# Novel real-time alignment and calibration of the LHCb detector and its performance

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on behalf of LHCb Collaboration

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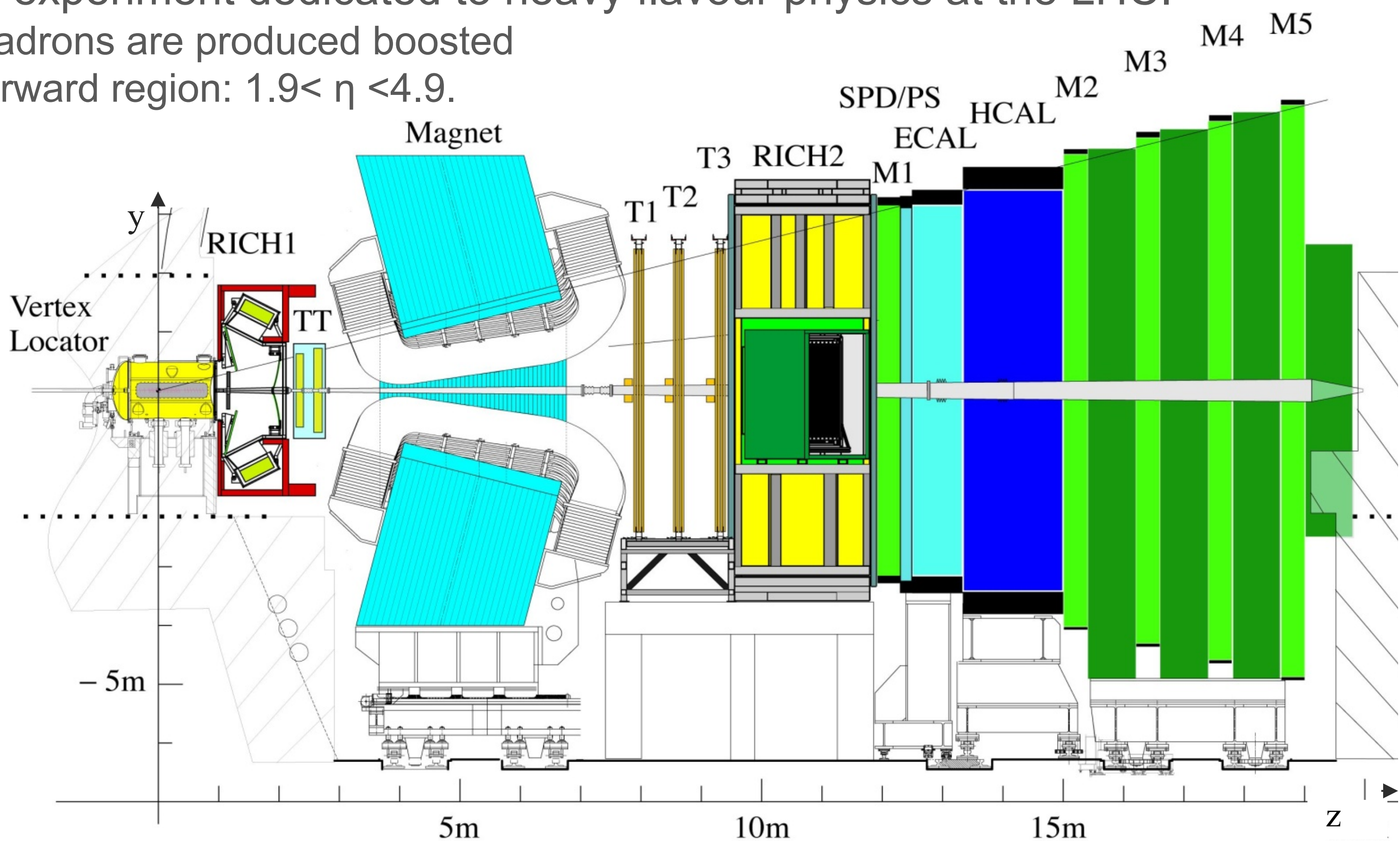
# Outline

- LHCb experiment
- Importance of the alignment and calibration
- Data taking strategy in Run1 and in Run2
- Real-time alignment and calibration
- Performance
- Impact on the physics
- Conclusions

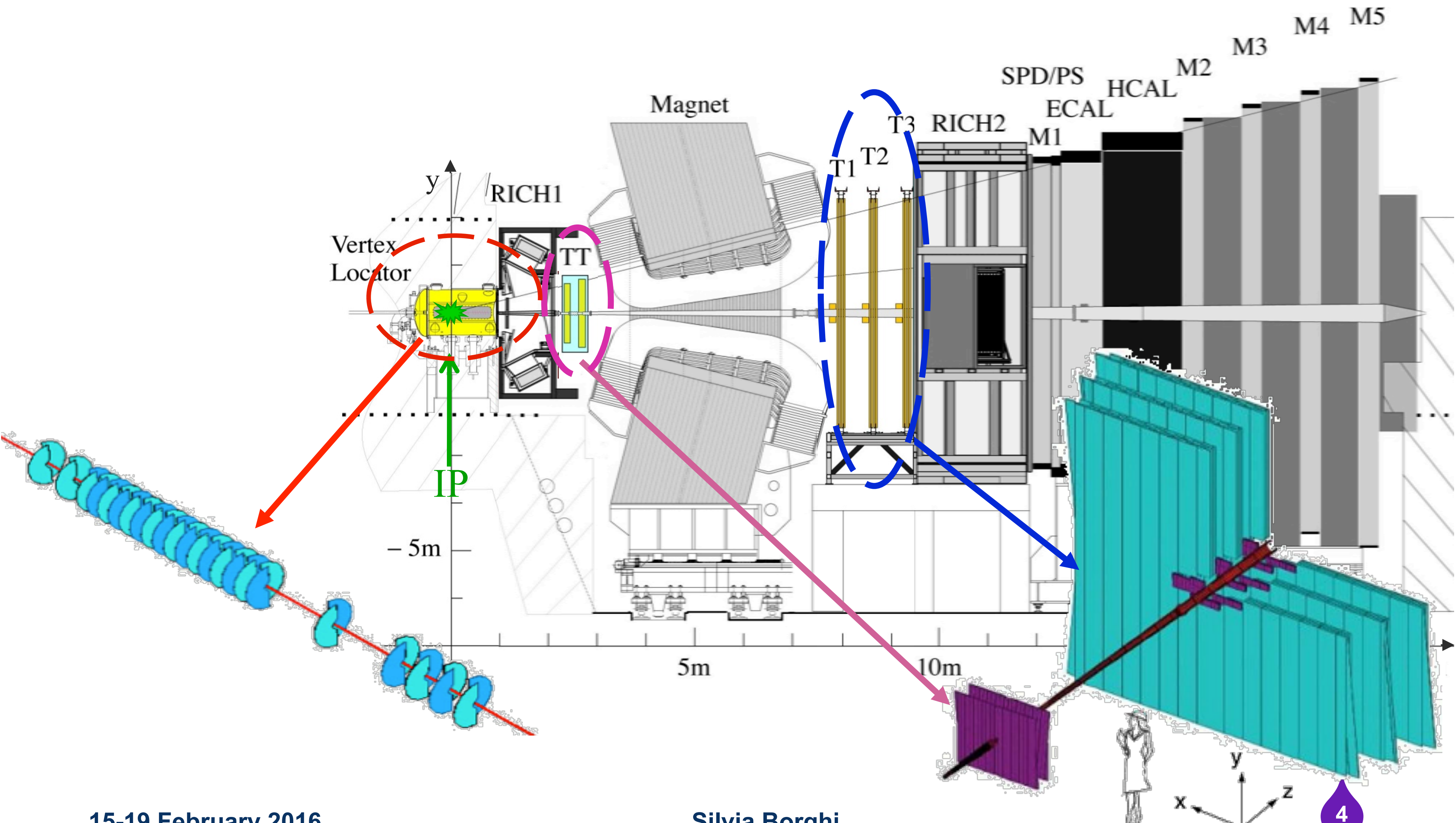
# Overview of LHCb detector

- LHCb is an experiment dedicated to heavy flavour physics at the LHC.
  - Heavy hadrons are produced boosted in the forward region: 1.9< η <4.9.




LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

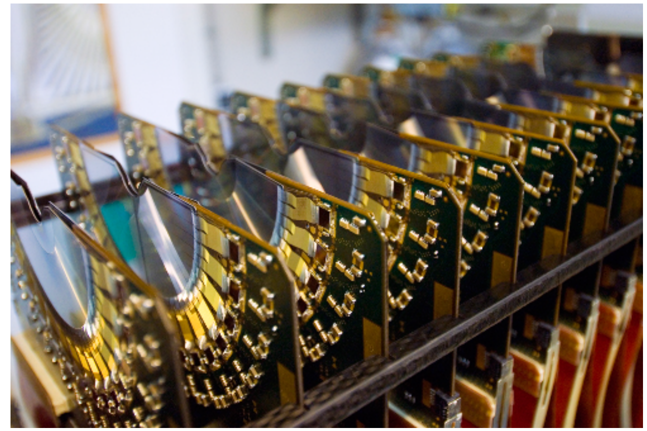
# Overview of LHCb detector



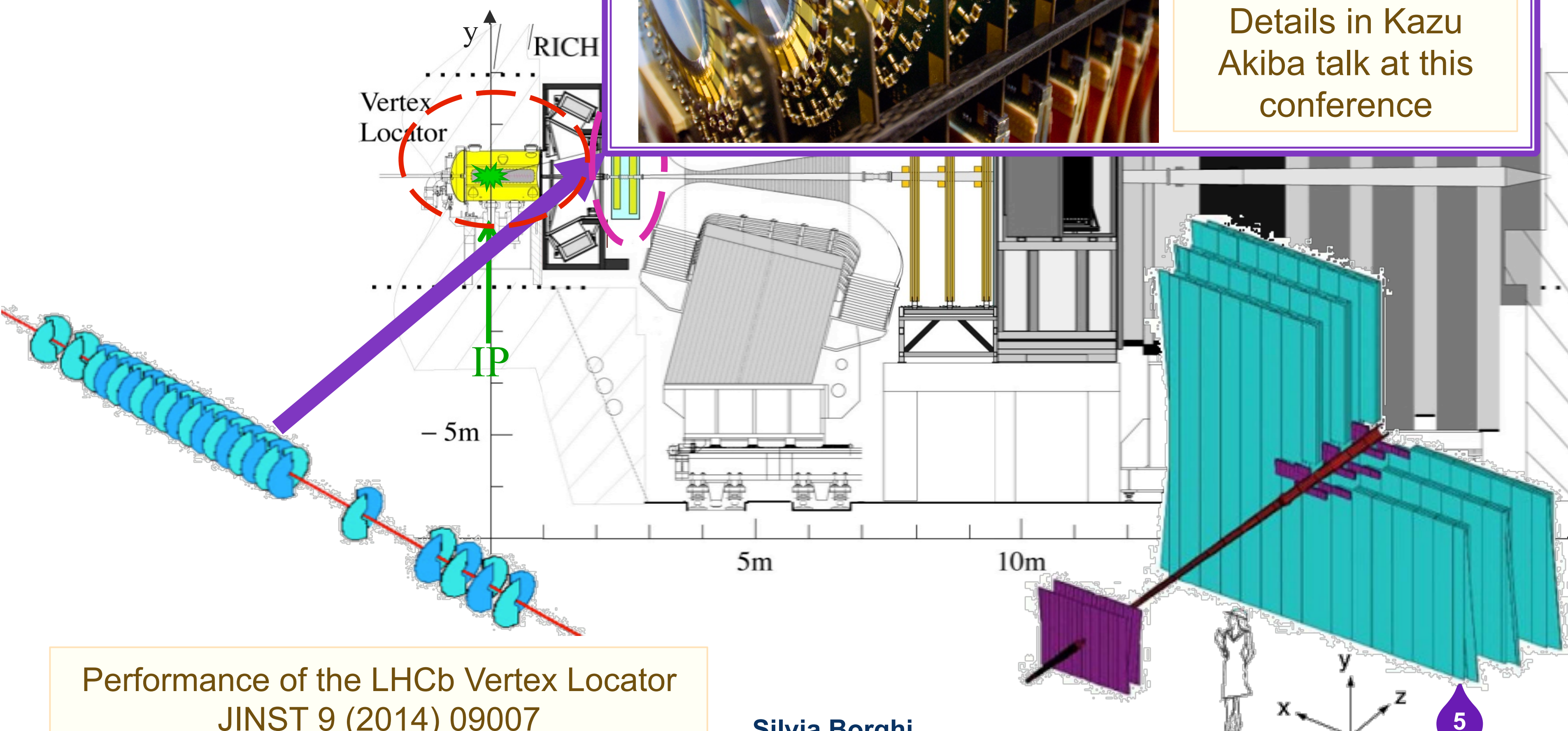
# Overvi

**Vertex detector (VELO):**

- 42 silicon micro-strip stations with R-Φ sensors
- 2 retractable halves, 8 mm from beam

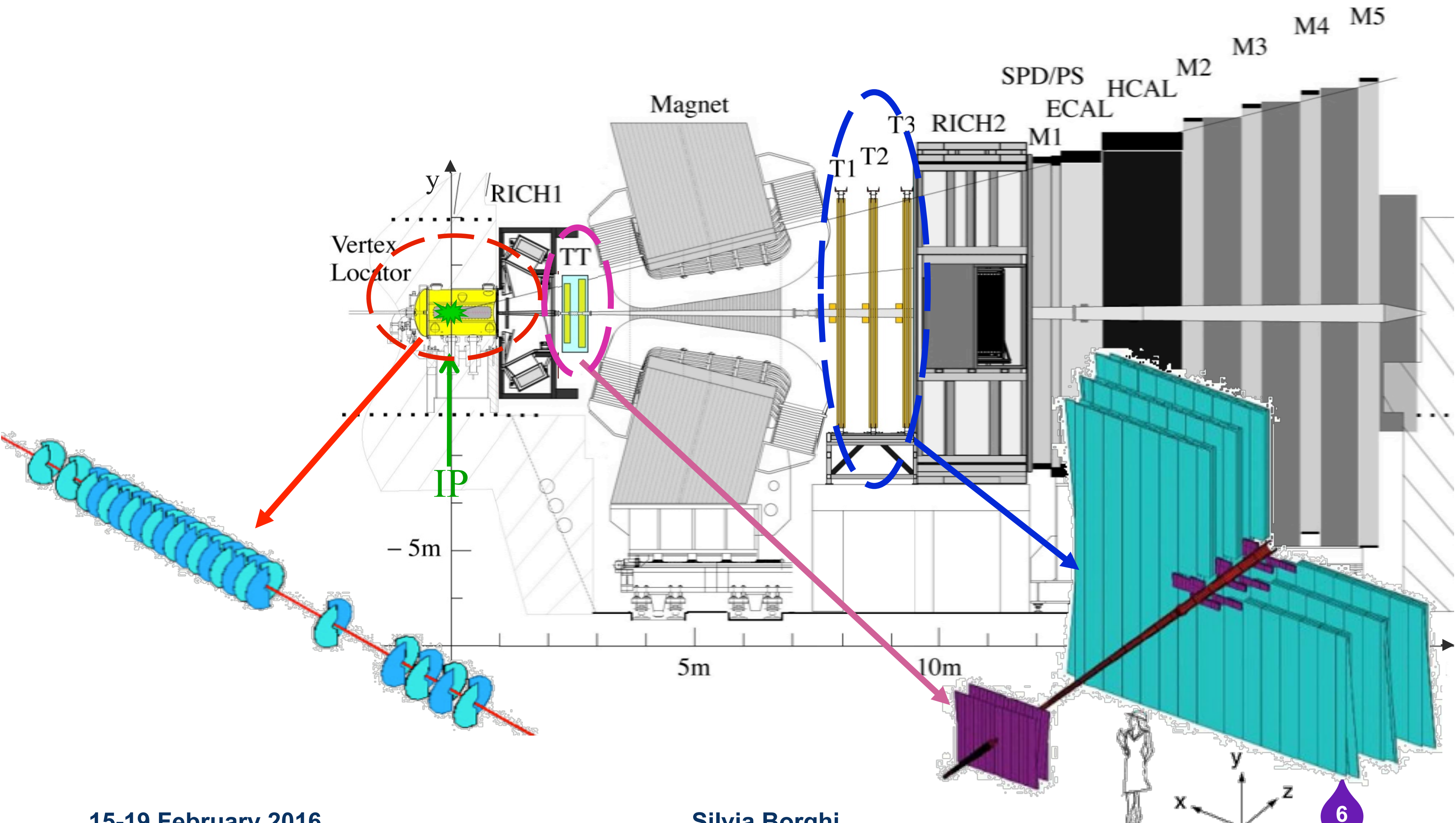


Details in Kazu Akiba talk at this conference




Performance of the LHCb Vertex Locator
JINST 9 (2014) 09007

# Overview of LHCb detector

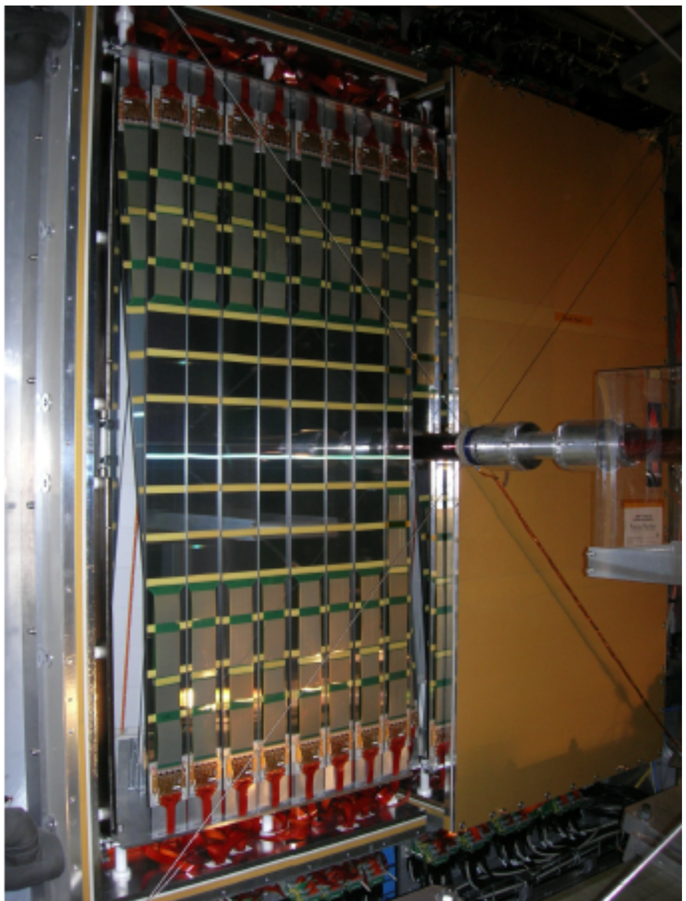


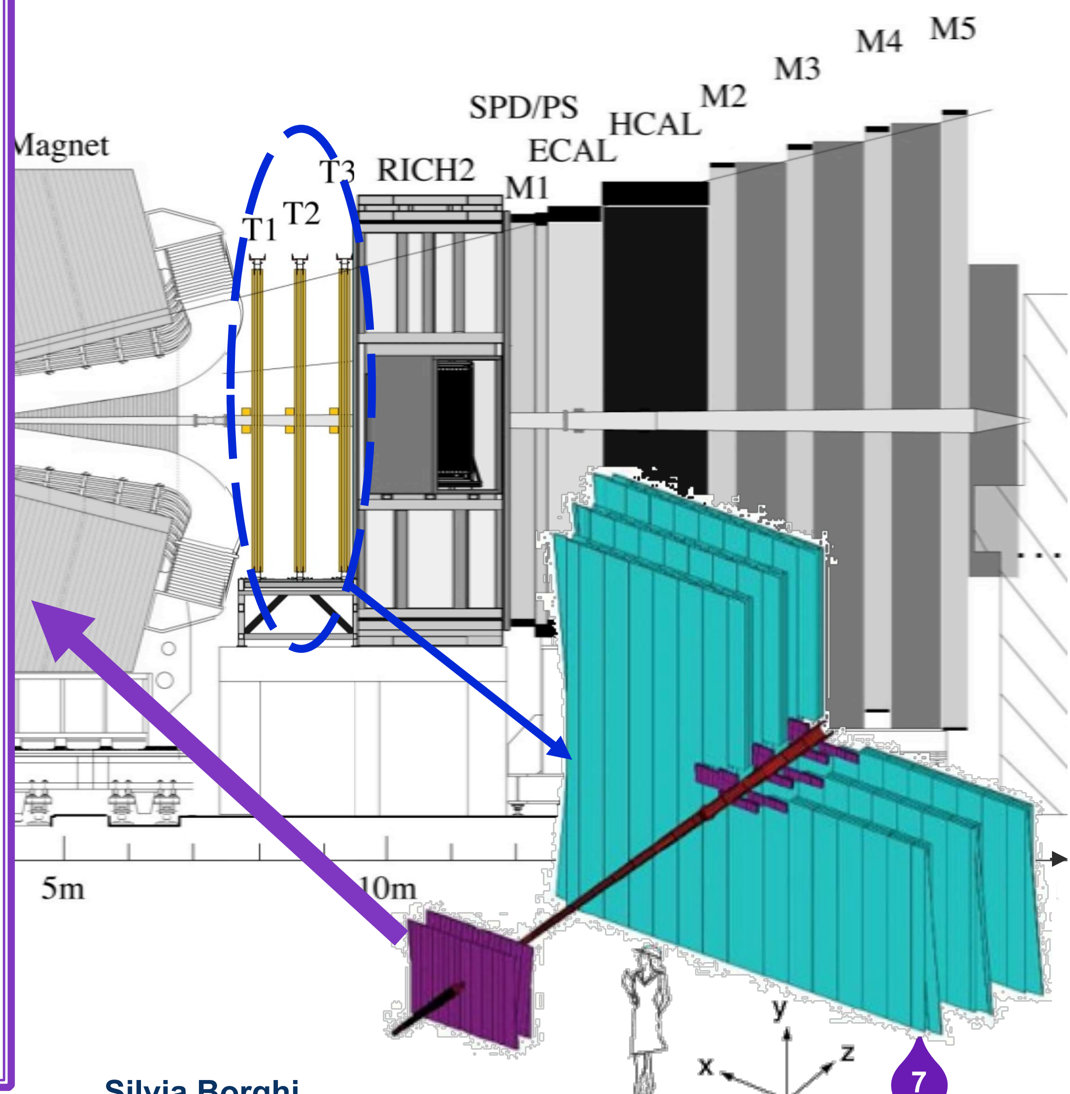
# Overview of LHCb detector

LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

**Tracker Turicensis (TT):**

- 4 planes (0º,+5º,-5º,0º) of silicon micro-strip sensors
- Total silicon area of 8 m$^2$

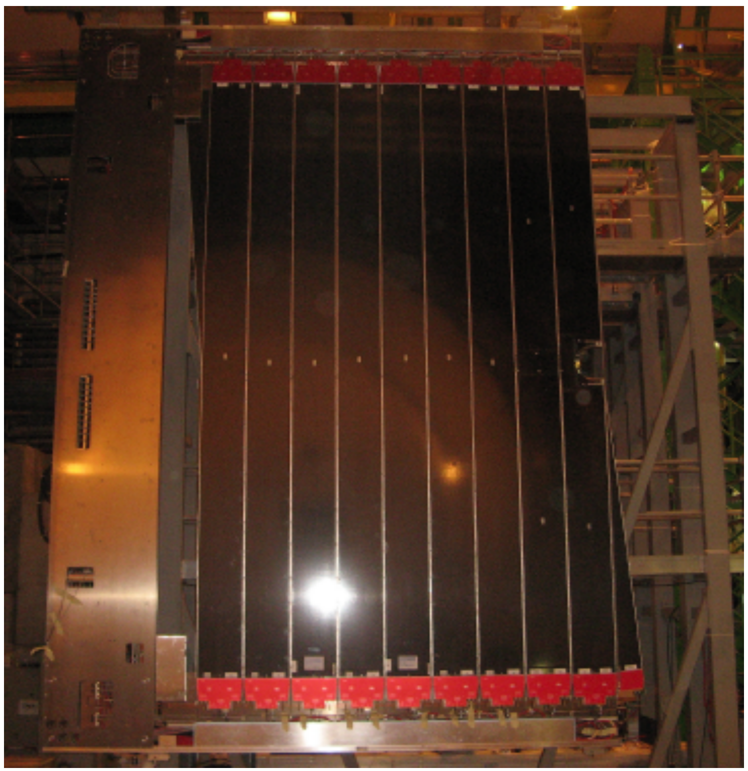




# Overview of LHCb detector

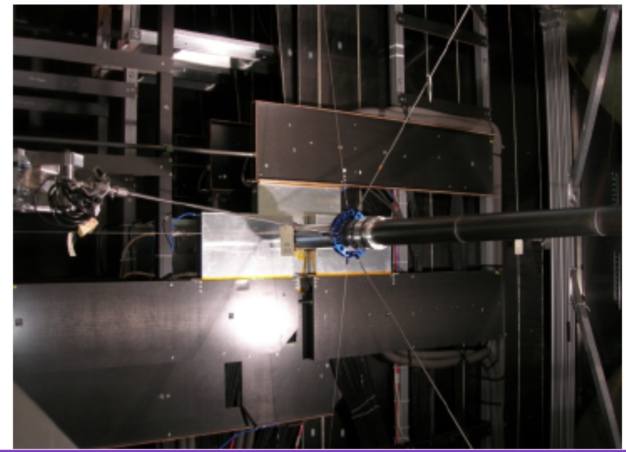
## Outer Trackers (OT):

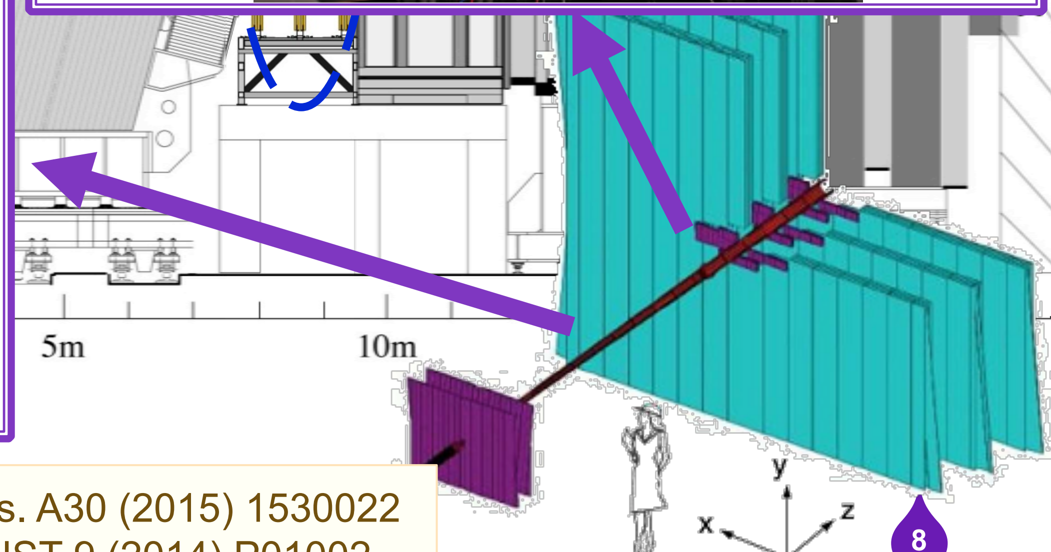
- 3 stations with 4 planes of straw tubes
- Gas Mixture $Ar/CO_2/O_2$ (70/28.5/1.5)%



## Inner Tracker (IT):

- 3 stations with 4 planes ($0^o$,$+5^o$,$-5^o$,$0^o$) of silicon micro-strip sensors
- Total silicon area of 4.2 $m^2$



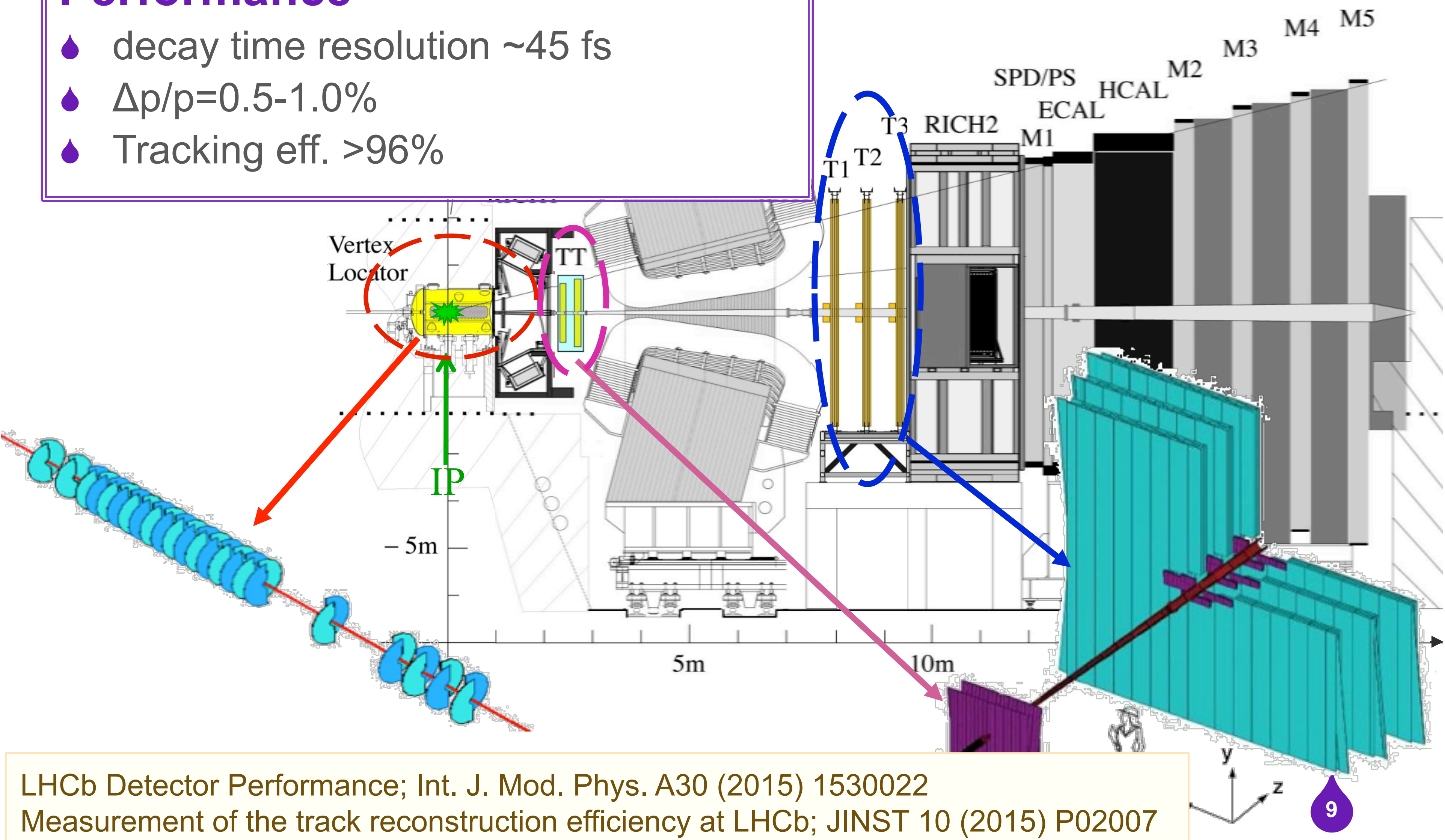



LHCb Detector Performance; Int. J. Mod. Phys. A30 (2015) 1530022
Performance of the LHCb Outer Tracker; JINST 9 (2014) P01002

# Overview of LHCb detector

## Performance

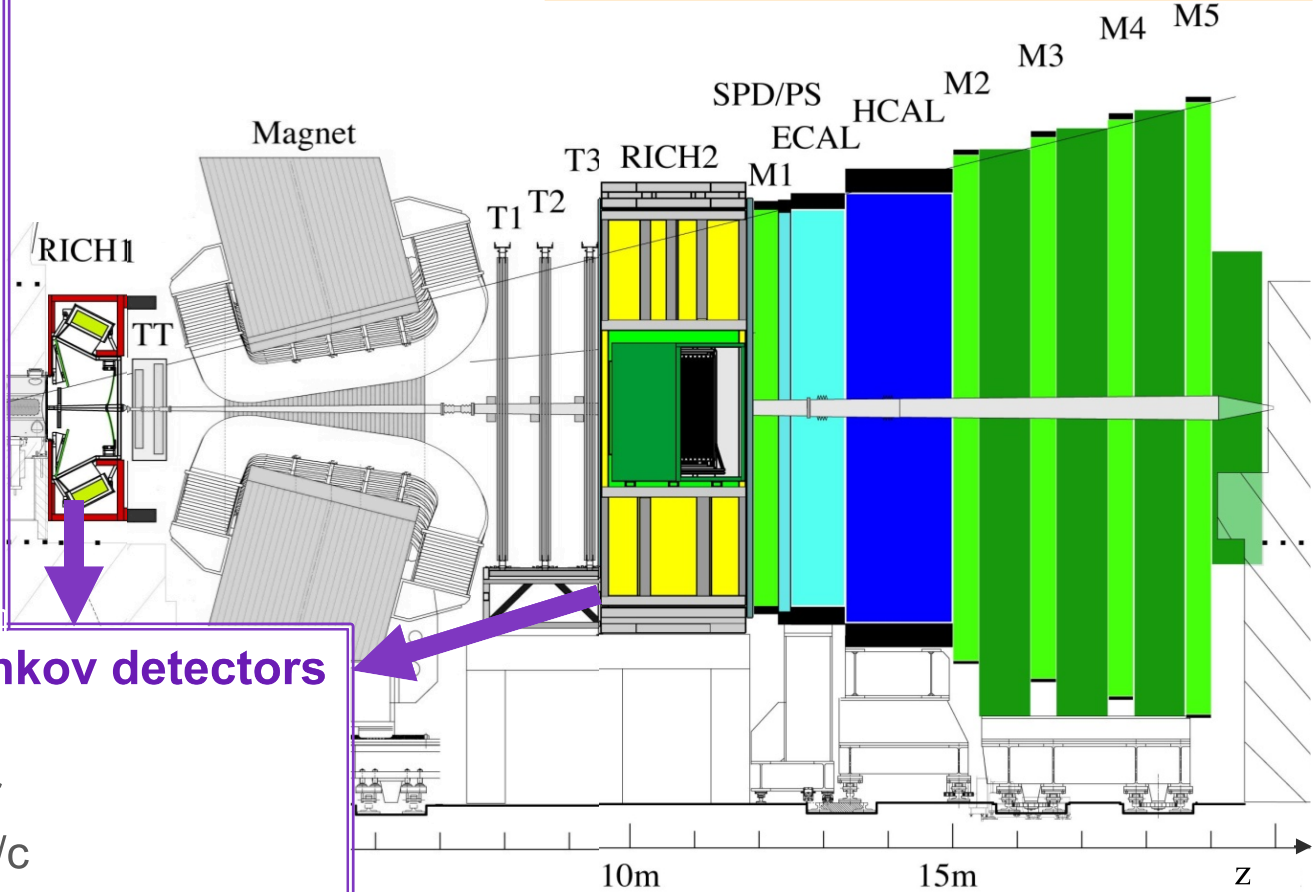
- decay time resolution ~45 fs
- Δp/p=0.5-1.0%
- Tracking eff. >96%




LHCb Detector Performance; Int. J. Mod. Phys. A30 (2015) 1530022
Measurement of the track reconstruction efficiency at LHCb; JINST 10 (2015) P02007

# Overview of LHCb detector

Performance of the LHCb RICH detector
Eur.Phys.J. C73 (2013) 2431




**Ring Imaging Cherenkov detectors**

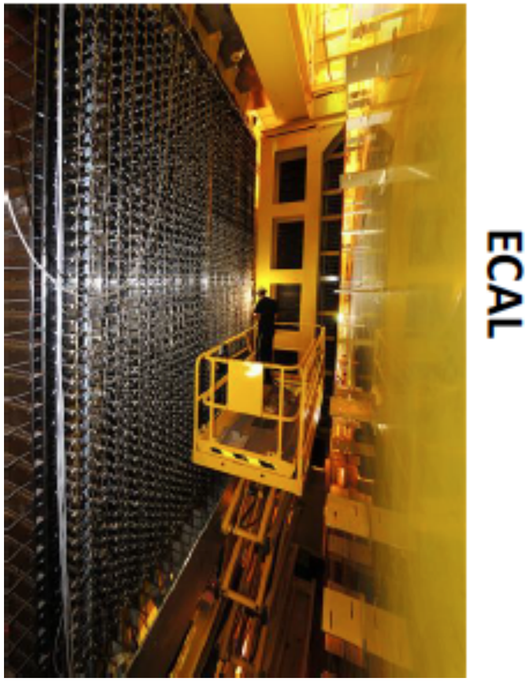
- RICH1:
  - $C_4F_{10}$ radiator
  - 2<p<40 GeV/c
- RICH2:
  - $CF_{10}$ radiator
  - 15<p<100 GeV/c

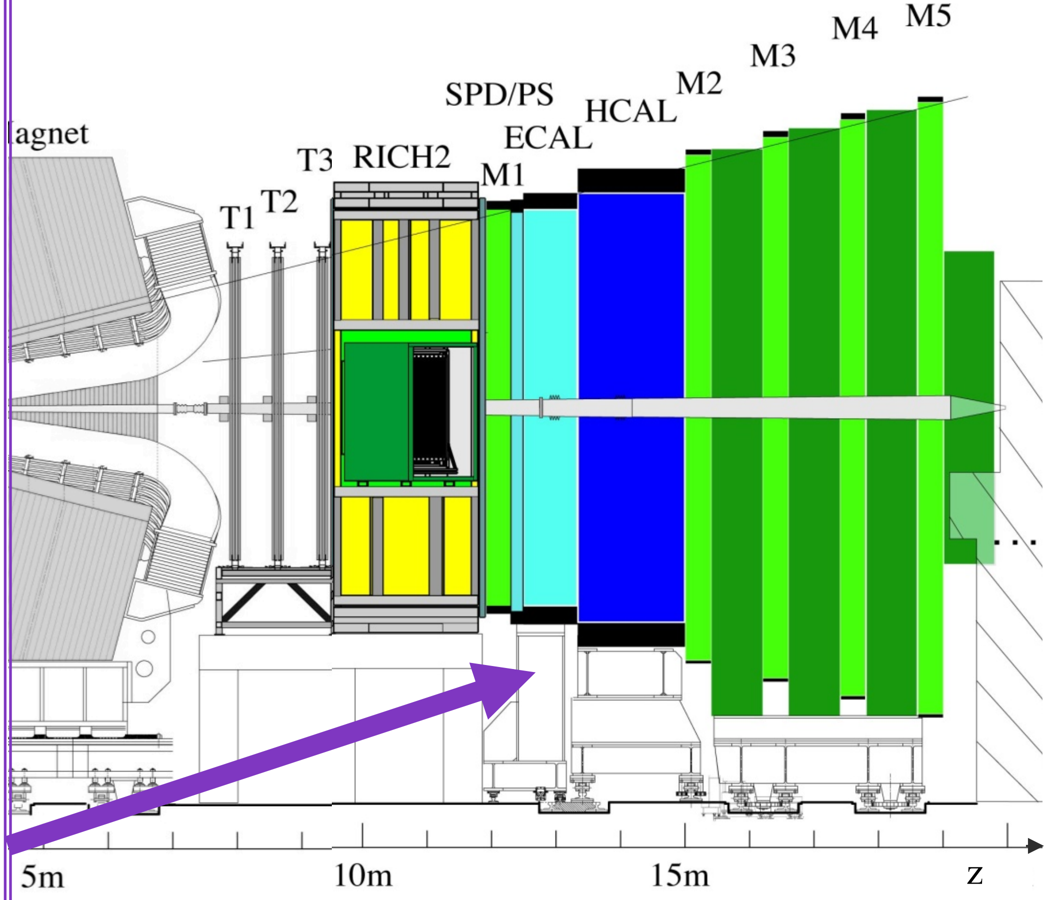
# Overview of LHCb detector

LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

**Electromagnetic and hadronic calorimeters (ECAL and HCAL)**

- Scintillator planes + absorber material planes
- Used in the level 0 trigger selection



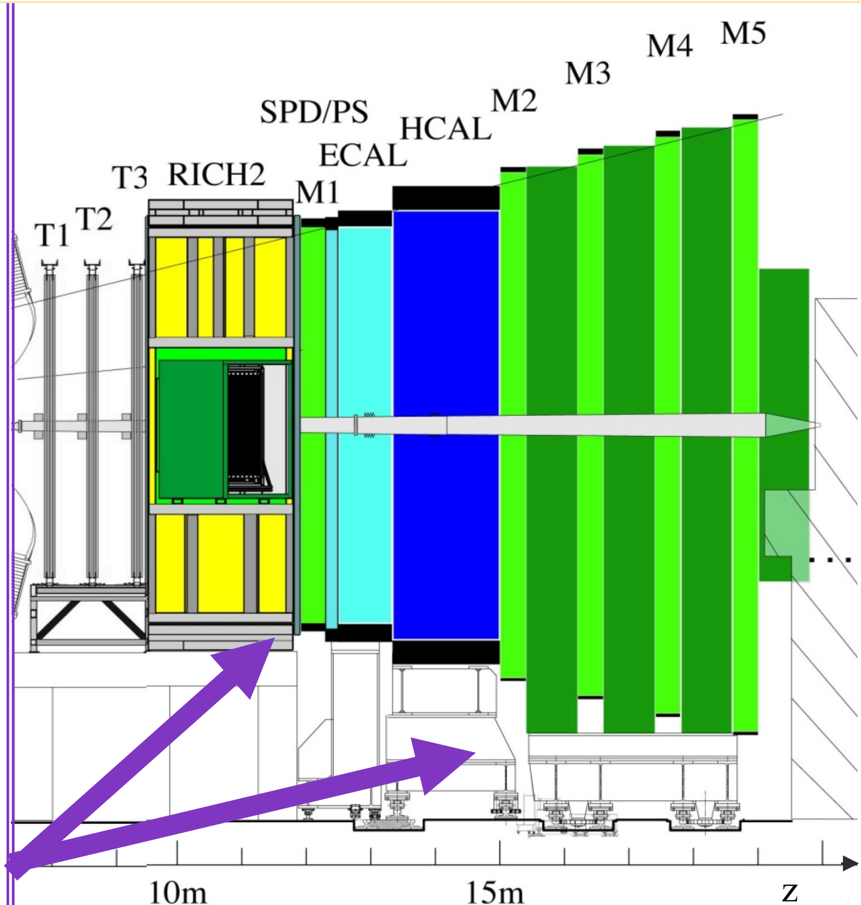



# Overview of LHCb detector

Performance of the Muon Identification system
JINST 8 (2013) P10020

## Muon system

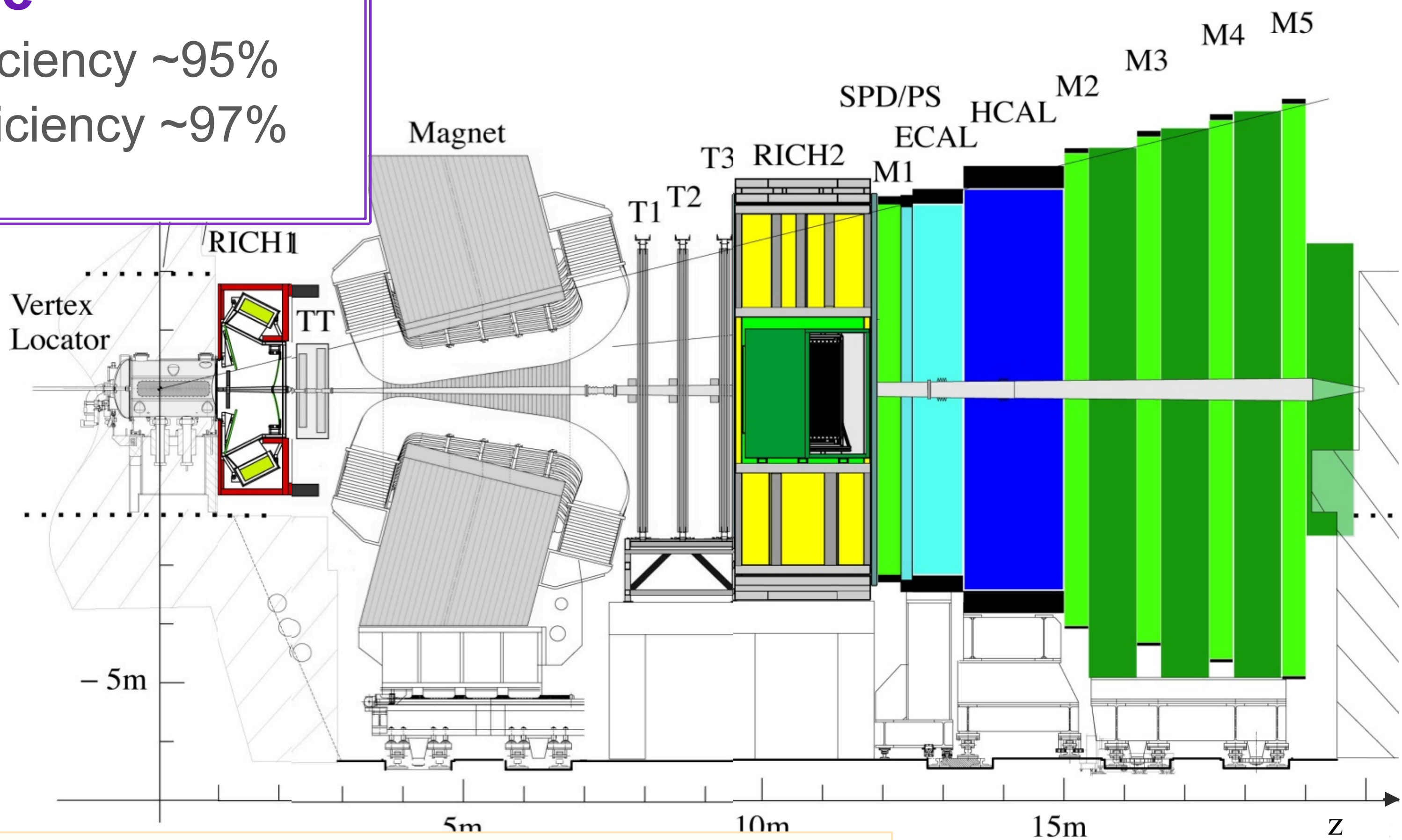
- 5 stations equipped with multi-wire proportional chambers
  - Inner part of the first station equipped with 12 GEM detectors
- Used in the level 0 trigger selection



# Overview of LHCb detector

## Performance

- Kaon ID efficiency ~95%
- Muon ID efficiency ~97%





LHCb Detector Performance; Int. J. Mod. Phys. A30 (2015) 1530022
Performance of the Muon Identification system; JINST 8 (2013) P10020
Performance of the LHCb RICH detector; Eur.Phys.J. C73 (2013) 24

# Alignment and Calibration

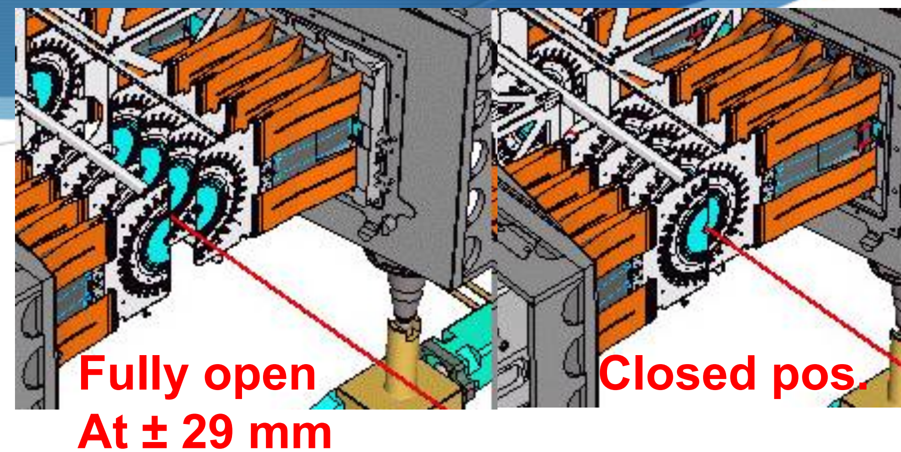
# Alignment and calibration

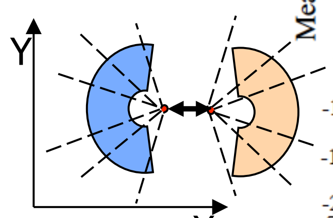
- Proper PID calibration and alignment are an essential element to get the best performance
- Spatial alignment
  - Survey measurements is the initial stage
  - Alignment based on the tracks needed to achieve the highest precision
  - Alignment could vary over time due to several factors, e.g. temperature, movement due to variation of operation conditions (e.g. magnet polarity change), mechanical intervention
- Calibration
  - The parameters of the detector could vary due to e.g. temperature, pressure, aging of the detector

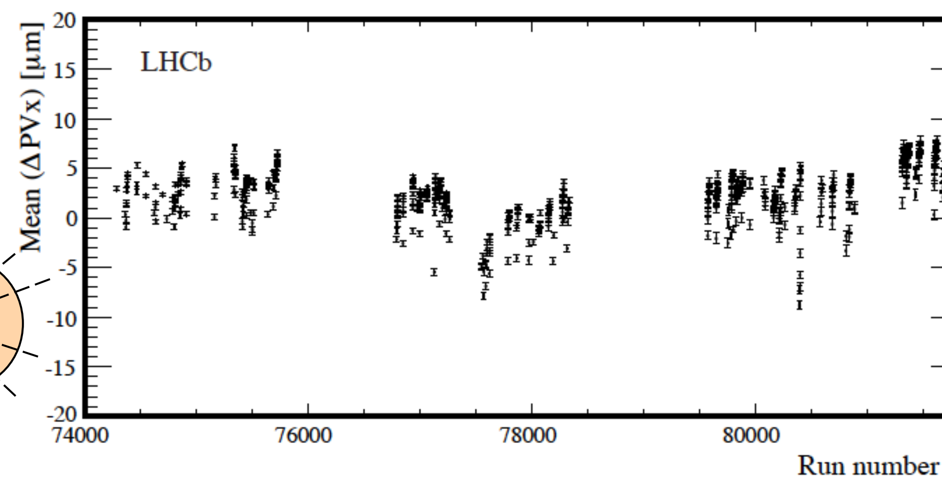
➡ Frequent updates of the alignment and calibration parameters could be needed to have stability of the detector performance

# Alignment stability for the VELO

- VELO centred around the beam for each fill when the beam declared stable
- Moved with stepper motors and position measured by resolvers with accuracy **O(10 μm)**
- Variations observed between fills during the Run I:
  - x: RMS 3.7 μm; max variation 9 μm
  - y: RMS 2.5 μm; max variation 6 μm
- Alignment to be determined at the begin of each fill



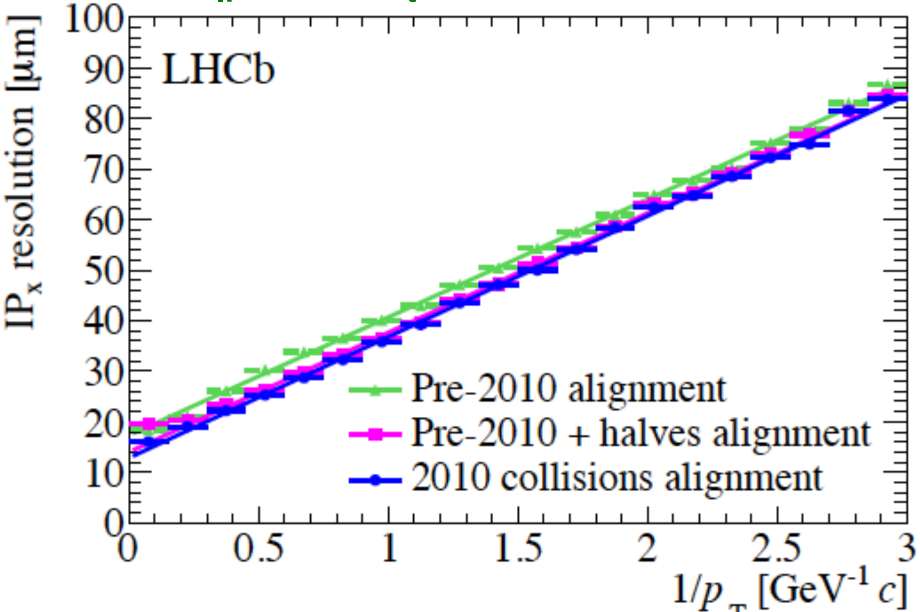



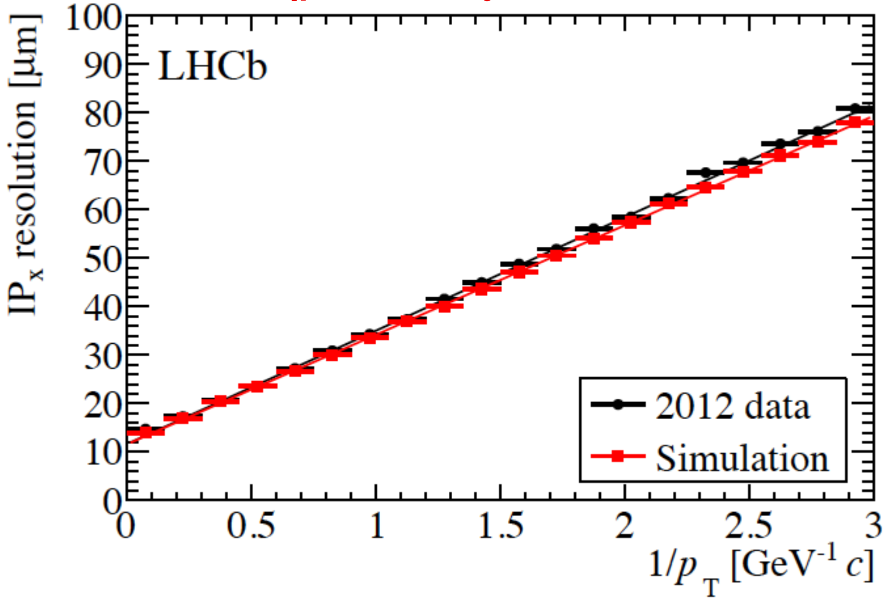

Performance of the LHCb Vertex Locator
JINST 9 (2014) 09007

# Importance of the alignment

**First full alignment**
**$\sigma_{IP}$(high $p_t$)=14.0 μm**




**Latest alignment**
**$\sigma_{IP}$(high $p_t$)=11.6 μm**

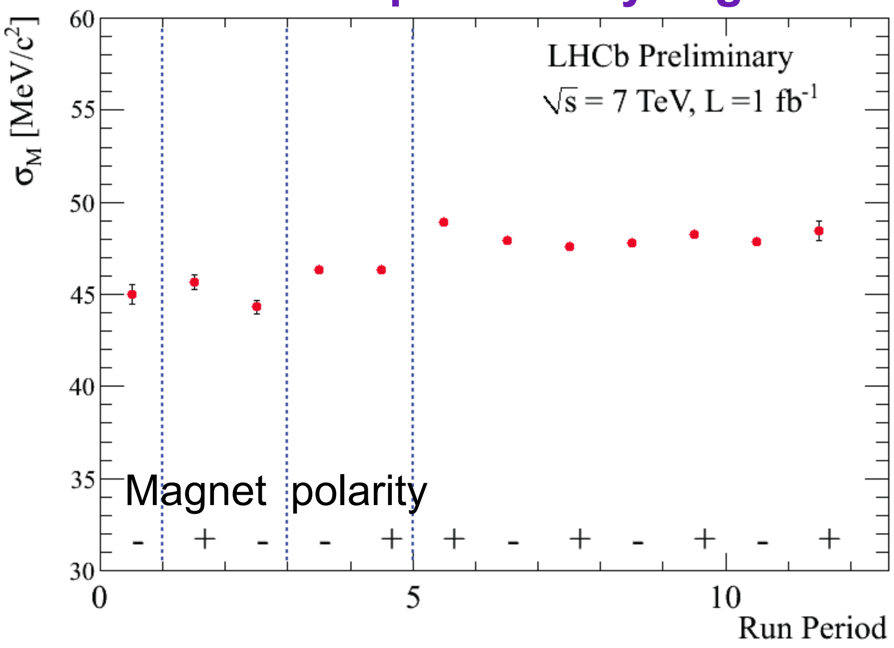



LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

# Alignment stability for tracker

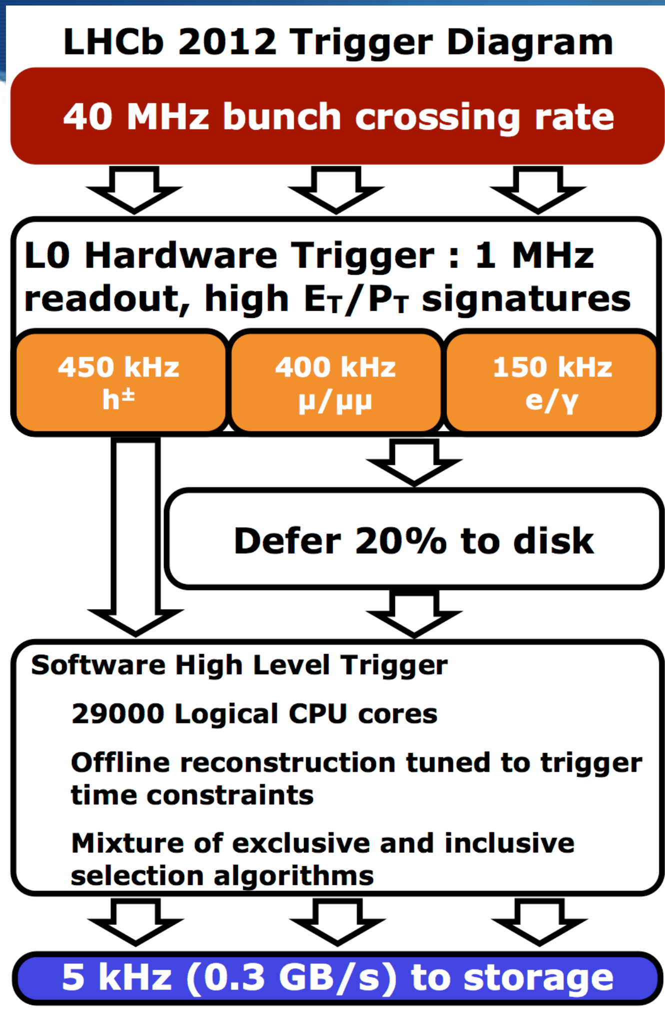
- Inner tracker stations move a few millimeters when turning on the magnet
  - Due to ferromagnetic cable connectors
  - Few days to stabilize
- Additional small variation over time not related to the magnet polarity change
- A misalignment in the tracking system affects both the mass resolution and the momentum scale

**Stability of $\Upsilon$ mass resolution over time with preliminary alignment**



# Strategy

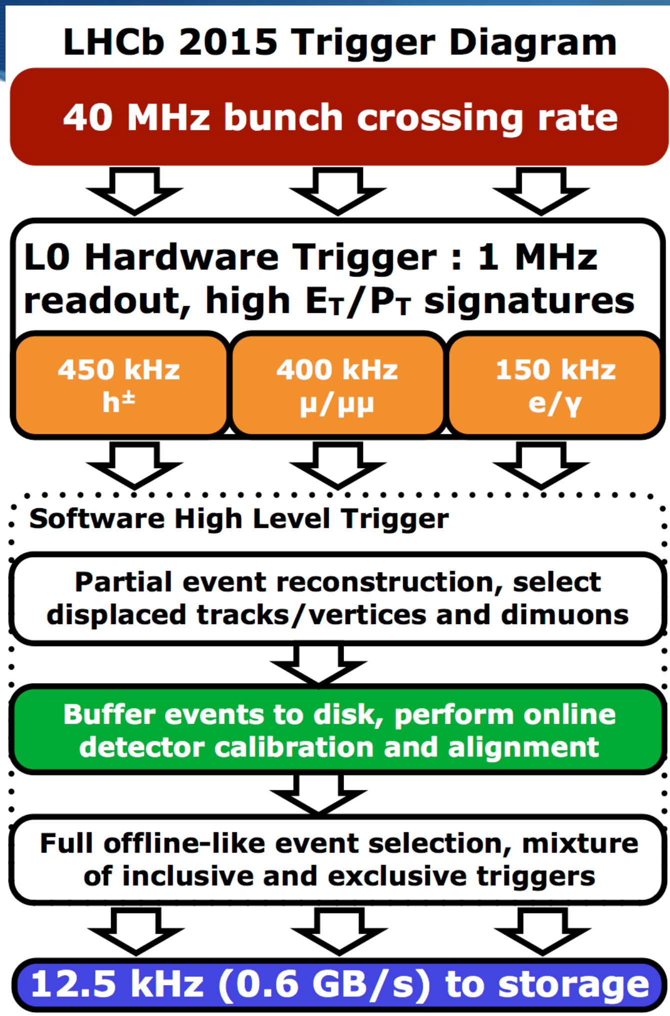
# Run 1 strategy




Performance of the LHCb high level trigger in 2012, J. Phys. Conf. Ser. 513 (2014) 012001

- In the trigger:
  - Preliminary calibration and alignment of the detector
  - Faster but less performing track and PID reconstruction
  - Only part of PID information used
- Offline reconstruction
  - Full and best performing alignment and calibration of the detector
  - Full reconstruction including all PID information

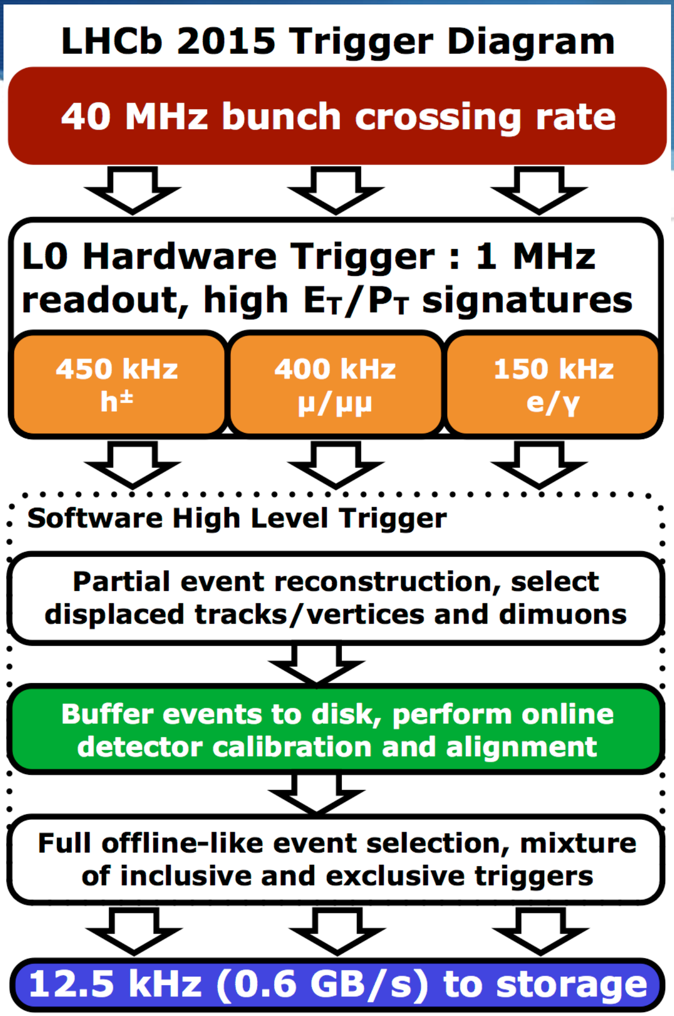
# Run 2 strategy




- Buffer all events to disk before running 2nd software level trigger (HLT2)
- Perform calibration of PID detectors and alignment of the full tracking system in real-time
  - → same constants in the trigger and offline reconstruction
- Last trigger level runs the same offline reconstruction
- This results to have in the trigger the full reconstruction with the best performance

➥ Allowing to profit of the best detector performance and of all PID information in the trigger selection

# Run 2 strategy




- Buffer all events to disk before running 2nd software level trigger (HLT2)
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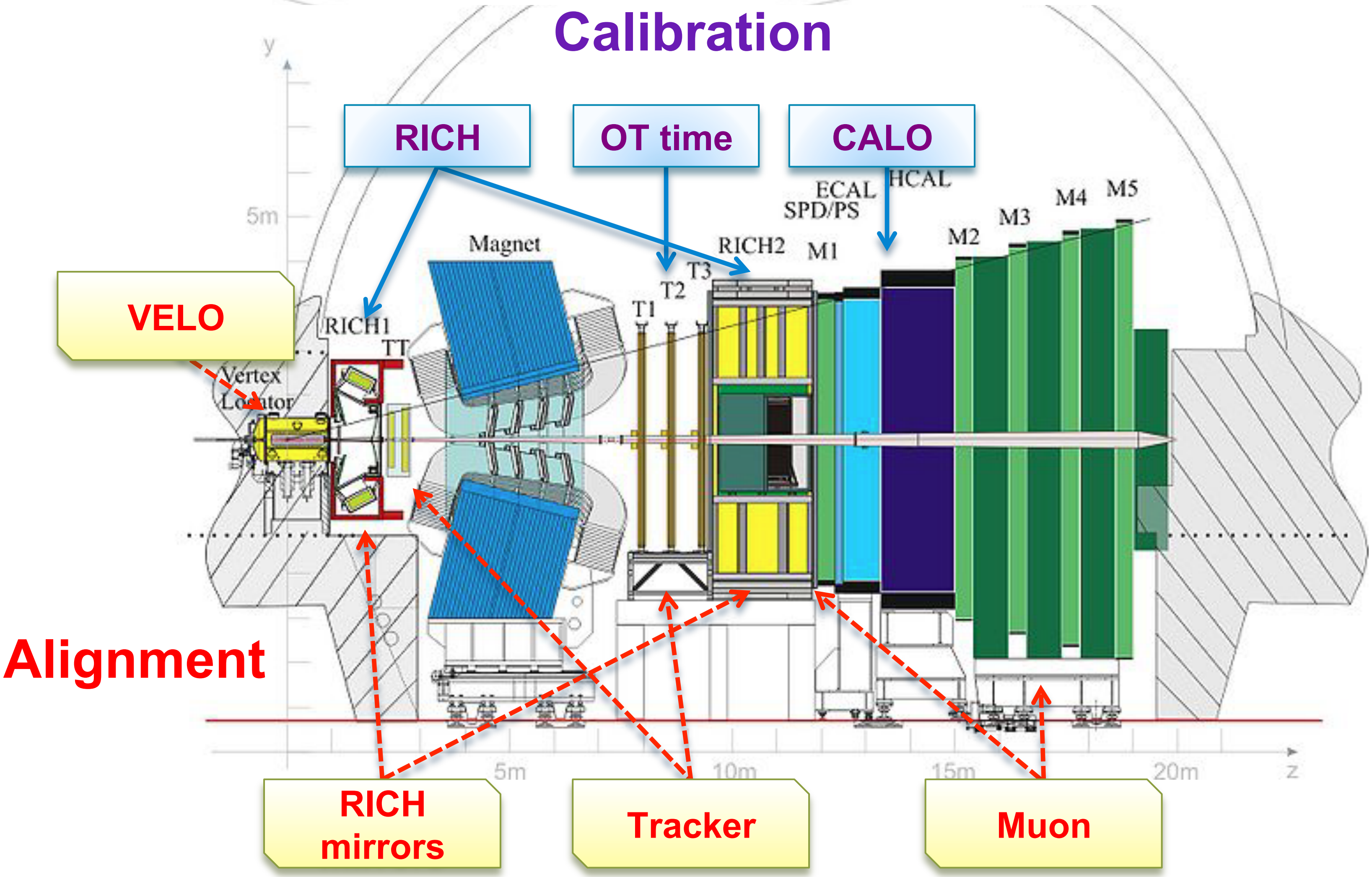
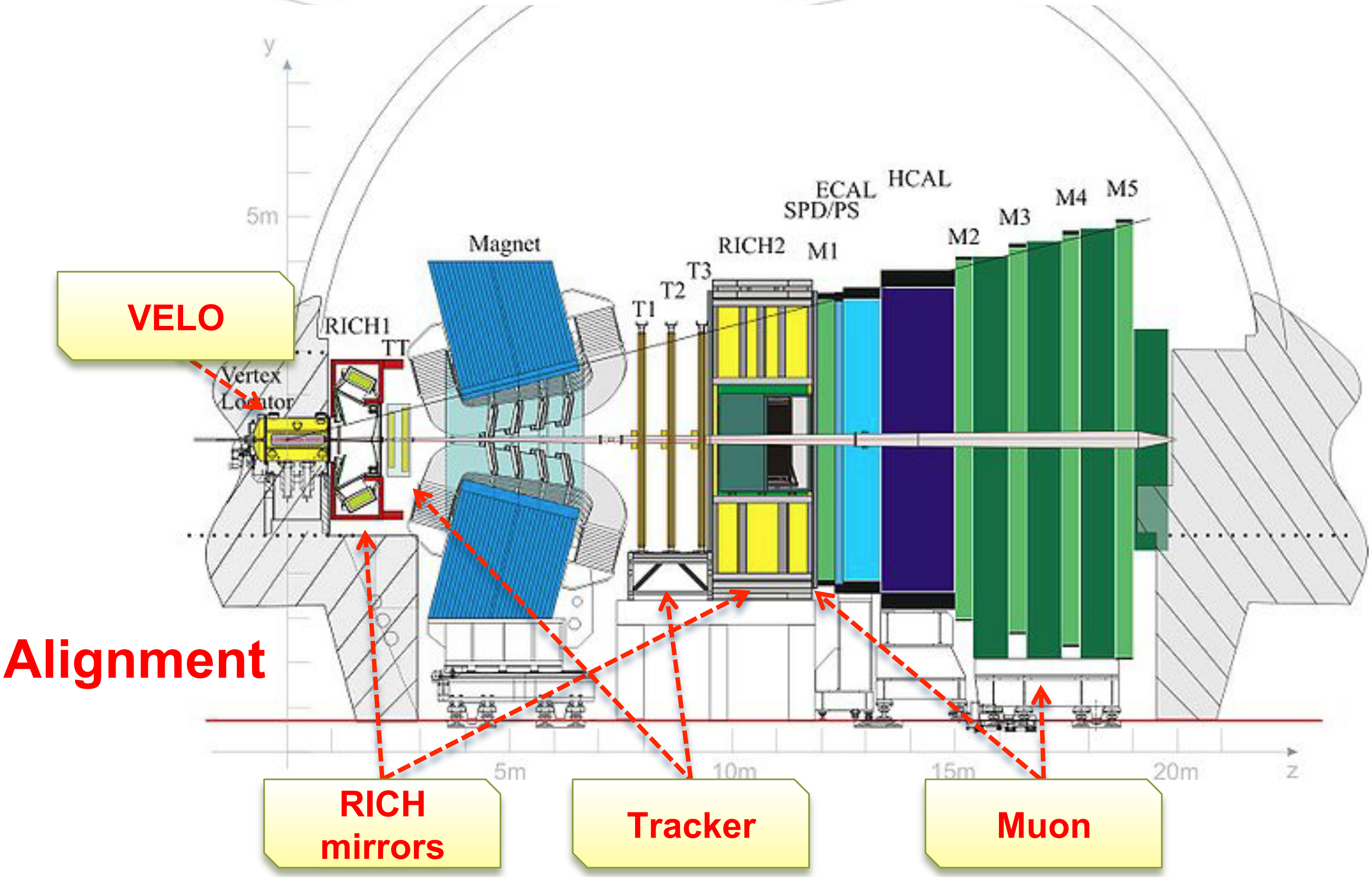
# Real-time alignment and calibration

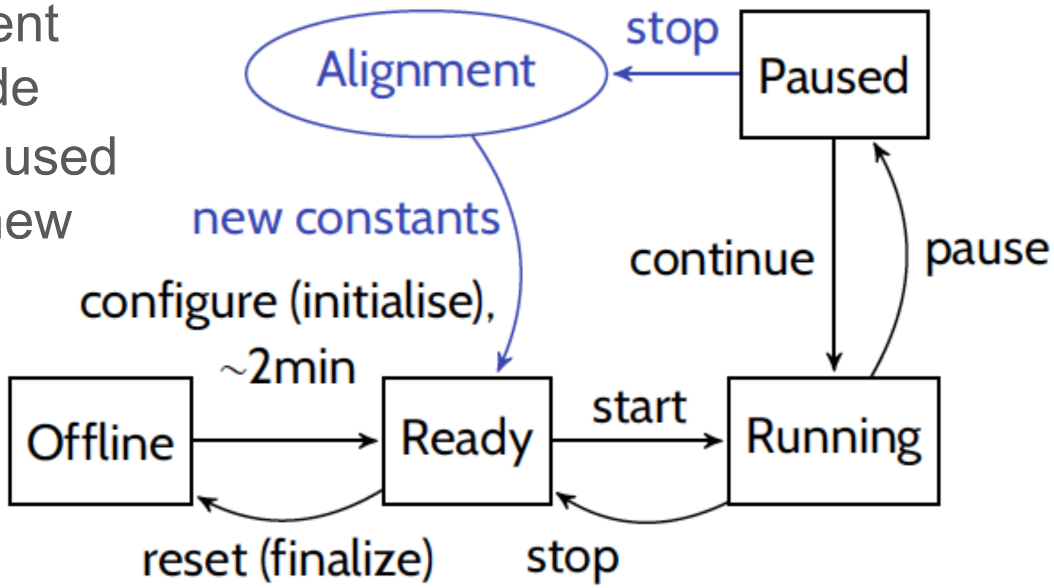


# Real-time alignment

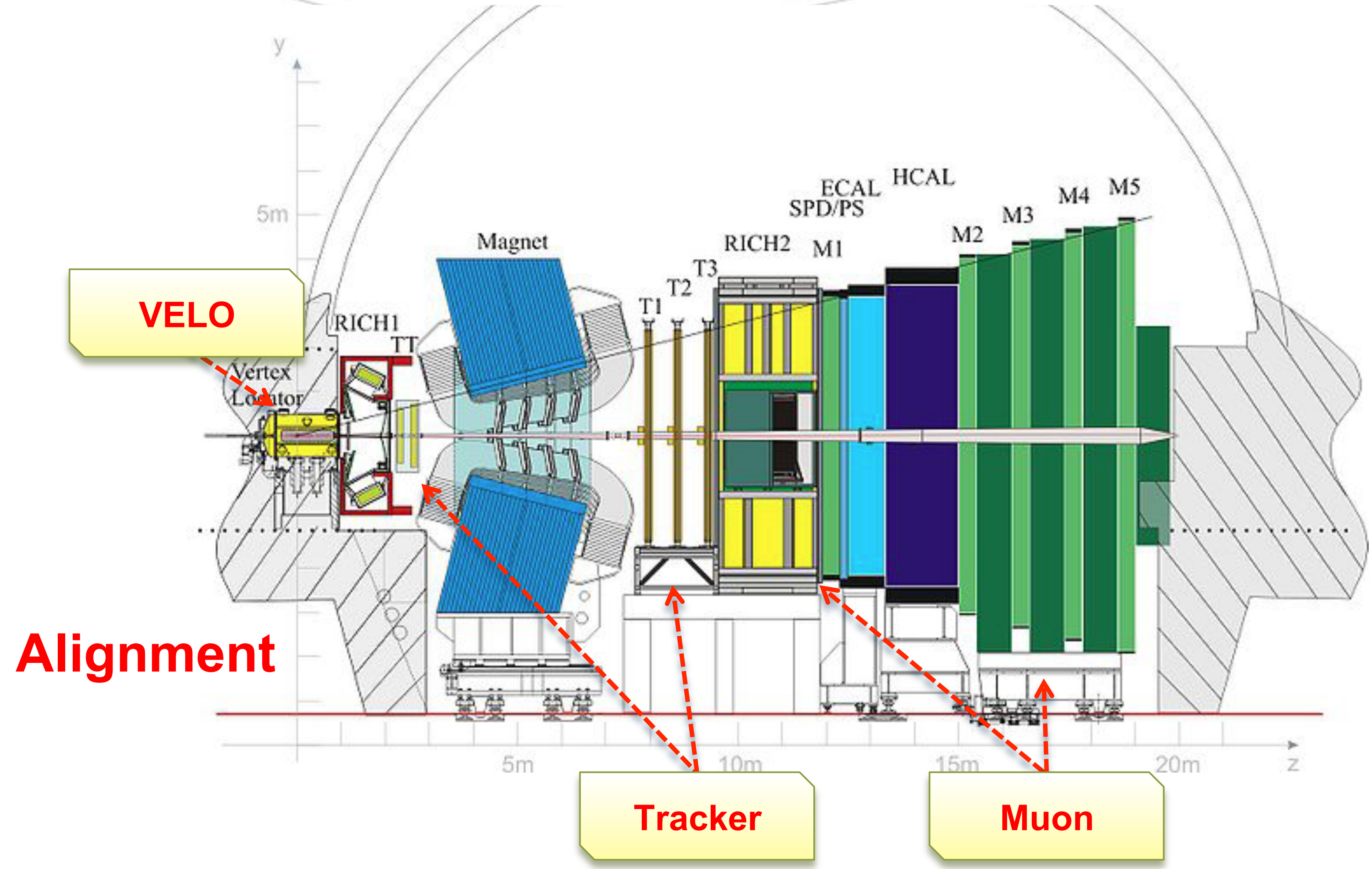


# Alignment framework

- Requirements:
  - To run as soon as enough data are collected
  - Iterative process
  - Provide the new constants as soon as possible
- New dedicated framework allows
  - Parallelization of the event reconstruction on ~1700 nodes of the trigger farm
  - Computing of the alignment constants on a single node
  - The evaluated constants used as input for an eventual new iteration.
  - Update the alignment constants in the trigger as soon as they are available if needed



# Real-time alignment of the tracker system



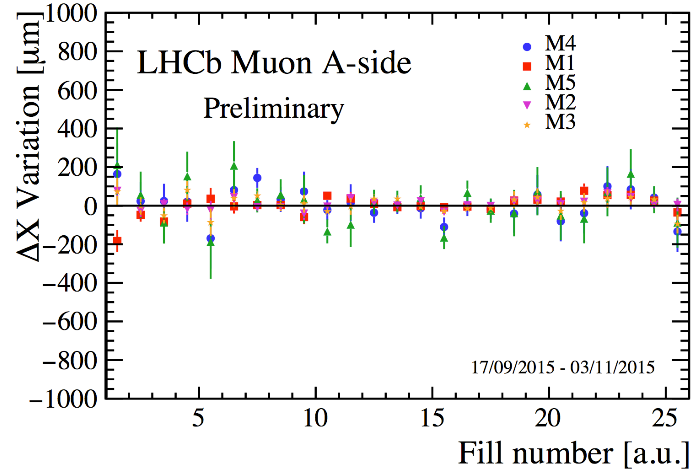
# Alignment

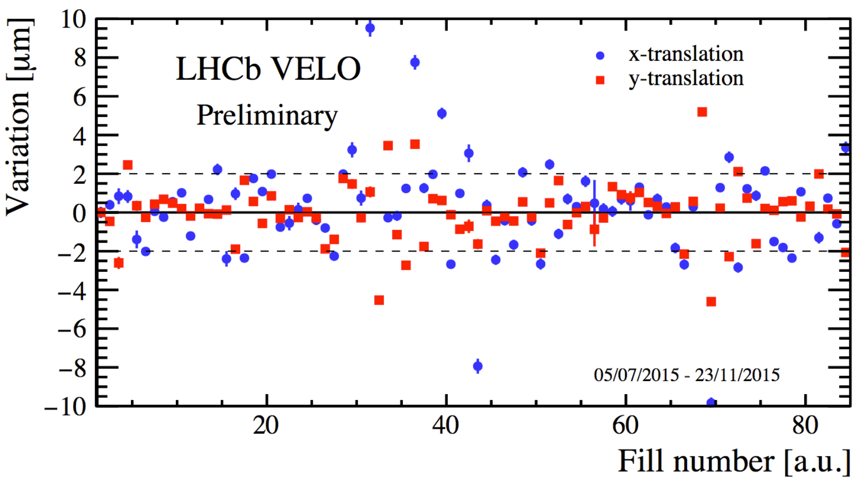
NIM A600 (2009) 471,
NIM A472 (2013) 48

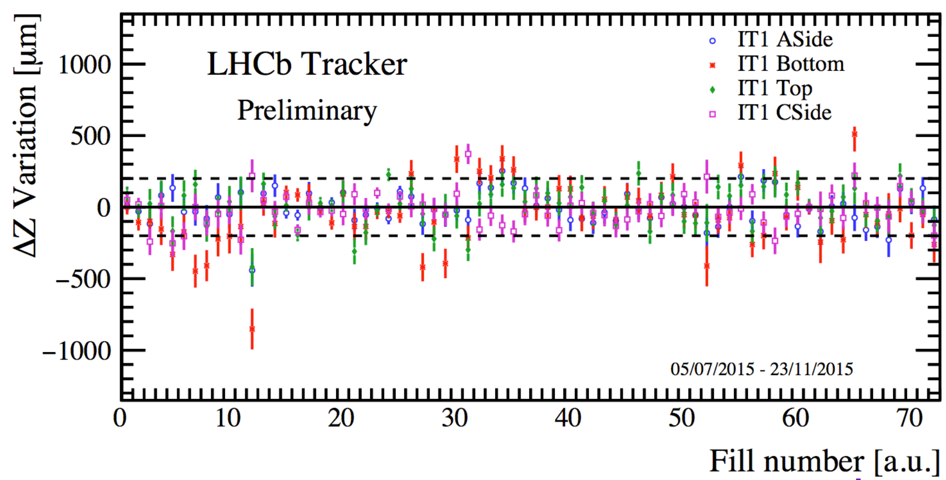
- 3 independent tasks for VELO, tracker and muon alignment
- A dedicated data sample for each task:
  - VELO: min. bias events
  - Tracker: $D^0$ sample
  - Muon: J/ψ sample
- Same method based on kalman filter
  - Taken into account multiple scattering and energy loss corrections
  - Using the magnetic field map
  - Consistent with track reconstruction
- Possibility to apply mass and vertex constraints (in addition to std constraint, e.g. fixing elements or average position)

# Real-time alignment

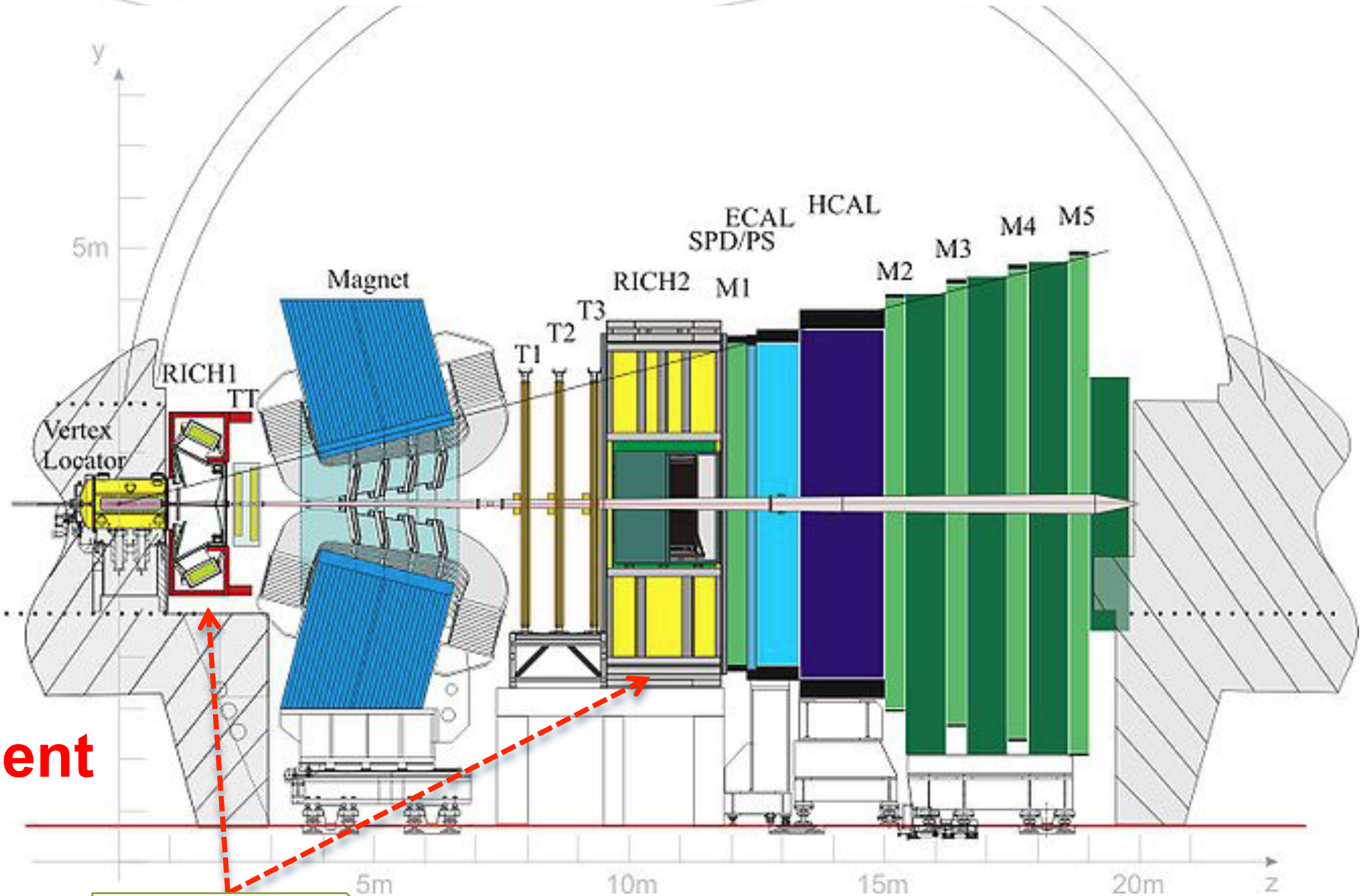
- Alignment of the full tracking system, about **700** elements
- Run automatically for each fill
- Automatic update of the constants only when needed
- Time required ~**7 minutes** for each task
- Alignment updates in Run2:
  - each 2/3 fills for the VELO
  - after each magnet polarity switch for the tracker
  - no update required, as expected, for the Muon chambers



# Real-time alignment: RICH mirrors

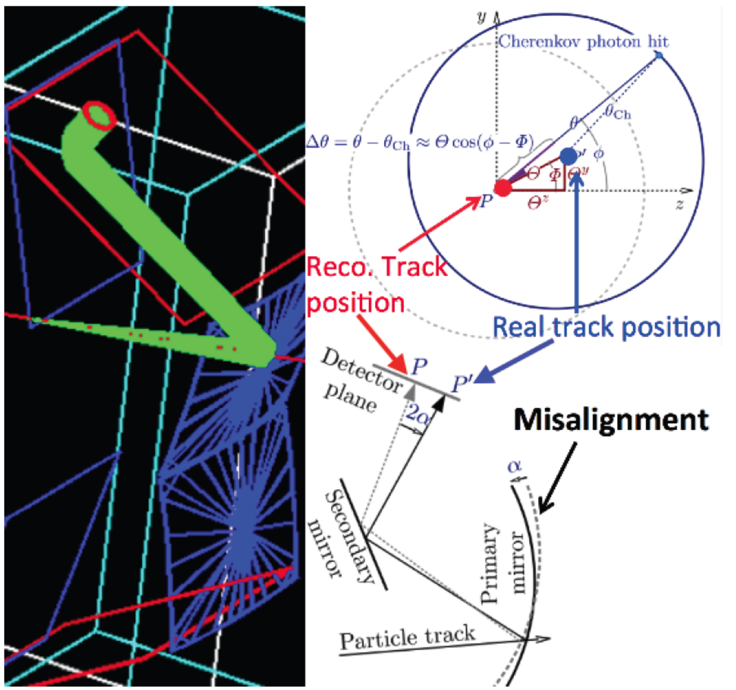


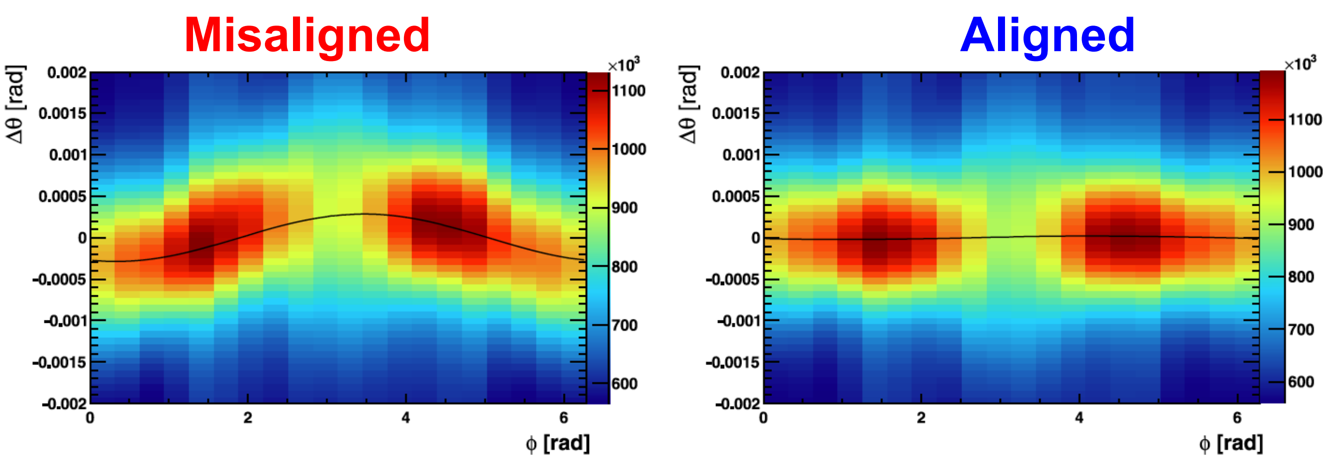

**Alignment**

**RICH mirrors**

# Rich mirror alignment

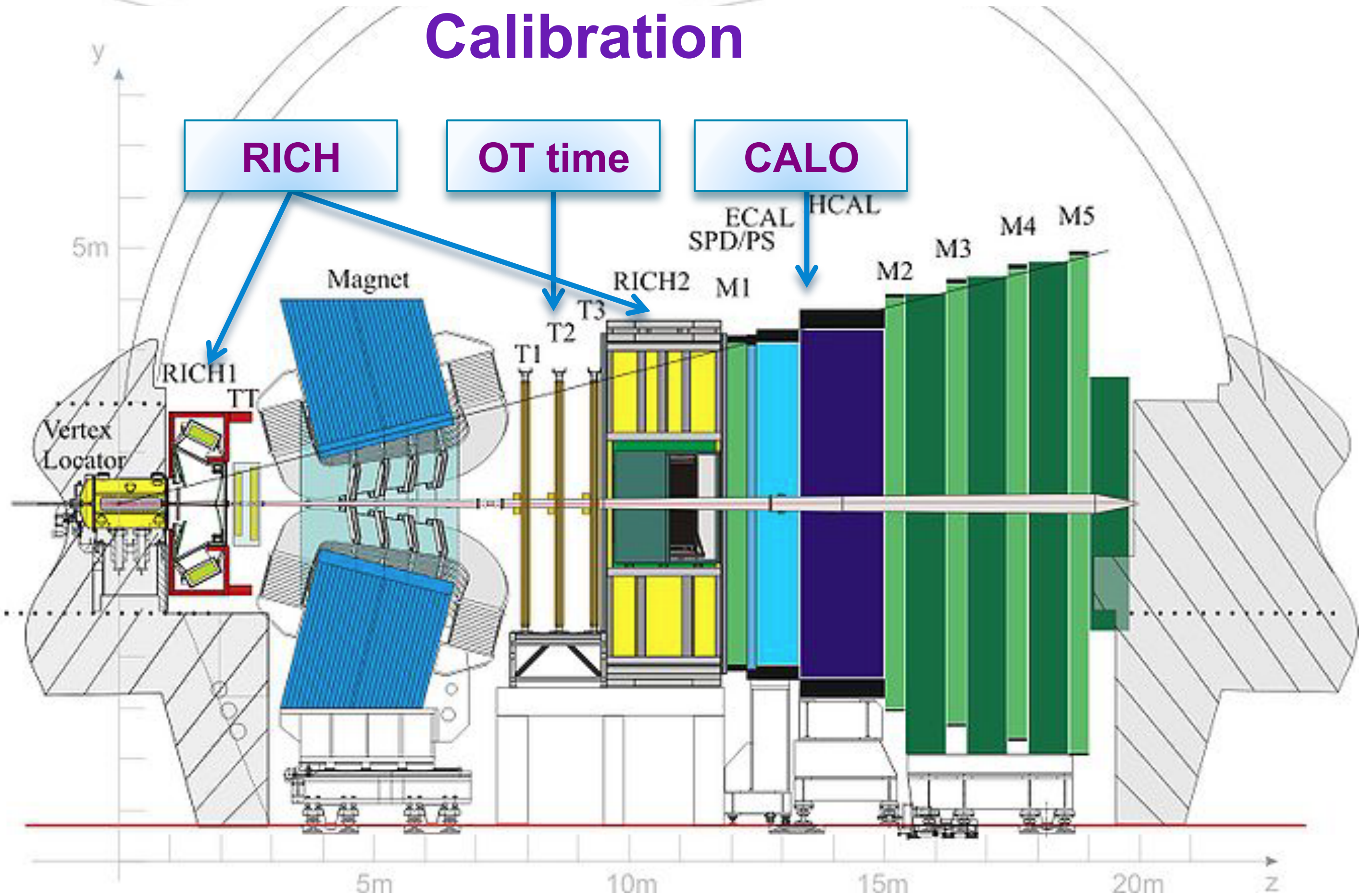
- Cherenkov photons focused on photon-detector plane by spherical and flat mirrors
- Center of Cherenkov ring corresponds to the intersection point of the track.
- Alignment is determined by fitting the Cherenkov opening angle as a function of the azimuthal angle of the ring
- 110 mirror pairs to align: **1090** constants
- Run as monitoring each few fills



# Real-time calibration

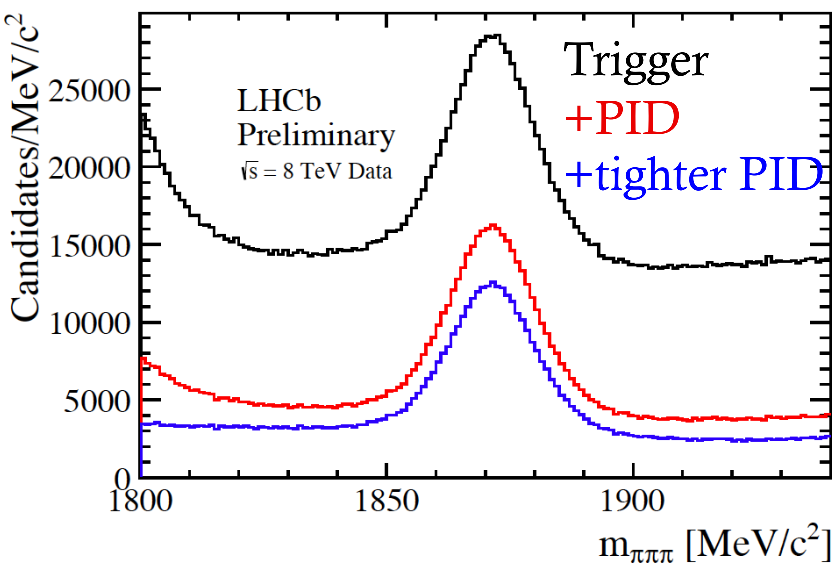
## Calibration



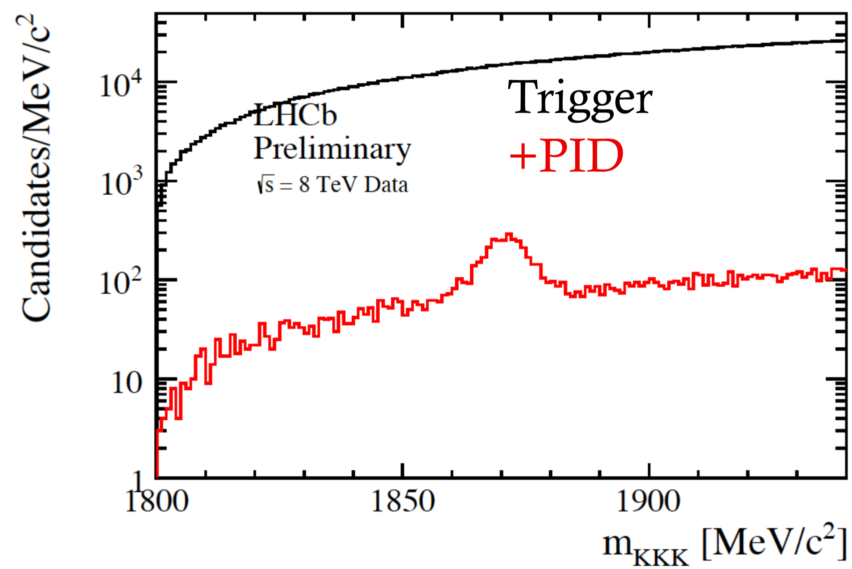
# PID importance

- Applying PID selection ➔ improve purity and mass resolution
- Improve performance of HLT selection, in particular in case of tighter selection
- PID requirements allowing exclusive selection and optimization the rate scaling for the CF modes (control channels in several measurements)

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



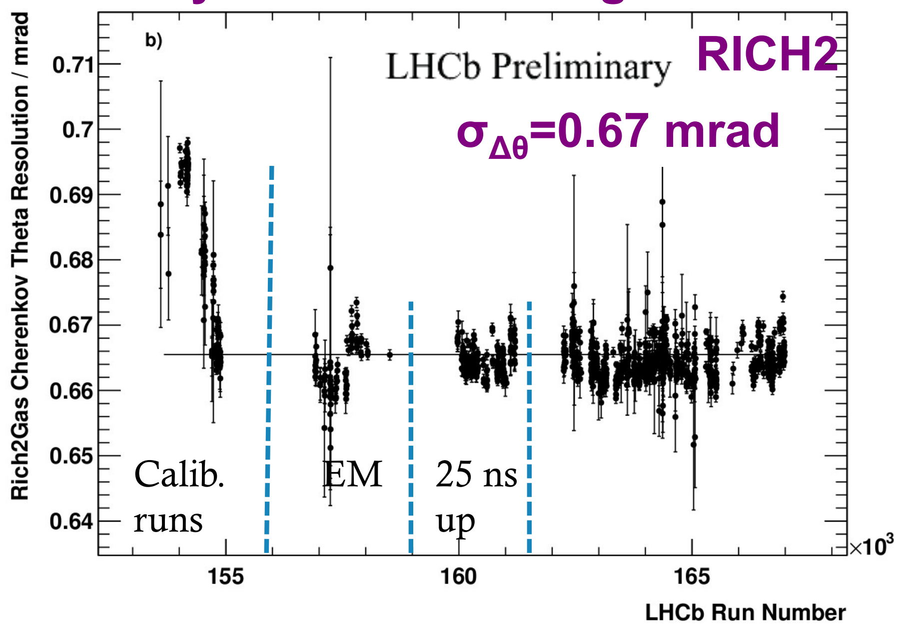

**DCS: $D^+ \to K^{+-}K^-K^+$**



# RICH calibration

- Calibration depends on the gas mixture, temperature and pressure
  - Refractive index (2 parameters)
  - Hybrid photon detector (HPD) calibration (1940 parameters)
- Automatically evaluated and updated for each run
- Calibration parameters used in the trigger thanks to the buffering all the events to the disk
- Performance stable during the full data taking monitored by the Cherenkov angle resolution

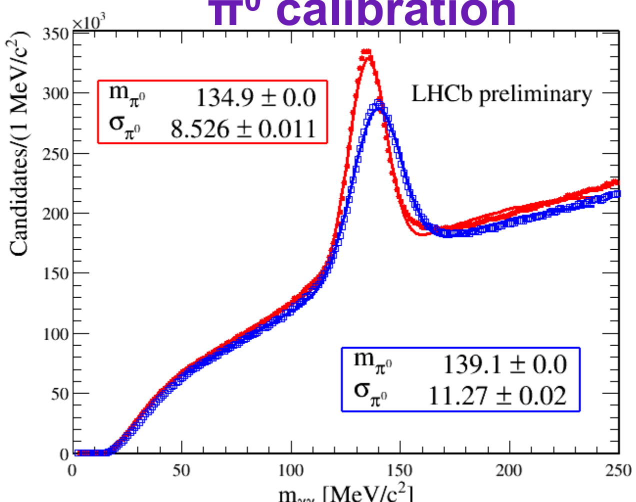
**Stability of cherenkov angle resolution**



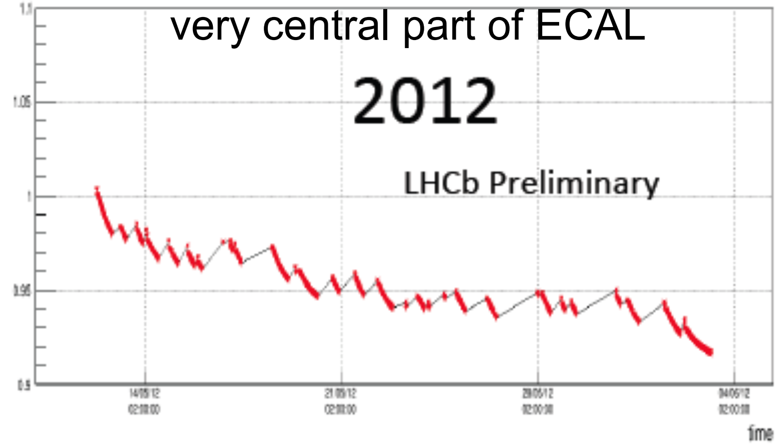
# Calorimeter calibration

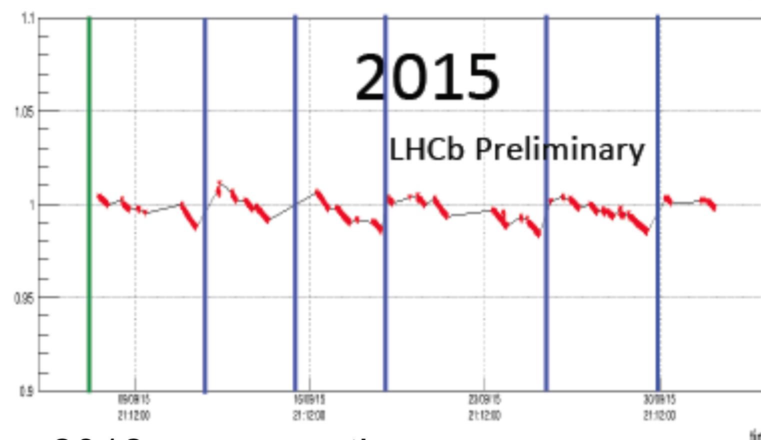
- Relative calibrations
  - Raw occupancy method: comparing the performance of each cell with a reference
  - LED monitoring system allows to detect ageing of the PMTs
- Absolute calibrations
  - $\pi^0$ calibration for ECAL: compute di-photon invariant mass.
  - Cs source scan for HCAL, evaluated during the technical stop

**$\pi^0$ calibration**




LED average over 456 cells in the very central part of ECAL

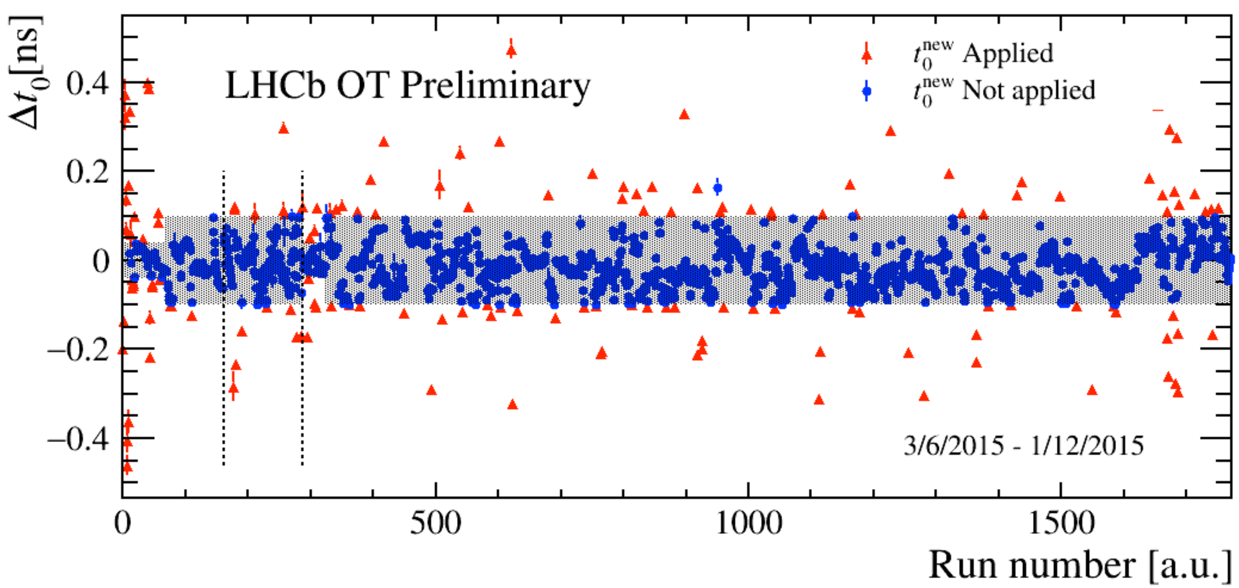



2012: no correction
2015: applied new $\pi^0$ calibration
applied new LED corrections

# Real-time OT calibration

- 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 shift of 0.5 ns leads to tracking inefficiency of ~2.5‰
- The module time calibration is stable with time and evaluated one per year

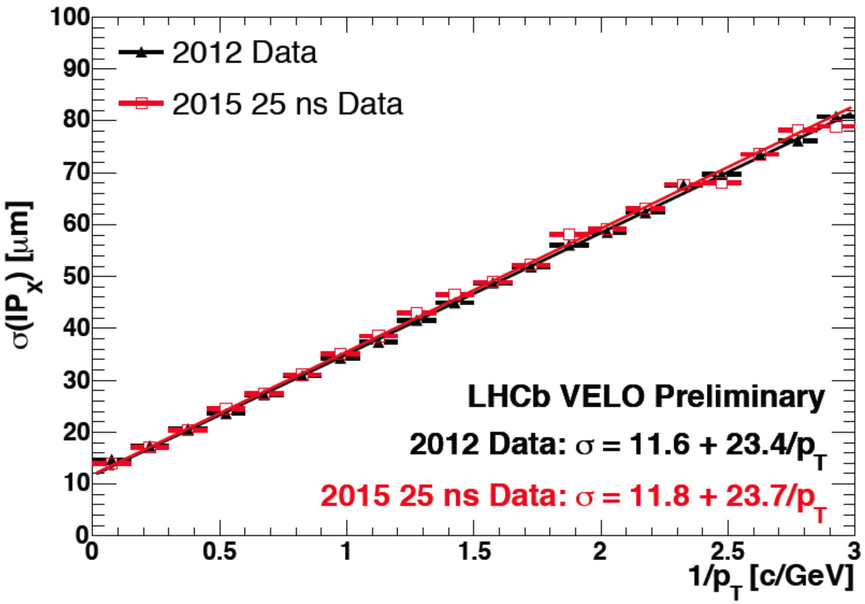


# Performance in Run2

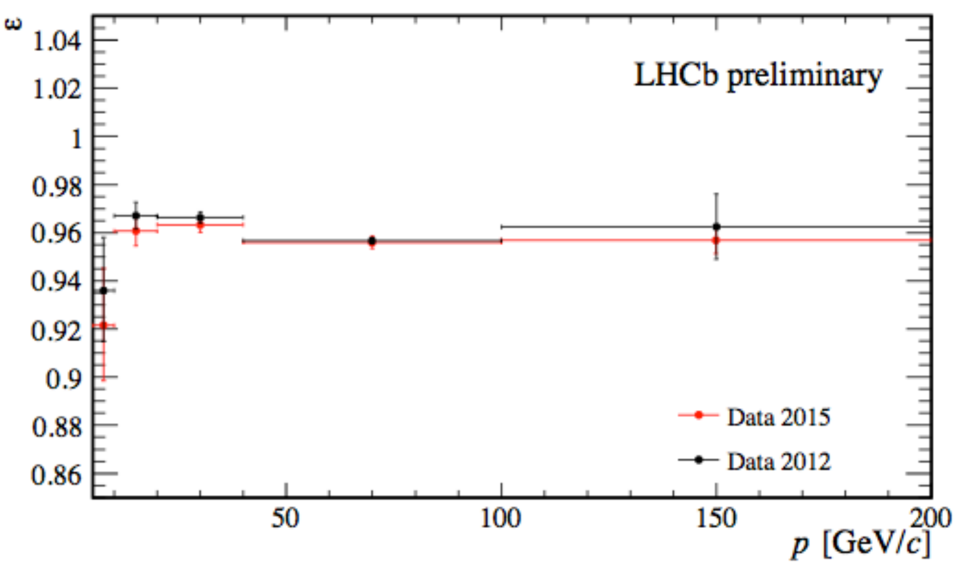
# Tracking Performance

- **Same offline performance as in Run1 directly in the trigger**

## IP resolution



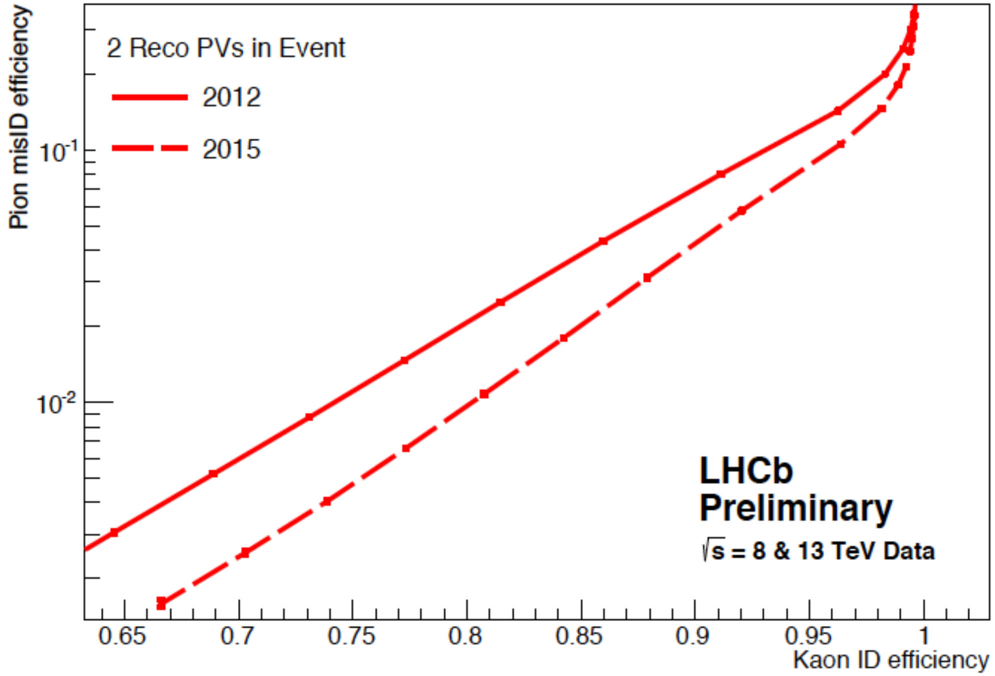

## Track efficiency



# PID Performance

- **Improved performance wrt Run1**

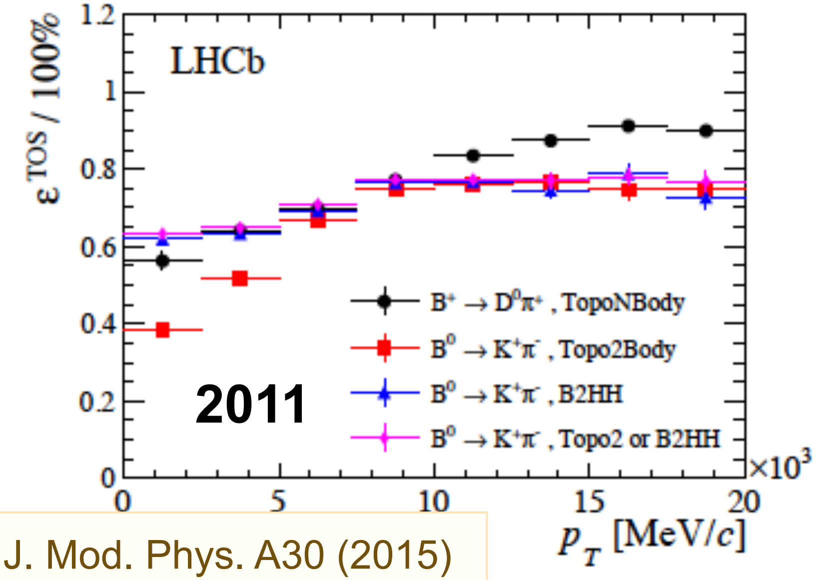
**Pion misidentification efficiency vs Kaon identification efficiency**

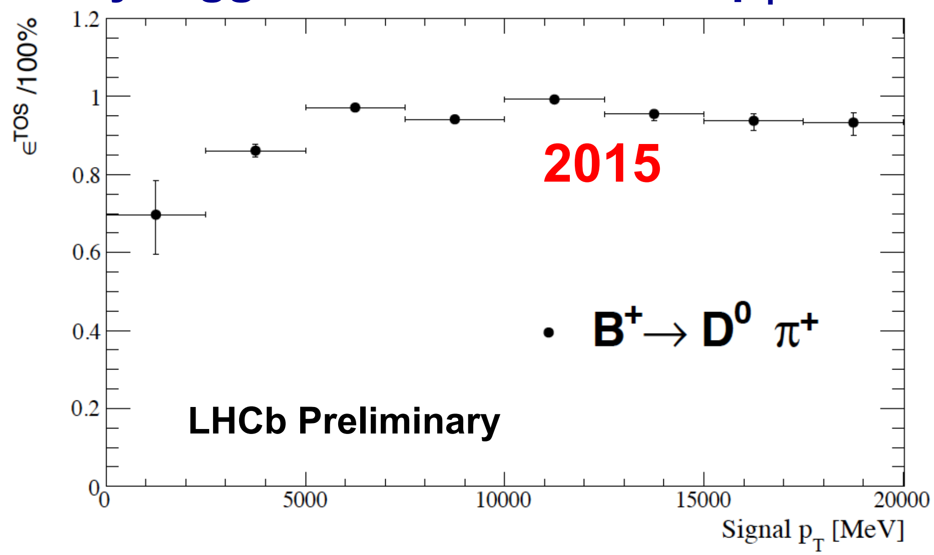


# Trigger performance

- Improvement of the trigger efficiency thanks to e.g.
  - Run the same offline reconstruction in the trigger
  - Having the detector fully calibrated and aligned
  - Using PID selection in the trigger

**Efficiency of the HLT2 inclusive beauty trigger as a function of B $p_T$**



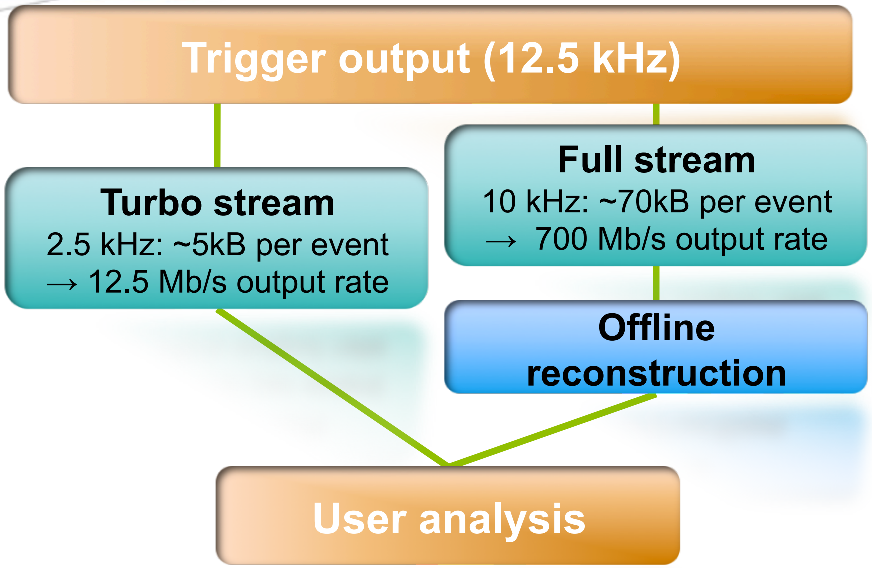




Int. J. Mod. Phys. A30 (2015)

Efficiency for $B^+ \to D^0\pi^+$ is ~75% → Efficiency for $B^+ \to D^0\pi^+$ is >90%

# "Turbo" stream

- Some analyses performed directly on the trigger output
- Storing only selected candidates to reduce event size
  ➔ Save ~90% of space
- Analysis with large yields: possible to reduce the pre-scaling of all the channels that were trigger output rate constrained



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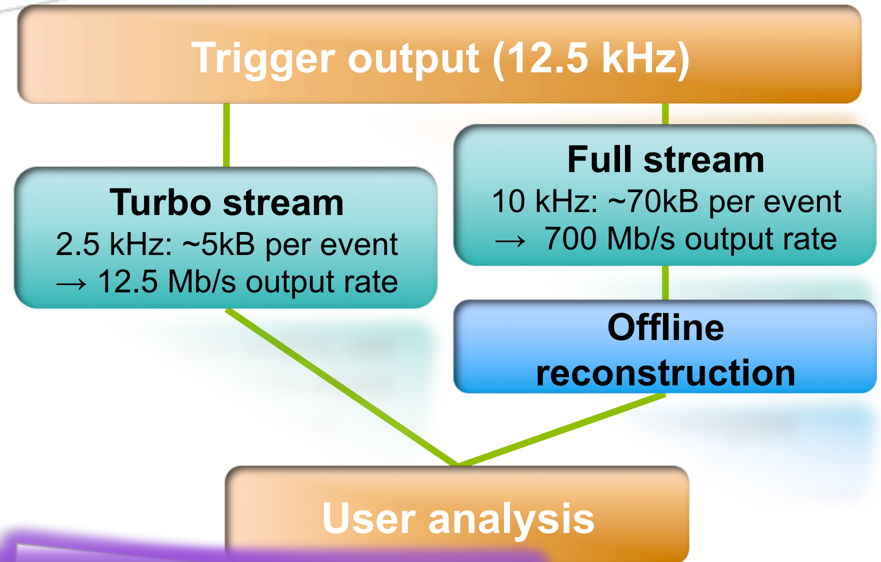
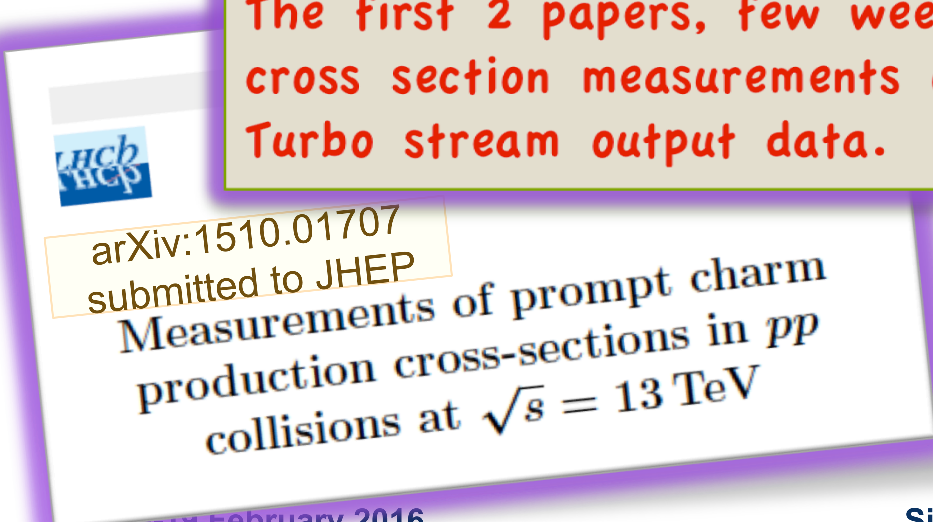
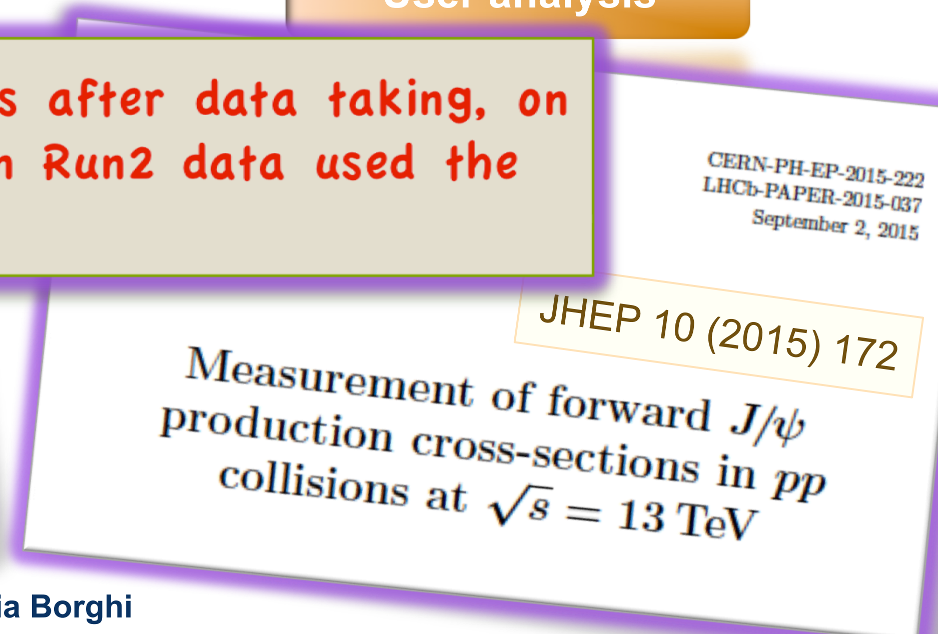
- Storing only selected candidates to reduce event size
  ➔ Save ~90% of space
- Analysis with large yields: possible to reduce the pre-scaling of all the channels that were trigger output rate constrained




The first 2 papers, few weeks after data taking, on cross section measurements on Run2 data used the Turbo stream output data.


arXiv:1510.01707
submitted to JHEP

Measurements of prompt charm production cross-sections in $pp$ collisions at $\sqrt{s} = 13$ TeV


CERN-PH-EP-2015-222
LHCb-PAPER-2015-037
September 2, 2015

JHEP 10 (2015) 172

Measurement of forward $J/\psi$ production cross-sections in $pp$ collisions at $\sqrt{s} = 13$ TeV

# Conclusions

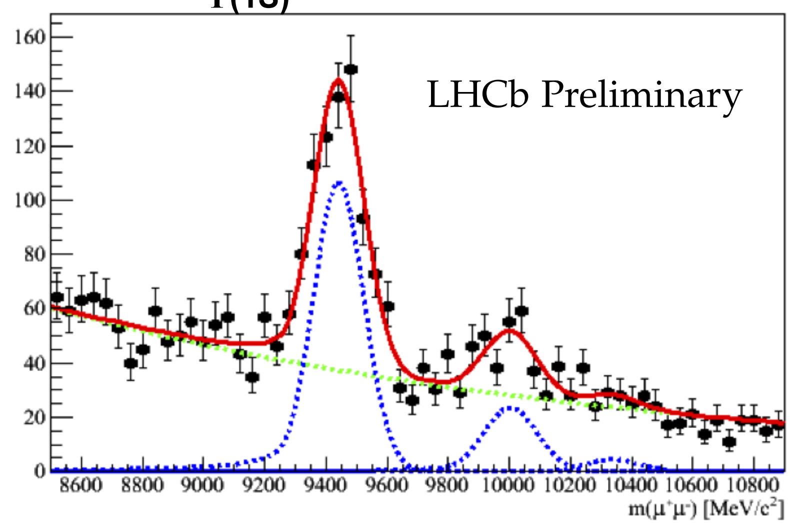
- New data taking strategy implemented at LHCb experiment
- Novel real-time alignment and calibration procedure: constants available in few minutes
- Profit of the best and full performance of the detector, including PID selection in the trigger
- Analysis performed directly on the trigger candidates
- This new strategy allows to increase our physics program with the same resources

# Backup

# Importance of the alignment

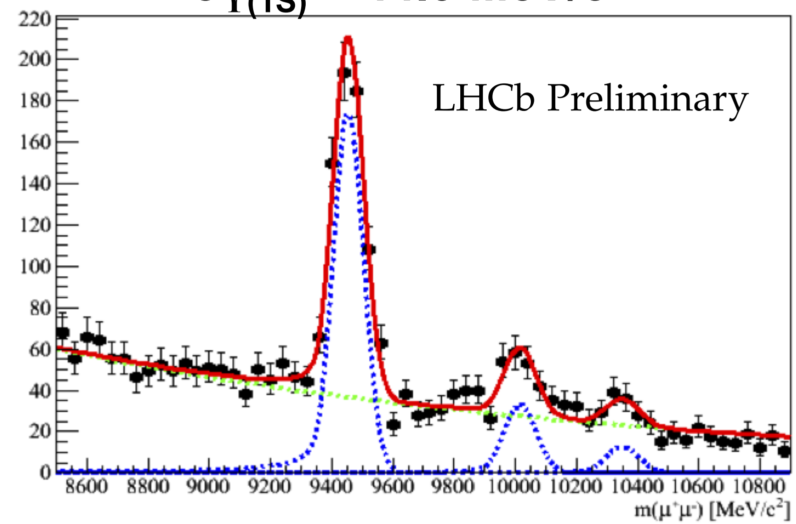
**First alignment**

**$\sigma_{\Upsilon(1S)}$ = 86 MeV/c²**

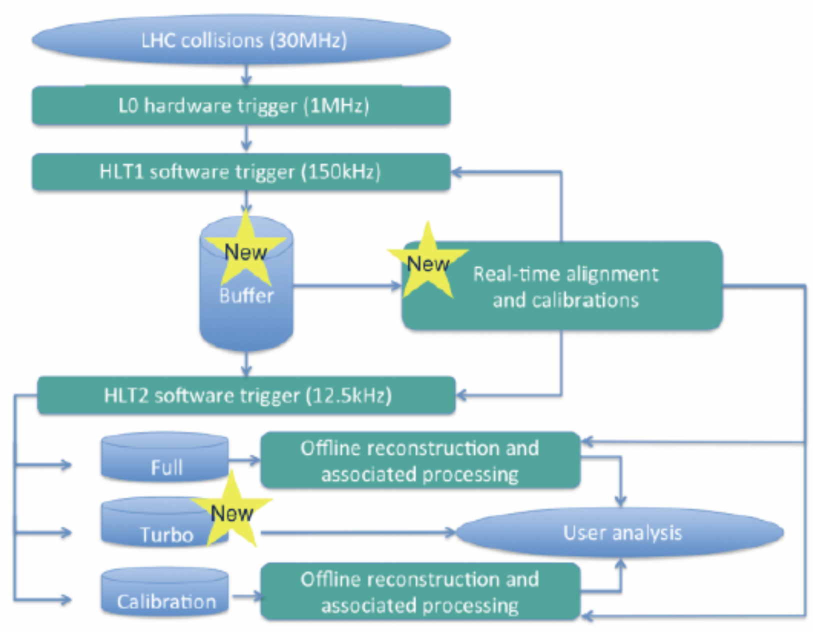



**Latest alignment**

**$\sigma_{\Upsilon(1S)}$ = 44.3 MeV/c²**



# New strategy for Run 1




- Buffer all events to disk before running HLT2
- Real-time alignment and calibration procedure before HLT2
- Same reconstruction in HLT2
- New Turbo stream for physics analysis: saving only the trigger candidates

# Online Alignment

- VELO alignment at begin of each fill
  - Split on 1700 nodes for the track reconstruction
  - $\chi^2$ minimization in one single node
  - Update immediately if needed
  - Expected to be updated often but not for each fill
- Tracker alignment as soon as enough data
  - Split on 1700 nodes for the track reconstruction
  - $\chi^2$ minimization in one single node
  - Update for the next run
  - Expected to be updated each ~2 weeks

| Number of alignment constants | |
|---|---|
| VELO | 86 |
| TT | 135 |
| IT | 64 |
| OT | 496 |

# Alignment

NIM A600 (2009) 471,
NIM A472 (2013) 48

- Standard method based on kalman filter
  - Taken into account multiple scattering and energy loss corrections
  - Using the magnetic field map
  - Consistent with track reconstruction
- Possibility to apply mass and vertex constraints (in addition to std constraint, e.g. fixing elements or average position)

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 ($\alpha$) minimizing a global $\chi^2$:

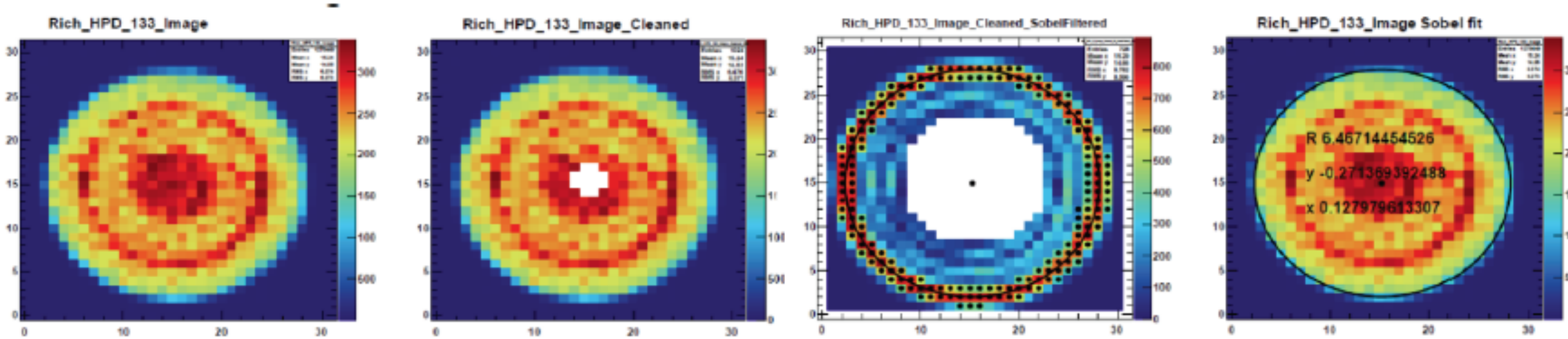
$$\alpha = \alpha_0 - \left(\frac{d^2\chi^2}{d\alpha^2}\right)^{-1}\Bigg|_{\alpha_0} \frac{d\chi^2}{d\alpha}\Bigg|_{\alpha_0}$$

Iterate until the $\chi^2$-difference is below a threshold

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

# RICH calibration

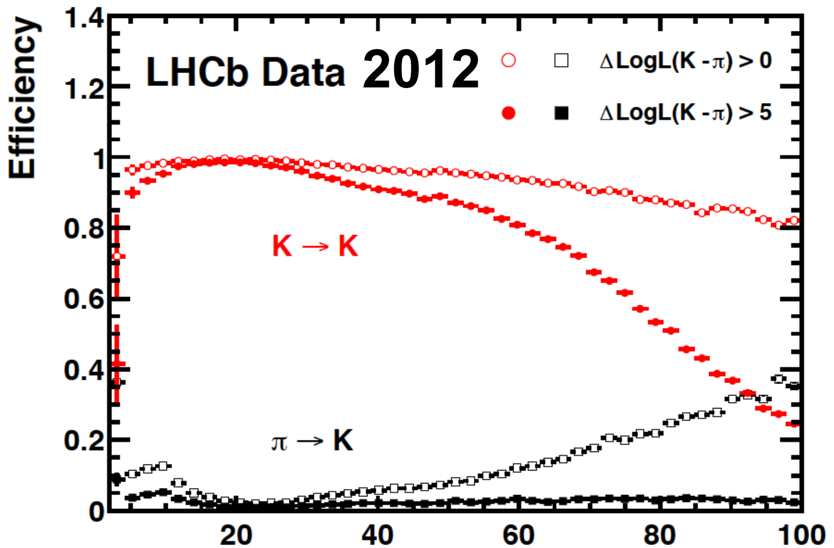
- Refractive index determined by fitting the difference between reconstructed and expected Cherenkov angle
  - Depends on the gas mixture, temperature and pressure
  - **2** parameters
- Hybrid photon detector (HPD) calibration is evaluated by fitting the anode images cleaned and using a Sobel filter to detect the edges
  - Affected by the magnetic and electric fields distortions
  - **1940** parameters

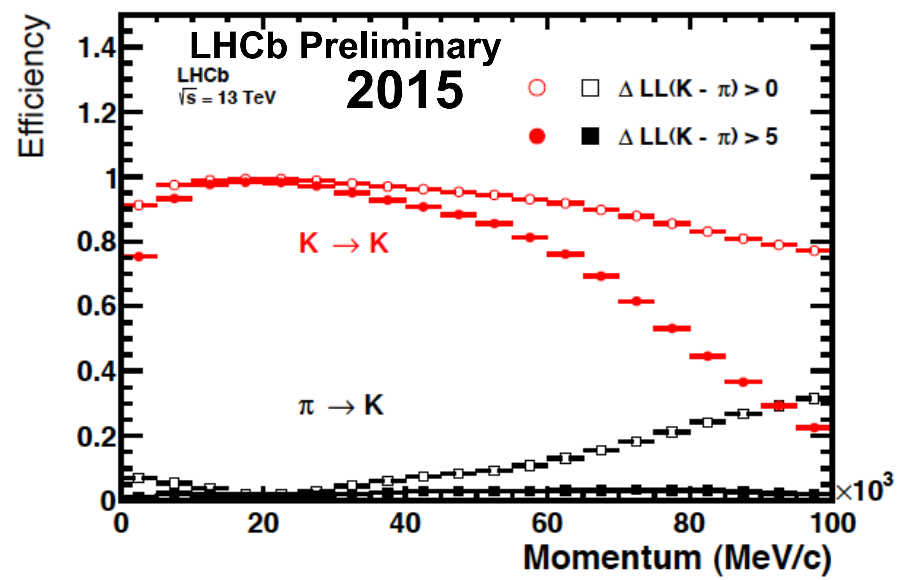


# PID Performance

- **Improved performance wrt Run1**

**Kaon identification efficiency and pion misidentification rate**




Int. J. Mod. Phys. A30 (2015)

# RICH calibration

- Implemented as an online analysis task, evaluated run by run
  - RICH refractive index and HPD image
- Based on histograms ➔ required time O(1 min)
- Work flow:

1. Take the last file of one run automatically (triggered by either when End-of-Run ("EOR") in the file name or  run number in the file name changed)
2. Run ref index job
3. Run HPD image job
4. Give signal to online that the calibration is done for this run