LHCb full-detector real-time alignment and calibration
Latest developments and perspectives

MANCHESTER 1824
The University of Manchester

LHCb

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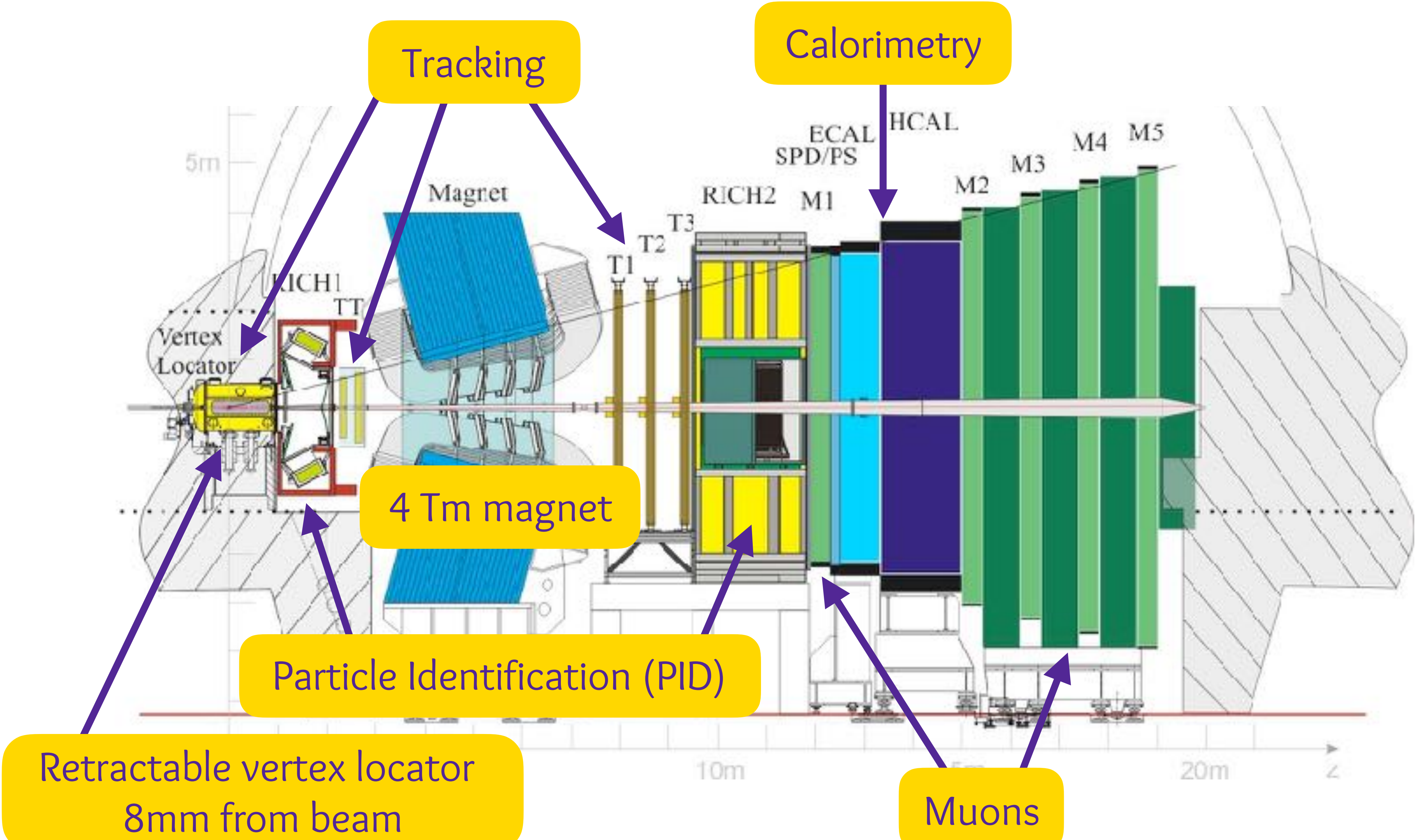
10th July @ CHEP 2018, Sofia

The LHCb Detector

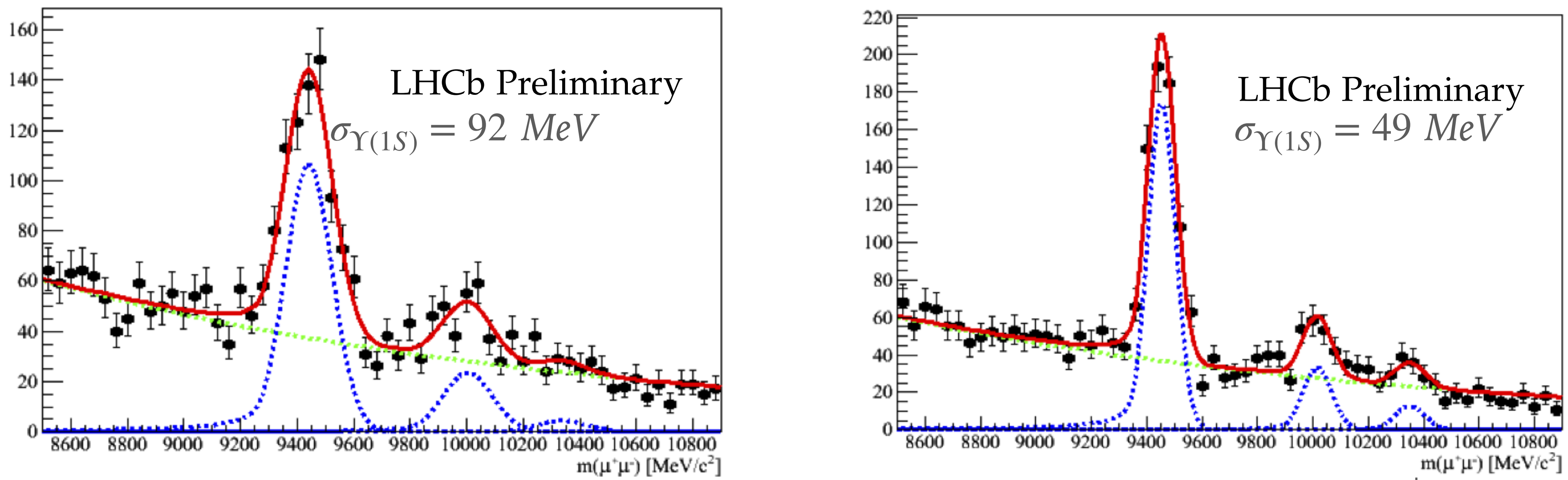
- Single arm forward spectrometer at the LHC covering $2 < \eta < 5$
- Dipole magnet with polarity changes every few weeks
- Physics program includes flavour physics, EW, exotica and heavy ions



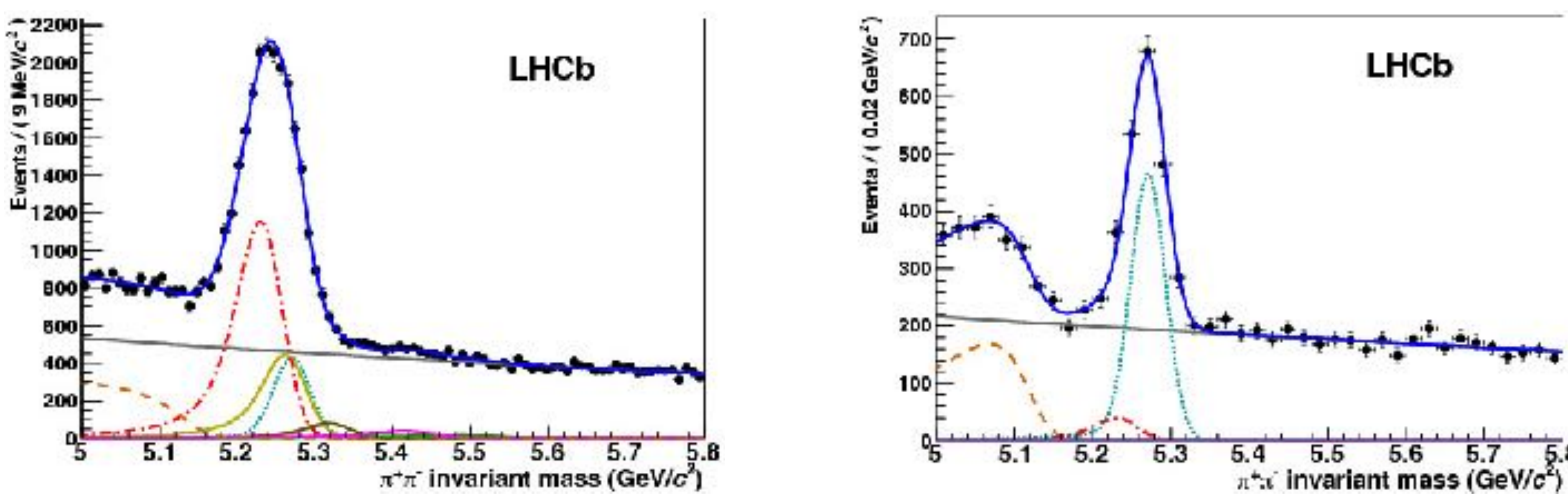
$\Delta p/p \approx 0.5\%$
$\Delta t \approx 45fs$
$\varepsilon^{track} \approx 96\%$
$\varepsilon^{PID}(K) \approx 95\%$
$\varepsilon^{PID}(mu) \approx 97\%$
$\varepsilon^{PID}(e) \approx 90\%$

Why do we need alignment and calibration?

- Better mass resolution
- Better particle identification (PID)
- Store less background → Allocate more bandwidth for physics!



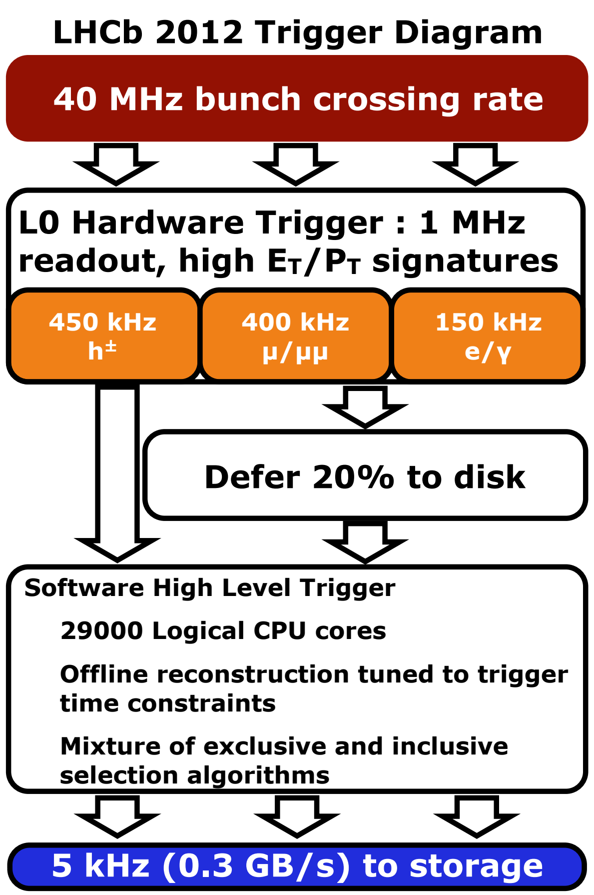
Difference between a preliminary and an improved alignment in $\Upsilon(1S) \rightarrow \mu^+\mu^-$

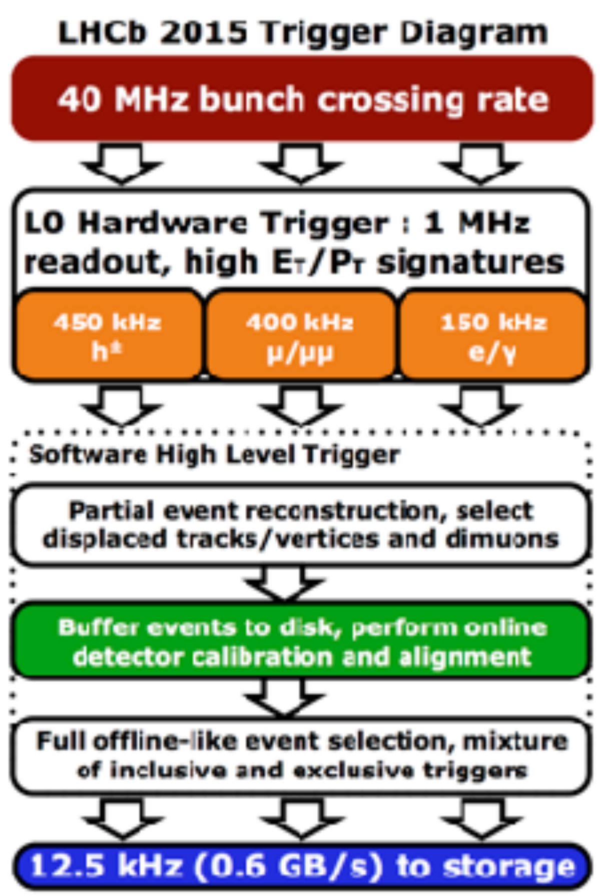


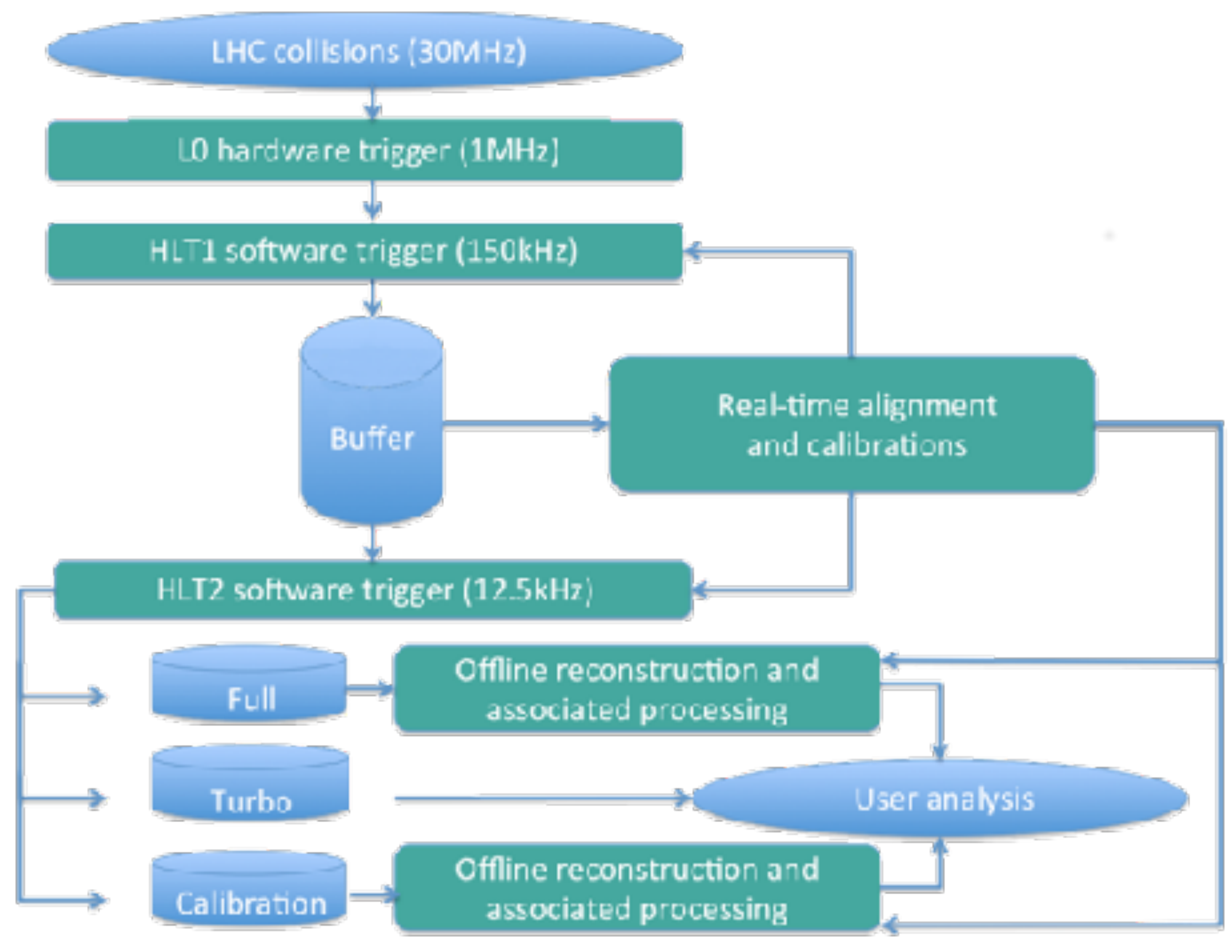
Invariant mass for $B^0 \rightarrow \pi^+\pi^-$ without (left) and with (right) PID applied

The LHCb trigger scheme

- In 2015 LHCb moved to a novel realtime analysis strategy
- Store only part of the event → allows for higher output bandwidth
- **Issue:** Requires offline quality alignment and calibration in the trigger
- **Solution:**
  - Automatically perform alignment and calibration online
  - Buffer events to disk while waiting for them to become available



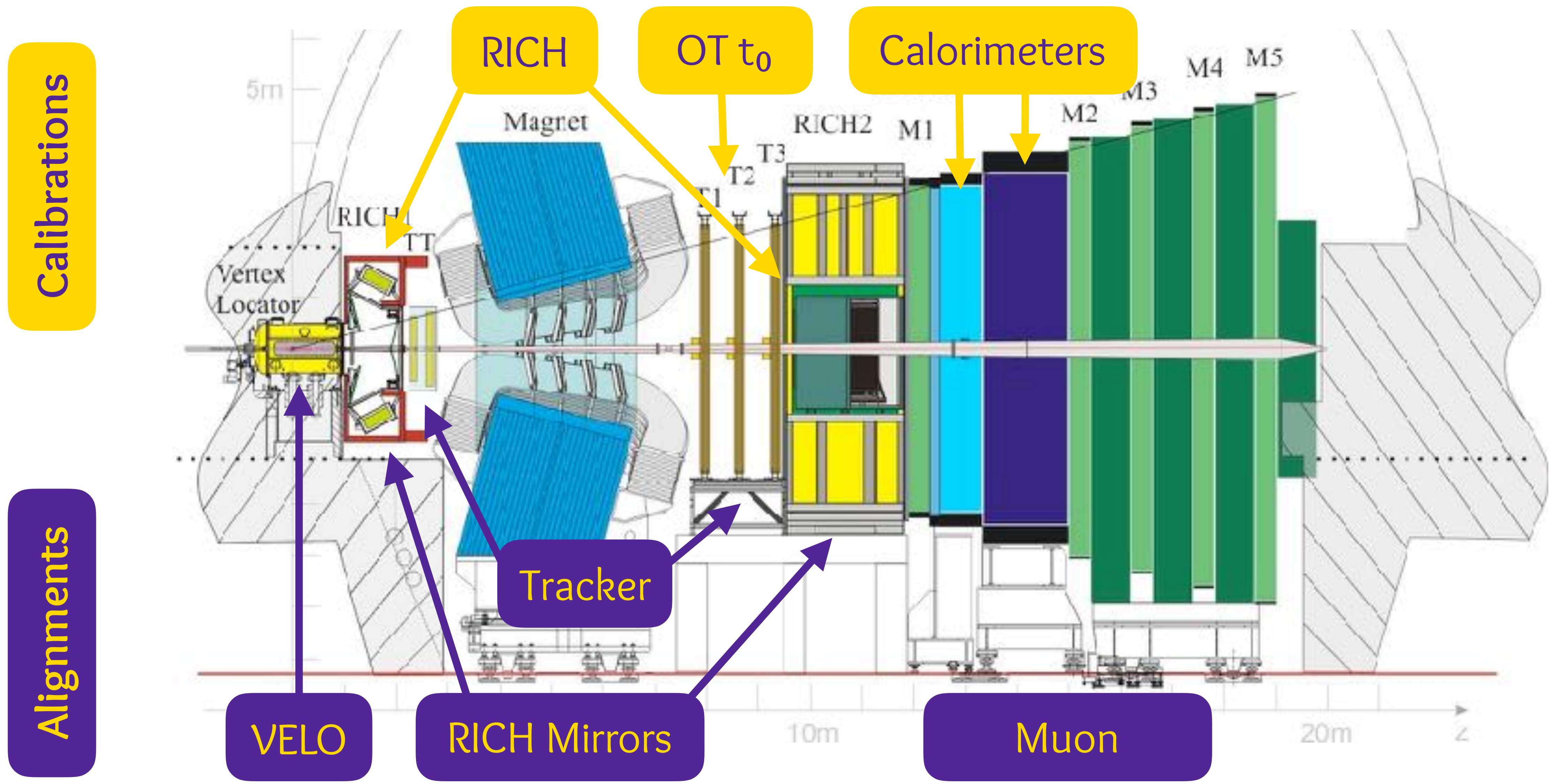




https://doi.org/10.1016/j.cpc.2016.07.022

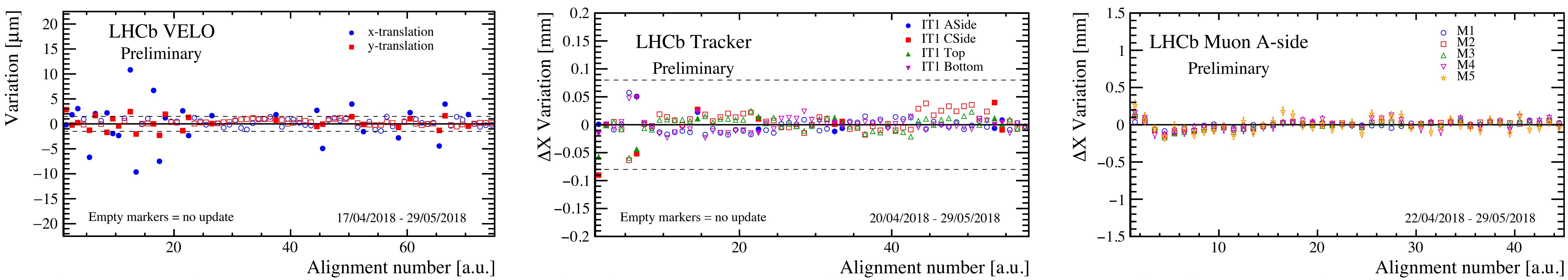
Online alignment and calibration

- Throughout Run 2 new online procedures have been added
- **New for 2018: All alignments and calibrations are now automated!**



Alignment of tracking detectors

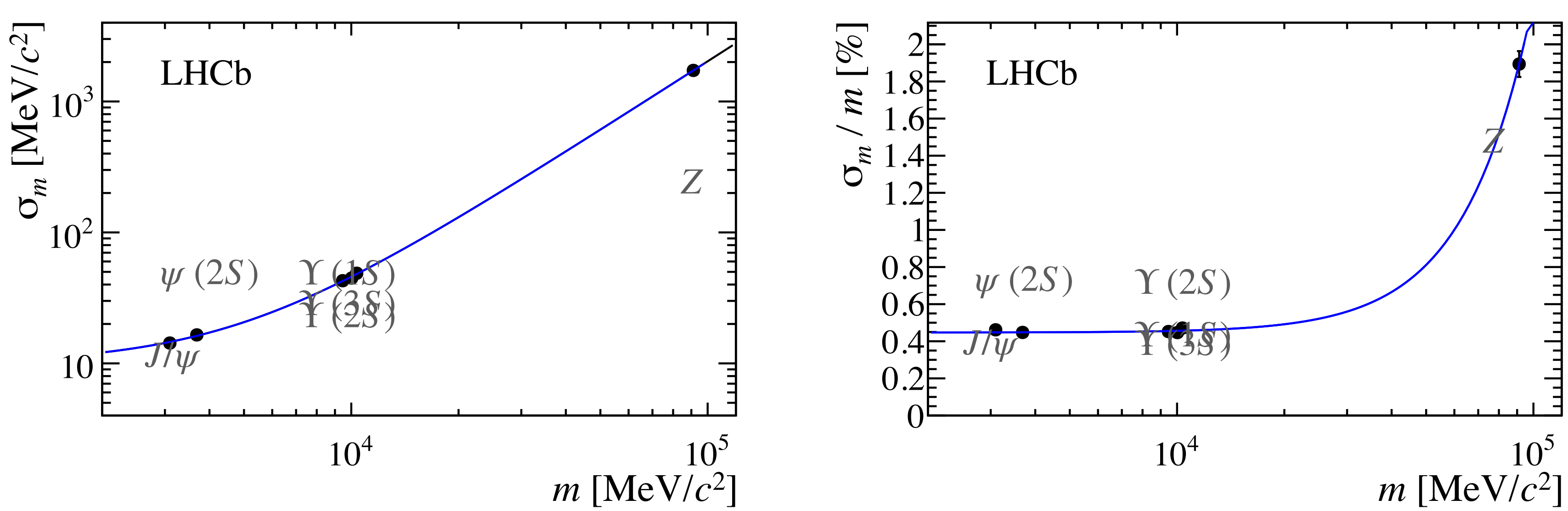
- All tracking alignments use a Kalman filter to minimise the global χ^2
- **Velo:**
  - Sample collected ~immediately, alignment takes ~2 minutes
  - Frequent updates due to movement at the beginning of each fill
- **Tracker:**
  - Sample collected in ~immediately, alignment takes ~7 minutes
  - Updates mostly expected after magnet polarity changes
- **Muon:**
  - Sample collected in ~3 hours, alignment takes ~7 minutes
  - No movement expected except after physical intervention



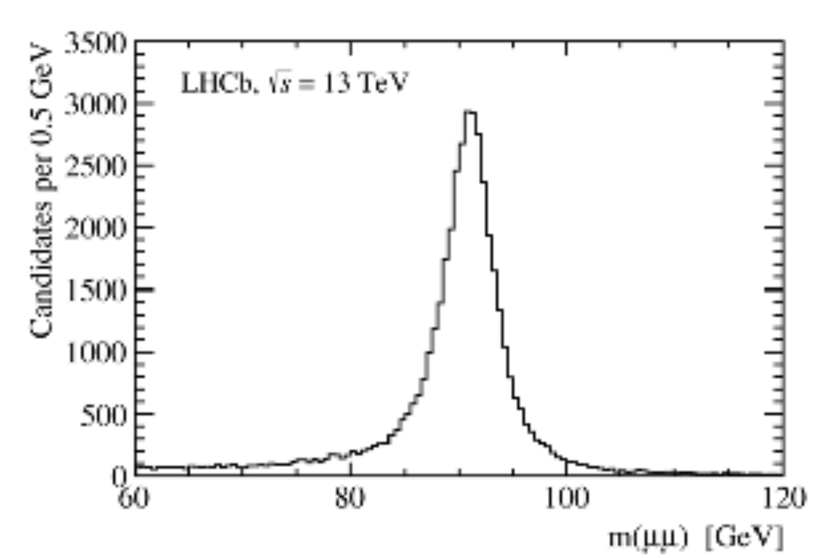
Changes of alignment constants each time the alignment is ran with solid markers represent the alignments that triggered and update. The horizontal dashed lines represent the minimum change required to trigger an update.

Tracking alignment for EW physics

- Natural Z width (~2.5 GeV) is close to the LHCb resolution (~2% @ 90 GeV)
- Electroweak physics often uses extremely high momentum tracks
  - Sensitive to dofs that can't be aligned online
  - But there are only about 100 $Z \to \mu^+\mu^-$ decays per hour in LHCb
- Recently moved to a new starting position
  - Created using $Z \to \mu^+\mu^-$ decays and tracks like the online sample
  - Negligible effect for most tracks but big improvement in $Z \to \mu^+\mu^-$



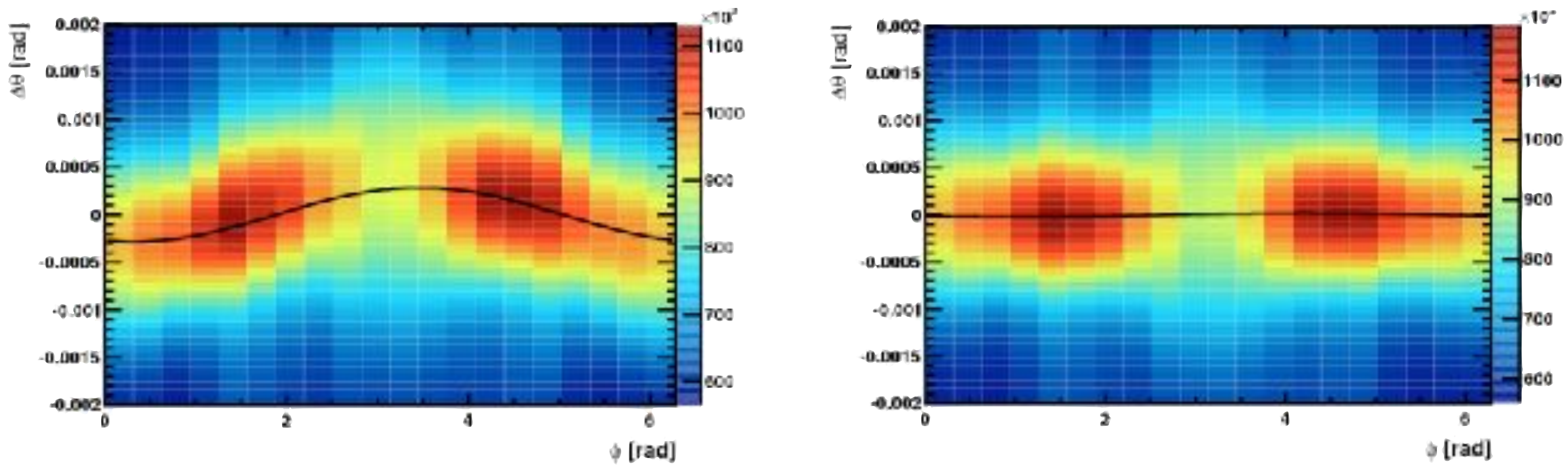
LHCb mass resolution as a function of mass
LHCB-DP-2014-002



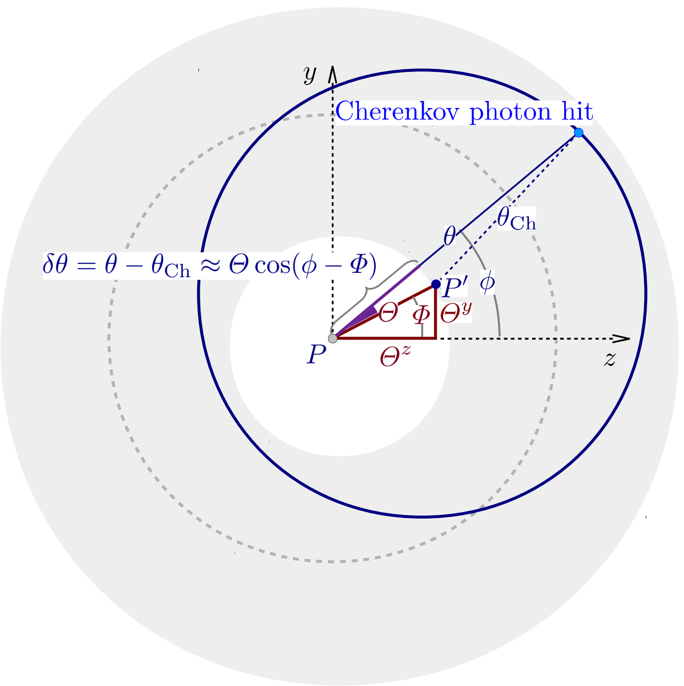
Z invariant mass in dimuon decays
LHCb-PAPER-2016-021

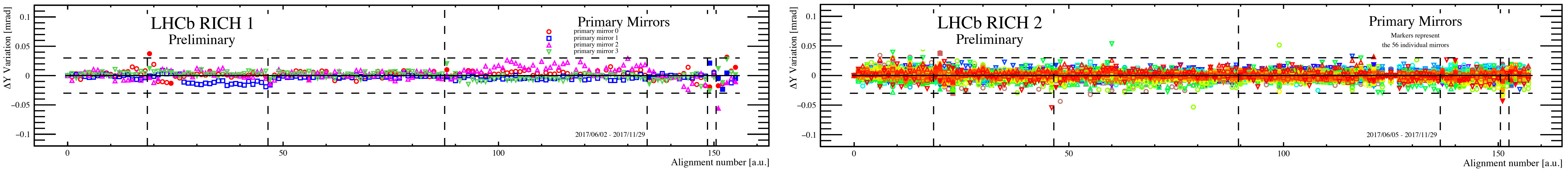
Alignment of RICH detectors

- Primary and secondary mirrors need to be aligned (110 mirror pairs)
- Fit the variation of Cherenkov angle **Δθ** as a function of polar angle
- Ran every fill, parameters typically change with magnet polarity flips
- Takes ~2 hours to collect data and ~20 minutes to run procedure
- Completely **automated** since 2017



Cherenkov angle vs phi for misaligned (left) and correctly aligned (right) mirrors

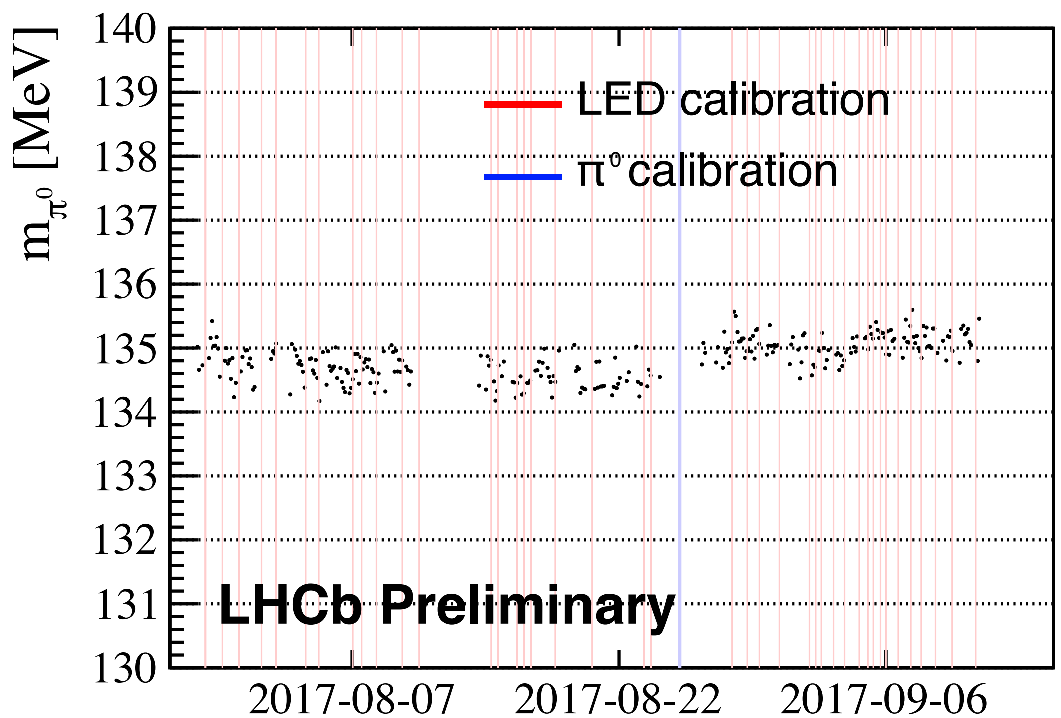




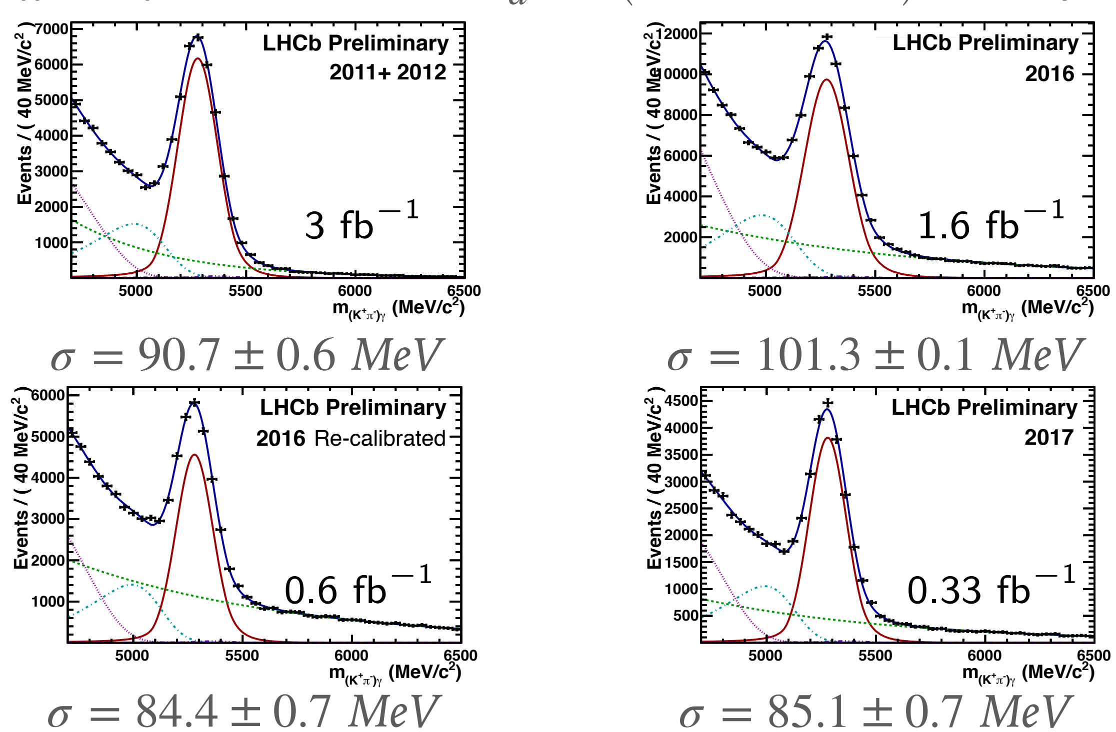
Difference in alignment constants of the primary mirrors of RICH 1 and RICH 2

Calorimeter calibration

- Required to counteract changes and ageing of the detector material
- **Relative calibration** end of every fill
  Compare LED monitoring system to a reference and update HV
  Reference updated after each absolute calibration
- **Absolute calibration:** ~once a month
  HCAL: Caesium scan performed during technical stops
  ECAL: Use 300M randomly selected events to fit π^0mass in each cell
- Relevant steps are now performed **automatically** online

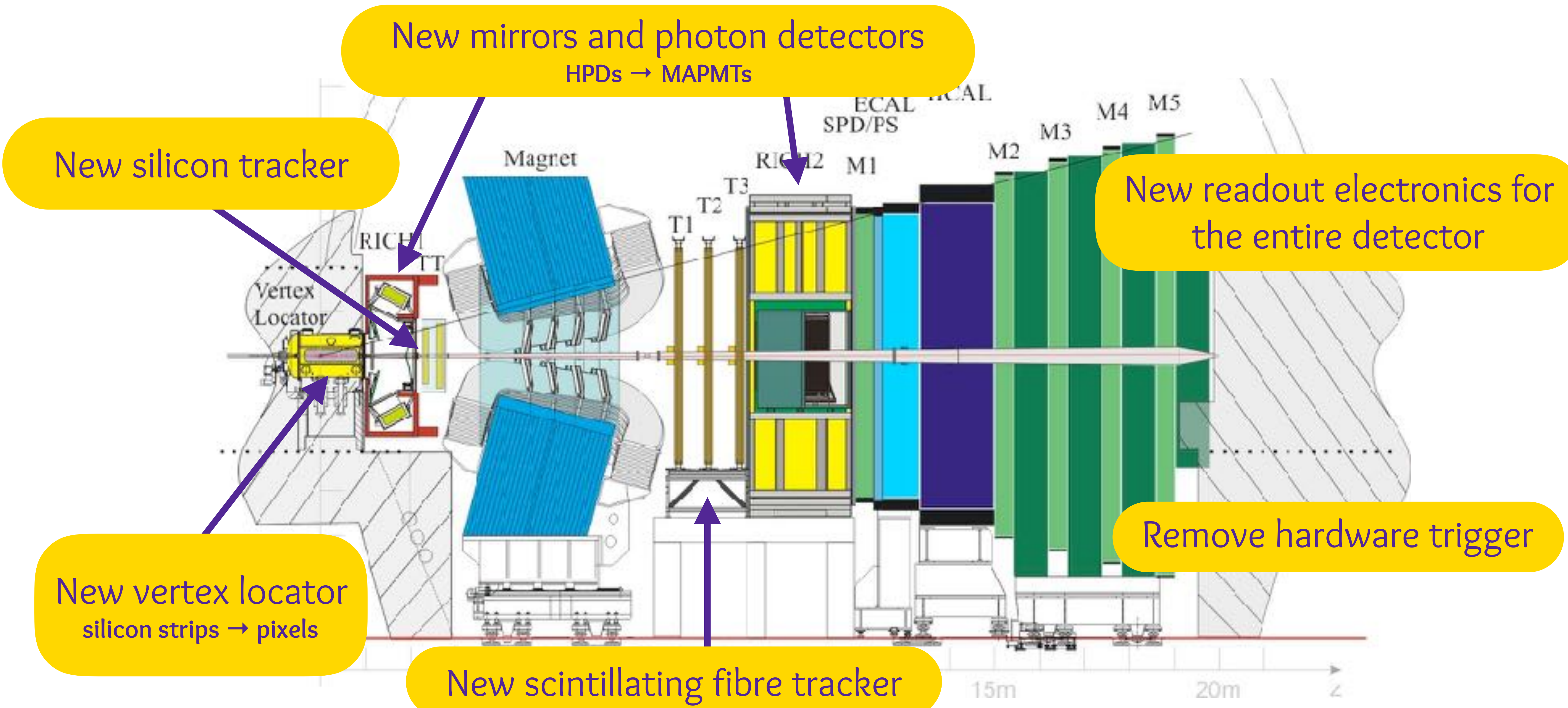


Effect of calibration in $B_d^0 \to (K^* \to K^+\pi^-)\gamma$ decays



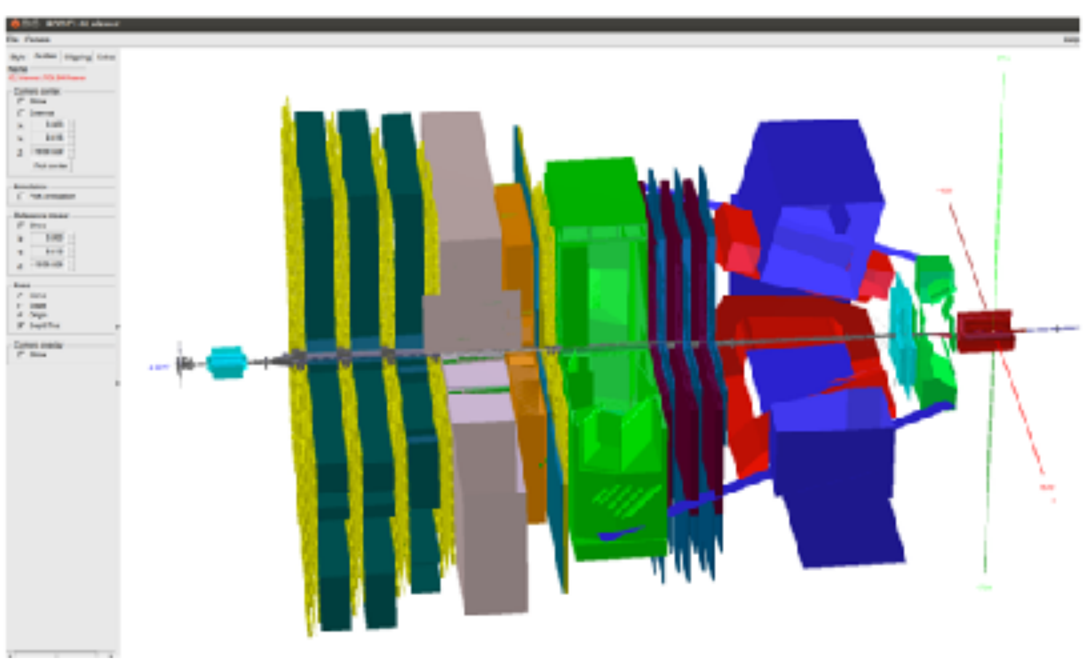
The LHCb upgrade

- During LS2 of the LHC LHCb will undergo its first major upgrade
- Move to an **all-software trigger** will dramatically **increase efficiencies**
  - But poses **extremely challenging** requirements for computing
- Realtime alignment and calibration is an **essential** part of the upgrade

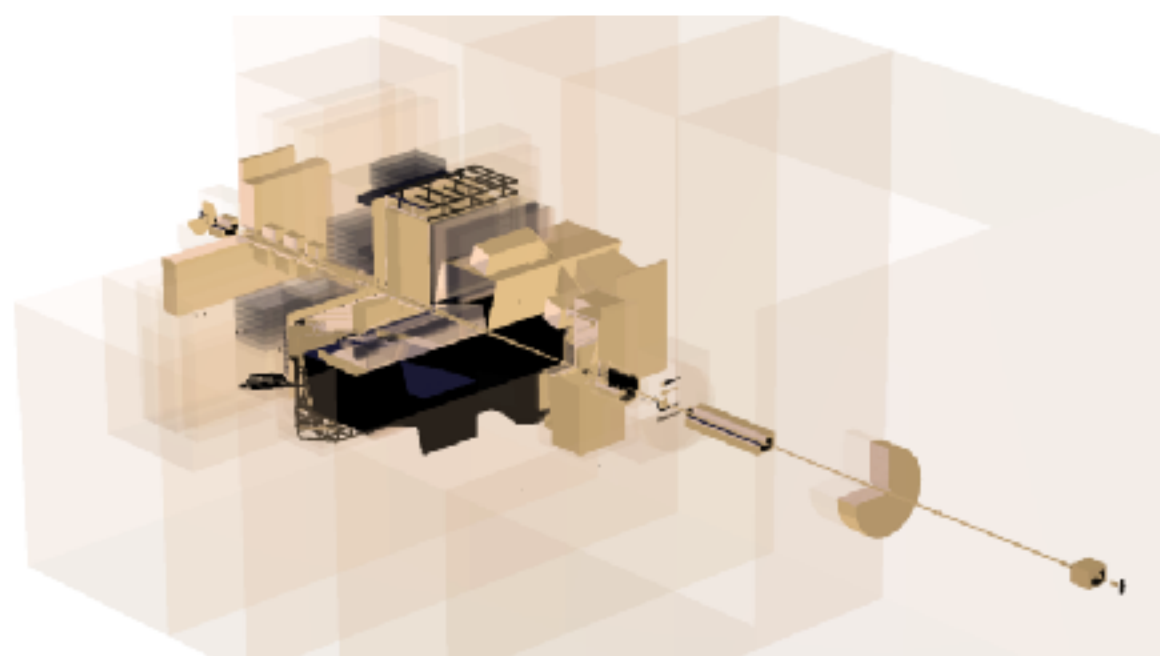


Geometry and conditions data

- Currently use a custom geometry and conditions framework
  - Codebase can't be easily adapted for multithreaded Gaudi
  - Many additional features would be desirable (simplified geometries)
- Considering a move to the DD4hep toolkit
  - Allows **common tools** to be used (visualisation, testing, etc.)
  - Prototype running with full geometry loaded using DD4hep
  - Work ongoing to convert tracking to use DD4hep
- See poster for details: "Perspectives for the migration of the LHCb geometry to the DD4hep toolkit"



Current geometry loaded using DD4hep and visualised using ROOT

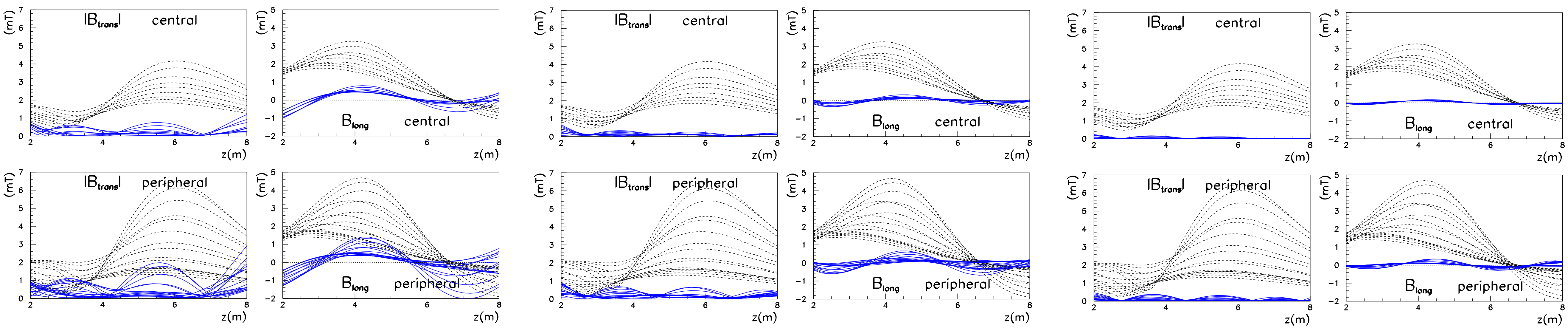


Upgrade geometry loaded using DD4hep

Magnetic field alignment

- LHCb's magnetic field was surveyed in 2011 and 2014
  - Measurements are known to not cover the full acceptance
- A recent paper by Pierre Billoir proposes using Maxwell compatible polynomials to correct for field parameters
  - Can then perform a global minimisation of the track χ^2 to extract corrections for geometric displacements and field corrections
- Shown to be effective for a toy spectrometer:

Up to degree 2 *Up to degree 4* *Up to degree 6*



Deviations from the true magnetic field before (grey) and after (blue) applying an alignment procedure using polynomials

- Work is ongoing within LHCb to test this with real experimental data

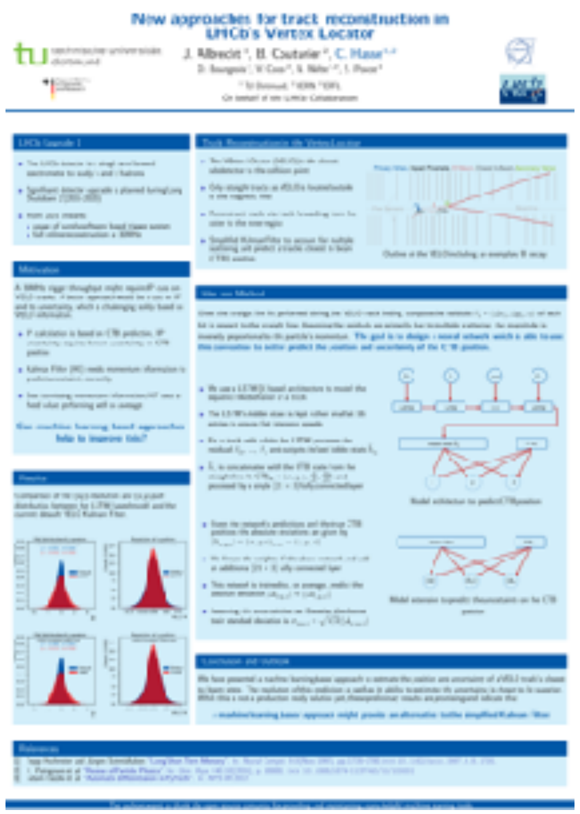
https://doi.org/10.1016/j.nima.2018.06.039

Summary

- LHCb continues to perform exceptionally well
  - Getting better data than ever despite being nearly 10 years young
- All alignments and calibrations are now running automatically online

- LHC Run 2 will soon come to an end and so is LHCb as we know it
- Lots of interesting upgrade preparations are underway including:

New approaches for track reconstruction in LHCb's Vertex Locator

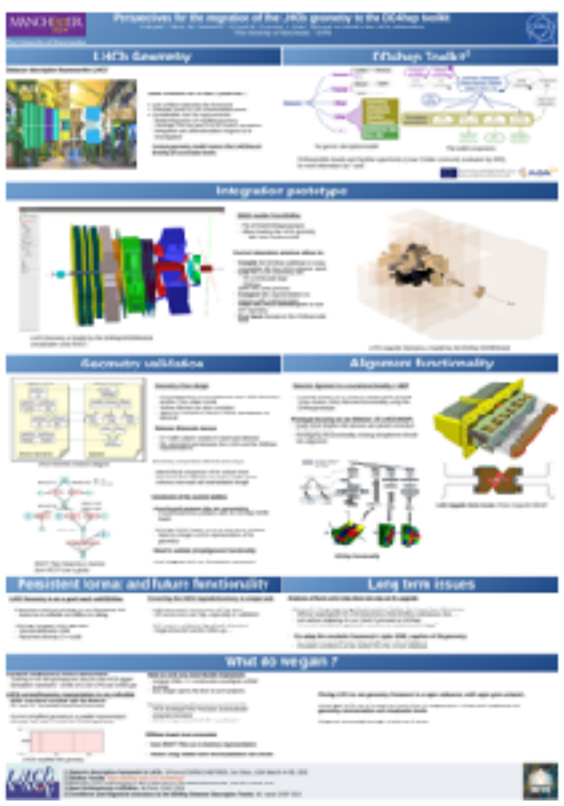


A 30MHz software trigger for the LHCb upgrade

Fast Kalman Filtering: new approaches for the LHCb upgrade

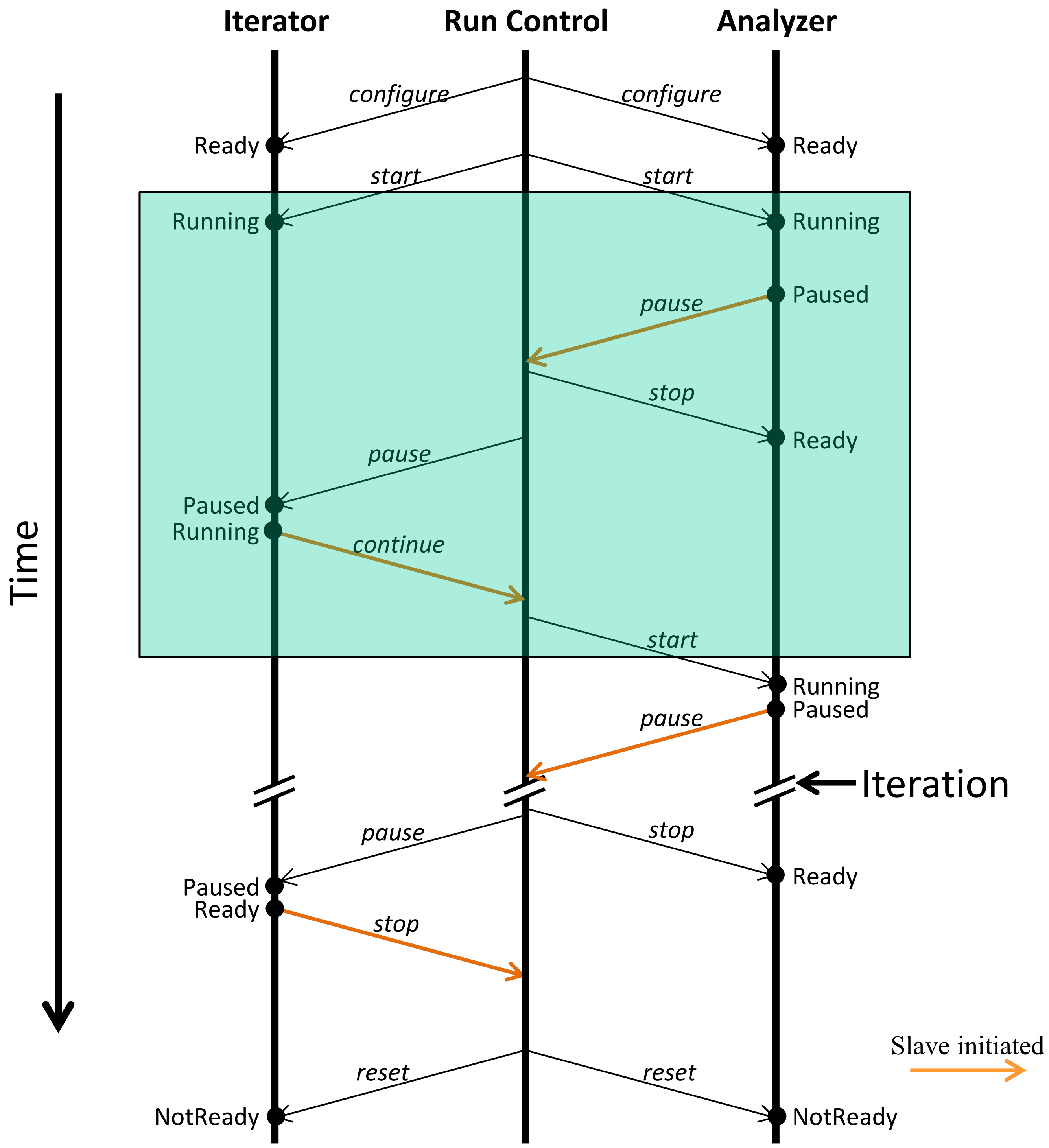
A Git-based Conditions Database backend for LHCb

Perspectives for the migration of the LHCb geometry to the DD4hep toolkit




Backup

Finite state machine for online alignment and calibration



- Each online alignment and calibration task is controlled by the same finite state machine
- One process of the analyser task runs on each of the ~1600 nodes in the trigger farm
- Overview of sequence:
  1. Iterator writes conditions in XML
  2. Each analyser reads these conditions and reconstructs events to produce a binary file “alignsummarydata” (ASD)
  3. Iterator combines the ASDs to compute the new conditions constants and writes these to XML
  4. Steps 2 & 3 repeat until the procedure converges. The new constants are then copied to the trigger area.

Automated tasks

Task	Update	Sample	Data collection	Duration	When?
Velo alignment	Automatic	50k minbias + beamgas	< 1 min	2 min	Every fill
Tracker alignment	Automatic	100k $D^0 \to K\pi$	< 1 min	7 min	Every fill
RICH mirror alignment	Automatic	3M good tracks	2 h	20 min	Every fill
Muon alignment	Expert	250k $J/\psi \to \mu^+ \mu^-$	3 h	7 min	Every fill
OT t_0 calibration	Automatic	Some minbias	15 min	O(min)	Every run
RICH Calibration	Automatic	Good tracks	15 min	O(min)	Every run
Relative CALO calibration	Automatic	LED monitoring system	N/A	2 min	Between fills
Absolute HCAL calibration	Expert	Caesium scan	N/A	2 hours	Technical stops
Absolute ECAL calibration	Automatic	300M minbias	O(4 weeks)	2 hours	When sample ready