Real-time alignment and calibration at the LHCb experiment

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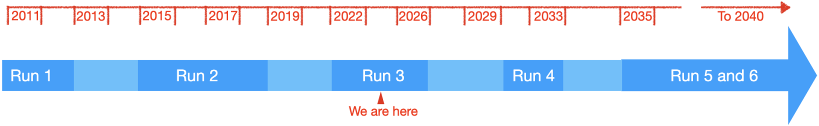
Outline

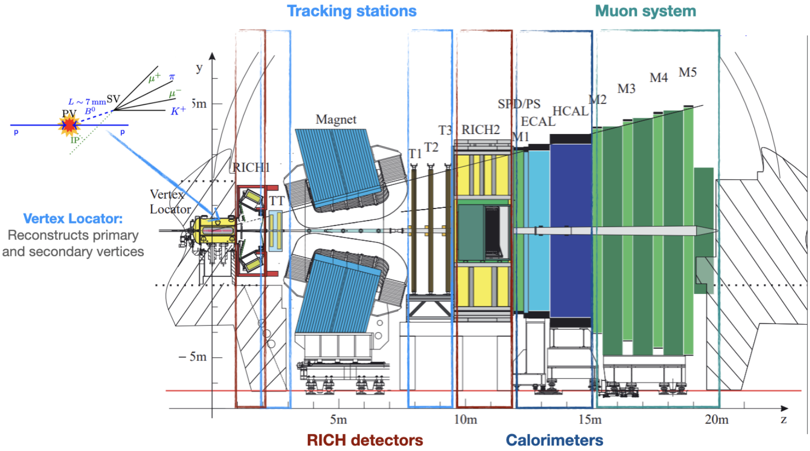
The LHCb experiment

- Designed to perform high precision measurements in flavour physics
- Large cross section of b and c hadrons $\rightarrow$ study all types of B and D decays
- Large physics programme regarding spectroscopy, electro-weak decays, heavy-ions



- Run 1 [2011-2012]: 7-8 TeV and 3 fb^{-1}
- Run 2 [2015-2018]: 13 TeV and 6 fb^{-1}
- Run 3 $\rightarrow$ collecting data at the moment
- Upgrade II $\rightarrow$ performance studies for detector design during the high luminosity LHC

The LHCb experiment in Run 1/2

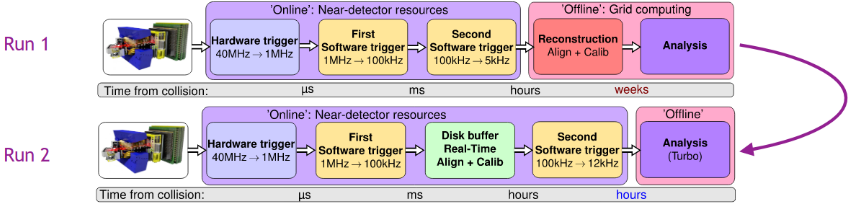


- Forward detector specialised in measuring properties of b and c hadrons

▸ JINST 3 (2008) S08005

Data taking strategy in Run 1 and Run 2

- New trigger model developed in Run 2 $\rightarrow$ real time analysis model
  JINST 14 (2019) P040065

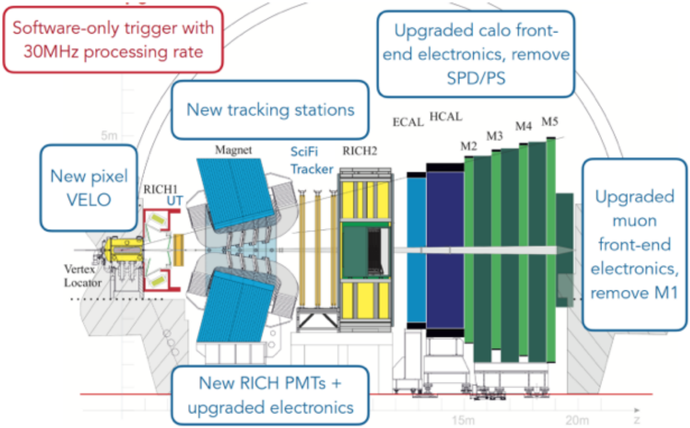


- Events buffered on disk while performing real-time alignment and calibration
- Physics analysis performed directly from the trigger output
- No offline processing in Run 2

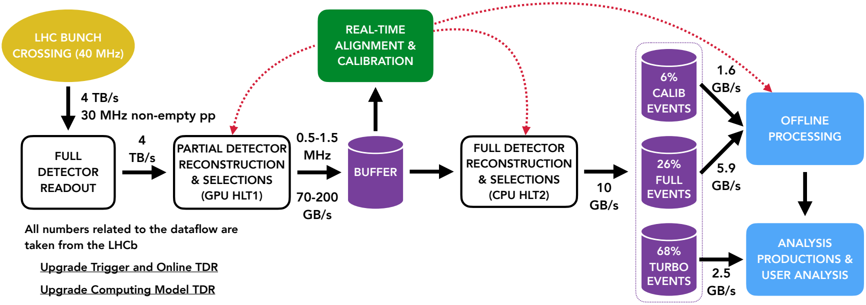
The LHCb experiment in Run 3

Brand new detector: Maintain the physics performance at harsher environment (5x higher luminosity)

‣ LHCb Upgrade TDR



The LHCb trigger in Run 3



All numbers related to the dataflow are taken from the LHCb

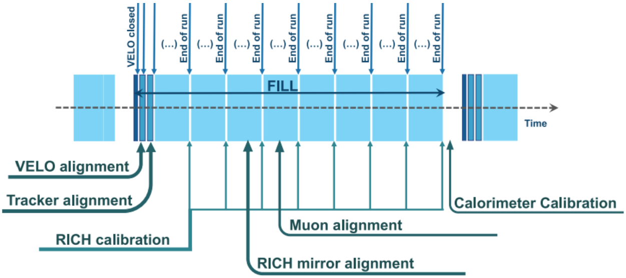
Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

1. Collision events selected with partial reconstruction (HLT1)
2. Selected events stored in a buffer
3. **Alignment and calibration** are executed
4. Alignment constants are updated if above threshold
5. Second software stage (HLT2) applies the full reconstruction

Alignment and Calibration in Run 3

- Run automatically at the start of each fill
- Compute the new alignment constants in few minutes
- Automatic update if the variations are significant



- Tracking alignment (VELO, UT, SciFi, Muon)
- RICH alignment
- RICH and CALO calibration

Tracking alignment

- Method based on Kalman filter track fit ‣ NIM A 600.2 (2009)
- Minimum χ^2 algorithm $\rightarrow$ determine the position of the detector elements

Reconstruct the tracks using the current alignment constants

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

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

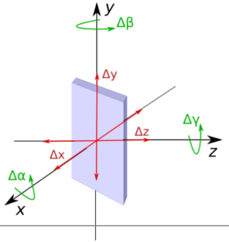
Compute a new set of alignment constants (α) minimizing a global χ^2:

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

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

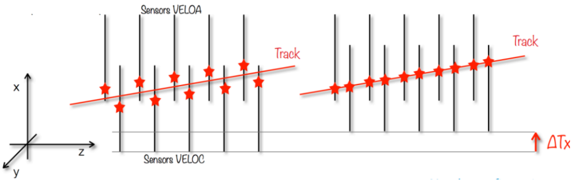
r: tracks residuals, V: covariance matrix, R: residuals' covariance matrix

- Alignment for 6 degrees of freedom: translations Tx, Ty, Tz and rotations Rx, Ry, Rz
- Vertex and mass constraints are used ‣ NIM A 712 (2013)

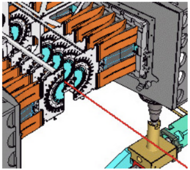


VELO alignment

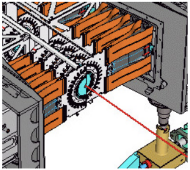
- VELO centered around the beam for each fill when the beam is declared stable



Opened at injection



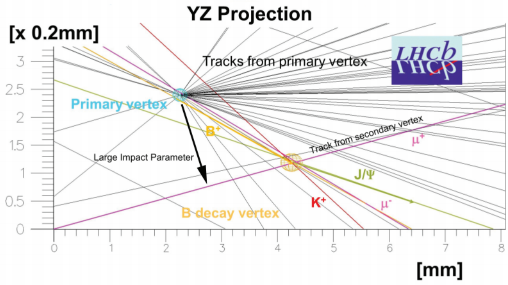
Closed when stable beam declared

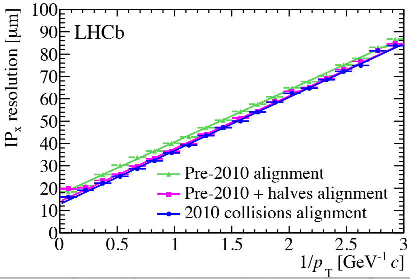


VELO alignment update tresholds

dof	Threshold
$T_x, T_y (\mu m)$	1.5
$T_z (\mu m)$	5
$R_x, R_y (\mu rad)$	4
$R_z (\mu rad)$	30

VELO alignment: why do we need it?





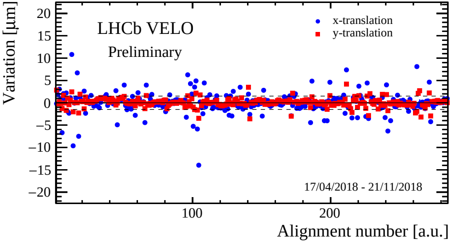
- Correctly distinguishing primary and secondary vertices
- Improves the quality of the impact parameter

Int. J. Mod. Phys. A 30, 1530022 (2015)

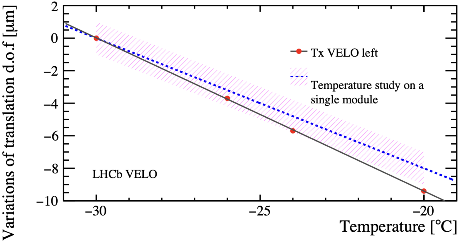
LHCb-TDR-13

VELO alignment: Run 2 performance

Alignment Stability



Temperature dependency

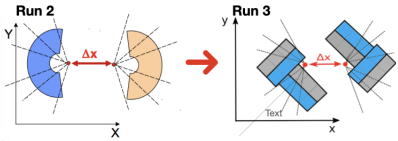


- Each point shows the difference between the initial and the new alignment constants
- Stable VELO alignment with update of constants every few fills
  ▸ LHCb-FIGURE-2019-015
- Variations of alignment constants describe well the temperature shrinkage (laboratory measurements)
  ▸ JINST 18 P10003 (2023)

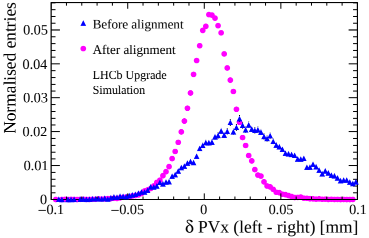
VELO alignment: look at Run 3

Simulation studies

- Pixel detector with new geometry

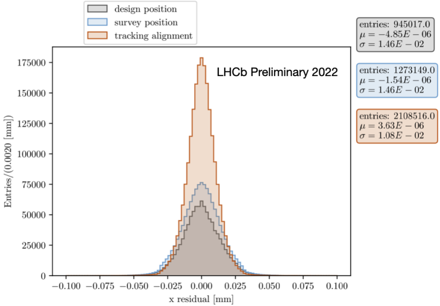


- Starting from misaligned detector (blue points)



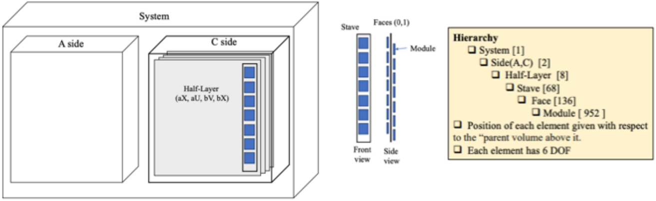
Look at the new data

- **Survey position**: as measured during VELO commissioning
- VELO alignment procedure improves residual distribution, 10 % more PVs reconstructed

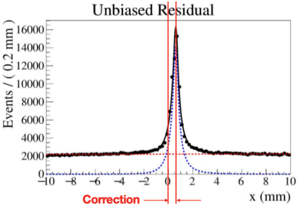


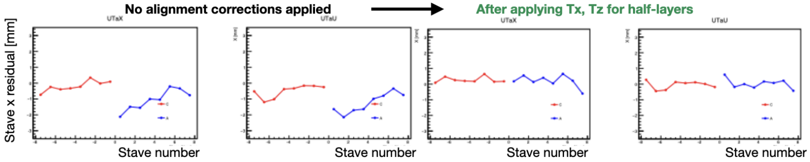
▸ LHCB-FIGURE-2022-016

UT alignment



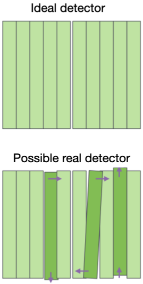
- Analyze residual plots apply initial correction
- Align staves in TxRz
- Align faces in Tx
- Align modules in TxRz





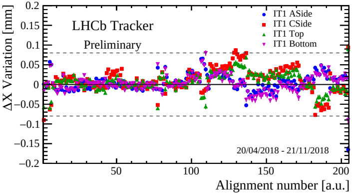
SciFi alignment

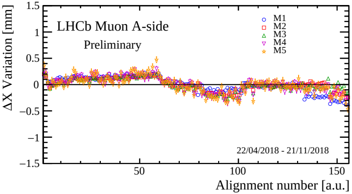
- Alignment of the tracking stations and its detector elements ($\sim$ 200 elements)
- Positions of tracking stations is affected by change of magnet polarity: variations of a few mm



- Misalignment in the tracking system affects the mass resolution and the momentum scale

Stability in Run 2





LHCb-FIGURE-2019-015

SciFi alignment: Curvature bias

A particle reconstructed by 2 oppositely charged tracks :

$$m^2 = m_+^2 + m_-^2 + 2p_+p_-(1-cos\theta)$$

- If momentum has a small bias:

$$m = m + (p_+\delta p_- + p_-\delta p_+)(1-cos\theta)$$

Case 1 : There is bias in T_x, δp_+ and δp_- have opposite variation

$$\delta m = (1-cos\theta)(p_- - p_+)\delta p \sim C\delta r(p_- - p_+)$$

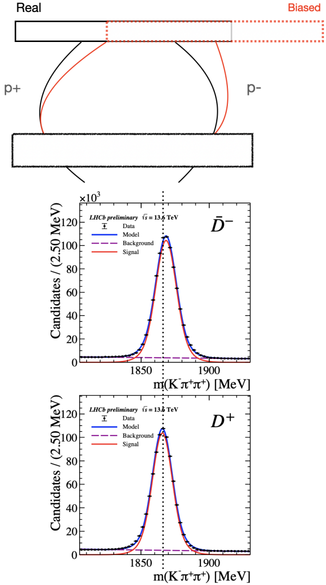
Note: mass shift over $(p_- - p_+)$

Case 2 : There is bias in T_z, δp_+ and δp_- have same variation

$$\delta m = (1-cos\theta)(p_- + p_+)\delta p \sim C\delta z\, t_x(p_- + p_+)$$

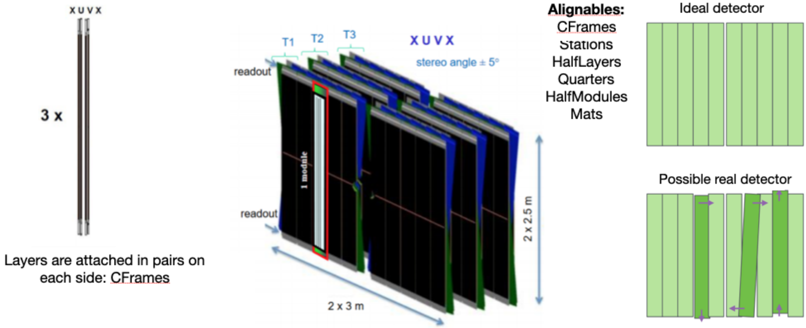
Note: mass shift to PDG value

- Residual misalignment in x $\rightarrow$ mass shift in opposite charged particles
- Bias in z position $\rightarrow$ shift of the mass
- Possible explanations of the mass shifts:
  - Magnetic field description
  - Alignment wrt VELO, UT, global rotations of detectors
  - Residual misalignment in z $\rightarrow$ can be fixed with alignment



SciFi alignment

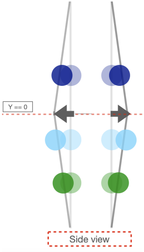
- Aligning for: CFrames, halfmodules + joint constraints, mats

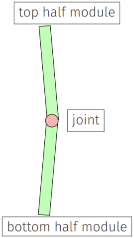


- Changes in SciFi configuration lead to significant effects in data performance
- Before data-taking CFrames are opened and closed along the x direction (routine hardware intervention)
- Necessary to align for TxRz DOFs

SciFi alignment: joint constraints

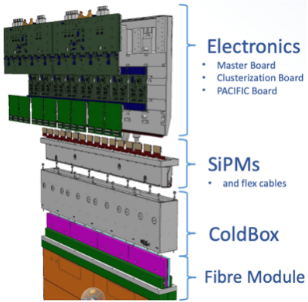
- SciFi modules are bending at the center, inwards or outwards along the beam direction: this introduces Rx of SciFi halfmodules in the alignment
- Half modules + joints reproduce the real shape



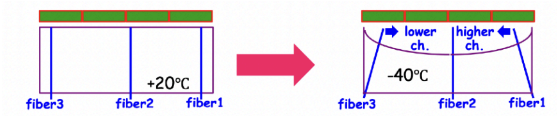


- Joints = survey constraint at the joint position
- Constraining two alignable elements: $\chi^2 = (p_A - p_B)^T V^{-1}(p_A - p_B)$
- Obtained Rx uncertainty $\sim$ 0.4 mrad $\rightarrow$ stability checks of the modules shape from hardware

SciFi alignment: Temperature calibration



- Each mat contains four SiPMs
- Placed in cold box cooled to $-40°$C
- Cooling bends the fibre mats $\rightarrow$ modified x mapping of hits
- Correlated with alignment in Tx of the SciFi modules
- Overall deformation of 0.2 mm expected

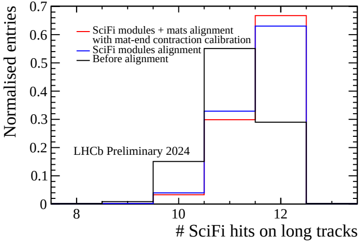


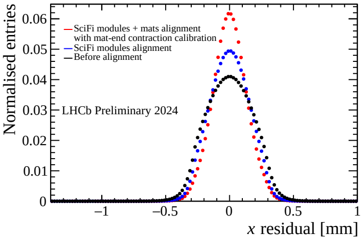
- Calibration conditions to SiPM channels in SciFi to correct for deformations caused by temperature differences
- Mat-end contraction calibration running simultaneously with the SciFi module alignment

SciFi alignment: Run 3 performance

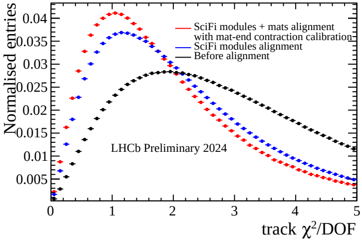
LHCb-FIGURE-2024-009

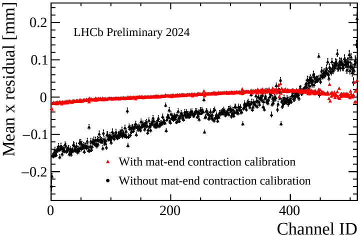
More associated hits on tracks and better track residuals



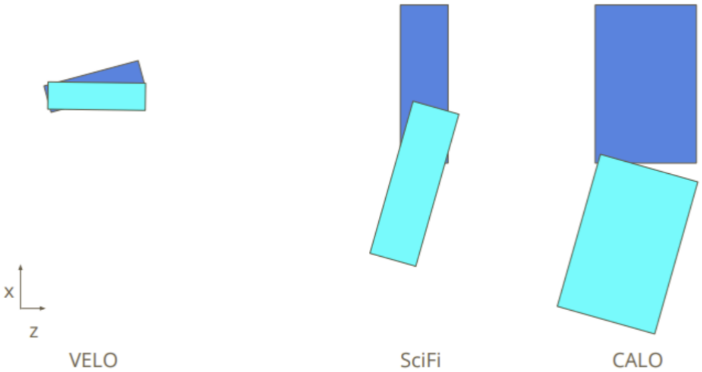


Improvement in track χ^2 and flat residuals per mat





Global alignment: why is it relevant?



- Simultaneously align all the tracking detectors for the first time in Run 3

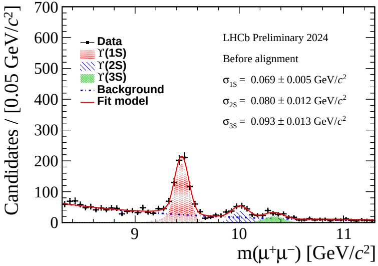
Global alignment: VELO + UT + SciFi

Alignment Configuration

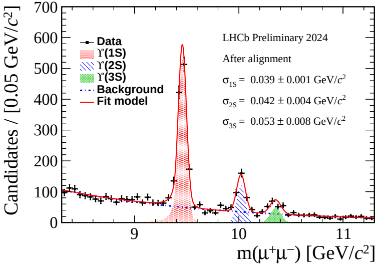
- VELO global position: TxTyTz RxRyRz
- VELO halves: TxTyTz RxRyRz
- UT layers: TxRzTz
- SciFi layers: TxRzTz

Reaching Run 2 performance in mass resolution

Before alignment



After alignment

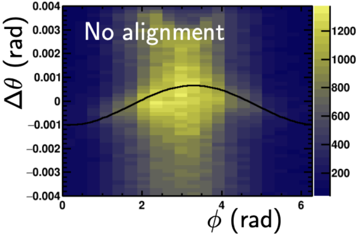


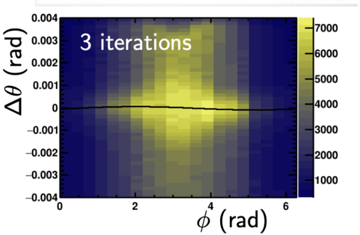
LHCb-FIGURE-2024-037

RICH alignment and calibration

- Special HLT1 selection
- Track and photon reconstruction
- Fitting the Cherenkov angle estimates the misalignment
- $\Delta\theta$ = Difference in measured and expected Cherenkov angle

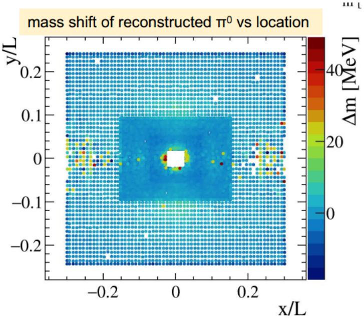
- The misalignment is converted to calibration constants for the refractive index





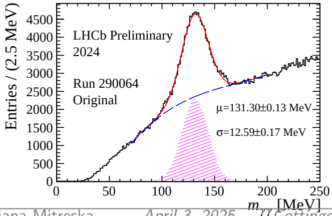
ECAL calibration with $\pi^0 \to \gamma\gamma$ ▸ LHCb-FIGURE-2024-009

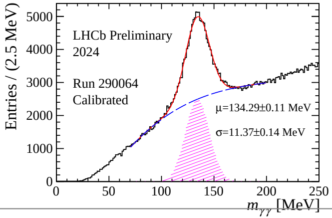
- Calibration based on the π^0 mass peak
- Fitting di-photon mass distributions in all ECAL cells ($\approx$ 6000 cells)



Challenges for Run 3:

- severe pileup brings more background
- Optimized selections and monitoring





Summary

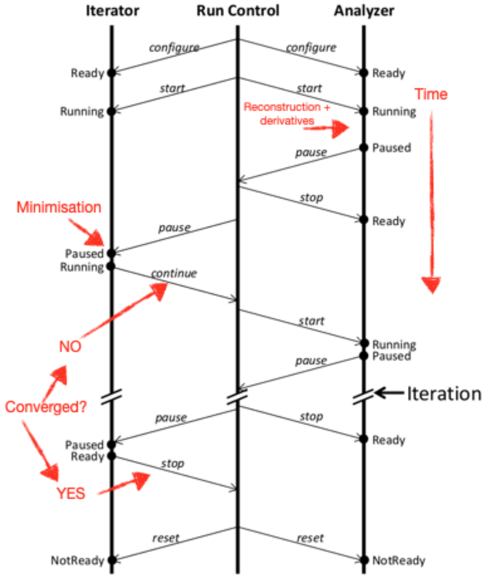
- The alignment of the tracking detectors configuration for Run 3 is evaluated with 2022, 2023 and 2024 data
- Different detector operation conditions strongly affect the alignment: different configurations needed depending on issues accounted
- Global tracking alignment configuration established
- Alignment and calibration procedures of the RICH detectors and the calorimeter are defined
- Alignment is crucial for good detector and physics performance
- Performance on Run 3 data comparable with Run 2
- Upgrade II LHCb presents high technical challenge to maintain the same performance as Run 3
- We are looking forward to more collisions!

Thank you!

BACKUP

Online alignment

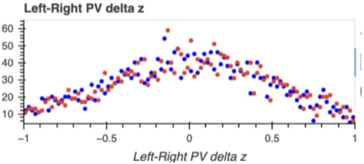
- **Analyzer**
  - run reconstruction
  - calculate and store derivatives
- **Iterator**
  - collect derivatives
  - perform minimisation
- **repeat the procedure**

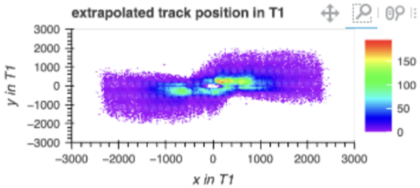


Online monitoring

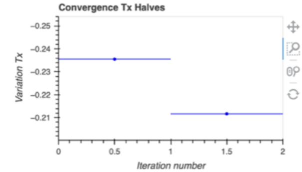
- Alignment of the VELO and SciFi running at the beginning of each fill
- Automatic update of detector positions
- Monitoring plots for alignment quality produced for each subdetector

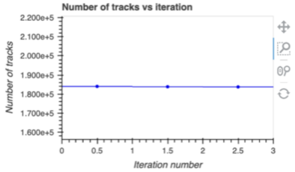
Reconstruction plots





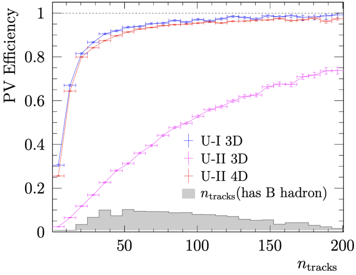
Alignment quantities per iteration





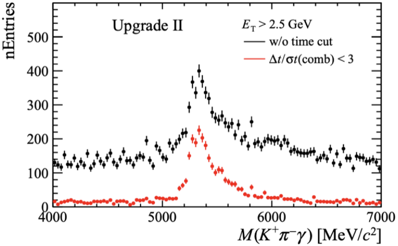
Looking ahead: LHCb Upgrade II

- Same or better performance than Run 3 in all detectors
- Tracking efficiency similar to Run 3
- Adding timing crucial in performance
- Improved Cherenkov angle resolution



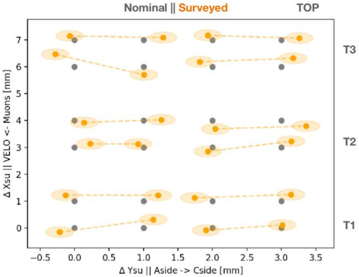
▸ LHCb Upgrade II TDR

Technology		Cher. angle res. [mrad]
RICH1	MaPMT (Run 3)	0.82
	SiPM	0.51
	SiPM & geometry	0.38
RICH2	MaPMT (Run 3)	0.50
	SiPM	0.42
	SiPM & geometry	0.22



SciFi alignment: CFrames survey

- Measurement of the CFrame positions, beginning of 2023
- Overall rotations and translations of the CFrames derived wrt design positions: translations at 200 μm, 80 μrad for Rx and Rz, 200 μrad for Ry



- Useful for faster convergence and increasing the number of reconstructed tracks in low populated regions
- Negligible differencies when including CFrames + survey on modules' positions $\rightarrow$ important to confirm the correct positions for the alignments without survey