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Reconstruction of Incomplete Decay Chain Using Strangeness Tracker

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Summary

State-of-the-art silicon trackers at the LHC are packing more and more layers of detectors close to the primary interaction regions of the LHC. In particular, the ALICE experiment just installed a 12 Gigapixel silicon tracker composed of 7 layers of detectors, with its innermost layer placed at only 2.3 cm from the interaction region. In high energy physics experiments, usually only charged particles with long lifetime ($c\tau >$ few meters) are directly tracked, but such a compact and precise new tracker allows us to explore the tracking of short lived objects. Among those, few of them are of particular interest, like Σ, Ξ and Ω baryons that can be used to study charm and beauty baryon decays and light hypernuclei. However, in Run 2 only the charged decay-channels could be studied. The aim of this project is to use the direct reconstruction of the short-lived ($c\tau \sim$ few cm) charged particles, similarly to what was done in bubble chamber experiments, combined with the partial reconstruction of their decay products to overcome the limitations encountered during Run 2. In particular, this development will make possible to study for the first time at collider experiment $\Sigma^- \to n^0 + \pi^-$ decay as well as all the hypertriton decays (i.e. ${}^3_\Lambda H \to {}^3H + \pi^0$) that were only accessible in bubble chamber experiments in the 1970s and for which little data are available.

Contents

1 Introduction

1.1 Scope of the project

In recent years ALICE detector has received several upgrades, one of which is particularly crucial to tracking and vertexing. The Inner Tracking System (ITS) is essential for determining primary vertex (PV) as well as for reconstructing secondary vertices for short-lived particles and tracking low transverse momentum particles. The addition of a new layer closer to the beam line [1], further improves track reconstruction of short-lived hadrons like Ξ, Σ, ${}^{3}_{\Lambda}H$ in what's called *strangeness tracking*. One of the novelty of this approach is that it allows to study incomplete decay topologies more efficiently.

Particularly interesting is the ${}^{3}_{\Lambda}H \rightarrow {}^{3}H + \pi^{0}$ decay, which has never been measured before. The exact branching ratio can give insight into the structure of the hypertriton as well as help verify $\Delta I = 1$ rule for this type of decays. Ultimately, the measurement of this decay channel will give more information on the nucleon$-\Lambda$ interaction and its role in the structure of neutron stars [2]. Unfortunately, reconstructing this ${}^{3}_{\Lambda}H$ decay channel is a difficult task because of the creation of neutral daughter particle, the π^{0}, that has very low reconstruction efficiency. However, this efficiency penalty can be avoided by studying the *kink topology* as we do in this analysis.

Strangeness tracker also allows us to study a topologically similar decay $\Sigma^{-} \rightarrow n^{0} + \pi^{-}$ (BR ~100%) (Fig. 1). Despite its less exotic nature, Σ^{-} is perhaps more important in solving the mysteries of neutron stars than hypertriton. It is the missing piece in the interaction parametrization through its $p - \Sigma^{-}$ interaction [3].

Although the Σ^{-} particle is much more likely to be created during collisions, it is still very difficult to observe it in the detector. To begin with, a relatively short lifetime of $1.48 \cdot 10^{-11}$ s ($c\tau \sim 4.4cm$) makes track reconstruction possible only for high momentum particles. For an efficient track reconstruction minimum of four hits are necessary, meaning that only Σ^{-} with flight distance longer than 19 cm can be reconstructed. In addition, because one of the daughter particle is neutral, we lose resolution and increase combinatorial background.

The goal of this project is to test the efficiency and resolution of track reconstruction in ITS detector as well as to separate said Σ^{-} decays from background, paying particular attention to the noise regenerated by $\Sigma^{+} \rightarrow n^{0} + \pi^{+}$ as the mass difference is $m_{\Sigma^{-}} - m_{\Sigma^{+}} < 10$ MeV$/c^{2}$. We hope that this work will contribute towards a better understanding of the hadronisation process from Quark-Gluon Plasma, neutron stars as well as analyse similar topology decays.

1.2 Femtoscopy

In any collider experiment, the interaction between two particles can be studied looking at the two particle correlation function, defined as [4]:

$$C_{P}^{ab}(q) = \frac{A_{P}^{ab}(q)}{B_{P}^{ab}(q)}\zeta_{P}(q) = \int S(r^{*})|\Psi(\vec{k}^{*}, \vec{r}^{*})|^{2}\mathrm{d}^{3}r^{*}$$

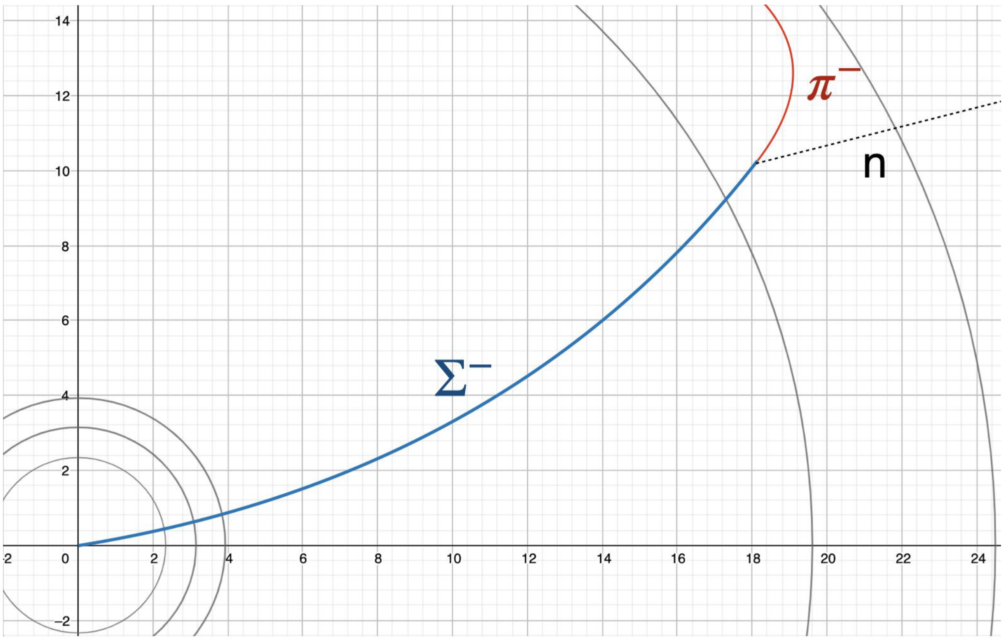


Figure 1: $\Sigma^- \rightarrow n^0 + \pi^-$ decay topology with ITS detector layers.

In this definition, $A_P^{ab}(q)$ is the relative transverse-momentum distribution of the signal, meaning that the particles are close in phase-space at PV, and $B_P^{ab}(q)$ is the the relative transverse-momentum distribution of the background (uncorrelated particles). To account for signal contamination and resolution a correction function $\zeta_P(q)$ is introduced. Assuming a single source for all the particles coming from the interaction region, this experimental ratio is equivalent to the convolution of the source structure ($S(r^*)$) and the wave function of the two interacting particles ($\Psi(\vec{k}^*, \vec{r}^*)$) expressed in terms of their relative momentum k^*. Even though in this work we do not use this technique, called femtoscopy, the data gathered from Σ^- analysis can be readily used to study $p - \Sigma^-$ interaction.

1.3 Simulation of Collisions

The data sets used in this project exclusively come from the Monte Carlo simulations as there has not been enough time to process the data from the Run 3.

The simulation process can be summarised as follows:

1. Pythia 8 is used to simulate the collisions, in this case pp collisions at $\sqrt{s}$=13.6 TeV
2. GEANT4 is used to propagate the generated particles and to model their interactions with the detector material
3. ALICE software digitizes the data so that the output reassembles real data taken at LHC.

In our case, in order to increase the statistical significance, additional Σ^- and Σ^+ had to be injected.

2 Data Analysis

2.1 Kinematic variables

In this project the main variables we used were transverse momentum (along x-y plane):

$$p_T = p \cdot \sin\theta$$

and pseudorapidity, as a measure of angle relative to beam axis:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

where θ is the angle relative to z-axis. In addition, we also used ϕ as an angle relative to a fixed x-axis. With these variables we are then able to calculate all components of momentum:

$$p_{\mathrm{x}} = p_{\mathrm{T}} \cos\phi$$
$$p_{\mathrm{y}} = p_{\mathrm{T}} \sin\phi$$
$$p_{\mathrm{z}} = p_{\mathrm{T}} \sinh\eta$$

and thus energy of a particle:

$$E = \sqrt{\mathbf{p} \cdot \mathbf{p} + m^2c^4}$$

2.2 Vertexing

Incomplete decay chain poses difficulty in accurately reconstructing tracks as we are only able to detect two out of three tracks. In a regular two-body decay channel, we could simply take two daughter particles and propagate them to a closest approach point and check for the mother track. However, in our project we are interested in a kink topology decays, where only one of the daughter's track is invisible to us. Figure 2 shows Distance to Closest Approach (DCA) for such decay.

For incomplete decay topology we only wanted to test the effectiveness of our DCA fitter thus only particles contributing to the signal were chosen using MC particle identification (PI). It is worth noting that ITS does not provide PI, however DCA fitter steps are identical for both cases. To implement DCA fitter we followed a simple algorithm:

1. Pick track in ITS detector for Σ^- (for real data it could be just a random track)

2. Propagate the track to primary vertex and constrain covariance matrix

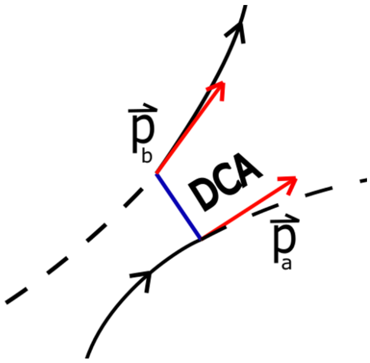


Figure 2: DCA between mother and daughter particles in kink topology.

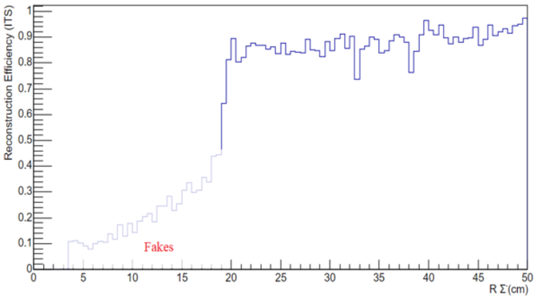
3. Pick track in ITS-TPC detector for π^- (again for real data it could be just a random track)
4. Find DCA and propagate both tracks
5. *Apply DCA, eta-phi, invariant mass, p_T, etc. cuts to reduce background if track were chosen randomly*

3 Results

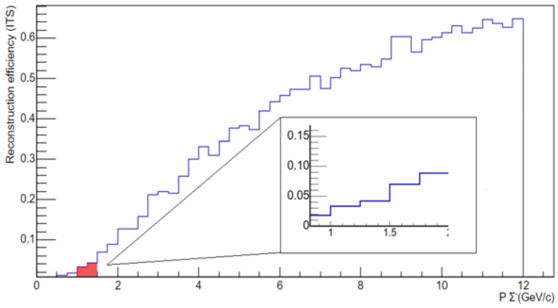
3.1 Preliminary results

At first we looked at the detector performance, namely the reconstruction efficiency for both Σ^- in ITS and π^- in ITS-TPC (inc. AB). For Σ^- we see that only for the decays that are above 19 cm we are starting to reconstruct real track whereas below only fake reconstruction are made. This is expected, since we need 4 hits in ITS to extrapolate a track and only at 19 cm the fourth layer is situated (Fig. 3a) We can also look at the efficiency versus momentum distribution (Fig. 3b). However, when we take into account that real Σ^- are produced in a transverse momentum window between $\sim$ 1-2 GeV/c, there only $\sim$ 5 percents of total generated Σ^- are reconstructed. As mentioned before, this boils down to a fact that Σ^- has relatively short lifetime of around $c\tau \sim 4.4cm$. For π^- the reconstruction efficiency is much more uniform for all range of transverse momentum as they have long lifetime (Fig. 4). Although we should expect a higher average efficiency rather than 35 percent.

Nonetheless, RUN 3 will have several orders of magnitude higher data rates than RUN 2 and even with a low efficiency we can expect significant number of data samples. What we are more interested in is high momentum resolution which is closely correlated with invariant mass reconstruction. For π^- the spread in momentum resolution is around 2 percents which is more than enough (Fig. 5b). On the other hand, Σ^- resolution spread is 17 percents (Fig. 5a) As before, we must emphasise that the graphs are made for flat momentum distribution of generated particles. For the real Σ^- momentum distribution, resolution spread is 12 percents. Nevertheless, we would like to improve these results.

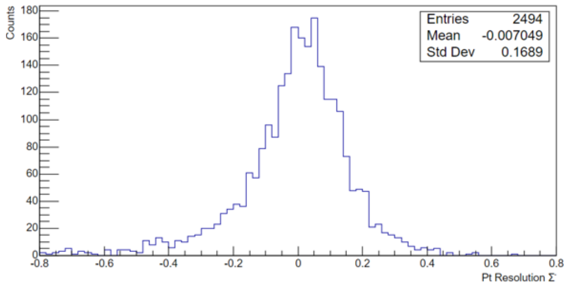


(a) Efficiency versus vertex radius

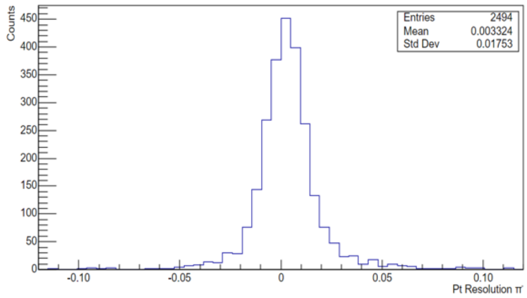


(b) Efficiency versus transverse momentum

Figure 3: Σ^- reconstruction efficiency in ITS detector.



(a) Σ^- momentum resolution



(b) π^- momentum resolution

Figure 5: Resolution of both Σ^- (a) and π^- (b). Resolution = (Generated - reconstructed)/reconstructed

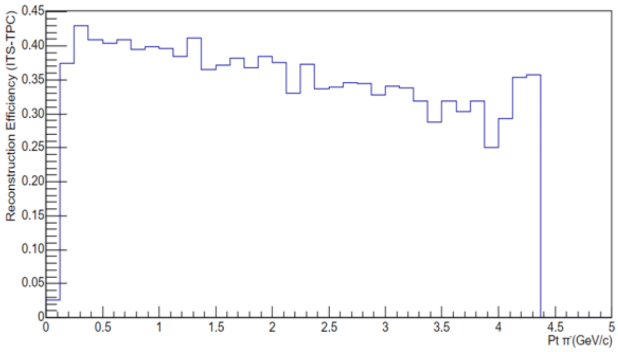
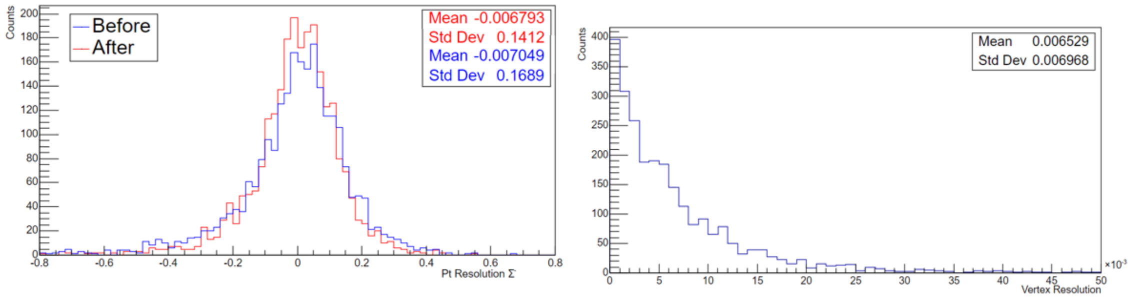


Figure 4: π^- reconstruction efficiency as a function of transverse momentum in ITS-TPC detector.

3.2 Main results

To improve the momentum, and thus mass, resolution we implemented the DCA fitter as described in Data Analysis section 2.2. This gave a reduction in Σ^- transverse momentum resolution spread of around 3 percents as depicted in Fig. 6a. We have also looked at the decay vertex reconstruction (Fig. 6b). New DCA fitter gave an error of 0.7 percent. In our



(a) Σ^- momentum resolution after DCA (red) and before (blue)

(b) Vertex resolution

Figure 6: Σ^- momentum and vertex resolution after DCA.

setup the correlation between momentum and position reconstruction is non-negligible, thus we have to require high accuracy in both when reconstructing a track. For π^- the DCA fitter had barely any effect. On the other hand, if we skipped the first step in the DCA fitter, namely constraining Σ^- track to pramary vertex, we only got 1 percent improvement in momentum resolution.

When we considered the invariant mass reconstruction we saw 5 MeV/c^2 improvement in spread as opposed to no DCA fitter (Fig. 7). This is a significant improvement, however in theory we are still unable to distinguish Σ^- and Σ^+ as their $\Delta m < 10MeV/c^2$. In practise, thing are more complicated since the reconstructed invariant mass of Σ^+ coincides with Σ^- peak (Fig. 8). At the moment, we are unable to justify the reason for such behaviour. If this problem persists, we might not be able to reliably separate Σ^+ and Σ^- even with much higher mass reconstruction precision.

DCA fitter was not the only algorithm we tried in this project. We have also implemented Kalman filter given in KFParticle library. However, for both the position and momentum reconstruction it gave less precise results than DCA fitter as depicted in Fig. 9.

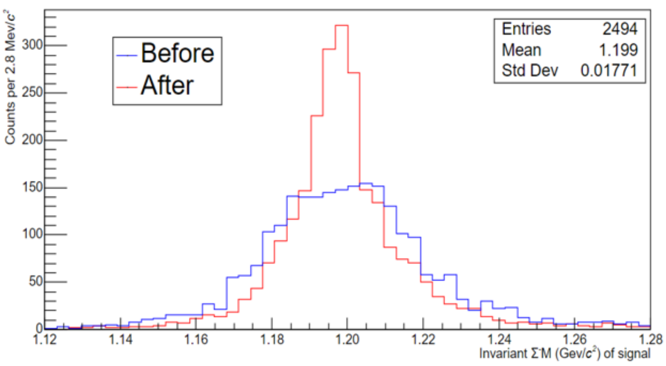
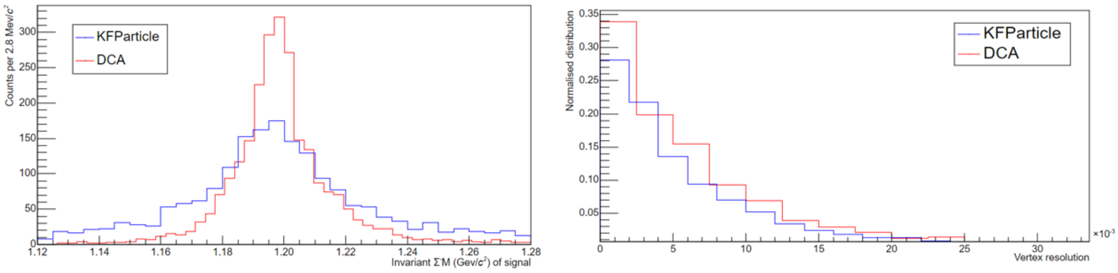


Figure 7: Σ^- invariant mass after DCA (red) and before (blue).



(a) Σ^- invariant mass

(b) Σ^- vertex resolution

Figure 9: Comparison between DCA (red) and Kalman filter (blue).

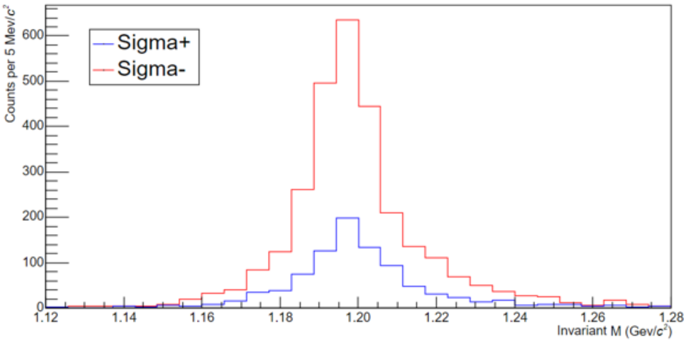


Figure 8: Σ^- (red) and Σ^+ (blue) invariant mass after DCA.

4 Conclusion and Outlook

We analysed the efficiency of the ITS and ITS-TPC (inc. AB) detectors. For the ITS the efficiency was high, averaging around 90 percent. However, we have expected higher efficiency for π^- reconstruction in ITS-TPC detector. Moreover, we also observed some duplicates between ITS-TPC and ITS-TPC After Burner which, in principle, would not be possible. Thus, more investigation is needed.

On the other hand, we were able to demonstrate that the resolution of the invariant mass reconstruction can be significantly improved with the DCA fitter. The question is: can it be further improved to allow better separation of Σ^- and Σ^+? Although first, one might need to look if Σ^+ mass can be properly reconstructed as at the moment it peaks were Σ^- mass peak should be.

During our analysis we have also noticed that for random associations the DCA fitter propagates tracks to primary vertex. We tried solving this issue by eliminating pions that are coming from primary vertex, however relatively big portion of pions were still omitted. Because DCA is used to make cuts this problem hinders the separation of signal from background significantly. For future work, one should have a closer look at how to solve this issue.

References

1. Reidt, F. *Upgrade of the ALICE ITS detector* arXiv:2111.08301 [physics]. Mar. 2022. http://arxiv.org/abs/2111.08301 (2022).
2. Mazzaschi, F. & on behalf of the ALICE collaboration. *Investigating the hyperon-nucleon strong interaction with a precision measurement of the hypertriton lifetime in ALICE* en. in *Proceedings of 40th International Conference on High Energy physics — PoS(ICHEP2020)* **390** (SISSA Medialab, Apr. 2021), 486. https://pos.sissa.it/390/486 (2022).
3. Tolos, L. & Fabbietti, L. Strangeness in Nuclei and Neutron Stars. *Prog. Part. Nucl. Phys.* **112,** 103770. arXiv: 2002.09223 [nucl-ex] (2020).
4. Lisa, M. A., Pratt, S., Soltz, R. & Wiedemann, U. FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress. *Annual Review of Nuclear and Particle Science* **55.** _eprint: https://doi.org/10.1146/annurev.nucl.55.090704.151533, 357–402. https://doi.org/10.1146/annurev.nucl.55.090704.151533 (2022) (2005).