***Secondo incontro sulla fisica con ioni pesanti a LHC***

*Turin, 9-10 October*

# *Identified particle production at the LHC: what have we learnt?*

F. Fionda
University of Bergen (NO)

# Introduction

- Identified hadrons in heavy-ion collisions are produced in apparent (near) ***thermal*** and ***chemical*** equilibrium → "*macroscopic*" description of the system
  - *Statistical Hadronization Model* to reproduce hadron abundances
  - *Hydrodynamic* models to describe collective flow (radial and elliptic)

  Almost successful at the LHC... however the ***dynamic origin*** of the equilibrium is not yet clear at the moment.

- Can we use the same "*language*" in small systems ? A priori it's not expected but ***striking commonalities*** observed in *multiplicity dependent* studies between small / large colliding systems inspire us the following key questions:
  - Is there any hint of *thermal* and / or *chemical* equilibrium in small systems ?
  - What is the role of th *event multiplicity* ?
  - what are the *microscopic processes* at play ? Are these related to AA ?

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  - Is there any hint of *thermal* and / or *chemical* equilibrium in small systems ?
    → **$p_T$ spectra shapes, hadrochemistry**
  - What is the role of th *event multiplicity* ?
    → **Comparison of different $\sqrt{s}$ / systems at similar multiplicities**
  - what are the *microscopic processes* at play ? Are these related to AA ?
    → **Comparison with models**

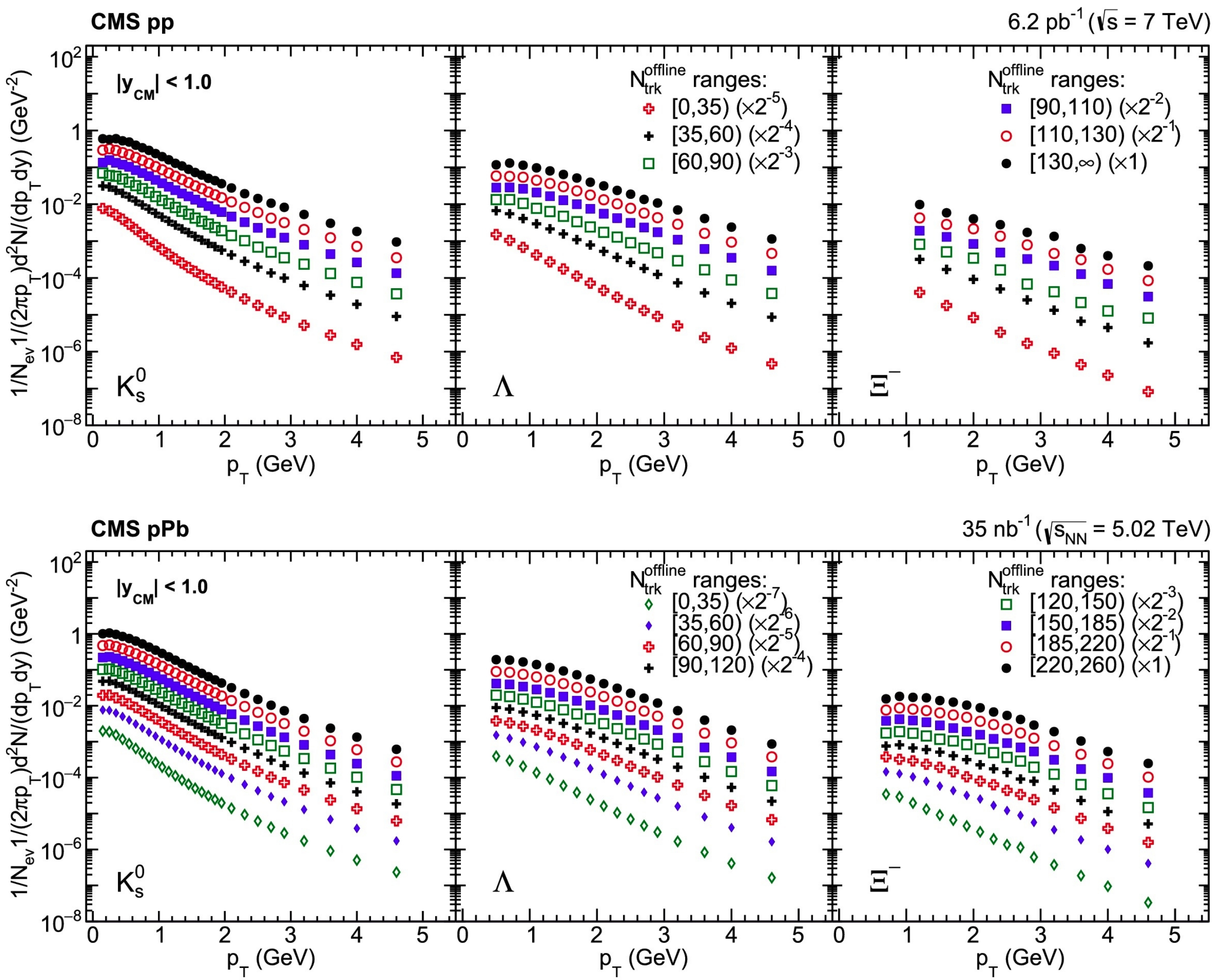
Multiplicity dependence study of **identified hadron production** (both $p_T$-spectra and integrated yields) is a powerful tool to shed light on these outstanding questions !

# Outline

- Identified hadron production at the LHC (mainly ALICE, CMS):
  - $p_T$ spectra shapes
  - Hadrochemistry
  - Evolution of particle production with $\sqrt{s}$ and multiplicity
  - Event shape studies
- Concluding remarks

# Transverse momentum spectra

[CMS, PLB 768 (2017) 103]




**pp, $\sqrt{s}$ = 7 TeV**

**pPb, $\sqrt{s_{NN}}$ = 5.02 TeV**

- Spectra become **harder** for increasing multiplicity
- In Pb-Pb interpreted in terms of collective expansion of a thermalized system (radial flow) which may require a fireball in a local thermodynamical (kinetic) equilibrium

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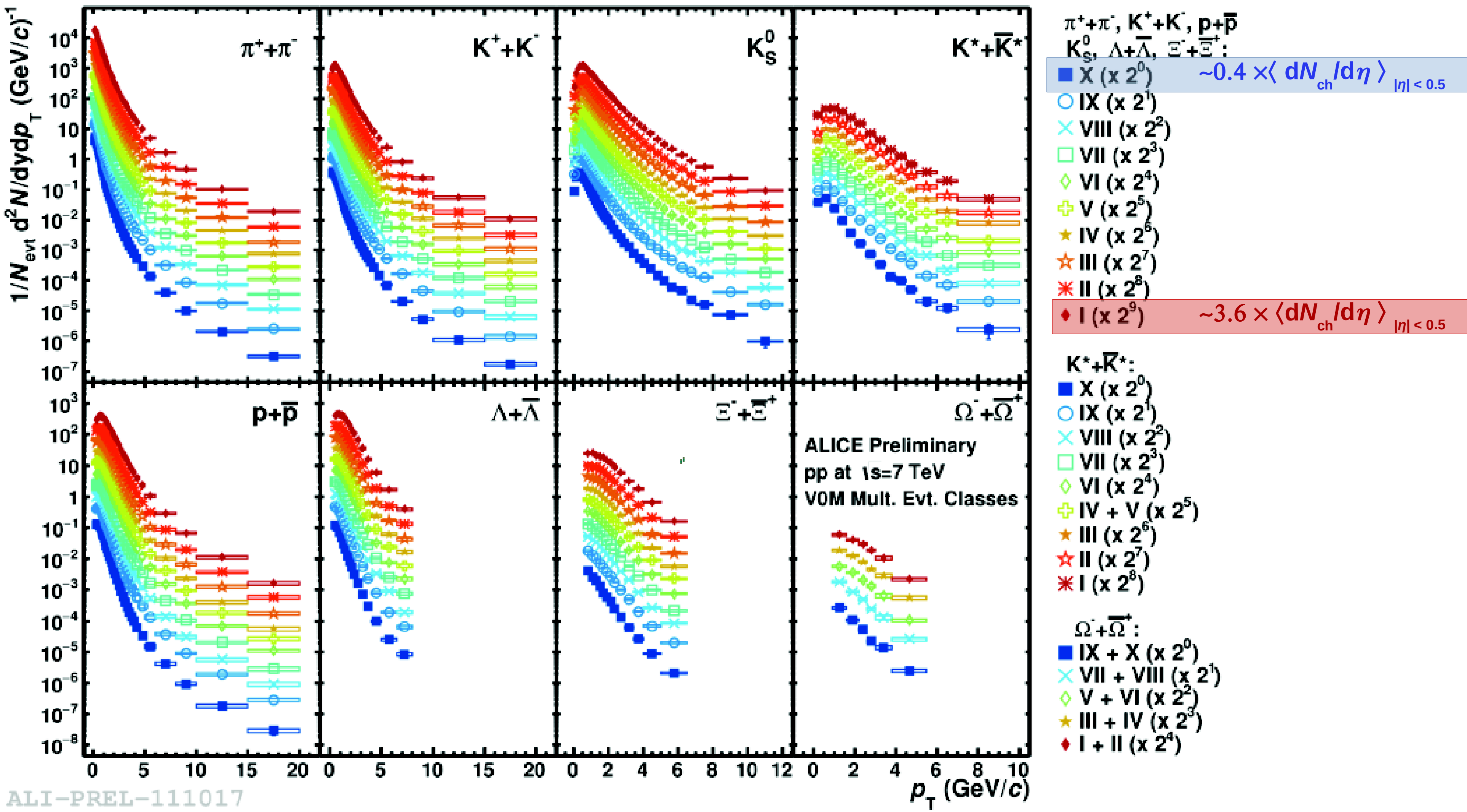


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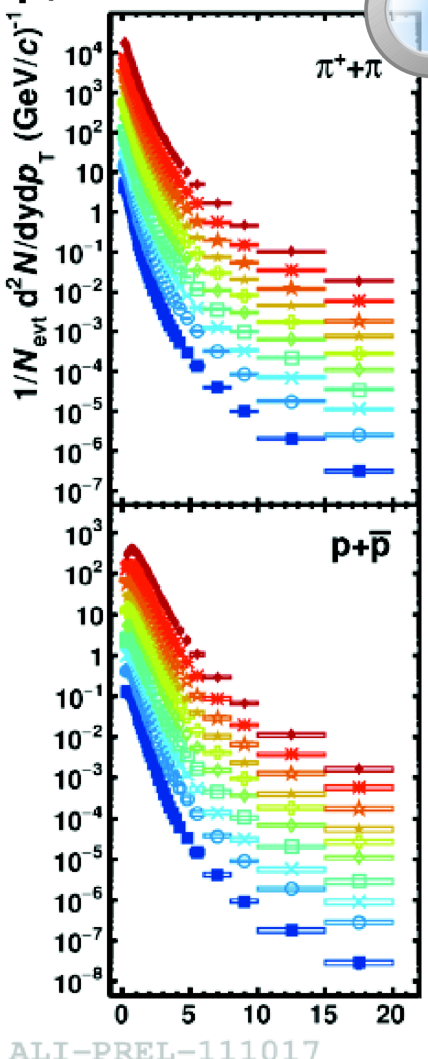
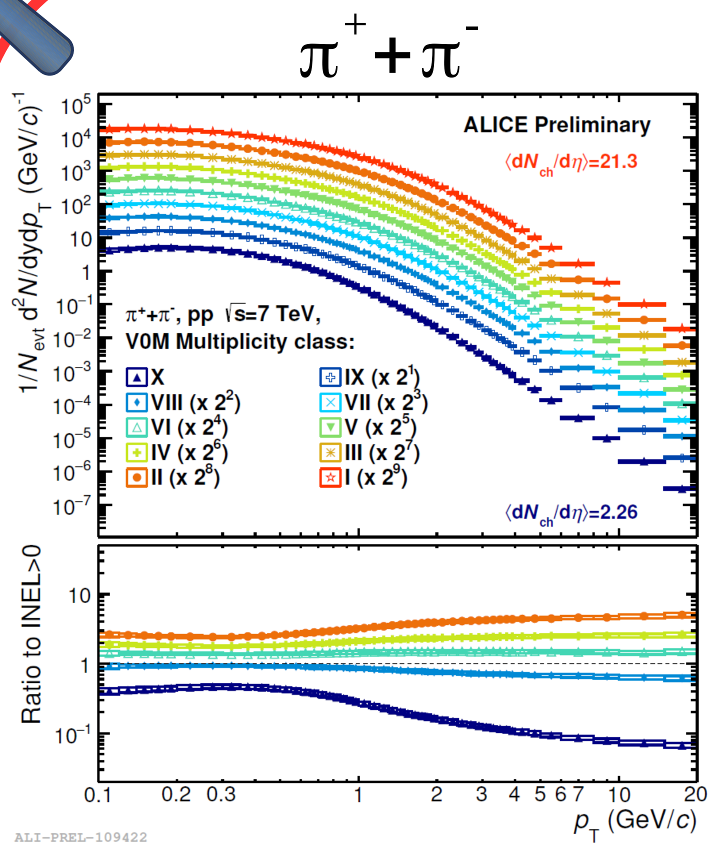
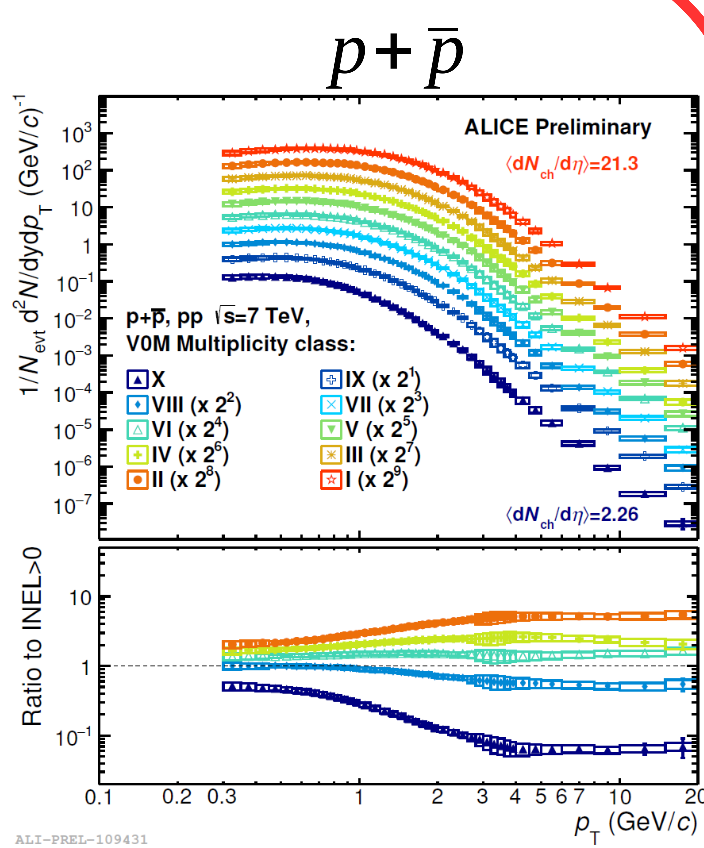
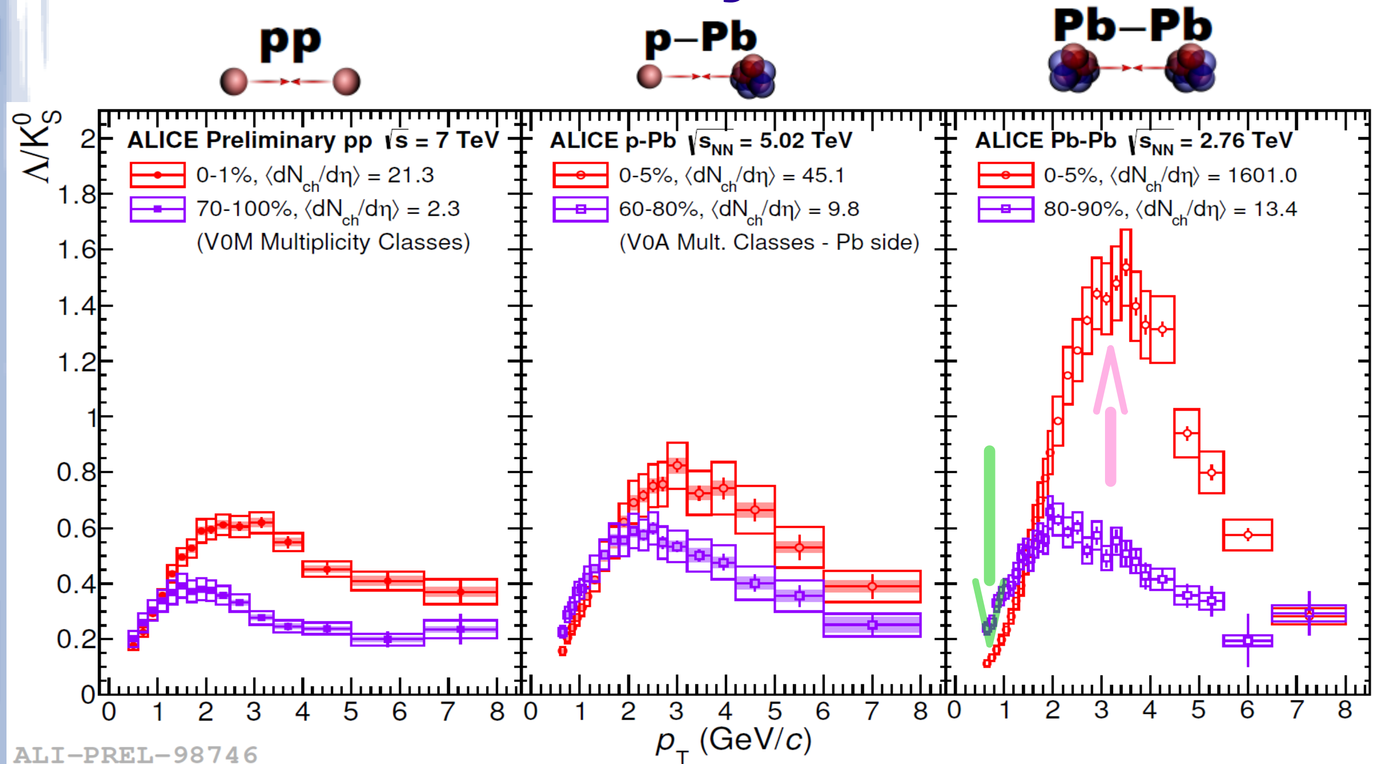


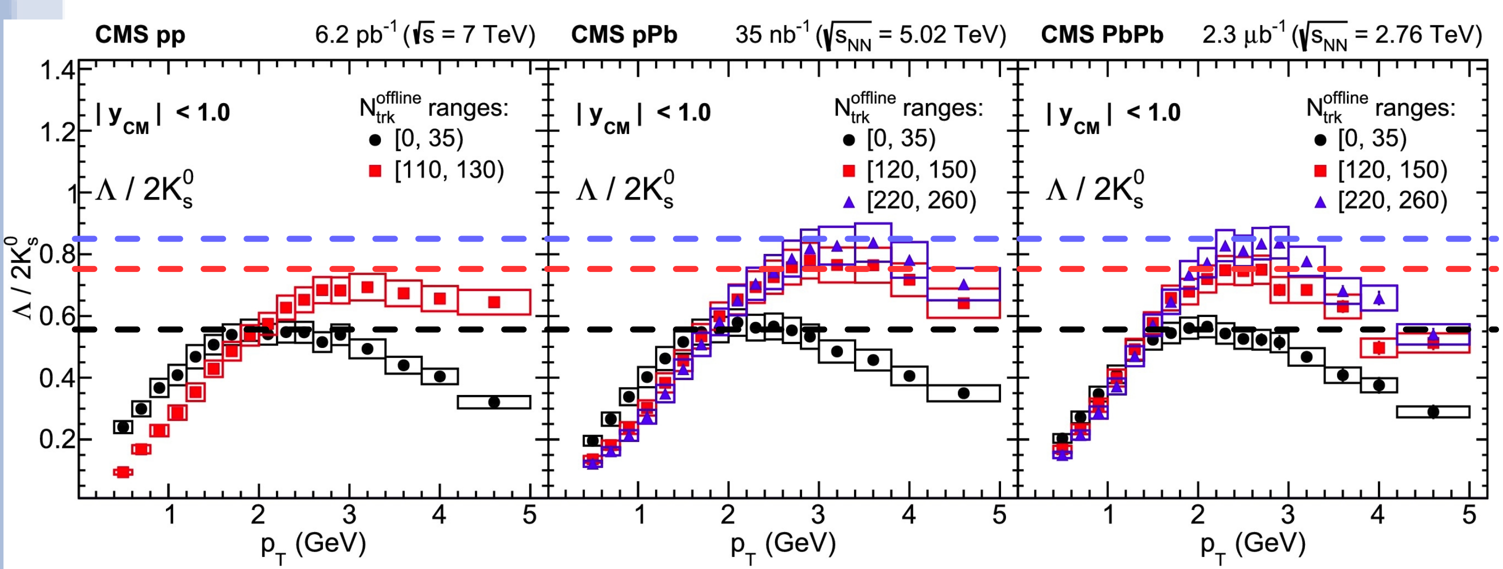




- Spectra become **harder** for increasing multiplicity
  - **flattening** of the spectra at low $p_T$, more pronounced for heavier particles
- In Pb-Pb interpreted in terms of collective expansion of a thermalized system (radial flow) which may require a fireball in a local thermodynamical (kinetic) equilibrium

# Baryon-to-meson ratio



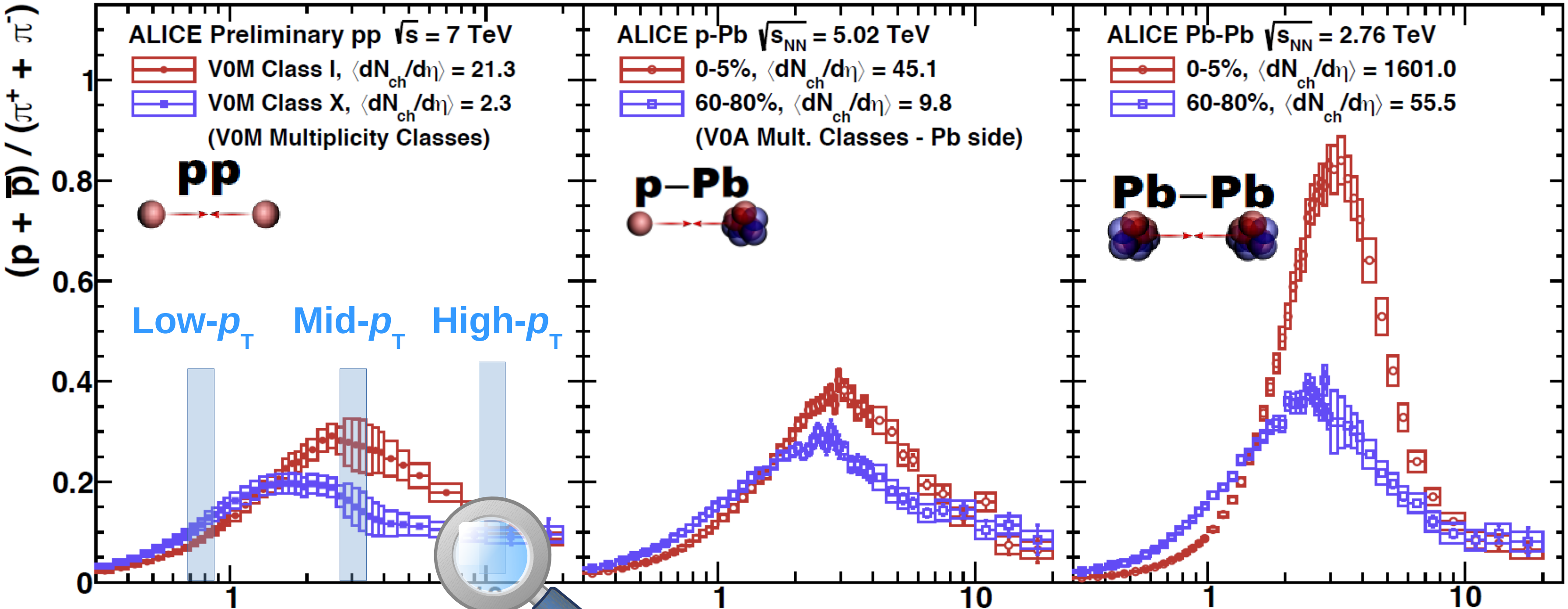

- Similar evolution observed in all colliding systems (different multiplicities!)
  - **Depletion** at low $p_T$
  - **Enhancement** at intermediate $p_T$
  - no modifications at high $p_T$
- In Pb-Pb discussed in terms of collective flow and / or quark recombination (depending on $p_T$ and centrality)




[CMS, PLB 768 (2017) 103]

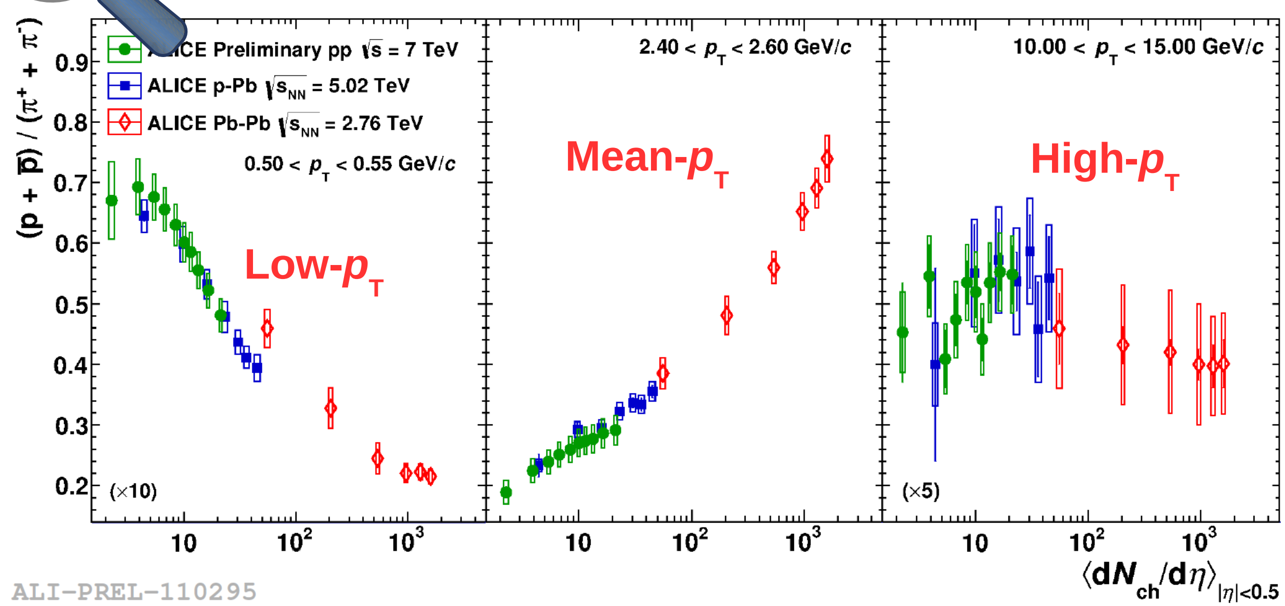
- Similar value of maximum in different colliding systems at similar multiplicities

# Baryon-to-meson ratio




- ✔ Remarkable smooth trend observed by ALICE across all colliding systems!

→ Points toward one ***common driving mechanism*** in all systems



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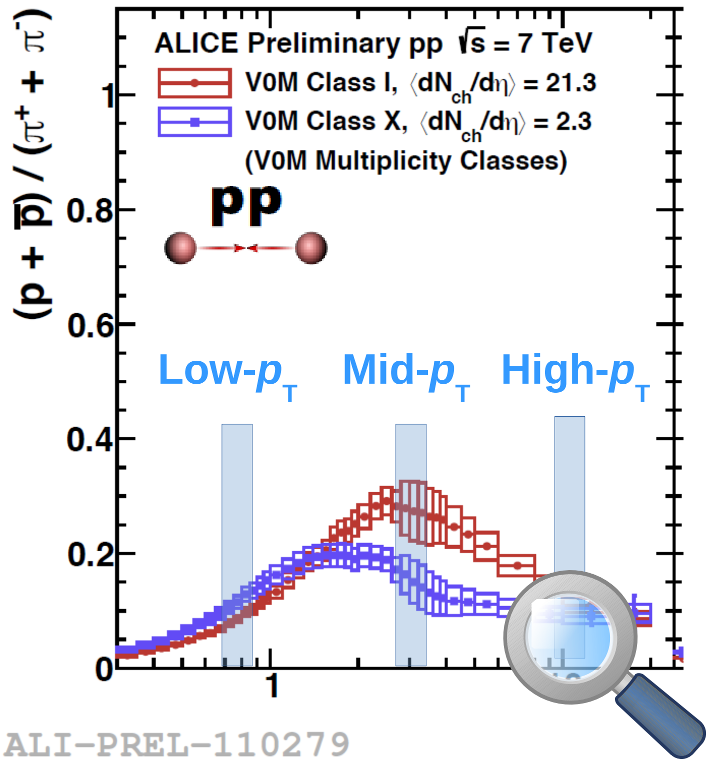
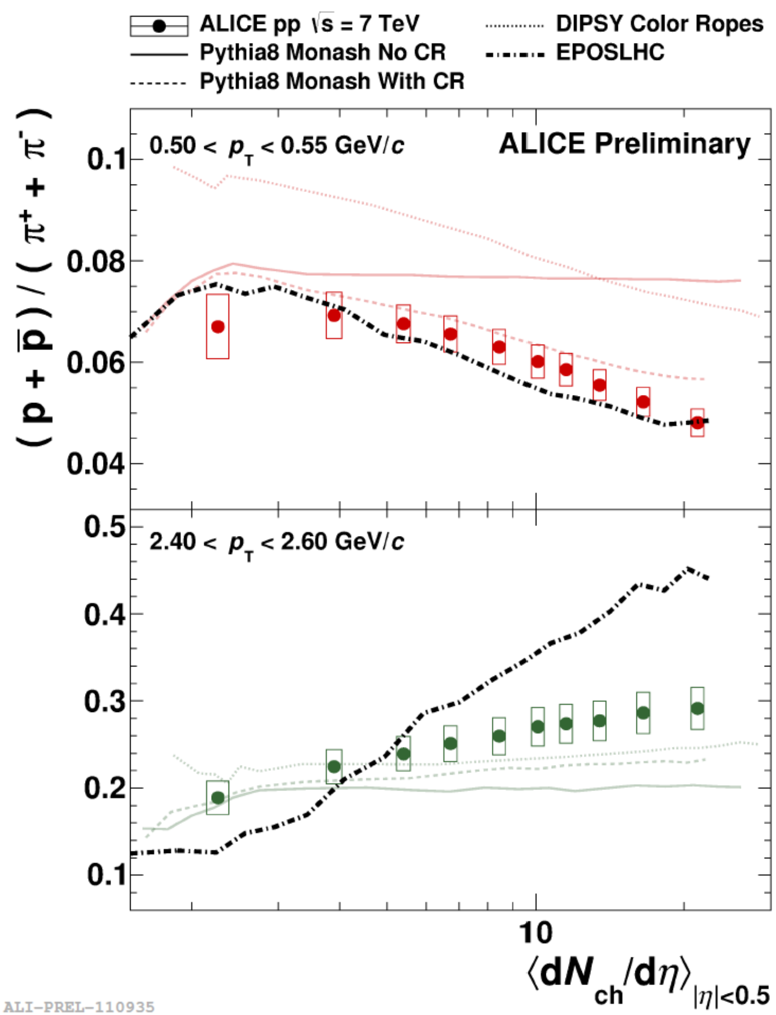
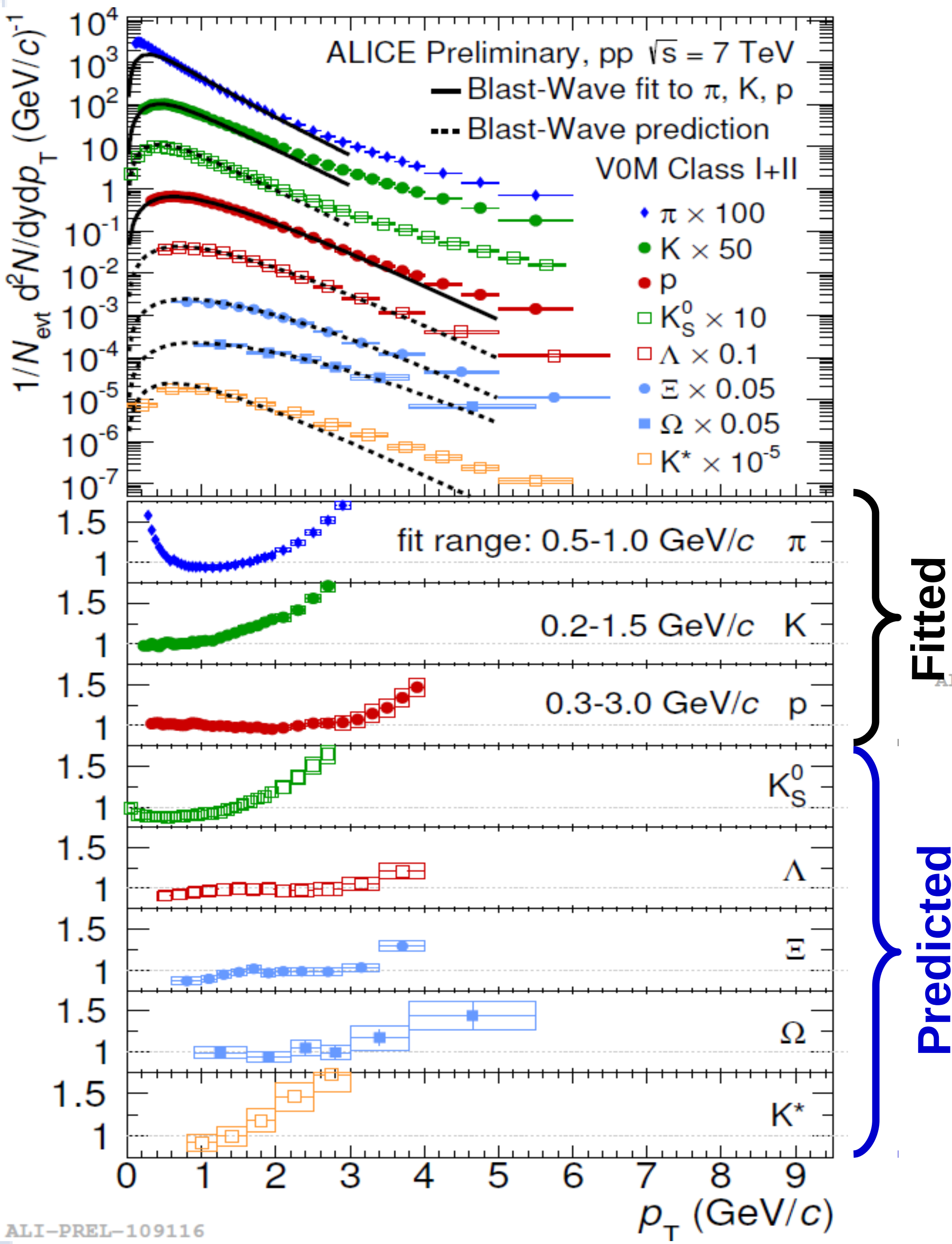


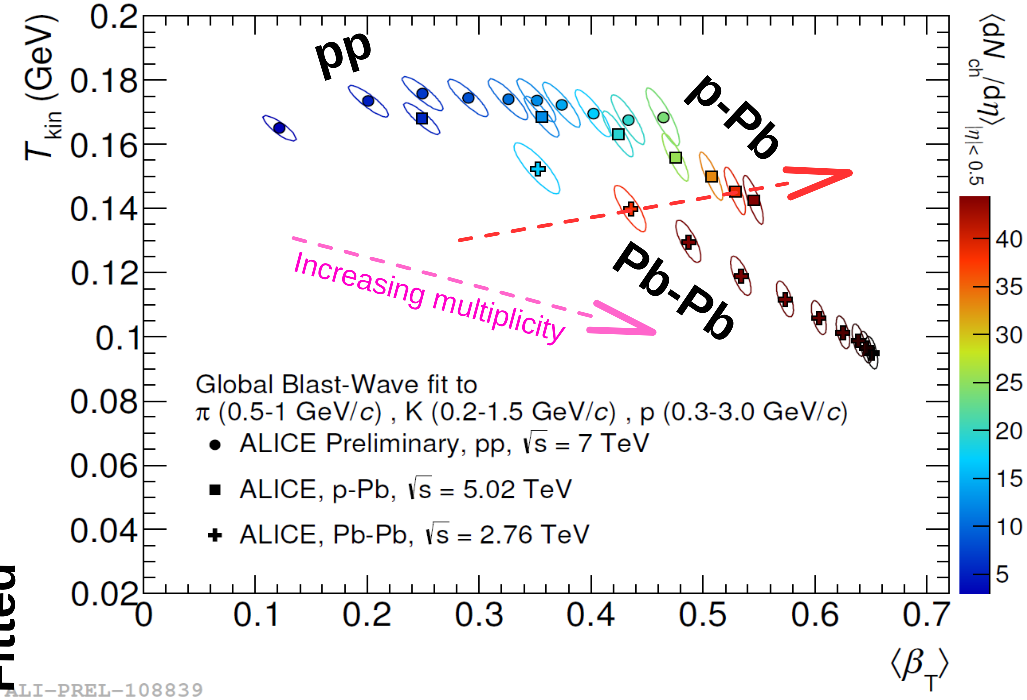

- PYTHIA8 (Monash): MPI + *Color Reconnection* may explain the observed behaviour at low / intermediate $p_T$
- **DIPSY**: ***Color Ropes*** create similar features as Color Reconnection.
- **EPOS LHC**: based on ***core-corona*** model
  - *collective expansion* of the core seems to overestimate the enhancement → **can we check this further ?**

- Comparison with models:



# Blast Wave model in pp




- ✔ Similar evolution in pp and p-Pb
- ✔ At similar multiplicities small systems have similar $\langle T_{Kin} \rangle$ but larger $\langle \beta_T \rangle$ → more **“explosive”** than Pb-Pb

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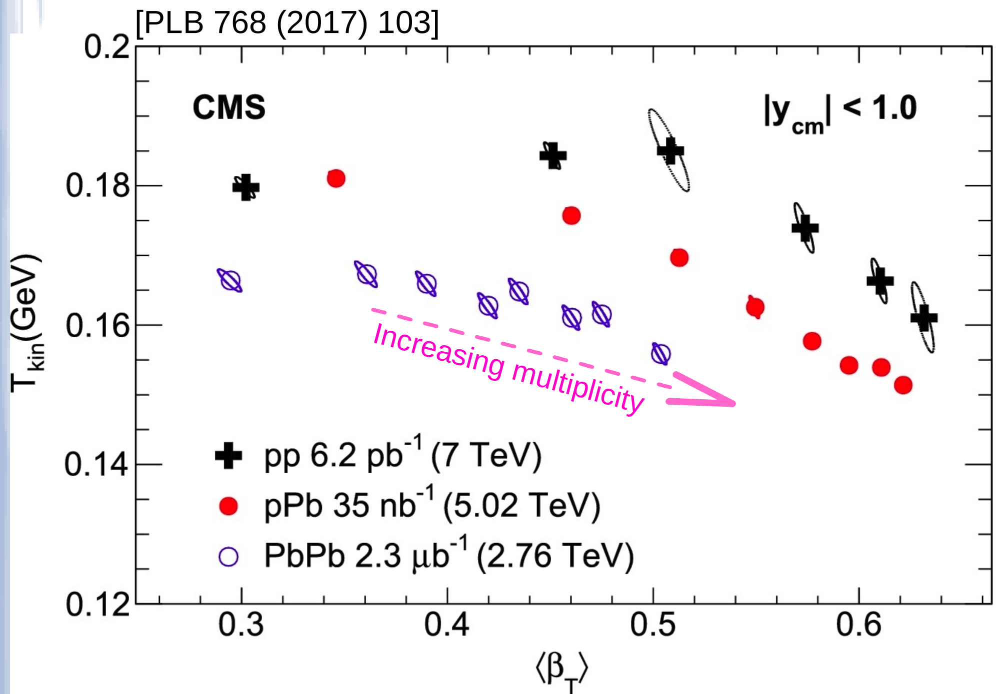


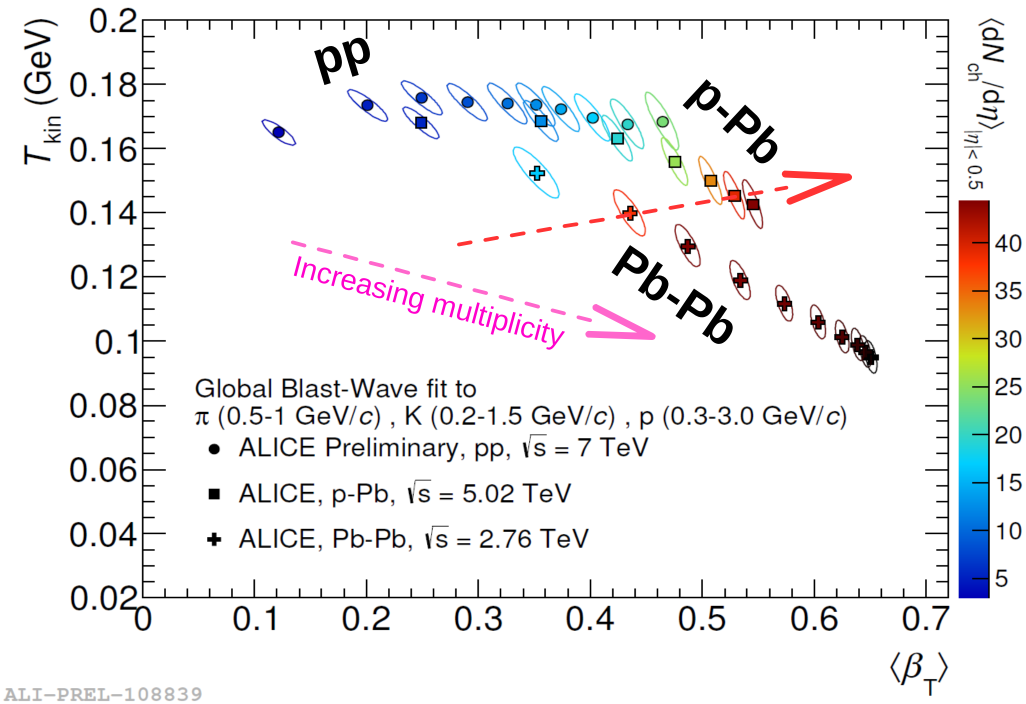


- Only strange particles ($\Lambda$, $K^0_S$) included in the fit
- Different evolution for pp and p-Pb

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## Remarks:

- Difficult to compare ALICE / CMS due to different fitting strategies (BW sensitive to particles included in the fit, ranges, uncertainties considered for spectra in the fit, etc.) → **to be addressed**

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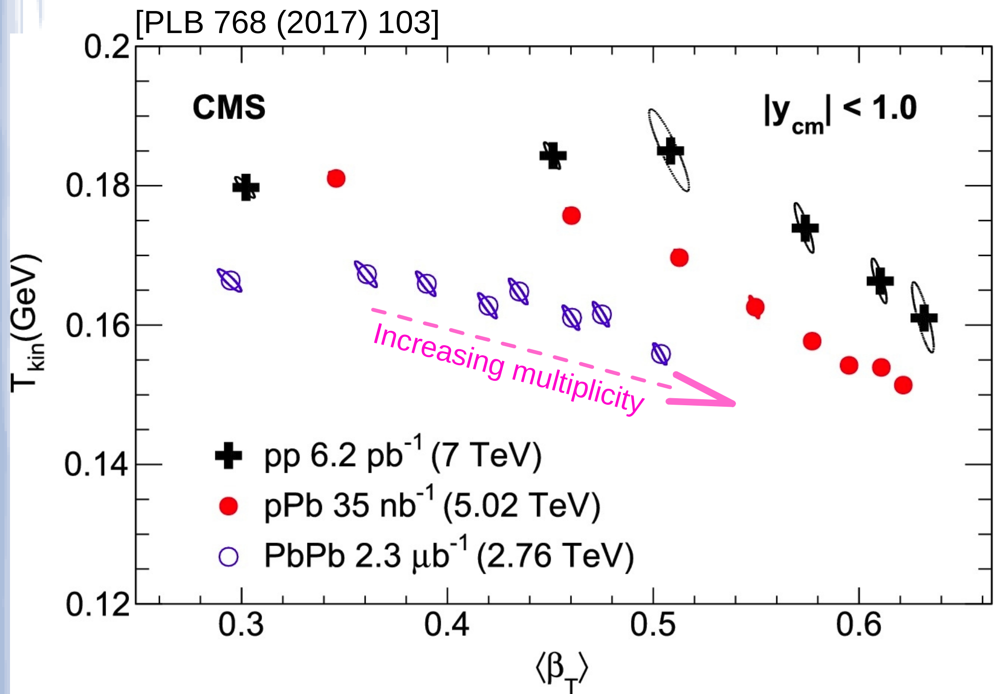


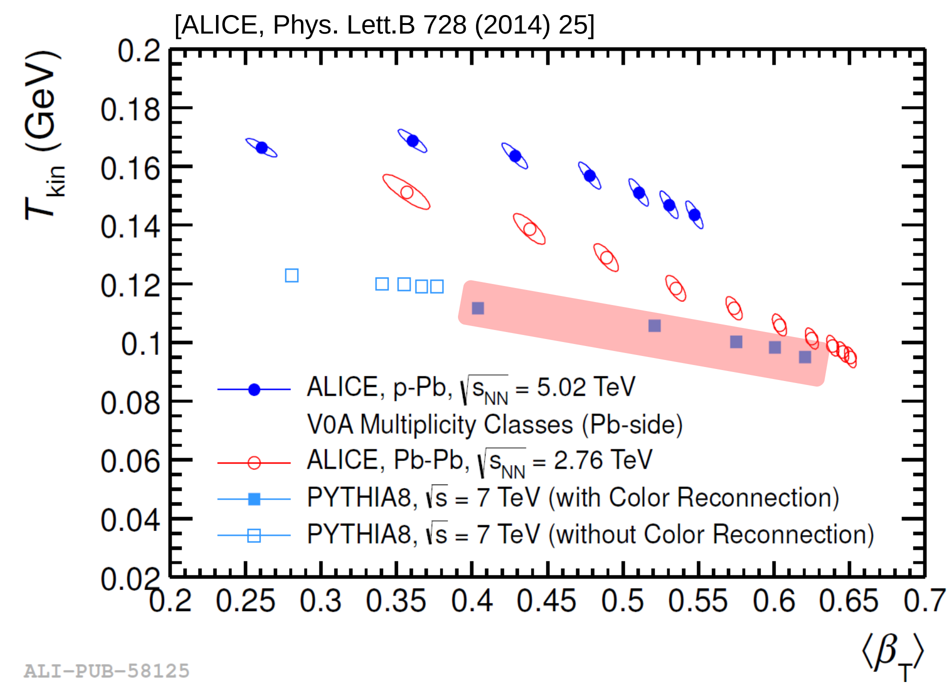


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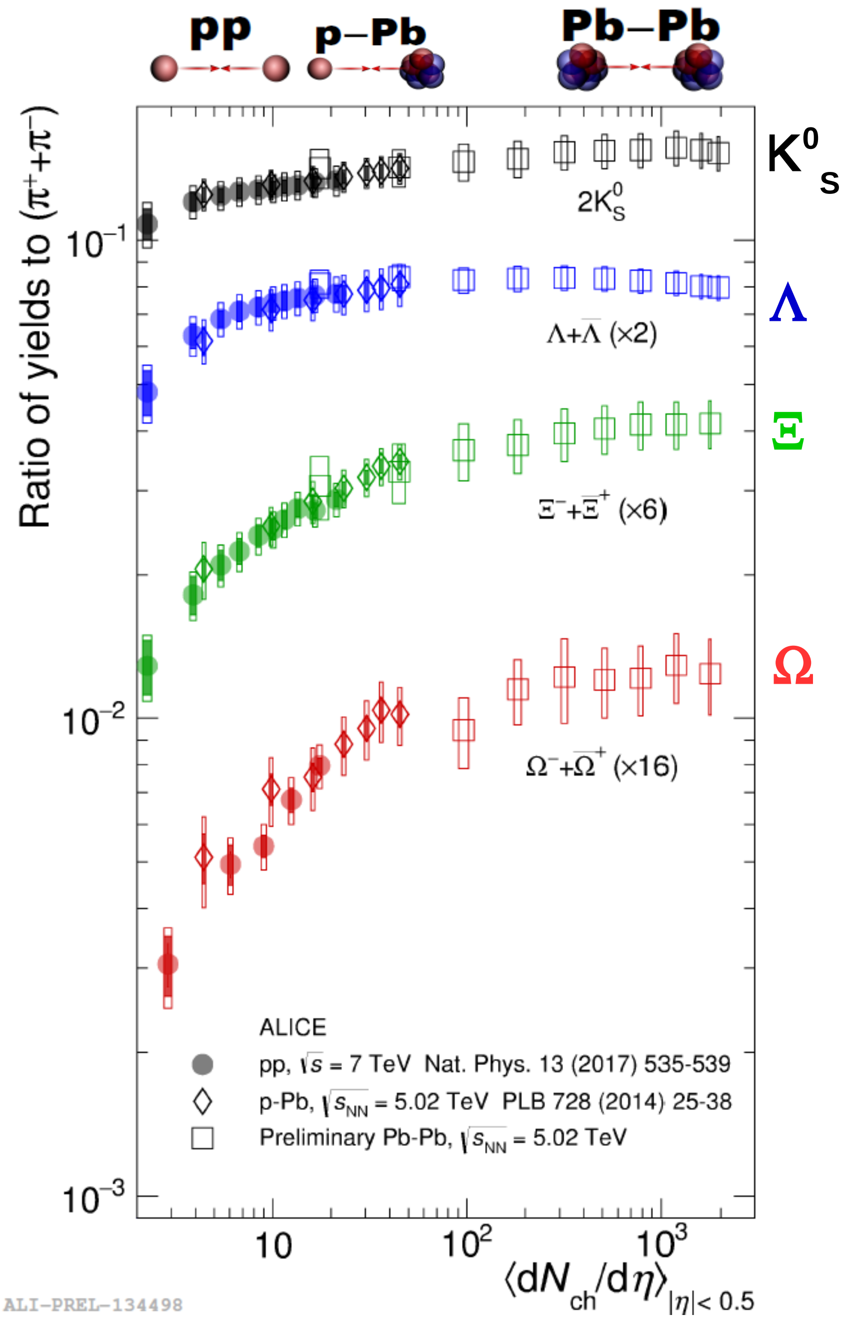
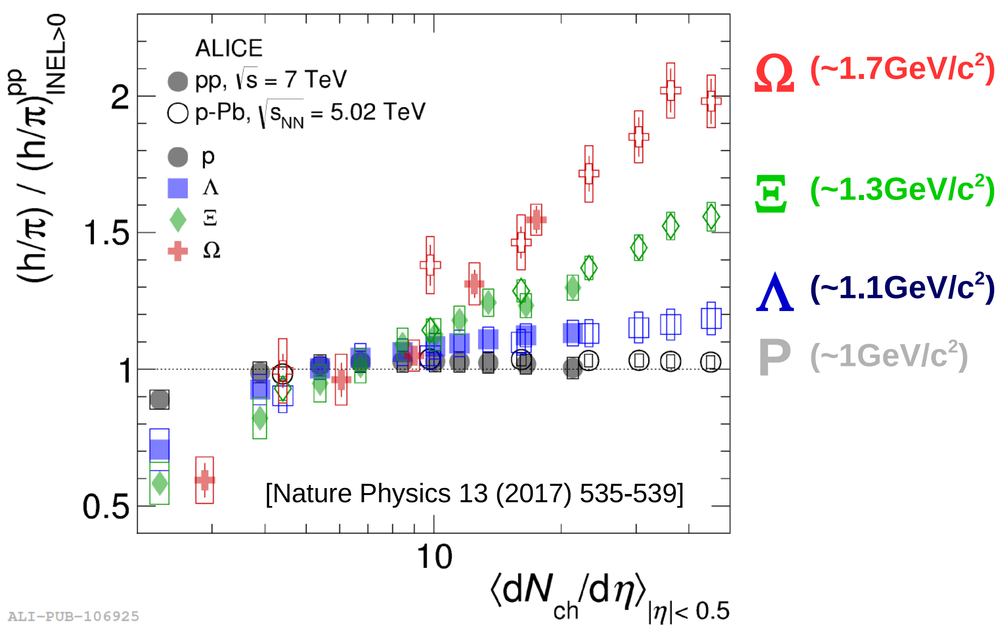
- ✔ Difficult to compare ALICE / CMS due to different fitting strategies (BW sensitive to particles included in the fit, ranges, uncertainties considered for spectra in the fit, etc.) → **to be addressed**
- ✔ **PYTHIA8 with Color Reconnection "mimic" collective-flow !**

# Hadrochemistry: Strangeness enhancement




- ✔ ***Strangeness enhancement*** historically considered one of the signature for the deconfinement in heavy-ion collisions
  - ✔ observed in small systems by ALICE !
  - ✔ It's not a baryon effect ! Could be a mass effect ?



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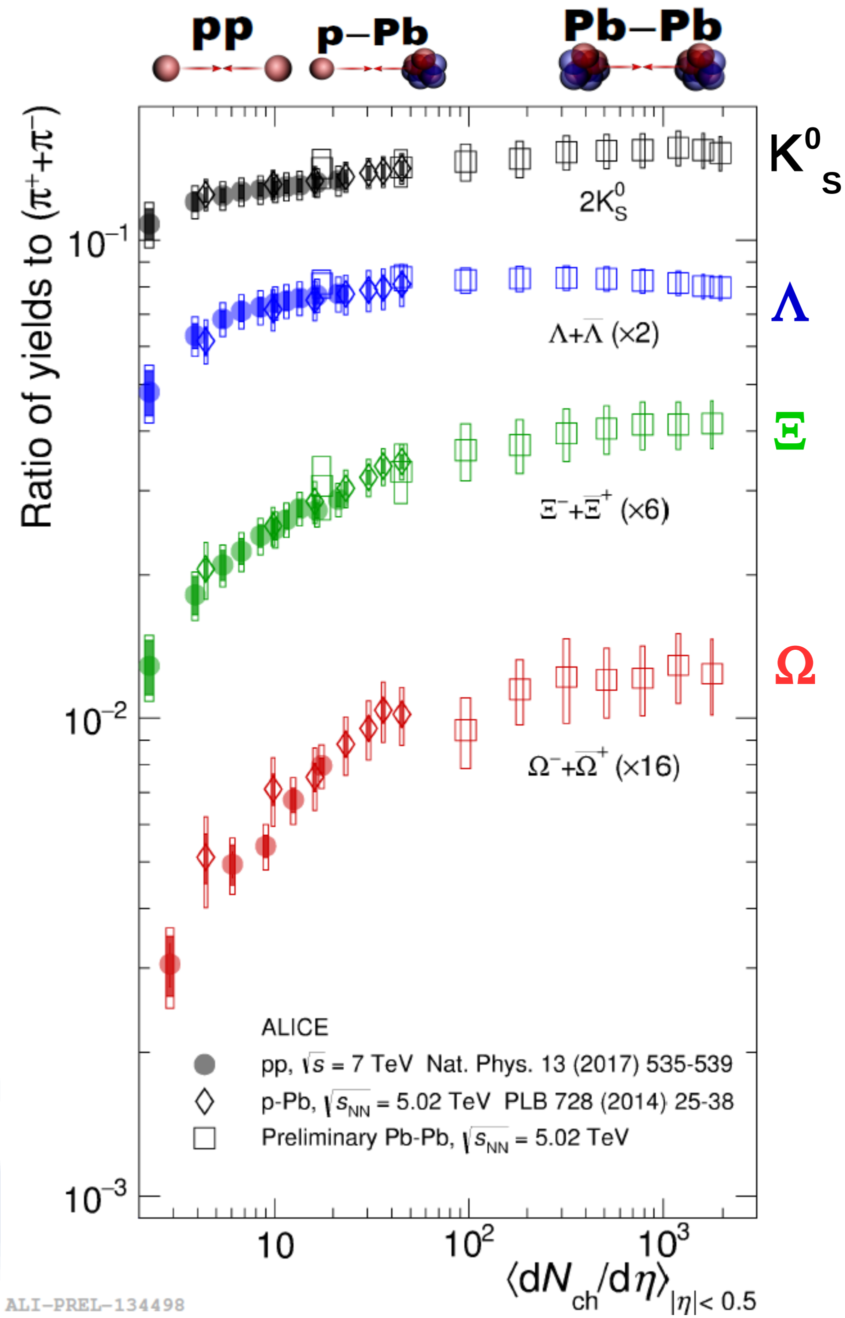


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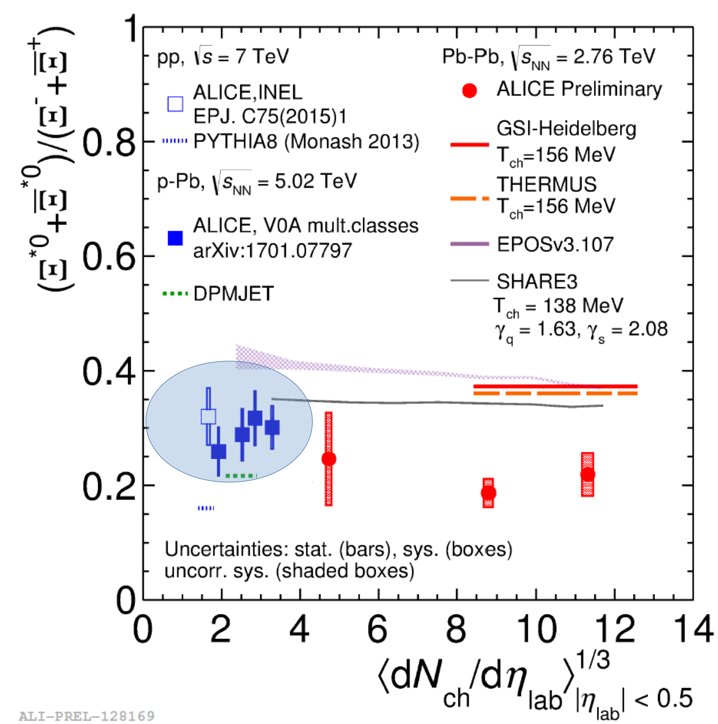
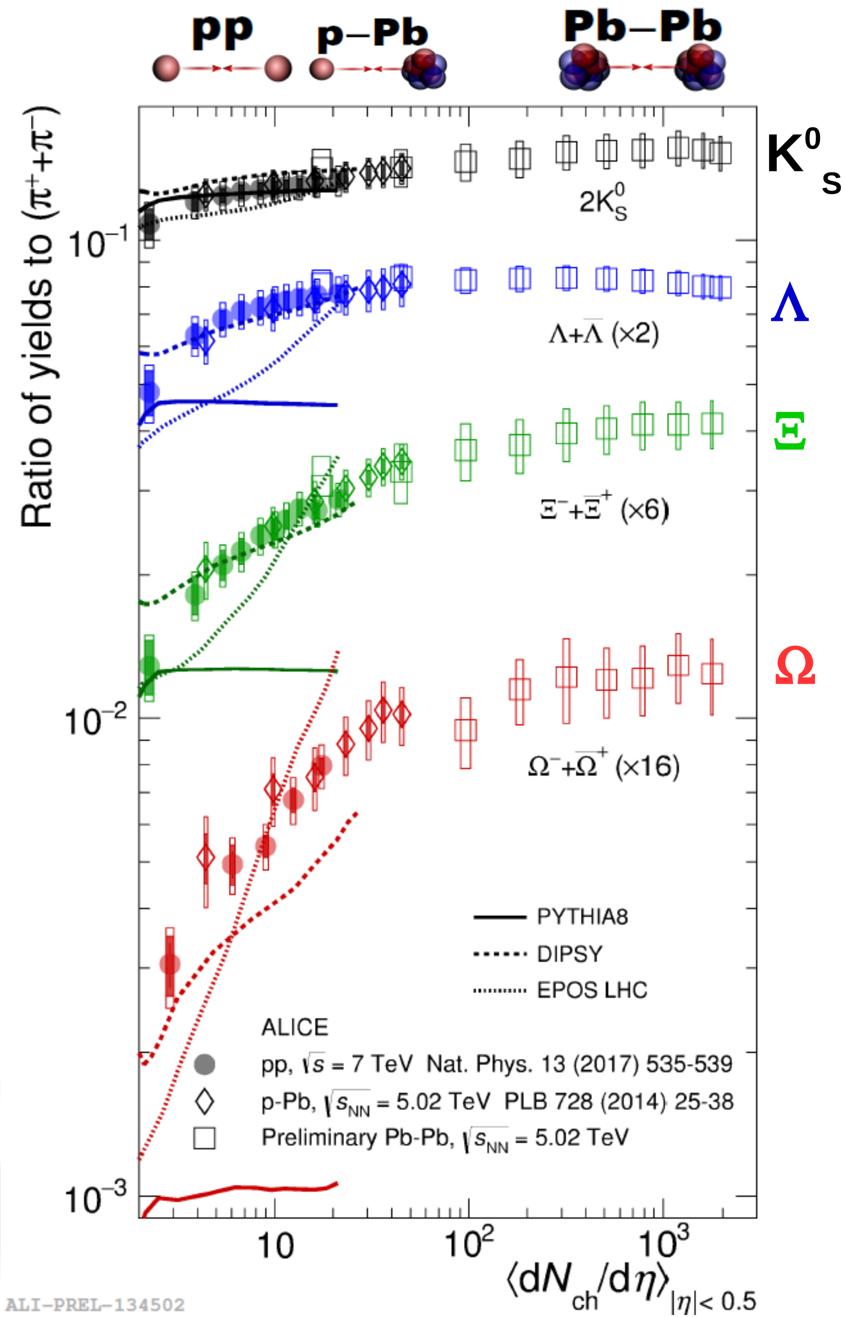
  - observed in small systems by ALICE !
  - It's not a baryon effect ! Could be a mass effect ?
  - $\Xi^{*0}/\Xi$ (and $\Sigma^{*\pm}/\Lambda$, not shown here) constant in p-Pb and compatible with pp integrated over multiplicity [$\Xi^{*0}$ and $\Sigma^{*\pm}$ have same strangeness content of $\Xi$ and $\Lambda$ respectively, but larger mass]




- **It is really a strangeness related effect !**

# Hadrochemistry: Strangeness enhancement




- ✔ Traditional soft-QCD models based on Multiple Parton Interactions (MPI), e.g. Pythia, are not able to reproduce the observed trends
  - ✔ Breaks concept of universality and factorization of fragmentation [JHEP01(2017)140]
- ✔ MPI based models that embed also effects from ***densely packed strings*** (DIPSY) or ***core-corona*** mechanism (EPOS) reproduce qualitatively the observed trends

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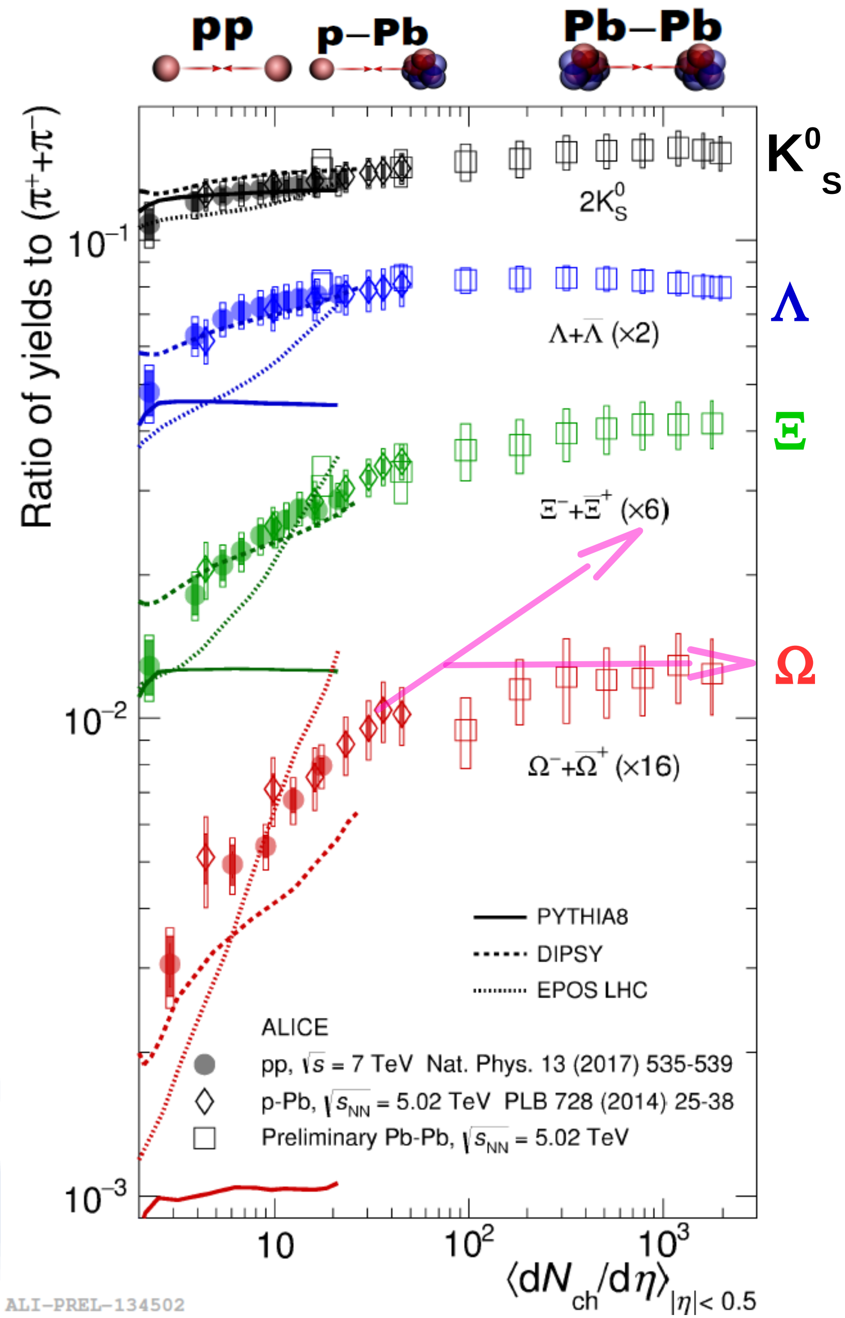


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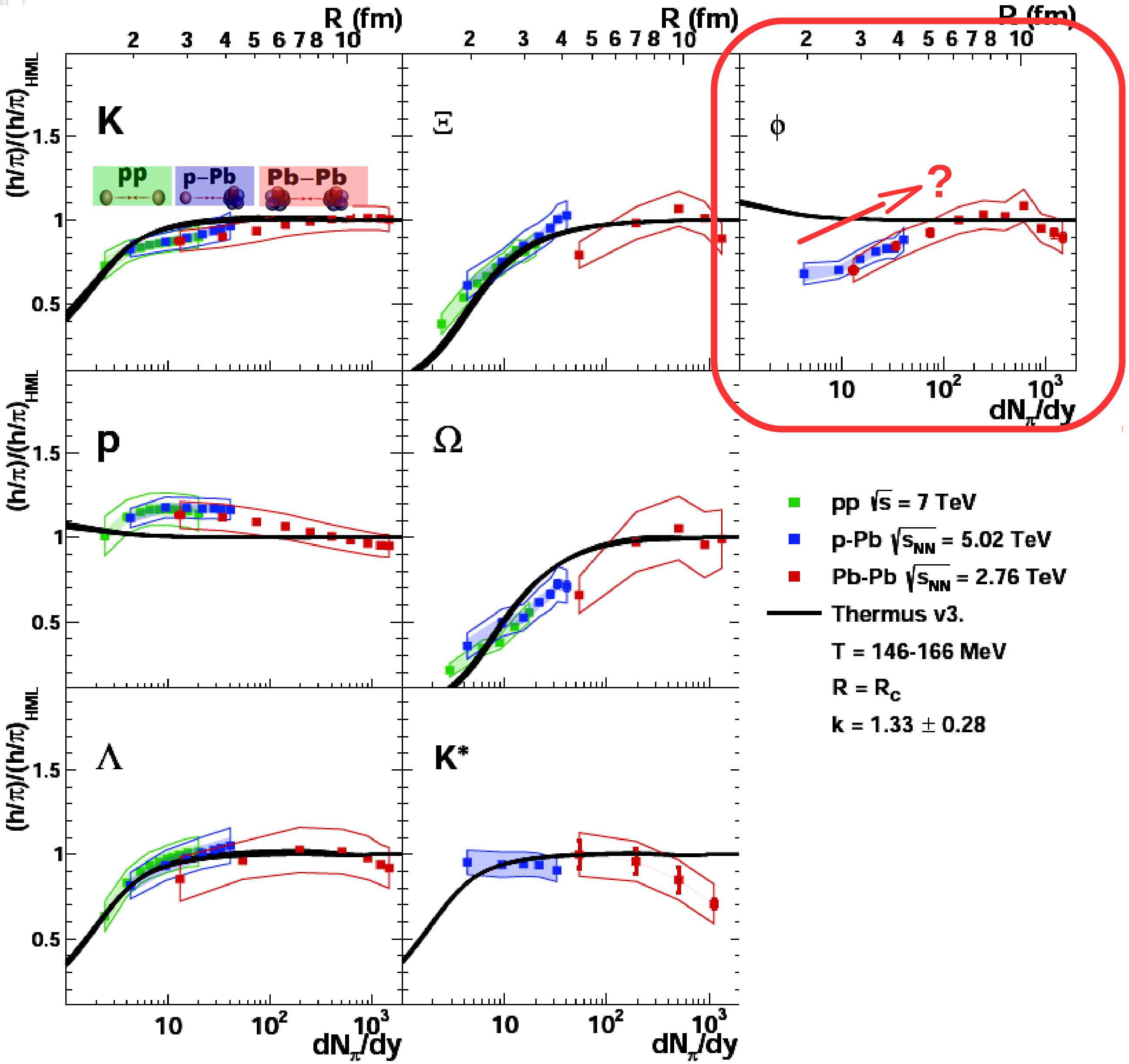
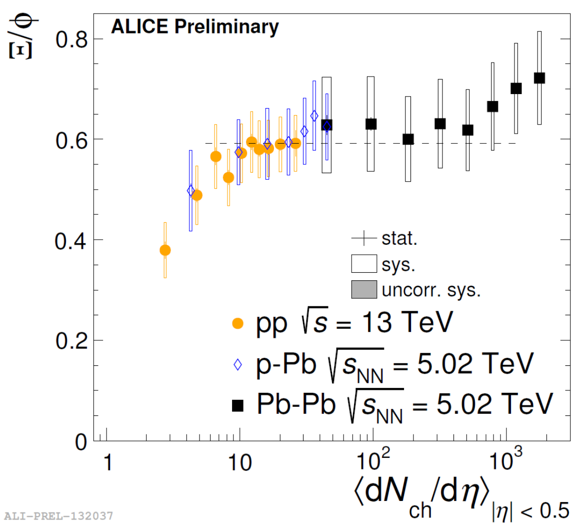
- ✔ MPI based models that embed also effects from ***densely packed strings*** (DIPSY) or ***core-corona*** mechanism (EPOS) reproduce qualitatively the observed trends
- ✔ **Outlook**: check if pp ratios at very high-multiplicity converge to Pb-Pb values (thermal equilibrium) → strangeness analysis ongoing in ALICE using ***high-multiplicity triggered*** data

# Hadrochemistry: comparison with thermal models

[V. Vislavicius, A. Kalweit, arXiv:1610.03001]




- Statistical (thermal) hadronization model → strange hadron production suppressed in small systems due to the local strangeness conservation (***canonical suppression***)
- Qualitative good agreement for K, Λ, Ξ, Ω
- **Significant deviation observed for the ϕ**




THERMUS: S. Wheaton and J. Cleymans, Comput. Phys. Commun. 180 (2009) 84

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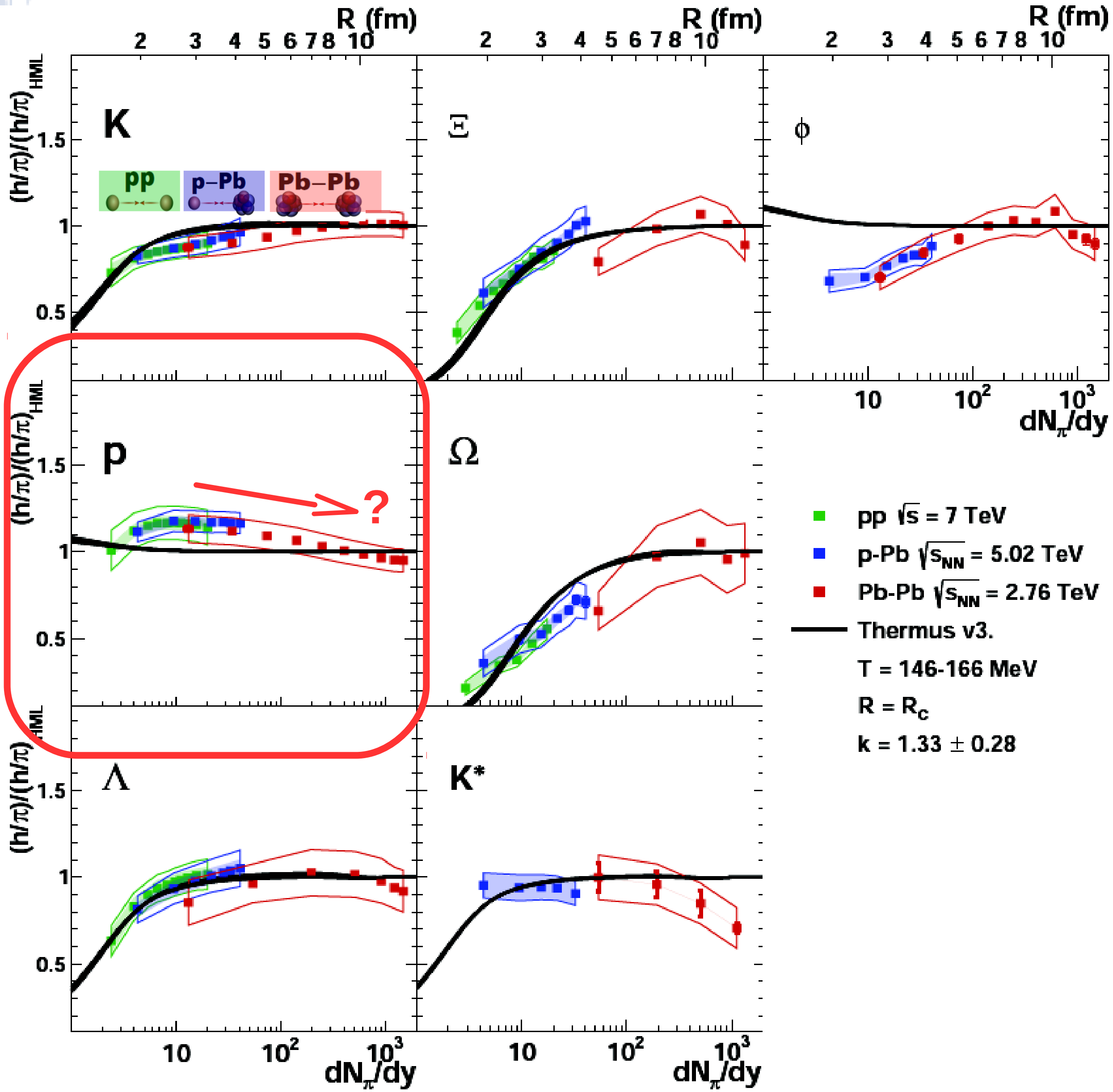


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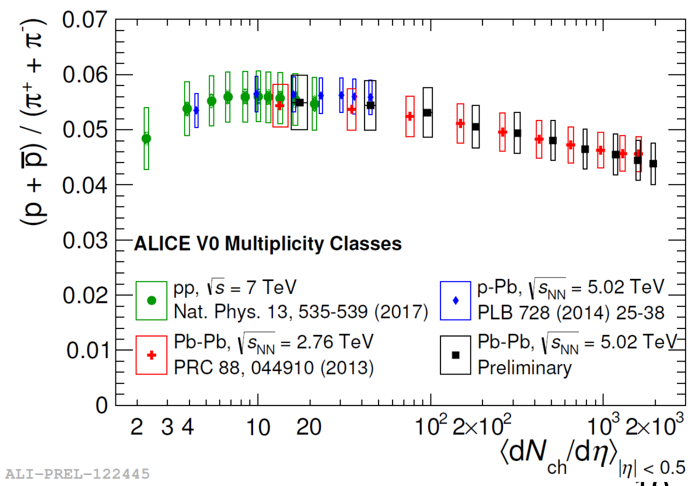
- ✔ Qualitative good agreement for K, Λ, Ξ, Ω
- ✔ **Decreasing trend for protons not yet understood. Possible explanation: hadronic re-scattering**

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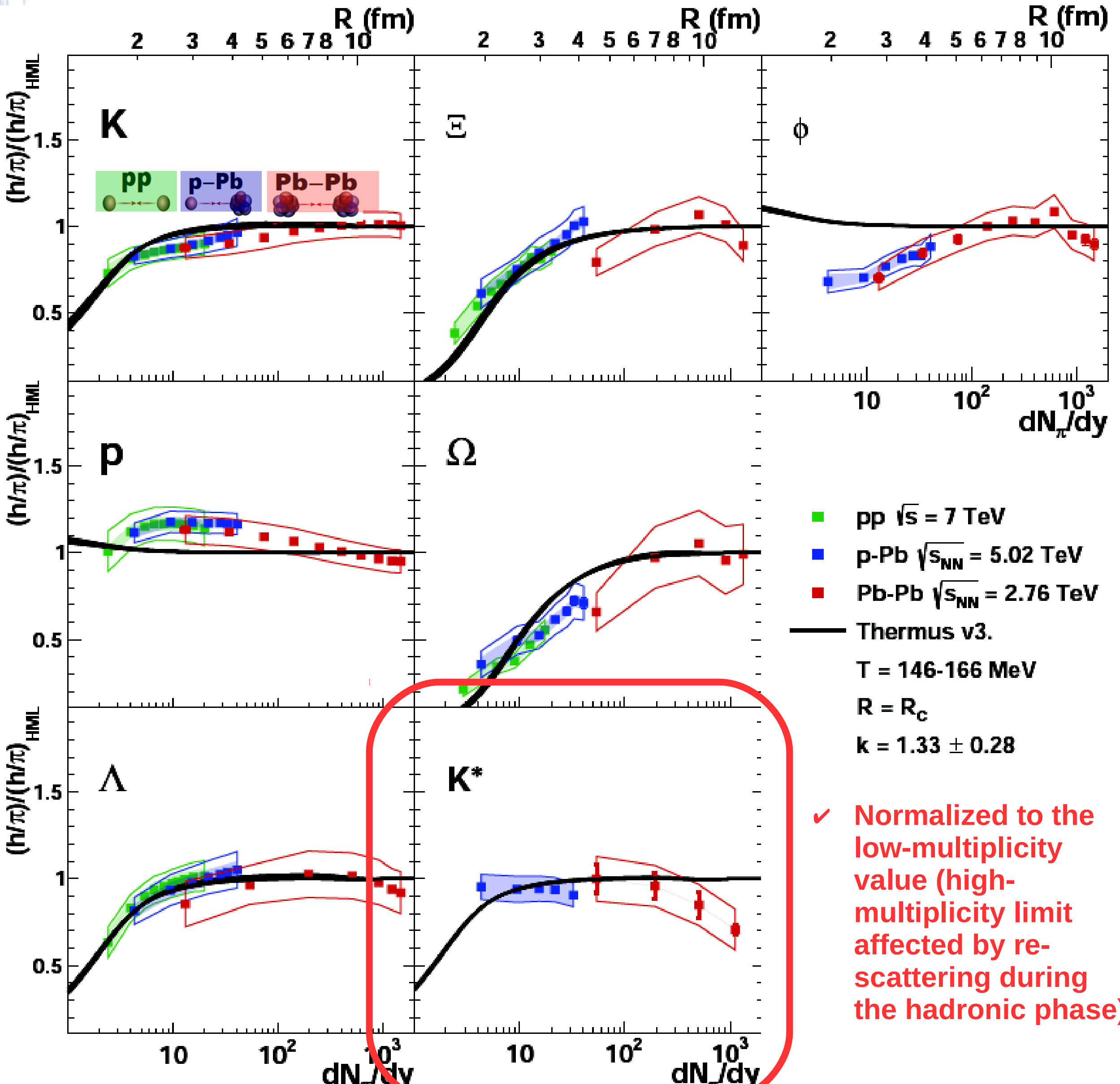
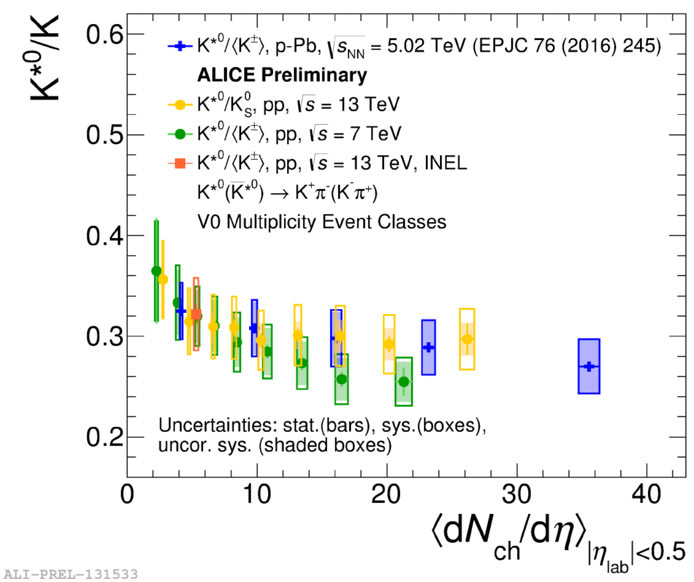


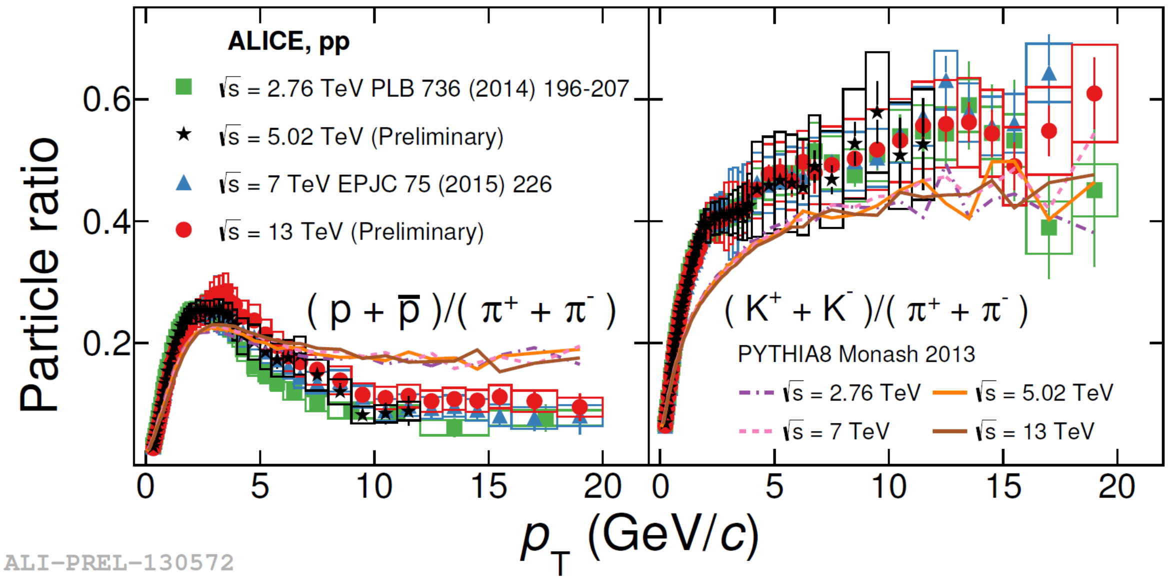

- Normalized to the low-multiplicity value (high-multiplicity limit affected by re-scattering during the hadronic phase)

THERMUS: S. Wheaton and J. Cleymans, Comput. Phys. Commun. 180 (2009) 84

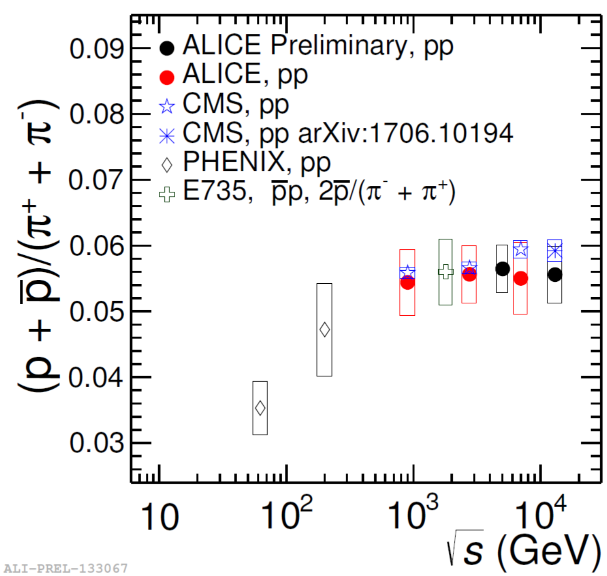
- Statistical (thermal) hadronization model → strange hadron production suppressed in small systems due to the local strangeness conservation (***canonical suppression***)
- Qualitative good agreement for K, Λ, Ξ, Ω
- **Multiplicity dependent suppression of K*/K in pp and pPb: is the same physics mechanism as in Pb-Pb (i.e. re-scattering) responsible ?**

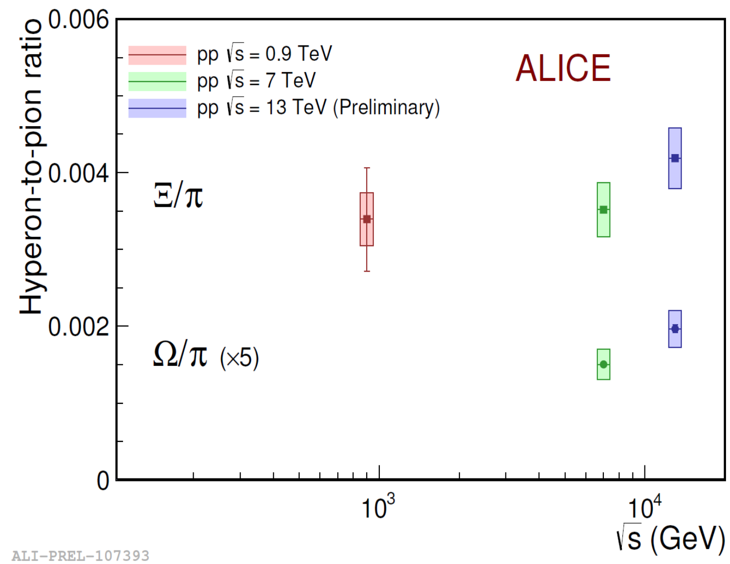


# Particle ratios: evolution with √s




- $p_T$ differential spectra:
  - K/π shows no significant evolution with √s
  - At higher √s maximum slightly shifted towards higher $p_T$ values for p/π
  - Pythia8 (Monash) doesn't reproduce the measured ratios



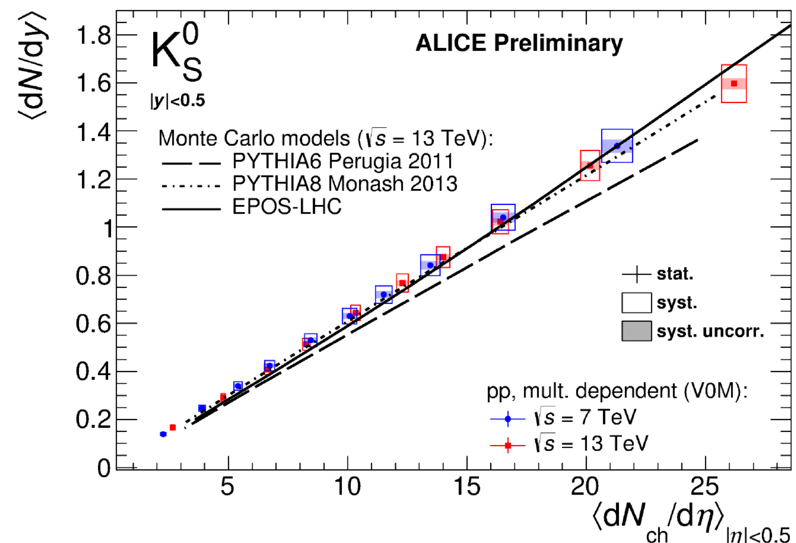




- $p_T$ integrated ratios:
  - p/π seems to saturate at LHC energies
  - Strange / π ratios show a hint of increase with √s

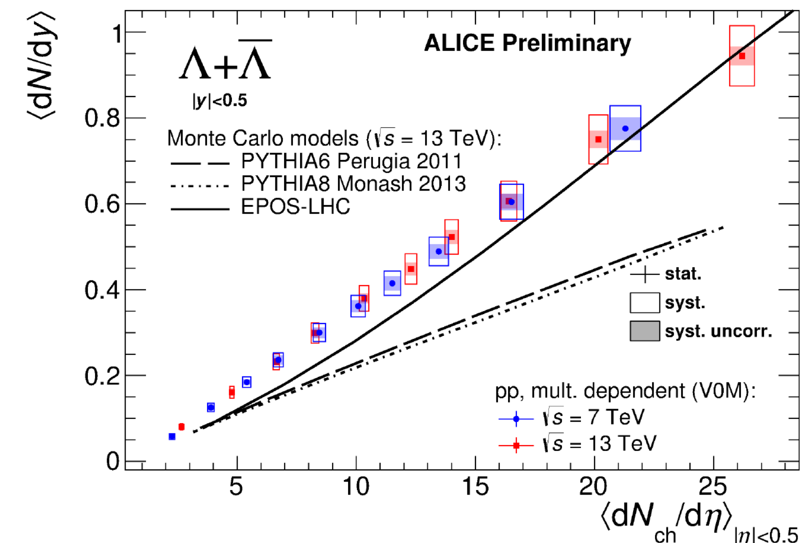
**How does it scale with the event multiplicity ?**

# Strangeness: evolution with multiplicity and √s

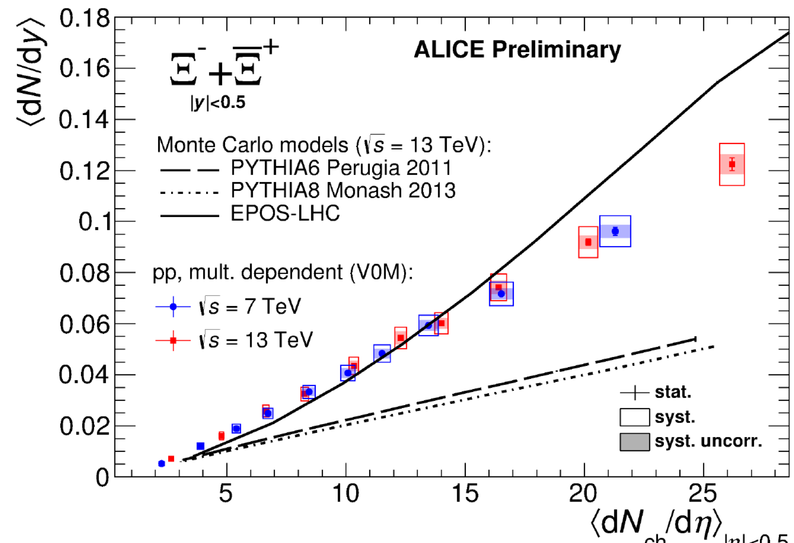
**7 TeV vs 13 TeV**



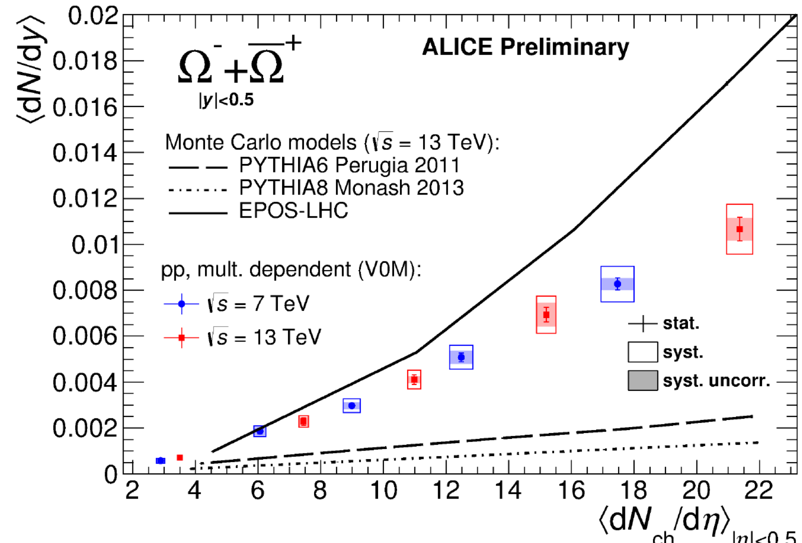
ALI-PREL-116310



ALI-PREL-116318



ALI-PREL-116322

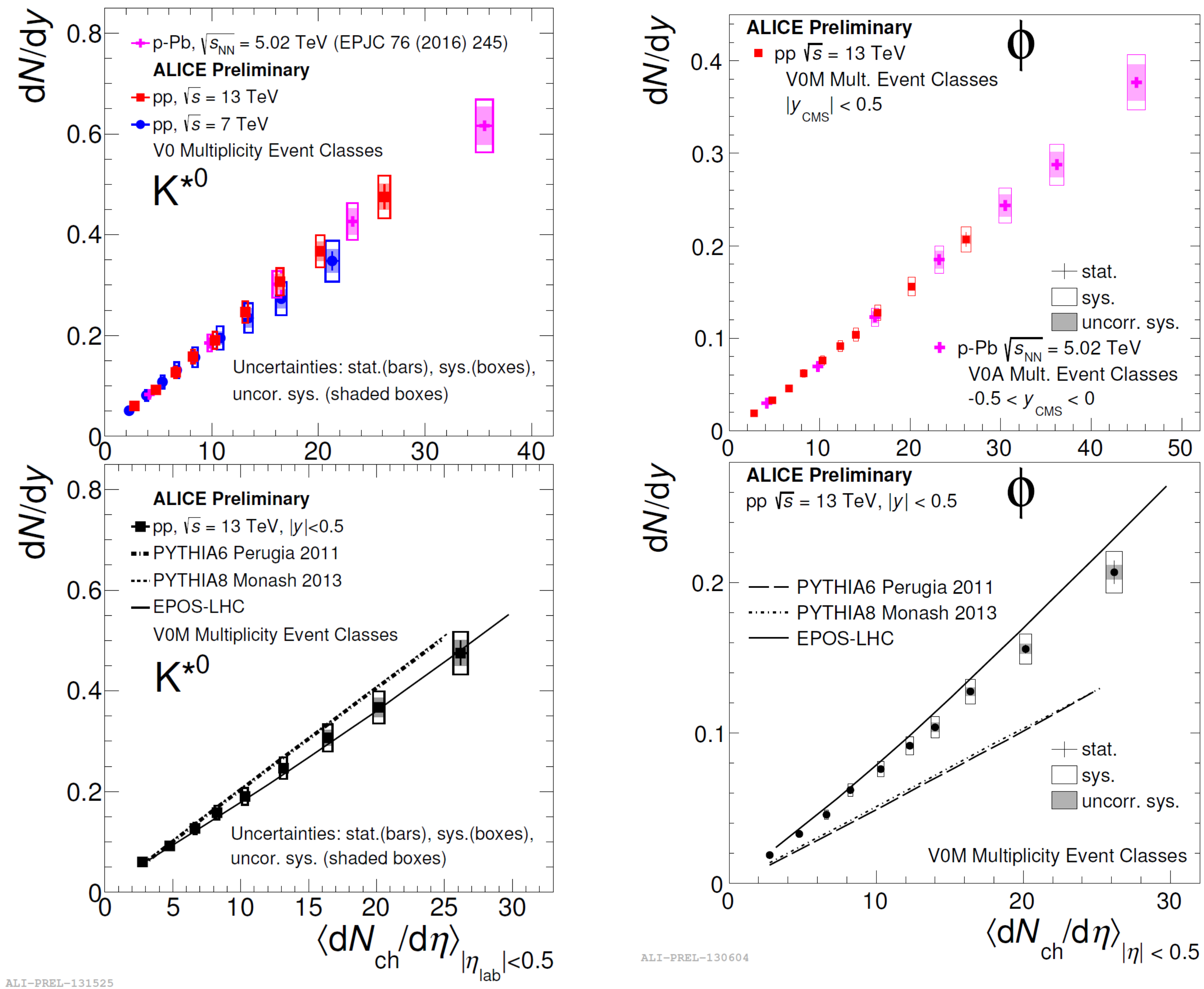


ALI-PREL-116326

- ✔ Multiplicity dependence doesn't change with initial conditions (i.e. √s) → strange-particle yields steered by charged-particle multiplicity produced in the final state
- ✔ Trends not simultaneously reproduced by any of the commonly used Monte Carlo models (production significantly underestimated by Pythia for (multi-)strange baryons)

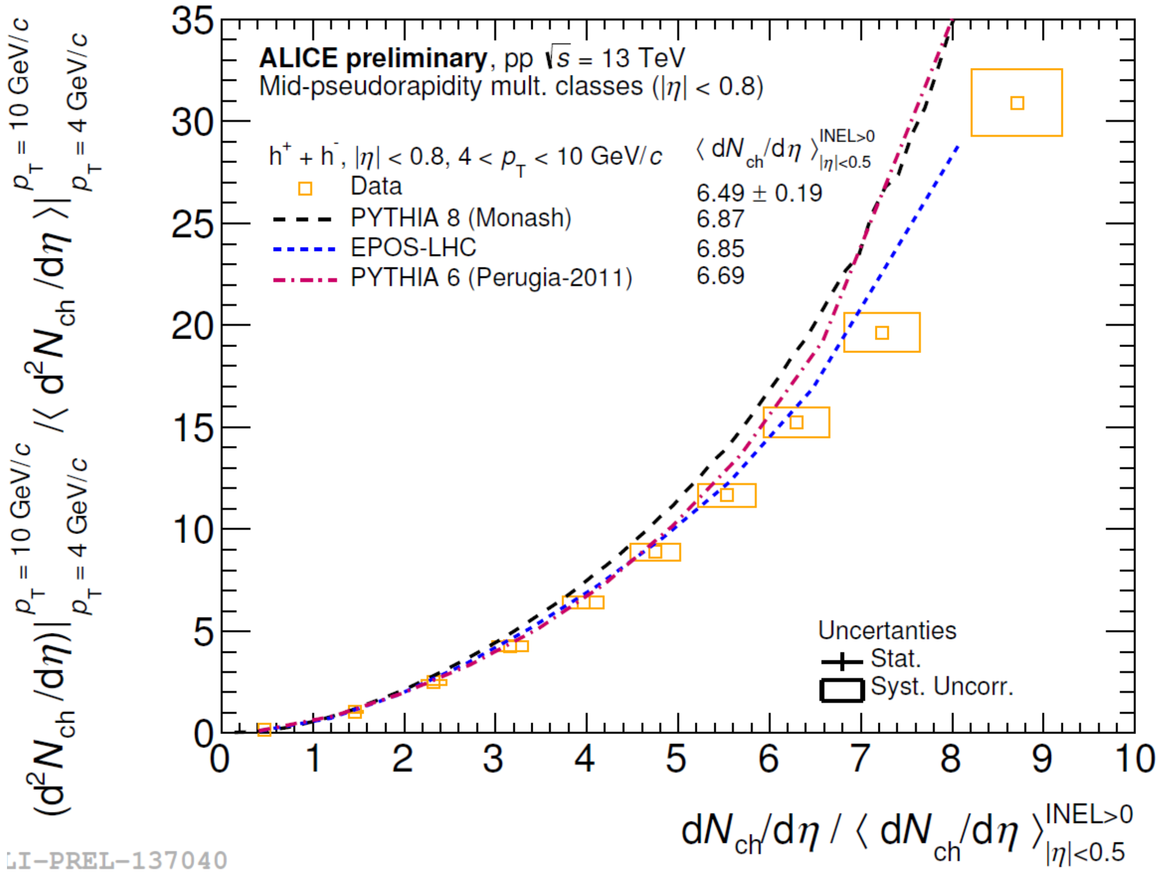
# Resonances: evolution with $\langle dN_{ch}/d\eta \rangle$ and $\sqrt{s}$

pp 7 TeV vs pp 13 TeV vs pPb 5.02 TeV




✔ Similar multiplicity dependence obtained for resonances

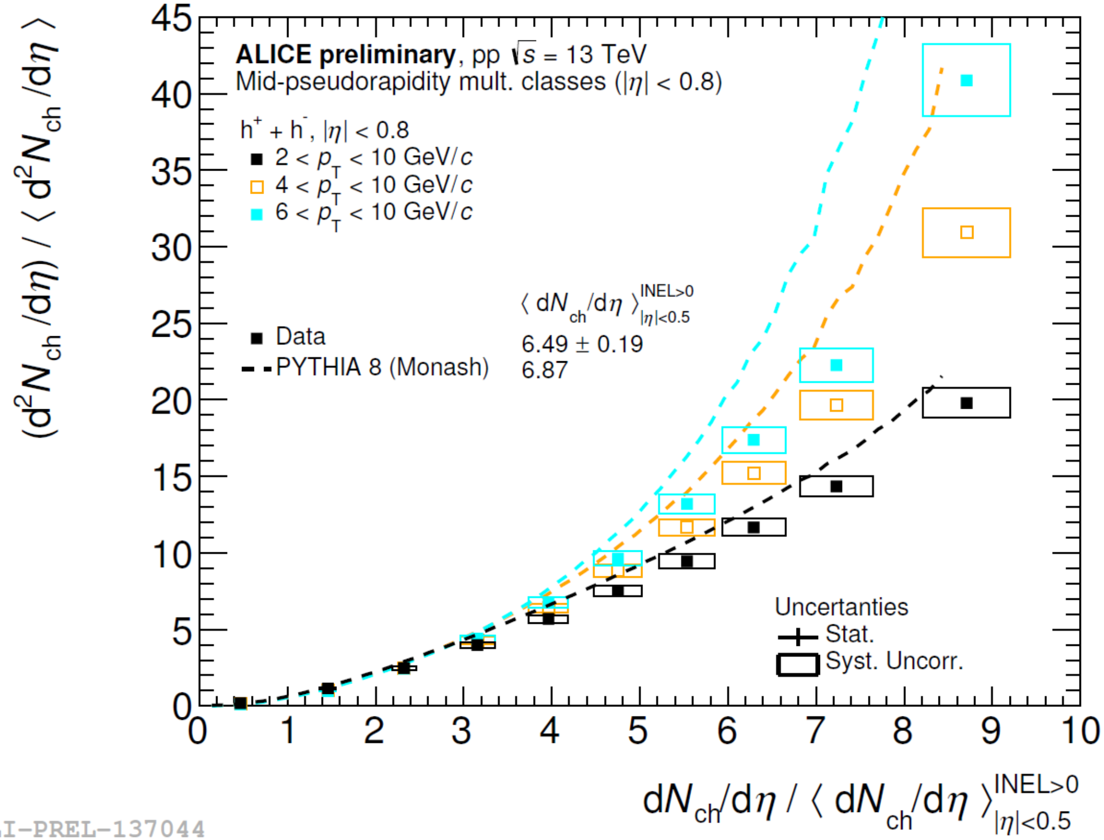
# Why only identified hadrons ?
# High-$p_T$ inclusive charged particles




- Is there any $p_T$ dependence ?

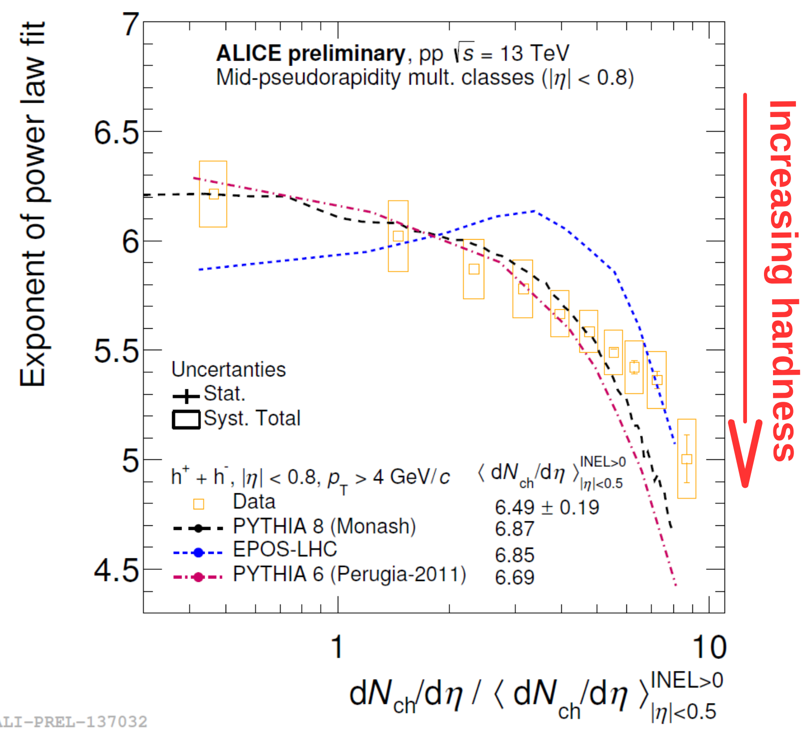
- Faster than linear increase observed for charged hadrons at high $p_T$
  - Similar trend observed for other hard processes (e.g D-mesons and J/ψ)
- All Monte Carlo models reproduce quite well the results for $p_T$ > 4 GeV/$c$

# Why only identified hadrons ?
# High-$p_T$ inclusive charged particles




ALI-PREL-137044

- ✔ Stronger increase with increasing $p_T$
- ✔ Qualitatively reproduced by PYTHIA models




ALI-PREL-137032

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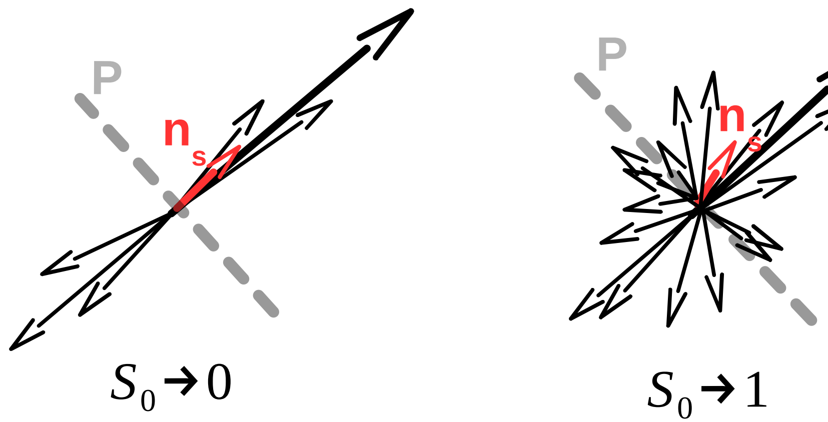
# Event shape studies

## Spherocity:

$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\mathbf{n}}_\mathbf{s}} \left( \frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{\mathbf{n}}_\mathbf{s}|}{\sum_i p_{\mathrm{T},i}} \right)^2$$

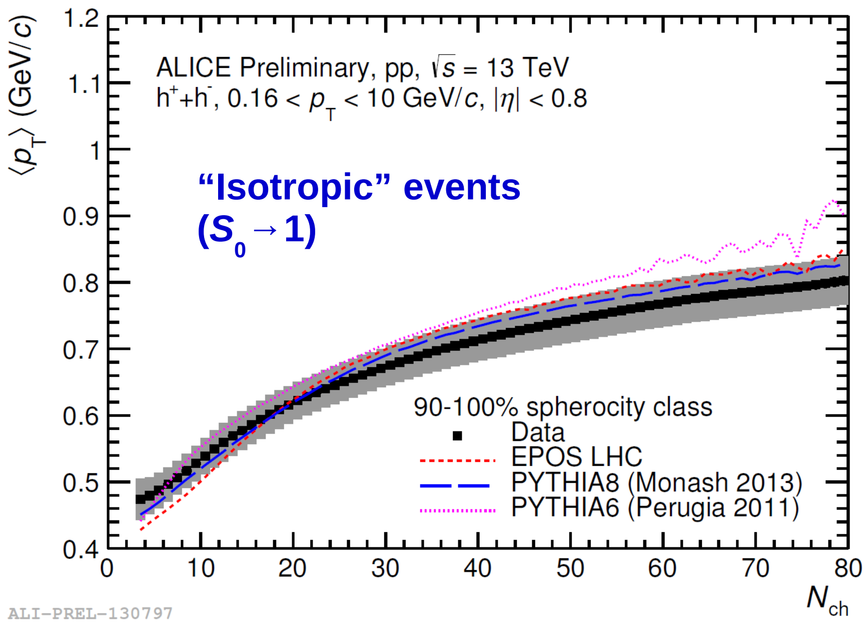
[ $p_T > 0.16$ GeV/$c$, $|\eta| < 0.8$ ]

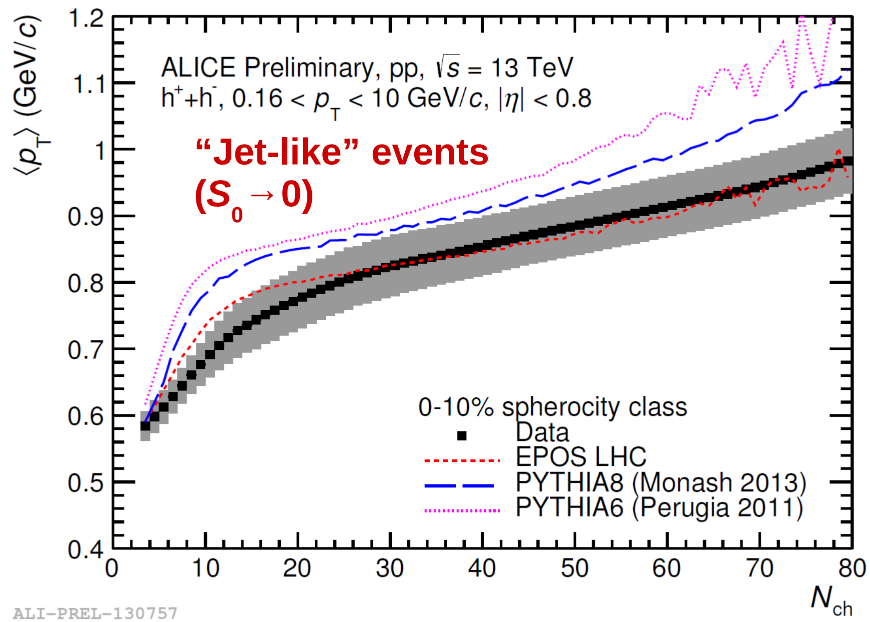



$\boldsymbol{n_s}$ defined in order to minimize the ratio above (≡ axis of the main scattering) → $S_0$ represents a measurement of the **out-of plane (P)** radiation → sensitive to "soft" physics

$$S_0 = \begin{cases} 0 & \text{"pencil-like" limit (hard events)} \\ 1 & \text{"isotropic" limit (soft events)} \end{cases}$$

✔ Possibility to study separately jet-like events and underlying event (UE)



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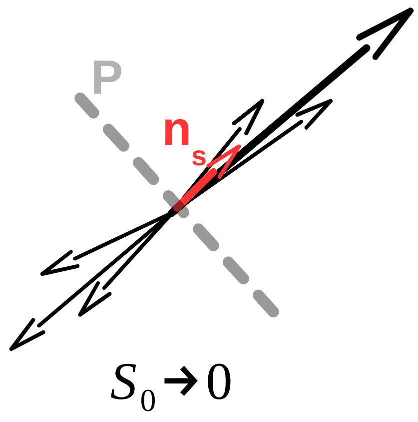
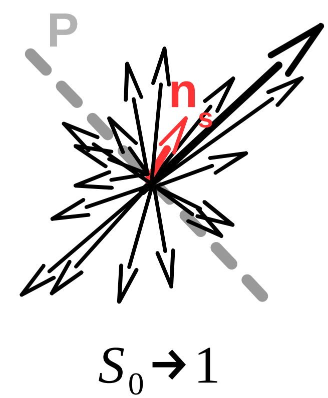
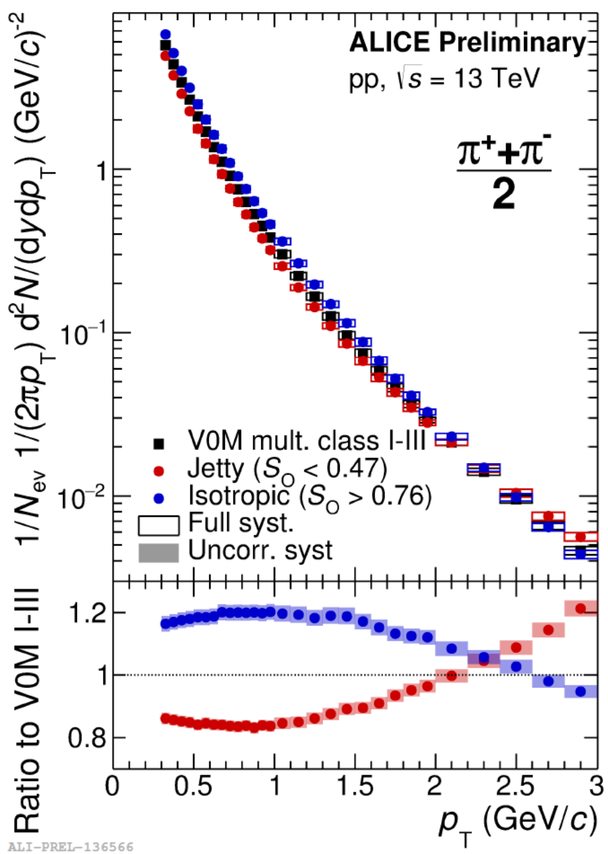
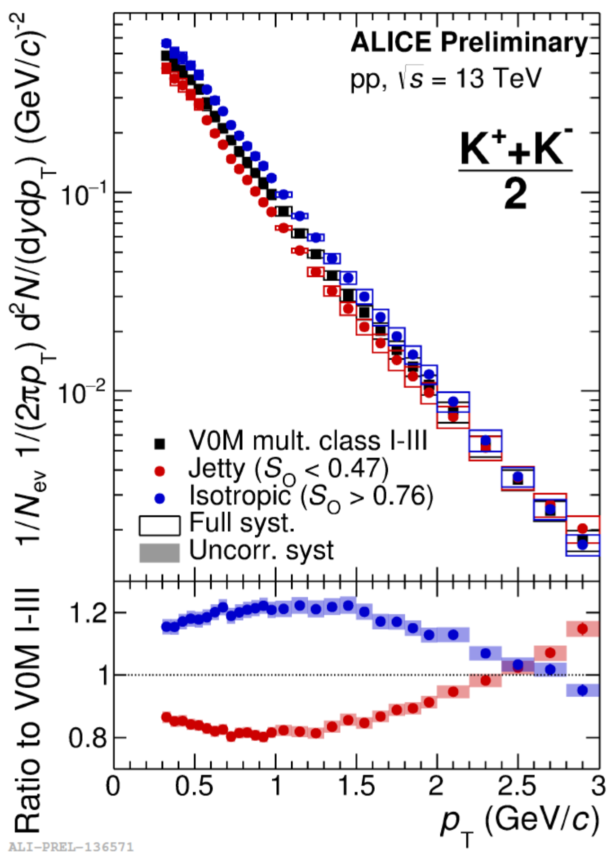
[ $p_\mathrm{T}$ > 0.16 GeV/$c$, $|\eta|$ < 0.8 ]

$\boldsymbol{n}_s$ defined in order to minimize the ratio above (≡ axis of the main scattering) → $S_0$ represents a measurement of the **out-of plane (P)** radiation → sensitive to "soft" physics




- ✔ First results including π, K ,P → modification of the $p_T$-spectra in jetty / isotropic events
- ✔ More differential studies including other identified particles (e.g. strangeness) vs $S_0$ will allow to put additional constraints for further tuning and/or new model ingredients !

# Concluding remarks

- A comprehensive study of identified "***bulk***" particle production in small systems at several $\sqrt{s}$ versus event multiplicity has been presented:
  - detailed studies of PID spectra shape confirm sign of **collectivity** in high multiplicity pp and pPb; origin and phenomenology still under investigation
  - **hadrochemistry**:
    - strangeness enhancement and baryon/meson ratio show a smooth evolution moving across all colliding systems
    - changes in the integrated particle ratios across different $\sqrt{s}$ are consistent with the increase observed in $\langle dN_{ch}/d\eta \rangle$
  - **comparison with models**: traditional soft-QCD models are not able to reproduce all observed features
    - Models that include effects from ***densely packed strings*** (DIPSY) or ***core-corona*** mechanism (EPOS) reproduce qualitatively the observed trends
- **High-$p_T$ charged particles** (i.e. coming from hard-processes) show a steep dependence vs multiplicity, similar to the one observed for heavy-flavour hadrons
  - Models that include MPI are able to describe observed features qualitatively
- First results on ***event shape*** studies show differences between particle production in jet / underlying event. More differential studies including other hadron species (e.g. strangeness) needed.

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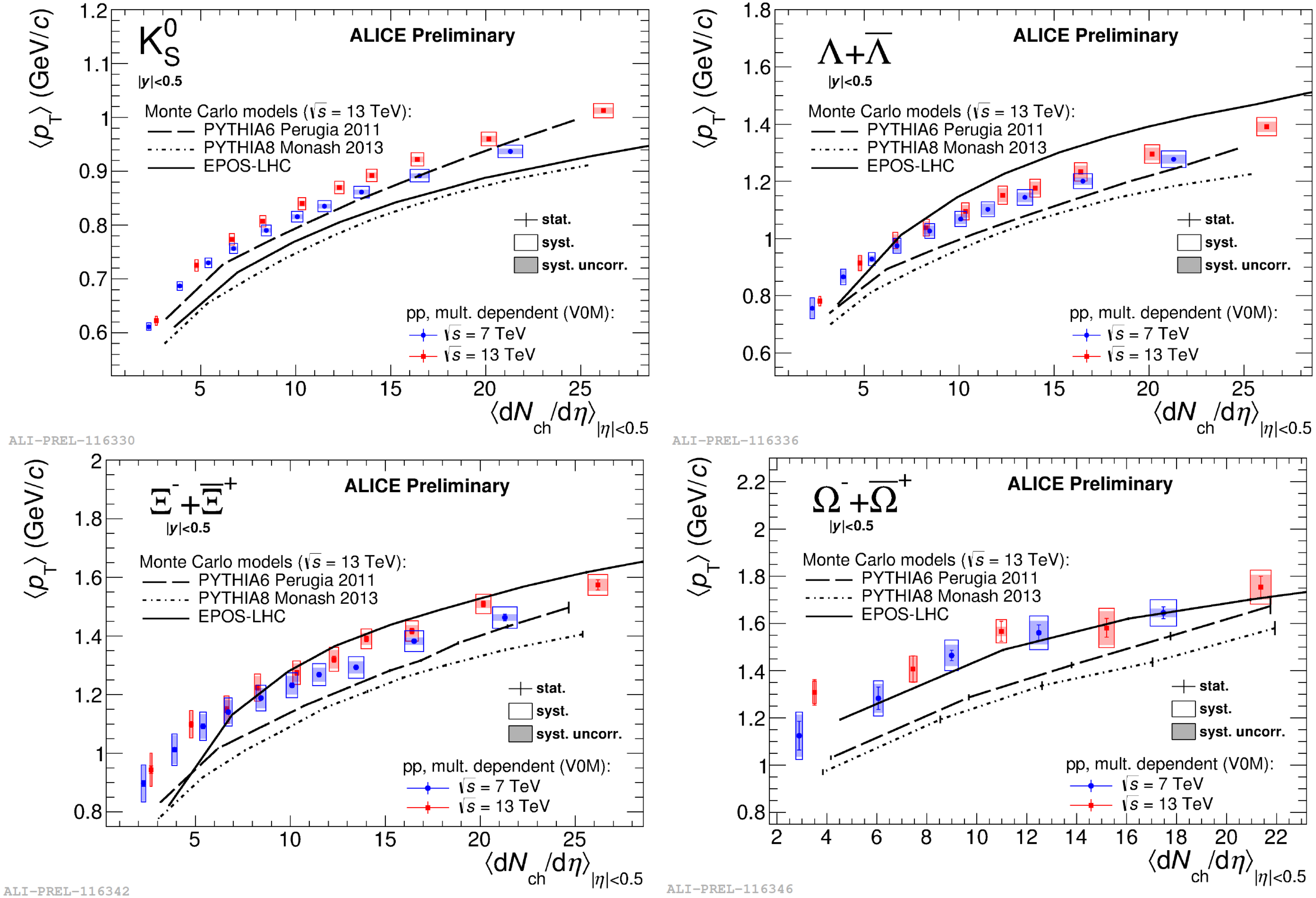
*Thank you for your attention!*

# BACK-UP

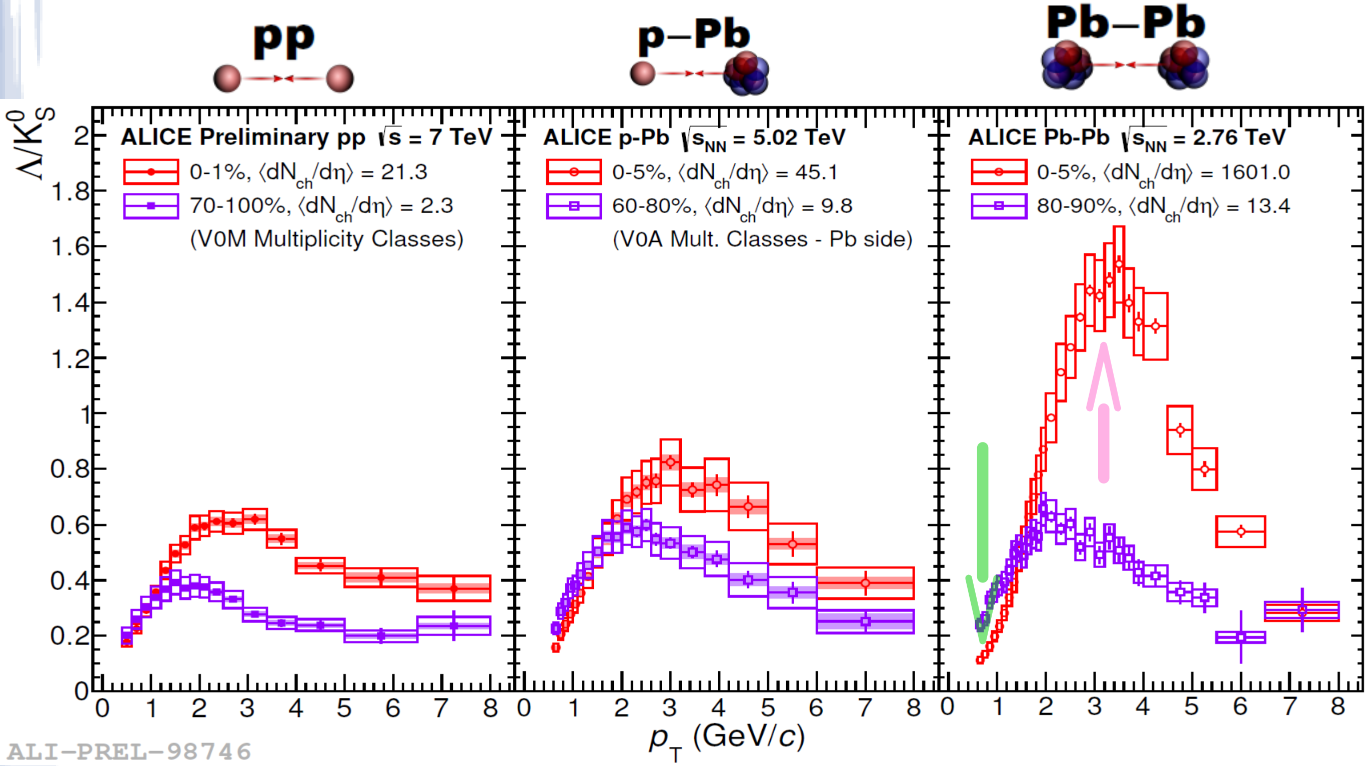
# Strangeness: evolution with multiplicity and √s

**pp 7 TeV vs pp 13 TeV**



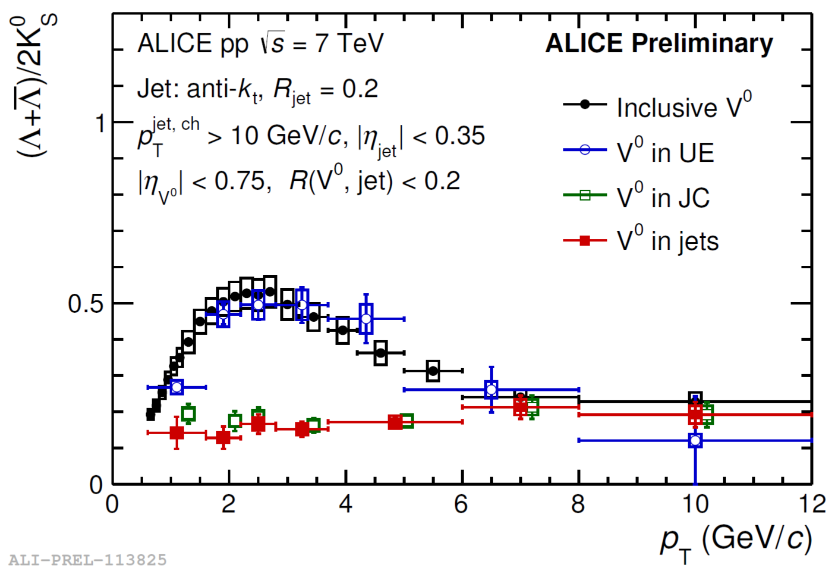

- ✔ $\langle p_T \rangle$ systematically larger at $\sqrt{s}$ = 13 TeV for $K^0_S$; not conclusive for $\Lambda$ and multi-strange baryons because of the large uncertainties
- ✔ Monte Carlo models reproduce only qualitatively the trends

# Baryon-to-meson ratio

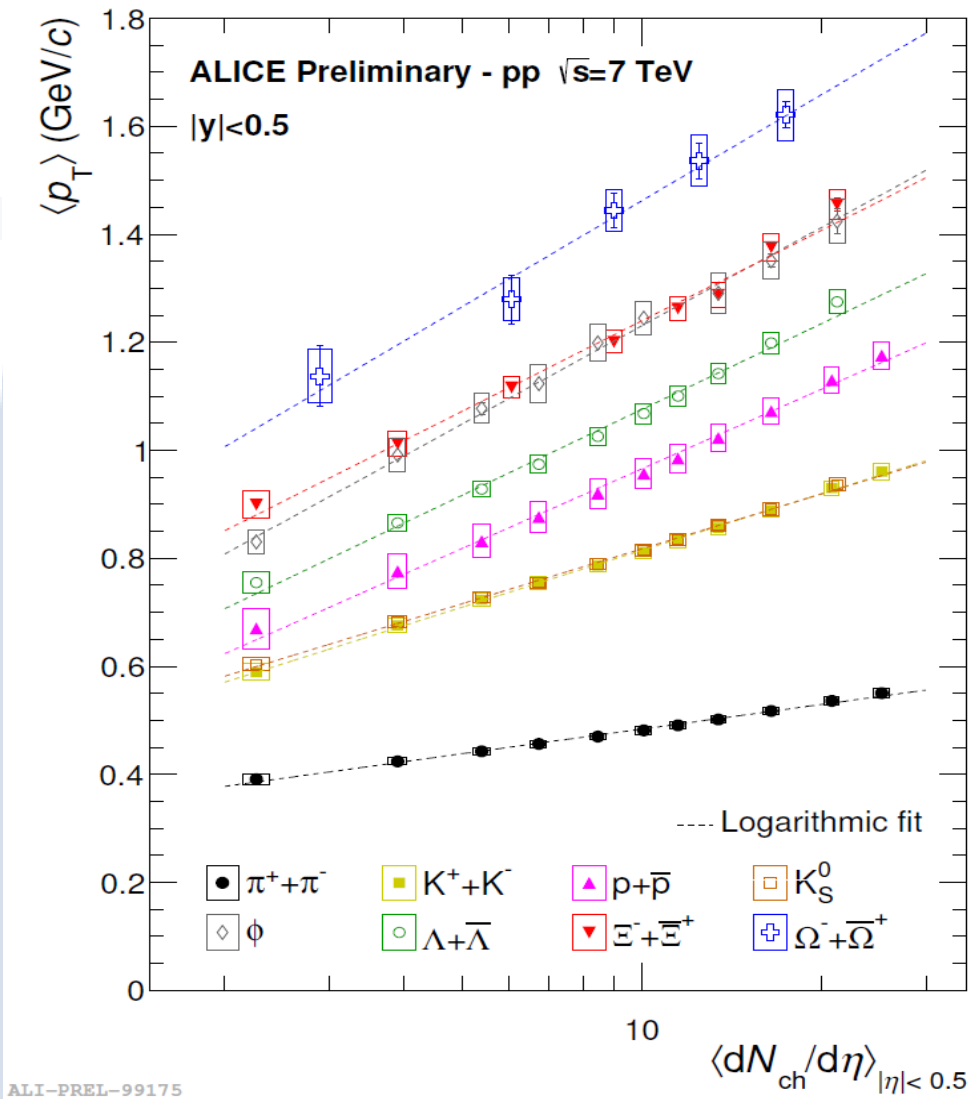



- Similar evolution observed in all colliding systems (different multiplicities!)
  - **Depletion** at low $p_T$
  - **Enhancement** at intermediate $p_T$
  - no modifications at high $p_T$
- In Pb-Pb discussed in terms of collective flow and / or quark recombination (depending on $p_T$ and centrality)

- Small remark: also in pp it is really a **bulk** effect!

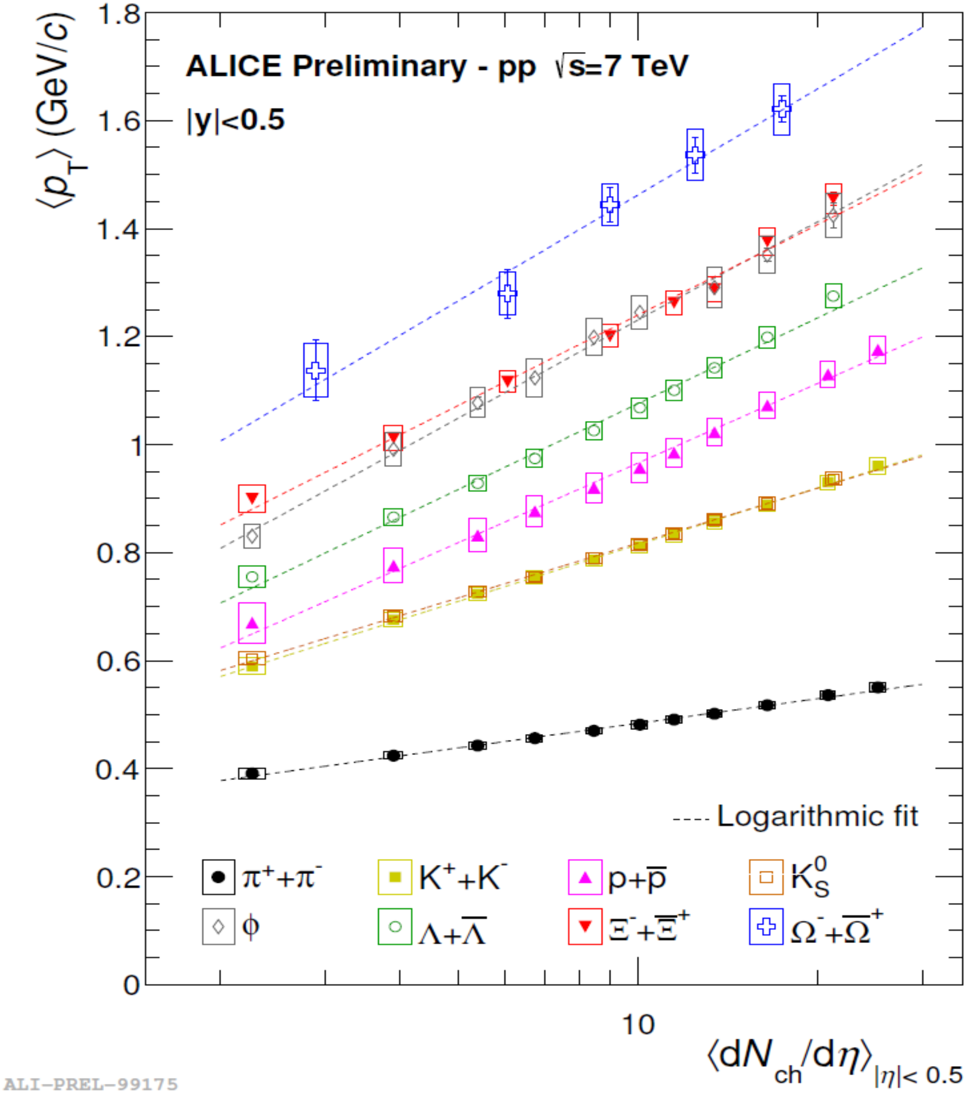


# $\langle p_T \rangle$ vs multiplicity




- Increasing of $\langle p_T \rangle$ as a function of multiplicity as a direct consequence of the hardening of the spectra
- Steeper increasing trend for heavier particles

# $\langle p_T \rangle$ vs multiplicity




- Increasing of $\langle p_T \rangle$ as a function of multiplicity as a direct consequence of the hardening of the spectra
- Steeper increasing trend for heavier particles
- Similar behaviour observed in p-Pb and Pb-Pb (not shown) as a function of multiplicity / centrality

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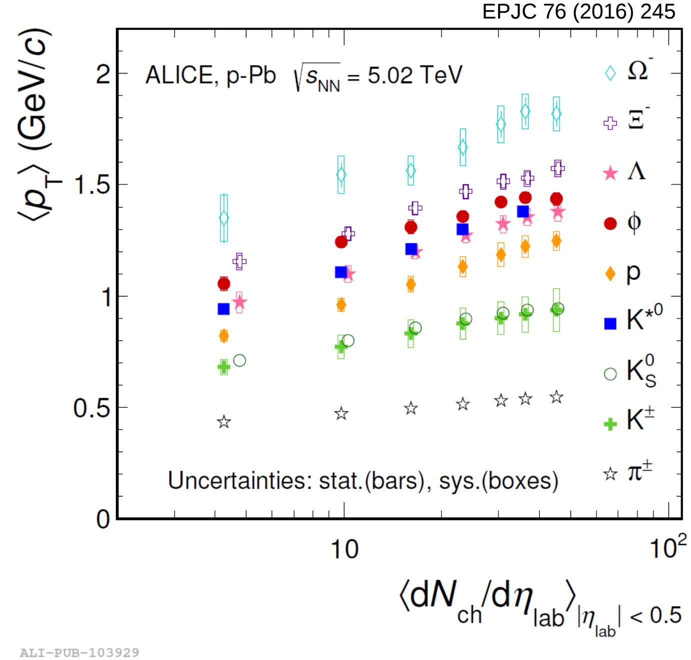
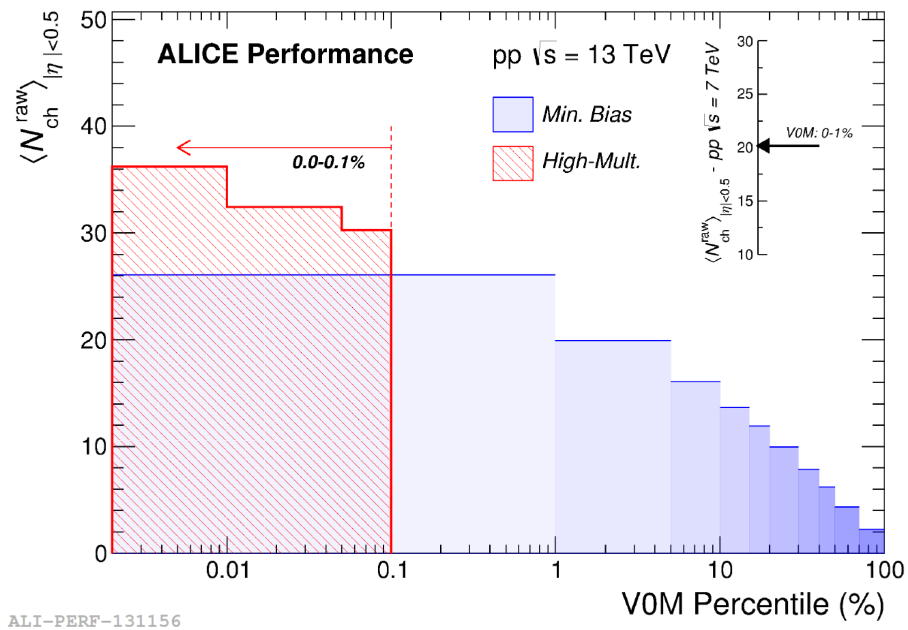
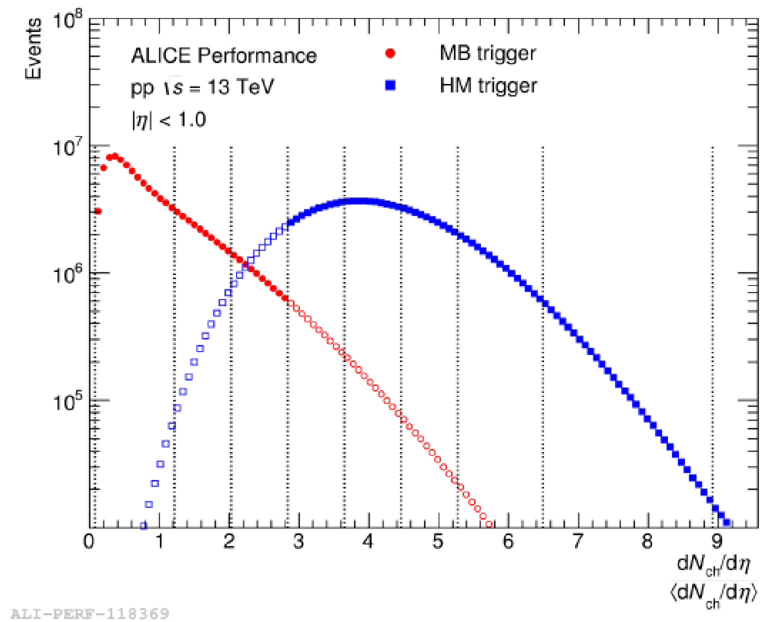
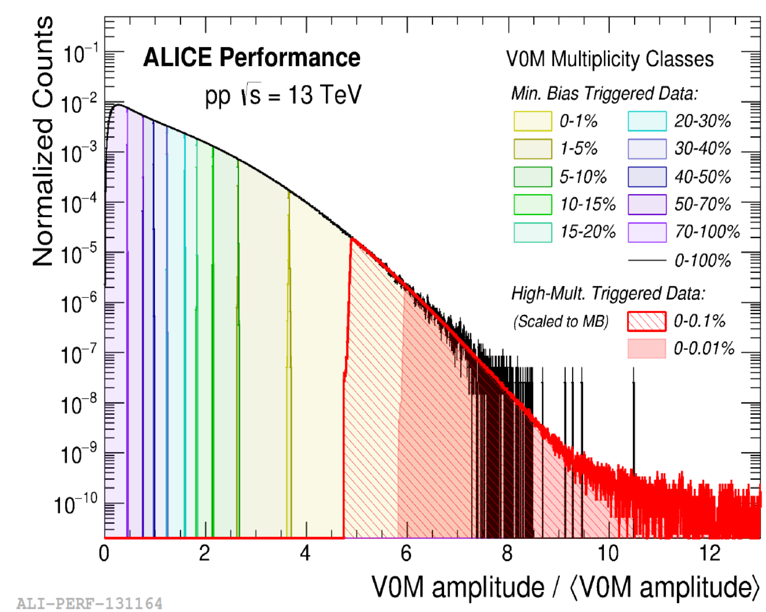


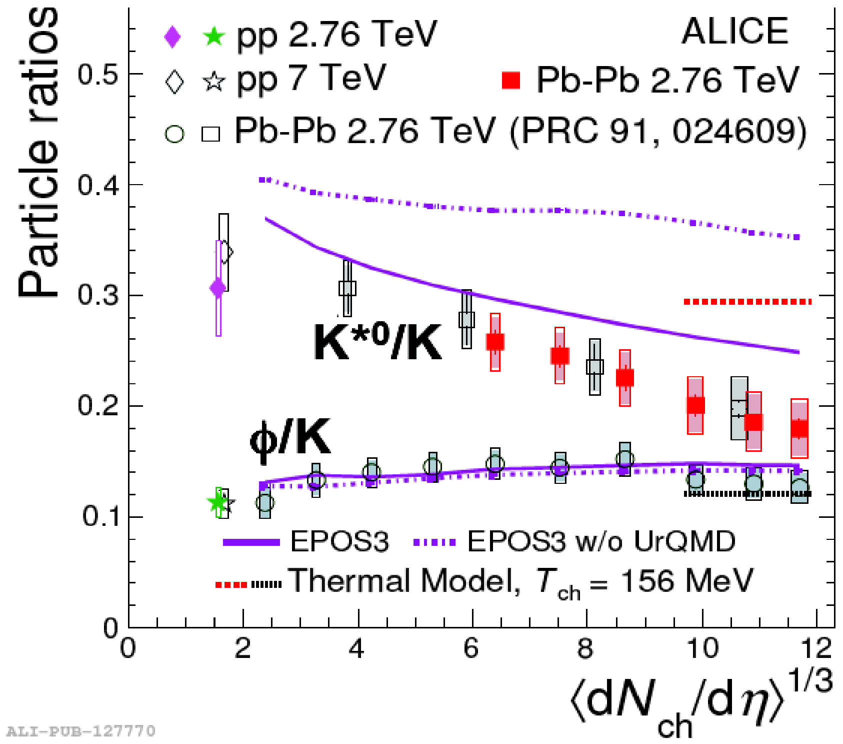
# High Multiplicity triggered data - ALICE



# Resonances



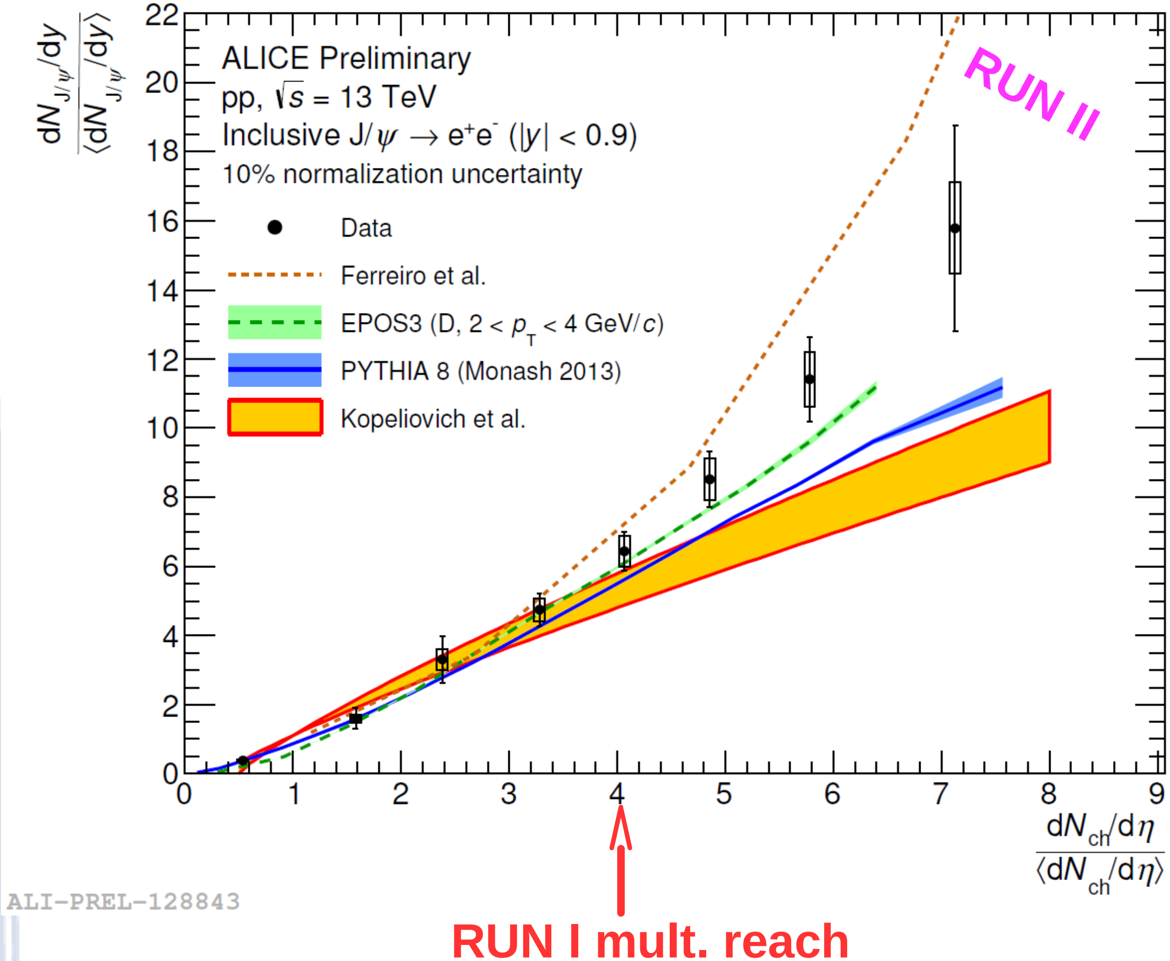

$\tau_{K^*} \sim 4.16$ fm/c

$\tau_{\phi} \sim 46$ fm/c

$\tau_{QGP} \sim 10$ fm/c

- Re-scattering for the $K^{*0}$ more dominant over re-generation
- Re-scattering not significant for the $\phi$

# Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV



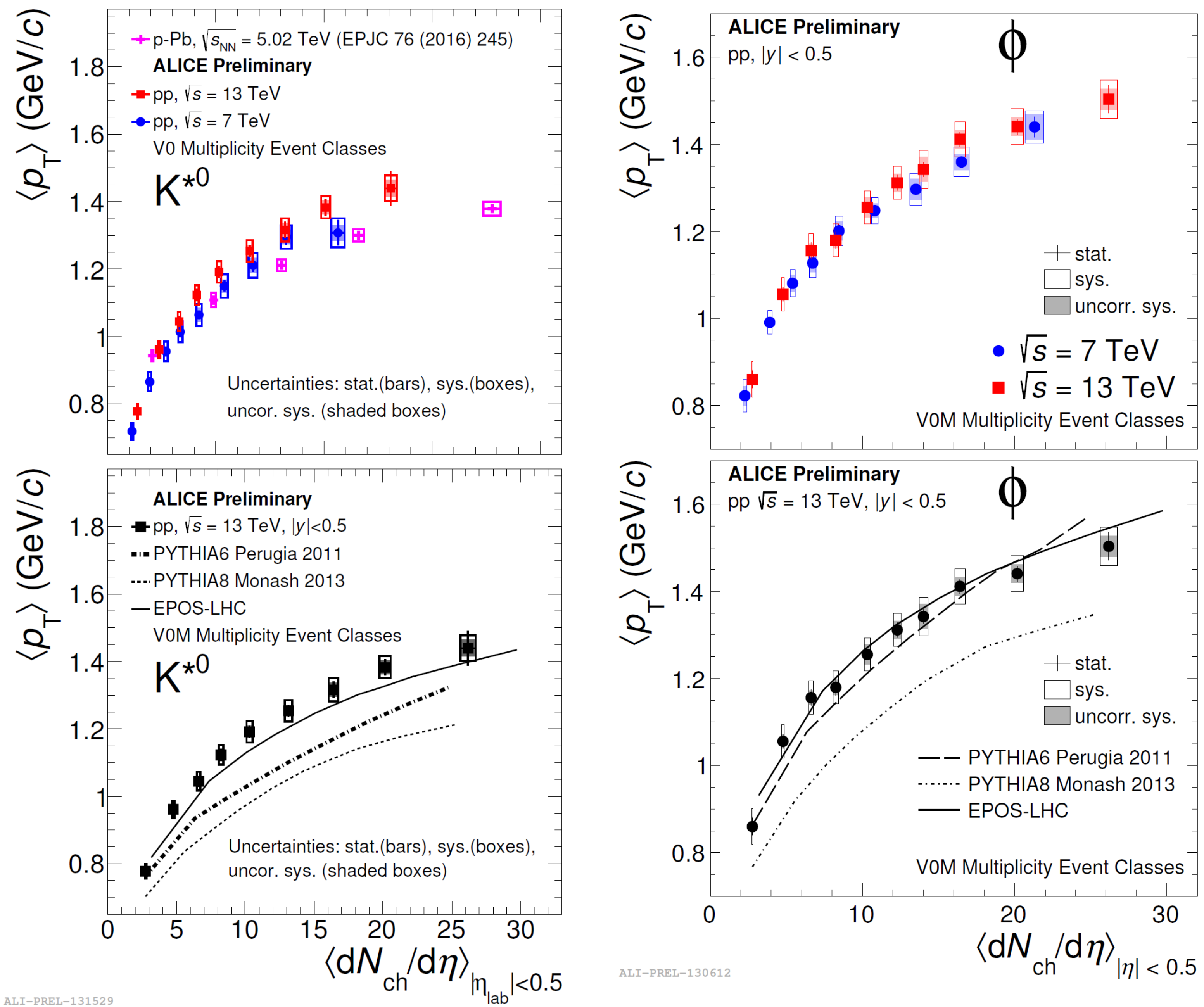

- **PYTHIA8 (Monash 2013)**
  - Initial hard processes
  - Hard processes in MPI
  - ISR / FSR
- **EPOS3**
  - Gribov-Regge formalism (MPI included)
  - Hydro evolution of the system
- **Kopeliovich et al.**
  - contributions of higher Fock states
- **Percolation model**
  - Soft sources stronger affected than hard sources with increasing density (multiplicity)


Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
PYTHIA8, Sjostrand et al., Comput.Phys.Comm.178(2008)
Kopeliovich et al., PRD88 (2013) 116002


- Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
- Faster than linear increase confirmed from Run II data analysis

# Resonances: evolution with $\langle dN_{ch}/d\eta \rangle$ and $\sqrt{s}$

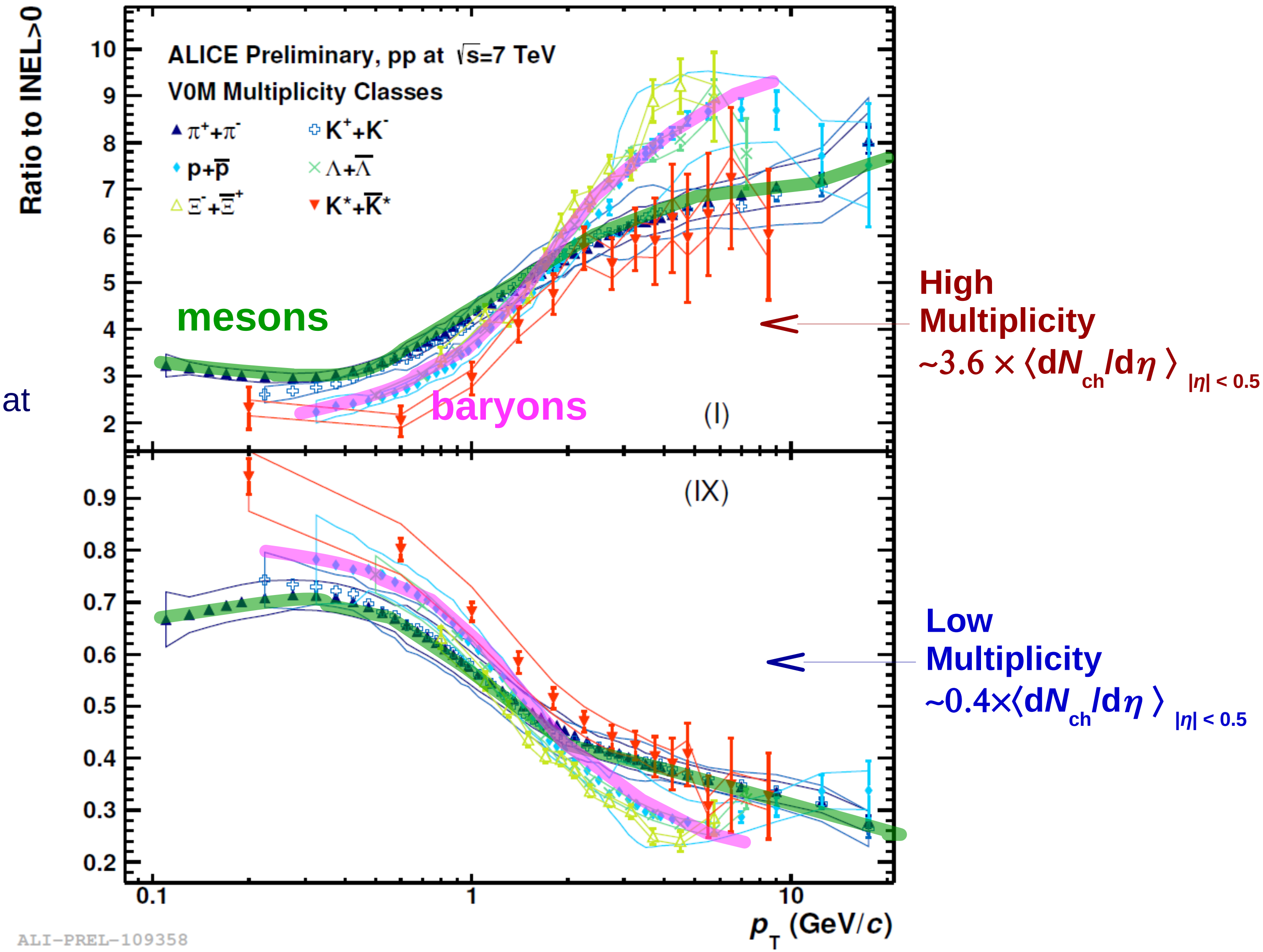
**pp 7 TeV vs pp 13 TeV vs pPb 5.02 TeV**



# Transverse momentum spectra

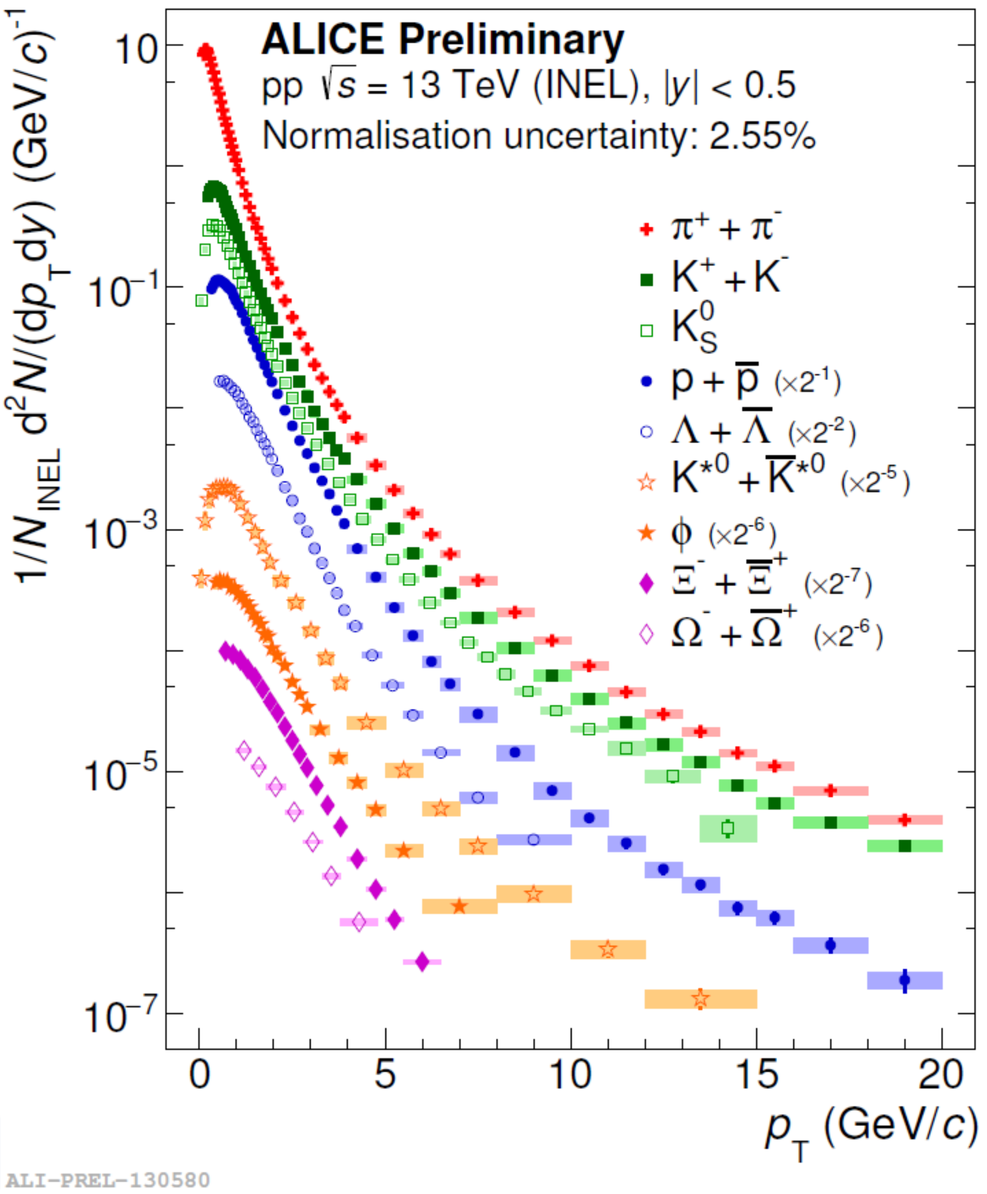
- Spectra modifications w.r.t INEL>0
  - Ratios become flat within uncertainties at high-pT
  - hint of a **baryon / meson** difference (except K*)

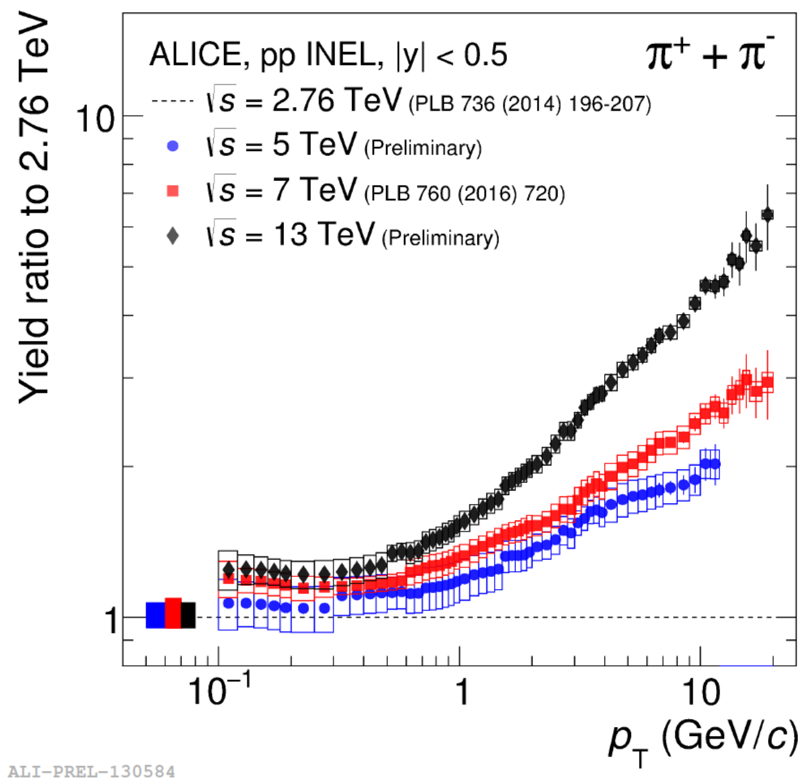
**pp, $\sqrt{s}$ = 7 TeV**




- Spectra become **harder** for increasing multiplicity
  - **flattening** of the spectra at low $p_T$, more pronounced for heavier particles
- In Pb-Pb interpreted in terms of collective expansion of a thermalized system (radial flow) which may require a fireball in a local thermodynamical (kinetic) equilibrium

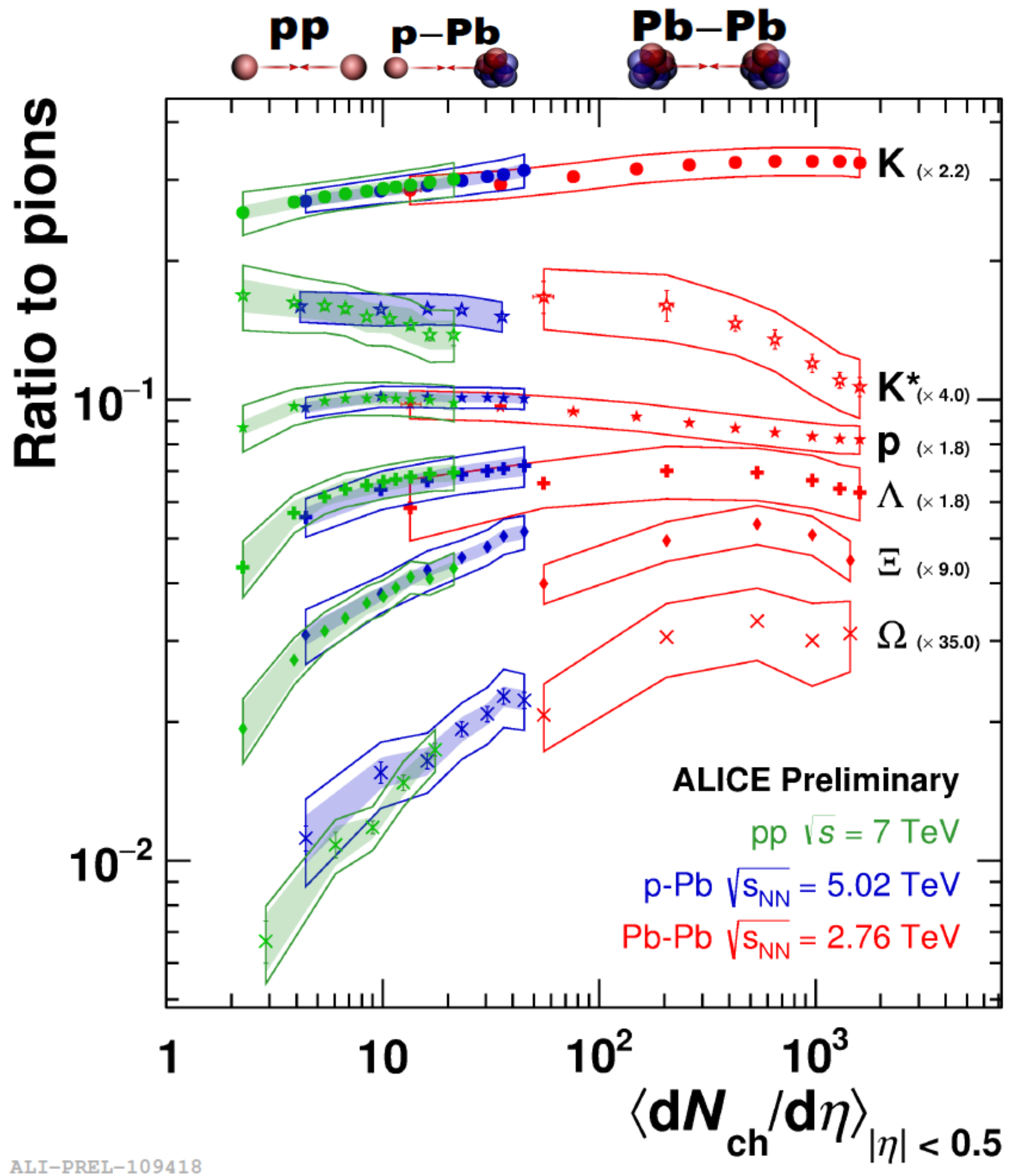
# Identified particle spectra in pp




- ✔ Identified particle spectra measured over a wide $p_T$ range
- ✔ Spectra become harder at higher √s

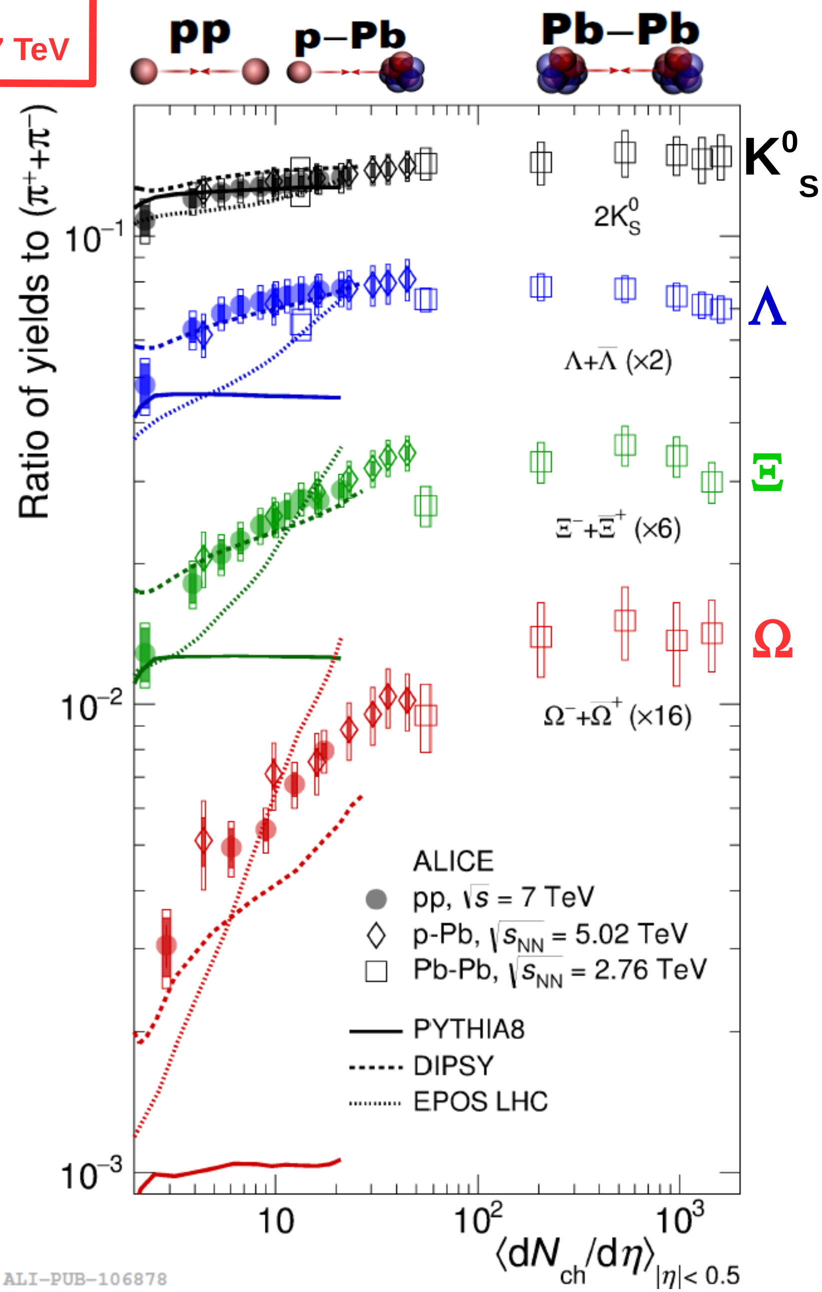
# Hadrochemistry: ratio to pions

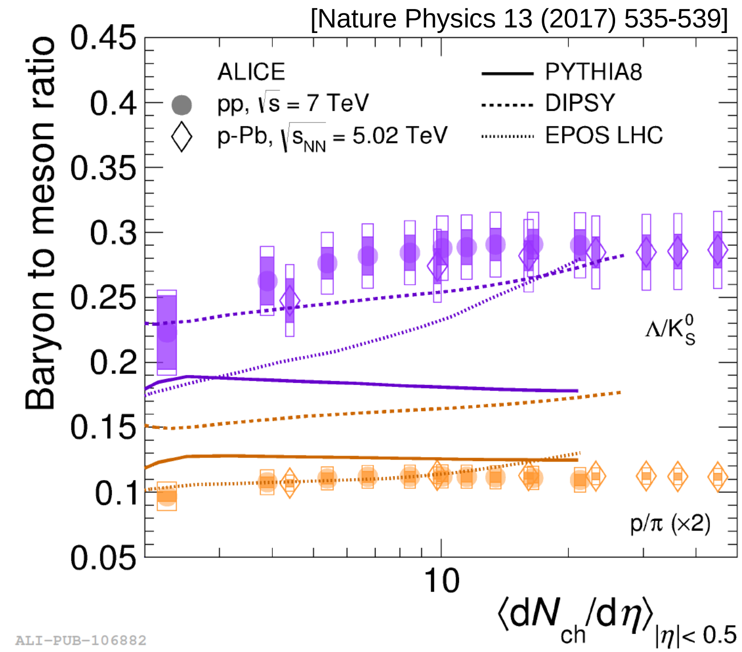


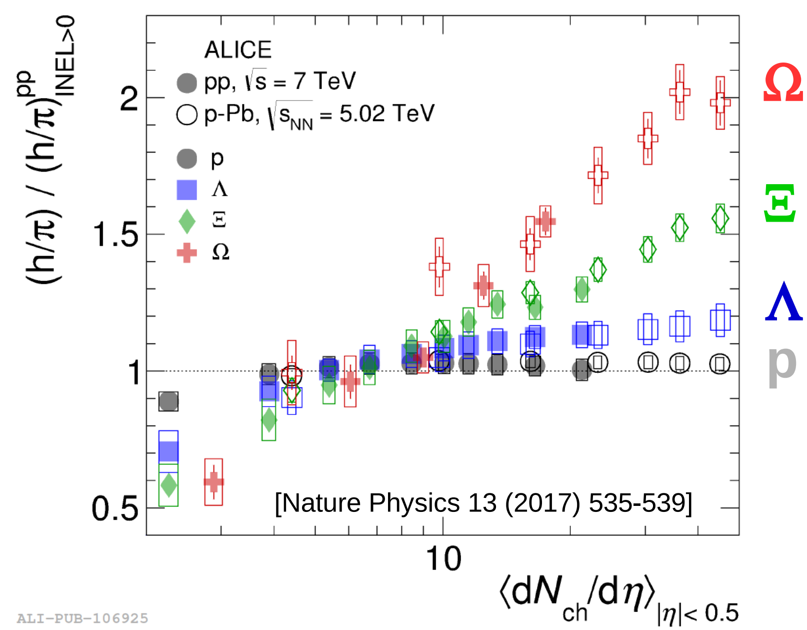

- Smooth evolution with $\langle dN_{ch}/d\eta \rangle$ across all colliding systems !
- Decrease of $K^*/\pi$ vs $\langle dN_{ch}/d\eta \rangle$ in Pb-Pb
- $p/\pi$ stays constant within uncertainties
- **Strangeness enhancement** observed in small systems

# Hadrochemistry: Strangeness enhancement

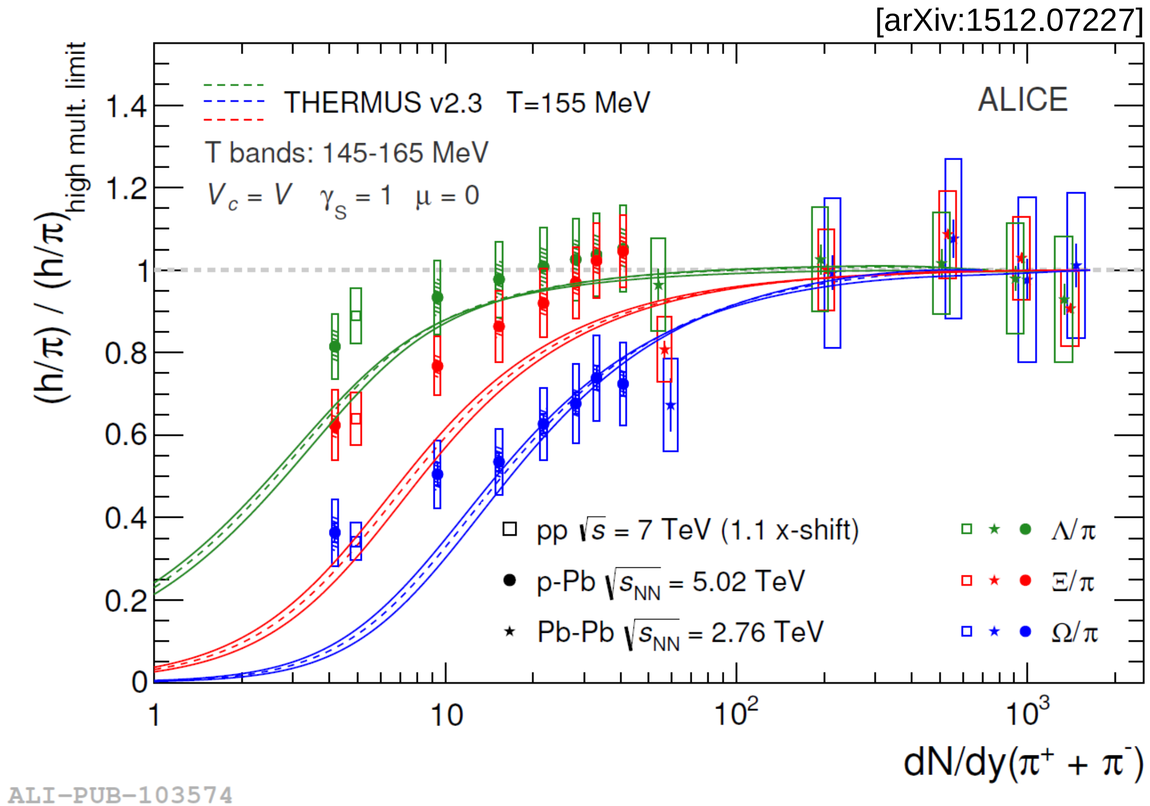
pp, √s = 7 TeV



# Strangeness enhancement in pp: is it canonical suppression ?




- Strange hadron to pion ratios normalized to their "large volume" values:
  - data: mean of the h/π ratio measured in central Pb-Pb (0-60%)
  - THERMUS: GC limit

- THERMUS: local conservation of strangeness quantum number within a correlation volume $V_C$ (Canonical ensemble used to describe the system) → phase space reduced for strange particle production as the volume of the system become smaller (canonical suppression)

- Strangeness suppression towards smaller system sizes within the canonical suppression picture is in qualitative agreement with the trend observed in the data