SM Precision Constraints at the LHC/ILC

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Abstract. The prospects for electroweak precision physics at the LHC and the ILC are reviewed. This includes projections for measurements of the effective $Z$ pole weak mixing angle, $\sin^2 \theta_{\text{eff}}$, as well as top quark, $W$ boson, and Higgs scalar properties. The upcoming years may also see very precise determinations of $\sin^2 \theta_{\text{eff}}$ from lower energies.

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INTRODUCTION

Fig. 1 is a summary of current electroweak precision physics. It shows the constraints from different types of observables on the Higgs boson and top quark masses, $M_H$ and $m_t$. The most important input are the $Z$-pole asymmetries from LEP and SLC [1, 2], shown as the dotted (brown) lines. The long-dashed (blue) lines correspond to the $W$-boson mass, $M_W = 80.394 \pm 0.029$ GeV, from LEP 2 [2] ($e^+ e^-$), UA2 [3] and the Tevatron [4, 5] ($p \bar{p}$). It is interesting that other (non-asymmetry) $Z$-pole measurements by themselves result in a finite region in the $M_H$–$m_t$ plane, shown as the closed (green) contour. These three types of constraints overlap in a common region and at $m_t$ values consistent with the Tevatron average of kinematic mass measurements [6], $m_t = 171.4 \pm 2.1$ GeV. The only conflicting data set is from low energies (dashed contour), driven by the NuTeV result on deep inelastic neutrino scattering off approximately isoscalar nuclear targets [7] which shows a 2.7 $\sigma$ deviation in the effective four-Fermi coupling for neutrino interactions with left-handed quarks. The combination of all precision data yields the filled (red) ellipse. There is mounting evidence for a relatively light Higgs boson with much of the 90% C.L. ellipse already excluded by direct searches at LEP 2 [8]. Combining these search results with the precision constraints yields the histogram in Fig. 2. The strong peak is due to the significant excess of Higgs-like events observed by the ALEPH Collaboration [10]. Most of the probability is for $M_H$ values below 130 GeV, in perfect agreement with expectations from supersymmetric extensions of the Standard Model (SM). The 95% C.L. upper limit, $M_H \leq 178$ GeV, can also be read

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off from Fig. 2. In summary, the global fit to all data yields,

\begin{align}
M_H &= 84^{+32}_{-25} \text{ GeV}, \\
         &= 171.4 \pm 2.1 \text{ GeV}, \\
\alpha_s(M_Z) &= 0.1216 \pm 0.0017,
\end{align}

(1)

where the result for \(M_H\) is only barely consistent (within 1 \(\sigma\)) with the lower limit from LEP 2 \([8]\), \(M_H > 114.4\) GeV. Some observables show interesting deviations (at the 2–3 \(\sigma\) level) from the SM, but the overall goodness of the global fit is reasonable, with a \(\chi^2\) of 47.3 for 42 degrees of freedom and a probability for a larger \(\chi^2\) of 27%.

When discussing future improvements for the key observables, \(m_t\), \(\sin^2 \theta_{\text{eff}}^{W}\), and \(M_W\), 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 \(\Delta M_W = -25\) MeV. But this 25 MeV decrease can be mimicked by \(\Delta m_t = -4\) 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 \(\Delta m_t = -6.6\) GeV or by \(\Delta \alpha(M_Z) = +0.0006\). Thus, \(\sin^2 \theta_{\text{eff}}^{W}\) is more (less) sensitive to \(\alpha(M_Z)\) (\(m_t\)) compared to \(M_W\), demonstrating complementarity and underlining the general advantage of having a diverse portfolio of measurements at ones disposal. 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. An example is the mass of the heavier top squark in the minimal supersymmetric SM \([11]\).
The Large Hadron Collider (LHC) is well on its way to produce first collisions in 2007 [12]. 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 [13] 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 [13].

LEP and SLC [1] dominate the current average $\sin^2 \theta_{\text{eff}}^W = 0.23152 \pm 0.00016$. Via leptonic forward-backward (FB) asymmetries, the Tevatron Run II is expected to add another combined $\pm 0.0003$ determination [14], 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 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 [15]. A breakthrough measurement at the LHC with a statis-
tical error as small as $\pm 0.00014$ [14, 15] is ambitious and 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.

At hadron colliders $M_W$ is determined by kinematic reconstruction. All channels and experiments combined, the Tevatron Run II will likely add a $\pm 30$ MeV constraint to the world average. The huge number of $W$ bosons will enable the LHC to provide further $\pm 15$ MeV uncertainty (it is assumed here that the additional precision that can be gained by cut optimization is compensated approximately by common systematics). This kind of measurement is 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 $\pm 10$ MeV [14], for a combined uncertainty about three times smaller than our benchmark of $\pm 25$ MeV.

The sensitivity of the total $W$ decay width, $\Gamma_W$, 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,

$$
\Gamma_W^{\text{indirect}} = \left[ \frac{\sigma(pp \rightarrow Z \rightarrow \ell^+\ell^-) \sigma(pp \rightarrow W \rightarrow \nu X)}{\sigma(pp \rightarrow W \rightarrow \ell\nu X)} \right]_{\text{exp.}} \times \left[ \frac{\sigma(pp \rightarrow W)}{\sigma(pp \rightarrow Z)} \right]_{\text{th.}} \times \frac{\Gamma_{\text{SM}}(W \rightarrow \ell\nu)}{B_{\text{LEP}}(Z \rightarrow \ell^+\ell^-)},
$$

(CDF currently quotes $\Gamma_W = 2.079 \pm 0.041$ GeV [16]) but the leptonic $W$ decay width, $\Gamma_{\text{SM}}(W \rightarrow \ell\nu)$, 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 [17] and LEP 2 [2] results gives, $\Gamma_W = 2.103 \pm 0.062$ GeV. The final Tevatron Run II is expected to contribute $\pm 50$ 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 $\pm 0.5\%$ error in $\Gamma_W$ may be in store.

Some of the Tevatron Run II results are already included in the current $\pm 2.1$ GeV [6] uncertainty in $m_t$, and with the expected total of about 8 fb$^{-1}$ the error may decrease by another factor of two. The LHC is anticipated to contribute a $\pm 1$ GeV determination from the lepton + jets channels alone [18]. The cleaner but lower statistics dilepton channels may provide another $\pm 1.7$ GeV determination, compared with $\pm 3$ GeV from the systematics limited all hadronic channel [18]. 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 $\pm 0.6$ GeV from the conversion from the pole mass (which is approximately what is being measured [19]) to a short-distance mass (such as $\overline{\text{MS}}$) which actually enters the loops. Folding this in, the grand total may give an error of about $\pm 1$ 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 $M_W$.

With 30 fb$^{-1}$ the LHC will also be able to determine the CKM parameter, $V_{tb}$, in single
top quark production to $\pm 5\%$ [20] (one expects $\pm 9\%$ from the Tevatron). Anomalous flavor changing neutral current decays, $t \to Vq$ (where $V$ is a gluon, $\gamma$, or $Z$, and $q \neq b$), can be searched for down to the $10^{-4} - 10^{-5}$ level [18]. This sensitivity gain by three orders of magnitude over current HERA bounds [22], will be relevant, e.g., for extra $W'$ bosons. Measuring $t\bar{t}$ spin correlations at the $10\%$ level [18] will allow to establish the top 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, $gg \to H$, and/or vector boson fusion, $qq' \to Hqq'$. Higgs couplings can generally be determined to $10-30\%$ [14]. The top Yukawa coupling is best studied in associated production, $pp \to t\bar{t}H$, to $20-30\%$ precision [18]. Most difficult proves the Higgs self-coupling, $\lambda$, whose measurement would need a luminosity upgrade [23]. With $3 \text{ ab}^{-1}$, $\lambda$ 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 [14].

**ILC**

While the hadron colliders are primarily discovery machines with remarkable capabilities for precision studies, the $e^+e^-$ International Linear Collider (ILC) — if built — would be a precision machine par excellence. In its first phase of operation the ILC would operate at center of mass energies from about 200 GeV (the reach of LEP 2) to 500 GeV, which would allow to scan the top and $ZH$ threshold regions. An integrated luminosity of 500 fb$^{-1}$ is expected in the first 4 years of running. The baseline design includes an at least 80% polarized electron beam. The second phase foresees an energy upgrade to around 1 TeV and the collection of 1 ab$^{-1}$ of data in 3–4 years. A relative de-

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2 After the conclusion of this conference, there was an announcement by the DØ Collaboration [21] of the first evidence of single top quark production. This translates into the bound $|V_{tb}| > 0.68$ (95% C.L.).
TABLE 2. Results and future expectations for $\sin^2 \theta_W$. Based on $\sqrt{L}$-scaling as appropriate for statistics dominated measurements, the last column extrapolates the Tevatron Run I precision to future hadron colliders. GigaZ refers to two years of data taking with $\mathcal{O}(10^6)$ $Z$ bosons and is scaled from the LEP 1 precision. JLab refers to Qweak \[28\] (see next Section) and the 12 GeV Møller experiment \[27\]. $\sqrt{P}$-scaling from E-158 \[26\] (with $P$ the beam power) is used for Møller scattering at JLab and ILC.

| fb$^{-1}$ per experiment | experimental value | error/goal | $\sqrt{L}$-scaling |
|--------------------------|--------------------|------------|---------------------|
| Tevatron Run I           | 0.072              | 0.2238     | 0.0050              | —         |
| SLC                      | 0.05               | 0.23098    | 0.00026             | —         |
| LEP 1                    | 0.20               | 0.23187    | 0.00021             | —         |
| currently                |                    | 0.23152    | 0.00016             | —         |
| Tevatron Run IIA         | 2                  |            | 0.0008              | 0.0009    |
| Tevatron Run IIB         | 8                  |            | 0.0003              | 0.0005    |
| JLab                     | $e^+e^-$, $e^+p$   |            | 0.0003              | 0.00024   |
| LHC high luminosity      | 400                |            | 0.00014             | 0.00008   |
| ILC                      | Møller             |            | 0.00007             | 0.00007   |
| GigaZ                    | 140                |            | 0.000013            | 0.000016  |

Termination of the jet energy scale is expected to within $\pm 0.3/\sqrt{E}$, where $E$ is the center of mass energy in GeV. Heavy quark tagging will also be important and is anticipated with an efficiency at the 50–60% (30–40%) level for $b$ ($c$) quarks.

The ILC comes with a variety of add-on options. For example, one may want to run it in other collision modes such as $\gamma\gamma$, $e^+\gamma$, or $e^-e^-$. Most relevant for precision physics would be the GigaZ mode \[11\], which would allow to repeat the LEP 1 program with 20 million $Z$ bosons daily. The physics motivation for this option is very high. In particular, the world’s best measurements of $\sin^2 \theta_W$ \[1\] have been provided by SLD ($\pm 0.00029$) from the left-right cross section asymmetry, $A_{LR} = A_e$, and the LEP groups ($\pm 0.00028$) from the forward-backward asymmetry for $b$-quark final states, $A_{FB} = 3/4 A_e A_b$, where $\sin^2 \theta_W$ is extracted from $A_e$, and where $A_b$ is well-known within the SM. These two measurements contribute greatly to our current knowledge of $M_H$. However, they disagree from each other by 3.1 $\sigma$ and it is important to resolve this discrepancy. It is conceivably due to new physics effects in $A_b$. Assuming this, one can turn $A_{FB}$ into a measurement of $A_b$ (taking $A_e$ from other asymmetries) and combine this with a more direct measurement of $A_b$ from SLD \[1\]. The result, $A_b = 0.899 \pm 0.013$, deviates by 2.8 $\sigma$ from the SM prediction ($A_b = 0.935$). GigaZ with its ultra-high rates combined with polarized electrons (unlike LEP 1) would be able to determine $A_b$ to $\pm 0.001$! Similarly, a high precision $WW$ threshold scan with $\mathcal{O}(10^6)$ $W$-pairs (“MegaW”) would allow to study the $W$ boson with unprecedented precision. See Table \[1\] for a summary of $M_W$ measurements. The option of $e^+$ polarization ($\gtrsim 50\%$) would allow additional cross-checks (and thus reduction in systematic uncertainties) and to measure new kinds of asymmetries. For more details see, Refs. \[24, 25\].

Even without the GigaZ option, the ILC might provide an ultra-high precision measurement of the weak mixing angle (more precise than the current or foreseeable world average) in polarized fixed target Møller scattering. This may by then be a third generation experiment, building on the E-158 pioneering measurement at SLAC \[26\] (which used the 50 GeV SLC electron beam and achieved a precision of $\pm 0.0014$ in $\sin^2 \theta_W$),
TABLE 3. Results and future expectations for $m_t$. The last column extrapolates the Tevatron Run I precision assuming that sensitivities scale as in background dominated types of experiments. At hadron colliders, a $\pm 0.6$ GeV theory uncertainty has to be added.

| fb$^{-1}$ per experiment | value [GeV] | error/goal | $\sqrt{L}$-scaling |
|--------------------------|-------------|------------|-------------------|
| Tevatron Run I           | 0.11        | 178.0      | 4.3               | — |
| summer 2005              | 0.43        | 172.7      | 2.9               | 3.1 |
| currently                | 1           | 171.4      | 2.1               | 2.5 |
| Tevatron Run IIA         | 2           | 172.7      | 2.0               | 2.1 |
| Tevatron Run IIB         | 8           | 172.7      | 1.2               | 1.5 |
| LHC low luminosity       | 10          | 172.7      | 0.9               | 1.4 |
| LHC high luminosity      | 400         | 172.7      | 0.7               | 0.6 |
| ILC                      | 300         | 172.7      | 0.1               | — |

and a potential effort (e2ePV [27]) at JLab (after the 12 GeV upgrade of CEBAF) with an anticipated error reduction by a factor of five. The ILC would then improve on JLab by an additional factor of four. Table 2 summarizes future prospects for $\sin^2 \theta_W$.

Spectacular improvements (see Table 3) would be possible for $m_t$, because the aforementioned short-distance mass can be extracted directly from the top threshold scan. Higgs production at the ILC would dominantly proceed through Higgs-strahlung, $e^+e^- \rightarrow ZH \rightarrow e^+e^-H (\mu^+\mu^-H)$. Associated production, $e^+e^- \rightarrow t\bar{t}H$, will be important for measurements of the top Yukawa coupling. It will be possible to determine the Higgs couplings $Hb\bar{b}, Ht\bar{t}, H\tau^+\tau^-, HW^+W^-$, and $HZZ$ to high precision, while the $Hc\bar{c}$ will be less precise. The self-coupling $\lambda$ can be obtained to $\pm 20\%$ (for $M_H = 120$ GeV) by using, e.g., the process $e^+e^- \rightarrow ZHH$. The total Higgs width would be known to 5%.

PERSPECTIVE: LOW ENERGY PRECISION MEASUREMENTS

Fixed-target Møller scattering was already mentioned above, both at high and relatively low energy, but all at very low momentum transfer, $\sqrt{Q^2} = \mathcal{O}(100$ MeV). A similar low-$Q^2$ experiment in elastic $e^-p$ scattering at JLab will determine the so-called weak charge of the proton, $Q^p_W$. With an expected polarization of $85 \pm 1\%$ the Qweak Collaboration [28] anticipates to measure the parity violating asymmetry, $A_{PV} \propto (Q^2 Q^p_W + Q^4 B)$. The $Q^4 B$ term is the leading form factor contribution and will be determined experimentally. The anticipated errors in $Q^p_W$ and the corresponding $\sin^2 \theta_W$ are $\pm 0.003$ and $\pm 0.0007$, respectively (for the calculation of the SM prediction, see Refs. [29, 30]).

One can also explore the kinematic regimes of quasi-elastic (QE) and deep inelastic scattering (DIS). The discrepancy in $\nu$-DIS (NuTeV [7]) has already been mentioned. The interpretation of the experiment is hampered, however, by a variety of theoretical issues. An $eD$-DIS experiment is approved at JLab [31] to use the current 6 GeV CEBAF beam and to repeat the historical SLAC experiment [32] with greater precision. One hopes to be able to collect additional data points after the 12 GeV CEBAF upgrade [33]. This would improve the SLAC result and the current world average on the combination of effective four-Fermi quark-lepton couplings $2C_{2u} - C_{2d}$ by factors of 54 and 17, respectively. The issues to be addressed are higher twist effects and charge symmetry
violating (CSV) parton distribution functions. Since higher twist effects are strongly $Q^2$ dependent and CSV should vary with the kinematic variable, $x$, while contributions from beyond the SM would be kinematics independent, one can separate all these possible effects by measuring a large array of data points. Thus, a great deal can be learned about the strong and weak interactions at the same time.

Determinations of $\sin^2 \theta_W$ from $\nu_e$-scattering are not competitive at present ($\pm 0.008$), but may be another future direction, in particular if $\beta$-beams or a $\nu_\mu$-factory became available with well-known $\nu$-flavor compositions and energy spectra. For example, a $\nu_e (\bar{\nu}_e)$ $\beta$-beam could provide a determination of $\sin^2 \theta_W$ to $\pm 0.0008$ ($\pm 0.0005$) [34], while a $\nu_\mu (\bar{\nu}_\mu)$ factory could achieve a precision of $\pm 0.0001$ ($\pm 0.0003$) [34]. Other electroweak measurements may also be possible at these facilities with high precision.

It should be stressed that these and other low energy tests of the SM (including leptonic anomalous magnetic moments, atomic parity violation, and many SM forbidden or highly suppressed processes) will remain very important even in the LHC era and beyond, because they are not only competitive with but also complementary to high energy experiments. The complementarity refers to experimental uncertainties, as well as to theoretical issues, and the way new physics may enter. Low energy experiments may also play a prominent role in deciphering what may be discovered at the energy frontier, even if no significant SM deviations are seen at low energies.

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