First experiences with the LHCb heterogeneous software trigger

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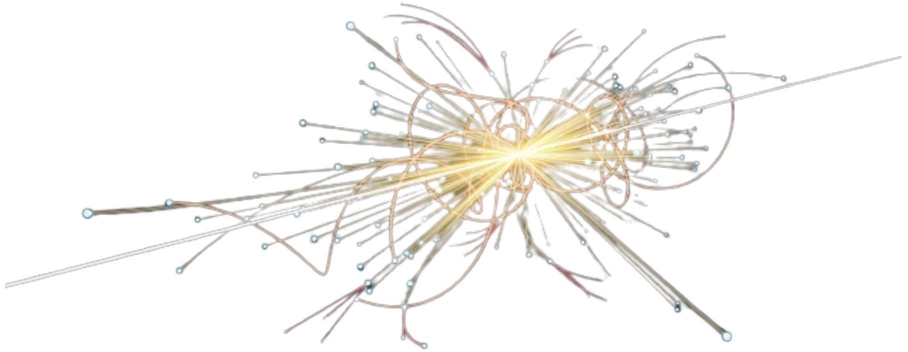
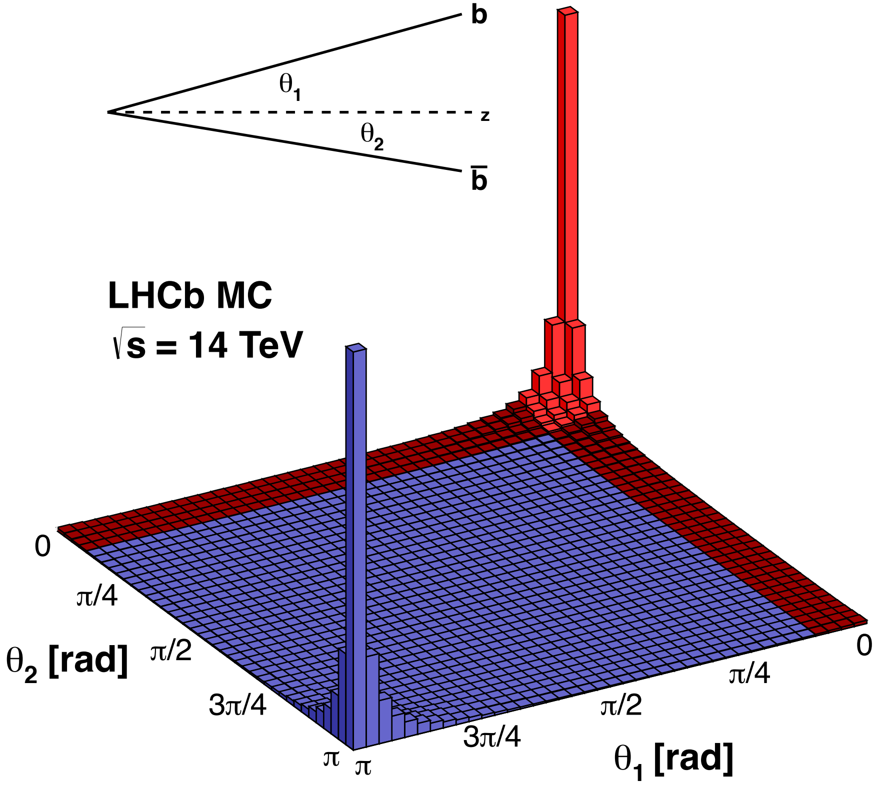
Introduction



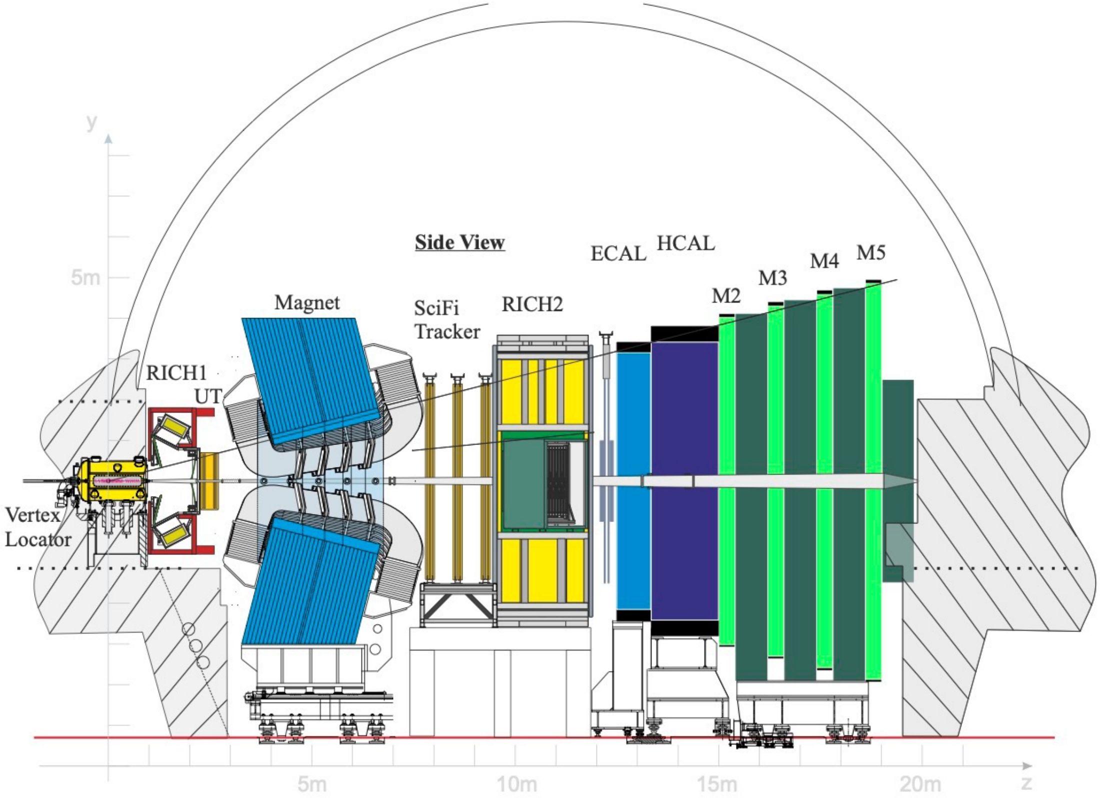
- LHC collides proton bunches every 25ns
- Colliding pairs of protons can form $b\bar{b}$ quark pairs
  - Usually close to the beamlines
- Measuring these allow exploitation of the ‘precision fontier’ in an attempt to find physics beyond the Standard Model
- High precision measurements of high frequency collisions → A lot of data!
  - Any experiment under these conditions will require a very good trigger system



[Christian Elasser](#)

LHCb experiment

- LHCb is a spectrometer experiment at the point 8 of the LHC, in France
  - Run 1 between 2011-2012, Run 2 between 2015-2018
- It was recently upgraded (final elements installed at the end of 2022) for Run 3 – ongoing
  - Increased the intantaneous luminosity 5× compared to Runs 1 and 2
  - This necessitates an entirely new trigger

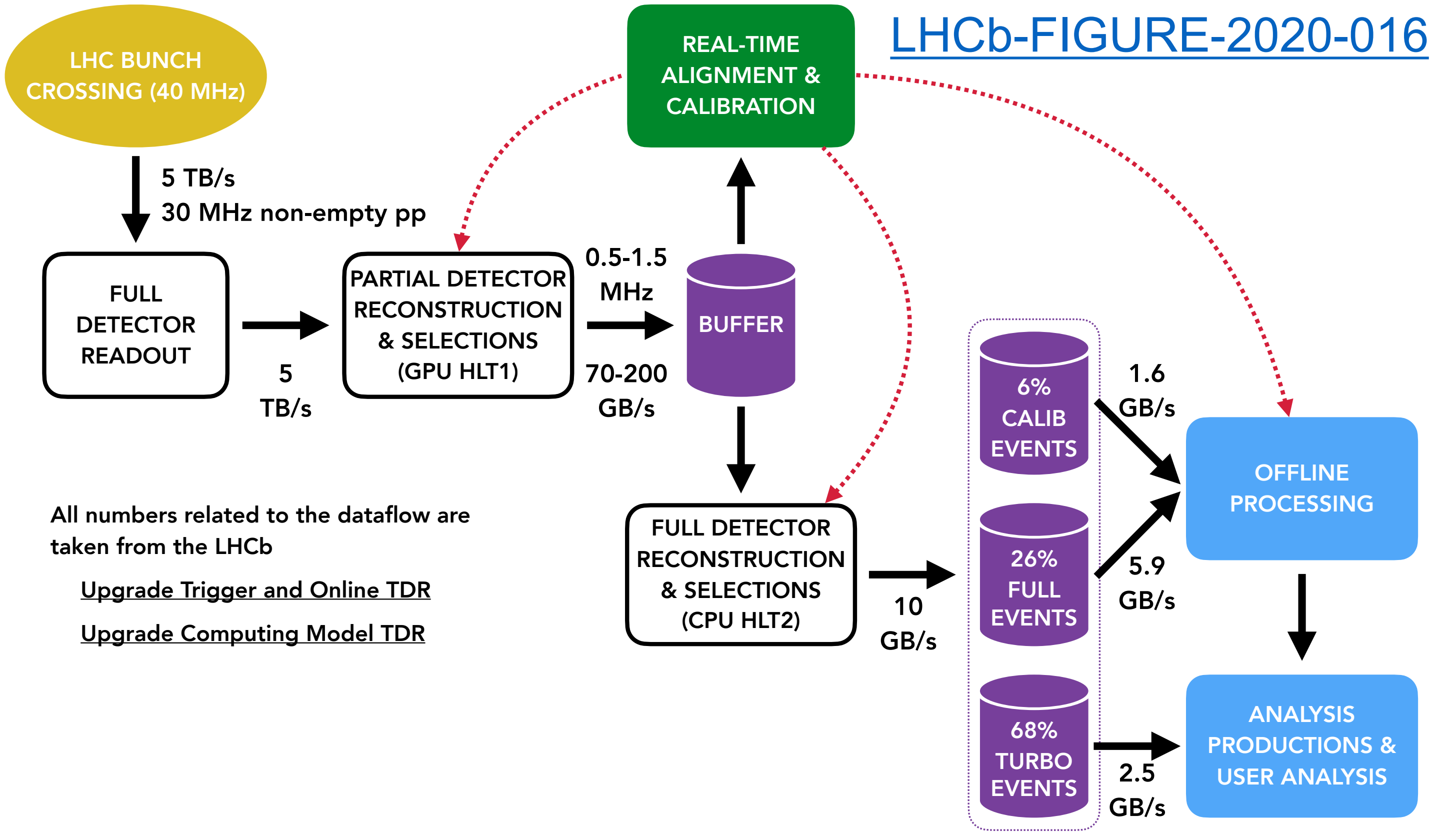


[The LHCb Upgrade I, 2023](#)

The trigger: general overview

- Data arrives at 5TB/s
  - Impossible to store in its entireity
- No hardware trigger
- HLT1
  - Processing into inclusive lines
  - Runs on GPUs
  - Outputs to a buffer
- Real time alignment
  - Improves detector response
- HLT2
  - Takes data from the buffer
  - Processing into exclusive lines
  - Runs on CPUs

LHCb-FIGURE-2020-016



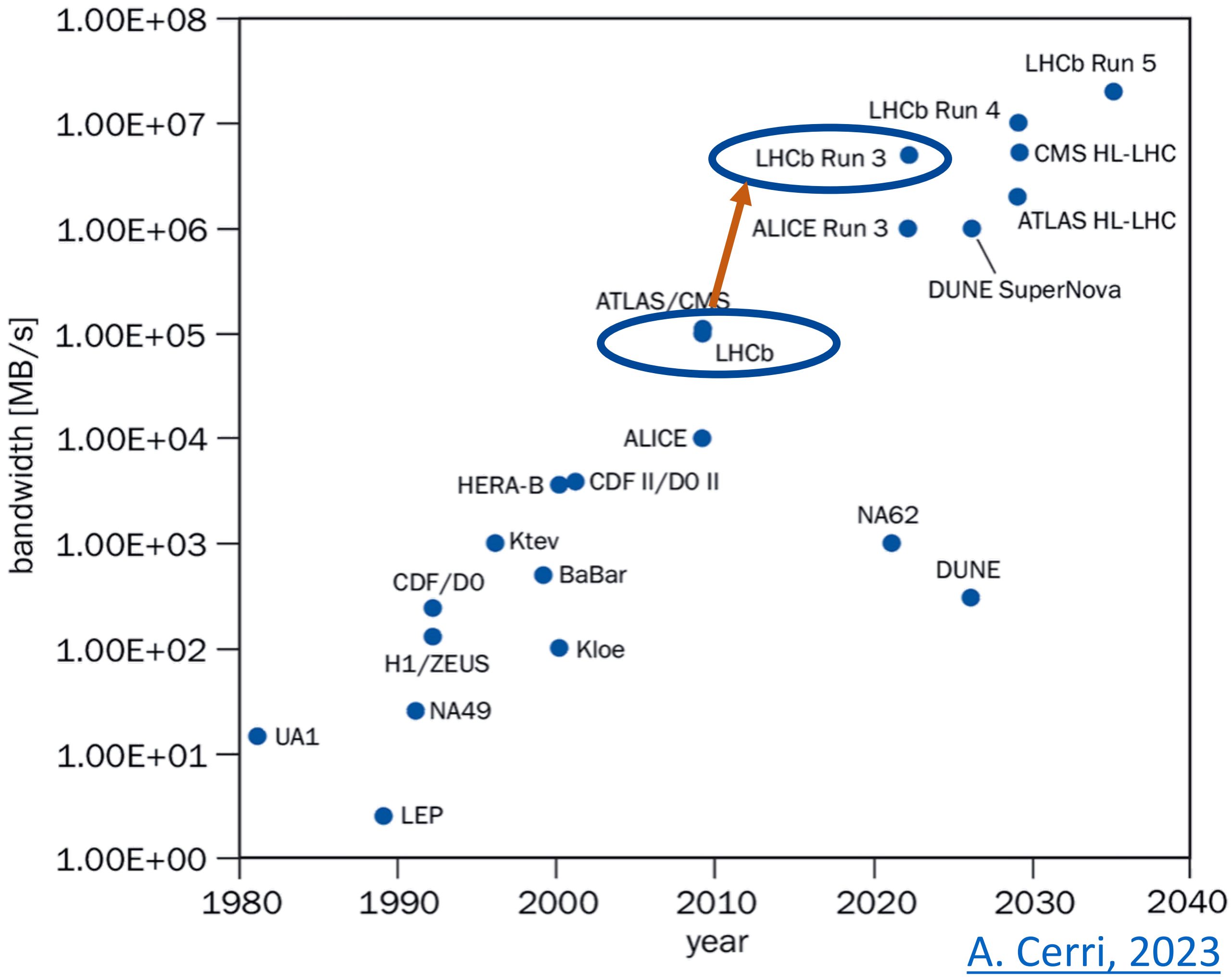
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

The trigger: HLT1 overview

- The data taken is impossible to store in its entirety
- Only the most interesting events are kept
  - Filtered into inclusive 'lines' – approximately 1/30 of all events
- Allen software package is used
  - Source written in Cuda with cross-architecture compatability
  - Despite bandwidth increasing, events can be reconstructed at the full detector output rate!

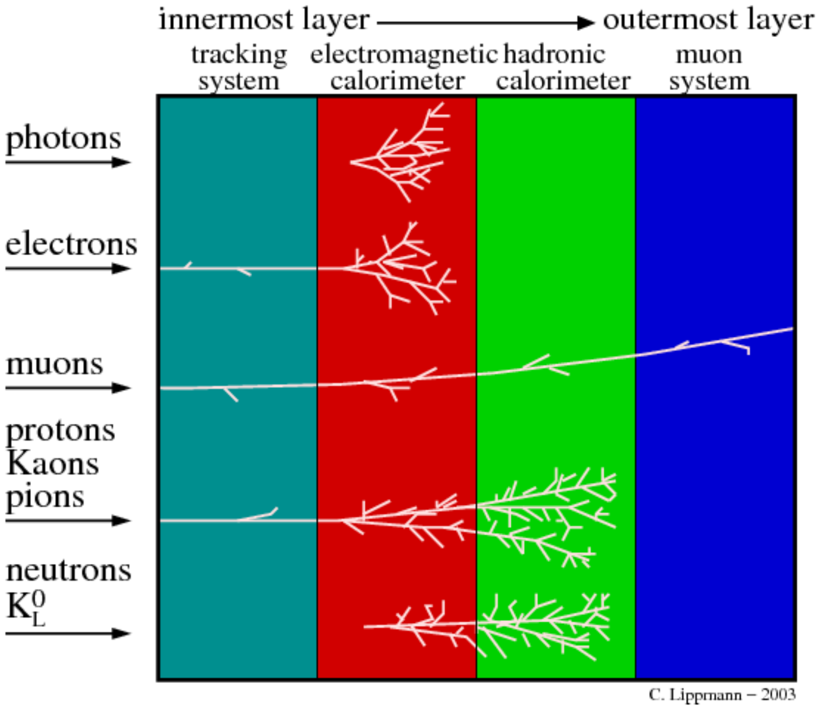


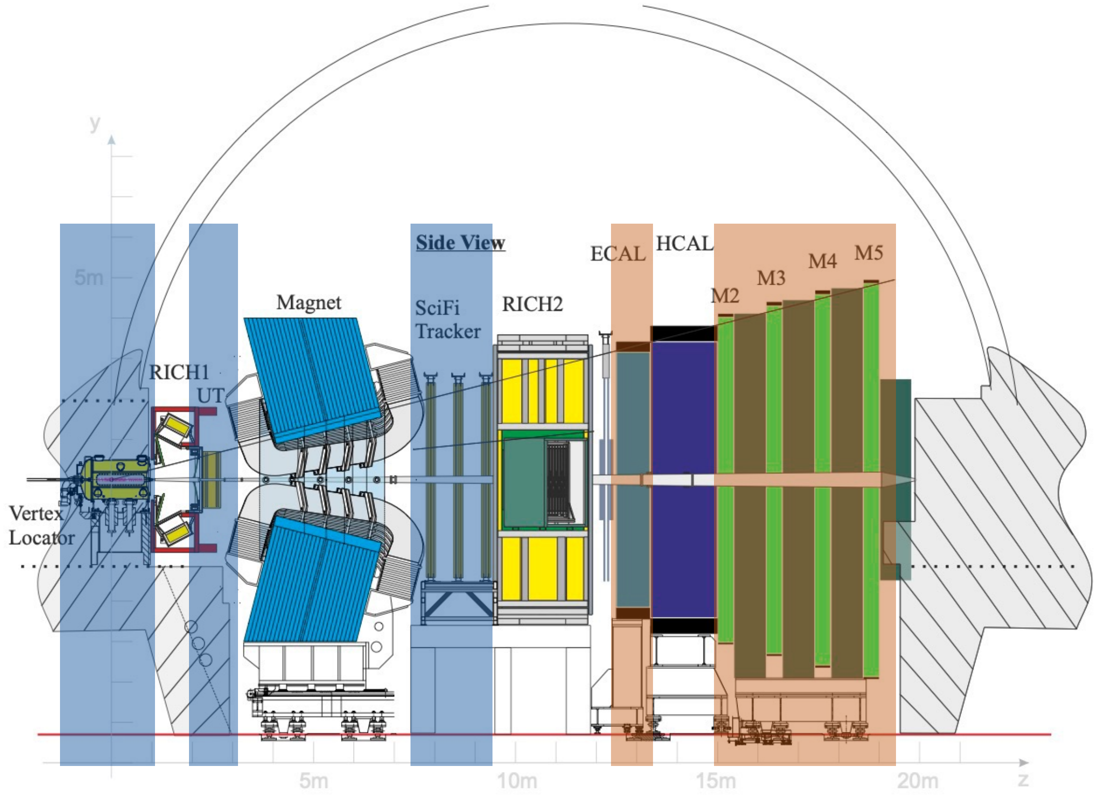
A. Cerri, 2023

The trigger: HLT1 inputs

- HLT1 does not use the entire detector for its inputs to maintain high throughput

- For tracking:
  - VELO
  - UT
  - SciFi

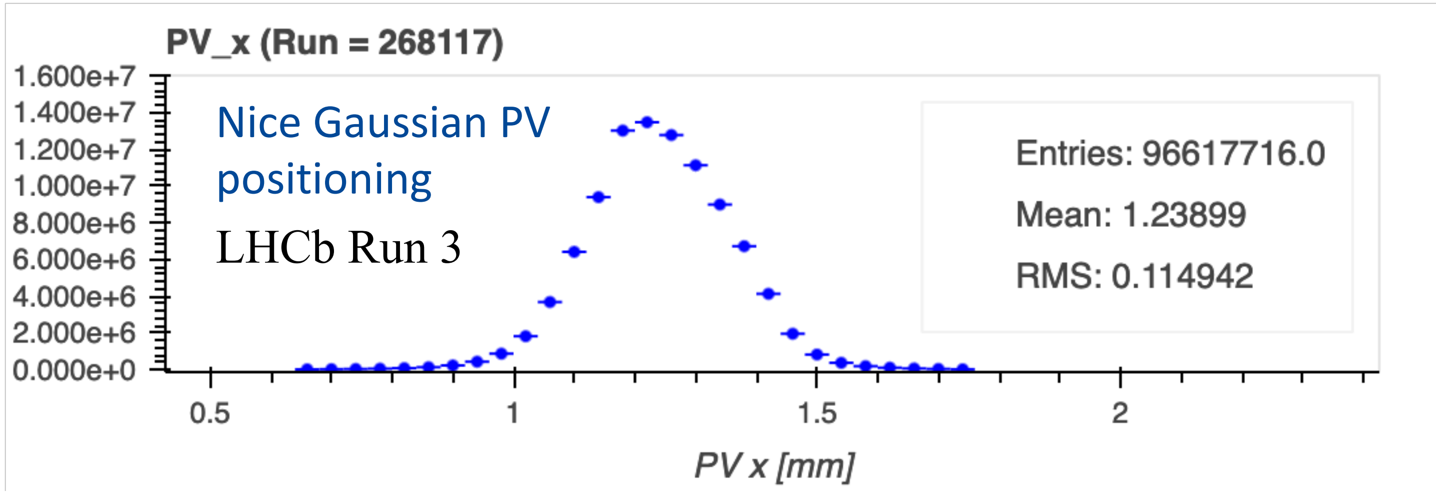


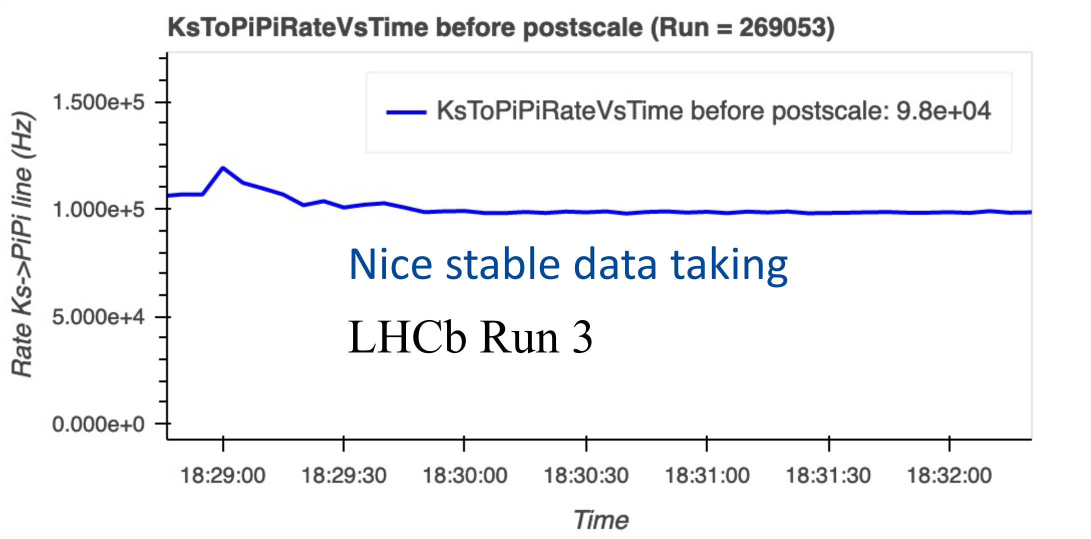


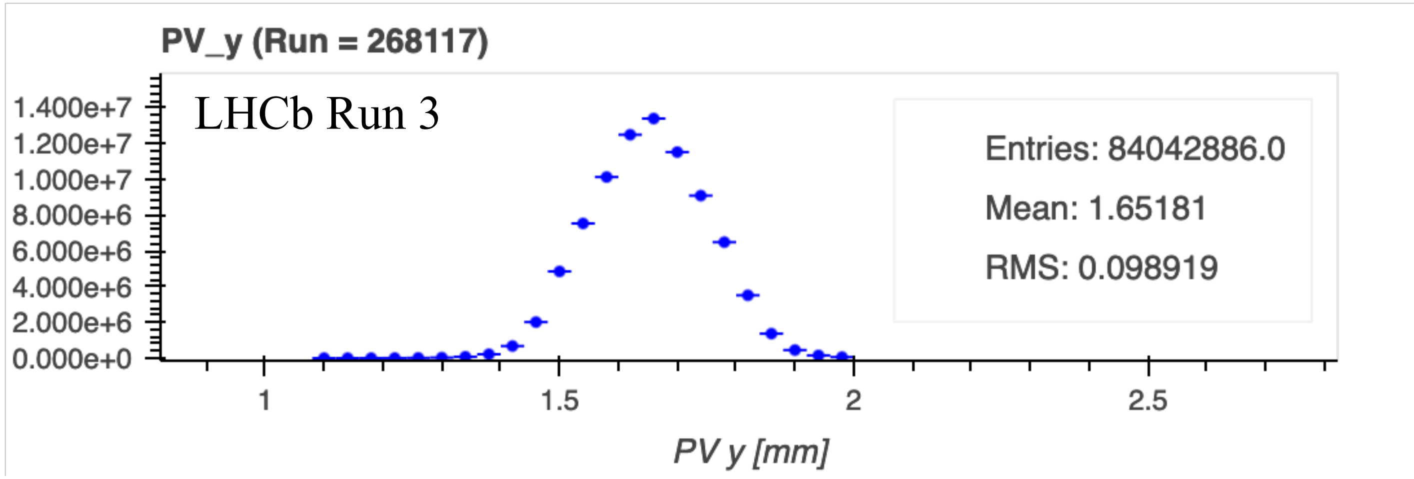
- For PID:
  - Muon stations
  - Electromagnetic calorimeter

HLT1 real-time monitoring

- Allen provides real-time monitoring of data as it is taken
  - Allows problems to be identified quickly

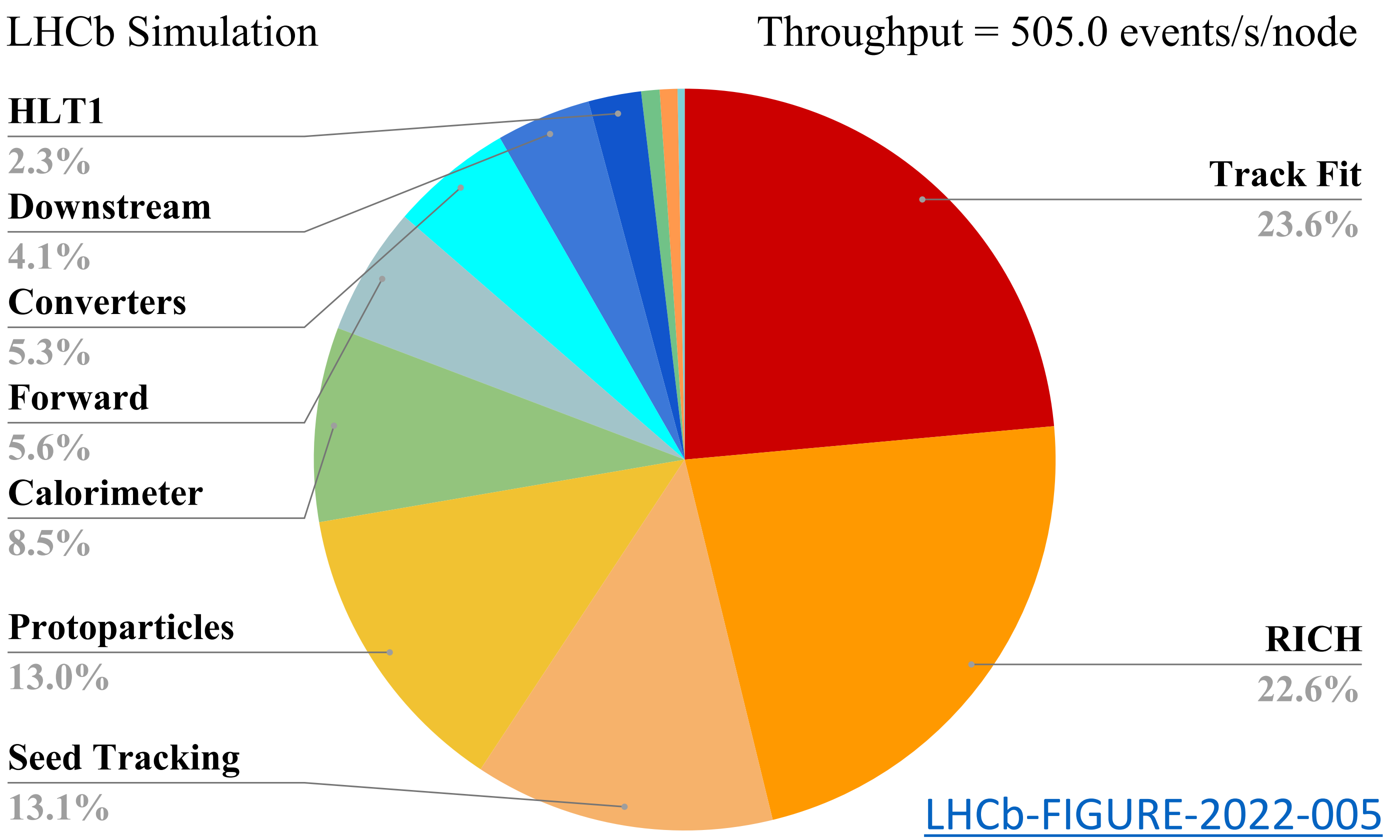






The trigger: HLT2 overview

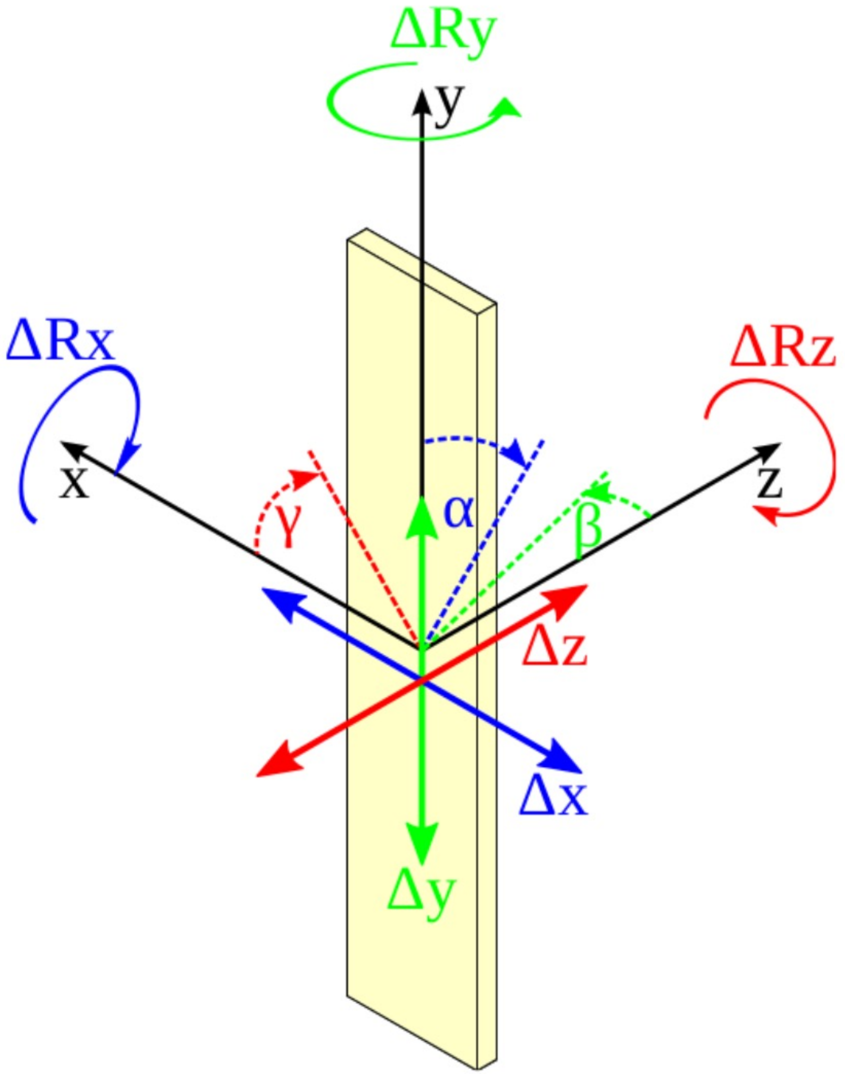
- Runs fully on CPUs
- Full reconstruction including PID from RICH subdetectors and a more sophisticated track fit and pattern recognition
- Filtered into exclusive lines with loose selection for physics
- Saves 'physics objects' into data streams
  - Sometimes also persists the raw machine output
- The final output is ~10GB/s to storage



LHCb-FIGURE-2022-005

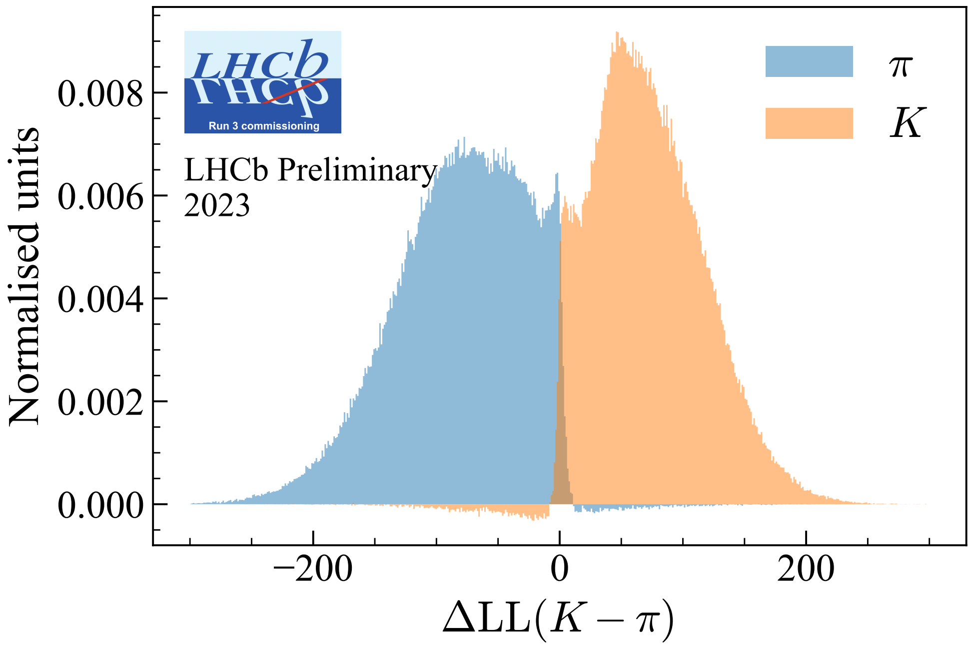
Alignment: overview

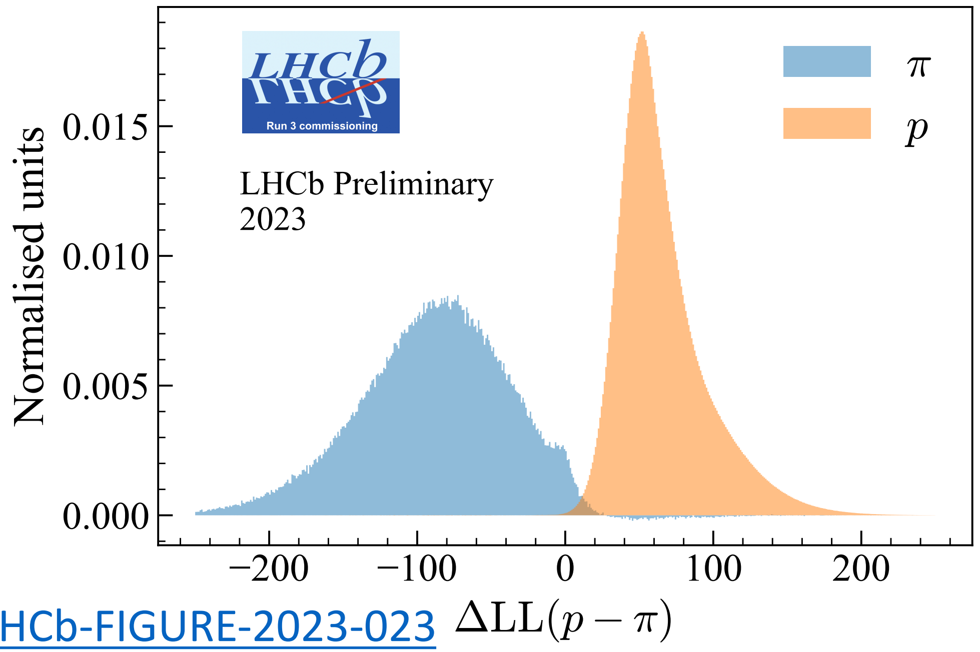
- The detector model used by trigger as well as for simulation follows the technical designs of where each piece should be
  - In reality each piece will be positioned slightly differently from the design
  - Not modelling this misalignment leads to poorer detector response
- The alignment project attempts to model the true position of each piece of the detector in 6 degrees of freedom in real time
  - This is solved in real time at LHCb using data from the buffer
  - Not a trivial problem!



Alignment: results – PID

- PID performance is already better than Run 2 for comparable numbers of primary vertices
  - Alignment of RICH mirrors
- Generally accounting for affects such as
  - Flexing of modules due to their own weight
  - Temperature contraction
  - Imprecission in installation

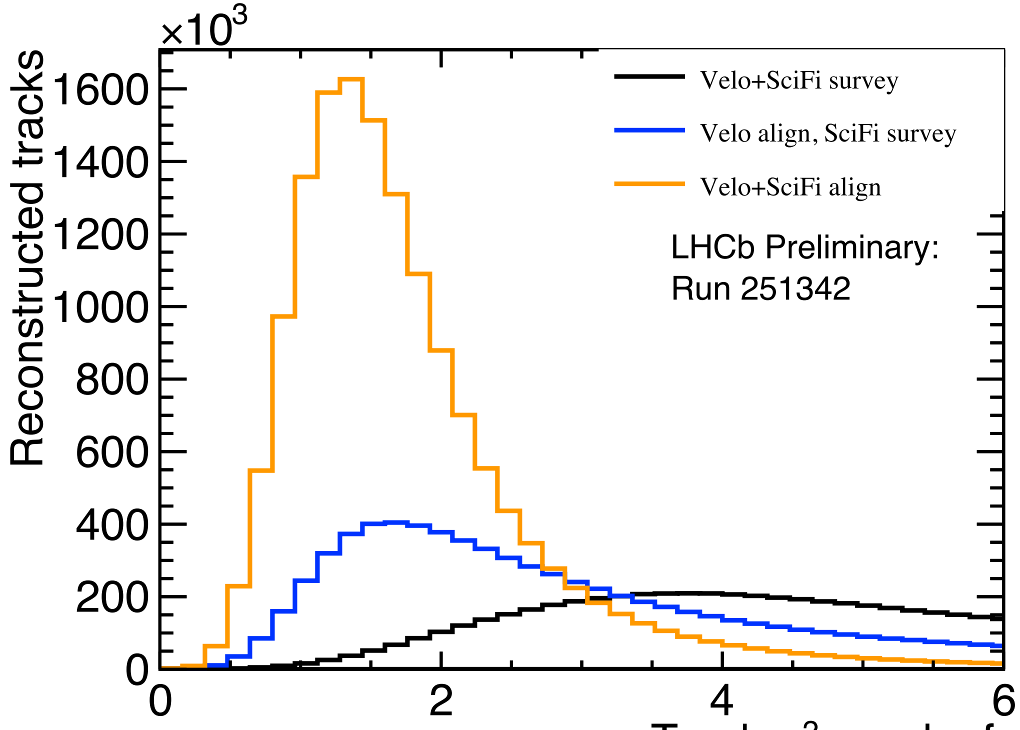




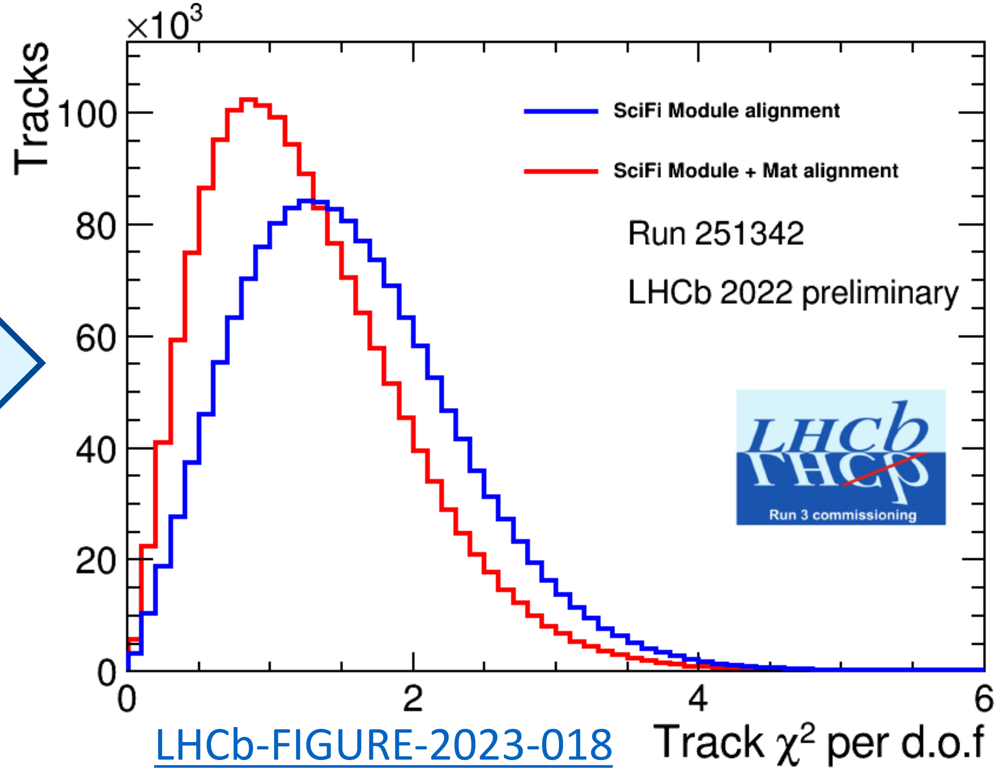
LHCb-FIGURE-2023-023

Alignment: results – Tracking

- The alignment in the SciFi modules was completed first, now finer tuning can be done of the mats – improving track quality



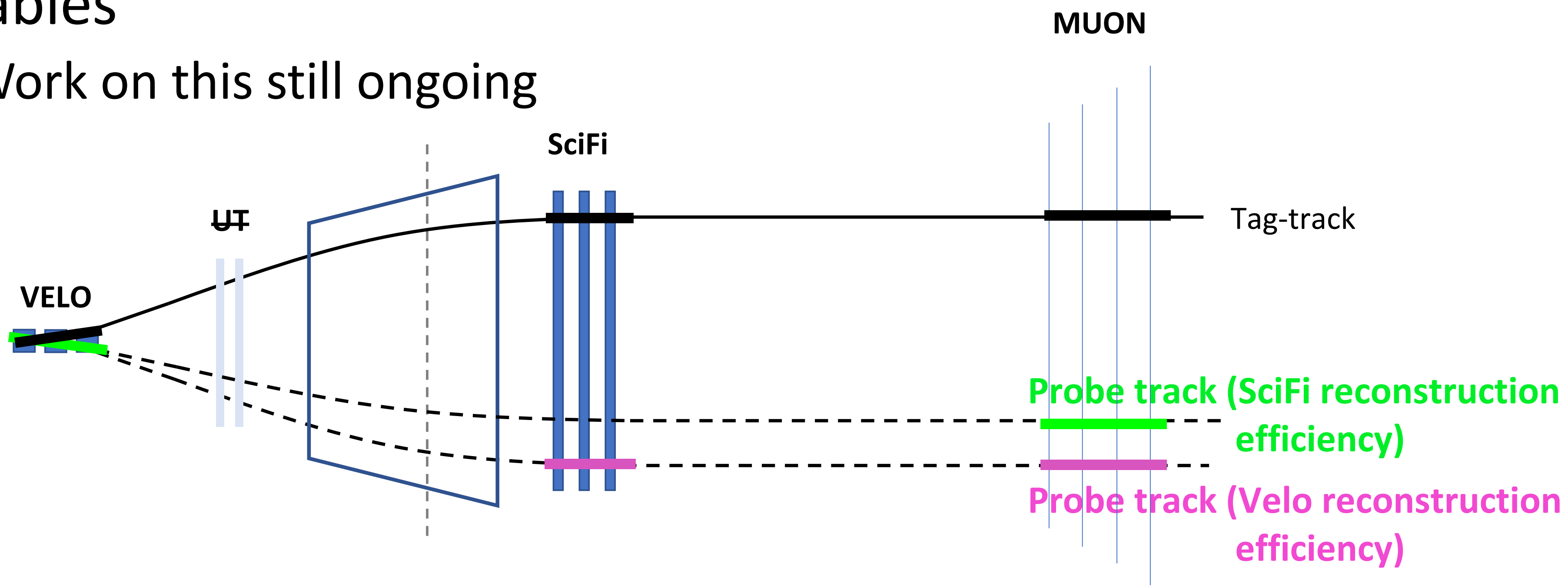
LHCb-FIGURE-2022-018



LHCb-FIGURE-2023-018

Data driven tracking efficiency

- Callibration of tracking efficiency is completed with the tag-and-probe method
- Allows data-driven tracking of efficiency as a function of kinematic variables
  - Work on this still ongoing

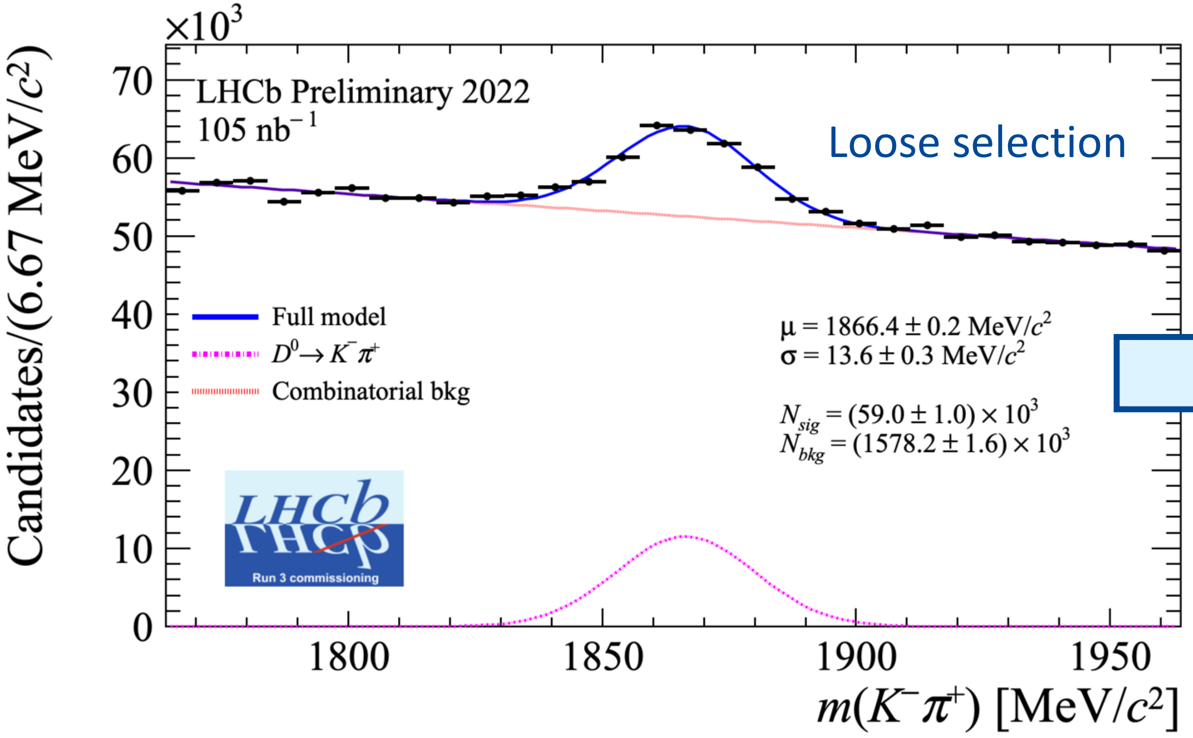


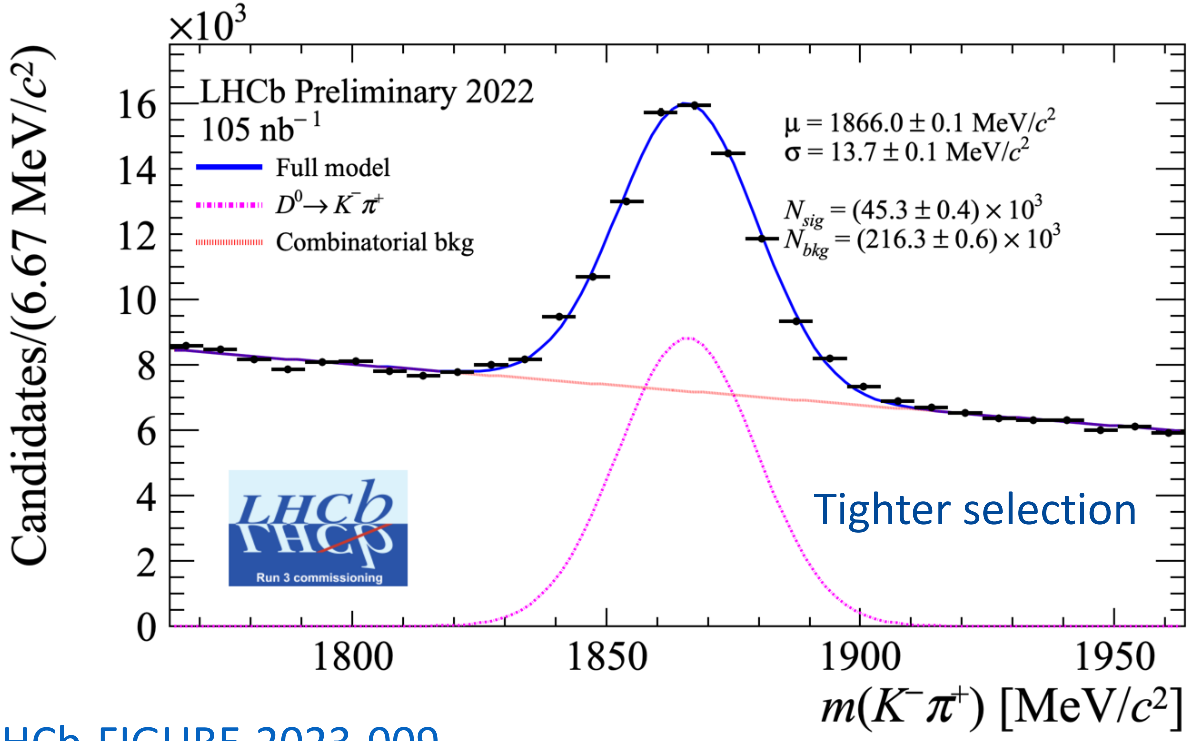
Looking at physics

The decays we’ve been able to find thanks to these efforts

Finding mass peaks with HLT1 – $D^0 \rightarrow K^-\pi^+$

- HLT1 is able to find mass peaks in real time!
  - Straight from raw detector output to clear signal with only minimal offline cuts in 2022!

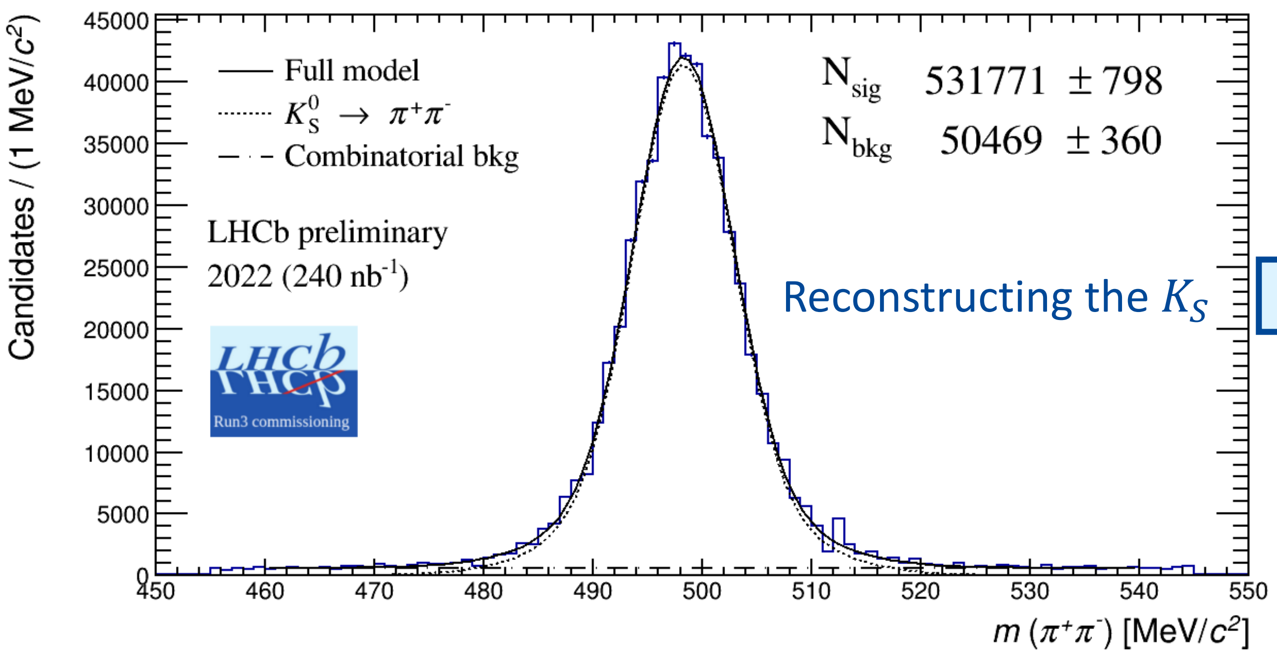


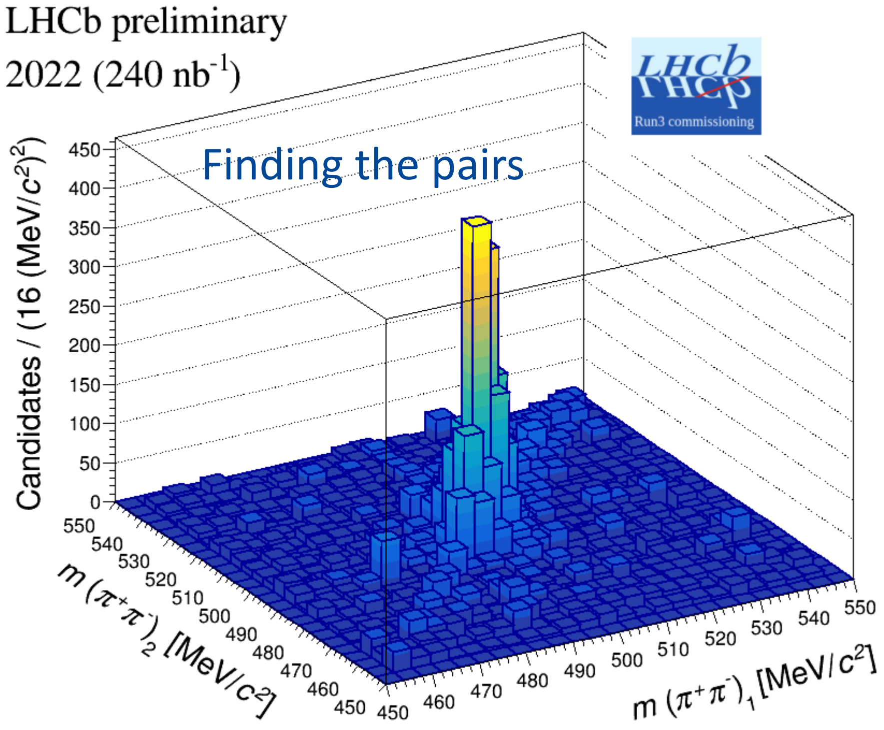


LHCb-FIGURE-2023-009

Finding mass peaks with HLT1 – $K_S \to \pi^+\pi^-$

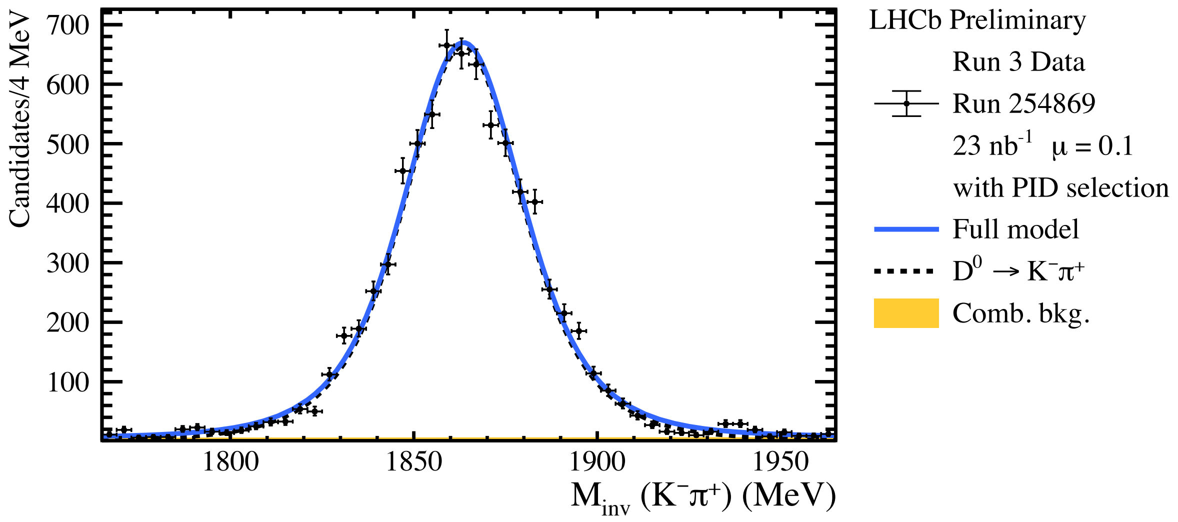
- $K_S K_S$ pairs can be isolated where $K_S \to \pi^+\pi^-$
  - Used for study of e.g. $D^0 \to K_S K_S$ decays



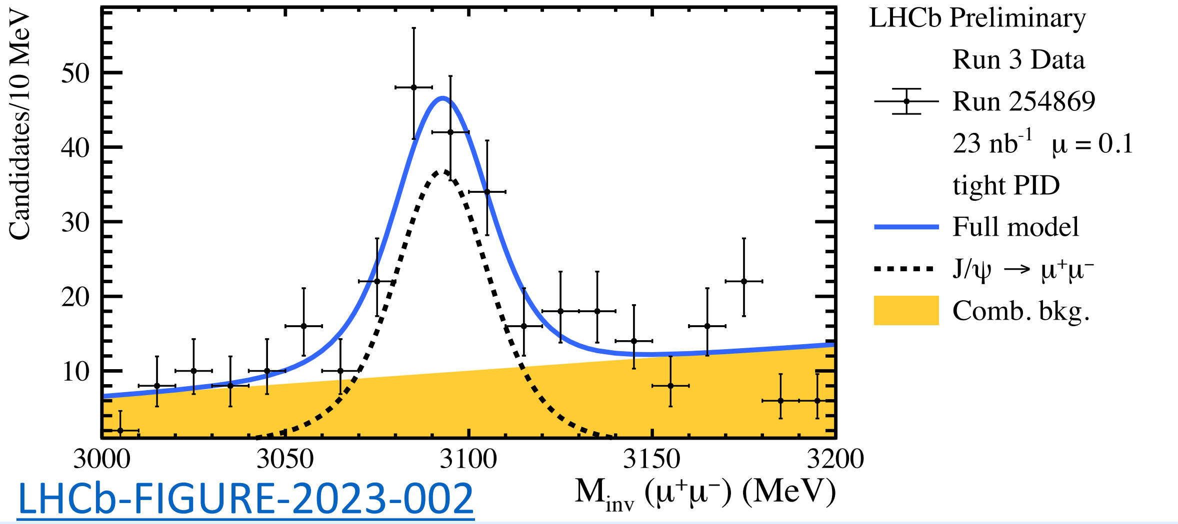


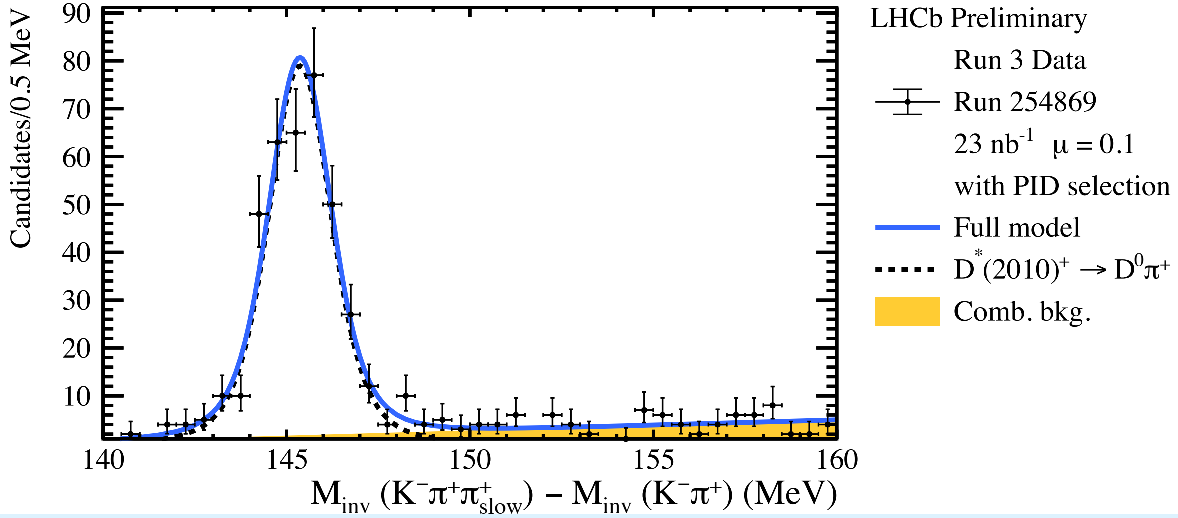
LHCb-FIGURE-2023-005

Adding HLT2 – $D \rightarrow K\pi, J/\psi \rightarrow \mu\mu, D^* \rightarrow D\pi$



- HLT2 uses 'exclusive' trigger lines
- All of these decay modes have been found in 2022 data!
  - Shown here with tighter PID requirements
  - Muon PID has since been improved further by better muon station alignment

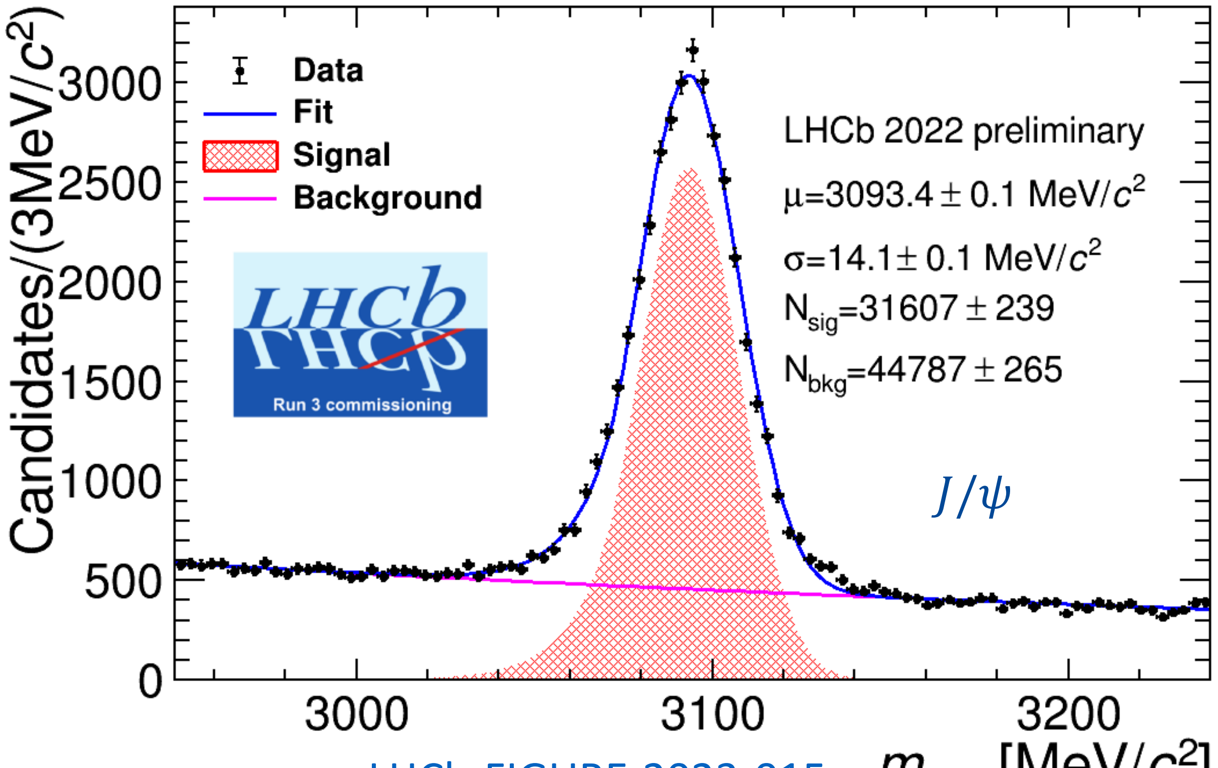




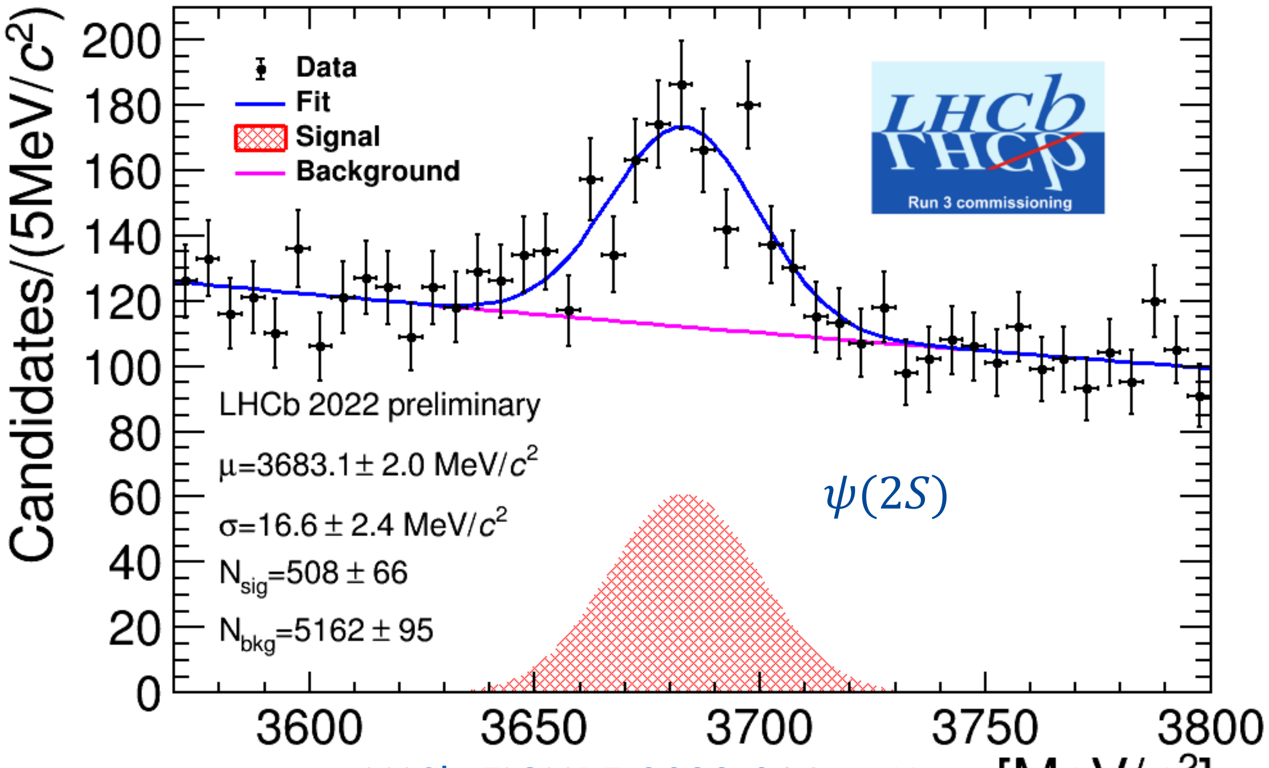
LHCb-FIGURE-2023-002

Finding excited states – $(cc) \to \mu\mu$

- Using HLT2, excited states have been found



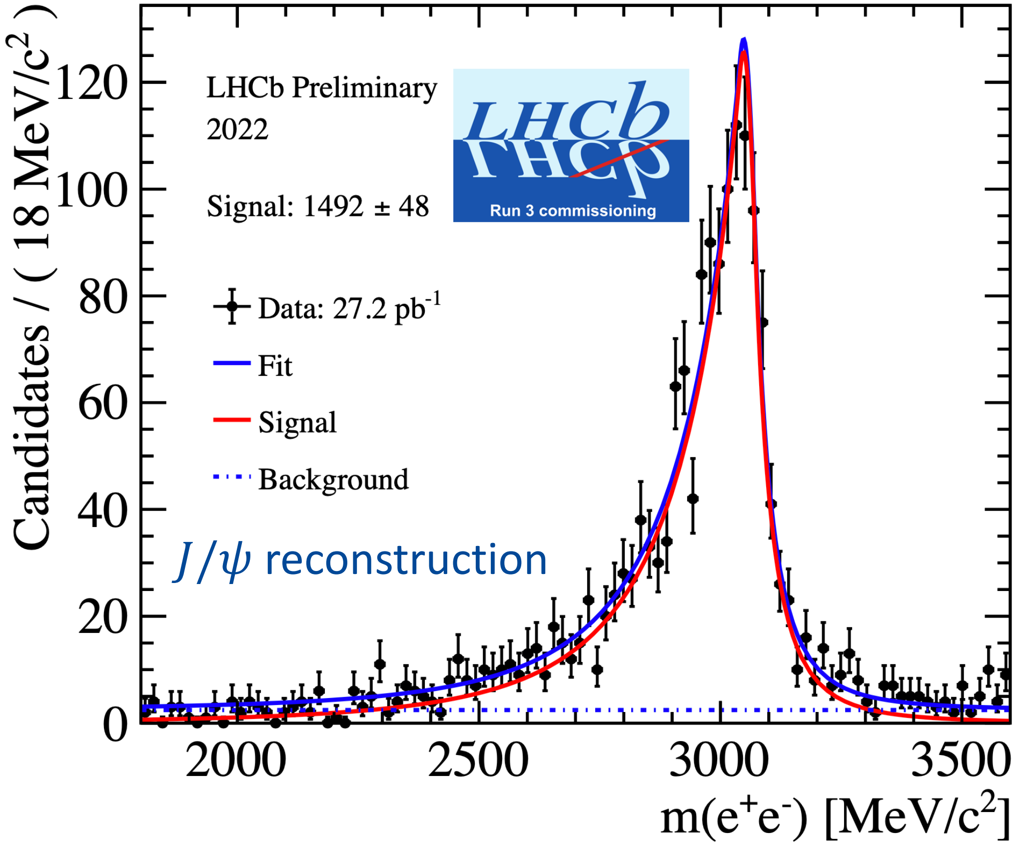
LHCb-FIGURE-2023-015

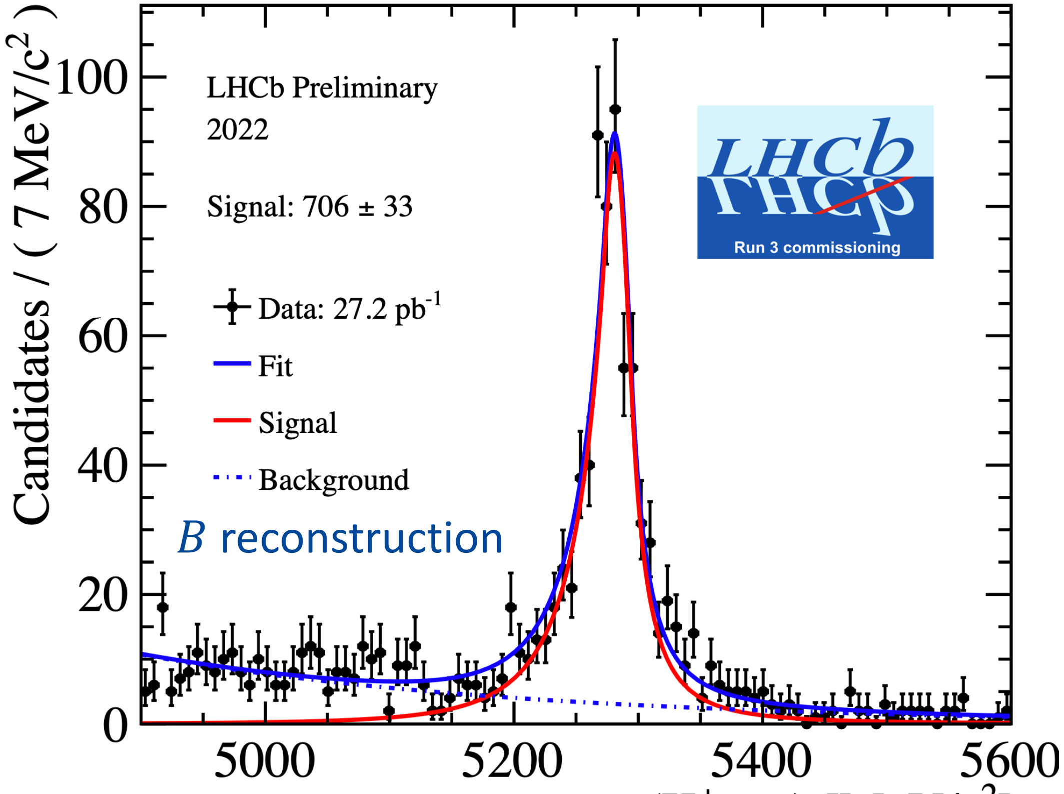


LHCb-FIGURE-2023-014

Electronic states – $B^+ \to [J/\psi \to ee]K^+$

- We can look at decays with a secondary vertex and with electrons

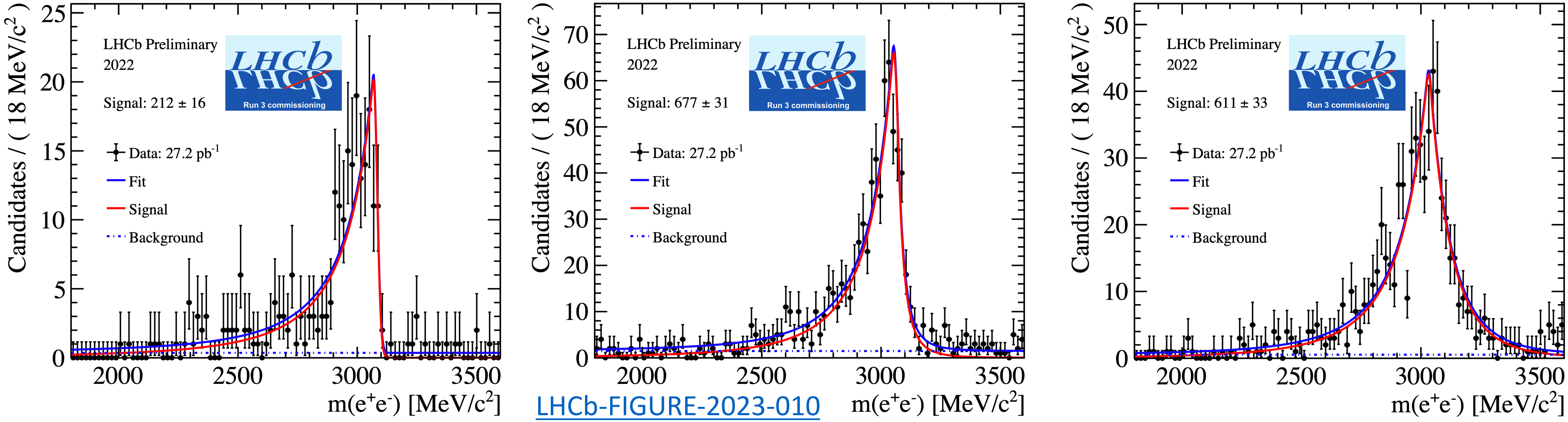




LHCb-FIGURE-2023-010

Electronic states – $B^+ \to [J/\psi \to ee]K^+$

- We can even look in different bremsstrahlung categories!
  - Higher brem gives a more-symmetric distribution for J/ψ as more energy can be recovered



LHCb-FIGURE-2023-010

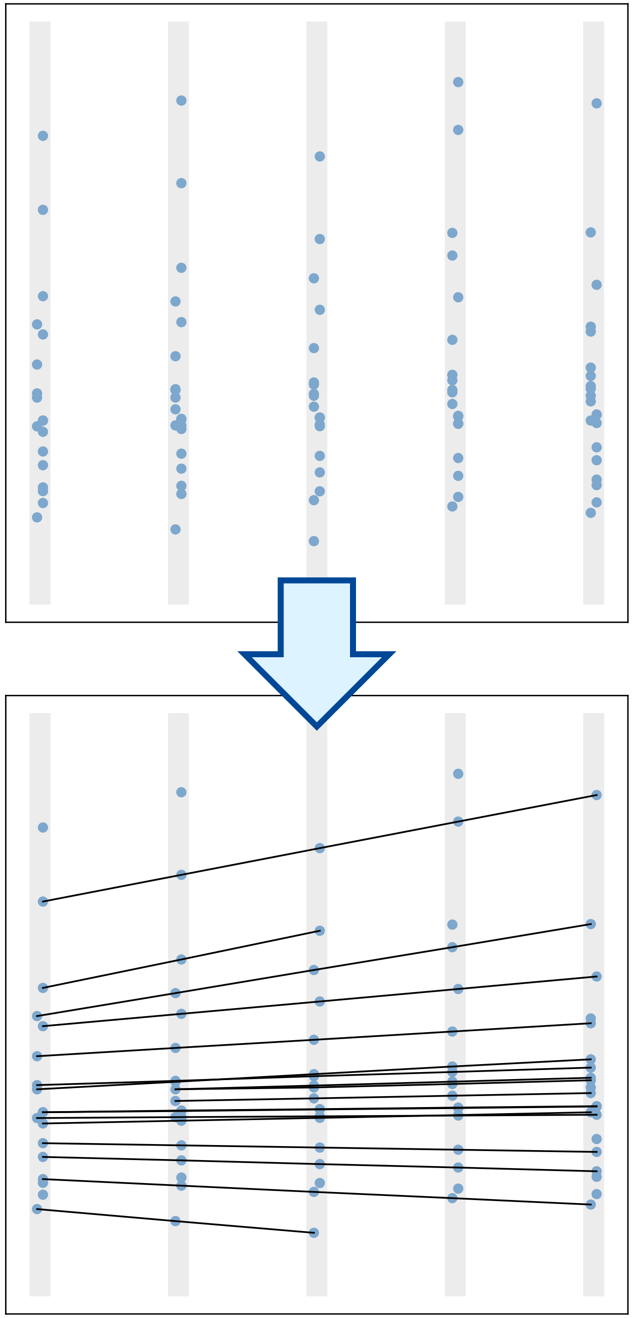
Summary & Conclusions

- LHCb's heterogeneous trigger is doing a fantastic job at reconstructing, filtering, and monitoring the data taken in Run 3 with a very high throughput
- Alignment measured from the output of HLT1 allows for optimised performance of the detector
- HLT2 allows for full reconstruction and PID information allowing for greatly suppressed background
- We have been able to use the output of our trigger system to reconstruct several decay modes in the comissioning of our detector

Backup

The trigger: HLT1 parallelism

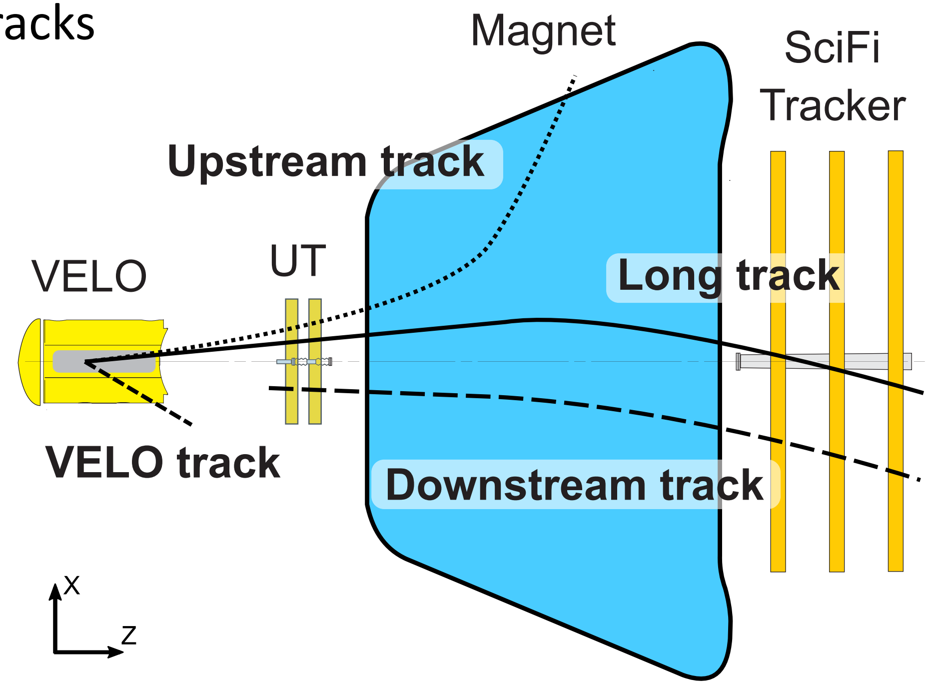
- Hardware acceleration is an obvious candidate for increasing trigger throughput
  - Easily parallelisable
- HLT1 is runs in parallel:
  - Within each event
  - Across events in a batch
  - Across batches
- Runs at a dedicated data centre
  - 6 modules × 132 racks × 2 GPUs/rack
    - Nvidia RTX A5000 cards are used running source code in Cuda



Pérez, Neufeld, Núñez, 2021

The trigger: HLT1 - examples of algorithms

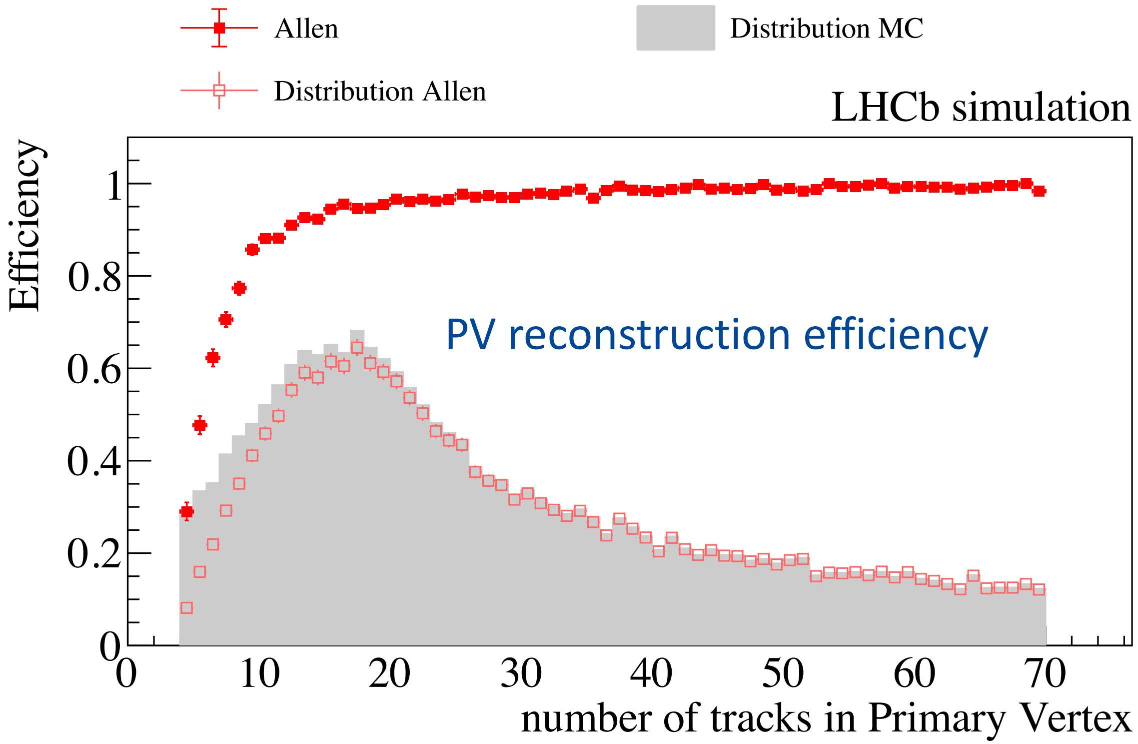
- Tracking can be done
  - Within any individual tracker – The VELO, UT or SciFi
  - Across trackers – “Long”, “Upstream” or “Downstream” tracks
    - This can be done using one of two different methods
      - Forward or Seeding/Matching
  - Tracking of electrons
    - Recovering and compensating for bremsstrahlung
  - Tracking gives access to kinematic variables
    - Useful for selection
- Basic PID
  - Identification of Muons and Electrons
- Event Reconstruction
  - Combining tracks into parent particles
  - Finding primary vertices (PVs)
- Machine learning
  - MLP’s, similar to those typical in LHCb analyses, may be applied for selection



Declara, Pérez et al, 2020

The trigger: HLT1 performance in simulation

- Efficiency of HLT1 may be given in bins of other variables
  - Some examples given



LHCb-FIGURE-2020-014