Timepix3 Luminosity Determination of 13 TeV Proton-Proton Collisions at the ATLAS Experiment

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Abstract—Medipix and Timepix devices, installed in the ATLAS cavern, have provided valuable complementary luminosity information. Results are presented from measurements with Timepix3 (TPX3) detectors. In contrast with previously employed frame-based data acquisition, the TPX3 detector remains active continuously, sending information on pixel hits as they occur. Hit- and cluster-counting methods were used for the luminosity determination of the LHC proton-proton collisions. The LHC luminosity versus time is determined using these two methods and fitted to a simple model, which incorporates luminosity reduction from single bunch and beam-beam interactions. The precision of the luminosity determination could be improved by counting the number of clusters, instead of just pixel hits. The internal precision and long-term stability of the TPX3 luminosity measurement are below 0.5%. TPX3, owing to its 1.56 ns time-tagging, is able to resolve the time structure of the luminosity due to the collisions of individual proton bunches when integrated over an LHC fill.

I. INTRODUCTION

Precision luminosity measurements are of particular importance for many analyses in high-energy physics. Networks of hybrid active pixel detectors from the Medipix/Timepix family [1] installed in ATLAS cavern [2] successfully demonstrated their potential to determine luminosity [3], [4]. Recently, the latest generation Timepix detectors, namely Timepix3 (TPX3) [5], were installed in the ATLAS cavern at CERN [6]. The TPX3 device closest to the LHC interaction point is used in this analysis to measure the primary and secondary particle fluxes originating from 13 TeV proton-proton collisions. The data were taken between April and October 2018 during the LHC Run-2 operation.

The use of the TPX3 device for luminosity measurements has several advantages compared to the previous luminosity measurements at the LHC during Run-1 (MPX devices) [3] and Run-2 (TPX devices) [4].

1) *The possibility of (quasi-) continuous operation:* The dead-time caused by the readout of the frames is about 6 s for MPX and 0.12 s for TPX devices, requiring a compromise between sensor occupancy and relative dead-time minimisation. Cluster-counting with MPX and TPX devices is possible with high particle fluxes only when the exposure time is much shorter than the dead-time. Otherwise, overlapping clusters could not be separated. Therefore, hit-counting is necessarily used for previous high rate luminosity analyses. Furthermore, the TPX devices can be operated in either of three modes: time-over-threshold (energy deposits, ToT), time-of-arrival (ToA), and counting (Medipix) mode; in contrast, the TPX3 device measures ToT and ToA information simultaneously. A novelty of TPX3 is the pixel-comparator-driven (event-driven) data transmission which replaces the frame-based transmission of the TPX devices.

2) *An improved cluster separation:* In the previous MPX and TPX luminosity analyses, no cluster (particle) counting with high statistics was possible. Thus, to achieve statistically significant short-term luminosity measurements, a hit-counting method was applied. The devices were used in the Medipix mode, where each pixel counts the number of pixel hits per frame. A source of statistical uncertainty arose from the large variance of hit counts per interacting particle. Owing to the precise pixel time-stamping of TPX3, cluster identification and separation could also be done in high flux conditions. This leads to a higher precision of the luminosity measurements. Furthermore in TPX3 data, clusters were defined by temporally and spatially concurrent hits on the sensor.

3) *A higher time resolution:* The previous MPX and TPX luminosity measurements were LHC bunch-integrated, as the exposure time was much longer than the bunch separation of 25 ns. As already demonstrated, with the time resolution of TPX3 and proper triggering, it was possible to resolve the bunch structure of the LHC beam [6]. This article provides a proof of principle, as it demonstrates the luminosity determination of individual colliding proton bunches when the data are integrated over an LHC fill.

In summary, an important innovation is that the TPX3 device allows for cluster counting up to high particle rates, since pixel data are digitized and read out as a stream rather than accumulated on-pixel until a full frame is transmitted. Additionally, if clusters partially overlap, they can now be reconstructed separately using the time stamps in the pixels.

Moreover, the two-layer structure of the TPX3 device doubles the measurement statistics and, in this analysis, allows one to determine the internal precision and long-term time stability of individual TPX3 devices. Here, ‘internal’ refers to the luminosity precision being determined only based on the TPX3 device and not with respect to other luminosity determination methods.

The ATLAS and CMS collaborations have elaborate systems that measure luminosity, as described in [7], [8], [9] (ATLAS) and [10], [11] (CMS).

The proceedings is structured as follows. First, the TPX3 device is described in Section II, followed by an introduction to the concept of LHC luminosity monitoring by hit-counting and cluster-counting in Section III. In Section IV the LHC luminosity versus time is determined and the internal TPX3 measurement precision is evaluated. Section V describes the internal precision of luminosity determination by computing the difference between two layers of the TPX3 device. The internal long-term luminosity precision is given in Section VI as obtained from the comparison of layer-1 and layer-2 luminosity measurements. The long-term stability with respect to other ATLAS luminosity monitors is described in Section VII. As a proof of principle, the luminosity determination of individual LHC bunch crossings is described in Section VIII, followed by conclusions in Section IX.

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Fig. 1. Time history of the TPX3 luminosity, as seen by TPX3 layer-1 using hit-counting in LHC fill 6677. The small dips, visible as variations from the descending curve, correspond to the times when the LHC operators performed small-amplitude beam-separation scans to optimize or increase the luminosity. A larger beam adjustment took place at about 15:30 CEST. LHC emittance scans were performed at the beginning (14:30 CEST) and at the end (2:10 CEST) of the fill. The approximate normalization between hit rate and luminosity is based on the peak instantaneous luminosity [17].

II. TPX3 DEVICE

The TPX3 device [5], [6] used for this analysis has two stacked hybrid silicon pixel sensors, named layer-1 and layer-2. Two synchronized single-sensor TPX3 devices are placed together in a face-to-face geometry. The silicon sensors consist of a matrix of 256×256 pixels of $55 \mu\text{m}$ pitch and a thickness of $500 \mu\text{m}$. The installation of this TPX3 device took place during the LHC winter shutdown 2017/2018 [6]. The TPX3 device is operated in addition to the previously installed network of double-layer Timepix (TPX) assemblies [12], [13]. An external trigger is used to relate the TPX3 data to the LHC orbit timing [6]. A correction is applied for the so-called time-walk effect to compensate for a high signal leading to an earlier time than a low signal [14].

The detection of charged particles in the TPX3 devices is based on the ionization energy deposited by the particles passing through the silicon sensor, where the induced signals are processed and digitized. Neutral particles, namely neutrons, need to be converted to charged particles before they can be detected. Therefore, a part of the silicon sensor on layer-2 (the layer farther from the IP) is covered by ^6LiF and polyethylene converters [15], [16]. Photons are directly converted in the sensor.

The TPX3 device is self-sufficient for luminosity monitoring. It collects data independently of the ATLAS data-recording chain and provides independent measurements of bunch-integrated LHC luminosity, including individual colliding bunch luminosity. During 2018 LHC proton-proton collisions, the maximal peak luminosities for an LHC fill were about $\mathcal{L} = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} = 20 \text{ nb}^{-1} \text{ s}^{-1}$ [17]. The corresponding TPX3 pixel count rate was about 30 hits/ms for layer-1 (with neutron converter) and 25 hits/ms for layer-2, with about 2 clusters/ms in each layer. Figure 1 shows an example of the luminosity from hit-counting measured with TPX3 layer-1 for LHC fill 6677, taken on 13-14 May 2018.

III. LHC LUMINOSITY FROM TPX3 HIT- AND CLUSTER-COUNTING

The data from the TPX3 device are used in so-called hit-counting, as well as cluster-counting analyses. The layers of the device have similar count rates. Their average for cluster-counting is given in Table I. Both layers measure the luminosity independently and their measurements are cross-checked.

TABLE I

TPX3 DEVICE LOCATION WITH RESPECT TO THE INTERACTION POINT. Z IS THE LONGITUDINAL DISTANCE FROM THE INTERACTION POINT ALONG THE BEAM AXIS AND R IS THE DISTANCE FROM THE BEAM AXIS. THEIR UNCERTAINTY IS ABOUT 10 MM. THE APPROXIMATE PARTICLE FLUX IS GIVEN AS AN AVERAGE OF DETECTOR LAYER-1 AND LAYER-2.

Device	Z (mm)	R (mm)	Clusters per unit sensor area and per unit luminosity ($\text{cm}^{-2}/\text{nb}^{-1}$)
TPX3	2830	3700	68

A small number of pixels becoming weak, unresponsive or noisy (most of them could be recovered by reloading the configuration) could have a significant effect on the luminosity measurement. Therefore, pixels of the TPX3 device with a count rate that is at least 5σ away from the mean are excluded. The width (sigma) and the mean are determined from Gaussian fits of the pixel hit count distribution, which were integrated over 3 hours. In each 3 hour time period, less than 0.1% of the pixels in layer-1 and layer-2 are excluded by this algorithm. This correction is taken into account for the clustering process as well as for the effective sensor area.

The hit rates for the two TPX3 layers are normalized to units of luminosity by multiplication with scaling factors. These two scaling factors are determined from the known LHC peak instantaneous luminosity [17] and the corresponding count rates in layer-1 and layer-2, as summarized in Table II. Normalization factors for cluster-counting are calculated using the same procedure and are given in Table II as well. All the normalization factors are only approximate, since the analysis focuses on the relative luminosity precision (not an absolute precision) during three time scales: LHC bunch-crossings of 25 ns, Luminosity Blocks (LBs) of 60 s, and long-term stability over months. On average, about 13 hits per cluster (particle) are observed.

TABLE II

APPROXIMATE NORMALIZATION ($1/n_f$) TO CONVERT HIT AND CLUSTER RATES TO LUMINOSITIES.

Layer	$1/n_f$ (hits/ nb^{-1})	$1/n_f$ (clusters/ nb^{-1})
1	1795	134
2	1680	136

IV. LHC LUMINOSITY CURVE AND TPX3 PRECISION

The TPX3 device has the capability to study the LHC luminosity curve with precision. In the following, LHC fill 6677 (proton-proton collisions) is analyzed, as recorded on 13-14 May 2018, spanning over 13 hours.

A. Fitted LHC Luminosity Curve

In a simple model, the loss rate of protons, assuming the number of protons in each colliding beam are equal (and given by N), is governed by:

$$-dN/dt = \lambda_{bb}N^2/N_0 + \lambda_g N, \quad (1)$$

where N_0 is the initial number of protons, and λ_{bb} and λ_g are the constants related to beam-beam (burning-off the proton bunches) and single bunch (e.g. beam-gas) interactions, respectively. This equation has a known solution, which is used as fit function:

$$N(t) = \frac{N_0 e^{-\lambda_g t}}{1 + \frac{\lambda_{bb}}{\lambda_g} (1 - e^{-\lambda_g t})}, \quad (2)$$

with the two limiting cases:

$$N(t) = N_0 e^{-\lambda_g t} \text{ for } \lambda_{bb} \ll \lambda_g \text{ and,} \quad (3)$$

$$N(t) = \frac{N_0}{1 + \lambda_{bb} t} \text{ for } \lambda_g \ll \lambda_{bb}. \quad (4)$$

Figure 2 shows the fit of the LHC luminosity curve. The curve is proportional to $N(t)^2$ and is fitted to TPX3 layer-1 data using cluster-counting, recorded in the time period from 13 May at 17:40 CEST to 14 May 2018 at 2:00 CEST. This time range excludes the LHC emittance scans and also larger beam adjustments, as the simple model cannot account for beam optimizations. The data taken in the same time range are fitted for hit- and cluster-counting for layer-1 and layer-2.

Fig. 2. Time history of the LHC luminosity, as seen by TPX3 layer-1 using cluster-counting in LHC Run 6677. The small dips, visible as variations from the descending curve, correspond to the times when the LHC operators performed small-amplitude beam-separation scans to optimize or increase the luminosity. The solid line shows the fit to the data by the function given in Eq. (2).

The fit describes the LHC luminosity versus time quite well. For this analysis the fit curve serves as a reference to determine the measurement precision.

B. Precision

In order to investigate the precision of the TPX3 luminosity measurements, the difference between the fit and the data is studied as a function of time. Figure 3 shows this difference using hit- and cluster-counting for layer-1 and layer-2. The

four distributions show no particular common structure and therefore no LHC luminosity variation beyond the 0.5% level. The visible variations arise from statistical and systematic uncertainties (TPX3 measurements) being convoluted with uncertainties arising due to fluctuations in the proton-proton collision rates.

TABLE III
PRECISION OF TPX3 LUMINOSITY MEASUREMENTS FOR LAYER-1 AND LAYER-2 FOR HIT- AND CLUSTER-COUNTING IN LHC FILL 6677. THE WIDTH OF THE GAUSSIAN FIT $\sigma_{(\text{data}-\text{fit})}/\text{fit}$ GIVES THE PRECISION OF THE MEASUREMENT AND σ_{pull} GIVES THE WIDTH OF THE PULL DISTRIBUTION FIT WITH STATISTICAL UNCERTAINTIES ONLY.

Method	$\sigma_{(\text{data}-\text{fit})}/\text{fit}$ (%)		σ_{pull}	
	Layer-1	Layer-2	Layer-1	Layer-2
hit-counting	0.86	0.87	8.73	8.97
cluster-counting	0.48	0.47	1.41	1.37

For the relative difference between data and the fitted luminosity curve (Figure 3), the corresponding Gaussian fit is shown in Figure 4 using cluster-counting. Relative internal precisions per LB are 0.86% (hit analysis) and 0.48% (cluster analysis), obtained with TPX3 layer-1. Similar precisions are obtained for layer-2, as given in Table III.

Figure 5 shows the pull distribution assuming statistical uncertainties only. Additionally, Table III lists the corresponding widths of the Gaussian fits of the pull distributions. While these widths are approximately unity for the cluster analysis, they are much larger for the hit analysis. The reason is that one interacting particle creates on average many hits and thus the hits are correlated. Moreover, the widths for the cluster-counting indicate that statistical uncertainties are dominant.

The effect of the small-amplitude beam-separation scans on the residual width was studied. The residual width is used to derive the short-term luminosity precision. The small dips in the luminosity curve indicate the time of the scans. For the LHC Run 6677, the effect of the amplitude scans was found to be small, as quantified in Table IV.

TABLE IV
EFFECT OF LHC SMALL-AMPLITUDE BEAM-SEPARATION SCANS ON THE PRECISION OF TPX3 LUMINOSITY MEASUREMENTS FOR LAYER-1 CLUSTER-COUNTING IN LHC FILL 6677. THE WIDTH OF THE GAUSSIAN FIT $\sigma_{(\text{data}-\text{fit})}/\text{fit}$ GIVES THE PRECISION OF THE MEASUREMENT AND σ_{pull} GIVES THE WIDTH OF THE PULL DISTRIBUTION FIT WITH STATISTICAL UNCERTAINTIES ONLY. THREE CASES ARE UNDER CONSIDERATION: 1) FITTING THE LHC LUMINOSITY CURVE WHILE IGNORING THE AMPLITUDE SCANS, 2) FITTING THE LHC LUMINOSITY CURVE WITH A SEPARATE LUMINOSITY AMPLITUDE AFTER EACH SCAN, AND 3) FITTING THE LHC LUMINOSITY CURVE WITH A SEPARATE LUMINOSITY AMPLITUDE, λ_{bb} AND λ_g AFTER EACH SCAN.

Case	$\sigma_{(\text{data}-\text{fit})}/\text{fit}$ (%)	σ_{pull}
1	0.48	1.42
2	0.43	1.22
3	0.40	1.15

In summary, the relative short-term luminosity measurement precision is less than 0.5% for the LB time interval using cluster-counting.

Fig. 3. Relative difference between data and fitted luminosity curve as a function of time, seen by TPX3 for layer-1 and layer-2, in hit- and cluster-counting analyses in LHC fill 6677. The statistical uncertainties in the hit-counting analysis are much smaller than in the cluster analysis. The cluster analysis takes the correlations into account, resulting from the fact that one particle typically creates many hits. The TPX3 data are grouped into LB time periods of typically 60 s.

V. SHORT-TERM PRECISION OF TPX3 DEVICE

In order to determine the internal short-term precision of the TPX3 device for luminosity measurements with a different technique, the relative difference in luminosities (L_1 and L_2) measured by layer-1 and layer-2 is studied as a function of time using cluster-counting. Figure 6 shows the relative difference for LHC fill 6677, while Figure 7 shows the corresponding precision as the width of the Gaussian fit. The resulting pull distribution is shown in Figure 8. The width of the pull distribution is approximately unity, which indicates that the statistical uncertainty is dominant.

Fig. 4. Gaussian fit of the relative difference between data and fitted luminosity curve seen by TPX3 for layer-1 in LHC fill 6677.

The obtained precision for the TPX3 luminosity determination is 0.56% with $\sigma_{\text{pull}} = 1.17$. Since the difference of two measurements (from layer-1 and layer-2) is calculated and the statistical significance of each measurement is about the same, the uncertainty of each measurement is about $\sqrt{2}$ of the overall uncertainty. Thus, this leads to a measurement precision for each TPX3 device of approximately 0.4% per LB time interval, which is about the same value as obtained in Section IV.

Fig. 5. Pull distribution defined as $(\text{data-fit})/\sigma_{\text{data}}$ where σ_{data} is the uncertainty from the cluster statistics. The data shown in Figure 4 are used (LHC fill 6677)..

Fig. 6. Relative difference between the luminosities measured by layer-1 and layer-2 of the TPX3 device as a function of time, using cluster-counting in LHC fill 6677. The TPX3 data are grouped into LB time periods of typically 60 s. Statistical error bars are shown.

Fig. 7. Gaussian fit of the relative difference between the luminosities measured by layer-1 and layer-2 of the TPX3 device as a function of time, using cluster-counting in LHC fill 6677.

Fig. 8. Pull distribution defined as $(L_1 - L_2) / \sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_i is the luminosity uncertainty from the cluster statistics for layer- i . The data shown in Figure 7 are used (LHC fill 6677).

VI. LONG-TERM STABILITY OF TPX3 DEVICE

The internal long-term time stability of the luminosity monitoring is determined for the TPX3 device by comparing the luminosity measured by the two separate sensitive layers. For this analysis the clusters are grouped corresponding to the time periods of the April to October 2018 LHC fills. A linear fit is applied to the relative luminosity difference versus time, as shown in Figure 9. The slope of the linear fit and the deviations per LHC fill are taken as a measure of time stability. The obtained slope value and its uncertainty is $(-0.09 \pm 0.01)\%$ per 100 days. The uncertainty is obtained from the fit. The slope shows that the luminosity ratio measured by layer-1 and layer-2 does not change with time within the measurement uncertainty. Thus, the size of the maximum deviation per LHC fill (about 0.4%) is shown in Figure 9. This is taken as an approximation of the internal long-term time stability of the luminosity measurements.

Fig. 9. Relative difference between the luminosities measured by layer-1 and layer-2 of the TPX3 device as a function of time, using cluster-counting. The 2018 TPX3 data are grouped into LHC fill time periods. The size of the statistical error bar is below the size of the data point. A linear fit is applied to determine the slope. LHC fills from April to October 2018.

VII. LONG-TERM STABILITY WITH RESPECT TO OTHER ATLAS LUMINOMETERS

The relative long-term stability of TPX3 luminosity measurements is already compared to that of other ATLAS luminometers for 2017 data [9]. Figure 10 shows the fractional differences between the run-integrated luminosities measured from TPX3, track-counting, EMEC, FCal, and TILE with respect to the baseline LUCID algorithm. The luminosity measurements from the other detectors are normalised to that of LUCID for a reference run. The values for each run are plotted as a function of the cumulative delivered luminosity fraction, ranging from zero at the start of the year to one at the end year. This results in an axis monotonically increasing in time. Short runs with less than about two hours data-taking are not shown. The run-to-run agreement between the various luminosity measurements is generally at the percent level or better for the bulk of the data, with various short- and long-term trends being visible.

Fig. 10. Fractional differences in run-integrated luminosity between the LUCID BiHitOR algorithm and the TPX3, track-counting, EMEC, FCAL, and TILE measurements, plotted as a function of the cumulative delivered luminosity normalised to the 2017 total. The luminosity measurements from the other detectors are normalised to that of LUCID in the reference run indicated by the arrow. The assigned $\pm 1.3\%$ long-term stability uncertainty is shown by the yellow band [9].

VIII. LHC LUMINOSITY OF INDIVIDUAL BUNCH CROSSINGS

The TPX3 time resolution (time granularity 1.56 ns) [5], [6] allows one to study the luminosity of individual LHC proton bunch crossings, which are 25 ns apart (bunch spacing). This is a novelty regarding the luminosity measurements with respect to the previous MPX and TPX luminosity measurements. The TPX3 bunch-by-bunch luminosity determination was also made possible by using an external trigger [6] which relates the LHC orbit time to the TPX3 data. In previous luminosity analyses with MPX and TPX devices, the exposure times are necessarily much longer than the bunch spacing. As a proof of principle, the bunch structure of LHC fill 6694 (17 May 2018) is investigated with TPX3. The relative bunch luminosity measurement precision is determined using the data integrated over the entire LHC fill.

The LHC proton collisions occur when the bunches cross each other from opposite sides. The 26.7 km LHC ring has 3564 potential bunch slots, which are separated by 25 ns in time. Not all bunch slots are filled and paired for collision. For example, LHC fill 6694 has 2162 bunches colliding in the ATLAS cavern. In this LHC fill, there are 15 so-called bunch trains with consecutive bunches filled and two isolated colliding bunches separated in time from the bunch trains. The bunch structure measured with layer-1 is shown in Figure 11. The 15 bunch trains and the two individual colliding bunches at 15,950 ns and 60,490 ns orbit times are visible. It is noted that the background level in the bunch trains increases during the first bunches. The reason could be that an exponential decrease of the signal peak per bunch crossing is observed with a decay time of about 30 ns, which is comparable in length with the bunch spacing of 25 ns.

A simple toy model is constructed to understand the background increase (arbitrary scale) during the bunch trains. For the toy model the signal of a single bunch crossing is approx-

imated with a Heaviside step function (constant amplitude) and an exponential decay. These signals are then summed according to the observed bunch structure. Figure 12 shows the modeled signal versus time for 10,800 ns to 16,800 ns orbit time which resembles the measurement shown in Figure 11.

Fig. 11. Bunch structure of individual bunch collisions observed with TPX3 for layer-1. Upper plot: 15 LHC bunch trains are visible, as well as two isolated colliding bunches at 15,950 ns and 60,490 ns orbit times. Lower plot: details for the orbit time range from 10,800 ns to 16,800 ns are shown. In this time range, three bunch trains and one isolated colliding bunch are observed. The data are integrated over LHC fill 6694.

Fig. 12. Illustration of the background increase during LHC bunch trains using a toy model, as described in the text. The increase of the background asymptotically reaches a constant level as observed in the data. The orbit time range from 10,800 ns to 16,800 ns corresponds to the LHC fill 6694. In this time range three bunch trains and one isolated bunch collision are modeled.

The toy model illustrates that the increase of the background during the bunch trains results from the overlap of signals due to previous bunch collisions. Moreover, it shows that the increased background level is asymptotically reached after a few consecutive bunch crossings within a bunch train.

The luminosity of each bunch crossing is determined by counting the total number of clusters in a time interval of 25 ns (bunch spacing) around the peak. A constant background of about 400 clusters is subtracted, as determined from the time periods between the bunch trains. This background results mostly from collisions, since the background due to electronic noise and activation of long-lived isotopes is only about 20 clusters, as evaluated in a period when no beams are circulating in the LHC ring. In addition, the extrapolated cluster rate from the previous peak is subtracted as well, based on the toy model.

The internal precision of the luminosity measurement per bunch crossing for the entire LHC fill is determined by comparing the luminosity measurements of layer-1 and layer-2. Figure 13 shows the corresponding precision as the width of the Gaussian fit. The resulting pull distribution is shown in Figure 14. Good agreement between the luminosity measurements using layer-1 and layer-2 is obtained and thus the luminosities determined by each layer are averaged. The absolute luminosity normalization is approximated based on the total integrated LHC fill luminosity [17]. Figure 15 shows that the precision of the relative luminosity measurement is about 5%, where the variation is defined as the width over mean of the Gaussian fit. This observed variation is the convolution of the TPX3 measurement precision (statistical and systematic) and the differences in the intensity of the individual LHC bunches. So far in this study, the possibility to classify the observed cluster types is not exploited. These types are characteristic for different particles (electrons, hadrons, nuclear fragments, neutrons) as a function of their occurrence during the bunch crossing time interval of 25 ns.

Fig. 13. Gaussian fit of the relative difference between the TPX3 luminosities per bunch crossing measured by layer-1 and layer-2. The data are integrated over LHC fill 6694.

Fig. 14. Pull distribution defined as $(L_1 - L_2)/\sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_i is the luminosity uncertainty from the cluster statistics for layer- i . The data shown in Figure 13 are used (LHC fill 6694).

Fig. 15. Variation of measured LHC luminosity per colliding bunch. The variation is defined as width over mean of the Gaussian fit to the data. The luminosity is averaged from the measurements of TPX3 layer-1 and layer-2. The observed variation (asymmetry) is due to the convolution of the TPX3 measurement precision and the differences in the (non-Gaussian) intensities of the individual LHC bunches. The data are integrated over LHC fill 6694.

IX. CONCLUSIONS

A double-layer TPX3 device installed in the ATLAS detector cavern has successfully taken data at the LHC during Run-2 13 TeV proton-proton collisions. The relative internal short-term precision of the TPX3 luminosity measurements was determined from the LHC luminosity curve to be less than 0.5% for 60 s time intervals. It was observed that cluster-counting improves the luminosity precision compared to hit-counting, since one particle typically corresponds to one cluster of hits. The internal short-term precision was determined in a complementary evaluation by studying the relative difference in luminosities measured by the two TPX3 sensor layers using cluster-counting and a relative precision of 0.4% was observed. The deviation from the internal long-term time stability of the TPX3 device for luminosity measurements was below 0.5%. When integrated over an entire LHC fill, it was demonstrated that the TPX3 device used in this study even has the capability to determine the time structure of the luminosity due to the collisions of individual LHC proton bunches.

ACKNOWLEDGMENT

The author would like to thank warmly the ATLAS Luminosity Group and the IEAP team for useful discussions and interactions, and the Medipix Collaboration for providing the Timepix3 assemblies. The project is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), and by the European Regional Development Fund-Project “Van de Graaff Accelerator - a Tunable Source of Monoenergetic Neutrons and Light Ions” (No. CZ.02.1.01/0.0/0.0/16_013/0001785).

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