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ALICE luminosity determination for p–Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

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Abstract

Luminosity determination in ALICE is based on visible cross sections measured in van der Meer scans. In 2016, the Large Hadron Collider provided proton-lead collisions at a centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV. There were two scans, one with the proton beam traveling towards the ALICE forward muon spectrometer and the second with the proton beam traveling in the opposite direction. During these scans cross sections were 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 covering $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$. This document describes the experimental setup for such measurements and reports their results.

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 σ_{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 σ_{inel} : $\sigma_{\text{vis}} = \varepsilon \sigma_{\text{inel}}$, where ε is the fraction of inelastic events that satisfy the trigger condition¹. 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 (σ_{vis}) is measured, the luminosity at the ALICE interaction point (IP2) is determined as the reference-process rate divided by σ_{vis} . This procedure does not require a knowledge of ε .

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 Δx , Δy 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

$$L = N_1 N_2 f_{\text{rev}} / (h_x h_y), \quad (1)$$

where f_{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 σ_{vis} for the chosen reference process is then

$$\sigma_{\text{vis}} = R(0, 0) / L. \quad (2)$$

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 2016, the LHC provided proton–lead collisions at a centre-of-mass energy $\sqrt{s_{\text{NN}}} = 8.16$ TeV. There were two data taking periods, one with the proton beam traveling towards the ALICE forward muon spectrometer, denoted by p–Pb below, and the second with the proton beam traveling in the opposite direction, denoted by Pb–p. The ALICE luminosity determination for these data samples is based on scans taken on November 23 and on December 2 for the p–Pb and Pb–p periods, respectively. In these scans cross sections were 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 previous documents [8, 9]; 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 vdM scans mentioned above, cross sections were 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 (η) 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

¹In the case of p–Pb collisions a small contamination by electromagnetic interactions may also affect the ε factor. This is not an issue for the luminosity determination, as the rate of electromagnetic interactions is also proportional to the luminosity

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 request that the longitudinal coordinate of the interaction vertex lies in the range $|z| < 30$ cm, where $z = 0$ is the nominal IP2 position². More details on this online cut, which aims to reject the background from beam-gas and beam-satellite interactions, are given in [8, 9].

During the p–Pb vdM scan session, the proton beam consisted of 702 bunches and the lead beam of 548 bunches. There were 216 bunch pairs colliding at IP2. The corresponding numbers for the Pb–p scan were 684, 540 and 224, respectively. The minimum spacing between two consecutive bunches in each beam alternated between 100 and 200 ns. The β^* value³ at IP2 was 2 m. The nominal half vertical crossing angle of the two beams at IP2 was $-212 \mu\text{rad}$, 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 0.2 mm, corresponding to about 4.5 times the RMS of the transverse beam profile (σ_{beam}). The reference-process rates were recorded separately for each colliding bunch pair. Two independent measurements per bunch pair were performed by repeating the horizontal and vertical scan pair twice. In addition, a length-scale calibration scan, described below, was performed. All of the above information applies to both the p–Pb and Pb–p scan sessions.

The proton bunch intensities were of the order of 2×10^{10} protons per bunch, while the lead bunch intensities were on the order of $1 (2) \times 10^8$ lead nuclei per bunch in the p–Pb (Pb–p) scan. The bunch-intensity measurement is provided by the LHC instrumentation [13]: a DC current transformer (DCCT), measuring the total beam intensity, and the ATLAS beam pick-up system (BPTX [14]) measuring the relative bunch populations. The measured beam intensity is corrected for the fraction of ghost and satellite charges⁴. 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]. Both measurements agree within their uncertainties. The resulting ghost-charge correction factors to the bunch-intensity product $N_1 N_2$ are 0.9908 ± 0.0004 (0.9903 ± 0.0004) for the first (second) scan for p–Pb and 0.9892 ± 0.0005 (0.9881 ± 0.0004) for the first (second) scan for Pb–p. The LDM provides in addition a measurement of the satellite-charge fraction. The satellite-charge correction factor to the bunch intensity product amounts to 0.9931 ± 0.0004 (0.9929 ± 0.0004) for the first (second) scan for p–Pb and 0.9926 ± 0.0005 (0.9923 ± 0.0004) for the first (second) scan for Pb–p. The quoted uncertainties on all these numbers are systematic.

² ALICE 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.

³The $\beta(z)$ 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 β^* denotes the value of the β function at the interaction point.

⁴The 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 [15], 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.

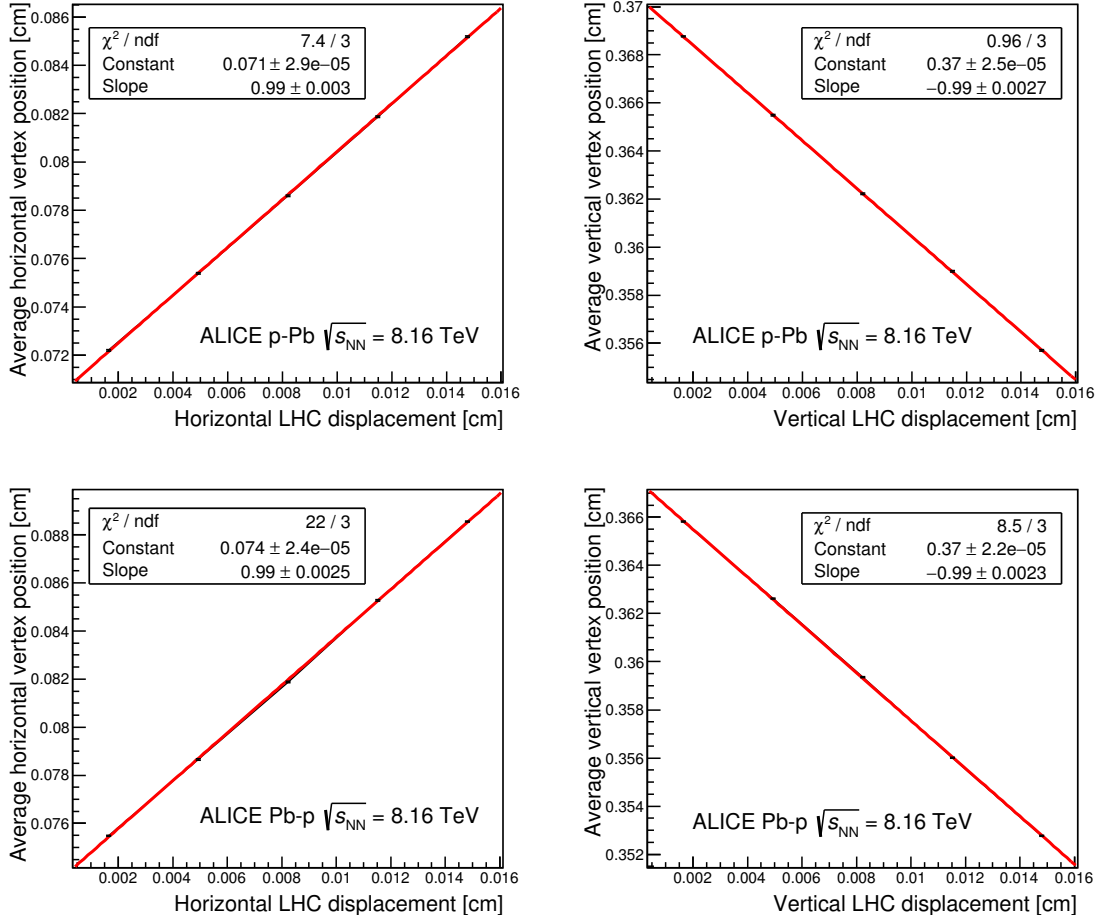


Fig. 1: (Colour online) Average horizontal (left) and vertical (right) vertex coordinate as a function of the nominal beam displacement in the length-scale calibration run, with superimposed linear fit (solid red line) for the p-Pb (upper) and Pb-p (lower) periods.

3 Analysis and results

The reader is referred to Ref. [8, 9] 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 nominal separation values are corrected 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, consisting of a Gaussian core multiplied by a polynomial of order six, where only the even terms are kept [8]; another model, which uses numerical integration instead of a fit, is 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 calibration is per-

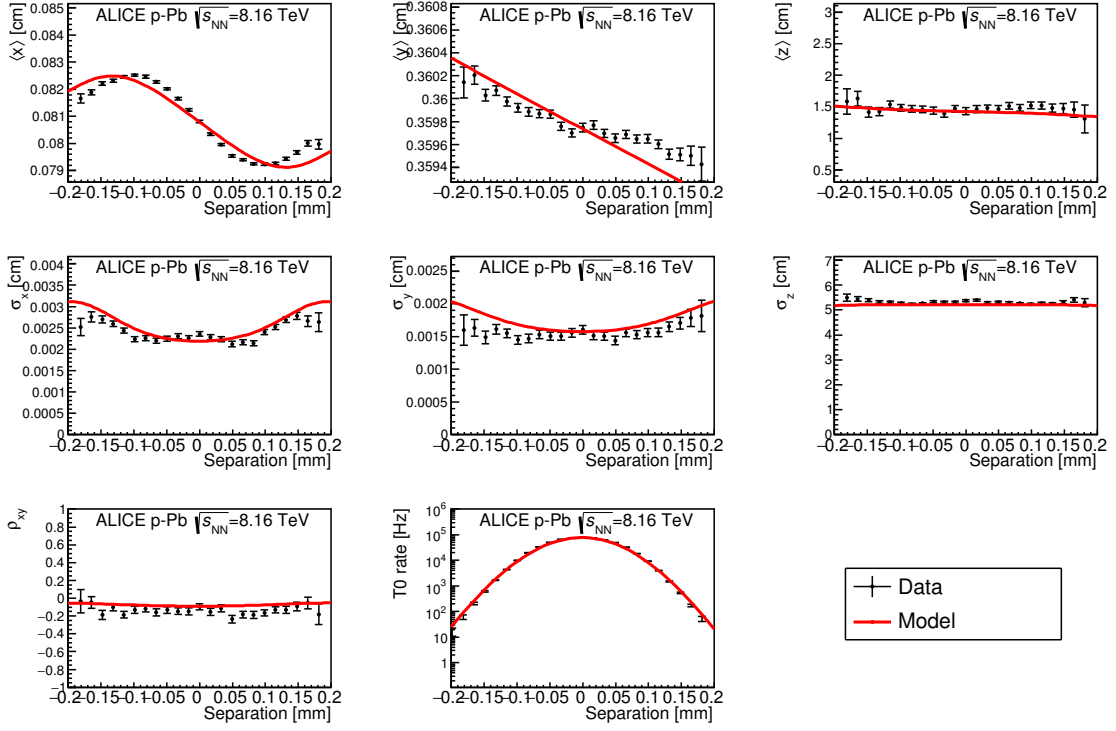


Fig. 2: (Colour online) Luminous region parameters and T0 rate as a function of separation during a horizontal scan in the p–Pb period, as fitted by a three-dimensional non-factorisable model [21] (dashed red line). The centroids are shown in the top row, the RMS sizes are shown in the middle row, the transverse tilt is shown in the bottom row together with the T0 rate.

formed in a dedicated run, where the two beams are moved simultaneously in the same direction in steps of equal size; the changes in the interaction vertex position provide a measurement of the actual beam displacement, which is used to extract a correction factor to the nominal displacement scale. 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 shown in Fig. 1. For both directions, the agreement between data and fit is not perfect (χ^2/ndf goes up to 7 in one case). To account for this, the fit is repeated after rescaling the uncertainties on the vertex position by $\sqrt{\chi^2/ndf}$. The final correction factor (obtained as the product of the two slopes) is 0.985 ± 0.005 and 0.988 ± 0.008 for the p–Pb and Pb–p periods, respectively.

The measured beam widths are combined with the bunch intensities and head-on rates to determine the visible cross sections according to Eq. (1) and Eq. (2). The results are corrected for non-factorisation effects, 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. An example of the fit is shown in Fig. 2. The agreement between data and fit is poor for some of the quantities. This can be partially explained by the fact, that, due to lack of statistics, only bunch-averaged quantities could be fitted. In light of this, the assigned uncertainty conservatively covers the full span between no correction and twice the correction found. The resulting correction factors to σ_{vis} are 1.006 ± 0.006 and 1.009 ± 0.009 for the p–Pb and Pb–p periods, respectively.

The visible cross sections showed a dependence on the product of the $N_1 N_2$ of the colliding bunch intensities, which pointed to an offset in the response curve of the device used to measure the bunch intensity. The offset was fitted from data and corrected for using the procedure outlined in [22].

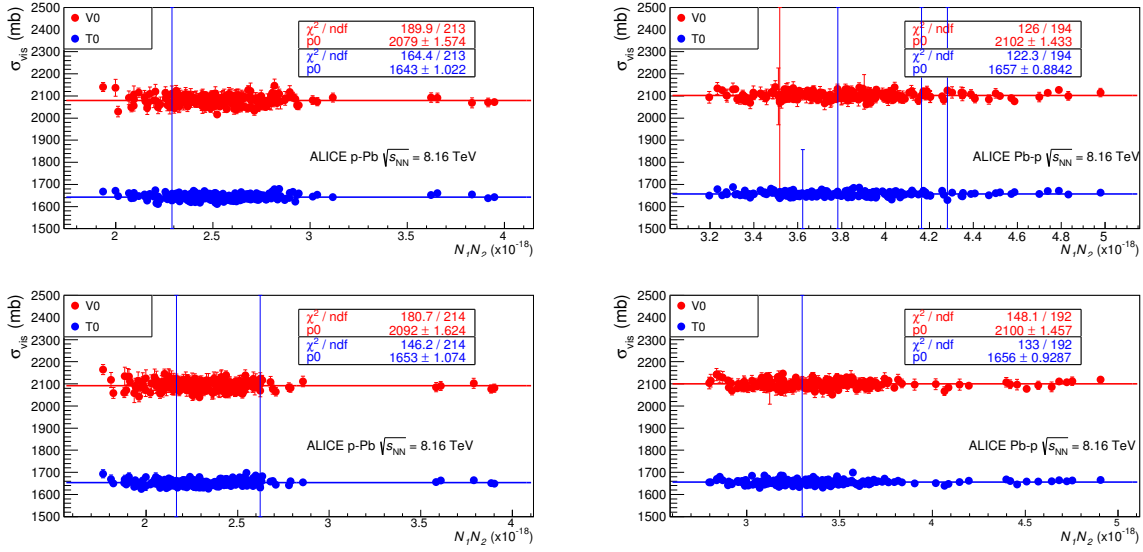


Fig. 3: (Colour online) Visible cross sections for the V0 (red) and T0 (blue) process measured in the first (top) and second (bottom) vdM scan in the p–Pb (left) and Pb–p (right) periods, as a function of the product of the intensities of the colliding bunch pair. The solid line is a constant fit to the data.

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_1N_2 of the colliding bunch intensities. After the offset correction, the visible cross sections show no dependence on N_1N_2 and the χ^2/dof of a constant fit is satisfactory for all scans. The combined effect of the beam-beam deflection and orbit drift correction is very small ($\ll 0.1\%$), only for the second scan in the p–Pb period reaches 0.7% . For both processes, and for the two scans, the weighted average of results from all colliding bunch pairs is computed (p_0 parameter in Fig. 3). The weighted average of the results of the two scans is retained as the final result: $\sigma_{T0} = 1.65 \text{ b}$ (1.66 b), $\sigma_{V0} = 2.09 \text{ b}$ (2.10 b) for the p–Pb (Pb–p) period, with statistical uncertainties on the order of 0.06% for T0 and 0.1% for V0. For both the T0 and the V0, the difference between the average cross sections obtained in the two scans is larger than expected from the statistical uncertainties, hence it is retained as a systematic uncertainty. A list of all the systematic uncertainties considered for the visible cross section measurement is presented in Tab. 1. Uncertainties not discussed above are evaluated as detailed in [8, 9]. Table 1 also shows the uncertainties that are correlated between the p–Pb and Pb–p measurements. Combining all the uncertainties one obtains a total systematic uncertainty of 1.9% (2.0%) for the V0 and 1.8% (1.8%) for the T0 visible cross sections in the p–Pb (Pb–p) period,

The results for the visible cross sections are then

$$\begin{aligned} \text{p-Pb: } \sigma_{T0} &= 1.65 \pm 0.03 \text{ (syst.) b, } \sigma_{V0} = 2.09 \pm 0.04 \text{ (syst.) b,} \\ \text{Pb-p: } \sigma_{T0} &= 1.66 \pm 0.03 \text{ (syst.) b, } \sigma_{V0} = 2.10 \pm 0.04 \text{ (syst.) b.} \end{aligned}$$

The statistical uncertainties are negligible with respect to the systematic ones.

In order to test the stability of the luminosity measurement provided by the T0 and the V0, the ratio between the luminosity obtained with these visible cross section in p–Pb and Pb–p collisions at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$ has been computed for all runs⁵ recorded in 2016 at this collision energy. During

⁵In 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 configuration. For the considered data-taking period, the duration of the run spanned from 6 minutes to 4 hours.

Uncertainty	p–Pb	Pb–p	Correlated
Transverse correlations	0.6%	0.9%	No
Scan-to-scan consistency	0.6%	0.1%	No
Length-scale calibration	0.5%	0.8%	No
Background subtraction	0.5% (< 0.1%) V0 (T0)	0.6% (0.3%) V0 (T0)	Yes
Intensity decay	0.6%	0.7%	No
Method dependence	0.4% (0.5%) V0 (T0)	0.9% (0.6%) V0 (T0)	No
Beam centring	0.1%	0.1%	No
Bunch size vs trigger	0.2%	0.4%	No
Absolute DCCT calibration	0.3%	0.3%	No
Orbit drift	0.7%	0.3%	No
Beam-beam deflection	< 0.1%	0.4%	Partially
Ghost charge	< 0.1%	< 0.1%	No
Satellite charge	< 0.1%	< 0.1%	No
Dynamic β^*	< 0.1%	< 0.1%	Partially
Total on visible cross section	1.5% (1.5%) V0 (T0)	1.9% (1.7%) V0 (T0)	
V0 vs T0 integrated luminosity	1.1%	0.6%	No
Total on integrated luminosity	1.9% (1.8%) V0 (T0)	2.0% (1.8%) V0 (T0)	
Correlated part	0.5% (< 0.1%) V0 (T0)	0.7% (0.5%) V0 (T0)	
Uncorrelated part	1.8% (1.8%) V0 (T0)	1.9% (1.7%) V0 (T0)	

Table 1: Relative uncertainties on the measurement of visible cross sections and luminosity in p–Pb and Pb–p collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The last column reports the correlation between the p–Pb and Pb–p measurements.

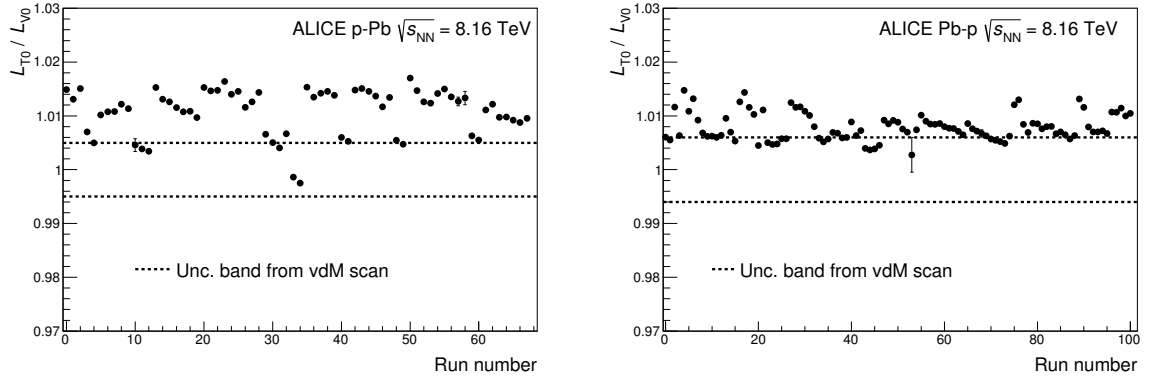


Fig. 4: Ratio of the T0-base luminosity to that of the V0-based one, for p–Pb (left) and Pb–p (right) collisions at $\sqrt{s_{NN}} = 8.16$ TeV, as a function of the time-ordered run number. The upper and lower lines define the uncertainty band on the luminosity ratio as expected from the vdM scan, obtained by combining those uncertainties that are uncorrelated between T0 and V0.

this period (about 20 days of data taking), collisions at IP2 were delivered in conditions very similar to those described for the vdM scans. ALICE took data with an average number of visible interactions, μ_{vis} , ranging from about 0.007 to about 0.1 for the V0. The reference process rates for T0 and V0 are determined from the raw rates with the same procedure used in the vdM scan and described in [8, 9]. They are then divided by the respective cross sections to obtain the ratio between the measured luminosities. The results are shown as a function of the progressive run number in Fig. 4. They point to the T0 measuring a systematically higher luminosity than the V0. Moreover, non-statistical fluctuations are present. In order to account for these observations, which deserve further investigation, the RMS difference from unity of the ratio is assigned as an additional uncertainty to the luminosity measurement, after

subtracting in quadrature the uncertainty on the ratio between the vdM-based cross sections, arising from the background subtraction. The resulting uncertainty is 1.1% (0.6%) for the p–Pb (Pb–p) configuration.

4 Conclusions

In 2016, ALICE took data with p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. In order to provide a reference for luminosity determination, vdM scans were 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% (1.8%) for the T0 and 1.9% (2.0%) for the V0 in the p–Pb (Pb–p) period. 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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