ALICE 2017 luminosity determination for pp collisions at $\sqrt{s} = 5$ TeV

ALICE Collaboration

Abstract

Luminosity determination in ALICE is based on visible cross sections measured in van der Meer scans. In November 2017, the Large Hadron Collider provided proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 5$ TeV. A van der Meer scan was performed, in which the cross section was measured for two classes of visible interactions, based on particle detection in the ALICE luminometers: the T0 detector with pseudorapidity coverage $4.6 < \eta < 4.9$, $-3.3 < \eta < -3.0$ and the V0 detector with pseudorapidity coverage $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$. This document describes the experimental setup for such a measurement and reports its results.

*See Appendix A for the list of collaboration members
1 Introduction

Luminosity determination in ALICE (A Large Ion Collider Experiment) [1] at the Large Hadron Collider (LHC) is based on visible cross sections measured in van der Meer (vdM) scans [2, 3]. The visible cross section $\sigma_{\text{vis}}$ seen by a given detector (or set of detectors) with a given trigger condition is a fraction of the total inelastic interaction cross section $\sigma_{\text{inel}}$: $\sigma_{\text{vis}} = \varepsilon \sigma_{\text{inel}}$, where $\varepsilon$ is the fraction of inelastic events that satisfy the trigger condition. In the following, a class of inelastic events satisfying a given trigger condition will be referred to as a reference process. Once the reference-process cross section ($\sigma_{\text{vis}}$) is measured, the luminosity at the ALICE interaction point (IP2) is determined as the reference-process rate divided by $\sigma_{\text{vis}}$. This procedure does not require a knowledge of $\varepsilon$.

In standard vdM scans, the two beams are moved across each other in the transverse directions $x$ (horizontal) and $y$ (vertical). The $x$ and $y$ scans are performed separately, the beams being head-on in the non-scanned direction. Measurement of the rate $R$ of the reference process as a function of the beam separation $\Delta x$, $\Delta y$ allows one to determine the luminosity $L$ for head-on collisions of a pair of bunches with particle intensities $N_1$ and $N_2$ as

$$L = \frac{N_1 N_2 f_{\text{rev}}}{(h_x h_y)},$$  \hspace{1cm} (1)$$

where $f_{\text{rev}}$ is the accelerator revolution frequency and $h_x$ and $h_y$ are the effective convolved beam widths in the two transverse directions. $h_x$ and $h_y$ are measured as the area below the $R(\Delta x, 0)$ and $R(0, \Delta y)$ curve (scan area), respectively, each divided by the head-on rate $R(0, 0)$. The cross section $\sigma_{\text{vis}}$ for the chosen reference process is then

$$\sigma_{\text{vis}} = \frac{R(0, 0)}{L}. $$ \hspace{1cm} (2)$$

The formalism of Eq. [1] assumes complete factorisation of the beam profiles in the two transverse directions, such that the beam overlap region is fully described by the product $h_x h_y$. Previous studies performed at the LHC [4–9] have shown that factorisation can be broken to a non-negligible level. Such non-factorisation effects can be studied and quantified by measuring the luminous region parameters via the distribution of interaction vertices, as a function of the beam separation.

In 2017, the LHC provided proton-proton (pp) collisions at a centre-of-mass energy $\sqrt{s} = 5$ TeV. The ALICE luminosity determination for this data sample is based on a vdM scan performed on November 12, 2017 (LHC fill 6380), in which the cross section was measured for two reference processes. In Sec. [2] the detectors used for the measurement are briefly described, along with the relevant machine parameters and the adopted scan procedure. The vdM scan analysis procedure is extensively described in a previous note [3] dedicated to the 2015 luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV; it is briefly recalled in Sec. [3] where the results and uncertainties for the visible cross section and the luminosity measurement are presented and discussed.

2 Experimental setup

In the November vdM scan, the cross section was measured for two reference processes: one is based on the V0 detector, the other on the T0 detector. A detailed description of these detectors is given in [1], and their performance is discussed in [10–12]. The V0 detector consists of two hodoscopes, with 32 scintillator tiles each, located on opposite sides of the IP2, at distances of 340 cm (V0A) and 90 cm (V0C) along the beam axis, covering the pseudorapidity ($\eta$) ranges $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C). The T0 detector consists of two arrays of 12 Cherenkov counters each, located on opposite sides of IP2, at distances of 370 cm (T0A) and 70 cm (T0C) along the beam axis, covering the pseudorapidity ranges $4.6 < \eta < 4.9$ (T0A) and $-3.3 < \eta < -3.0$ (T0C). Note that the clockwise-travelling LHC beam moves from side A to side C. The C side is the one hosting the ALICE muon arm [1].
The V0-based trigger condition, chosen as the reference process, requires at least one hit in each detector hodoscope, i.e. on both sides of IP2. A similar trigger condition defines the T0-based reference process, with the additional condition that the longitudinal coordinate of the interaction vertex lies in the range |z| < 30 cm, where z = 0 is the nominal IP2 position. More details on this online cut, which rejects the background from beam-gas and beam-satellite interactions, are given in [8].

During the vdM scan session, each proton beam consisted of 50 bunches and 22 bunch pairs were colliding at IP2. The minimum spacing between two consecutive bunches in each beam was 1 µs. The β* value at IP2 was 10 m. The nominal half vertical crossing angle of the two beams at IP2 was −365 µrad, the minus sign indicating that the two beams exit the crossing region with negative y coordinate with respect to the beam axis. The current in the ALICE solenoid (dipole) was 30 kA (6 kA), corresponding to a field strength of 0.5 T (0.7 T). The maximum beam separation during the scan was about 0.6 mm, corresponding to about six times the RMS of the transverse beam profile. The reference-process rates were recorded separately for each colliding bunch pair. Two pairs of horizontal and vertical scans were performed, to obtain two independent cross-section measurements per bunch pair. In addition, a length-scale calibration scan was performed.

The bunch intensities were on the order of 8-9×10¹⁰ protons per bunch. The bunch-intensity measurement is provided by the LHC instrumentation [13]: a DC current transformer (DCCT), measuring the total beam intensity, and a fast beam current transformer (fBCT), measuring the relative bunch intensities. For the relative bunch intensities, data from a second device, the ATLAS beam pick-up system (BPTX [14]) is also used. The measured beam intensity is corrected for the fraction of ghost and satellite charge. A measurement of ghost charge is provided independently by the LHCb collaboration, via the rate of beam-gas collisions occurring in nominally empty bunch slots, as described in [16], and by the LHC Longitudinal Density Monitor (LDM), which measures synchrotron radiation photons emitted by the beams [17]. The LDM provides in addition a measurement of the satellite-charge fraction. For this fill, the combined ghost- and satellite-charge correction factor to the bunch intensity product is found to be less than 0.1%.

3 Analysis and results

The reader is referred to Ref. [8] for a detailed description of all the analysis steps. Here, we briefly recall the main analysis features and provide numerical values for the relevant quantities entering the analysis.

The rates for the T0- and V0-based reference processes are determined from the raw trigger rates by taking into account contamination from beam-background, pileup effects and time-dependence of the bunch intensities. The correction for fake coincidences originating from pileup (see Eq. (3) in [8]) uses the ratios of single-side (A&C and C&A), i.e. no signal on one of the two sides) to two-side (A&C) events \( \alpha = \mu_{A&C}/\mu_{vis} \) and \( \beta = \mu_{C&A}/\mu_{vis} \), where \( \mu \) is the average number of events of a given type in a bunch crossing: \( \mu_{vis} = \mu_{A&C} = L \sigma_{vis} \), and similarly for \( \mu_{A&C} \) and \( \mu_{C&A} \). The \( \alpha \) and \( \beta \) parameters were determined by a simultaneous fit to the measured rates of A&C, C&A and A&C coincidences at various luminosities during the vdM scan, and found to be \( \alpha = 0.63 \), \( \beta = 0.57 \) for the T0 and \( \alpha = 0.088 \), \( \beta = 0.071 \) for the V0, with negligible statistical uncertainty. The nominal separation values are corrected

1ALICE uses a right-handed orthogonal Cartesian system whose origin is at the LHC Interaction Point 2 (IP2). The z axis is parallel to the mean beam direction at IP2 and points along the LHC Beam 2 (i.e. LHC anticlockwise). The x axis is horizontal and points approximately towards the center of the LHC. The y axis is approximately vertical and points upwards.

2The \( \beta(z) \) function describes the single-particle motion and determines the variation of the beam envelope as a function of the coordinate along the beam orbit (z). The notation \( \beta \) denotes the value of the \( \beta \) function at the interaction point.

3The radio-frequency (RF) configuration of the LHC is such that the accelerator orbit is divided in 3564 slots of 25 ns each. Each slot is further divided in ten buckets of 2.5 ns each. In nominally filled slots, the particle bunch is captured in the central bucket of the slot. Following the convention established in [13], the charge circulating outside of the nominally filled slots is referred to as ghost charge; the charge circulating within a nominally filled slot but not captured in the central bucket is referred to as satellite charge.
Fig. 1: (Colour online) Rates of the $T_0$ (top) and $V_0$ (bottom) reference process as a function of beam separation for one typical pair of colliding bunches in the first horizontal (left) and vertical (right) vdM scan. The solid red curve is a fit according to a modified Gaussian function [8].

for beam-beam deflection [18] and orbit drifts.

The luminous region parameters used for the length-scale and non-factorisation corrections are measured via the distribution of interaction vertices, determined with the ALICE Inner Tracking System [19] and Time Projection Chamber [20] detectors.

The scan curves are fitted with a modified Gaussian function (see Eq. (4) in [8]). An example of the fit is shown in Fig. 1. Two more models, one based on a double Gaussian function and one which uses numerical integration instead of a fit, are also used to evaluate systematic uncertainties. For each scan, the effective beam widths $h_x$, $h_y$ and the head-on rate $R(0,0)$ are computed from the fit parameters. The beam widths are corrected by a length-scale calibration factor measured in a dedicated scan. The horizontal (vertical) factor is the slope parameter of a linear fit to the measured horizontal (vertical) vertex displacement versus the nominal one. Both fits are illustrated in Fig. 2. In order to account for the fit quality, the uncertainties on the fitted slopes are rescaled by $\sqrt{\chi^2/ndf}$ (only where such a quantity is larger than one). The final correction factor (obtained as the product of the two slopes) is $0.986 \pm 0.002$.

The measured beam widths are combined with the bunch intensities and head-on rates to determine the visible cross sections (Eq. 1 and 2). The possible impact of non-factorisation effects is evaluated by simultaneously fitting the rates and the luminous region parameters (positions, sizes, transverse tilt) with a three-dimensional non-factorisable double-Gaussian model [21], and computing the bias on the head-on luminosity with respect to a factorisable model.
ALICE luminosity determination for pp collisions at $\sqrt{s} = 5$ TeV (2017)

Fig. 2: (Colour online) Average horizontal (left) and vertical (right) vertex coordinate as a function of the nominal beam displacement in the length-scale calibration run, with superimposed linear fit (solid red line).

The procedure is repeated with several fitting schemes, both on a bunch-integrated and a bunch-by-bunch basis. The maximum observed bias (0.1%) is quoted as a systematic uncertainty.

The measured visible cross sections for the T0-based (V0-based) reference process in the two scans are shown in Fig. 3 for all the colliding bunch pairs, as a function of the product $N_1 N_2$ of the colliding bunch intensities. No significant dependence of the results on $N_1 N_2$ is observed. The combined effect of the beam-beam deflection and orbit drift correction is about 1.4% for the first scan, and slightly smaller for the second scan. The effect of orbit drift alone is about 0.1%. The results from the two scans (cf. Fig. 3 and 4) differ by 0.5% (0.4%) for T0 (V0), which is larger than the statistical uncertainties. Hence, the difference is retained as a systematic uncertainty. The weighted average of the results of the two scans is retained as the final result: $\sigma_{T0} = 20.82 \pm 0.01 \text{ (stat.) mb, } \sigma_{V0} = 50.87 \pm 0.04 \text{ (stat.) mb.}$
Fig. 4: Visible cross section for the V0 measured in the first (top) and second (bottom) vdM scan, as a function of the product of the intensities of the colliding bunch pair. Only the statistical uncertainties are shown. The solid line is a constant fit to the data.

Comparing the ratio $\sigma_{T0}/\sigma_{V0}$ obtained from the vdM scan (where, for head-on beams, $\mu_{vis} \approx 0.2$ for the V0) to the ratio between the T0 and V0 rates measured at lower interaction rate ($\mu_{vis} \approx 0.02$ for the V0) in the same LHC fill as the vdM scan, a difference of 0.7% is measured. To account for such a discrepancy of the ratio an uncorrelated systematic uncertainty of $0.7%/\sqrt{2}$, associated to the pileup correction, is assigned to both cross sections. A list of all the systematic uncertainties considered for the visible cross-section measurement is presented in Table 1. Uncertainties not discussed above are evaluated as detailed in [8]. Combining all the uncertainties one obtains for the T0 (V0) a total systematic uncertainty of 1.5% (1.8%), with an uncorrelated component between the two measurements arising from pileup and background subtraction. The statistical uncertainties are negligible with respect to the systematic ones.

The 2017 campaign at $\sqrt{s} = 5$ TeV consisted of about 10 days of data-taking. With the exception of the first two fills, in all the used filling schemes the minimum spacing between consecutive bunches was 25 ns. In order to test the stability of the luminosity measurement provided by the T0 and the V0 for this data set, the ratio between the luminosities measured by the two detectors has been computed for all recorded runs. For each run, the integrated luminosity is measured from the counts of the T0- and V0-based triggers; these are corrected for background and pileup with the same procedure, described in [8], used in the vdM scan, and divided by the corresponding cross section. The results are shown as a function of the run end time in Fig. 5 left. In the first 40 runs, taken at relatively low $\mu_{vis}$ (typically $\approx 0.003$ for V0), the ratio is systematically lower than unity, by about 1%. In the last 10 runs, taken at higher $\mu_{vis}$ (typically $\approx 0.04$ for V0), the ratio is systematically higher than unity, again by about 1%. Possible explanations for such a behaviour are non-perfect background subtraction at low $\mu_{vis}$, and non perfect pileup correction or a decrease of the V0 efficiency at higher $\mu_{vis}$. Fig. 5, right, depicts the distribution of the luminosity ratio over all runs. Each run is weighted with the corresponding integrated luminosity. The mean quadratic difference from unity of the ratio is 1.1%, and is assigned as a systematic uncertainty to the luminosity measurement, to be combined with the uncertainties on the visible cross sections (see Table 1).

\(^4\)In the ALICE nomenclature, a run is a set of data collected within a start and a stop of the data acquisition, under stable detector and trigger configurations. For the considered data-taking period, the duration of a run ranges from $\approx 13$ minutes to $\approx 11$ hours.
Table 1: Relative uncertainties on the measurement of visible cross sections and luminosity in pp collisions at $\sqrt{s} = 5$ TeV.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-factorisation</td>
<td>0.1%</td>
</tr>
<tr>
<td>Orbit drift</td>
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</tr>
<tr>
<td>Beam-beam deflection</td>
<td>0.5%</td>
</tr>
<tr>
<td>Dynamic $\beta^*$</td>
<td>0.2%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.2% (T0), 1.1% (V0)</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.5%</td>
</tr>
<tr>
<td>Length-scale calibration</td>
<td>0.2%</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.5%</td>
</tr>
<tr>
<td>$h_x/h_y$ consistency (T0 vs V0)</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Luminosity decay</td>
<td>0.9%</td>
</tr>
<tr>
<td>Bunch-by-bunch consistency</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Scan-to-scan consistency</td>
<td>0.5% (T0), 0.4% (V0)</td>
</tr>
<tr>
<td>Beam centreing</td>
<td>0.2%</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>0.4%</td>
</tr>
<tr>
<td>Total on visible cross section</td>
<td>1.5% (T0), 1.8% (V0)</td>
</tr>
<tr>
<td>Stability and consistency</td>
<td>1.1%</td>
</tr>
<tr>
<td>Total on luminosity</td>
<td>1.8% (T0), 2.1% (V0)</td>
</tr>
</tbody>
</table>

Fig. 5: Left, ratio of the T0-based ($L_{T0}$) to the V0-based ($L_{V0}$) luminosity for pp collisions at $\sqrt{s} = 5$ TeV, as a function of time during the 2017 campaign. Right, distribution of $L_{T0} / L_{V0}$, after weighting each run with the corresponding integrated luminosity ($L_{int}$).

4 Conclusions

In 2017, the ALICE experiment took data with pp collisions at $\sqrt{s} = 5$ TeV. In order to provide a reference for luminosity determination, a vdM scan was performed and visible cross sections were measured for two processes, based on the T0 (with pseudorapidity coverage $4.6 < \eta < 4.9, -3.3 < \eta < -3.0$) and V0 ($2.8 < \eta < 5.1, -3.7 < \eta < -1.7$) detectors. The two detectors provide independent measurements of the luminosity, with a total uncertainty of 1.8% for the T0 and 2.1% for the V0. A detailed list of the origin and size of the considered uncertainties for both, the visible cross section and the luminosity measurement, is reported in Table 1.
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References


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