Beams scan based Absolute Normalization of the CMS Luminosity Measurement

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Abstract

A campaign of dedicated measurements based on the scan of the LHC beams in the transverse plane at the interaction points have been performed in October 2010. Based on a technique first proposed by Van der Meer, these experiments are used to determine the effective crossing area of the beams that together with the measurement of the beam currents provide an absolute estimation of the LHC luminosity. This document describes the analysis of the CMS data collected during such beam scans and summarizes the results concerning the normalization factor exploited to evaluate the integrated luminosity delivered at the CMS interaction point.

INTRODUCTION

The precise measurement of the production cross sections is a key component of the LHC physics program. The accurate determination of the accelerator luminosity and its related uncertainties is therefore mandatory to achieve this result. The CMS detector [1] exploits the measurements of the forward hadronic calorimeters (HF) to estimate the instantaneous luminosity in real time [2] (in the following referred to 'HF online' method), by means of a dedicated data acquisition system. The event data logged by the central DAQ are also used offline ('HF offline' and 'vertex counting' methods) as cross checks of the online estimates.

A commonly used way to calibrate the instantaneous luminosity measurement consists in determining at the same time in a dedicated experimental setup, both the event rate (R_0) and the absolute luminosity (L_0) on the basis of the beam and optics parameters

$$R_0/L_0 = \sigma_{vis} \tag{1}$$

The quantity σ_{vis} (visible cross section) is then used as constant factor to obtain the instantaneous luminosity during the standard physics operations:

$$L(t) = R(t)/\sigma_{vis} \tag{2}$$

A method originally proposed by Simon Van der Meer and first exploited at the CERN ISR [3] has been adopted at the LHC during the 2010 run [4]. The procedure consists in scanning the beams against each other in the transverse plane to determine their overlap region, hereafter named effective area (A_{Eff}). At the same time the individual bunch currents are measured by dedicated devices (DC BCT and fast BCT [5]). The mathematical bases of the method are described in details for instance in [6], here we only summarize the relevant conclusions. We assume that beams' directions are parallel and that the tridimensional particle density functions can be factorized into the product of three independent one-dimensional functions ($\rho(\vec{r}, t) = \rho_x(x)\rho_y(y)\rho_z(z, t)$). Both these assumptions will be discussed later. The luminosity (and thus the interaction rate) dependence on the beams displacements $\Delta x, \Delta y$ in the transverse plane results in this case to be:

$$\frac{L(\Delta x, \Delta y)}{\nu N_1 N_2} = \frac{R(\Delta x, \Delta y)}{\nu N_1 N_2 \sigma_{vis}} = \int \rho_{1,x}(x)\rho_{2,x}(x - \Delta x)dx \int \rho_{1,y}(y)\rho_{2,y}(y - \Delta y)dy \tag{3}$$

Where we considered only two circulating bunches with frequency ν and total charge population N_1 and N_2 for beam 1 and beam 2. The visible cross section can then be measured by separating the beams in the transverse plane and by integrating in $\Delta x \Delta y$ over the whole plane, obtaining:

$$\sigma_{vis} = \frac{\int R(\Delta x, \Delta y_0)d\Delta x \cdot \int R(\Delta x_0, \Delta y)d\Delta y}{\nu N_1 N_2 R(\Delta x_0, \Delta y_0)} \tag{4}$$

It is worth noticing that this formulation does not set any requirements on the original beam separation $\Delta x_0, \Delta y_0$ (those who are not integrated out), in particular they do not need to be exactly null, i.e. a perfect overall is not necessary at the beginning of the transverse plane scan [6].

In the traditional Van der Meer method, the information related to the luminous region, i.e. the distribution of the collision vertices at the interaction point, is integrated away (cfr. Formula 3). A modern collider experiment as CMS features extremely powerful tracking and vertexing devices, capable of reconstructing collision vertices with a precision of $\mathcal{O}(10)$ micrometers [7]. Recently a new approach has been proposed which makes use of the luminous region as measured by the detector and exploits that to estimate the effective area by means of the reconstruction of the individual beam shapes [6]. The basic idea is rather simple and consists in inverting the integrations in Equations 3 and 4, i.e. first perform the integration over the beam separation and then on the coordinate variable. Hereafter we refer to the scan coordinate as ξ with the latter corresponding with enough precision to either of the CMS transverse axes. Still assuming the possibility of factorizing the density functions, we get for the rate $R(\xi)$ the following relation:

$$\begin{aligned} R(\xi) &\propto \int \rho_1(\xi)\rho_2(\xi - \Delta\xi)d\Delta\xi = \\ &\rho_1(\xi)\int \rho_2(\xi - \Delta\xi)d\Delta\xi = \rho_1(\xi) \end{aligned} \tag{5}$$

where the last equality arises from the normalization of the beam density functions. The Van der Meer scans (VdM scans) are performed with the beams progressively displaced by finite steps, the integral of Eq. 5 is therefore replaced by a sum:

$$R(\xi) \propto \rho_1(\xi) \sum_s \rho_2(\xi - \xi_s)(\Delta\xi_{s+1} - \Delta\xi_s) = \rho_1(\xi) \sum_s \rho_2(\xi - \xi_s)\delta\xi \qquad (6)$$

where the sum extends over the number of steps performed during the scan. Here we assume the step sizes to be the same along the scan ($\forall s, \Delta\xi_{s+1} - \Delta\xi_s = \delta\xi$). This spots out the main feature of this alternative approach: as long as they are the same, the actual beams' displacements during the scan do not need to be known.

The finite vertex position resolution (V) smears the distribution of the collision vertices affecting therefore the measurement of the beam density functions:

$$R(\xi) \propto \sum_s [(\rho_1(\xi)\rho_2(\xi - \xi_s)) \otimes V]\delta\xi = \rho_1(\xi) \otimes V \quad (7)$$

where the last equality holds for density functions represented by linear superpositions of Gaussian functions. The vertex resolution V has then to be known and unfolded from $R(\xi)$ to obtain the bare beam density function.

Once $\rho_1(x, y)$ and $\rho_2(x, y)$ are determined (as $\rho_i(x, y) = \rho_i(x)\rho_i(y)$), the effective area is simply computed from the integration in the transverse plane of their product:

$$A_{\text{Eff}} = \frac{1}{\int \rho_1(x, y)\rho_2(x, y)dxdy} \qquad (8)$$

EXPERIMENTAL SETUP

Two sets of VdM scans have been performed at the CMS interaction point (IP5) in October 2010, during LHC fills 1386 (October 1^{st}) and 1422 (October 15^{th}). The beam optics parameters relevant for the luminosity analysis for the two fills were the same as for the standard physics operations. The expected beam width (σ_b) at the interaction point was $\sim 60\ \mu$m, whereas the half crossing angle was $\sim 100\mu\text{rad}$. The other beam parameters not affecting the optics were set such to improve the conditions for the luminosity measurement. The number of colliding bunch pairs at IP5 were limited to 6 and 3 for fill 1386 and 1422 respectively in order to be capable of recording enough statistics to allow an independent analysis of each of them. The chosen value for the bunch intensity resulted from the trade-off between the optimal working point for the beam current measuring devices (the higher current the less relevant the effect of the constant noise [8]) and the need to limit the beam-beam effect (the lower the intensity the more negligible the collective interaction among the bunches in collision[9]). For both fills the bunch intensity resulted to be $\sim 7 \cdot 10^{10}$ protons per bunch corresponding to an average number of 1.2 inelastic events per crossing.

The scans performed during the two fills differed in the way the beams were moved against each other: during fill 1386 ('double beam scan'), the beams were both taken away from their nominal position symmetrically along a given transverse coordinate up to a total separation of 6 nominal σ_b The beams were then moved at the same time towards each other at steps of $\frac{\sigma_b}{2}$ till they reached the positions opposite to their initial ones. Both the horizontal and the vertical planes were scanned in this way. The scan of fill 1422 ('single beam scan') was performed instead with one beam at the time kept at its nominal position and the other steered from $-280\mu\text{m}$ to $+280\mu\text{m}$ corresponding to a maximum separation of $4.5\sigma_b$ Both beams were scanned in both vertical and horizontal planes with a step size of $\frac{\sigma_b}{2}$. The resulting four individual beam scans are named X1, X2, Y1 and Y2 hereafter in the document (where for instance X1 stands for the scan with beam 1 at rest and beam moved along the horizontal plane). In all cases the time spent on each scan step was 25 seconds.

As mentioned in the introduction, CMS uses a dedicated and independent data acquisition system to record continuously the HF signals allowing the online measurement of the luminosity. For both fills 1386 and 1422, the CMS central trigger and DAQ adopted a special configuration conceived specifically for the VdM scans. It was chosen not to record data from more than 3 bunch crossings, therefore for fill 1386, three out six bunch crossings were masked out at trigger level. Only two kind of triggers were exploited:

- **Zero Bias.** The coincidence of beam-pickup transformer (BPTX) signals from both beams was the only trigger requirement. The first trigger level (L1) output rate (corresponding exactly to the beams revolution frequency times the number of colliding bunch pairs in CMS) was reduced by the High Level Trigger (HLT) to $\sim$ 500 Hz by applying a constant pre-scale factor.

- **Minimum Bias.** At L1, in addition to the coincidence of the BPTX signals, at least one hit from one of the beam scintillator counters (BSC) was required. The corresponding event rate was therefore luminosity dependent with a maximum of $\sim$ 25 kHz when the beams were perfectly overlapping. The rate fell exponentially with the beam separation as $\exp{(-\frac{\delta^2}{4\sigma_b^2})}$. In order to maximize the logging rate a variable pre-scale factor was applied at HLT level such to keep the minimum bias event rate to disk below 1.5 kHz throughout the scan.

The overall recorded event rate never exceeded 2 kHz corresponding to a data bandwidth to disk of $\sim 500\ \text{MB/sec}$ well affordable by the CMS storage system. The average dead time resulted to be negligible.

As explain in the next session, in addition to the standard VdM scans, a calibration scan has been performed to calibrate the length scale of the effective area measurement. This has been done parasitically during a standard LHC physics fill, 1439, with nominal bunch intensity ($\sim 1.1 \cdot 10^{11}$ protons per bunch) and large number of bunches. During both vertical and horizontal scans, the beams were kept at a distance $d_{LS} = \sqrt{2}\sigma_b \sim 70\mu\mathrm{m}$ and steered along the scan plane such that each beam spanned $5d_{LS}$ (5 steps per plane, 30 seconds each). The distance d_{LS} was chosen in order to maximize the sensitivity of the instantaneous luminosity on the beam separation, i.e $\max\{\frac{\partial L}{\partial d}\} = \frac{\partial L}{\partial d}\big|_{d_{LS}}$.

LENGTH SCALE CALIBRATION

In the standard VdM procedure the relative positions of the two beams is computed on the bases of magnetic field model of the corrector dipoles magnets used to steer the beams at the interaction points. In order to calibrate this length scale, the measurements of the experiments tracking systems are used as reference. This is achieved by comparing the predicted displacement of the beams with the movement of the center of the luminous region (known as beam-spot) obtained from the distribution of the reconstructed interaction vertices. Each beam would in principle require a different calibration factor for each plane. The definitions that follow are used to correlated such factors for a given plane, namely α_1 and α_2 for beam 1 and beam 2 respectively, to the position of the beam-spot and the instantaneous luminosity variation. For x_i and x'_i respectively the nominal and actual displacements for the i^{th} beam we thus have:

$$x'_i \equiv \alpha_i x_i \tag{9}$$

At the start of the scan, the two beams are positioned as shown in Fig.1 and their displacements are

$$x'_{10} = x_{10} \equiv 0 \qquad \text{and} \qquad x'_{20} = \alpha_2 x_{20} = \alpha_2 d_{LS} \tag{10}$$

where d_{LS} is the nominal separation ($= \sqrt{2}\sigma_b$).

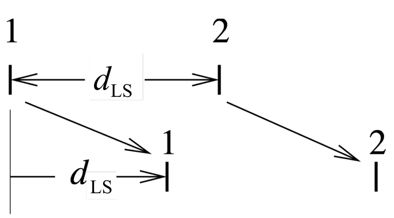

Figure 1: Distance parameters for length-scale scan.

It is convenient to define the average scale factor ($\bar{\alpha}$) and the difference between the scale factors of the two beams (ϵ):

$$\bar{\alpha} = \frac{\alpha_1 + \alpha_2}{2} \qquad \text{and} \qquad \epsilon = \alpha_2 - \alpha_1 \tag{11}$$

where $\bar{\alpha} \sim 1$ and $\epsilon \sim 0$. The difference of the beam-spot position between two consecutive scan steps is thus given by:

$$d_{BS} = \bar{\alpha} d_{LS} \tag{12}$$

In the case the two beams shared the same correction factor ($\epsilon = 0$) then the distance between the beams would remain the same through the scan with no variation in the instantaneous luminosity. A variation of the latter between two consecutive scan steps, expressed as variation of the average number of interaction per crossing, can be used to estimate ϵ:

$$\frac{\delta\mu}{\mu} \simeq -\frac{\epsilon\bar{\alpha}d_{LS}^2}{2\sigma_b^2} \Rightarrow \epsilon \simeq -\frac{\delta\mu}{\mu} \tag{13}$$

where the last equality arises from the fact that $d_{LS} \simeq \sigma_b$ has been chosen for the length scale calibration scan.

It is worth noticing that in the case the VdM scan is performed by moving the two beams at the same time ("double beam scans") by a nominally identical amount, $d_j/2$, in opposite directions, the true separation of the beams is given by:

$$\Delta x_j = x'_{2j} - x'_{1j} = \alpha_2\frac{d_j}{2} + \alpha_1\frac{d_j}{2} = \bar{\alpha}d_j \tag{14}$$

In other words, the actual beam separation is just the nominal beam separation scaled by $\bar{\alpha}$.

Table reports the values obtained from the fits to the length scale calibration scan data along with the inferred values for α_1 and α_2 in both the x and y scans, assuming that $d_{LS} = 70\ \mu$m and $\sigma_b = 57\ \mu$m[1]. Although the latter two values are uncertain to a few percent, they are used to determine a correction which is itself at the 1% level, so that this slight uncertainty can be neglected.

Table 1: Length scale parameters from the fits and the inferred values of $\bar{\alpha}$, ϵ, α_1 and α_2.

	x		y	
	Value	Error	Value	Error
$\bar{\alpha}$	0.9933	0.0013	0.9902	0.0013
μ_0	1.909	0.004	1.775	0.004
μ slope	-1.47×10^{-4}	0.40×10^{-4}	1.37×10^{-4}	0.37×10^{-4}
ϵ	0.0070	0.0019	-0.0071	0.0019
α_1	0.9898	0.0016	0.9937	0.0016
α_2	0.9968	0.0016	0.9867	0.0016

TRADITIONAL VDM ANALYSIS

In the traditional VdM method, the interaction rate as a function of the beam separation is measured and Equation 4 is used to determine the visible cross section. Double Gaussian function is found out to best fit the data and especially the tail of the distribution. For this analysis we assume the beam density functions to be totally uncorrelated in the vertical and horizontal plane. For each plane we have:

$$f_x(x) = \frac{h_x}{\sqrt{2\pi}\sigma_{1x}}e^{\frac{-x^2}{2\sigma_{1x}^2}} + \frac{(1-h_x)}{\sqrt{2\pi}\sigma_{2x}}e^{\frac{-x^2}{2\sigma_{2x}^2}}, \tag{15}$$

[1]The value of σ_b for fill 1439 was derived from the size of the luminous region under the assumption of identical Gaussian beams.

where the effective beam size[2] $\sigma_{\text{eff}}(j)$ for each scan plane j is given by

$$\sigma_{\text{eff}}(j) \equiv \left(\frac{\sigma_{1j}\sigma_{2j}}{h_j\sigma_{2j} + (1-h_j)\sigma_{1j}}\right). \quad (16)$$

In the following the methods used to measure the interaction rate are described. These procedures are based on "zero-counting", i.e. the average number of interactions per crossing is estimated from the fraction p_0 of events with no "counts" through the Poisson relation $\mu = -\ln p_0$. This approach requires in principle very little corrections due to pileup events.

Online methods

The CMS online luminosity measurement employs signals from the HF, which covers the pseudorapidity range $3 < |\eta| < 5$. Two methods for extracting a real-time relative instantaneous luminosity with the HF have been implemented in firmware. The first is based on "zero counting',' in which the average fraction of empty towers is used to infer the mean number of interactions per bunch crossing. The second method exploits the linear relationship between the average transverse energy per tower and the luminosity. In both cases, the detector occupancy and the E_T-sum data are gathered into histograms that have one bin for each of the 3564 possible bunch crossings. The main advantage of the online methods is indeed the very high statistics leading to a statistical precision on the A_{Eff} measurement of $\sim 0.1\%$.

Offline methods

Two offline algorithms were developed for luminosity monitoring. First is based on energy depositions in the HF, while the other uses reconstructed tracks for vertex finding.

- The **HF method** is based on the coincidence of $\sum E_T$ depositions of at least 1 GeV in the forward and backward HF arrays (the sum in each HF runs over all towers). Timing cuts, where $|t_{HF}| < 8$ ns for both HF+ and HF-, are imposed to eliminate non-collision backgrounds.
- The **Vertex method** requires that at least one vertex with at least 2 tracks be found in the event. The z-position of the vertex is required to lie within 150 mm of the center of the interaction region

To remove possible biases associated with trigger efficiency and dead time, events selected by the zero bias trigger are used. For both methods we estimate the mean number of good events per bunch crossing, μ, through "zero counting" by measuring the observed fraction of zero bias triggers with *no* good events. The linearity of the response of the offline methods for different ranges of instantaneous luminosity is verified against the online measurements that benefits from a much higher statistics. The variation in response is tiny and affects the estimations of A_{Eff} from both the HF method and Vertex method by few per mill. The statistical uncertainty on A_{Eff} derived from the fit is $\sim 0.5\%$.

The plots in Figure 2 show a few examples of data distributions and corresponding fitting functions for the double beam scan of fill 1386. Online and offline methods are represented respectively in the upper and lower plots. The individual effective area measurements for both single and double beam scans as obtained by the traditional VdM analysis are summarized in Table 3.

[2] The beam size here is the convolution of both beams.

BEAM IMAGING ANALYSIS

Equation 5 states that one beam can be used as a point-like light source to get the image of the other one. To be totally independent on the reference positions given by the accelerator and rely only on the measurement performed by the tracking and vertexing systems, one beam has to be kept at rest with respect to CMS and the other scanned through it (i.e. the reference frame in which Eq. 5 is defined must be the CMS one). This is exactly the way the single beam scan has been performed during fill 1422. The functional form of $R(\xi)$ in Eq. 5 is obtained from the distribution of the reconstructed collision vertices along the scan coordinate. Events selected by the Minimum Bias trigger are considered. In addition offline selections are applied on reconstructed primary vertices (PV) to achieve an average vertex position error of $\sim 25\ \mu$m. $R(\xi)$ for each beam and each transverse coordinate is constructed by summing up the PV position distribution of each scan step. Every entry of the final distribution is weighted to take into account the pre-scale factor and the dead time associated to the corresponding event.

The bare beam profile functional form ($\rho(\xi)$) is obtained from $R(\xi)$ by performing an unbinned maximum likelihood fit assuming as density function (PDF) a double Gaussian for $\rho(\xi)$ and a simple Gaussian for the vertex position resolution ($V(\xi; \mu = 0, \sigma_r)$). In order to properly take into account the event by event dependency on the vertex position error a conditional probability function is used for the vertex resolution. The PDF used for fitting $R(\xi)$ can be expressed as:

$$f(\xi) = [\frac{h_\xi}{\sqrt{2\pi}\sigma_{1\xi}} e^{\frac{(\xi-\mu_\xi)^2}{2\sigma_{1\xi}^2}} + \frac{(1-h_\xi)}{\sqrt{2\pi}\sigma_{2\xi}} e^{\frac{(\xi-\mu_\xi)^2}{2\sigma_{2\xi}^2}}] \otimes V(\xi; \mu = 0, \sigma_r | d(\sigma_r)) \quad (17)$$

here $d(\sigma_r)$ is the density function of vertex resolution's width σ_r obtained from the distribution of the vertex position error as measured from data.

Biases Estimation and Correction

Vertex Position Resolution Scale A bad estimate of the scale of the vertex position error and therefore of the width of the vertex resolution would directly affect the evaluation

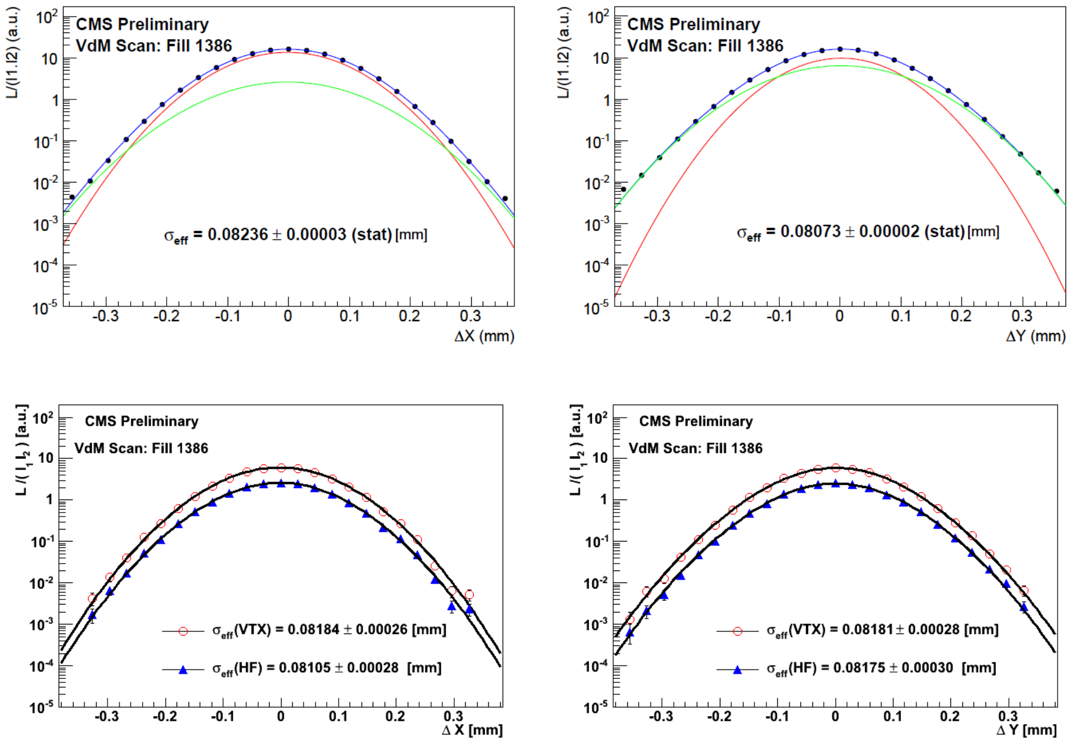

Figure 2: **Upper plots:** Van der Meer scans for the online method summed over all bunch crossings combined in the horizontal (X) and vertical (Y) planes for Fill 1386. For the upper plots, the red, green, and blue curves respectively represent the two Gaussian components of the fit and their sum. **Lower Plots:** Van der Meer scans for the offline methods summed over bunch crossings combined in the horizontal (X) and vertical (Y) planes for Fill 1386. The open circles (red) represent the offline vertex method and the filled triangles (blue) represent the offline HF coincidence method.

of $\rho(\xi)$ (in a rough approximation $\sigma_R^2 = \sigma_\rho^2 + \sigma_r^2$, where σ_R is the width of $R(\xi)$ and σ_ρ is the width of the beam density function). In order to compute accurately the scale of vertex position uncertainty we measure it directly on data adopting a technique described in [7]: the set of tracks used to reconstruct the vertex are randomly spitted into two subsets which are then independently exploited to define two new vertices. The distance between these is thus compared with the position error assigned by the reconstruction algorithm to the original vertex. The width of the relative pull distribution is then used as rescaling factor to be applied to σ_r. Such rescale factor is proved to be independent on the vertex parameters (i.e. mainly the number of input tracks) and results to be $\simeq 0.89$ with a precision of 1%.

Vertex Reconstruction Efficiency The validity of Equations 5-7 relies on the constancy of the primary vertex reconstruction efficiency throughout the scan. Such efficiency possibly depends on the average number of collision per crossing. In order to quantify the relative variation of efficiency during the single beam scan, we studied it on Monte Carlo generated minimum bias events characterized by different pileup scenarios matching what expected for the different beam separations. Given the low value of the maximum pileup occurring in fill 1422, the efficiency variation is very small ($< 0.5\%$), resulting in a negligible overall correction.

Crossing Angle The non zero crossing angle in the horizontal plane implies that the plane orthogonal to the beam being measured is not parallel to the CMS transverse plane, therefore the equalities in Equation 5 do not hold exactly. As demonstrated in [6], it is however possible to reestablish the validity of Eq. 5 by projecting the measurements (i.e. the reconstructed vertex position) into the plane orthogonal to the beam direction accordingly to:

$$x_{1,2} = x - z \sin \alpha_{1,2} \tag{18}$$

This allows measuring the unbiased transverse profile of the beam along its direction. However, as discussed in [6], the actual area contributing to the luminosity result to be wider still due to the presence of the crossing angle. The effective area needs therefore to be rescaled according to the formula:

$$A_{\text{Eff}} \mapsto A_{\text{Eff}} \sqrt{1 + \left(\frac{\sigma_z \sin \alpha}{\sigma_x}\right)^2} \tag{19}$$

where we have assumed the two beams to have the same longitudinal (σ_z) and transverse dimensions (σ_x). The value of σ_z has been estimated from the data multiplying by a factor $\sqrt{2}$ the longitudinal luminous region size (from the assumption of Gaussian beam profiles), whereas for σ_x we used the average of the values obtained from the fit of the individual beam profiles and reported in table 2. The corrections on the horizontal effective areas deriving from Equations 18 and 19 correspond respectively to $\sim -0.7\%$ and $\sim +1\%$, yielding to a rather small net correction.

Fit Results

The plots in Figure 3 display the data distribution ($R(\xi)$) and the corresponding fitting functions for one of the bunch pair colliding at CMS during fill 1422.

Table 2 lists the widths of the individual beam shapes $\rho_i(\xi)$ defined as $\Sigma^{\xi}_{\mathrm{Eff,i}} = \frac{1}{\sqrt{2}\int \rho_i(\xi)^2 d\xi}$. The uncertainties are statistical from the fit, they have been determined by randomly varying the fit parameters by $\pm 1\sigma$ accordingly to the covariance matrix and considering the 68% range of the corresponding distribution of A_{eff}.

Table 2: Widths of the individual beam images. The reported error are statistical from the fit.

	BX 1	BX 51	BX 101
$\Sigma^X_{\mathrm{eff},1}$ (μm)	$54.5^{+0.5}_{-0.1}$	$53.1^{+0.1}_{-0.3}$	$53.1^{+0.1}_{-0.1}$
$\Sigma^X_{\mathrm{eff},2}$ (μm)	$54.5^{+0.1}_{-0.2}$	$54.2^{+0.1}_{-0.2}$	$55.0^{+0.1}_{-0.2}$
$\Sigma^Y_{\mathrm{eff},1}$ (μm)	$61.1^{+0.1}_{-0.5}$	$59.0^{+0.1}_{-0.1}$	$59.9^{+0.1}_{-0.5}$
$\Sigma^Y_{\mathrm{eff},2}$ (μm)	$61.3^{+0.1}_{-0.4}$	$62.2^{+0.5}_{-0.4}$	$61.8^{+0.1}_{-0.5}$

The values for the effective areas averaged over the three colliding bunch pairs of fill 1422 are reported in Table 3. The quoted errors are derived from the RMS of the values for each bunch pair.

Systematic Uncertainties

Three main sources of systematics are identified: those related to the fit procedure, the ones deriving from the finite vertex resolution and finally the uncertainty due to the limited beam scan range. Other possible effects whose contributions are verified to be negligible are listed in the end.

Fit Procedure In order to test the performances of the our fit procedure, a Monte Carlo simulation has been developed reproducing the main features of the single beam scans. Several pseudo experiments have been performed assuming beam parameters similar to what observed from fill 1422 data and the value of the generated A^{ξ}_{Eff} have been compared with the one obtained from the maximum likelihood fit. The fit results to be unbiased and the statistic error ($\sim 0.4\%$) is well in agreement with those obtained from the fit to the data.

Vertex Resolution Scale The precision with which such factor is known translates into an uncertainty on the effective area. We studied this dependency empirically, performing the fit to $R(\xi)$ with the rescale factor varied by $\pm 4\%$ and $\pm 2\%$. The results are shown in the plots of Fig. 4.

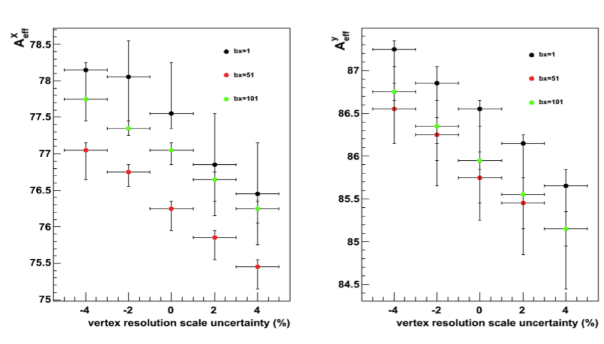

Figure 4: Variation of the computed A_{Eff} (left: horizontal plane, right: vertical plane. The color code represent the three BX colliding a CMS) as a function of the uncertainty on the vertex resolution scale.

For small variations of the scale factor, the relation between the latter and the effective area is linear, $\Delta A_{\mathrm{Eff}}/A_{\mathrm{Eff}} = m\Delta\sigma_r/\sigma_r$. The coefficient m is obtained from the linear fit of the plots in Fig. 4, resulting to be ~ 0.25; given the uncertainty on the vertex resolution scale factor of 1%, the corresponding systematic uncertainty to the estimates on $A^{X,Y}_{\mathrm{Eff}}$ is $\pm 0.25\%$.

Scan Range In order to estimate the effect of the limited scan range in Equation 6 (for the single beam scan, the allowed scan range was ± 4.5 nominal σ_b), we studied the dependency of the measured $A^{X,Y}_{\mathrm{Eff}}$ on the latter: for each plane the value of the effective area resulting from summing the data on restricted ranges (± 3.0, ± 3.5 and ± 4.0 σ_b) are used to extrapolate A_{Eff} beyond the maximum available range.

The Horizontal plane results to be probed completely, whereas for the vertical beam profiles there are indication that a small fraction of the particle distribution may be left not fully probed, i.e. the difference between the extrapolated A_{Eff} values and the actual values obtained on the basis of the available range amounts to 0.5%. Such difference is used to correct the central values for A^Y_{Eff}.

Other (negligible) Systematics Uncertainties Other possible sources of systematics effects have been examined and have been confirmed to have a negligible effect on the measured effective area:

- CMS vertex position measurement scale
- Primary Vertex quality cuts
- PV reco performances as a function of BS position
- Tilts between the CMS and LHC reference frames
- Crossing Angle

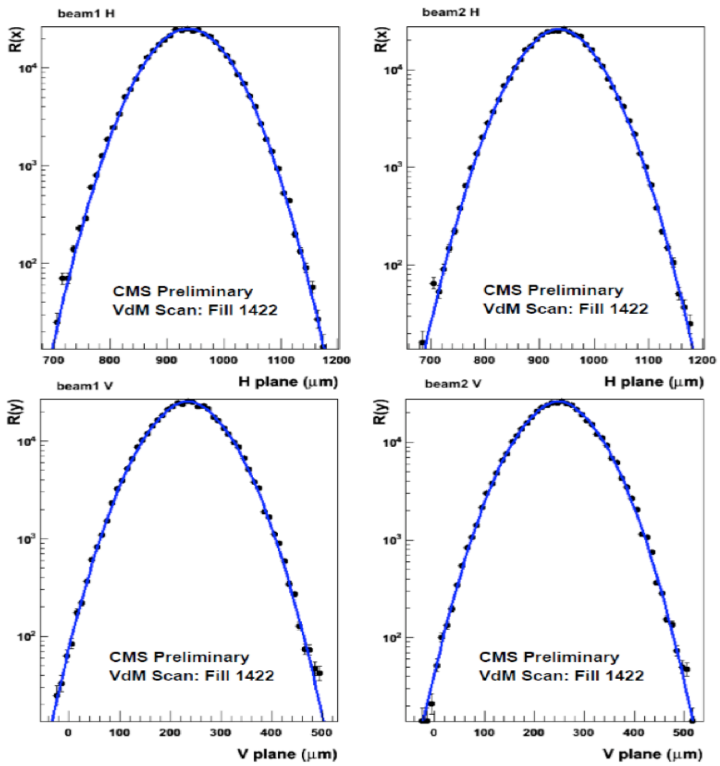

Figure 3: Beam-shape functions for Fill 1422 derived using the beam-imaging method. **Upper Left:** shape of beam 1 in the horizontal direction. **Upper Right:** shape of beam 2 in the horizontal direction. **Lower Left:** shape of beam 1 in the vertical direction. **Lower Right:** shape of beam 2 in the vertical direction.

LUMINOSITY NORMALIZATION RESULTS

Emittance Correction

During the lifetime of a fill, the proton beams in the LHC tend to undergo "emittance blow-up", a process whereby the emittance of the beam increases with time. This effect is important for VdM scans that take place over a period of time such that the instantaneous luminosity of the beams has significantly decreased between the horizontal and vertical scans used to measure σ_x and σ_y. To correct for this effect we exploit the measurements performed by telescopes (BSRT) [10] that provide a bunch by bunch profiling by gathering the synchrotron-light produced by the beam itself. The emittance is then derived from the value of the beta function at the location of these devices.

The visible cross section is best estimated when the dependency of the luminosity on the beams' displacement is minimal, i.e. when the latter is nominally zero. This define the measurement's zero points. The values of the effective areas for the horizontal and vertical plane need to be extrapolated to each zero point accordingly to the specific emittance evolution as obtained from the BRST which in good approximation results to be linear with time:

$$\sigma_{x,y}(t_i) = \sigma_{x,y}(t_0) + m_{\sigma_{x,y}} \Delta t \tag{20}$$

Here $\Delta t = t_i - t_0$, t_i is the time at a given zero-point and t_0 is the time at the maximum of the scan from which the width was measured; $m_{\sigma_{x,y}}$ are the slopes computed from the fit of the BRST data, corresponding to $\sim 1.3 \cdot 10^{-4}$ μm/s and $\sim 3 \cdot 10^{-4}$ μm/s for the horizontal and vertical plane respectively.

Beam Current Measurement

The intensity of each individual colliding bunch is obtained by the combined measurements performed by the DC BCT and fast BCT as explained in details in [8] where the results and relative uncertainties are also reported. An analysis has been performed to determine the amount of charges present in satellite bunches next to the main colliding bunches (5 ns away) based on timing of the signals in the electromagnetic calorimeter. Due to the crossing angle, possible displaced collisions are very much suppressed limiting the sensitivity of the method. For both fill 1386 and 1422 upper bounds have been however set, constraining the satellite population to a few per mill relative to the main bunch intensity.

Results

The results concerning the visible cross section are summarized in table 3. Each method described before provides an estimation of the horizontal and vertical $A_{\rm Eff}$ averaged on the values obtained for each colliding bunch pair. The luminosity calibration factor is expressed as a ratio of the visible cross section measured here and the one used during 2010 LHC run in CMS [2]. We combined the results of three methods exploited such to define five estimates of the calibration ratio (the four possible combinations resulting from the standard VdM analysis of the single beam scan are averaged into one single measurement). The standard deviation of the values obtained for this ratio is 2.51%.

SYSTEMATIC UNCERTAINTIES

Several contributions to the systematic error have been evaluated. A summary appears in Table 4. Individual entries of this table are discussed below. The last two listed in the table and discussed in the text ("HF drift" and "Afterglow") do not concern the luminosity normalization but rather the real-time luminosity measurement during standard physics operations.

Table 4: Summary of contributions to the overall systematic error. All values are percentages. The total error is obtained by adding all components in quadrature.

Term	**Error (%)**
Method & Fill Variation	2.5
Beam Background	< 0.1
Beam Shape	0.3
Non-linear correlations	0.9
Length-Scale Calibration	0.3
Emittance Slope	0.2
Beam Intensity	2.9
HF drift	0.5
Afterglow	0.5
Total	4.0

Method and Fill Variation Following a conservative approach we assume the uncertainty on the visible sigma due to the effective are measurement can be estimated from the variation of the results on the latter obtained by the various methods exploited. The RMS of the five estimates of $A_{\rm Eff}$ summarized in table 3 is thus assumed as uncertainty.

Beam Background This refers to possible backgrounds from non-collision sources and was found to be a negligible effect.

Method & Fill Variation This error reflects the observed RMS variation in the five values of $A_{\rm Eff}$ obtained using different methods and fills shown in Table 3.

Beam Shape In carrying out the fits, we assumed that the beam density function is uncorrelated in the vertical and horizontal planes and that in each plane a double Gaussian is best describing the beam profile. The former assumption has been discussed in [11] and is estimated to lead to an uncertainty of 0.9% (quoted as "Non-linear correlation" in Table 4). We tested the latter assumption performing the fit with different density functions: the variation on the resulting $A_{\rm Eff}$ never exceeds 0.3%.

Length-Scale Calibration For the traditional Van der Meer scans the $A_{\rm Eff}$ values depend on knowing the amount by which the beams have been displaced. This information is provided by the LHC. The LHC values are cross-checked and corrected using beam-position measurements from the CMS vertex detector, as described previously. Given the small amount of the correction, the corresponding error is estimated to be 0.3%.

Emittance Slope Since scans in the horizontal and vertical planes inevitably occur at different times, one cannot directly obtain a snapshot in time that includes all of the factors in the luminosity expression (Eq. 20). Rather, one must extrapolate the $A_{\rm Eff}$ values measured during the scans to a common point in time. To take into account evolution of the beam sizes, emittance data provided by the LHC is used. The typical correction is of order 1%. The 0.2% error quoted represents the uncertainty in those corrections.

Beam Intensity The luminosity depends directly on the number of circulating protons. The measurement of this current is the responsibility of the LHC. The systematic uncertainty on this measurement is determined by the Beam Current Normalization Working Group [8]. The quoted error of 2.9% includes scale uncertainties associated with direct current transformers used to measure the beam intensities as well uncertainties in the offset of the fast beam current transformers used to determine how that current is distributed among the circulating bunches.

HF Drift The calibration procedures described in this note were carried out over a relatively short period of time in October 2010, whereas CMS has acquired data over a period extending from March to November of 2010. Drifts in the calibration of the HF, which is the primary luminometer for CMS, could therefore contribute an additional systematic uncertainty to the luminosity value used in a given analysis. To check for such drifts, we compare the ratio of the luminosity measured by the HF online to the luminosity determined using the offline vertex counting method. Based on this study, we conclude that drifts in the calibration of the HF contribute 0.5% to the overall systematic error.

HF Afterglow The response of the HF to *pp* collisions has a small tail that extends over many (~ 100) bunch crossings. For runs where many bunches are filled, the tails from

Table 3: Summary of relative luminosity calibrations obtained from the various methods. The beam width values have units of microns. Values for the online and offline methods have been corrected for the length-scale calibration. The errors are statistical. The column marked “Ratio” indicates the calibration factor relative to the calibration factor obtained using the scans in spring 2010 [2]. The five numbers in the rightmost column that enter the overall average are highlighted in bold font.

HF Online Method				
Fill	Scan Pair	A^x_{Eff} (μm)	A^y_{Eff} (μm)	Ratio
1386	—	81.81 ± 0.03	79.94 ± 0.02	**1.018**
1422	X1–Y1	76.30 ± 0.04	82.88 ± 0.04	1.007
	X2–Y1	76.83 ± 0.04	82.88 ± 0.04	1.008
	X1–Y2	76.30 ± 0.04	83.80 ± 0.04	0.992
	X2–Y2	76.83 ± 0.04	83.80 ± 0.04	0.993
			1422 Average	**1.000**
Offline Methods				
Fill	Scan Pair	A^x_{Eff} (μm)	A^y_{Eff} (μm)	Ratio
1386	N/A	81.79 ± 0.28	80.33 ± 0.30	**1.013**
1422	X1–Y1	77.53 ± 0.26	84.47 ± 0.30	0.972
	X2–Y1	77.63 ± 0.29	84.47 ± 0.30	0.979
	X1–Y2	77.53 ± 0.26	85.11 ± 0.32	0.961
	X2–Y2	77.63 ± 0.29	85.11 ± 0.32	0.968
			1422 Average	**0.970**
Beam Imaging Method				
Fill	Scan Pair	A^x_{Eff} (μm)	A^y_{Eff} (μm)	Ratio
1422	N/A	77.06 ± 0.21	86.03 ± 0.21	**0.962**
			Overall Average	**0.993**
			RMS	**2.51%**

each bunch crossing add up to contribute an apparent luminosity at the few per-mil level. We conservatively estimate a contribution to the systematic error of 0.5% from this source.

CONCLUSIONS

The Van Der Meer scan performed in October have been used to determine the absolute calibration factor for the CMS luminosity measurement. Different methodologies have been exploited to analyze the scan data to determine the effective area, providing results consistent at 2.5% level. In particular the beam imaging technique has been proved to be a valid complementary approach for the determination of A_{Eff}. The new calibration factor is very similar (to 0.7% level) to the one used for the 2010 run. The CMS luminosity measurement uncertainty derived from this analysis amounts to 4%.

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