NICA-SPD Workshop in Dubna
4-8 June 2019

Σ^0 production at LHC with ALICE

as the example of the detection of low p_{T} photon

- Introduction
- Photon detection at ALICE
- Σ^0 detection
- Results on Σ^0 production in pp collisions at $\sqrt{s} = 7$ TeV
- Summary and Outlook

Alexander Borissov, Dubna, JINR, 05.06.2019

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 $\hbar = \frac{h}{2\pi}$.

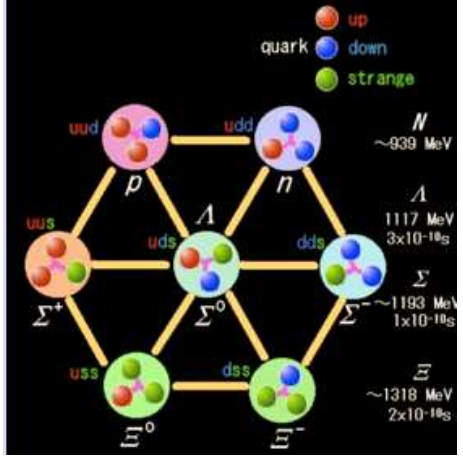
PDG parameters of studied hadronic resonances and ground states

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

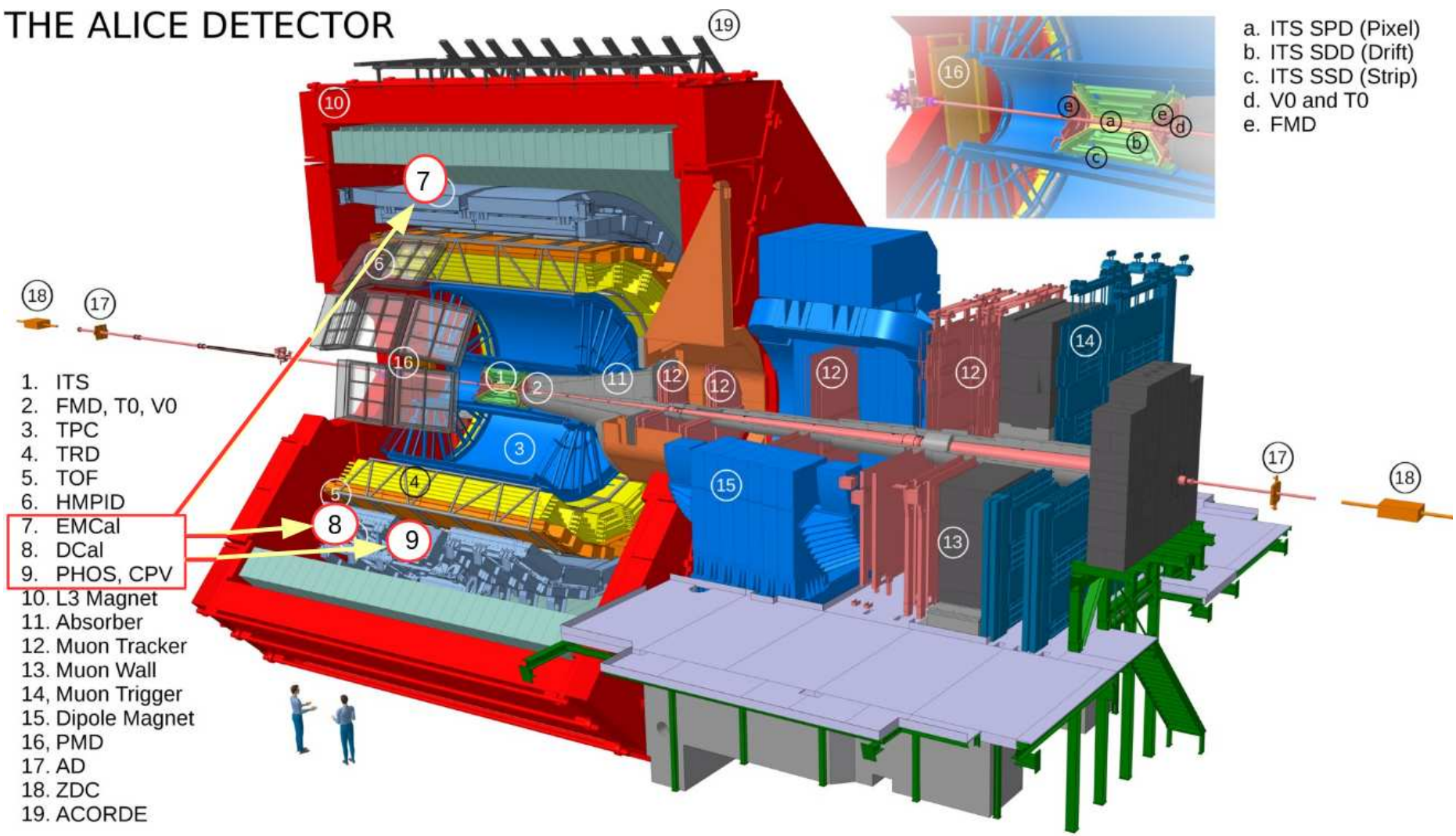
Measured in **pp (0.9, 2.76, 5.02, 7.0, 8.0, 13.0 TeV)**, **p-Pb (5.02 TeV)**, and **Pb-Pb (2.76, 5.02 TeV)** collisions at ALICE

Σ^0 in pp collisions



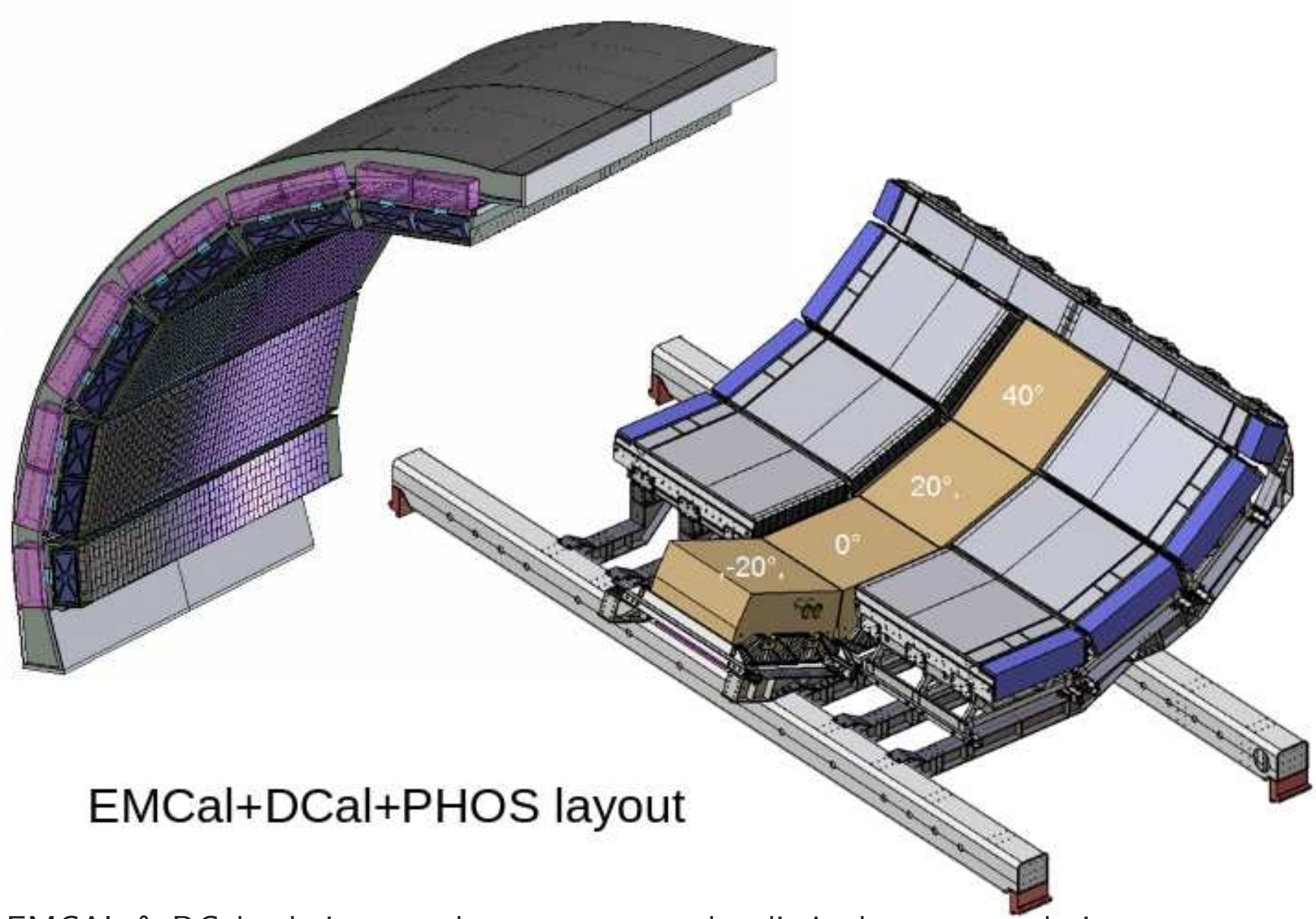
- Comparison with the Λ baryon, which has the same quark content but different isospin.
- Contribution to the understanding of hadron production mechanisms, input for comparison with statistical hadronisation model such as THERMUS.
- Reference for tuning Monte Carlo event generators such as PYTHIA, EPOS and DIPSY.
- Baseline for comparison with PbPb data.
- Comparison with the limited set of the world data available at energies less than 91 GeV.
- Discrimination of prompt and decay hyperons: prompt Λs vs ones from Σ^0 decay.
- Constrain feed-down corrections for protons, pions and direct photons at low transverse momenta.

The ALICE detector in LHC runs 1 and 2



ITS and TPC and are mainly used for the reconstruction of the decay products of resonances.
V0A+V0C and ZDC for multiplicity, centrality, trigger and timing.
Unique particle identification, high granularity for high multiplicity, tracking down to p_{T} 0.1 GeV/c.
Total size of ALICE 16$\times$ 26 meters, weight $\sim$ 10000 tons.

Photon detection in ALICE calorimeters



EMCal+DCal+PHOS layout

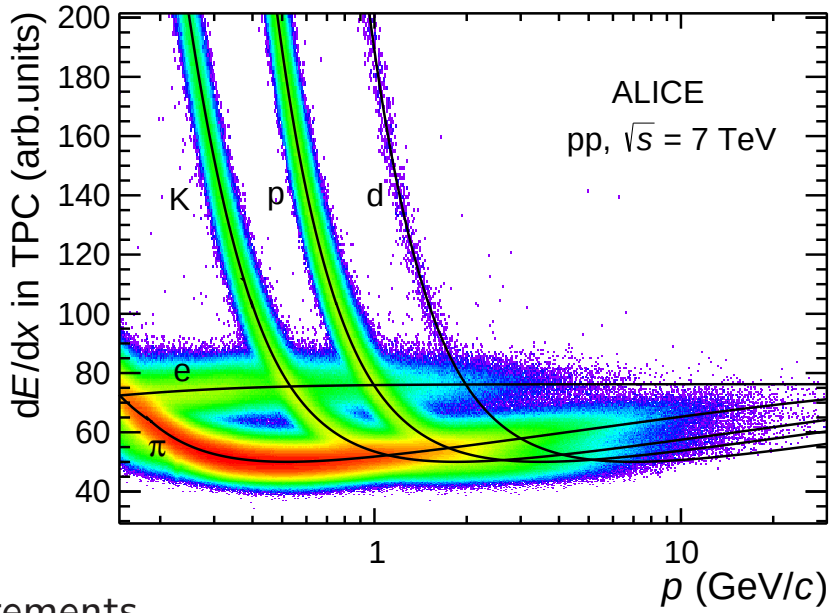
- EMCAL & DCal calorimeters: large acceptance but limited energy resolution
- PHOS calorimeter: good energy resolution but limited acceptance (60^o, $|\eta| < 0.135$)

Photon detection in ALICE calorimeters

	EMCal/DCal	PHOS
Active element	Sampling 77 layers (1.44 mm Pb, 1.6 mm Sci) with WSF light collection	Homogeneous crystals $PbWO_4$
Moliere radius	3.2 cm	2.0 cm
Photodetector	APD 5x5 mm^2	APD 5x5 mm^2
Depth	$20X_0$	$20X_0$
Acceptance	EMCal: $\|y\|<0.7$, $\Delta\varphi=107°$ DCal: $0.22<\|y\|<0.7$, $\Delta\varphi=67°$	$\|y\|<0.13$, $\Delta\varphi=70°$
Granularity	Cell 6x6 cm2, $\Delta\varphi\cdot\Delta\eta=0.0143\cdot0.0143$	Cell 2.2x2.2 cm, $\Delta\varphi\cdot\Delta\eta=0.0048\cdot0.0048$
Modularity	EMCAL: 10+2(1/3) modules DCAL: 6(2/3)+2(1/3) modules 17664 cells	3+1/2 modules 12544 cells
Dynamic range	0-250 GeV	0-100 GeV
Energy resolution	$\sigma_E/E = 4.8\%/E \oplus 11.3\%/\sqrt{E} \oplus 1.7\%$	$\sigma_E/E = 1.8\%/E \oplus 3.3\%/\sqrt{E} \oplus 1.1\%$
Distance from IP	428 cm, 0.7-0.9X_0	460 cm, $0.2X_0$

Photon Conversion Method (PCM)

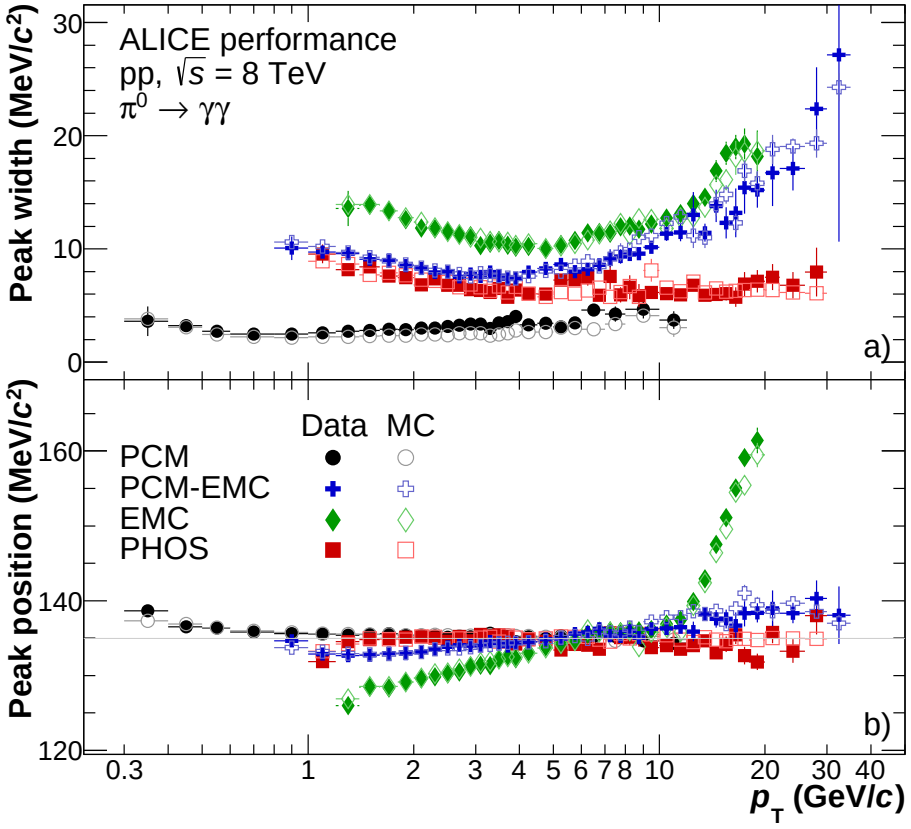
- Inner tracking system (ITS)
  - 2 layers of pixel detectors (SPD)
  - 2 layers of drift detectors (SDD)
  - 2 layers of strip detectors (SSD)
  - large acceptance: $0^o < \phi < 360^o$, $|\eta| < 0.9$

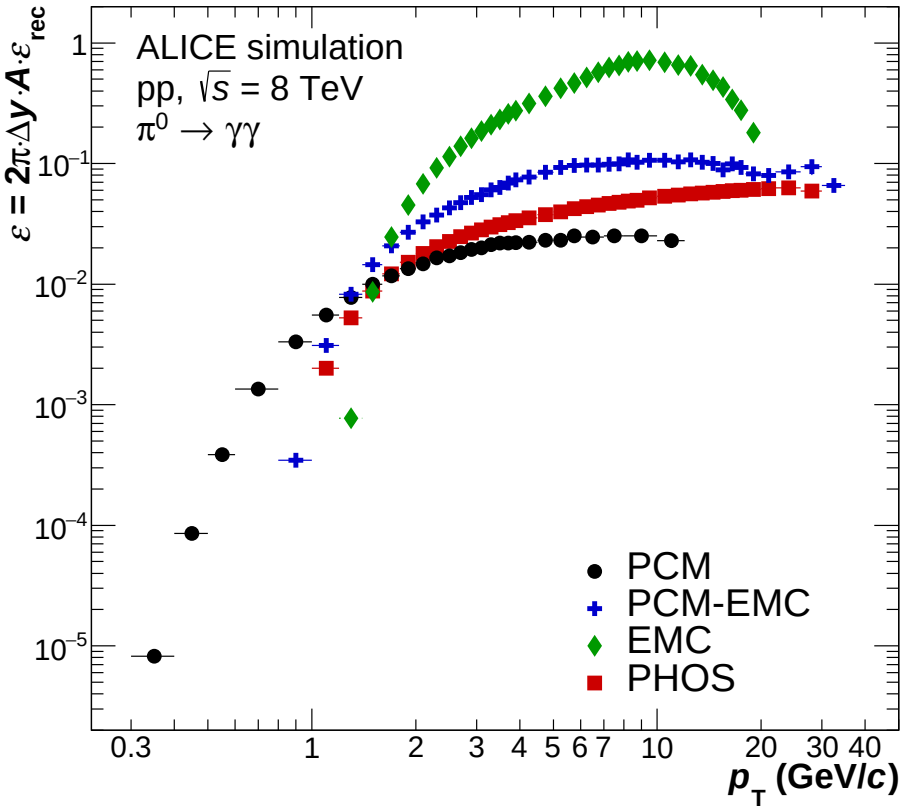


- Time projection chamber (TPC)
  - barrel with d = 5 m, r = 5 m
  - large acceptance: $0^o < \phi < 3600^o$, $|\eta| < 0.9$
  - unique particle identification due to dE/dx measurements
  - 72 readout chambers

- Conversions in both detectors
  - $X/X_0 = 11.4 \pm 0.5$ %, probability ~ 8 %
  - 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
  - $e^+(e^-)$ identification: TPC dE/dx inside -6 and 7 σ

Example of π^0 detection





- Combination of independent results provides cross-check and significantly reduces final uncertainties
- Different technologies allow wide extension of p_{T} range

$\Longrightarrow$ π^0 data extracted at $0.3 < p_{\mathrm{T}} < 35$ GeV/c

Examples of inclusive photon detection in ALICE

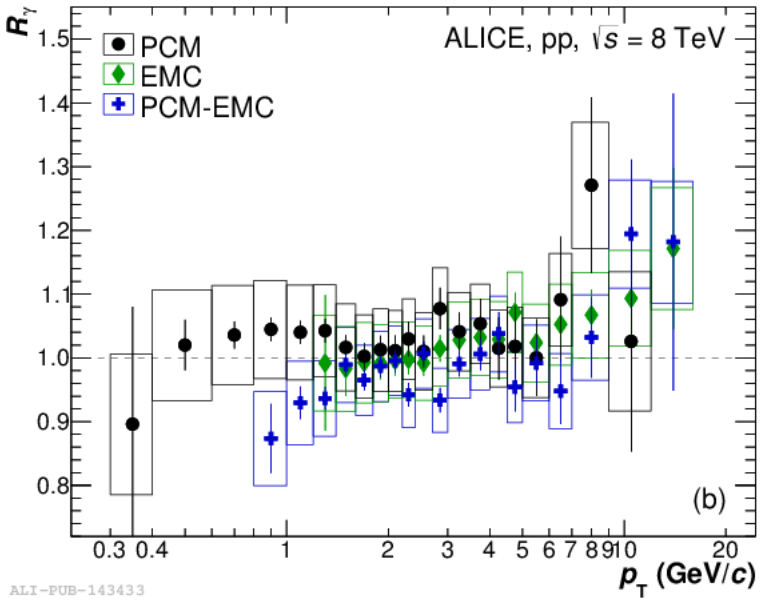
- $R_\gamma = \frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}}$

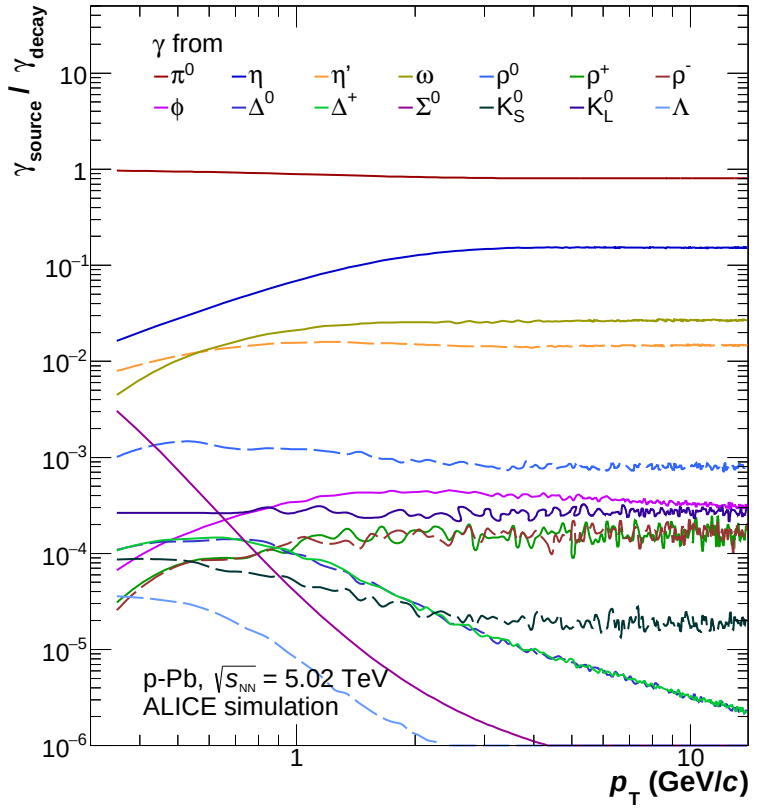
  if $R_\gamma > 1 \rightarrow$ direct photon signal,
  Numerator: measured γ_{inc} spectrum per π^0
  Denominator: estimated sum of γ_{decay} per π^0

- p_{T} reach: $0.3 < p_{\mathrm{T}} < 32$ GeV/c

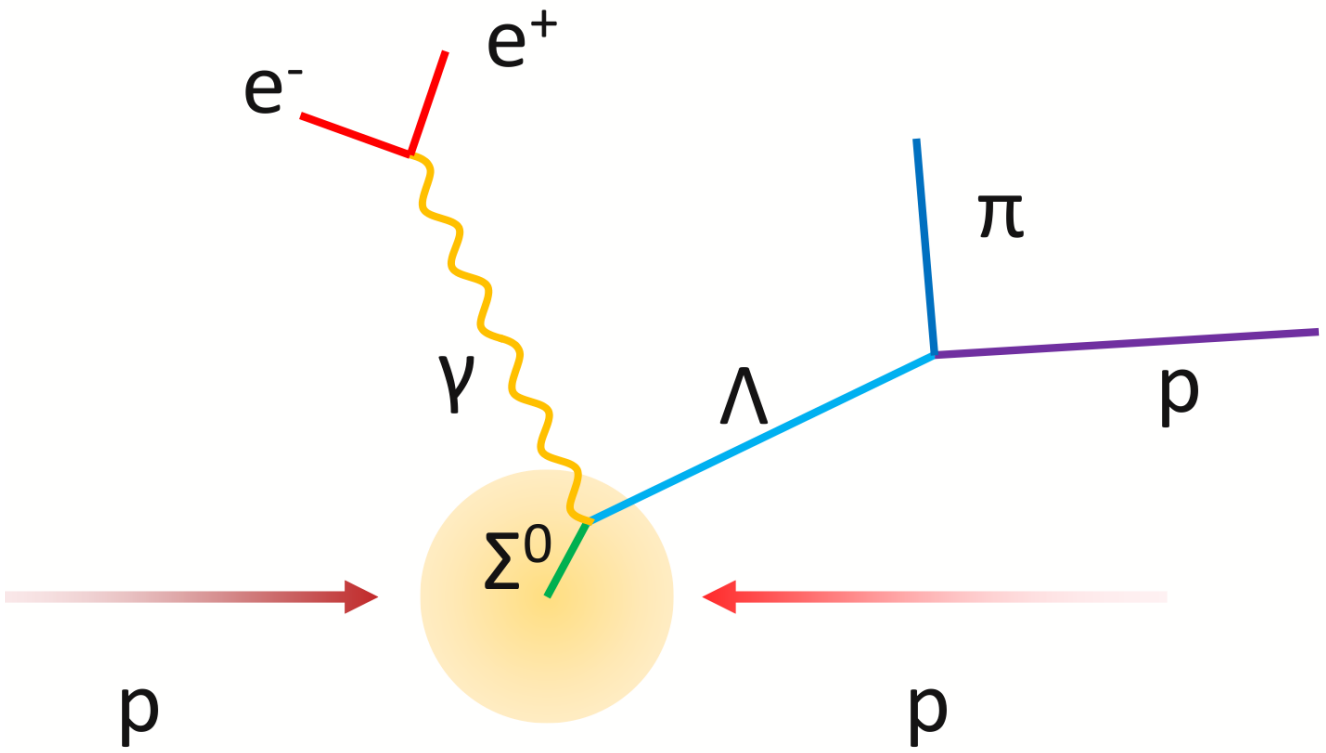
- No significant excess at low p_{T} observed

- Σ^0 contributes at low p_{T}
  ...as the additional reason for its measurement



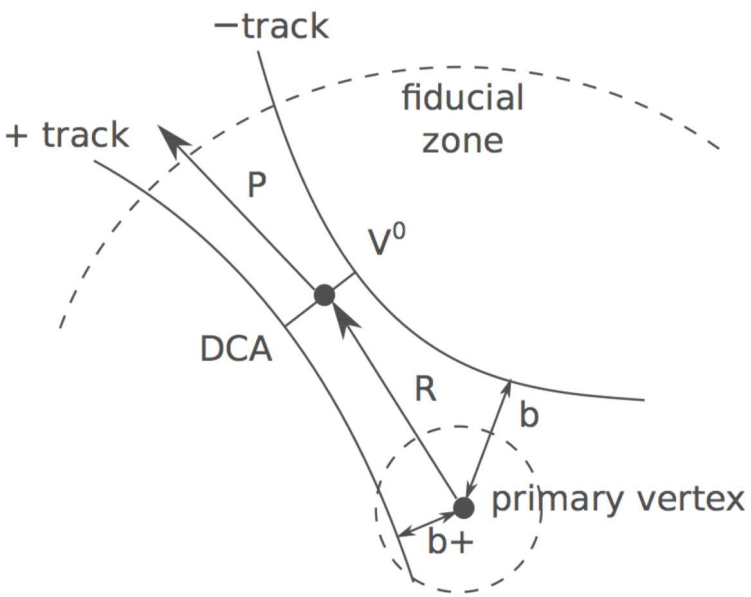


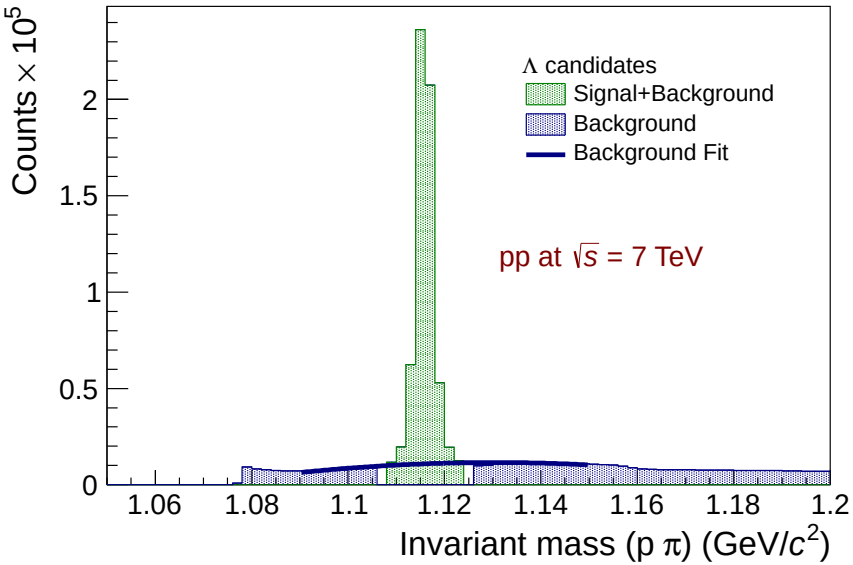
Detection of $\Sigma^0 \to \Lambda + \gamma$ and $\overline{\Sigma}^0 \to \bar{\Lambda} + \gamma$



(without the lifetime scale)

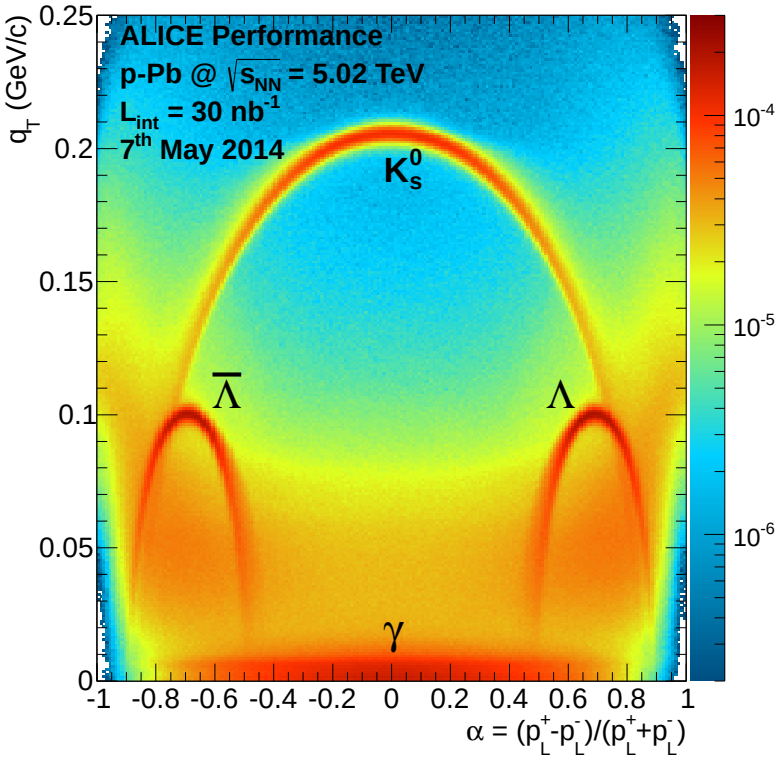
$\Lambda\ (\bar{\Lambda}\ ) \rightarrow \mathrm{p}\pi^{-}(\bar{\mathrm{p}}\pi^{+})$ detection

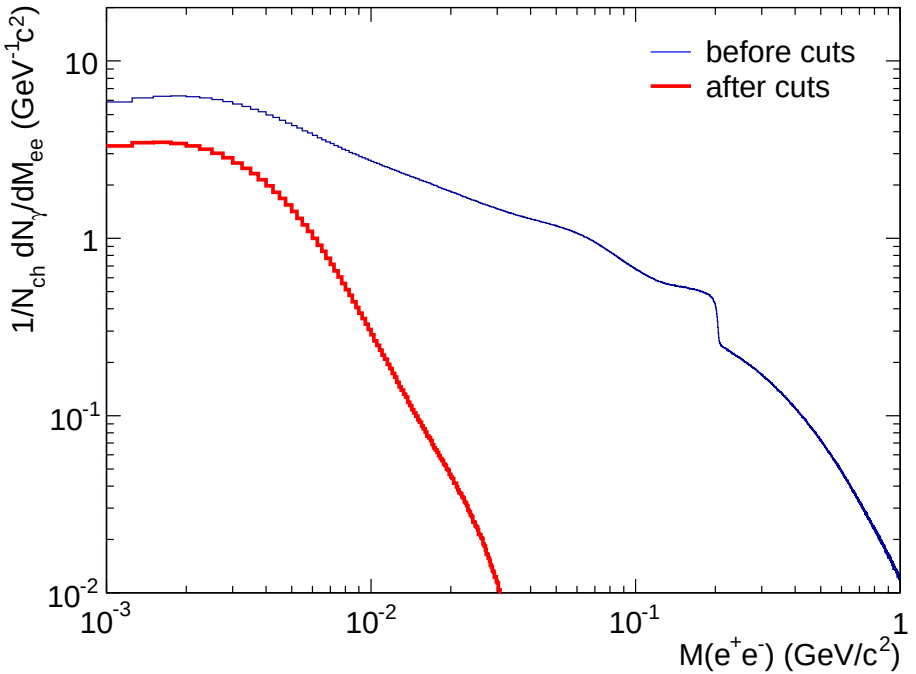




- secondary vertex (V0) with oppositely charged tracks
- V0 radius $R = \sqrt{x_{V0}^2 + y_{V0}^2}$ $(0.5 < R < 180$ cm)
- distance of closest approach (b) between positive (negative) track and primary vertex > 0.06 cm
- pointing angle θ_Λ between P and a vector connecting the primary vertex and the 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
- note, ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ is detected in a similar approach

γ reconstruction

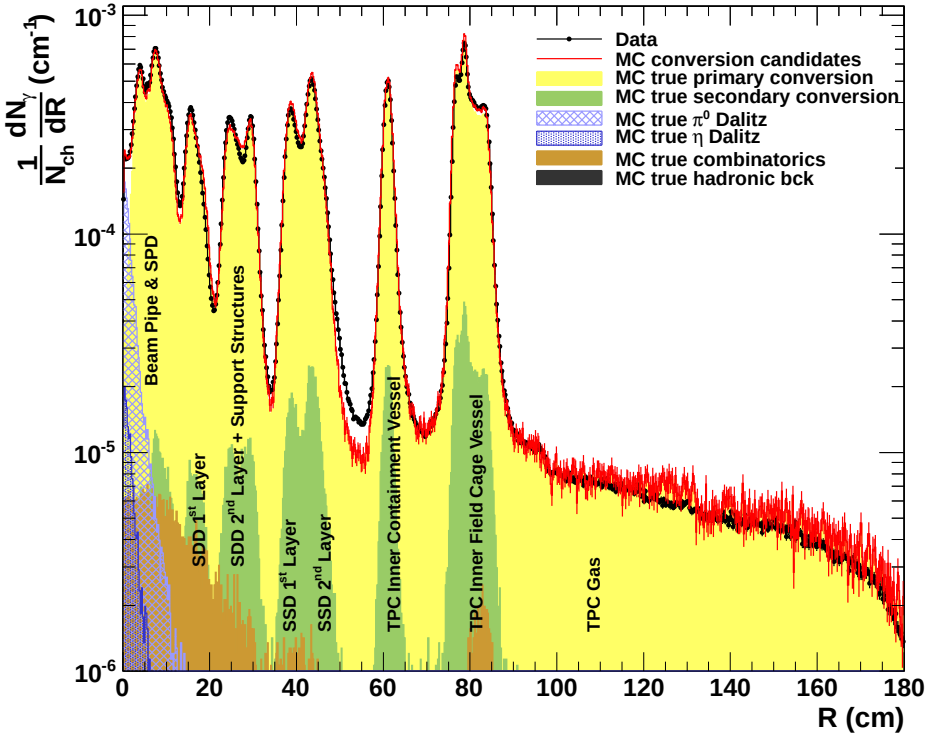


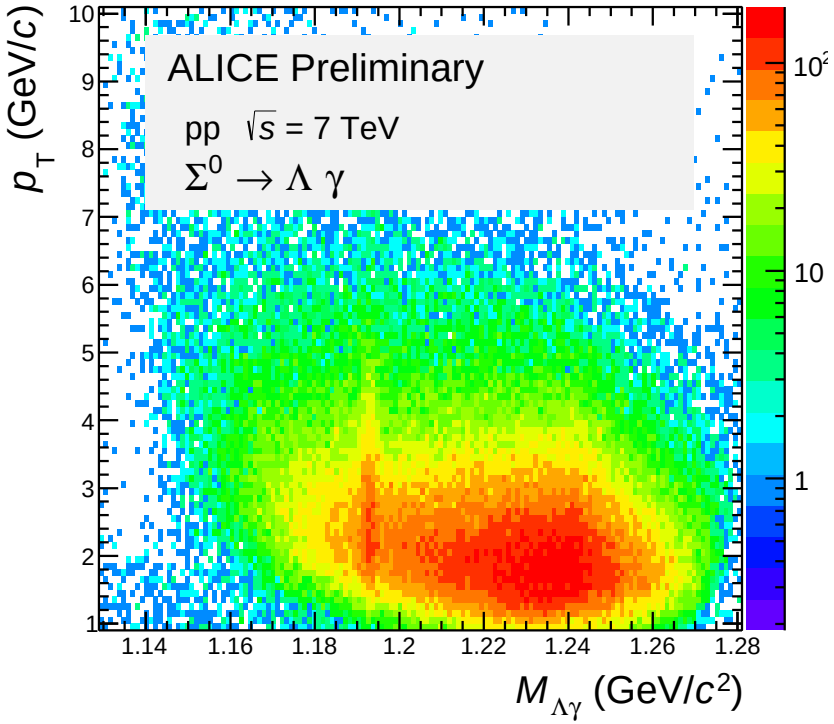


- $e^+(e^-)$ track selection
  - min track $p_{\mathrm{T}} > 50$ MeV/c
  - distance to primary vertex $5 < R < 180$ cm
- cut on the angle between e^+e^- pair plane and the plane perpendicular to the magnetic field of the ALICE magnet
- remaining V0 (Λ , K^0_S) removed with further selections: $q_T < 0.05$, 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 $\bar{\Sigma}^0 \to \bar{\Lambda} + \gamma$

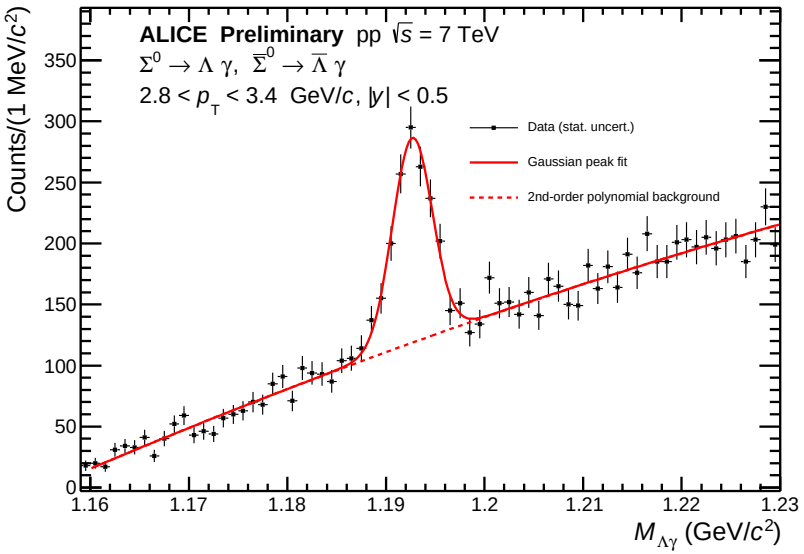


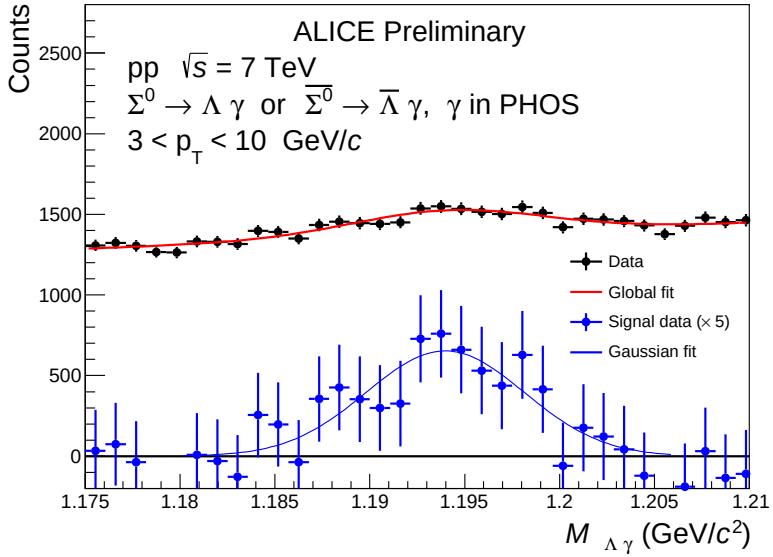


- $\gamma \to e^+ + e^-$ is detected through the secondary V^0 vertex with Photon Conversion Method (PCM) in the central barrel detectors

- 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).

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

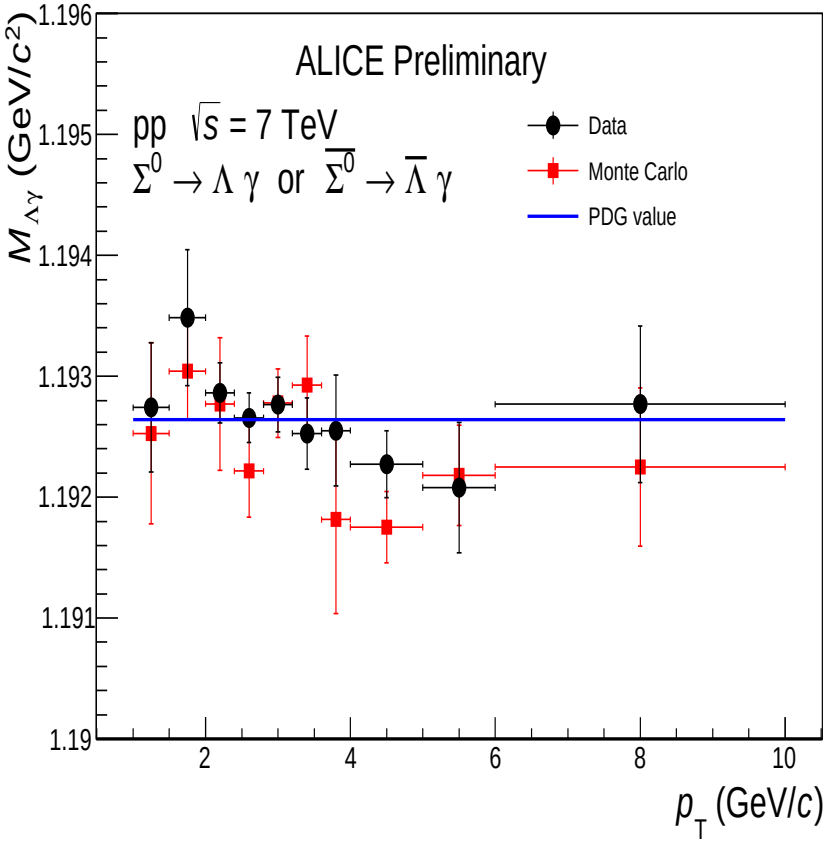


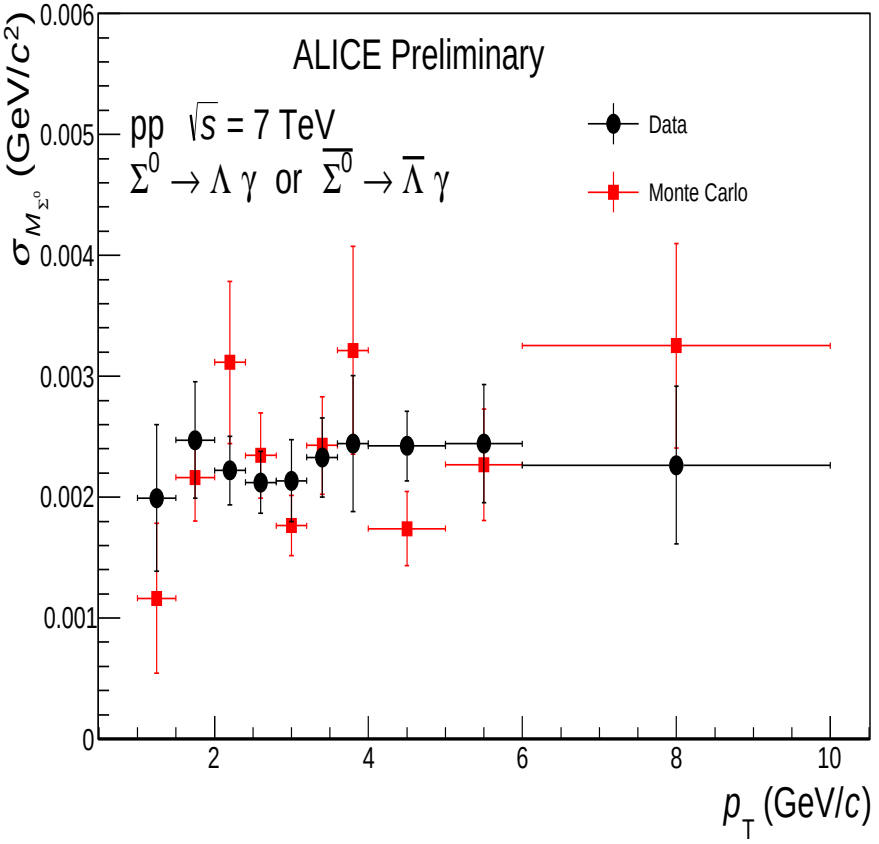


- Σ^0 invariant mass is calculated from the mass of the selected Λ and γ candidates.
  Note low $E_\gamma \approx$ 300 MeV.
  $\Longrightarrow$ Clean Σ^0 invariant mass peak.

- Proof-of-principle: Σ^0 peak is also observed with photon detected in PHOS calorimeter, but with worse mass resolution.
- No Σ^0 invariant mass peak observed with photon in EMCAL due to the noise and resolution

Σ^0 mass and width





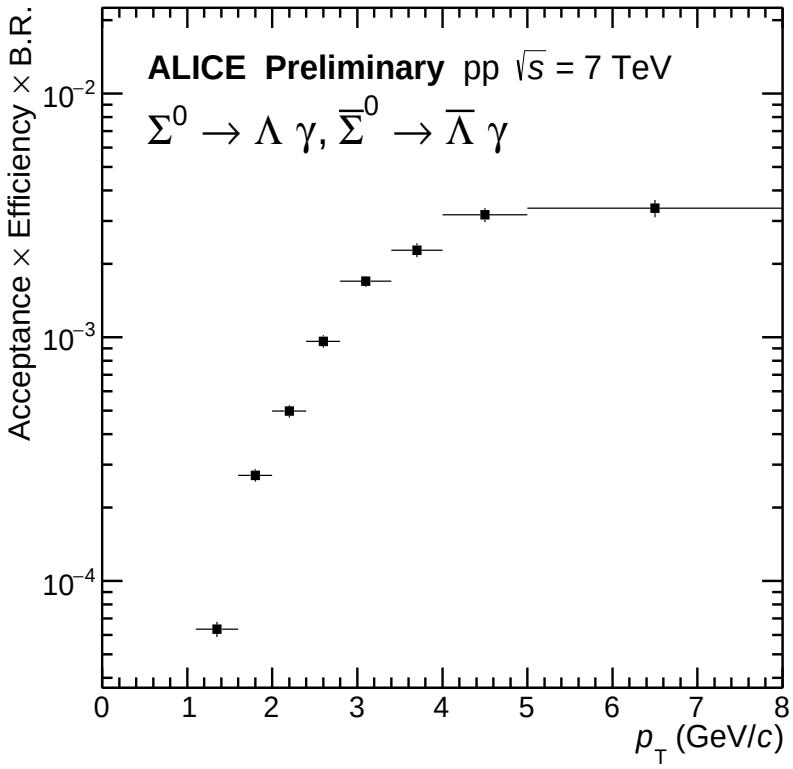
$\Longrightarrow$ Reconstructed peak position is in good agreement with the PDG value.

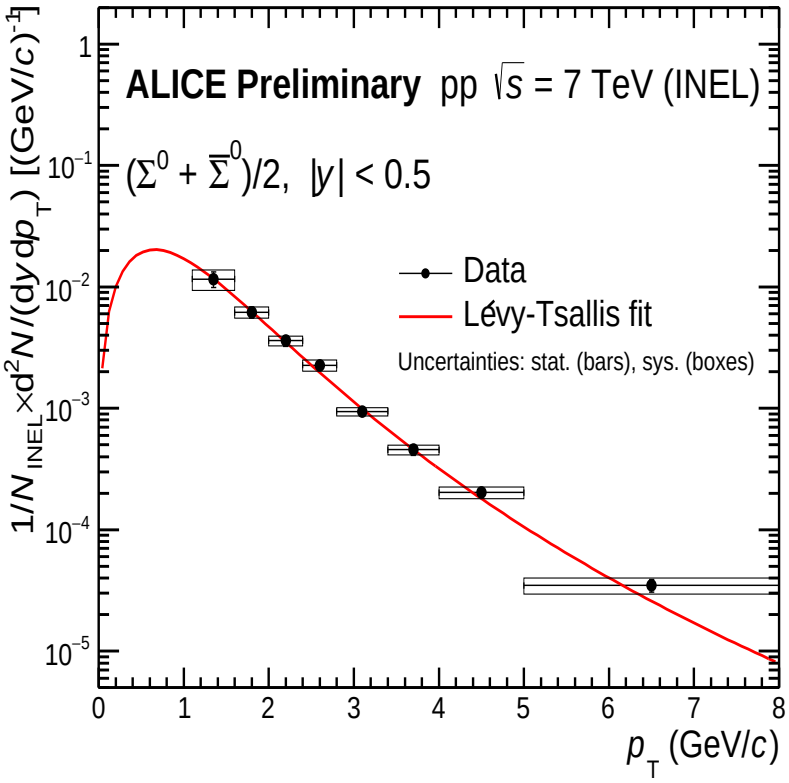
PDG: $\Sigma^{0PDG} = 1192.642 \pm 0.024$ MeV

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

$\Longrightarrow$ Σ^0 mass resolution $\sigma_M^{PCM} = 2$ MeV at $2.8 < p < 3.4$ GeV/c

Σ^0 spectrum and Lévy-Tsallis fit



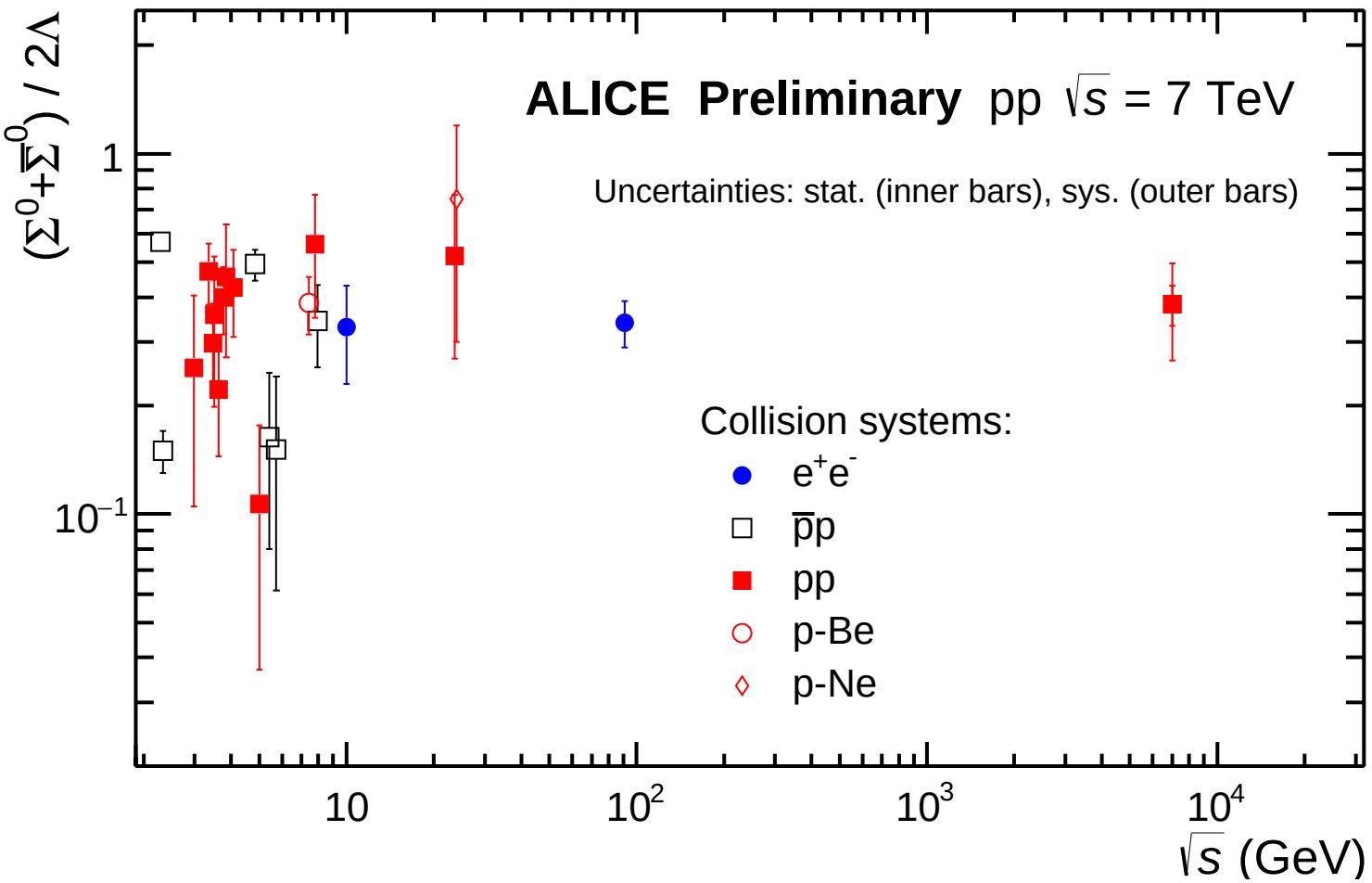


γ conversion probability (~ 0.085)

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%.

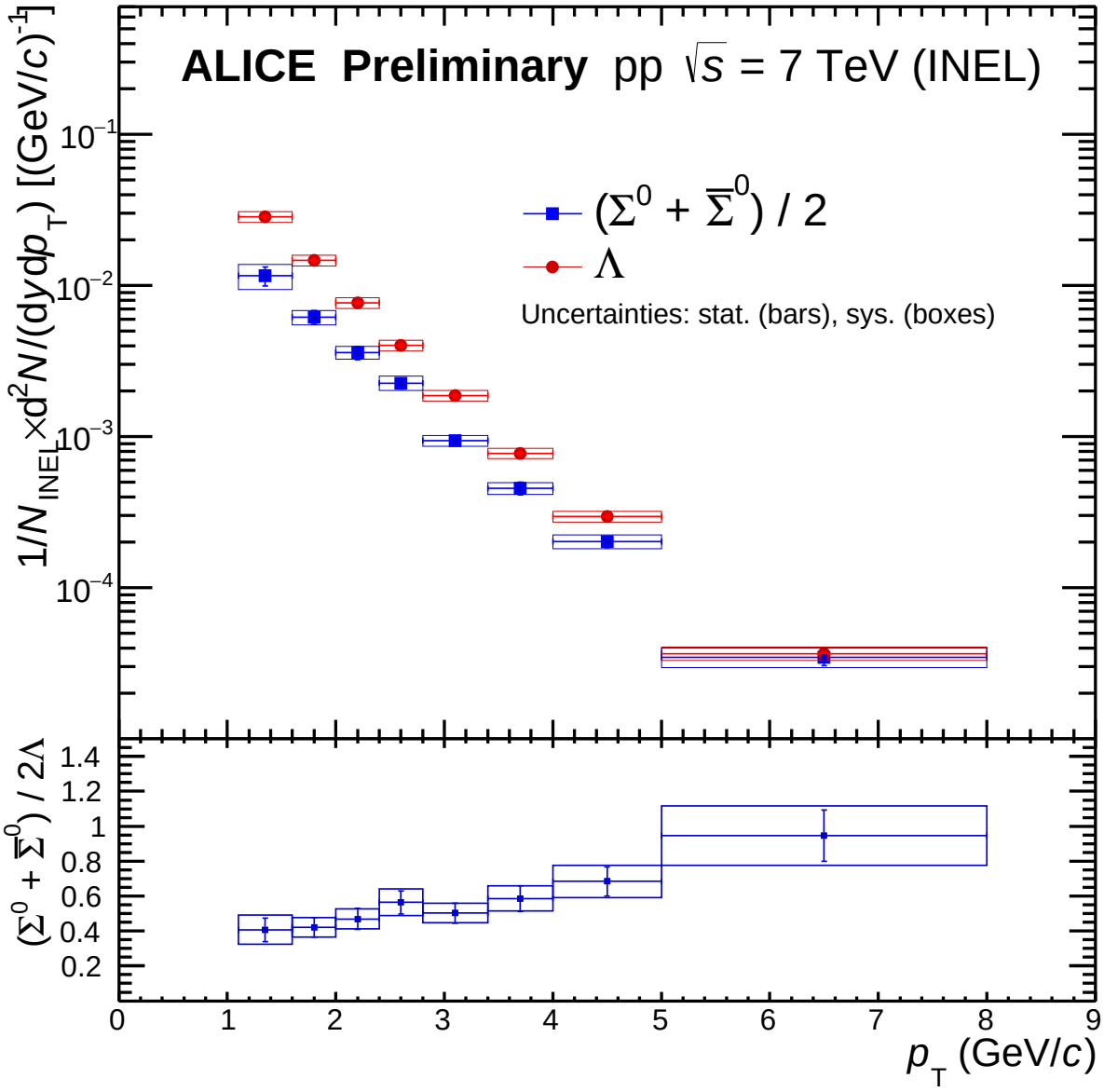
ALICE measurement and world data



- First measurement at LHC of $\frac{\Sigma^0}{\Lambda}$ cross section ratio complements world data from lower energies, including pp collisions at $\sqrt{s} \approx 10$ GeV

- e^+e^- data at $\sqrt{s} = 91$ GeV from L3 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



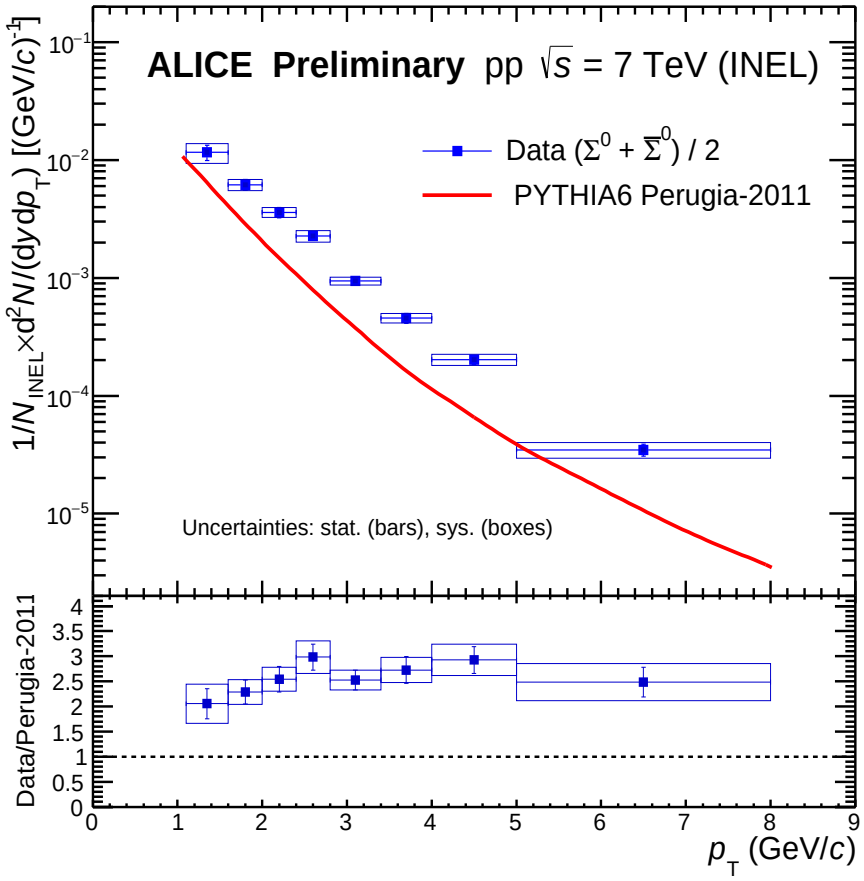
$\Longrightarrow$ **Increasing trend of the $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio with p_{T}**

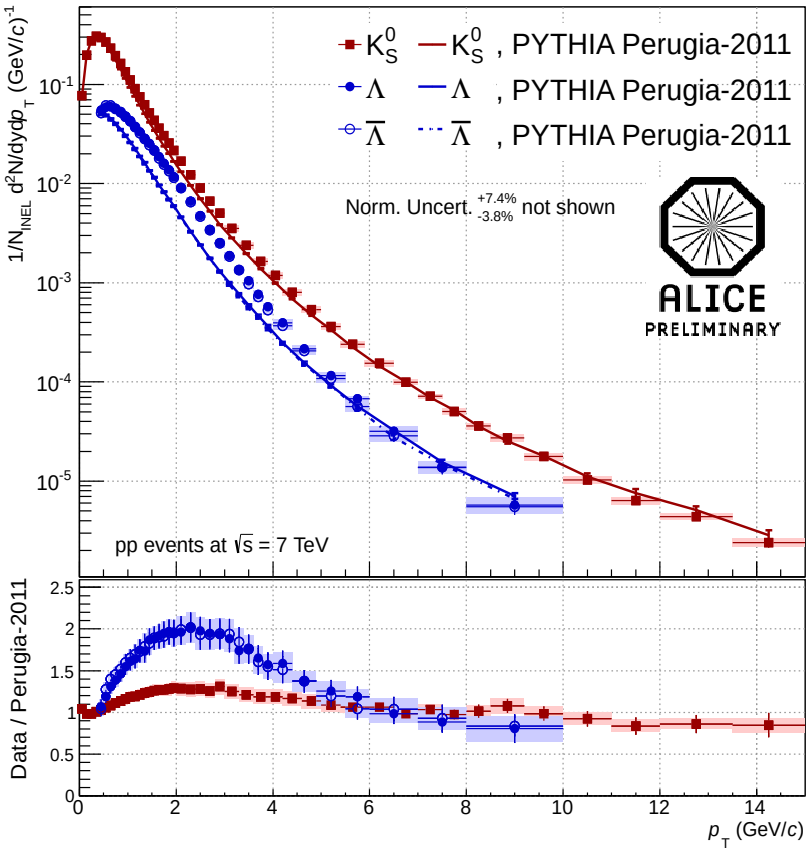
Possible indication on different contributions of primordial and final Σ^0 and Λ production.

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

Σ^0 and Λ vs PYTHIA6

(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**

Summary

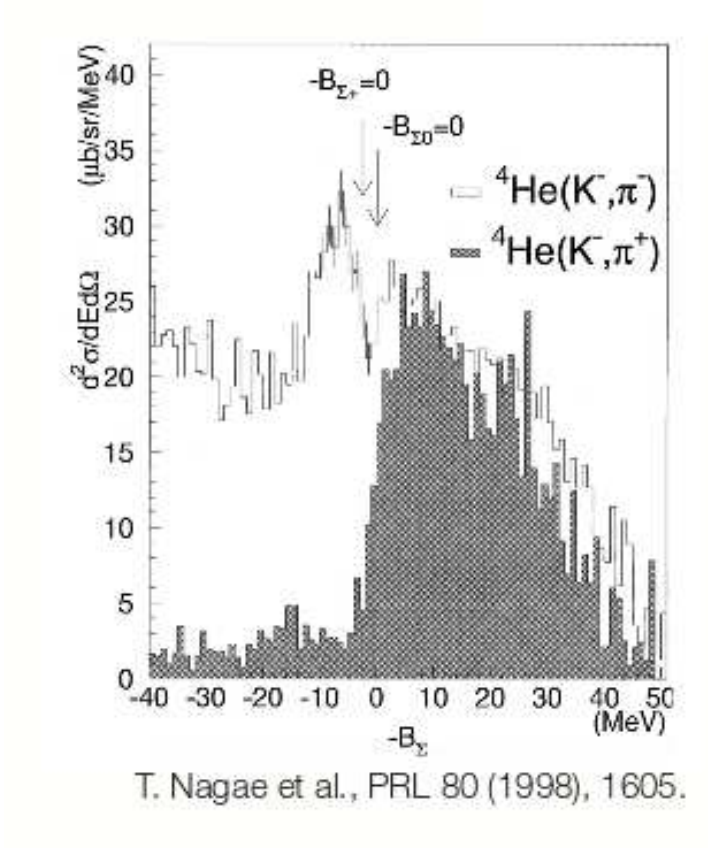
- Photon detection detection at ALICE performed in the range of p_{T} from 0.3 up to 40 GeV/c
- Many results on direct photons, π^0 and η mesons and resonances are published by ALICE
- First measurement of cross section ratio $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ at $\sqrt{s} = 7$ TeV at the LHC.
  - 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.
- First results indicating p-Σ^0 correlations are presented now in talks of Prof. L. Fabietti, A. Mathis on the Femtoscopy conference in Dubna. Overview of resonance production is done by E. Fragiacomo.

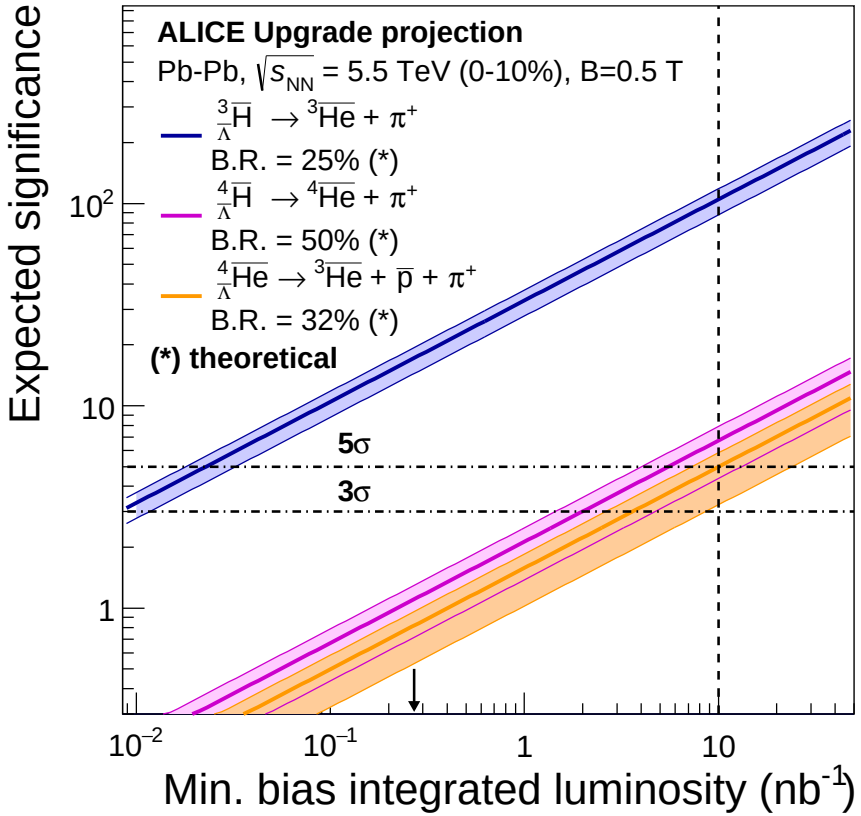
$\Longrightarrow$ **Further investigations are very interesting and needed**

Outlook. Search of ${}^{3}_{\Sigma^0}\mathrm{H}$ and ${}^{3}_{\overline{\Sigma^0}}\overline{\mathrm{H}}$ in LHC runs 3 & 4

on the base of the strategy of Σ^0 and ${}^{3}_{\Lambda}\mathrm{H}$ detection in LHC runs 1 and 2

Scarce data indicate hypernucleus ${}^{4}_{\Sigma^0}\mathrm{He}$





Large statistics for ${}^{3}_{\Lambda}\mathrm{H}$ (${}^{3}_{\overline{\Lambda}}\overline{\mathrm{H}}$) estimated for LHC runs 3 & 4

see subsection 3.2.4 in LHC Yellow Report "Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams", arXiv:1812.06772 [hep-ph], CERN-LPCC-2018-07)


Σ^0

Backup. p_{T} of reconstructed simulated Σ^0 and Λ (left), γ (right)