Electroweak Physics at LHC

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Abstract. The prospects for electroweak physics at the LHC are reviewed focusing mainly on precision studies. This includes projections for measurements of the effective Z pole weak mixing angle, \(\sin^2 \theta^\text{eff}_W\), of top quark, W boson, and Higgs scalar properties, and new physics searches.

PACS. 12.15.-y Electroweak interactions – 13.85.-t Hadron-induced high- and super-high-energy interactions

1 Introduction

The Large Hadron Collider (LHC) is well on its way to produce first collisions in 2007. Initial physics runs are scheduled for 2008 with several fb\(^{-1}\) of data and the precision program can be expected to take off in 2009. The low luminosity phase with about 10 fb\(^{-1}\) of data (corresponding to 150 million W bosons, 15 million Z bosons, and 11 million top quarks) per year and experiment \(1\) will already allow most precision studies to be performed. Some specific measurements, most notably competitive results on \(\sin^2 \theta^\text{eff}_W\), will probably have to wait for the high luminosity phase with \(\mathcal{O}(100\,\text{fb}^{-1})\) per year and experiment. The determination of the Higgs self-coupling would even call for a luminosity upgrade by another order of magnitude.

Good knowledge of the lepton and jet energy scales will be crucial. Initially these will be known to 1% and 10%, respectively, but with sufficient data one can use the Z boson mass for calibration, allowing 0.02% and 1% determinations. Furthermore, a 2% measurement of the luminosity and 60% b-tagging efficiency can be assumed. \(1\)

To give a point of reference, a combination of all currently available precision data yields for the Higgs mass,

\[M_H = 88^{+34}_{-26}\,\text{GeV},\]

and for the strong coupling, \(\alpha_s(M_Z) = 0.1216 \pm 0.0017\).

The fit value for the top quark mass, \(m_t = 172.5 \pm 2.3\,\text{GeV}\), is dominated by and coincides with the Tevatron combination \(2\). The \(\chi^2/\text{d.o.f.}\) at the minimum of the global fit is 47.4/42 with a probability for a larger \(\chi^2\) of 26%. The 90% CL range for \(M_H\) is 47 GeV < \(M_H\) < 146 GeV, where upon inclusion of direct search results from LEP 2 \(3\) the 95% CL upper limit increases to 185 GeV. Besides the notorious list of 1.5 to 3 \(\sigma\) deviations, the electroweak Standard Model (SM) remains in very good shape. One of the largest discrepancies is the NuTeV result \(4\) on deep inelastic neutrino scattering (\(\nu\)-DIS) which comes with several challenging theory issues \(5\).

When discussing future improvements for the key observables, \(m_t, \sin^2 \theta^\text{eff}_W\), and the W boson mass, \(M_W\), it is useful to keep some benchmark values in mind. An increase of \(M_H\) from 100 to 150 GeV (distinguishing between these values provides a rough discriminator between minimal supersymmetry and the SM) is equivalent to a change in \(M_W\) by \(\Delta M_W = -25\,\text{MeV}\). On the other hand, this 25 MeV decrease can be mimicked by \(\Delta m_t = -4\,\text{GeV}\), and also by an increase of the fine structure constant at the Z scale, \(\Delta \alpha(M_Z) = +0.0014\). We know \(\alpha(M_Z)\) an order of magnitude better than this — despite hadronic uncertainties in its relation to the fine structure constant in the Thomson limit. On the other hand, improving \(m_t\) will be important. The same shift in \(M_H\) is also equivalent to \(\Delta \sin^2 \theta^\text{eff}_W = +0.00021\), which in turn can be mimicked by \(\Delta m_t = -6.6\,\text{GeV}\) or by \(\Delta \alpha(M_Z) = +0.0006\). Once the Higgs boson has been discovered and its mass determined kinematically, these observables are then free to constrain heavy new particles which cannot be produced or detected directly. As an example serves the mass of the heavier top squark eigenstate in the minimal supersymmetric standard model at certain parameter values \(6\).

2 High precision measurements

LEP and SLC \(7\) almost completely dominate the current average Z pole weak mixing angle, \(\sin^2 \theta^\text{eff}_W = 0.23152 \pm 0.00016\). Via measurements of leptonic forward-backward (FB) asymmetries, the Tevatron Run II is expected to add another combined \(\pm0.0003\) determination \(8\), competitive with the most precise measurements from LEP (the FB asymmetry for \(b\bar{b}\) final states) and SLD (the initial state polarization asymmetry). Having \(p\bar{p}\) collisions are a crucial advantage here. At the LHC, by contrast, one has to focus on events with a kinematics suggesting that a

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valence quark was involved in the collision and which proton provided it (Z rapidity tag). This will be possible for a small fraction of events only, requiring high luminosity running. Furthermore, sufficient rapidity coverage of $|\eta| < 2.5$ will be necessary for even a modest $\pm 0.00066$ determination $^{9}$. Incidentally, a similar precision is expected from fixed target elastic proton scattering by the Qweak experiment $^{10}$ using the polarized electron beam at JLab. A breakthrough measurement at the LHC with an error as small as $\pm 0.00014$ $^{5,9}$ will require a much more challenging rapidity coverage of $|\eta| < 4.9$ for jets and missing transverse energy. Thus, it is presently unclear what the impact of the LHC on $\sin^2 \theta_W^{\text{eff}}$ will be. On the other hand, as has been covered at this meeting, there may be further opportunities at JLab after the 12 GeV upgrade of CEBAF in parity violating deep inelastic scattering (DIS-Parity) $^{11}$ building on the current 6 GeV DIS-Parity effort $^{12}$, and most notably, from an improved measurement of polarized Møller scattering (e2ePV) $^{13}$, reducing the error of the E 158 experiment at SLAC $^{14}$ by about a factor of four (see Fig. 1).

Our current knowledge regarding $M_W$ and $m_t$ is summarized in Fig. 2. The height of the uppermost (blue) ellipse is the average, $M_W = 80.410 \pm 0.032$ GeV, of final UA2 $^{15}$ and Tevatron Run I $^{16,17,18}$ results. With the exception of a less precise threshold determination at LEP 2, all these results are based on direct reconstruction$^{1}$. The other (green) 1 $\sigma$ ellipse is from all data excluding $M_W$ and the Tevatron $m_t$. Its elongated shape arises because one combination is tightly constrained by $\sin^2 \theta_W^{\text{eff}}$, while the orthogonal one is from less precise measurements including low energy ob-

\footnote{Frequently, $\nu$-DIS results are also represented as measurements of $M_W$, since this accounts to a good approximation for the $m_t$ dependence in the SM. This is, however, a coincidence and, in general, $\nu$-DIS is affected differently by new physics than $M_W$, and $\nu$ and $\bar{\nu}$ scattering actually provide two independent observables, although $\bar{\nu}$-DIS is usually less accurate.}
observables and the partial $Z$ decay width into $b\bar{b}$ pairs [7] (with a very different $m_t$ dependence than other neutral current observables). Fig. 2 demonstrates that the direct and indirect contours in the $M_W - m_t$ plane are consistent with each other and independently favor small Higgs masses, $M_H \lesssim 150$ GeV. All channels and experiments combined, the Tevatron Run II will likely add another ±30 MeV constraint. The huge number of $W$ bosons will enable the LHC to provide further ±30 MeV measurements per experiment and lepton channel ($e$ and $\mu$) for a combined ±15 MeV uncertainty (it is assumed here that the additional precision that can be gained by cut optimization is compensated approximately by common systematics). The measurements are limited by the lepton energy and momentum scales, but these can be controlled using leptonic $Z$ decays. With the even larger data samples of the high luminosity phase, one may alternatively consider the $W/Z$ transverse mass ratio, opening the avenue to a largely independent measurement with an error as low as ±10 MeV [8], for a combined uncertainty about three times smaller than our benchmark of ±25 MeV.

The total $W$ decay width, $\Gamma_W$, represents another observable of relevance to oblique parameters, but its sensitivity to new physics and its complementarity to and correlation with other quantities depends on how it is obtained. It can be extracted indirectly through measurements of cross section ratios,

$$\frac{\sigma(pp \to Z \to \ell^+\ell^-X)}{\sigma(pp \to W \to \ell\nu X)} \text{exp.} \times \frac{\sigma(pp \to W)}{\sigma(pp \to Z)}_\text{th.} \times \frac{\Gamma_{\text{SM}}(W \to \ell\nu)}{\mathcal{B}_{\text{LEP}}(Z \to \ell^+\ell^-)}.$$ 

(CDF currently quotes $\Gamma_W = 2.079 \pm 0.041$ GeV [21]) but the leptonic $W$ decay width has to be input from the SM. More interesting is therefore the direct method using
the tail of the transverse mass distribution. An average of final Tevatron Run I and preliminary DØ II [22] and LEP 2 [19] results gives, $\Gamma_W = 2.103 \pm 0.062$ GeV. The final Tevatron Run II is expected to contribute ±50 MeV measurements for each channel and experiment. Detailed studies for the LHC are not yet available, but historically the absolute error in $\Gamma_W$ at hadron colliders has traced roughly the one in $M_W$. If this trend carries over to the LHC, a ±0.5% error of $\Gamma_W$ may be in store.

Some Tevatron Run II results are already included in the current ±2.3 GeV [2] uncertainty in $m_t$, and with the expected total of 8 fb$^{-1}$ the error may decrease by another factor of two. The LHC is anticipated to contribute a ±1 GeV determination from the lepton plus jets channels alone [23]. The cleaner but lower statistics dilepton channels may provide another ±1.7 GeV determination, compared with ±3 GeV from the systematics limited all hadronic channel [28]. The combination of these channels (all dominated by the $b$ jet energy scale) would yield an error close to the additional irreducible theoretical uncertainty of ±0.6 GeV from the conversion from the pole mass (which is approximately what is being measured [24]) to a short distance mass (such as $M_{\text{MS}}$) which actually enters the loops. Folding this in, the grand total may give an error of about ±1 GeV, so that the parametric uncertainty from $m_t$ in the SM prediction for $M_W$ would be somewhat smaller than the anticipated experimental error in $M_W$.

### 3 Other electroweak physics

With 30 fb$^{-1}$ of data, the LHC will also be able to determine the CKM parameter, $V_{tb}$, in single top quark production to ±5% [25] (one expects ±9% from the Tevatron Run II although no single top events have been observed so far). Anomalous flavor changing neutral current decays, $t \rightarrow V q$ (where $V$ is a gluon, photon, or $Z$ boson, and $q \neq b$), can be searched for down to the $10^{-4}$ level [23]. This is a sensitivity gain by three orders of magnitude over current HERA bounds [26], and relevant, e.g. to extra $W'$ bosons. Measuring $t\bar{t}$ spin correlations at the 10% level [23] will allow to establish the top quark as a spin 1/2 particle, to study non-standard production mechanisms (e.g. through resonances), and to discriminate between $W^+b$ and charged Higgs ($H^+b$) decays.

If the Higgs boson exists, its production at the LHC will proceed primarily through gluon fusion, $gg \rightarrow H$, and/or vector boson fusion, $qq' \rightarrow Hqq'$. Higgs couplings
can generally be determined to $10 - 30\%$ \cite{8}. The top Yukawa coupling is best studied in associated production, $pp \rightarrow t\bar{t}H$, to $20 - 30\%$ precision \cite{24}. Most difficult proves the Higgs self-coupling, $\lambda$, whose measurement would need a luminosity upgrade. With $3 \text{ ab}^{-1}$ of data, $\lambda$ can be measured to $\pm 20\%$, for $150 \text{ GeV} < M_H < 200 \text{ GeV}$, while only $\pm 70\%$ precision would be possible for a lighter (and weaker coupled) Higgs boson \cite{8}.

The LHC is, of course, primarily a discovery machine with the outstanding task to find the Higgs boson or else to rule out its existence \cite{28}. As an example for a potential discovery beyond the SM, an extra $Z'$ ($W'$) boson would reveal itself through a high dilepton invariant ($\nu \ell Z$ transverse) mass peak. Current $Z'$ limits (which depend on the nature of the $Z'$) ranging from 650 to 850 GeV from CDF \cite{27} and from 434 GeV to 1.8 TeV from LEP 2 \cite{19} can be extended to 4.2–5 TeV with 100 fb$^{-1}$ of data, while 1 ab$^{-1}$ from an upgraded LHC would add another TeV to the reach \cite{24}.

In some cases one can turn things around and use electroweak physics to understand the LHC. For example, by computing $W$ and $Z$ cross sections and comparing them to LHC production rates one can extract the luminosity of the machine. This assumes knowledge of the relevant parton density functions (PDFs) which will probably be available with $\pm 2\%$ uncertainties reflecting the limitation of the method \cite{25}. In turn, one can obtain information on $u$ and $d$ quark PDFs by measuring the $W^\pm$ charge asymmetry, defined as the differential (with respect to the $e^\pm$ rapidity) cross section asymmetry \cite{8}.

4 Conclusions

The LHC is posed to achieve breakthrough discoveries in the electroweak symmetry breaking sector. As for precision measurements, one can expect particularly great improvements in $M_W$, while a competitive measurement of $sin^2\theta_W$ will be possible with large rapidity coverage only. Measurements of $m_t$, $f_W$, Yukawa and Higgs self-couplings will be performed and the top quark will be subjected to detailed studies.

At a meeting on parity violation these measurements should be put into context with low energy precision measurements which will remain important complements even with the LHC in operation. This is because (i) they are capable of contributing results on $sin^2\theta_W$ which can compete both with $Z$ pole factories and hadron colliders (see Fig. 1), (ii) they are subject to entirely different experimental and theoretical issues, and (iii) they are generally affected quite differently by beyond the SM physics.

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References

1. ATLAS Collaboration: P. Pralavorio et al., PoS HEP2005 (2006) 294.
2. Tevatron Electroweak Working Group and CDF and DØ Collaborations: E. Brubaker et al., e-print hep-ex/0503039
3. LEP Working Group for Higgs boson searches and ALEPH, DELPHI, L3, and OPAL Collaborations: R. Barate et al., Phys. Lett. B565 (2003) 61–75.
4. NuTeV Collaboration: G. P. Zeller et al., Phys. Rev. Lett. 88 (2002) 091802.
5. T. Londergran, these Proceedings.
6. J. Erler, S. Heinemeyer, W. Hollik, G. Weiglein, and P. M. Zerwas, Phys. Lett. B486 (2000) 125–133.
7. ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, LEP Electroweak Working Group and SLD Electroweak and Heavy Flavour Groups: S. Schael et al., Phys. Rept. 427 (2006) 257.
8. U. Baur, to appear in the Proceedings of the Hadron Collider Physics Symposium 2005 (HCP 2005), Les Diablerets, Switzerland, July 4–9, 2005, e-print hep-ph/0511064
9. W. Quayle, in the Proceedings of the 32nd International Conference on High-Energy Physics (ICHEP 04), Beijing, China, Aug 16–22, 2004, ed. H. Chen, D. Du, W. Li, and C. Lu (World Scientific, Hackensack 2005) Vol. 1, 531–534.
10. S. Page, these Proceedings.
11. P. Souder, these Proceedings.
12. X. Zheng, these Proceedings.
13. D. Mack, these Proceedings.
14. K. Kumar, these Proceedings.
15. UA2 Collaboration: J. Alitti et al., Phys. Lett. B276 (1992) 354–364.
16. CDF Collaboration: A. A. Affolder et al., Phys. Rev. D64 (2001) 052001.
17. DØ Collaboration: V. M. Abazov et al., Phys. Rev. D66 (2002) 012001.
18. CDF and DØ Collaborations: V. M. Abazov et al., Phys. Rev. D70 (2004) 092008.
19. ALEPH, DELPHI, L3, and OPAL Collaborations and LEP Electroweak Working Group: J. Alcaraz et al., e-print hep-ex/0511027
20. M. E. Peskin and T. Takeuchi, Phys. Rev. D46 (1992) 381–409.
21. CDF II Collaboration: D. Acosta et al., Phys. Rev. Lett. 94 (2005) 091803.
22. Tevatron Electroweak Working Group and CDF and DØ Collaborations: B. Amselmskas et al., e-print hep-ex/0510077
23. J. Womersley, PoS TOP2006 (2006) 038.
24. M. C. Smith and S. S. Willenbrock, Phys. Rev. Lett. 79 (1997) 3825–3828.
25. K. Mazumdar, AIP Conf. Proc. 792 (2005) 587–590.
26. ZEUS and H1 Collaborations: J. Ferrando et al., Eur. Phys. J. C33 (2004) S761–S763.
27. CDF Collaboration: A. Abulencia et al., Phys. Rev. Lett. 96 (2006) 211801.
28. M. Escaler, AIP Conf. Proc. 792 (2005) 623–626.
29. S. Godfrey, in the Proceedings of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), ed. N. Graf, eConf C010630 (2001) P344, e-print hep-ph/0201093.