Resonance production in ALICE

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What are resonances?

- Resonances are excited hadronic states that decay due to strong interaction, with lifetimes comparable to that of the fireball produced in heavy-ion collisions
- Copiously produced and measurable in different collision systems even at top multiplicities
- pp: baseline measurements, tests of QCD
- p-Pb: nPDFs, parton rescattering, onset of collectivity
- Pb-Pb: properties of the QGP and the hadronic phase

Why resonances?

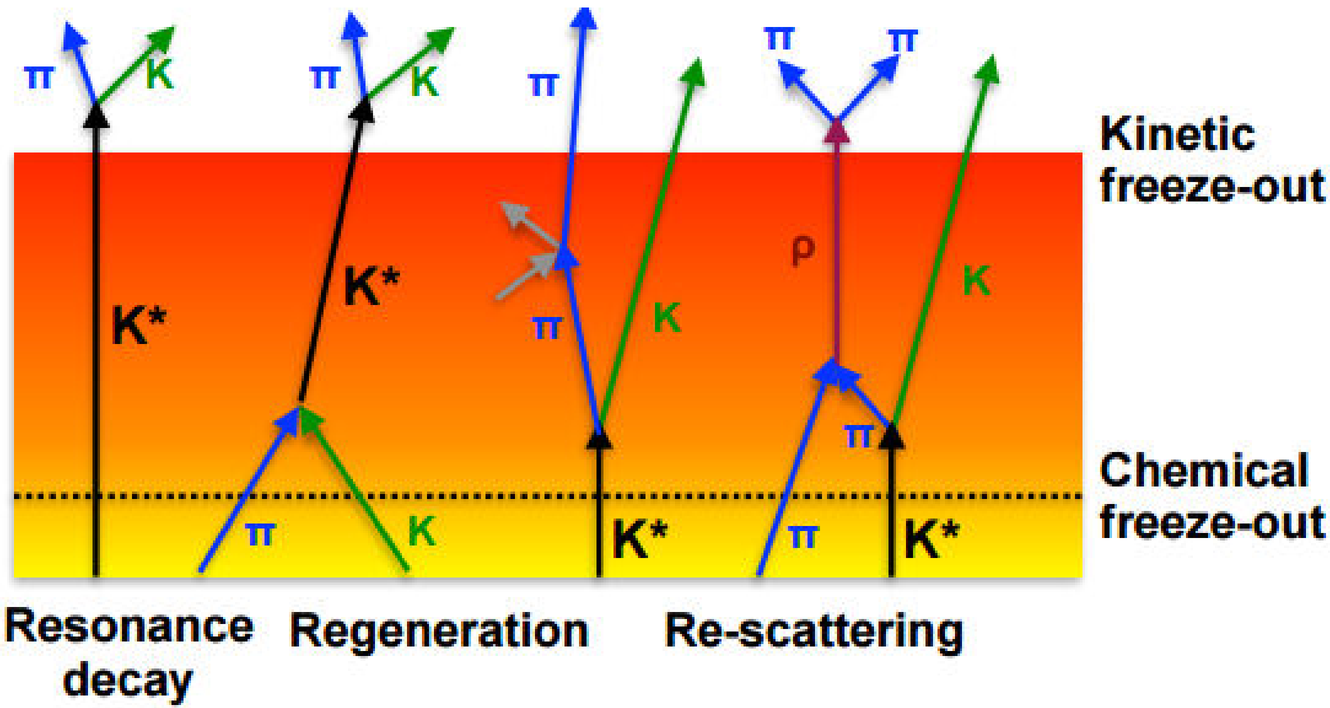
- Different masses and quark content
  → systematic study of parton energy loss at **high p_T**: flavor dependence
- Mesons with masses similar to that of a proton
  → study anomalous baryon-to-meson ratio at **intermediate p_T**: hydro vs. recombination
- Short lifetimes
  → chiral symmetry restoration: mass/width modifications at **low p_T**
  → study properties of the hadronic phase: lifetime, density

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 ($\pi K \to K^{*0}$, $KK \to \phi$ etc.) → increased yields



Hadronic phase

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

- Resonances with lifetimes comparable to that of the fireball are a very promising tool 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
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- UrQMD [1-2] : rescattering and regeneration are most important at $p_T < 2$ GeV/c
  → focus is on **low p_T** measurements

[1] S.A. Bass *et al.*, Prog. Part. Nucl. Phys. 41, 255 (1998);
[2] M. Bleicher *et al.*, J. Phys. G25, 1859 (1999)

Reconstruction of resonances

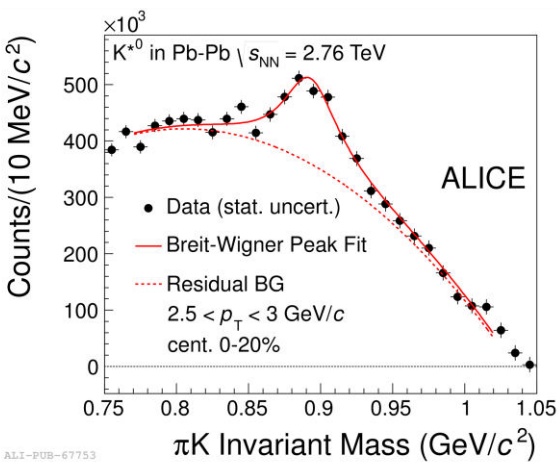
- All resonances are studied via invariant mass method
  → reconstruction and identification of daughter particles
- Select hadronic decay channels with large BR and charged daughters

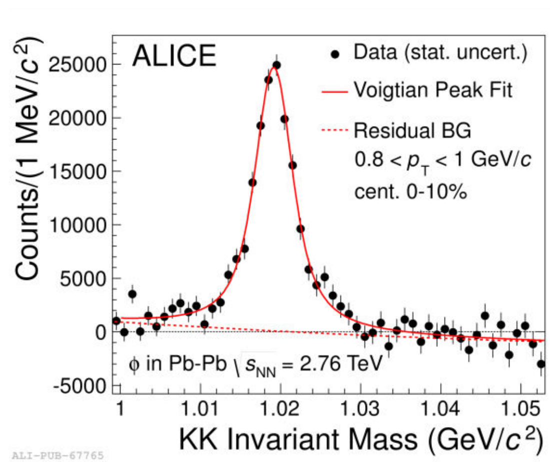
Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi^-$	100
K^{*0}	896	47.4	π^-K^+	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
Λ^*	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

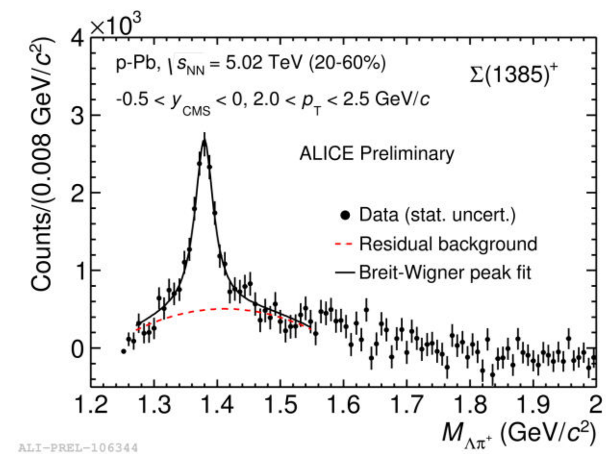
- Different collision systems and energies:
  - ✓ pp at $\sqrt{s}$ = 2.76, 7 and 13 TeV
  - ✓ p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓ Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 and 5 TeV

Invariant mass spectra: K^{*0}, ϕ, Σ^{*+}

- Peaks after subtraction of mixed-event or like-sign background
- Fitted to polynomial for residual background (jets, mis-reconstructed particles etc.) + Voigtian function (Γ, mass resolution) for signal



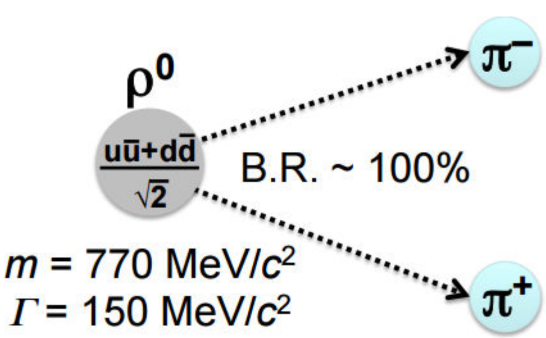


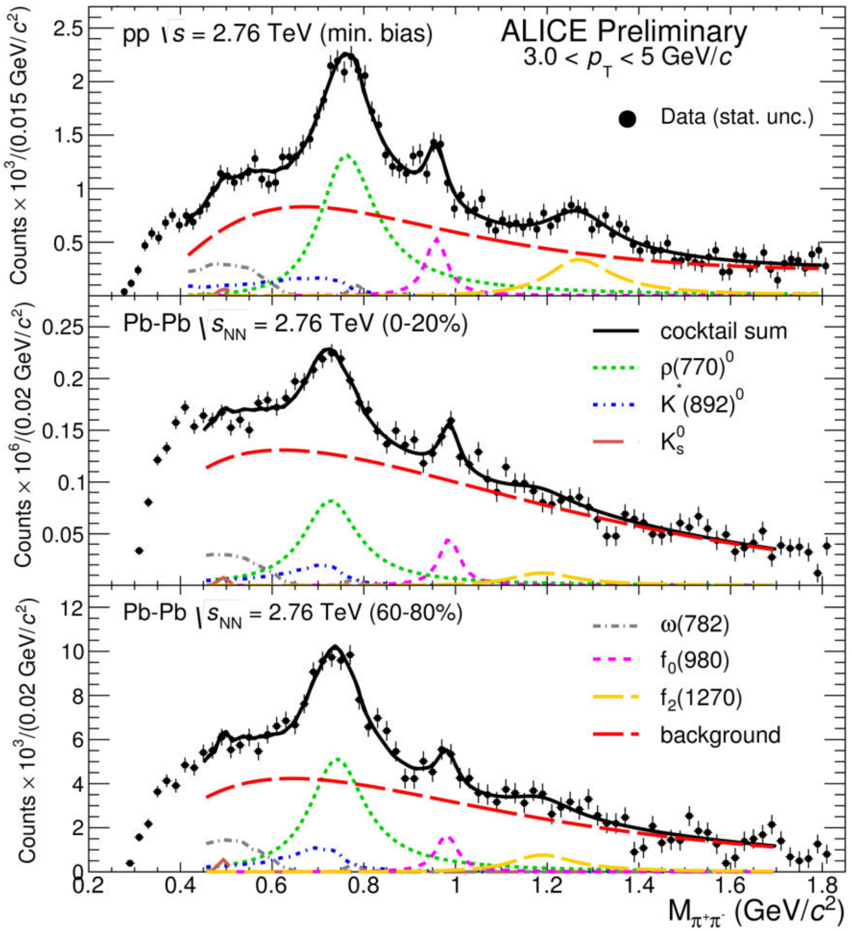


So far ALICE does not observe significant modifications of resonance line shapes

Invariant mass spectra: $\rho \to \pi\pi$

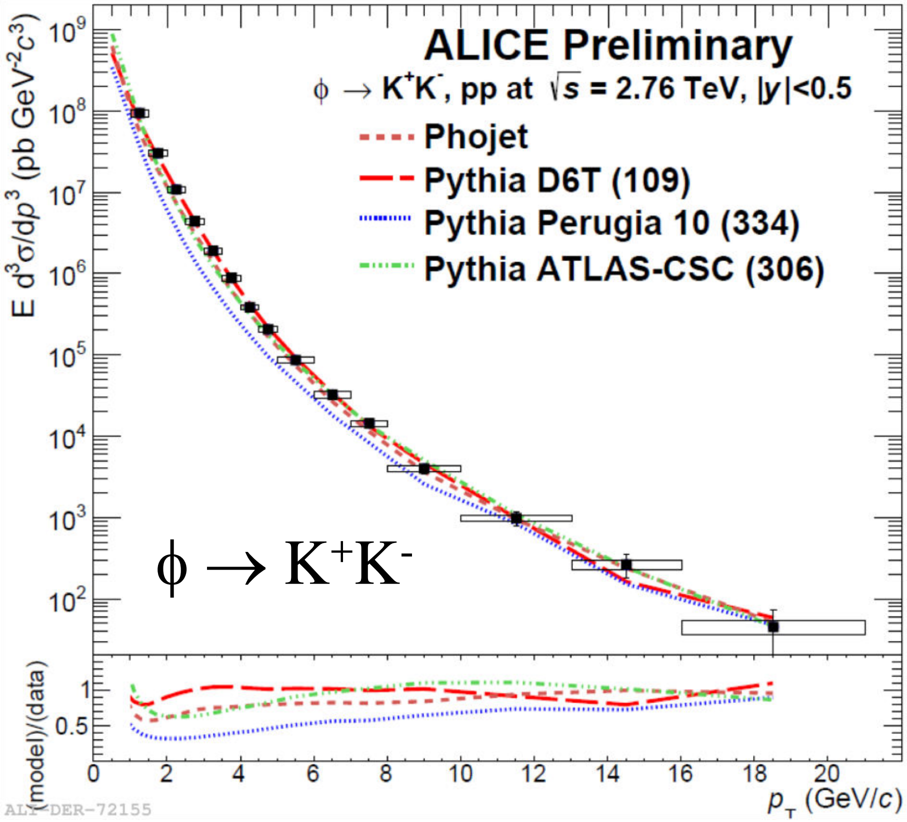
- Need to account for a cocktail in the residual background: K_s, ω, K^{*0}, f_0, f_2
- Full line shape analysis for ρ is not possible, only mass is free
- Vacuum peak model: RBW ⊗ Phase Space ⊗ Eff(m) ⊗ Söding interference term [1]

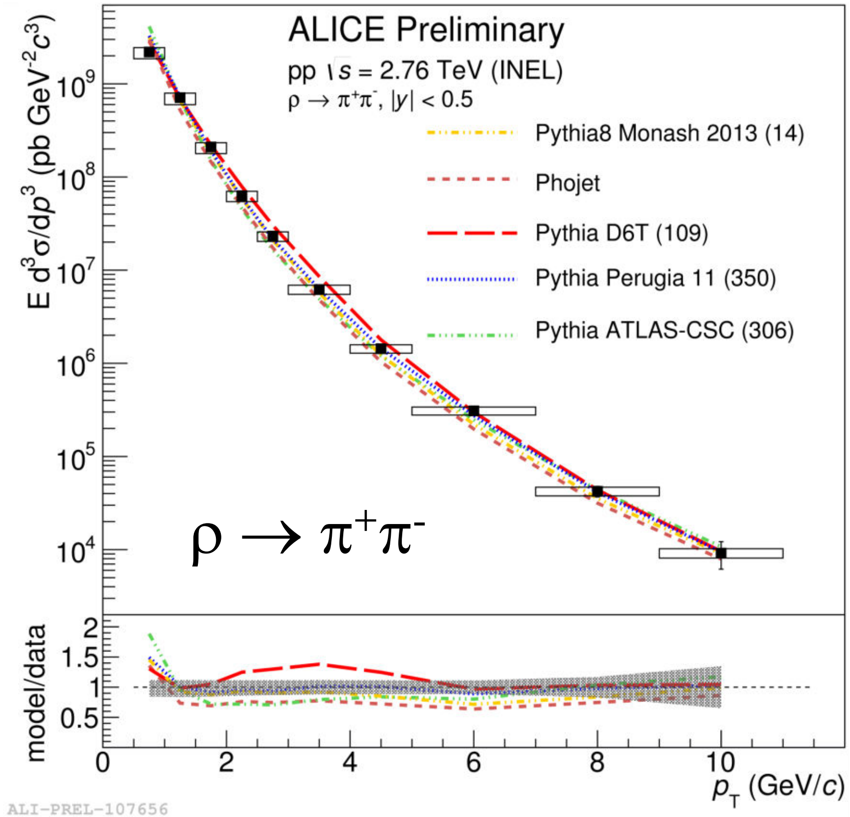




[1] P. Soding, Phys.Lett. 19 (1966) 702–704.

Spectra in pp collisions

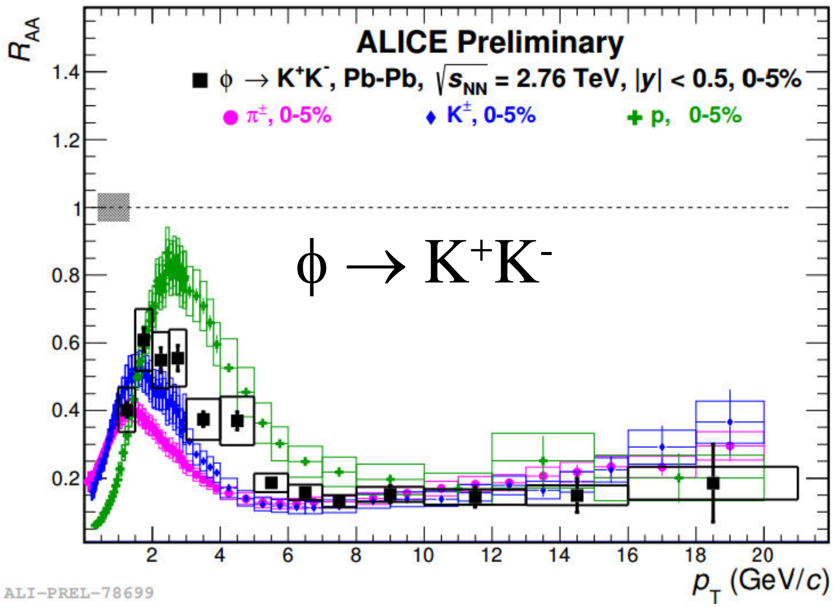


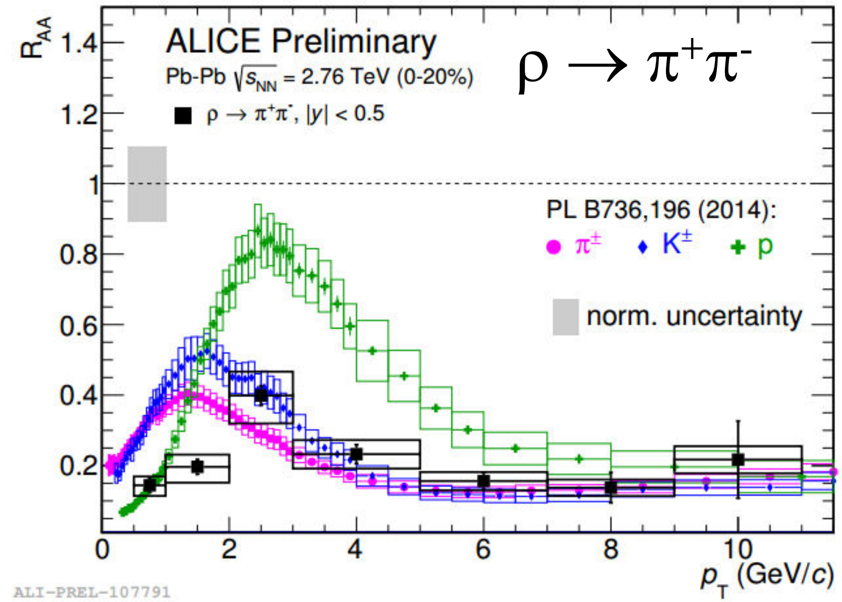


- Resonances are measured in a wide p_T range, up to ~ 10-20 GeV/c
- Pythia and Phojet are consistent with data at high p_T, worse situation at low p_T
- Used as a reference for p-Pb and Pb-Pb

Results at high p_T

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

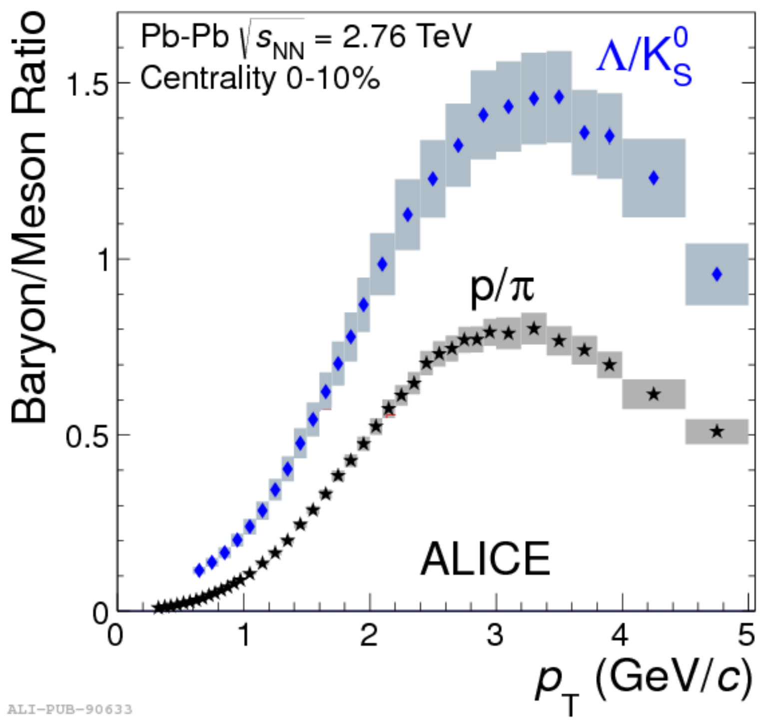




- In central Pb-Pb collisions light hadrons are similarly suppressed at high p_T
  → no flavor/mass dependence
- Production of light hadrons is not suppressed in p-Pb collisions at high p_T, $R_{pPb} \sim 1$

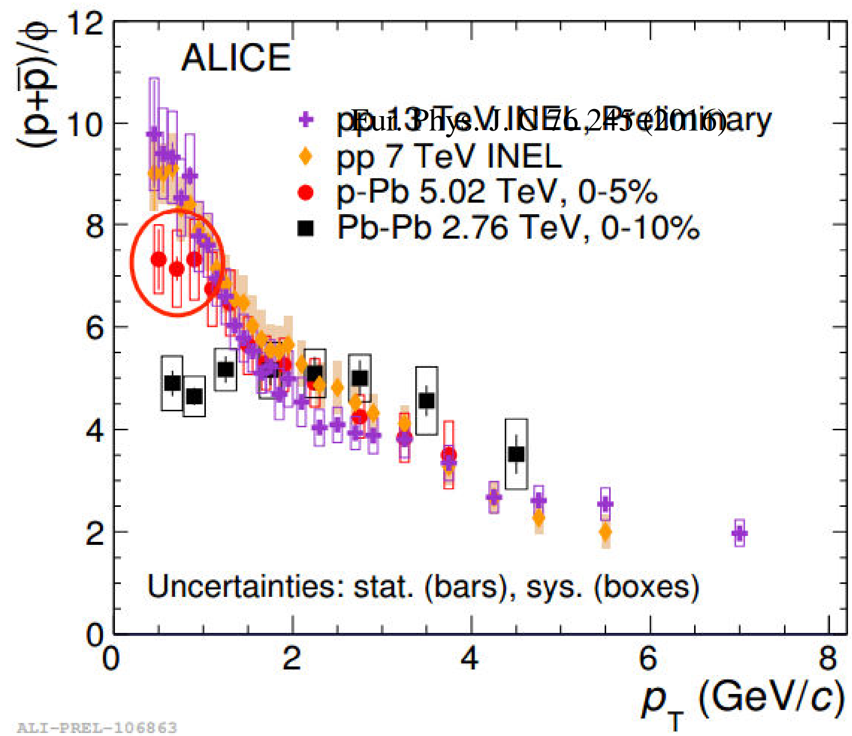
Intermediate p_T range

- Baryon anomaly manifested in increased baryon-to-meson (p/π, Λ/K_s^0) ratios
- Driving force of enhancement is not yet fully understood:
  - ✓ particle mass (hydro)?
  - ✓ quark count (recombination)?
- ϕ is ideally suited for tests as it is a meson with mass very close to that of a proton:
  - ✓ $\Delta m_\phi \sim 80$ MeV/c^2



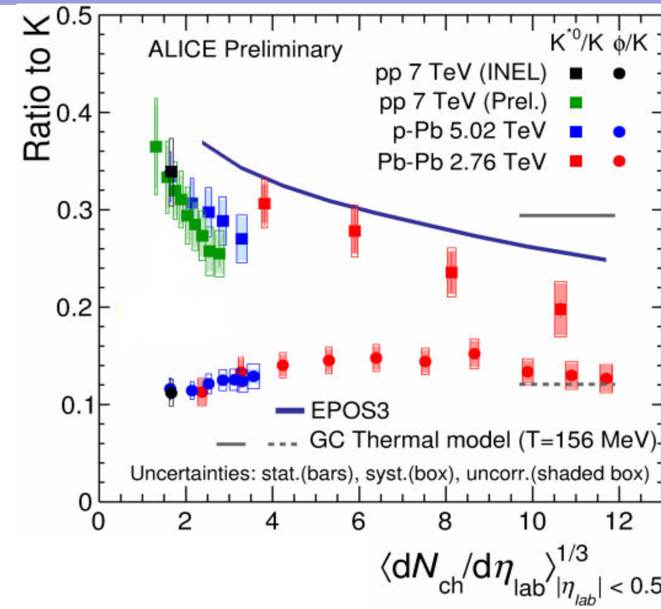
Particle ratios: p/ϕ(p_T)

- In peripheral p-Pb and Pb-Pb collisions ratios are similar to that in pp
- p/ϕ(p_T) evolve with centrality and flatten in most central Pb-Pb collisions
  - → similar spectral shapes of p and ϕ
  - → spectral shapes are determined by masses, consistent with hydrodynamic evolution
- p/ϕ in high-multiplicity p-Pb indicates flattering of the ratio at $p_T < 1.5$ GeV/c
  → hint of the onset of collective behaviour in p-Pb?

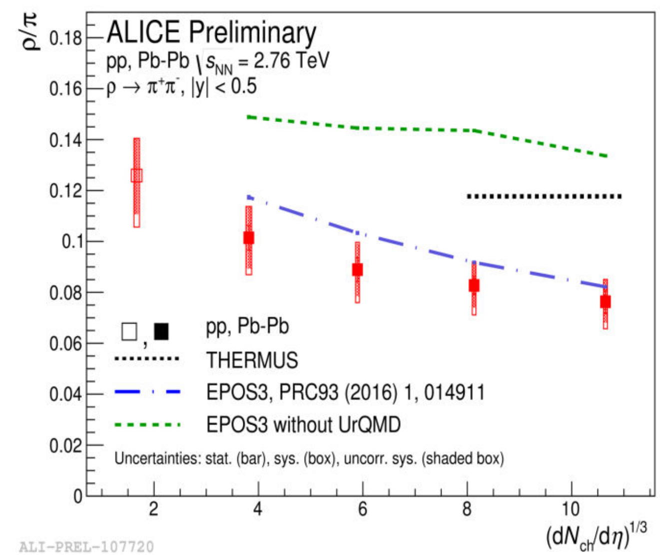


Low p_T: ratios to stable particles

- ϕ/K:
  - ✓ no strong centrality dependence
  - ✓ consistent for pp, p-Pb and Pb-Pb
  - ✓ consistent with thermal models (Andronic et al., J. Phys. G38(2011)124081)
  - ✓ No rescattering/regeneration due to long lifetime
- K^{*0}/K, ρ/π:
  - ✓ suppression from pp to central Pb-Pb
  - ✓ central Pb-Pb is inconsistent with thermal models
  - ✓ well described by EPOS3 with UrQMD
  - ✓ domination of rescattering over regeneration
- K^{*0}/K:
  - ✓ Multiplicity dependent suppression in pp and p-Pb



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

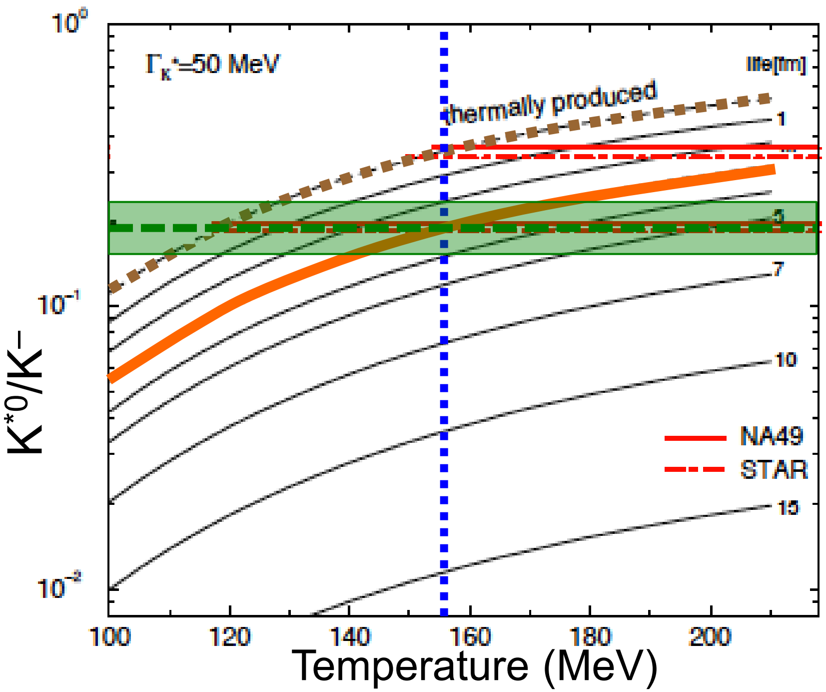


Hadronic phase

- Simple model:
  - ✓ all K^{*0} that decayed before kinetic freeze-out are lost due to rescattering
  - ✓ regeneration and time dilation are ignored
  - ✓ Yield(central Pb-Pb) = Yield(pp)·exp(-Δt/τ), τ = 4.16 fm/*c* → Δt = 2.25±0.75 fm/*c*
  - ✓ Lower limit for hadronic phase lifetime: **Δt > 1.5 fm/*c***

- More advanced models [1,2] couple particle ratios to temperature and hadronic phase lifetime Δt:
  - ✓ T = 156 MeV from thermal fits
  - ✓ K^{*0}/K= 0.20 ±0.01 (stat) ± 0.03 (syst)

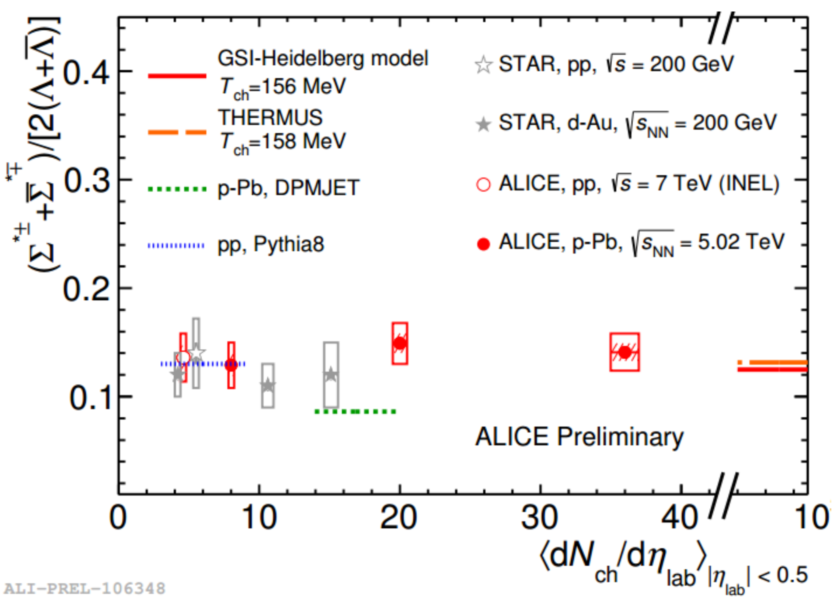
  → **Δt > 2 fm/*c***

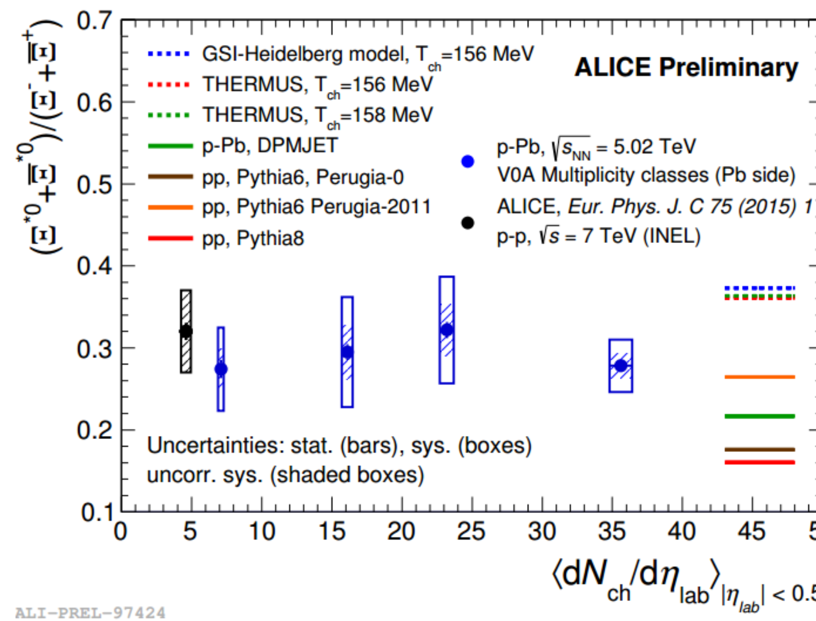


[1] G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002)
[2] C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

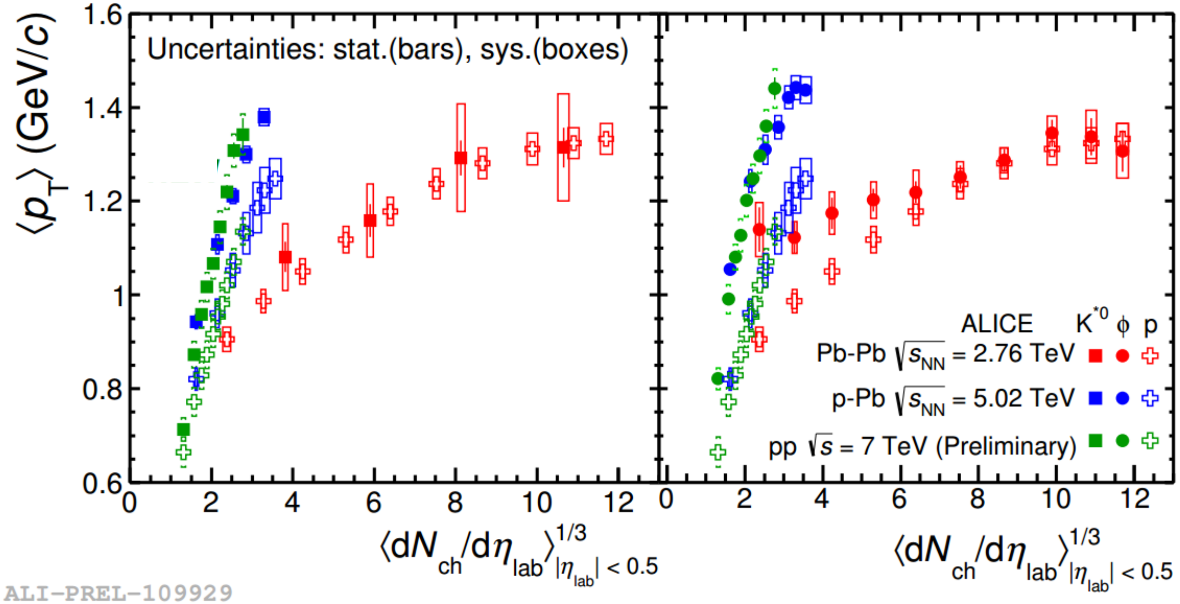
Low p_T: ratios to stable particles in pp, p-Pb

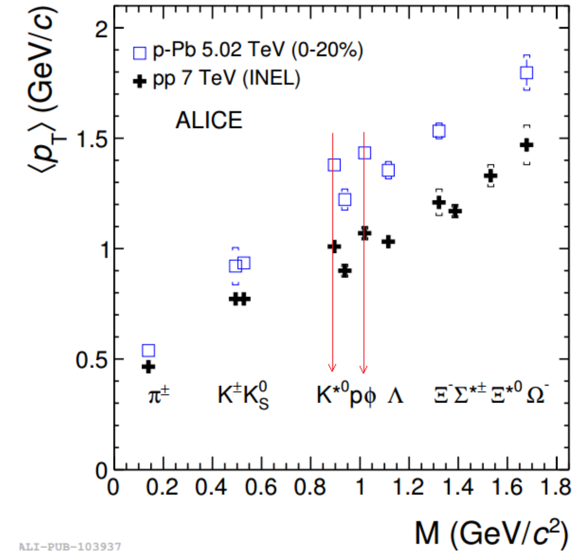
- Ratios of excited to stable hyperons with same strangeness content vs. multiplicity
- Ratios do not depend on multiplicity and collision energy
  → no dominant effect between regeneration rescattering
- $\Sigma^{*\pm}/\Lambda$: consistent with PYTHIA8 and thermal models; DPMJET is lower
- Ξ^{*0}/Ξ: higher than PYTHIA8 and DPMJET but lower than the thermal models





Mean p_T





- Mean $<p_T>$ vs. multiplicity in pp, p-Pb and Pb-Pb
- Central Pb-Pb: particles of similar mass have same $<p_T>$ → consistent with hydrodynamics
- pp and p-Pb:
  - ✓ smooth transition from pp to p-Pb
  - ✓ $<p_T>$ rises faster with multiplicity, reaching values similar to central Pb-Pb
    → *stronger radial flow, different particle production mechanisms?*
  - ✓ mass ordering of $<p_T>$ for particles of different masses →violated for K^{*0} and ϕ
    → *baryon/meson difference or feature of resonances?*

Summary

- ✓ ALICE has measured an evolution of spectra shapes with multiplicity in pp, p-Pb and Pb-Pb. In pp and p-Pb, $\langle p_T \rangle$ for resonances does not follow the mass ordering while it is the case for central Pb-Pb
- ✓ The effects of rescattering in the hadronic phase have been observed, K^{*0}/K and ρ/π ratios are suppressed in central Pb-Pb while the ϕ/K ratio stays unchanged. Lower limit for the hadronic phase lifetime $\Delta t \sim 1.5\text{-}2$ fm/c
- ✓ p/ϕ ratio indicates that shapes of particle spectra are mostly defined by particle masses, which is consistent with hydrodynamical models. The flattening of p/ϕ in central p-Pb at low p_T may hint at the onset of collective effects
- ✓ In central Pb-Pb, the production of all hadrons is similarly suppressed at high transverse momentum.

Backup slides

ALICE experiment

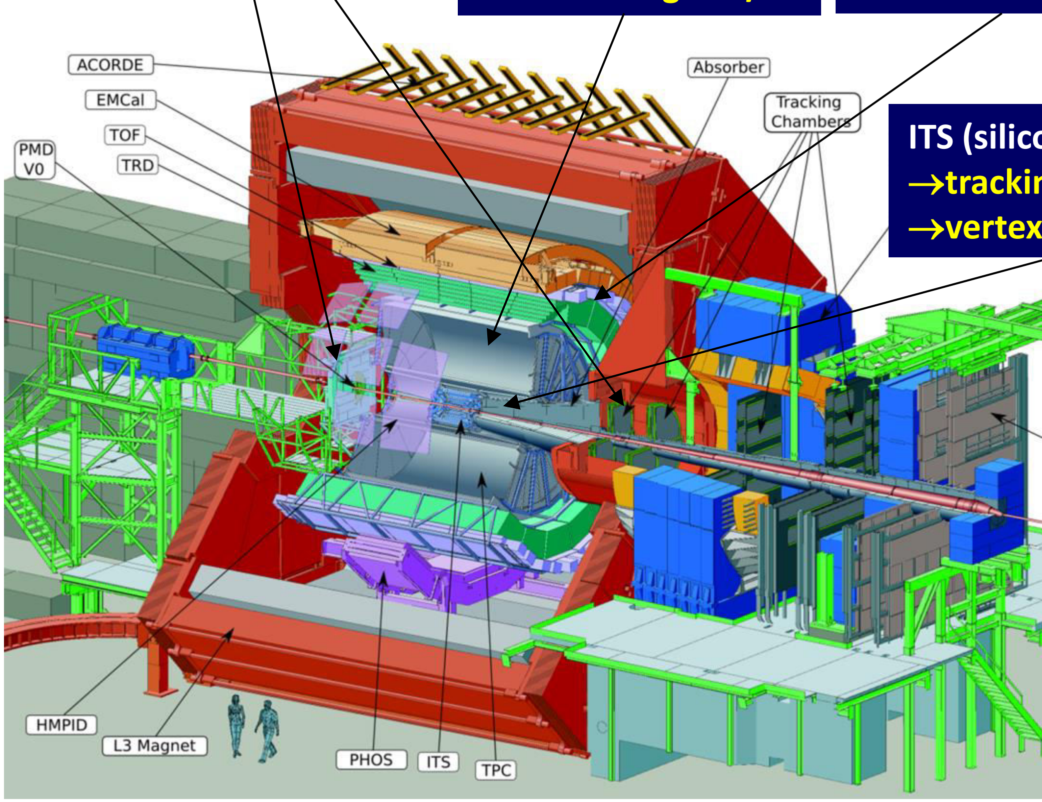
Int. J. Mod. Phys. A 29 1430044 (2014)

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

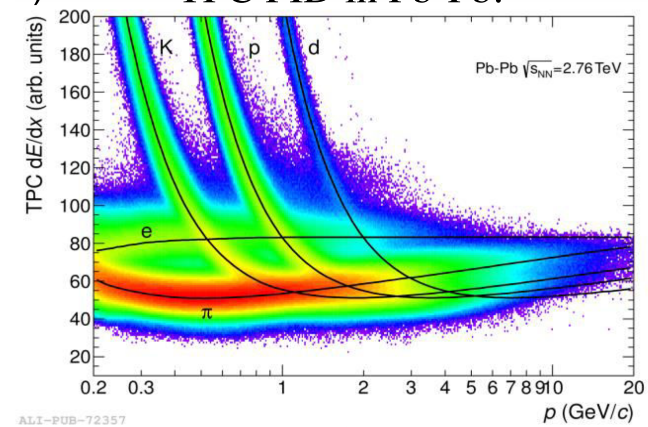
TPC:
→tracking
→PID through d*E*/dx

TOF:
→PID through momentum and ToF

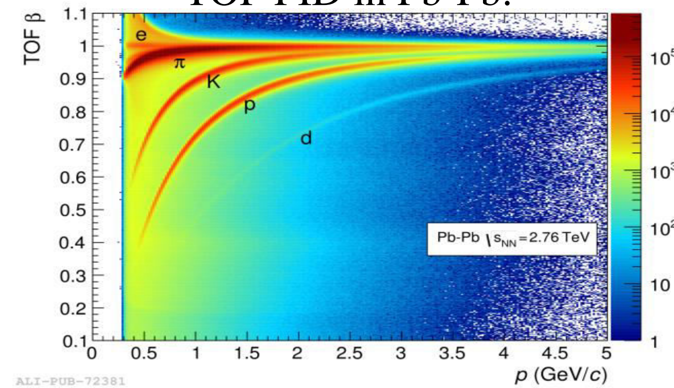
ITS (silicon):
→tracking
→vertexing



TPC PID in Pb-Pb:



TOF PID in Pb-Pb:



p_T ranges for 3σ separation (in GeV/c)

	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

EPOS3 + UrQMD

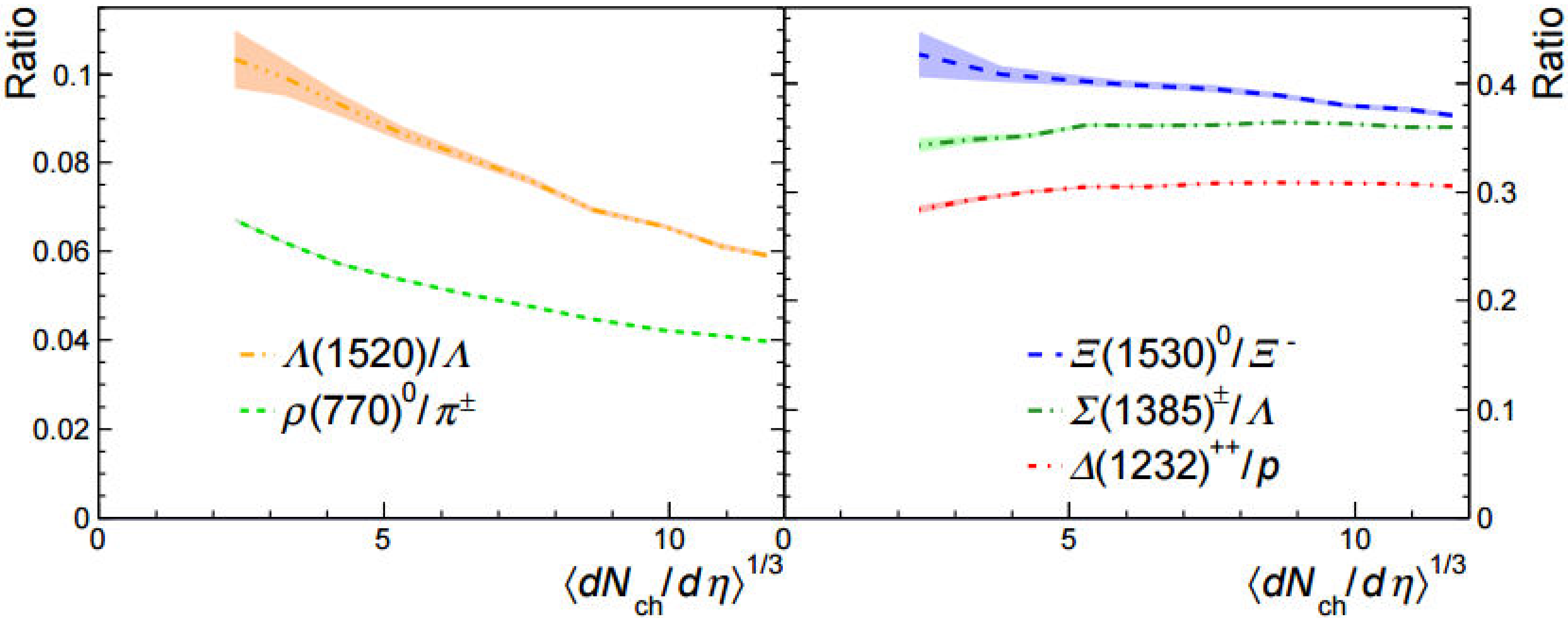
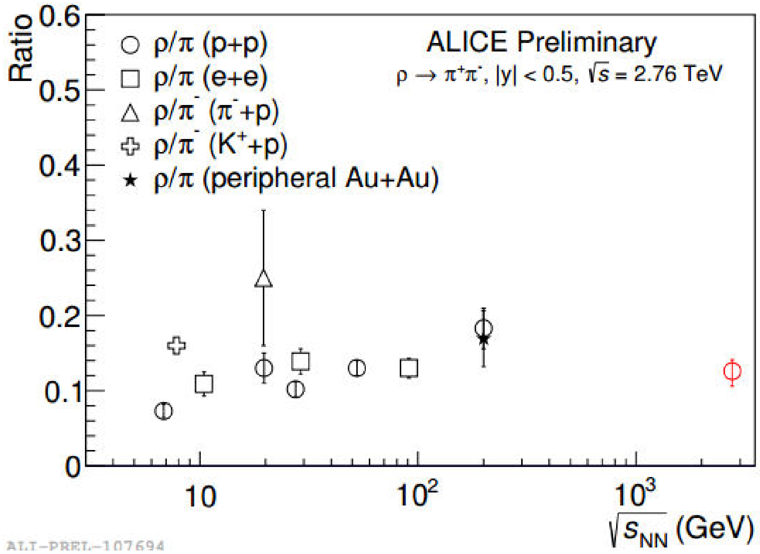
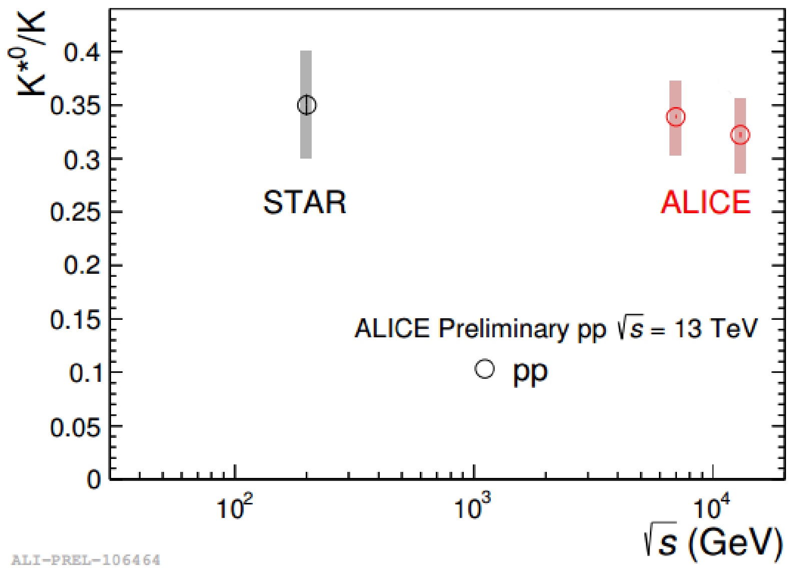
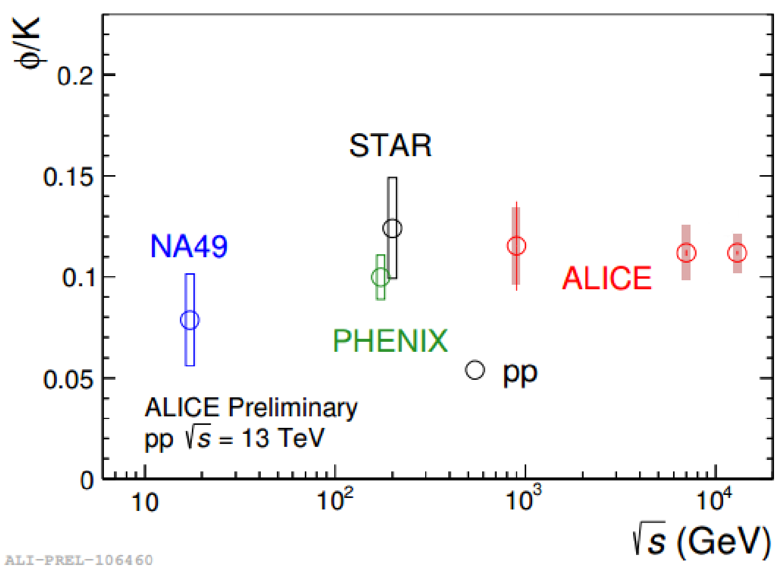


FIG. 13: Ratio of integrated yields $\Sigma(1385)^{\pm}/\Lambda$ and $\rho(770)^0/\pi^{\pm}$ (left) $\Xi(1530)^0/\Xi^-$, $\Sigma(1385)^{\pm}/\Lambda$ and $\Delta(1232)^{++}/p$ (right) for multiple centrality intervals calculated using EPOS3 with UrQMD ON (numerators and denominators are sums of particles 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 ($|\eta| < 0.5$).

Low p_T: ratios to stable particles in pp







- ρ/π, K^{*0}/K and ϕ/K do not depend on collision energy through 2-3 orders of magnitude

Comparison to RHIC

- ϕ/K and K^{*0}/K follow the same trend at RHIC and the LHC, ratios are consistent within uncertainties

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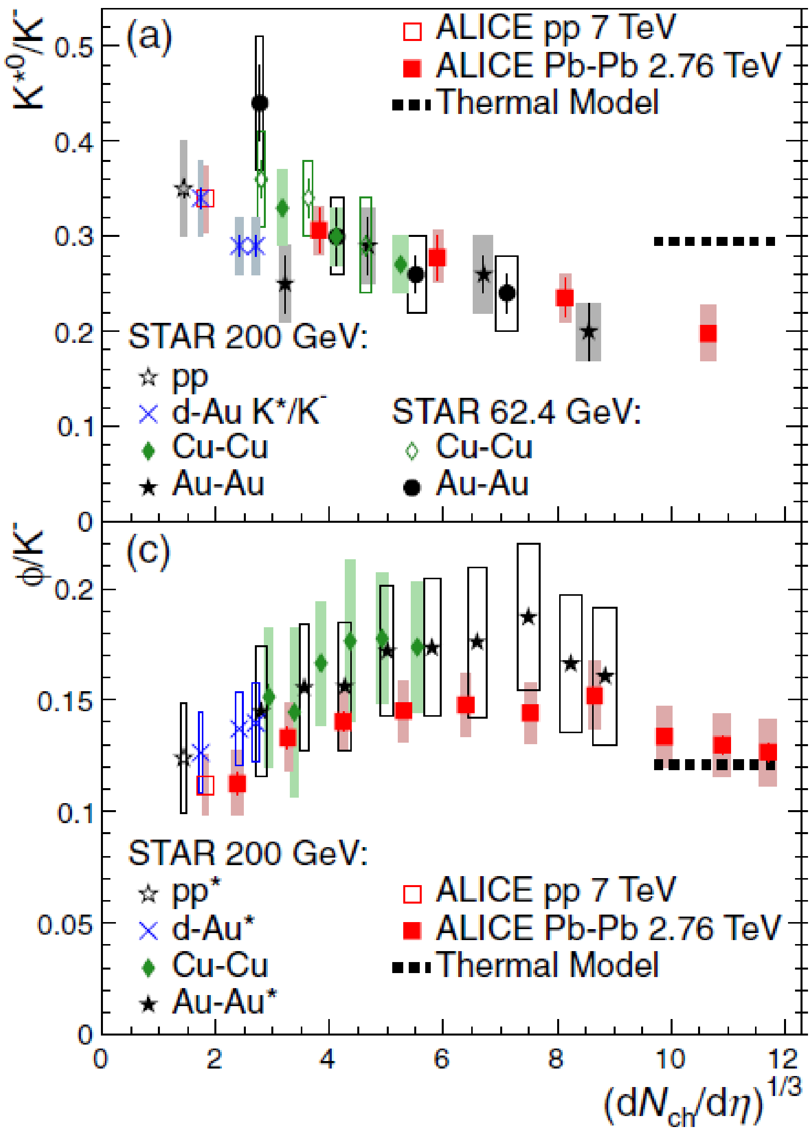
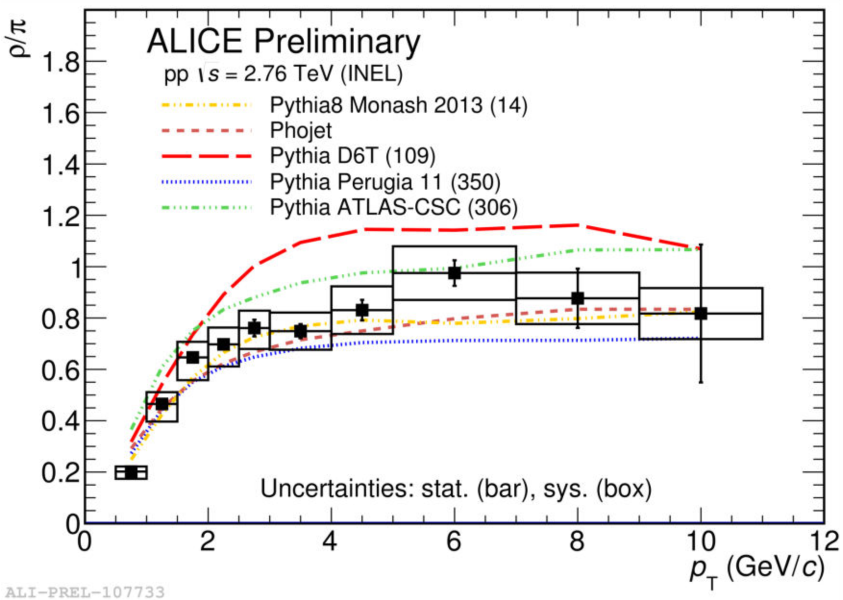
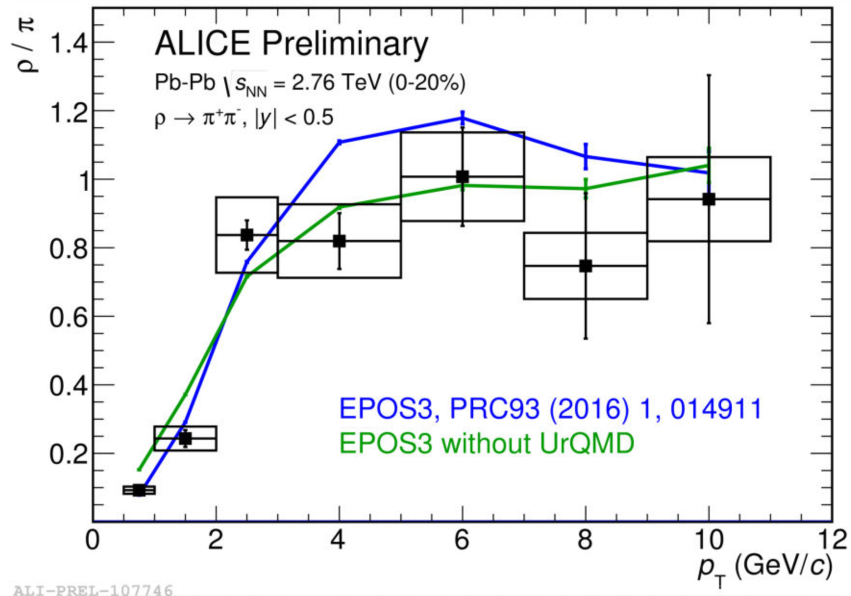


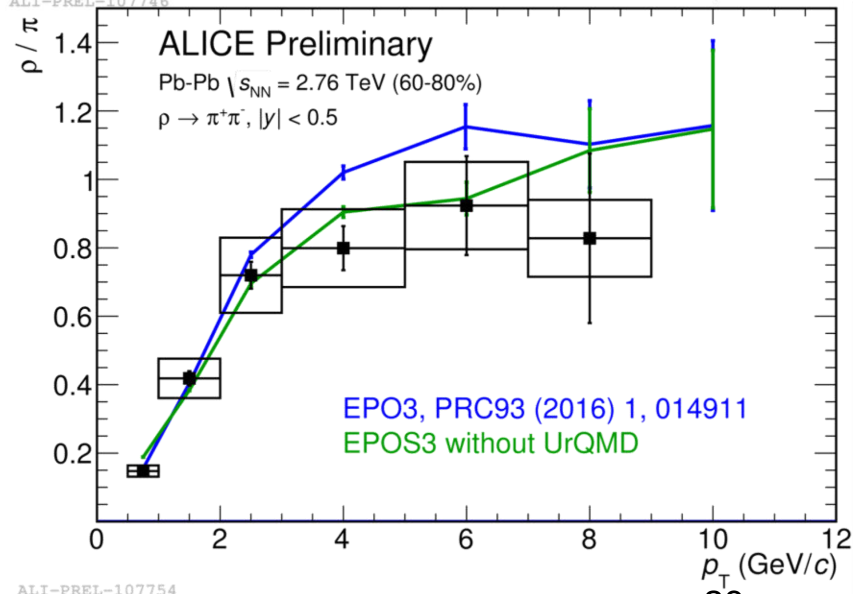
ρ/π ratio vs. p_T



- pp:
- ✓ ρ/π is very similar to ω/π
- ✓ different Pythia and Phojet tunes differ by ~ 50%

- Pb-Pb:
- ✓ ρ/π(p_T) differs from that in pp
- ✓ modifications are limited to low p_T
- ✓ trends are reproduced by EPOS with UrQMD
  → rescattering in the hadronic phase





Outlook

- Run-2 data analysis, higher energies and data samples
- Larger collection of resonances, more results in Pb-Pb (Λ^*, $\Sigma^{*\pm}$, Ξ^{*0})
- First look at invariant mass spectra: