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Impact of Vertex Detectors on Luminosity Calibration Measurements at the LHC

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Direct luminosity measurements have been performed at the LHC interaction points using both the van der Meer scan method and the novel beam-gas imaging method. This note outlines how vertex detectors contribute to this experimental effort.

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1. Introduction

The ability to measure luminosity on an absolute scale is of general interest in colliding-beam particle physics experiments at storage rings. It allows to determine the absolute cross-section value of reaction processes and to quantify the performance of the machine. For instance, at the CERN Large Hadron Collider (LHC), which has started physics operation in the year 2009, the LHC experiments can use precise cross-section measurements to constrain QCD-based models of *pp* interactions and to detect or quantify new phenomena due to physics beyond the Standard Model of particle physics. In some cases, the required accuracy on the absolute value of the cross section lies around 2% [1], a challenging target that is being approached at the LHC.

The luminosity L for two counter-rotating bunches (here, 1 stands for Beam1 and 2 for Beam2) with time- and position-dependent density functions $\rho_1(\mathbf{x},t)$ and $\rho_2(\mathbf{x},t)$ is given by

$$L = f N_1 N_2 2c \cos^2\alpha \int \rho_1(x,y,z,t)\,\rho_2(x,y,z,t)\,d^3x\,dt \,. \tag{1.1}$$

Here, α is the half crossing angle, f the revolution frequency and N_i denotes the total number of protons in the bunch of beam i that contribute to the luminosity. Ultra-relativistic particles have been assumed. The bunch particle densities $\rho_1(\mathbf{x},t)$ and $\rho_2(\mathbf{x},t)$ are normalized such that their individual integrals over full space are unity. Since the early phase of LHC operation, a series of experiments were carried out to perform first luminosity calibration measurements at each Interaction Point (IP). Two methods were employed: the "van der Meer scan" method (VDM) and the "beam-gas imaging" method (BGI).

In the VDM method [2] a reaction rate is measured as a function of the relative beam separations Δ_x and Δ_y (along the two transverse axes). The luminosity becomes a function of these separations and, for any given process of cross section $\sigma_{\rm P}$, the reaction rate is $R(\Delta_x,\Delta_y) = \sigma_{\rm P}\, L(\Delta_x,\Delta_y)$. When integrated over the displacements, the measured rate gives the cross section (independent of the beam overlap integral). If the density distributions can be factorized, then two scans are sufficient to obtain the cross section: one along a constant y-separation Δ_{y0} and one along a constant x-separation Δ_{x0}. It can be shown that, even in the presence of a non-zero crossing angle [3],

$$\sigma_{\rm P} = \frac{\int R(\Delta_x,\Delta_{y0})\,d\Delta_x \cdot \int R(\Delta_{x0},\Delta_y)\,d\Delta_y}{f N_1 N_2 \cos\alpha\; R(\Delta_{x0},\Delta_{y0})} \,. \tag{1.2}$$

It is assumed that effects due to bunch evolution during the scans (shape distortions or transverse kicks due to beam-beam effects, emittance growth, bunch current decay), effects due to the transverse bunch distribution tails and effects of the absolute length scale calibration against magnet current trims either are negligible or can be corrected for.

In the BGI method, the beams are left untouched and interactions between beam protons ("*p*") and nuclei ("*A*") of the residual gas are detected [4]. Reconstructing such distinctive *p*-*A* vertices allows one to obtain an image of the transverse bunch profile along the beam trajectory. From the two individual bunch profiles, it is then possible to reconstruct the beam-overlap integral. The simultaneous reconstruction of the luminous region with the vertex detector can also be used to further constrain the overlap parameters[1]. When combined, reconstructed *p*-*A* vertex distributions

[1] As suggested by J. Panman.

mainly constrain the distance between the beams and the ratio of their transverse sizes, while the (much more copious!) reconstructed *p*-*p* vertex distributions constrain the convoluted beam sizes.

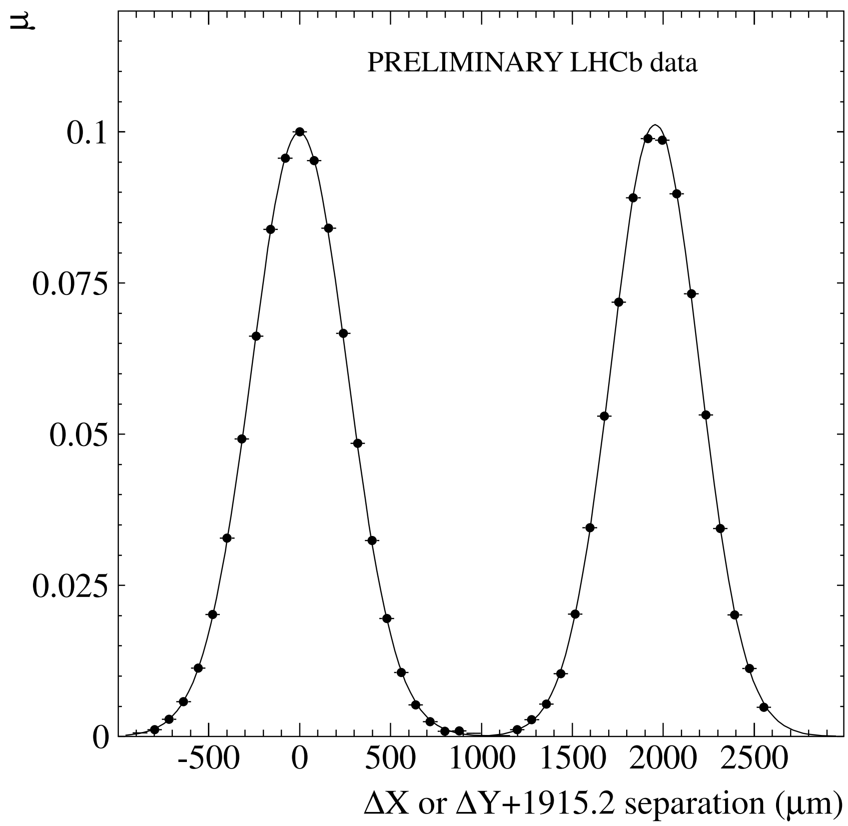

Figure 1: Rate as a function of beam separation in a LHCb VDM scan (x and y). The y separation has been shifted for clarity. The rate is given here as μ, the average number of interactions per crossing. Courtesy of LHCb Collaboration.

For the BGI method a vertex resolution is needed that is comparable or smaller than the transverse beam sizes. Furthermore, the acceptance of the vertex detector must be suitable for detecting beam-gas interactions in the vicinity of the IP, as is the case at LHCb. In that experiment, at the typical residual gas pressure of $\sim 2 \cdot 10^{-9}$ mbar (dominated by hydrogen gas, H_2), a beam-gas interaction rate of about $R \approx n\,d\,\sigma_{pA}\,f\,N \approx 0.2$ Hz is obtained per bunch of $N = 10^{11}$ protons, for free (i.e. without any attempt to increase the rate). Here, $n \approx 10^8$ cm^{-3} was used for the density of gas protons, $\sigma_{pA} \approx 37$ mb for the *p*-*A* inelastic cross section of 3.5 TeV protons on protons at rest ($\sqrt{s} = 81$ GeV) and $d \approx 50$ cm for the length over which beam-gas interaction can be reconstructed by the LHCb vertex detector (VELO). At the LHC injection energy (450 GeV), the cross section is slightly reduced, $\sigma_{pA} \approx 33$ mb.

Compared to the VDM method, the disadvantage of a small rate (which, however, could be increased by controlling the residual vacuum pressure) is balanced by the advantages that (i) the method is non-disruptive, the beams do not move, and (ii) the method can be applied at any time, while taking physics data.

Figure 1 shows an example plot coming out of a VDM scan in IP8 (LHCb). It shows the rate (here given as μ, the average number of visible interactions per crossing). A first scan was made horizontally (x), followed by a second scan in the vertical direction (y).

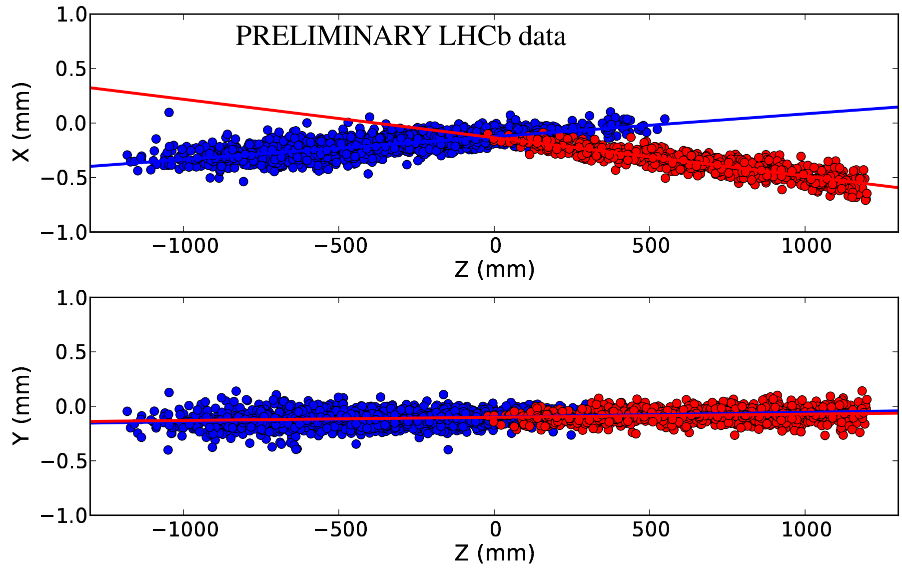

Figure 2: Image of the colliding LHC beams at IP8 obtained by vertex reconstruction of beam-gas interactions with the LHCb VELO. Blue dots: Beam1. Red dots: Beam2. The lines are the results of a linear fit to the vertex positions. The full crossing angle of approximately 540 μrad due to the LHC dipole spectrometer is visible in the x-z plane. Courtesy of LHCb Collaboration.

The BGI method was applied by LHCb over several LHC fills. An example image of the two LHC beams is shown in fig. 2 which was obtained by plotting the positions of the reconstructed beam-gas interaction vertices at IP8. In this case, the beam energy was 3.5 TeV. The lines are the results of a linear fit to the vertex positions.

The VDM and BGI methods provide a measurement of the beam-overlap integral. For determining the luminosity, the bunch population product $N_1 N_2$ appearing in eq. 1.1 was also measured. The bunch intensity measurement for the LHC ring was provided by eight current transformers [5], two DC current transformers (DCCT) and two fast beam current transformers (FBCT) installed on the vacuum chamber of each circulating beam. The DCCT gave a measurement of the total current circulating in each ring, irrespective of the time structure of the beams. The FBCT gave a measurement of the relative bunch populations in each of the 3564 nominal (25 ns) slots of each beam.

The final accuracy obtained on the measured cross section reached 3 to 4%, still dominated by the uncertainties from the bunch current measurements [6, 7]. Ongoing studies show that the latter might be reduced to the 1-2% level which, if succesful, would shift the attention to other sources of uncertainties such as those from beam displacement reproducibility, linearity, absolute scale, or from the factorization assumption, or from the ghost charge determination, etc. Most of these uncertainties can be addressed with the help of vertex reconstruction, as illustrated next.

2. Contribution of vertex detectors

Vertex detectors can and do contribute in many ways to the luminosity calibration measurements at the LHC. As described above, the BGI method heavily relies on the ability to precisely reconstruct *p*-*A* and *p*-*p* interaction vertices. Ideally, the beam size should be sufficiently larger than the transverse vertex resolution, such that the observed beam profiles and luminous region shape are less affected by detector effects. In the LHCb measurements, the beam sizes were of the order of $\sim 80\ \mu$m, while the vertex resolution for *p*-*p* events was about 10 to 50 μm (depending on track multiplicity) and it was a factor 1 to 3 times larger for *p*-*A* vertices (depending on $z_{\rm vtx}$). Therefore, an understanding of the vertex resolution was needed. The measured *p*-*p* vertex resolutions in *x* and *y* are shown in fig. 3 and are compared to the results of a Monte-Carlo simulation.

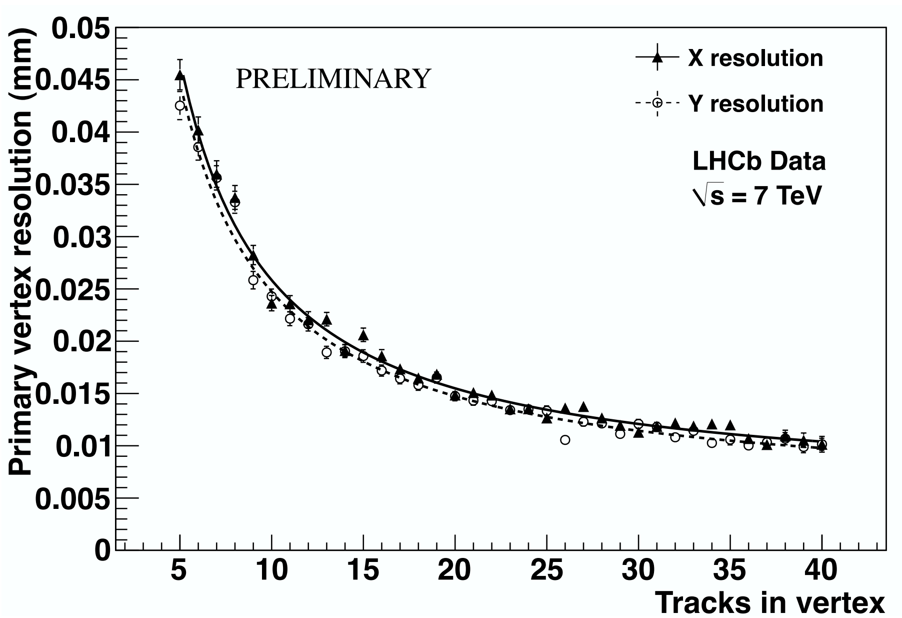

Figure 3: Measured LHCb *x* and *y* vertex resolution for *p*-*p* events (solid triangles and empty circles) as a function of track multiplicity, compared to the results of a Monte-Carlo simulation (continuous and dashed curves). Courtesy of LHCb Collaboration.

It was also recently suggested that imaging of the luminous region during VDM scans can be used to extract the individual beam shapes [3] (without using beam-gas interaction). This provides yet another way to reconstruct the beam overlap. In addition to its use for measuring the beam overlap, the vertex detectors played a crucial role in the following aspects of the luminosity calibration experiments.

2.1 Length scale calibration

The beam displacements during a VDM scan are achieved by local bumps in the beam trajectories. These are calculated based on the knowledge of the machine magnet properties. In order to measure the actual displacements, imaging of the luminous region by vertex reconstruction was carried out for different positions of the luminous region. This calibrates the “length scale” of the local bumps. At the LHC, the comparison of the predicted and measured displacements were always found in excellent agreement, typically within about 1%, for all IPs and for all optics used, indicating an excellent understanding of the machine magnets and geometry.

2.2 Ghost charge

Currently, the total current stored in the LHC is measured with the DCCT and the sums of the relative bunch populations (measured by the FBCT) are normalized to the total current. This may introduce an error, since the FBCT is not sensitive to bunch charges below a given threshold value. In order to determine the “ghost” charge in those bunch slots were none is expected, the *p-A* rate was used which was measured at LHCb with the vertex detector for each of the 3564 LHC bunch slots [6, 7, 9]. The rate for those crossings with no bunch expected in either beam was compared to the rate in the crossings with one bunch in only one of the two beams. In this way a measurement of the proton ghost charge was obtained which, in the worst case observed thus far, amounted to about 1.5%. The measured ghost charge can be subtracted from the total current in order to obtain a more accurate normalization of the summed bunch populations.

2.3 Charge contained in satellite bunches

As mentioned above, not all the protons are captured in the nominal RF buckets. The method described in the previous subsection explains how the ghost charge in the nominally empty 25 ns slots can be measured from *p-A* rates. However, the actual LHC RF frequency is 400 MHz, i.e. the (35640) RF buckets are spaced by 2.5 ns and only one in ten is nominally used for capturing bunches. The LHCb *p-A* method, due to intrinsic timing properties, is not sensitive to possible “satellite” bunches within the 25 ns slot of a colliding nominal bunch. The FBCT integrates the charge over the 25 ns slot, while the nominal bunch is contained within the central 2.5 ns RF bucket. It was therefore important to quantify the charge contained in neighbouring RF buckets by another method. Again, vertex detectors played a role here.

Figure 4 shows the ATLAS primary vertex distribution for a selected VDM scan fill at the LHC, after correcting for the vertex reconstruction efficiency. The central peak is due to interactions from the colliding main bunches. Two additional peaks are clearly visible at $z \approx \pm 75$ cm and are attributed to interactions from the crossing of the main bunches with a satellite bunch displaced by ± 5 ns relative to the main bunch. Note that the crossing angle was nominally zero, in this case. The rate above background in a given z bin around a selected z value was used as a measure of the relative luminosity at the associated z.

Another example (this one from CMS) is displayed in fig. 5 which shows the reconstructed vertex distribution for the two sides of the endcap tracker for the same LHC fill. This gave a broader z_{vtx} acceptance, but a reduced z resolution compared to the barrel tracker for the nominal luminous region. The analysis was carried out separately for the two sides of the tracker. The CMS results showed contributions from satellites at ± 5, 10 and 15 ns.

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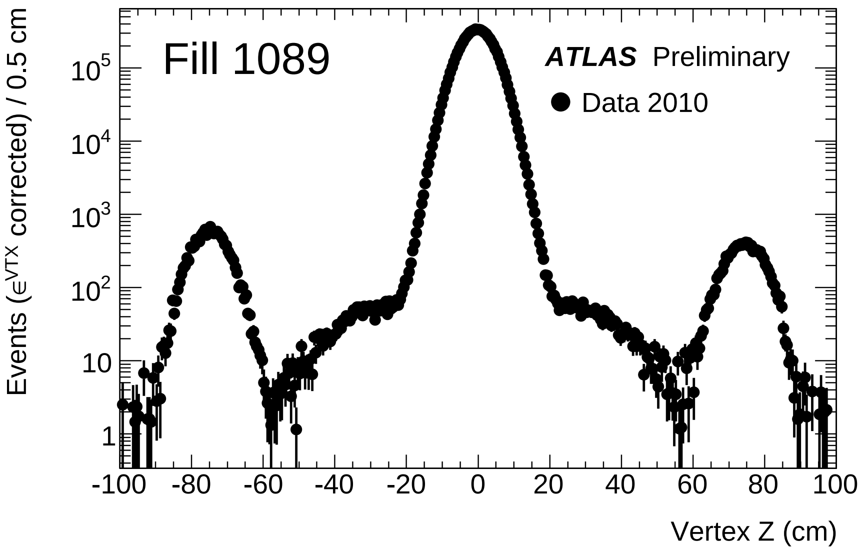

Figure 4: ATLAS primary vertex distribution as a function of z_{vtx} for a selected VDM scan fill at the LHC, after correcting for vertex reconstruction efficiency. Figure from [8]. Courtesy of ATLAS Collaboration.

Based on these measurements, and complementary timing measurements, it was possible to establish that satellite bunches introduce corrections of less than 1% on the bunch charge normalization.

2.4 Possible *xy* correlation effects

The assumption that the *x* and *y* distributions can be factorized simplifies the execution of VDM scans. Indeed, under that assumption, only two scans (one at fixed *x* with varying *y* and one at fixed *y* with varying *x*) are needed. If the factorization assumption is not applicable, a "raster" scan (grid scan) is required, which takes more beam time. It is therefore important to be able to address the validity of this assumption. At the LHC, scans have been performed with an offset in either *x* or *y* to address this issue. In addition, analyses are ongoing which try to quantify the validity of the factorization assumption based on the vertex disributions. So far, the preliminary results seem to confirm this validity, within the boundaries of the achieved accuracy on the luminosity calibration. These results will become important when trying to reduce the final uncertainty of the luminosity calibration measurements.

2.5 Crossing angle and bunch length

There are several ways to measure the crossing angle. At the LHC, two methods that used vertex detectors were explored.

At LHCb, the BGI method gives a direct measurement of the individual beam trajectories at the IP which give the *x* and *y* slopes relative to the vertex detector *z* axis. From these it is possible to extract the crossing angles in both the *xz* and *yz* planes. Figure 2 shows the measured vertices in

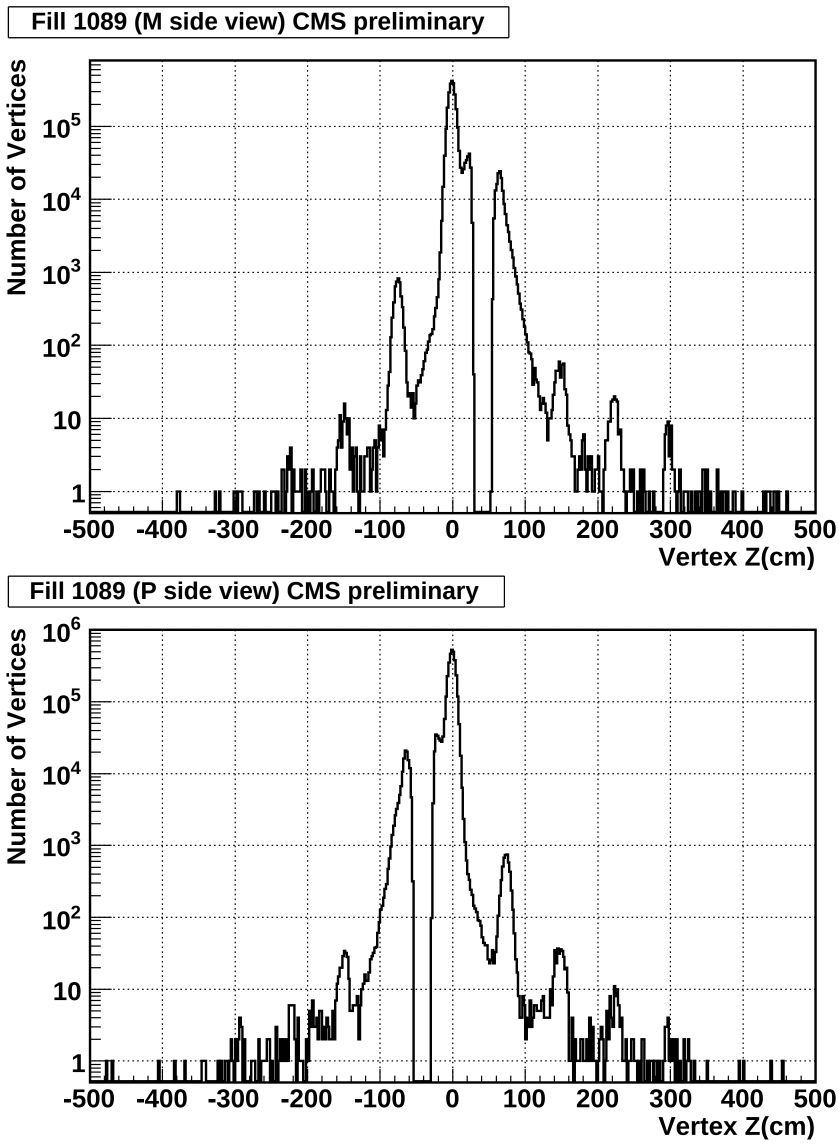

Figure 5: Vertex distribution as a function of z for the same fill as in fig. 4, before correcting for vertex reconstruction efficiency, using the two endcap wheels of the CMS tracker. Figure from [6]. Courtesy of CMS Collaboration.

the two projections from which the angles can be extracted. The crossing angle was measured in this case to an accuracy better than 20 μrad.

Another way is to use luminous region imaging obtained during a VDM scan. One expects that the z mean of the luminous region z_{lum} moves when the beam separation in the crossing plane (here xz) is changed. Assuming the beams are of pure 3-dimensional Gaussian shape, the slope of this relation is given by

$$\frac{\delta z_{\text{lum}}}{\delta \Delta_x} = \frac{\tan\alpha}{2}\left(1 - \frac{\sigma^2_{\text{lum},z}}{\sigma^2_{\text{lum},x}}\frac{1}{\cos^2\alpha}\right) \approx \frac{\tan\alpha}{2}\left(1 - \frac{\sigma^2_{\text{lum},z}}{\sigma^2_{\text{lum},x}}\right) \tag{2.1}$$

where the $\sigma^2_{\mathrm{lum},w}$ ($w = x$ or z) are the Gaussian variances of the luminous region vertex distribution in the crossing plane. Therefore, the crossing angle can be extracted from the measured slope ($\cos^2\alpha$ can be set to 1 for most practical purposes).

Note that, under the same assumptions, there is also an interesting relation between the convoluted bunch length and the luminous region sizes:

$$\frac{1}{\sigma^2_{\mathrm{lum},z}} = \frac{\tan^2\alpha}{\sigma^2_{\mathrm{lum},x}} + \frac{2\cos^2\alpha}{\sigma^2_z} \tag{2.2}$$

i.e. the quadratic mean (between the two beams) $\sigma_z = \sqrt{(\sigma^2_{z,1} + \sigma^2_{z,2})/2}$ of the bunch lengths $\sigma_{z,1}$ and $\sigma_{z,2}$ can be measured from the x and z variances of the luminous region provided the crossing angle is known.

2.6 Non-reproducibility effects in scans

Several calibration experiments using VDM scans were carried out at each IP. Uncertainties associated with non-reproducibility of the scans were in general small compared to the currently achieved accuracy on the bunch population product normalization. However, several effects (at the level of $\sim 1\%$) possibly related to non-reproducibility of the beam displacements may have been observed and are still under investigation. These may become important if the uncertainties of the bunch population normalization are reduced. Studies of possible hysteresis effects or other distortions of the beam displacements during VDM scans will be required and will almost certainly involve the measurement of vertex distributions.

3. Summary

A report was given on luminosity calibration measurements performed at the LHC and on the role of vertex detectors in these experiments. The calibration experiments were based on two methods: the van der Meer scan method and the beam-gas imaging method. In the near future, when the uncertainties on the bunch population measurements will be reduced, the final precision on cross section normalization at the LHC might well be driven by our ability to use and interpret vertex detectors data.

4. Acknowledgements

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References

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