Luminosity algorithms for BCM1F upgrade at CMS

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Abstract

The BCM1F detector is a part of the Beam Conditions and Radiation Monitoring system installed in the CMS detector of the LHC experiment. Its purpose is to respond to fast beam flux changes in order to protect the CMS from radiation-caused damage. After the LHC Long Shutdown 1, BCM1F will have to operate efficiently at higher beam energies and is foreseen to deliver online luminosity. The aim of the analysis presented in this report is to develop luminosity algorithms appropriate for measuring particle flux at high collision rate. Algorithms for 8 and 24 diamond sensors are discussed, with the latter being required in terms of the upcoming BCM1F upgrade. Presented results are obtained for events generated with FOCUS - FLUKA Monte Carlo simulation of proton-proton collisions in the CMS detector.

Contents

1 Motivation

The LHC upgrade to higher energy and luminosity is now in progress. When it is completed, Fast Beam Conditions Monitor (subdetector of the CMS - one of the LHC's experiments), will have to keep its good performance at energies twice as high as at present. The detector is therefore going to be expanded from the currently operating 8 to 24 diamond sensors. At center-of-mass energies of 13 TeV, the number of pp collisions per bunch crossing can exceed one hundred, which results in a much higher flux of created particles. Under these circumstances, the probability of registering a hit by any one of diamond sensors is almost one. In order to be still sensitive to flux changes, one needs to develop more complex logics for flux measurements. The presented work describes luminosity algorithms appropriate for this purpose.

2 The LHC accelerator [1]

The Large Hadron Collider (LHC) is the biggest currently operating particle collider. It has been built by the European Organization for Nuclear Research (CERN) and is placed on the border between France and Switzerland, near Geneva. The collider was launched in 2008 and in April 2012 it reached center-of-mass energy equal to 8 TeV. For most of its operating time, the LHC collides two proton beams. The goal energy for proton-proton collisions is 14 TeV and it is planned for 2015.

One of the main goals of LHC was to either discover or exclude the existence of Higgs boson. In July 2012 CMS and ATLAS experiments by the LHC announced the discovery of a new boson with mass around 126 GeV/c^2 consistent with Standard Model theoretical expectations. Other LHC physics goals are the search for supersymmetric particles, study of collisions at TeV region and heavy ion scattering with lead beams. A scheme of the LHC accelerator with its main experiments is shown in Fig 1.

2.1 Accelerator construction

The accelerator tunnel has a circumference of 27 km and is located at a depth of 50 to 175 meters below ground. LHC uses the tunnel previously used by the e^+e^- Large Electron Positron Collider (LEP). Inside the tunnel, there are two pipes for the beams travelling in opposite directions. The beam curvature is achieved using 1232 dipole magnets of length of about 15 m; additionally, the beam is being focused by 392 quadrupole magnets. A total of more than 1600 superconducting magnets were installed at the accelerator. The windings of the magnets are made of an alloy of niobium and titanium for which to maintain superconductive properties a temperature below 1.9 K is required. Some of the accelerator properties are shown in Table 1.

	By the end of 2012	Planned
Energy	8 TeV	14 TeV
Time between bunch crossings	50 ns	25 ns
Number of bunches in a beam	1380	2808

Table 1: LHC accelerator properties.

2.2 Experiments at the LHC

The four main experiments built at the LHC are: ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment) and LHCb. The first two are general purpose experiments, ALICE is targeted to the nuclear physics lead-lead collisions studies, while LHCb was built for precise b quark measurements (CP violation).

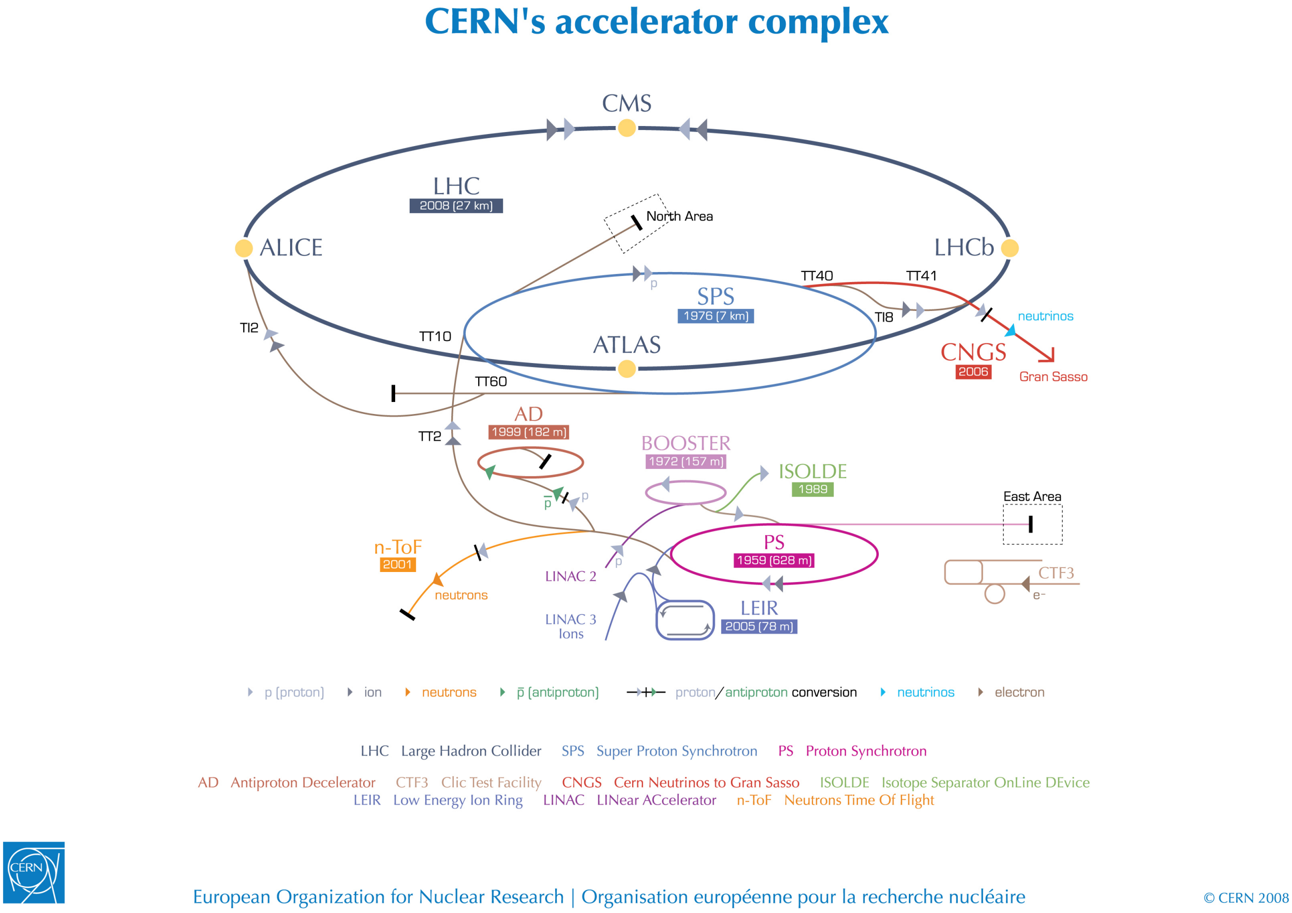

Figure 1: The LHC accelerator, storage ring and its preaccelerators.

3 The CMS experiment [2]

3.1 Detector construction

The CMS detector (Compact Muon Solenoid) is one of the two largest detectors build at the LHC accelerator. Its diameter is approximately 15 m, its length 21.5 m, and its total weight is 12.5 kt. It is a general purpose detector with a concentric subdetector structure. The subdetectors from the most inner are:

- Vertex detector - a silicon pixel detector with very precise spatial granularity. It is used for measuring particle tracks very close to the interaction point in order to reconstruct the primary vertex position and possible secondary vertices.
- Tracker - a silicon detector in which the particle momenta and directions are measured.
- Electromagnetic calorimeter (ECAL) - built from $PbWO_4$ crystals. Its goal is to measure the energy and position of electromagnetically interacting particles such as electrons, positrons or photons.
- Hadron calorimeter (HCAL) - made from steel and brass interchanged with scintillator layers. It is used to measure strongly interacting particles such as protons, neutrons or pions.
- Magnet solenoid - a magnet creating a solenoidal magnetic field of 3.8 T. The field causes all electrically charged particles to bend and the track curvature is used to determine the momentum.

- Muon detector system - a system of three different detector subsystems: Drift Tube Chambers, Cathode Strip Chambers and Resistive Plate Chambers used for muon momentum measurements and muon triggers.

The CMS detector with all the layers is shown on Fig. 2.

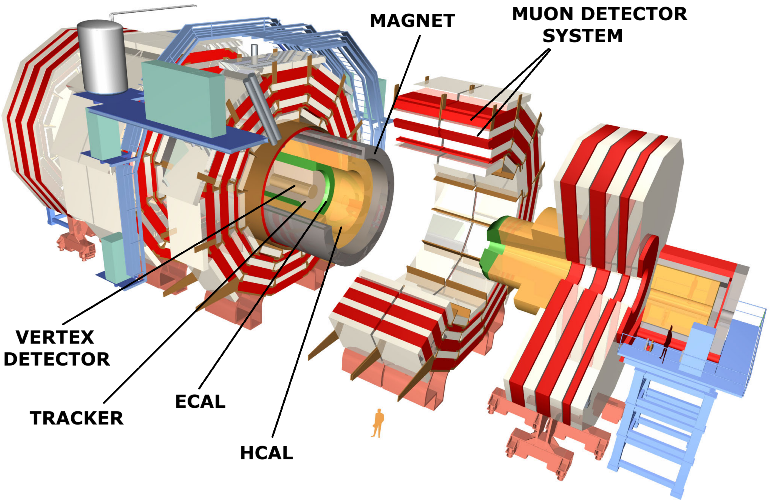

Figure 2: The CMS detector.

4 Fast Beam Conditions Monitor BCM1F [3]

The CMS detector is constantly exposed to high radiation originating from beam halo and collision products. The highest level of radiation appears for the innermost detectors, particularly for the pixel detector. Despite using radiation-hard materials, any uncontrolled beam losses could cause irreversible detector damage. In order to respond to rapid losses, as well as to perform long term studies of the collected ionisation dose, the Beam Conditions and Radiation Monitoring system (BRM) was installed near the beam pipe. The Fast Beam Conditions Monitor (BCM1F) is a part of BRM and serves specifically the purpose of monitoring fast variations of beam conditions. It has a very good time resolution - about one nanosecond, which is less than the time between bunch crossings (see Table 1). The BCM1F is therefore able to monitor the beam bunch-by-bunch and almost immediately react to any potentially damaging beam losses. In 2012 it was demonstrated that BCM1F can be used as an on-line luminometer.

4.1 BCM1F overview

The BCM1F detector was composed of 8 single-crystal CVD (Chemical Vapor Deposition) diamond sensors. The sensors are installed near the pixel detector of CMS, 4 sensors on either side of the interaction point (IP), in two planes perpendicular to the beam axis, each 1.8 m from IP, as shown in Fig. 3 and Fig. 4. Each sensor has a surface area of only 5x5 mm^2 and is 0.5 mm thick. Products from collisions arrive at the sensors approximately 6 ns after the bunch crossing. The distance between diamonds and interaction point was chosen to be optimal for sufficient time separation between incoming and outgoing halo particles. To each sensor a radiation hard amplifier is connected. The analog optical signal is sent to the counting room, where signals are digitized and offline analysis is performed.

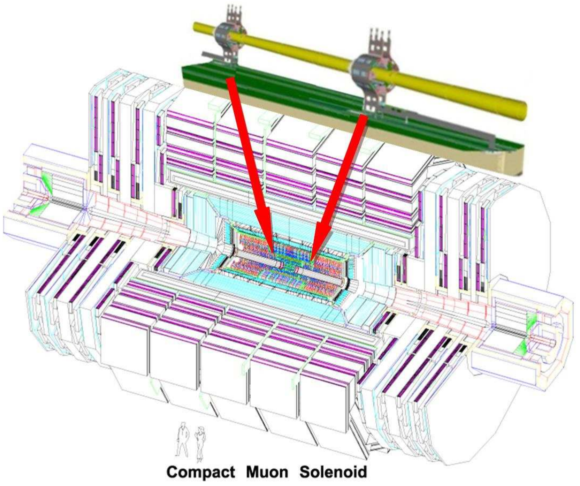

Figure 3: Placement of two planes with BCM1F sensors.

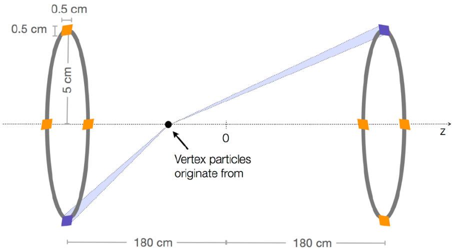

Figure 4: Scheme of BCM1F sensors positions.

4.2 LHC Long Shutdown 1

Since February 2013 the LHC has been in its first Long Shutdown (LS1) period, which will last until end of 2014. During this time a series of upgrades on the accelerator and detectors will be carried out. After the shutdown, LHC will operate at 6.5 GeV energy per proton beam and the time between bunch crossings will decrease to 25 ns [4]. The BCM1F detector needs to be adapted to the new conditions, otherwise its performance due to larger particle flux would be deteriorated. Therefore, 24 diamonds (12 on either side) will be installed instead of the current 8. To gain more effective performance, each sensor is subdivided in two pads and each pad will be readout separately.

5 Tools

Presented analysis was performed on events generated with FOCUS (FLUKA for CMS Users) package. FLUKA [5] is a Monte Carlo package designed to generate particle interactions and simulate their propagation through matter. FOCUS package was developed to generate proton - proton (pp) collisions specifically and it has the CMS detector's geometry implemented. Nevertheless, FOCUS is not yet complete and it is still at the testing stage. For the purpose of this work, collisions at the center-of-mass energy of 14 TeV were generated. Analysis was performed using the ROOT data analysis framework [6].

6 Methods

Charged particles that traverse through the CMS detector can ionise the diamonds and leave tracks in the BCM1F sensors. Therefore, from individual sensors information, one can approximate the beam flux, and monitor beam conditions on bunch-by-bunch basis. In order to operate efficiently on the LHC beam, fast and simple logic decisions must be made. Based on the number of hit sensors, the 'luminosity algorithms' are defined. Their general purpose is calculation of the hit probabilities for given sensor combinations. In other words, an algorithm checks whether particles created in one pp collision passed through some specified sensors (specified combination of sensors). If they did, the event is counted and contributes to the calculated probability. To be more specific, hit probability is defined with the formula (1):

$$\text{probability} = \frac{N_{pass}}{N_{events}}, \tag{1}$$

where N_{pass} denotes number of events (pp collisions) that satisfied the algorithm's criterion - left hit in a given sensor or a combination of sensors, and N_{events} is the number of all generated pp collisions.

Particles generated in pp collisions need about 6 ns to travel from the IP to BCM1F sensors. Fig. 5 presents the distribution of the time of registered hits, with respect to the particle's creation time. FOCUS-generated particles arrive at the BCM1F sensors at the expected time. In order to avoid performing the analysis on particles from secondary interactions, only particles appearing in the time window $3-6$ ns were taken into account. If more than one particle reached the same sensor within one collision, only the first particle would be registered by the detector, due to electronics dead-time. This applies also to the developed algorithms - they are not sensitive to the number of particles crossing one sensor within the same collision, but simply count the number of hit sensors.

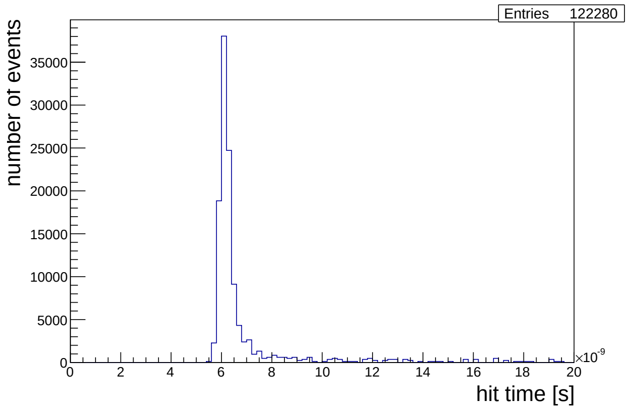

Figure 5: Time of hit registration by the BCM1F sensors with respect to the bunch crossing time.

The number of interacting proton pairs per bunch crossing is not constant - it could be zero and in most cases it doesn't exceed 30 (120 after the LS1). The offline analysis enables to predict the hit probabilities for different values of interacting protons, which is fundamental for further online beam conditions study. In this work, the total number of generated pp collisions was 3960. Those collisions were subdivided into smaller groups containing different numbers of events - from 1 to 30 (120). Every group was subsequently treated as one new 'event', which this time corresponded to the more physical situation with more than one proton pair interacting per bunch crossing. The 'pileup' was defined as a number of pp collisions included in an event, minus one (e.g. for events with just one pp collision, pileup was equal to zero). To summarise, one set of generated pp collisions was repeatedly divided into smaller groups. The amount of included collisions depended on the desired pileup value. With this approach, hit probabilities obtained for different pileup values are highly correlated.

7 Results for 8 sensors

In Fig. 6 hit probabilities calculated for individual sensors for different pileup values are presented. Fig. 7 presents locations and technical names of BCM1F sensors in the 8 sensors case, before the LS1. Since the BCM1F detector is symmetric, obtained probabilities should be consistent for all sensors. Within the error bars, good agreement can be observed.

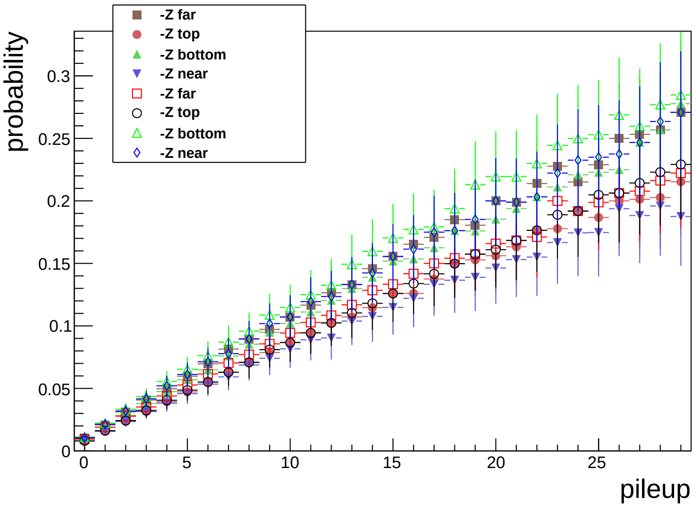

Figure 6: Hit probabilities for individual sensors in 8-sensor case.

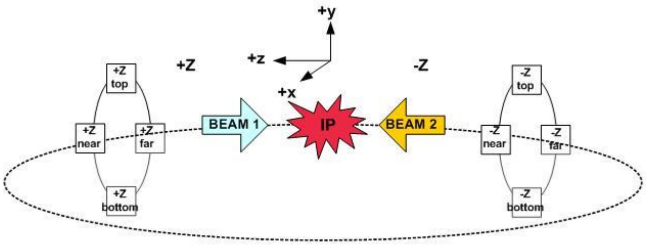

Figure 7: Technical names of BCM1F sensors.

For low pileup values (which was the case before the LS1) measurements based on individual sensors provided sufficient data for monitoring beam conditions. Nevertheless, probability that particle traversed through one specified sensor is not satisfactorily high at pileup values near zero. In order to observe higher probabilities and perform more complete analysis, some luminosity algorithms were used:

- Z minus OR Z plus - calculates the probability that any hit at all occurred in an event. Z minus and Z plus refer to the coordinate system (Fig. 7): Z minus denotes all sensors from the plane situated on one side of the IP and respectively Z plus denotes all sensors from the other plane. This algorithm is simple logic OR of signals from both planes.

- Z minus no Z plus - calculates the probability that there was any hit in the sensors from Z minus plane and at the same time there was no hit in the sensors from Z plus plane.

- Z plus no Z minus - adequately to previous algorithm, this one calculates the probability that there was any hit in the sensors from Z plus plane and at the same time there was no hit in the sensors from Z minus plane.

- Z minus AND Z plus - calculates the probability that for a given bunch crossing any sensor from Z minus side and any sensor from Z plus side registered a hit.

Probabilities obtained for these algorithms are presented in Fig. 8. It can be observed, that for pileup ~ 30, the 'Z minus OR Z plus' algorithm already saturates at one. The 'Z minus AND Z plus' follows it but does not saturate. Although at the old LHC center-of-mass energy this algorithm could be used for beam conditions monitoring at high pileup, it will not be the case for planned LHC energies. Fig. 9 presents results for the same algorithms as in Fig. 8, but obtained for 24 sensors at 14 TeV center-of-mass energy. Clearly, both algorithms discussed so far are not giving any distinguishable signal for much higher pileup, and therefore can not be used for beam conditions monitoring. Algorithms 'Z minus no Z plus' and 'Z plus no Z minus' could successfully work before the LS1 as well, but according to the simulation results they decrease to zero for upgraded LHC case.

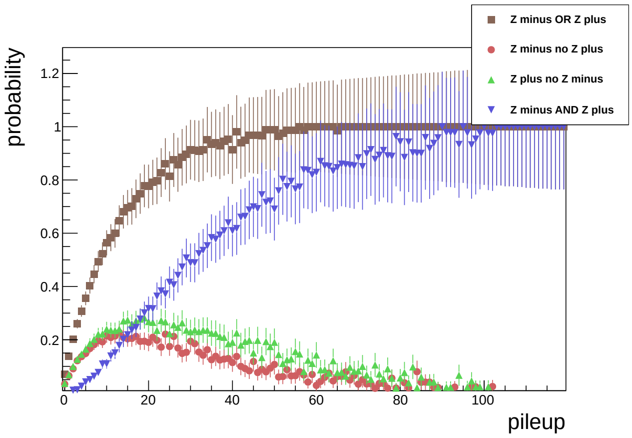

Figure 8: Probabilities for luminosity algorithms in 8-sensor case.

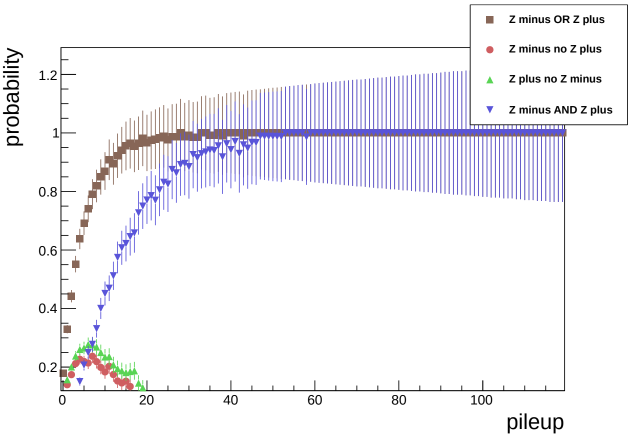

Figure 9: Probabilities for luminosity algorithms in 24-sensor case.

8 Results for 24 sensors

Fig. 11 presents hit probabilities for individual sensors calculated for 24 sensors scenario. Due to small statistics the obtained values have large uncertainties, which makes the plot illegible at high pileup. Therefore, hit probabilities of only 6 sensors (out of 24) are shown in Fig. 11. The results for the remaining sensors are consistent with presented probabilities within the uncertainties. Since CMS is symmetric in φ and $\pm$Z, hit probabilities should not differ between sensors, and such tendency can be observed. Individual hit probabilities can provide valuable input to beam conditions monitoring, as they rise linearly with pileup and do not reach maximal hit probability at the LHC energies.

In Fig. 11 hit probabilities for the most interesting luminosity algorithms among all of developed are presented. Description of their names is listed below:

- A - B sensors - (with A and B being integer numbers) calculates the probability that at least A hits and no more than B hits were registered on one side of the IP and that the number of hits registered on the other side of the IP was between A - B as well.
- One side cross - calculates the probability that on any side of the IP sensors hit in one event formed a cross (as shown in Fig. 10).

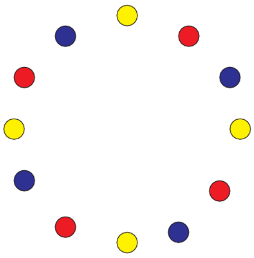

Figure 10: To satisfy the 'One side cross' algorithm all of yellow or red or blue sensors must be hit in an event.

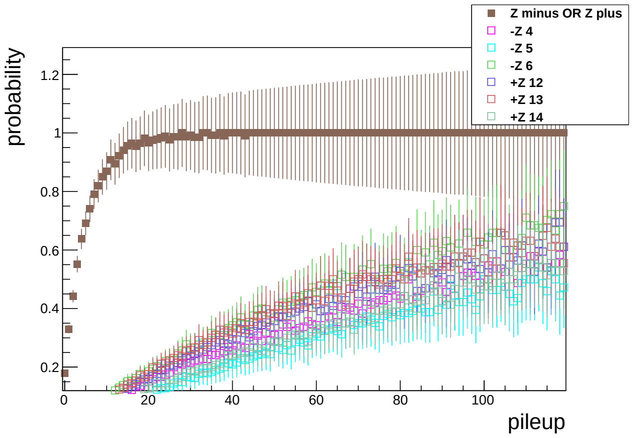

Figure 11: Hit probabilities for individual sensors in 24-sensor case plotted for 6 example sensors from both: +Z and -Z side of the IP.

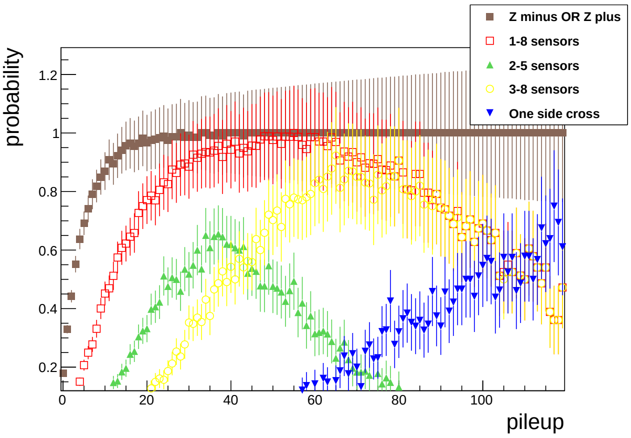

Figure 12: Hit probabilities for luminosity algorithms in 24-sensor case.

Except for the 'Z minus OR Z plus' algorithm, which is shown just as a reference, each one of the presented luminosity algorithms can be successfully applied to monitoring beam conditions in a specified pileup range. Unfortunately, none of them works in the whole desired (0-120) range. Therefore, further study should be conducted on this matter. Nevertheless, in the initial running period pileup will still be low as luminosity-calibration scans will be performed. Hence some of the developed low-pileup algorithms could work under these conditions.

9 Conclusions

Proton-proton collisions were generated using FOCUS Monte Carlo simulation. The resulting events were divided into groups and all produced particles in such group were treated as if they were created in one bunch crossing. For such defined events, hit probabilities for individual sensors in 8 and 24 sensors scenarios were calculated. After the LS1, monitoring individual sensors could successfully serve the purpose of beam flux measurements as the hit probabilities do not saturate at one for high pileup. Subsequently, luminosity algorithms for 24 sensors at the center-of-mass energy of 14 TeV were discussed. Developed algorithms could be useful for beam conditions monitoring in specified pileup ranges, but not in the whole range of interest, therefore the algorithms should be the object of further study.

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