Precision Measurements of Induced Radioactivity and Absolute Luminosity Determination With TPX Detectors in LHC Proton–Proton Collisions at 13 TeV

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***Abstract*— A network of Timepix (TPX) devices installed in the ATLAS cavern measures the Large Hadron Collider (LHC) luminosity as a stand-alone system. The data were recorded from 13-TeV proton–proton collisions in 2016. Using two TPX devices, the number of hits created by particles passing the pixel matrices was counted. Absolute luminosity is determined with the van der Meer scan technique by separating the LHC proton beams and measuring the widths of the beams in low-intensity LHC proton–proton collisions. The exact determination of the activation background contributes to the overall precision of the TPX luminosity measurements. The activation background varies in time due to induced radioactivity at the different positions of the TPX devices in the ATLAS cavern. The activation at a given time depends on the history of the LHC operation. A detailed study of induced radioactivity has been performed to reduce the uncertainty on both the relative and absolute luminosity measurements.**

***Index Terms*— Active pixel sensors, colliding beam accelerators, Large Hadron Collider (LHC), luminosity, radiation monitoring.**

I. Introduction

A TIMEPIX (TPX) detector network [1] of 16 devices was installed in the ATLAS cavern at CERN. Each TPX device consists of two stacked hybrid silicon pixel sensors. The silicon sensors consist of a matrix of 256×256 pixels of 55 μm pitch and thickness of 300 μm (further indicated as layer-1) and 500 μm (layer-2) [2]. The readout chips connected to these sensors have the original TPX design [3], [4]. The installation of the TPX devices took place during the Large Hadron Collider (LHC) upgrade shutdown transition from Run-1 to Run-2 in 2013/2014. The first time period of LHC operation at $\sqrt{s} = 7$ TeV is called Run-1, and the second time period of LHC operation at $\sqrt{s} = 13$ TeV is called Run-2. These double-layer TPX devices replaced the previously operational network that employed single-layer Medipix (MPX) assemblies [5], [6].

These TPX devices measure the primary and secondary particle fluxes resulting from 13-TeV proton–proton collisions. The data were taken in 2016 during the second year of LHC Run-2 operation.

Precision luminosity measurements are of particular importance for many physics analyses in high-energy physics. The use of the TPX network in LHC Run-2 for luminosity measurements has several advantages compared to the previous luminosity measurements [7] at LHC during Run-1 that used MPX devices. The two-layer hodoscope structure of the TPX devices doubles the measurement statistics and allows one to determine the precision and long-term time stability of individual TPX devices [8]. The dead time caused by the readout was reduced compared to MPX from about 6 to 0.12 s allowing a much higher data acquisition rate. Also, the TPX devices are operated in three different modes [3], [4]: hit-counting, time-over-threshold (energy deposits and cluster-counting), and time-of-arrival (cluster-counting). For these luminosity measurements, the devices operating in hit counting mode were used.

The TPX network collects data independently of the ATLAS data-recording chain and provides independent measurements of the bunch-integrated LHC luminosity. In particular, van der Meer (vdM) scans [9] can be used for an absolute luminosity calibration. In 2016, vdM scans were performed on May 18 and 27 and recorded with the TPX detector network. Unlike in the 2015 vdM analysis [8], the two scan periods close in time allow a comparison of the absolute luminosity calibrations and thus contribute to the estimate of the luminosity uncertainty. These vdM scans serve for an absolute calibration of the TPX luminosity measurements. It is self-sufficient for luminosity monitoring and operates as an independent luminosity monitor.

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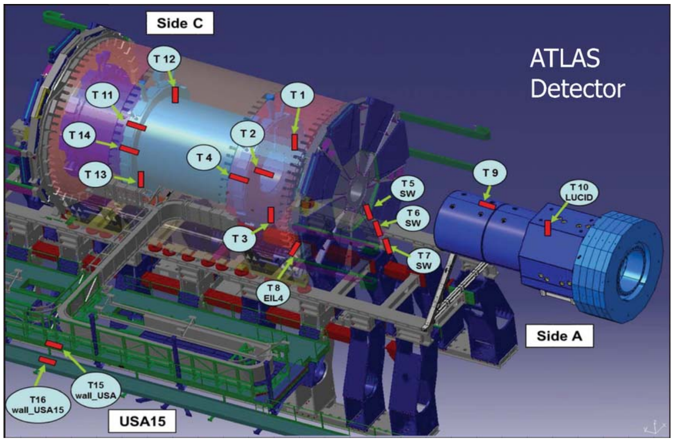

Fig. 1. Overview of TPX detector positions in the ATLAS detector (partial illustration) and in the ATLAS cavern. The data of the devices TPX02 and TPX12 (indicated as T2 and T12) were used for this analysis.

TABLE I

TPX Device Locations With Respect to the Interaction Point. Z Is the Longitudinal Distance From the Interaction Point and R Is the Distance From the Beam Axis. Their Uncertainty Is About 10 mm. The Particle Fluxes, Normalized to 100% Acquisition Time, Are Also Listed

Device	Z (mm)	R (mm)	TPX clusters per unit sensor area and per unit luminosity $(\mathrm{cm}^{-2}/\mathrm{nb}^{-1})$ Layer-1	Layer-2
TPX02	3540	1115	67900	77900
TPX12	-3540	1146	63800	72300

The detection of charged particles in the TPX devices is based on the ionization energy deposited by particles passing through the silicon sensor. The signals are processed and digitized during an adjustable exposure time (frame acquisition time) for each pixel. Neutral particles, namely, neutrons, however, need to be converted to charged particles before they can be detected. Therefore, a part of each silicon sensor is covered by ^{6}LiF and polyethylene converters [2], [10].

Thirteen out of the sixteen installed devices have been used for the luminosity analysis. Two devices were found to be inoperational after the closing of the ATLAS detector and one device was intentionally located far away from the interaction point, and therefore, it was not sensitive enough for luminosity measurements. Fig. 1 illustrates the locations of all TPX devices, and Table I lists the locations of the devices TPX02 and TPX12 used in this analysis [8], and their numbers of registered passing particles (clusters), normalized to 100% acquisition time. It was noted that the number of clusters for the 500 μm sensor is about 20% larger compared to the 300 μm sensor [8]. This percentage is lower than might be expected from the 40% larger sensitive volume, because the extended clusters induced by a single particle count mostly "one" in the thin as well as the thick sensor. The number of photon conversions and fast neutron interactions, however, will increase with the sensitive volume. The analysis described in this paper is focused on the precision luminosity determination with the devices TPX02 and TPX12, which are operated with 1-s exposure time and analyzed for hit-counting [8]. As their positions are very similar in R and Z coordinates on opposite sides of the proton–proton interaction point, their count rates are very similar. During 2016 LHC proton–proton collisions, typical luminosities at the beginning of the LHC fills were $\mathcal{L} = 5 - 10 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 5000 - 10\,000\ \mu\mathrm{b}^{-1}\mathrm{s}^{-1}$ and the count rate was a few 10^6 hits/s per TPX layer. The luminosity during the vdM scans was only about 2.5 $\mu\mathrm{b}^{-1}\mathrm{s}^{-1}$. The scans were taken on May 18 and 27, 2016, during LHC fills 4945 and 4954, respectively.

This paper is structured as follows. First, the concept of LHC luminosity monitoring from TPX hit-counting is introduced in Section II. The induced radioactivity (activation) and its effect on the luminosity determination is addressed in Section III. Section IV describes the vdM scan analyses for an absolute luminosity calibration. Conclusions are given in Section V.

II. LHC Luminosity From TPX Hit-Counting

The data from the TPX02 and TPX12 devices were used in hit-counting mode (so-called MPX mode, in which hits in the same pixel during the exposure time are added). Both TPX devices have similar count rates. The devices measure the luminosity independently and their measurements are cross-checked with each other. A constant exposure time of 1 s was used for the entire 2016 data-taking period.

A small number of pixels becoming weak (having a significantly smaller count rate than the average of all pixels) or noisy (having a significantly larger count rate than the average of all pixels) could have a significant effect on the luminosity measurement. Therefore, pixels with a count rate that is more than 3σ away from the mean are excluded for each sensor region (uncovered and with converters [2]). This requirement identifies up to 8% of the pixels on layer-1 and layer-2 both for TPX02 and TPX12 per LHC fill, plus 5%–10% of pixels at the boundaries of the sensor regions and at the edges of the sensor matrix. Then, identified pixels in at least one LHC fill were removed for all (about 200) 2016 LHC fills to remove 30%–40% of the total number of pixels of the sensors. The effect of the pixel removal on the analysis was also studied with 2σ and 5σ criteria, with the result that the analysis outcome remains unchanged.

The hit rate for the TPX02 and TPX12 layer-1 and layer-2 sensors is normalized to units of luminosity by multiplying with a normalization factor as given in Section IV.

In order to increase the precision of the luminosity determination, the induced radioactivity of material in the ATLAS cavern has been determined by a dedicated study. The induced radioactivity varies for each data-taking period and the activation count rate is subtracted from the total count rate before conversion to luminosity.

In addition to the hit-counting, luminosity can be measured with the two other modes of TPX operation based on cluster-counting and summed energy deposits. These luminosity measurements will be addressed in a separate publication.

The relation between the number of hits and clusters (particles) is investigated in order to determine the statistical uncertainty of the luminosity measurement from hit-counting. The average ratio of hits per cluster is approximately $R = N_{\mathrm{hit}}/N_{\mathrm{cl}} = 10$, which was obtained with TPX data from a low-intensity LHC fill for which the clusters on the sensors were well separated. This factor is used for the statistical uncertainty determination in Section IV assuming that one cluster corresponds to one independent particle passing the device [7].

The ATLAS and CMS collaborations have elaborate systems of luminosity measurements, described in [11], [12] and [13], [14], respectively. A comparative study of their results and the TPX luminosity monitoring is beyond the scope of this paper.

III. Induced Radioactivity (Activation)

The high rate head-on collisions of protons at high luminosity at the LHC yield large multiplicities of secondary particles such as pions, kaons, neutrons, and protons. The interactions of primary and secondary particles with materials in the ATLAS environment produce large amounts of neutrons and material activation, including detectors and their electronics. The size and effective duration of the generated activation depends on incident fluxes, the activation cross sections, and the radionuclides half-lifes. The activation of material parts mainly depends on their geometry and location within the ATLAS environment, and the types of nuclei. The activation is expected to grow with LHC luminosity and duration of LHC operations [6]. The activation contribution to the total count rate was already observed with the MPX detector network [6].

The TPX detectors become themselves activated as the result of the interaction of particles with the silicon layer, materials of microelectronics readout, and duralumin box of the TPX detectors. Evaluation of the activation of a given TPX detector requires the precise knowledge of its material composition, which is unknown at present, and spectral flux distributions (high-energy protons and neutrons) calculated using Monte Carlo transport code such as Fluka and GCalor [6].

The self-activation of the detectors was under experimental investigation. In the case of "inner" devices where TPX devices are surrounded by a large amount of material, the self-activation contribution is negligible. The self-activation of the TPX devices was measured during LHC shutdowns when there was the possibility to remove some devices from the ATLAS cavern [6].

Owing to their sensitivity to electrons and gamma rays, TPX detectors can measure radioactive decays. Activation is observed with most of TPX detectors at the end of the LHC fills, and for this precision determination TPX02 and TPX12 are used, with layer-1 and layer-2.

The contribution of activations with different lifetimes was determined iteratively in time periods right after the high-intensity proton–proton collisions, starting with the component of the shortest measurable lifetime, described by a single exponential function. The result of the fit was subtracted from the data and the next component was fit. Seven components were identified with their lifetimes listed in Table II.

TABLE II

Lifetimes of Components From Activation Contributions to the Total TPX Count Rates

Components	1	2	3	4	5	6	7
Life times	25.7 (s)	2.82 (min)	33.0 (min)	3.58 (h)	16.8 (h)	6.94 (days)	102 (days)

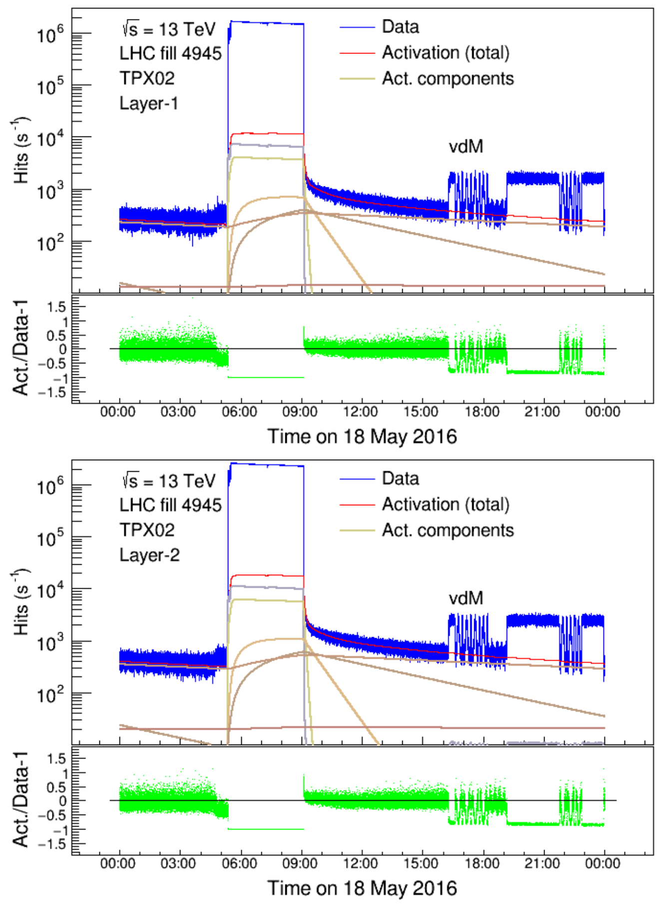

Fig. 2. Hit rate measured with TPX02 layer-1 and layer-2 before and after the vdM scan on May 18, 2016, as a function of time. Each data point shows the count rate of a 1-s frame. Initially, a small background rate is observed. Then, at about 5:00, high-intensity LHC proton beams are filled in the accelerator and a small increase of count rate is observed. Subsequently, high-intensity proton collisions take place with count rate above 10^6 s^{-1}. After the high-intensity proton collisions, the falling activation curve is clearly recognizable. The vdM scan with low-intensity LHC proton beams starts around 16:00. The determined total activation rate and six components with different lifetimes are also shown. During the high-intensity collisions, the activation contribution to the total count rate is at the percent level. The ratio of determined activation and data rates minus one is well centered around zero for the time periods between the proton–proton collisions indicating a good description of the activation count rate. LHC vdM fill 4945.

The mean activation count rate N^i_{act} at each given time depends on the history of the LHC operation. This is described by an iterative formula for the ith time step

$$N^i_{\mathrm{act}} = \sum_{k=1}^{n} N^{i-1,k}_{\mathrm{act}} \mathrm{e}^{-\lambda_k \tau} + \left(N^i_{\mathrm{tot}} - N^{i-1}_{\mathrm{act}}\right) \times \theta\left(N^i_{\mathrm{tot}} - N^{i-1}_{\mathrm{act}}\right) \sum_{k=1}^{n} Y_k (1 - \mathrm{e}^{-\lambda_k \tau}) \quad (1)$$

where n is the number of activated components, $N^{i-1,k}_{\mathrm{act}}$ is the activation count rate at the beginning of a frame caused by the

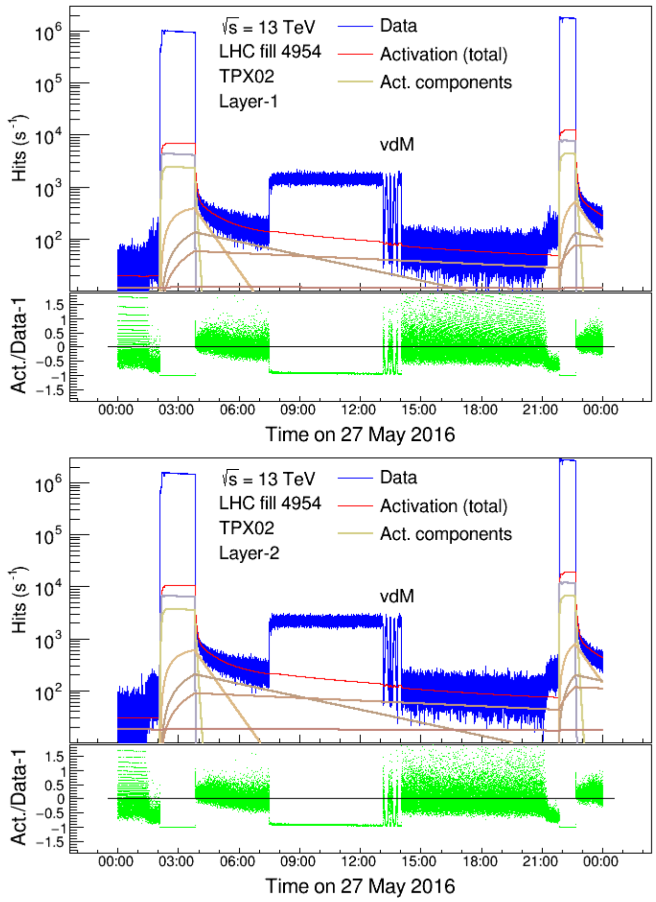

Fig. 3. Hit rate measured with TPX02 layer-1 and layer-2 before and after the vdM scan on May 27, 2016, as a function of time, as described in Fig. 2. LHC vdM fill 4954.

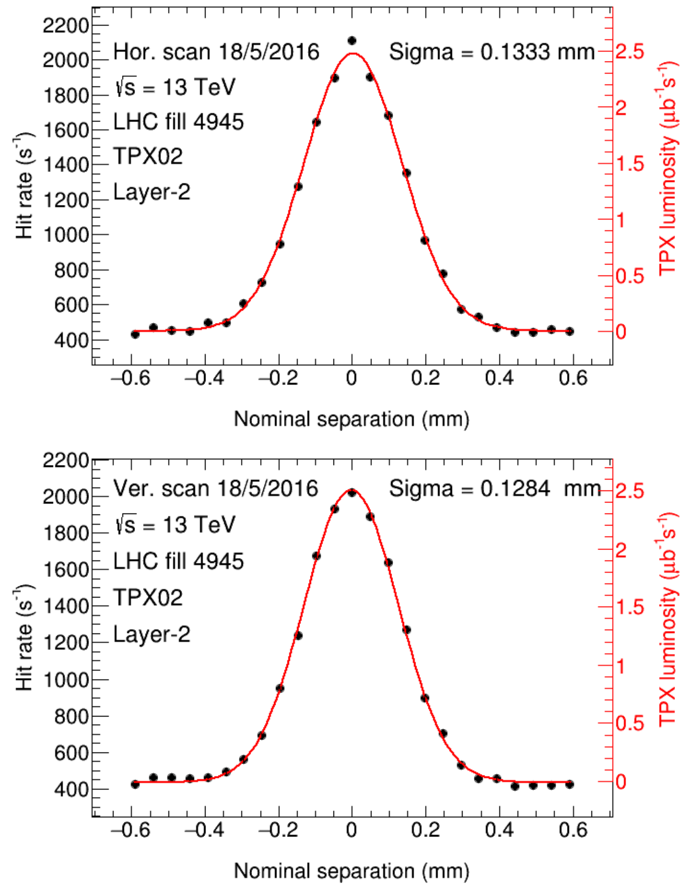

Fig. 4. Luminosity from hit-counting as a function of nominal beam separation measured with TPX02 layer-2 during the first horizontal and vertical vdM scan on May 18, 2016. Each data point shows the measured instantaneous luminosity before background subtraction. Because the exposure time is significantly shorter than the duration of a scan step, the TPX samplings are averaged per scan step. The TPX samplings that partially or totally overlap with nonquiescent scan steps (varying beam separation) are not shown. The fit function is the sum of a single Gaussian (representing the proper luminosity in this scan) and a constant term that accounts for induced radioactivity (activation), instrumental noise, and single-beam-induced background. The TPX normalization uses the horizontal and the vertical beamwidth. LHC vdM fill 4945.

kth component, $N^i_{\rm tot}$ is the total count rate at the beginning of a frame, λ_k is the decay constant, τ is the time period between the end of the $(i-1)$th frame and the end of the ith frame, and Y_k is a normalization constant determined from the fit of the activation curve. At the end of the $(i-1)$th frame, the count rate has slightly changed from its beginning, giving the starting count rate for the ith frame.

Fig. 2 shows the measured count rate and the determined activation contribution on May 18, 2016, during which the first 2016 vdM scan was taken, and Fig. 3 shows the corresponding distributions for May 27, 2016, during which the second 2016 vdM scan was taken. The activation contribution is clearly recognizable, and the count rates in the time periods between the proton–proton collisions are well described by the activation curve. Therefore, the activation count rate determined by the same function during the proton collision periods is well described. The activation contribution to the total count rate is about 1% during the high-intensity proton–proton collisions.

For the TPX luminosity measurement during the whole 2016 data-taking period, the activation count rate has been subtracted from the total count rate before the TPX count rates are converted to luminosity. The effect on the relative luminosity measurements for different LHC fills is mostly due to the long lifetime components of the induced radioactivity as the additional hit rate depends on the history of the LHC operation. The absolute luminosity measurements profit from the exact determination of background rates, for example, in calibration transfer studies, where the absolute luminosity normalization at low LHC intensity is transferred to regular high-intensity LHC operation to achieve a luminosity precision at the percent level. This paper of activation constitutes an improvement of the precision luminosity determination compared to the previous study [8]. While in the study of the 2015 data, no significant effect of activation was observed [8] (a flat background correction was applied for each LHC fill), in this study of the 2016 data with about nine times higher integrated particle fluxes, more detailed activation studies were performed and activation corrections were applied for individual frames. These frame-by-frame corrections were in particular useful in so-called calibration transfer studies, where

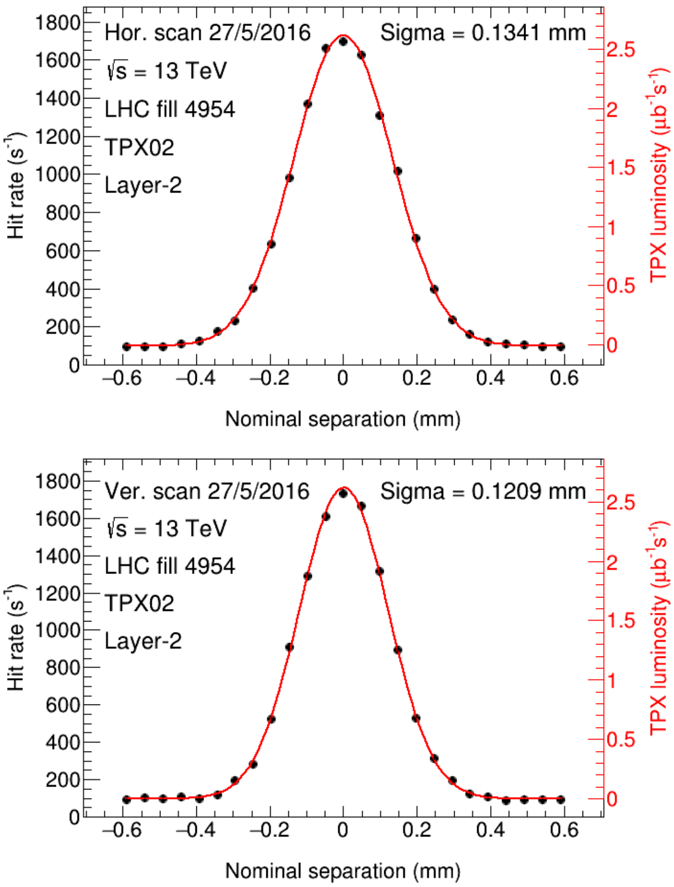

Fig. 5. Luminosity from hit-counting as a function of nominal beam separation measured with TPX02 layer-2 during the first horizontal and vertical vdM scan on May 27, 2016, as described in Fig. 4. LHC vdM fill 4954.

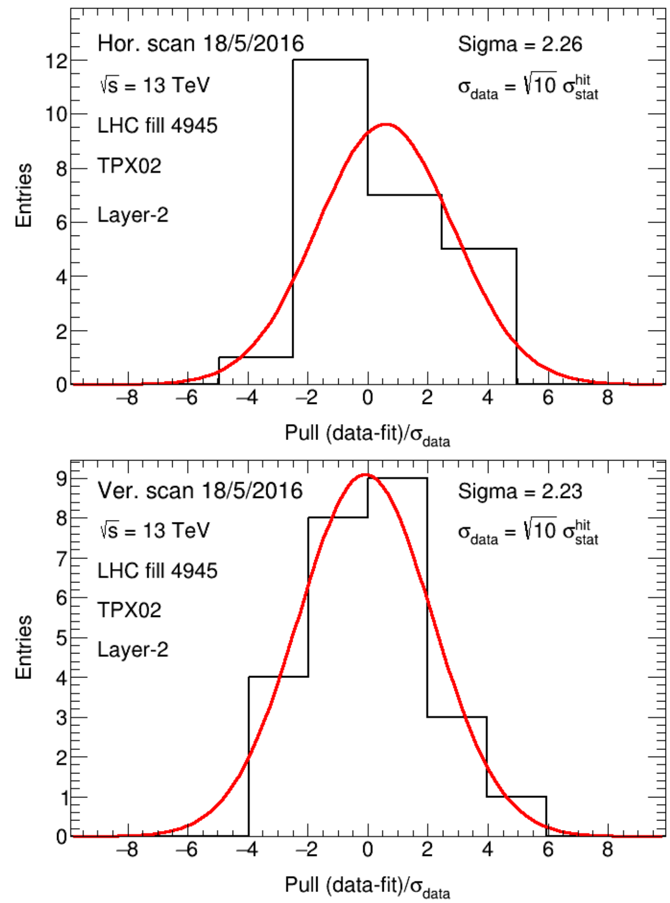

Fig. 6. Pull distribution defined as (data-fit)/σ_{data}, where $\sigma_{\text{data}} = \sqrt{R} \cdot \sigma^{\text{hit}}_{\text{stat.}}$ with $R = N_{\text{hit}}/N_{\text{cl}} = 10$ for TPX02 layer-2. The data shown in Fig. 4 are used. LHC fill 4945.

the effects of extrapolating the calibrations taken at low-intensity LHC vdM fills to high-intensity regular LHC fills were investigated.

IV. Van der Meer Scans

The vdM scans are used for an absolute luminosity calibration at the LHC. This scan technique was pioneered by Simon van der Meer at CERN in the 1960s [9] to determine the absolute luminosity in a simple way. It involves scanning the LHC beams through one another to determine their sizes in terms of the horizontal and vertical widths of the beams at the point of collision. These width measurements are then combined with information of the number of circulating protons, allowing the determination of an absolute luminosity scale. The vdM scan analyses are based on the data taken on May 18 and 27, 2016.

The LHC beam separation dependence of the measured TPX luminosity is well represented by the sum of a single Gaussian and a constant. The constant describes the background, including the count rate from activation, which is assumed to be constant in time during the short time periods when the LHC beams were separated in several steps up to about ± 0.6 mm. Fig. 4 shows the results of the scan on May 18, 2016, and Fig. 5 shows the results of the scan on May 27, 2016. The absolute luminosity normalization is derived from the combination of the hit rate, the horizontal and vertical convoluted widths, and the average bunch currents.

The measurement uncertainty of the TPX devices can be determined with respect to the expected statistical uncertainty. For this paper, the pull distributions, defined as (data-fit)/σ_{data}, were determined, where $\sigma_{\text{data}} = \sqrt{R} \cdot \sigma^{\text{hit}}_{\text{stat.}}$, $\sigma^{\text{hit}}_{\text{stat.}} = \text{data}/\sqrt{N_{\text{hit}}}$, and $R = 10$. Fig. 6 shows the pull distribution for the first vertical vdM scan on May 18, 2016, as seen by TPX02 layer-2. For the same sensor, the pull distribution is shown in Fig. 7 for the data taken on May 27, 2016. The sigma of the pull distribution averaged over TPX02 and TPX12, layer-1 and layer-2 for both horizontal and vertical scans, is 2.0 ± 0.3, which indicates that additional uncertainties are present beyond the determined statistical uncertainties. Furthermore, transverse proton-bunch profiles are not expected to be perfectly Gaussian; and even if they were, a scan curve summed over Gaussian bunches of different widths would not be strictly Gaussian. Therefore, non-Gaussian contributions to the vdM-scan curves may contribute, at some level, to the widening of the pull distribution.

For TPX02 layer-2 (May 27, 2016, data), the widths of the beam sizes (horizontal and vertical nominal beam separations) and their statistical uncertainties are $\Sigma_x = (134.1 \pm 0.5)$ μm and $\Sigma_y = (120.9 \pm 0.5)$ μm, respectively.

TABLE III

vdM Scan Results for 2016 Data. The Scan Was Performed on May 18 (LHC Fill 4945), and the First Horizontal and Vertical Scans Were Used. The Fit Results for the First Bunch-Averaged Horizontal Σ_x and Vertical Σ_y Convoluted Beam Sizes Are Given, as Well as the Specific Luminosity. The Peak Luminosity Takes the LHC Operation Parameters Into Account. The Hit Rate at the Peak Is Averaged Over the Horizontal and Vertical Scans. Normalization Factors ($1/n_f$) Convert Hit Rates to Luminosities. The Larger Values are for the Thicker Sensor Layer

Device	Layer	Σ_x (μm)	Σ_y (μm)	$L_{specific}$ ($\mu b^{-1}s^{-1}/10^{25}$)	L_{peak} ($\mu b^{-1}s^{-1}$)	N_{peak} (hits/s)	$1/n_f$ (hits/μb^{-1})
TPX02	1	132.2	128.6	105.3	2.512	1020	405.8
TPX02	2	133.3	128.4	104.6	2.485	1602	639.0
TPX12	1	131.6	127.1	107.0	2.554	905.4	357.2
TPX12	2	134.1	129.0	103.5	2.469	1564	634.2

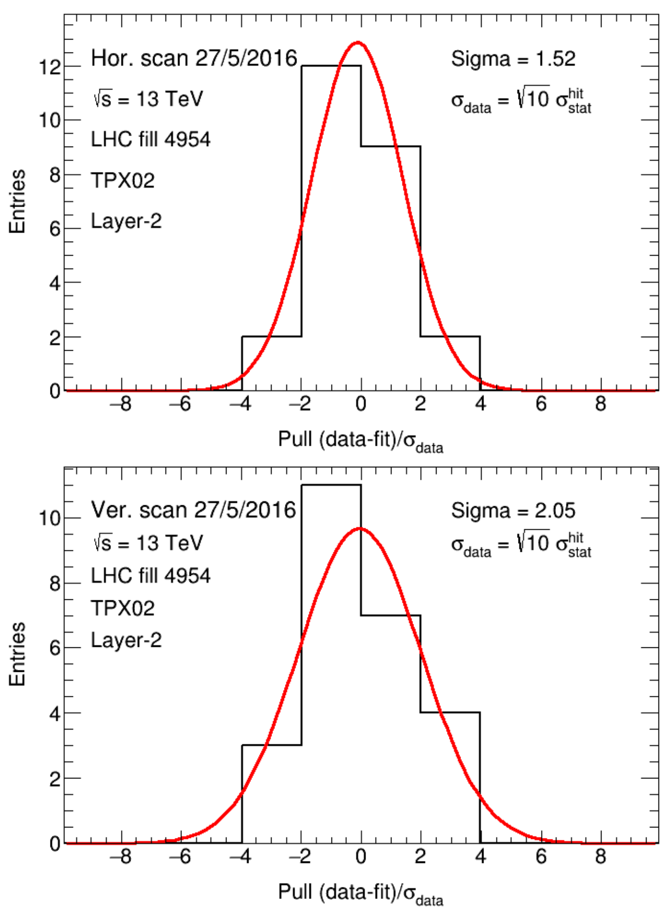

Fig. 7. Pull distribution defined as (data-fit)/σ_{data}, where $\sigma_{data} = \sqrt{R} \cdot \sigma^{hit}_{stat}$. with $R = N_{hit}/N_{cl} = 10$ for TPX02 layer-2. The data shown in Fig. 5 are used. LHC fill 4954.

The luminosity can be calculated as

$$L_{TPX} = N_b N_{p1} N_{p2} f/(2\pi\, \Sigma_x\, \Sigma_y), \tag{2}$$

where N_b is the number of bunch crossings producing collisions per machine revolution, N_{p1} and N_{p2} are the average bunch populations (number of protons) in beams 1 and 2, respectively, f is the machine revolution frequency (11 245.5 Hz), and Σ_x and Σ_y are the convoluted horizontal and vertical beam sizes. The LHC parameters for fill 4954 are [15] as follow.

1) *Number of Bunches:* $N_b = 32$.
2) *Average Number of Protons (in Units 10^{11}) per Bunch in Beam 1 and in Beam 2:* $N_{p1} = 47.85/56 = 0.8545$ and $N_{p2} = 44.94/52 = 0.8642$, respectively.

Thus, the resulting luminosity is $L_{TPX} = 2.609\ \mu b^{-1}s^{-1}$ with a 0.6% uncertainty from the horizontal and vertical beamwidth measurements.

The corresponding specific luminosity is

$$L_{specific} = L_{TPX}/(N_b N_{p1} N_{p2}) = f/(2\pi\, \Sigma_x\, \Sigma_y). \tag{3}$$

Tables III and IV summarize the scan results for the first pair of vdM scans (horizontal and vertical) registered with TPX02 and TPX12 with both their layers.

For TPX02 layer-2, the fits of horizontal and vertical scans provide (1629 ± 9) and (1667 ± 10) hits/s, respectively, at the peak above the background. The average number is (1648 ± 7) hits/s. Thus, the normalization factor n_f between the TPX02 layer-2 hit rate and the instantaneous LHC luminosity is

$$n_f = \frac{2.609\ \mu b^{-1}s^{-1}}{1648\ \text{hits}^{-1}} = 1.583 \cdot 10^{-3}\ \mu b^{-1}/\text{hit}. \tag{4}$$

The normalization factors for the other layers were calculated using the same procedure, and the results are summarized in Table V for the average of the May 18 and 27, 2016, scans. Table V also lists the relative uncertainties between the normalization factors determined in both scans. Conservatively, the largest uncertainty of ±1.5% is assigned to all four normalization factors.

The normalization factor for the absolute luminosity is only approximate since the TPX exposure time is much longer than the bunch spacing. Therefore, the bunch-integrated luminosity averages over the different bunch profiles. In order to estimate the resulting uncertainty, a simulation with 29 overlapping Gaussian distributions was performed [7], which led to an estimate of the resulting uncertainty on the normalization factor (from this source only) of about 1%.

Although further uncertainties could arise from non-Gaussian shapes, this paper shows that the Gaussian approximation of the sum of Gaussians is quite robust with the TPX system and the luminosity approximation by bunch integration is a sensible approach. No attempt was made for a precise determination of the total uncertainty, which would require a dedicated study [11], [12].

TABLE IV

VDM SCAN RESULTS FOR 2016 DATA. THE SCAN WAS PERFORMED ON MAY 27 (LHC FILL 4954), AND THE FIRST HORIZONTAL AND VERTICAL SCANS WERE USED. THE FIT RESULTS FOR THE FIRST BUNCH-AVERAGED HORIZONTAL Σ_x AND VERTICAL Σ_y CONVOLUTED BEAM SIZES ARE GIVEN, AS WELL AS THE SPECIFIC LUMINOSITY. THE PEAK LUMINOSITY TAKES THE LHC OPERATION PARAMETERS INTO ACCOUNT. THE HIT RATE AT THE PEAK IS AVERAGED OVER THE HORIZONTAL AND VERTICAL SCANS. NORMALIZATION FACTORS $(1/n_f)$ CONVERT HIT RATES TO LUMINOSITIES. THE LARGER VALUES ARE FOR THE THICKER SENSOR LAYER

Device	Layer	Σ_{x} (μm)	Σ_{y} (μm)	L_{specific} $(\mu\mathrm{b}^{-1}\mathrm{s}^{-1}/10^{25})$	L_{peak} $(\mu\mathrm{b}^{-1}\mathrm{s}^{-1})$	N_{peak} (hits/s)	$1/n_{\mathrm{f}}$ (hits/$\mu\mathrm{b}^{-1}$)
TPX02	1	133.2	119.4	112.5	2.659	1082	406.9
TPX02	2	134.1	120.9	110.5	2.611	1648	631.7
TPX12	1	133.5	121.2	110.6	2.614	940.5	359.8
TPX12	2	132.2	121.3	111.6	2.638	1566	615.4

TABLE V

NORMALIZATION $(1/n_f)$ TO CONVERT HIT RATES TO LUMINOSITIES. THE LARGER VALUES ARE FOR THE THICKER SENSOR LAYER. THE RELATIVE UNCERTAINTY WITH RESPECT TO THE MAY 18 AND 27, 2016, MEASUREMENTS IS ALSO LISTED

Device	Layer	$1/n_{\mathrm{f}}$ (hits/$\mu\mathrm{b}^{-1}$)	Uncertainty (in %)
TPX02	1	406.3	± 0.1
TPX02	2	635.3	± 0.6
TPX12	1	358.5	± 0.4
TPX12	2	624.8	± 1.5

V. CONCLUSION

The network of TPX devices installed in the ATLAS detector cavern has successfully taken data at LHC during Run-2 with 13-TeV proton–proton collisions in 2016. The hit rates from induced radioactivity (activation) have been determined in-between and during the LHC proton–proton collisions, which are taken into account in the TPX hit luminosity measurements. An approximate absolute luminosity calibration was determined from two vdM scans in 2016. Agreement of the normalization factors for the absolute luminosity determination between the two vdM scans is at $\pm 1.5\%$.

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