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Electroweak physics and the top quark mass at the large hadron collider

Catherine Mackay

University of Bristol, Bristol, UK

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Abstract. The Large Hadron Collider will allow electroweak studies to be performed in as yet unexplored kinematic regions. The collider constraints on the Standard Model parameters (W boson mass, top quark mass and hence the uncertainty on the Higgs boson mass) are presented. Single top quark production, which provides a direct measurement of the CKM matrix element V_{tb}, is described. Studies of triple gauge boson couplings are also presented.

1 Introduction

The Large Hadron Collider (LHC) presently under construction at CERN is designed to collide protons at a centre-of-mass energy of 14 TeV and a luminosity of 10^{34} cm^{-2} s^{-1}. The detectors, A Large Toroidal LHC ApparatuS (ATLAS) [1] and the Compact Muon Solenoid (CMS) [2], are both general purpose 4π detectors.

The interaction region of the ATLAS experiment is surrounded by silicon pixel and silicon strip detectors. Behind is a transition radiation detector, based on straw detectors. A 2 T solenoid is located outside the tracker, in front of the calorimetry. The calorimetry comprises a finely segmented lead-and-liquid-argon sampling electromagnetic calorimeter and a hadron calorimeter of plastic scintillator tiles embedded in iron. The magnet is instrumented with separate trigger and high precision tracking chambers for muons.

The interaction region of the CMS experiment is surrounded by an inner tracking system of microstrip and pixel detectors. The calorimetry consists of a finely segmented lead-tungstate electromagnetic calorimeter and a hadron calorimeter of plastic scintillator tiles inserted between copper absorber plates. Outside the calorimetry is the 4 T superconducting solenoid coupled with a multilayer muon system. The muon spectrometer comprises drift tubes, cathode strip chambers and resistive plate chambers.

2 The W boson mass

To date, the W boson mass is known with a precision of ± 34 MeV/c^2 [3] from measurements at LEP2 and the Tevatron. Improvements on the W boson mass measurement also provide improvements on the Higgs boson mass. The W boson mass is one of the parameters of the Standard Model and is related to other parameters in the theory (the QED fine structure constant α, the Fermi constant G_F and the Weinberg angle sin θ_W) by 1,

$$m_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}.\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}, \tag{1}$$

where Δr accounts for the electroweak corrections which amount to about 4% [6] in the Standard Model. The radiative corrections depend on the top quark mass as m_t^2 and on the Higgs boson mass as log m_H. Therefore, precise measurements of both the W boson mass and the top quark mass constrain the mass of the Standard Model Higgs boson. To ensure that the W boson mass does not become the dominant error in the estimation of the Higgs boson mass, the W boson mass needs to be known with a precision of 15 MeV/c^2 if the top quark mass is known with an accuracy of 2 GeV/c^2 as is expected at the LHC.

At the LHC the cross section for the process pp $\rightarrow$ W + X with the W boson decaying to an electron or muon is 30 nb. In both experiments, at low luminosity (10 fb^{-1}), about 300 million events are expected per year. After all cuts, 60 million W bosons are expected in one year of data taking at low luminosity in each experiment, approximately a factor 50 larger than the statistics expected from Run II at the Tevatron. Due to the large event sample the statistical uncertainty of the mass measurement should be less than 2 MeV/c^2 for an integrated luminosity of 10 fb^{-1}. The transverse mass distribution of the W boson including the expected detector resolution from the ATLAS experiment is shown in Fig. 1.

Since the W boson mass is obtained by fitting the experimental distribution of the transverse mass with simulated event samples, the main systematic uncertainty comes from the modeling of the data, i.e. the physics and detector simulation. The sources of error and their contributions are shown in Table 1. Most of these uncertainties

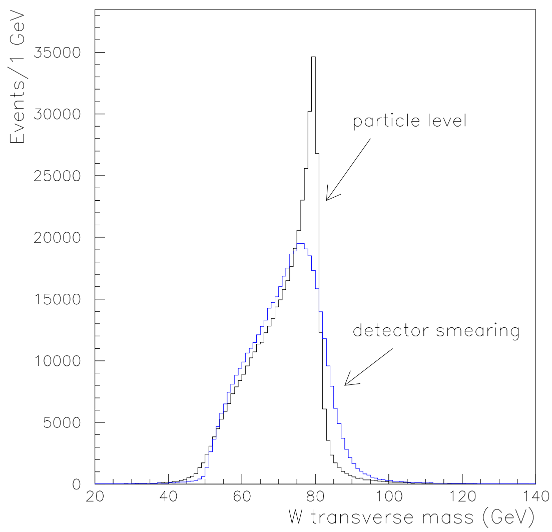

Fig. 1. W boson transverse mass distribution including expected detector resolution

will be constrained in situ by using data samples such as leptonic Z decays, which will determine the lepton energy scale, measure the detector resolution, model the detector response to the W boson recoil and the p_T spectrum of the Z boson.

Table 1. Sources of error and their individual contributions

Source	Δm_W (MeV/c^2)
Statistics	< 2
E-p scale	15
Energy resolution	5
Recoil model	5
Lepton identification	5
p_T^W	5
Parton distribution functions	<10
W width	7
Radiative decays	10
Background	5
Total	**< 25**

At low luminosity, with only one lepton species and one detector, an accuracy of about 25 MeV/c^2 can be expected. By combining the lepton channels, a precision of better than 20 MeV/c^2 is achievable and by further combining the two experiments an accuracy of better than 15 MeV/c^2 is expected. This will reduce the error on log m_H by a factor of 2 from 0.2 to 0.1.

3 The mass of the top quark

Precision measurement of the top quark mass provides several tests of the Standard Model and, together with m_W, helps set constraints on the mass of the Higgs boson. One of the main backgrounds to new physics processes such as the production and decay of the Higgs boson and SUSY particles is $t\bar{t}$ production. In addition, top events can be used to calibrate the calorimeter jet scale and precision measurements in the top sector can provide information on the fermion mass hierarchy.

The CDF and D0 experiments at the Tevatron have measured the mass of the top quark to $m_t = 174.3 \pm 5.1$ GeV/c^2 [3,4]. At Run 2 the precision is expected to improve to ~ 3 GeV/c^2. The prospects of further improving the top quark mass measurement at the LHC have been studied with different approaches [5,6,7]. In each case the precision is limited by systematic uncertainties.

For tagging purposes, top quark mass analyses at the LHC require one top quark to decay semi-leptonically while the other is allowed to decay hadronically: $t\bar{t} \to bW^+ \, \bar{b} \, W^- \to \ell^\pm \, \nu \, b\bar{b} \, q\bar{q}$. The reconstructed top quark mass distribution is shown in Fig. 2 for 10 fb^{-1} of data, including the contribution of background processes as indicated. The contributing fraction of signal events with taus from the leptonically decaying W boson and the background are superimposed. The dominant background process is the W boson production.

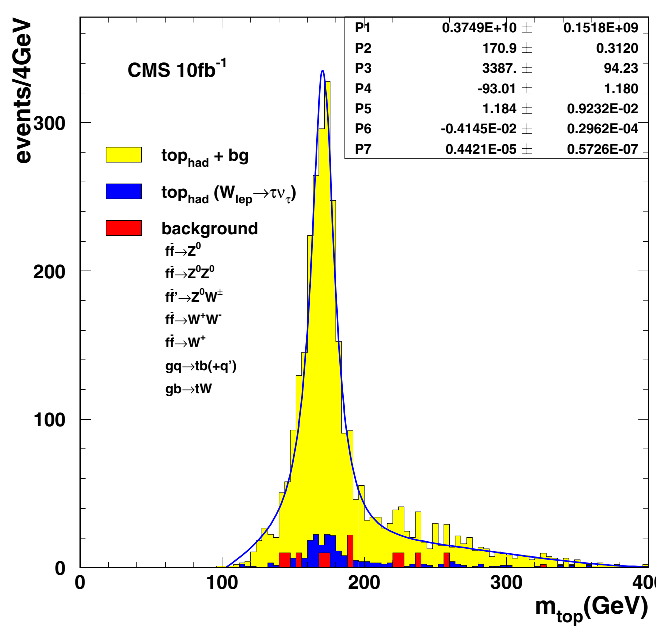

Fig. 2. The reconstructed top quark mass distribution including backgrounds with 10 fb^{-1} at the LHC

The predicted error on the top quark mass from the semi-leptonic channel is less than or equal to 1.3 GeV/c^2 [5]. The error from the di-lepton channel is less than 2 GeV/c^2 [6]. Another method of measuring the top quark mass is to use semi-leptonic decays with a $J/\psi(\mu\mu)$ in the final state [7]. The b jet from the opposite top quark is required to contain another muon from tagging. However, the branching suppression is severe, and an integrated luminosity of 500 fb^{-1} is required to reach a sta-

Table 2. Statistical and theoretical errors for each process

Process	S/B	$S/\sqrt{B}$	Δ V_{tb}/V_{tb} Statistical	Δ V_{tb}/V_{tb} Theory
W-g	4.9	239	0.51%	7.5%
Wt	0.24	25	2.2%	9.5%
W*	0.55	22	2.8%	3.8%

tistical error of 0.9 GeV/c^2. A combined precision of Δm_t less than 1 GeV/c^2 is therefore achievable at the LHC.

4 Single top quark production

The top quark is the only quark which decays so rapidly that it does not have time to form strong bound states. Investigation of top quarks can therefore provide a very clean source of fundamental information. Single top quark production is copious at the LHC and allows a probe of the Wtb vertex and direct measurement of the CKM matrix element V_{tb}. Any deviation to the expected cross section may also be a sign for new physics, for example of a heavy vector boson $W^{'}$.

The production of single top quarks is directly proportional to the square of the CKM matrix element, V_{tb}. The measurement of V_{tb} is itself an important confirmation of the CKM formulation of quark mixing in the Standard Model. Since the rate of single top quark production is large, the statistical accuracy will be good and the direct measurement of V_{tb} through single top quark production may well have the smallest systematic errors [8]. The expected statistical and theoretical errors for each process are shown in Table 2. The main sources of systematic errors will be from b jet tagging, luminosity and theory.

5 Triple gauge boson couplings

Measurements of the triple gauge boson couplings of the W, Z and γ provide a powerful test of the Standard Model. Furthermore, measuring these vertices may be a probe of new physics, through anomalous gauge boson vertices. Hadron collisions provide a unique opportunity of probing the structure of triple gauge boson vertices in a direct and essentially model independent way [9].

Any anomalies in the couplings are expected to result in an excess of events over the Standard Model prediction. Non-standard WWγ couplings, in particular, result in an increase of the Wγ cross section at high photon transverse momentum [10,11,12]. The expected limits on the couplings are extracted using a maximum likelihood fit to the transverse momentum spectrum of the photon [12]. The limits on $\Delta\kappa$ and λ, the CP conserving couplings of the WWγ vertex, for 10 fb^{-1} and 100 fb^{-1} with a form factor scale of 10 TeV are shown in Fig. 3.

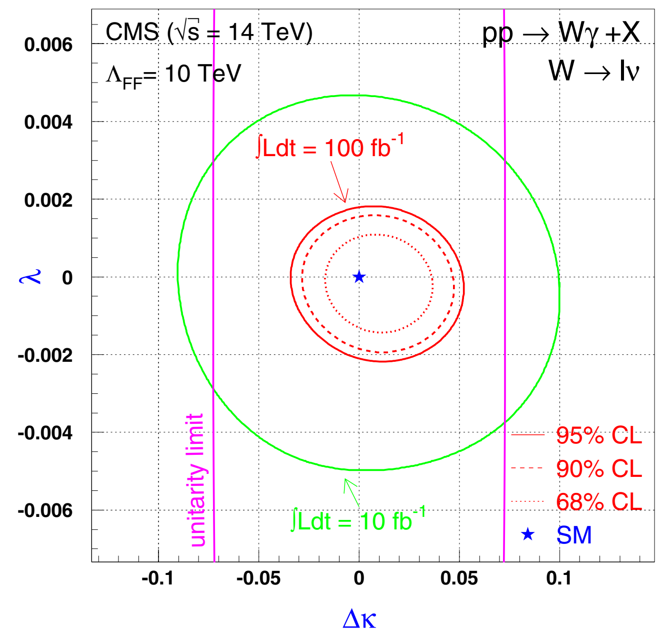

Fig. 3. The limits on $\Delta\kappa$ and λ for 10 fb^{-1} and 100 fb^{-1} with a form factor scale of 10 TeV

6 Summary

The Large Hadron Collider Detectors, ATLAS and CMS are designed to make precision measurements of Standard Model parameters. The collider will also open up unexplored regions of phase space, provide very high statistics and will be a W, Z, b and t factory.

The W boson mass can be measured at the LHC with a precision of 15 MeV/c^2, with a combination of the results from the two lepton channels and both detectors. The top quark mass will be measured with a precision of 1 GeV/c^2. These measurements improve the error on log m_H by a factor of 2 compared to the current measurement.

Triple gauge boson coupling measurements allow further tests of the Standard Model and are a valuable test for new physics. The Large Hadron Collider can improve the limits on these couplings by an order of magnitude.

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