Searches for very long-lived particles in LHCb

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on behalf of the LHCb collaboration

LLP2024: Fourteenth workshop of the Long-Lived Particle Community
4/7/24

Today

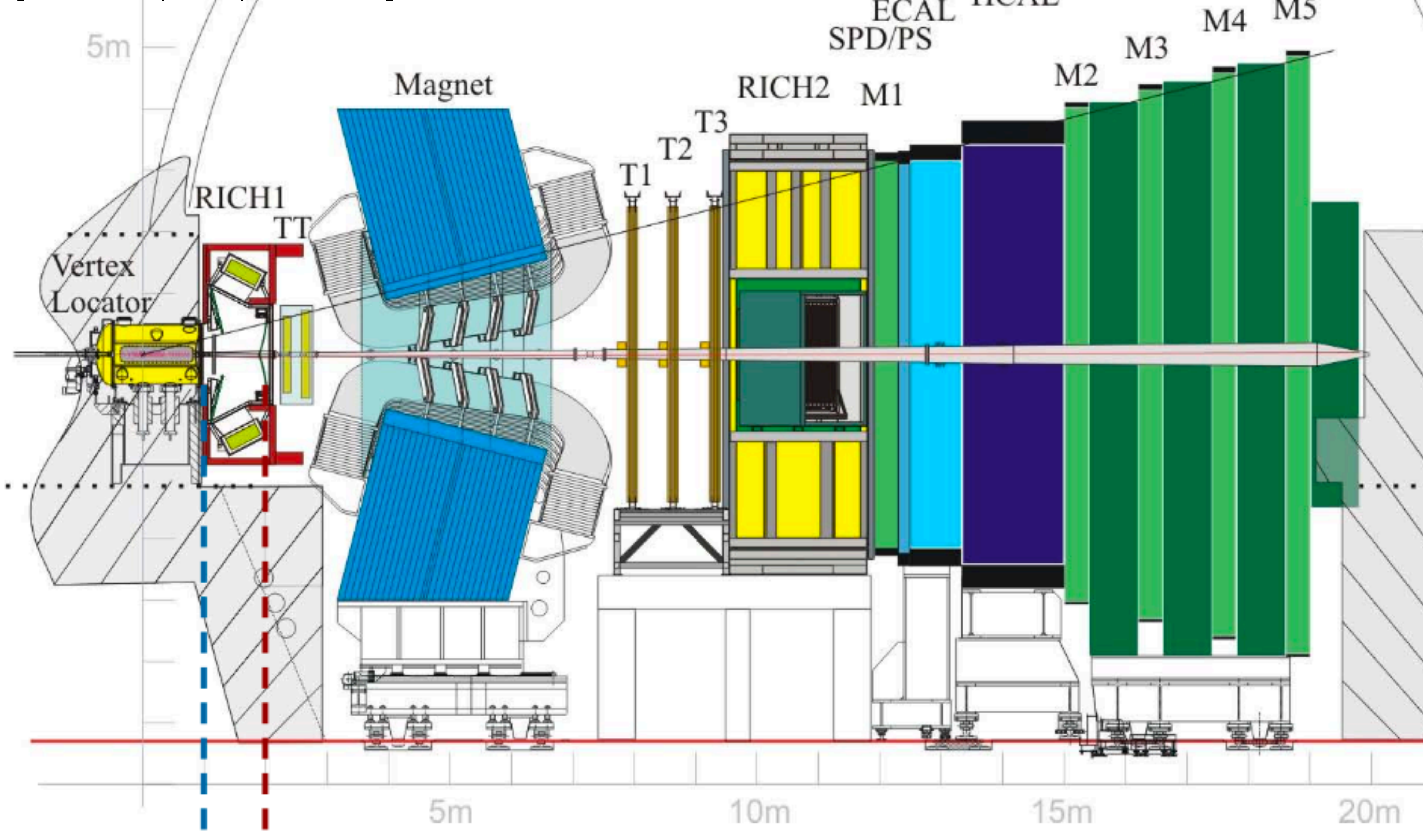
- LHCb overview
- LHCb trigger
- Very long-lived decays before the magnet region
- Very long-lived decays in the magnet region
- Very long-lived decays in the muon stations
- Summary and prospects

Introduction

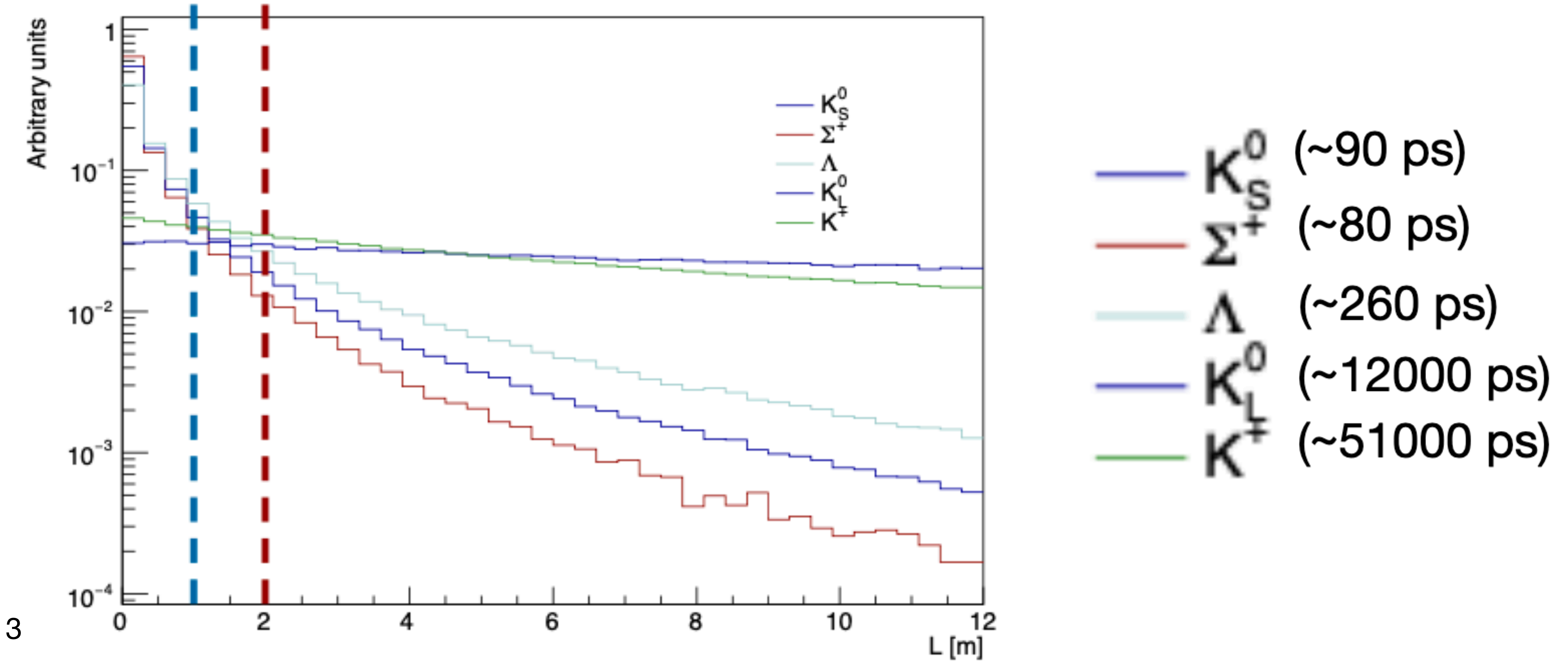
In a nutshell

- What do I mean by a very long lived particle (LLP)?
    - Here we will talk about reconstructing LLPs with **lifetimes > 100 ps**
    - These decay topologies can happen **metres from the interaction point**
- How are we doing this?
    - Until now, LLP searches 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**
    - Made possible through **upgraded detector** and **fully software trigger**

[JINST 3 (2008), S08005]



[JHEP 05 (2019), 048]

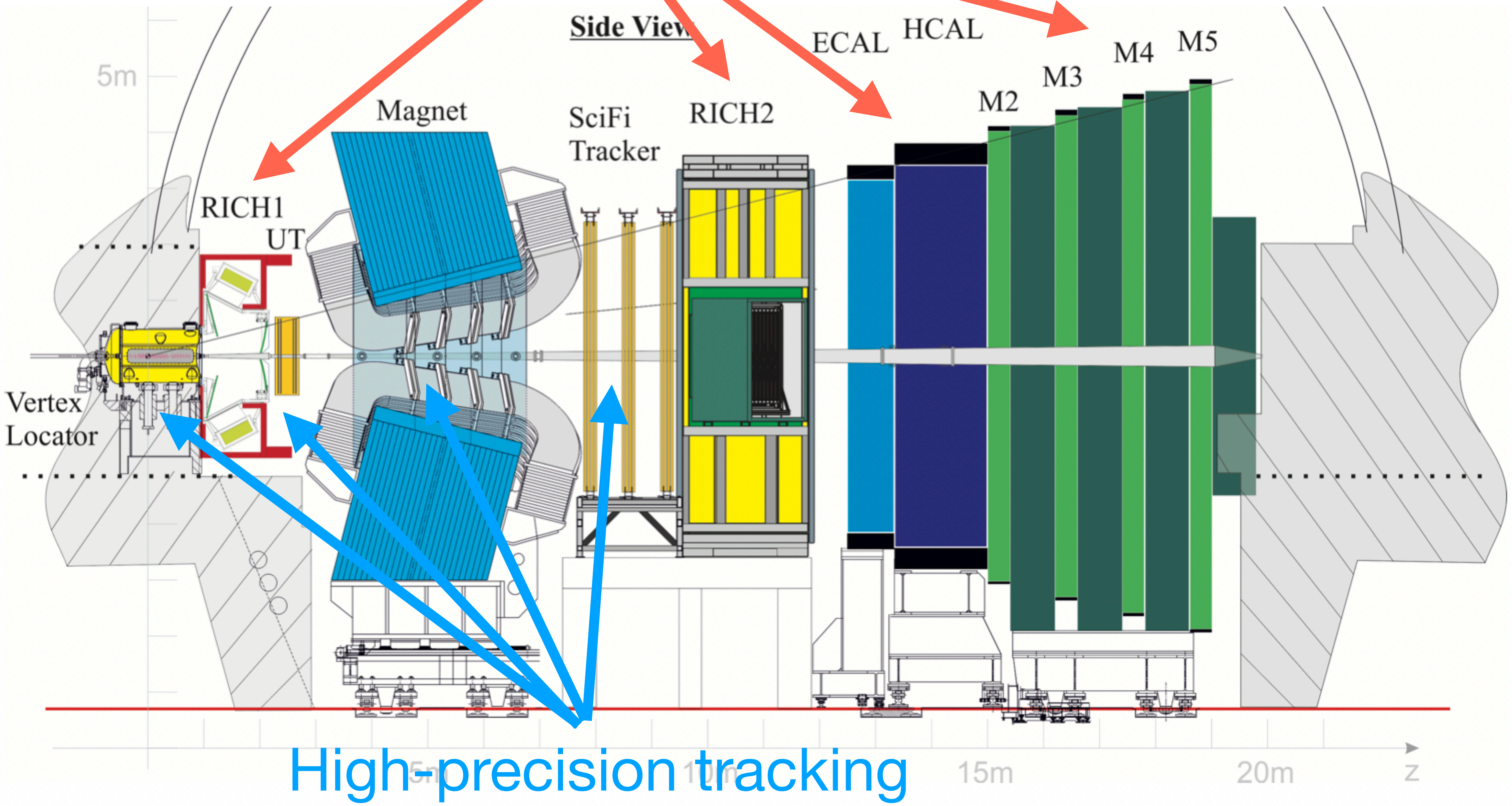


LHCb overview

LHCb overview

Excellent particle identification

- 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



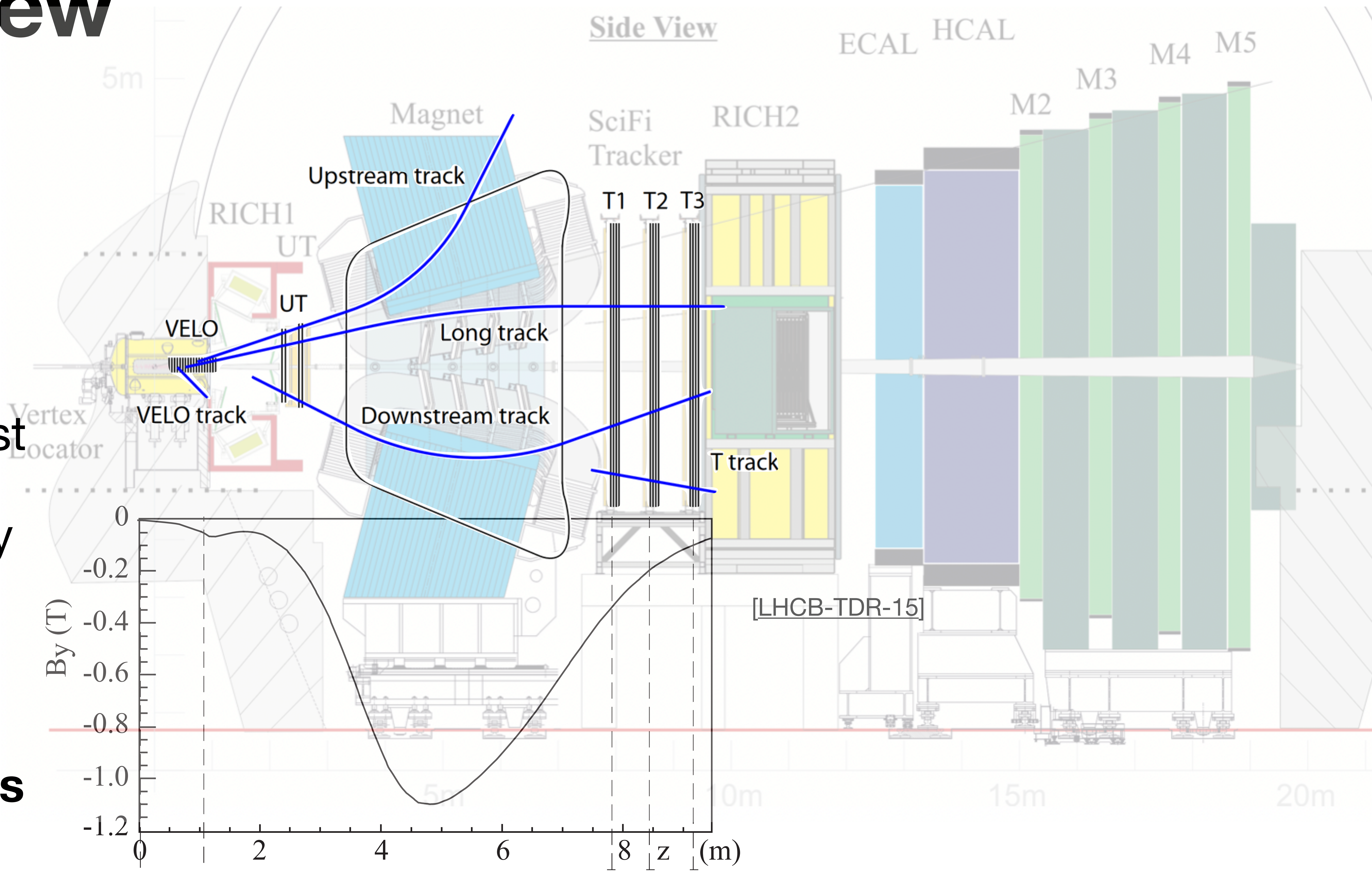
High-precision tracking and vertex reconstruction

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

LHCb overview

Track types

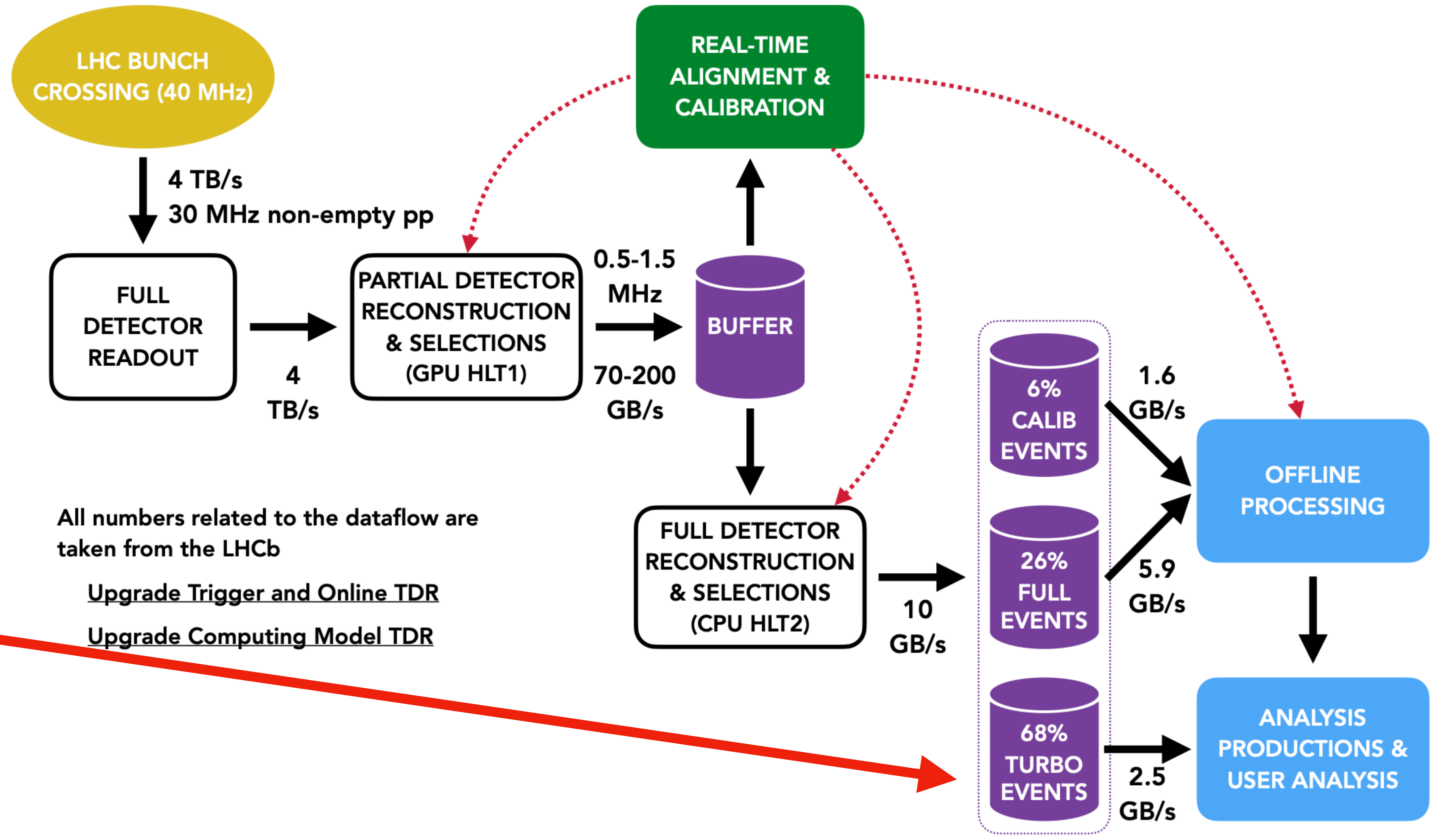
- Tracks named according to where they have hits
- Long tracks have best precision, but can only be used to study decays close to interaction point
- Using **Downstream** and **T tracks unlocks higher lifetimes**



[LHCB-TDR-15]

Trigger

- Fully software trigger
- Data analysed in real time (**Real Time Analysis,** RTA)
- Event rate reduced by factor 30 by HLT1, further factor 10 by HLT2
- **Selective persistence**
    - **Only information of interest is recorded** for future analysis in most cases
- In principle **all subdetectors can be accessed in lowest level trigger** which would be difficult with hardware triggers



[LHCB-TDR-021]

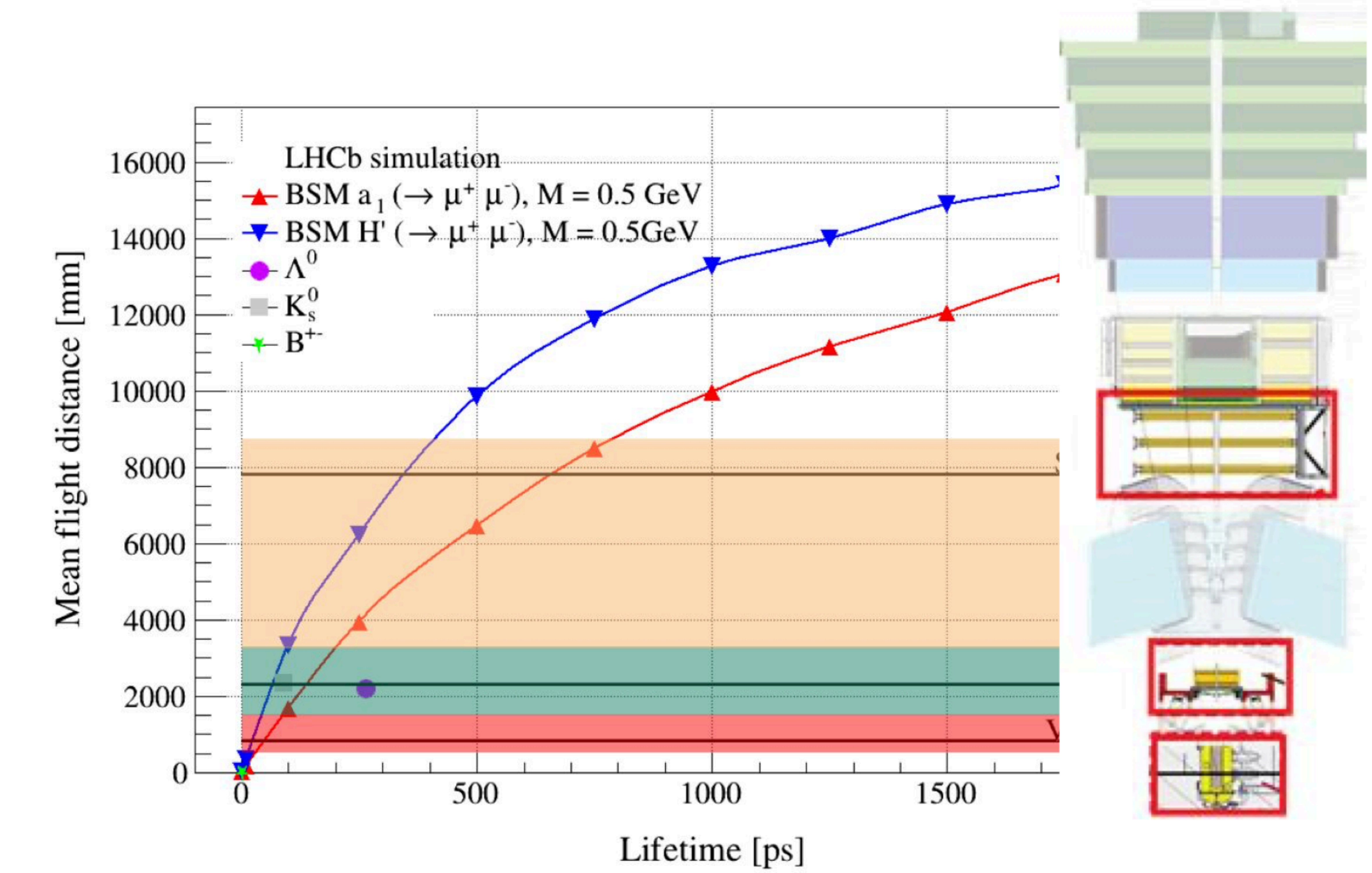
Very long-lived decays before the magnet region

Downstream

*Estimated from simulation

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

- **Downstream tracks** originate from decays between the VELO and the UT (up to 2 m from interaction point)
- Many particles with **lifetimes greater than 100 ps** will **decay outside the VELO**
    - Can be reconstructed with Downstream tracks
- Must be selected by **HLT1**
    - New ***Downstream* algorithm**

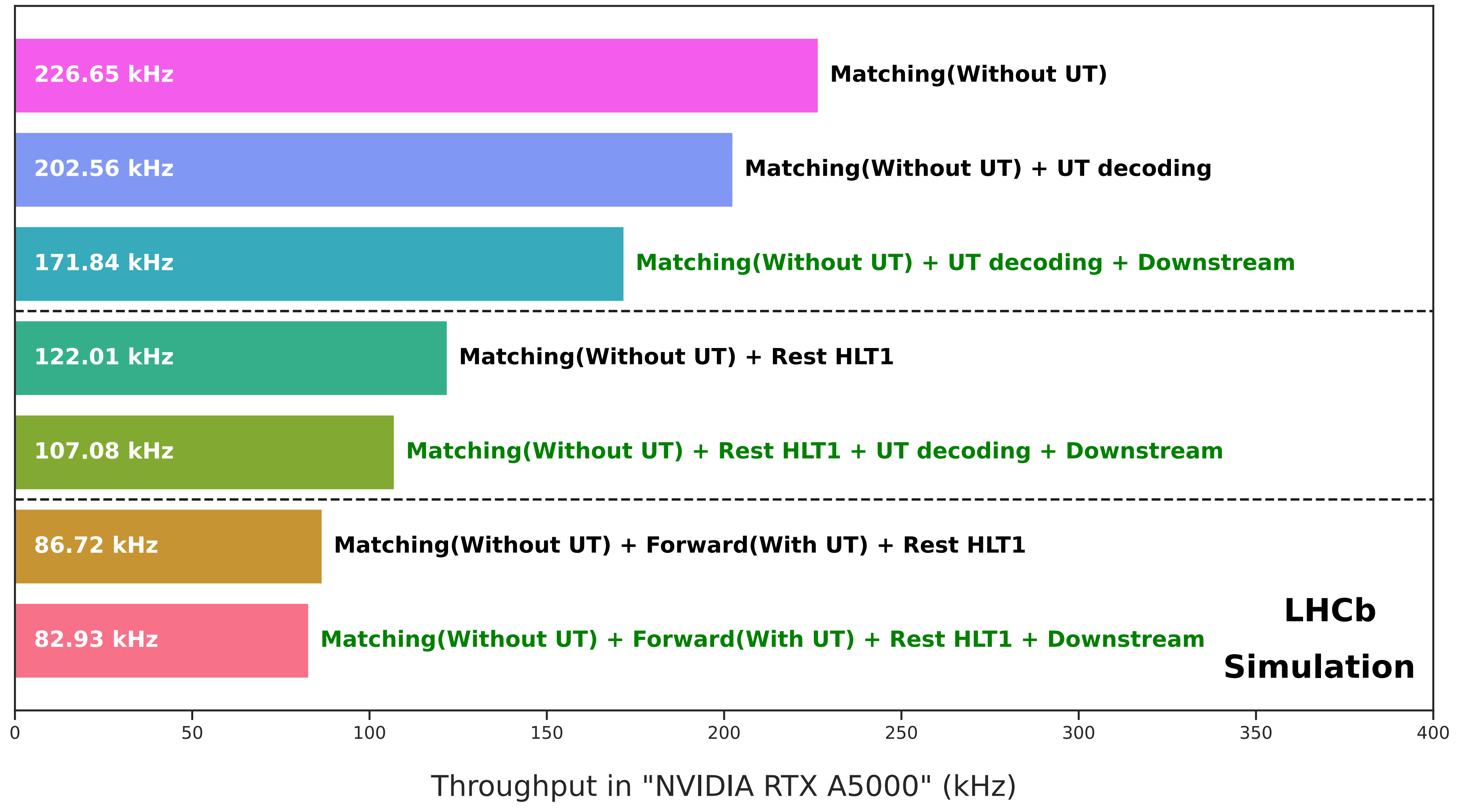


L. Calefice *et al*. (2022). Frontiers in Big Data, 2022.1008737

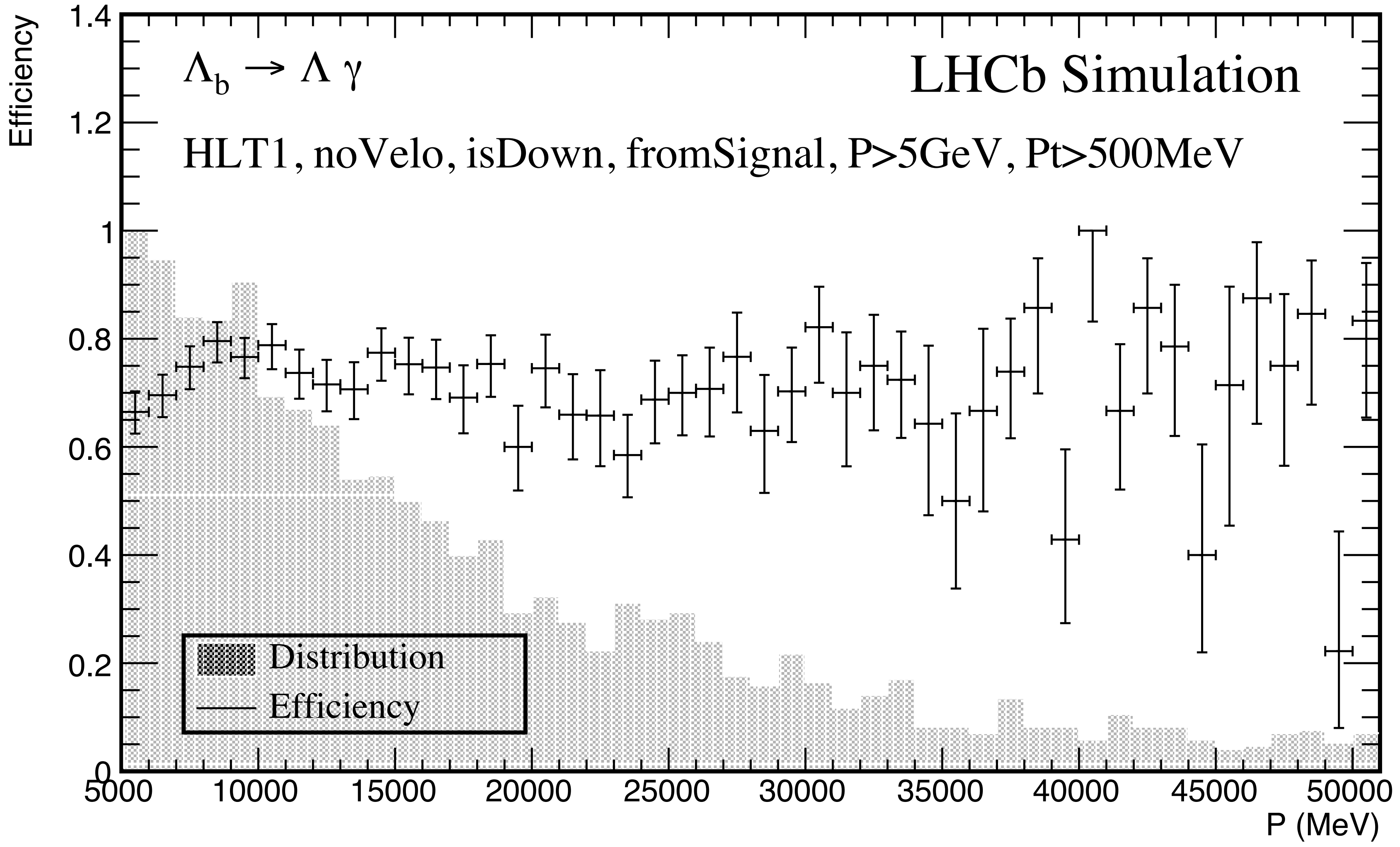
Downstream algorithm

Overview

- Developed to **increase sensitivity to Λ and K_S^0 decays**
- Expanded to **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 around 80% of ghost tracks



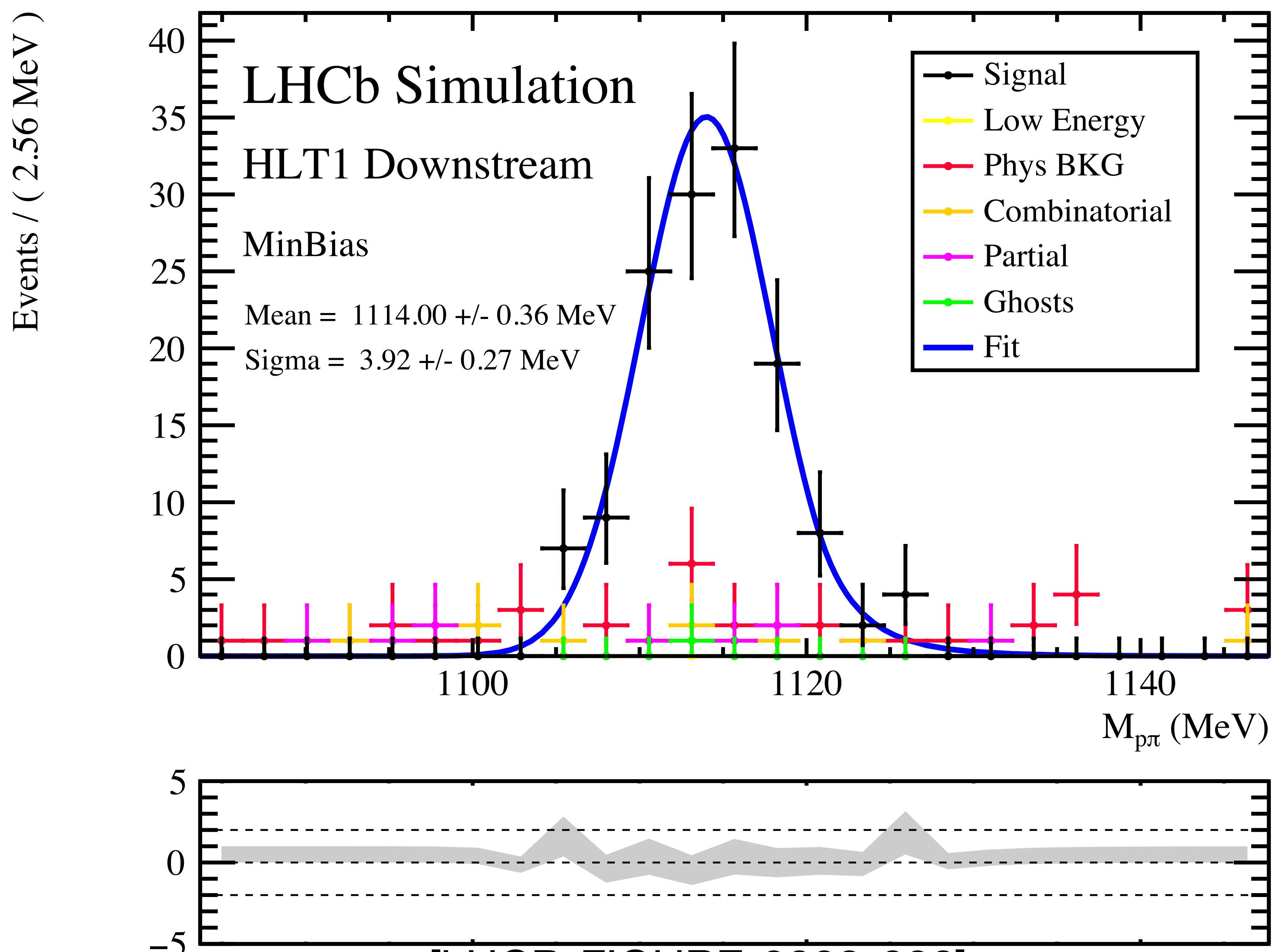
[LHCB-FIGURE-2023-028]



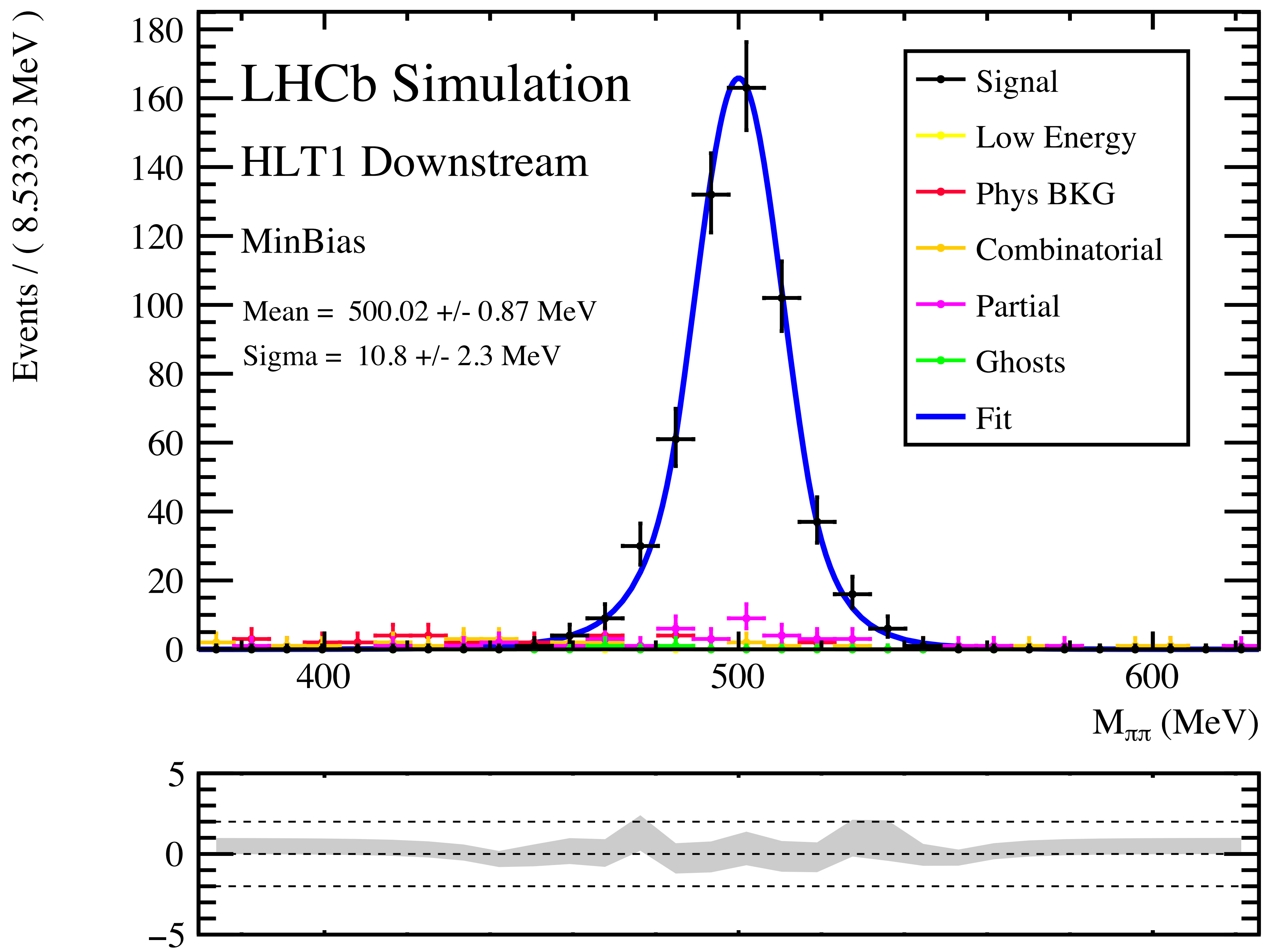
Downstream algorithm

Candidate selection

- Track extrapolation before UT is non-linear due to residual magnetic field in the region
  - $x(z) = x_0 + t_x(z - z_0) + \gamma(z - z_0)^2$
    - Where $\gamma = \gamma(q/p)$ is coefficient of track non-linearity
- **Kalman-filter based vertexing**
- Successfully reconstructs mass distribution of Λ and K^0_S
- **NN-based classifier** for monitoring and selection at HLT1



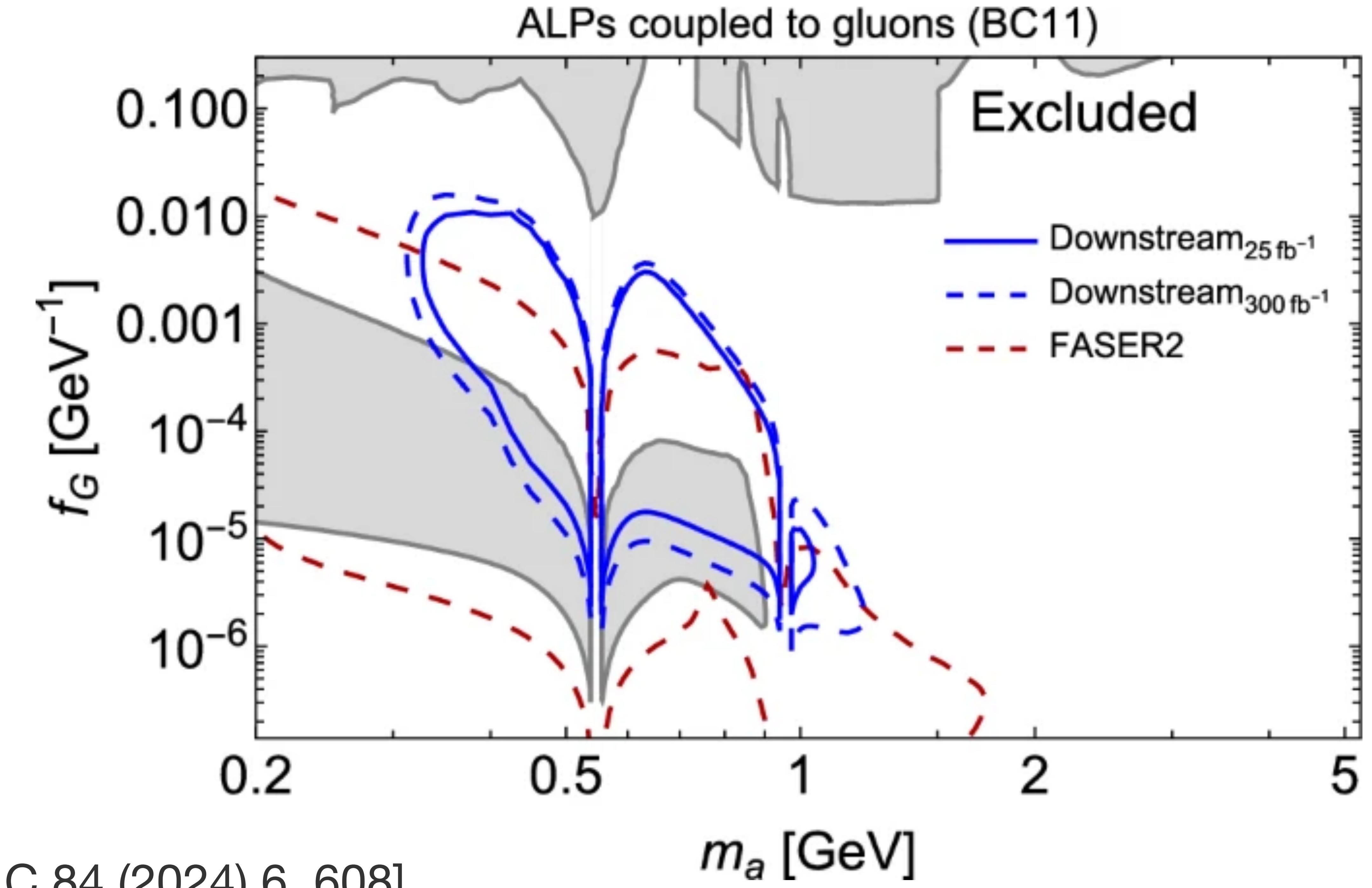
[LHCB-FIGURE-2023-028]



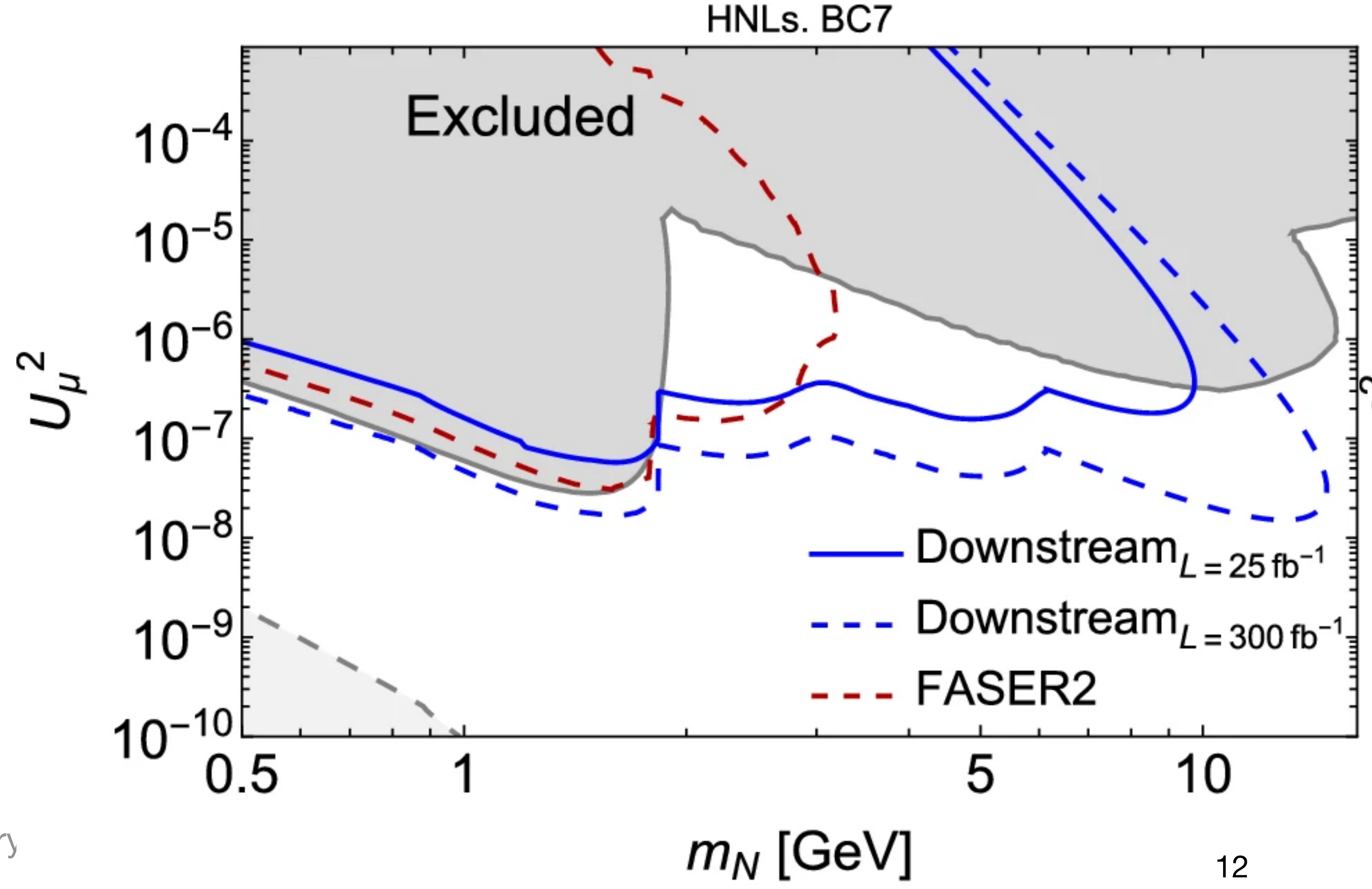
Prospects

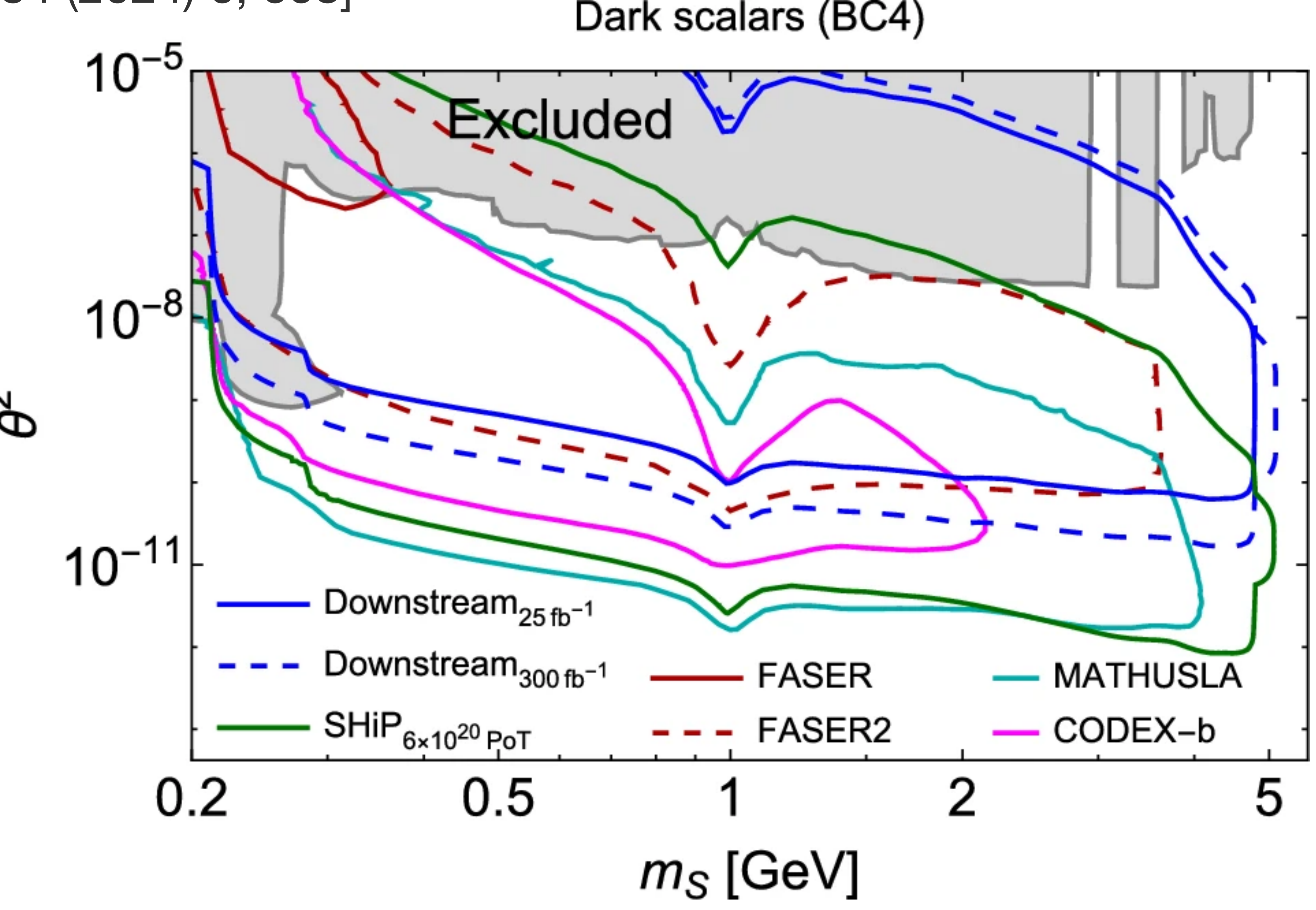
- Based on HLT1 efficiencies only (no HLT2 or offline selection considered), external paper [Eur.Phys.J.C 84 (2024) 6, 608]

- LHCb with Downstream is 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]

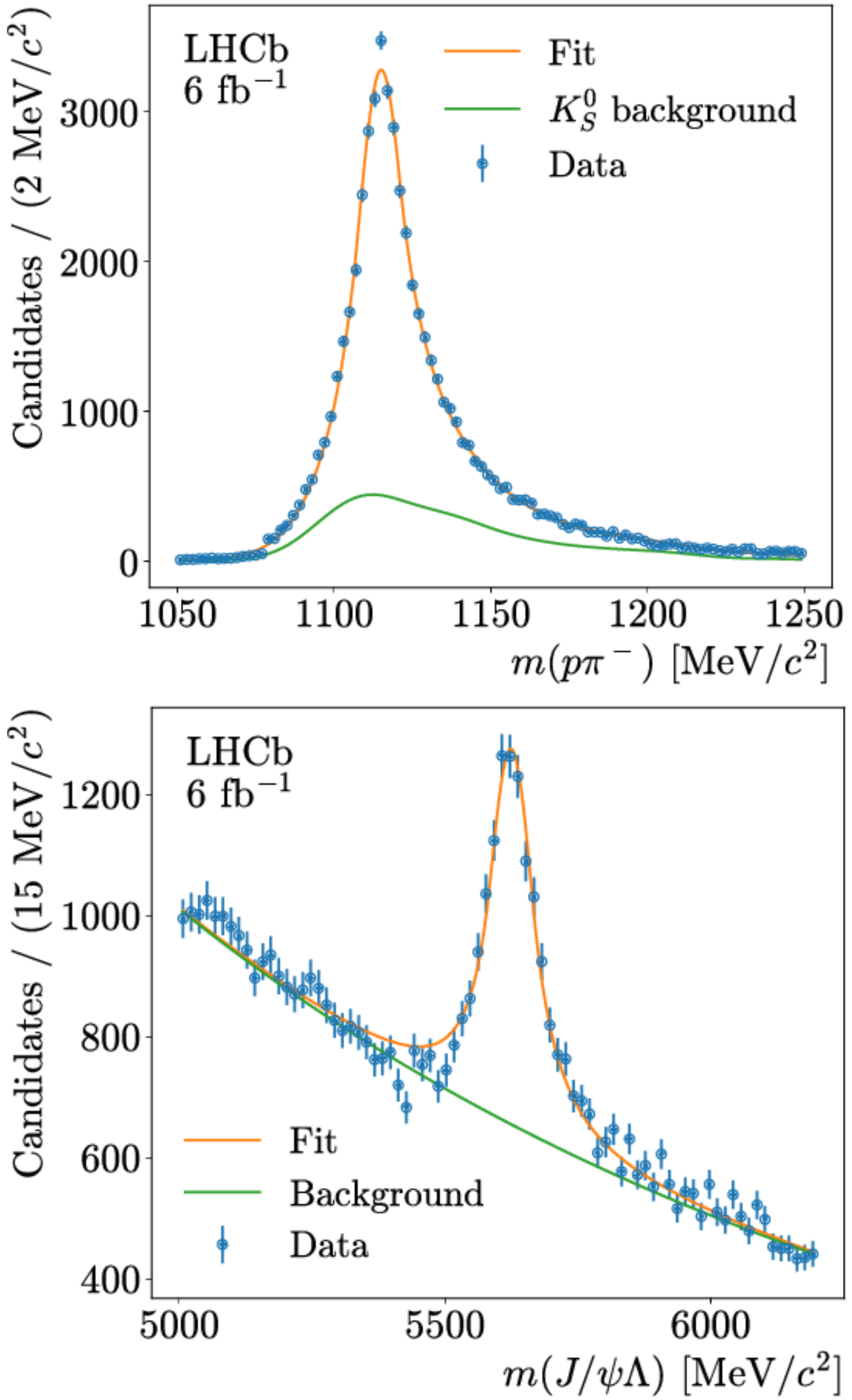




Very long-lived decays in the magnet region

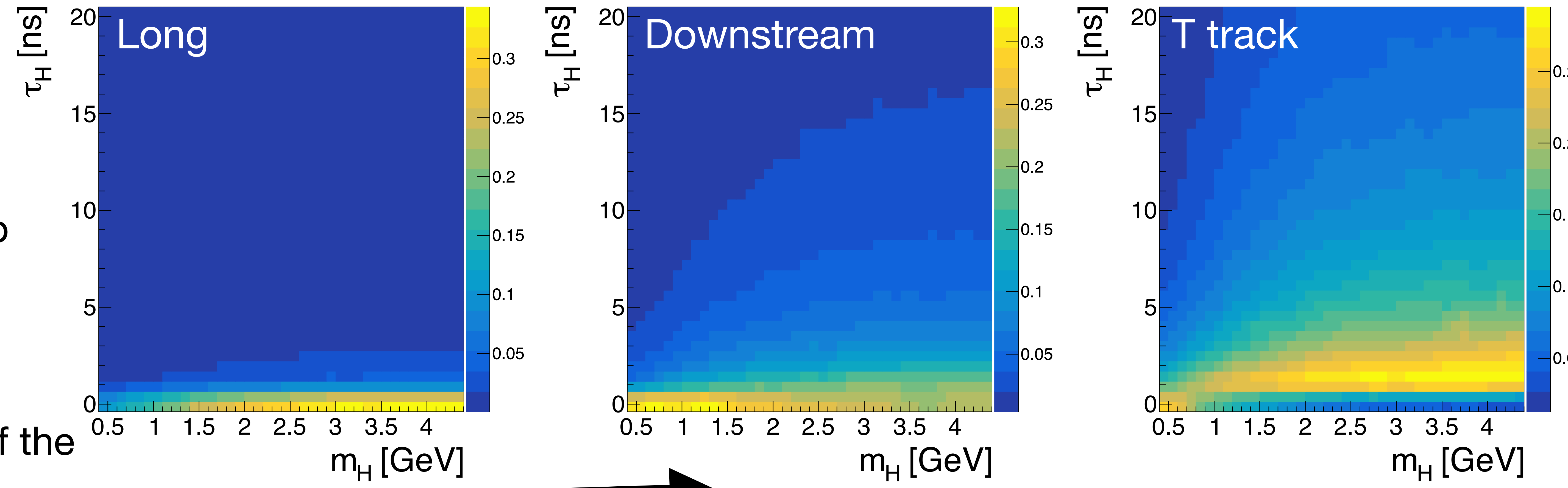
Decays in the magnet region

- 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

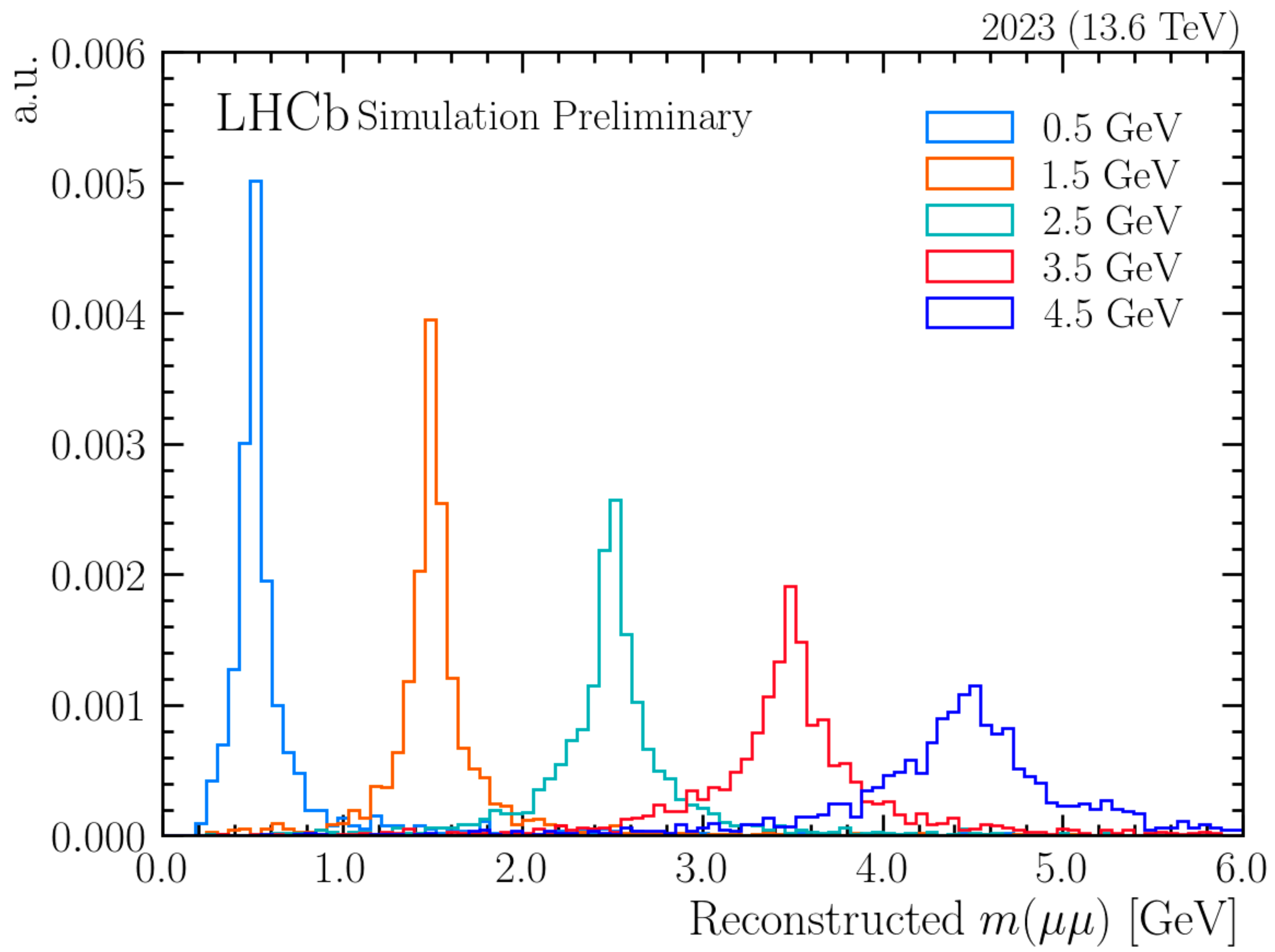


[arXiv:2211.10920]

Decays in the magnet region



- Searches with **T tracks** offer **complementary** acceptance to searches with **Long and Downstream tracks**
- Example shown $B^0 \rightarrow K^+H'(\rightarrow \mu^+\mu^-)$
- The acceptance efficiency changes with lifetime and mass of the LLP
- 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**
- The initial HLT2 lines depend on a Long track component to trigger HLT1
- Initial lines target **dark scalars** and **HNLs**

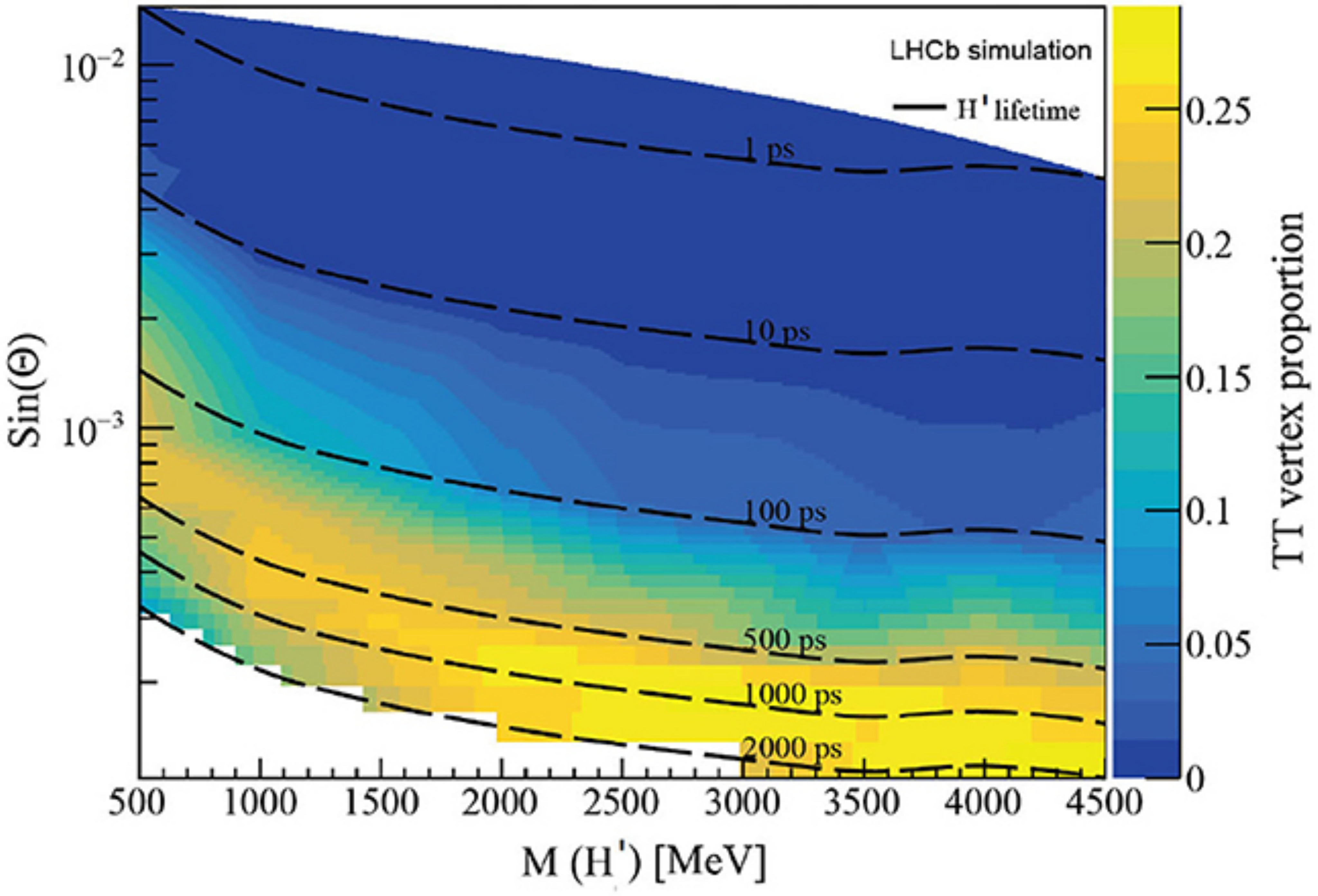


[LHCB-FIGURE-2023-026]

Decays in the magnet region

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

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

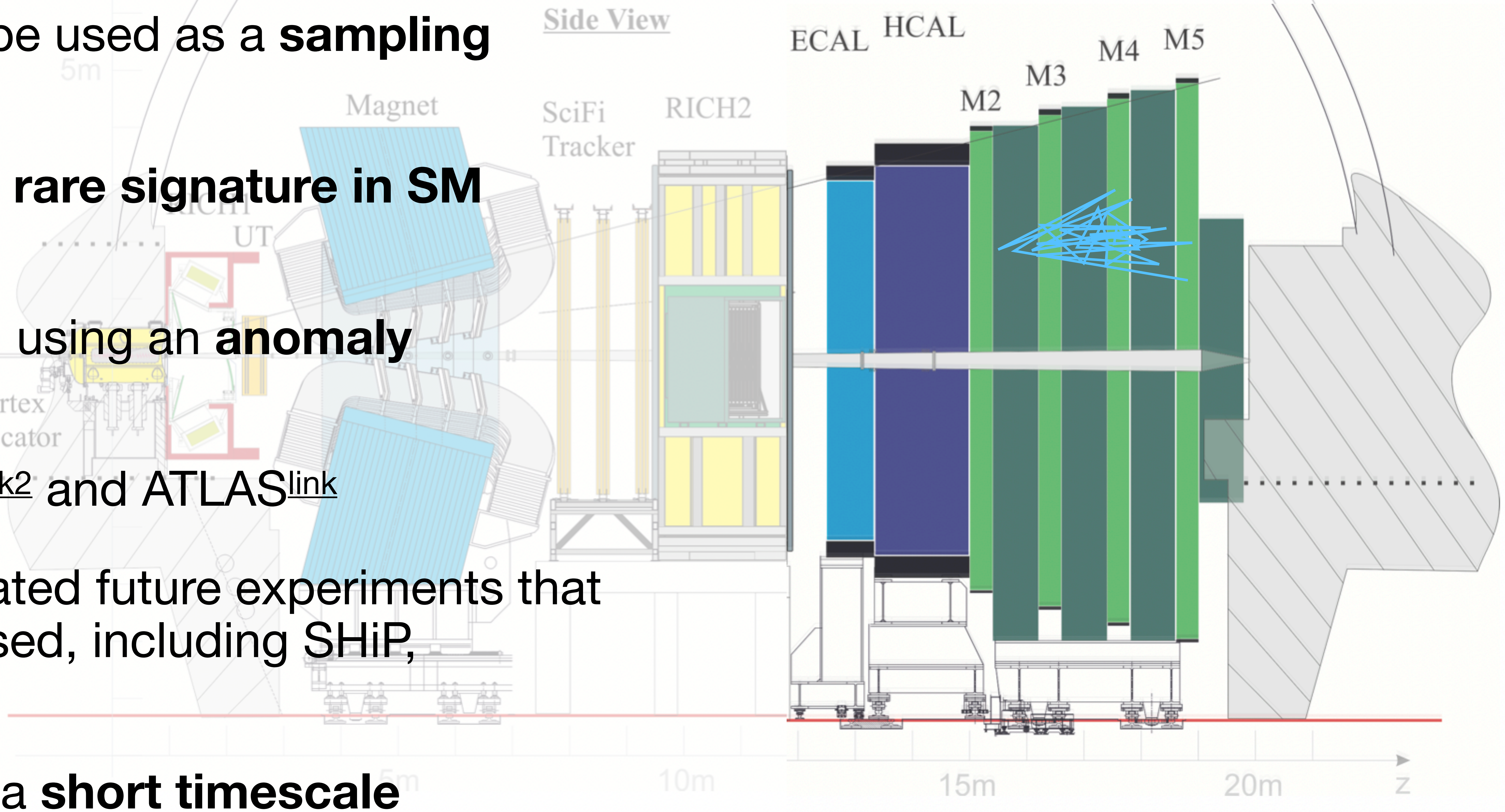


[Front.Big Data 5 (2022), 1008737]

Very long-lived decays in the muon stations

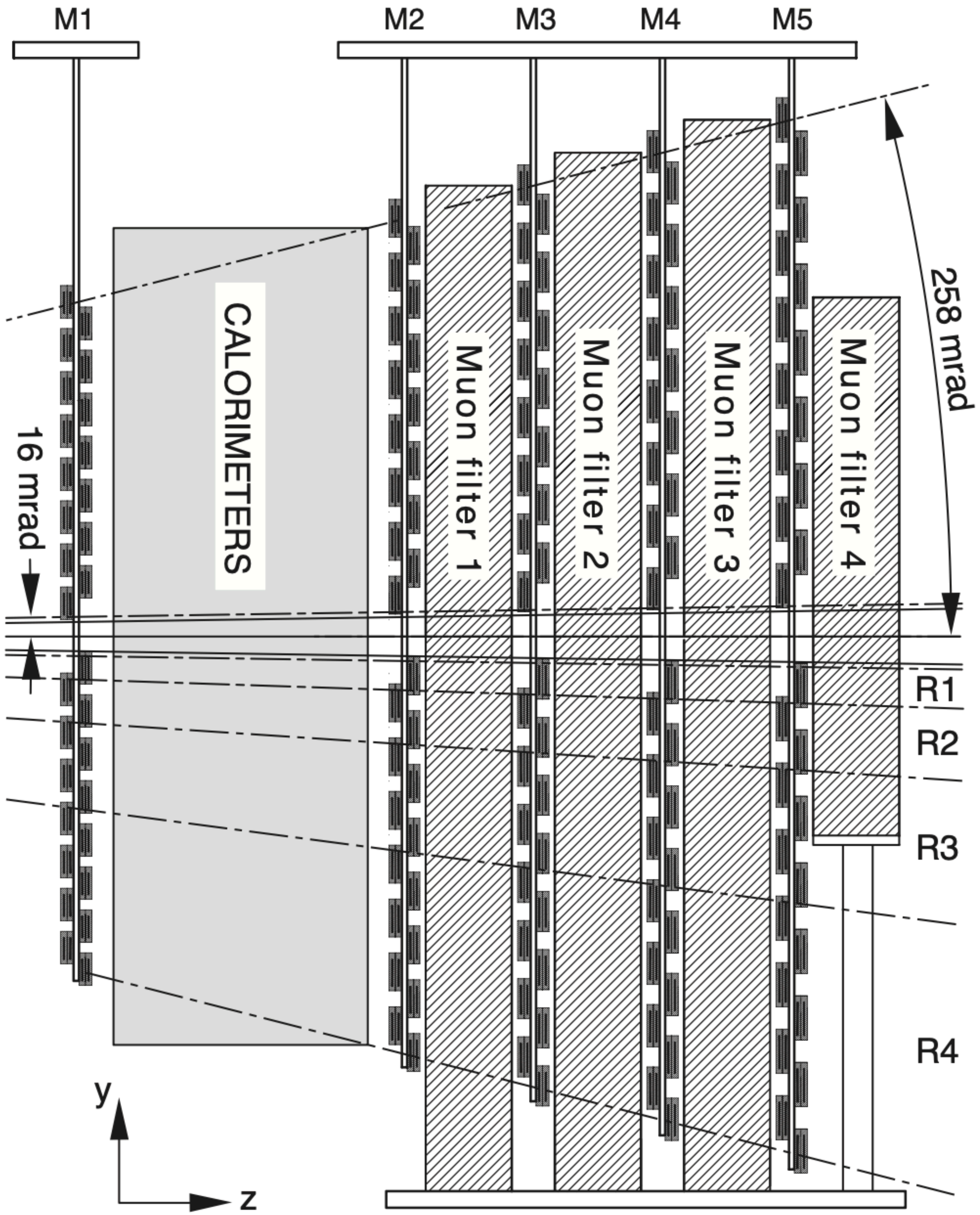
Muon showers

- The **muon system** in LHCb can be used as a **sampling calorimeter**
  - **Showers** in muon stations are **rare signature in SM physics**
    - Signatures can be detected using an **anomaly detection approach**
  - Similar searches by CMS[link1,link2] and ATLAS[link]
  - Approach to be used in dedicated future experiments that have been accepted or proposed, including SHiP, MATHUSLA, and others
  - **LHCb** is able to contribute on a **short timescale**



Muon stations

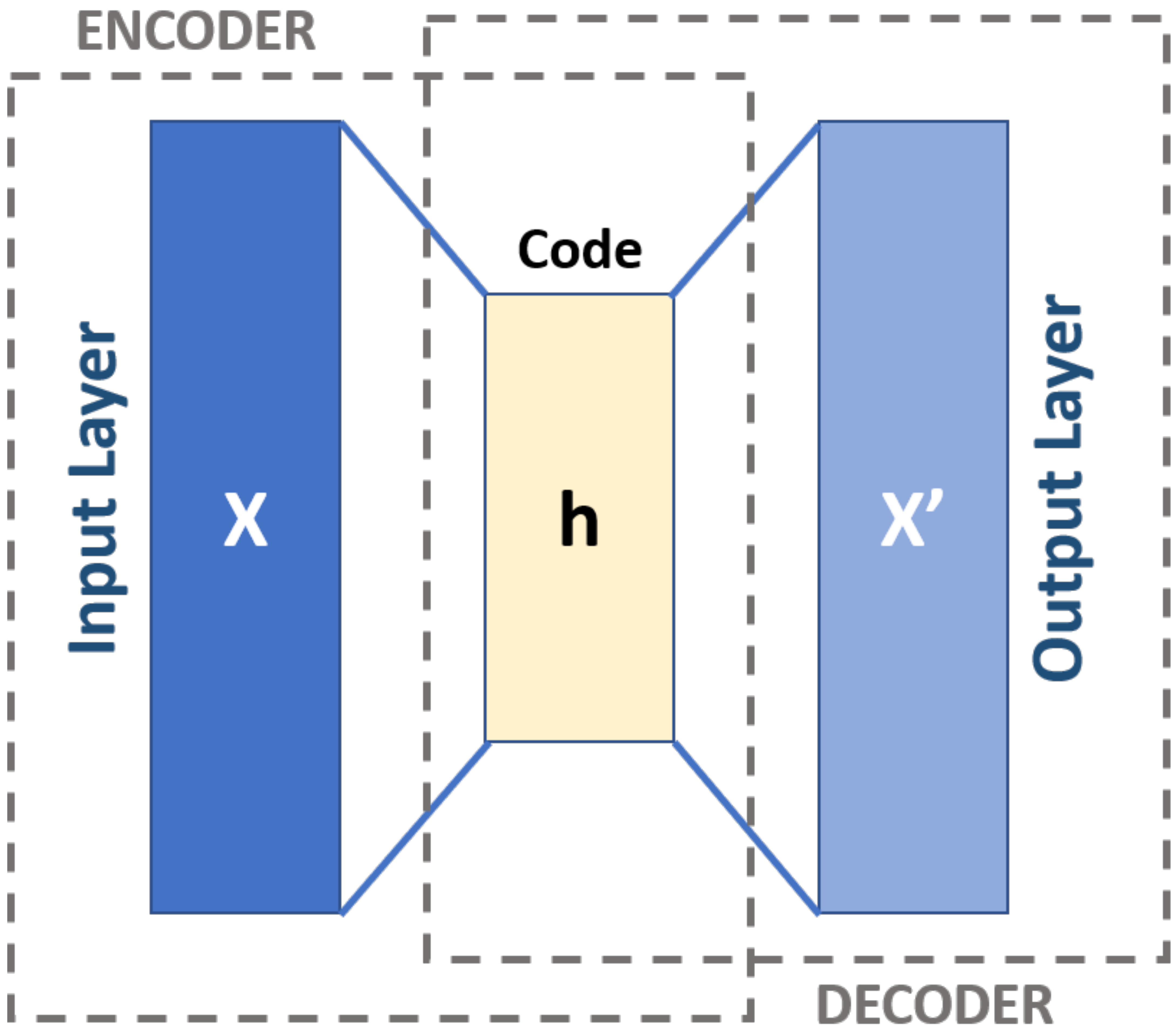
- Four multiwire proportional chambers (M2-M5) located about 15-19 m from interaction point
- Three iron layers of each $4.8\lambda_I$ (80 cm of iron)
- Large decay volume
- Not designed for shower detection — no energy deposit measurements
- Very clean environment



[CERN-LHCC- 2001-010] [LHCb-TDR-004]

Normalised autoencoders

- Signal identified through anomaly detection using **normalised autoencoders**
- These consist of **encoder** and **decoder neural networks**
    - Information **compression** and **decompression** to and from **latent space of lower dimensionality**
    - Train on **background** to minimise the **reconstruction error** (difference between original data and encoded then decoded data)
- Train on unfiltered pp interactions
    - Evaluate efficiency on axion sample considering only decays in muon chambers

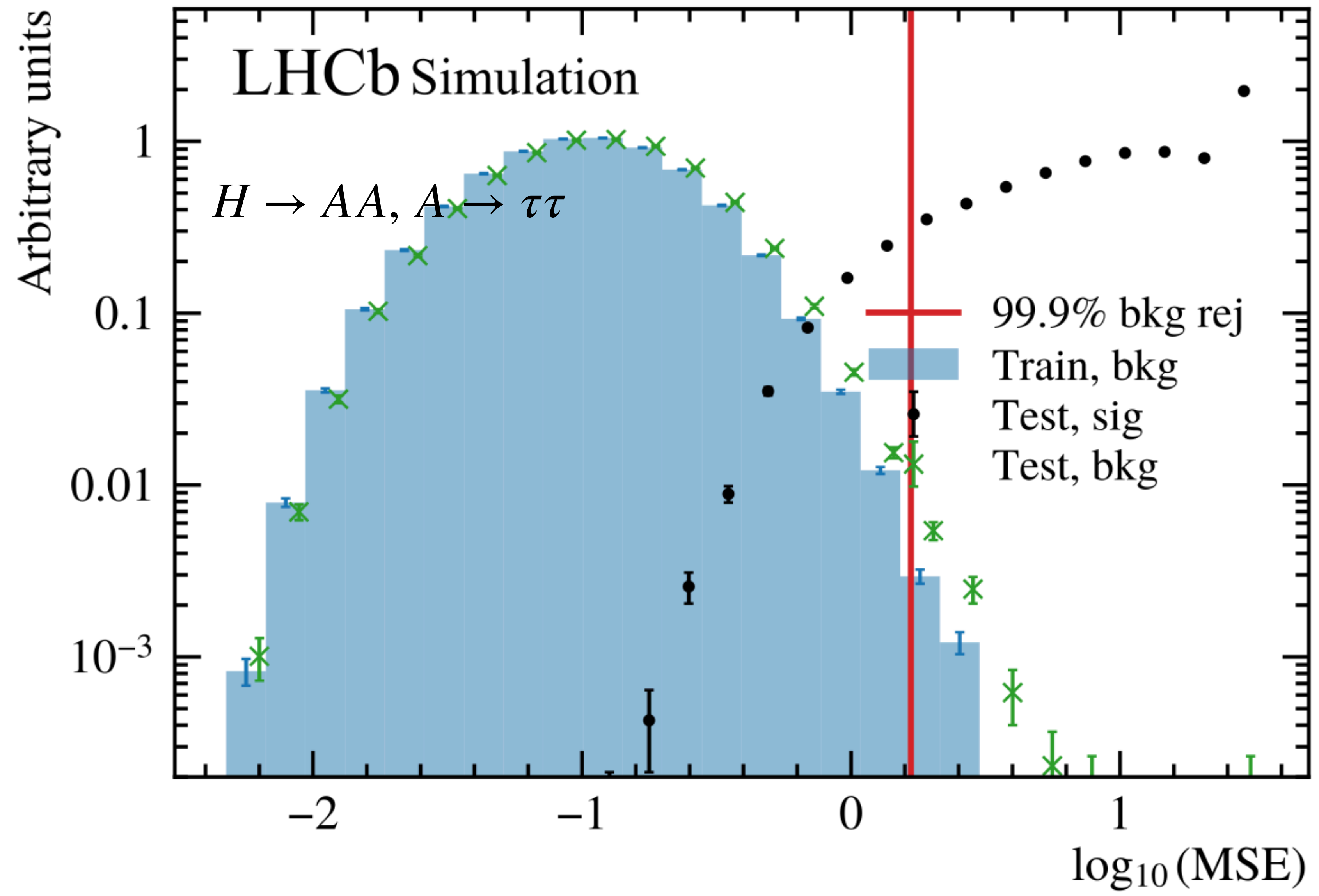


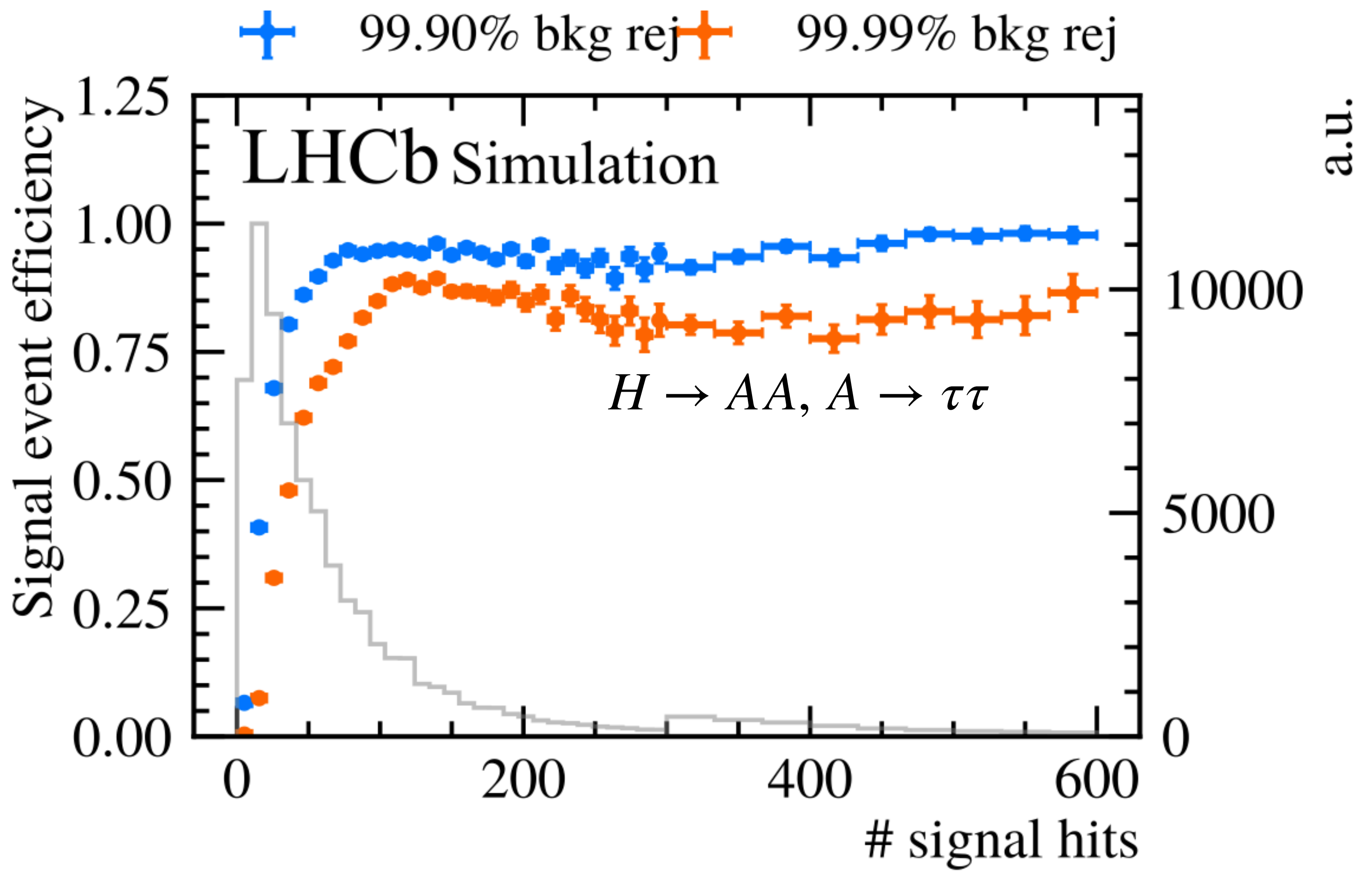
Source: wikipedia

Performance

- Reconstruction error provides a discriminant variable
  - Much larger for signal
- **Similar/better than BDT and NN classifiers** using signal samples
- Can be **fully data-driven** by training on only background taken from data
- Implemented now in HLT2
  - HLT1 coming soon

[LHCB-FIGURE-2024-015]





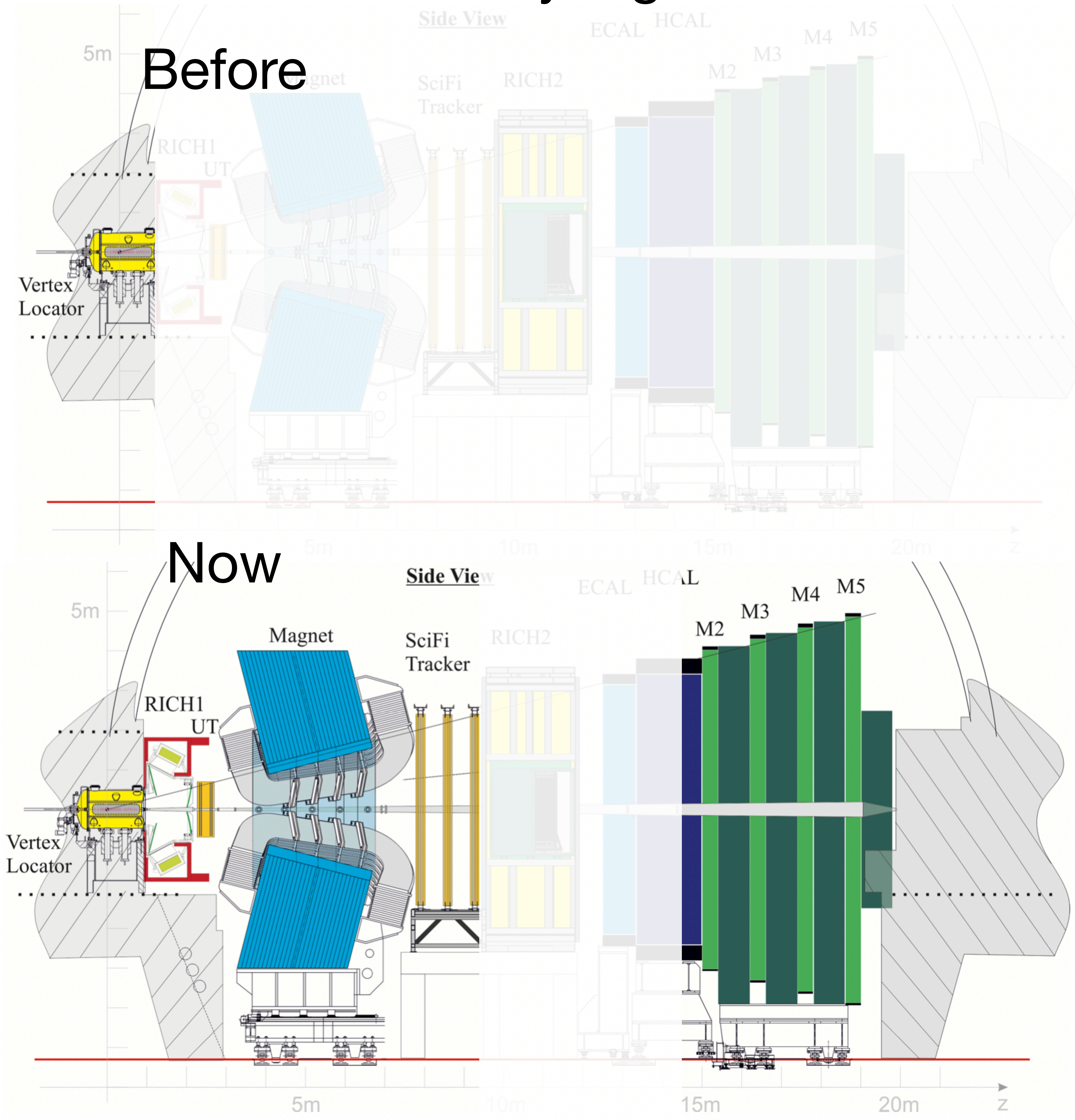
Sample	Efficiency [%]
Axion, 10 GeV	80.0 ± 0.5
HNL, 1.6 GeV	10.3 ± 0.3
HNL, 4 GeV	15.7 ± 0.3

Summary and prospects

Prospects

- The physics reach of LHCb is extended by exploiting subdetectors far from the interaction point to identify LLP decays
- This increases accessible lifetimes from **$\mathcal{O}$(100 ps) to $\mathcal{O}$(10 ns)**
- Increases available decay region from 10s **centimetres** to 10s **metres** in the forward region
- **LHCb** can contribute further to lifetime frontier on a **short timescale**
- Stay tuned for future results

Accessible decay regions



Summary

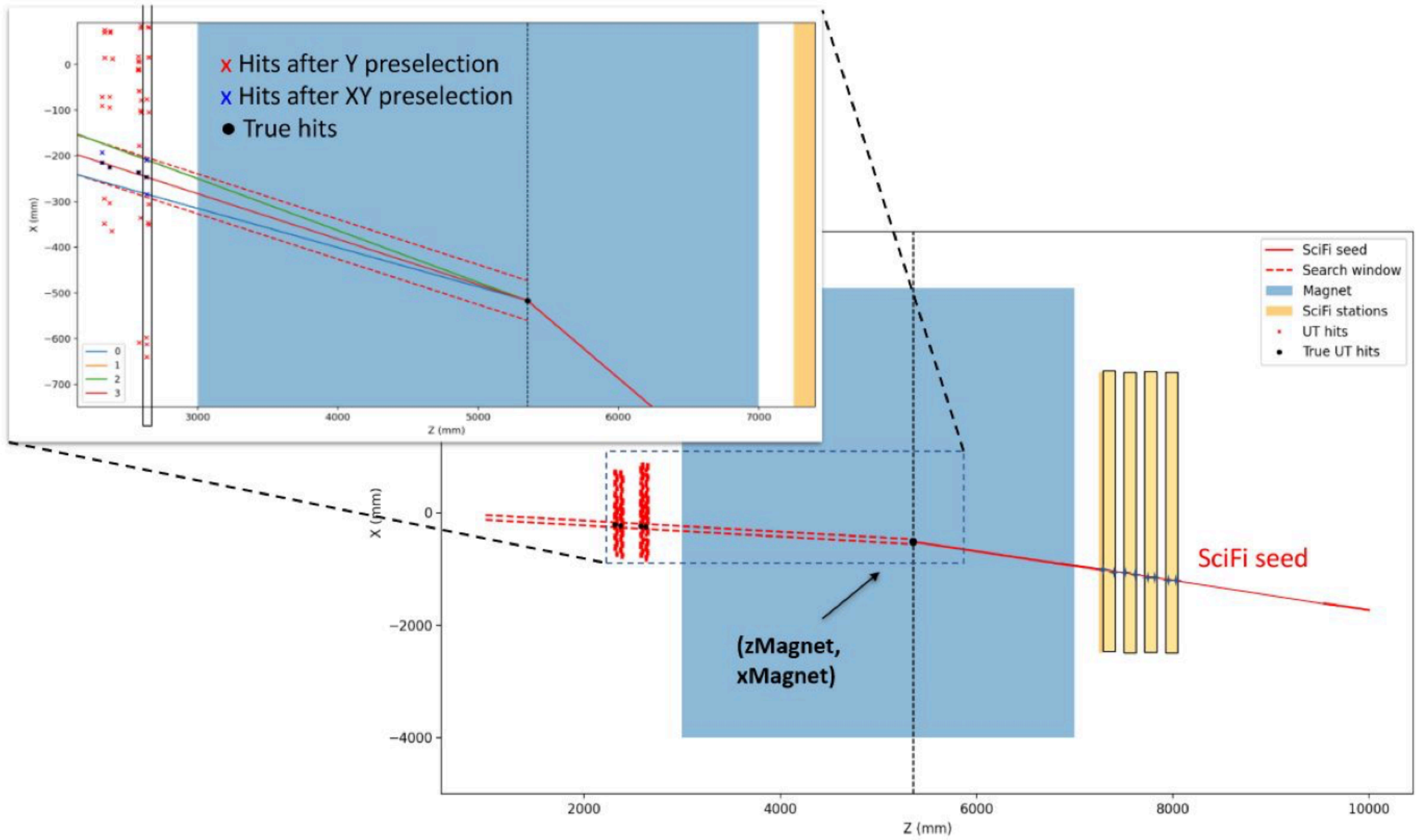
- Have shown three new approaches to reconstruct LLPs with lifetimes over 100 ps in LHCb
- With the ***Downstream* algorithm** we can now identify particles decaying up to **2 m** forward of the interaction point in HLT1
- Reconstructing **decays in the magnet region** allows to select decays up to **7.6 m** forward of the interaction point
- Identifying **decays in the muon chambers** using normalised autoencoders allows to reconstruct decays up to **19 m** from interaction point

Backup

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

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

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

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CTD2023 11.10.2023 A Downstream algorithm for HLT1 at LHCb

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

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