



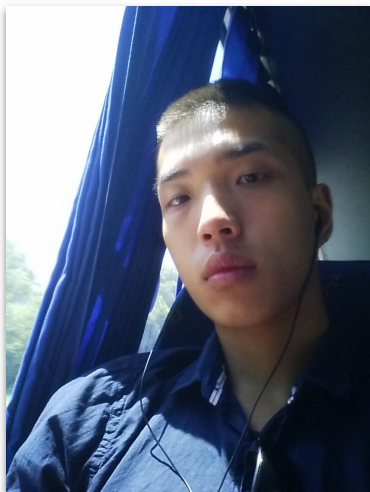
中国科学院大学
University of Chinese Academy of Sciences



LHCb Real-Time Reconstruction and New Physics Searches

Jiahui Zhuo (UCAS)

About Me



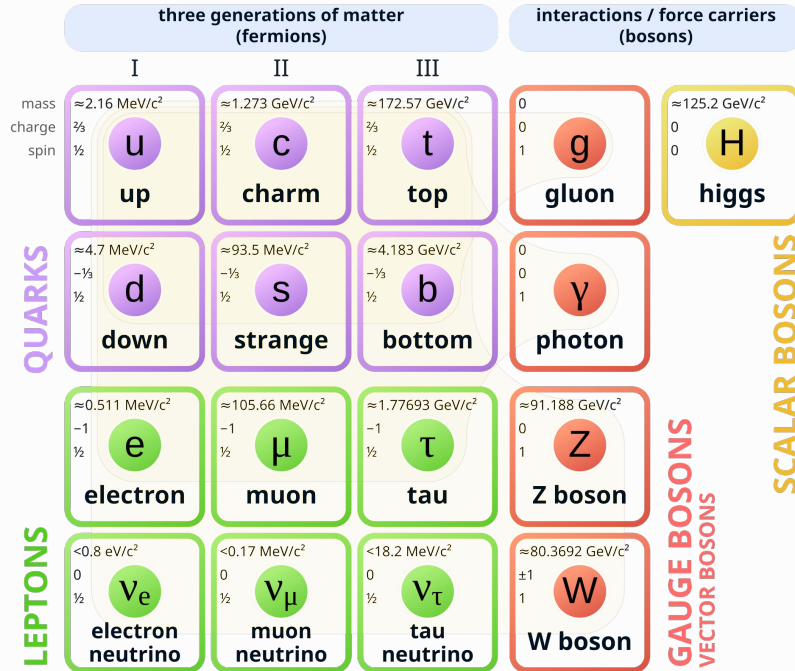
- **JIAHUI ZHUO GAO**
- **Ph.D., Universitat de València (IFIC-CSIC), 2026**
- **LHCb Trigger & Real-Time Analysis**
- **One of main developer & maintainer, LHCb HLT1 (Run 3)**
- **Convener, LHCb Retina DWT Simulation & Software WG**
- **2024 LHCb Early Career Scientist Award**

I

Introduction

The Standard Model

Standard Model of Elementary Particles



The Standard Model is the most precisely tested theory in physics

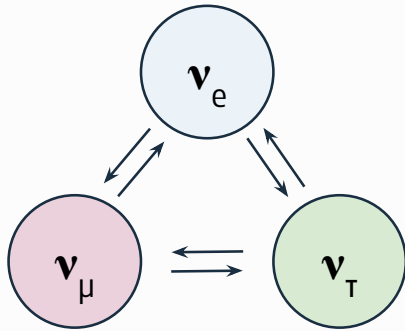
$$\left. \frac{g_e - 2}{2} \right|_{\text{SM}} = 0.001\,159\,652\,181\,643(764)^{[1]}$$

$$\left. \frac{g_e - 2}{2} \right|_{\text{exp}} = 0.001\,159\,652\,180\,59(13)^{[2]}$$

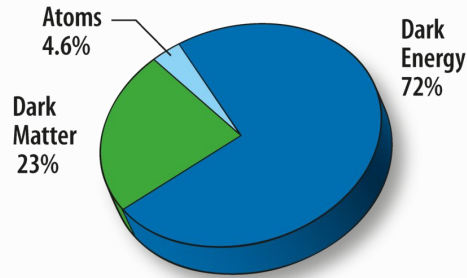
[1] [10.3390/atoms7010028](https://arxiv.org/abs/10.3390/atoms7010028) [2] [10.1103/PhysRevLett.130.071801](https://arxiv.org/abs/10.1103/PhysRevLett.130.071801)

The Standard Model

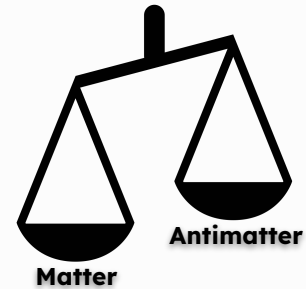
Yet, the Standard Model leaves several fundamental phenomena unexplained.



Neutrino masses



Dark matter &
Dark energy



Matter-antimatter
asymmetry

The Standard Model

Two Approaches to Search for New Physics at Colliders



DIRECT SEARCHES

On-shell production

Produce new particles directly.
Sensitive to new physics at the energy frontier

New particle

High energy



INDIRECT SEARCHES

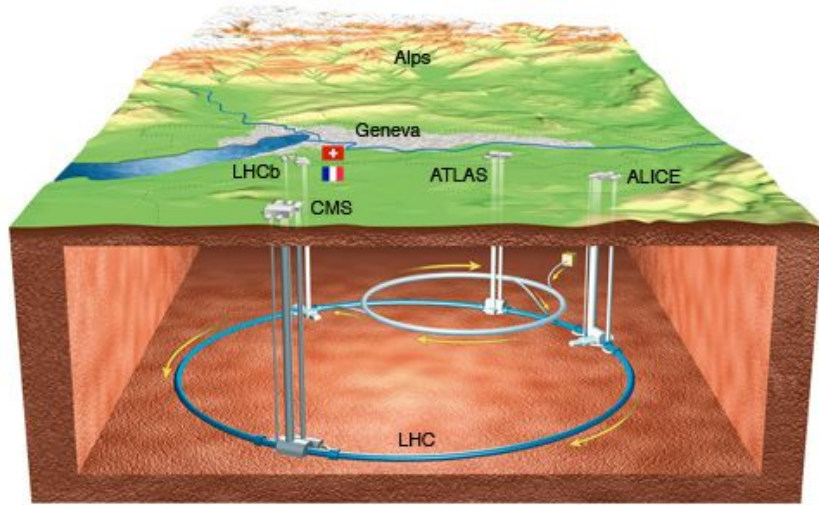
Precision measurements

Detect deviations from SM predictions.
Sensitive to new physics beyond the direct energy reach

Rare decays

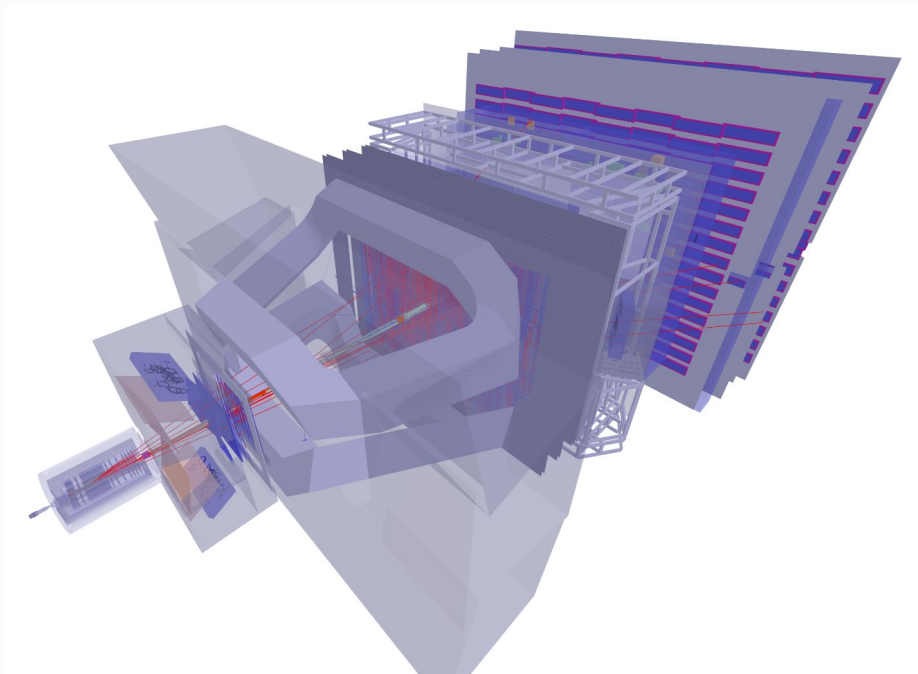
CP violation

The Large Hadron Collider

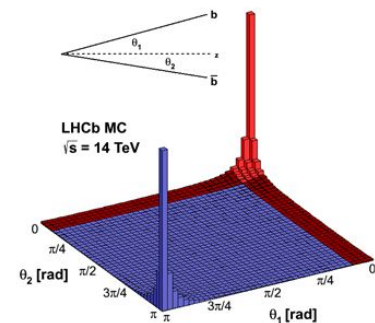
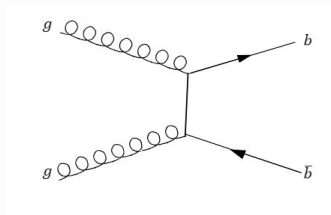


- Located at CERN, on the French-Swiss border near Geneva
- 27 km circumference, 100 m underground
- Colliding protons at up to 13.6 TeV
- Four main experiments: ATLAS, CMS, ALICE, and LHCb

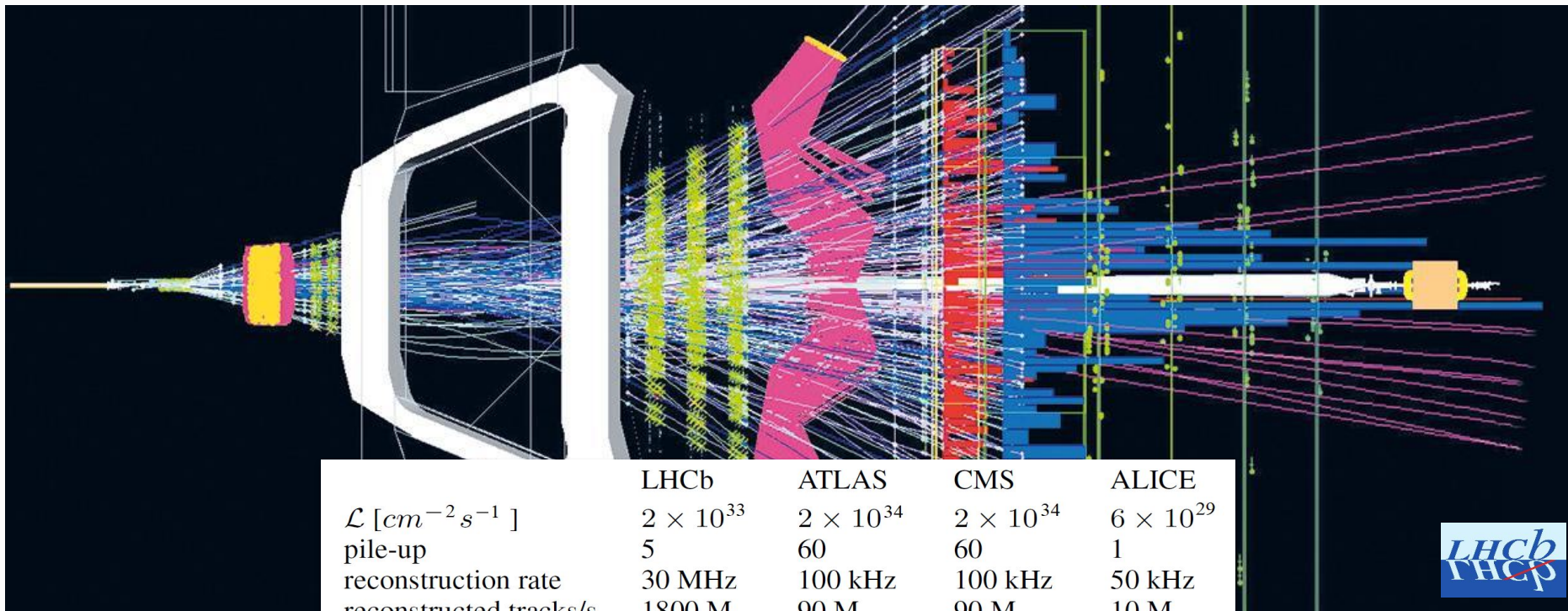
The LHCb experiment



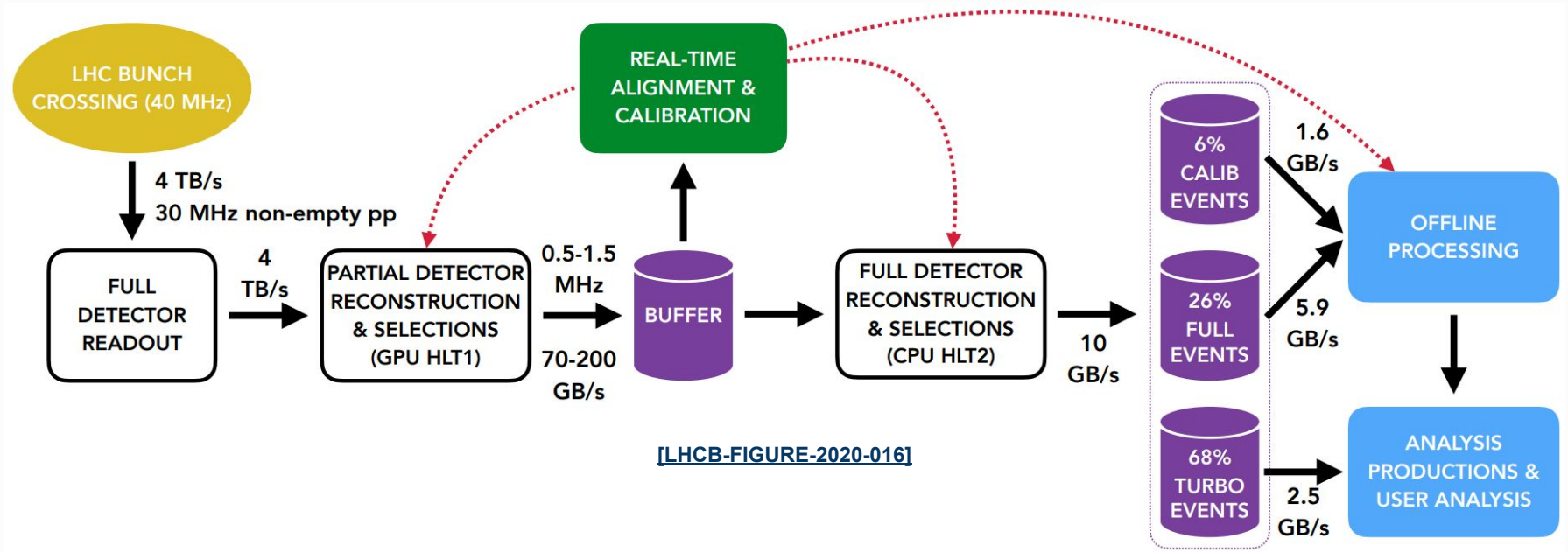
- Forward spectrometer ($2 < \eta < 5$)
- Covering $\sim 40\%$ of $b\bar{b}$ pairs
- $\sigma(m_B) \sim 25$ MeV for 2-body decays
- Muon ID efficiency $\sim 97\%$



LHCb trigger system



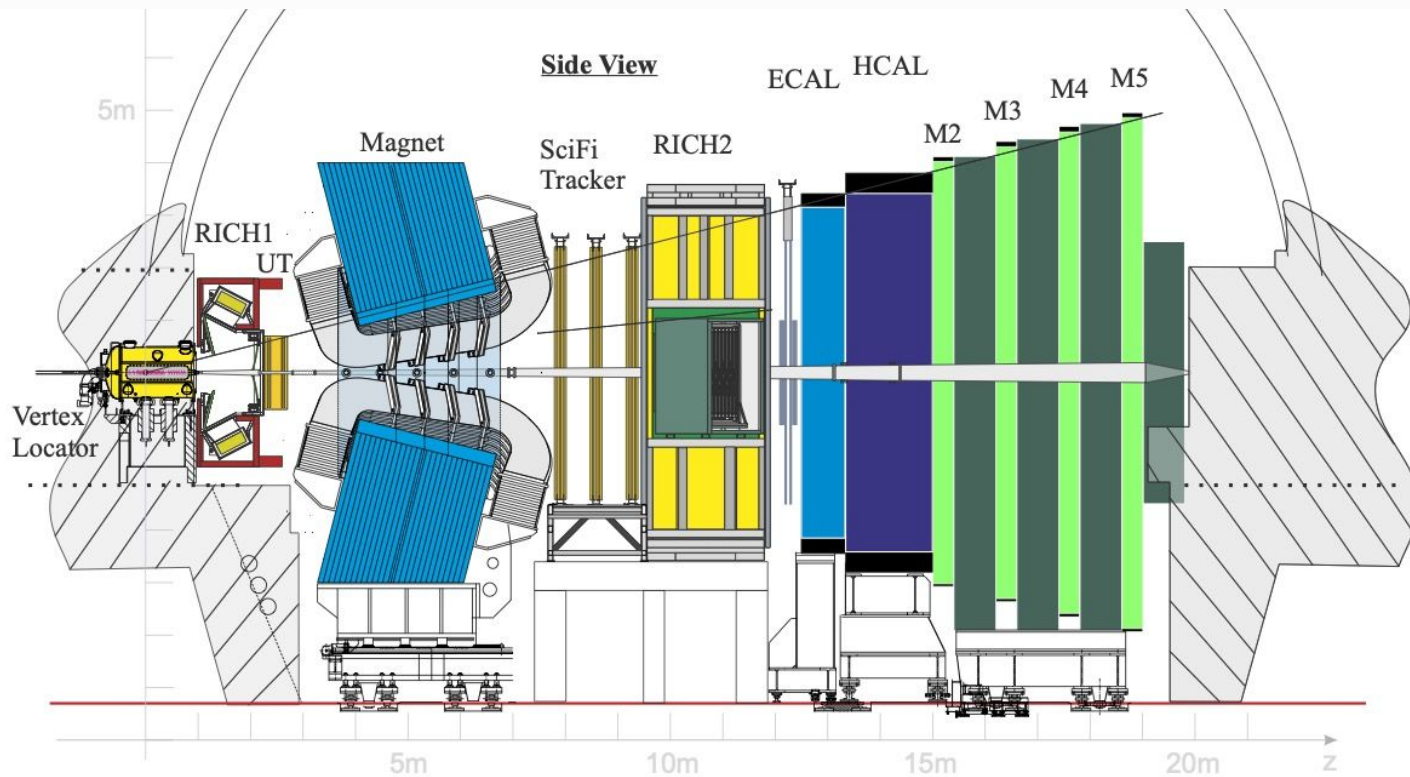
Trigger system



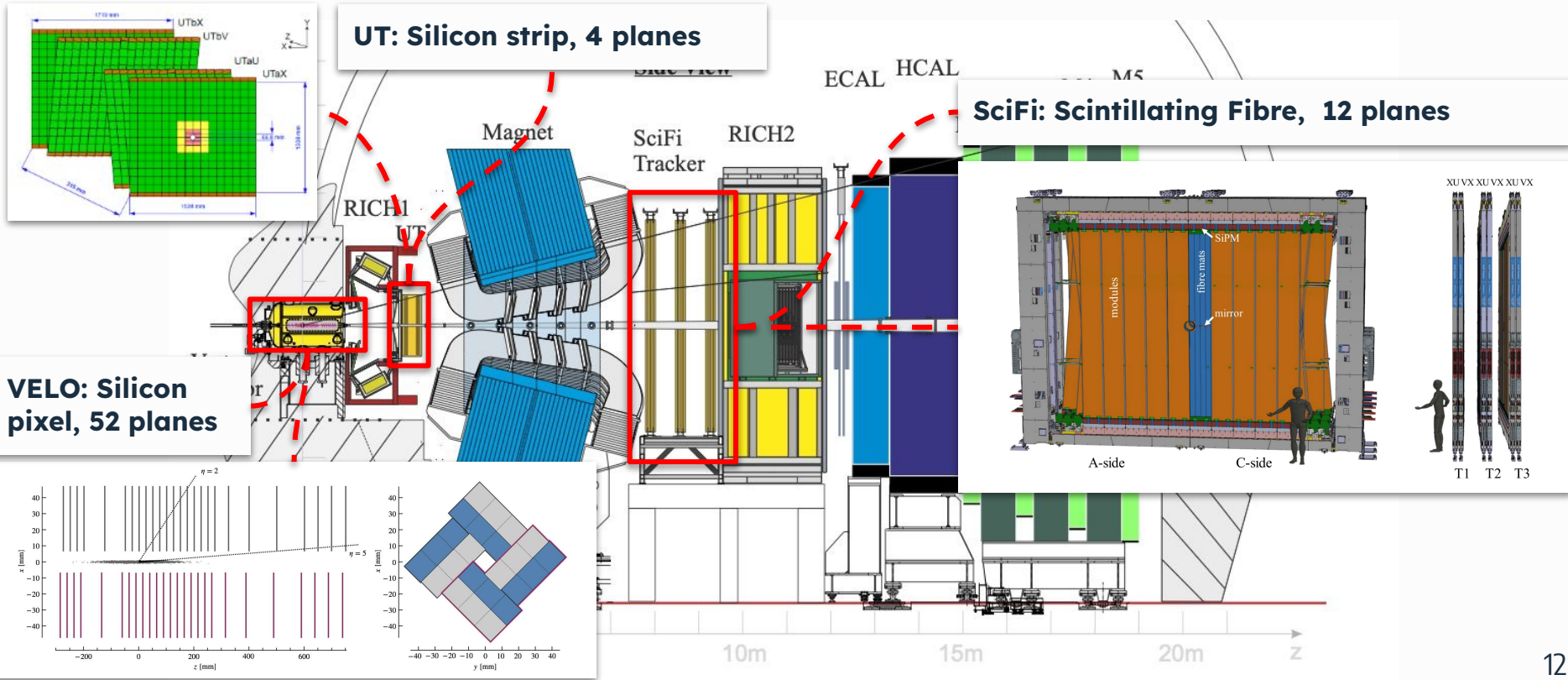
HLT1 runs as a GPU-based application (Allen) to handle high data throughput.

[Comput Softw Big Sci 4, 7 (2020)]

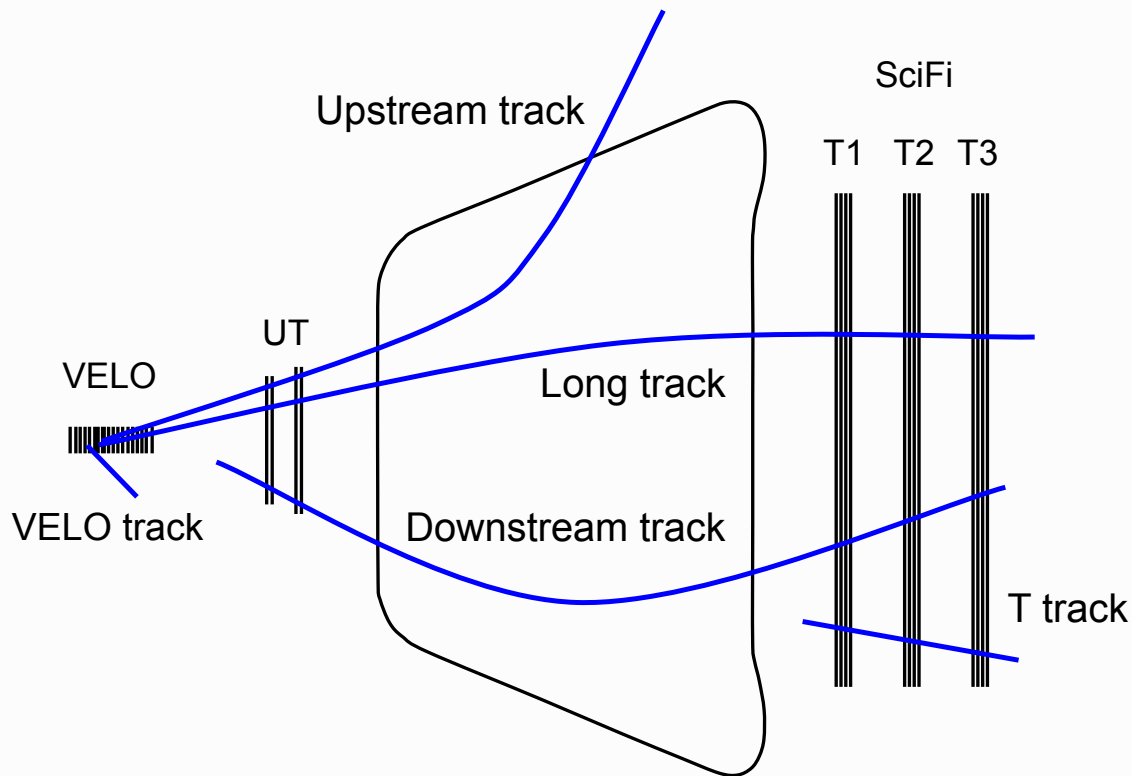
The LHCb detector



Tracking detectors



Track types

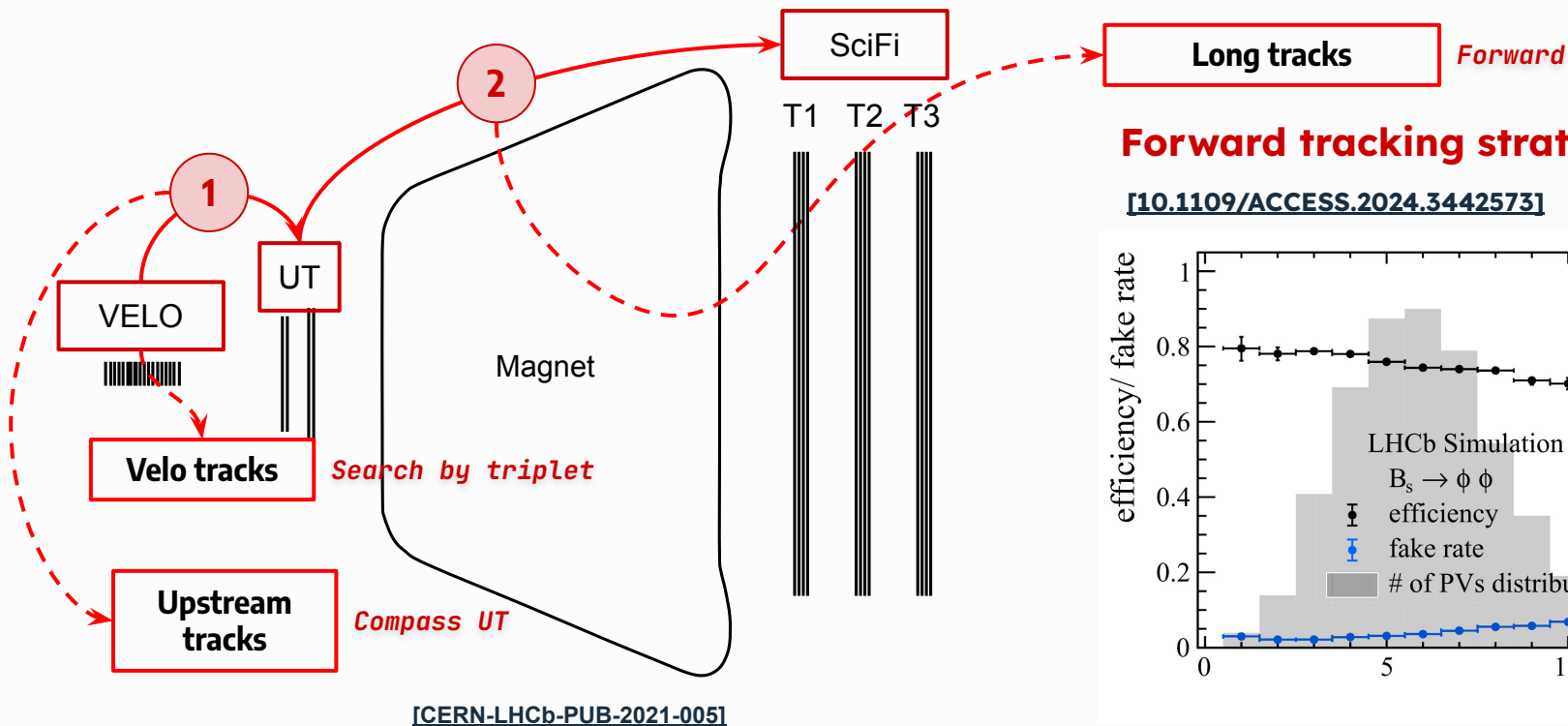


- **Long** tracks provide the best momentum and position resolution.
- **Downstream** tracks reconstruct decays occurring after the VELO.
- **Long** and **downstream** tracks are the most used in physics analyses.

II

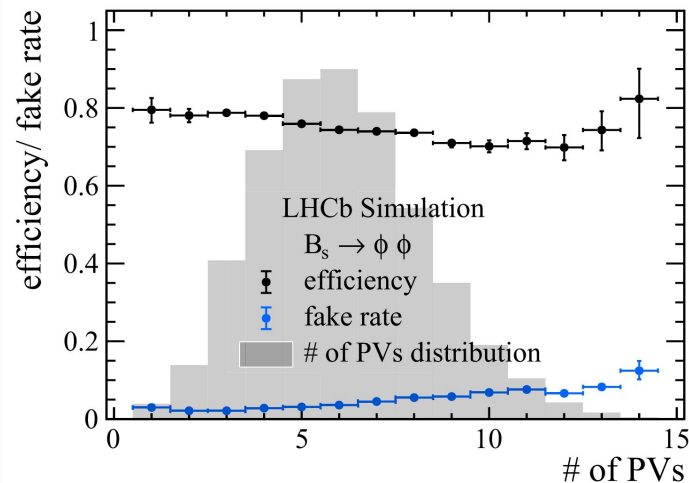
HLT1 Tracking

LHCb tracking strategy

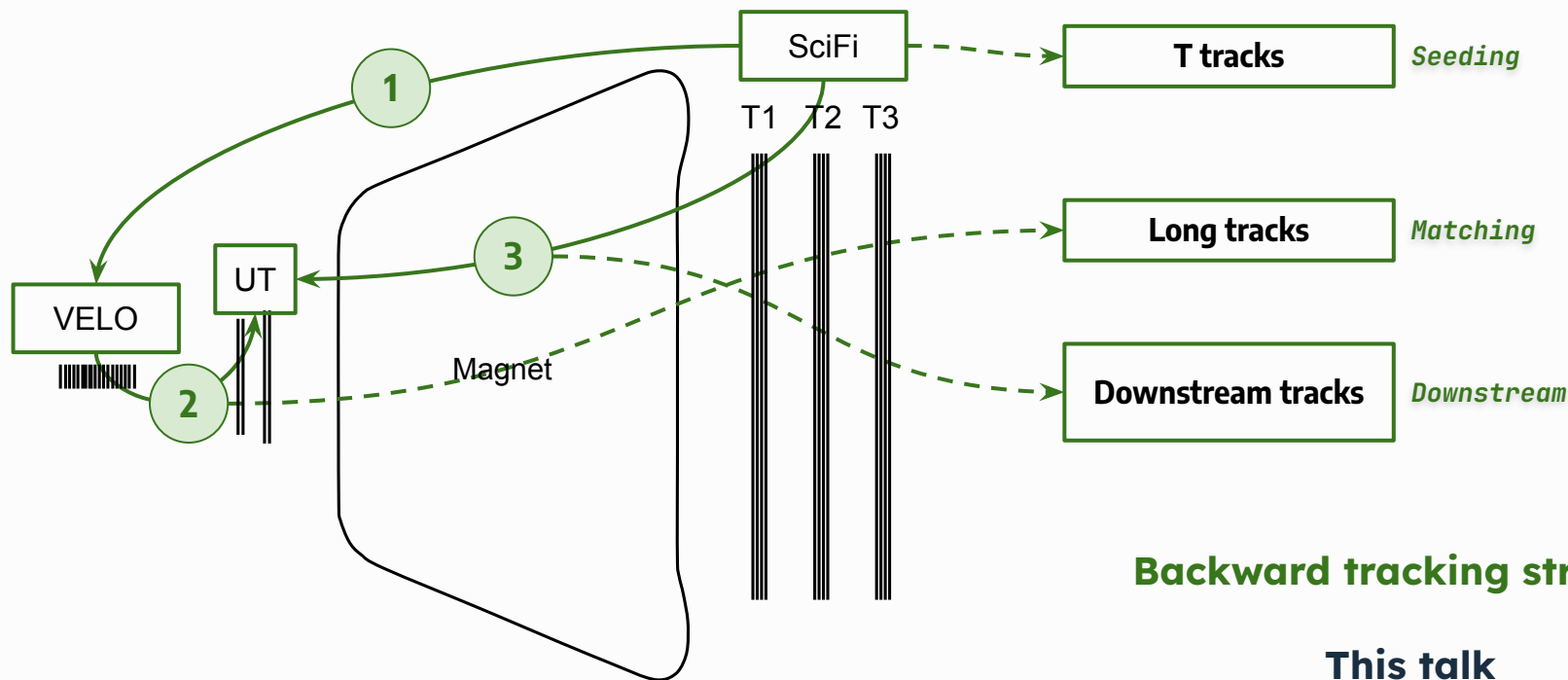


Forward tracking strategy

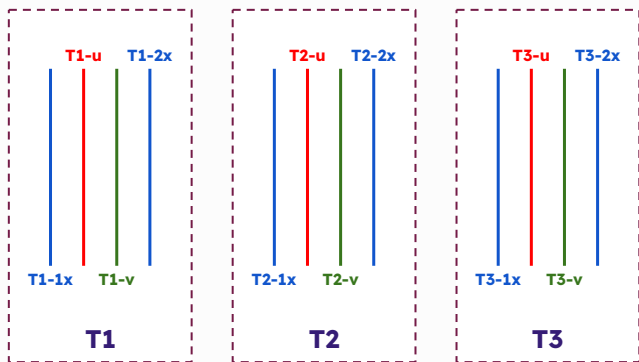
[\[10.1109/ACCESS.2024.3442573\]](#)



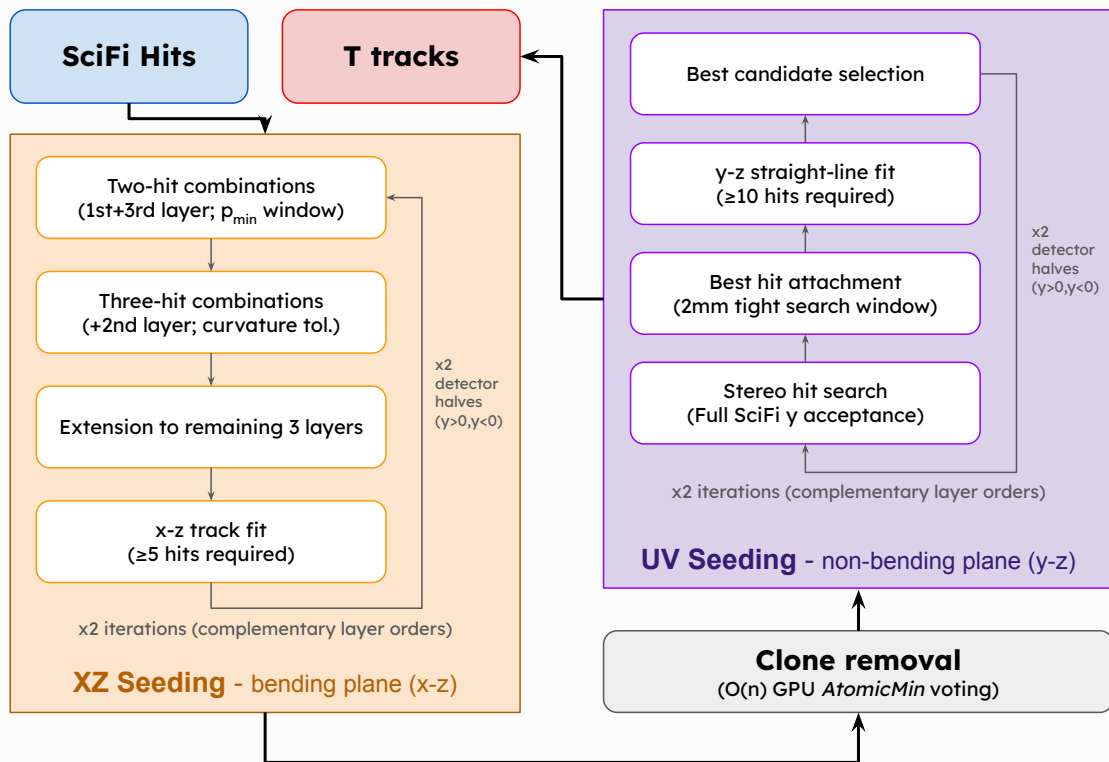
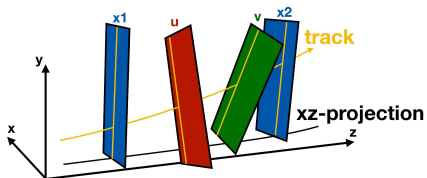
LHCb tracking strategy



HLT1 Seeding

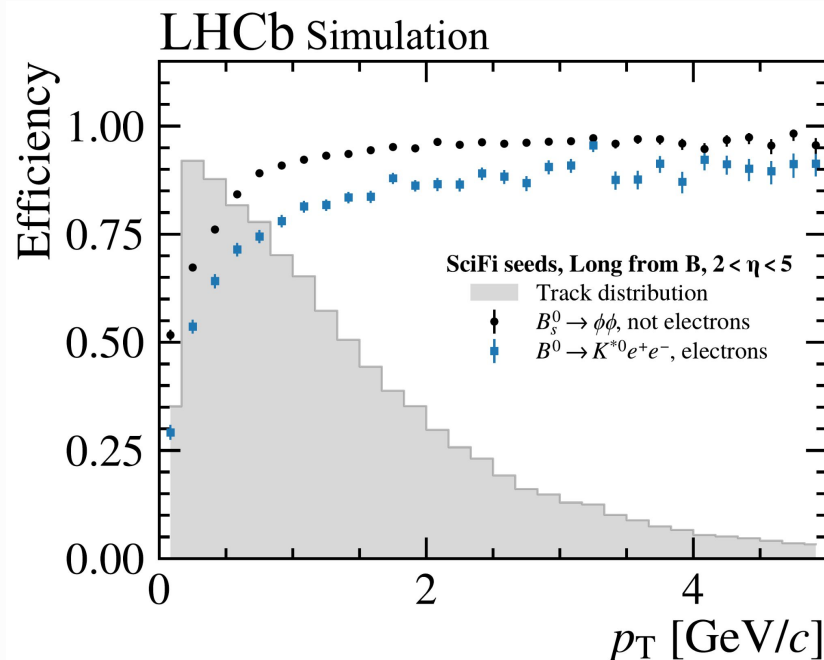
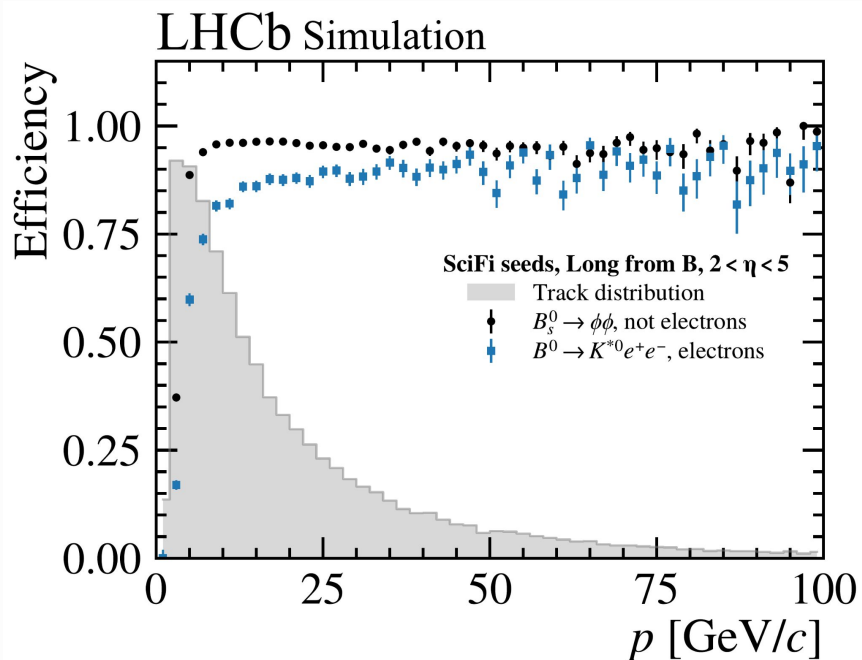


Iteration	Triplet layers			Extension layers		
	1st	2nd	3rd	4th	5th	6th
1	T1-1x	T2-1x	T3-1x	T1-2x	T2-2x	T3-2x
2	T1-2x	T2-2x	T3-2x	T1-1x	T2-1x	T3-1x



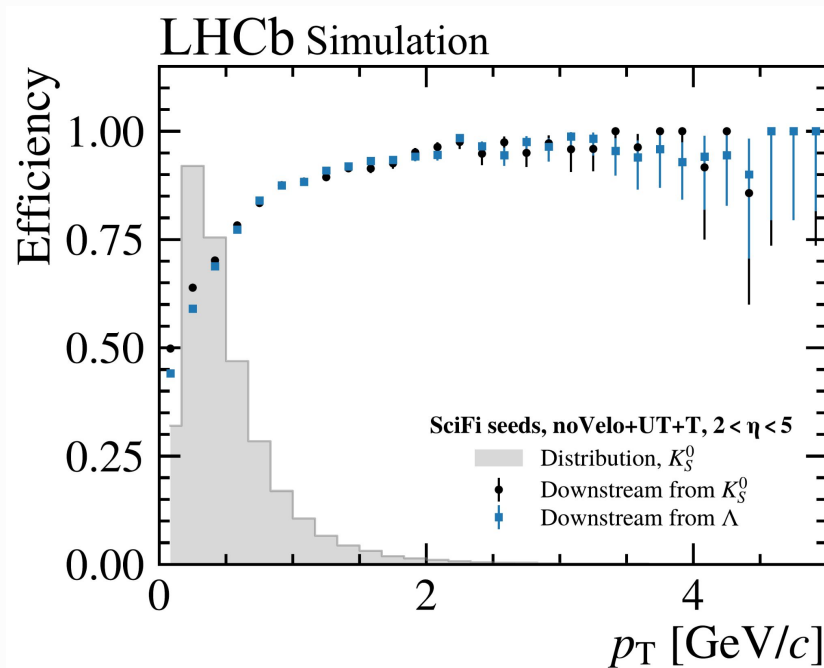
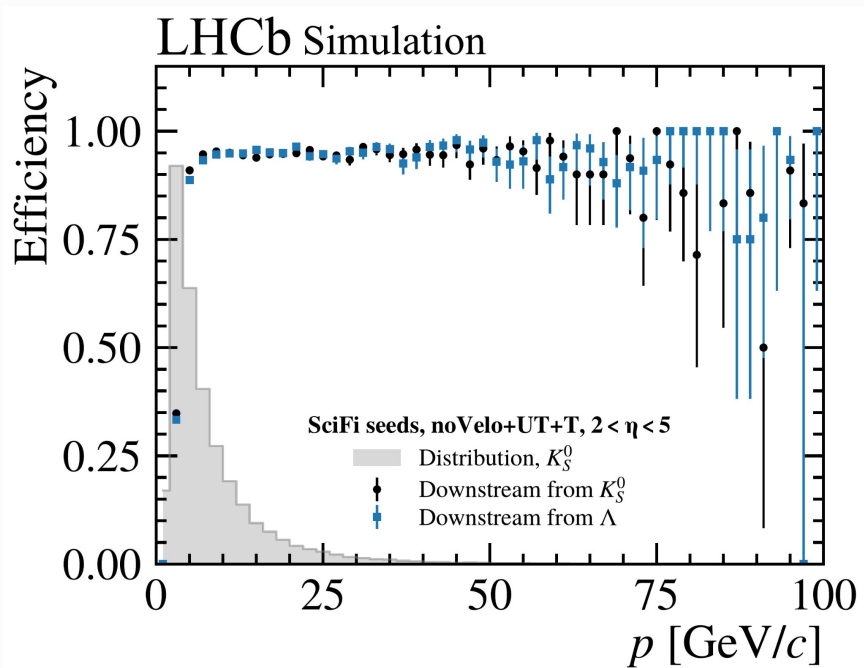
HLT1 seeding

Efficiency (Long tracks)



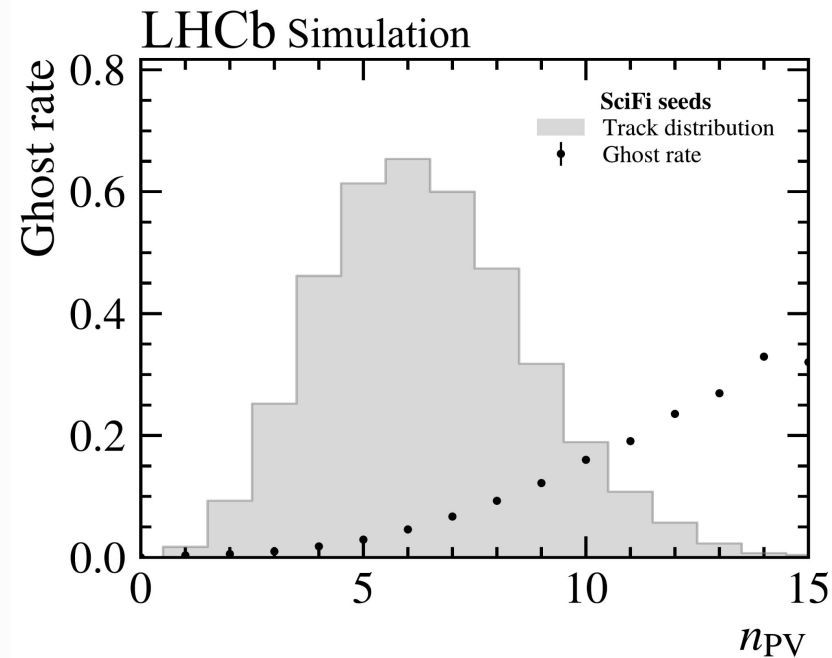
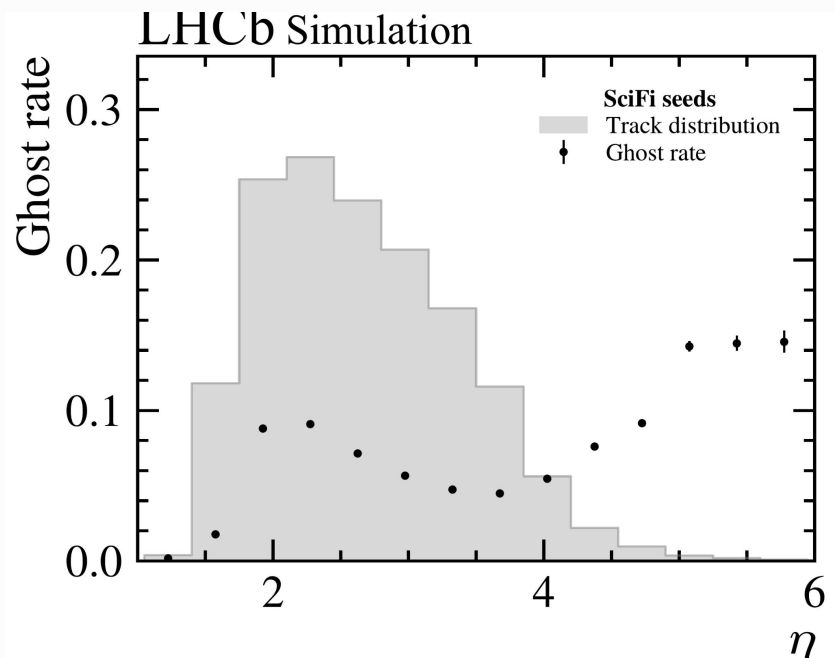
HLT1 seeding

Efficiency (Downstream tracks)



HLT1 seeding

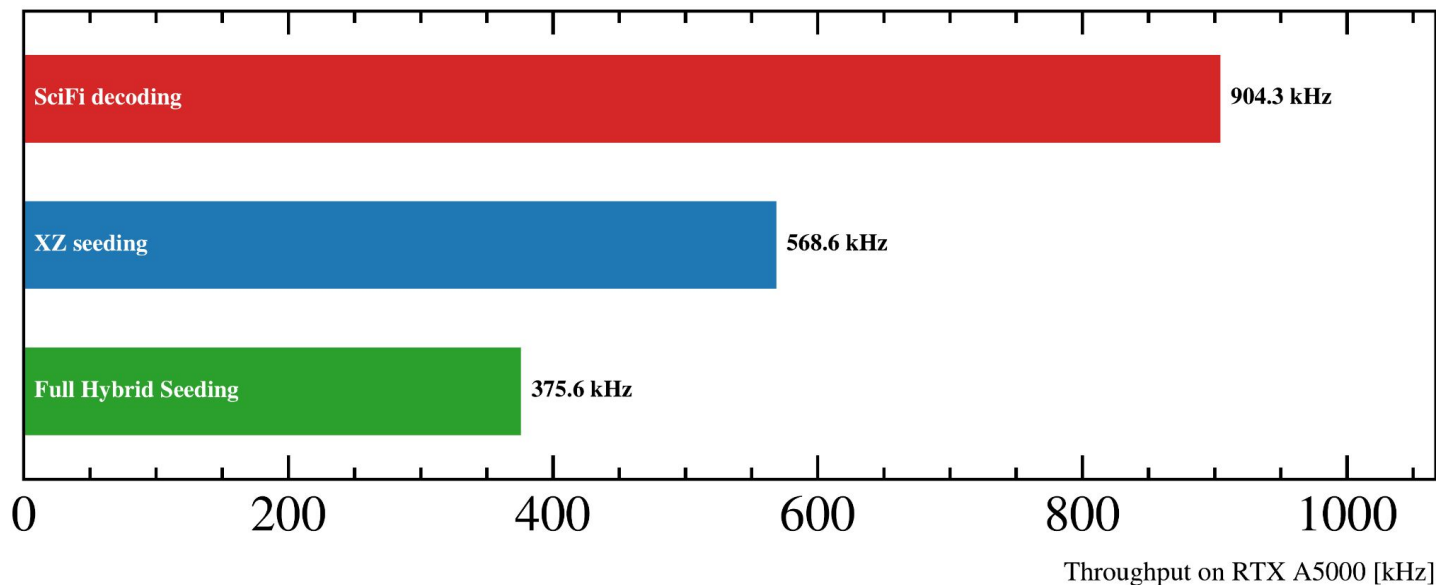
Ghost rate



HLT1 seeding

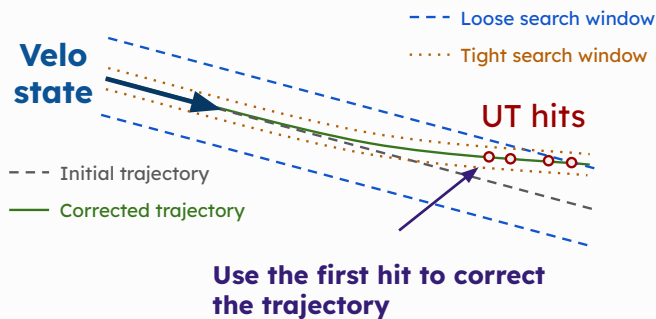
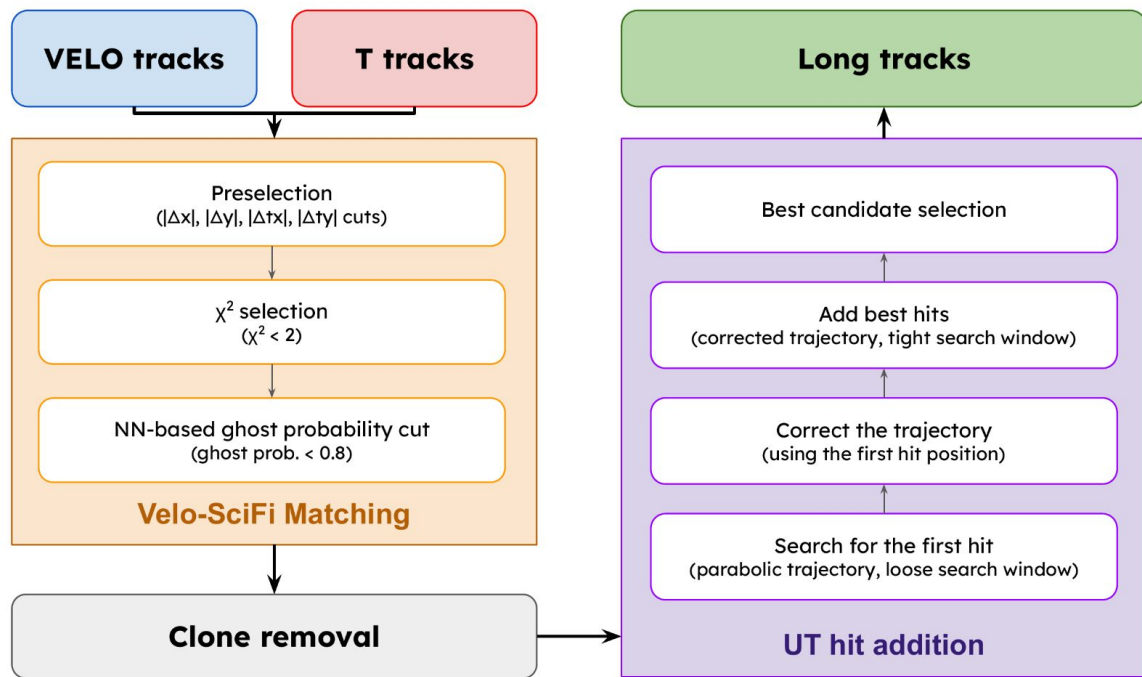
Throughput

LHCb Simulation



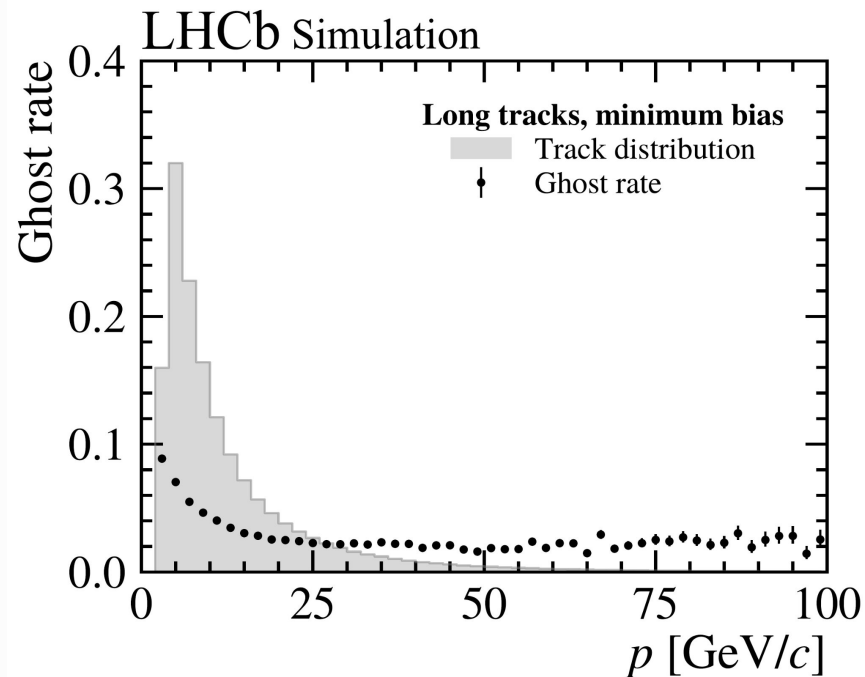
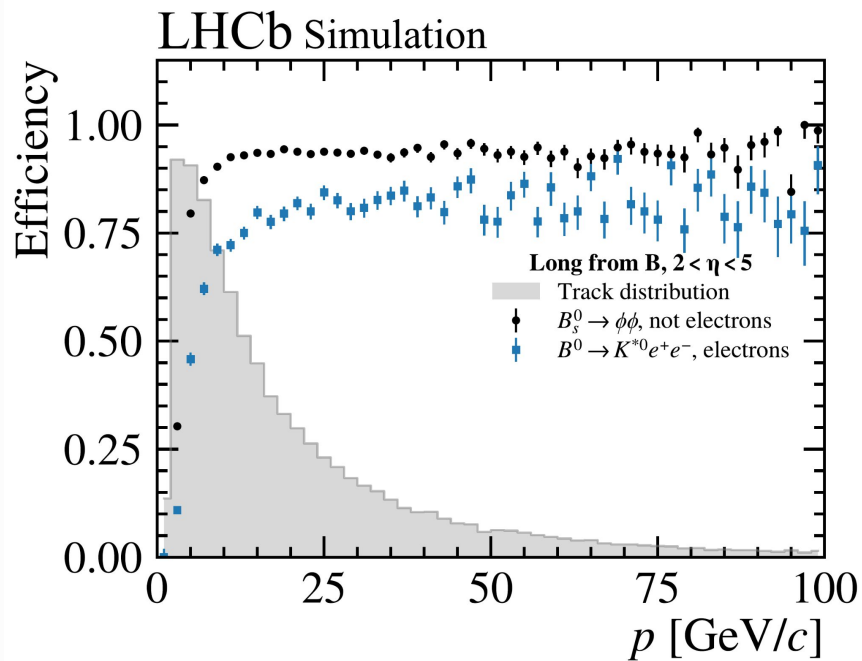
- In Run 3, we have **O(500)** NVIDIA A5000s.
- Each GPU must operate at **> 60 kHz** to meet the **30 MHz** requirement.

HLT1 matching



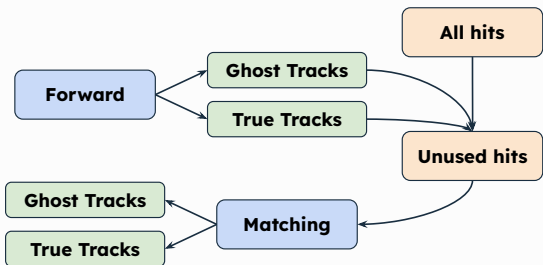
$$x(z) = x_{\text{VELO}} + t_x^{\text{VELO}} \cdot (z - z_{\text{endVelo}}) + y_x \cdot (z - z_{\text{endVelo}})^2,$$
$$y(z) = y_{\text{VELO}} + t_y^{\text{VELO}} \cdot (z - z_{\text{endVelo}}),$$

HLT1 matching

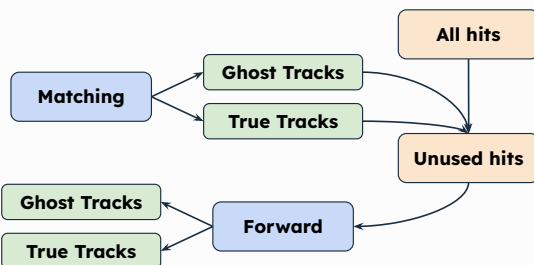


HLT1 matching

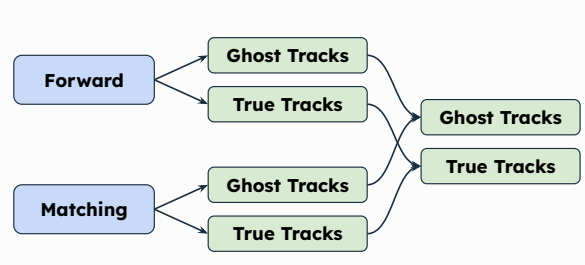
- The idea is to combine the **matching** and **forward** tracking in HLT1 to achieve higher physics performance.
- There are **3 different strategies** of combinations:



Forward then matching

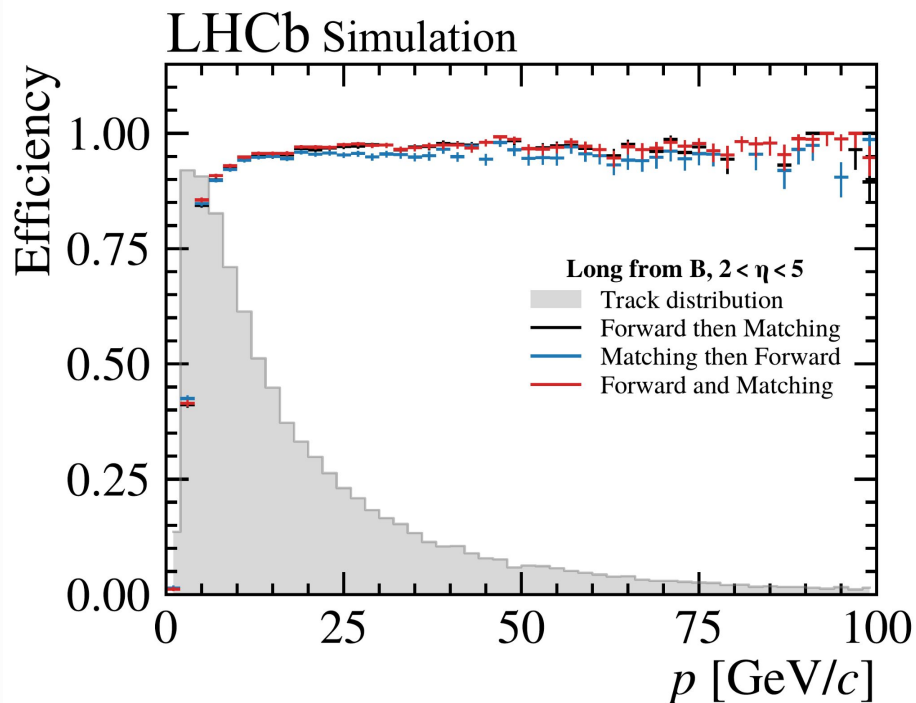


Matching then forward

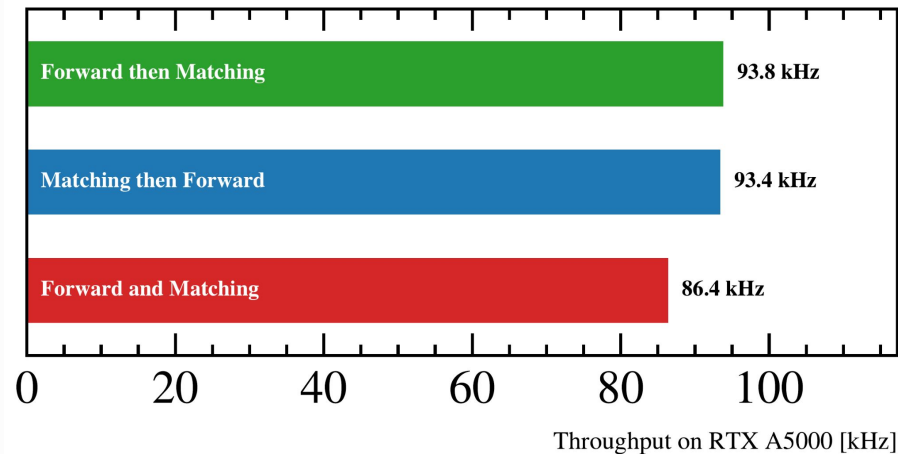


Forward and matching

HLT1 matching

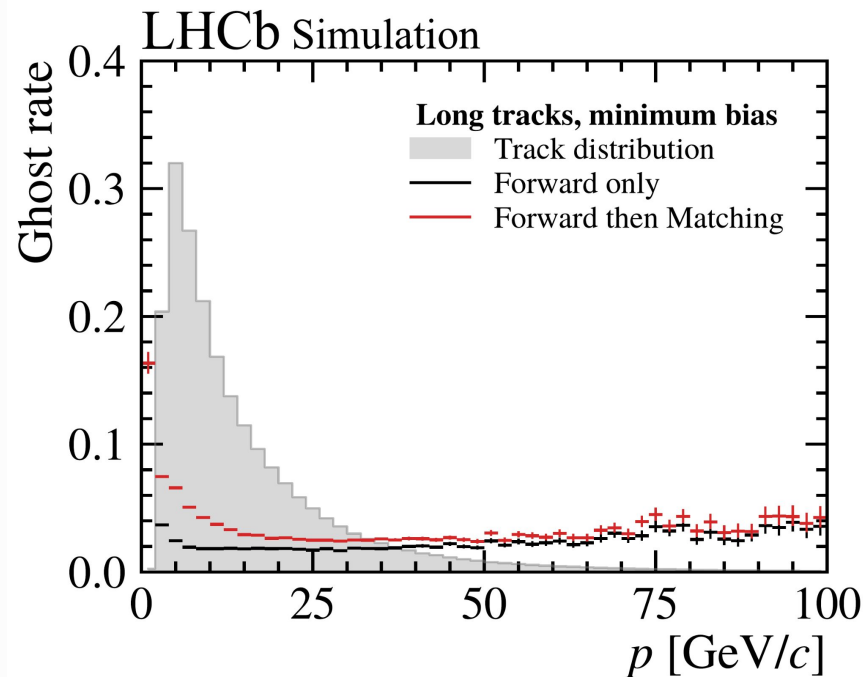
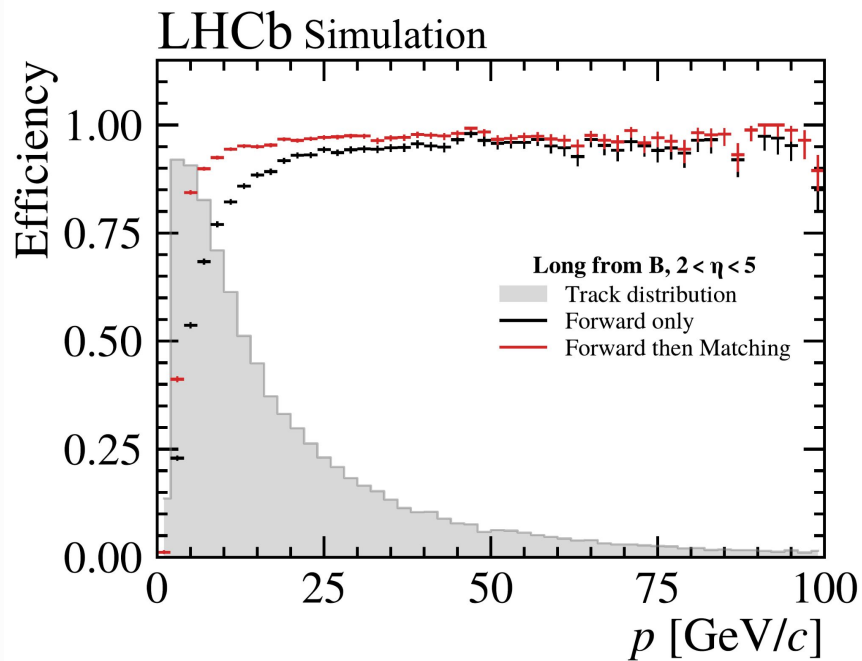


LHCb Simulation

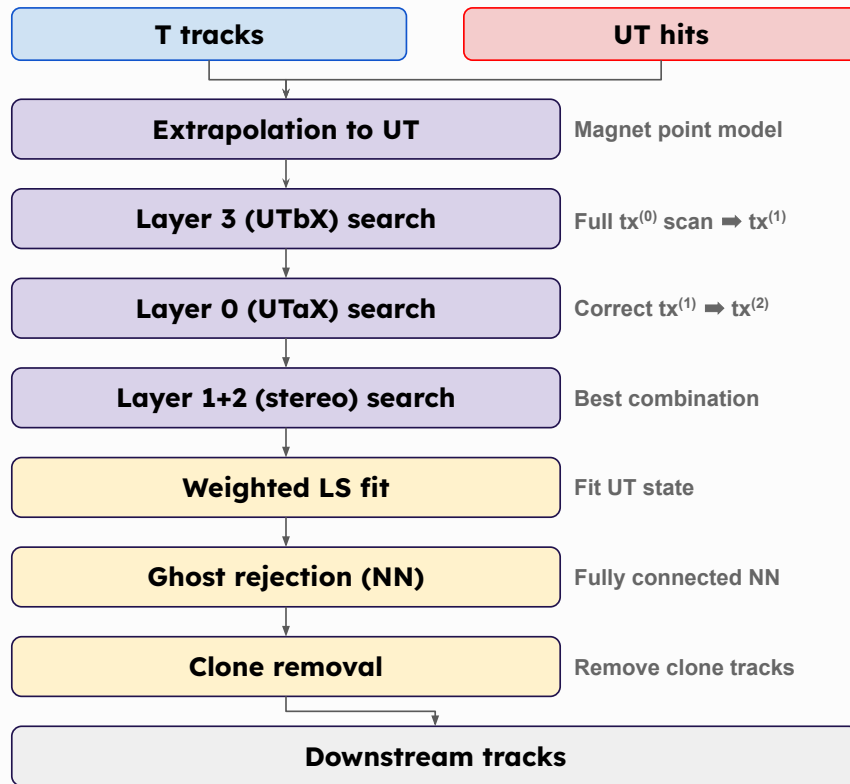
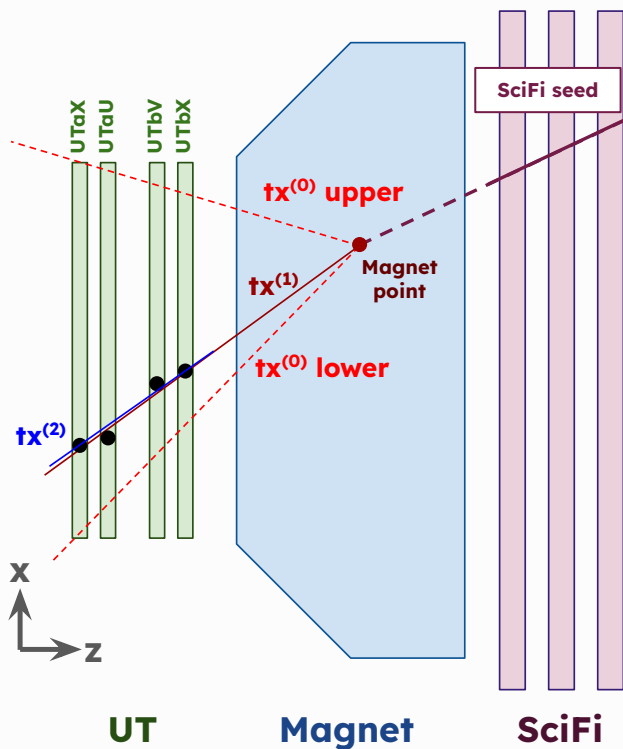


Finally, the **Forward then matching** scheme was chosen as the new HLT1 baseline.

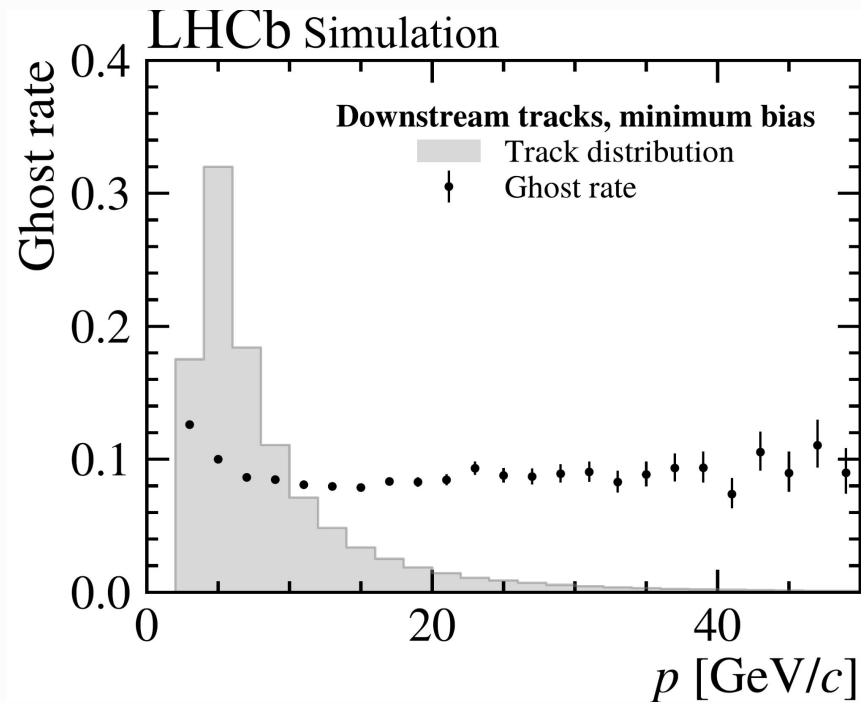
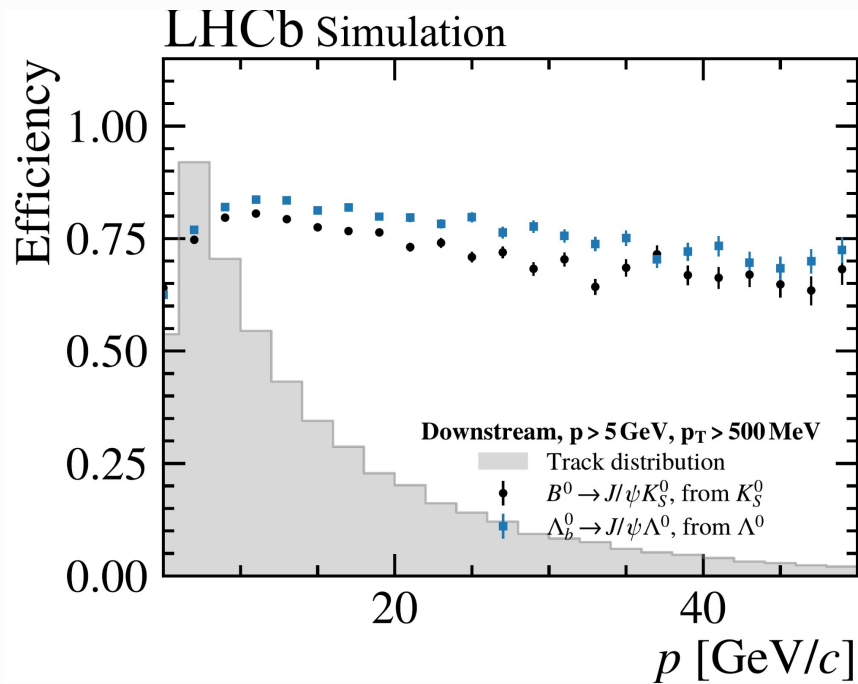
HLT1 matching



HLT1 downstream

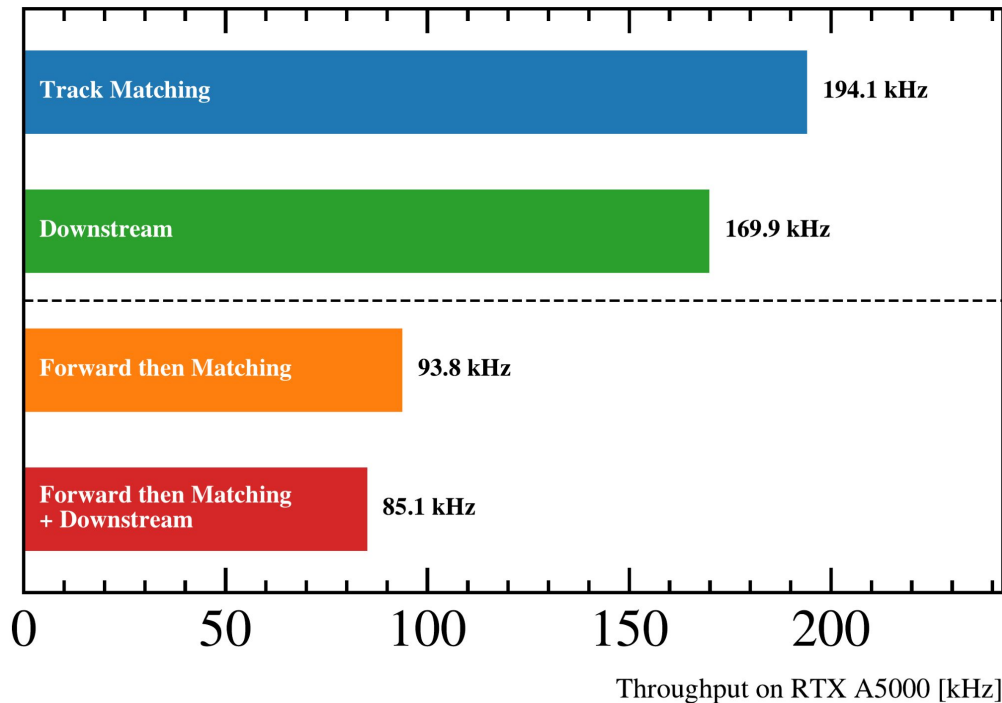


HLT1 downstream



HLT1 downstream

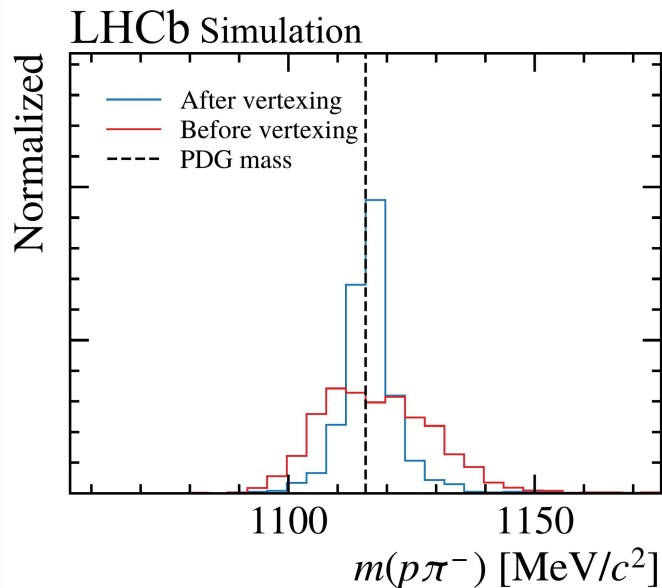
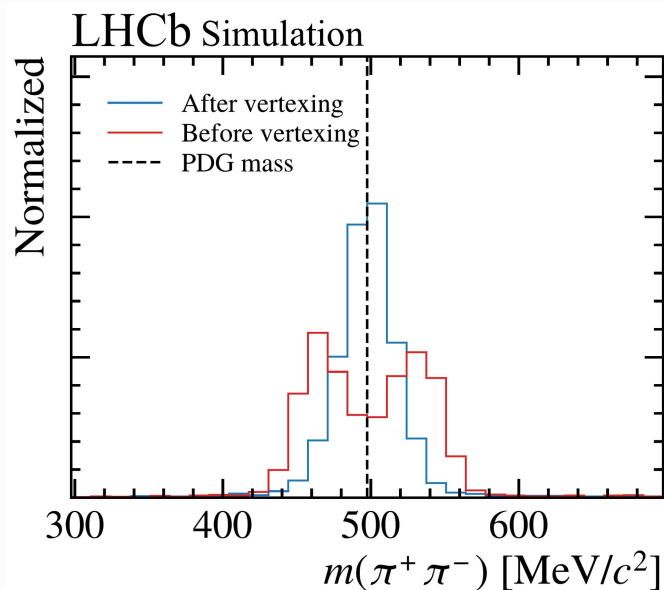
LHCb Simulation



- Adding the downstream tracking reduces the throughput by approximately 9%.
- This cost is modest compared to the total HLT1 computing budget; the final throughput is still well above the 60 kHz requirement.

HLT1 downstream

- Having downstream tracking in HLT1 is not enough, we also need to reconstruct physics: the K_s^0 and Λ decays: a new **vertexing** algorithm was also developed for downstream tracks.



Two HLT1 trigger lines were then developed to select displaced K_s^0 and Λ decays.

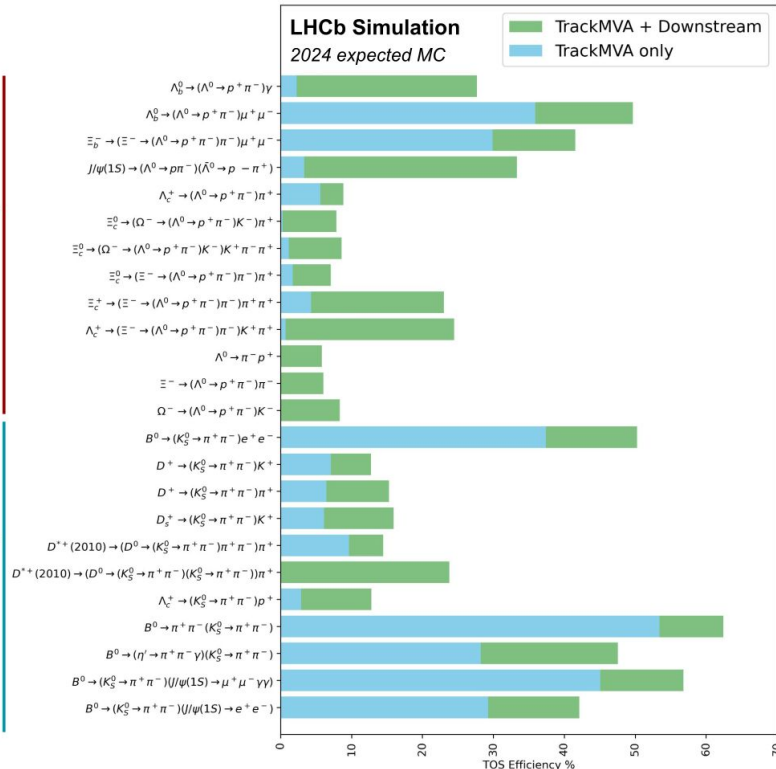
HLT1 downstream

- The K^0 s and Λ decays have large lifetimes, and therefore tend to decay outside the VELO.
- The new **HLT1 downstream tracking triggers** can significantly improve the HLT1 trigger efficiency for various physics analyses involving K^0_s and Λ decays.

HLT1 Downstream effect

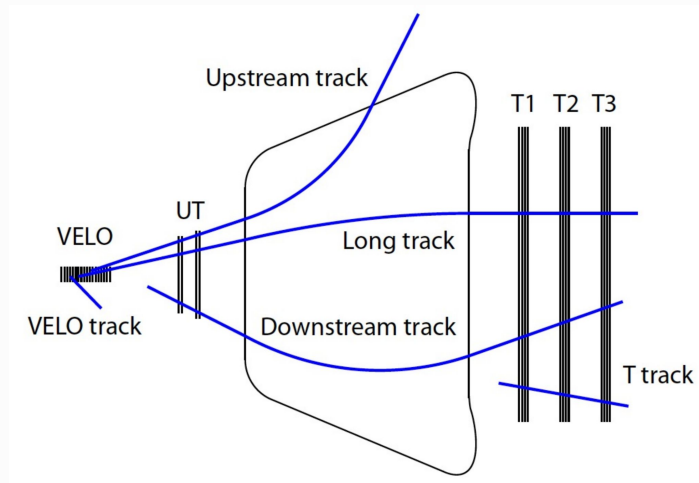
Λ^0 decays

K^0 decays

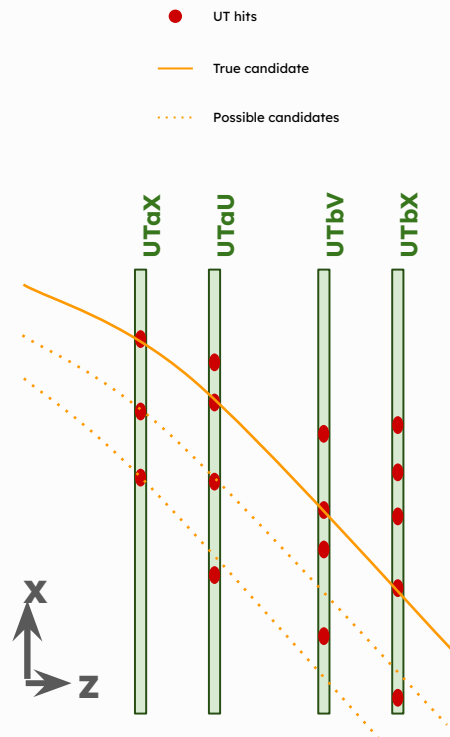
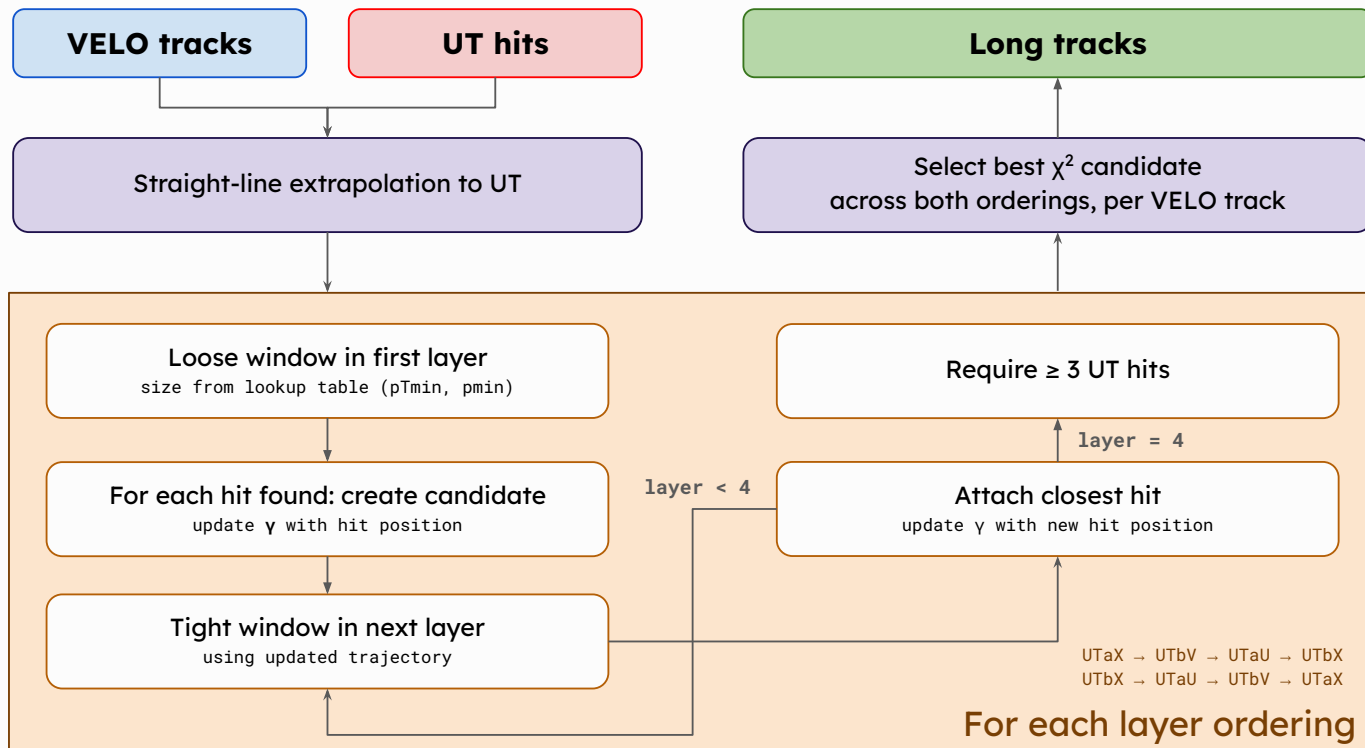


HLT1 upstream

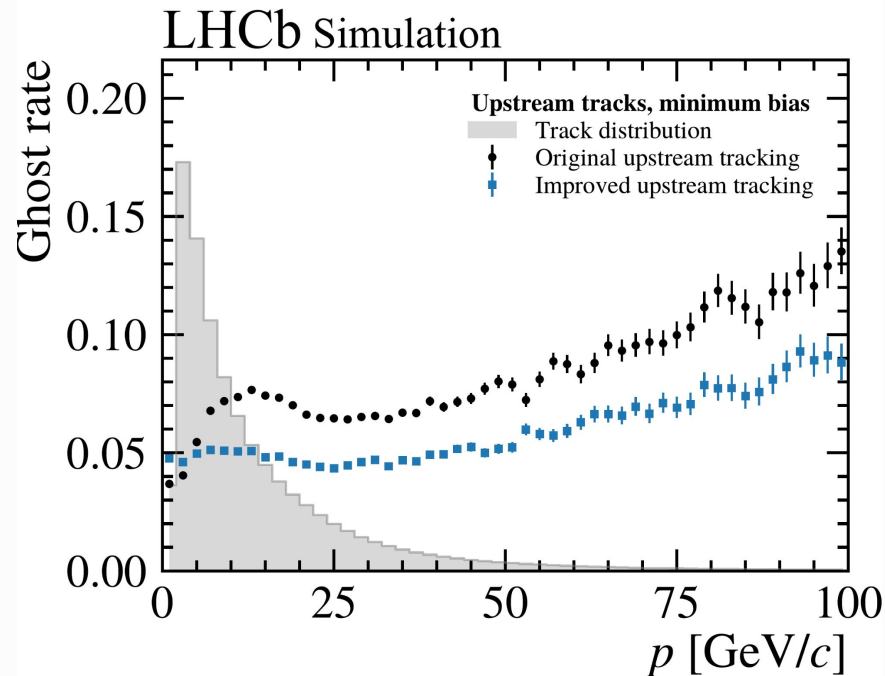
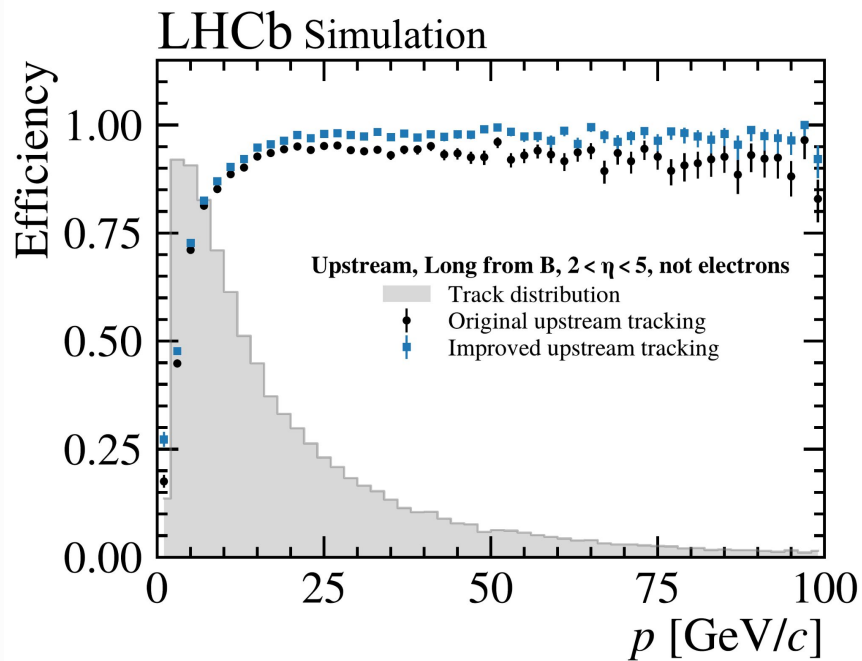
- The HLT1 **forward** tracking uses **upstream tracks** as input to extrapolate them forward into the **SciFi**.
- The **UT pattern recognition** experience gained from the **matching** and **downstream** tracking helped us improve the **HLT1 upstream tracking algorithm**.
- The new HLT1 upstream tracking is designed following the **matching** UT hit search strategy.



HLT1 upstream

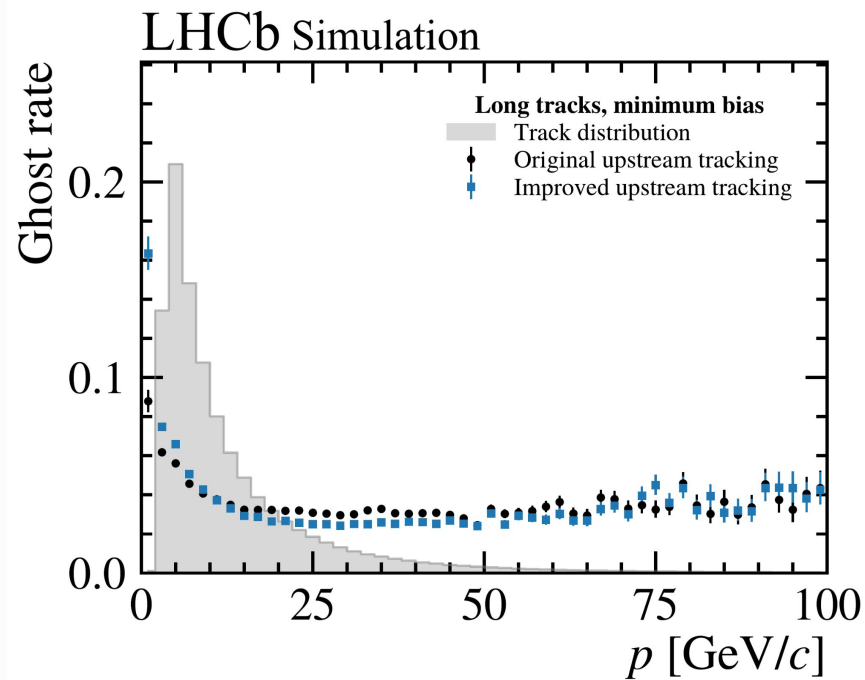
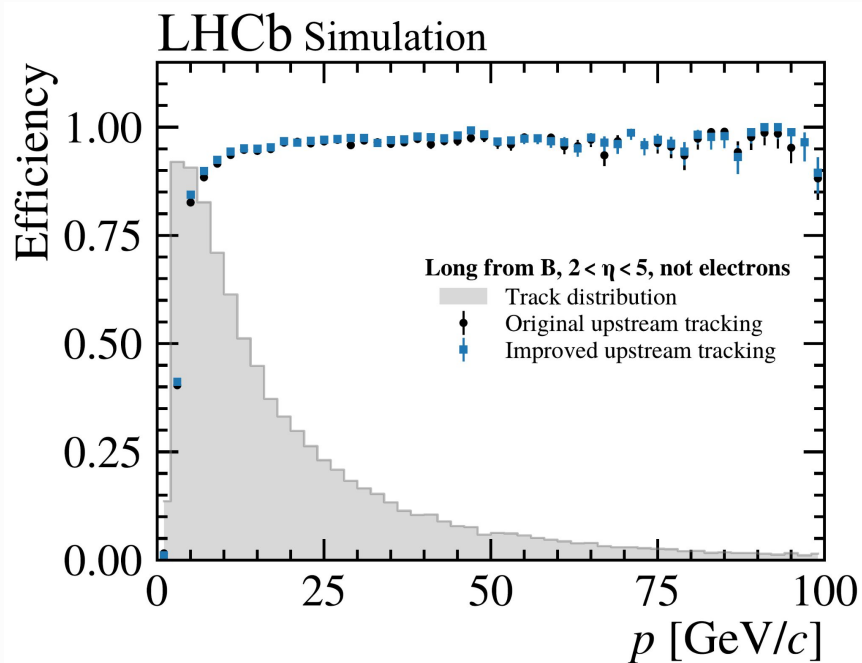


HLT1 upstream



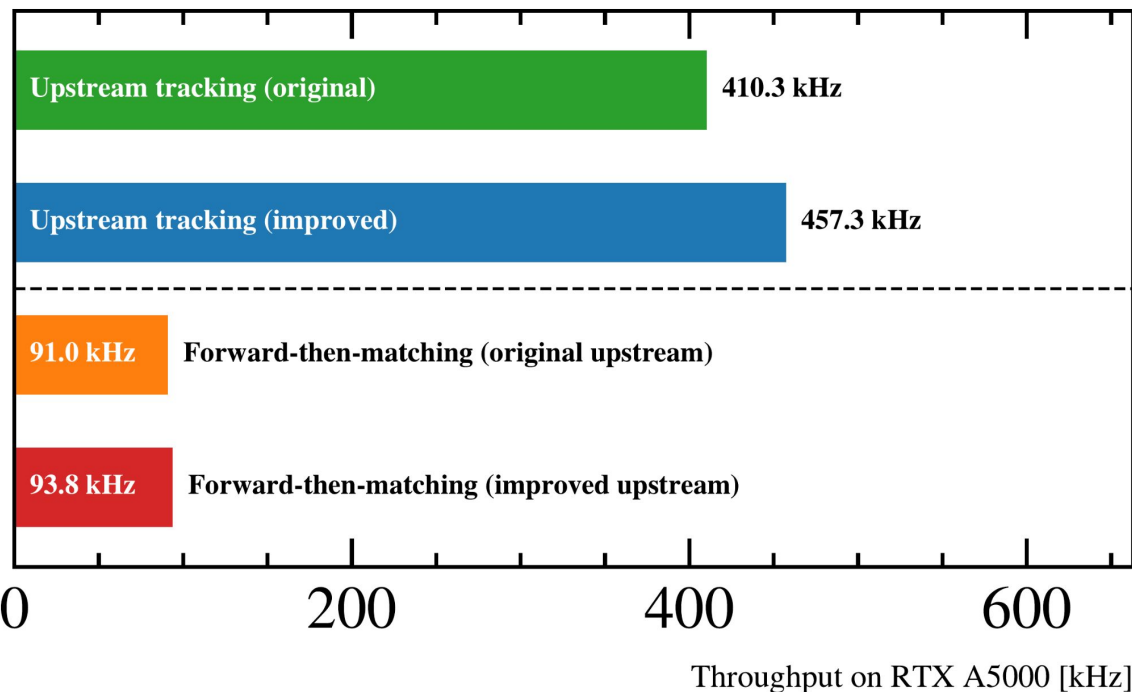
HLT1 upstream

Impacts in Forward then Matching



HLT1 upstream

LHCb Simulation



- In summary, the **new** HLT1 upstream tracking offers:
 - **Better efficiency**
 - **Better ghost rate**
 - **Better throughput**
- **It's a free lunch!**

III

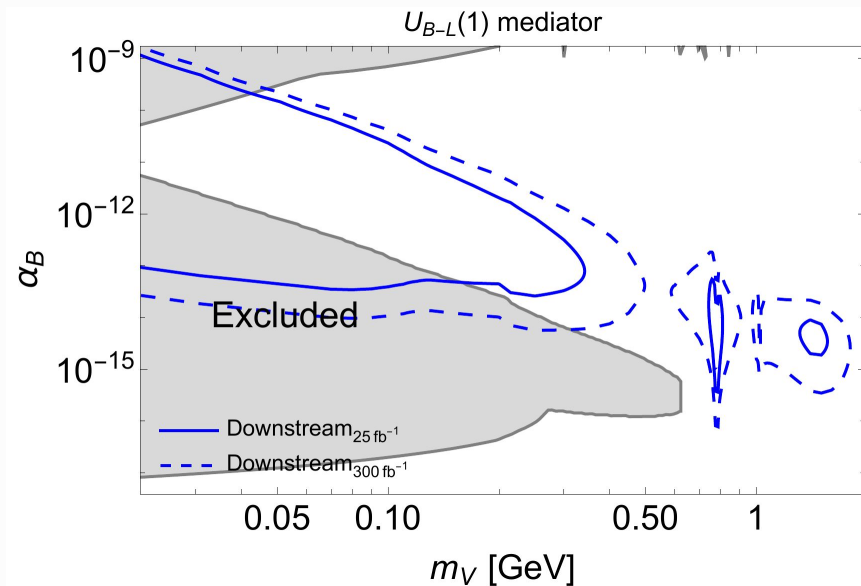
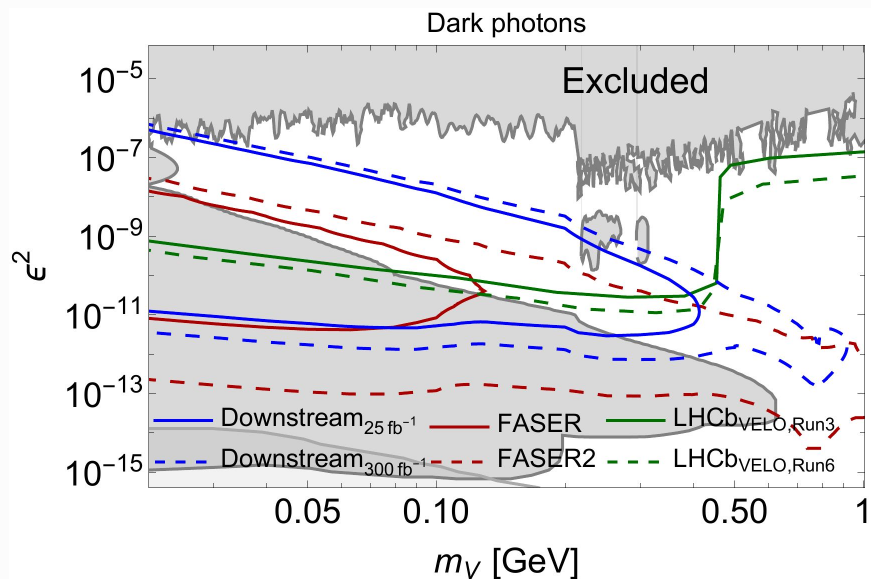
BSM LLP searches

BSM LLP searches

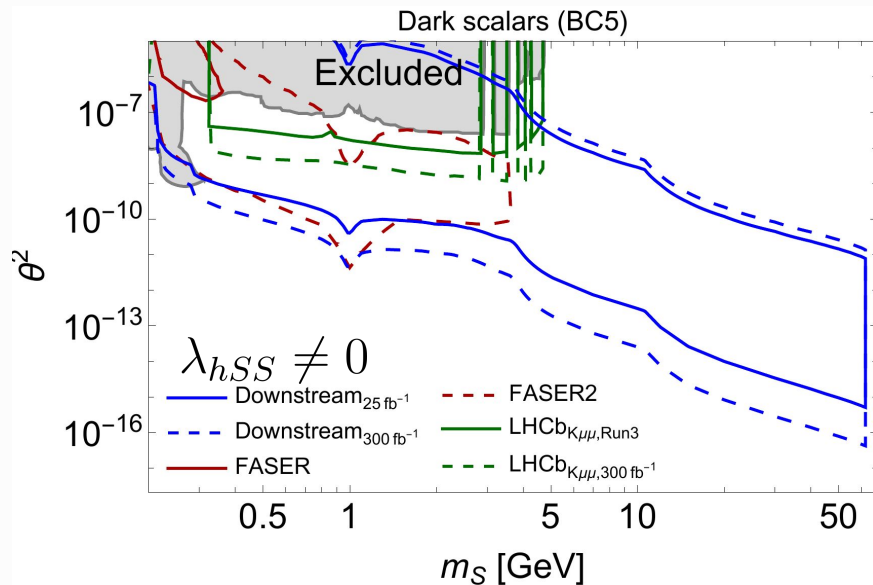
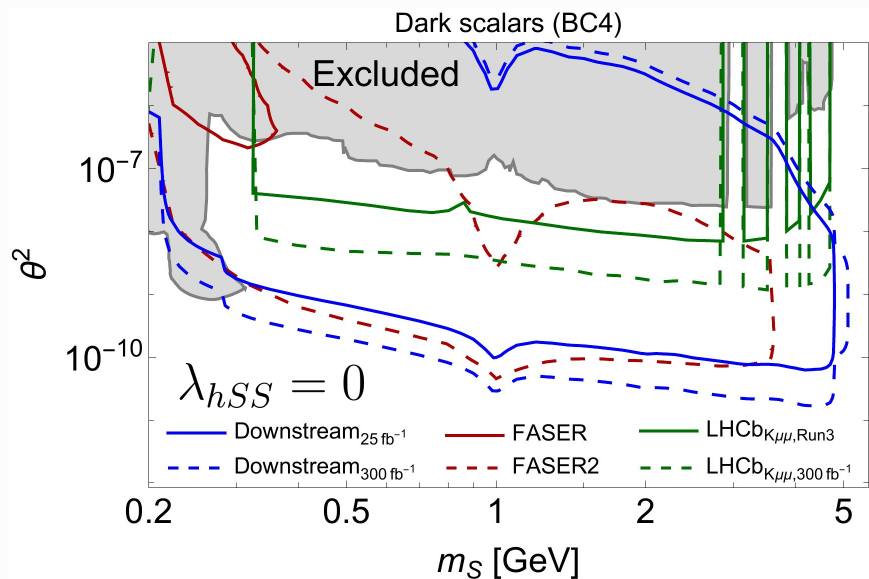
- During the development of HLT1 downstream tracking, it became clear that the same capability also gives LHCb sensitivity to beyond-the-Standard-Model (BSM) long-lived particles.

Model	Production	Visible decays
Dark photon [V] (BC1) $B - L$ mediator	$\pi^0/\eta/\eta' \rightarrow VX$, Bremsstrahlung, Drell-Yan	$\ell^+\ell^-$, $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, K^+K^-
Higgs-like scalar [S] (BC4, BC5)	$B_{(s)} \rightarrow SX_s$, $B \rightarrow SSX$, $h \rightarrow SS$	$\ell^+\ell^-$, $\pi^+\pi^-$, K^+K^- , $c\bar{c}$, gg
HNL [N] (BC6–8)	$B/D \rightarrow NX$, $W \rightarrow N\ell$	$\ell q\bar{q}'$, $\nu q\bar{q}$, $\nu\ell\bar{\ell}'$
ALP [a] (BC10, BC11)	$B_{(s)} \rightarrow aX_s$, $\pi^0/\eta/\eta'$ mixing, Drell-Yan	$\ell^+\ell^-$, $\eta 2\pi$, 4π , gg

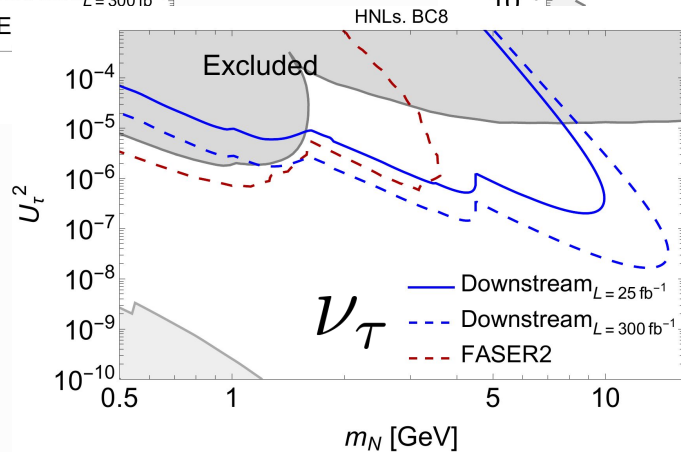
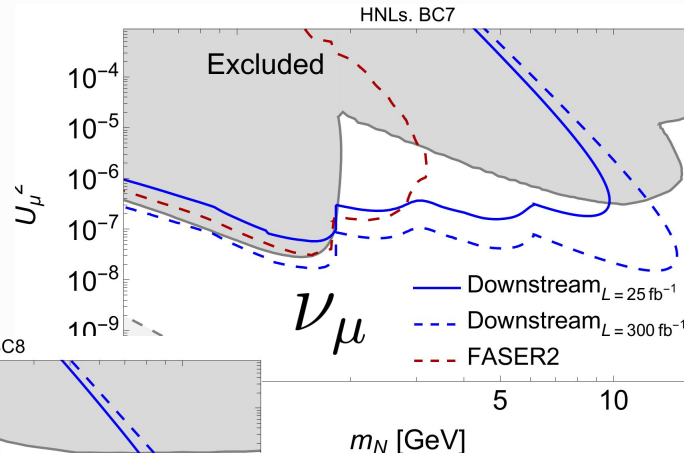
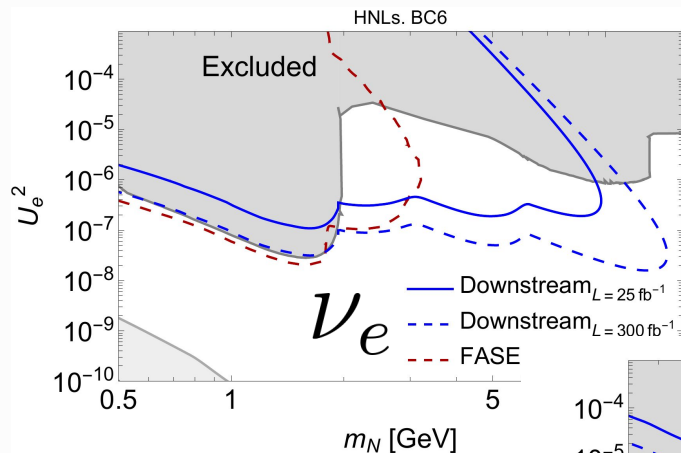
BSM LLP searches



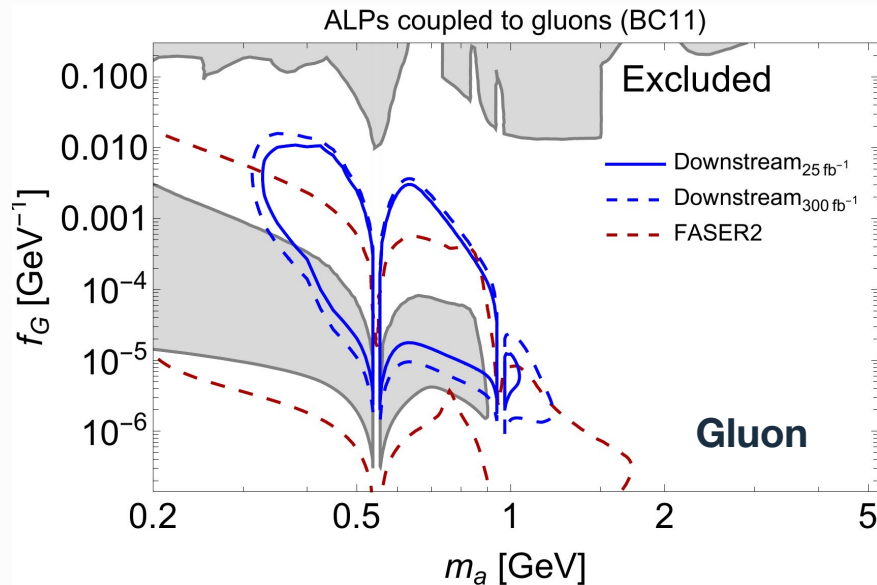
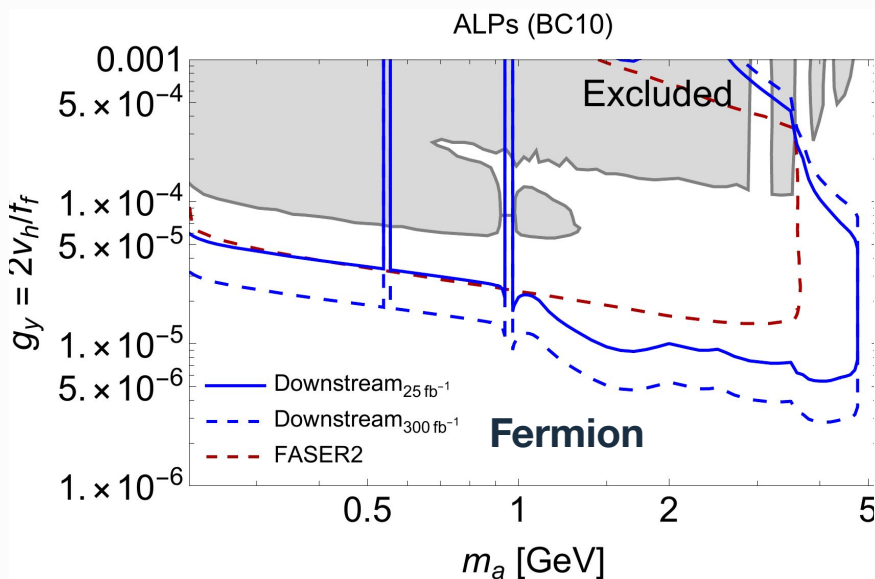
BSM LLP searches



BSM LLP searches

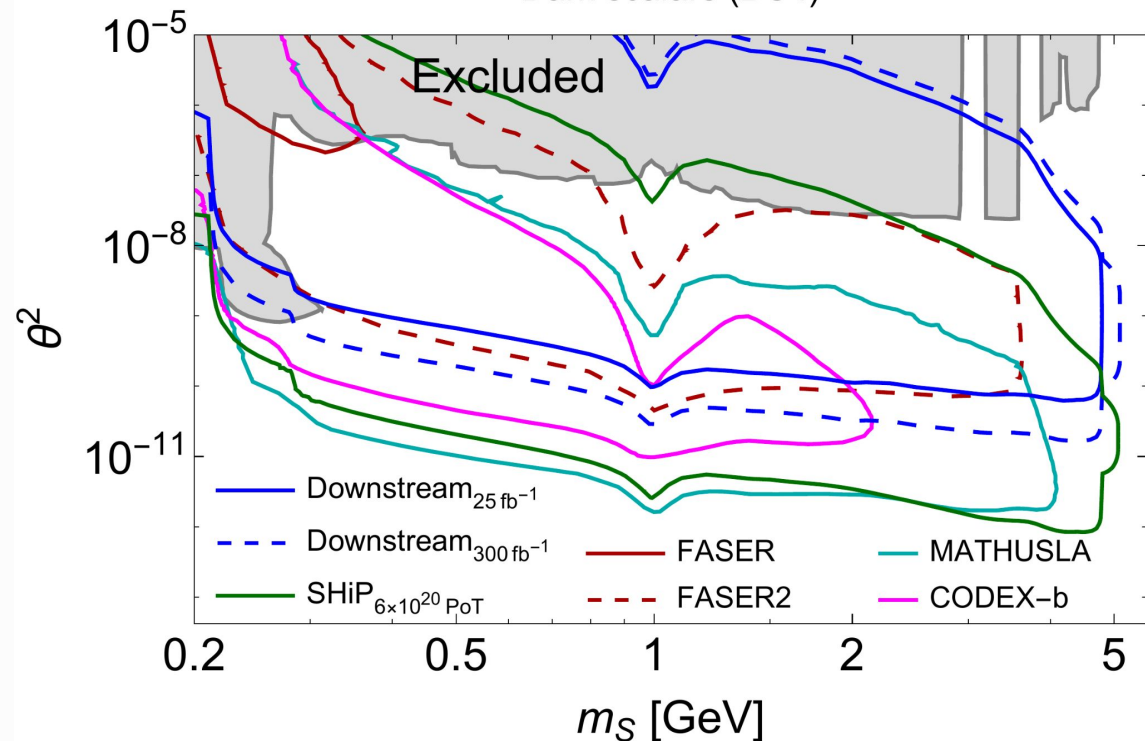


BSM LLP searches



BSM LLP searches

Dark scalars (BC4)



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THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Experimental Physics

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

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Abstract For years, it has been believed that the main LHC detectors can play only a limited 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 allow hits in the LHCb vertex tracker. In particular, for many LLP scenarios, LHCb may be as sensitive as the proposed experiments beyond the main LHC detectors for various LLP models, including heavy neutral leptons, dark scalars, dark photons, and axion-like particles.

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 “portal” [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.

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, however, the SM falls short in explaining numerous observed phenomena across the realms of particle physics, astrophysics, and cosmology. One avenue for 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 “portal” [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 $B \rightarrow \ell + N$, where the momentum of the lepton ℓ is insufficient for triggering.

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IV

Summary

Summary

- In high-luminosity experiments like LHCb, trigger capability directly limits physics potential.
- Developing real-time reconstruction algorithms for software triggers expands physics reach.
 - Matching: low-momentum physics
 - Downstream: long-lived particles
- All algorithms officially deployed in LHCb Run 3 data-taking
- Measurable gain in LHCb's physics capabilities

Etapa	Algoritmo	Run 2	Run 3
HLT1	VELO standalone	✓	✓
	Upstream tracking	✓	✓*
	Forward tracking	✓	✓
	SciFi seeding	—	✓*
	VELO-SciFi matching	—	✓*
	Downstream tracking	—	✓*

* = author's contribution

Publications

- Calefice L et al. (2022) “*Effect of the high-level trigger for detecting long-lived particles at LHCb.*” Front. Big Data 5:1008737. doi: 10.3389/fdata.2022.1008737
- Volodymyr Gorkavenko et al. “*LHCb potential to discover long-lived new physics particles with lifetimes above 100 ps*”. In: Eur. Phys. J.C 84 (2024), p. 608. doi: 10.1140/epjc/s10052-024-12906-3.
- V. Kholoimov et al. “*A Downstream and Vertexing Algorithm for Long Lived Particles (LLP) Selection at the First High Level Trigger (HLT1) of LHCb*”. In: Comput. Softw. Big Sci. 9.1 (2025). doi: 10.1007/s41781-025-00141-8.

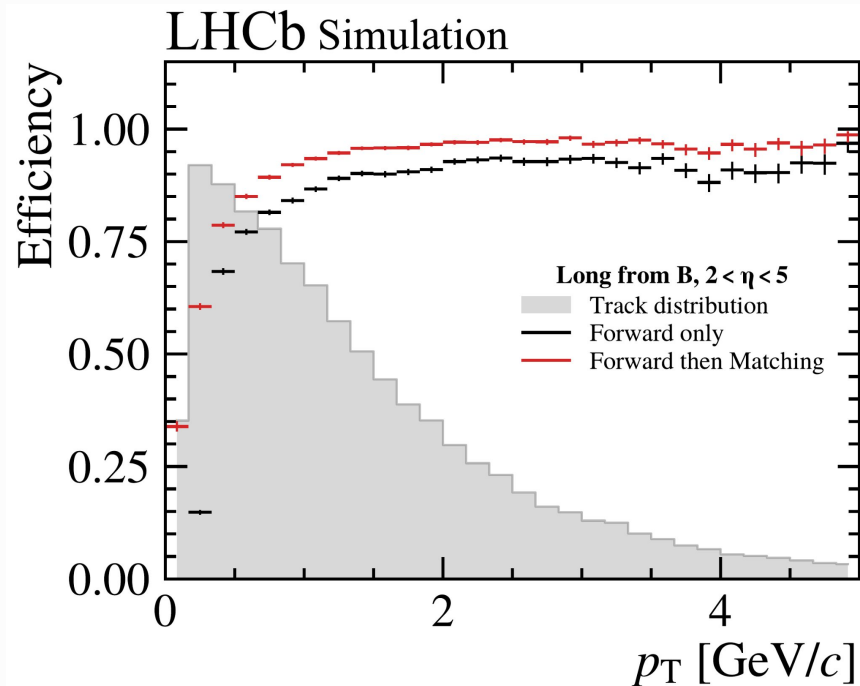
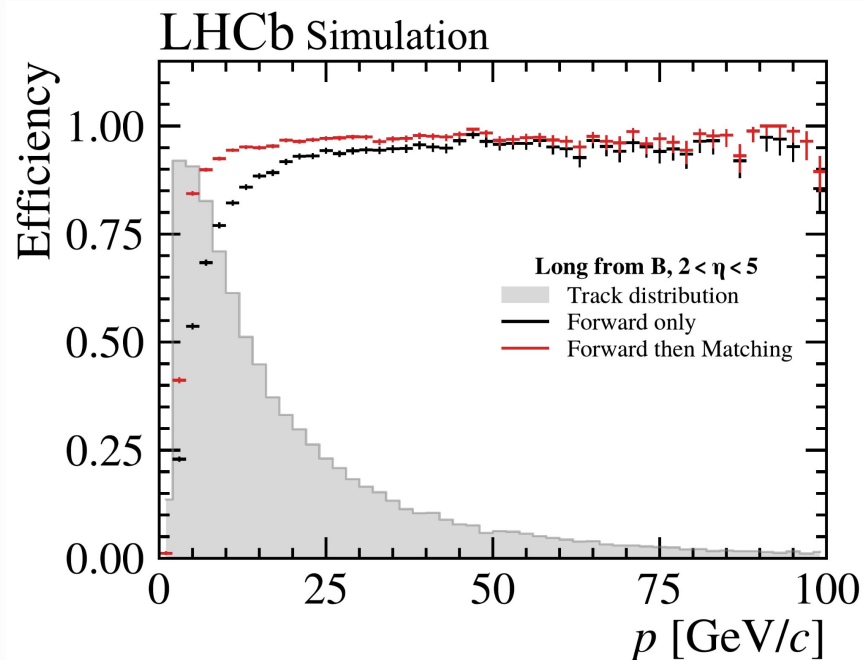
A new paper titled “Seeding and Matching algorithms for the first GPU-based High Level Trigger of the LHCb experiment” has been submitted to EPJC and is currently under review.

A thick, vertical orange bar with rounded ends, positioned on the left side of the slide, separating the white background from the dark blue background.

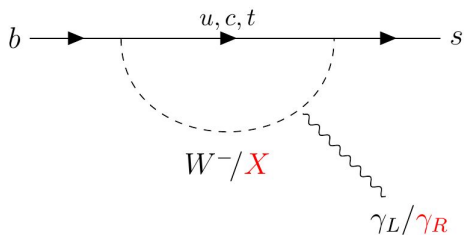
Backup

HLT1 matching

Physics performance



The physics motivation



My first PhD analysis

- The $b \rightarrow s\gamma$ transition is a Flavour-Changing Neutral Current (FCNC) process, which is very rare and highly sensitive to NP contributions.
- The photon is mostly left-handed:

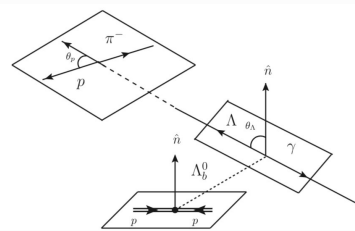
$$O_7 \propto \boxed{m_b \bar{s} \sigma^{\mu\nu} F_{\mu\nu} (1 + \gamma_5) b} + \boxed{m_s \bar{s} \sigma^{\mu\nu} F_{\mu\nu} (1 - \gamma_5) b}$$

$$\tan \psi = \boxed{\|A_R(b_L \rightarrow s_R \gamma_R)\|} / \boxed{\|A_L(b_R \rightarrow s_L \gamma_L)\|} \approx m_s/m_b$$

- Measuring the photon polarization of such a transition is very sensitive to the NP contributions.

$$\Lambda_b \left\{ \begin{array}{c} \mathbf{b} \\ \mathbf{d} \\ \mathbf{u} \end{array} \right\} \left\{ \begin{array}{c} \mathbf{s} \\ \mathbf{d} \\ \mathbf{u} \end{array} \right\} \Lambda$$

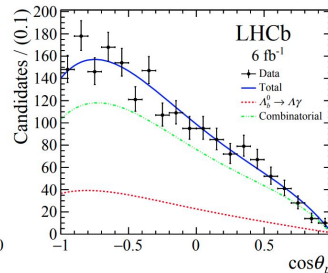
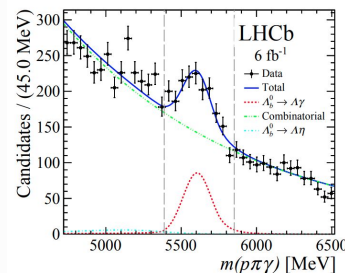
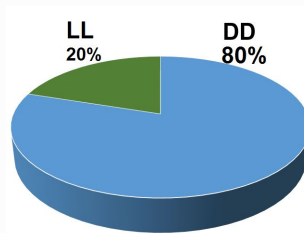
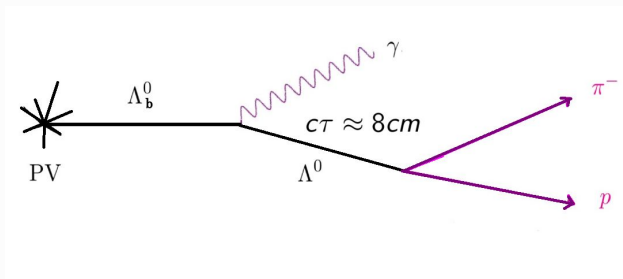
$$\frac{d\Gamma}{d(\cos \theta_p)} \propto 1 - \alpha_\gamma \alpha_A \cos \theta_p,$$



$$\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}$$

Such photon polarization can be measured through the angular distribution of $\Lambda_b \rightarrow \Lambda \gamma$ decays.

The physics motivation



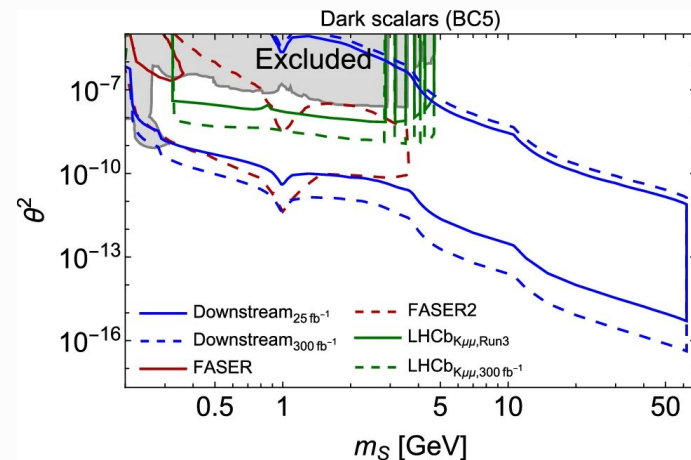
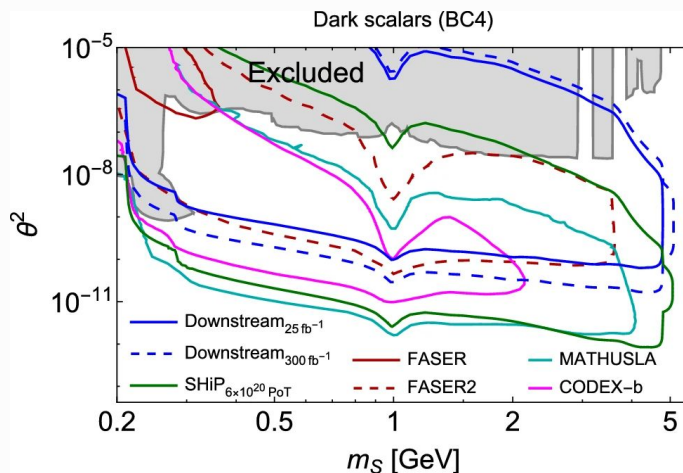
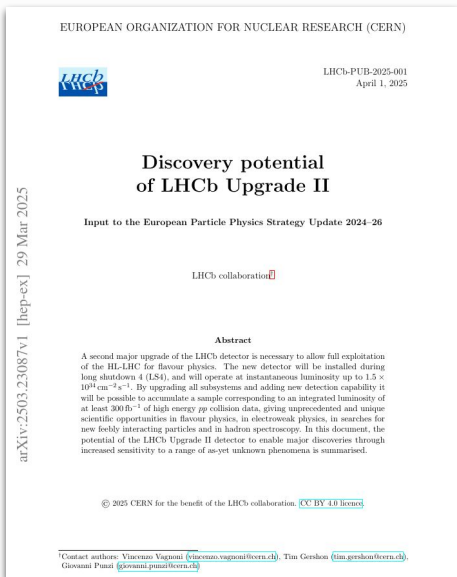
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26} \text{ (stat.) }^{+0.04}_{-0.13} \text{ (syst.)}$$

- The Run 2 measurement is strongly **statistics-limited**.
- Λ^0 is a SM long-lived particle: it usually decays **outside the VELO acceptance**, and only **~20%** of such decays can be reconstructed with **long tracks**.
- Although most decays are within the downstream track acceptance, the **lack of downstream tracking** triggers in **HLT1** during **Run 2** resulted in a signal efficiency of **less than 10%**.

We need a downstream tracking trigger in HLT1 for Run 3.

Potential of Downstream tracks

Potential of the Downstream algorithm for LLP searches:



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

doi.org/10.48550/arXiv.2503.23087

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

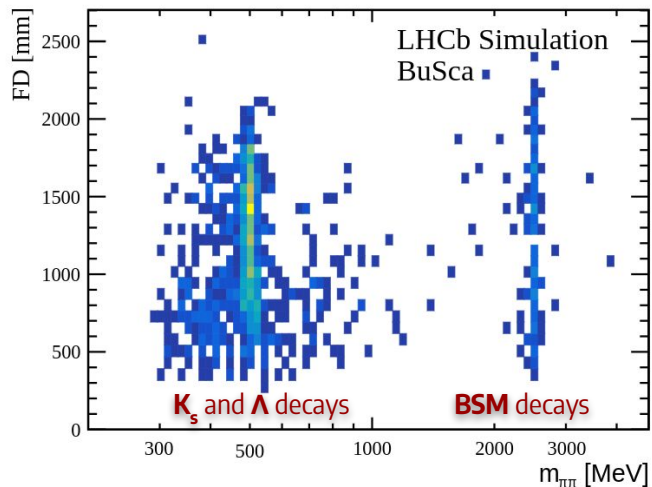
What is BuSca?



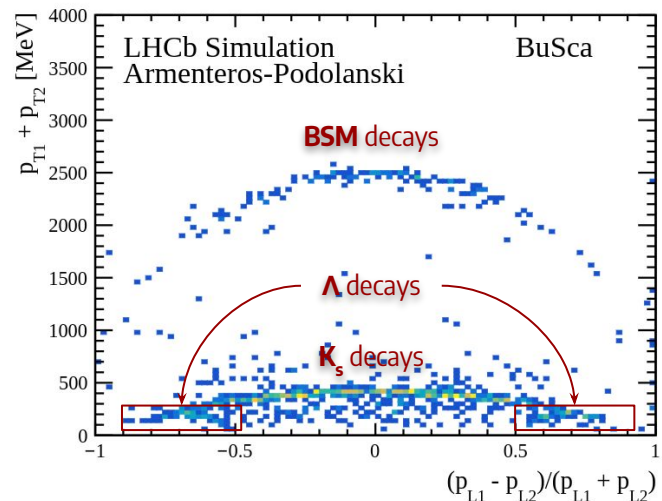
BuSca means 'search' in Spanish

- 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 enable real-time anomaly detection.
 - 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.
- For now, BuSca targets only **downstream tracks** for better momentum resolution than **T tracks**.

BuSca monitoring



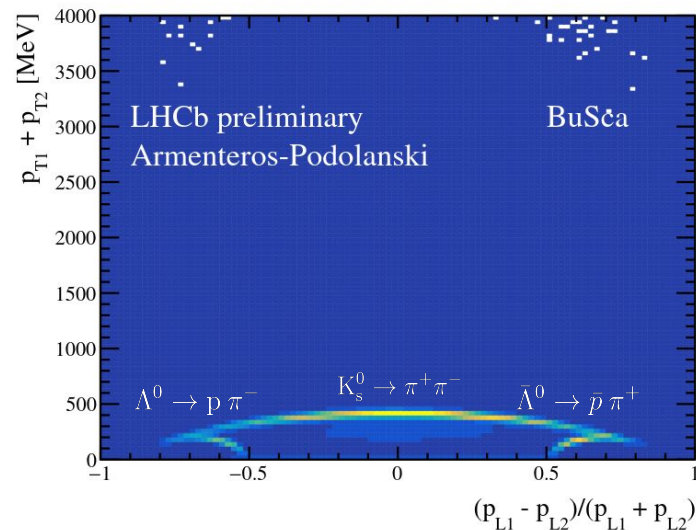
[LHCB-FIGURE-2024-036]



- 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

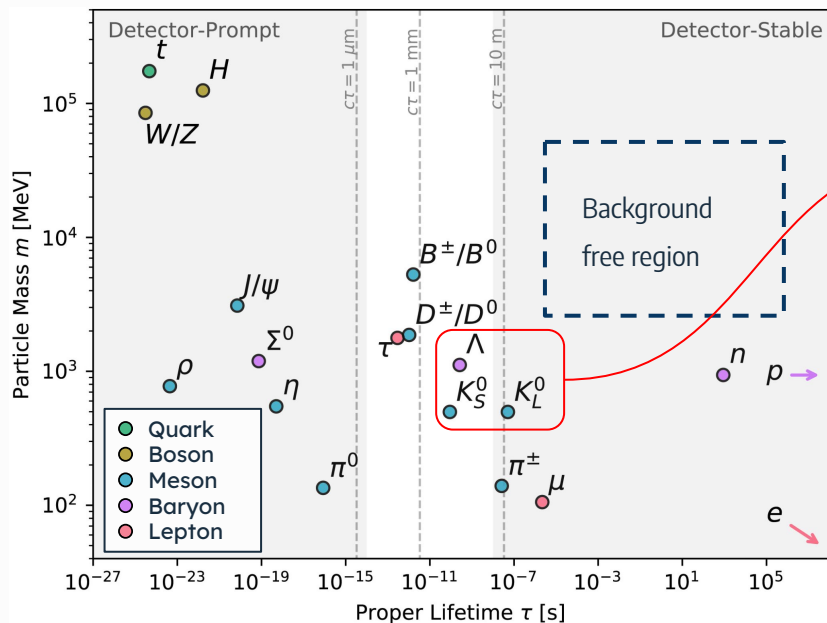
- **HLT1 trigger lines** were developed to select high-quality displaced downstream vertices:
 - **Same-sign** line for **combinatorial background** studies.
 - **Prescaled** line for inclusive selection.
 - **Di-muon** and **di-electron** lines for **leptonic** final states.
 - **High-mass** line to trigger on candidates up to **50 GeV**.
- The **HLT2** lines were developed to store events triggered by **HLT1**:
 - **Requires** the HLT1 BuSca trigger decision.
 - Stores all **relevant downstream vertices** for offline background studies.



[LHCb-FIGURE-2024-36]

BuSca background studies

Physics backgrounds



- **Strange decays:**

- K_S^0, K_L^0 and Λ^0 .
- Can be vetoed using kinematic and mass cuts.

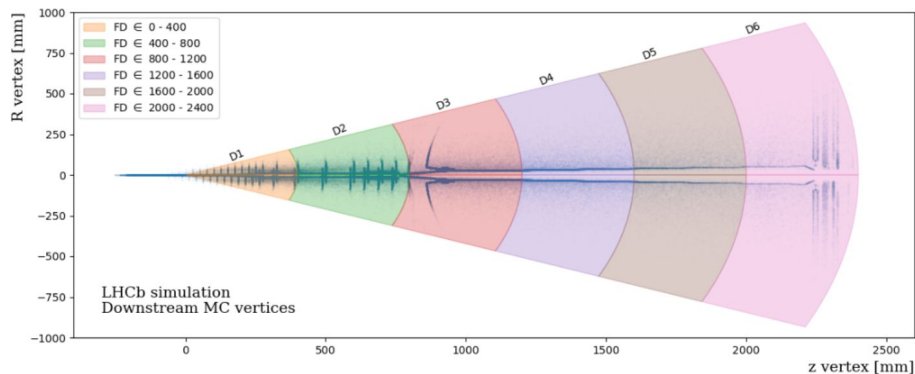
- Another **hadronic resonances**:

- $B^0, D^0, \eta, \rho, \Sigma^0$... etc.
- Short lifetimes, can be vetoed using flight distance cuts.

BuSca background studies

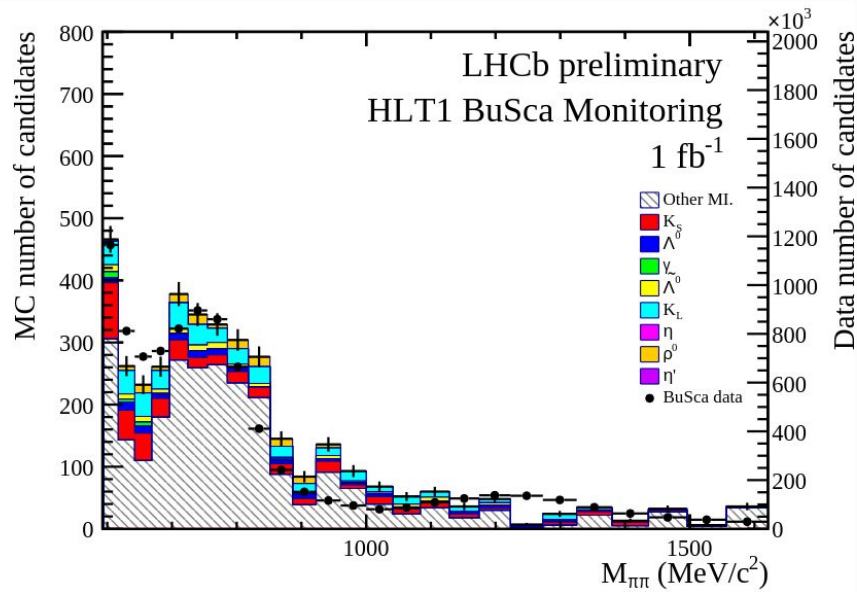
Material interactions

- **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.



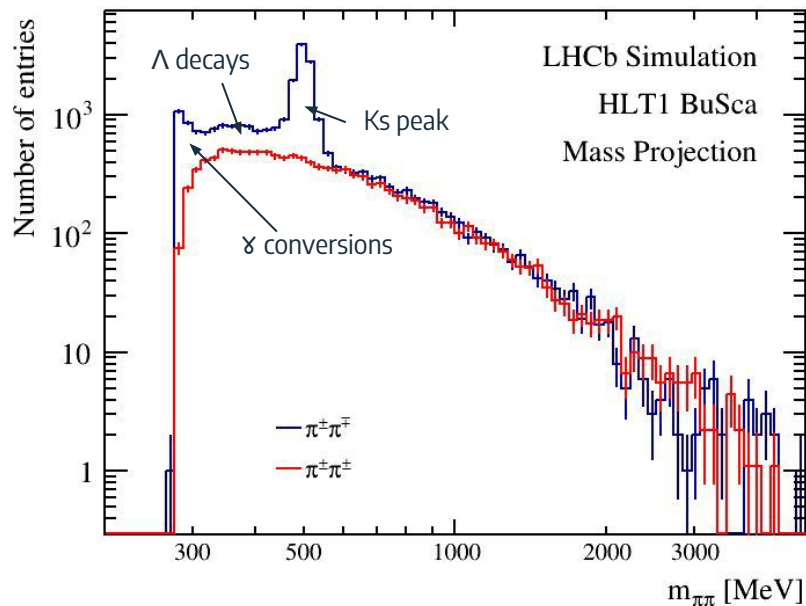
[LHCb-FIGURE-2024-036]

[LHCb-FIGURE-2025-002]



BuSca background studies

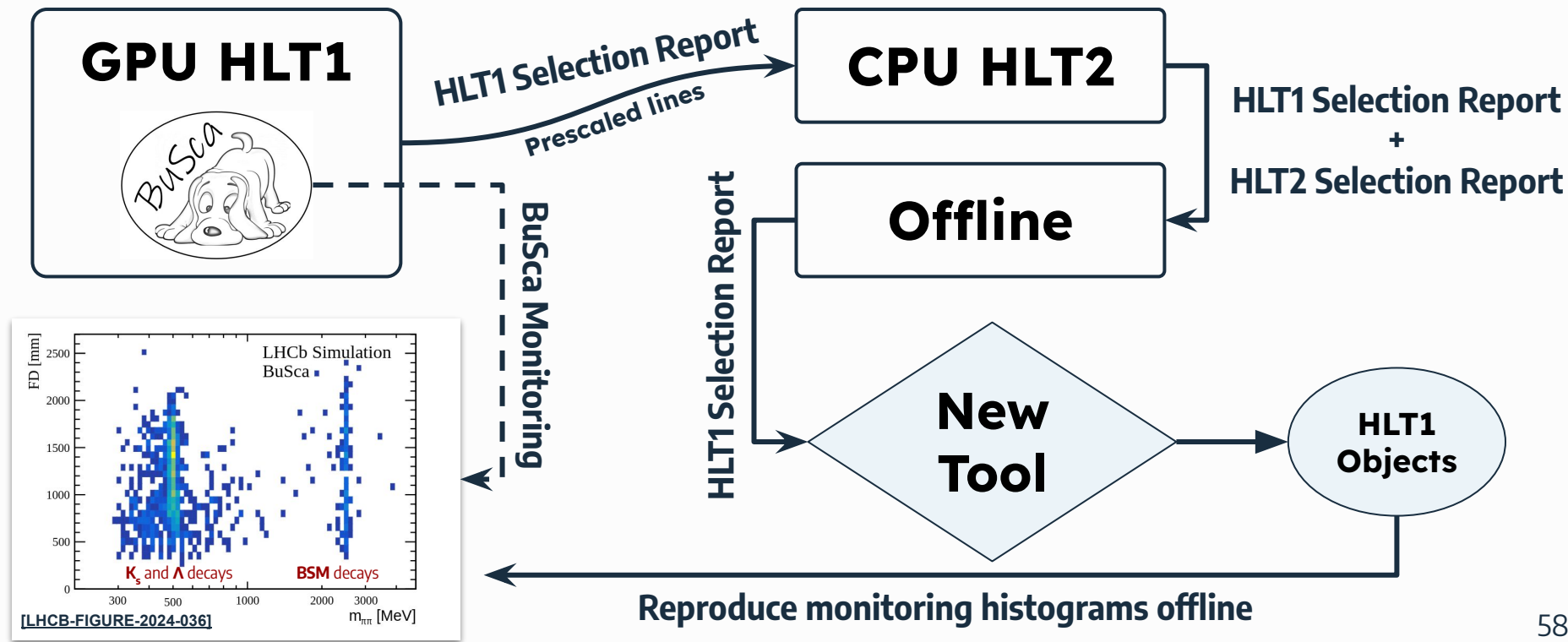
Combinatorial backgrounds



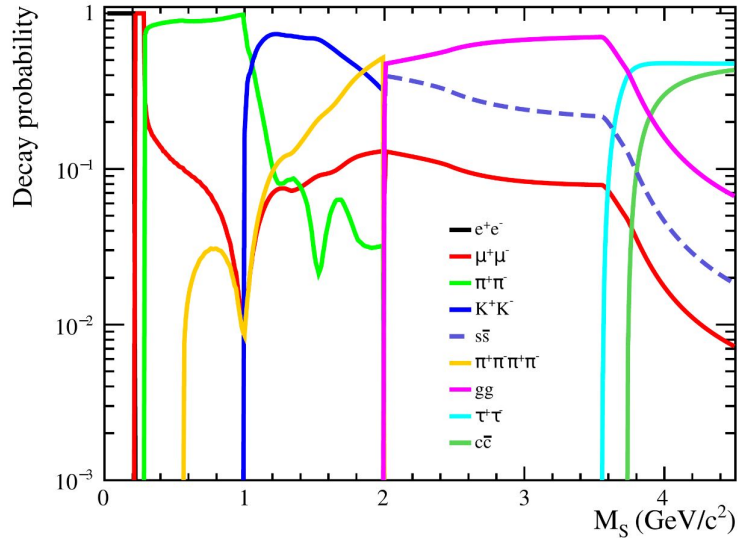
[LHCb-FIGURE-2024-36]

- 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 analysis tools



BuSca prospects



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

- LLPs with $m > 2 \text{ GeV}/c^2$ can decay via gg , $s\bar{s}$, $c\bar{c}$, and $\tau^+\tau^-$.
- These channels produce **multi-track displaced vertices** (> 3 tracks).
- Hadronic modes ($c\bar{c}$, gg) often yield **high track multiplicity**.
- **Multi-body** downstream secondary vertex reconstruction therefore provides a powerful handle for **high-mass** LLP searches.
- HLT1 reconstruction **implemented**, BuSca integration planned for **Run 4**.
- Monitoring: track multiplicity vs flight distance (2D histograms).