Study of Σ^0 production in pp at 7 TeV and resonances studies at ALICE

- Introduction
- Detection of resonances
- Σ^0 world data and Σ^0/Λ cross section ratio
- Tests of QCD inspired MC event generators in pp data
- The study of the hadronic phase
- Summary

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Resonances

A resonance is the peak located around a certain energy found in differential cross sections of scattering experiments (Wikipedia). The width of the resonance (Γ) is related to its lifetime (τ) by the relation $\Gamma = \frac{\hbar}{\tau}$, where $\hbar = \frac{h}{2\pi}$.

PDG parameters of studied hadronic resonances and ground states

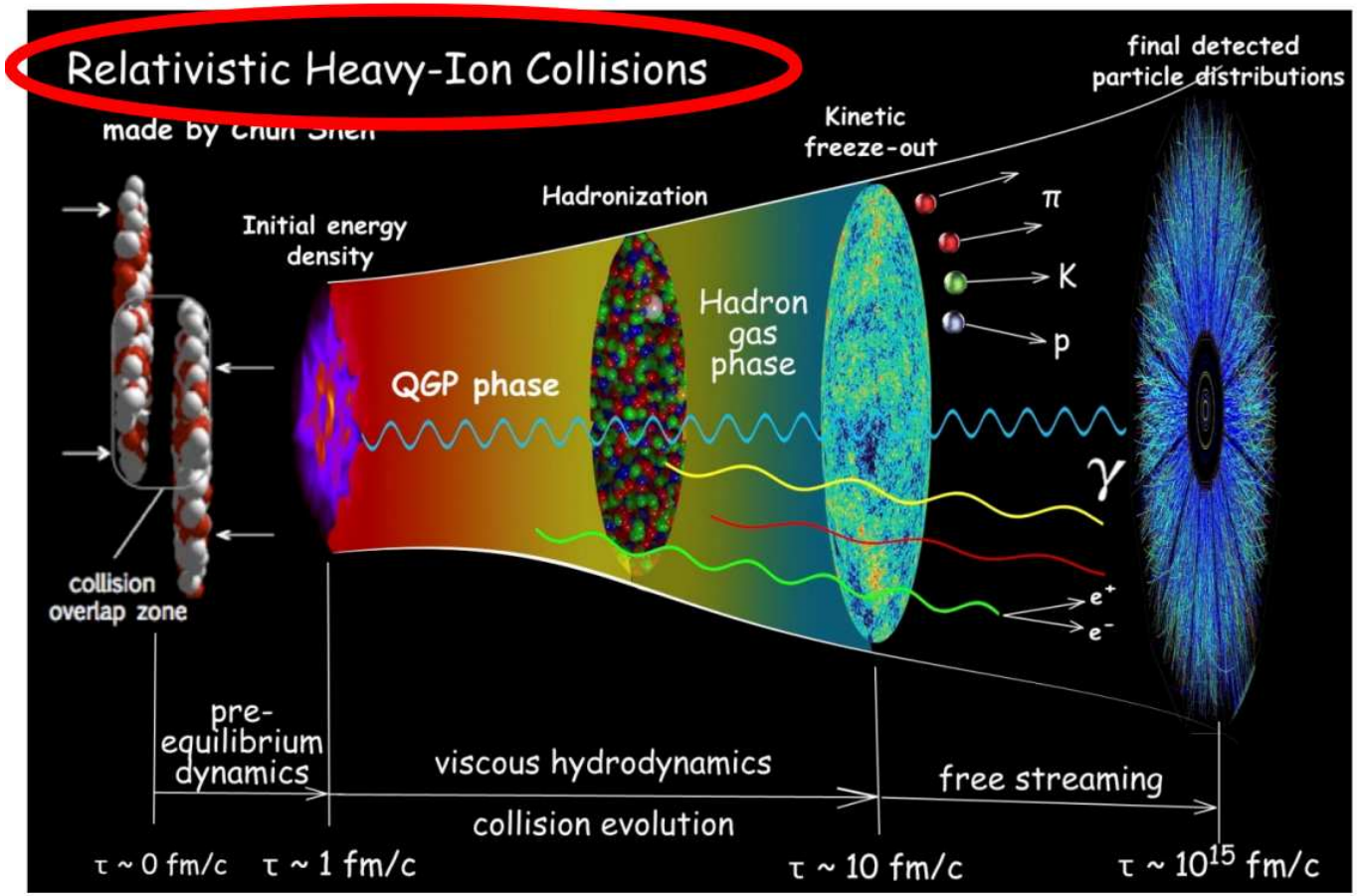
Particle	Quarks	Mass (MeV/c^2)	Width (MeV/c^2)	Lifetime (fm/c)	Decay*	Branching ratio (%)
ρ^0	$(u\bar{u} + d\bar{d})/\sqrt{2}$	770	150	1.3	$\pi^+\pi^-$	100
K^{*0}	$d\bar{s}$	896	47.4	4.17	π^-K^+	66.7
ϕ	$s\bar{s}$	1019	4.27	46.2	K^-K^+	48.9
Λ	uds	1115	~ 0	7.89 cm	p+π^- (1)	63.9
$\Lambda(1520)$	uds	1520	15.7	12.6	K^-p	22
Σ^0	uds	1192	~ 0	22 200	$\Lambda + \gamma$ (2)	100
$\Sigma(1385)^+$	uus	1383	36.0	5.51	$\Lambda + \pi^+$	87.0
$\Sigma(1385)^-$	dds	1387	39.4	5.01	$\Lambda + \pi^-$	87.0
Ξ^-	dds	1321	~ 0	4.91 cm	$\Lambda + \pi^-$ (1)	99.9
$\Xi(1530)^0$	uss	1532	9.1	21.7	$\Xi^- + \pi^+$	42.6

*Decay: strong if no label, 1 - weak, 2 - electromagnetic

Measured in **pp (0.9, 2.76, 5.02, 7.0, 8.0, 13.0 TeV)**, **p-Pb (5.02 TeV)**, and **Pb-Pb (2.76, 5.02 TeV)** collisions

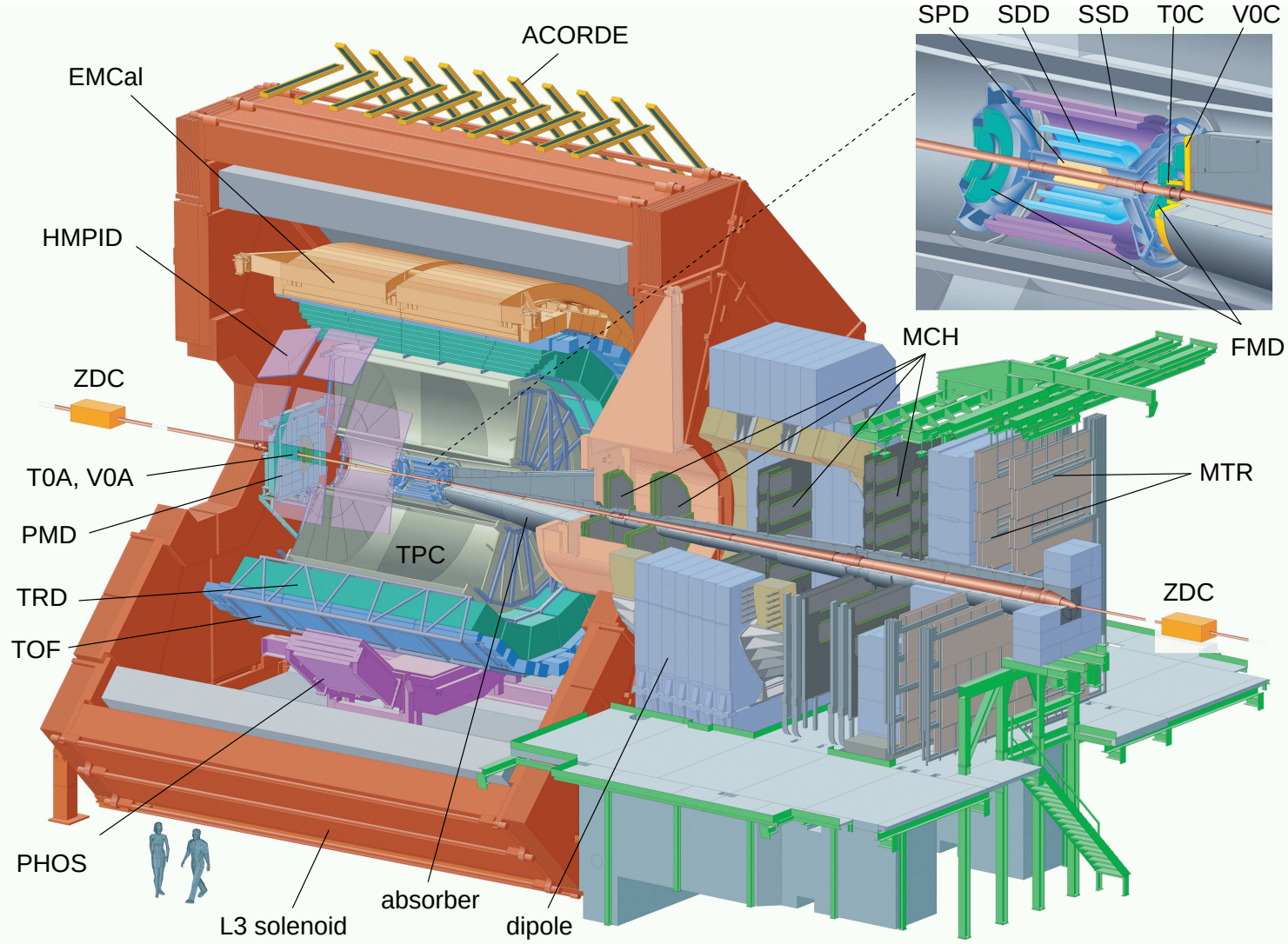
Why resonances?

- Copiously produced and measurable in different collision systems
  - pp: baseline measurements, test of QCD inspired MC event generators
  - p-Pb: cold nuclear matter effects, onset of collectivity (talk of F.Bellini)
  - Pb-Pb: properties the hadronic phase and collectivity.
- Different quark contents allow to study flavor dependence of energy loss in Pb-Pb collisions.
- Resonances with different lifetimes are used to study the properties of the hadronic phase in Pb-Pb collisions.



Detection of resonances

The ALICE detector



ITS, TPC and TOF are mainly used for the reconstruction of the decay of resonances, V0A+V0C and ZDC for multiplicity, centrality, trigger and timing

(talks of H.Beck, F.Bellini, M.Broz and E.Bruna)

Centrality and multiplicity classes in ALICE

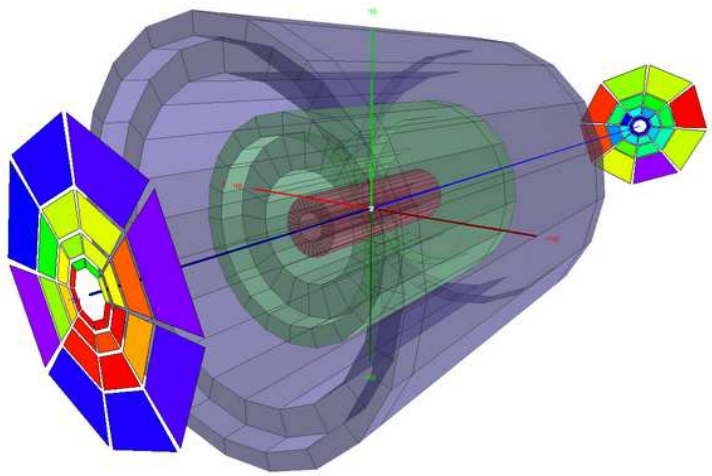
- **Event multiplicity/centrality classes are defined based on the amplitude measured in the V0 scintillators, placed at 2.8 $< \eta <$ 5.1 (V0A) and -3.7 $< \eta <$ -1.7 (V0C)**

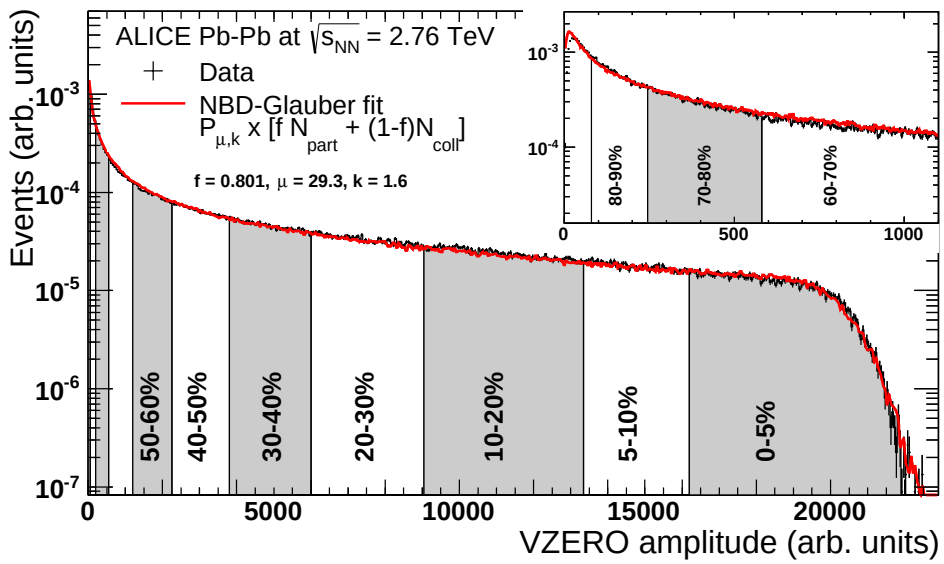
- $\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta|$ <0.5 to avoid biases in multiplicity determination

- In Pb-Pb the Glauber model is used to relate the V0A&V0C amplitude distribution to the geometry of the collision

0-5%: $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle_{|\eta|<0.5} = 1601 \pm 60$
$\langle N_{part} \rangle = 328.8 \pm 3.1$

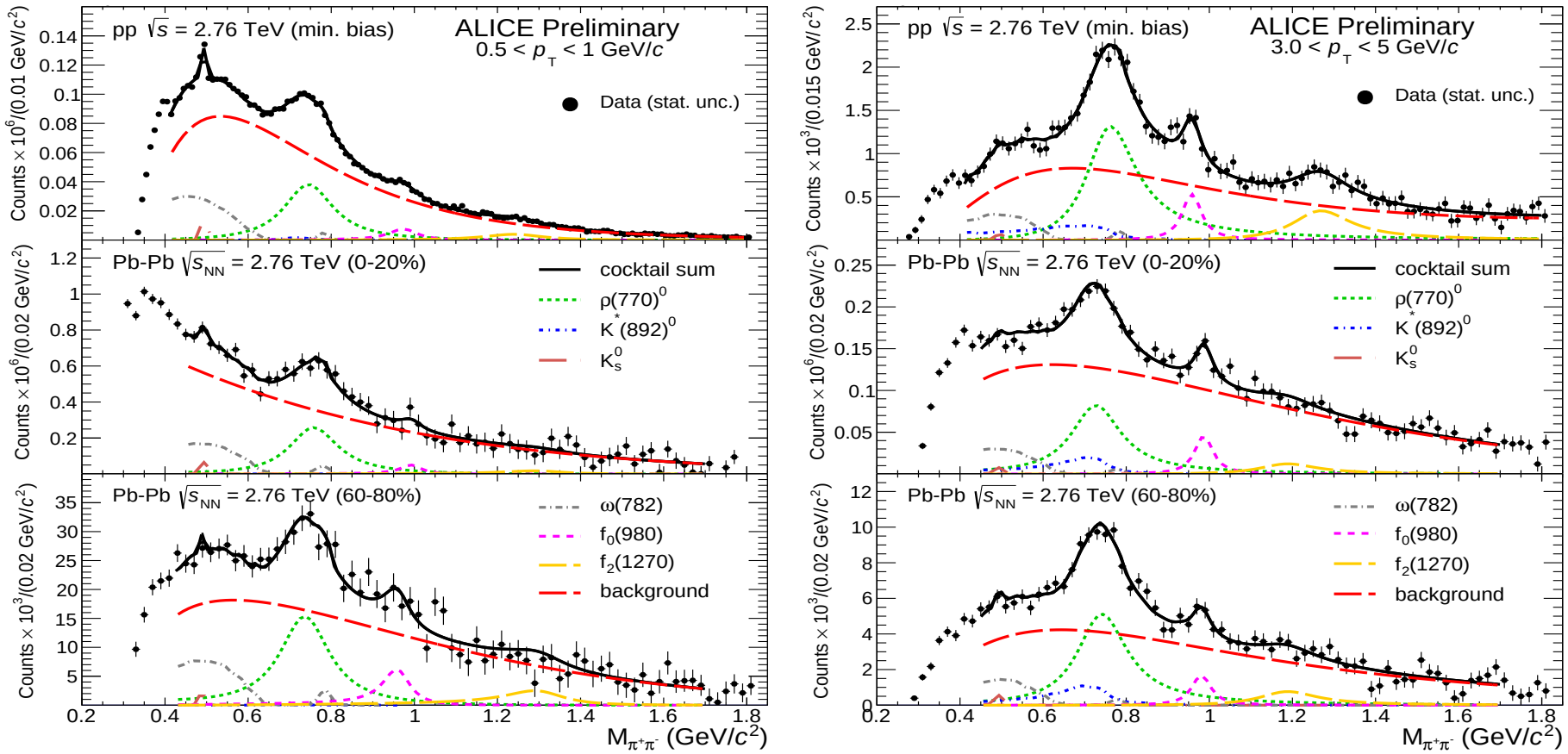
70-80%: $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle_{|\eta|<0.5} = 35 \pm 2$
$\langle N_{part} \rangle = 15.8 \pm 0.6$





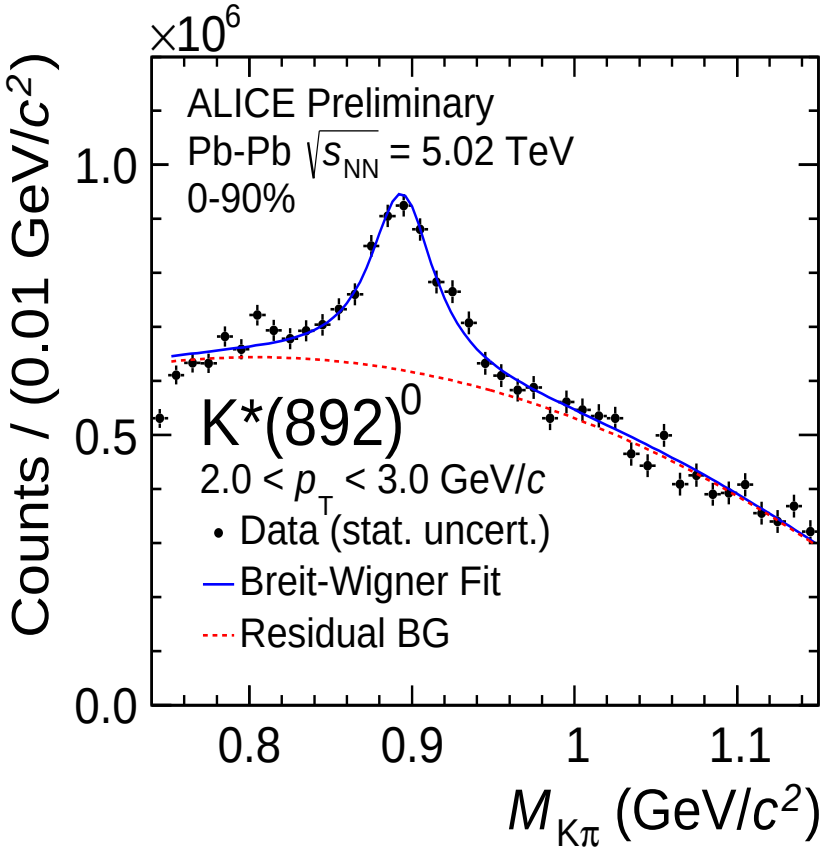
ALICE, PRL 106 (2011) 032301; ALICE, PRC 88 (2013) 044909; ALICE, PRC 91 (2015) 064905

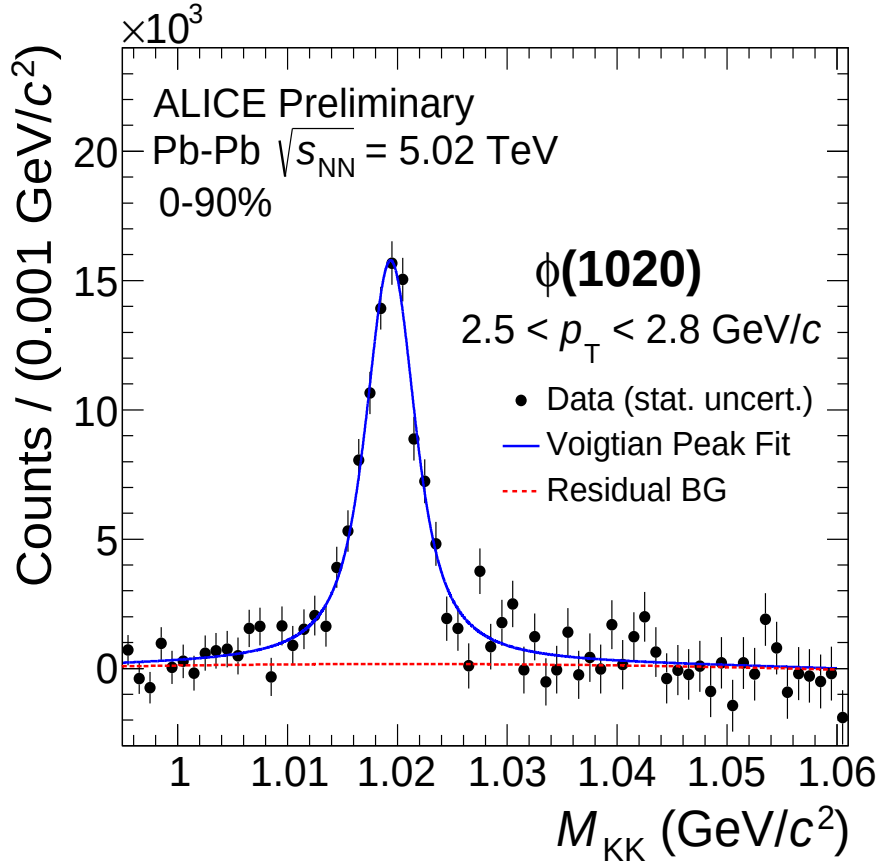
$\rho^0 \rightarrow \pi^+\pi^-$



- Analyzed in pp and Pb-Pb collisions at 2.76 TeV
- Subtract like-charge combinatorial background
- Fit with residual background + cocktail (K^0_S, K^{*0}, ω, f_0, f_2)
- Peak model : Rel. Breit-Wigner$\otimes$Phase Space$\otimes$Mass-Dependent Efficiency$\otimes$ Söding Interference Term (M.J.Matison et al., Phys. Rev. D 9, 1872 (1974))

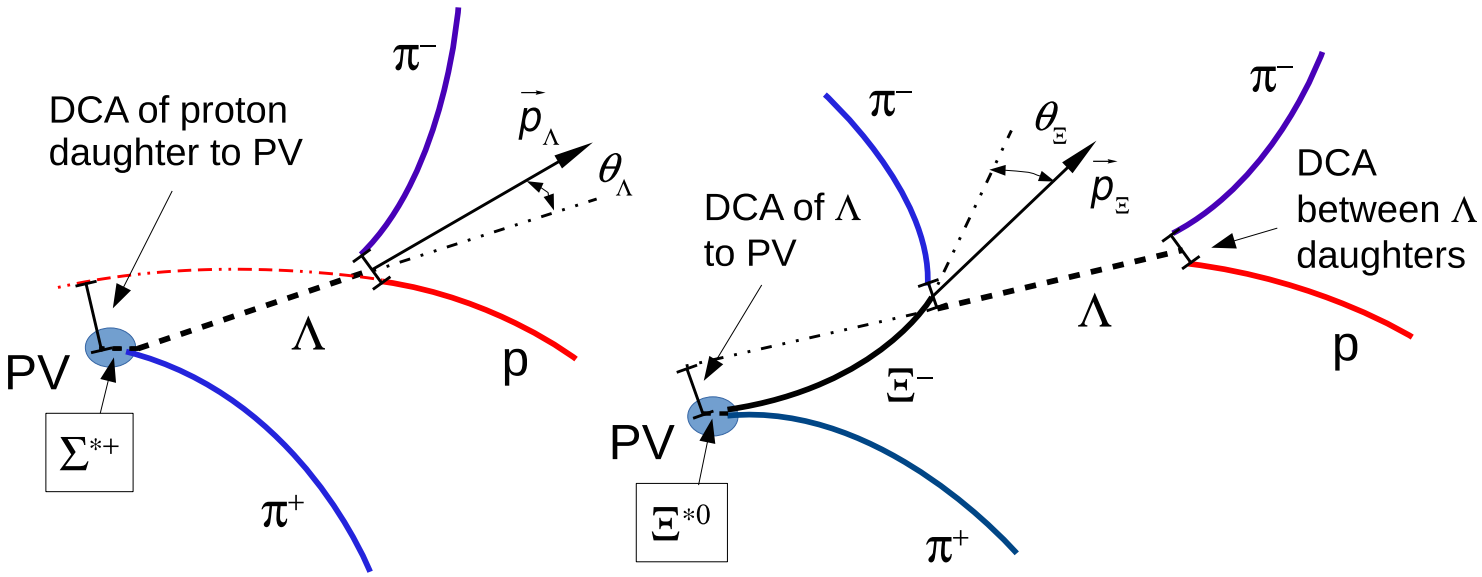
$K^{*0} \rightarrow K^{+} + \pi^{-}$ and $\phi \rightarrow K^{-} + K^{+}$





- Analyzed in pp collisions at 0.9, 2.76, 7.0, 13.0 TeV; p-Pb collisions at 5.02 TeV; Pb-Pb collisions at 2.76 & 5.02 TeV
- Subtract mixed-event or like-charge combinatorial background
- Residual background is described with polynomial of seconf order
- Peak fit: Breit-Wigner (K^{*0}) or Voigtian which is Breit-Wigner$\otimes$Gaussian (ϕ)

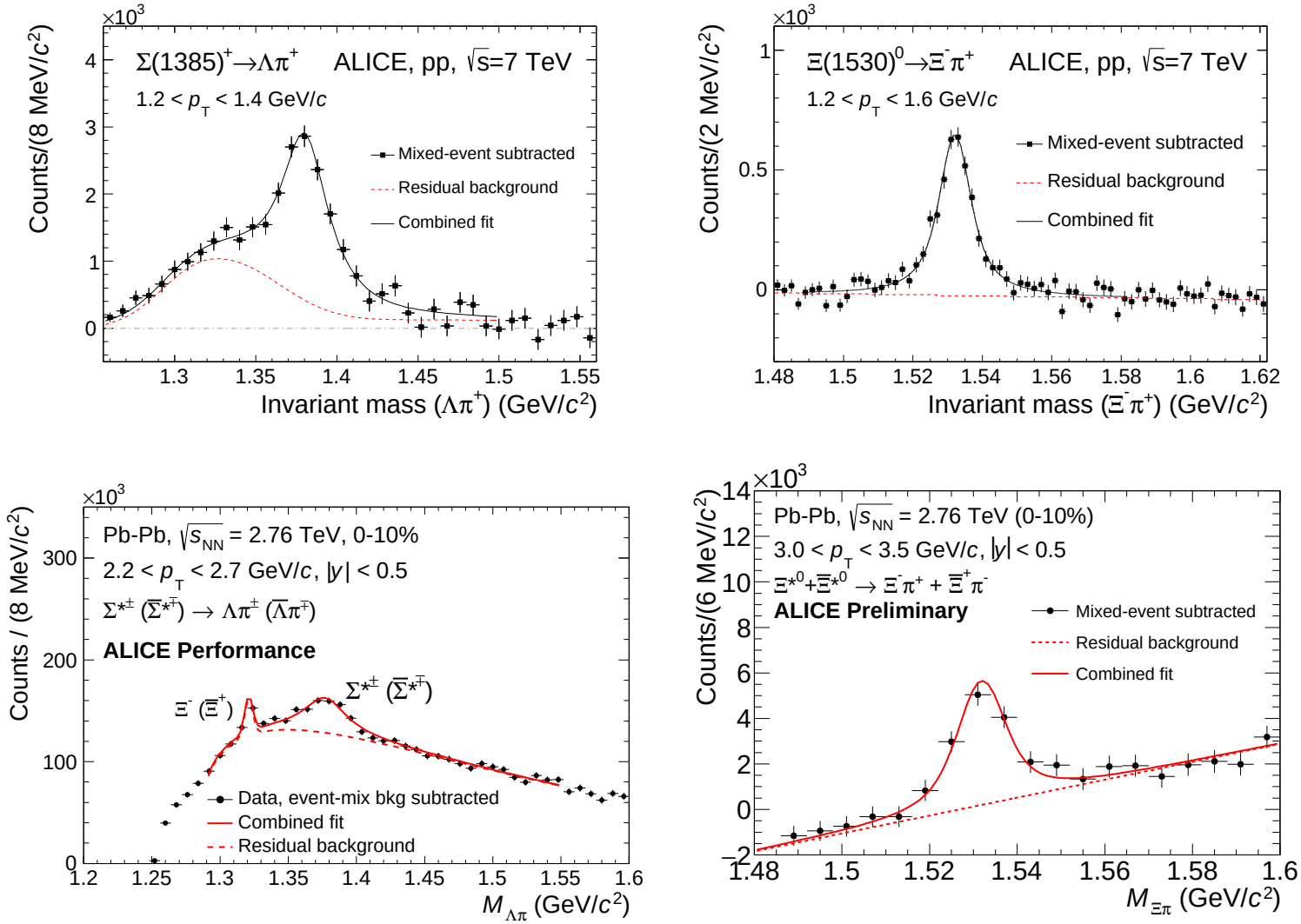
$\Sigma(1385)^{\pm} \rightarrow \Lambda + \pi^{\pm}$ and $\Xi(1530)^{0} \rightarrow \Xi^{-} + \pi^{+}$



- Analyzed in pp collisions at 7 TeV & pPb collisions at 5.02 TeV, Ξ^{*0} also in PbPb collisions at 2.76 TeV
- Identification is based on topological selections

(pp: ALICE, Eur. Phys. J. C 75 (2015) 1; p-Pb: ALICE, arXiv:1701.07797 [nucl-ex])

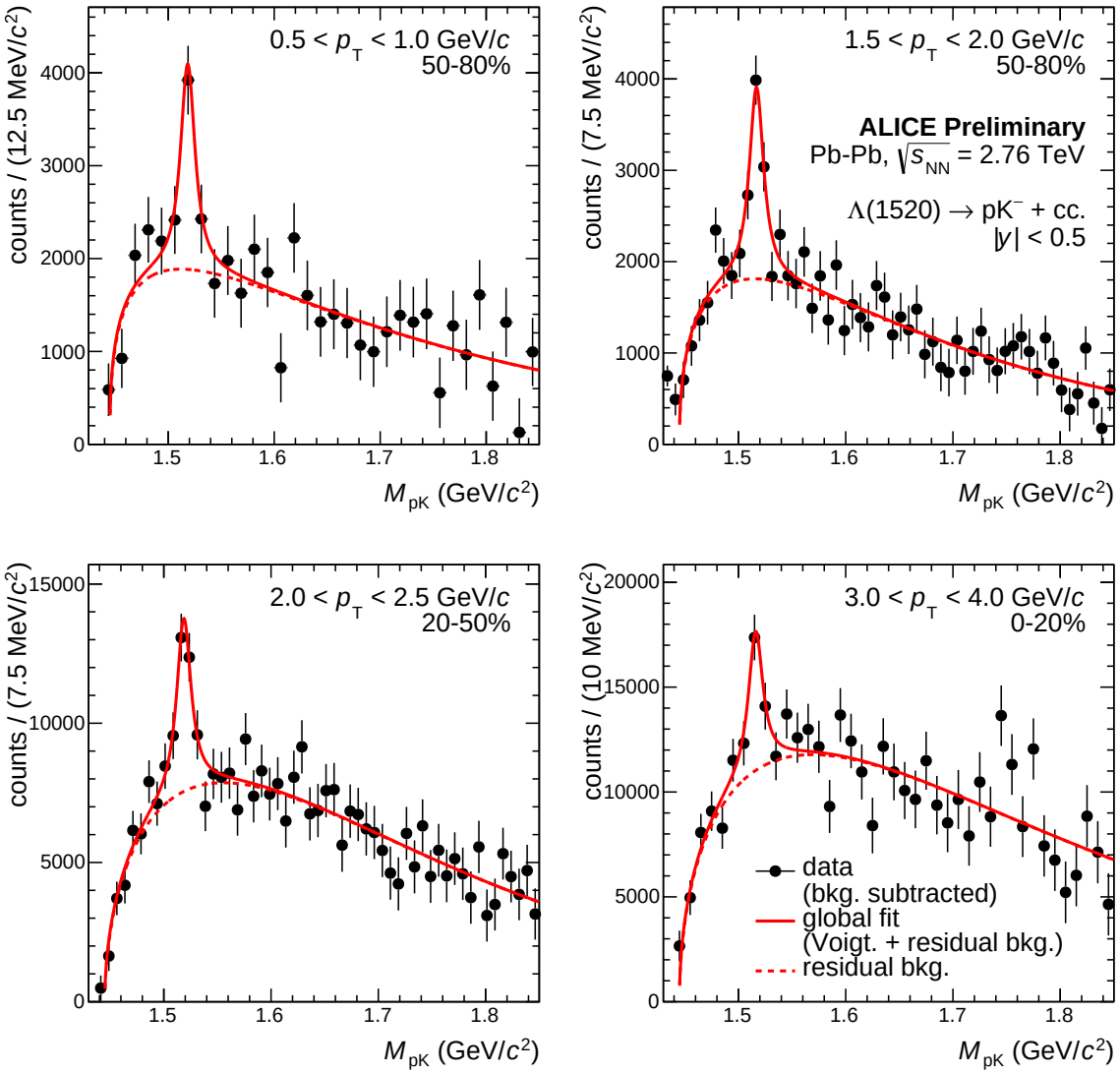
$\Sigma(1385)^{\pm}$ and $\Xi(1530)^{0}$



(ALICE, Eur. Phys. J. C 75 (2015) 1)

- Mixed-event combinatorial background subtracted
- Residual background is described with second order polynomial
- Peaks: Breit-Wigner ($\Sigma^{*\pm}$) or Voigtian (Ξ^{*0})

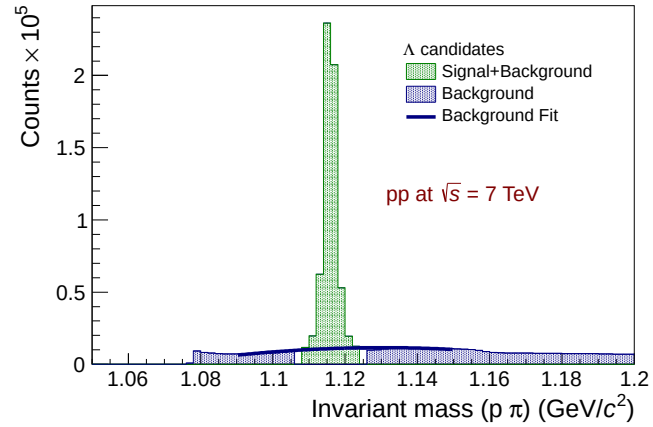
$\Lambda(1520) \rightarrow p + \mathbf{K}^-$



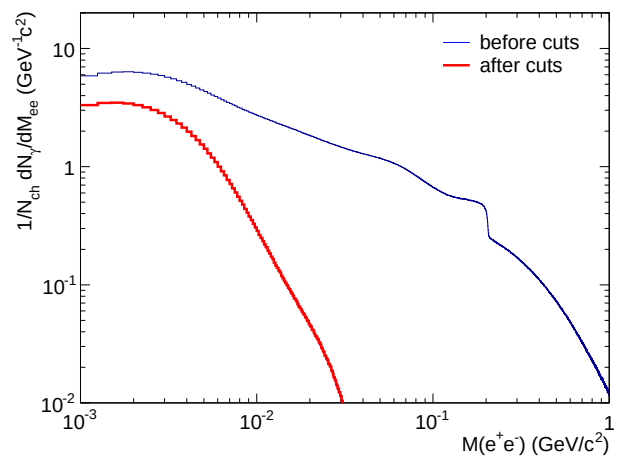
- Measured in Pb-Pb 2.76 TeV, ongoing in pp 7, 13 TeV, p-Pb 5.02 TeV
- Mixed-event unlike-sign background subtracted
- Voigtian signal
- Residual background parameterised by a generalised Maxwell-Boltzmann distribution

$\Sigma^0 \to \Lambda + \gamma$ and $\bar{\Sigma}^0 \to \bar{\Lambda} + \gamma$

- $\Lambda \to \mathrm{p} + \pi^-$ and $\bar{\Lambda} \to \bar{\mathrm{p}} + \pi^+$ is detected through the secondary V^0 vertex in the central barrel detectors

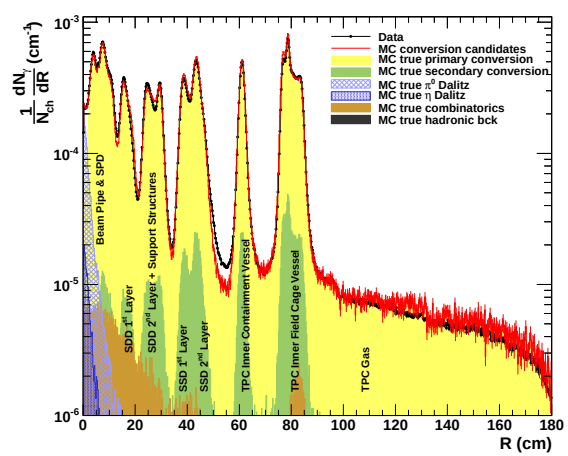


- $\gamma \to \mathrm{e}^+ + \mathrm{e}^-$ is detected through the secondary V^0 vertex with Photon Conversion Method (PCM) in the central barrel detectors



- The distribution of the conversion points is well reproduced by MC. The radiation thickness of the detector material integrated for $R < 180$ cm and $|\eta| < 0.9$ is determined as 11.4 $\pm 0.5\%$ X_0.

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



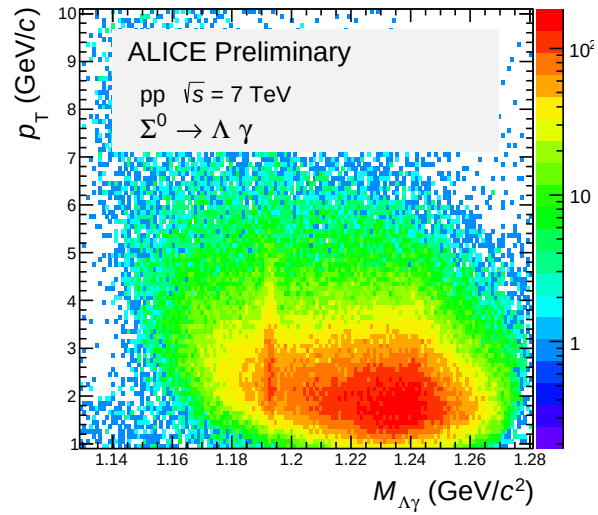
$\Sigma^0 \to \Lambda + \gamma$ and $\bar{\Sigma}^0 \to \bar{\Lambda} + \gamma$ decays

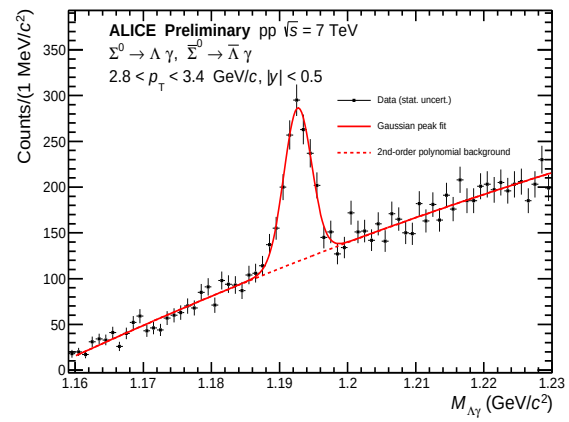
- $\Sigma^0(1192)$:
  - quark content: uds
  - isospin 1
  - $c\tau = 22200$ fm
  - branching ratio $\approx 100\%$

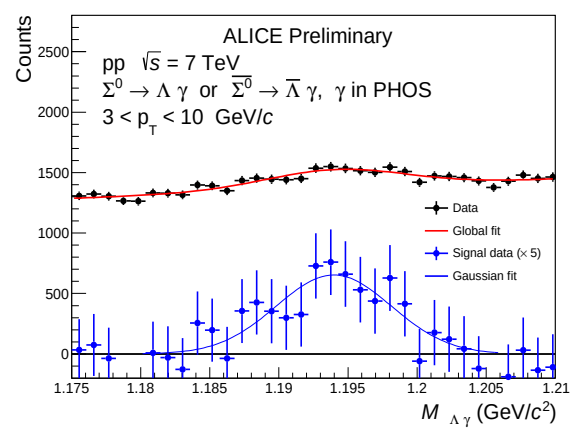
- Invariant mass analysis of the selected Λ and γ candidates.
  Note low $E_\gamma \approx$ 100 MeV.

- Amount of detected Σ^0 with PCM is limited by the probability of photon conversion in the ALICE central tracking system (~ 0.085) and its reconstruction efficiency (~ 0.6).

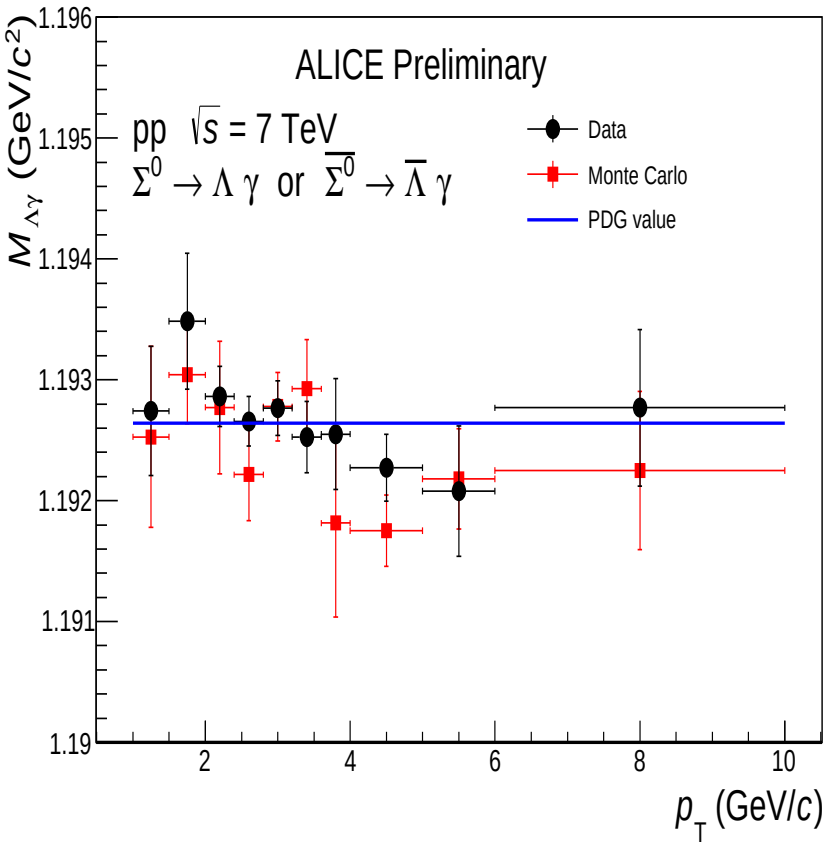
- Proof-of-principle: Σ^0 peak is also observed with photon detected in PHOS calorimeter, but with worse resolution:
  $M^{\Sigma^0}_{\gamma PHOS} = 1194.1 \pm 0.6$ MeV
  $\sigma_M = 5.1 \pm 0.5$ MeV

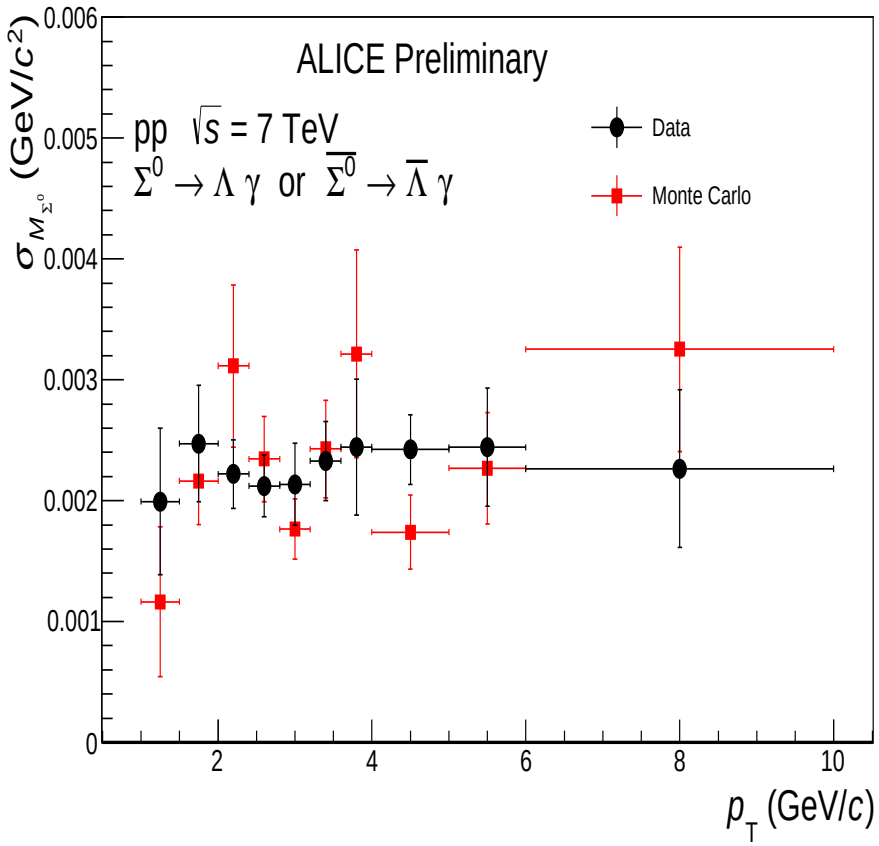






Σ^0 mass and width

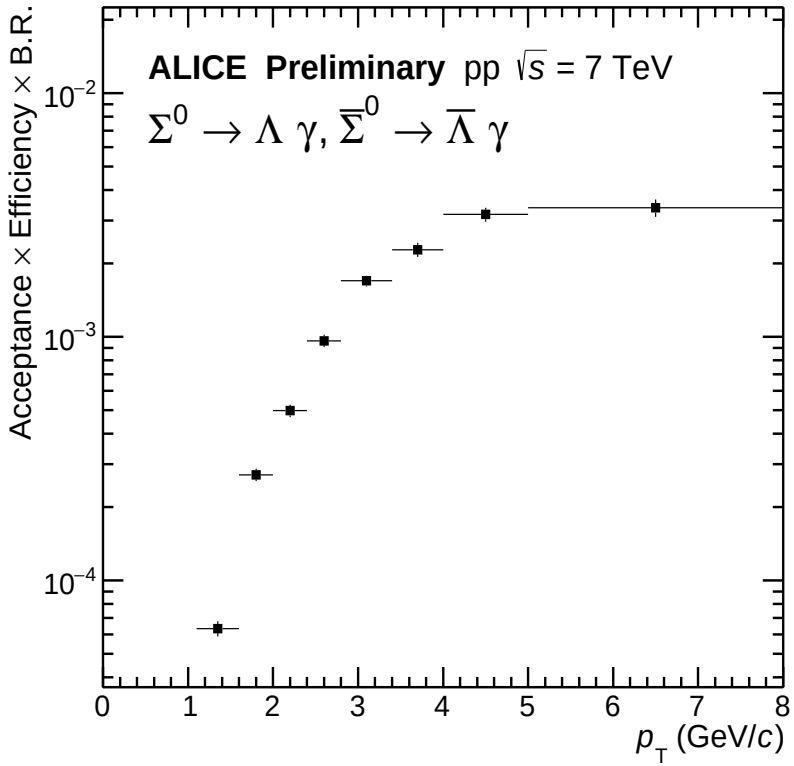


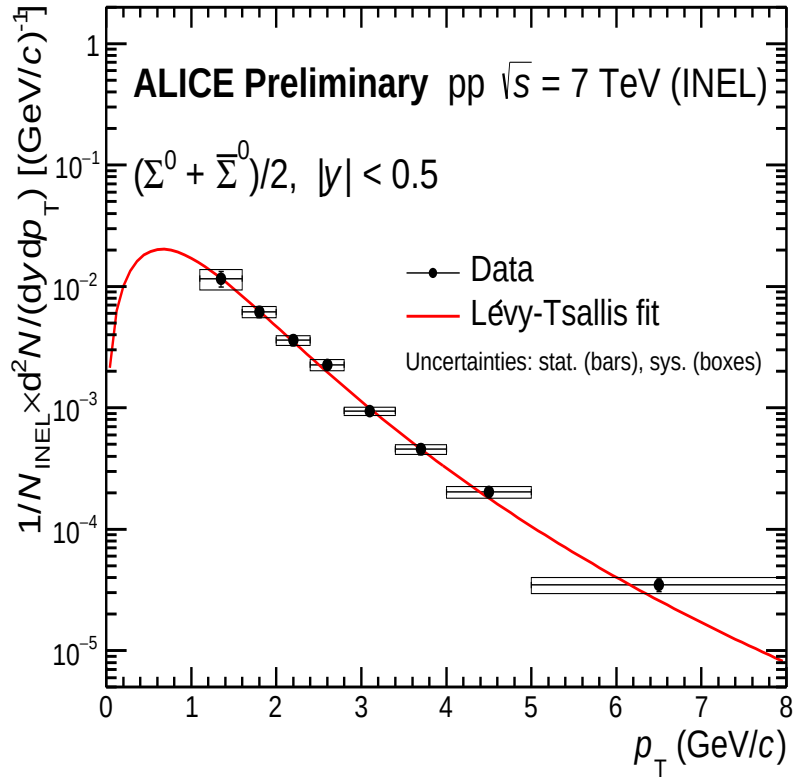


$\Longrightarrow$ Reconstructed peak position is in good agreement with the PDG value.
PDG: $\Sigma^{0PDG} = 1192.642 \pm 0.024$ MeV

$\Longrightarrow$ The width is determined only by the detector resolution due to the long lifetime of the Σ^0 and is in agreement with the simulations.

Σ^0 spectrum and Lévy-Tsallis fit



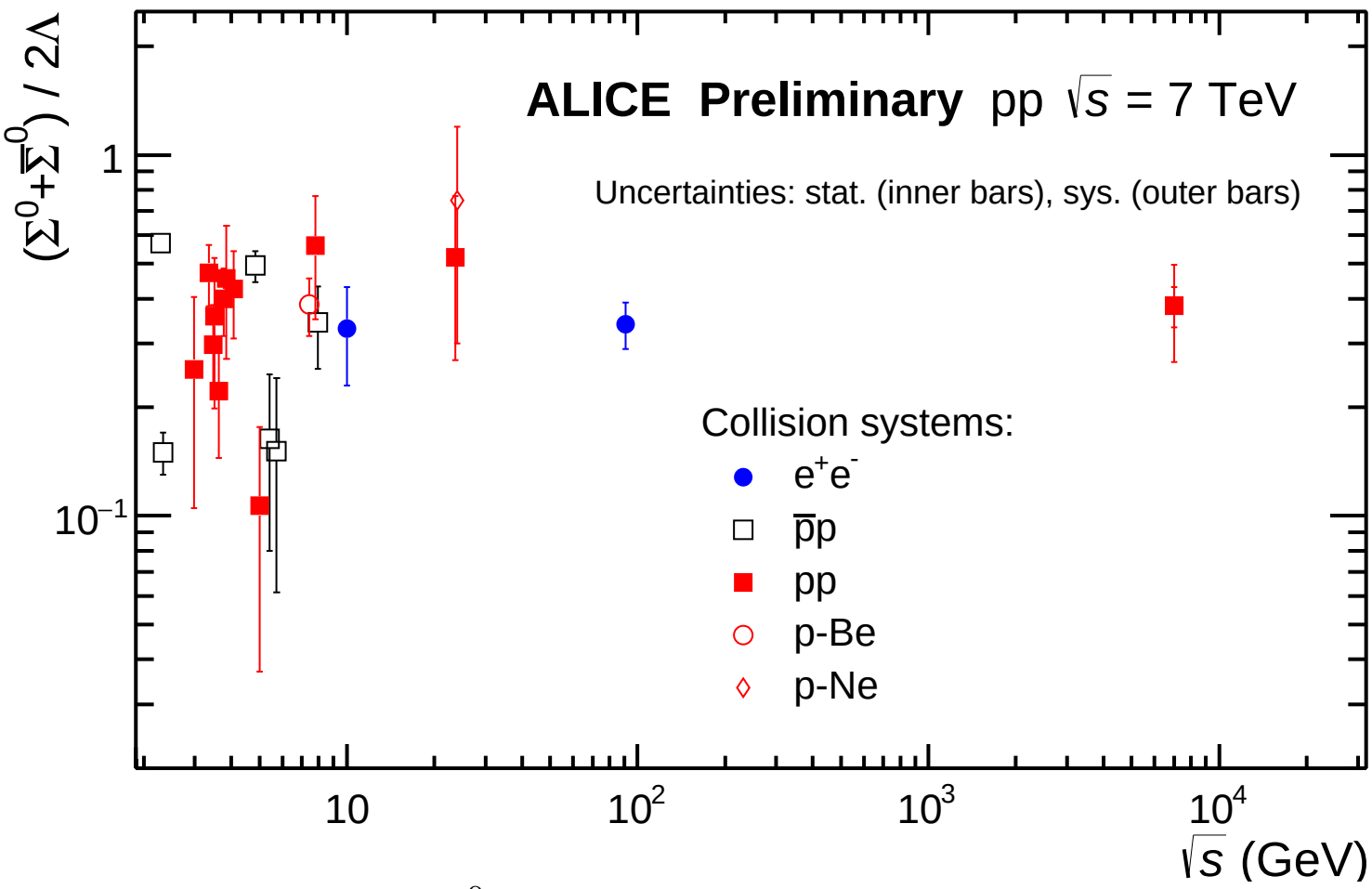


γ conversion probability $\times$ efficiency $\sim$0.05

The p_{T} -integrated yield is determined by summing up the spectrum in the measured range and the extrapolation to $p_{\mathrm{T}} = 0$ based on the Lévy-Tsallis fit.

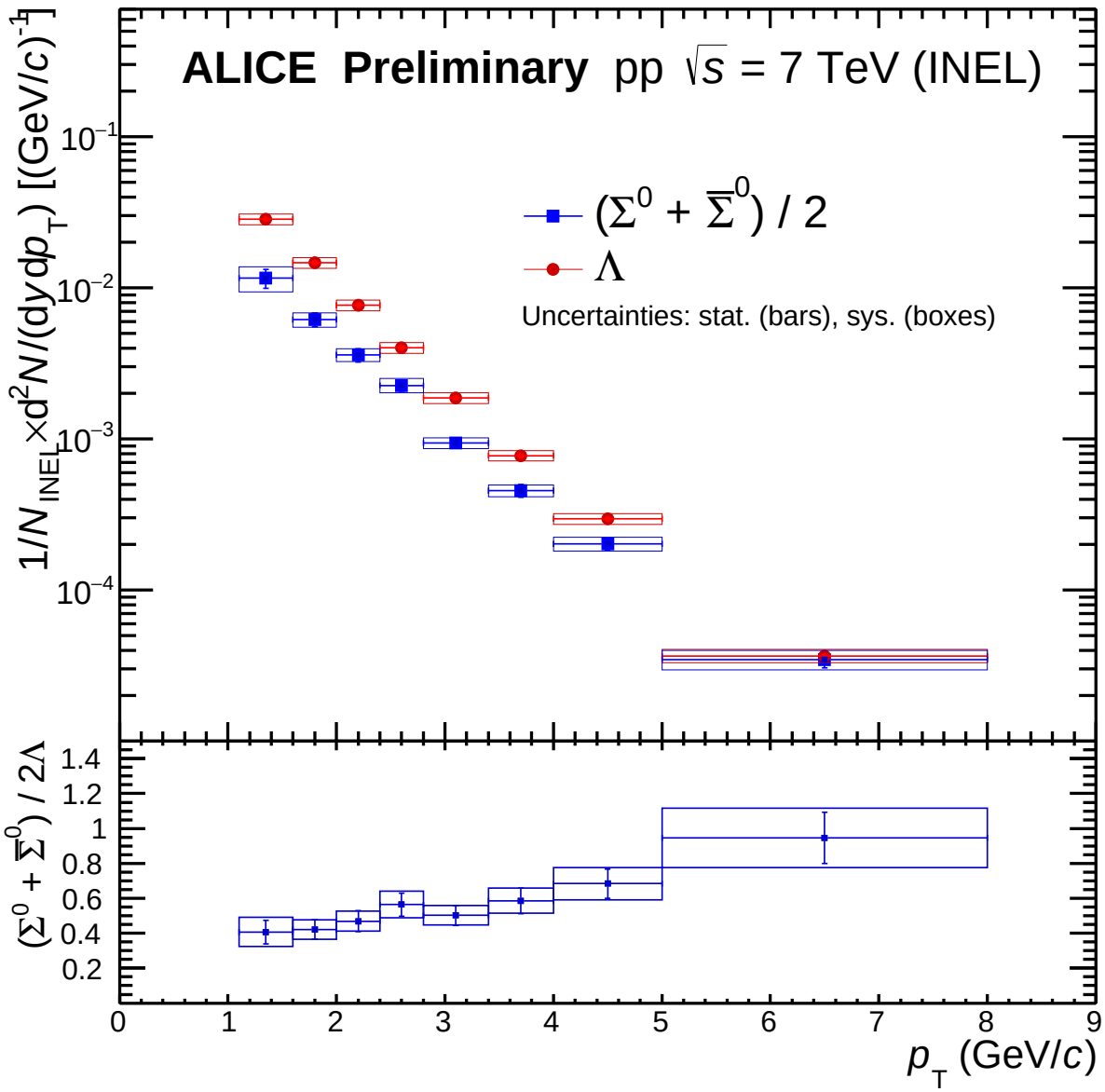
$\sim$ 60% of the yield is in the extrapolated region between 0 and 1.1 GeV$/c$. Relative uncertainty of the yield due to the extrapolation is $\sim$ 18%.

ALICE measurement and world data



- First measurement at LHC of $\frac{\Sigma^0}{\Lambda}$ cross section ratio complements wold data at low energies (G.Van Buren arXiv:nucl-ex/0512018)
- e^+e^- data at $\sqrt{s} = 91$ GeV from L3 experiment at LEP reported $\frac{\Sigma^0}{\Lambda} = 0.33 \pm 0.03$, where both Σ^0 and Λ were detected in hadronic Z decays (M. Acciarri et al, L3 collab., Phys. Lett. B 479 (2000) 79-88.)

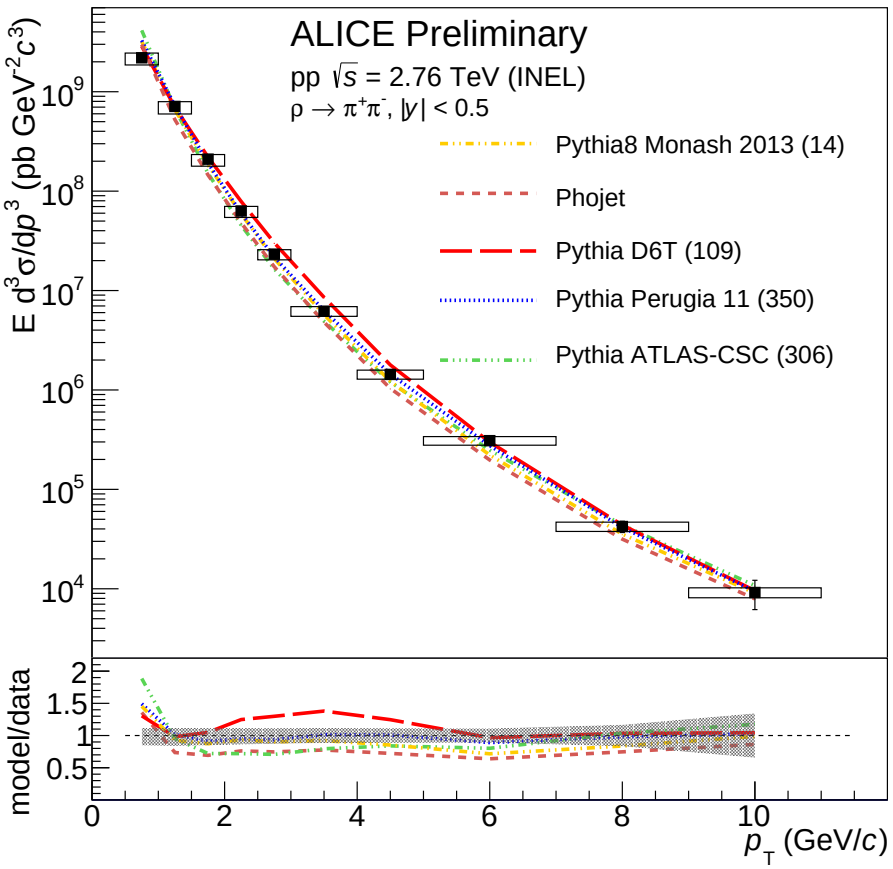
p_{T} -differential $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio

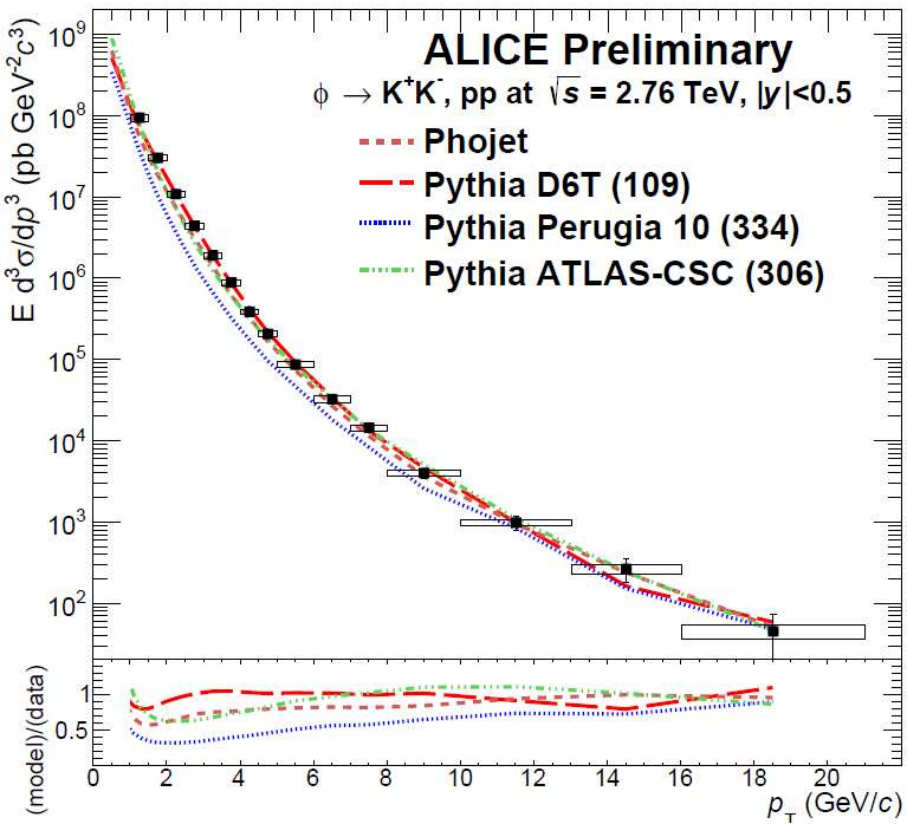


⟹ **Increasing trend of the $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio with p_{T}**

Tests of QCD-inspired MC event generators in pp data

ρ^0 and ϕ vs MC generators

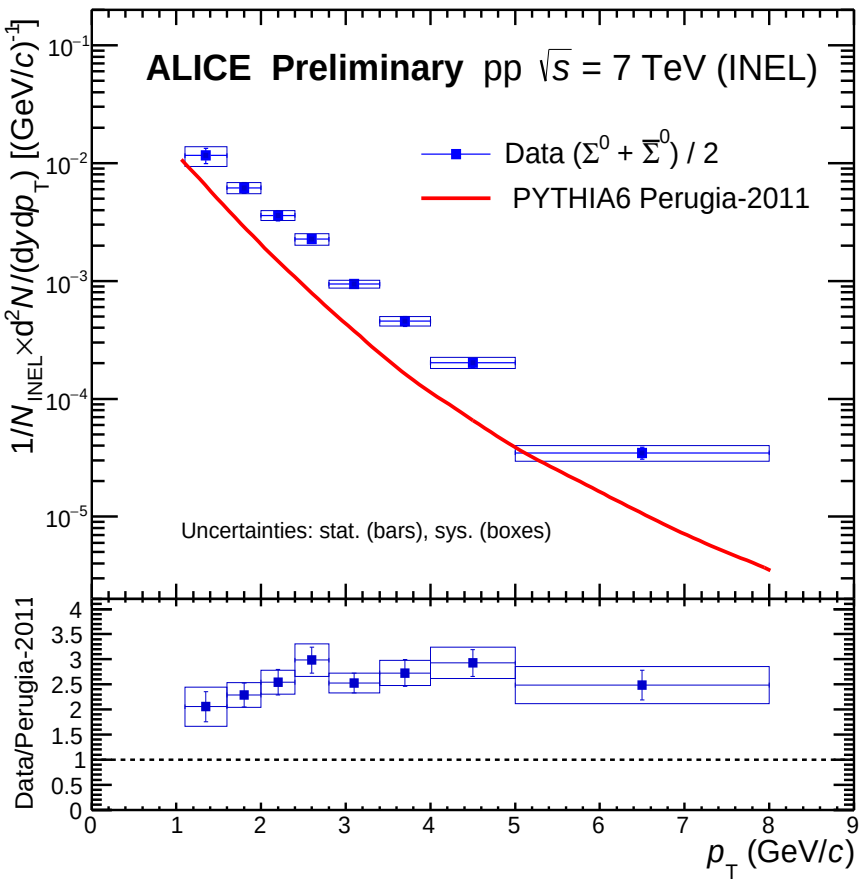


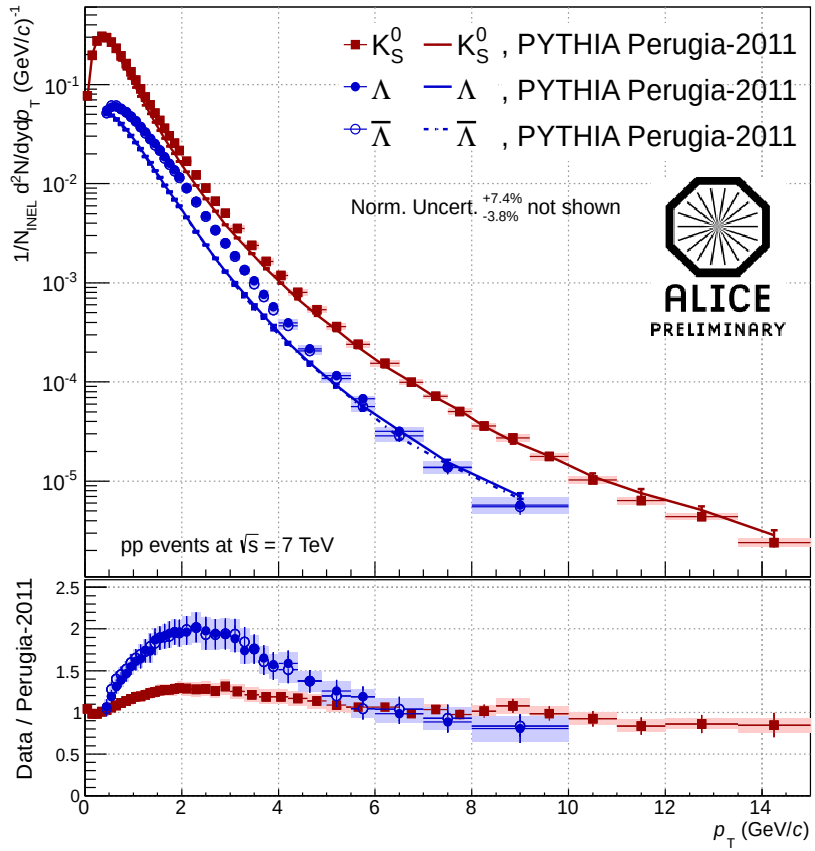


- ρ^0: in pp collisions at 2.76 TeV: all models overpredict at $p_{\mathrm{T}} \leq 1$ GeV/c
- ρ^0, ϕ: PHOJET, PYTHIA ATLAS-CSC, PYTHIA Monash 2013 tend to under-predict yields for $p_{\mathrm{T}} > 1$ GeV/c
- **ϕ: PYTHIA D6T describes data, over-predicts ρ^0 yield for 2 $< p_{\mathrm{T}} <$ 5 GeV/c**
- **ρ^0: PYTHIA Perugia 11 describes data within uncertainties for $p_{\mathrm{T}} >$ 1 GeV/c**

Σ^0 and Λ vs PYTHIA6

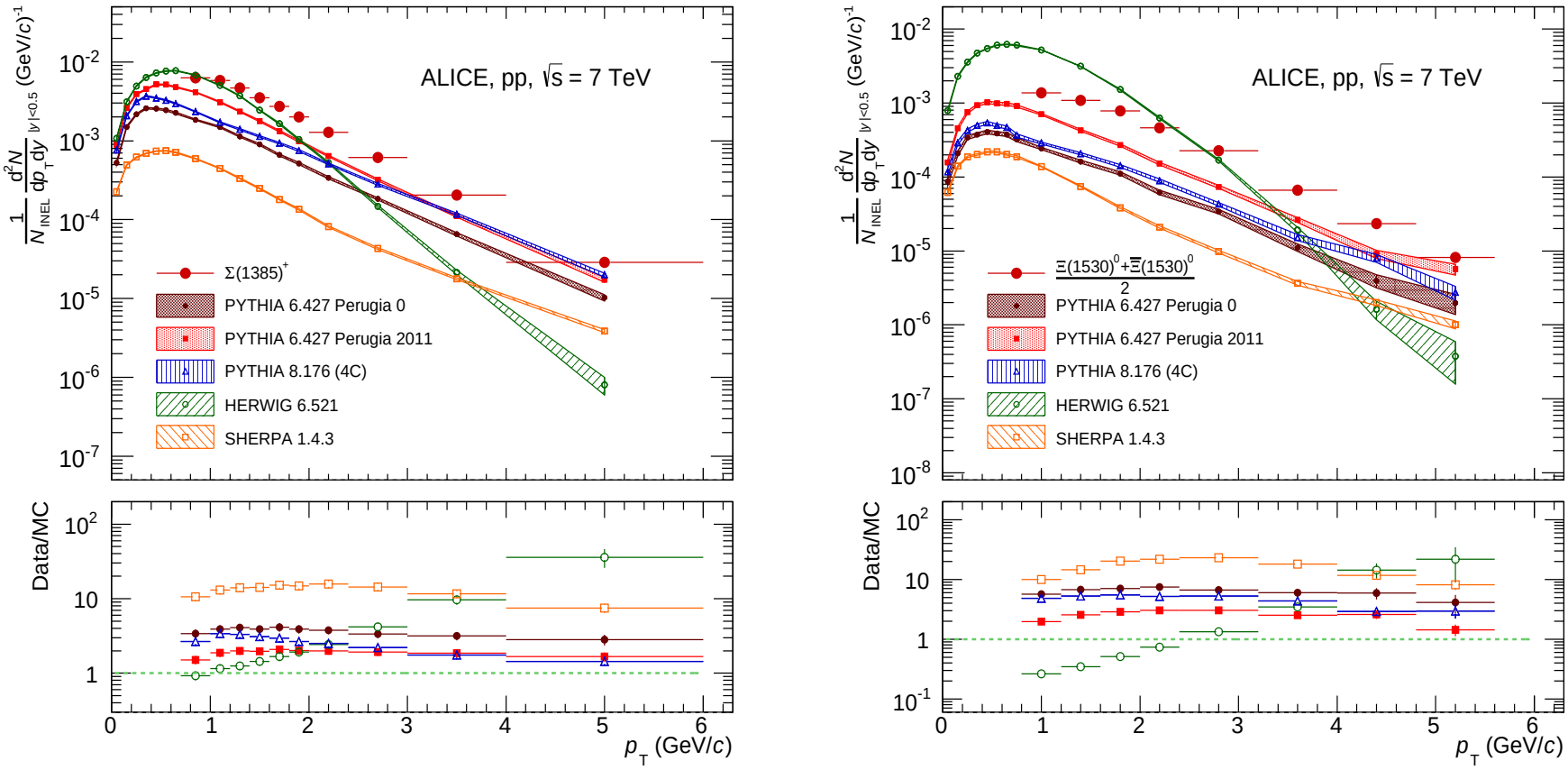
(ALICE, Phys. Rev. Lett. 111 (2013) 222301; D.D.Chinellato arXiv:1211.7298 [hep-ex])





⟹ **PYTHIA6 Perugia-2011 clearly underestimates the production of both ground-state hyperons in the intermediate p_{T} -range**

$\Sigma(1385)^{\pm}$ and $\Xi(1530)^{0}$ vs models



(ALICE, Eur. Phys. J. C 75 (2015) 1)

- **PYTHIA underpredicts the data**
- PYTHIA 4C with color reconnection gives qualitative agreement in spectral shape
- HERWIG predicts a much softer production than other models and data.
- SHERPA describes the spectral shape, but largely underestimates the yields

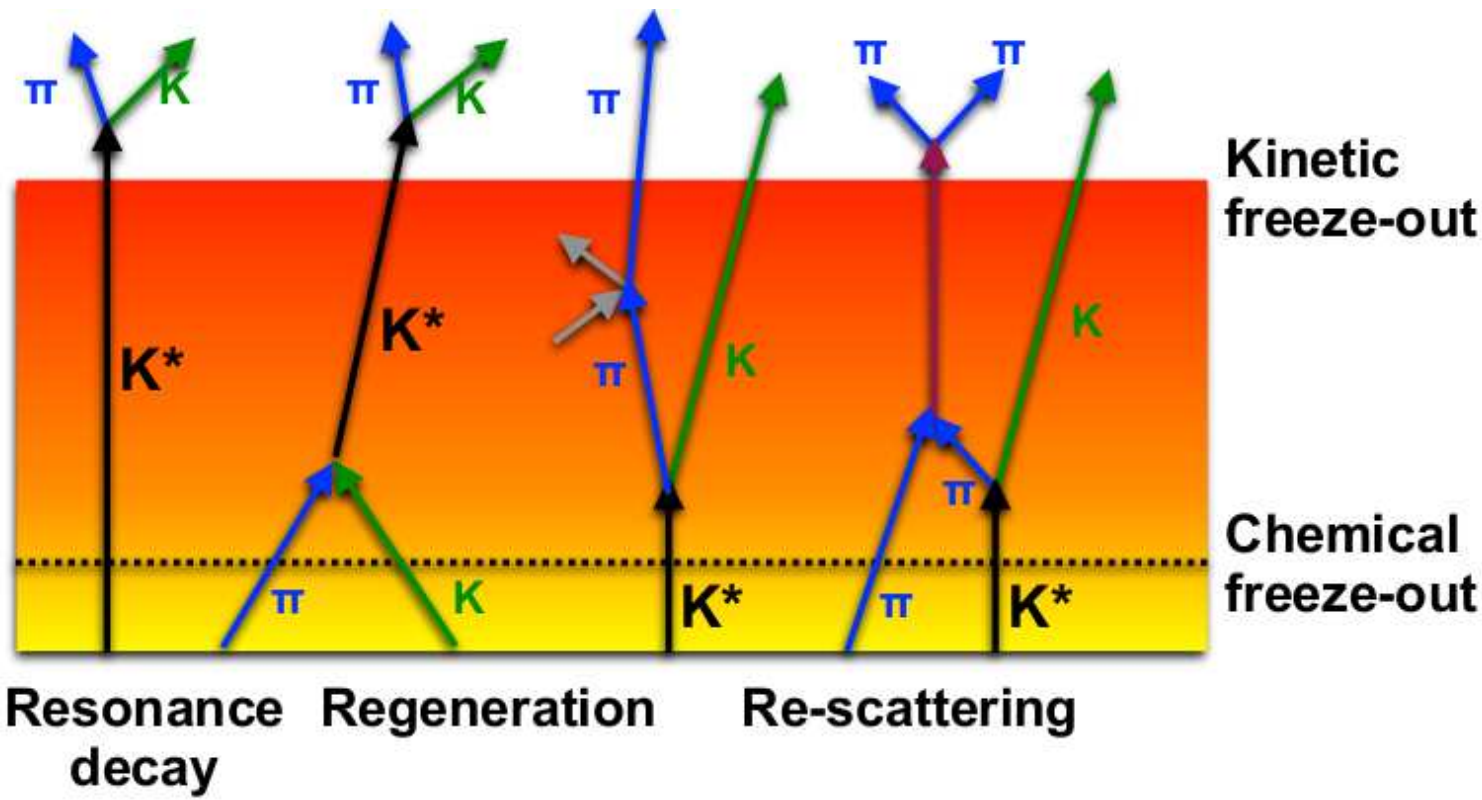
Study of hadronic phase

Hadronic phase

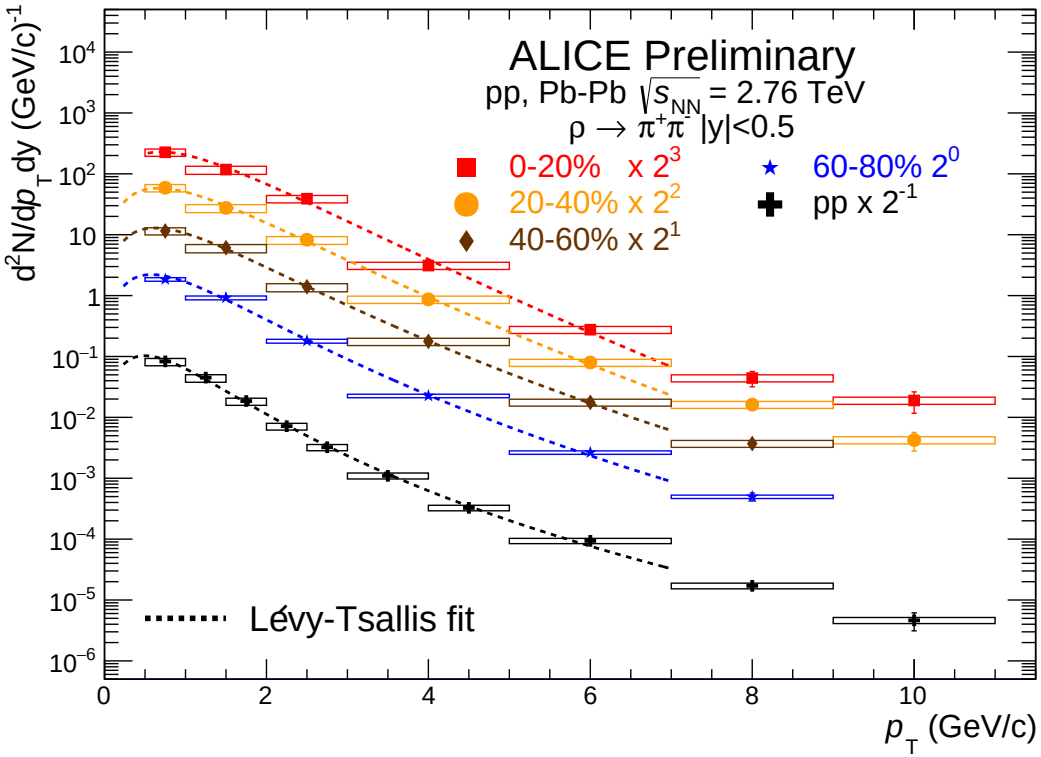
Resonance yields are determined at chemical freeze-out, when inelastic interactions cease.

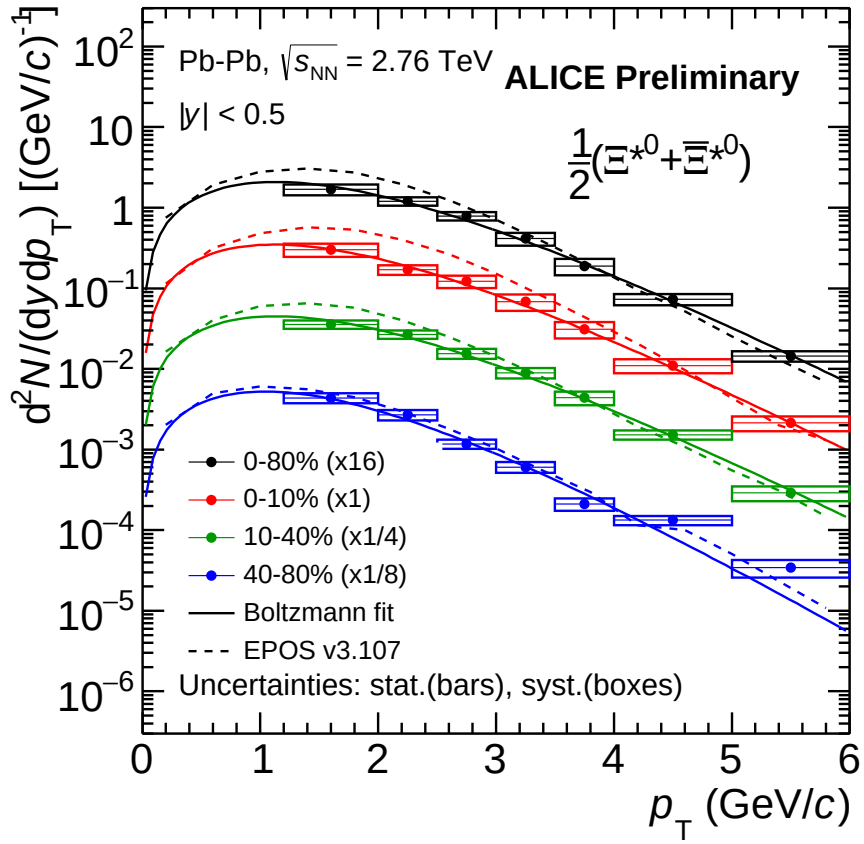
Between chemical and kinetic freeze-out the yields can be modified by (pseudo) elastic interactions in the hadronic medium

- regeneration: pseudo-elastic scattering of decay products ($\pi^+ + \pi^- \rightarrow \rho^0$, π+K$\rightarrow$K^{*0}, etc.) $\Longrightarrow$ increased yields
- re-scattering: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance $\Longrightarrow$ mother particle is not reconstructed $\Longrightarrow$ loss of signal



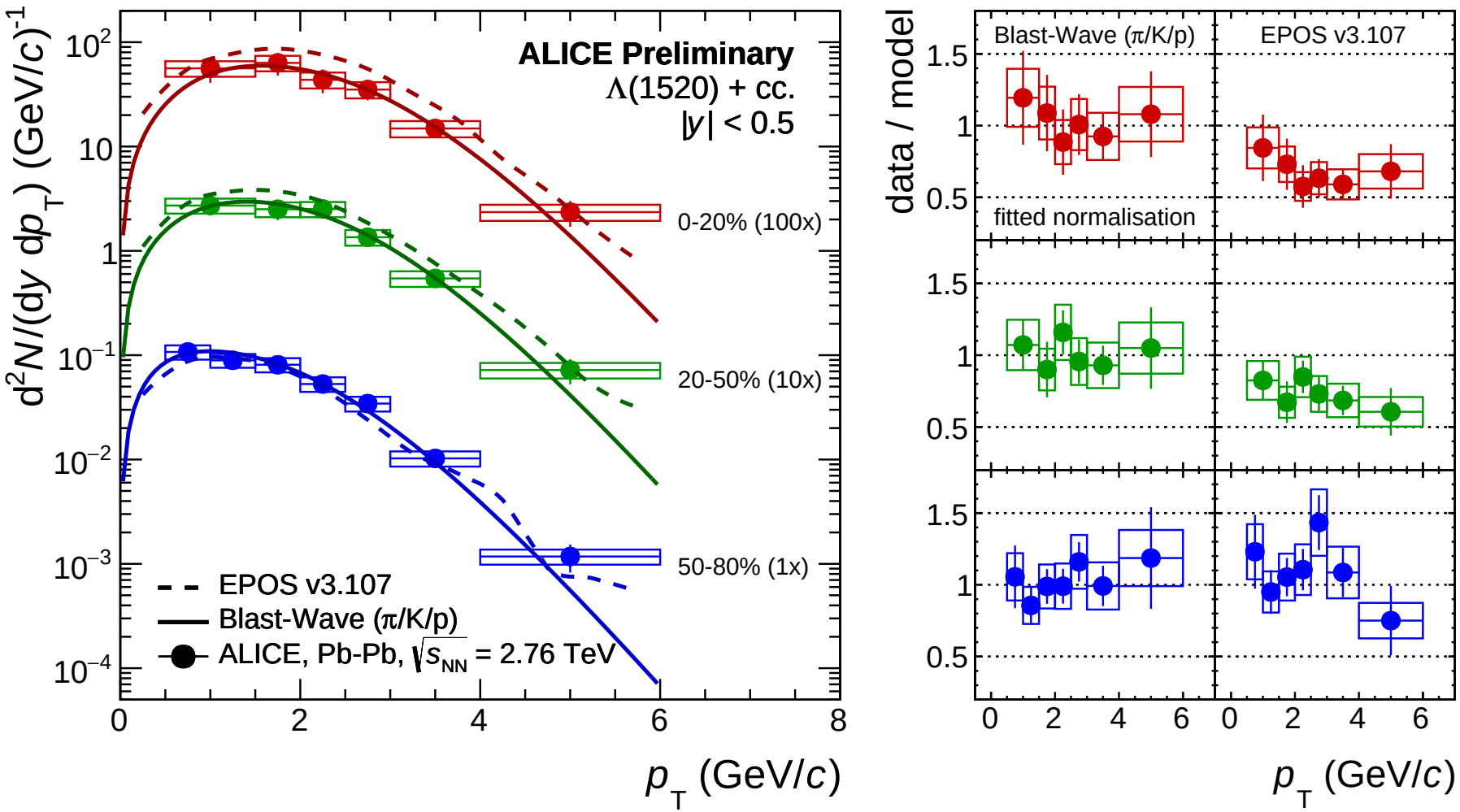
New ρ^0 and Ξ^* spectra in Pb-Pb





- Lévy-Tsallis fit for ρ^0 and Boltzmann fit for Ξ^* describes the data
- EPOS3 model (A.Knospe et al., Phys.Rev. C 93 (2016) 014911) slightly over-predicts the yield for central collisions.

New $\Lambda(1520)$ spectrum in Pb-Pb



- Blast-wave prediction (A.Schnedermann et al., Phys.Rev. C 48 (1993) 2462) with parameters from $\pi/K/p$ (ALICE, Phys.Rev. C 88 (2013) 044910)
- EPOS3 model (A.Knospe et al., Phys.Rev. C 93 (2016) 014911) slightly over-predicts the yield for central collisions.

ρ^0/π and K^{*0}/K in Pb-Pb

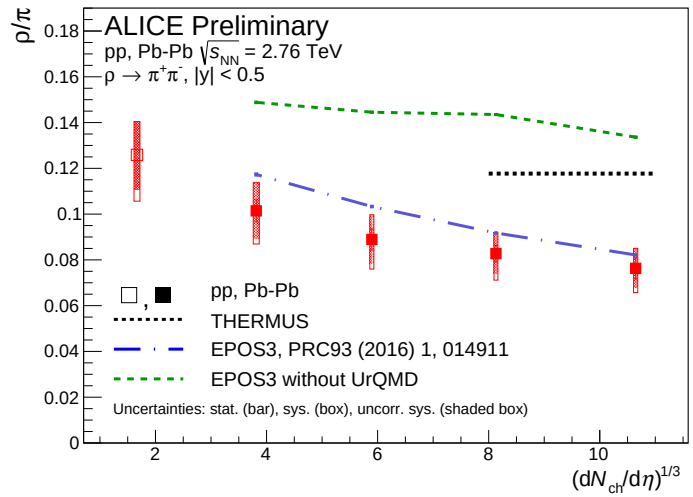
- ρ^0/π, K^{*0}/K ratios are suppressed in the most central PbPb collisions with respect to pp and peripheral PbPb collisions.
- ϕ/K has weak centrality dependence without any suppression

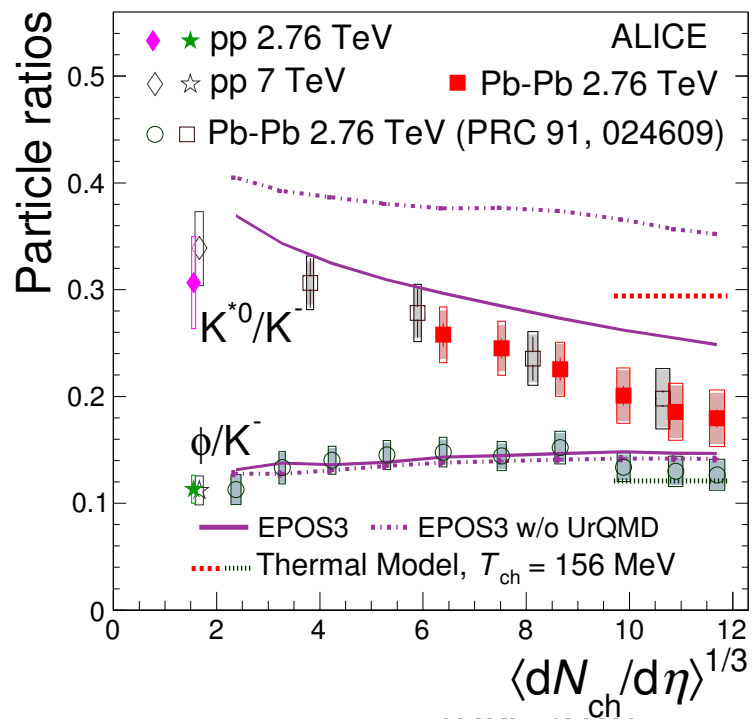
(ALICE, arXiv:1702.00555; Phys. Rev. C 91 024609 (2015); Eur. Phys. J. C 76 245 (2016))

$\Longrightarrow$ Strong suppression of ρ^0/π and K^{*0}/K suggests that the rescattering of their decay products in the hadronic medium reduces the short-lived resonance yield.

$\Longrightarrow$ The suppression is described by EPOS3 with hadronic cascade modeled by UrQMD.

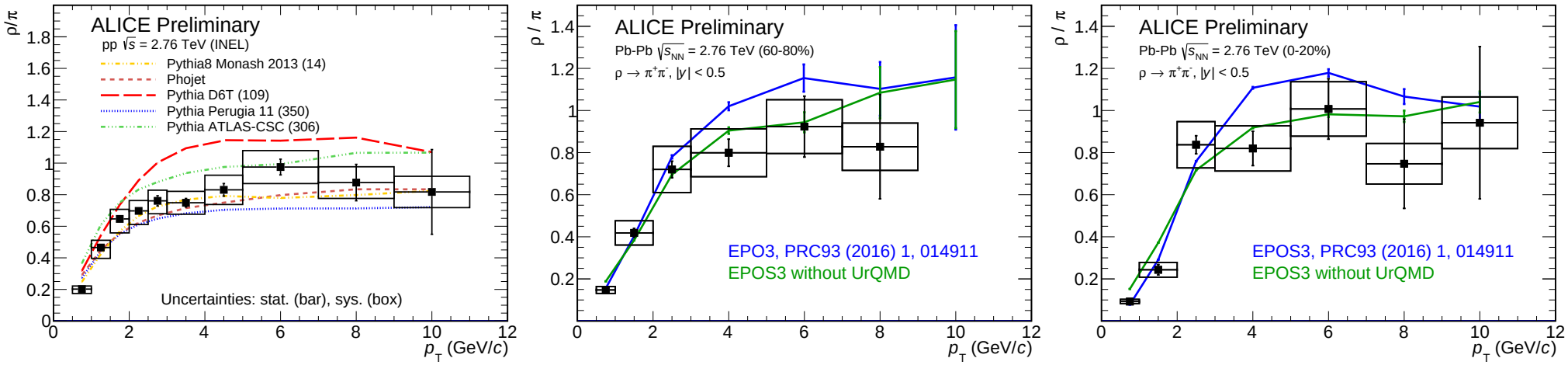
Note, that ϕ yields are not affected significantly, as its lifetime is long enough to decay outside the hadronic medium ($\tau_\phi \sim 10 \times \tau_{K*0}$ and $\tau_\phi \sim 35 \times \tau_{\rho 0}$).





ρ^0/π ratio vs. p_{T} in pp and Pb-Pb

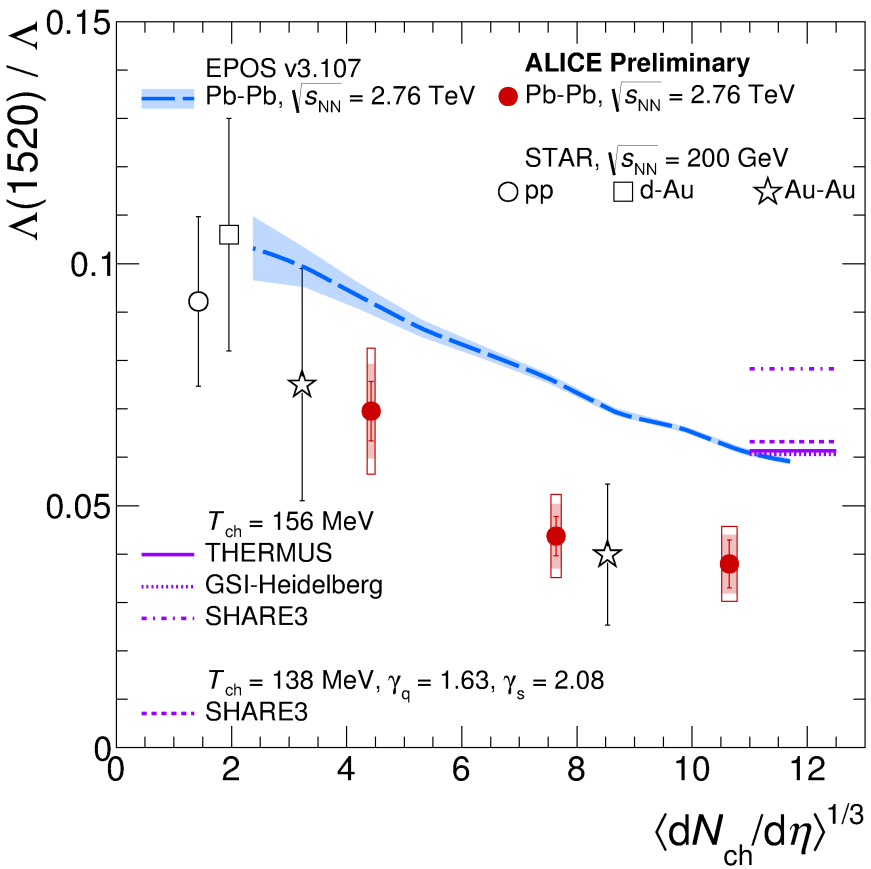
Evolution of the ρ^0/π ratio from pp to peripheral Pb-Pb, to central Pb-Pb collisions

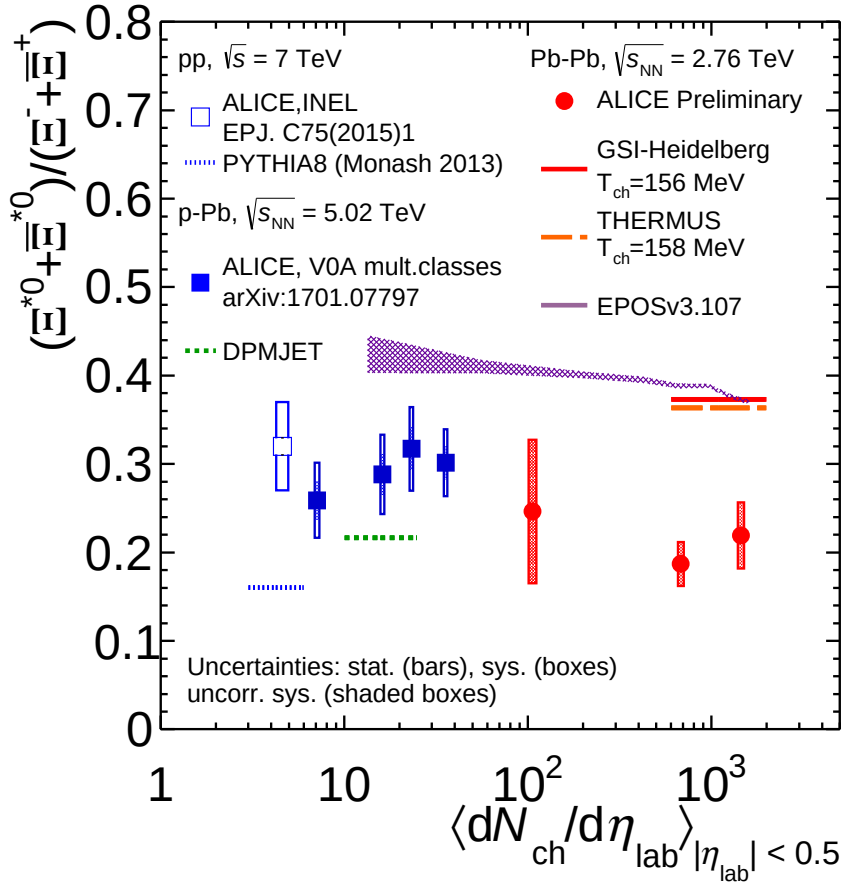


- ρ^0 is suppresed in central collisions (0-20%) in Pb-Pb for $p_{\mathrm{T}} < 2$ GeV$/c$.
- EPO3S without UrQMD overestimates the observed ratio at low p_{T} .
- EPOS3 with UrQMD better reproduces the ratio at low p_{T} .

$\Longrightarrow$ Hints at reduction of ρ^0 yield due to dominance of re-scattering over regeneration processes

Λ (1520)/Λ and $\Xi(1530)^0/\Xi$ in Pb-Pb



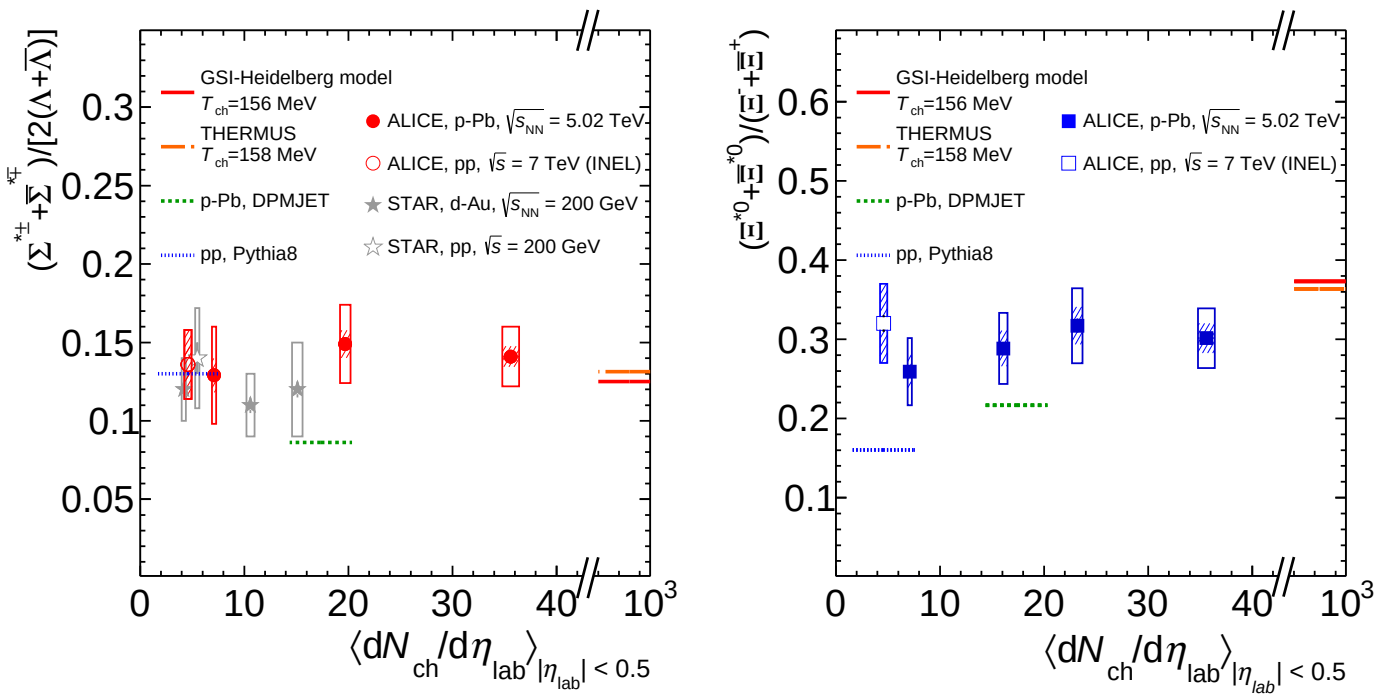


- $\Lambda(1520)$ suppression in central collisions in comparison with peripheral
- The EPOS3 model employing UrQMD qualitatively reproduces the trend.

- Smaller ratio of $\Xi(1530)^0/\Xi$ in Pb-Pb than in p-Pb collisions may be the indication on the centrality dependence
- $\Xi(1530)^0/\Xi$ in central Pb-Pb is found to be suppressed with respect to the thermal model prediction. EPOS3 with UrQMD predicts a flatter trend with centrality

$\Sigma(1385)^{\pm}/\Lambda$ and $\Xi(1530)^{0}/\Xi$ in p-Pb

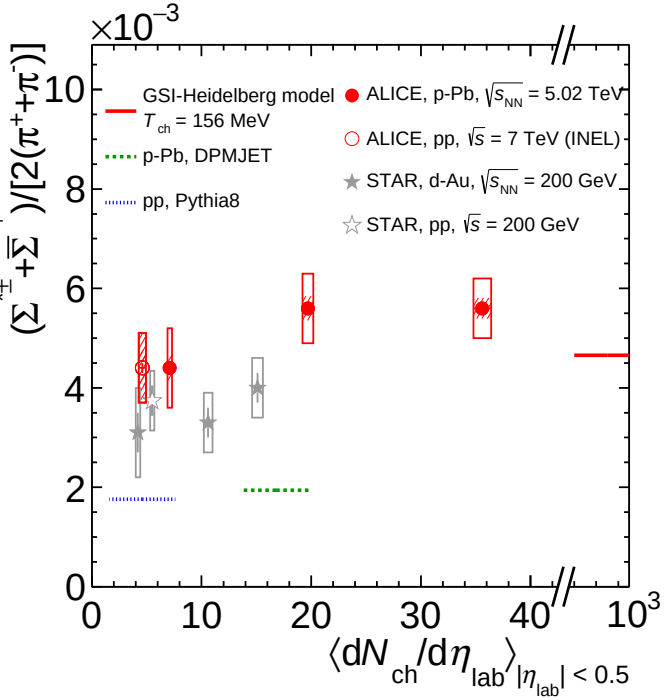
(ALICE, arXiv:1701.07797 [nucl-ex])

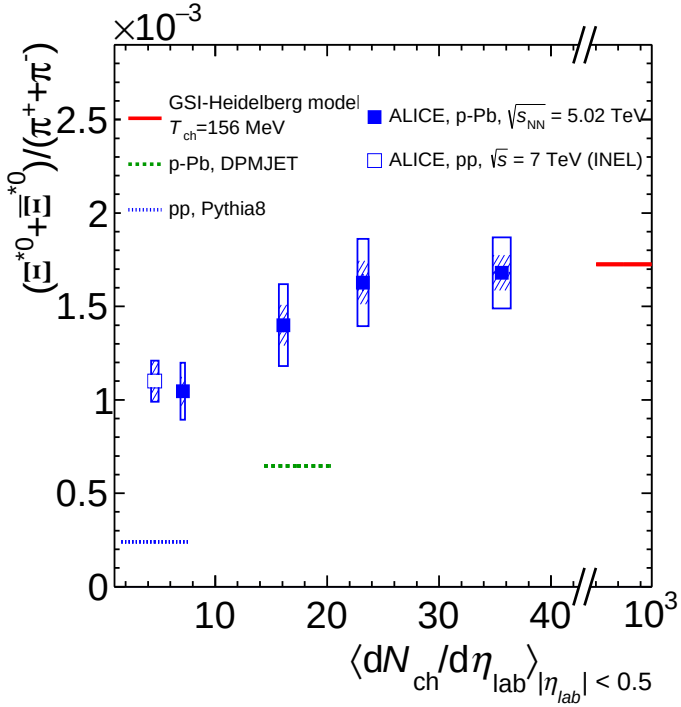


- $\Sigma(1385)^{\pm}/\Lambda$ and $\Xi(1530)^{0}/\Xi$ constant ratios in p-Pb
  - are remarkable, despite their very different lifetimes, spin and mass

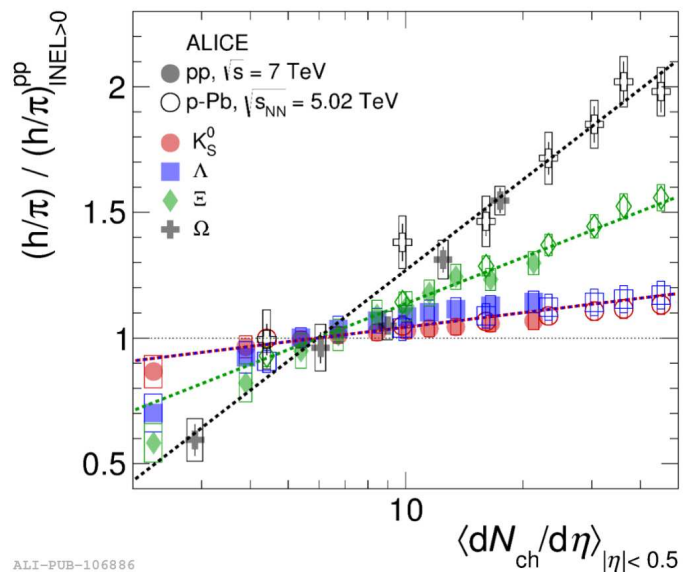
$\Sigma(1385)^{\pm}/\pi$ and $\Xi(1530)^{0}/\pi$ in p-Pb

(ALICE, arXiv:1701.07797)





(ALICE, arXiv:1606.07424)



- $\Sigma(1385)^{\pm}/\pi$ and $\Xi(1530)^{0}/\pi$ ratios of yields in p-Pb increase by 40-60% relative to results in pp collisions, depending on the strangeness contents
- Clear dependence of the slope of double-ratio of the ground-state hyperons to pions on strangeness content

$\Longrightarrow$ **Indication that the strangeness enhancement in p-Pb depends predominantly on strangeness content**

Summary 1: pp data

- **First measurement of cross section ratio $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ at $\sqrt{s}$ = 7 TeV at the LHC.**
  - The results can help to constrain production models and contribute to the previously very limited set of world data.
  - Knowledge of Σ^0 production rates are important to constrain feed-down corrections for proton and pion spectra.
  - Dedicated paper is under development, analysis of ALICE p-Pb and Pb-Pb data has started.

$\Longrightarrow$ **Reasonable agreement with QCD based generators is seen for ρ and ϕ p_{T} -spectra.**

$\Longrightarrow$ **Disagreement with the generators is observed for Λ , Σ^0 , $\Sigma(1385)^{\pm}$, and $\Xi(1530)^0$ p_{T} -spectra.**

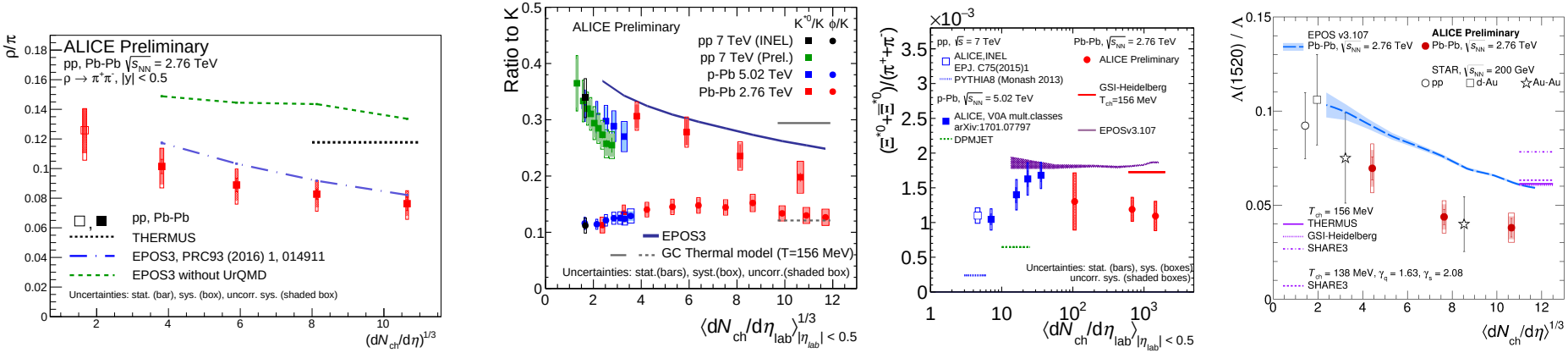
Summary 2: p-Pb and Pb-Pb data

- The $\Sigma^{*\pm}/\Lambda$, Ξ^{*0}/Ξ and $\Sigma^{*\pm}/\pi$, Ξ^{*0}/π ratios indicate that the strangeness enhancement observed in p-Pb collisions depends predominantly on the strangeness content, rather than on the hyperon mass.

- The $\Xi^{*\pm}/\Xi$ results in Pb-Pb indicate a significant suppression with respect to the thermal model predictions and a hint of a centrality dependence.

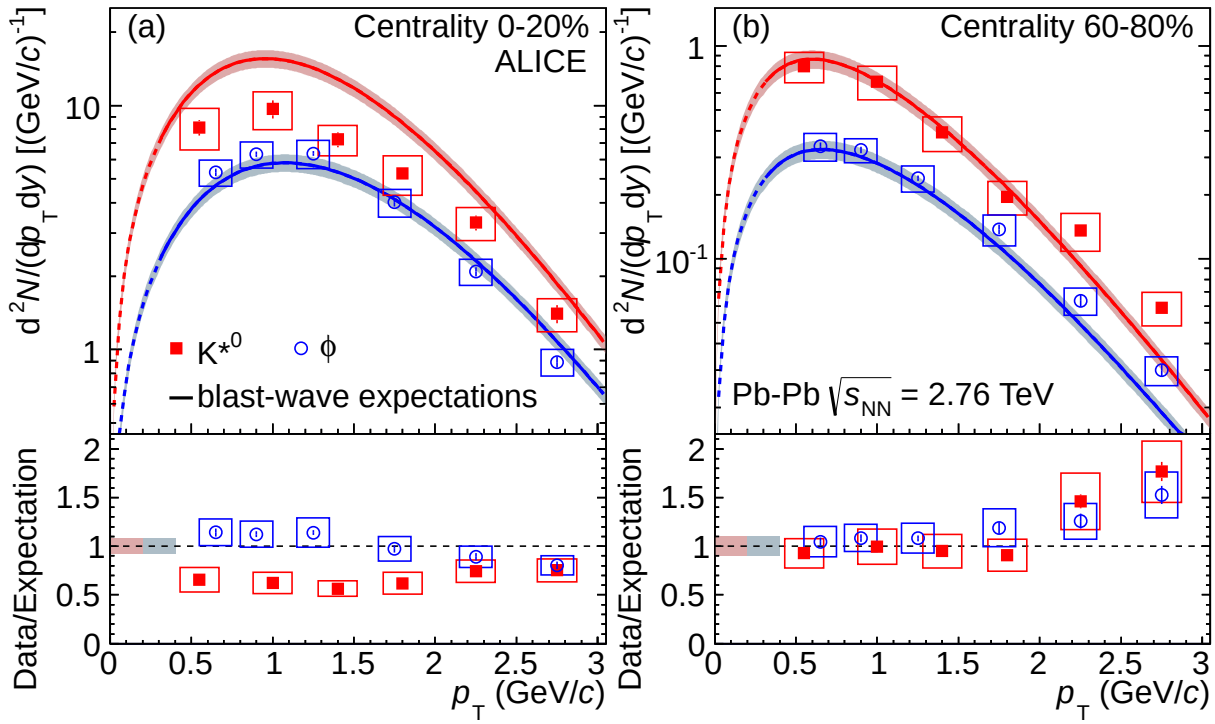
- **EPOS3 model with UrQMD qualitatively reproduces the ratios of the resonances spectra in Pb-Pb data.**

- **A set of ALICE measurements of resonance to long-lived hadrons ratios suggest that short-lived resonance production (ρ^0, K^{*0}, Λ^*, Ξ^{*0}) is affected by re-scattering in the hadronic phase, mainly at low-p_T .**



Backup slides

K^{*0} and ϕ spectra w.r.t. calculation

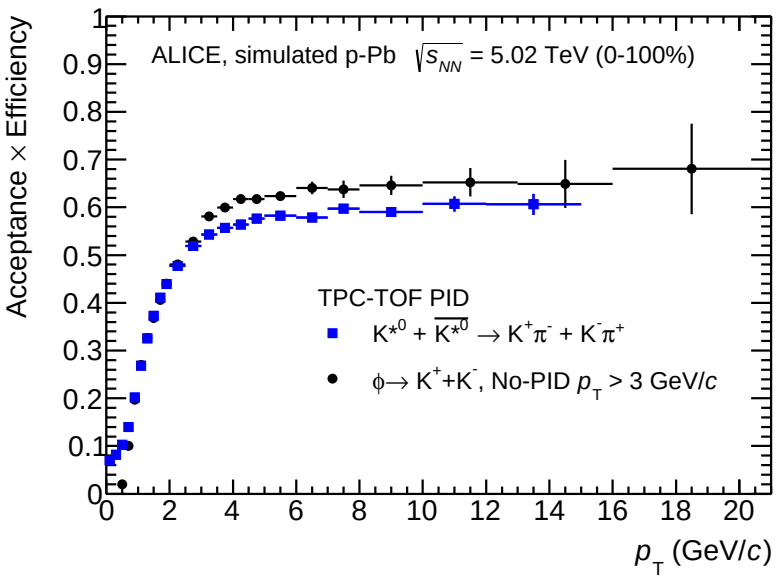


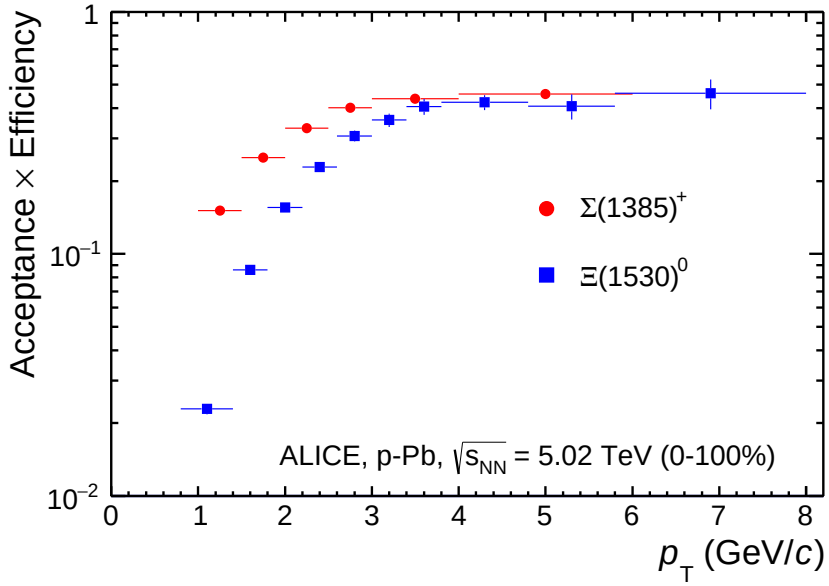
(ALICE, Phys. Rev. C 88 044910 (2013))

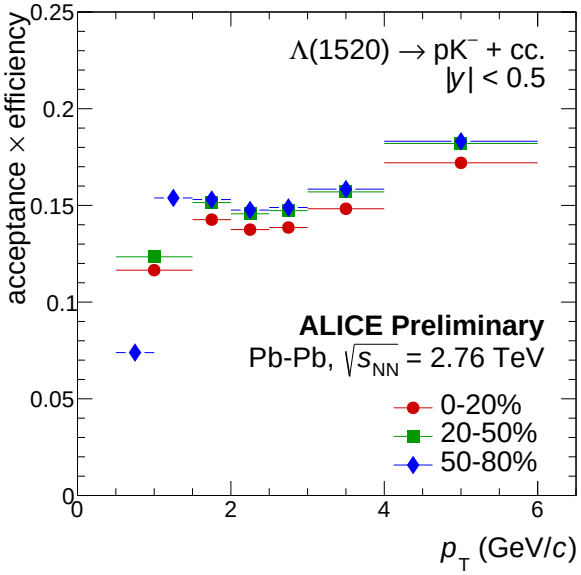
- p_{T} distribution from blast-wave model
  shape: parameters (Tkin, n, β) from combined fits of π/K/p in PbPb
  normalization: K yield $\times$ K^{*0}/K ratio from thermal model (Tch=156 MeV)

- **Central collisions, K^{*0}: reduction of yield for $p_{\mathrm{T}} <$ 3GeV/c is consistent with re-scattering picture**
- **Central collisions, ϕ: no suppression**

Backup. Acceptance×efficiency factors







Backup mean p_T