NOVEL REAL-TIME ALIGNMENT AND CALIBRATION AND TRACK RECONSTRUCTION FOR THE UPGRADE AT THE LHCb DETECTOR.

ACAT 2016

RENATO QUAGLIANI ON BEHALF OF THE LHCb COLLABORATION

LAL ORSAY (FR) AND BRISTOL UNIVERSITY (UK).

VALPARAÍSO, CHILE

21/01/2016

LHCb EXPERIMENT

LHCb is a high precision experiment designed to:

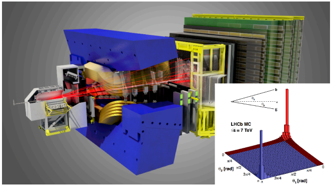
- Measure CP-violation using hadrons containing b and c quarks.
- Indirect searches of new physics trough SM strongly suppressed decay modes.

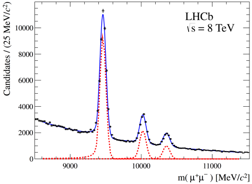
LHCb is a forward spectrometer:

- Heavy hadrons are produced boosted in the forward region: $1.9 < \eta < 4.9$.

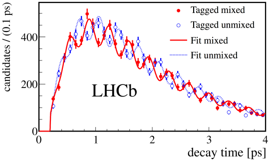
Requirements:

1. **Excellent tracking**(p, impact parameters and σ_{PV}):
   - $\sigma_{IP} \sim 20\ \mu$m.
   - $\epsilon_{\text{tracking}} > 96\%$.
   - $\frac{\delta p}{p} \sim 0.5 - 1.0\%$.
2. **Excellent τ_{decay} resolution**:
   - $\sigma_{\tau_{decay}} \sim 45$ fs for B mesons.
3. **Excellent particle identification (PID)**
   - ϵ_K-ID $\sim 95\%$.
   - ϵ_μ-ID $\sim 97\%$.





[J. High Energy Phys. 06 (2013) 064]



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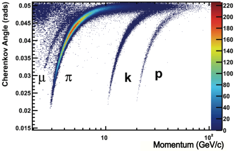
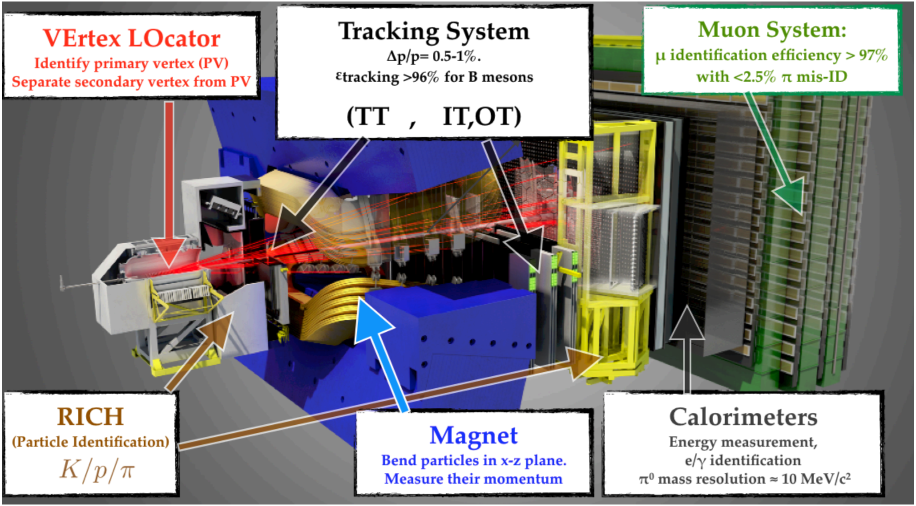


[Eur. Phys. J. C 73 (2013) 2431]

LHCb IN A NUTSHELL



VErtex LOcator
Identify primary vertex (PV)
Separate secondary vertex from PV

Tracking System
$\Delta p/p = 0.5\text{-}1\%$.
$\varepsilon_{tracking} > 96\%$ for B mesons
(TT , IT,OT)

Muon System:
μ identification efficiency > 97%
with <2.5% π mis-ID

RICH
(Particle Identification)
$K/p/\pi$

Magnet
Bend particles in x-z plane.
Measure their momentum

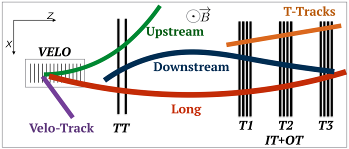
Calorimeters
Energy measurement,
e/γ identification
π^0 mass resolution ≈ 10 MeV/c^2

●LHCb [7] ●VELO [6] ●Tracking system [5] [12] ●Muon System [14] ●RICH [8] ●Magnet [10] ●Calorimeters [9]

TRACKING AT LHCb

Pattern recognition

- **Velo Tracking** : reconstruct tracks in VELO.
- **Forward Tracking** : combine VELO tracks with hits in downstream tracker (IT + OT).
- **Seeding and matching** : segments in IT + OT matched to VELO segment.
- **Add TT hits to long tracks** : add hits after forward.
- **Downstream tracking** : extend segments in IT +OT in TT.
- **Velo-TT tracking** : VELO tracks extended to hits in TT.
  - Provide charge and p estimation.
  - Can be used to reduce timing and reduce search windows in forward.



Long tracks are the most used ones in physics analysis.

Tracking at LHCb : track fitting

- Use Kalman fit for parameter estimation taking into account multi-scattering and energy losses.
- Neural net classifier for fake tracks applied.
- Clone killing procedure for redundancy.

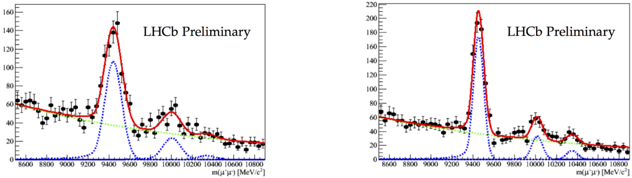
LESSON FROM RUN I: ALIGNMENT IMPORTANCE

Alignment of the detector → achieve best physics performance.

- **Vertex detector alignment crucial to isolate secondary vertices in b and c hadrons decays.** Improve σ_{IP_x}(high p_T) from 14 to 11.6μm.
- **Optimal tracking system alignment → better $\delta p/p$ and mass resolution.**

$m_{\mu^+\mu^-}$ distribution

1st Alignment → Better alignment

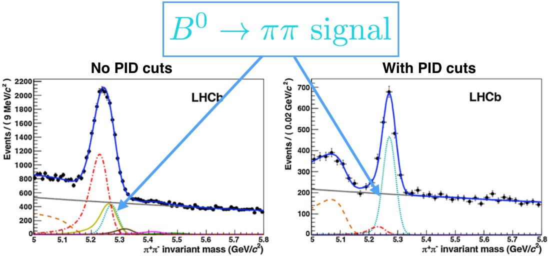


$\sigma_{\Upsilon\rightarrow\mu^+\mu^-} = 92\ \mathrm{MeV/c^2}$ → $\sigma_{\Upsilon\rightarrow\mu^+\mu^-} = 49\ \mathrm{MeV/c^2}$

LESSON FROM RUN I: CALIBRATION IMPORTANCE

Exclusive hadron selections (*PID*) require the full calibration of the RICH detectors.

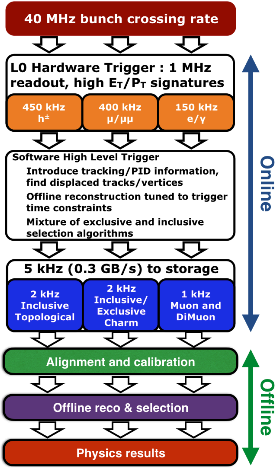
- Improve purity and mass resolution.
- Higher performance of online selection, especially for tighter selection (e.g. exclusive selection of $D^0 \to K^-\pi^+$ candidates).
- **PID requirements allow exclusive selection and optimization of the rate.**


$B^0 \to \pi\pi$ signal

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,
$B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)

LHCb TRIGGER IN RUN I

LHCb 2012 Trigger Diagram



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

Introduce tracking/PID information, find displaced tracks/vertices

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

Alignment and calibration

Offline reco & selection

Physics results

Run I Strategy

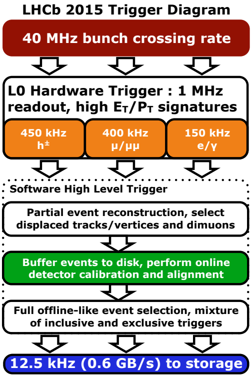
- **L0 hardware trigger**: high p_{T} and E_{T} signature in muon and calorimeter systems.
- 20 % data deferred to disk, use inter-fill time for processing.
- **High Level Trigger**(HLT):
  - Two stage flexible software trigger (HLT1, HLT2).
  - Online track reconstruction and PV finding:
    - Simplified reconstruction w.r.t. offline (tracking strategy, simplified material description, 1 Kalman fit iteration).
    - Preliminary alignment and calibration.
    - *PID* info not fully calibrated (marginally used).
  - HLT and offline with different alignment and calibration.
- **Alignment and calibration** evaluated offline.
- **Processing of the data at the end of the year** with the latest and greatest alignment and calibration constants for the physics results.

New idea for Run II

Have the best performance in HLT2 and even perform physics analysis on HLT2 output
→**Real-time alignment and calibration**

LHCb TRIGGER IN RUN II

See also: A.Johannes talk, Monday track I.



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$ | **400 kHz $\mu/\mu\mu$** | **150 kHz e/γ**

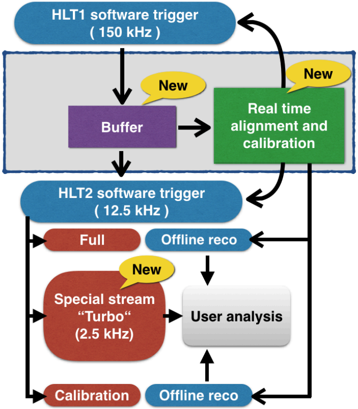
Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage



HLT1 software trigger (150 kHz)

New **Buffer**

New **Real time alignment and calibration**

HLT2 software trigger (12.5 kHz)

Full **Offline reco**

New **Special stream "Turbo" (2.5 kHz)**

User analysis

Calibration **Offline reco**

Conditions	Run I	Run II
$\sqrt{s}$	7-8 TeV	13 TeV
Bunch spacing	50 ns	25 ns
Pile-up	1.7	1.3-2.4
Output rate HLT1	80 kHz	150 kHz
Output rate HLT2	5 kHz	12.5 kHz
Time budget HLT1	20 ms/evt	35 ms/evt
Time budget HLT2	150 ms/evt	350 ms/evt

Need same reconstruction and performances achieved offline in HLT2

- Mandatory timing improvements to fit in timing budget.

REAL-TIME ALIGNMENT AND CALIBRATION

General strategy

- Automatic evaluation of alignment and calibration constants at regular intervals , *i.e.*, per fill or per run (task dependent).
- Dedicated data sample collected with specific trigger (HLT1 reco and trigger selection).
- Buffering of events while performing alignment and calibration (5 PB available).
- **Few minutes** to compute new constants and update them if needed.
- Same alignment and calibration constants used both by trigger and offline reconstruction. *PID* selections applied at trigger level.
- Offline reconstruction moved into HLT2 thanks to timing improvements.

What do we gain?

1. **Same performances online/offline.**
2. **More effective trigger selection.**
3. **Stability of alignment → boost physics performance.**
4. **Analysis directly on trigger output: store only signal candidates saves disk space.**

Challenges

1. **Same tracking online and offline : timing (350 ms/event)**
2. **Real-time alignment and calibration framework** fitting timing requirements and guarantee stability.
3. **Fully employs the improved resources** : servers for Run II 2 times more powerful. (29 K → 50 K logical cores.)

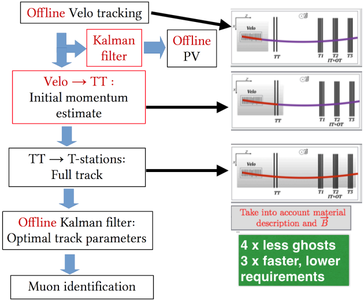
CHALLENGES - OPTIMIZATION OF RECONSTRUCTION CHAIN

Tracking optimization

1. **Optimization of the code (memory access, vectorization).**
2. **New reconstruction chain in HLT1 and simplified geometry in Kalman fit.**
3. **Re-implementation and re-tuning algorithms.**
4. **Offline tracking sequence 2 times faster than in Run I**

→ Permit to run same tracking online (in HLT2) and offline with same performances.

Run II HLT1 tracking sequence



Offline Velo tracking

Kalman filter

Offline PV

Velo → TT : Initial momentum estimate

TT → T-stations: Full track

Offline Kalman filter: Optimal track parameters

Muon identification

Take into account material description and $\vec{B}$

4 x less ghosts
3 x faster, lower requirements

Tracking improvements

- **HLT1 tracking sequence:**
  - Introduction of the VeloTT algorithm.
  - → 3 times faster and 4 times less ghost rate wrt Run I.
- **HLT2 tracking sequence:**
  - Start from HLT1 tracks→ 2^{nd} iteration of forward tracking.
  - $\epsilon^{forward}_{tracking} > 90\%$, tracks from B and 12 % ghost rate.
  - Run all the other tracking algorithms.
  - 2 times faster than in Run I

REAL-TIME ALIGNMENT AND CALIBRATION : ALIGNMENT.

HLT1 selects dedicated events for each task at the start of the fill, processed in parallel on $\sim$ 1700 nodes and single node compute updated alignment constants.

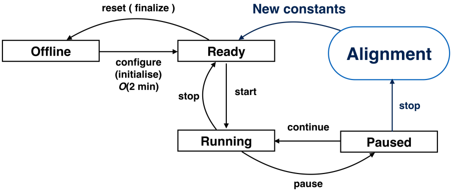
Two tasks defined: analyser, iterator

Tracking alignment:

- Analyser on multiple nodes: massive parallel track reconstruction based on alignment from iterator.
- Iterator on a single node: combine analyser output, χ^2 minimization and update alignment constants for next iteration.

RICH alignment :

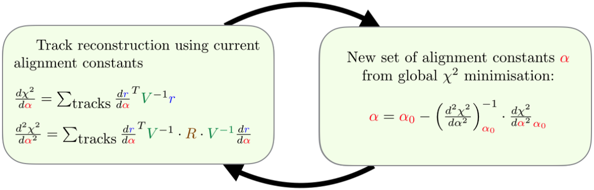
- Analyser on multiple nodes: Track, photon reconstruction and histograms filling.
- Iterator on single node: histograms merging and fitting to extract updated alignment constants.



Finite state machine defining the analyser and iterator behavior.

VELO, TRACKER AND MUON SYSTEM ALIGNMENT (1)

Iterative procedure minimizing the residuals of a Kalman fit on a sample of already reconstructed tracks. [13] [11]



Track reconstruction using current alignment constants

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

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

New set of alignment constants α from global χ^2 minimisation:

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

Iterative procedure stops when χ^2 difference is below threshold

α: alignment constants; r: track residuals;

V: covariance matrix; R: residual's covariance matrix

Tracking alignment procedure

- Run automatically for each fill
- Update constants only when needed
- $\sim$ 7 minutes for each tasks.
- Use vertices and particle masses as constraints to avoid biases.

VELO, TRACKER AND MUON SYSTEM ALIGNMENT (2)

- 3 translation and 3 rotation constants for each detector element.
- Evaluate variation of constants w.r.t. input values used for that fill.

VELO (86 elements)

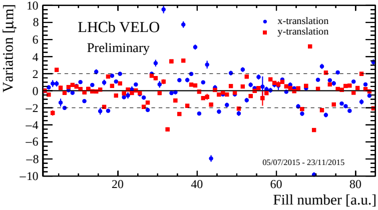
- VELO opens and closes each fill: update expected each fill.
- Updates each 2/3 fills.

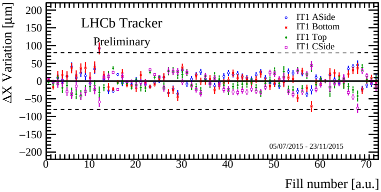
Trackers (TT,IT,OT) (697 elements)

- Alignment run after the VELO every fill: update expected every few weeks.
- Updates after each magnet polarity switch.

Muon stations (10 elements)

- Alignment run for every fill.
- No update required, as expected → monitoring.





Fully commissioned and running fully automatic

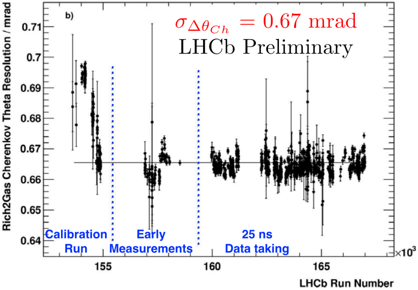
RICH MIRROR ALIGNMENT

Rich alignment - Logic

- LHCb has 2 RICH detectors.
- Cherenkov light reflected by spherical and flat mirrors and photon detector plane reconstruct the cherenkov rings.
- Center of cherenkov ring corresponds to the interaction point of the track.
- Looking to $\Delta(\theta_{Ch})$ vs ϕ using selected reconstructed tracks can correct misalignment of mirrors.
- Run every 1-2 fills, used as monitoring.

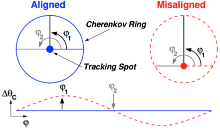
RICH II

Stability of Cherenkov angle resolution

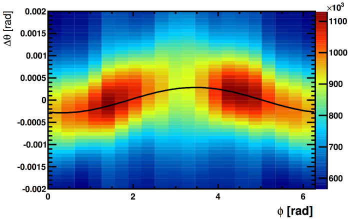


$$\Delta\theta_C = \theta_x \cdot \cos\phi + \theta_y \cdot \sin\phi$$

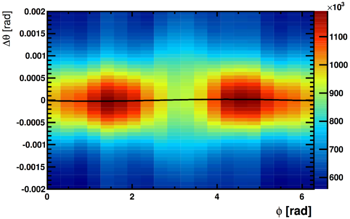
$$\Delta\theta_C = \theta_{meas} - \theta_{exp}$$



Before alignment



After alignment



REAL TIME CALIBRATION

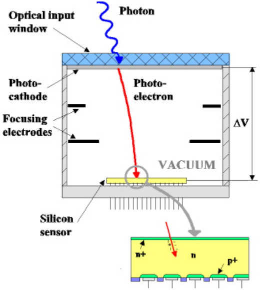
Real time calibration - general strategy

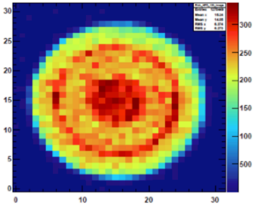
- **Evaluated fitting monitoring histograms**
- **Run on a single CPU as an online task.**
- **Don't need an iterative procedure.**
- **Evaluated run by run: if too short, use same constants of previous run.**

Real time calibration - RICH

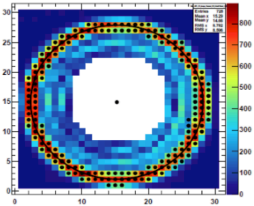
Real time calibration - RICH

- **Refractive index (2 constants)**
  - Fit the difference between expected and measured Cherenkov angle. Scale factor as correction.
  - Account for temperature, pression and gas mixture variation.
- **Hybrid photon detector (1940 constants)** :
  - Used to detect Cherenkov photons.
  - Correct for the effect of $\overrightarrow{B}$, $\overrightarrow{E}$ on anode image.
  - Use of a Sobel filter to detect edges and then fit.





Before calibration

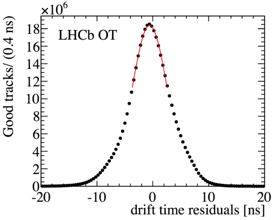


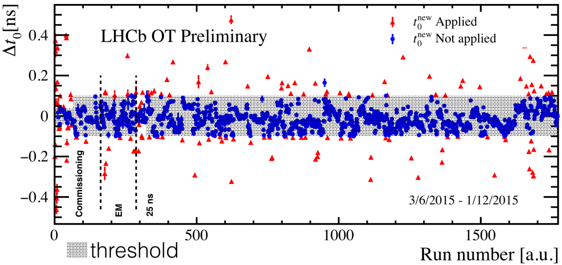
After cleaning and Sobel filter

REAL TIME CALIBRATION - OUTER TRACKER

Real time calibration - Outer tracker

- **t_0 calibration: measured drift time compared to estimated one from tracking.**
    - t_0 encodes the read-out delays and the LHCb clock.
    - Gas detector: track distance → drift time measurement.
    - Need synchronization with LHCb clock (*pp* collision time).
    - Average drift time residual can be determined online ($\sim$ 5000 tracks).





Real time calibration - Calorimeter calibration

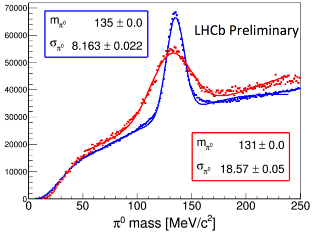
Real time calibration - Calorimeter

- **Relative: LED monitoring**(used)
  - Detect ageing of the PMTs
  - Performed/updated evey fill for ECAL and HCAL.
  - ∼ 15 minutes to have corrections available.
- **Relative: occupancy method**(commissioning)
  - Per-cell occupancy comparison to reference sample.
  - $\mathrm{Occ}_{\mathrm{Ratio}} \propto$ HV ratio
- **Absolute: using π^0**(used):
  - **π^0 mass peak to obtain per-cell calibration coefficient.**
  - On HLT farm as alignment task.
  - Done every months. Few hours to have results.
- **Absolute: ^{137}Cs source scan**(used)
  - Done every technical stop.

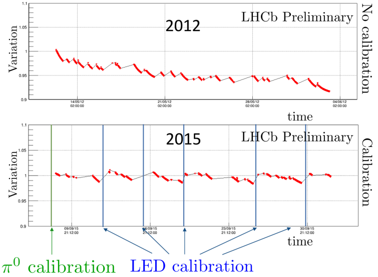
Importance

- Have stable L0 trigger rates.
- Account for aging effects adjusting HV settings.
- Critical for real-time physics analysis with neutrals.

π⁰-calibration



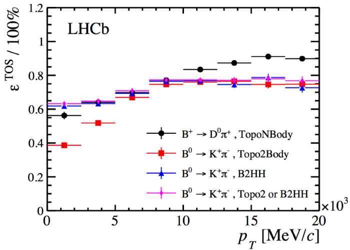
Relative amplitude variation
(456 cells in the very central part of ECAL)



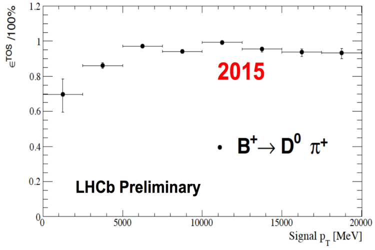
VALIDATION AND TURBO STREAM

Offline reconstruction available online.

- Better performance and using hadron *PID* information in the trigger → higher $\epsilon_{trigger}$
    1. For example: $B^+ \to D^0\pi^+$: $\sim 75\% \to \geq 90\%$. See also: A.Johannes talk, Monday, track I.
- Use HLT2 output directly for physics analysis.
- Turbo stream saves 90% of disk space : write only information on signal candidates.
- Ideal for analysis with large yield ($O(10^6)$).
- Extremely quick for physics results:
    1. Measurement of forward J/ψ production cross-section in *pp* collisions at $\sqrt{s}$ =13 TeV. (10 days after data taking)
    2. Measurements of prompt charm production cross-sections in *pp* collisions at $\sqrt{s}$ = 13 TeV. (few weeks after data taking)



[New J. Phys. 15 (2013) 053021]



LHCb upgrade

LHCb UPGRADE: FROM RUN II TO RUN III

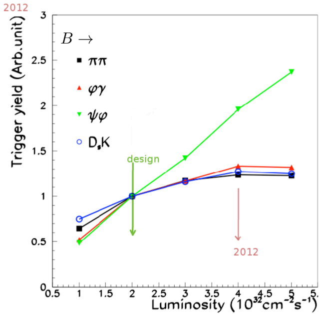
Higher $\mathcal{L} = 2 \times 10^{33} cm^{-2} s^{-1}$ (4× Run II) luminosity.

PHYSICS

- Much more data (expected to collect at least 5 fb^{-1} per year)
- Improve precision down to theoretical level for $\cancel{CP}$ observable.

Problem

- Tighter p_{T} cut to stay within the 1 MHz read-out limitation in L0 hadronic trigger.
- Tighter cut → flattens of trigger yield for hadronic final states.

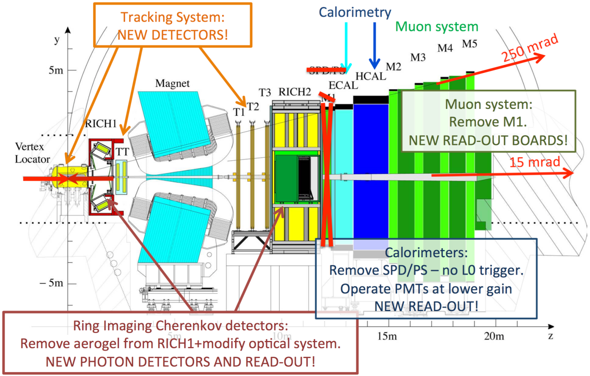


[CERN-LHCC-2011-001]

Solution: upgrade 2020

1. **All sub-detector read-out at 40 MHz.**
   → Build/mount new detectors and read-out.
2. **Fully implemented software trigger.**
   → Stringent timing limitations.
3. **Keep strategy of Run II for the real time alignment and calibration.**

DETECTOR UPGRADE FOR LHCb



Tracking System:
NEW DETECTORS!

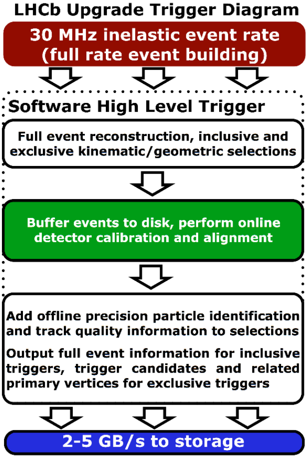
Muon system:
Remove M1.
NEW READ-OUT BOARDS!

Calorimeters:
Remove SPD/PS – no L0 trigger.
Operate PMTs at lower gain
NEW READ-OUT!

Ring Imaging Cherenkov detectors:
Remove aerogel from RICH1+modify optical system.
NEW PHOTON DETECTORS AND READ-OUT!

- **Read-out** : almost all new to cope for 40 MHz read-out.
- Replace whole tracking system and upgrade *PID* detectors ([CERN-LHCC-2013-022] [1]).
- Remove some of L0 trigger detectors (M1, SPD).

TRIGGER FOR THE UPGRADE



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

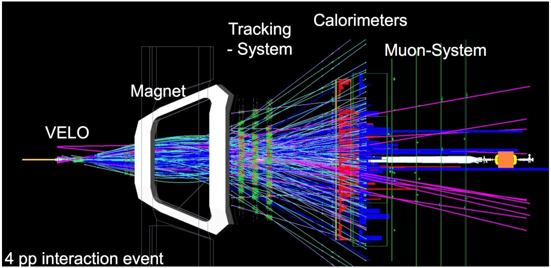
2-5 GB/s to storage

[CERN-LHCC-2014-016] [4]

Full software trigger : driving criteria.

- Much more information at trigger level needed to categorize the more complex event topology.
- **Tracking at 30 MHz.**
- Single CPU timing budget is estimated to be 13 ms.
- Upgrade tracking sequence needs to be aligned to offline selections.
- Permit to use offline-quality *PID* from online calibration and alignment.
- Remaining CPU timing budget excluding tracking used to apply offline-quality trigger selections.
- Fully exploit the new detectors potentiality and optimize resources to achieve best physics performance.

UPGRADE CHALLENGES AT LHCb : TRACKING.



The event topology is more complex at the upgrade conditions:

- More primary vertices : $\nu = 2 \rightarrow 7.6$.
- Higher track multiplicity ($\overline{n_{track}} \sim 70 \rightarrow 180$).
- Bunch-to-bunch spillover.

The relevant challenges for tracking are:

- Suppress fake tracks rate.
- Low processing time in the trigger (less than $\sim 13\ \mathrm{ms}$ per event on a single CPU.).
- Maintain high tracking efficiency, *i.e.*, $> 90\ \%\ p > 5\ \mathrm{GeV}/c$.
- Excellent momentum, time, and vertex resolution.

DETECTOR UPGRADE

Velo upgrade

- Hybrid pixel sensors closer to beam pipe (5.5 $\text{mm} \rightarrow 3.5\,\text{mm}$)
- Geometry simplify VELO, simpler track reconstruction.
- Better $\epsilon_{tracking}$ and σ_{IP-3D}.

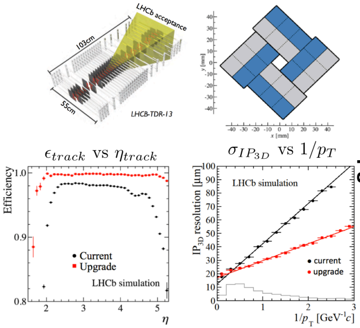
Upstream Tracker

- Finer granularity and larger acceptance.
- 4 layers in *stereo* configuration.

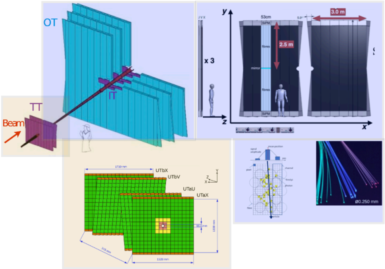
Scintillating Fiber tracker

- Less complex than IT and OT.
- 2.5 m long fibers read-out by *SiPM*.
- $\sigma_{x-z} \sim 100\mu$m.

VELO upgrade TDR [2]
Trackers upgrade TDR [3]

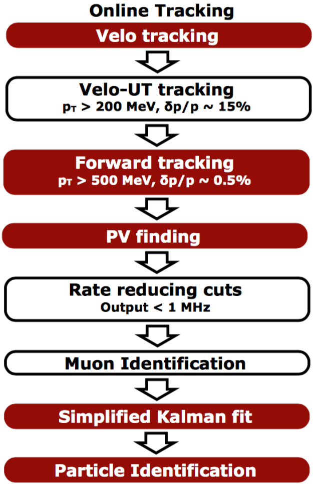


Velo upgrade



Trackers

TRACKING IN LHCb 2020 HLT



Online Tracking

Velo tracking

Velo-UT tracking
p_T > 200 MeV, δp/p ~ 15%

Forward tracking
p_T > 500 MeV, δp/p ~ 0.5%

PV finding

Rate reducing cuts
Output < 1 MHz

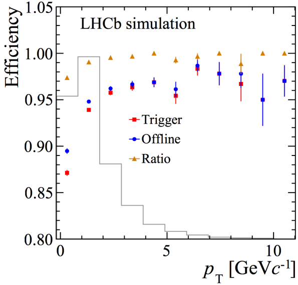
Muon Identification

Simplified Kalman fit

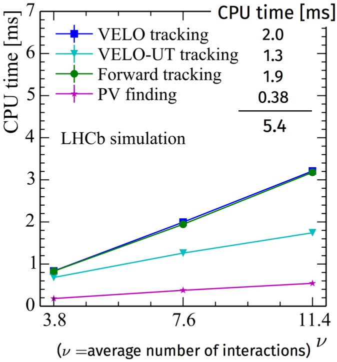
Particle Identification

Online tracking at collision rate

- Offline : no velo-ut and $p_t > 70\,\mathrm{MeV}/c$.
- Compared to offline the online tracking sequence is 98.7 % efficient.
- 92.5 % efficiency for tracks from B with $p_T > 0.5\,\mathrm{GeV}/c$.
- p_T <0.5 GeV/c available with lower resolution.



TRACKING IN LHCb 2020 HLT



Online tracking at collision rate

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- 92.5 % efficiency for tracks from B with $p_T > 0.5\,\mathrm{GeV}/c$.
- $p_T < 0.5\ \mathrm{GeV}/c$ available with lower resolution.
- **Event Filter Farm : 1000 nodes × 400 instances per node (projection) → 13 ms on today CPU limits with a 30 MHz input rate.**
- **Fast reconstruction sequence is ≃ 50 % of it , i.e. 5.4 ms.**
- **Lot of new ideas are on going : fully exploit parallelization and vectorization of the code, efforts in trying other HW architectures like GPUs and improvements of tracking algorithms.**

CONCLUSIONS

ONLINE ALIGNMENT AND CALIBRATION

- LHCb is the first HEP experiment implementing a fully automatic tracking system alignment, *PID* calibration and track reconstruction in the online system.
- Achieved thanks to the huge effort in tracking improvements and development of the new automatic procedure.
- LHCb evaluates the alignment constants for each fill in few minutes and calibration constants for each run.
- New stream (Turbo) for direct analysis saves space and allow to achieve physics results few days after data taking.

LHCb upgrade tracking

- New tracking detectors with improved performances.
- Fast online tracking sequence already in place (50 % of the available 13 ms).
- Work ongoing to improve even further the performance.
- Really ambitious program for the upgrade: tracking at collision rate, real-time alignment and reconstruction and physics analysis at the trigger output.

Thanks for your attention!

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CONTENTS

TIMING

Reconstruction	Run II	Run I
HLT1 rate	$\sim$ 150 kHz	$\sim$ 80 kHz
HLT1 time	$\sim$ 35 ms	$\sim$ 20 ms
Track finding	$\sim$ 100 ms	
Calorimeter reco	$\sim$ 50 ms	
RICH PID	$\sim$ 180 ms	
Muon ID	$\sim$ 2 ms	
Total HLT2	$\sim$ 350 ms	$\sim$ 150 ms
HLT2 rate	$\sim$ 12.5 kHz	$\sim$ 5 kHz

Timing of algorithms and trigger rate

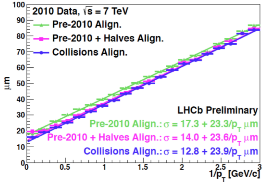
LESSON FROM RUN I: ALIGNMENT IMPORTANCE

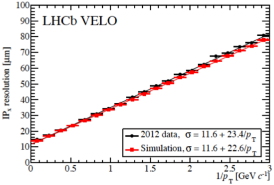
Alignment of the detector → achieve best physics performance.

- **Vertex detector alignment is crucial to isolate secondary vertices in b and c hadrons decays.**

σ_{IP_x} vs. $1/p_T$

1^{st}Alignment → Better alignment





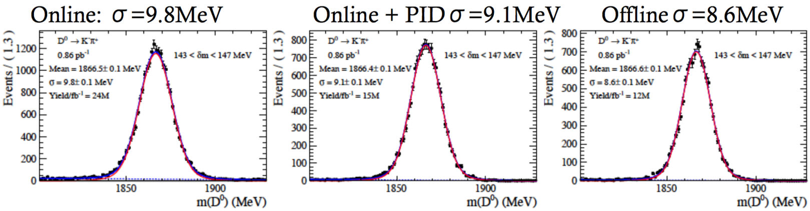
σ_{IP_x}(high p_T)= 14.0 μm → σ_{IP_x}(high p_T)= 11.6 μm

LESSON FROM RUN I: CALIBRATION IMPORTANCE

Exclusive hadron selections (*PID*) requires the full calibration of the RICH detectors.

- **Improve purity and mass resolution.**
- **Higher performances of online selection, especially for tighter selection (e.g. exclusive selection of $D^0 \to K^-\pi^+$ candidates).**

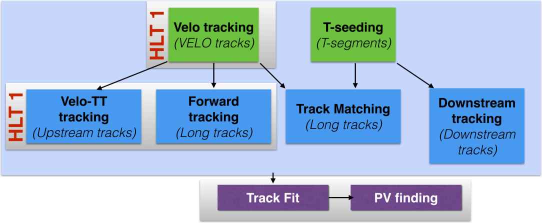
$D^0 \to K^-\pi^+$ invariant mass distribution


Online: σ =9.8MeV

Online + PID σ =9.1MeV

Offline σ =8.6MeV

PATTERN RECONSTRUCTION AT LHCb



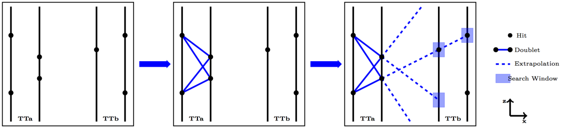
Pattern recognition at LHCb

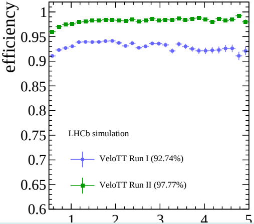
- Forward tracking and track matching used to make long tracks.
- Use VeloTT as input for the forward tracking.
- Track fit performed with Kalman filter procedure.
- Pattern recognition algorithms has internal track quality estimator and usage of local approximation of $\overrightarrow{B}$ field.

VeloTT algorithm

VeloTT logic

- Linear extrapolation of VELO segments to TT (upstream the magnet)
- Hits collected in within a search window around extrapolation.
- Doublets are created in the first two layers.
- Extrapolate doublets to $3^{rd}/4^{th}$ and collect compatible hits.
- If no 4 hit candidates found, repeat procedure staring from last two layers.
- Fit each track minimizing the χ^2 and estimation of $\frac{q}{p}$ ($\frac{\delta p}{p} \sim 15\%$.
- Best Velo + TT hits selected based on # layers and χ^2.
- $\epsilon_{tracking} > 97\%$ ($p_T > 200\,\mathrm{MeV}/c$) with $n_{layers} \geq 3$, but TT doesn't cover all the LHCb acceptance. → need to recover for that.
- Run II implementation: 3 times faster and 4 times less ghost rate (6%) w.r.t. Run I.

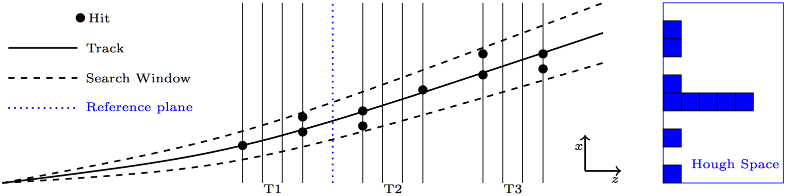




FORWARD ALGORITHM

Forward algorithm logic

- Linear extrapolation VELO tracks to T-stations.
- Open search windows in x for each layer. **Charge knowledge can be used to reduce it**
- Use VELO track and $\overrightarrow{B}$ field to project each selected hit to the z position of a reference plane.
- Same particle's hits should be projected to same x → **Hough transform**.
- Fit clusters and outliers removal.
- Use cluster search to add stereo hits.
- Refit, outlier removal and best track selected.



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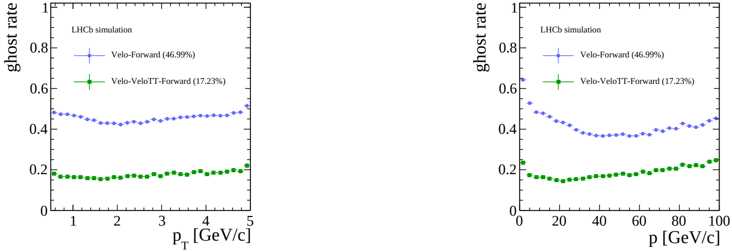
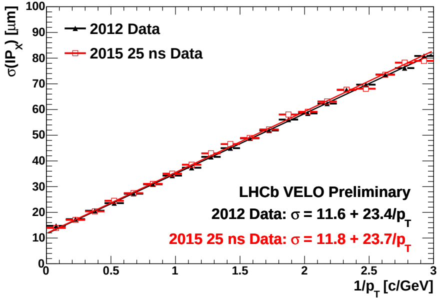
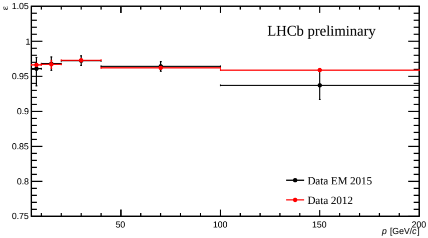


TRACKING PERFORMANCES IN RUN II





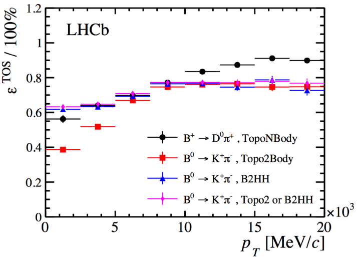
Run II vs Run I tracking performances

- Same reconstruction offline in HLT2 trigger.
- Same $\sigma_{IP_{x,y}}$ as offline reconstruction in Run II.
- Same tracking efficiency as offline reconstruction in Run II.

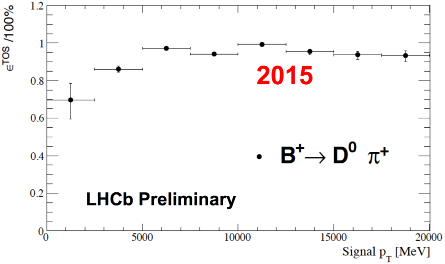
TRIGGER PERFORMANCES IN RUN II

- Offline reconstruction in HLT2.
- Fully calibrated and aligned detector.
- *PID* selections in the trigger.

HLT2 inclusive beauty trigger vs B p_{T}.



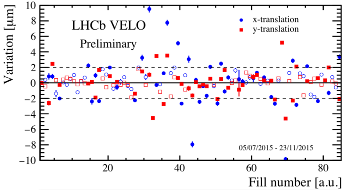
Int. J. Mod. Phys. A30 (2015)



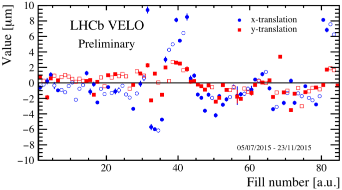
$B^+ \to D^0\pi^+$ trigger efficiency selection: ~ 75 % $\to \geq 90\%$.

VELO ALIGNMENT STABILITY

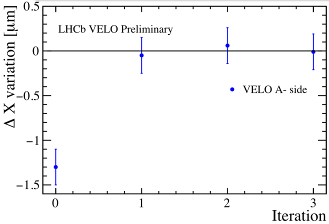
X,Y alignment constants variation wrt previous fill values.



$t_{X,Y}$ alignment constants variation wrt previous fill values.



Convergence of the VELO alignment obtained for a specify fill. Variation wrt previous iteration.



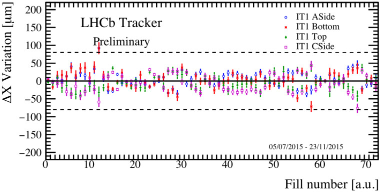
□ □ **trigger an update**

■ ■ **do not trigger an update**

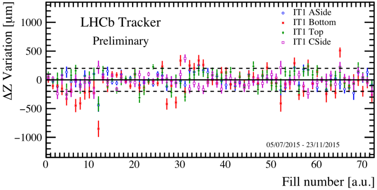
······ **threshold for update**

TRACKER ALIGNMENT STABILITY

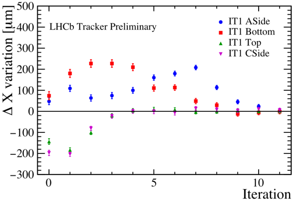
IT alignment x



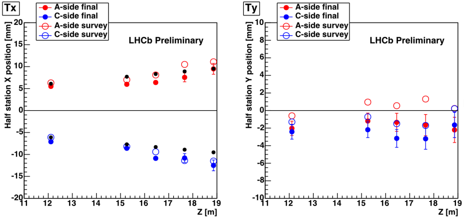
IT alignment z



Convergence in case of large misalignment



MUON ALIGNMENT STABILITY

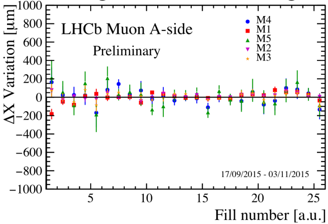


●● **Displacement wrt ideal position**

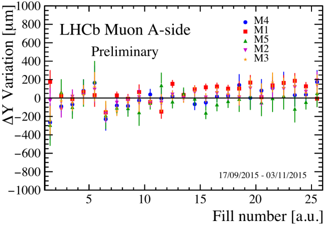
○○ **Survey**

● **Reference position**

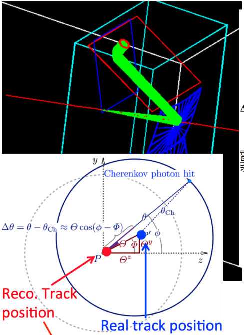
Muon chambers X variation wrt alignment in data taking

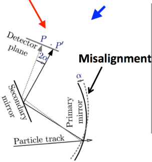


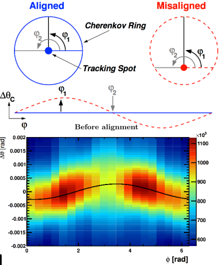
Muon chambers Y variation wrt alignment in data taking



RICH ALIGNMENT





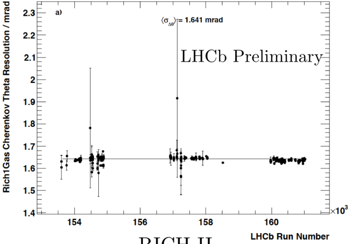


- Evaluated run by run
- 1090 alignment constants
- 16 (RICH I) , 94 (RICH II) mirrors.
- 30 minutes to run.
- Run online when enough stats collected

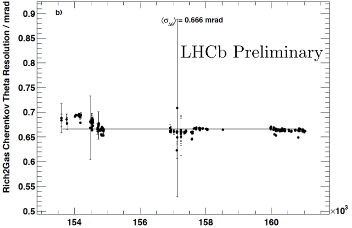
Misalignment on detector plane

$$\Delta\theta_C = \theta_x \cdot \cos\phi + \theta_y \cdot \sin\phi$$
$$\Delta\theta_C = \theta_{meas} - \theta_{exp}$$

RICH I
Stability of Cherenkov angle resolution



RICH II
Stability of Cherenkov angle resolution



LHCb AND LHC PLAN FOR THE UPGRADE

.

2011 - 2012 (RUN I)

1. 50 ns bunch spacing.
2. $\sqrt{s} = 7$ TeV (2011), 8 TeV (2012).
3. $\int \mathcal{L} = 3\ \text{fb}^{-1}$.
4. $\mathcal{L} = 4{\cdot}10^{32}\,\text{cm}^2\ \text{s}^{-1}$.

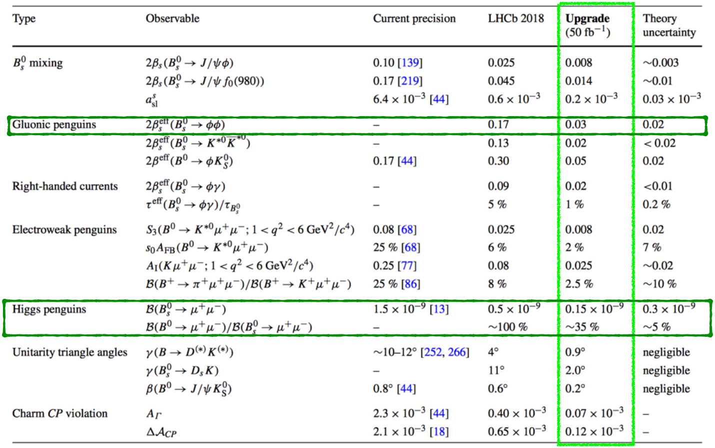
2015-2018 (RUN II)

1. 25 ns bunch spacing.
2. $\sqrt{s} = 13$ TeV.
3. $\int \mathcal{L} > 5\ \text{fb}^{-1}$.
4. $\mathcal{L} = 4{\cdot}10^{32}\,\text{cm}^2\ \text{s}^{-1}$.

2020-2025++ (RUN III)

1. 25 ns bunch spacing.
2. $\sqrt{s} = 14$ TeV.
3. $\int \mathcal{L} > 50\ \text{fb}^{-1}$.
4. $\mathcal{L} = 20{\cdot}10^{32}\,\text{cm}^2\ \text{s}^{-1}$.

LHCb EXPECTED SENSITIVITY



Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\ \mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	~0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	0.014	~0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	<0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	0.25 [77]	0.08	0.025	~0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	~10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~100 %	~35 %	~5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	~10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

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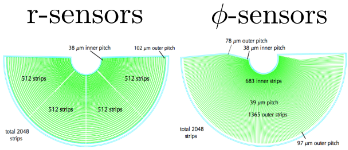
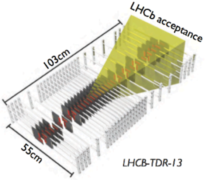
LHCb UPGRADE - TRACKING SYSTEM UPGRADE

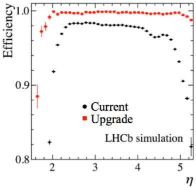
Silicon microstrip sensors → hybrid pixel sensors

- Pixel layout simplify VELO pattern recognition. (less ambiguities)
- Read-out at 40 MHz and closer to beam: from 5.5 mm to 3.5 mm.
- **Efficiencies and σ_{IP} improved wrt current VELO.**

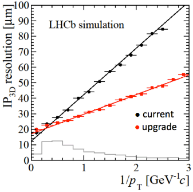


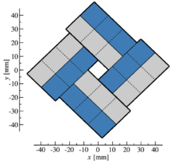


ϵ_{track} vs η_{track}



$\sigma_{IP_{3D}}$ vs $1/p_T$

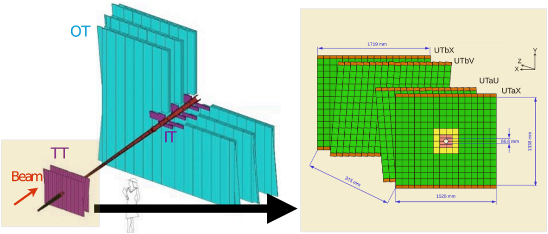




LHCb UPGRADE - TRACKERS

Tracker Turicensis (TT) → Upstream tracker (UT)

- **Upstream the magnet**: 4 layers of single sided silicon strip detector in *stereo* configuration.
- Larger acceptance wrt TT in Run I and II.
- Finer segmentation and 250 μm thickness (was 500 μm in TT).
  - As in Run II , VELO-UT tracking provides a first p estimate $\frac{\delta p}{p} \sim 15 - 25\%$, but better momentum estimation.
- Also here VELO-UT tracks used as input to look downstream the magnet (reduce ghosts and execution time).



LHCb UPGRADE - TRACKERS

Inner/Outer Tracker → Scintillating fiber tracker (SciFi)

- **Downstream the magnet**: fibers runs perpendicularly to the tracks bending plane, fast read-out by *SiPM*.
  - 3 stations with 4 layers each in $x-u-v-x$ configuration ($\pm 5^\circ$) to access the non-bending plane track motion.
  - 2.5 m long fibers ($\Phi = 250\ \mu$m) read-out by silicon photo-multipliers at 40 MHz (channel pitch 250 μm) $\rightarrow \sigma_{\text{x-z plane}} \simeq 100\ \mu$m .
  - SciFi is an omogeneous detector much simpler than OT + IT, simpler pattern recognition.