ELECTROWEAK PHYSICS AT THE LHC

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The ATLAS and CMS experiments at the LHC have vast potential for electroweak measurements and the 14 TeV center-of-mass energy will in addition allow new regimes of electroweak phenomena to be explored. The extreme brightness (luminosity) of the LHC beam crossings will allow substantial improvements in the measurement of the mass of the top quark and the W boson. A significant improvement in the determination of the coupling in three vector boson vertices will be possible; it will also be possible to make a rough measurement of the Higgs boson couplings once the Higgs is observed. Measurements of the forward-backward asymmetry in $Z \to ee$ decays will provide competitive measurements of the Weinberg angle.

Tests of dynamical symmetry breaking will be made from studies of vector boson scattering at high energies; these tests are feasible thanks to the forward jet tagging capabilities of ATLAS and CMS. Electroweak single-top production will allow a new direct measurement of V_{tb} and of the top polarisation.

1 Introduction

The Large Hadron Collider (LHC), slated to begin operation in 2007, will collide protons at a center-of-mass energy of 14 TeV. Its design luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ will allow it to produce particles such as top quarks and W and Z bosons so copiously that many precision measurements will be limited by systematic rather than statistical errors. Two general-purpose detectors, ATLAS[1] and CMS[2], will study these collisions in order to shed light on the physics of the top quark, understand the nature of Electroweak Symmetry Breaking, and search for signs of physics beyond the Standard Model. Here, we focus on the prospects for electroweak physics at these detectors.

2 Higgs Mass Constraints

The standard model predicts the following relationship among several of its parameters[3]:

$$M_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}\frac{1}{\sin\theta_W\sqrt{1-\Delta R}} \qquad (1)$$

where M_W is the mass of the W boson, α is the QED fine structure constant, G_F is the Fermi coupling constant, θ_W is the Weinberg angle, and ΔR is a term dependent on radiative corrections. ΔR depends on the top quark mass, M_t, and the Higgs boson mass, M_H, as M_t^2 and $\log(M_H)$, respectively.

Equation 1 is often used to put limits on the Higgs mass in the Standard Model. The parameters α and G_F are known to very high precision[4], so the constraint on the Higgs mass can be improved most by measuring M_W, M_t, and θ_W to higher precision. With the precision measurements of these parameters that will be performed at LHC, it is expected that the Higgs mass will be constrained to within 30% of its nominal value.[5]

2.1 Measurement of M_W

To achieve equal weights in a χ^2 test, it is necessary for the error on the W mass, ΔM_W, to be about 0.7% of the error on the measurement of the top mass, ΔM_t. This means that if the top mass is measured to a precision better than 2 GeV, then it is desirable to know the W mass to a precision of better than 15 MeV. By contrast, the expected error on the W mass after Tevatron Run II is roughly 30 MeV; this provides a strong incentive for LHC to improve the error on the W mass measurement. At hadron colliders, the

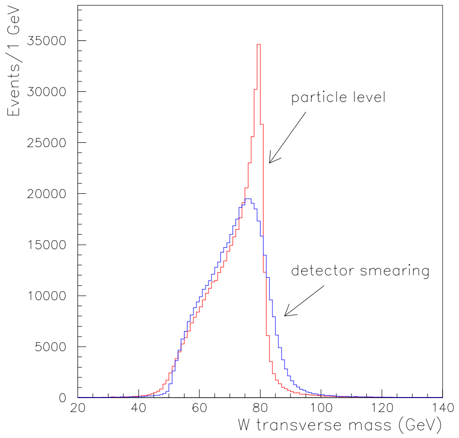

Figure 1. The transverse mass of the W. The red curve is the distribution at the particle level, and the blue curve is the distribution after detector smearing is applied. The edge at roughly the 80 GeV is sensitive to the W mass.

W mass measurement is typically performed by exploiting the M_W dependence of the peak in the W transverse mass (M_T) spectrum, shown in Figure 1 (reproduced from the ATLAS Technical Design Report[1].) The procedure involves generating an expected M_T distribution for each of several different values of the W mass and performing a fit to extract the W mass. We expect that one detector exploiting one decay mode of the W will be able to achieve a mass resolution of 25 MeV, one detector combining both the e and μ channels will be able to achieve a mass resolution of 20 MeV, and both detectors working together will reduce this figure to 15 MeV. We note that this method will only work well at low luminosity ($10^{33}\text{cm}^{-2}\text{s}^{-1}$), as pile-up events will smear the transverse mass distribution considerably. However, with the large cross-section (30 nb) for single W production at LHC, statistical errors on this measurement will be small during low-luminosity running.

2.2 Measurement of $\sin^2\theta_W$

The extraction of the weak mixing angle at LHC is performed by measuring the forward-backward asymmetry in $Z/\gamma^* \to l^+l^-$ production. The forward-backward asymmetry measurement is possible at a proton-proton collider because the valence quarks in the proton tend to carry slightly more momentum that sea quarks. Hence, the Z boson (produced by the annihilation of a quark with an antiquark) tends to be produced with a boost relative to the lab frame; by tagging the direction of the Z boson, one can make a reasonable guess at which beam produced the quark and which produced the antiquark. The forward-backward asymmetry A_{fb} is related to the effective leptonic weak mixing angle $\sin^2\theta^{lep}_{eff}$ by the relation

$$A_{fb} = a(b - \sin^2\theta^{lep}_{eff}) \tag{2}$$

where a and b are parameters that are given by the theory[6]. The angle θ^{lep}_{eff} is related to the true mixing angle θ_W by radiative corrections[7]. If one of the two electrons from $Z \to e^+e^-$ decays is allowed to have $|\eta| > 2.5$ and can be tagged with a jet rejection of about 100 in the forward region, then it is expected that one detector at LHC will be able to measure $\sin^2\theta^{lep}_{eff}$ with a statistical error of 0.00014.

2.3 Measurement of M_t

There are several ways to extract the top mass at LHC; the most promising analysis is based on the decay mode $pp \to t\bar{t} \to l\nu b + jjb$. LHC can measure the top mass to a precision of roughly 1 GeV [8,9]. We note in passing that studies of the ATLAS and CMS sensitivities to Electroweak single-top production have also been performed.[1,10].

3 Coupling Measurements

In this section, we discuss coupling measurements as a means to test the Standard Model at LHC.

Detector	Bounds
ATLAS (30 fb^{-1})	$-0.0035 < \lambda_\gamma < 0.0035$ $-0.0073 < \lambda_Z < 0.0073$ $-0.075 < \Delta\kappa_\gamma < 0.076$ $-0.11 < \Delta\kappa_Z < 0.12$ $-0.0086 < \Delta g_Z^1 < 0.011$
CMS (100 fb^{-1})	$-0.034 < \Delta\kappa_\gamma < 0.052$ $-0.0021 < \lambda_\gamma < 0.0018$

Table 1. The expected precision on the measurements of several of the triple gauge coupling parameters at ATLAS and CMS. The results for CMS assume a form-factor scale $\Lambda = 10$ TeV, while the ATLAS results take $\Lambda \to \infty$. Both studies take systematic errors into account.

3.1 Triple Gauge Coupling Measurements

In the Standard Model, the structure of interactions among gauge bosons is exactly determined, as these interactions directly reflect the gauge structure of the theory. Hence, any deviation from the predicted values could indicate new physics. As an example, we consider the $WW\gamma$ and WWZ vertices.[11,12,13] Together, the most general lorentz-invariant forms of these vertices that conserve parity and charge separatey are described by five parameters: κ_γ, κ_Z, λ_γ, λ_Z, and g_Z^1. By examining $W\gamma$ and WZ events, one can test for a deviation of these parameters from their Standard Model values. Studies have been performed within the context of the ATLAS and CMS detectors to assess the LHC sensitivity to the Triple Gauge Couplings; the resuts are presented in Table 1.

3.2 Higgs Coupling Measurements

The Standard Model predicts the strengths of the couplings of the Higgs to the massive particles; alternative models of the Symmetry Breaking sector often lead to couplings which are enhanced or supressed relative to their Standard Model values. At the LHC, it is possible to perform rough measurements of some of the Higgs couplings. In order to extract an estimate of the Higgs coupling to a given particle, one must assume that there is only one Higgs close to the measured value of M_H, that it is both CP-even and spin-0, that only known particles couple to it, and that the sum of all visible branching ratios agrees with the Standard Model prediction. Details about how necessary these assumptions are, what channels are considered in the measurement of the couplings, and the accuracy of these measurements are available in a recent study from ATLAS[14]; here, we simply state the result that ratios of couplings can be measured with one detector to an accuracy typically better than 60% (and in some cases as good as 10%), while absolute couplings can be measured to an accuracy typically better than 80% (and in some cases as good as 10%).

4 Vector Boson Scattering

Ultimately, the most general way to understand the Electroweak symmetry breaking sector is to study Vector Boson Scattering. This process, depicted in Figure 2, occurs when a pair of weak bosons ($W^\pm$ or Z) radiated from the incident quarks scatter off each other to produce a final state consisting of two weak bosons plus two hard (and often forward) jets arising from the struck quarks. In the event that there is no Higgs-like resonance of the kind often considered in searches for Standard Model Higgs bosons, it may be the case that the interactions of the longitudinal components of the $W^\pm$ and Z are enhanced by strong interactions at high energies. This motivates searches for a number of distinctive signatures: $W^+W^- + 2j$ and $Z^0Z^0 + 2j$, which have been studied in the context of Standard Model Higgs searches, as well as $W^\pm Z^0 + 2j$ and like-sign $W^\pm W^\pm + 2j$ production, which we discuss here. A study performed in the context of the ATLAS detector[15] examined Vector Boson Scattering in these final states for a Chiral Lagrangian scenario; some of the results are summarized

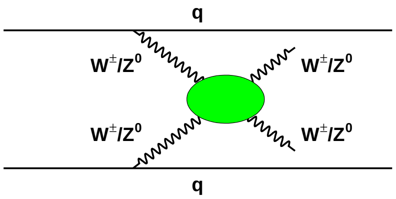

Figure 2. Vector boson scattering. The shaded region represents any interaction among the vector bosons.

Channel	Process	Evt. Rate
$W_L Z_L$	Signal	7.3
	$Zt\bar{t}$	15
	$W_T Z_T$	10.8
$W_L W_L$	Signal	4.6
	$W_T W_T$	14
	Double Brehm.	0
	$Wt\bar{t}$	0
	WZ	0.3

Table 2. Expected numbers of events for signal and various backgrounds after 500 fb^{-1} at ATLAS in the WZ and like-sign WW Vector Boson Scattering channels.

in Table 2. These results indicate that, while it is possible to study Vector Boson Scattering in the WZ and same-sign WW channels in some scenarios, it could be quite challenging and may require input from both the ATLAS and CMS detectors.

5 Summary

The LHC has tremendous potential to test the predictions of the Standard Model. Precision measurements of M_W, M_t, and the Weinberg angle at the LHC will constrain the Higgs mass to within 30% of its nominal value. The triple gauge boson couplings can be measured with very high precision. If the Higgs is discovered, its couplings can be extracted as well; Vector Boson Scattering searches will provide insight into the nature of the Electroweak symmetry breaking sector in the event that there is no Higgs resonance.

References

1. ATLAS Detector and Physics Performance, CERN/LHCC 99-15 (1999)
2. G. L. Bayatin *et al.*, CMS Technical Proposal, CERN/LHCC 94-38x (1994)
3. G. Altarelli, R.Kleiss, C. Verzegnassi eds., CERN report 89-08 (1989), and the references therein.
4. S. Eidelmann *et al.*, Phys. Lett. **B592** (2004)
5. U. Baur, hep-ph/0304266 (2003), and the references contained therein.
6. K. Sliwa, S. Riley, and U. Baur, ATLAS internal note ATL-PHYS-2000-018, and the references therein.
7. For a recent discussion of the relationship between the Weak mixing angle and $\sin^2\theta^{lep}_{eff}$, see, for example, A. Ferroglia *et al.*, Eur. Phys. J. C34(2004)165-171
8. I. Boranjovic *et al.*, ATLAS Scientific note SN-ATLAS-2004-040
9. L. Sonnenschein, CMS Internal note CMS-NOTE-2001-001
10. D. Green *et al.*, CMS Internal note CMS-NOTE-1999-048
11. M. Dobbs and M. Lefebvre, ATLAS Internal note ATL-PHYS-2002-022
12. M. Dobbs and M. Lefebvre, ATLAS Internal note ATL-PHYS-2002-023
13. Th. Müller, D. Neuberger, and W. H. Thümmel, CMS Internal note CMS-NOTE-2000-017. An slightly newer estimate of the Triple Gauge coupling limits is available in C. K. Mackay and P. R. Hobson, CMS Internal note CMS-NOTE-2001-056, but because Mackay and Hobson take $\Lambda = 2$ TeV, it is difficult to compare their results with the results of the corresponding ATLAS study.
14. M. Dührssen, ATLAS Internal note ATL-PHYS-2003-030
15. G. Azuelos, R. Mazini, and K. Strahl, ATLAS Internal note ATL-PHYS-99-023