Novel real-time alignment and calibration of the LHCb detector in Run II

VERTEX 2015

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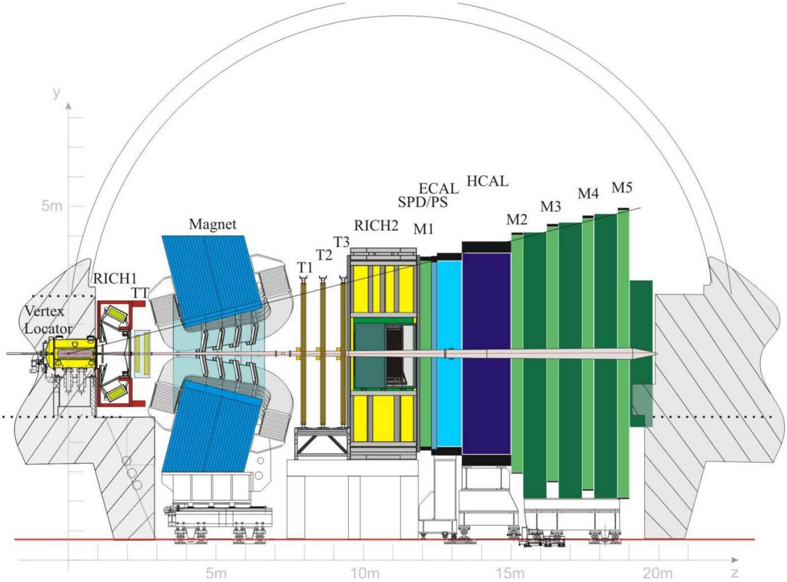
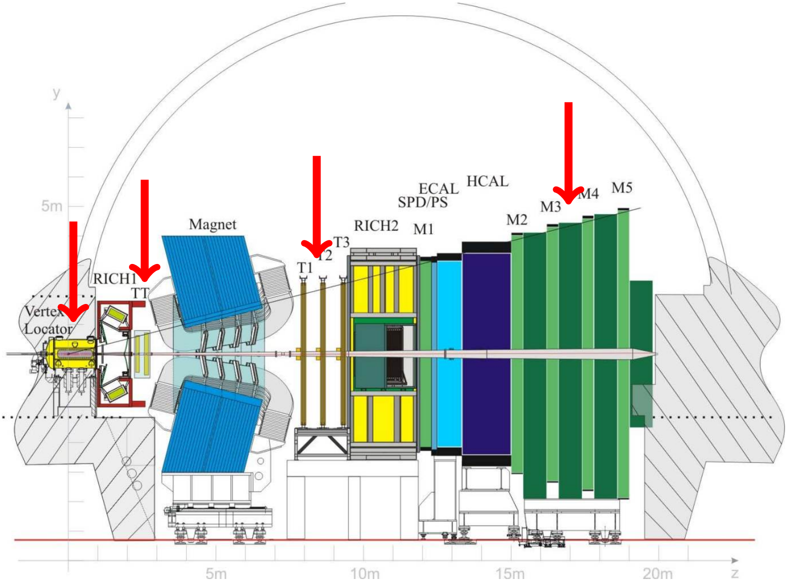
5 June 2015

Overview

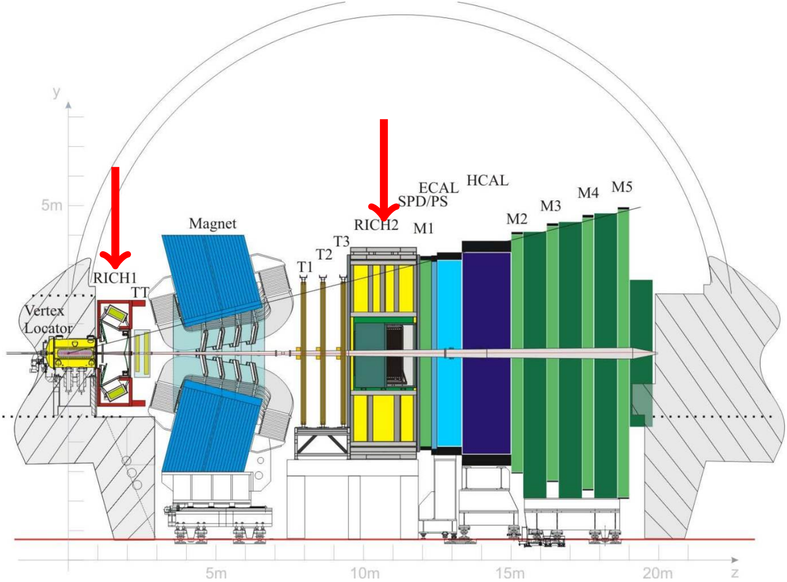
LHCb detector



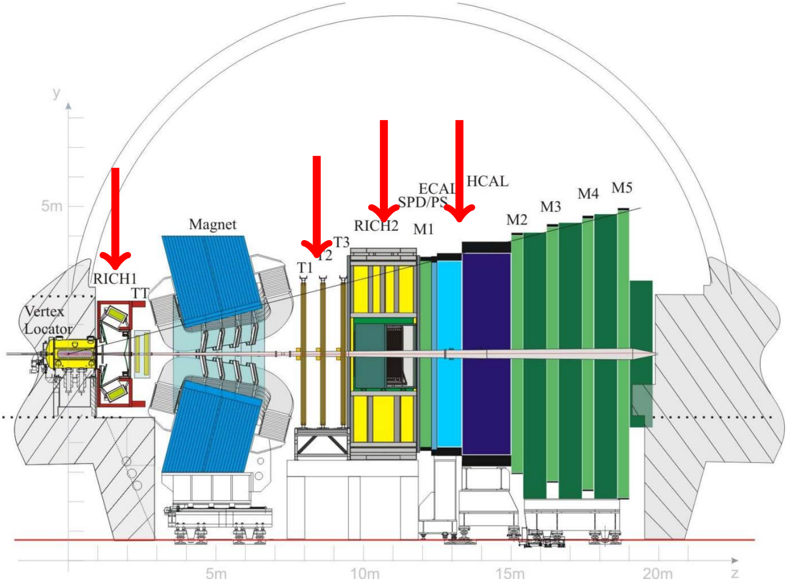
LHCb detector



LHCb detector



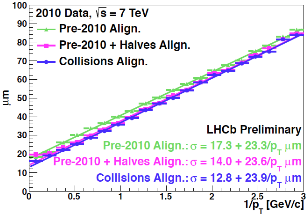
LHCb detector



Importance of alignment and calibration

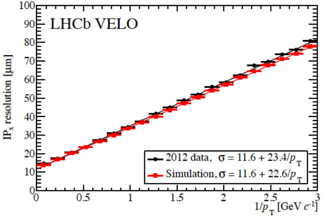
- Spatial alignment of the detector and the accurate calibration of its subcomponents are essential to achieve the best physics performance
  1) Accurate alignment of the VELO essential for primary-secondary vertices discrimination, excellent impact parameter and proper time resolution

First alignment



$\sigma_{\text{IP}_x}(\text{high } p_T) = 14.0\ \mu\text{m}$

Better alignment



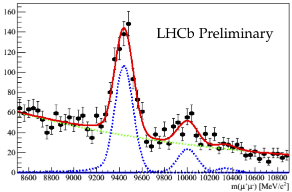
$\sigma_{\text{IP}_x}(\text{high } p_T) = 11.6\ \mu\text{m}$

Impact parameter x resolution vs $1/p_T$

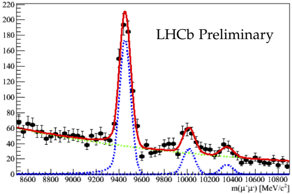
Importance of alignment and calibration

- Spatial alignment of the detector and the accurate calibration of its subcomponents are essential to achieve the best physics performance
  2) better alignment of the tracking system improves the mass resolution

First alignment
$\sigma_{\Upsilon} = 92$ MeV/c^2



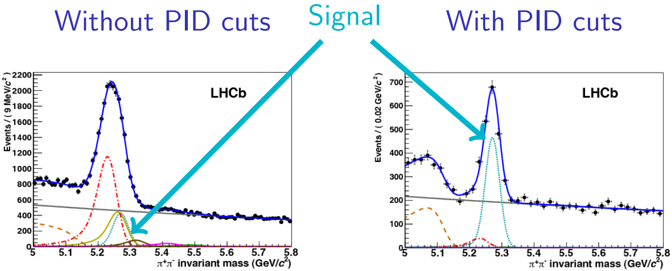
Better alignment
$\sigma_{\Upsilon} = 49$ MeV/c^2



Invariant mass distribution for $\Upsilon \to \mu\mu$

Importance of alignment and calibration

- Spatial alignment of the detector and the accurate calibration of its subcomponents are essential to achieve the best physics performance
- Complete calibration of the RICH detector needed for exclusive selection using hadron particle identification criteria



Invariant mass distribution for $B^0 \to \pi\pi$ decay ($B^0 \to \pi\pi$, $B^0 \to K\pi$, $B^0 \to$ 3-bodies, $B_s \to KK$, $B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)

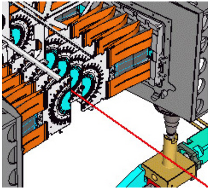
Lessons from Run I: stability of the VELO alignment

- VELO centered around the beam for each fill when the beam is declared stable
- Moved with stepper motors and position measured by resolvers with accuracy $\mathcal{O}(10\,\mu\text{m})$
- Variations observed between fills during the Run I:

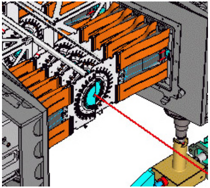
  x: RMS 3.7 μm; max variation $\pm$ 9 μm

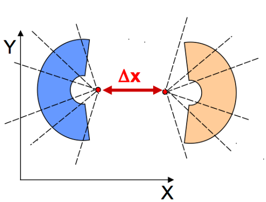
  y: RMS 2.5 μm; max variation $\pm$ 6 μm

Opened at injection

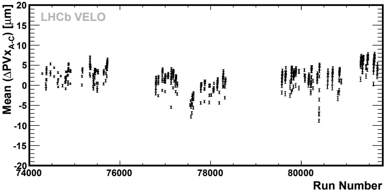


Closed when stable beam declared





Alignment stability

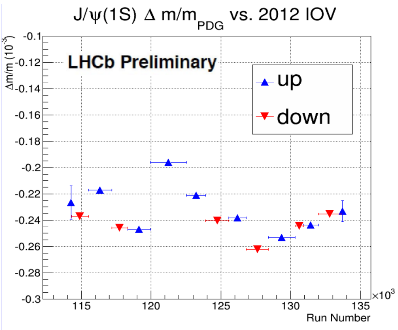


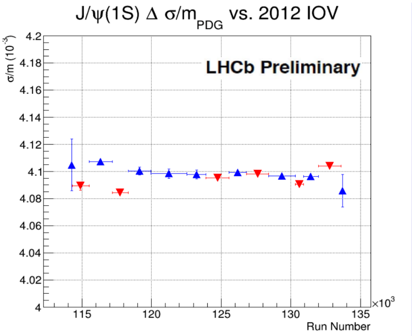
Lessons from Run I: stability of tracker alignment

- Magnet polarity switched every few weeks
- Tracking stations move a few millimeters when turning on the magnet
- Additional small variation over time not related to the magnet polarity change
- A misalignment in the tracking system affects both the mass resolution and the momentum scale

$\Delta m \sim -0.7 \pm 0.1$ meV

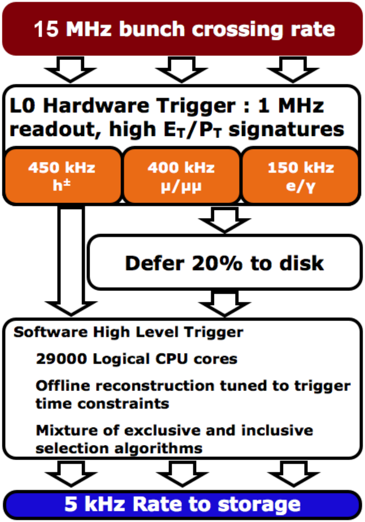
$\sigma \sim 12.30 \pm 0.03$ MeV





Trigger during Run I

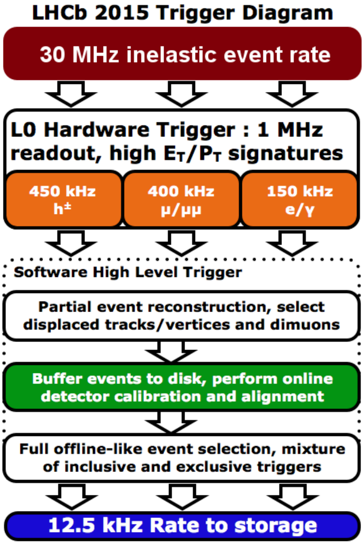
LHCb Run I trigger diagram



- Calorimeters and Muon detectors read at bunch crossing rate
- Only 20% deferred to disk
- trigger used simplified reconstruction tuned to meet trigger time constraints
- Detector calibration and improved alignment obtained offline on triggered data
- Processing of the data for most of physics results at the end of the year with the latest constants

Trigger strategy for Run II

LHCb 2015 trigger diagram

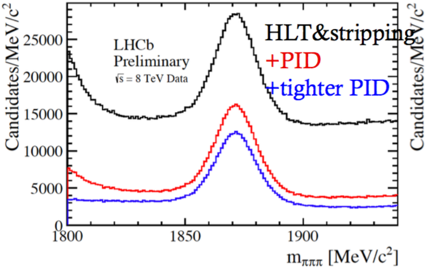


- Events from lower trigger levels can be buffered on disk while performing real-time alignment and calibration
- Last trigger level uses the same reconstruction as offline
- Same alignment and calibration constants used by the trigger and the offline reconstruction
- Some analysis performed directly on the trigger output

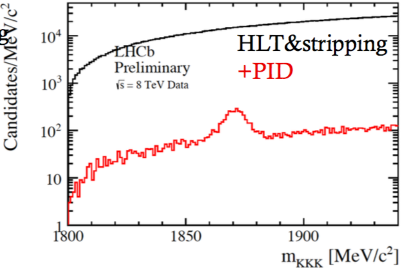
Trigger strategy for Run II

- Same reconstruction as offline and complete alignment and PID calibration allows to apply a tighter selection on kinematic quantities
- RICH Calibration allows to use hadron particle identification in selection e.g. boost efficiency for Cabibbo suppressed decays while keeping the rate low by pre-scaling the Cabibbo favoured contrepart

CS: $D^+ \to \pi^+\pi^-\pi^+$



DCS: $D^+ \to K^+K^-K^+$



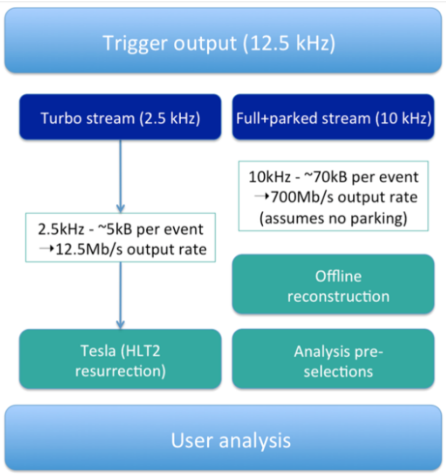
Turbo stream

Raw data: electronic signals recorded from the detector ($\sim$ 70kB/event)

Analysis level: information of signal candidate tracks ($\sim$ 5kB/event)

Analyse directly on trigger output?

- Save more events in less space
- Real-time alignment and calibration essential
- Testing mode where raw events are still kept



Real-time alignment and calibration

General strategy

- Automatic evaluation at regular intervals, eg. beginning of the run or fill depending on the task
- Dedicated data sample to perform alignment or calibration collected with a specific trigger selection line for each task
- Compute the new alignment or calibration constants in a few minutes
- Update the constants only if needed
- The same new alignment and calibration constants will be used both by the trigger and the offline reconstruction

Advantages

- Have the same performance online and offline
- More effective trigger selection
- Stability of the alignment quality, hence physics performance
- Some analysis performed directly on the trigger output

Tracking alignment procedure

- Based on an iterative procedure

Reconstruct the tracks using the current alignment constants

$$\frac{d\chi^2}{d\alpha} = 2 \sum_{\text{tracks}} \frac{dr}{d\alpha}^T V^{-1} r$$

$$\frac{d^2\chi^2}{d\alpha^2} = 2 \sum_{\text{tracks}} \frac{dr}{d\alpha}^T V^{-1} R V^{-1} \frac{dr}{d\alpha}$$

Compute a new set of alignment constants (α) minimizing a global χ^2:

$$\alpha = \alpha_0 - \left(\frac{d^2\chi^2}{d\alpha^2} \right)^{-1} \Bigg|_{\alpha_0} \frac{d\chi^2}{d\alpha} \Bigg|_{\alpha_0}$$

Iterate until the χ^2-difference is below a threshold

r: tracks residuals, V: covariance matrix, R: residuals' covariance matrix

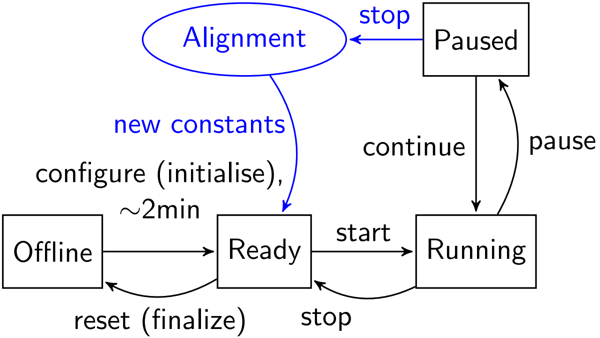
- Kalman filter takes into account magnetic field and material effects
- Consistent with track reconstruction
- Use vertices and particle masses as constraints to avoid global distorsions

Real-time alignment framework

Two kinds of alignment tasks defined:

Analyser: perform the track reconstruction based on the alignment constants computed by the iterator. Many instances run in parallel on $\sim$ 1700 nodes of the HLT farm

Iterator: collects the output of the analysers and minimizes the χ^2 computing the alignment constants for the next iteration. It runs on a single node



Real-time tracking alignment

VELO

- Alignment evaluated at the beginning of each fill
- Update expected often but not for each fill

Tracker (TT, IT, OT)

- Alignment run after the VELO at the beginning of each fill
- Update expected every few weeks

Muon stations

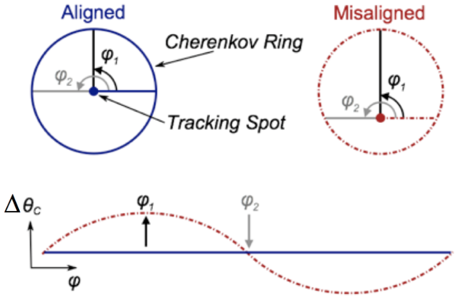
- Alignment run for each fill
- Variation not expected, run as a monitor

Number of elements to be aligned

VELO:	86
TT:	135
IT:	64
OT:	496
Muons:	20

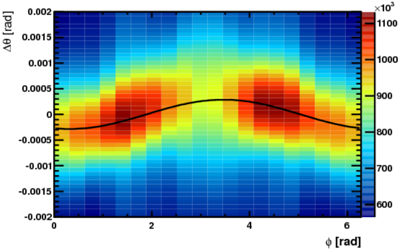
RICH mirror alignment

- Two RICH detectors
- Cherenkov photons focused on photon-detector plane by spherical and flat mirrors
- An imaginary track reflected through the RICH mirrors should be in the center of the Cherenkov ring
- The distribution of the $\Delta\Theta$ against ϕ results in a sinusidal distribution in case of misalignment of the mirrors
- Fit the distribution to calculate alignment constants

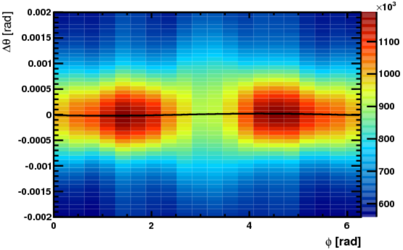


RICH mirror alignment

Before mirror alignment



After mirror alignment



- Same framework as tracking alignment

  Analysers: Photon reconstruction done in parallel

  Iterator: Fit of the $\Delta\Theta$ distribution on a single node
- Evaluated for each fill
- Variation not expected but used as a monitoring

mirror pairs to align

RICH1 16

RICH2 94

1090 alignment constants

Real-time calibration

Strategy

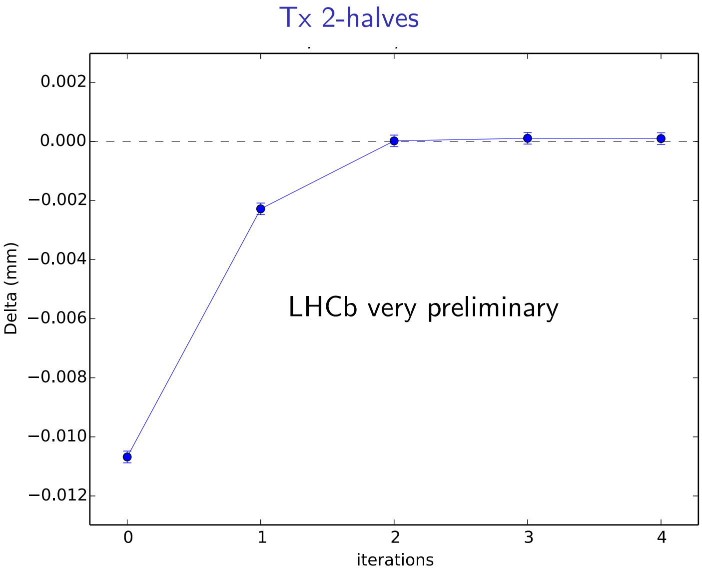
- Evaluation of the calibration parameters by fitting monitoring histograms
- Evaluated on a single CPU

- Global time alignment of the Outer tracker
  - Evaluated from the distance of the track to the wire
  - Executed each fill, update expected every few weeks
- RICH calibration
  - Refractive index (2 constants)
    - depends on gas mixture, temperature, pressure
    - calibrated by fitting expected Cherenkov angles
  - Hybrid photon detector (1940 constants)
    - Correct for electrostatic effects
  - Evaluated and updated every run
- Calorimeter calibration
  - High voltage adjusted each fill based on the gain changes calculated from the occupancy profile

Conclusion

- During Run II LHCb will perform real-time alignment and calibration
- Dedicated framework in place to parallelise the alignment task on the multi-core farm used for the trigger
- Trigger selection with same reconstruction and same calibration constants as offline
- Tighter selection and use of hadron particle identification in the trigger
- Physics analysis directly on the trigger thanks to the same online-offline reconstruction and performance

Commissioning the automatic procedure is ongoing



BACKUP

LHCb

- acceptance: $2 < \eta < 5$; covers $\sim 4\%$ of solid angle captures $\sim 40\%$ of beauty cross-section
- RICH1: $1 < p < 60$ GeV
  RICH2: $15 < p < 100$ GeV
- Performance:

Decay time resolution:	$30 - 50$ fs
Vertex resolution:	$sim 13\,\mu$m in x and y, $69\,\mu$m in z for vertex with 25 tracks
$\Delta p/p$:	0.4% at 5 GeV, 0.6% at 100 GeV
Muon ID:	$\varepsilon(\mu/\mu) = 95\%$, $\varepsilon(\pi/\mu) \sim 1\%$
RICH ID:	$\varepsilon(K/K) = 95\%$, $\varepsilon(K/\pi) \sim 5\%$
CALO ID:	$\varepsilon(e/e) = 95\%$, mis-ID $\sim 5\%$

Running Conditions from Run I to Run II

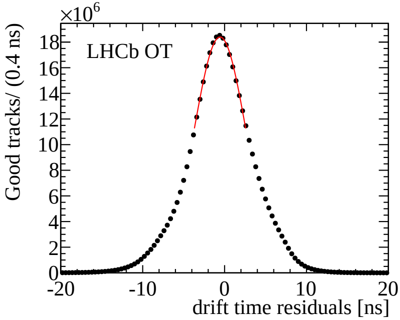
- Higher energy: $\sqrt{s} = 7/8$ TeV $\Longrightarrow$ 13 TeV
  - 15% increase inelastic collision rate
  - 20% increase of multiplicity per collision
  - 60% increase of $\sigma_{b\bar{b}}$ and $\sigma_{c\bar{c}}$
- Reduced bunch spacing: 50 ns $\Longrightarrow$ 25 ns
- Similar instantaneous luminosities: $4 \cdot 10^{32}$ cm^{-2} s^{-1}

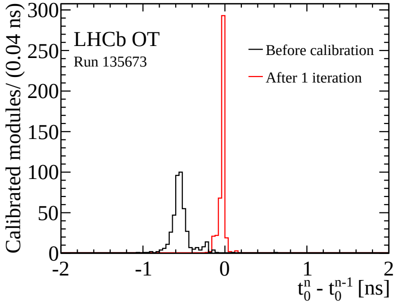
Trigger

	Run I	Run II
Output rate HLT1	80 kHz	150 kHz
Time budget HLT1	20 ms/event	35 ms/event
Time budget HLT2	150 ms/event	350 ms/event

Global time alignment of the outer tracker (OT)

- In straw tubes measured drift time may be different from time estimated from the distance of the track to the wire
- Mainly due to the difference between the collision time and the LHCb clock: common to all modules
- A single condition which accounts for the global time alignment
- Evaluated fitting the distribution of drift-time residuals
- Executed for each fill, update expected every few weeks



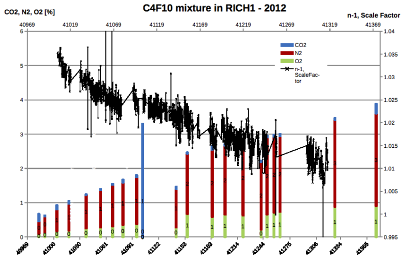


RICH calibration

Evaluated and updated every run

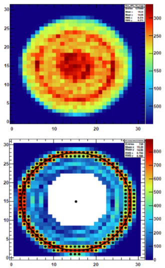
Refractive index

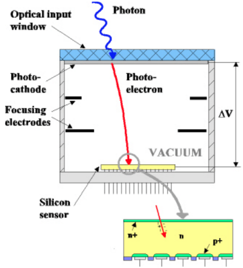
- The refractive index depends on the gas mixture, temperature and pressure.
- Calibrated by fitting expected Cherenkov angles.



HPD image

- Affected by magnetic/electric fields.
- Anode images cleaned, Sobel filter used to detect edge.





Calorimeter calibration

Occupancy

$$\text{Occ}_{\text{cell},i} = \frac{\text{Num events passing ACD threshold(s)}}{\text{Num events}}$$

Occupacy method

- Compare occupancy wrt reference sample
- Ratio of occupancy proportional to tho changes in hardware characteristics
- Change HV if occupancy ratio passes some criteria

Absolute calibration: Offline, using π^0

Relative calibration: Online, using occupancy method