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High Energy Physics and Quantum Field Theory
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Production of Σ^0 hyperon at LHC with ALICE

- Introduction
- Detection of Σ^0
- Σ^0 world data and Σ^0/Λ cross section ratio
- Tests of QCD inspired MC event generators
- Summary and outlook

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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, 8.16 TeV), Xe-Xe (5.44 TeV) and Pb-Pb (2.76, 5.02 TeV)** collisions at ALICE

Resonances in different collision systems

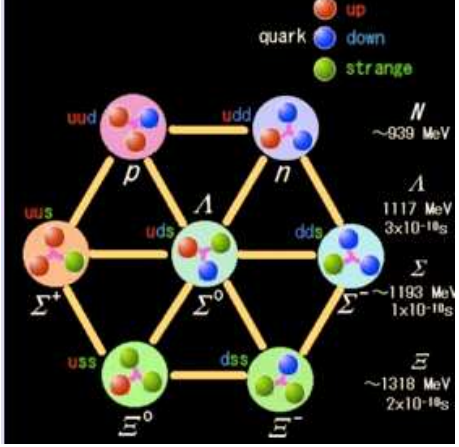
- Copiously produced and measurable in different collision systems
  $\Longrightarrow$ benefit from precise measurements of p_{T} spectra and yields

- pp: baseline measurements
  - contribution to the understanding of hadron production mechanisms
  - tuning of QCD inspired Monte Carlo event generators
  - onset of collectivity

- p-Pb: cold nuclear matter effects, onset of collectivity

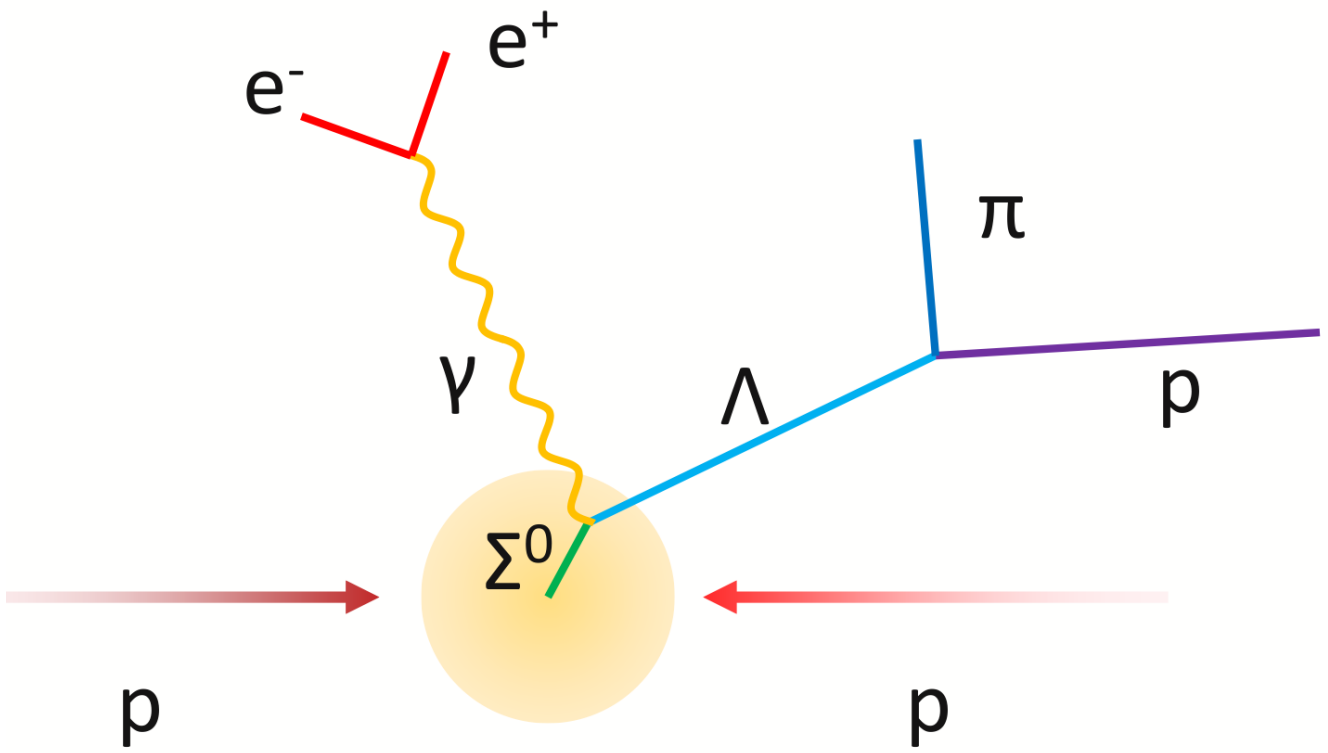
- Pb-Pb: properties of the hadronic phase and collectivity.
  - Different quark contents allow to study flavor dependence of energy loss in Pb-Pb collisions.
  - Resonances with different lifetimes are used to study the properties of the hadronic phase in Pb-Pb collisions

Σ^0 in pp collisions



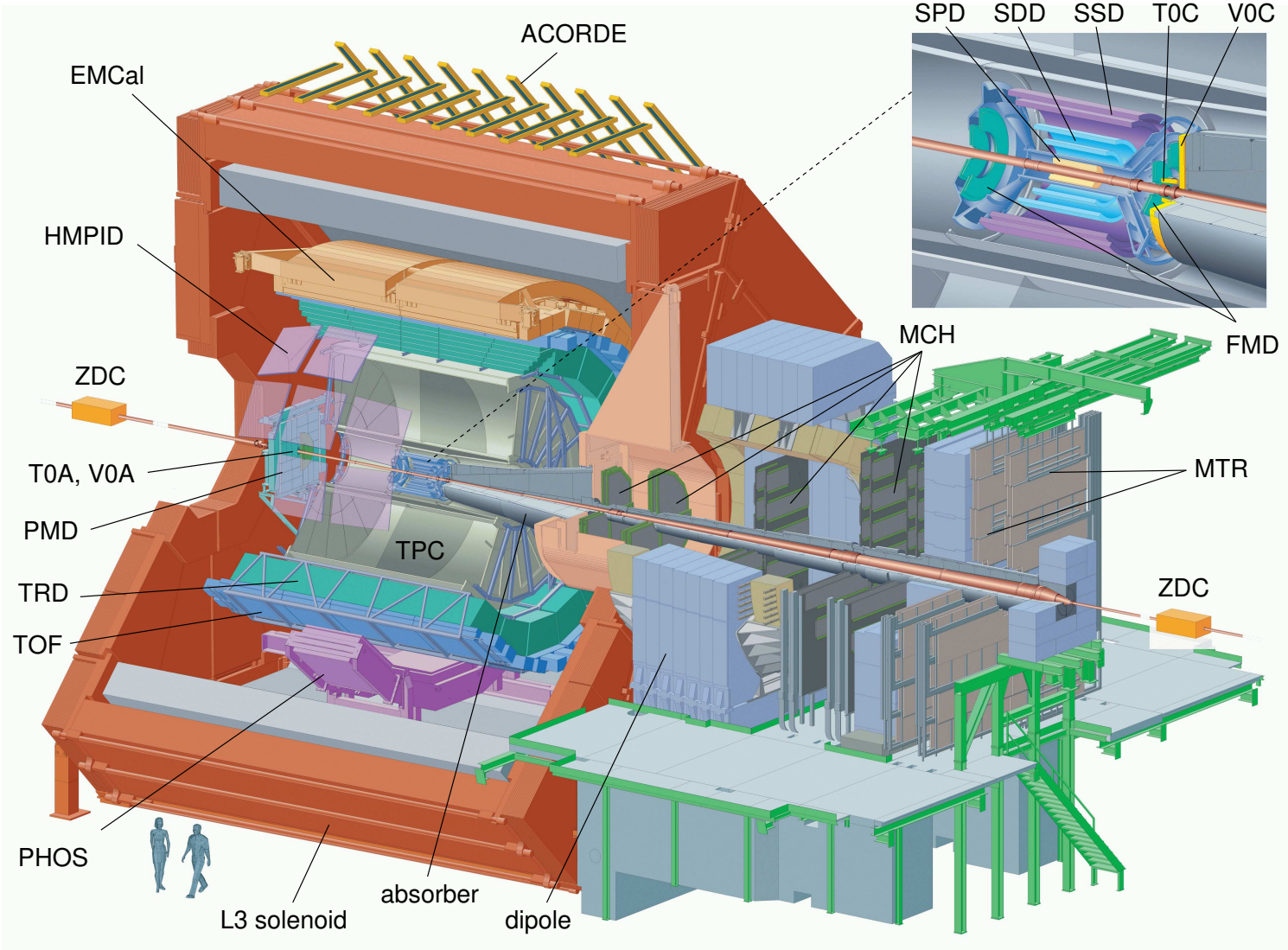
- **No experimental measurements at energies larger than 91 GeV.**
- Constrain feed-down corrections for protons, pions and direct photons at low transverse momenta.
- Discrimination of prompt and decay hyperons: prompt Λs vs ones from Σ^0 decay.
- Comparison with the Λ baryon, which has the same quark content but different isospin.
- Contribution to the understanding of hadron production mechanisms, input and comparison with statistical hadronisation models such as THERMUS.
- Reference for tuning Monte Carlo event generators such as PYTHIA, EPOS and DIPSY.
- Baseline for comparison with PbPb data.

Topology of the detection of $\Sigma^0 \to \Lambda + \gamma$ and $\overline{\Sigma}^0 \to \bar{\Lambda} + \gamma$



(without the lifetime scale, yellow circle only for Σ^0 vizualization)

The ALICE detector



ITS, TPC and TOF are mainly used for the for reconstruction and identification of tracks

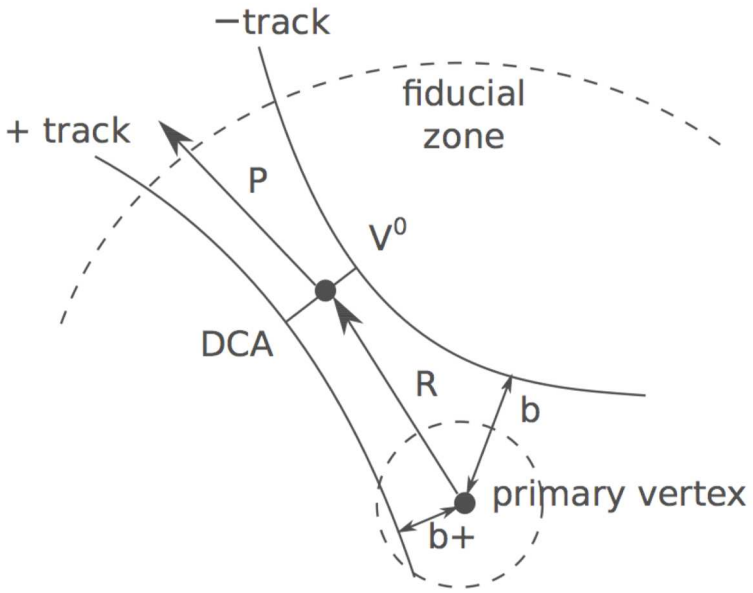
V0A+V0C and ZDC for multiplicity, centrality, trigger and timing.

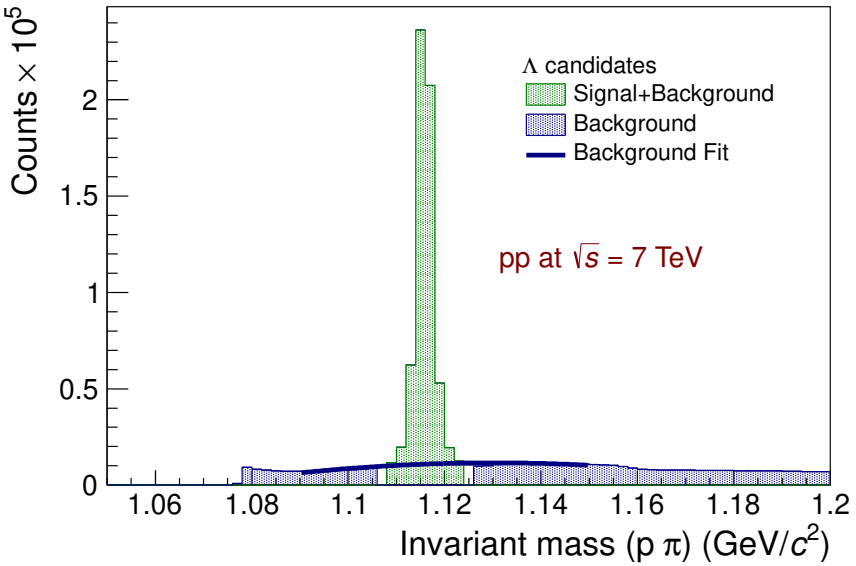
Unique particle identification, high granularity, tracking down to p_{T} 0.1 GeV/c.

Size 16$\times$ 26 meters, weight $\sim$ 10000 tons.

$\Lambda\ (\bar{\Lambda}\ ) \rightarrow p\pi^{-}(\bar{p}\pi^{+})$ detection

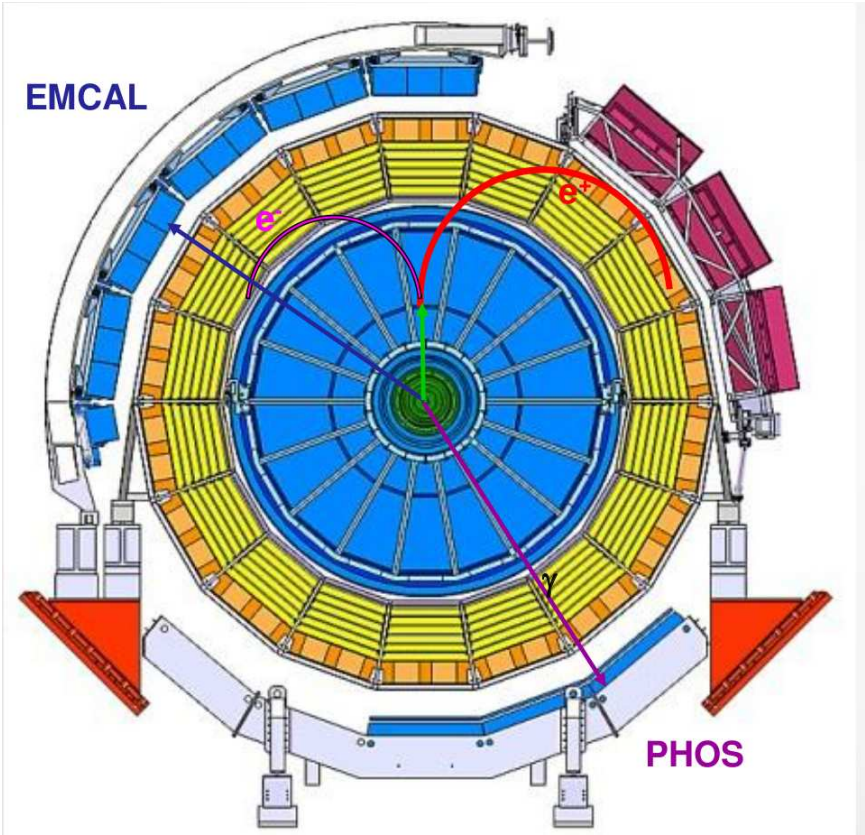
(ALICE collab., Eur. Phys. J. C 73 (2013) 2496)

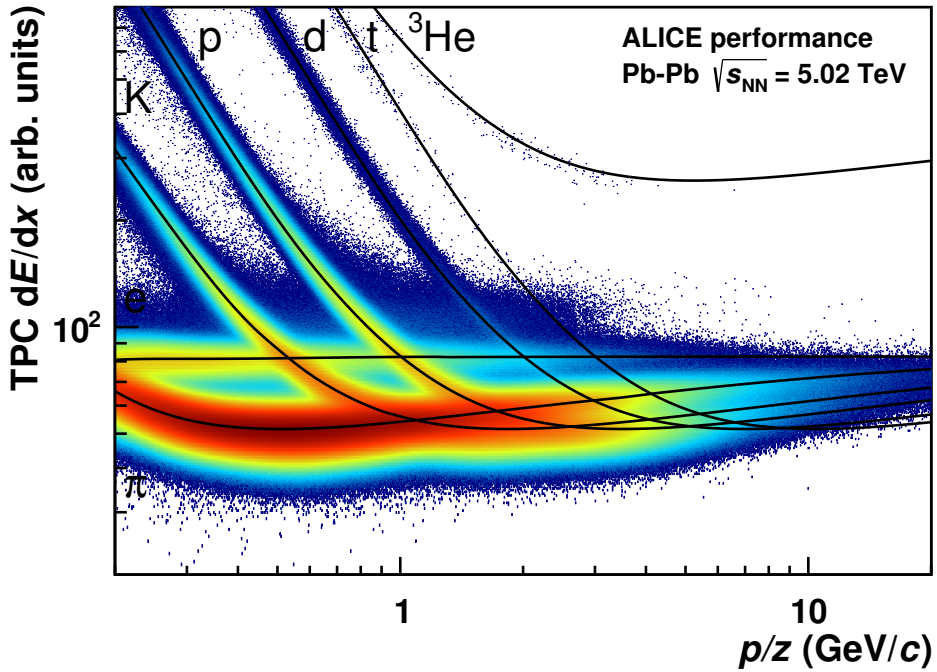




- secondary vertex (V^0) with oppositely charged tracks
- V^0 radius $R = \sqrt{x_{V^0}^2 + y_{V^0}^2}$ $(0.5 < R < 180$ cm)
- distance of closest approach (b) between positive (neg.) track and primary vertex > 0.06 cm
- pointing angle θ_Λ between P and a vector connecting the primary vertex and the V0 position $\cos\theta_\Lambda > 0.993$
- for Σ^0 analysis Λ selected in narrow region of $1.110 < M_{\Lambda\ (\bar{\Lambda}\ )} < 1.20$ GeV$/c^2$

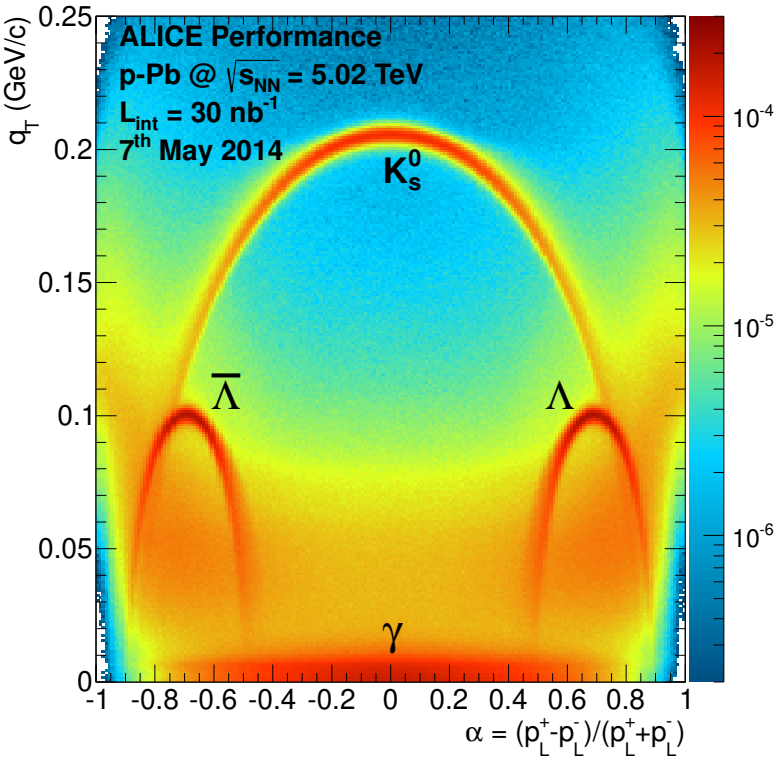
Photon detection in ALICE

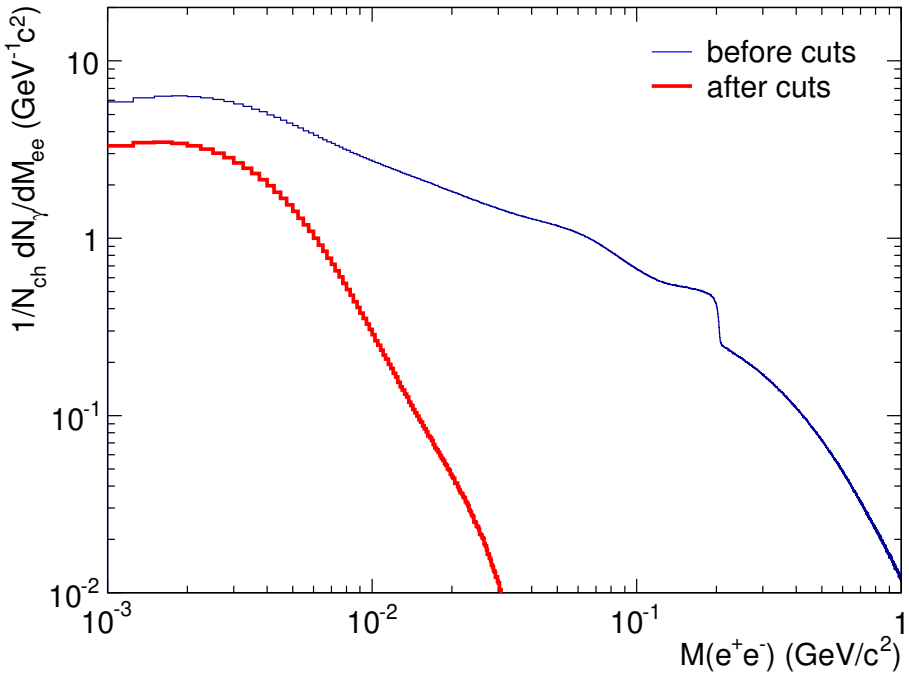




- EMCAL: large acceptance (100^o, $|\eta| < 0.9$) but limited energy resolution
- PHOS: good energy resolution but limited acceptance (60^o, $|\eta| < 0.135$)
- Photon Conversion Method (PCM)
  - good momentum resolution at low $p_{\mathrm{T}} \sim 1 - 5$ %
  - excellent particle identification capabilities in large p_{T} range 0.1 - 20 GeV/c
  - full azimuthal angle coverage ($|\eta| < 0.9$)
  - small conversion probability (~ 8.5 %)

γ reconstruction

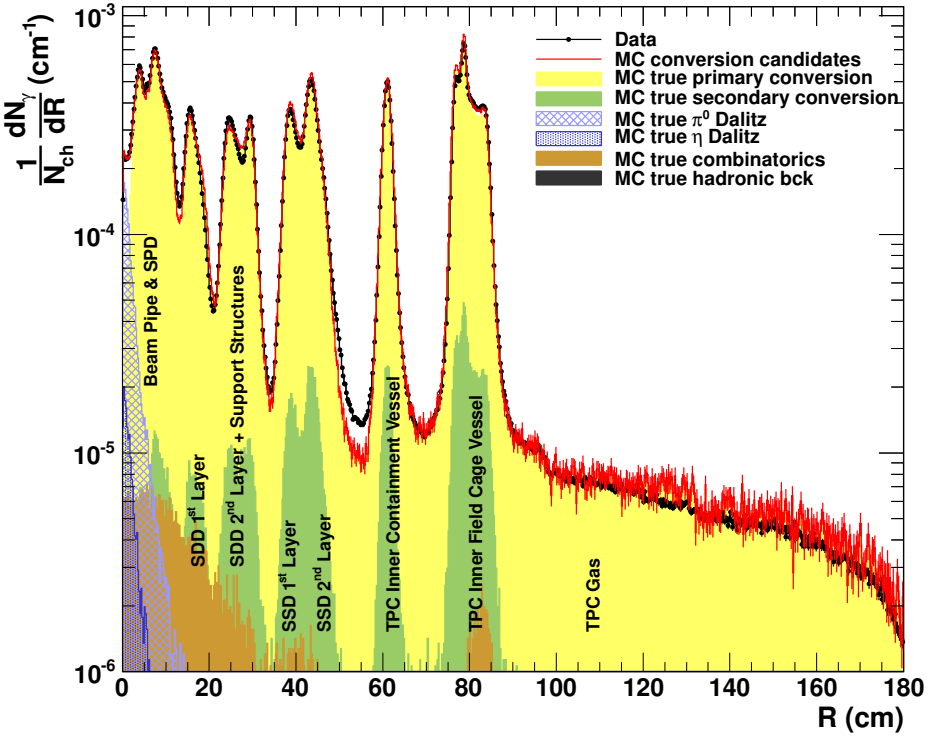


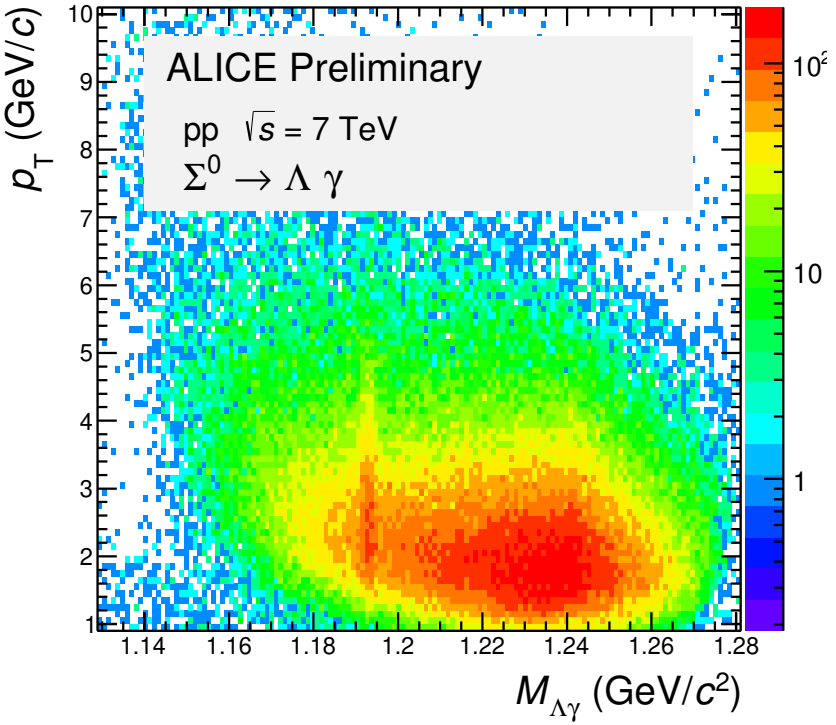


- $e^+(e^-)$ track selection with track $p_{\mathrm{T}} > 50$ MeV/c
- γ conversion vertex at distance to primary vertex $5 < R < 180$ cm
- cut on the angle between e^+e^- pair plane and the plane perpendicular to the magnetic field of the ALICE magnet
- remaining V0 (Λ , K^0_S) removed with further selections: $q_{\mathrm{T}} < 0.05$, corresponding to transverse momentum of e^+ with respect to the γ momentum.

  $\Longrightarrow$ small contamination of the photon sample

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

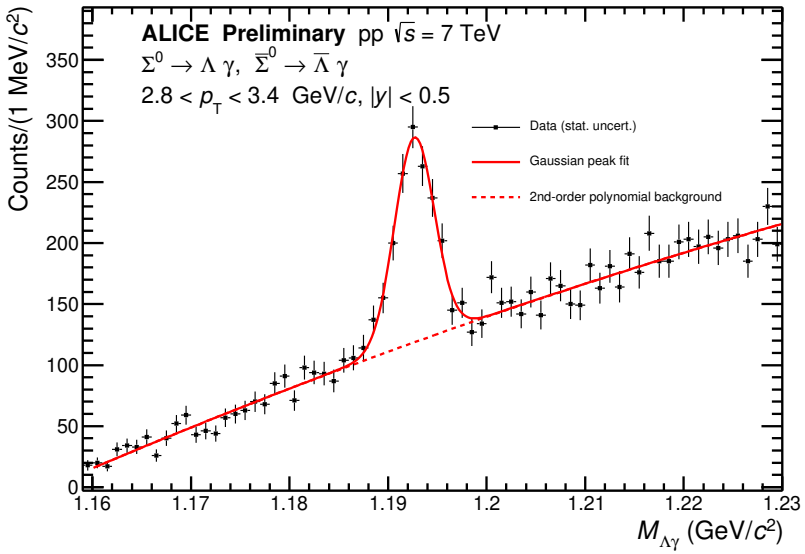


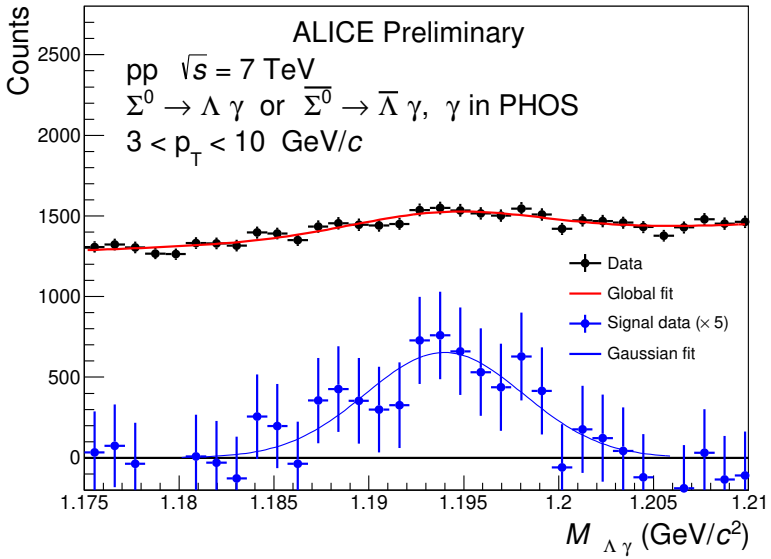


- $\gamma \to e^+ + e^-$ is detected through the secondary V^0 vertex with Photon Conversion Method (PCM) in the central barrel detectors
- The distribution of the conversion points is well reproduced by MC. The radiation thickness of the detector material integrated for $R < 180$ cm and $|\eta| < 0.9$ is determined to be 11.4 $\pm 0.5\%$ X_0 (ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044).

  $\Longrightarrow$ Clear Σ^0 invariant mass peak

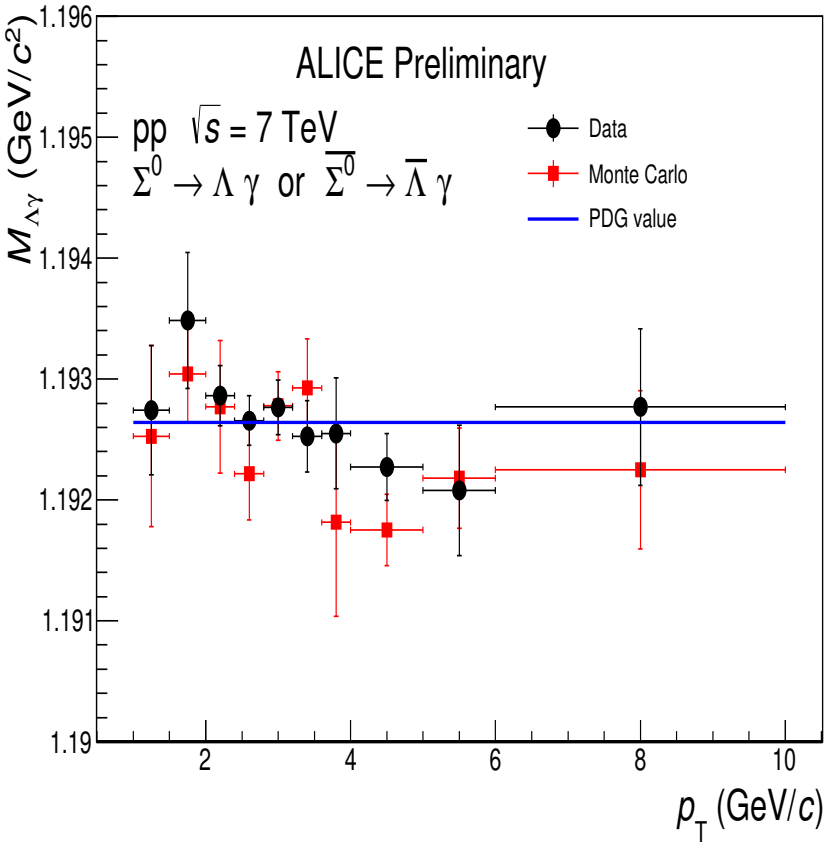
$\Sigma^0 \to \Lambda + \gamma$ and $\bar{\Sigma}^0 \to \bar{\Lambda} + \gamma$ decays

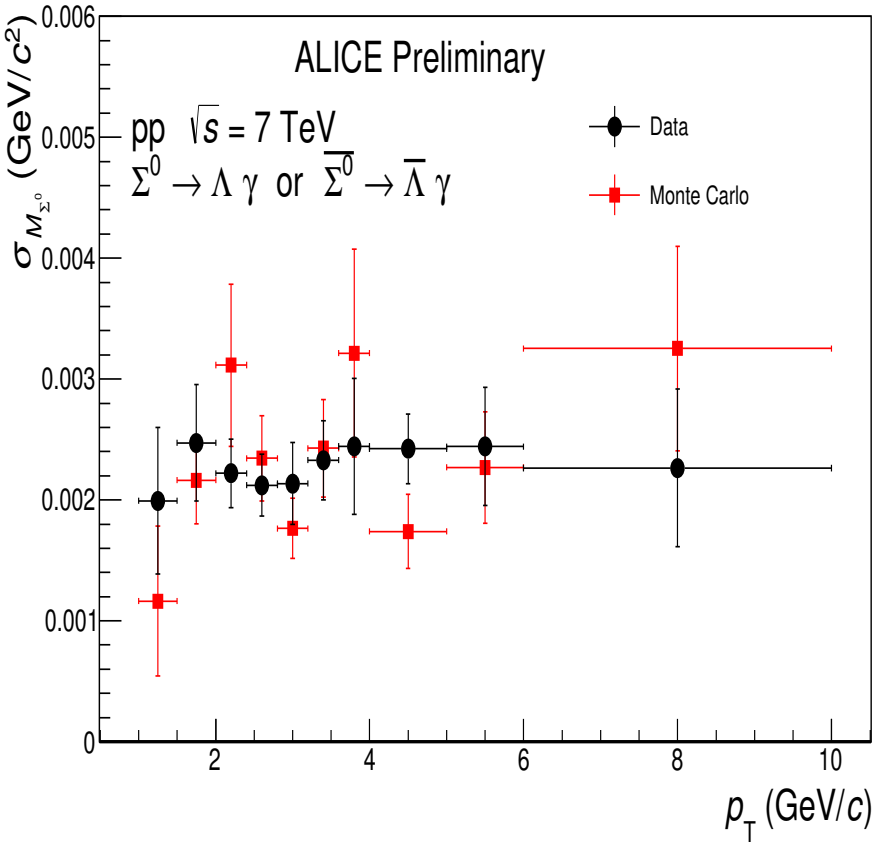




- Σ^0 invariant mass is calculated from the mass of the selected Λ and γ candidates. **Note low $E_\gamma \approx$ 100 MeV.**
- Σ^0 mass resolution $\sigma_M^{PCM} = 2$ MeV/c^2 at $2.8 < p_{\mathrm{T}} < 3.4$ GeV/c
- Proof-of-principle: Σ^0 peak is also observed with photon detected in PHOS calorimeter, but with worse mass resolution.

Σ^0 mass and width

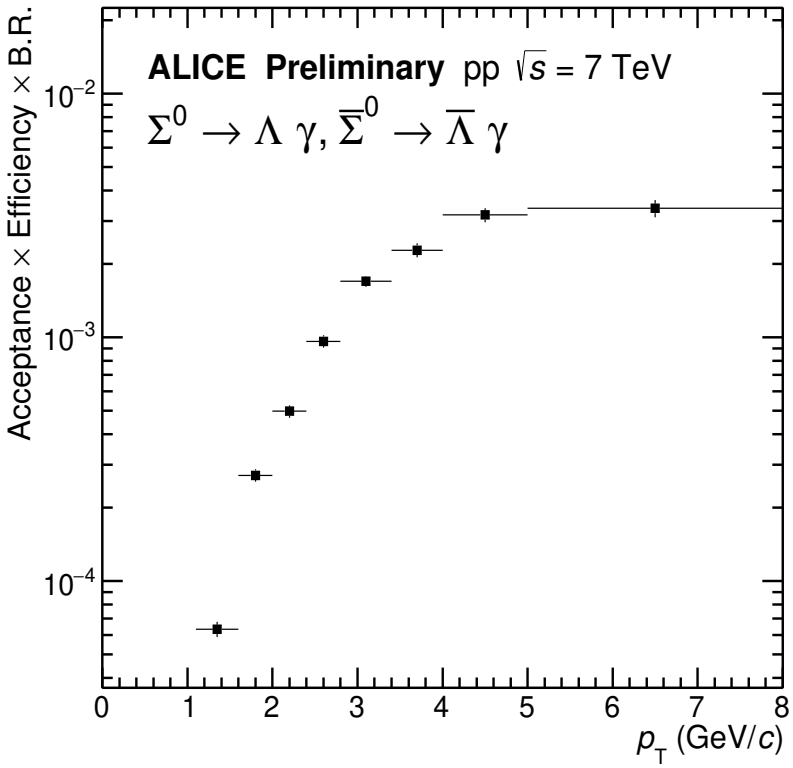


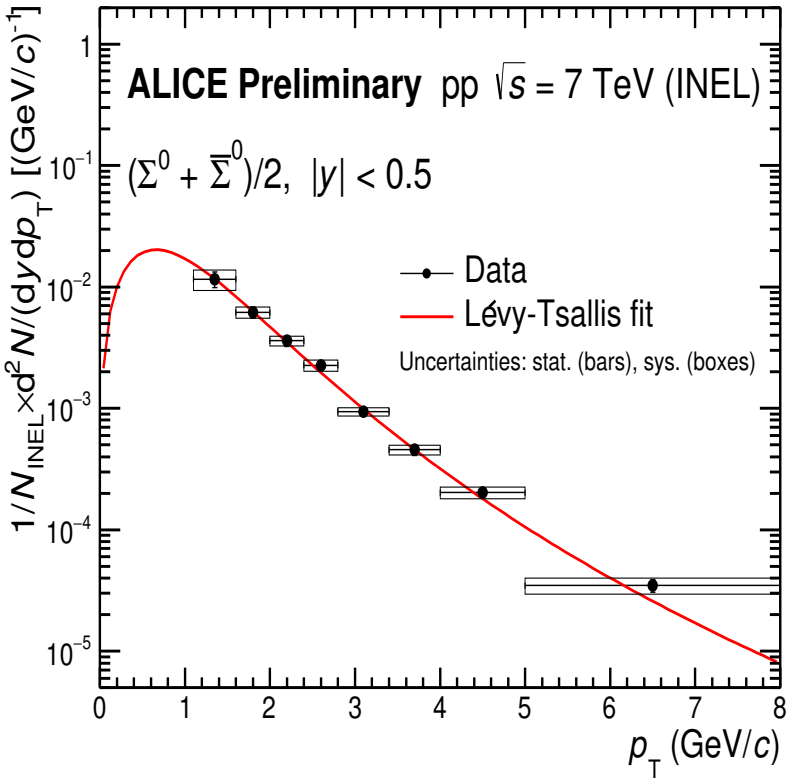


$\Longrightarrow$ Reconstructed peak position is in good agreement with the PDG value:
$M_{PDG}(\Sigma^0) = 1192.642 \pm 0.024$ MeV/c^2

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

Σ^0 spectrum and Lévy-Tsallis fit



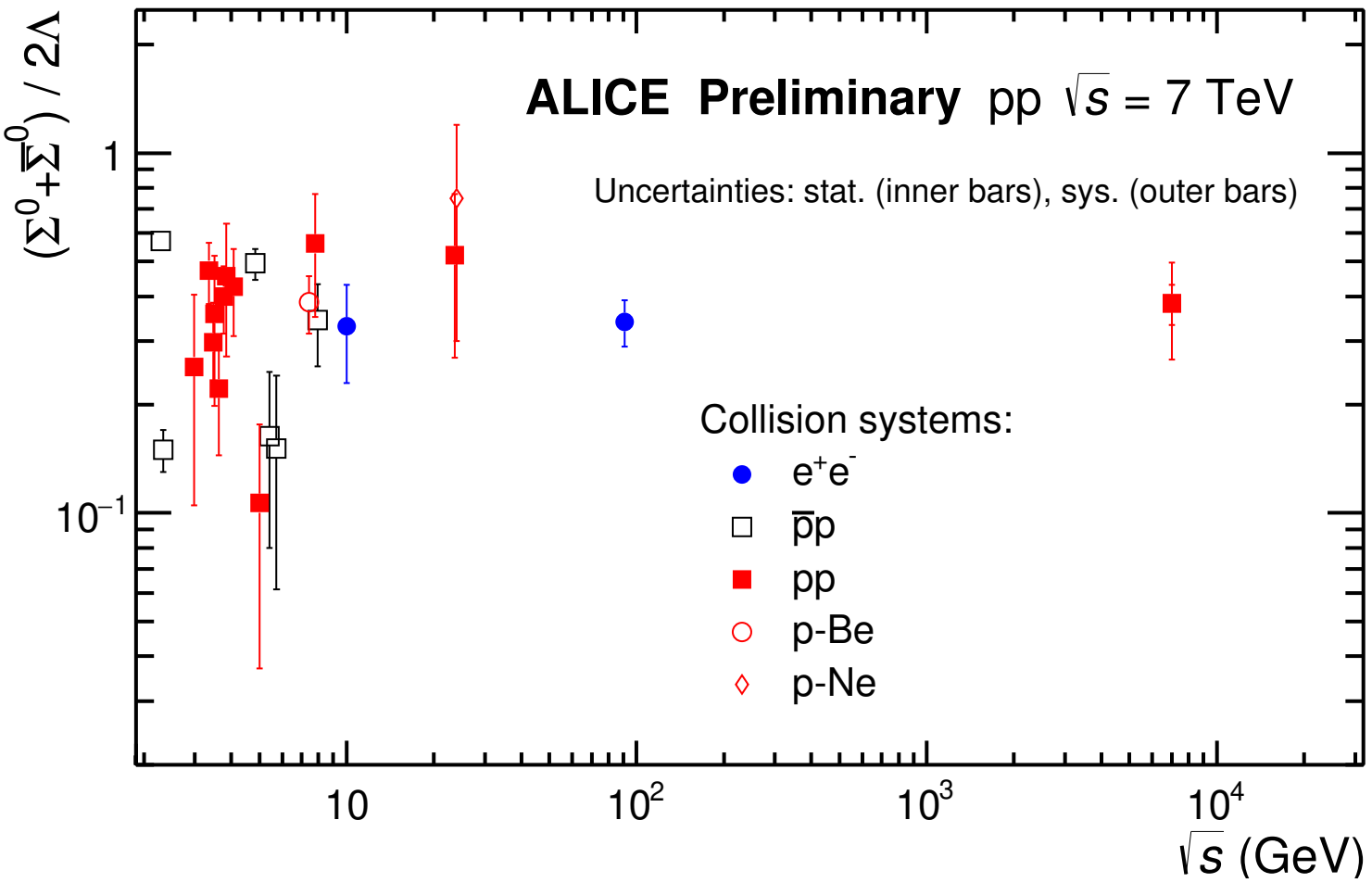


γ conversion probability (~ 0.085)

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.

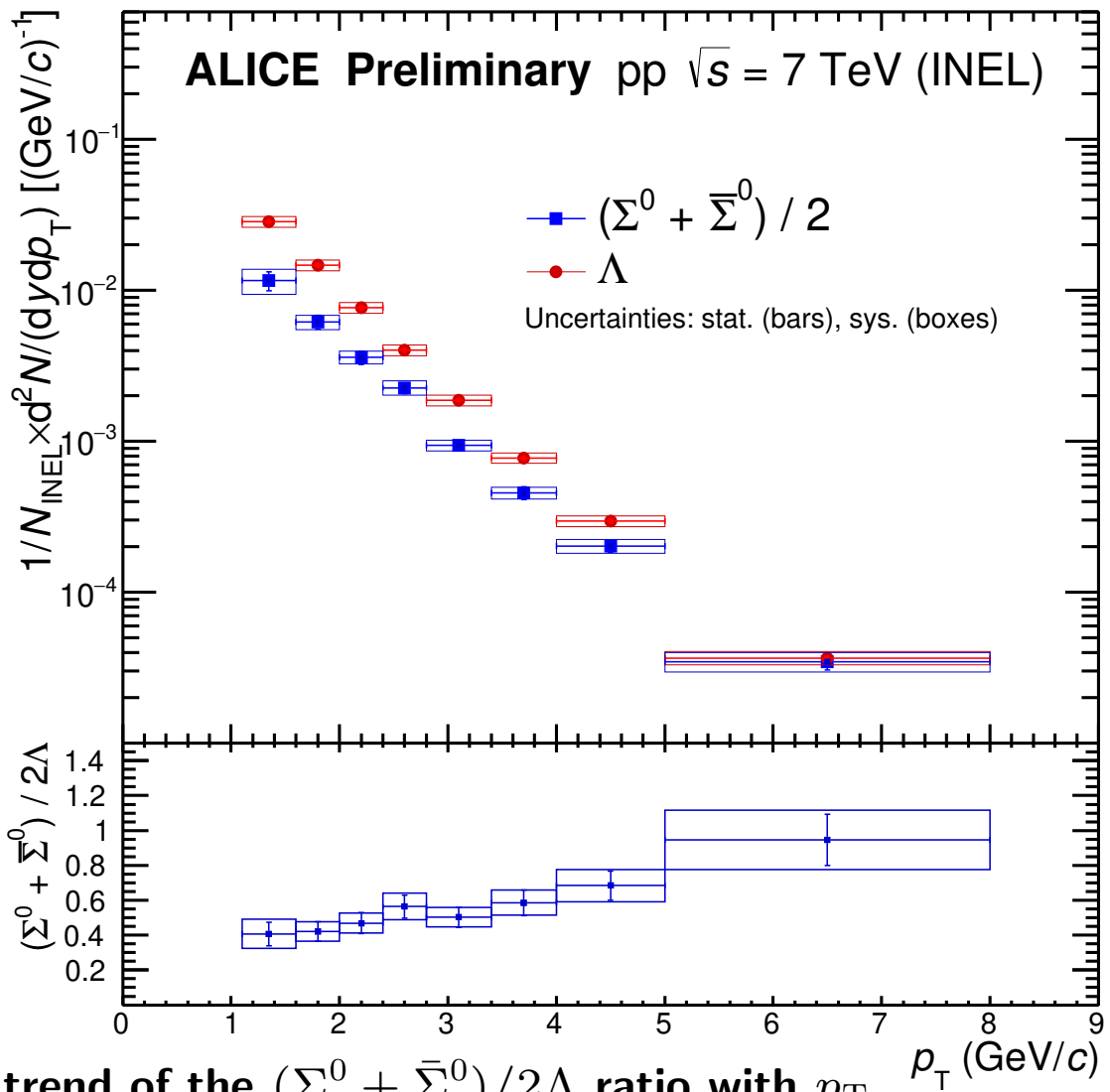
$\sim$ 60% of the yield is in the extrapolated region between 0 and 1.1 GeV/c. Relative uncertainty of the yield due to the extrapolation is $\sim$ 18%.

ALICE measurement and world data



- First measurement at LHC of $\frac{\Sigma^0}{\Lambda}$ cross section ratio complements world data from lower energies
- 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 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

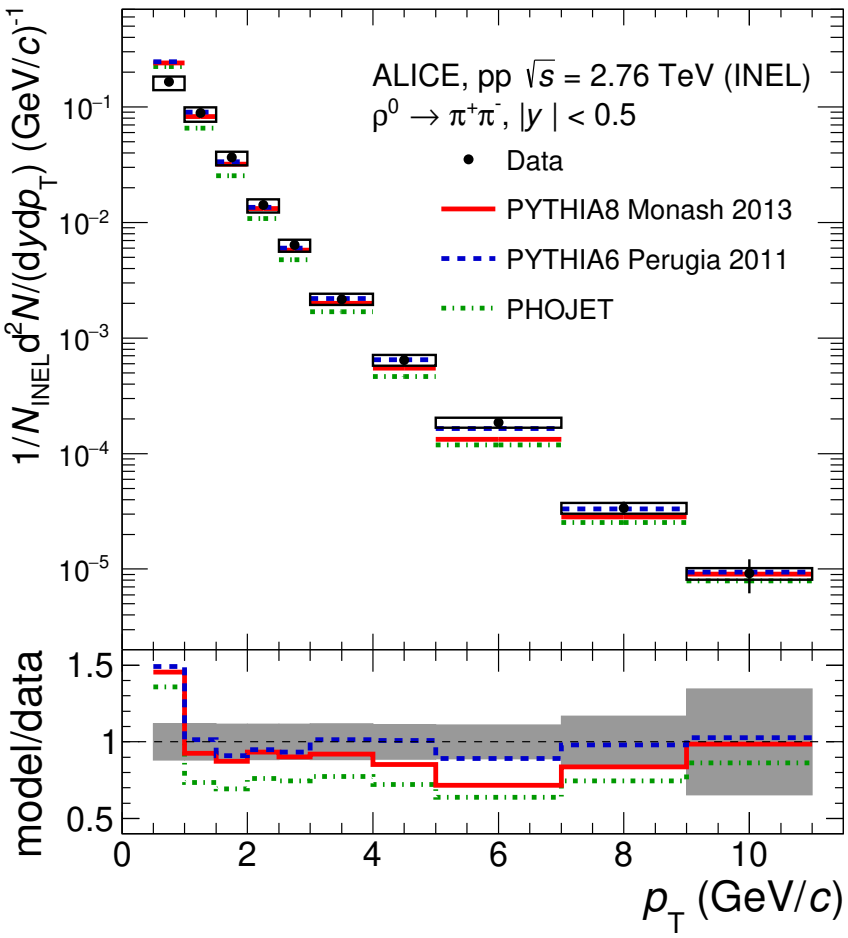


$\Longrightarrow$ **Increasing trend of the $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio with p_{T} as the indication of different contributions of primordial and final Σ^0 and Λ production.**

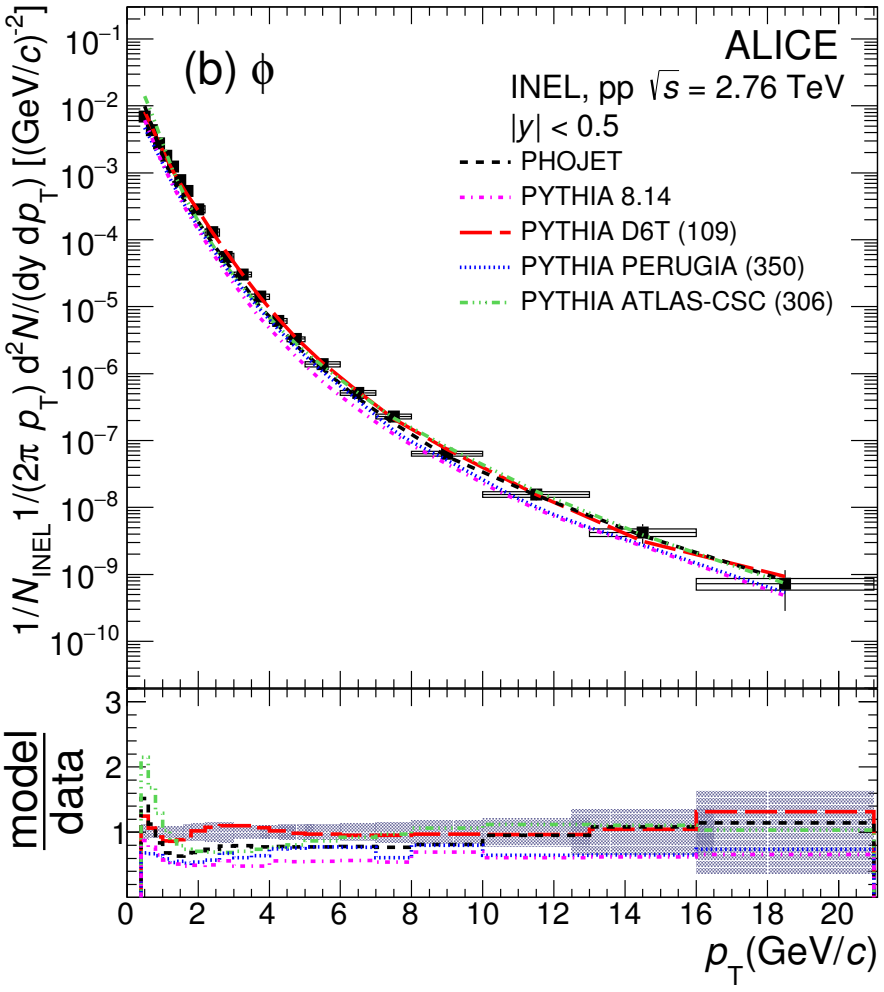
$\Longrightarrow$ **More data are needed! LHC run II data are under analysis.**

Tests of QCD-inspired MC event generators in pp data

ρ^0 and ϕ vs MC generators



Phys. Rev. C 99, 064901 (2019)

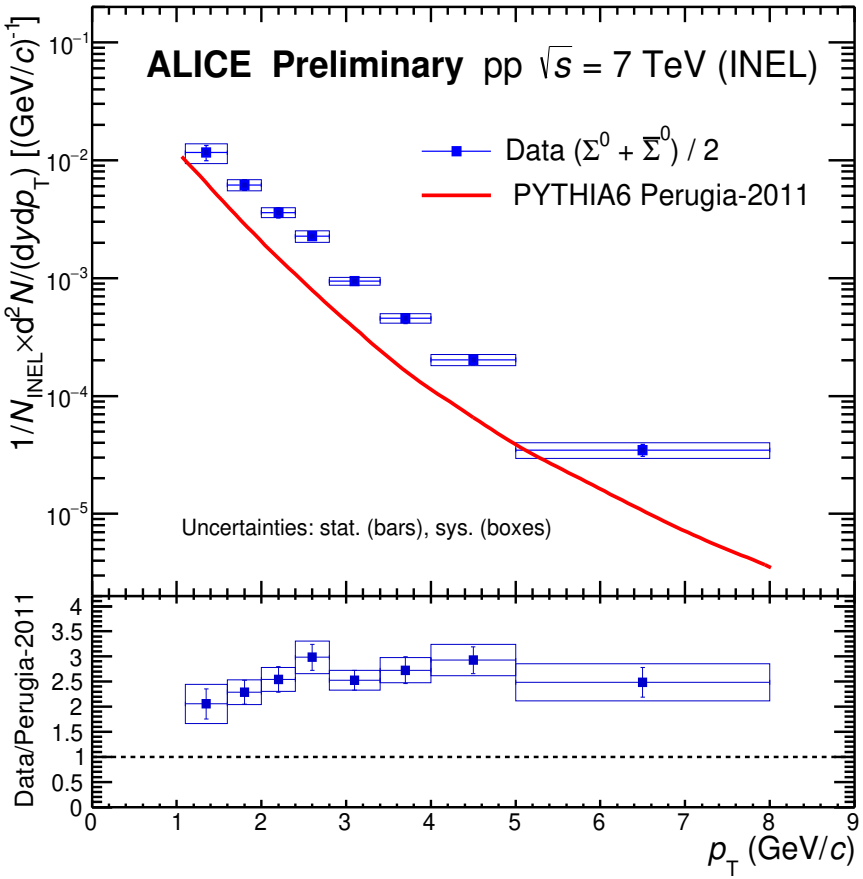


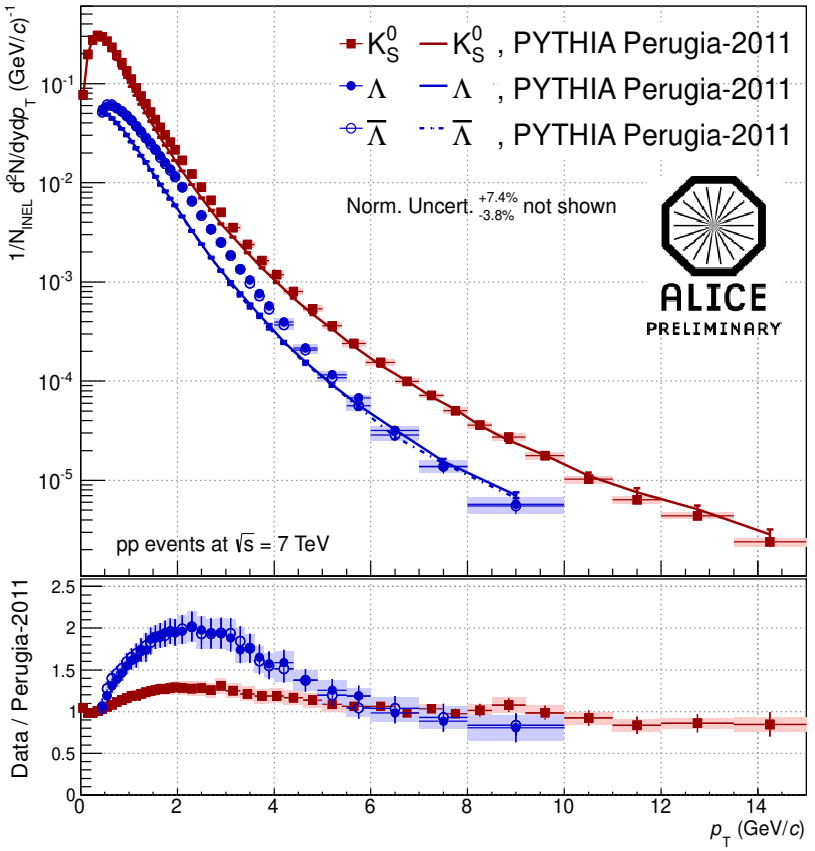
Phys. Rev. C 95 064606 (2017)

- ρ^0: **PYTHIA6 Perugia 2011 describes data within uncertainties for $p_{\mathrm{T}} > 1$ GeV/c**
- ϕ: **PYTHIA D6T describes data**

Σ^0 and Λ vs PYTHIA6

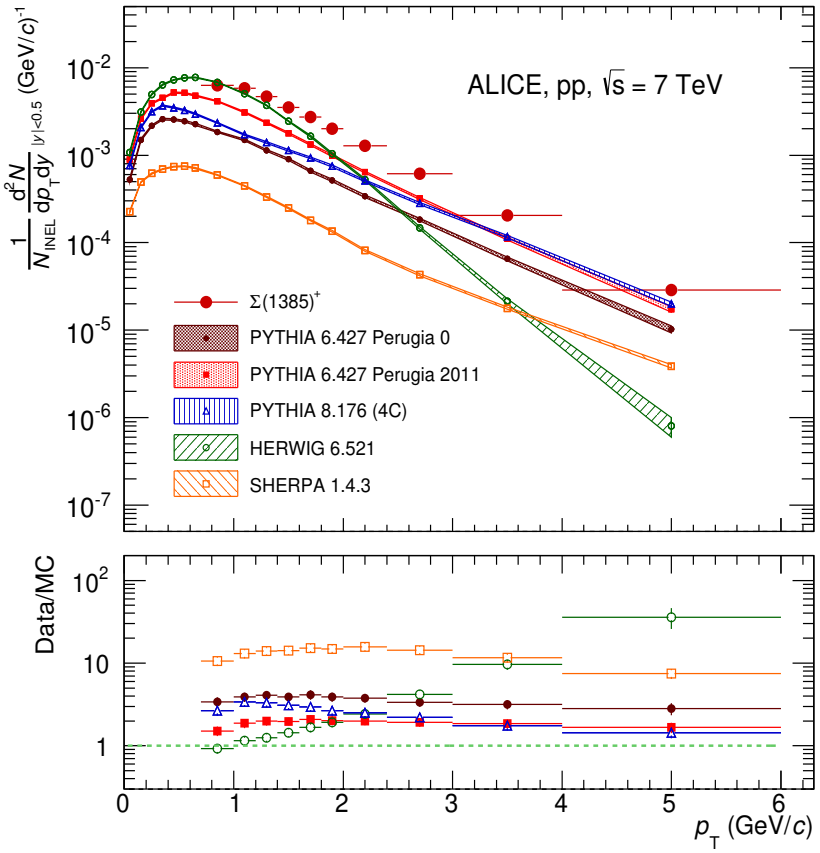
(ALICE, Phys. Rev. Lett. 111 (2013) 222301; D.D.Chinellato arXiv:1211.7298 [hep-ex])

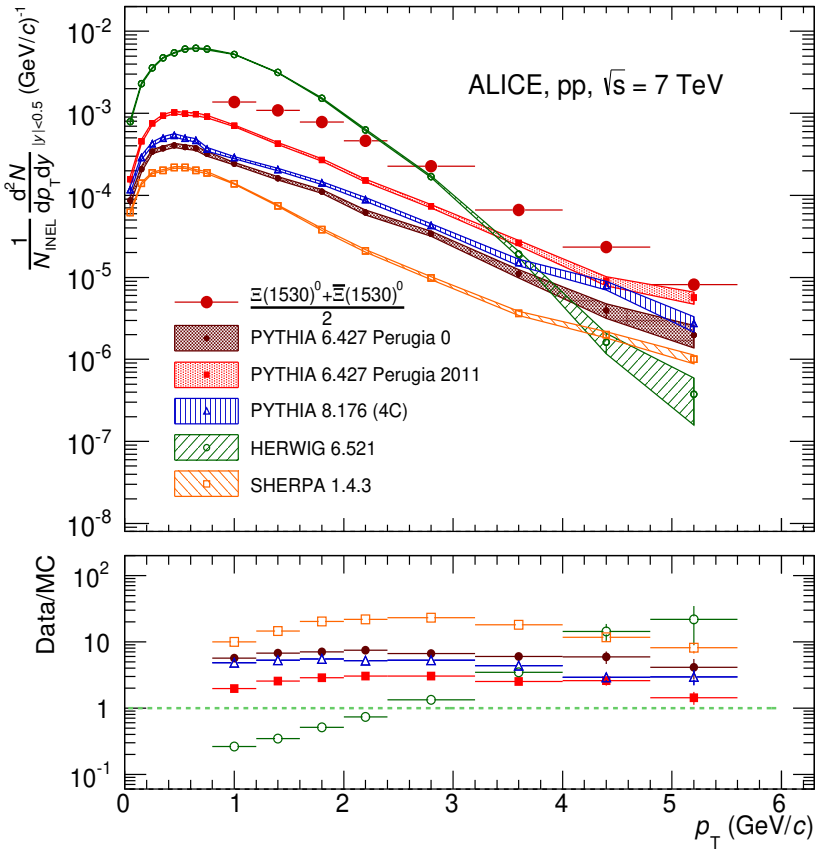




$\Longrightarrow$ **PYTHIA6 Perugia-2011 clearly underestimates the production of both ground-state hyperons in the intermediate p_{T} -range**

$\Sigma(1385)^{\pm}$ 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

Summary

- **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 in preparation, analysis of ALICE p-Pb and Pb-Pb data has started.

- **Hyperons call for finer tunes of MC models and generators**
  - Reasonable agreement with QCD based generators is seen for ρ and ϕ p_{T} -spectra.
  - **Disagreement with the PYTHIA-based generators is observed for Λ , Σ^0 , $\Sigma(1385)^{\pm}$, and $\Xi(1530)^0$ p_{T} -spectra.**

$\Longrightarrow$ **Further investigations are very interesting and needed**


Σ^0