One person's trash is another person's treasure: expanding physics reach with unused tracks in LHCb

Connecting the dots 2022 | Princeton, NJ, USA

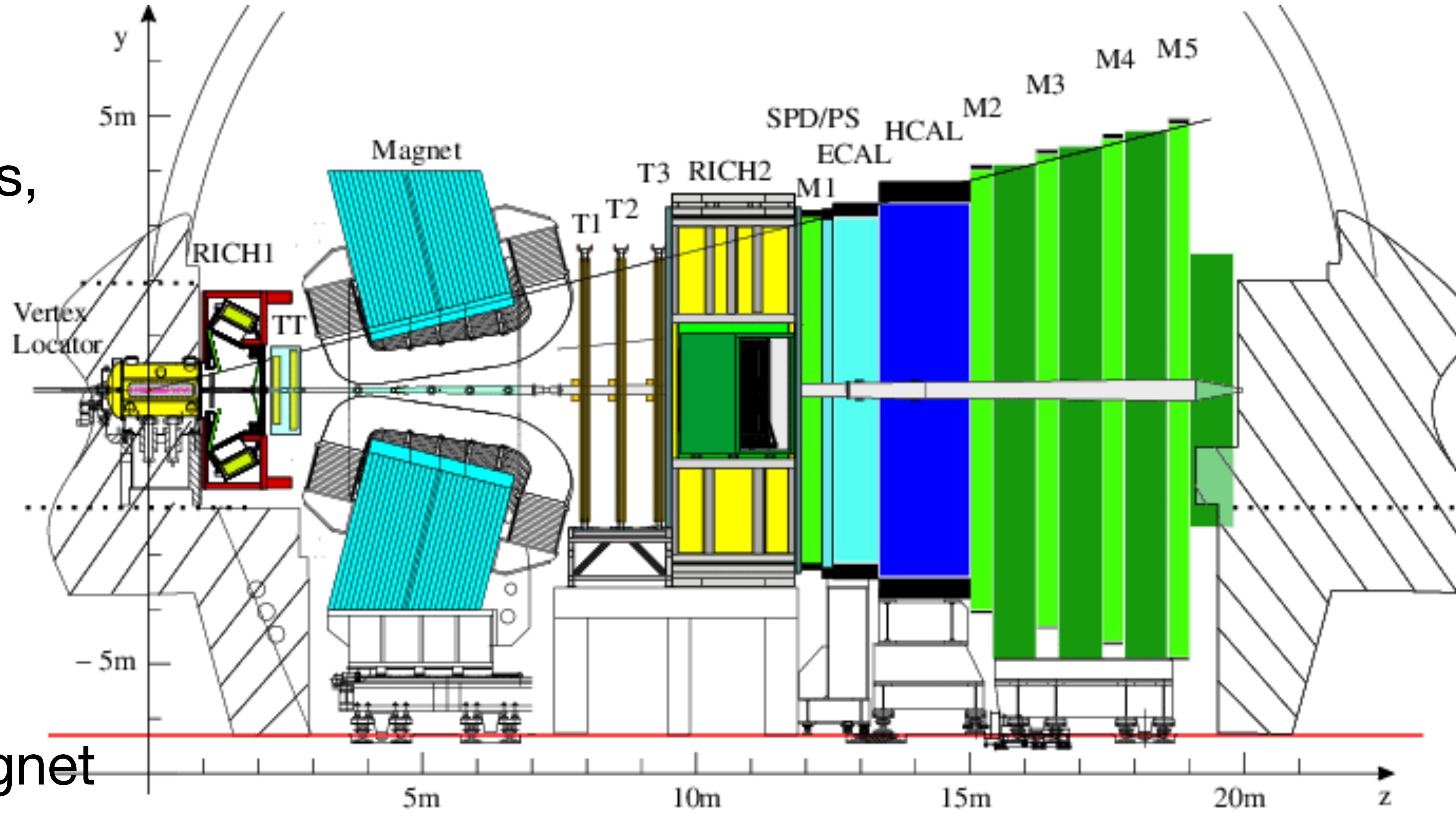
Izaac Sanderswood, IFIC - University of Valencia, on behalf of LHCb RTA project

Overview

- LHCb detector
- Physics motivation
  - EDM & MDM searches
  - BSM LLP searches
- Feasibility & challenges
- Future
  - Phase I upgrade
  - Run-3
  - Offline analysis

LHCb detector

- General-purpose single-arm forward spectrometer
- Pseudorapidity range $2 < \eta < 5$
- Optimised for study of particles containing b or c quarks, though physics programme has **expanded** beyond this
- Three tracking subdetectors:
    - VELO (vertex locator) located around the beamspot
    - TT (Tracking Turicensis) located before the dipole magnet
    - T1-T3 (tracking stations) located after the dipole magnet
- Also comprised of two RICH detectors for PID, ECAL, HCAL and muon stations
- Phase-I upgrade for Run-3

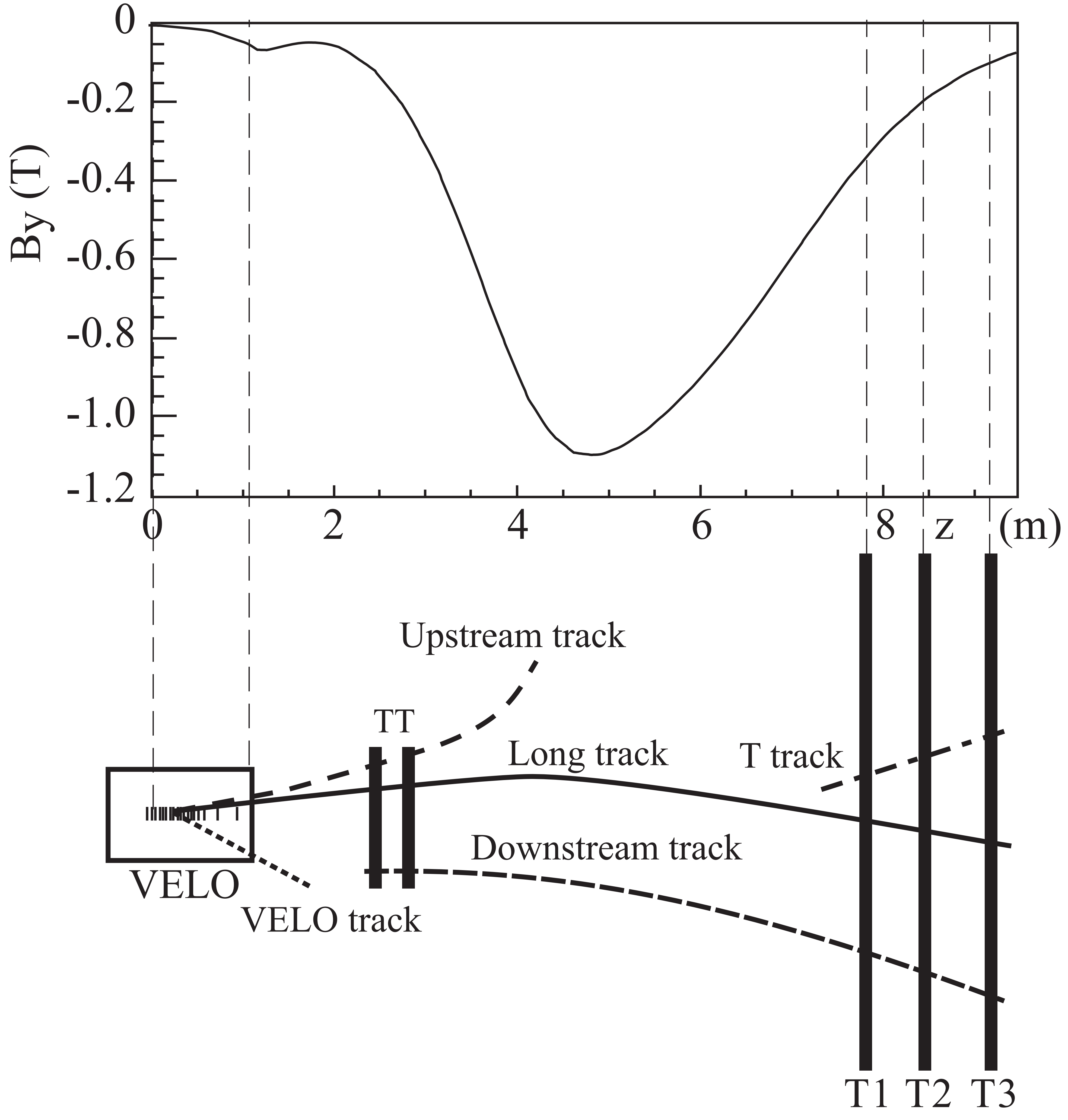


Source Int.J.Mod.Phys.A 30 (2015) 07

LHCb tracks

- In LHCb tracks are reconstructed from segments in the different tracking subdetectors
- 4 categories of tracks according to where they have hits:
  - VELO tracks
  - Upstream tracks
  - Downstream tracks
  - Long tracks
  - T tracks
- Thus far, only Long and Downstream tracks are used for physics analysis, limiting the maximum decay length to ~2 m
  - Longer tracks are better measured so are preferred
- **Standalone T tracks have not previously been used for physics analysis**

Source Int.J.Mod.Phys.A 30 (2015) 07



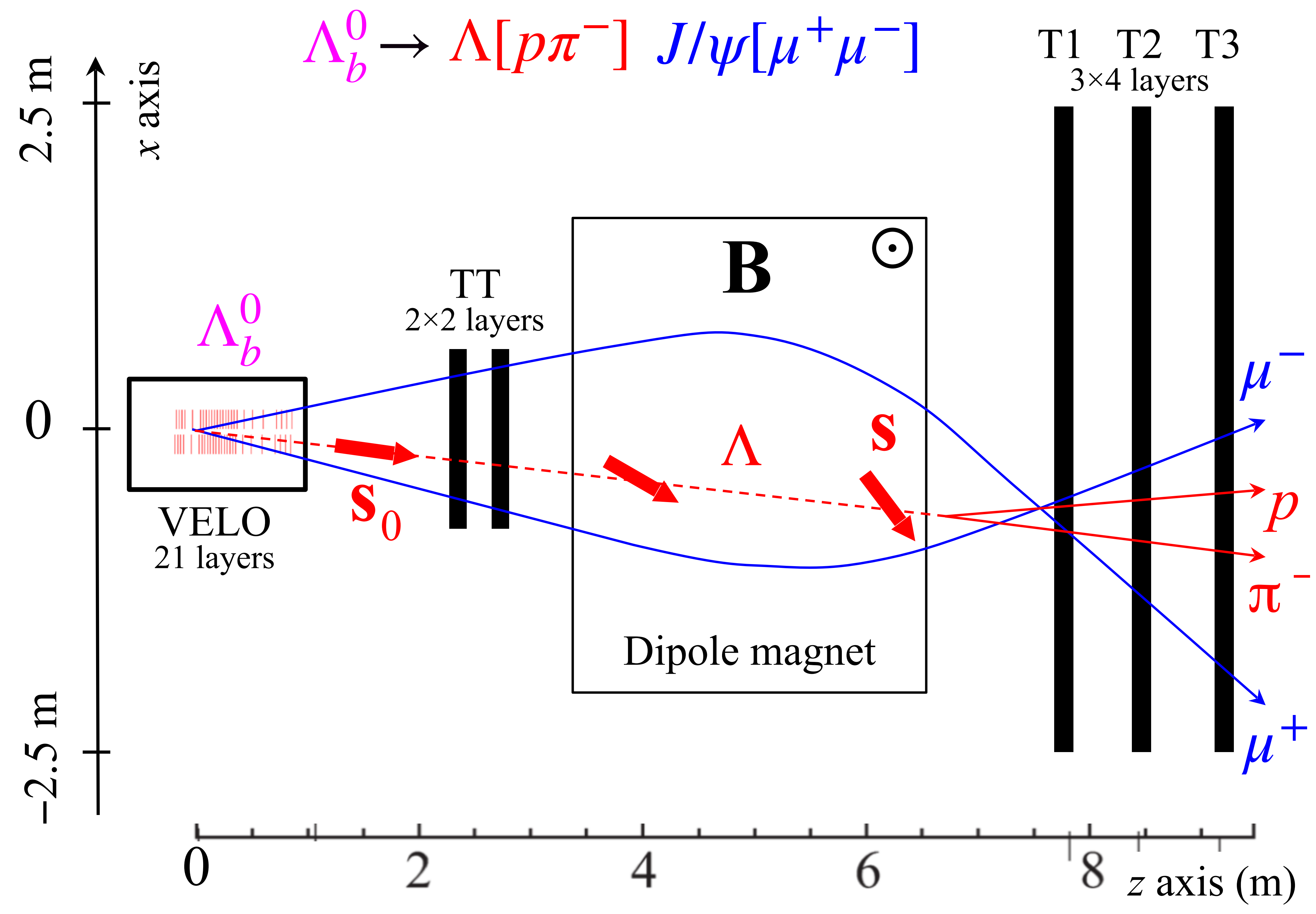
Physics motivation

Motivation

- LHCb was designed to study particles decaying upstream of the magnet after ~ ps
- However, it is possible to **reconstruct particles** with a decay flight distance > 2.6 m **using only T tracks**
- Up to now, there have been no analyses with particles reconstructed only from T tracks
  - Reduced magnetic field → **reduced momentum resolution**
- Reconstruction of these particles would extend the physics reach of LHCb by permitting SM & BSM long-lived particle analyses:
  - **Measurement of electric and magnetic dipole moments** (EDM and MDM) [Proposed in Eur. Phys. J. C 77, 181 (2017)]
  - **Searches for BSM LLPs** with particles decaying up to 7.6 m from interaction point

Motivation: EDM and MDM measurements of baryons

- Electric and magnetic dipole moments (EDM & MDM) can be measured by **exploiting the spin precession** of particles that **pass through dipole magnet** before decaying
    - Requires sources of **polarised baryons** not aligned with the magnetic field (e.g. from weak b- and c-baryon decays), and sufficient reconstruction of decays after magnet → requires reconstruction of particles from T tracks
        - e.g. Λ's produced in Λ_b^0 decays measured to be maximally polarised [Phys.Lett.B 724 (2013) 27-35, JHEP 06 (2020) 110]
- Sources of CPV in the SM predict **minuscule EDMs**
    - EDM measurements are sensitive to new sources of CPV and increases due to BSM physics
    - Λ baryon EDM was last measured 40 years ago [Phys. Rev. D 23, 814(R)]
    - Could improve EDM limits by **2 orders of magnitude**
- MDM measurements of lambda & anti lambda baryon provide a **direct test of CPT symmetry**
- Proposed in Eur. Phys. J. C 77, 181 (2017)



Motivation: BSM LLP searches

- LLPs present in nearly every BSM theory
- LHCb is well suited to search for **LLPs produced in B and D hadron** decays
  - Is able to reconstruct hadronic (i.e. $\chi_{\mathrm{BSMLLP}} \to h^+h^-$) signatures in addition to muons and jets
- So far, searches for LLPs in LHCb have only used **Long tracks**, excluded χ's with mass $200 \lesssim m(\chi) \lesssim 4{,}700$ MeV, lifetimes up to ~10 ps
  - This means that LLP searches have been **limited by the size of the VELO** subdetector around the beam spot, cτ ≲ 30 cm
- By using tracks made exclusively from hits downstream of magnet, particles decaying **up to 7.6 m from interaction point** can be reconstructed, corresponding to **lifetimes ~few ns**
- For overview of BSM searches see e.g. M Borsato et al 2022 Rep. Prog. Phys. 85 024201

Motivation: BSM LLP searches

- Plots show the reconstructibility in LHCb of a hidden Higgs (h^0) decaying to a dimuon pair, produced in $B \to K^{(*)}h^0(\to \mu\mu)$ decays (longer lifetime towards the bottom of the plot)

Feasibility & challenges

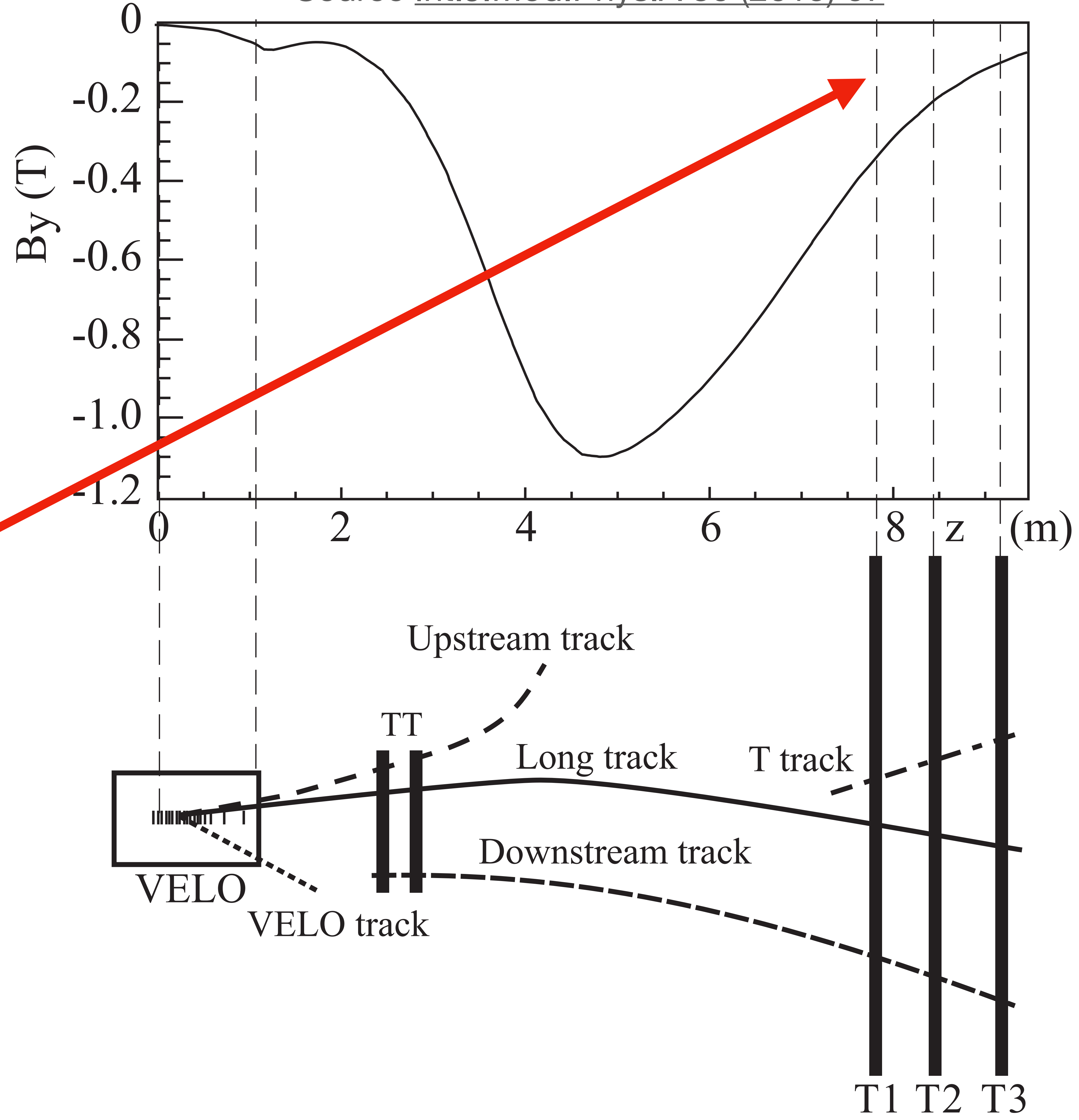
Feasibility

- Feasibility studies have been performed using two SM benchmark channels with Run 2 data
  - $\Lambda_b^0 \to J/\psi\Lambda, \Lambda \to p\pi^-$
  - $B^0 \to J/\psi K_S^0, K_S^0 \to \pi^+\pi^-$
- Only events where the Λ or K_S^0 decays downstream of magnet are reconstructed
- By reconstructing a prompt $J/\psi \to \mu\mu$ with Long tracks, a kinematically constrained fit of the whole decay chain can be performed

Feasibility

- Two main challenges to address:
  - Extrapolating over several metres through an inhomogeneous magnetic field
    - Overcome by using 5th-order Runge-Kutta extrapolation
  - Reduced momentum resolution due to lower magnetic field strength
    - Developing a multivariate classifier (Histogram-based BDT [HBDT] from scikit-learn) and using Armenteros-Podolanski technique* helps greatly improves selection performance and mitigates cross-feed from other long-lived decays

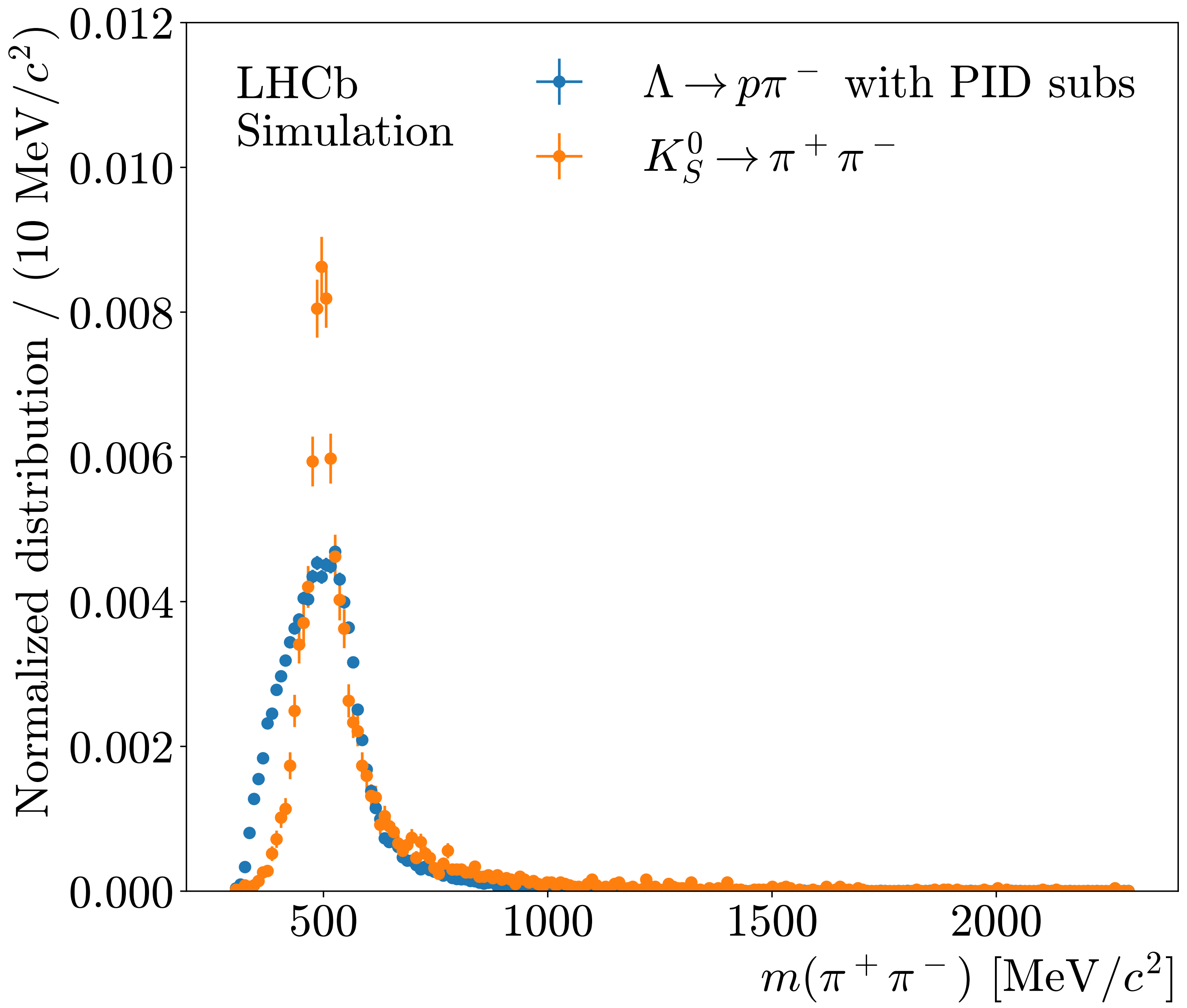
Source Int.J.Mod.Phys.A 30 (2015) 07

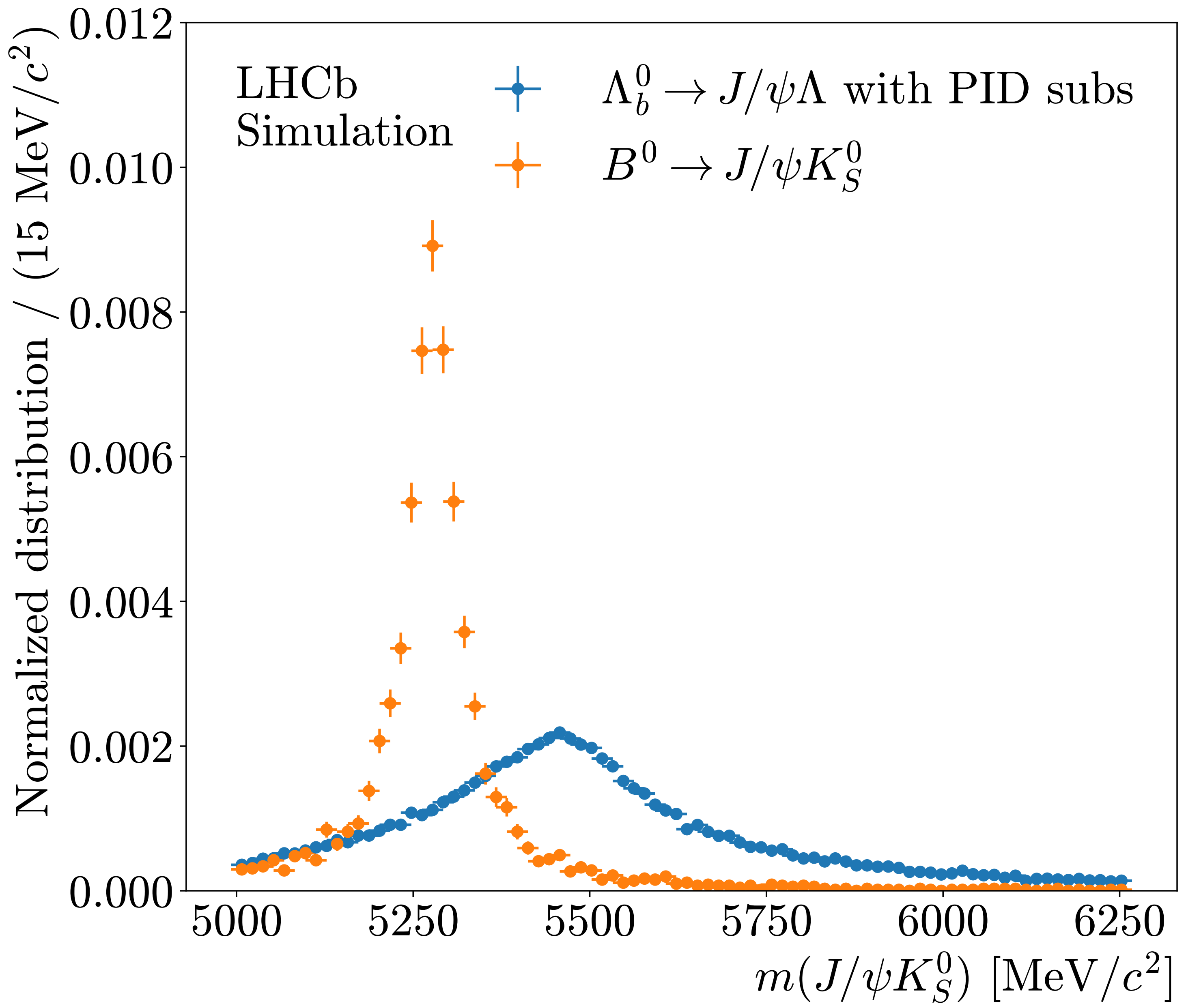


*[The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 45:360, 13-30]

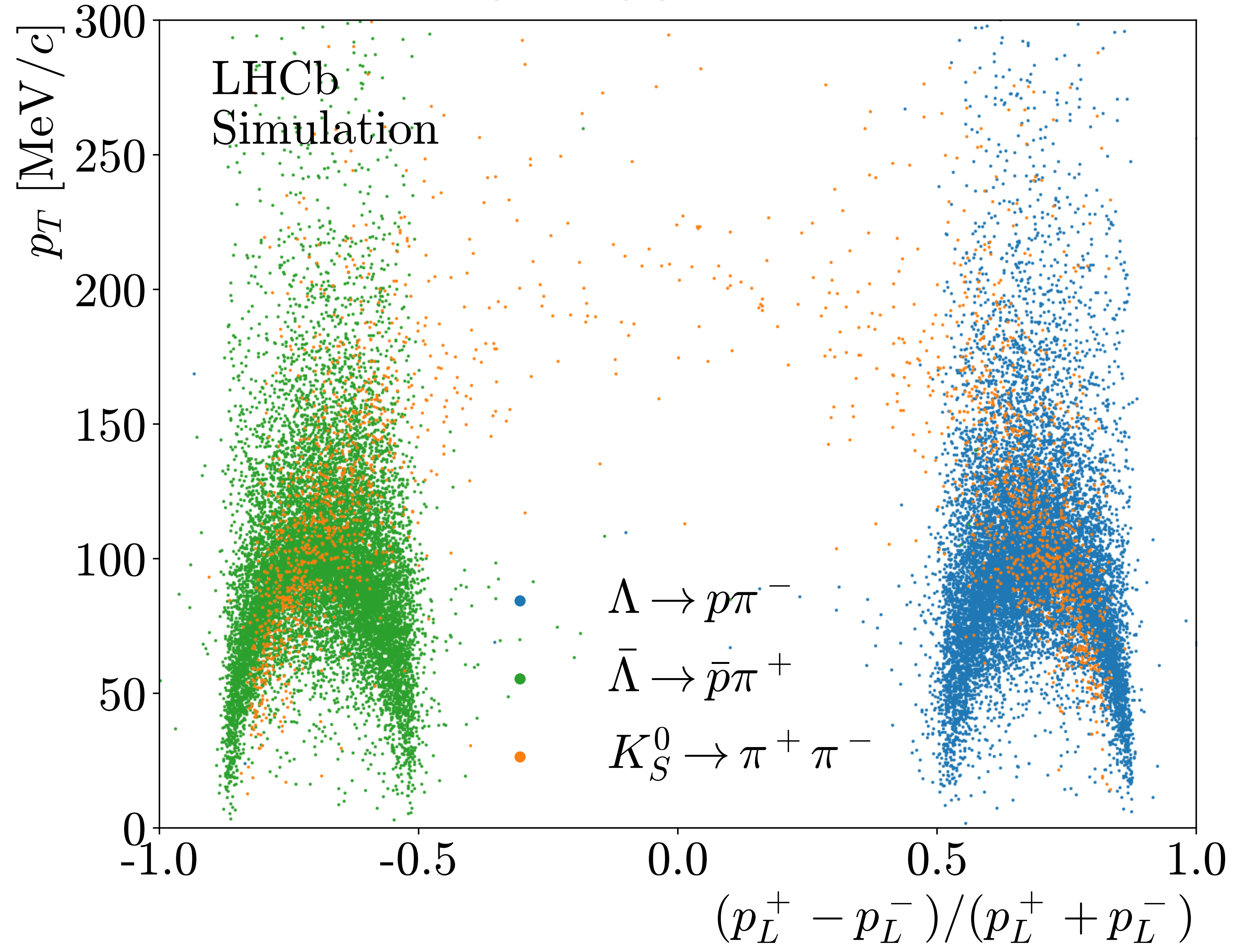
Feasibility

$\Lambda_b \to J/\psi\Lambda$





LHCB-FIGURE-2022-009

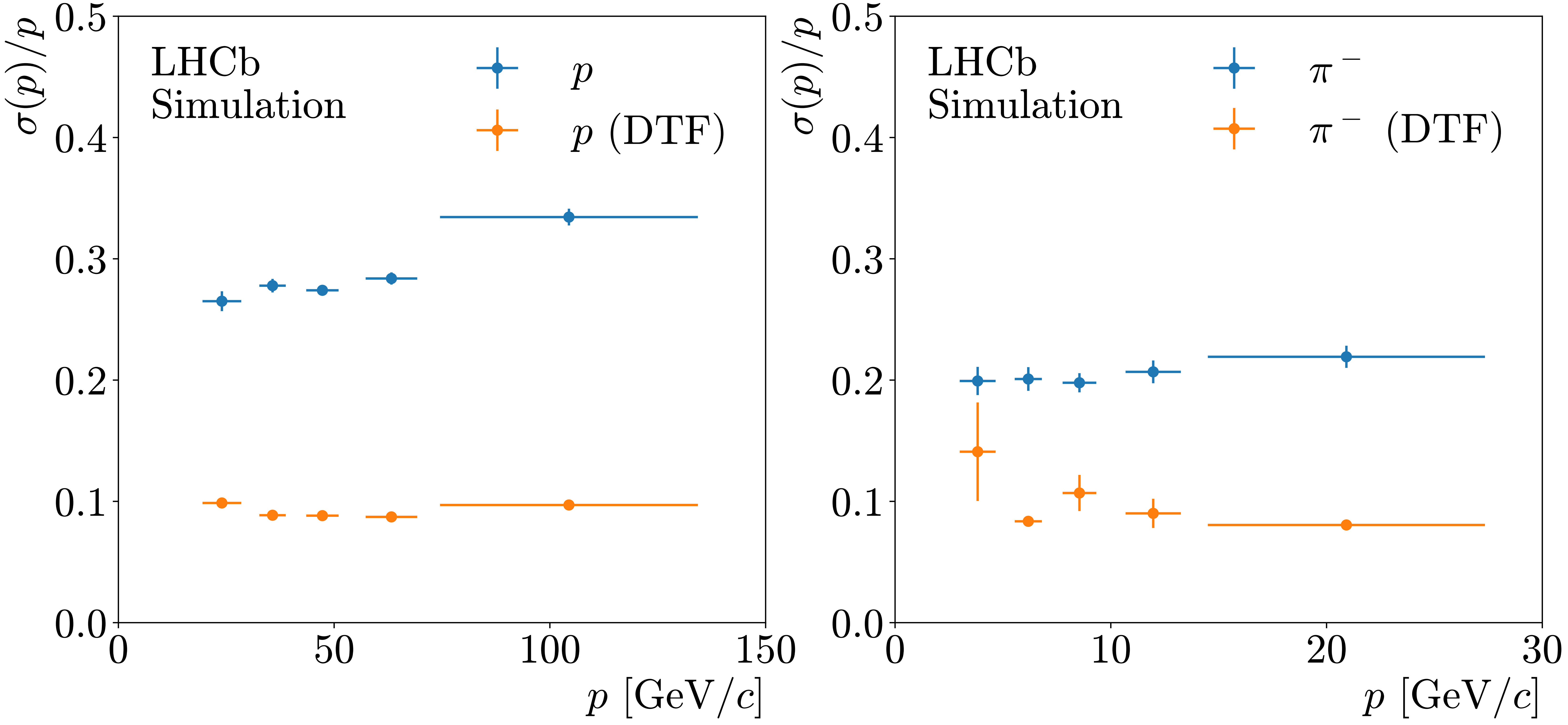


- The mass peaks of the Λ/K_S^0 are overlapping so not possible to distinguish through mass cuts → lower momentum resolution leads to lower mass resolution
- RICH2 PID is not available in Run-2 for T tracks
- Can instead be distinguished using Armenteros-Podolanski (AP) technique

Feasibility

$\Lambda_b \to J/\psi \Lambda$

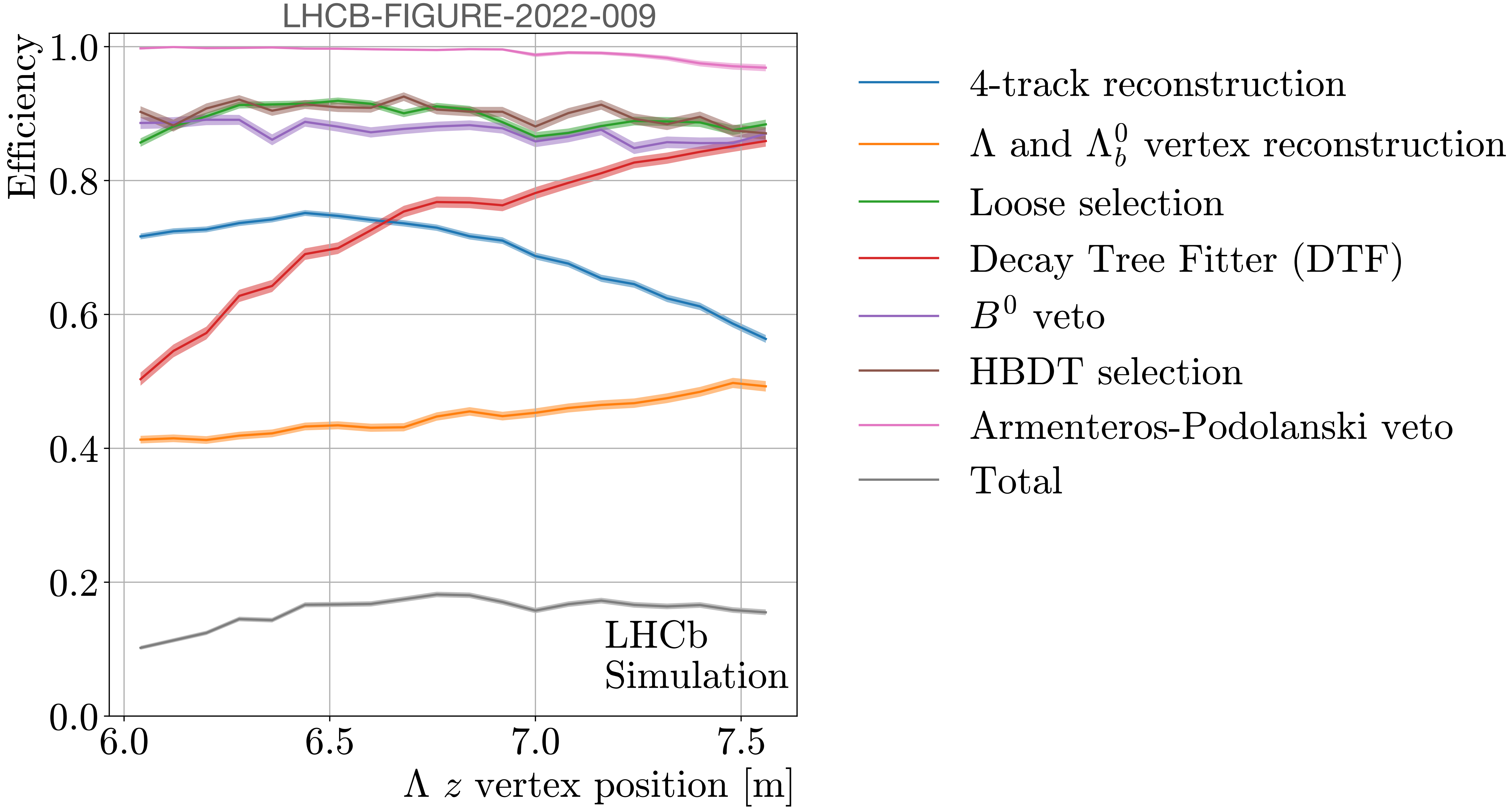
LHCB-FIGURE-2022-009



- Momentum resolution is improved using a mass constrained fit (Decay Tree Fitter) [Nucl. Instrum. Meth. 694 A552 (2005) 566], with masses of Λ and J/ψ constrained

Feasibility

$\Lambda_b \rightarrow J/\psi\Lambda$



$\Lambda_b^0 \rightarrow J/\psi\Lambda$ signal

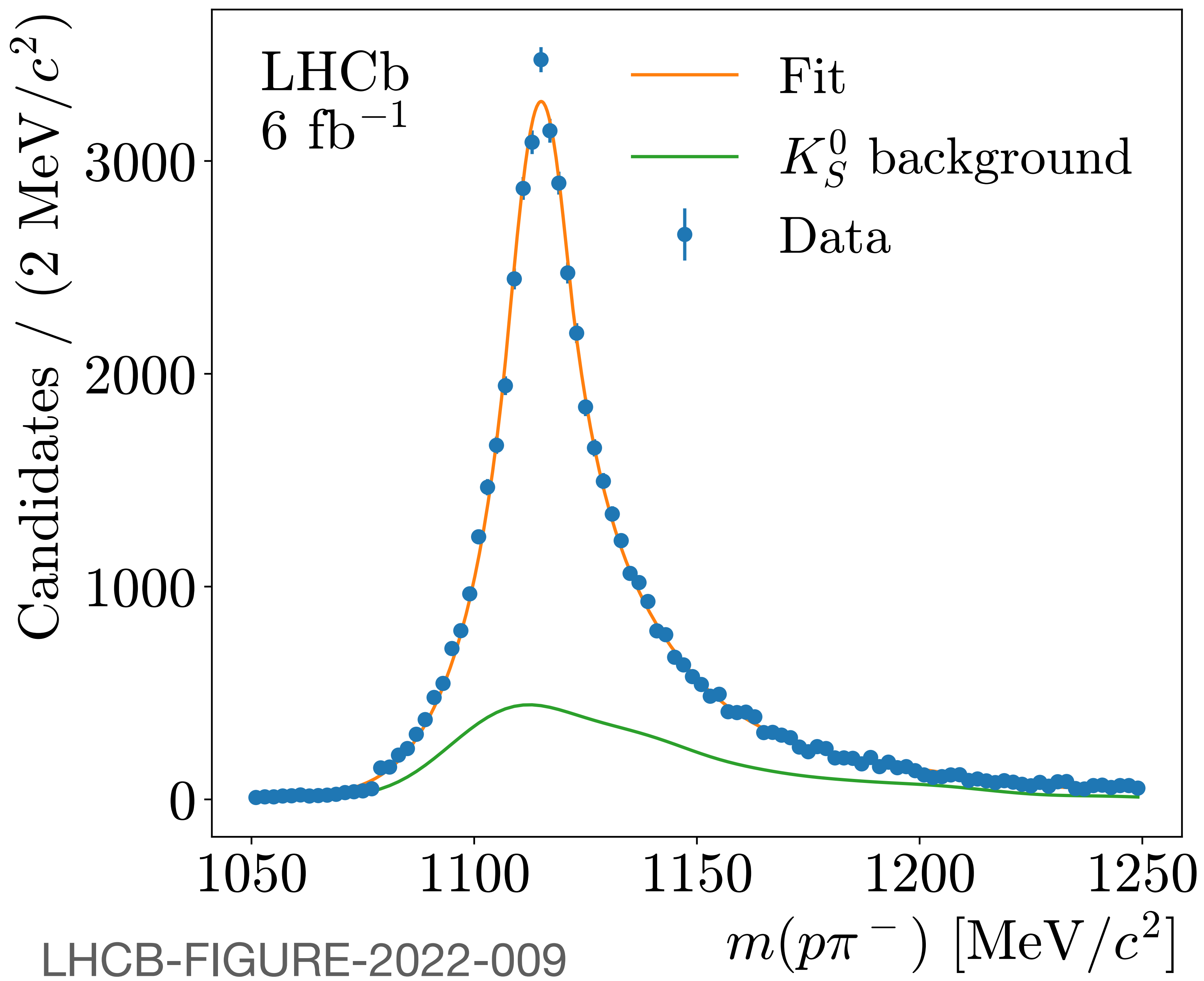
Efficiencies calculated wrt to reconstructible particles (i.e. within acceptance)

Low vertex reconstruction efficiency → investigating remedies

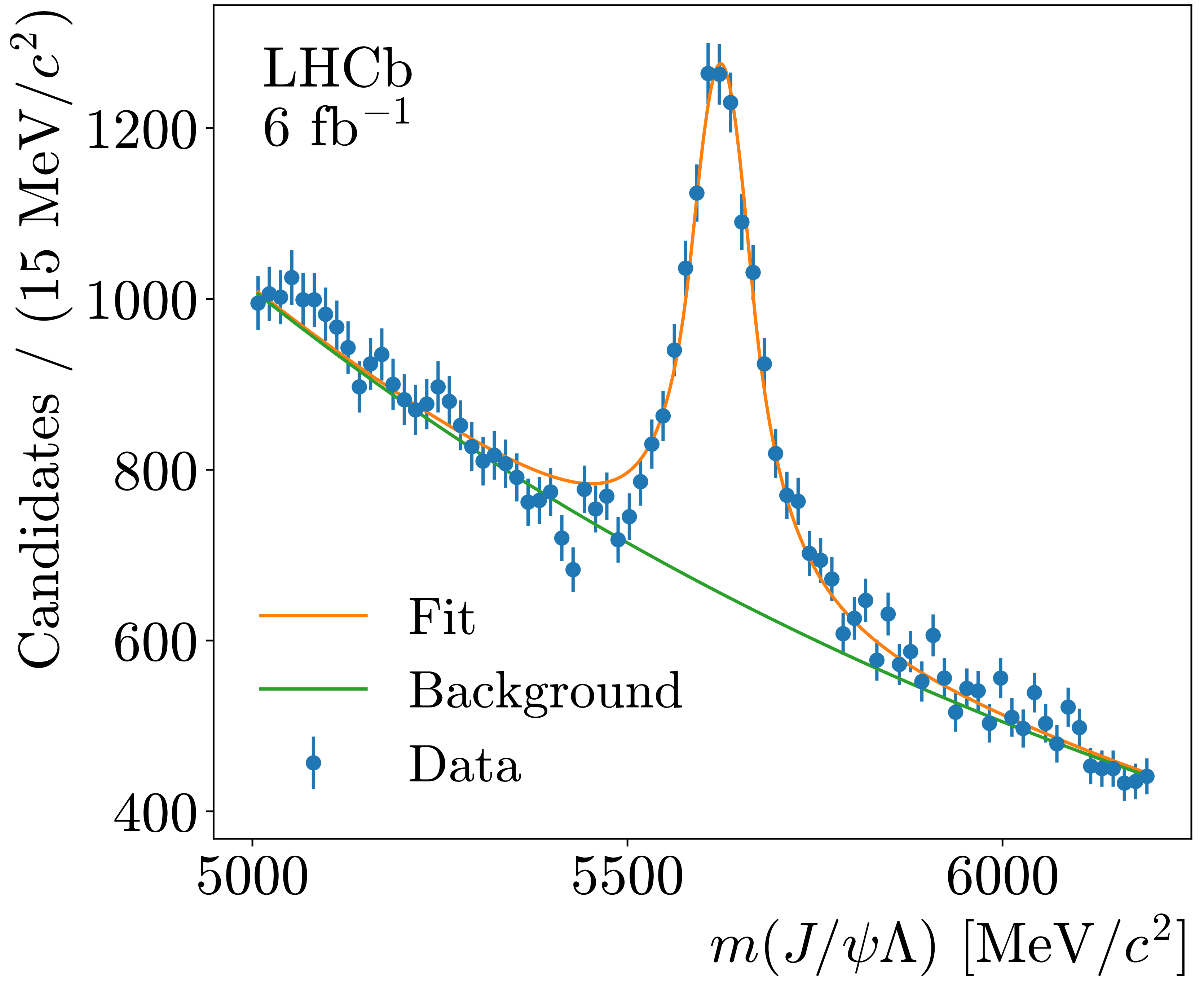
Feasibility

$\Lambda_b \to J/\psi\Lambda$

- Plots show the invariant mass distributions for $\Lambda \to p\pi$ (top), and $\Lambda_b^0 \to J/\psi\Lambda$ (bottom)
- After all selections applied, including HBDT, AP veto, B^0 veto and decay tree fit
- Mass resolutions of 8 MeV and 41 MeV respectively

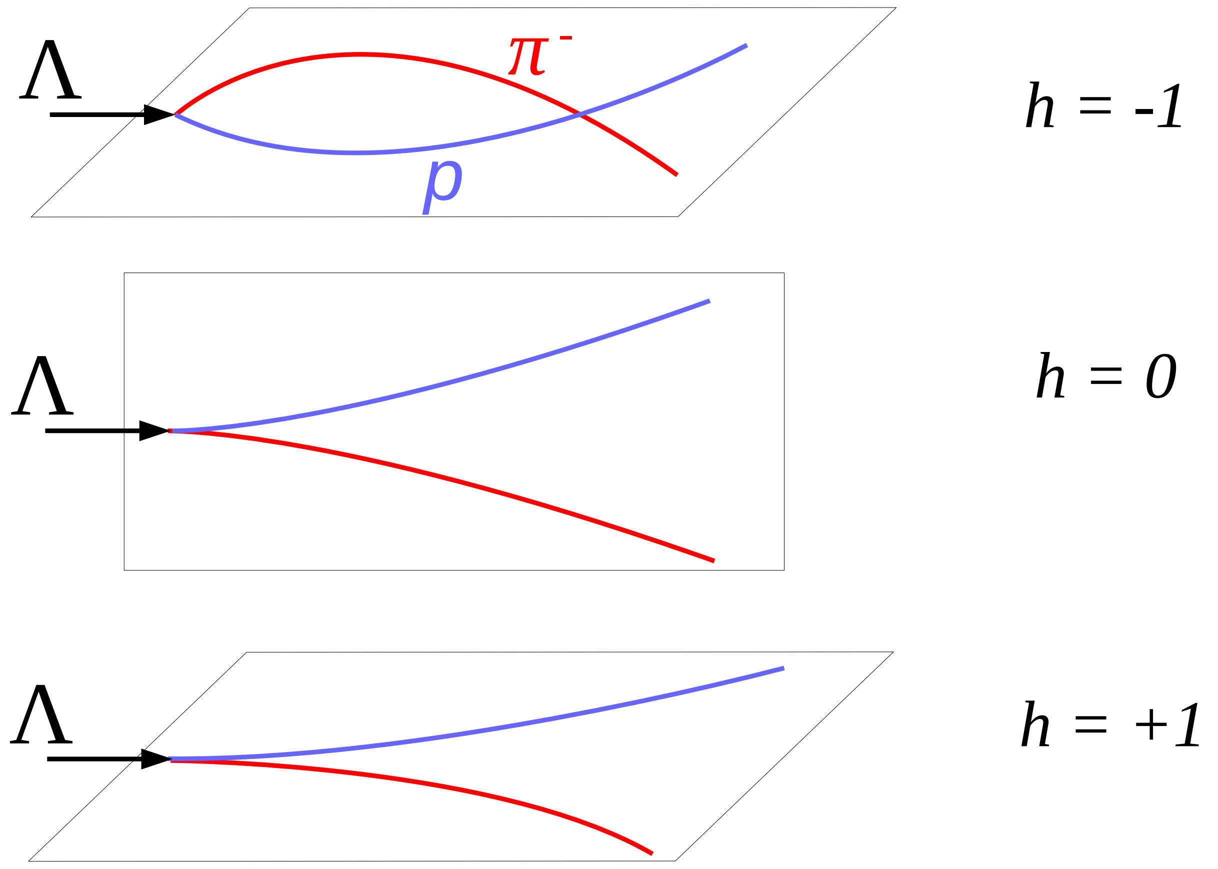


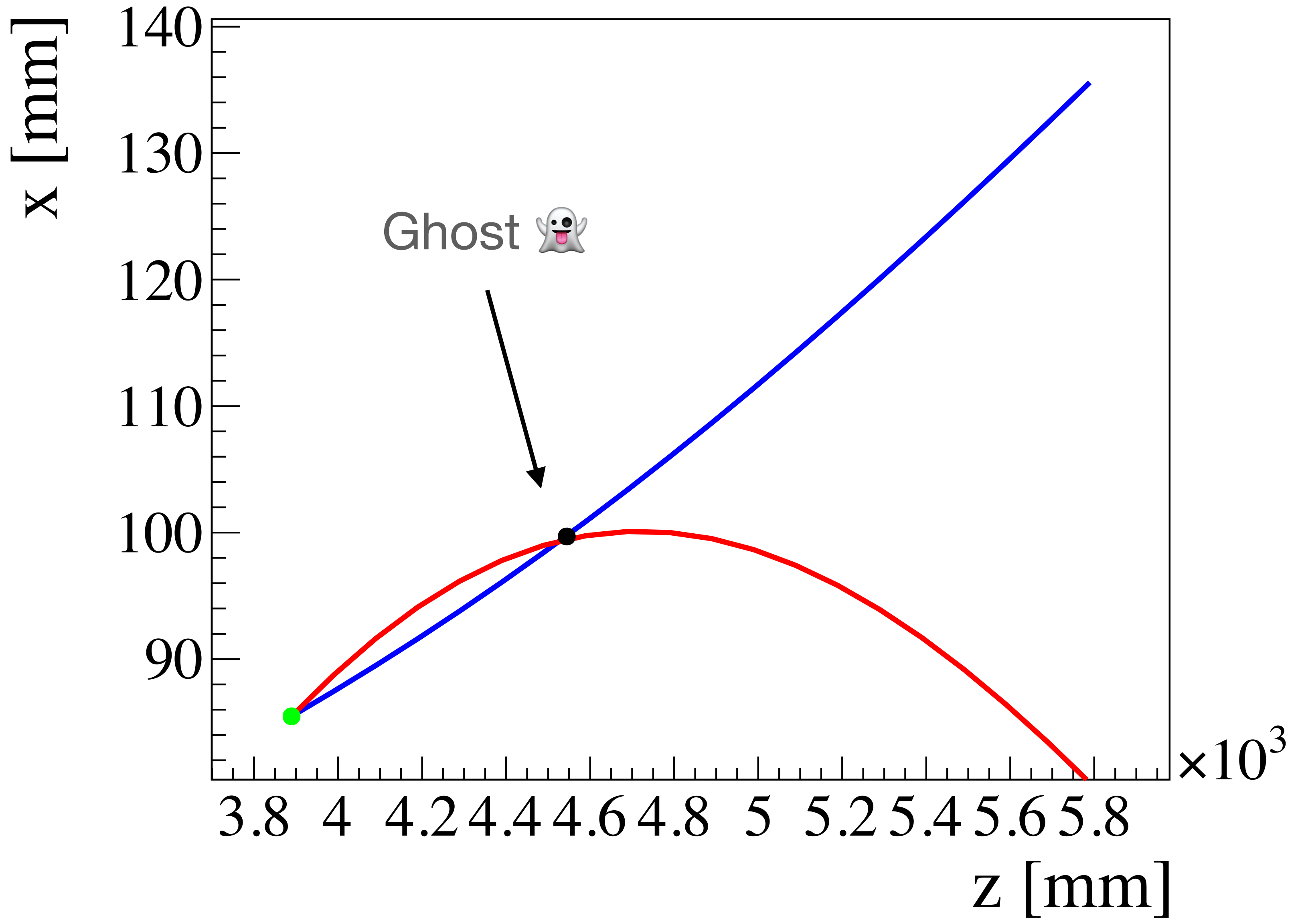
LHCB-FIGURE-2022-009

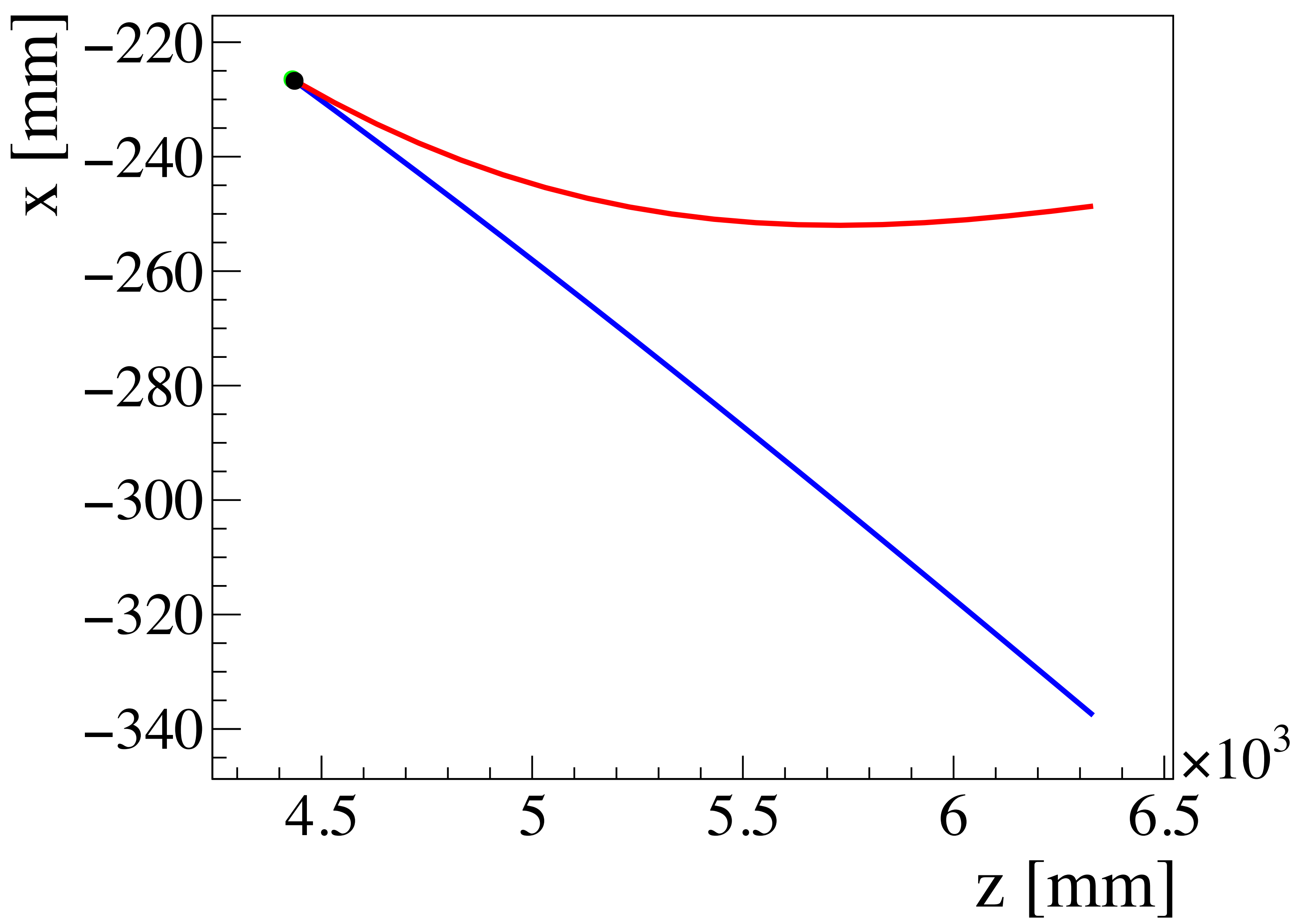


Challenges

- Vertex reconstruction becomes more challenging the further the decay vertex is from the tracking stations
- The low Q value in Λ→pπ decays means a small aperture between the tracks
    - The p & π tracks can cross twice within the resolution, creating an additional “ghost” vertex
- Can be partially identified using the horizontality, h:
- $h = \pm M_{\text{pol}} \hat{a}_y, \ \vec{a} = \vec{p}_{p^{\pm}} \times \vec{p}_{\pi^{\mp}}$



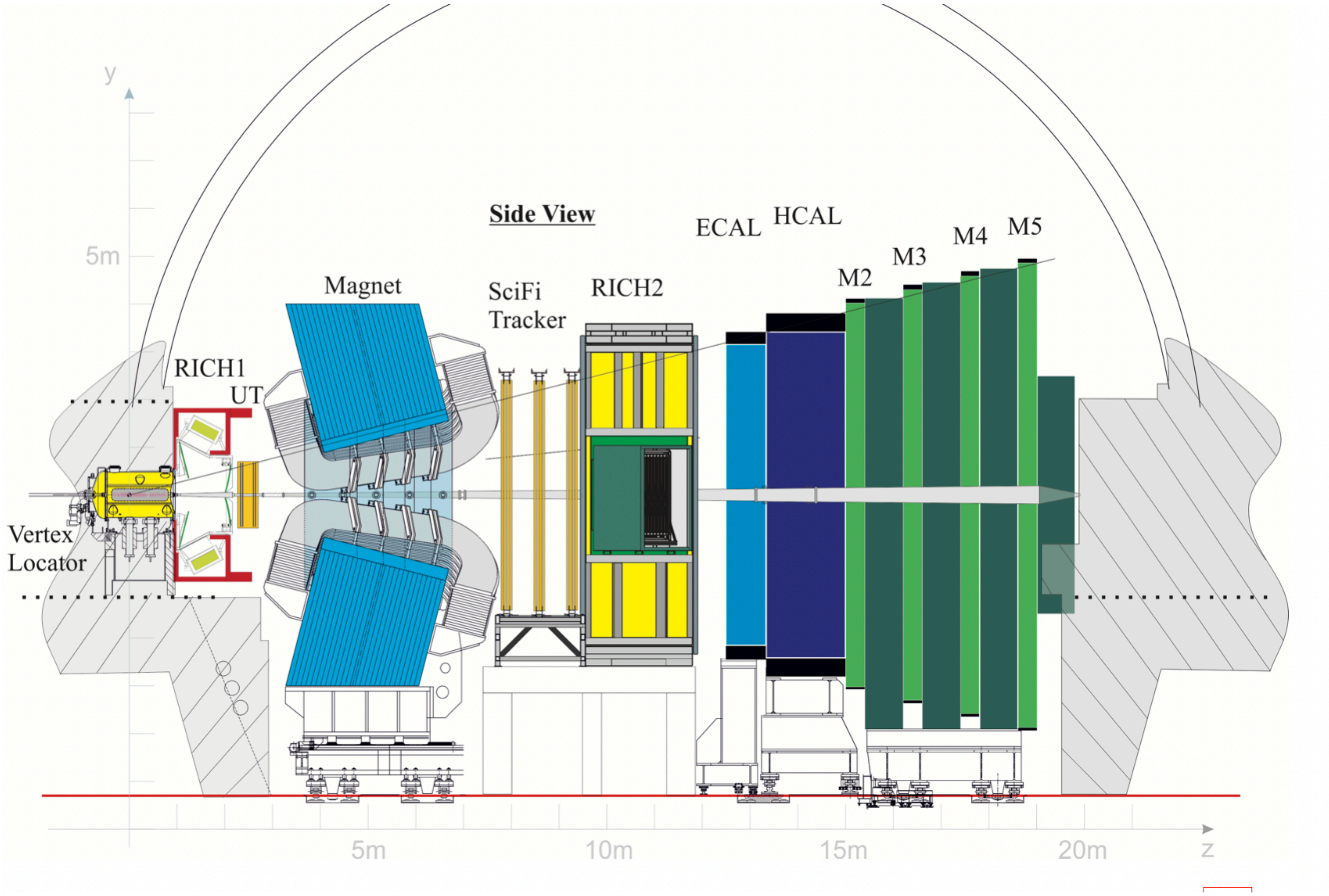




Future: Run-3 and offline analysis

LHCb Phase-I upgrade

- Includes new trackers, vertex detector and electronics
  - New VELO, TT replaced by UT (Upstream Tracker), T1-T3 replaced by SciFi (Scintillating fibre) tracker
- **Fully software based trigger** will operate at an average pp bunch crossing **rate of 30 MHz**
  - Previously limited to ~1 MHz
- HLT1 including reconstruction on GPUs (Comput.Softw.Big Sci. 4 (2020), LHCB-TDR-021, 2020)



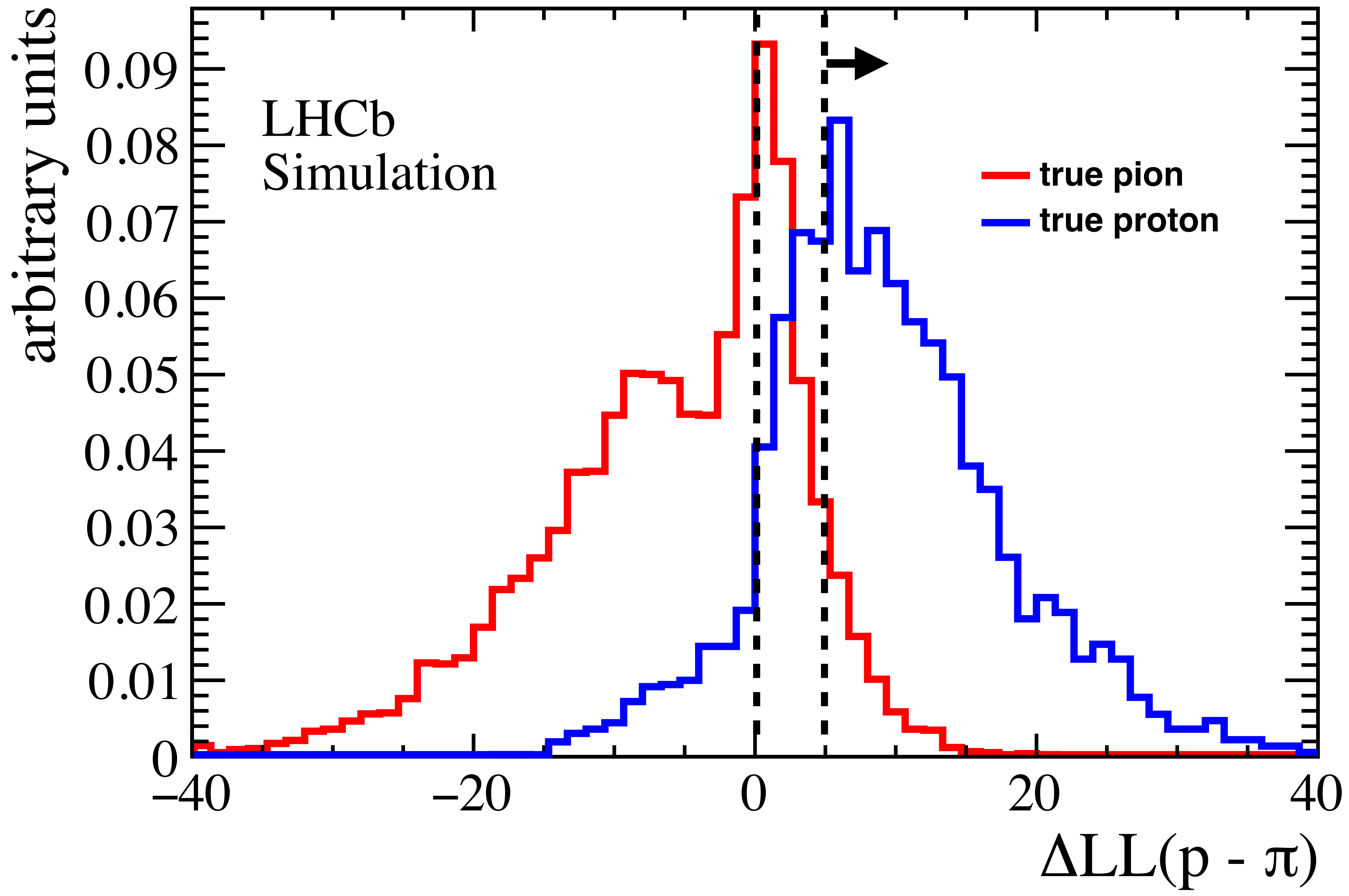
Source: LHCB-TDR-15

Future: Run-3

- LHCb's upgraded trigger is versatile and adaptable, allowing for **real time analysis** of events
- Work well underway to include T track particles in the Run-3 HLT2 trigger, which will improve over the Run-2 feasibility studies:
  - PID information from RICH detector downstream of magnet
  - Optimisation of Kalman-Filtering for T tracks
  - Investigating optimisation of vertexing
- Dedicated trigger lines can expand the physics reach of LHCb
  - Starting first with the benchmark channels, but plan to expand, including BSM LLP searches
- Exploring the possibility of T track lines running on HLT1

Future: Run-3

LHCB-FIGURE-2022-008



(Very preliminary) The difference in log likelihood between the proton and pion hypotheses for true proton and true pion T tracks with associated RICH2 info in Run 3 MC. RICH2 info was not added to T tracks in Run-2.

Future: offline analysis

- Expanded use of PID — from RICH2, muon stations but also AP technique
- Expect to expand use of MVA and ML techniques to optimise selections and vertexing
- Investigating sensitivity and analyses for EDM/MDM measurements and BSM LLP searches
- Investigating further ways to improve momentum resolution by exploiting information the other sub detectors downstream of the magnet

Summary

- The physics reach of LHCb can be extended by reconstructing particles decaying downstream of the dipole magnet
  - Permits electric and magnetic dipole measurements
  - Can significantly extend reach of BSM LLP searches at HLT2
- This has been demonstrated using $\Lambda_b^0 \to J/\psi\Lambda^0$, and $B \to J/\psi K_S^0$ in Run-2 data — paper to be released in next few weeks
- Excited to bring new results as Run-3 gets under way

Backup

Discriminating variables

- The classifier includes kinematic and topological variables:
  - the longitudinal and transverse momenta of the proton, pion and J/ψ candidates
  - the coordinates of the Λ decay vertex
  - the cosine of the angle between the momentum and the flight direction of the Λ and Λ_b^0 decaying particles
  - the χ^2_{vtx}, χ^2_{IP} and χ^2_{dist} of the Λ and Λ_b^0 candidates
  - the status flags (converged/failed) of the decay chain vertex fit with and without the Λ mass constraint