CHARACTERIZATION OF INTERACTION-POINT BEAM PARAMETERS USING THE *pp* EVENT-VERTEX DISTRIBUTION RECONSTRUCTED IN THE ATLAS DETECTOR AT THE LHC

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Abstract

We present results from the measurement of the 3-D luminosity distribution with the ATLAS detector during early running. The spatial distribution of *pp* interactions is reconstructed by a dedicated algorithm in the High-Level Trigger that fits tracks and primary event vertices in real time, and by an offline algorithm that takes full advantage of the high tracking efficiency and resolution of the Inner Detector through an unbinned maximum-likelihood fit. The number of vertices provides online monitoring of the luminosity, while luminous-centroid motion mirrors IP-orbit and RF-phase drifts. The x, y and z luminous widths reflect the evolution of the transverse and longitudinal emittances. The length scales of the IP orbit bumps, which directly impact the accuracy of the transverse convolved beam sizes measured during van der Meer scans, are calibrated offline against the measured displacement of the luminous centroid; this significantly improves the accuracy of the absolute luminosity calibration. The simultaneous determination, during such scans, of the transverse convolved beam sizes (from the luminosity variation) and of the corresponding luminous sizes can be used to disentangle the IP sizes of the two beams.

INTRODUCTION

The LHC produced collisions for the first time with the full ATLAS detector [1] recording data in December 2009 at the injection energy of 450 GeV per beam. Operations resumed in Spring 2010, with the first collisions at $\sqrt{s} = 7$ TeV achieved on March 30, 2010. Interaction point (IP) parameters typical of the results reported in this paper are listed in Table 1.

The part of the ATLAS Inner Detector (ID) used for event-vertex reconstruction consists of silicon pixel and strip detectors, arranged in a cylindrical geometry and immersed in a 2 T solenoidal field. The first stage of the ATLAS DAQ system that accesses the tracking data is the Level-2 (L2) trigger, which runs on a farm of hundreds of processors and is capable of performing online partial-event reconstruction at rates of up to 75 kHz. Events passing the trigger selection are stored on disk and are subsequently processed by the ID offline reconstruction software, where more elaborate algorithms can be brought to bear.

Table 1: Typical beam parameters during early LHC operation through Apr 26, 2010. n_c is the number of colliding bunches, N_b the bunch charge, ϵ_N the normalized transverse emittance, β^* the IP β-function, σ_z the bunch length, and $\mathcal{L}$ the luminosity.

$\sqrt{s}$ (TeV)	0.9	7.0
n_c	1 - 9	1 - 2
N_b (protons/bunch)	1.5 $\times 10^{10}$	1.1 $\times 10^{10}$
$\epsilon_{N\,x,y}$ (μm-rad)	2 - 4	1.5 - 10
$\beta^*_{x,y}$ (m)	11	11 - 2
σ_z (mm)	65	30 - 60
$\mathcal{L}$ (cm^{-2} s^{-1})	1 - 3 $\times 10^{26}$	0.1 - 1.2 $\times 10^{28}$

EXPERIMENTAL METHOD

A minimum-bias trigger, requiring at least one or two hits in a scintillator-counter array on either side of the IP in coincidence with two beam pickup signals, is used to seed a full scan of the ID data for finding and fitting tracks [2]. The primary vertex in the event is reconstructed by a fast algorithm that requires as few as two tracks with $p_{\mathrm{T}} > 1$ GeV in the pseudorapidity range $|\eta| < 2.5$. This dedicated L2 algorithm reconstructs and monitors the distribution of event vertices, aggregated across the farm in real time.

Primary event vertices are also reconstructed offline and combined into an unbinned maximum-likelihood fit to extract luminous-region parameters. To reject background and ensure a good position resolution, only vertices formed from at least 4 tracks are considered. Under the assumption that the vertex distribution is a 3-D Gaussian, the fit extracts its centroid position, its orientation and its longitudinal and resolution-corrected transverse sizes. The transverse vertex resolution depends on the multiplicity and momentum of the associated tracks and is on the order of 75 μm. The accuracy of the resolution-correcting procedure is quantified from the data by analyzing the displacement of vertices resulting from splitting a single primary vertex into two vertices with half the number of tracks each [2].

LUMINOUS-REGION ANALYSIS

The luminosity distribution is characterized by the luminous-centroid coordinates, the horizontal and vertical luminous-tilt angles, the transverse luminous sizes $\sigma_{x\mathcal{L}}$ and

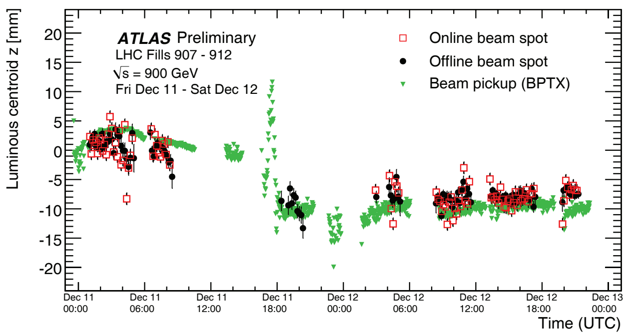

Figure 1: Evolution of the longitudinal centroid positions as measured by vertex fitting (black circles and red squares) or using electrostatic beam pickups (green triangles).

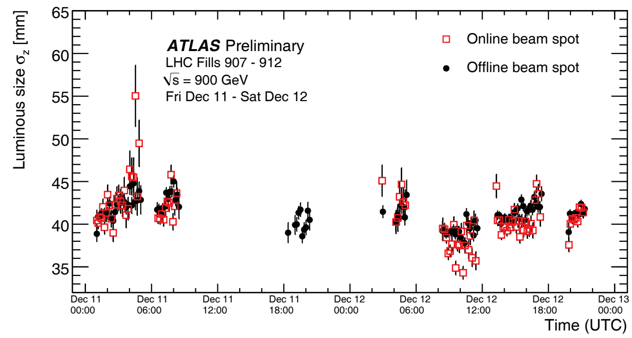

Figure 2: Luminous-length history at $\sqrt{s} = 900$ GeV.

$\sigma_{y\mathcal{L}}$ and the luminous length $\sigma_{z\mathcal{L}}$ [3]. These observables mirror the parameters of the distribution of event vertices listed in the previous section.

The vertical luminous size is related to the vertical size of beams 1 and 2 by

$$\sigma_{y\mathcal{L}} = \left({\sigma_{y1}}^{-2} + {\sigma_{y2}}^{-2}\right)^{-1/2} \tag{1}$$

and similarly for $\sigma_{x\mathcal{L}}$. Provided the hourglass effect is negligible, the luminous length $\sigma_{z\mathcal{L}}$ equals half the longitudinal *convolved beam size* Σ_z, with

$$\Sigma_j = \sqrt{{\sigma_{j1}}^2 + {\sigma_{j2}}^2} \qquad (j = x, y, z)\ . \tag{2}$$

The transverse convolved beam sizes Σ_x, Σ_y are measured by transverse luminosity scans, and are simply related to the specific luminosity ($\mathcal{L}_{sp} \sim 1/\left(2\pi\, \Sigma_x\, \Sigma_y\right)$).

The time evolution of the luminous-centroid position is recorded online at approximately two-minute intervals, and independently reconstructed offline with updated detector-calibration and alignment constants. Over the course of the 2009 run, and with the exception of a couple of step changes associated with orbit adjustments, the transverse luminous centroid remained within a ± 25 μm envelope, implying an orbit stability at the level of a few percent of the IP beam size at 450 GeV [2]. The vertex-based determinations of the longitudinal position of the collision point are compared in Fig. 1 to that extracted from the arrival times (corrected for cable-length differences) of the colliding bunches as measured by beam pickups: the agreement is compelling.

The luminous length is extracted online from a Gaussian fit to the longitudinal vertex distribution or equivalently from the offline maximum-likelihood fit. Fig. 2 illustrates its evolution over part of the 900 GeV run. The rate of increase is about 2.5 % over 3.5 hours, indicating a longitudinal-emittance growth in the LHC, which is fairly reproducible from fill to fill. The typical value of $\sigma_{z\mathcal{L}} =$ 40-45 mm is noticeably smaller than that predicted from the nominal bunch length of 11 cm at that energy. In the transverse plane, the vertexing resolution contributes significantly (and, at high energy, dominates) the observed width of the transverse vertex distributions: the corresponding luminous sizes are extracted using the offline maximum-likelihood method. A history of $\sigma_{y\mathcal{L}}$ over part of the 2009 run is presented in Fig. 3. While roughly consistent with the value of 200 μm predicted using the nominal value of $\epsilon_N = 3.75$ μm and $\beta^* = 11$ m, the vertical luminous size was systematically 20 % to 50 % larger than the horizontal size. Its systematic increase during most fills was found to be correlated with the vertical-emittance growth observed on the (then uncalibrated) synchrotron-light monitor of beam 2.

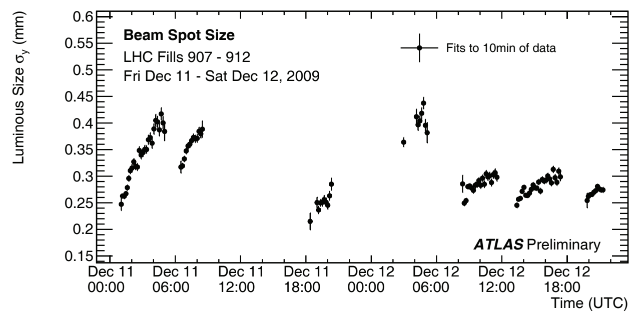

Figure 3: History of $\sigma_{y\mathcal{L}}$ (corrected for resolution) at $\sqrt{s} = 900$ GeV. Errors are statistical only.

These observations are confirmed by a systematic comparison between measured and expected luminous sizes at $\sqrt{s} = 7$ TeV (Fig. 4). Here ATLAS measurements of $\sigma_{y\mathcal{L}}$ are compared with a prediction based on wire-scanner measurements of the vertical emittances, together with β^* values determined by the phase-advance method. The predicted single-beam sizes are combined to infer the luminous size using Eq. 1. The errors attached to the luminous-size measurements are statistical only. The corresponding systematic uncertainty on $\sigma_{x\mathcal{L}}$ and $\sigma_{y\mathcal{L}}$ is 5 to 10 μm, dominated by the correction for the vertexing resolution. No error bars are shown on the luminous sizes inferred from accelerator parameters: they are estimated to be roughly 10 % on each of ϵ_N and β^*. The agreement between the ATLAS and the LHC measurements is remarkable.

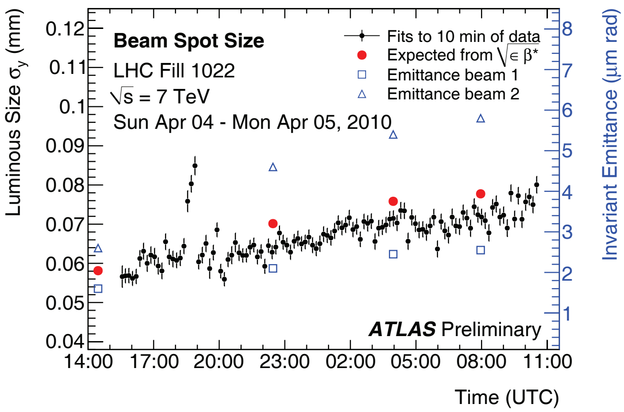

Figure 4: Vertical luminous size measured by ATLAS and corrected for instrumental resolution (points with error bars), compared with that predicted (red circles) using emittances (blue squares and triangles) and IP β-functions measured independently.

LUMINOSITY SCANS

Beam-beam scans provide a simple method [4] for calibrating the absolute luminosity by measuring simultaneously Σ_x, Σ_y, the charges of the colliding bunches, and any quantity proportional to the collision rate. The convolved beam sizes are determined by scanning one beam transversely across the other and recording the event rate variation as a function of the two-beam separation. Such a scan was performed [2] at the ATLAS IP during early 7 TeV operation, albeit over a limited separation range and only for luminosity-optimization purposes. Gaussian fits of the online primary-vertex counting rate *vs.* beam separation yield $\Sigma_x = (94\pm1)\,\mu$m and $\Sigma_y = (123\pm1)\,\mu$m, where the errors are statistical only. As discussed below, these results are compatible with expectations, and as such constitute a confirmation of the feasibility of the method at the LHC. But they should be interpreted with caution because these scans were not yet tailored to careful Σ measurements.

In order to extract the luminosity from such scan data, it is critical to determine very precisely the absolute length scale of the closed-orbit beam-separation bumps: a relative scale uncertainty of several percent would translate into the same systematic uncertainty on Σ_x and/or Σ_y. The vertexing ability of the ATLAS ID, together with its precisely-known geometry, provide a powerful calibration tool for this scale. The location of the luminous centroid is first measured with the beams colliding at their nominal position. Both beams are then moved together by programming the same transverse displacement into both closed-orbit bumps, and the luminous-centroid position is measured anew. The procedure [2] is repeated at a minimum of three positions in both the horizontal and vertical directions. The input bump amplitudes were found to agree almost perfectly with the measured absolute displacements of the luminous centroid; the associated systematic scale uncertainty is estimated at roughly $\pm2\,\%$ in each plane.

Table 2: Comparison of single-beam ($\sigma_{ib}^{\rm pred}$) and luminous ($\sigma_{i\mathcal{L}}^{\rm pred}$) sizes predicted using the emittances $\overline{\epsilon}_{ib}$ measured with wire scanners, with the corresponding values ($\sigma_{ib}^{\rm meas}$) inferred from the combination of the directly-measured convolved ($\Sigma_i^{\rm meas}$) and luminous ($\sigma_{i\mathcal{L}}^{\rm meas}$) sizes during LHC fill 1022. The errors are statistical only.

$i\ b$	$\overline{\epsilon}_{ib}$	$\sigma_{i\mathcal{L}}^{\rm pred}$	$\sigma_{i\mathcal{L}}^{\rm meas}$	$\Sigma_i^{\rm meas}$	$\sigma_{ib}^{\rm pred}$	$\sigma_{ib}^{\rm meas}$
x 1	1.71	53.0	46 ± 2	94 ± 1	71.0	59^{+7}_{-6}
x 2	2.15				79.6	73^{+4}_{-7}
y 1	1.85	60.0	60 ± 2	123 ± 1	73.9	77^{+10}_{-6}
y 2	3.60				103.0	96^{+4}_{-9}

Because the transverse convolved beam sizes and the luminous widths depend differently on the single-beam sizes σ_{ib} ($i = x, y;\ b = 1, 2$), a simultaneous measurement of Σ_x, Σ_y and of $\sigma_{x\mathcal{L}}$, $\sigma_{y\mathcal{L}}$ at zero beam separation yields [3] a direct determination (up to a two-fold ambiguity) of the individual transverse sizes of beams 1 and 2:

$$\sigma_{1,2}{}^2 = \Sigma^2/2 \pm \sqrt{\Sigma^4/4 - \Sigma^2\,\sigma_{\mathcal{L}}{}^2}\,. \qquad (3)$$

The results can be validated (and the ambiguity sometimes lifted) by comparing them to single-beam IP sizes determined from measured emittances and lattice functions. This is illustrated in Table 2 using the convolved beam sizes determined during the luminosity-optimization scans discussed earlier, together with the luminous sizes measured immediately afterwards.

CONCLUSION

We have used the ATLAS Inner Detector, Trigger and Offline infrastructure to measure luminous-region parameters and their time evolution at the LHC. Primary-vertex distributions provide an experimental characterization of the spatial luminosity distribution. These measurements were successfully correlated with data from beam pickups, synchrotron-light monitors and wire scanners. The absolute length scales of the closed-orbit bumps, which are crucial to the absolute luminosity calibration, were calibrated against luminous-centroid displacements. The potential for simultaneously measuring the transverse convolved and luminous sizes, and for plausibly extracting single-beam sizes at the IP, was successfully demonstrated during an early luminosity scan, yielding encouraging agreement between direct measurements and expectations from machine parameters.

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