Searches for displaced Scalar decays to di-muons: LHCb's extended reach in Run 3

EPS-HEP 2025 - Marseille

Simone Libralon on behalf of the LHCb Collaboration | Marseille | 9/07/2025

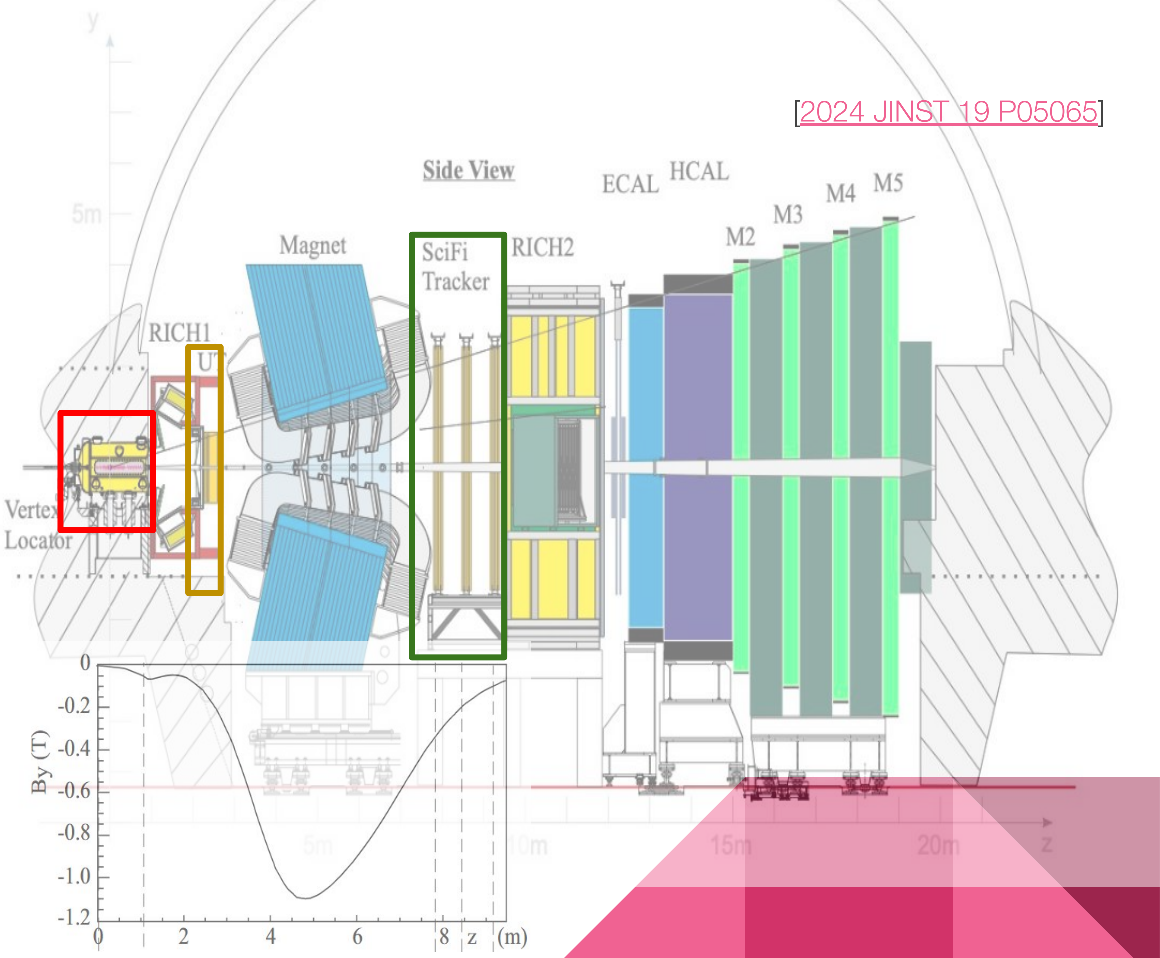
Overview of LHCb

Tracking detectors

- **Discrete Tracking System**
  - LHCb tracking is made with different detectors along the beam line
- Unique coverage in the forward region, 2 < η < 5, optimised for heavy flavour physics
- **Key Components**
  - VELO (Vertex Locator) close to the interaction point
  - UT (Upstream Tracker) upstream of magnet
  - SciFi stations downstream of the magnet
  - Magnet region in between
- Fully **software-based trigger** in Run 3
  - HLT1 (30 MHz in, 1 MHz out)
  - HLT2 (1 MHz in, 10 GB/s out)

See Dorothea's talk on upgraded trigger system

[2024 JINST 19 P05065]



Overview of LHCb

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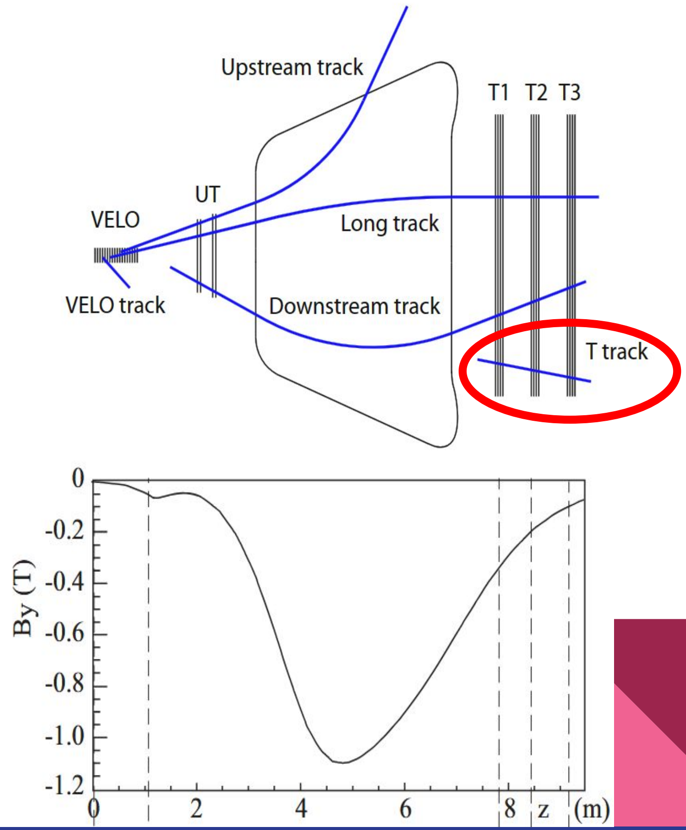
Main Track types

- Tracks classified according to where they have hits
  - **Long tracks** (z ≤ 0.4 m): hits in all tracking sub-detectors
    - Best precision, but can only be used to study decays close to interaction point
  - **Downstream tracks** (0.5 m ≤ z ≤ 2.0 m): hits in UT and SciFi, ideal for searches of displaced vertices
  - **T tracks** (2.0 m ≤ z ≤ 7.6 m) are reconstructed only with SciFi, not relying on VELO or UT hits
    - **Weak magnetic field** impacts momentum resolution
- **Idea: exploit T tracks** for reconstructing LLP decays in magnet region, **far from the interaction point**
  - Implemented dedicated track and vertex reconstruction for T tracks

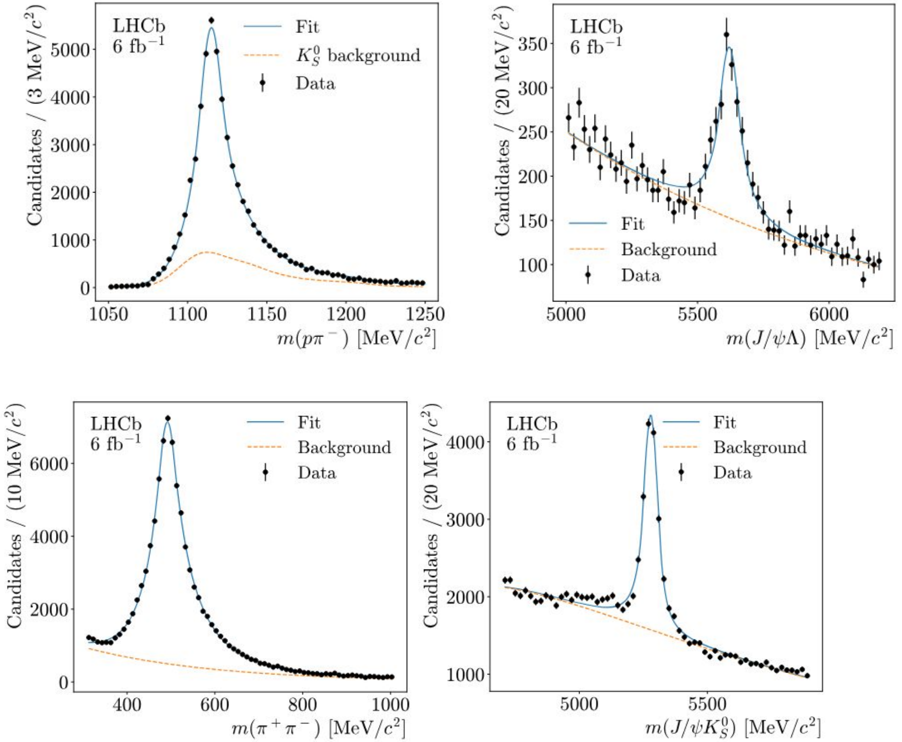


Decays in the magnet region

Feasibility

- Strategy initially developed for **EDM/MDM measurements with hyperons** decaying up to 7.6 m from interaction point [Eur. Phys. J. C 77, 181 (2017)]
- Reconstruct Λ^0 and K_S^0 decaying in the magnet region using **only T tracks**
  - Demonstrated in $\Lambda_b^0 \to J/\psi\Lambda^0$, $B^0 \to J/\psi K_S^0$ decays in Run 2 data [Eur. Phys. J. C 85, 7 (2025)]
  - Implemented in HLT2 for Run 3
- If Λ^0 and K_S^0 with very-displaced vertices can be studied, **BSM LLPs with large lifetimes become plausible targets**

Λ^0 and K_S^0 decaying 6 < z < 7.6 m

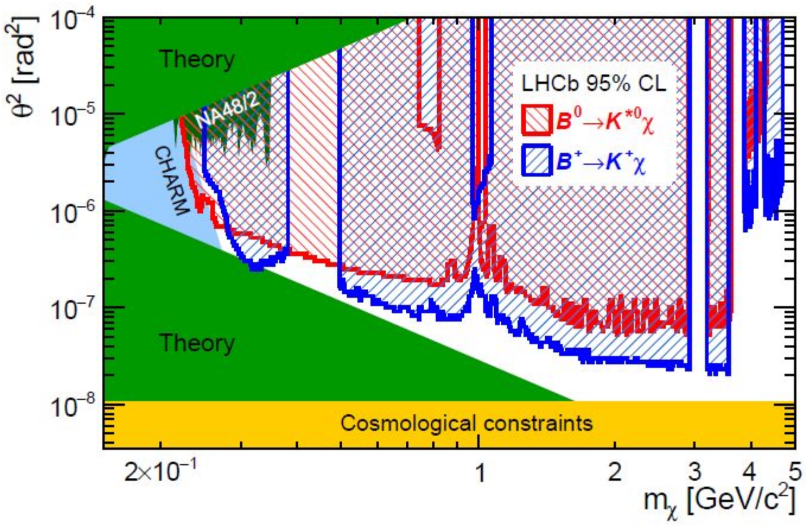


Application to BSM searches

LLPs BSM searches at LHCb

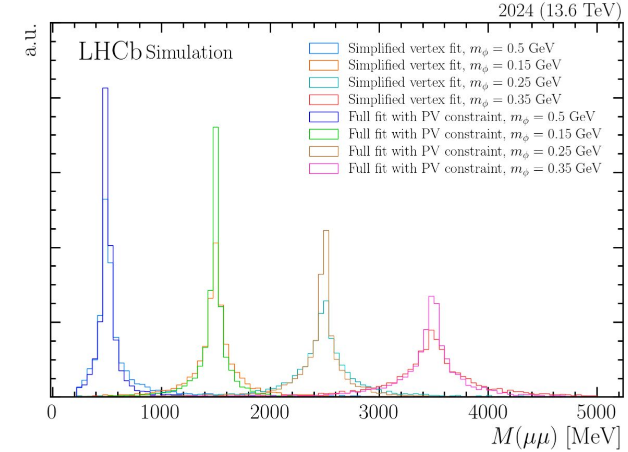
- Long-lived **dark scalars** already studied in LHCb with Run 1 data, using **Long tracks** [PhysRevD.95.071101]
  - Fully exclusive approach
  - Small decay volume probed
- **New approach** for Run 3, exploiting the LHCb tracking system
  - Exploring **other track types to increase decay volume**, with inclusive approach, probing **longer lifetimes**
    - See Jiahui's talk on Downstream and BuSca
  - **Use T tracks** to search for BSM LLPs decaying in the magnet region, **between 2.5 and 7.6 metres**
    - Expect little-to-no physics background: mis-ID, combinatorial, material interactions
- This opens new, **largely unexplored**, region of LLP parameter space, making **LHCb competitive with dedicated experiments**

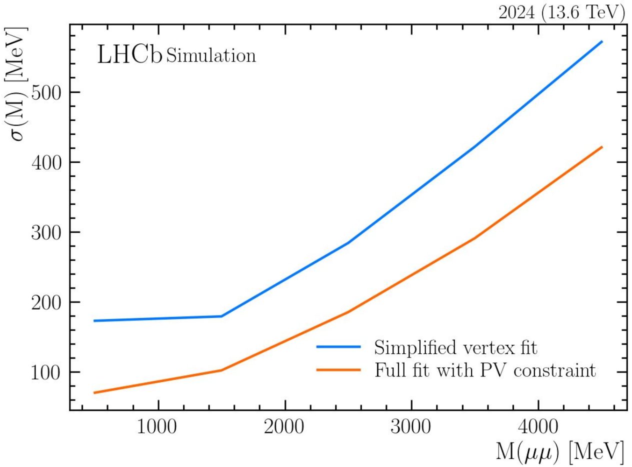
See more details in Lisa's talk



Mass resolution and vertexing

- Mass resolution for decays in the magnet region **degrades as the LLP mass increases**
  - As mass increases, **so does the Q-value** of the decay → higher momenta of daughter particles
  - **Weak magnetic field** over SciFi stations → **smaller momentum resolution at higher momenta**
  - Simplified track vertexing for T tracks at HLT2 to manage throughput
- **Offline Improvements**
  - Offline refitting with a PV constraint improves mass resolution significantly



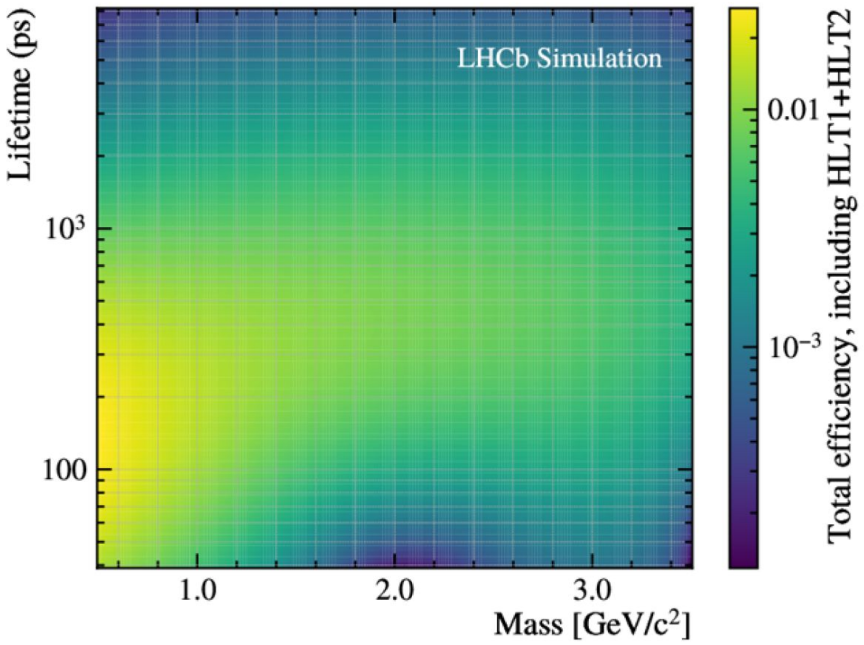


[LHCB-FIGURE-2025-001]

Trigger and Online selection

- Preliminary estimate on MC of acceptance and trigger (HLT1+HLT2) efficiency for $B^0 \to K^* H'(\to \mu^+\mu^-)$
- **HLT1 efficiency** depends on specific B decay
  - Estimated ~40% wrt total events
- **HLT2** selection is **inclusive**: look to all di-muon candidates in magnet region,
  - Optimised selection on kinematics, PID, and track combination, no cuts on LLP mass
  - Estimated 15-35% efficiency wrt HLT1 using $B^0 \to K^* H'(\to \mu^+\mu^-)$

Total (online) efficiency = Acceptance × (HLT1 efficiency) × (HLT2 efficiency)

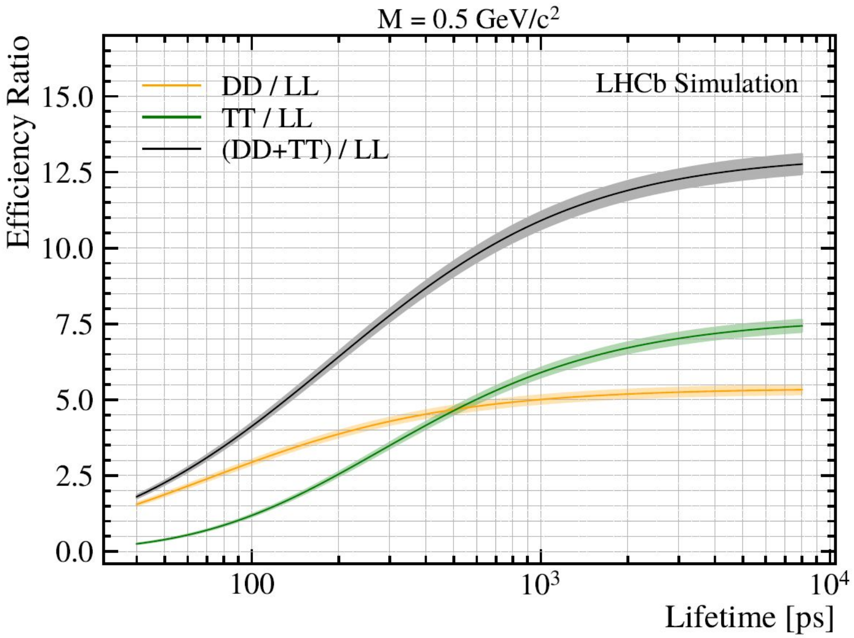


[LHCB-FIGURE-2025-001]

Advantages of using T tracks

- **As lifetime increases**, the ratio of **decays reconstructed with T tracks (TT) increases**, with respect to Long (LL) and Downstream (DD)

- Including Downstream and T tracks, can increase the decay volume, **accessing higher lifetimes, with larger yields** wrt only Long tracks

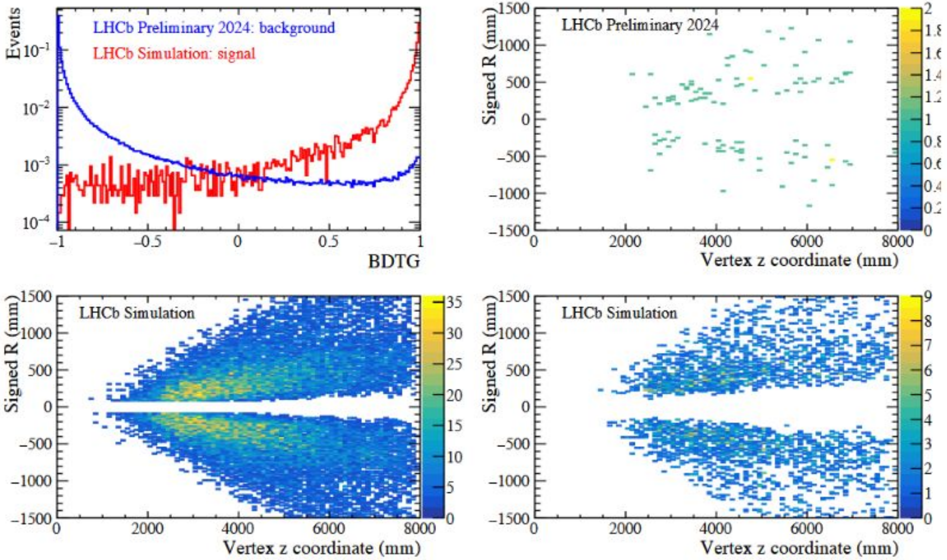


[LHCB-FIGURE-2025-001]

Offline selection

- Unblinded a small portion of 2024 data (150 pb^{-1}) to study background contributions

- Preliminary **BDT selection**
  - Expect 1-2 event per pb^{-1} keeping 60% of signal

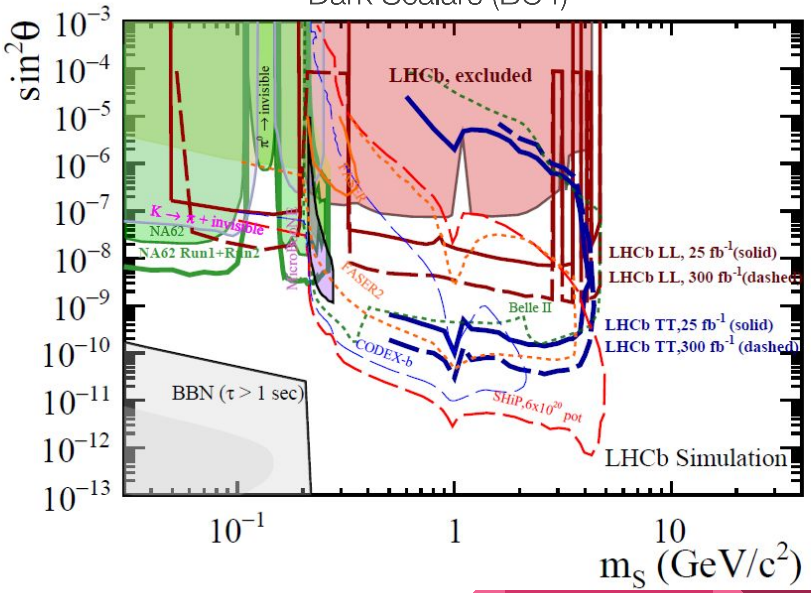


[LHCB-FIGURE-2025-001]

Preliminary Sensitivity Estimate

- **Caveats**
  - HLT1 depends on the rest of the B decay (e.g. K^* in $B^0 \to K^*(\to K^-\pi^+)H'(\to \mu^+\mu^-)$)
    - Efficiency on this channel, could vary up to factor 2 in other channels $\to$ under investigation
  - Offline selection efficiency not included
  - Zero background regime assumed
- **Key takeaway**
  - Studying **decays in the magnet region** with the current detector and trigger **makes LHCb competitive with dedicated LLP experiments** at smaller couplings in this mass range

Dark Scalars (BC4)



[LHCB-FIGURE-2025-001]

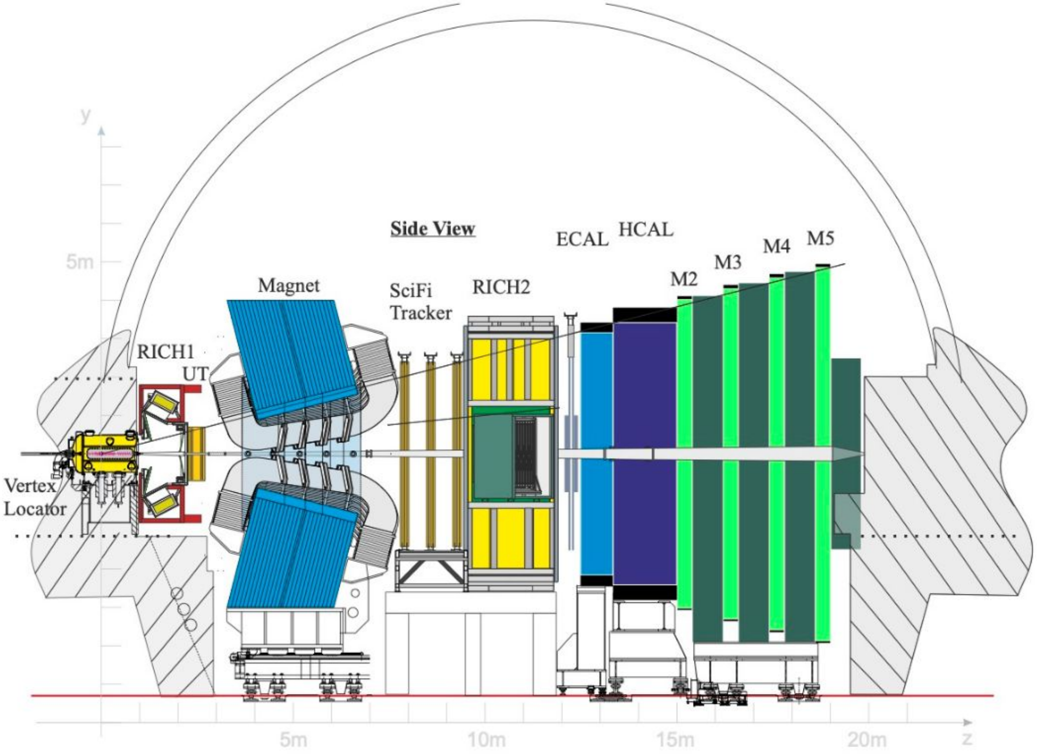
Summary and Conclusions

- **Strong motivation to search for Dark Scalars and other LLPs in LHCb's forward geometry**
  - T tracks enable reconstruction of decays in the magnet region
  - Unique opportunities with LHCb's PID system
- **Feasibility**
  - Run 2 studies with and decays show that **very displaced particles ($2.5 < z < 7.6$ m) are achievable targets**
  - Data collected in Run 3 using dedicated BSM dimuon LLP triggers
  - Analysis of 2024 data in progress
- **Next Steps**
  - Improve triggers, continue developing analysis

Thanks for the attention!

Overview of LHCb

- Single forward-arm spectrometer with focus on c- and b-physics
  - High precision tracking and vertex reconstruction
  - Excellent PID performances
- Phase space region $2 < \eta < 5$ forward of the interaction
  - Complementary to ATLAS and CMS
- Fully software-based two-level trigger:
  - **HLT1** (30 MHz in, 1 MHz out)
  - **HLT2** (1 MHz in, 10 GB/s out)



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Challenges in reconstructing T tracks

- T tracks are very special & challenging objects
  - Low momentum resolution dominated by the **low curvature** (**low** intensity **magnetic field**) and **short lever arm** in the SciFi region
  - **Large extrapolation** distances, **vertexing** and **kinematic fitting** in a volume with **high and non-uniform** magnetic field
- Implemented **dedicated particle vertex fitter** for T tracks **in HLT2,** with single **RK extrapolator**, using track states
  - Dedicated reconstruction for T tracks under development in HLT1
- Several bottlenecks using standard tools, for Long tracks
  - **Low efficiencies** when applying kinematic constraints to LLP
  - **Low mass and vertex resolutions**

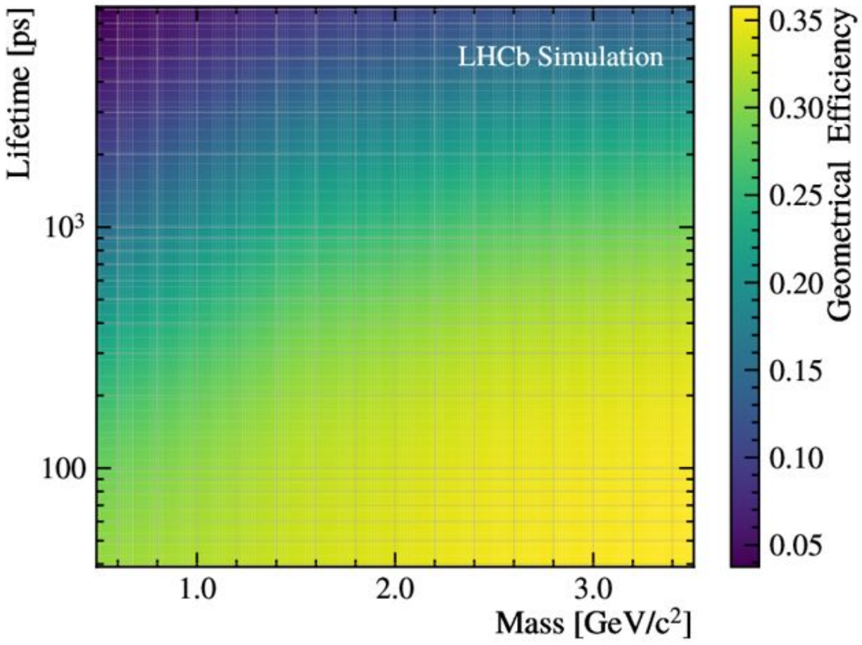
Efficiency maps with simulated events

- Generated MC for $B^0 \to K^*(\to K^-\pi^+)H'(\to \mu^+\mu^-)$ with lifetime = 3 ns
- Reweight MC from generated to alternate lifetimes with the following per-event weights:

$$w_i = \frac{\tau_{\text{gen}}}{\tau_{\text{target}}} \frac{e^{-t_i/\tau_{\text{target}}}}{e^{-t_i/\tau_{\text{gen}}}}$$

  - τ_{gen}: generated dark scalar lifetime
  - τ_{target}: target lifetime
  - τ_{i}: proper time in the event

Acceptance efficiency



Next steps

- Expect **efficiency gains from HLT2 selection optimisation**
    - Improved topological selection and optimisation of selection algorithms to go in later this year
    - Improved vertex reconstruction for T tracks
- Inclusion of **calorimeter information for T tracks** for 2025
    - Improved PID, especially for muons from pions/kaons, hadron identification
- Exploring expansion to other modes
    - **Hadron signatures**
    - RICH2 detector will benefit, e.g. kaon identification, less performant compared to Long tracks