Luminosity Monitoring and Normalization in ATLAS and CMS

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Abstract — The methodologies for luminosity monitoring and normalization at the LHC are reviewed along with the dedicated detectors of the ATLAS and CMS experiments.

1 Introduction

The measurement of the luminosity is essential for any cross-section calculation. Its importance for the LHC physics program is outlined in section 2. The Instantaneous Luminosity L is defined in a process independent way by:

$$\frac{dN}{dt} = L \times \sigma$$

Where dN/dt is the interaction rate of a reference process with cross section σ. The integrated Luminosity $\mathcal{L}(\Delta_t)$ is also defined in an analogous way based on the total number of events produced in a given time interval Δ_t:

$$N = \mathcal{L} \times \sigma$$

Measuring the luminosity requires the theoretical or experimental knowledge of the cross section σ. On top of that, the observed rate (or total number of events) needs to be corrected taking into account the detector inefficiencies and the possible background sources.

This difficult task is typically separated in different steps which may also achieve redundant information. The first of these sub-tasks consists in the measurement of the relative instantaneous luminosity using dedicated forward detectors (see section 4). The specific methods adopted to address this problem typically quote dL/dt with a high statistical precision while keeping a large uncertainty on the absolute instantaneous luminosity figure (L). The measurement of the relative luminosity is required in order to combine the trigger chains (including those with time-dependent pre-scales) for an efficient beam usage and yield optimization. On top of that it is also essential to provide a quick feedback of the running conditions, monitoring the relevant backgrounds. Of course the relative measurements can always be turned into absolute measurement at a later stage, using a large variety of complementary normalization methodologies (see section 5).

2 Motivations of the Luminosity Measurements at the LHC

In order to determine the experimental cross sections for the observed physics processes, an estimation of the absolute luminosity is needed. In fact a careful study of "well known" processes will be one of the first steps of the LHC experiments as it can provide possible signatures of new physics which consist in deviations with respect to the Standard Model (SM) predictions.

Just to illustrate few examples, we will concentrate on the impact of the Luminosity measurement on the physics of the Higgs boson at the LHC. Assuming that the Higgs boson will be discovered, one of the most important goals in the High Energy Physics will be represented by the precision measurement of the Higgs properties (mass, width, production rates, branching ratios). Such measurement should give further insights into the electroweak symmetry-breaking mechanism and into the way the Higgs couples to fermions and bosons, and in some cases it could provide clear indications of possible deviations from the SM predictions.

As reported in the ATLAS Physics TDR [1], the luminosity measurement may represent the main source of systematic for the determination of the Higgs branching ratios at an integrated luminosity of 300 fb^{-1}. This is well illustrated by Fig. 1, which reports the relative precision on the measurement of the Higgs-boson rates for various channels as a function on m_{H}, considering two values for the luminosity uncertainty: 5% and 10%. For an Higgs Mass of 200 GeV, the uncertainty in the determination of branching ratio of the decay into ZZ turns out to be 12% (7%) assuming that the luminosity is known with an uncertainty of 10% (5%).

The uncertainty on the integrated luminosity is expected to be the main systematics also for what concerns the measurement of the $\tan\beta$ parameter for a Minimal Supersymmetric Standard Model Higgs. Fig. 2 does report the error on the uncertainty on the $\tan\beta$ measurement for both final states with photons and muons, assuming m_{A} = 150 GeV, a total integrated luminosity of 300 fb^{-1} and a conservative assumption of a 10% error on its determination.

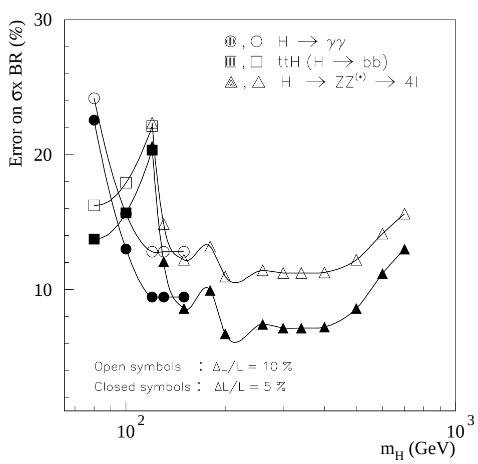

Figure 1: Relative precision on the measurement of the Higgs-boson rate ($\sigma \times \mathrm{BR}$) for various channels as a function on m_{H} assuming an integrated luminosity of 300 fb^{-1}. The luminosity is assumed to be known to 10% (open symbols) or to 5% (black symbols).

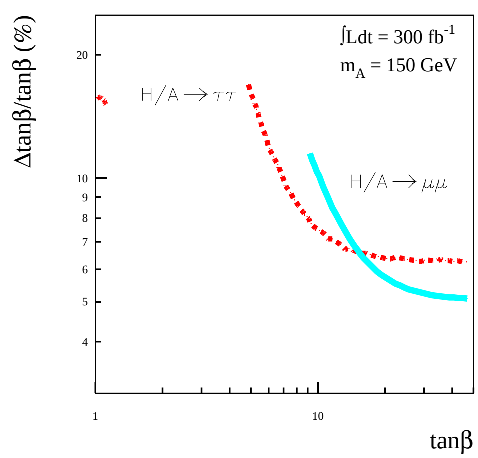

Figure 2: Expected precision on the measurement of $\tan\beta$, for an integrated luminosity of 300 fb^{-1} and for $m_{\mathrm{A}} = 150$ GeV.

3 Forward Detectors at ATLAS, CMS and TOTEM

ATLAS, CMS and TOTEM are equipped with a large variety of forward detectors to fulfill a rich physics program which goes from the measurement of the total proton-proton cross section at $\sqrt{s}$ = 14 TeV to more specialized research lines in diffraction, $\gamma\gamma$ and heavy ion. Here we will briefly summarize some of the detector highlights for each experiment which turn out to be relevant in the context of luminosity monitoring and normalization.

The ATLAS Beam Controlling Monitor (BCM) comprises two stations with four diamond sensors of 1×1 cm^2 at 1.8 m from the interaction region on each side, it covers a pseudo-rapidity gap from 3.9 to 4.1. This detector is expected to provide monitoring information about anomalous beam conditions (beam-gas and beam-collimator interaction events, beam loss). It is designed to work for the full luminosity range of LHC with a sufficient time resolution to identify individual bunch crossings. Its capability to distinguish proton-proton interactions from the background relies on the time of flight information: only proton-proton interactions achieve synchronous signals on the two sides.

The ATLAS Minimum Bias Trigger Scintillator (MBTS) system has eight wedge-shape plastic scintillators installed on the front face of LAr end-cap cryostat at $\pm$ 3.6 m from the ATLAS interaction region. Each scintillator covers $\Delta\phi = 2\pi/8$ and consists of two separated sections ($2.1 < \eta_{inn} < 2.8 < \eta_{out} < 3.8$). The scintillators are made of Polystyrene doped with fluorescing agent and the light emitted is collected by wavelength-shifting optical fibers embedded in grooves in the scintillator. The MBTS goal is to trigger minimum bias events vetoing halo events for $L < 5 \times 10^{32} cm^{-2}s^{-1}$ and to contribute to the level one trigger. It will be mostly used during the commissioning phase. Although the lifetime of the detector will be limited by the significant radiation damage, at least in the initial stage, the MBTS measurement of the minimum bias trigger rate will provide an essential luminosity monitor information.

The approved design for the upgrade to the forward system of ATLAS incorporates a relative luminosity monitoring using LUCID (LUminosity measurement using Cherenkov Integrating Detector), a system of 40 (2 x 20) Cherenkov tubes, surrounding the beam pipe at $\pm$17 m from the ATLAS interaction region with pseudo-rapidity coverage 5.4 $< |\eta| <$ 6.1. The 40 Aluminium tubes are filled with a Cherenkov radiator gas (C_4F_{10}) at 1 bar pressure. The Cherenkov light is collected by photomultipliers either directly coupled to the tubes or linked via optical fibres. LUCID will be able to monitor the collision-by-collision luminosity by detecting and counting the number of charged particles coming from the impact point. The time resolution of this detector is of the order of 140 ps. The amplitude resolution is also excellent (as shown in section 4 it is possible to count even multiple tracks per tube and no saturation is observed even at highest luminosity).

ALFA (Absolute Luminosity for ATLAS) is a system of ultra-small-angle detectors, located at 240 m on either side of the ATLAS interaction region to measure elastically scattered protons in the vicinity of the LHC beam, with angles in the μrad range. It consists of 4 station of Roman Pots (RP) inserts in the beam pipe equipped with position sensitive detectors. The sensitive detectors consist in 20 $\times$ 64 square 0.5 $\times$ 0.5 mm^2 scintillating fibers on ceramic substrate read out by 24 Multi-anode photo-multipliers with 64 channels. The detector follows a U/V geometry with 45 degree stereo layers, 64 fibers per plane in a module, 10 double sided modules per pot. The up and down detectors overlap for relative alignment purposes.

The CMS Hadron Forward Calorimeter (HF) is located at $\pm$11.2 m from the interaction point and covers the pseudo-rapidity range $3 < \eta < 5$. Each HF endcap is divided into 36 segments in azimuth and 12 segments in pseudo-rapidity, resulting in 432 towers per side, each of them corresponding to a physical channel. The calorimetric towers are made of steel absorbers and embedded radiation hard quartz fibers, which provide a fast collection of Cherenkov light. Signals from the HF photo-tubes are digitized on a bunch by bunch basis using a dedicated chip, and then routed to a set of 36 Trigger and Readout (HTR) boards each of which services 24 HF physical towers. In order to extraxct the luminosity signal from the HTR an additional mezzanine board called the HF luminosity transmitter (HLX) is mounted on each of the HTR boards. Each HLX board collects the channel occupancy and $\sum E_T$ data from one HTR and transmits it using a 100Mbps Ethernet Tranceiver. The data collected by the 36 HLX cards is sent via UDP to a 1Gbps enabled Ethernet switch at a rate of 1.8 Mbps per card. This data is multicast to two identical servers that collect the data from all the boards and transfer the data to a separate server that services the various clients (online Data Base, CMS and LHC control rooms, etc.).

The TOTEM experimental set-up consists of two tracking telescopes T1 and T2, as well as RP stations, one on either side of the CMS interaction region. The T1 and T2 telescopes consist of CSC (Cathode Strip Chambers) and GEM (Gas Electron Multipliers) chambers respectively, and will detect charged particles in the regions 3.2 $<$ $|\eta| <$ 5 and 5 $< |\eta| <$ 6.6. The TOTEM RP stations will be placed at a distance of $\pm$147 m and $\pm$220 m from the CMS interaction region. Each station will consist of two units, 2.5 m and 4 m apart, each with one horizontally and two vertically movable pots equipped with silicon strip detectors.

4 Measurement of the Relative Instantaneous Luminosity with Forward Detectors

ATLAS and CMS started a big effort in studying methods to measure the relative instantaneous luminosity with a 1% statistical accuracy. The methods used to extract the luminosity have to demonstrate linearity over a large luminosity range. In addition, the real time operation should be performed by a dedicated data acquisition system, independent from the central one.

The online luminosity measurement in CMS is based on the HF, which is sensitive to a large fraction of the inelastic cross section [2]. The design goal for the real time measurement is to determine the average luminosity in less than one second. ATLAS relies on LUCID, that basically counts the charged particles produced in the inelastic scattering. It will measure both the instantaneous and the integrated relative luminosity, the first bunch by bunch and the second in a period of time (the Luminosity Block) that lasts about one minute.

Three counting techniques for extracting the real time luminosity signal from the luminosity monitors have been studied: *Zero counting, hits counting* and *particles counting*. On top of these counting techniques, a methodology based on the energy measurement may also be adopted at the highest luminosity.

The Zero counting method is based on the probability of having a beam crossing (BX) without interactions. Assuming that the number of interactions per BX follows the Poisson statistics, one finds that at $L = 10^{33}\mathrm{cm}^{-1}\mathrm{s}^{-1}$ around 70% of the BXs produce two or more proton-proton interactions. Distinguishing between a BX with zero and a BX with one or more interactions is simpler than counting the exact number of interactions. Inverting the equation for the Poisson distribution one can express μ, i.e. the average number of interactions per beam crossing in terms of $p(0)$, i.e. the probability of no interactions in a beam crossing: $\mu = -\ln\ p(0)$. As the average number of interactions per BX increases the number of ”Zero's” decreases leading to ”Zero starvation”.
The LUCID detector, composed by 20 tubes per side, will only use this method for $L < 10^{33}\mathrm{cm}^{-1}\mathrm{s}^{-1}$. In fact it will be affected by Zero starvation and lose linearity from $\langle\mu\rangle \gtrsim 1$. The HF, instead, may use each of its 864 physical towers in order to make 864 quasi independent measurements for each BX, adopting the Zero counting method even at higher luminosity . As shown by Fig. 3, a straightforward counting is possible with HF, since nearly all the interactions produce $\sum E_T$ well above the expected noise of 2 photo-electrons per tower.

The hit counting method is based on counting the number of towers (HF) or tubes (LUCID) with a signal above threshold for each BX. This quantity is linearly related to the luminosity, provided there's a negligible probability of multiple hits in the same detector element (saturation).
LUCID adopts the hit counting method as a reference for luminosity measurement at low and medium luminosity ($L \lesssim 10^{33}\mathrm{cm}^{-1}\mathrm{s}^{-1}$). The HF will mostly use the hit counting method at low luminosity, where the number of ”Zero's” will be too high to achieve a statistically significant measurement of $p(0)$ in one second.

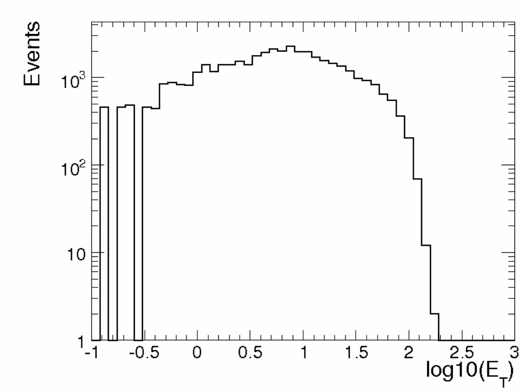

Figure 3: E_T spectrum of single interactions in the HF.

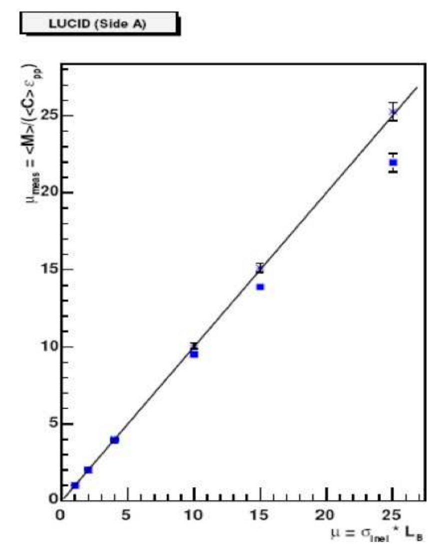

Figure 4: Reconstructed average number of interactions versus the real number of interactions per beam crossing according to the particle counting (solid line) and hit counting (squares) methods. Saturation effects result in deviation from linearity. [3]

In order to prevent saturation at the highest luminosity ($L \sim 10^{34}\mathrm{cm}^{-1}\mathrm{s}^{-1}$) LUCID and HF will use different techniques. The method adopted by LUCID consists in sampling the charged multiplicity. This is possible thanks to the fact that the number of photons detected in the tubes turns out to be fairly proportional to the number of hitting tracks. The HF will rather rely on the measurement of the total transverse energy ($\sum E_T$) deposited in the towers. Indeed, both the sampled charged multiplicity and the sampled transverse energy are supposed to be proportional to the average number of interactions per BX (hence to the luminosity). The linearity performances of the LUCID detector for both the hit and particle counting methods are shown in Fig. 4.

5 Normalization of the Luminosity Measurement

5.1 The Absolute Luminosity from Beam Parameters

The collider luminosity is an intrinsic characteristic of any accelerator and can be expressed in terms of the beam parameters. For the LHC the formula is:

$$L = F \frac{f \sum_{i=1}^{k_b} N_{1i} N_{2i}}{4\pi \sigma_x^* \sigma_y^*} \quad (1)$$

where F is a factor which accounts for the beam crossing angle, f = 11.2 kHz is the beam-revolution frequency, N_{1i} and N_{2i} are the numbers of protons in the colliding bunches, k_b is the number of bunches and σ_x^* and σ_y^* are the transverse bunch widths at the interaction point. This quantity is usually parameterized as

$$L = F \frac{f k_b N^2}{4\pi \epsilon_N \frac{\beta^*}{\gamma}} \quad (2)$$

where the number of protons is assumed the same for each bunch ($N_{1i} \simeq N_{2i} \simeq N$) and the beam dimensions are expressed via the normalized emittance ($\epsilon_N = \sigma_x^* \sigma_y^* \gamma/\beta$), the value at the impact point of the amplitude function β and the beam Lorentz factor γ.

One possibility for the LHC experiments is to obtain the absolute normalization for the luminosity by using ”Van der Meer” scan of the beam profiles [4]. The absolute luminosity can be calculated by plugging the beam parameters into the above expression. The least certain of the input parameters are the horizontal and vertical beam sizes, meaning that if one can provide a direct measure of the size parameters, the uncertainty in the luminosity can be substantially reduced. To measure the beam sizes, one needs to sweep the beams through one another at the interaction point by inserting a magnetic bump of variable size (i.e. the separation bumps orbit correctors). This methodology should achieve a 10% % precision on the determination of the absolute luminosity.

5.2 Normalization to the Inelastic Cross Section

The TOTEM experiment [5] will measure the total proton-proton cross-section at the LHC with a precision of 1% by using a luminosity independent method based on the simultaneous evaluation of the total elastic and inelastic rates. This method requires a precise measurement of the inelastic rate with a good pseudo-rapidity coverage. The expected precision for the measurement of the inelastic proton-proton cross section at $\sqrt{s} = 14$ TeV is of the order of 5%, while the measurement of the total single diffractive cross section will be affected by a 10% error. These figures can be used to provide an absolute normalization of the luminosity monitors based on the counting of the generic proton-proton interactions (or on their absence). A precision close to 5% is possible provided single diffractive events are detected with a similar efficiency with respect to the not diffractive ones.

5.3 The Coulomb Scattering

This method has previously been employed by the UA4 collaboration [6], and is currently being envisaged by the ATLAS collaboration that plans to exploit the performances of the ALFA detector [7], which allows to measure the elastic scattering in the forward direction down to 3μrad.

The measurement of the angular distribution of elastically scattered protons at very small angles provides a simultaneous determination of the luminosity, the total hadronic cross-section, the ρ parameter and the proton nuclear slope.

The measurement is performed during dedicated runs at $\beta^* \simeq$ 2500 m, and the luminosity is extracted from the theoretically well known Coulomb cross-section with a 2-3 % precision. The same data are used to normalize the luminosity monitors which provide the instant luminosity information during normal physics running at low β^*.

5.4 How to Exploit Heavy Boson Production

Heavy boson production is one of the dominant processes at the LHC. Several millions of clean W and Z events with leptonic final states events will be collected quickly, resulting in relative statistical errors well below 1%.

The theoretical calculations for $pp \to W \to l\nu$ and $pp \to Z \to l^+l^-$ processes are very advanced, providing one of the best understood LHC final states. In perturbative QCD, the total cross sections for these reactions are known at the next-to-next-to-leading order (NNLO) level. In addition to these fixed order results, predictions based on the resummation of threshold effects are also available [8].

The main source of theoretical uncertainty on the total $pp \rightarrow W \rightarrow l\nu$ and $pp \rightarrow Z \rightarrow l^+l^-$ cross sections can be factorized in the parton distribution functions (PDF) [9]. Although the measurement of the lepton rapidity distributions should reduce the PDF uncertainties, it seems currently hard to bring this contribution below the 4-5% level.

However, the number of $pp \rightarrow Z \rightarrow l^+l^-$ events collected inside the detector acceptance ($N_{Z\rightarrow l^+l^-}$) provides a convenient normalization quantity which can be measured with a precision at the 2-3% level [10], independently from the knowledge of the luminosity.

One may use such quantity in order to predict the number of events (N_{bkg}) of a lower rate process collected for the same integrated luminosity:

$$N_{bkg} = R \times N_{Z\rightarrow l^+l^-}$$

where R is calculated using a Monte Carlo generator providing a detailed description of the final states for both processes. The theoretical uncertainties affecting the estimation of R are often less relevant with respect to the ones which apply to the total cross sections.

6 Conclusions

In this article, we have reviewed the techniques for luminosity monitoring and normalization in ATLAS and CMS, which make extensive usage of the detectors in the forward region. A statistical precision better than 1% with a very good linearity performance over several orders of magnitude is achieved on the measurement of the relative luminosity by the monitoring systems. A 2-3% precision on the measurement of the absolute luminosity will be possible at high β^*, relying on the measurement of the elastically scattered protons at very small angles which will provide a first normalization of the luminosity monitors. Complementary information from several physics processes (including the beam related ones) will be used to provide a direct estimation of the absolute luminosity at low β^*. The information from heavy boson production along with a correct handling of the theoretical uncertainties may provide an alternative to the luminosity measurement for the normalization of the expected SM background rates to searches.

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