Selecting long-lived particles in the first level trigger at LHCb

Lorenzo Pica - on behalf of LHCb RTA project

Twelfth workshop of the LLP community - 4/11/2022

LHCb experiment

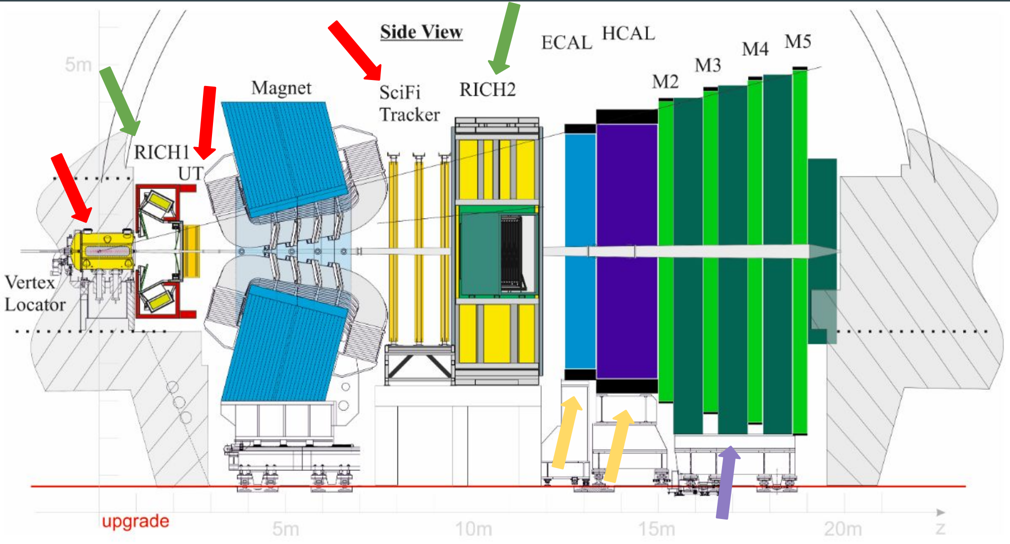
LHCb is a forward single-arm spectrometer:

- tracking system $\longrightarrow$ excellent momentum and displaced vertex identification performance
- Ring Imaging Cherenkov Detectors $\longrightarrow$ Particle IDentification (PID) - π, *K*, *p* separation
- calorimeters $\longrightarrow$ PID + γ and π^0 detection
- Muon chambers $\longrightarrow$ muon identification

$\longrightarrow$ specialized in study of *beauty* and *charm* hadron decays

Covering the $2 < \eta < 5$ region
$\longrightarrow$ complementary to other LHC experiments

Run 3 of LHC just started on July 2022 after LS2 - LHCb underwent a major upgrade:
- complete replacement of DAQ and trigger system
- run at 5x higher luminosity w.r.t. Run 2
  $\longrightarrow$ 50 fb^{-1} target before end of Run 4



Long-lived particle (LLP) physics case at LHCb

LLP decays are involved in several physics channels interesting for LHCb

Standard Model LLP:

- charm-hadrons CPV additional observations
  → $D^0 \to K_S^0 K_S^0$, $D^0 \to K_S^0 \pi^+ \pi^-$
- $K_S^0 \to \mu^+ \mu^-$ BR measurement → highly sensitive to non-SM contributions
- $B^0 \to J/\psi\ K_S^0$ → $sin(2\beta)$ measurement
- $B^0 \to K_S^0 K_S^0$ and $B^0 \to K_S^0 K_S^0 K_S^0$ → CPV measurement

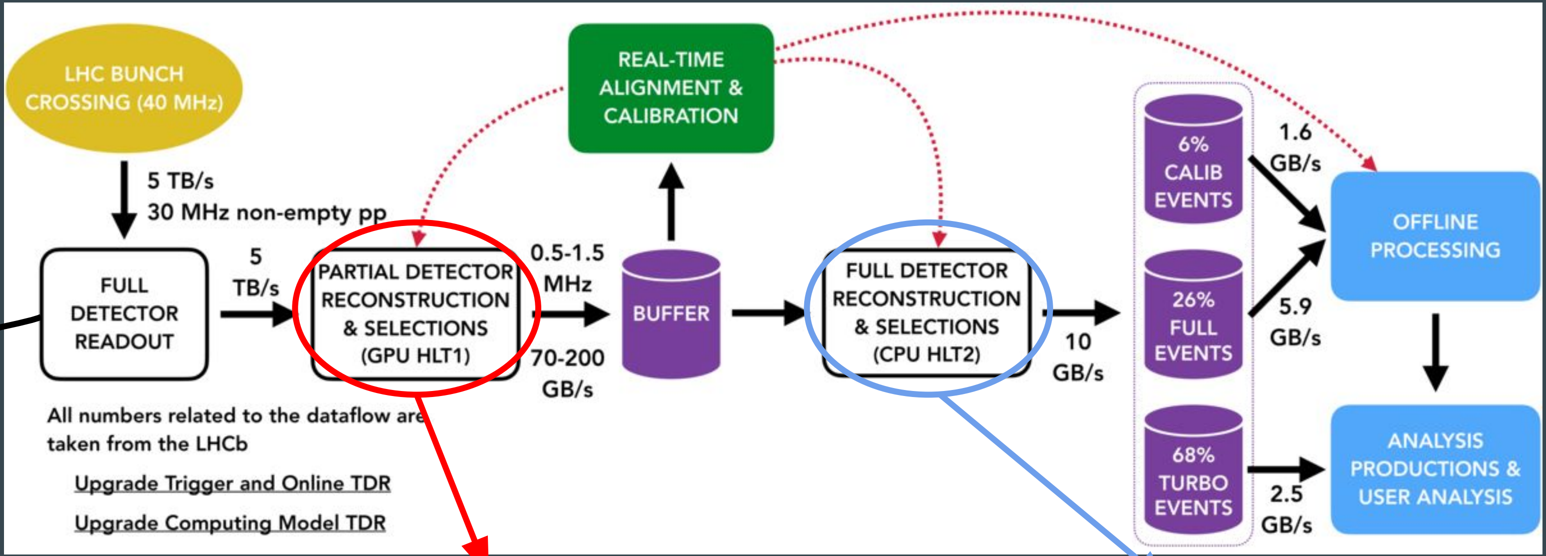
Exotics LLP decays:

- leptons from displaced vertices, Majorana neutrinos, dark photons

→ LHCb offers pseudorapidity coverage complementary to other LHC experiments

Long-Lived Particles studies can profit from this upgraded system:
→ dedicated *online* selections can be a game-changer to enhance efficiency

LHCb Upgraded DAQ and Trigger



Hardware trigger removal
(L0 output Run 1/2 1.1 MHz)
→ now full 30 MHz readout
→ triggerless DAQ

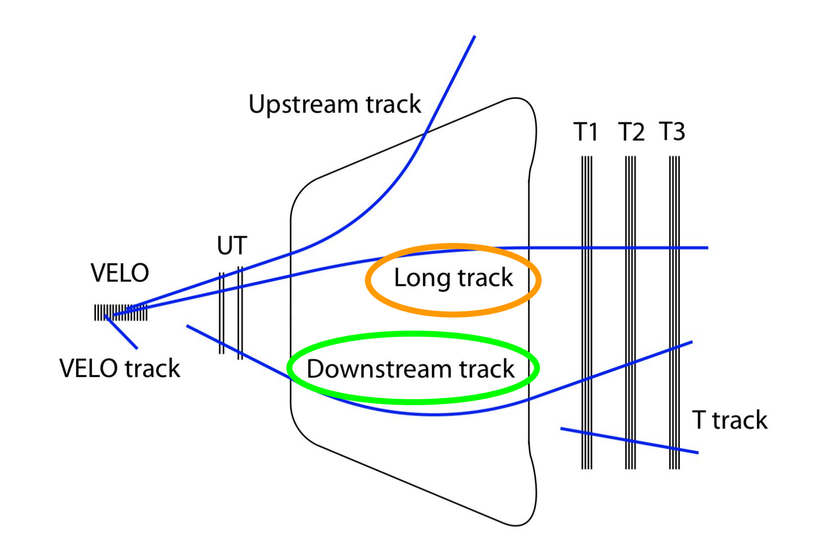
HLT1 first trigger level
(30 MHz → 1 MHz)
→ now on GPU boards
→ partial event reconstruction
→ selections application

HLT2 second trigger level
→ full event reconstruction
→ complex selections application

30 MHz event reconstruction: HLT1

Entire 30 MHz rate of data input to HLT1 - partial event reconstruction:

- reconstruction of Long tracks (VELO+UT+SciFi)
- 2-track vertices identification
  → complex selections run on these candidates
- Downstream tracks (UT+SciFi) not reconstructed at this stage (more later)



Much larger flexibility than Run 2 first trigger level
→ calorimeter or muon energy deposit

LLP decay signatures very different from *beauty* ones:

- exploit HLT1 flexibility to introduce specific trigger selections
- moving LLP identification back in the trigger sequence → improve trigger efficiency for these candidates

Feasibility of this strategy being proven already in Run 3

→ moved identification and selection of K_S^0 from HLT2 to HLT1 level
→ first example of early K_S^0 selection for physics purposes

Selecting single K_S^0 candidates at HLT1 level at LHCb

Several physics channels can benefit from early K_S^0 triggering:

- increase efficiency for physics channels that can only be triggered through K_S^0 $\rightarrow D^0 \rightarrow K_S^0 K_S^0$, $B^0 \rightarrow K_S^0 K_S^0$, $B^0 \rightarrow K_S^0 \pi^0$
- avoid bias due to trigger selections $\rightarrow D^0 \rightarrow K_S^0 \pi\pi$, $B^0 \rightarrow K_S^0 \pi\pi$

Set of selections (*trigger line*) applied to reconstructed 2-track vertices:

$\chi^2/\mathrm{ndf}_{track}(\pi)$	< 2.5
$\chi^2_{\mathrm{IP}}(\pi)$	> 50
$p_{\mathrm{T}}(\pi)$	$> 470\ \mathrm{MeV}/c$
$p(\pi)$	$> 5\ \mathrm{GeV}/c$
$\lvert m(\pi^+\pi^-) - m(K^0_{\mathrm{S}})\rvert$	$< 45\ \mathrm{MeV}/c^2$
$\chi^2_{vtx}(K^0_{\mathrm{S}})$	< 20
$\eta(K^0_{\mathrm{S}})$	$2 < \eta(K^0_{\mathrm{S}}) < 4.2$
$p_{\mathrm{T}}(K^0_{\mathrm{S}})$	$> 2500\ \mathrm{MeV}/c$
$cos(\theta_{DIRA})$	> 0.99
$cos(\theta_{\pi\pi})$	> 0.99
$\frac{IP(\pi^+)\times IP(\pi^-)}{IP(K^0_S)}$	$> 0.72\ \mathrm{mm}$

K_S^0 reconstructed in the $\pi^+\pi^-$ final state

Specific K_S^0 signatures reduce background acceptance:

- very large displacement - long flight distance
- specific invariant mass

Other selections loosened to increase efficiency:

- π from K_S^0 decays often with low $p_T(\pi)$
  $\rightarrow$ p_T threshold just above reconstruction cuts

Only 4% of HLT1 output bandwidth occupied
Proof for of early LLP triggering feasibility!

Single K_S^0 line performance

Novel line shows good efficiency on benchmark channels:

- $D^0 \to K_S^0 K_S^0$ $\to$ HLT1 efficiency x 2.6
- $B^0 \to K_S^0 K_S^0$ $\to$ +20% HLT1 efficiency (reaching 77%)
- $B^0 \to K_S^0 \pi^0$ $\to$ +45% HLT1 efficiency
- $D^0 \to K_S^0 \pi^+ \pi^-$ $\to$ efficiency $O \sim$ general purpose HLT1 lines

Successfully improve efficiency for channels with only K_S^0 in their final state

Provide good statistics sample w/o any selection on π from D^0

Efficiencies computed exploiting Run 3 LHCb simulation

Negligible impact on computation time/throughput $\to$ selections applied on already reconstructed candidates

Minimal background acceptance despite being a "general-purpose" K_S^0 line

$\to$ not dedicated to single channel

$\to$ exploit at maximum LLP particle decay characteristics

This strategy can be pushed even further $\to$ select K_S^0 pairs instead of single candidate

Select K_S^0 pairs at HLT1

Generalize single K_S^0-line approach:

- accept two K_S^0 candidates passing identical selections

$\chi^2/\text{ndf}_{track}(\pi)$	< 2.5
$\chi^2_{\text{IP}}(\pi)$	> 15
$p_{\text{T}}(\pi)$	$> 425\,\text{MeV}/c$
$p(\pi)$	$> 3\,\text{GeV}/c$
$\lvert m(\pi^+\pi^-) - m(K^0_{\text{S}})\rvert$	$< 45\ \text{MeV}/c^2$
$\chi^2_{vtx}(K^0_{\text{S}})$	< 20
$\eta(K^0_{\text{S}})$	$2 < \eta(K^0_{\text{S}}) < 4.2$
$p_{\text{T}}(K^0_{\text{S}})$	$> 1150\ \text{MeV}/c$
$cos(\theta_{DIRA})$	> 0.99
$cos(\theta_{\pi\pi})$	> 0.99
$\frac{IP(\pi^+)\times IP(\pi^-)}{IP(K^0_S)}$	$> 0.23\ \text{mm}$

Selections looser than single-K_S^0 line

- requirement for a K_S^0 pair keeps background acceptance low
- no mother particle selections
- maintain “general-purpose” approach (HLT1 still not single-channel oriented)

→ could be pushed even further with channel-specific selections

<1% of HLT1 output bandwidth occupied!

Line performance tested on $K_S^0K_S^0$ final state channels ($D^0 \to K_S^0K_S^0$, $B^0 \to K_S^0K_S^0$):

- efficiency larger than HLT1 high-rate lines (trigger on single- and two-track displaced candidates)

→ very specific selections on LLP candidates can provide good efficiency with very low background acceptance

What can we do more?

Novel HLT1 lines important first step to prove feasibility of LLP dedicated HLT1 lines

One crucial piece still missing:

- online selection limited to tracks originating inside the VELO acceptance
- lots of LLP decay outside the VELO
  $\longrightarrow$ revealed and selected only with Downstream tracks

Decay Mode	D/L
$\Lambda_c^+ \to \Lambda\pi^+$	2.3
$D^0 \to K_S^0\pi^+\pi^-$	1.5
$B^0 \to J/\psi K_S^0$	1.1
$B_s^0 \to K_S^0 K^-\pi^+$	1.0
$B^+ \to D^0 K^+,\ D^0 \to K_S^0\pi^+\pi^-$	0.8
$\Lambda_b^0 \to J/\psi\Lambda$	1.5

Majority of LLP decay can only be revealed with Downstream tracks!

Downstream tracks not reconstructed at HLT1 level at the moment:

- forward detectors tracking extremely time-expensive
- large number of events containing LLP decays not retained

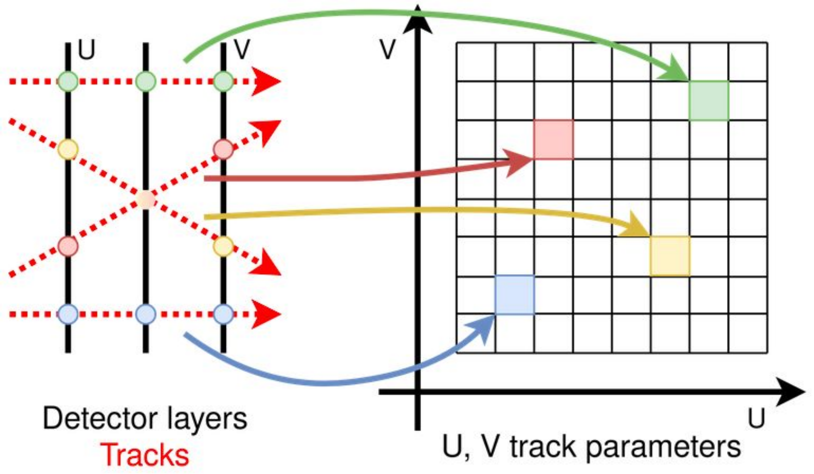
Efforts ongoing to reconstruct Downstream tracks already at HLT1:

- GPU implementation $\longrightarrow$ SciFi tracking + UT extension
  $\longrightarrow$ see Diego's talk for more info!
- SciFi seeding and Downstream track identification anyway extremely time consuming

Implementation of a dedicated device could save significant amount of time during HLT1 processing

Downstream triggering at LHCb

INFN R&D project ongoing for LHCb forward detectors tracking dedicated device in Run 4 - Downstream Tracker:



- exploitation of RETINA architecture
  → pattern recognition algorithm inspired by mammals vision

- highly-parallel behavior - perfectly fits FPGA implementation
  → solve SciFi tracking really fast

Downstream Tracker as a "virtual detector" - tracks reconstruction before event building:

- extremely low latency → feed tracks directly to HLT1!
- Downstream triggering at HLT1 + gain time for more complex tasks
  → move reconstruction at earlier stage

First steps of Downstream Tracker installation already in place:

- cluster-finding algorithm already exploited in VELO reconstruction in Run 3
- subsystem reconstructing ¼ of VELO will run on Run 3 data
  → Proof of concept for Downstream Tracker implementation

Summary

LHCb is going to start taking data with an upgraded system:

- tracking and trigger system completely upgraded
- full 30 MHz readout and online selections - no hardware trigger

Exploit HLT1 flexibility to increase LLP decays online selection efficiency:

- LLP reconstruction at earlier stages

Installation of two novel HLT1 lines proves strategy feasibility:

- single K_S^0 candidate and K_S^0 candidates pair selection
- test on LLP-final state benchmark samples

→ LLP-specific selections show good efficiency and low background acceptance
→ lines already started taking data in Run 3 → we can learn a lot from new data

LLP efficiency still limited by lack of HLT1 Downstream-tracking:

- R&D for FPGA-based Downstream Tracker ongoing
  → online reconstruction of Downstream tracks - feed HLT1 with tracks

BACKUP SLIDES

Hardware level removal

Hardware trigger level efficiency limiting factor in Run 2:

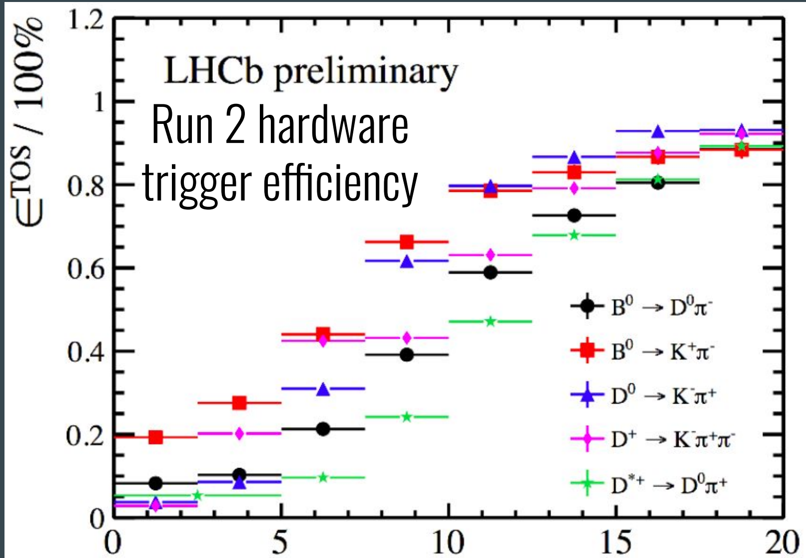
- relies on fastest detectors only
  → trigger on calorimeter and muon detectors
- no complex selections applicable

Focus on few benchmark physics channels
→ mostly trigger on *beauty* decay signatures

HLT1 and HLT2 present in Run 2
→ receiving only events selected by L0

LHCb is now able to readout the full 30 MHz of non-empty LHC *pp* collision rate

Hardware trigger removal can offer large trigger efficiency gain for lots of channels



[2014 *JINST* 9 C09015]

Single K_S^0 line efficiency

Efficiency has been estimated for some benchmark decays exploiting simulated samples and official LHCb code:

Sample	ϵ(TrackMVA $\vee$ TwoTrackMVA)	$\epsilon(K_S^0\text{-line})$	ϵ(TrackMVA $\vee$ TwoTrackMVA $\vee$ K_S^0-line)
$D^0 \to K_S^0 K_S^0$	$(5.5 \pm 1.2)\%$	$(11.0 \pm 1.6)\%$	$(14.4 \pm 1.8)\%$
$B^0 \to K_S^0 K_S^0$	$(63 \pm 6)\%$	$(56 \pm 6)\%$	$(77 \pm 5)\%$
$D^0 \to K_S^0 \pi^+ \pi^-$	$(6.3 \pm 0.7)\%$	$(2.7 \pm 0.5)\%$	$(8.2 \pm 0.7)\%$
$B^0 \to K_S^0 \pi^+ \pi^-$	$(54.2 \pm 1.5)\%$	$(9.0 \pm 0.9)\%$	$(57.0 \pm 1.5)\%$
$B^0 \to K_S^0 \pi^0$	$(17.4 \pm 0.8)\%$	$(16.2 \pm 0.8)\%$	$(25.3 \pm 0.9)\%$

(Computed on simulated samples exploiting official LHCb code)

TwoK_S^0 line efficiencies

Efficiency estimated on $D^0 \to K_S^0 K_S^0$ (left) and $B^0 \to K_S^0 K_S^0$ (right) is:

HLT1 line	Efficiency [%]
TrackMVA	2.9 ± 0.9
TwoTrackMVA	2.6 ± 0.8
K_S^0-Line	11.0 ± 1.6
TwoK_S^0-Line	3.9 ± 1.0

HLT1 line	Efficiency [%]
TrackMVA	57.6 ± 6.1
TwoTrackMVA	22.7 ± 5.2
K_S^0-Line	56.1 ± 6.1
TwoK_S^0-Line	24.2 ± 5.3

Efficiency gain limited by p_T selection
→ can't be looser due to reconstruction cuts