Downstream tracking at LHCb

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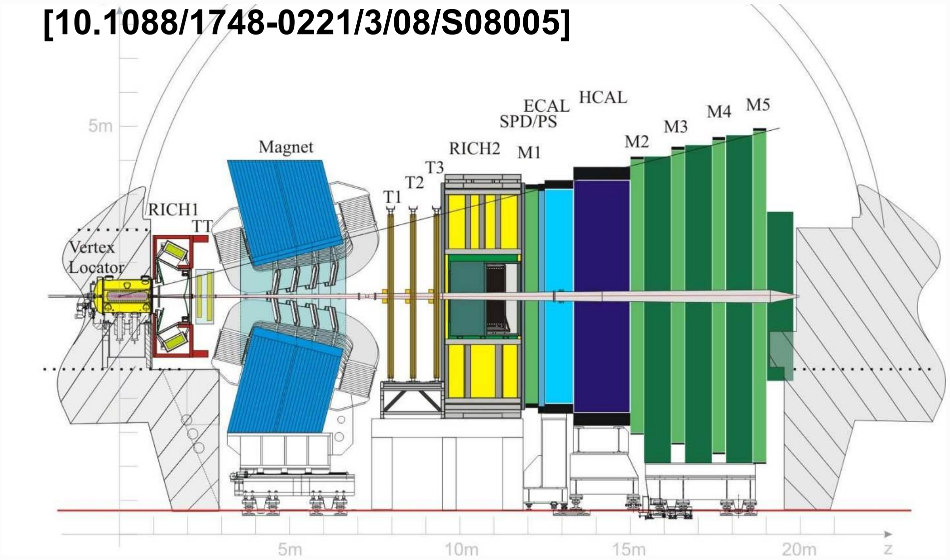
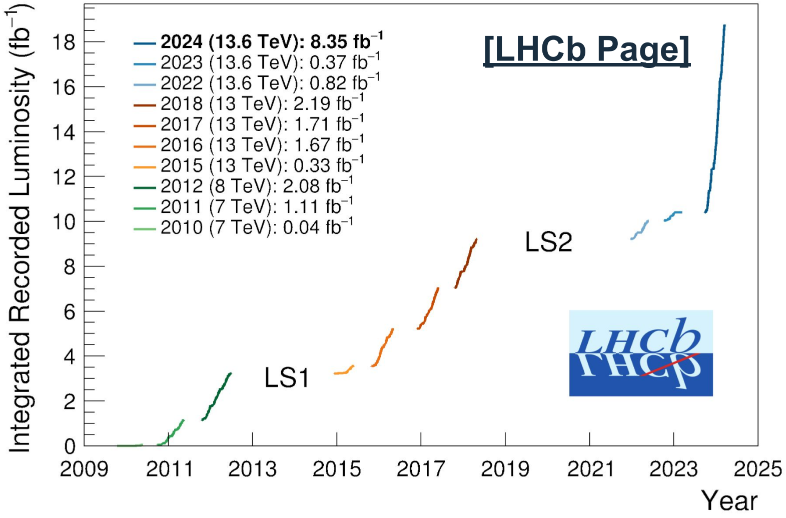
Outline

- LHCb experiment:
  - LHCb Trigger system
  - LHCb Tracking system
- HLT tracking sequences in Run 3
- Real data performance
- HLT1 Downstream lines
- Summary

LHCb experiment

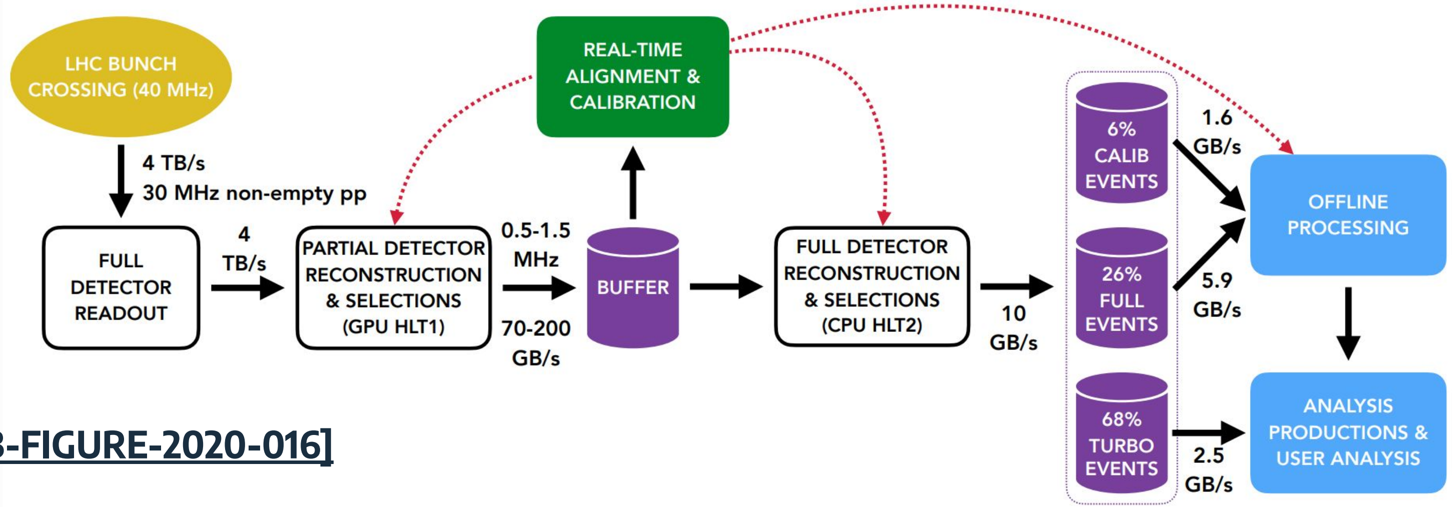
[10.1088/1748-0221/3/08/S08005]





- Forward spectrometer ($2<\eta<5$)
- 3 fb^{-1} from Run 1, 6 fb^{-1} from Run 2, 8.3 fb^{-1} from Run 3 (until Oct 13, 2024)
- Excellent tracking ($\sigma(m_B)$~25 MeV for 2-body decays) and PID performance (μ_{ID}~97%)

LHCb experiment: trigger system

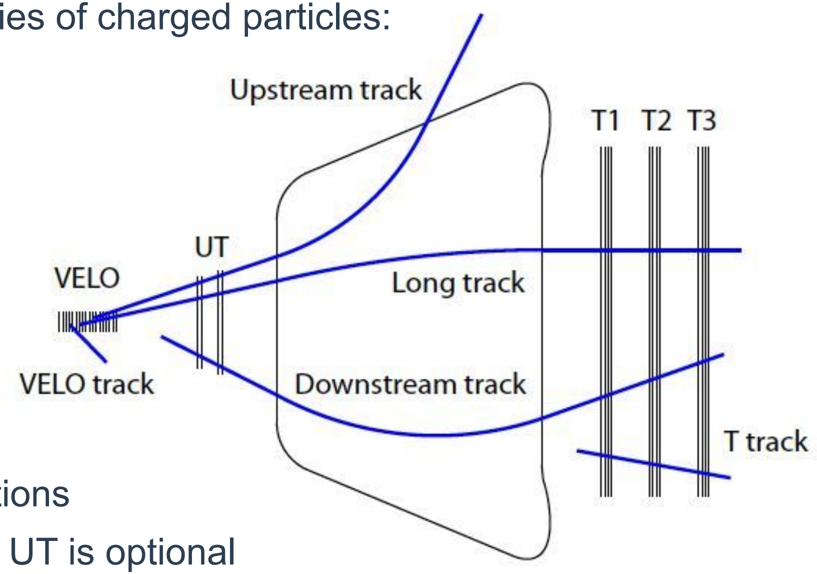


[LHCB-FIGURE-2020-016]

- The removal of the **L0** trigger: **HLT1** have to process read-out data at **30 MHz** and output the filtered data to the buffer at **1 MHz**.
- Both **HLT1** and **HLT2** perform real time event reconstruction, including clustering, tracking, and vertexing, and make trigger decisions based on the reconstructed objects.

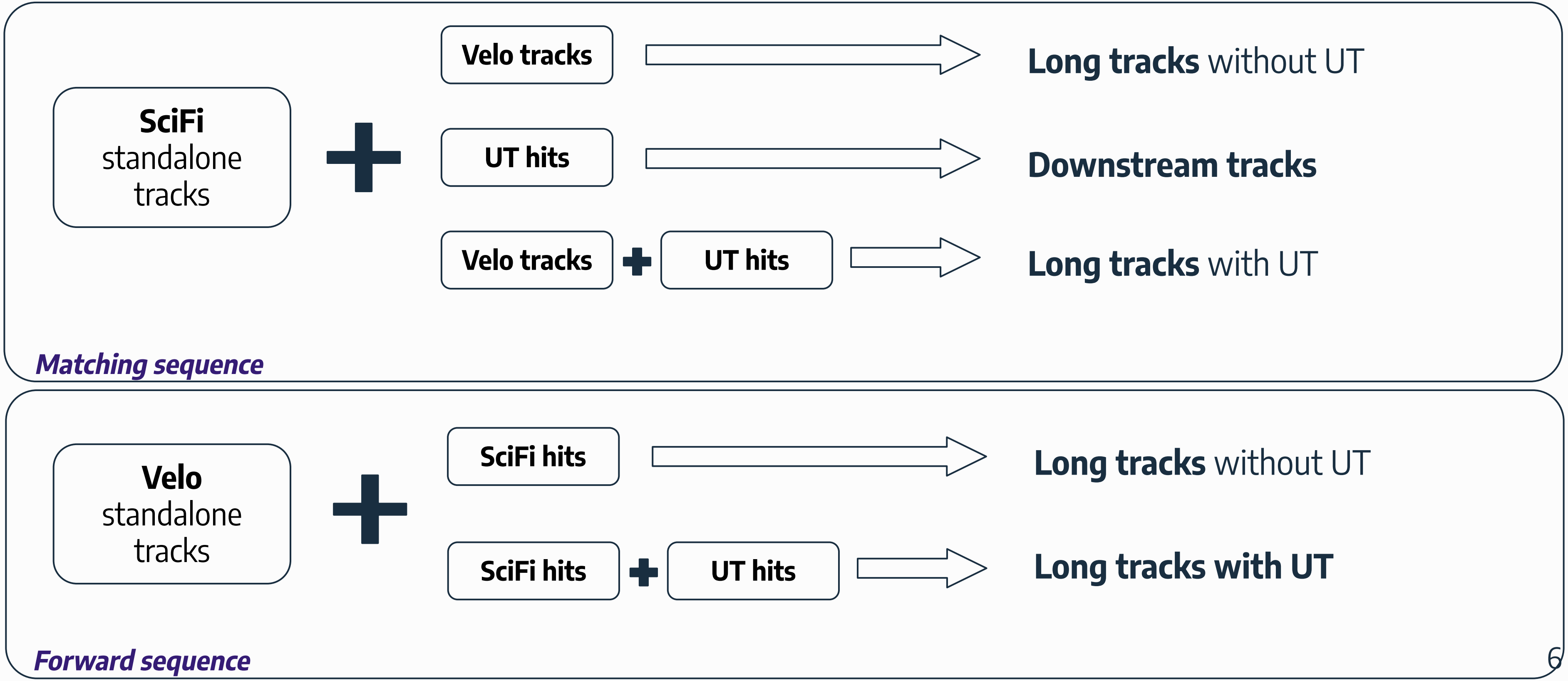
LHCb experiment: tracking system

- LHCb has three different trackers to reconstruct the trajectories of charged particles:
  - Vertex Locator (**VELO**)
  - Upstream Tracker (**UT**)
  - Scintillating Fibres (**SciFi**) / **T stations**
- The different track types defined in LHCb:
  - **VELO tracks**: have hits in the VELO
  - **Upstream tracks**: have hits in the VELO and UT
  - **T tracks**: have hits in the T stations
  - **Downstream tracks**: have hits in UT and the T stations
  - **Long tracks**: have hits in VELO and the T stations, UT is optional

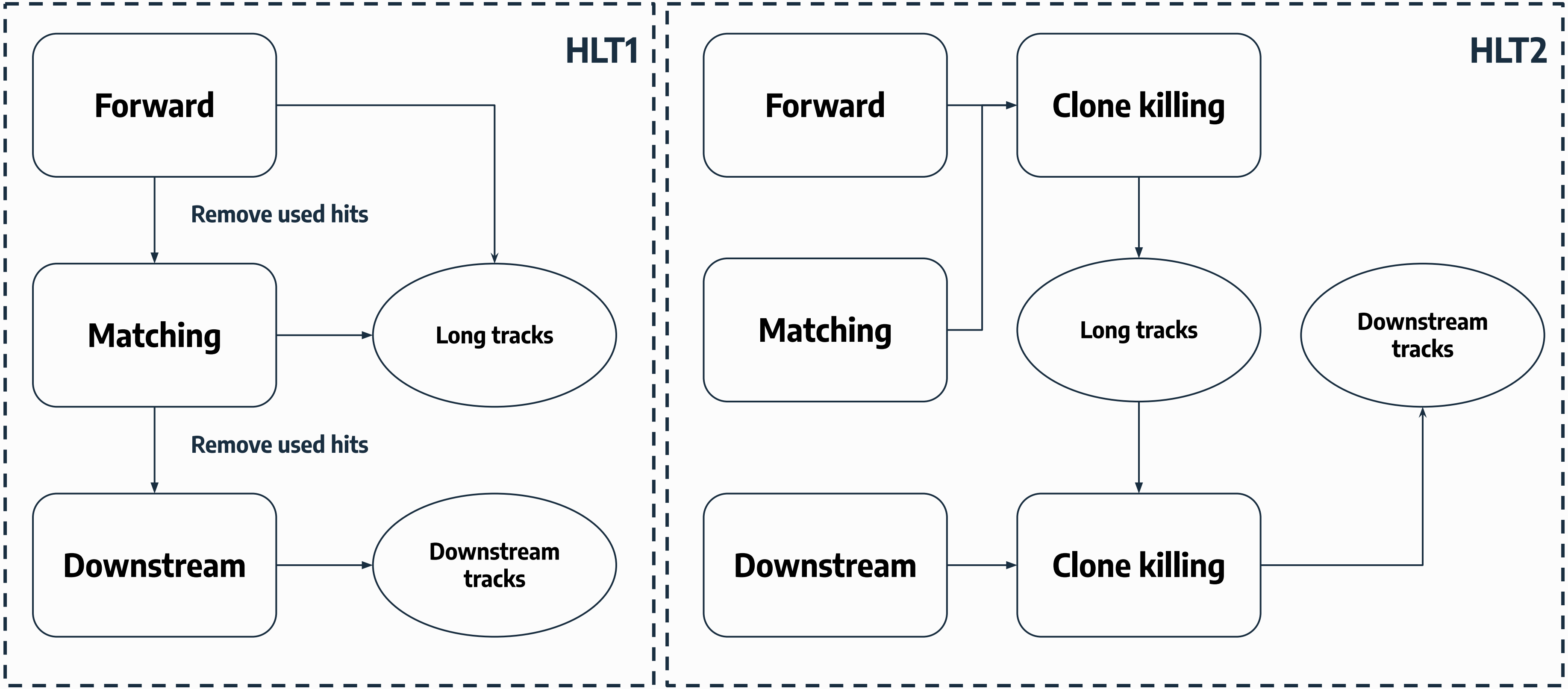


Long tracks and **downstream tracks** are used for most physics analyses, the other types either serve as a component of another track type or are mainly used for detector studies.

HLT tracking sequences in Run 3



HLT tracking sequences in Run 3



Downstream tracking

- **HLT2 Downstream is migrated from Run2.**
- **HLT1 Downstream timeline:**

Jan 2023

Algorithm developed and code review started.

Dec 2023

Code approved and merged into the main branch.

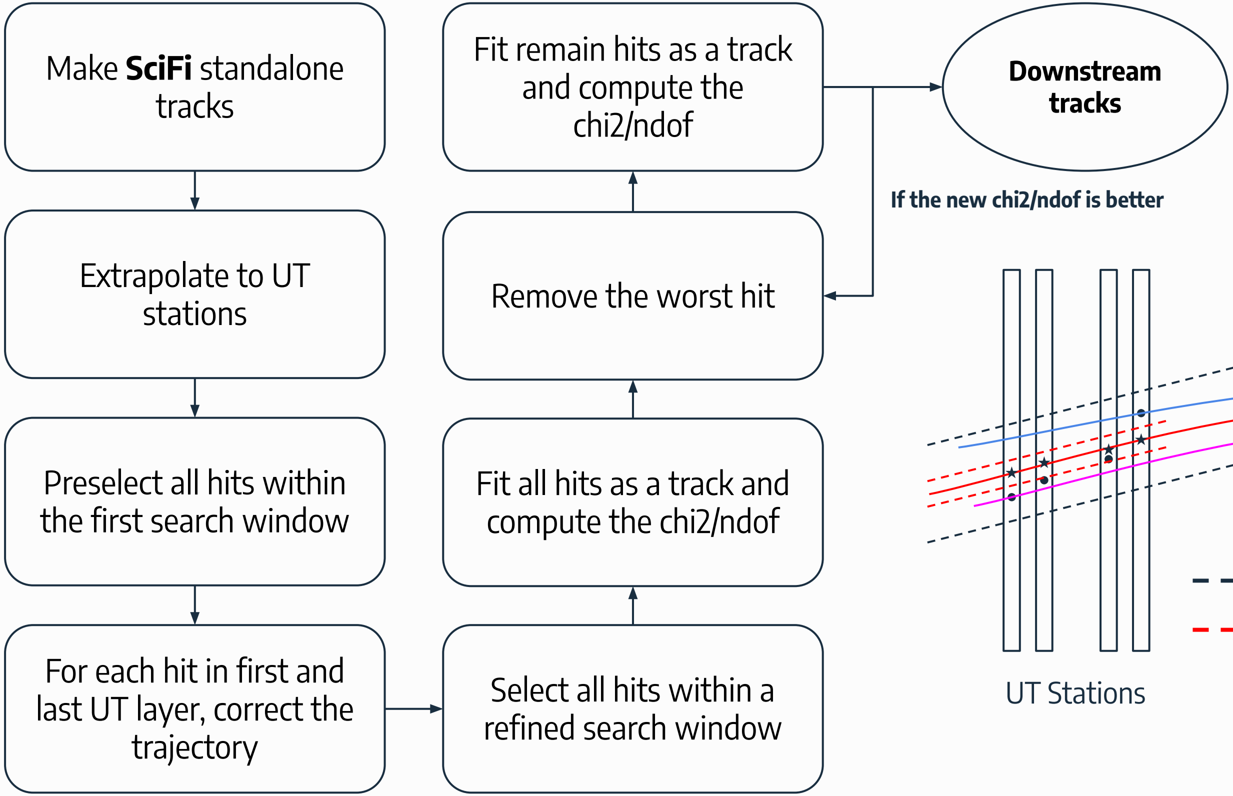
Aug 2024

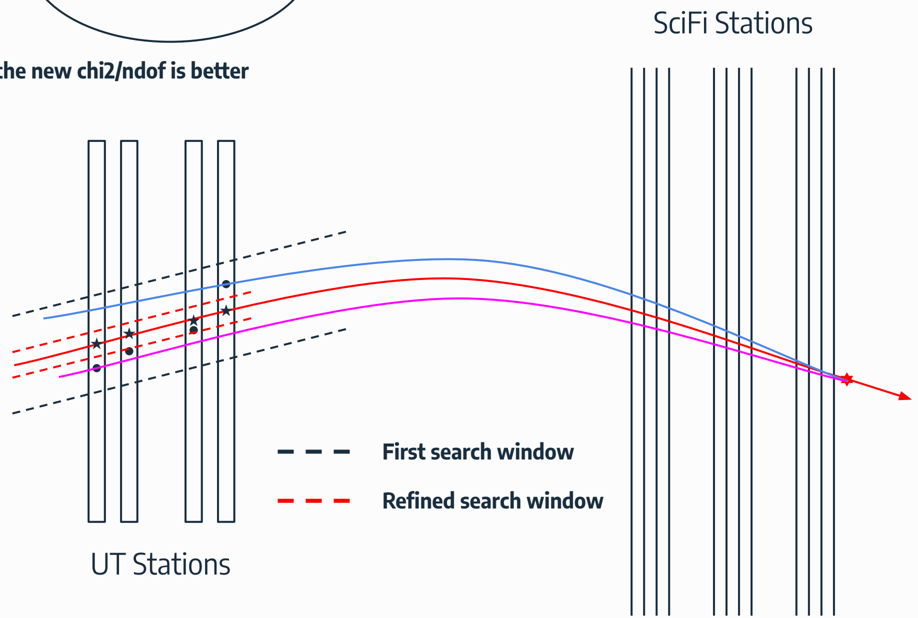
UT integrated into HLT1.

Oct 2024

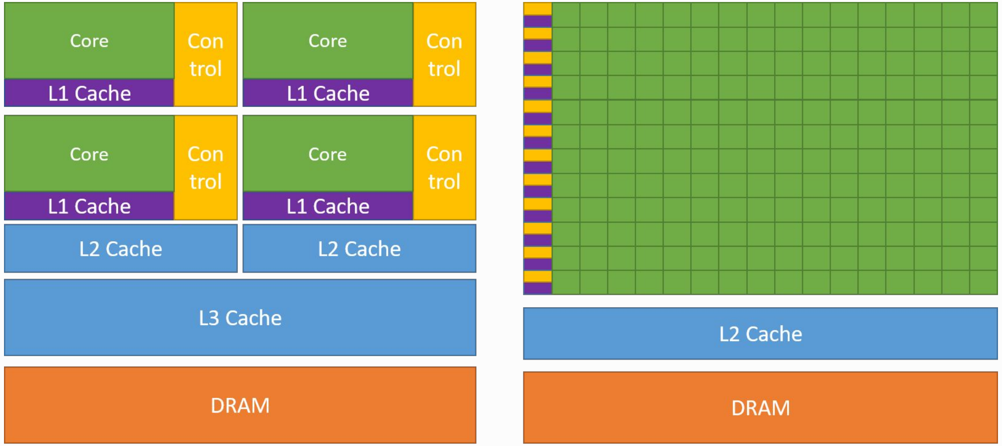
Downstream running in HLT1.

HLT2 Downstream tracking





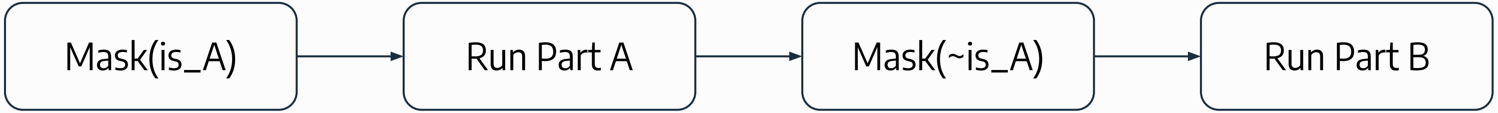
HLT1 Downstream tracking



CPU GPU

```
if ( is_A )
{
      // Some threads go here (Part A)
}
else
{
      // Some threads go here (Part B)
}
```

- Each 32 threads form a **warp**, all threads shared the same **controller** and **L1 cache** in the same **warp**.



HLT1 Downstream tracking

Make **SciFi** standalone tracks

↓

Extrapolate to UT stations

↓

Open first search window in the last UT layer

↓

For each hit correct the trajectory

→

Open refined search window in the remaining layers

↑

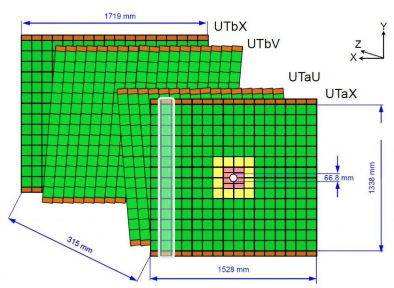
Find the closest hit in the first layer, and the two closest hits in the second and third layers.

↑

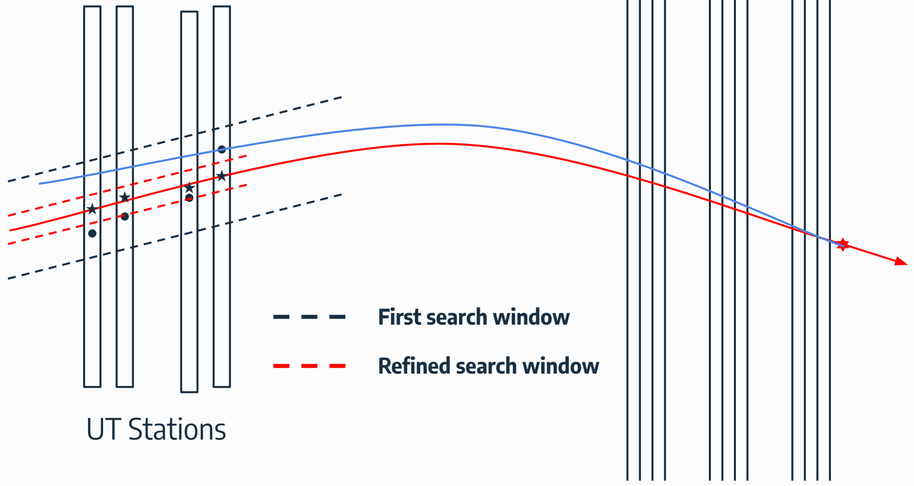
Select the best hit combination for the second and third layers.

↑

Downstream tracks



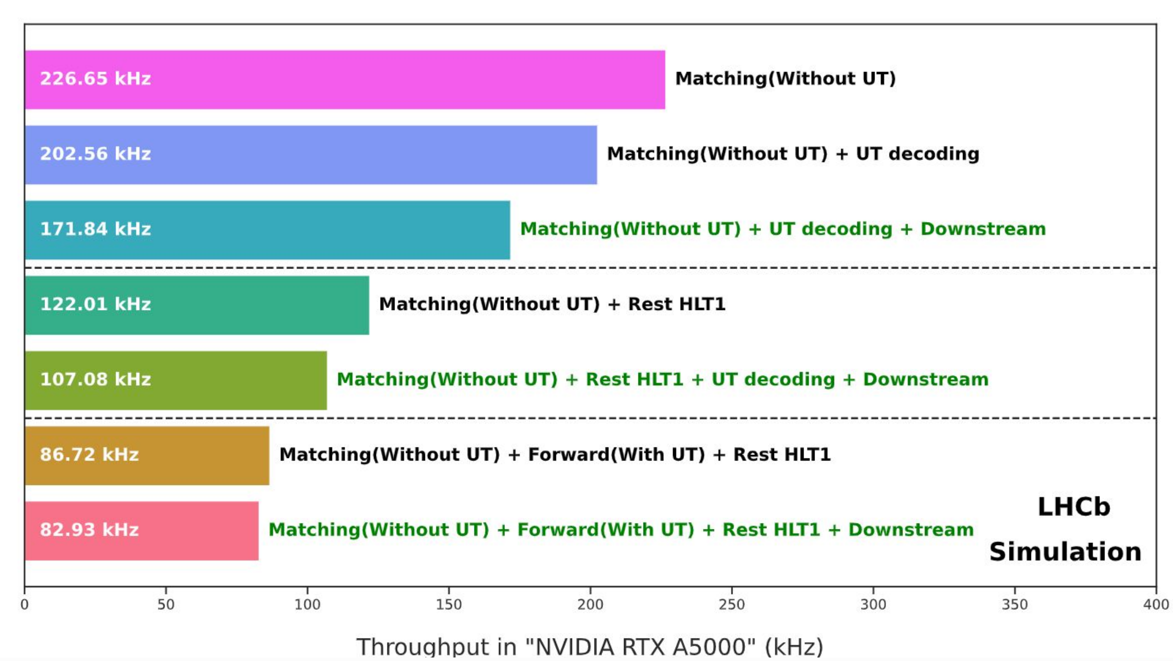
$$Hit_x = Hit_{x(y=0)} + dx/dy\ Hit_y$$



HLT1 Downstream tracking

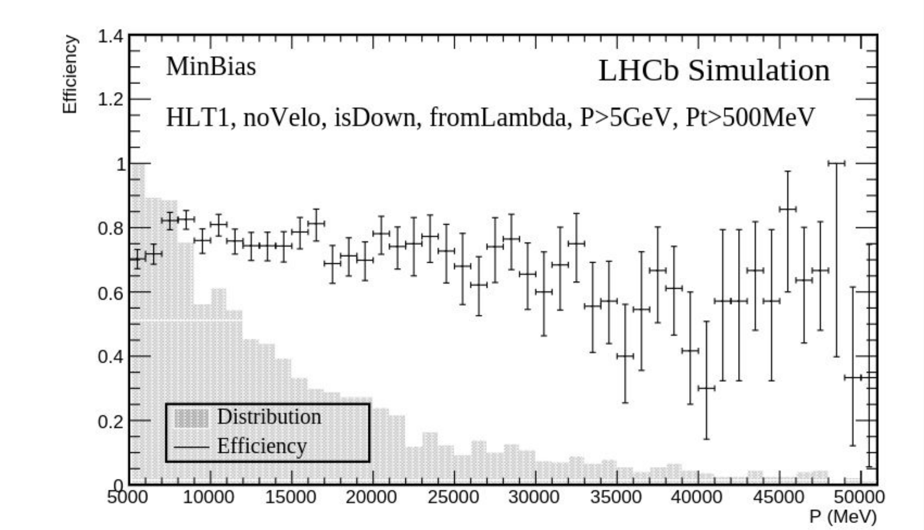
[LHCB-FIGURE-2023-028]

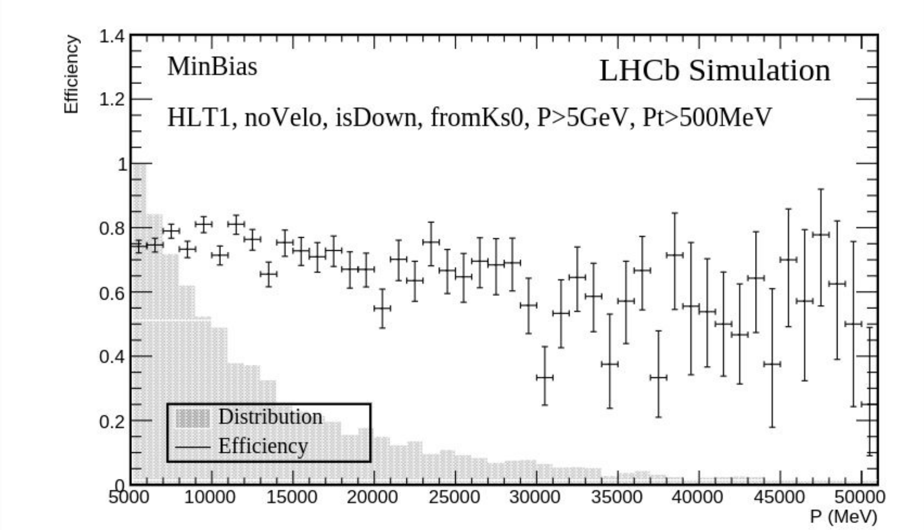
- HLT1 can support up to approximately 500 GPUs.
- Each GPU needs to process at 60 kHz to meet the 30 MHz target.
- Alternatively, each GPU should process at 55 kHz to reach the 27 MHz target.
- In real data, we run the entire HLT1 at 73 kHz without downstream, and at 67.5 kHz with downstream.



HLT1 Downstream tracking

[LHCB-FIGURE-2023-028]

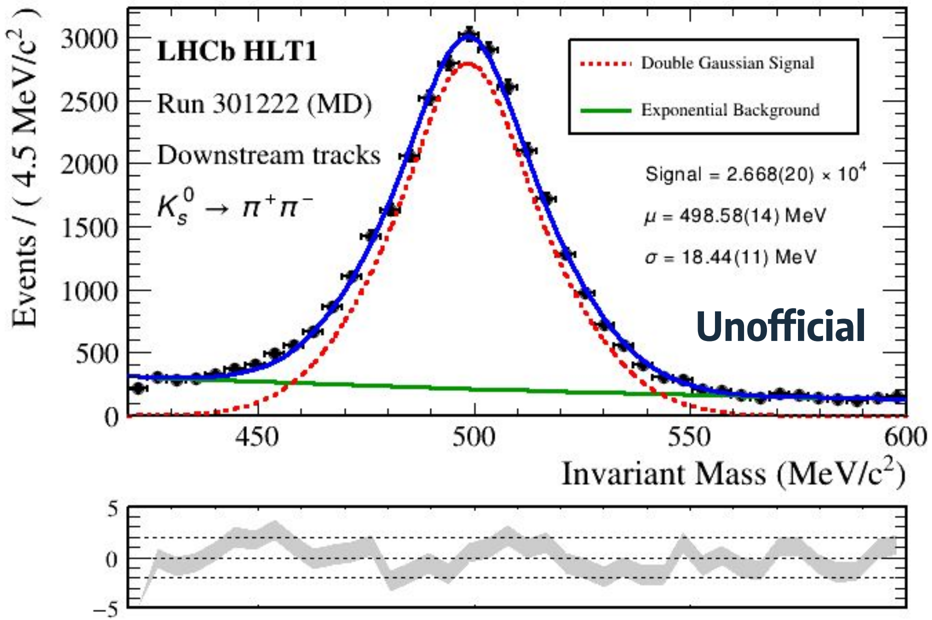


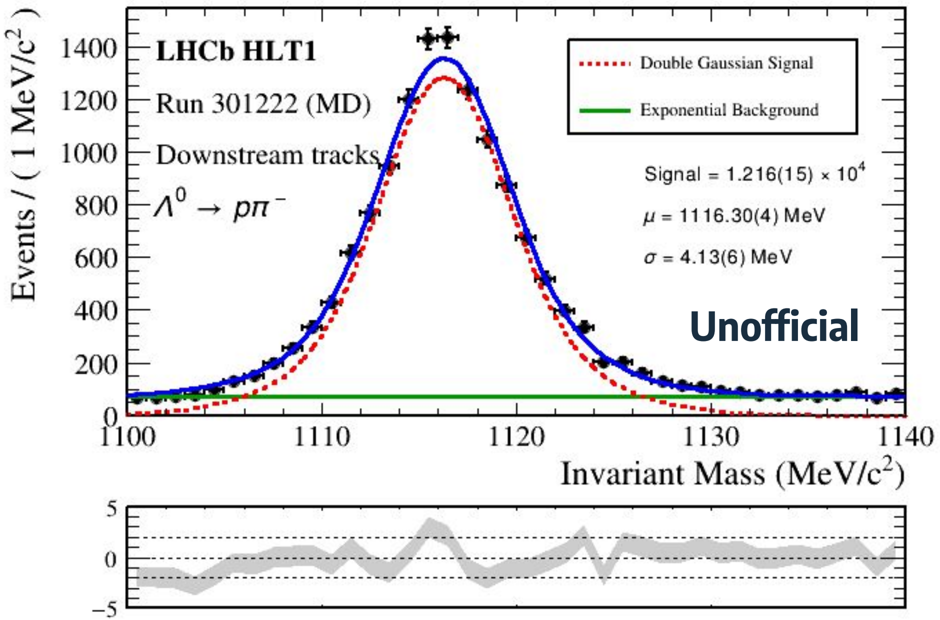


- The **HLT1 downstream tracking** achieves approximately **75% tracking efficiency** for both $\mathbf{\Lambda^0}$ and $\mathbf{K_s^0}$, which is similar to the HLT2 performance.
- The tracking performance is independent of decay types, showing the similar efficiency for both $\mathbf{\Lambda^0}$ and $\mathbf{K_s^0}$.

Real data performance

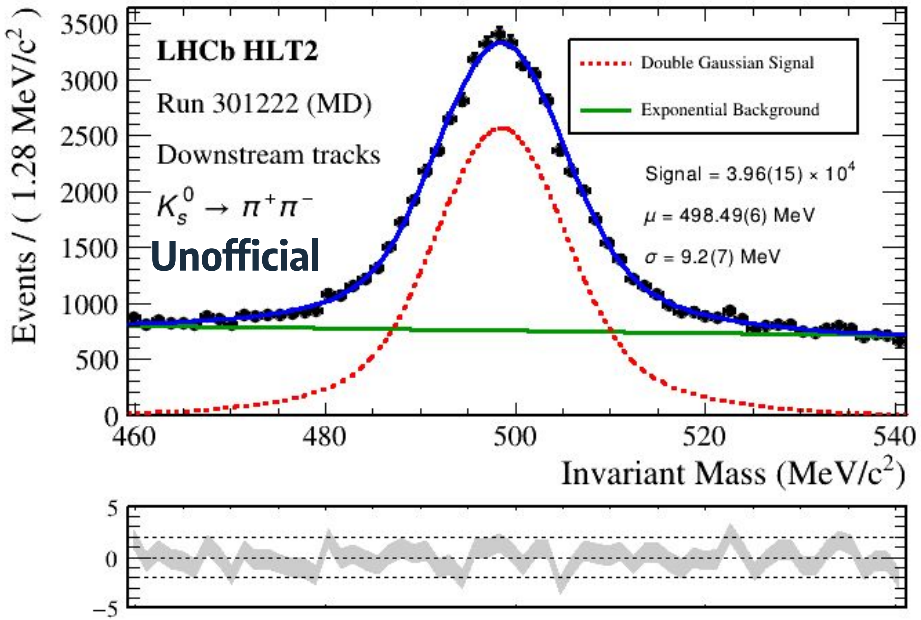
HLT1 Downstream

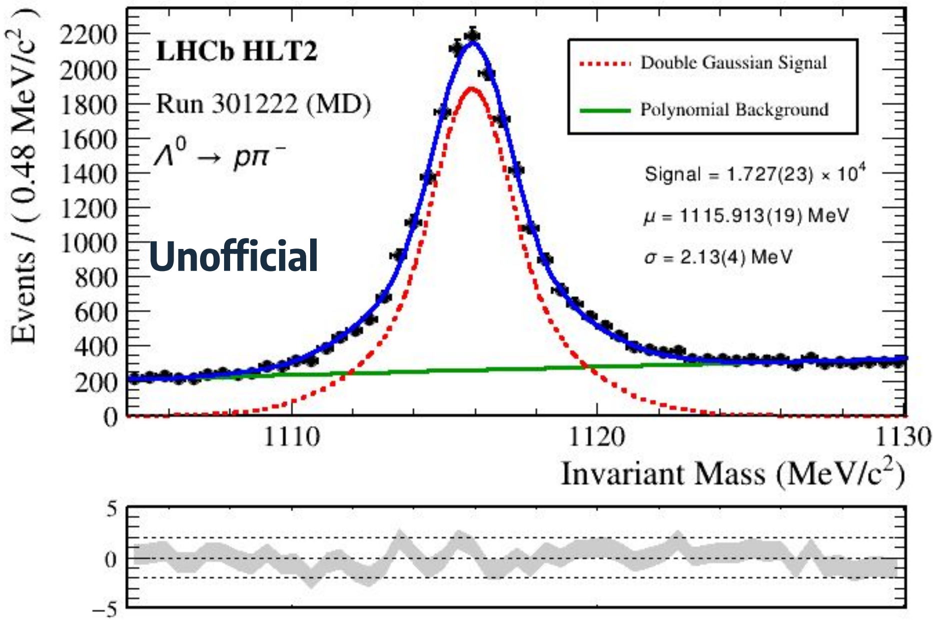




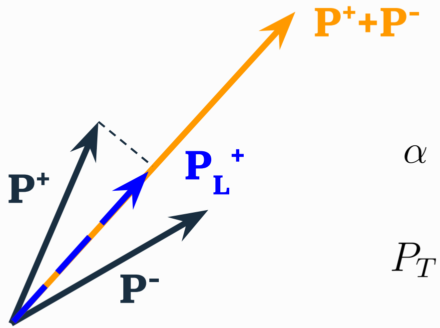
Real data performance

HLT2 Downstream





Armenteros-Podolanski Plot



$$\alpha = \frac{P_L^+ - P_L^-}{P_L^+ + P_L^-}$$

$$P_T = P_T^+ = P_T^-$$

In the (α, PT)-plane, particles from a two body decay define an ellipse:

$$\frac{(\alpha - \alpha_0)^2}{r_\alpha^2} + \frac{P_T^2}{P_{cm}^2} = 1$$

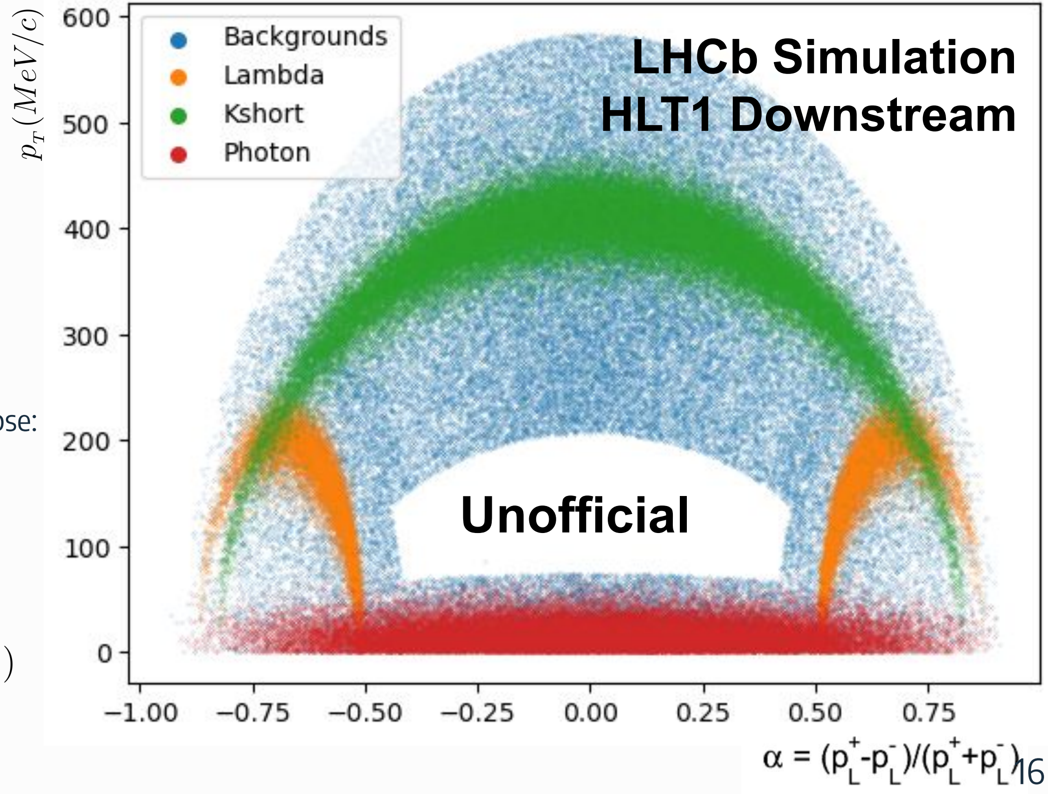
Where:

$$(\alpha_0, 0) = (\frac{m_1^2 - m_2^2}{M^2}, 0)$$

center of the ellipse

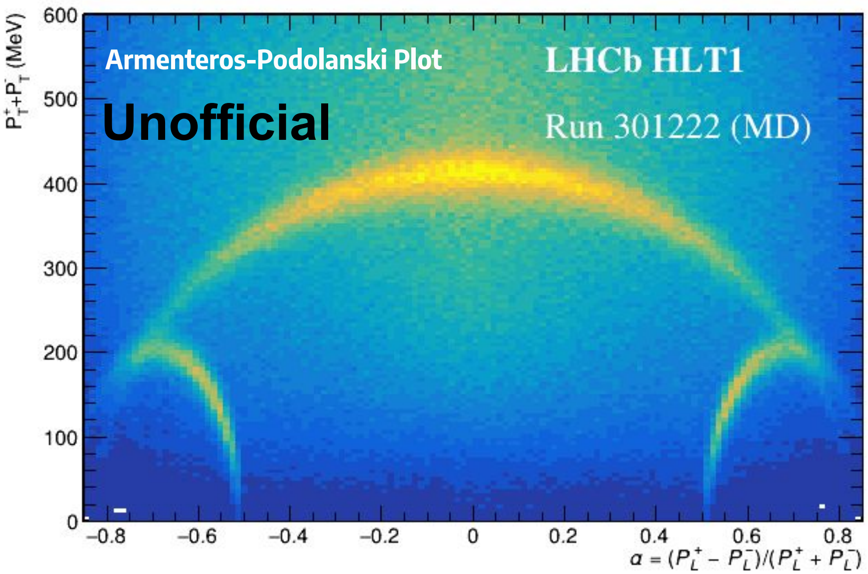
$$(r_\alpha, r_{P_T}) = (\frac{2P_{cm}}{M}, P_{cm})$$

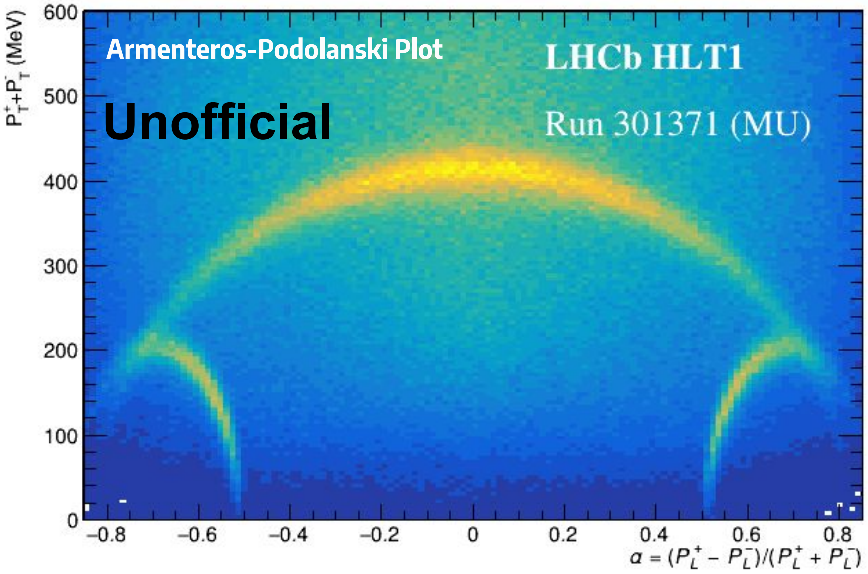
radii of the ellipse



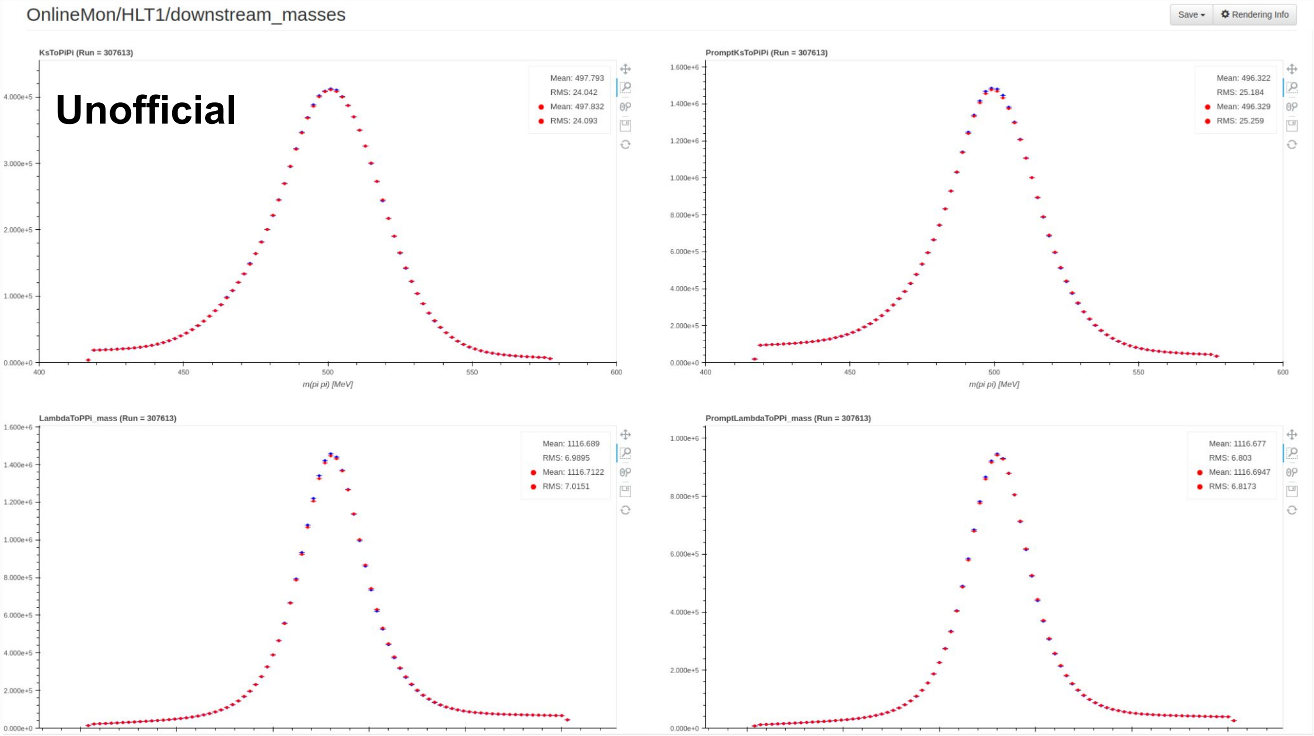
Armenteros-Podolanski Plot

HLT1 Downstream





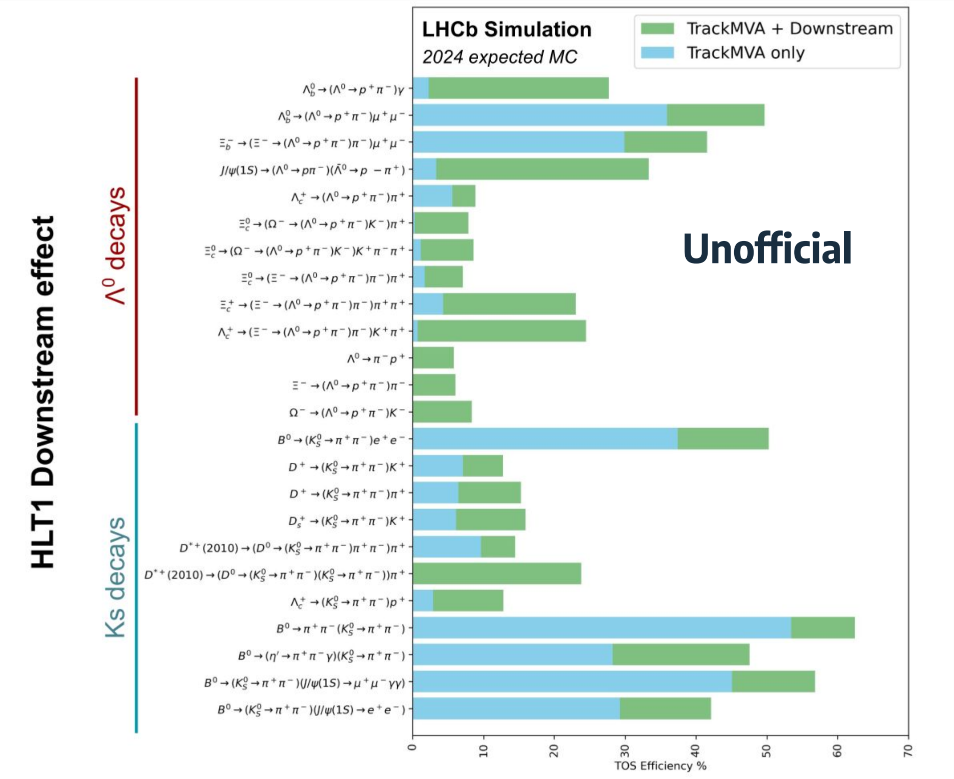
Run 3 data-taking



LHCb began data-taking with HLT1 downstream starting last night!

HLT1 Downstream lines

- The trigger efficiency for **Λ^0** and **K_s^0** is very poor with long tracks due to their long lifetimes; both tend to decay after the Velo, making it impossible to reconstruct them with long tracks.
- The new HLT1 **Λ^0** and **K_s^0** downstream lines may significantly improve the trigger efficiency for many different physics channels that rely on **Λ^0** and **K_s^0** to trigger the event.
- Calo and Muon information (isMuon and isElectron) are used to veto lepton IDs in these lines.



Summary

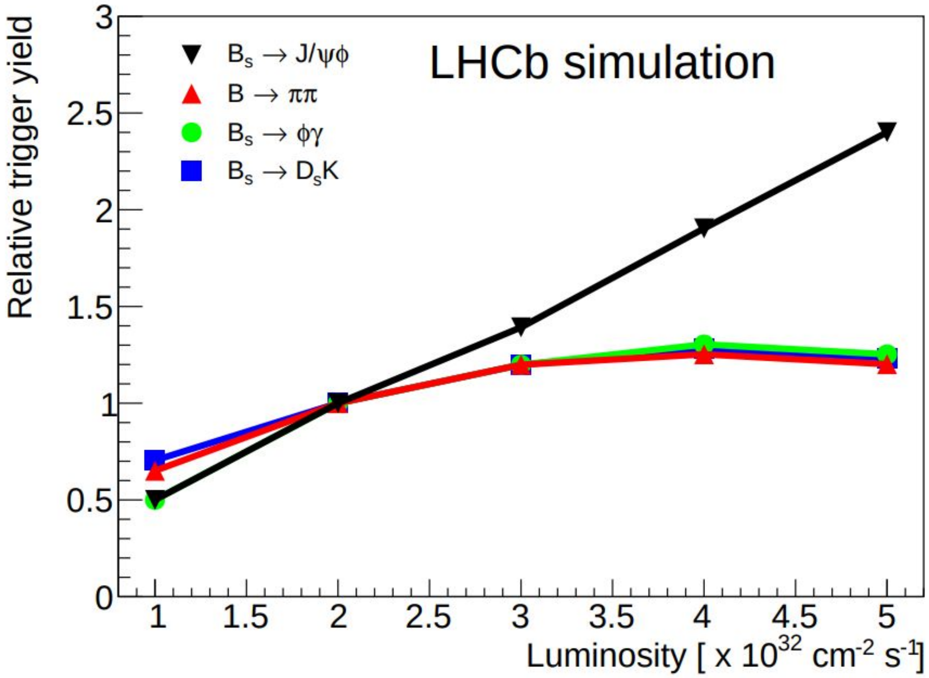
- Downstream tracking is now available in both HLT1 and HLT2.
- HLT1 downstream tracking was finally deployed and began running in data-taking in October 2024.
- The new HLT1 downstream trigger lines are expected to enhance trigger efficiency for various physics channels that rely on Λ^0 and K_s^0 decays to trigger events.

Stay tuned!

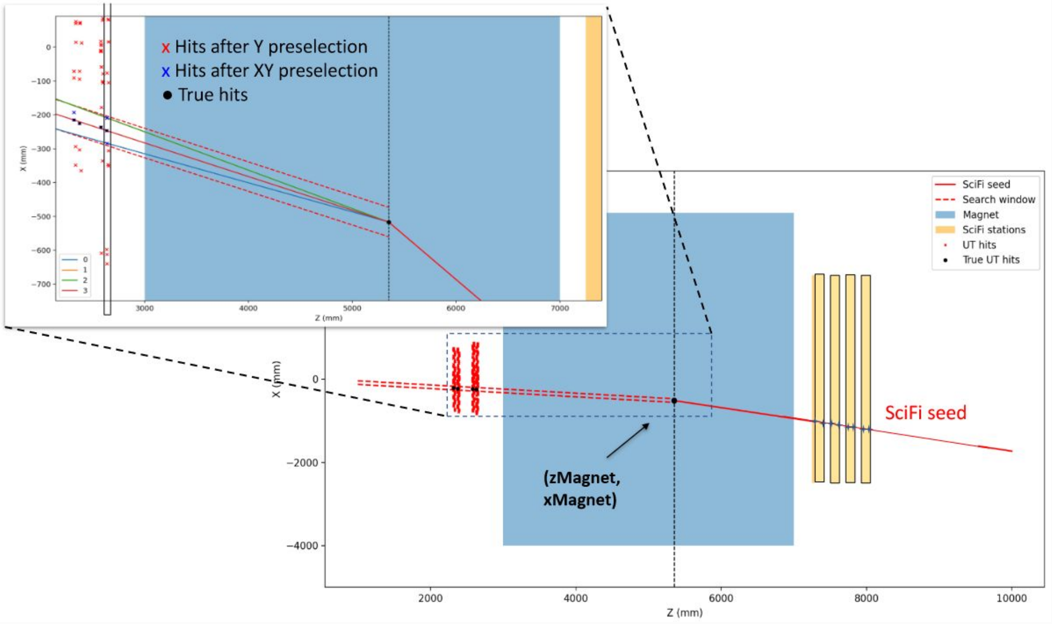
Thank you for your attention

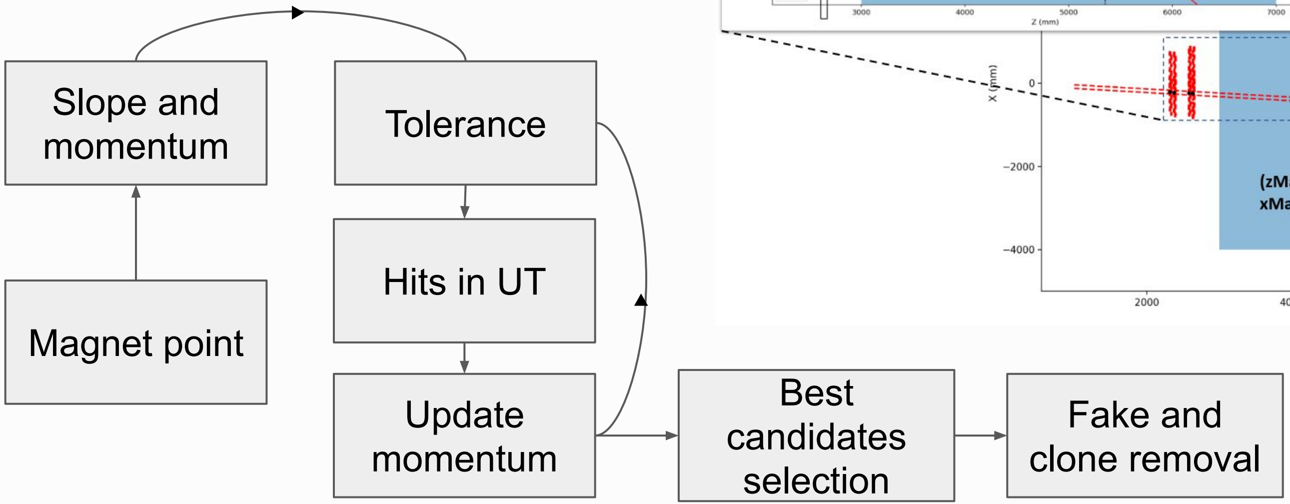
Backup

L0 saturation in Run3

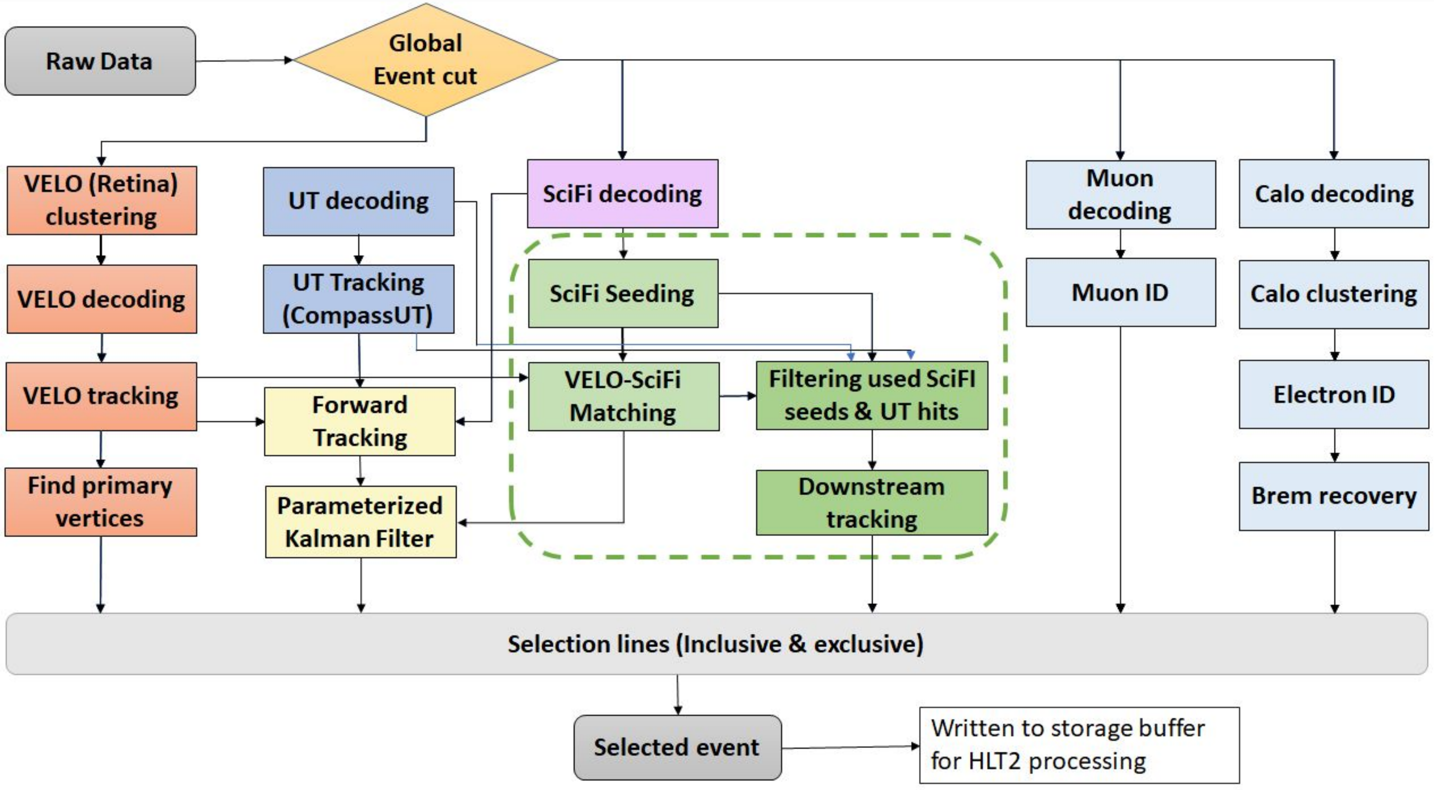


HLT1 Downstream tracking





HLT1 Downstream tracking



HLT1 tracking sequences

Matching sequence

SciFi standalone tracks +

- **Velo tracks** → **Long tracks** without UT — **Done** (Allen!742)
- **UT hits** → **Downstream tracks** — **Done** (Allen!1095)
- **Velo tracks** + **UT hits** → **Long tracks** with UT — **Done** (Allen!1525)

HybridSeeding on GPUs
Allen!742

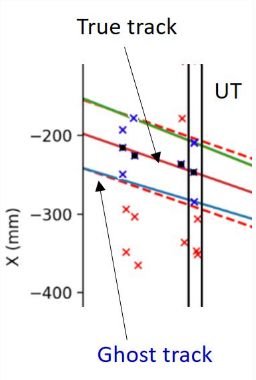
Forward sequence

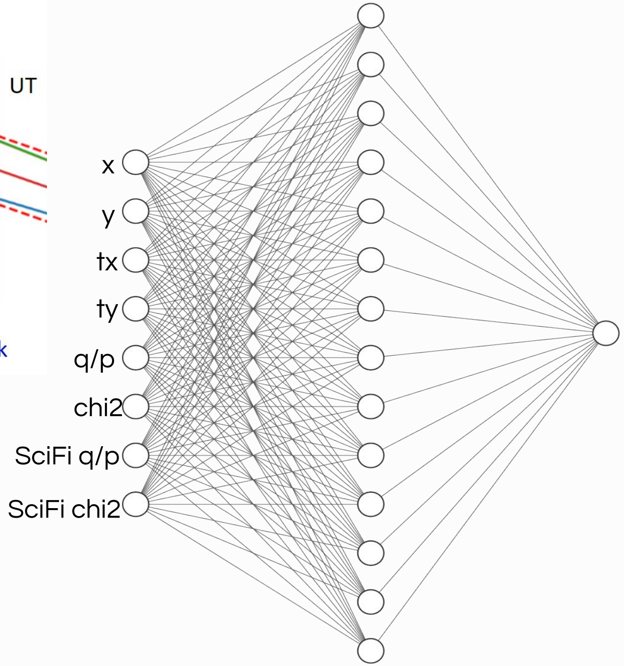
Velo standalone tracks +

- **SciFi hits** → **Long tracks** without UT — **Allen baseline**
- **SciFi hits** + **UT hits** → **Long tracks with UT** — **Allen baseline**

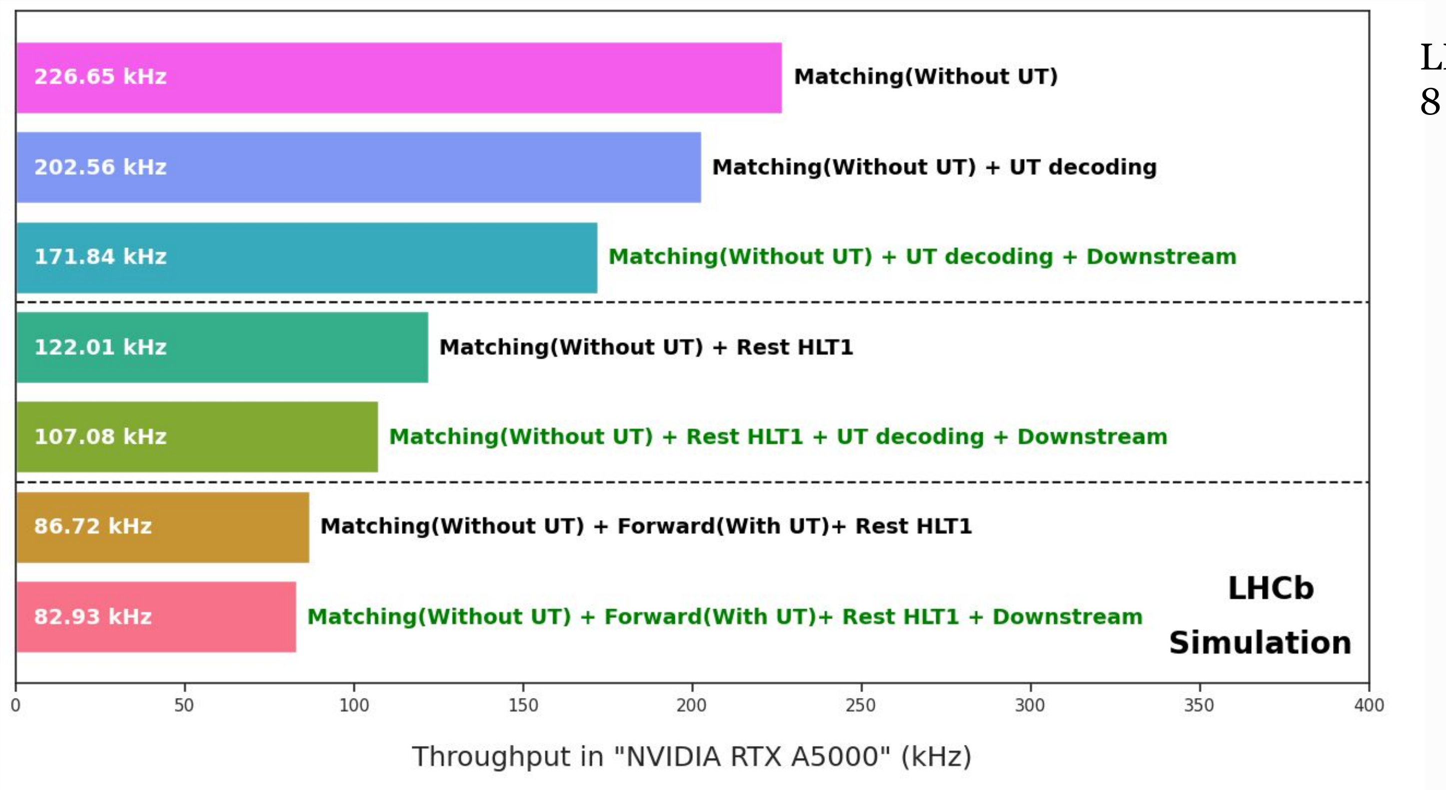
HLT1 Downstream tracking

- A single hidden (14 nodes) layer fully connected NN
- It utilizes **8 variables** as input:
  - *Downstream* track state (**$x, y, t_x, t_y, q/p, \mathcal{X}^2$**)
  - SciFi track properties (**$q/p, \mathcal{X}_y^2$**)
- The model was trained using $B_s \to \phi\phi$ events.
- In order to boost speed, certain C++/CUDA tricks are applied, such as using **static structs**, employing **fast math functions**, and **unwinding for-loops**.





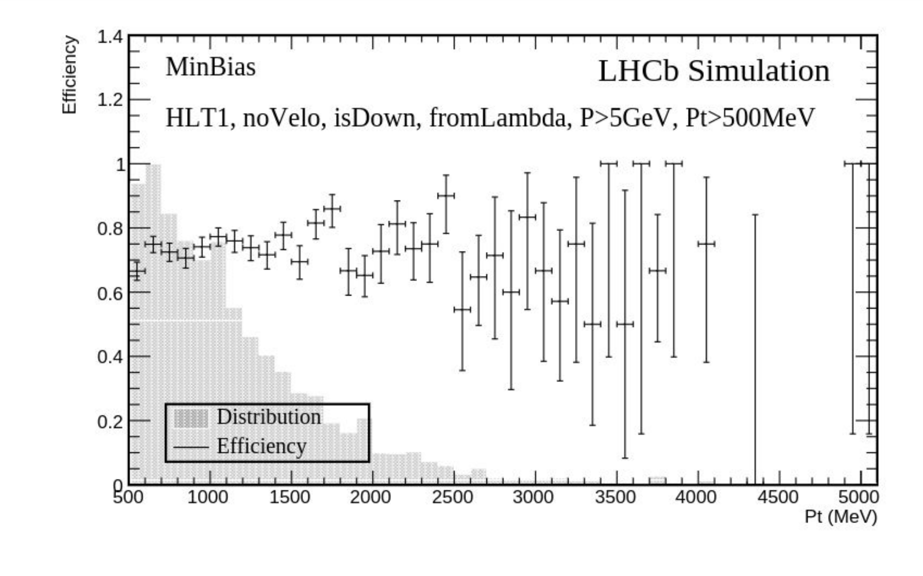
HLT1 Downstream tracking

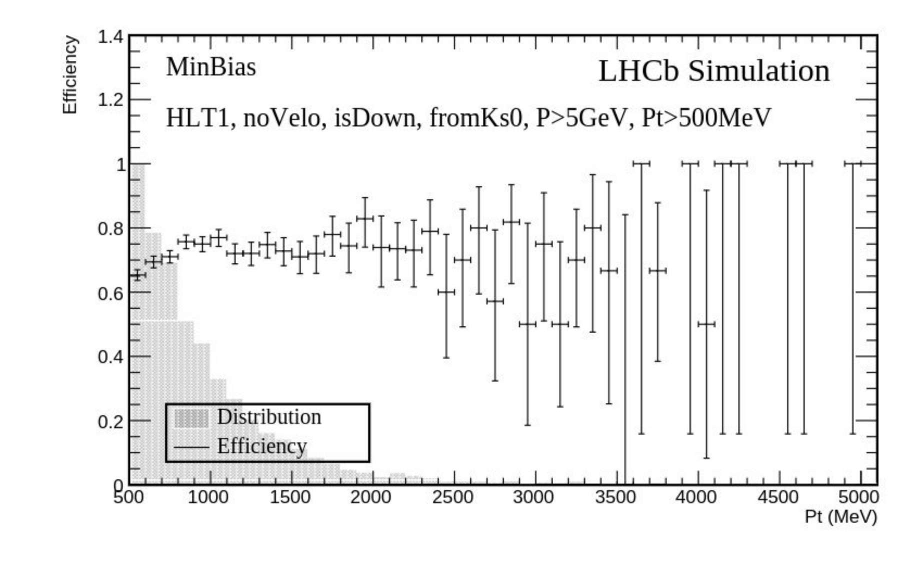


LHCb-FIGURE-2023-028

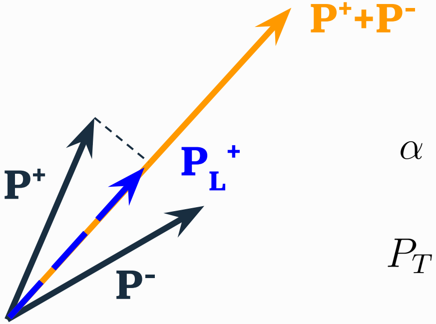
HLT1 Downstream tracking

Efficiency vs PT





Armenteros-Podolanski Plot



$$\alpha = \frac{P_L^+ - P_L^-}{P_L^+ + P_L^-}$$

$$P_T = P_T^+ = P_T^-$$

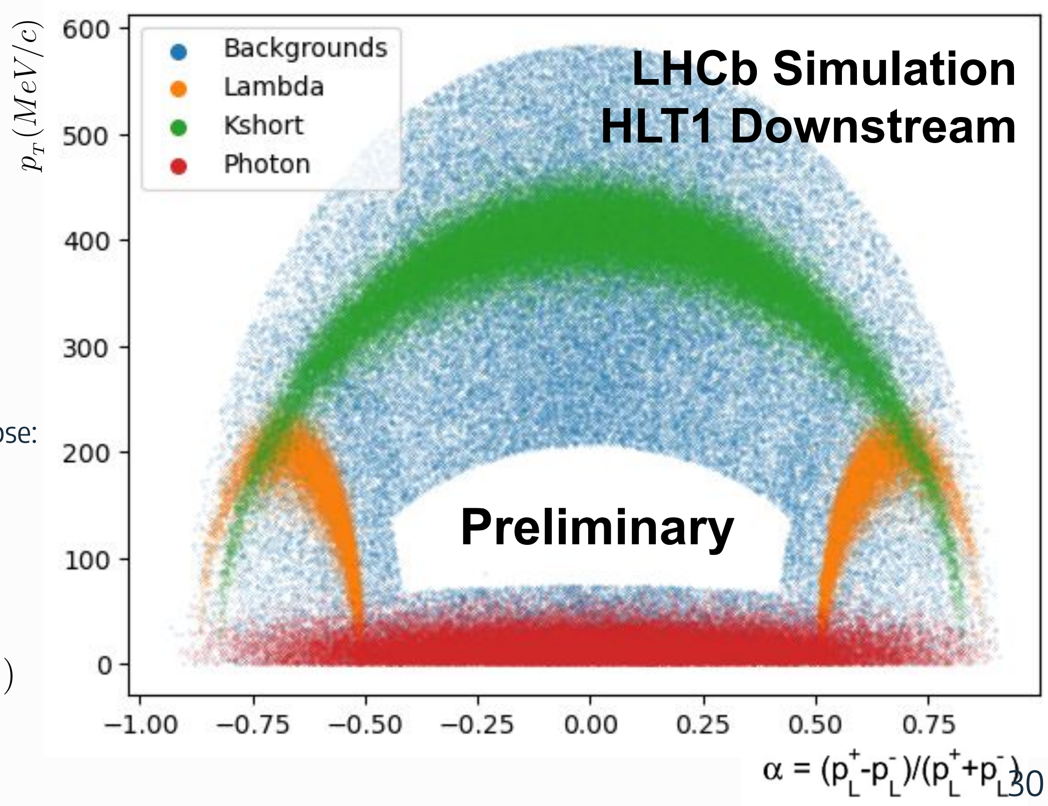
In the (α, PT)-plane, particles from a two body decay define an ellipse:

$$\frac{(\alpha-\alpha_0)^2}{r_\alpha^2} + \frac{P_T^2}{P_{cm}^2} = 1$$

Where:

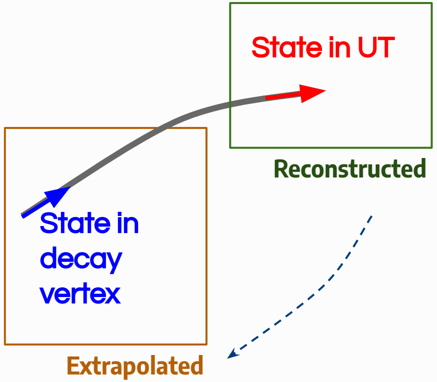
$$(\alpha_0, 0) = (\frac{m_1^2 - m_2^2}{M^2}, 0) \qquad (r_\alpha, r_{P_T}) = (\frac{2P_{cm}}{M}, P_{cm})$$

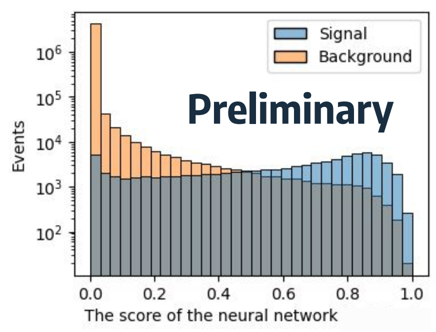
center of the ellipse | radii of the ellipse

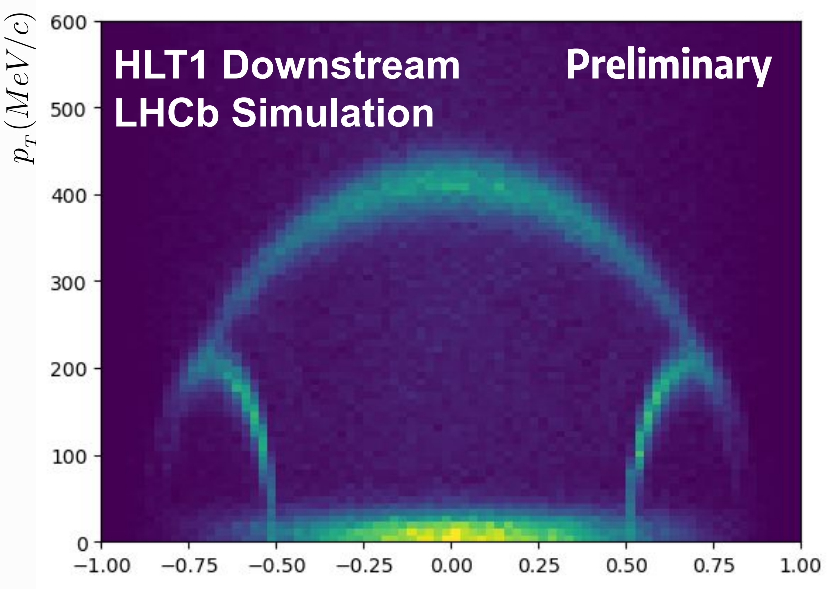


HLT1 Downstream vertexing

Allen!1198







$\alpha = (p_L^+ - p_L^-)/(p_L^+ + p_L^-)$

- After tracking, we can **combine** two downstream tracks to reconstruct secondary vertices (**decay vertices**).
- Considering the **approximation** of a **homogeneous** magnetic field in Y direction, the trajectory is parabolic in the XZ plane.
- We use a **neural network (NN)-based selector** to evaluate each vertex, requiring the quality to be larger than 0.1 (**a very loose cut**).
- We observe the **ellipses** of Λ^0, K_s^0, and converted photons in the **Armenteros-Podolanski** plot.

$$\frac{(\alpha - \alpha_0)^2}{r_\alpha^2} + \frac{p_T^2}{p_{cm}^2} = 1$$

HLT1 Downstream lines

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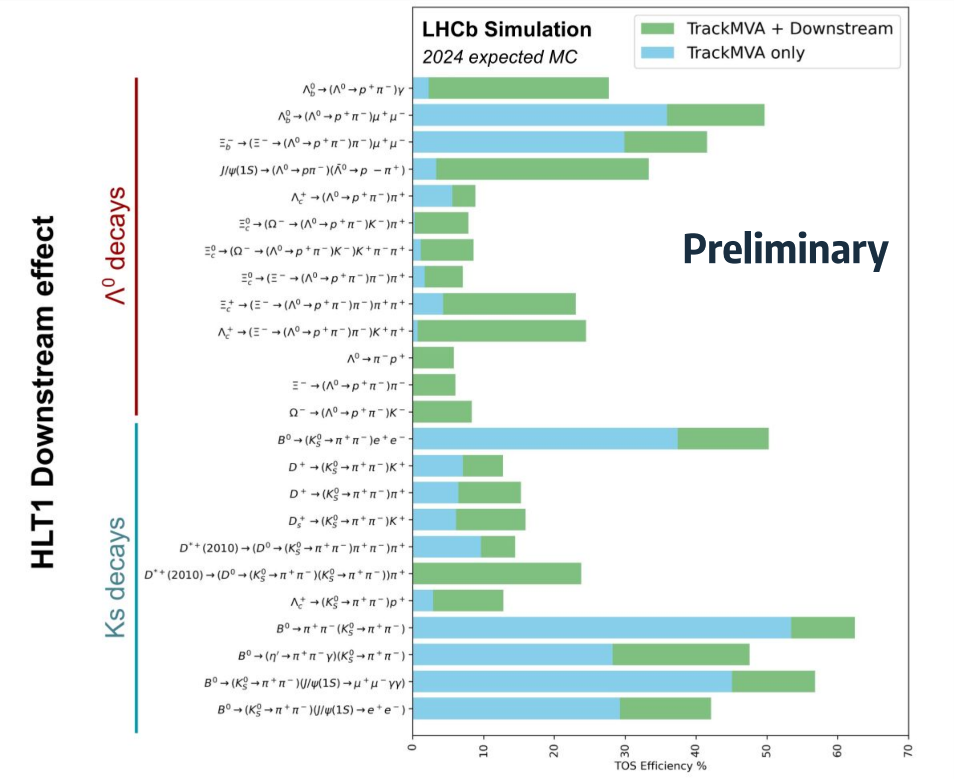
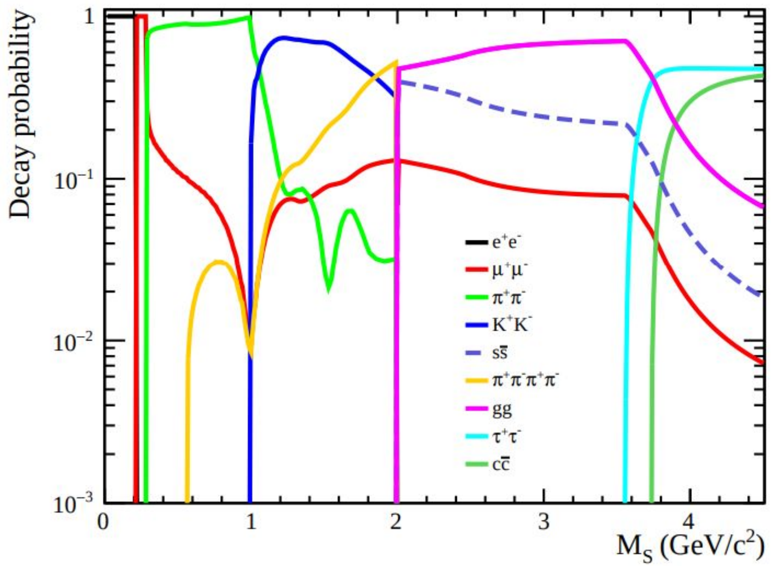


Search for long living particles (LLPs)

[https://doi.org/10.1140/epjc/s10052-024-12906-3]

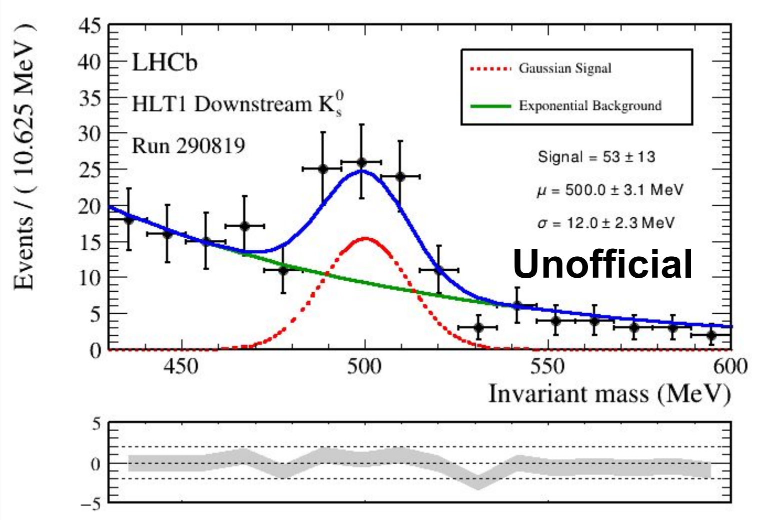
- Until now, LLP searches in LHCb have focused on **decays in the VELO** (through **long tracks**), up to **~30 cm** from interaction point.
- By exploiting downstream tracks, the physics reach of LHCb is expanded to **~2 m**.
- Many **BSM** models predict **LLPs** such as Heavy Neutral Leptons (**HNLs**), Axion-like particles (**ALPs**) and Dark Scalars.

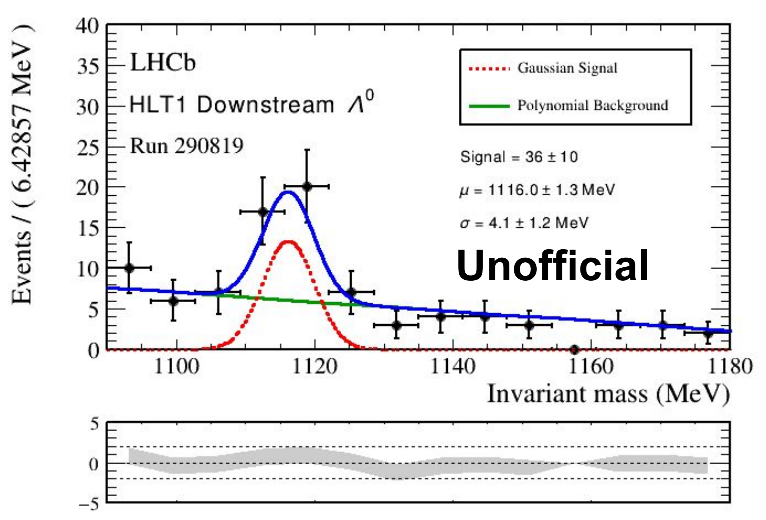


Decay probabilities of a dark scalar into different channels as a function of its mass and normalised to unity

HLT1 Downstream lines

Allen!1198



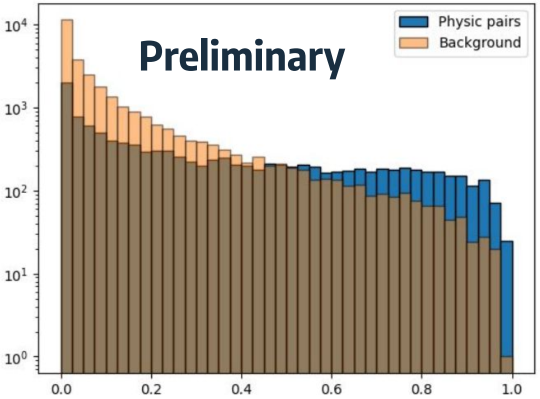


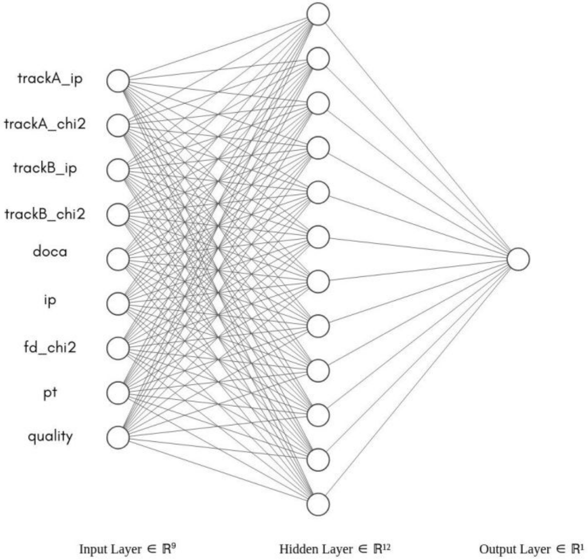
- We checked the HLT1 downstream lines with early 2024 data. Since in this data UT has very high ADC thresholds and half of the UT poorly aligned, we loosened the NN threshold to fit the background distribution.
- Despite these conditions, we successfully observed the mass peaks of both $\mathbf{\Lambda^0}$ and $\mathbf{K_s^0}$ with downstream tracks in HLT1, and a reasonable mass resolution was achieved (slightly larger than MC).

Project BuSca: Buffer Scanning

Selection procedure

Idea: create track quality selection model independent neural network, which can select all physics pairs

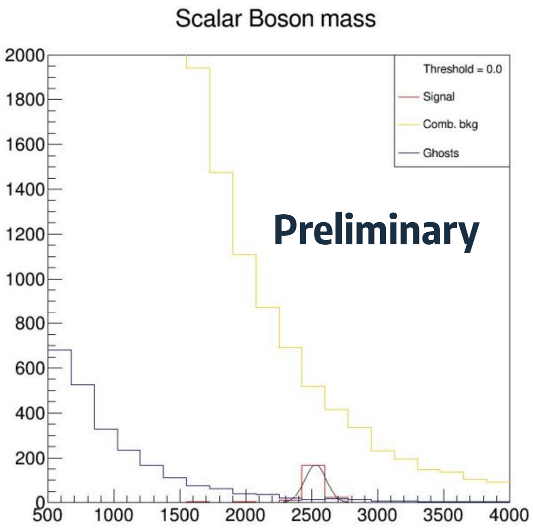


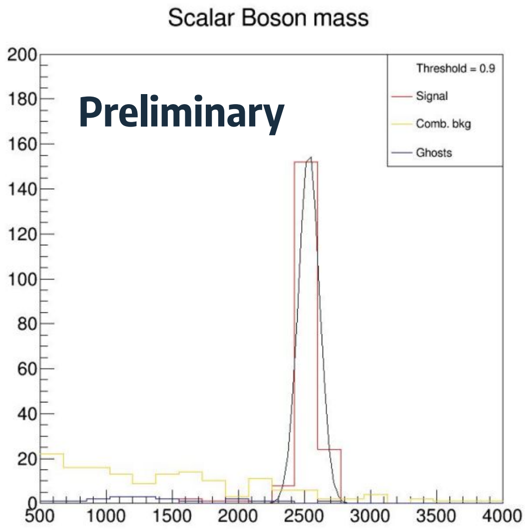


Project BuSca: Buffer Scanning

Background reduction

NN performance is showed by combinatorial background rejection.





Search for long living particles (LLPs)

[PBC BSM Report, arXiv:1901.009966, J.Phys.G 47 (2020) 1, 010501]

Portal	Coupling	
Vector: Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	BC1, BC2, BC3
Scalar: Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$	BC4, BC5
Fermion: Heavy Neutral Lepton, N	$y_N L H N$	BC6, BC7, BC8
Pseudo-scalar: Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$	BC9, BC10, BC11

Sensitivity to Higgs-like scalars

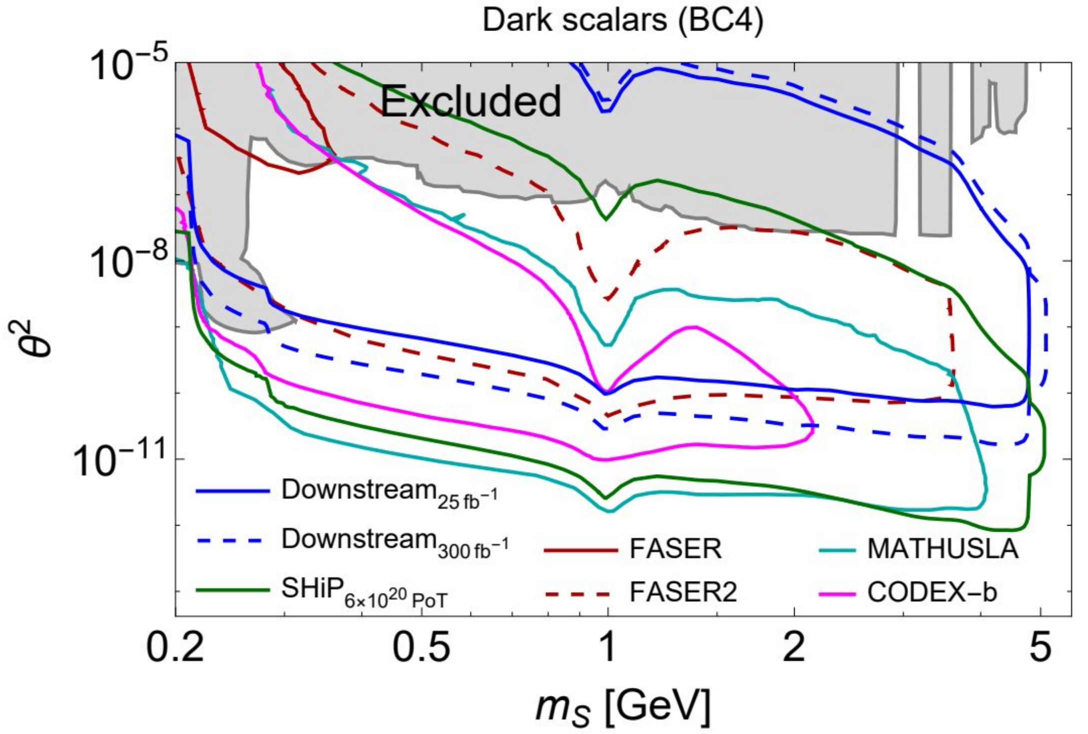


Fig. 10. Comparison of the sensitivities of future proposed and approved experiments to the model of Higgs-like scalars (BC4).