CMS Forward Detectors for Luminosity Measurements

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on behalf of the PLT and FSC CMS groups

Abstract

We describe two CMS forward detector systems that will be used for luminosity measurements. One is the Pixel Luminosity Telescopes (PLT) a dedicated luminosity monitor based on diamond pixel sensors. This device will provide a measure of the relative luminosity in CMS to a statistical and systematic precision of the order of 1%. The other is the Forward Shower Counter (FSC) system of very far forward scintillators. This system could play an essential role in allowing the two-photon process $pp \rightarrow pp\mu\mu$ to be used as an absolute luminosity measure by allowing the fraction of events with proton dissociation to be determined.

INTRODUCTION

Two forward detector systems that will contribute to the measurement of luminosity in CMS are the Pixel Luminosity Telescopes (PLT) [1] and the Forward Shower Counters (FSC) [2]. The PLT is a dedicated luminosity monitor based on diamond pixel sensors. It is designed to measure the relative luminosity on a bunch-by-bunch basis to a precision of the order of 1% and to be stable to this precision over the full lifetime of CMS. The FSC is a set of very forward scintillators sensitive to showers produced by high rapidity particles that interact in the beam pipe. It is designed to study forward physics and can be used to tag small angle scattering events in which one or both of the protons undergo dissociation. Discriminating these events will be important for determining the fraction of dissociative events in the two-photon events $pp \rightarrow pp\gamma^*\gamma^* \rightarrow pp\mu\mu$ that have been proposed [3] for determining the absolute luminosity to high precision.

PLT

The PLT consists of arrays of eight small-angle telescopes, shown in Fig. 1, located on each end of CMS at a distance of approximately 1.75 m from the interaction point and about 5 cm from the beam line corresponding to $|\eta| \approx 4.2$. Each telescope is 7.5 cm long and consists of three equally-spaced planes of mono-crystalline diamond pixel sensors. The pixel sensors have an active area of 4 mm $\times$ 4 mm and are bump-bonded to the CMS PSI46 pixel readout chip [4]. The luminosity measurement consists of counting the number of telescopes with 3-fold coincidences in each bunch crossing using a fast, 40 MHz, output of the PSI46V readout chip. In addition, the addresses and pulse heights of those pixels over threshold will also be readout but at a lower rate of 1 to 10 kHz. As described below, this full pixel information is important in keeping systematics errors at or below the 1% level.

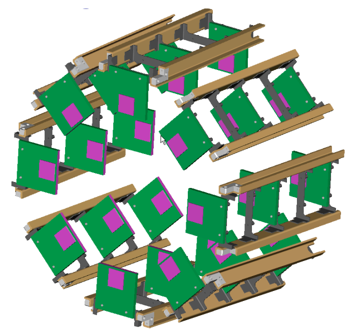

Figure 1: Array of PLT telescopes.

Statistical Precision

Pythia 6.2 was used to simulate particle hits in the PLT. At a luminosity of 10^{34} cm^{-2}s^{-1}, there will be approximately 2 coincidences per bunch crossing in the entire PLT corresponding to a total rate of approximately 80 MHz and a bunch-by-bunch rate of $\approx$ 30 kHz for each of the 2808 filled bunch crossing in an LHC orbit. This is sufficient to yield a statistical precision of 1% on the bunch-by–bunch luminosity in less than a second.

A full pixel readout rate of 1 kHz, gives $\approx$ 2 kHz of tracks recorded in the PLT yielding a 1% statistical precision on the bunch integrated luminosity in 5 s and on the bunch-by-bunch luminosity in four hours.

Systematic Errors

In order to take full advantage of this statistical precision, the systematic errors must be controlled to this precision as well. The main contributions to systematic errors arise from accidentals, track overlaps and the dependence of the acceptance on the position of the interaction point. Particles originating from interactions in material can cause accidental hits in the telescope planes giving a fake 3-fold coincidence rate leading to an overestimate of the luminosity. Fig. 2 shows the fraction of 3-fold coincidences due to accidentals as a function of the number of interactions per bunch crossing. At twenty interactions per bunch crossing, the accidental fraction is about 4%. Two particles passing through a telescope in a single bunch crossing will give only one 3-fold coincidence leading to an underestimate of the luminosity. Fig. 3 shows the fraction of 3-fold coincidences in which two particles overlap in a single telescope. At twenty interactions per bunch crossing, the overlap fraction is about 8%. Both of these effects can be corrected to a few per cent of themselves by using the track information from the full pixel readout.

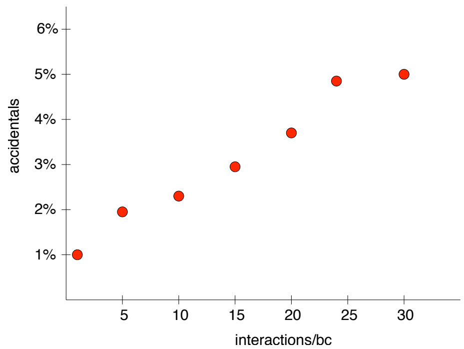

Figure 2: Percentage of accidental 3-fold coincidences as a function of the number of interactions per bunch crossing.

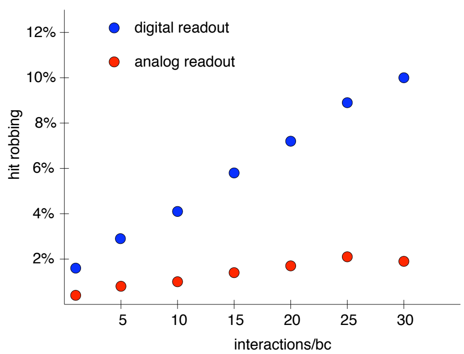

Figure 3: Percentage of 3-fold coincidences with track overlap as a function of the number of interactions per bunch crossing. Blue points are with the whole 4 mm $\times$ 4 mm sensor as a single active area. Red points are with the active area segmented into 300 μm-wide columns.

The solid angle acceptance of each PLT telescope is determined by the most downstream plane that is slightly smaller in active area than the other two. This makes the acceptance insensitive to radial drifts of the interaction point. As shown in Figs. 4 and 5, the acceptance is flat to 1% for a radial displacement of up to 1 cm if the radial displacement is directly toward a telescope and up to 4 mm if the radial displacement is directly between two telescopes. In the longitudinal direction, the acceptance is flat to 1% for displacements up to $\pm$ 30 cm. These displacements are well within the expected excursions of the interaction point.

Long Term Stability

In order for the luminosity measurement to be consistent to 1% throughout separated running periods, the PLT must have long term stability. There are three aspects to the PLT stablity. First, the PLT must be insensitive to changes in CMS acceptance and trigger. It has, therefore, been designed to be an independent system with its own data acquisition and trigger. Second, since the PLT must be removed for access to the CMS pixel detectors, its repositioning accuracy must be such to keep resulting changes in acceptance less than 1%. This is achieved with a cassette and carriage system that allows for precise surveying of the telescope positions and assures repositioning accuracy. Third, the efficiency of the PLT sensors must be known to better than 1% throughout the entire lifetime of CMS. This is achieved in two ways. Use of mono crystalline diamond sensors assures that the signal distribution, Fig. 6, will be well above the 3,000 electrons pixel threshold setting. The pulse height of the diamond sensor will decrease with irradiation, however, the separation of signal from threshold will be maintained up to a fluence of greater than 1.5 $\times 10^{15}$ 24 GeV protons per cm^2, as shown in Fig. 7, corresponding to the full LHC lifetime of 500 fb^{-1} of integrated luminosity. In addition, the information from the full pixel readout will allow continual monitoring of the efficiency of each sensor plane.

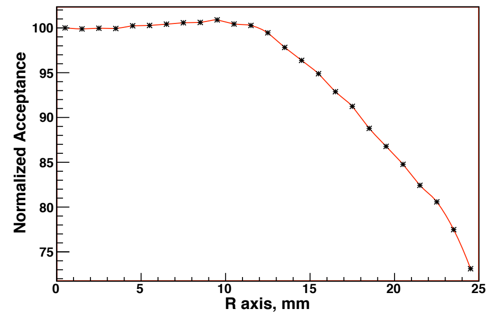

Figure 4: Percent acceptance as function of interaction point radial displacement directly toward a telescope.

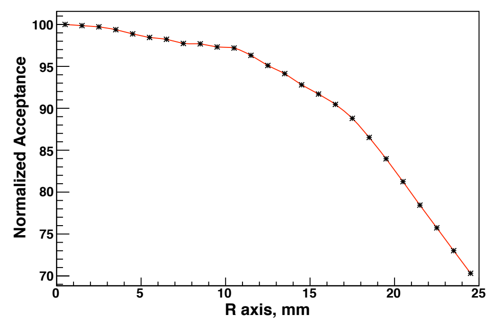

Figure 5: Percent acceptance as function of interaction point radial displacement directly between two telescopes.

FSC

The FSC consists of pairs of 25 cm $\times$ 25 cm scintillators surrounding the beam pipe at distances of 59 m and 85 m and four scintillators at 114 m on either side of the interaction point covering the rapidity range, $6 < |\eta| < 8$. It will detect showers produced by very forward particle interacting in the beam pipe.

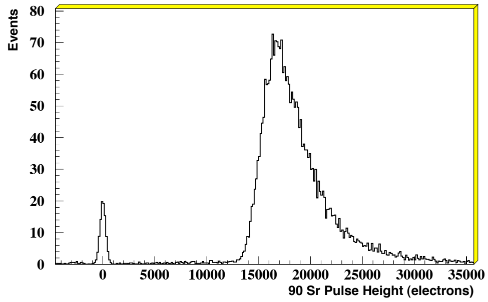

Figure 6: Pulse height distribution in electrons of a monocrystalline diamond sensor for traversing ^{90}Sr β particles.

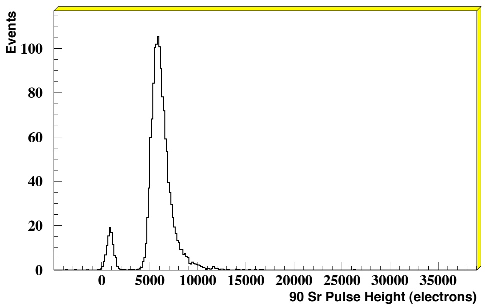

Figure 7: Pulse height distribution in electrons of a monocrystalline diamond sensor for traversing ^{90}Sr β particles irradiated to 1.5 $\times 10^{15}$ 24 GeV protons per cm^2.

Two Photon Process

The two photon process shown in Fig. 8 where X is a lepton pair is a purely electromagnetic process and can, therefor, be calculated to high precision. It has been proposed as a way of obtaining a high precision measure of the absolute luminosity. This method requires: triggering on the low mass lepton pair, identifying events in the presence of pile up and, since the scattered protons are not detected, distinguishing events without proton Coulomb dissociation from those where one or both protons dissociate.

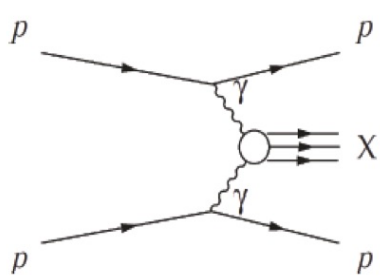

Figure 8: Two photon process.

Event Selection

The two photon events are distinguished by a low mass lepton pair. The trigger will be limited to low mass muon pairs due to the difficulty of triggering on low mass electron pairs. Events without pile up will be rare and it will, therefore, be necessary to identify the two photon events in the presence of pile up. In order to reduce background, events will be selected for which there are no other tracks associated with the di-muon vertex. The only remaining handle on background rejection is the kinematics of the muon pair. These will be back-to-back in the transverse plane and will have a small total transverse momentum. Fig. 9 shows the difference between π and the azimuthal angle between the muons, $\left|\pi - |\Delta\phi_{\mu\mu}|\right|$ while Fig. 10 shows the transverse momentum of the muon pair, $p_T^{\mu\mu}$ where the distributions are from a generator level LPAIR simulation [5] with no detector smearing. In addition to the non-dissociative events of interest, the distributions for events with single and double proton dissociation are also shown. Since these type of events are not as precisely calculated as the non-dissociative events and since they contribute approximately 30% and 10%, respectively, to the event sample, they will need to be corrected for.

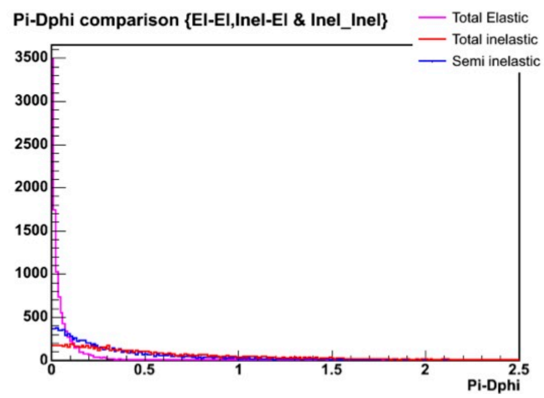

Figure 9: Difference between π and the azimuthal angle between the two muons, $\left|\pi - |\Delta\phi_{\mu\mu}|\right|$, in $pp \rightarrow pp\mu\mu$ events. Curves shown are for events without proton Coulomb dissociation (magenta), single proton dissociation (blue) and double dissociation (red) and were generated with LPAIR.

Rejection of Events with Proton Coulomb Dissociation

Although tight cuts on the kinematical distributions in Figs. 9 and 10 could be used to reduce the non-dissociative backgrounds, the efficiency and rejection factor of the cuts must be known very precisely and the simulation is not reliable to the level needed. Instead, single, double and non-dissociative events can be tagged based on whether there is activity in the FSC on one or both detector sides. The relative amounts and the kinematical distributions of the three types of events can then be experimentally determined and used as templates to determine the fraction of single and double dissociation events that remain after the cuts.

Using the activity in the FSC to tag the three types of events requires that the events be free of pile up. Events without pile up can be selected by requiring that there be no

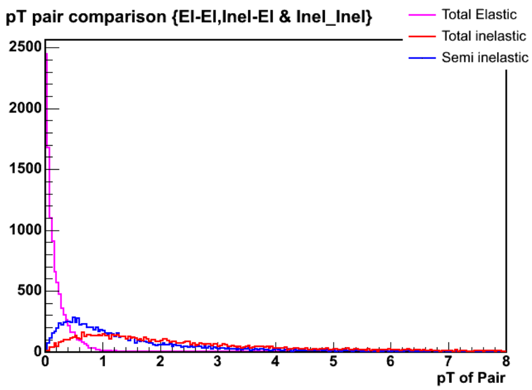

Figure 10: Transverse momentum of the the muon pair, $p_T^{\mu\mu}$, in $pp \to pp\mu\mu$ events. Curves shown are for events without proton Coulomb dissociation (magenta), single proton dissociation (blue) and double dissociation (red) and were generated with LPAIR.

particle activity except for the the two muons in the CMS detector excluding the FSC. Since events without pile up will be rare if the average number of interactions per bunch crossing is large, this measurement will need to be made during early running while the luminosity is not too large.

The effective luminosity, $L_{\rm eff}$, of single interaction (no pile up) bunch crossings as a function of the instantaneous luminosity is shown in Fig. 11. For instantaneous luminosities between 10^{32} and 10^{33} cm^{-2}s^{-1}, the integrated effective luminosity is 1 to 4 pb^{-1} per 10 hour store. Assuming, 200 hours of running at instantaneous luminosities between 10^{32} and 10^{33} cm^{-2}s^{-1} and using the LPAIR estimated $pp \to pp\mu\mu$ cross section of 12 pb, there will be about 2,000 two photon events.

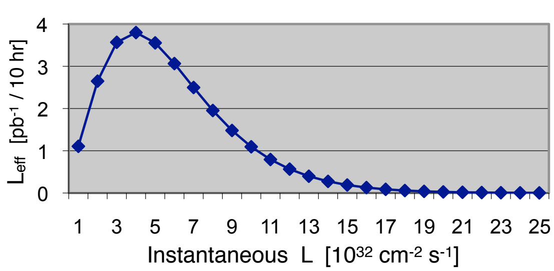

Figure 11: Effective luminosity, $L_{\rm eff}$ of single interaction bunch crossings in units of pb^{-1} per 10 hours as a function of the instantaneous luminosity. [6]

SUMMARY

The PLT will achieve a 1% resolution on the relative bunch-by-bunch luminosity in approximately 1 s. Its hybrid readout that includes a full readout of pixel hit information will allow the systematic errors to be controlled to the 1% level. It is designed to have long term stability through precision repositioning and through control of efficiencies by the use of mono-crystalline diamond sensors. The FSC by allowing for corrections due to proton dissociative events will be key for obtaining an absolute luminosity calibration from the two-photon process, $pp \to pp\mu\mu$. In order, to determine the $\mu\mu$ kinematical distributions for single and double dissociative events, events without pile up will need to be selected. Estimates indicate that there may be approximately 2,000 $pp \to pp\mu\mu$ no pile up events in the 2011-2012 LHC run.

ACKNOWLEDGMENTS

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