Improving the present precision of the electroweak parameters at the LHC: a forlorn hope?*

Mieczyslaw Witold Krasny LPNHE, Université Pierre et Marie Curie Paris 6, Université Denis Diderot Paris 7, CNRS/IN2P3, Paris, France

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At the LHC, an improvement of the present precision of the electroweak parameters is both mandatory and difficult. In the analysis strategies proposed so far, shortcuts have been made that are justified for proton–antiproton collisions at the Tevatron, but not for proton–proton collisions at the LHC. The root of the problem lies in the inadequate knowledge of parton density functions of the proton. It is argued that more precise parton density functions of the proton are needed, and an LHC-specific analysis strategy ought to be pursued. Proposals are made on both issues.

1 Introduction

In much the same way as precise measurements of radiative corrections served to test and establish QED, precise measurements of input parameters and their use in the calculation of radiative corrections in the Electroweak Standard Model serve as benchmarks for new theoretical concepts. Therefore, besides the direct searches for new phenomena, the precision measurement of parameters of the Electroweak Standard Model[1] —e.g., the W mass—with greater precision than available from LEP and the Tevatron, is an important and indispensable part of the LHC programme.

Whilst the Z mass (M_{Z}) is well measured to ± 2.1 MeV/c^2 [1], M_{W} is measured at the Tevatron to ± 31 MeV/c^2 [2] and at LEP to ± 33 MeV/c^2 [3]. Of the three independent input parameters of the Electroweak Standard Model, M_{W}, M_{Z} and the fine-structure constant, M_{W} is by one order of magnitude less precise than M_{Z} that is second-best.

Although a precision of M_{W} that matches the precision of M_{Z} is experimentally not within reach, a much better precision than available today is desirable to exploit the full potential of the relation between M_{W} and the Fermi coupling constant G_{F} that is also well measured with a relative precision of 1×10^{-5}.

The relation between G_{F} and the three input parameters, M_{W}, M_{Z} and the fine-structure constant, is a cornerstone of the Electroweak Standard Model. Radiative corrections of this relation that depend *inter alia* on the mass of the Higgs boson, suggest a broad range for the Higgs mass that is nevertheless well within reach at the LHC. However, in case the Higgs boson will not be found, the hunt for alternative models of electroweak symmetry breaking will be

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[1]Hereafter referred to as 'electroweak parameters'.

on. Then the highest possible precision of M_{W} will be a central issue, for a better measured relation between the quantities G_{F}, M_{W}, M_{Z}, and the fine-structure constant, will put more stringent constraints on theoretical models.

In previous analyses, it was claimed that an M_{W} precision of 10 MeV/c^2 or better will be obtained at the LHC [4, 5]. This note questions such claims and argues that shortcuts have been made that are not justified, and hence the claimed measurement precision is much too optimistic. The reason is that the analysis of $p_{\mathrm{T,l}}$ spectra from leptonic W and Z boson decays in $\mathrm{p\bar{p}}$ collisions at the Tevatron—that served as template for the respective analyses at the LHC—benefits from symmetry properties that are absent in pp collisions at the LHC. A considerably better knowledge of the $u_{\mathrm{v}} - d_{\mathrm{v}}$, $s - c$, and b parton density functions (PDFs) of the proton[2] than available today is needed, together with an LHC-specific measurement and analysis programme.

No improvement of the current situation is expected unless special experimental efforts are made to obtain the missing high-precision PDFs. Two ways forward are discussed. One is to complement the pp programme of the LHC with a deuteron-deuteron collision programme. Another is to obtain missing input from a new high-precision muon–nucleon scattering experiment, and to analyze these data coherently with LHC pp and Tevatron $\mathrm{p\bar{p}}$ data.

2 The LHC precision limits

It is advocated and widely believed that the proton PDFs are precise enough not to pose a limitation for LHC data analysis. In the following, a 5% error of the x dependence of the PDFs of the u_{v} and d_{v} is considered as a realistic estimate. The present experimental uncertainty of the PDF of the c quark is at the 10% level[3]. The present experimental uncertainty of the PDF of the b quark is at the 20%

The root of the problem for the use of current proton PDFs in the analysis of W and Z production and decay at the LHC arises from 'compensating' PDF changes: a change of the PDF of one quark can be compensated by a change of the PDF of the other quark of the same family that leaves the Z rapidity distribution nearly invariant and hence escapes detection[4].

The above uncertainties of PDFs are incorporated in the simulation of p_{T} spectra from W^+, W^- and Z leptonic decays. This simulation uses the LHAPDF package [7] of PDFs, and PYTHIA 6.4 [6] for the modelling of the QCD/QED initial-state parton shower and its hadronization; the transverse momentum k_{T} of quarks and antiquarks is the one incorporated in PYTHIA. The tool for event generation is WINHAC 1.31 [8], a Monte Carlo generator for single W production in hadronic collisions, and subsequent leptonic decay. WINHAC includes also neutral-current processes with γ and Z bosons in the intermediate state. The novel feature of WINHAC is that it describes W and Z production and decay in terms of spin amplitudes [9]. These involve, besides all possible spin configurations of the W and Z bosons, also the ones of the initial- and final-state fermions. The advantage of this approach is that one has explicit control over all spin states, and thus over transverse and longitudinal boson polarization amplitudes and their interferences.

[2]Throughout this paper, PDFs refer to the proton.

[3]Theoretical calculations of heavy-quark PDFs from the gluon PDF are claimed to have a smaller error margin.

[4]The condition of invariance of the Z rapidity distribution, and hence invisibility even in high-statistics data samples, is decisive: if the measured Z rapidity distribution looked differently than expected from the current proton PDFs, an appropriate change of the proton PDFs would be unavoidable.

As an example LHC detector, ATLAS is chosen. Charged leptons from W and Z decays are accepted with $p_\mathrm{T} > 20$ GeV/c and $|\eta| < 2.5$. The approximate range of x for W and Z production in the above kinematical region is 5×10^{-2} to 7×10^{-4}. The event statistics correspond to an integrated luminosity of 10 fb^{-1}. Both the electron- and muon decay channels of W and Z are considered. Since in pp collisions the spectra of positive and negative leptons are to be analyzed separately, it is natural to make the same distinction also for the leptons from Z decay. Along this line of reasoning, 'Z^+' and 'Z^-' lepton p_T spectra are generated, in analogy to 'W^+' and 'W^-' lepton p_T spectra[5]. All spectra are generated with various proton PDF configurations. The Z^+ and Z^- lepton p_T spectra are corrected for the evolution from $Q^2 = M_\mathrm{W}^2$ to $Q^2 = M_\mathrm{Z}^2$.

From a fit of the Jacobian peaks in the p_T distributions and by calibrating with the known Z mass, the W^+ and W^- masses are determined. The biases of M_W caused by the allowed compensating changes of the PDFs of quarks of the 1st family are at the 70 MeV/c level. The biases of M_W caused by the allowed compensating changes of the PDFs of quarks of the 2nd family are at the 130 MeV/c level. The biases of M_W caused by the allowed changes of the PDF of the b quark are at the 40 MeV/c level The conclusion is, when allowing for compensating PDF changes and a realistic PDF error margin, that there is no way to obtain M_W with a precision at the 10 MeV/c^2 level with the currently available proton PDFs.

There is also no way to improve, at the LHC collider, the present precision of the other electroweak parameters. For example, allowing for compensating PDF changes leads to an uncertainty of $\mathcal{O}(100)$ MeV/c^2 for M_W and for the difference $M_{\mathrm{W}^+} - M_{\mathrm{W}^-}$, an uncertainty of $\mathcal{O}(40)$ MeV/c^2 for Γ_W , and an uncertainty of $\mathcal{O}(0.001)$ for $\sin^2\theta_\mathrm{W}$. Already for an integrated luminosity as small as 1 fb^{-1} the errors that result from the uncertainties of today's missing input, are larger than statistical and systematic errors stemming from the LHC data.

3 Ways forward

3.1 Two-dimensional PDFs

In our view improving the present precision of the electroweak parameters requires overhauling of the analysis framework developed at the Tevatron, in particular, it requires replacing one-dimensional PDFs by the two dimensional PDFs. The differential of the two-dimensional PDF of the quark q, $\mathrm{d}q(x, k_\mathrm{T}; Q^2)$, denotes the number $\mathrm{d}N$ of quarks of type q with a fraction of the proton longitudinal momentum in the range $[x, x + \mathrm{d}x]$, with a transverse momentum in the range $[k_\mathrm{T}, k_\mathrm{T} + \mathrm{d}k_\mathrm{T}]$, at the scale Q^2.

3.2 Deuteron–deuteron collisions at the LHC

The impact of the uncertainties from missing input PDFs can be considerably reduced by operating the LHC with isoscalar beams. The natural choice is to collide deuteron beams. The deuteron beams restore isospin symmetry for the quarks of the 1st family. The four independent k_T-integrated PDFs $u(x)$, $d(x)$, $\bar{u}(x)$ and $\bar{d}(x)$ are reduced to two: $u(x) + d(x)$ and $\bar{u}(x) + \bar{d}(x)$. Equality of W^+ and W^- production is restored and the spin-density matrices of W and Z

[5]This appears appropriate as a non-zero longitudinal Z polarization causes the p_T spectra of the positive and negative decay leptons to be slightly different, for the charge-dependent correlation of the Z spin with the emission of charged decay leptons.

produced by quarks of the 1st family are nearly the same. If the contributions from quarks of the 2nd and 3rd family could be neglected, the isospin symmetry of deuterons at the LHC would play the same role as the matter–antimatter symmetry at the Tevatron. In principle, high-statistics data from dd collisions at the LHC would be sufficient to provide electroweak parameters with the desired precision. However, caveats remain.

3.3 pp at the LHC, p$\bar{\text{p}}$ at the Tevatron, and muon–nucleon scattering combined

The concept of solving the missing-input problem by dd collisions in the LHC is elegant and technically feasible, though not realistic in the near future. Therefore, an alternative is proposed: obtaining with sufficient precision from a joint analysis of Tevatron p$\bar{\text{p}}$ data, of data from a new muon–nucleon scattering experiment, and of LHC pp data, all needed PDFs with adequate precision. The muon–nucleon scattering experiment would measure from the deep-inelastic scattering of $\mathcal{O}(100)$ GeV/c muons on stationary hydrogen and deuterium targets the asymmetry

$$\mathcal{A}_{\rm DIS}^{\rm p,n} \quad = \quad \frac{\sigma(\mu,\mathrm{p}) - \sigma(\mu,\mathrm{n})}{\sigma(\mu,\mathrm{p}) + \sigma(\mu,\mathrm{n})} \tag{1}$$

With the inclusion of the muon–nucleon scattering data, the problem of missing high-precision PDFs for the analysis of LHC pp data is solved. A Letter of Intent [10] for such an experiment was submitted to CERN Programme Committees. Therein, the exposure of the COMPASS detector to the muon beam of the CERN–SPS was proposed.

4 Conclusion

Unless efforts as discussed in this paper are undertaken, the precision of the W mass, and of other parameters of the Electroweak Standard Model, will not be improved at the LHC. Thus a chance may be missed towards understanding the mechanism that regularizes the unitarity problem of this Model.

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