Strangeness enhancement studies at the ALICE experiment

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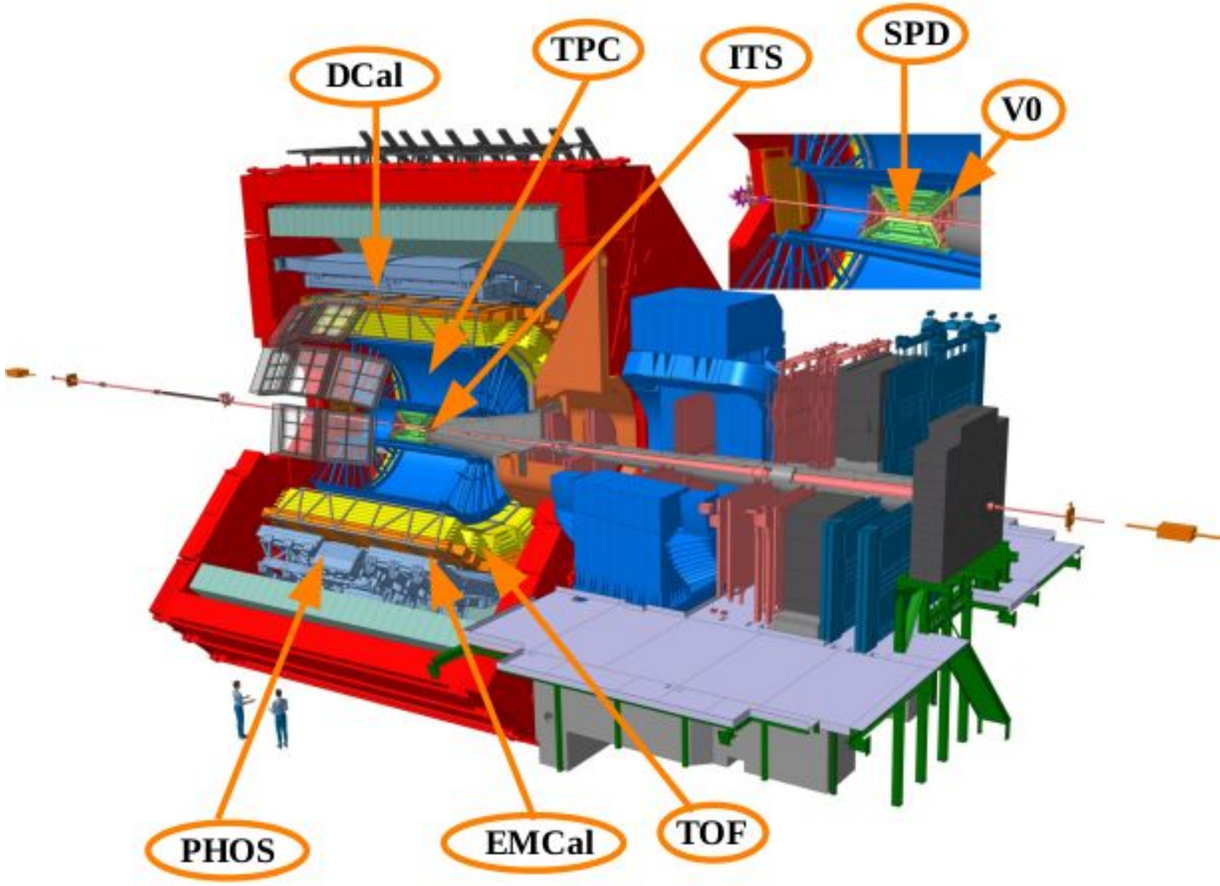
The ALICE detector

- Tracking down to low transverse momentum is provided by the Inner Tracking System (ITS) and Time Projection Chamber (TPC)

- Charged particle identification is done with Time Projection Chamber (TPC) and Time-of-Flight (TOF)

- Electromagnetic calorimeters: PHOS, EMCal and DCal

- V0 and SPD are used for multiplicity estimation

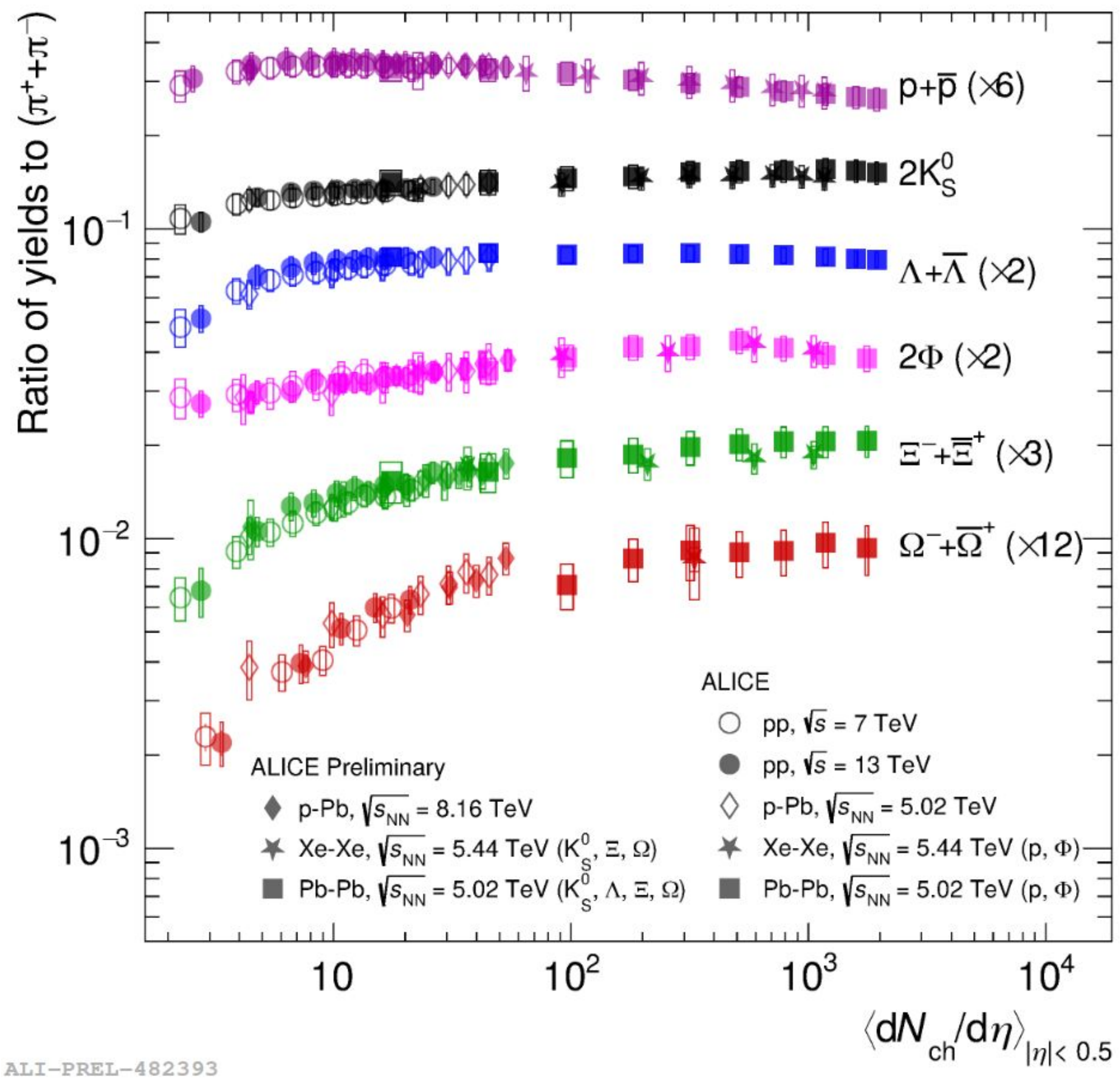


Strangeness studies

Strangeness enhancement was one of the first proposed signatures of QGP formation

Measurements of the multiplicity and centrality dependence of strange and multi-strange hadron production have been performed by ALICE in:

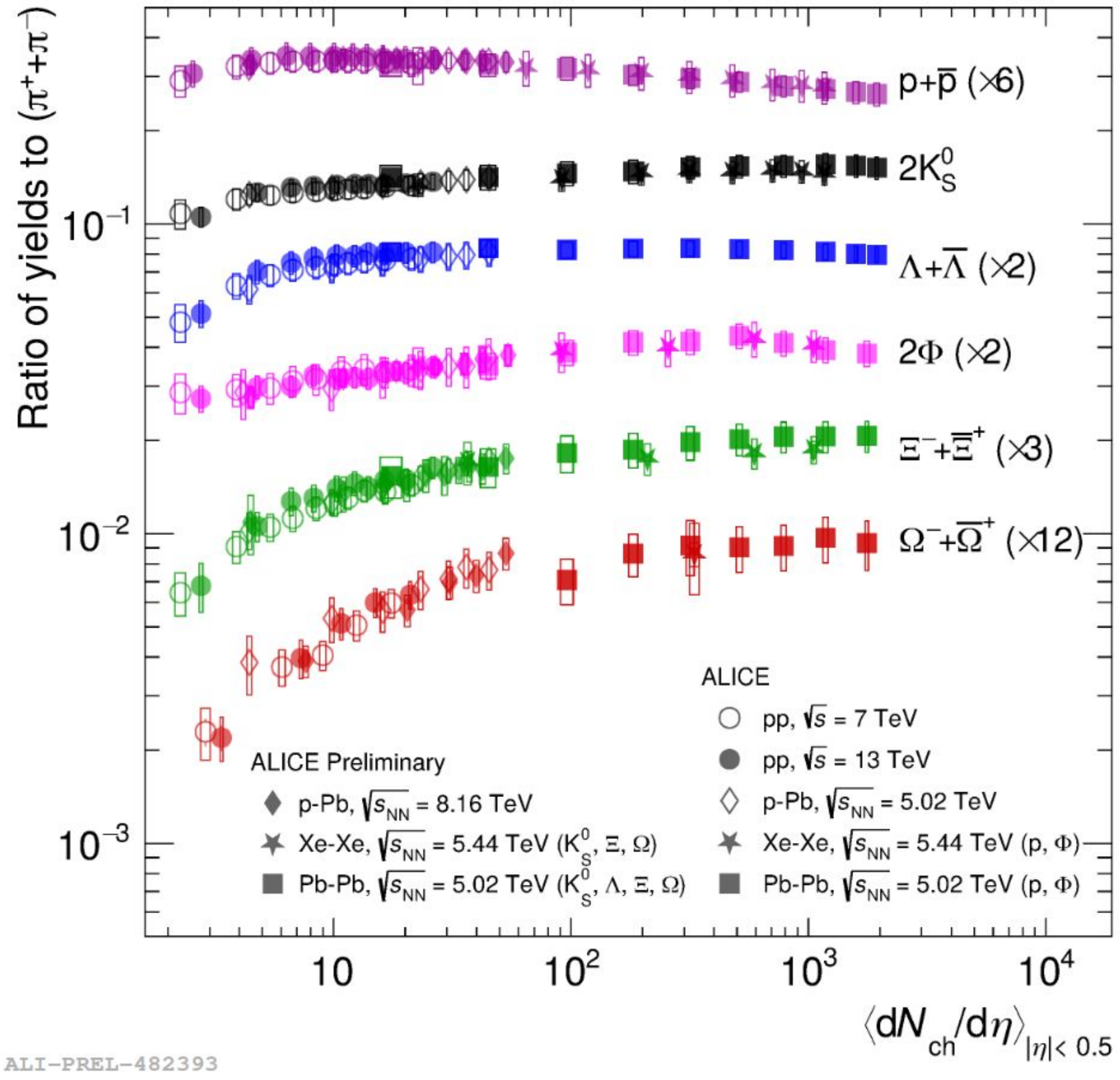
- high-multiplicity **proton–proton (pp)** collisions [Nature Phys 13, 535–539 (2017)]
- **proton–lead (p–Pb)** collisions [Phys. Lett. B 728, 25–38 (2014); Phys. Lett. B 758, 389–401 (2016)]
- **lead–lead (Pb–Pb)** collisions [Phys. Lett. B 728, 216–227 (2014); Phys. Rev. Lett. 111, 222301 (2013)]



Strangeness studies

Strange-hadron to pion yield ratios in pp, p–Pb and Pb–Pb as a function of the charged-particle multiplicity:

- h/π increases from low multiplicity pp collisions, saturating for central Pb–Pb
- Continuous evolution smoothly connecting different collision systems and energies
- Strange content hierarchy: $S_\Omega > S_\Xi > S_\Lambda$, where S - number of strange or anti-strange quarks



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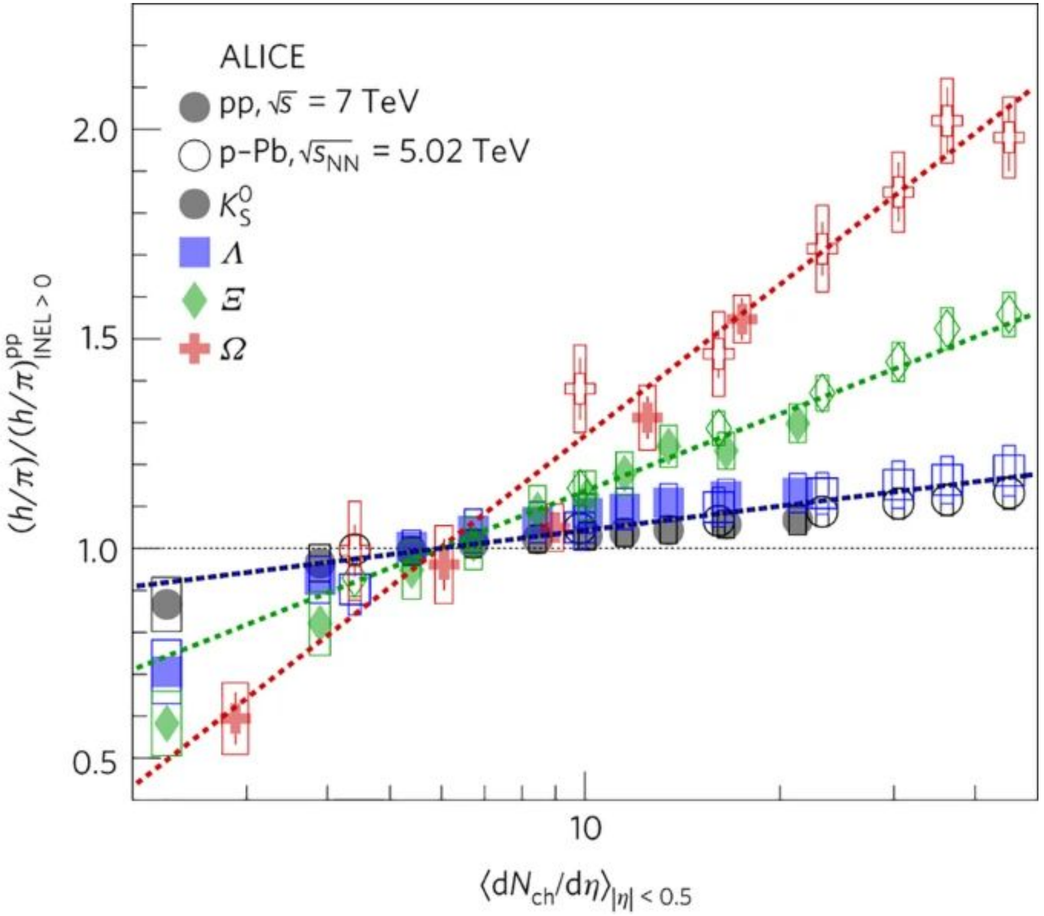

[Nature Phys 13, 535–539 (2017)]

Motivation

- The strangeness content of the final state in ultrarelativistic heavy-ion collisions has been studied through measurements of kaons, Λ, Ξ and Ω, but not yet Σ
- Σ-hyperons carry a significant fraction (~⅓ of Λ) of the strangeness produced in the collision and are a useful probe of QGP formation [Phys. Rev. D 101, 034506]
- Previously, only Σ^0 was measured by ALICE at the LHC

$\Sigma^+ = \mathrm{uus}$

$m = 1189.37 \pm 0.07\ \mathrm{MeV}/c^2$

$\Sigma^+ \rightarrow p\pi^0 (51.57 \pm 0.30)\ \%$

$\Sigma^+ \rightarrow n\pi^+ (48.31 \pm 0.30)\ \%$

$\Sigma^- = \mathrm{dds}$

$m = 1197.449 \pm 0.030\ \mathrm{MeV}/c^2$

$\Sigma^- \rightarrow n\pi^- (98.848 \pm 0.005)\ \%$

$\Sigma^0 = \mathrm{uds}$

$m = 1192.642 \pm 0.014\ \mathrm{MeV}/c^2$

$\Sigma^0 \rightarrow \Lambda\gamma (100)\ \%$

Motivation

- Monte-Carlo models predictions of strange hadron production can be tested
- However, the measurement is a **challenging task**, because all decays of all Σ states **involves neutral decay products**, thus requiring high-resolution calorimeters or usage of Photon Conversion Method (PCM)
- Several approaches of charged measurement were developed during LHC Run 2
- Measurement of N-Σ correlation should shed a light on the presence of Σ-hyperons in neutron stars and constrain their Equation-of-State
- Previously, only p-Σ^0 interaction via femtoscopy was measured [Phys.Lett.B 805, 135419 (2020)]

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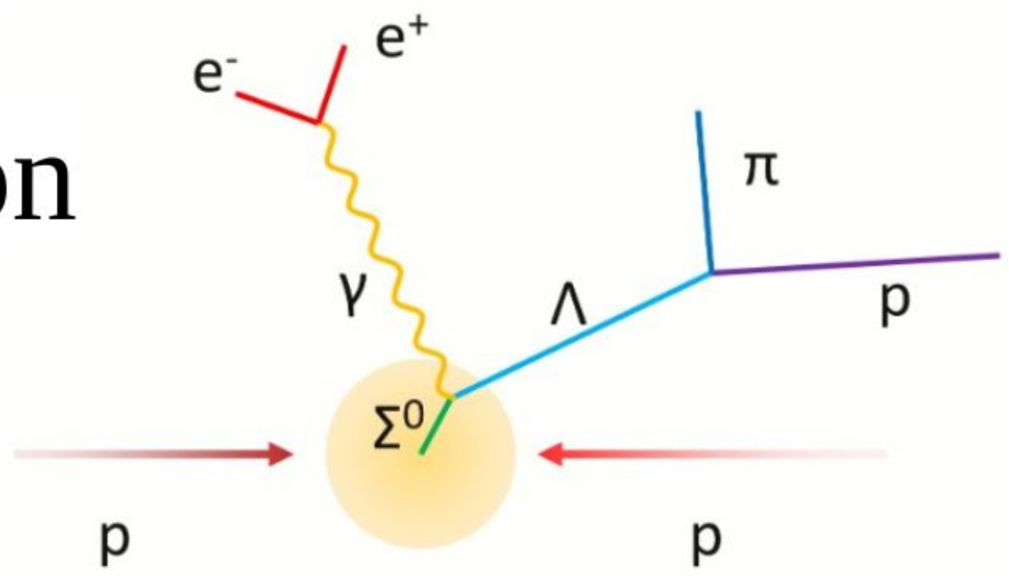
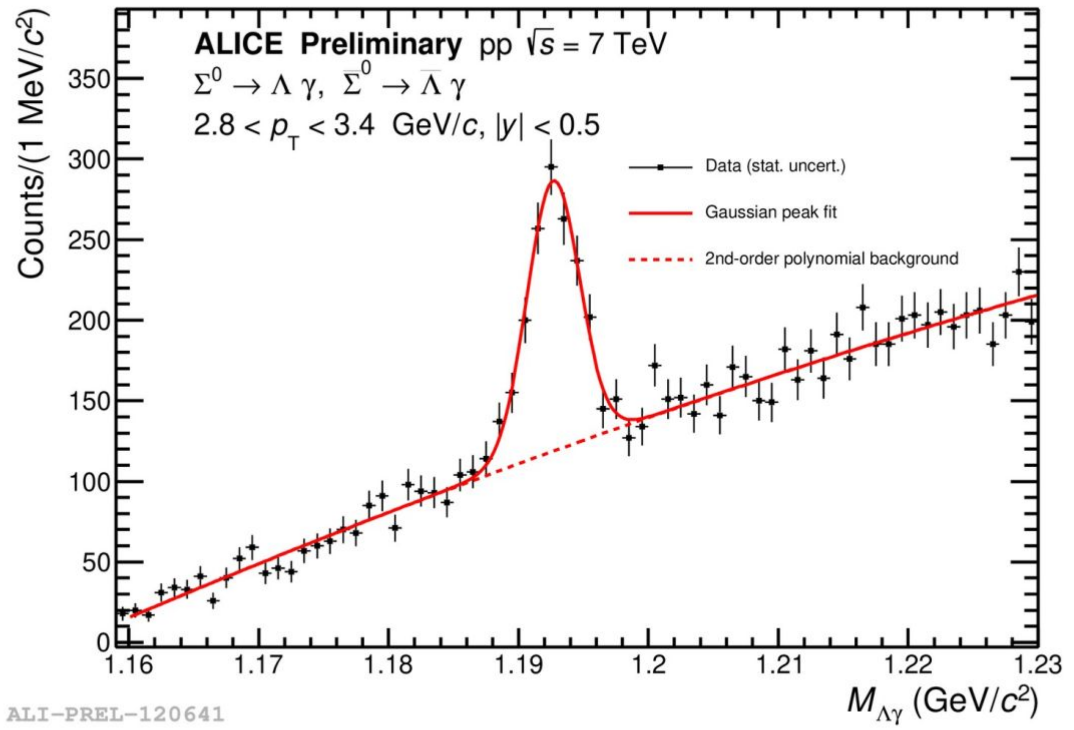
Σ^0 and $\bar{\Sigma}^0$ reconstruction



- Λ is reconstructed using its decay into proton and pion

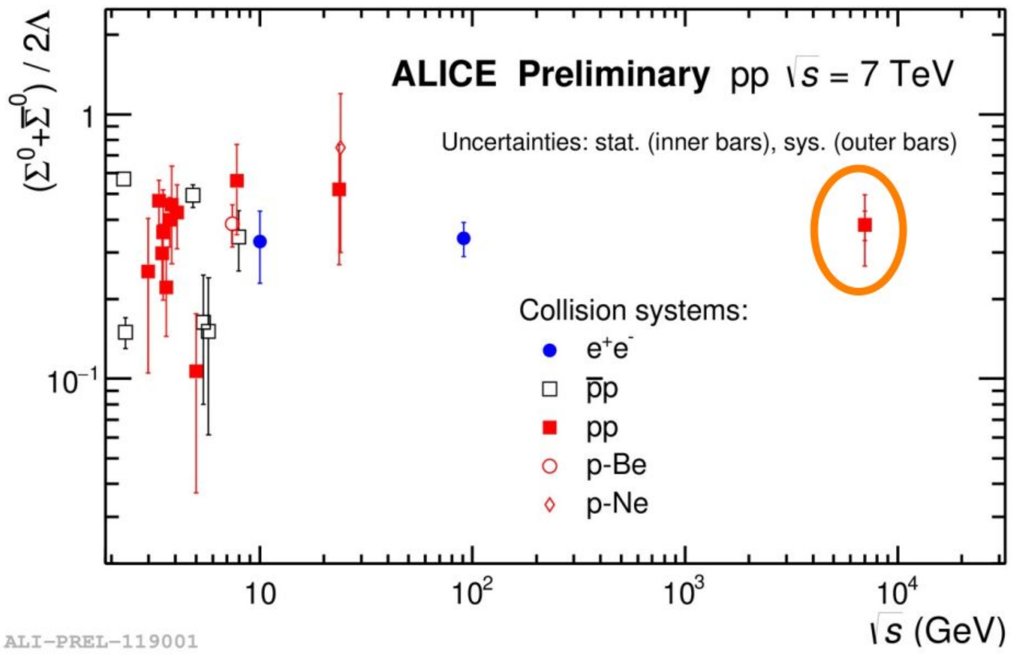
- γ is reconstructed via Photon Conversion Method (PCM)

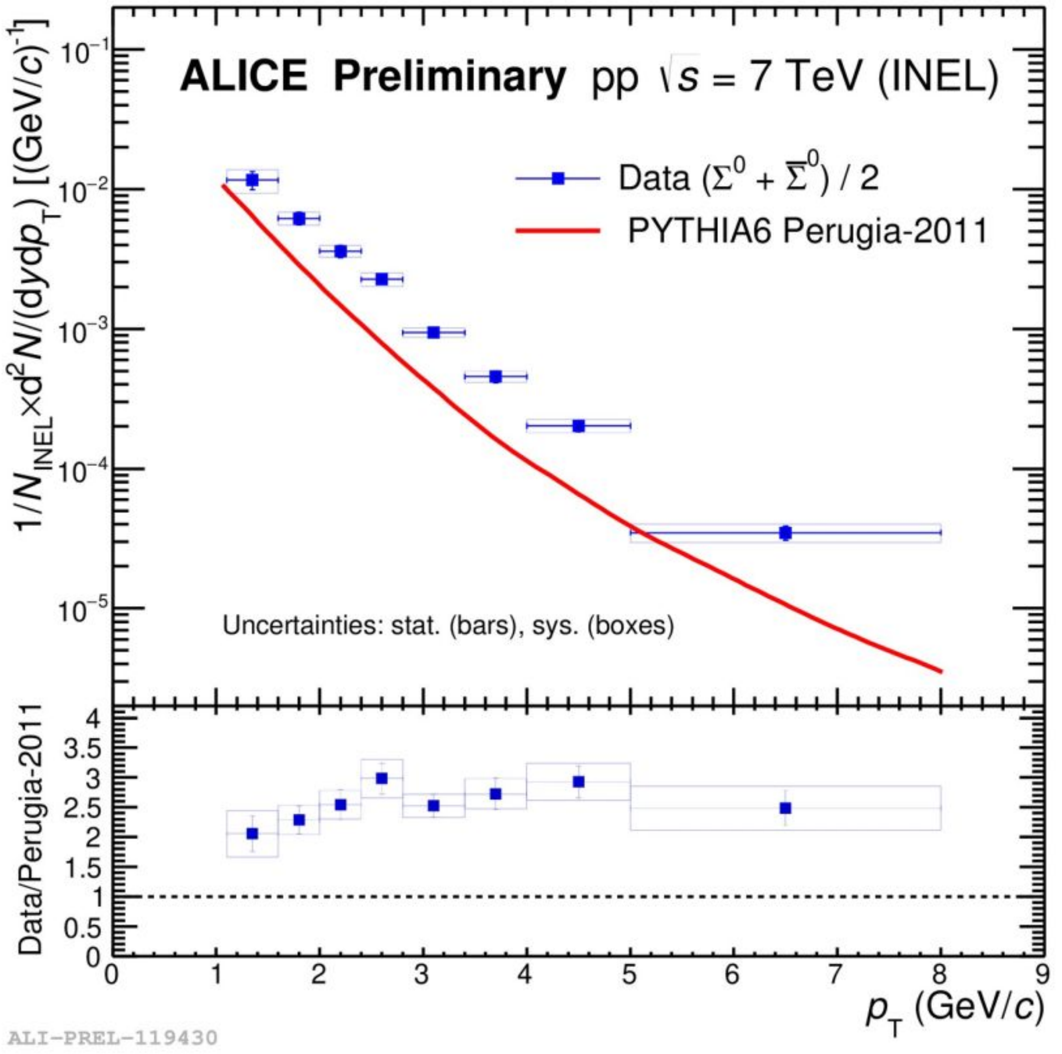
- Invariant mass distribution is constructed using selected candidates



Σ^0 and $\bar{\Sigma}^0$ measurement

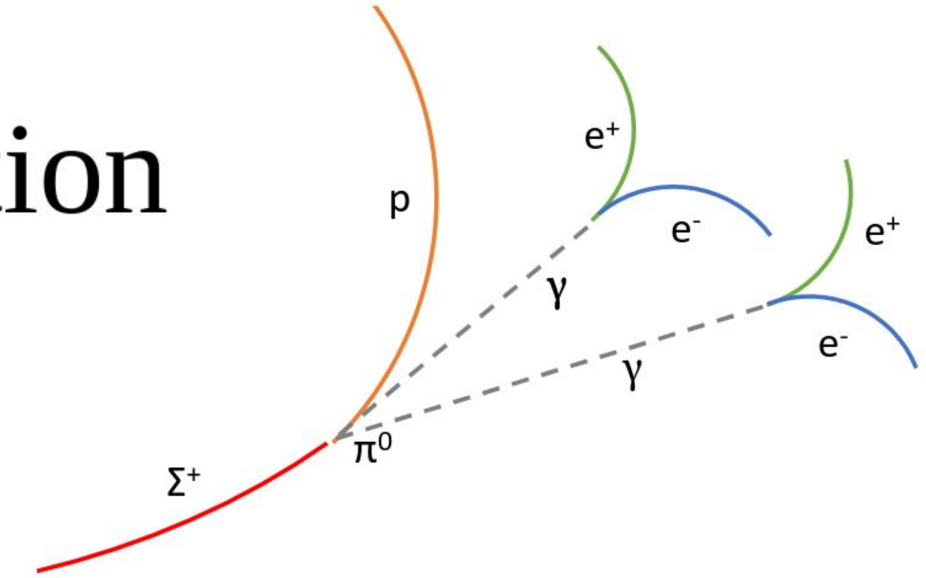
- $(\Sigma^0 + \bar{\Sigma}^0)/2\Lambda$ ratio complements world data from lower energies
- PYTHIA6 [JHEP 05, 026 (2006)] underestimates the production of Σ^0

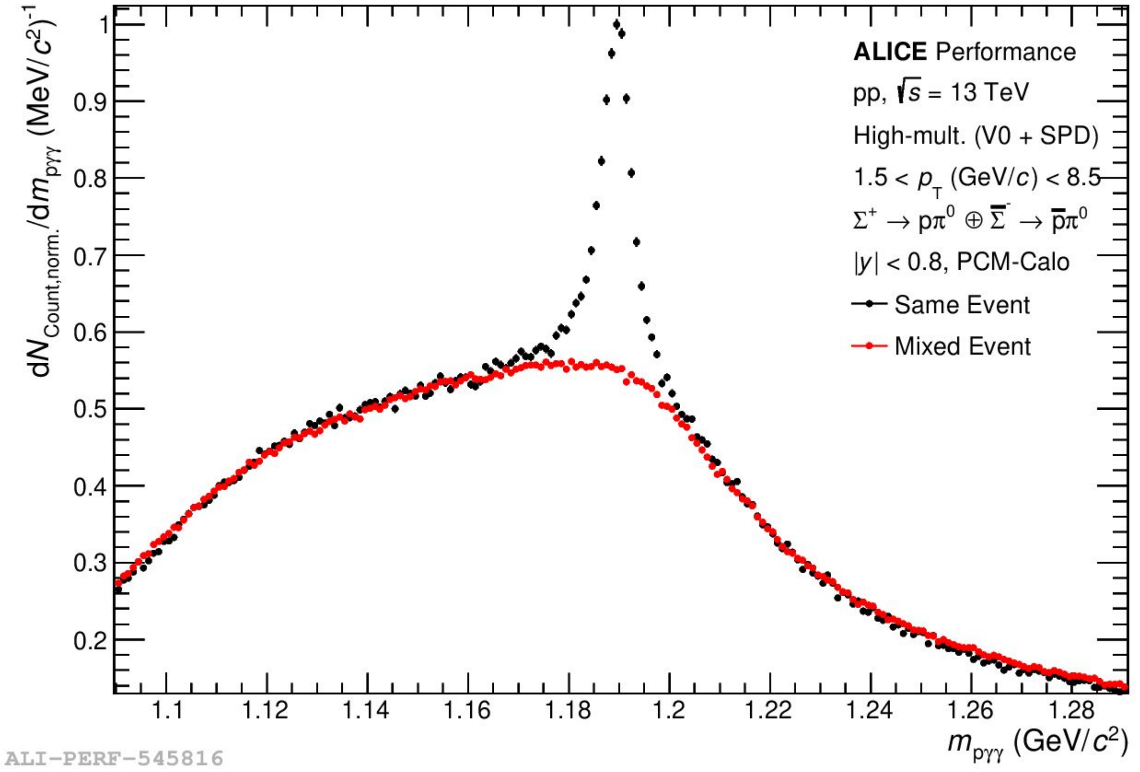




Σ^+ and $\bar{\Sigma}^-$ reconstruction

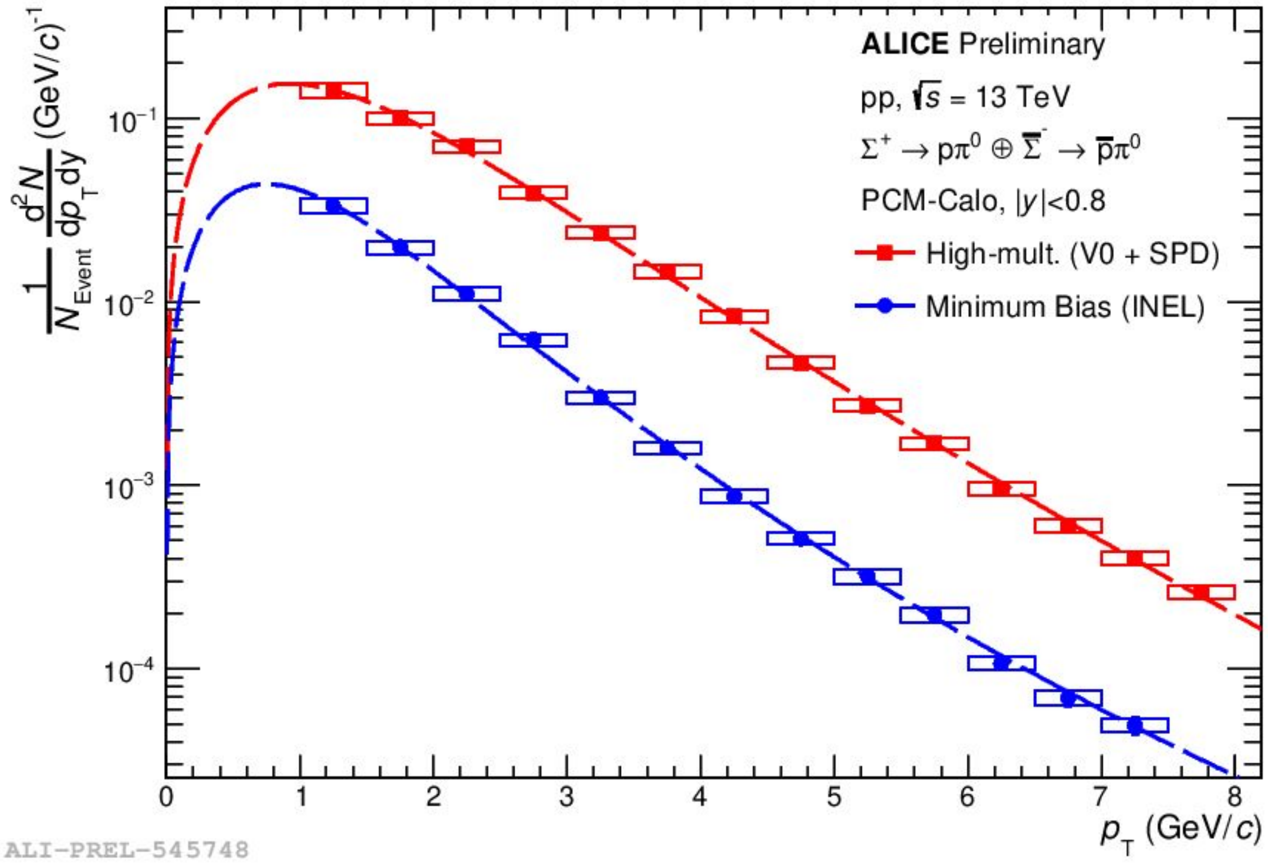
- Proton is detected and identified using the tracking system
- Two γ can be detected either in calorimeters (PHOS, EMCal, DCal) or via PCM
- Both PCM-Calo and PCM-PCM techniques give results that are in agreement with each other
- Secondary vertex can be reconstructed using only γ measured with PCM





Σ^+ and $\bar{\Sigma}^-$ measurement

- Spectrum is measured both in Minimum Bias and High Multiplicity collisions
- Mean multiplicity in MB is around 7.18 and in HM 30.46



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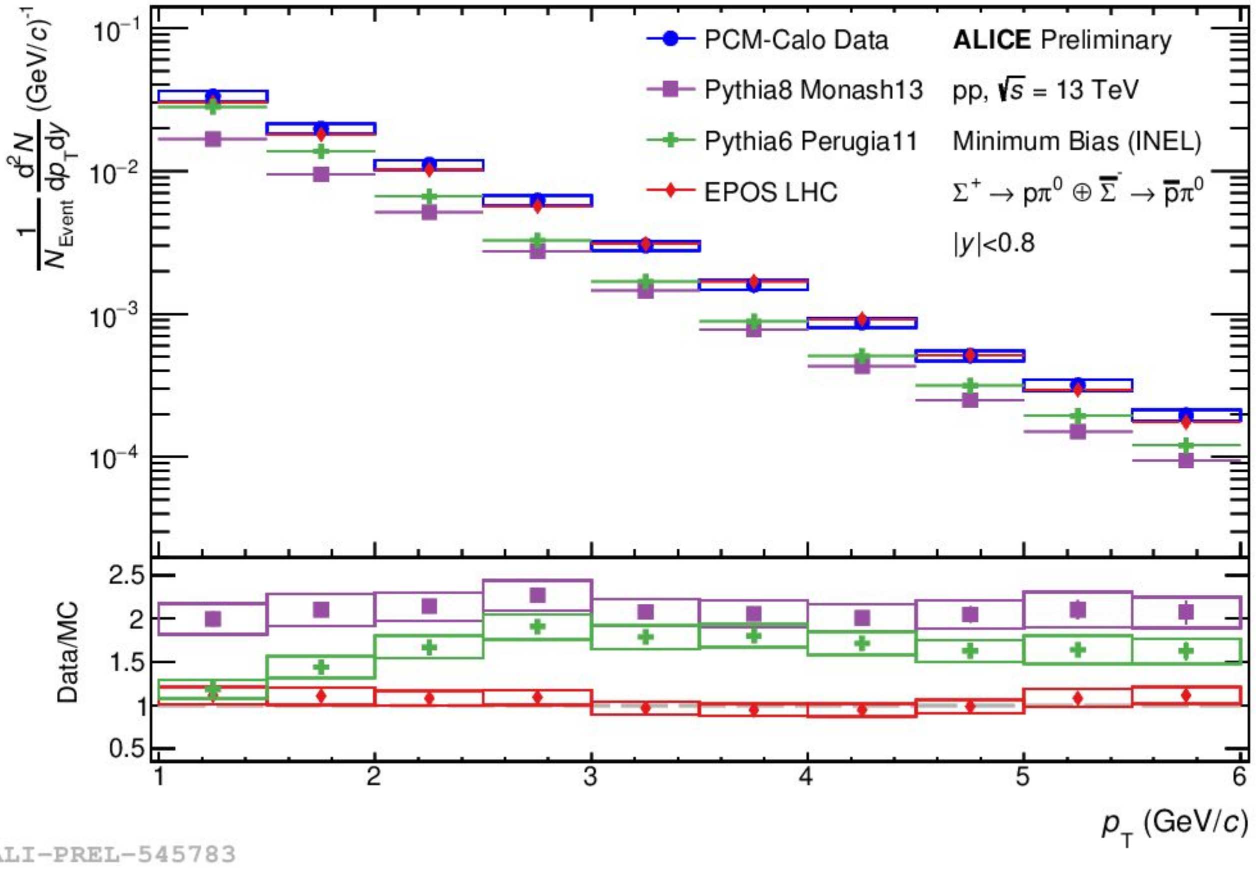
- Spectrum is well reproduced by EPOS LHC generator [Phys. Rev. C 92, 034906], while PYTHIA8 [arXiv:2203.11601] catches the shape, but underestimates the yield
- PYTHIA6 [JHEP 05, 026 (2006)] does not describe the shape of the spectrum at low transverse momentum and underestimates the yield



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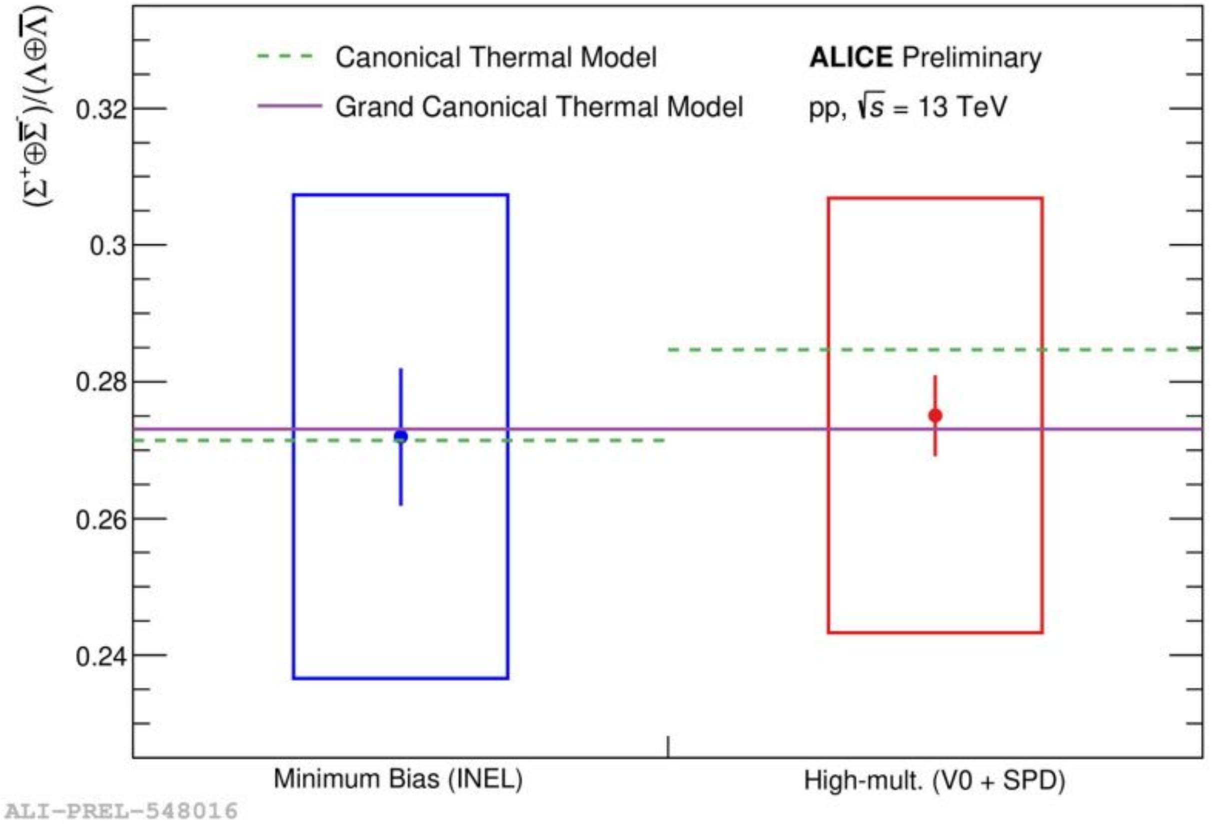
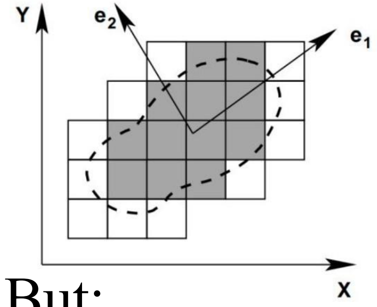
- PYTHIA6 [JHEP 05, 026 (2006)] does not describe the shape of the spectrum at low transverse momentum and underestimates the yield
- Σ/Λ ratio is in good agreement with canonical and grand canonical thermal model calculations
- Within the uncertainties the yield ratio do not change in MB and HM events



Antineutron identification in PHOS

How we can identify $\bar{n}$:

- Deposited energy of annihilation
- Neutrality (CPV, charged particle veto)
- Dispersion of cluster (M20, M02 – eigenvalues of S matrix)



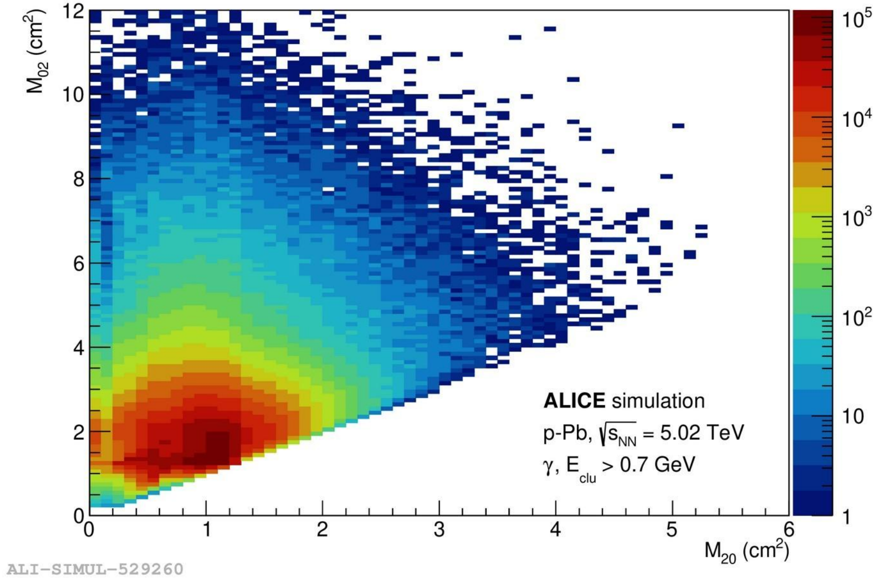
$$S = \begin{pmatrix} s_{xx} & s_{xz} \\ s_{zx} & s_{zz} \end{pmatrix}$$

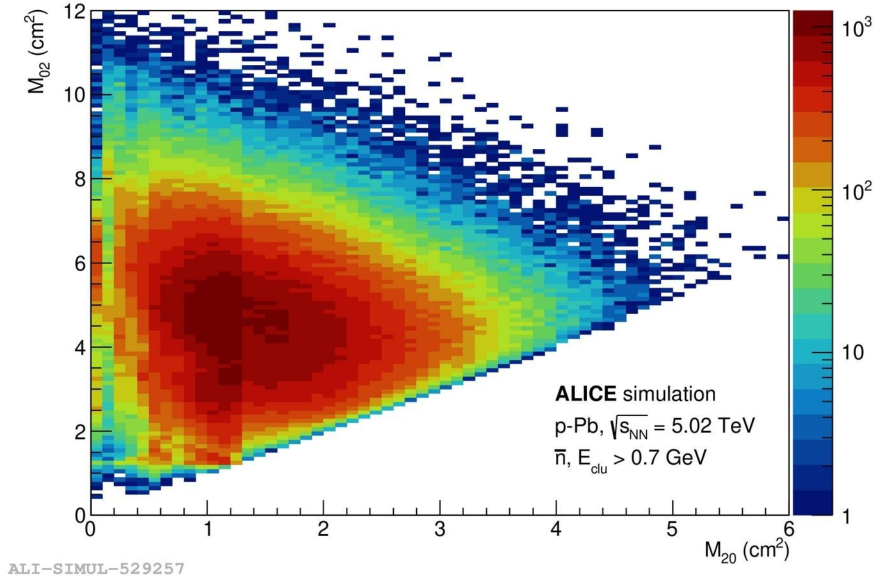
$$s_{xx} = \langle (x - \bar{x})^2 \rangle$$

$$s_{xz} = \langle (x - \bar{x})(z - \bar{z}) \rangle$$

But:

- Cannot measure momentum based on deposited energy
- Use Time-of-Flight to reconstruct antineutron momentum



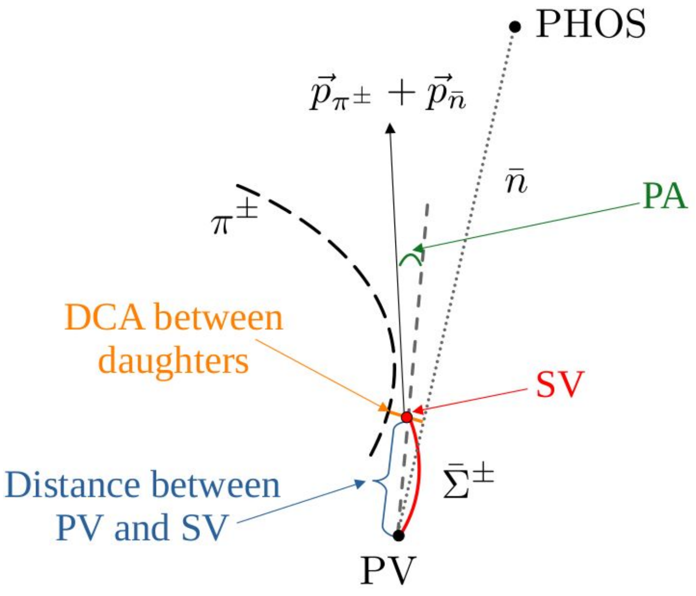


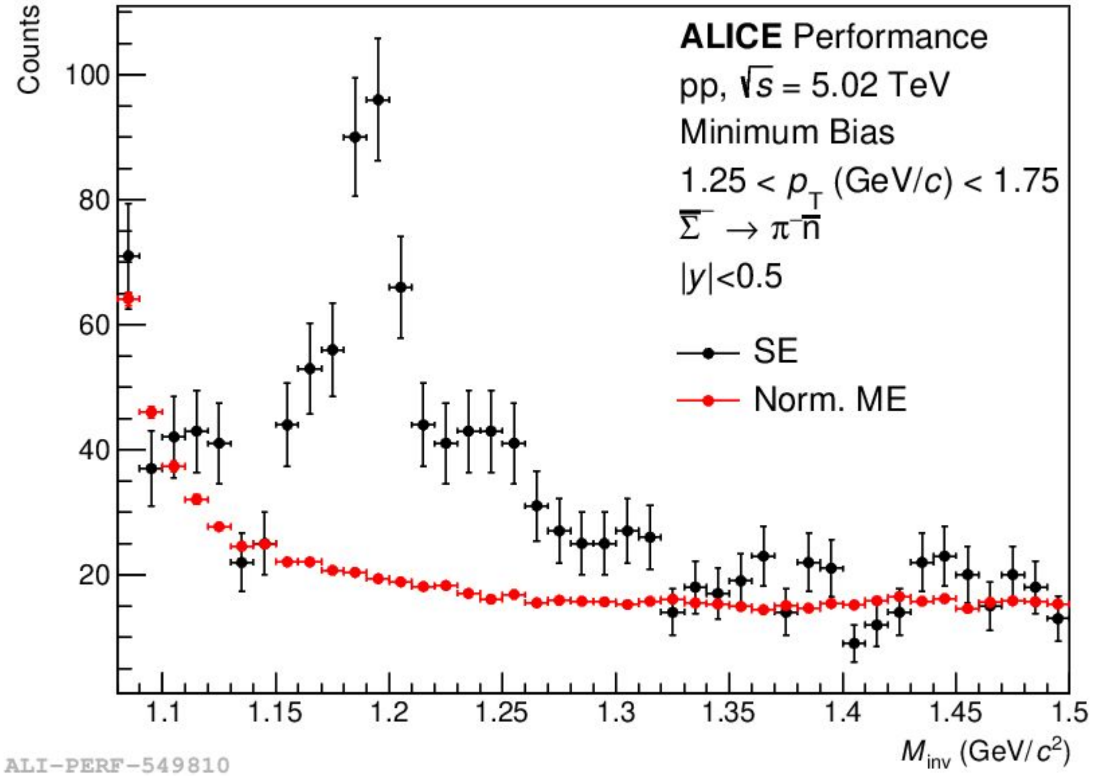
$\bar{\Sigma}^{+}$ and $\bar{\Sigma}^{-}$ reconstruction

- Secondary vertex is reconstructed, and topological selections are used to increase signal to background ratio

- Antineutron and pion candidates are combined to obtain invariant mass distribution

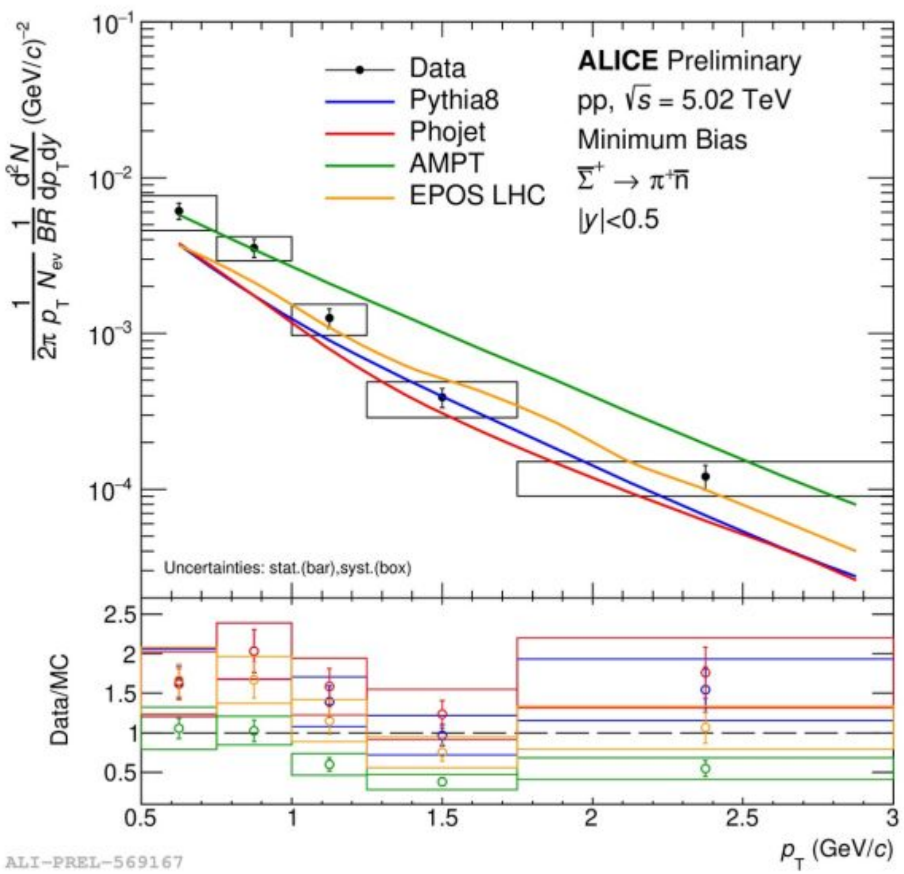
- Signal peak has non-gaussian shape due to finite time resolution of PHOS

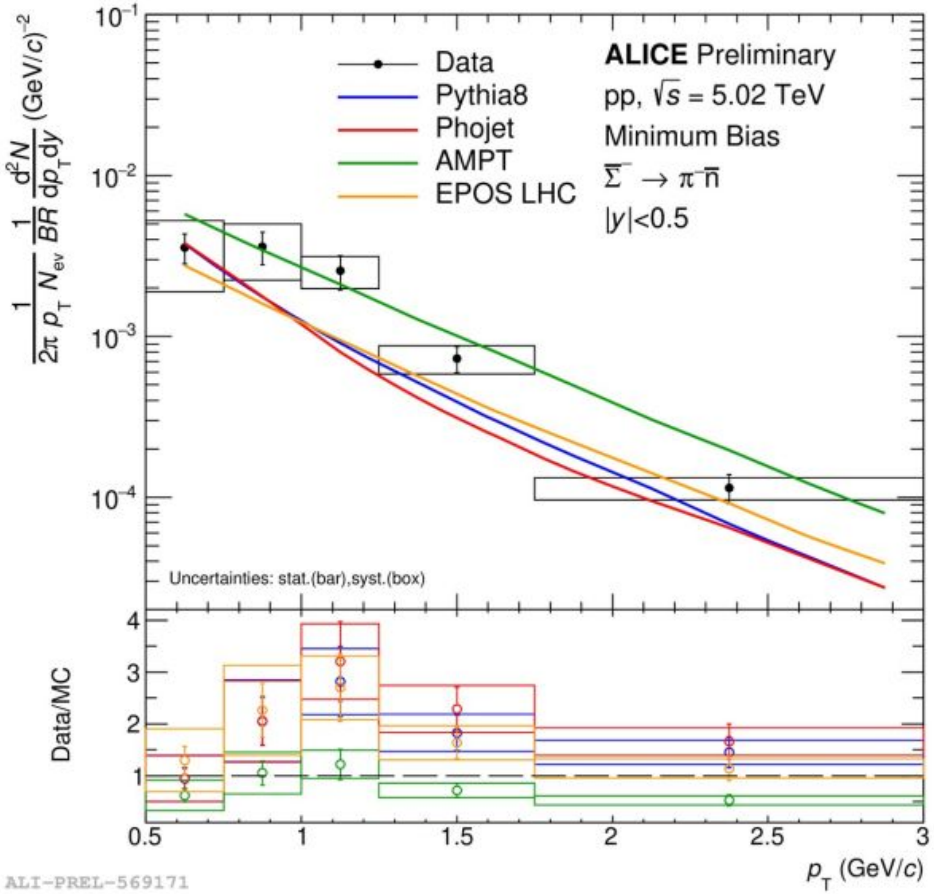




$\bar{\Sigma}^+$ and $\bar{\Sigma}^-$ measurement in pp

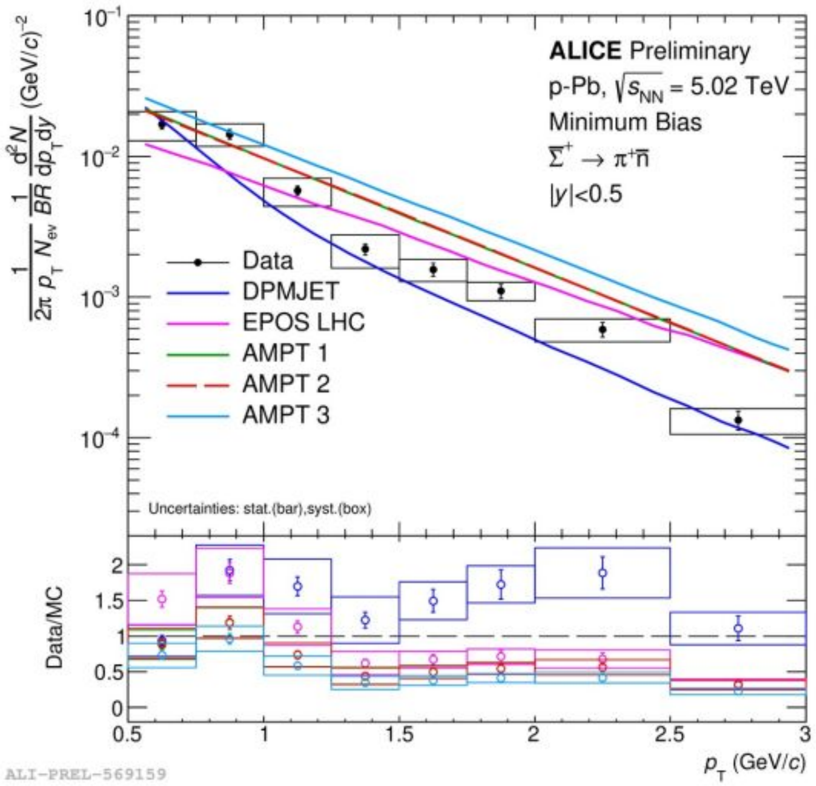
- EPOS LHC [Phys. Rev. C 92, 034906], PYTHIA8 Monash13 [arXiv:2203.11601] and Phojet [arXiv:hep-ph/9803437] show good agreement with data points within large uncertainties
- AMPT [Phys.Rev.C72:064901] have a good agreement at low p_T and overestimates the yield at high p_T

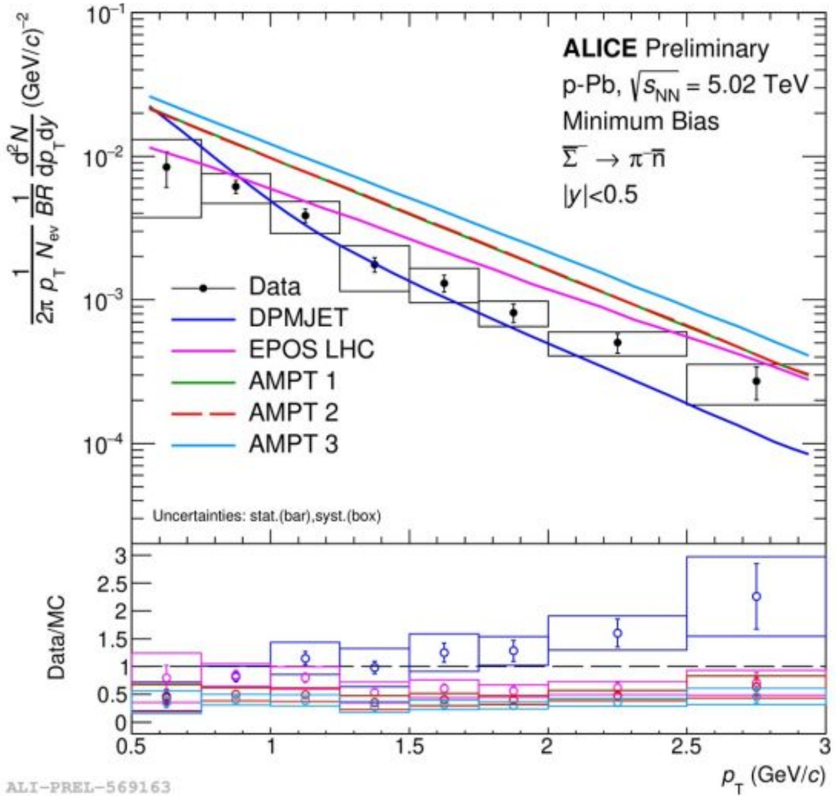




$\bar{\Sigma}^{+}$ and $\bar{\Sigma}^{-}$ measurement in p-Pb

- All AMPT [Phys.Rev.C72:064901] generator options tend to overestimate the yield (see back-up for options description)
- DPMJET [arXiv:hep-ph/0012252] shows good agreement at high p_{T} but have a rise at low p_{T}, which is not common to other models
- EPOS LHC [Phys. Rev. C 92, 034906] works slightly better for the whole p_{T} range within large uncertainties





Conclusion

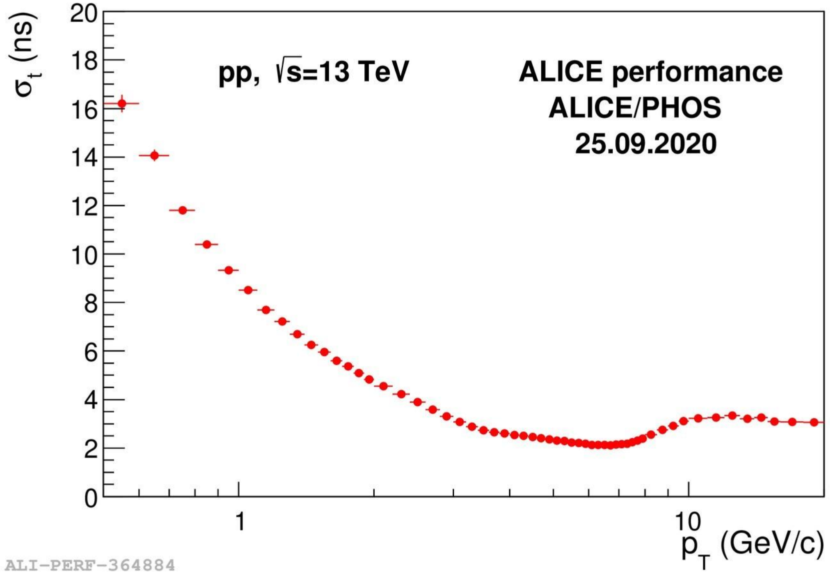
- Strangeness studies can be extended with Σ-hyperon measurements
- Method for antineutron reconstruction was proposed, which opens up a variety of new observables
- Obtained results are more or less consistent with EPOS LHC [Phys. Rev. C 92, 034906] predictions, and can be used to constrain other MC generators
- Σ was studied both in High Multiplicity and Minimum Bias pp collisions and Σ/Λ ratio is consistent with Thermal model prediction
- More precise measurement of Σ-hyperons, Σ-hypernuclei search and hadron-Σ interactions measurement is foreseen at LHC with ALICE in Run 3 in 2022–2025

Thank you for your attention!

PHOS

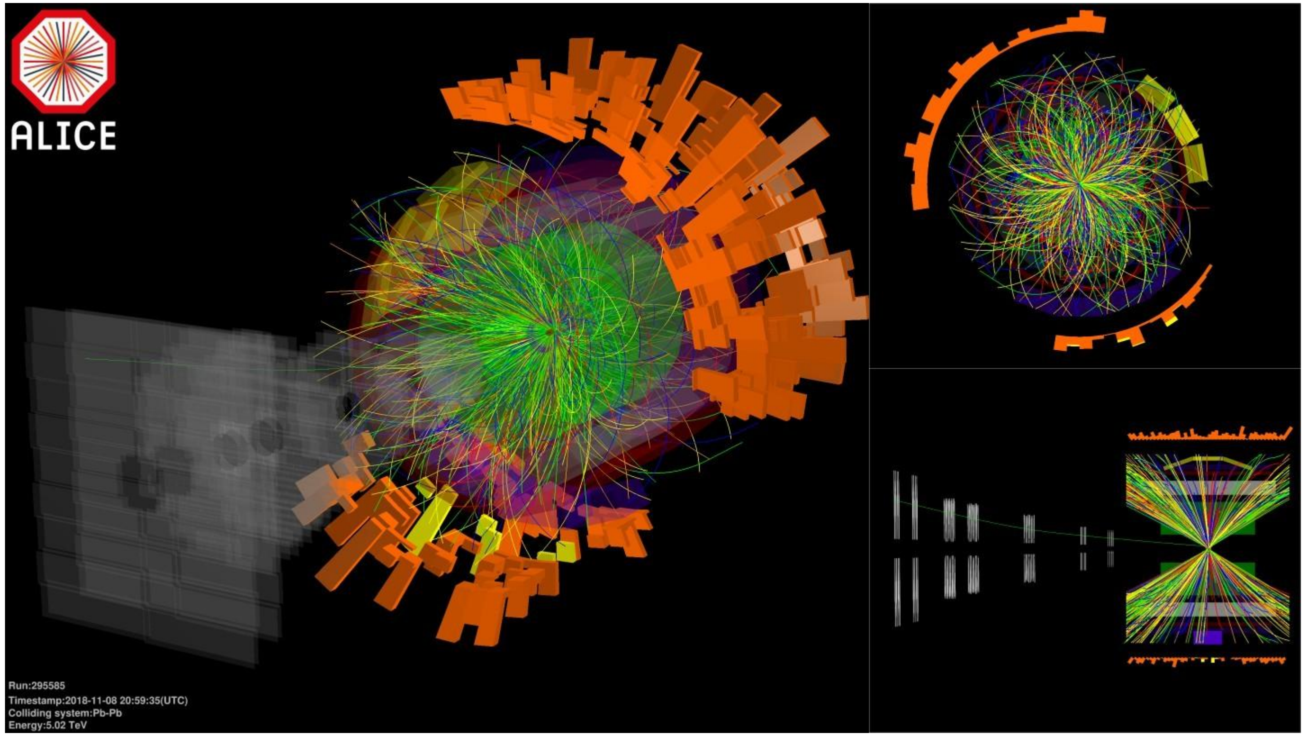
- PHOS - high granularity photon spectrometer based on PbWO4 crystals located at the bottom of the ALICE
- The PHOS is dedicated to the search for electromagnetic radiation from the hot strongly interacting matter in nucleus-nucleus interactions at high energies, as well as for measurements of meson spectra via their decays on photons
- Time of flight (TOF) of particles that form clusters in PHOS can be measured

PHOS time resolution



Event selection

- p-Pb and pp collisions at $\sqrt{s} = 5.02\ \mathrm{TeV}$
- Minimum Bias trigger (V0A & V0C)
- |Vertex z position| ≤ 10 cm
- Pile-up rejection
- INEL and NSD events



- MC and Data were analyzed
- Selected events:

  p-Pb Data: $2.7 \cdot 10^8$

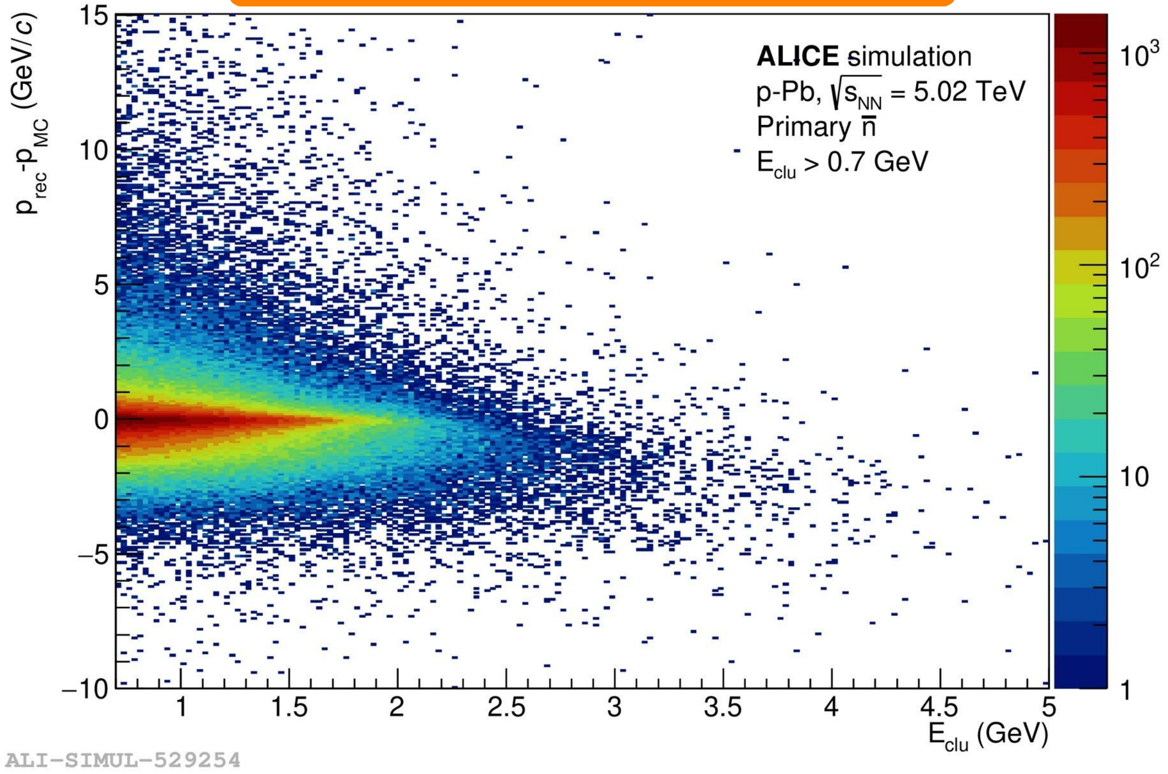
  p-Pb MC: $2.0 \cdot 10^8$

  pp Data: $3.2 \cdot 10^8$

  pp MC: $4.0 \cdot 10^8$

Reconstruction of $\bar{n}$ momentum

Momentum reconstruction from time of flight



$$p_{\text{rec}} = \frac{m_{\bar{n}}}{\sqrt{\left(\frac{t_{\text{TOF}} \cdot c}{L}\right)^2 - 1}}$$

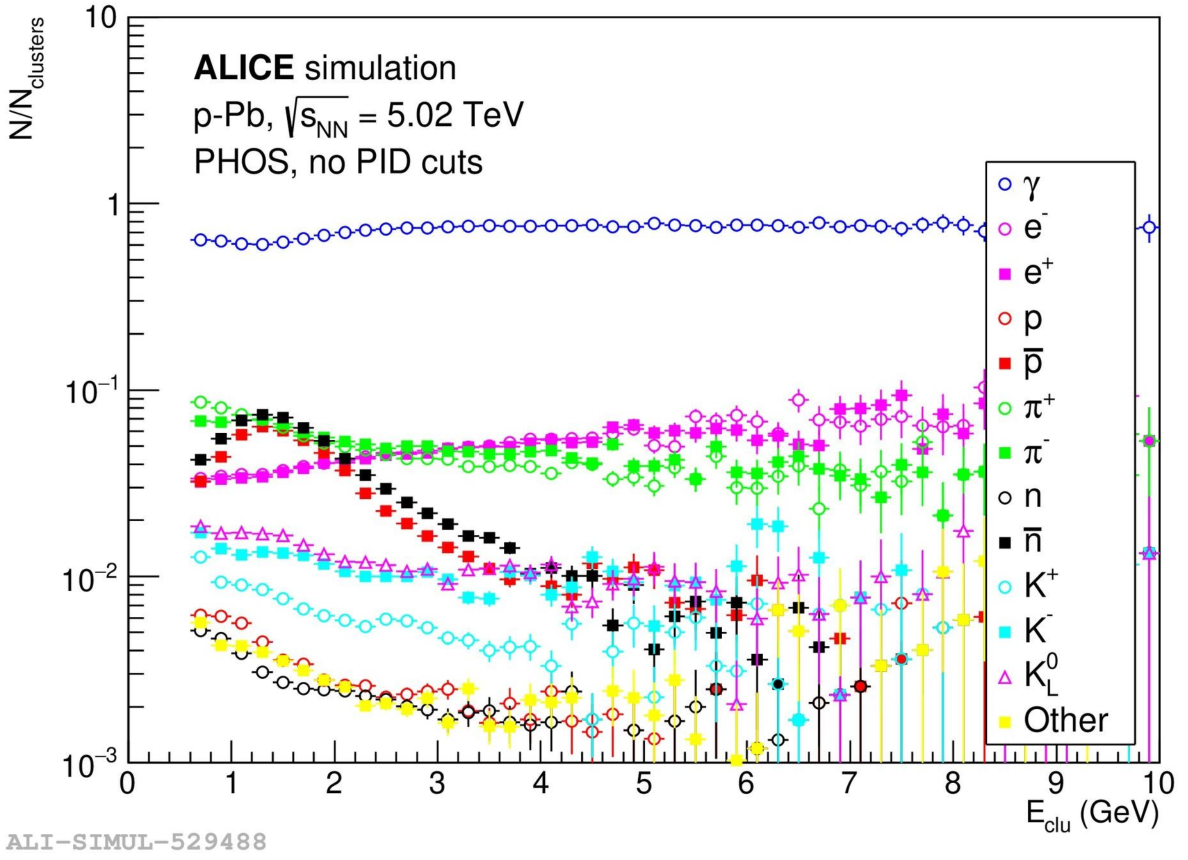
L - distance between primary vertex and cluster coordinate in PHOS, m (about 4.6 m)

$m_{\bar{n}}$ - antineutron mass, $0.939485\ \text{GeV}/c^2$

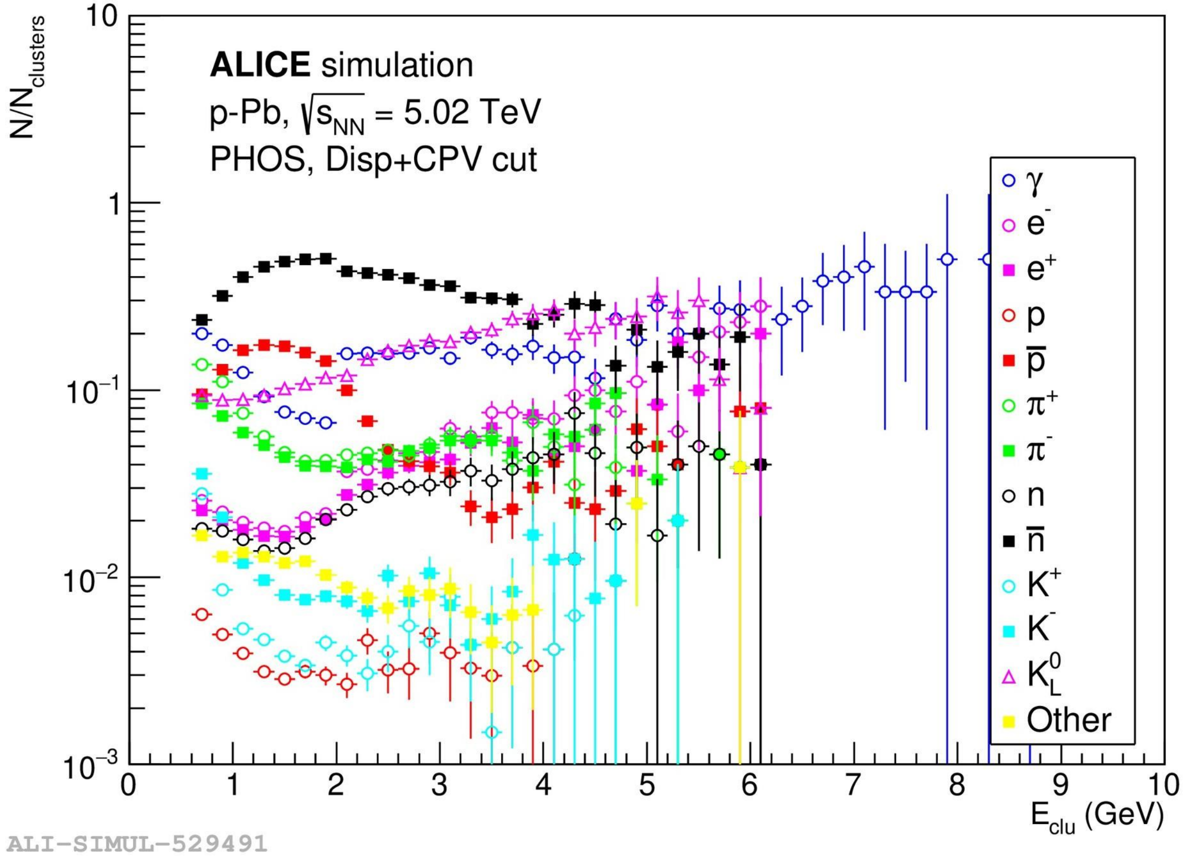
t_{TOF} - time of flight, s

Fraction of different type of clusters

- After applying CPV and Dispersion cuts the fraction of antineutron clusters reaches ~50%



Without CPV and Dispersion cuts



With CPV and Dispersion cuts

Track and cluster candidate selections

$\bar{\Sigma}$ → $\bar{n}$, π

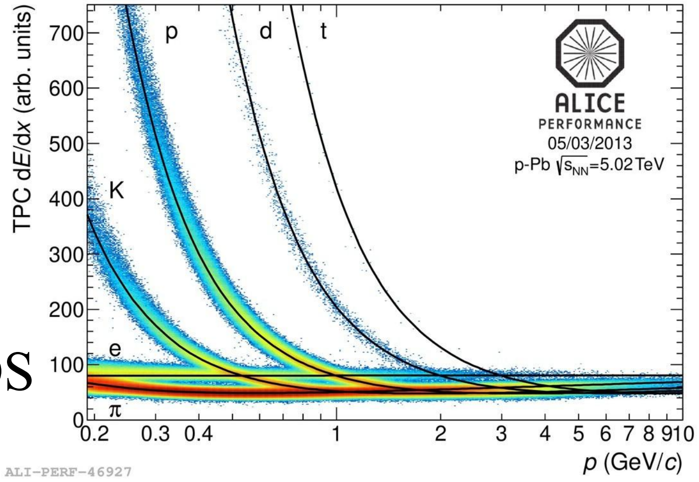
Clusters in calorimeter:

- $E_{\mathrm{clu}} \geq 0.6$ GeV
- $\mathrm{M02} > 0.2\ \mathrm{cm}^2$
- $N_{\mathrm{cells}} \geq 7$
- $\mathrm{CPV} > 10\sigma$ (charged particle veto)
- Dispersion cut for : $\bar{n}$ $\mathrm{M02} \geq -\mathrm{M20} + 4$
- $0 < \mathrm{TOF} - t_\gamma < 150$ ns

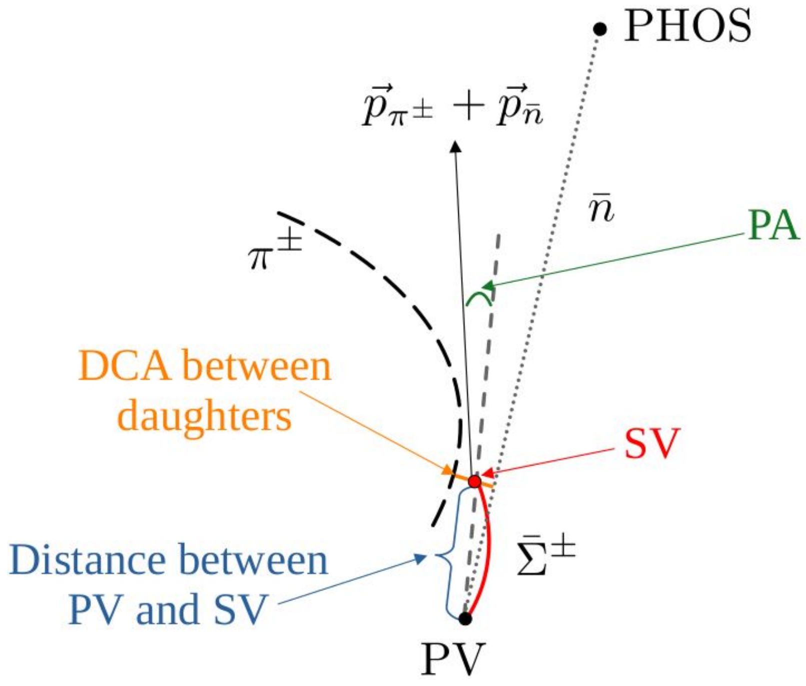
where t_γ is photon TOF to PHOS

Tracks in tracking system:

- $|\eta| < 0.8$
- TPC dE/dx: 3σ band around π line
- Number of TPC clusters more than 60



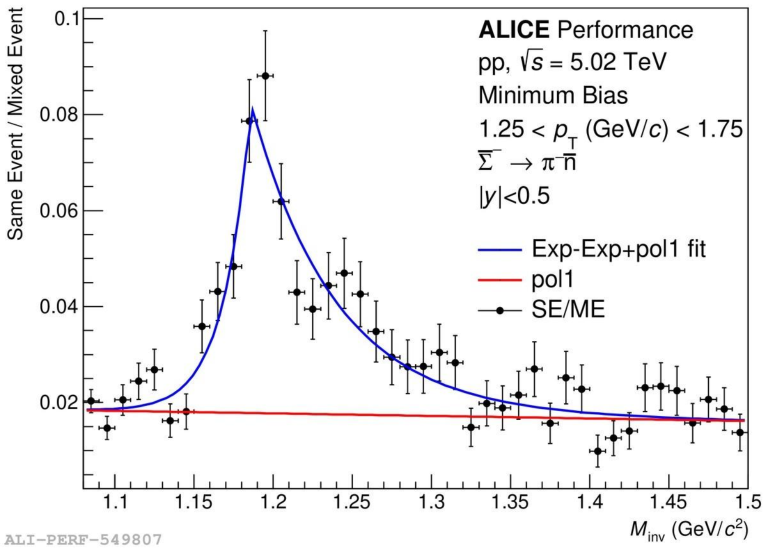
Topological selections



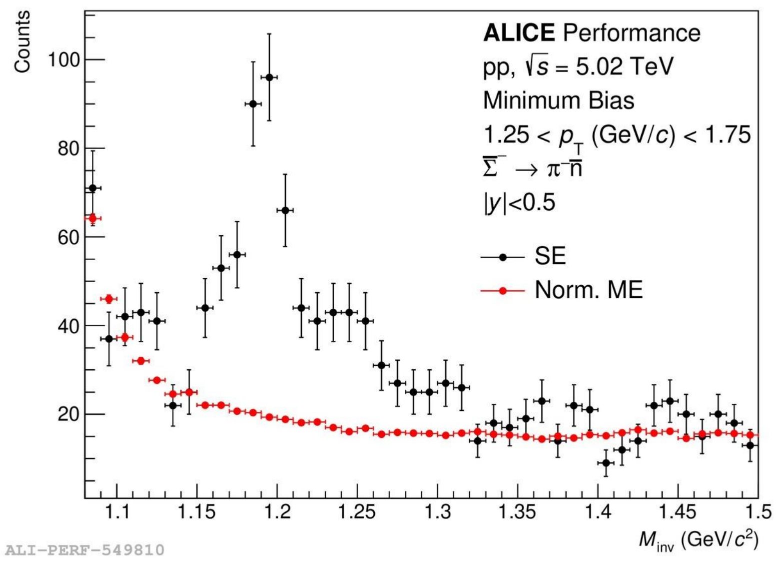
Topological selections in backup slides

Signal extraction: $\bar{\Sigma}^-$

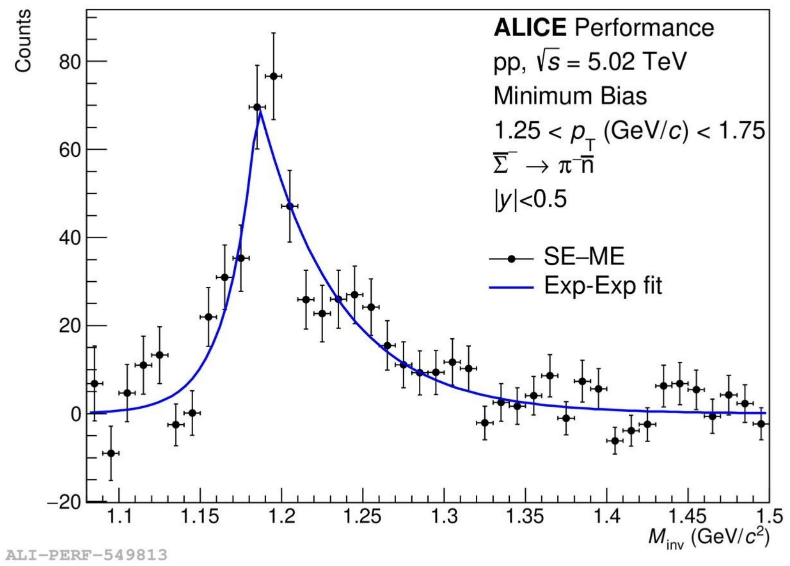
- Applying all the obtained cuts, the distribution of the invariant mass for pairs of a track (pi-meson) and a cluster in the calorimeter (antineutron) is constructed
- Same Event and Mixed Event distributions are obtained



SE to ME ratio fitted with Pol1 and Exp-Exp function



SE and ME. ME is normalized on first order polynom obtained from SE/ME fit



SE after the ME subtraction. Peak fit performed with Exp-Exp function