A Search for the Higgs boson produced in association with top quarks in multilepton final states at ATLAS

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ABSTRACT

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Abstract abstract.

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Preface

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Chris Lester
CERN, Fall 2014

CHAPTER 1

Introduction

Here is a citation [1].

Chapter 2

Theoretical Background

The Standard Model of particle physics is an extradinarly successful description of the fundamental constituents of matter and their interactions. Experiments over the past 50 years have verified the extremely precise prediction of the SM; this success has culminated most recently in the discovery of the Higgs Boson. This chapter provides a brief introduction to the structure of the SM and how scientists are able to test it using hadron collider but focuses primarily on the physics of the Higgs boson and its decays to top quarks. Particular attention is given to the importance of a measurement of the rate at which Higgs Bosons are produced in association of top quarks in the context of our theoretical understanding of the SM.

2.1 The Standard Model

The Standard Model (SM) is an example of a quantum field theory that describes the interactions of all of the known fundamental particles (with the exception of the gravitational interaction). It was developed over the course of the course of many years as the result of both theoretical and experimental discoveries. Particles are understood to be excitations of the more fundamental object of the theory, the fiel The dynamics and interactions of the fields are derived from the Standard Model Lagrangian, which is constructed to be symmetric under local gauge transformations of the group $SU(3) \times SU(2) \times U(1)$. $SU(3)$ is the gauge group for the color, $SU(2)$ is the gauge group for weak iso spin, and $U(1)$ is the group for weak hypercharge.

Gauging the symmetries demands the introduction of 8 massless gluons, or the boson (full integer spin) carriers of the strong force from the generators $SU(3)$ symmetry, and the 4 massless electroweak bosons, carriers for the weak and electronmagnetic forces from the 3 generators of the $SU(2)$ and 1 generator of the $U(1)$ group. The gauge symmetry also allows the theory to be renormalizable, meaning that unwanted infinities can be absorbed into observables from theory in a way that allows the theory to be able to predict phyiscs at multiple energy scales. Singlets of the $SU(3)$ group are fermions (half-integer spin particles) called leptons (electron, muon, tau, and associated neutrinos) and do not interact with the strong, where as doublets of the $SU(3)$ group are called quarks (up, down, strange, charm, top, bottom) and do interact with the strong force. The SM is a chiral theory: the weak force violates parity, as it only couples to left-chiral particles or right-chiral antiparticles. This in a sense suggests that right-chiral and left-chiral fermions are different particles coming different fields, which are different representations of the weak-isopsin group.

So far, 3 separate generations of both quarks and leptons have been discovered, differing only by mass. The reason for this 3-fold replication is not known. The heaviest of which is the top quark, discovered at the Tevatron in 1996. The gluon and the 4 electroweak bosons have also been found (W^+, W^-, Z^0, and γ).

2.2 Electoweak Symmetry Breaking and the Higgs

Despite the simple structure of theory, the discovery of massive fundamental particles creates two sets of problems both related to $SU(2) \times U(1)$ gauge invaraince. First, the force-carrying bosons must enter the theory without mass in order for gauge symmetry to be preserved. Second, adding fermion masses to theory in an ad-hoc way allows the right-chiral and left-chiral fermions to mix. Since they possesses different quantum numbers, as different representations of the weak-isospin group, this too breaks gauge invariance.

To solve these problems, spontaneousy electro-weak symmetry breaking (EWSB) is introduced via the Brout-Englert-Higgs(BEH) mechanism. Massive scalar fields, in an electro-weak doublets, are introduced into the theory with 4 degrees of freedom and a specific potential, which includes self-interaction provides the mechanism for spontaneous symmetry breaking. The fermion fields interact with Higgs field with via a Yukawa coupling term, which unites the left and right chiral fields of a single particle type. The minimum of the potential does not occur when the expectation of the field is zero. The field eventually falls to a state, where it aquires a vacuum-expectation value. However, a non-zero field must therefore point in a particular direction of weak-isospin space, breaking the symmetry.

The consquences of this spontaneousy symmetry breaking are tremendous. First, the universe is filled with the Higgs field at its new vaccuum expectation value. The theory can be expanded around the new mininum and 3 of the degrees of freedom can be interpreted as the longitundinal polarizations of the W^+, W^-, and Z^0, while the 4th remains a scalar field, called the Higgs field. The weak bosons thus aquire a mass and the yukawa couplings of the scalar field to the fermions now behave like a mass term at the new mininum.

2.2.1 The Standard Model Parameters

Although the SM structure can be set by specifiying the gauge groups, EWSB mechanism, and acknolwedging the 3-fold replication of the fermions, confronting the SM with experiment requires the measurment of 17[1] free parameters, which are uncontrained from the theory. These free parameters include the fermion masses, coupling constants, the angles and phase of the mixing between quarks, constants from the massive neutrino sector, and constants from the higgs and electroweak sector[2].

Experiments have provided a number of measurements over the years of various parameters of the SM. Although the Higgs Boson particle was only discovered recently, the integration of the Higgs field into SM mean that the *vev* could be constrained prior to discovery from other measurements. The Higgs mass, however, remained theoretically unconstrained. However, it could be inferred in the context of the SM constainted via its dependence on loop corrections from the top mass (M_t) and the W mass (M_W). The GFitter collaboration assembles all relevant electroweak obervable measurements into a statistical model and then allows certain measurements to float within their uncertainty to allow for parameter overconstraints among multple measurements. Figure 2.1 shows the fitted constaints on 4 key SM parameters (M_H, M_W, M_t, $sin^2\theta_w$) and actual measuremetns. The addition to the fit of the measured Higgs mass from the ATLAS and CMS collaborations creates a small tension, as the other observables prefer the mass to be much lower ($\sim$ 80 GeV/c^2). The tension in the combined electroweak fit (including the Higgs) is not statsitcally significant with a p-value of 0.07.

2.3 Collider Physics and the Higgs

Particle physicists accelerate particles to extremely high energies and force them to interact through collisions. Typically, the particles accelerated are electrons or protons, since they are stable. Electron-positron collider machines have a rich history of discovery and measurement in particle physics. The advantage of electron accelerators is that the colliding element is itself a fundamental particle. However, due synchotron radiation, curvature of the beam line becomes problematic for high energy beams. Hadron colliders, specifically, proton-proton and proton-anti-proton (like the Large Hadron

[1] There are additional parameters from neutrino mass terms and mixing but it is unclear how to include these into the Standard Model, since it does not predict right-chiral neutrinos

[2] The electroweak sector includes parameters like mass of the $W^{\pm}$ and Z^0 bosons, the weak mixing angle,$sin^2\theta_w$, the fermi constant G_F, and Higgs Mass and vacuum-expecation value. These parameters however are not wholly indepenent. As discussed above, it is only necessary theoretically to specify the two parameters relevant to the Higgs potential and the two coupling associated with the gauge groups

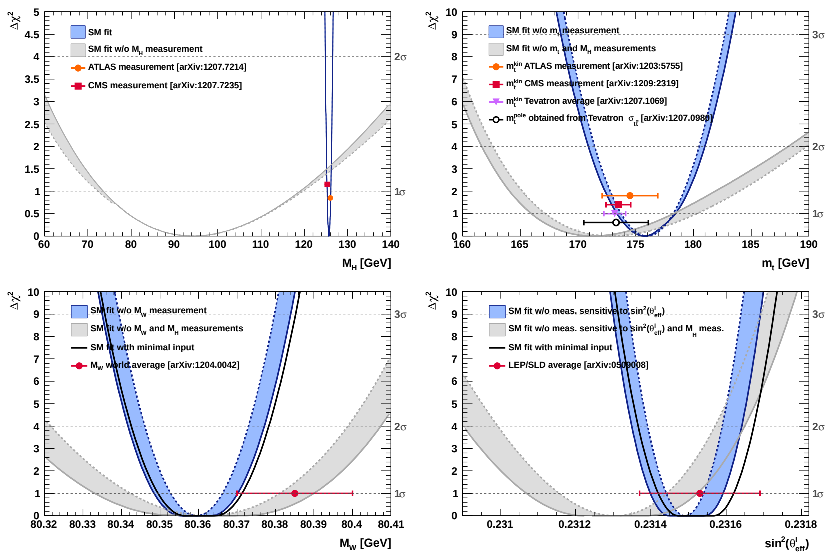

Figure 2.1: χ^2 as a function of the Higgs mass (topleft), the top quark mass (top right), the W boson mass (bottom left) and the effective weak mixing angle (bottom right) for the combined SM fit from the GFitter group. The data points placed along $\chi^2 = 1$ represent direct measurements of the respective observable and their $\pm 1\sigma$ uncertainties. The grey (blue) bands show the results when excluding (including) the new M_H measurements from (in) the fits.

Collider) colliders can be accellerated in rings without large losses due to synchotron radiation, but the actual colliding objects at high energies are the constitutent quarks and gluons. This complicates analysis because the initial state of the system is not clear on a per-collision basis and there is not conservation of momentum along the beam direction. Collider physics rely on form-factor descriptions of the colliding hadrons (usually protons) that describe the fraction of momentum carried by the hadrons constituent 'partons'. These are called parton-distribution functions, seen in Figure 2.2, and are integrated through the theoreritical calculations of various collision processes.

At the Large Hadron collider, therefore the types of initial states are quark-quark, quark-gluon, and gluon-gluon. Gluon collisions dominate overall, due to the large number of gluons inside the proton seen in the figure. Though the relative importance of different initial states changes with the energy scale of the collision and the type of final state sought after.

A prime movitavation for the construction of the Large Hadron Collider was the discovery or exclusion of the Higgs boson. LEP and the Tevatron excluded large swaths of possible Higgs boson masses, especially below 114 GeV/$c^2$and the unitarity of certain diagrams including the $WWWW$ vertex required the mass to be below about 1 TeV.

Despite the ubiquity of Higgs couplings, Higgs boson production at the LHC is a low rate process.

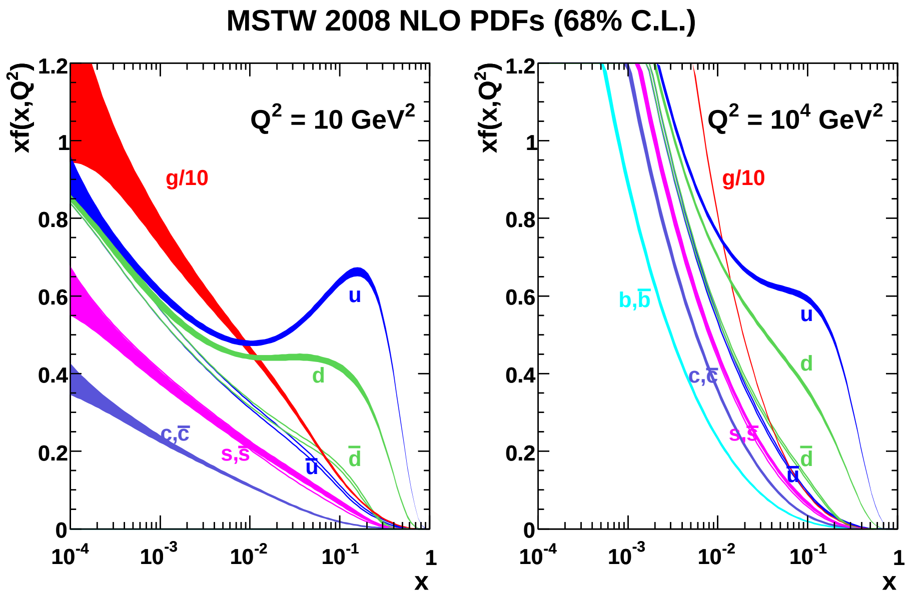

Figure 2.2: Proton Parton Distribution Functions (PDFs) form the MSTW Collaboration at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2

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Because it couples to fermions proporitonal to mass and because the colliding particles must be stable and therefore light, production of the Higgs must occur through virutal states.

The Higgs boson can be produced through collision at the Large Hadron Collider via 4 mechanisms: gluon-fusion, vector-boson fusion, associated production or higgs strahlung, and production in association with top quarks. The diagrams are shown in Figure **??** and the production cross-sections as a function of Higgs mass for the 8 TeV LHC proton-proton runinng are shown in Figure 2.3. The largest production cross-section is via the gluon fusion channel at 20 pb, which proceeds through a fermuion loop that is dominated by the top quark, because of its large yukawa coupling to the Higgs. Because the Higgs' couples to every massive particle, it has a rich decay topology also seen in Figure 2.3, especially for $m_H = 100$. Studies of Higgs properties at hadron colliders offers rich tests of the Standard Model, which is already overconstrained, and ample room for searches for new physics. These tests specifically can verifiy the link between Yukawa coupling and the particles mass andfurther cosntrain details of EWSB by examing Higgs coupling to the weak bosons.

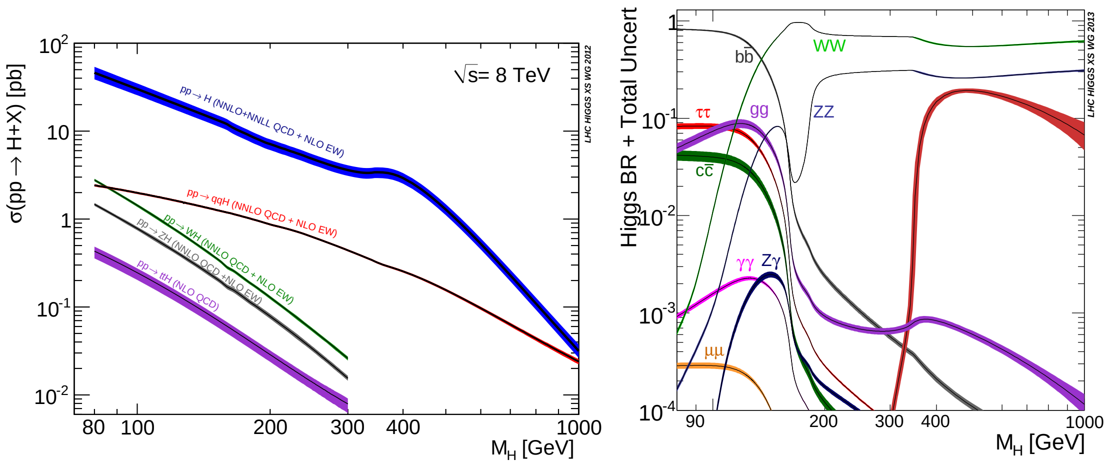

Figure 2.3: Proton Parton Distribution Functions (PDFs) form the MSTW Collaboration at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2

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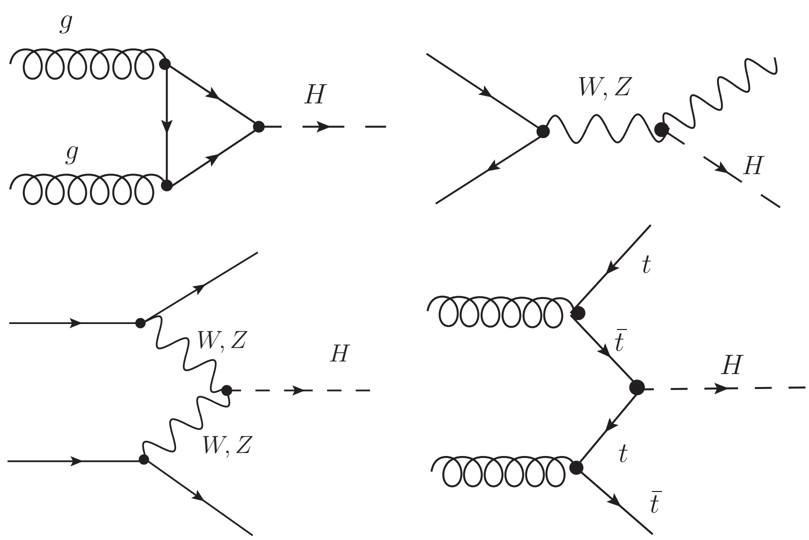

Figure 2.4: Proton Parton Distribution Functions (PDFs) form the MSTW Collaboration at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2

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2.3.1 Higgs Discovery at the LHC

In 2012 both ATLAS and CMS announced the discovery of a new boson consistent with the Higgs by examining the results of Higgs seaches in a number of decay channels ($H \rightarrow W^+W^-$,$H \rightarrow Z^0Z^0$, and $H \rightarrow \gamma\gamma$) in the 2011 dataset at $\sqrt{s}$ =7 TeV and part of the 2012 dataset at $\sqrt{s} = 8TeV$. By 2013 and 2014, both experiments have updated and/or finalized their results for the full 2011 and 2012 datasets. I will focus on the ATLAS results in the following.

2.3.2 Higgs Decays to Top Quarks

2.4 Isseus

Chapter 3

The Large Hadron Collider

Chapter 4

The ATLAS Experiment

4.1 Data

4.2 Simulation

CHAPTER 5

Electrons

5.1 Electrons at Hadron Colliders

5.2 Reconstruction of Electron at ATLAS

5.3 Identification of Electrons at ATLAS

5.3.1 Pile-up

5.3.2 Trigger vs. Offline

5.3.3 2011 Menu

5.3.4 2012 Menu

5.3.5 Electron Likelihood

5.4 Measurement of Electron Efficiency at ATLAS

5.4.1 Techniques

5.4.2 Issues

Chapter 6

Search for the TTH Decay in the Multilepton Channel

6.1 Introduction

6.2 Event Selection

6.3 Optimization

6.4 Background Measurements

6.5 Systematic Assessment

6.6 Results

6.7 Combination

Chapter 7

Conclusions

7.1 Higgs Results in Review

7.2 Prospects for Future

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[1] ATLAS Collaboration, *ATLAS detector and physics performance: Technical Design Report*. CERN, Geneva, 1999. 1