Predicting Optimal Cuts for the Higgs Signal at the Large Hadron Collider

Joe Mitchell

Abstract

We give an introduction to the Standard Model, with emphasis on the Higgs Mechanism and Electroweak symmetry breaking. We then discuss finding the Higgs boson in the Large Hadron Collider, including a discussion of efficient cuts to improve the ration of signal cross seciton to background cross section.

1 Introduction to the Standard Model

The Standard Model describes the basic constituents of matter and three of the four fundamental forces in the universe. Matter is described by a collection of fields. The elementary particles and fundamental interactions are described by the Standard Model Lagrangian.

1.1 Particles

The particles of the Standard Model may be divided into two categories: fermions and bosons. The fermions are associated with half integral spin fields which make up what is normally considered matter, such as protons, neutrons, and electrons. The bosons are associated with the integral spin fields which serve as mediator fields in the interactions of fermions, giving such forces as the electromagnetic force. All particles have an associated antiparticle with the same mass, but opposite quantum numbers.

There are twelve known fundamental fermions, and these may be divided into three generations. Each generation has four particles in it: an up-like quark with $+\frac{2}{3}e$ charge, a down-like quark with $-\frac{1}{3}e$ charge, a lepton with $-e$ charge, and a neutral, massless neutrino. In the first generation these are called up quark, down quark, electron, electron-neutrino. In the second: charm quark, strange quark, muon, muon-neutrino. In the third: top quark, bottom quark, tau, and tau-neutrino. The masses of corresponding particles increase in each successive generation, except for the massless neutrino.

There are thirteen known fundamental bosons, twelve of them confirmed by experiment. The photon A_μ mediates the electromagnetic force. The weak vector bosons $W_\mu^\pm$ and Z_μ mediate the weak force that participates in many decays. The eight gluons G_μ^i mediate the strong force that governs nuclear binding and quark confinement.The Higgs boson H provides a mechanism for Electroweak symmetry, and is as of yet unconfirmed.

	Up-like	Down-like	Lepton	Neutrino
Generation 1	u, u_1	d, d_1	e^-, e_1	ν_e, ν_1
Generation 2	c, u_2	s, d_2	μ^-, e_2	ν_μ, ν_2
Generation 3	t, u_3	b, d_3	τ^-, e_3	ν_τ, ν_3
Charge	$+\frac{2}{3}e$	$-\frac{1}{3}e$	$-e$	0

Table 1: Fermions

Also of interest are particular linear combinations of the massive Z_μ and the massless photon A_μ, and linear combinations of the charged vector bosons W_μ^+ and W_μ^-:

$$B_\mu = A_\mu \cos\theta_W - Z_\mu \sin\theta_W \qquad W_\mu^1 = \frac{1}{\sqrt{2}}(W_\mu^- + W_\mu^+)$$

$$W_\mu^3 = A_\mu \sin\theta_W + Z_\mu \cos\theta_W \qquad W_\mu^2 = \frac{1}{\sqrt{2}i}(W_\mu^- - W_\mu^+)$$

1.2 Interactions

The Standard Model is invariant under the symmetry group $SU_c(3) \times SU_L(2) \times U_Y(1)$. The c means "color", the L refers to the fact that only left handed fermions transform under the group, and the Y refers to the fact that this group is associated with the weak hypercharge quantum number Y. The generators of the groups are associated with gauge bosons:

$$SU_c(3) \to 8G_\mu^i \qquad SU_L(2) \to 3W_\mu^a \qquad U_Y(1) \to B_\mu$$

It is not the physical particles A_μ, Z_μ, W_μ^-, and W_μ^+ that are associated with the symmetries of the Standard Model, but the linear combinations W_μ^1, W_μ^2, W_μ^3, and B_μ. Those physical states come out from these after the Higgs mechanism and the spontaneous breaking of the Electroweak symmetry, shown in the next section. After symmetry breaking, we can write a Lagrangian perturbed around the ground state minimum using the physical particles. The Standard Model Lagrangian has several parts, which can be divided into the Higgs, Strong, and Electroweak sectors.

The Higgs Interaction Lagrangian after symmetry breaking gives the couplings of the Higgs boson to other fundamental fields:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & -\frac{m_H^2}{2}H^2 - \frac{m_H^2}{2v}H^3 - \frac{m_H^2}{8v^2}H^4 \\ & -\left(\frac{1}{v}H + \frac{1}{2v^2}H^2\right)\left(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu\right) \\ & -\frac{1}{v}H \sum_{n=\text{generation}} \left(m_n^l \bar{e}_n e_n + m_n^u \bar{u}_n u_n + m_n^d \bar{d}_n d_n\right) \end{aligned} \tag{1}$$

Note the symmetry breaking vacuum expectation value, $v \approx 246$ GeV. $M_Z = \frac{ev}{2\sin\theta_W \cos\theta_W}$ The first line shows that the Higgs boson has mass and has third and fourth order self couplings. The second line gives it's couplings to the W and Z particles, both one and two Higgs couplings. The third line shows how it couples to the fermions, in proportion to their masses. The Higgs particle couples to neither the gluon fields nor the photon field.

The strong force is mediated by the gluons. We are more concerned with the Electroweak and Higgs sectors, so it suffices to say that the gluons couple only to themselves and quarks. The primary signals and backgrounds in which we are interested have no QCD couplings, and we use the parton model for the proton composition.

Now the electroweak couplings. The electroweak Lagrangian will be expressed as the sum of several Lagrangians:

$$\mathcal{L}_{\text{Electroweak}} = \mathcal{L}_{\text{cubic}} + \mathcal{L}_{\text{quartic}} + \mathcal{L}_{\text{CC}} + \mathcal{L}_{\text{NC}} + \mathcal{L}_{\text{EM}} \tag{2}$$

The cubic Lagrangian term includes WWA and WWZ couplings, the first in proportion to the W boson's charge e, and the second in proportion to $e \cot \theta_W$. The quartic Lagrangian term includes $WWWW$, $WWZZ$, $WWAA$, and $WWZA$ couplings.

The charged current Lagrangian is associated with couplings between the charged weak boson $W_\mu^\pm$ and fermions. W interacts with an electron and electron-neutrino or muon and muon-neutrino and so forth, but does not mix flavor because the neutrino is massless. Any mixing can be overlooked by redefining the physical state of the neutrino to account for this mixing. However, W-quark couplings do mix flavor, so we must use the CKM matrix V_{mn} to mix the quarks from their mass eigenstates to their electroweak eigenstates. That is, W interacts with the up-like quarks, $\{u_i\}$, and the electroweak eigenstates of the down-like quarks, $\{V_{im}d_m\}$.

The neutral current Lagrangian is associated with couplings between the neutral weak boson Z_μ and fermions. Unlike the charged current, the neutral current does preserve flavor, as a result of the GIM mechanism. Z only couples $u \leftrightarrow u$ or $d \leftrightarrow d$, etc.

The electromagnetic Lagrangian is as expected, coupling a photon to a fermion in proportion to the charge of the fermion. In macroscopic terms, this results in the everyday electromagnetic force. Since the photon is massless unlike the weak bosons and unconfined unlike the gluons, it has infinite range.

	H	G	W	Z	A
H	Yes	No	Yes	Yes	No
G	No	Yes	No	No	No
W	Yes	No	Yes	Yes	Yes
Z	Yes	No	Yes	No	No
A	No	No	Yes	No	No
Charged Lepton	Yes	No	Yes	Yes	Yes
Lepton Neutrino	No	No	Yes	Yes	No
Up-Like Quark	Yes	Yes	CKM	Yes	Yes
Down-Like Quark	Yes	Yes	CKM	Yes	Yes

Table 2: Interactions with Gauge Bosons

The Lagrangian is a bit cluttered expressed in terms of these particles. More importantly, the fact that the weak vector bosons have mass makes the Lagrangian unrenormalizable without any additional terms. In essence, this means that the model would not be predictive, it would need an infinite number of measurements before a prediction could be made, and so no predictions could be made. This is the primary reason that the Higgs particle has been introduced, even while it has not been confirmed. The Higgs Mechanism says that the Higgs field does not have a minimum at zero, as the other fields do. The field acquires a nonzero expectation value and spontaneously breaks the Electroweak symmetry.

1.3 Electroweak Symmetry Breaking

Introduce the Electroweak sector of the Standard Model in terms of its symmetries, with the particles W_μ^1, W_μ^2, W_μ^3, and B_μ, and a complex field ϕ that functions as a doublet under the $SU_L(2)$ symmetry, with hypercharge $Y = 1$.

$$\phi = \begin{pmatrix} (\phi_1 + i\phi_2)/\sqrt{2} \\ (\phi_3 + i\phi_4)/\sqrt{2} \end{pmatrix} \qquad \text{with } \phi_i \in \mathbb{R}$$

All of these particles are massless now. This scalar field has four degrees of freedom, and is invariant under the transformation $\phi \to e^{i\alpha}\phi$. Define a potential over ϕ, called the Higgs potential, and say that the minimum of the Higgs potential is not at $\phi = 0$. The form of the potential is:

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \qquad \mu^2 > 0,\ \lambda > 0$$

The potential has a minimum at $\phi^\dagger\phi = \frac{\mu^2}{2\lambda} = v^2/2$. We cannot look at interactions by perturbing the field around 0, since this is not a minimum, but a maximum, of the potential,

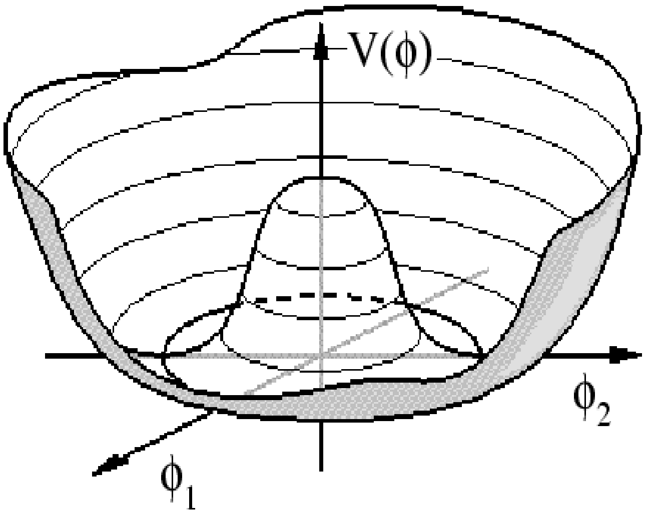

Figure 1: Higgs Potential

and so the ground state of the system doesn't have the Higgs field around zero, but the points $\phi^\dagger\phi = \frac{v^2}{2}$. So we perturb around a point where the potential is a minimum. We have some freedom to pick where to perturb, so we pick $\phi_1 = \phi_2 = \phi_4 = 0$, and $\phi_3 = \frac{v+H(x)}{\sqrt{2}}$, where $H(x)$ is a real scalar field, which we will now call the Higgs field. The terms that are introduced into the Lagrangian through this redefinition act as mass terms for three linear combinations of the four guage fields. The number of degrees of freedom is the same: before we had eight from the up and down polarization states of the four massless guage fields, and four from the scalar field and now we have nine from the three massive guage fields, two from the massless guage field, and one from the Higgs field.

This redefinition of the field gives mass to the W and Z fields through the terms introduced by the nonzero expectation value of the Higgs field. The original W^a_μ particles have some coupling to the Higgs field, and the B_μ particle has some other coupling. After the spontaneous symmetry breaking, the W^1_μ, W^2_μ symmetry is unbroken, so their equal coupling to the Higgs field gives the same mass. However, it is benefitial to talk about their EM eigenstates, W^+_μ and W^-_μ, which also have the same mass. The W^3_μ and B_μ particles can mix to form a particle that does not couple to the Higgs field, A_μ, so that this particle has infinite range. The orthogonal linear combination of W^3_μ and B_μ is the particle Z_μ, which is massive. The strangeness of the guage boson masses has been explained. Relations now hold for the interactions and masses of the weak vector bosons, e.g. $M_W = \frac{ve}{2\sin\theta_W}$ and $M_Z = \frac{M_W}{\cos\theta_W}$.

This model has the additional benefit that any massless fermions that couple to the Higgs field will acquire a masslike term in the Lagrangian, due to this v.e.v. In other words, particles will still couple to the Higgs field even at low energies and these couplings act as a mass for the particles. A fermion's mass will be proportional to its coupling to the Higgs field, as can be seen from the corresponding term in the Lagrangian.

$$\mathcal{L}_{\text{Higgs-fermion}} = \sum_{\text{fermions}} \left(-g_f \bar{f} \frac{(v+H)}{\sqrt{2}} f \right)$$

$$m_f \equiv \frac{g_f v}{\sqrt{2}} \Rightarrow \mathcal{L}_{\text{Higgs-fermion}} = \sum_{\text{fermions}} \left(-m_f \bar{f} f - \frac{m_f}{v} \bar{f} f H \right)$$

It should be noted that this gives no new information about a fermion's mass, except that if the mass is due solely to this Higgs mechanism, then it will proportional to the fermion's Higgs coupling. The Higgs mechanism is simply a convenient way of introducing a fermion mass into physical theory.

The Higgs field is the only unconfirmed portion of the Standard Model, the model with the most predictive power yet discovered. It is obvious why the verification or denouncement of this theory is of much interest. It is the cause for much of the motivation of the Large Hadron Collider that is coming online soon. Predicting optimal cuts to improve the signal to background ratios in this particle accelerator is of importance, and this paper is devoted to that end.

2 Improving Signal to Background Ratios

In order to know if the Higgs particle exists, we simulate events where it exists and events where it does not exist, then compare the two with experiment. For more accurate results, we cut out events that do not show significant difference between signal and background events. Our major cuts include the triple W cut and like sign dilepton cut, in addition to cuts removing A, Z, and single W events.

At energies less than about 135 GeV, the dominant decay for the Higgs boson is $H \to b\bar{b}$. However, at higher energies, where the Standard Model Higgs mass is predicted, the highest amplitude Higgs interaction is HWW, the Higgs interaction with a $W^{\pm}$ weak vector boson. A natural event to consider is of the form $u\bar{d} \to W^+ \to W^+H \to W^+W^+W^-$. However, the W bosons will decay before they reach the detectors. Therefore we consider the decay products of W^+: $l^+\nu_l$ or jj'.

We require that of the three W particles, two of the same sign decay into leptons and neutrinos. This is to suppress complicated QCD processes and known electroweak processes, and is also because lepton properties are more easily analyzed than jet properties. The third W decays into either an opposite sign lepton and neutrino or opposite sign quark pair. The leptons should have high transverse momentum p_T and be isolated in terms of cone isolation, with $R = 0.4$, where $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, $\eta = -\ln\tan\frac{\theta}{2}$ is the pseudorapidity, θ is the polar angle with respect to the beam pipe, and ϕ is the azimuthal angle. The signal:

$$\begin{aligned}
qq' &\to W^+ \to W^+H \to W^+W^+W^- \to l^+\nu_l l^+\nu_l l^-\bar{\nu}_l \\
qq' &\to W^- \to W^-H \to W^-W^-W^+ \to l^-\bar{\nu}_l l^-\bar{\nu}_l l^+\nu_l \\
qq' &\to W^+ \to W^+H \to W^+W^+W^- \to l^+\nu_l l^+\nu_l jj' \\
qq' &\to W^- \to W^-H \to W^-W^+W^- \to l^-\bar{\nu}_l l^-\bar{\nu}_l jj'
\end{aligned} \tag{3}$$

There are also Higgs events with like sign dilepton output particles that involve not three Ws, but one W and two Zs. However, since this will contribute less and also since cutting out Z events will remove much of the background, we do not consider these events.

The background for like sign dilepton output is still very significant, but we can do much to reduce it. The leptons and neutrinos could decay from Z and A particles, in decays such as $Z \to e^+e^-$ and $Z \to \nu_e\bar{\nu}_e$ instead of W decays. To exclude such events, we calculate the transverse mass of opposite sign charged leptons, and veto the event if the transverse mass is around M_Z or around $M_A = 0$. This will primarily leave W decays.

Note that the apparatus cannot detect neutrinos. This means that in addition to the backgrounds giving three leptons and three neutrinos, we must also consider backgrounds giving three leptons and one neutrino. There is a quantity relating to the neutrinos that may be deduced from data: missing transverse energy $\not{E}_T$ or MET, which is the combined transverse momenta of all invisible particles. We can calculate the transverse mass of each charged lepton with the MET. If any of these transverse masses are around M_W, then there is likely only a single neutrino, and it decays with a lepton from W. If not, and if no dilepton transverse masses are around M_Z or M_A, then the event is likely to come from a triple W process.

One complication is that in the Higgs decay $H \rightarrow W^+W^-$, one of the W particles will be off its mass shell. The mass of the Higgs boson is less than double the mass of W, so it cannot produce two on shell W particles. Producing two off shell Ws is highly suppressed, but one off shell is expected. So we must be careful when dealing with the W particles.

What remains is to simulate triple W signal events and triple W background events, to optimize cuts on the various parameters such as p_T for each lepton, and to calculate the cross section of signal and of background events. These may be compared to experiment to say whether or not the Higgs particle exists.

3 Results

We simulated the signal events (3), and the background W to like sign dilepton output. We used both MadGraph/MadEvent and a custom FORTRAN application of MadGraph to generate the events.

3.1 Simulation Programs

MadGraph/MadEvent is a composition of programs consisting of:

1. MadGraph: Gives scattering amplitude from input and output particles to the basic interaction
2. Pythia: Takes MadGraph input and generates final states for a high energy detector
3. PGS: Simple but realistic detector which mimics output of experimental data from Pythia input
4. Graphics and analysis for Pythia or PGS data

MadGraph is a program that generates lowest order Feynman diagrams and scattering amplitudes for given input particles and output particles, with an optional intermediate state. We verified that it works through analytical computation and the scattering amplitude program FORM.

Pythia takes the parton distribution of the particles used in the collider, protons for the LHC, and computes the initial state of the quark collisions. Then it uses MadGraph to calculate the scattering amplitude of the basic interaction. Finally, it decays the particles output from the interaction to give the states that the detector would see.

PGS takes the final states of Pythia, and generates what a detector would see, including the smearing of measured quantities. It outputs in a format that is analyzable by ROOT, a graphics program in use by experimentalists.

To verify the accuracy of Pythia and PGS, and also to provide more flexibility in event generation, we implemented a FORTRAN program that performs a similar function, giving the cross section of collisions, using MadGraph for scattering amplitude calculations.

3.2 Cross Sections

We checked that our method was consistent with ther results of the CDF paper [1]. They predict that in the Tevatron Collider, the number of relevant backgrounds is 188 ± 24 and the number of signal events is 0.38. With the stated integrated luminoscity of 2.7fb^{-1}, this means cross sections of about 70fb and 0.14fb, respectively. Checking the energy 1.96TeV relevant to the Tevatron, this is in agreement with our results.

We are in the process of finding optimal cuts for the events in the Large Hadron Collider, Higgs and background dilepton signals. We would also like to implement additional cuts involving the parameter M_{T2} that has been studied recently in such papers as [2]. This variable is a way to deal with decays involving two invisible particles instead of just the one that MET can study. Perhaps we could eliminate more of the triple W background through its use. However, many of the applications of M_{T2} require that there are two and only two invisible particles that decay from two identical unstable particles. The variable may therefore not be useful for triple lepton processes. However, the like sign lepton, opposite sign jet pair events may indeed be more closely analyzed by such a variable.

References

[1] The CDF Collaboration, "Search for the Wh Production Using High-p_T Isolated Like-Sign Dilepton Events in Run-II with $2.7fb^-2$." CDF/ANAL/EXOTIC/PUBLIC/7307. Version 3.0. December 19, 2008.

[2] H. Cheng and Z. Han, "Minimal kinematic constraints and m_{T2}." JHEP. **12** 2008 063.

[3] C. Burgess and G. Moore, *The Standard Model: A Primer*, Cambridge University Press, first edition, 1997.

[4] F. Halzen and A. Martin, *Quarks & Leptons*, John Wiley & Sons, first edition, 1984.