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Searches for displaced Scalar decays to dimuons: LHCb's extended reach in Run 3

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A detailed study exploiting novel trigger and reconstruction techniques developed to search for Beyond Standard Model (BSM) Long-Lived Particles (LLPs) with very displaced vertices is presented. Building on feasibility studies that have successfully reconstructed Standard Model decays occurring up to 7.6 m forward of the interaction point in LHCb's magnet region, the search for LLPs into charged final states exploits LHCb's unique forward geometry and segmented tracking system—comprising the Vertex Locator, Upstream Tracker, and SciFi stations—to extend sensitivity into previously inaccessible regions.

This proceedings contribution will cover innovative trigger strategies implemented in LHCb's software trigger for inclusively selecting decays to dimuons displaced up to 7.6 m from the interaction point, alongside advanced offline selection methods using multivariate analysis methods to robustly suppress background while maintaining high signal efficiency. Preliminary sensitivity estimates for Dark Higgs $H' \to \mu^+\mu^-$ search indicate that these approaches can achieve competitive performance compared to dedicated LLP experiments. Future prospects will also be discussed. This work aims to provide a comprehensive framework for enhancing LLP discovery potential at LHCb and offers insights that could be beneficial for the broader BSM LLP search community.

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1. Introduction

The search for Beyond the Standard Model (BSM) particles is motivated by scenarios in the dark sector and other new physics paradigms predicting particles with long lifetimes that can decay far from their production point [1–5]. Recent studies have investigated the potential of the LHCb detector for triggering on and reconstructing these unique signatures [6]. In this note, emphasis is placed on the reconstruction of decays that occur in the magnet region, from approximately 2.5 m to 7.6 m downstream of the interaction point. The unique forward geometry and discrete tracking system of LHCb are exploited to extend the sensitivity to Long-Lived Particles (LLPs), even in regions where other detectors may lack coverage.

2. The LHCb Detector and Tracking System

The LHCb detector [7, 8] features a tracking system designed to provide high-precision measurements in the pseudorapidity region $2 < \eta < 5$. The tracking system is made of three subsystems:

- Vertex Locator (VELO): Surrounding the interaction point, the VELO offers high-resolution vertex reconstruction and provides a crucial estimation of the track slopes right after the proton-proton interaction.
- Upstream Tracker (UT): Placed just before the magnet, the UT provides additional tracking information with accurate measurement of the slopes of the particles before they enter the magnetic field region and it plays an important role in improving momentum resolution and reconstruction efficiency in high multiplicity events.
- Scintillating Fibre (SciFi) Tracker: Located downstream of the magnet, the SciFi tracking stations are critical for reconstructing the momentum of particles after they traverse the magnetic field.

The dipole magnet, placed between the UT and the SciFi stations, is important for momentum measurement. Moreover, LHCb is equipped with a full software trigger that has been deployed in Run 3, with two sequential High Level Trigger (HLT) stages, HLT1 and HLT2, both running event reconstruction and selection algorithms. The design of the detector allows for the reconstruction of different types of tracks:

- Long tracks: Reconstructed using hits in at least the VELO and SciFi stations. These tracks provide the highest precision but are typically limited to reconstruct decays close to the interaction point. The inclusion of UT information helps to reduce the "ghost track" rate from mis-matched VELO and SciFi segments.
- Downstream tracks: Reconstructed from hits in the UT and SciFi stations, allowing for the analysis of decays occurring further downstream, up to about 2.5 m.
- T tracks: Reconstructed only with SciFi hits, these tracks enable the reconstruction of LLP decays that occur up to 7.6 m from the interaction point.

Figure 1 provides a schematic overview of the tracking system, highlighting the placement of the VELO, UT, and SciFi stations relative to the magnet region.

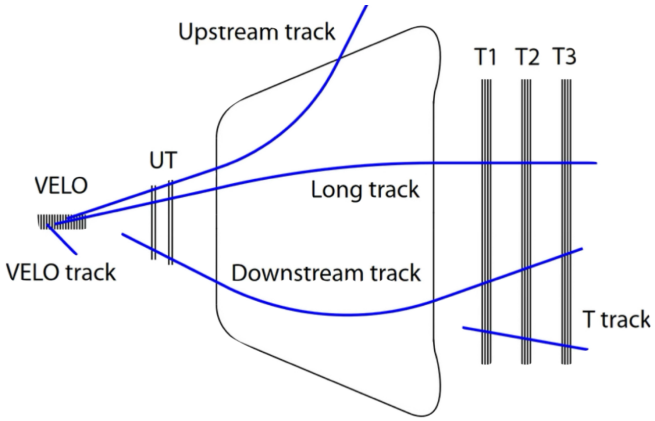

Figure 1: Schematic diagram of the LHCb tracking system, indicating the locations of the VELO, UT, and SciFi stations [8].

3. Feasibility Studies and Reconstruction of Displaced Decays

The feasibility of this approach has been demonstrated, in order to study the electric and magnetic dipole moments of Λ baryons [6]. In these studies, decays occurring between 6 m and 7.6 m from the interaction point were successfully reconstructed. Figure 2 shows the invariant mass distributions obtained for Λ baryons and K^0_S mesons, with clearly visible peaks indicating the viability of the reconstruction strategy. These studies demonstrate that if Λ and K^0_S can be reconstructed and their decay properties studied at such large distances from the interaction point, then BSM LLPs with very high lifetimes ($\tau \sim O(10\,\text{ns})$) become plausible targets. The reconstruction methods developed have been implemented in HLT2.

4. $b \to sH'(\to \mu^+\mu^-)$ efficiency

The expected efficiencies for $b \to sH'(\to \mu^+\mu^-)$ decays have been evaluated using simulated $B^0 \to K^{*0}H'(\to \mu^+\mu^-)$ decays with different H' masses $(0.5, 1.5, 2.5, 3.5$ GeV) and lifetimes (3, 16 ns). The geometrical acceptance efficiency of the detector requires that the prompt tracks and H' have polar angles $\theta < 500$ mrad and that the reconstructed vertex lies within 8 m of the nominal proton-proton interaction point, and it is estimated to range between 30%-35%. The trigger efficiency is influenced by different factors in HLT1 and HLT2:

- HLT1: the HLT1 efficiency depends on track signatures, including one- and two-track topologies. Therefore, in these studies, it is independent of the LLP but depends on the decay of the B decay and the associated kaon. An estimated average efficiency of approximately 40% is observed for the studied channel.
- HLT2: This trigger level employs kinematic, muon identification and topological criteria aimed at selecting the displaced LLP vertices in the magnet region. It is designed to be inclusive, targeting any dimuon signature in the magnet region, with performance ranging between 15% and 35%.

Figure 3 illustrates the dependence of the trigger efficiency on the LLP lifetime and mass.

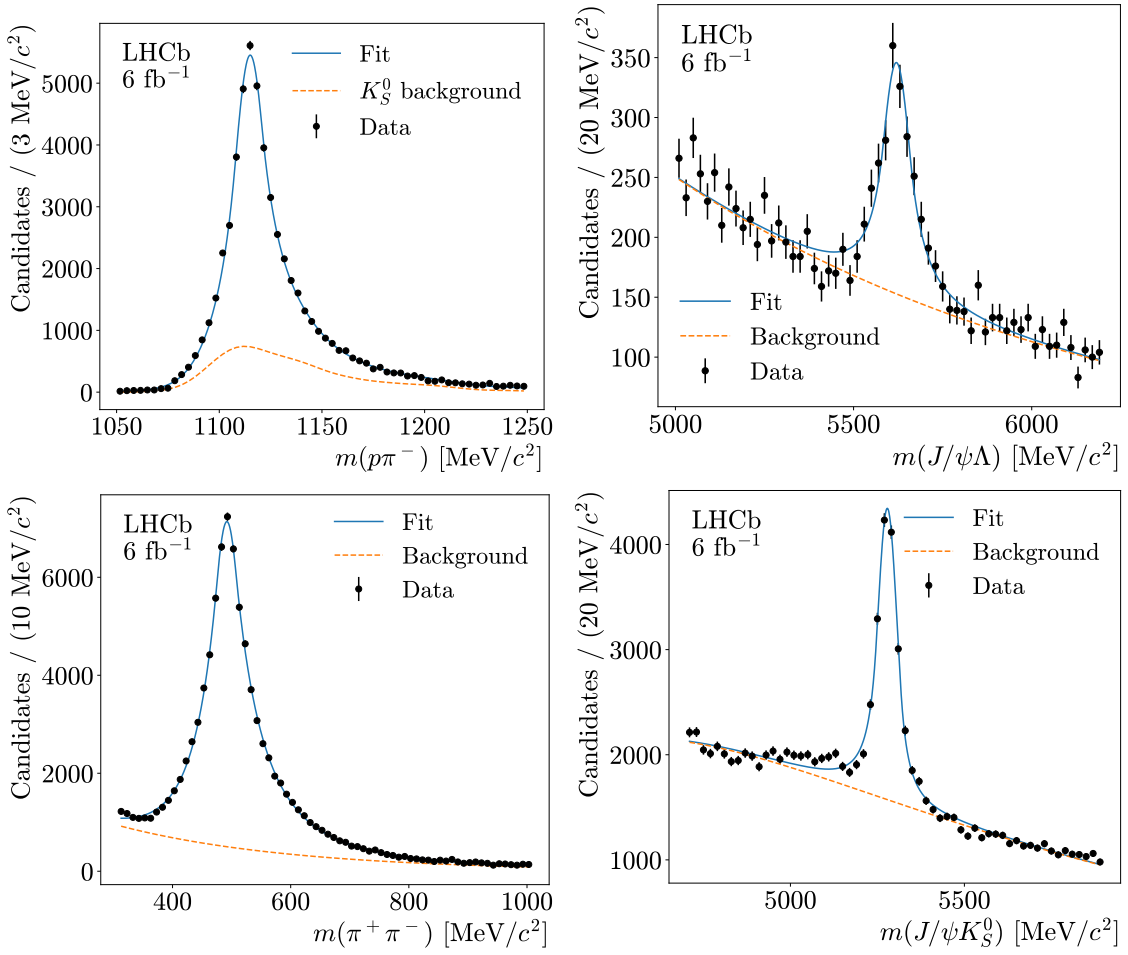

Figure 2: Invariant mass distributions of Λ baryons (top) and K^0_S mesons (bottom) reconstructed from decays occurring in the magnet region between 6 m and 7.6 m. [6]

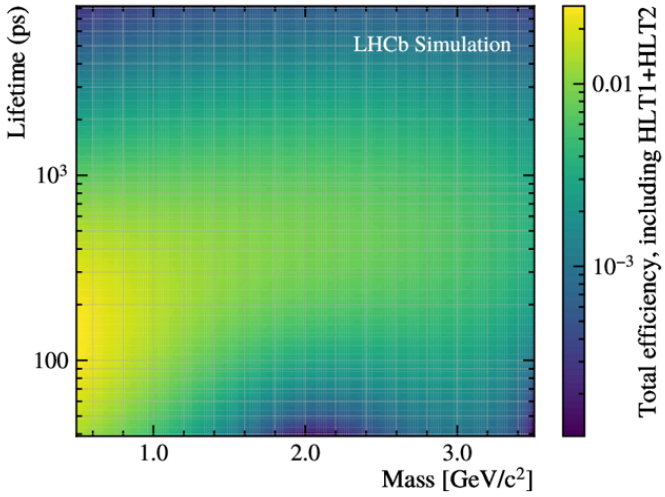

Figure 3: Total trigger efficiency, including acceptance, as a function of LLP lifetime and mass [9].

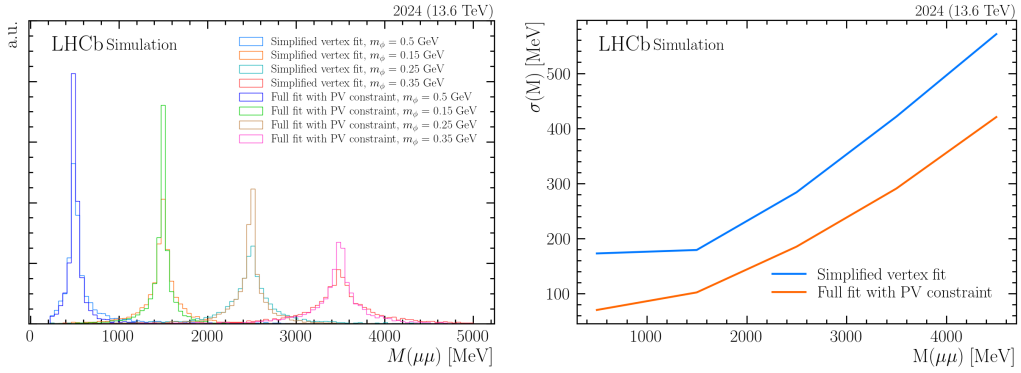

Figure 4: Dimuon invariant mass distributions of simulated $\phi \to \mu^+\mu^-$ decays with different ϕ masses (left) and mass resolution dependency with respect to the LLP mass (right), with simplified vertex fit and with full kinematic fit with primary vertex constrain [9].

5. Offline Selection

The weak magnetic field and short lever arm across the SciFi stations pose several challenges for reconstruction and affects mass resolution, especially as the LLP mass increases. The increase in the amount of energy released, namely the Q-value of the decay, combined with the reduced magnetic field across the SciFi stations, leads to a degradation in momentum resolution of the daughter tracks. Offline kinematic refitting techniques [10] using a primary vertex constraint help to mitigate this issue and improve the mass resolution, as shown in Figure 4. It is important to note that the background distribution is expected to decrease exponentially, so despite the width of the search window increases as a function of mass, the expected number of background events decreases. Robust background rejection is critical when searching for rare LLP decays. Offline selections have been developed based on a boosted decision tree (BDT) classifier, which combines multiple kinematic and topological variables. The BDT was trained using both data and simulated signal events, and a threshold on the BDT score was chosen to reduce the background level to approximately one to two events per pb^{-1}. Figure 5 shows the performance comparison between the BDT output for data and Monte Carlo simulations. Despite the BDT has not yet been fully optimized, initial studies indicate that further improvements in signal efficiency can be achieved without compromising the low background levels.

6. Preliminary sensitivity estimates

A preliminary sensitivity estimate has been derived using the current detector and trigger performance, though without offline selection criteria. This estimate, while still subject to further tuning, indicates that the reconstruction of decays in the magnet region leads LHCb to have a competitive sensitivity with respect to dedicated LLP experiments, particularly in the region of lower couplings. Figure 6 illustrates the reach of the approach described in this proceeding compared to dedicated LLP experiments, and highlights the gain in sensitivity that can is obtained by using decays that occur in the magnet region, between 2.5 m and 7.6 m (TT) with respect to the one with decays close to the interaction point (LL). Continued optimisation of the trigger and

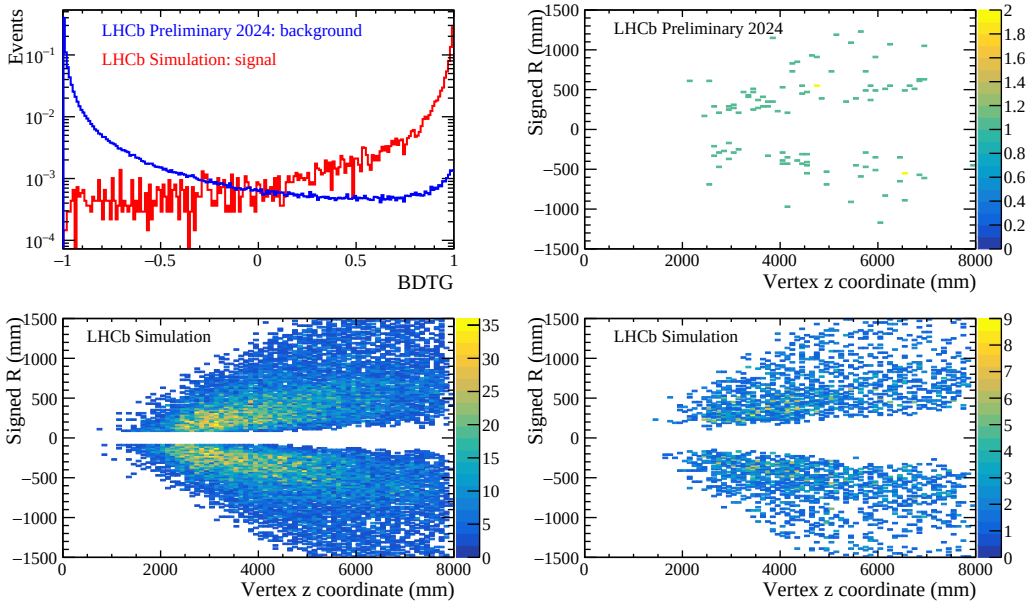

Figure 5: BDT performance for data and simulated signal events (top left), with residual background radial distribution after selection (top right). Simulated signal radial distributions before (bottom left) and after (bottom right) selection [9].

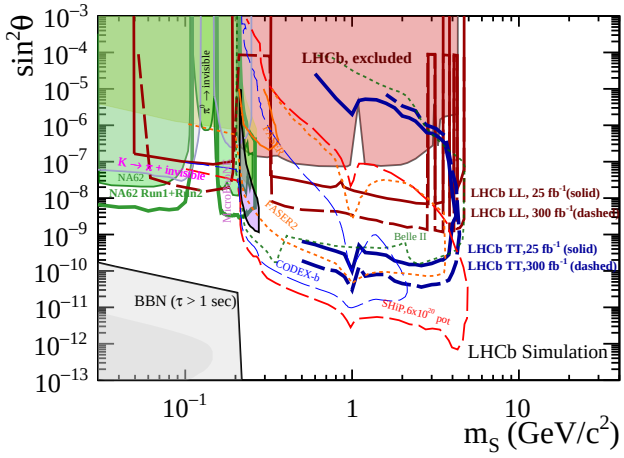

Figure 6: Comparison of the sensitivity of the current LHCb approach to other LLP experiments [9].

offline selections is anticipated to further enhance the sensitivity of the LHCb detector to new physics phenomena.

7. Conclusion

A study of trigger and reconstruction strategies for LLPs with very displaced vertices has been presented. The unique forward geometry and discrete tracking system of the LHCb detector facilitate the reconstruction of decays in the magnet region, thereby extending sensitivity to long-lived particles decaying far from the interaction point. Feasibility studies based on Λ and K^0_S

reconstructions have validated the approach, and preliminary sensitivity estimates indicate that the LHCb detector is competitive with dedicated LLP experiments in exploring new physics scenarios. Future work will focus on further optimisation of the HLT2 trigger, refinement of offline selection algorithms, and expansion to additional decay modes. The integration of additional detector information, such as calorimeter and advanced hadron identification, is expected to improve the sensitivity and overall performance.

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