Production of Σ hyperons and search of Σ^0-hypernuclei at LHC with ALICE

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Plan

- Introduction
- Detection of Σ^0
- Σ^0 world data and Σ^0/Λ cross section ratio
- First observation of Σ^+, $\bar{\Sigma}^-$ at LHC
- Search for Σ^0-hypernuclei
- Summary

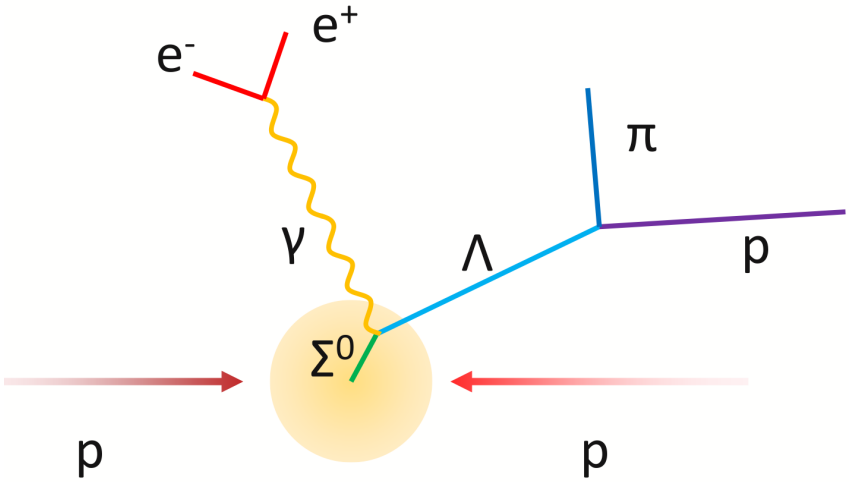
Σ^0 cross section in pp collisions

Particle	Quarks	Mass (MeV/c^2)	Width (MeV/c^2)	Lifetime (fm/c)	EM decay	Branching ratio (%)
Σ^0	uds	1192	~ 0	22 200	$\Lambda + \gamma$	100

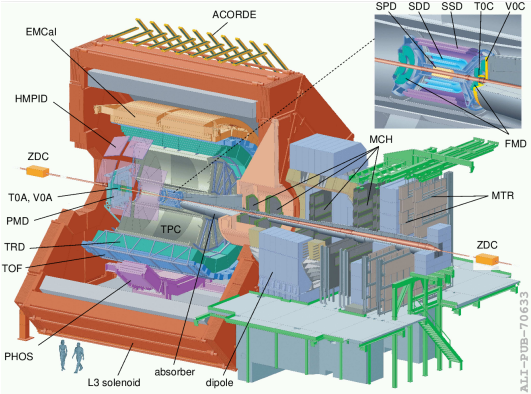
(PDG collab., "Review of Particle Physics", PTEP, **2022**, 083C01, 2022)

- **No production cross section measurements at energies larger than 91 GeV**
- Comparison with the Λ baryon, which has the same quark content but different isospin.
- Discrimination of prompt and secondary hyperons from weak decays.
- Constrain feed-down corrections for protons, pions and direct photons at low transverse momenta.
- Contribution to the understanding of hadron production mechanisms.
- Reference for tuning Monte Carlo event generators such as PYTHIA, EPOS and DIPSY.
- Baseline for comparison with Pb–Pb data.

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

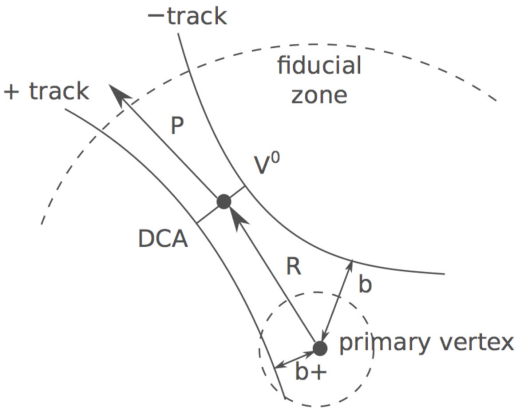


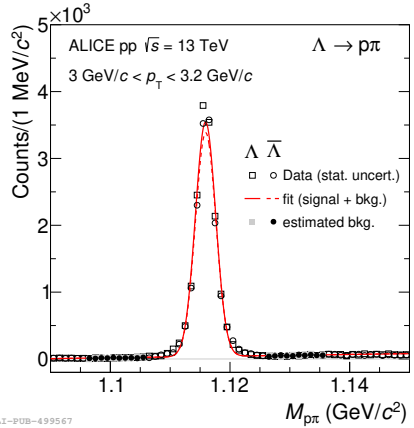
The ALICE detector



ITS, TPC and TOF are mainly used for reconstruction and identification of tracks
V0A+V0C and ZDC for multiplicity, centrality, trigger and timing.
Unique particle identification, high granularity, tracking down to $p_{\mathrm{T}} = 0.1$ GeV/c.
Size 16× 26 meters, weight $\sim$ 10000 tons.

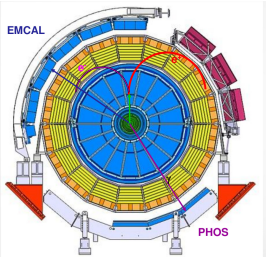
$\Lambda \to p\pi^-$ detection (ALICE collab., Eur. Phys. J. C 81 (2021) 256)

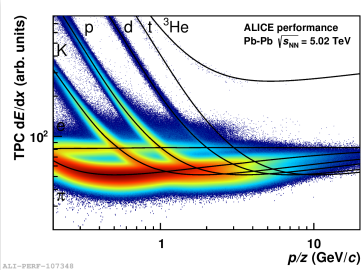




- secondary vertex (V^0) with oppositely charged tracks
- distance of closest approach (b) between positive track and primary vertex > 0.06 cm
- cos of the angle between V0 momentum and vector connecting primary and secondary vertices > 0.993

Photon detection at ALICE

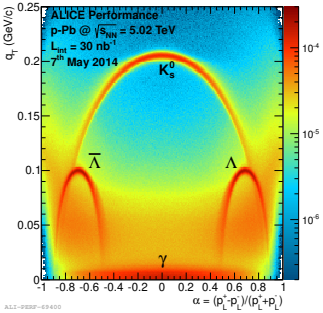


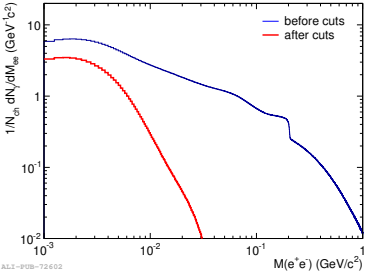


- EMCAL: large acceptance (100°, $|\eta| < 0.9$) but limited energy resolution
- PHOS: good energy resolution but limited acceptance (60°, $|\eta| < 0.135$)
- Photon Conversion Method (PCM)
- good momentum resolution at low $p_{\mathrm{T}} \sim 1 - 5$ %
- excellent particle identification capabilities in large p_{T} range 0.1 - 20 GeV/c
- full azimuthal angle coverage ($|\eta| < 0.9$)
- conversion probability < 0.085

(ALICE collab., JINST, **3**, S08002, 2008; ALICE collab., Int. J. Mod. Phys., **A29**, 1430044, 2014)

γ reconstruction with PCM

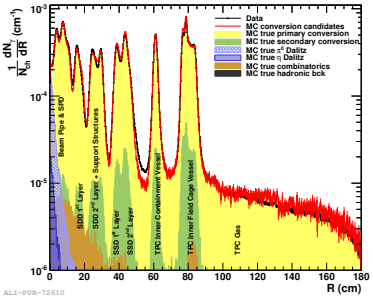


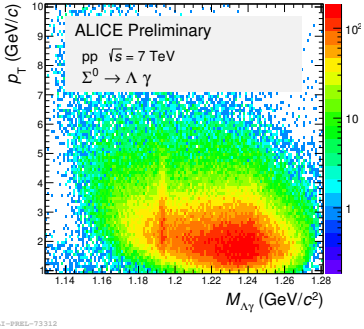


- $e^+(e^-)$ track selection with track $p_{\mathrm{T}} > 50$ MeV$/c$
- γ conversion vertex at distance to primary vertex $5 < R < 180$ cm
- remaining V0 (Λ, K^0_S) removed with further selections: $q_{\mathrm{T}} < 0.05$, corresponding to transverse momentum of e^+ with respect to the γ momentum.

$\Longrightarrow$ **small background contamination in the photon sample**

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

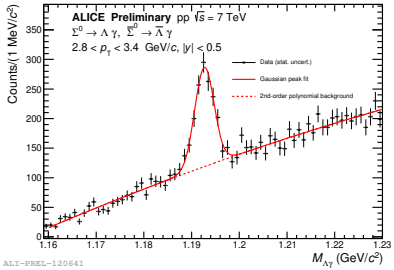


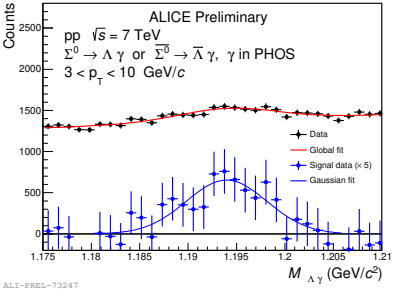


- $\gamma \to e^+ + e^-$ is detected through the secondary V^0 vertex with Photon Conversion Method (PCM) in the central barrel detectors
- The distribution of the conversion points is well reproduced by MC. The radiation thickness of the detector material integrated for $R < 180$ cm and $|\eta| < 0.9$ 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**

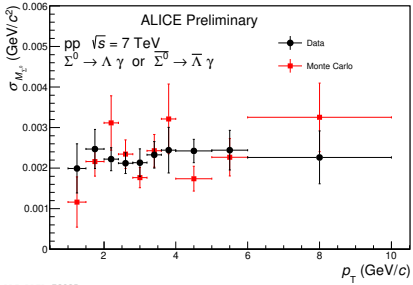
Mass of $\Sigma^0 \to \Lambda + \gamma$ and $\bar{\Sigma}^0 \to \bar{\Lambda} + \gamma$

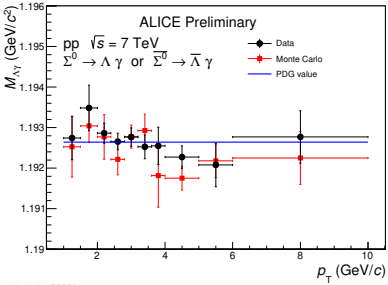




- Σ^0 invariant mass is calculated from the four-momenta of the selected Λ and γ candidates.
  Note low $E_\gamma \approx 100$ MeV.
- Σ^0 mass resolution $\sigma_M^{PCM} = 2$ MeV$/c^2$ at $2.8 < p_{\mathrm{T}} < 3.4$ GeV$/c$
- Proof-of-principle: Σ^0 peak is also observed with photon detected in PHOS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

Σ^0 mass and width from PCM

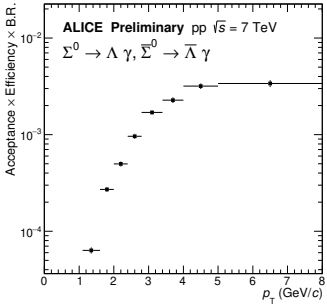




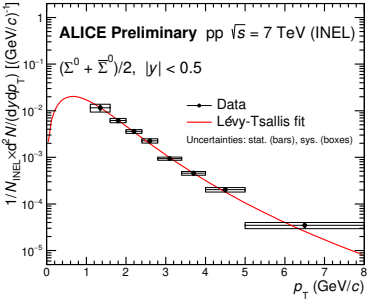
$\Longrightarrow$ Reconstructed peak position is in good agreement with the PDG value:
$M_{PDG}(\Sigma^0) = 1192.642 \pm 0.024$ MeV/c^2

$\Longrightarrow$ 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 corrections, spectrum and Lévy-Tsallis fit



ALI-PREL-119423



ALI-PREL-118997

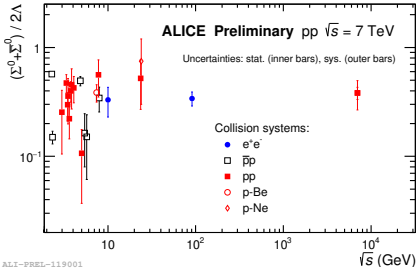
γ conversion probability < 0.085

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 $\sim 18\%$.

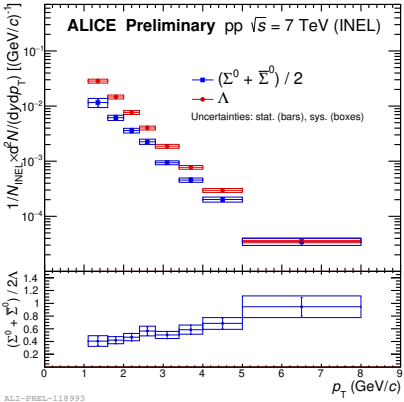
ALICE measurement and world data



- First measurement at LHC of $\left(\Sigma^0 + \bar{\Sigma}^0\right)/2\Lambda$ cross section ratio complements world data from lower energies
- e^+e^- data at $\sqrt{s} = 91$ GeV from L3 experiment at LEP reported $\left(\Sigma^0 + \bar{\Sigma}^0\right)/2\Lambda = 0.33 \pm 0.03$, where both Σ^0 and Λ detected in hadronic Z decays

(M. Acciarri et al, L3 collab., Phys. Lett. B 479 (2000) 79-88.)

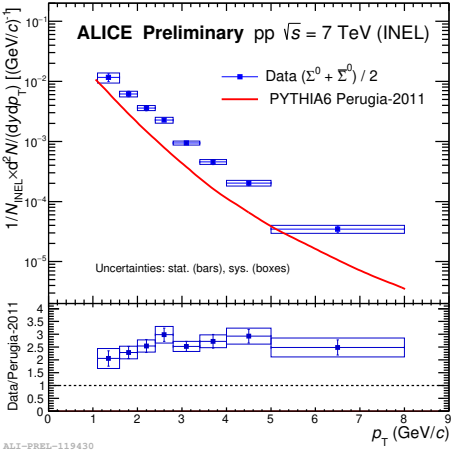
p_T-differential $\left(\Sigma^0 + \bar{\Sigma}^0\right)/2\Lambda$ ratio

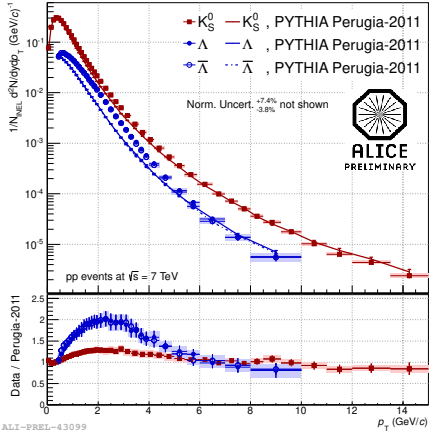


$\Longrightarrow$ **Increasing trend of the $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio with p_T is an indication of different contributions of primordial and final Σ^0 and Λ production.**

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

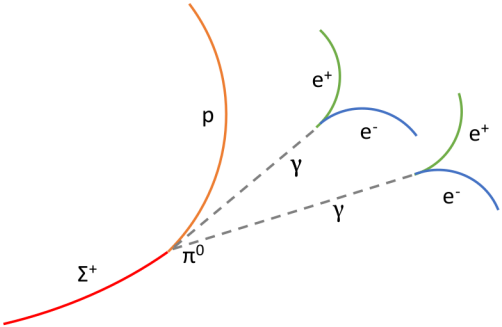
Σ^0 and Λ vs generators

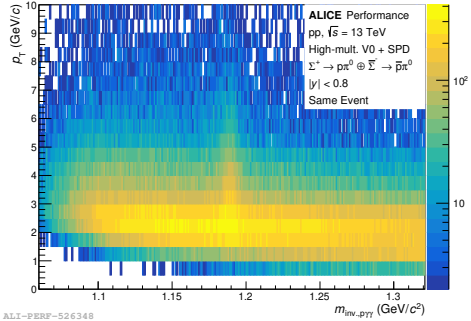




$\Longrightarrow$ PYTHIA6 Perugia-2011 clearly underestimates the production of both ground-state hyperons in the intermediate p_{T}-range

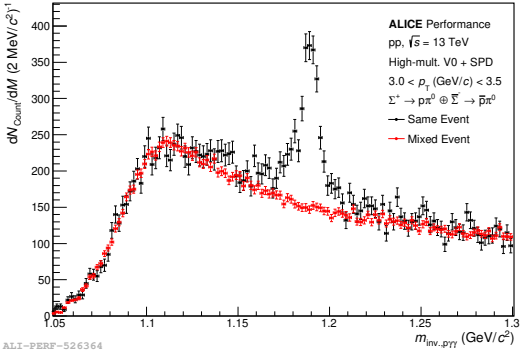
First observation of $\Sigma^+(\bar{\Sigma}^-) \to p(\bar{p}) + \pi^0(\gamma\gamma)$ at LHC

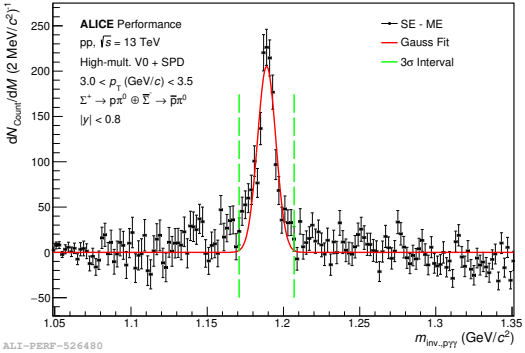




Two photons were observed using PCM and High Multiplisity Trigger

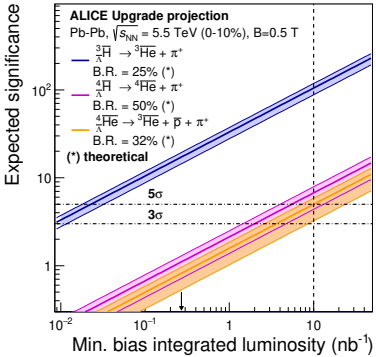
Mass peak of $\Sigma^+ + \bar{\Sigma}^-$



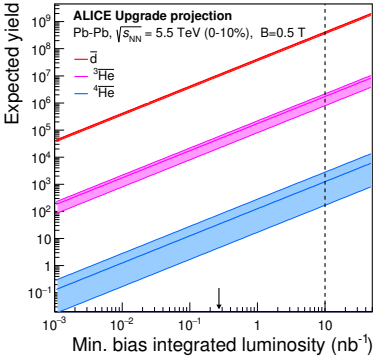


Clean peak after background subtraction. **Further analysis is in progress**

Projection for the next LHC data taking period



ALI-SIMUL-312332



ALI-SIMUL-312336

- Expected higher integrated luminosity: ~ 10 nb^{-1} ($\sim$8x10^{9} collisions at 0-10 % centrality)
- New ITS: less material budget and more precise tracking for the identification of hyper-nuclei

Search for ${}^{3}_{\Sigma^0}H$ and ${}^{4}_{\Sigma^0}He$ in LHC runs 3&4

Production mechanisms similar to the ones considered for Λ hypernuclei like strangeness exchange (K^-, $\pi^{\pm}$)

(T.Nagae et al., Phys. Rev. Lett. 80 (1998) 1605)

Search for

$$ {}^{3}_{\Sigma^0}H^3({}^{3}_{\overline{\Sigma}^0}H) \rightarrow \Lambda(\overline{\Lambda}) + d $$

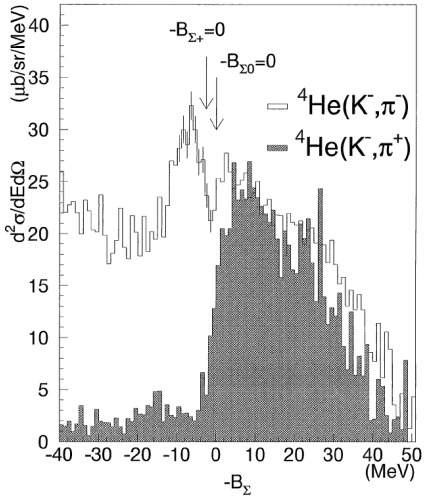
and

$$ {}^{3}_{\Sigma^0}H({}^{3}_{\overline{\Sigma}^0}H) \rightarrow {}^{3}_{\Lambda}\ H({}^{3}_{\overline{\Lambda}}H) + \gamma $$

on the basis of observed

$$ {}^{3}_{\Lambda}H^3({}^{3}_{\overline{\Lambda}}H) \rightarrow {}^{3}\ He(\overline{{}^{3}He}) + \pi^{-(+)} $$

(Z.Citron et al. "Future physics opportunities for high-density QCD at the LHC with heavy-ion...", arXiv:1812.06772 [hep-ph], CERN-LPCC-2018-07)

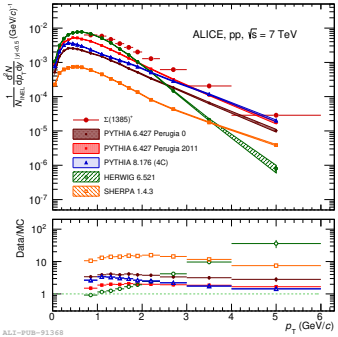


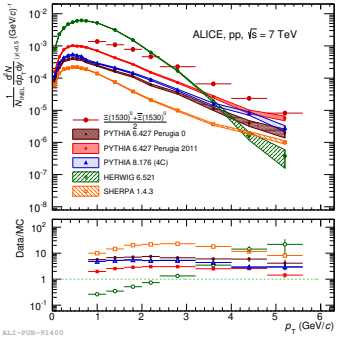
Summary and outlook

- First measurement of $\Sigma^0(\bar{\Sigma}^0)$ production cross section in pp collisions at 7 TeV.
  $\Longrightarrow$ The results can help to constrain production models and contribute to the previously very limited set of world data.
  $\Longrightarrow$ Dedicated paper is under development, analysis of pp data at 13 TeV has started.
- First observation of Σ^+, $\bar{\Sigma}^-$ with ALICE at LHC
- Σ^0-hypernuclei search is foreseen at LHC with ALICE in Run 3 in 2022–2025 years.

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

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