BuSca: New Strategies for LLP Searches at 30 MHz at LHCb

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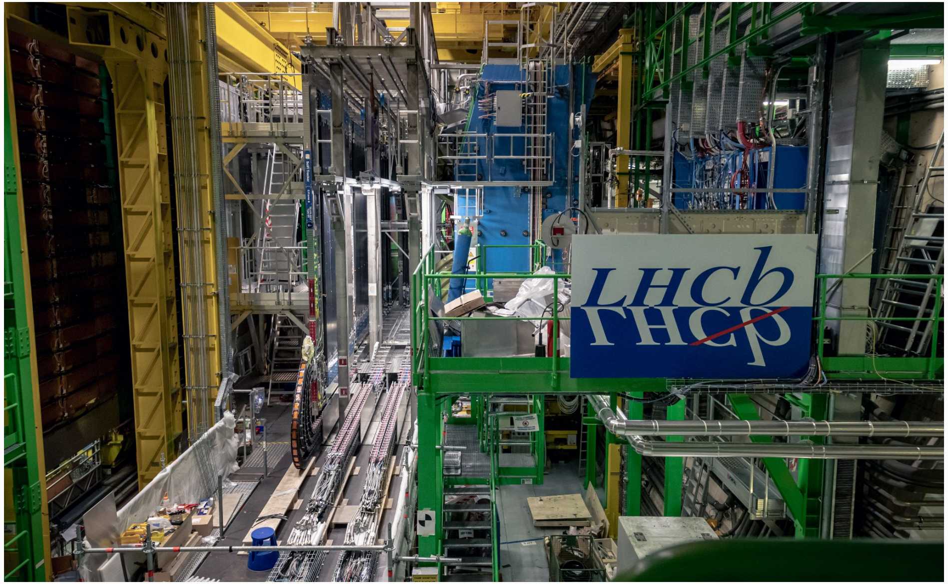
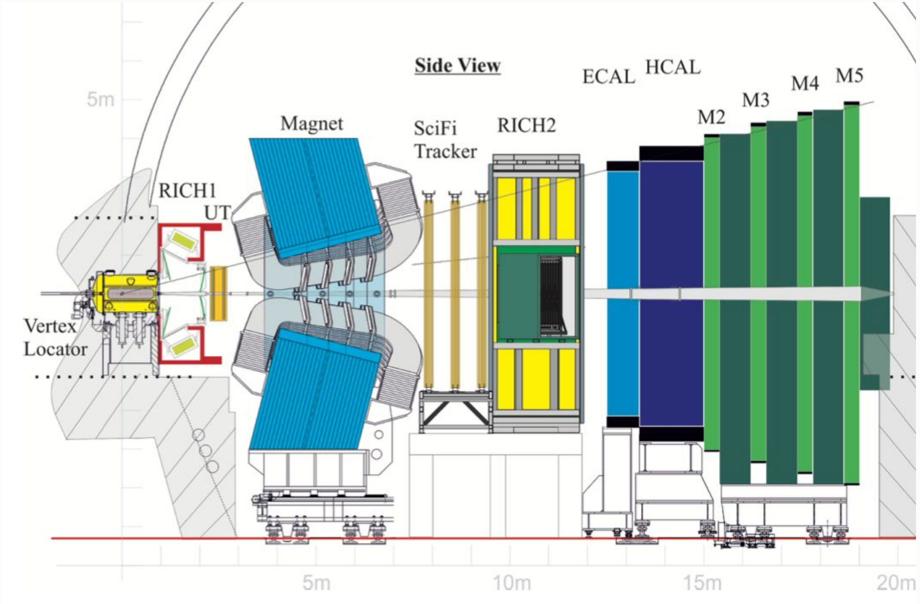
6–11 July 2025, EPS-HEP 2025, Marseille, France

Outline

- LHCb experiment
- LHCb trigger system
- LHCb tracking system
- Downstream tracking
- BuSca strategy
- BuSca background studies
- Summary



LHCb experiment



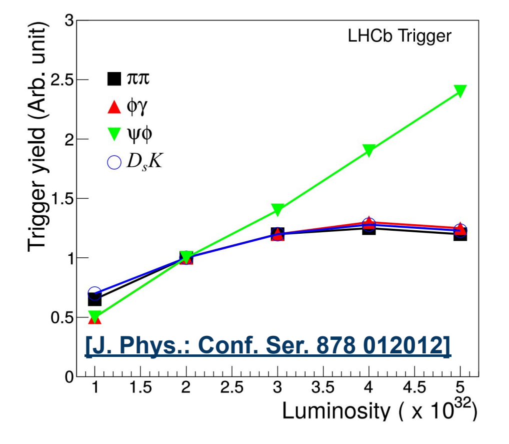
[CERN-LHCC-2014-001; LHCB-TDR-015]

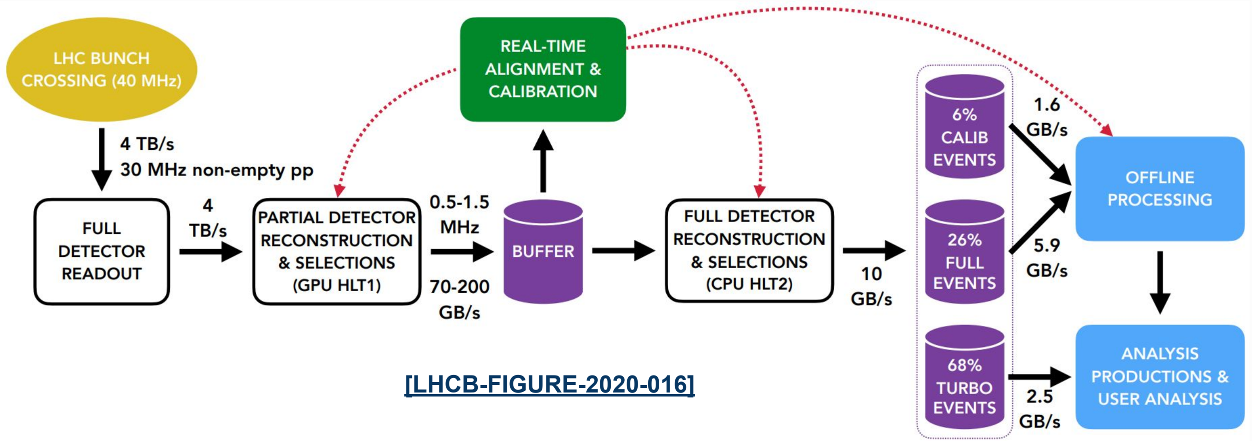
- **LHCb** is one of the four main experiments at the **LHC**, focused on precise measurements in the **beauty** and **charm sectors**.
- For **Run 3** data-taking, LHCb must handle an instantaneous luminosity **x 5** larger than Run 2 ($\mathcal{L}_{\text{inst.}} = 2 \cdot 10^{33} cm^{-2} s^{-1}$), with a average **pile-up** of 5.2 ($<\mu>= 5.2$).
- The **LHCb detector** has been **upgraded** to handle higher radiation damage and increased track multiplicity, and an **upgraded trigger system** has been developed to manage it.

For details on the upgraded tracking and PID performance, see Giovanni's talk

LHCb trigger system

For details of real-time alignment & calibration, see Miguel's talk





- The **hardware trigger (L0)** in Run 2 reached saturation at higher luminosity ⟶ Removal of **L0** in **Run 3** and **HLT1** operating at **30 MHz**.
- **HLT1** and **HLT2** are **fully software-based** triggers that perform **Real-Time Analysis** (RTA) to reconstruct events and make trigger decisions based on the reconstructed objects.
- To handle the high throughput requirements, **HLT1** now runs as a **GPU-based** application called **Allen** during data-taking.

For details of luminosity determination, see Fabio's talk

For details of the trigger system, see Dorothea's talk

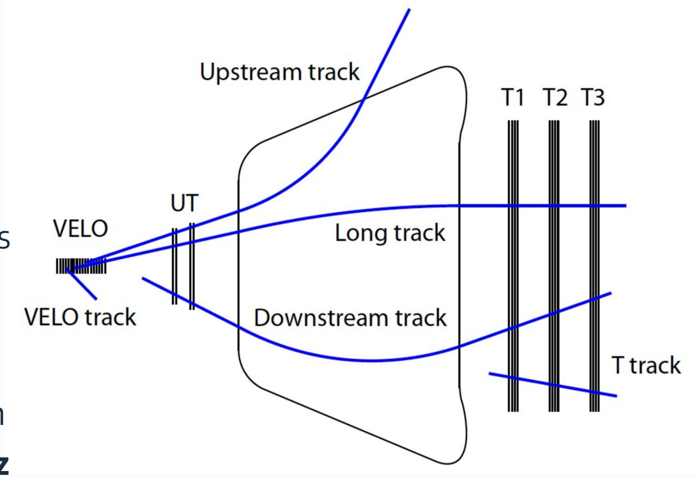
LHCb tracking system

- In the **LHCb tracking system**, reconstructed tracks are classified based on their detector hits:
  - **Long track**: Hits in VELO and SciFi, optionally UT.
  - **Downstream track**: Hits in UT and SciFi only.
  - **T track**: Hits in SciFi only.
- Both **Downstream** and **T tracks** can reconstruct **LLP** decays occurring **beyond the VELO**, significantly extending the effective decay volume (**2m** for Downstream tracks and **8m** for T tracks):
  - → **The LHCb detector is well-suited for BSM LLP searches!**
- In **Run 3**, LHCb introduced a new **downstream tracking** and **vertexing** algorithm in **HLT1** for the first time. It makes it possible to trigger on **BSM LLP decays** at **30 MHz** by reconstructing highly displaced decay vertices from these tracks.

[Comput Softw Big Sci 9, 10 (2025)]

Search for $A' \to \mu^+\mu^-$ Decays
[PRL 124 (2020) 041801]

Search for Hidden-Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$ Decays
[PRL 115 (2015) 161802]



[CERN-LHCb-PUB-2021-005]

For BSM LLP searches with T tracks in LHCb, see Simone's talk

Discovery potential of Downstream

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

LHCb-PUB-2025-001
April 1, 2025

arXiv:2503.23087v1 [hep-ex] 29 Mar 2025

Discovery potential of LHCb Upgrade II

Input to the European Particle Physics Strategy Update 2024–26

LHCb collaboration[†]

Abstract

A second major upgrade of the LHCb detector is necessary to allow full exploitation of the HL-LHC for flavour physics. The new detector will be installed during long shutdown 4 (LS4), and will operate at instantaneous luminosity up to $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. By upgrading all subsystems and adding new detection capability it will be possible to accumulate a sample corresponding to an integrated luminosity of at least $300\,\mathrm{fb}^{-1}$ of high energy pp collision data, giving unprecedented and unique scientific opportunities in flavour physics, in electroweak physics, in searches for new feebly interacting particles and in hadron spectroscopy. In this document, the potential of the LHCb Upgrade II detector to enable major discoveries through increased sensitivity to a range of as-yet unknown phenomena is summarised.

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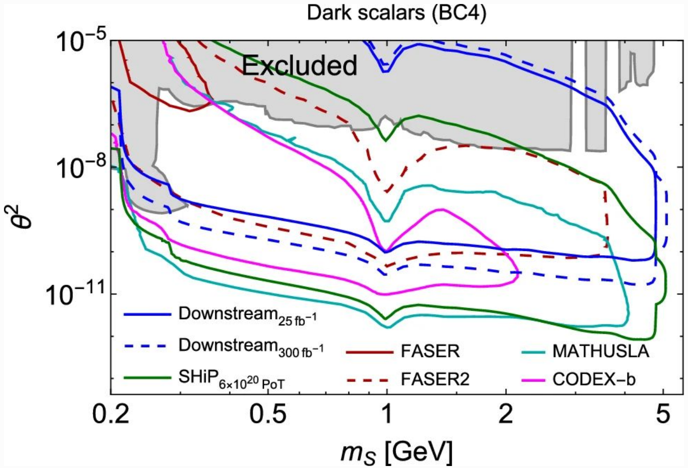
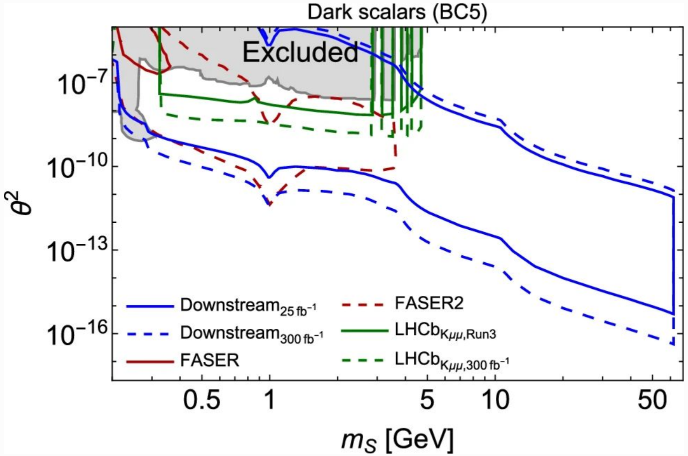
[doi.org/10.48550/arXiv.2503.23087]

Potential of the Downstream algorithm for LLP searches:





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

Sensitivity extended **two orders of magnitude**! (similar for HNL or ALPs)

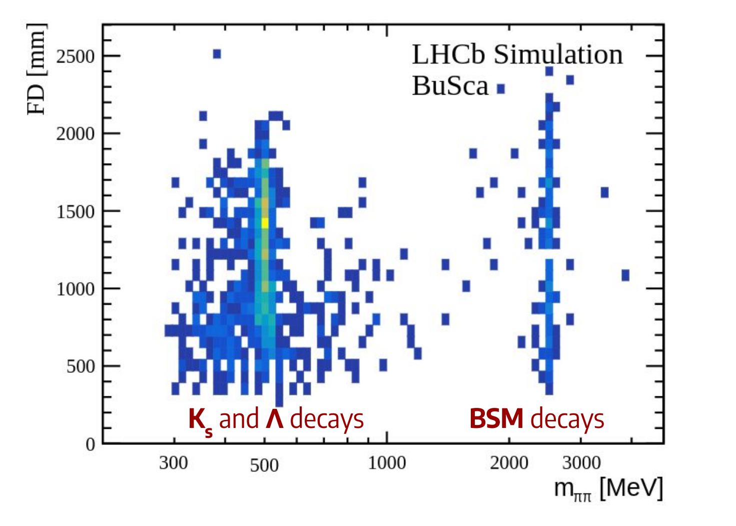
What is BuSca?

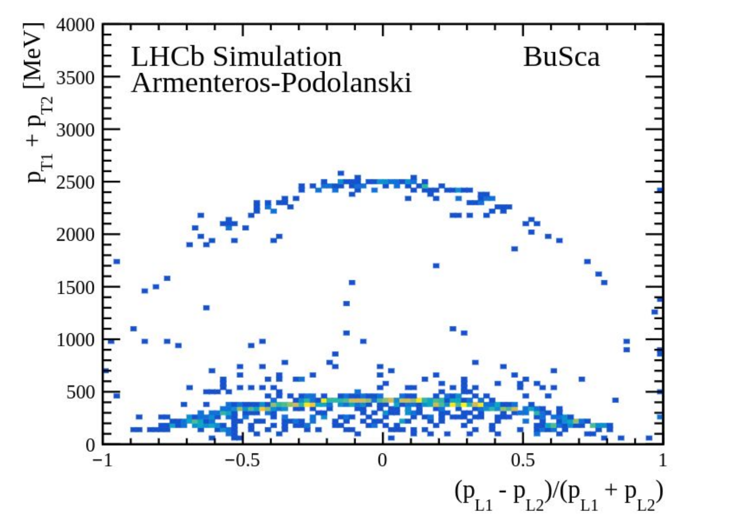
BuSca means 'search' in Spanish

- After **L0 removal**, all detector readouts are temporarily stored in a buffer while waiting for HLT1 processing.
  - The BuSca project gets its name from “**Buffer Scanning for BSM LLP searches**”.
- BuSca consists of several components running directly at **30 MHz**:
  - A **real-time**, histogram-based **monitoring** system:
    - Trigger-less histograms at **30 MHz** enable real-time anomaly detection.
    - Provides hints for trigger line development.
  - A set of **HLT1** + **HLT2** trigger lines to select general BSM displaced vertices:
    - **Model-independent** – LLPs don’t necessarily originate from B mesons.
    - Focuses on **two-body decays** with different end states.
    - A more **general trigger line** is also available for future analyses, including **multi-body decays**.

- Currently, **BuSca** targets only **downstream tracks** for a better momentum resolution with respect to **T tracks** but will be extended to other track types in the future.

BuSca monitoring



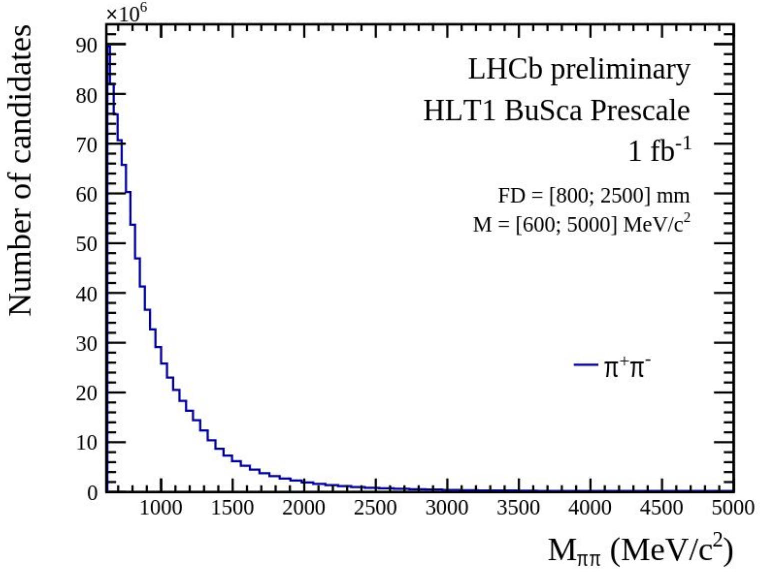


[LHCB-FIGURE-2024-036]

- In 2024, two different **2D histograms** are set up for each HLT1 BuSca trigger line:
  - **Mass** vs. **Flight Distance** → Directly visualizes highly displaced mass peaks.
  - **Armenteros-Podolanski** Plot → Identifies two-body decays independent of mass assumptions.
- In 2025, a third **2D histogram**, helicity vs mass, is added.

BuSca trigger lines

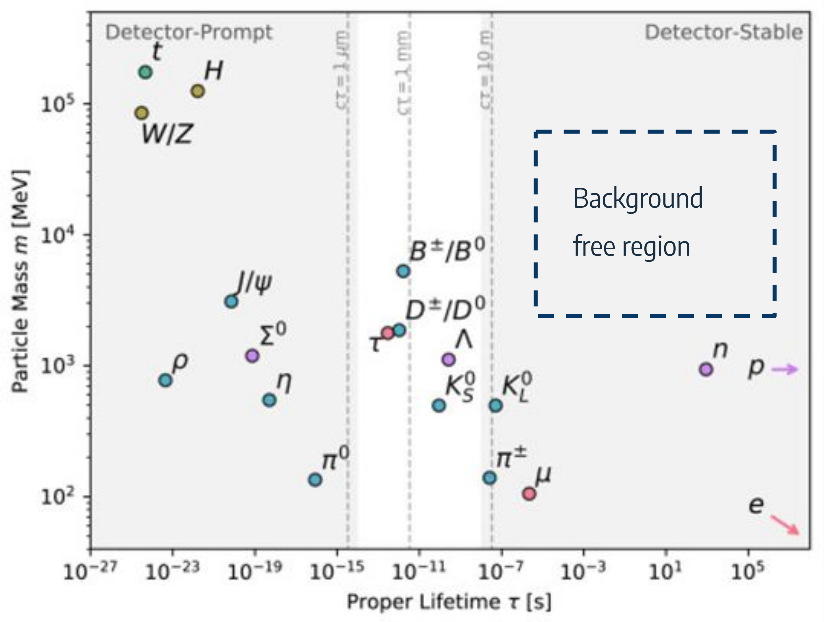
- **HLT1 trigger lines** were developed to select high-quality displaced downstream vertices:
  - **Hlt1DownstreamBuScaSameSign**: Combinatorial background study.
  - **Hlt1DownstreamBuScaPreScaled**: General selection.
  - **Hlt1DownstreamBuScaMuon**: Di-muon decays.
  - **Hlt1DownstreamBuScaElectron**: Di-electron decays.
  - **Hlt1DownstreamBuScaHighMass:** Di-muon and Di-hadron lines to trigger up to 50 GeV.
- The **HLT2** lines was developed to store events triggered by **HLT1**:
  - **Requires** the HLT1 BuSca trigger decision.
  - Stores all **relevant downstream vertices** for offline background studies.



[LHCb-FIGURE-2025-002]

BuSca background studies

Physics backgrounds



[Prog. in Part. and Nuc. Phys. 106 (19)210]

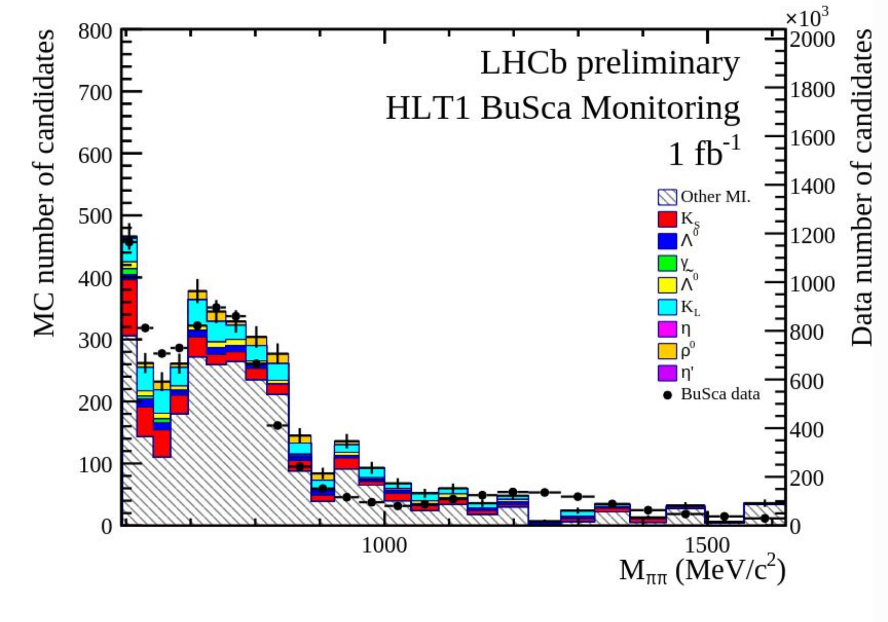
- **Strange decays**:
  - $\mathbf{K_s^0}$, $\mathbf{K_L^0}$ and $\mathbf{\Lambda^0}$.
  - Can be vetoed using kinematic and mass cuts.
- Another **hadronic resonances**:
  - **J/ψ**, **ψ**, **ϕ(1020)**, **ψ(2S)**, **ψ(3770)** ... etc.
  - Short lifetimes, can be vetoed using flight distance cuts.

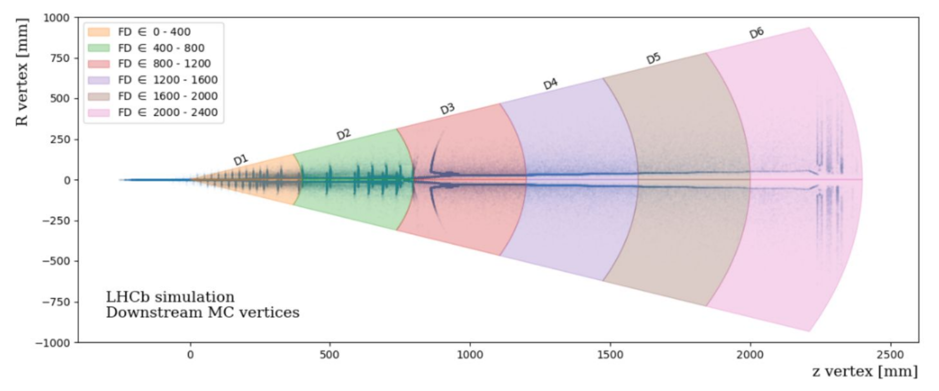
BuSca background studies

Material interactions

- **Light resonances** can be produced from **material interactions**:
  - **ρ**, **f_2**, **η**, **ω** ... etc.
  - Their vertices are concentrated in specific regions of space.
  - Can be vetoed using geometry cuts.

[LHCb-FIGURE-2025-002]

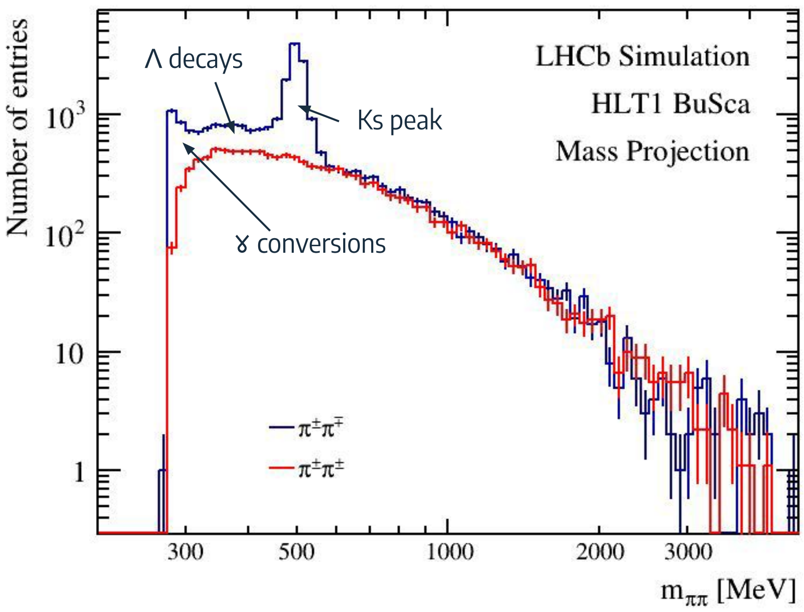




[LHCB-FIGURE-2024-036]

BuSca background studies

Combinatorial backgrounds

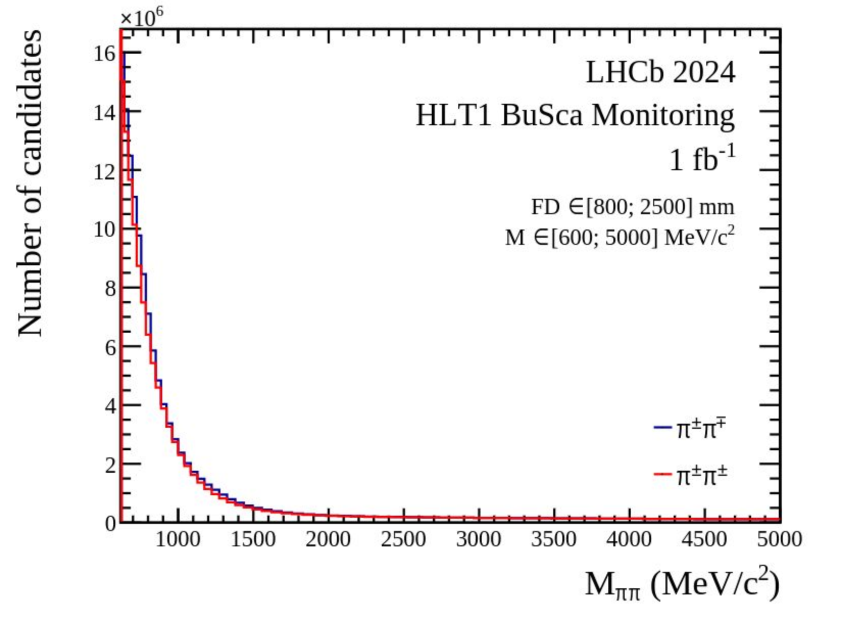


[LHCB-FIGURE-2024-36]

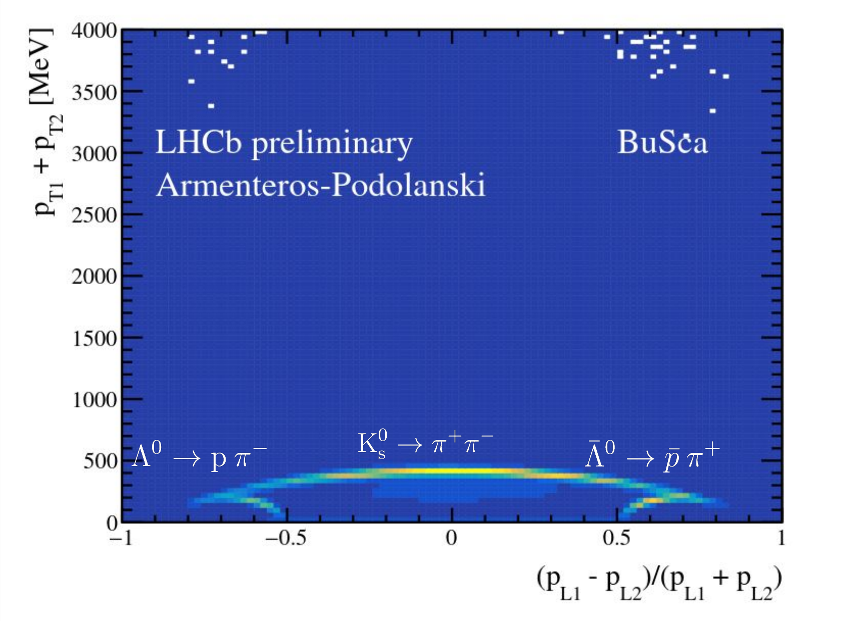
- Formed by **random combinations** of two downstream tracks.
- Currently the **dominant background**, it decreases with mass.
- **Kinematic distributions** can be modeled using **same-sign** downstream vertices:
  - **MVA models** can be trained on same-sign downstream vertices from real data to **suppress this background**.
  - Expected suppression by applying **tight cuts** on the MVA model.

BuSca background studies

Combinatorial backgrounds



[LHCb-FIGURE-2025-002]



[LHCB-FIGURE-2024-36]

Summary

- The LHCb detector is sensitive to **BSM LLP** searches via **Downstream tracks** and **T tracks**.
- The **upgraded LHCb trigger system** and **new real-time reconstruction algorithms** have enabled the possibility of triggering **BSM LLP decays** at **30 MHz**.
- The **BuSca system** is set up in **Run 3** to search for general BSM LLP decays using **Downstream tracks** in the LHCb experiment:
  - The real-time **monitoring system** can detect anomalies in key variables such as **mass**, **lifetime**, **helicity**, and **Armenteros-Podolanski observables**.
  - It currently focuses on **general very displayed two-body decays** and is expected to be extended to multi-body decays in the future.
  - **Background studies** show that physics backgrounds, material interactions, and combinatorial backgrounds can be controlled.

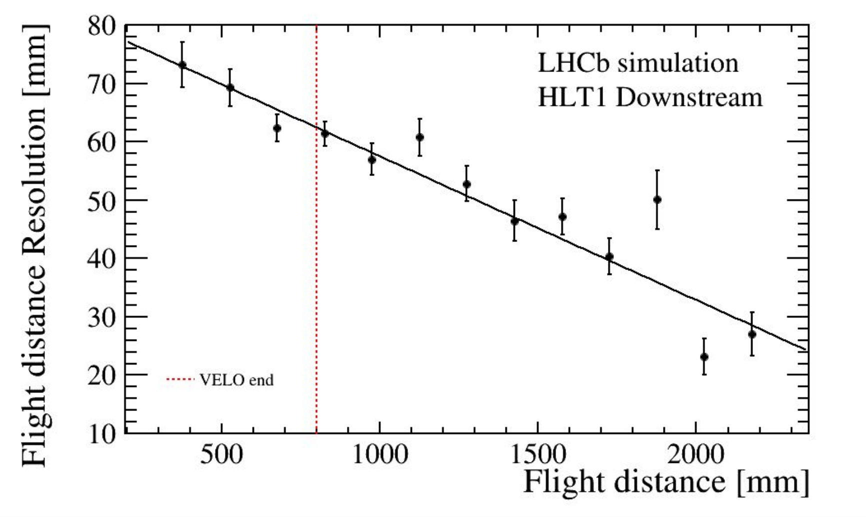
Thanks for listening!

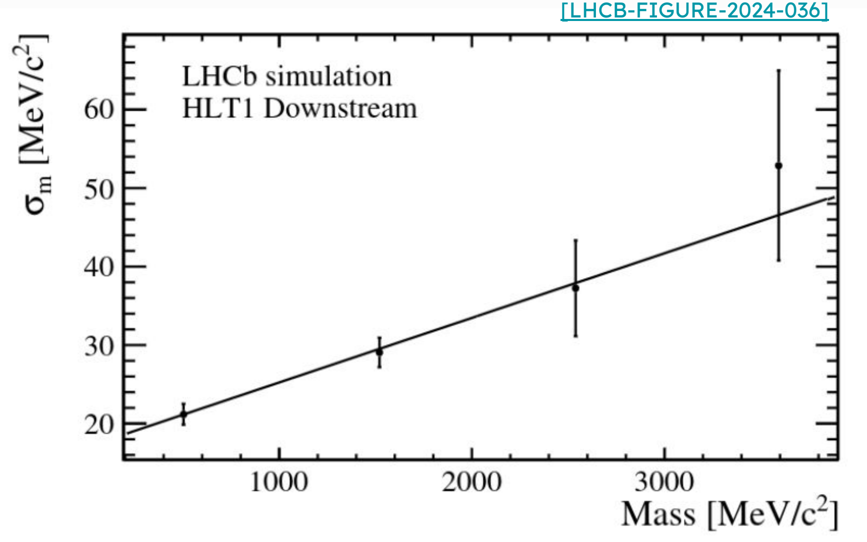
Any questions?

Backup

Downstream for BSM LLP

[LHCB-FIGURE-2024-036]





Binning is adapted according to the expected mass and FD resolution:

$$\sigma_{FD} = 80 - FD \cdot 0.02 \quad [mm]$$

$$\sigma_m = m \cdot 0.02 \quad [MeV/c^2]$$

LHCb experiment

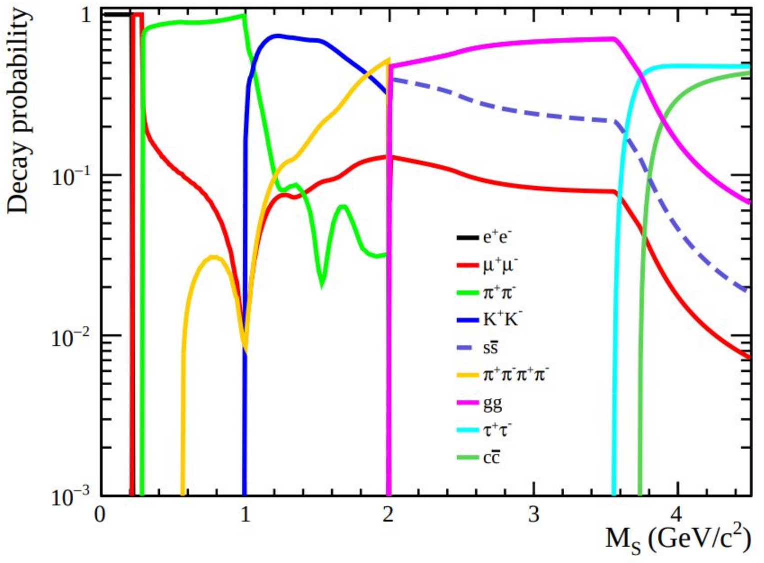
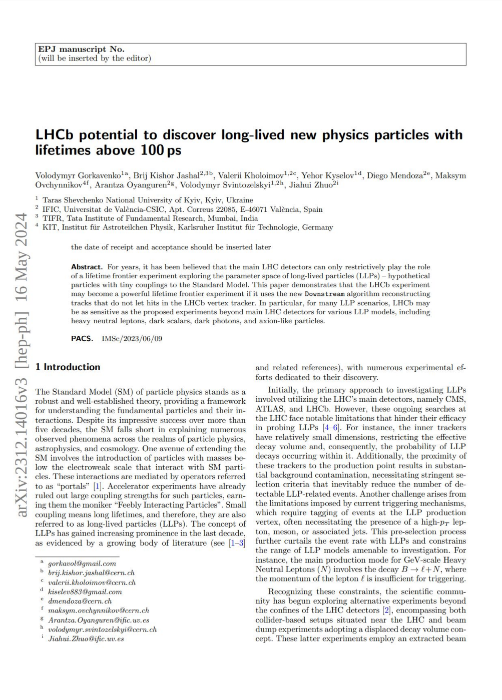


Fig. 4. Decay probabilities of a dark scalar into different channels as a function of its mass and normalised to unity [22].



EPJ manuscript No.
(will be inserted by the editor)

LHCb potential to discover long-lived new physics particles with lifetimes above 100 ps

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the date of receipt and acceptance should be inserted later

Abstract. For years, it has been believed that the main LHC detectors can only restrictively play the role of a lifetime frontier experiment exploring the parameter space of long-lived particles (LLPs) – hypothetical particles with tiny couplings to the Standard Model. This paper demonstrates that the LHCb experiment may become a powerful lifetime frontier experiment if it uses the new `Downstream` algorithm reconstructing tracks that do not let hits in the LHCb vertex tracker. In particular, for many LLP scenarios, LHCb may be as sensitive as the proposed experiments beyond main LHC detectors for various LLP models, including heavy neutral leptons, dark scalars, dark photons, and axion-like particles.

PACS. IMSc/2023/06/09

arXiv:2312.14016v3 [hep-ph] 16 May 2024

1 Introduction

The Standard Model (SM) of particle physics stands as a robust and well-established theory, providing a framework for understanding the fundamental particles and their interactions. Despite its impressive success over more than five decades, the SM falls short in explaining numerous observed phenomena across the realms of particle physics, astrophysics, and cosmology. One avenue of extending the SM involves the introduction of particles with masses below the electroweak scale that interact with SM particles. These interactions are mediated by operators referred to as "portals" [1]. Accelerator experiments have already ruled out large coupling strengths for such particles, earning them the moniker "Feebly Interacting Particles". Small coupling means long lifetimes, and therefore, they are also referred to as long-lived particles (LLPs). The concept of LLPs has gained increasing prominence in the last decade, as evidenced by a growing body of literature (see [1–3] and related references), with numerous experimental efforts dedicated to their discovery.

Initially, the primary approach to investigating LLPs involved utilizing the LHC's main detectors, namely CMS, ATLAS, and LHCb. However, these ongoing searches at the LHC face notable limitations that hinder their efficacy in probing LLPs [4–6]. For instance, the inner trackers have relatively small dimensions, restricting the effective decay volume and, consequently, the probability of LLP decays occurring within it. Additionally, the proximity of these trackers to the production point results in substantial background contamination, necessitating stringent selection criteria that inevitably reduce the number of detectable LLP-related events. Another challenge arises from the limitations imposed by current triggering mechanisms, which require tagging of events at the LLP production vertex, often necessitating the presence of a high-p_T lepton, meson, or associated jets. This pre-selection process further curtails the event rate with LLPs and constrains the range of LLP models amenable to investigation. For instance, the main production mode for GeV-scale Heavy Neutral Leptons (N) involves the decay $B \to \ell + N$, where the momentum of the lepton ℓ is insufficient for triggering.

Recognizing these constraints, the scientific community has begun exploring alternative experiments beyond the confines of the LHC detectors [2], encompassing both collider-based setups situated near the LHC and beam dump experiments adopting a displaced decay volume concept. These latter experiments employ an extracted beam

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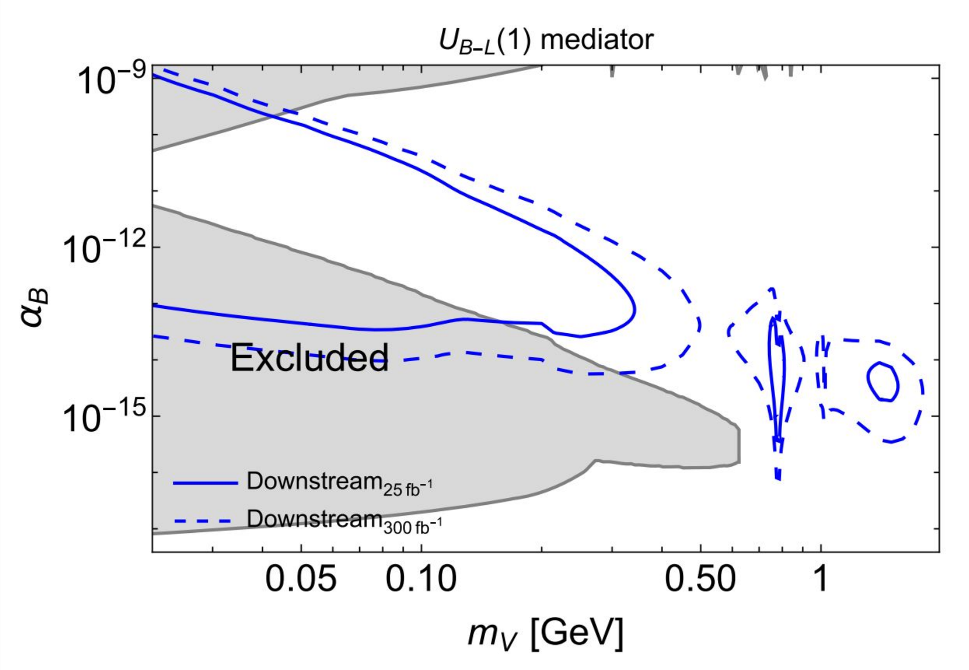
[Eur. Phys. J. C 84, 608 (2024)]

Downstream for BSM LLP

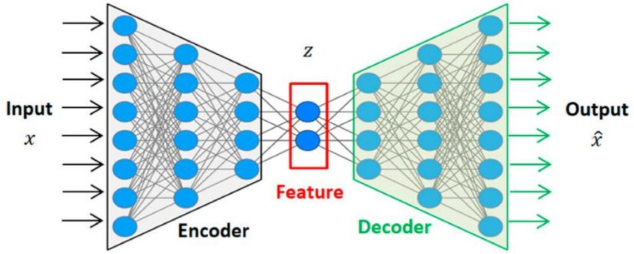


[Eur. Phys. J. C 84, 608 (2024)]

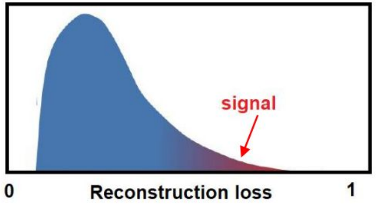
- Another example of sensitivity improvement with downstream tracks is the search for **dark photon**.
- This signature is **unrelated** to **b-decays**:
  - Trigger Independent of Signal (**TIS**) on b-decays is not longer helpful.
  - Dedicated **HLT1 trigger lines** are required.
  - Background studies are essential.
- For more details, see the second part of this talk: **the BuSca project**.

Autoencoder

Aiming to suppress the combinatorial background using an autoencoder trained on same-sign track-pairs data.



The difference between the original and reconstructed data can be used as an effective anomaly score in monitoring.



Trying to define regions where new physics is more probable: open HLT1 lines to collect and analyse these data.