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

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Lorenzo Pica on behalf of the LHCb collaboration
Corfu Summer Institute - Workshop on Future Accelerators
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LHCb RTA

LHCb

SCUOLA NORMALE SUPERIORE

INFN
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Long-lived particles role

11th LLP workshop introduction

Long-lived particles play a big role
in present HEP landscape

Large number of LLP-related collaborations → present and future experiments

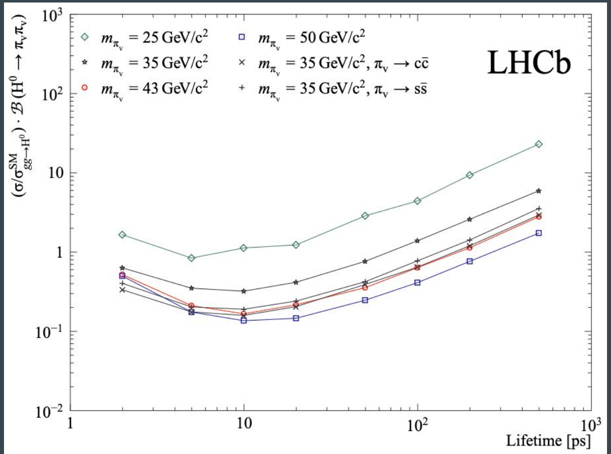
Large experimental conditions variety

- Energy working point
- Luminosity
- Collider/fixed target
- Collided particles

Beyond Standard Model LLP Physics

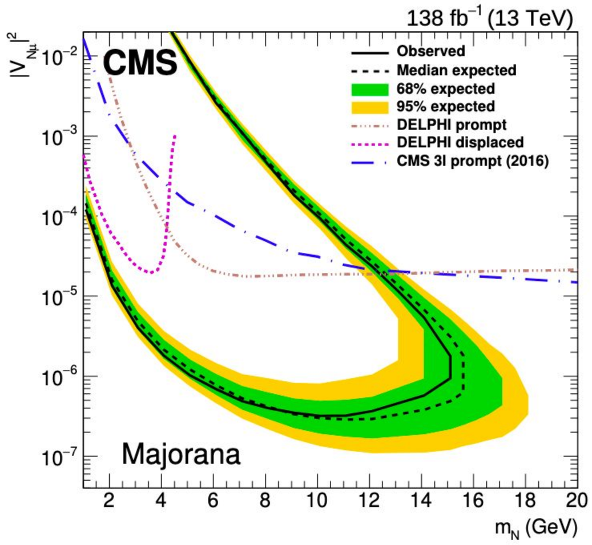
Huge variety of Beyond Standard Model (BSM) Physics cases involving LLP (just some examples)

Higgs portal - hadron/lepton final state



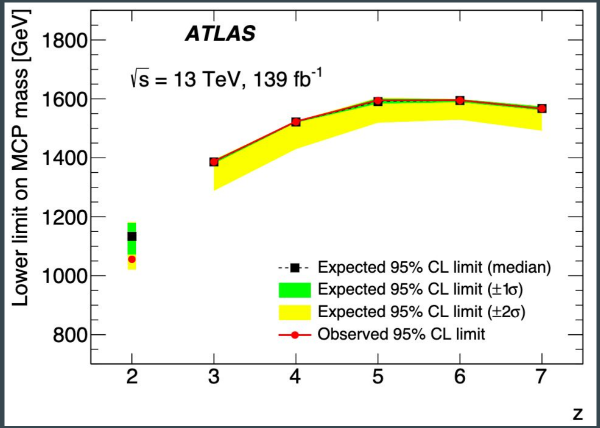
[*Eur.Phys.J.C* 77 (2017) 12, 812]

Heavy Neutral Leptons



[JHEP 07 (2022) 081]

Multi-Charged SUSY



[(arXiv) 2303.13613]

Beyond Standard Model LLP Physics

And many others!

SUSY

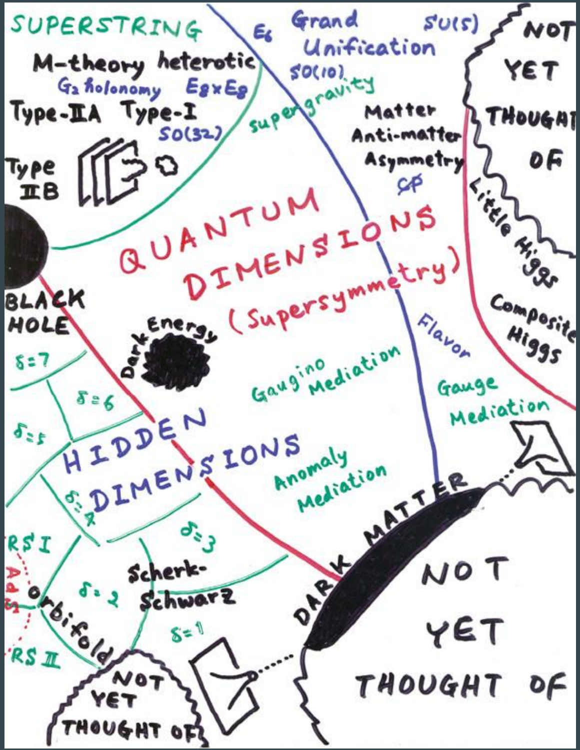
Dark photons

QCD Axions

Dark Higgs

Axion-like particles

Dark Matter models



Standard Model LLP

Do not forget about SM!

$BR\,(K_S^0 \rightarrow \mu^+\mu^-)$

↓

High sensitivity to non-SM contributions

Charm CPV additional observations

↓

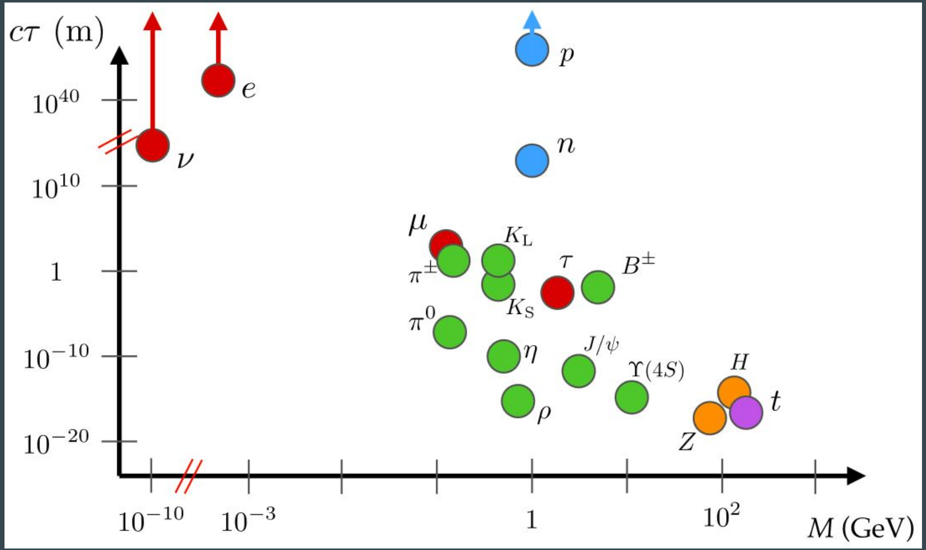
$D^0 \rightarrow K_S^0 K_S^0,\ D^0 \rightarrow K_S^0 \pi^+ \pi^-$

$B^0 \rightarrow J/\psi\ K_S^0$

↓

$sin\,(2\beta)$ measurement

J. Phys. G: Nucl. Part. Phys. 47 (2020) 090501



SM LLP perfect “playground” to start with
→ known and measurable objects

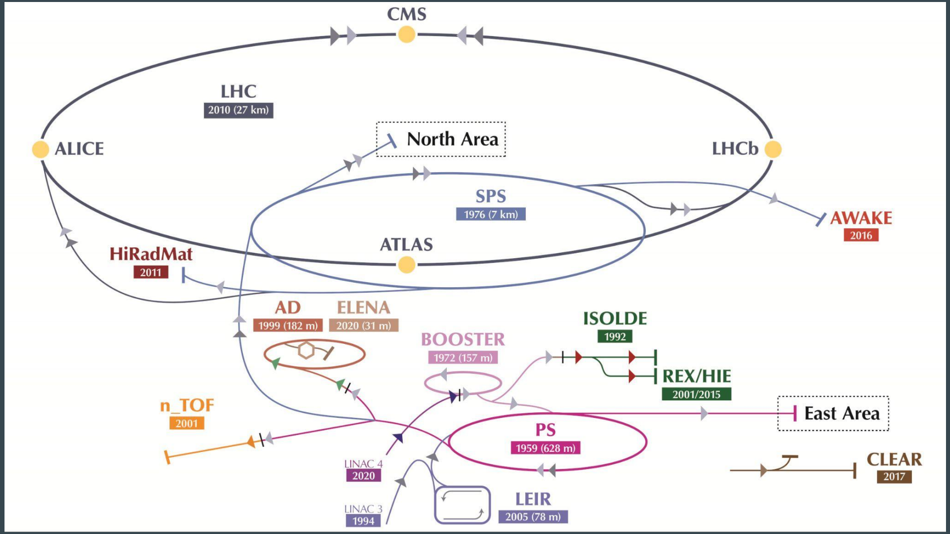
LLP at LHC

LHC unique conditions:

- huge production cross section
- large instantaneous luminosity
- several different experiments
- long timescale perspective

Huge LLP production
→ very large statistics potentiality
→ high-precision measurements

But large production is just one ingredient
→ triggering and selecting LLP tricky task!

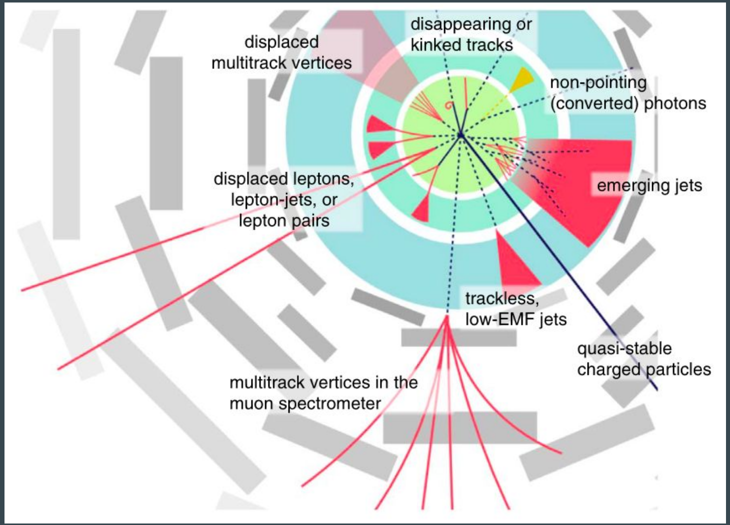


LLP triggering

Prompt objects
→ high-p_T tracks, energy deposit, missing energy

LLP decay signatures:

- large flight distance → escaping most precise detectors
- displaced tracks and vertices → tracking
- low p_T → large background



Tracking + vertexing necessary for these triggers

Complex task → Processing time → Late in the trigger (so far) → Limited efficiency

Need to move it earlier!

LHCb first LHC experiment approaching early tracking/vertexing

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

LHCb tracking system

LHCb PID system

LHCb Muon system

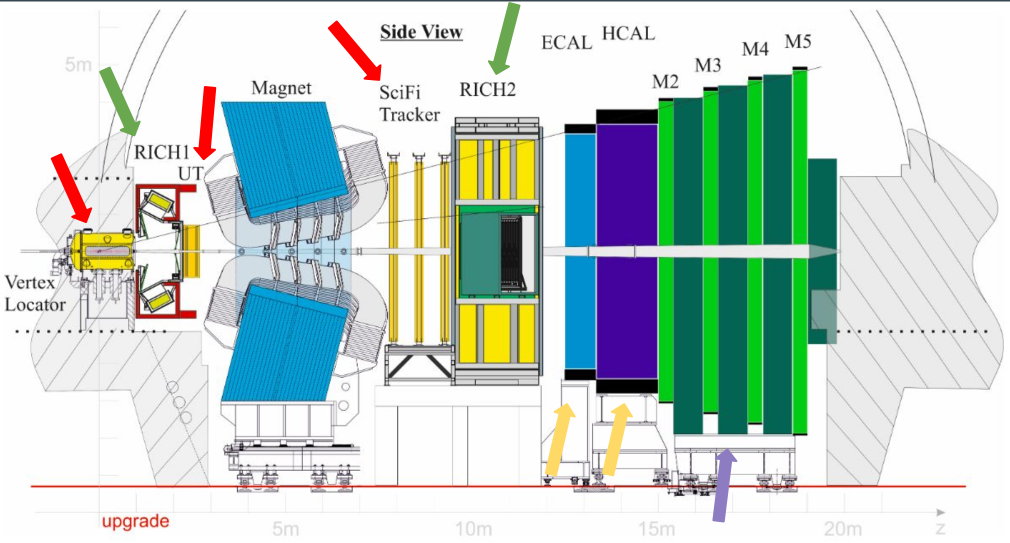
$\longrightarrow$ *beauty* and *charm* hadron focused

$2 < \eta < 5$ acceptance

$\longrightarrow$ complementary to other LHC experiments

LHCb major upgrade during LS2 (FTDR):

- complete replacement of DAQ and trigger system
- 50 fb^{-1} target before end of Run 4

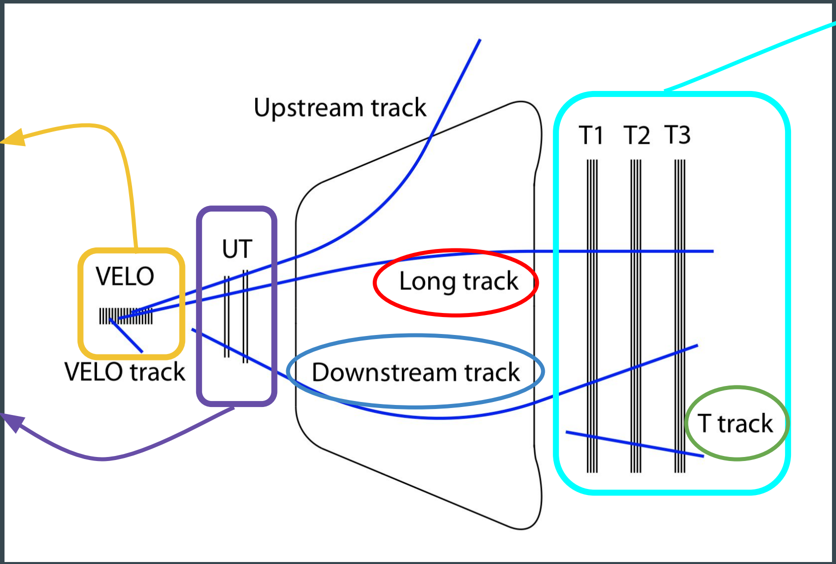


LHCb tracking system

LHCb tracking system

VErtex LOcator (VELO):
- silicon pixel detector
- high IP and p/p_T resolution

Upstream Tracker (UT)
- first momentum estimate
- help ghost reduction



Scintillating Fibre stations (SciFi)
- downstream the magnet
- worse resolution w.r.t. VELO

Long tracks → VELO + UT + SciFi

Downstream tracks → UT + SciFi

T-tracks → SciFi

↑ better IP/p_T resolution

↓ larger LLP acceptance

↓ more computationally expensive

LHCb real-time approach

LHCb in Run 1 & 2:

- 30 MHz → 1.1 MHz - calo + muon hardware trigger (L0)
- reconstruction on triggered events
  → no LLP triggering

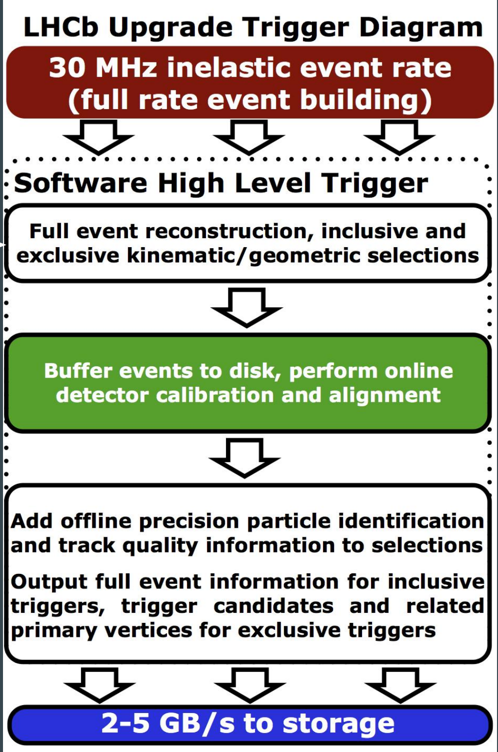
LHCb Run 3 Upgrade:

- L0 removal → 2 x hadron final state efficiency
- 30 MHz readout + tracking + (partial) vertexing (GPU-based HLT1)
  → HLT1 reconstructs Long tracks only
  (Downstream too computationally expensive)

Full 30 MHz LLP trigger and selection possible for the first time!

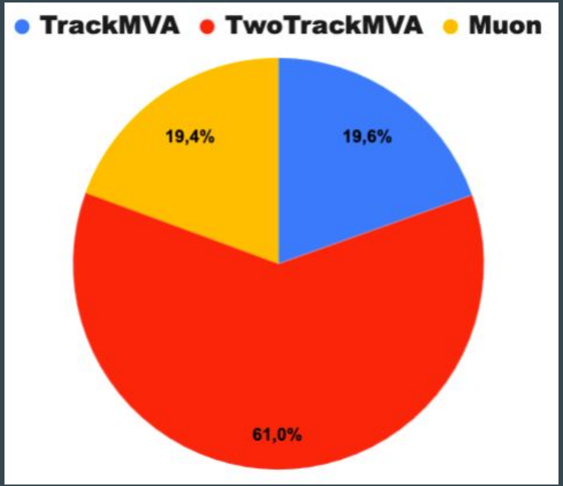
Possible, but... how? Rate sustainable?

LHCb upgraded trigger



Run 3 early V^0 triggering

Comput Softw Big Sci 4, 7 (2020)



Early LLP triggering at LHCb in Run 3 very challenging:

- 30 MHz $\longrightarrow$ 1 MHz reduction
  (> 80% output prompt decays)

High signal acceptance + large background rejection

Possible with high-flexibility GPU-based LHCb HLT1:

- 30 MHz tracking and vertexing
- trigger on complex selections

Two novel LLP-focused HLT1 selections (trigger *lines*) $\longrightarrow$

TwoTrackKs – single K_S^0 candidate

TwoKs – K_S^0 candidates pair

First ever at LHCb $\longrightarrow$ crucial step in developing LLP early triggering

TwoTrackKs line simulation studies

Selections optimized through numerical optimization (TMVA)

$\chi^2/\mathrm{ndf}_{track}(\pi)$	< 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 mm

Variables definitions in backup

Exploit specific K_S^0 signatures:

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

Loose selections to increase efficiency:

- p_T threshold just above reconstruction cuts

Efficiency at HLT1 estimate on simulation:

$D^0 \to K_S^0 K_S^0$ $\to$ x 2.6

$B^0 \to K_S^0 K_S^0$ $\to$ +20% (reaching 77%)

$B^0 \to K_S^0 \pi^0$ $\to$ +45%

$D^0 \to K_S^0 \pi^+ \pi^-$ $\to$ efficiency close to general-purpose HLT1 lines

+40 kHz at HLT1 $\to$ rate cost 4% of HLT1 output bandwidth

TwoKs HLT1 line simulation studies

Select two K_S^0 candidates passing identical selections $\rightarrow$ TwoTrackKs line extension

Same TMVA numerical optimization

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

Selections looser w.r.t. TwoTrackKs line

$\rightarrow$ K_S^0 pair requirement keeps background acceptance low

$D^0 \rightarrow K_S^0 K_S^0$, $B^0 \rightarrow K_S^0 K_S^0$ efficiency estimate:

- ε(TwoKs) > ε(TrackMVA), ε(TwoTrackMVA) (general-purpose, track-based lines)
- ε(TwoKs) < ε(TwoTrackKs) (limited by p_T reconstruction cuts)

Rate cost < 1% HLT1 bandwidth!

Impact on HLT1 throughput

Which is the cost of vertexing?

Displaced vertices reconstruction:

- ran independently from TwoTrackKs, TwoKs
  → general-purpose TwoTrackMVA selection
- negligible impact on HLT1 throughput – ~% GPU timing
  → keep 30 MHz processing frequence
  → loose track filters reduce combinatorics

TwoKs selection not based on additional vertexing

→ negligible timing impact

From simulation to real data

Novel HLT1 lines on simulation:

- good efficiency
- limited rate cost
- low throughput impact

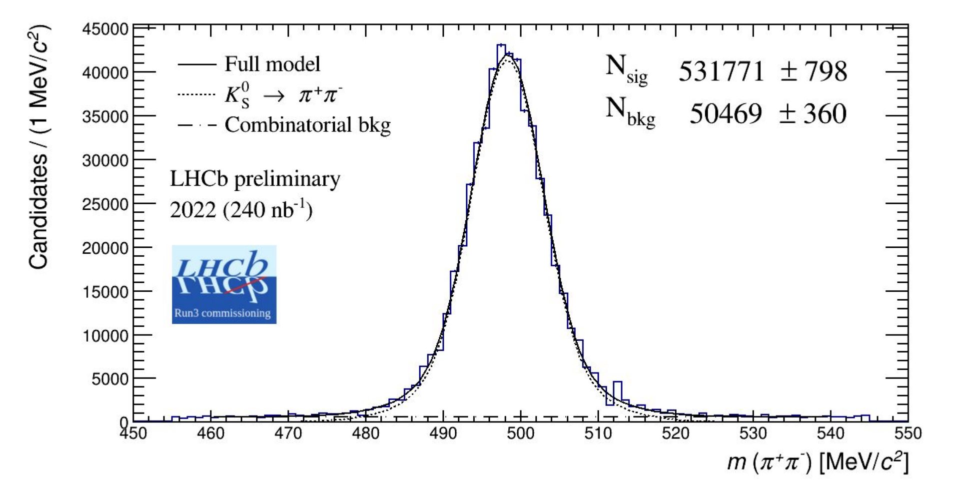
Run 3 2022 data (and novel detector + trigger system) crucial first test:

- *strange* production simulation difficult in *pp* collisions
- commissioning detector in progress

  → data anyway crucial for novel HLT1 lines commissioning

Analysis of small 2022 data sub-sample → 240 nb^{-1}

First TwoTrackKs candidates in Run 3 data



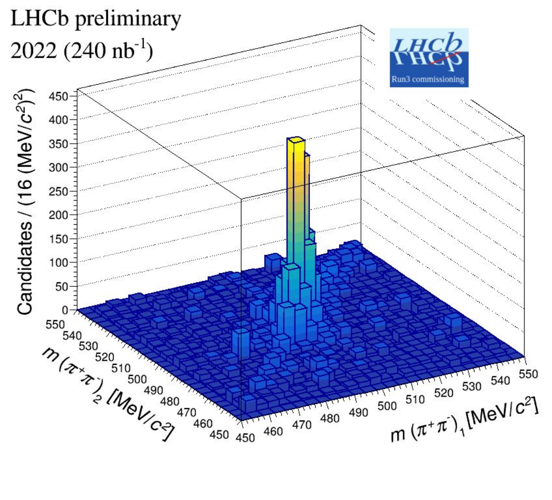
μ	Rate [kHz]
1.1	1.24 ± 0.08
3.1	4.2 ± 0.5
5.32 (Simulation)	74 ± 7

- K_S^0 peak clearly visible
- Good gaussian shape + modest background $\longrightarrow$ good purity

- very reasonable rate!
- increasing with $\mu \longrightarrow$ still below predictions
- efficiency still not checked $\longrightarrow$ rate could slightly vary

K_S^0 decays successfully triggered in *pp* collisions with affordable rate

Triggered K_S^0 pairs, in data



μ	Rate [kHz]
1.1	0.05 ± 0.02
3.1	2.5 ± 0.4
5.32 (Simulation)	13 ± 3

- Clear presence of two real K_S^0 candidates
- ~ 2.5 k events with two real K_S^0 in the peak
- Trigger line S/B ~ 25 %

- rate again reasonable
- faster increase
  → expected - 4-track trigger

Physical sample of real K_S^0 pairs in few preliminary data → more complex selections feasibility

The next step

Positive results for TwoTrackKs and TwoKs on real data:

- affordable rate
- good purity

→ Long tracks only up to this point!

Significant fraction of LLP decays not retained → decaying outside VELO

What if we trigger also K_S^0 decaying outside VELO acceptance?

Sample	Efficiency gain factor
$D^0 \to K_S^0 K_S^0$	3.7
$D^0 \to K_S^0 \pi^+ \pi^-$	4.1
$B^0 \to K_S^0 K_S^0$	6.7
$B^0 \to K_S^0 \pi^+ \pi^-$	2.5

Significant efficiency gain with only one low-rate HLT1 line extended to Downstream triggering!

→ ongoing LHCb efforts toward HLT1 Downstream triggering (10.3389/fdata.2022.1008737)

Downstream K_S^0 triggering rate cost

What is the rate cost of including Downstream tracking at HLT1 level?

Run 2 (2018) minimum bias sample exploitation
$\longrightarrow$ real *pp* collisions for more reliability

Line	Rate [kHz]
1-track $\vee$ 2-track	1518 ± 92
1-track $\vee$ 2-track $\vee$ K_S^0 line (long tracks only)	1518 ± 92
1-track $\vee$ 2-track $\vee$ K_S^0 line (long and downstream tracks)	1767 ± 99

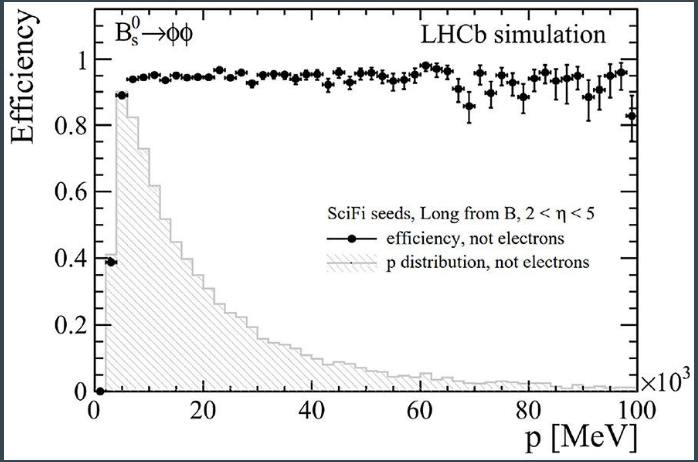
HLT1 total rate estimate for scale
$\longrightarrow$ same order of magnitude of LHCb official simulations

HLT1 total rate adding Downstream tracking on K_S^0 line
$\longrightarrow$ +15% increase!

Limited rate increase when adding Downstream LLP triggering

Downstream tracking efforts

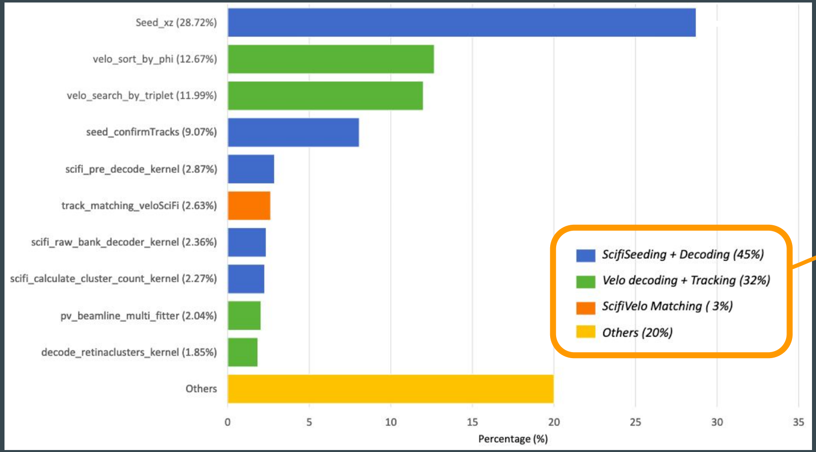
10.3389/fdata.2022.1008737



Efforts ongoing to reconstruct Downstream tracks already in HLT1:

- GPU implementation
  → SciFi standalone tracking
  → UT extension

HLT1 algorithm breakdown



SciFi seeding and Downstream track identification anyway extremely computationally expensive

SciFi tracking 45% of overall HLT1 budget!

Tracking-dedicated device could save significant amount of HLT1 processing time

Downstream triggering with FPGAs

LHCb advanced R&D, so-called Downstream Tracker (DWT):

- Run 4 and beyond
- 30 MHz forward tracking (SciFi / UT + SciFi)

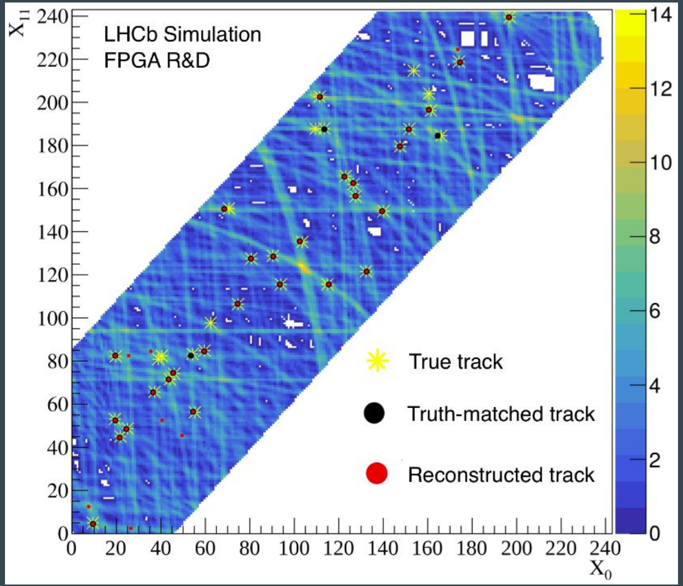
FPGA-based device (so-called RETINA algorithm):

- solve heavy pattern recognition right after readout
- "virtual detector" - tracks appear as raw data

DWT benefits:

- Downstream tracking + triggering at HLT1
  → achieve seen efficiency gain
- save time for more complex tasks
  → move reconstruction at earlier stage
  → early V^0 triggering first step toward this
  → step towards even higher luminosities and harder tasks

1525 (2020) 012101 (ACAT 2019)



Reconstructed tracks appear as clusters in transformed u-v space

Conclusions

30 MHz V^0 triggering in *pp* collisions achieved at LHCb for the first time:

- large predicted efficiency gain
- crucial test on real Run 3 data

  → demonstrated affordable rate + good purity of collected candidates

Established early LLP reconstruction:

- important proof of concept

  → extension to other LLP - improve SM and BSM studies

Going beyond LLP:

- early tracking + vertexing allow channel-dedicated triggering

  → unavoidable step in larger luminosities scenarios

Path towards ever better reconstruction at earlier stages of DAQ

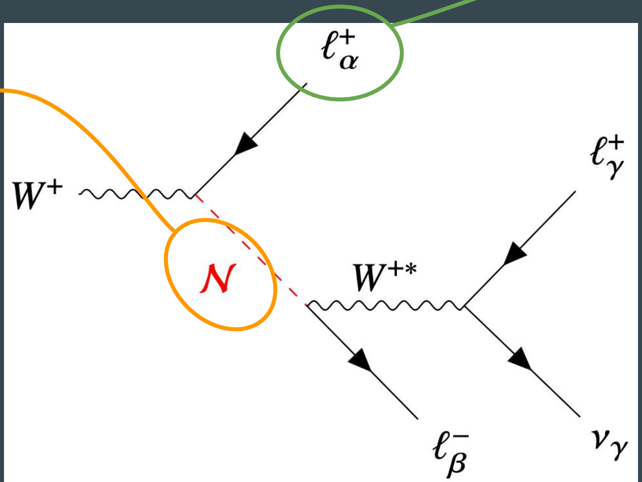
→ exploit FPGAs to embed track reconstruction in detector readout

BACKUP SLIDES

Heavy Neutral Leptons

Huge variety of Beyond Standard Model (BSM) Physics cases involving LLP (just some examples)

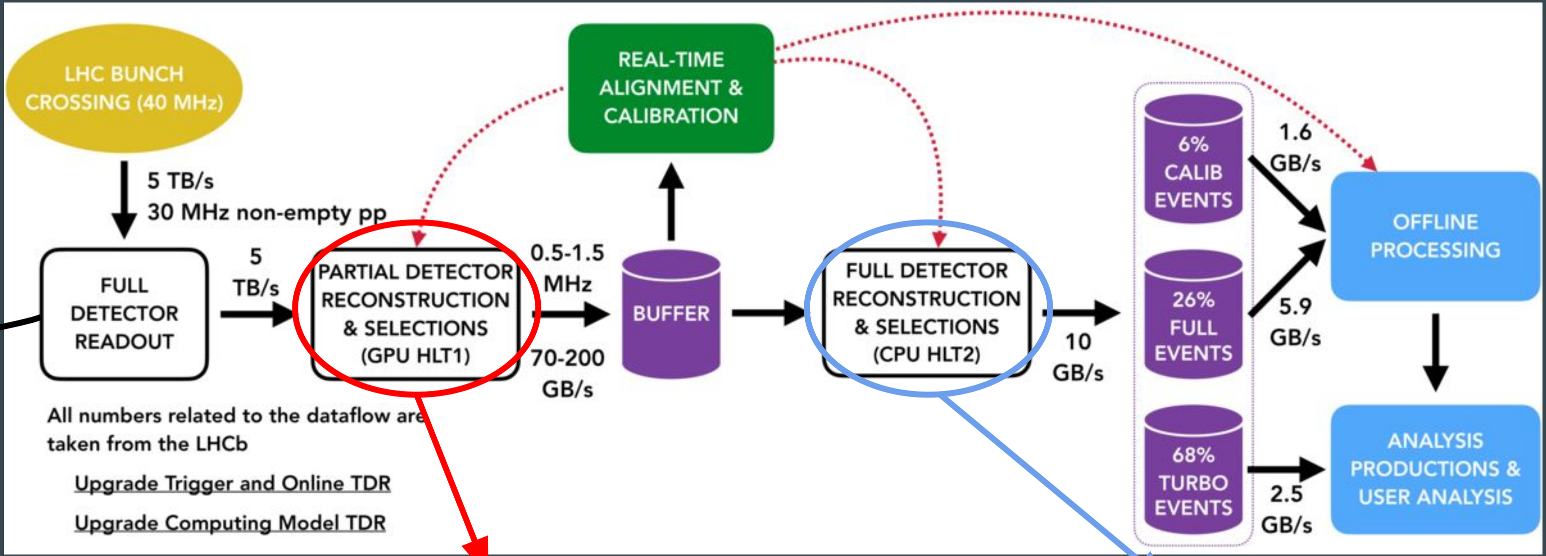
Heavy Neutral Leptons



Heavy BSM LLP
→ W boson coupling

Triggering on lepton from W

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

Variables definitions

- IP : Impact Parameter
- χ^2_{IP} : Impact parameter significance
- $\theta_{\pi\pi}$: angle between the two K_S^0 daughters
- θ_{DIRA} : angle between $p\,(K_S^0)$ and the direction given by K_S^0 origin and decay vertices

Rate cost estimate of Downstream K_S^0 triggering

Rate increase has been estimated with an offline emulator:

- exploitation of Run 2 minimum bias sample
  → real *pp* collisions data more reliable than simulation
- all possible 2-track Long and Downstream combinations reconstructed offline
- compute event acceptance rate α
  → Long only for TrackMVA and TwoTrackMVA - Long + Downstream for K_S^0 line
- compute HLT1 rate scaling acceptance with Run 3 pile-up (PU)

$$\text{rate} = 30\text{ MHz} \times \alpha \times \text{PU(Run 3-4)/PU(Run 2)}$$

Estimate obtained from this procedure shows a +15% increase in HLT1 rate