Tracking long-lived particles at LHCb with the new software trigger

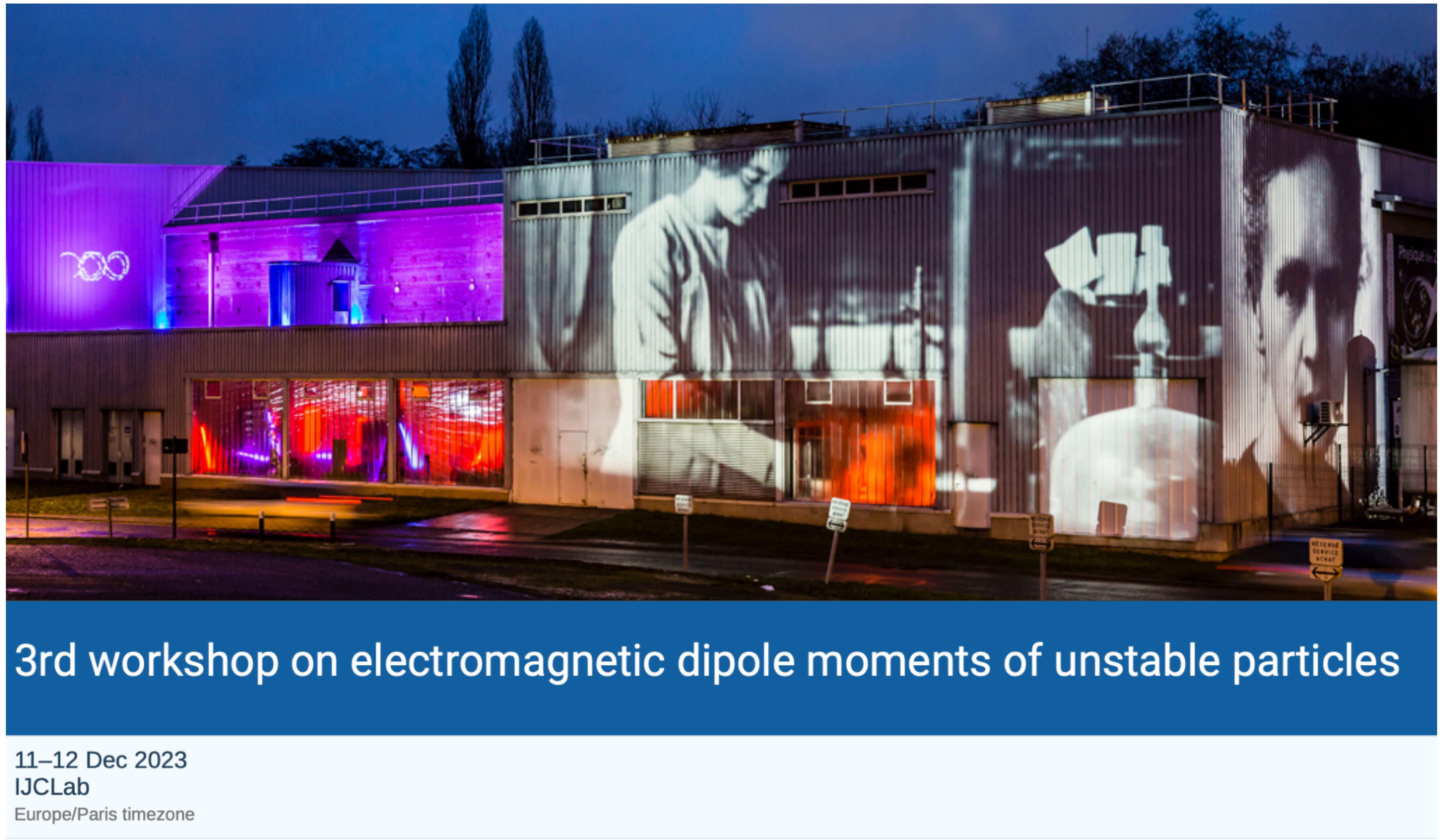
Izaac Sanderswood on behalf of the group

11/12/23 | 3rd workshop on electromagnetic dipole moments of unstable particles

Tracking long-lived particles at LHCb with the new software trigger

Overview

- LHCb detector
- Trigger and tracking
- Long-lived particle vertex finding and fitting in HLT1
- Long-lived particle vertex finding and fitting in HLT2
- Topological track filtering
- Applications to strangeness physics
- Applications to BSM searches
- Conclusion

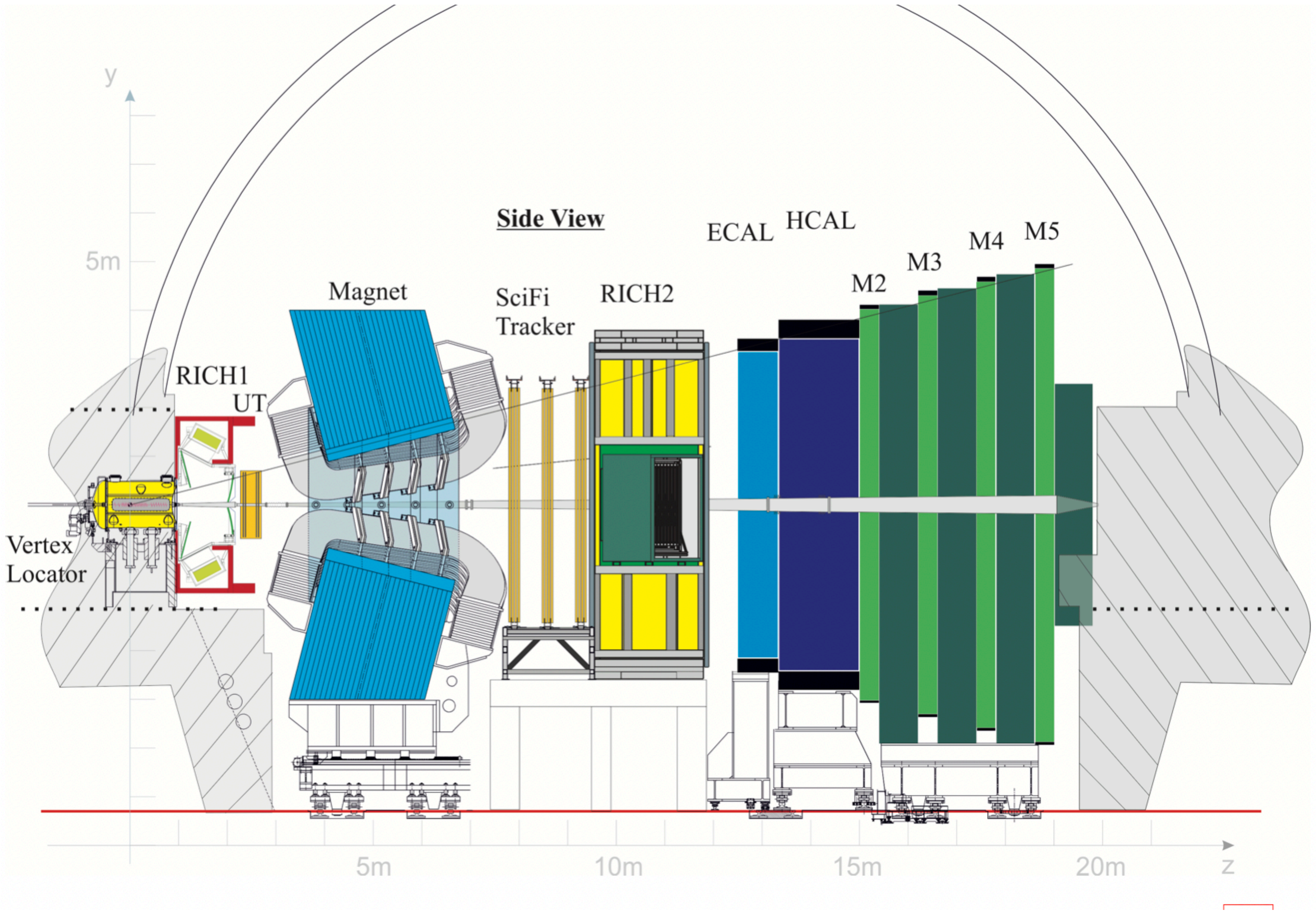


Introduction

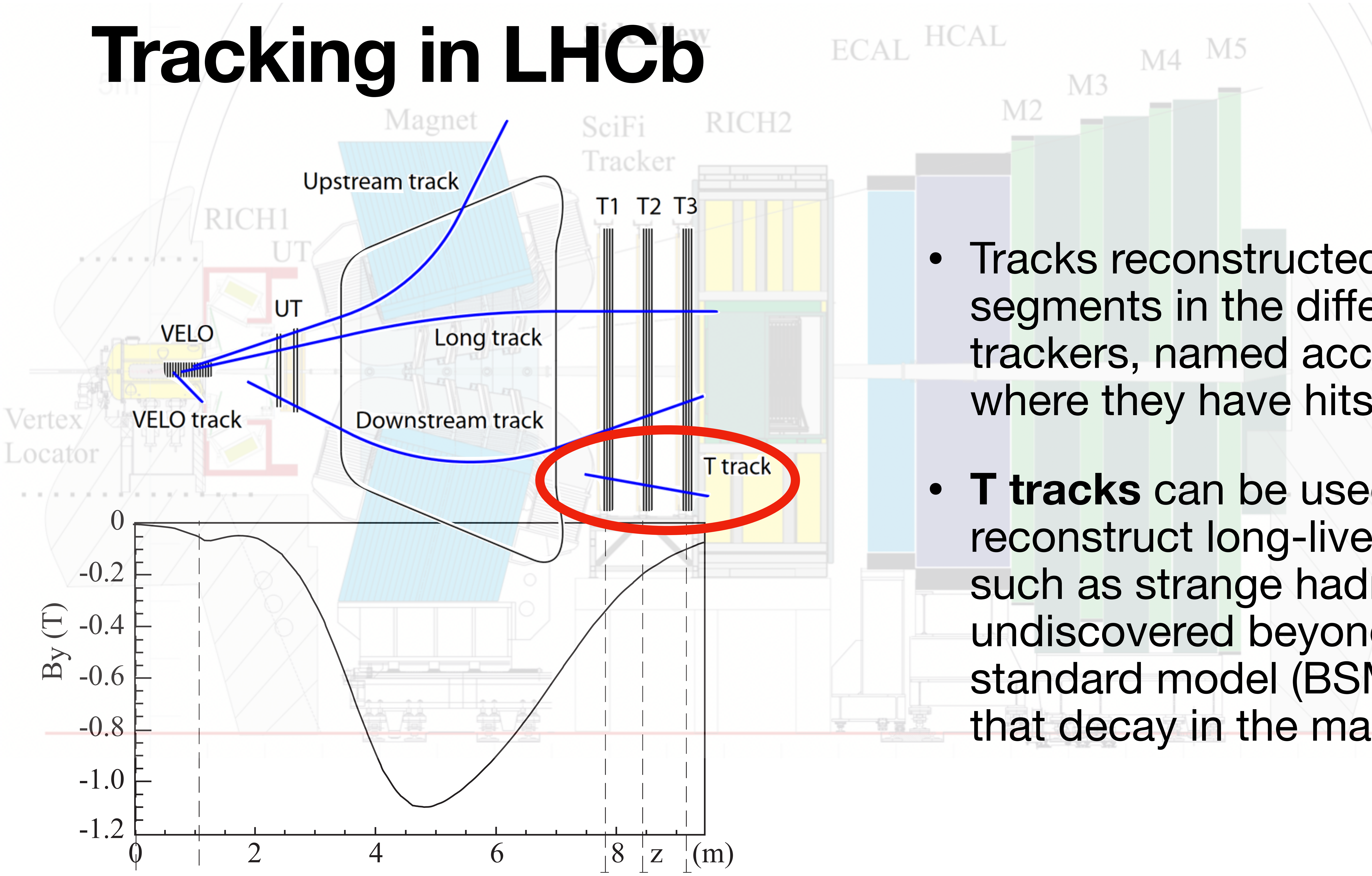
- The LHCb detector is optimised for the study of *b*- and *c*-hadron decays, with a physics programme extending beyond this
- New types of decays can be studied thanks to the switch to a fully software-based trigger from Run 3 onwards
- This presents opportunities in particular for strangeness physics and searches for undiscovered particles, which may decay far from the interaction point
- By reconstructing decays in the region of LHCb's dipole magnet, the fiducial volume available for decays increases by around four times compared to only considering decays before the magnet, and the decays can be used for EDM/MDM measurements
- In order to trigger on these signatures, new techniques must be developed with a focus on throughput and bandwidth

LHCb

- Forward arm spectrometer, $2 < \eta < 5$
- Particle tracking system is comprised of:
  - Silicon pixel vertex locator (VELO) around the interaction point
  - Silicon-strip upstream tracker (UT) in front of the large-aperture dipole magnet
  - Three scintillating fibre tracker (SciFi Tracker) stations downstream of the magnet
- Particle identification (PID) is provided by:
  - Two ring imaging Cherenkov detectors (RICH1 and RICH2) located upstream and downstream of the magnet respectively
  - Electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)
  - Four stations of muon chambers (M2-5).



Tracking in LHCb

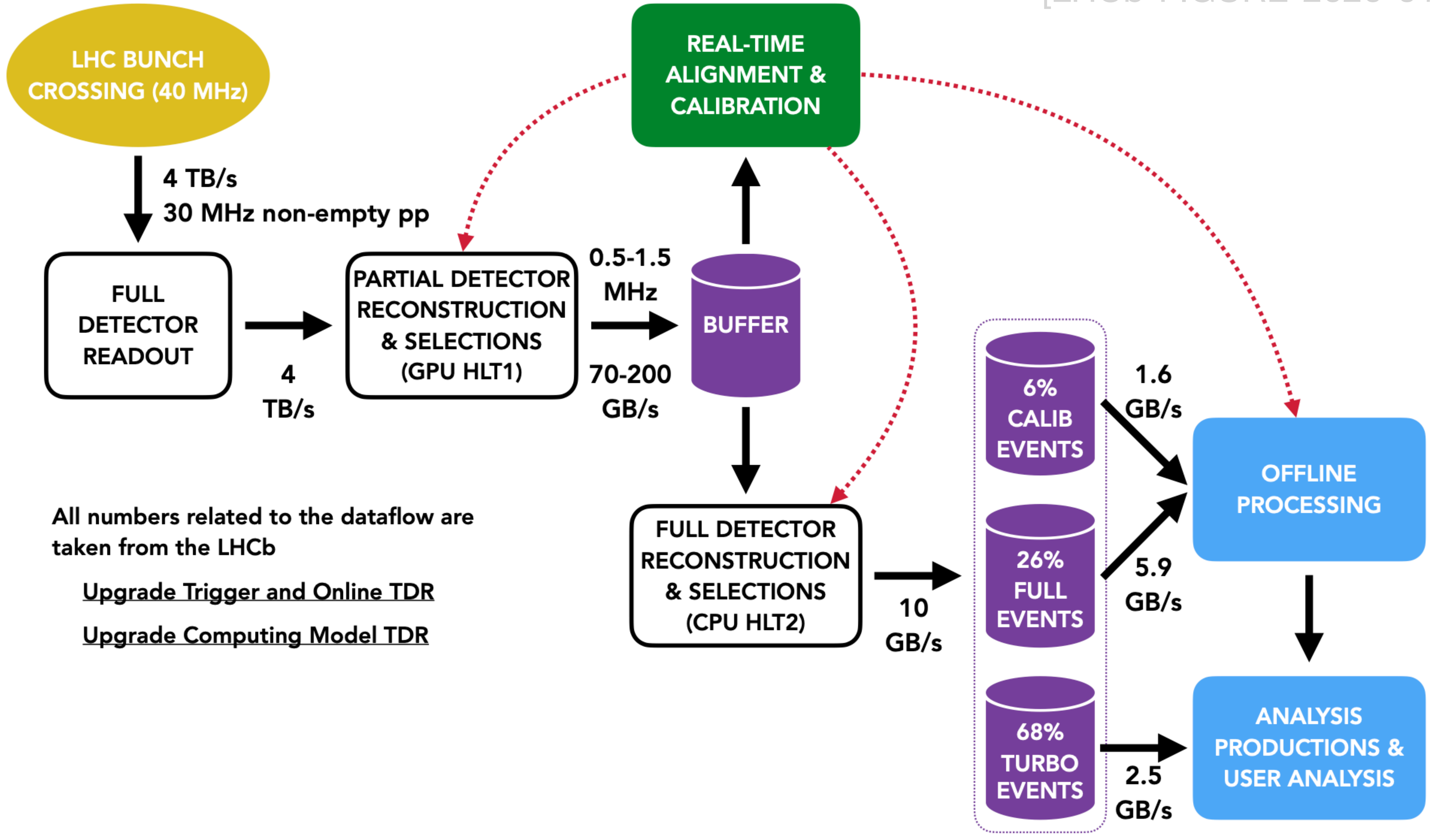


- Tracks reconstructed from segments in the different trackers, named according to where they have hits
- **T tracks** can be used to reconstruct long-lived particles such as strange hadrons, or undiscovered beyond the standard model (BSM) particles, that decay in the magnet region

LHCb trigger

- For Run 3 LHCb has removed its hardware trigger
- Two-level software trigger: HLT1 (GPU) and HLT2 (CPU)
- Reduces data volume from 4 TB/s to 10 GB/s
- HLT1 provides a simplified reconstruction to reduce event rate by a factor 20
- HLT2 provides a full offline quality reconstruction to select signatures and reduce event rate by another factor 20
    - In general, only reconstructed objects belonging to the decay signature are persisted → Real Time Analysis (RTA) of data

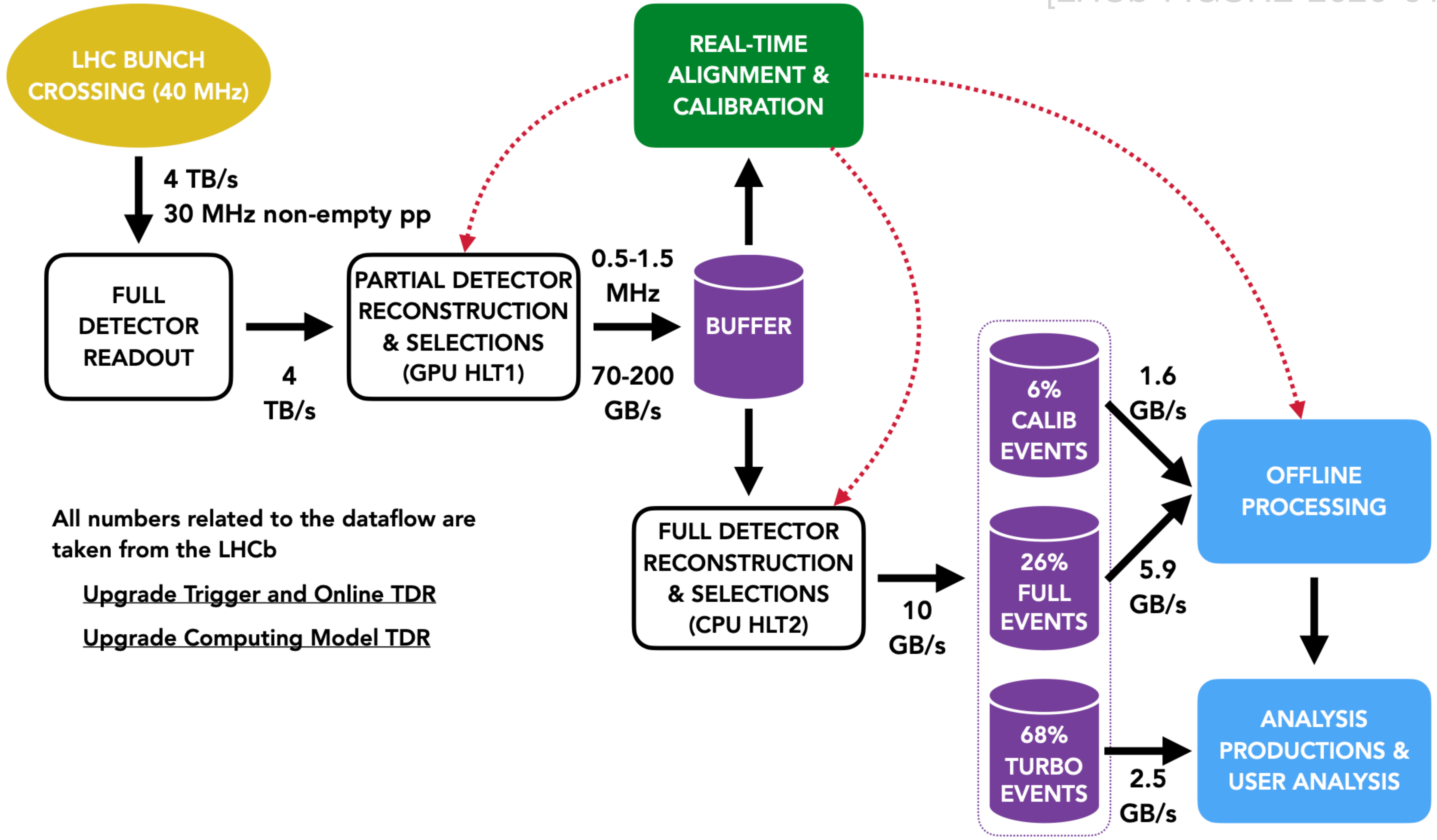
[LHCb-FIGURE-2020-016]



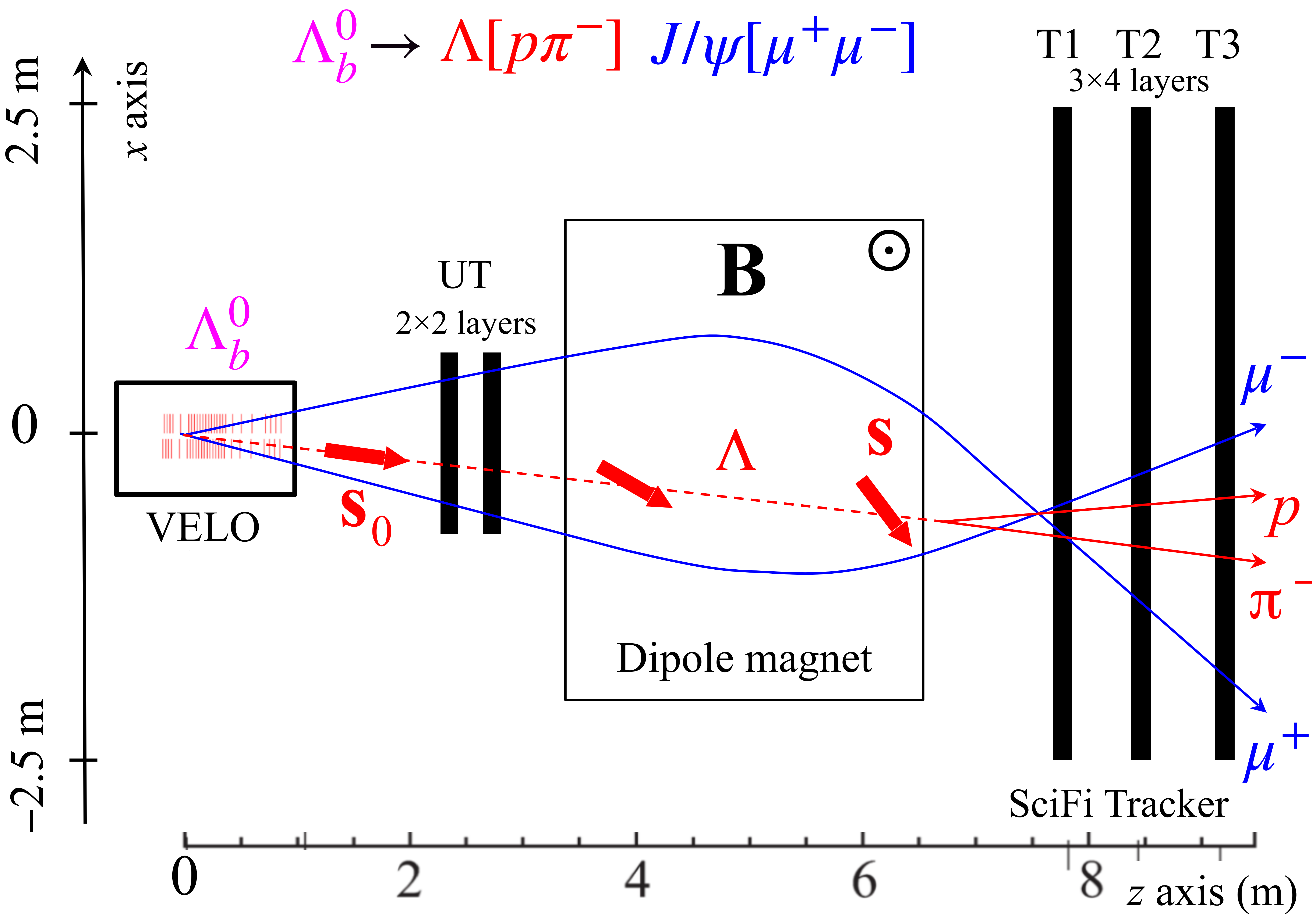
LHCb trigger

- Algorithms and selections must meet strict throughput (events processed per unit time) and bandwidth (size of output data) requirements
- In particular, for decays in the magnet region there are three primary challenges which must be addressed:
    - Poor track momentum resolution
    - Extrapolation of trajectories through a strong, inhomogeneous magnetic field
    - Large track combinatorics

[LHCb-FIGURE-2020-016]

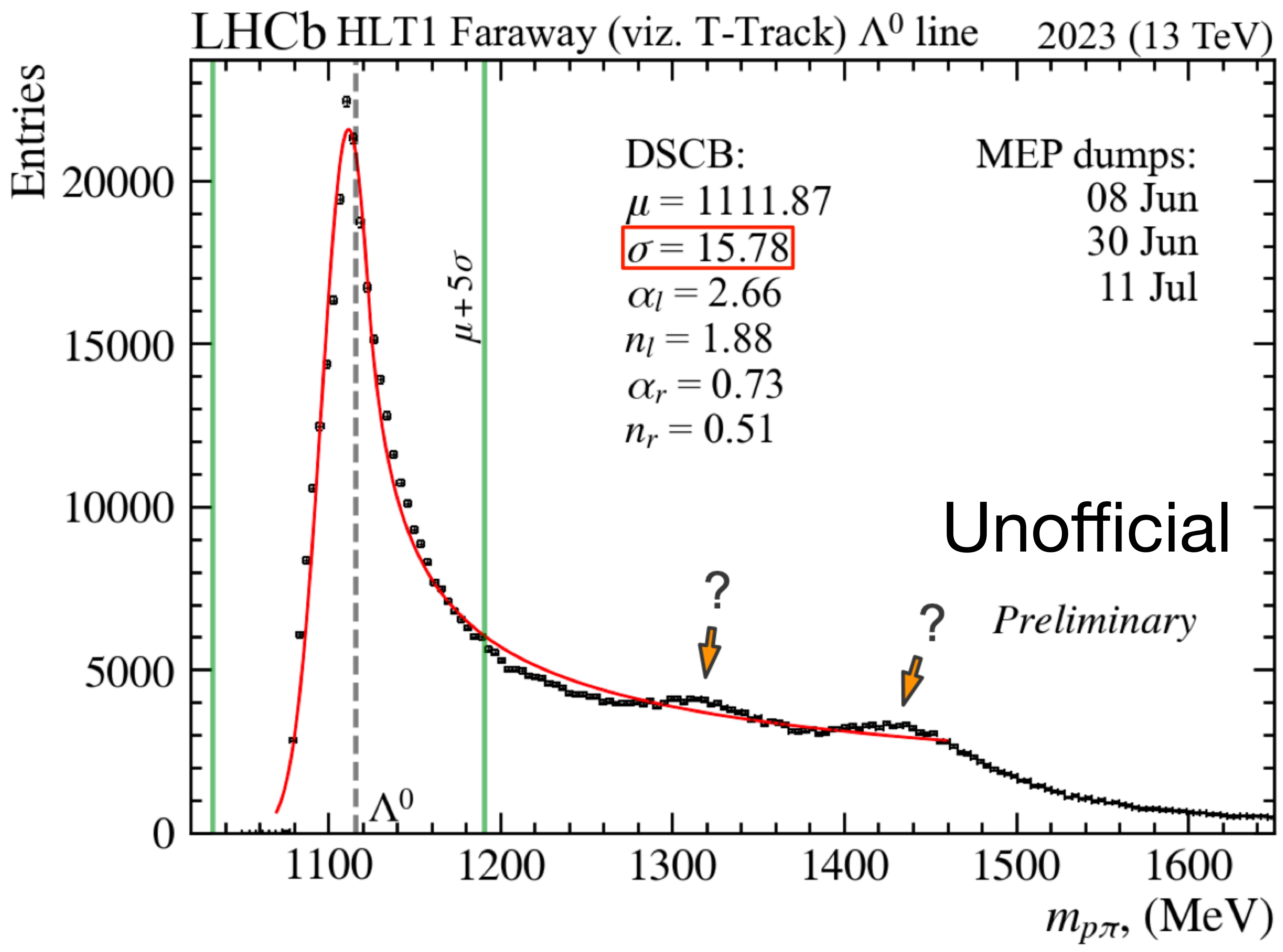


Event topology



HLT1 T tracks

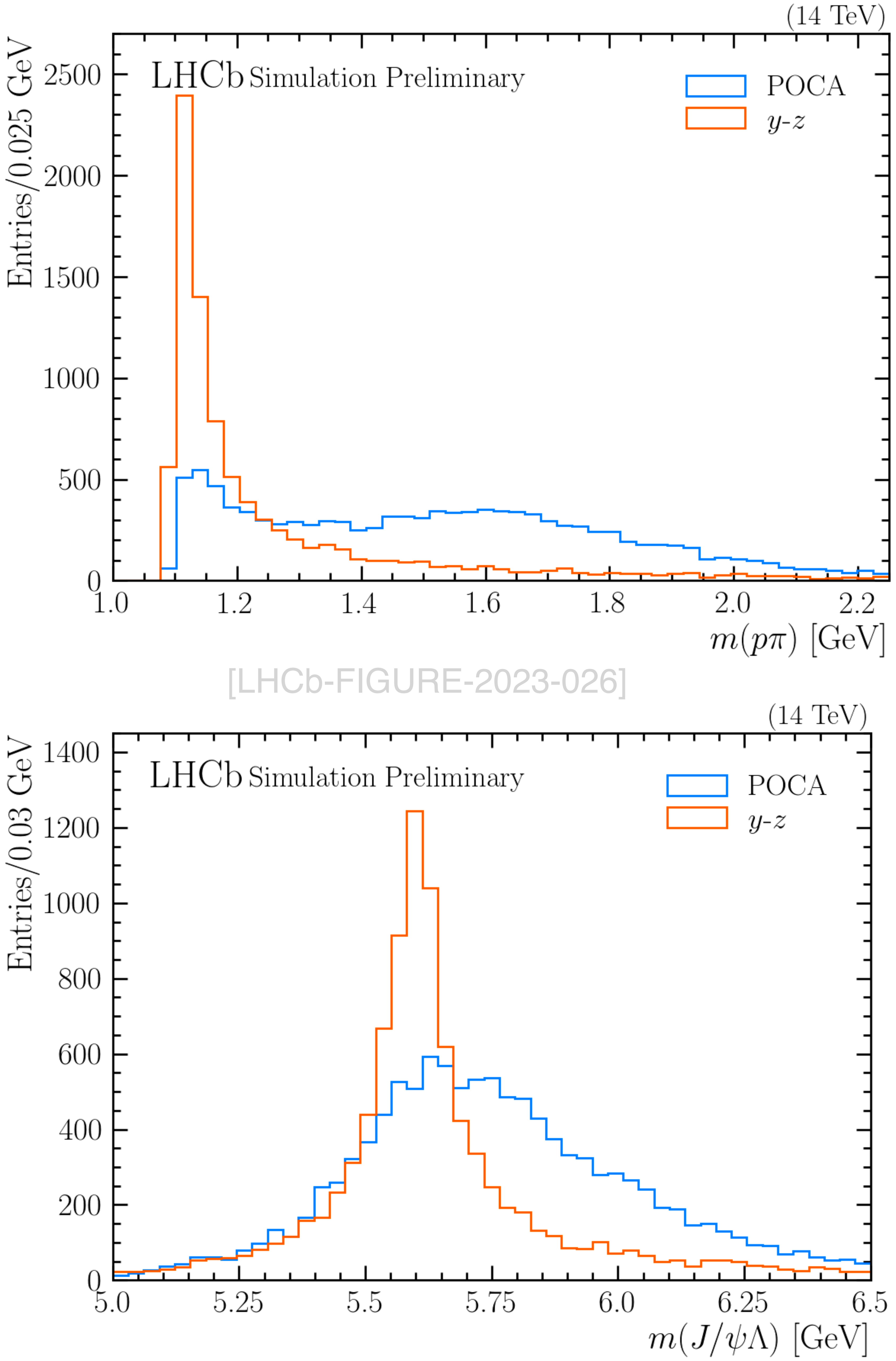
- Runs on remaining SciFi segments after Long and Downstream track matching
- Preselection of tracks from geometrical considerations
- Uses empirical extrapolation track model with parametrisation obtained from simulation to fit vertices
- Events selected using a neural network that uses quality and kinematical variables of daughter tracks and vertex as input
- Reduces throughput by around 1.5%
- WIP



Extremely displaced vertex finding and fitting

HLT2

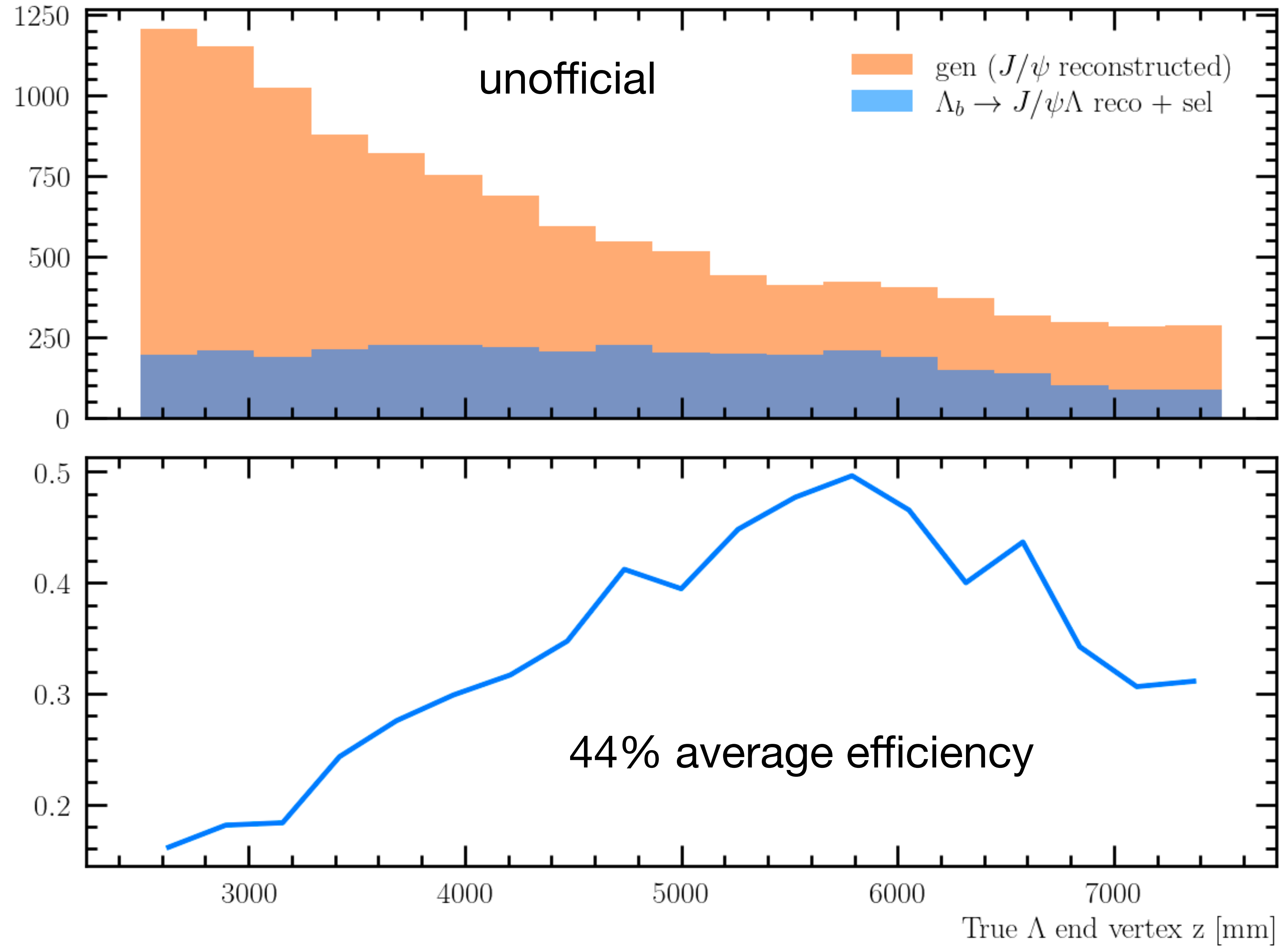
- Flexibility of HLT2 can be exploited to require clear signature in signal decay reconstructed first to control throughput (e.g. $J/\psi \to \mu\mu$)
- Narrow opening angle of Λ and K_S^0 decay products used to reduce combinations in place of mass cuts
- Exploit linearity of tracks in *y-z* plane to reject track pairs that do not cross in the magnet region
- For vertex fitting, use detailed 5th-order Runge-Kutta extrapolation in first iteration, polynomial interpolation after as compromise between timing and accuracy
- Mass resolution dramatically improved by using *y-z* intersection instead of default point-of-closest approach (POCA) for vertex seed
- Further optimisations being investigated to simplify extrapolator to improve speed
- Mass resolution can be further improved by offline fitting

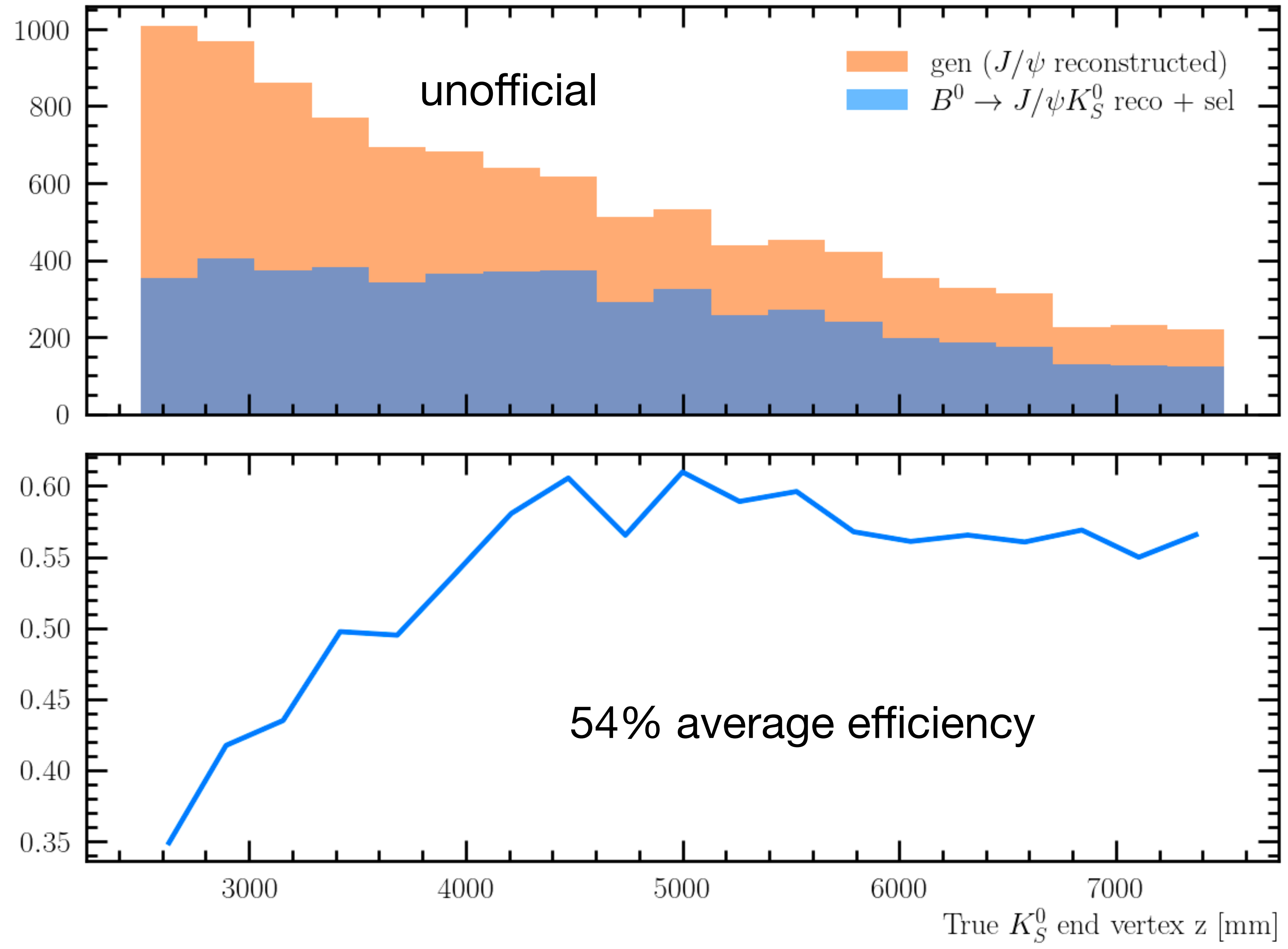


[LHCb-FIGURE-2023-026]

Extremely displaced vertex finding and fitting
HLT2

- Output rates $\mathcal{O}$(10 Hz) after vertexing T track and Long track combinations
- Currently deployed in trigger for $\Lambda_b^0 \to J/\psi\Lambda$, $B^0 \to J/\psi K_S^0$, $J/\psi \to \Lambda\overline{\Lambda}$ decays
- Efficiencies shown after selections and vertexing wrt generated events where is J/ψ→μμ reconstructed
- To be updated for 2024 conditions

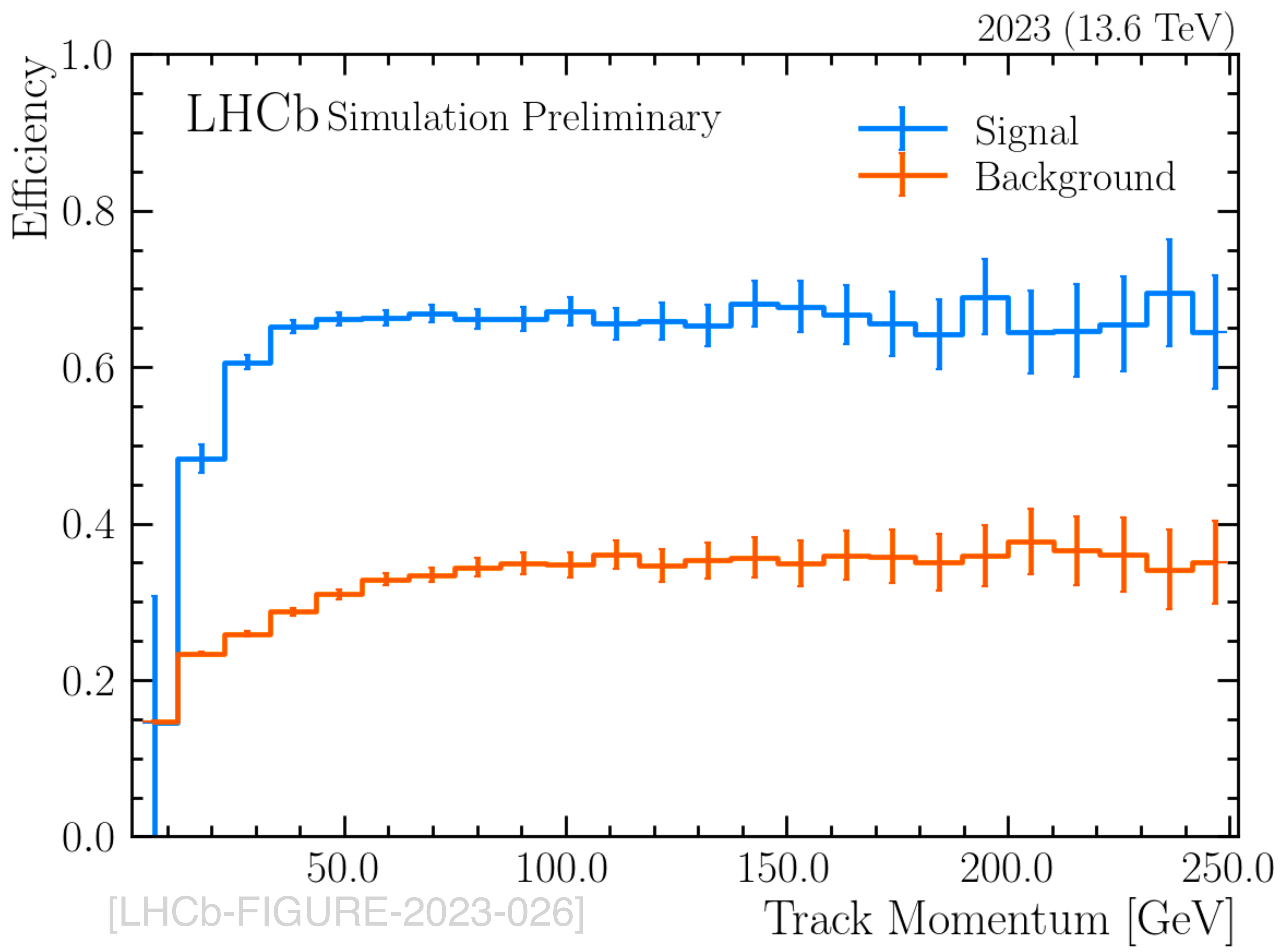




Topological track filtering

HLT2

- Not all processes have clear signatures to reduce combinatorics
- Not possible to run reconstruction and extrapolate all T tracks in the event without significant throughput reduction
- Filter tracks before full reconstruction using two MVAs — gradient boosted BDTs from CatBoost library
- Use a BDT to **filter single tracks, then** use a BDT to **filter pairs (vertex candidates)** of remaining tracks
- Currently optimised for Λ and K_S^0
- **Reduces impact on throughput** and combinations by 70%-85% whilst maintaining around 70% of signal



[LHCb-FIGURE-2023-026]

- BDT variables are:

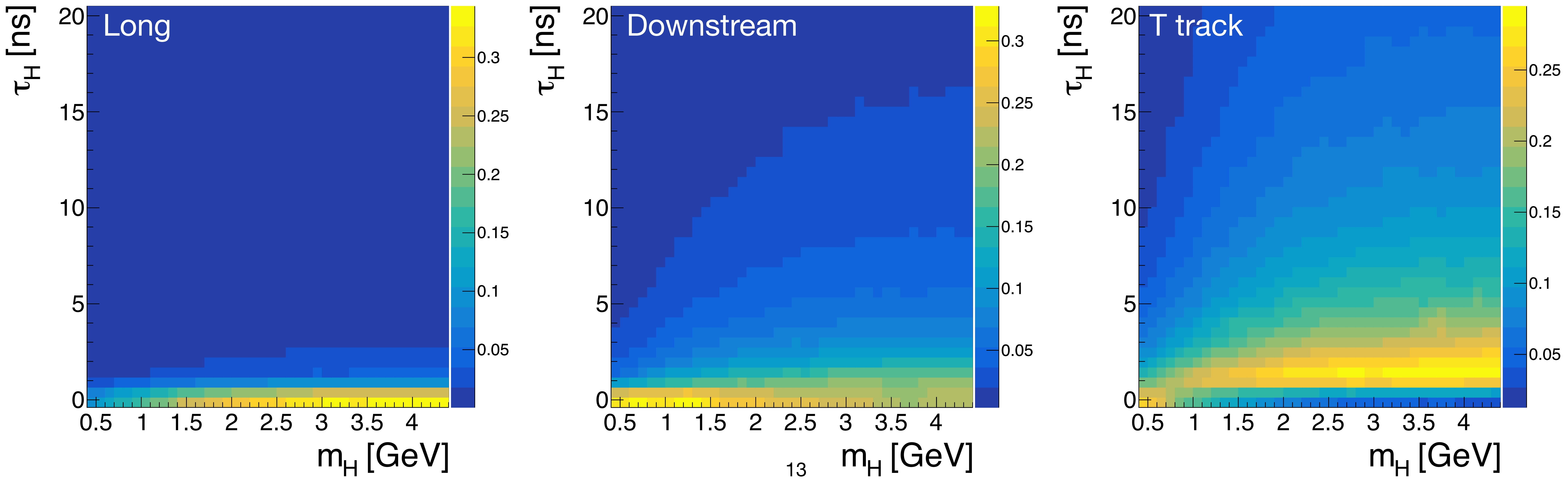
  Single track: p_T, p_z, η, y, r

  Track pair: $\Delta y, \Delta r, \text{sign}(t_y^1 \cdot t_y^2), \Delta t_y, \Delta t_x, y_{yz}, z_{yz}$

- Currently deployed in trigger for $\Xi_c^0 \to \Lambda K^- \pi^+$, $\Xi_c^0 \to \Xi^- \pi^+$, $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ decays
- Performance expected to improve in 2024 as closed VELO and UT will improve Long and Downstream tracking → less background

BSM prospects

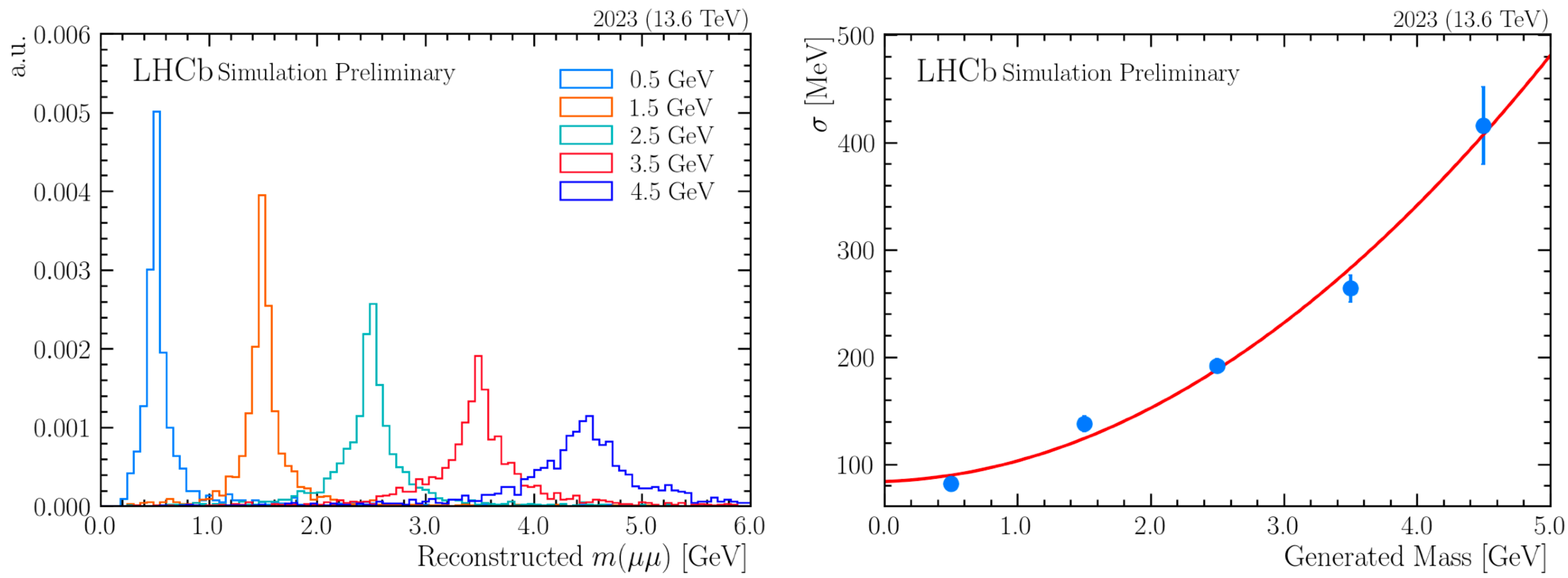
- These techniques are being adapted for BSM LLP searches
- Complementary detector acceptance to searches using Long and Downstream tracks
- Dedicated triggers will extend acceptance of LHCb's tracking system to 7.5 m, lifetimes up to $\mathcal{O}(10\text{ ns})$ in a region of little-to-no physics background
- Example channel $B^+ \to K^+ H'(\to \mu^+\mu^-)$



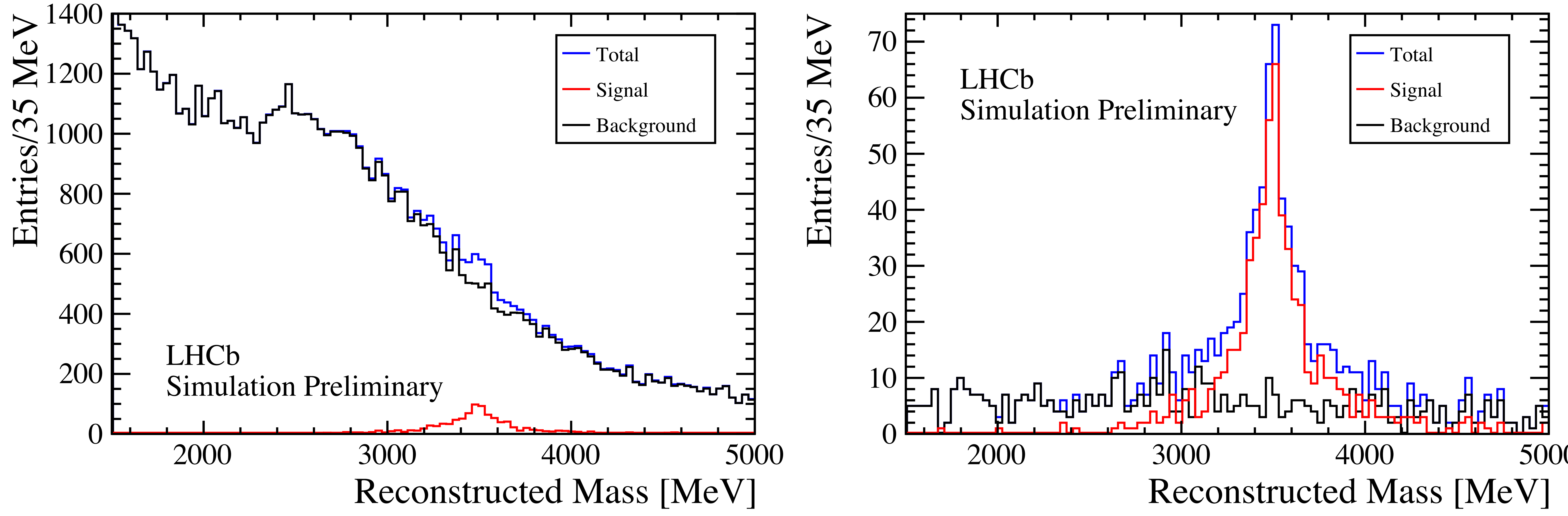
BSM prospects

- Dimuon invariant mass and mass resolution in trigger shown for 5 values $m(\mathrm{LLP}) < m(B) - m(K)$ for decays in magnet region
  - Could be improved offline using decay tree fit with *B* mass constraint
- Example of how combinatorial background can be suppressed through dedicated MVA-based track filtering

Variables: p_{T}, p_z, IP, χ^2_{IP}, $\Delta\mathrm{LL}(p - \pi)$, $\Delta\mathrm{LL}(K - \pi)$, $\Delta\mathrm{LL}(\mu - \pi)^{\mathrm{calo}}$, t_x, t_y



[LHCb-FIGURE-2023-026]



Summary & conclusion

- The flexibility of LHCb's fully software trigger is being exploited to trigger on long-lived signatures
- This requires a dedicated vertex finding and fitting strategies, and topological track filtering to stay within tight throughput and bandwidth constraints
- This is being used to collect data for EDM/MDM measurements of strange baryons
- The same techniques are also being adapted for BSM particle searches

Thanks for listening