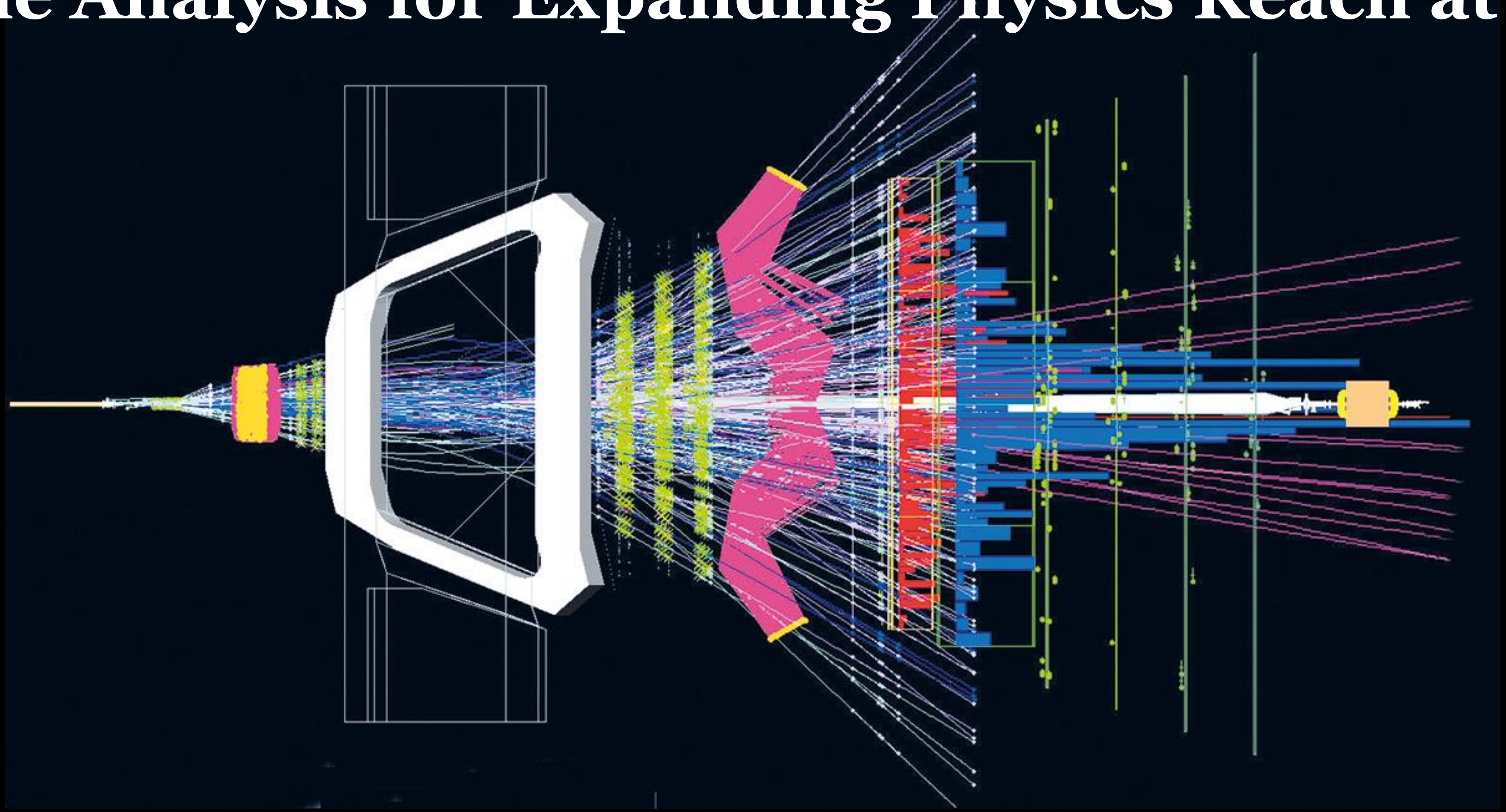
RAL - PPD Seminar

08-05-2024

Triggering new discoveries: Advancements in Real-Time Analysis for Expanding Physics Reach at LHCb



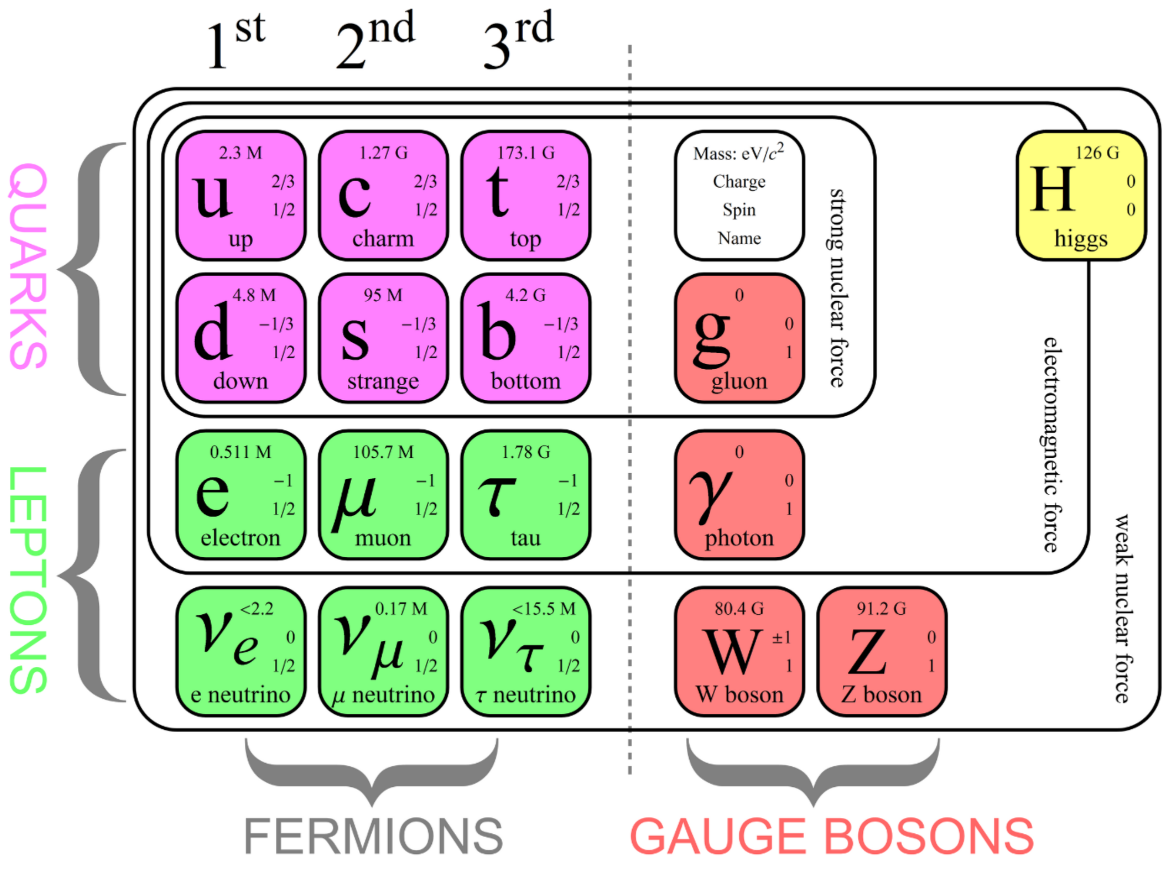
Brij Kishor Jashal

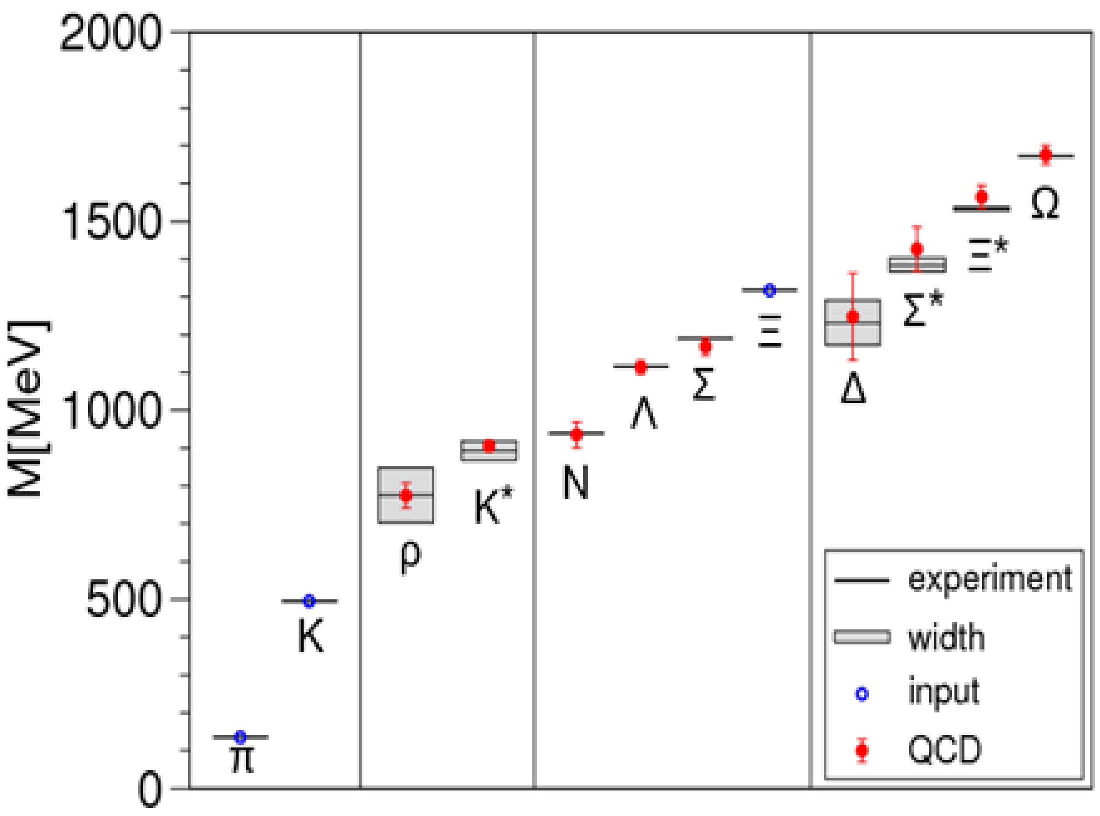
Outline

CERN-THESIS-2023-249
arXiv:2312.14016

- Introduction
  - Physics motivation
  - The LHCb Experiment
- Real time analysis
  - Advanced High Level Trigger 1 algorithms
  - Physics impact for long lived particles
- Summary

Fundamental particles



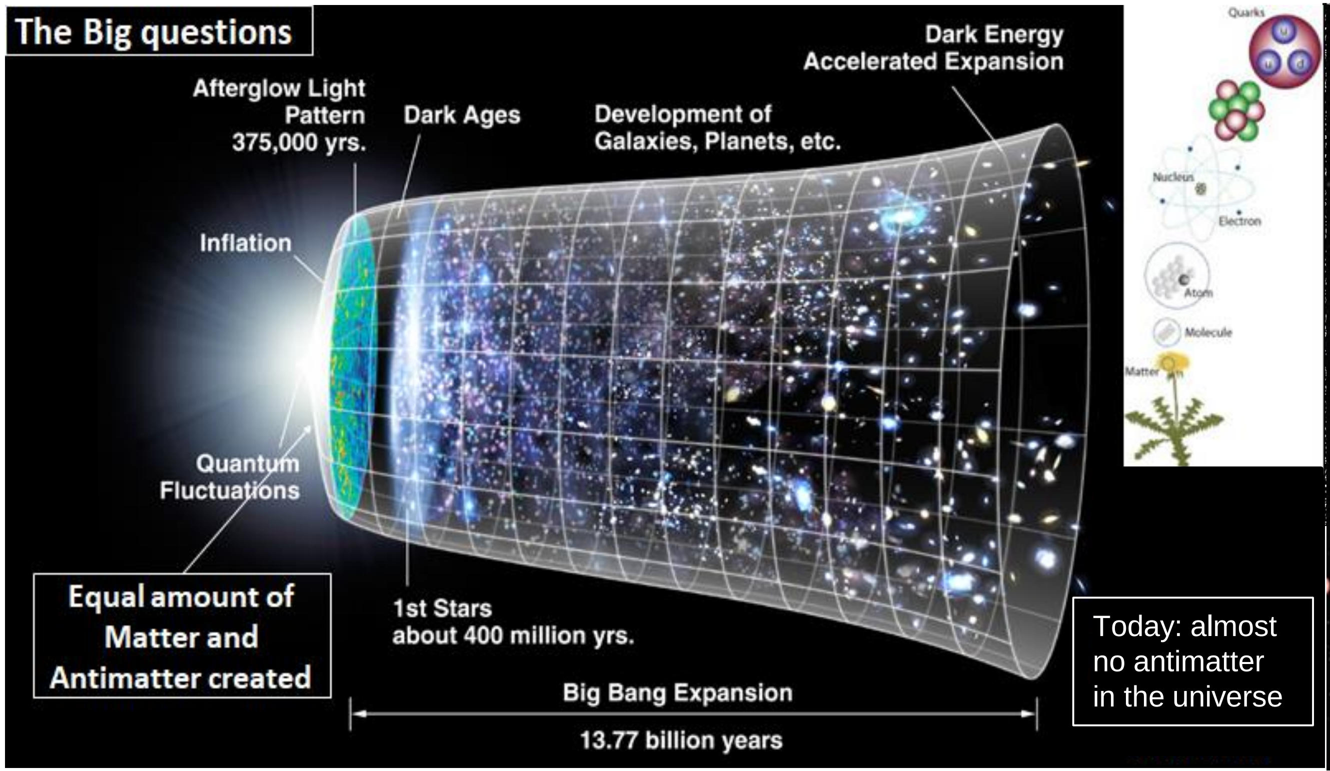


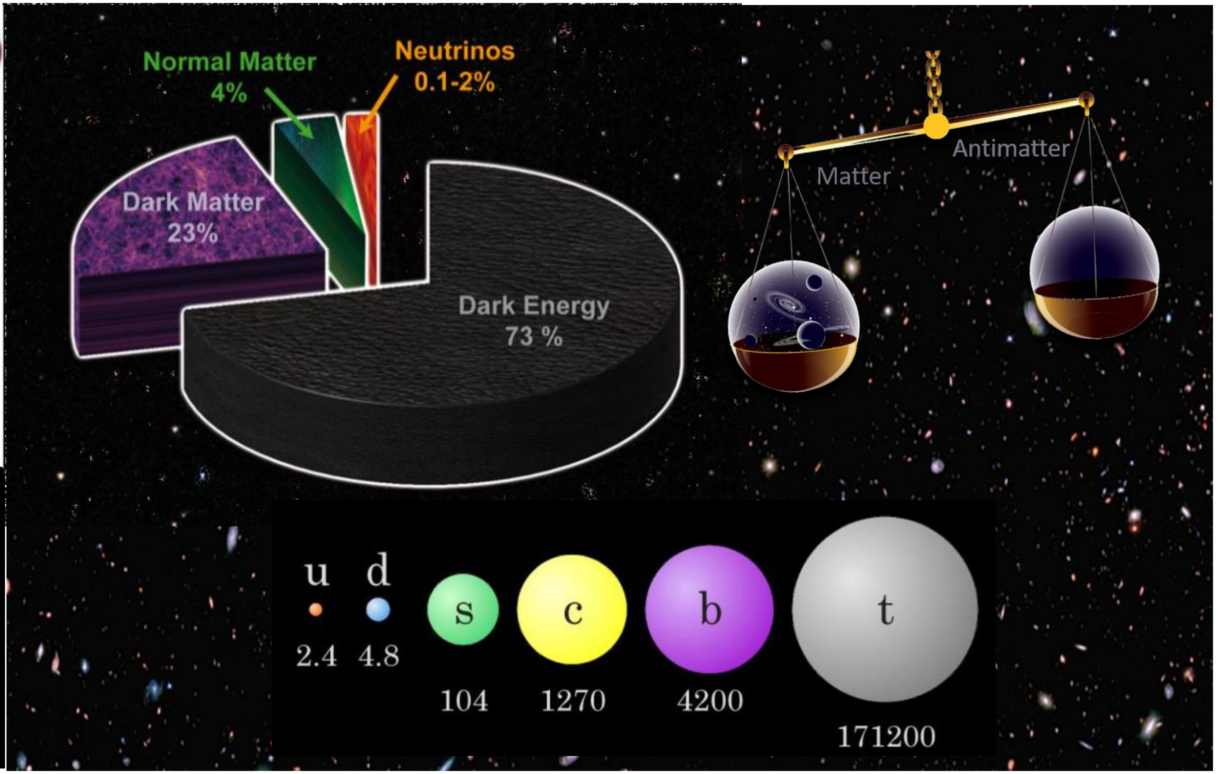
Hadron spectrum

Provides framework for understanding the behaviour of the fundamental particles and their interactions through strong, weak and EM forces

Amazing predictive capabilities

The Big question



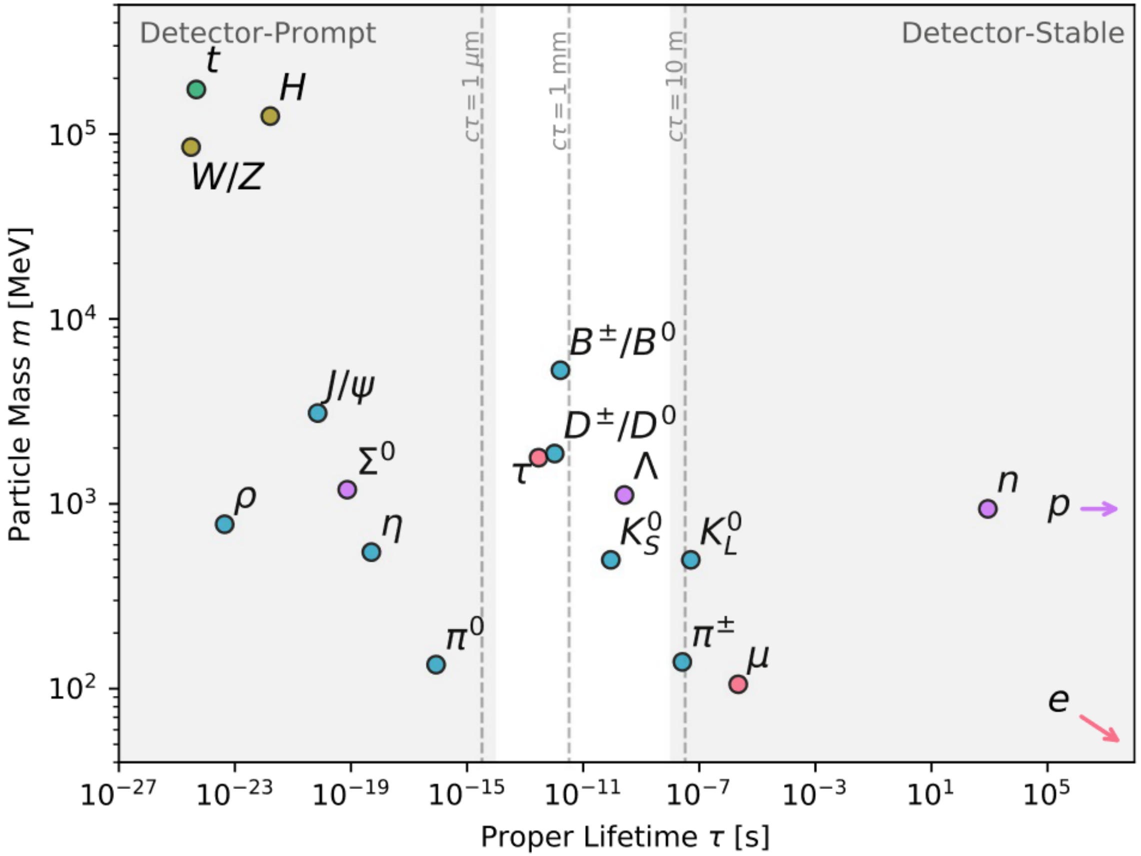


Study of behaviour of fundamental particles in the early universe could help in answering many questions

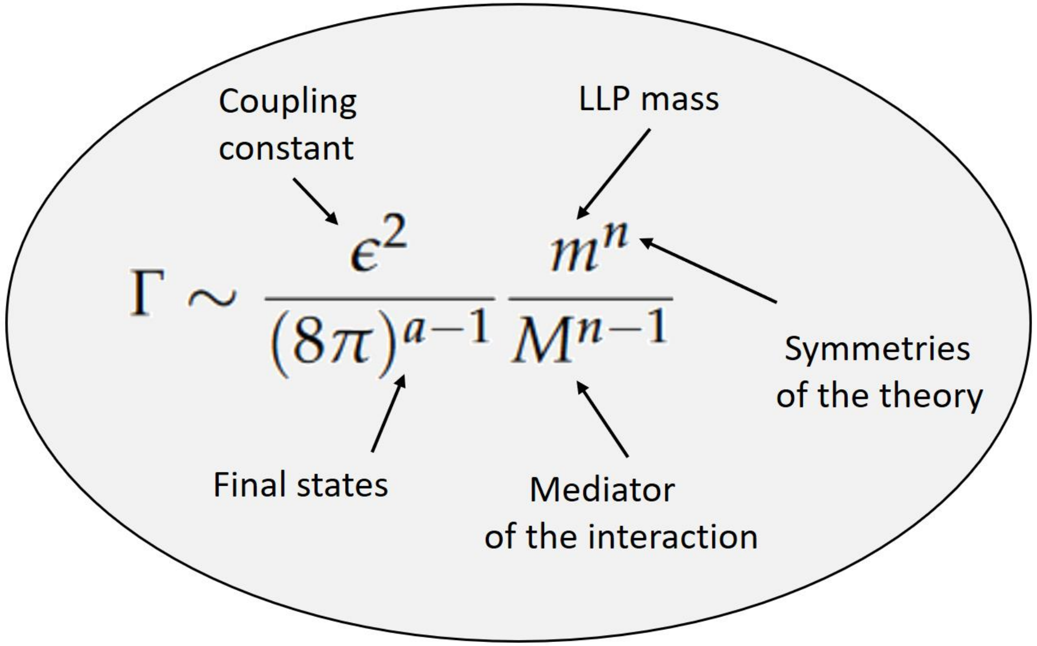
Long-lived particles (LLPs):

Long living particle are a excellent probes for new physics searches in SM and beyond.

- Particle lifetimes in the SM range from τ ~ 2 x 10^{-25} s (the Z boson) through to τ ~ > 10^{34} years (stable) (proton, electron).



$$\tau = 1/\,\Gamma$$

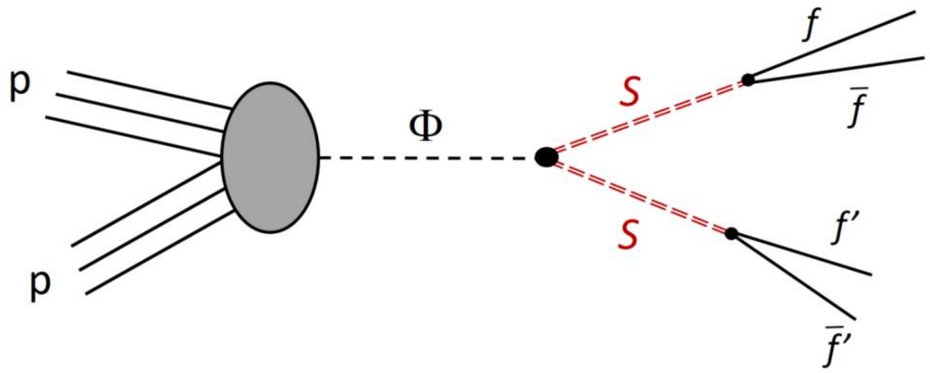


$$\Gamma \sim \frac{\epsilon^2}{(8\pi)^{a-1}} \frac{m^n}{M^{n-1}}$$

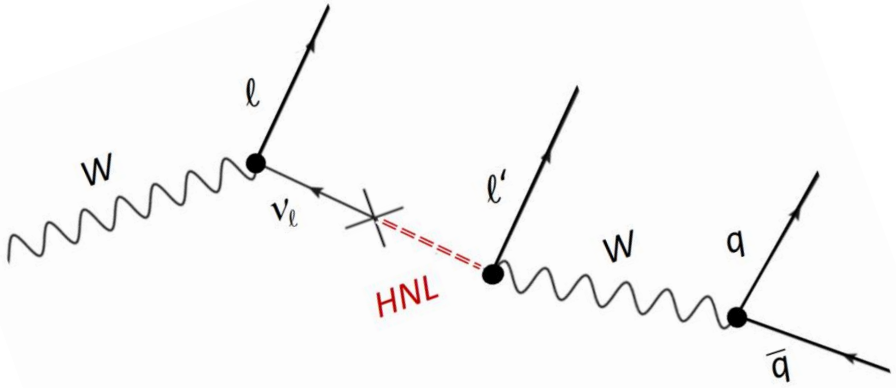
LLPs beyond the SM:

Some BSM scenarios which can include LLPs:

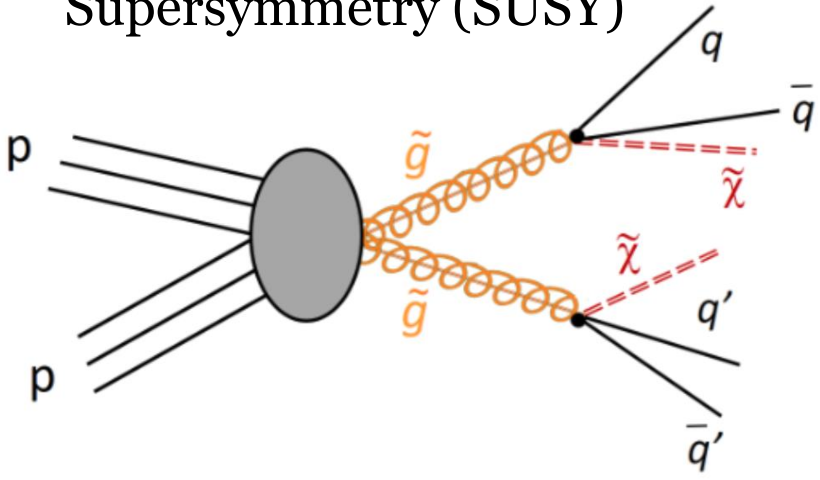
Hidden Sector particles



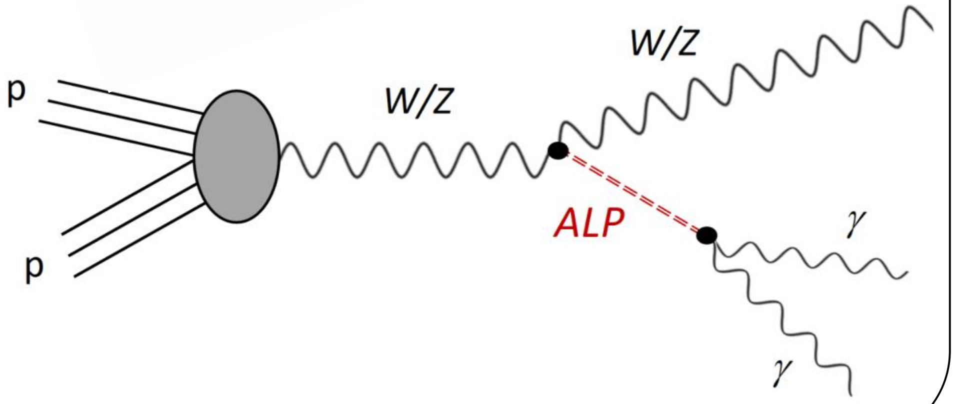
Heavy Neutral Leptons (HNLs)



Supersymmetry (SUSY)



Axion-Like Particles (ALPs):



Long-lived particles (LLPs)

10.48550/arXiv.2110.14675

arXiv:2110.14675v1 [hep-ex] 27 Oct 2021

Review of opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider

Produced for the LPCC Long-Lived Particles Working Group.

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Report on Progress

Unleashing the full power of LHCb to probe stealth new physics

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CrossMark

Abstract
In this paper, we describe the potential of the LHCb experiment to detect stealth physics. This refers to dynamics beyond the standard model that would elude searches that focus on energetic objects or precision measurements of known processes. Stealth signatures include long-lived particles and light resonances that are produced very rarely or together with overwhelming backgrounds. We will discuss why LHCb is equipped to discover this kind of physics at the Large Hadron Collider and provide examples of well-motivated theoretical models that can be probed with great detail at the experiment.

Keywords: LHCb, stealth physics, BSM physics, hidden sectors, long-lived particles, dark matter

(Some figures may appear in colour only in the online journal)

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Effect of the high-level trigger for detecting long-lived particles at LHCb

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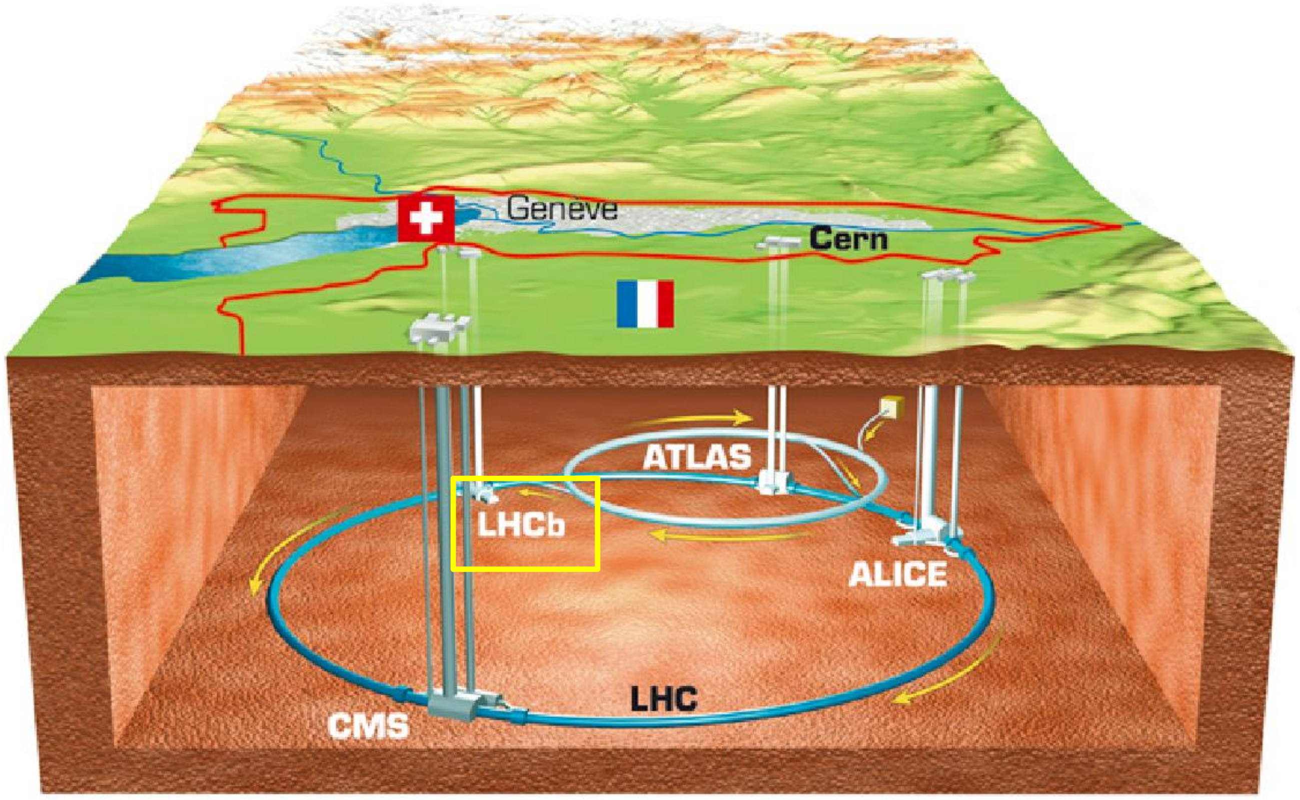
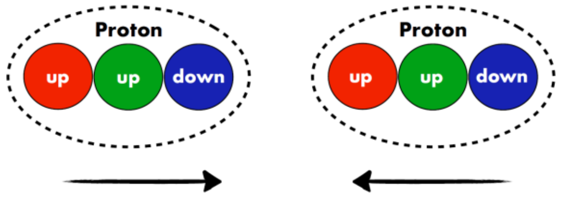
Long-lived particles (LLPs) show up in many extensions of the Standard Model, but they are challenging to search for with current detectors, due to their very displaced vertices. This study evaluated the ability of the trigger algorithms used in the Large Hadron Collider beauty (LHCb) experiment to detect long-lived particles and attempted to adapt them to enhance the sensitivity of this experiment to undiscovered long-lived particles. A model with a Higgs portal to a dark sector is tested, and the sensitivity reach is discussed. In the LHCb tracking system, the farthest tracking station from the collision point is the scintillating fiber tracker, the SciFi detector. One of the challenges in the track reconstruction is to deal with the large amount of and combinatorics of hits in the LHCb detector. A dedicated algorithm has been developed to cope with the large data output. When fully implemented, this algorithm would greatly increase the available statistics for any long-lived particle search in the forward region and would additionally improve the sensitivity of analyses dealing with Standard Model particles of large lifetime, such as K^0_S or Λ^0 hadrons.

Development of reconstruction strategies and algorithms at high level trigger to detect long-lived particles

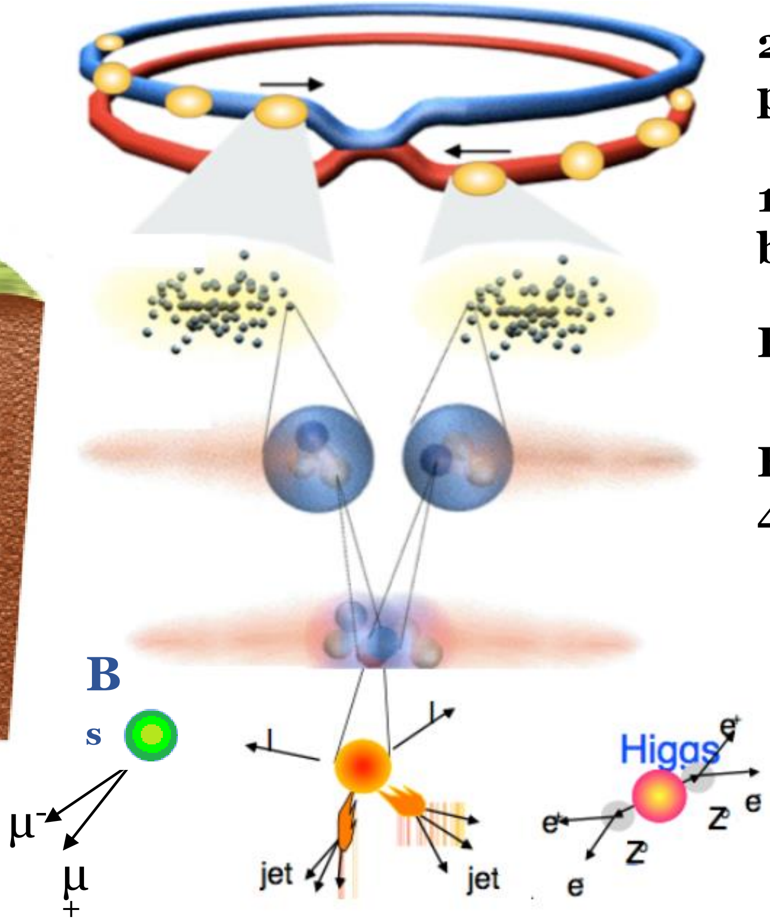
Introduction: the LHCb experiment

The Large Hadron Collider at CERN





Proton-proton collision



2028 bunches of protons per beam

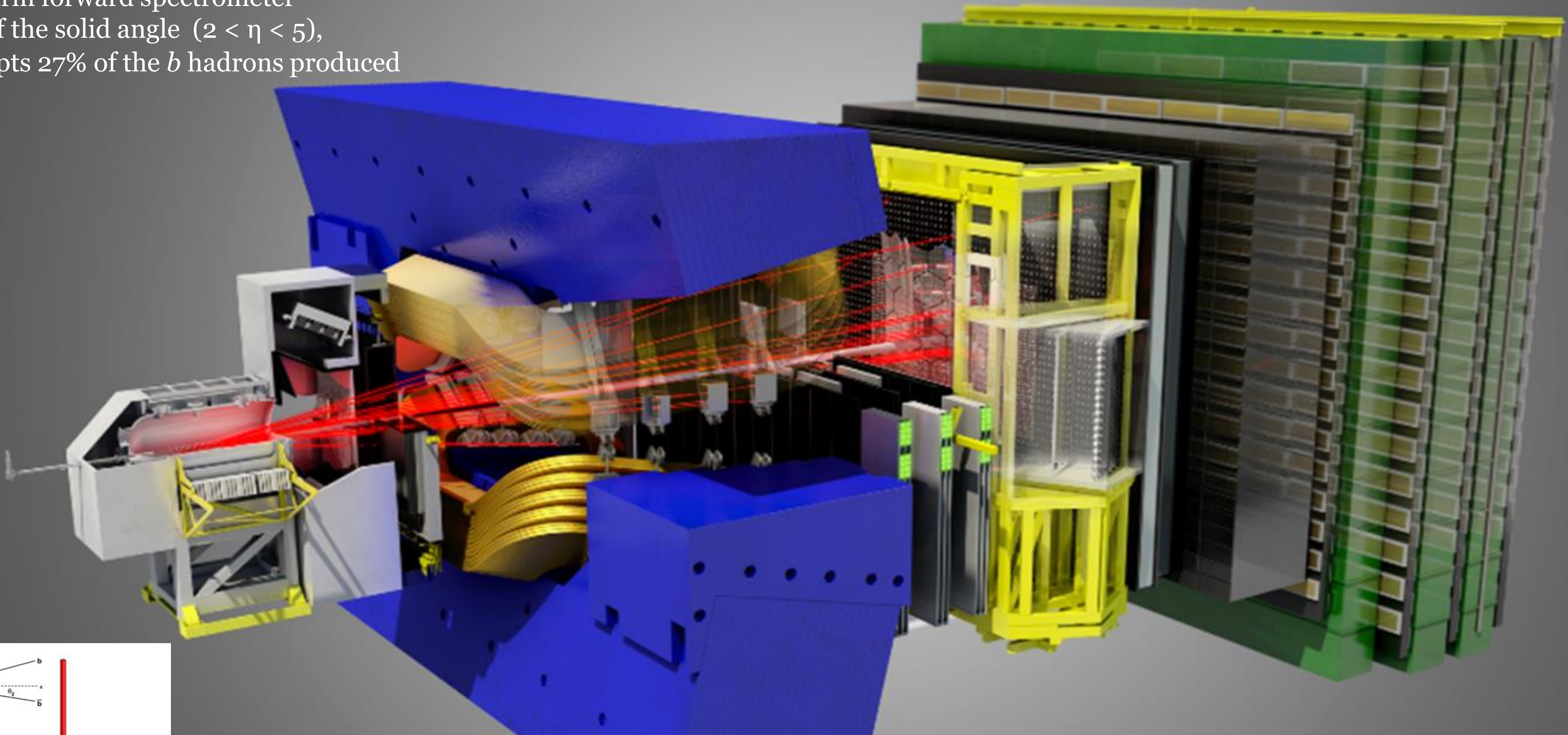
10^{11} protons per bunch

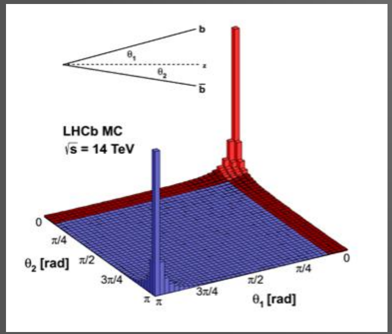
Beam energy of ~7 TeV

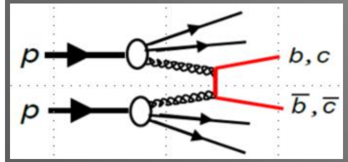
Bunch crossing rate 40 MHz,

The LHCb experiment

$b\bar{b}$ production cross-section ~ 600 μb at 13 TeV (300 μb at 7Tev)
Single arm forward spectrometer
~ 4% of the solid angle (2 < η < 5),
~ accepts 27% of the b hadrons produced



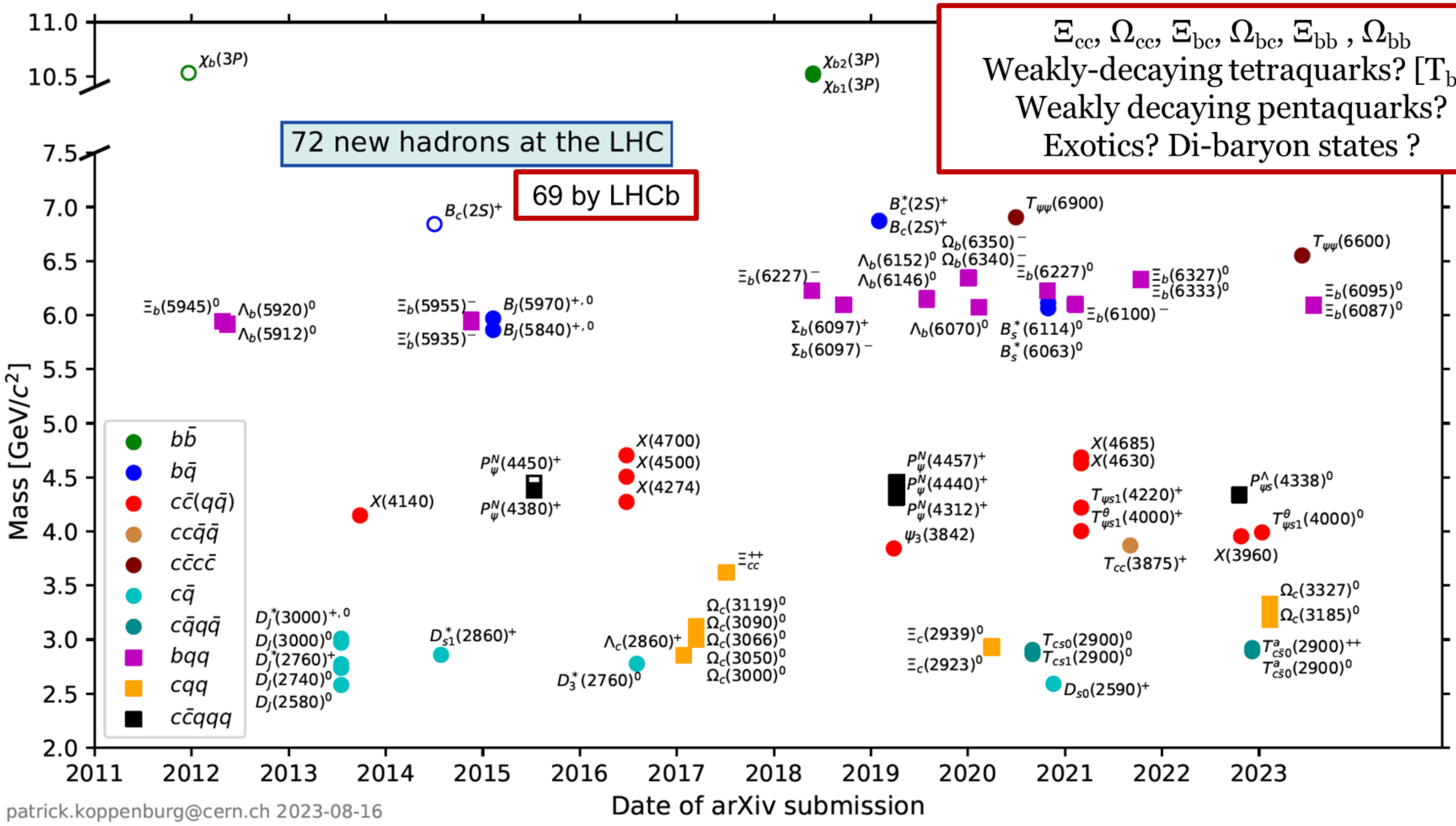




History of LHCb: 10.1140/epjh/s13129-021-00002-z

Run I and II

$\mathcal{L}_{inst} = 4 \times 10^{32} cm^{-2} s^{-1}$

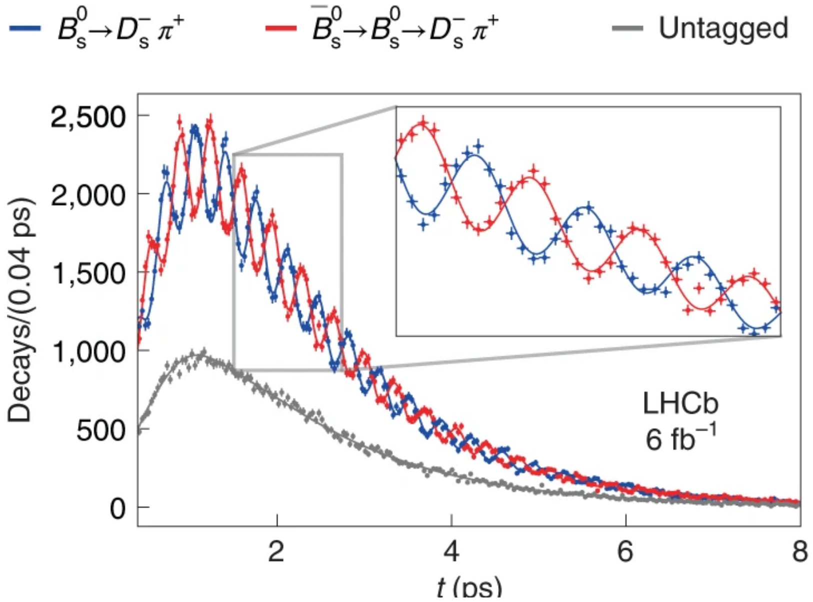


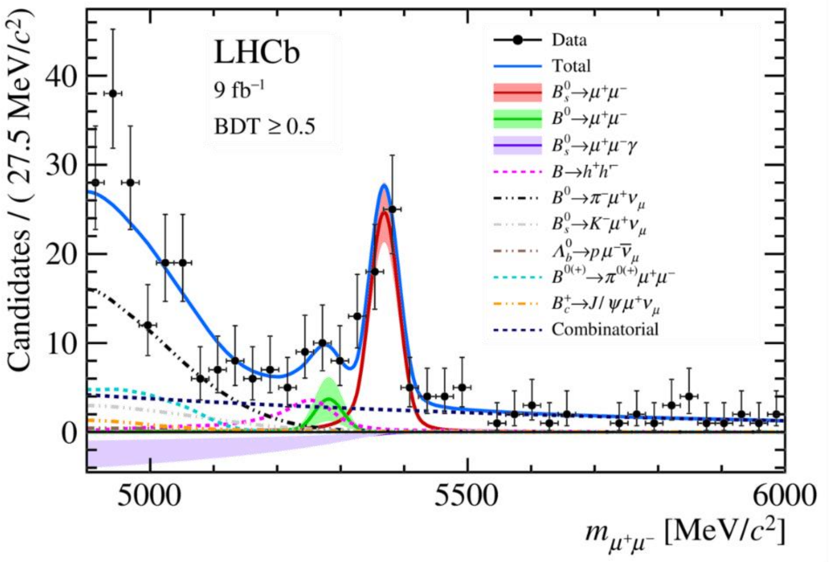
Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, Ξ_{bb} , Ω_{bb}

Weakly-decaying tetraquarks? [T_{bb}]

Weakly decaying pentaquarks?

Exotics? Di-baryon states ?



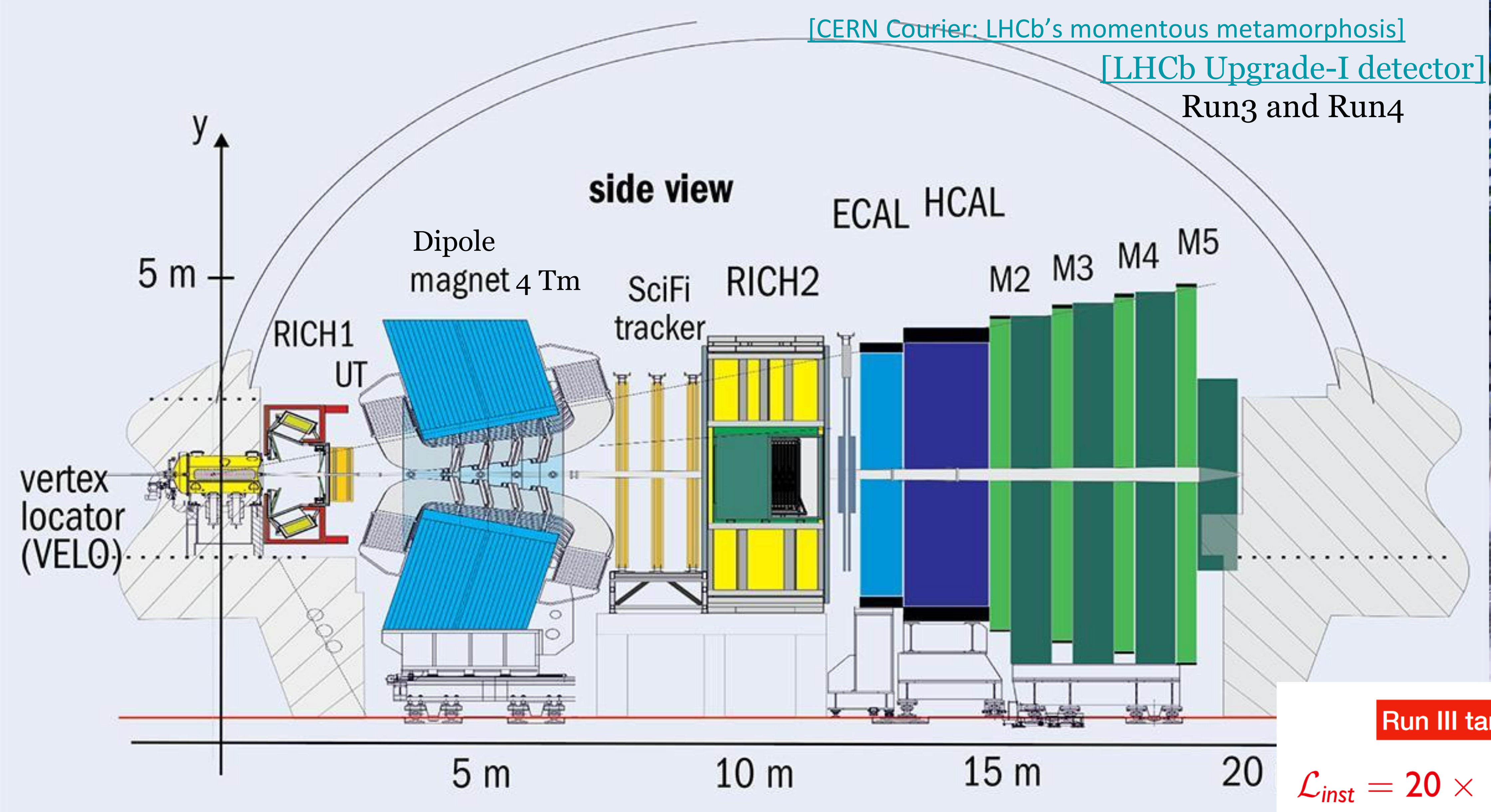


The LHCb experiment

[CERN Courier: LHCb's momentous metamorphosis]

[LHCb Upgrade-I detector]

Run3 and Run4

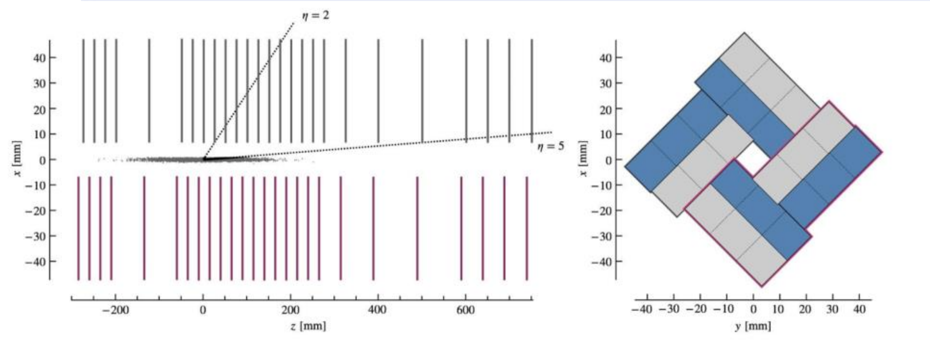


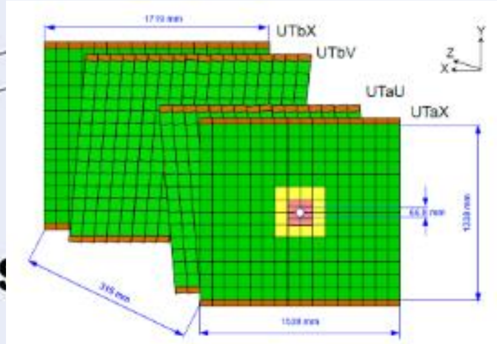
Run III target

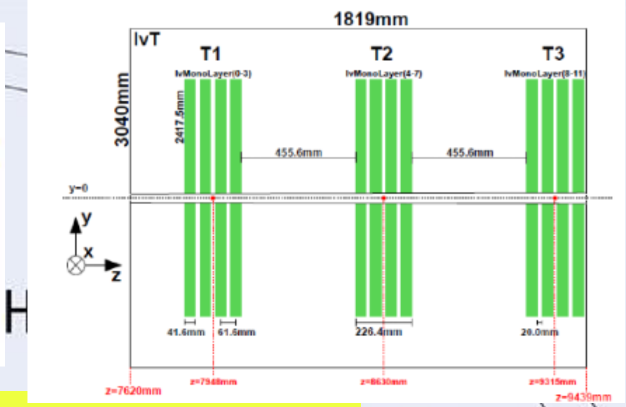
$\mathcal{L}_{inst} = 20 \times 10^{32} cm^{-2} s^{-1}$

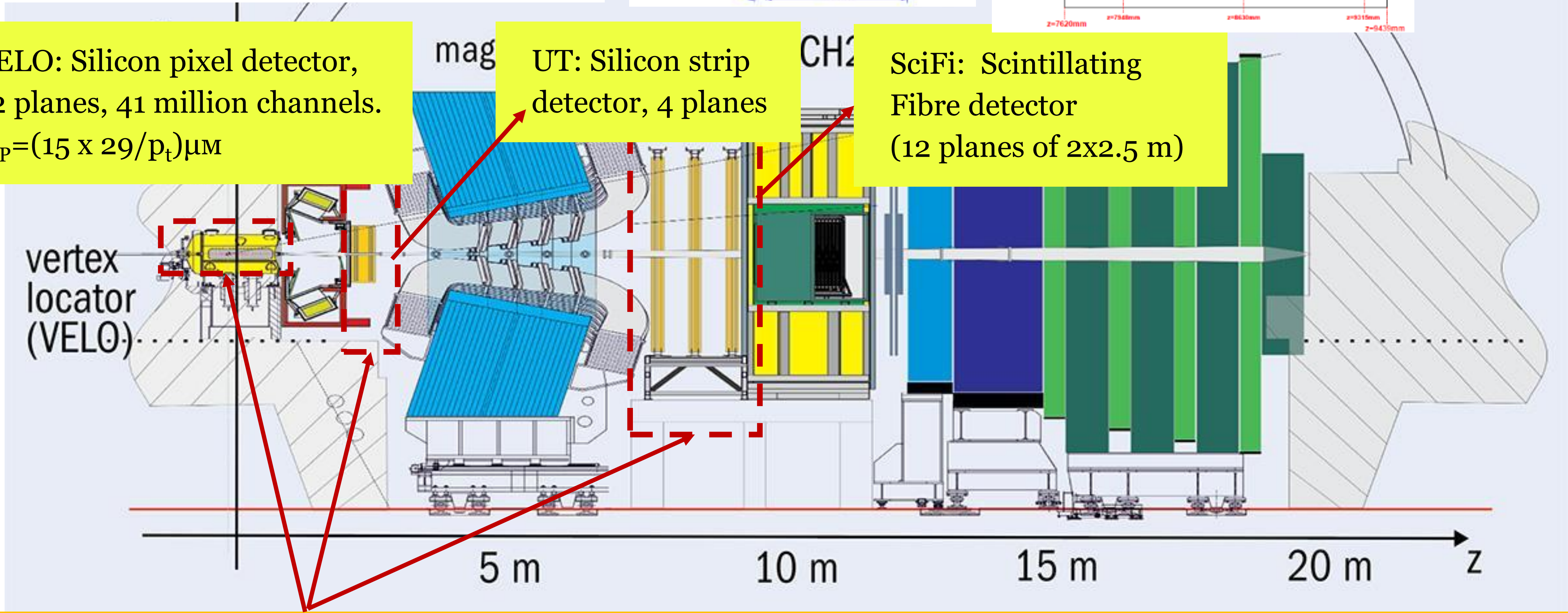
New detector with over 90% of active detector channels replaced

The LHCb experiment









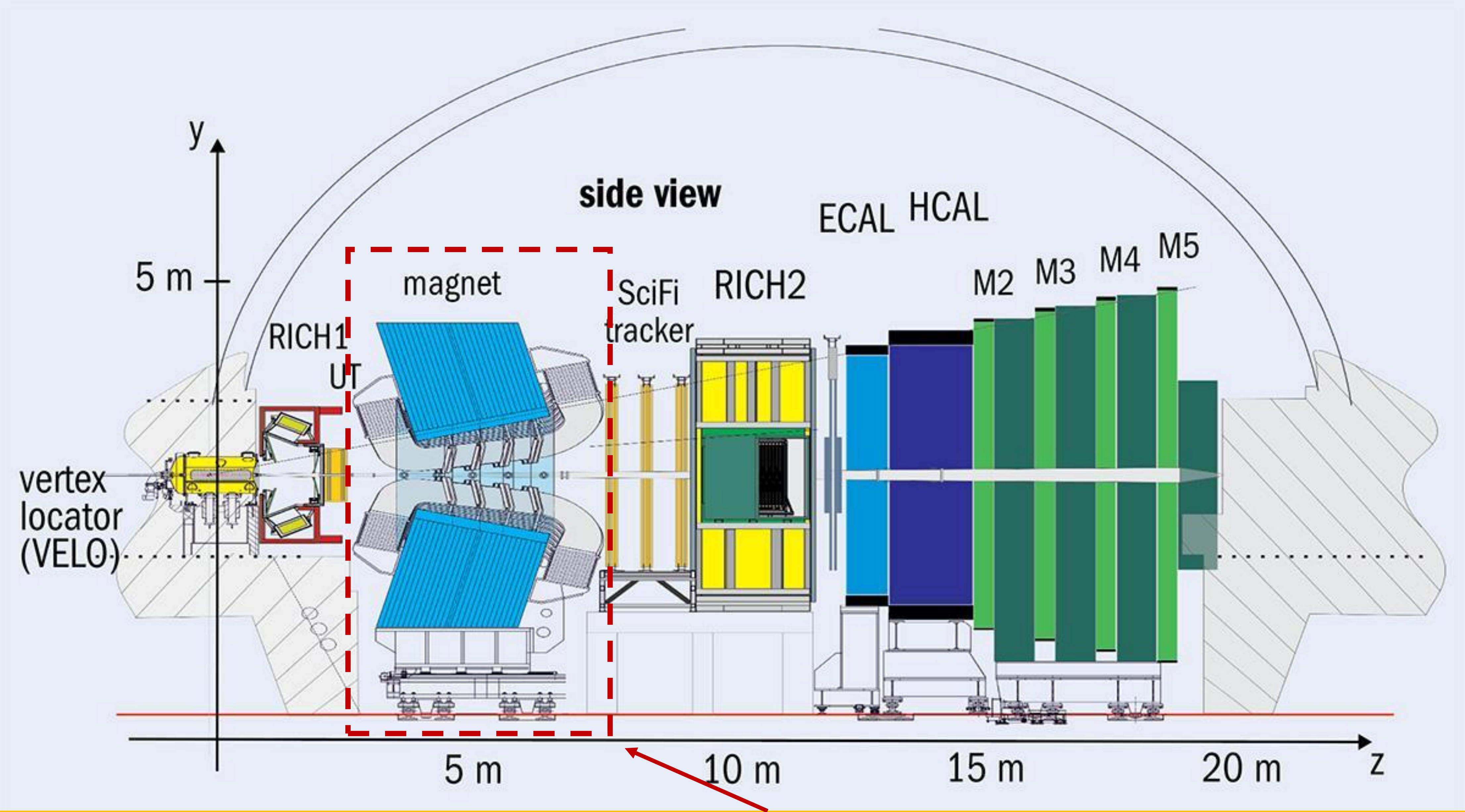
VELO: Silicon pixel detector, 52 planes, 41 million channels. σ_{IP}=(15 x 29/p_t)μм

UT: Silicon strip detector, 4 planes

SciFi: Scintillating Fibre detector (12 planes of 2x2.5 m)

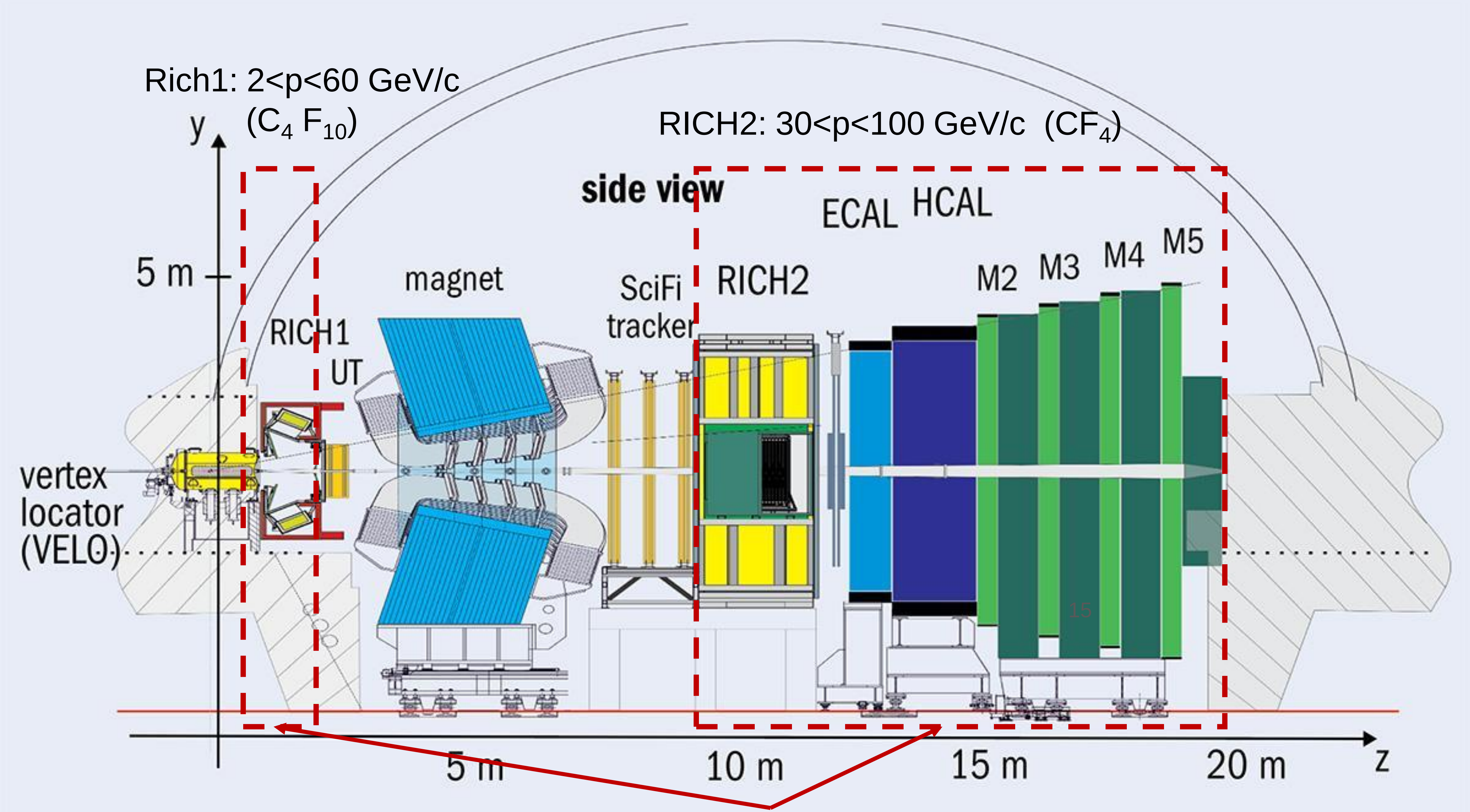
Tracking detectors: detect charged particles and localise the decay vertex

The LHCb experiment



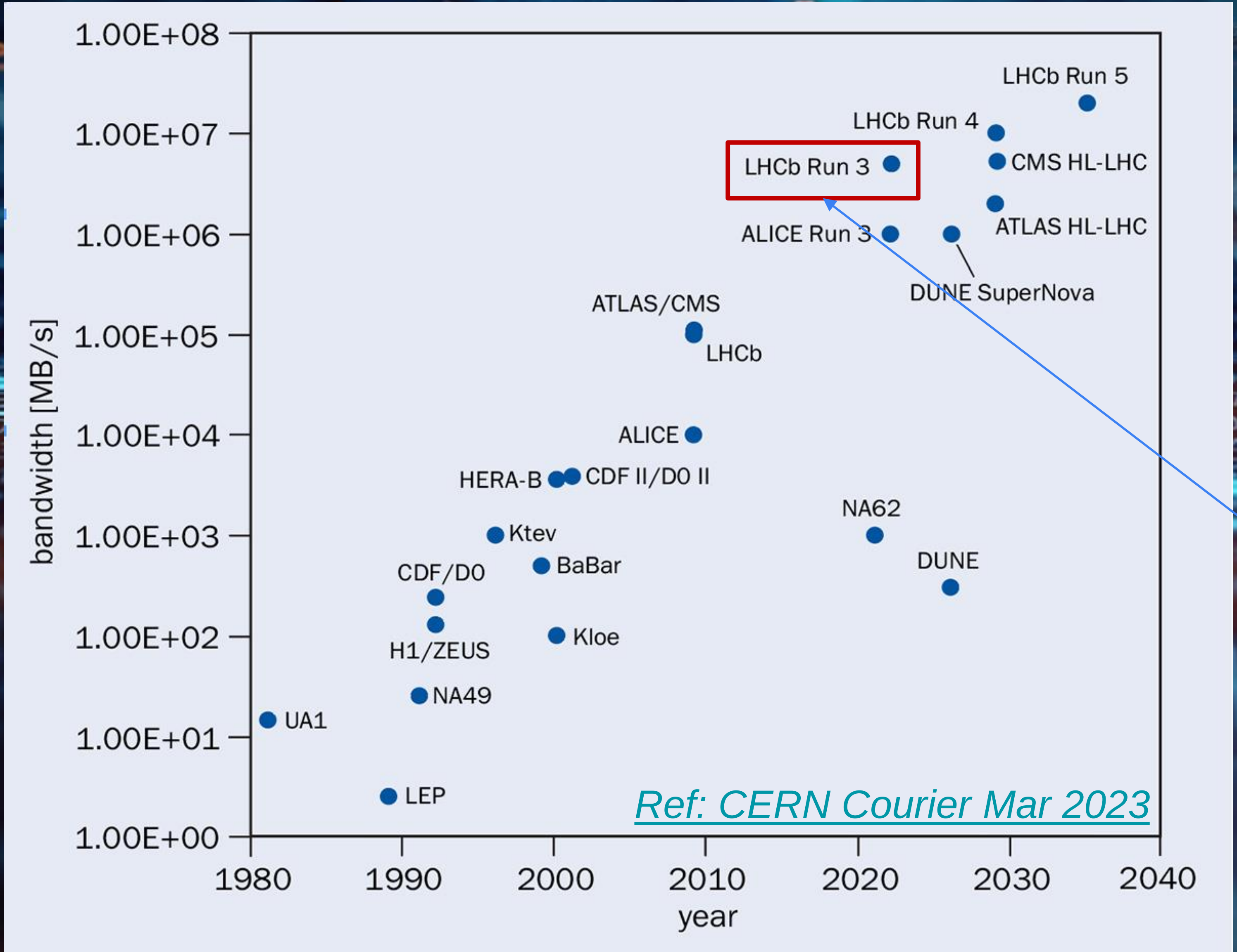
Dipole Magnet (~4 Tm): bend charged particles path to measure momentum

The LHCb experiment



RICH1 and 2, calorimeters, and muon chambers for particle identification

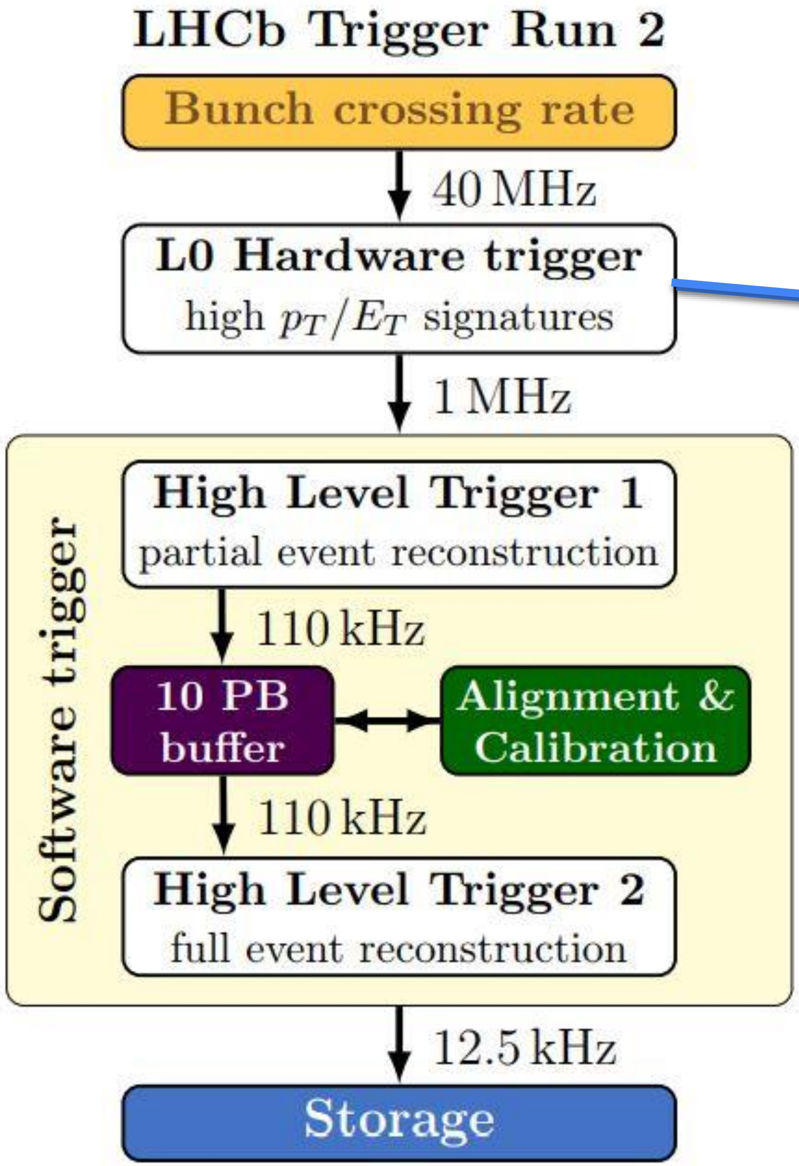
Computing Challenges (The problem now)

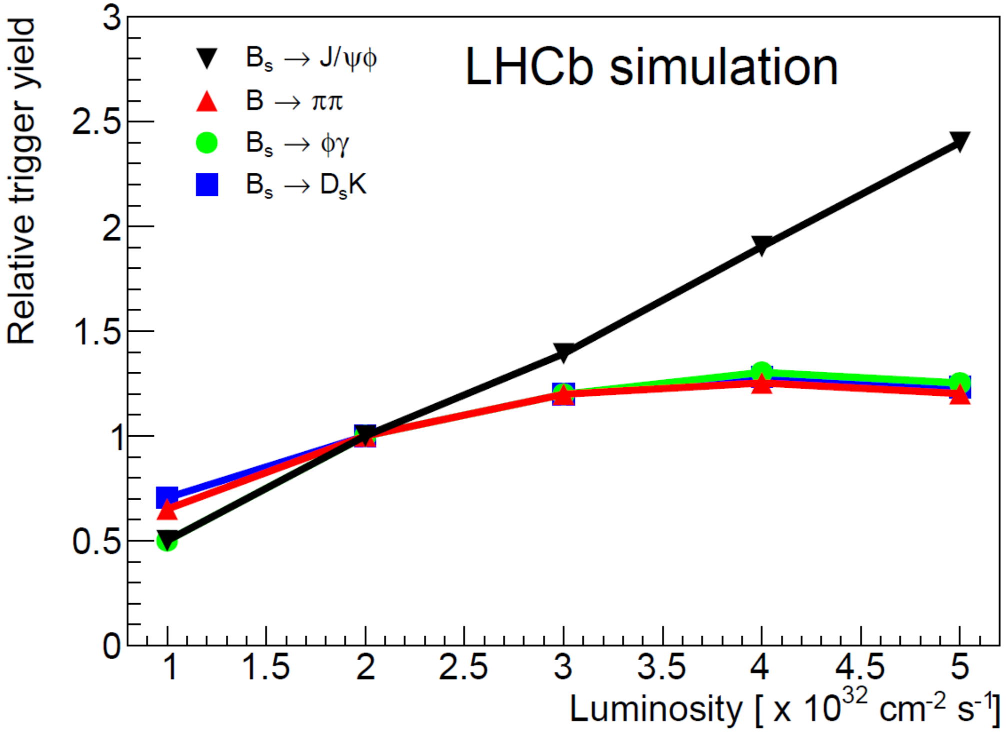


40 Tbits/sec
~ 115 Peta bytes per day

The biggest real-time data processing challenge in HEP

The LHCb experiment: Trigger system





- At high luminosities, hardware trigger cannot cope with the event rate and starts rejecting interesting events.
- Need to study properties of events in real time of collision.

Trigger system: (Run-III)

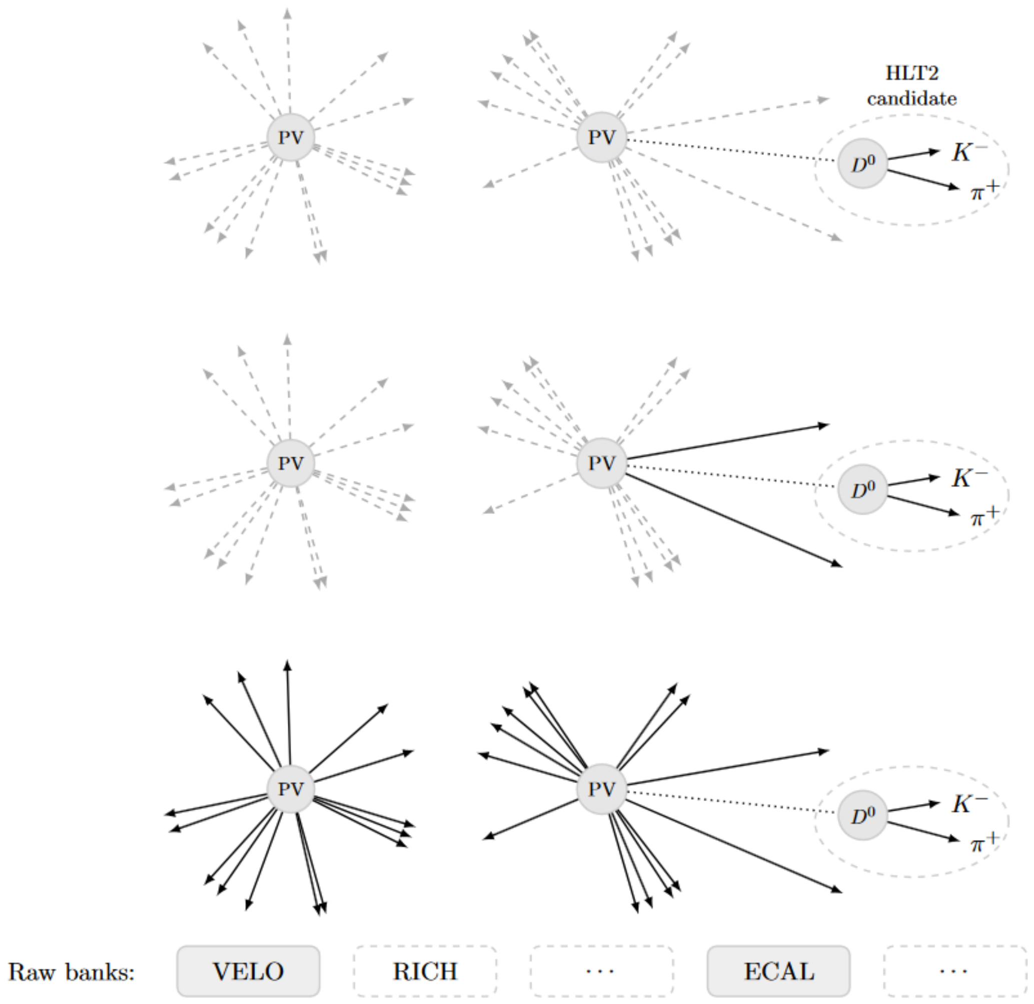
What to keep and what to discard ?

we have to be also very careful with what we dismiss..

Real Time Analysis

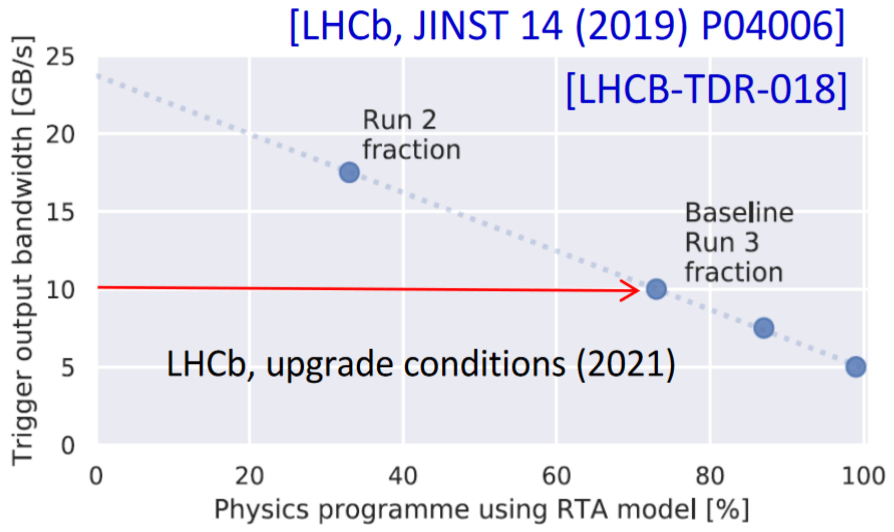
Real Time Analysis (RTA)

Bandwidth [GB/s] ~ Trigger output rate [kHz] x Average event size [MB]

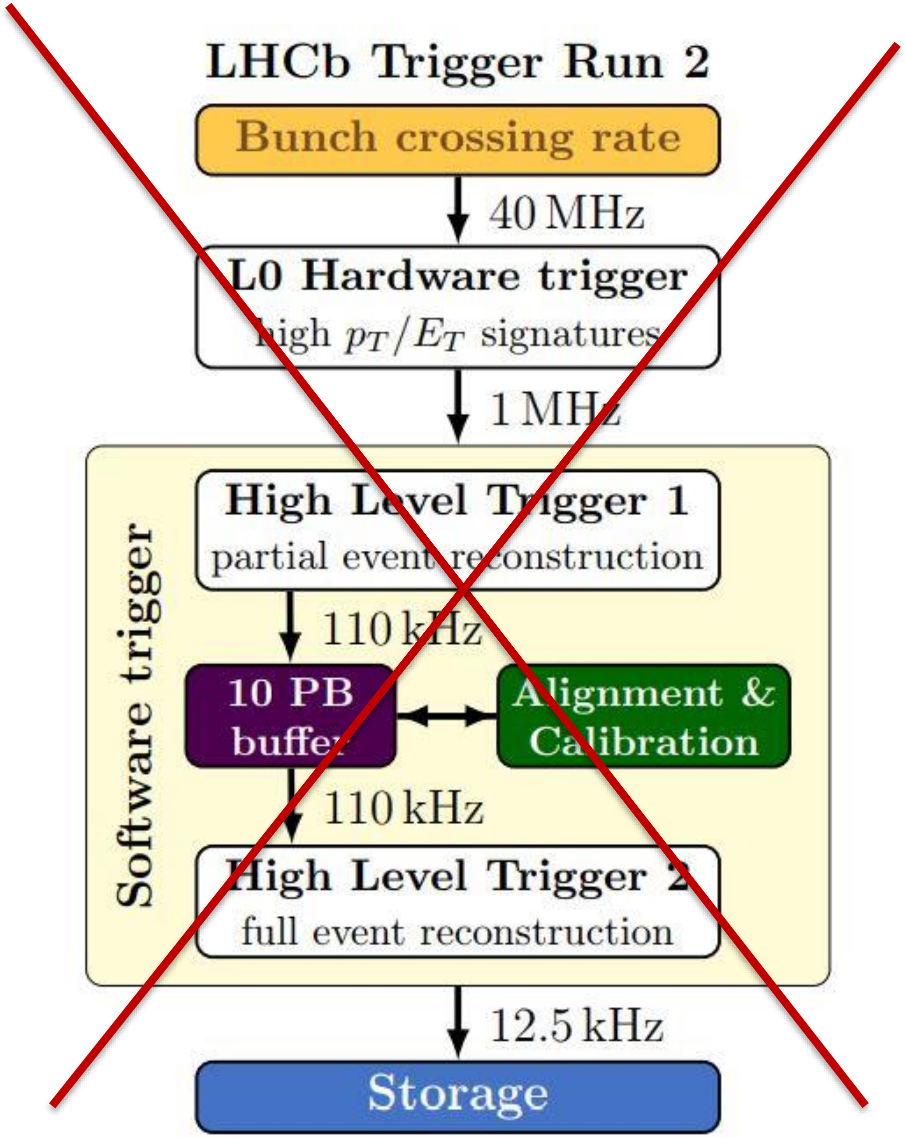


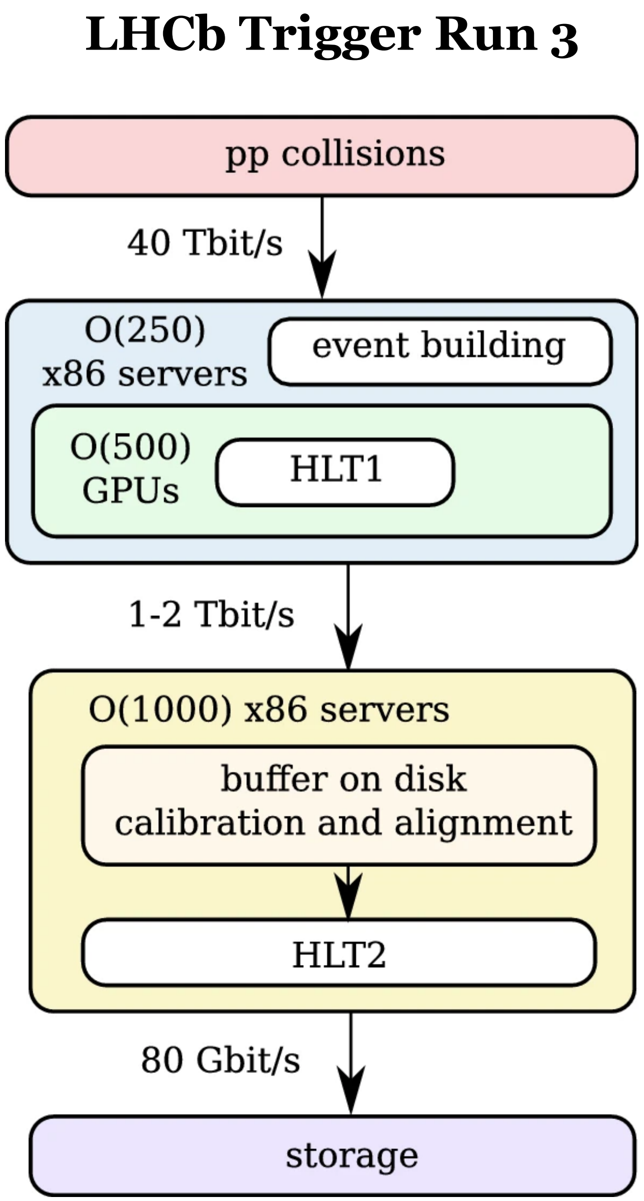
- Need to **reduce the event size**
Instead of raw data from the detector, store only the relevant information of interesting events.

- Need to reconstruct and **analyse** the events to select them in **real time.**

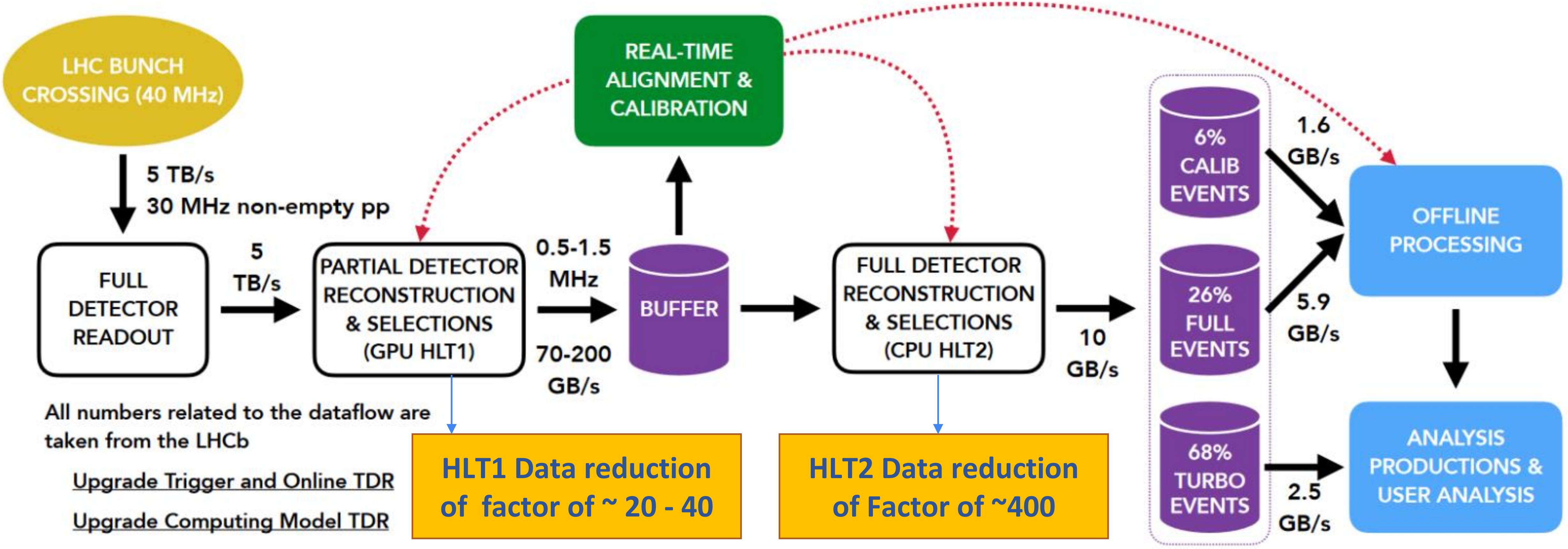


New trigger strategy



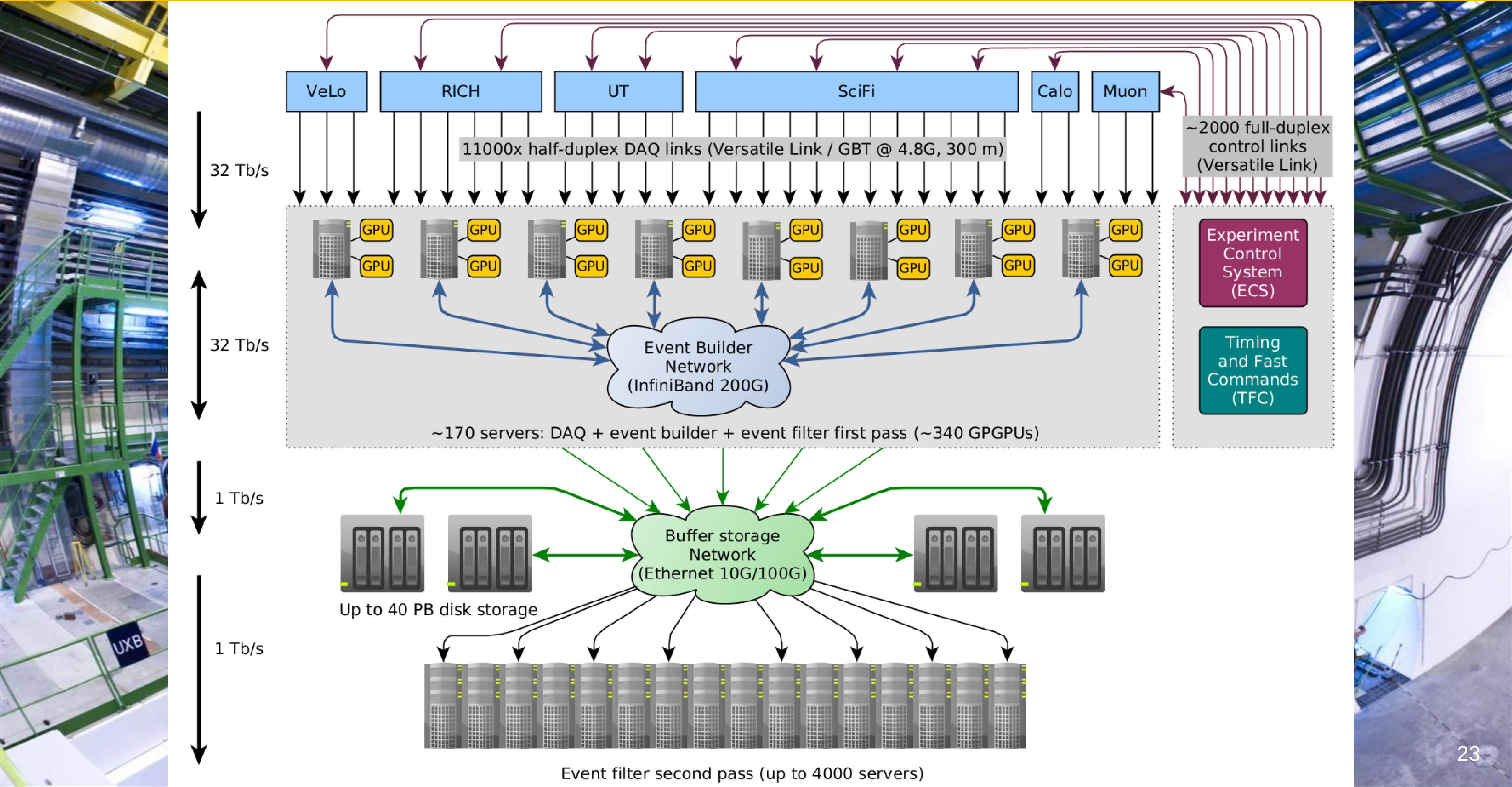


LHCb Run3 Trigger



HLT1: Partial reconstruction of charged particle trajectories and few simple selection lines
HLT2: Full reconstruction and selection based on different decay chains and signatures
Must reduce without the loss in fidelity

LHCb Run3 Trigger

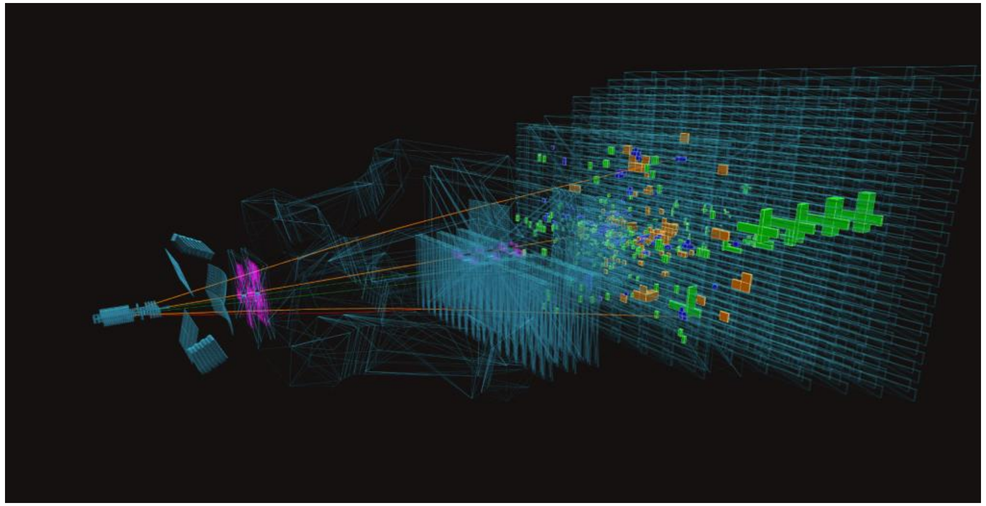


HLT1 software framework

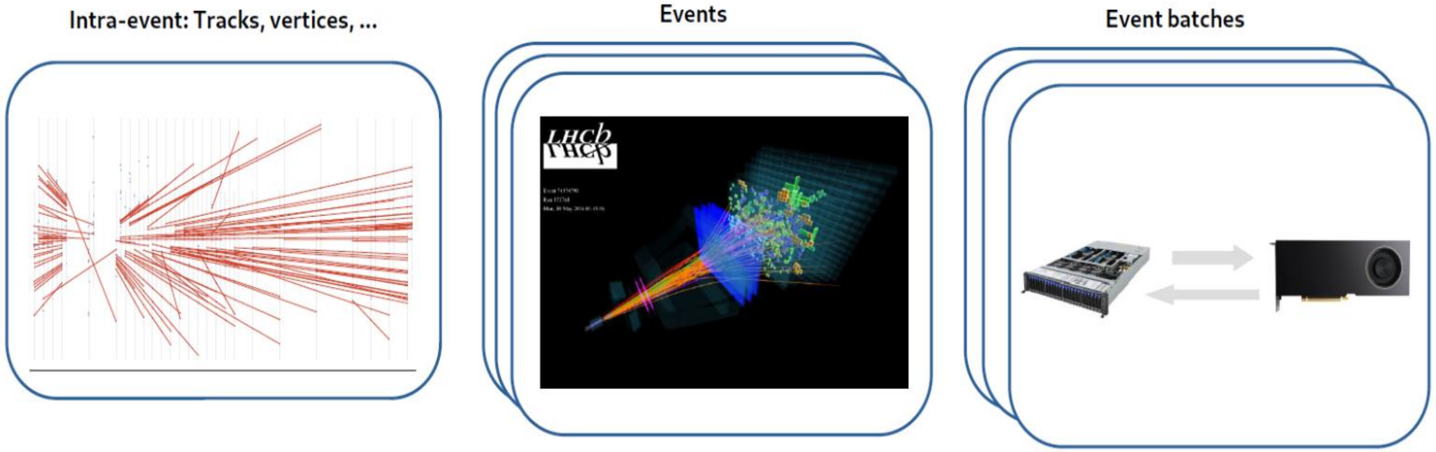
What is tracking and why do we need it ?

Track reconstruction (Tracking)

What
- Tracking deals with converting the signal from a subdetector (hits, clusters…) into a trajectory.
- Roughly speaking, two phases: pattern recognition and track fitting

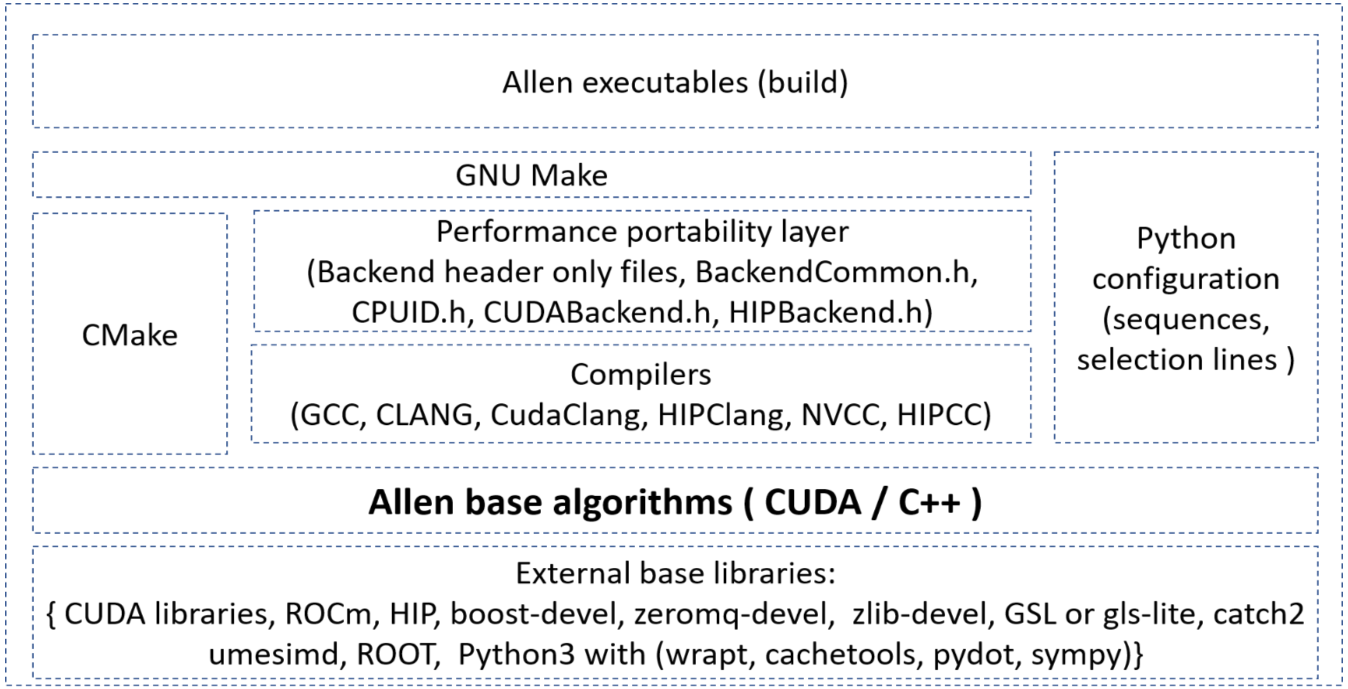


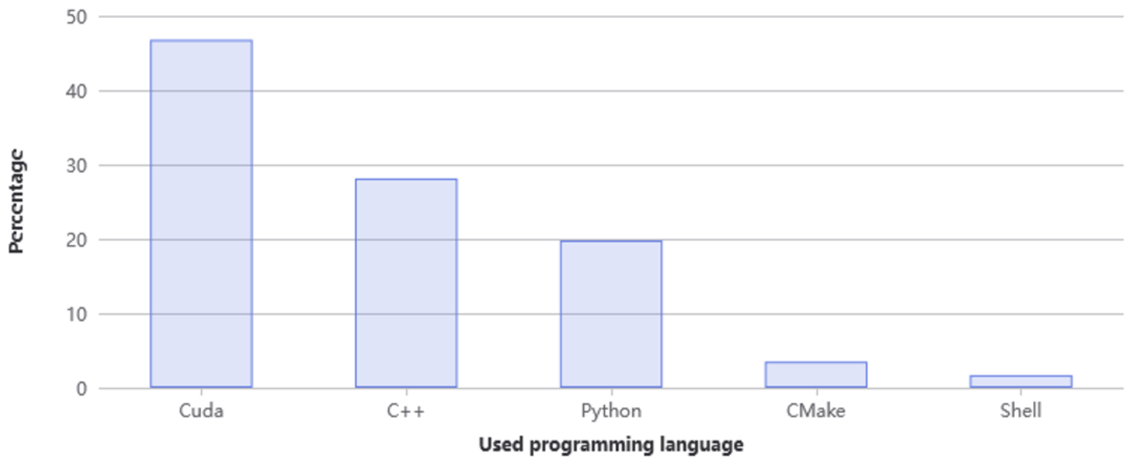
Why
- We need to reconstruct trajectories of particles in our detector to:
  - Build vertices, measure decay topologies;
  - Measure momenta → measure invariant masses, angular variables (so… do physics).



HLT1 software framework

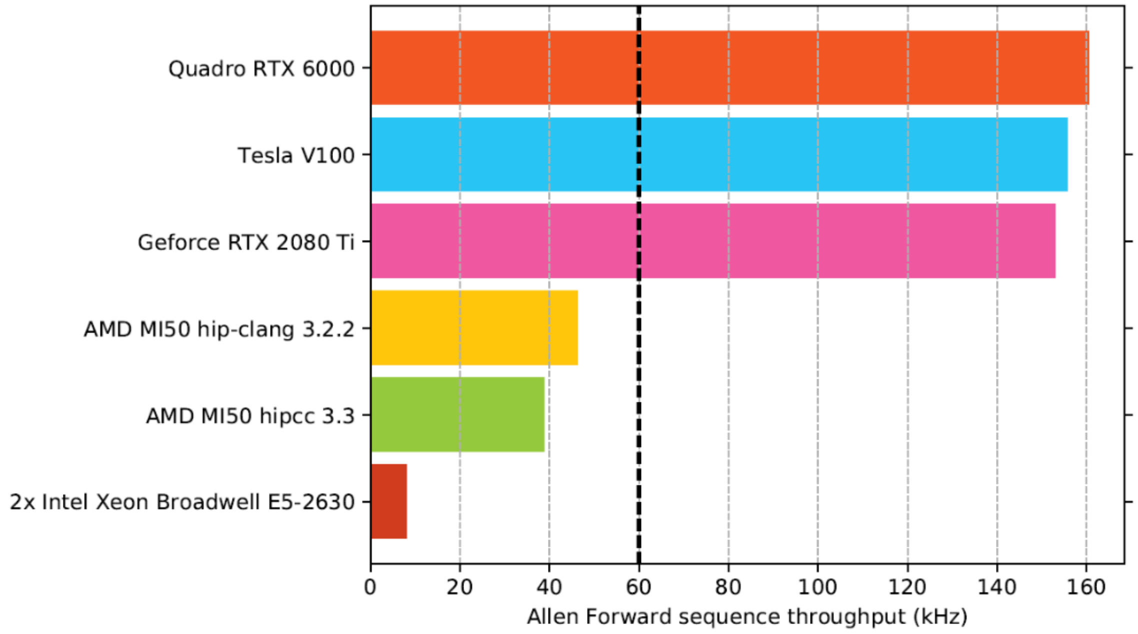
- Allen software project: Framework developed for processing LHCb´s HLT1 on GPUs
- Standalone software project: https://gitlab.cern.ch/lhcb/Allen
- Primarily developed using CUDA to process events in parallel and exploit data-parallelism within events
- Single Instruction Multiple Threads (SIMT) design with custom **performance portability layer.**





HLT1 framework: Performance Portability Layer (PPL)

Framework supports multiple platforms and architectures: Heterogeneous



allenpr BOT 6:33 PM

Throughput of branch `master (cba2475b)`, sequence `hlt1_pp_default` over dataset `upgrade-magdown-sim10-up08-30000000-digi_01_retinacluster` build options `default`:

NVIDIA GeForce RTX 3090	194.90 kHz (1.01x)
NVIDIA RTX A6000	193.36 kHz (1.02x)
NVIDIA RTX A5000	156.89 kHz (0.98x)
MI100	124.00 kHz (1.00x)
NVIDIA GeForce RTX 2080 Ti	123.29 kHz
AMD EPYC 7502 32-Core	21.33 kHz (1.00x)

20 40 60 80 100 120 140 160 180 200

Allen software project: GPU based HLT1 at LHCb

Computing and Software for Big Science (2020) 4:7
https://doi.org/10.1007/s41781-020-00039-7

ORIGINAL ARTICLE

Allen: A High-Level Trigger on GPUs for LHCb

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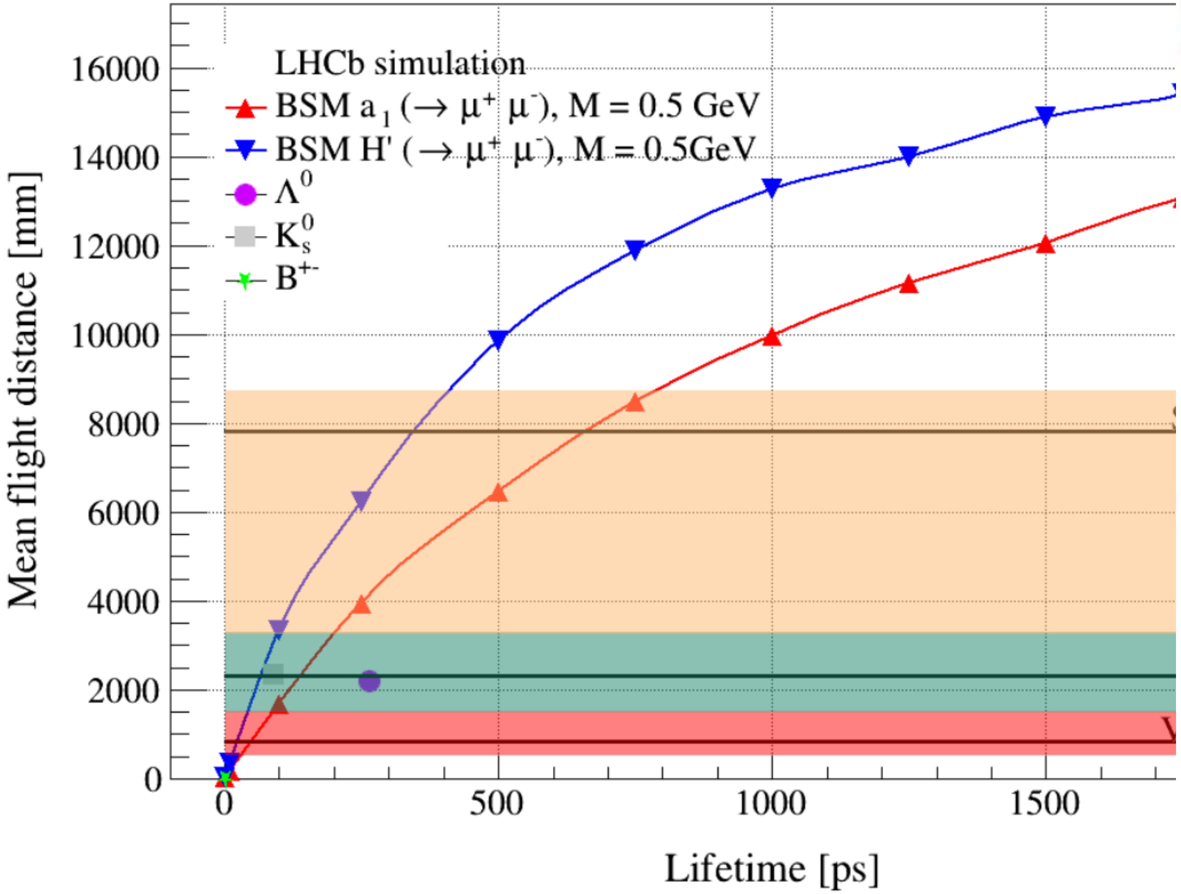
Abstract
We describe a fully GPU-based implementation of the first level trigger for the upgrade of the LHCb detector, due to start data taking in 2021. We demonstrate that our implementation, named Allen, can process the 40 Tbit/s data rate of the upgraded LHCb detector and perform a wide variety of pattern recognition tasks. These include finding the trajectories of charged particles, finding proton–proton collision points, identifying particles as hadrons or muons, and finding the displaced decay vertices of long-lived particles. We further demonstrate that Allen can be implemented in around 500 scientific or consumer GPU cards, that it is not I/O bound, and can be operated at the full LHC collision rate of 30 MHz. Allen is the first complete high-throughput GPU trigger proposed for a HEP experiment.

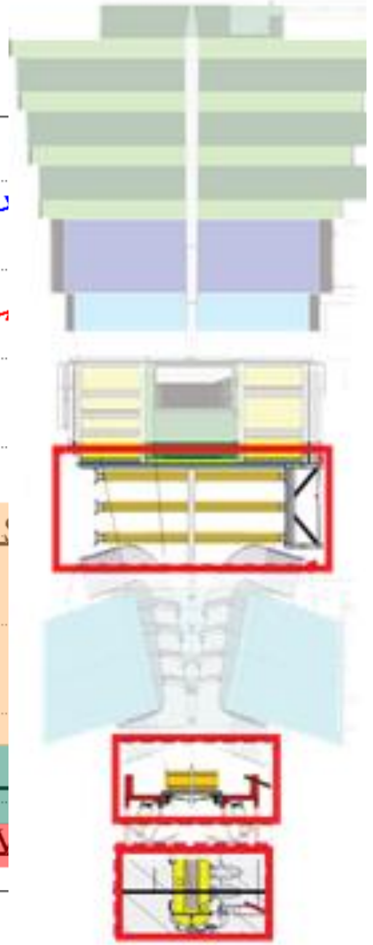
Keywords GPU · Real-time data selection · Trigger · LHCb

Long-lived particles and Tracking

BSM/SM Long-lived particles and Tracking (Why ?)

- Particles with displaced secondary vertex (LLPs)
  - Distance between primary and secondary vertex >~ 3 m
  - $L = \beta\gamma.c.\tau$
  - e.g. Ks^0 Λ^0 , Ξ^-. with typical boost of $\beta\gamma$ ~10-100 and lifetime $\tau \sim 10^{-11} - 10^{-10}$ s . c
  - No dedicated reconstruction or selection at HLT1 level in Run1 and 2

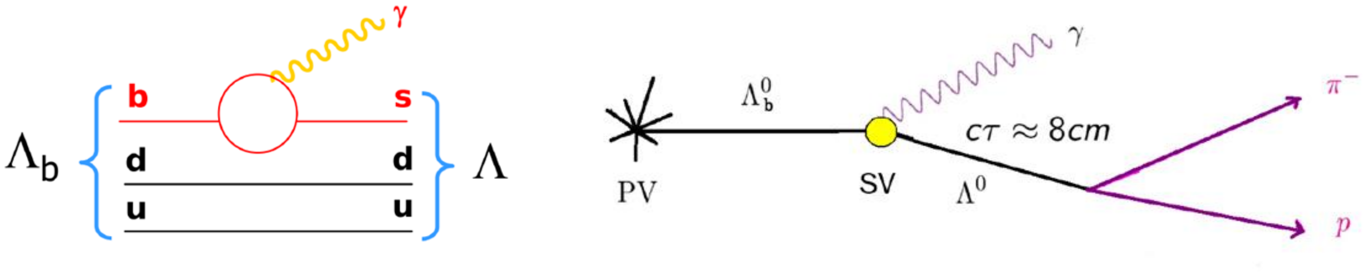




Frontiers in Big data 2022.1008737

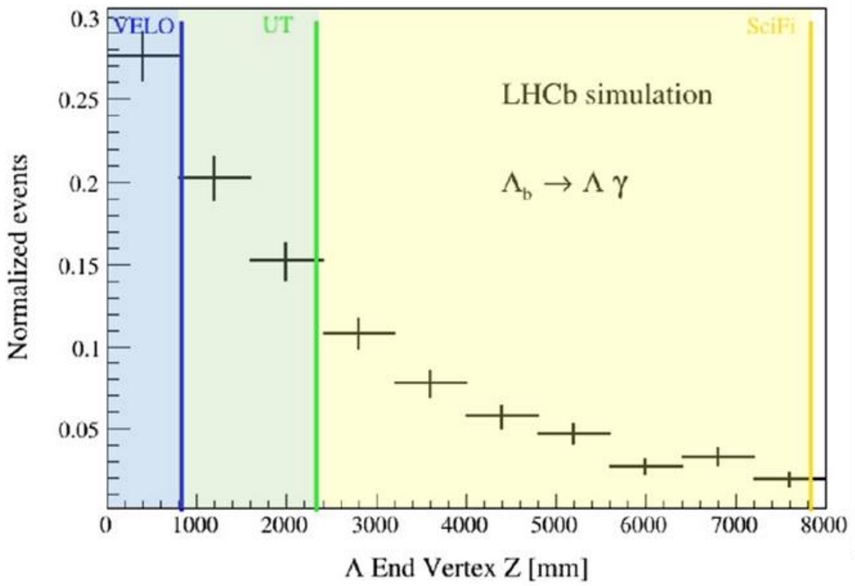
LLPs in SM

- Λ are decay products of *b*-baryon decays which have a rich spin structure

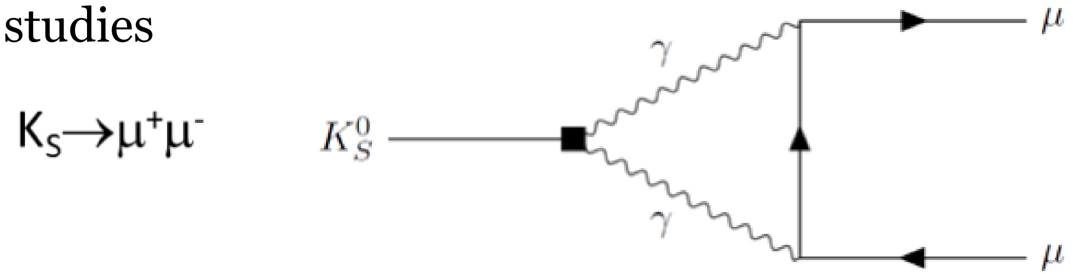


	LL	DD	TT	HLT1 eff (TOS)
Λ^0	12%	51%	37%	< 10%

without downstream

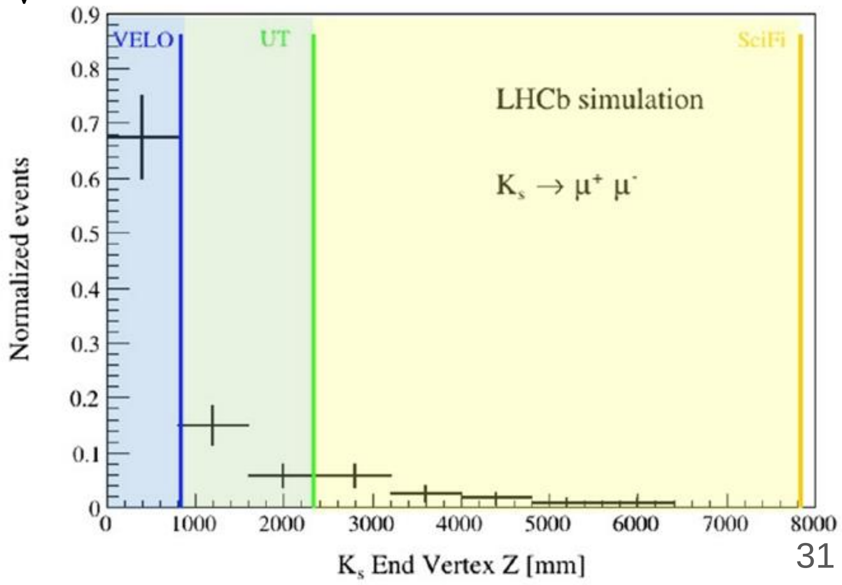


- K_s are common decay products in *b* and charm decays → important for CPV studies



	LL	DD	TT	HLT1 eff (TOS)
K_s^0	46 %	38 %	16 %	< 25%

without downstream



BSM / NP Long-Lived Particles and Tracking (Why?)

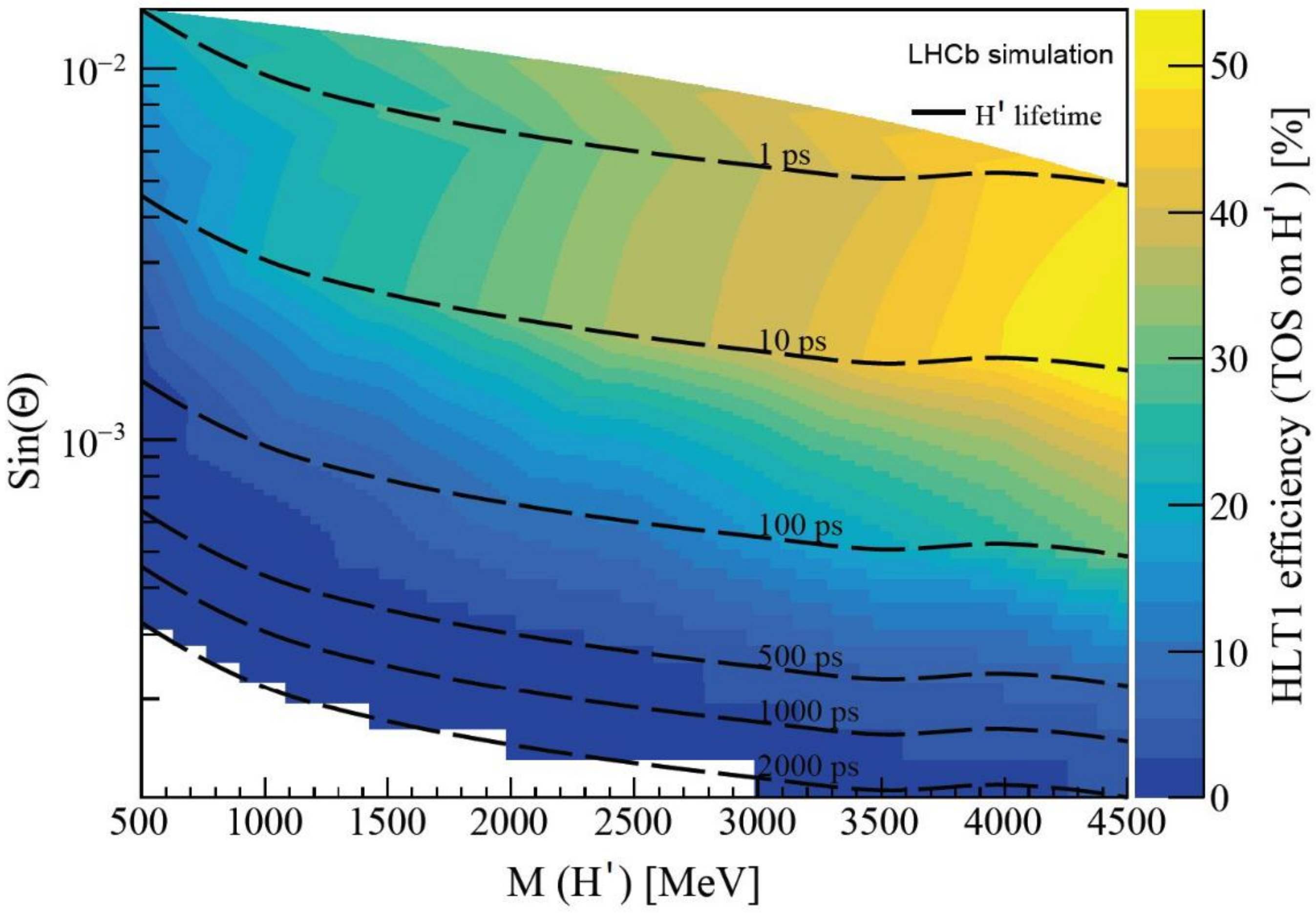
BSM: sensitivity to $B^+ \rightarrow K^+ H' [\rightarrow \mu^+\mu^-]$

[Frontiers in Big data 2022.1008737]

HLT1 effect when triggering on the H' decay products:

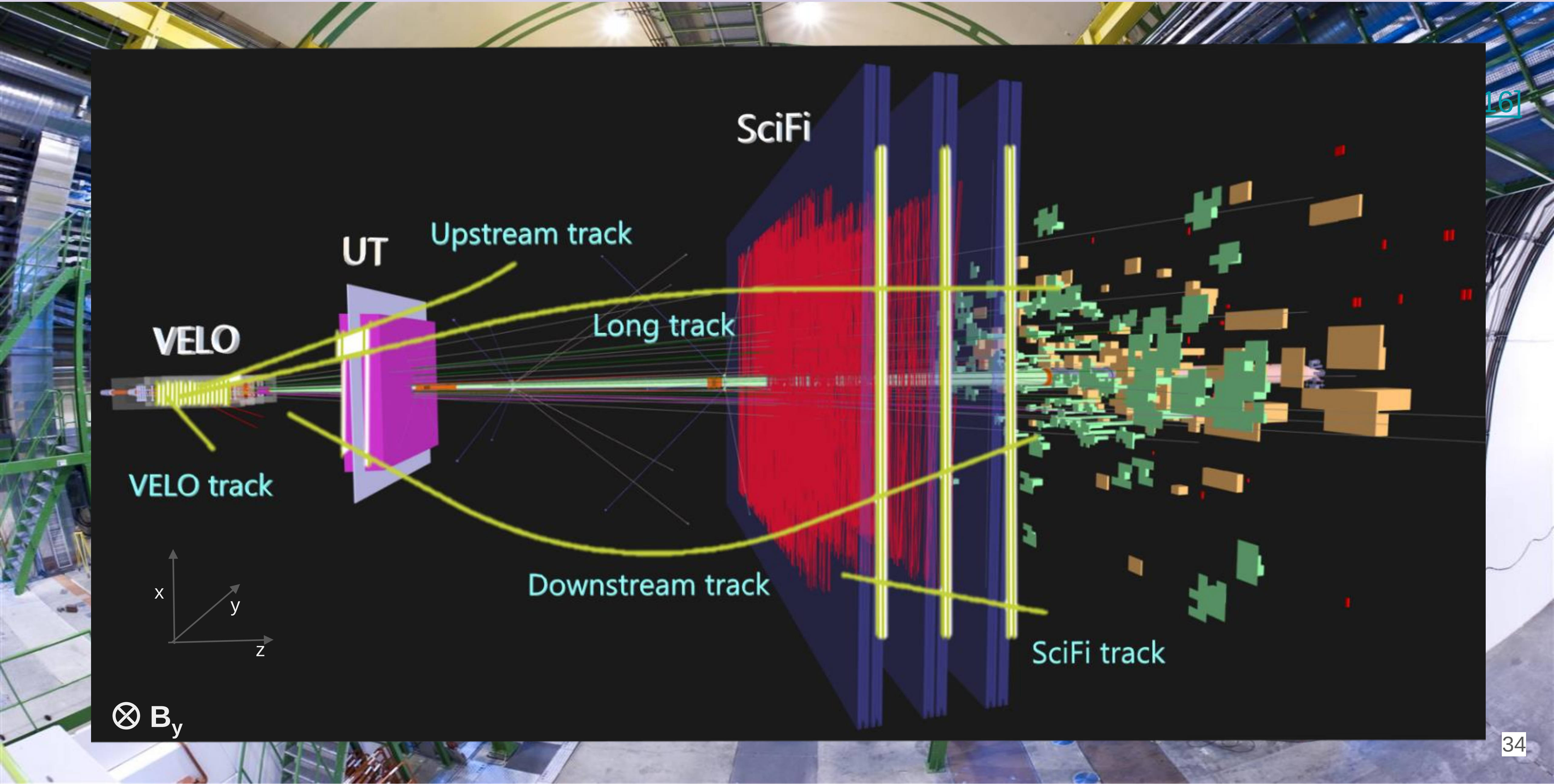
- Decent efficiency (30-50 %) for low lifetime
- Poor efficiency (< 10 %) for τ > 100 ps
- Loss in sensitivity for small H' mass

Need for dedicated LLP trigger if H' is long-lived



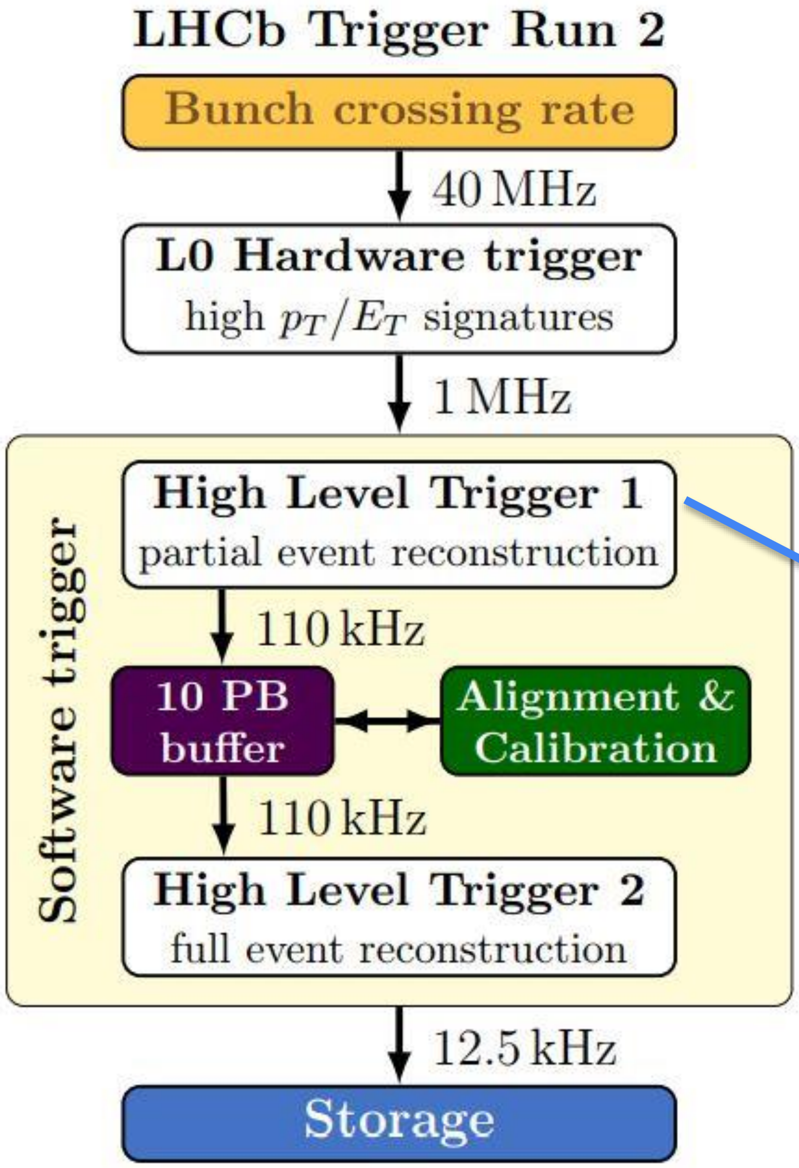
HLT1 Algorithms

Algorithms: LHCb track types



[16]

Algorithms: HLT1 sequence (Run-2)



LHCb Run2 HLT1 trigger configuration

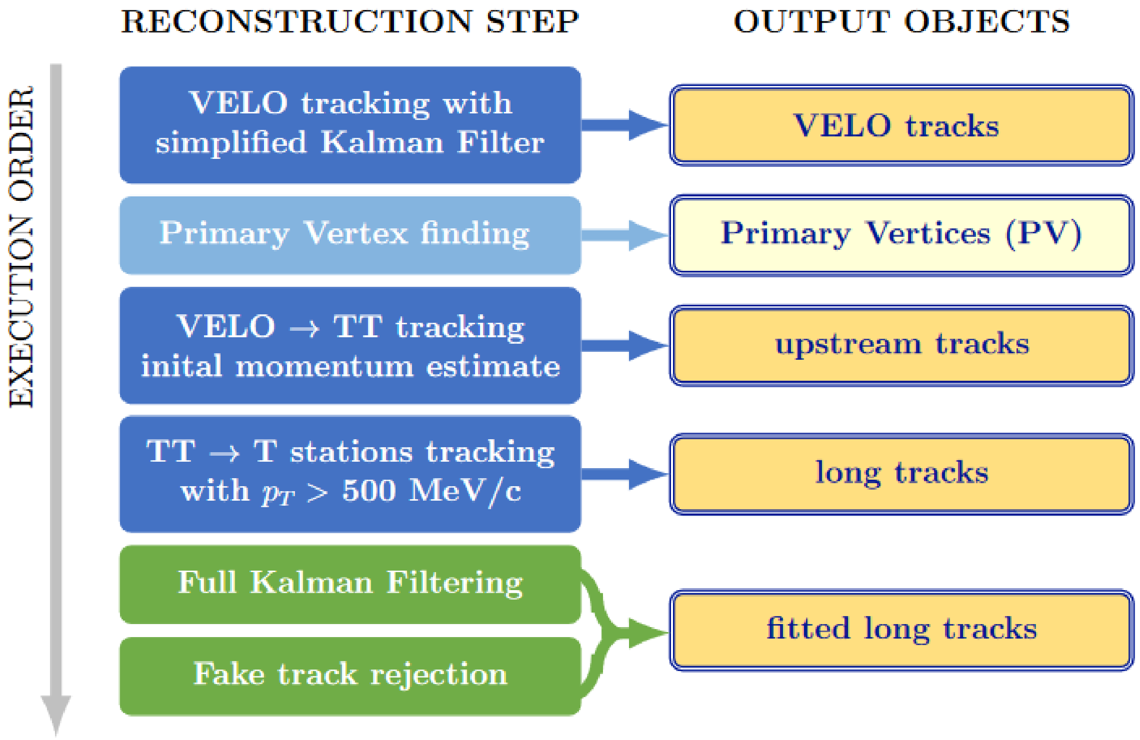
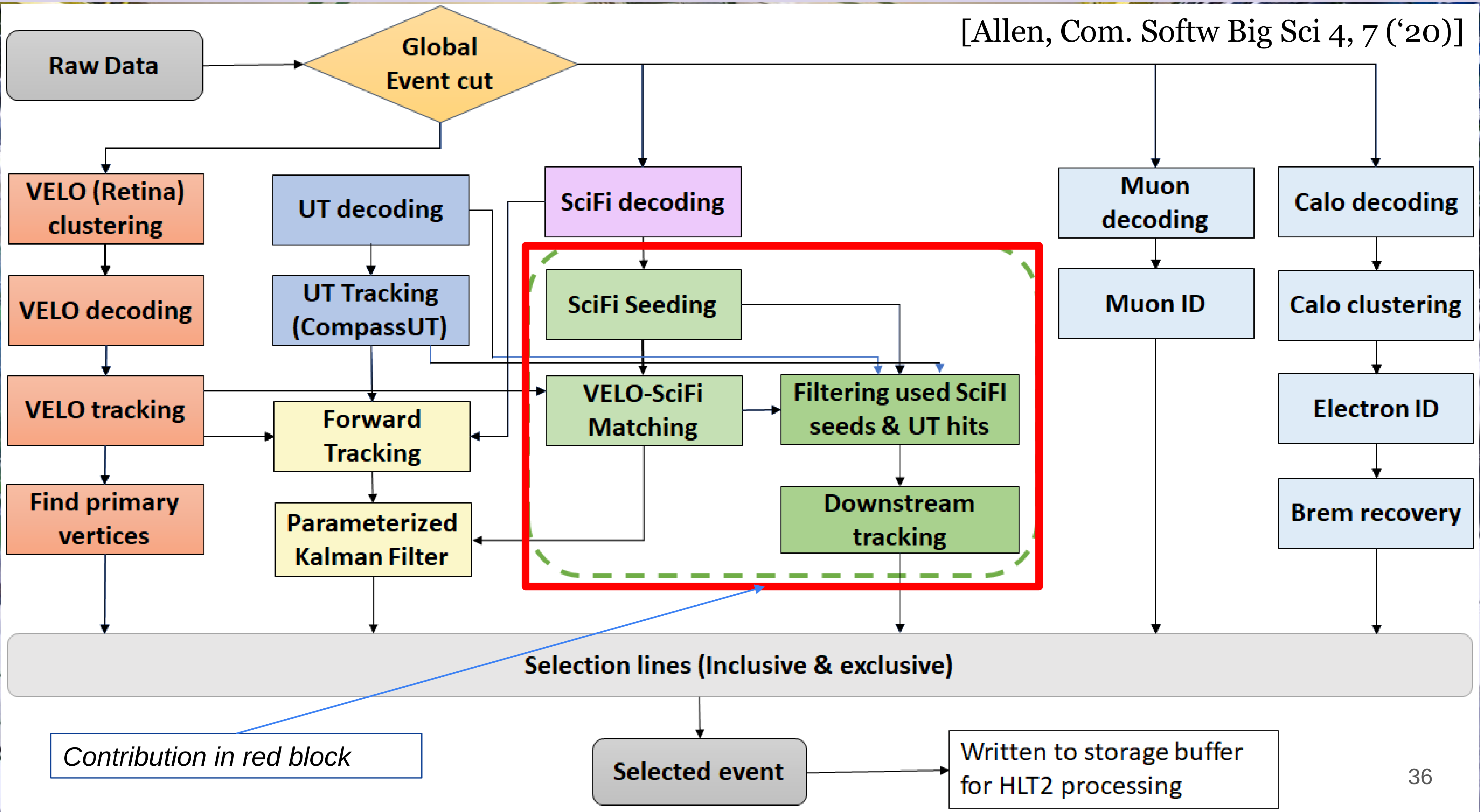
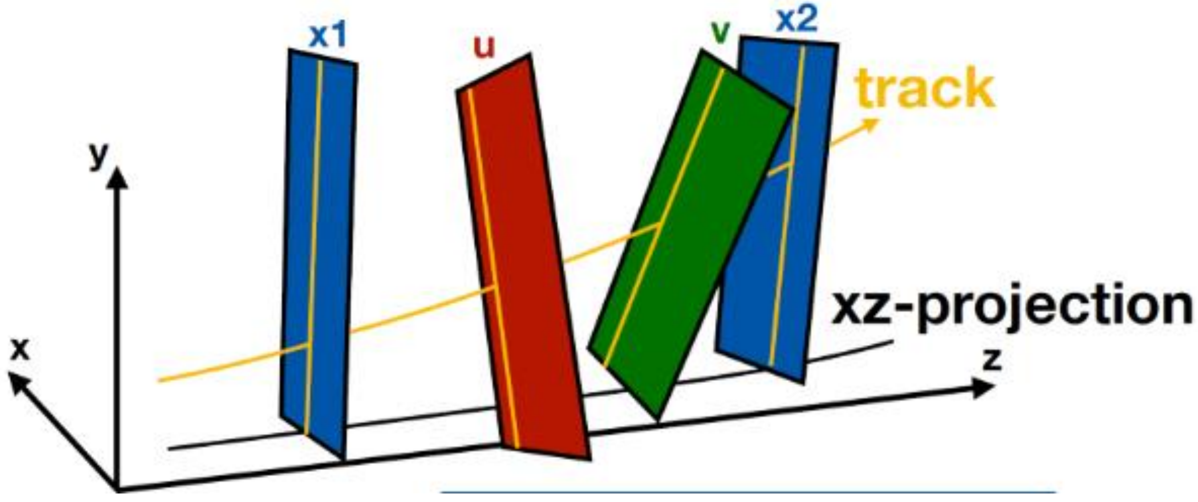


Figure 4: Sketch of the HLT1 track and vertex reconstruction.

Algorithms: HLT1 sequence (Run-3)



Algorithms: SciFi Seeding and Velo-SciFi Matching



Standalone SciFi seeding algorithm (HybridSeeding)

- 2.7 meters long fibers, 250 μm diameter
- 12 layer with ~450 hits each (average),
- 3 stations spread over 1.8 meters ub x-u-v-x geometry, u and v being layers titled by a +/- 5° stereo angle

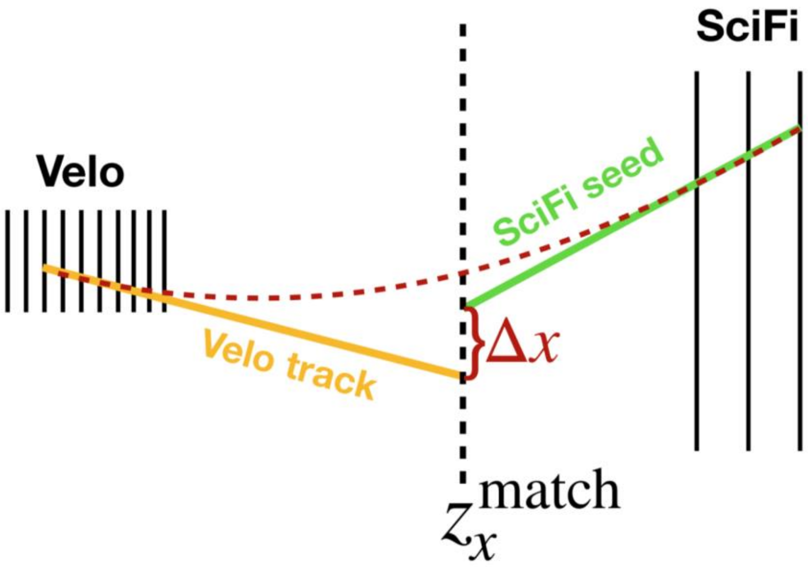
➢ Two iterations with two main components of algorithm

Seeding XZ

Seeding confirmTracks

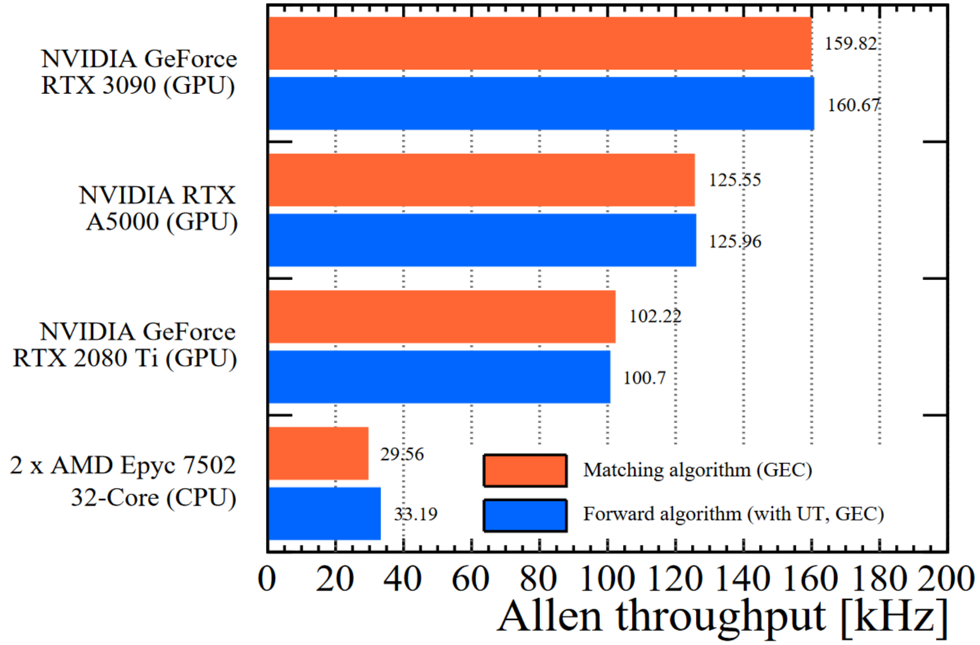
Velo-SciFi Matching

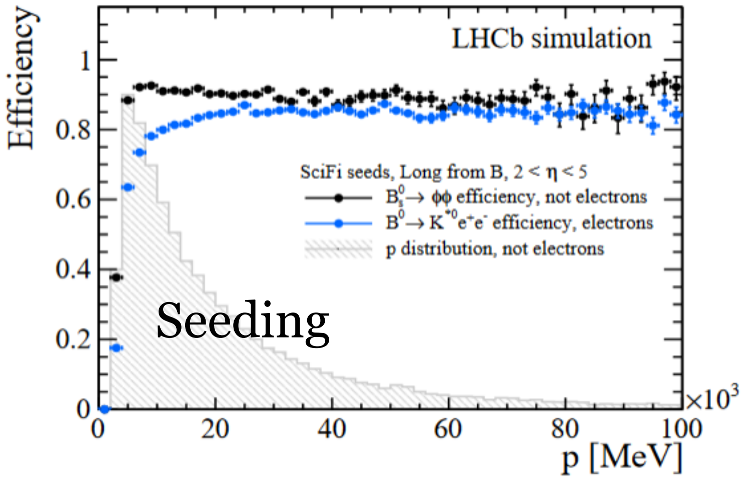
- SciFi seeds matched to Velo tracks to produce Long tracks
- Start with SciFi seeds and parallelize over SciFi loops
- Velo/SciFi seeds extrapolated to magnet as lines ("Kink" approximation)

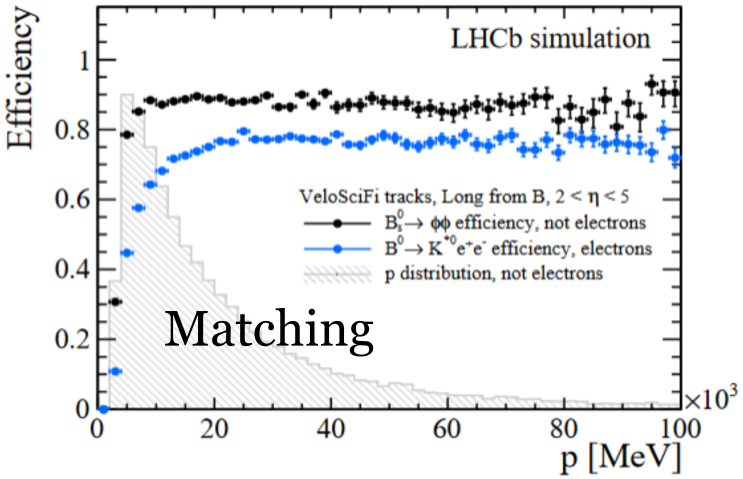


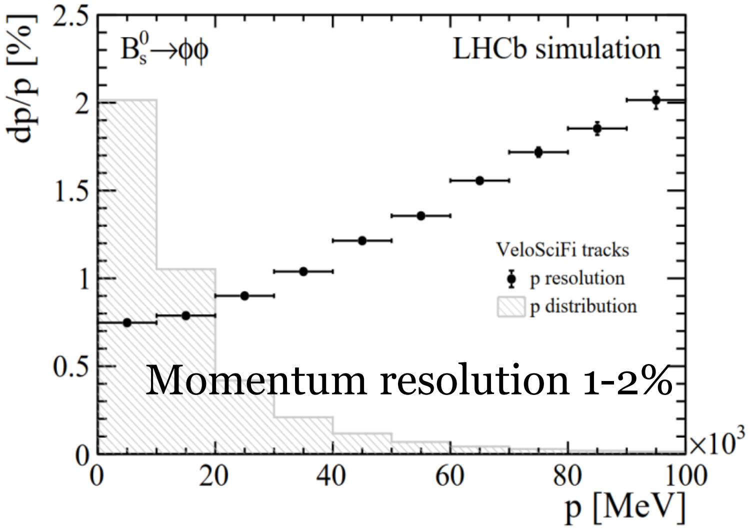
Algorithms: Performance: Seeding + VeloSciFi Matching

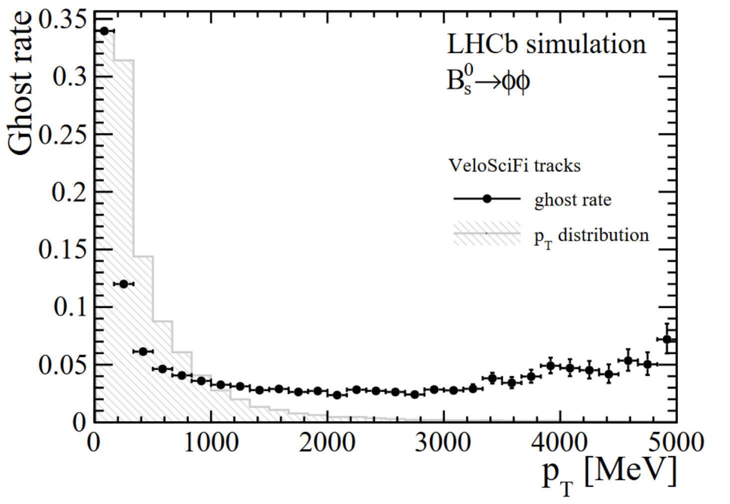
Matching produces standard long tracks covering entire detector



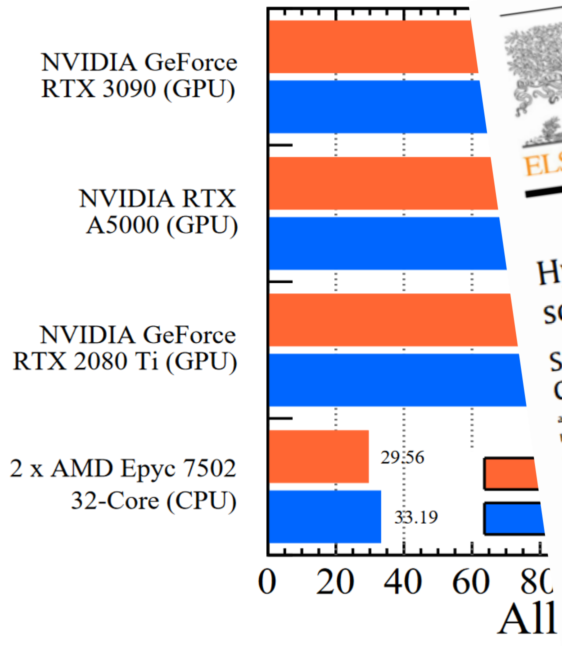


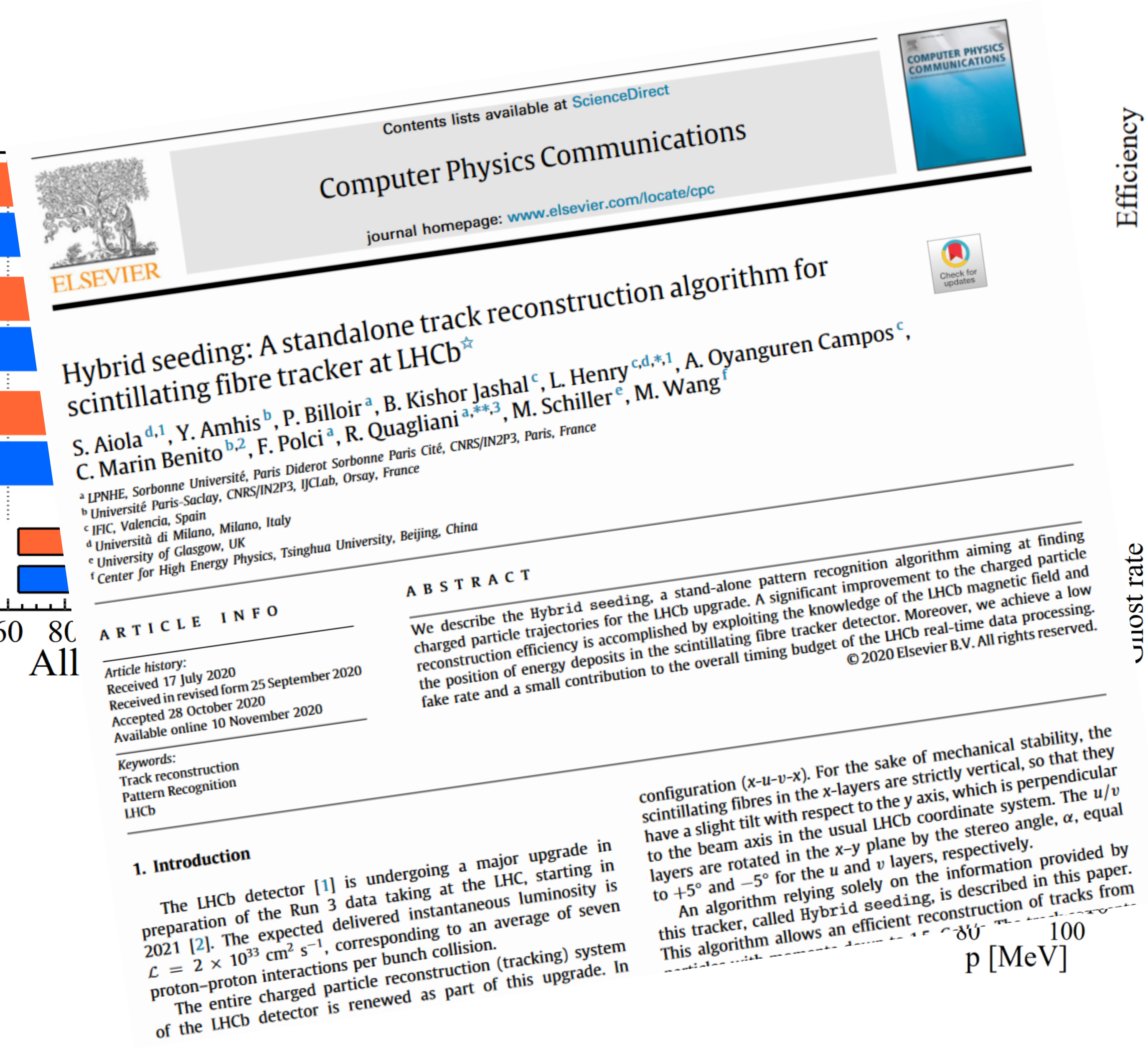






Algorithms: Performance: Seeding + VeloSciFi Matching





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Hybrid seeding: A standalone track reconstruction algorithm for scintillating fibre tracker at LHCb☆

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ABSTRACT

We describe the Hybrid seeding, a stand-alone pattern recognition algorithm aiming at finding charged particle trajectories for the LHCb upgrade. A significant improvement to the charged particle reconstruction efficiency is accomplished by exploiting the knowledge of the LHCb magnetic field and the position of energy deposits in the scintillating fibre tracker detector. Moreover, we achieve a low fake rate and a small contribution to the overall timing budget of the LHCb real-time data processing.

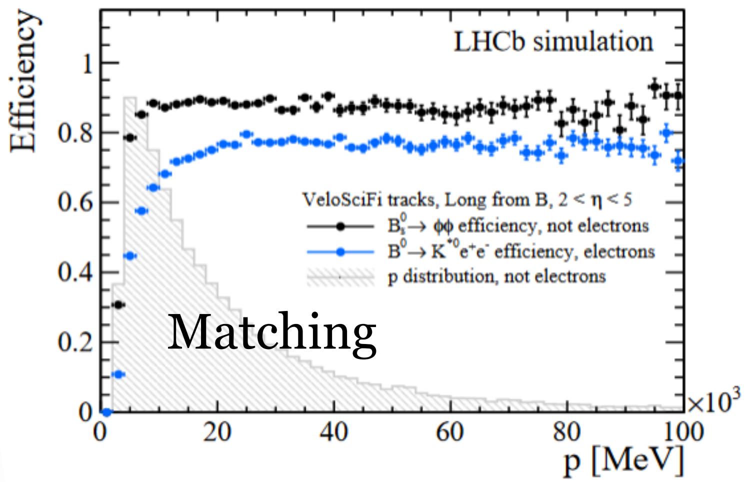
1. Introduction

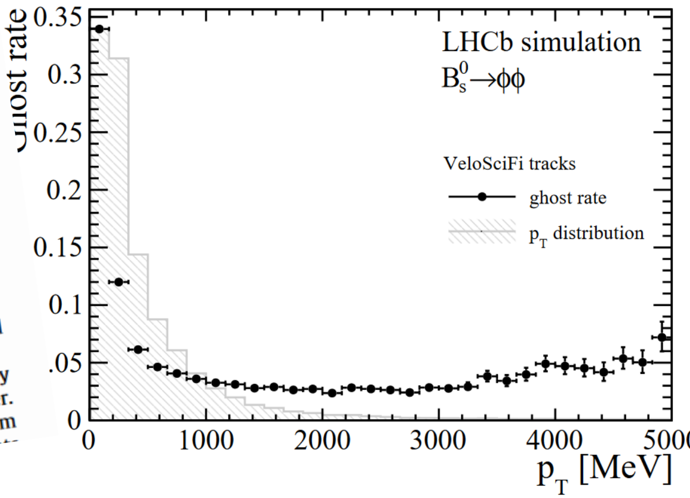
The LHCb detector [1] is undergoing a major upgrade in preparation of the Run 3 data taking at the LHC, starting in 2021 [2]. The expected delivered instantaneous luminosity is $\mathcal{L} = 2 \times 10^{33}$ cm^2 s^{-1}, corresponding to an average of seven proton–proton interactions per bunch collision.

The entire charged particle reconstruction (tracking) system of the LHCb detector is renewed as part of this upgrade. In

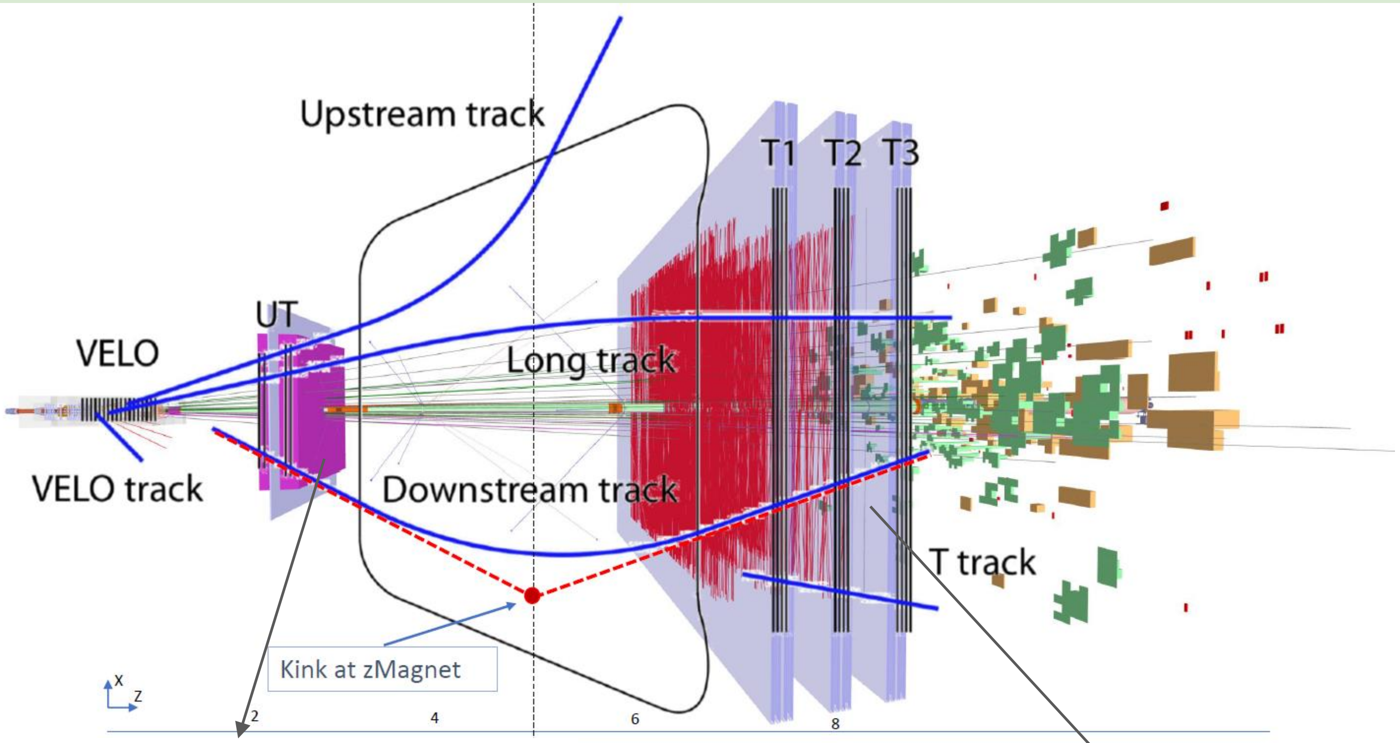
configuration (x-u-v-x). For the sake of mechanical stability, the scintillating fibres in the x-layers are strictly vertical, so that they have a slight tilt with respect to the y axis, which is perpendicular to the beam axis in the usual LHCb coordinate system. The u/v layers are rotated in the x–y plane by the stereo angle, α, equal to $+5°$ and $-5°$ for the u and v layers, respectively.

An algorithm relying solely on the information provided by this tracker, called Hybrid seeding, is described in this paper. This algorithm allows an efficient reconstruction of tracks from



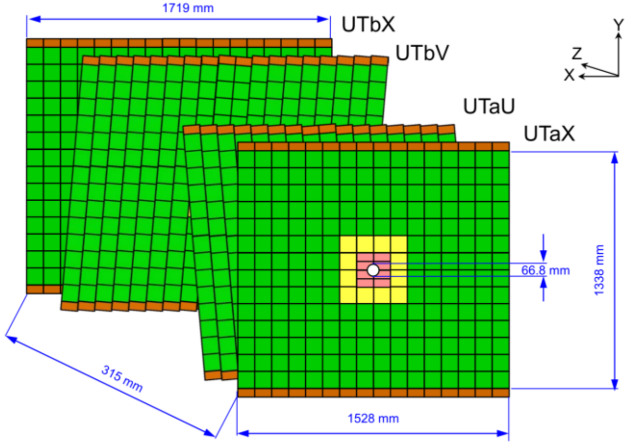


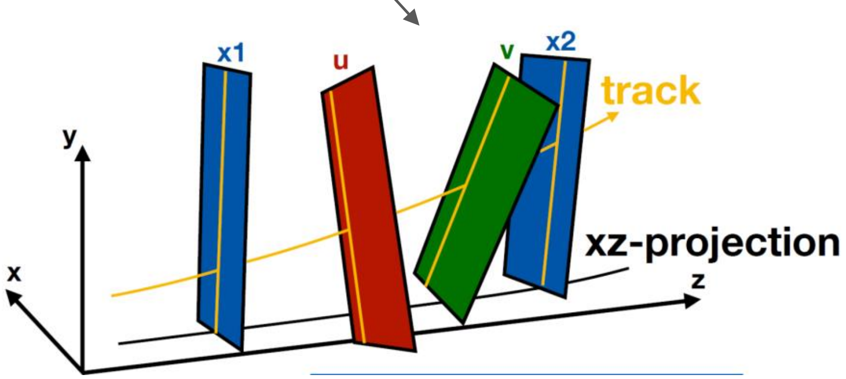
Downstream algorithm: design strategy



Extrapolate SciFi seeds to UT

- Take the output of SciFi seeding
- Filter out the used seeds
- Extrapolate to UT stations (through *magnet point*)



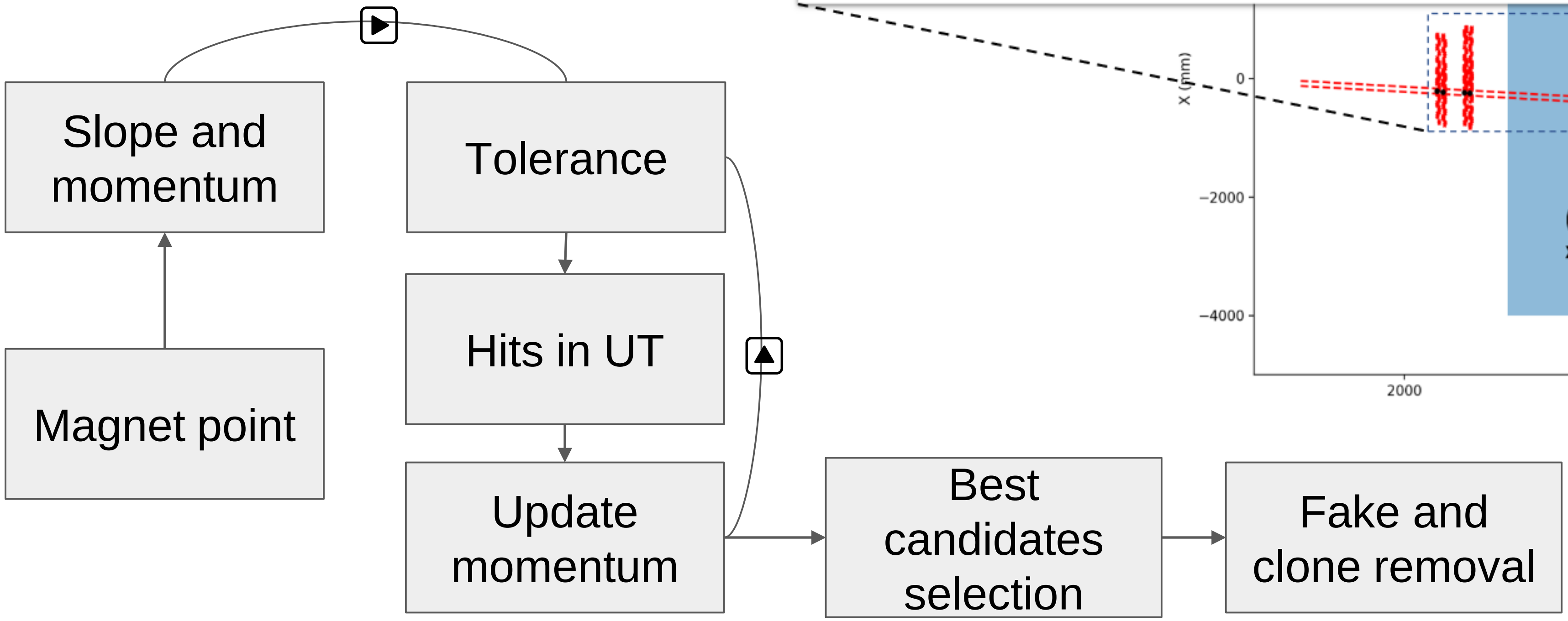


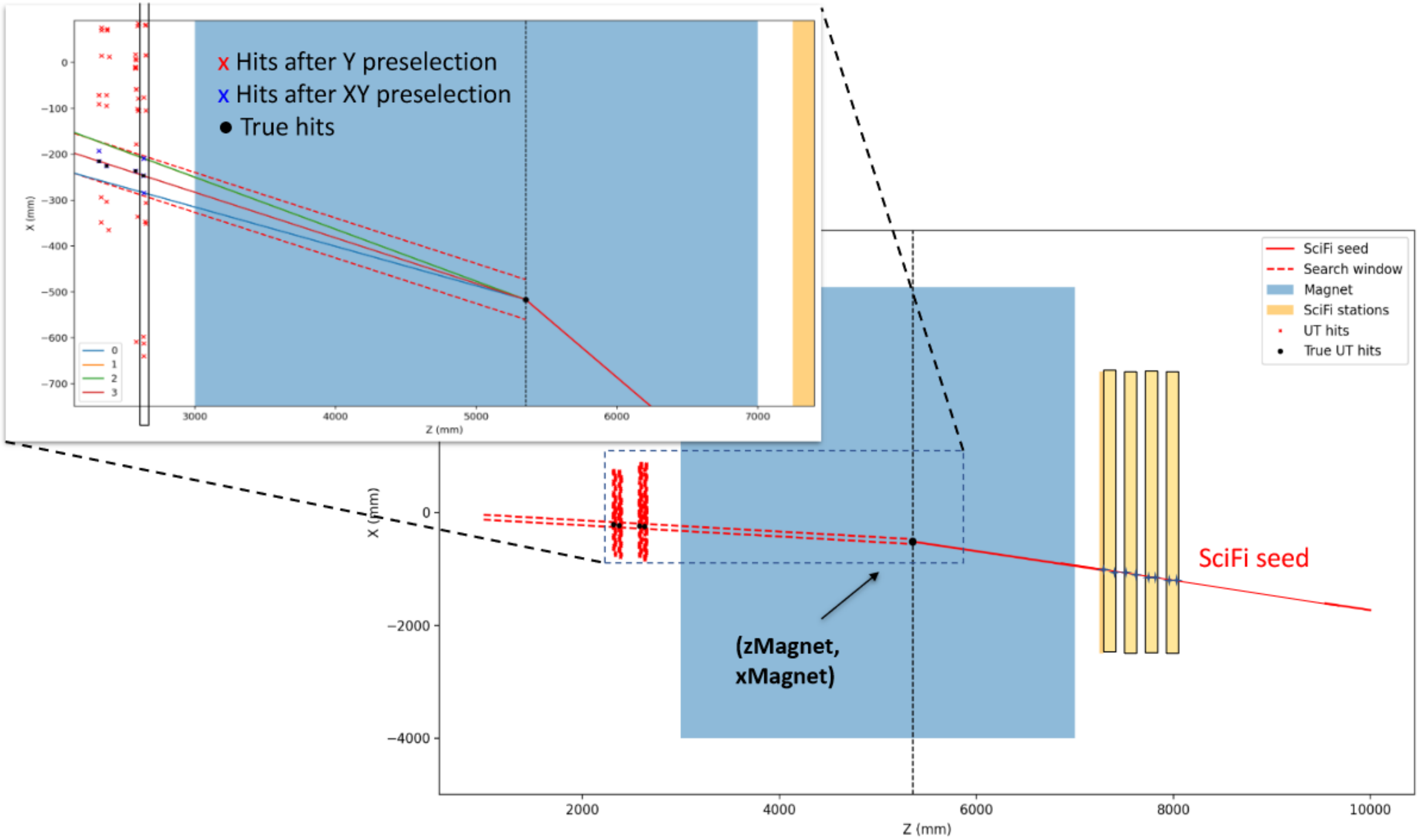
Downstream algorithm: track model

Track state:

$$\vec{S}_i = (x, y, t_x, t_y, q/p)^T$$

Tracking model:





Downstream algorithm: implementation

Algorithm is divided into 3 main kernel functions:

Kernel function 1:
128 SciFi seeds per thread block

- Filtering used SciFi seeds
- For each input SciFi seed, extrapolate to last x layer (UTbX)
- Store up to 10 best candidates
- Update slope of each candidate using magnet point and hit position.

Kernel function 2:
256 candidates per thread block

- Add hits from rest of the UT layers
- Find best combination of U/V hits
- Compute the scores based on distance b/w extrapolation and real UT hit positions

Kernel function 3:
256 candidates per thread block

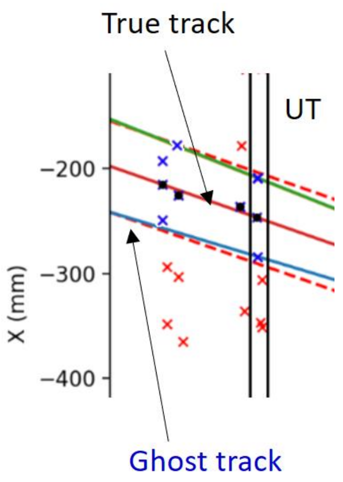
- Find best candidate based on the scores from previous function
- Check for hit duplication
- Perform ghost killing

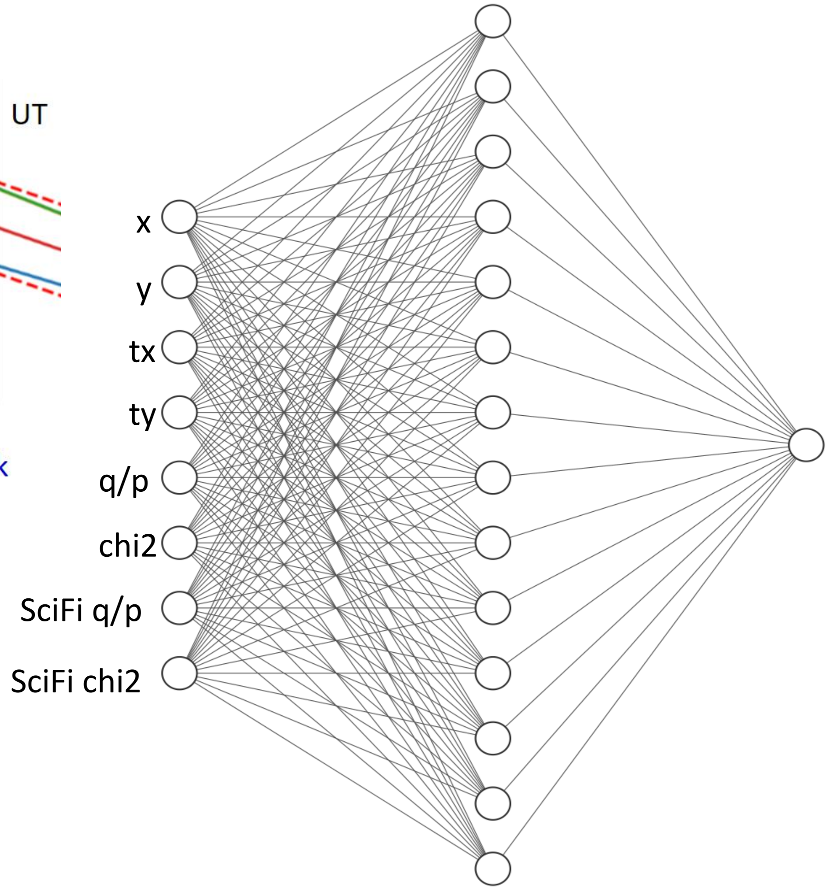
Prepare output:

- Copy hits and tracks to output (compact SOA container)
- Create standard multi-event viewer

Downstream algorithm: ghost killer neural network

- A single hidden (14 nodes) layer fully connected NN
- It utilizes **8 variables** as input:
  - *Downstream* track state ($\mathbf{x, y, t_x, t_y, q/p, \chi^2}$)
  - SciFi track properties ($\mathbf{q/p, \chi_y^2}$)
- 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**.





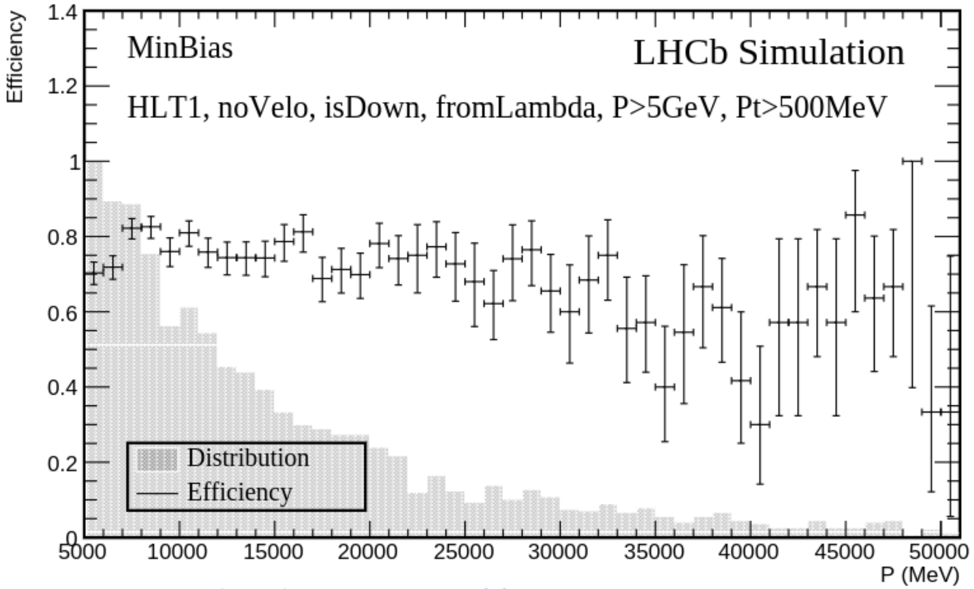

```
namespace DownstreamGhostKiller {

  namespace Model {
    constexpr unsigned num_node = 14;
    constexpr unsigned num_input = 8;
```

```
...
namespace ActivateFunction {
  // rectified linear unit
  __device__ inline float relu(const float x) {
    return x > 0 ? x : 0;
  }
  // sigmoid
  __device__ inline float sigmoid(const float x) {
    return __fdividef(1.0f, 1.0f + __expf(-x));
  }
} // namespace ActivateFunction
```

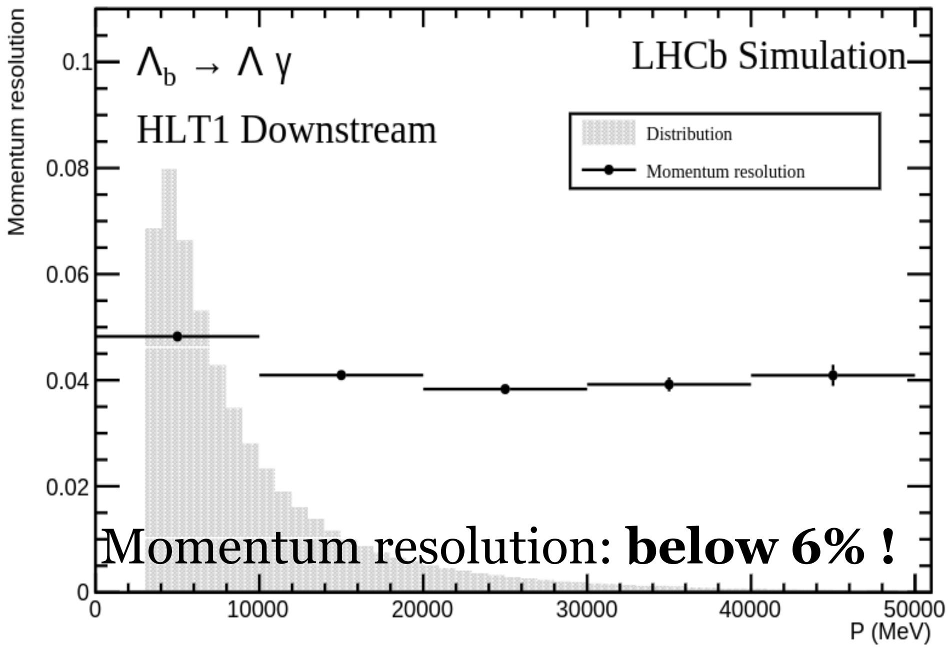
```
// First layer
DownstreamHelpers::unwind<0, Model::num_node>([&](int i) {
  DownstreamHelpers::unwind<0, Model::num_input>([&](int j) {
    h1[i] += input[j] * Model::weights1[i][j];
  });
  h1[i] = ActivateFunction::relu(h1[i] + Model::bias1[i]);
});
```

Downstream algorithm: Physics performance Λ and K_s

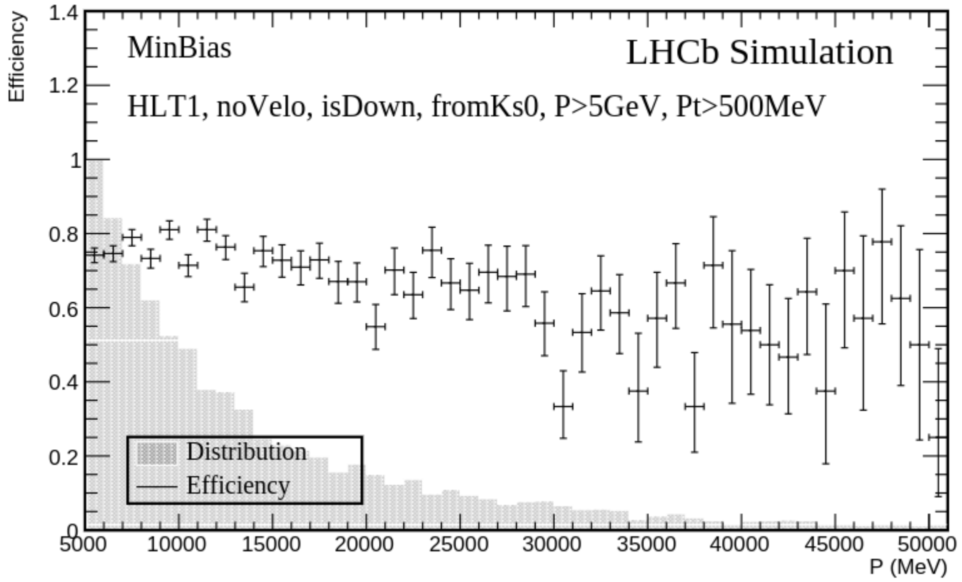
LHCb-FIGURE-2023-028

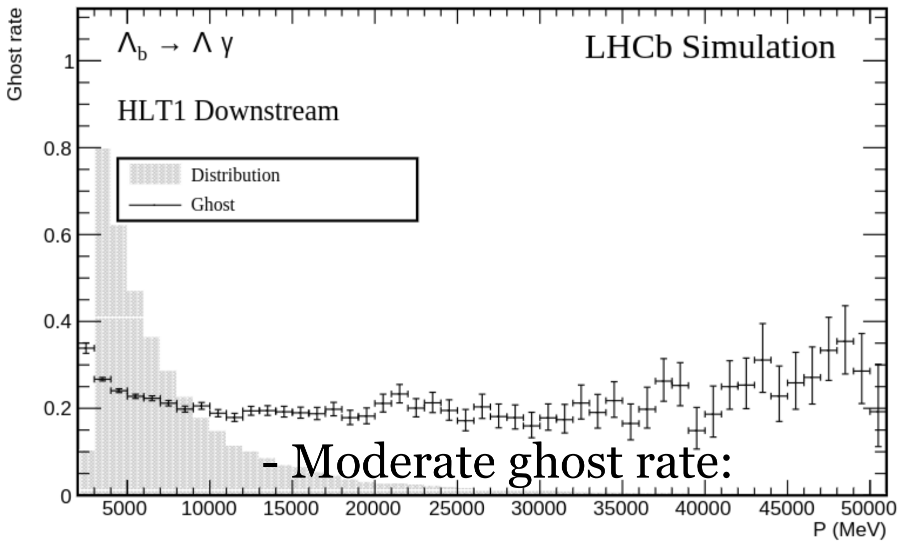


- Good physics efficiency: **<u>75-80%</u>**



Momentum resolution: **below 6% !**





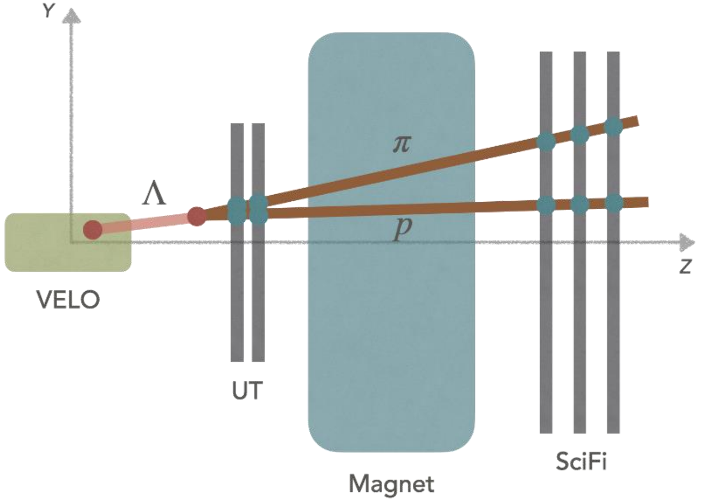
- Moderate ghost rate:

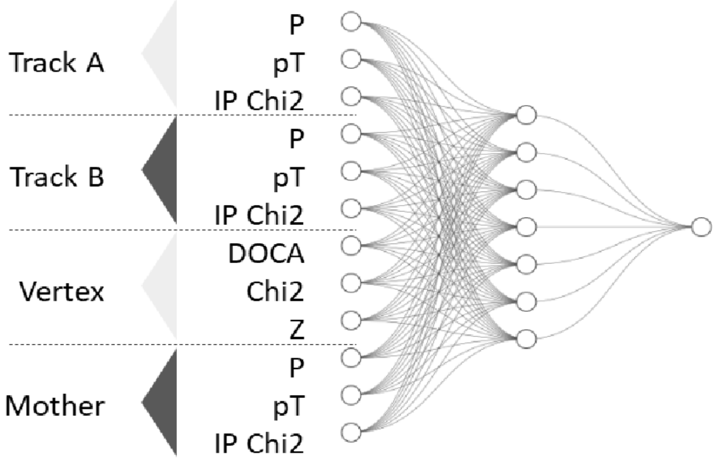
Trigger lines using HLT1 *Downstream*

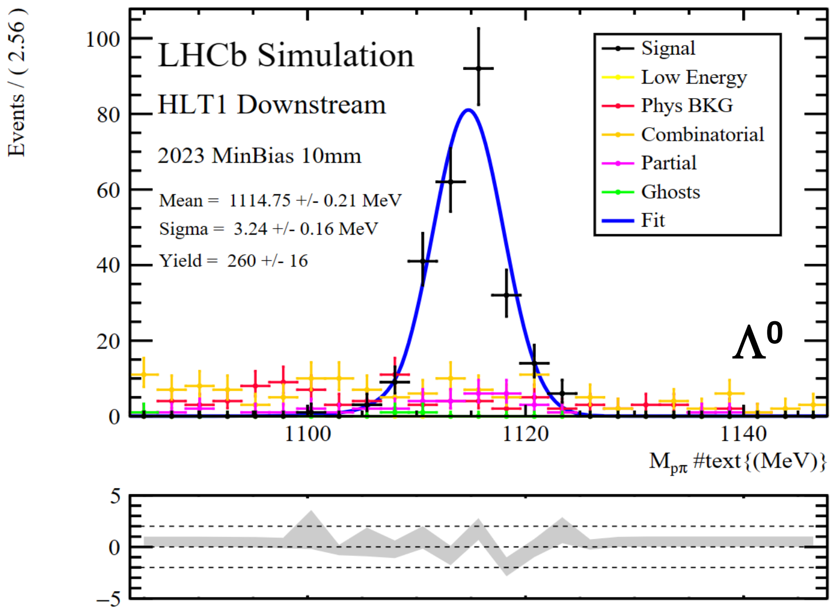
For developing the trigger (selection) lines for decays involving two tracks (Λ's and K_s's) requires **vertexing.**

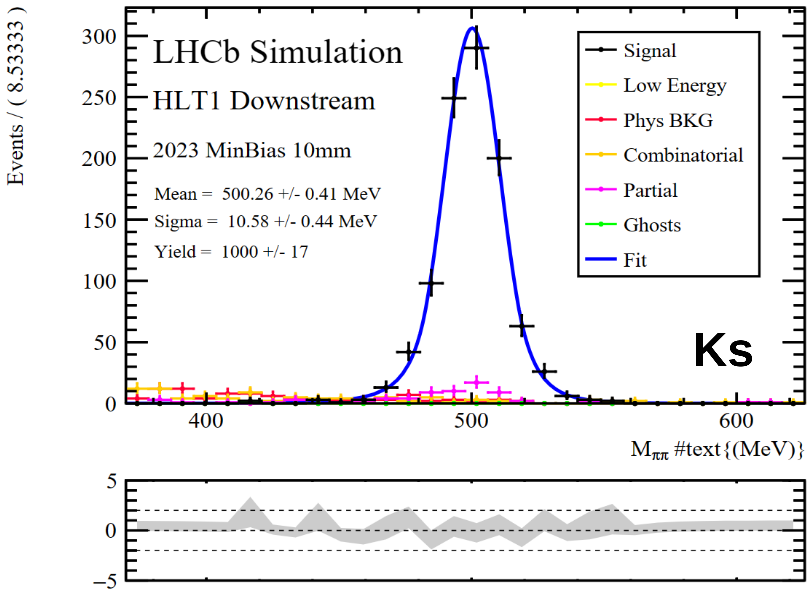
- Vertex reconstruction of two downstream tracks requires extrapolating from UT to the origin vertex

- High throughput with good background rejection in selection lines.





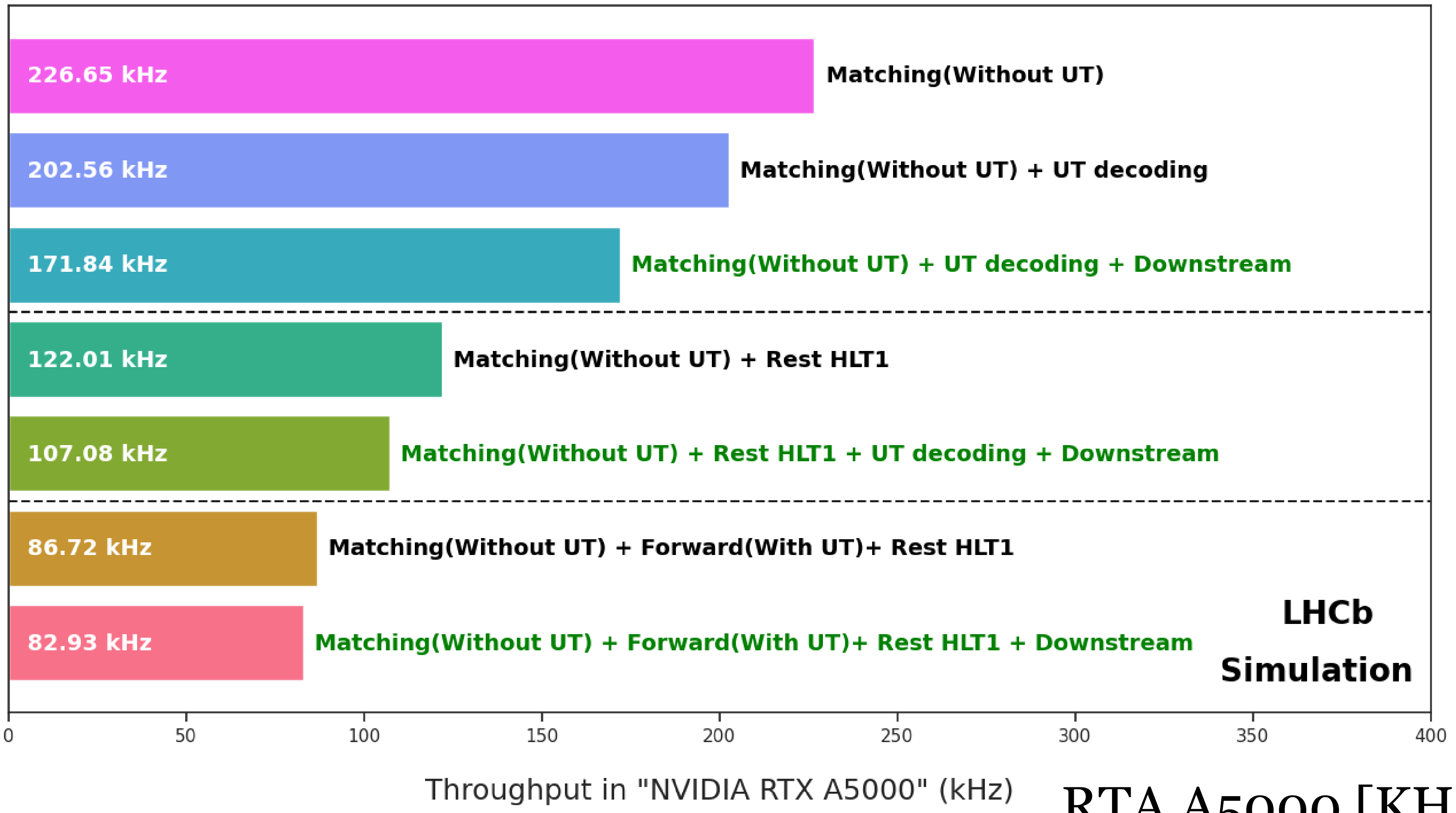




Downstream algorithm: Throughput of HLT1 sequences (Today)

HLT1 sequence for *long* and *downstream* tracking reconstruction:

LHCb-FIGURE-2023-028

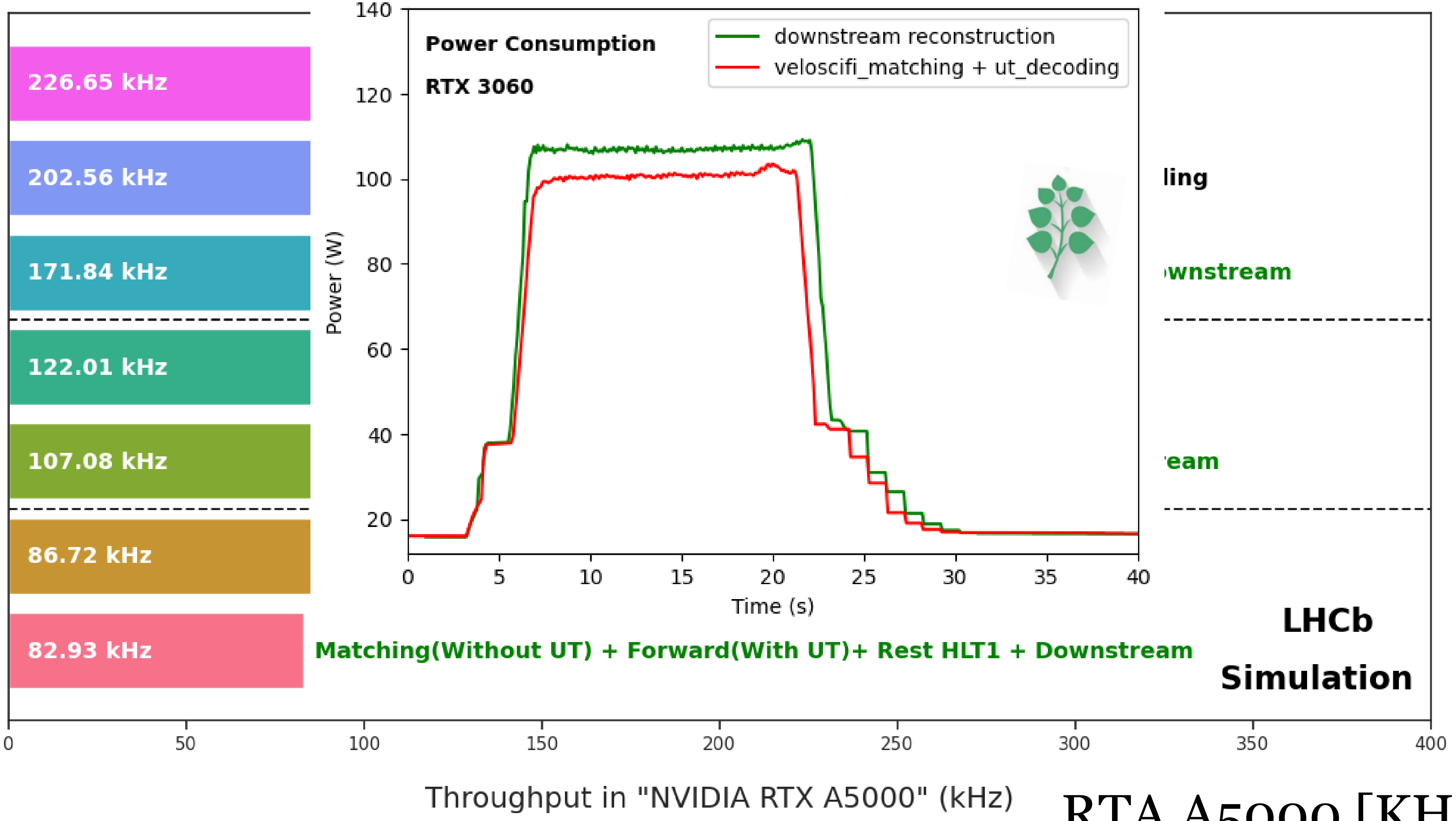


RTA A5000 [KHz]

Downstream algorithm: Throughput of HLT1 sequences (Today)

HLT1 sequence for *long* and *downstream* tracking reconstruction:

LHCb-FIGURE-2023-028



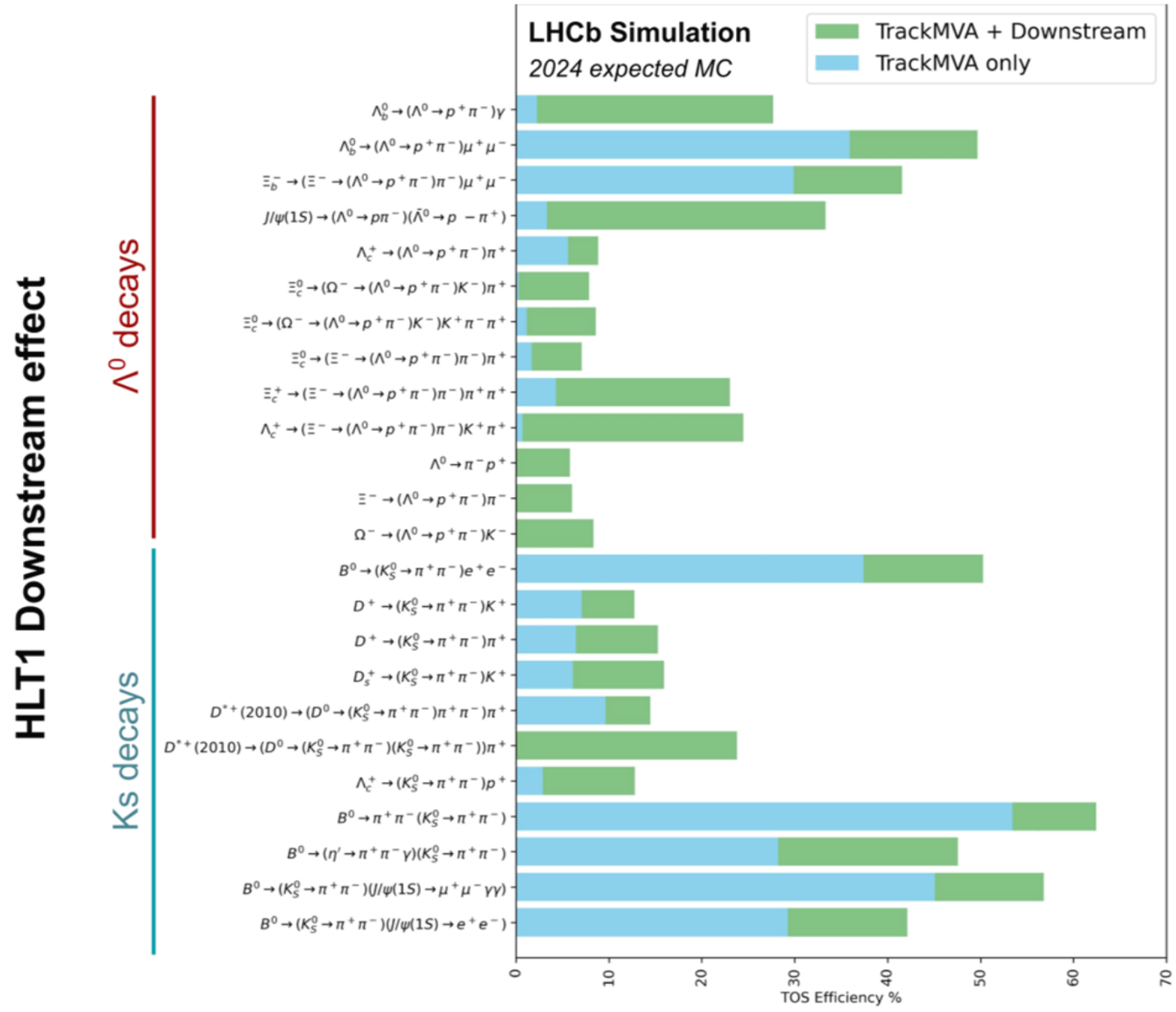
RTA A5000 [KHz]

Physics impact of *Downstream*

Physics impact of *Downstream:* SM

Impact on many other decay channels

Channel	DD/LL proportion	Interest
***b*-hadron decays**		
$\Lambda_b^0 \to \Lambda\gamma$	3.4	γ polarization, BR
$\Xi_b^- \to \Xi^-\gamma$	25	γ polarization, BR
$\Omega_b^- \to \Omega^-\gamma$	13	γ polariation, BR
$B^+ \to K_S^0 K_S^0 \pi^+$	2.8	CPV, BR
$B^+ \to K_S^0 K_S^0 K^+$	2.7	CPV, BR
$B_s^0 \to K_S^0 K_S^0$	3.6	CPV, BR
Charm physics		
$\Lambda c^+ \to \Lambda K^+$	4.4	Polarization studies
$\Xi_c^- \to \Xi^-\pi^-$	8.4	Polarization studies
$D^0 \to K_S^0 K_S^0$	1.8	CPV
$J/\psi \to \Lambda\bar{\Lambda}$	4.8	Polarization studies, BR
Strange physics		
$K_S^0 \to \mu^+\mu^-$	0.6	BR
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	0.8	BR
$K_S^0 \to \gamma\mu^+\mu^-$	0.8	BR

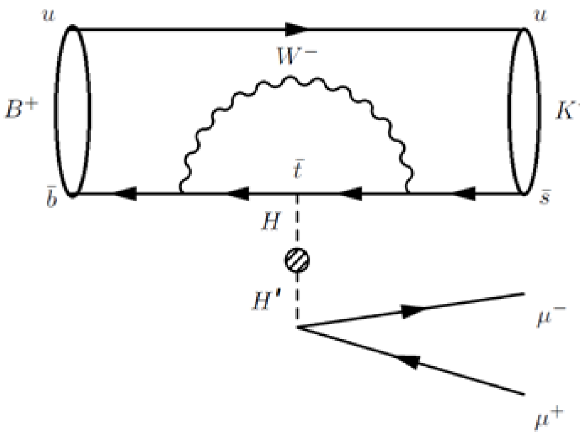


Physics impact of *Downstream: BSM*

LHCb's capabilities of probing BSM physics can significantly increase due to *Downstream* tracking at HLT1

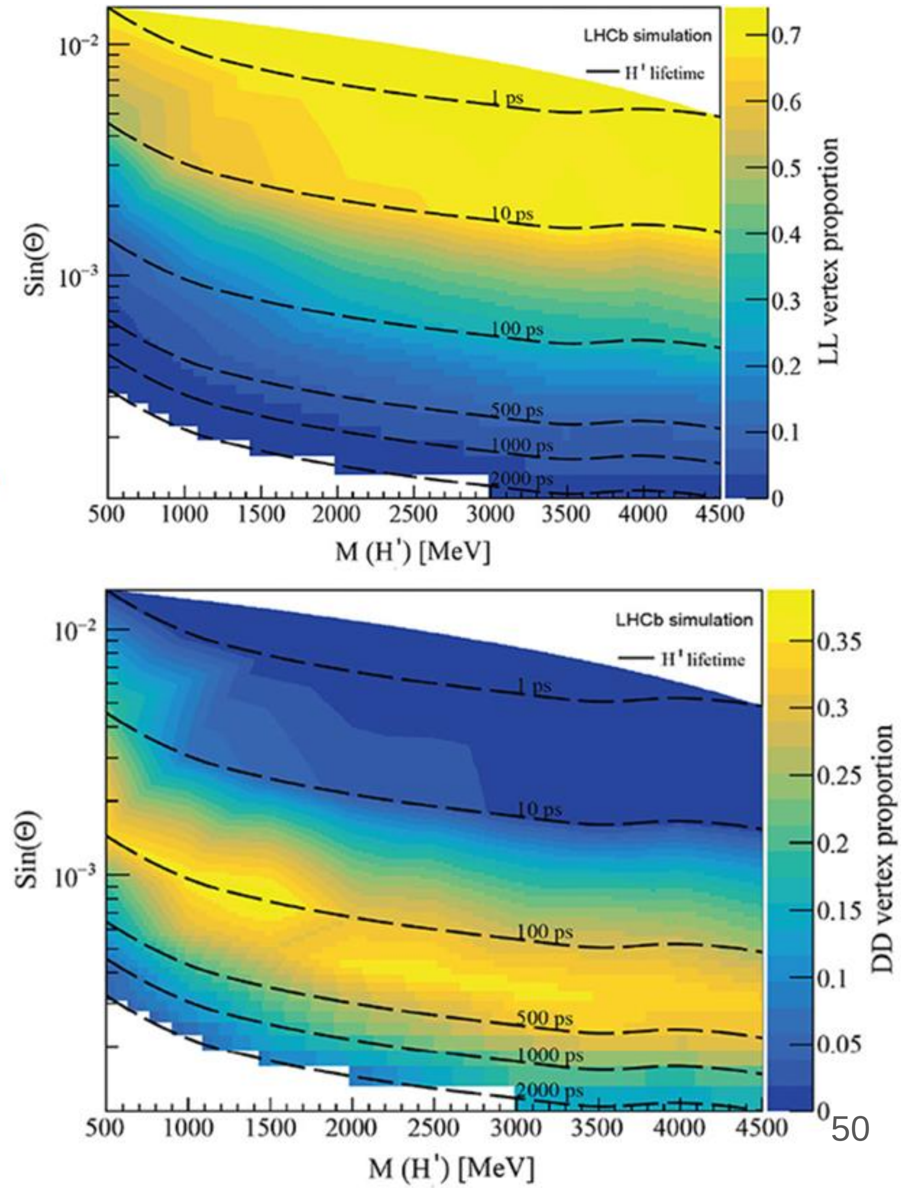
Dark boson in the Hidden sector: the SM Higgs mixes with H'

h = H cos θ + H' sin θ



$$\Gamma(H' \to \ell\ell) = \sin^2\theta \frac{G_F m_{H'} m_\ell^2}{4\sqrt{2}\pi}\left(1 - \frac{4m_\ell^2}{m_{H'}^2}\right)^{3/2}$$

$B \to H'(\to \mu^+\mu^-)K$



Impact of the trigger on H' signal (TOS) at HLT1 level:

- High suppression for low H' mass for t < 10ps
- Strong suppression for t > 10ps in all range of H' masses

Physics impact of *Downstream: Growing interest*

2312.14016

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

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the date of receipt and acceptance should be inserted later

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

PACS. IMSc/2023/06/09

Physics impact of *Downstream: LHCb as lifetime frontier experiment*

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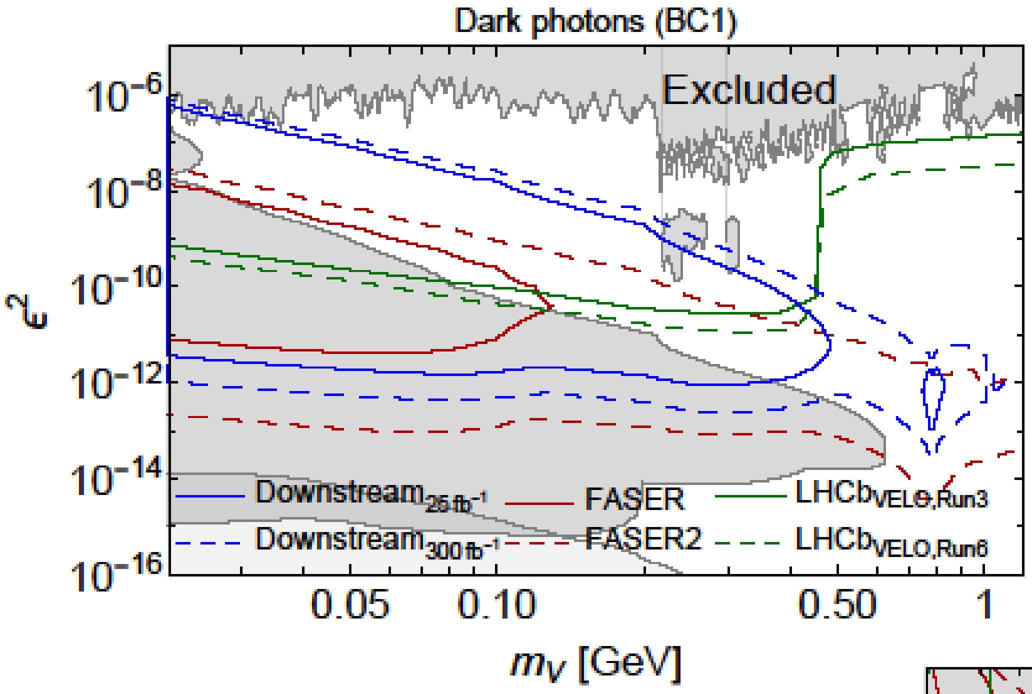

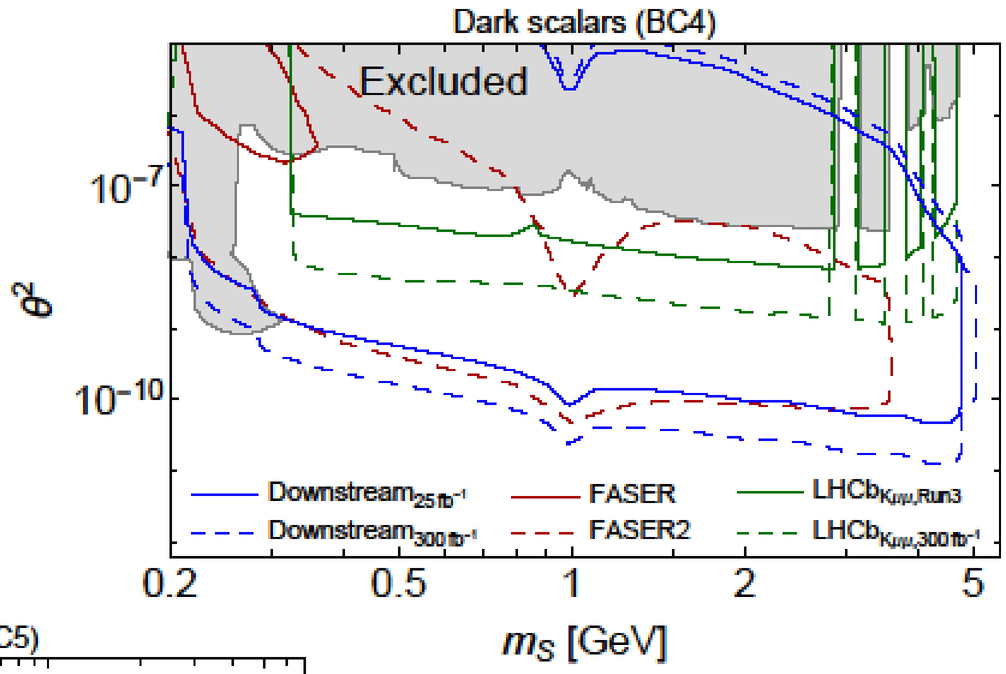

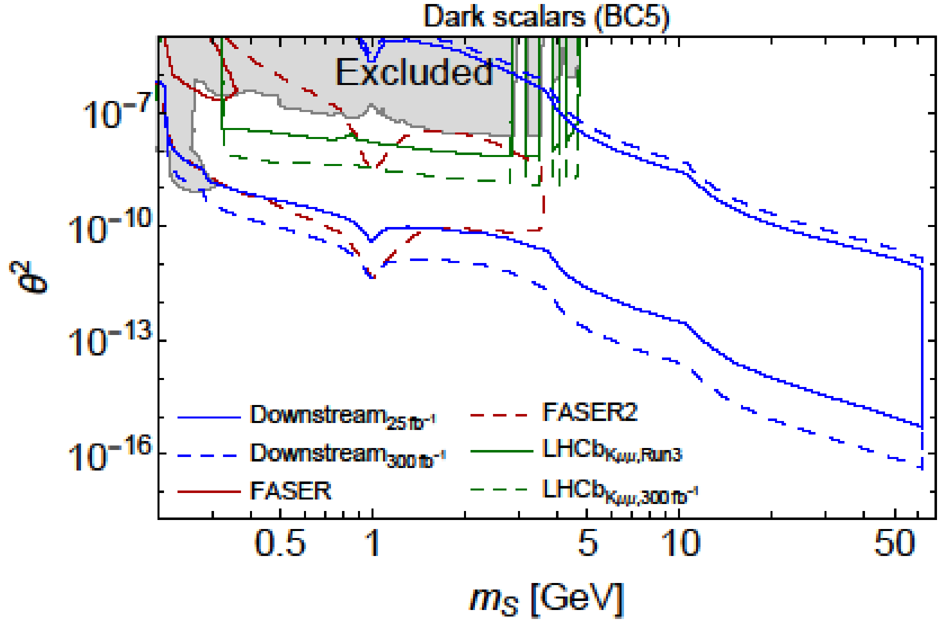

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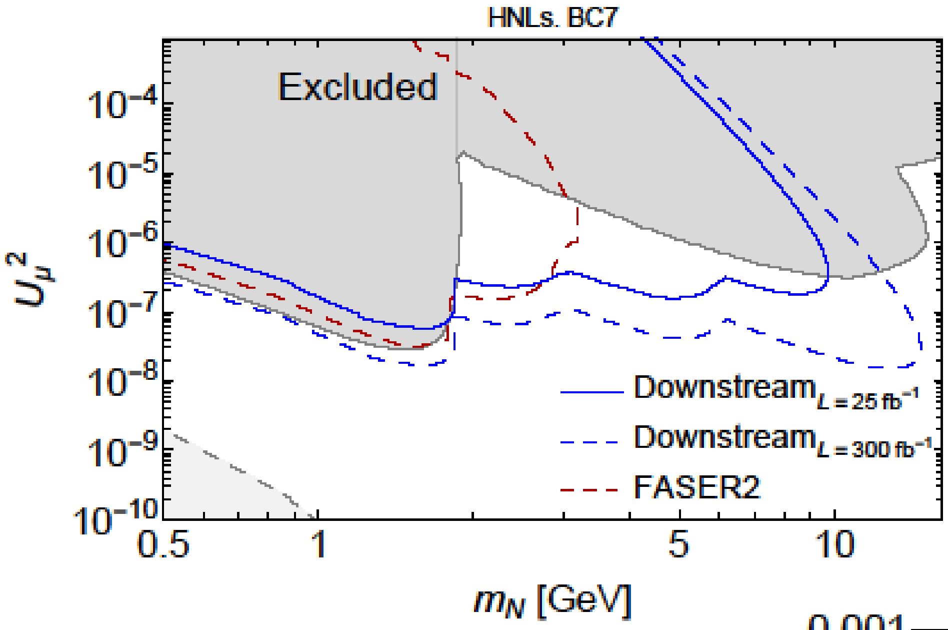

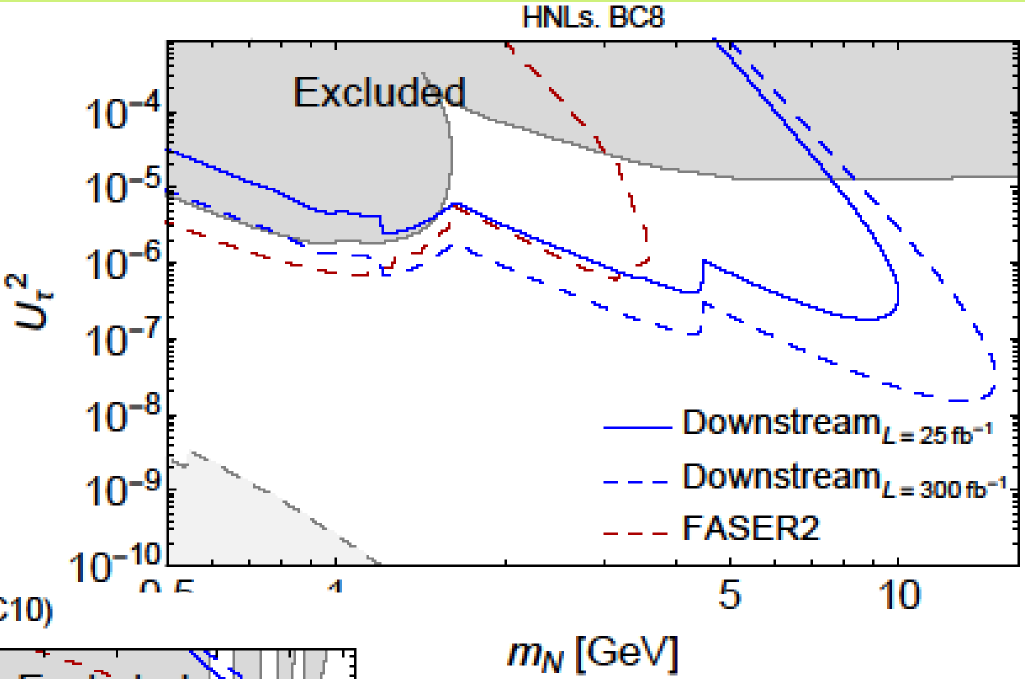

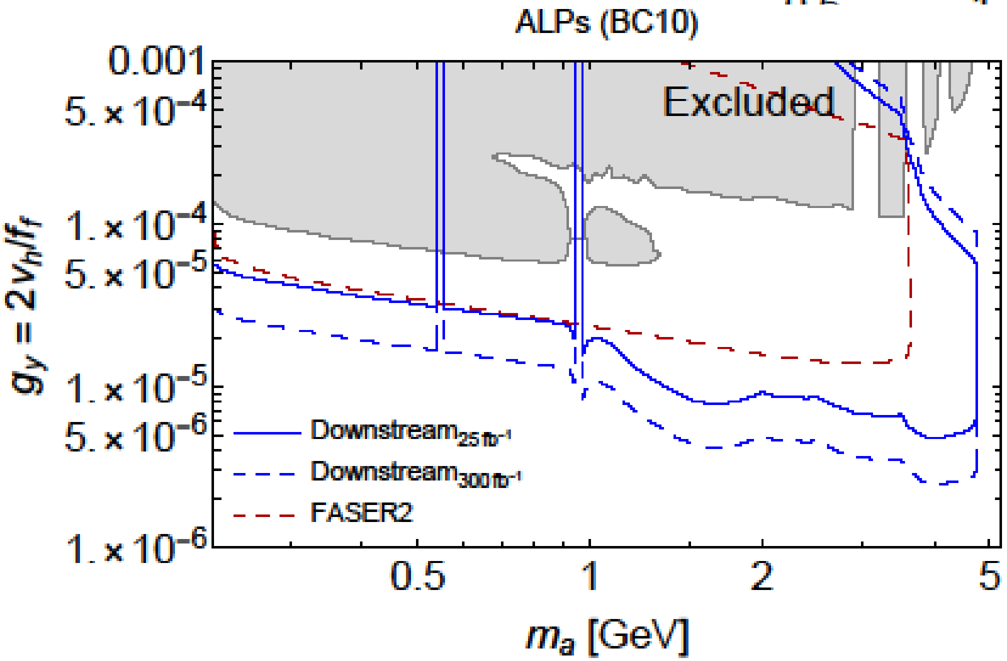

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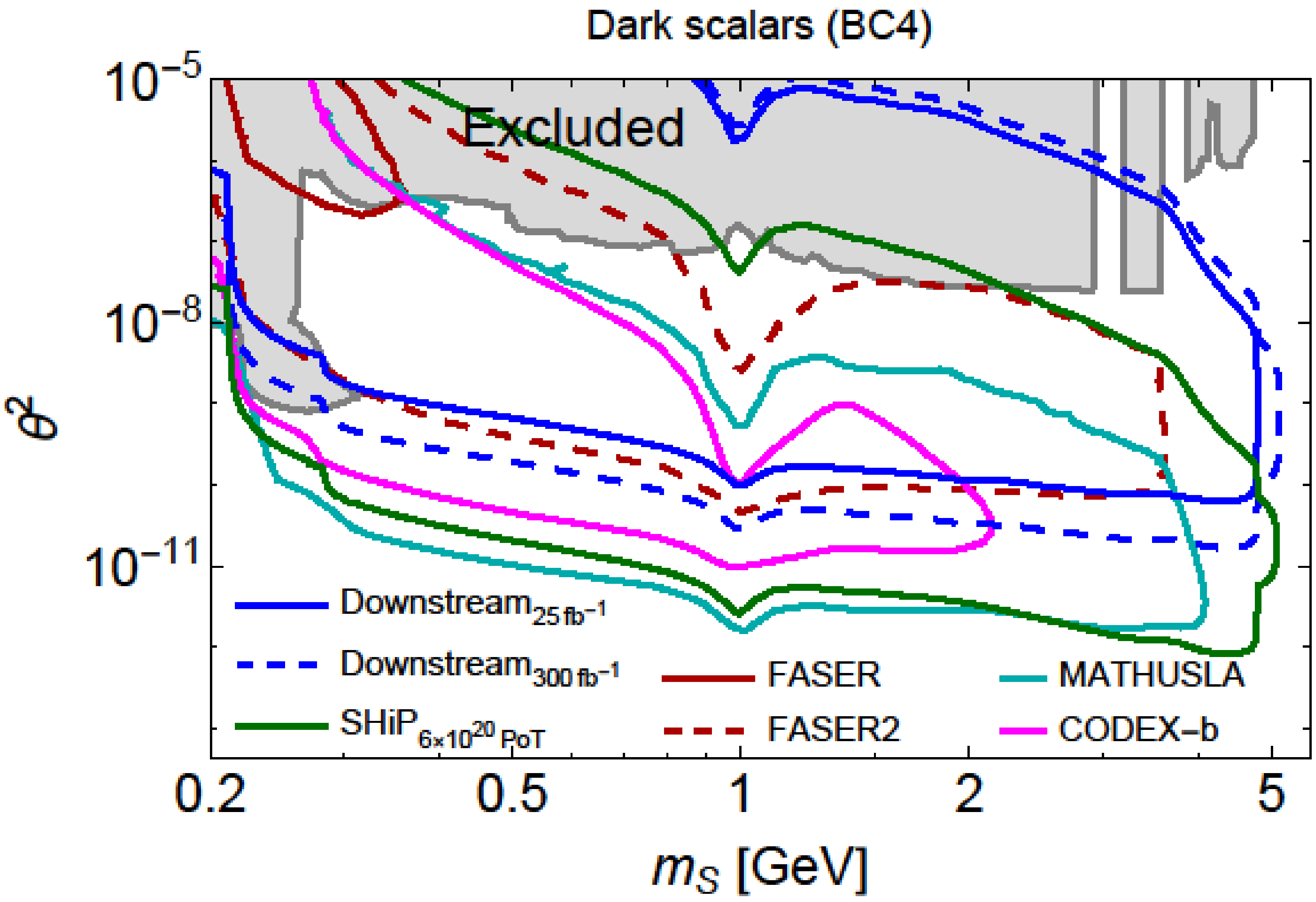


Summary

- LHCb as lifetime frontier experiment
  - In Run1 and Run2 LHCb could probe lifetimes of upto 100 ps
  - But now in Run3 with new HLT1 with downstream algorithm it is possible to probe BSM physics for lifetimes from 100 ps to 2000 ps.
  - Not just the BSM, but also huge impetus to the physics program with SM LLPs
  - Huge physics gains made possible by investing in software and algorithms.

Thank you

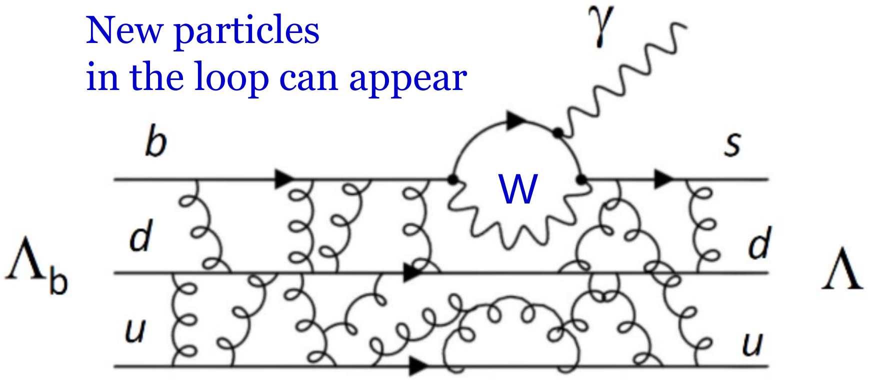
LLPs in the SM:

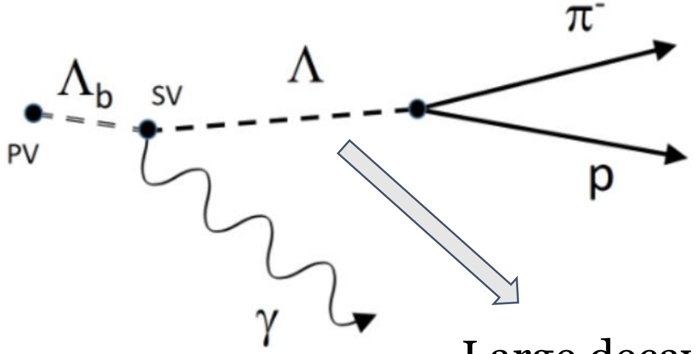
Strange particles:

- K_s are common decay products in *b* and charm decays → important for CPV studies
- Λ are decay products of *b*-baryon decays which have a rich spin structure

E.g - the rare radiative decay $\Lambda_b \to \Lambda\, \gamma$ is very sensitive to BSM physics

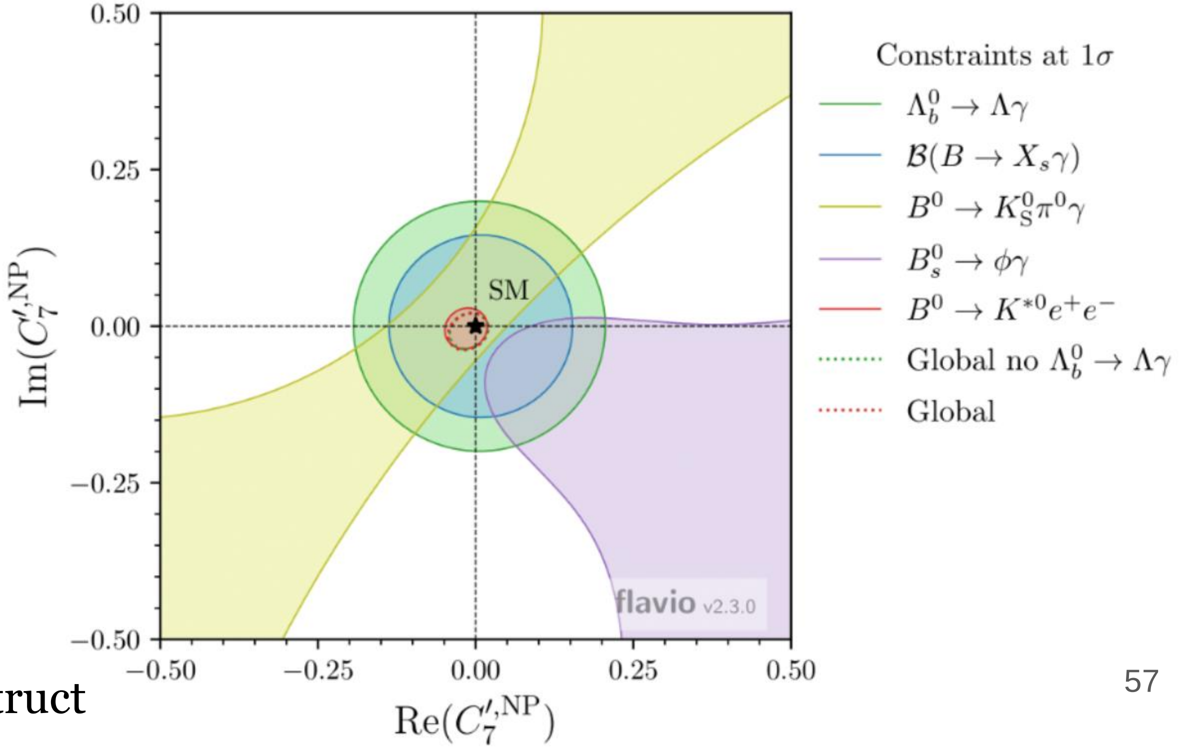
New particles
in the loop can appear





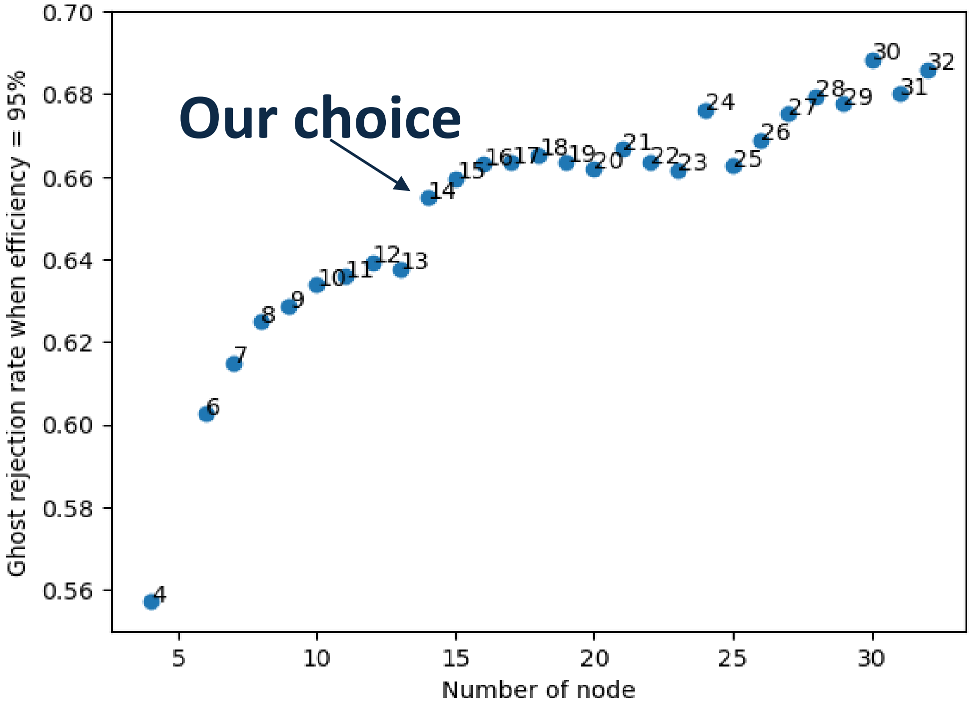
Large decay length
($c\tau$= 8cm) → difficult to reconstruct

→ Measurement of the branching ratio
→ Measurement of the photon polarization



Algorithm design: ghost killer neural network

Ghost rejection vs number of nodes in the hidden layer



Num Operation = Num Input * Num node

Distribution of the classifier output: default threshold value 0.5