LHCb BEAM-GAS IMAGING RESULTS

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Abstract

The high resolution of the LHCb vertex detector makes it possible to perform precise measurements of vertices of beam-gas and beam-beam interactions and allows beam parameters such as positions, angles and widths to be determined. Using the directly measured beam properties the novel beam-gas imaging method is applied in LHCb for absolute luminosity determination. In this contribution we briefly describe the method and the preliminary results obtained with May 2010 data.

INTRODUCTION

The methods for measuring the absolute luminosity are generally divided into indirect and direct ones. Some of the indirect methods to be used at the LHC are:

- Optical Theorem - can be used to determine the absolute luminosity without knowing the beam intensities. ALTAS-ALFA [1] and TOTEM [2] are going to measure the elastic scattering of protons with detectors located about 200 m away from IP 1 and 5 respectively.
- Use precisely calculable process. For example in e+/e- colliders the Bhabha scattering process is used. At LHC the most promising candidates are the QED processes of Z and elastic muon pair production, both of which are going to be used in LHCb. A more complete description of the prospects for these measurements can be found elsewhere in these proceedings [3].
- Reference cross-section - once any absolute cross-section has been measured it can be used as a reference to calculate the cross-section for other processes.

The direct methods determine the luminosity by measuring the beam parameters:

- Wire method [4] - scan thin wires across the beams and measure rates.
- Van der Meer method [5] - scan beams across each other and measure rates.
- Beam-gas imaging method [6] - reconstruct beam-gas interaction vertices to measure the beam angles, positions and shapes. Results from the application of this method are discussed in this contribution.
- Beam imaging during van der Meer scan - a recently proposed method [7] to measure the beam profiles and overlap by vertex reconstruction of beam-beam interactions.

For absolute luminosity normalization in 2010 the LHC and each of its large experiments performed van der Meer scans. Detailed descriptions of the procedure and the results can be found elsewhere in these proceedings [8, 9, 10, 11].

The beam-gas method for absolute luminosity determination was proposed by M. Ferro-Luzzi in 2005 and was applied for a first time in LHCb (see [12, 13, 14]) using the first LHC data collected in the end of 2009. This measurement represents the only absolute cross-section normalization performed by the LHC experiments at 900 GeV.

In this contribution we report on the further application and results of the method, using 7 TeV center-of-mass energy data collected by LHCb in 2010. Apart from the common beam current measurement, the beam-gas imaging provides an absolute luminosity normalization, which is independent from the one obtained with the van der Meer method.

BEAM-GAS IMAGING METHOD

The luminosity for a single pair of counter-rotating bunches can be expressed with the following general formula [15]:

$$L = fN_1N_2K \int \rho_1(\vec{r},t)\rho_2(\vec{r},t)\, d^3\vec{r}\, dt, \qquad (1)$$

where f is the bunch revolution frequency, N_i are the number of particles in the colliding bunches, $K = \sqrt{(\vec{v_1} - \vec{v_2})^2 - \frac{(\vec{v_1}\times\vec{v_2})^2}{c^2}}$ is the Møller kinematic relativistic factor, c is the speed of light, $\vec{v_i}$ are the bunch velocities and $\rho_i(\vec{r},t)$ are the bunch densities, normalized such that their integral over full space is equal to 1 at any moment t: $\int \rho_i(\vec{r},t)\, d^3\vec{r}\, dt = 1$.

As described in [7], for the case of no crossing angle, the luminosity formula can be written as a function only of the transverse profiles of the colliding bunches $\rho_i^{\perp}(x,y)$:

$$L = fN_1N_2 \int \rho_1^{\perp}(x,y)\rho_2^{\perp}(x,y)\, dx\, dy \qquad (2)$$

The effect on the luminosity for the case of non-collinear beams is described later, in the section *Analysis Overview*. The beam-gas imaging method aims at measuring the overlap integral for a given bunch-pair by measuring the angles, offsets and transverse profiles of the two colliding bunches. This is achieved by reconstructing beam-gas interaction vertices. The gas used as a *visualizing medium* can be the residual gas in the beam vacuum pipe, which consists mainly of relatively light atoms like hydrogen, carbon and oxygen, or a specially designed gas-injection system can be used to create a controlled pressure bump in the region of the LHCb vertex detector. The later would allow to perform the beam profile measurements in a shorter time, thus reducing the effects from potential beam instability. In addition, the injection of gas with high atomic number, like xenon, will result in high multiplicity interaction vertices and improved primary vertex resolution.

An important prerequisite for the proper reconstruction of the bunch profiles is the transverse homogeneity of the visualizing gas. A dedicated test performed in October 2010 measured the beam-gas interaction rates as function of beam displacement in a plane perpendicular to the beam axis. The beams were moved within ± 150 μm (approximately 3 times the beam width) from their nominal position in both x and y. This allowed us to set a limit on the distortion of the measured beam profiles due to transverse inhomogeneity of the residual gas. The needed beam overlap correction from a non-uniform transverse distribution of the residual gas was found to be smaller than 0.05% and was neglected.

The principal precision limitations of the beam-gas method are:

- Vertex resolution - its knowledge plays increasingly important role as the beam sizes become smaller than the resolution.
- Beam-gas rate - determines the time needed to *snapshot* the beam profiles and the associated statistical uncertainty.
- Beam stability - in case of fluctuations of the beam orbits and sizes non-trivial systematic effects need to be taken into account.

It is important to note that in contrast to the van der Meer method the beam-gas imaging method does not involve movement of the beams. This means that possible beam-beam effects are constant and potential effects which depend on the beam displacement, like hysteresis, can be avoided. Furthermore, the beam-gas imaging method is applicable during physics fills.

PRELIMINARY RESULTS FROM MAY 2010 DATA

LHCb [16] is a forward spectrometer covering the pseudo-rapidity range of $\eta \in [2;5]$. It is equipped with a vertex detector (Vertex Locator, VELO), positioned around the interaction point. The VELO consists of two retractable halves, each having 21 modules of radial and azimuthal silicon-strip sensors with half-circle shape, see Fig. 1. Its excellent acceptance for beam-gas and beam-beam interactions is determined by its length of almost a meter and the small inner radius of the sensors, which approach the beam to merely 8 mm when the VELO is at its nominal, closed position. The two most upstream stations (left side of figure 1), the so called *Pile-Up System*, are used in the Level-0 trigger. The VELO is the sub-detector essential for the application of the beam-gas imaging method at LHCb.

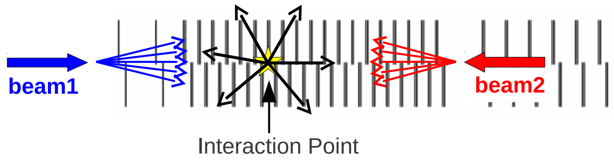


Figure 1: A sketch of the VELO, including the 2 Pile-Up stations on the left. The thick arrows indicate the direction of the LHC beams (beam1 going from left to right), while the thin ones show example directions of flight of the products of the beam-gas and beam-beam interactions.

Running Conditions and Beam-gas Trigger

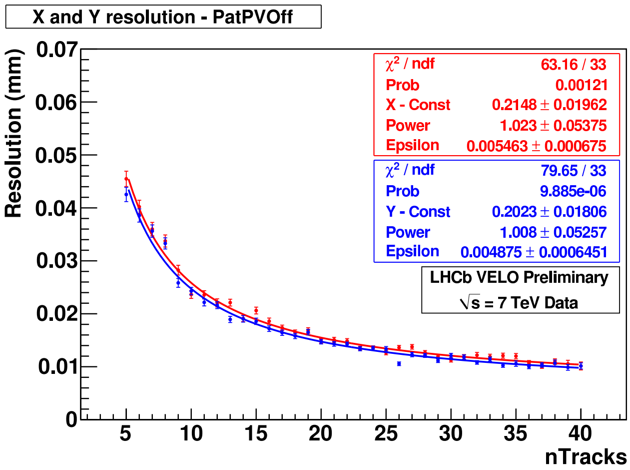
The data used for the results described in this contribution was taken in May 2010 when there were between 2 and 13 bunches per beam and the number of colliding pairs at LHCb varied between 1 and 8. The trigger included a dedicated selection for events containing beam-gas interactions. The relevant hardware (Level-0) triggers are:

- Beam1-gas: select events with a Calorimeter transverse energy sum larger than 3 GeV and a Pile-Up System multiplicity lower than 40.
- Beam2-gas: select events with a Calorimeter transverse energy sum smaller than 6 GeV and a Pile-Up System multiplicity larger than 9.

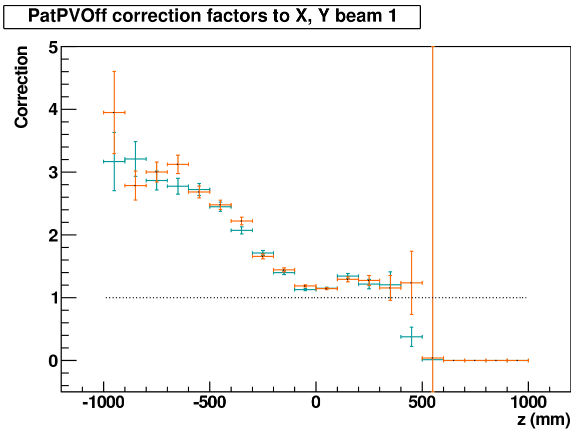
These triggers were enabled in all b-e and e-b crossings (throughout this contribution 'e' is used for denoting an empty bunch slot and 'b' - a bunch slot filled with protons). For the colliding bunches no beam-gas Level-0 trigger was used and the beam-gas events were selected only if they passed any of the 'physics' trigger channels or if they happen to coincide with a proton collision, which fired any of the Level-0 trigger channels. In May 2010 the LHCb hardware trigger was non-selective and the beam-gas interactions in b-b crossings were triggered efficiently. At the High Level Trigger a simple proto-vertexing algorithm selected events by looking for accumulation of tracks around a point on the z axis. The same algorithm was used for the b-e, e-b and b-b crossings, but different z-selection cuts were applied. For example during b-b crossings only interactions with $z < -350$ mm or $z > 250$ mm were selected.

VELO Vertex Resolution

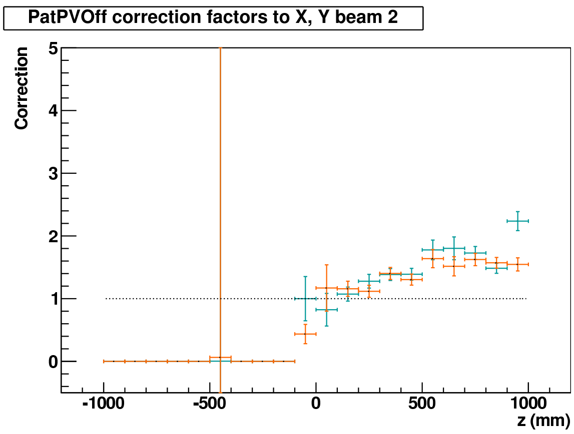
The VELO primary vertex resolution was determined from data in the following way. We randomly split the reconstructed VELO tracks in two equal samples, run a vertexing algorithm on each of them and require that the two reconstructed vertices have equal number of tracks. The width of the distribution of the distance between the two vertices divided by $\sqrt{2}$ gives the resolution estimate for the



(a) Beam-beam resolution in x and y.



(b) Beam1-gas resolution correction factor in x and y.



(c) Beam2-gas resolution correction factor in x and y.

Figure 2: (a) VELO primary vertex resolution in the transverse directions x and y for beam-beam interactions. (b) and (c) resolution corrections in x and y for beam1-gas and beam2-gas interactions, accounting for the z-dependence of the resolution.

half-track vertices. The resolution is parametrized with a Gaussian in two steps. First we estimate the resolution for beam-beam interactions as function of the number of tracks in the vertex, see Fig. 2(a). The used parametrization function has the following form:

$$R(N) = \frac{\sigma_0}{N^{0.5+\frac{\delta}{N^2}}} + \epsilon, \tag{3}$$

where σ_0 is a parameter determining the resolution for small number of tracks, N is the number of tracks per vertex, the power δ accounts for the deviation from the $1/\sqrt{N}$ behavior and ϵ is the asymptotic resolution for large number of tracks per vertex. Later, by comparing the resolution for beam-gas and beam-beam vertices with the same number of tracks, we calculate a correction factor which takes into account the z-dependence of the resolution. Fig. 2(b) and Fig. 2(c) show the beam-gas correction factor as function of z. Finally, the parametrized vertex resolution is used to unfold the true size of the beams.

Analysis Overview

To measure the beam positions and transverse profiles we plot the position of the beam-gas vertices in the x-z and y-z planes. In Fig. 3 we show an example for the case of b-e and e-b crossings. The straight line fits provide the beam angles in the corresponding planes. In general we observe an agreement between the expected and measured beam angles. It is important to note that the colliding bunches are the only relevant ones for the luminosity measurement, because we need to measure the overlap integral for the colliding bunch-pairs.

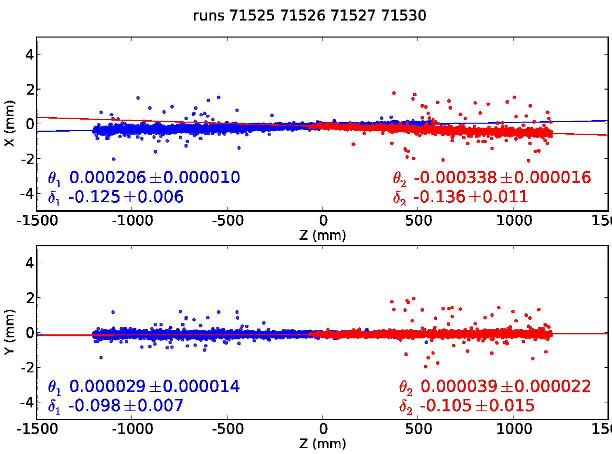
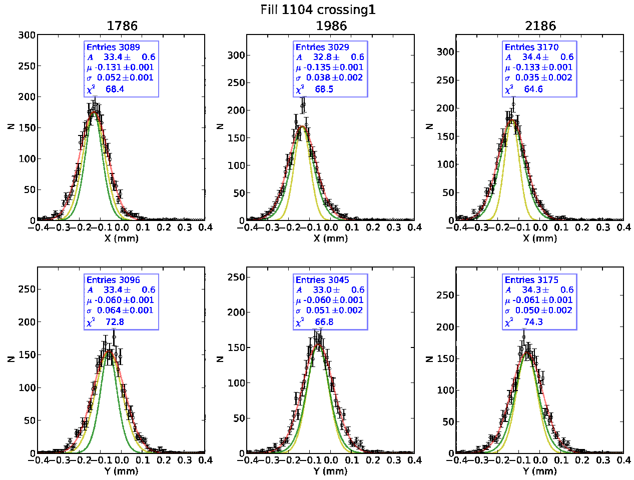
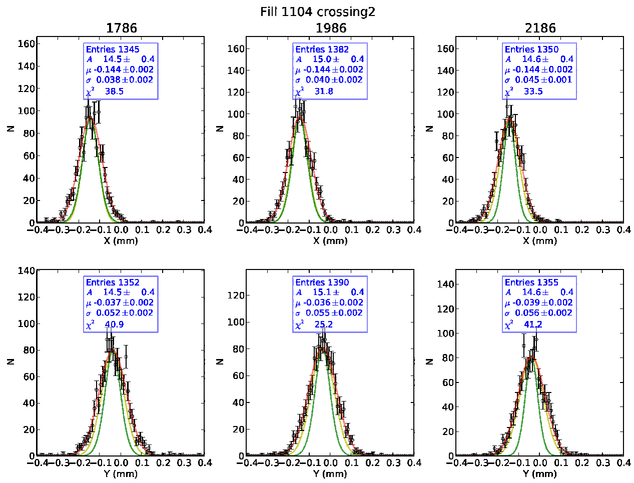


Figure 3: Position of reconstructed beam-gas interaction vertices during b-e and e-b crossings for a May 2010 fill. The measured crossing angles in the horizontal and vertical planes (544 ± 26 and -10 ± 36 μrad respectively) agree reasonably well with the expectations (540 and 0 μrad respectively).

The bunch x and y profiles are obtained from the projection of the x-z and y-z beam-gas vertex distributions onto a plane perpendicular to the beam direction. As an example in Fig. 4 we show the x and y profiles of three colliding bunch-pairs.



(a) Bunches of beam1. Top: x profile, Bottom: y profile.



(b) Bunches of beam2. Top: x profile, Bottom: y profile.

Figure 4: x and y profiles of three colliding bunch-pairs. The different lines represent the raw measured size, the vertex resolution and the unfolded size.

The true bunch size is obtained after deconvolving the vertex resolution. Equally importantly, we use the following relations between the position and size of the luminous region (μ_{BB} and σ_{BB}) and the positions and sizes of the individual beams (μ_1, μ_2, σ_1 and σ_2) as a constraint in the fits.

$$\sigma_{BB}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \qquad \mu_{BB} = \frac{\mu_1 \sigma_2^2 + \mu_2 \sigma_1^2}{\sigma_1^2 + \sigma_2^2} \tag{4}$$

This improves significantly the precision of the beam size measurements.

The calculation of the overlap integral is done initially by integration of the product of two Gaussians representing the widths and positions found with the procedure mentioned above. As the beam profiles are measured in a plane perpendicular to the beam direction we have not yet taken into account the fact that the bunches are tilted and do not collide head-on. The crossing angle correction to be applied on the overlap integral can be approximated with the following formula:

$$C_{\text{crossing angle}} = \sqrt{1 + \left(\frac{\theta_c \, \sigma_z}{\sigma_x}\right)^2}, \tag{5}$$

where θ_c is the half crossing angle and σ_x and σ_z are the bunch sizes in the crossing angle plane. The longitudinal beam size is measured from the beam spot assuming that the two beams have equal size. For the beam conditions in May 2010 the crossing angle overlap correction factor was about 0.95. Formula 5 is a good approximation for the case of no transverse offsets and equal bunch sizes. We now use a numerical calculation which makes a small difference (0.5%).

Preliminary Results with May 2010 Data

With the use of the beam-gas imaging method and following the outlined procedure we performed seven independent measurements of an LHCb-specific reference cross-section. The beam currents, essentially needed for this method, were obtained following the same procedure as described in [17]. The main uncertainties contributing to the overall precision of the cross-section measurement come from the bunch widths (3%), their relative positions (3%) and crossing angle (1%). The measurement of the beam intensities was done with precision of 5% and has dominant contribution to the overall uncertainty. The preliminary results of the analysis are summarized in Fig. 5. For multi-bunch fills the results obtained for each colliding pair were averaged.

The absolute scale knowledge is propagated through the full LHCb dataset with the use of several independent luminosity monitors.

CONCLUSIONS

The beam-gas imaging method was applied on data collected by LHCb in May 2010 and provided an absolute luminosity normalization with uncertainty of 10%, dominated by the knowledge of the beam intensities. The measured LHCb-specific cross-section is in agreement with the measurement performed with the van der Meer method.

In the beginning of 2011 a more refined analysis was performed, providing an improved precision of the beam parameters measured by LHCb. Most notably this later analysis profited from an improved knowledge of the beam currents which allowed a significant reduction of the absolute luminosity normalization uncertainty.

Further precision improvements are possible in dedicated fills with broader beams or fills where both beam-gas and van der Meer methods can be applied simultaneously. In a addition, a controlled pressure bump in the LHCb interaction region would allow us to apply the beam-gas imag-

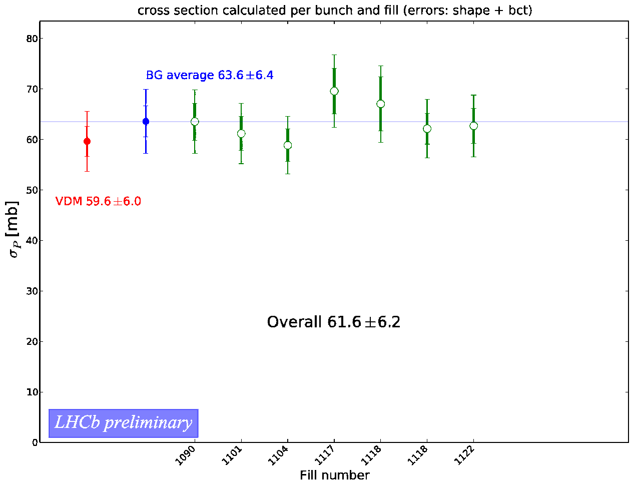


Figure 5: Preliminary results for an LHCb-specific cross-section measured with the beam-gas imaging method. The results for seven different physics fills taken in May 2010 are compared with the ones obtained from a van der Meer scan performed in April 2010.

ing method in a shorter time, decreasing the effects from beam instabilities.

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