Proceedings of the CTD 2022
PROC-CTD2022-34
LHCb-PROC-2022-019
August 2, 2022

Expanding Physics Reach with Unused Tracks in LHCb

Izaac Sanderswood

On behalf of LHCb collaboration,
Instituto de Física Corpuscular
Universitat de València, Spain

ABSTRACT

The physics reach of the LHCb detector can be extended by reconstructing particles with a long lifetime that decay in the magnet region, using only tracks from downstream of the dipole magnet. This allows for electromagnetic dipole moment measurements, and increases the reach of undiscovered long-lived particle searches. However, using tracks to reconstruct particles decaying in this region is challenging, particularly due to the increased combinatorics and reduced momentum and vertex resolutions, which is why it has not been done until now. New approaches have been developed to meet the challenges and prepare for physics analysis from these previously unused tracks. These proceedings present the feasibility demonstration studies using Run-2 data, as well as discussing new developments to expand these techniques to fully exploit the dataset to be acquired during Run-3.

PRESENTED AT

Connecting the Dots Workshop (CTD 2022)
May 31 - June 2, 2022

1 Introduction

These proceedings describe the reconstruction of particles in LHCb, using tracks comprised exclusively of hits from after the dipole magnet. This expands the physics reach of the detector by enabling new kinds of measurements, such as electromagnetic dipole moments and beyond the Standard Model (BSM) long-lived particle (LLP) searches over significantly longer distances. This endeavor presents certain reconstruction challenges, primarily due to reduced momentum resolution, as well as extrapolation over large distances to arbitrary locations through a strong inhomogeneous magnetic field. The approaches to these challenges are described below. An overview of the different track types defined in LHCb is described in Sec. 2, the physics motivation is described in Sec. 3, the feasibility studies are presented in Sec. 4, the prospects for Run-3 are briefly described in Sec. 5 and a summary is presented in Sec. 6.

2 LHCb tracks

The tracking system of LHCb [1] is comprised of three subdetectors and a dipole magnet. Tracks are reconstructed from segments in the different subdetectors, and are categorised according to the location of hits. The categories are summarised below:

Velo tracks are comprised exclusively of hits in the VELO (VErtex LOcator) subdetector around the interaction point.

Upstream tracks are comprised of hits in the VELO and the TT (UT from Run-3), named as such because the TT (UT) is located upstream of the magnet.

Downstream tracks are comprised of hits in the TT (UT) and tracking stations T1-T3 (SciFi from Run-3), named as such because T1-T3 (SciFi) are located downstream of the magnet.

Long tracks are comprised of hits in at least the VELO and T1-T3.

T tracks are comprised only of hits in T1-T3 (SciFi), i.e. from hits downstream of the magnet.

Long and Downstream tracks are better measured since they have more hits and traverse the entire magnet, which provides superior momentum resolution. Long tracks have a typical momentum resolution σ_p/p less than 1% [2], whereas for T tracks it is around 25%. For this reason, the LHCb physics programme focuses almost entirely on Long and Downstream tracks. However, this limits the maximum decay length of a particle to around 2 m from the interaction point. It is possible to reconstruct particles from T tracks, extending the maximum decay length up to $\sim$7.6 m.

3 Motivation

LHCb is designed and optimised to study particles decaying upstream of the dipole magnet after a few picoseconds. The reconstruction of particles decaying beyond this region has two key physics motivations: dipole moment measurements and the undiscovered long-lived particle (LLP) searches. These are summarised below.

3.1 Electromagnetic dipole moment measurements

Electric and magnetic dipole moments (EDM and MDM respectively) can be measured by exploiting the spin precession of particles that pass through the dipole magnet before decaying. As proposed in [3], this requires a source of polarised particles not aligned with the magnetic field and sufficient reconstruction of decays after the magnet. An example is shown in Fig. 1.

The SM predicts minuscule EDMs. Therefore, enhanced EDMs would be indicative of BSM physics in the form of new sources of CP-violation. By reconstructing particles that decay as they pass through the magnet in LHCb, experimental EDM limits will be greatly improved. For example, the EDM of the Λ baryon

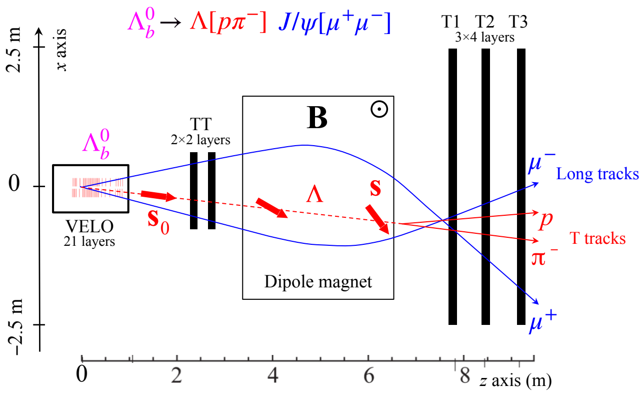

Figure 1: The spin precession of a Λ that originates in $\Lambda_b^0 \to J/\psi\Lambda$, and decays downstream of the magnet.

was last measured some 40 years ago [4]. With the full Run-4 dataset, this limit can be surpassed by between one and two orders of magnitude using the method proposed in [3]. Furthermore, a measurement comparing the MDMs of Λ and $\overline{\Lambda}$ will provide a direct test of CPT symmetry.

3.2 Undiscovered long-lived particle searches

Long-lived particles are present in nearly every beyond the Standard Model (BSM) theory, though none have been discovered so far. LHCb is particularly well suited to search for LLPs produced in the decays of b- and c-hadrons, as well as decays to hadronic signatures, such as pions and kaons, that would benefit from particle identification. Thus far, searches in LHCb have only included Long tracks, meaning they are limited by the size of the VELO subdetector around the beamspot with a decay length $c\tau \lesssim 30$ cm. Analyses using T tracks extend the maximum allowed decay length to ~ 7.6 m, corresponding to lifetimes of up to a few nanoseconds.

4 Feasibility

A study has been performed to demonstrate the feasibility of analyses including T tracks. This tests the suitability of existing LHCb tools and identifies challenges in the approach that would affect a full physics analysis. The goal of the feasibility study is to accurately determine the vertex positions and invariant mass peaks in the $\Lambda_b^0 \to J/\psi\Lambda$ and $B^0 \to J/\psi K_S^0$ channels, using the dataset collected in Run-2 corresponding to 6 fb^{-1}. The strategy is summarised as follows:

- Trigger on detached muon pair from $J/\psi \to \mu^+\mu^-$.
- Make a preselection based on kinematic variables.
- Use a boosted decision tree (BDT) classifier that includes kinematic, topological and fit quality variables.
- Veto the physical backgrounds, using both mass cuts and the Armenteros-Podolanski technique [6].
- Fit the invariant mass distributions in simulation and data, with the fit to data constrained by the fit to MC.

The BDT uses the `scikit-learn` histogrammed-BDT model [5]. It is trained on 43,000 simulated signal events, and 6 million background events reconstructed from data. The training is performed on 90% of the sample, and the remaining 10% is used to assess performance. The operating point is set applying a threshold of 0.366 to the BDT response, with the value determined by the optimal signal to background significance.

The primary challenge of reconstruction with T tracks is the reduced momentum resolution due to lower magnetic field downstream of the magnet, as this affects the mass resolution and vertex reconstruction. The other key challenge is the extrapolation of the tracks to arbitrary locations through the strong, inhomogeneous magnetic field of LHCb's dipole magnet. With no exact analytic solution, a 5th order Runge-Kutta method must used to numerically approximate the trajectory.

4.1 Particle Identification

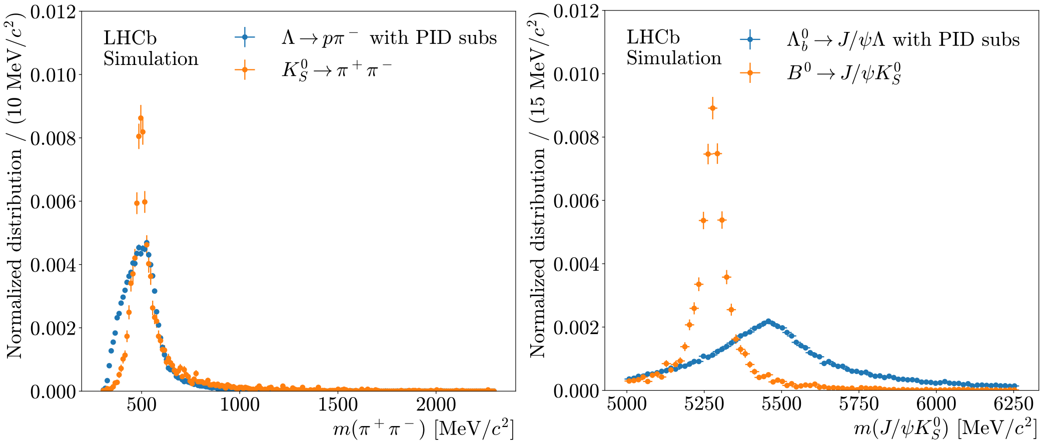

Figure 2: The invariant mass distributions of (left) $\Lambda \to p\pi^-$ and (right) $\Lambda_b^0 \to J/\psi\Lambda$.

$B^0 \to J/\psi K_S^0$ is a physical background to $\Lambda_b^0 \to J/\psi\Lambda$ decays. A worse momentum resolution implies a worse mass resolution. Thus, there is little separation in the mass distributions of $\Lambda \to p\pi^-$ and $K_S \to \pi^+\pi^-$, shown in Fig. 2, so these decays cannot be distinguished by defining suitable regions of invariant mass. The effect is less severe in mass distributions of Λ_b^0 vs B^0, so an acceptable mass veto can be applied. In LHCb, Particle Identification (PID) parameters are normally calculated with information from the two RICH subdetectors (upstream and downstream of the magnet) as well as the calorimeters and muon stations. PID parameters are not calculated for T tracks in Run-2 data since they were never used in analysis. The Armenteros-Podolanski technique can be employed instead to distinguish $\Lambda \to p\pi^-$ and $K_S \to \pi^+\pi^-$ using kinematics, as shown in Fig. 3. The region between the Λ and $\overline{\Lambda}$ distributions can be vetoed to reduce the contribution from K_S^0 decays.

4.2 Momentum resolution

The relatively poor momentum resolution is improved by fitting the full decay tree with kinematic constraints imposed. The fit is performed using Decay Tree Fitter (DTF) [7]. It is constrained using the masses of the Λ and J/ψ. This improves the momentum resolution by a factor of 3 (2) for protons (pions) to around $\sigma(p)/p = 10\%$. For comparison, Long tracks tend to have a resolution less than 1% [2].

4.3 Efficiency

The effect of the different selection criteria on the overall efficiency is shown in Fig. 5. The greatest loss in efficiency is caused by the vertex fitting. Potential reasons for this are discussed below.

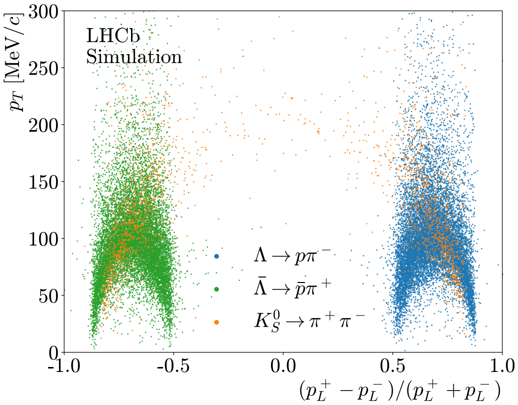

Figure 3: Armenteros-Podolanski distributions for $\Lambda \to p\pi^-$ and $K_S \to \pi^+\pi^-$ decays.

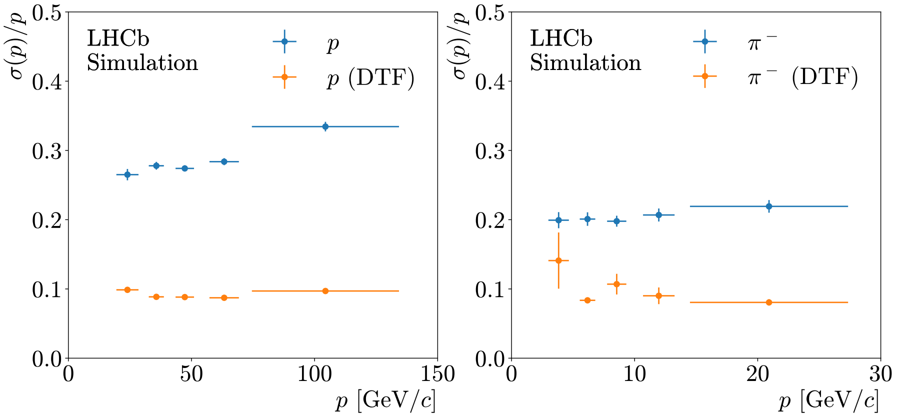

Figure 4: Momentum resolution before and after applying DTF, for protons and pions, in $\Lambda \to p\pi^-$ decays.

4.4 Mass fits

Fig. 6 shows the invariant mass distributions of $\Lambda \to p\pi^-$ and $\Lambda_b^0 \to J/\psi\Lambda$ candidates in data, after all selection criteria are applied. The signal distributions are well described by asymmetric and symmetric (respectively) double-tail Crystal Ball functions. The tail parameters of the symmetric distribution are fixed to values obtained from a fit to simulated $\Lambda_b^0 \to J/\psi\Lambda$ events. The mass resolutions in data are measured to be 8 MeV and 41 MeV respectively. This demonstrates that it is possible to perform meaningful physics analysis by reconstructing particles from T tracks.

4.5 Ghost vertices

As shown in the figure, vertex reconstruction becomes more challenging the further the decay vertex is from the tracking stations. This is in part due to the low Q value in $\Lambda \to p\pi^-$ decays, meaning a small opening angle between the proton and pion. Therefore the tracks can cross twice within the resolution, which creates an additional "ghost" vertex that cannot be distinguished using standard vertex reconstruction. This ghost vertex can be partially identified by the horizontality, h, defined as:

$$h = \pm M_{\mathrm{pol}}\hat{a}_y,\ \vec{a} = \vec{p}_{p^\pm} \times \vec{p}_{\pi^\mp}$$

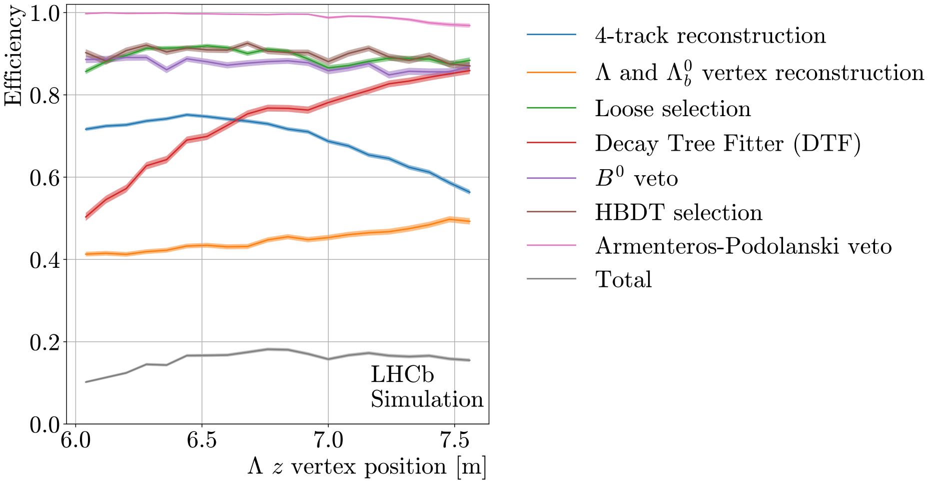

Figure 5: The efficiency is calculated with respect to particles reconstructible within LHCb. The effect of the different selection criteria on the is shown.

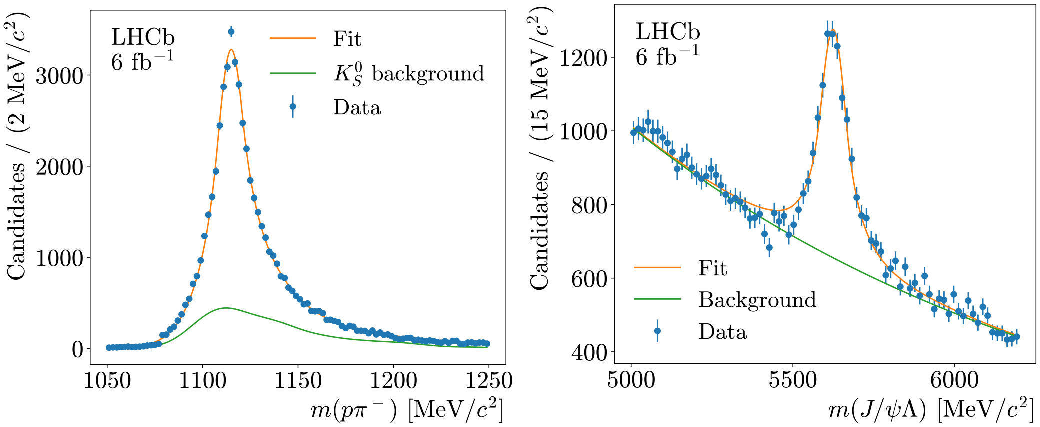

Figure 6: The fitted invariant mass distributions in data for (left) $\Lambda \to p\pi^-$ and (right) $\Lambda_b^0 \to J/\psi\Lambda$.

Requiring events to have a positive horizontality removes most ghost vertices, thereby significantly improving the vertex bias. However this approach has a low efficiency of about 20%.

5 Run-3

LHCb's upgraded software trigger is versatile and adaptable, allowing for real time analysis of events. This framework is easily expanded to include the reconstruction of particles from T tracks in higher-level-trigger-2 (HLT2), which includes full event reconstruction. This means that PID information for T tracks, including RICH2 information, will now be calculated. Very preliminary studies indicate that this offers adequate distinction between protons and pions, shown in Fig. 7, and could thus be used for both online and offline analysis in future. The Kalman filtering of T tracks is being optimised, and a new vertex finder is being used that could offer improved reconstruction efficiency for T tracks.

There are several T track HLT2 lines in development for Run-3, starting with the two benchmark channels,

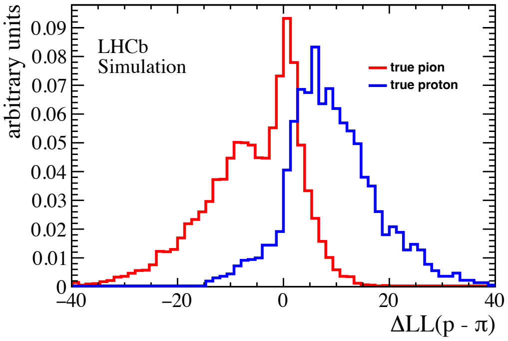

Figure 7: Very preliminary demonstration of the proton/pion discrimination in Run-3 simulation for T tracks with RICH2 information.

$\Lambda_b^0 \to J/\psi\Lambda$ and $B^0 \to J/\psi K_S^0$. There are plans to include T track BSM LLP lines, once the sensitivity of these channels has been determined.

6 Summary and outlook

The physics reach of LHCb can be extended by reconstructing particles decaying in the magnet region, as this would permit electric and magnetic dipole moment measurements as well as significantly extending the reach of BSM LLP searches. The feasibility of reconstructing such particles has been demonstrated here using Run-2 data. Work is being undertaken so that HLT2 lines are in place for Run-3 to take full advantage of this source of physics.

The next step in this approach is to mitigate the vertex reconstruction issues, and perform a full EDM measurement. The study of additional channels and sensitivity studies for BSM LLP searches is also underway.

ACKNOWLEDGEMENTS

The author would like to express gratitude to the LHCb computing, online, DPA and simulation teams for their support and for maintaining the software without which the presented work would not have been possible.

References

[1] LHCb Collaboration, "The LHCb Detector at the LHC," JINST **3**, S08005 (2008)

[2] LHCb Collaboration, "LHCb Detector Performance," Int. J. Mod. Phys. A, **30**, 07, 1530022 (2015)

[3] Botella, F. J. and Garcia Martin, L. M. and Marangotto, D. and Vidal, F. Martinez and Merli, A. and Neri, N. and Oyanguren, A. and Vidal, J. Ruiz, "On the search for the electric dipole moment of strange and charm baryons at LHC", Eur. Phys. J. C **77** 3, 181 (2017) [arXiv:1612.06769]

[4] Pondrom, L. and Handler, R. and Sheaff, M. and Cox, P. T. and Dworkin, J. and Overseth, O. E. and Devlin, T. and Schachinger, L. and Heller, K., "New limit on the electric dipole moment of the Λ hyperon," Phys. Rev. D, **23** 3, 814–816 (1981)

[5] Pedregosa, Fabian and others, “Scikit-learn: Machine learning in Python”, J. Machine Learning **12** 2825 (2011),

[6] J. Podolanski and R. Armenteros , “III. Analysis of V-events”, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, **45** 360 13-30 (1954)

[7] Wouter D. Hulsbergen, “Decay chain fitting with a Kalman filter,” Nucl. Instrum. Meth. A, **552**, 566–575 (2005)