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Σ^0 and $\overline{\Sigma}^0$ Production in pp Collisions at $\sqrt{s} = 7$ TeV

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Abstract

The first measurements of Σ^0 and $\overline{\Sigma}^0$ baryons' transverse momentum (p_{T}) spectra, integrated yields and mean p_{T} in pp collisions at the LHC are reported. The Σ^0 ($\overline{\Sigma}^0$) signal is reconstructed via the Λ ($\overline{\Lambda}$) + γ decay channel by invariant mass analysis. The Λ ($\overline{\Lambda}$) baryon is reconstructed by its decay into p + π^- ($\overline{\mathrm{p}} + \pi^+$), while the photon is detected exploiting the unique capability of the ALICE detector to measure low energy photons via conversion into $\mathrm{e}^+\mathrm{e}^-$ pairs. The yield of Σ^0 is compared to that of the Λ baryon, which has the same quark content but different isospin. These data contribute to the understanding of hadron production mechanisms and provide a reference for constraining QCD-inspired models and tuning Monte Carlo event generators such as PYTHIA.

*See Appendix A for the list of collaboration members

Contents

1 Introduction

The study of strange baryons and their resonances in proton-proton collisions provides a reference for tuning QCD inspired event generators and contributes to the understanding of strangeness production mechanisms. Colliding projectiles initially contain no strange valence quarks indeed and therefore all strange particles are created in the collisions. In particular, Σ measurements can help to understand production mechanisms of baryons with non-zero isospin. These are an important complement of the Lambda data as these particles have similar mass ($m_\Sigma - m_\Lambda \sim 77$ MeV) and equal quark content (uds), but different isospin value (I_Λ =0, I_Σ =1) [1]. Furthermore a yield ratio of Σ^0 to Λ can provide a hint to understand a charge and/or isospin independency of the $\Sigma^\pm$ and Σ^0 due to the same $I(J^p)$, analogy to the yield ratio of π^0/η [?].

All Λ ($\overline{\Lambda}$) measurements include a feed-down from Σ^0 ($\overline{\Sigma^0}$). In fact, the main decay of the Σ^0 ($\overline{\Sigma^0}$) is the electromagnetic one (Σ^0 ($\overline{\Sigma^0}$)$\rightarrow \Lambda$ ($\overline{\Lambda}$) + γ) with a 100 % branching ratio. Usually this feed-down contribution is not considered for the Λ ($\overline{\Lambda}$) spectrum and as a consequence, model predictions for Λ ($\overline{\Lambda}$) baryons are compared with data including secondary Λ ($\overline{\Lambda}$) originated from Σ^0 ($\overline{\Sigma^0}$) [?]. Thus the measurement of the Σ^0 ($\overline{\Sigma^0}$) spectrum enables us to estimate the contribution of the secondary Λ ($\overline{\Lambda}$) in the hyperon spectrum. Furthermore, the Σ^0 production rates can be also an important measure to correct the p_T spectra of proton, pion and photon with taking into account the feed-down contributions from Σ^0 .

Comparison of hyperon data with models as PYTHIA [2] and EPOS [3] permits to investigate their production mechanism. In particular, at LHC energies a significant disagreement was observed in p_T spectrum of Λ between PYTHIA6 Perugia 2011 [2] predictions and measurements of ALICE [4] and ATLAS [5] experiments. In this respect, the measurement of the p_T spectrum of Σ^0 and the ratio of Σ^0 to Λ at the LHC energy are fundamental for the tuning of the models and to understand the hadronic mechanism processes.

In this paper the first measurement of the Σ^0 ($\overline{\Sigma^0}$) transverse momentum spectrum and its integrated yield measured at mid-rapidity with ALICE detector in inelastic pp collisions at $\sqrt{s}$ =7 TeV are presented and compared with the Λ results in the same collisions. This enriches the existing data set limited until now to low energy collisions results.

2 Experimental setup and event selection

Since a complete and detailed description of the ALICE detector and of its performance during the LHC Run 1 (2010-2013) can be found in refs [6, 7], we briefly outline only two sub-detectors utilized for Σ^0 analysis: Inner Tracking System (ITS) and the Time Projection Chamber (TPC) below.

Vertex reconstruction and tracking in the central-barrel and charged-hadron identification are performed with the Inner Tracking System (ITS) [6] and the Time-Projection Chamber (TPC) [8], which are located inside a solenoidal magnet providing a magnetic field of 0.5 T parallel to the LHC beam axis. The ITS is composed of six cylindrical layers of silicon detectors, located at radii between 4 and 43 cm from the nominal beam axis with covering a pseudo-rapidity range of $|\eta| < 0.9$ and the full azimuth. The two innermost layers consist of Silicon Pixel Detectors (SPD), the two intermediate layers of Silicon Drift Detectors (SDD) and the two outermost layers of Silicon Strip Detector (SSD). The spatial resolution of the ITS enables measuring the distance of closest approach (DCA) of tracks to the primary vertex with a resolution better than 75 μm in the transverse plane for $p_\mathrm{T} > 1$ GeV/c in pp collisions [9]. The Time Projection Chamber (TPC) is a large (90 m^3) cylindrical gaseous detector filled with a mixture of Ne/CO_2 /N_2 (85.7/9.5/4.8%). It covers radially between 85 and 250 cm from the beam axis and a pseudo-rapidity range of $|\eta| < 0.9$ over the full azimuth, and provides track reconstruction with up to 159 space points, with a spatial resolution of 500 μm along the beam direction and in the transverse direction for tracks with η=0 [8]. In addition, it enables particle identifications via the measurement of the specific ionization energy loss (dE/dx) with a resolution of approximately 5.2% in pp collisions [7].

The data sample analyzed in this paper was recorded during the LHC pp run at $\sqrt{s} =$ 7 TeV in 2010 (only ? or - 2013?) using a magnetic field of 0.5 T, with both field polarities and a minimum-bias (MB) trigger which requires at least one hit in either SPD or the one of the V0 detectors. While SPD covers $|\eta| < 2.0$, the two V0 detectors, each consisting of scintillator tiles, are installed on both sides of the interaction point and cover -3.7 $< \eta <$ -1.7 and 2.8 $< \eta <$ 5.1 [10–12].

These (What is 'these'?) are used for triggering (Is it the same to f_{inel}, which must be same to the MB_{OR} = INEL?) and for rejecting beam-gas interactions (What is it?). Due to the low luminosity of this (Where can I find it?) data taking a high-efficiency (85.2 % [12]) MB trigger (It is NOT the MB, but MB_{OR}!) was used. The contamination from beam-induced background is removed offline by using the timing information and correlations (Which correlation?) in the V0-A,V0-C and SPD detectors, as discussed in detail in ref.[7] (Is this related to N$_{offlinetrigger}$? But how?). The probability of collision pileup per triggered event was below 3 % [12](How is it treated? Is it also taken into account for the final N$_{norm}$), but how?. A total amount of about 500 million MB events has been utilized for the analysis.

Events used for the data analysis are further required to have just one reconstructed primary vertex (PV), events containing more than one distinct vertex are tagged as pileup and are discarded. The PV is determined by tracks reconstructed in the ITS and Time Projection Chamber (TPC), and track segments in the SPD [7]. MB events are selected when the PV is positioned along the beam axis within $\pm$10 cm from the center of the ALICE detector The vertex reconstruction efficiency is 92.8 % [12]. These are all unnecessarily reapeated even with confusion!

Question: in [12], MB$_{OR}$ = INEL = at least one hit at SPD OR one of V0s
NSD = an additional condition of coincidence of two V0s = MB$_{AND}$
What was used? MB$_{OR}$ or MB$_{AND}$?
MB$_{AND}$/MB$_{OR}$ = 0.873 in [9, 13] f_{inel} = trigger efficiency for INEL = 87%, f_{vtx} = vertex reconstruction within $\pm$10cm = 88%
What is then N_{in} and $N_{offilinetrigger}$? Nowhere I can find it.
what is the relation between N_{norm} and N_{MB}?

3 Data analysis

Σ^0 were reconstructed by its electromagnetic decay (Σ^0 ($\overline{\Sigma^0}$) $\rightarrow \Lambda\,(\overline{\Lambda}\,) + \gamma$) which has a 100 % branching ratio. The main feature of this decay is the low energy of the energy of the emitted photon $\approx$ 100 MeV (any reference? Why is it relevant?). The Photon Conversion Method (PCM) in the central tracking system was used for photon identification employing the ITS and the TPC [7, 11, 14]. It reconstructs and identifies the vertices (V0$_\gamma$) of photon conversions to e^+e^- pair generatedi in the material of the inner detectors. For ALICE detector the probability of photon conversion in the central tracking system is about 0.08 and the reconstruction efficiency is about 0.67 [11]. Reliability of the method is based on the good agreement of the actual material budget and the simulated one [7]. Then both the decay products of the Σ^0 were identified as secondary vertices (V0): $V0_\Lambda$ of the weak decay $\Lambda\,(\overline{\Lambda}\,) \rightarrow p(\bar{p}) + \pi^+(\pi^-)$ and $V0_\gamma$ of the photon conversion during tracking procedure.

In the PCM analysis, photons are reconstructed as vertices (V0$_\gamma$) of electron and positron pair [11, 14–16]. The tracks for e^- (e^+) candidates are basically selected if: (1) $|\eta| < 0.9$, (2) $p_{\rm T} > 0.05$ GeV/c, (3) the ratio of the number of reconstructed to findable TPC clusters is larger than 0.35. For the particle identification of $e^-(e^+)$ tracks, the specific energy loss of electrons (positrons) in the TPC was required to be within a band between $-6\sigma_e$ and $7\sigma_e$ around the average dE/dx-value depending on $p_{\rm T}$, where σ_e is a standard deviation of the measured dE/dx distribution for $e^-(e^+)$. In addition, in order to reduce pion and kaon contaminations by rejecting the tracks with $|{\rm d}E/{\rm dx}| < 1\sigma_{\pi,K}$ for $p_{\rm T} < 0.5$ GeV/c, where $\sigma_{\pi,K}$

are the standard deviations of measured dE/dx distribution for pions (σ_π) and kaons (σ_K), respectively.

To select photons among all secondary vertices, further selection was performed on the level of the reconstructed V0$_\gamma$ [11, 14]. To remove π^0 and η meson Dalitz decays, the transverse distance (why only R$_T$?) of V0$_\gamma$ from PV have to be larger than 5 cm and smaller than 180 cm due to the V0 reconstruction procedure. Finally, the photons only with $p_{\rm T} > 0.020$ GeV/c and $|\eta| < 0.9$ are accepted. Additional cuts of $q_{\rm T} = p_e \sin\Theta_{\gamma,e} < 0.06$ GeV/c, where p_e is electron momentum and $\Theta_{\gamma,e}$ is the angle between γ momentum (p_γ) and electron momentum [17], and $\Psi_{pair} < 0.20$, where Ψ_{pair} is the angle between the plane perpendicular to the magnetic field ($x-y$) plane and the plane of the $e^-(e^+)$ pair [16] are applied for increasing the purity of $e^-(e^+)$ from γ.

To select Λ from Σ^0, the similar selection-criteria of the secondary vertex ($V0_\Lambda$) used in [4, 18, 19] with exploiting the weak decay topology of $\Lambda\ (\overline{\Lambda}\ ) \rightarrow p\pi^-(\bar{p}\pi^+)$ (branching ratio of 63.9% and decay length of $c\tau = 7.89$ cm [1]), is applied. The distance of closest approach (DCA) between positive and negative tracks from V0$_\Lambda$ and PV (Why PV?) was selected to be larger than 0.06 cm, and the cosine of the pointing angle Θ between the sum of daughter momenta and the line that connects the PV and V0$_\Lambda$, was requested to be greater than 0.993. The transverse distance between V0$^\Lambda$ and PV is requested to be between 0.5 and 180 cm. An Armenteros-Podolanski cut on $\Lambda: 0.01 < \alpha < 0.17$ and $0.2 < |q_{\rm T}| < 0.9$ was applied, where $\alpha_\Lambda = |\frac{p_l^p - p_l^\pi}{p_l^p + p_l^\pi}|$, where p_l^i is the longitudinal momentum of a particle i (p or π) with respect to the Λ momentum direction, $q_{\rm T}$ corresponds to transverse momentum of proton with respect to the Λ momentum. The Λ invariant mass ($M_{\rm p\pi}$) was selected within the interval of $1.110 < M_{\rm p\pi} < 1.120$ GeV/c^2 to reduce the amount of combinatorial background of Σ^0 invariant mass peak. Note, the nominal Λ mass (m_Λ) with its uncertainty is $\rm m_\Lambda = 1115.683 \pm 0.006$ [1].

	γ	Λ	Σ^0
$p_{\rm T}$	> 0.020	> 0.4	> 1.1
$\|\eta\|$	< 0.9	< 0.5	< 0.5
α	-	(0.01, 0.17)	> 0.6
$q_{\rm T}$	< 0.06	(0.2, 0.9)	< 0.12

Table 1: The final selection criteria of Σ^0 and its daughter particles.

In order to enhance the significance of the Σ^0 signal, softer cuts on Λ selection than those used in Λ [18, 19] and the additional phase-space cuts on Σ^0 as $\alpha = |\frac{p_l^\gamma - p_l^\Lambda}{p_l^\gamma + p_l^\Lambda}| > 0.6$ and $p_{\rm T} < 0.12$, (p_T ? or q_T?) are applied. Furthermore the rapidity range ($|y|$ (not $|\eta|$?)) less than 0.5 is selected for comparing directly with Λ results. The final ranges of the criteria are summarized in Table 1.

3.1 Signal extraction

The $\Sigma^0 + \overline{\Sigma}^0$ signals were extracted from invariant-mass distributions in each $p_{\rm T}$-bin of Σ^0 for the range of 1.1 up to 8 GeV/c. For the estimates of raw yield of the signal, a Gaussian function added to a third-order polynomial is applied to describe the signal and background for the range of $1.160 < M_{\Lambda\gamma} < 1.230$ GeV/c^2 in each $p_{\rm T}$-bin. Examples of invariant mass distribution are presented in Fig. 1 for two different $p_{\rm T}$-bins.

The mean value ($M_{\Lambda\gamma} = 1192.94 \pm 0.035 MeV/\mathrm{c}^2$) of the $\Sigma^0 + \overline{\Sigma}^0$ invariant masses from the fit results in all $p_{\rm T}$-bins agrees well to the PDG value [1]: 1192.642 ± 0.024 MeV/c^2. The standard deviations of the Σ^0 signals extracted from the fits to data are about 2.2 MeV for $1.1 < p_{\rm T} < 1.6$ GeV/c and about 1.2 MeV for $p_{\rm T} > 2$ GeV/c, which are in a good agreement with the ones estimated by the fits to the simulated distributions. (How about then between 1.6 – 2 GeV/c?) The increase of the width at low $p_{\rm T}$ is mainly due to the low-energy photons.

The raw yield is obtained by integrating the Gaussian signal function in the region ± 3 standard deviation

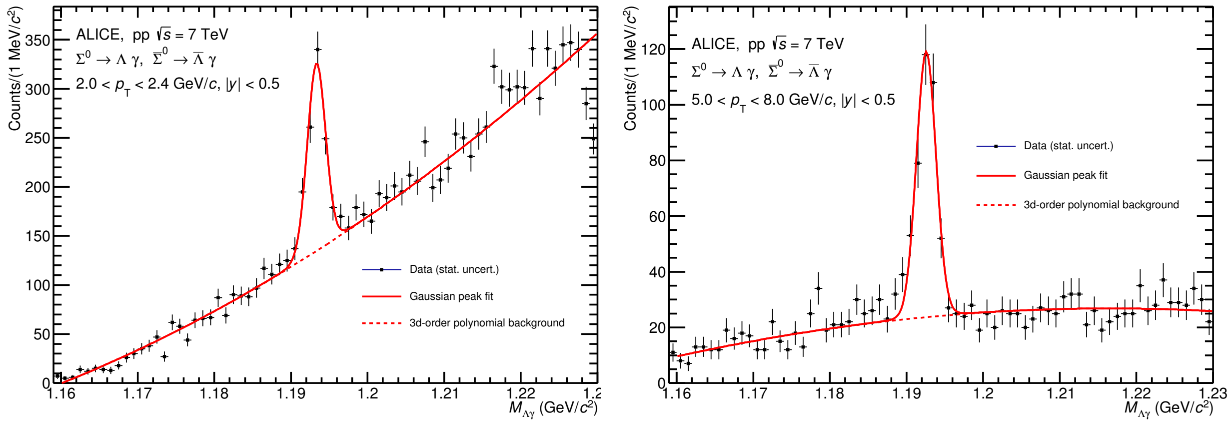

Fig. 1: Invariant mass distributions of $\Lambda\gamma$ and $\bar{\Lambda}\gamma$ pairs in p_{T} bins 1.6 – 2.0 and 4.0 – 5.0 GeV/c. The solid and dashed curves indicate a fit to the data using a third-order polynomial function with and without a Gaussian peak for the signal and background description, respectively.

in each p_{T} bin. The statistical uncertainties on the raw yields range between 3-6%. The different approaches with various signal and background estimations and the calculations of Σ^0 yields are discussed for the systematic uncertainties in section 3.3.

3.2 Corrections and normalization

By using the PYTHIA6 Perugia-2011 event generator [2] and the GEANT 3.21 package [20], the Σ^0 signals are reconstructed in each p_{T} from a generated sample of about 542 million MB pp events, and the correction factors ($A \times \varepsilon$) are estimated from the ratio between the number of reconstructed and generated Σ^0 hyperons in the same p_{T} and rapidity interval. The p_{T} distribution of correction factors multiplied by branching ratios (B.R.) for Σ^0 is shown in Fig. 2. The correction factors for Σ^0 and $\overline{\Sigma^0}$ are checked, respectively, and are consistent between each other in the measured p_{T} -interval between 1.1 and 8 GeV/c. Raw yields are thus corrected for the geometrical acceptance and the reconstruction efficiency (A $\times$ ε) of the detector with taking into account the branching ratio of Λ decay.

The MB spectrum was normalized to the number of N_{norm} events after applying the correction factors for trigger efficiency and event selection including primary vertex reconstruction and rejection of pileup events It was done analogous to the approach implemented in PCM package which was already used in several publications of ALICE [12, 14] . All those corrections result in a total scaling factor of 0.922 for the calculation of the total number of events used in Eq. 3.

The MB spectrum was normalized to the number of N_{norm} events after applying the correction factors for trigger efficiency and event selection including primary vertex reconstruction and rejection of pileup events. The yield of Σ^0 as a function of p_{T} is after background subtraction N^{Σ^0}:

$$\frac{d^2N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{1}{N_{MB}} \frac{N^{\Sigma^0}}{\Delta y \Delta p_{\mathrm{T}}} \frac{f_{vtx} \times f_{inel}}{A\varepsilon}, \tag{1}$$

where $N_{MB} = N_{in} - N_{OfflineTrigger}$ - trigger hits in either of two VZERO detectors, the factor f_{vtx} is the fraction of triggered events for which a good primary vertex is found, f_{inel} is the fraction of inelastic collisions that fulfill the trigger conditions. It was done analogous to the approach implemented in PCM package which was already used in several publications of ALICE [12, 14] . All those corrections result in a total scaling factor of 0.922 for the calculation of the total number of events used in Eq. 3.

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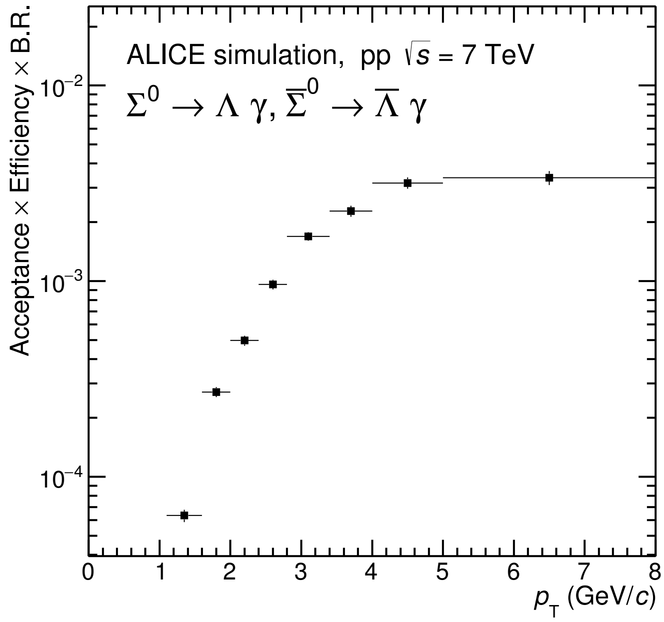

Fig. 2: The geometrical acceptance and the reconstruction efficiency (A $\times$ ε) multiplied by B.R. for Σ^0 in $|y| <$ 0.5 for MB events, obtained with PYTHIA6 Perugia-2011 event generator [2] ($\overline{\Sigma^0}$ must be removed in the plot!). Only statistical uncertainties are shown.(why? How much is the systematic uncertainties for each $p_{\rm T}$? - nowhere explained even also not in 3.3.)

What was used? MB_{OR} or MB_{AND}?
$MB_{AND}/MB_{OR} = 0.873$ in [9, 13] f_{inel} = trigger efficiency for INEL = 87%, f_{vtx} = vertex reconstruction within $\pm$10cm = 88%
What is then N_{in} and $N_{offilinetrigger}$? Nowhere I can find it.
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3.3 Systematic uncertainties

The total Σ^0 systematic uncertainty is determined by four general sources:

$$\sigma_{syst} = \sqrt{\sigma_{\gamma}^2 + \sigma_{\Lambda}^2 + \sigma_{\Sigma^0}^2 + \sigma_{mat}^2}, \tag{2}$$

where σ_{γ} and σ_{Λ} are the relative systematic uncertainties for the photon (γ) and Λ ($\bar{\Lambda}$) selections for the Σ^0 ($\overline{\Sigma^0}$) resonance, respectively, while σ_{Σ^0} and σ_{mat} are the systematic uncertainty due to the extraction of Σ^0 + $\overline{\Sigma^0}$ signals and the limited knowledge of the material budget for the conversion photon, relatively. As two V0s for reconstruction of Σ^0 + $\overline{\Sigma^0}$ resonances are independently analyzed with the photon conversion ($\gamma \rightarrow e^+e^-$) and the weak decay ($\Lambda \rightarrow \mathrm{p} + \pi^-$ and $\overline{\Lambda} \rightarrow \bar{\mathrm{p}} + \pi^+$), the corresponding systematic uncertainties are fully independent. Note, that quite low yield of the detected Σ^0 + $\overline{\Sigma^0}$ limits the possibility of the extraction of several components of the systematic uncertainties which were investigated in stand-alone analysis of Λ and isolated photon production with much larger statistics.(Do we need this argument? For what?)

The main sources of systematic uncertainties for Λ selection are following: the pointing angle Θ, $V0_{\Lambda}$ position, DCA between the Λ decay products, the ratio of the number of the reconstructed to the findable TPC clusters and, the difference between the proper lifetimes estimated from the difference $L\frac{m^{\Lambda} - m^{K^0_S}}{p}$, where L is defined as the distance between primary and $V0^{\Lambda}$ vertex and p is its momentum.(What is it? It was not mentioned before at all! The uncertainties of PID of daughter particles MUST be included, instead.) The relative systematic uncertainties estimated in this analysis for the Λ identification vary between 3 to 11 % depending p_{T} , see Table 2, and are consistent with the ones estimated for Λ results in [4, 18].

The main source of the photon reconstruction uncertainty for PCM is determined by the identification of $V0^{\gamma}$. The uncertainty of identification of e^+ and e^- tracks is estimated with varying the restrictions of σ_e in the TPC relative to the nominal dE/dx, and the contamination criteria ($\sigma_{\pi,\mathrm{K}}$) of pions and kaons [11]. The limits of the accepted $V0^{\gamma}$ were also varied to evaluate its stability. The contribution of photon selection systematic uncertainty varies 4 to 12 % also depending p_{T} .

The systematic uncertainty of Σ^0 +$\overline{\Sigma^0}$ yield extraction is estimated by varying the conditions of the background subtraction and raw-yield calculation of the invariant mass peaks shown in Fig. 1. The various combinations of the signal and the background distributions estimated by a mixed-event (e^+e^- pairs from different events) and a second-order polynomial, and the bin-counting method are applied for the for raw-yield extraction. The systematic uncertainties of raw-yield extraction range 2 to 10.5 %.

All systematic uncertainties are summarized in Table 2 for all p_{T} , and the mean value of the total systematic uncertainty averaged over all p_{T} -bins is 11.84 %.

σ_{Λ}	3 - 11 %
σ_{γ}	4 - 12 %
σ_{Σ^0}	2 - 10.5 %
Material budget	4.5 %
Total %	8 - 17

Table 2: Systematic uncertainties in Σ^0 yield. The single valued uncertainties are p_{T} independent. Values given in ranges correspond to the minimum and maximum uncertainties.

4 Results and discussion

4.1 Transverse momentum spectrum

The corrected yield at mid-rapidity (dN/dy) of (Σ^0 +$\overline{\Sigma^0}$)/2 per event in p_{T} produced from inelastic pp collisions at 7 TeV is shown in Fig. 3. The measurements span the p_{T} range is from to 1.1 to 8 GeV/c. It was checked that the spectra obtained separately for Σ^0 and $\overline{\Sigma^0}$ are equal inside the uncertainties.

The spectra are fitted with a Lévy-Tsallis function [22],

$$\frac{1}{N_{norm}}\frac{\mathrm{d}^2N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = p_{\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}y}\frac{(n-1)(n-2)}{nC[nC+m_0(n-2)]}\left[1+\frac{\sqrt{p_{\mathrm{T}}^2+m_0^2}-m_0}{nC}\right]^{-n}, \tag{3}$$

where N_{norm} is the number of MB events after the application of the correction factors, (How and where is the N_{norm} defined? Isn't it the N_{INEL}, as labeled in Fig. 3??) m_0 is the PDG value of m_{Σ^0} [1]. Free parameter of the fit are the n, C and dN/dy, which represents the particle yield per unit of rapidity. This fit function is widely used to describe all identified particle spectra in pp collisions[18, 23, 24], and to extract the integrated total yield for all p_{T} .

Finally, the integrated yield at mid-rapidity for Σ^0 of $\mathrm{d}N/\mathrm{d}y = 0.0256 \pm 0.0083_{(total)} = 0.0256 \pm 0.0038_{(stat)} \pm 0.0047_{(syst)} \pm 0.0057_{(extrap)}$ is obtained from Lévy-Tsallis fit of Fig. 3. The uncertainty (not shown (why?)) related to the overall normalization to inelastic events (or cross section) is fully correlated (with what?) and it amounts to +7.3% and -3.5 % [23, 25]. The value of the mean $\langle p_{\mathrm{T}} \rangle$ of Σ^0 was taken

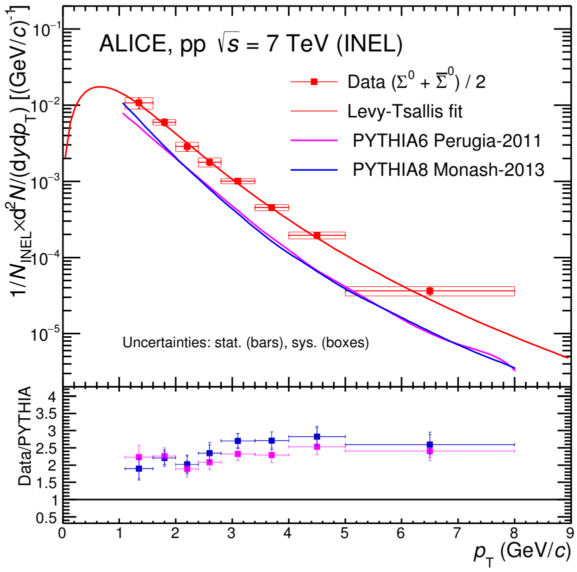

Fig. 3: (Top panel) Transverse momentum spectrum of both (Σ^0 +$\overline{\Sigma^0}$)/2 in the rapidity range $|y| < 0.5$. Statistical (bars) and systematic (boxes) uncertainties are included. The solid line represents Lévy-Tsallis fit, the dashed and dot-dashed lines (The figure must be updated for w/b (no color)) represents the spectrum from PYTHIA6 Perugia-2011 [2] and PYTHIA-8 Monash-2013 [21] generators. (Bottom panel) Ratio of (Σ^0 +$\overline{\Sigma^0}$)/2 yield to the simulated ones for each generator in p_T .

from the result of the fit without the uncertainty on material budget (why? What is then with σ_{mat} as shown in Table **??**? Isn't it included to the σ_{syst}?): $\langle p_T \rangle$= 1.161 ± 0.085 ($\pm 0.076_{stat} \pm 0.038_{syst}$).

The values of dN/dy and $\langle p_T \rangle$ were calculated by using the experimental spectrum in the measured p_T -range and the Lévy-Tsallis fit function outside of the measured p_T -range. Note that the fraction of the fit-function in the unmeasured p_T region between 0 and 1.1 GeV, i.e. from the low-p_T extrapolation to the total dN/dy is quite significant and equal to 0.58 from Lévy-Tsallis fit and 0.57 from Boltzmann-Gibbs Blast-Wave fit [26]. The uncertainty of the yield due to extrapolation to the unmeasured p_T -range was calculated by varying of the fit functions and is included as an independent source of the total uncertainty. The m_T-exponential, p_T -exponential, Fermi-Dirac, Boltzmann, Bose-Einstein Blast-Wave and Bose-Einstein fits [27, 28] are applied from the region of $p_T = 0$ up to 4.0 GeV/c, where almost full statistics is presented. The weighted difference, with the weight corresponding to the probability of the fit, is used for the estimate of extrapolation uncertainty. (Fit functions are differently weighted? Why? Do we need this comment?) The fraction from the high-p_T extrapolation is found to be negligible.

The transverse momentum spectra of (Σ^0 +$\overline{\Sigma^0}$)/2 is compared to both the Perugia-2011 tune of the PYTHIA generator [2] and Monash-2013 tune [21], see Fig. 3. One can see that the applied generators significantly underestimate the dN/dyin p_T , accordingly the overall production of Σ^0 and $\overline{\Sigma^0}$. Note that similar one is concluded from the comparison of Λ production at ALICE with PYTHIA Perugia-2011 event generator [18, 19]. (THERMUS MUST be compared and discussed!)

4.2 $\frac{\Sigma^0}{\Lambda}$ ratio

The ratios of (Σ^0 +$\overline{\Sigma^0}$)/2Λ from data [29], PYTHIA 6-Perugia 2011 [2] and PYTHIA 8-Monash 2013 [21] are presented as a function of p_T in Fig. 4. Note the trend of the monotonic increase of the ratio from data with p_T , while the ratios from both generators do show weird or practically no p_T -dependence. Despite of large uncertainties, Σ^0 in low p_T is significantly suppressed relative to Λ . This suppression of Σ^0 in low p_T is inordinately exaggerated in the generators due to underestimated Σ^0 and overestimated Λ -yields, as shown in the previous section 4.1 and [29]. (THERMUS MUST be compared and discussed!)

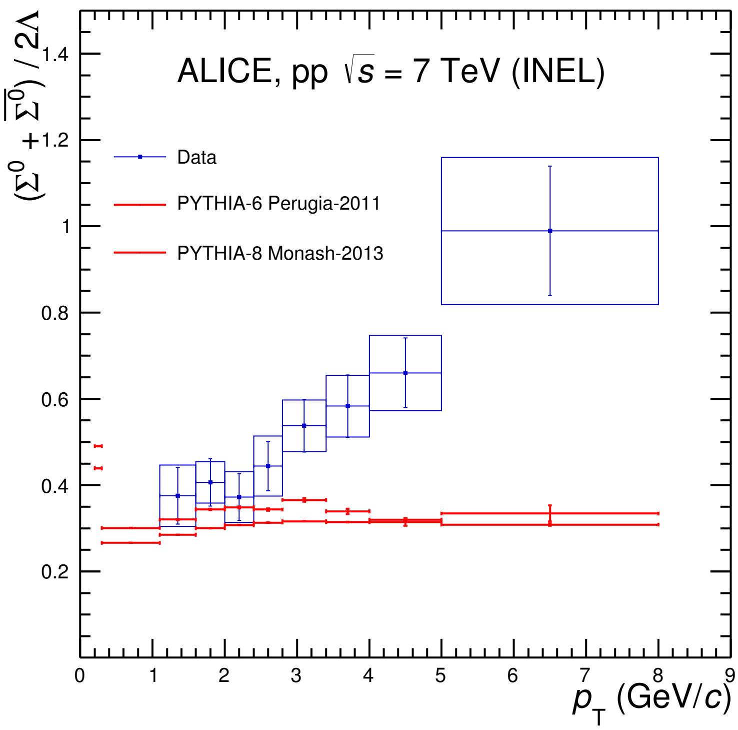

Fig. 4: The differential ratios of Σ^0 +$\overline{\Sigma^0}$)/2 to Λ from data [29] in the same bins of p_T (blue points). (The ratio (line) from the Lévy-Tsallis curves based on Σ^0 and Λ data is drawn in full range of p_T . ???) The red points indicate the same ratios from PYTHIA 6-Perugia 2011 and magenta points from PYTHIA 8-Monash 2013, respectively.

The integrated yield ratios of Σ^0 to Λ from various collision systems at different enrgies are shown as a function of $\sqrt{s}$ in Fig. 5. The integrated yield ratio measured with ALICE in pp collisions at $\sqrt{s} =$ 7 TeV is $0.337 \pm 0.111(\text{total}) = 0.337 \pm 0.051(\text{stat}) \pm 0.099(\text{syst})$, where the extrapolation uncertainty is included into the systematic error. While yields of Σ^0 have been measured in many different collision systems at low and intermediate energies, there exist only few results in high energy collisions including the ALICE result. The relatively new and more precise COSY-TOF pp data from Ref. [30, 31] see Fig. 5, have been published as the function of $\varepsilon = \sqrt{s} - (m_p + m_K + m_{\Lambda,\Sigma^0})$ and correspond to $\sqrt{s} \approx 2$ GeV/c. The cross section ratio $\frac{\Sigma^0}{\Lambda} \approx 0.45 \pm 0.05$.
The STAR detector reconstructed the electromagnetic decay ($\Sigma^0 \to \Lambda + \gamma$) via the weak decay of the $\Lambda \to p + \pi^-$ and γ conversions into e^+e^- pairs in the detector material [31, 32]. The cross section ratio $\Sigma^0/\Lambda = 0.16^{+0.41}_{-0.09}$ was thus obtained in minimum bias 0.2 TeV d+Au collisions. Note that STAR data with so large errors were published only in a conference proceeding [32] by the collaboration due to the limited statistics. Note: The STAR result is, however, also cited in the regular paper [31] The most precise data are from L3 experiment [33, 34], where both Σ^0 and Λ have been measured as a product of Z boson decays, as shown in Fig. 5, where $\Sigma^0/\Lambda \approx 0.33 \pm 0.03$ (This value is hardly confirmed from the two papers [33, 34] , and the phenomenology paper [31] DID NOT cite this L3 value!). These data in wide range of $\sqrt{s}$ support the convergence of the Σ^0 /Λ -ratio as expected by [31]. High energy nuclear collisions are of particular interest for the final state interactions [31] and the possibility of measuring isospin degeneracy factors from Σ^0 and Λ yields and of opening new channels of hyperon production via partonic degrees of freedom [35].

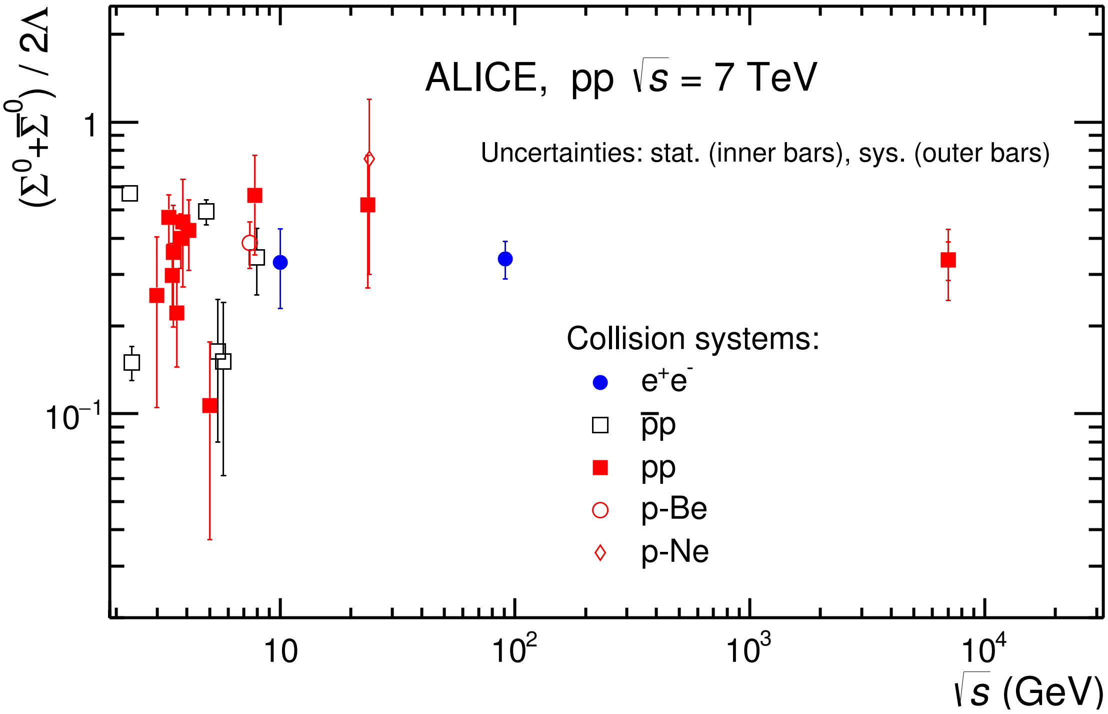

Fig. 5: Energy dependence of Σ^0 to Λ cross section ratio Which points to include - to be discussed.

5 Conclusions

In summary, Σ^0 ($\overline{\Sigma^0}$) hyperons produced in pp collisions at $\sqrt{s} = 7$ TeV are successfully reconstructed via electromagnetic decay to Λ ($\overline{\Lambda}$) and γ. The p_{T} distribution of $(\Sigma^0 + \overline{\Sigma^0})/2$ is obtained and compared with two different versions of PYTHIA generators, which both significantly underestimate the differential yields. So far no generator is found to explain the Σ^0 yield produced in pp collisions at $\sqrt{s} = 7$ TeV. Furthermore the differential yield ratios of Σ^0 to Λ from data and the generators are compared and the significant underestimates of Σ^0/Λ in both generators are observed in high p_{T}.

The integrated yield ratio measured in pp collisions at $\sqrt{s} = 7$ TeV is $(\Sigma^0 + \overline{\Sigma^0})/2\Lambda = 0.337 \pm 0.111(\text{total}) = 0.337 \pm 0.051(\text{stat}) \pm 0.099(\text{syst})$, where the systematic uncertainty includes the Lévy-Tsallis fits of Σ^0 and Λ spectra extrapolated to the unmeasured low p_{T}. So far this $(\Sigma^0 + \overline{\Sigma^0})/2\Lambda$ at the highest energy collision system uniquely contributes to consistency of an isospin degeneracy factor, 1/3 with the same ratios in various collisions at different energies from world-wide experiments. The current measurement represents a relevant baseline for further investigation in p-Pb and Pb-Pb collisions.

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