5th International Conference on New Frontiers in Physics ICNFP2016, 6-14 July 2016

LHCb detector and trigger performance in Run II

Francesca DORDEI, CERN

On behalf of the LHCb Collaboration

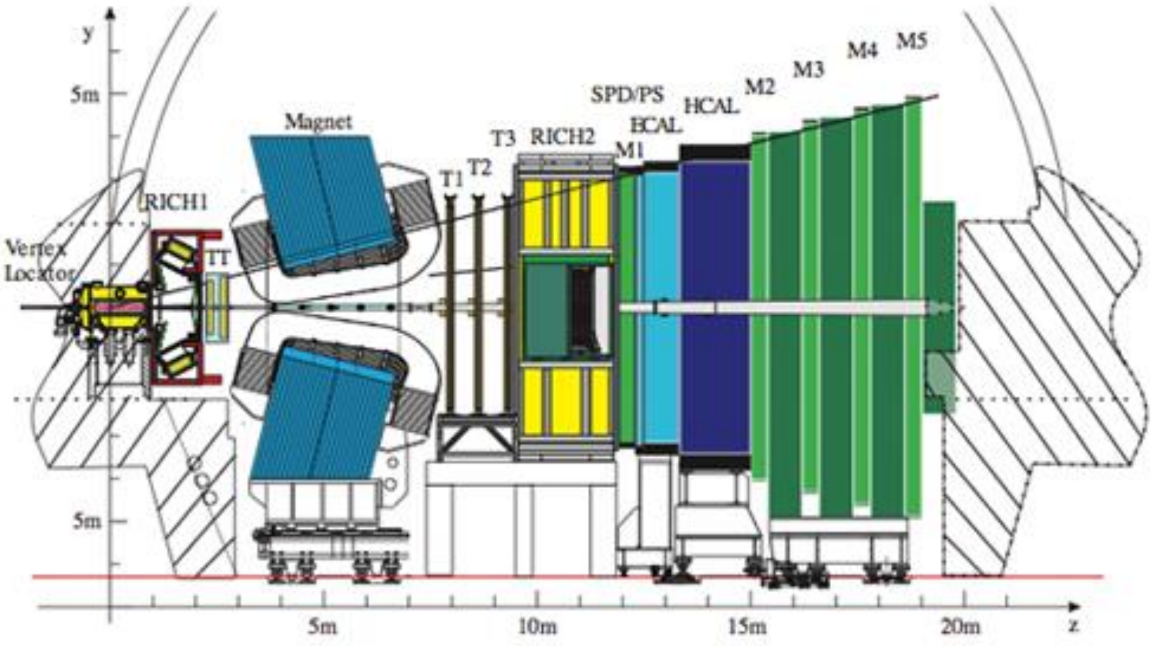
The LHCb EXPERIMENT

- LHCb: single arm spectrometer at LHC dedicated to beauty and charm physics
  - Covering a pseudorapidity range unique among the LHC detectors, $2 < \eta < 5$

- **Primary goal:** look for indirect evidence of new physics in CP-violation and rare decays of beauty and charms hadrons

- This requires:
  1. **Excellent tracking** (momentum, impact parameters and primary vertex resolution)
  2. **Excellent decay time resolution**
  3. **Excellent particle identification**

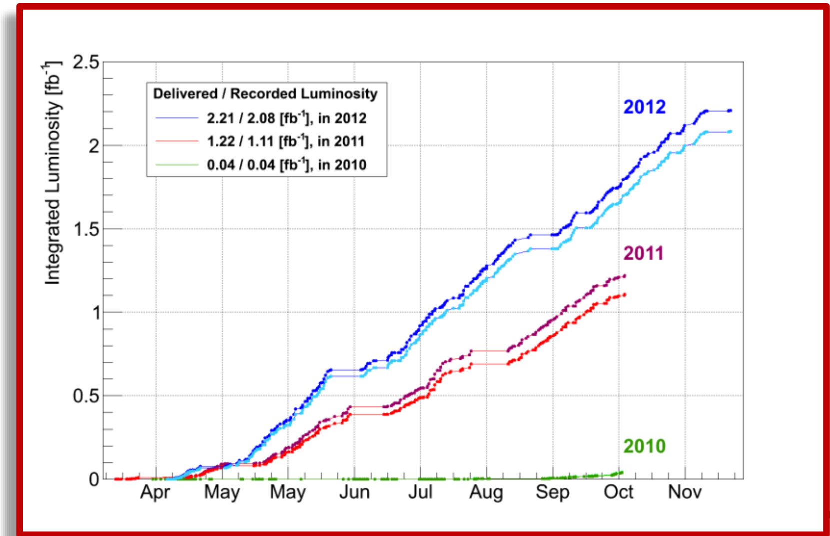
[LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022]



SETTING THE STAGE

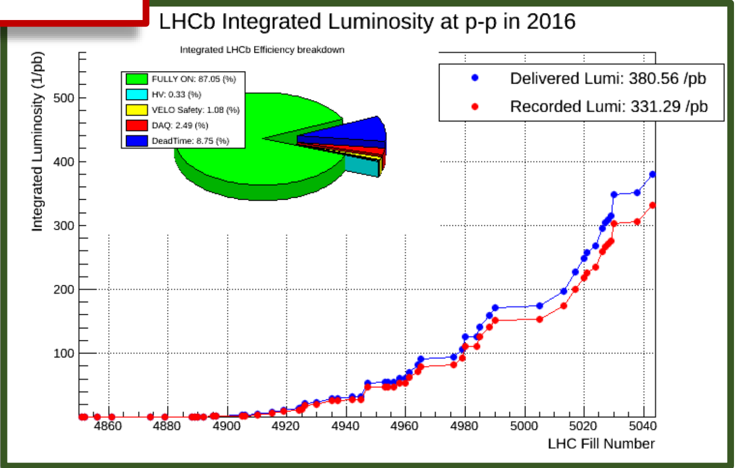
Recent past, Run I (2010 - 2012)

- Very successful running and triggering
  over 300 publications so far
- 1/2 fb^{-1} collected at beam energy 7/8 TeV
- p-A collisions also recorded
- Still a lot to do with Run I data



Present, Run II (2015 - 2018)

- Increased beam energy 8 TeV→13 TeV – Similar luminosity as in Run I ($\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Identical LHCb detector
- Completely revised trigger



Future, called Upgrade, Run III, (2020++)

- Many changes to the detector foreseen.

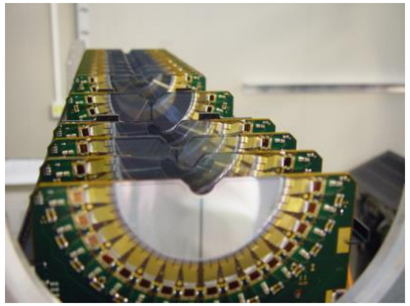
[Framework TDR for the LHCb Upgrade: Technical Design Report (2012)]

THE TRACKER BEFORE MAGNET

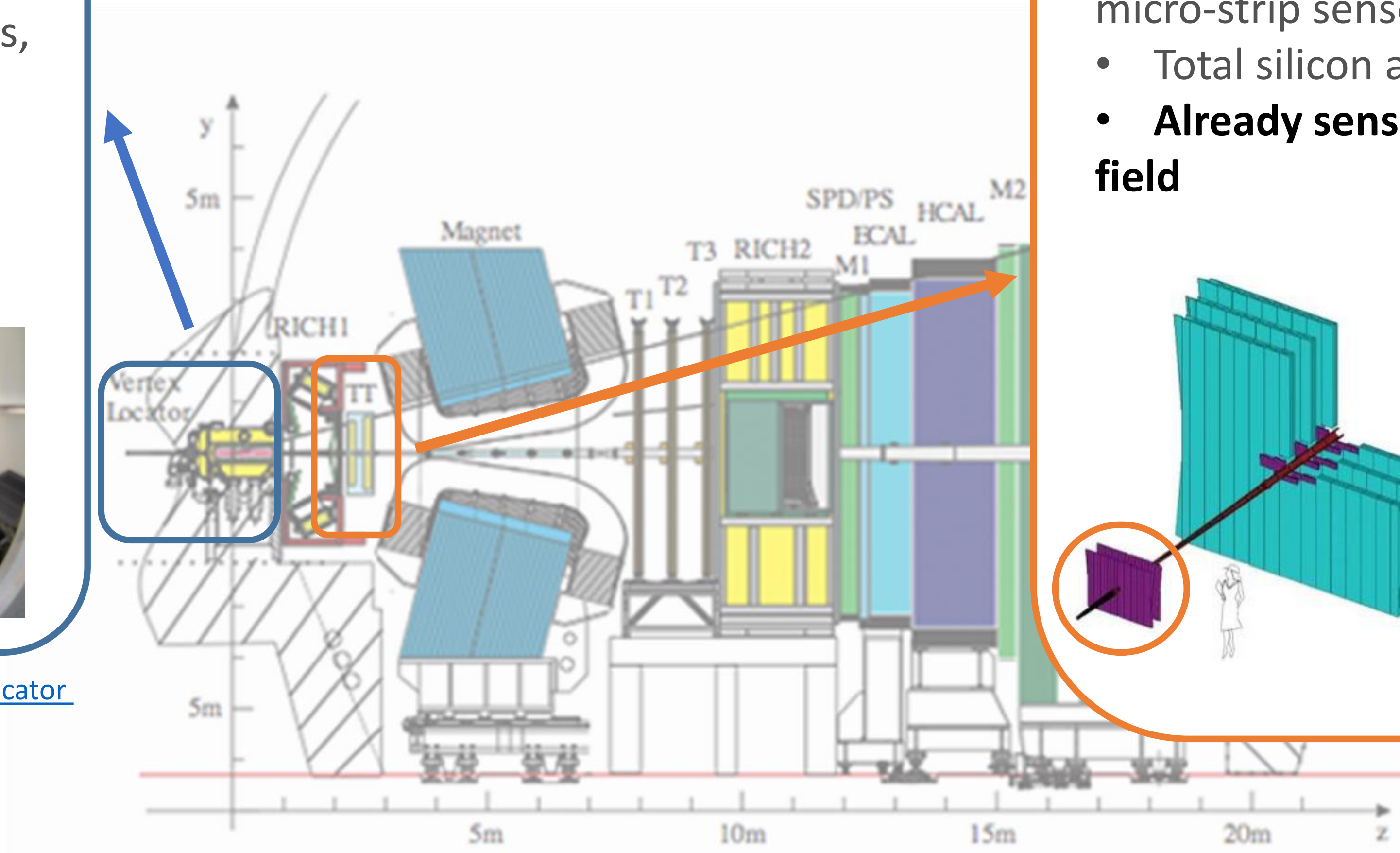
The Vertex Locator

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

Run I decay time resolution: ~45 fs

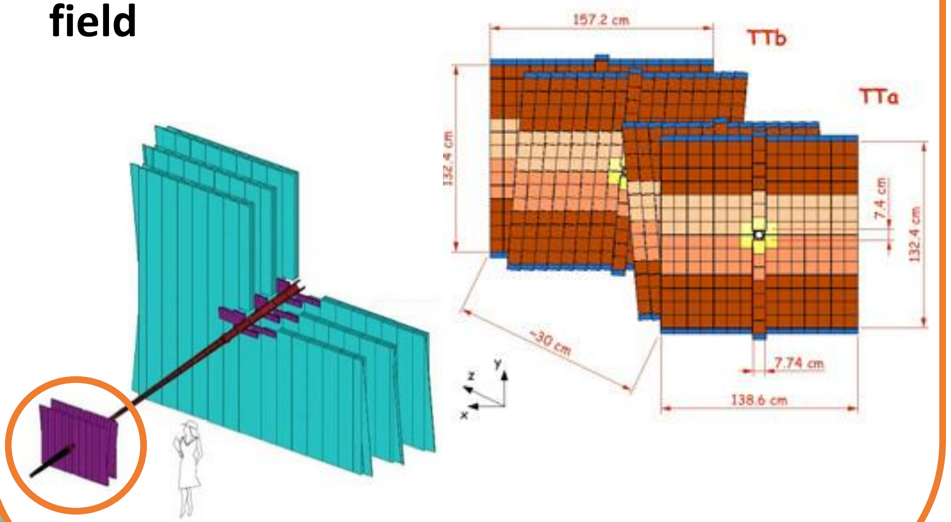


Performance of the LHCb Vertex Locator
JINST 9 (2014) 09007



Tracker Turicensis (TT)

- Four planes (0˚,+5˚,-5˚, 0˚) of silicon micro-strip sensor
- Total silicon area of 8 m^2
- **Already sensitive to the magnetic field**



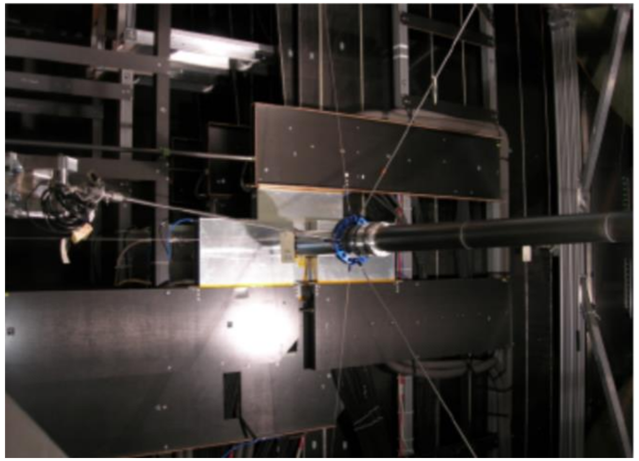
LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015) 1530022

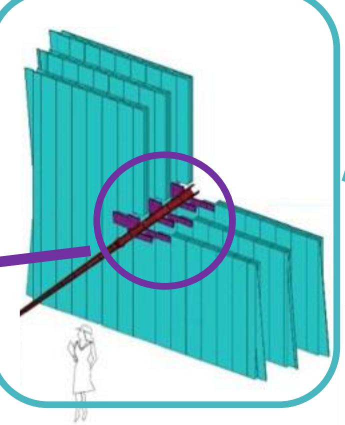
THE TRACKER AFTER MAGNET

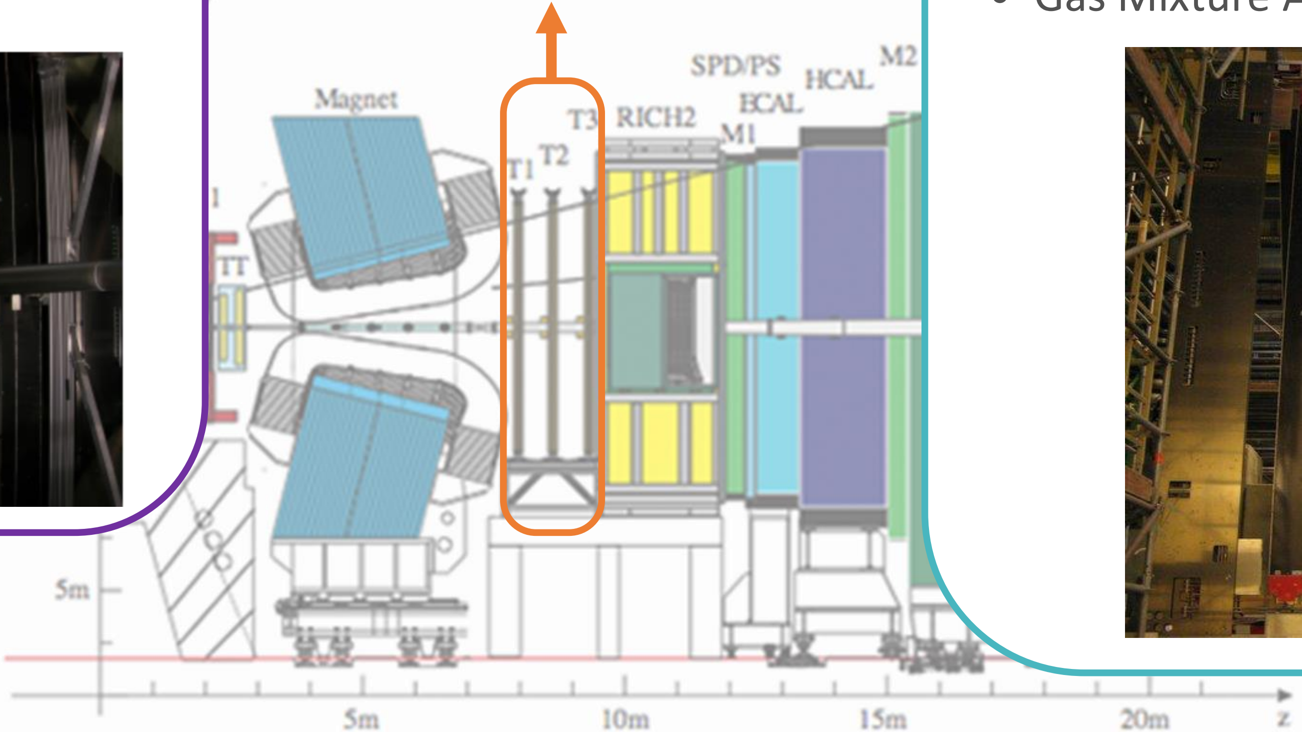
The Inner Tracker (IT)

Three stations each with four planes of silicon micro-strip sensors around the beam pipe

- Total silicon area of 4.2 m^2







Outer Tracker (OT)

Three stations each with four planes (0˚,+5˚,-5˚, 0˚) of straw tubes

- Gas Mixture $Ar/CO_2/O_2$ (70/28.5/1.5)

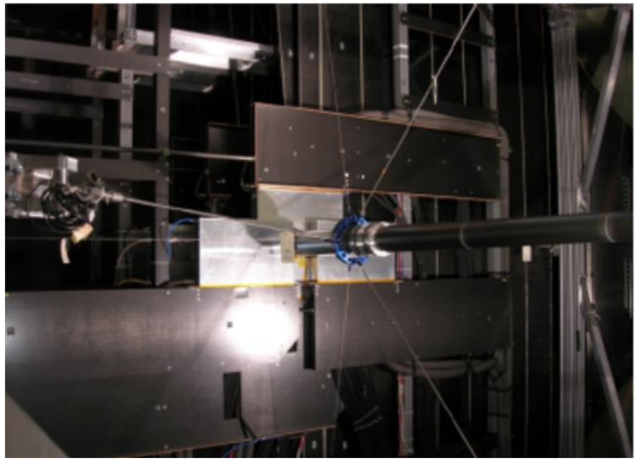
Performance of the LHCb Outer Tracker; JINST 9 (2014) P01002

THE TRACKER AFTER MAGNET

The Inner Tracker (IT)

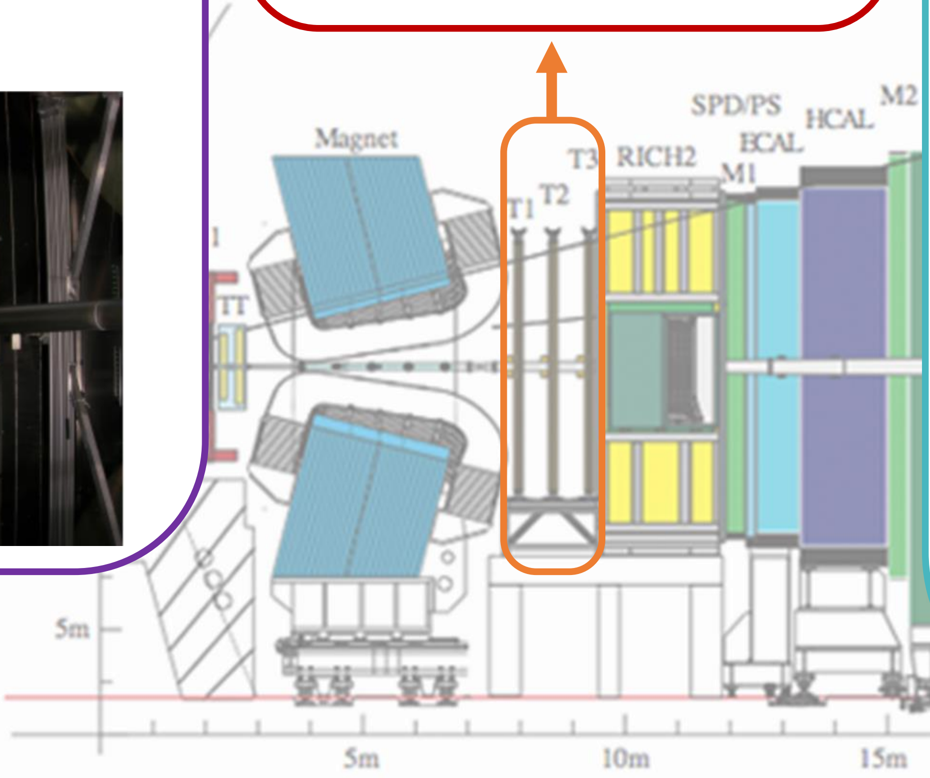
Three stations each with four planes of silicon micro-strip sensors around the beam pipe

- Total silicon area of 4.2 m^2



Tracking performances in Run I:

- **$\Delta p/p$ = 0.5-1%**
- **Tracking eff. > 96%**



Outer Tracker (OT)

Three stations each with four planes (0˚,+5˚,-5˚, 0˚) of straw tubes

- Gas Mixture Ar/CO_2/O_2 (70/28.5/1.5)

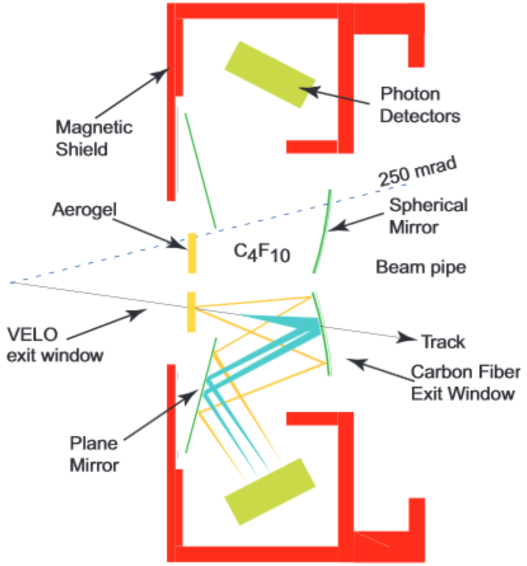
[Performance of the LHCb Outer Tracker; JINST 9 (2014) P01002]

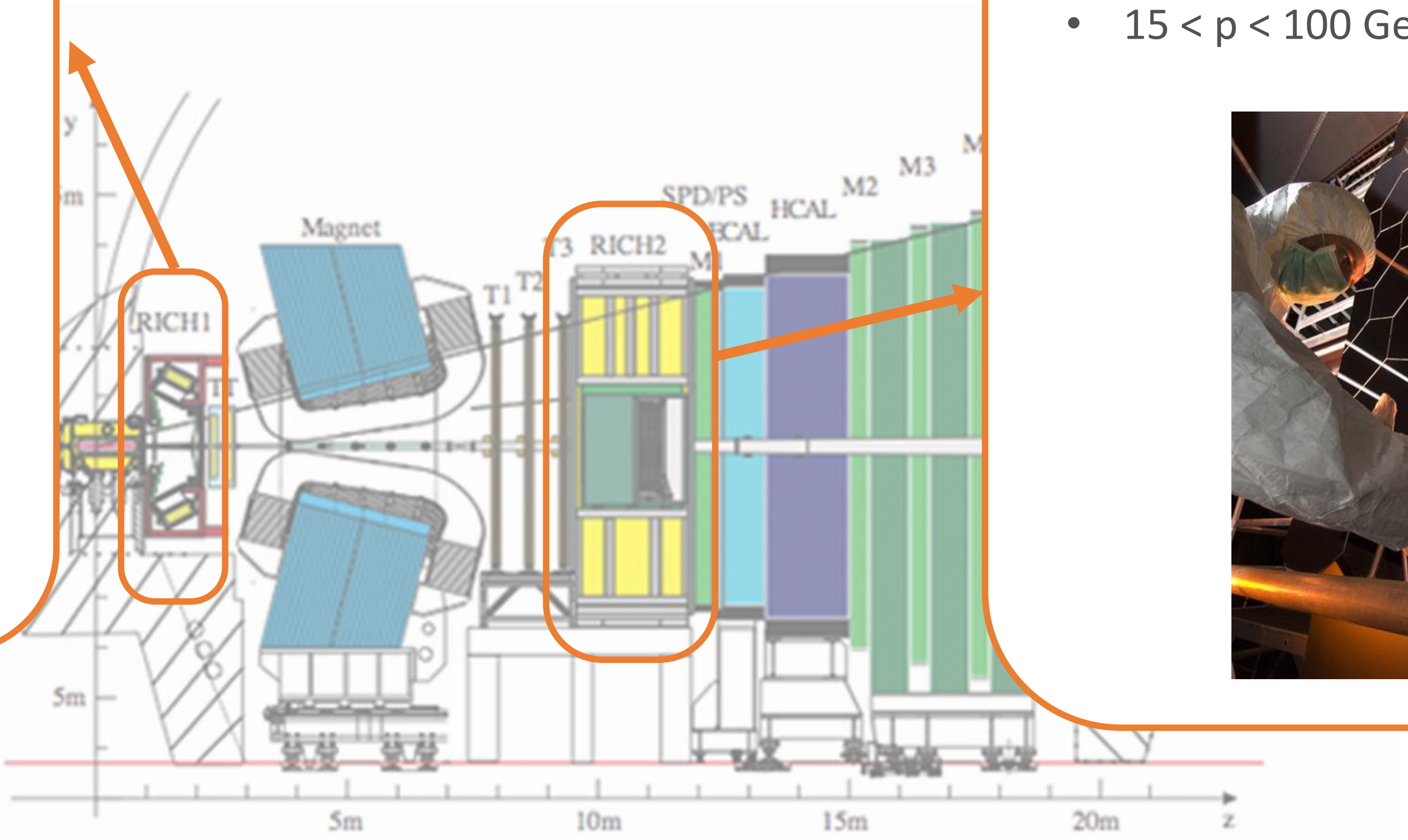
PARTICLE IDENTIFICATION

[Performance of the LHCb RICH detector ad the LHC
Eur.Phys.J. C73 (2013) 2431]

RICH 1

- Upstream of the magnet
- C_4F_{10} radiator
- $10 < p < 65$ GeV/c

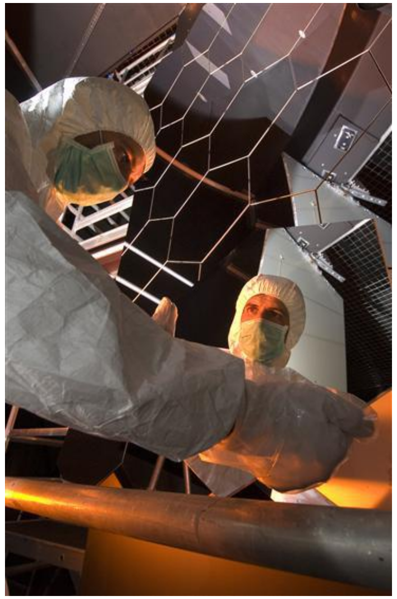




RICH 2

Downstream of the magnet

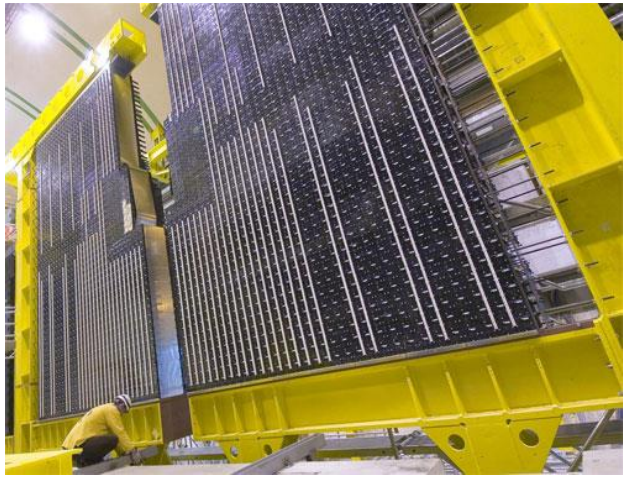
- CF_4 radiator
- $15 < p < 100$ GeV/c



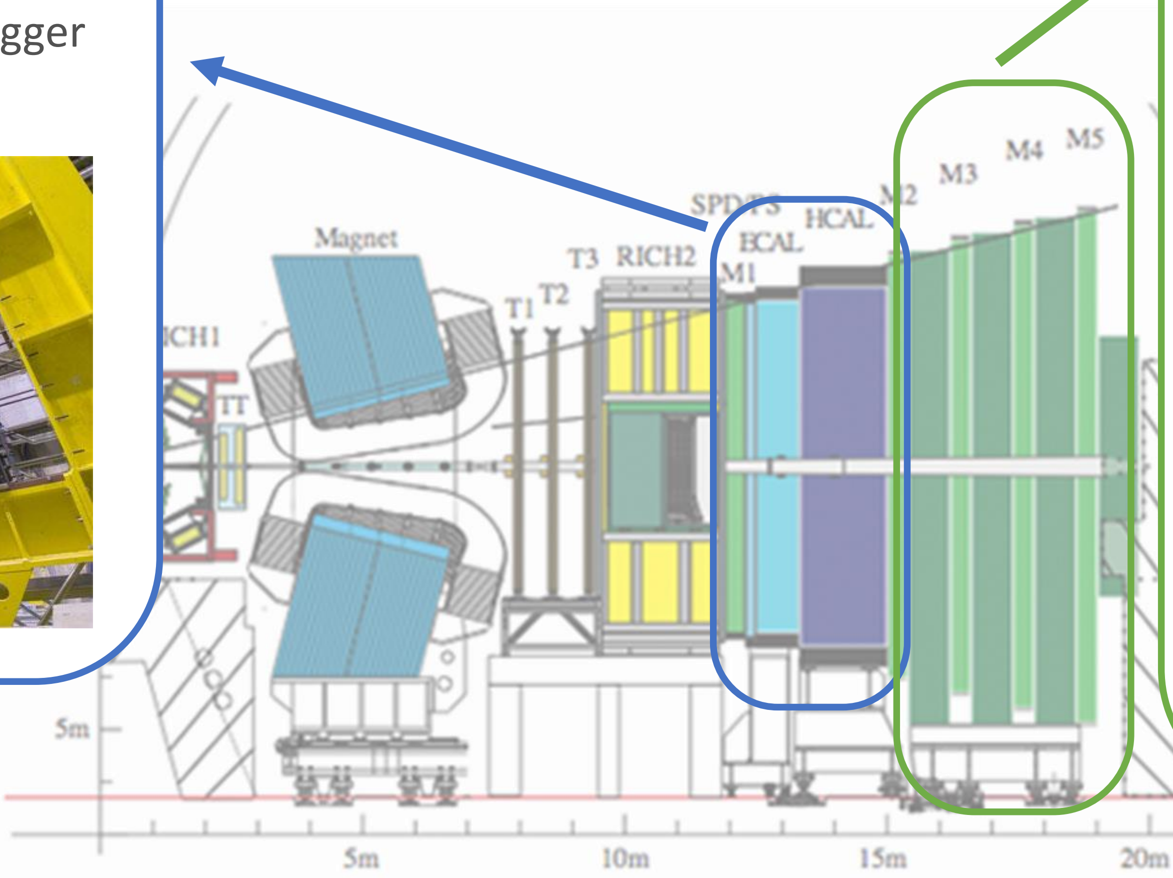
PARTICLE IDENTIFICATION

Electromagnetic CAL & Hadron CAL

- Scintillator planes + absorber material planes
- Used in the hardware trigger (L0) selection



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



MUON CHAMBERS

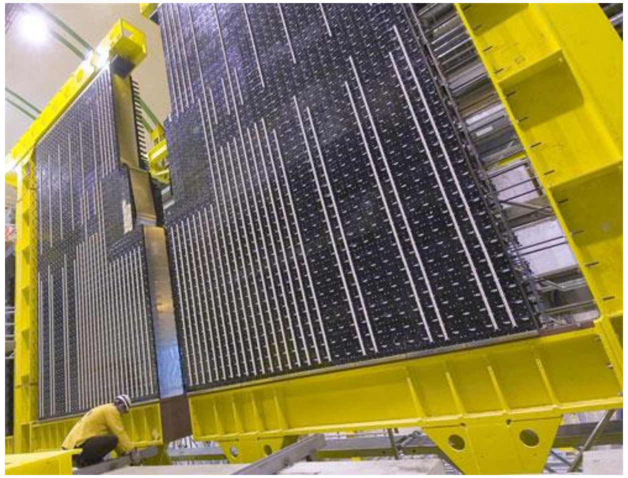
- 5 stations, each equipped with 276 multi-wire proportional chambers
- Inner part of the first station equipped with 12 GEM detectors
- Used in L0 trigger selection

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

PARTICLE IDENTIFICATION

Electromagnetic CAL & Hadron CAL

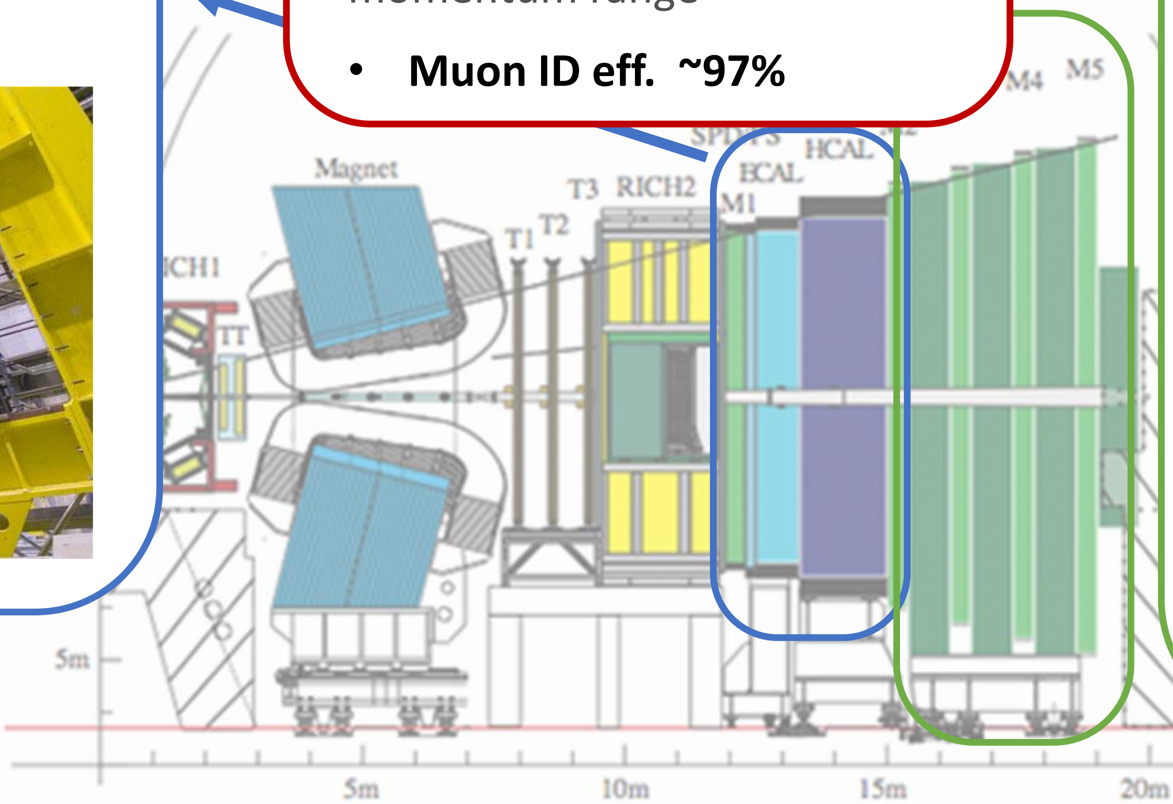
- Scintillator planes + absorber material planes
- Used in the hardware trigger (L0) selection



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

PID performance in Run I:

- **Kaon ID eff. ~95%**
- **Pion mis-ID** fraction of **~10%** over the full 2-100GeV/c momentum range
- **Muon ID eff. ~97%**



MUON CHAMBERS

- 5 stations, each equipped with 276 multi-wire proportional chambers
- Inner part of the first station equipped with 12 GEM detectors
- Used in L0 trigger selection

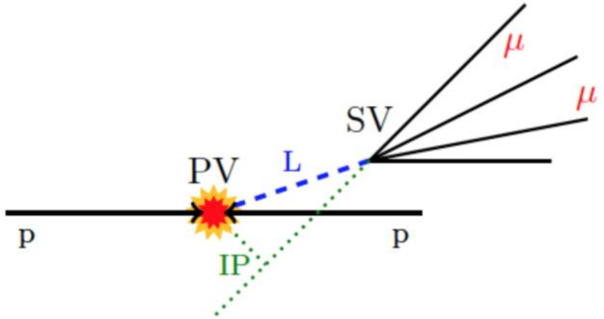
[Performance of the Muon Identification system JINST 8 (2013) P10020]

TRIGGER PRINCIPLES

BEAUTY SIGNATURES

- Mass m$(B^+) = 5.28$ GeV
- Daughter p_T $\mathcal{O}(1$ GeV$)$
- Lifetime $\tau(B^+) \sim 1.6$ ps
- Flight distance ~ 1 cm
- Common signature: detached $\mu\mu$
  $B \to J/\Psi(\to \mu\mu)X$

45 kHz



1 MHz

CHARM SIGNATURES

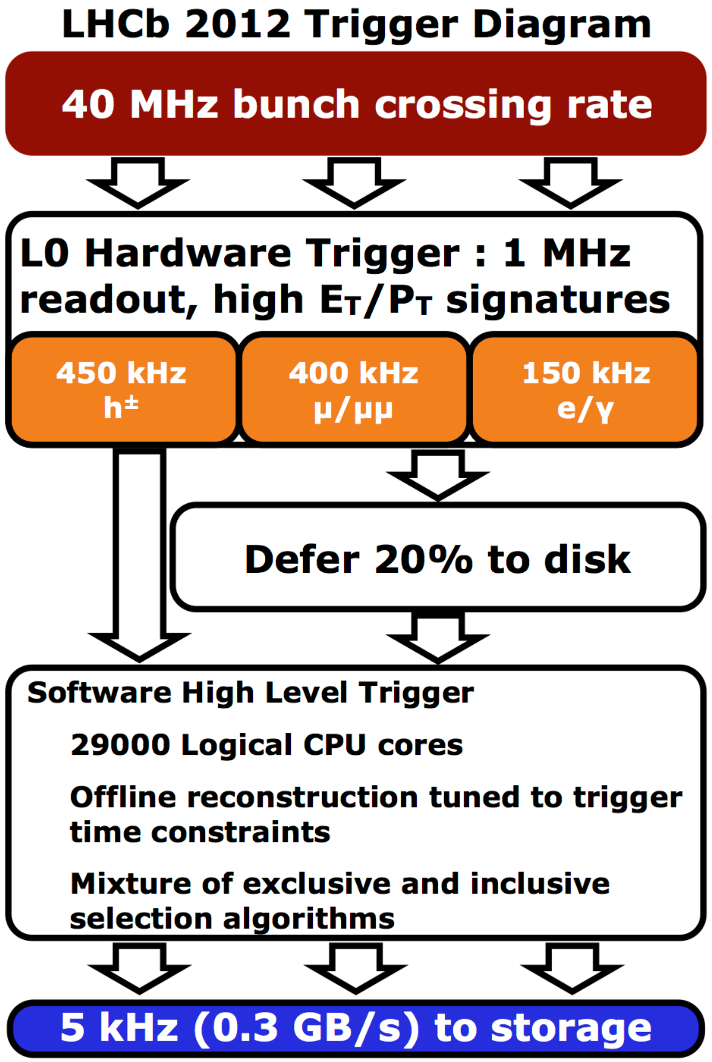
- Mass m$(D^0) = 1.86$ GeV
- Sizeable daughter p_T
- Lifetime $\tau(D^0) \sim 0.4$ ps
- Flight distance ~ 4 mm
- Can be produced in B decays

For LHCb, **more data is more important than higher energy**

- **Direct searches:** more energy $\rightarrow$ new particles could appear above threshold.
- **Indirect searches:** precision measurement $\rightarrow$ gain from increased production rates.

- However, digesting more data is a **challenge**

TRIGGER CONFIGURATION IN RUN I



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

Hardware trigger (L0): LHCb detector read out at 1 MHz

- Based on multiplicity, calorimeters and muon detectors.
- Fixed latency of 4 μs.
- Reduces rate to 1 MHz.

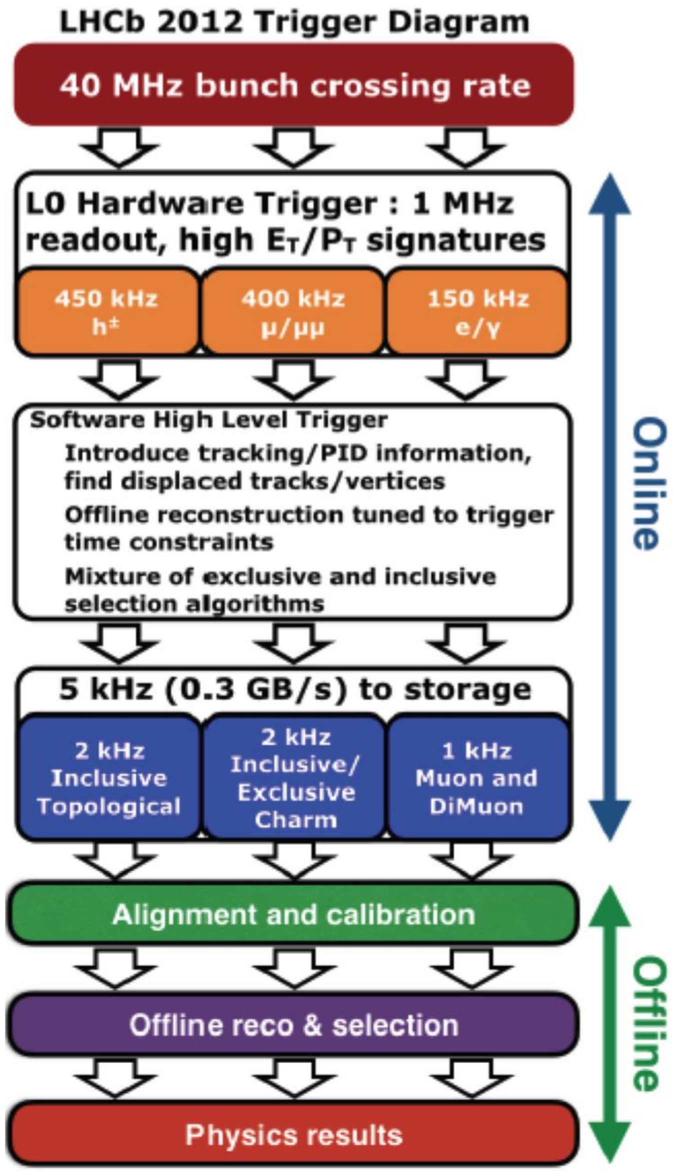
Software trigger (HLT): Runs on HLT farm Split in two stages

1. **HLT1** performs a partial event reconstruction and an inclusive selection of signal candidates.

1. **HLT2**
   - **full simplified** event reconstruction
   - Output rate 5 kHz

- In 2012 introduced the deferred trigger: keep the trigger farm busy between fills
- Total time budget $\mathcal{O}(35)$ ms/event

OFFLINE & ONLINE RECONSTRUCTION



Online reconstruction:

- Best possible within CPU budget
- Preliminary alignment and calibration of the detector
- Faster but less performing track and PID reconstruction (only part of the PID information available)

Offline reconstruction:

- Best performance regardless of CPU Differences
- Full and best performing detector alignment and calibration
- Full reconstruction including full PID information

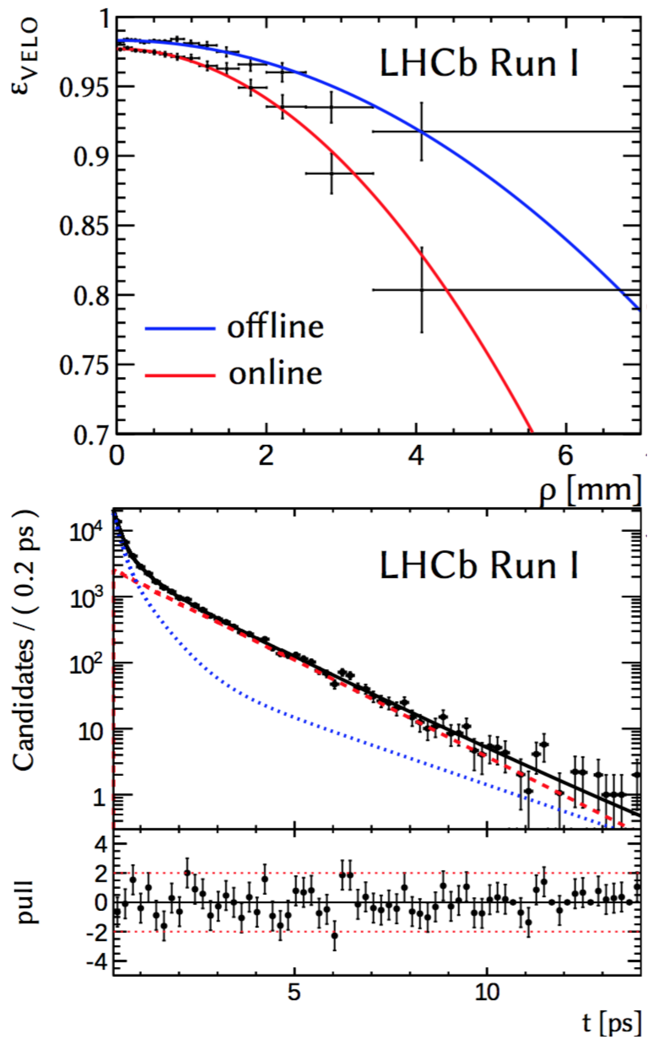
$\boxed{\text{Trigger} \neq \text{Offline}}$

Disadvantages of this model

- Takes time: alignment and calibration applied after data taking, reconstruction run twice.
- Costs money: uses a lot of computing resources;
- Costs physics: loss of imperfectly reconstructed data in trigger.

OFFLINE & ONLINE RECONSTRUCTION

Run 1 example:
Lifetime measurement



JHEP 04(2014)114

Online reconstruction:

- Best possible within CPU budget
- Preliminary alignment and calibration of the detector
- Faster but less performing track and PID reconstruction (only part of the PID information available)

Offline reconstruction:

- Best performance regardless of CPU Differences
- Full and best performing detector alignment and calibration
- Full reconstruction including full PID information

Trigger ≠ Offline

Disadvantages of this model

- Takes time: alignment and calibration applied after data taking, reconstruction run twice.
- Costs money: uses a lot of computing resources;
- Costs physics: loss of imperfectly reconstructed data in trigger.

NOVEL CONCEPT IN HEP

Do physics directly on the HLT output!

Advantages:

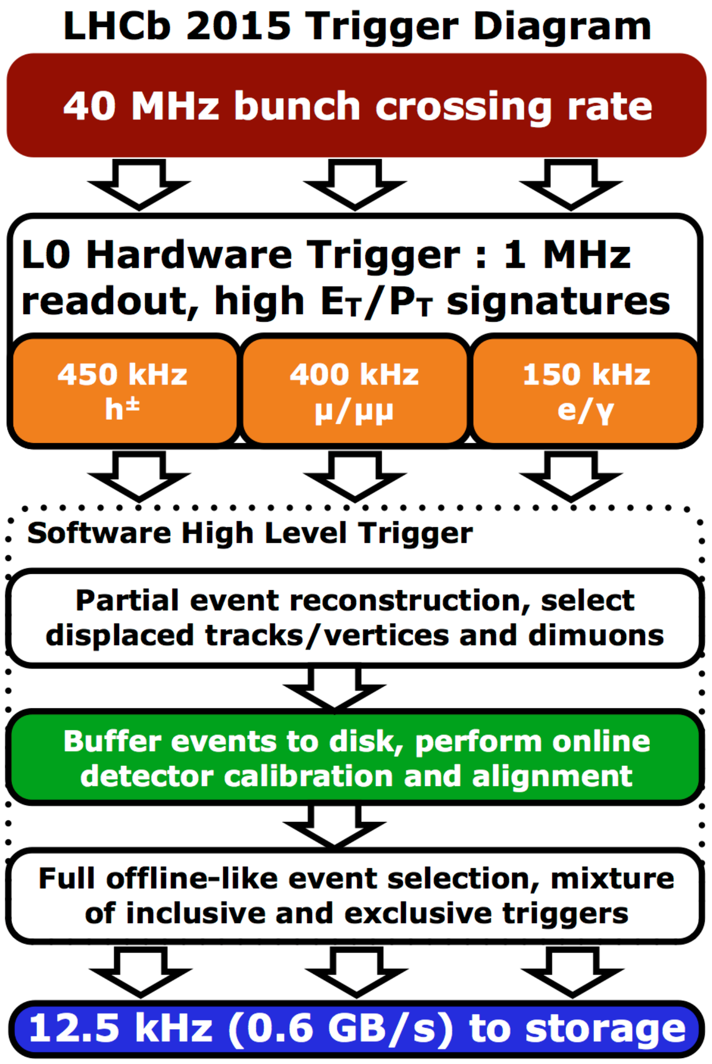
- **Same reconstruction online and offline**
- No need of offline data processing (data available ~ immediately after HLT2 has processed them)
- Save only candidates used in the trigger → possibility to reduce the pre-scaling of high branching ratio channels (like for charm physics)

→ **Do much more physics with the given resources!**

But, it is a difficult challenge:

- Do the full reconstruction in few hundreds ms achieving offline performance (same or better than in Run I)
- Managing to do the full alignment and calibration of the detectors in real-time
- Being able to select efficiently many signals already at trigger level

TRIGGER CONFIGURATION IN RUN II



- Same L0 hardware trigger as in Run I, with higher thresholds
- HLT software 40% faster
- **All events are buffered to disk** before running second software level of trigger

- Stable beams 30-70(!)% of the time
- Buffer events to allow for out of fill processing
- 5 PB (10 PB) buffer on local disks in 2015(2016)

It gives us enough time to:

- Perform calibration of PID detectors and alignment of the full tracking system in real-time
  → **Same alignment and calibration constants online and offline**

- Last trigger level runs the offline-quality reconstruction
  → **Same full reconstruction online and offline: best performance**

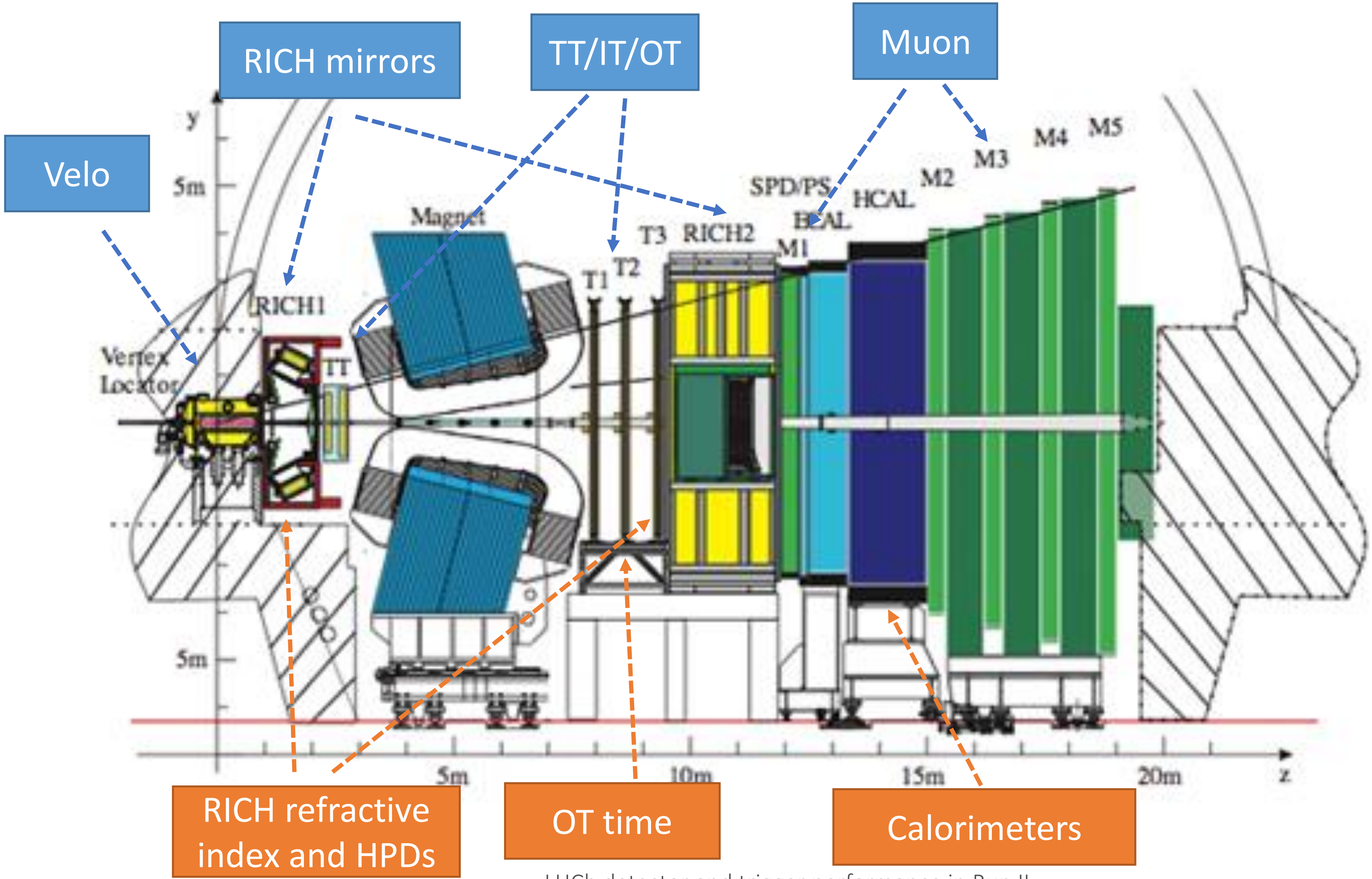
Trigger = Offline

- Output rate 12.5 kHz

ALIGNMENT AND CALIBRATION IN RUN II

Same online and offline reconstructions requires prompt alignment and calibration:

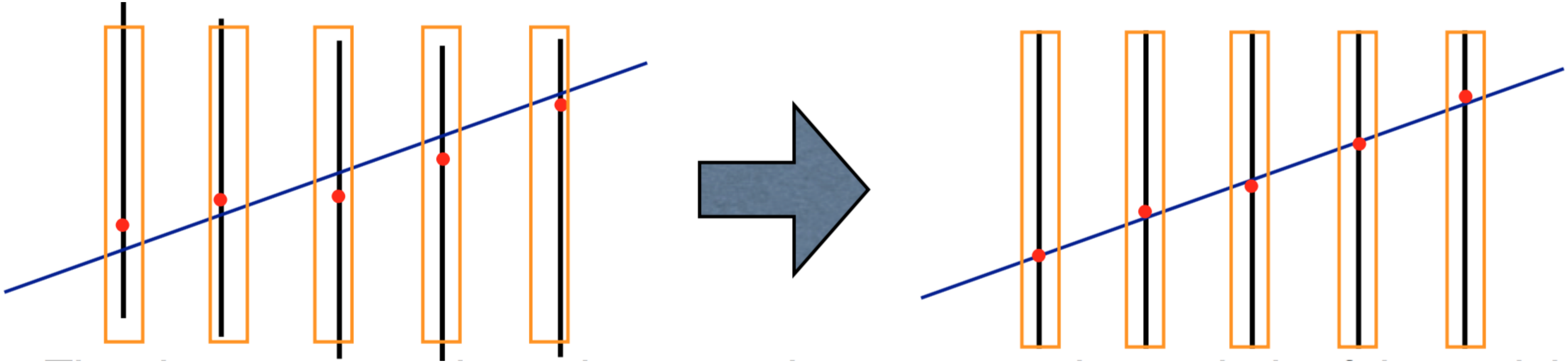
Alignments



Calibrations

TRACKER ALIGNMENT IN RUN II

Alignment is evaluated by **minimizing the residuals of the track hits**



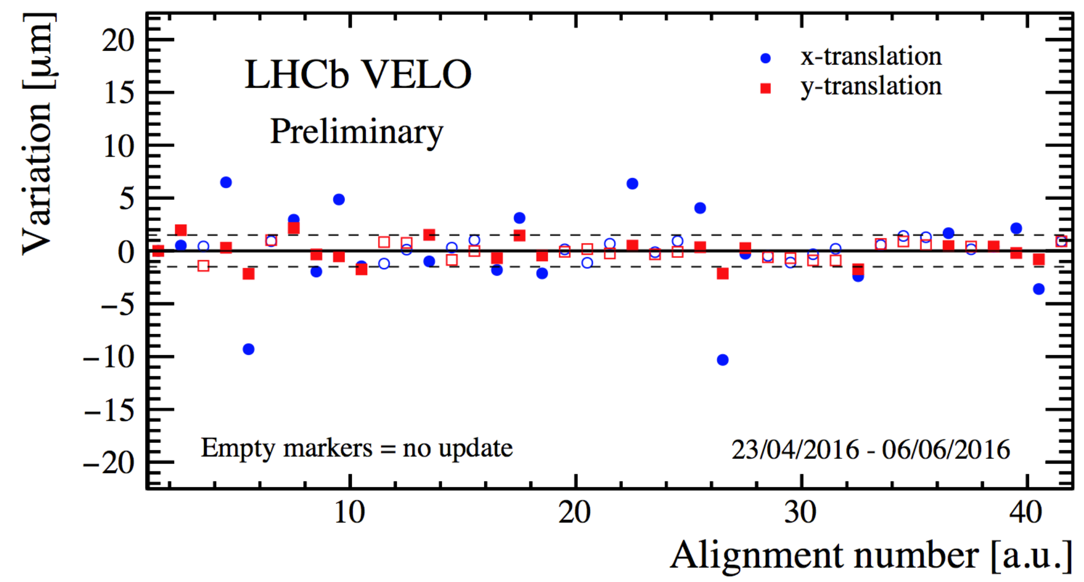
- Automatic evaluation at regular intervals, once per fill
- Dedicated data sample collected with specific trigger selection line for each system, e.g. $D^0 \rightarrow K^+\pi^-$ for Tracker and $J/\Psi \rightarrow \mu^+\mu^-$ for Muon system.
- Compute the new alignment constants in few minutes after enough data is collected
- Update the constants only if needed
- **The same new alignment constants are used both by the trigger and the offline reconstruction**

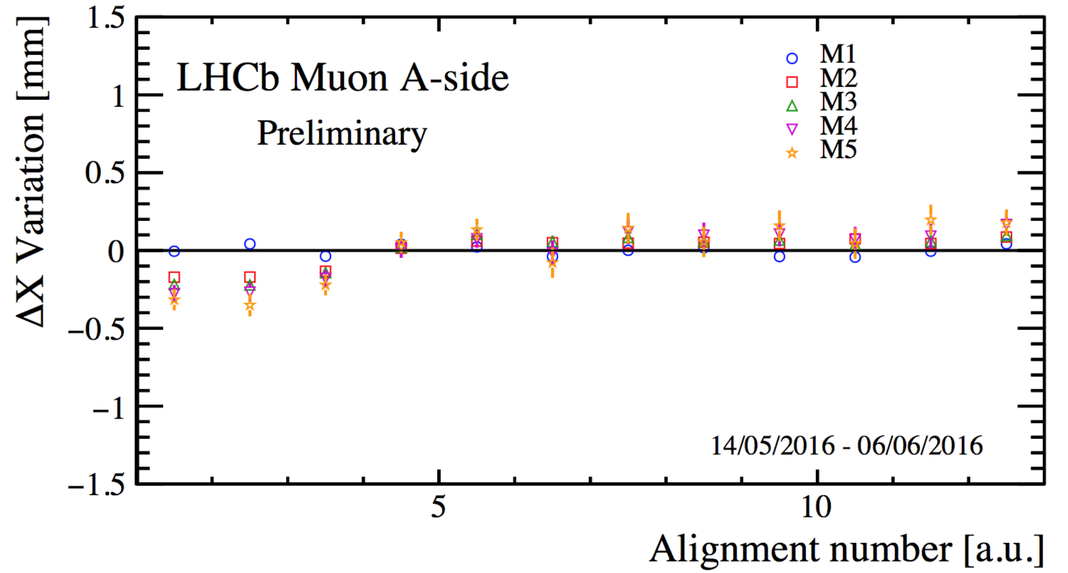
TRACKER ALIGNMENT IN RUN II

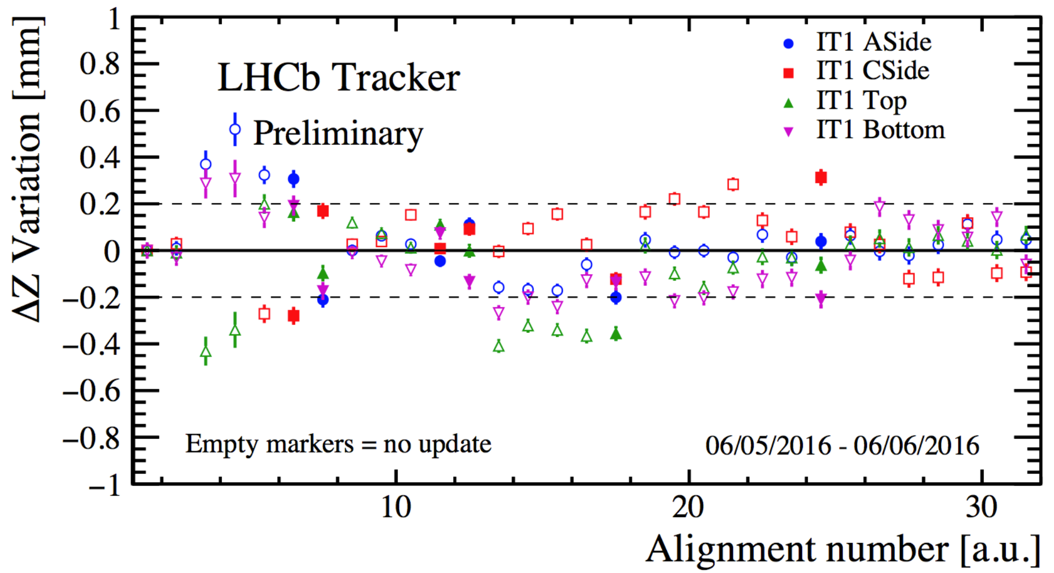
New plots from 2016!

- **~ 700 elements to be aligned** for translations and rotations. Each task takes ~7 minutes

1. **VELO** updates every 2-3 fills.
2. **Tracker (TT, IT, OT)** updates every several fills and at magnet polarity change.
3. **Muon** runs as monitoring, constants updated only after hardware intervention.





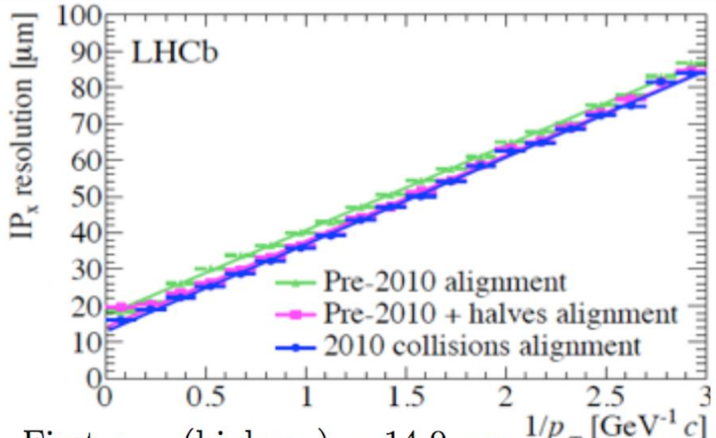


ALIGNMENT IMPORTANCE

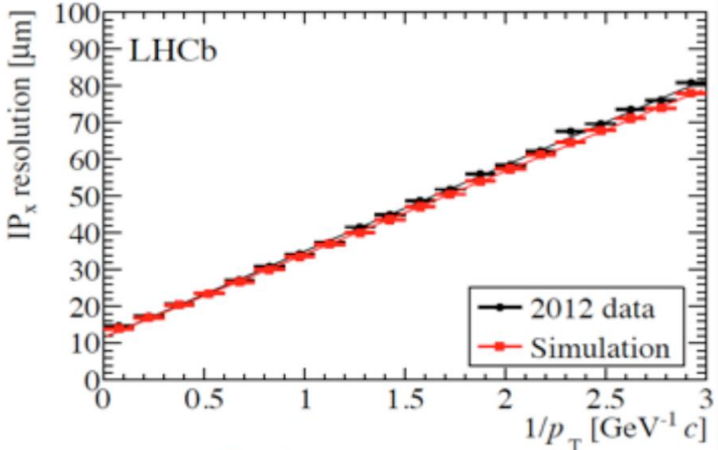
Physics performance relies on spatial alignment and calibration of the detector

- Examples: VELO alignment is essential for PV discrimination, **IP and proper time resolution**, **better alignment improves mass resolution**, **use of PID allows for more exclusive selections**

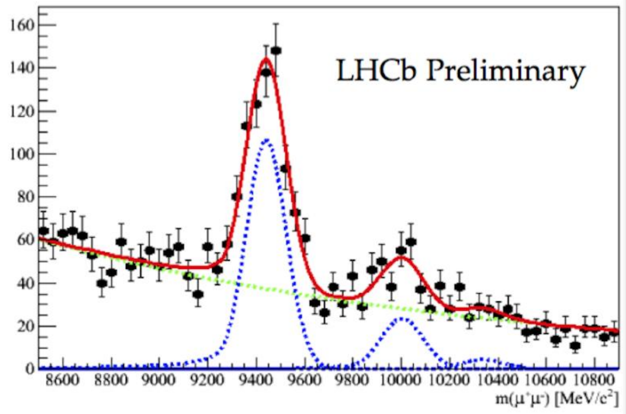
JINST 9, 09007 (2014).



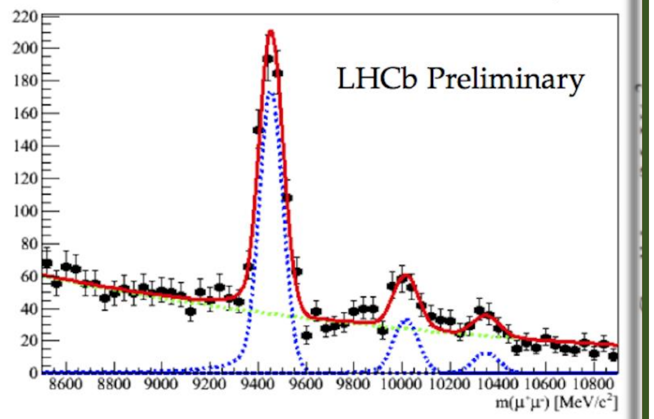
First σ_{IP} (high p_T) = 14.0 μm



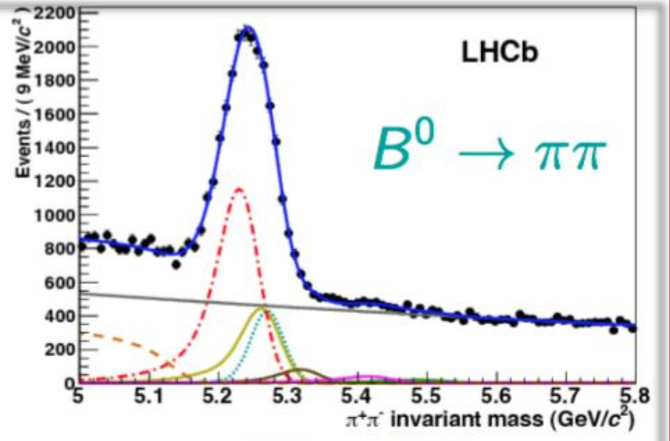
Latest σ_{IP} (high p_T) = 11.6 μm



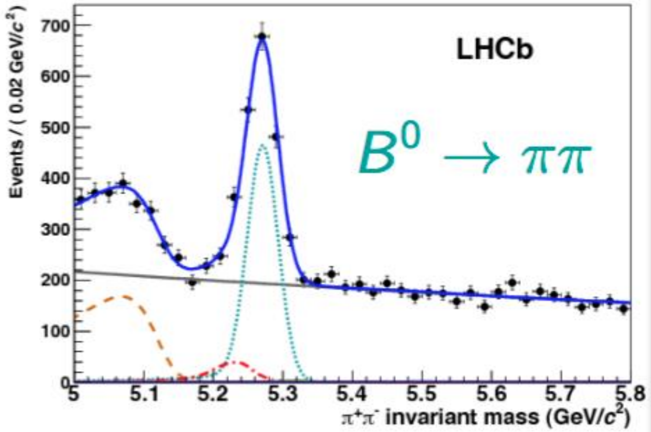
First alignment σ_{Υ} = 92 MeV/c^2



Latest alignment σ_{Υ} = 49 MeV/c^2



Without PID



With PID

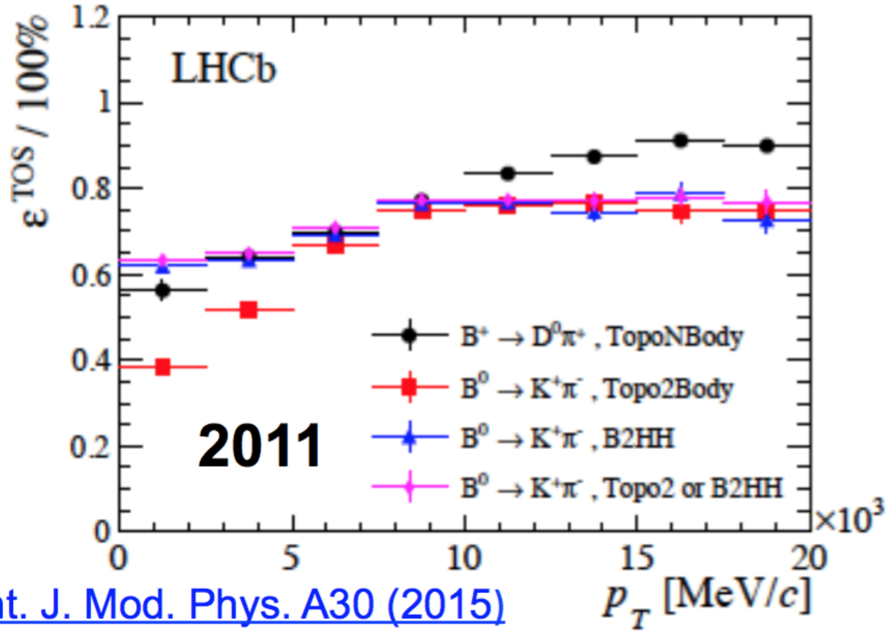
JHEP 1210 (2012) 037

TRIGGER PERFORMANCE

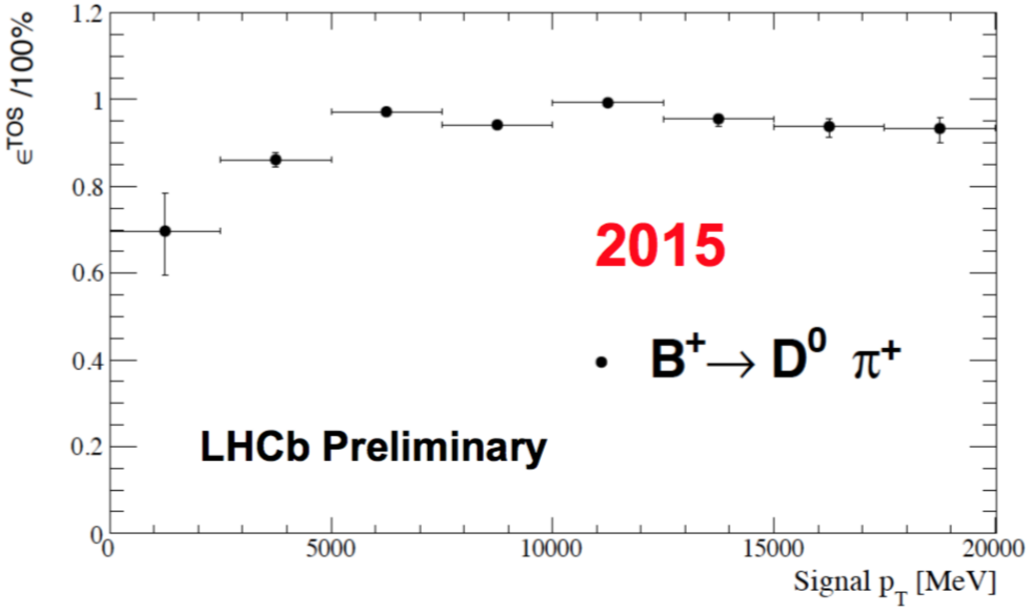
Improvement of the trigger efficiency thanks to e.g.

- 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)

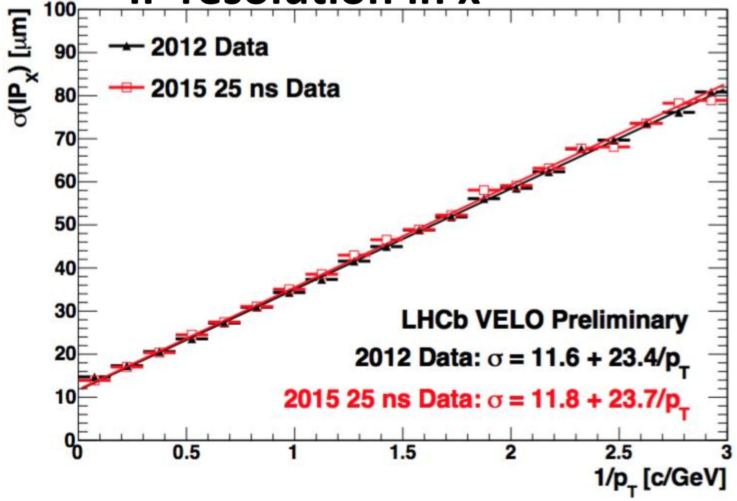


Efficiency for $B^+ \to D^0\pi^+$ is ~75% Run II **Efficiency for $B^+ \to D^0\pi^+$ is >90%**

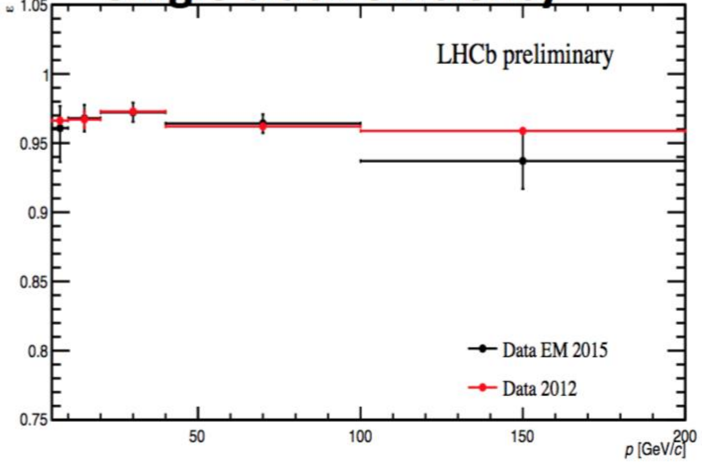
RUN II DETECTOR PERFORMANCE

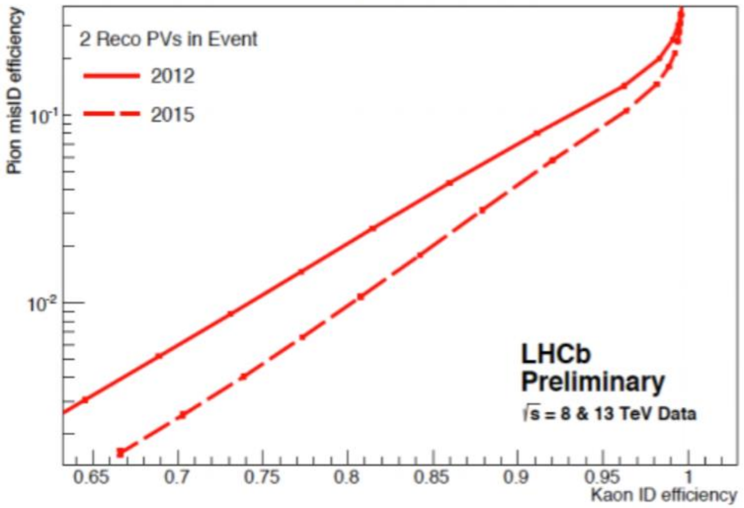
Same or better than offline performances for tracking and PID in Run I but directly at trigger level!!!

IP resolution in x



Single track efficiency





[Int. J. Mod. Phys. A30 (2015) 1530022](#)

Pion misID eff. vs Kaon ID eff.

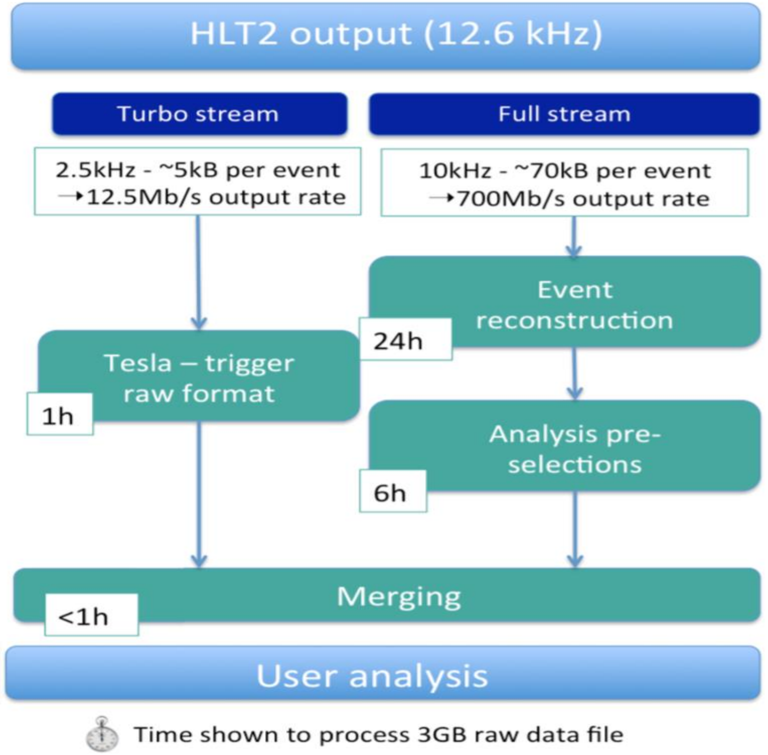
TURBO AND TURBO++

Part of the physics programme needs billions of recorded candidates (e.g. charm analyses): but with no need for the rest of the event.

Solution → **"TURBO" STREAM**

Saves candidates directly after the trigger:

- Reduced event size:
    - **~5 kB** vs ~70 kB
- No need of offline reconstruction: **possible to perform analysis immediately after data taking**
- Dedicated ~2.5 kHz of the output (10 kHz for full)



Persistency of the Reconstruction info for the Full, in addition to those selected by the trigger

- Plus higher level variables (i.e. hits in a cone region around the track) available for few lines.

Out of the 420 HLT2 lines in 2016, 150 choose Turbo.

Turbo++ New in 2016!!

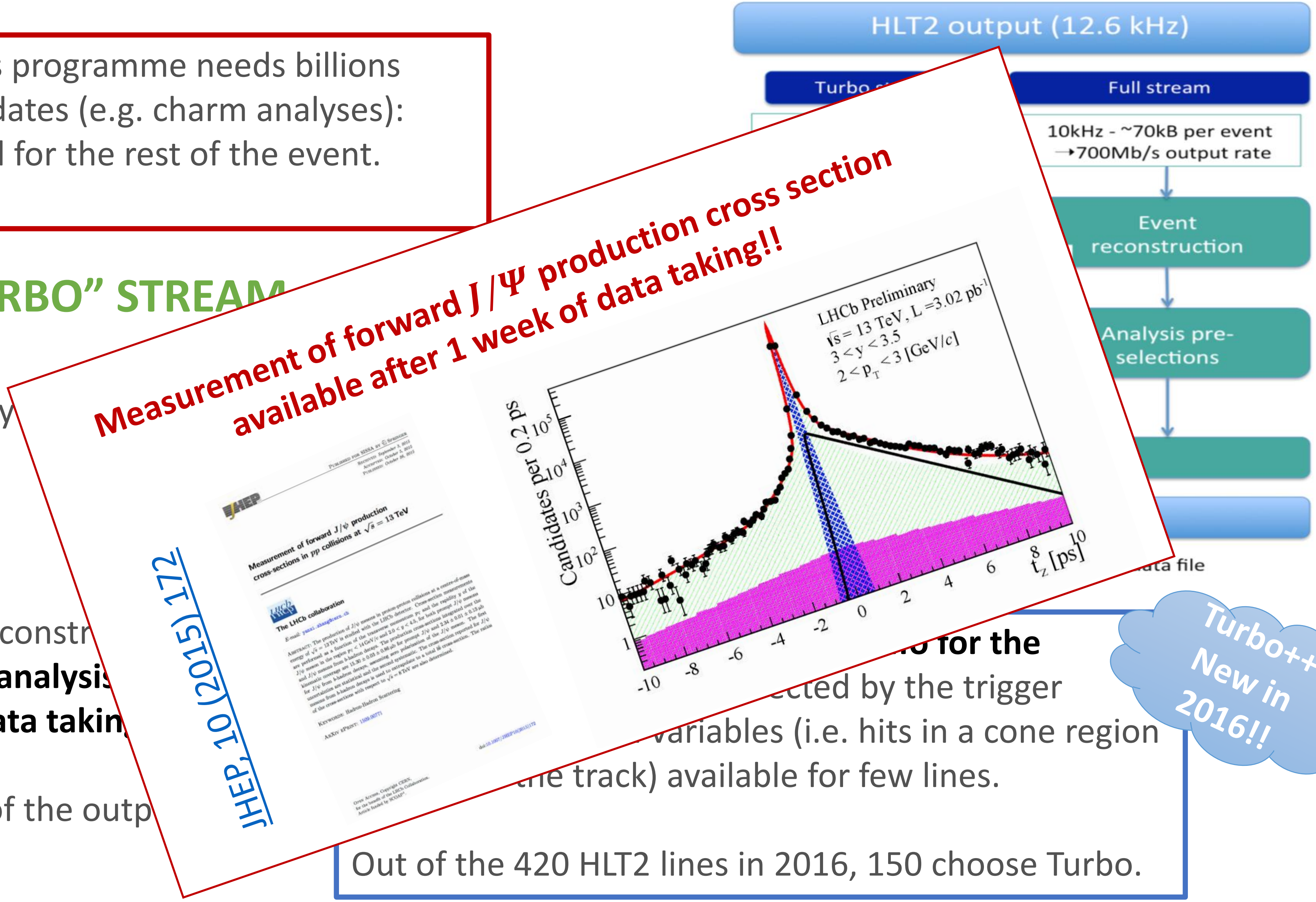
TURBO AND TURBO++

Part of the physics programme needs billions of recorded candidates (e.g. charm analyses): but with no need for the rest of the event.

Solution **"TURBO" STREAM**

Saves candidates directly

- Reduced event size:
  - **~5 kB** vs ~70 kB
- No need of offline reconstr **possible to perform analysis immediately after data takin**
- Dedicated ~2.5 kHz of the outp (10 kHz for full)



...o for the ...cted by the trigger ...variables (i.e. hits in a cone region ...he track) available for few lines.

Out of the 420 HLT2 lines in 2016, 150 choose Turbo.

Turbo++ New in 2016!!

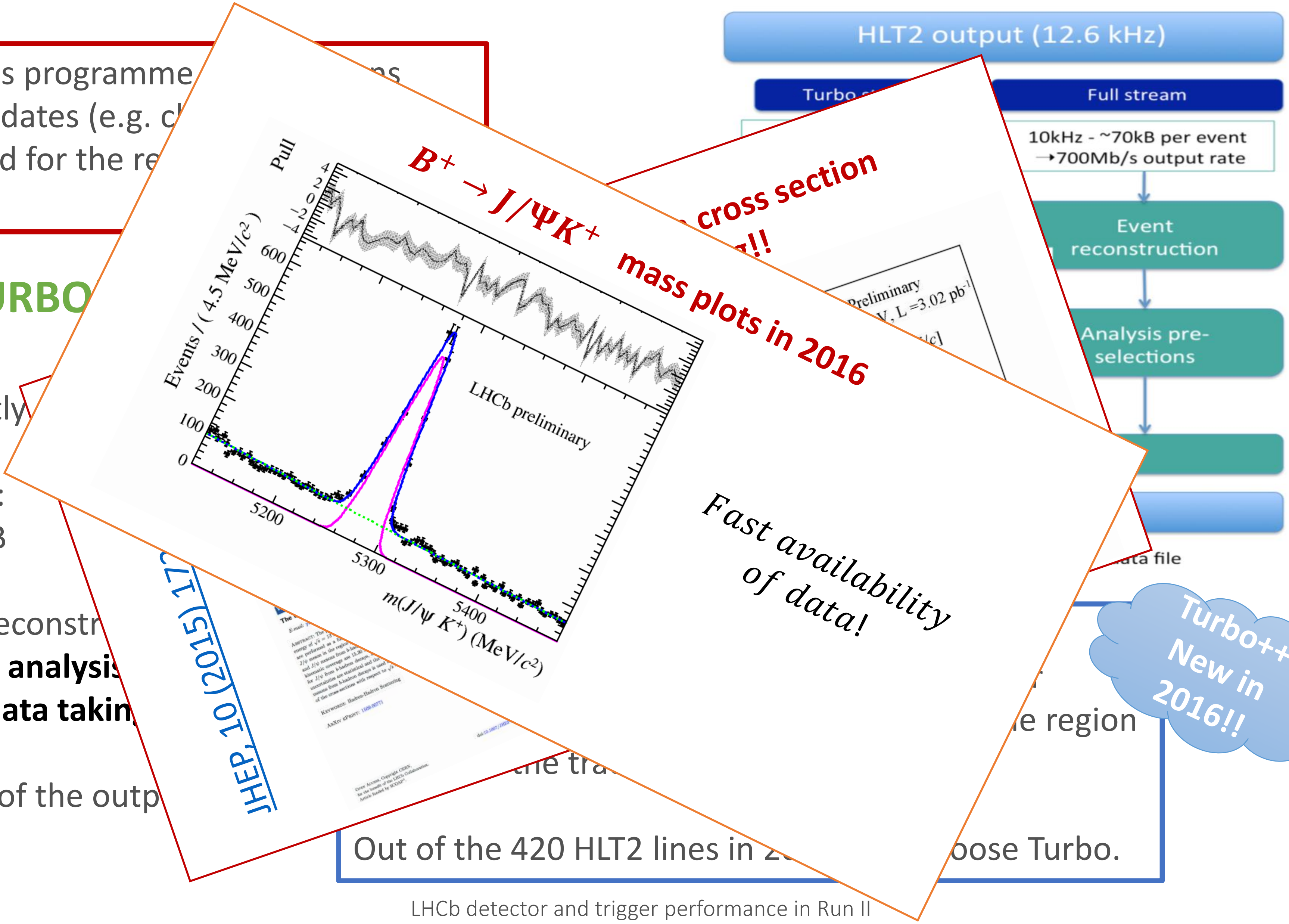
TURBO AND TURBO++

Part of the physics programme ... ns
of recorded candidates (e.g. c...
but with no need for the re...

Solution "TURBO

Saves candidates directly

- Reduced event size:
  - **~5 kB** vs ~70 kB
- No need of offline reconstr... **possible to perform analysis immediately after data takin...**
- Dedicated ~2.5 kHz of the outp... (10 kHz for full)



...e region
...the tra...

Out of the 420 HLT2 lines in 2... ...oose Turbo.

Turbo++ New in 2016!!

CONCLUSIONS

Completely revised strategy implemented at LHCb for Run II:

LHCb is the first HEP experiment with a full calibration, alignment and reconstruction done in real-time!

- Run I offline performances are already achieved in the trigger;
- Turbo increase our physics program using same resources, allowing to make analyses ~24h after data taking;
- **New development for 2016**: Turbo++. o choose how much, and which variables of the events to be computed and saved according to the physics measurement;
- Not the end of the story: working on improving and speeding up

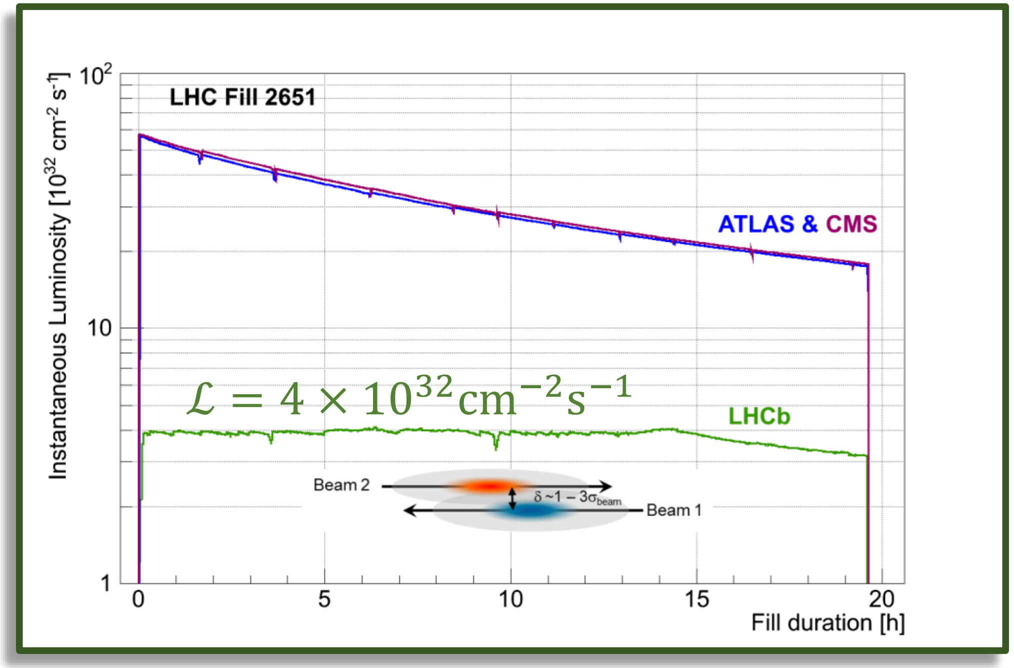
  the reconstruction, alignment, calibration and data processing.

- Coming also soon: **upgrade**!

Thanks for your attention!

Backup slides

DATA TAKING

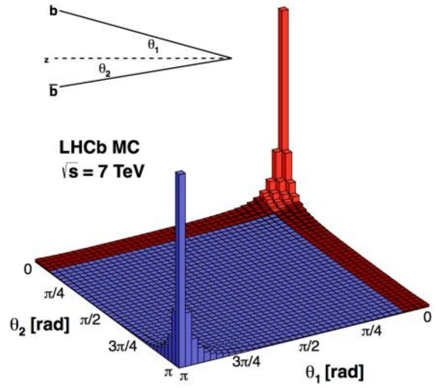


Luminosity levelling

Stable running and trigger conditions for LHCb even with LHC running at high luminosity.

Achieved changing the beam focus before collisions.

Extremely large σ(bb) and σ(cc) in LHC hadron collisions.

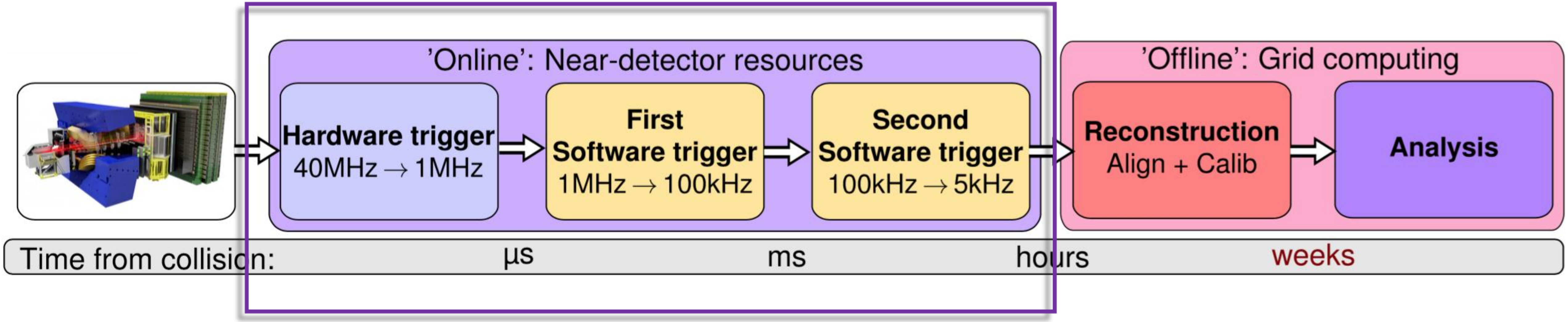


Conditions for Run 2:

- σ(bb) ~ 45 kHz and σ(cc) ~1MHz, at 13TeV in acceptance [HF cross section ~2× with respect to Run 1]
- Bunch spacing 25ns (smaller pileup)
- Almost same luminosity

DATA PROCESSING IN RUN I

LHCb processed data similar to the other LHC experiments:



Disadvantages of this model

- Takes time: alignment and calibration applied after data taking, reconstruction run twice.
- Costs money: uses a lot of computing resources;
- Costs physics: loss of imperfectly reconstructed data in trigger.

ALIGNMENT IN RUN II

ALIGNMENT

New dedicated framework allows

- Parallelization of the event reconstruction on ~1700 nodes of the trigger farm
- Perform the minimization of χ^2on a single node
- Iterative process
- Update the alignment constants as soon as they are available, if needed

Tracks reconstruction using current align. constants

Iterate until χ^2 is below threshold.

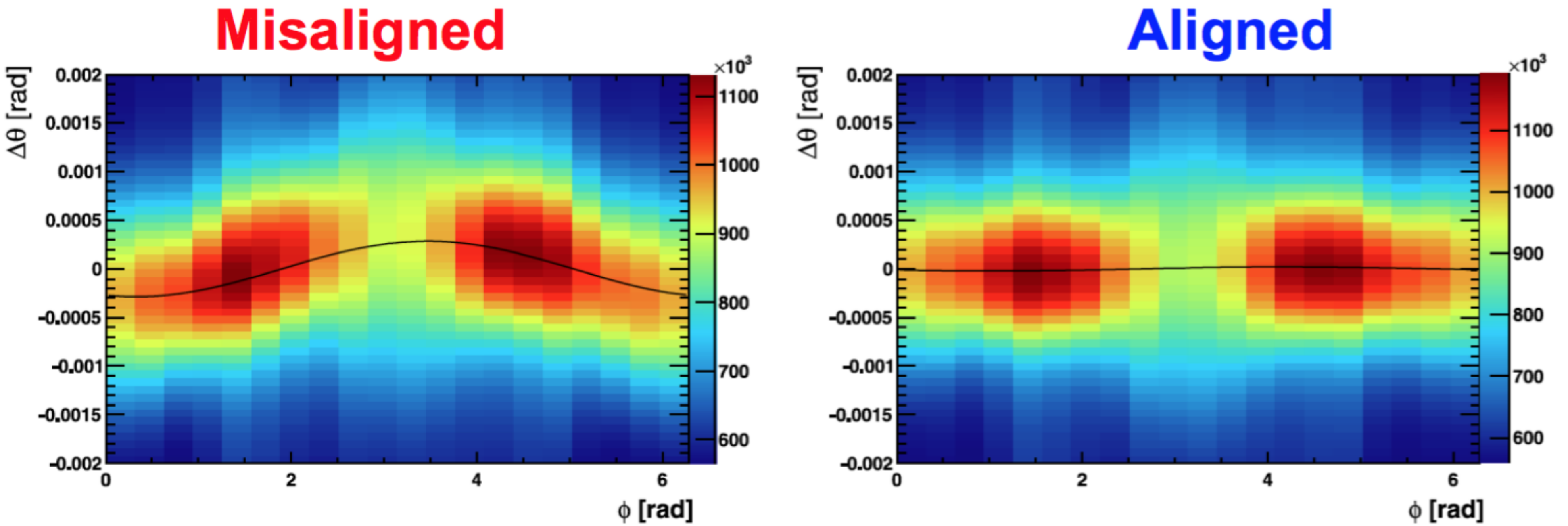
Compute a new set of constants by minimizing a global

RICH 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**

New for 2016:
Optimization and speed up!

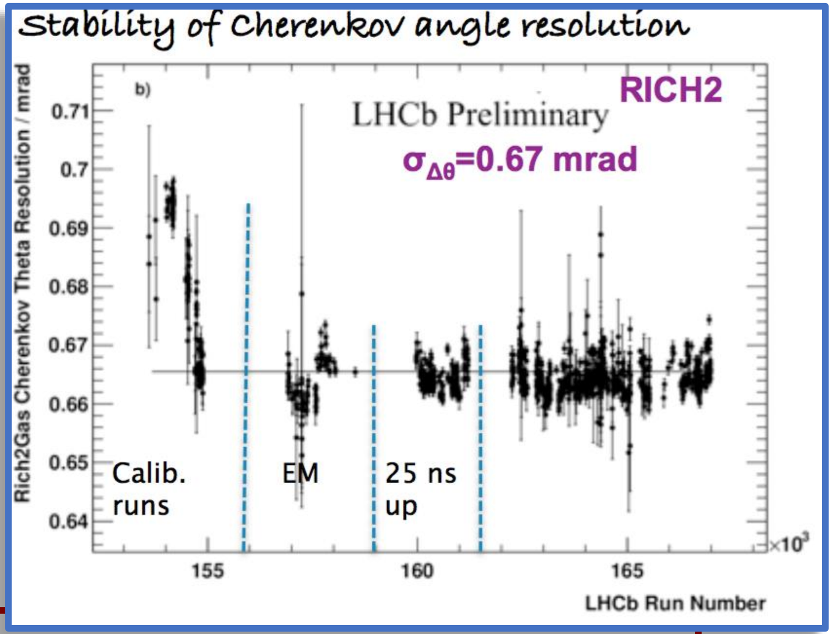
Runs only as monitoring every fill

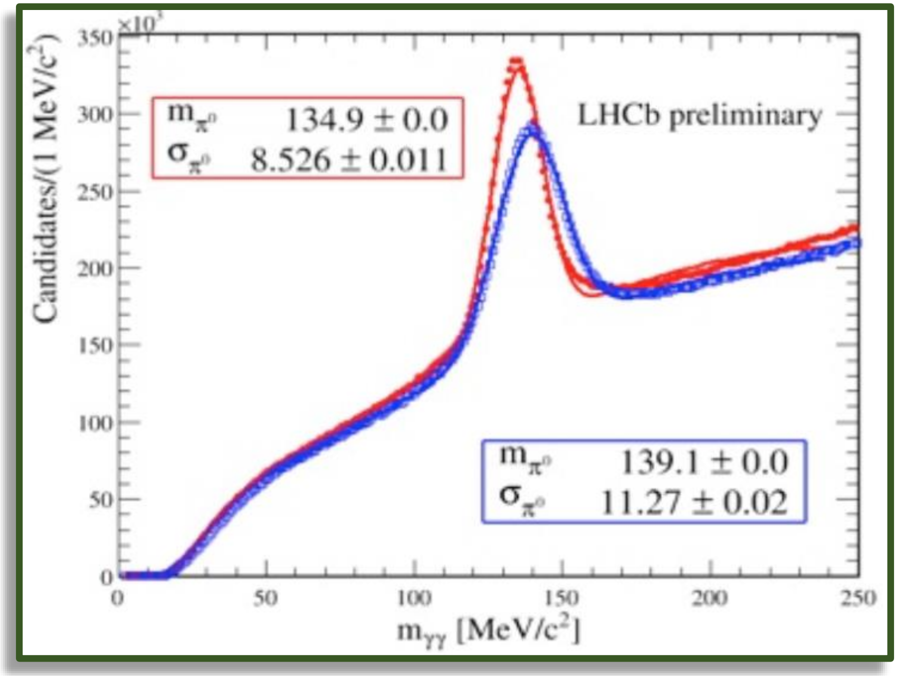


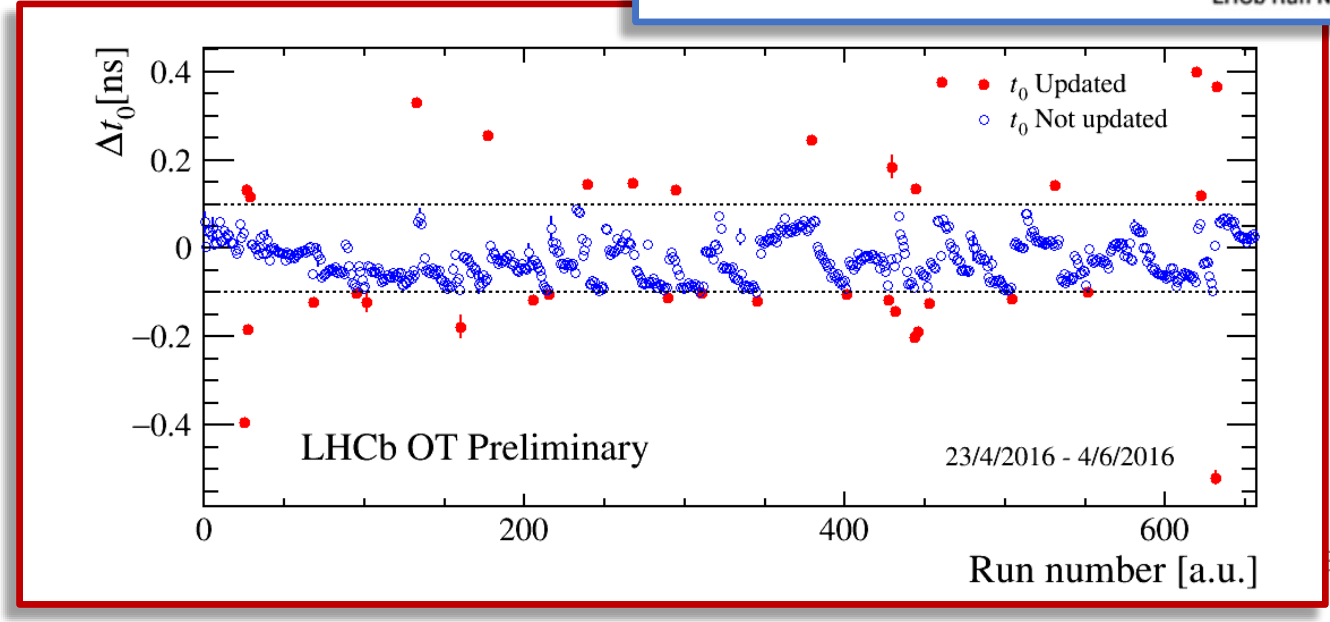
CALIBRATION

Calibrations run on the monitoring histograms for ~every run

- **OT calibration**: global time alignment of the OT wrt LHC clock
- **RICH**: refractive index calibration and HPD image calibration
- **Calorimeter** calibrations run on monitoring histograms for ~every fill **[stable L0 conditions]**







OPTIMIZATION OF RECONSTRUCTION IN RUN II

New resources: farm nearly doubled wrt Run I, 10PB disk space to buffer the events between HLT1 and HLT2

- Big effort in speeding up the reconstruction:
  - Code optimization (vectorization, memory access)
  - New reconstruction chain in HLT1 and simplified geometry in Kalman filter
  - Re-implementation and/or re-tuning of the algorithms (HLT1 and HLT2)
  - Run I offline reconstruction 2 times faster

Offline Run I reconstruction can run in the Trigger in Run II, with same or better performance!!