Prospects for Precise Electroweak Physics at the LHC

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In addition to its discovery potential, the LHC offers unique possibilities for precise measurements in the electroweak sector. In the present note, results of several electroweak analyses are presented; measurements of the top quark and $W$ boson masses, triple gauge couplings as well as forward-backward asymmetry measurements. All electroweak measurements at the LHC benefit from large cross sections due to the high CM energy, which combined with the high expected luminosities gives rise to very large data samples.

1 Introduction

Since the masses of the top quark, of the $W$ boson and of the Higgs bosons are related through loop corrections, precise measurements of the top quark and of the $W$ boson masses allow to put constraint on the Higgs boson mass, both within the Standard Model and in SUSY extensions [2]. Thus, regardless of the results of the direct Higgs search, a precise determination of the $W$ boson and top quark masses is of paramount importance, and below methods are presented aiming to perform these measurements to the highest possible precision with the ATLAS and CMS experiments.

All presented results are based on simulations with 14 TeV center of mass energy, although the energy at LHC start-up will be lower. The analyses presented here assume a well understood and calibrated detector, and should be considered as prospects of what one can expect to measure on a long timescale.

2 Top quark mass measurement

The production cross-section of the top quark pairs at the LHC is 833 pb at NLO [3]. It is dominated by gluon scattering (90%). This means that the LHC can be considered a top quark factory, with more that 800,000 top quark pairs produced per fb$^{-1}$. Once produced, the top quark decays dominantly into a $b$ quark and a $W$ boson. The final state topologies of $t\bar{t}$ events are defined by the $W$ bosons decays. The following experimental signatures can be identified:

- **Fully leptonic events**, where both $W$ bosons decay into a lepton-neutrino pair (resulting in an event with two charged leptons, two neutrinos and two $b$-jets).
- **Fully hadronic events**, where both $W$ bosons decay hadronically, which gives at least six jets in the event).
- **Semi-leptonic events**, where one of the $W$ bosons decay leptonically and the other hadronically. The presence of a single high $p_T$ lepton allows to suppress the Standard Model $W$+jets and QCD background.

In the following, the focus is put on the semi-leptonic channel, whereas results from the fully hadronic and fully leptonic channels can be found in [4].

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2.1 Semi-leptonic channel

In the ATLAS analysis presented in [5] several methods to reconstruct the top quark were studied - here only the $\chi^2$ method is described. With this method, the signal selection proceeds as follows. Exactly one isolated lepton: $|\eta| < 2.5$, $p_T^\ell > 25$ GeV, $p_T^{\ell}\ell > 20$ GeV, missing $E_T > 20$ GeV, at least 4 jets with $p_T > 40$ GeV - two of which are $b$-tagged. Since only the mass of the hadronic decaying top quark is reconstructed, the main systematics are expected to be related to the jet energy scale (JES). In order to minimize the systematic error due to the uncertainty on the JES, the jets are calibrated \textit{in situ} by minimizing the following $\chi^2$ for each jet pair:

$$\chi^2 = \frac{(M_{jj}(\alpha_E^1, \alpha_E^2) - M_{PDG}^W)^2}{(\Gamma_{PDG}^W)^2} + \frac{(E_{jj}(1 - \alpha_E^1))^2}{\sigma_j^2} + \frac{(E_{jj}(1 - \alpha_E^2))^2}{\sigma_j^2},$$

where $\alpha_E^i$ are the individual scale factors of the jet energies $E_{jj}$, which have resolutions $\sigma_j$. After a cut around the $W$ boson mass of $\pm 2\Gamma_{PDG}^W = 4.2$ GeV [6], the final signal corresponding to a data sample of 1 fb$^{-1}$ is shown in Figure 1.

Table 1: Systematic uncertainties in the semi-leptonic top quark mass measurement.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Effect on $m_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.2 GeV/%</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>0.7 GeV/%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\approx 0.3$ GeV</td>
</tr>
<tr>
<td>$b$ quark fragmentation</td>
<td>$\leq 0.1$ GeV</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>negligible</td>
</tr>
</tbody>
</table>

As mentioned above, the main contributions to the systematic uncertainties come from miscalibrations of the reconstructed light and $b$-jets energies. To study the impact of JES on the top quark mass measurement, the light jet and $b$-jet momenta are varied separately applying scaling factors. The resulting top quark mass is found to depend linearly on the scaling factors, with the $b$-jet scale having the larger impact as shown in Table 1.

Ultimately, the $b$-jet scale will be measured in $Z+b$ jet events, but initially this data sample will have too limited statistics, and one is forced to derive the $b$-jet scale from the light scale applying a MC correction.

The systematic error from ISR/FSR radiation has been estimated from shifts in the top quark mass in AcerMC $t\bar{t}$ samples with varying ISR/FSR parameters, whereas the uncertainty due to $b$ quark fragmentation is estimated by varying the Peterson factor within its uncertainty. Finally, the background shape will be measured from data, but the selection criteria ensures that the contribution is low, and variations in the size have no notable effect on the mass measurement.

A precision of the order of 1 to 3.5 GeV should be achievable with 1 fb$^{-1}$, assuming a jet energy scale uncertainty of 1 to 5%.

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3 W boson mass measurement

A precise measurement of the W boson mass is important to constrain the mass of the Higgs boson in the Standard Model. As in the case of the top quark mass analysis, the LHC experiments expect to collect a significantly larger W boson data sample due to an increase in production cross-section combined with expected higher luminosities. For the final measurement, a data set of $10 \text{ fb}^{-1}$ is used, containing about 60 million reconstructed W bosons in the electron and muon channels. Moreover a Z boson sample about an order of magnitude smaller will be collected, and this is of great importance for the W boson mass measurement, since the large Z boson sample allows very precise calibration of e.g. lepton energy scale from the precisely known Z boson properties. Below an introduction to the W boson mass measurements at the ATLAS experiment is presented [5], whereas a corresponding study from the CMS experiment is available in [7].

Once produced the W bosons decay either hadronically, which is not useful for precision measurements, or democratically into the 3 lepton flavours. Due to the presence of additional neutrinos in the $\tau$ decay, this channel is excluded from precision measurements. Since the longitudinal momenta of the participating quarks are unknown, only the transverse W boson mass, $M_W^{\perp}$, can be reconstructed. This quantity is sensitive to the W boson mass through a Jacobian peak. Also sensitive to $M_W$ is the transverse lepton momentum, $p_T^l$, which has the advantage compared to $M_W^{\perp}$ of being less sensitive to detector resolution, but on the other hand more sensitive to the boson $p_T$. Thus one can benefit from measuring the W boson mass using both distributions, since their systematics will differ.

In both cases, the extraction of the W boson mass proceeds through a template method: Templates of e.g. $p_T^l$ distributions are produced with varying W boson mass, and compared to the distribution in data. Since no analytical function is able to satisfactorily describe the $p_T^l$ distributions, the comparison between data and templates proceeds through a bin-by-bin $\chi^2$ test, which has the advantage of not only providing the mass of the W boson giving the best fit, but also the corresponding error. In the absence of real data, the method is developed using Z and W boson MC samples, the point being to develop a technique in which the detector resolution, linearity etc is measured using the precisely reconstructed Z boson events and used afterwards on the W boson events.

In order to apply this approach, it must first be verified that the fitting techniques works (i.e. does not introduce a bias to the W boson mass measurements), and that the results found in Z boson events can be ported to W events without introducing a bias. To accomplish this, the ratio between the reconstructed and true energy is fitted in bins of $(\eta, p_T^l)$ for both W and Z bosons. Next, the generator level kinematics is smeared using the parameters of the fits to validate the unbiasedness of the method. An example of this is

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Calibration of the detector response. The plots shows the good agreement between the best fit of the smeared/scaled detector response to the full reconstruction.}
\end{figure}
shown in Figure 2 for $W$ boson events.

Finally, the detector smearing functions measured for $Z$ boson events, are applied to the generator level kinematics of $W$ boson events, resulting in the $p_T$ distribution shown in Figure 3. From the $\chi^2$ distributions corresponding to the comparison of the two histograms in this figure, the resulting $W$ boson mass can be extracted: $M_W = 80.466 \pm 110(stat) \pm 114(exp) \pm 25(PDF)$ MeV for a simulated data sample corresponding to 15 pb$^{-1}$.

In order to estimate the final systematic errors from detector scale and resolution, the measurements of the relative scale ($\delta\alpha$) and resolution ($\delta\sigma$) of Figure 2 are scaled to 10 fb$^{-1}$:

$$
\delta M(\alpha) = \frac{\delta\alpha}{\alpha} \cdot \frac{\partial M}{\partial \sigma_{rel}} \sqrt{\frac{L_{sample}}{L_{final}}} = 0.0003 \cdot 0.9952 \cdot \frac{800\text{ MeV/}\% \cdot \sqrt{200\text{ pb}^{-1}}}{10\text{ fb}^{-1}} \approx 4\text{ MeV} \quad (1)
$$

$$
\delta M(\sigma) = \frac{\delta\sigma}{\sigma} \cdot \frac{\partial M}{\partial \sigma_{rel}} \sqrt{\frac{L_{sample}}{L_{final}}} = 0.0003 \cdot 0.0207 \cdot \frac{0.8\text{ MeV/}\% \cdot \sqrt{200\text{ pb}^{-1}}}{10\text{ fb}^{-1}} \approx 1\text{ MeV} \quad (2)
$$

Note that the above naive scaling assumes an energy independent calibration of the detector scale and resolution, which is perhaps unambitious.

The template technique have been used to evaluate all the systematics, which are expected to affect the $W$ boson mass measurement. In several cases, present knowledge in the pre-data taking period prevents the evaluation of the errors with good certainty. For example, naively varying the parton density functions within their uncertainty suggests an error on the $W$ boson mass of the order of 25 MeV. However, using the fact that the PDF for $W$ and $Z$ bosons are strongly correlated combined with the expected increase in the PDF precision possible with the LHC, it should be feasible to reduce this error, see Ref. [8] for details.

Similar arguments holds for the systematic error due to uncertainties in the $W$ boson $p_T$ spectrum. For FSR the existence of generators with significantly higher precision than what currently exists are expected. In summary, the study of the systematic sources affecting the $W$ boson mass measurement, have not yet revealed any reason why the error on the $W$ boson mass would not be significantly reduced compared to the present world average with LHC measurements.

4 Triple Gauge Couplings

Another important test of the Standard Model is the measurements of the Triple Gauge Couplings (TGC). At the LHC, the cross-sections for these processes are typically an order of magnitude larger than at the Tevatron. Tens to hundreds of events are expected in the various channels within the first fb$^{-1}$.

Apart from measuring the Standard Model allowed charged TGC cross-sections ($WWZ$, $WW\gamma$), one can search for neutral TGC ($ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$) which are not allowed in the Standard Model at tree level. Descriptions of neutral TGC studies can be found in [5].
An example from the CMS experiment of a study of charged TGC using the $WZ$ channel is described in this section.

To select $Z$ bosons, the invariant mass of all $ee$ and $\mu\mu$ pairs is reconstructed and required to be in the range: $50 \text{ GeV} < M_{ll} < 120 \text{ GeV}$ - additional $Z$ boson candidates are vetoed. Next, a third lepton is associated with the $W$ boson decay, and a neutrino is selected indirectly by requiring missing transverse energy such that the transverse $W$ boson mass exceeds 50 GeV. The information from the $Z$ boson mass peak and from the $W$ boson transverse mass are then combined and this allows to evaluate the discovery potential. It is concluded that a $5\sigma$ observation is possible with a data set of $350 \text{ pb}^{-1}$. Additional studies show that observation of all Standard Model di-boson processes should be possible with less than $1 \text{ fb}^{-1}$ [9].

5 Forward Backward Asymmetry

In $pp \rightarrow Z/\gamma \rightarrow ll$ events, electroweak neutral current violates parity and lead to an asymmetry in the polar emission angle of the lepton in the di-lepton rest-frame. This asymmetry is called the forward-backward asymmetry, $A_{FB}$, and is inferred from the measured angular distributions through the relation:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta} = \frac{3}{8} N_c [1 + \frac{4}{3} A_{FB} \cos\theta + \cos^2\theta]$$

where $\theta$ is the angle between the negatively charged lepton and the momentum vector of the quark in the di-lepton system. In order to perform the measurement, one must know, which was the initial direction of the quark and of the anti-quark forming the $Z/\gamma$. Since, at the LHC the initial quark direction is not known with certainty, the assumption is made that the quark direction equals that of the $Z$ boson boost. Monte Carlo studies show that this assumption is more likely to be correct at large di-lepton rapidities. This is one of the reasons that the analysis is performed with electrons rather than with muons since the calorimeter coverage extends to larger $\eta$ values than the muon systems (both in ATLAS and in CMS). From the measurement of $A_{FB}$, a measurement of the weak mixing angle can be inferred using assumptions on the PDF. Conversely, the measurement of $A_{FB}$ can be used to constrain the PDF sets. The final precision expected with $100 \text{ fb}^{-1}$ of data is of the order $10^{-4}$ in the weak mixing angle, with a systematic error of the same order of magnitude [5]. The prospects are that the LHC experiments will be competitive with current available experiments, in what concerns the weak mixing angle measurement.

References

[1] Slides: http://indico.cern.ch/contributionDisplay.py?contribId=38&sessionId=2&confId=53294