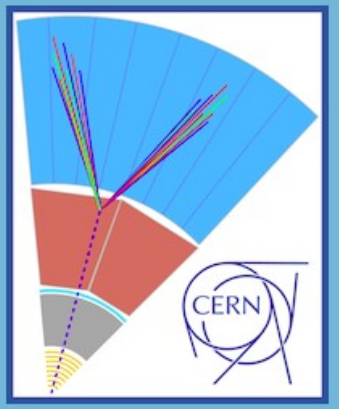


Searching for long-lived particles at the LHC and beyond:
Twelfth workshop of the LLP Community

October 31, 2022 to November 4, 2022

Impact of the High Level Trigger for detecting Long-Lived Particles at LHCb

L. Calefice, A. Hennequin, L. Henry, B. Jashal, **Diego Mendoza**, A. Oyanguren,
I. Sanderswood, C. Vázquez Sierra, J. Zhuo, C. Agapopoulou, V. Svintozelskyi

part of LHCb-RTA Collaboration
04/11/2022

Outline

Talk based on the recent publication: Oyanguren et al. (2022)

Introduction
- ✗ LHCb detector in Run 3
- ✗ Tracking system and track types
- ✗ The High Level Trigger (HLT)
- ✗ LLPs at LHCb

Physics case: Sensitivity studies of long-lived particles
- ✗ Standard Model: $\mathbf{\Lambda^0}$ and $\mathbf{K^0_s}$
- ✗ Beyond the Standard Model: Dark Boson and Composite scalar Higgs

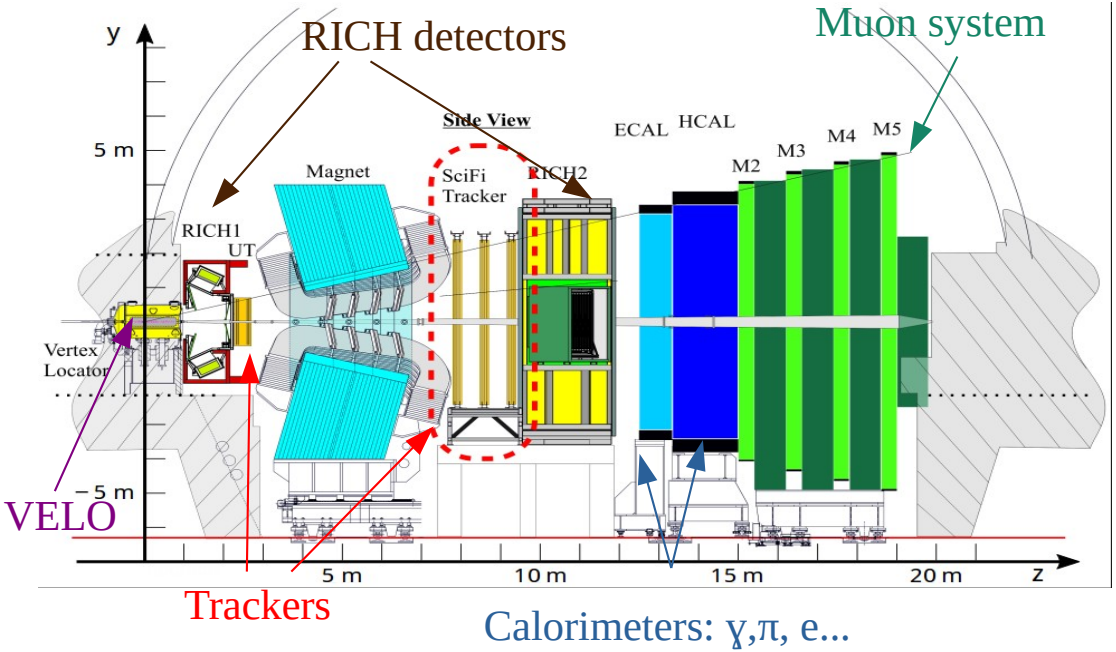
Prospects: the SciFi seeding algorithm

Conclusions

LHCb detector in Run 3

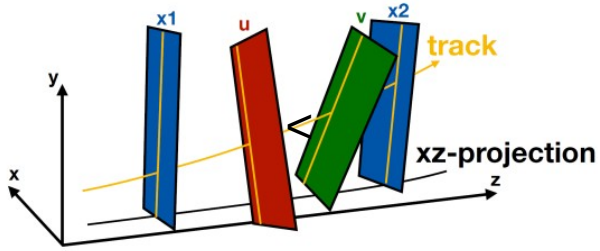
- ✗ Single-arm spectrometer in the **forward direction**
- ✗ Originally designed for specialised study of beauty and charm hadrons
- ✗ Detector design:
  - Excellent secondary vertex resolution
  - Low-p_T cut for tracking (0.5 GeV/c)
  - Dipole magnet
  - Particle ID: calorimeters, muon systems and Ring Imaging Cherenkov (RICH) detectors
- ✗ Upgrade:
  - $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$
  - Purely software-based trigger @ 30 MHz → **First time in a LHC experiment**

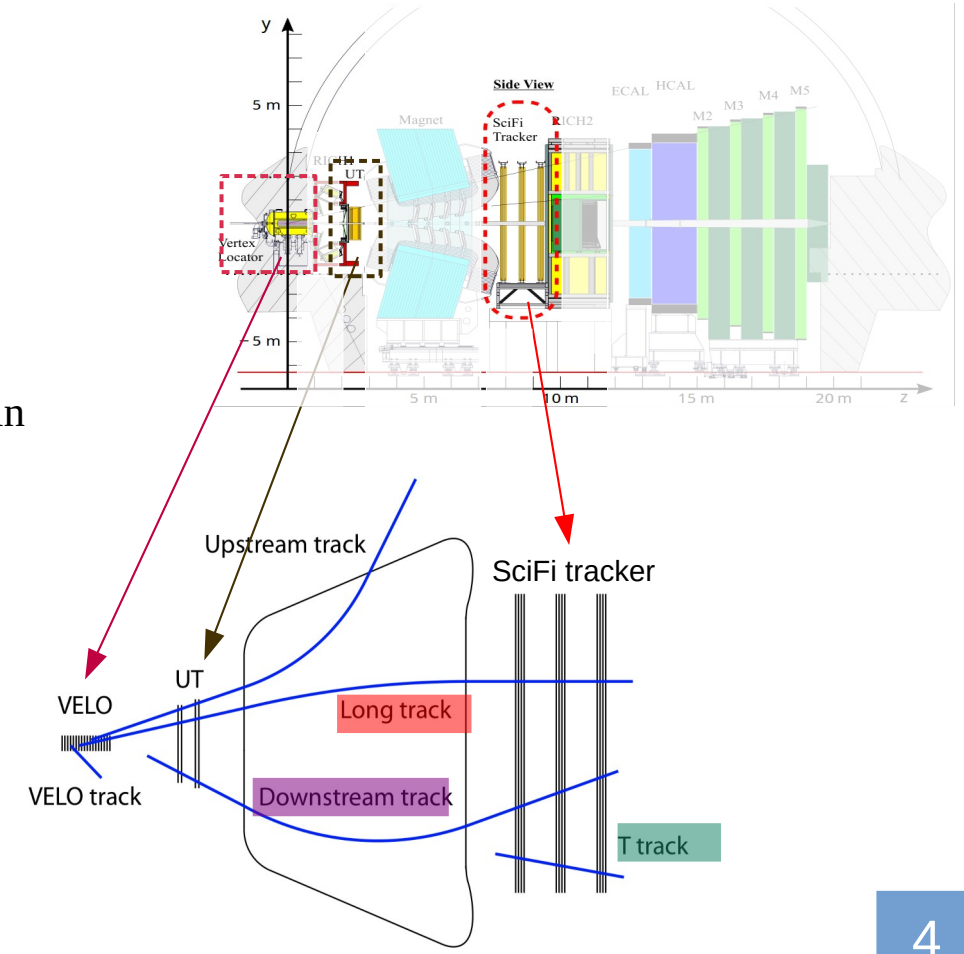
Alves et al. (2018) LHCb (2014a)



LHCb tracking system and track types

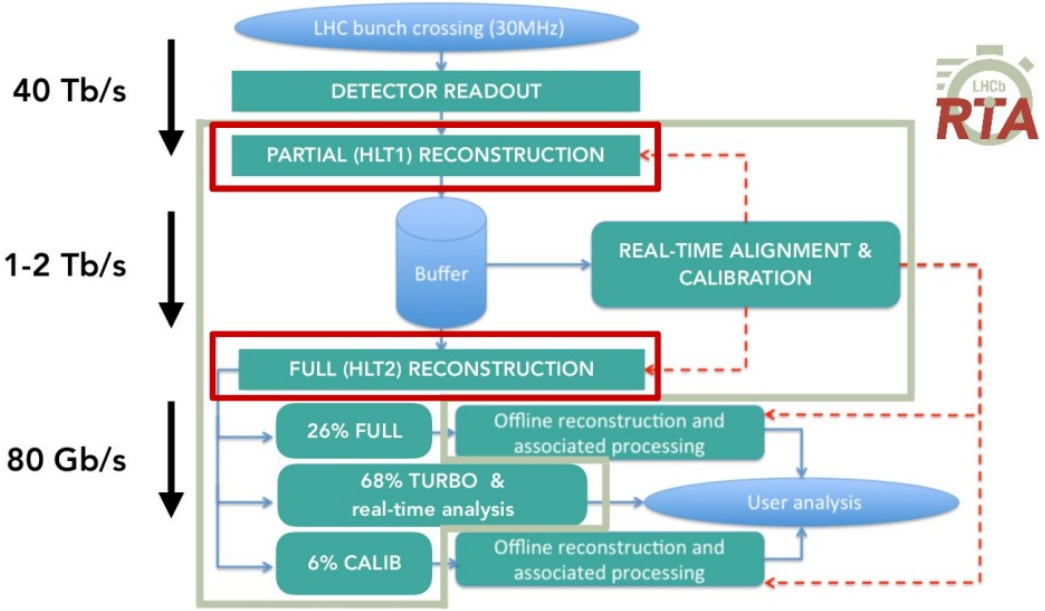
- ✗ Three sub-detectors: VELO, UT and SciFi + magnet
  - Estimation of particle momentum and track origin
- ✗ Main track types for physics analysis:
  - Long: signal in VELO and SciFi (minimum) + UT (full)
  - Downstream: signal in UT and SciFi
  - T: hits only in SciFi
- ✗ In simulations, reconstructible tracks meet certain threshold in each subsystem:
  - VELO: 3 pixel sensors with 1 digit each
  - UT: two clusters from layers 1-2 and 3-4
  - SciFi: 1 hit per cluster and 1 stereo cluster per station





The HLT trigger

Aaij et al. (2020)



HLT1 (GPUs):

- Event rate reduction: 30 MHz to 1 MHz
- Fast and partial reconstruction, real-time calibration and alignment
- Need for efficiency and low latency

HLT2 (CPU)

- gives a flow of 2-5 Gb/s to storage
- Relies on offline-quality reconstructed objects
- Full reconstruction, must be complete for further analysis

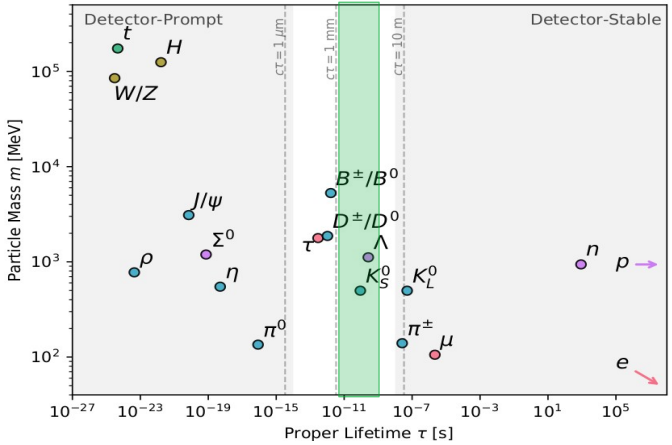
Track type	Long	Downstream	T
HLT1	Used	Not used	Not used
HLT2	Used	Used	Not used
Efficiency	High	Low	Very low

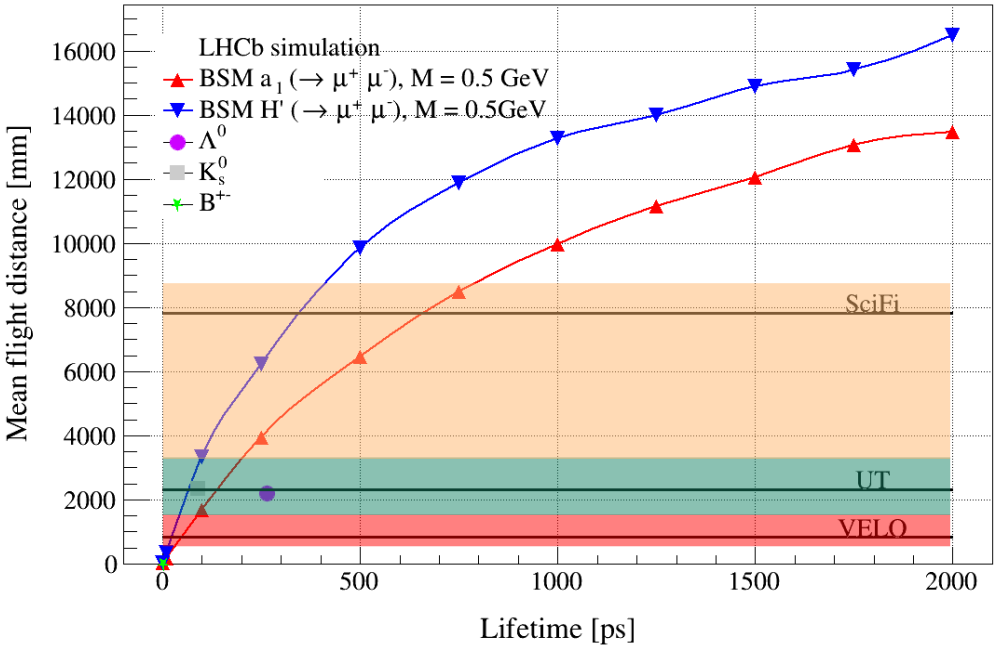
How relevant can downstream and T tracks be in reconstruction of events?

LLPs at LHCb

- ✗ LLPs present in SM and many BSM extensions
- ✗ Expected track types depend on LLP flight distance
- ✗ Mean flight distance of LLPs at LHCb? Not only depends on lifetime
  - lower mass ➡ larger boost ➡ **higher flight distance**

Lee et al. (2019)





K_s and Λ^0 do not travel that far, and already an impact in sensitivity. Can we really hunt for LLPs?

Downstream and T tracks:
Not considered in HLT1 decision, signal lost!

Long tracks: what HLT1 relies on

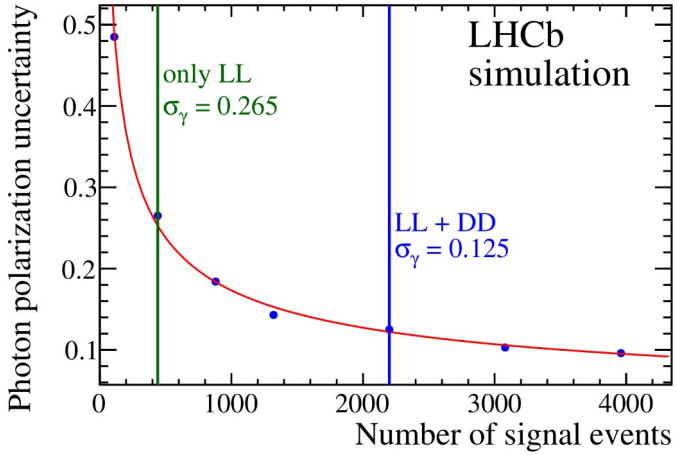
Physics case: LLPs in the Standard Model

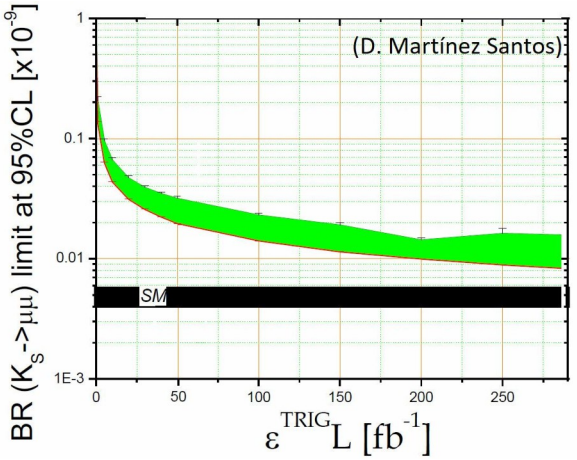
LLPs in the SM: Λ^0 and K_s^0

- ✗ Lifetime around 100 ps
- ✗ Involved in many studies of observables
- ✗ Case 1: $\Lambda_b \rightarrow \Lambda^0 [\rightarrow p\,\pi^-]\,\gamma$
  - Rare decay
  - Related to models with non-standard right-handed currents: G. Martínez et al. (2019)
- ✗ Case 2: $K_s^0 \rightarrow \mu^+\mu^-$
  - Suppressed decay in the SM, not measured experimentally yet
  - Related to BSM scenarios:

    SUSY: Zhu (2019)

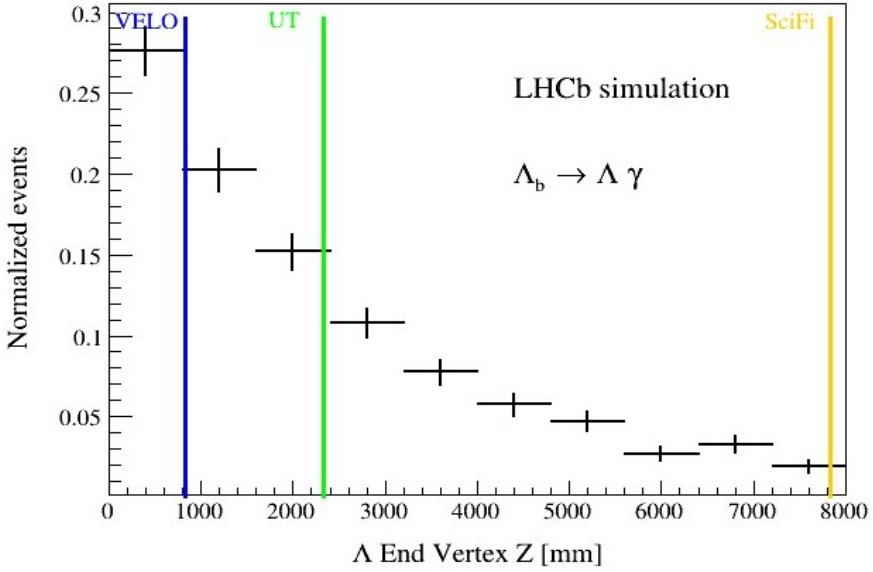
    leptoquarks: Bobeth et al. (2018)

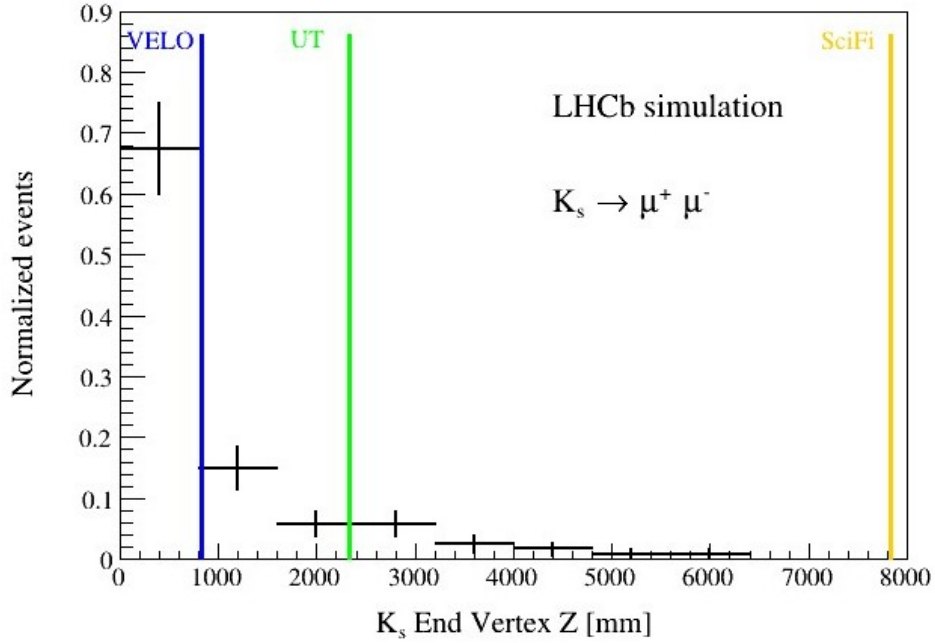




Sensitivity to Λ^0 and K_s^0

- ✗ Generation of 10000 events each
- ✗ Estimation of displaced vertices type (LL, DD, TT)
- ✗ HLT1 reconstruction efficiency (trigger on the signal, TOS)
  - General lines: OneTrackMVA and TwoTrackMVA





	LL	DD	TT	HLT1 eff (TOS)
Λ^0	12%	51%	37%	< 10%
K_s^0	46 %	38 %	16 %	< 25%

Physics case: LLPs Beyond the Standard Model (BSM)

Higgs portal to Dark Matter

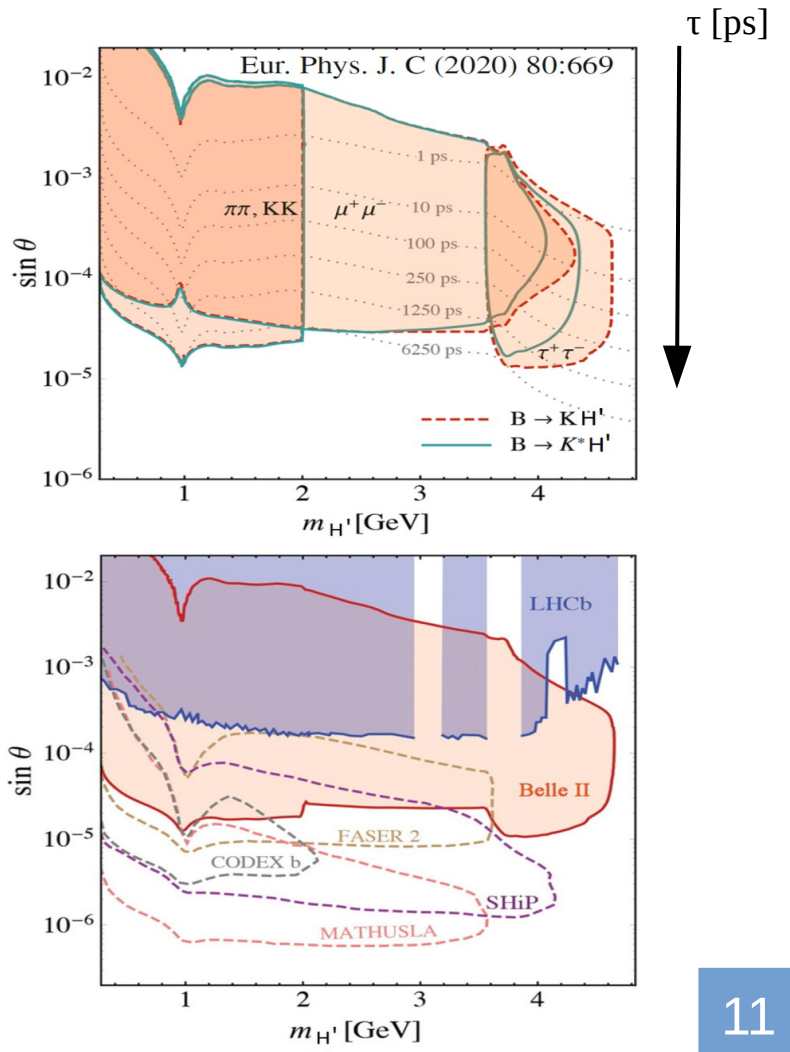
- ✗ State: SM 125 GeV Higgs boson (H) and one of unknown mass (H')

  $h = H \cos\theta + H' \sin\theta$, θ: mixing angle

- ✗ H' serving as mediator to the Dark Sector
- ✗ b → s H' vertex: interest in rare B meson decay
- ✗ Signature B → K H' [→ f f]
  - Presence of displaced vertices
  - H' reconstruction from decay kinematics and decay particles
  - Sensitivity depends on H' lifetime

If H' is long-lived, the two final decay particles would not be selected by HLT1

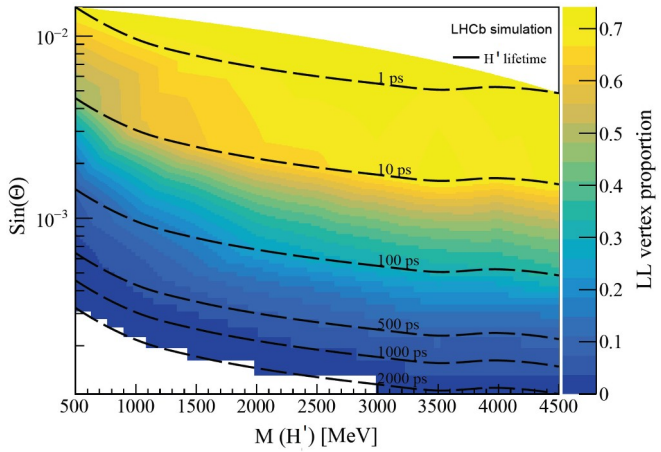
Kachanovich et al. (2019)

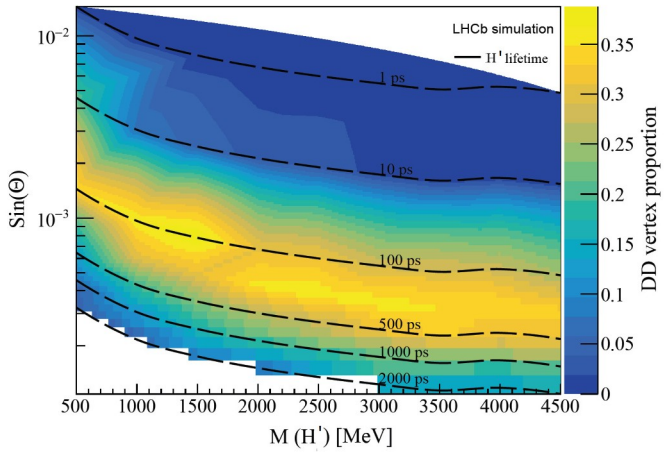


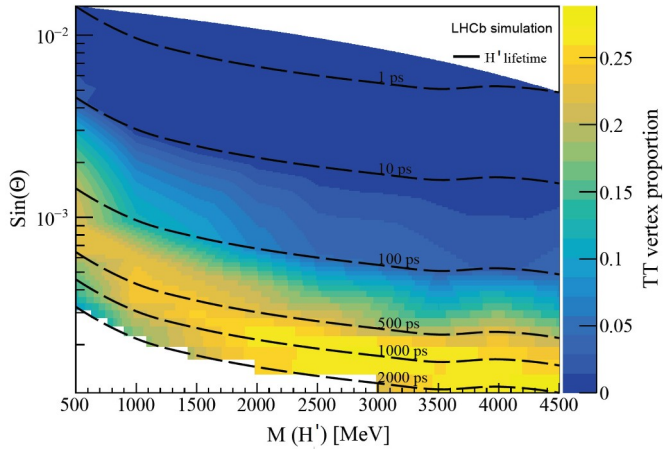
Sensitivity to $B^+ \to K^+ H' [\to \mu^+\mu^-]$

✗ Generation of 99 MC samples with 7000 events each: { τ in [1 - 2000] ps ; M in [500 - 4500] MeV }

✗ Reconstructibility of H' decay vertices (LL, DD, TT):





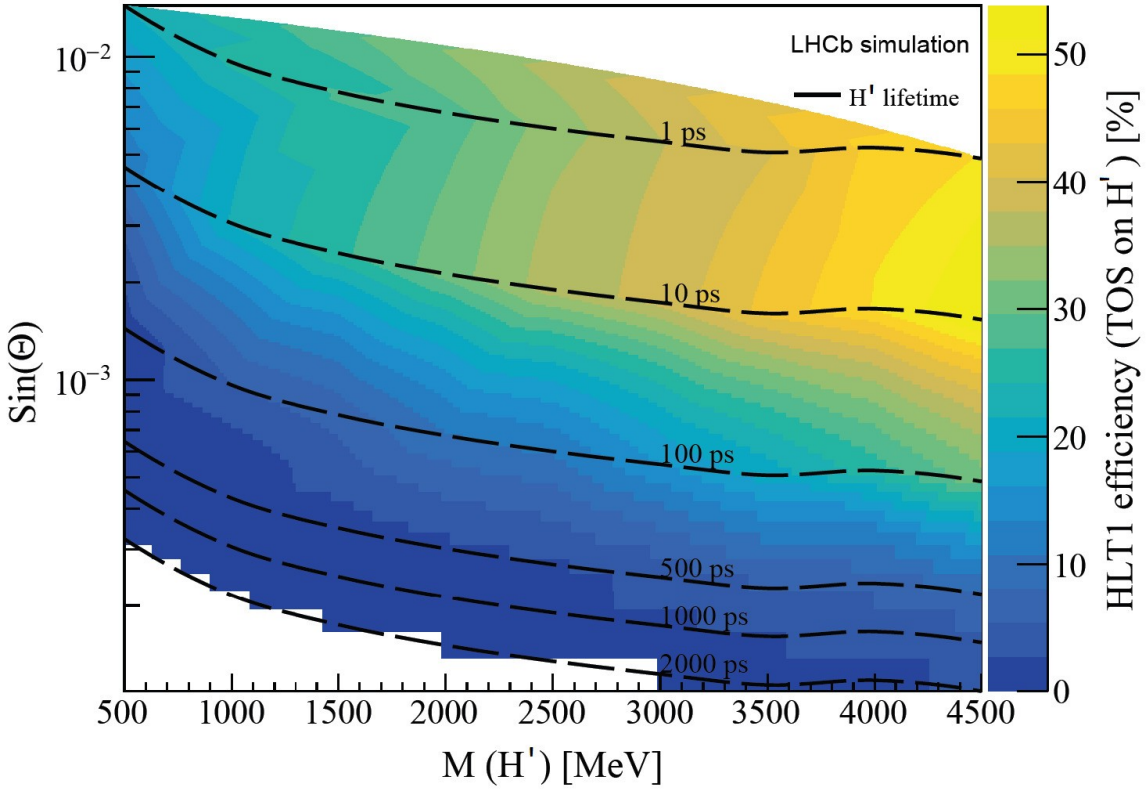


Similar results found for $H' \to K^+K^-$ and for the vector Higgs in $B^0 \to K^*(892)\, H' [\to \mu^+\mu^-]$

✗ Relevance of DD and TT vertices for lifetimes τ > 10 ps
<u>How does this affect the signal reconstruction of LHCb trigger?</u>

BSM: sensitivity to $B^+ \to K^+ H' [\to \mu^+\mu^-]$

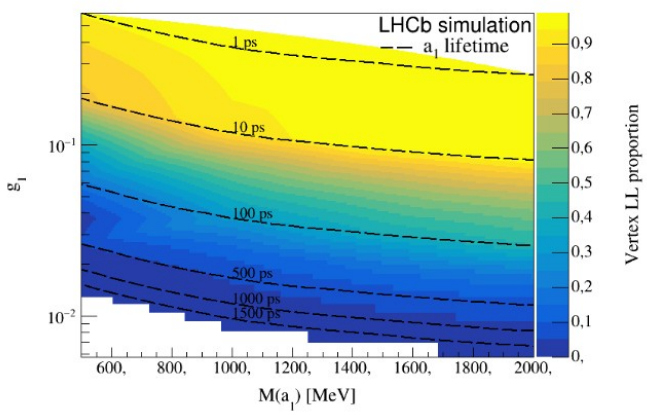
LHCb HLT1 effect when triggering on the H’ decay products (Trigger on Signal, TOS):

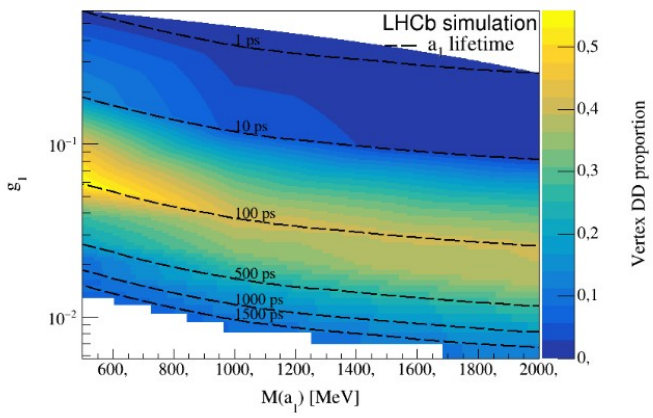


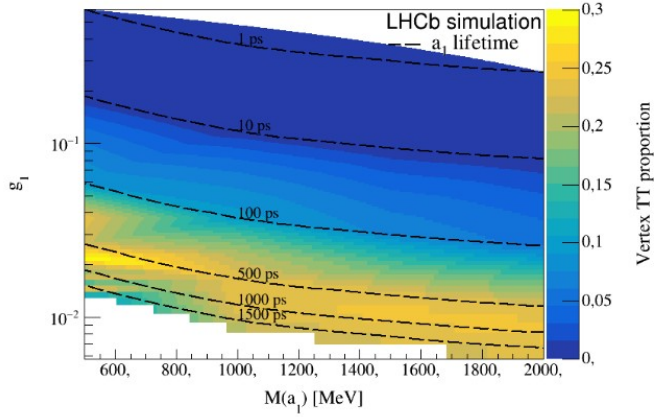
- Decent efficiency (**30-50 %**) for low lifetime
- Poor efficiency (< **10 %**) for τ > 100 ps
- Loss in sensitivity for small H’ mass

Sensitivity to $B^+ \to K^+ a_1[\to \mu^+\mu^-] a_2[\to \mu^+\mu^-]$

- ✗ Composite scalar Higgs model of low mass (< 2500 MeV) Blance et al. (2019)
- ✗ Generation of 44 MC samples, 10000 events each
- ✗ Study of displaced vertices reconstructibility: M. Jiménez (2022)
  - Compatible with previous results:





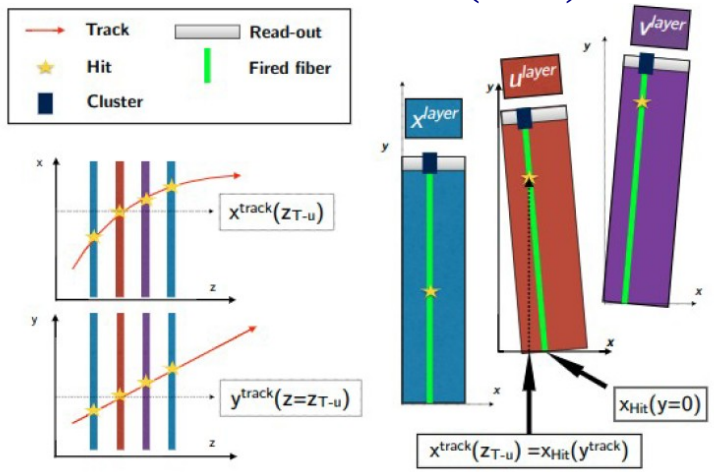


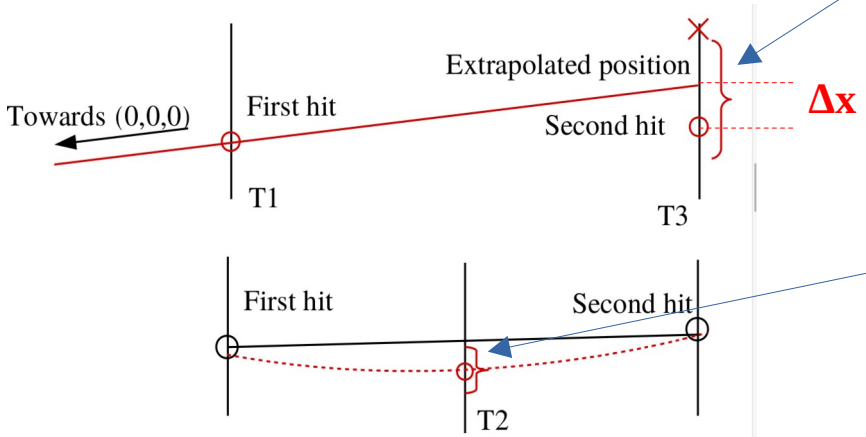
Prospects: The SciFi seeding algorithm

The Hybrid Seeding strategy

Aiola et al. (2021)

- ✗ An iterative reconstruction algorithm to reconstruct track segments
- ✗ SciFi: three stations with x-u-v-x geometry
  u and v layers titled by +/- 5º stereo angle
- ✗ X-Z plane: parabolic trajectory with cubic correction
- ✗ Residual B_y field: easier to get y trajectory (straight line)
- ✗ **Seeding in XZ:**
  First assumption: origin in (0,0,0) and infinite momentum
  Open search windows in T3 from a hit in T1: tolerance window around the projected position





But second hit is not aligned with first hit and (0,0,0)

Δx allows to estimate charge and momentum

narrower window to look for 3rd hit in T2

At least 5 hits to provide a track candidate (many ghosts!)

The Hybrid Seeding strategy

Aiola et al. (2021)

- ✗ X-Z trajectories provide x(z) track equations. How to find y coordinate?
- ✗ **U/V layers:**

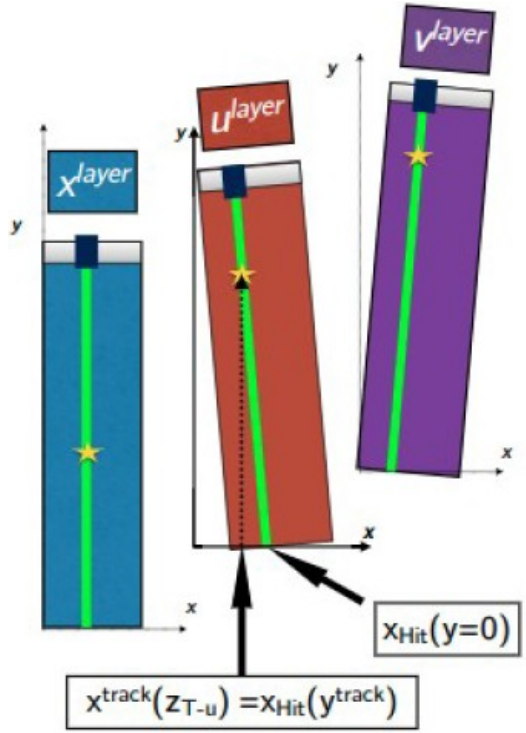
  Estimate of x-position in the first U layer from x(z) trajectory

  Assumption: trajectories coming from the origin ➡ define $\mathbf{t}_y$ slope

  Open search window in next U/V layer

  For each combination found, new hits are seek in further layers

  Minimum of 10 hits for track candidate



Good quality tracks are used for further tracking, matching with:

VELO segments
Long tracks

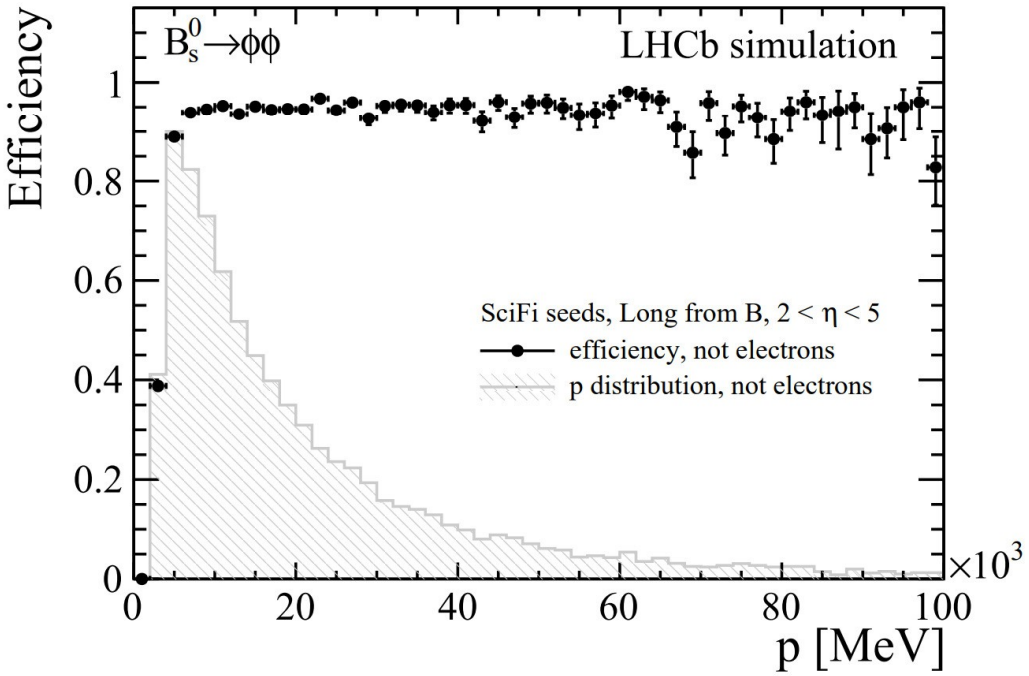
UT hits
Downstream tracks

… or to construct T-tracks (remaing tracklets)

In development

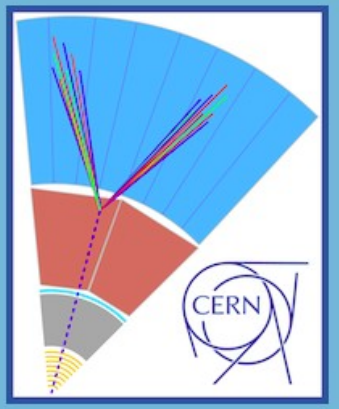
The Hybrid Seeding performance

- ✗ Recent optimization and configuration in GPUs architecture of LHCb trigger
- ✗ High parallelism and reimplementation of U/V hit addition
- ✗ Decay channel tested: $B_s \rightarrow \phi\phi$, with $\phi \rightarrow K^+K^-$



Conclusions

- ✗ LHCb major upgrade for Run 3, collecting data from proton-proton collision at 30 MHz
- ✗ First stage of the trigger is fully based on GPU software architecture for the first time (Allen project)
- ✗ Limited trigger efficiency expected for LLPs, in both SM and BSM cases
- ✗ Relevance of Downstream and T tracks for physics analysis
- ✗ The SciFi seeding, highly-parallelized algorithm on GPUs
  - Already running in Run3 using Long tracks
  - Under development for Downstream tracking
- ✗ Promising results to come, stay tuned!



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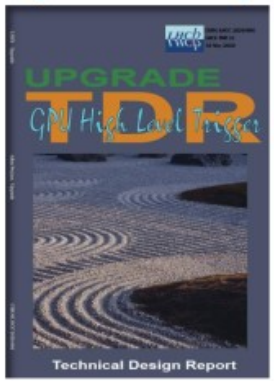
part of LHCb-RTA Collaboration

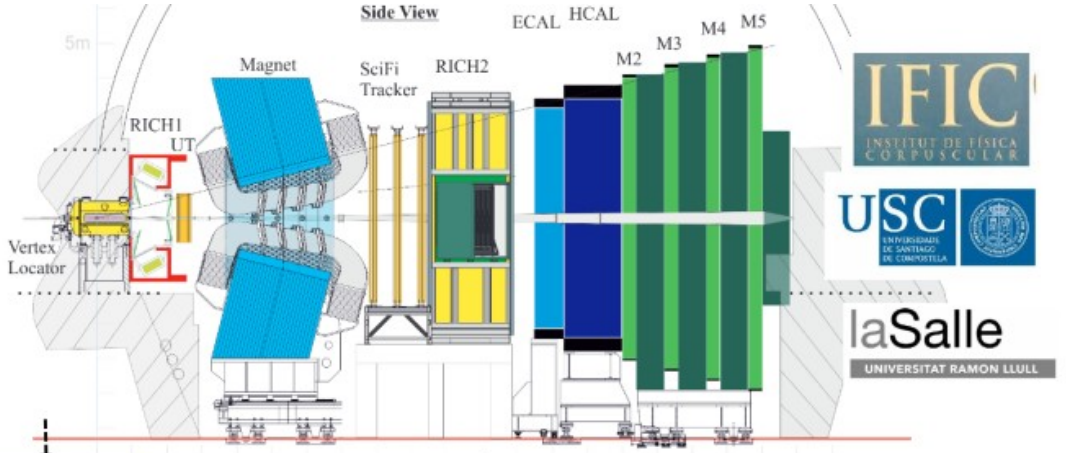
05/11/2022

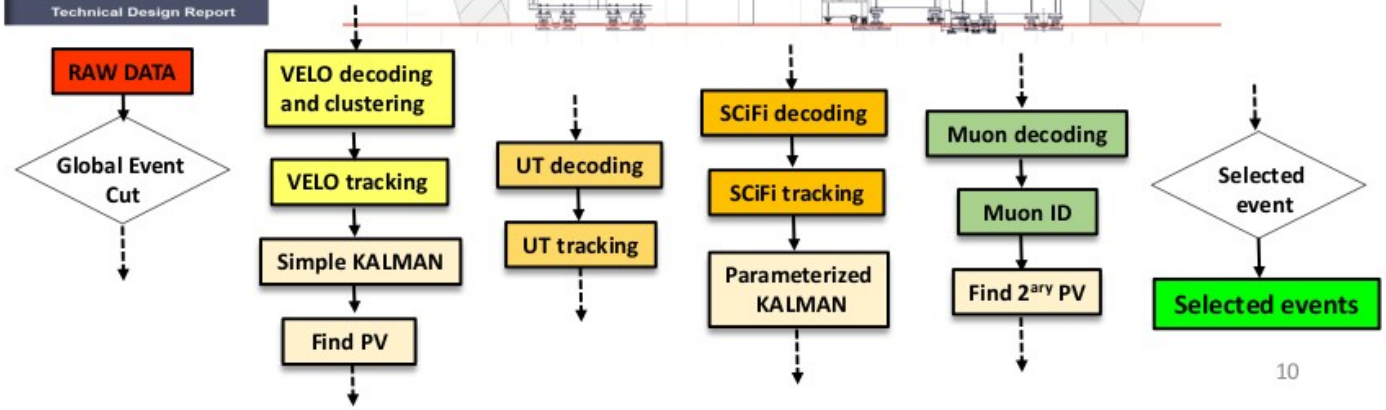
Backup slides

LHCb trigger upgrade

[LHCB-TDR-021]







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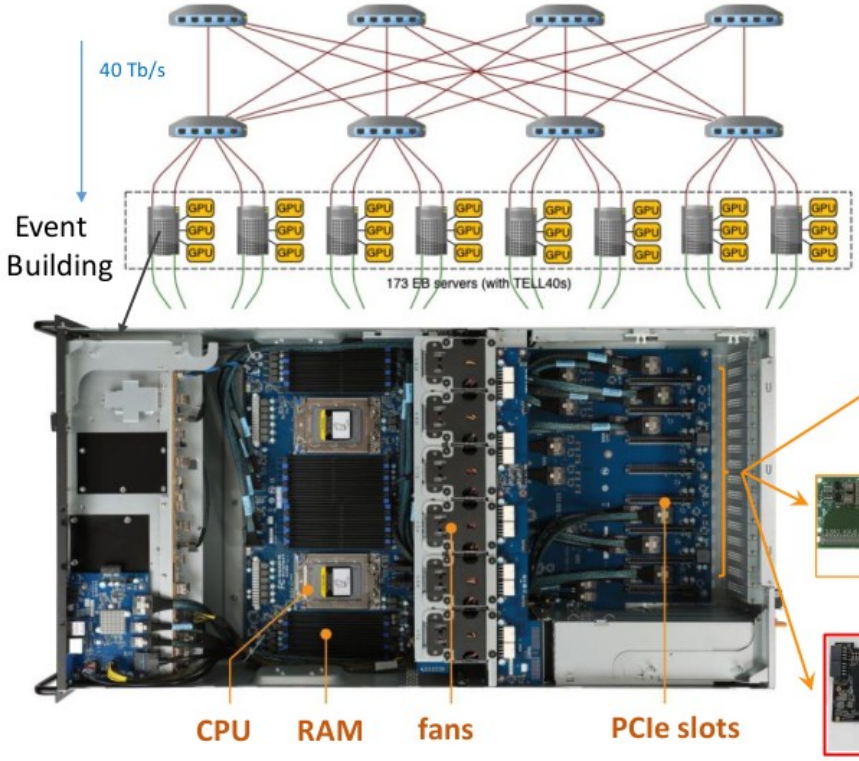
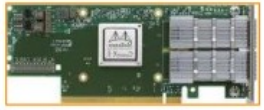
LHCb trigger upgrade

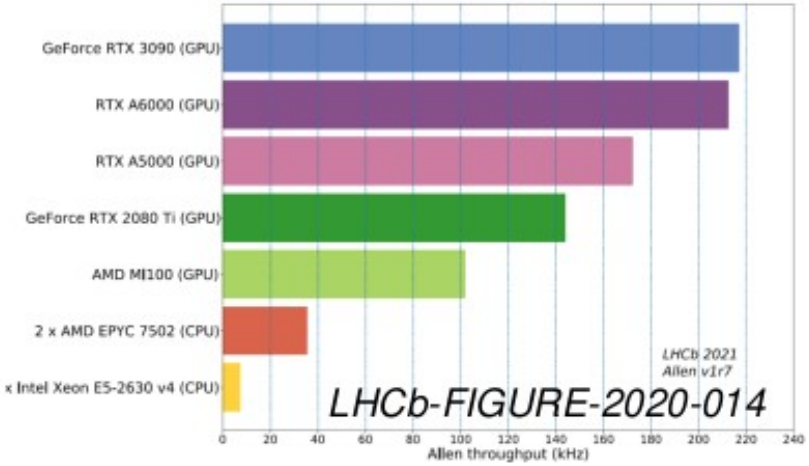


3 PCIe40 (FPGAs)

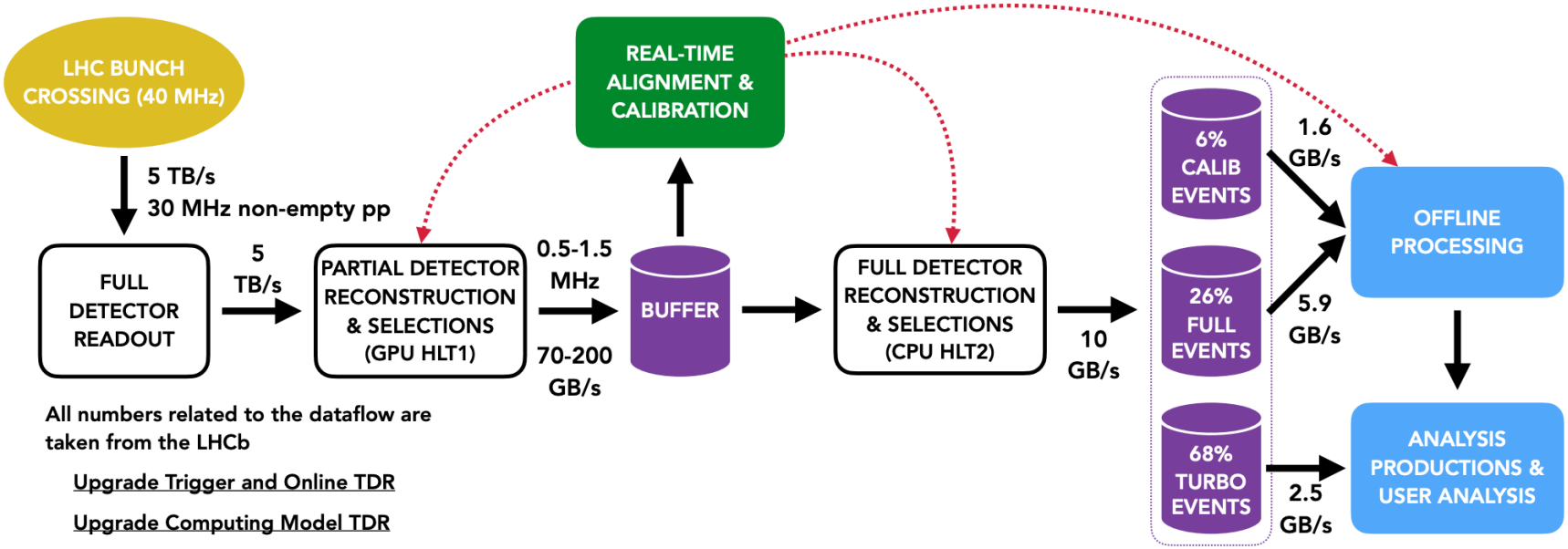


2 network connections

1-3 GPUs



Data flow in HLT



All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

Detailed information in MC generation

Use of LHCb simulation framework Gauss v55r0

- Generator phase:
  - PYTHIA 8, pp collision at 14 TeV, ν = 7.6
  - EvtGen for b-decays

- Simulation phase:
  - Geant4 for particle interaction with the detector
  - Magnet configuration: down

Changing particles masses/lifetimes

- ✗ Open one of the decay files provided by DecFiles package
- ✗ Change the event number to avoid conflict with already existing numbers in your workspace:

  Generation().EventType = myEventNum

- ✗ Provide a .dec file in the same directory with a proper name:

  ToolSvc().EvtGenDecay.UserDecayFile = "./myEventNum.dec"

- ✗ Change **mass** (MeV) and **lifetime** (ps) variables from particle properties

  ParticlePropertySvc().Particles = ["H_10 87 25 0.0 0.235 1.0000e-10 Higgs0 25 0.000000e+000"]

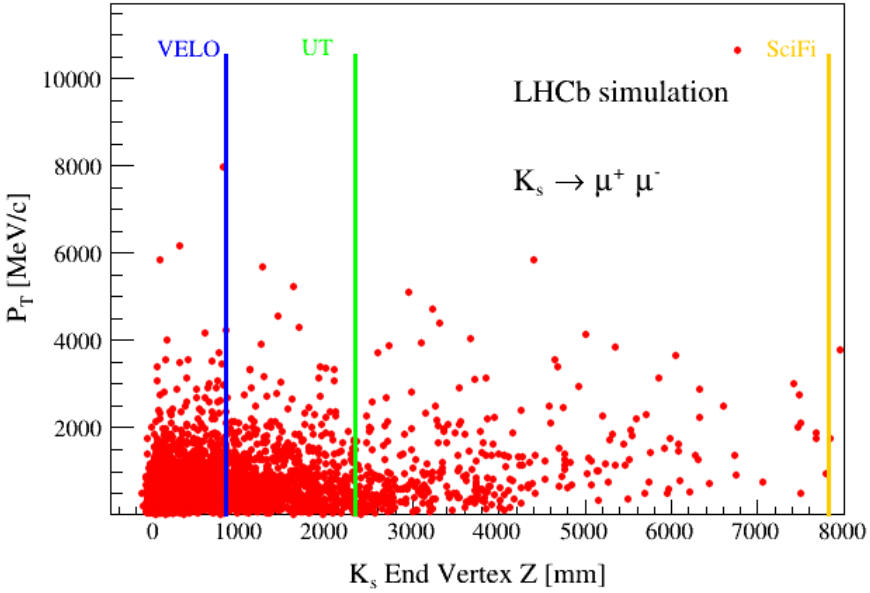
- ✗ In our case, no change of other parameters: phase-space width, spin...

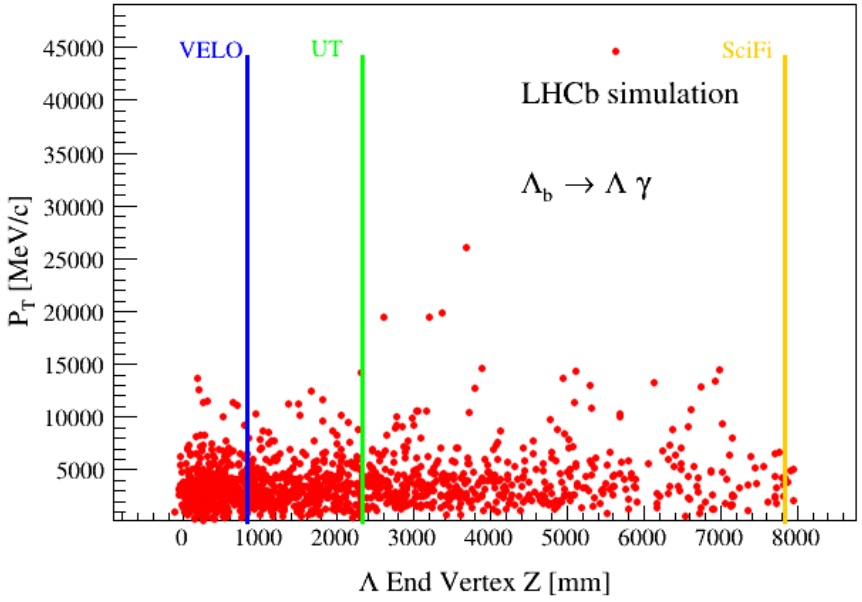
Samples in mass and lifetime 2D region (H')

- ✗ Events are generated following the previous method for next parameters:
- ✗ Lifetime values (ps): [1,10,100,250,500,750,1000,1250,1500,1750,2000]
- ✗ Mass values (MeV): [500,1000,1500,2000,2500,3000,3500,4000,4500]
- ✗ 11 x 9 = 99 samples, 7000 events each
- ✗ A TGraph is filled with the desired information (i.e. LL vertex proportion)
- ✗ From the Tgraph, 2D Delunay interpolation to create a 2D histogram of desired binning (Ref: ROOT_delunay_interp)

MC samples of SM particles

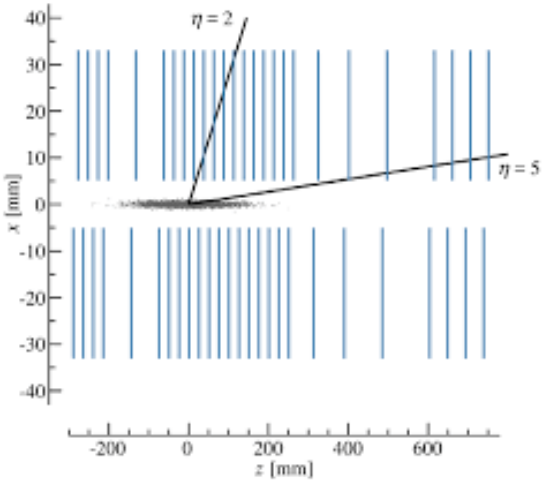
- ✗ Λ^0 : M = 1115.683 ± 0.006 MeV, τ= (2.631±0.020)×10^{-10} s
- ✗ K_s^0 : M = 497.611±0.013 MeV, τ= (8.954±0.004)×10^{-11} s
- ✗ 1 MC sample, 10000 events each





Decays in the VELO limit

- ✗ Particles decaying in the limit of VELO might not leave signal
- ✗ Potential LL vertices, measured as DD
- ✗ Relevent issue in relation to LLPs (see Lambda and kaon case)



	LL	DD	TT
Λ^0	12%	51%	37%
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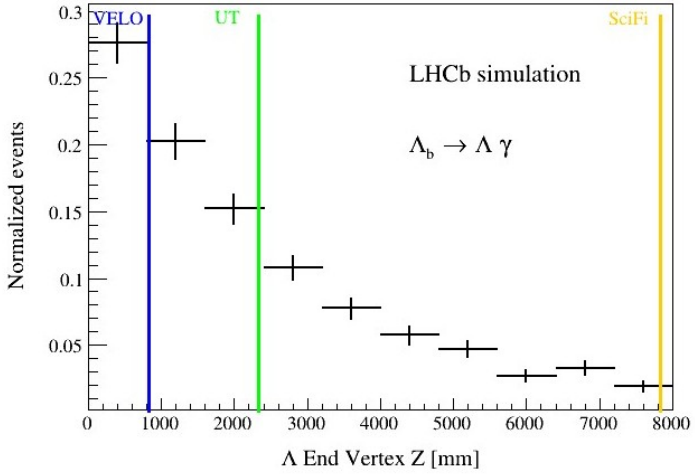

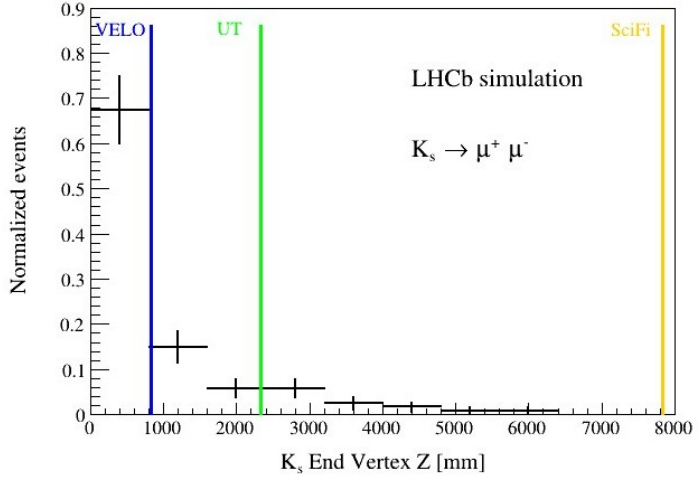

Sensitivity to $B^+ \to K^+ H' [\to K^+K^-]$