Proton - proton luminosity, standard candles and PDFs at the LHC

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1 Introduction

The Large Hadron Collider (LHC) is expected to start colliding proton beams in 2009, and is expected to reach design parameters in energy and luminosity sometime later and deliver a few fb^{-1} per year of data at the 14 TeV collision energy.

During the past 15 years many theoretical calculations and experimental simulations have demonstrated a huge potential to perform many accurate tests of the Standard Model (SM) with LHC data, which could yield insight into new physics mechanisms.

To make these tests, the experiments identify a particular signature X and observe, using a variety of selection criteria, a certain number of events in a given data taking period. After correcting this event rate for backgrounds and the selection efficiency, the number is converted into a cross section. The cross section, $\sigma_{pp\to X}$ can be compared with theoretical predictions[1] according to the formula: $N_{corrected} = \sigma_{pp\to X} \times L_{pp}$ where L_{pp} is the recorded proton proton luminosity.

Besides the statistical errors of a measurement, the systematic error is related to the uncertainties from the L_{pp} determination, the background and efficiency corrections within the detector acceptance and from extrapolations into the uncovered very forward rapidity regions. The interpretation of an observed cross section within the SM requires further the knowledge of the theoretical cross section. Thus the uncertainties of the proton parton distribution function (PDF) have to be considered also.

In this Section we describe the status and perspectives of the ATLAS, CMS and LHCb, the three LHC pp collision detectors [1], to determine the proton proton luminosity normalization. The investigated methods are known and studied since many years and can be separated into the absolute (1) direct and (2) indirect proton proton luminosity determination. A third approach (3) tries to measure and calculate final states only relative to well understood reactions which depend on the parton-parton luminosity and are as such largely independent of the knowledge of the pp luminosity.

- Absolute, direct or indirect, proton proton luminosity normalization: If the absolute approach is used, the interpretations of a measured reaction cross section depends still on the knowledge of parton distribution function (PDF), which must be obtained from other experiments. Examples are:

[1] Alternatively, one can also apply a Monte Carlo simulation to the theoretical prediction and compare the number of background corrected events directly.

  - The proton proton luminosity normalization is based on the measurements of the beam currents and shapes. While the beam currents can be accurately determined using beam transformers, the beam profiles are more difficult to determine directly and usually constitute the dominant source of uncertainty on a luminosity measurement using this technique. The use of the machine luminosity determination using beam parameter measurements [2] and [3] will be described in Section 3.1. Alternatively one can try to measure the beam profiles also within the experiments using the precision vertex detectors. A short description of this idea, currently pursued within the LHCb collaboration, is also given in Section 3.1.
  - The simultaneous measurements of a pair of cross sections that are connected with each other quadratically via the optical theorem. A well known example of this is the measurement of the total inelastic cross section and the elastic cross section at very high pseudorapidities $|\eta| \approx 9$ and will be described in Section 3.3.
    So called instantaneous or real time luminosity measurements are based on "stable" high rate measurements of particular final state reactions. Once the ratio of such reactions to the pp luminosity determination has been measured, those reactions can be subsequently used as independent luminosity monitors. Some possibilities are discussed in Section 3.4.
  - The indirect absolute proton proton luminosity normalization is based on the theoretically well understood "two photon" reaction $pp \rightarrow pp\mu\mu$ [4, 5] (Section 3.5). This reaction could perhaps be considered as the equivalent of the luminosity counting in e^+e^- experiments using forward Bhabha scattering.

- Indirect pp luminosity measurements use final states, so called "standard candles", with well known theoretical cross sections (Section 4).
  Obviously, the resulting proton proton luminosity can only be as good as the theoretical and experimental knowledge of the "standard candle" reaction. The theoretically and experimentally best understood LHC reactions are the inclusive production of W and Z bosons with subsequent leptonic decays. Their large cross section combined with experimentally well defined final states, e.g. almost background free Z and W event samples can be selected over a relative large rapidity range, makes them the preferred LHC "standard candle" reaction. Other interesting candidates are the high p_t jet - boson (= γ, W or Z) final states. The indirect luminosity method requires also some knowledge of the PDFs, and of course, if one follows this approach, the cross section of the "standard candle" reaction becomes an input and can not be measured anymore. Thus, only well understood reactions should be considered as candidate reactions.
- pp luminosity independent relative rate measurements using "standard candle" reactions.
  In addition to the above indirect pp luminosity determinations, "standard candle" reactions allow to perform luminosity independent relative event rate calculations and measurements. This approach has already been used successfully in the past and more details were discussed during the past HERA-LHC workshop meetings [6]. For some reactions, this approach appears to be much easier and more accurate than standard cross section measurements and their interpretations. Perhaps the best known example at hadron colliders is the measurement and its interpretation of the production ratio for Z and W events,

where Tevatron experiments have reached accuracies of about 1-2% [7, 8]. Another example is related to relative branching ratio and lifetime measurements as used for b-flavored hadrons.

Furthermore the rapidity distributions of leptonic W and Z decays at the LHC are very sensitive to the PDF parameterization and, as was pointed out 10 years ago [9], one can use these reactions to determine the parton luminosity directly and very accurately over a large x (= parton momentum/proton momentum) range. In fact, W and Z production with low transverse momentum were found in this analysis to be very sensitive to $q\bar{q}$ luminosities, and the jet-boson final states, e.g. the jet-γ, Z, W final states at high transverse momentum are sensitive to the gluon luminosity.

In the following we attempt to describe the preparations and the status of the different luminosity measurements and their expected accuracies within ATLAS, CMS and LHCb. Obviously, all these direct and indirect methods should and will be pursued. In Section 5 we compare the advantages and disadvantages of the different methods. Even though some methods look more interesting and rewarding than others, it should be clear from the beginning that as many independent pp luminosity determinations as possible need to be performed by the experiments.

We also try to quantify the systematic accuracies which might be achieved over the next few years. As these errors depend somewhat on the overall achieved luminosity, we need in addition a hypothetical working scenario for the first 4 LHC years. We thus assume that during the first year, hopefully 2009, data at different center of mass energies can be collected by ATLAS and CMS. During the following three physics years we expect that 10 TeV will be the highest collision energy in year I and that at most 100 pb^{-1} can be collected. We assume further that during the following two years the design energy of 14 TeV can be achieved and that a luminosity of about 1 fb^{-1} and 10 fb^{-1} can be collected respectively per year. During the first few years similar numbers are expected for the LHCb experiment. However once the LHC reaches the first and second phase design luminosity of 10^{33}/cm^2/sec and 10^{34}/cm^2/sec it is expected that the LHCb experiment will run at an average luminosity of 2×10^{32}/cm^2/sec (resulting in about 2 fb^{-1}/per year).

2 Luminosity relevant design of ATLAS/CMS and LHCb

In the following we give a short description of the expected performance with respect to lepton and jet identification capabilities. Especially the electron and muon measurement capabilities are important for the identification of events with leptonic decays of W and Z bosons.

Both ATLAS and CMS are large so called omni purpose experiments with a large acceptance and precision measurement capabilities for high p_t electrons, muons and photons. Currently, the simulations of both experiments show very similar performance for a large variety of LHC physics reactions with and without jets. For the purpose of this Section we focus on the possibility to identify the production of inclusive W and Z decays with subsequent decays to electrons and muons. Both experiments expect excellent trigger accuracies for isolated leptons and it is expected that electrons and muons with momenta above 20-25 GeV can be triggered with high efficiency and up to $|\eta|$ of about 2.5. The special design of the ATLAS forward muon spectrometer should allow to detect muons with good accuracy even up to $|\eta|$ of 2.7.

The operation of ALFA, a very far forward detector placed about 240 m down the beam line, is envisaged by the ATLAS collaboration to provide an absolute luminosity measurement, either using special optics LHC running and the use of the optical theorem or using the total cross section measurement from the dedicated TOTEM experiment installed near CMS; results from this device can be expected from 2010 and on-wards. In addition to absolute luminosity measurements from ALFA the two detectors LUCID and the Zero-Degree-Calorimeter (CDC) [10] are sensitive to the relative luminosity at time scales of single bunch crossings.

A similar approach for absolute and relative luminosity measurements is foreseen by the CMS experiment. Here it is planned that dedicated forward detectors, the Hadron Forward Calorimeter (HF) and the ZDC device provide similar results as the ones in ATLAS.

Another technique that is expected to be available early on is a luminosity-independent measurement of the pp total cross section. This will be done using a forward detector built by the TOTEM experiment [11].

The LHCb experiment [12] has been designed to search for New Physics at the LHC through precision measurements of CP violating observables and the study of rare decays in the b-quark sector. Since the $b\bar{b}$ pairs resulting from the proton-proton collisions at the LHC will both be produced at small polar angles and in the same forward or backward cone, LHCb has been designed as a single-arm forward spectrometer covering the pseudo rapidity range $1.9 < \eta < 4.9$. The LHCb tracking system, which is composed of a silicon vertex detector, a warm dipole magnet and four planar tracking stations, will provide a momentum resolution of $\delta P/P = (0.3 + 0.0014 P/GeV)\%$ [13]. Muon identification is primarily achieved using a set of five planar multi-wire proportional chambers, one placed in front of the calorimeter system and four behind, and it is expected that for the momenta range 3-150GeV/c an identification efficiency of $\sim$98% and an associated pion dis-identification rate of $\sim$1% will be achieved. The reconstruction of primary and secondary vertices, a task of crucial importance at b physics experiments, will be virtually impossible in the high particle multiplicity environment present with the nominal LHC running luminosity of $10^{34} cm^{-2} s^{-1}$ - LHCb has therefore been designed to run at the lower luminosity of $2 \times 10^{32} cm^{-2} s^{-1}$.

Recent LHCb simulations have shown that leptonic W and Z decays to muons can be identified with a small background in the forward and very forward rapidity region starting from η of 1.9 and up to values larger than 4. As will be discussed later in more detail, the common muon acceptance region for the three LHC experiments between 1.9 and about 2.5 will allow to cross check and normalize the W and Z measurements in this region. Consequently the unique large rapidity from 2.5 to 4.9 can be used by LHCb to investigate the very low x range of the PDFs for the first time.

The absolute luminosity at LHCb will be obtained either directly, by making measurements of the beam parameters, or indirectly via a measurement of the event rate of an accurately predicted physics process.

As will be explained in the following Sections, all experiments will try to perform as many as possible direct and indirect absolute and relative luminosity measurements and will, if available, at least during the first years, also use luminosity numbers from the machine group.

2.1 Lepton triggering and W/Z identification.

Generally, the lepton trigger selections depend on the instantaneous luminosity and some pre-scaling might eventually needed. However, current simulations by all experiments show that the envisaged $|\eta|$ and p_t thresholds will not limit the measurement accuracies of leptons originating from W and Z decays.

The lepton trigger selections that generally perceived to be used for most W and Z related analysis are very similar in ATLAS and CMS as indicated in Table 1.

	Trigger selection e		Trigger selection μ	
Experiment	p_T	$\|\eta\|$	p_T	$\|\eta\|$
ATLAS	25 GeV	2.5	20 GeV	2.7
CMS	20 GeV	2.5	20 GeV	2.1
LHCb*	–	–	2.5 GeV	1.9-4.9

Table 1: For ATLAS and CMS the lepton trigger/selection p_t thresholds are given for single isolated leptons. *For the LHCb threshold is given for the muon pair mass instead of single muons and only positive values of η are covered.

Trigger and reconstruction efficiencies for leptonic W and Z decays within the acceptance of the detectors have been estimated for ATLAS to be 97.7% and 80.0% for electrons and 84.3% and 95.1% for muons, respectively. The reconstruction efficiency includes the trigger efficiencies and the off-line electron and muon selections used later to identify clean inclusive W and Z event samples [14].

The current equivalent trigger and off-line efficiencies for CMS are about 85% and 77% for electrons and combined about 85% for single muons [15]. Similar efficiency numbers for muons from W and Z decays are expected within the LHCb acceptance region [16]. Current simulations show that these numbers can be determined with high accuracies, reaching perhaps 1% or better, at least for isolated leptons[2] which have a transverse momentum some GeV above the trigger thresholds. For lower momenta near the thresholds or for additional special trigger conditions somewhat larger systematic uncertainties can be expected.

3 Direct and indirect absolute pp luminosity measurements

Three different absolute proton proton luminosity measurements are discussed in this Section. (1) The machine luminosity determination using beam parameter measurements [17], (2) the luminosity independent total pp cross section measurement combined with the measurement of the elastic pp scattering rate [11] and (3) the measurement of the "two photon" reaction $pp \rightarrow pp\mu\mu$ [4, 5]. As will be discussed in more detail in Section 5, only method (3) can be performed during the normal collision data taking. For method (1) some special methods, which take the actual detector performance during each run into account, need to be developed. Method 2 uses a two phase approach (a) a special machine optics run with low luminosity to determine the total

[2] As isolated high p_t photons are triggered essentially like electrons similar accuracies for both particle types can be assumed.

cross section and (b) a normalization to some high rate final state reactions which can be counted during normal physics runs.

3.1 Proton-proton luminosity from machine parameters[3]

The luminosity for colliding beams can be directly obtained from geometry and numbers of particles flowing per time unit [2]. This can be used to determine the absolute LHC luminosity from machine parameters without prior knowledge of pp scattering cross sections. The principle is briefly outlined here. More details can be found in [3].

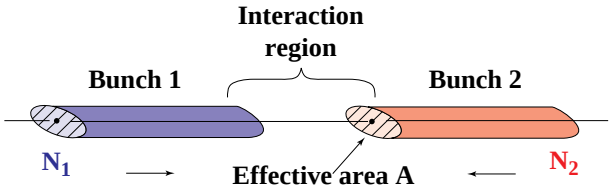

Fig. 1: Luminosity from particles flux and geometry.

For two bunches of N_1 and N_2 particles colliding head-on in an interaction region as sketched in Fig.1 with the frequency f the luminosity is given as

$$\mathcal{L} = \frac{N_1\, N_2\, f}{A_{\rm eff}}\ . \tag{1}$$

$A_{\rm eff}$ is the *effective transverse area* in which the collisions take place. For a uniform transverse particle distribution, $A_{\rm eff}$ would be directly equal to the transverse beam cross section. More generally, the effective area can be calculated from the overlap integral of the two transverse beam distributions $g_1(x,y)$, $g_2(x,y)$ according to

$$\frac{1}{A_{\rm eff}} = \int\ g_1(x,y)\, g_2(x,y)\ dx\, dy\ . \tag{2}$$

For equal Gaussian beams

$$g_1 = g_2 = \frac{1}{2\pi\sigma_x\sigma_y}\ \exp\ \left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right] \tag{3}$$

we obtain for head-on collisions $A_{\rm eff} = 4\pi\ \sigma_x\sigma_y$ so that

$$\mathcal{L} = \frac{N_1\, N_2\, f}{4\pi\sigma_x\sigma_y}\ . \tag{4}$$

The collision frequency f is accurately known. The number of particles circulating in a storage ring is measured using beam current transformers to roughly 1% precision [17].

The main uncertainty in the absolute luminosity determination from machine parameters is expected to originate in the knowledge of the transverse beam dimensions. Safe operation

[3]Contributing author: H. Burkhardt

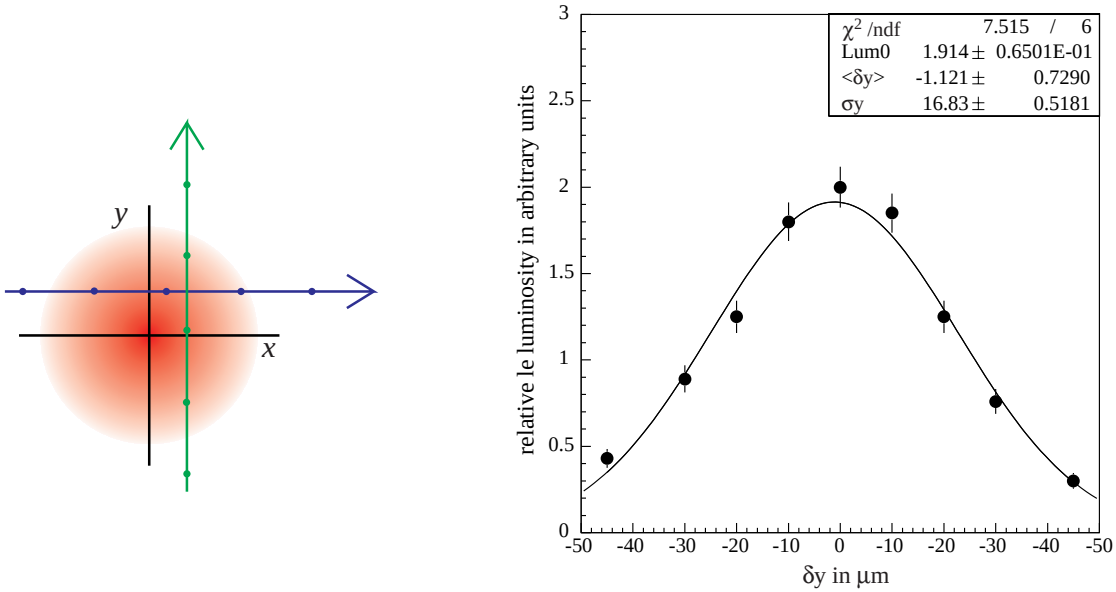

Fig. 2: Schematic view of the steps involved in an orthogonal separation scan proposed for the LHC (left) and a possible result in one direction (based on early LEP data) shown on the right.

of the LHC requires a rather good knowledge of the optics and beam sizes and we expect that this should already allow a determination of the luminosity from machine parameters to about $20 - 30$ percent. A much better accuracy can be obtained when the size of the overlap region at the interaction points is determined by measuring the relative luminosity as a function of lateral beam separation, as illustrated in Fig. 2. This technique was pioneered at the ISR [18] and allowed to reduce the uncertainty to below 1%, [19, 20].

For the more complicated LHC and early operation, a 10% overall uncertainty in the absolute LHC machine luminosity calibration should be a realistic goal. The actual precision will depend on the running time and effort which is invested. A relatively small number of scans under favorable beam conditions will in principle be sufficient to obtain and verify the reproducibility in the absolute luminosity calibration. While fast scans may always be useful to optimize collisions, we assume that any dedicated, detailed luminosity scans will become obsolete when the other, cross section based luminosity determinations described in these proceedings allow for smaller uncertainties.

Optimal running conditions are moderate bunch intensities, large bunch spacings, no crossing angle and $\beta^* = 2\,\mathrm{m}$ or larger. These conditions are in fact what is proposed anyway for the initial LHC operation with 43 – 156 bunches per beam. Statistics are not expected to be a problem. For early operation at top energy (10 - 14 TeV) with 43 bunches and 4×10^{10} particles per bunch, before beams are squeezed. at a $\beta^* = 11\,\mathrm{m}$, we already expect luminosities of the order of $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ resulting in event rates of 10^4 Hz, for a cross section of 0.01 barn as typical for the low angle luminosity monitors.

From the LHC injectors, we expect bunch by bunch variations of about 10% in intensity and 20% in emittance. For the large spacing between bunches in the operation with up to 156

bunches, there is no need for crossing angles at the interaction points. Parasitic beam-beam effects will be negligible. All bunches in each beam will follow the same equilibrium orbit and collide at the same central position.

Calibration runs require good running conditions and in particular good beam lifetimes. Bunch by bunch differences are not expected to change significantly during a scan. Storing bunch intensities at the beginning and end of a scan and using one set of timed averaged bunch intensities for a scan should be sufficient. To avoid any bias, it will be important to use the correct pairing of bunch intensities and relative luminosities in the calculation of absolute bunch luminosities according to Eq. 1, before any summing or averaging over different bunches.

We are currently preparing an on-line application for automatic luminosity scans[4]. Scan parameters like range, step size and duration can be set before the start of the scan. Once the parameters are defined, it is possible to launch automatic horizontal and vertical separation scans in the LHC interactions regions. For a detailed scan, we may choose a range from -4 to +4 σ in nominal beam size in steps of 0.5 σ, resulting in 17 equidistant points. If we wait 1 s between points to allow for the magnets to change and for 2 s integration time, the scan time would still be below a minute per plane. Details are currently being worked out in close collaboration with the experiments. Exchanging all data bunch-by-bunch at a 1 Hz rate between the machine control room (CCC) and the experiments would be rather demanding and risks to saturate current capacities.

For the initial running, it will be sufficient to exchange average values at about 1 Hz rate. It allows quality monitoring and the determination of the peak position. For the detailed off line analysis, we only have to rely on local logging and timing information synchronized to at least 1 s precision at the beginning of the scan. With fixed time interval defined and saved before the scan, this allows for off-line synchronization of the detailed data and a complete bunch by bunch analysis.

3.2 Direct measurements of the absolute luminosity at LHCb

LHCb plans to measure the absolute luminosity using both the Van Der Meer scan, [18], and beam-gas techniques following a more recently proposed method [21]. Here one tries to determine the transverse beam profiles at colliding beam experiments utilizing the precision vertex detectors found at modern HEP experiments to reconstruct beam gas interactions near the beams crossing point. The vertex resolution in the transverse direction at LHCb can be parameterized by the relation

$$\sigma_{x,y} = \frac{100\mu m}{\sqrt{N_{tracks}}} \tag{5}$$

where N_{tracks} is the number of tracks originating from the vertex. Since the nominal transverse bunch size at LHCb will be $100\mu m$, the reconstruction of beam-gas vertices's, which will have a track multiplicity of ~ 10, will enable the measurement of the colliding bunch profiles and the beam overlap integral. This method is currently under investigation by the LHCb collaboration and is expected to result in a luminosity measurement with an associated uncertainty of 3-5%.

[4]Done by Simon White, as part of his PhD thesis work on the LHC machine luminosity determination

3.3 Absolute pp luminosity from specialized detectors and from the total cross section measurement

ATLAS and CMS are planning to perform absolute and relative pp luminosity measurements using dedicated luminosity instruments.

Three particular luminosity instruments will operate around the ATLAS interaction point. The absolute luminosity measurement will be provided by ALFA [10] placed 240m down the beam line and due to operate in 2010. This measurement requires some special optics low luminosity running of the LHC and should be able to measure the very low angle Coulomb scattering reaction. The expected precision is of the order 3%, depending on yet unknown LHC parameters during running. The ALFA detector can also measure the absolute luminosity using the optical theorem if the Coulomb region can not be reached. Extrapolating the elastic cross section to very low momentum transfer $t = 0$ and using the total cross section as measured by TOTEM [11] (located at the CMS interaction point) current simulations indicate that a precision of about 3% might also be reached with this method. In addition to absolute luminosity measurements from ALFA, LUCID and a Zero-Degree-Calorimeter (ZDC) [10] are sensitive to the relative single bunch crossings luminosity. LUCID and ZDC will however not give absolute measurements.

A similar approach is currently foreseen by the CMS collaboration [22].

3.4 Real time relative luminosity measurements

A large number of instantaneous relative luminosity measurements have been discussed during the past years by ATLAS, CMS and LHCb and more details can be found in the three presentations given during the "standard candle" session of this workshop [23]. As an example we outline in the following some ideas discussed within CMS.

Multiple techniques capable of providing suitable luminosity information in real time have been identified in CMS. One technique employs signals from the forward hadron calorimeter (HF) while another, called the Pixel Luminosity Telescope (PLT), uses a set of purpose-built particle tracking telescopes based on single-crystal diamond pixel detectors. At this writing, the PLT has not been formally approved, but is under study. The methods based on signals from the HF described are the ones being most vigorously pursued.

Two methods for extracting a real-time relative instantaneous luminosity with the HF have been studied. The first method is based on "zero counting," in which the average fraction of empty towers is used to infer the mean number of interactions per bunch crossing. The second method called "EtSum method" exploits the linear relationship between the average transverse energy per tower and the luminosity.

Outputs of the QIE chips used to digitize the signals from the HF PMTs on a bunch-by-bunch basis are routed to a set of 36 HCAL Trigger and Readout (HTR) boards, each of which services 24 HF physical channels. In order to derive a luminosity signal from the HTR, an additional mezzanine board called the HF luminosity transmitter (HLX) is mounted on each of the HTR boards. The HLX collects channel occupancy and E_T sum data to create eight histograms: two sets of three occupancy histograms, one E_T-sum histogram, and one additional occupancy histogram. These histograms comprise about 70 KB of data, which is transmitted at a rate of approximately 1.6 Mbps to a dedicated luminosity server via an Ethernet switch that

aggregates the data from multiple HLX boards for further processing.

Although all HF channels can be read by the HLX, MC studies indicate that the best linearity is obtained using only the inner four η rings. The algorithm has been optimized to minimize sensitivity to pedestal drifts, gain changes and other related effects. Both "Zero Counting" and the "EtSum" method have demonstrated linearity up to LHC design luminosity. A statistical error of about 1% will be achieved at $\mathrm{fewtimes} \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ Hence the dominant error on the absolute luminosity will result from the normalization of the online relative luminosity.

3.5 Proton-proton luminosity from the reaction $\mathrm{pp} \to \mathrm{pp}\mu\mu$

The QED process $pp \to pp\mu^+\mu^-$, where a $\mu^+\mu^-$ pair is produced via photon-photon scattering, was first proposed for luminosity measurements at hadron colliders in [4]. At the LHC such pairs will be predominantly produced with small transverse momenta, at small polar angles and in the same forward or backward cone.

All three experiments are considering to use the well calculated $pp \to pp\mu\mu$ process for measuring absolute luminosity. The theoretical understanding of this QED photon-photon scattering reactions is considered to be accurate to better than 1%. Consequently this final state is thus often considered to be the perfect theoretical luminosity process. However, the experimental identification of this process requires to select muon pairs with low mass and within a well understood acceptance. The measurement of this reaction at a hadron collider appears to be much more difficult than the corresponding measurements of the reaction $ee \to ee\mu\mu$ at LEP. The systematic measurement error for example in L3 and after several years of data taking was about $\pm$3% [24]

Current simulations by the three LHC experiments indicate that the final state can be identified using straight forward criteria. For ATLAS and CMS one finds that about 1000 accepted events could at best be expected for an integrated luminosity of 1 fb^{-1}, resulting in a statistical error of about $\pm$ 3%.

For example the ATLAS study selects oppositely charged back-to-back muon tracks with $p_T > 6$ GeV and $|\eta| < 2.2$ with an invariant mass less than 60 GeV and a common vertex with no other tracks originating from it (isolation), yields a cross section of 1.33 pb. Thus, about 1300 events can be expected for running periods with a luminosity of 1 fb^{-1} and yielding a potential statistical error of 3%. However, backgrounds not only from pile up events will be a critical issue. Some proton tagging with high luminosity roman pots is currently investigated but this will certainly reduce the accepted cross section and introduce additional acceptance errors. Similar conclusions have been reached by simulations performed within the CMS collaboration. Consequently, both experiments expect that, during the coming years, this reaction will be mainly used as a cross check of the other methods.

The cross section for this process where both muons lie inside the LHCb acceptance and have a combined invariant mass greater than 2.5GeV is ≈ 88 pb. The expected uncertainty is perhaps 1% or smaller and comes mainly from rescattering corrections [5], i.e. strong interactions between the interacting protons.

The feasibility of using the elastic two photon process $pp \to p + \mu^+\mu^- + p$ to make luminosity measurements at LHCb was first explored in [25] and has recently been investigated in

more detail by members of the LHCb collaboration [26]. A variety of background processes have been studied: dimuons produced via inelastic two-photon fusion and double pomeron exchange; low mass Drell-Yan pairs; QCD processes such as $b\bar{b} \rightarrow \mu^+\mu^- + X$; and the combinatoric backgrounds caused by K/π mis-identification. A simple offline selection has been developed that requires: the dimuon pair transverse momentum to be less than 50MeV/c; the dimuon invariant mass to be in the range $2.5GeV/c^2 < M_{\mu\mu} < 20GeV/c^2$; and a charged particle multiplicity of less than 3 (i.e. the event should contain a $\mu^+\mu^-$ pair and no other charged particles). These criteria select $\sim 27\%$ of the signal events that pass the trigger and are reconstructed and result in a background contamination that is $(4.1 \pm 0.5(stat.) \pm 1.0(syst.))\%$ of the signal level with the dominant contribution due K/π mis-identification. Overall it is expected that $\sim 10^4$ $pp \rightarrow p + \mu^+\mu^- + p$ events will be triggered, reconstructed and selected at LHCb during one nominal year of data taking ($2fb^{-1}$). Systematic uncertainties on a luminosity measurement at LHCb using this channel are estimated to be $\sim 1.31\%$ and are dominated by the uncertainty on the predicted cross section for events containing dimuons produced via double pomeron exchange, an uncertainty that is expected to be reduced in the near future. A measurement of the absolute luminosity at LHCb using this channel and a dataset of $2fb^{-1}$ will therefore be possible with an associated uncertainty of $\sim 1.5\%$.

In summary, the accurate measurement of this theoretically well understood reaction looks like an interesting challenge for the LHC experiments. Interesting results can be expected once integrated luminosities of 5 fb^{-1} and more can be accumulated for ATLAS and CMS and about 1 fb^{-1} for LHCb. Of course, it remains to be proven, if the systematic uncertainties under real data taking conditions can indeed be reduced to the interesting 1% level.

4 Indirect and relative pp luminosity measurements

The methods to measure the absolute proton proton luminosity and their limitations have been described in the previous chapter.

In this Section we will describe the possibilities to measure the luminosity indirectly using well defined processes, so called "Standard Candles" and their use to further constrain the PDFs and discuss the possibility to "measure" directly the parton-parton luminosities.

Before describing the details of these indirect approaches, a qualitative comparison of luminosity measurements at e^+e^- colliders and hadron colliders might be useful. The most important difference appears to be that in the e^+e^- case one studies point like parton parton interactions. In contrast, at hadron hadron interactions one studies the collision of protons and other hadrons made of quarks and gluons. As a result, in one case the Bhabha elastic scattering reaction $e^+e^- \rightarrow e^+e^-$ at low Q^2 reaction can be calculated to high accuracy and the observed rate can be used as a luminosity normalization tool. In contrast, the elastic proton proton scattering cross section can not be calculated at the LHC nor at any other hadron colliders. As a consequence, absolute normalization procedures depend always on the measurement accuracy of the pp total cross section. Even though it is in principle possible to determine the pp total cross section in a luminosity independent way using special forward detectors like planned by the TOTEM or the ALFA experiments, the accuracy will be limited ultimately and after a few years of LHC operation to perhaps a few %.

Furthermore, as essentially all interesting high Q^2 LHC reactions are parton parton collisions, the majority of experimental results and their interpretation require the knowledge of parton distribution functions and thus the parton luminosities.

Following this reasoning, more than 10 years ago, the inclusive production of W and Z bosons with subsequent leptonic decays has been proposed as the ultimate precision parton parton luminosity monitor at the LHC [9]. The following points summarize the arguments why W and Z production are indeed the ideal "Standard Candles" at the LHC.

- The electroweak couplings of W and Z bosons to quarks and leptons are known from the LEP measurements to accuracies smaller than 1% and the large cross section of leptonic decays W and Z bosons allows that these final states can be identified over a large rapidity range with large essentially background free samples.
- Systematic, efficiency corrected counting accuracies within the detector acceptance of 1% or better might be envisioned during the early LHC running. In fact it is believed that the relative production rate of W and Z can be measured within the detector acceptance with accuracies well below 1%.
- Theoretical calculations for the W and Z resonance production are the most advanced and accurately known LHC processes. Other potentially more interesting LHC reactions, like various diboson pair production final states are expected to have always larger, either statistical or systematic, experimental and theoretical uncertainties than the W and Z production.
- The current PDF accuracies, using the latest results from HERA and other experiments demonstrate that the knowledge of the quark and anti quark accuracies are already allowing to predict the W and Z cross at 14 TeV center of mass energies to perhaps 5% or better. The measurable rapidity and p_t distributions of the Z boson and the corresponding ones for the charged leptons from W decays can be used to improve the corresponding parton luminosity functions.

Obviously, the use of W and Z bosons as a luminosity tool requires that the absolute cross section becomes an input, thus it can not be measured anymore. As a result this method has been criticized as being "a quick hack at best". In contrast, advocates of this method point out that this would not be a noticeable loss for the LHC physics program.

4.1 Using the reaction $pp \to Z \to \ell^+\ell^-$ to measure L_{pp}

Very similar and straight forward selection criteria for the identification of leptonic Z decays, depending somewhat on the detector details and the acceptance region, are applied by ATLAS, CMS and LHCb. In the following the current selection strategy in ATLAS and LHCb are described.

4.2 Measuring Z and W production, experimental approaches in ATLAS

The ATLAS W and Z cross section measurements are based on the following selections in the electron and muon channels:

- A typical selection of $W \to e\nu$ requires that events with "good" electrons have to fulfill the additional kinematic acceptance criteria:

$p_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.4$.
The criteria for $W \rightarrow \mu\nu$ muons are similar where $p_T > 25$ GeV and $|\eta| < 2.5$. is required. Furthermore, in order to classify the event as a W event, the reconstructed missing transverse momentum and the transverse mass should fulfill $E_T(miss) > 25GeV$ and $m_T(W) > 40$ GeV.

- The selection of $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ requires that a pair of oppositely charged electrons or muons is found. Due to lower background the electrons should have $p_T > 15$ GeV and $|\eta| < 2.4$ and their invariant mass should be between 80-100 GeV.
  Similar criteria are applied for the muons with $p_T > 15$ GeV and $|\eta| < 2.5$. The reconstructed mass should be between 71-111 GeV.

Following this selection and some standard Monte Carlo simulations, the expected number of reconstructed events per 10 pb^{-1} at $\sqrt{s} = 14$ TeV are about 45000, 5500 for W and Z decays to electrons and 60000, and 5000 for the decays to muons, respectively. Thus, even with a small data sample of only 10 pb^{-1}, the statistical uncertainty for the Z counting comes close to 1% in each channel.

Systematic uncertainties from the experimental selection are dominated by the Z efficiency determination and from backgrounds in the W selection. Other sources of uncertainties originate from the knowledge of energy scale and the resolution. The lepton efficiencies are evaluated by considering $Z \rightarrow \ell\ell$ events and using the so called "tag and probe" method, like for example described by the D0 experiment [7, 8]. The efficiency uncertainty associated with the precision of this method has been estimated for a data sample of 50 pb^{-1} (1 fb^{-1}) of data to be 2% (0.4%) for W and 3% (0.7%) for Z events. The backgrounds for W events are of the order 4% in the electron channel and 7% in the muon channel. The main contributions are from other W or Z decays, and are thus well understood, leading to background uncertainties of the order 4% for both channels if a sample 50 pb^{-1} is analyzed. For much larger samples it is expected that uncertainties at or below 1% can be achieved. The backgrounds for the Z decays are very small, and can be determined accurately from mass spectrum, and hence does not carry any sizable uncertainty. It has been demonstrated, that the detector scales and resolutions can be determined very accurately [14], and the associated uncertainties are therefore also close to negligible.
Some detailed studies demonstrate that eventually the systematic error between 1-2% or even smaller might be achieved for the W and Z counting and within the detector acceptance up to rapidities of about 2.5.

In order to use this number for the pp luminosity determination the total inclusive W and Z cross-section at NNLO can be used. These have been calculated to be 20510 pb and 2015pb, respectively [27]. Variations in models, floating parameters, and other theoretical uncertainties lead to significant variations in the estimates. The uncertainties on these calculation are estimated to be 5% or smaller. This uncertainty appears to be currently dominated by the PDF uncertainties needed to extrapolate to the experimentally uncovered large rapidity region. More discussions about these uncertainties can be found for example at [28] and [29].

It can be assumed that the detailed studies of the rapidity distributions within the acceptance region with W and Z decays might eventually lead to further error reductions.

4.3 Measuring Z production, experimental approach in LHCb

The uncertainty on the predicted Z production cross section at the LHC comes from two sources: the uncertainty on the NNLO partonic cross section prediction [27], which contributes an uncertainty of $< 1\%$, and uncertainties in our understanding of the proton Parton Distribution Functions (PDFs) which, for the latest MSTW fit [30], contribute an uncertainty of $\sim 3\%$ for Z bosons produced with rapidities in the range $-5 < y < 5$.

A measurement of the Z production rate at LHCb via the channel $Z \rightarrow \mu^+\mu^-$, which provides a final state that is both clean and fully reconstructible, can be achieved with high efficiency and little background contamination. In addition, since the dimuon trigger stream at LHCb [31] requires two muons with an invariant mass larger than 2.5GeV and a summed transverse momentum ($P_T^1 + P_T^2$) greater than 1.4GeV, a high trigger efficiency of $\sim 95\%$ is expected for these events. A variety of background sources for this channel have been investigated: other electroweak processes such as $Z \rightarrow \tau^+\tau^-$ where both taus decay to muons and neutrinos; QCD processes such as $b\bar{b} \rightarrow \mu^+\mu^- + X$; and events where two hadrons with an invariant mass near the Z mass are both mis-identified as muons. To deal with these backgrounds an off-line selection has been developed [32] that requires: the dimuon invariant mass to be within 20 GeV of the Z mass; the higher and lower transverse momentum muons to be greater than 20 GeV and 15 GeV respectively; the impact parameter of both muons is consistent with the primary vertex; and both muons have associated hadronic energy that is less than 50 GeV. For $Z \rightarrow \mu^+\mu^-$ events that are triggered and reconstructed at LHCb, these off-line selection criteria will select $91 \pm 1\%$ of the signal events while reducing the background to $(3.0 \pm 2.9)\%$ of the signal level with the dominant contribution due to the combinatoric backgrounds from pion and kaon mis-identification. It is expected that these backgrounds can be well understood from real data or removed using muon isolation criteria. Overall it is expected that $Z \rightarrow \mu^+\mu^-$ events will be triggered, reconstructed and selected at LHCb at a rate of $\sim 190 evts/pb^{-1}$. Systematic uncertainties have also been investigated and it is expected that with as little as $5pb^{-1}$ of data the experimental efficiency (trigger, tracking, muon identification etc.) can be measured with an uncertainty of $\sim 1.5\%$ enabling a luminosity measurement with an uncertainty of $\sim 3.5\%$.

4.4 PDF and relative parton-parton luminosity measurements

Theoretically well understood reactions at the LHC offer the possibility to use their rapidity distributions to improve todays knowledge of PDFs. Especially the resonance production of W and Z bosons with leptonic decays with low and high transverse momentum and the production of isolated high p_t γ-Jet events have been demonstrated to be very sensitive to the relative parton distribution functions. Simulations from ATLAS and CMS have shown that experimental errors on these rapidity regions up to $|y|$ of about 2.5 can probably performed with accuracies eventually reaching perhaps 1% or better. The possibility to cross-check the measurements with W and Z decays to (a) electron(s) and (b) muon(s) and between both experiments will of course help to reach the accuracy.

During the past years simulation studies from the LHCb collaboration have shown that the experiment has a unique potential to extend the acceptance region from ATLAS and CMS for muons up to rapidity values at least up to 4.5. Furthermore, the existing overlap region for y

between 1.9 and 2.5 should allow to reduce normalisation uncertainties. Obviously, these rapidity values are understood as being reasonably accurate but qualitative values and more precise values will be defined once real data will allow to define a well understood fiducial volume of the detectors.

In addition, the LHCb collaboration has investigated the possibility to identify clean samples of very low mass Drell-Yan mu-pair events. The results indicate that such pairs can be measured within their acceptance region down to masses of 5 GeV. Such a measurement would in principle allow to measure PDFs for x values approaching extremely low values of 10^{-6} for the first time [33].

It should be clear that such measurements, which are known to be very sensitive to quark, antiquark and gluon relative parton luminosities will not allow an absolute PDF normalisation. Such an improvement of absolute PDF normalisation would require the accurate knowledge of the proton-proton luminosity to better than todays perhaps $\pm$ 3% PDF accuracy obtained from the HERA measurements over a large x range and obviously lower Q^2. The alternative approach to combine the relative parton luminosities over the larger x, Q^2 range using the sum rules has, to our knowledge, so far not been studied in sufficient detail.

A more detailed analysis of the different experimental approaches to improve the PDFs are interesting but are beyond the scope of this note about the luminosity. Nevertheless we hope that the experimentalists of the three collaboration will start to combine their efforts and will pursue the PDF measurements, in direct collaboration with theorists, during the coming years.

5 Comparing the different pp luminosity measurements

A relatively large number of pp luminosity measurements has been proposed and the most relevant have been discussed in this note. Here we try to give a critical overview of the different methods and their potential problems. Despite these advantages and disadvantage it should be clear that it is important to perform as many as possible independent luminosity methods during the coming years.

- **The machine luminosity determination using beam parameters:**
  This method will be pursued independently of the experiments and its main purpose will be to optimize the performance of the LHC and thus providing a maximum number of physics collisions for the experiments. The potential to use this number as an almost instantaneous absolute luminosity number with uncertainties of perhaps $\pm$ 10% (and eventually $\pm$ 5%), assuming that non gaussian tails of the beam can be controlled to this accuracy will certainly be useful to the experiments. Of course the experiments would lose somewhat their "independence" and still need to combine this number with their actual active running time.
  However, one should remember that the Tevatron experiments did not use this method for their measurements.
  The method to determine the beam size using the LHCb precision vertex detector look very promising and it is hoped that their approach might result in a pp luminosity measurement with an associated uncertainty of 3-5%.
- **Total cross section and absolute luminosity normalisation with specialized far for-**

ward Detectors:
The luminosity independent total pp cross section measurement is planned by the TOTEM collaboration and by the ALFA detector. Using these numbers both ATLAS and CMS plan to obtain the pp luminosity from the counting of the pp elastic scattering counting numbers from the forward detectors which thus depend on the knowledge of the total cross section measurement. In order to obtain this number some few weeks of special optics and low luminosity LHC running are required. As all LHC experiments are very keen to obtain as quickly as possible some reasonable luminosity at 14 TeV center of mass energy it is not likely that those special LHC data taking will happen during the first year(s) of data taking. Furthermore, despite the hope that the total cross section can be determined in principle with an interesting accuracy of $\pm$ 1%, it remains to be demonstrated with real LHC running. In this respect it is worth remembering that the two independent measurements of the total cross section at the Tevatron differed by 12% while much smaller errors were obtained by the individual experiments. As a result the average value with an error of $\pm 6\%$ was used for the luminosity normalisation.

- **Luminosity determination using $Z \to \ell\ell$:**
This method provides an accurate large statistic relative luminosity number. It will be as accurate as the theoretical cross section calculation, which is based on the absolute knowledge of the PDFs from other experiments, from unknown higher order corrections and their incomplete Monte Carlo implementation. Todays uncertainties are estimated to be about 5%. It has been estimated, assuming the experiments perform as expected, that the potential Z counting accuracy within the acceptance region including efficiency corrections might quickly reach $\pm$1%. The extrapolation to the uncovered rapidity space, mainly due to the worse knowledge of the PDFs in this region, increases the error to perhaps 3%. Taking other theoretical uncertainties into account an error of $\pm$5% is currently estimated. Of course, advocates of the Z normalisation method like to point out that the real power of this method starts once relative measurements, covering similar partons and similar ranges of the parton distribution functions will be performed with statistical errors below 5%. Examples where such a normalization procedure looks especially interesting are the relative cross section measurements of $N(Z)/N(W)$, $N(W^+)/N(W^-)$, high mass Drell-Yan events with respect to Z events and diboson final states decaying to leptons. Of course, correlations and anticorrelations between quark and gluon dominated production rates exist and need to be carefully investigated before similar advantages for the gluon PDFs can eventually be exploited. The loss of an independent Z cross section measurement would of course be a fact of life.
- **pp luminosity from the reaction $\mathrm{pp} \to \mathrm{pp}\mu\mu$:**
A measurement of this reaction offers in principle a direct and theoretically accurate proton proton luminosity value. Unfortunately current simulations from the experiments indicate that the accepted cross section is relatively small and only a few 1000 events can be expected per fb^{-1}. The different simulation results indicate that the backgrounds can be suppressed sufficiently without increasing the experimental systematics too much. Simulation studies [34] in CMS find that in the absence of pile-up, of the order 7000 events/fb can be selected. Apart from pile-up a leading source of systematic error is the contamina-

tion of the signal with events in which one of the protons dissociates. In the absence of pile-up, the use of the Zero-Degree-Calorimeters (one on each side of IP) and the Castor calorimeter (in 2009/10 available only on one side of the IP) in veto can improve the signal to background ratio from ~ 1 to ~ 3. Hence in CMS this method may provide a means of measuring the absolute luminosity in the first LHC data with a total error of below 10%. In addition, the current simulation results indicate that small systematic errors of perhaps 1-2% might eventually be achievable[5] once a yearly luminosity of 5-10 fb^{-1} in ATLAS and CMS (2 fb^{-1} for LHCb) might be recorded. It remains to be seen if muons with transverse momenta well below 20 GeV can indeed be measured as accurately as muons with transverse momenta above 25 GeV.

5.1 Which luminosity accuracy might be achievable and when

Of course the potential time dependent accuracy of the different luminosity methods can only be guessed today as such numbers depend obviously on the LHC machine performance during the coming years. For the purpose of this Section we are mainly interested in measurements at the 14 TeV center of mass energy and assume that the following "data samples" would define such "years". Of course, it could be hoped that the luminosity and energy increase would go much faster resulting in "some" shorter LHC years. Thus we assume that the first 14 TeV year, currently expected to be 2010, will correspond to 0.1 fb^{-1}, followed by a 1 fb^{-1} year. During the third and fourth year ATLAS and CMS expect to collect about 5 fb^{-1} and 10 fb^{-1} while LHCb expects to collect roughly 2 fb^{-1} per year. We assume further that the special optics low luminosity data taking periods requiring perhaps a few weeks for TOTEM and similar for ALFA will take only place during the year when more than 1 fb^{-1} per year or more can be expected.

As a result, for the first two 14 TeV running years, realistic luminosity numbers could come from (1) the machine group and (2) from the indirect method using the inclusive production of Z events with leptonic decays.

As has been pointed out in Section 3.1 the method (1) would, without any additional efforts by the machine group, allow a first estimate with a $\pm$ 20-30% luminosity accuracy. We assume however that, due to the delay of the real 14 TeV start to 2010, enough resources could be found that people within the machine group could carefully prepare for the necessary beam parameter measurements and that the experiments will do the corresponding efforts to correct such a machine luminosity number for real detector data taking one could hope for a 10% measurement for 2010 and a 5% accuracy for 2011.

In contrast, method (2) would by definition be an integrated part of any imaginable experimental LHC data taking period. In fact, if enough attention is put into the Z counting method, the data expected during 2010 running might already reach statistical errors of $\pm$ 2% per 5 pb^{-1} periods. Thus perhaps about 10-20 such periods could be defined during the entire year and systematic errors for the lepton efficiency correction within the detector acceptance could reach similar $\pm$ 2-3% accuracies. During the following years these errors might decrease further to 1% or better. Once the rate of any "stable" simple high rate final states and even trigger rates relative

[5] It might be interesting to study the experience from similar measurements at the experimentally ideal conditions of LEP, where uncertainties above $\pm$ 3% have been reported [24].

to the Z counting rate has been determined, such relative event rates can be used subsequently to track the "run" luminosity and even the real time luminosity with similar accuracy.

Theoretical limitations of the cross section knowledge, not expected to improve without LHC data taking, would limit the accuracy to about $\pm$ 5%. The expected detailed analysis of the 2010 rapidity distributions of W, Z and γ-jet events will allow some improvements for the years 2011 and beyond. We can thus expect that appropriate ratio measurements like the cross section ratio measurements of $Z/W^{\pm}$ and W^{-}/W^{+} will already reach systematic accuracies of $\pm$ 1-2% during 2010 and 1% or better in the following years. Measurement of b physics, either in LHCb or in ATLAS and CMS might in any case prefer to perform luminosity independent measurements and relate any of the "new" measurements to some relatively well known and measurable B-hadron decays.

It is also worth pointing out that currently no other high Q^2 reaction has been envisioned, which might be measurable to a systematic precision of better than 5-10% and a luminosity of up to 1fb^{-1}. In addition, most of the interesting high Q^2 electroweak final states will unfortunately even be limited for the first few LHC years to statistical accuracies to 5% or more.

The prospect for the other luminosity measurements start to become at earliest interesting only once a few 100 pb^{-1} can be recorded. Consequently one can expect to obtain a statistical interesting accuracy from the reaction $pp \rightarrow pp\mu\mu$ after 2010. Similar, it looks unlikely that low luminosity special optics run will be performed before 2011. Consequently one might hope that few % accurate total cross section numbers become available before the 2012 data taking period will start.

6 Summary and Outlook

A large variety of potentially interesting pp luminosity measurements, proposed during the past 10-15 years, are presented in this Section.

Realistically only the machine luminosity measurement and the counting of the Z production might reach interesting accuracies of 5% before 2011. For all practical purposes it looks that both methods should be prepared in great detail before the data taking at 14 TeV collision energies will start in 2010.

We believe that a working group, consisting of interested members of the three pp collider experiments and interested theorists, should be formed to prepare the necessary Monte Carlo tools to make the best possible use of the soon expected W and Z data, not only for the pp luminosity normalization but even more for the detailed investigations of the parton parton luminosity determination and their use to predict other event rates for diboson production processes and high mass Drell-Yan events.

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