

Z boson as “the standard candle” for high-precision W boson physics at LHC^a

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Abstract. In this paper we propose a strategy for measuring the inclusive W boson production processes at LHC. This strategy exploits simultaneously the unique flexibility of the LHC collider in running variable beam particle species at variable beam energies, and the configuration flexibility of the LHC detectors. We propose their concrete settings for a precision measurement of the standard model parameters. These dedicated settings optimise the use of the Z boson and Drell–Yan-pair production processes as “the standard reference candles”. The presented strategy allows one to factorise and to directly measure those of the QCD effects that affect differently the W and Z production processes. It reduces to a level of $\mathcal{O}(10^{-4})$ the impact of uncertainties in the partonic distribution functions (PDFs) and in the transverse momentum of the quarks on the measurement precision. Last but not the least, it reduces by a factor of 10 the impact of systematic measurement errors, such as the energy scale and the measurement resolution, on the W boson production observables.

1 Introduction

The LHC collider will soon become the unique W and Z boson production factory. For the first time the collected number of W boson production events is expected to be limited by the available event storage band-width rather than by their production rate. About 300 million W and 20 million Z events are expected to be collected over one year of LHC operation at the nominal luminosity. High-precision studies of their static properties, their propagation in vacuum and in hadronic matter, their hard interactions with matter and with the radiation quanta are expected to provide decisive experimental insight into the mechanism governing the electroweak symmetry breaking.

One of the major challenges for the above exploratory program is to design measurement strategies that both are robust and assure the highest achievable precision in controlling the detection and reconstruction systematic biases.

The robustness of a strategy can be quantified in terms of its sensitivity to the modelling ambiguities of the effective LHC wide-band partonic beams – in particular to the modelling of their strong interaction “noise.” A robust

strategy should, in our view, be insensitive to the modelling aspects of their colour and flavour dependent properties. In such a strategy the effects of strong interactions of partonic beams, whether or not they are controlled by perturbative QCD, and the effects of their flavour composition must be factorised from the effects of propagation, interactions and decays of electroweak bosons and measured rather than modelled. The above factorisation is, in our view, particularly important for the first round of measurements at LHC. It assures that even small novel electroweak effects are not erroneously absorbed in the modelling ambiguities of the flavour composition and strong interactions of partonic beams.

The ultimate, high systematic precision measurements must not only use a well-understood, precisely calibrated and aligned detector but, in addition, the measurement strategy must be carefully planned, so that the remaining uncertainties of the detector response have the smallest possible impact on the precision of the measurement. Special care must be taken to avoid systematic biases driven by the correlation between the systematic effects of the detector response and those related to incomplete (approximate) physics modelling. Last but not the least, the systematic precision of the measurements must be validated by the “systematic-control” measurements using dedicated modes of the LHC and detector operation.

This paper presents an attempt to define such a robust strategy for high-precision studies of the inclusive W boson production, propagation and decay processes. The pro-

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posed strategy uses the Z boson and the lepton pair production processes as *the standard reference candles* and exploits the capacities of the LHC collider to run variable beam particle species at variable collision energies as well as its detectors to run in dedicated operation modes. The observables introduced in this paper exploit such a flexibility to minimise the impact of the relative modelling and measurement uncertainties of the W and Z boson production and decay processes on the measurement accuracy.

The paper is organised as follows. In Sect. 2 the sources of asymmetries in measuring the W and Z boson production and decay processes at hadronic colliders are traced. In Sect. 3 the elements of the strategy attempting to reduce the influence of the above asymmetries on the measurement precision are presented. In Sect. 4 the Monte Carlo tools used in the evaluation of the merits of the presented strategy are presented, while in Sect. 5 the detector model and the measurement simulation method are discussed. Two numerical examples of the gains in measurement precision of the dedicated observables are presented in Sect. 6. Finally, in Sect. 7 the method of factorisation of those of the QCD effects that influence differently the W and Z boson production processes is proposed, and the method of measurement of these effects is discussed.

2 W and Z bosons at hadronic colliders

2.1 Introductory remarks

If the partonic structure of the LHC beams were fully controlled by QCD, the Z and W boson production rates would be predicted with a precision limited only by the accuracy of the standard model (SM) parameters determining their masses, widths and couplings to leptons and quarks. The Z boson mass and its width have been measured at LEP and SLC with an accuracy of, respectively, $\mathcal{O}(10^{-5})$ and $\mathcal{O}(10^{-3})$ [1]. Such a precision is beyond the reach of hadronic colliders. The W boson mass and its decay width have been measured with sizably inferior precision with respect to the Z bosons ones – a factor of 15 worse for the mass and a factor of 20 worse for the decay width [1]. Any improvement in their measurement accuracy, if matched with the improvement on the top mass precision, could provide a stringent indirect test of the Higgs mechanism of regularising the high-energy behaviour of the SM amplitudes that is complementary to the direct searches of Higgs particle(s).

Several scenarios of precision measurements of the standard model parameters at LHC have been elaborated [2, 3]. The specificity of the strategy presented in this paper is that it introduces the same measurement procedure for the W and Z boson production processes. Our basic goal is to minimise the extrapolation ambiguities from the Z boson production processes to the W boson ones in order to optimally use the former as “*the high-precision standard candle*”. The target for such a method is to achieve a comparable precision for the measurements of the W and the Z boson production processes. The starting point is to

understand the asymmetries in the Z and W boson production and decay mechanisms and in their detection and reconstruction methods. The effects resulted from such asymmetries are grouped in this paper in three categories:

- physics effects;
- measurement effects;
- event selection effects.

2.2 Physics effects

The leading process of vector bosons production at hadron colliders is the Drell–Yan process of quark–antiquark annihilation. For this process, as well as for the sub-leading process of W and Z boson bremsstrahlung by the decelerated quarks, the weak-isospin composition of the beam particles plays an important role in creating the W and Z boson production asymmetries. The net excess of the u -valence quarks over the d -valence quarks in the proton beams is reflected mainly in the asymmetries of the rapidity distributions of the W and Z bosons. These asymmetries can only be partially reduced by relating the rapidity distribution for Z bosons to the sum of distributions for the W^+ and W^- bosons. The remaining asymmetry is driven by the weak-isospin asymmetry of the sea quarks, which is poorly known. The flavour dependent PDFs are not constrained by the data in the small- x region that is relevant for the bulk of the W and Z boson production processes at the LHC energies. They rely not only on the low-energy measurements [4] but, more importantly, on the assumed x -dependent form of the extrapolation of these measurements to the small- x region [5].

The difference of the masses of the W and Z bosons gives rise to the following three important effects. Firstly, for a given vector-boson rapidity, different parton x regions are probed for the Z and W bosons. Any uncertainty in the x -dependence of the PDFs derived from the QCD analysis of the deep-inelastic lepton scattering (DIS) data is reflected in the uncertainties of the relative rapidity distributions of the Z and W bosons. Secondly, the resolution scale of partonic distributions is different for the Z and W boson production processes. This effect could, in principle, be controlled by perturbative QCD, if the partonic distributions were measured at a fixed resolution scale with high precision, and if the QCD coupling constant would be known to a very high accuracy. Since neither of the two above conditions is satisfied, the corresponding uncertainty must be taken into account for high-precision measurements. Another important strong interaction effect that gives rise to the W and Z boson production asymmetry is driven by the differences in the effective transverse momentum, k_T , and the off-shellness of partons taking part in the Drell–Yan process. This asymmetry is difficult to predict because of the interplay of the leading- and higher-twist perturbative effects [6] and of the non-perturbative effects, both determining the effective centre-of-collision energy dependent partonic emittance. The emittance of the LHC partonic beams could be measured in dedicated LHC runs using hybrid, partially stripped ion beams, as proposed in [7].

The differences between the masses of the down-type and the up-type quarks, amplified by CKM mixing of the down-quark flavours, contribute as well to the asymmetry in the production rates and rapidity distributions of the Z and W bosons. This asymmetry, often neglected, must be taken in consideration for high-precision relative measurements in the Z and W boson sectors.

The charged current (CC) coupling of quarks to W bosons is of the $V - A$ type, while their coupling to Z bosons is a coherent mixture of the $V - A$ and $V + A$ couplings. This difference is reflected in the asymmetries in the angular distributions of leptons originating from the decays of the W and Z bosons. In addition, at the LHC energies, the above asymmetries could be amplified by the asymmetry in production and propagation of the longitudinally polarised W and Z bosons.

The radiative corrections differently affect the W and Z boson production and decay amplitudes. While the effects of the QCD radiative corrections are driven mainly by the mass difference of the W and Z bosons, the effects of the electroweak radiative corrections lead to several, more subtle, effects. First of all, the virtual electroweak corrections affect differently the W and Z boson absolute production rates. In addition, the radiation of photons affects differently the W and Z boson propagation and decay. This is mainly driven by the following differences in the interference pattern: (a) those of the amplitudes for the photon emission from each of the charged leptons in Z boson decays; (b) those of the amplitudes for the photon emission from the charged lepton and the W boson.

2.3 Measurement effects

The main difference in measuring the W and Z boson production processes is obvious: the lepton momentum can be directly measured, while the neutrino momentum can be reconstructed only indirectly, by using the reconstructed momenta of all the particles produced in the collision of the beam particles.

In the LHC colliding-beam environment the majority of particles produced at small angles, with respect to the beam-collision axis, cannot be detected. Therefore, the neutrino momentum is bound to be measured with largely inferior precision when compared to that of the charged lepton. While the value of its transverse component can be determined from the sum of transverse momenta of the detected particles, the longitudinal one can be estimated only, up to the two-fold ambiguity, using the narrow W -width approximation. Moreover, in the LHC environment characterised by a large event pile-up probability, the modelling of the neutrino momentum reconstruction biases is bound to be more difficult than at the Tevatron. Therefore, in our view, the high-precision measurements at LHC must be based solely on the inclusive charged lepton(s) observables.

The differences in the distributions of the pseudorapidity η_l and of the transverse momentum p_{T}^l for charged leptons coming respectively from W and Z boson decays are driven predominantly by the differences in the vec-

tor boson masses and in the p_{T} distributions of their parents. Leptons coming from Z boson decays have, in general, larger transverse momenta. Their pseudorapidities are less correlated with the rapidity of their parents than the ones of charged leptons coming from W boson decays. The lepton momentum dependent measurement errors will thus differently affect the W and Z boson samples.

2.4 Event selection effects

Both the Z and the W boson samples can be selected using the single inclusive lepton Level-1 triggers. However, the subsequent on-line and off-line selection algorithms must use the reconstructed momenta of both leptons in order to reject the excessive background of the conventional strong interaction processes. The asymmetry in the reconstruction precision and in the resolution tails of the neutrino and in the charged lepton momenta gives rise to the uncertainty of the relative acceptance corrections for the W and Z boson events. In addition, while the W boson events do not contaminate the Z boson sample, the reverse may happen if one of the leptons is produced outside the detector fiducial volume and/or if it is not identified. Finally, each of the leptons from the Z boson decay can give rise to the Level-1 trigger charged lepton signatures. Therefore Z boson events will be accepted with higher efficiency than the W boson ones, if pre-selected by the Level-1 trigger system on the basis of the single-lepton signatures.

3 Measurement strategy

The optimal use of the Z boson as *the standard candle* for the W boson production processes must take into account the asymmetries discussed in the previous section and organise the measurements in a way that diminishes their significance for the measurements of suitably chosen observables.

In this section we present the basic elements of the measurement strategy. They allow us to minimise the relative physics modelling, measurement and event selection uncertainties discussed in the previous section. These elements could be used selectively; all them are technically feasible at LHC, but only some of them at Tevatron.

The basic elements of the presented strategy are listed below.

- Collect data at the two CM-energies: $\sqrt{s_1}$ and $\sqrt{s_2} = (M_Z/M_W) \times \sqrt{s_1}$. These two settings allow one to keep the momentum fractions of the partons producing the Z and W bosons equal if the W boson sample is collected at the CM-energy $\sqrt{s_1}$ and the Z boson sample at the CM-energy $\sqrt{s_2}$.
- Run light isoscalar beams at LHC (for example the deuterium, helium or oxygen beams) to restore the weak-isospin democracy of the beam particles, both in the valence and in the sea sector.

- Rescale the solenoid current while running at the two CM-energies $\sqrt{s_1}$ and $\sqrt{s_2}$ by a factor $i_2/i_1 = M_Z/M_W$ to equalise (up to the effects of the QCD radiative corrections) the distribution of the curvature radius ρ_l for charged leptons originating from the decays of the Z and W bosons.
- Collect a fraction of data with no magnetic field to control the asymmetries in the trigger efficiencies and in the measured track parameters due to the radiation of photons (resolving the relative size of the interference terms in the W and Z boson decays).
- Perform both the lepton charge aware and the lepton charge blind analysis to mimic $V - A$ and $V + A$ mixing of the Z bosons to the final-state leptons using the W^+ and W^- data.
- Use centrally produced W bosons to control the asymmetries in the angular distribution of positively and negatively charged leptons in the W^+ and W^- decays.
- Apply the dedicated triggering and the data selection scheme to minimise the uncertainty in the relative efficiency and the acceptance corrections for the Z and W boson samples of events. This scheme consists of using the inclusive charged lepton Level-1 trigger followed by the Z/W -symmetric cut in the reconstructed lepton-track curvature ρ_l in the high-level trigger and in the off-line event selection phases. The high-level trigger selection criteria for the second lepton must assure democracy for the W and Z boson samples. This is achieved by searching for a second, same flavour but opposite charge lepton in the selected bunch crossings. If such a track is found to point to the same vertex it is removed from the charged track sample and the event is flagged as the Z boson event. The missing transverse momentum estimate is then based on the remaining vertex-pointing charged tracks in a way that is identical for the W and the Z boson samples.
- Use the dedicated procedure to measure those of the QCD effects that are different for the W and Z bosons. This procedure will be discussed in detail in Sect. 7.

Several of the above elements require some flexibility in the machine and in the detector operation modes. We are aware that the proposed modes must not disturb the canonical LHC research program requiring the highest collision energy and stable detector and TDAQ settings. Running flexible operation modes may simply be postponed to the mature phase of the LHC operation when the major quest will be the precision of the dedicated measurements rather than the exploration of the highest achievable energy and luminosity scales. The HERA example shows clearly that, after reaching the luminosity increase plateau, new operation modes must be tried to preserve the quality of the experimental program of the collider.

Taking data with the dedicated triggering scheme requires a dedicated preparatory effort, but it is technically straightforward. Reducing the solenoid current, even if technically feasible, requires a substantial dedicated effort in understanding the performance of the trackers in the new magnetic field environment. This effort may, however, turn out to be very useful for better understanding

of the systematic errors of the LHC measurements. Similarly, running the LHC beams for a small fraction of time at the 10% lower energy is feasible. It is important to note that a small drop of the delivered luminosity for these runs may be compensated by a larger band width for the recorded W production events. On the other hand, running one of the proposed low- Z (the charge number) isoscalar beams in the LHC collider, even if technically feasible, is not foreseen in the present LHC plans. This paper can thus be considered as one of the attempts to build the case for running the isoscalar light-ion beams in the advanced phase of the LHC collider operation. Let us stress that if the LHC collider can deliver a luminosity that scales as $L_{AA} = L_{pp}/A^2$ for light isoscalar ion beams, then the event rates containing the high- p_T signatures will be similar for the proton and for the light-ion collisions. This condition is met e.g. for the eRHIC project at BNL [8]. It is important to note that in the experimental environment of the LHC collider, characterised by multiple proton–proton collisions taking place in the same bunch crossing, light isoscalar ions do not bring any additional complication due to the presence of several hard-process spectator nucleons in the beam particles. They merely replace the distance at which the multiple soft interactions take place from the micrometer scale to the femtometer scale. As a consequence, they change only the dispersion in the distribution of the nucleon–nucleon collision multiplicity per bunch crossing. This important feature could allow us to reopen, at high luminosity, the physics program of the soft and diffractive collisions while preserving the high rate of hard partonic processes.

4 Monte Carlo tools

The optimal Z boson and W boson Monte Carlo generators (optimal for the measurement strategy advocated in this paper), should be based on the same framework and numerical methods, an identical SM parameter representation, and the same modelling of the QCD processes. Such twin generators are presently being developed by two of us (WP and AS) [9, 10].

In the present study we use the Monte Carlo event generator WINHAC [9], version 1.22 [11], for studies of the W and Z production and decays.

At its present development stage, WINHAC contains only the leading-order process of creation of W bosons but includes already the electroweak (EW) radiative corrections in leptonic W decays. The collinear configurations of initial quarks are generated from the PDFs in which the perturbative QCD effects are included through appropriate scaling violation. Non-collinear configurations of initial quarks are generated at present using the PYTHIA LO-type parton showers [12]. In the future they will be generated by the dedicated constrained initial-state parton shower algorithms, matched with the NLO contributions to the hard process – such an extension is presently under development. These aspects are discussed in more detail in [13–15].

A large array of PDF parametrisations is provided through the LHAPDF package [16]. This standard package incorporates the nuclear PDFs on top of those for the proton beams. The nuclear PDFs include the nuclear shadowing effects parametrised by the EKS group [17]. This parametrisation is the DGLAP extrapolation of the DIS data taken with several nuclear targets to the scales involved in production of the W bosons and to the nucleus type used in the studies presented.

Since, at hadron colliders, the W bosons can be identified efficiently only through their leptonic decay channels, in WINHAC such decays are the only ones that are considered. The process of leptonic W boson decays is described within the framework of the Yennie–Frautschi–Suura exclusive exponentiation [18], in which all the infrared QED effects are re-summed to infinite order, while the residual non-infrared EW corrections are calculated perturbatively. In the current version of the program the latter corrections are included up to $\mathcal{O}(\alpha)$. WINHAC went successfully through several numerical tests [9] and was also compared with the independent Monte Carlo program HORACE [19].

In the current version of WINHAC we have included the Born-level neutral-current ($Z + \gamma$) Drell–Yan process. For the non-collinear configurations it uses the same interface to the PYTHIA LO-type parton showers [12] as in the case of the W boson production. The QED and the EW corrections are not included in the present version of the program. A dedicated event generator for the Z boson production and decay, called ZINHAC, is in the process of development [10].

The important merit of the WINHAC event generator, for the measurement strategy presented in this paper, is that the W and Z boson production and decay processes are described using the spin amplitude formalism. The spin amplitudes are calculated separately for the weak bosons production and for their decays. They correspond to all possible spin configurations of the intermediate W and Z bosons and the initial- and final-state fermions. The matrix element for the charged current Drell–Yan process is obtained by coherently summing the production and decay amplitudes over the intermediate W and Z boson spin states. The amplitudes are evaluated numerically for given four-momenta and polarisations of the particles. They can be calculated in any Lorentz frame in which the corresponding particles four-momenta are defined; for more details see [9]. The advantage of using the spin amplitudes is that one can control the spin states, in particular the production of longitudinally and transversely polarised W and Z bosons.

One of the novelties of the measurement strategy discussed in this paper is the factorisation of electroweak and strong interaction effects. For the precision measurements of the electroweak parameters the latter are proposed to be determined using the dedicated procedure based solely on the data. Their partial inclusion in the present studies (reduced only to perturbative ones, and implemented in the approximate LO form) is merely to indicate the size of the corrections and to test the proposed factorisation procedure. On the other hand, all the state-of-the-art electroweak

effects that can only be partly controlled experimentally must eventually be implemented in the WINHAC and ZINHAC generators for the high-precision studies of the high-statistics LHC data.

5 Detector model and Monte Carlo studies

At LHC, the high-precision measurements of the W boson production observables will be based on the samples of at least 10^8 recorded W boson production events. Full detector simulation of a comparable sample of Monte Carlo events is both unrealistic and unnecessary. The precision measurements will be bound to use the correction factors (efficiencies, acceptances, etc.) derived directly from the data and/or in form of the parametrised response of the detector.

In the studies presented in this paper we use the average response functions of the ATLAS tracker to charged particles as specified in [2]. We restrict our studies to particles produced in the pseudorapidity range $-2.5 \leq \eta_l \leq 2.5$. In the future the response functions of the LHC detectors will be determined *in situ* from the measurements of the decay products of the known narrow resonances. The ATLAS detector response functions are used here merely for the initial estimate of the size of the systematic measurement effects.

We have generated, using the dedicated processor farms, several large samples (10^8 events) of the Z and W boson production events using the WINHAC generator. The generated Z and W boson samples have been processed using either the average or the “biased” detector response functions. The biases studied included shifts in the scale of the reconstructed momenta and in the detector resolution. The Z boson production events have been generated at $\sqrt{s_n} = 14$ TeV (proton beams) and $\sqrt{s_2} = 7$ TeV/nucleon (isoscalar ion beams). The W production events have been generated both at the CM-energy of $\sqrt{s_n}$ (proton beams) and at the energy $\sqrt{s_1} = (M_W/M_Z)\sqrt{s_2}$ (isoscalar ion beams). For the samples generated at the CM-energies of $\sqrt{s_n}$ and $\sqrt{s_2}$ the solenoid-coil current $i(s)$ has been set to the nominal value i_n , corresponding to the assumed tracker response functions [2]. For the samples generated at the energy $\sqrt{s_1}$ the coil current has been rescaled down by a factor equal to the ratio of the W and Z boson masses.

The W and Z boson events have been selected by demanding the presence of the charged lepton with the track curvature radius ρ_l satisfying the following conditions:

$$\rho_l \leq \rho_l^c = \frac{i(s)}{i_n} \frac{1}{p_T^c(s)},$$

where

$$p_T^c(s_n) = p_T^c(s_2) = 20 \text{ GeV}, \quad p_T^c(s_1) = p_T^c(s_n) \frac{M_W}{M_Z},$$

$$i(s_n) = i(s_2) = i_n, \quad i(s_1) = i_n \frac{M_W}{M_Z},$$

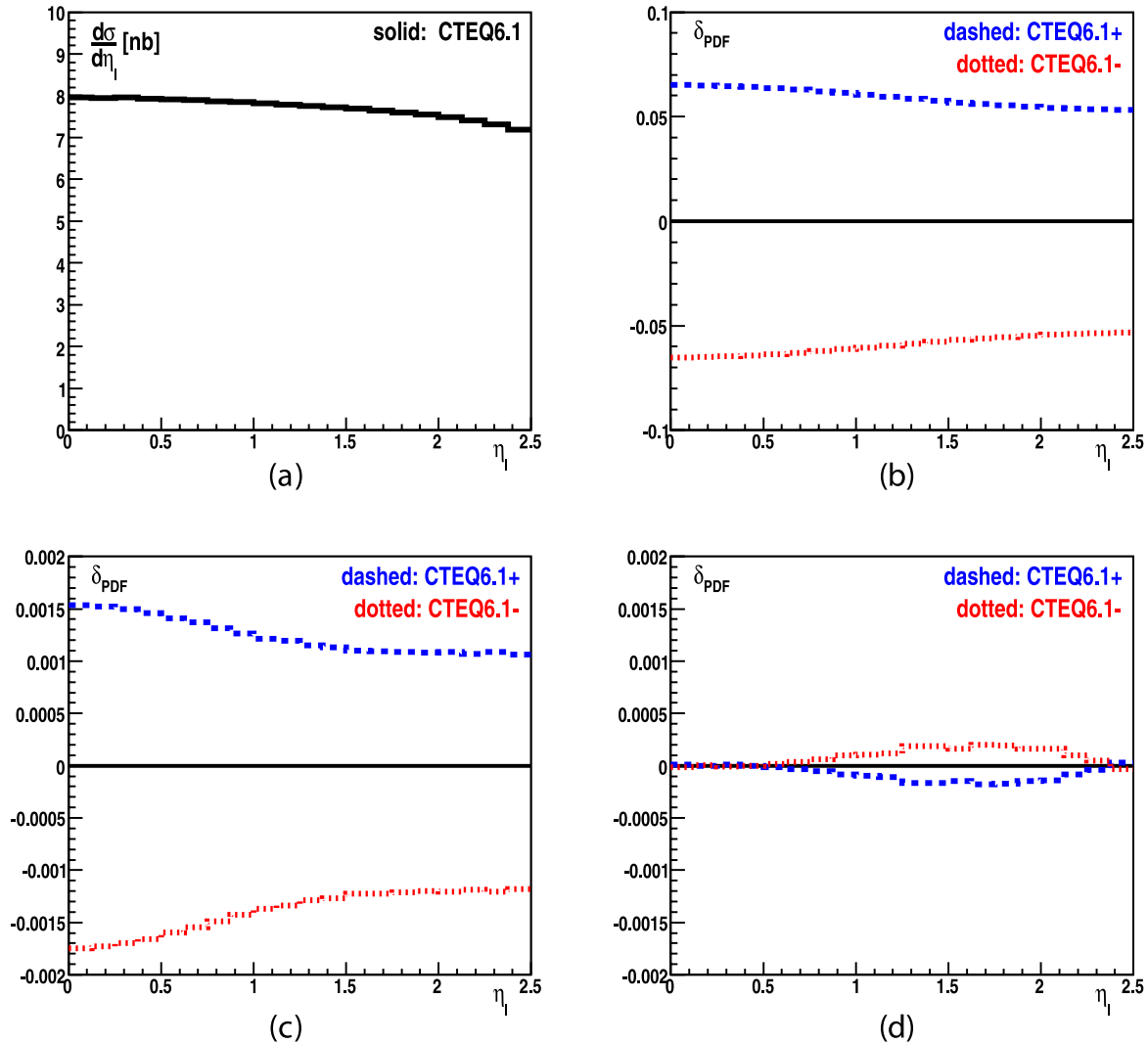


Fig. 1. (a) The distribution of the lepton pseudorapidity η_l for proton–proton collisions at LHC; (b) the systematic uncertainty $\delta_{PDF} = \frac{d\sigma/d\eta_l(\text{CTEQ6.1}\pm) - d\sigma/d\eta_l(\text{CTEQ6.1})}{d\sigma/d\eta_l(\text{CTEQ6.1})}$ of the η_l distribution reflecting the PDF uncertainty; (c) as above, but for the ratio of the η_l distributions for the W and Z -boson samples; (d) as above, but for the collision of the isoscalar beams, the rescaled collision energy and the rescaled magnetic field (see the text for details)

and the pseudorapidity η_l within the following range

$$-2.5 \leq \eta_l \leq 2.5.$$

In the case of Z bosons and lepton pair event samples we first randomly choose one of the two leptons and select an event only if this lepton satisfies the same selection criteria as specified above for the W boson event samples. Note that by specifying the selection condition in terms of the radius of the track curvature rather than in terms of the transverse momentum and by rescaling the solenoid current and CM-energy we achieve almost symmetric selection of the W boson and the Z boson events¹.

¹ The remaining residual asymmetry reflects the differences in the transverse momentum of the Z and W bosons and in the angular distributions of the charged leptons.

6 Reduction of systematic and modelling uncertainties; examples

In this section we discuss two numerical examples of improving the measurement precision of the dedicated W boson observables. These improvements can be achieved using the first three elements of the strategy presented in Sect. 3. The construction of dedicated, precision-measurement observables must assure their stability both with respect to the measurement biases of the lepton kinematics and with respect to the modelling ambiguities of the partonic beams at LHC. Their sensitivity to the W boson production, propagation and decay dynamics must remain the same as for the classical observables.

In the present studies we do not investigate the contribution of the QCD background to the selected sam-

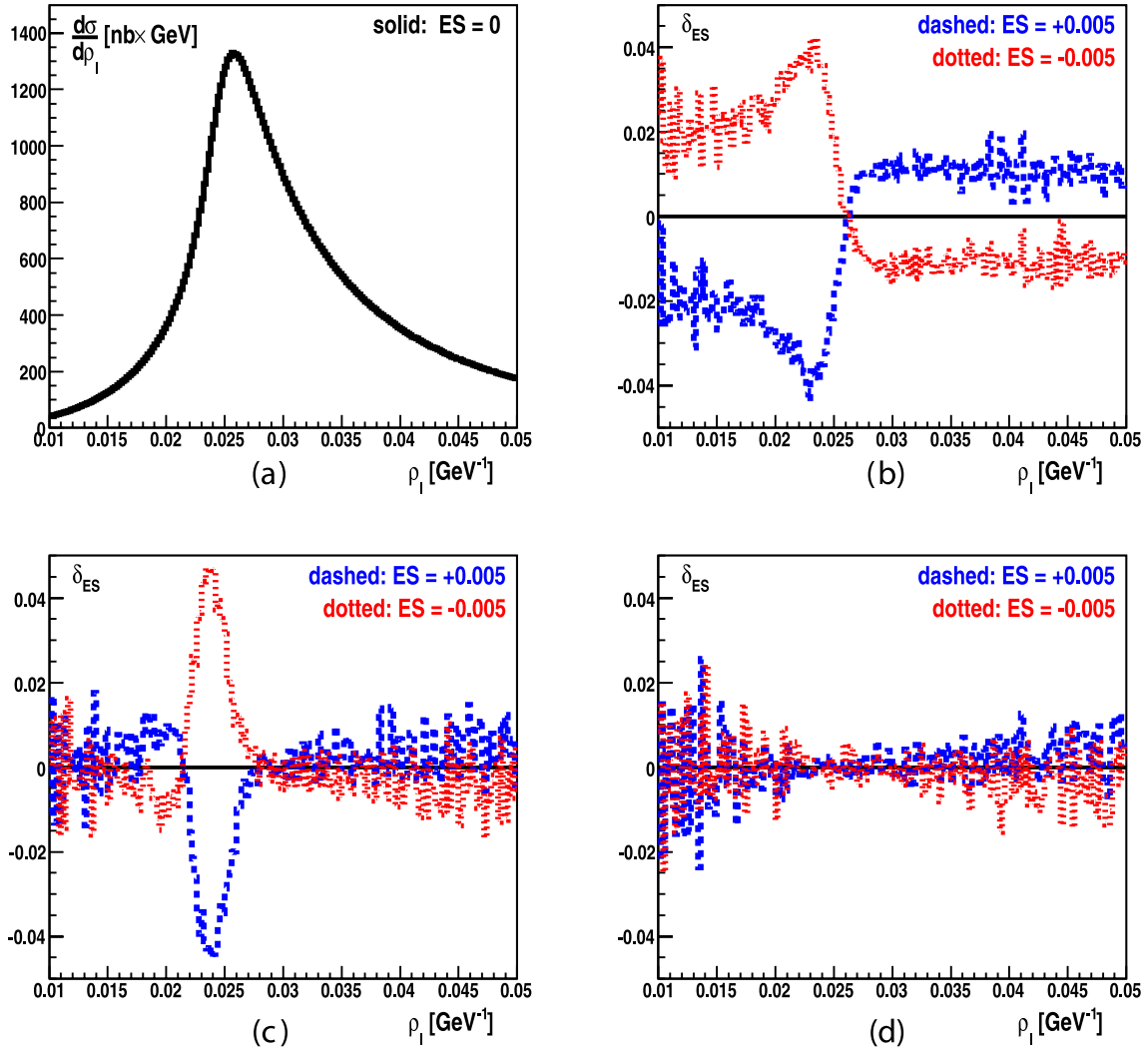


Fig. 2. (a) The distribution of the lepton track curvature radius ρ_l for proton–proton collisions at LHC; (b) the systematic uncertainty $\delta_{\text{ES}} = \frac{d\sigma/d\rho_l(\text{ES}\pm) - d\sigma/d\rho_l(\text{ES})}{d\sigma/d\rho_l(\text{ES})}$ of the ρ_l distribution generated by the lepton-momentum scale uncertainty; (c) as above, but for the ratio of the ρ_l distributions for the W and Z boson samples; (d) as above, but for the collision of the isoscalar beams, the rescaled collision energy and the rescaled magnetic field (see the text for details)

ples of the W and Z boson events. Earlier studies [20] have shown that the QCD background contamination is small, and its uncertainty will have a negligible effect on the final measurement precision. Moreover, we do not evaluate here the gains coming from those elements of the measurement strategy proposed in Sect. 3 that aim at reducing the impact of the asymmetries in the relative size of the electromagnetic radiative corrections due to real photon emissions. The latter, of high importance for the precision measurements, will be presented in a separate communication, when the implementation of these processes in the ZINHAC generator is finalised. As long as radiation processes are neglected the electron and the muon track reconstruction quality remain the same. In the following, ‘leptons’ will either mean electrons or muons.

In Fig. 1a we show the charged lepton pseudorapidity distribution for the $pp \rightarrow W + X$, $W \rightarrow l\nu$ process at the

CM-energy of $\sqrt{s_n}$, for the CTEQ6.1 partonic density distributions [21]. The contribution to the uncertainty of this distribution coming from the uncertainties in the partonic distribution functions (PDFs) and determined using the method proposed in [22] is shown in Fig. 1b. This uncertainty may be diminished to the per-mil level, as shown in Fig. 1c, by replacing the pseudorapidity distribution by the ratio of the charged lepton pseudorapidity distributions for the W and Z boson production events.

For further reduction of the impact of the uncertainty of the PDFs we propose to measure the isoscalar beam collision observable, defined by

$$R_{WZ}^{\text{iso}} = \frac{d\sigma_W^{\text{iso}}(s_1, i(s_1))}{d\sigma_Z^{\text{iso}}(s_2, i(s_2))}. \quad (1)$$

This observable is plotted in Fig. 1d as a function of the lepton pseudorapidity for the deuterium beams. Its sensi-

tivity to the uncertainty in the partonic distribution functions is reduced to a level below 2×10^{-4} . This residual uncertainty is driven predominantly by the CKM mixing of down-quark flavours and by the differences of the masses of the down- and up-type quarks. The uncertainty due to the asymmetry in the shadowing effects for the W and Z boson production is negligible owing to the smallness of the shadowing effects for light ions, their weak-isospin invariance, and their very mild resolution-scale dependence in the vicinity of the M_W scale.

Note that the W and Z boson samples would have to be collected over the distinct beam running periods. The quoted accuracy thus concerns the shape of the R_{WZ}^{iso} ratio. The precise normalisation of R_{WZ}^{iso} , which is sensitive to the ratio of Γ_W/Γ_Z , requires the dedicated method of absolute cross-normalisation of the event samples collected at the two CM-energies. Such a scheme, aiming at the per-mil precision, is being developed [23]. Another method of getting rid of the uncertainty in the absolute normalisation of R_{WZ}^{iso} is presented in the next section.

The dominant factor limiting the precision of the measurement of the W boson mass is the uncertainty in the scale of the lepton transverse momentum (energy). To improve its present precision, the lepton energy and momentum scale must be known to better than 0.02% [20]. The measurement strategy discussed in this paper allows us to drastically reduce the influence of the scale error on the measurement of the W boson mass.

In Fig. 2a we present the distribution of the curvature radius ρ_l of the lepton track originating from the decays of the W bosons produced in the pp collisions at the nominal LHC energy. The peak position and the shape of this distribution is sensitive both to the W boson mass and to the lepton momentum scale bias. In Fig. 2b we show the effect of the change in the scale of the reconstructed lepton transverse momentum: $p_T^{\text{rec}} = p_T^{\text{true}}(1 \pm \varepsilon_s)$ for $\varepsilon_s = 0.005$. A scale uncertainty of this magnitude leads to errors of up to 4% of the ρ_l distribution, which, in turn, give rise to an uncertainty of the measured W boson mass of about 500 MeV. This uncertainty is only slightly reduced when normalising the distribution for W bosons to the corresponding one for Z bosons, as shown in Fig. 2c.

The R_{WZ}^{iso} observable, if measured in dedicated runs of isoscalar beams at the two CM-energy and solenoid-current settings, allows us to drastically reduce the above uncertainty. This observable is plotted in Fig. 2d as a function of ρ_l . In the peak region sensitive to the W boson mass the impact of the lepton momentum scale uncertainty on the R_{WZ}^{iso} observable is reduced by the factor of 10 with respect to the direct measurement of the ρ_l distribution in the nominal-energy proton-beam runs.

7 Factorisation of QCD effects

The rescaling of the energy of the LHC beams allows us to consider the formation of the Z and W bosons on the same footing – for a given rapidity of the Z and W bosons the fractions of the proton momentum carried by annihilating

partons are, by construction, the same. However, this holds exactly only for collinear massless partons.

In reality, the R_{WZ}^{iso} observable defined in Sect. 6 is still sensitive to several effects that must be experimentally controlled for high-precision measurements. Firstly, it is sensitive to the scale dependence of partonic distributions, which is governed by the QCD coupling constant $\alpha_s(M_W)$, and by the scale dependent factor $\ln(M_W^2/M_Z^2)$. It is also sensitive to the effective distributions of the transverse momenta k_T and the off-shellness m_* of the annihilating quarks, which can only be partly controlled by perturbative QCD. Last but not the least, the R_{WZ}^{iso} observable is sensitive to the relative normalisation of the Z and W boson samples taken in separate runs.

In order to get rid of the above effects, rather than to model them, we propose to select samples of events containing a pair of opposite charge and same flavour leptons and to measure the ratio of the integrated lepton pair production rates

$$C_{\text{QCD}} = \frac{\left(\int_{M_Z-3\Gamma_Z}^{M_Z+3\Gamma_Z} N^{l+l-}(s_2, i(s_2), M^{l+l-}) \times dM^{l+l-} \right)}{\left(\int_{M_W-3\Gamma_W}^{M_W+3\Gamma_W} f_{\text{BW}}(s^{l+l-}; M_W, \Gamma_W) w_{\text{EW}} \times N^{l+l-}(s_1, i(s_1), M^{l+l-}) dM^{l+l-} \right)} \quad (2)$$

as a function of ρ_l and as a function of η_l of the randomly chosen lepton. The rates N^{l+l-} in the above formula are integrated over the invariant mass M^{l+l-} of the lepton pairs in the regions $(M_Z - 3\Gamma_Z, M_Z + 3\Gamma_Z)$, and $(M_W - 3\Gamma_W, M_W + 3\Gamma_W)$, respectively. Each event having a reconstructed invariant mass in the latter region is weighted by the Breit–Wigner function

$$f_{\text{BW}}(s^{l+l-}; M_W, \Gamma_W) = \frac{1}{\pi} \frac{M_W \Gamma_W}{(s^{l+l-} - M_W^2)^2 + M_W^2 \Gamma_W^2},$$

where $s^{l+l-} = (M^{l+l-})^2$, and by the QCD independent normalisation factor w_{EW} . This factor is defined so that the integral of the weighted lepton invariant mass spectrum in the region of $(M_W - 3\Gamma_W, M_W + 3\Gamma_W)$ is equal to the cross section of a Z -like boson having the mass and the width of the W boson². The lepton pair production events used in the determination of the $C_{\text{QCD}}(\eta_l)$ and $C_{\text{QCD}}(\rho_l)$ correction functions must be triggered and selected on the basis of the presence of two same flavour, opposite charge lepton candidates. Each of the lepton must satisfy the kinematical selection criteria specified in Sect. 5. This requirement, stronger than the corresponding one for the Z boson sample of events discussed in Sect. 5, is necessary to reduce the background to the inclusive lepton samples in the lepton pair invariant mass region outside the Z -peak.

The $C_{\text{QCD}}(\eta_l)$ and $C_{\text{QCD}}(\rho_l)$ correction functions will be determined directly from the lepton pair production data for given input functions w_{EW} and $f_{\text{BW}}(s^{l+l-};$

² The weighting procedure takes care of the residual asymmetries of the angular distributions of the leptons produced in the region of the Z -peak and in the region outside the Z -peak.

M_W, Γ_W). Since these functions are sensitive to the SM parameters, they should, in principle, be calculated iteratively. In the first iteration step the PDG values of the parameters can be used. The corresponding correction functions C_{QCD} would then be used to determine their more precise values from the analysis of the QCD effects corrected R_{WZ}^{iso} observables. The improved values could then be used in the next iteration step.

In Fig. 3 we present our initial estimate of the size of the correction functions $C_{\text{QCD}}(\eta_l)$ and $C_{\text{QCD}}(\rho_l)$, using the CTEQ parametrisation of the PDFs and the corresponding value of the QCD coupling constant [21]. In order to understand the relative size of the scaling violation effects and the effects due to the transverse momentum of the quarks, the $C_{\text{QCD}}(\eta_l)$ and $C_{\text{QCD}}(\rho_l)$ correction functions have been determined first assuming $k_T = 0$ and $m_* = 0$, Fig. 3a and c, respectively, and then using their PYTHIA modelling [12], Fig. 3b and d, respectively. The correction sizes are at the level of a few percent. If the partonic k_T ef-

fects are neglected, the correction functions are flat. Their inclusion modifies sizably the $C_{\text{QCD}}(\rho_l)$ function, which is highly sensitive to the relative shape of the partonic k_T distribution in the W and Z boson production events. It is important to note that the above corrections must be determined and applied at the raw data level. This is an important merit of the proposed correction method, which, by construction, takes care of the QCD effects independently of the level of understanding of the detector performance.

In Fig. 4 we show the uncorrected ratios R_{WZ}^{iso} for the η_l and ρ_l distributions, Fig. 4a and c, respectively, and the ratio corrected for the relative QCD effects in W and Z boson production,

$$R_{WZ} = R_{WZ}^{\text{iso}} C_{\text{QCD}}. \quad (3)$$

Figure 4b and d, respectively, are for the η_l and ρ_l distributions. We propose that the latter ratio be used for high-precision determination of the M_W and Γ_W param-

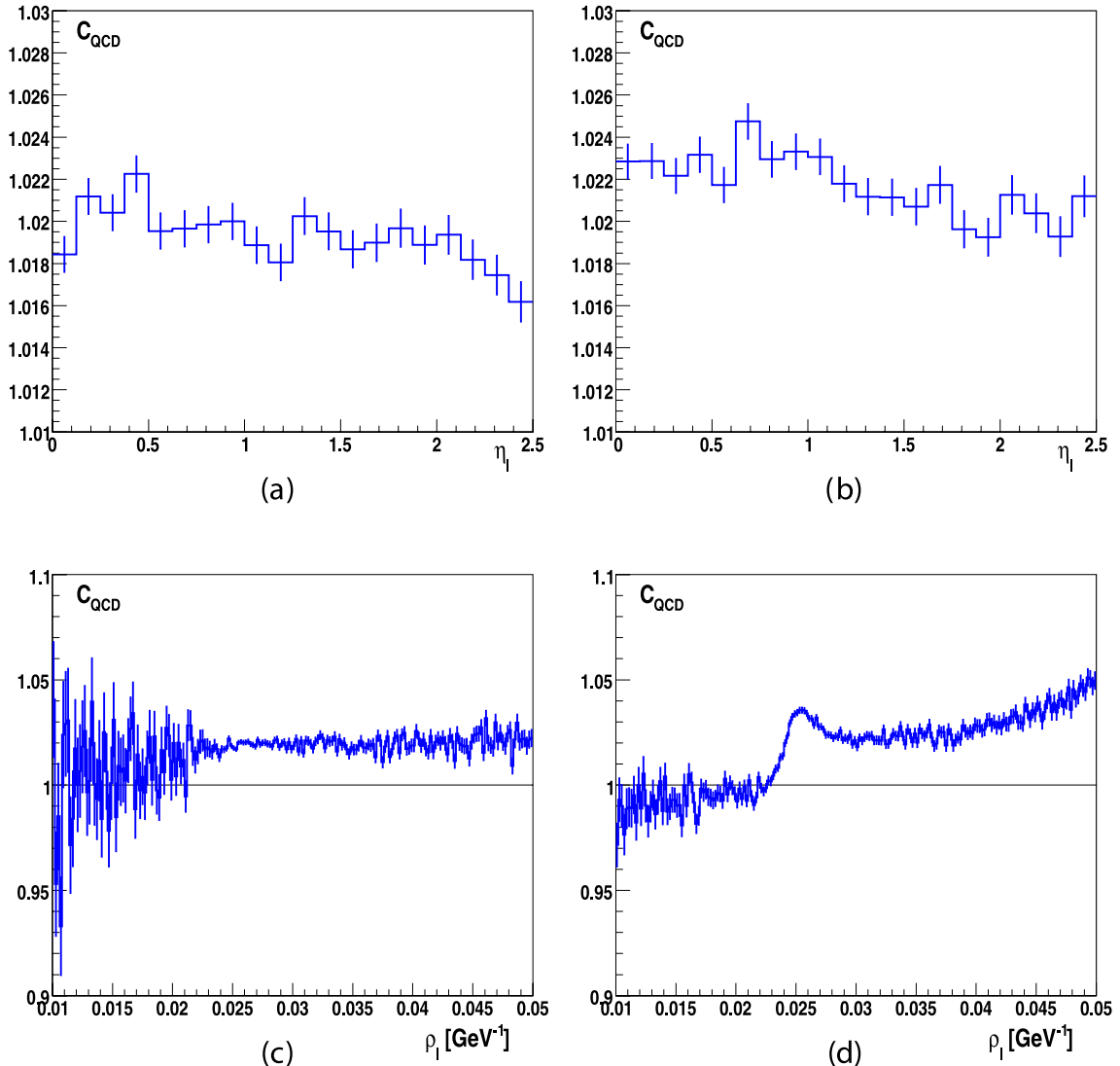


Fig. 3. The $C_{\text{QCD}}(\eta_l)$ and $C_{\text{QCD}}(\rho_l)$ correction functions (see the text for detailed explanation) for collinear partons, (a) and (c), respectively, and for PYTHIA modelling of their transverse momenta, (b) and (d), respectively

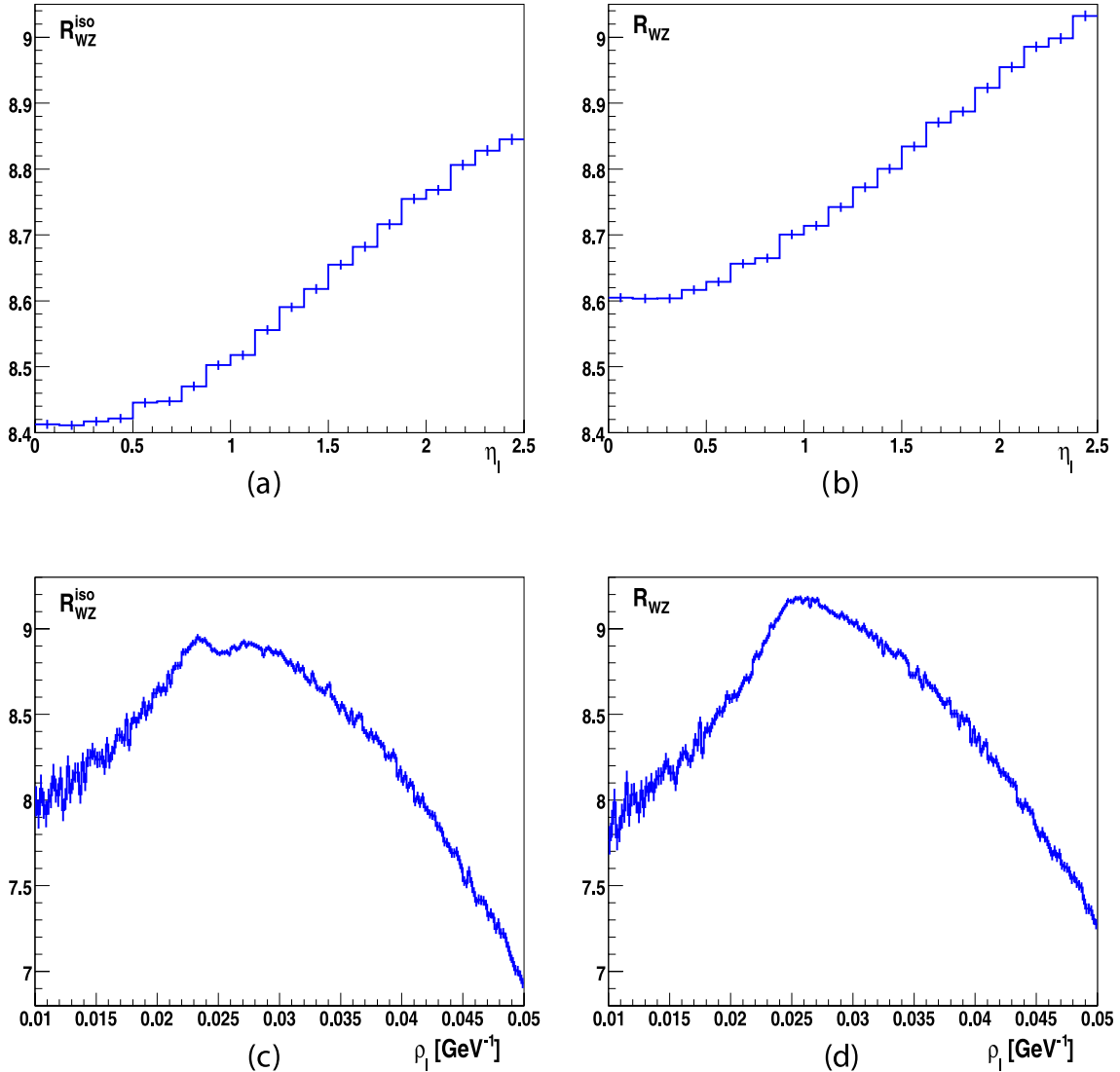


Fig. 4. Uncorrected ratios R_{WZ}^{iso} and the QCD-corrected ratios R_{WZ} plotted as a function of η_l , (a) and (b), respectively, and as a function of ρ_l , (c) and (d), respectively

ters at LHC. The estimation of the achievable precision of such a method will be discussed in a separate paper [24].

It remains to be noted that the QCD effects corrected ratios are insensitive to the precision of the relative normalisation of the two data sets taken at the energies $\sqrt{s_1}$ and $\sqrt{s_2}$. Their final precision will be limited entirely by the statistical accuracy of the lepton pair event samples. The basic merit of the observables introduced in Sect. 6 is that their QCD correction factors are sufficiently small to make the iteration of the electroweak parameters, discussed earlier in this section, unnecessary for the measurement precision down to the level of $\mathcal{O}(10^{-4})$.

8 Conclusions

In this paper we have proposed a strategy of using the Z boson as *the standard candle* for the high-precision

measurements of the W boson observables at the LHC. Our goal was to propose the measurement method and to define the dedicated observables that are insensitive to the ambiguities in modelling of the colour and flavour degrees of freedom of the effective partonic beams. In addition, our goal was to minimise the impact of those of the systematic errors that differently affect the W and Z boson production processes. We have demonstrated that the effect of the uncertainties in the partonic distribution functions can be reduced from the level of 5% for the standard observables to the level of 2×10^{-4} for the observables proposed in this paper, while preserving their sensitivity to the SM parameters. We have demonstrated that the sensitivity of the proposed observables to the scale error of the reconstructed lepton momentum, the dominant source of systematic error of the measured W boson mass, can be reduced by the factor of 10. We have defined the measurement procedure in which the relative effects of strong interaction of quarks producing the W and Z bosons are

factorised out and measured directly. Such a procedure could allow us to determine the SM parameters with no need of modelling the perturbative and non-perturbative QCD effects in the Monte Carlo generators. The methods developed in this paper will be used in the dedicated studies of the achievable precision of the SM parameters measurements at LHC. These studies will be reported in separate papers.

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