**Livio Bianchi** *
Università & INFN Torino

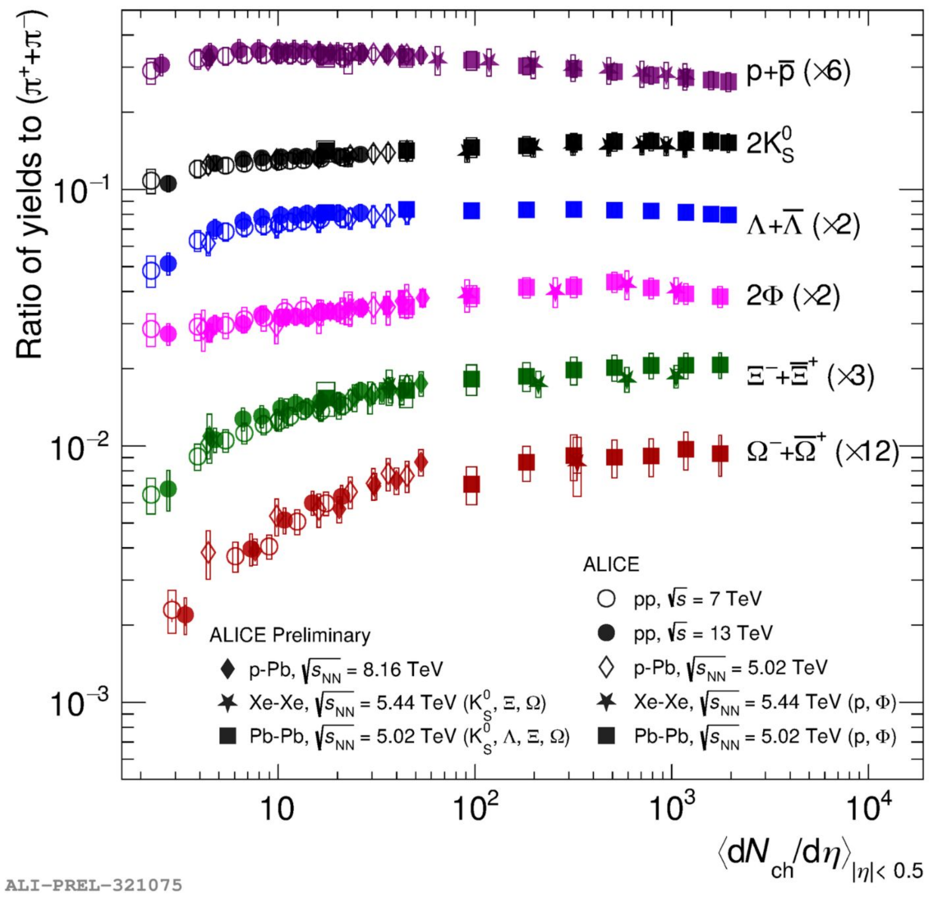
# Selected news on strangeness production at the LHC

*QCD challenges from pp to AA*
Münster 2-6 Sep. 2024

* Livio.Bianchi@cern.ch

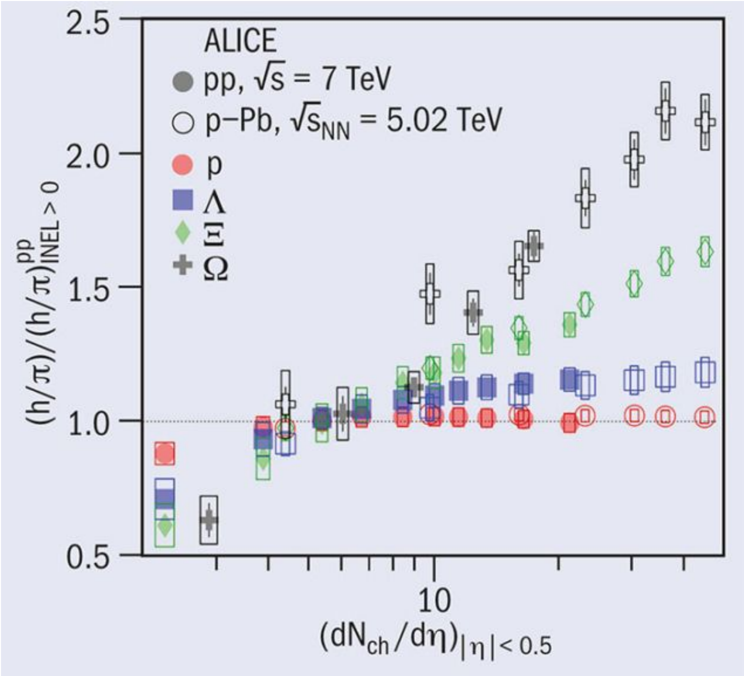
# Strange hadron yields from small to large systems

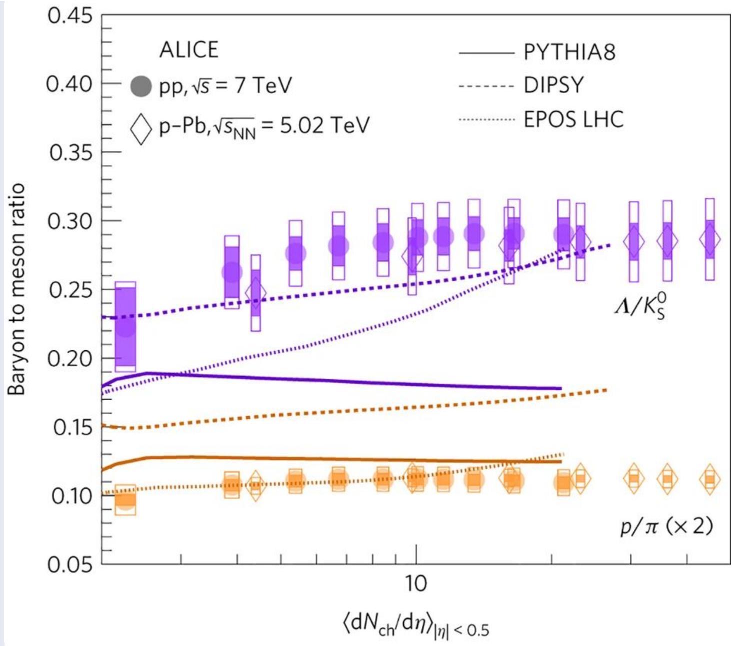
ALICE, Nature Physics 13, 535–539 (2017)




Iconic figure at the LHC:

- smooth strangeness enhancement (SE) VS final state multiplicity
- Strange content hierarchy: **SE($\Omega$) > SE($\Xi$) > SE($\Lambda$,$K^0_S$)**
- strangeness- and not baryon-related
- peculiar role of ϕ meson

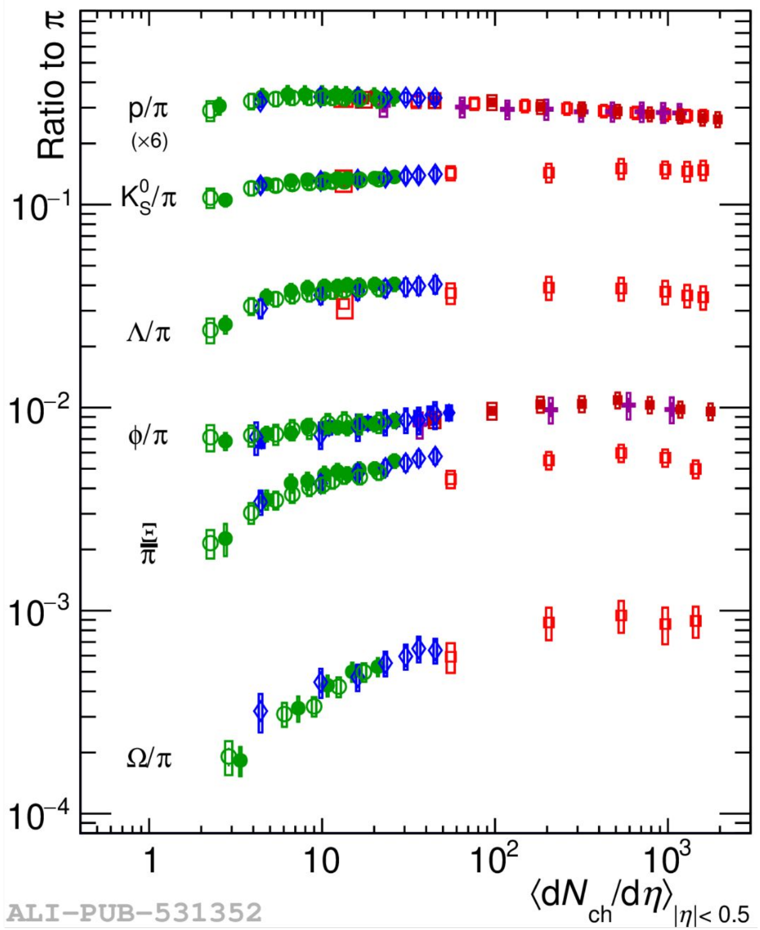


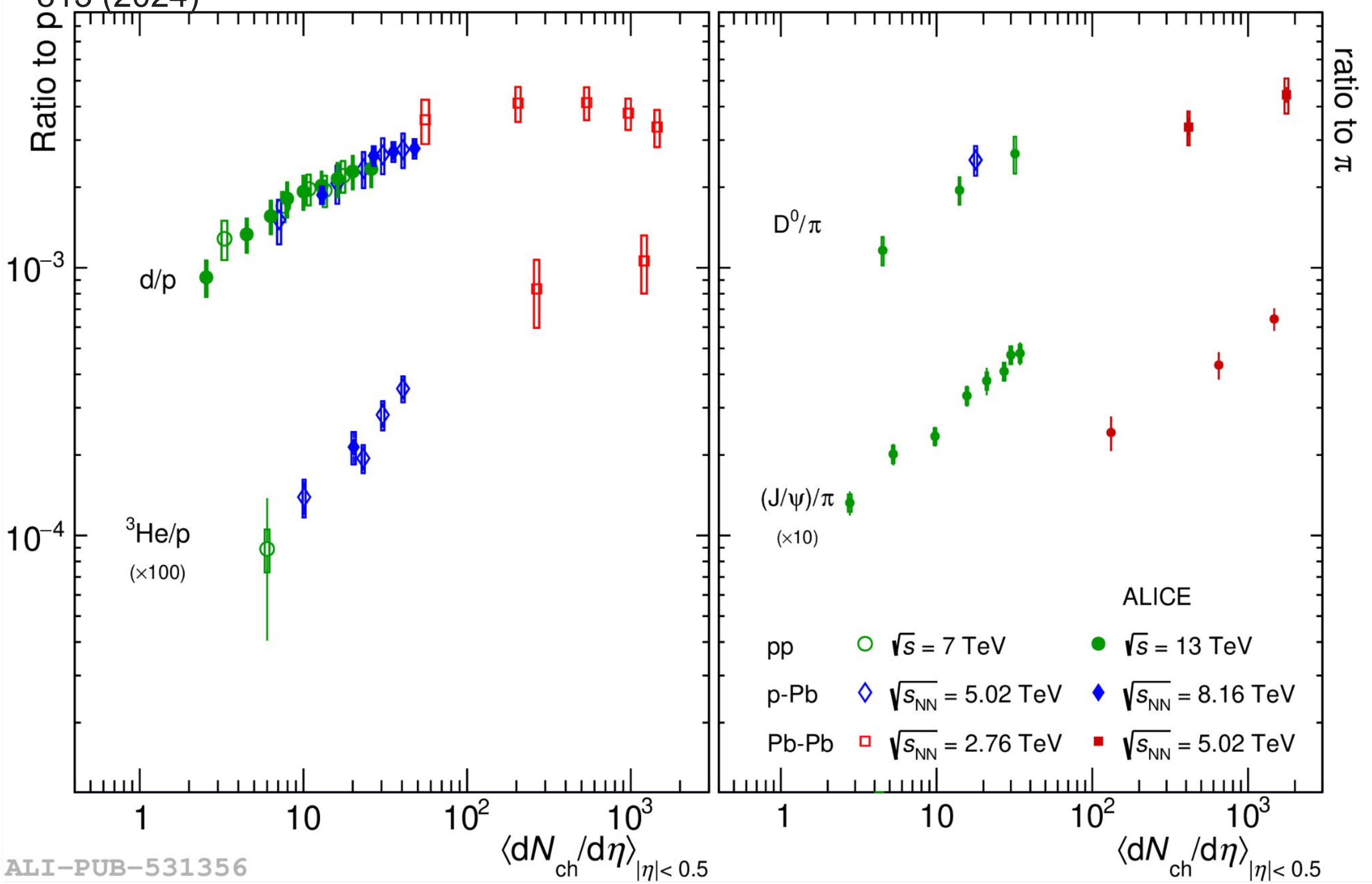
# Strange, but also not strange!



ALICE Collaboration, The ALICE experiment: a journey through QCD, *Eur. Phys. J. C* **84**, 813 (2024)




↑
**Strangeness**



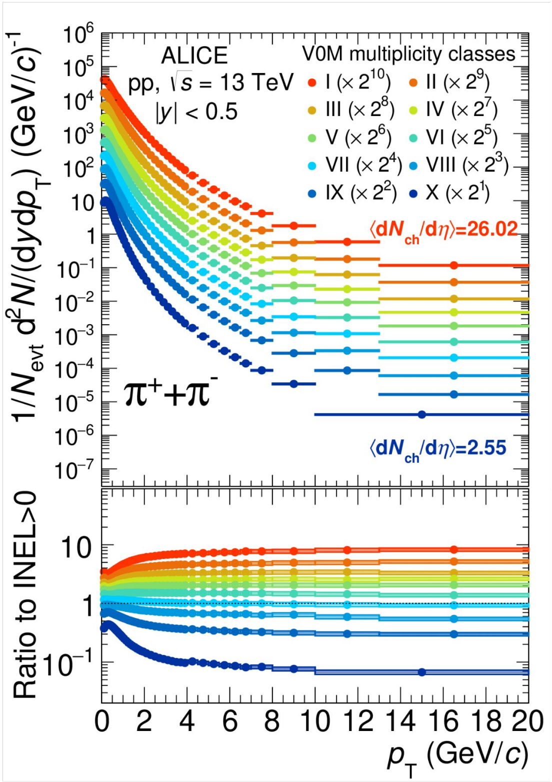

↑
**Nuclei**

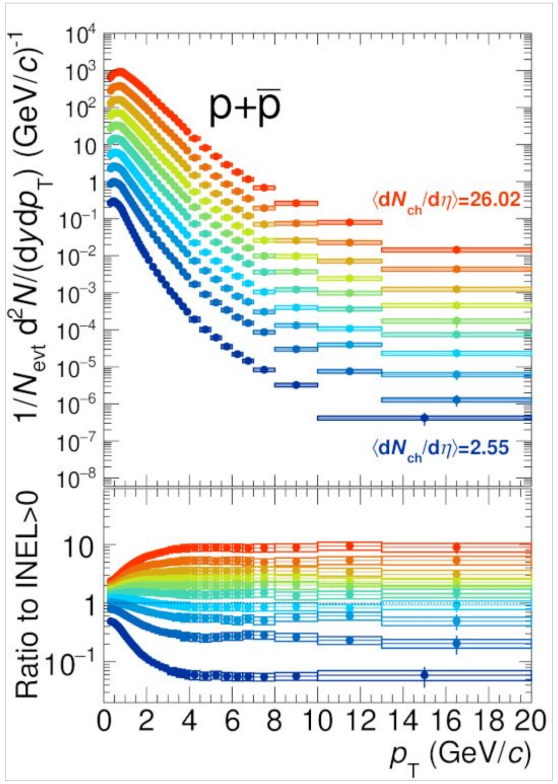
↑
**Charm**

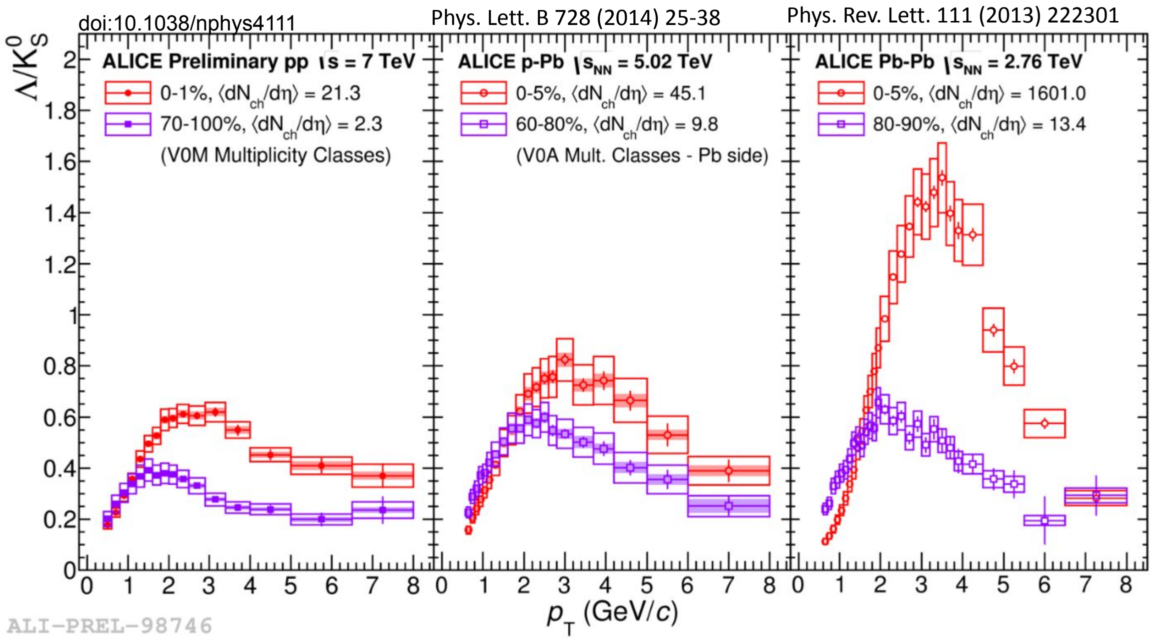
# Spectra modification in pp and p-Pb







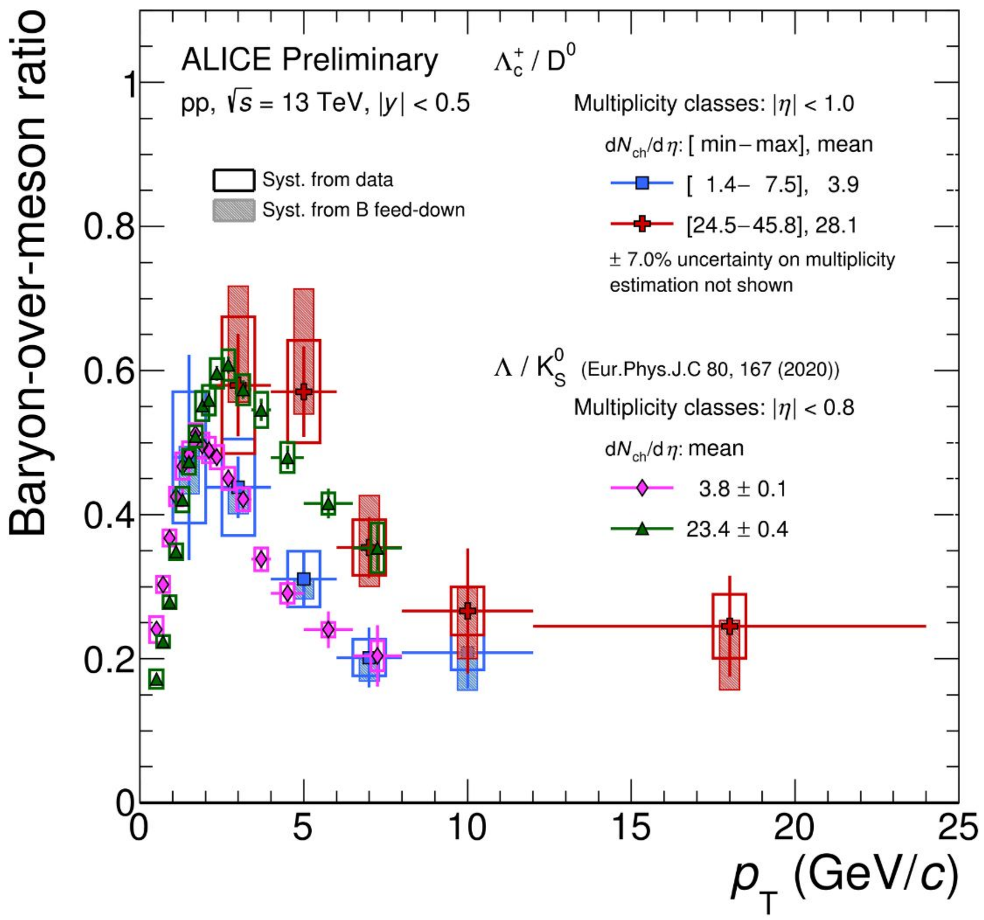




The ratio depends on the event multiplicity in a **qualitatively similar** way **in pp, p-Pb and Pb-Pb**

In **small systems spectra evolve** with $\langle dN_{ch}/d\eta \rangle$ in a qualitative **similar way as in heavy ion collisions** (valid for all identified particles studied)

The magnitude is smaller in pp with respect to p-Pb and Pb-Pb, but note that for similar percentiles $\langle dN_{ch}/d\eta \rangle$ is dramatically different among the three systems

# excursus: baryon/meson anomaly for hard probes




ALI−PREL−348097

**Striking similarities between light and heavy flavors in small systems**

Intriguing observation:

- Hydro for charm? Hard to believe! Not supported by A-A observations:
  ↪ low-$p_T$ hierarchy $v_2^h > v_2^c > v_2^{cc}$
  ↪ $\Lambda/K_S^0 > \Lambda_c/D_0$
  ⇒ Challenges hydro hypothesis for light flavors in pp
- Coalescence at intermediate $p_T$ with same net effect for light and heavy flavors?

Need to extend $\Lambda_c/D_0$ at lower $p_T$ and with larger statistics

# Recent extensions: P($n_s$)

Livio Bianchi
QCDCppAA
3 Sep 2024



Unique opportunity to test the connection between average-charged and strange particle multiplicity production throughout very extreme situations

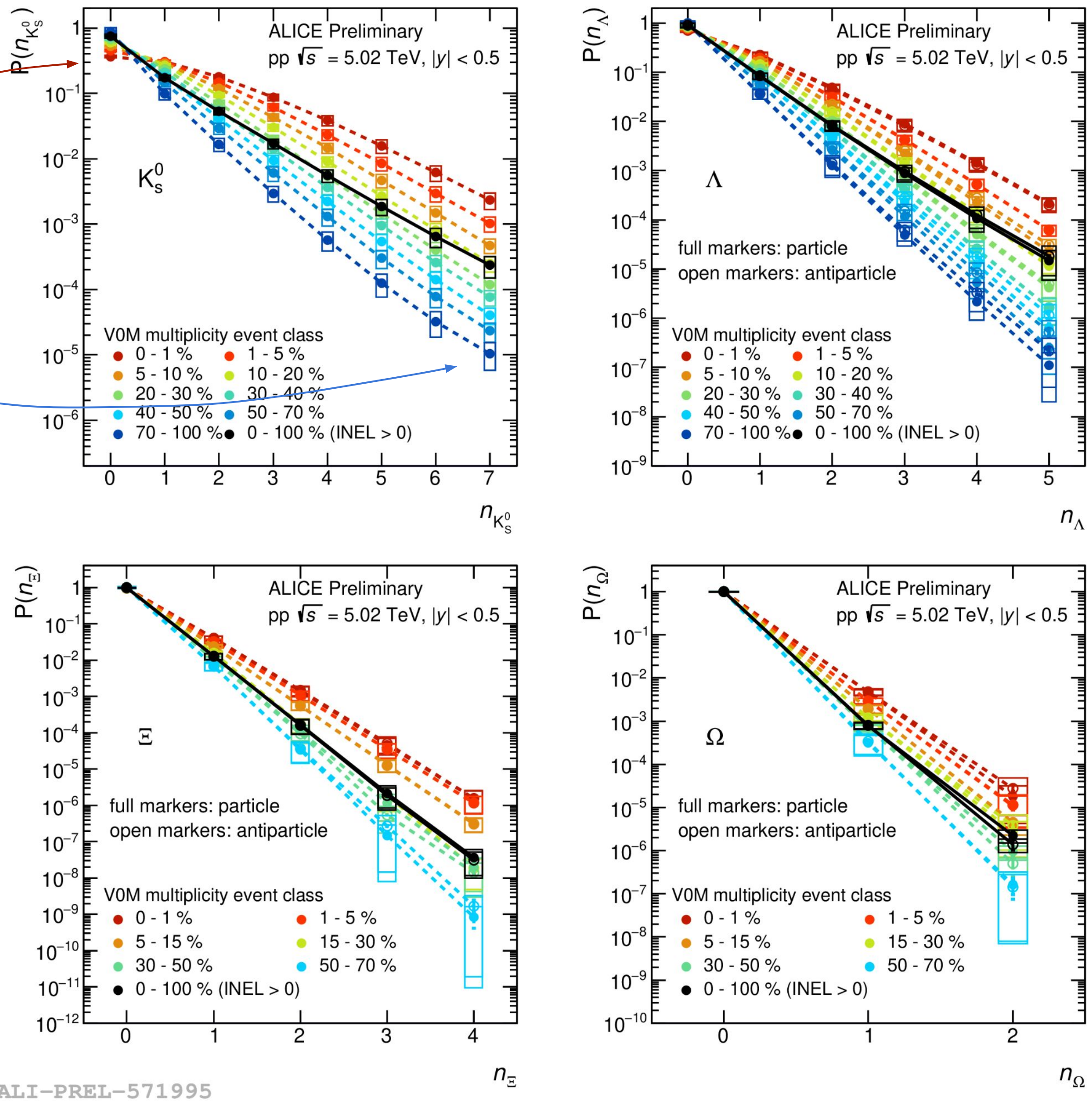
⟨dNch/dη⟩ ~ 20
0 $K^0_S$

⟨dNch/dη⟩ ~ 3
7 $K^0_S$

From this strange particle multiplicity distribution, the average production yield of *n* particles per event can be calculated through:

$$\langle Y_{nS}\rangle = \sum_{i=n}^{n^{max}} \frac{i!}{n!(i-n)!}\cdot P(n)$$

- $\langle Y_{1S}\rangle$ is the average of the multiplicity distribution (corresponding to what was called "dN/dy" or "yield" in previous publications)
- $\langle Y_{n>1\,S}\rangle$ identifies the average production yield of doublets, triplets, ..., multiplets of the given particle.



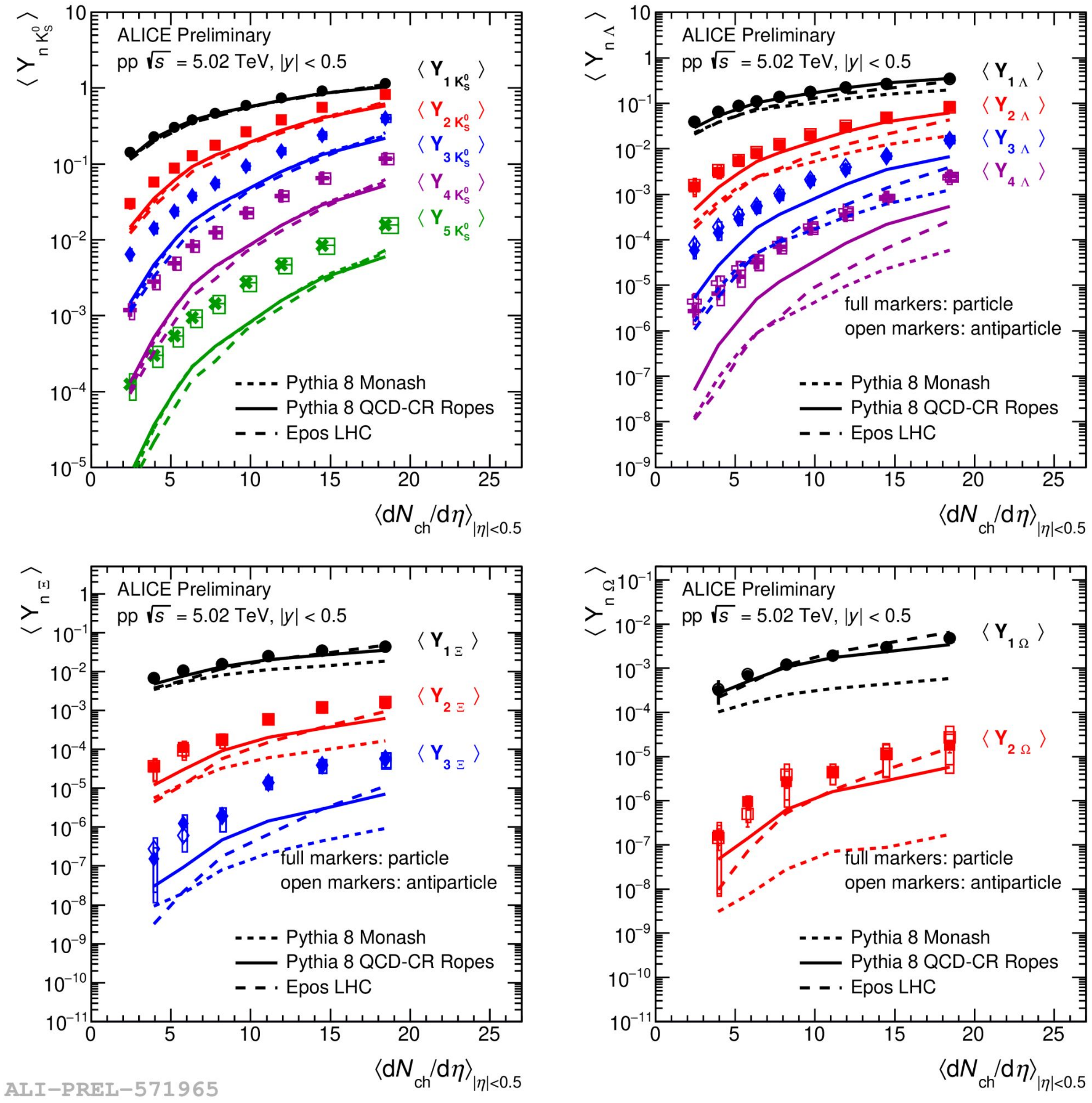
# $\langle Y_{n\,S} \rangle$ : multiplets production yields

Agreement with models deteriorates with increasing *n*

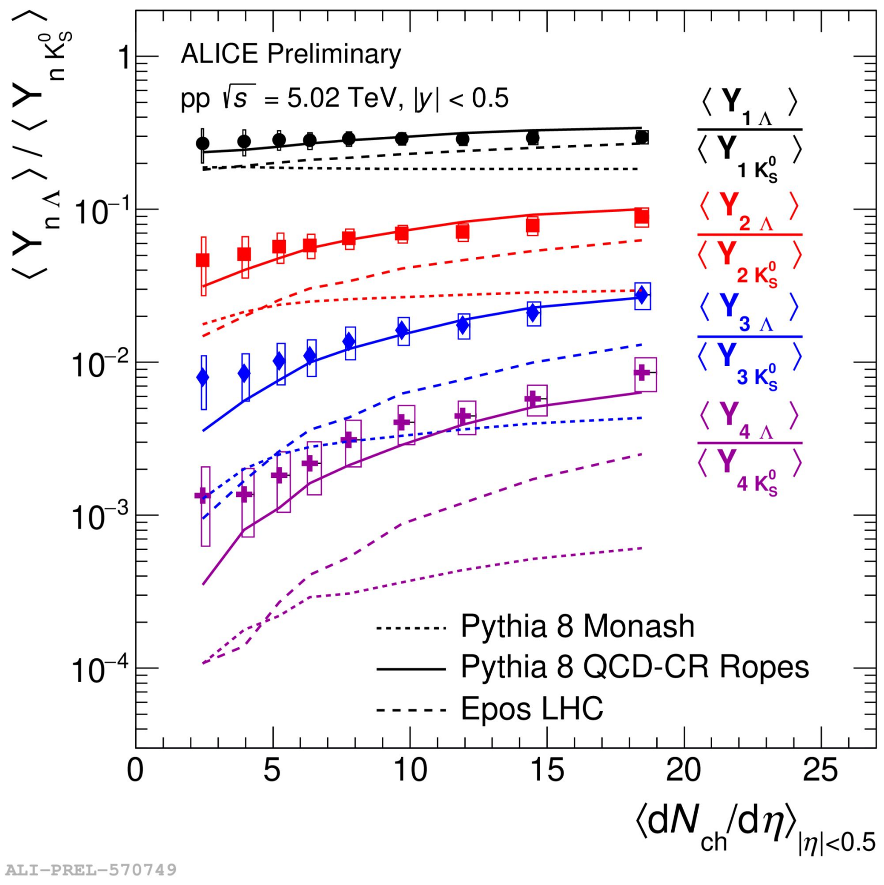
Comparison to models very statistics demanding! 10B events here. Would be interesting to see comparison to EPOS 4

No difference in predictions from Monash and QCD-CR Ropes for $K^0_S$, while large improvements for baryons ⟶ trend with multiplicity well described, but undershooting

EPOS-LHC: better agreement at high multiplicity than at low



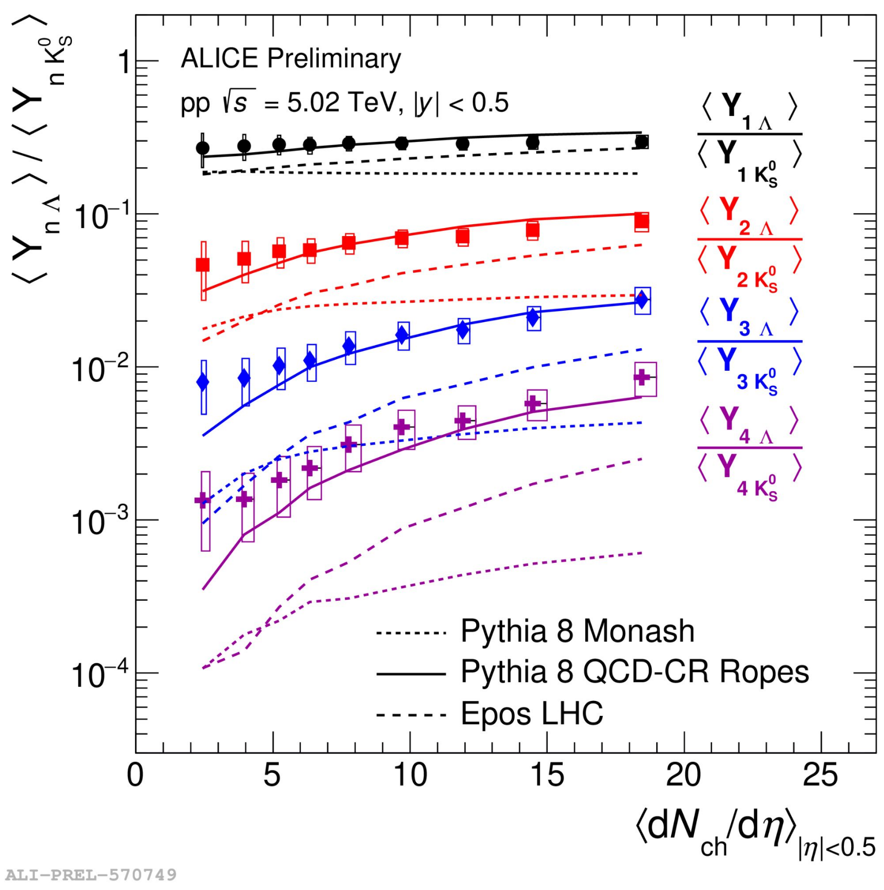
# ΔS=0 ratios

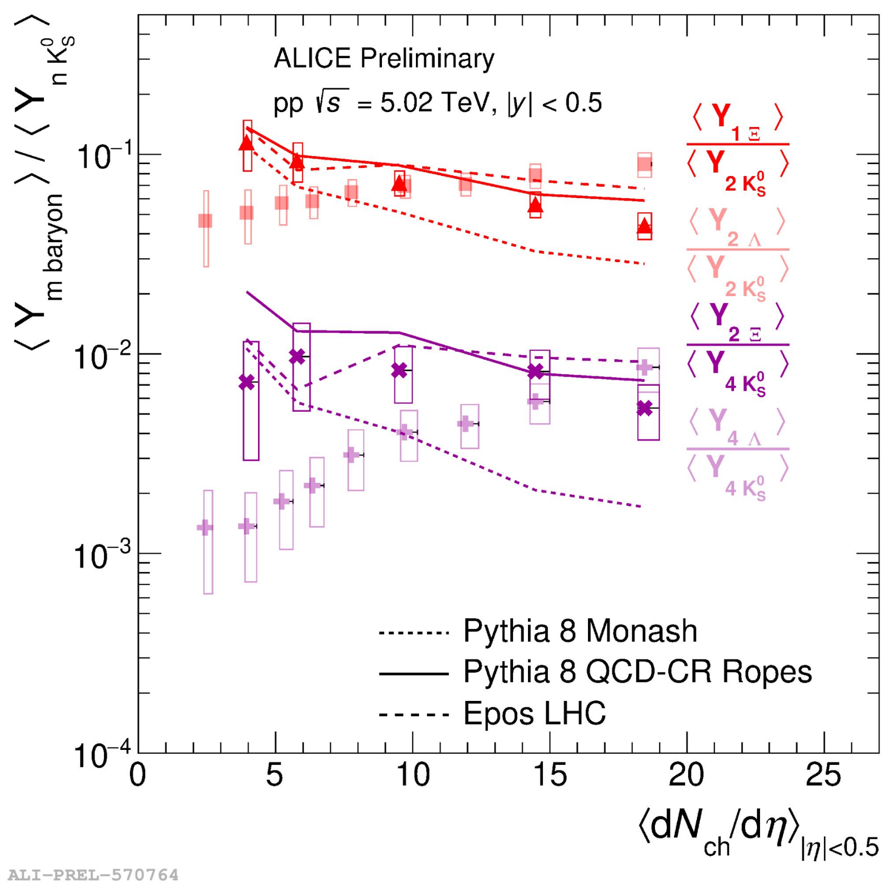



Enhancement with multiplicity not connected to strangeness unbalance (mass? baryon number? … )

Very well described by Pythia 8 QCD-CR Ropes

# ΔS=0 ratios




Again, good description by Pythia 8 QCD-CR Ropes which does a good job in re-connecting strange to lighter quarks

**Is it all played by QCD-CR or ropes actually plays a role?**

Many more ratios to come!

Enhancement with multiplicity not connected to strangeness unbalance (mass? baryon number? … )

Very well described by Pythia 8 QCD-CR Ropes

Not mass ($m_{\Xi} > 2*m_{K0S}$)
Not baryon number

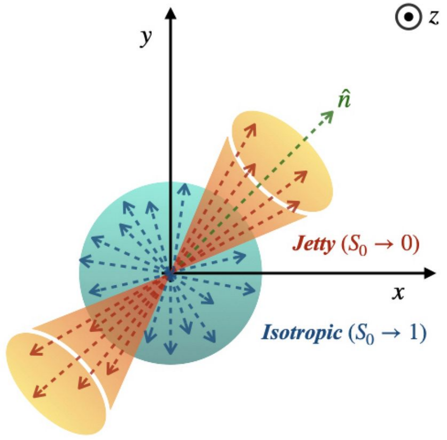
number of light quarks involved!

# Production in- and out-of-jet

# Are spectra modified in the same way in- and out-of-the jet?

Livio Bianchi
QCDCppAA
3 Sep 2024






pp collisions feature complicated topologies. Jets and Underlying Event (UE) coexist

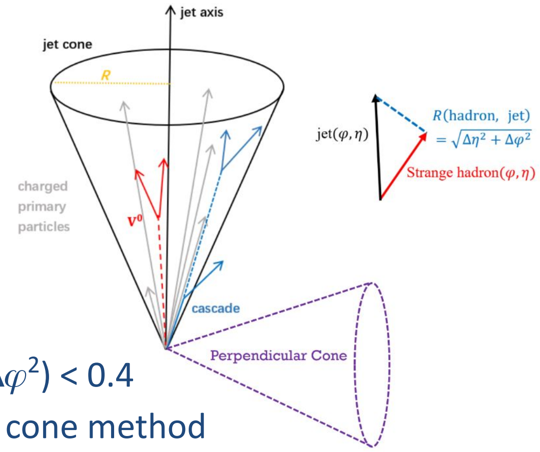
Expect QGP-like features to emerge in UE rather than in boosted jets

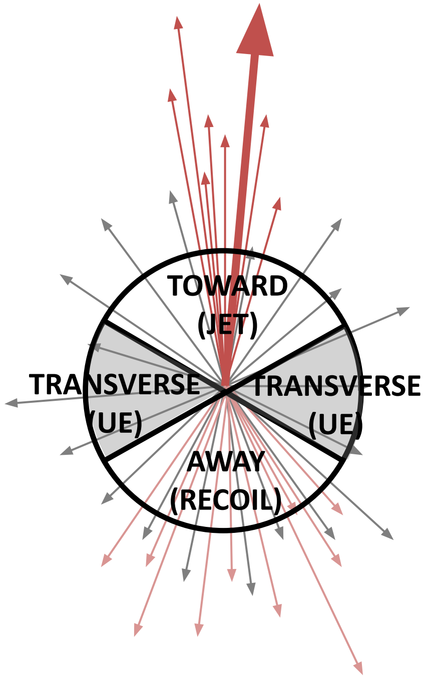
**Leading hadron method:**

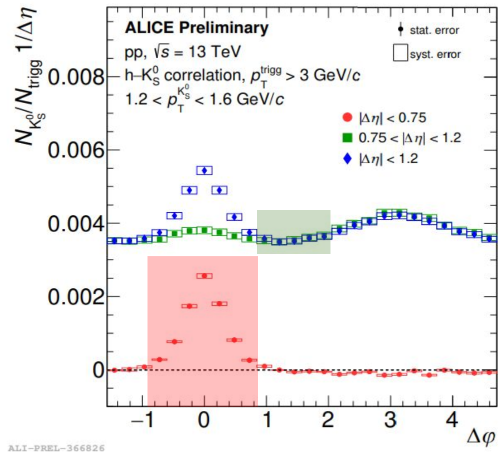
- jet direction: the one of the highest $p_T$ hadron
- $p_T^{leading}$ > 4-5 GeV/c
- hadron-strange correlation method to extract particle yields in- and out-of-the jet

**Jet finding:**

- Charged track selection: $|\eta| < 0.9$, $p_T > 0.15$ GeV/$c$
- Jet finder: anti-$k_T$, $R = 0.4$, $|\eta_{jet}| < 0.35$, $p_{T,jet} > 10$ GeV/$c$
- Strange particles found in:
  - Jet Cone →
    $R_{\text{Strange hadron, jet}} = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)} < 0.4$
  - Underlying Event → perp. cone method
  - Jet fragmentation → JE = JC - UE



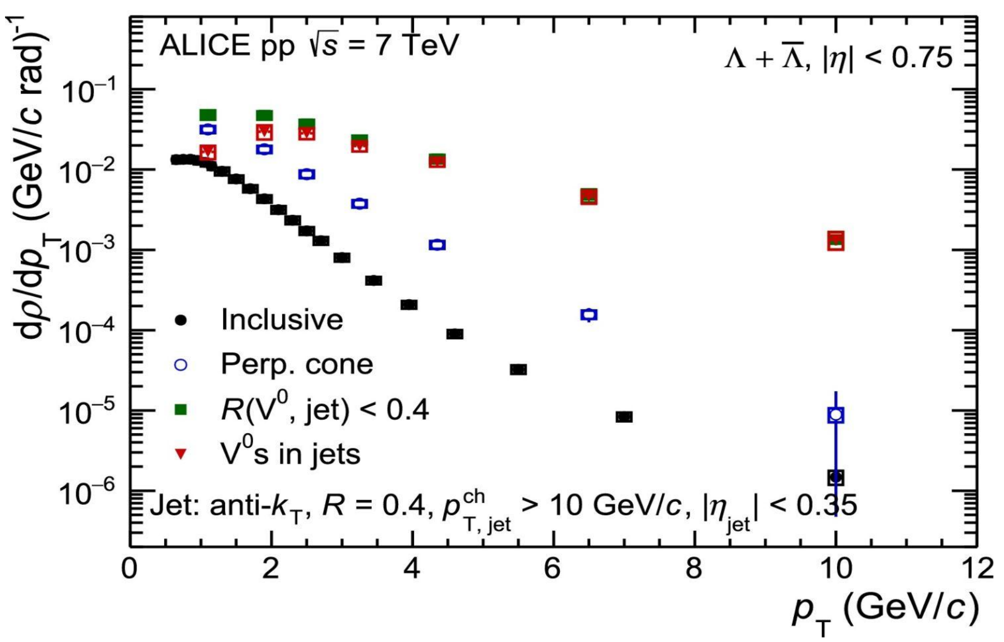



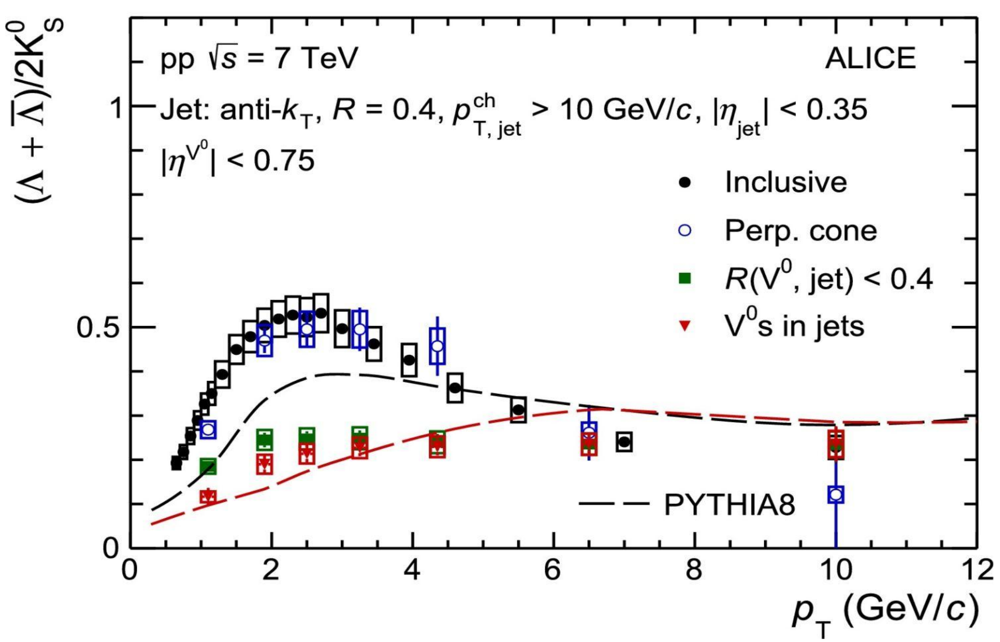



# baryon/meson anomaly in- and out-of-jet in pp



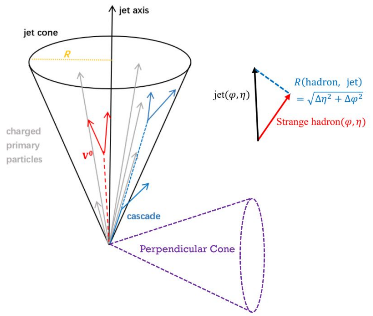
ALICE, Phys. Lett. B 827 (2022) 136984




Spectra are harder in the jet than in the perpendicular cone (UE)

Dynamics in the baryon/meson are dominated by what observed in the UE

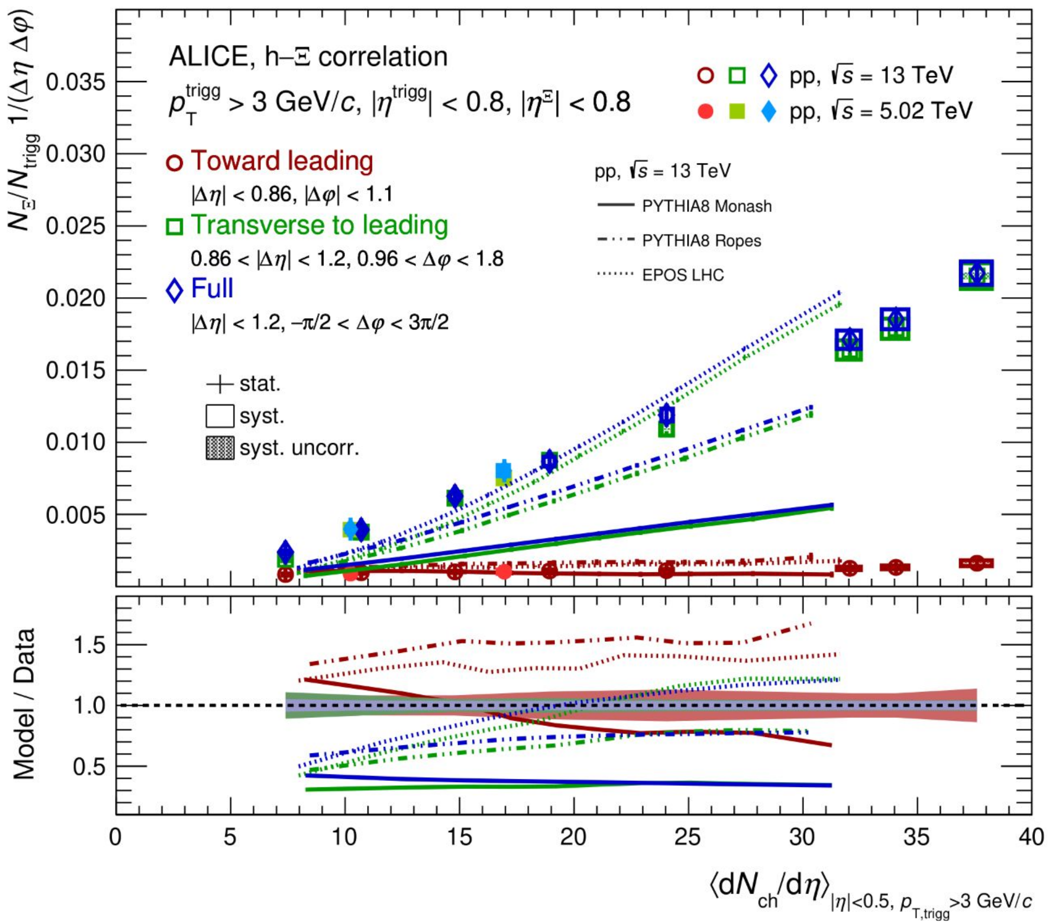


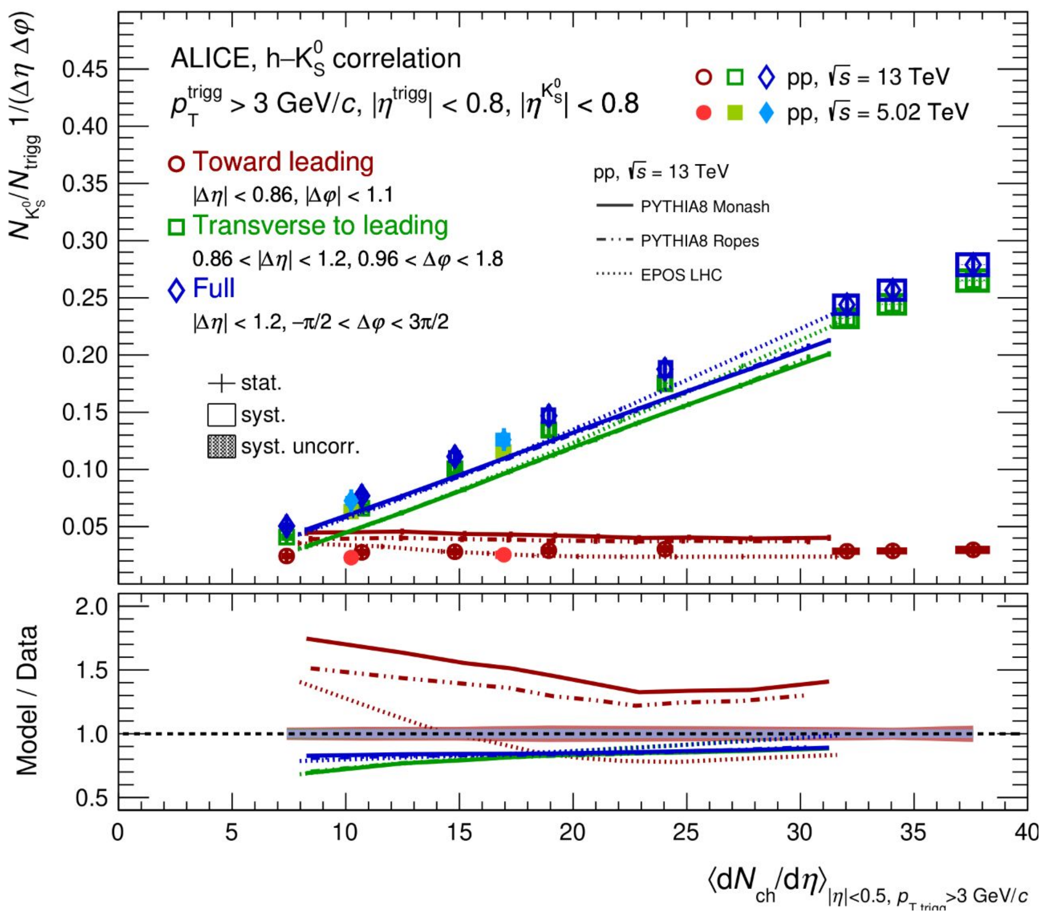

Statistics-hungry analysis, but missing the multiplicity dependence we miss part of the fun!

Need to change our “definition” of jet

# Strangeness enhancement in- and out-of-the jet

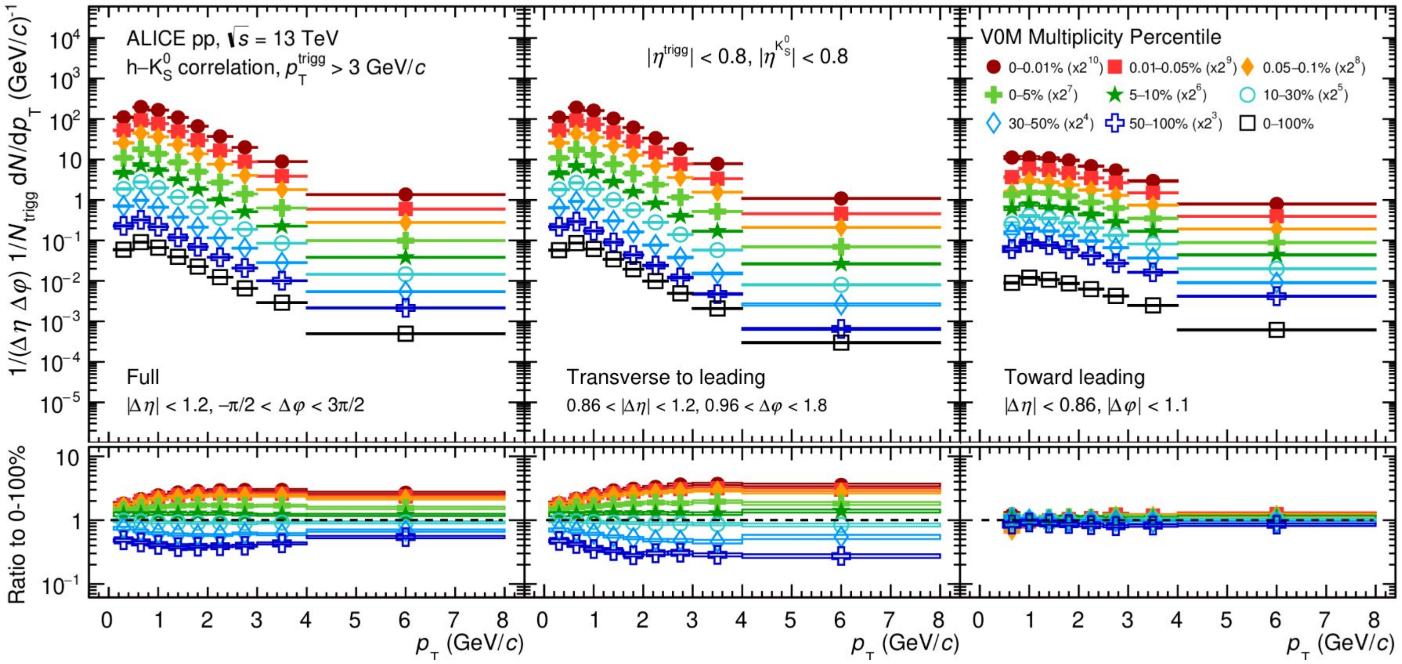
ALICE Collaboration, arXiv:2405.14511




(multi-)strange hadrons are mostly produced outside the jet
[in events with a leading particle with $p_T$ > 3-4 GeV/$c$]

… spectra evolution observed only in the transverse to leading…

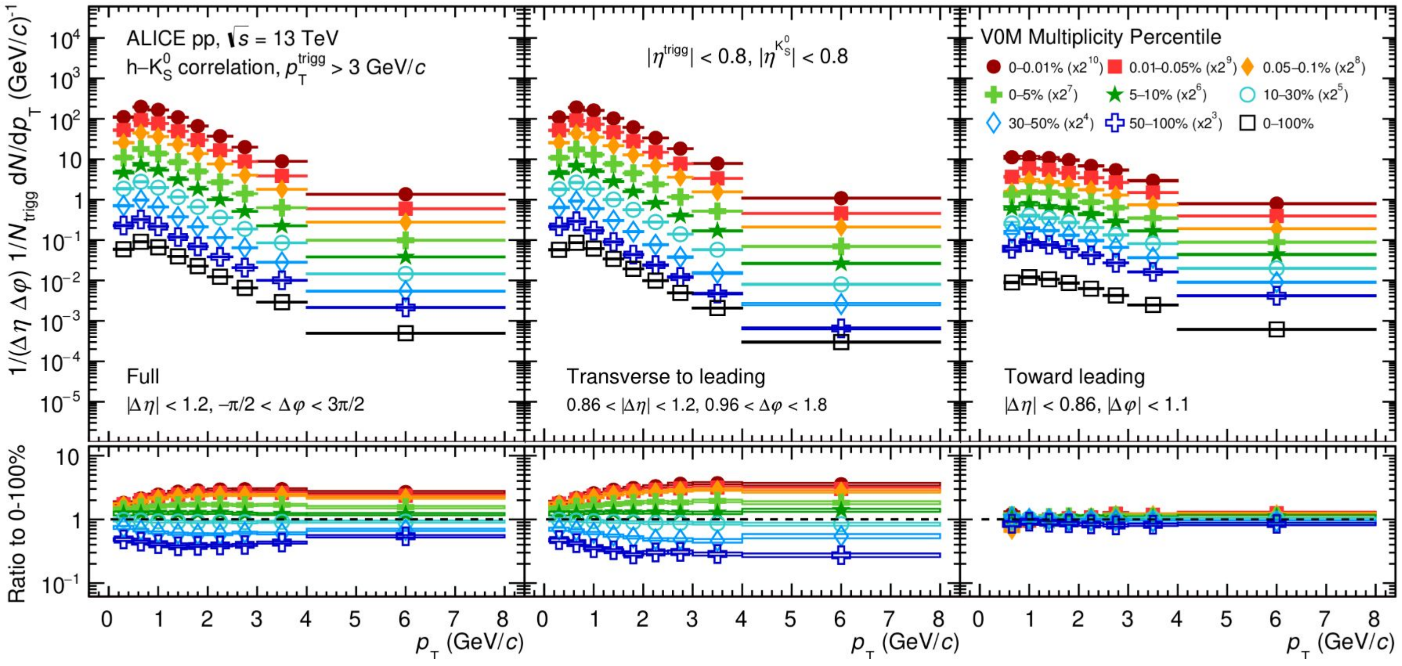



ALICE Collaboration, arXiv:2405.14511

# Strangeness enhancement in- and out-of-the jet

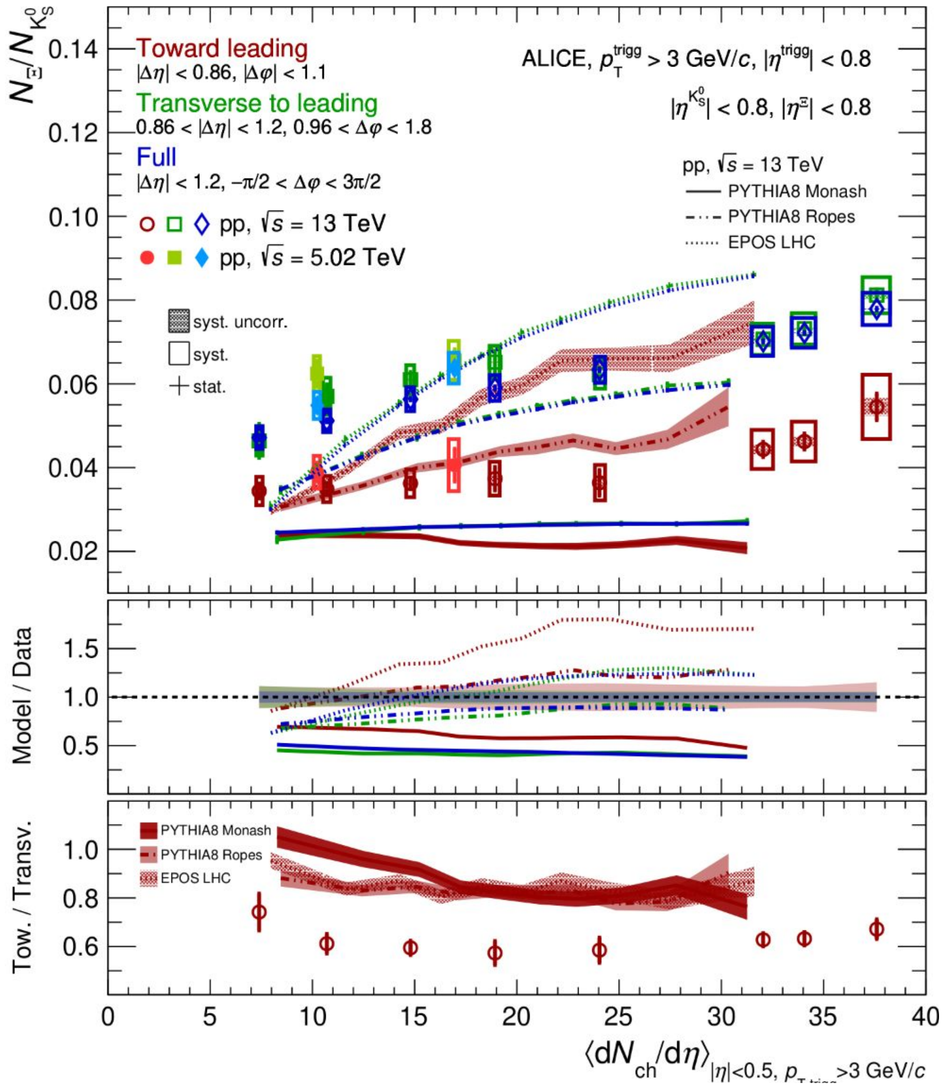


… spectra evolution observed only in the transverse to leading…



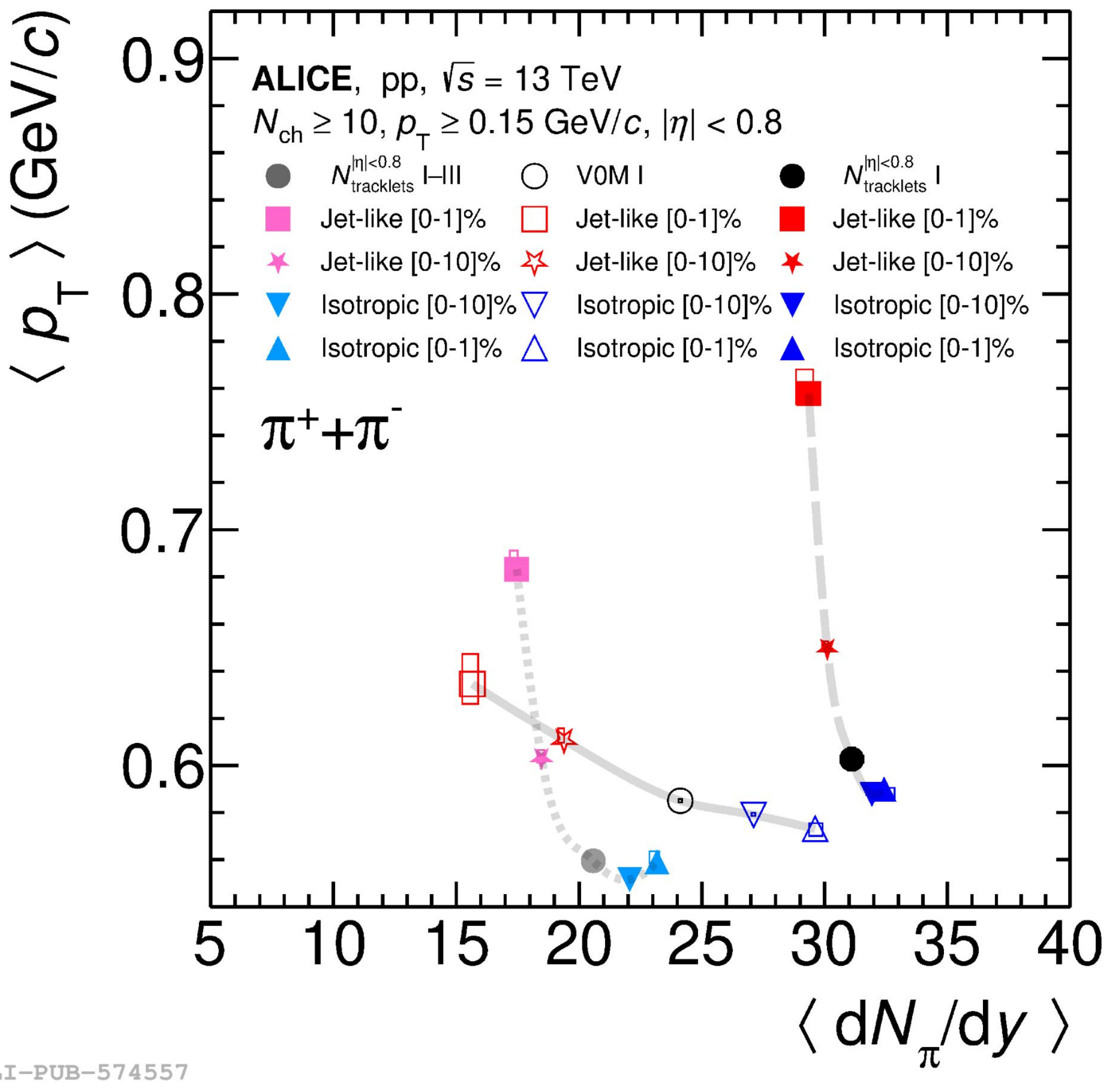

ALICE Collaboration, arXiv:2405.14511

… but (in-) and (out-of-)jet SE looks ~the same…



# New classifiers

# Spherocity




ALI-PUB-574557

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

A measurement of the degree of collimation of the spray of particles:

- $S_O \rightarrow 0$ very collimated - jet-like topology
- $S_O \rightarrow 1$ spherical event - collective system?

Fixed multiplicity at mid-rapidity

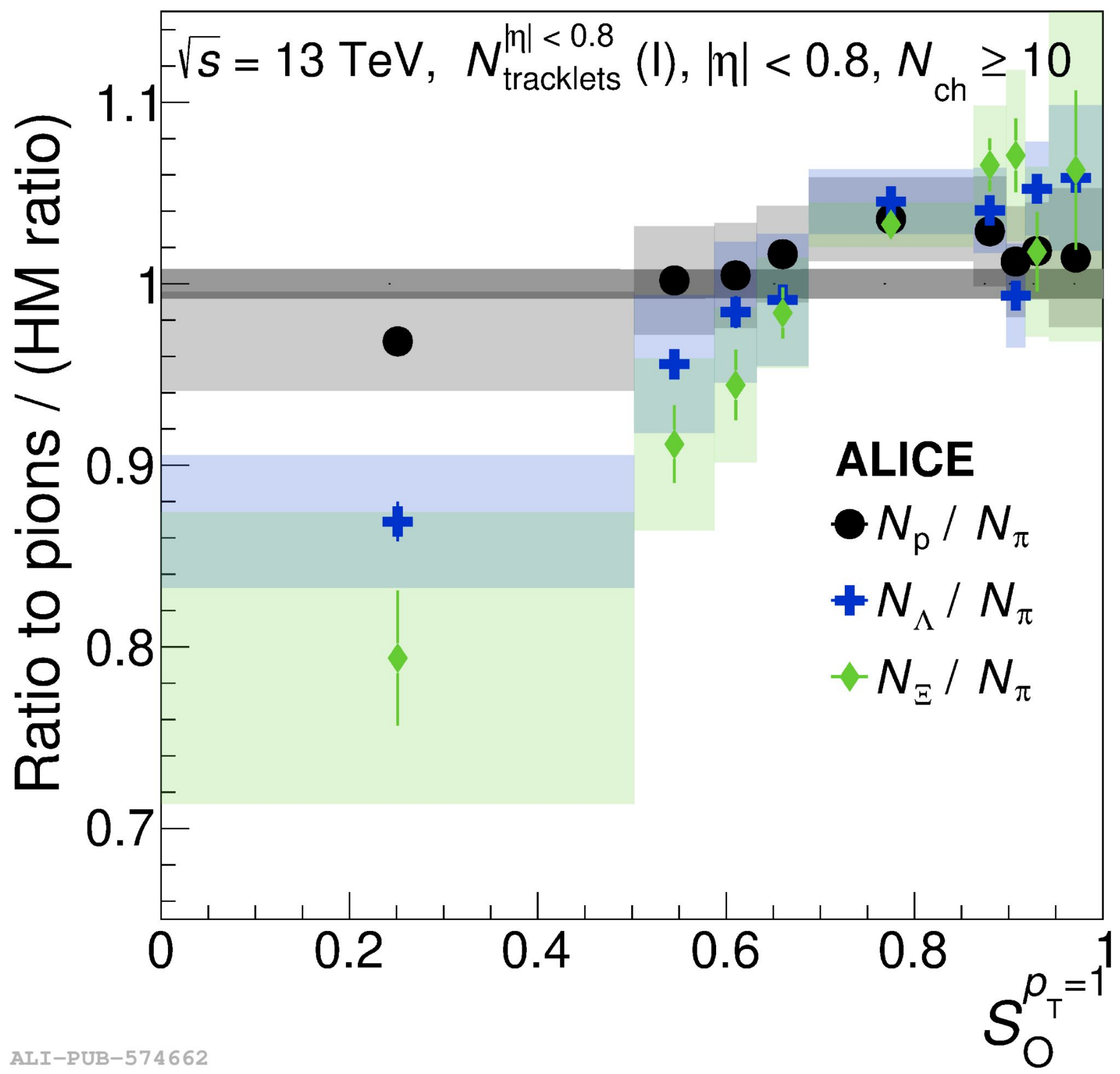
↪ $S_O$ is correlated to the $\langle p_T \rangle$ of pions

Fixed multiplicity at forward rapidity:

↪ $S_O$ is only mildly correlated to $\langle p_T \rangle$, but more correlated to $dN_\pi/dy$

# SE in HM VS Spherocity

ALICE Collaboration, *J. High Energ. Phys.* **2024**, 184 (2024)

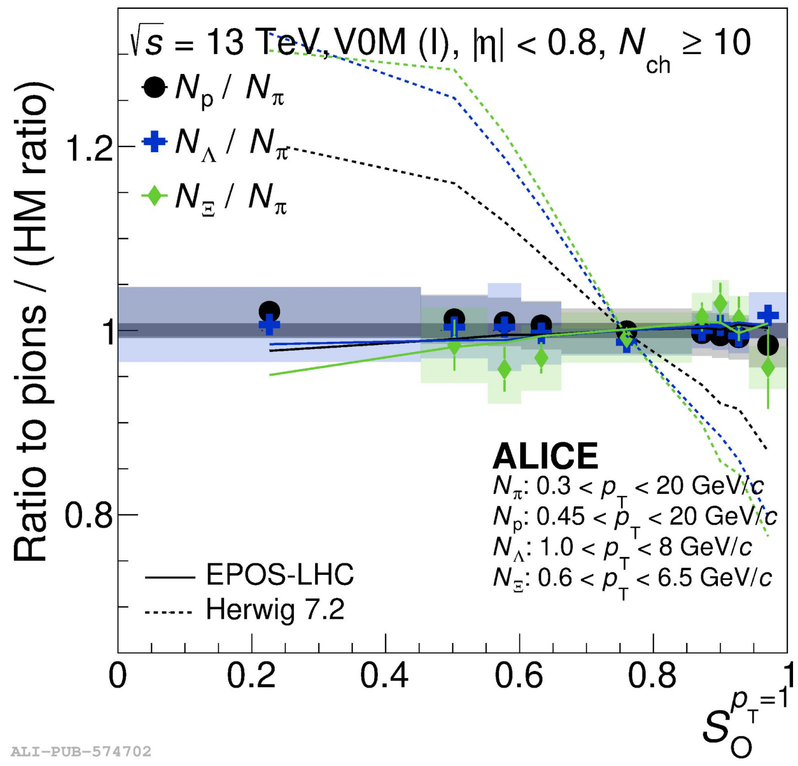



Fixed multiplicity at mid-rapidity

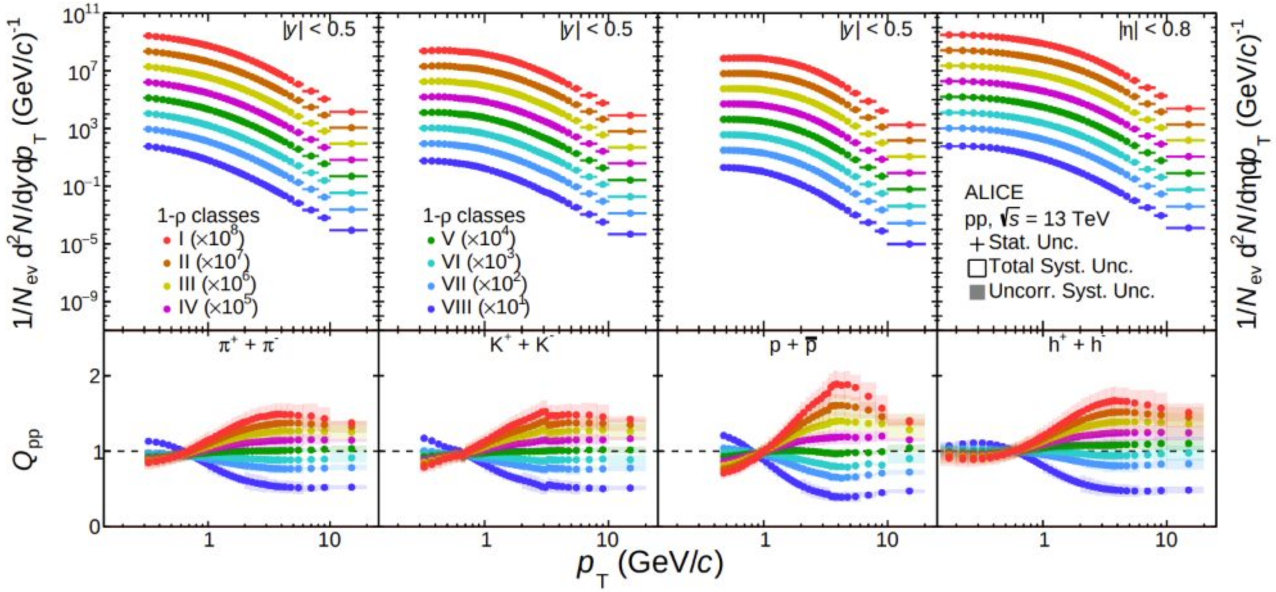
↪ High $S_O$ → larger strangeness production

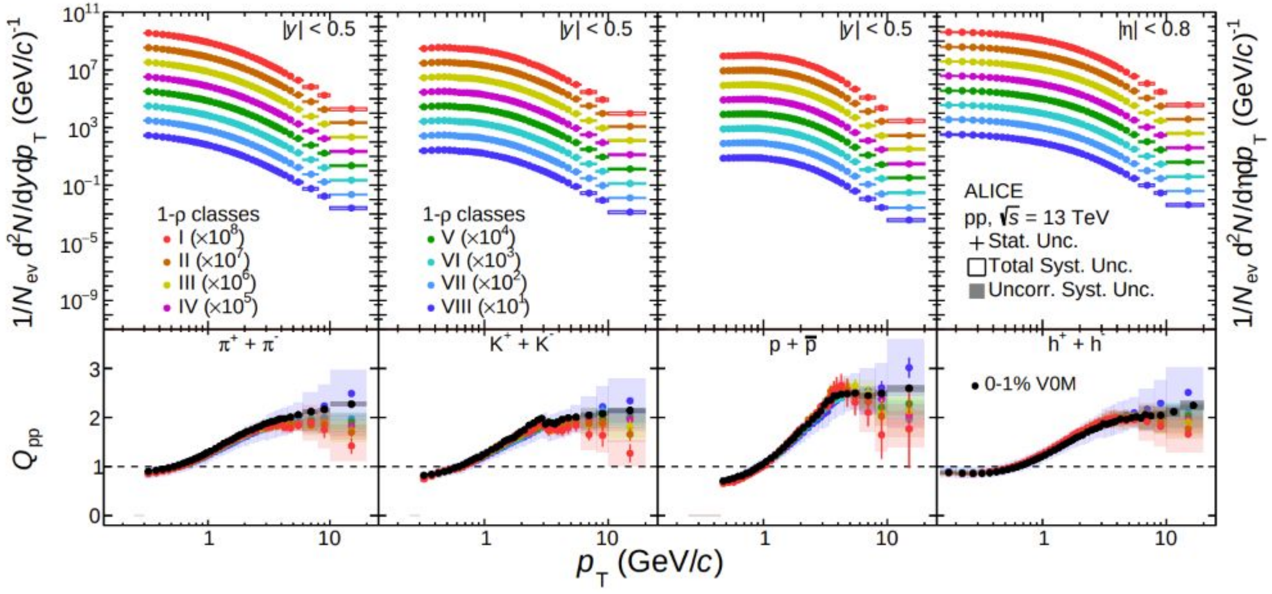
Fixed multiplicity at forward rapidity:

↪ in this case $S_O$ is not a good knob for strangeness



# Flattenicity



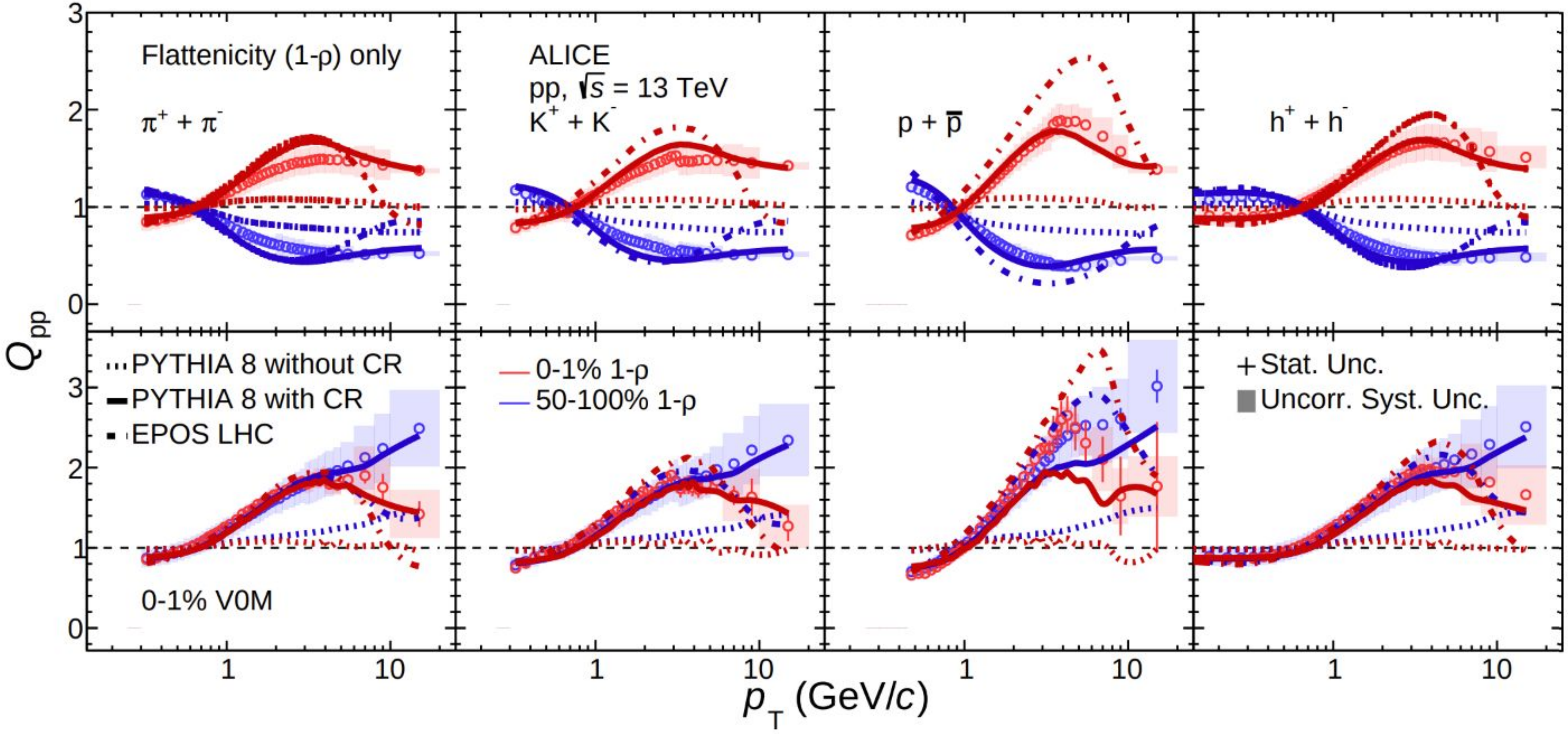

$$\rho = \frac{\sqrt{\sum_{i=1}^{64} (N_{ch}^{cell,i} - \langle N_{ch}^{cell} \rangle)^2 / N_{cell}^2}}{\langle N_{ch}^{cell} \rangle}$$

A measurement of the local multiplicity fluctuations in the V0M detector:

- 1-ρ ⟶0 high flattenicity - large $N_{MPI}$
- 1-ρ⟶ 1 small flattenicity - small $N_{MPI}$

Flattenicity (which is mostly a multiplicity estimator) is able to deplete the high-pT bias

… and the effect is reproduced by Pythia only with CR



# Up for discussion

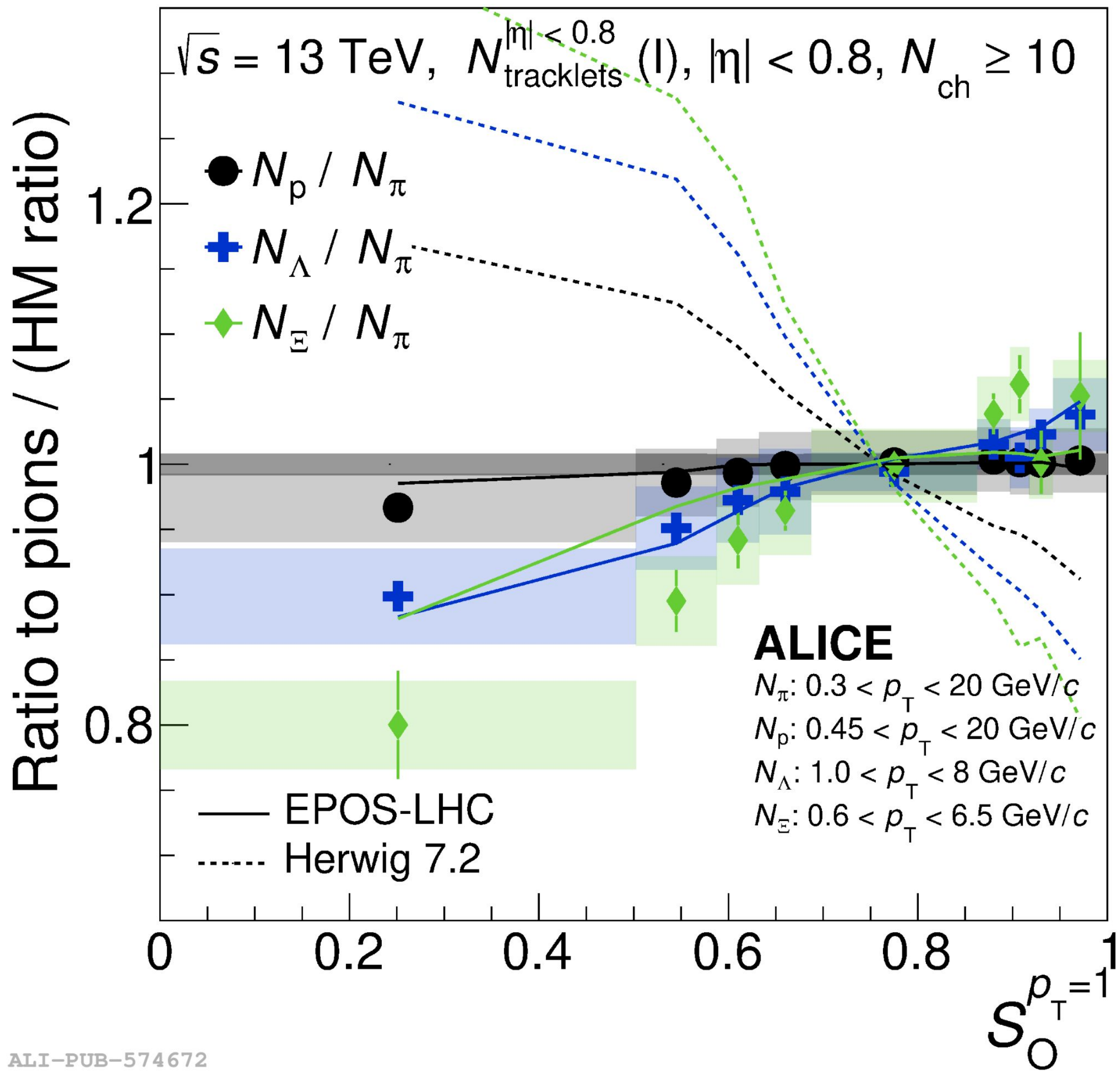
# Wrap-up

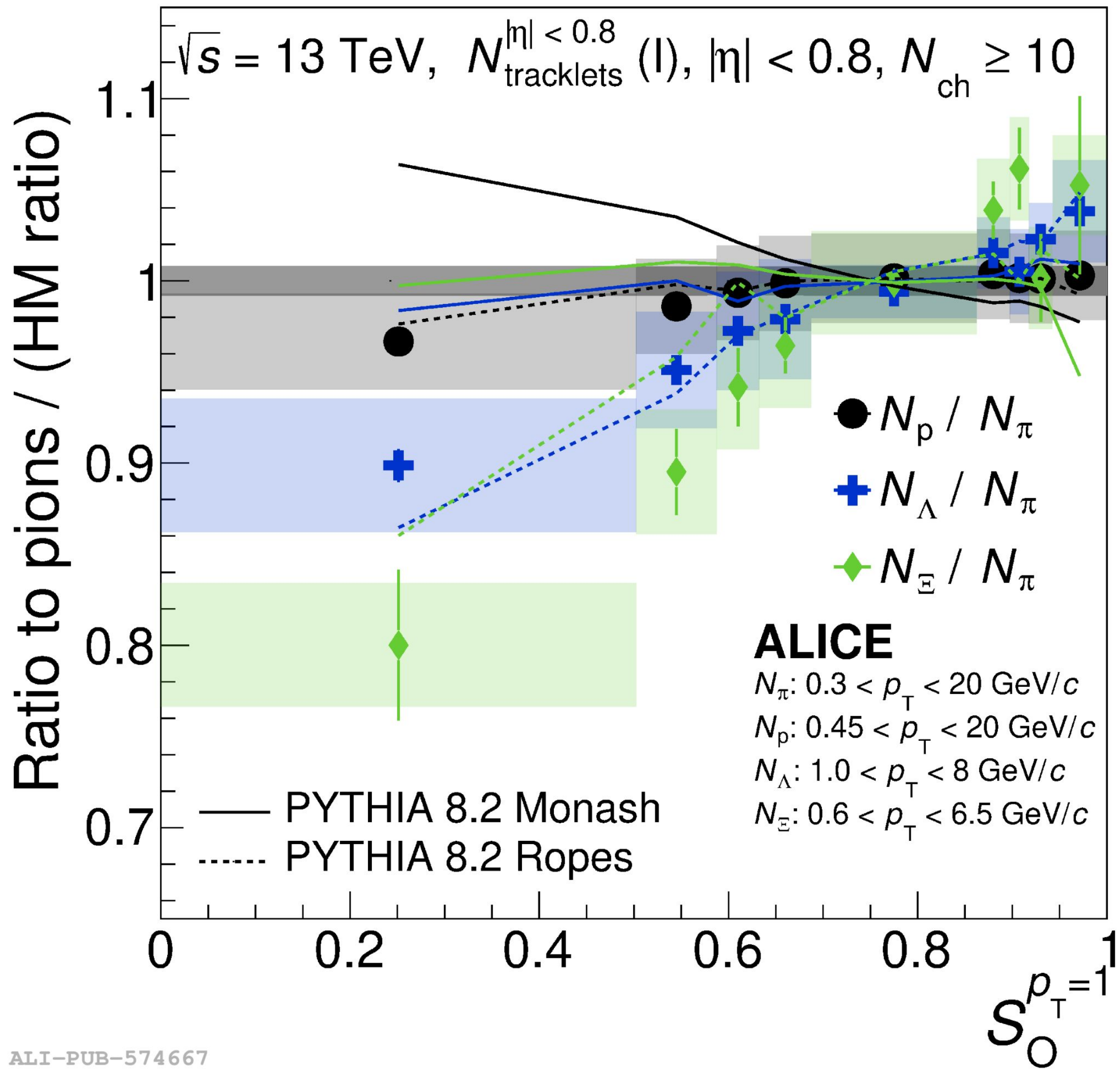


- In the years strangeness enhancement is turning into a “less-common stuff” enhancement
  - connection to charm hadronization?
  - does strangeness retain a “higher status”? Probably not
- Multiple (multi-)strange hadron production VS V0M multiplicity
  - ratio of multiplet yields shows enhancing $\Lambda/K^0_S$ ratio and $2\Xi/4K^0_S$ decreases with multiplicity. Light quarks are playing a role!
    would coalescence calculations get these trends?
  - near future: several other ratios (e.g. SE at its extremes!)
  - CR junctions nicely re-connects strangeness with lighter quarks. Yet strangeness abundance remains a challenge. Does Rope actually help?
- In and out-of jet studies seem point to:
  - strangeness production dominance and spectra evolution only outside the jet
  - SE outside the jet and (potentially) same SE in the jet. Does this observation challenge the Core-Corona approach?
- New classifiers:
  - spherocity correlates to SE at fixed local multiplicity but not at fixed forward multiplicity
    - is this coming from its correlation to $p_T$? Despite this, we have a knob to tune strangeness at fixed multiplicity
  - flattenicity aims at removing the high-$p_T$ bias
    - current result hints at potential success. Larger statistics may help

# Fix $N_{ch}$ - SE VS Spherocity - Model comparison

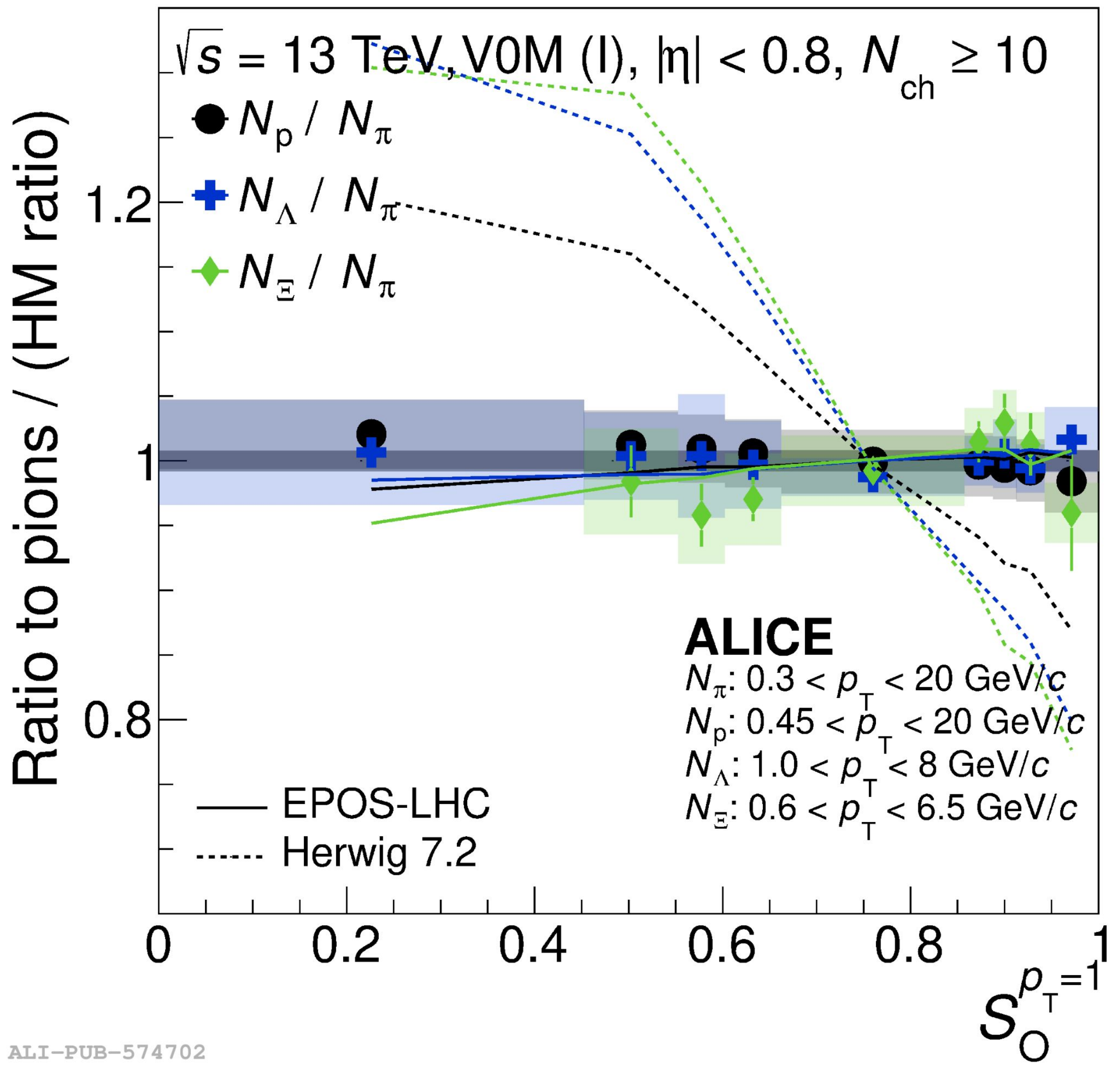


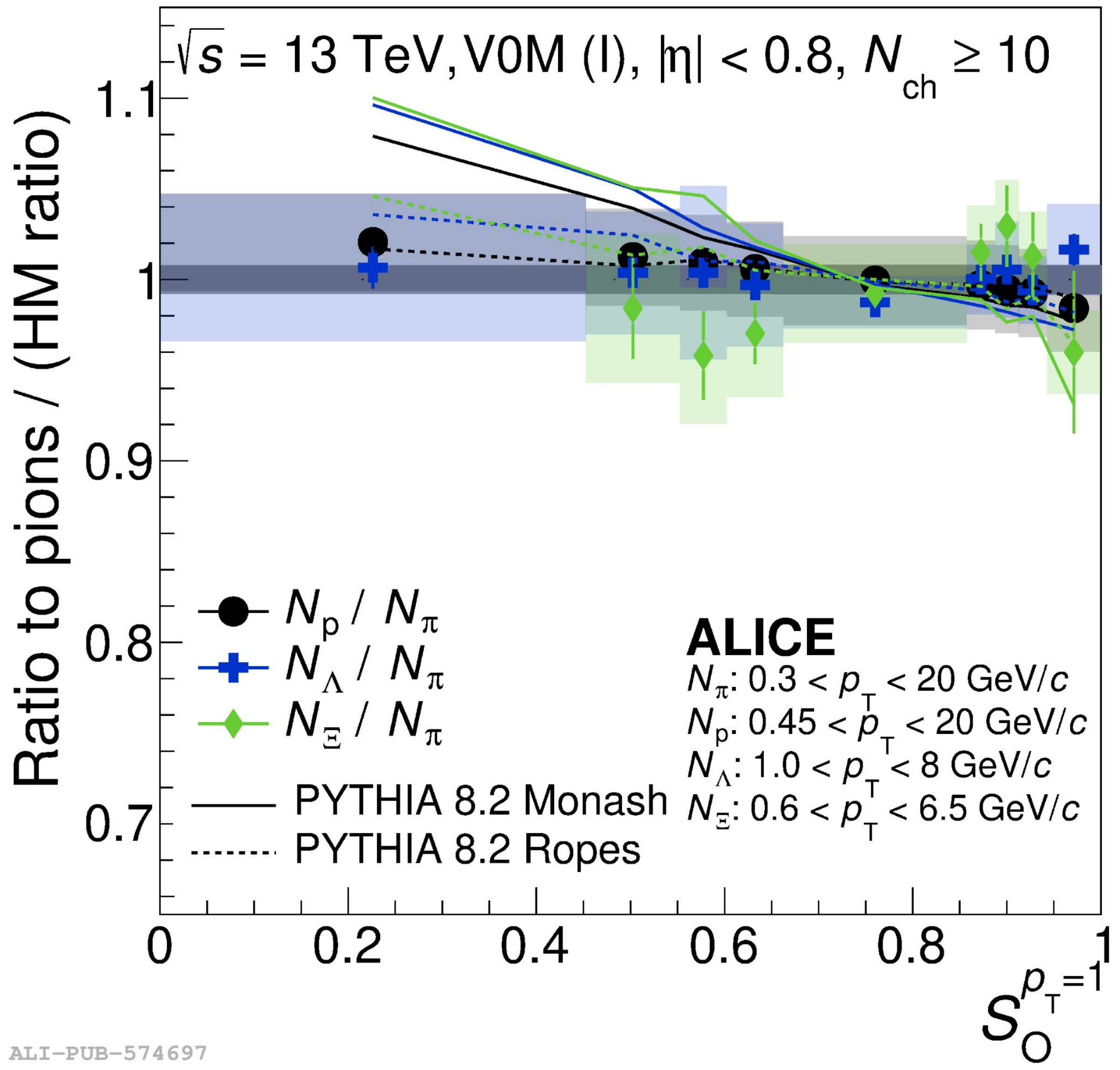


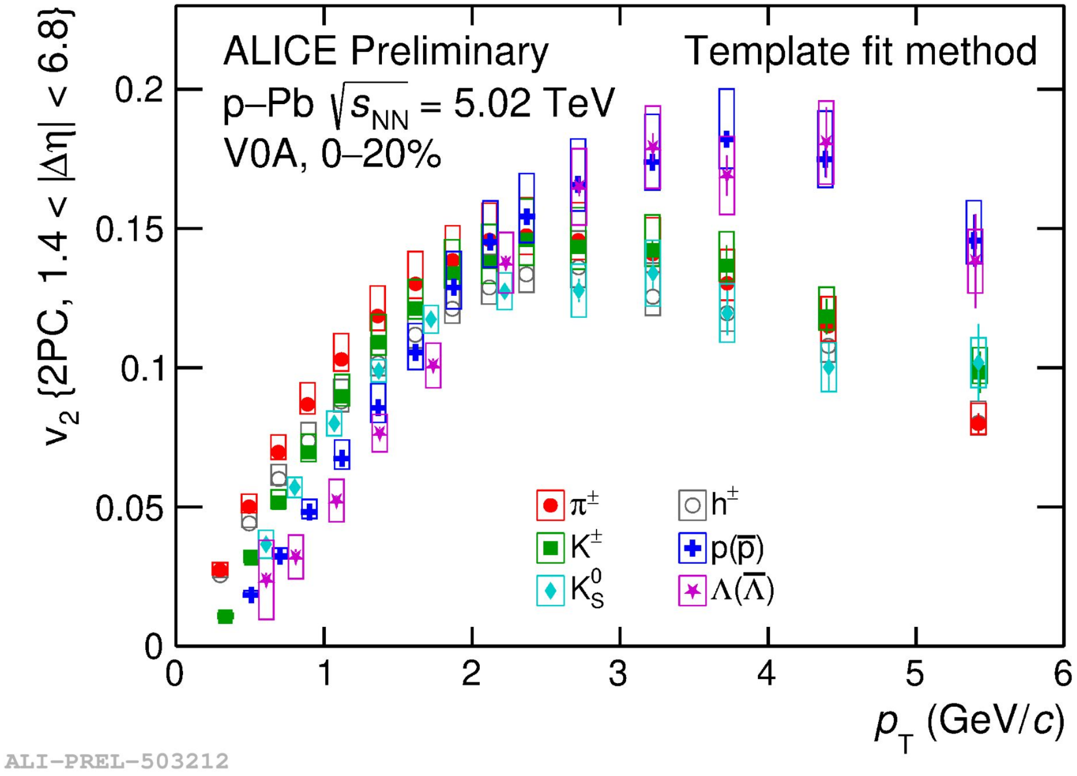
# Fix V0M - no SE VS Spherocity - model comparison

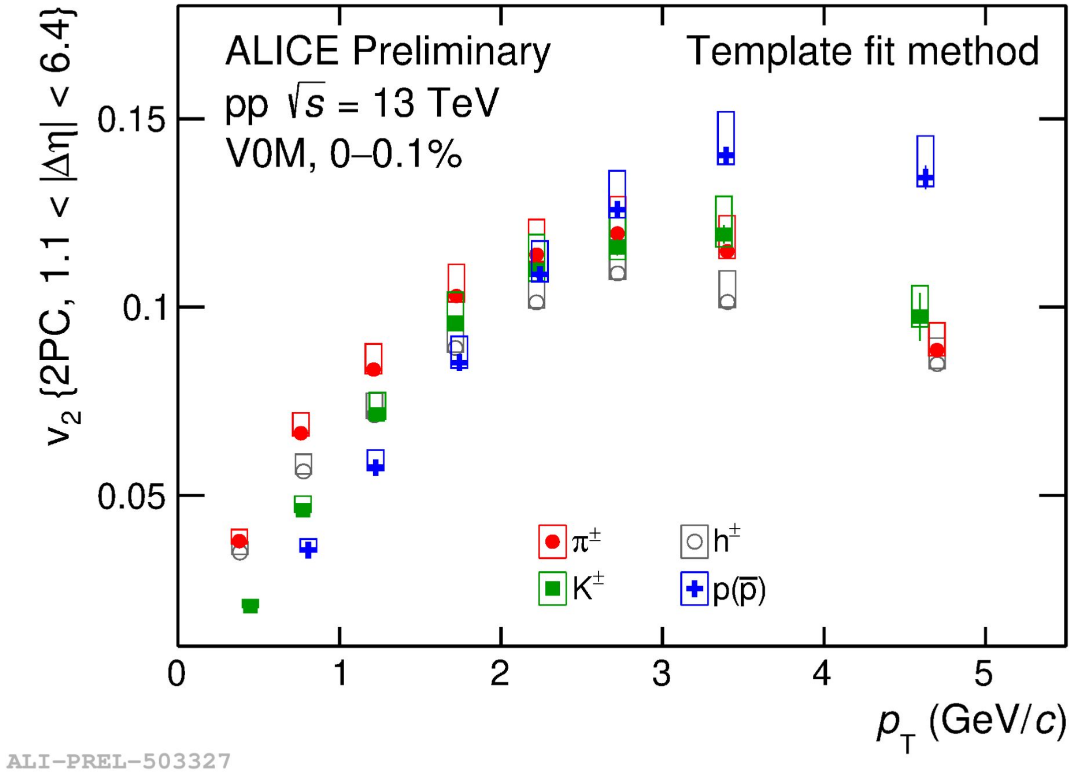




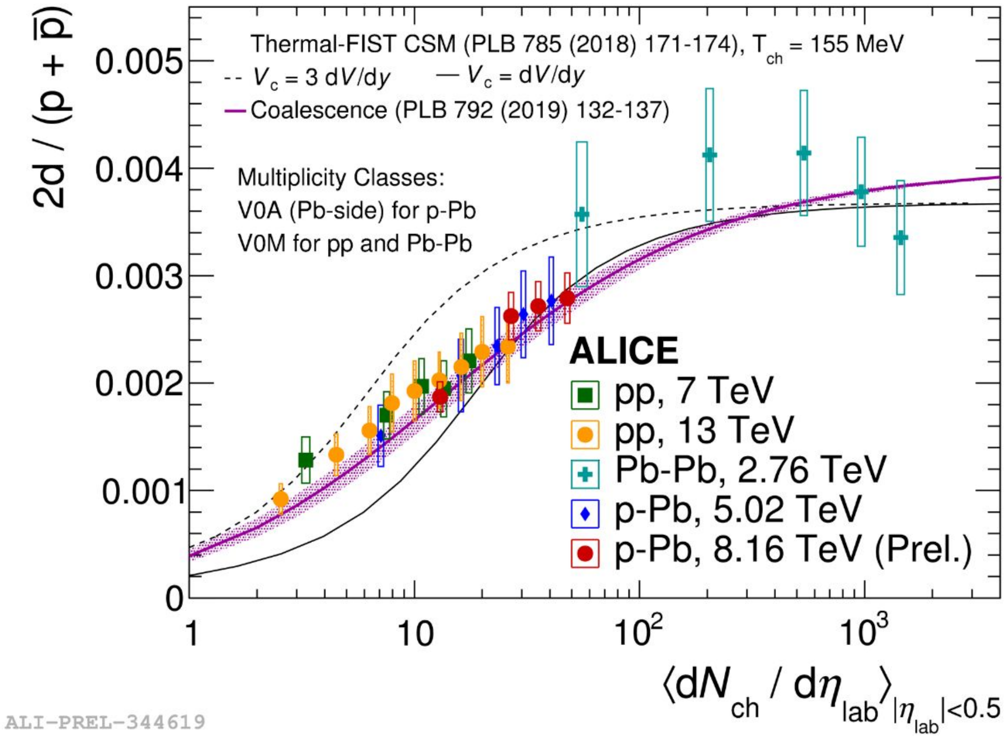
# $v_2$ of identified hadrons in pp and p-Pb

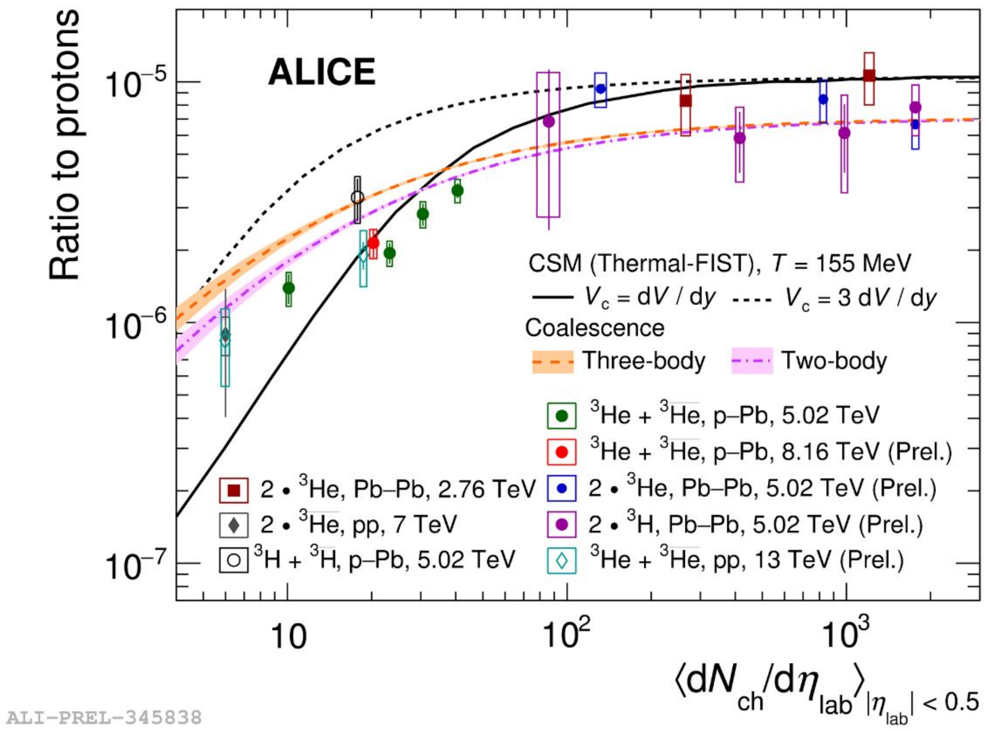



Not only we observe $v_2$ in small systems, but the **particle hierarchy** (in different $p_T$ regions) is the one that we **expect from hydro** and observe in Pb-Pb collisions

# Not only strangeness: nuclei evolve too!



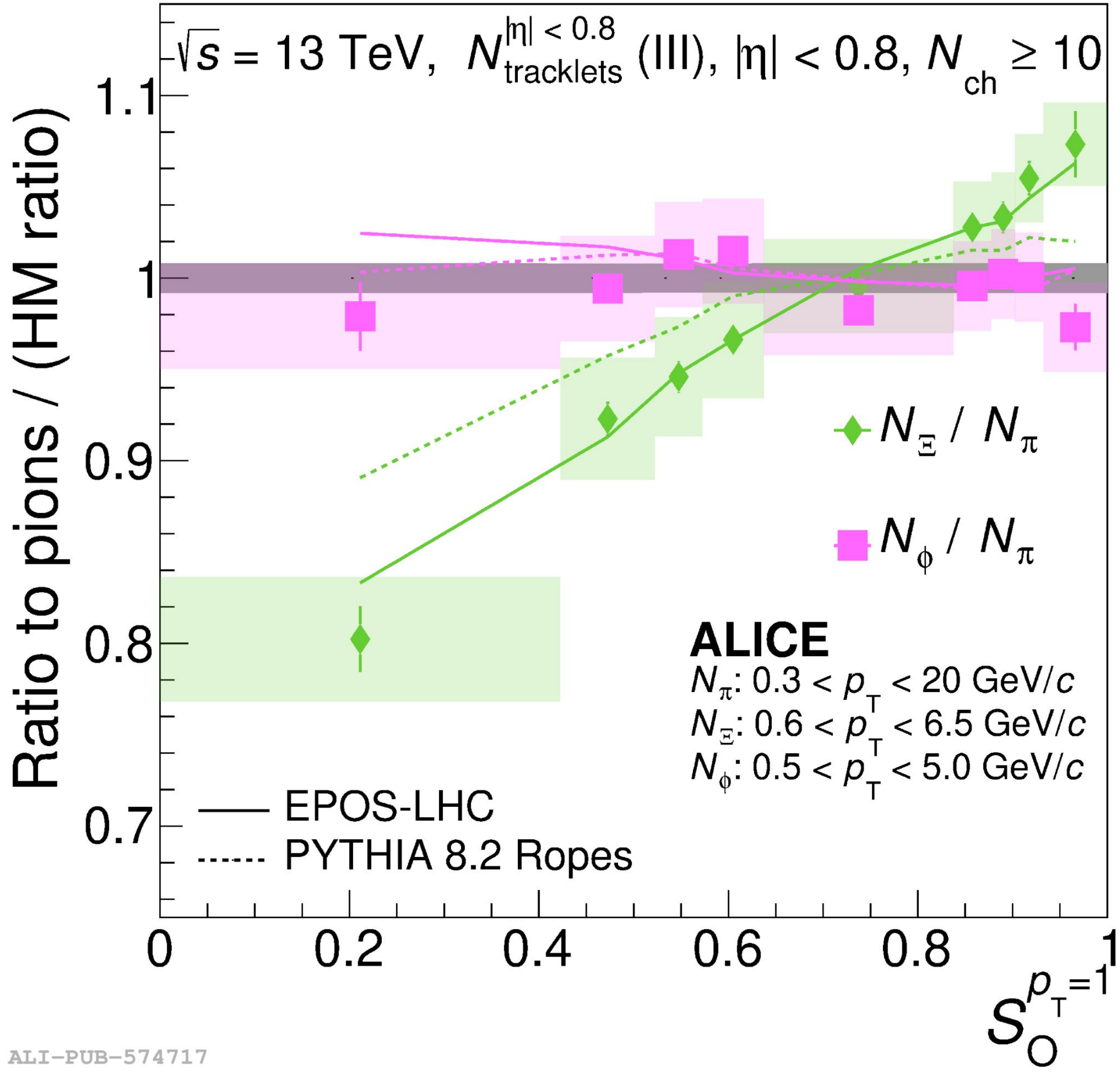

**d, $^{3}$He and $^{3}$H significantly enhanced throughout multiplicity**!

What causes this enhancement? Lifting of canonical suppression? Coalescence probability at kinetic freeze-out?

Qualitative agreement with Thermal Canonical Statistical Model and coalescence model.

# SE in HM VS Spherocity

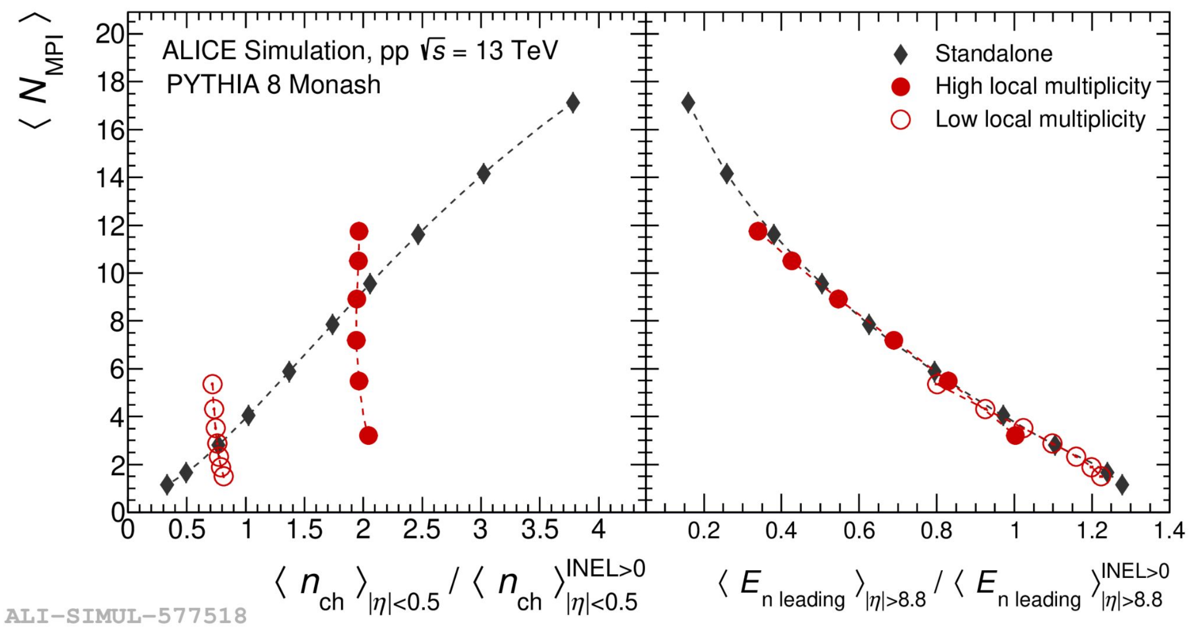


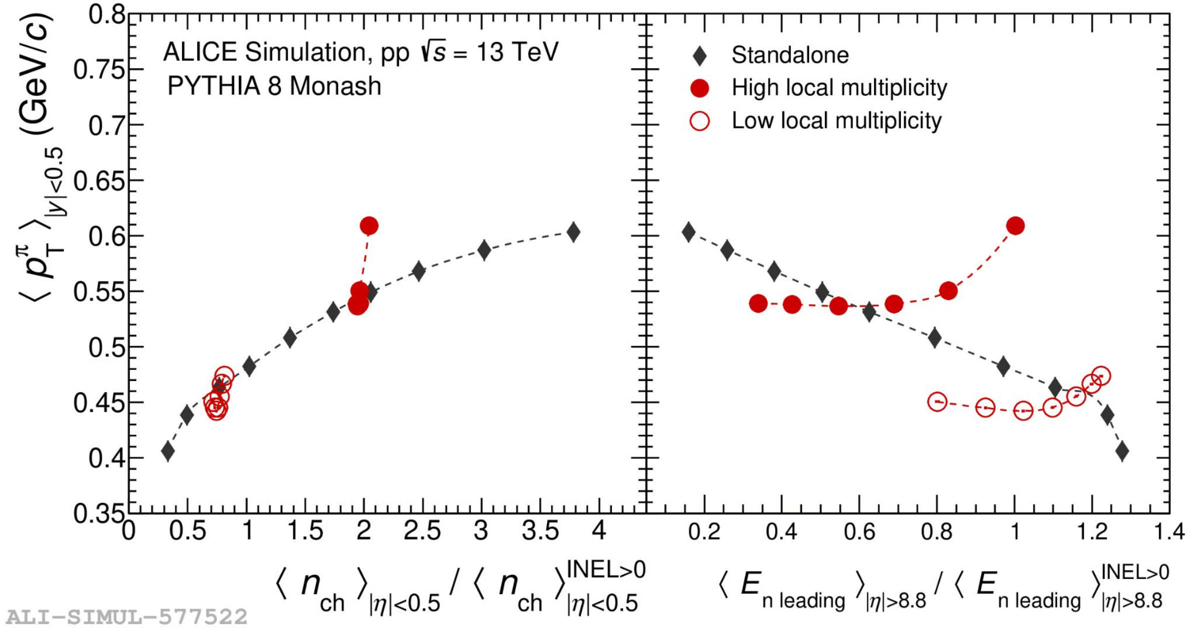



ALI-PUB-574717

# Forward energy anti-correlated to $N_{MPI}$



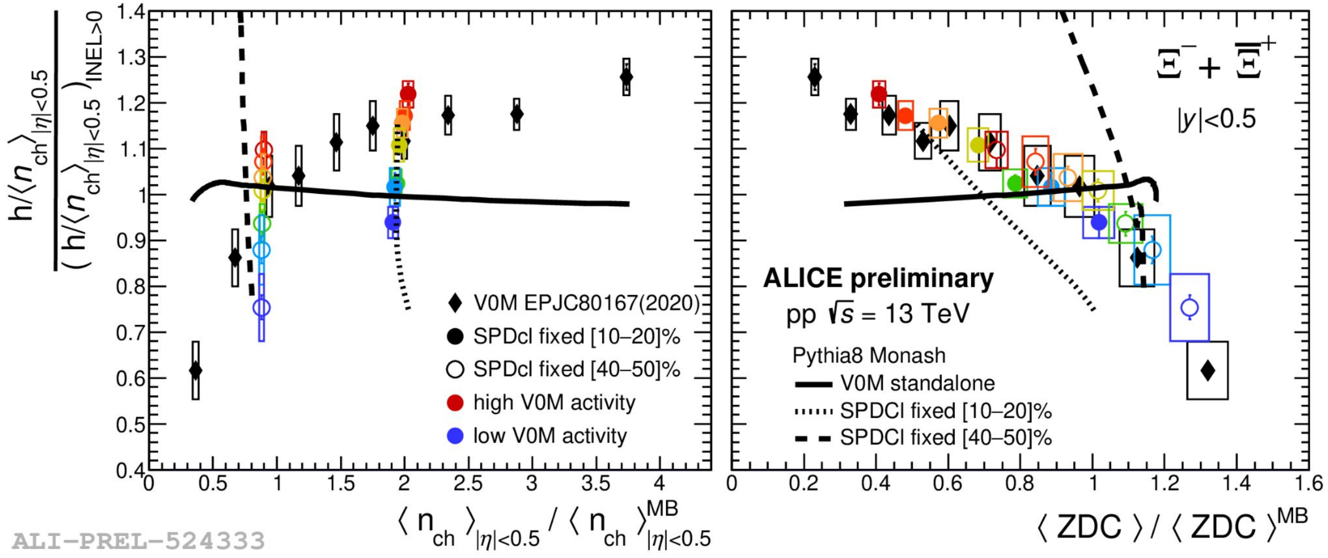


# Strange baryon enhancement VS forward energy

Livio Bianchi
QCDCppAA
3 Sep 2024






In pp collisions strangeness production is found to increase with midrapidity multiplicity and to be anti-correlated with the leading energy

Multi-differential approach to disentangle the contribution of multiplicity and effective energy to strange particle production:

- an increase in strange baryon production is observed at fixed midrapidity multiplicity
- strangeness production shows a correlation with the effective energy following a universal trend with the leading energy detected by the ZDC