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LHCb VELO Closing Control, Vertex Resolution and Luminosity Measurement

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The LHCb VErtex LOcator (VELO) surrounds the collision point at IP8 of the LHC ring and performs precise tracking and vertexing. This silicon micro-strip detector is built in two halves, which each move independently in the transverse plane so as to approach the collision region during data taking, but retract whilst the beams are injected and adjusted. The closing procedure of the VELO is detailed, along with an analysis of the primary vertex resolution and a description of the role of the VELO in the LHCb luminosity measurement.

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1. Introduction

The LHCb experiment, based at CERN's Large Hadron Collider, has been designed primarily to study B-physics [1]. The study of CP violation and rare decays in the B-meson sector requires accurate measurement of decay lifetimes and impact parameters, both for flavour tagging and background rejection. Precise vertex reconstruction is therefore of fundamental importance, in order to resolve production and decay vertices. The VErtex LOcator (VELO) has been designed to fulfil this role, by providing tracking information close to the proton-proton collision region.

The VELO consists of 42 semi-circular silicon micro-strip modules, each made from two sensors mounted back-to-back. One of these sensors has a radial (R) geometry and the other an azimuthal (Φ) geometry. Each sensor has 2048 strips, with pitch varying between 40 and 100 μm.

The 42 modules are arranged in two halves of 21 modules each, see Figure 1. Within each half, the module spacing varies, with a concentrated region of 30 mm spaced modules surrounding the interaction region, and additional modules distributed more sparsely into the forward region. This is done to minimise the material budget of the detector. The modules of one half are offset relative to the other, to allow for a slight overlap between the two halves. This results in full ϕ coverage, and also allows for the possibility of tracks traversing both VELO halves, which is extremely useful for alignment purposes.

In addition, each half has two single sided modules with only a radial geometry, which are used to detect, and possibly veto, multiple proton-proton interactions. These pile-up modules are also crucial for triggering on beam-gas events, which spray along the beam pipe but in the opposite direction from the rest of the LHCb detector.

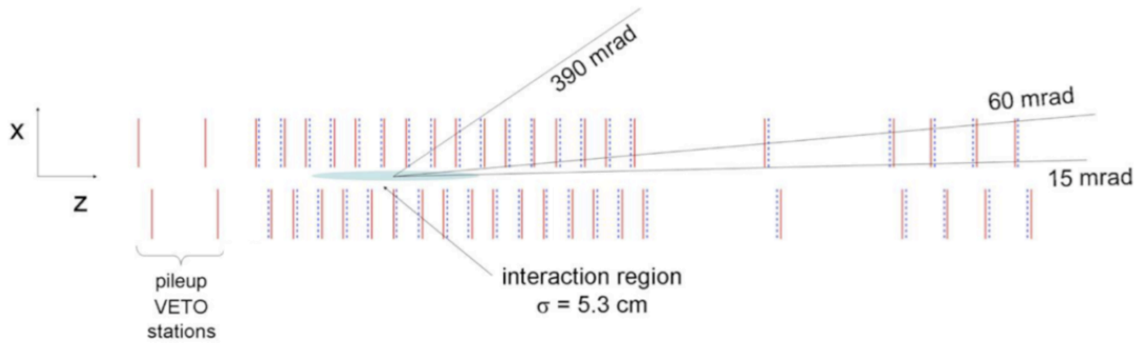

Figure 1: Schematic of the two VELO halves, as seen from above. The two rows consist of 21 modules, where each module is made up of two silicon sensors mounted back-to-back. The VETO or pile-up stations are seen on the left. As a detector safety consideration, the VELO halves are retracted during beam injection and adjust, but closed around stable beams. The right handed co-ordinate system is shown.

The two halves can be moved horizontally and vertically in the (x,y) plane transverse to the beam axis (z). During LHC injection at 450 GeV, the beam sizes and their crossing angle are significantly larger than after the ramp to 3.5 TeV. Additionally, beam stability is not guaranteed during ramp and adjust, so throughout these periods the VELO is kept retracted at ± 29 mm on each side. For data taking with stable beams, the two halves are closed about the beam, bringing active silicon to a distance of 8.2 mm from the beam-line. Further details on the VELO design are provided elsewhere [2].

2. VELO closing

A procedure for safe and efficient closure of the VELO during stable beams has been implemented. This process has been conceived to run automatically during the lifetime of LHCb, but has been operated manually in the early stages of running.

2.1 Prerequisites to closing

The LHC Central Control Centre (CCC) broadcasts definite states of the machine to the experiments. Before movement occurs, the flags indicating "stable beams" and "moveable devices allowed in" must be positive. This indicates that the CCC has finished adjusting the circulating beams and considers them safe for the VELO to approach. The VELO (in its retracted position) is powered by raising the silicon bias voltage from 10 V to 150 V; first one module on each side is biased and then all modules. During this time, occupancies, silicon bias currents and module temperatures are all monitored manually by the shifter, and automatically by the PVSS power-on panel [3].

2.2 The closing procedure

VELO closure is achieved in four steps. During the motion from $x = \pm 29$ mm to the closed position, the halves pause at $x = \pm 14$ mm, ± 5 mm and ± 1 mm. This is primarily done to verify detector safety, but is also required in order to reconstruct the luminous region and to measure the current resolver position. Potentiometers provide a real-time measurement of the half positions, even during movement. The resolvers are much more accurate, but can only provide a measurement when stationary. Instead of closing to a predefined position, for each fill the VELO reconstructs the beam collisions and closes symmetrically around them. In each step, the horizontal movement happens first, and then the vertical movement. However, the high level trigger is robust to small displacements and the position repeatability has been measured as 5-10 μm, so the vertical movement is only performed if the distance to the beams is calculated to be greater than 50 μm.

During the pauses in movement, the safety of the detector is verified by taking data from a number of sources:

- Silicon bias currents in the VELO modules are monitored to check for any sharp rises that would be indicative of a large particle flux through the silicon. These measurements are hardware based and very reliable compared with processed data (e.g. occupancies) which in principle are highly biased by the LHCb trigger.
- Two LHC beam condition monitors (BCMs) are used to monitor backgrounds and hence the stability of the beams in proximity to the detector [4]. These are located on either side of the VELO, and use diamond sensors. The threshold above which the VELO will not close is 2% of that used by the CCC to initiate a beam dump.
- The VELO reconstructs beam-beam vertices, therefore ensuring that the modules do not enter the interaction region. Straight line tracks and loose vertexing criteria are employed.
- Additionally, LHCb receives fast beam position information from four beam position monitors (BPMs) [5]. A horizontal and a vertical monitor are located on either side of the LHCb

cavern. Both instantaneous position and rate of change of position are measured and must fall below chosen values. This is done in addition to the vertexing and consistency is required between the independent measurements. The BPM data is also relied upon during short periods of time when the DAQ is down (e.g. the trigger is stopped to change the run) and no vertices are being reconstructed.

A closing manager has been written in the standard LHCb PVSS control system [3]. The interface panel shows the closing process happening in real-time, see Figure 2. Currently the whole procedure takes $6-7$ minutes to close fully, including the 2.5 minutes that it takes the motors to move each half 29 mm. Retracting the VELO therefore takes only 2.5 minutes, as no safety checks or calculations are made. It is expected that a fully automatic procedure will reduce the closing time to ~ 4 minutes.

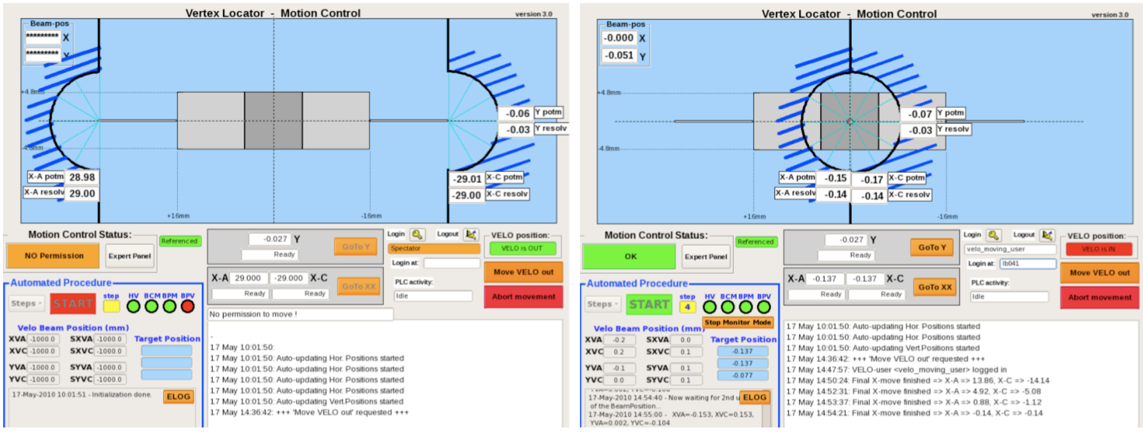

Figure 2: Screenshots of the PVSS closing manager, showing the VELO in the retracted position (left) and then after closing (right). This panel updates in real-time during the closing procedure.

Figure 3 shows how the reconstructed vertex position changes during the closing process, where the positions are defined in the local frame of each VELO half. Peaks indicate the positions where the VELO paused to check safety and calculate the beam's position. It is clear from the peak widths that the reconstruction resolution improves as the VELO approaches the interaction region. The smear of vertices were reconstructed during the movement of the two halves.

3. Beam monitoring with the VELO

Once the VELO is closed about the beam, the safety monitoring continues to check for any changes in beam position or detector parameters. A demonstration of the VELO's beam monitoring capabilities is seen during the LHC Van der Meer (luminosity) scans, see Figure 4. In this example, one beam has been scanned through the other horizontally, which the VELO has picked up in the horizontal position of the collisions. As expected, there is no corresponding change in the vertical position of vertices.

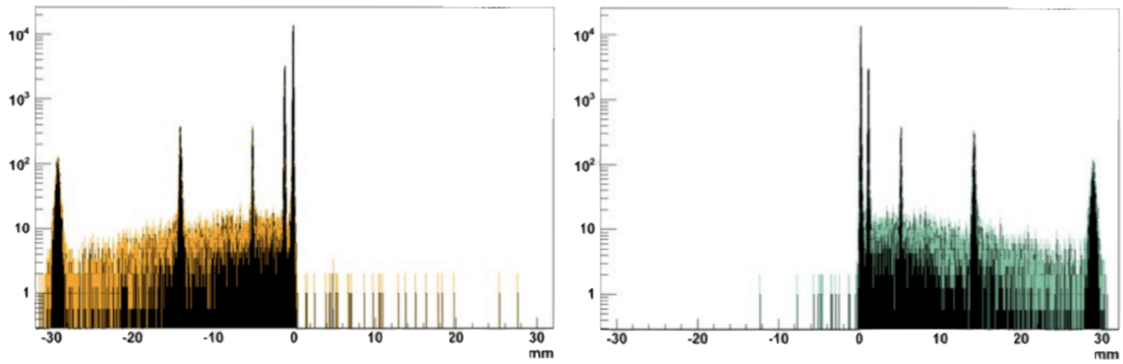

Figure 3: The closing as seen through the eyes of the VELO, with vertex positions reported in the local frame of each half. The positions where the VELO paused (±29, ±14, ±5, ±1, 0 mm) are clearly visible.

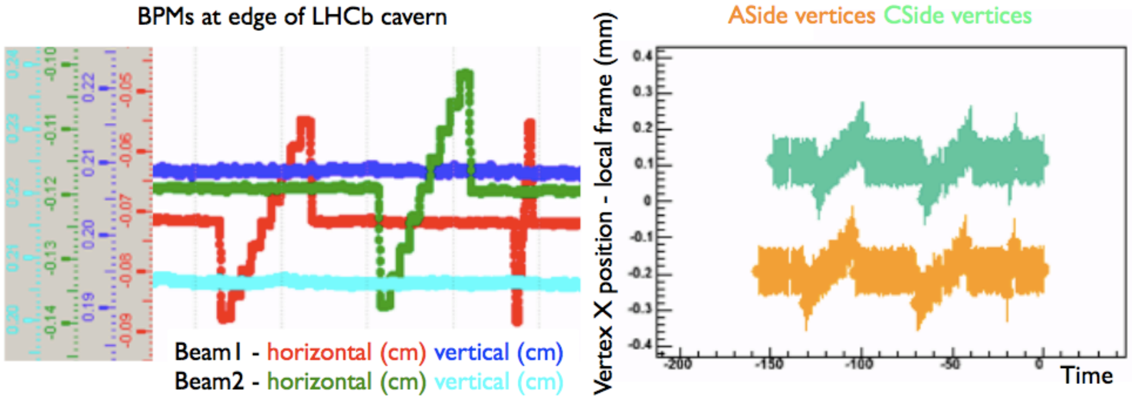

Figure 4: During a Van der Meer scan, the movement of the two beams in the horizontal plane (seen in the BPMs, left) manifests itself as a change in the x position of the reconstructed vertices (right). The offset between A and C side vertices is due to measurements being made in the local frame of each half.

4. Vertex resolution

4.1 Method

The primary vertex resolution is strongly correlated to the number of tracks making the vertex; the track multiplicity. This dependency was established using data from recent $\sqrt{s} = 7$ TeV physics runs, and is also seen in LHCb Monte Carlo. Vertex reconstruction is described elsewhere [6].

The general method for determining the resolution is to measure the same vertex twice. This was done by randomly splitting all the tracks from an event into two, and creating a vertex from each set. If two vertices were made with an equal multiplicity, the difference in their positions was calculated. Repeating for all events, a series of residual histograms is produced for varying track multiplicity. The width of the residual histogram is related to the resolution by a factor $\sqrt{2}$ (there being two contributions of the resolution in each residual measurement). In data, an average vertex is made from 25 tracks (see Figure 5), so this is used as the point of comparison between data and Monte Carlo. Resolution also depends on track p_T, however no track ordering was done. The random split method was verified in Monte Carlo as giving the true resolution within uncertainties.

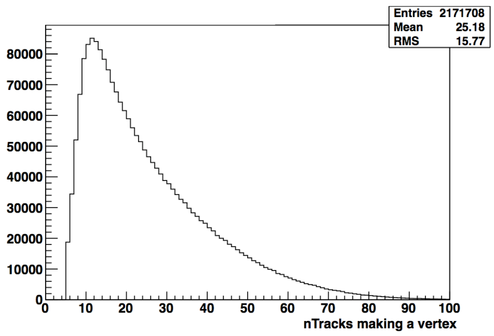

Figure 5: Number of tracks making a vertex in beam-beam events. An average vertex is made of 25 tracks. The highest number of tracks making vertices is around 80, which makes it difficult to calculate the resolution above 40 tracks as the total number of tracks must be split in two.

4.2 Results

This method was applied to data taken at $\sqrt{s}$ =7 TeV. A Gaussian function was fitted to each residual distribution, and the resolution (σ_{res}) taken as the Gaussian $\sigma/\sqrt{2}$. These measurements are seen in Figure 6, where the resolution is plotted as function of the number of tracks. Between 20 and 40 tracks the data points are fitted with the function $\sigma_{\rm res} = \sigma_0/\sqrt{N}$, where σ_0 is the fitted constant and N is the number of tracks. In data, $\sigma_0 = 80 \pm 0.4$ μm in x and y and 456 ± 3 μm in z, corresponding to a 25 track resolution of 16 ± 0.1 μm in the transverse plane, and 93 ± 1 μm in z.

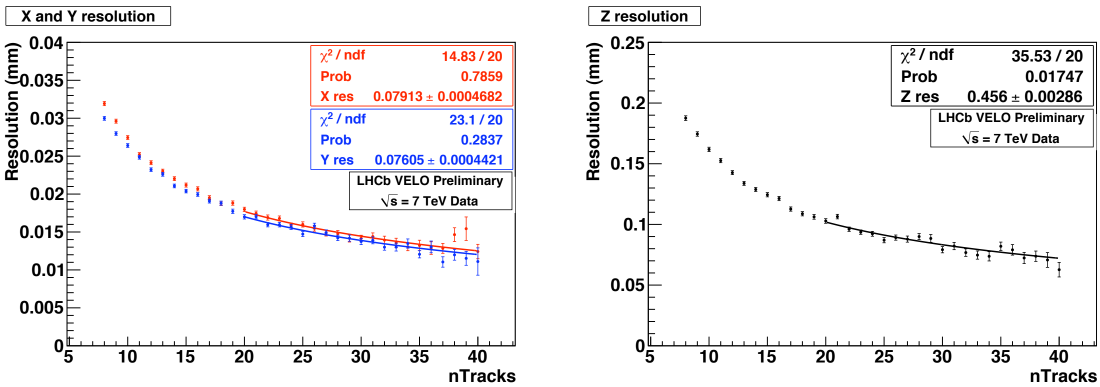

Figure 6: Resolutions as a function of track multiplicity in data. The data points are fitted between 20 and 40 tracks with the function $\sigma_{\rm res} = \sigma_0/\sqrt{N}$, where σ_0 is the fitted constant and N is the number of tracks.

An identical method was applied to Monte Carlo, producing very similar plots. The resolution in the transverse plane for a track multiplicity of 25 was calculated to be around 12 μm, with 57 μm resolution in the z direction. When compared with Monte Carlo, the z resolution in data appears more degraded than the resolution in the transverse plane. However, taken together these figures are in fact consistent with a scenario in which the VELO modules are misaligned by around 10 μm [7]. The systematic uncertainty due to half mis-alignment was estimated by offsetting the two halves by (10, 5, 25) μm in (x, y, z), the result being uncertainties of $(0.1, 0.1, 1)$ μm. Additionally, the systematic uncertainty due to sensor misalignment has been estimated to be 3 μm in the transverse plane, and $30 - 50$ μm in z. The status of the alignment is covered in more detail elsewhere [8, 9].

5. Luminosity measurement

5.1 Introduction

The luminosity delivered during the 2009 physics runs was determined directly using beam parameters [10]. This enables cross section measurements to be performed with these data [11].

Simplistically, for N bunches the luminosity $\mathscr{L}$ can be determined by considering the equation:

$$\mathscr{L} = f \sum_{i=1}^{N} \frac{n_{1i} n_{2i}}{A_{\mathrm{eff}i}} \tag{5.1}$$

where f is the frequency of revolution of the LHC, n is the number of protons per bunch, and $A_{\mathrm{eff}i}$ is the effective area of collision between two bunches. This is calculated using an overlap integral, and takes into account any offset between the bunch positions, their different widths, and the beam crossing angle.

The revolution frequency of the LHC ring is 11.2 kHz, and beam-current information measured by the machine gives the number of particles per bunch, typically 10^{10} in 2009. Finally, the VELO is used to reconstruct the two beams individually, and the overlap integral calculated.

Due to the low energy of the $\sqrt{s} = 0.9$ TeV runs, the beams' widths and crossing angle were larger than normal. Therefore, as a detector safety consideration, data was taken with the VELO half-open at $\pm$15 mm.

5.2 Beam-gas trigger and reconstruction

Coverage in regions of high pseudorapidity allows the VELO to reconstruct beam-gas events, as can be seen in Figure 7. The "gas" is made-up of the residual particles within the primary LHC vacuum, which in the region of the VELO has a pressure of 10^{-9} mbar. Events lying between -1500 < z (mm) < 1500 can be reconstructed, where the VELO occupies a range of approximately -200 < z (mm) < 800.

The rate of beam-gas events seen in the 2009 pilot runs was approximately 1 Hz for beam 1 events, and 0.1 Hz for beam 2 events. This was achieved using a minimum bias trigger, where beam 1 events were required to have > 2 hits in the SPD and a cluster of p_T > 240 MeV in the hadron calorimeter. Beam 2 events, which spray in the opposite direction to most of the LHCb angular coverage, were required to have > 7 hits in the pile-up detector.

5.3 Resolution of beam-gas events

The overlap integral requires input of the bare beam sizes, however this is measured convoluted with a detector resolution function. In order to correctly calculate the effective area, the resolution was parametrised, and unfolded from the measured beam sizes to achieve the bare beam profiles.

The resolution of beam-gas vertices depends on the number of tracks making each vertex, and on the z position of the vertex. Due to the partially open VELO, and the boosted nature of beam-gas events, the average number of tracks in a vertex is much lower than for the beam-beam scenario and the resolution at each N is worse. However the $1/\sqrt{N}$ behaviour is broadly followed. The dependence on z position is due to the geometry of the VELO and the track extrapolation distance. It was found that the dependence on position was linear and independent of the number of tracks.

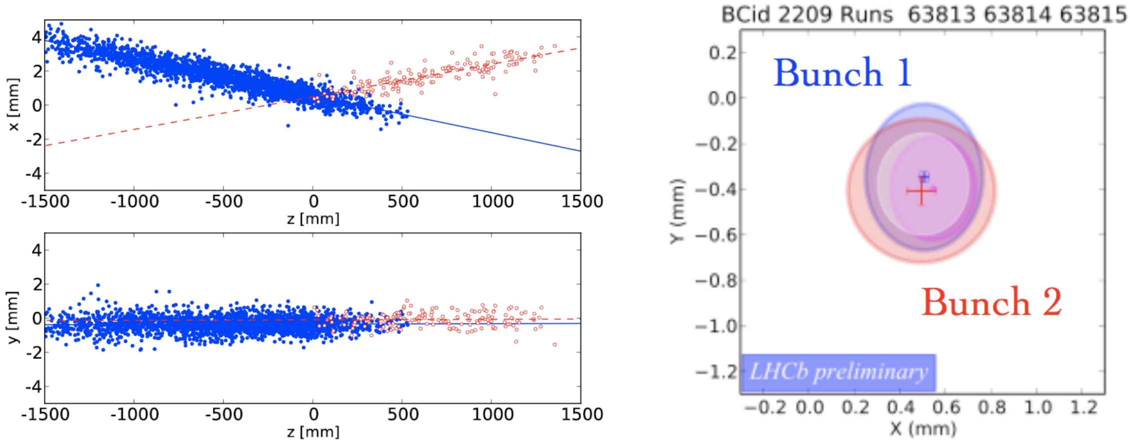

Figure 7: Left: Scatter plot of beam gas events reconstructed by the VELO in the longitudinal (x,z) and (y,z) planes. Blue shows beam 1, red beam 2. The crossing angle is clearly seen. Right: Measured 1σ contour of each beam at the interaction point, shown in the (x,y) plane. The measured luminous region is shown in purple, and the predicted luminous region white.

5.4 Result from 2009 runs

In this way, the resolution of beam-gas events was parametrised in terms of the track multiplicity and z position. This was unfolded from the measured beam widths to give bare beam sizes, which were then used in the overlap integral to find the effective area, see Figure 8. In the $\sqrt{s} = 0.9$ TeV runs of late 2009, LHCb collected $6.8 \pm 1\ \mu\mathrm{b}^{-1}$ of luminosity to be used in first data analyses. The dominant uncertainty is from the beam-current measurements.

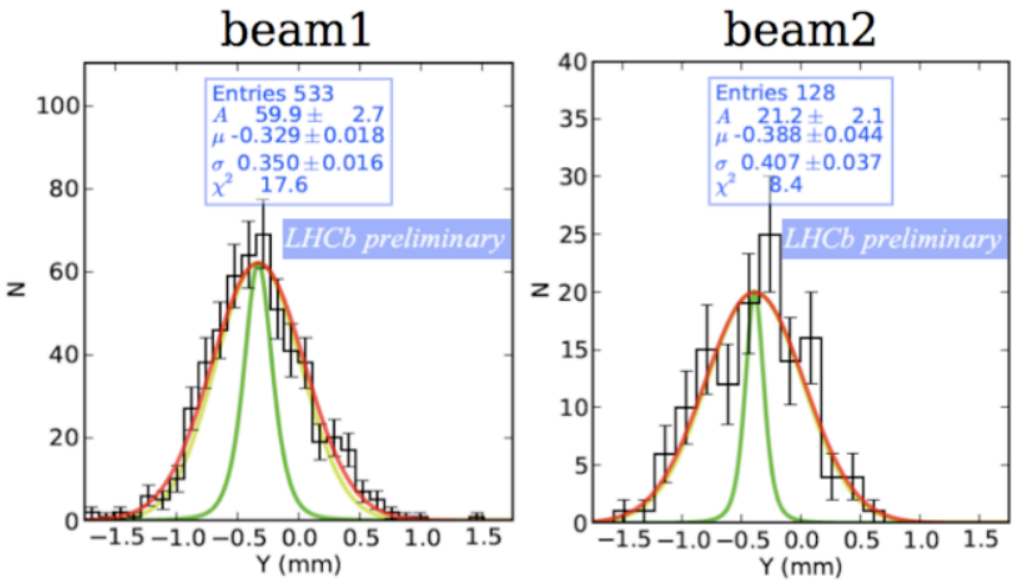

Figure 8: The measured beam sizes (red), and the vertex resolutions (green) for beam 1 and beam 2. The resolution is unfolded from the measured size to give the bare beam profile (yellow - close to the red).

6. Conclusion

The VELO closing procedure is an automated process, designed to safely and efficiently close the VELO around the LHC beams. The process currently takes about 6 minutes and completes closure in 4 movement steps, pausing to verify detector safety, measure the resolver positions and reconstruct the luminous region.

For a typical vertex of 25 tracks, the primary vertex resolution of the VELO has been measured as $16 \pm 0.1 \pm 0.1 \pm 3$ μm in the transverse plane and $93 \pm 1 \pm 1 \pm 50$ μm in z, where the first uncertainty is statistical, the second is the systematic due to half misalignment, and the third is the systematic due to sensor misalignment. This resolution is expected to further improve as the calibration and understanding of the VELO advances.

The VELO's coverage into regions of high pseudorapidity facilitates the reconstruction of beam-gas events. Determining the individual widths of the beams with the VELO, and their resolutions, is of crucial importance for the measurement of the absolute luminosity by LHCb.

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