Reconstruction of long-lived particles in LHCb using T tracks

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2nd workshop on electromagnetic dipole moments of unstable particles | Gargnano | 28/9/22

Today

LHCb overview

Motivation

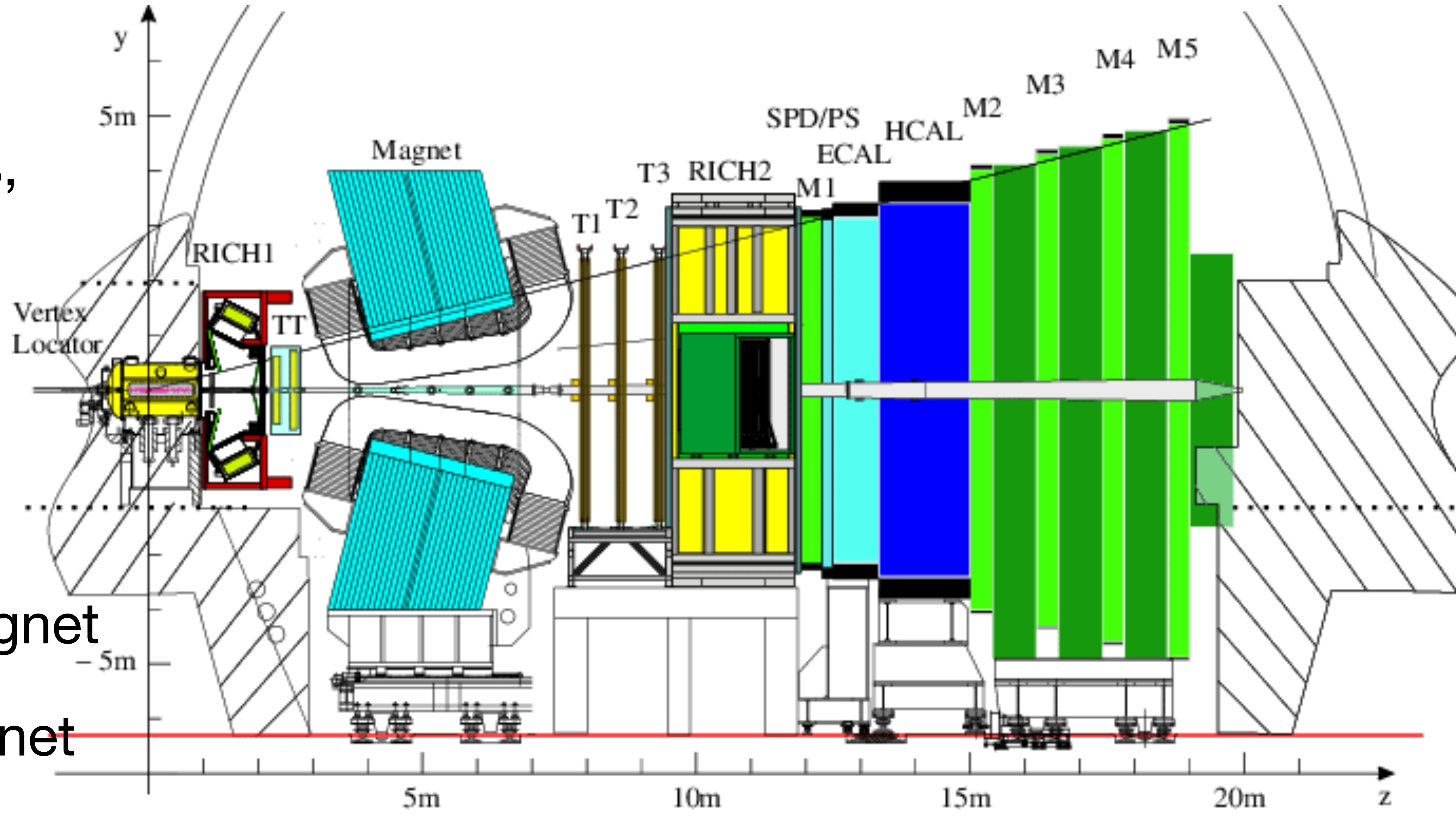
Run 2 feasibility studies

Online event reconstruction & selection in Run 3

Summary

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 is continually **expanding** 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

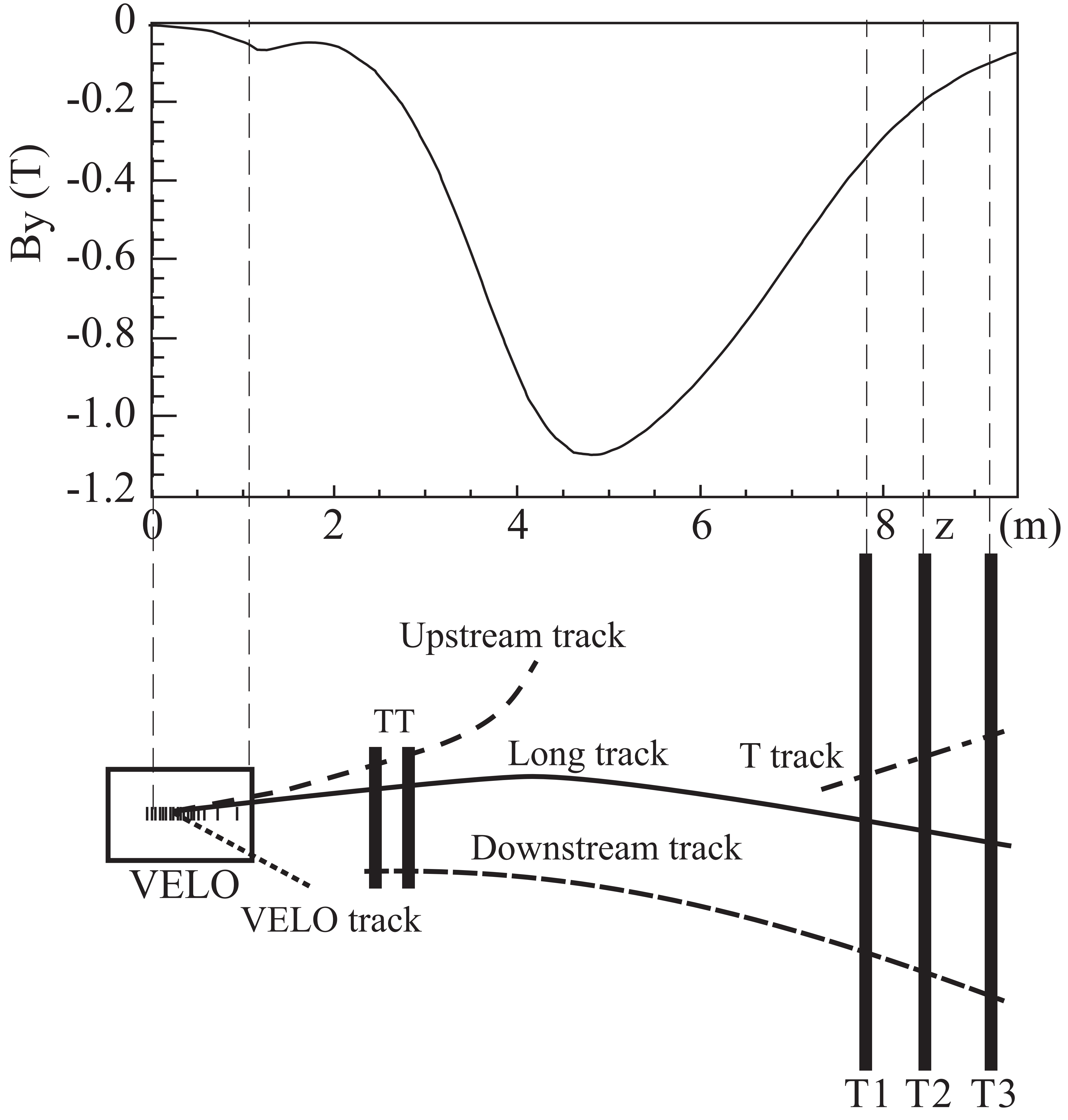


Source Int.J.Mod.Phys.A 30 (2015) 07

LHCb tracks

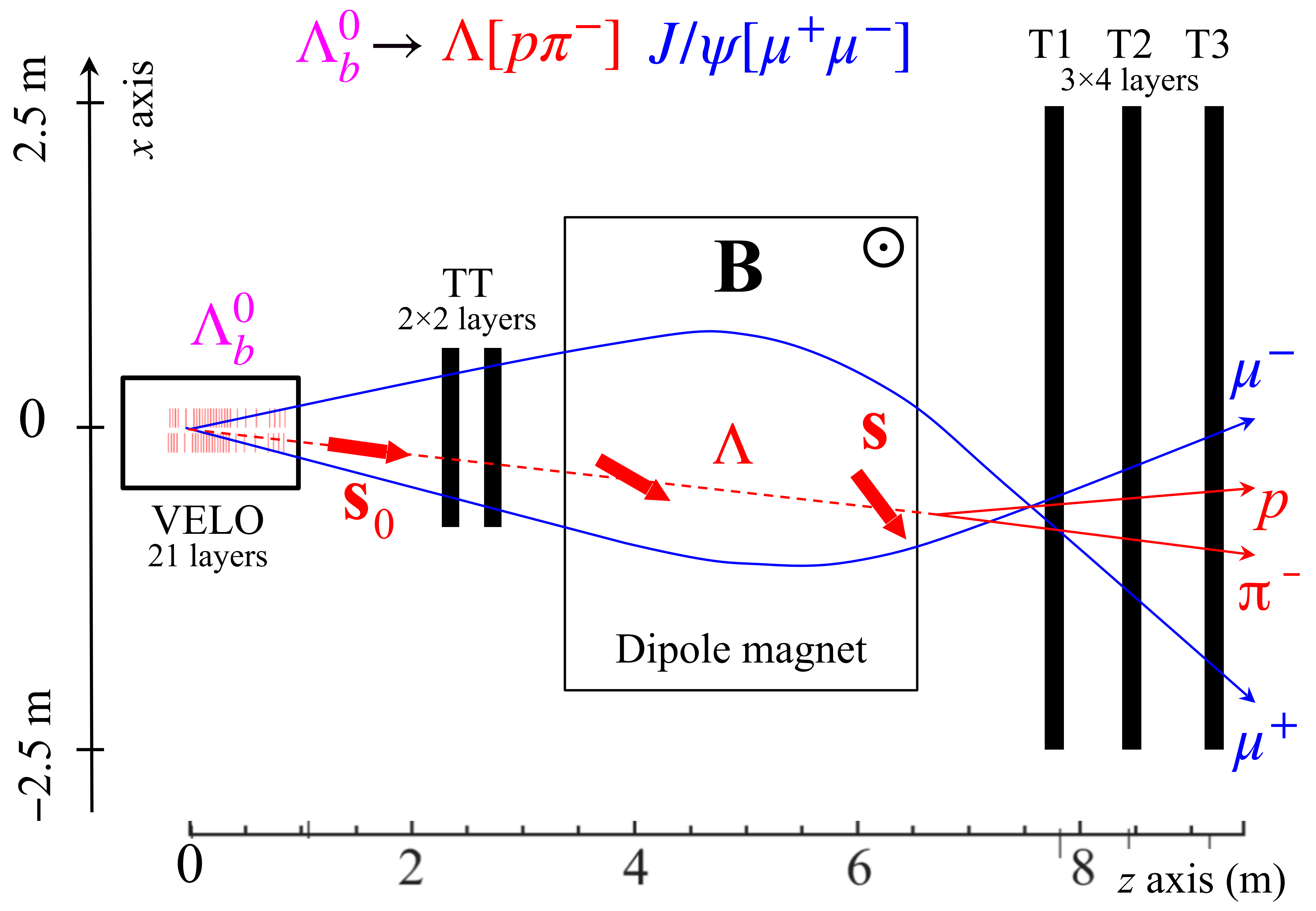
- In LHCb tracks are reconstructed from segments in the different tracking subdetectors
- 4 categories of tracks according to where they have hits:
  - VELO tracks
  - Upstream tracks
  - Downstream tracks
  - Long tracks
  - T tracks
- Thus far, only Long and Downstream tracks are used for physics analysis, 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



Motivation: EDM and MDM measurements of baryons

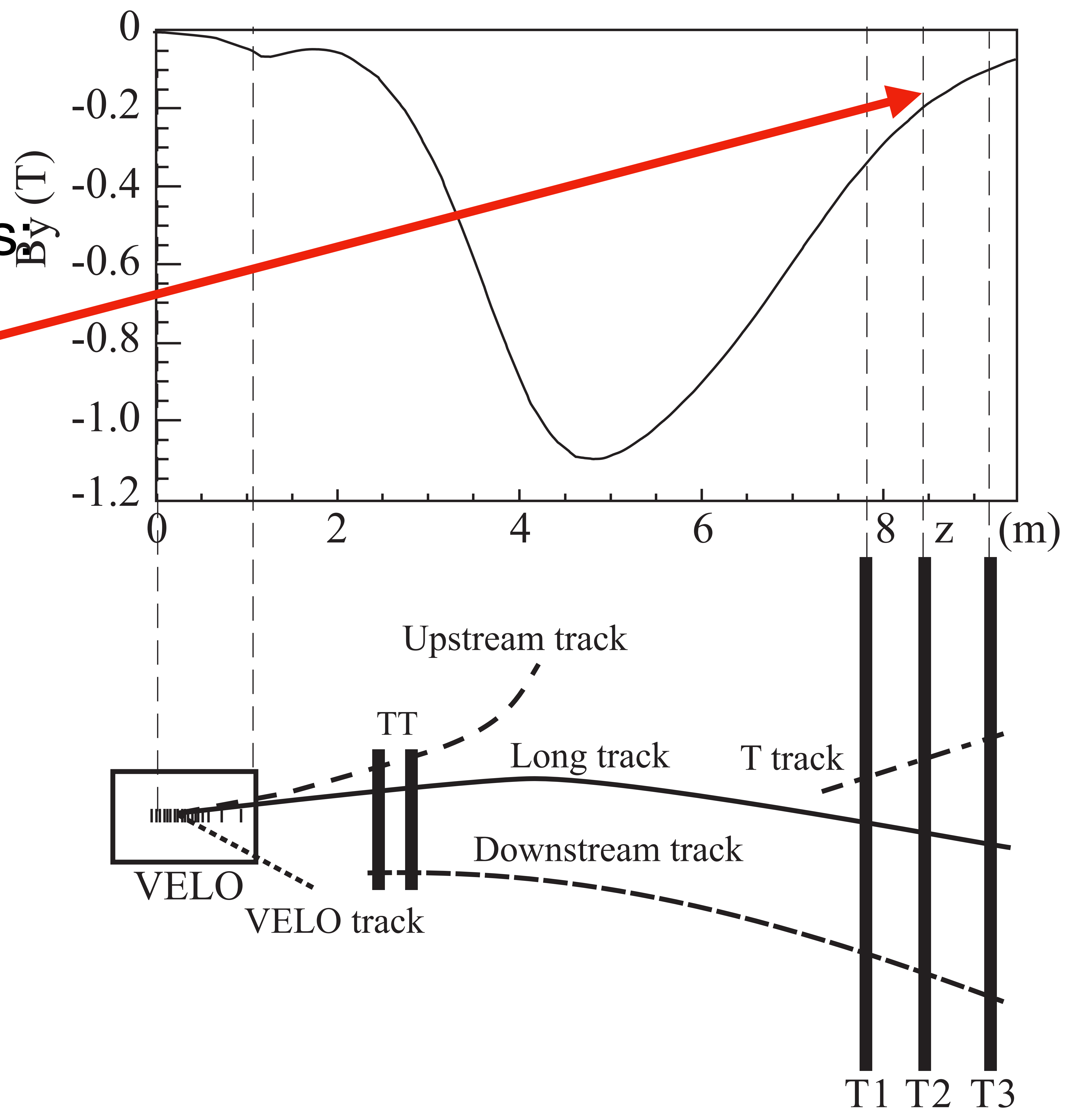
- Electric and magnetic dipole moments (EDM & MDM) can be measured by **exploiting the spin precession** of particles that **pass through dipole magnet** before decaying
  - Requires sources of **polarised baryons** not aligned with the magnetic field (e.g. from weak b- and c-baryon decays), and sufficient 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)



Run 2 feasibility studies

Challenges of reconstruction with T tracks

- Two key challenges of reconstruction with T tracks:
- 1. Reduced momentum resolution
  - Due to reduced magnetic field in region of tracking stations
  - Implies reduced invariant mass resolutions
- 2. Extrapolating over several metres through a strong, inhomogeneous magnetic field
  - Track propagation must be calculated using numerical methods — 5th order Runge Kutta



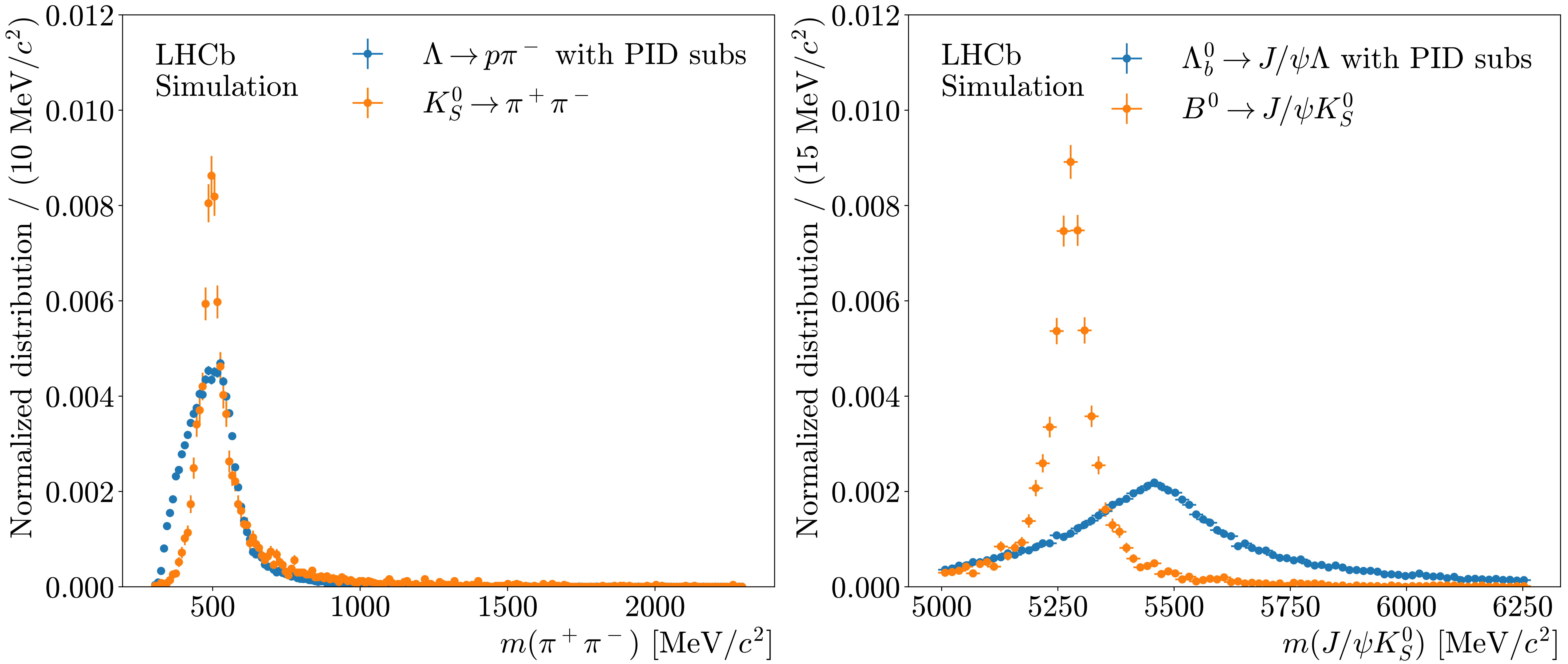
Feasibility

- 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
- Use a multivariate classifier (Histogram-based BDT [HBDT] from scikit-learn) and Armenteros-Podolanski technique* helps to greatly improves selection performance and mitigates cross-feed from other long-lived decays

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

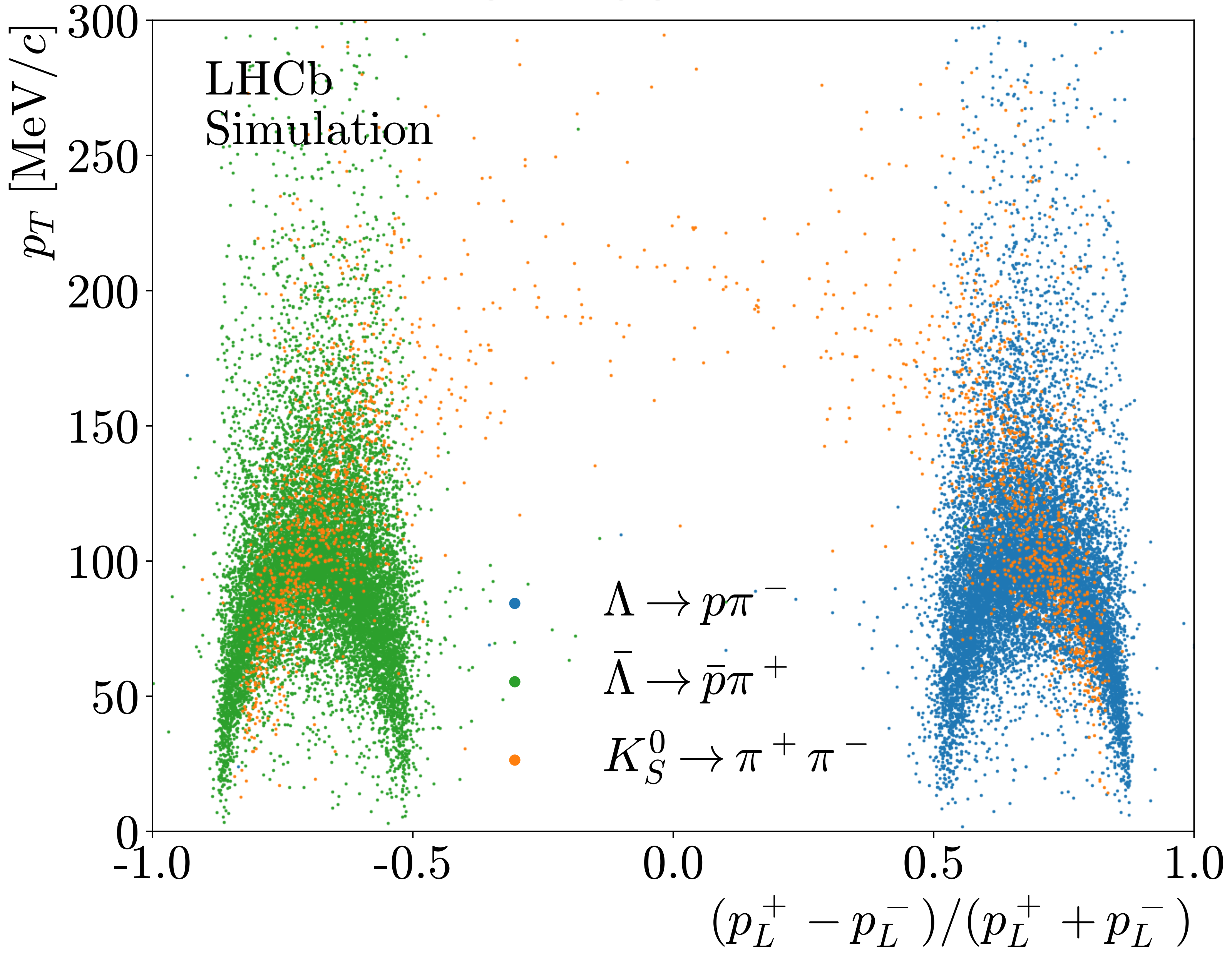
Feasibility

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



LHCB-FIGURE-2022-009

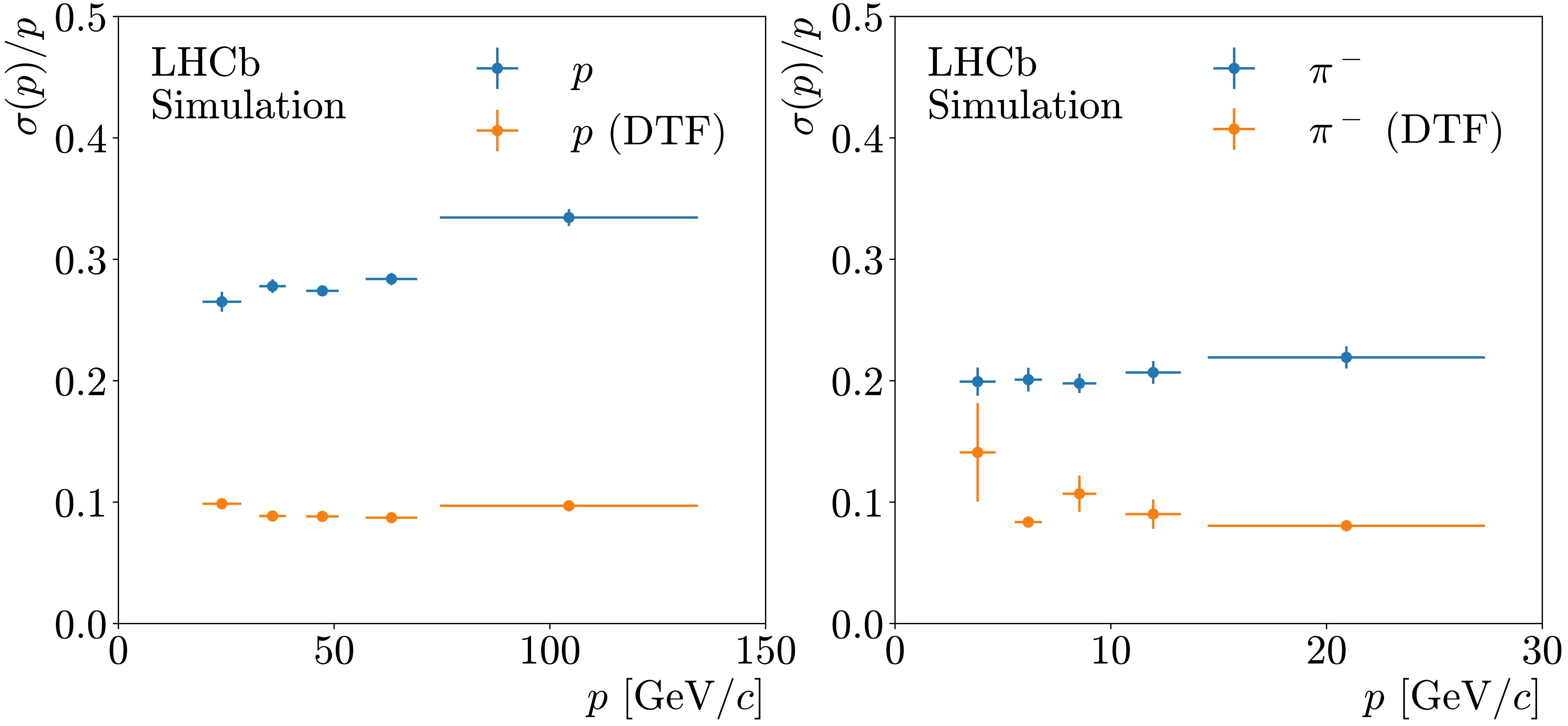
- $\Lambda \to p\pi^-$ and $K_S^0 \to \pi^+\pi^-$ have same topology
- Mass peaks are overlapping so not possible to distinguish through mass cuts → lower momentum resolution leads to lower mass resolution
- RICH2 PID is not available in Run-2 for T tracks
- Can instead be distinguished using Armenteros-Podolanski (AP) technique



Feasibility

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

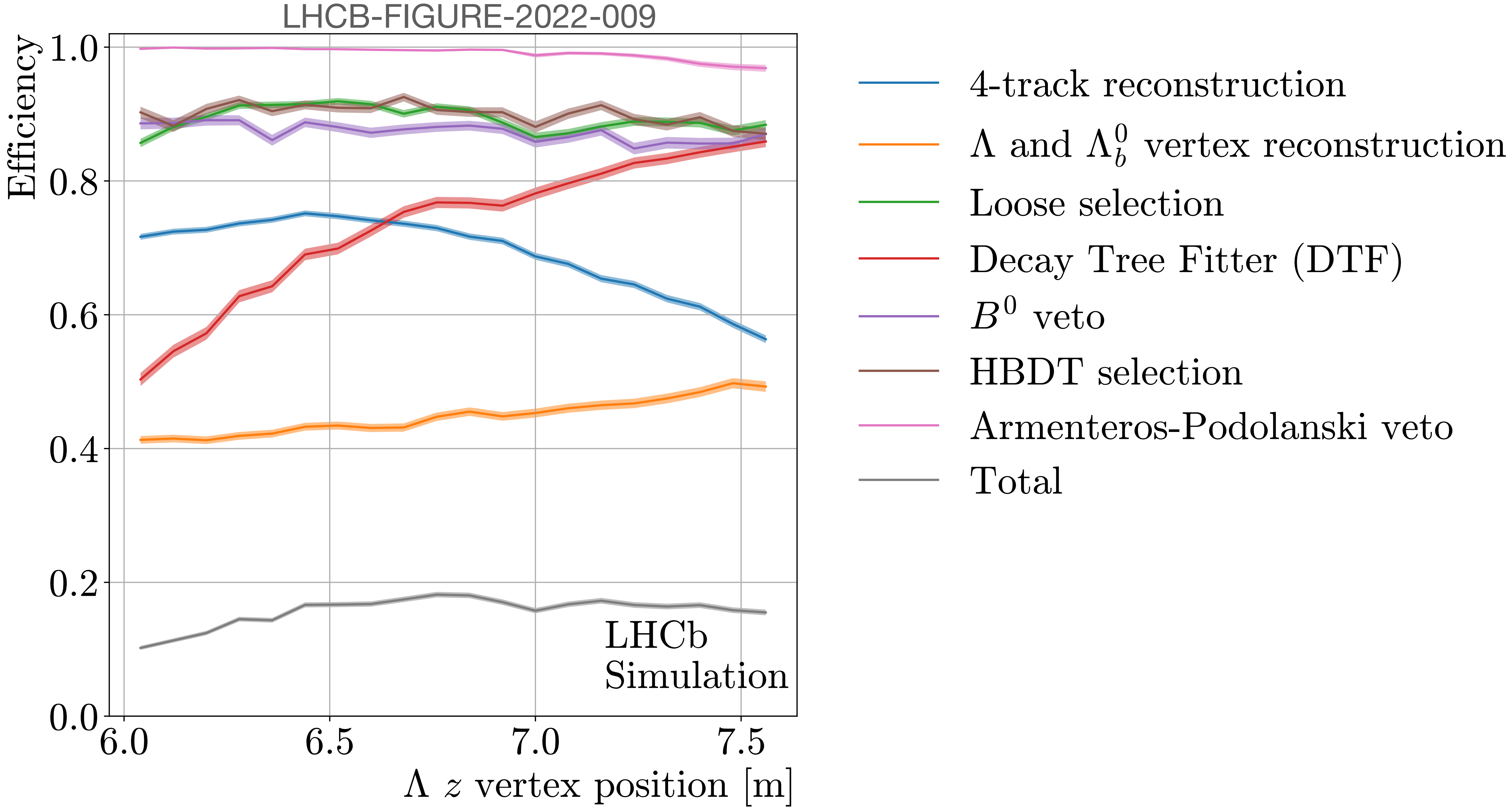
LHCB-FIGURE-2022-009



- 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

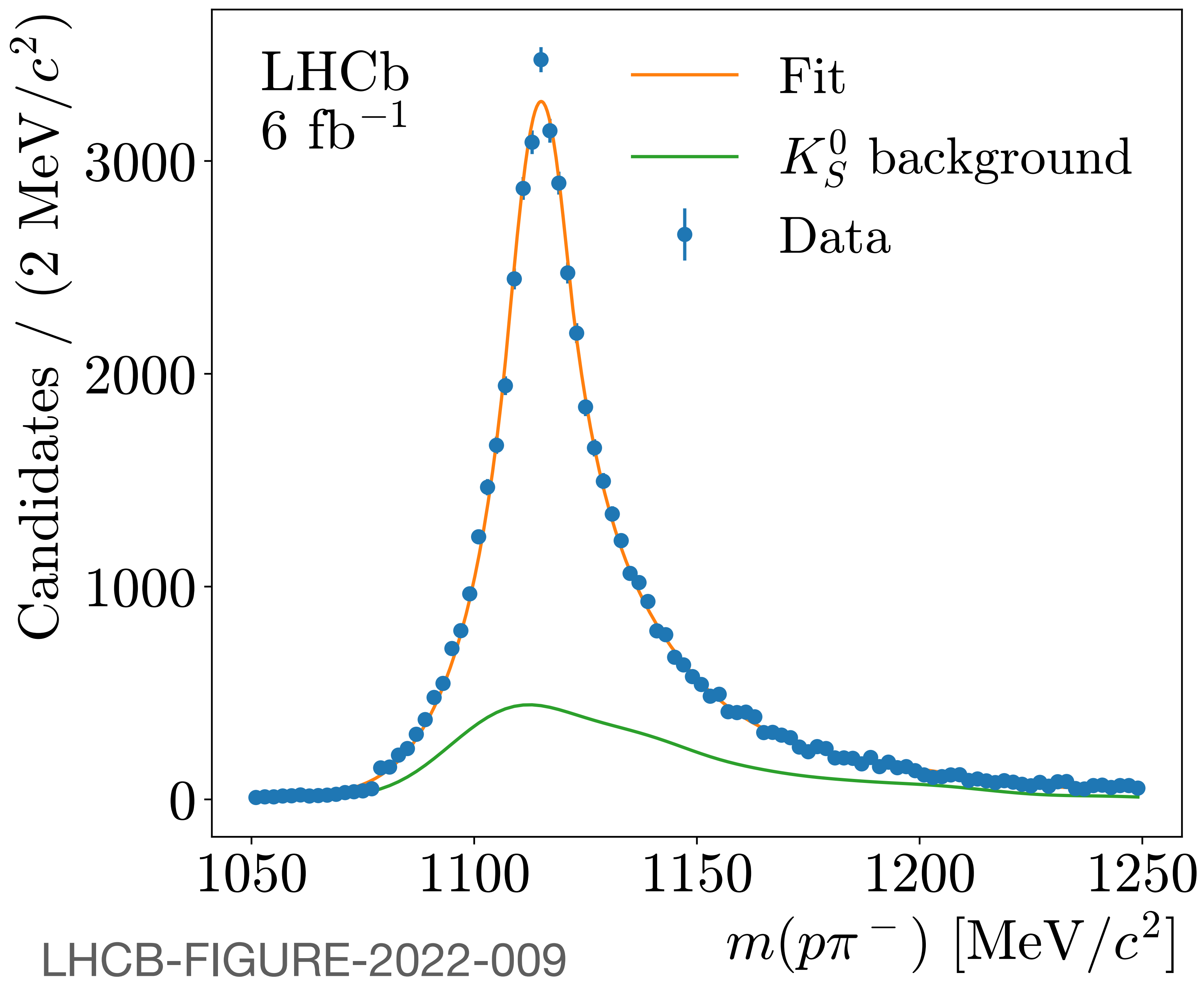
Efficiencies calculated wrt to reconstructible particles (i.e. within acceptance)

Low vertex reconstruction efficiency → investigating remedies (see Giorgia's talk)

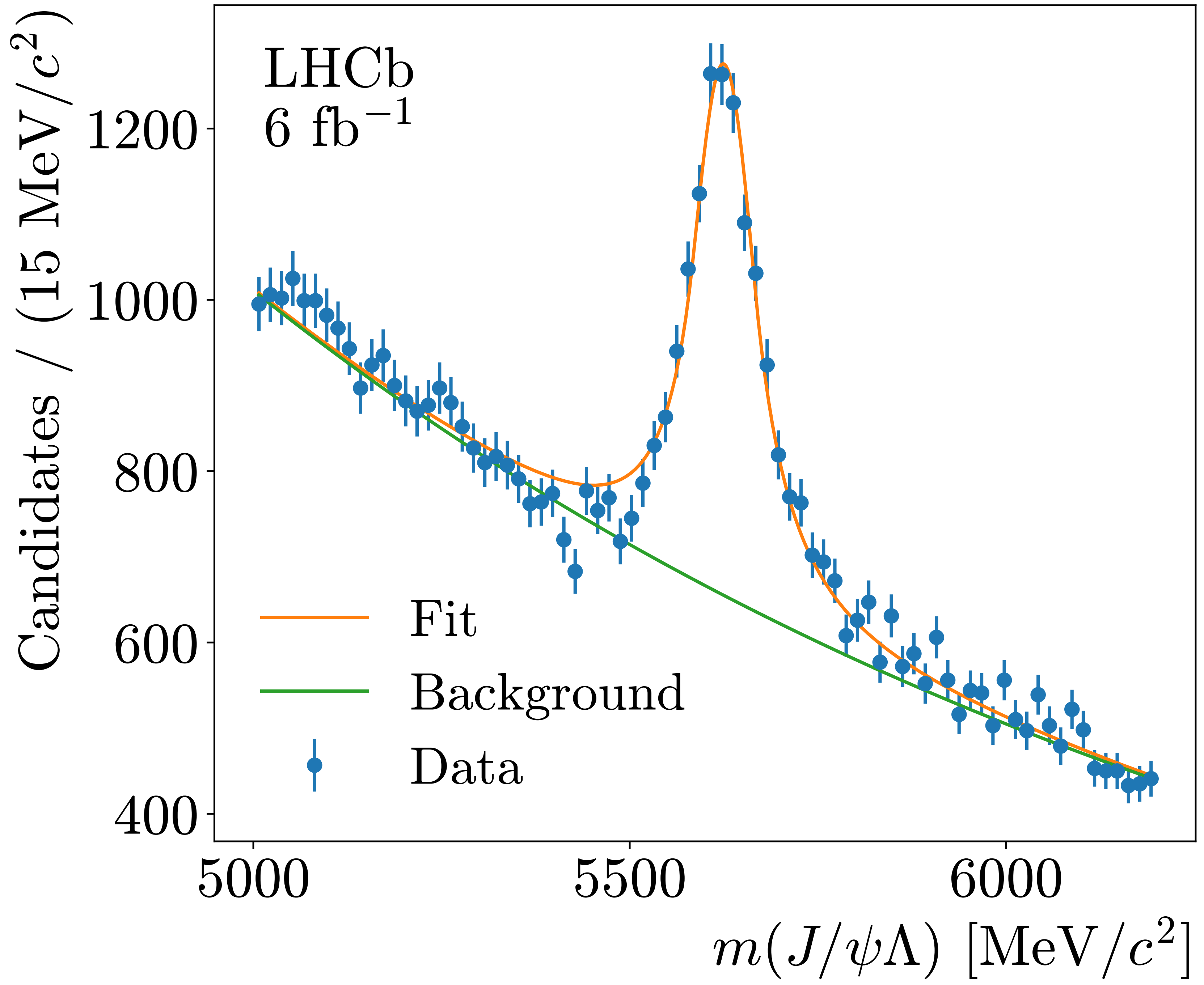
Feasibility

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

- 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



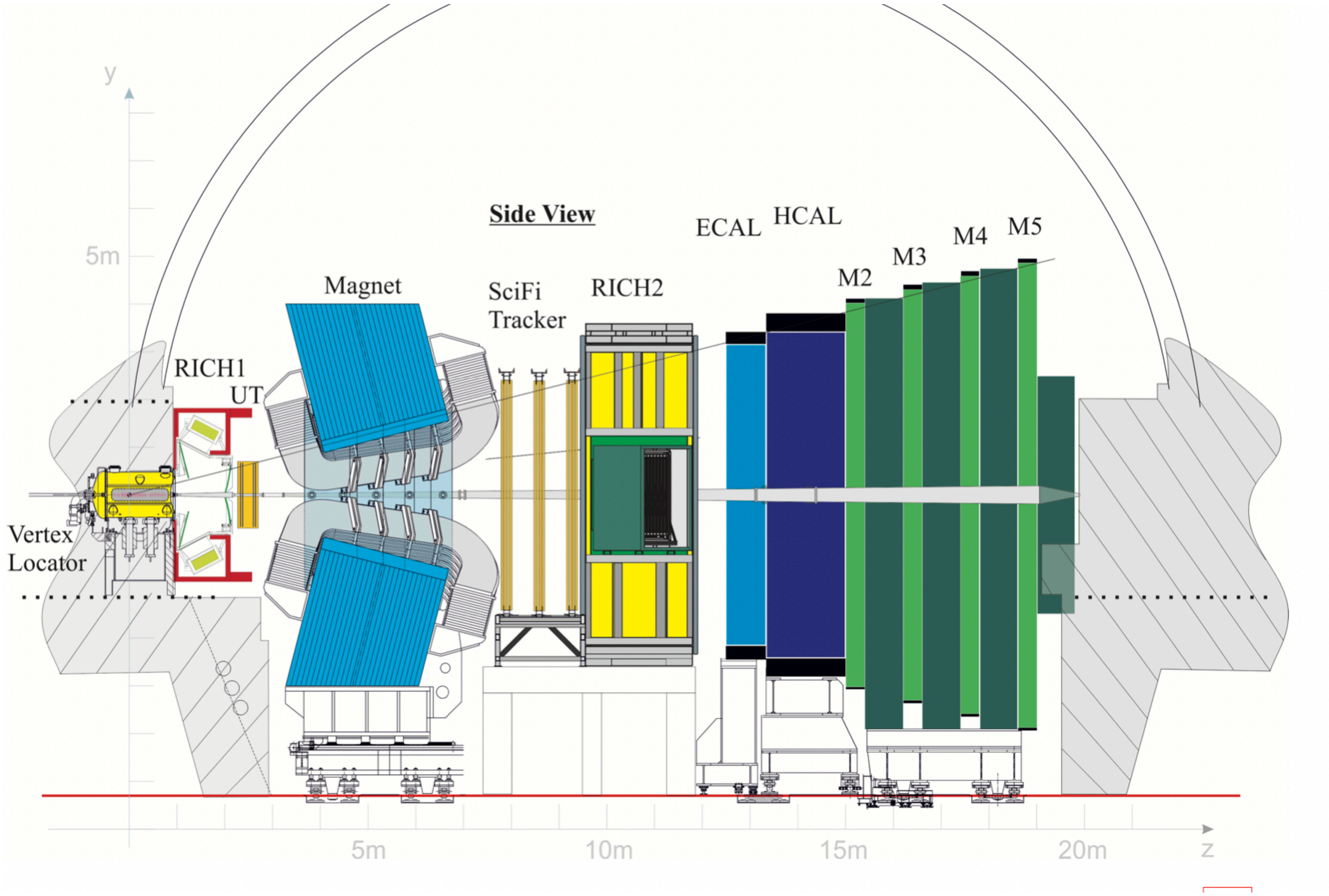
LHCB-FIGURE-2022-009



Run 3 reconstruction (WIP)

LHCb Phase-I upgrade

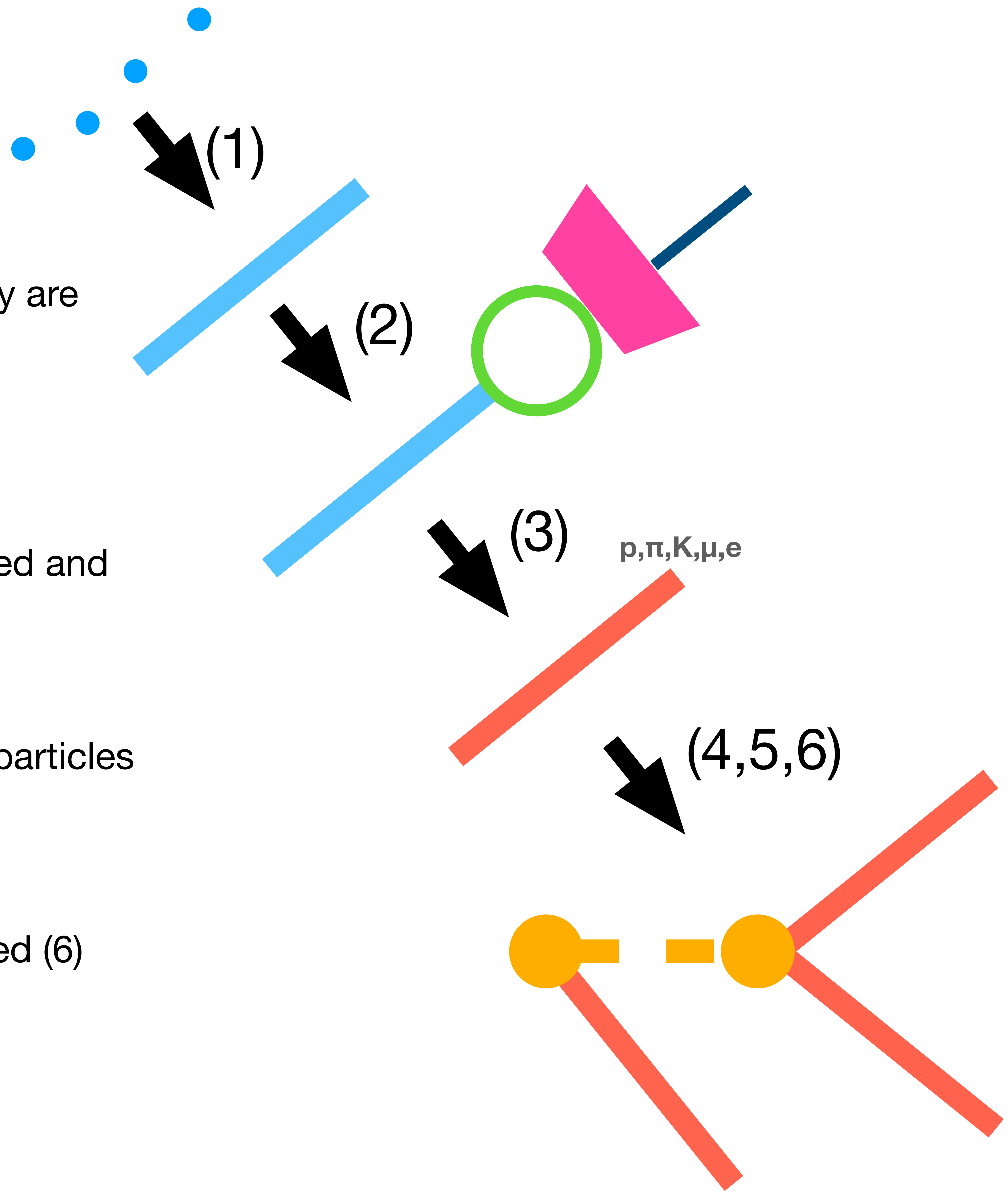
- Includes new trackers, vertex detector and electronics
  - New VELO, TT replaced by UT (Upstream Tracker), T1-T3 replaced by SciFi (Scintillating fibre) tracker
- **Fully software based trigger** will operate at an average pp bunch crossing **rate of 30 MHz**
  - Previously limited to ~1 MHz
- Partial reconstruction in HLT1 running on GPUs (Comput.Softw.Big Sci. 4 (2020), LHCB-TDR-021, 2020), reduces rates by a factor of 30-60 (see talk from Christina)
- Full reconstruction in HLT2 — events analysed and selected in real time



Source: LHCB-TDR-15

LHCb reconstruction chain

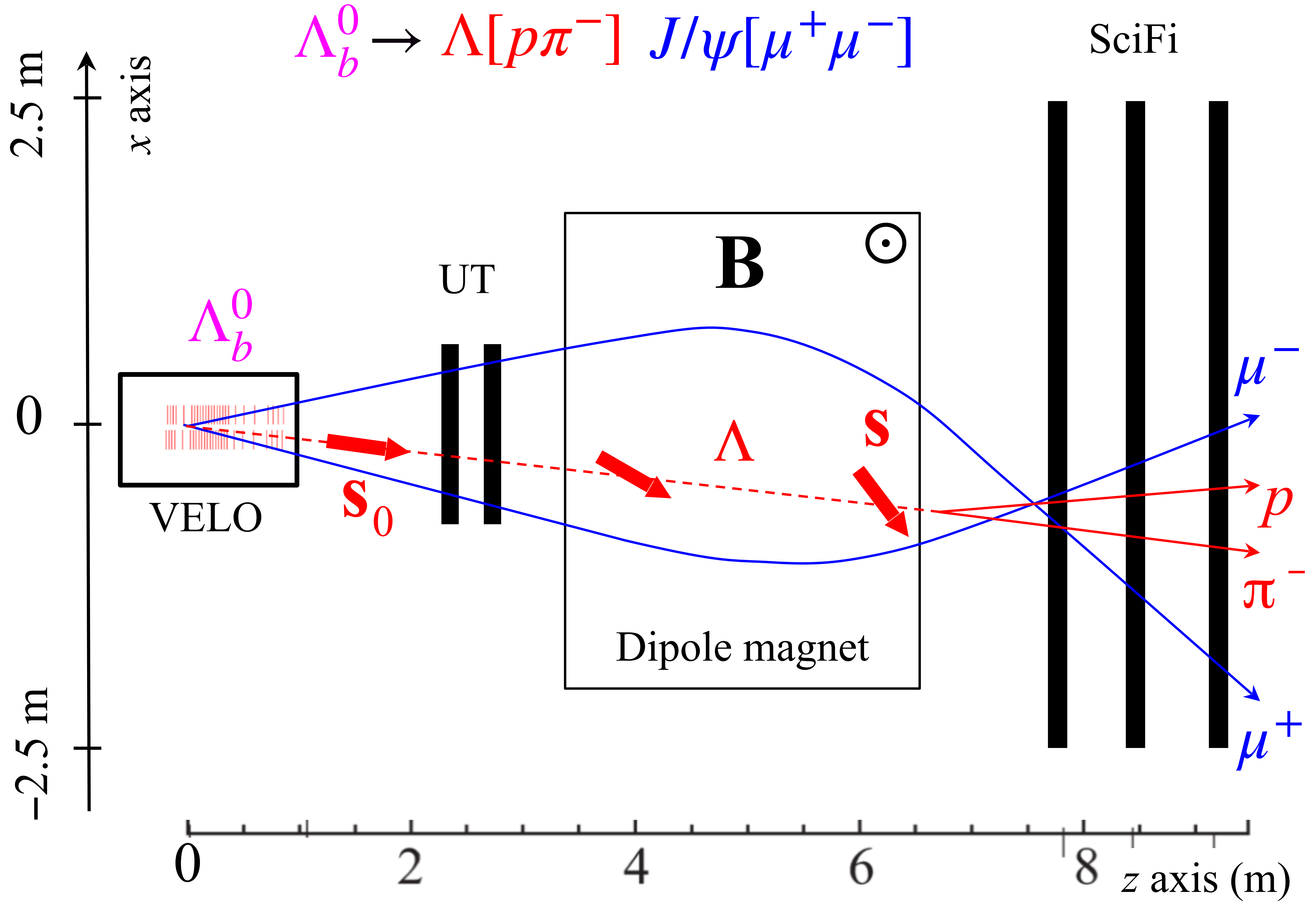
- For Run-3 events in LHCb are fully reconstructed in HLT2 — they are reconstructed and selected in real time
- This generally occurs as an iterative process:
  - Tracks are fitted and selected (1)
    - PID information from the various subdetectors is calculated and associated to the individual tracks (2)
      - Particle hypotheses are assigned (3)
        - Final state particles are combined into composite particles usually by vertexing (4)
          - Composite particles may then be combined (5)
            - Repeat until desired decay chain is combined (6)
- Primary vertices, neutrals also reconstructed
- Selections can be applied in each stage



$\Lambda_b \to \Lambda \to (p\pi)\ J/\psi(\to \mu\mu)$

Overview

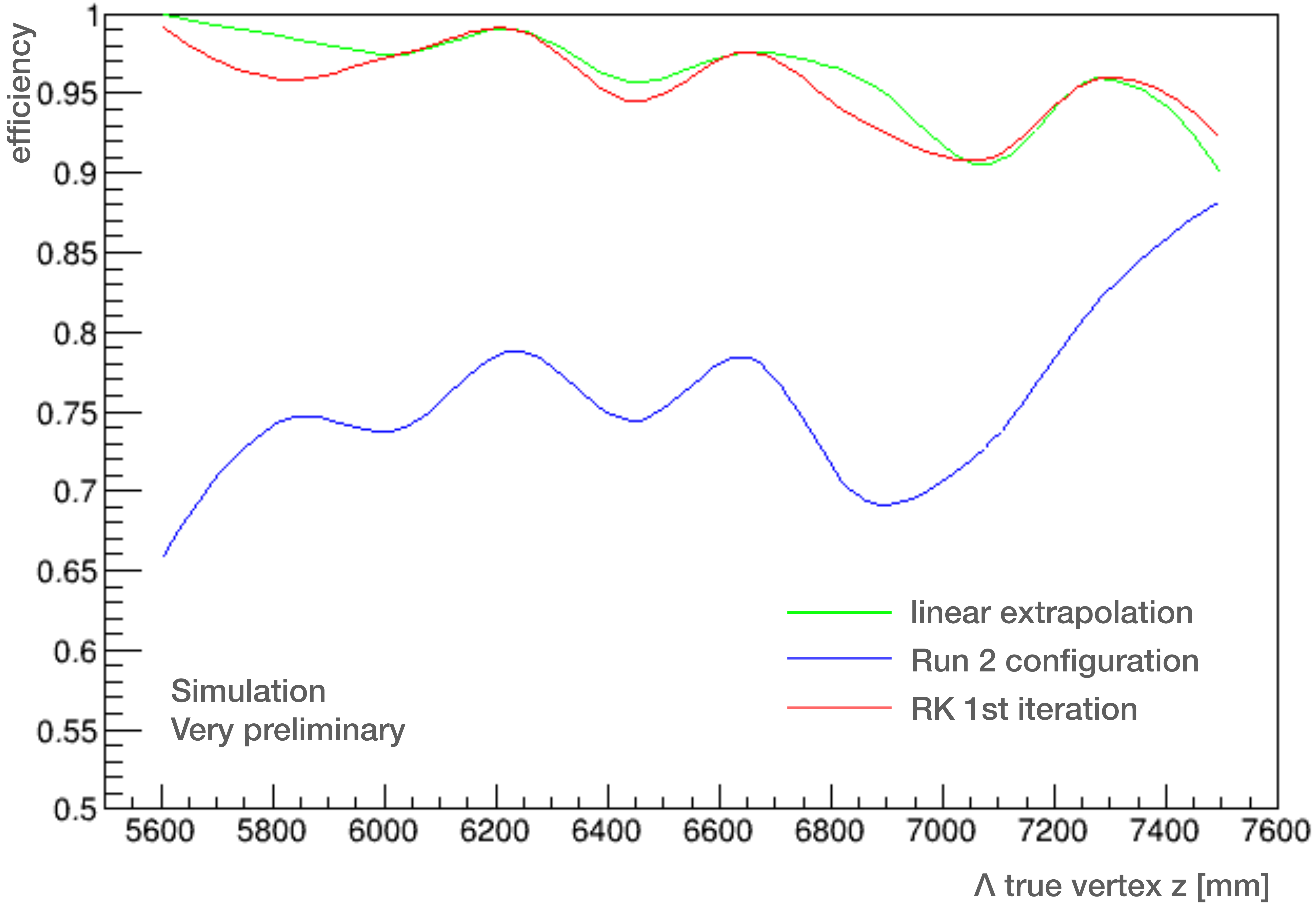
- Start by reconstructing detached J/ψ from muons
  - Helps to reduce rates
- Then filter T tracks based on kinematics
- Calculate PID information for remaining T tracks
- Select proton and pion candidates as all T tracks with RICH2 information available
  - See talk from Mengzehn about using RICH2
- Combine tracks into Lambda candidates
- Combine with J/ψ candidates into Λ_b candidates
- Challenge: build a pure and efficient trigger line
  - In this context background a positive decision in minimum bias interactions



Vertexing efficiency

Extrapolators

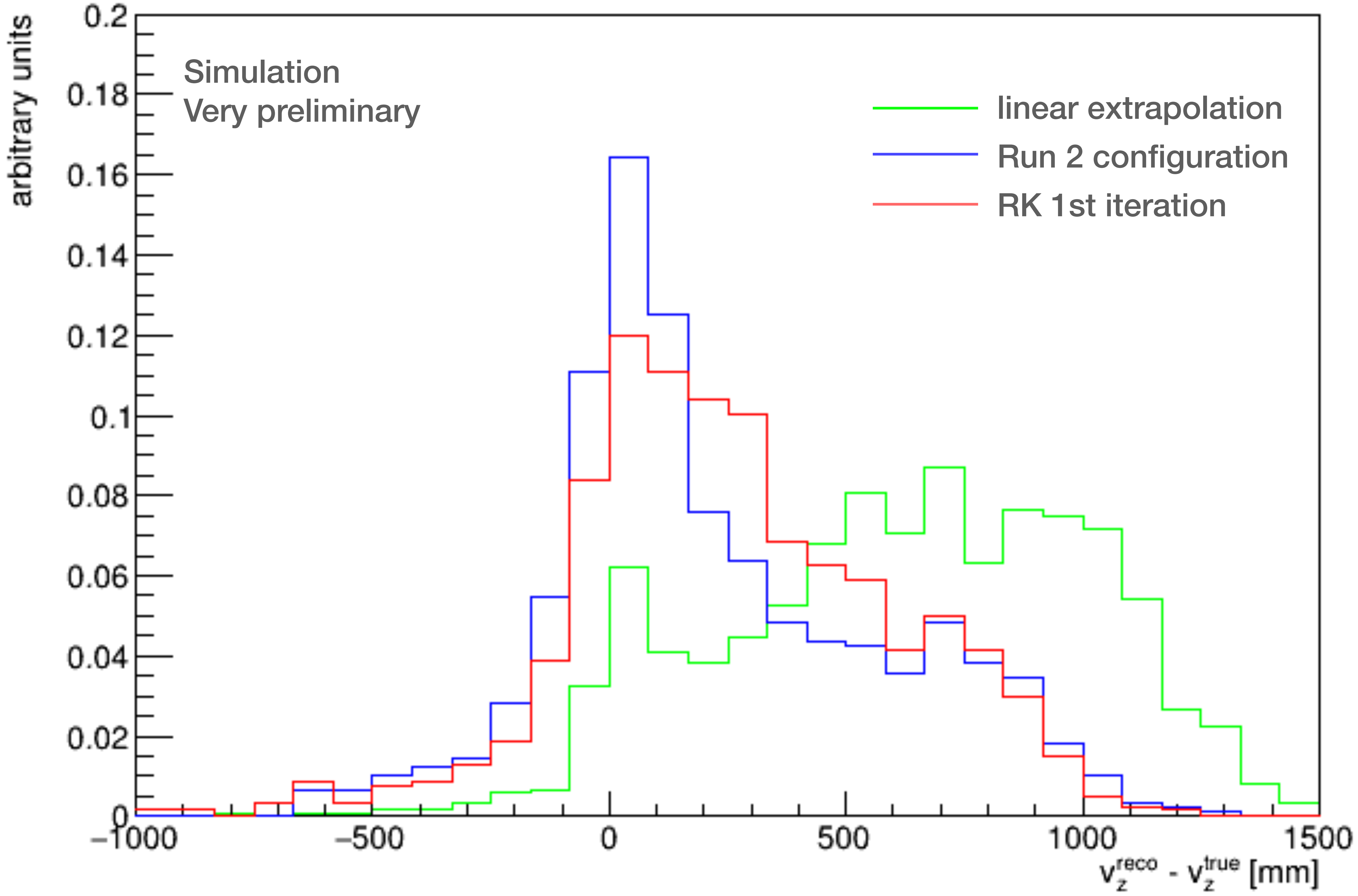
- Run 3 uses a new faster vertex fitter
- By default this does not support the Runge Kutta extrapolator (RK)
- Instead uses a linear extrapolation
- In the context of online selection is Runge Kutta required?
    - Tested with RK in first iteration of vertex fit, with linear extrapolation in subsequent iterations
    - Show Run 2 vertex fitter with RK in every iteration for comparison
    - Linear extrapolation shows highest selection efficiency



Vertex z bias

Extrapolators

- Without a RK extrapolation in each iteration the vertex position bias increases
- It tends to be pulled towards the SciFi detector
- This leads to very poor invariant mass distribution



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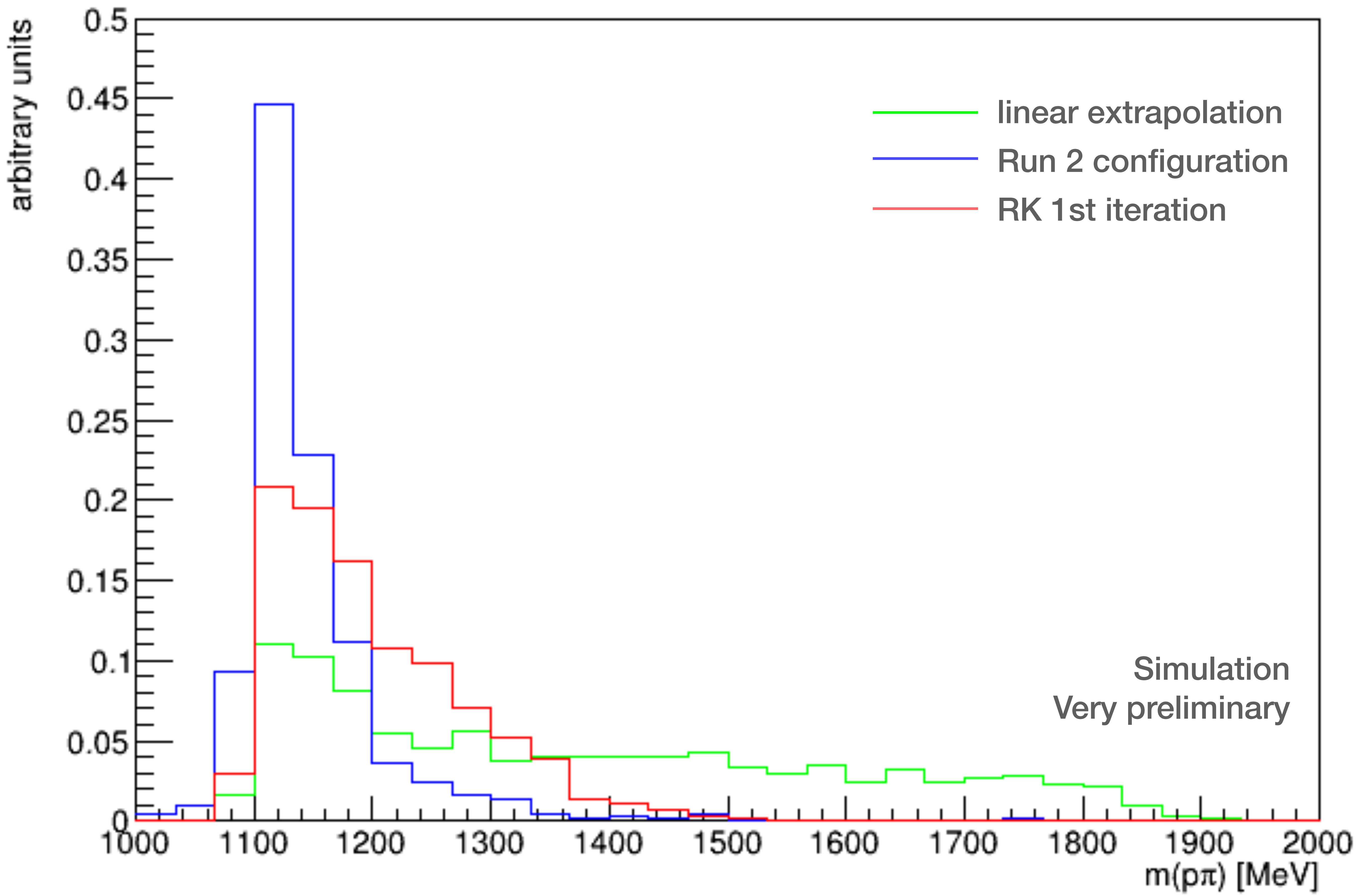
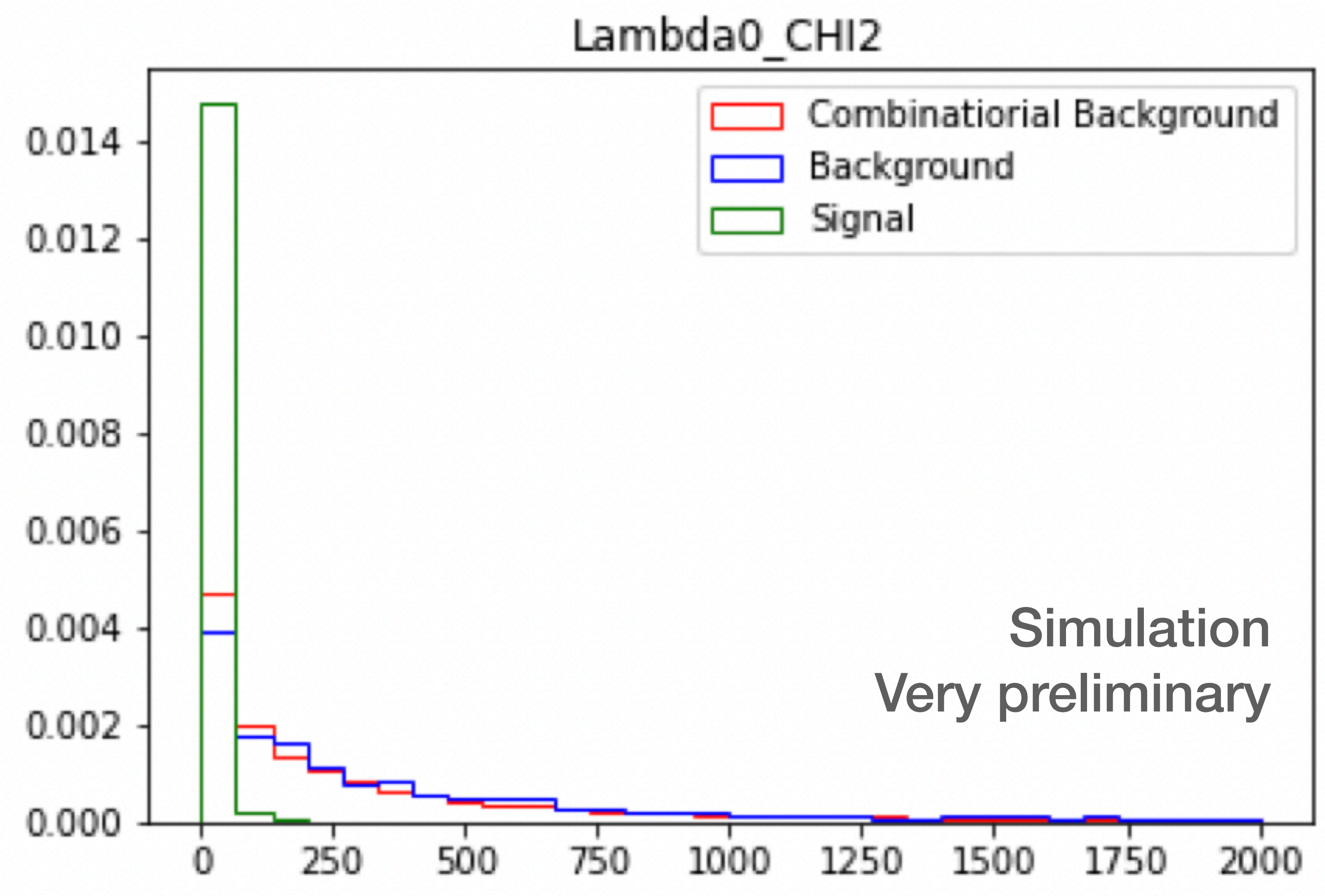
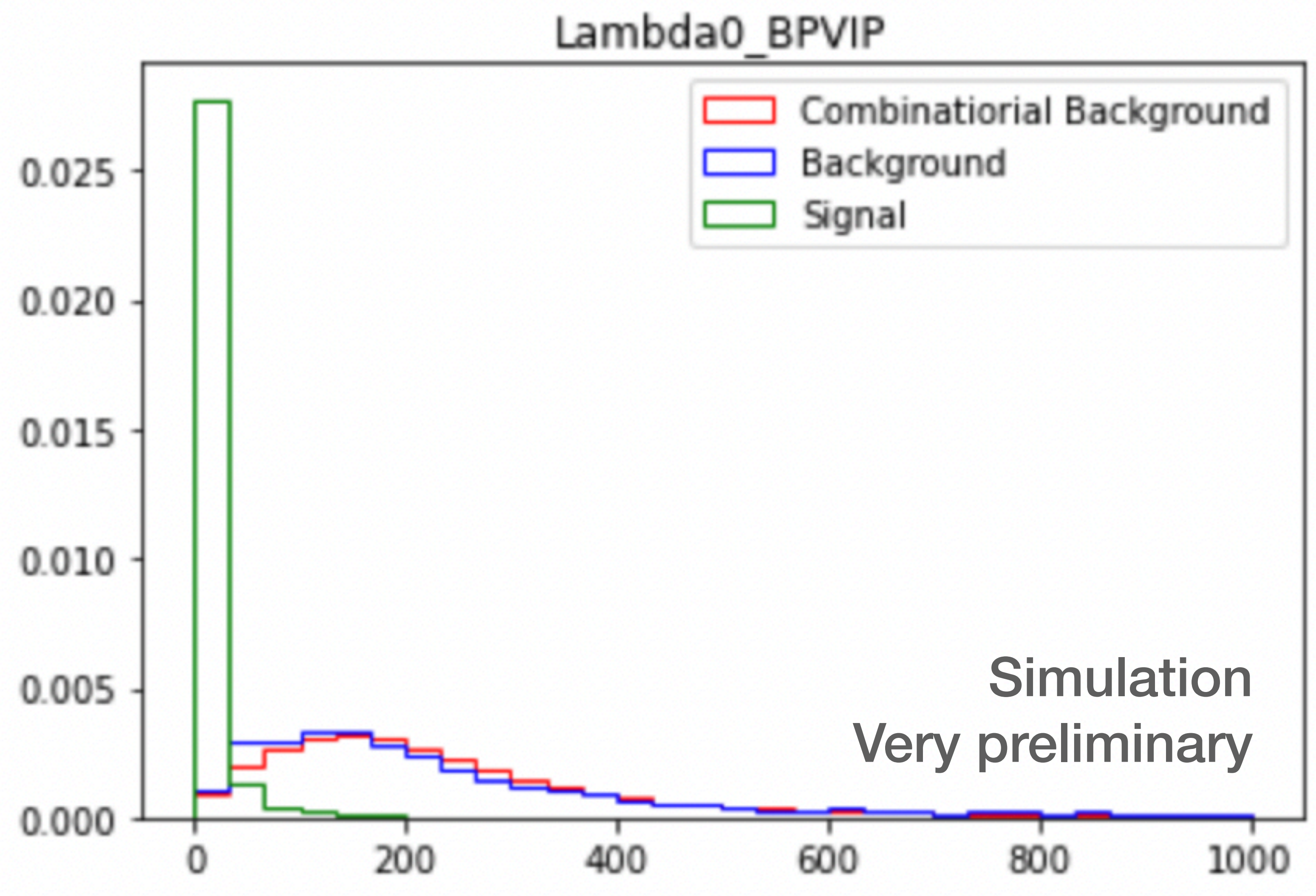


Selections

- The vertices provide enough discrimination with background across a range of parameters in spite of large biases
  - Is also constrained by J/ψ → μμ
- Estimate that with selections applied to tracks and vertices can constrain rates on minimum bias data to $\mathcal{O}(10)$ Hz
  - Without cutting on invariant mass or vertex position
- Linear or single RK extrapolation offers ~20% higher selection efficiency compared to Run 2 vertex fitter
- Proper extrapolation could be performed offline for analysis





Summary & outlook

- The physics reach of LHCb can be extended by reconstructing particles decaying downstream of the dipole magnet
  - Permits electric and magnetic dipole measurements
- 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
- These processes are being incorporated into LHCb's upgraded Run-3 HLT2 trigger

Backup

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)

PID information

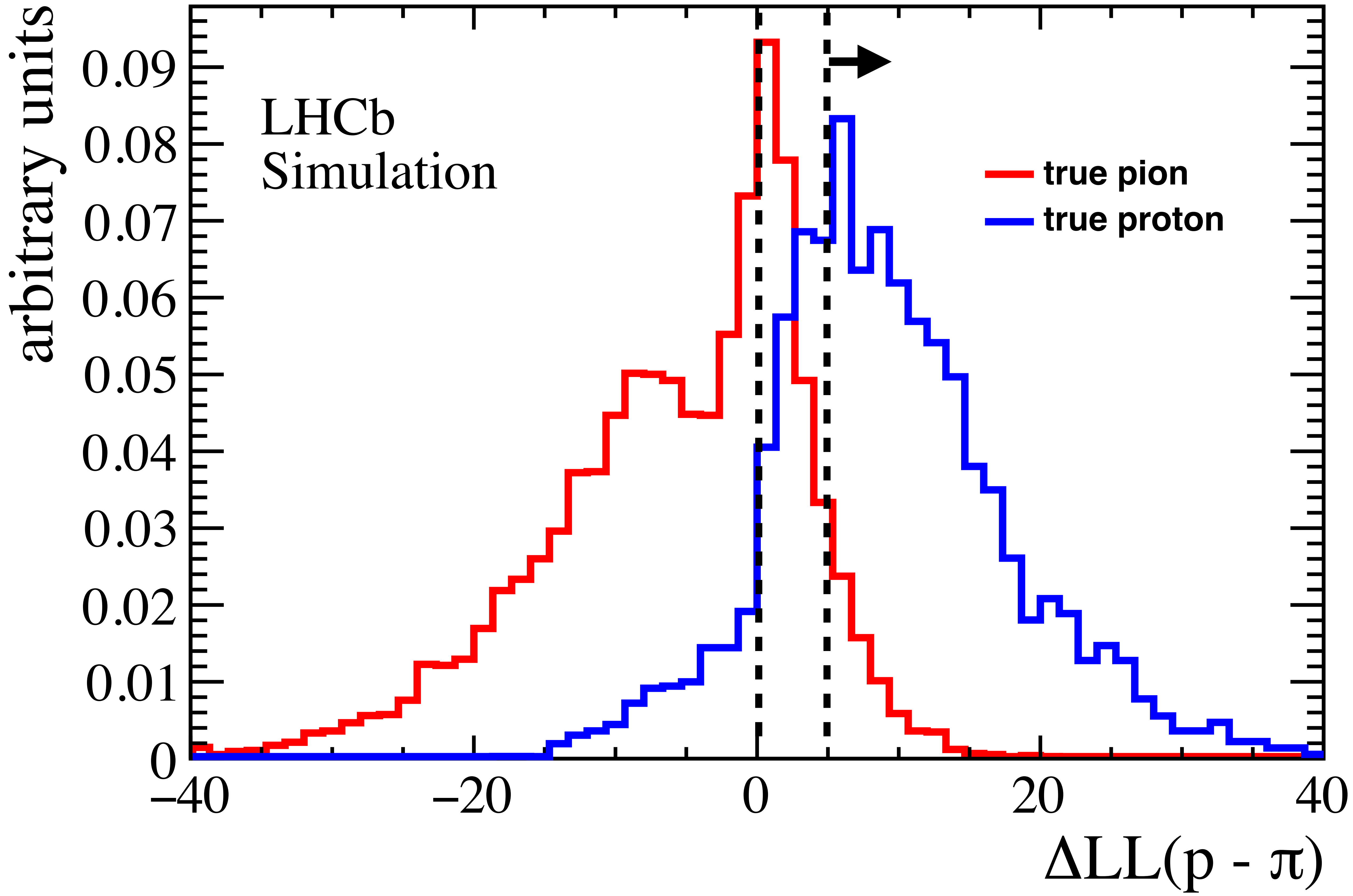
Overview

- PID information is calculated from three systems: the calorimeter, the RICH detectors and the muon stations
    - T tracks are located after RICH1 so this cannot be used
- The primary role of RICH is the identification of charged hadrons (p, K, π)
    - This reduces the combinatorial background and allows topologically identical processes to be distinguished, e.g. $\Lambda \to p\pi$ and $K_s \to \pi\pi$
- The calorimeters identify hadrons and electrons by matching energy deposits in the hadronic and electronic calorimeters to tracks
- Tracks in muon stations are matched to tracks from the tracking system to identify muons
- This information is not calculated for T tracks in Run 2, but will be calculated in Run 3
- Global PID values are calculated by combining the information from the three detectors as a ΔLL wrt pion hypotheses

PID information

Combined ΔLL

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 and calorimeter info in Run 3 MC. RICH2 info was not added to T tracks in Run-2.