Enhanced production of (multi-)strange hadrons in high multiplicity pp collisions

18th FPCP, 10th June 2020

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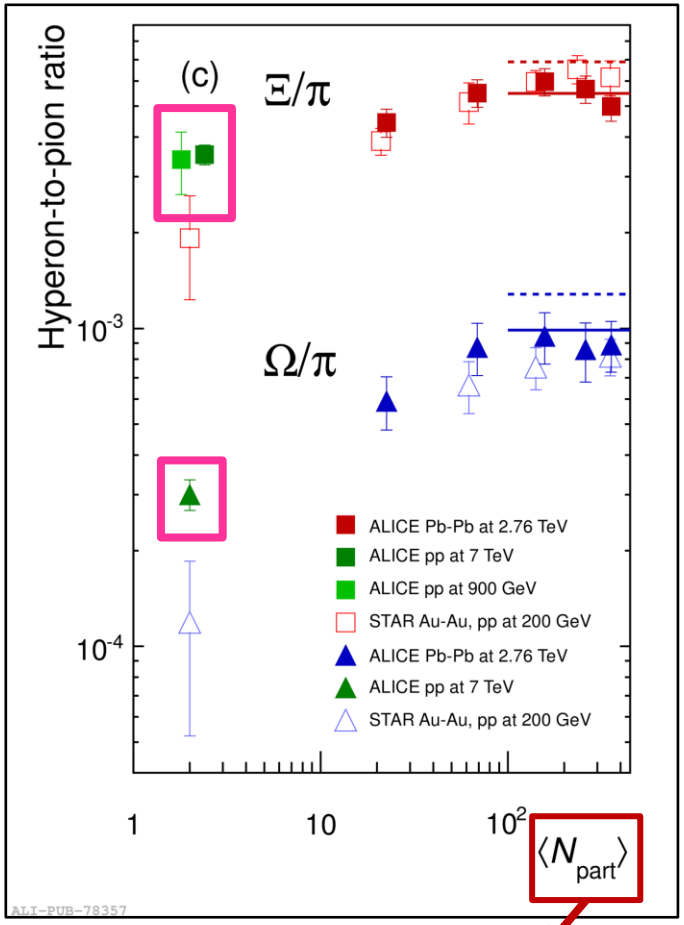
Università degli studi di Torino
University of Witwatersrand and iThemba LABS

Physics motivation

Strange hadron production: key tool for understanding hadronization in different environments

ALICE Coll., PLB 734, 409-410 (2014)



Nucleons participating in a collision

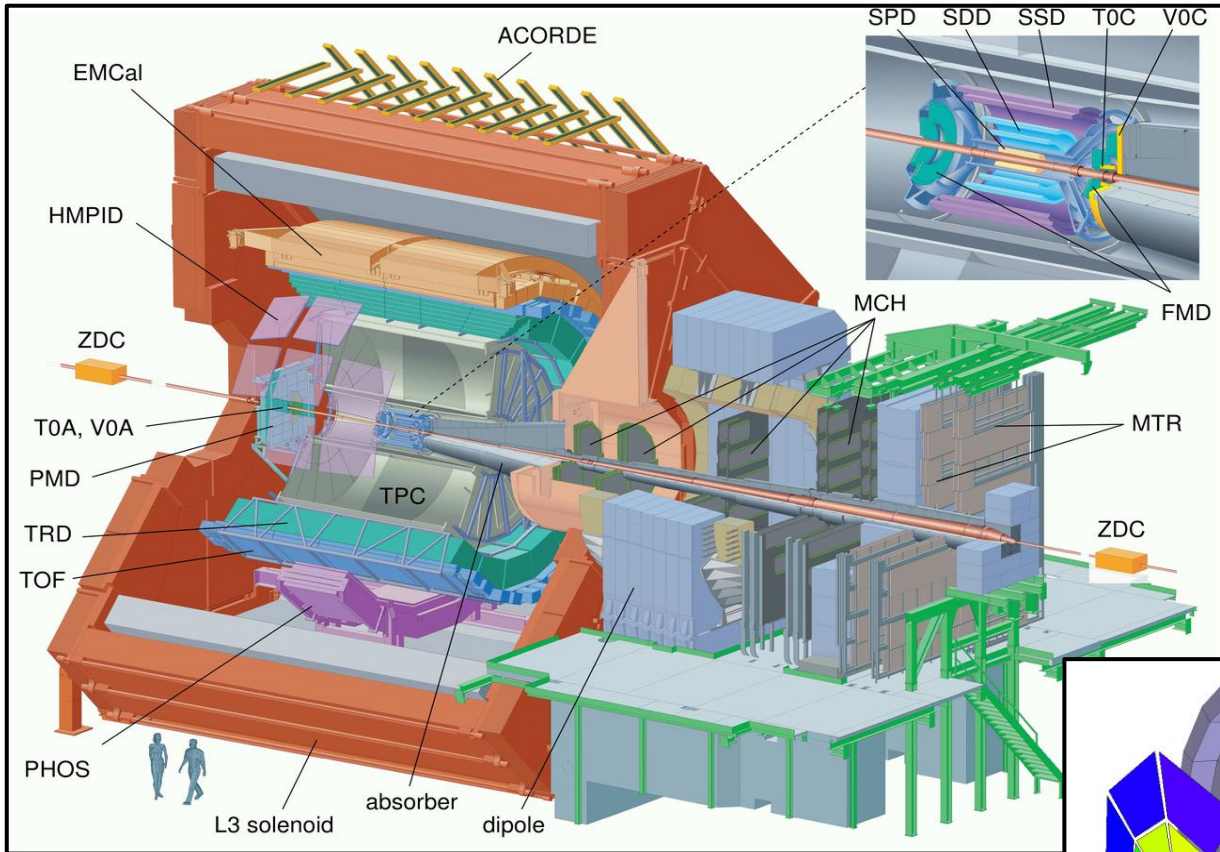
Strangeness enahancement:

- Enahanced production of strange hadrons was observed in heavy-ion collisions with respect to elementary collisions
- Originally proposed as a signature of **QGP formation** in nuclear collisions (Rafelsky, Muller[1])
  - *Lower Q-value for $s\bar{s}$ relative to $H_s H_{\bar{s}}$ formation*
  - *Faster equilibration in partonic medium*

[1] Koch, Muller, Rafelski, Phys. Rep. 142, 167–262 (1986)

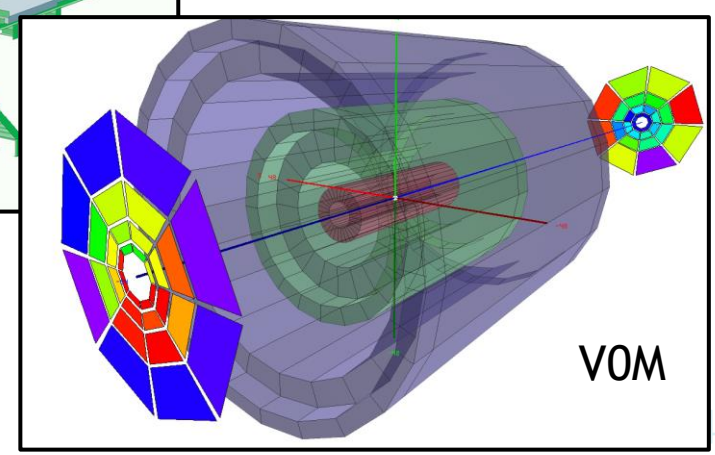
ALICE at LHC:

Detectors used for strangeness analysis:



V0A (2.8< η <5.1) and V0C (-3.7< η <-1.7)
Forward-rapidity arrays of scintillators
-triggering,
beam gas rejection,
multiplicity estimator

TOF ($|\eta| < 0.9$)
Made by MRPCs
-PID
-pile-up rejection



ITS ($|\eta| < 0.9$)
6 layers of silicon detectors
-triggering, tracking, (secondary) vertexing, PID (dE/dx)

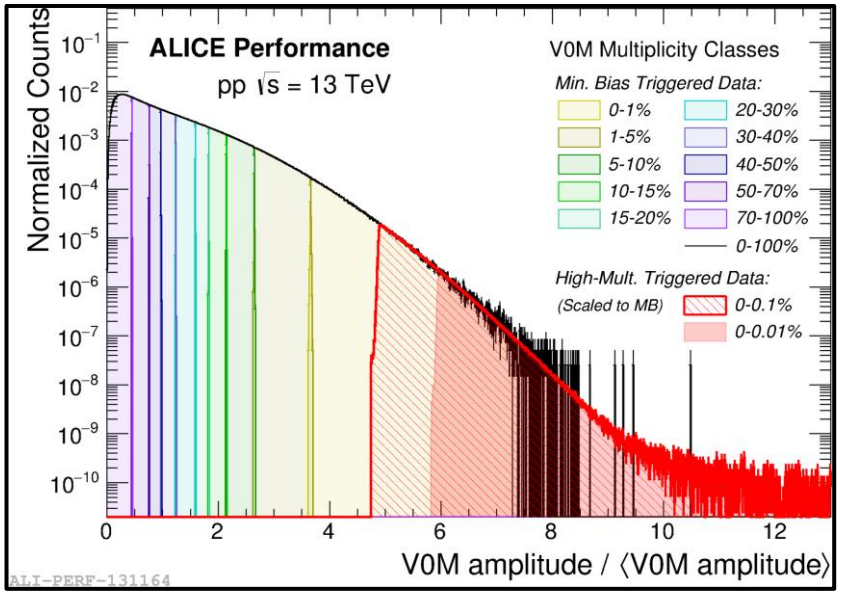
TPC ($|\eta| < 0.9$)
Gas-filled detector
-tracking, vertexing, PID (dE/dx)

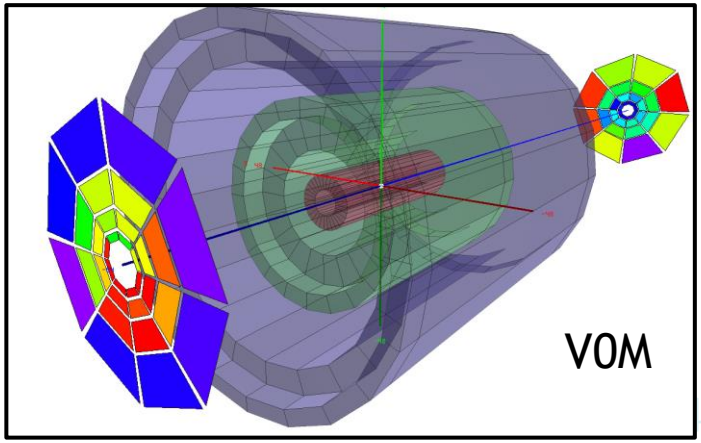
Multiplicity estimation

Multiplicity→Number of particles produced in a defined kinematic region

Multiplicity estimation:

- data sample divided in V0M amplitude classes
- **Average multiplicity**→ measurement of the primary charged particles at central rapidity for each V0M amplitude class

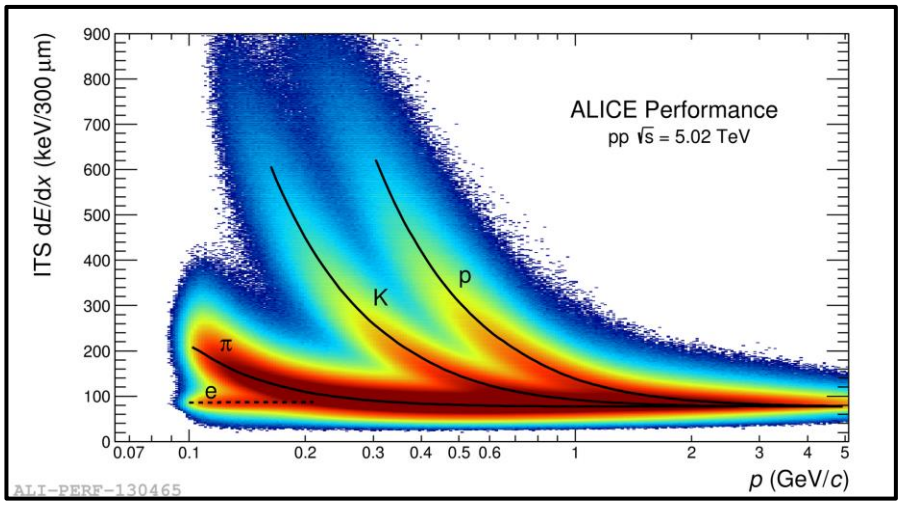




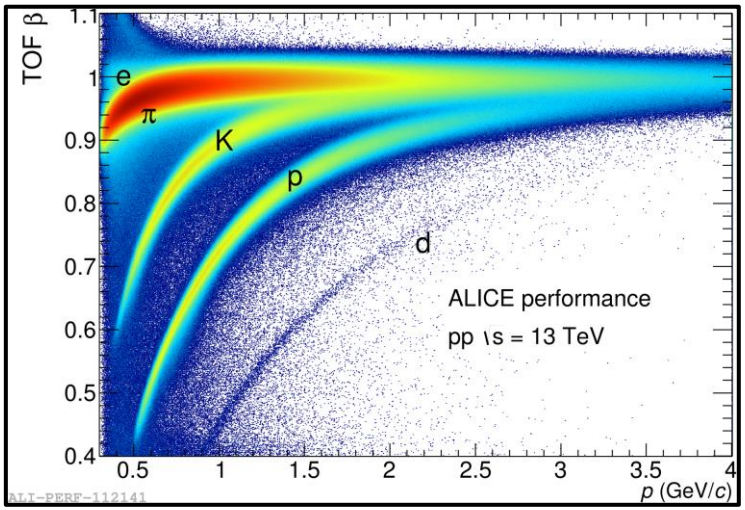
PID with central barel detectors

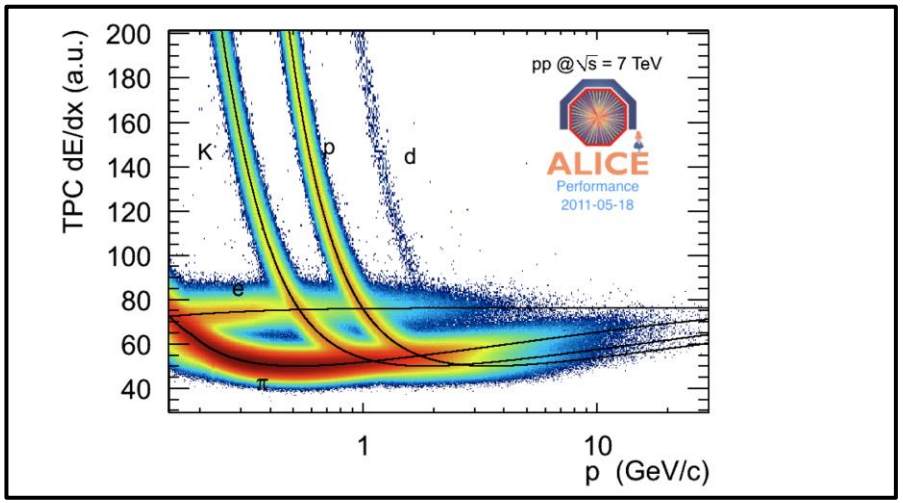
Particle Identification techniques:

- Energy Loss→ ITS TPC



- Time of Flight→TOF



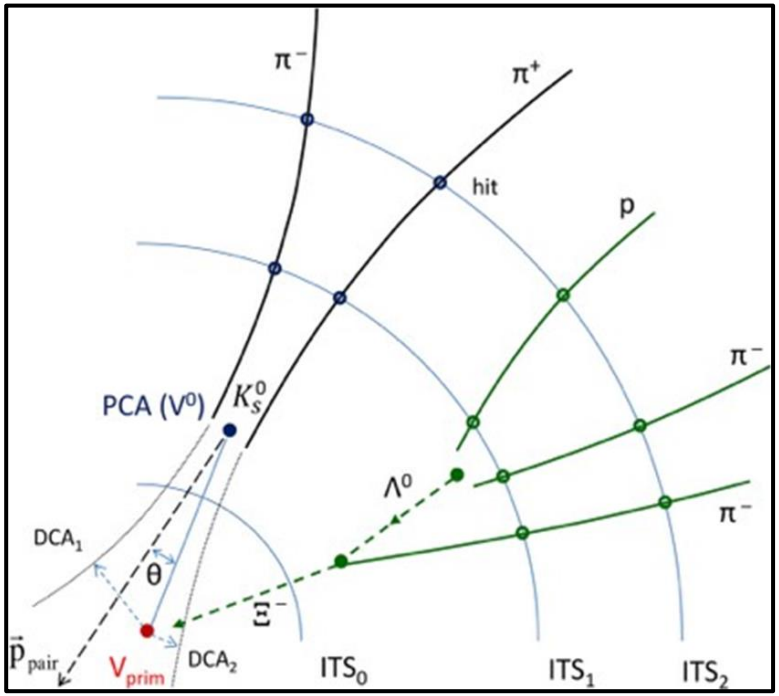


Analyses in pp collisions at LHC

	vs multiplicity	Published results on strangeness
$\sqrt{s} = 900\ GeV$	No	ALICE Collaboration, Eur. Phys. J. C 71 (2011) 1594
$\sqrt{s} = 7\ TeV$	*Yes*	ALICE Collaboration, Nature Physics 13, 535–539 (2017)
$\sqrt{s} = 13\ TeV$	*Yes*	ALICE Collaboration, Eur. Phys. J. C 80 (2020) 167
$\sqrt{s} = 5.02\ TeV$	*Yes*	NEW for this conference!

Strange hadron identification

Particle reconstruction via weak decay topology.
Cuts are applied on kinematical, geometrical and topological variables.



V0s:

- $\Lambda \rightarrow p + \pi^-$ / $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ **(BR= 69.2%)**
- $K_S^0 \rightarrow \pi^+ + \pi^-$ **(BR= 63.9%)**

Neutral particles decaying into two particles with opposite charge →**charge conservation**

Cascades:

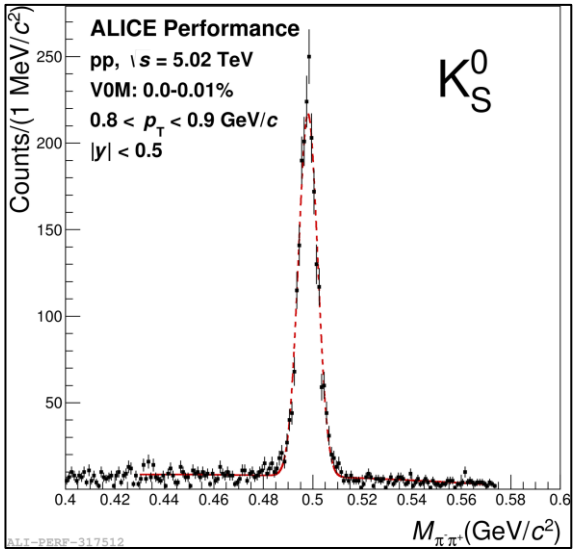
- $\Xi^- \rightarrow \Lambda + \pi^-$ / $\bar{\Xi}^+ \rightarrow \bar{\Lambda} + \pi^+$ **(BR=99.9%)**
- $\Omega^- \rightarrow \Lambda + K^-$ / $\bar{\Omega}^+ \rightarrow \bar{\Lambda} + K^+$ **(BR= 67.8%)**

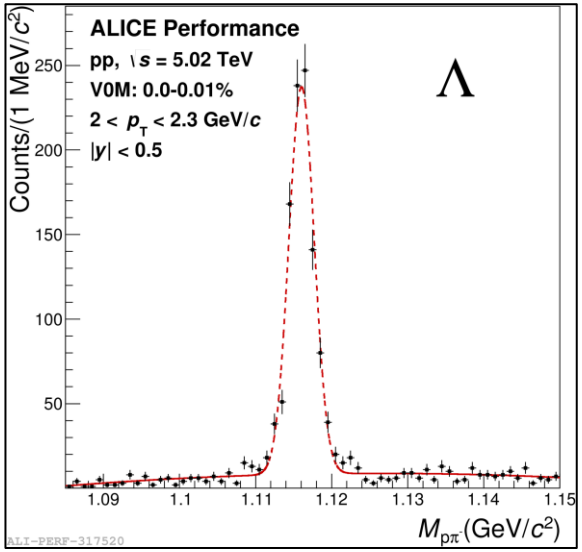
The reconstructed Λ candidate is associated to a "bachelor" track to obtain the cascade candidate

K_S^0	Λ	Ξ	Ω
M=497.61 MeV/c²	M=1115.68 MeV/c²	M=1321.71 MeV/c²	M=1672.45 MeV/c²
cτ= 2.68 cm	cτ= 7.89 cm	cτ= 4.91 cm	cτ= 2.46 cm

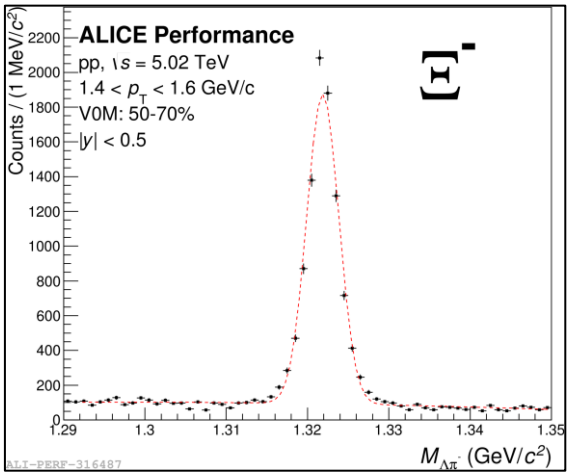
Strange hadron identification

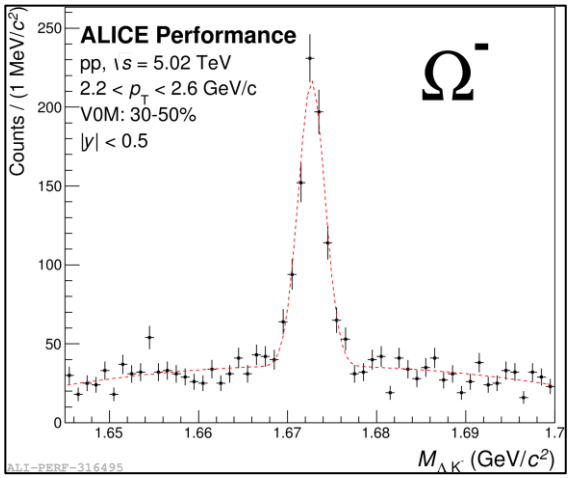
Invariant mass distributions for **V0s** and **Cascades** reconstructed for selected p_T and multiplicity bins→polynomial background and Gaussian peak





NEW!





Strange hadron identification

The ϕ meson is reconstructed via invariant mass analysis from $K^{\pm}$ identified with TPC and TOF

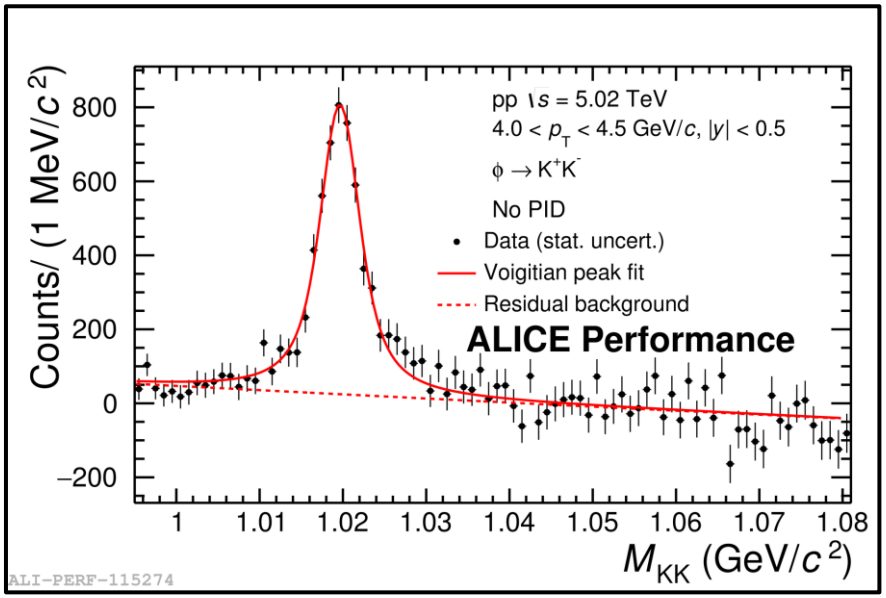
- Geometrical and kinematical cuts
- Primary tracks selection
- TPC PID selection $|N\sigma_{K,TPC}| < 2$ with TOF "veto" $|N\sigma_{K,TOF}| < 3$

Invariant mass spectra

- Combinatorial background subtraction
- Polynomial residual background and Voigitian peak fit

$\phi \rightarrow K^{+} + K^{-}$ **(BR= 48.9%)**

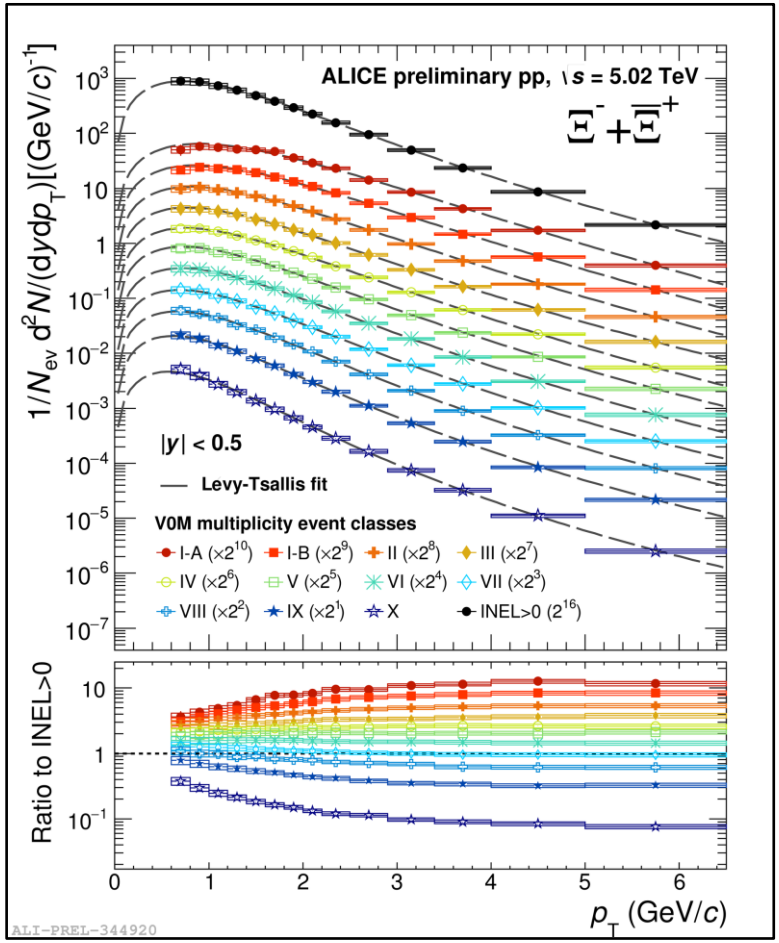
M = 1019.5 MeV/c^2
cτ = 46.5 fm

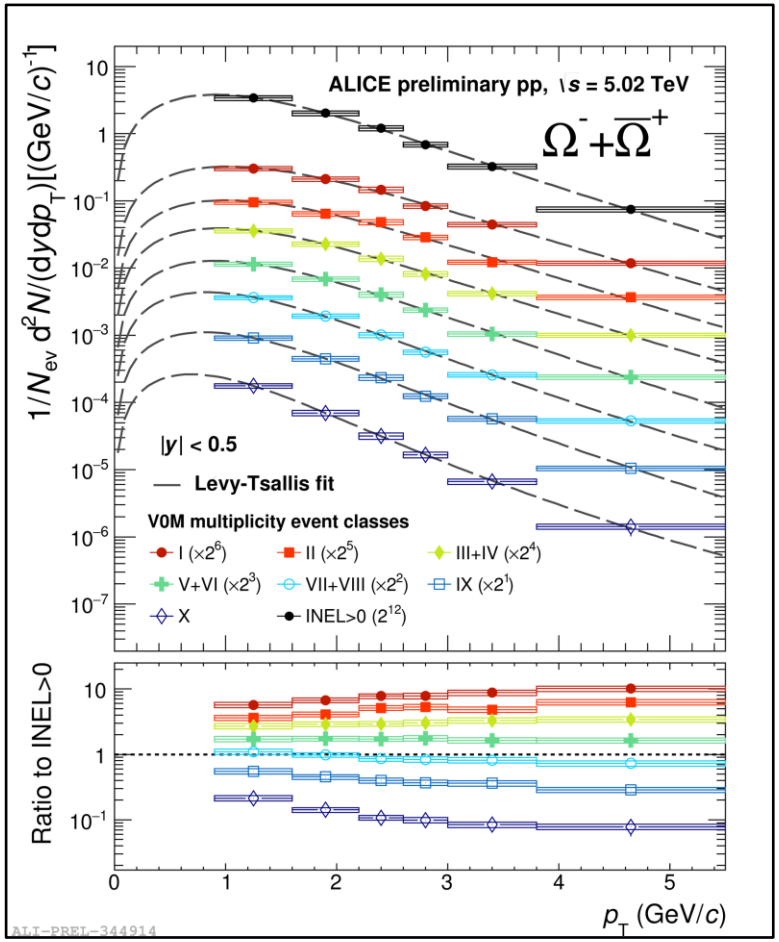


Corrected spectra vs p_T

p_T distribution of strange hadrons for different multiplicity classes

NEW!





The p_T spectra became harder as the multiplicity increases→ evolution is similar to large systems where **spectra hardering** is connected to hydrodinamical radial expansion of the produced medium (**radial flow**)

Blast-Wave model

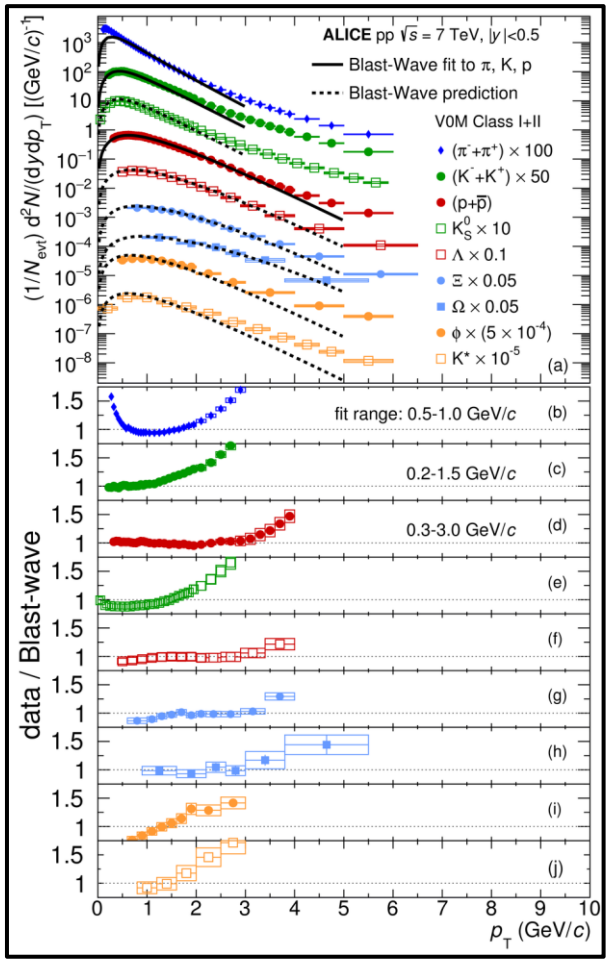
Blast-Wave model:

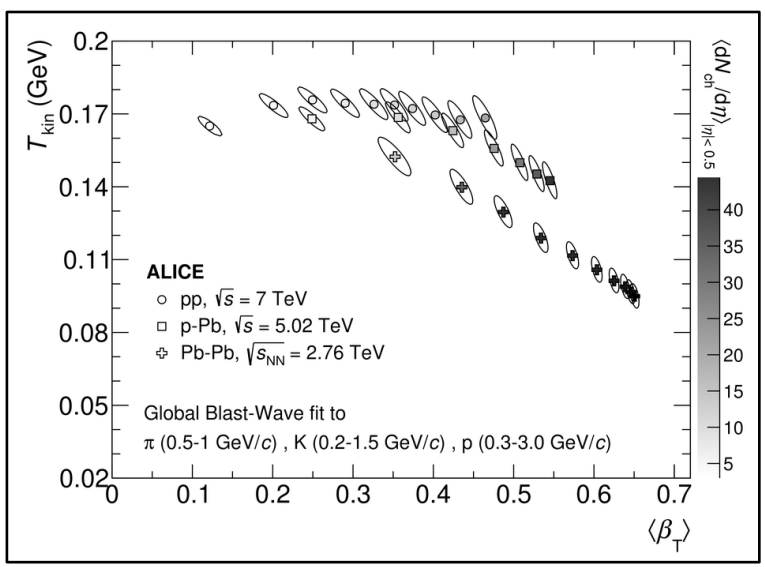
- Thermalized medium (QGP) expands with a common $\langle\beta_T\rangle$ and undergoes to istanteneous kinematic freeze-out at T_{kin}

Simultaneous BW fit to π, K and p spectra to:

➢ Predict spectra of K_S^0, Λ, Ω, Ξ, K^{*0} and ϕ

- Strange hadrons spectra reasonably described by BW model→strange particles follow a common motion→**radial flow**
- Not true for resonances!





➢ Evaluate T_{kin} vs $\langle\beta_T\rangle$

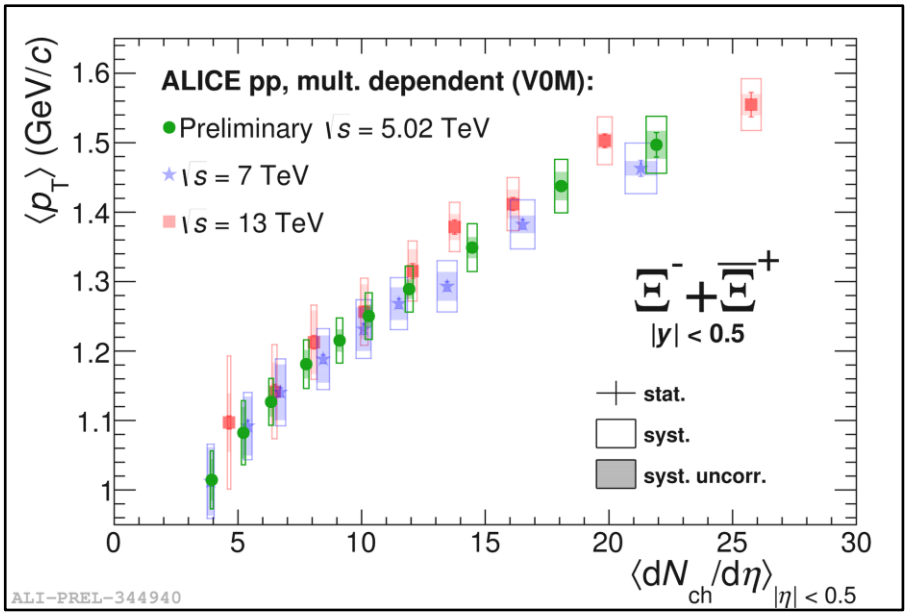
- At similar multiplicities:
  - Similar values for pp and p-Pb collisions
  - Lower values for Pb-Pb collisions

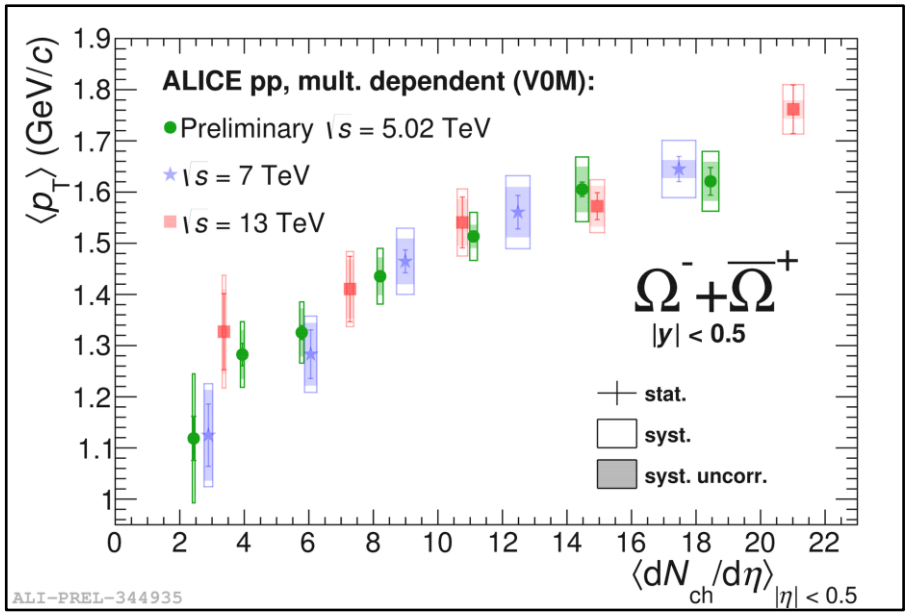
ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

Mean p_T

Avarage p_T as a function of multiplicity is obtained from the corrected spectra and the extrapolation at p_T=0 GeV/c with Lévy-Tsallis fit function

NEW!

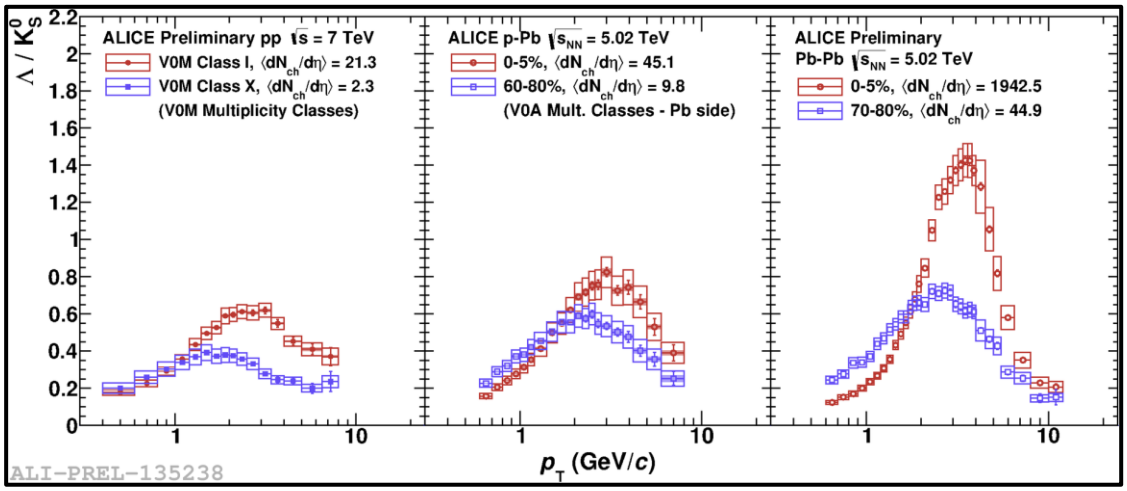


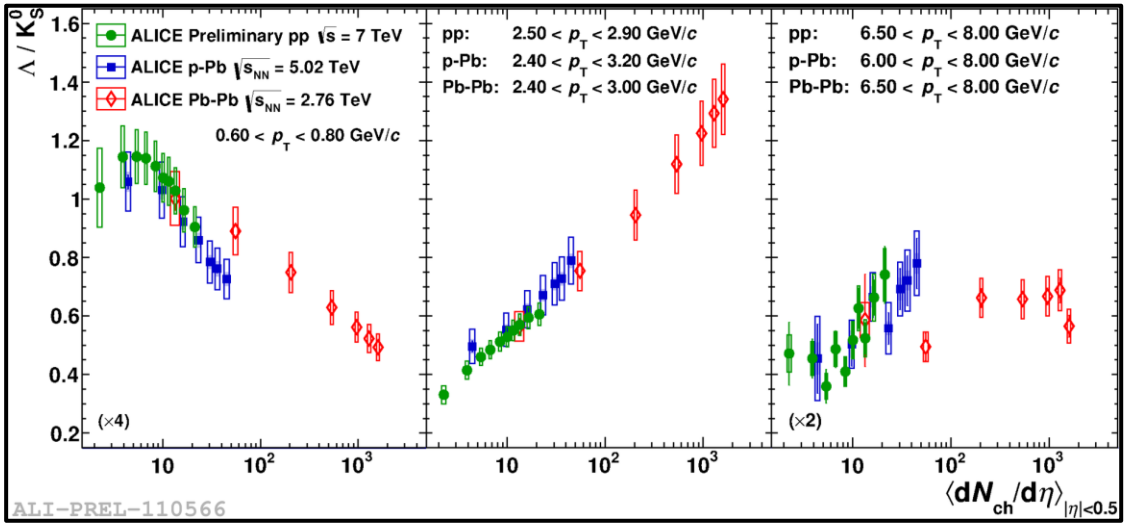


The new results $\sqrt{s} = 5.02\ TeV$ are consistent with the previous analyses at $\sqrt{s} = 7$ and $13\ TeV$:

- Mean p_T increases as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
- **Average p_T is not dependent on the energy of the system**

Baryon to meson ratio





Λ/K_S^0 enhancement present in all collision systems at the LHC:

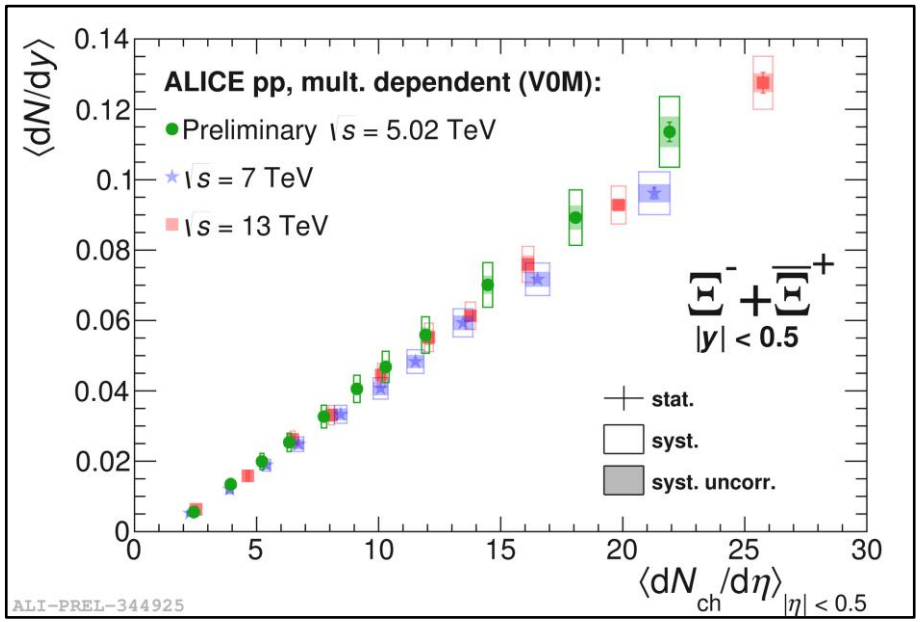
- The effect is larger in larger colliding systems
- Smooth evolution with multiplicity when selecting specific p_T intervals
- <u>Radial flow (QGP) in small systems?</u>

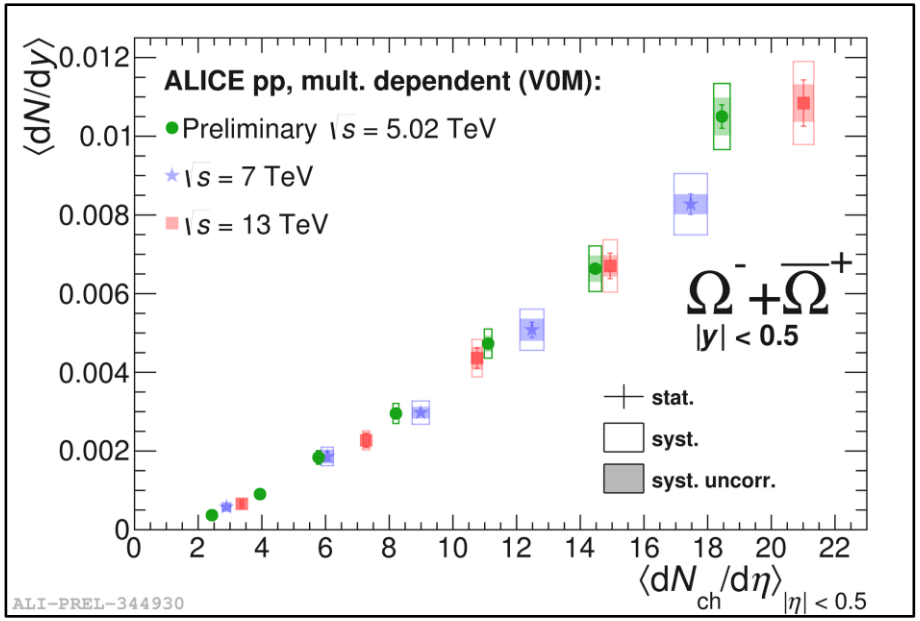
ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

p_T-integrated Yield

NEW!

p_T -integrated yield as a function of multiplicity obtained integrating the corrected spectra and the Lévy-Tsallis function down to 0 GeV/c

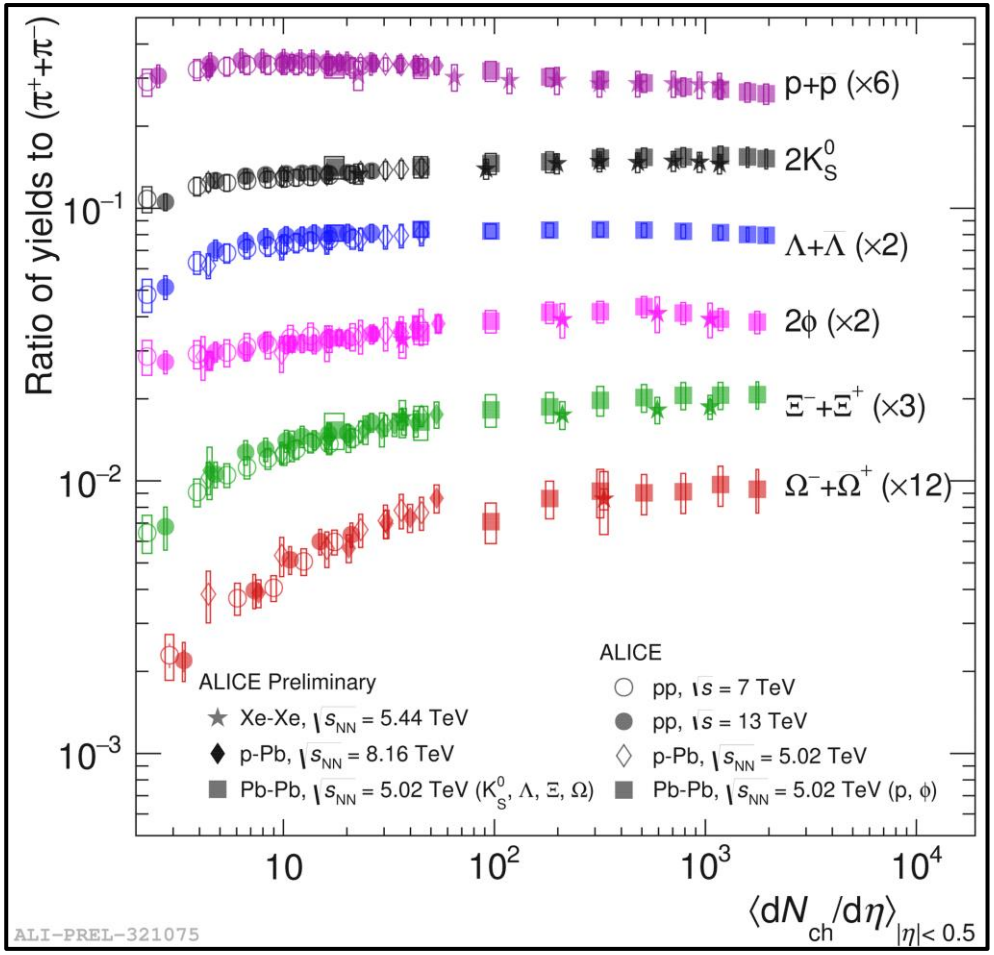




The <dN/dy> at $\sqrt{s} = 5.02\ TeV$ is in good agreement with the previous analyses results at $\sqrt{s} = 7 \text{ and } 13\ TeV$ so, it is not dependent on the energy of the system

Hadrochemistry

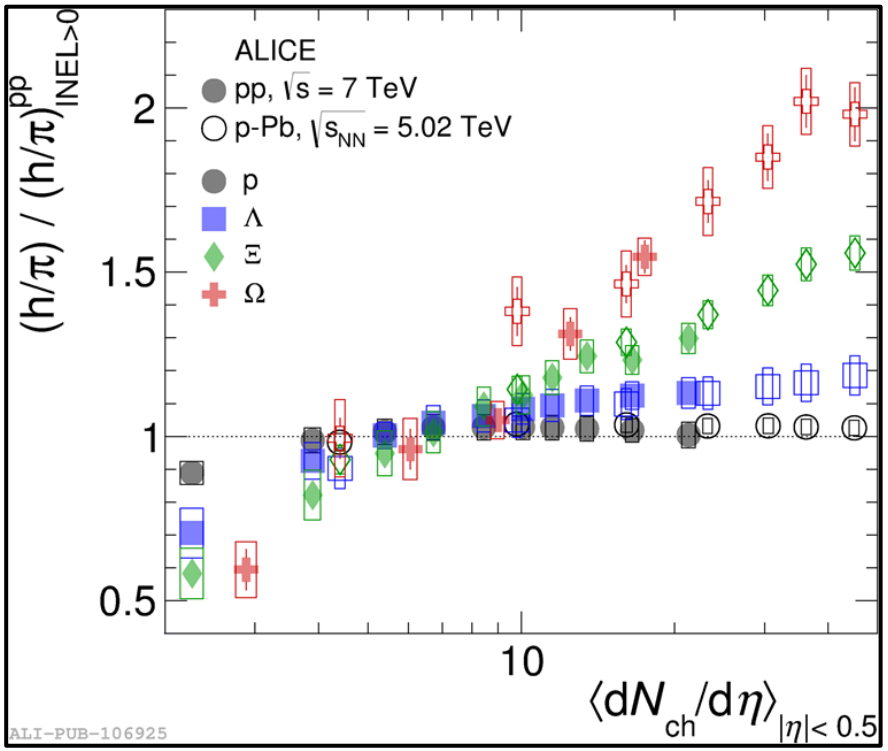
p_T-integrated yield ratios to $(\pi^+ + \pi^-)$ vs multiplicity:



- The ratio shows an enhanced trend from low multiplicity pp to central Pb-Pb collisions for strange hadrons
- Smooth evolution among pp, p-Pb and Pb-Pb collisions
- Saturation is observed in (semi-) central Pb-Pb collisions

Hadrochemistry

p_T-integrated yield ratio to $(\pi^+ + \pi^-)$ over the p_T-integrated yield ratio to $(\pi^+ + \pi^-)$ in INEL>0



Ω s=3

Ξ s=2

Λ s=1

p s=0

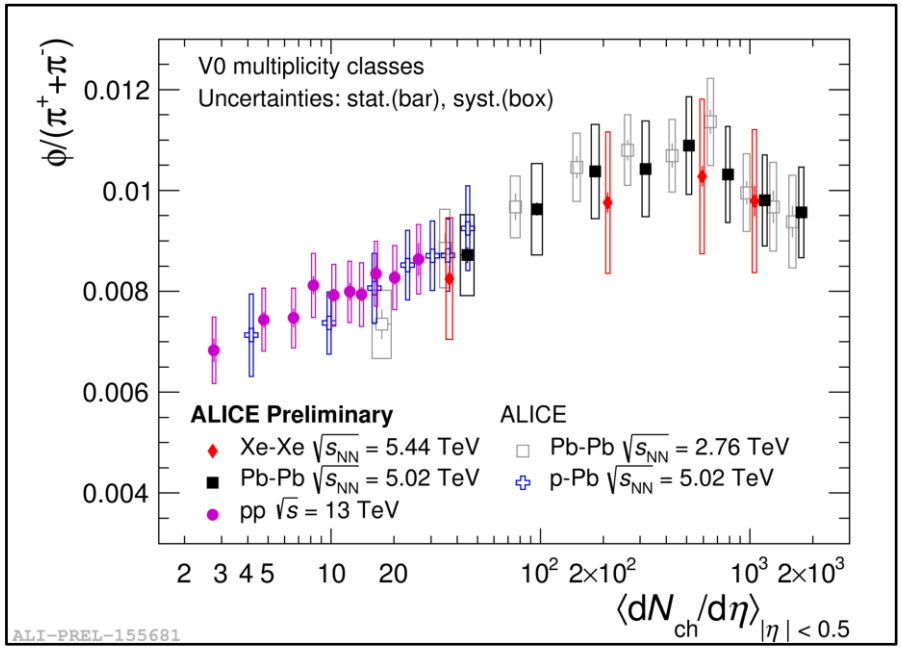
# of strange quarks

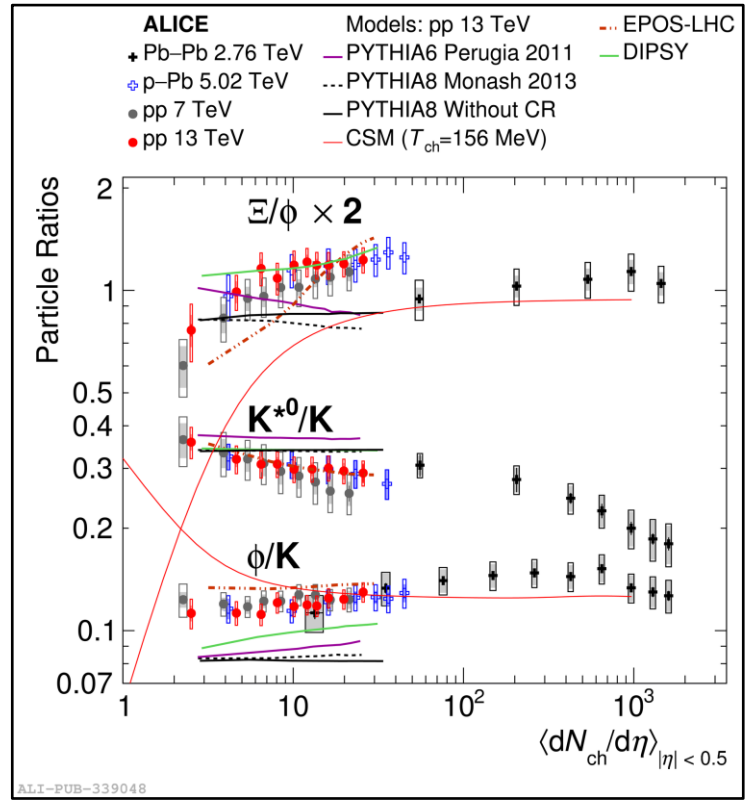
ALICE Collaboration, Nature Physics 13, 535–539 (2017)

Enhancement proportional to the **strangeness content** of the hadron

Hadrochemistry

The ϕ meson has hidden strangeness ($s\bar{s}$ total S=0)





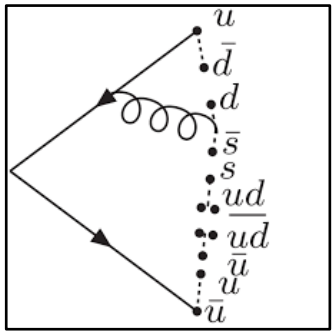
The ϕ meson enhanced as a $1 < S < 2$ particle

ALICE Collaboration, CERN-EP-2019-245

Model comparison: PYTHIA & DIPSY

PHYTHIA Lund string model:

- Confined color fields→ **"string"** with tension ~ 1 GeV/fm
- String breaking → hadron formation
- MPI + Color Reconnection mechanisms at play in high energy hadronic interactions



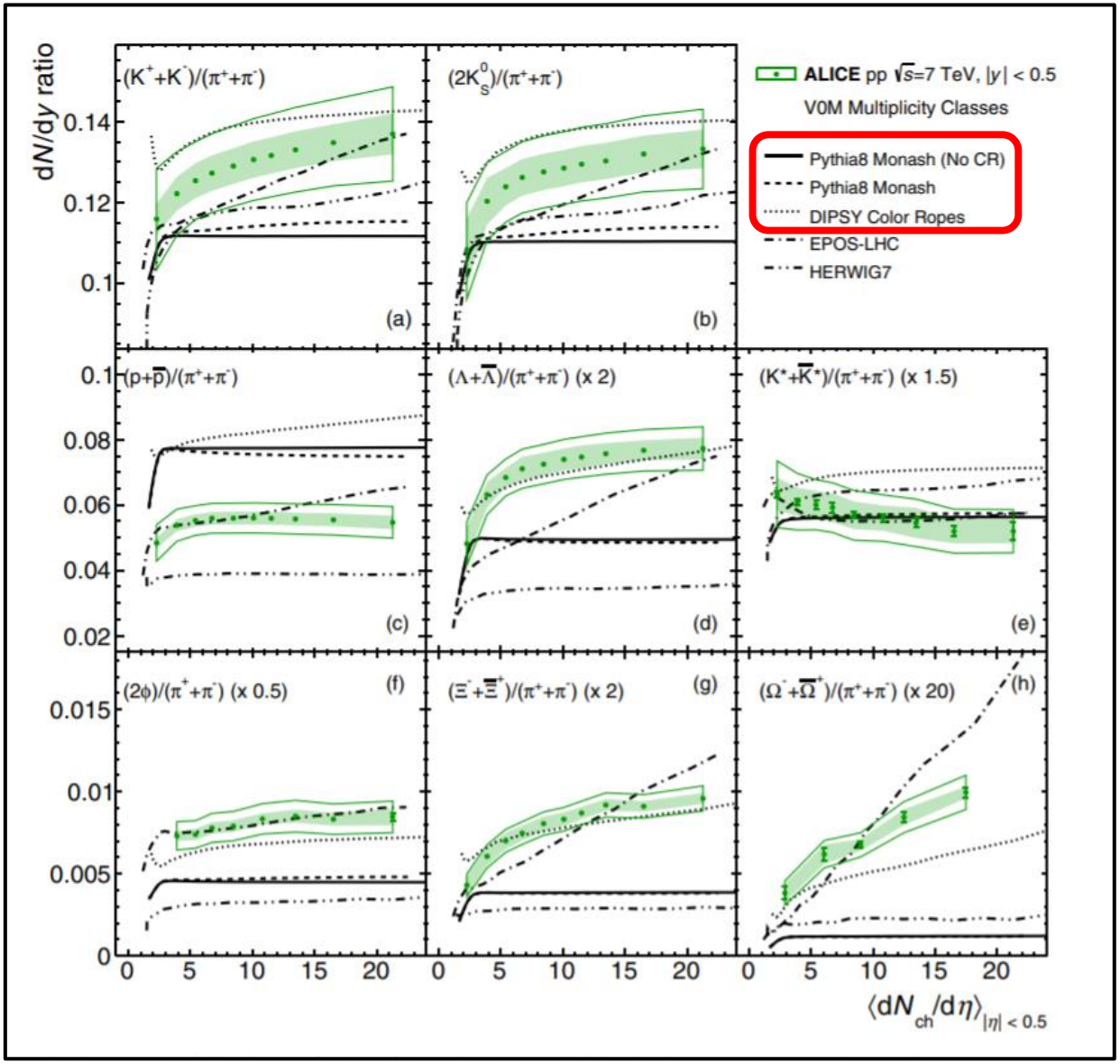
DIPSY: partonic model

- implements color ropes in high density environment:
  - ➢ densely packed strings → increase in string tension
  - ➢ Higher string tension → more baryons and more flavours ≠(u,d)

Model comparison: PYTHIA & DIPSY

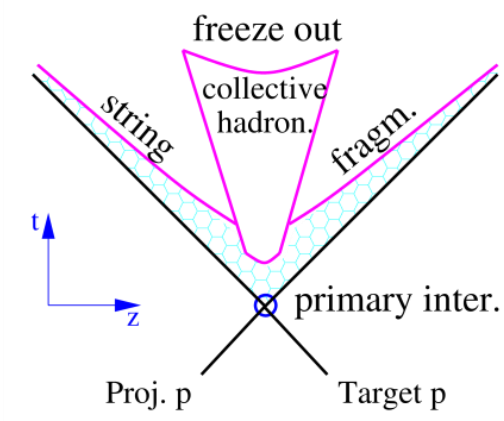
PYTHIA underestimates strangeness production in pp and no progression with multiplicity is foreseen

DIPSY in qualitative agreement with measured ratios



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

Model comparison: EPOS LHC



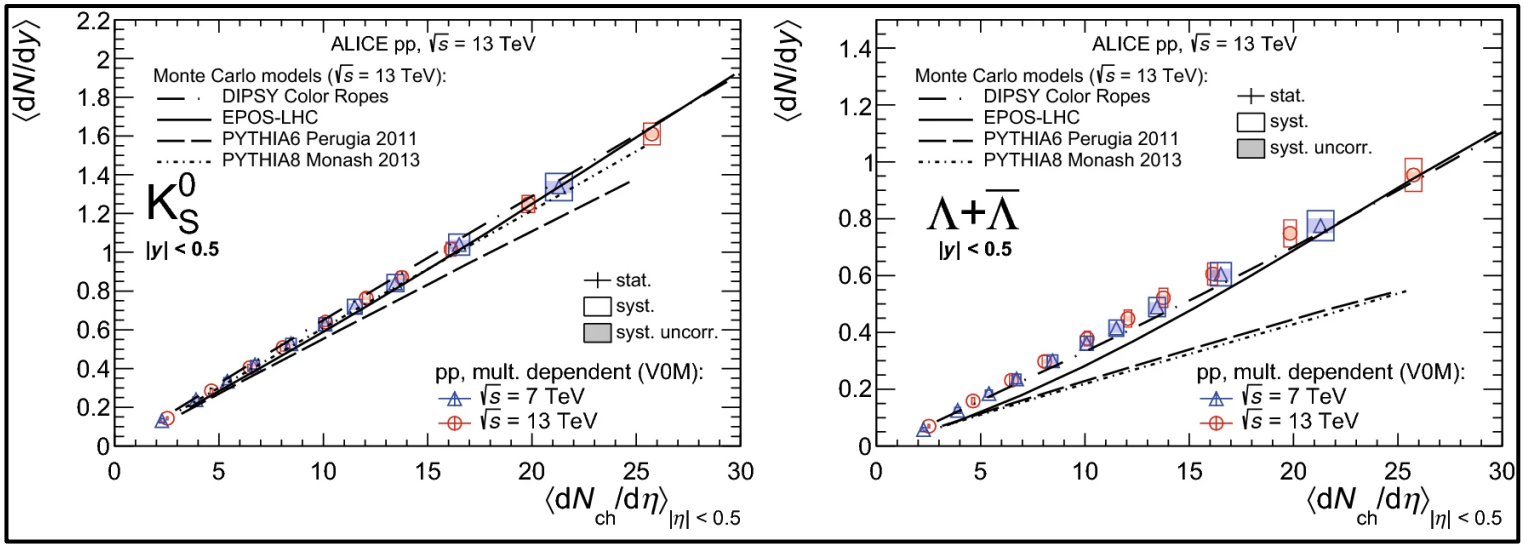
NOTE: Does this imply QGP in small systems?

EPOS LHC model implementing a double regime scenario

- **CORONA**: strings can hadronize as in the Lund approach
- **CORE**: hydrodynamic system, hadronization happens statistically at a common T_H

Hadron evolution explained by core-to-corona ratio changing in events with different final state multiplicity

EPOS LHC qualitatively describes enhancement pattern



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

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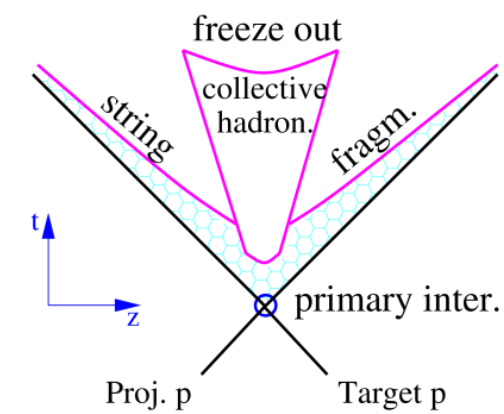

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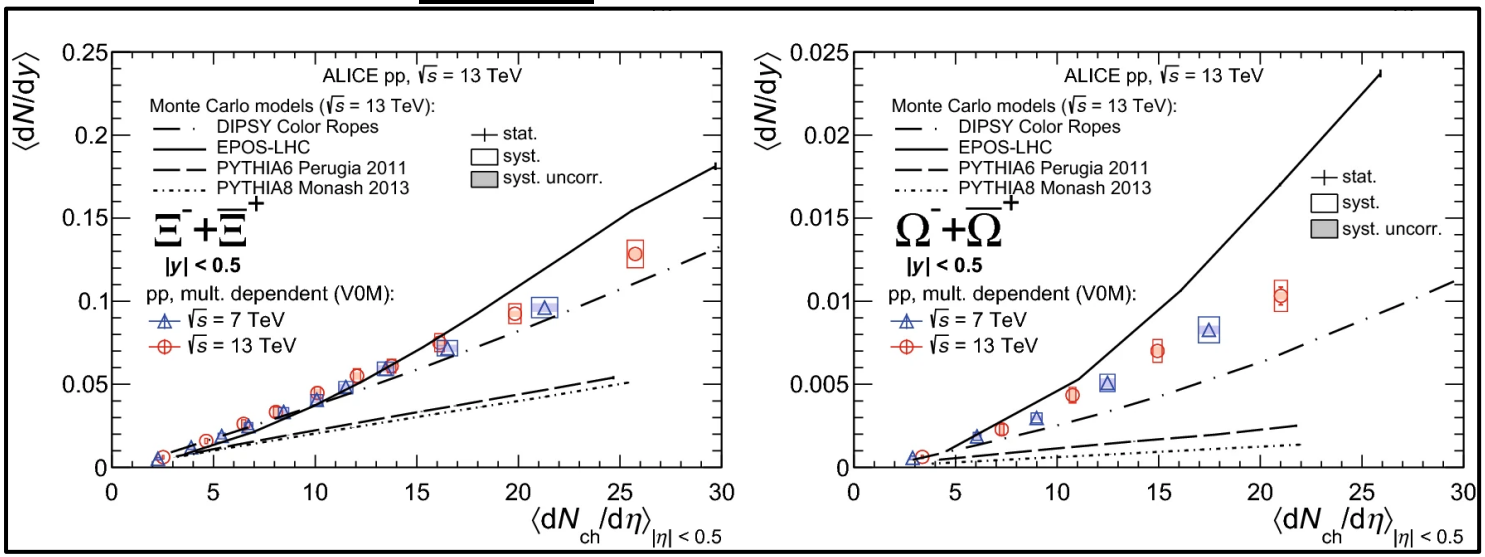
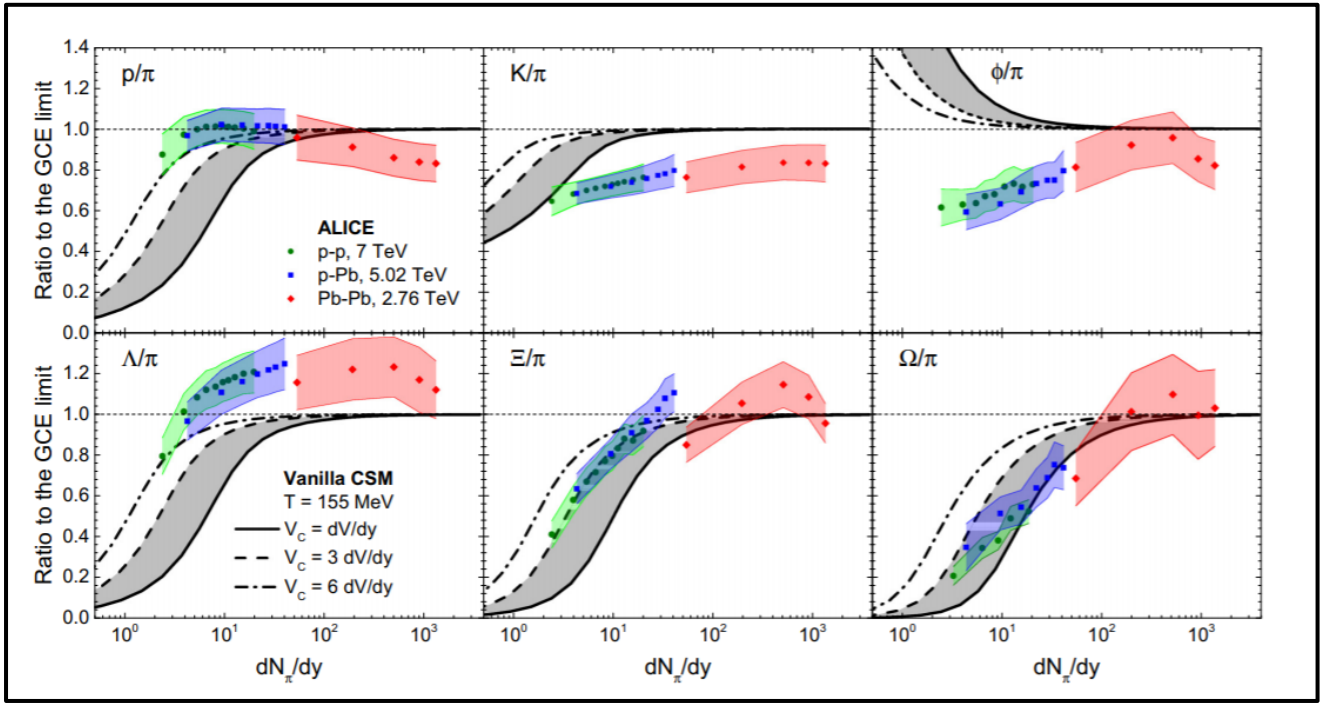


ALICE collaboration, Eur. Phys. J. C 80 (2020) 167

Model comparison: CSM

Satistical hadronization thermal model → particles spilling from an ideal hadron resonances gas in thermal and chemical equilibrium at chemical freeze-out stage



Canonical Statistical Model (CSM):

- as multiplicity decreases, quantum numbers (Q,B,S) are forced to be conserved in smaller and smaller volumes
- It qualitatively describes Ω, Ξ ratio but there are issues for p and K
- It fails to describe ϕ

V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

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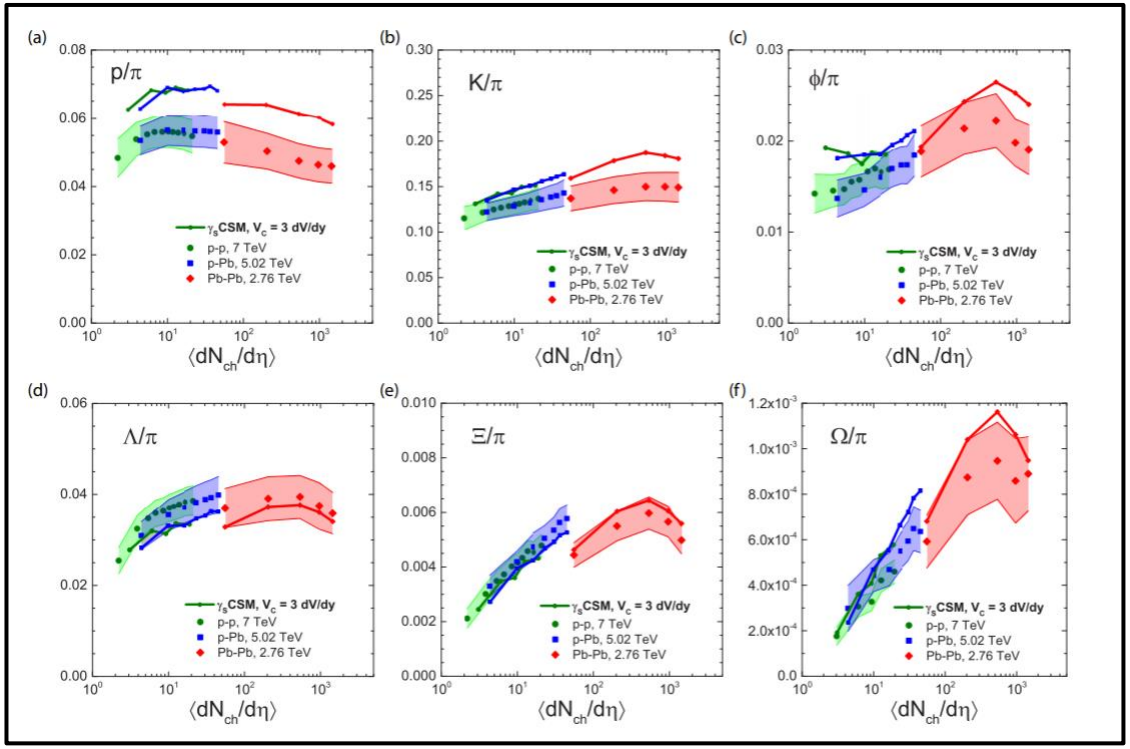


Canonical Statistical Model + γ_s (γ_sCSM) :

- Introducing undersaturation parameter γ_s (incomplete equilibration of S) and fitting also T_{ch} and dV/dy in all systems
- Better agreement, but still problems with p, K and ϕ

V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Summary:

- Analysis of data collected during the LHC Run1 and Run 2 shows **strangeness enhancement,** which saturates at high-multiplicity
- Typical features traditionally observed in A-A collisions also present in pp and p-A collisions
- The steepness of the enhancement pattern is proportional to the **valence strange quark content** in the hadron

- **Microscopic models**

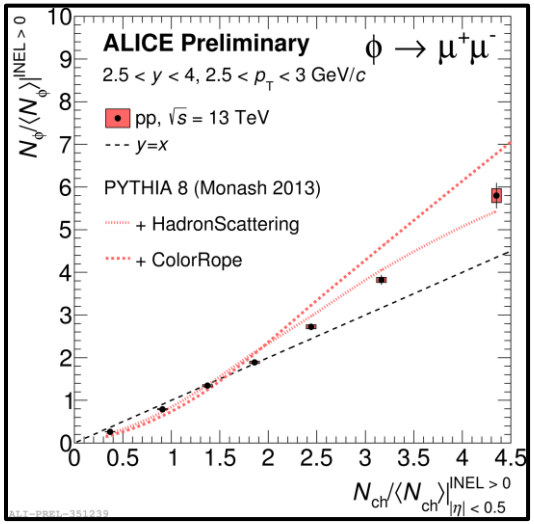
  PYTHIA strong disagreement with data

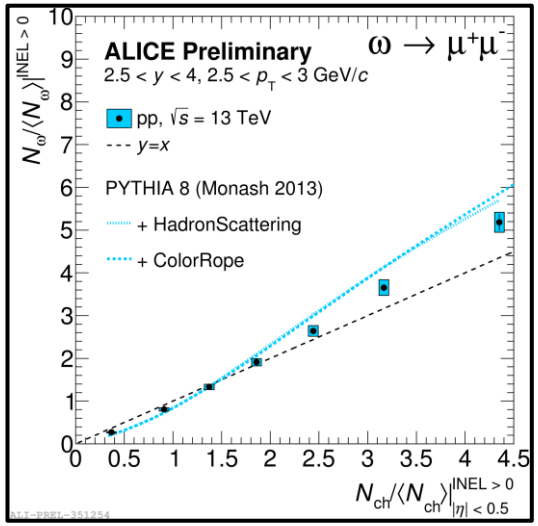
  DIPSY and **EPOS** qualitatively describe the observed trend, but the quantitative description needs further refinements
- **Macroscopic model**

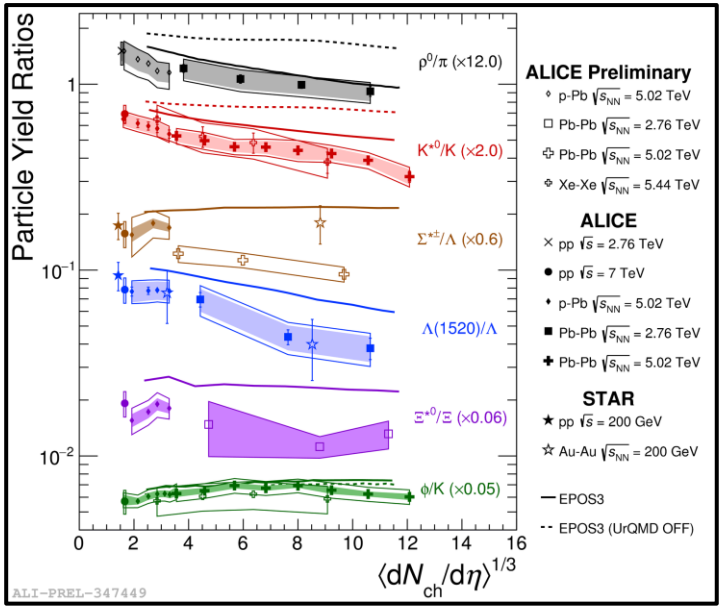
  γ_s**CSM** is capable of describing the hadron yields with roughly 15% relative accuracy

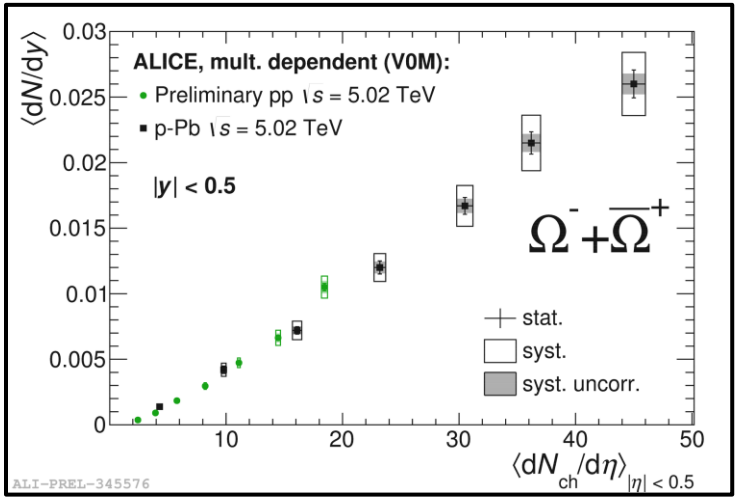
  ϕ is still a weak point (and p and K)

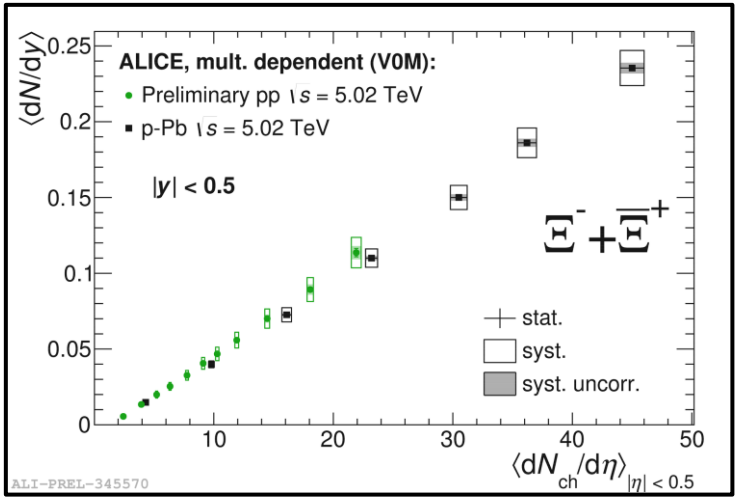
Other new results:











Thank you