Strangeness Production in small collision systems with ALICE

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ISMD2022 Pitlochry Scotland

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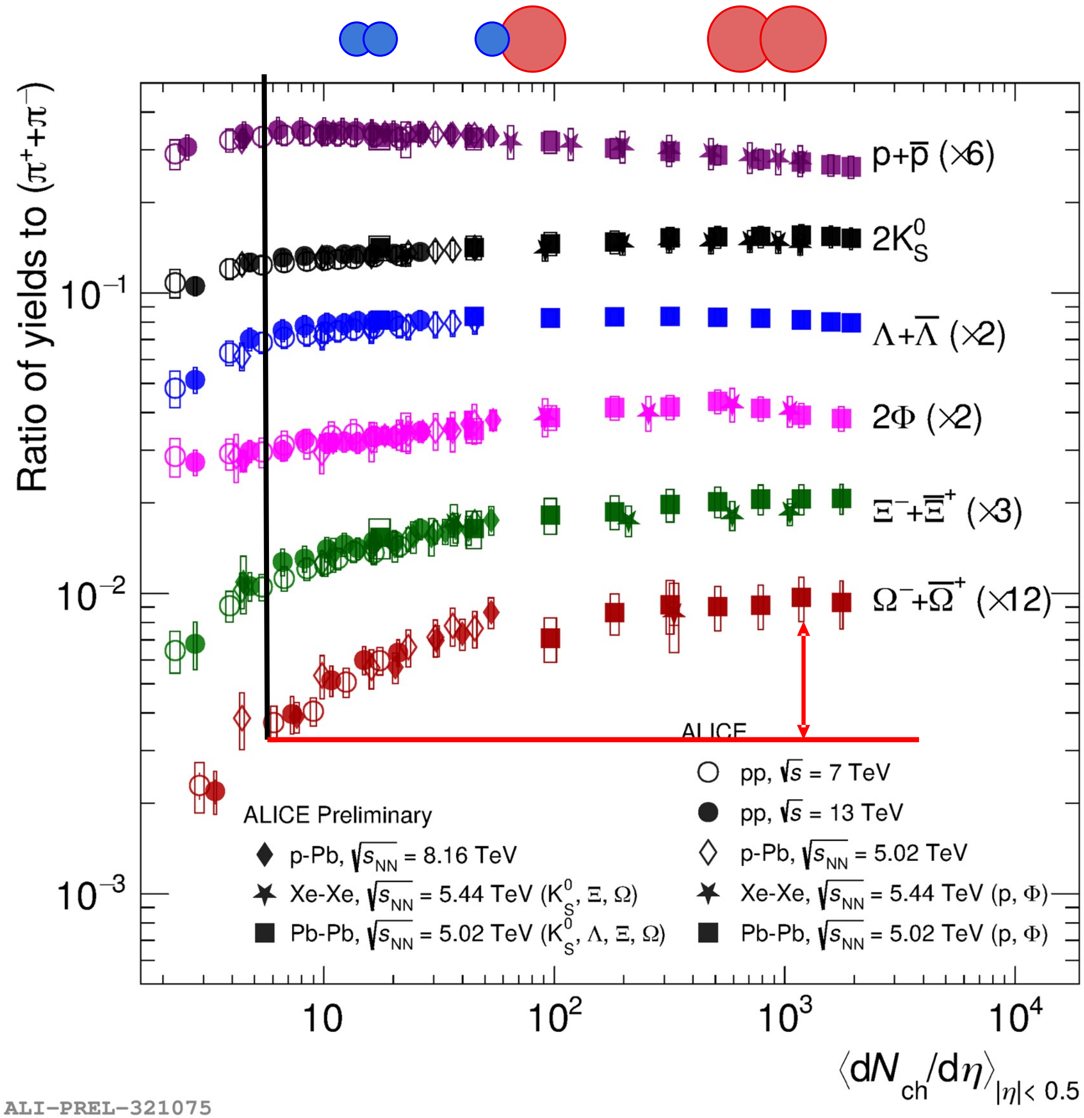
What are we looking for in small systems?

- The study of soft probes allows to characterize with high precision the hot and dense medium (QGP) produced in heavy-ion collisions. These are useful to
  - Study collective phenomena
    - High energy density, large medium developing radial and anisotropic flow
  - Disentangle hadronic phase effects
    - Large system -→ nuclei formation at kinetic freeze-out (coalescence)?
    - Short-living resonance disappearance (rescattering)?
- ………. and extension to small collision systems
  - How can we use small systems to better interpret large systems observations
  - Do the observations in small collision systems imply QGP formation there?

Exploiting small collision systems we can have deeper insight on collective effects observed in A—A collisions

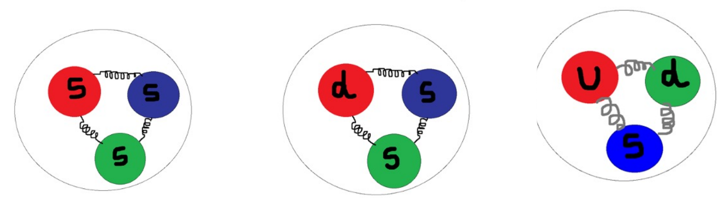
Strangeness Enhancement :



ALICE has measured the ratio of strange to non-strange hadron yields versus multiplicities in different collision systems and energies

- ➢ increases with multiplicity
- ➢ smoothly evolves across different collision system
- ➢ no dependence on collision energy for similar multiplicities
- ➢ enhancement is larger for particles with larger strangeness content

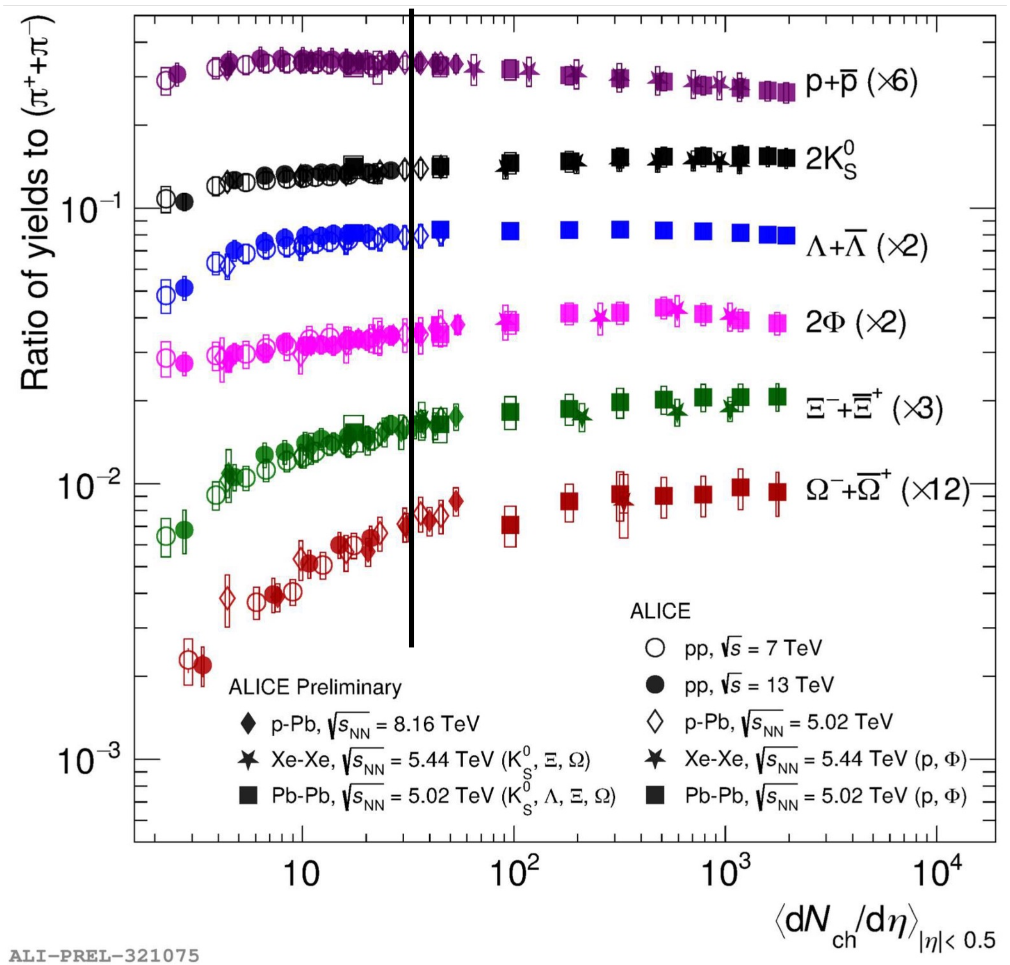
E(Ω) > E(Ξ) > E(Λ)



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

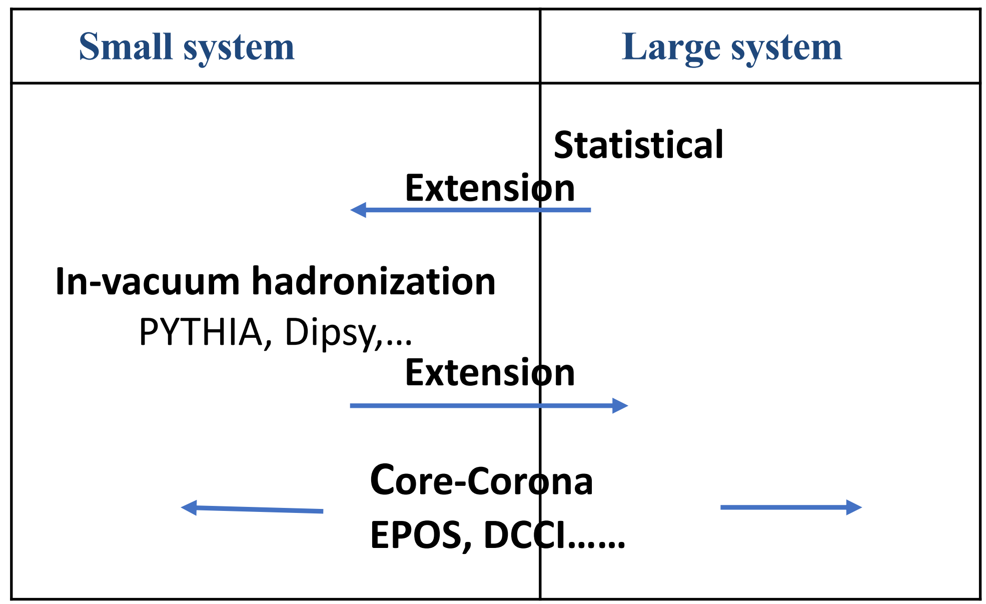
Strangeness Production :

multiplicity, collision energy and system size

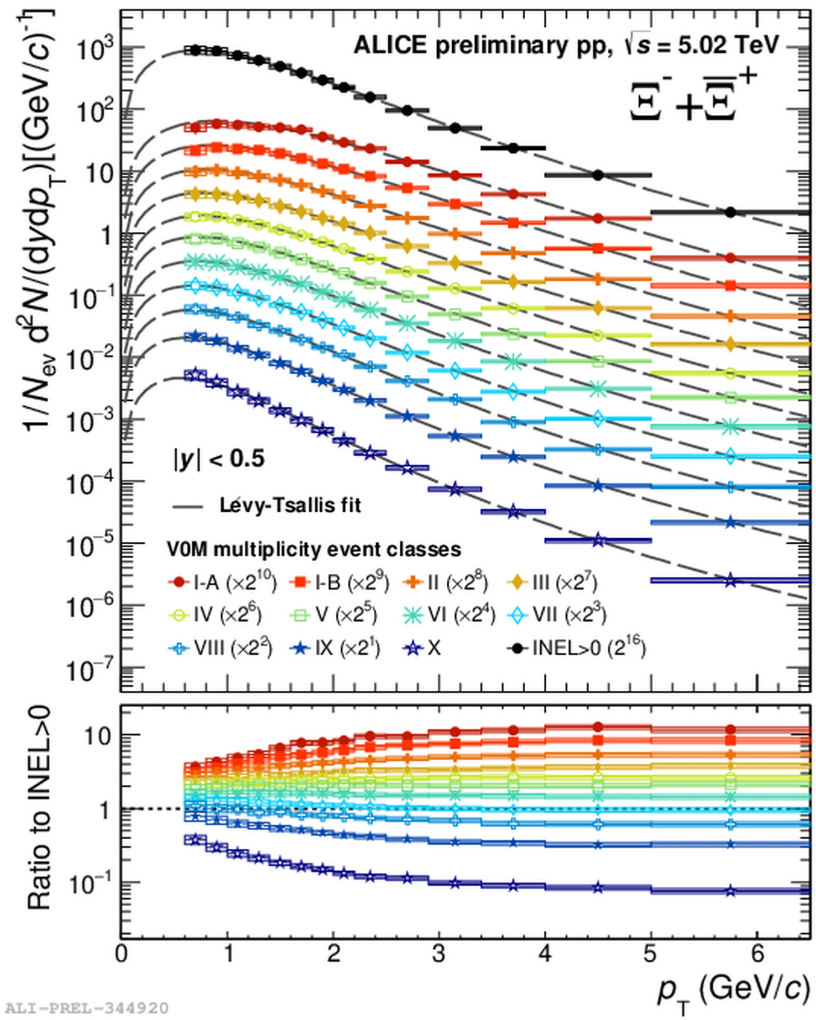


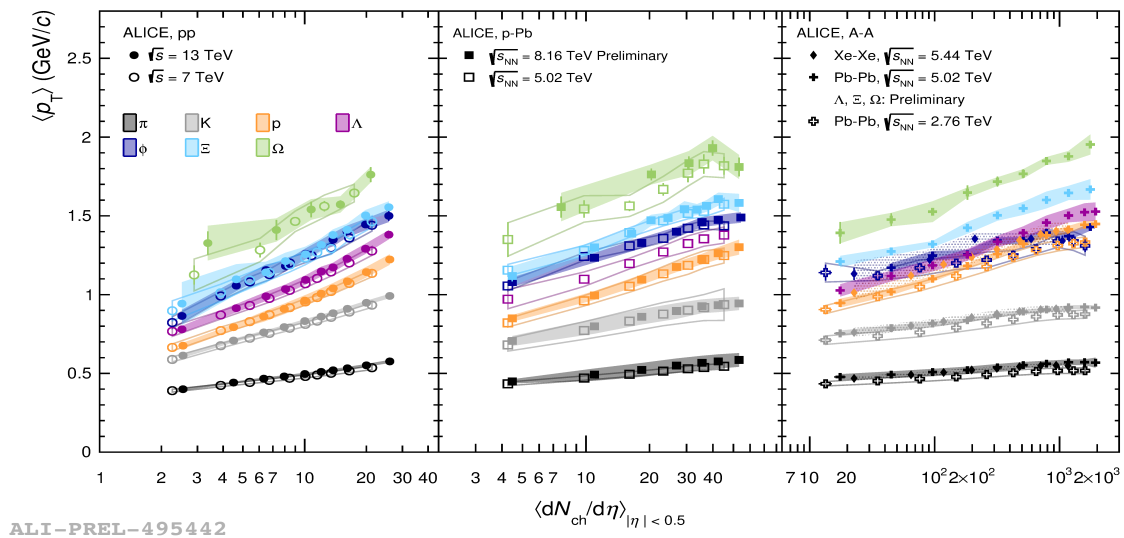
- High-multiplicity pp: ~ same hadrochemistry as in a fully thermalized system

Results from small systems (p—p and p—Pb) address some of the questions



p_T differential yields of strange particles

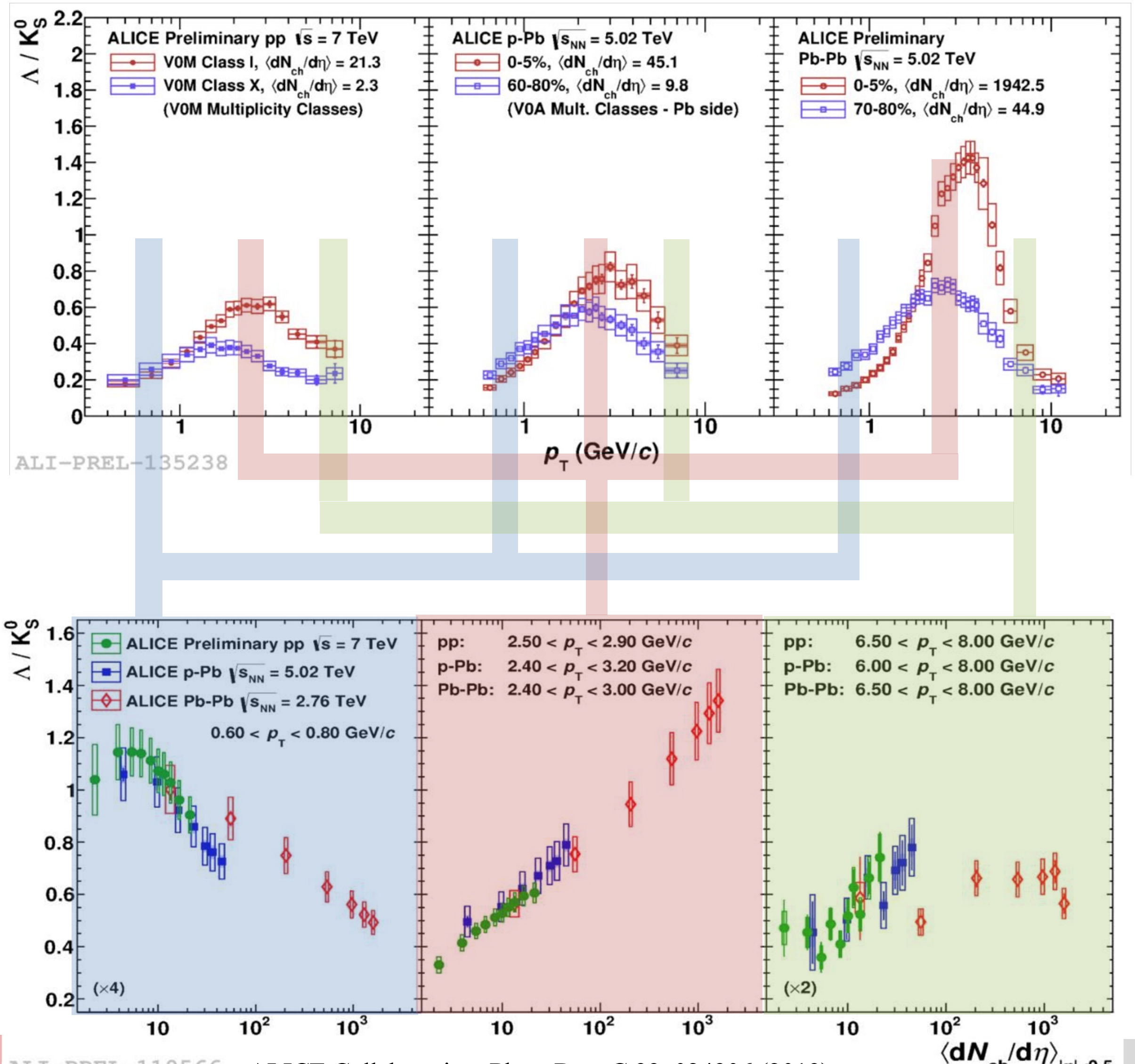




- Clear evolution of particle spectra with multiplicity
- Spectra harden towards higher multiplicity as observed in p—Pb and Pb—Pb

Hints of collective phenomena in small systems ?

Baryon to Meson Ratio



ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

- Smooth evolution with multiplicity when selecting specific p_T intervals
- Radial flow in small systems?
- exhibits a universal pattern for all collision systems ➔ common mechanism at work that depends solely on final-state multiplicity density.
- integrated particle ratios, which are observed to depend on ⟨dNch/dη⟩ in approximately the same way for any colliding system
- Application of hydro far from equilibrium under study
- PYTHIA with CR can describe the low-p_T trend observed in pp

ALICE @ LHC

ALICE

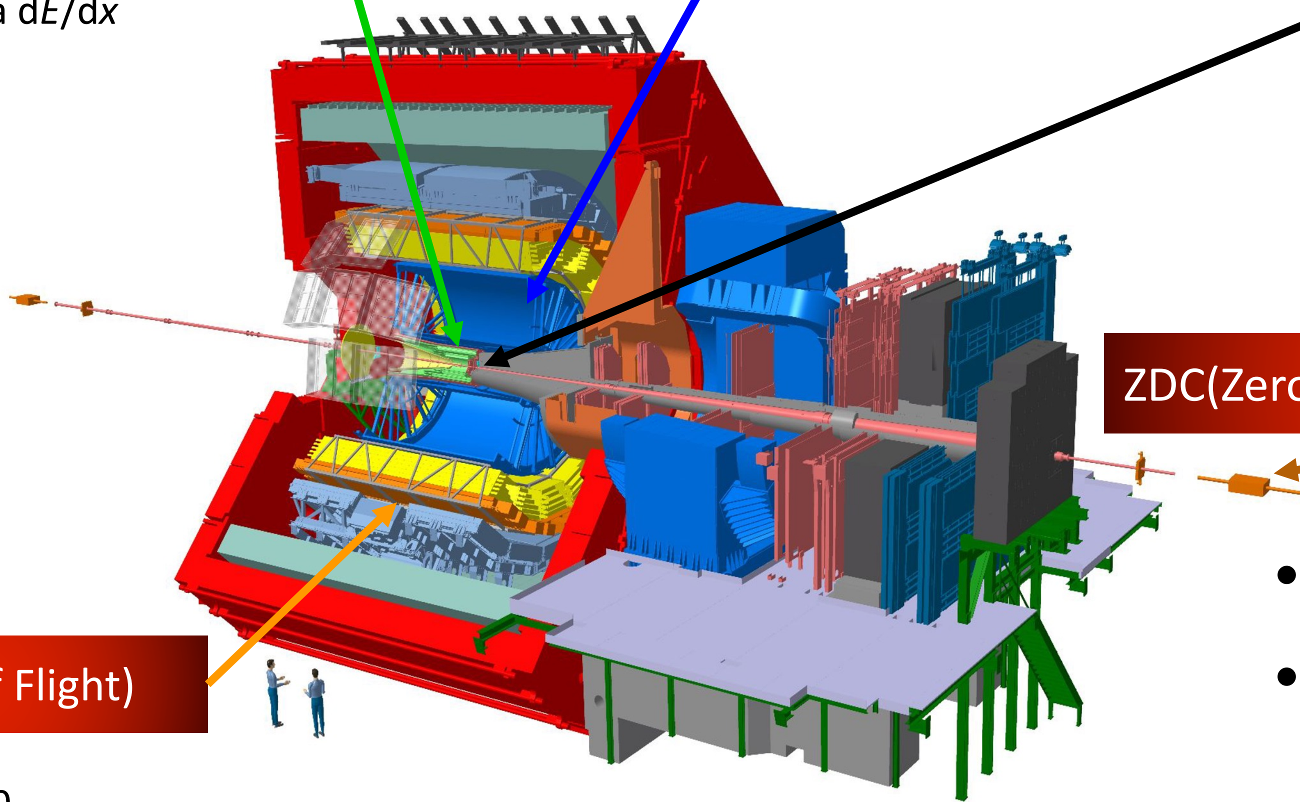
K_S^0, Λ, Ξ and Ω ➔ identified by reconstructing their weak decay daughter tracks in the central pseudorapidity region

ITS (Inner Tracking System) and TPC (Time Projection Chamber)

- $|\eta| < 0.9$
- Tracking and vertexing
- PID via dE/dx

V0

- $2.8 < \eta < 5.1$ (V0A), $-3.7 < \eta < -1.7$ (V0C)
- Multiplicity percentile classes based on the V0 signal amplitude



ZDC(Zero Degree Calorimeter)

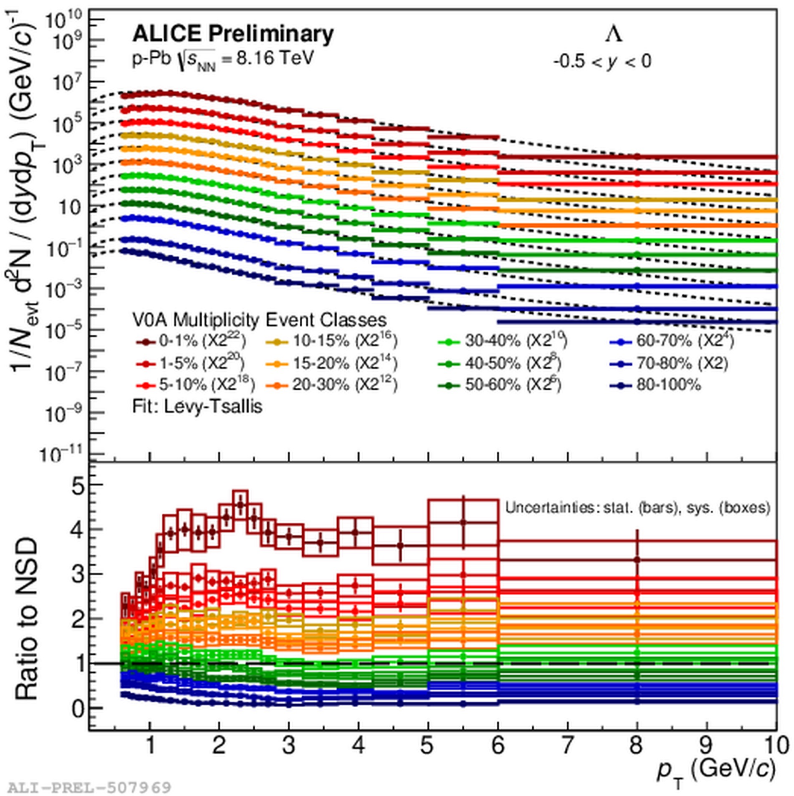
- $|\eta| > 8.8$ (ZN), $6.5 < |\eta| < 7.4$ (ZP)
- Energy percentile classes based on the energy deposits of forward emitted particles

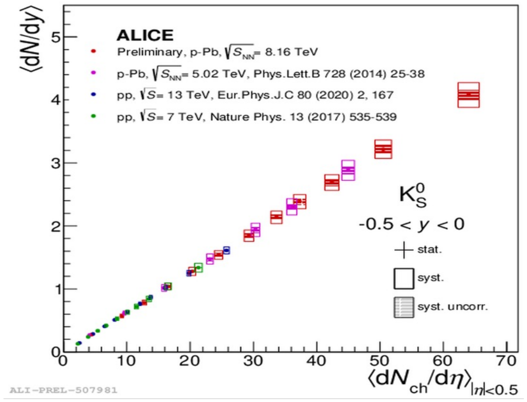
TOF(Time Of Flight)

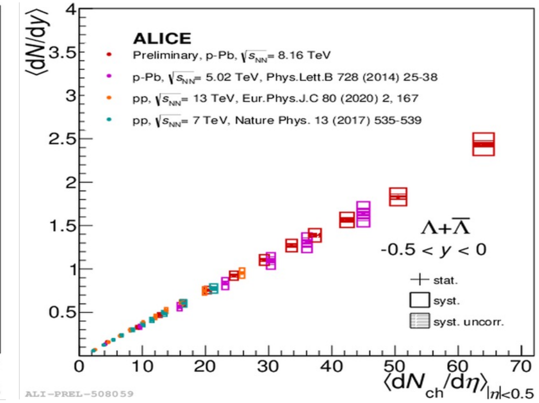
- $|\eta| < 0.9$
- PID via Time-Of-Flight technique

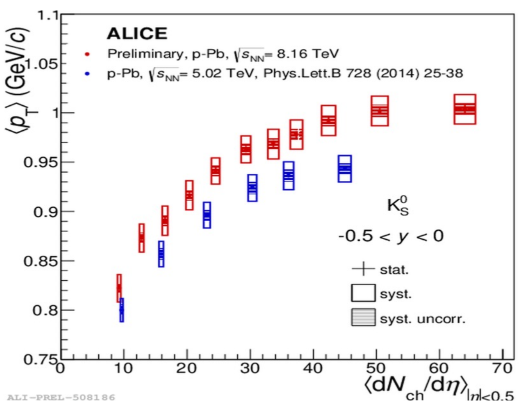
Recent results

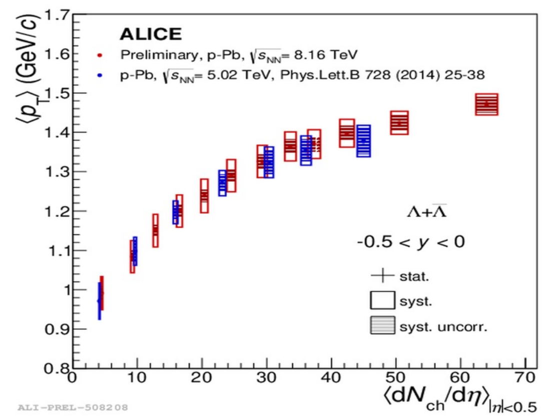
Strangeness Production in small systems





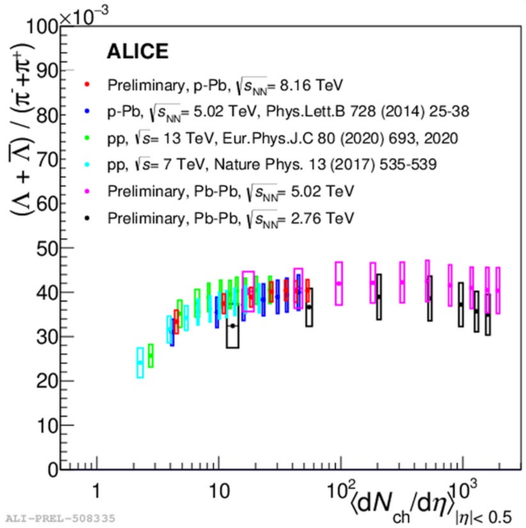


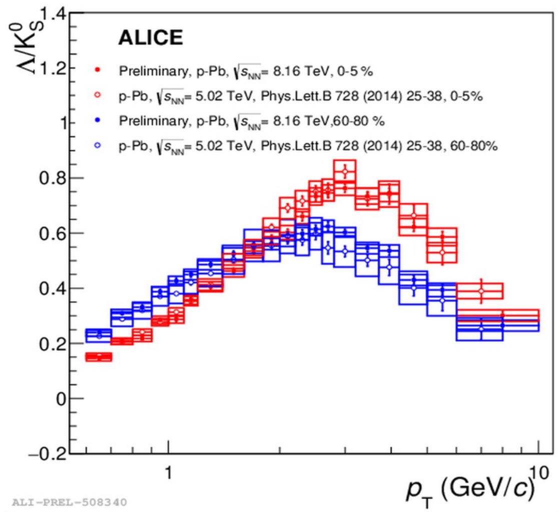




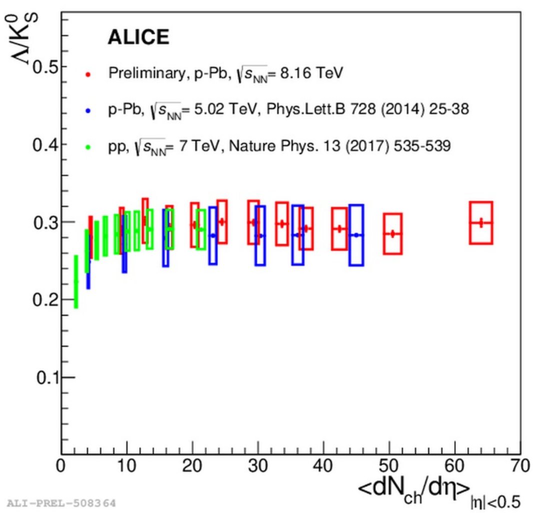
- p_T - spectra hardening is observed moving from low multiplicity to high multiplicity region
- Yields of strange particles measured in different systems as a function of multiplicity lie on the same trend
- Both dN/dy and $\langle p_T \rangle$ increase as a function of multiplicity

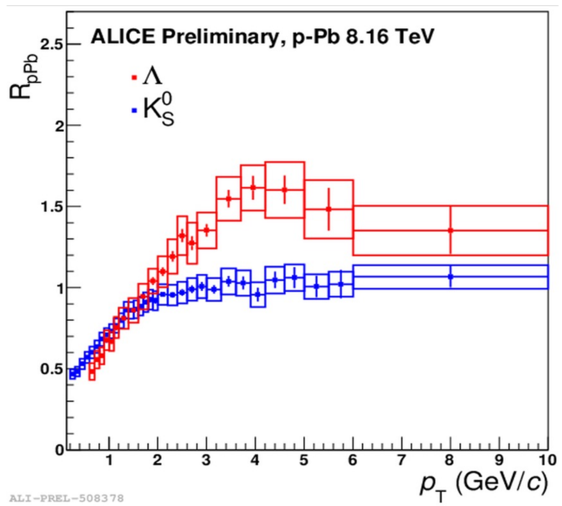
Strangeness Production in small systems





- The Λ / π and K^0_S/π ratios increase with multiplicity and then reach a saturation in central Pb-Pb collisions (consistent with the statistical hadronization model).
- Λ / K^0_S ratio shows no significant change as a function of multiplicity
  - Strangeness enhancement is not driven by mass nor it is a baryon/meson effect
- Λ / K^0_S ratio as a function of p_T shows peak at intermediate (Baryon enhancement)
  - interplay of radial flow and parton recombination at intermediate p_T
- Mass ordering of R_{pPb} at intermediate p_T which is
  - qualitatively similar to that in Pb–Pb collisions (Mass ordering or baryon meson splitting?)

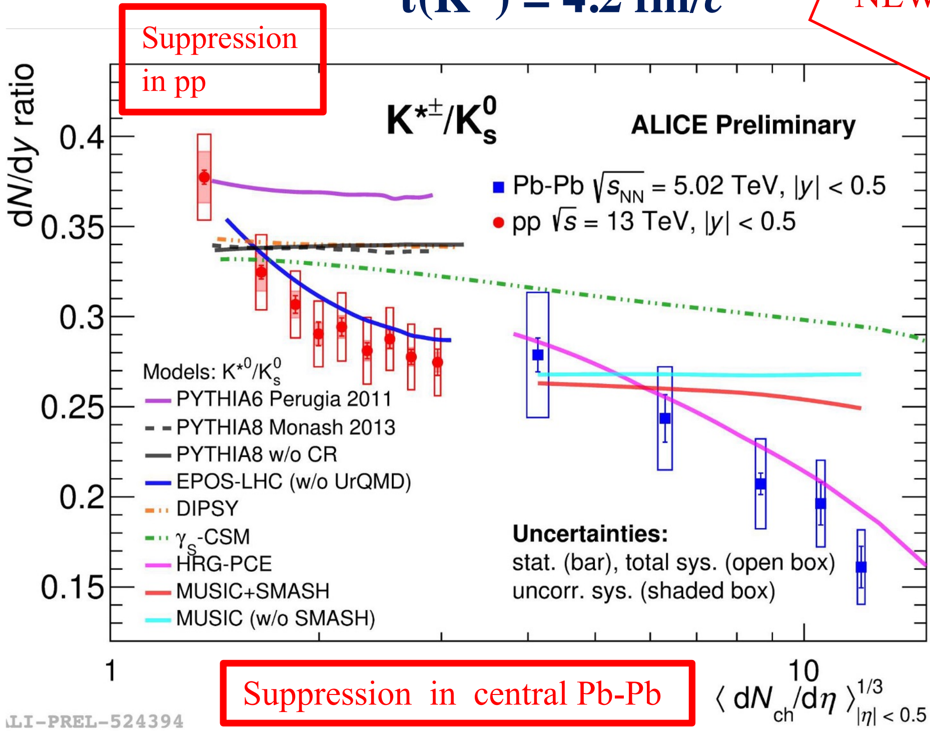




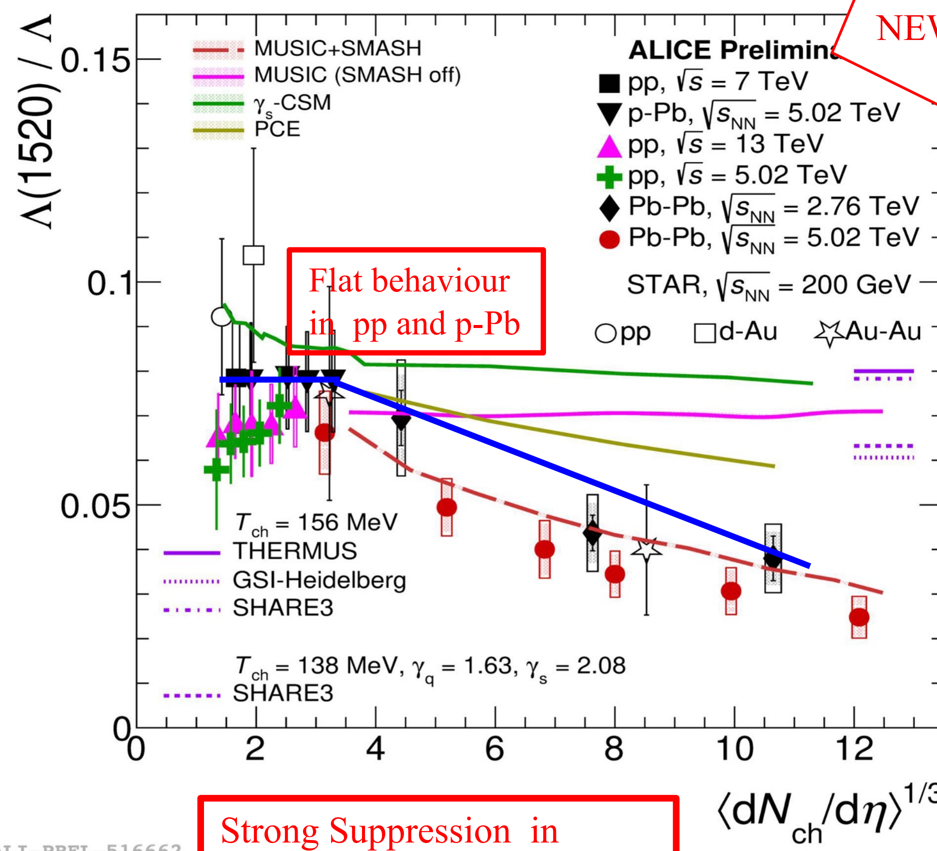
Particle Ratio

ALICE

$\tau(K^*) = 4.2$ fm/c



$\tau(\Lambda^*) = 12.6$ fm/c



- In small systems K*(892) shows effects that mimic those observed in Pb—Pb while in Λ*(1520) we observe a decreasing trend only in Pb—Pb
- These effects are due to the life time of the two particles species and their life time in the hadronic phase.

PCE: PRC102(2020)024909
MUSIC:arXiv:2105.07539
THERMUS: Comput. Phys. Commun. 180 (2009) 84
GSI-Heidelberg: PL B673 (2009) 142
SHARE3: Comput. Phys. Commun. 185 (20014) 2056
STAR data: PR C78 (2008) 044906
γ-CSM:Phys.Rev.C 100 (2019) 5, 054906
EPOS3:10.1103/PhysRevC.93.014911
ALICE: Phys. Rev. C 99, (2019) 024905 ALICE: Eur. Phys. J. C 80 (2020) 160

Angular correlation studies

ANGULAR CORRELATION METHOD

1) Trigger particle as a proxy for the jet axis ($p_T > 3$ GeV/c)
2) Identification of associated particles (strange hadrons)
3) Angular correlation between trigger and associated particles

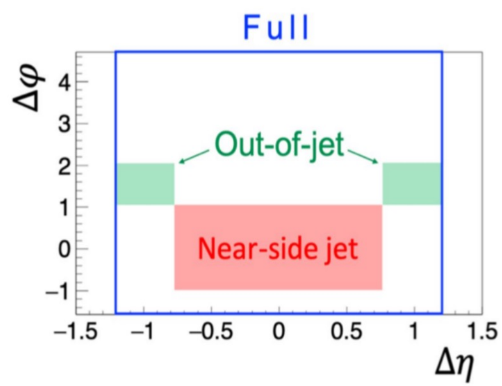
$\Delta\varphi = \varphi_{Trig} - \varphi_{Assoc}$

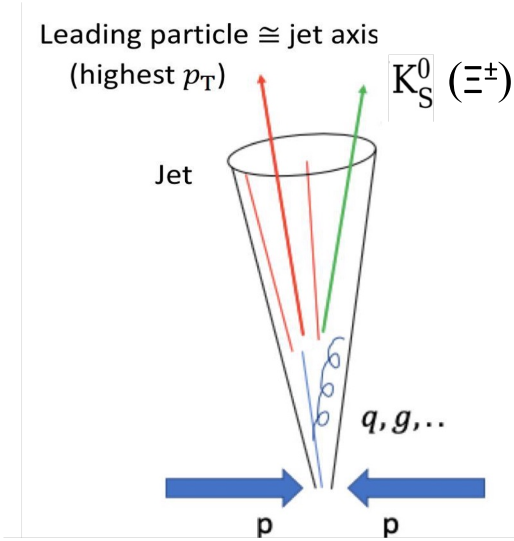
$\Delta\eta = \eta_{Trig} - \eta_{Assoc}$

φ: azimuthal angle

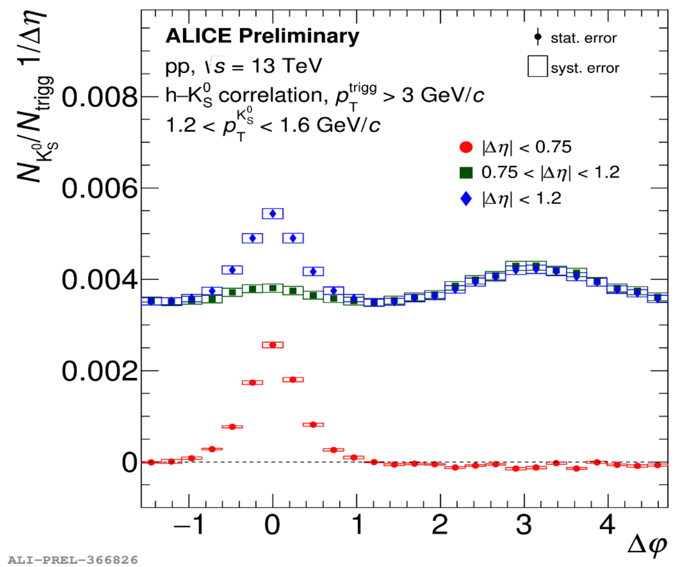
$\eta = -\ln(\tan(\theta/2))$

θ: polar angle





From identified pions and protons ALICE reconstructs K^0_S via V0 decay topology and via cascade decay topology



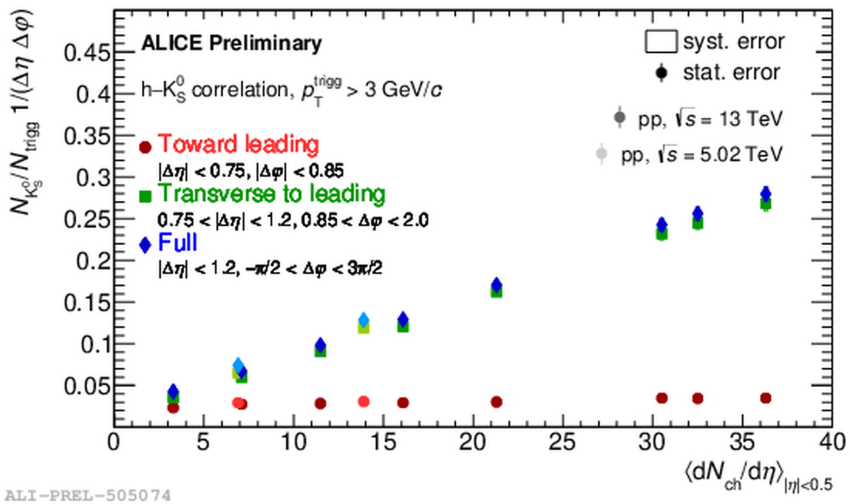
The near-side-jet contribution is obtained subtracting the full and out-of-jet yields in the selected $\Delta\varphi$-$\Delta\eta$ region

Toward leading = Full – Transverse-to-leading

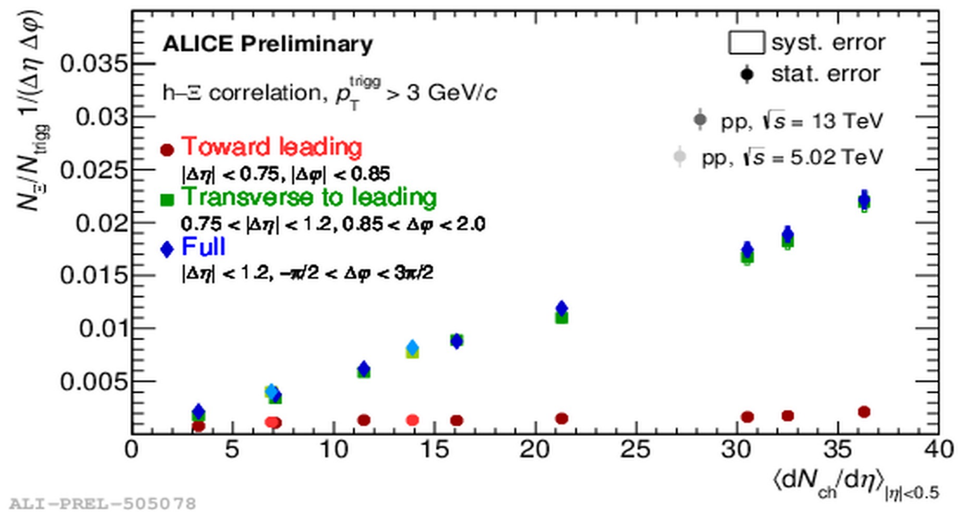
Angular correlation: in and out-of-jets

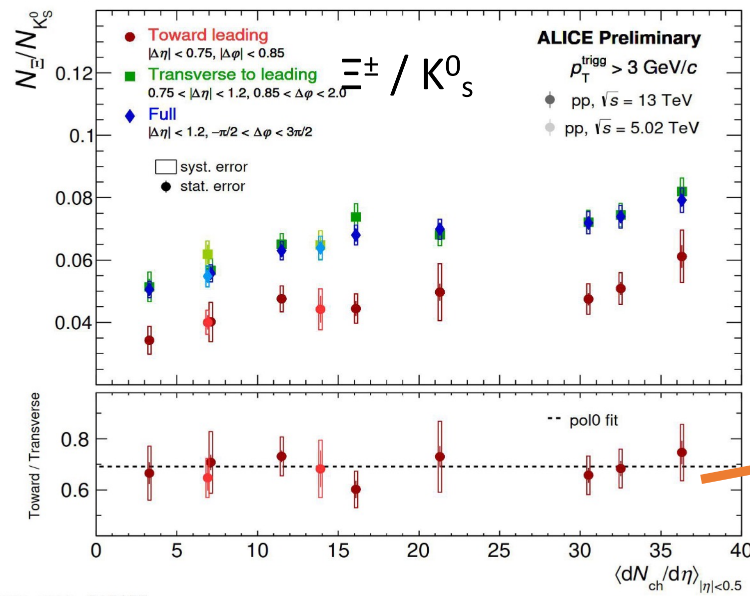
ALICE

K^0_s



$\Xi^{\pm}$





- ➢ Full and out-of-jet (transverse to leading) yields increase with multiplicity
- ➢ Near-side-jet yields have very weak dependence on multiplicity
- ➢ No dependence on centre-of-mass energy
- ➢ The out-of-jet Ξ/K^0_s yield ratio increases with multiplicity ➔ Large strangeness content of Ξ w.r.t K^0_s
- ➢ The near-side-jet Ξ/K^0_s yield ratio shows a hint of increase with multiplicity

Out-of-jet processes are the dominant contribution to the full yield ratio

Effective energy

Charged particle multiplicity in pp collision is characteristic of hadronic final state and is strongly correlated to Initial effective energy

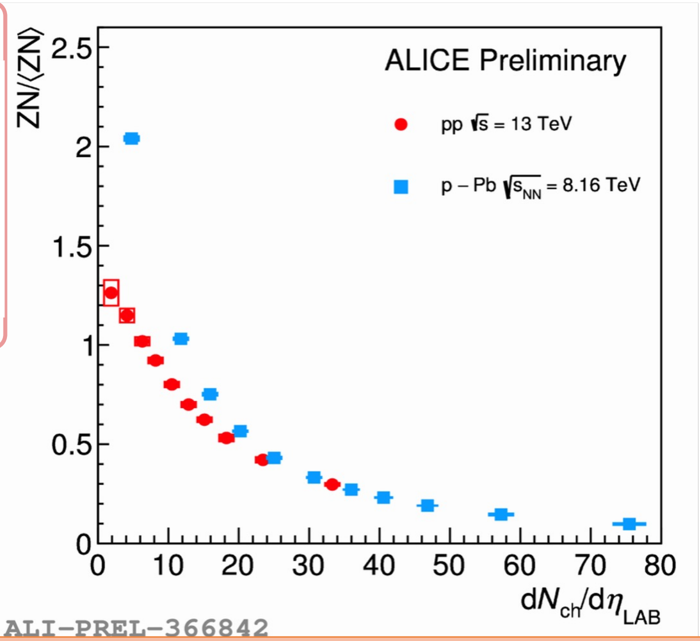
ALICE can measure

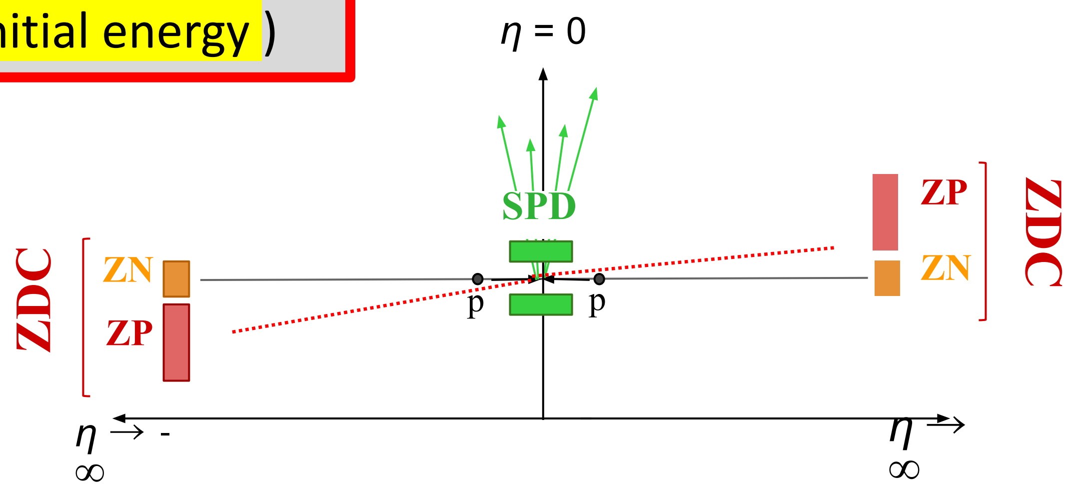
- midrapidity multiplicity(SPD)
- Leading energy (ZDC) $E_{eff} = \sqrt{s} - E_{leading} \approx \sqrt{s} - E_{ZDC}$
- Forward multilicity (V0M=V0A+V0C)

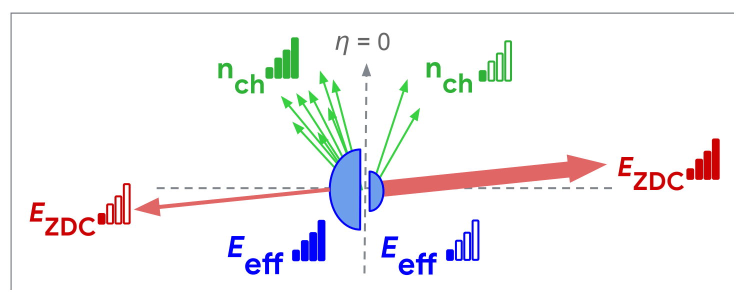
Effective energy

Energy available for particle production in the initial stages of pp collision (Effective energy < Initial energy)

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

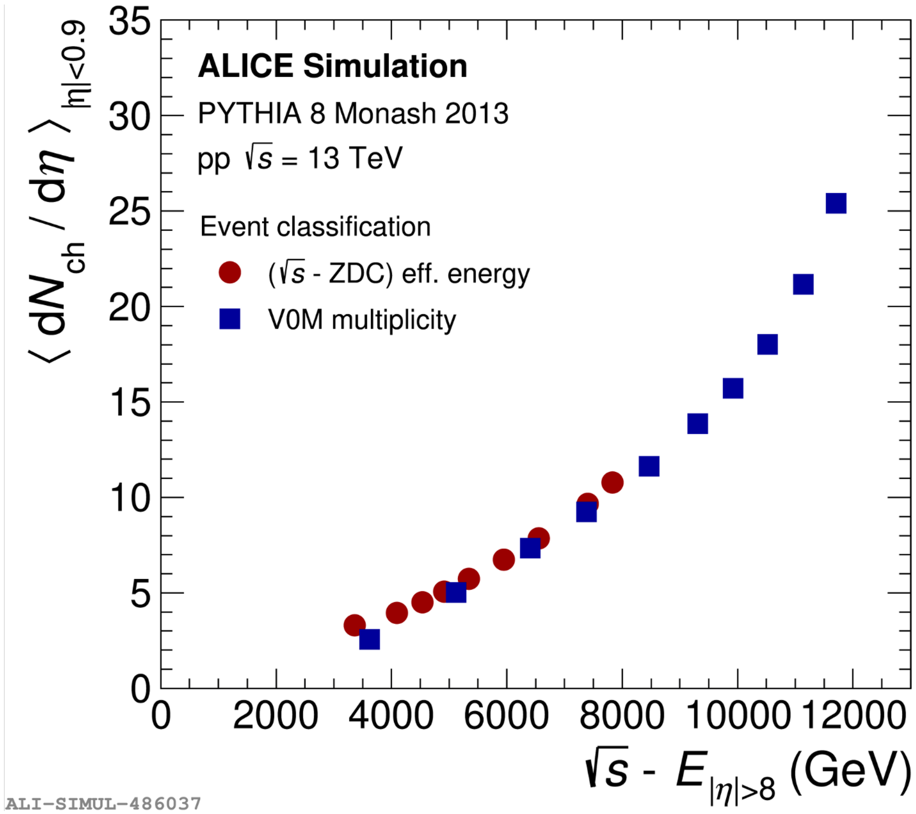






Effective energy and multiplicity are correlated

Multiplicity classes: V0 and ZDC Combined



Both monte carlo simulation and data confirm

effective energy and multiplicity are correlated

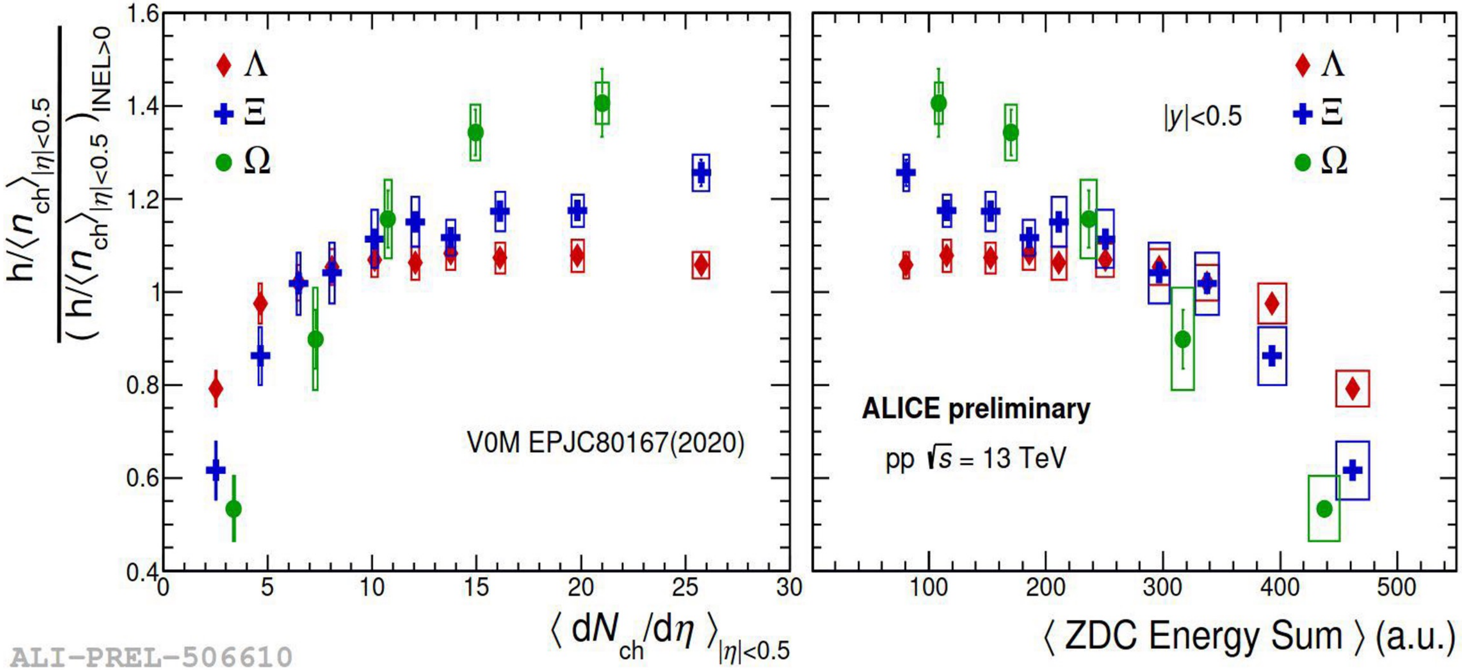
- data show forward energy decreases with increasing particle multiplicity at midrapidity
- simulation shows that V0 and ZDC based event classes have sensitivity to multiplicity and effective energy

★ Standalone analyses are not able to disentangle initial and final state effects

★ Combined classes could help to discriminate

Strangeness Production:

Energy and Multiplicity class (Single Differential Class)



final state proxy

initial state proxy

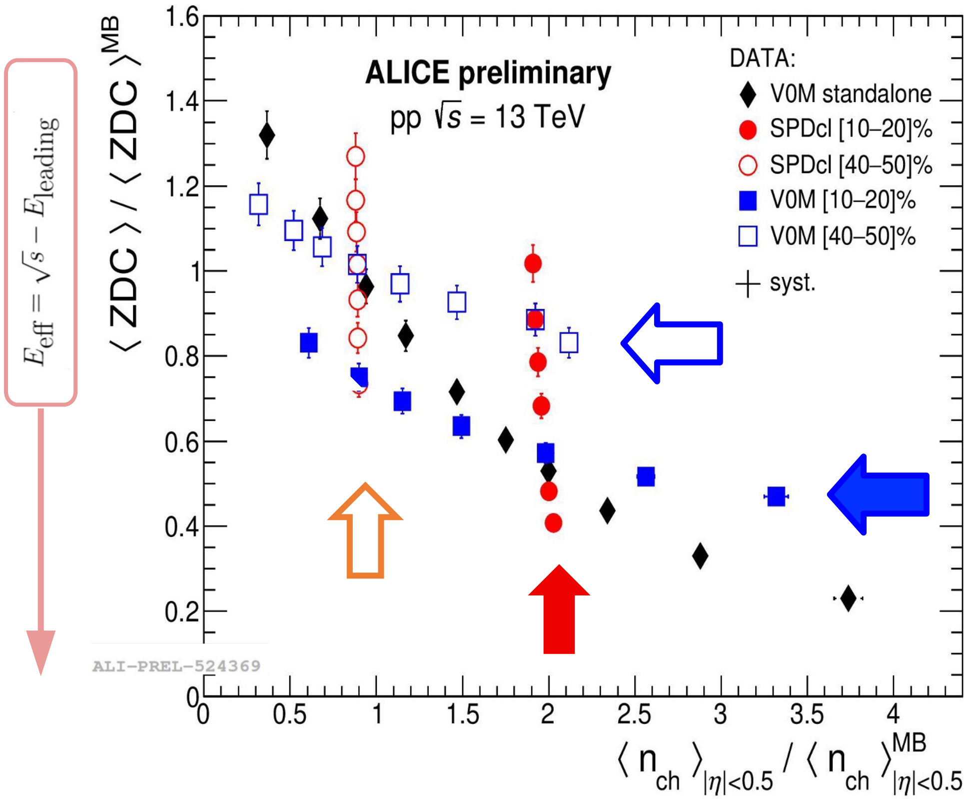
(Self-normalized) ratio of yields to the average charged particle multiplicity (in INEL>0) with multiplicity selected through V0 and ZDC

Strangeness production per charged particle:

- increases with midrapidity multiplicity (left)
- is anticorrelated with the ZDC energy (right)

Multi-differential class

The forward energy decreases with increasing particle multiplicity produced at midrapidity



♦ Standalone V0 event classes

Event classes defined using V0 and SPD (clusters):

● ○ SPD class fixed+ V0M selections:

Fixed multiplicity at midrapidity + different forward energy deposits in the ZDC

● SPDcl fixed in [10-20]%
○ SPDcl fixed in [40-50]%

□ ■ V0M class fixed+ SPD selections:

ZDC energy fixed in a small range + different multiplicity produced in the event

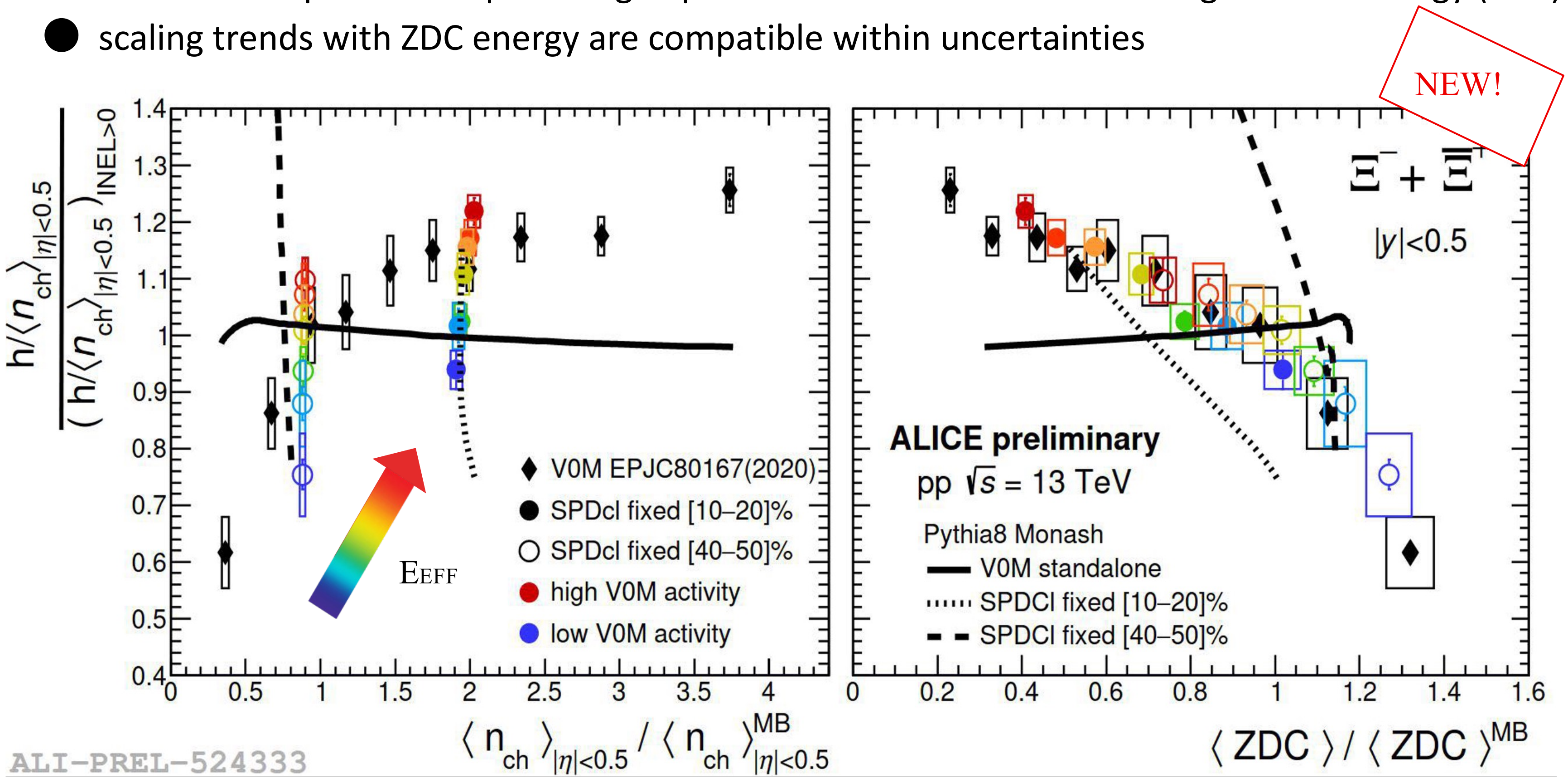
■ V0M fixed in [10-20]%
□ V0M fixed in [40-50]%

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

Strangeness production at fixed multiplicity

In events with the same particle multiplicity produced:

- increase in Ξ production per charged particle is observed for decreasing forward energy (ZDC)
- scaling trends with ZDC energy are compatible within uncertainties



The Pythia Monash 2013 tune fails to reproduce the results

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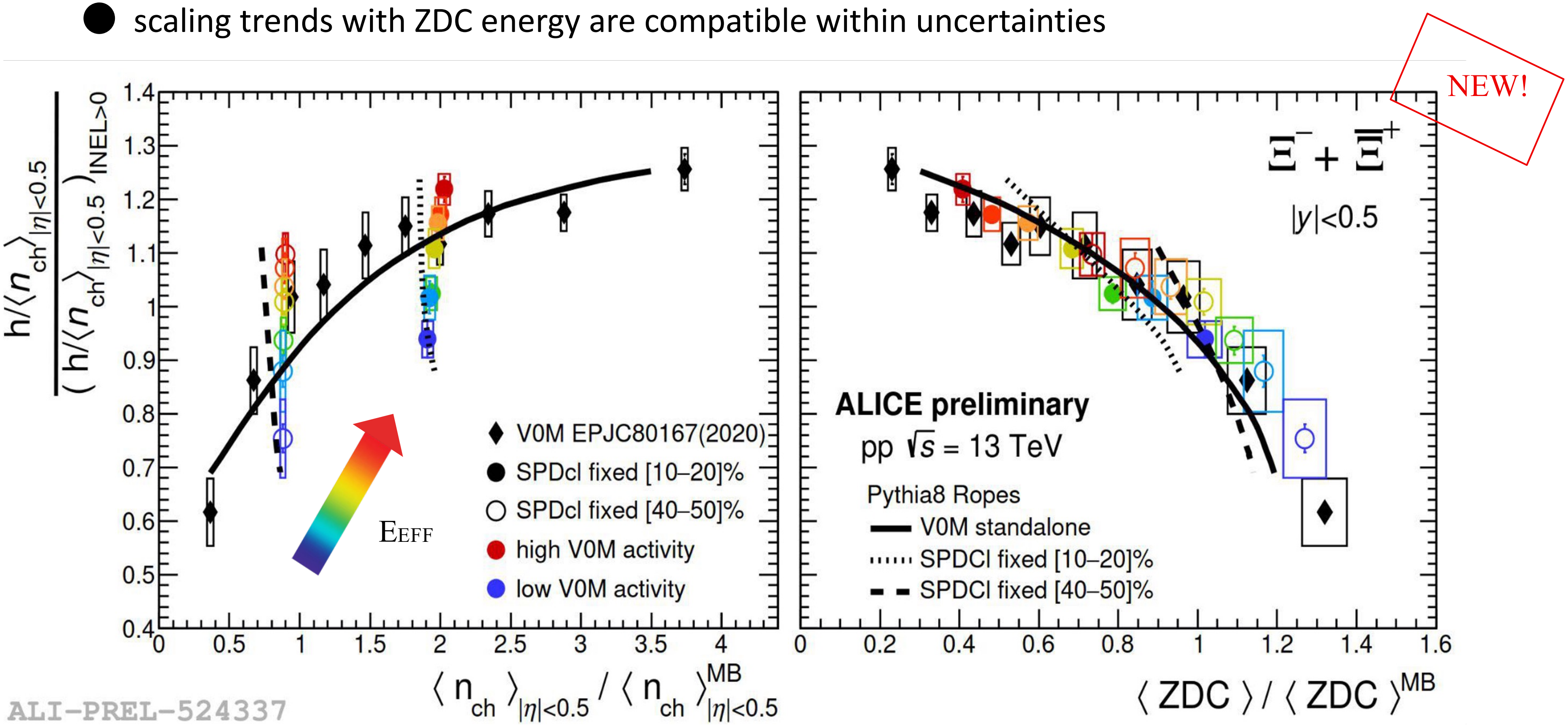
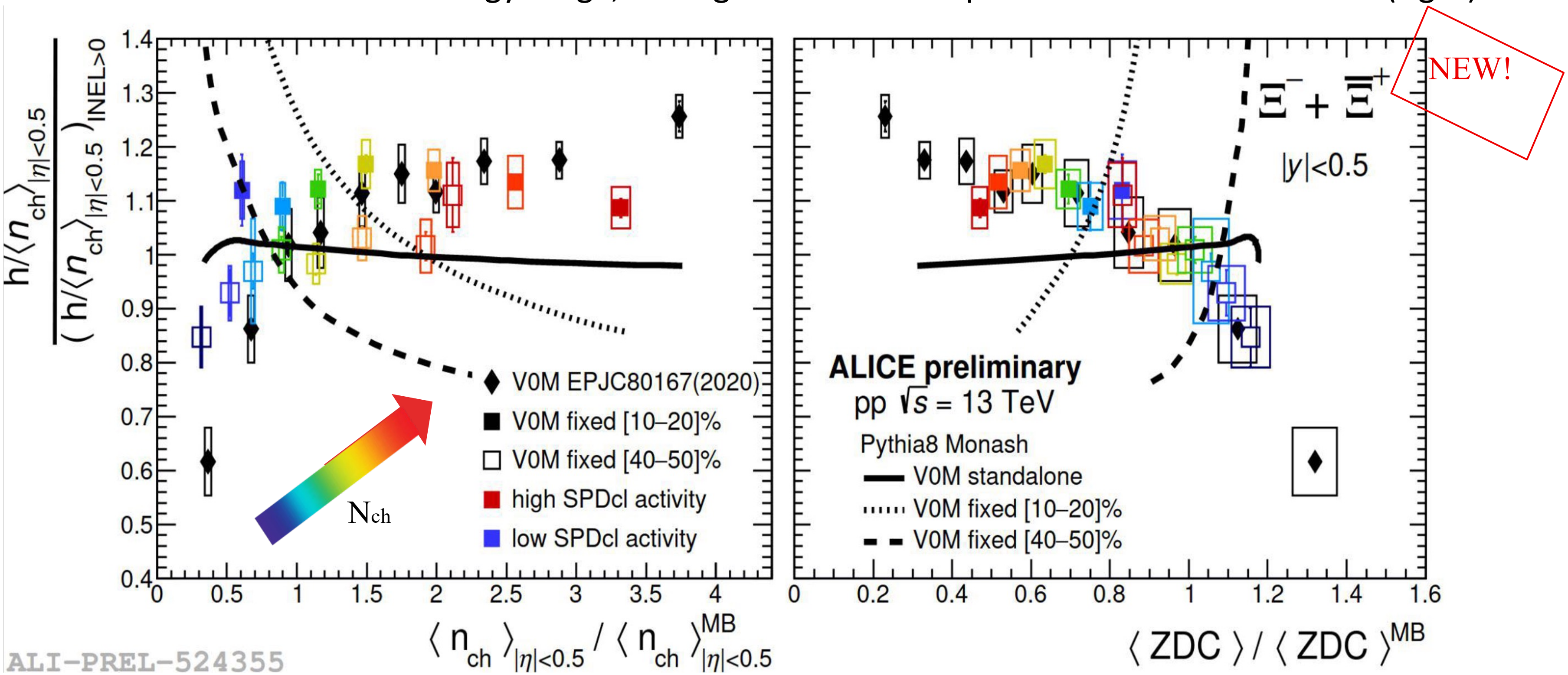


Including color Ropes in the model improves the data

Strangeness Production at fixed forward Energy

In events with ZDC energy deposits fixed in a small range:

- strangeness enhancement with multiplicity is reduced (left)
- within the small ZDC energy range, scaling trends are compatible within uncertainties (right)



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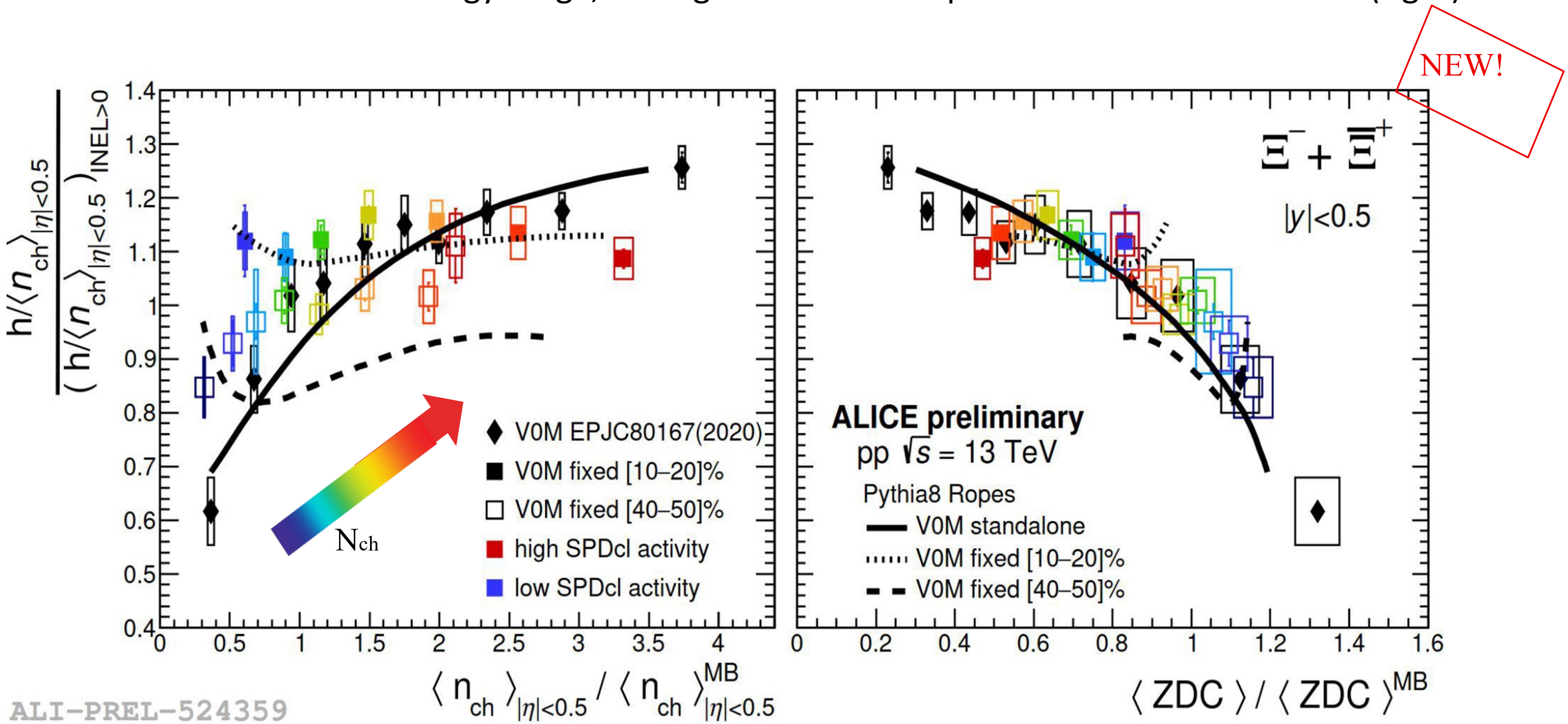

Including color ropes in the model improves the data

Summary: What have we learnt so far

- ❑ Emergence of phenomenona typically connected to a collective expansion of the medium observed in small systems
- ❑ New insight into strangeness enhancement: role of effective energy and production in- and out-of-jet
  - ALICE exploits a **multi-differential approach** to disentangle the contribution of multiplicity and effective energy to strange particle production
    - an **increase** in strangeness production is **observed at fixed midrapidity multiplicity** strangeness production shows a **strong correlation with the effective energy**
    - following a **universal trend** with the leading energy detected by the ZDC
  - Studying the relative contribution of hard and out-of-jet processes to strangeness production:
    - **transverse-to-leading processes** give the **dominant contribution** to strangeness production
    - **strangeness enhancement** with multiplicity is observed in **toward** and **transverse-to-leading** processes

Outlook

- Further multi-differential studies to explore the correlation between the effective energy and the relative contribution of in-jet and out-of-jet processes can help shed light on the origin of strangeness enhancement in pp collisions

- Studies of strangeness production in small systems 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)

Thank you!

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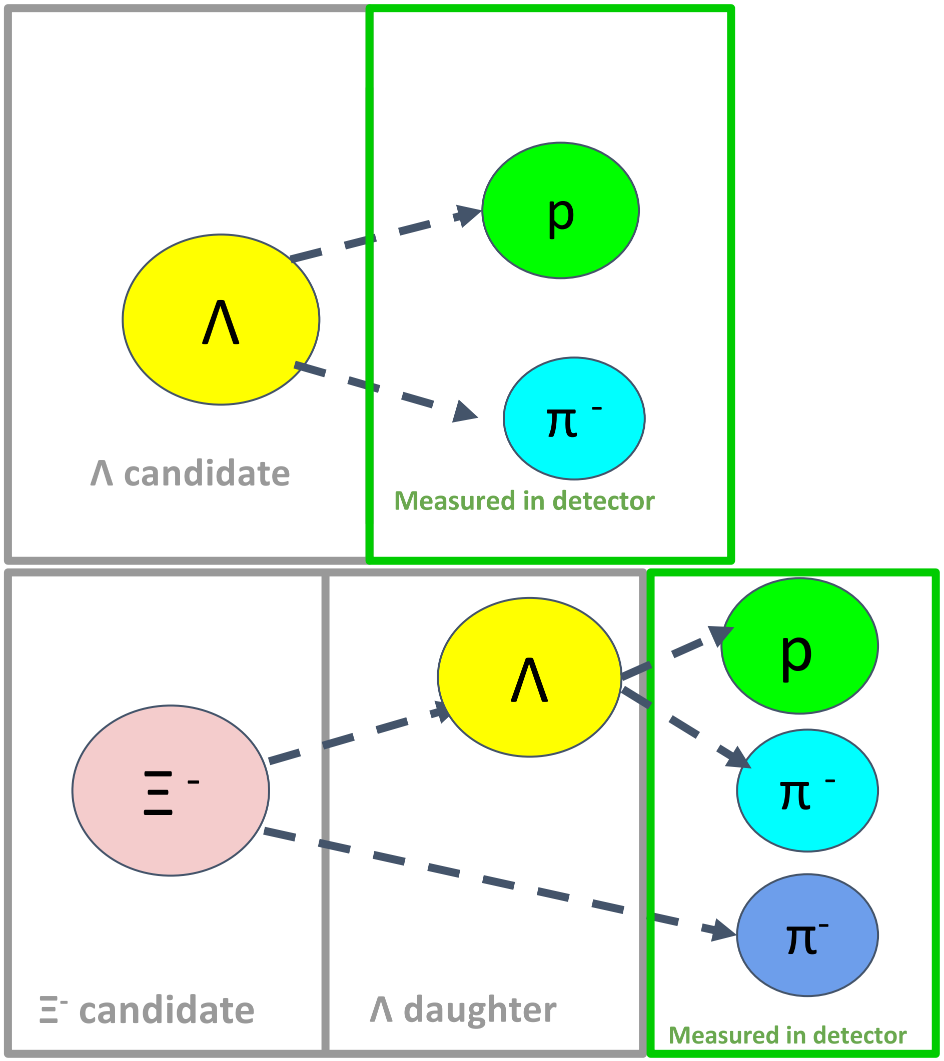
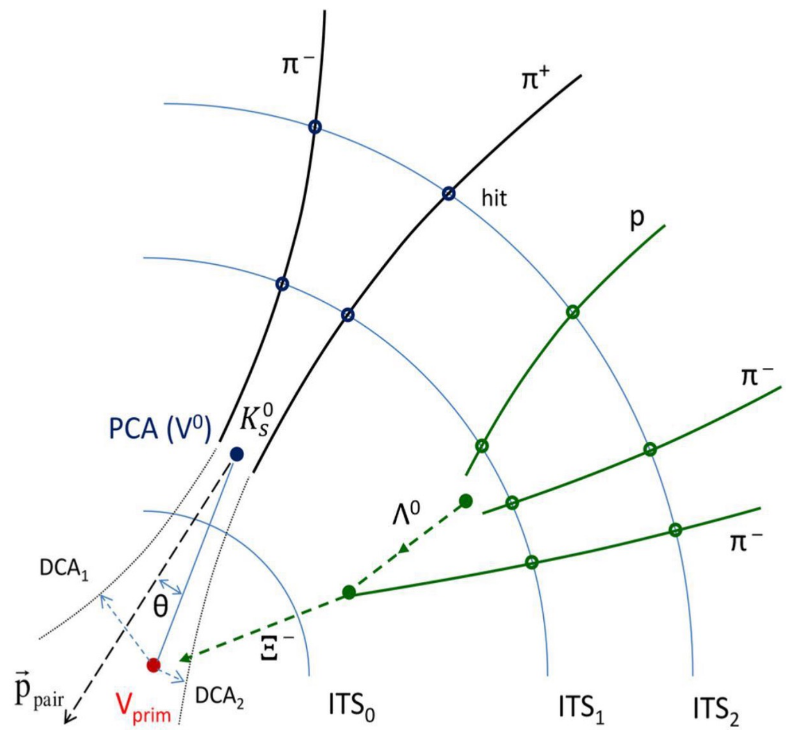
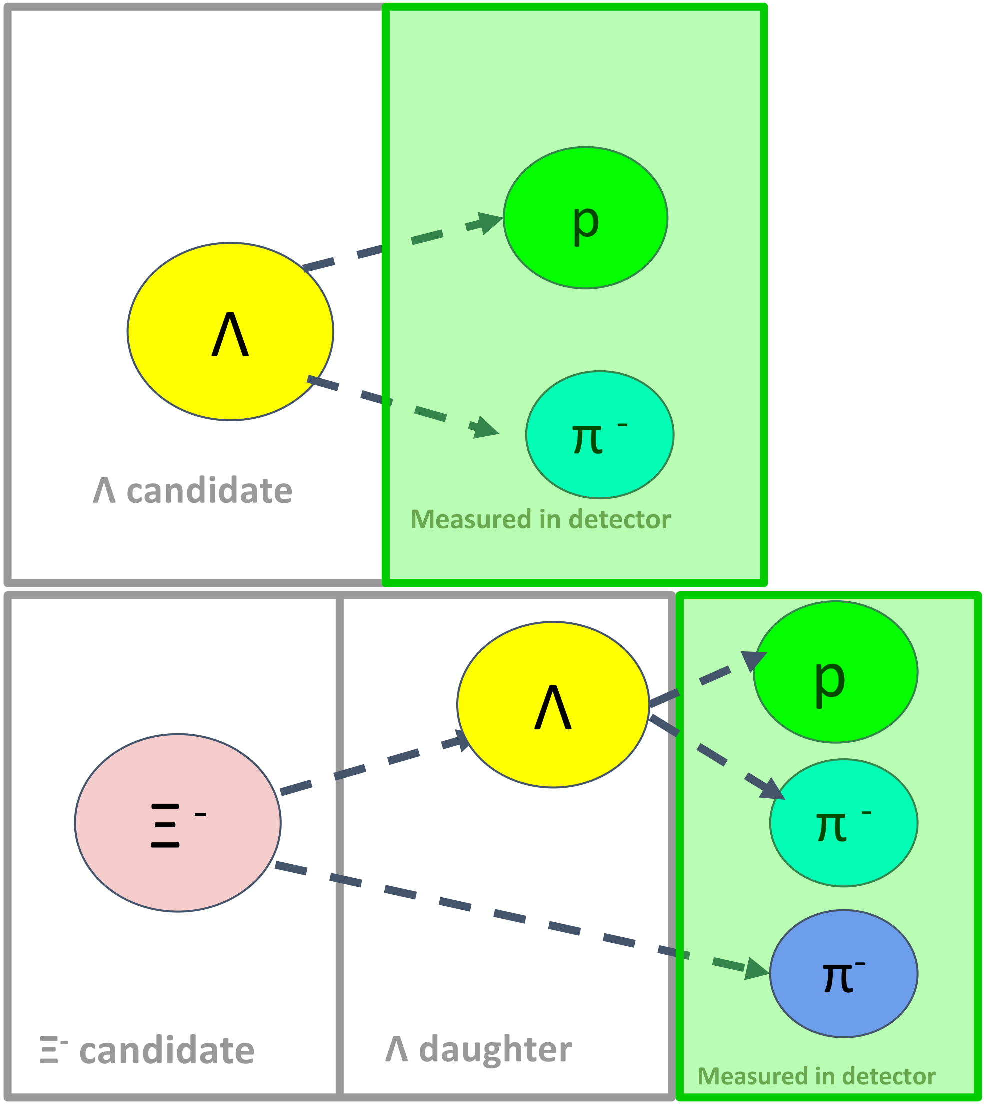
Backup Slides

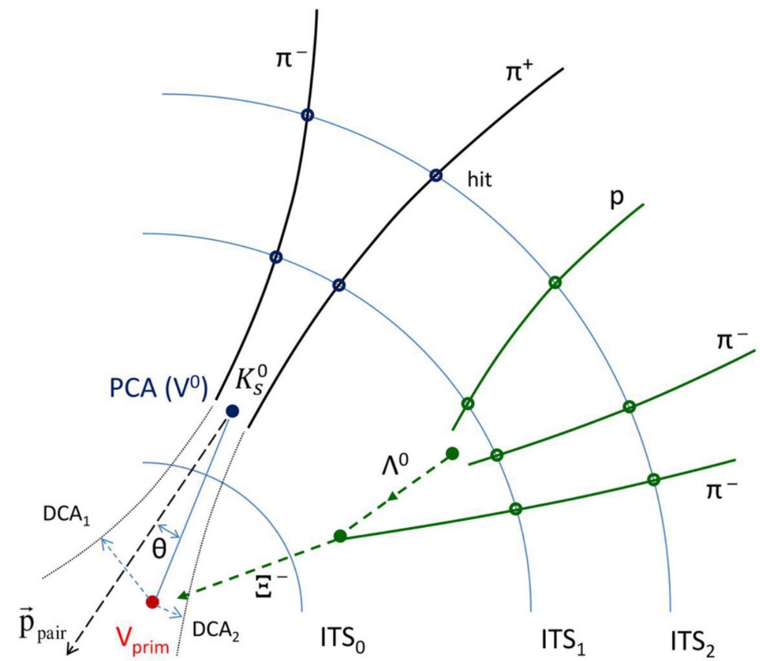
Strange particle identification @ALICE





Strange particle identification @ALICE



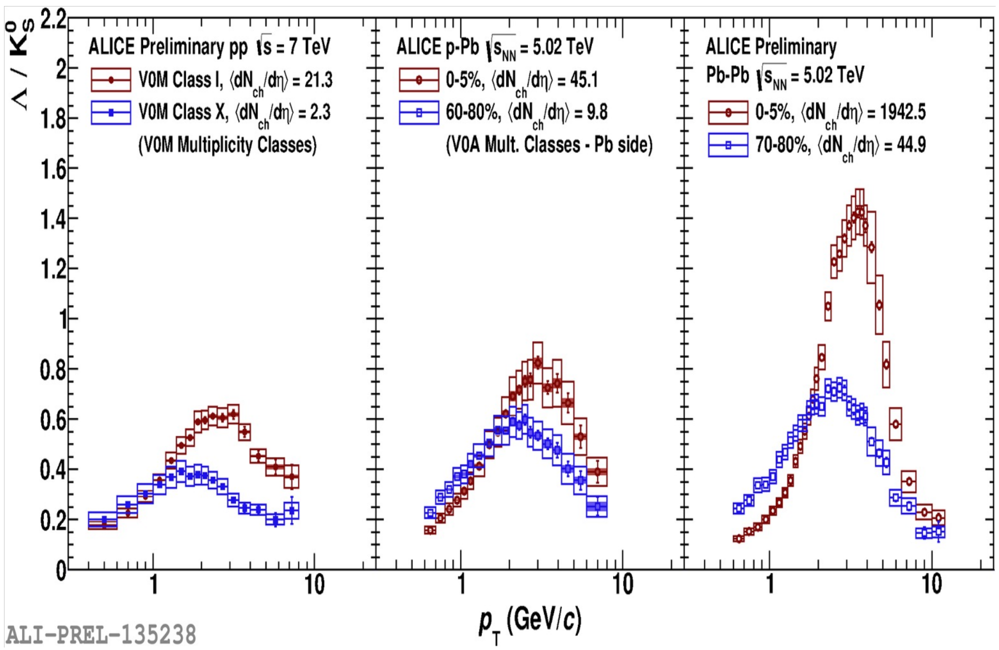


Baryon to Meson Ratio

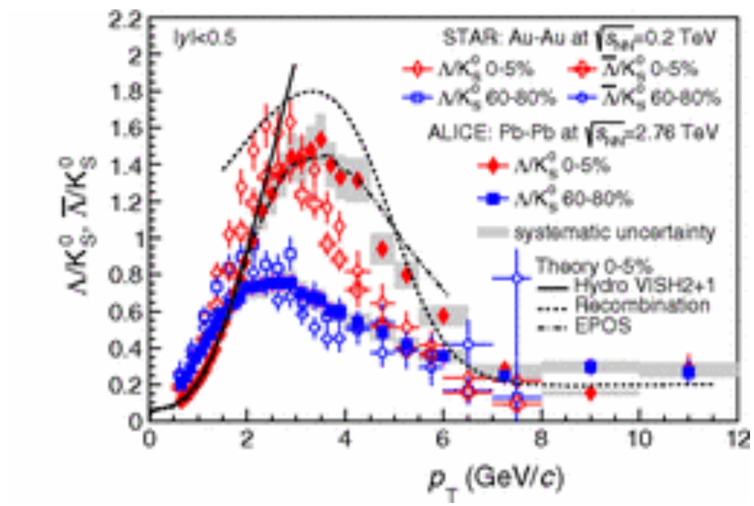
Enhancement of Λ/K^0_s at intermediate p_T (~ 3 GeV)

- ❖ Similar behaviour observed in different collision systems (pp, p-Pb and Pb-Pb) and also in p/π ratio
- ❖ Larger effect in collisions characterised by a larger charged particle multiplicity

Hints of collective phenomena in small systems?



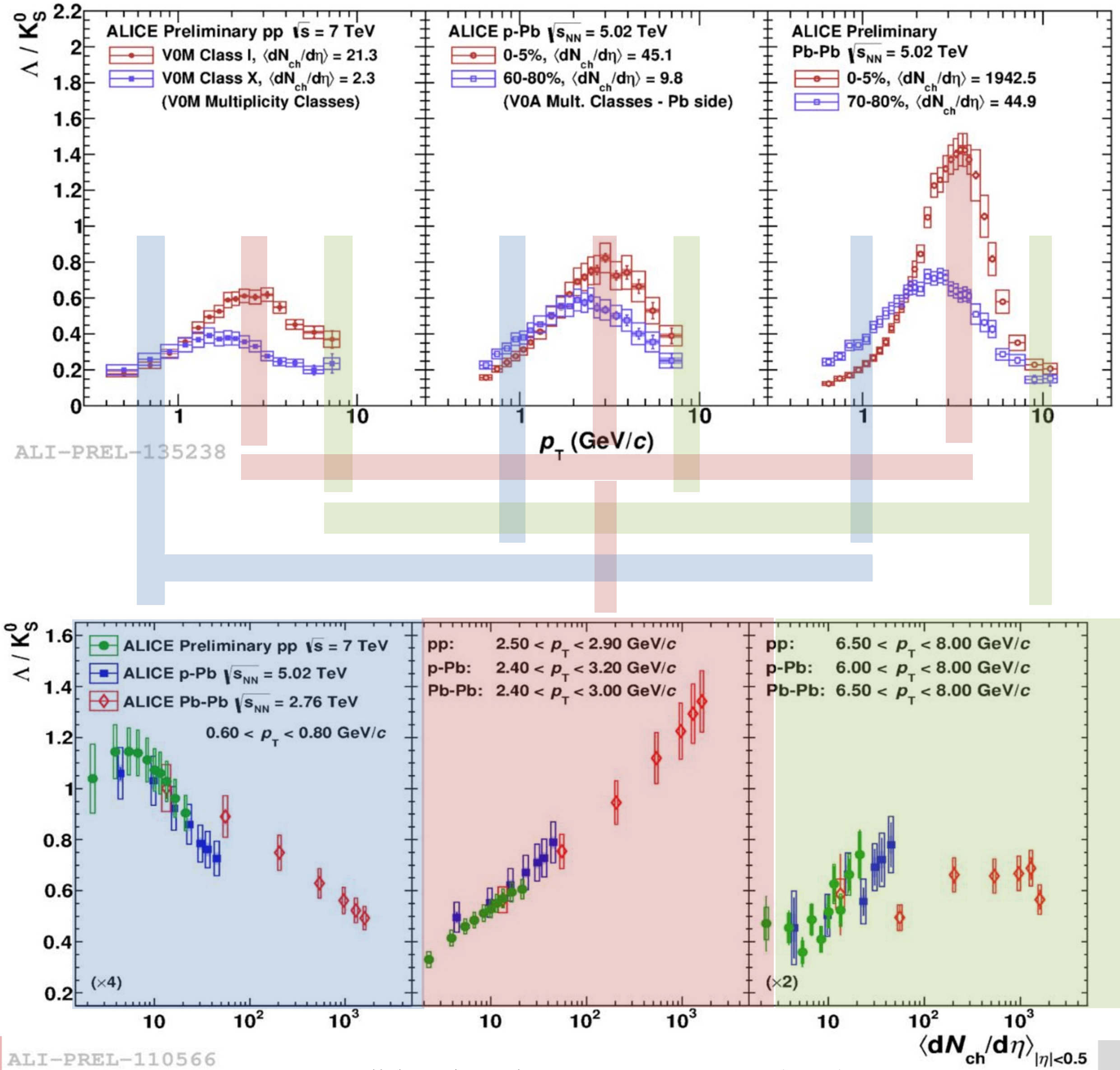
ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)



ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 222301

Interplay between recombination and radial flow

Baryon to Meson Ratio



- Smooth evolution with multiplicity when selecting specific p_T intervals
- Radial flow in small systems?
- Application of hydro far from equilibrium under study
- PYTHIA with CR can describe the low-p_T trend observed in pp

ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)