Evolution of trigger and TDAQ system for rare decay searches at LHCb

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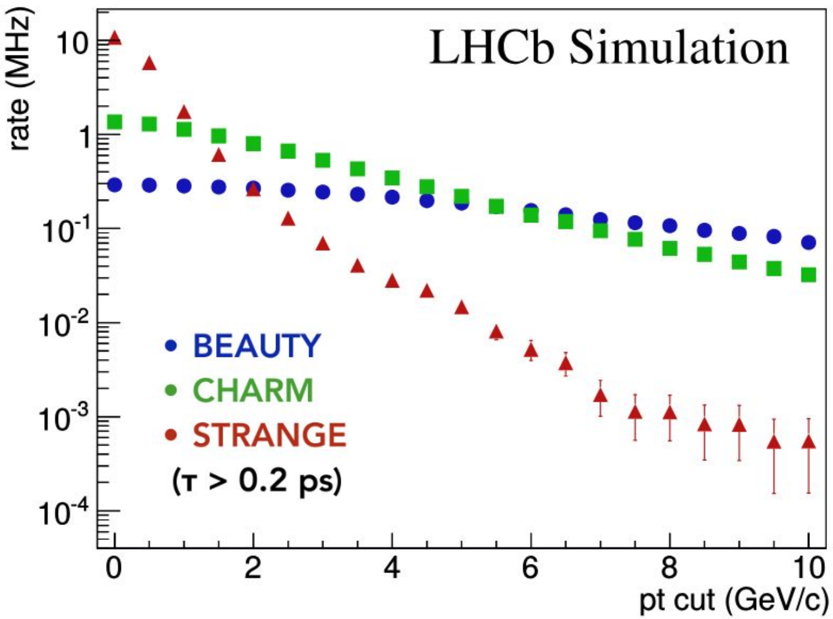
Bologna, 14/11/2024

Introduction

- LHCb: broad physics program
  - CPV & CKM, hadronic spectroscopy, rare decays, lepton universality tests, electroweak physics, dark sector, heavy ions, fixed target...
- At √s = 13 TeV
  - Charm production rate: ~1 MHz
  - Beauty production rate: ~ 45 kHz
  - In Run 3, we can store offline 10Gb/s → ~50 kHz
- Need a flexible trigger!

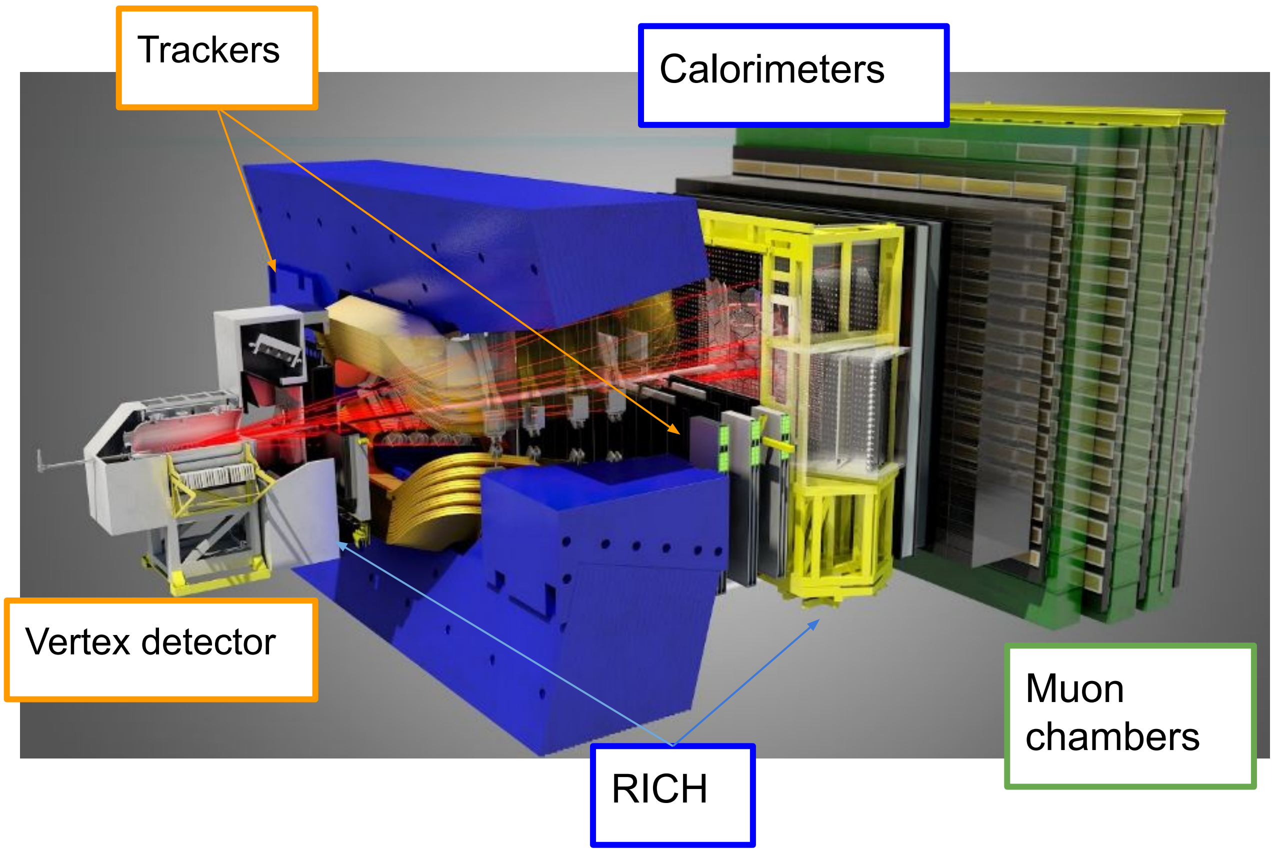
LHCb-TDR-016

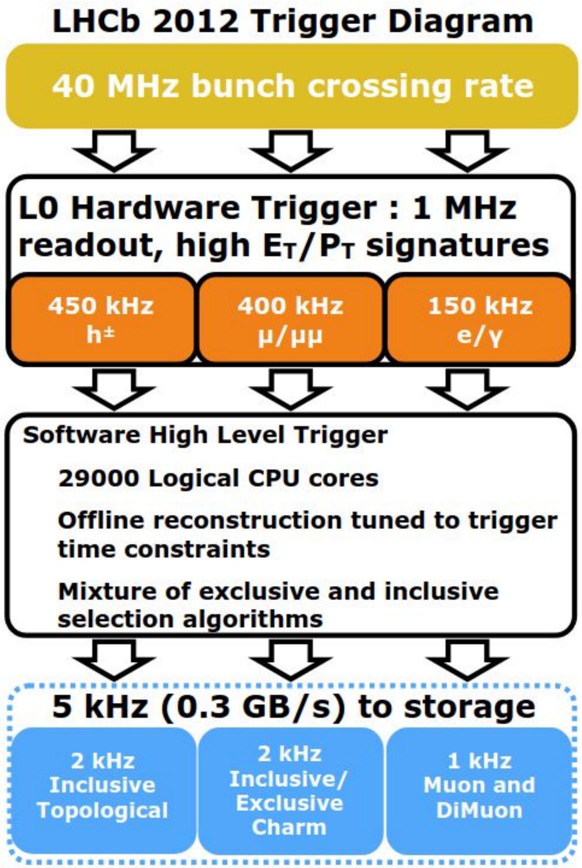


Trigger in Run 1

LHCb-FIGURE-2020-016

❖ L0 hardware trigger (Muon and Calorimeter information), followed by two-stage software trigger

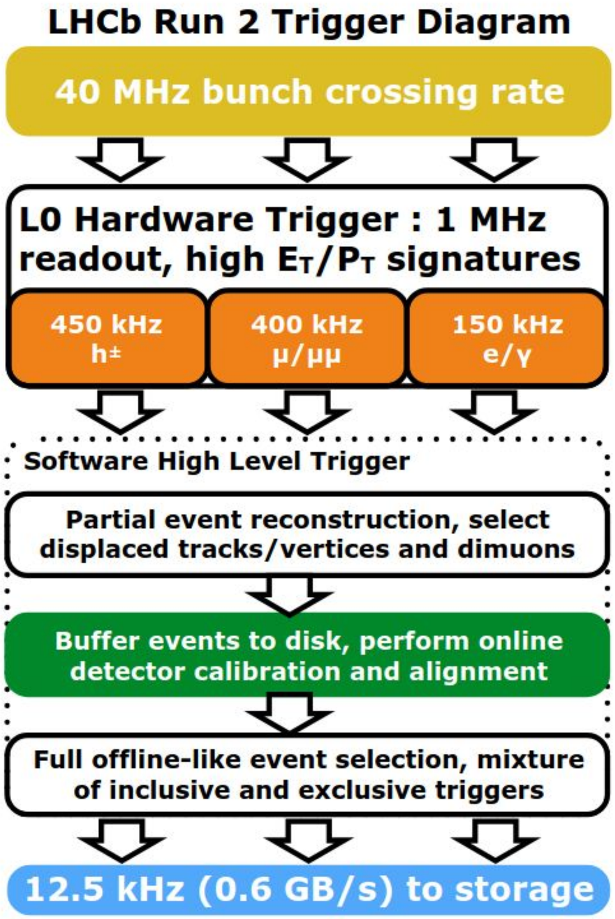


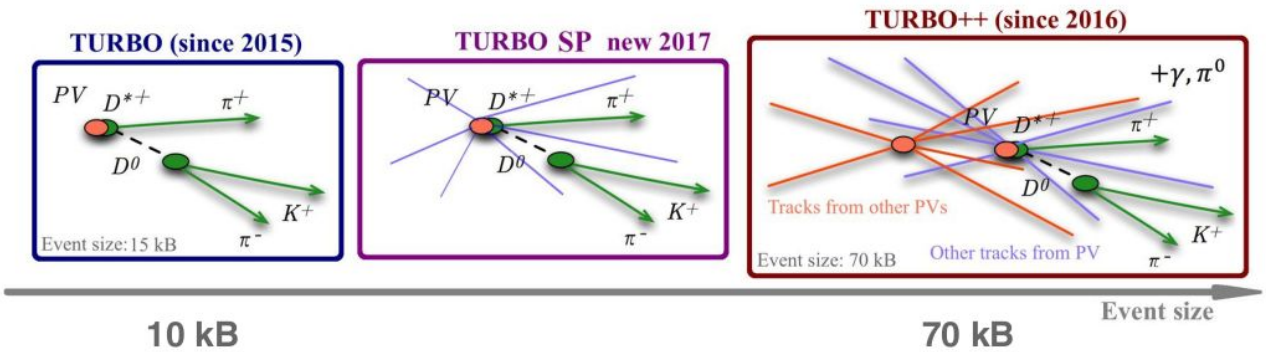


Trigger in Run 2

LHCb-FIGURE-2020-016

- Similar trigger strategy in Run 2
- Ability to use trigger output for analysis and discard raw detector information in trigger (Turbo model)
  - Fundamental for the collection of the large charm dataset used for first observation of CPV

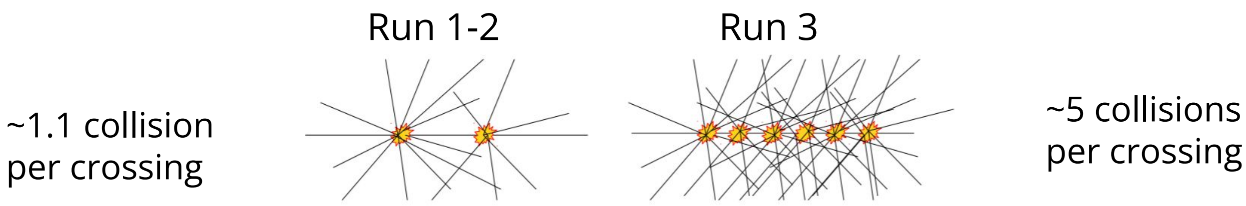




$$\text{Trigger bandwidth } [\mathrm{MB\,s^{-1}}] \propto \text{Trigger rate [kHz]} \times \text{Average event size [kB]}$$

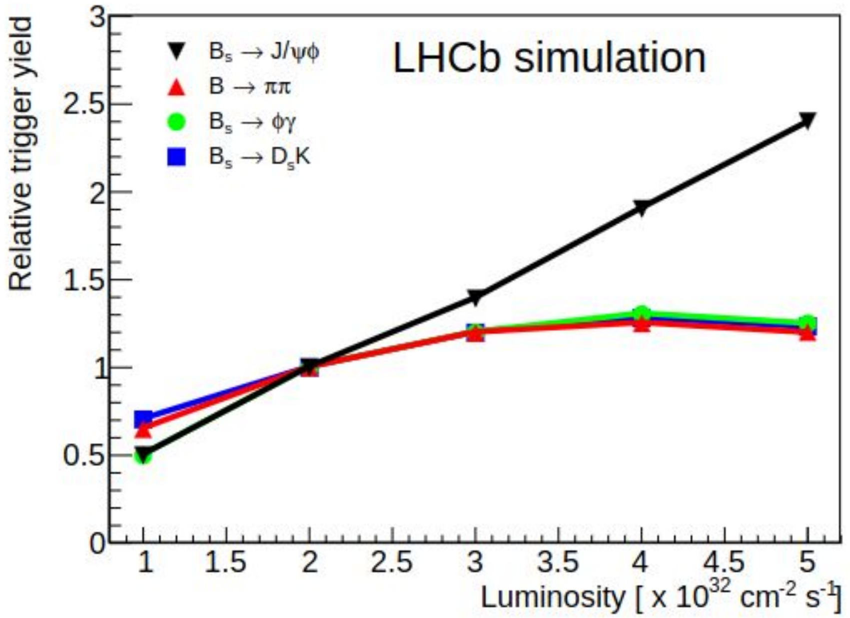
LHCb in Run 3

- ❖ LHCb Run 1 and Run 2: huge success!
- ❖ The majority of measurements is statistically limited
  - ➢ → LHCb Upgrade I: 5x instantaneous luminosity
- ❖ Improve physics performance, despite the more challenging environment
  - ➢ Completely new tracking and trigger system



Trigger in Run 3

- Higher instantaneous luminosity
  - Tight p_T and E_T cuts saturate hadronic channels → L0 trigger removed
  - Software trigger process events at the full LHC collision rate
  - → room for improving trigger efficiency w.r.t. Run 2



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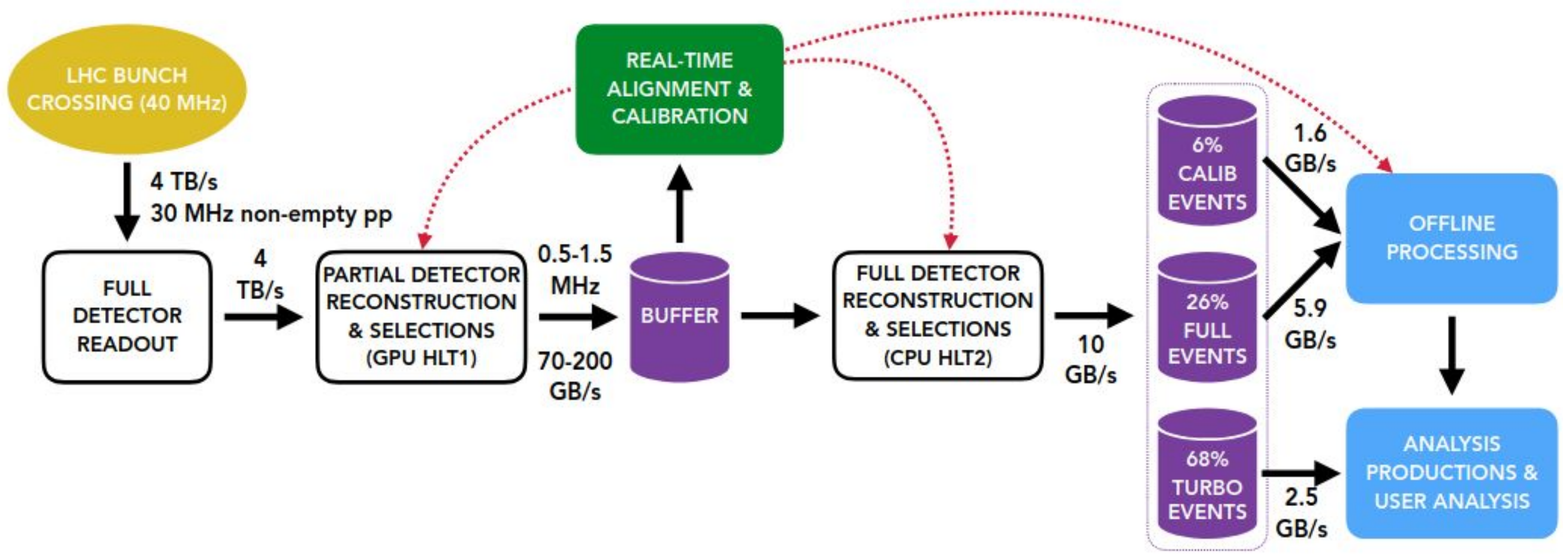
Trigger in Run 3

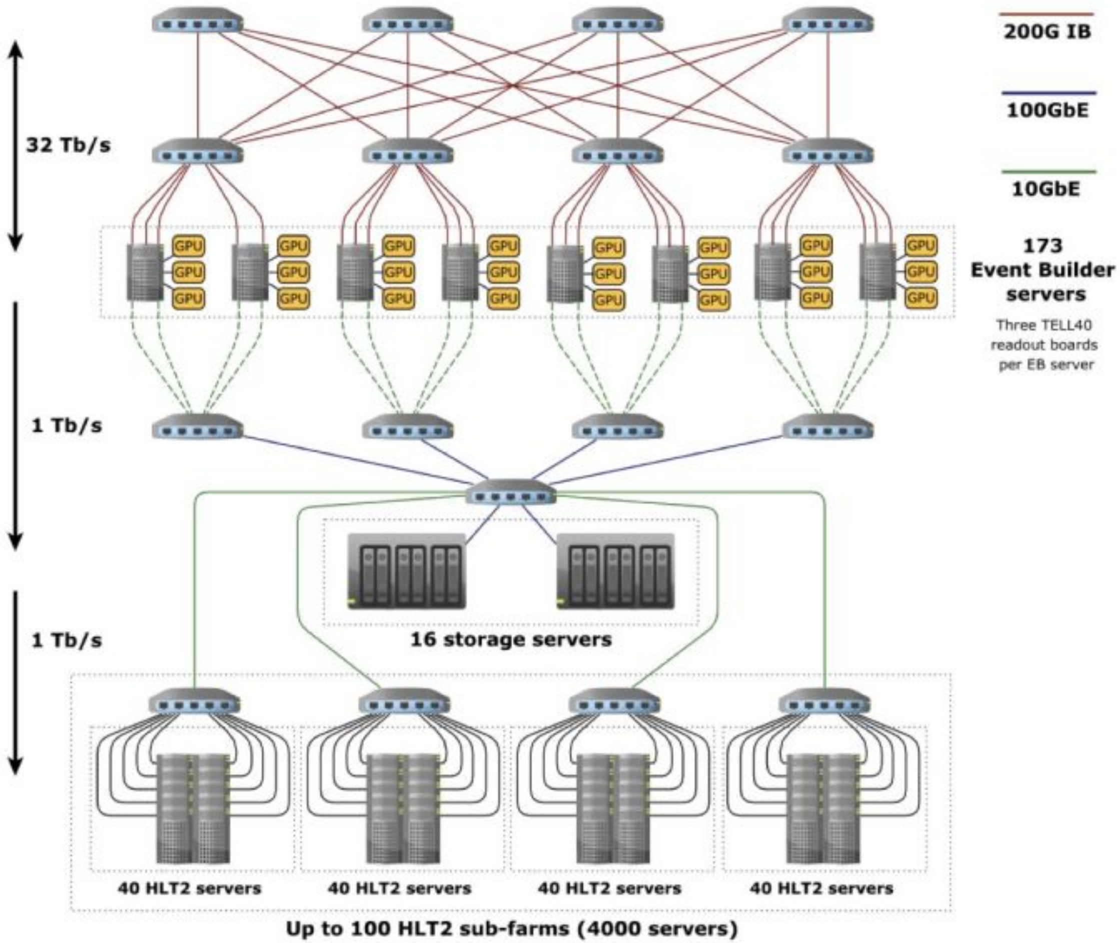
- ❖ Full detector readout @ LHC crossing rate
- ❖ Two-stage software trigger (HLT1 on GPUs, HLT2 on CPUs)
- ❖ 10 GB/s of data for offline processing

LHCb-FIGURE-2020-016



HLT1 in Run 3

- GPU choice matches LHCb DAQ architecture
  - GPUs hosted by Event Builder Nodes
    →reduce data at earlier stage
    →smaller and simpler network



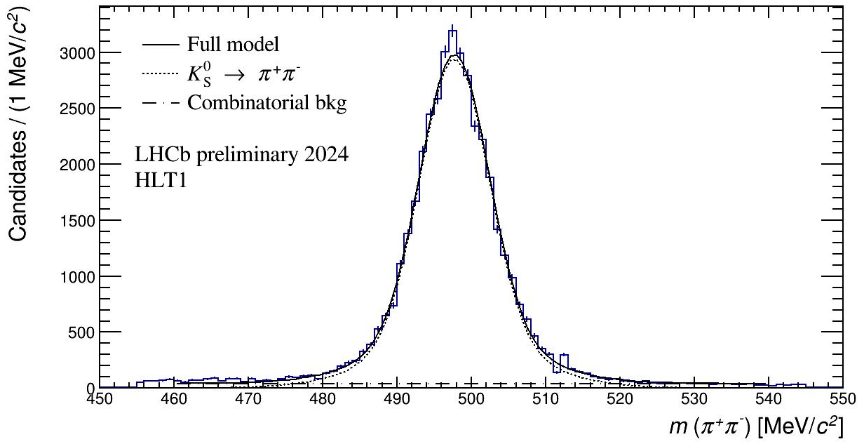
More flexibility in designing selections

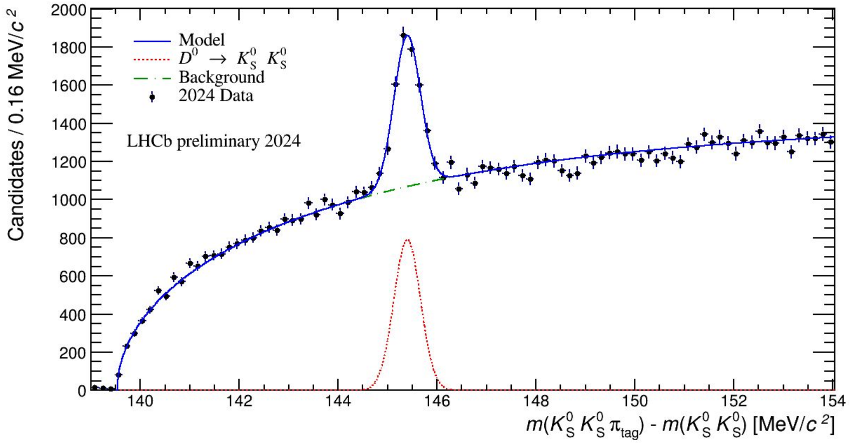
❖ Software trigger → flexibility in design selections

➢ K_S^0 candidates reconstructed directly at the first level of the trigger!

➢ Dedicated selections to collect single K_S^0 and pairs of K_S^0 → increase efficiency in selecting decays like $D^0 \rightarrow K_S^0 K_S^0$

LHCb-FIGURE-2024-008
LHCb-FIGURE-2024-013
PoS(CORFU2023)015

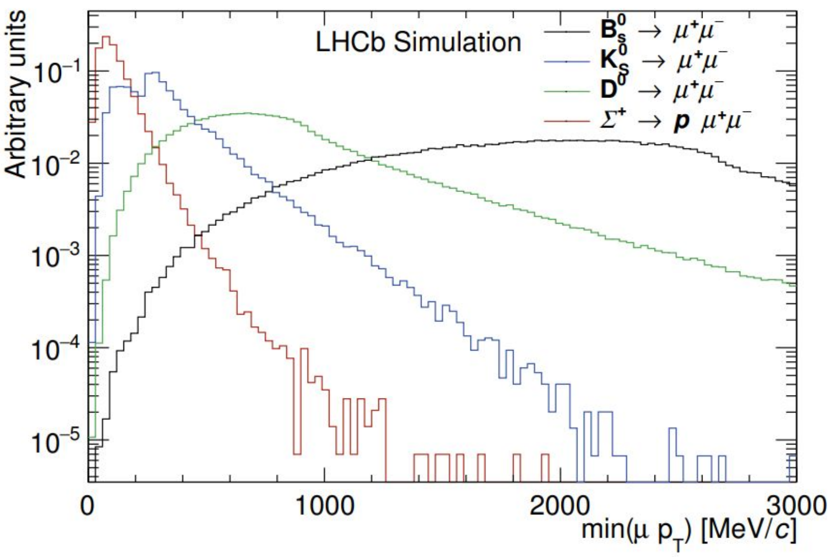




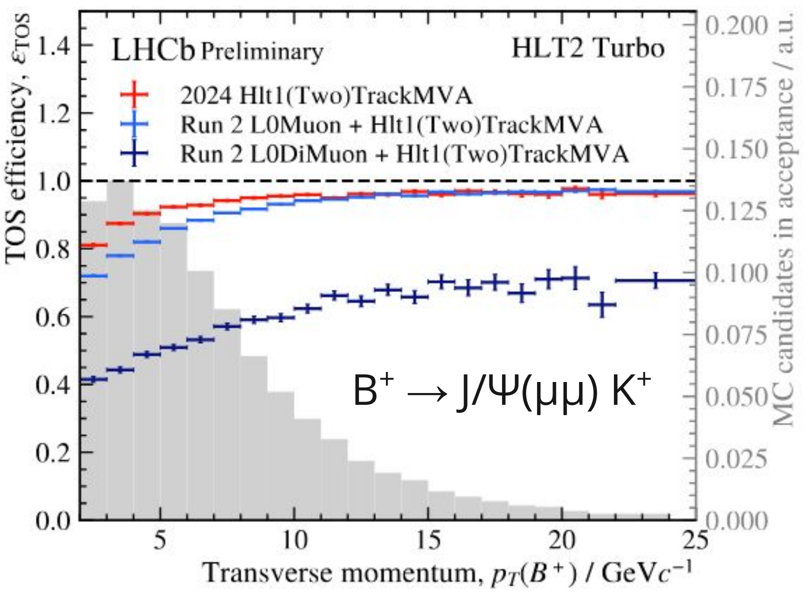
Impact on trigger efficiencies

❖ Recover soft muons: particularly relevant for strange, charm and tau physics

LHCb-PUB-2017-023



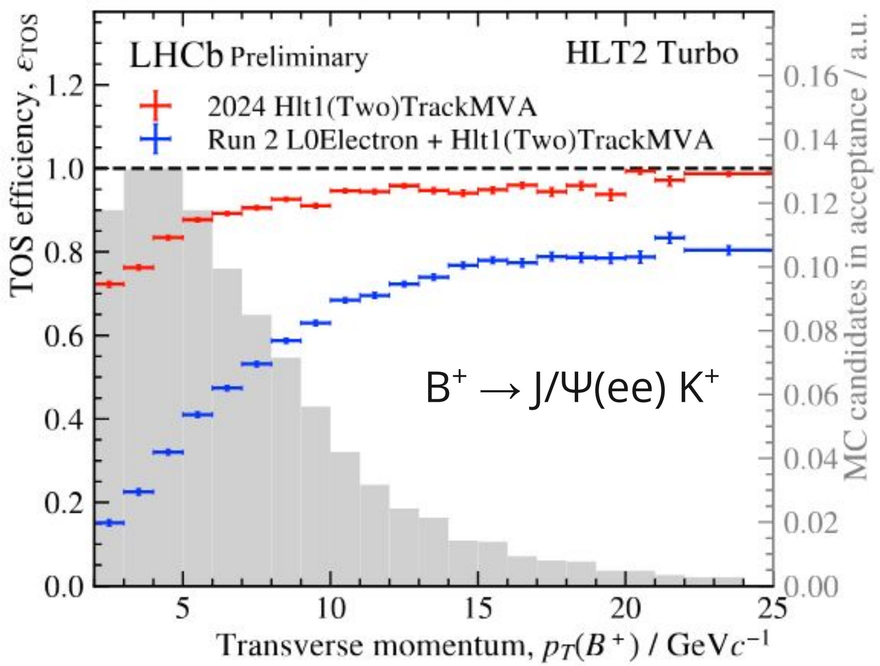
LHCb-FIGURE-2024-030



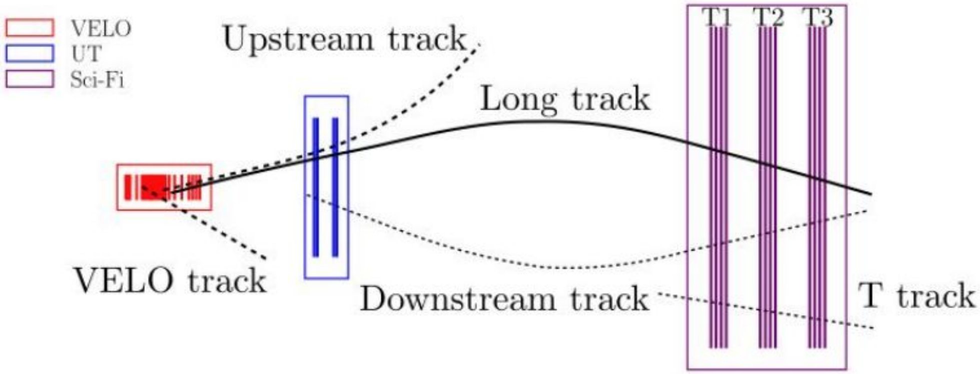
Impact on trigger efficiencies (2)

❖ Electron modes: large efficiency increase and better kinematic overlap with the muon samples

LHCb-FIGURE-2024-030



A word on rare kaon decays

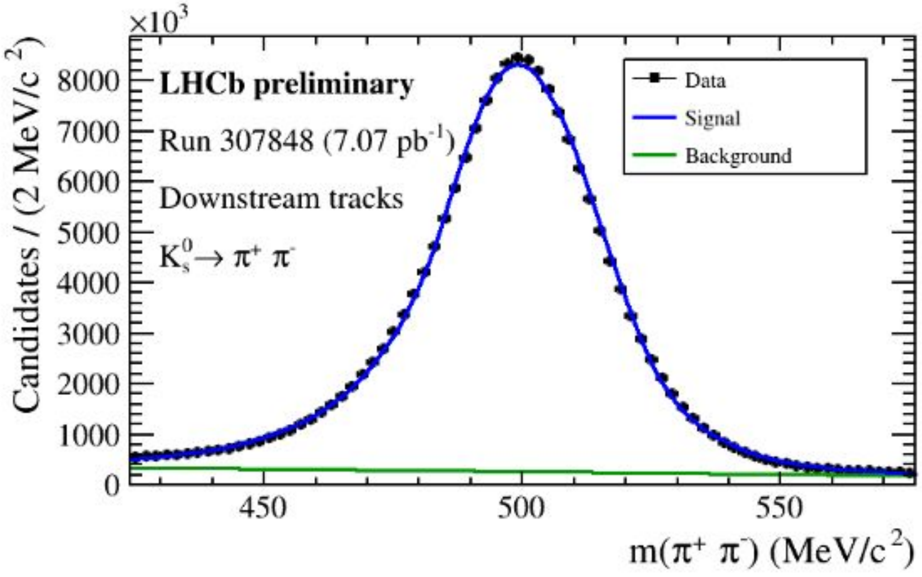


- Search for $K_S^0 \rightarrow \mu^+\mu^-$ and $K_S^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ done using full Run 1+ Run 2 dataset
  - No signal observed [PRL 125, 231801 (2020)] [PRD 108 (2023) L031102]
  - Only long tracks used in the analysis
  - No downstream tracking at HLT1 in Run 1 and Run 2 → low trigger efficiency

Downstream tracking at HLT1

- Downstream tracking included in the HLT1 reconstruction in the last ~two weeks of 2024 pp data-taking!
- Room for improving efficiency in many channels, including: rare kaon decays, LLP, radiative decays with converted photons

LHCb-FIGURE-2024-035

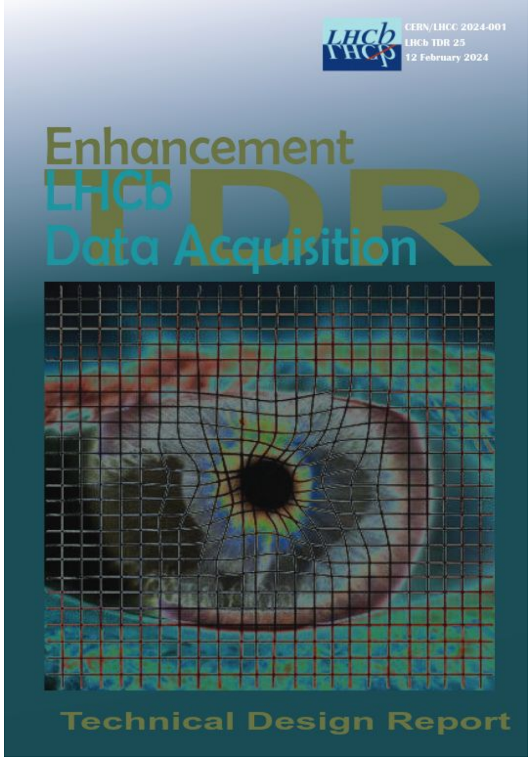


Looking ahead: LHCb Upgrade II

- FTDR approved in 2022 and Scoping Document submitted to LHCC
- Instantaneous luminosity will increase by a factor 7.5
  - Large data volumes, more complex events
  - Larger B/W to the trigger
  - More computing power needed
- 200 TB/s of data, to be processed in real time and reduced by ~4 orders of magnitude before sending to permanent storage
- 4D reconstruction: timing added to tracking and ECAL detectors to better isolate signals
- R&D activities to explore other heterogeneous architectures

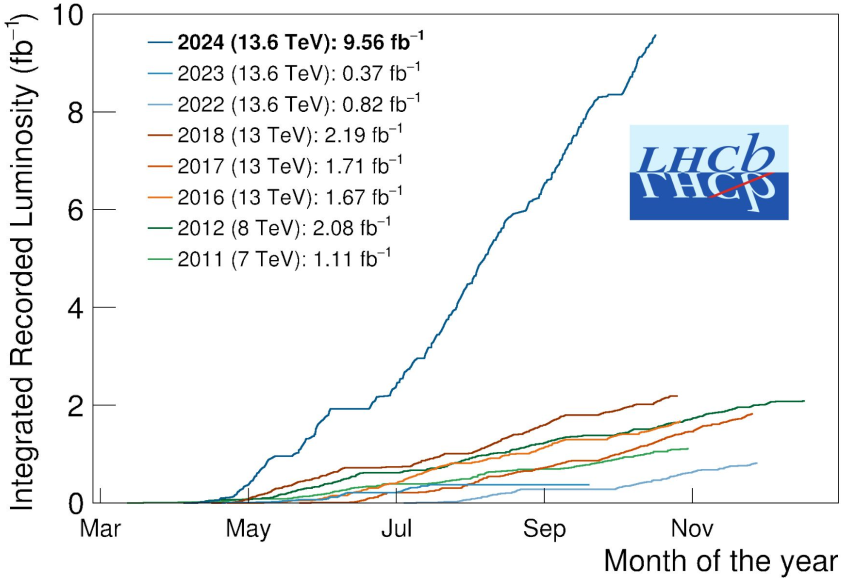
Real-time tracking on FPGAs

- Idea: reconstruct tracks even before event-building on FPGAs (see F.Terzuoli's talk)
- Run 4: reconstruct tracks downstream of the magnet   LHCb-PUB-2024-001
- It will also open the possibility to drop some raw data at readout level →save bandwidth
- VELO clustering on FPGAs (default in Run 3) allows to drop raw pixel data and save ~14% of DAQ bandwidth



Conclusions

- Thanks to its flexible trigger, LHCb giving major contributions in rare decays of beauty, charm and strange hadrons
- Detector and trigger fully upgraded before start of Run 3 data-taking
- About 9.5fb^{-1} of data taken in 2024 are now being analysed
- LHCb Upgrade II is becoming a reality
  - More challenges (but also opportunities) ahead



Backup slides

LHCb in Run 3

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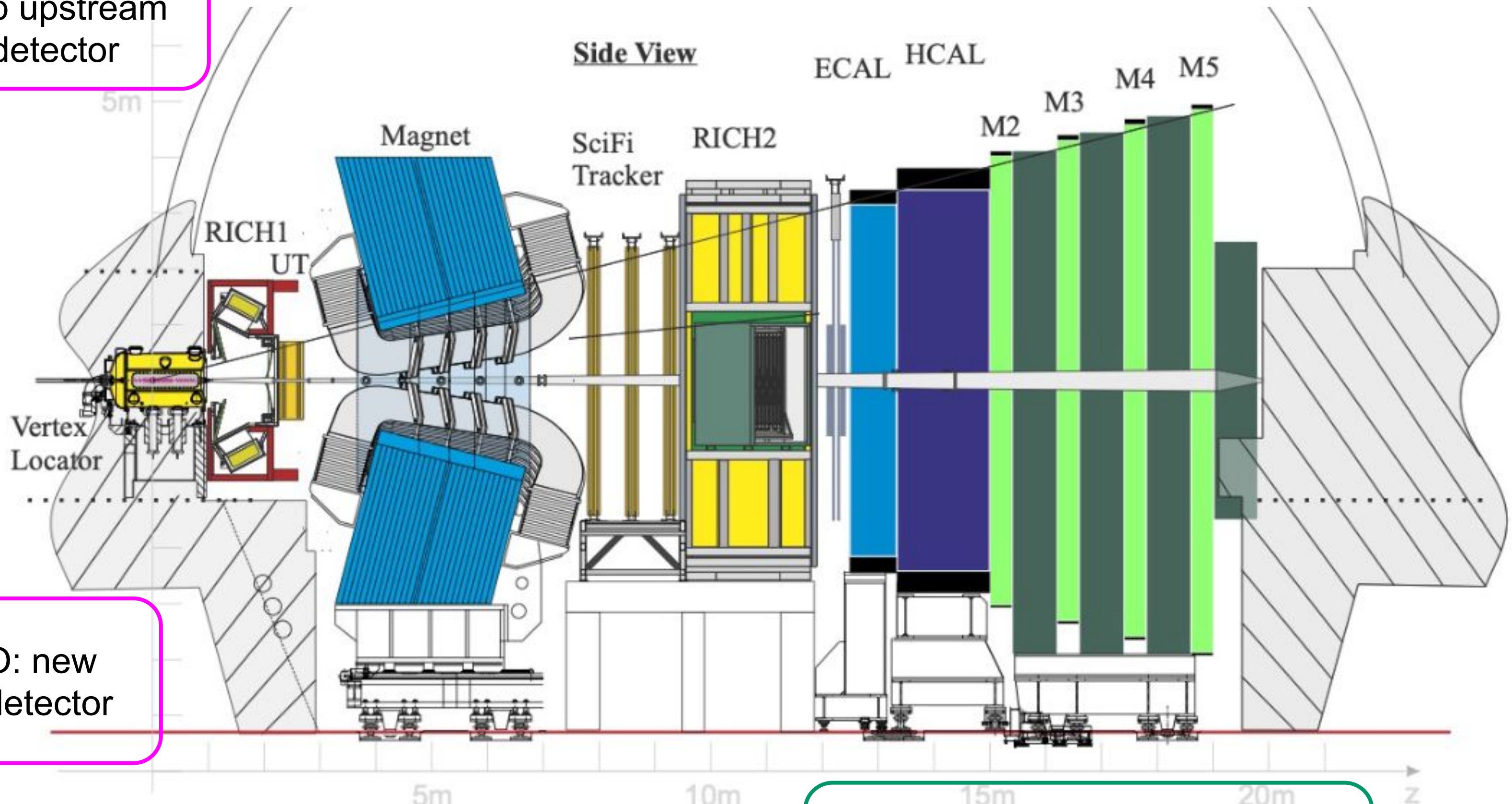
SciFi: new scintillating fibres downstream detector

RICH: new mechanics, optics, photodetectors

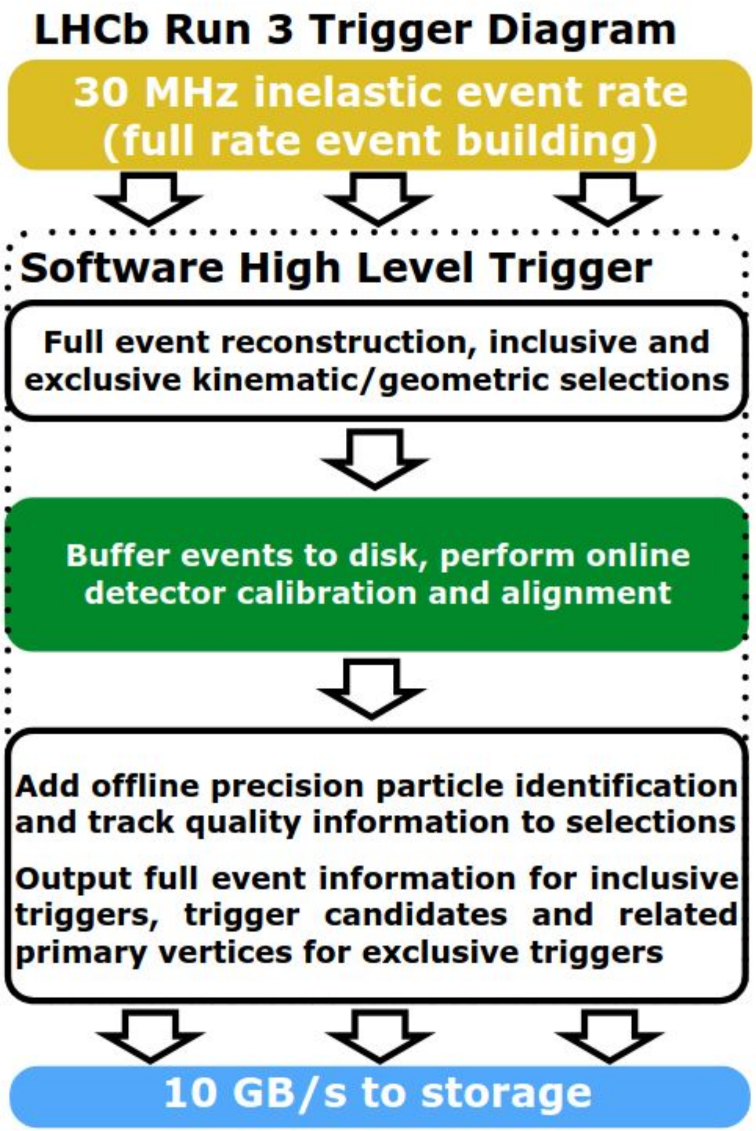
UT: new silicon strip upstream detector



VELO: new pixel detector

New frontend electronics and new DAQ for all sub-detectors!

Trigger in Run 3



Data-taking

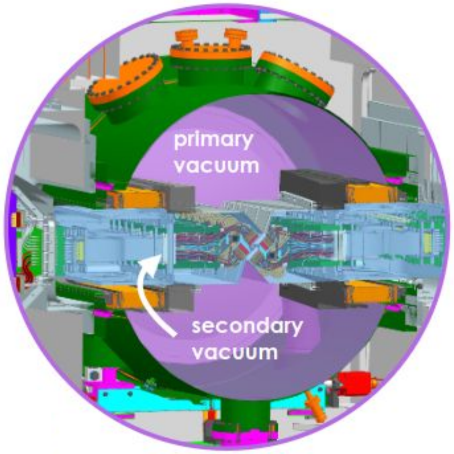
❖ **2022**

➢ all detectors installed but UT

➢ local commissioning of subdetectors

➢ global commissioning of trigger, alignment and calibration

➢ VELO routinely closed in the last couple of months

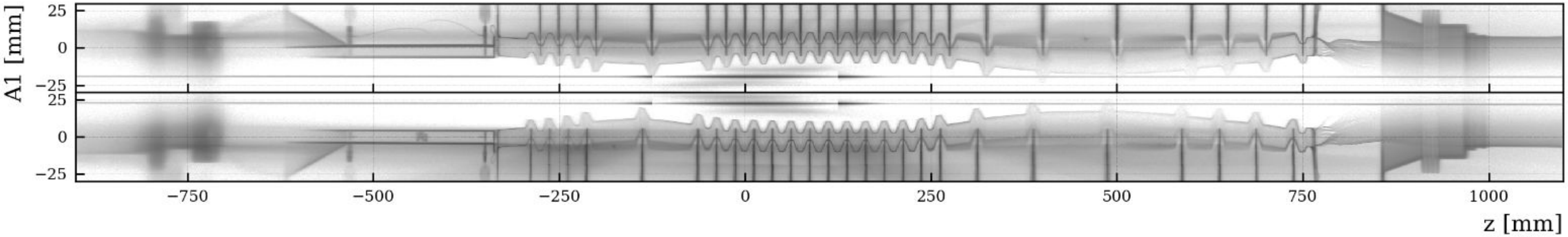


❖ **2023**

➢ LHC vacuum incident in the VELO in Jan: operated with VELO gap of 49 mm

➢ UT completed installation

➢ collected data during ion run



Data-taking (2)

❖ **2024**

- ➢ VELO RF-box replaced
- ➢ UT included in global data-taking after June TS

Selfie of the new RF-box and VELO modules with reconstructed hadronic interaction vertices