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Luminosity from thermal neutron counting with MPX detectors and relation to ATLAS reference luminosity at $\sqrt{s} = 8$ TeV proton-proton collisions

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ABSTRACT: A luminosity determination based on thermal neutron counting with six MPX silicon pixel devices installed in the ATLAS cavern is presented. Recently, the ATLAS Collaboration published final $\sqrt{s} = 8$ TeV luminosity results. This made possible to perform a detailed comparison and verify the potential of the thermal neutron counting as a novel method for luminosity measurements to supplement the well-established presently used procedures. This measurement is unique to the MPX network and has the advantage that the neutrons, which pass the MPX devices, cannot result from activation processes of material nearby. Good agreement is found between the MPX neutron counting results and the ATLAS reference luminosity. The differences between the ATLAS and MPX luminosity measurements are described by a Gaussian distribution with width of 1.5%.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Neutron detectors (cold, thermal, fast neutrons); Performance of High Energy Physics Detectors

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1 Introduction

The precision measurement of the LHC luminosity is important for many physics analyses performed by the ATLAS and CMS collaborations at CERN and thus the luminosity measurements attract much attention. The ATLAS and CMS collaborations have elaborate systems of luminosity measurements, described in [1] and [2], respectively. In ATLAS the reference luminosity is based on several detectors capable of track counting per bunch crossing. Additional algorithms, sensitive to the instantaneous luminosity summed over all bunches, provide relative luminosity monitoring on time scales of a few seconds rather than of a bunch crossing, allowing independent checks of the linearity and long-term stability. Hit counting in the Medipix-2 (MPX) system is one of these additional algorithms [3]. The MPX detectors are hybrid silicon pixel devices, installed at different locations in the ATLAS detector [4] and in its cavern. Their locations are illustrated in figure 1.

A comparison of ATLAS results and the luminosity measured with MPX devices was beyond the scope of the recent MPX paper [3], however, results from MPX hit counting was included in the ATLAS publication [5]. In this publication the MPX luminosity measurement from thermal neutron counting is confronted with the ATLAS results. This measurement is unique to the MPX network and has the advantage that the neutrons, which pass the MPX devices, cannot result from activation processes of material nearby. Thermal neutron counting was not used so far as a cross-check algorithm in ATLAS, owing to its high statistical uncertainty. The statistical sensitivity of thermal neutron counting will improve with the new TPX detectors installed presently in ATLAS [6]. We assess here possible systematic uncertainties of thermal neutron counting by a detailed comparative study with ATLAS [5] for which the numerical luminosity information has been provided recently.

Any additional information on luminosity will to some extent improve the overall measurement by addressing different type of systematic uncertainty and reducing the statistical uncertainty. This comparison is thus highly motivated. It is novel and became possible only recently with the release of detailed ATLAS luminosity results in the time period overlapping with the MPX measurements.

The MPX devices (MPX01 to MPX13) are based on the Medipix-2 hybrid silicon pixel detectors which were developed by the Medipix-2 Collaboration [7]. They consist of a $\approx 2 \text{ cm}^2$ silicon sensor matrix of 256×256 cells, bump-bonded to a readout chip. Each matrix element ($55 \times 55 \mu\text{m}^2$ pixel, $300 \mu\text{m}$ thick) is connected to its respective readout chain integrated on the readout chip.

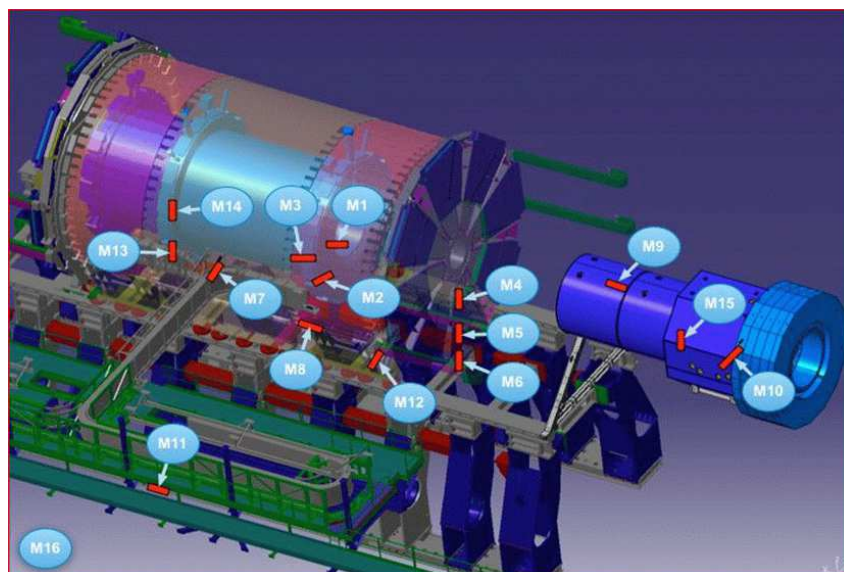


Figure 1. Overview of MPX detector positions in the ATLAS detector (partial illustration) and in the ATLAS cavern. The data of the devices MPX07 to MPX12 (indicated as M7 to M12) were used for the neutron counting luminosity measurement.

The detection of charged particles in the MPX devices is based on the ionization energy deposited by particles passing through the silicon sensor. For each pixel, the resulting signals are amplified and counted during an adjustable exposure time window (frame). Neutral particles, however, need to be converted to charged particles before they can be detected. Therefore, a part of each silicon sensor is covered with a ${}^6\text{LiF}$ converter for thermal neutron detection. Pulse height discriminators determine the input energy window and provide noise suppression.

One of the important features of the MPX devices is the ability to record and identify clusters. These are defined as patterns of adjacent pixels with energy deposits defined in [8], section 2.2. Different particles that traverse the device cause different cluster shapes, which allow particle identification and the distinction between keV-MeV electrons, photons, energetic hadrons, alpha particles and ion-fragments. A counter in each pixel records interacting quanta of radiation, photons, neutrons, electrons, minimum ionizing particles, and ions with energy deposits falling within the preset energy window [8, 9]. The data is stored frame-by-frame. After the exposure is closed, it takes about 6 s to transmit the status of the full 65536 pixel matrix. The electronic shutter is closed and the device is not sensitive during this readout process (dead-time).

The devices MPX07 to MPX12 are used for the presented analysis of the neutron counting luminosity. Their locations are given in table 1, which also lists the respective count rates per unit sensor area and per unit integrated luminosity.

In the following, section 2 describes the luminosity measurements from thermal neutron counting. The comparison of the MPX results with the results from the ATLAS luminosity measurement are given in section 3.

Table 1. MPX 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. Only devices with low cluster rates are used for the thermal neutron counting analysis as indicated. Ordering in the table is given with decreasing particle flux.

Device	Z (m)	R (m)	Measured MPX clusters per unit sensor area and per unit luminosity ($\text{cm}^{-2}/\text{nb}^{-1}$)
MPX09	15.39	1.56	5.8
MPX12	7.23	6.25	3.9
MPX08	4.02	4.40	1.2
MPX10	22.88	5.19	1.0
MPX07	0.35	4.59	0.45
MPX11	4.86	16.69	0.30

2 MPX luminosity from thermal neutron counting

Thermal neutrons are detected by MPX devices via ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reactions in a ${}^6\text{LiF}$ converter layer with thickness of about $3 \text{ mg}/\text{cm}^2$ on average [8], section 2.1. The tritons and alpha particles from the neutron conversion are registered by Si-sensors as large round-shaped pixel clusters, so-called heavy blobs (HB). The typical detection efficiency for thermal neutrons is 1%, determined from individual calibrations of the MPX devices in a thermal neutron field [8], section 2.3. Hence, the HB count rate is proportional to the number of neutrons passing the devices. It is used as a measure of instantaneous luminosity since neutrons are generated in the primary and secondary interactions from the proton-proton collisions. The measured neutron radiation field agrees well with the simulations performed with methods similar to those reported in ref. [8], section 6.5.

For the devices MPX07 to MPX12 the pixel matrix occupancy is sufficiently small for pattern recognition and to determine the HB (thermal neutron) count rate. A dedicated study was performed to determine the misidentification of heavy blobs which are lost due to the overlap with other clusters [8], section 2.2. The resulting correction factors, specific to each MPX device, depend on the number of clusters per frame (i.e., on the LHC collision rate, on the device location and on the exposure time). The precision of these correction factors was estimated to be better than 1%.

The distribution of heavy blobs per frame recorded within the region covered with a ${}^6\text{LiF}$ converter is well described by a Poisson distribution, as demonstrated in [10].

For the luminosity determination, the overlap corrected number of heavy blobs (cHB) is used for each MPX device. The number of cHB per frame is converted into the number of cHB per luminosity block (LB) [3]. Frames are selected which lie within the time window of the LB and the numbers of cHB of these frames are averaged. Only those LBs are used for which all MPX devices (MPX07-12) were operational.

These LBs are grouped into time periods corresponding to an ATLAS run with varying length from about one to twelve hours. The precise time ranges of the ATLAS runs are used [5]. For each LB time interval the number of cHB are summed over all six MPX devices used in this analysis.

The summed cHB are converted into luminosity by using a normalization factor such that the luminosity ratio determined from MPX hits [3] and MPX clusters is unity for the data taken on 16 September 2012.

For each device and each time period the statistical uncertainty is $1/\sqrt{N_{\text{HB}}}$, where N_{HB} is the summed number of heavy blobs without applying the overlap correction factor. The statistical uncertainties are dominant in the analysis of HB counting in the ${}^6\text{LiF}$ -covered detector region since the HB count rate is rather small (a few HB counts per frame).

3 Comparison of MPX and ATLAS luminosity measurements

The ATLAS luminosity measurements are based on several luminometers and the detailed studies led to an overall uncertainty of 1.9% [5]. For this comparative study of the MPX thermal neutron luminosity with the ATLAS luminosity measurements, the ATLAS run-by-run consistency is relevant. The relative ATLAS run-by-run uncertainty is 0.5% [5].

The ratio of the ATLAS reference luminosity [5] L_{ATLAS} and the MPX luminosity measurements is shown in figure 2 as a function of time. The data of each recorded run are combined and the statistical uncertainty is indicated by the error bars. A few runs are very short (less than one hour) and thus the accumulated number of heavy blob clusters is small, leading to a large statistical uncertainty.

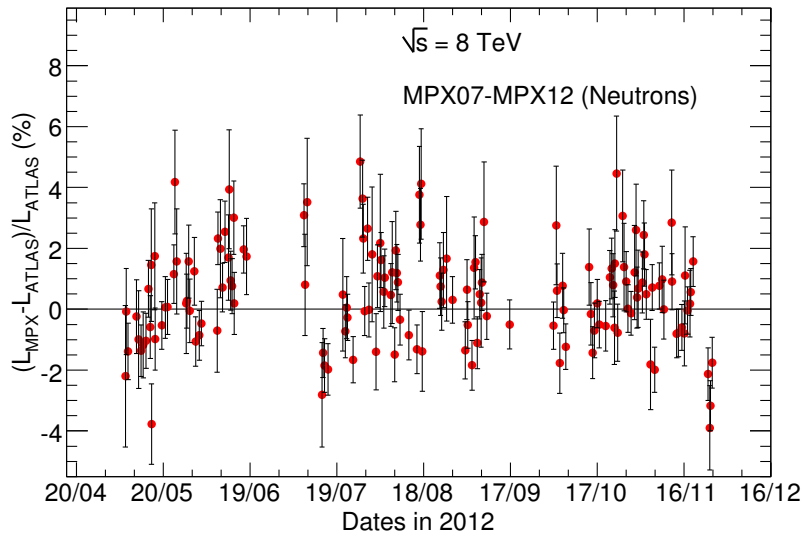


Figure 2. Evolution in time of the fractional difference in run-integrated luminosity between the MPX neutron-counting and the ATLAS reference luminosity. Each point shows the mean difference for a single run as defined in the text. The error bars are statistical only, and convoluted with 0.5% relative uncertainty from the ATLAS reference measurement. The MPX neutron luminosity is normalized to the MPX hit luminosity [3] such that their ratio for the data taken on 16 September 2012 is unity. The data of the devices MPX07-MPX12 are combined.

The relative differences between the MPX and ATLAS luminosity measurements are approximately described by a single Gaussian fit with width of $(1.48 \pm 0.13)\%$ (figure 3). The width is dominated by the statistical uncertainty of the MPX measurement.

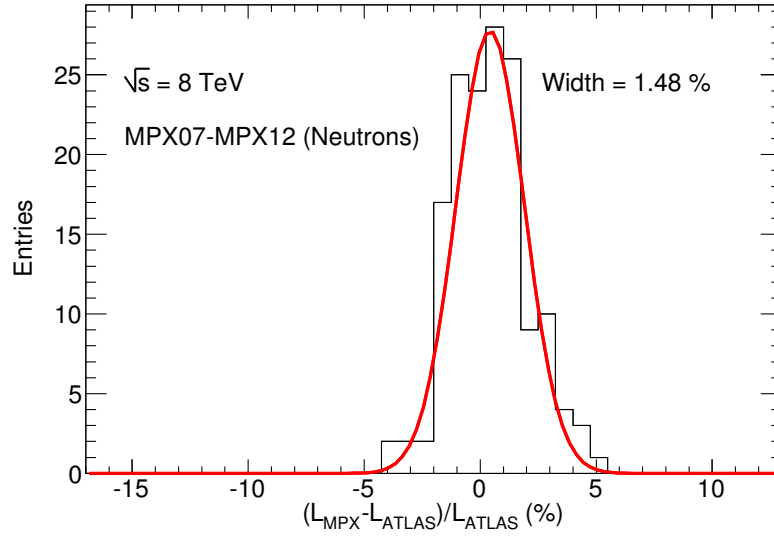


Figure 3. Residual distributions defined as $(L_{\text{MPX}} - L_{\text{ATLAS}}) / L_{\text{ATLAS}}$. A Gaussian fit is applied. The MPX neutron luminosity is normalized to the MPX hit luminosity [3] such that their ratio for the data (as defined in the text) taken on 16 September 2012 is unity. The data of the devices MPX07-MPX12 are combined.

The pull distribution is shown in figure 4, assuming that the relative uncertainty is governed only by $1/\sqrt{N_{\text{HB}}}$. The Gaussian fit of the pull distribution has a width (sigma) of 1.36 ± 0.08 . It demonstrates that the uncertainty of the neutron counting luminosity is close to the statistical expectation.

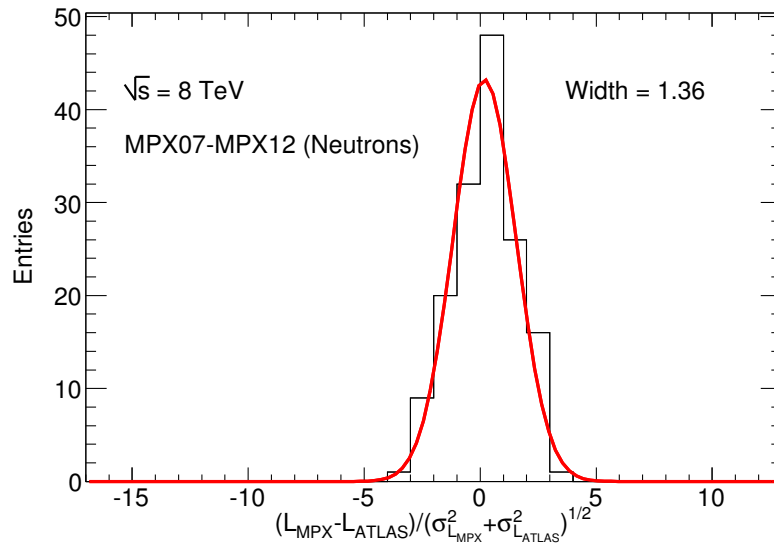


Figure 4. Pull distribution $(L_{\text{MPX}} - L_{\text{ATLAS}}) / (\sigma_{L_{\text{MPX}}}^2 + \sigma_{L_{\text{ATLAS}}}^2)^{1/2}$, where $\sigma_{L_{\text{MPX}}}$ is the statistical uncertainty on the thermal neutron counting, and $\sigma_{L_{\text{ATLAS}}}$ the run-by-run uncertainty on the ATLAS reference luminosity. The relative ATLAS reference uncertainty is 0.5%. A Gaussian fit is applied. The MPX neutron luminosity is normalized to the MPX hit luminosity [3] such that their ratio for the data (as defined in the text) taken on 16 September 2012 is unity. The data of the devices MPX07-MPX12 are combined.

The thermal neutron analysis is independent of activation effects of materials near the MPX devices. Although activation effects were observed in the MPX hit analysis from the production of light particles [3], the activation energy is too small to produce neutrons. Therefore, differently than in the hit counting luminosity measurement, this particular uncertainty is absent in the present analysis.

4 Conclusions

An independent approach to determine the LHC luminosity is presented using thermal neutron counting. The results are compared with recently published ATLAS luminosity results. Good agreement is found within the statistical uncertainties. For a run-by-run analysis the relative precision is 1.5%. There is complementarity of the cluster counting and the earlier published hit counting, and also a different set of MPX devices were used. While a hit luminosity analysis has high statistics and its uncertainty is dominated by systematic effects with a precision of 0.3%, the presented cluster analysis is dominated by statistical uncertainties owing to the limited cluster statistics. The neutron analysis is not affected by radioactive activation effects of material near the devices. A network of TPX devices (upgraded successors of the MPX devices) has been installed as a replacement of the MPX network for the Run-2 LHC operation [6]. With this TPX network higher cluster rates are being recorded and it is anticipated that the statistical uncertainty in the thermal neutron luminosity analysis can be reduced.

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