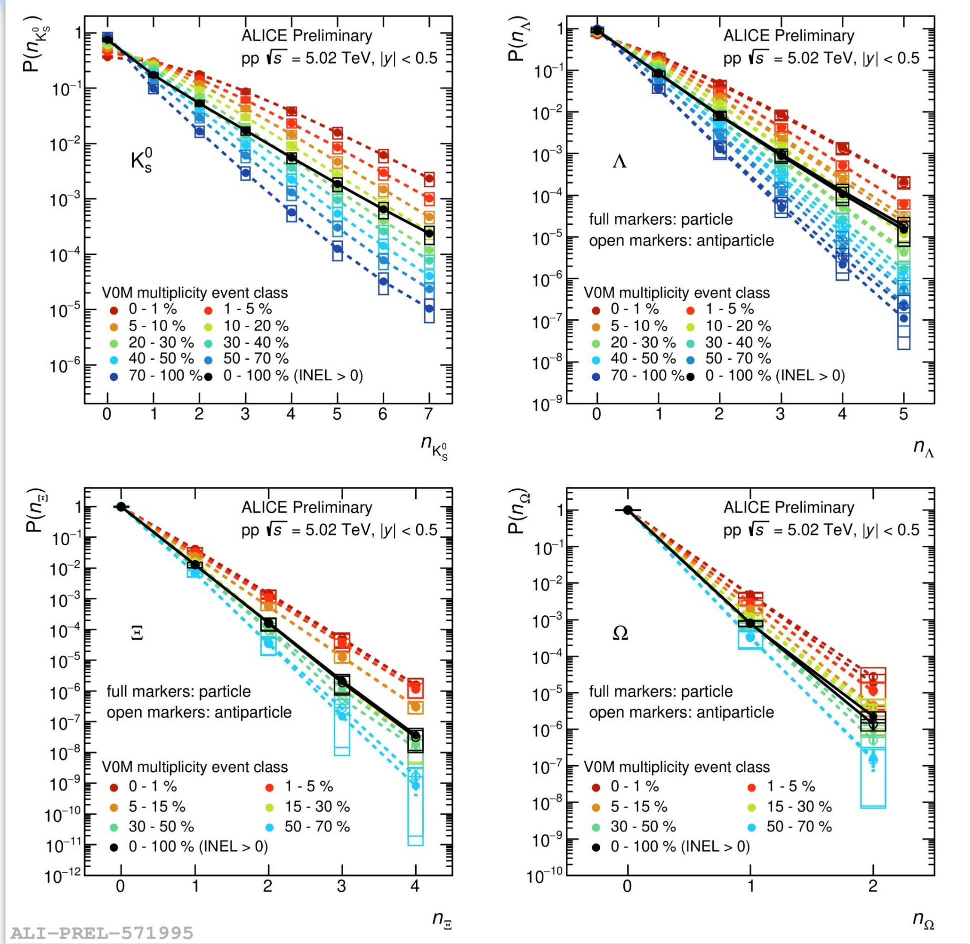
<u>Response matrix:</u>

probability of reconstructing *i* particles given that *j* particles were generated



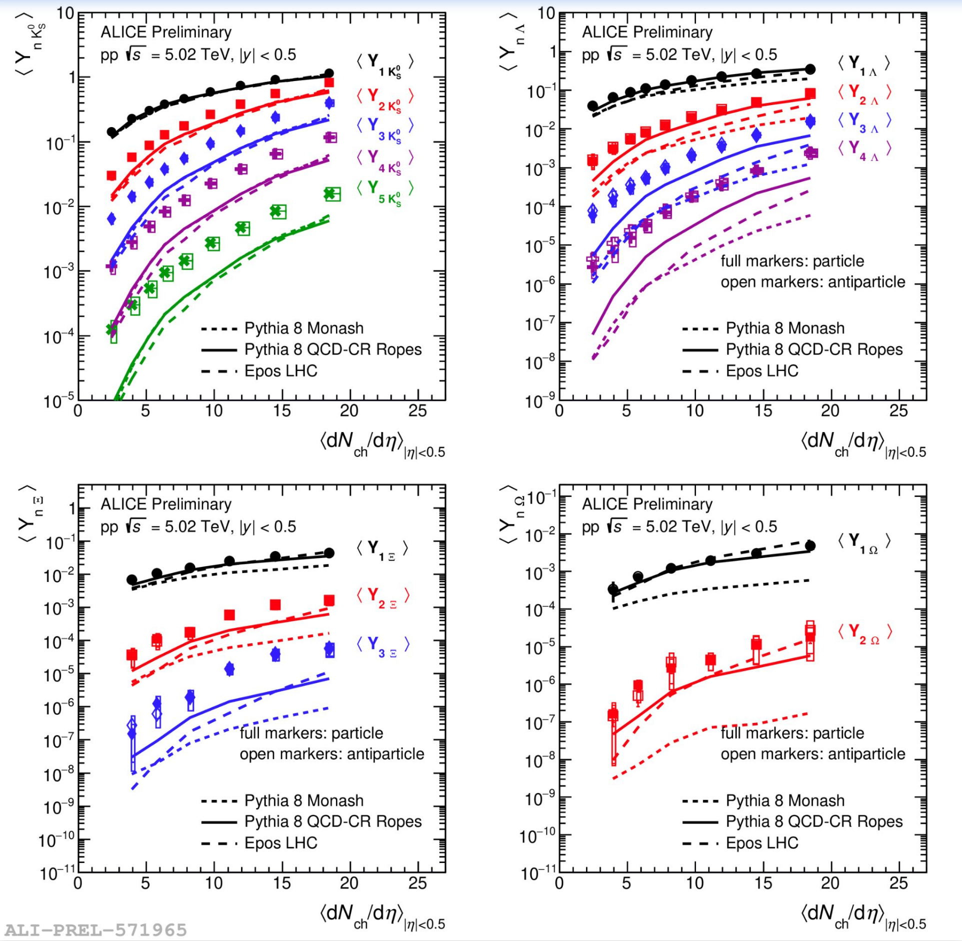
Bayesian unfolding procedure applied





Probability to produce *n* particles of a given species per event $P(n_S)$

- As expected at the LHC energies, a good agreement between particle and antiparticle was obtained from the highest to the lowest multiplicity class
- **Spanning across large ranges of strange/multiplicity variations, all the way to very "extreme" situations** (e.g. 7 K^0_S at low average charged-particle multiplicity, 0 K^0_S at high average charged-particle multiplicity)



Average production yield of 1, 2, 3, … particles/event:

$$< Y_{k-part} >= \sum_{n=k}^{\infty} \frac{n!}{k!(n-k)!} P(n)$$

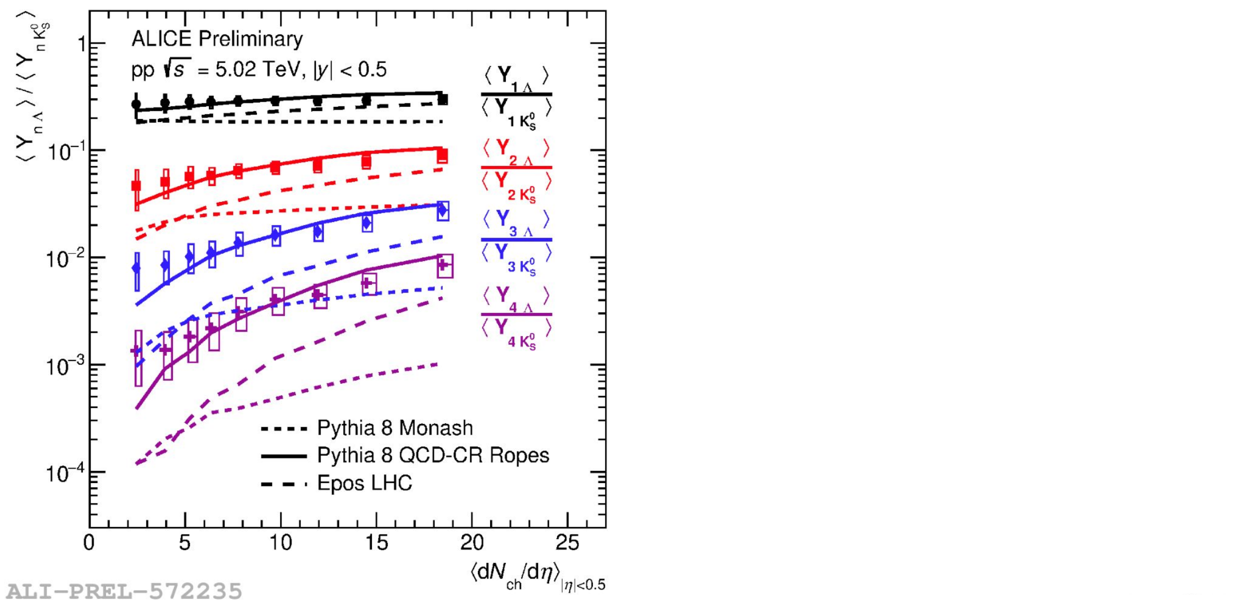
- The increase with multiplicity of the probability to produce multiple strange hadrons is more than linear
- *NOTE*: checked and verified the good agreement between <$Y_{1\text{-part}}$> and previous results ([2,3])
- Model comparison:
  - K^0_S: no difference between Pythia 8 Monash and Pythia 8 QCD-CR Ropes
  - for baryons: Pythia 8 QCD-CR Ropes approaches the data at high multiplicity; Epos LHC does a rather good job at high multiplicity, but shows larger discrepancy at low multiplicity

[2] ALICE Coll., Nature Physics 13 (2017) 535–539
[3] ALICE Coll., Eur. Phys. J. C 80 (2020) 2, 167

Yield ratios with $\Delta S = 0$

$n\Lambda/nK^0_S$ - important to factor-out non strangeness related effects

- **Increase of Λ/K^0_S vs multiplicity when looking at multiple hadron production!**
- Is it baryon enhancement?



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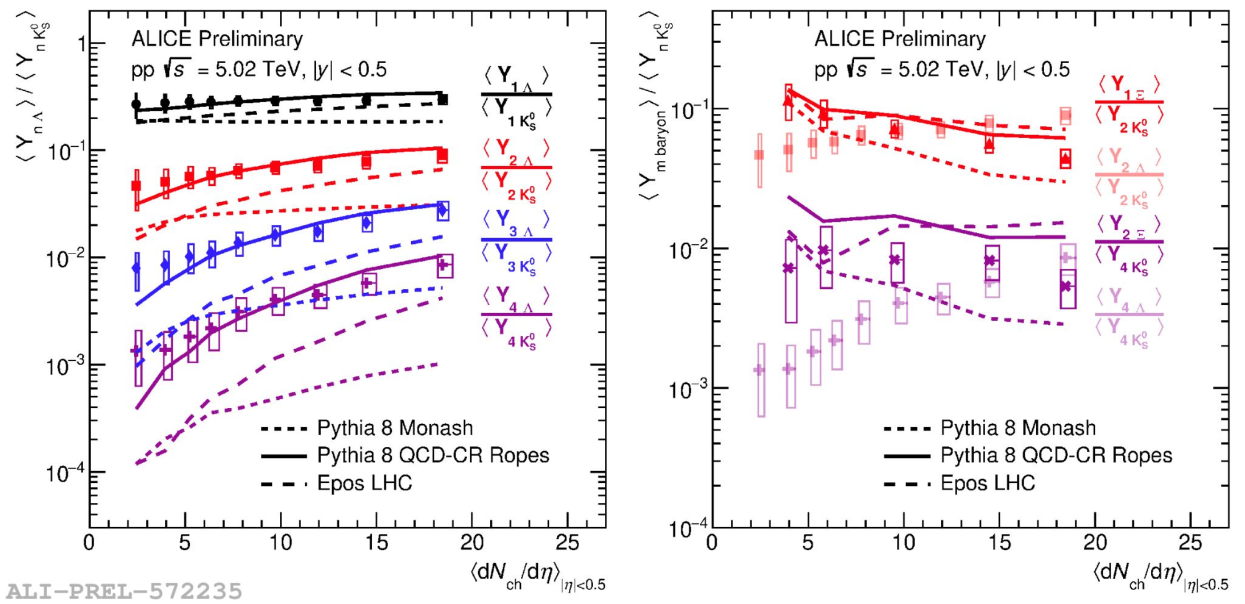

m baryons/nK^0_S - testing hadron production at fixed S and with different light quark content

- **larger number of light quarks involved in the denominator → decreasing trend**
  - High multiplicity: it is simpler to pair *s*-quarks with light quarks (very abundant)
  - Low multiplicity: the shortage of light quarks enhances the probability of multi-strange baryon formation

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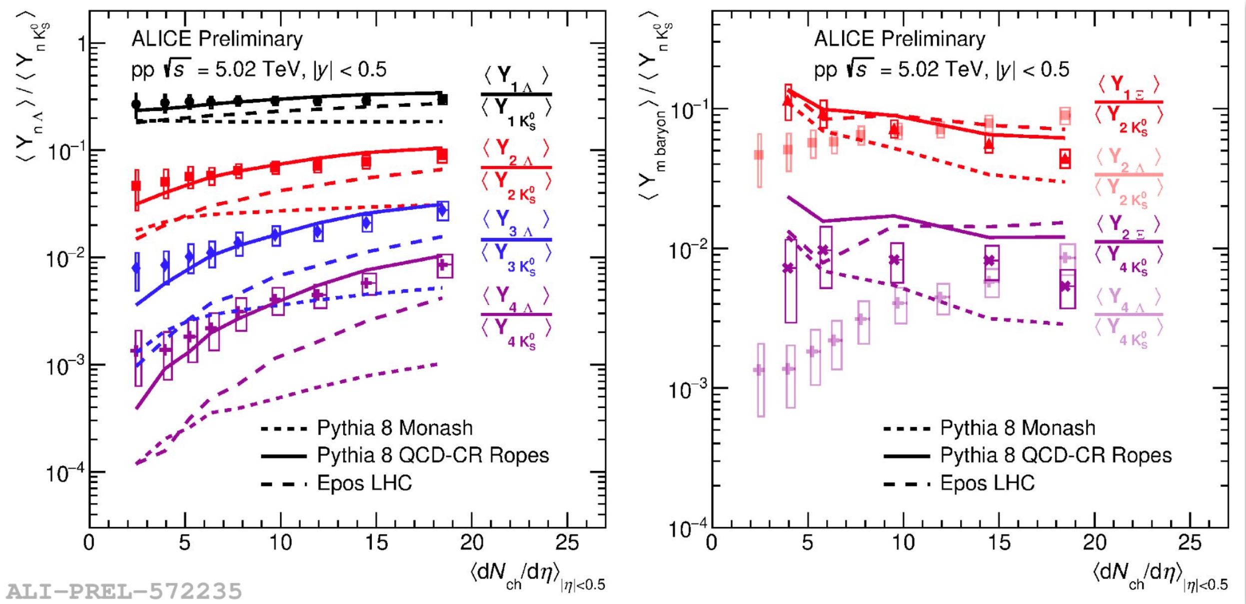

<u>Model comparison</u>:
All trends are rather well reproduced by Pythia 8 QCD-CR Ropes
→ strange quark production rate remains a puzzle, but once S is created the model of re-connection with light quarks catches the trends observed in the data

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Yield ratios with ΔS = 0

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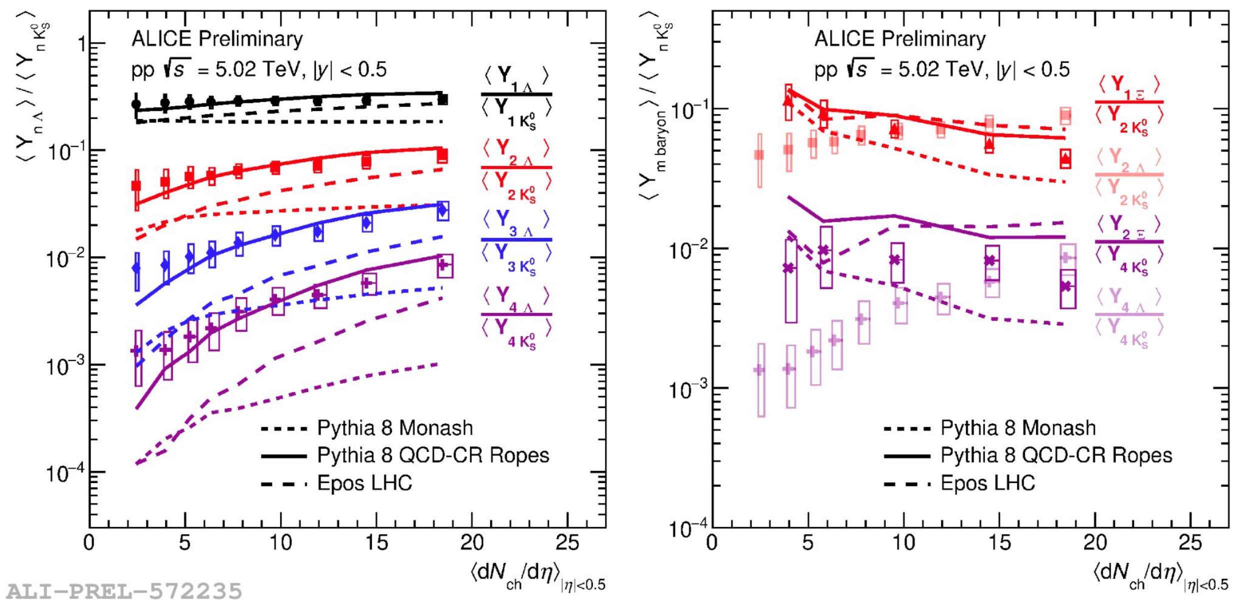

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MESSAGE #3

The measurement of $P(n_S)$ represents a unique opportunity to test the connection between average charged- and strange- particle production

- Classifying HM events using the transverse spherocity (azimuthal topology):
  - $S_0^{p_T=1}$ can be used to select strangeness enhanced/suppressed events
  - **topologies driven by soft physics** are consistent with the average HM events, **jet-like events** seem to be clear **outliers** (rare hard processes play little role for bulk observables)

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- Trying to decouple global properties and locally effects using the effective energy:
  - strangeness enhancement in pp collisions was **observed** at **fixed midrapidity multiplicity** and shows a **strong correlation with the effective energy** (initial stage)

Summary

- Classifying HM events using the transverse spherocity (azimuthal topology):
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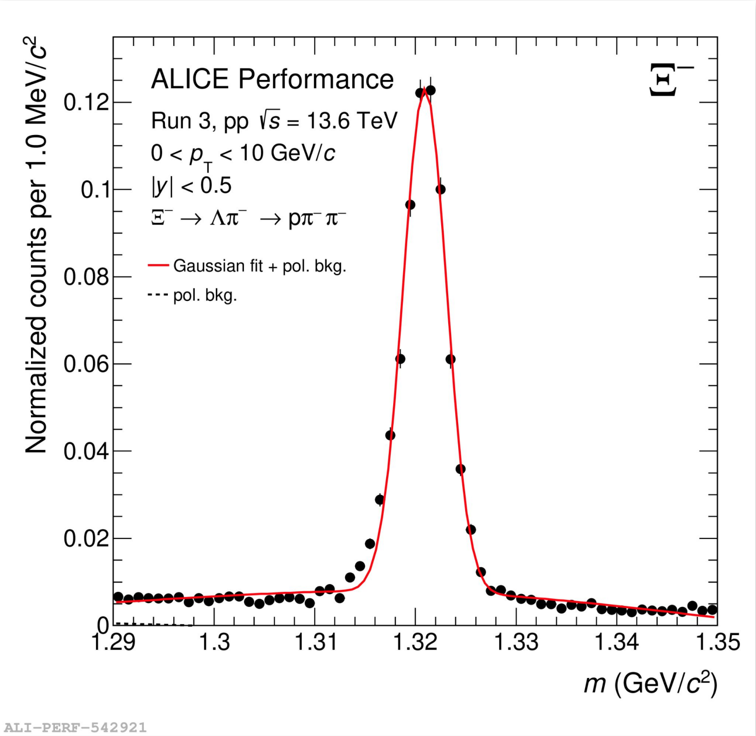
- Trying to decouple global properties and locally effects using the effective energy:
    - strangeness enhancement in pp collisions was **observed** at **fixed midrapidity multiplicity** and shows a **strong correlation with the effective energy** (initial stage)

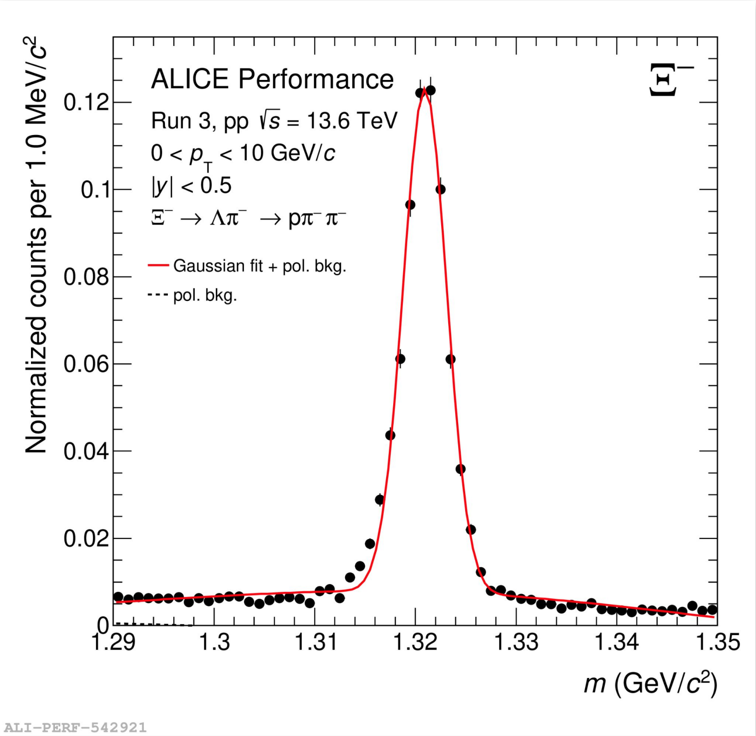
- Measuring (multi-)strange particle multiplicity distribution:
    - relevant extension of the traditional yield determination, as it tests at a higher order the strange hadron production mechanisms
    - **multiple strange hadron production yields** ratio with $\Delta S = 0$:
        - 2-, 3-, 4- Λ/K^0_S yield ratios increase with multiplicity (baryon-related effect)
        - m multi-strange baryons/n K^0_S decrease with multiplicity → decreasing the charged-particle multiplicity means depleting the number of light quarks, while keeping the number of s quarks fixed in the event
        - outlook: ratios with $\Delta S > 0$ → strangeness enhancement at its extremes!

Outlook - Run 3



- During the Run 3 data taking campaign started in 2022, ALICE plans to collect $\mathcal{O}(10^{12})$ collisions (**x 3000 wrt Run 2**)
- In order to cope with the available storage resources, events are selected using **software triggers** (*filters*) that exploit the **full reconstruction of each event**
- Several software filters have been developed for the selection of **events with strange hadron candidates** e.g. events containing multiple strange hadron candidates

Larger available statistics (3/4 order of magnitude higher) **will be especially useful for multi-strange analyses**



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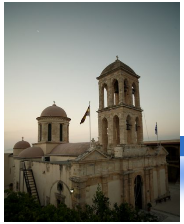


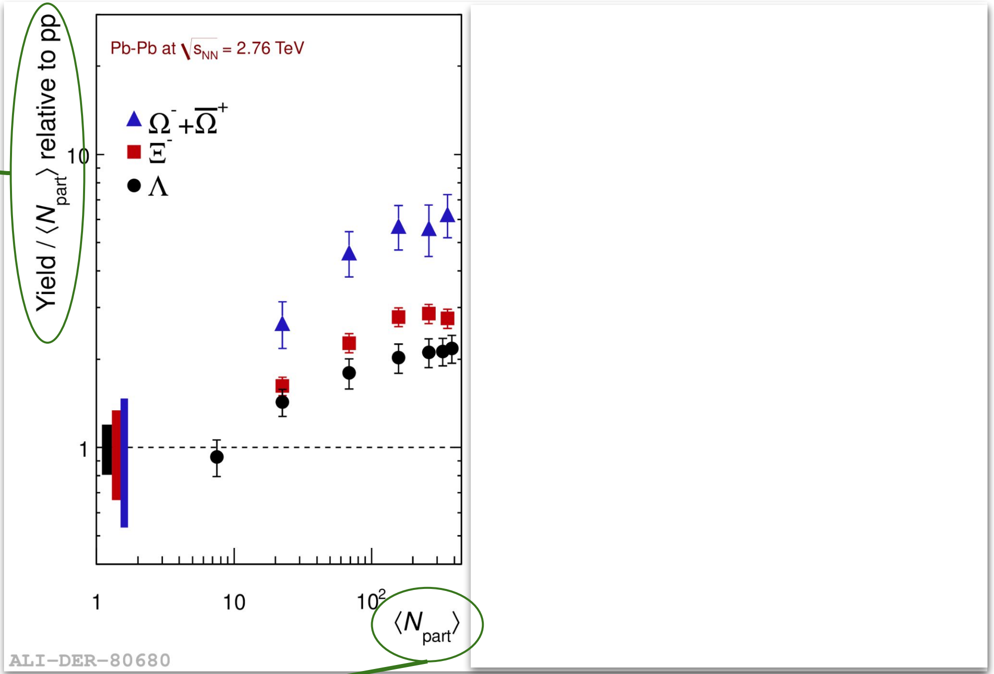
Back up


XIII International Conference
on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

ALICE Coll., arxiv.org/1307.5543

$$\frac{\text{stange particle yields in A-A collisions / Npart}}{\text{stange particle yields in pp/p-Be collisions / Npart}}$$

- For a given collision energy **the relative strange hadron yield grows with the centrality of the collision and with the strangeness content of the baryons**



average number of nucleons that participate to the collision

ALICE Coll., arxiv.org/1307.5543

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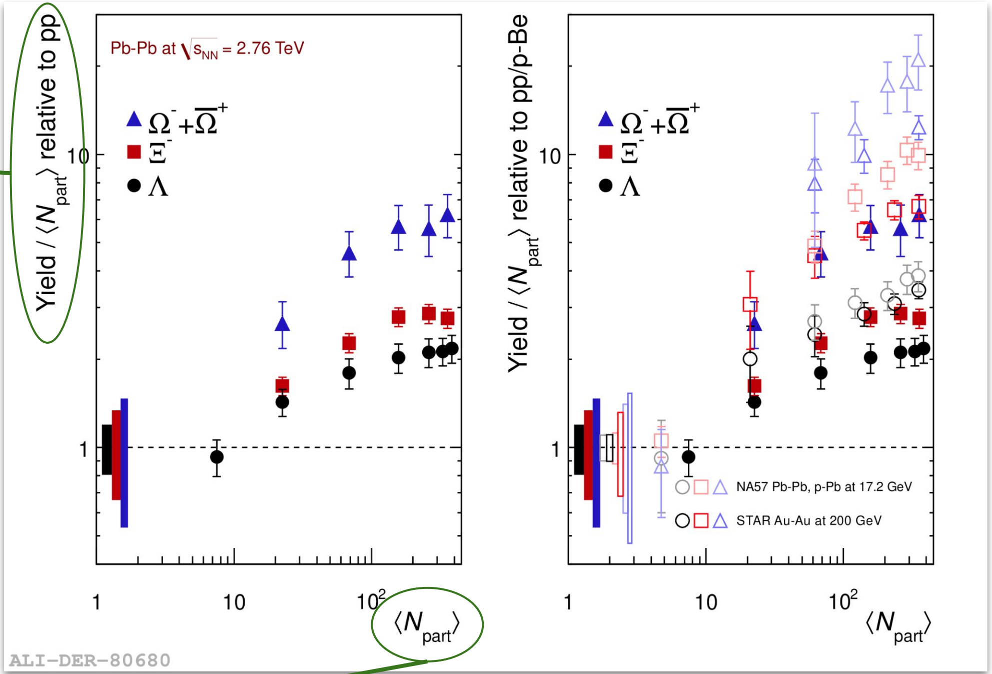
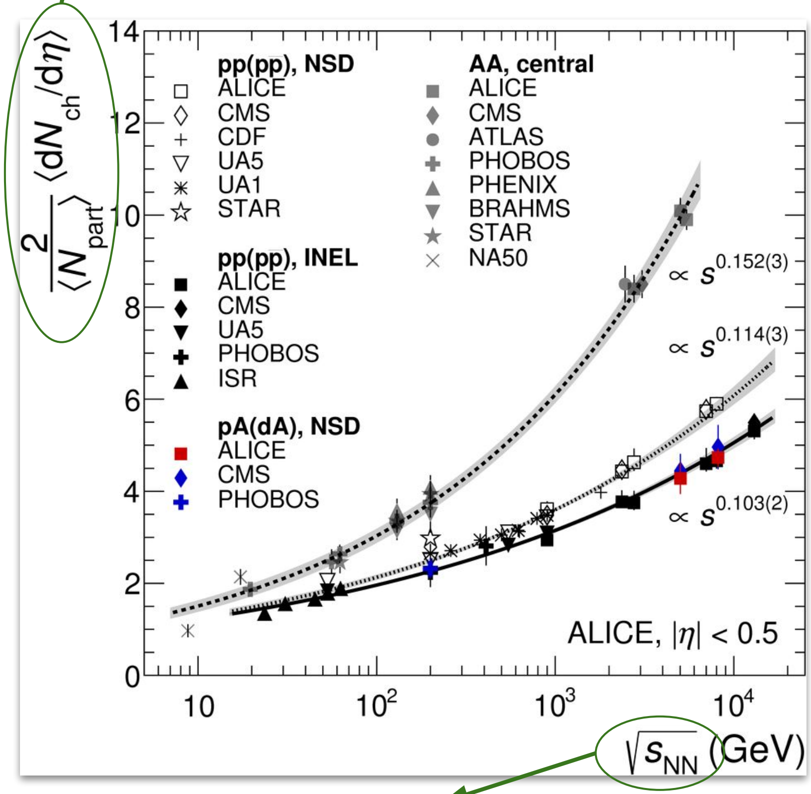
- For a given collision energy **the relative strange hadron yield grows with the centrality of the collision and with the strangeness content of the baryons**
- **Energy hierarchy problem**: ratio larger for lower energy collisions
  - If SE is related to an energy balance in a saturated medium, different enhancements depending on √s would not be expected: the Q-value to produce an $s\bar{s}$ pair is the same for all √s.
  - If the difference comes from a non complete saturation at lower energies, it should lead to larger enhancement as $\sqrt{s_{NN}}$ increases.



average number of nucleons that participate to the collision average charged-particle multiplicity



centre-of-mass energy

For all systems the number of charged-particles produced at central rapidity enhances as √s increases.

- **explanation of the energy hierarchy**: the higher the energy in the pp reference, the higher the average charged-particle multiplicity and, hence, the lower the ratio between yields in A-A and pp
  - pp is not an ideal reference

ALICE Coll., arxiv.org/1812.01312

Kinematical and **geometrical** criteria are used to reconstruct candidates for strange hadrons

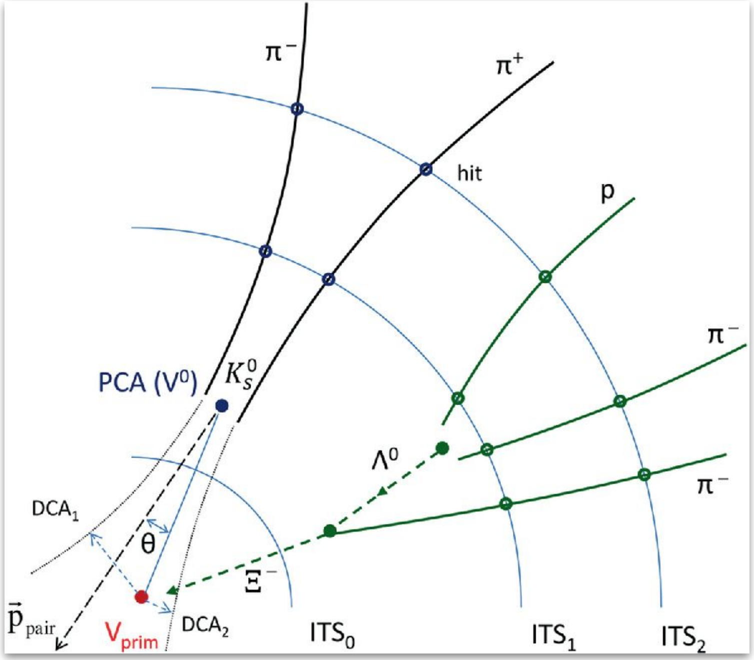
Identification of (multi-)strange hadrons is based on two topologies:

- **V0**
  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 V0 + charged particle

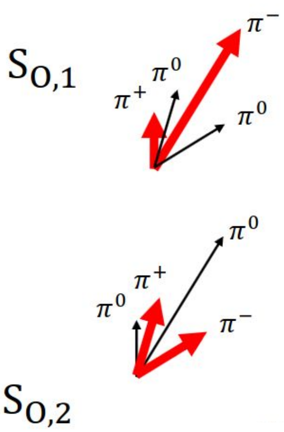
  $\Xi^- \rightarrow \Lambda + \pi^-$
  $\Omega^- \rightarrow \Lambda + K^-$

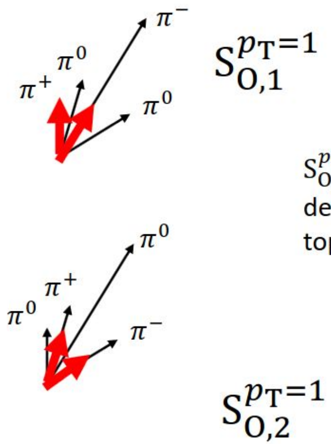


$S_0^{\,p\mathrm{T}=1}$ is measured as S_0, but only considers the angular component

$$S_O = \frac{\pi^2}{4}\min_{\hat{n}}\left(\frac{\Sigma_i |p_T \times \hat{n}|}{\Sigma_i p_{T_i}}\right)^2 \quad \rightarrow \quad S_O^{p_T=1} = \frac{\pi^2}{4}\min_{\hat{n}}\left(\frac{\Sigma_i |\hat{p}_T \times \hat{n}|}{N_{trk}}\right)^2$$

$S_{O,1}$ and $S_{O,2}$ will describe two completely different topologies!



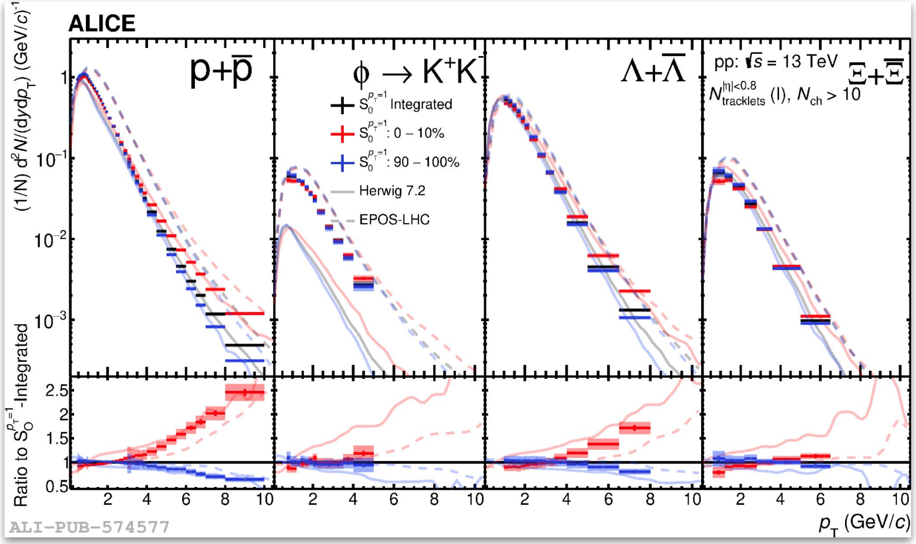


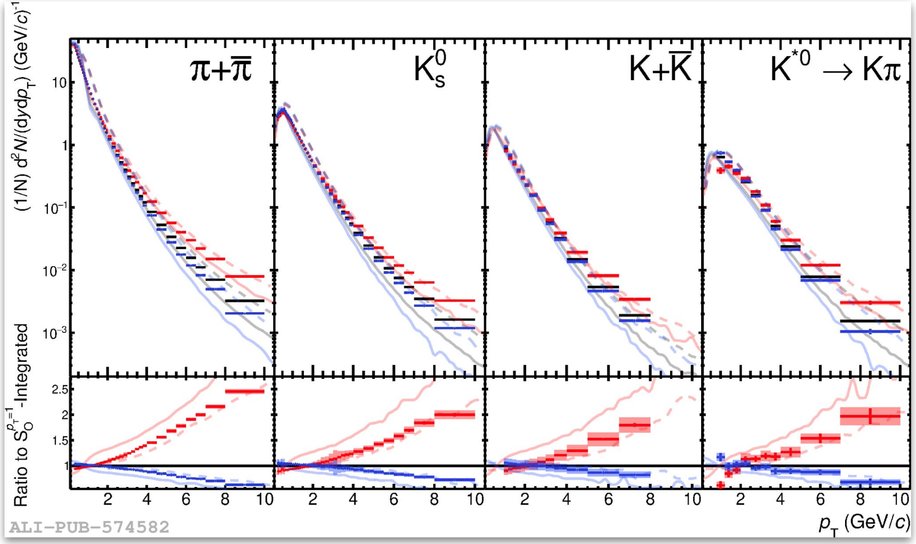
$S_{O,1}^{p_T=1}$ and $S_{O,2}^{p_T=1}$ will describe two similar topologies.

Baryons

Mesons

ALICE Coll., JHEP 05 (2024) 184





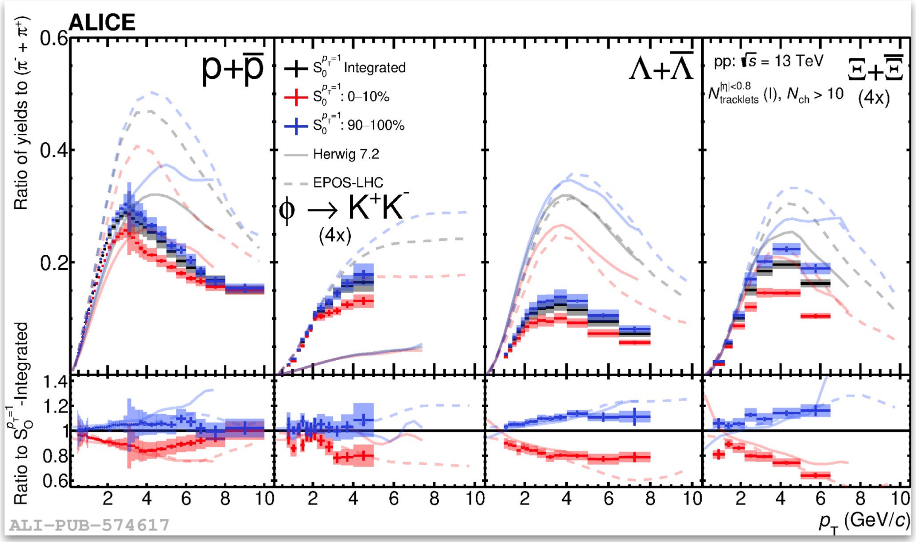
- Trends are consistent between all observed particle species:
  - for **jet-like events**: suppression at low-p_T, but enhancement at high-p_T (viceversa for **isotropic events**)
- Model comparison:
  - EPOS LHC overestimates the total yields, but is able to describe the $S_0^{p_T=1}$ - differential interplay for the mesons quite well

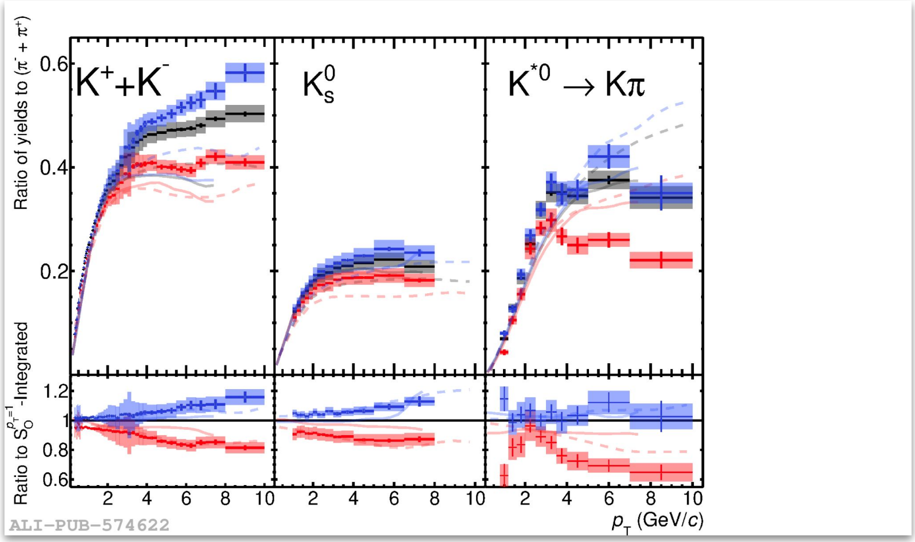
p_T spectra X-to-π ratios (top 1% of $N_{tracklets}^{|\eta|<0.8}$, 10% $S_0^{p_T=1}$ classes) - 2

Baryons

Mesons

ALICE Coll., [JHEP 05 (2024) 184](https://)



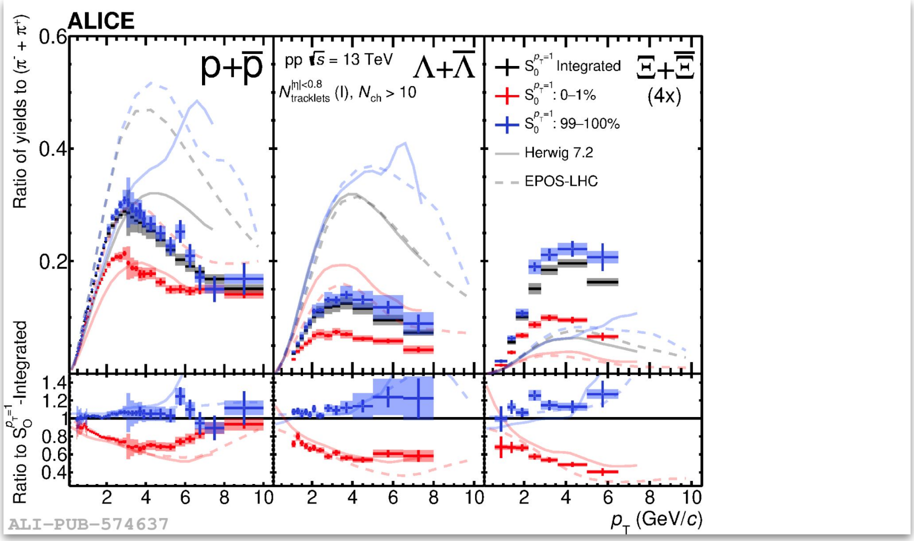


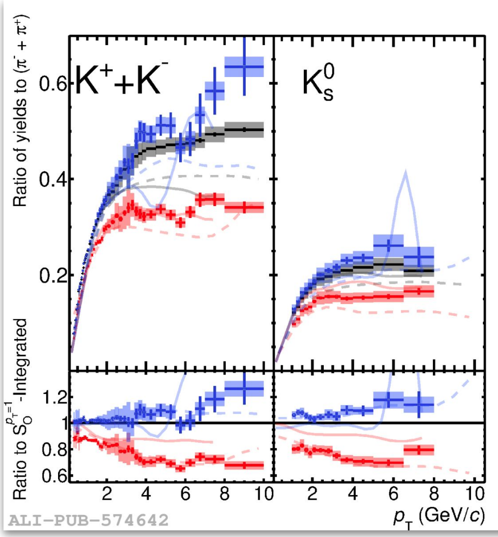
- Enhancement of strangeness yield in isotropic events, suppression in jet-like events → **strange particle production is favored in isotropic topologies**
- Selecting top 1% of $N_{tracklets}^{|\eta|<0.8}$, 1% $S_0^{pT=1}$ classes (see slide 29): more pronounced suppression in jet-like events
- Model comparison:
  - EPOS LHC and Herwing 7.2 are able to qualitatively describe some trends, but are not able to describe the full evolution, mainly towards larger p_T

Baryons

Mesons

ALICE Coll., JHEP 05 (2024) 184





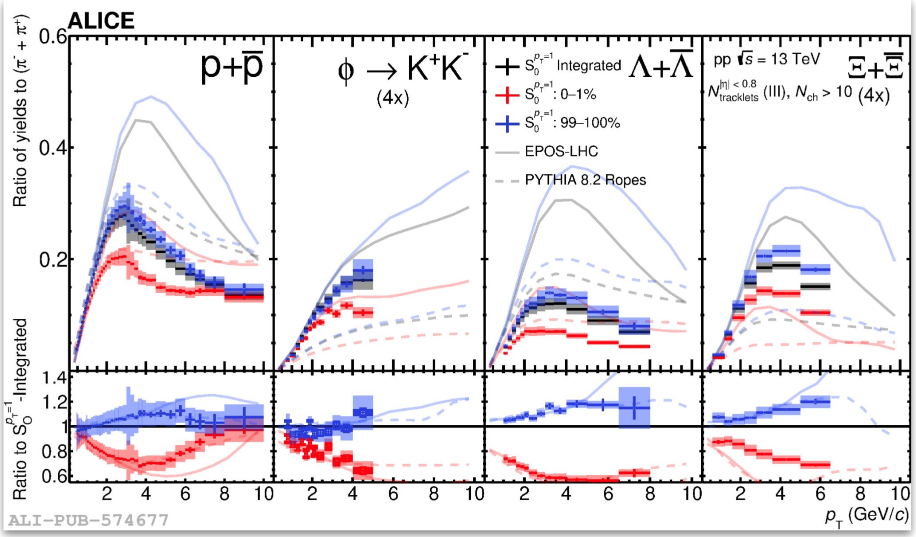
NOTE: Resonances are excluded due to low statistics

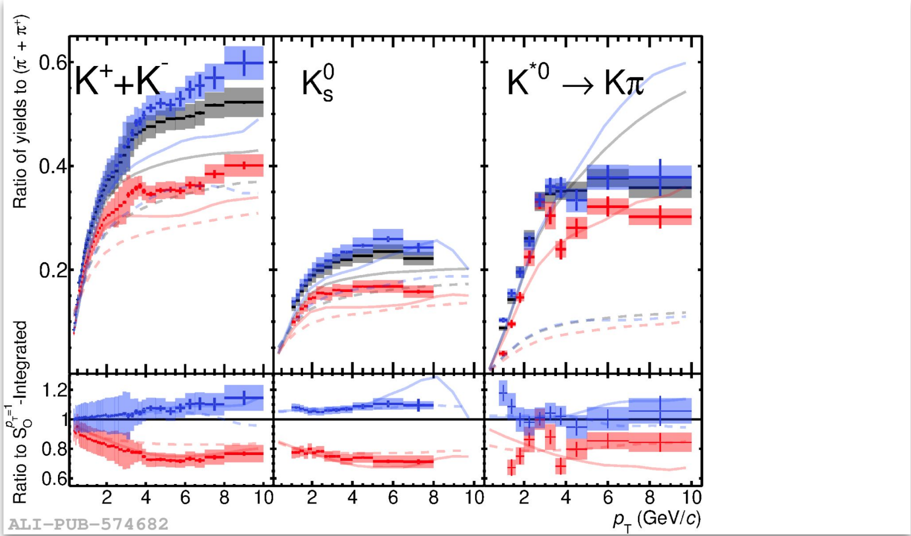
- Selecting top 1% of $N_{tracklets}^{|\eta|<0.8}$, 1% $S_0^{pT=1}$ classes: more pronounced suppression in **jet-like events** → **the abundance of strange hadrons in high-multiplicity events are produced in events that are associated to soft physics in terms of azimuthal topology**

Baryons

Mesons

ALICE Coll., JHEP 05 (2024) 184





- Broadened multiplicity range (0-10% of $N_{tracklets}^{|\eta|<0.8}$, 1% $S_0^{pT=1}$ classes) in order to include resonances

p_T spectra X-to-π ratios (top 1% V0M, 10% $S_0^{p_T=1}$ classes)

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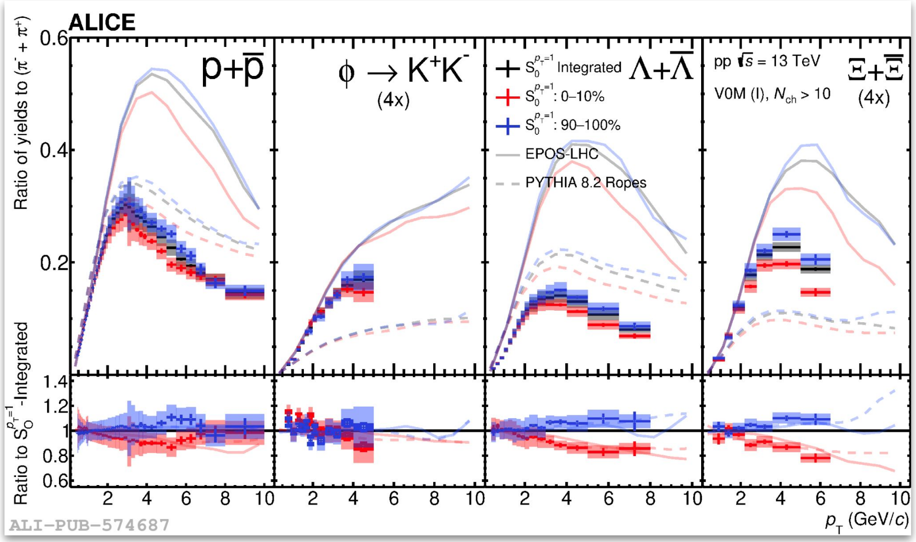
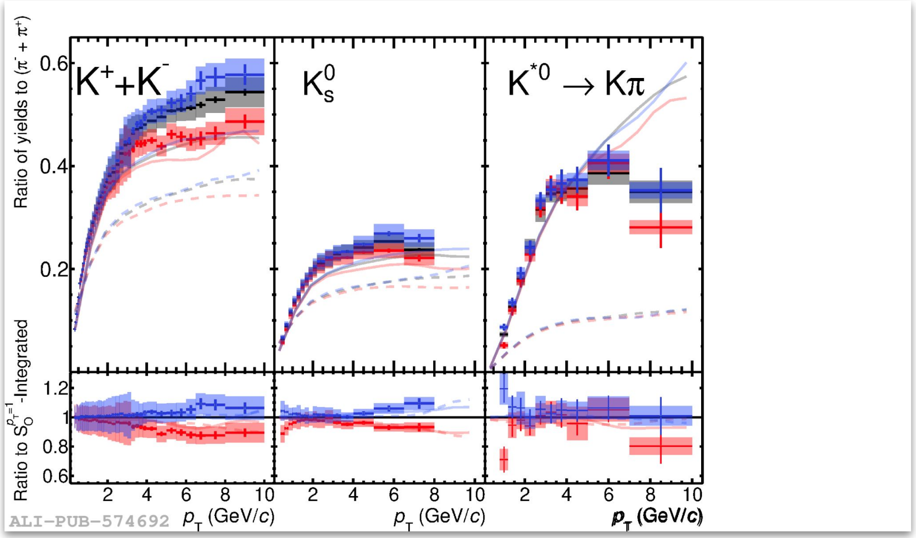
Baryons



Mesons

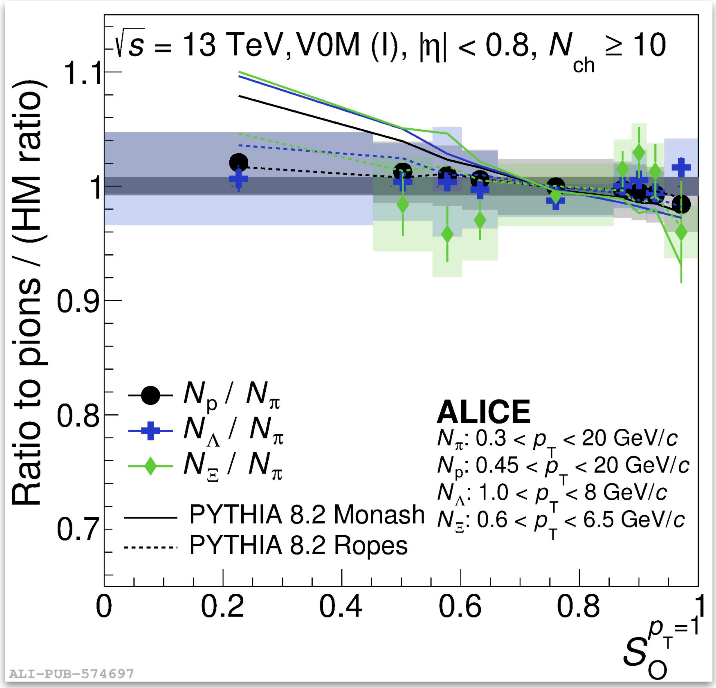
ALICE Coll., [JHEP 05 (2024) 184]

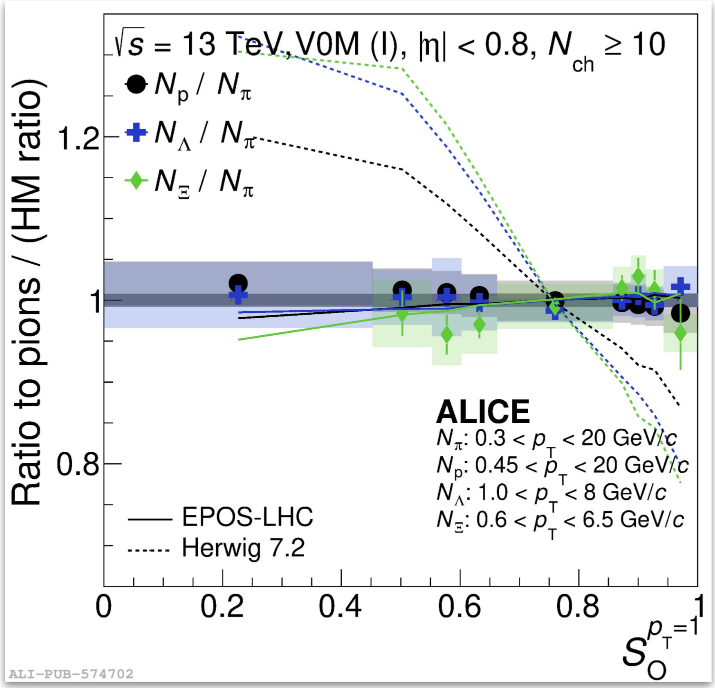


- Estimating the multiplicity at forward using V0 detectors **the observed effects is comparatively weak to either percentile of tracklets**

ALICE Coll., JHEP 05 (2024) 184

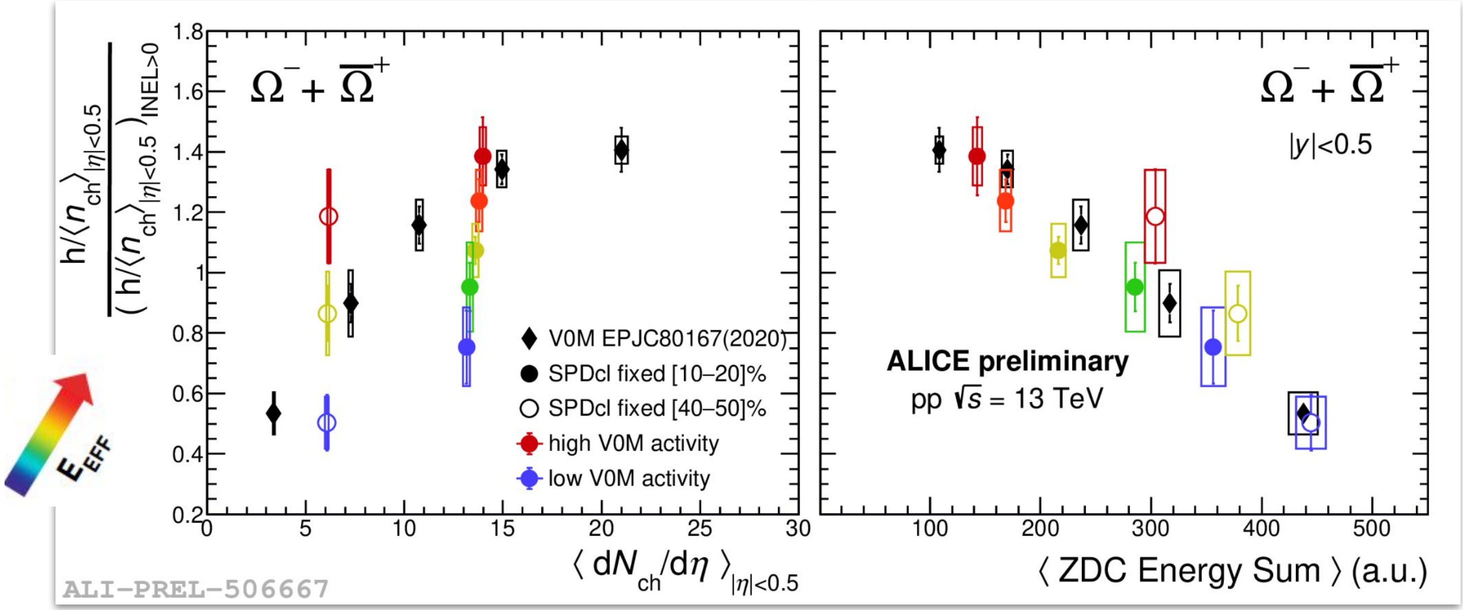
- Selecting high multiplicity with V0M detectors the evolution as a function of $S_0^{p_T=1}$ is almost flat
- Model comparison:
  - Both EPOS LHC and PYTHIA 8.2 Ropes hadronization framework are able to qualitatively predict the insensitivity of strange particle production





Ω yields normalised to the charged particle multiplicity, **fixing the multiplicity at midrapidity**:

- **increase** for **decreasing forward energy (increasing E_{eff})** – left
- scaling trends with ZDC energy are **compatible with standalone classes**– right



Run 3 data will allow to extend this approach to more classes having larger available statistics

Iterative procedure based on the Bayes' theorem using a picture of causes C ("true values") and effects E ("observed values")

$$P(C_i|E_j) = \frac{P(E_j|C_i)\cdot\pi(C_i)}{\sum_{i=1}^{n_C} P(E_j|C_i)\cdot\pi(C_i)}$$

$P(E_j|C_i)$ estimated by using Monte Carlo (response matrix)

$P(C_i|E_j)$ → probability that different C_i were responsible for the observed effect E_j → GOAL

$\pi(C_i)$ → prior probabilities (initially arbitrary, but updated on subsequent iterations)

- Choosing a prior distribution in order to apply Bayes' theorem → posterior probability matrix obtained
- Applied to "observed spectra" → 1st estimation of the corrected spectra
- The corrected spectra obtained in the previous step becomes the prior probability and the correction proceeds as before
- Procedure is re-iterated until stability is achieved (**regularization parameter: n_{iter}**)

$$\hat{n}(C_i) = \frac{1}{\epsilon_i}\sum_{j=1}^{n_E} n(E_j)\cdot P(C_i|E_j) = \sum_{j=1}^{n_E} M_{ij}\cdot n(E_j)$$

expected number of events in the cause bin *i*

→ M_{ij} is the unfolding matrix: $M_{ij} = \frac{P(E_j|C_i)\cdot\pi(C_i)}{\epsilon_i\cdot\sum_{l=1}^{n_C} P(E_j|C_l)\cdot\pi(C_l)}$

→ $n(E_j)$ measurements (effects)

→ ϵ_i efficiencies

unfolding errors: covariance matrix

$$V(\hat{n}(C_k),\hat{n}(C_l)) = \sum_{i,j=1}^{n_E} \frac{\partial\hat{n}(C_k)}{\partial n(E_i)} V(n(E_i),n(E_j)) \frac{\partial\hat{n}(C_l)}{\partial n(E_j)}$$

G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem"