Measurement of hadronic resonances with ALICE at the LHC

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(for the ALICE collaboration)

Resonances in ALICE

- A wide variety of resonances is studied with ALICE:

$\rho(770)$	$K^*(892)^0$	$K^*(892)^+$	$\phi(1020)$	$\Sigma(1385)^\pm$	$\Lambda(1520)$	$\Xi(1530)$
$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	$u\bar{s}$	$s\bar{s}$	uus dds	uds	uss

- Resonances are excited hadronic states with lifetimes comparable to that of the fireball produced in heavy-ion collisions:
  - ✓ sensitive to the re-scattering and regeneration processes occurring between the chemical and the kinetic freeze-outs → can be used to study properties and lifetime of the late hadronic phase
- Resonances differ by mass and quark content:
  - ✓ insights on the multiplicity-dependent enhancement of strangeness production

ALICE experiment

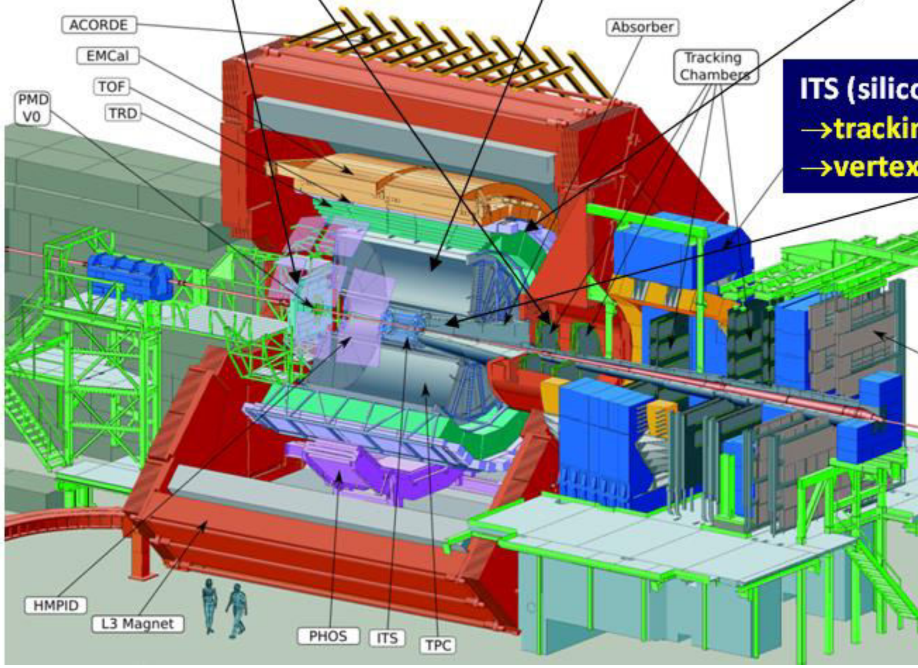
Int. J. Mod. Phys. A 29 1430044 (2014)

VZERO scintillator detectors:
→centrality determination in Pb-Pb
→multiplicity event classes in pp,p-Pb

TPC:
→tracking
→PID through dE/dx

TOF:
→PID through momentum and ToF

ITS (silicon):
→tracking
→vertexing



- Resonances are measured in hadronic decays with invariant mass method → reconstruction and identification of daughter particles

Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi^-$	100
K^{*0}	896	47.4	π^-K^+	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

p_T ranges for 3σ separation

	TPC	TOF
π	0.2 - 0.7	0.5 - 2.0
K	0.3 - 0.6	0.5 - 2.0
p	0.5 - 1.0	0.5 - 2.5

- Different collision systems:

✓ pp at $\sqrt{s}$ = 2.76, 5.02, 7, 13 TeV
✓ p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
✓ Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

Hadronic phase

- Reconstructed resonance yields in heavy ion collisions are defined by:
  - ✓ resonance yields at chemical freeze-out
  - ✓ hadronic processes between chemical and kinetic freeze-outs:

    rescattering: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal

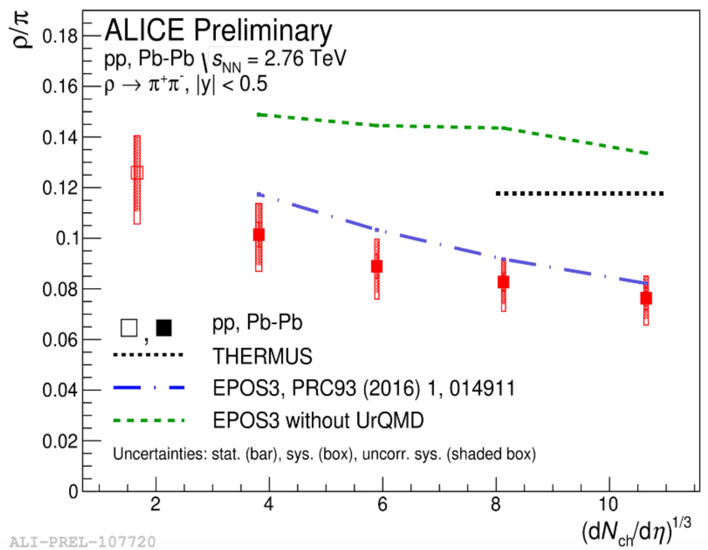
    regeneration: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields

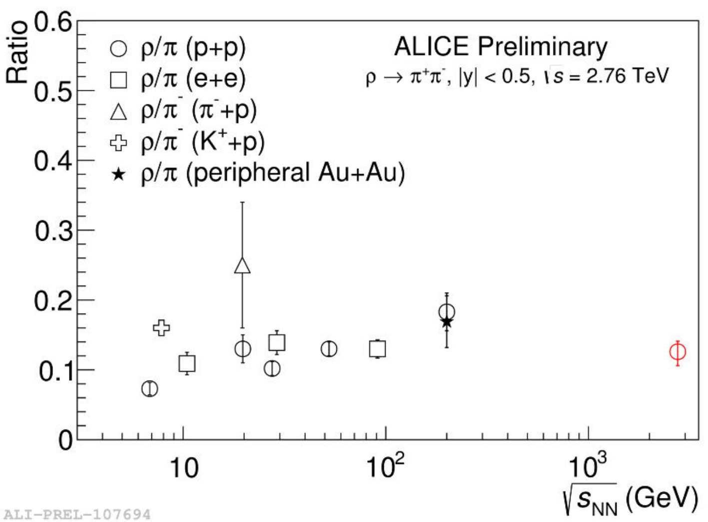
- Effect of hadronic processes depends on:
  - ✓ lifetime and density of hadronic phase
  - ✓ resonance lifetime and scattering cross sections

- Resonances with lifetimes comparable to that of the fireball are well suited to study properties of the hadronic phase

	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

Particle ratios: ρ/π





increasing lifetime →

	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
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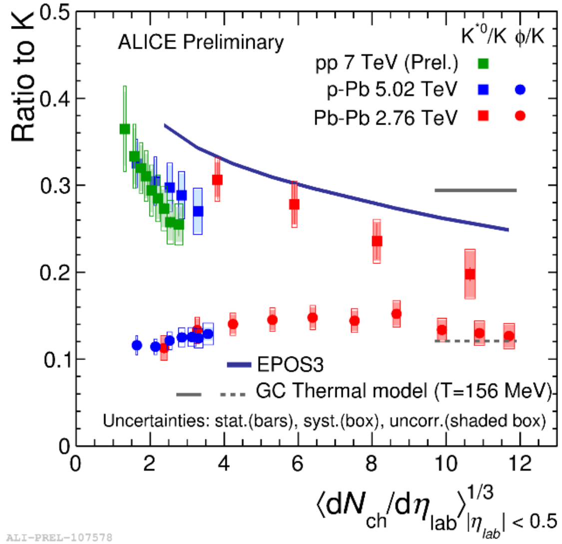
- ρ/π:
  - ✓ suppression from pp to central Pb-Pb
  - ✓ central Pb-Pb is inconsistent with thermal models
  - ✓ reproduced by EPOS3 with UrQMD
  - ✓ domination of rescattering over regeneration

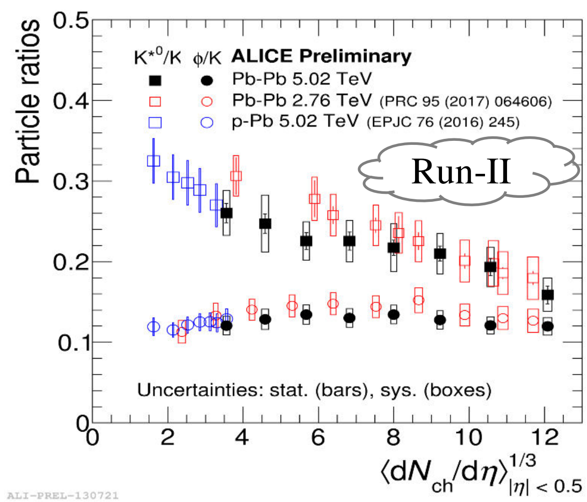
- Ratio in elementary collisions does not depend on collision energy, $\sqrt{s}$ > 10 GeV, within uncertainties

Z. Phys., vol. C61, 1994.
Phys. Lett., vol. B158, 1985.
Z. Phys., vol. C72, 1996.
Phys. Lett., vol. 48B, 1974.
Phys. Lett., vol. B60, 1976.
Z. Phys., vol. C50, 1991.
Z. Phys., vol. C9, 1981.
Nucl. Phys., vol. B176, 1980.
Phys. Lett., vol. B56, 1975.

Particle ratios: K^{*0}/K and ϕ/K

Eur. Phys. J. C 76 245 (2016)
Phys. Rev. C 91 024609 (2015)
J. Phys. G38(2011)124081





increasing lifetime →

	ρ(770)	K^*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	ϕ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- ϕ/K:
  - ✓ No significant multiplicity dependence
  - ✓ consistent for pp, p-Pb and Pb-Pb
  - ✓ consistent with thermal models
  - ✓ no rescattering/regeneration due to long lifetime

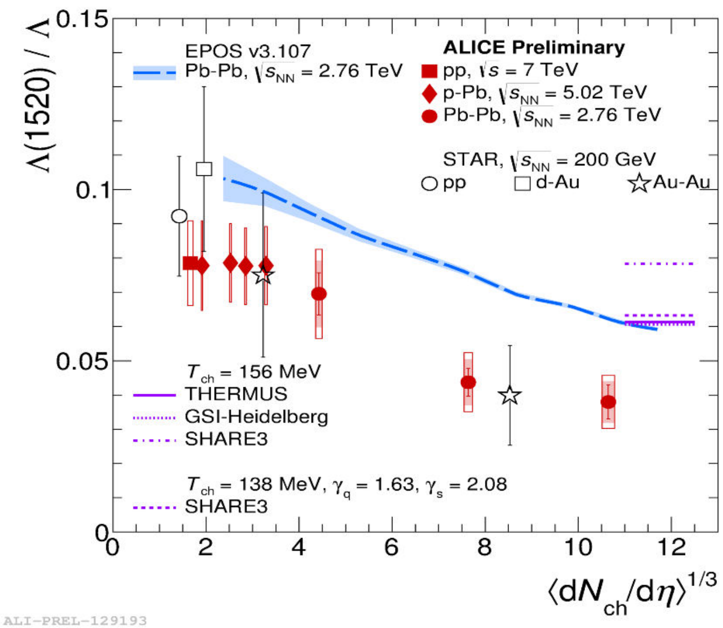
- K^{*0}/K:
  - ✓ suppression from pp to central Pb-Pb
  - ✓ central Pb-Pb is lower than thermal models
  - ✓ reproduced by EPOS3 with UrQMD
  - ✓ domination of rescattering over regeneration
  - ✓ smooth evolution with multiplicity in pp/p-Pb towards Pb-Pb→ rescattering in small systems?

- Ratios in pp, p-A and A-A do not show strong dependence on collision energy, $\sqrt{s}$ = 0.2–13 TeV

Particle ratios: Λ^*/Λ

increasing lifetime →

	ρ(770)	K*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$



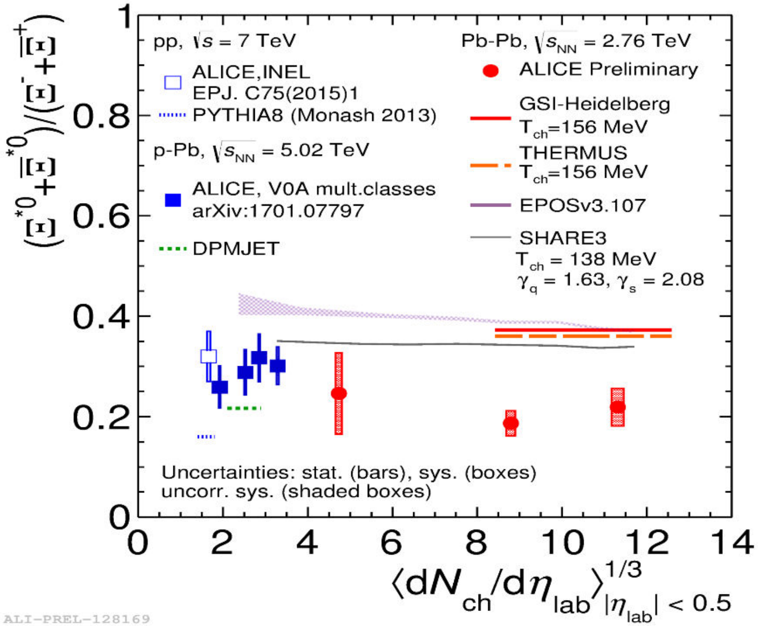
- Λ^*/Λ:
  - ✓ suppression from pp to central Pb-Pb
  - ✓ central Pb-Pb is inconsistent with thermal models
  - ✓ qualitatively reproduced by EPOS3 with UrQMD
  - ✓ domination of rescattering over regeneration
  - ✓ smooth evolution with multiplicity in pp/p-Pb towards Pb-Pb, no suppression in small systems

- Ratios in pp, p-A and A-A do not show strong dependence on collision energy, $\sqrt{s}$ = 0.2–5.02 TeV

Particle ratios: Ξ*/Ξ

increasing lifetime →

	ρ(770)	K^*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

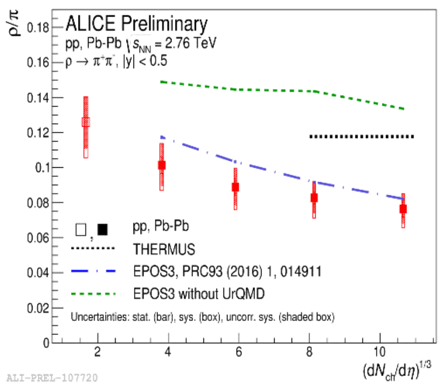


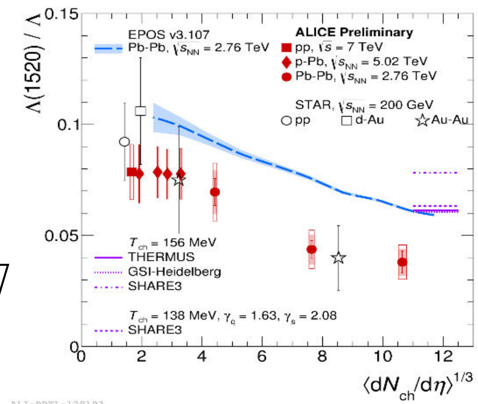
- Ξ^*/Ξ:
  - ✓ no multiplicity dependence in pp, p-Pb
  - ✓ hint of suppression in central Pb-Pb, systematic uncertainties are to be reduced
  - ✓ models do not predict significant multiplicity dependence of the ratio
  - ✓ thermal models overestimate the ratio in Pb-Pb
  - ✓ Pythia8 and DPMJET underestimate the ratio in pp and p-Pb

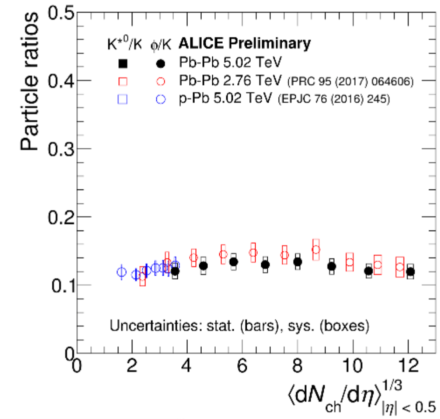
Summary of ratios

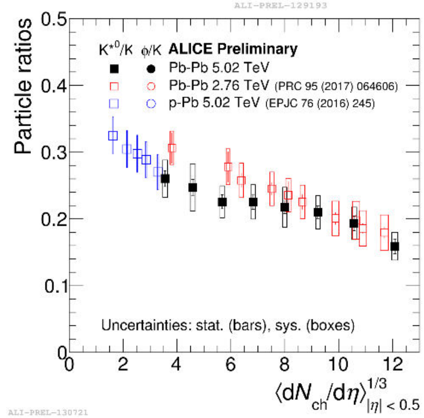
increasing lifetime →

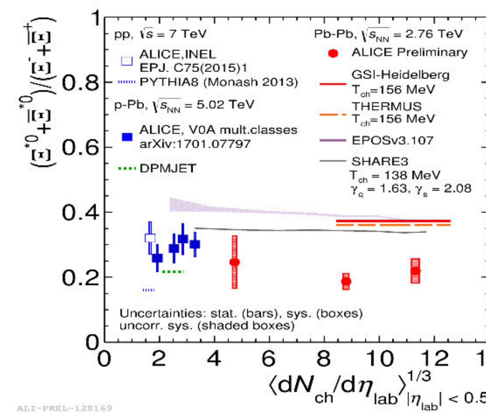
	ρ(770)	K^*(892)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$









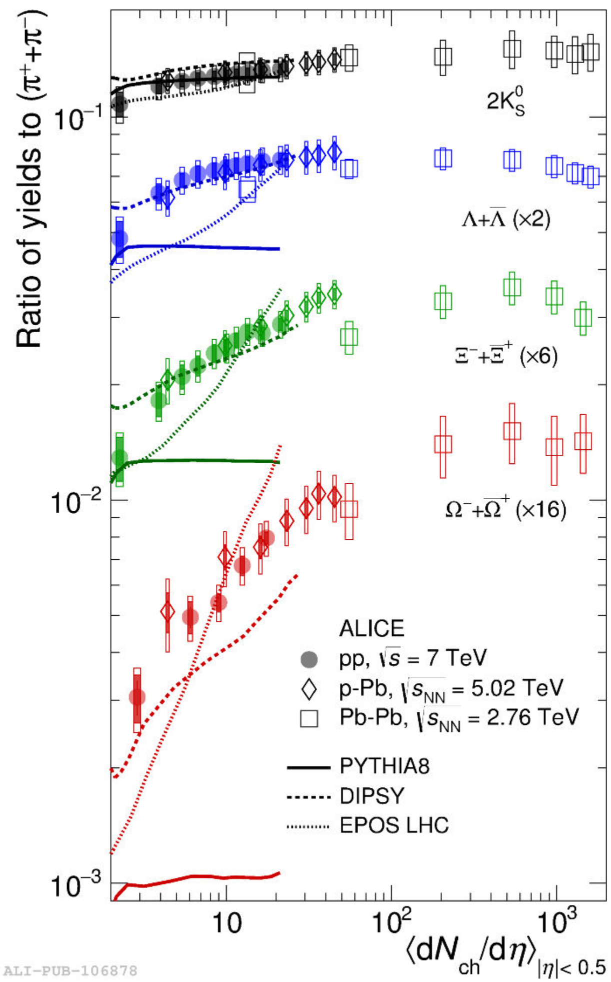


- Results support the existence of a hadronic phase long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- Lower limit for the lifetime of the hadronic phase, τ > 2 fm/*c*

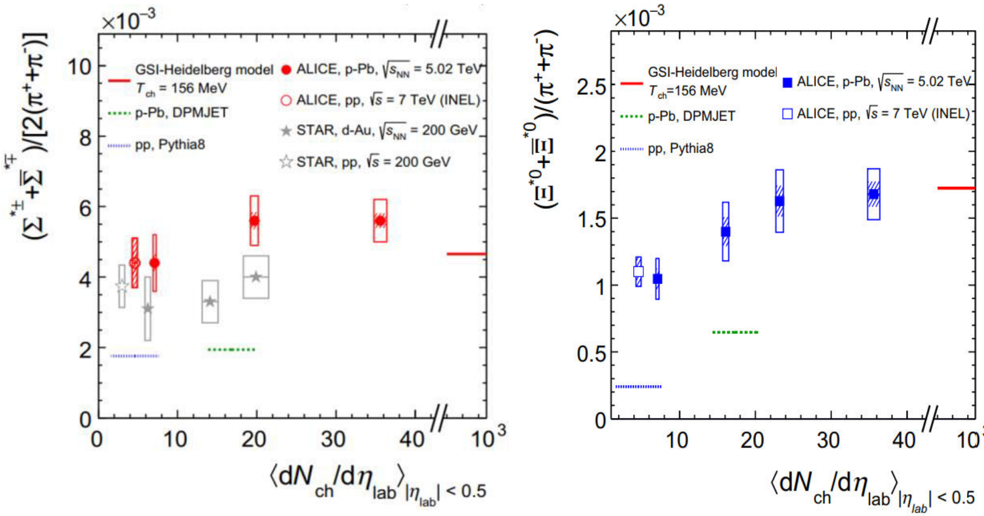
G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002); C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

Enhanced strangeness production

Nature Phys. 13 (2017) 535



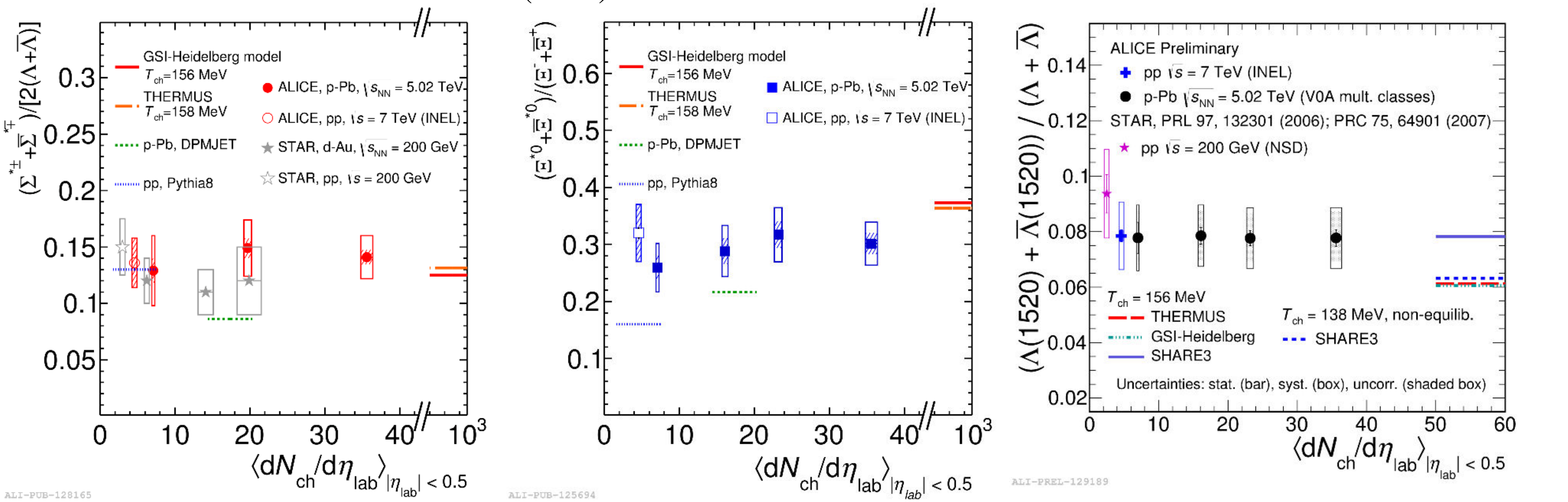
EPJ C77 (2017) 389



- Clear increase of strangeness production from pp to Pb-Pb
- First observation of enhanced production of strange particles in high-multiplicity pp collisions
- Strange resonances show increasing patterns depending on the strangeness content → consistent with observations for ground-state hadrons
- Thermal model predictions for Pb-Pb are consistent with the highest multiplicity results in p-Pb while PYTHIA and DPMJET underestimate data

Enhanced strangeness production

EPJ C77 (2017) 389



- Ratios of resonances to stable particles with the same strangeness do not depend on multiplicity in pp and p-Pb → confirms that strangeness enhancement depends predominantly on the strangeness content, rather than on the particle mass
- Ratios do not show strong dependence on collision energy, $\sqrt{s} = 0.2–5.02$ TeV
- No model reproduces all measurements simultaneously

Summary

- Results support the existence of a hadronic phase in central heavy-ion collisions that lasts long enough to cause a significant reduction of the reconstructed yields of short lived resonances. Similar effects are observed in high-multiplicity collisions of small systems
- In small systems strangeness enhancement as a function of multiplicity is found to be driven by particle strangeness content and not by mass
- Shapes of particle spectra are mostly defined by particle masses, which is consistent with hydrodynamical models

Backup

EPOS3 + UrQMD

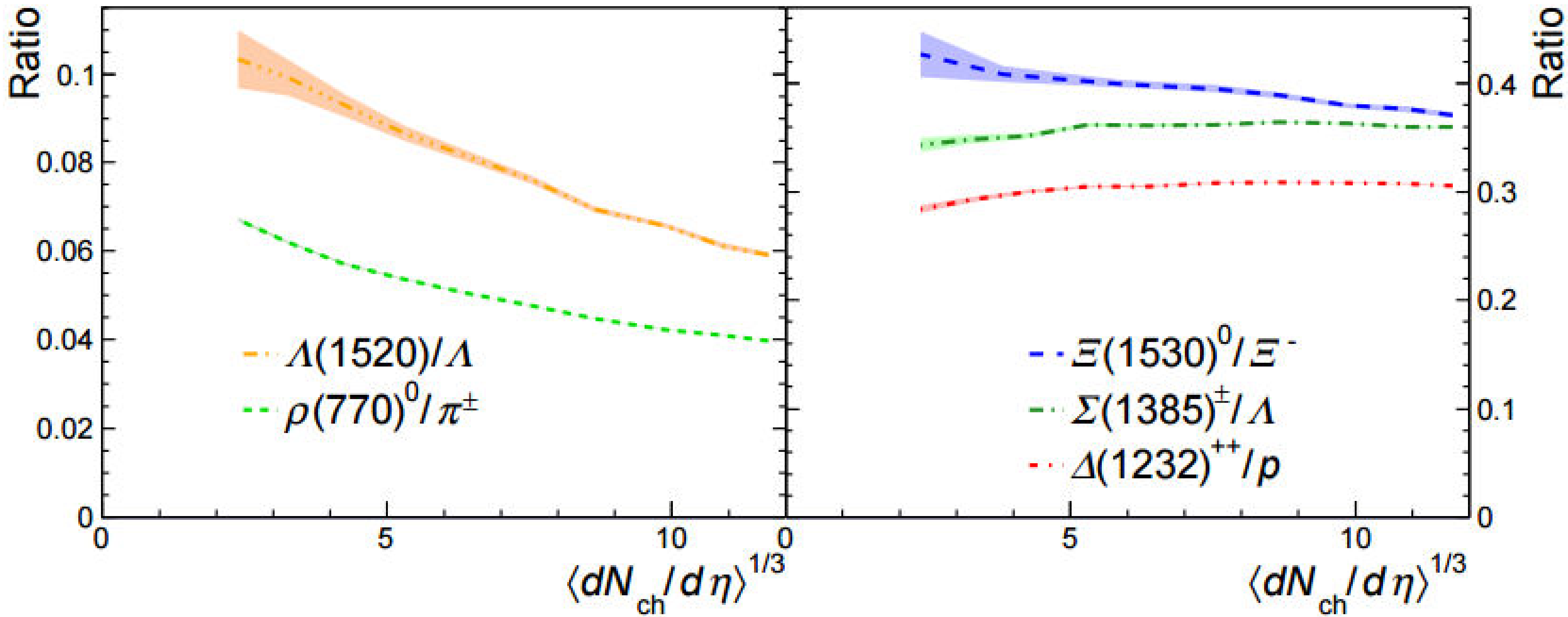
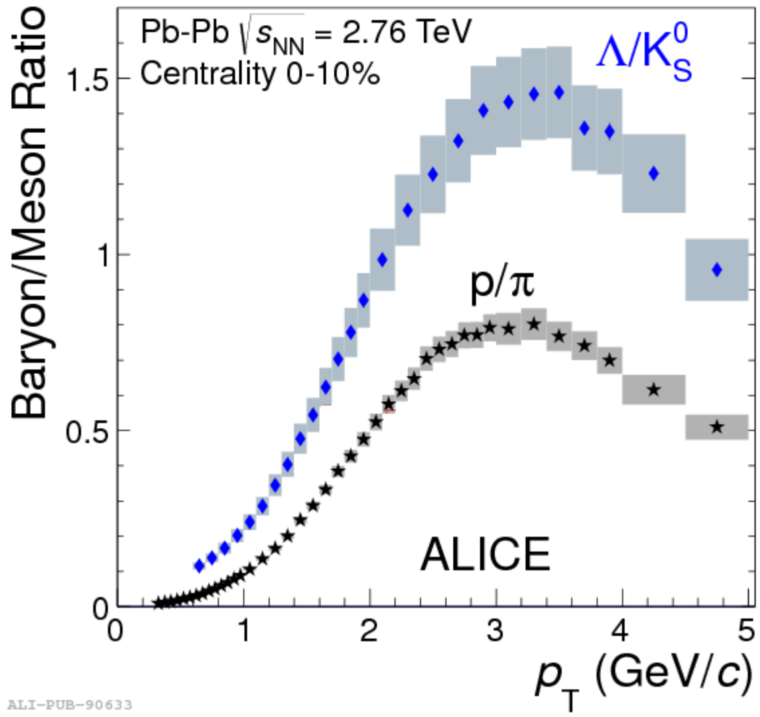


FIG. 13: Ratio of integrated yields $\Sigma(1385)^{\pm}/\Lambda$ and $\rho(770)^0/\pi^{\pm}$ (left) $\Xi(1530)^0/\Xi^-$, $\Sigma(1385)^{\pm}/\Lambda$ and $\Delta(1232)^{++}/p$ (right) for multiple centrality intervals calculated using EPOS3 with UrQMD ON (numerators and denominators are sums of particles and antiparticles). The shaded bands around the EPOS3 curves represent their statistical uncertainties. The theoretical data are plotted as functions of the values of $\langle dN_{ch}/d\eta\rangle^{1/3}$ measured by the ALICE experiment [28] at mid rapidity ($|\eta| < 0.5$).

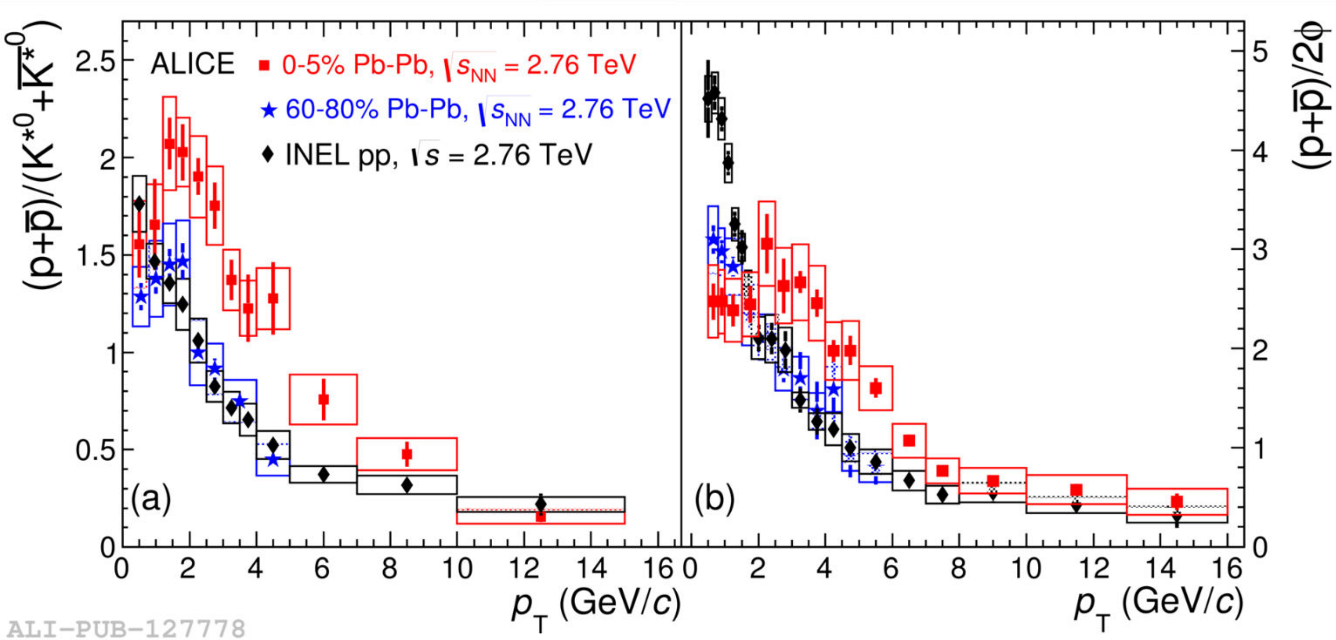
Baryon-to-meson ratios

- Baryon anomaly manifested in increased baryon-to-meson (p/π, Λ/K_s^0) ratios at intermediate momentum
- Driving force of enhancement is not yet fully understood:
  - ✓ particle mass (hydro)?
  - ✓ quark count (recombination)?
- ϕ and K* are ideally suited for tests as mesons with masses very close to that of a proton:
  - ✓ Δm_{ϕ}~ 80 MeV/c^2, Δm_{K^*}~ -45 MeV/c^2



Particle ratios: p/ϕ(p_T), p/K*(p_T)

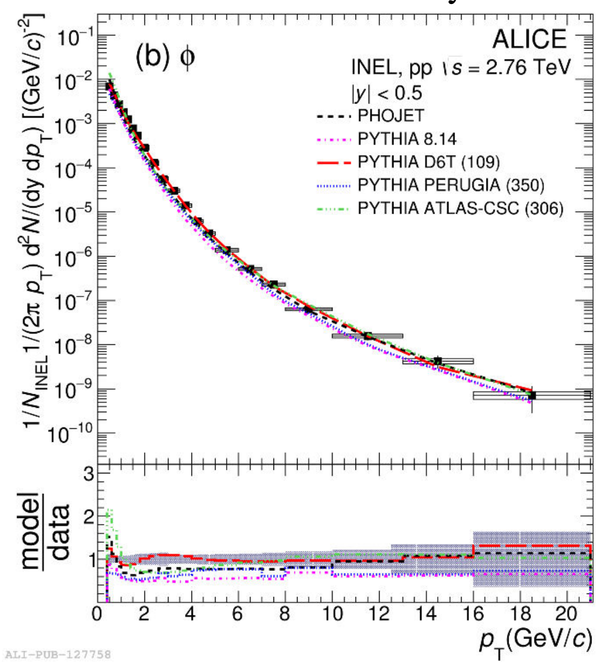
Phys. Rev. C 95 (2017) 064606

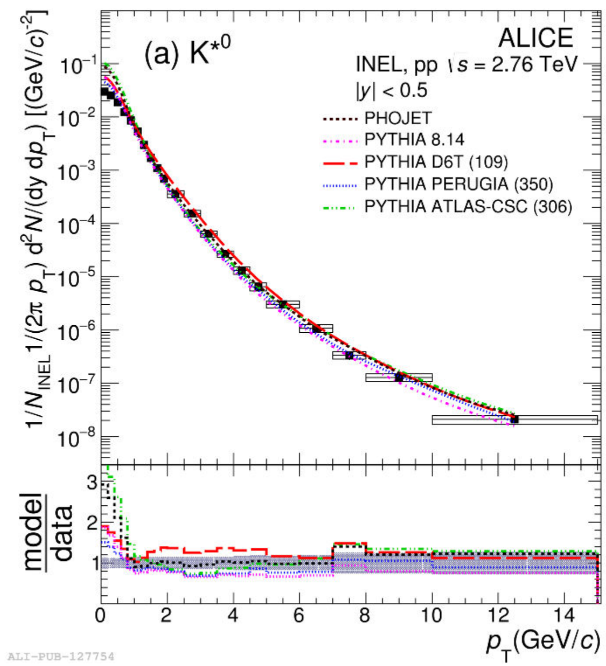


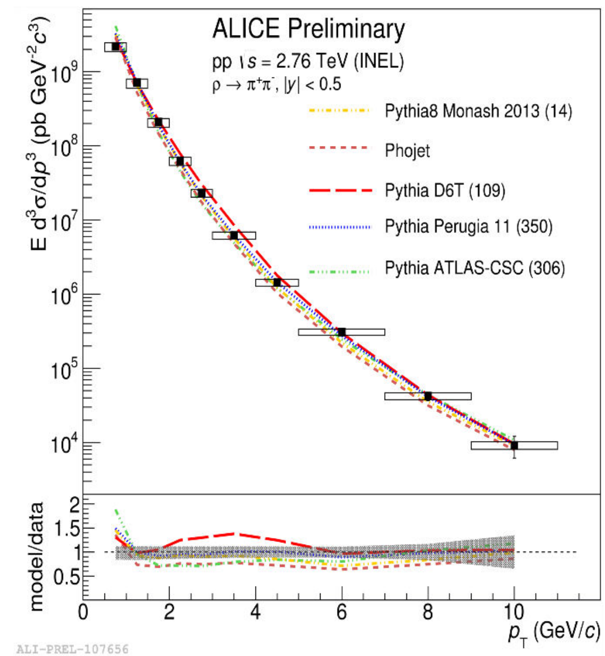
- Ratios evolve from pp to central Pb–Pb collisions → change of the spectral shapes
- In central Pb–Pb the ratios show weak p_T dependence at p_T < 4 GeV/c
- Similarity of K^{*0} , p, φ spectral shapes at p_T <4 GeV/c suggests that the shapes are mostly defined by hadron masses as expected from hydrodynamic models
- Some models which combine recombination and flow can also describe the data, PRC 92 054904 (2015)

High-p_T production

Phys. Rev. C 95 (2017) 064606





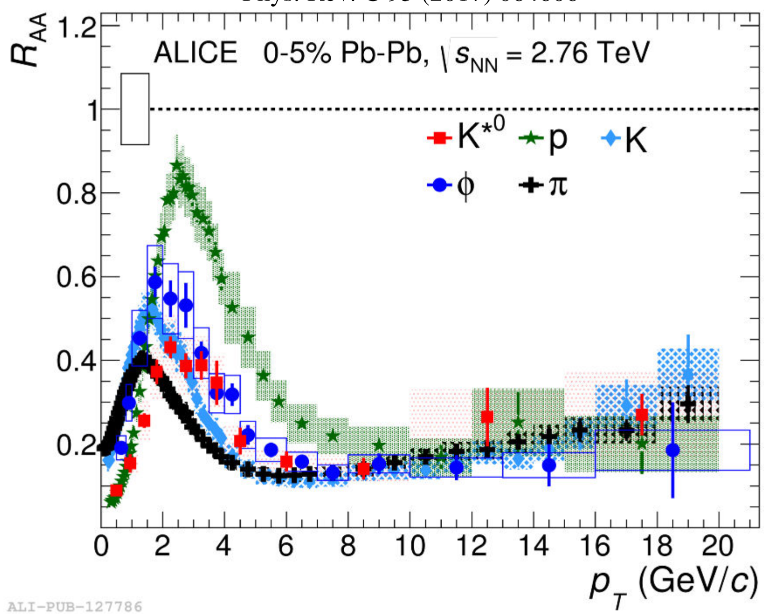


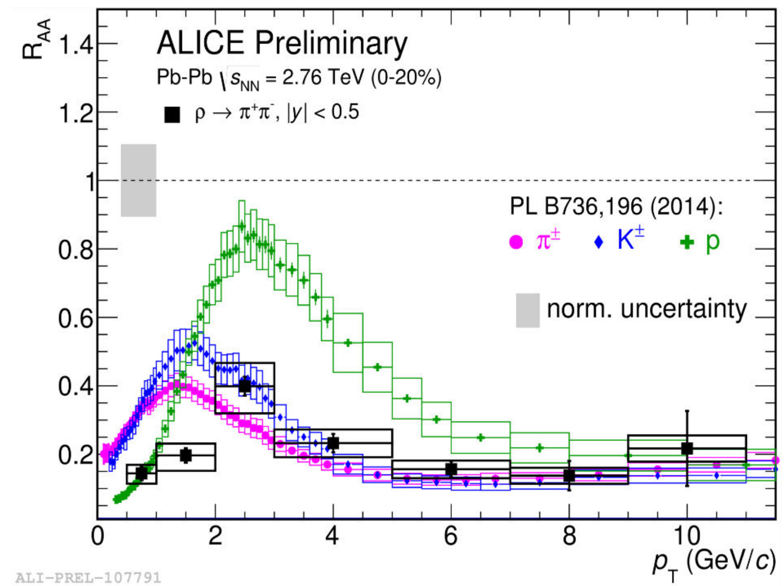
- Some of the resonances are measured in a wide p_T range, up to ~ 10-20 GeV/c
- Pythia and Phojet reasonably reproduce measurements at high p_T, worse situation at low p_T
- Used as a reference for Pb-Pb

High-p_T parton energy loss

- Nuclear modification factor: $R_{AA}(p_T) = \frac{Yield_{A-A}(p_T)}{Yield_{pp}(p_T) \cdot N_{coll}}$

Phys. Rev. C 95 (2017) 064606





- In central Pb-Pb collisions light hadrons are similarly suppressed at high p_T → no flavor/mass dependence
- Similar behavior of light hadrons is also observed in p-Pb collisions at high p_T
- R_{AA} measurements at top LHC energy of 5.02 TeV are fully consistent with the measurements shown in this slide