Reconstruction, performance and physics opportunities with long-lived particles with lifetime exceeding 100 ps at LHCb

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on behalf of the LHCb RTA collaboration

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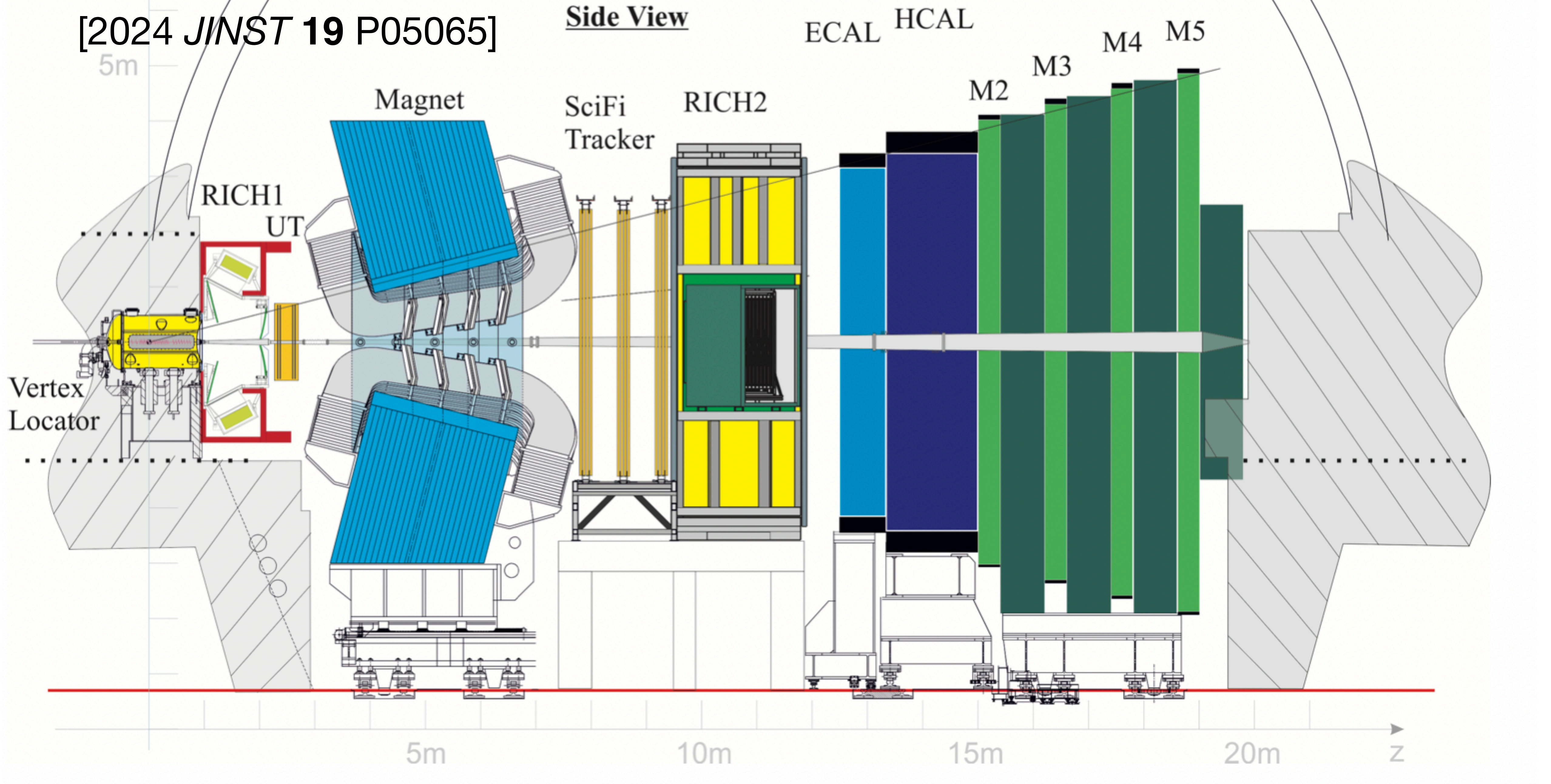
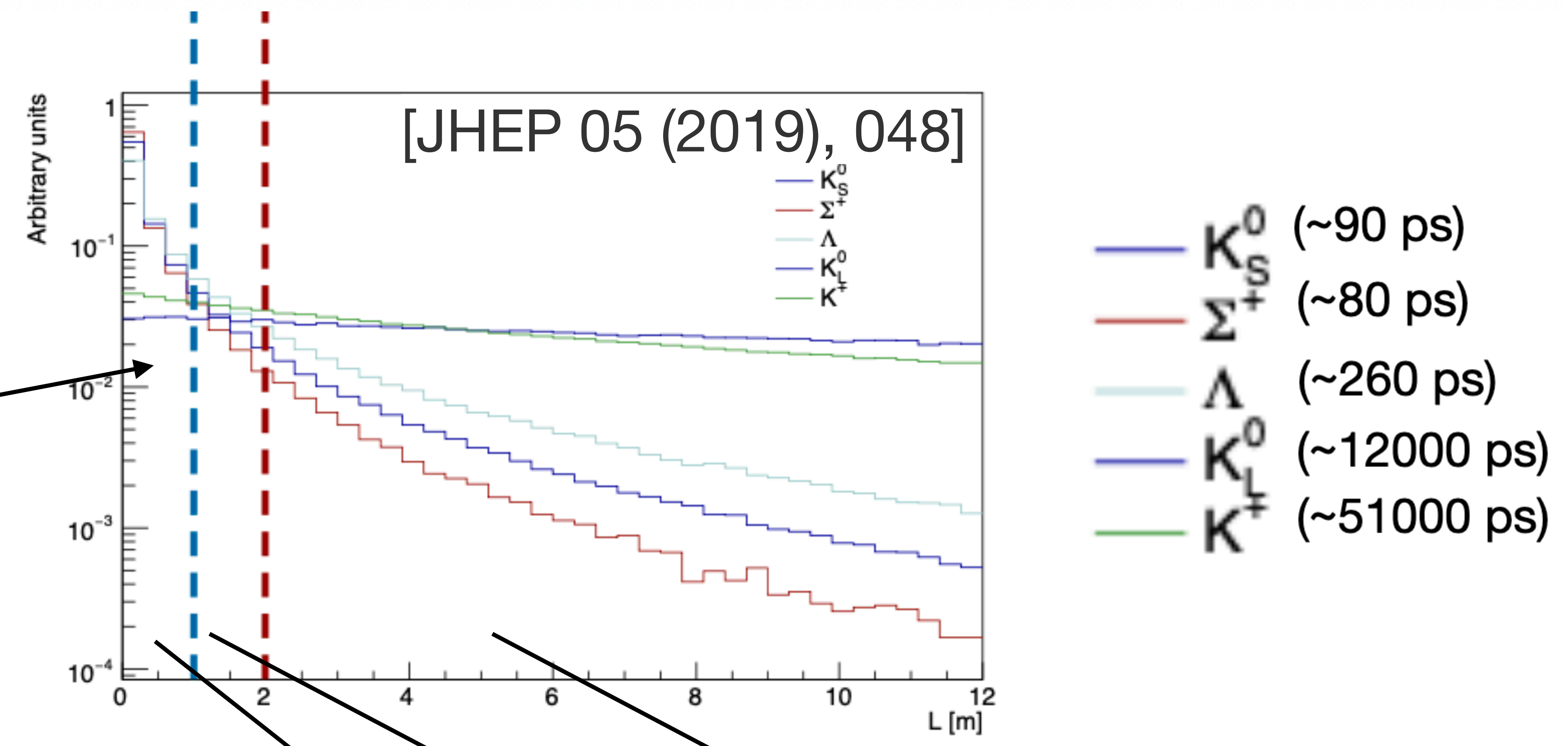
Introduction

In a nutshell

- Here we will talk about reconstructing LLPs in LHCb with **lifetimes > 100 ps**
  - These decay topologies may happen **metres from the interaction point**
  - Must be selected by trigger system to be analysed later
- How are we doing this?
  - Until now, LLP analyses in LHCb have focused on decays in the VELO, up to ~30 cm from interaction point
  - By exploiting subdetectors **several metres from the interaction point** in new ways for new types of analyses, the **physics reach** of **LHCb** is **expanded** for **particle searches** and **hyperon measurements**
  - These techniques benefit from **upgraded detector** and **fully software trigger**





[Front.Big Data 5 (2022), 1008737]

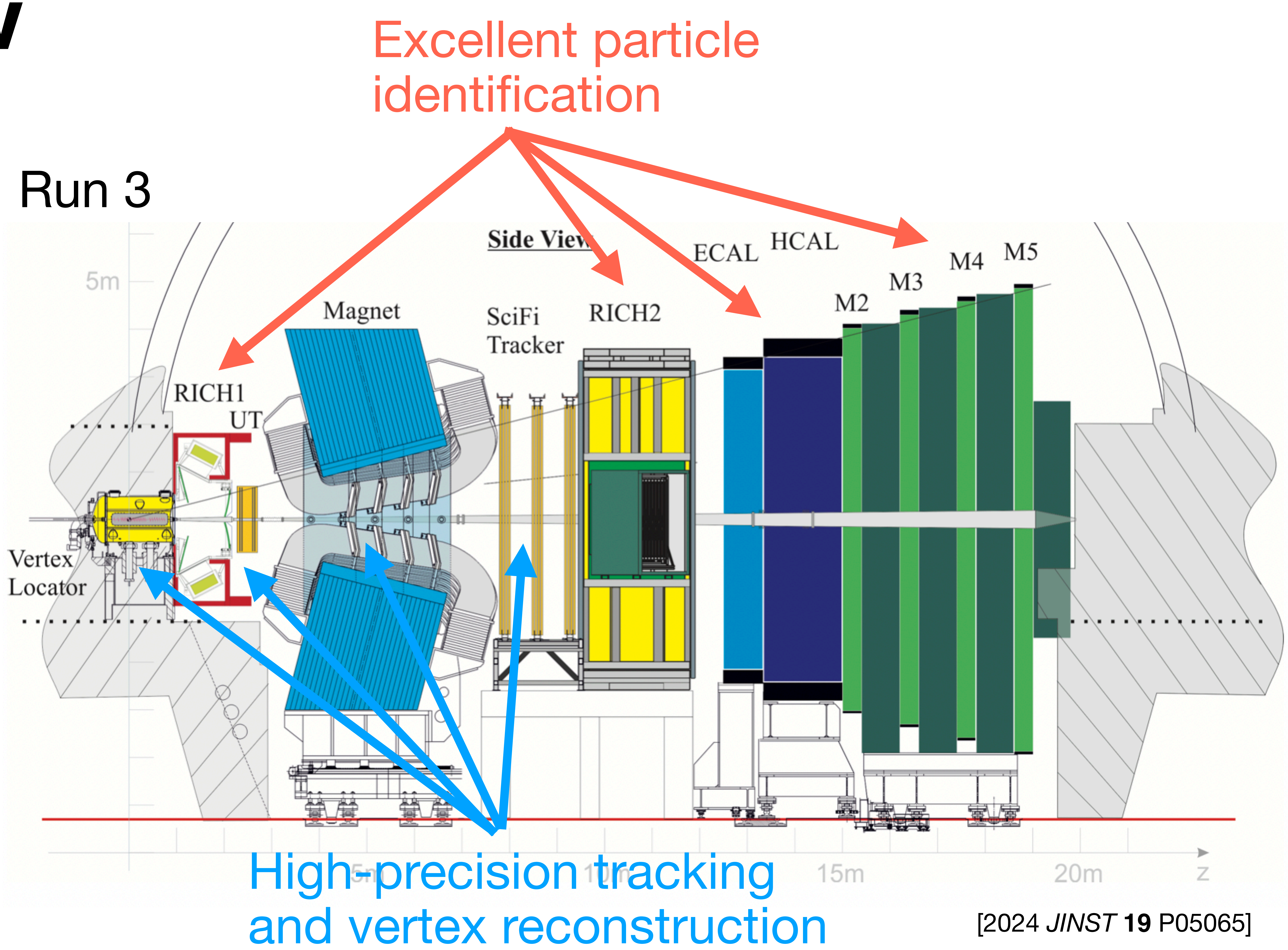
Simulation	LL	DD	TT	HLT1 eff (TOS) (LL only)
Λ^0	12%	51%	37%	< 10%
K_s^0	46 %	38 %	16 %	< 25%

LHCb overview

LHCb overview

- Forward-arm spectrometer with a focus on c- and b-physics
- Phase space region $2 < \eta < 5$ forward of the interaction point
    - Complementary to ATLAS and CMS

Run 3

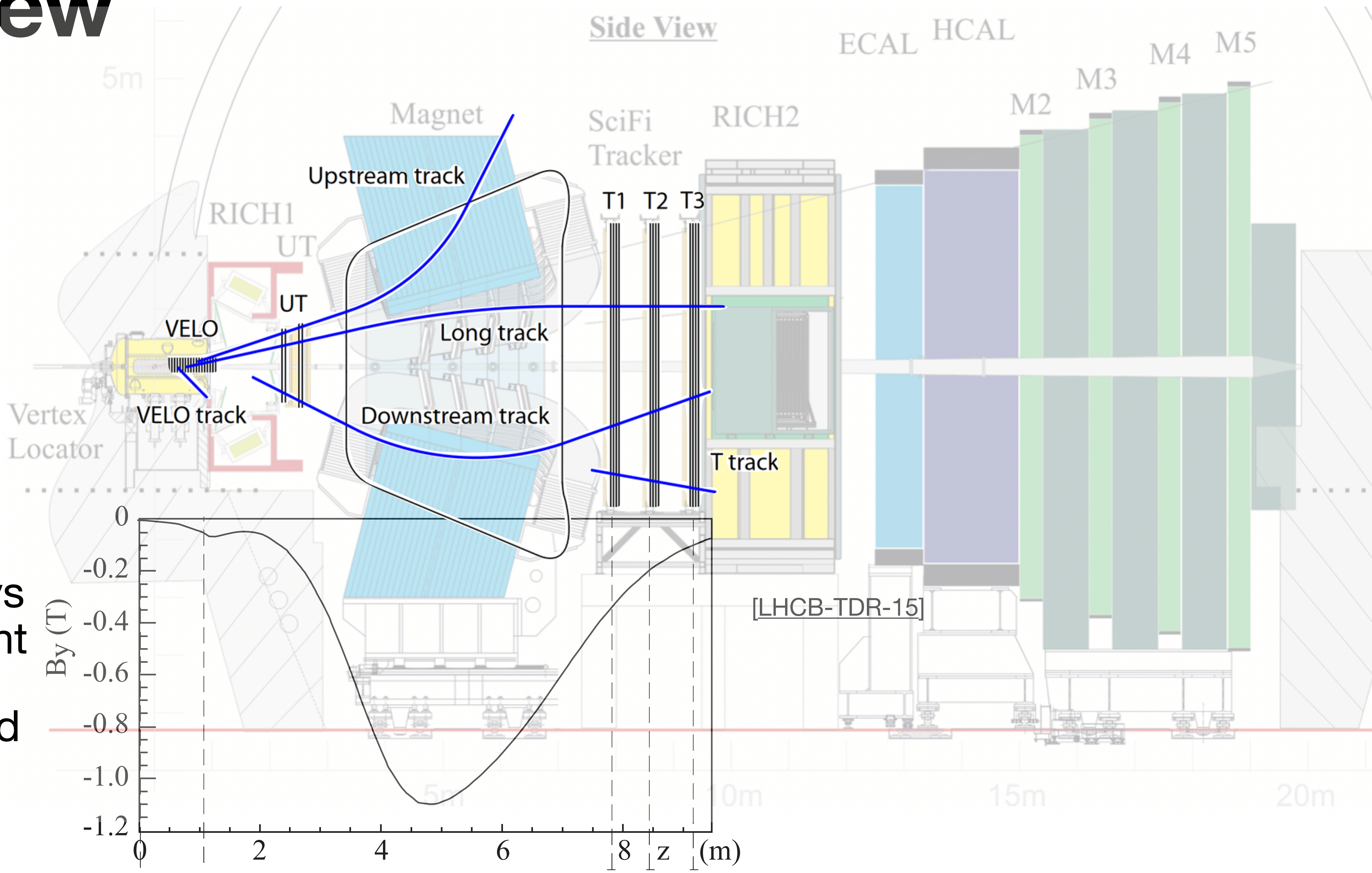


[2024 *JINST* **19** P05065]

LHCb overview

Track types

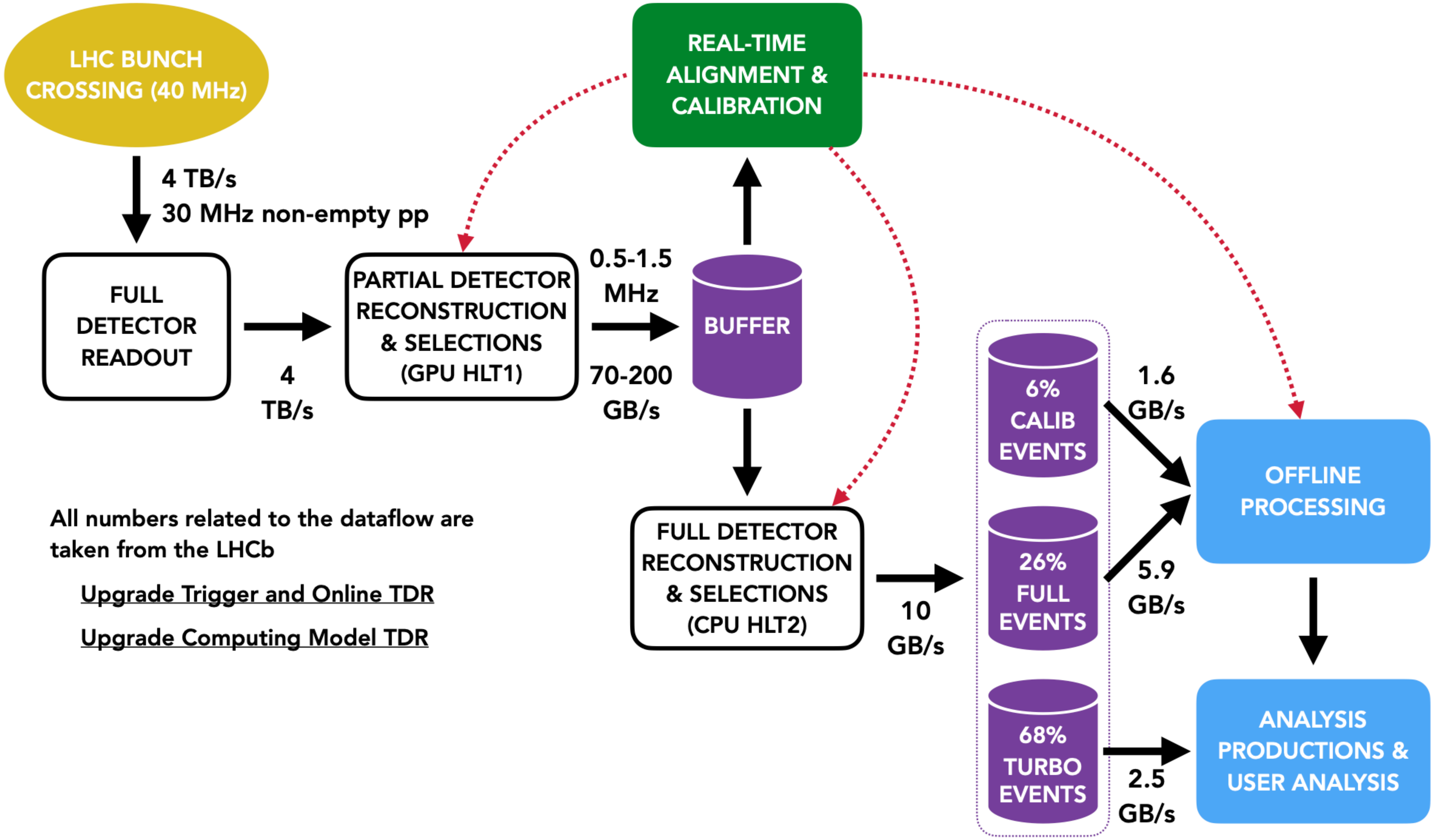
- Discrete tracker
  - Tracks named according to where they have hits
- Long tracks have best precision, but can only be used to study decays close to interaction point
- Using **Downstream** and **T tracks unlocks higher lifetimes**



[LHCB-TDR-15]

Trigger

- Fully software trigger
- Data analysed in real time (**Real Time Analysis,** RTA)
- HLT1 runs on GPUs performing partial event reconstruction, reducing event rate by a factor 30
- HLT2 runs on CPUs performing full quality event reconstruction, reducing event rate by a further factor 10
- Events are generally selected by reconstructing candidate topologies
- In principle **all subdetectors can be accessed in lowest level trigger** which would be difficult with hardware triggers



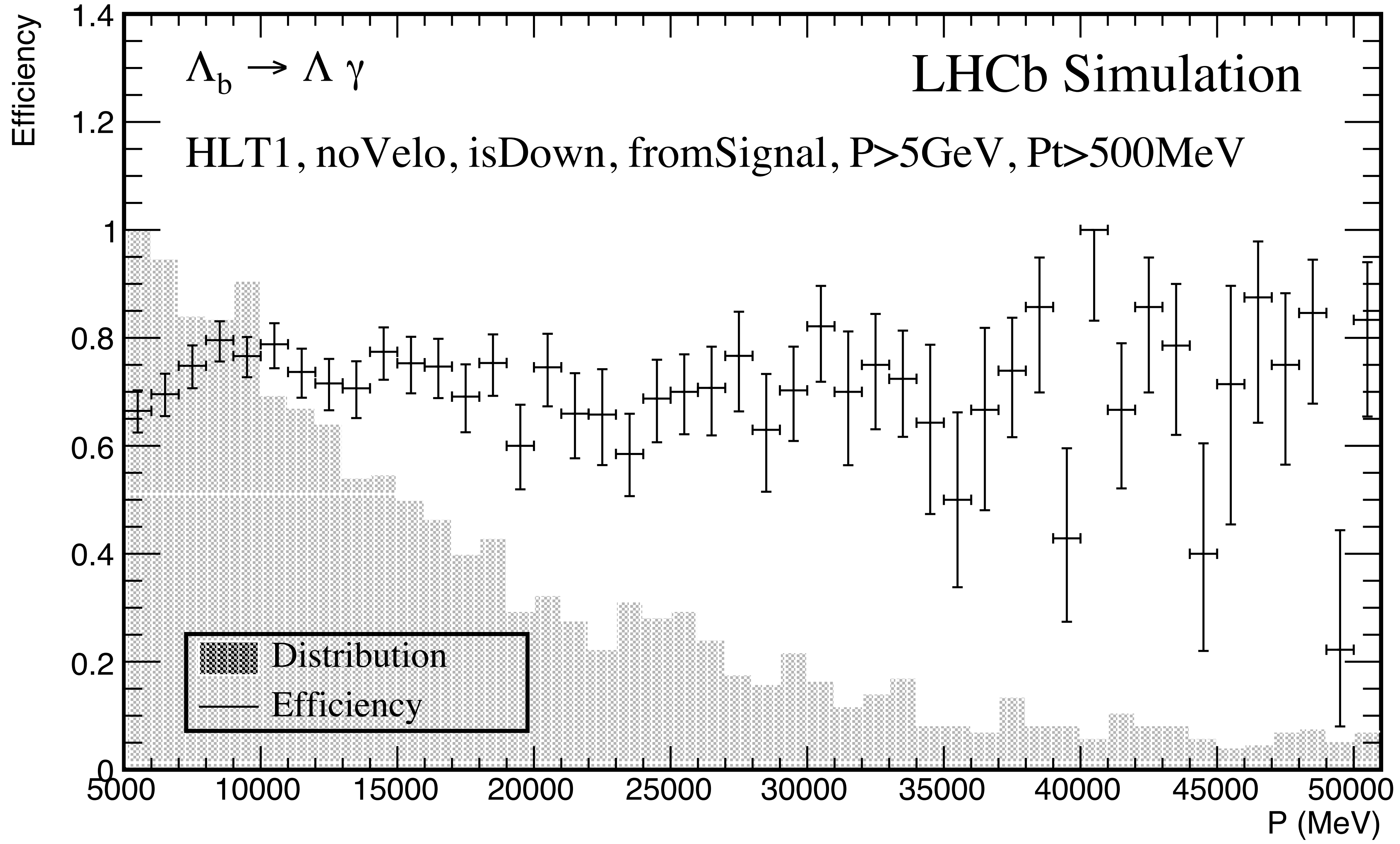
[LHCB-TDR-021]

Decays before the magnet region

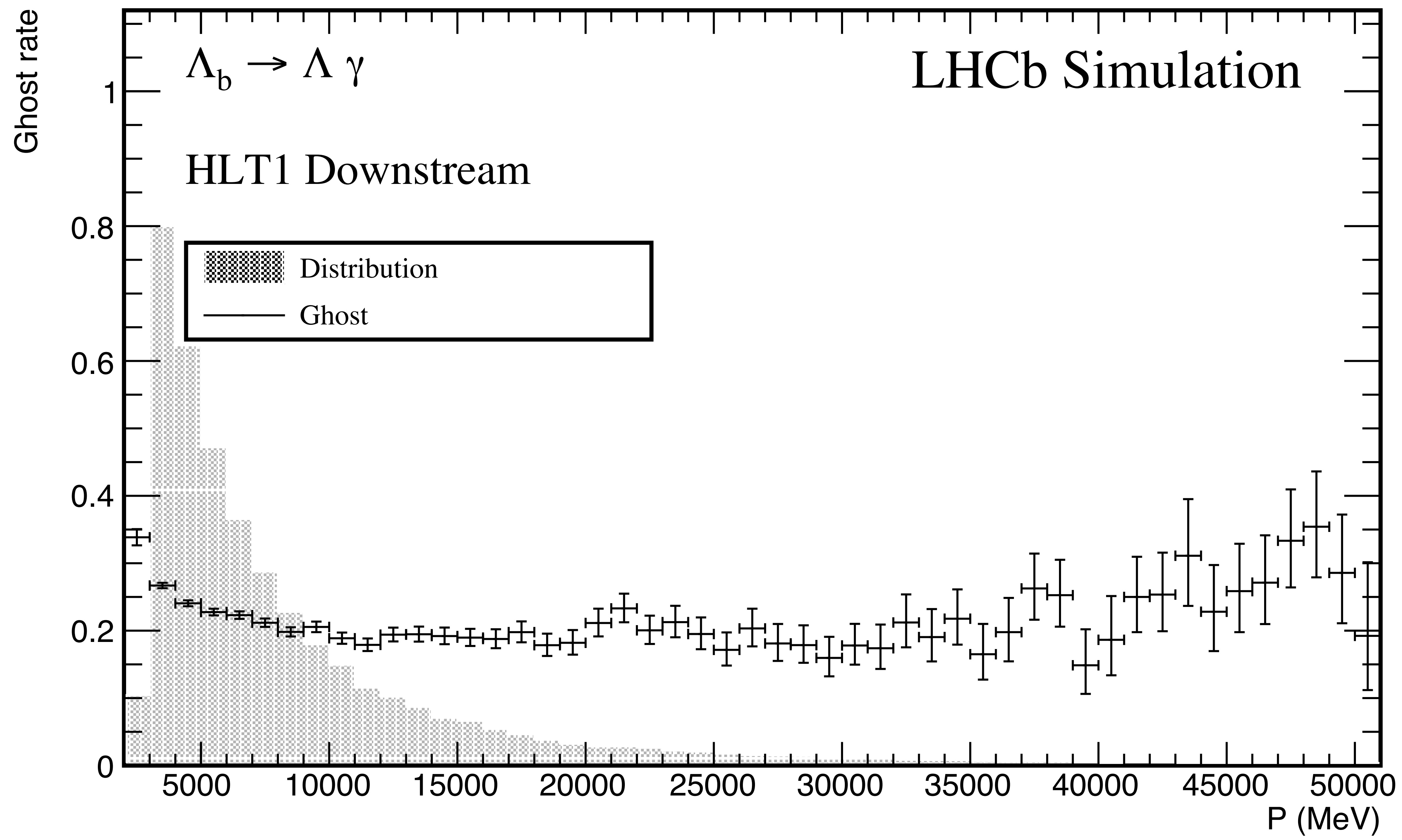
Downstream algorithm

Overview

- New Downstream algorithm [CERN-THESIS-2023-249] developed and tested, but not yet in production
- Developed to **increase sensitivity to Λ and K_S^0 decays** in **HLT1**
- Expanded to Beyond the Standard Model **(BSM) particle searches**
- Downstream tracks are found by matching SciFi seeds extrapolated through the UT using a bespoke track model
- A single hidden layer (14 nodes) neural network (NN) used to remove over 80% of ghost tracks



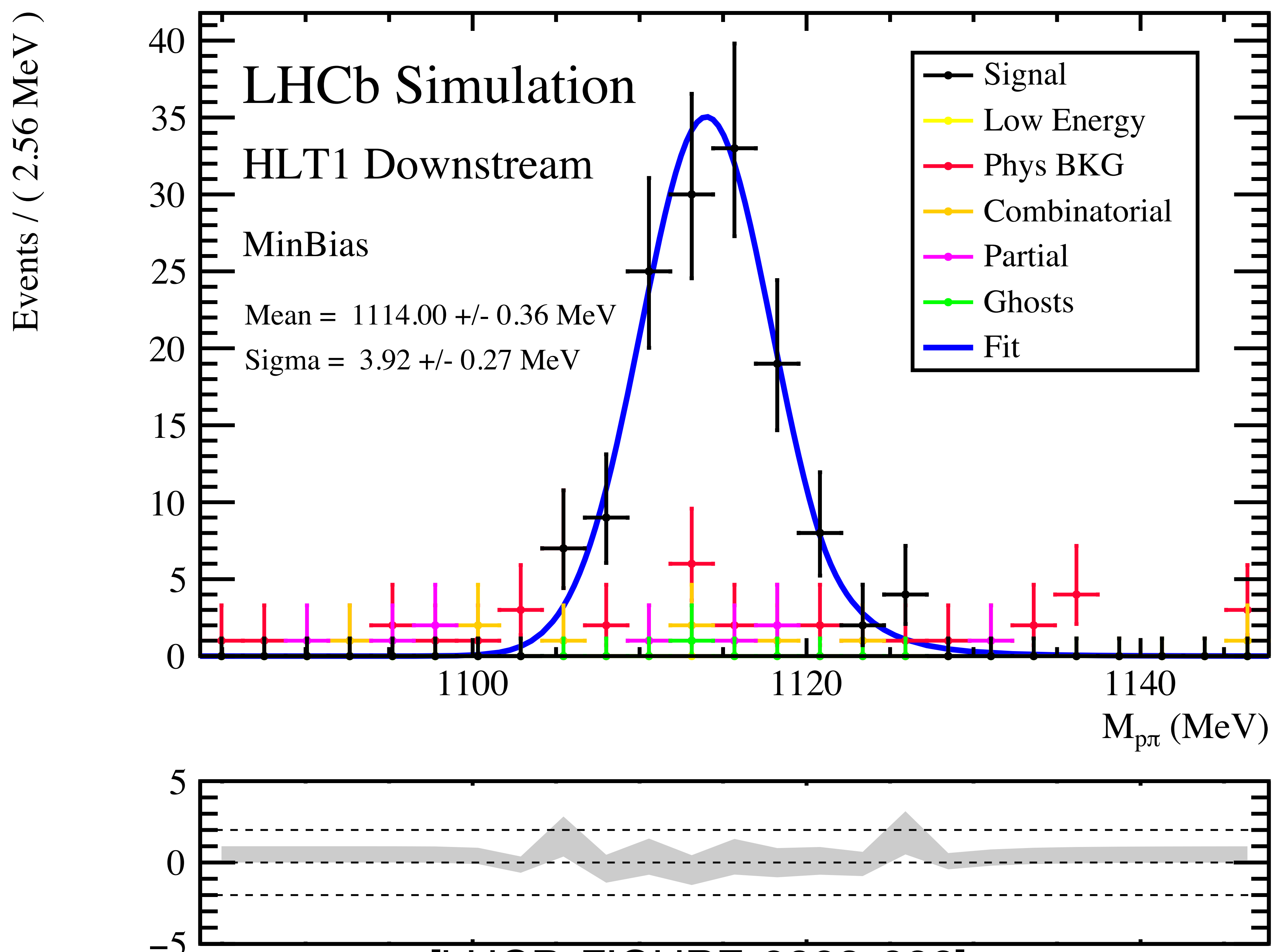
[LHCB-FIGURE-2023-028]



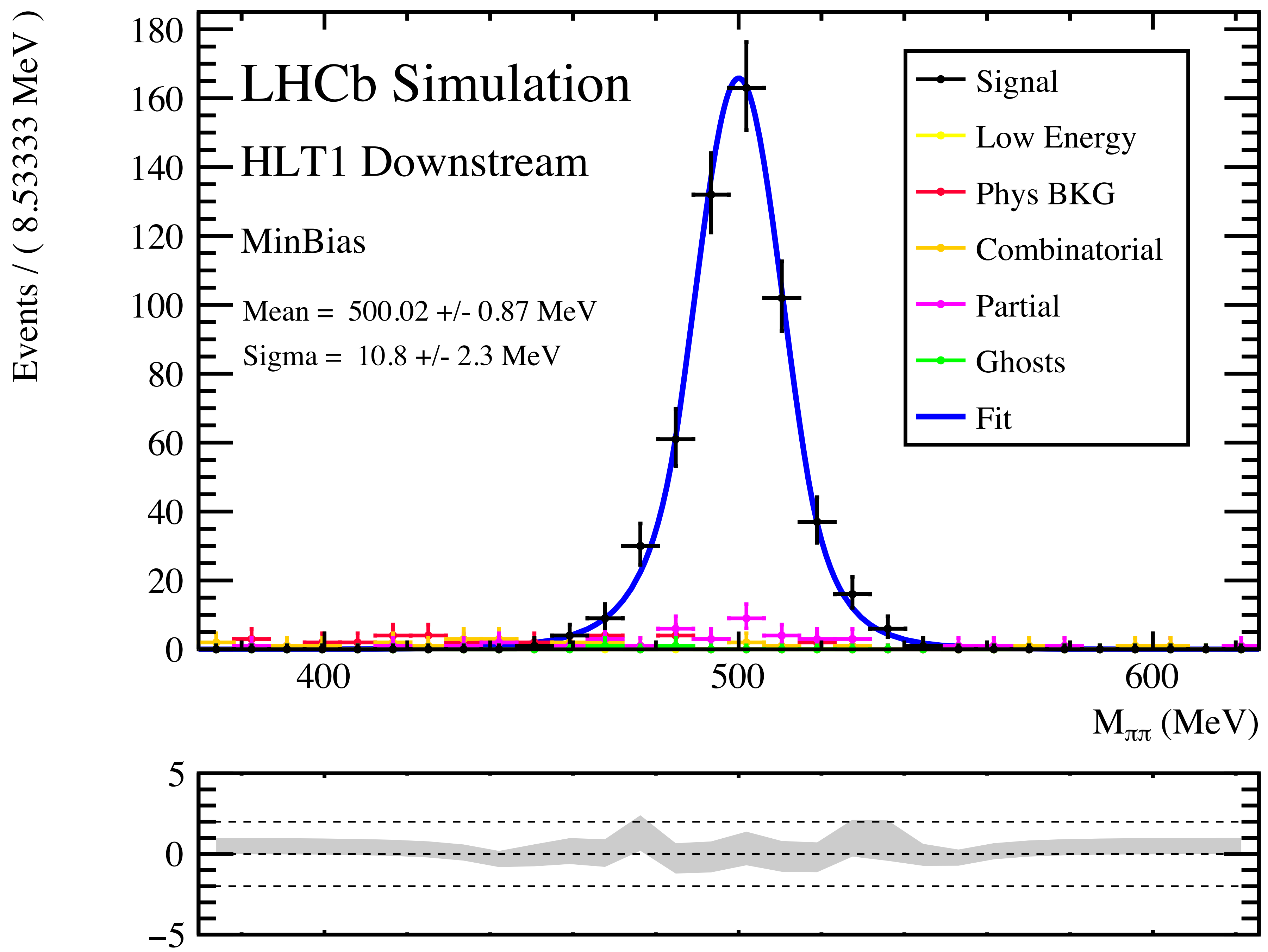
Downstream algorithm

Candidate selection

- Track extrapolation before UT is non-linear due to residual magnetic field in the region
- **Uses kalman-filter based vertexing**
- Successfully reconstructs mass distribution of Λ and K_S^0
- **NN-based classifier** for monitoring and selection at HLT1



[LHCB-FIGURE-2023-028]



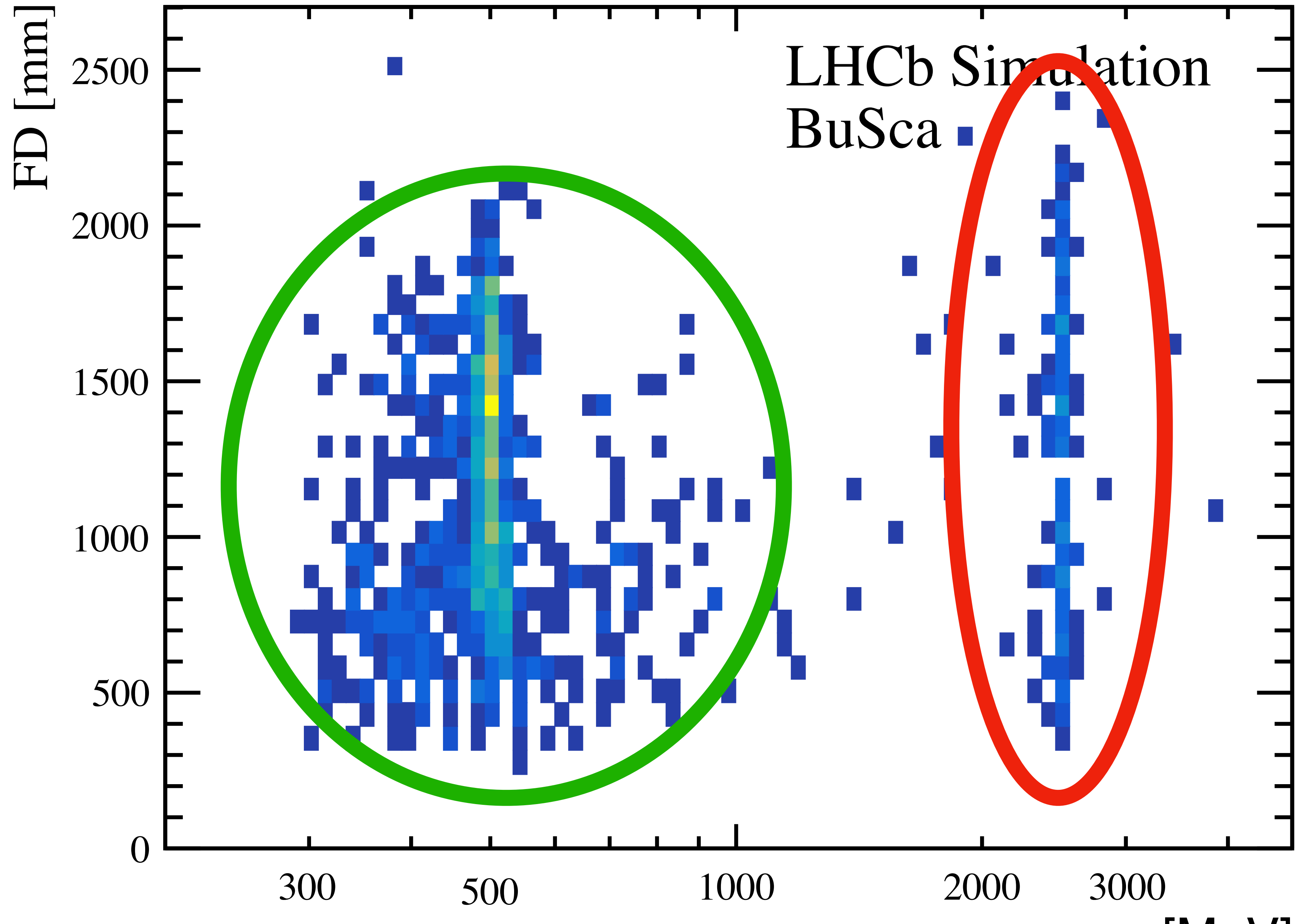
BusCa

<u>Buffer</u><u>Sca</u>nner

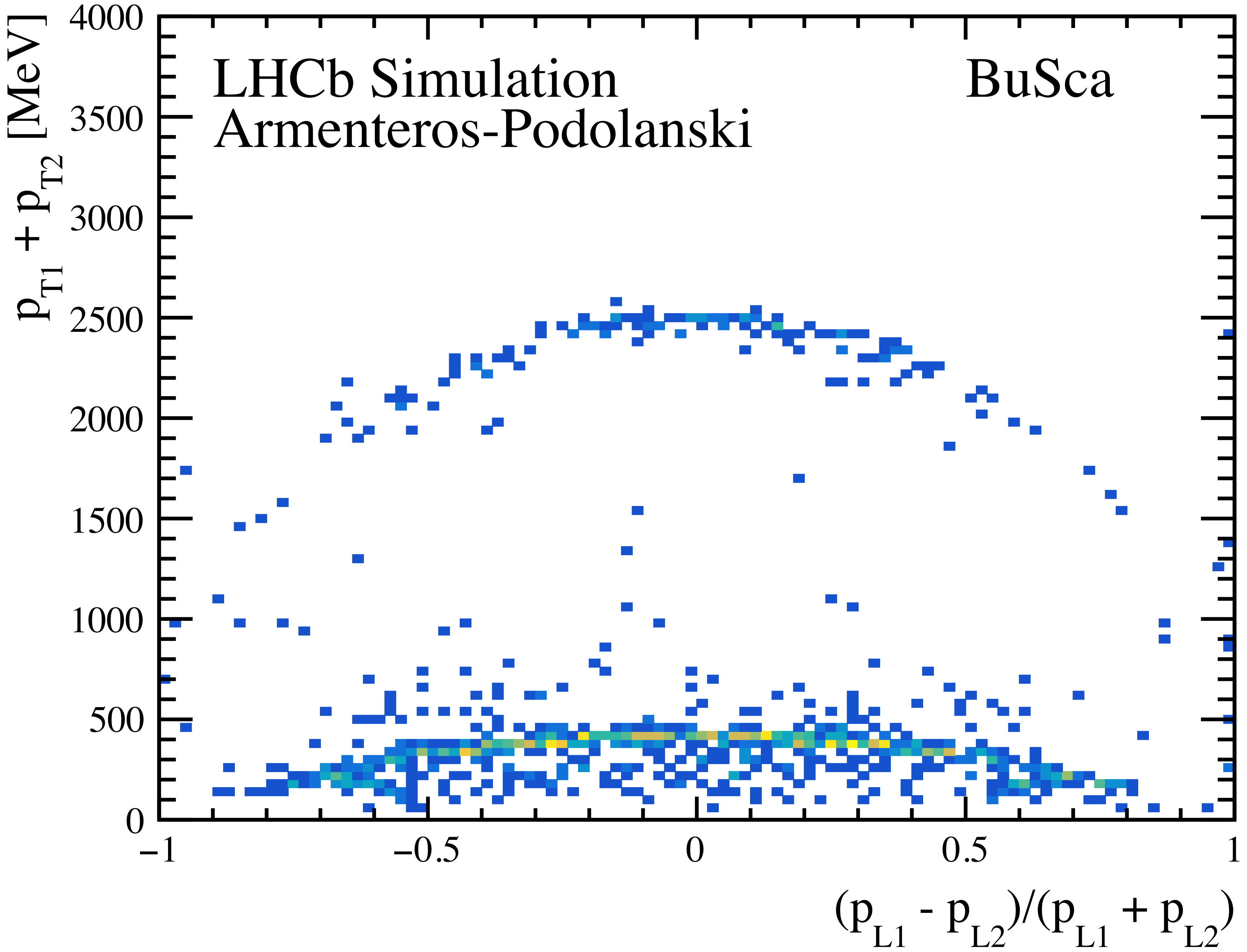
- **Bandwidth** is a **limited** resource
- To avoid increasing bandwidth, cumulatively monitor the Downstream vertexing without persisting events (i.e. perform a buffer scan, **BuSca**) [LHCB-FIGURE-2024-018]
- Activate trigger for specific region only if an unexpected **hotspot** appears in that region
- Covering regions with no physical background
- Information about **mass** of LLP and daughter particles can be accessed **from Armenteros-Podolanski distribution**

Corresponds to Λ and K^0_S

Would correspond to a dimuon resonance with a mass of 2500 MeV and lifetime of 400ps

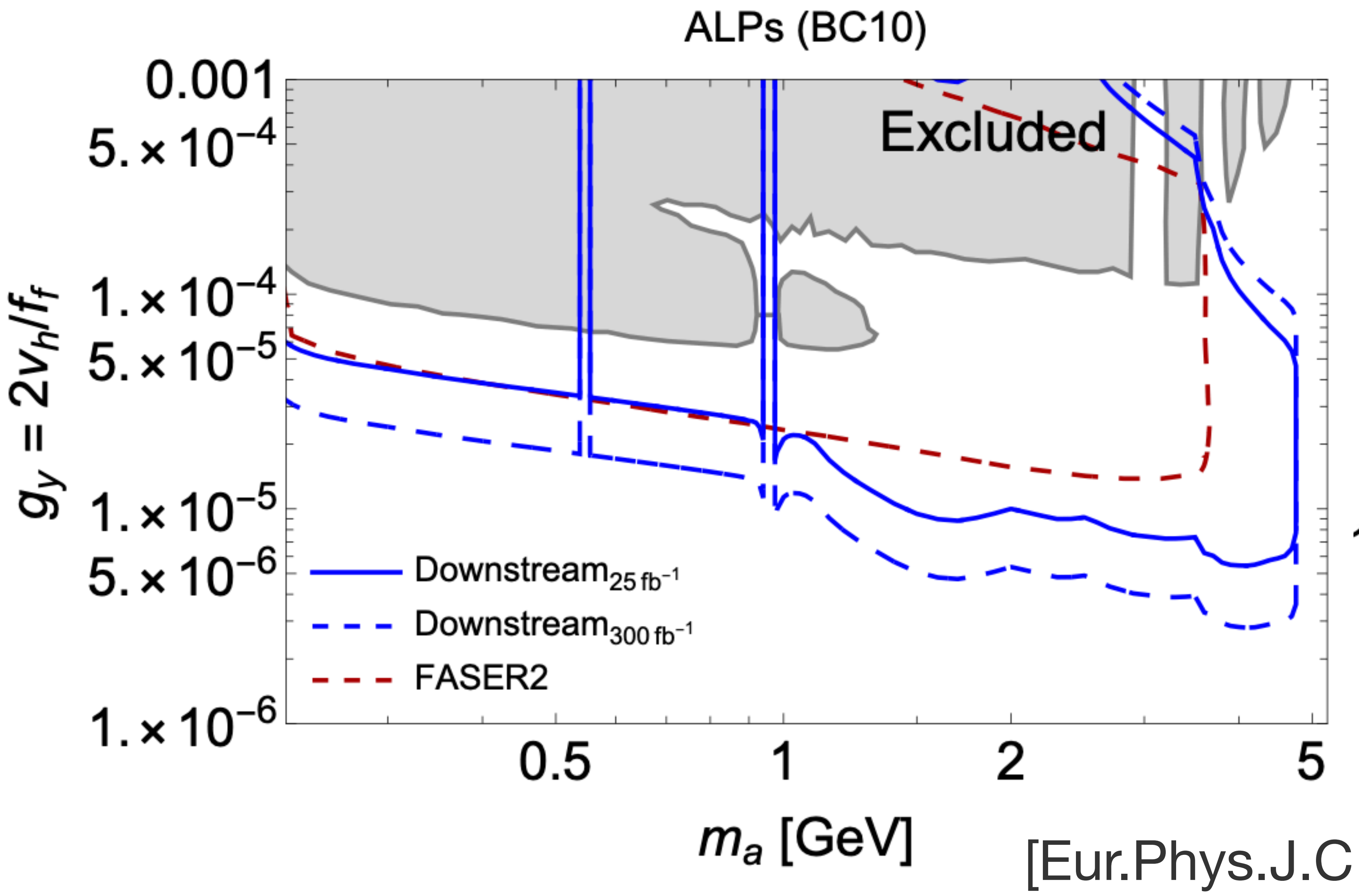


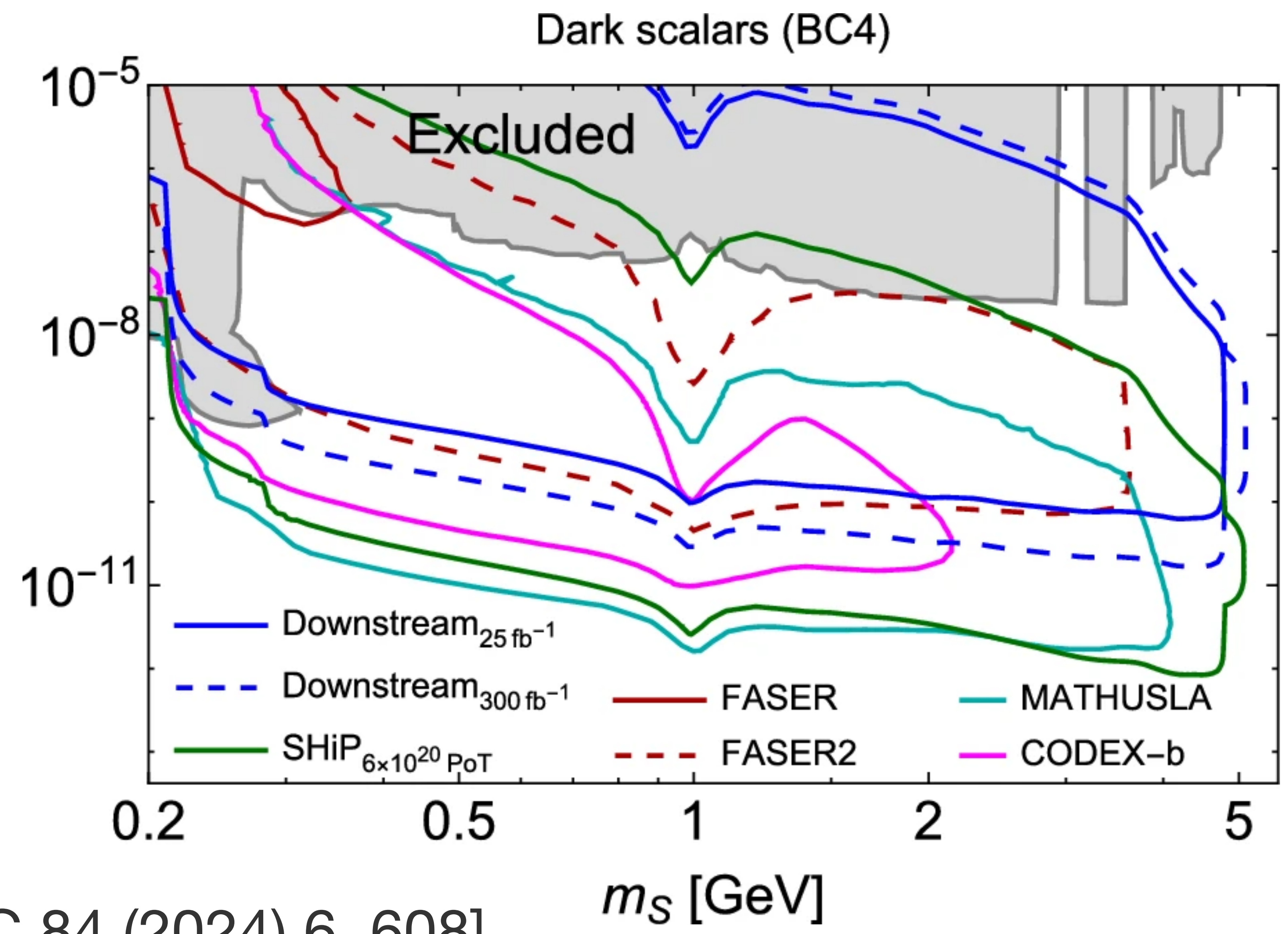
[LHCB-FIGURE-2024-018]



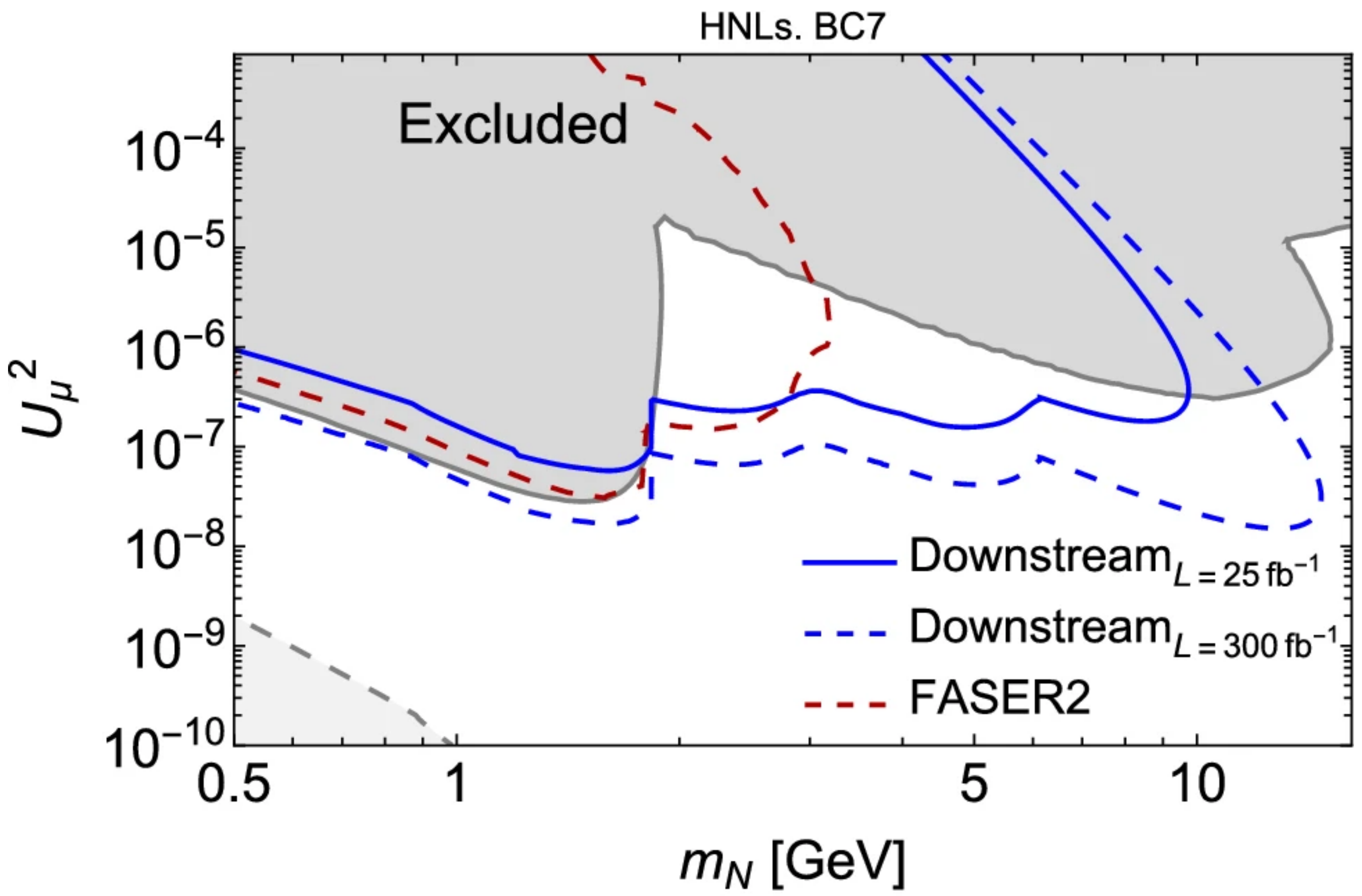
Prospects

- Projected sensitivities with Downstream [Eur.Phys.J.C 84 (2024) 6, 608, *V. Gorkavenko et al.*]
  - Considering acceptance efficiency, HLT1 reconstruction efficiency and HLT1 selection efficiency for signal with Downstream
- LHCb with Downstream could be competitive with FASER in models such as Heavy Neutral Leptons (HNLs), Axion-like particles (ALPs) and Dark Scalars





[Eur.Phys.J.C 84 (2024) 6, 608]



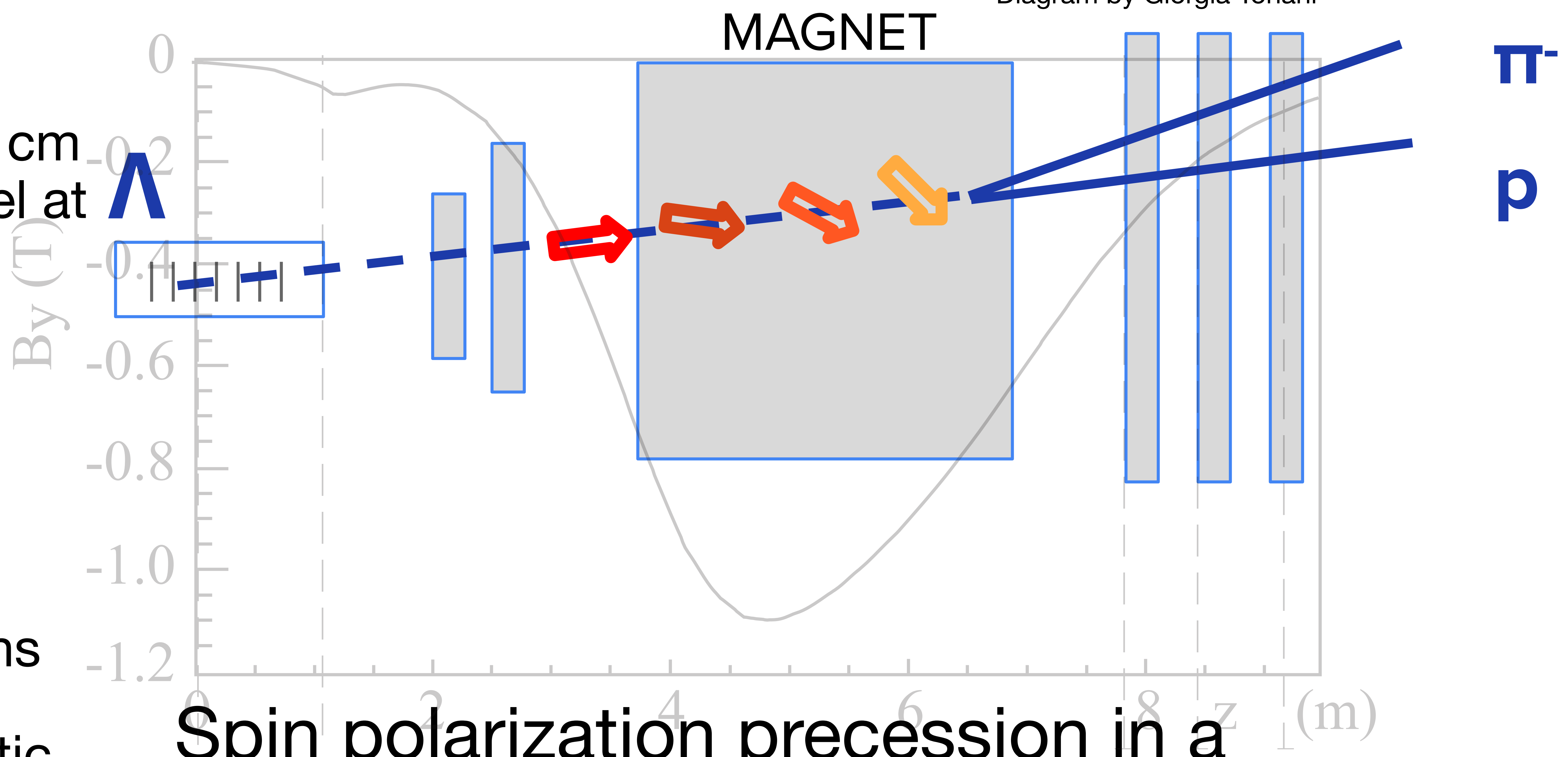
Decays in the magnet region

Decays in the magnet region

Motivation

- Λ electric dipole moment and magnetic dipole moment measurements [Eur. Phys. J. C 77, 181 (2017)]
- SM prediction (from neutron EDM): EDM < 10^{-26} e cm → sensitive to physics Beyond the Standard Model at the current experimental sensitivity
    - Lambda EDM precision could be improved by about 2 orders of magnitude with full LHCb dataset
- MDM measurement of particle and anti-particle → CPT invariance test: never performed for Λ baryons
- Reconstruction is challenging due to weak magnetic field over the tracking stations, but a strong inhomogeneous field across the decay region

Diagram by Giorgia Tonani

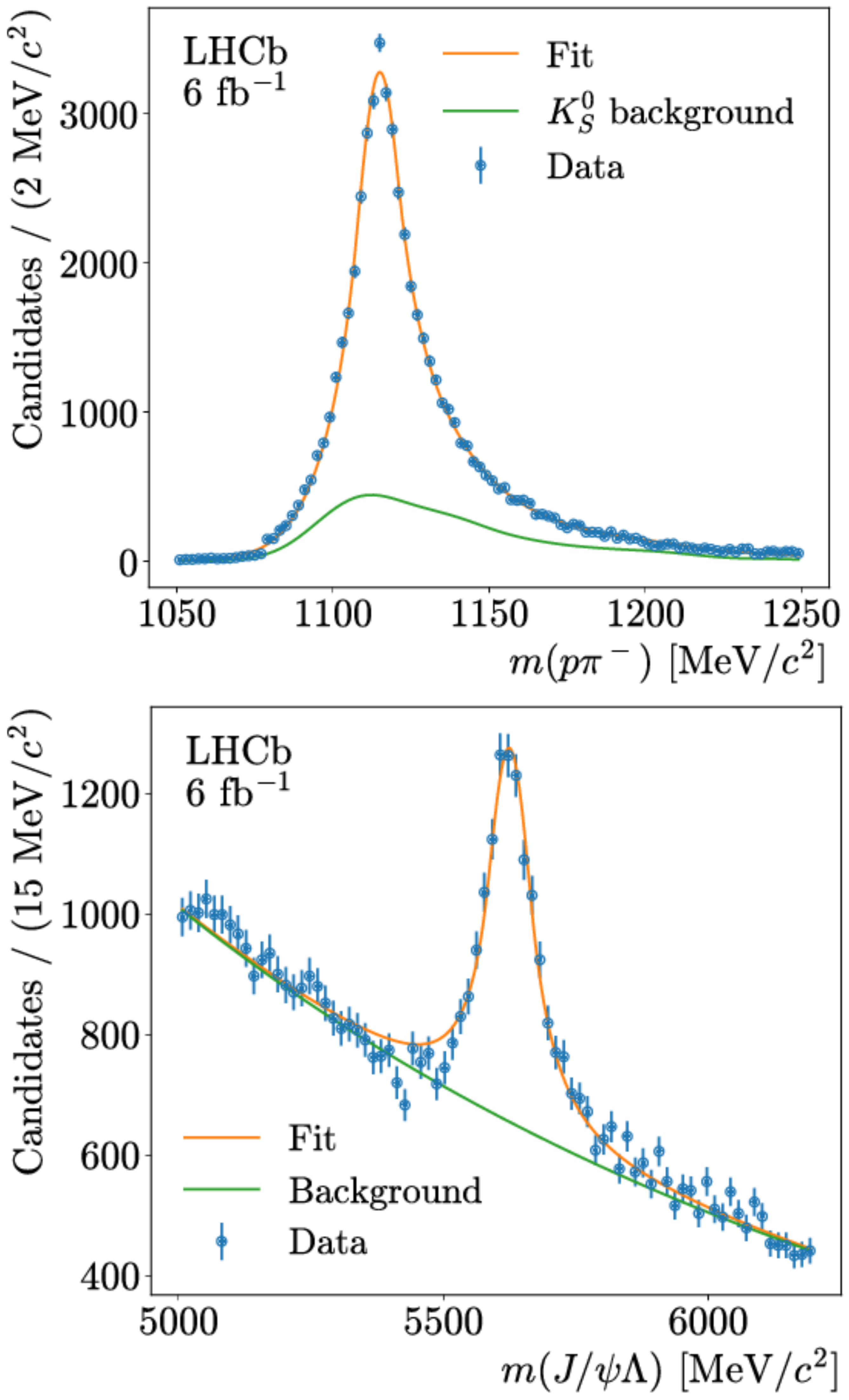


Spin polarization precession in a magnetic field

Decays in the magnet region

Feasibility

- Strategy initially developed for **electric/magnetic dipole moment measurements with hyperons** decaying up to 7.6 m from interaction point
- Reconstruct Λ and K_S^0 decaying after traversing magnet using **only hits in the tracking stations (SciFi) (T tracks)**
  - Demonstrated in $\Lambda_b \to J/\psi\Lambda$, $B^0 \to J/\psi K_S^0$ decays in Run 2 data [arXiv:2211.10920]
  - Implemented in HLT2 for Run 3
- Techniques can be **applied to BSM searches**
  - Starting with two-track decays



[arXiv:2211.10920]

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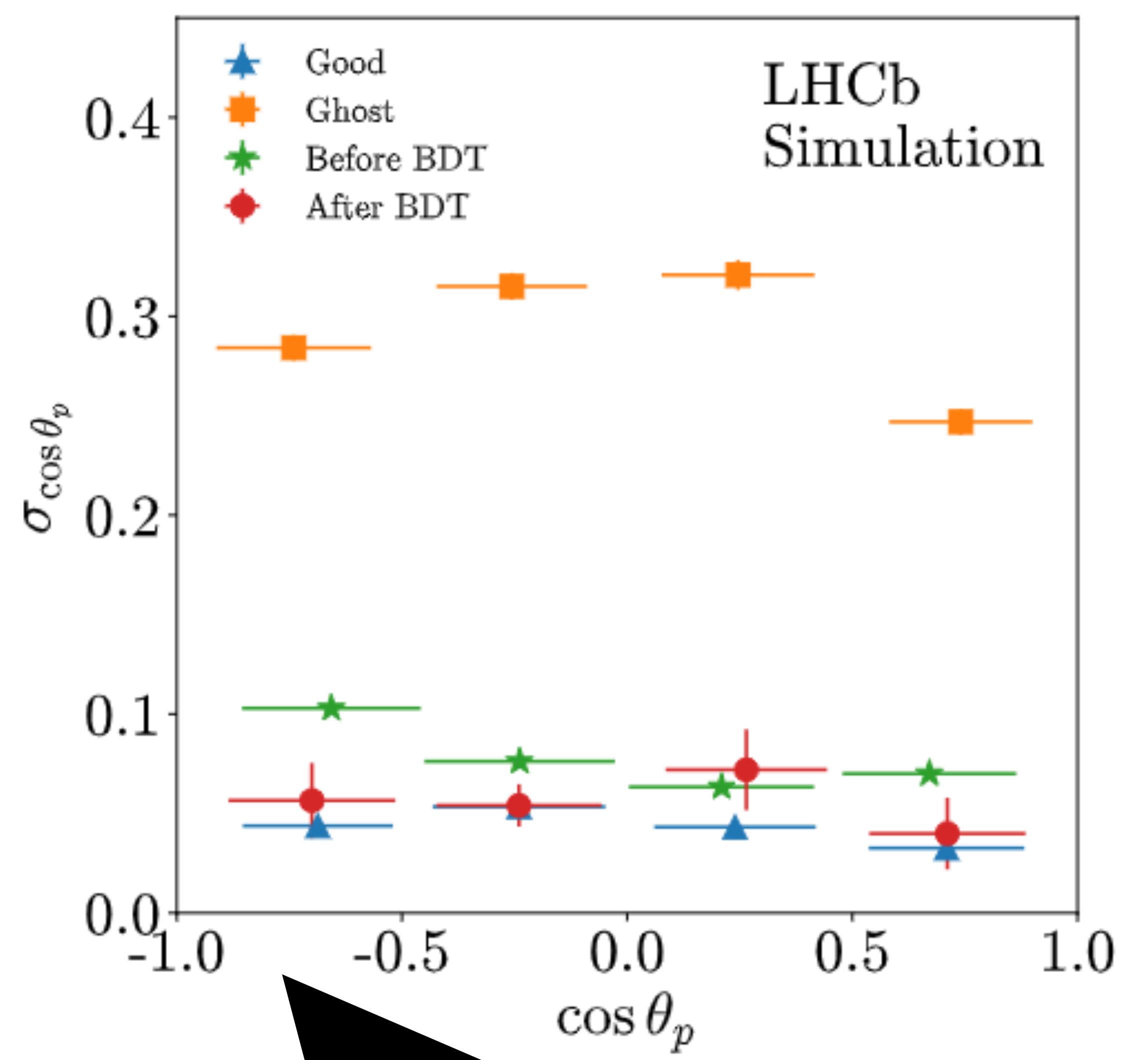
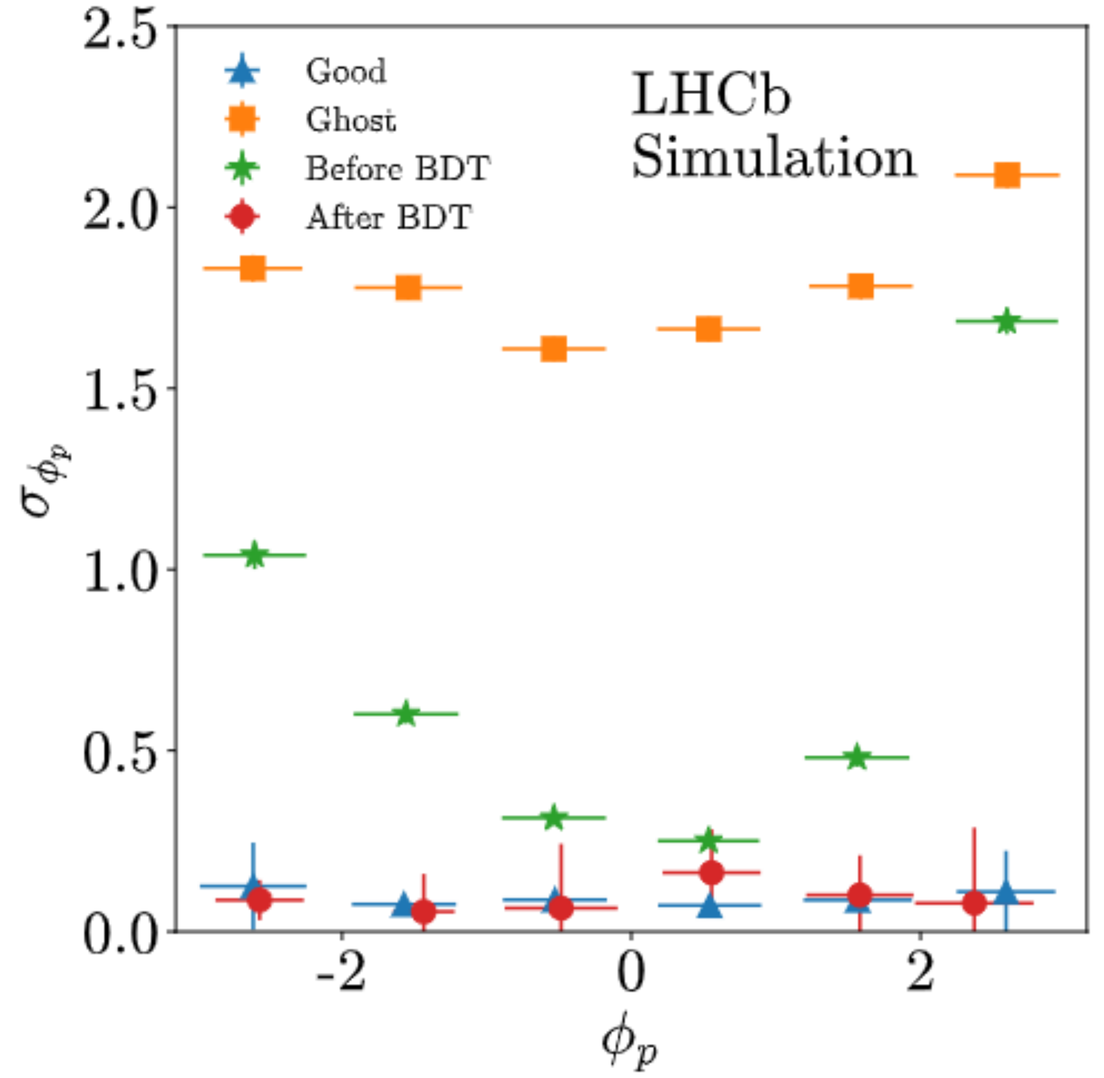
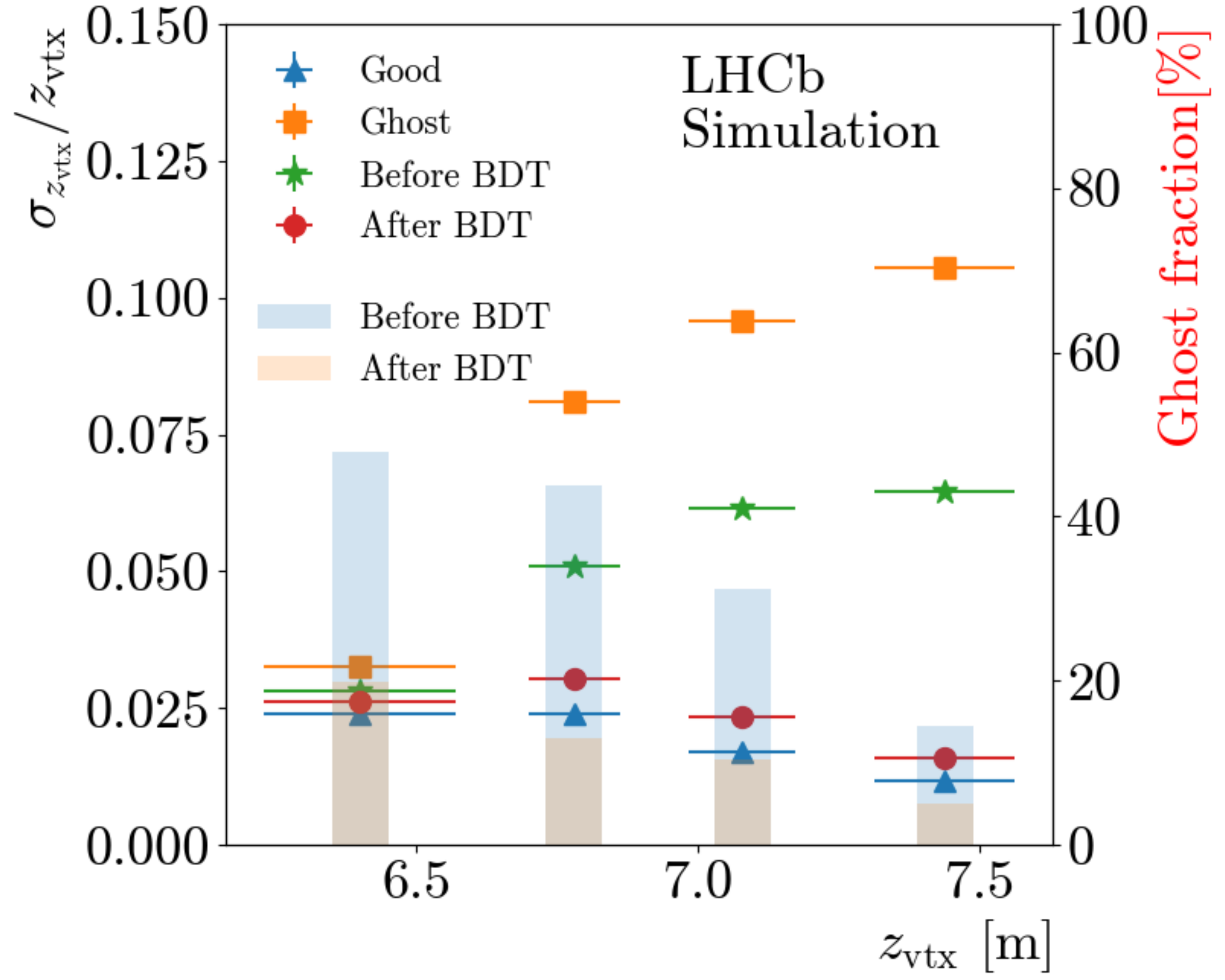
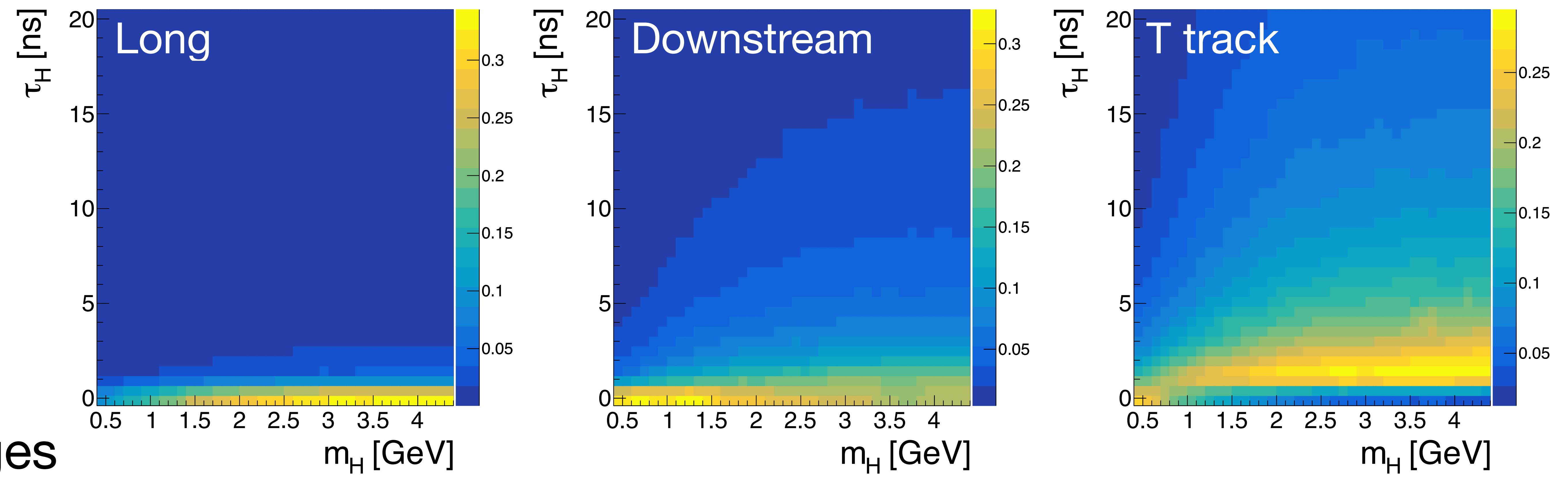




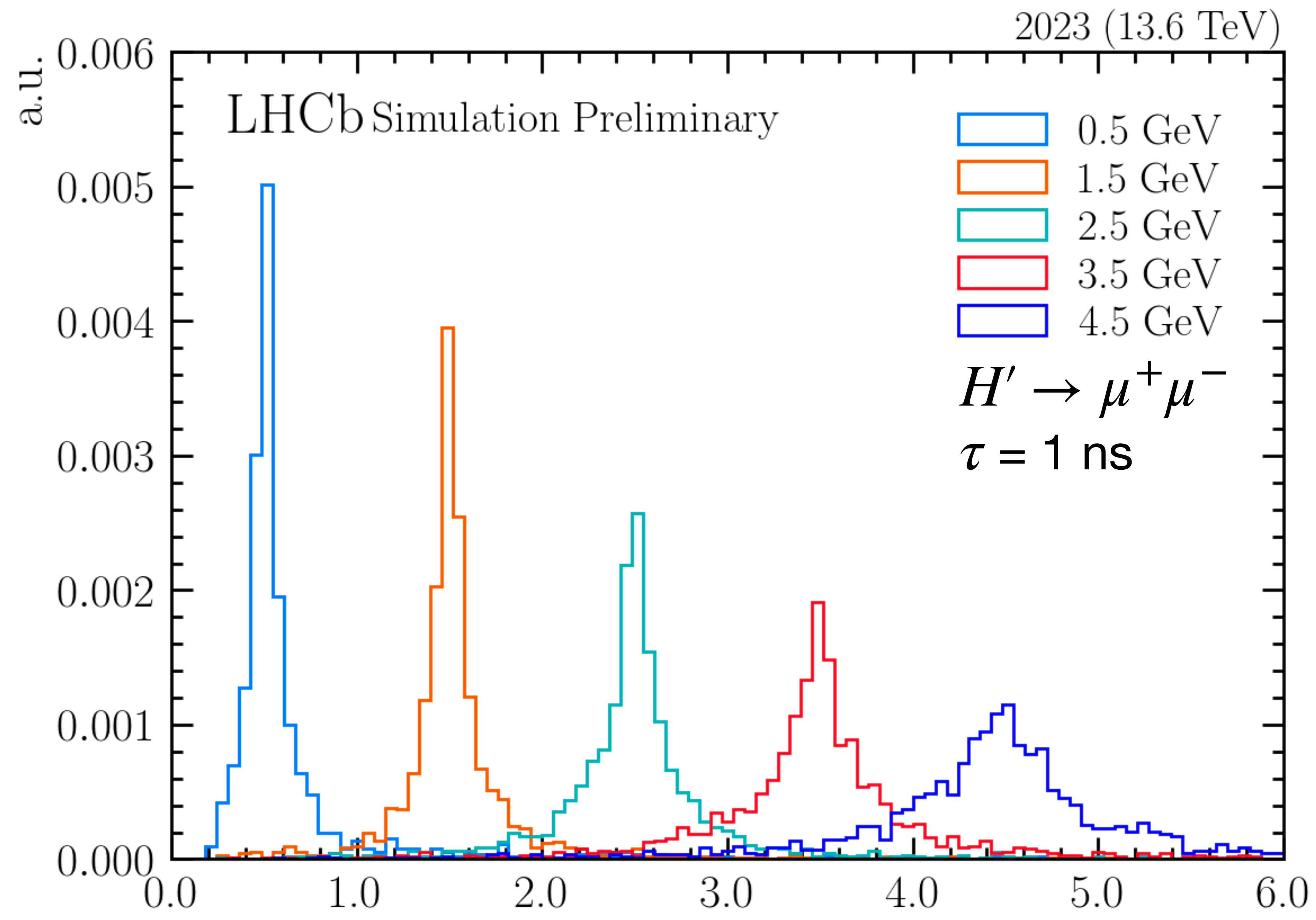


Decays in the magnet region

- Searches with **T tracks** offer **complementary** acceptance to searches with **Long and Downstream tracks**
- The **mass resolution** performance in HLT2 changes as a function of the LLP mass
  - Work underway to improve, but limited by the **weak magnetic field in the SciFi**
  - **Offline kinematic fit of decay tree with primary vertex and B mass constraints** should provide a **mass resolution less than 10 MeV**
- Initial HLT2 lines target **dark scalars** and **HNLs**
- Trigger in **HLT1** in development to increase acceptance



$B^0 \to K^+ H'(\to \mu^+\mu^-)$ dimuon acceptance efficiencies for different lifetimes and masses



[LHCB-FIGURE-2023-026]

Summary and prospects

Summary and prospects

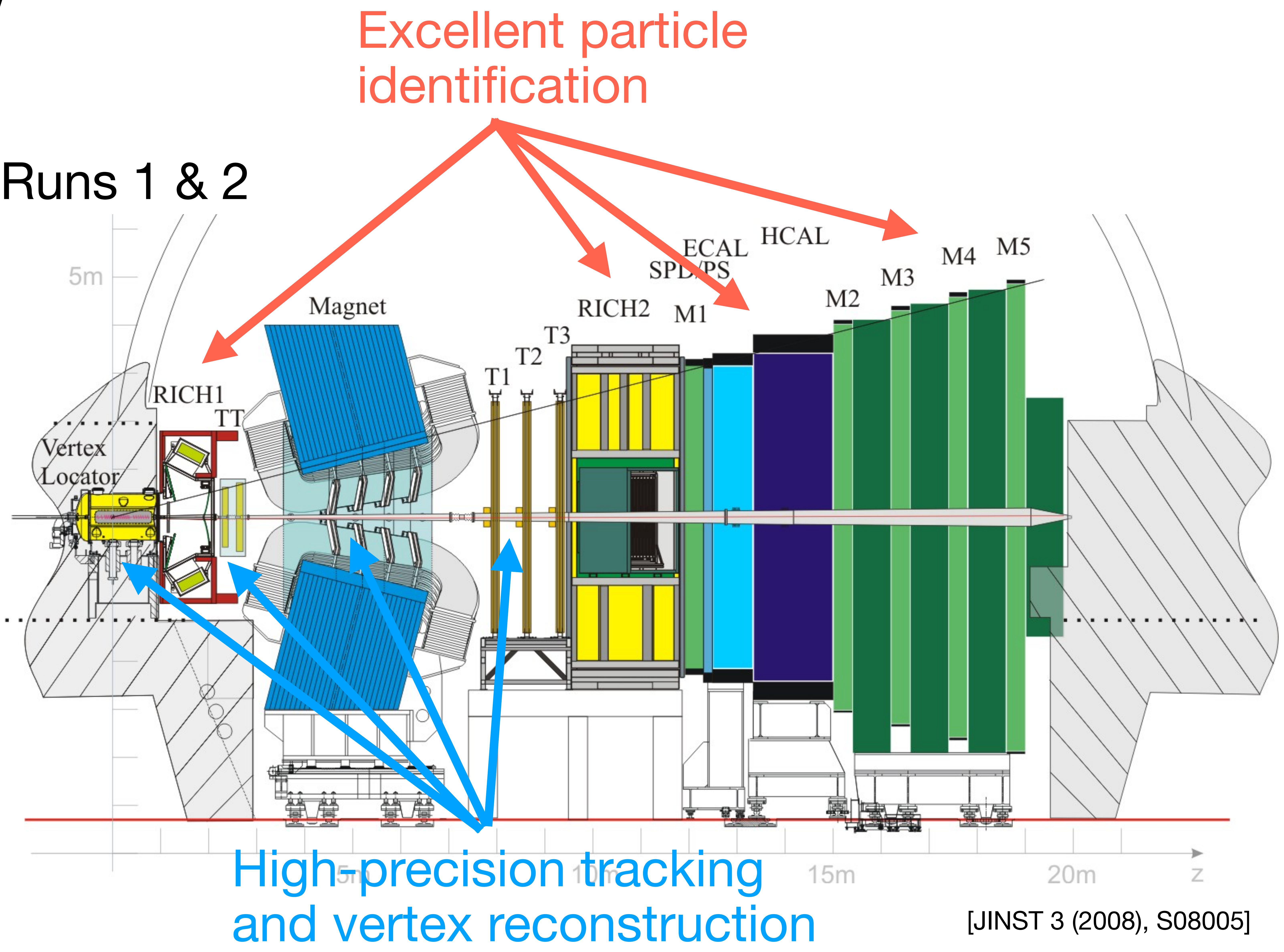
- The physics reach of LHCb is extended by exploiting subdetectors far from the interaction point to identify LLP decays
- With the ***Downstream* algorithm** we can now identify particles decaying up to **2 m** forward of the interaction point in HLT1
- Reconstructing **decays in the magnet region** allows to select decays up to **7.6 m** forward of the interaction point
- Increases available decay region from **centimetres** to **metres** in the forward region
- This enables studies of new channels and electromagnetic **dipole moment** measurements
- **LHCb** can contribute further to lifetime frontier on a **short timescale** with new BSM searches
- Stay tuned for future results

Backup

LHCb overview

- Forward-arm spectrometer with a focus on c- and b-physics
- Phase space region $2 < \eta < 5$ forward of the interaction point
  - Complementary to ATLAS and CMS

Runs 1 & 2

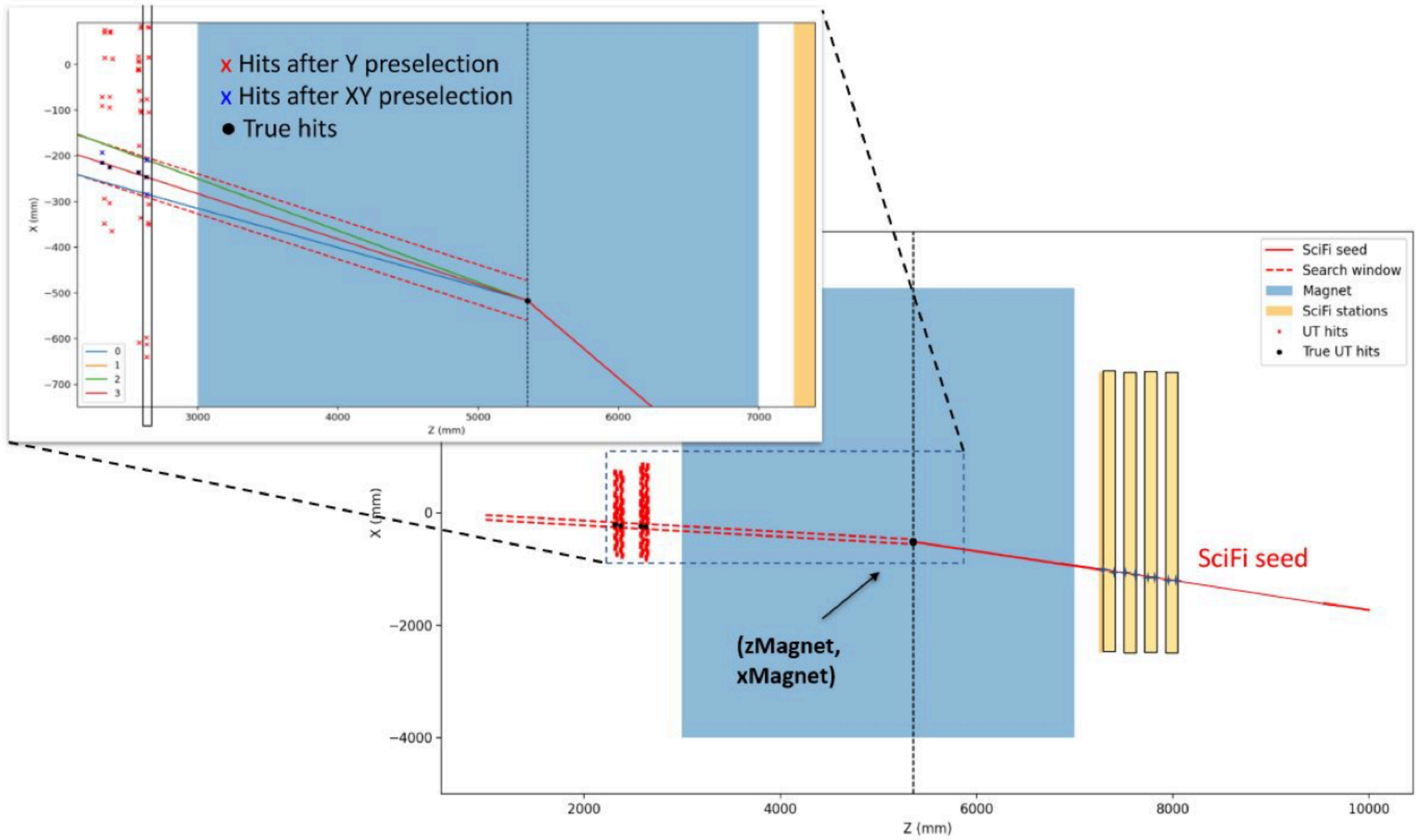


[JINST 3 (2008), S08005]

HLT1 Downstream track model [From CTD2023]

Algorithm design: track model

$$\vec{S}_i = (x, y, t_x, t_y, q/p)^T$$



Particle movement through magnet (Kink)

$$z_{\text{Magnet}} = \alpha_0 + \alpha_1 \cdot t_y^2 + \alpha_2 \cdot t_x^2 + \alpha_3 \cdot \frac{q}{p} + \alpha_4 \cdot |x_{\text{SciFi}}| + \alpha_5 \cdot |y_{\text{SciFi}}| + \alpha_6 \cdot |t_y| + \alpha_7 \cdot |t_x|.$$

$$x_{\text{Magnet}} = x_{\text{SciFi}} + t_{x_{\text{SciFi}}} \cdot (z_{\text{Magnet}} - z_{\text{SciFi}}).$$

$$y_{\text{Magnet}} = (y_{\text{SciFi}} + dy) + t_{y_{\text{Magnet}}} \cdot (z_{\text{Magnet}} - z_{\text{SciFi}}).$$

$$t_{y_{\text{Magnet}}} = t_{y_{\text{SciFi}}} + dt_y.$$

dy and dt_y are the special extrapolation corrections In y_{Magnet} since its extracted from stereo tilt

$$dy = \beta_0 + \beta_1 \cdot y_{\text{SciFi}} + \beta_2 \cdot t_{y_{\text{SciFi}}} + \beta_3 \cdot q/p.$$

$$dt_y = \gamma_0 + \gamma_1 \cdot y_{\text{SciFi}} + \gamma_2 \cdot t_{y_{\text{SciFi}}} + \gamma_3 \cdot q/p.$$

HLT1 Downstream track model [From CTD2023]

Algorithm design: track model

First slope estimation

$$\text{First\_}t_{xUT} = \frac{x_{\text{Magnet}}}{z_{\text{Magnet}}} + dt_x,$$

Correction to the first slope

$$dt_x = \alpha_0 + \alpha_1 \cdot t_{y_{\text{SciFi}}} + \alpha_2 \cdot q/p.$$

Expected position at layer_i

$$y_{\text{layer}_i} = y_{\text{Magnet}} + t_y \times (z_{\text{layer}_i} - z_{\text{Magnet}}),$$
$$x_{\text{layer}_i} = x_{\text{Magnet}} + t_x \times (z_{\text{layer}_i} - z_{\text{Magnet}}).$$

(Find UT hits and build UT track)

Tolerances:

For X layers i.e. UTbX and UTaX

$$T(layer_i) = \alpha_0 + \alpha_1 \cdot |q/p|$$

For UV layers i.e. UTbV and UTaU

$$T(layer_i) = \alpha_0 + \alpha_1 \cdot |q/p| + \alpha_2 \cdot |(q/p)^2|$$

Momentum estimation

$$q/p = \frac{\Delta_{\text{slope}}}{\gamma_0 + \gamma_1 \cdot t_x^2 + \gamma_2 \cdot t_y^2} \cdot \text{magnet\_polarity}$$

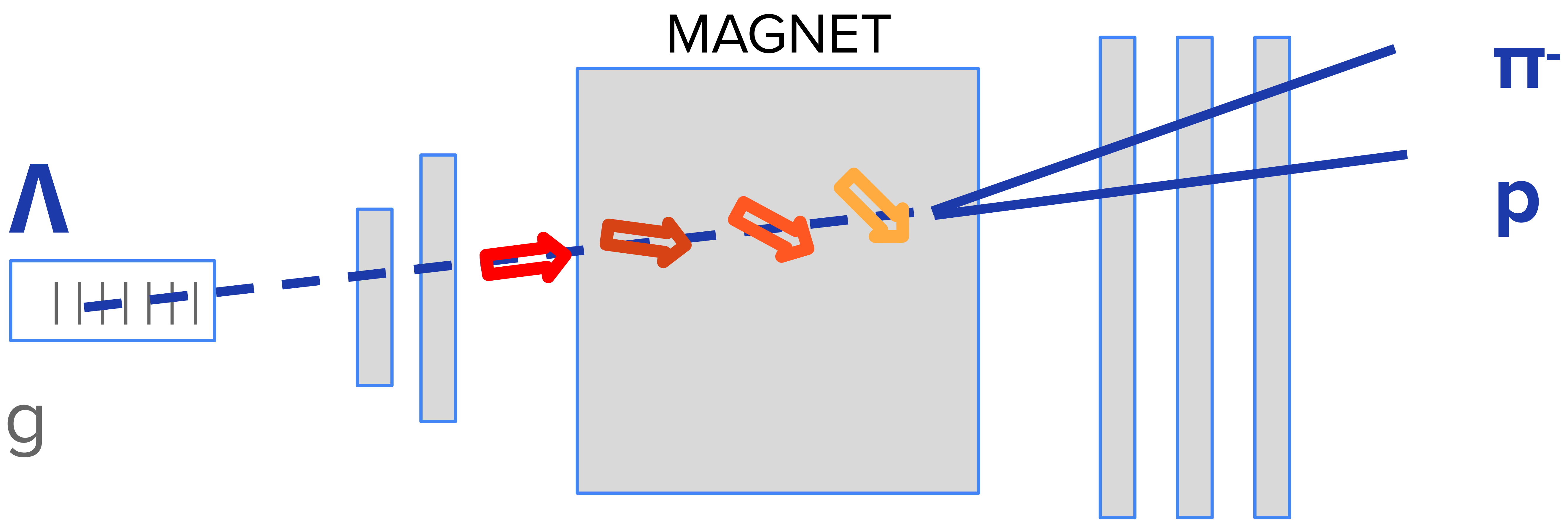
[1] Phys. Rev. Lett., 2:435–436, May 1959

Λ electromagnetic dipole moments: how?

METHOD: spin polarization **precession** in a magnetic field

Dynamics of spin in an external magnetic field given by the T-BMT equations [1], in the lab frame:

$$\frac{d\vec{P}}{dl} = \vec{P} \times \vec{\Phi}$$



Λ baryons are neutral particles, assuming

E = 0 (as in LHCb detector)

$$\vec{\Phi} = \frac{\mu_B}{\beta\hbar c}\left[g\left(\vec{D} - \frac{\gamma\beta(\vec{\beta}\cdot\vec{D})}{\gamma+1}\right) + d\vec{\beta}\times\vec{D}\right], \ \vec{D} = \int \vec{B}dl \,,$$

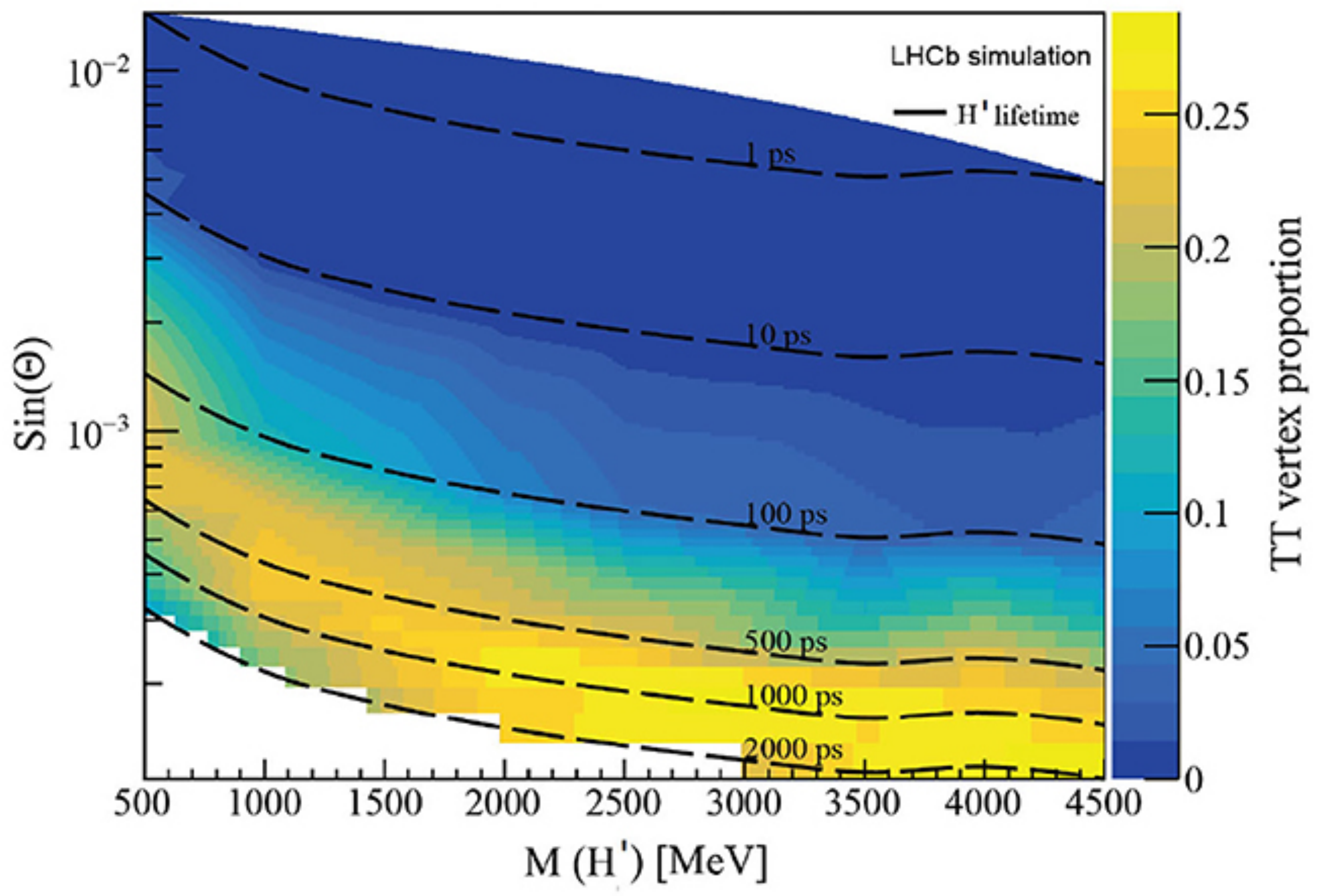
T-BMT equation of motion: $\vec{\omega}' = \vec{\Phi}/\Phi,$

$$\vec{P}(l) = (\vec{P}_0\cdot\vec{\omega}')\vec{\omega}' + [\vec{P}_0 - (\vec{P}_0\cdot\vec{\omega}')\vec{\omega}']\cos\phi + (\vec{P}_0\times\vec{\omega}')\sin\phi$$

Decays in the magnet region

- Trigger in HLT1 in progress for these types of decays to increase trigger efficiency
  - Uses a bespoke track model to account for inhomogeneous magnetic field
  - Events selected using NN

$B^0 \to K^{(*)} H'(\to \mu\mu)$



[Front.Big Data 5 (2022), 1008737]