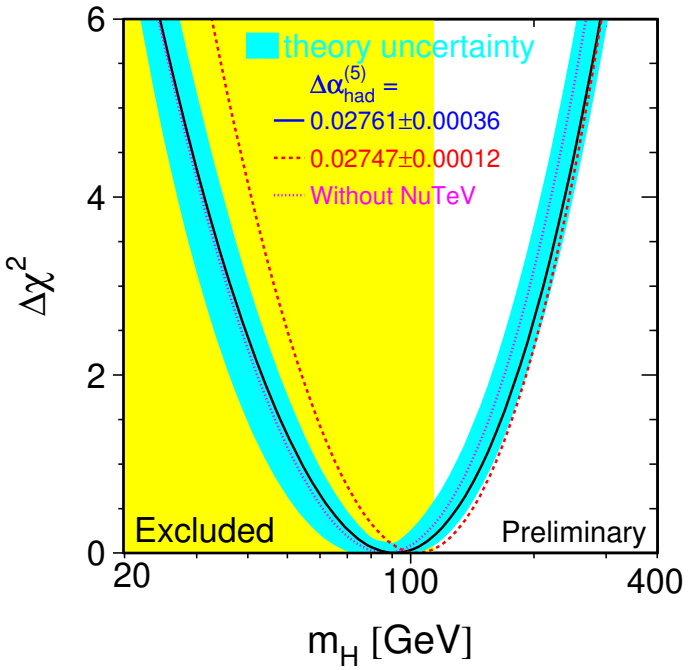
DESY-PROC-2003-01
MPP-2003-50
August 2003

ELECTROWEAK PRECISION DATA AND THE HIGGS MASS



Proceedings of the Workshop at DESY-Zeuthen, Feb. 28 - March 1, 2003

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ISSN 1435-8077; ISBN 3-935702-12-4

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Synopsis

The successful completion of the LEP experiments at CERN, the SLD experiment at SLAC, and the Tevatron Run I at Fermilab leave us with a large variety of high-precision measurements of properties of the massive electroweak gauge bosons W and Z, and of the top quark, which are the heaviest known elementary particles. These particles play a key role in the Standard Electroweak theory, which together with Quantum Chromodynamics (the theory of Strong interactions) provide the Standard Model (SM) of elementary particles. The consistent formulation of the SM as a quantum field theory allows us to evaluate observables in a mathematically consistent manner that is mainly limited by technical issues, such as the complexity of formulas, numerical stability, etc. In this way, it was possible to confront theory and experiment at the level of 0.1–1% for the high-precision observables measured at LEP, SLC, and Tevatron. This success rendered the last decade the era of electroweak precision physics.

In the evaluation of perturbative higher-order corrections in general all parameters of the theory enter, even those that are not yet directly measured in experiments. Owing to this feature, it was possible to constrain the mass m_t of the top quark before its discovery in 1995 at the Tevatron by confronting precisely measured Z-resonance observables with predictions including m_t-dependent corrections. The same strategy was followed in recent years in order to constrain the mass M_H of the not yet discovered Higgs boson by fitting all SM parameters, including M_H, to the whole set of high-precision data. However, the sensitivity of the corrections to M_H is rather weak, viz. roughly like $\alpha \ln(M_H/M_Z)$, in contrast to the former constraint on m_t, where corrections proportional to $G_F m_t^2$ occur. Therefore, setting bounds on M_H requires both a very high experimental precision and a correspondingly high accuracy in the theoretical predictions, rendering the task a non-trivial subject.

The fit of the SM parameters to data, which in particular yields the constraints on M_H, was continuously updated over recent years by various authors. Without going into details, the best-fit value for M_H turns out to be slightly below the 95% C.L. lower bound of about 114 GeV from the direct search at LEP, well compatible with this bound on the one standard deviation level. The 95% C.L. upper limit for M_H is of the order of 200 GeV. Although this result looks nicely consistent and rather promising for Higgs-boson searches at future colliders, the whole SM fit suffers from a bad fit quality. For instance, the fit to the experimental data set of Summer 2002 leads to an overall probability of only 1.3%, at first sight revealing that the SM is in serious trouble. However, before discarding the SM the sources of the bad fit quality have to be examined carefully:

- Already since the first results from SLD on the left-right asymmetry A_{LR} appeared, there was some controversy when the corresponding value for the leptonic effective weak mixing angle $\sin^2\theta_{eff}^{lept}$ was compared to results from LEP1, where the most precise value on $\sin^2\theta_{eff}^{lept}$ is derived from the forward-backward asymmetry A_{FB}^b for bottom-quark production. The two measurements deviate from each other by about 3σ in $\sin^2\theta_{eff}^{lept}$. While A_{LR} prefers a Higgs-boson mass of 50 GeV, a bit more than $1\,\sigma$ below the lower bound of 114 GeV (95% C.L.), the LEP measurement of A_{FB}^b favours M_H of the size 400 GeV. Combining the two independent measurements

results in a compromise value for M_H in conjunction with a reduction of the fit quality.

- The direct measurement of the W-boson mass M_W also plays a crucial role in constraining the Higgs-boson mass. The measured value of M_W, loosely speaking, determines which compromise value for M_H (resulting from the fit to $\sin^2\theta^{lept}_{eff}$) is favoured. The direct reconstructions of M_W from W-pair production at LEP2 and Drell-Yan-like single-W production at Tevatron are perfectly compatible and favour a low Higgs-boson mass of about 50 GeV. It should, however, be noticed that the world average of M_W changed by 0.7σ from Summer 2002 to Winter 2003 (owing to corrections in the ALEPH data analysis), a fact which reflects that the data analyses (including the assessments of systematic errors) are not yet finalised.

- Recently the NuTeV collaboration published their results on neutrino–nucleon scattering, which should also be included in the set of precision measurements. The measured ratio of neutral-current and charged-current cross sections is mainly sensitive to the so-called "on-shell weak mixing angle", which is equivalent to the ratio M_W/M_Z of the W- to the Z-boson mass. Owing to the extremely well determined value of M_Z from LEP1, the NuTeV measurement is often quoted as an indirect measurement of M_W. The NuTeV result is about 3σ away from the directly measured value and from the fitted result of M_W. This disagreement does, however, not influence the fit result for the Higgs-boson mass, because, compared to the experimental uncertainties, the Higgs-mass sensitivity of the NuTeV measurement is much smaller than the one of the direct determination of M_W and of $\sin^2\theta^{lept}_{eff}$. The disagreement rather turns the fit probability to a very low value.

- Moreover, the overall fit of the SM parameters to the precision data sensitively depends on the value of the running electromagnetic coupling $\alpha(Q^2)$ at the electroweak scale, usually quantified by the value at $Q^2 = M_Z^2$. The quantity $\alpha(M_Z^2)$ cannot be predicted by perturbation theory, mainly because of the occurrence of hadronic resonances at low Q^2 values; $\alpha(M_Z^2)$ is also not directly accessible by experiments. Therefore, it is determined in a fit of the hadronic vacuum polarisation either to the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ in the low-energy range, or to the τ spectral function measured in τ decays. The two methods lead to values for the hadronic contribution to $\Delta\alpha(M_Z^2)$ that differ by about 0.8σ. Moreover, the possibility to improve the error of the input value $\alpha(M_Z^2)$ in the SM fits by exploiting theoretical results from perturbative QCD is still under discussion. An improvement in the determination of $\alpha(M_Z^2)$ is certainly desirable, but it cannot be expected that modifications in $\alpha(M_Z^2)$ change the overall SM at a qualitative level.

Already this short survey of features in the SM fit to data demonstrates the complexity of the subject, rendering its interpretation a delicate issue.

Presently, assessments of the SM fit to data extend over a large range – a situation that is not satisfactory. The meeting of theoretical and experimental experts should help to clarify this unpleasant situation by careful and critical analyses of the error estimates. The subject of the mini-workshop, organised under the auspices of the DESY/ECFA

LoopVerein, was a critical discussion aimed at improving the understanding of errors in the theoretical calculations and experimental analyses of the high-precision electroweak data that are exploited to derive estimates of the Higgs mass in the SM and beyond. Specifically, the following issues were addressed in detail:

- the status of the overall fit to the electroweak precision data, in particular of the SM Higgs-mass estimates;
- specific theoretical topics:
  - pseudo versus realistic observables at the Z resonance;
  - theoretical uncertainties in precision calculations for pseudo observables;
  - determination of $\alpha(M_Z^2)$;
  - QCD uncertainties at NuTeV;
  - Bhabha scattering and luminosity measurement;
  - status of analyses in supersymmetric extensions of the SM;
- specific experimental topics:
  - A_{FB}^b and b-tagging uncertainties;
  - A_{LR} and polarisation determination;
  - M_W from lepton and hadron colliders;
  - results from the NuTeV experiment;
- critical summary of theoretical and experimental uncertainties, and consequences for Higgs-mass estimates.

The selection of these topics should help to work out how robust the fit of the SM and, specifically, of M_H actually is if one or another experimental or theoretical result is questioned or even discarded, where possible loop holes in assessments of systematic errors could be found, or in which directions further improvements could be achieved.

Electronic versions of the talks may be found at the web-page
`http://www.ifh.de/www_users/zeus/moenig/ew_workshop/agenda.html`

S. Dittmaier and K. Mönig

Acknowledgements

The Organising Committee of the workshop thanks all participants for their interesting contributions during the meeting and in the proceedings. We thank the colleagues from DESY Zeuthen for providing the technical support and the kind hospitality at Zeuthen, and T. Hahn from MPI for some help in preparing the proceedings document. Finally, the financial support by DESY is gratefully acknowledged.

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