CERN Summer Student Project Report

Alignment of the VELO detector on the Z axis using secondary vertexes reconstruction

Gianluca Zunica[a], Supervisors: Silvia Borghi, Lucia Grillo, Christopher Burr

[a]*Sapienza Universita di Roma*

Abstract

LHCb is one of the four main experiments at the LHC, designed to perform CP violation measurements and heavy flavor physics. The LHCb Vertex locator (VELO) is used to reconstruct primary and secondary vertexes from collisions with an accuracy of 5-10μm. To deliver said resolution, the position of the VELO must be precisely known. This is provided by a survey and refined using a 3 step track-based software procedure. Said procedure is accurate ($\mathcal{O}(\mu\text{m})$) for correcting x and y axis misalignments while its efficiency decreases when dealing with the so called "weak modes". Here a technique for constraining "weak modes", specifically scalings on z axis, using secondary vertex reconstruction is proposed and analyzed. Results from preliminary studies are presented, showing that the method has a resolution consistent with the one of the standard software procedure. Suggestions for further refinements and studies are given.

1. Introduction

The VELO is the innermost detector of the LHCb experiment: a silicon microstrip detector consisting of 42 semicircular sensors organized in 21 modules of r-ϕ pairs arranged in two retractable halves. The semicircular sensors goes as near as 3 mm to the beam, making the detector aperture smaller than the one required by the LHC beams during injection. For this reason, the two halves are retracted during each fill and closed again when stable beams are declared [1]. Despite having been assembled with a high precision, the only way to suitably align the detector during data-taking is through a track-

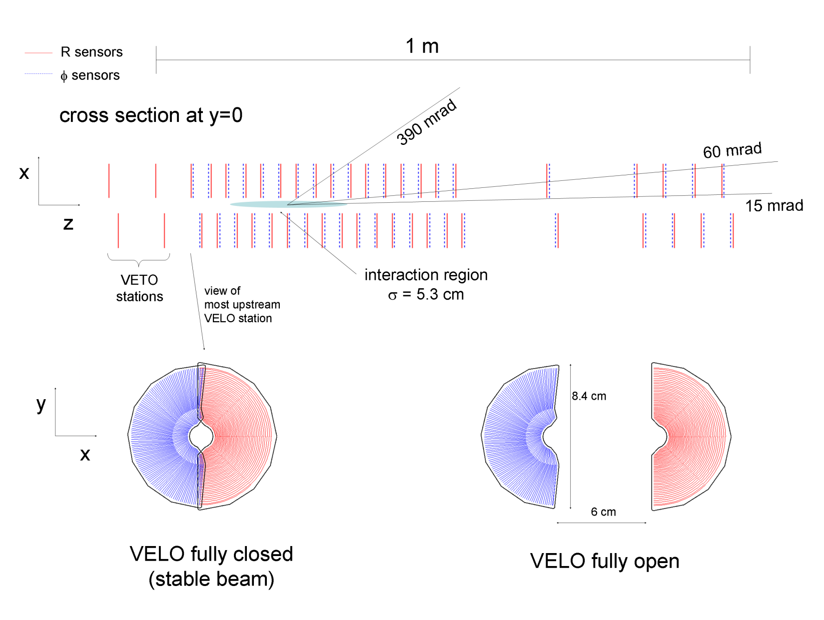

Figure 1: VELO layout. On top: xz plane view of the detector. Down left: VELO halves fully closed with the overlapping region well visible. Down right: VELO halves fully open

based software alignment procedure. Imprecisions due to the movement of the VELO halves increased the need for accurate alignment. Said procedure is performed after every fill at the re-insertion of the halves [2]. The layout of the detector is shown in Fig. 1, along with the VELO reference frame. In this report the part of the detector with coordinate $x > 0$ will be referred as "Up" (e.g. Up modules), the ones with $x < 0$ as "Down".

2. Alignment Procedure

To allow the VELO achieve its full resolution (single hit precision of 5-10μm), precise alignment constraints have to be computed. The standard alignment procedure is structured as follows:

- Mechanical survey: performed only once at the installation of the detector

- Three step track-based software alignment:

    1. Alignment of r and ϕ sensors within a module

2. Alignment of all modules within each half
3. Alignment of the halves respect to each other

The mechanical survey delivers a relative r-ϕ sensor position resolution of 5 μm within a single module. The track-based procedure has proven successful in delivering a precision on x and y translations, tilts and rotation around the z axis well within the system requirement. Nevertheless, putting strict constraints on the "weak modes" has proven difficult via this procedure. An extensive treatment of the alignment procedure with detailed informations about its resolution can be found in Reference [2].

2.1. "Weak modes"

The "weak modes", shown in Fig. 2 are deformations which are difficult to unfold with tracks. The linear deformations not effectively constrainable with the standard VELO software alignment procedure are:

- Global translation
- Global rotation
- Shearing
- Scaling

This report focuses on the scaling.

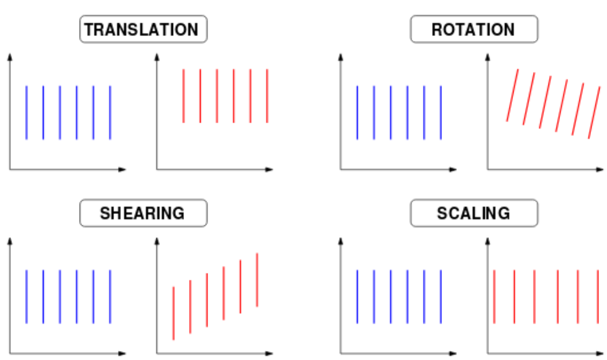

Figure 2: VELO "weak modes": in blue the position of aligned sensors, in red the misaligned one

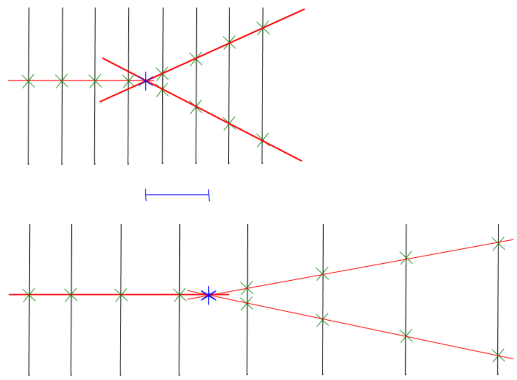

Figure 3: In black: sensors; in green: particle hits on sensors; in red: reconstructed tracks; in blue: reconstructed vertex; blue line: reconstruction bias . Reconstructed tracks and vertex in the standard configuration (up). Scaling is introduced (down): the angle between the tracks changes, and an error in the spacial reconstruction is induced.

2.2. Scaling effects

Scaling introduces a bias in the angle between reconstructed tracks (Fig. 3). This leads to two different scenarios:

- Vertex position reconstruction bias: spacial errors are introduces in the vertex reconstruction
- Missing vertex: reconstruction algorithm fails to reconstruct the vertex

As result, reduced vertex reconstruction efficiency and increased spread in the spacial distribution of reconstructed vertexes are expected.

3. Secondary Vertex Reconstruction

Precise knowledge of the position of the VELO is essential to allow the detector deliver full performance. To achieve this goal it has been proposed the idea to create a 2D map the detector using secondary vertexes of interaction with the VELO material. This could allow to infer the exact location of the detector and detect possible undetected scaling effects.

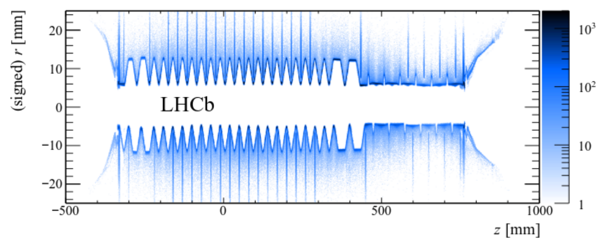

Figure 4: 2D map of the xz view of the velo at $y = 0$;[1]

3.1. Methodology

To reconstruct a complete map of the detector, events distributed along the VELO are needed. This means simulating Beam-Gas Monte Carlo events. Beam-gas simulated runs simulate the injection of helium or neon gas into the beam crossing region, providing a large number of collisions distributed throughout the whole VELO. Monte Carlo events allow to have control over the generated events (e.g same underlaying events for all the analysis). To save time the "Tracker-only" option was used: events were generated without the RICH & CALO detectors.

3.1.1. Generation-analysis chain

100 millions events are generated and analyzed through the following software chain:

1. Gauss: Generation of the physics process and interaction of the particles produced with the detector
2. Boole: Digitization of the detector response
3. Brunel: Software reconstruction of the events from detector readout information to reconstructed object as tracks and vertexes
4. Bender: Analysis of tracks and vertexes properties (e.g. vertexes position information) to store in a root file

The information stored in the root file are then further analyzed by a C++ macro. Generation and digitization are executed with the aligned version of the VELO while the reconstruction is performed through 5 different VELO configurations

- No scaling
- 0.05 mm scaling

- 0.1 mm scaling
- 0.2 mm scaling
- 1 mm scaling

Generating and propagating signals trough different versions of the VELO allow to determine which could the effects of an undetected scaling be on the data and if it's possible to detect such a misalignment.

3.1.2. Applying the scaling

To apply the scaling the modules position is obtained from the VELO database configuration files: z coordinate of the "stations" (average coordinate of the nearest facing Up-Down module pairs) is read and a shift to the standard station position is calculated using the following algorithm:

$$\epsilon_s = \frac{(z_s - z_0)}{(z_s + z_0)} \times s \tag{1}$$

where, for each station, ϵ_s is the computed shift, z_s is the z position of the station, z_0 is the z position of the first station, s is the magnitude of the scaling.

The same shift is then applied to each Up-Down module belonging to the same station. The database file containing each modules z position are then modified accordingly adding the calculated shift.
The magnitude of the shift increases with the station number (e.g the most downstream station is shifted the most).

4. Analysis of reconstructed vertexes

4.1. 2D maps and vertexes selection

Vertex positions are stored in the root created by Bender are analyzed using the C++ macro. 2D histograms are produces with the information of the position of the vertexes to obtain detailed maps of the VELO on different planes as shown in Fig 5.

These maps contains vertexes arising from the beam collisions with the gas and the RF foil wrapped around the modules (Fig 6), while only those arising from the sensors carries useful information. Thus, successive cuts are applied. First, a radial cut centered on the beam is applied to remove beam-gas interaction vertexes and the RF foil. Further cuts are then applied to

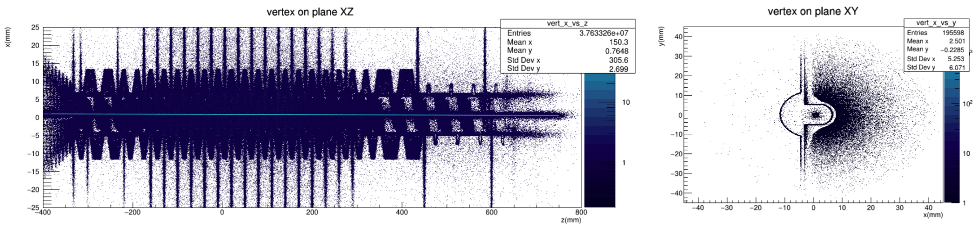

Figure 5: 2D histograms rendering maps of different plane views of the VELO. On the left, the xz plane; on the right the xy plane.

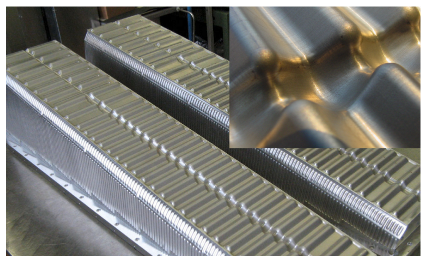

Figure 6: Image of the RF foil wrapped around the sensors

remove vertexes arising from the remaining RF foils parts are applied. The effect of the applied cut can be observed in Fig 7

After the cuts the map only contains the vertexes arising from material interactions with the sensors themselves.

4.2. Z distributions and reconstructed module positions

The information about the z coordinate of the vertexes surviving the cuts are stored in 1D histograms (Fig 8).

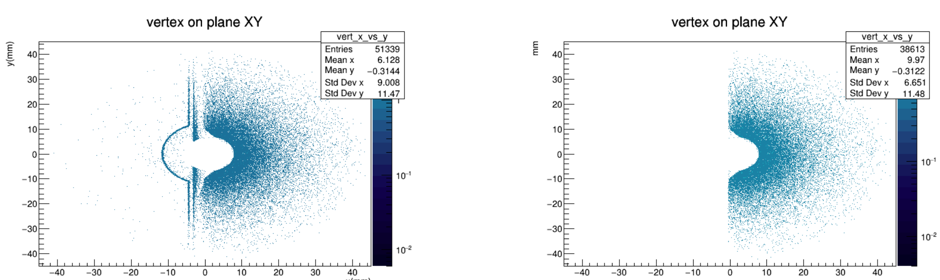

Figure 7: Succession of the cuts applied to the reconstructed vertexes

The distribution is relative to a module, with peaks corresponding to r and ϕ sensor. One histogram for each module, up and down, is made. The distributions are then fitted with 3 independent gaussians: 2 for the peaks (the sensors), one for the background (vertexes from particle decays near and between then sensors). The parameters of the fit give for position and thickness of the modules, in particular:

- Mean: reconstructed position z
- Sigma: reconstructed thickness

At the end of the process from the position of the reconstructed vertexes and the 2D maps we have now access to the actual information about the modules position and thickness. Fit results are then saved to file for further analysis.

5. Detecting scaling effects

Two major effects have been observed when analyzing the 2D maps: efficiency drop and broader distributions resulting from errors in the spacial vertex reconstruction,both clearly visible in Fig 9.

As clear from Fig 9 in the two extreme cases of no scaling and 1 mm scaling the distribution of reconstructed vertexes appear broader and the reconstruction less efficient: both effects were expected.

A side effect directly linked to the broader distribution of vertexes is the reconstructed thickness increase, as shown in Fig 10:

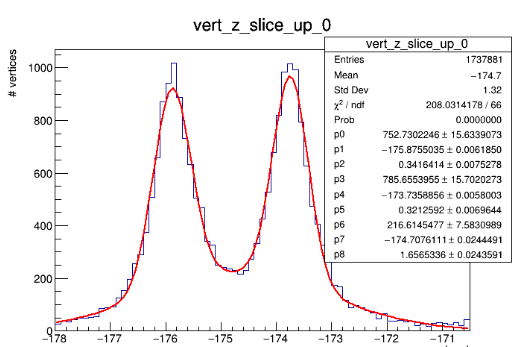

Figure 8: z vertexes modules distribution example

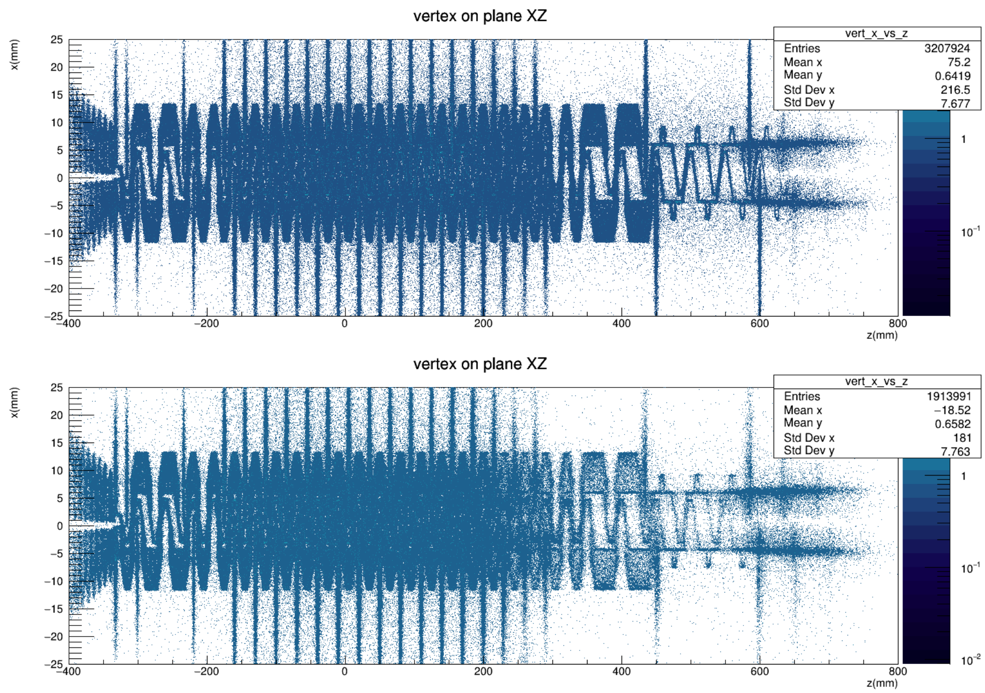

Figure 9: Scaling effects: reconstructed thickness increase. On top: non scaled version; on the Bottom the 1 mm scaled version

When the shift begin to stack up the scaling effects can become more severe (Fig 11): the thickness increase and the reconstruction efficiency drop make the sensors indistinguishable, leaving a broad gaussian in their place.

6. Analysis of fit results

The fit parameters are analyzed by a second C++ macro. The absolute value of residuals with errors and pulls of reconstructed position and thickness of each scaled version of the VELO are computed and plotted for each sensor. All the fit for all the VELO version except for the 1 mm scaling, used only as dummy model, are performed with the same set of parameters to avoid bias in the results. For each scaling magnitude the mean residuals, and similarly for sigma, are calculated as:

$$r = |\mu_{unscaled} - \mu_{scaled}| \tag{2}$$

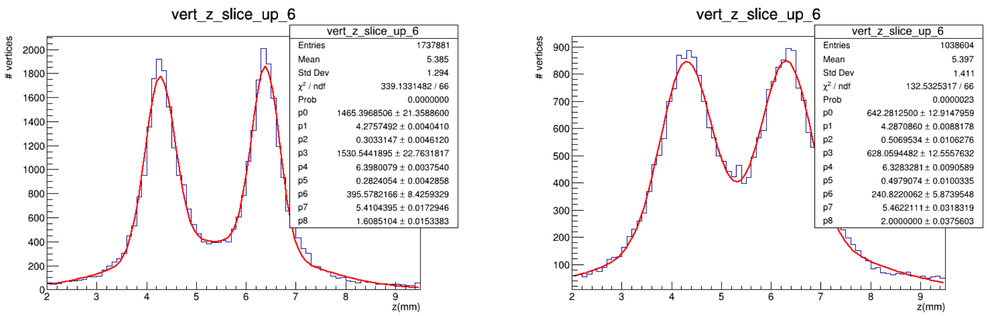

Figure 10: Reconstructed thickness increase as result of scaling (module 6 Up). No scaled VELO (left), 1 mm scaled VELO (down).

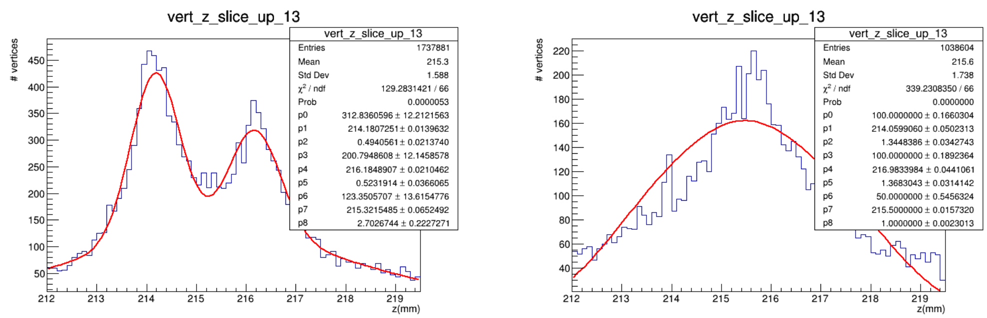

Figure 11: Example of severe consequence of the scaling: the sensors of module 13 up on the non scaled VELO (left) are no longer distinguishable after 1 mm scaling is applied (right).

where r is the calculated residual, $\mu_{unscaled}$ and μ_{scaled} are, respectively, the mean values of the gaussians in the unscaled and scaled case. A pull with a value equal or bigger than 1 flags discernibility between the two cases. Pulls are calculated as follow:

$$p = |\frac{(\mu_{unscaled} - \mu_{scaled})}{\sqrt{\sigma^2_{\mu\ unscaled} - \sigma^2_{\mu\ scaled}}}| \tag{3}$$

where p is the pull, $\mu_{unscaled}$ and μ_{scaled} are again the mean values of the gaussians, $\sigma_{\mu\ unscaled}$ and $\sigma_{\mu\ scaled}$ are the errors on the mean value for the unscaled and scaled case. Given that all events for all scalings origins from the same underlying event (see section 3) a correlation factor equal to

$$\rho(\sigma^2_{\mu\ unscaled} \times \sigma^2_{\mu\ scaled}) \tag{4}$$

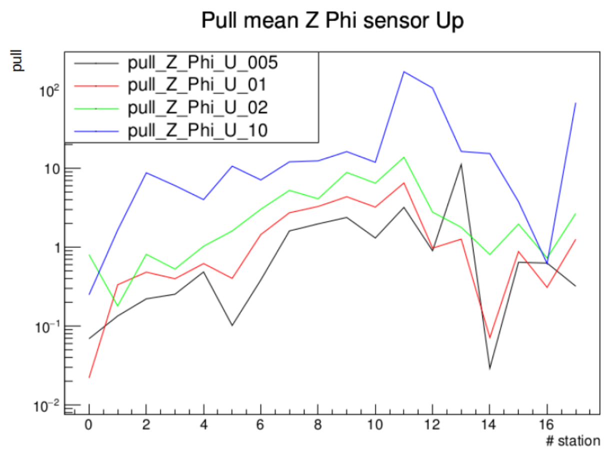

Figure 12: Computed Pulls for all scalings for the reconstructed position of r sensors "Up"

should appear in 3 denominator. In this analysis it was not computed.

6.1. Pulls of reconstructed position

A significant result for the ϕ module in the up stations is shown in Fig 12:

A clear trend is observable. Focusing on the 0.2, 0.1 and 0.05 mm scaling, the shift of the sensors respect their unscaled position increase with the scaling. Concerning the 0.2 mm case, it is clearly distinguishable from the unscaled version already from module 4. Scaling 0.1 mm is distinguishable from module 6 and 0.05 mm from module 7.

6.2. Pulls of reconstructed thickness

Additional information is provided by the sigma (alias reconstructed thickness) analysis (Fig 13) .

A clear trend appears again: more scaling applied results in increased thickness. Again, 0.2 mm scaling is clearly distinguishable, while the results are not as clear for the smaller ones. Both plots shows no error bars: the error bars should be equal to the correlation factor (equation 4). As this was not calculated, it doesn't appear in the plots.

7. Conclusions

A method employing secondary vertex reconstruction for detecting misalignments in "weak modes", specifically scaling, is presented. 100 million

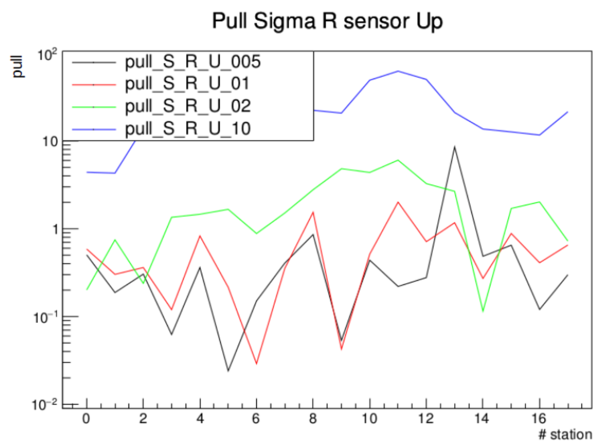

Figure 13: Computed Pulls for all scalings for the reconstructed thickness of r sensors "Up"

Monte Carlo beam-gas "Tracker-only" events are generated and digitized with the standard LHCb configuration. Reconstruction of tracks and vertexes is then performed through 5 different scaled VELO versions:no scaling (used as reference), 0.05 mm, 0.1 mm, 0.2 mm and 1mm scaling. 2D maps of the VELO material are produced and information relative to the vertexes arising only from the modules are collected and Z distribution of the modules are filled. Said distributions are fitted with 3 independent gaussians and the fit parameters corresponding to mean (reconstructed position) and sigma (reconstructed thickness) are saved to file and further analyzed. Pulls and residuals of the scaled reconstructed position and thickness are computed and plotted. The plots show a clear trend: more scaling applied translates in shifted modules and increased thickness. The method had proved capable of resolving scaling down to 100 μm, achieving a resolution as good as the standard software alignment one. To further improve the results carrying on more studies with more statistics ($\mathcal{O}(10)$ more vertexes at least) and smaller scalings is recommended. A more refined function for fitting the Z distributions is highly advised in order to further refine the results and investigate the maximum achievable resolution that can be achieved with this method.

8. References

[1] M.Alexander, W.Barter, A.Bay et al., Mapping the material in the LCHb vertex locator using secondary hadronic interactions, arXiv (2018).

https://arxiv.org/abs/1803.07466.

[2] S.Viret, C.Parkes, M.Gersabeck, Alignment procedure of the LHCb vertex detector, Nuclear Instrument and Methods in Physics Research A (2008) 157–163. https://arxiv.org/abs/0807.5067.