The LHCb trigger system

In Run 3 scope (2022-2026)

on behalf of LHCb collaboration

LHCb experiment

LHCb in a nutshell:

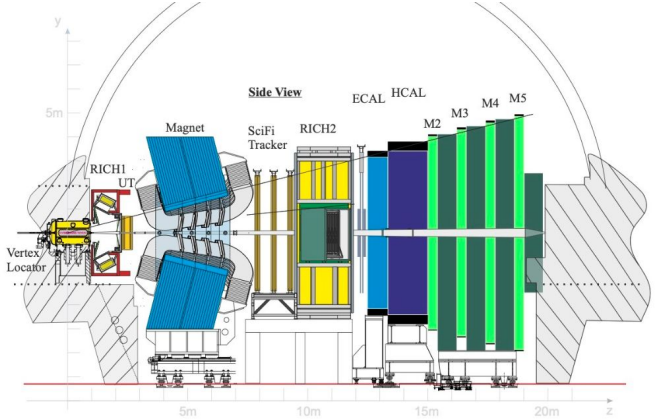
- Precision measurements in Heavy Flavour Physics
- Many research fields - rare decays and CPV (core program), but also spectroscopy, QCD, heavy ions…

JINST 3 (2008) S08005 – The LHCb experiment

- Now in the middle of Run 3 (2022 - 2026)

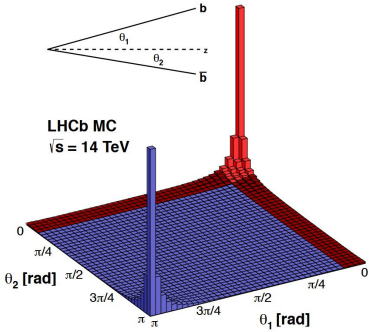
LHCb-DP-2022-02 – The LHCb Upgrade I

- Spectrometer well-instrumented in forward region
- Designed to run with 40 MHz readout and at instantaneous luminosity L = 2×10^{33} cm^{-2} s^{-1}
- Upgrade II in the scoping phase



LHCb spectrometer
JINST 19 (2024) P05065

Distribution of b-quark pairs
How b pairs distribute after produced in collisions and go into the same cone (red color - at least one from the pair seen in LHCb forward acceptance)

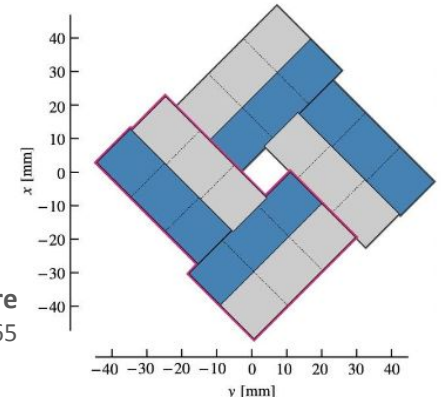


LHCb tracking detectors

Vertex Locator (VELO) - surrounds the beams collision region, primary vertex reconstruction

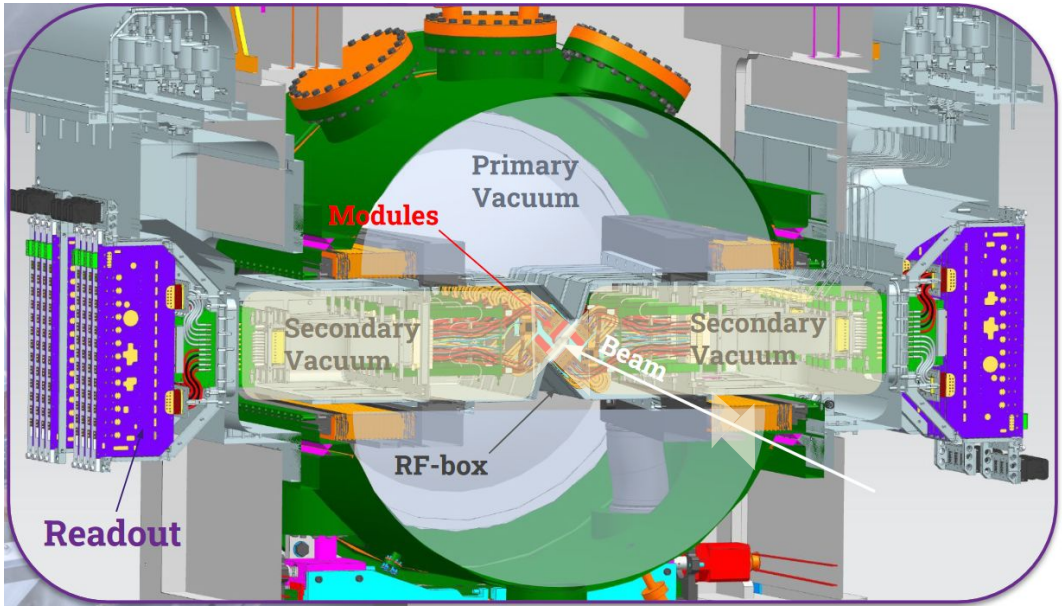
Upstream Tracker (UT)

Scintillator Fibres (SciFi)



VELO aperture
JINST 19 (2024) 05, P05065

Vertex Locator
The scheme of front view of the detector with readout boards and a vacuum tank. CERN-LHCC-2013-021

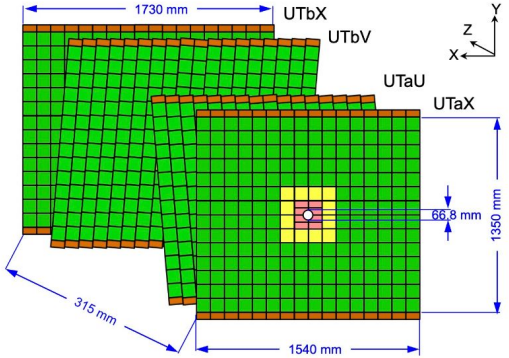


LHCb tracking detectors

Vertex Locator (VELO)

Upstream Tracker (UT) - covers the plane before LHCb Magnet

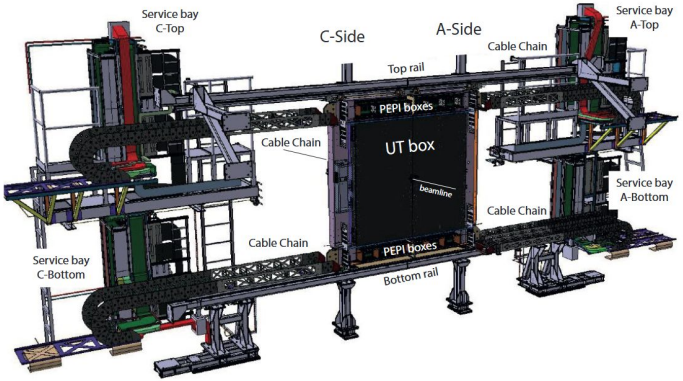
Scintillator Fibres (SciFi) - covers the wide plane after the LHCb Magnet



Silicon planes of Upstream Tracker
JINST 19 (2024) 05, P05065

Scintillator Fibres
The front and profile view of detector planes
JINST 19 (2024) 05, P05065

Upstream Tracker
The detector together with mechanical setup
JINST 19 (2024) 05, P05065



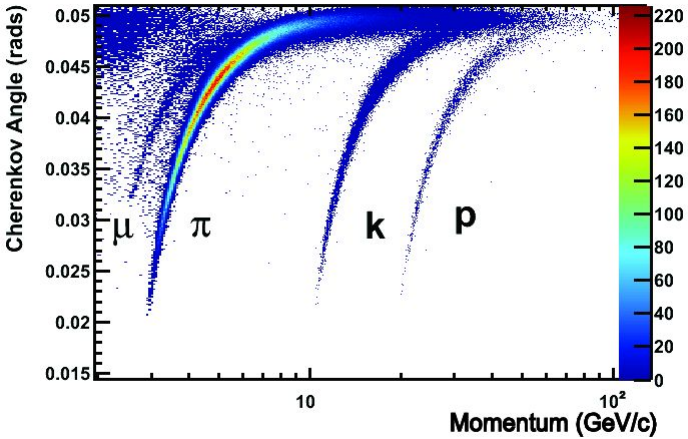
LHCb PID detectors

2 Ring-Imaging Cherenkov detectors (RICH1 & RICH2)

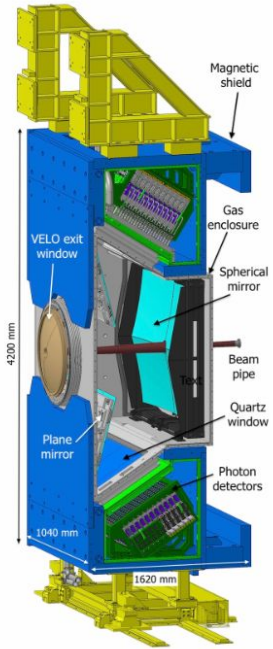
Calorimeters (ECAL and HCAL)

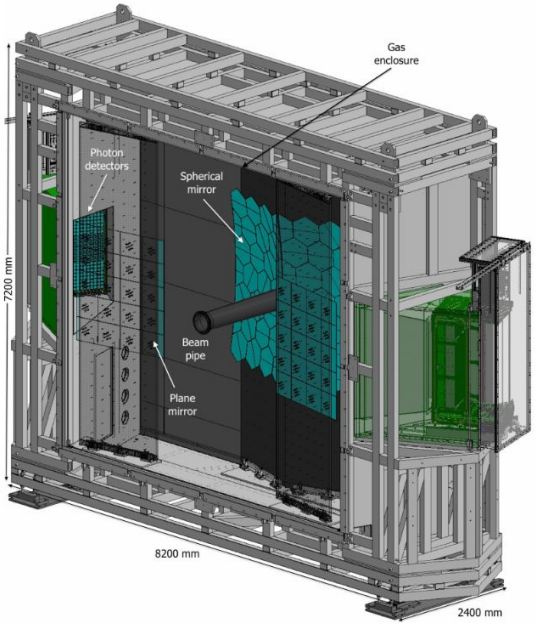
Muon system

Reconstructed Cherenkov angle as a function of track momentum in the C4F10 radiator in RICH1
LHCB-DP-2012-003



RICH detectors
Schematic view of RICH1 (left) and RICH2 (right)
from JINST 17 (2022) C11006





LHCb PID detectors

2 Ring-Imaging Cherenkov (RICH1 & RICH2)

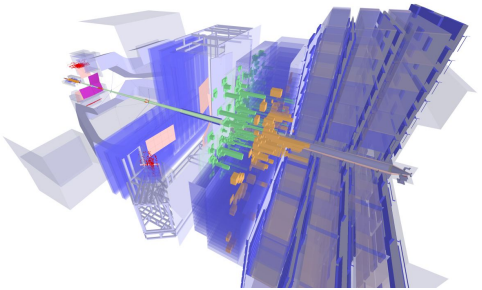
Calorimeters (ECAL and HCAL)

Muon system

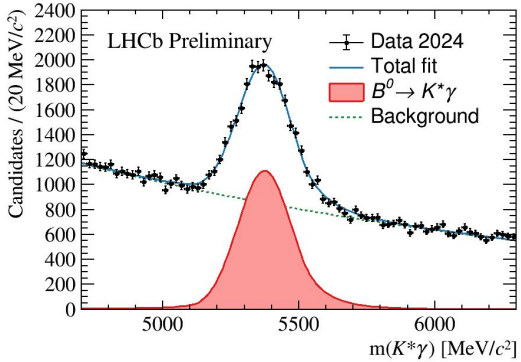
Muon chambers
Floor view between M1 and M2
LHCb-PHO-BEPI-2009-001-1

Calorimeters
ECAL (front) and HCAL (back) view after installation

LHCb Event Display
LHCb-PHO-GEN-2022-001
A 13.6 TeV pp-collision event in LHCb, red chunks for RICH light, green and yellow for ECAL and HCAL.

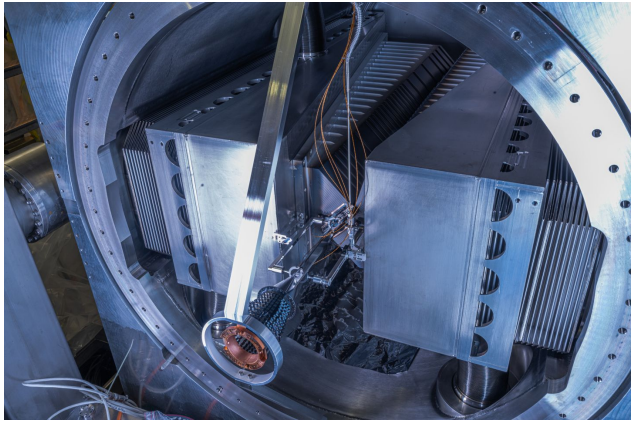


ECAL performance on a benchmark K*γ, mass distribution for up to July 2024
LHCb-FIGURE-2024-017



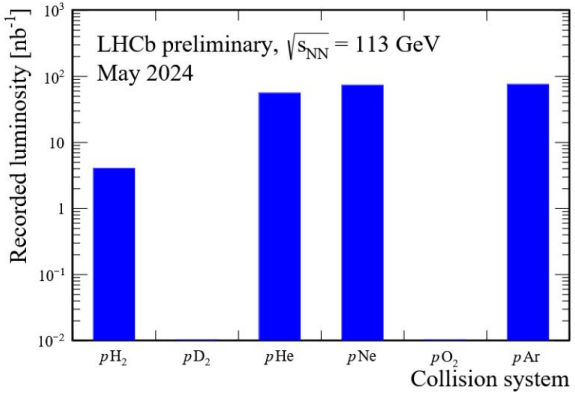
SMOG2 (System for Measuring Overlap with Gas)

- Injects noble gases into beam pipe
- LHCb is highest-energy fixed-target experiment

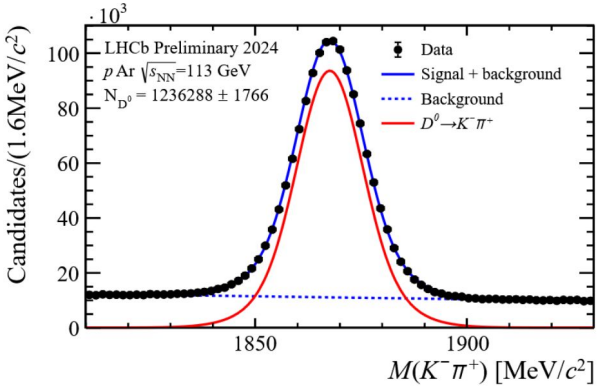


SMOG2 cell
VELO vacuum tank and box in the background
CERN-PHOTO-202008-103

Collected online luminosities with SMOG2 in the different collision systems in May 2024
LHCb-FIGURE-2024-005



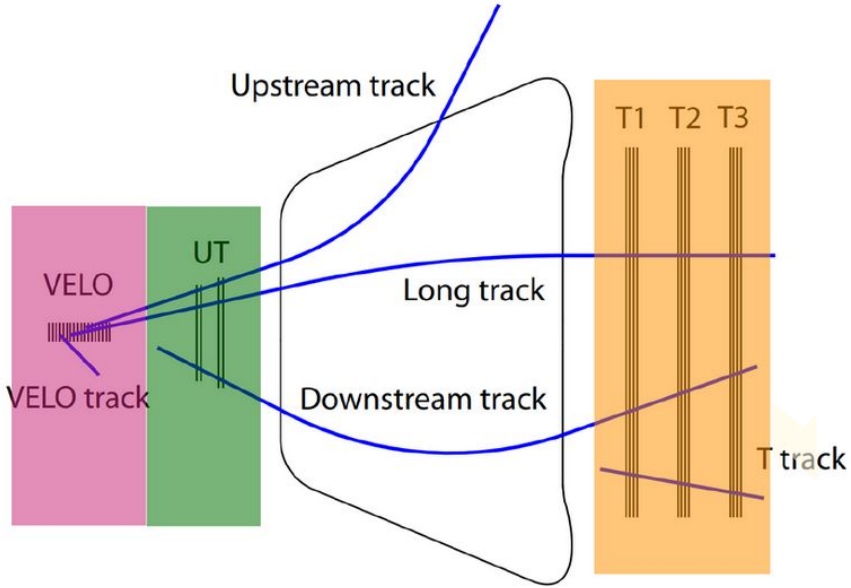
Invariant mass distribution for $K^-\pi^+$ candidates in collisions, collected during 88 hours of Argon injection.
LHCb-FIGURE-2024-023



The track types

Depending on which tracking detectors the charged particle goes through, the LHCb distinguishes the following types of tracks:

- VELO track
- Upstream track
- Long track
- Downstream track
- T track



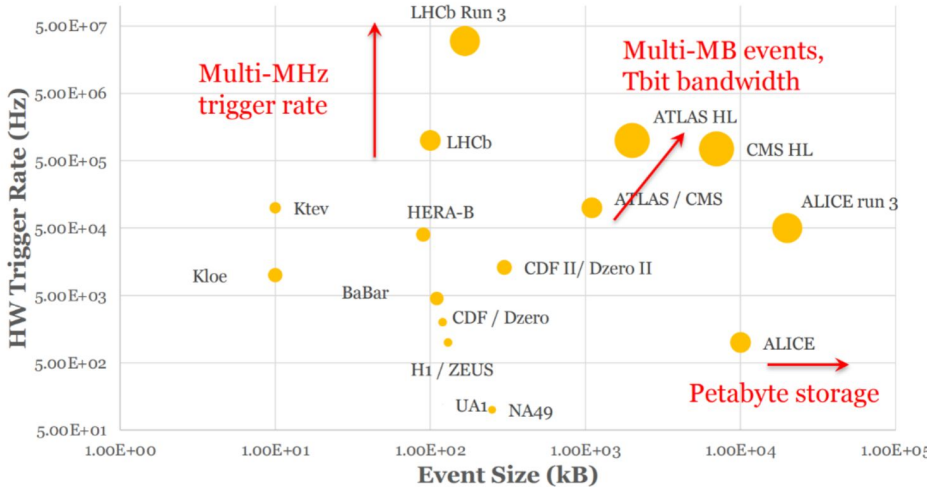
Challenges for trigger

Motivation:

- Physics program of LHCb needs a fully software trigger (multi-MHz trigger rate)

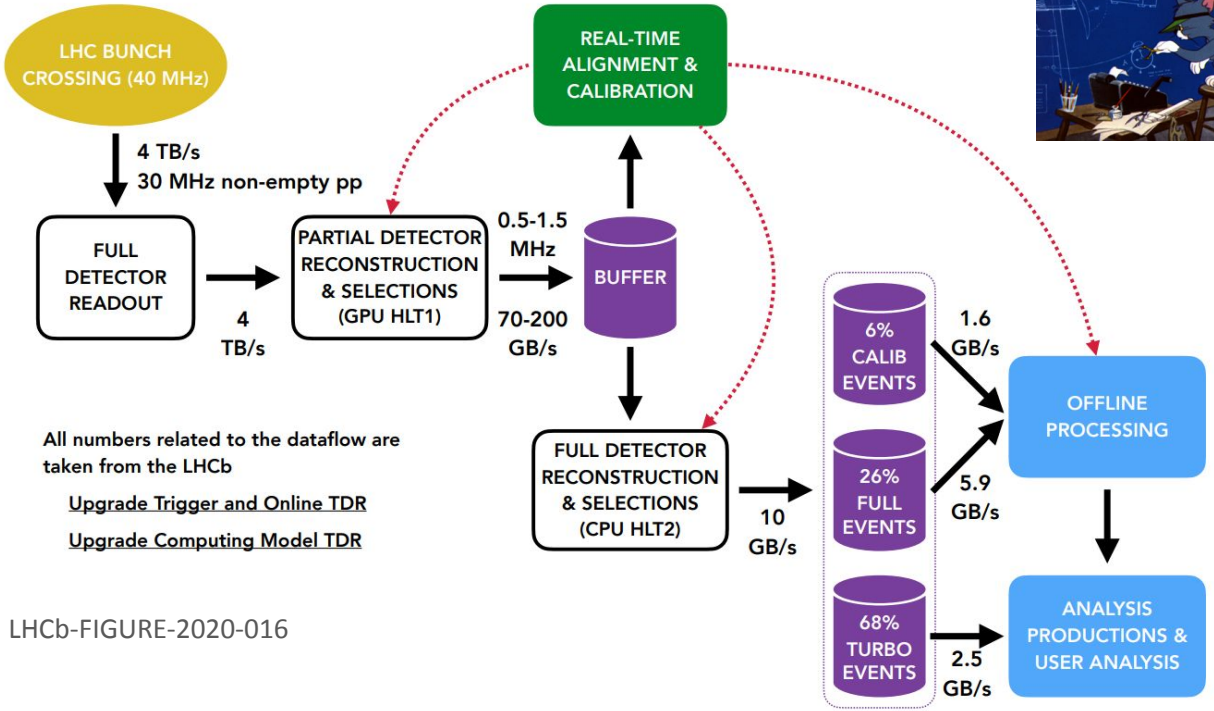
Challenges for the trigger system:

- Trivial case: trigger on interesting events
- Online detector calibration and alignment
- Flexible trigger lines
- Hardware budget and limited storage
- Software quality

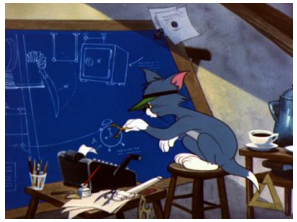


A. Cerri LHCP 2022

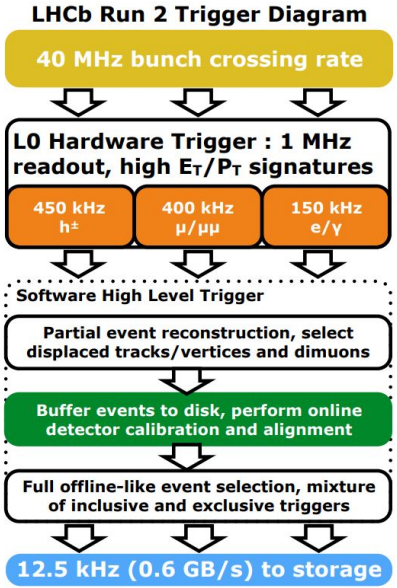
Trigger overview



LHCb-FIGURE-2020-016



A previous (Run 2) trigger scheme:
Hardware trigger (L0) before GPU successor in Run 3.
Main con of that trigger was saturation of many hadronic channels when increasing instantaneous luminosity.



HLT1

Event readout @ 30 MHz (40 MHz LHC but intervals between trains of collisions)

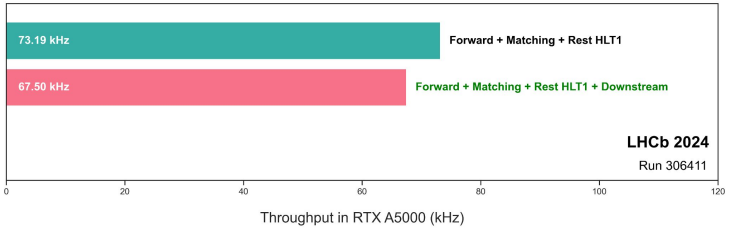
Reduces data rate 30 MHz -> 1 MHz

Performs partial event reconstruction (track and primary vertex reconstruction, …) and primary selection (single displaced tracks, …)

HLT1 runs two track reconstruction approaches, which perform better for different region of momentum:

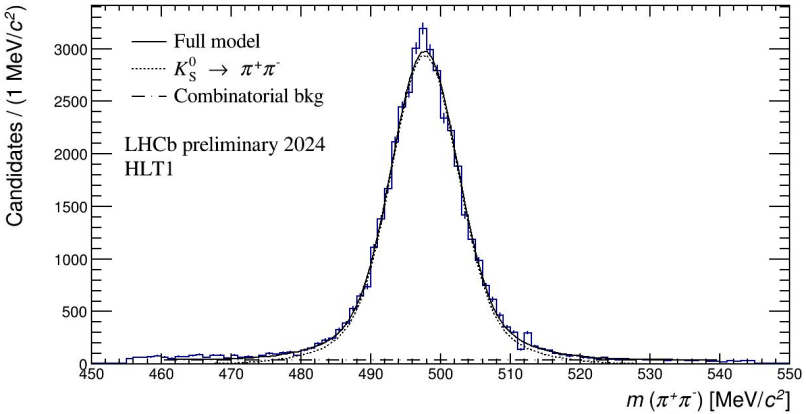
- Seeding and matching
- Forward tracking

LHCb-FIGURE-2024-035



TwoTracksKs HLT1 line, early 2024 data taking, 1.4 nb^{-1}

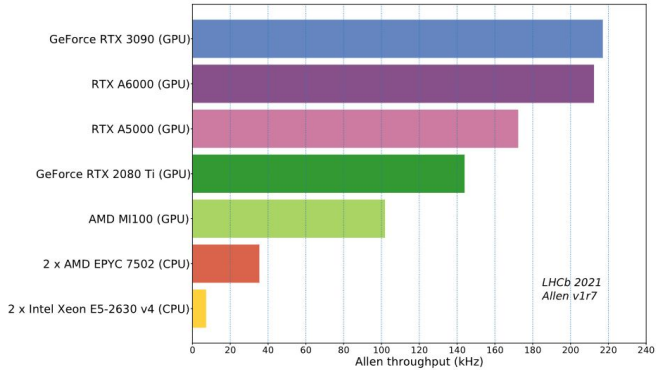
LHCb-FIGURE-2024-013



HLT1

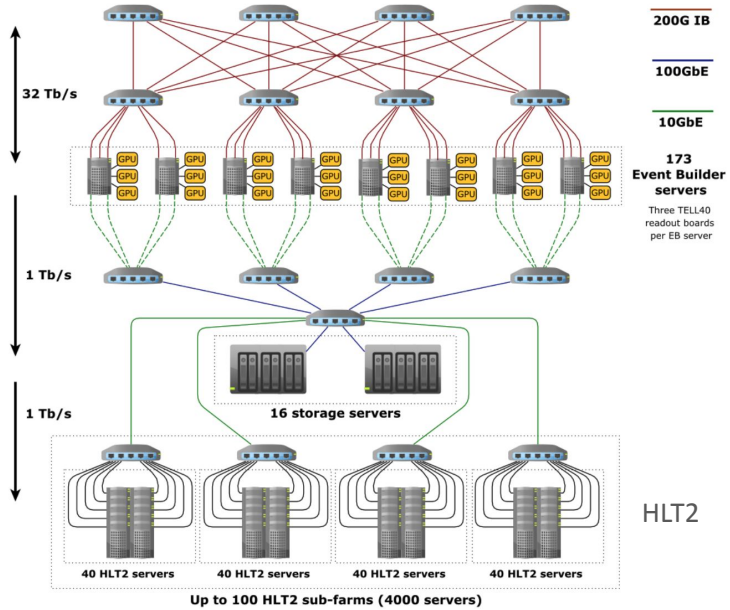
HLT1 is GPU based

- Use-case matches parallelism paradigm
- Events are independent (however batches of events are processed together)
- Combines well with LHCb Event Builder
- About 500 GPUs NVIDIA RTX A5000 (300 in TDR)



Allen (next slide) throughput for the entire HLT1 sequence LHCB-FIGURE-2020-014

Data Acquisition System



LHCb computing farm LHCb-DP-2021-003

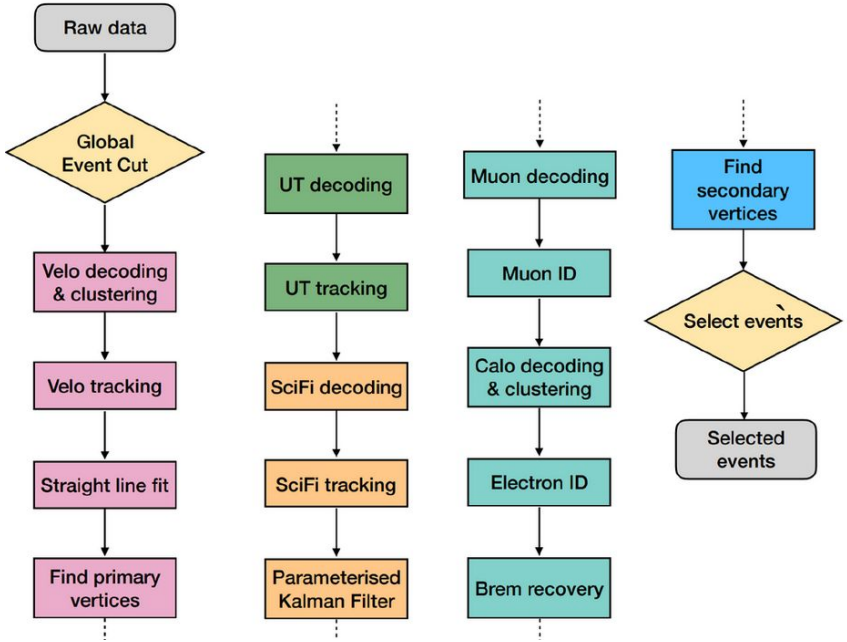
HLT1 software

Software for HLT1 is Allen

- Written mostly in CUDA
- https://allen-doc.docs.cern.ch/index.html
- Publication: Comput. Softw. Big Sci. 4, 7 (2020)

Trigger lines are python configurables

- Described by Trigger Configuration Key (TCK)
- Flexible to change or develop new conditions
- Possible to change TCK in the same software release
- Integrated/partly automated in GitLab pipelines



Block scheme of HLT1 algorithms
From Comput. Softw. Big Sci. 4, 7 (2020)
Rhomb block reduces the data rate, rectangle block is an algorithm block.

Alignment and calibration

Embedded into the trigger system

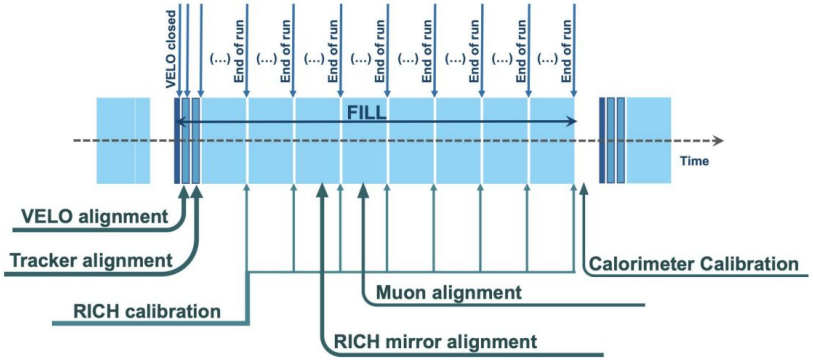
- Uses a subset of data after HLT1
- Performs tasks online with 5 dedicated lines
- Feeds HLT2 and ex-post HLT1
- Eliminates differences between online and offline reconstruction and efficiencies

Essential during data taking …

- Calibration for PID detectors
- Spatial alignment for trackers

… and for the detector monitoring!

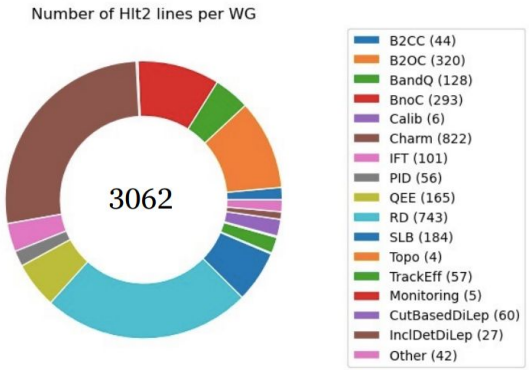
Alignment and calibration
A scheme as a function of LHC fill.
After VELO is closed, the alignment of trackers is (repeatedly) done, followed by alignment or calibrations of other LHCb detectors.

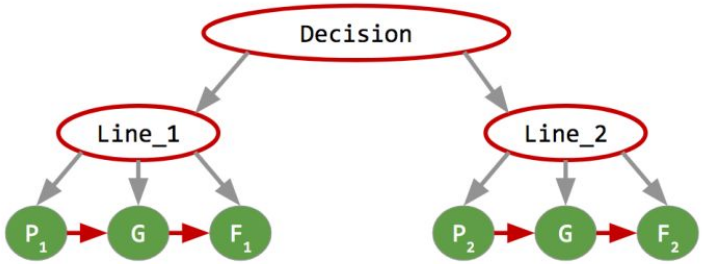


HLT2

Full event reconstruction and selection on CPU farm

- Inclusive and exclusive selection with O(3000) physics lines
- Reduces data rate to 20 kHz - the limiting factor is bandwidth of HLT2 output (next slide)
- Physics lines are written in Python, and get converted into C++ code -> flexibility

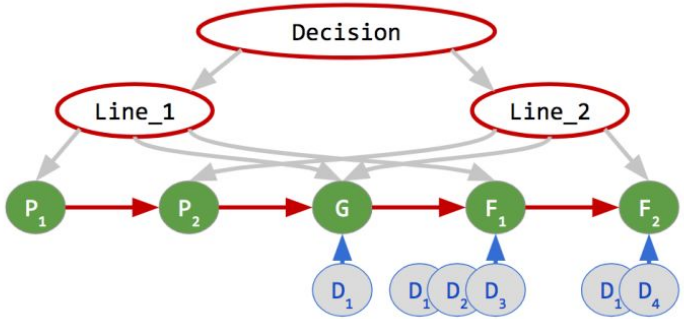




HLT2 Event Scheduler

Not optimized (above) and optimized (below) for node sharing

2020 J. Phys. Conf. Ser. 1525 012052



HLT2 event models

Bandwidth (GB/s, Event Size x Rate) is hardware-limited to 3.6 GB/s for save-to-disk (10 GB/s save-to-tape)

- Solution: smart reduction of event size may reduce bandwidth with no impact on Physics

LHCb defines various models of events:

- Full event - all reconstructed objects
- Turbo event - essential information (signal) for a requested analysis (e.g. Primary Vertex, …)
- Selective event with flexible definition
- TurCal event

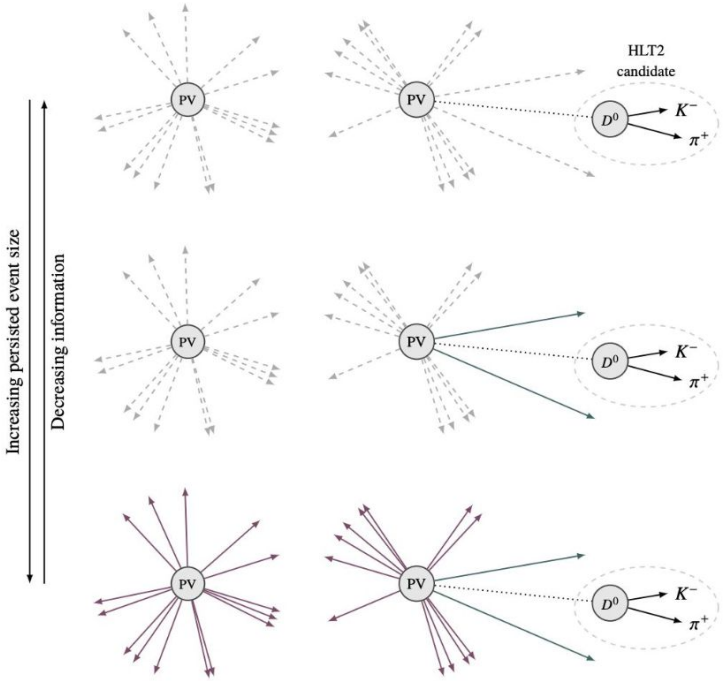


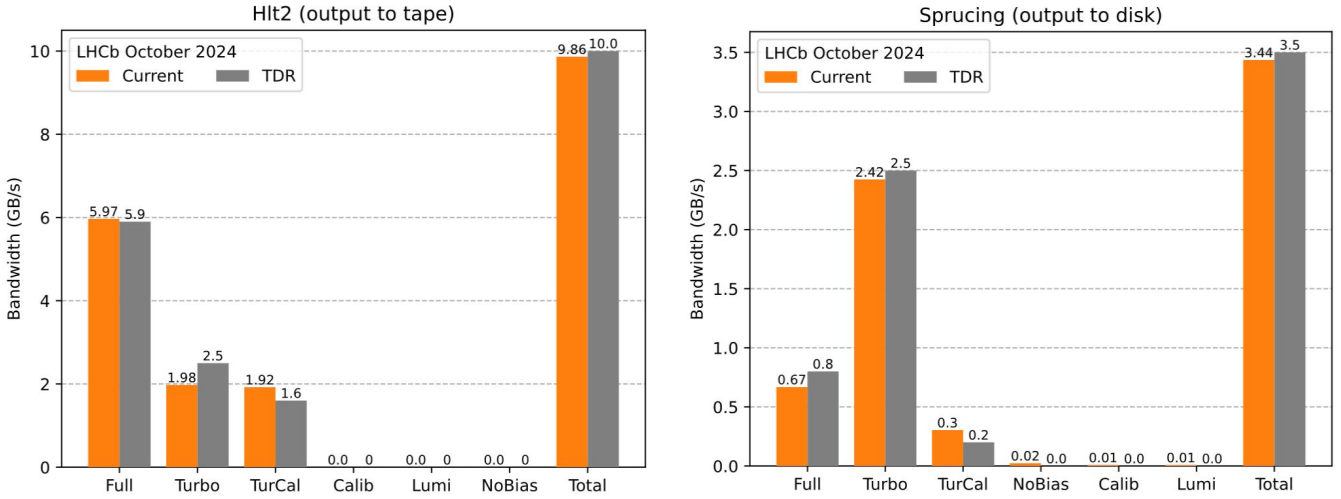
Illustration of event size reduction
In Turbo stream (top) not essential data is discarded
JINST 14 P04006

HLT2 performance

HLT2 achieved performance from TDR

- Graphs below come from October 2024
- For these, HLT1 had an output rate of around 1.2 MHz (20% higher than TDR)
- Taken at nominal LHCb Run 3 pile-up

LHCb-FIGURE-2024-034



LHCb production software

Production software

- A stack of Gaudi-based projects with backward dependencies
- Automatic daily testing - LHCb Nightly Builds
- Many-platform test suite scheduled by Jenkins
- Tests executed for current and legacy slots
- The stack of projects includes not only production software for Triggers, also Alignment, Simulation, …

LHCb Nightly Builds

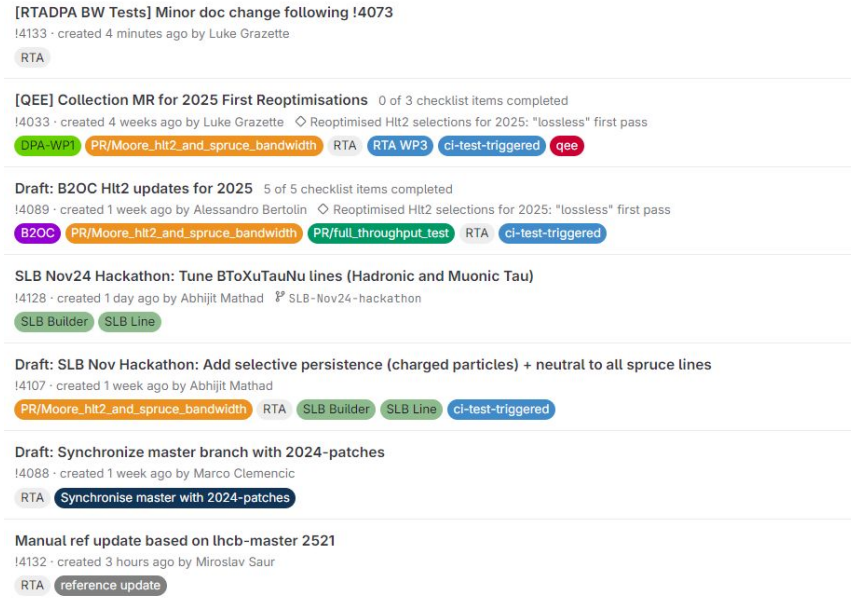
LHCb Nighlty Build
For many platforms, a full test suite from all software projects that aim to be used in production

LHCb developing software

Developing software

- Via GitLab Merge Requests
- A CI-test is available to call at any moment, for Jenkins to schedule the full test suite
- Managed by software shifters and maintainers
- Very detailed code review
- Tests include throughput and bandwidth to check the impact on triggers

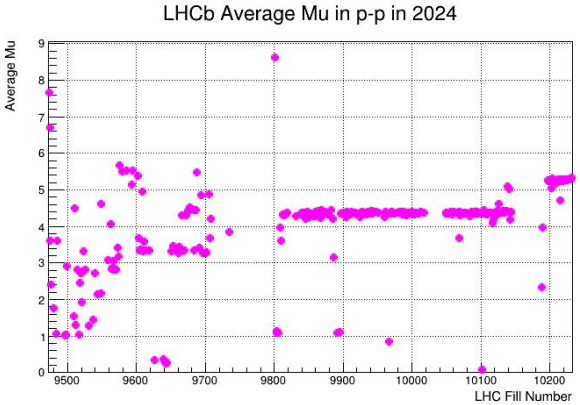
Software development
Continuous development (in this case Moore) with new merge requests appearing hourly.



Summary of 2024 operation

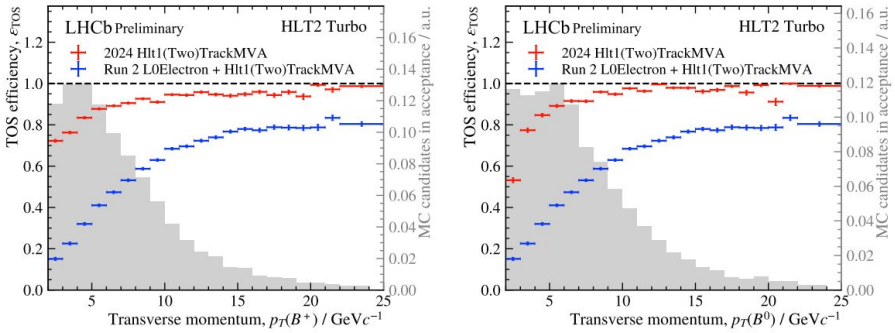
LHCb did great this year!

- Expected integrated luminosity for proton-proton recorded by LHCb was achieved
- And first time PbPb data taken with full detector!



LHCb average mu:
How LHCb increased mu during the year (LHC's fill 9800 is 19 of June)

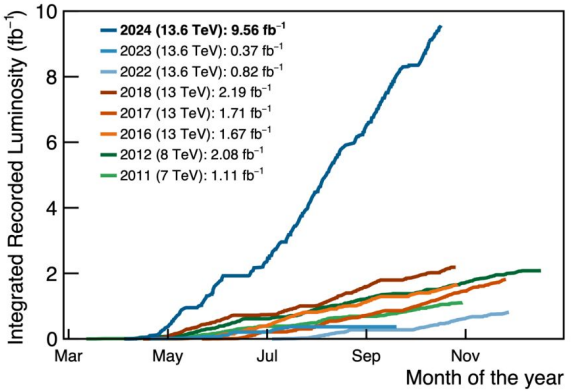
Efficiency compared to Run2
LHCb-FIGURE-2024-030



(a) TOS efficiencies in $B^+ \to J/\psi\,(e^+e^-)\,K^+$.

(b) TOS efficiencies in $B^0 \to J/\psi\,(e^+e^-)\,K^{*0}$.

Data collected by LHCb
Summary plot for all Runs since LHCb start in 2011.



Thanks for attention!

The LHCb RTA group