Physics of Higgs Bosons

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We briefly review the theory and phenomenology of Higgs boson physics, and include a presentation of the latest experimental results, concentrating with preference on the results from the ATLAS Experiment.
I. HIGGS MECHANISM IN A $U(1)$ GAUGE THEORY

From the Higgs field point of view, the $U(1)$ gauge symmetry implies that the transformation over the $\Phi$ field is,

$$\Phi \rightarrow \Phi' = e^{-iq\theta(x)} \Phi$$  \hspace{1cm} (1)

where $\Phi$ is a complex Higgs field, $q$ is the $U(1)$ charge of the Higgs field, $\theta(x)$ is the space-time dependent transformation parameter, and the objects $\exp[-iq\theta(x)]$ form a representation of the $U(1)$ group.

The lagrangian is taken as,

$$L = \left[ (\partial_\mu - iqA_\mu) \Phi^\dagger \right] \left[ (\partial^\mu + iqA^\mu) \Phi \right] - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\Phi^\dagger \Phi)$$  \hspace{1cm} (2)

where $A_\mu$ is the gauge field, with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and

$$A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \theta$$  \hspace{1cm} (3)

is the $U(1)$ transformation of the gauge field. For the Higgs potential we take,

$$V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$  \hspace{1cm} (4)

where $\mu^2$ has units of mass squared and $\lambda$ is a dimensionless parameter that accounts for the quartic Higgs self interaction. The Higgs potential is shown in Fig. 1 for two different values of the sign of $\mu^2$.

It is understood that the vacuum is the state with minimum energy, otherwise the extra energy could be used to create a particle, and the state would cease to be vacuum. The vacuum expectation value of the Higgs field $\langle \Phi \rangle = v$ is the crucial quantity that gives mass to the gauge boson $A_\mu$, as we will see. Therefore, the situation $\mu^2 > 0$ at the left of Fig. 1 is not useful, and we need a non zero value for $v$, thus

$$\mu^2 < 0$$  \hspace{1cm} (5)

In fact, the Higgs field is complex, thus the minimum of the Higgs potential is a circle in this complex plane, as indicated in Fig. 2. This vev though can always be chosen as real because gauge invariance allow us to choose a gauge where $\Phi' = \exp(-iq\theta)\Phi$ is real. Since the vev is not gauge invariant, it is said that the gauge symmetry has been spontaneously broken.
FIG. 1: Higgs potential for two different signs of $\mu^2$.

FIG. 2: Higgs potential in the complex plane of the Higgs field.

If we replace the Higgs field in eq. (4) by its vev, the potential becomes $V = \mu^2 v^2 + \lambda v^4$, and looking for the minimum we find the following minimization condition,

$$\frac{\partial V}{\partial v} \equiv t = 2\mu^2 v + 4\lambda v^3 = 0$$

or tadpole equation. From here we confirm that $\mu^2 = -2\lambda v^2$ is negative. The Higgs mass can be directly obtained from the second derivative of the potential,

$$\frac{1}{2} \frac{\partial^2 V}{\partial v^2} \equiv m_H^2 = \mu^2 + 6\lambda v^2 = 4\lambda v^2$$

as we will confirm below.
If in the gauge where the Higgs field is real we redefine the Higgs field as

\[ \Phi'(x) = v + \frac{1}{\sqrt{2}} H(x) \]  

we find a lagrangian,

\[
\mathcal{L} = \left[ (\partial_\mu - iqA_\mu) \left( v + H/\sqrt{2} \right) \right] \left[ (\partial^\mu + iqA^\mu) \left( v + H/\sqrt{2} \right) \right] - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} \\
- \mu^2 \left( v + H/\sqrt{2} \right)^2 - \lambda \left( v + H/\sqrt{2} \right)^4
\]  

We drop the constant, which is irrelevant in this context, and divide the lagrangian into two pieces,

\[ \mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}} \]  

The free lagrangian contains the terms,

\[
\mathcal{L}_{\text{free}} = \frac{1}{2} \partial_\mu H \partial^\mu H - m_H^2 H^2 - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} + q^2 v^2 A_\mu A^\mu
\]  

while the lagrangian that includes the interactions is,

\[
\mathcal{L}_{\text{int}} = q^2 A_\mu A^\mu \left( \sqrt{2}vH + \frac{1}{2} H^2 \right) - \lambda \left( \sqrt{2}vH^3 + \frac{1}{4} H^4 \right)
\]

From the free lagrangian in eq. (11) we see that the Higgs boson \( H \) has a mass proportional to the quartic self coupling \( \lambda \). In addition, a mass has been generated for the gauge boson \( m_A = 2q^2v^2 \), which is proportional to the Higgs vev. Notice that this mass cannot be included by hand in the lagrangian since it is not gauge invariant.

Schematically, the interactions in eq. (12) are represented by the following Feynman rules,

\[
\begin{array}{c}
A \rightarrow \cdots H \\
A \rightarrow \cdots H^* \\
H \rightarrow \cdots H \\
H^* \rightarrow \cdots H \\
H \rightarrow \cdots H^* \\
H^* \rightarrow \cdots H^*
\end{array}
\]

of which only the first one is relevant for the present Higgs boson search.
II. HIGGS MECHANISM IN A SU(2) × U(1) GAUGE THEORY

Here we study the Higgs mechanism in the Standard Model. In addition to the (electroweak) gauge group $SU(2) \times U(1)$, it is assumed there is a unique Higgs doublet,

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

(13)

with hypercharge $Y_{\Phi} = 1$. The relevant part of the lagrangian is,

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi)$$

(14)

with

$$D_\mu \Phi = \left( \partial_\mu + \frac{i}{2} g' B_\mu + \frac{i}{2} g W^{\rho}_\mu \sigma^{\rho} \right) \Phi$$

(15)

The lagrangian is invariant under the gauge transformation,

$$\Phi \to \Phi' = e^{-i\theta} U \Phi$$

(16)

where $U$ is a $SU(2)$ 2 × 2 matrix. The Higgs potential is the same as in eq. (4), with the only difference that now the Higgs field is a complex doublet. Since $Q = I_3 + Y/2$, the lower ($I_3 = -1/2$) Higgs field is electrically neutral. A gauge transformation can take us to the unitary gauge where $\phi_1 = \phi_2 = \phi_4 = 0$. In this gauge, the Higgs vev is

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

(17)

(note the change in normalization of the Higgs vev). If we do the analogous field redefinition as in eq. (8)

$$\Phi = \begin{pmatrix} 0 \\ (v + H)/\sqrt{2} \end{pmatrix}$$

(18)

we find gauge boson masses,

$$m_{\gamma}^2 = 0, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2, \quad m_W^2 = \frac{1}{4}g^2v^2$$

(19)
and the measurement of the gauge boson masses and other couplings implies the value $v = 246$ GeV. The Higgs kinetic terms leads to,

\begin{equation}
(D^\mu \Phi) \dagger (D^\mu \Phi) = \frac{1}{2} \partial_\mu H \partial^\mu H + m_W^2 W^\mu W^-\mu + \frac{1}{2} g^2 W^\mu W^-\mu (vH + H^2/2) + \frac{1}{2} m_Z^2 Z^\mu Z^-\mu + \frac{1}{4} (g^2 + g'^2) Z^\mu Z^-\mu (vH + H^2/2)
\end{equation}

(20)

generating the following Feynman rules,

\[ W W H = ig m_W g^{\mu \nu} \]
\[ Z Z H = ig m_Z g^{\mu \nu} \]

which are very important for the production and decay of the Higgs particle. If the Higgs boson had only couplings to gauge bosons, we would find the following set of branching ratios.

![Branching ratios of a fermiophobic Higgs boson.](image)

FIG. 3: Branching ratios of a fermiophobic Higgs boson.
As we will see in the next section, the SM Higgs boson also couples to fermions. But extensions of the Higgs sector of the SM can contain Higgs bosons that do not couple to fermions: fermiophobic Higgs bosons.
III. FERMION MASSES

The Higgs mechanism can be used also to give mass to the fermions. In this analysis we exclude the neutrinos. Consider first the charged leptons. They can acquire a mass via the vev of the Higgs doublet. We define the following lepton doublet and singlet,

\[
L = \begin{pmatrix} \nu_{eL} \\ e\bar{L} \end{pmatrix}, \quad e_R
\]

(21)

which transform as a doublet under \(SU(2)\). In addition, it transform under \(U(1)\) with an hypercharge \(Y_{e_L} = -1\). The right handed electron is a singlet under \(SU(2)\) and transform under \(U(1)\) with an hypercharge \(Y_{e_R} = -2\). With this we can write the following Yukawa term,

\[
\mathcal{L}_{Yuk} = -f_e \left[ (L^\dagger \Phi) e_R + e_R^\dagger \left( \Phi^\dagger L \right) \right]
\]

(22)

In the unitary gauge we find,

\[
\mathcal{L}_{Yuk} = -f_e \left( e_R^\dagger e_R + e_R^\dagger e_L \right) \left( v + H \right) / \sqrt{2}
\]

(23)

Thus, a Dirac mass is generated for the charged lepton,

\[
m_e = \frac{1}{\sqrt{2}} f_e v
\]

(24)

which is proportional to the Higgs vev and the Yukawa coupling. In addition, a Yukawa interaction between the Higgs boson and the lepton is formed,

\[
e^+ \overset{\text{\(H\)}}{\rightarrow} \quad \text{\(\frac{i}{\sqrt{2}} h_e = \frac{i v m_e}{2 m_W}\)}
\]

As we can see, the Higgs boson interacts with the lepton with a strength given by the Yukawa coupling: the heavier the lepton, the stronger the interaction. Analogous masses and interactions are obtained for the heavier generations.

In the case of quarks, we define an \(SU(2)\) left doublet and two right singlets,

\[
Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R , \quad d_R
\]

(25)
with hypercharges $Y_Q = 1/3$, $Y_{u_R} = 4/3$, and $Y_{d_R} = -2/3$. The relevant Yukawa term for down-type quarks in the lagrangian has the form,

$$\mathcal{L}_{Yuk} = -f_d \left[ (Q^\dagger \Phi) d_R + d_R^\dagger (\Phi^\dagger Q) \right]$$

With the same mechanism as before, the down-type quark receives a mass,

$$m_d = \frac{1}{\sqrt{2}} f_d v \tag{27}$$

and a Yukawa interaction,

$$\overline{d} \rightarrow H = \frac{i}{\sqrt{2}} h_d = i \frac{g m_d}{2 m_W}$$

which is also proportional to the mass of the quark. The case for the up-type quark is less obvious. The previous terms are based on the fact that $(Q^\dagger \Phi)$ is an $SU(2)$ invariant with combined hypercharge 2/3 that can be cancelled by $d_R$. For the up-type quarks we use the fact that $(\Phi^T i \sigma_2 Q)$ is also an $SU(2)$ invariant with combined hypercharge 4/3 that can be cancelled by $u_R^\dagger$,

$$\mathcal{L}_{Yuk} = f_u \left[ (Q^\dagger i \sigma_2 \Phi^*) u_R - u_R^\dagger (\Phi^T i \sigma_2 Q) \right] \tag{28}$$

which leads to the mass,

$$m_u = \frac{1}{\sqrt{2}} f_u v \tag{29}$$

and a Yukawa interaction,

$$\overline{u} \rightarrow H = \frac{i}{\sqrt{2}} h_u = i \frac{g m_u}{2 m_W}$$
Notice that in the three cases, when including three generations, the Yukawa couplings can be promoted to $3 \times 3$ Yukawa matrices, which may or may not be diagonal.

The Branching Ratios of a SM Higgs boson, including decays into leptons, are shown in Fig. 4. At low Higgs masses the decays into $b\bar{b}$, $c\bar{c}$, and $\tau^+\tau^-$ dominates over the $\gamma\gamma$ decay. In addition, the $t\bar{t}$ decay appears at the top quark threshold.

FIG. 4: Branching ratios of a SM Higgs boson.

FIG. 5: Total width of the SM Higgs boson.
In Fig. 5 we can see the total width of the SM Higgs boson. It grows very fast with the mass $m_H$, from a few MeV at low masses to more than 100 GeV at large masses. For comparison we have also supersymmetric Higgs bosons, which will be introduced later.
IV. UNITARITY OF $W$-$W$ SCATTERING

The high energy behaviour of the $W$-$W$ scattering allow us to show the role of the Higgs boson. Consider the scattering,

$$W^+(p_1) + W^-(p_2) \rightarrow W^+(k_1) + W^-(k_2)$$

(30)

The relevant diagrams in the Standard Model involving only gauge bosons are,

and the ones involving the SM Higgs boson,

The best strategy is to work in the Centre of Mass frame of reference, with the incoming $W$ bosons in the $z$ axis. In this case, the incoming four momenta are,

$$p_1 = (E, 0, 0, p) \quad p_2 = (E, 0, 0, -p)$$

(31)

with $E^2 = p^2 + m_W^2$. We have the freedom to choose the orientation of the $x$ and $y$ axis, we choose it such that the outgoing $W$ bosons lie in the $yz$ plane. In this case the outgoing $W$ four momenta are,

$$k_1 = (E, 0, p \sin \theta, p \cos \theta) \quad k_2 = (E, 0, -p \sin \theta, -p \cos \theta)$$

(32)
where $\theta$ is the scattering angle. We are interested in the high energy behaviour of this scattering. The longitudinal polarization of the $W$ bosons are responsible for the high energy terms, and the transverse polarizations can be neglected. The longitudinal polarizations are,

$$
\varepsilon_L(p_{1,2}) = (p, 0, 0, \pm E)/m_W \quad \varepsilon_L(k_{1,2}) = (p, \pm E \sin \theta, \pm E \cos \theta)/m_W
$$

which are normalized $\varepsilon^2 = -1$ and satisfy the Lorentz condition $\varepsilon(q) \cdot q = 0$. The amplitude for the graphs involving three gauge boson vertices is,

$$
M_{3gb} = g^2 p^4 m_W^4 \left( 3 - 6 \cos \theta - \cos^2 \theta \right) + g^2 p^2 m_W^2 \left( 9 - 11 \cos \theta - 4 \cos^2 \theta \right) + ...
$$

where we have neglected terms that do not grow with the momentum $p$. Similarly, the diagram with four gauge bosons gives the following amplitude,

$$
M_{4gb} = -g^2 p^4 m_W^4 \left( 3 - 6 \cos \theta - \cos^2 \theta \right) + g^2 p^2 m_W^2 \left( -8 + 12 \cos \theta + 4 \cos^2 \theta \right) + ...
$$

Interestingly, the terms proportional to $p^4$ cancel among the gauge boson graphs, but not the $p^2$ terms. Notice that these terms are unwanted because when $p$ is arbitrarily increased we do not want the amplitude to arbitrarily increase also, since perturbation theory breaks down.

The graphs involving a Higgs boson contribute with,

$$
M_H = -g^2 p^2 m_W^2 \left( 1 + \cos \theta \right) + g^2 m_H^2 m_W^2 \left( \frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right) + ...
$$

with $t = -2p^2(1 - \cos \theta)$. From here we see that the Higgs boson graphs are necessary to cancel the $p^2$ terms, otherwise the cross section could grow unacceptably large. The total amplitude includes the also important terms proportional to the Higgs mass,

$$
M = \frac{g^2 m_H^2}{4 m_W^2} \left( \frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right) + ...
$$

This term does not diverge at large momentum $p$, but could be too large for a large Higgs boson mass. The differential cross section is in terms of the amplitude,

$$
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |M|^2
$$

To study the effect of a large Higgs mass on this cross section, we do the partial wave decomposition of the amplitude,

$$
M = 8\pi \sum_j (2j + 1) A_j P_j(\cos \theta)
$$
where the \( P_j(x) \) are the Legendre polynomials. Since these polynomials are orthogonal and have a definite normalization,

\[
\int_{-1}^{1} dx \, P_i(x) P_j(x) = \frac{2}{2j + 1} \delta_{ij}
\]  

(40)

the total cross section becomes very simple,

\[
\sigma = \frac{4\pi}{s} \sum_j (2j + 1)|A_j|^2
\]

(41)

The optical theorem states that,

\[
\sigma = \frac{1}{2s} \operatorname{Im} \mathcal{M} (\theta = 0)
\]

(42)

with each of these partial waves satisfying a "unitarity bound" that in our language is expressed as,

\[
|A_j|^2 = \operatorname{Im} A_j \quad \Rightarrow \quad A_j = e^{i\delta_j} \sin \delta_j
\]

(43)

which means that any of the partial wave amplitudes cannot exceed unity. From eq. (37) we find,

\[
A_0 = -\frac{m^2_H}{64\pi m_W^2} \left[ 2 + \frac{m^2_H}{s - m^2_H} - \frac{m^2_H}{s} \ln \left( 1 + \frac{s}{m^2_H} \right) \right]
\]

(44)

and if we take the limit \( s \gg m^2_H \) we get,

\[
A_0 \longrightarrow -\frac{m^2_H}{32\pi m_W^2}
\]

(45)

Since this partial wave amplitude must have a magnitude smaller than unity we obtain the following limit for the Higgs mass,

\[
m_H < \sqrt{32\pi m_W} \approx 800 \text{ GeV}
\]

(46)

with more precise calculations reaching the 1 TeV limit. So, the lesson is, unitarity needs a Higgs boson, with a mass not larger than 1 TeV. The alternative is that perturbation theory breaks down at these energies, thus, some strong interaction between \( W \) gauge bosons should appear.
V. HIGGS BOSONS IN THE MSSM

In the Minimal Supersymmetric Standard Model we need two Higgs doublets $H_d$ and $H_u$ with hypercharges $Y_{H_d} = -1$ and $Y_{H_u} = 1$. The Higgs potential is,

$$V = \frac{1}{8} (g^2 + g'^2) \left( |H_u|^2 - |H_d|^2 \right)^2 + \frac{1}{2} g^2 |H_d^+ H_u| \left| \begin{array}{c}
m^2_{1H} |H_d|^2 + m^2_{2H} |H_u|^2 - m^2_{12} (H_d^T i\sigma_2 H_u + h.c) \end{array} \right. \right)$$

(47)

where in the first line we have the supersymmetric quartic Higgs self interactions, in the second line we have $m^2_{1H}$ and $m^2_{2H}$ mass terms that receive contributions from the supersymmetric higgsino mass and soft supersymmetry breaking mass terms, and $m^2_{12}$ which is a purely soft mass term.

Notice that the quartic coupling $\lambda$ in the SM is replaced by gauge couplings in the MSSM. The fixed value of these couplings is the reason why the lightest Higgs boson in the MSSM cannot be as heavy as the SM Higgs.

Under certain reasonable conditions on the soft masses, the electroweak symmetry is spontaneously broken when the two Higgs doublets acquire a non-trivial vev. We do the replacement,

$$H_d = \left( \begin{array}{c}
\frac{1}{\sqrt{2}} (v_d + \chi_d + i\phi_d) \\
H_d^- 
\end{array} \right), \quad H_u = \left( \begin{array}{c}
H_u^+ \\
\frac{1}{\sqrt{2}} (v_u + \chi_u + i\phi_u)
\end{array} \right)$$

(48)

Gauge boson masses are generated in a similar way as in the SM, obtaining

$$m^2_W = \frac{1}{4} g^2 (v_u^2 + v_d^2), \quad m^2_Z = \frac{1}{4} (g^2 + g'^2) (v_u^2 + v_d^2)$$

(49)

These masses come from the Higgs kinetic terms, and there is a contribution from both Higgs bosons. Thus, electroweak measurements imply $v_u^2 + v_d^2 = 246 \text{ GeV}$. The relative size of the two vevs is undetermined, and we define,

$$\tan \beta = \frac{v_u}{v_d}$$

(50)

The tadpole equations in the MSSM are equal to,

$$\frac{\partial V}{\partial v_u} \equiv t_u = m^2_{2H} v_u - m^2_{12} v_d + \frac{1}{4} g^2 v_d^2 v_u + \frac{1}{8} (g^2 + g'^2) (v_u^2 - v_d^2) v_u = 0$$

$$\frac{\partial V}{\partial v_d} \equiv t_d = m^2_{1H} v_d - m^2_{12} v_u + \frac{1}{4} g^2 v_u^2 v_d - \frac{1}{8} (g^2 + g'^2) (v_u^2 - v_d^2) v_d = 0$$

(51)
and are usually used to determine $m_{1H}^2$ and $m_{2H}^2$ for a given pair of vevs.

The mass terms are grouped in the lagrangian with the following matrices,

$$V_{quadratic} = \frac{1}{2}(\chi_d, \chi_u) M_\chi^2 (\chi_d, \chi_u) + \frac{1}{2}(\phi_d, \phi_u) M_\phi^2 (\phi_d, \phi_u) + (H_d^-, H_u^-) M_\pm^2 (H_d^+, H_u^+)$$

The simplest mass matrix is the one for the CP-odd Higgs bosons,

$$M_{\phi}^2 = \begin{pmatrix} m_{12}^2 t_\beta + t_d/v_d & m_{12}^2 \\ m_{12}^2 & m_{12}^2/t_\beta + t_u/v_u \end{pmatrix}$$

After the tadpoles are set to zero, this mass matrix is diagonalized with a rotation by an angle $\beta$. One of the eigenvalues is zero and corresponds to the unphysical massless neutral Goldstone boson. The second eigenvalue is the physical CP-odd Higgs $A$ with a mass,

$$m_A^2 = \frac{m_{12}^2}{s_\beta c_\beta}$$

Following in simplicity is the mass matrix for the charged Higgs bosons,

$$M_\pm^2 = M_{\phi}^2 + m_W^2 \begin{pmatrix} s_\beta^2 & s_\beta c_\beta \\ s_\beta c_\beta & c_\beta^2 \end{pmatrix}$$

This mass matrix is also diagonalized with a rotation by an angle $\beta$. One of the eigenvalues is also zero, and corresponds to the unphysical charged Goldstone boson. The second eigenvalue is the mass of the charged Higgs boson $H^\pm$,

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

The last mass matrix corresponds to the CP-even neutral Higgs bosons,

$$M_\chi^2 = \begin{pmatrix} m_A s_\beta^2 + m_Z c_\beta^2 & -(m_A^2 + m_Z^2) s_\beta c_\beta \\ -(m_A^2 + m_Z^2) s_\beta c_\beta & m_A c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix}$$

where we have already set the tadpole to zero. This matrix is diagonalized with a rotation by an angle $\alpha$ which satisfy,

$$\sin 2\alpha = -\frac{m_H^2 + m_h^2}{m_H^2 - m_h^2} \sin 2\beta$$

and the two eigenvalues are the light and heavy CP-even Higgs masses,

$$m_{H, h}^2 = \frac{1}{2} \left[ m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta} \right]$$

Notice the following,
• The minimum value for the light Higgs mass at tree-level is \( m_h = 0 \), and it is obtained for \( \tan \beta = 1 \).

• The maximum value for the light tree-level Higgs mass is \( m_h = m_Z \), and it is obtained for \( \tan \beta \to \infty \).

• In the decoupling limit \( m_A \to \infty \) we obtain \( m_h \to m_Z c_{2\beta} \).

The feature that the light Higgs mass cannot be arbitrarily large is related to the fact that the quartic couplings are given by the gauge couplings instead of an arbitrary parameter \( \lambda \) as in the SM.

![Graph](image)

**FIG. 6:** The radiatively corrected light CP-even Higgs mass is plotted as a function of \( \tan \beta \), for the maximal mixing [upper band] and minimal mixing [lower band] benchmark cases. The central value of the shaded bands corresponds to \( M_t = 175 \) GeV, while the upper [lower] edge of the bands correspond to increasing [decreasing] \( M_t \) by 5 GeV. Also, \( m_A = 1 \) TeV and the diagonal soft squark squared-masses are assumed to be degenerate: \( M_{SU/SY} \equiv M_Q = M_U = M_D = 1 \) TeV. [Carena, Haber, 2002]

The Higgs bosons kinetic terms leads to Higgs interactions with gauge bosons analogous to the ones in the SM. Among these Feynman rules we find,
This has implications on the production and decay of the Higgs boson, since in the MSSM these couplings are smaller than in the SM.

The fermion mass terms and Yukawa interactions come from the Yukawa terms in the superpotential,

\[
W_Y = h_e \left( \bar{H}_d^T i \sigma_2 \hat{L} \right) \hat{c}_R + h_d \left( \bar{H}_d^T i \sigma_2 \hat{Q} \right) \hat{d}_R + h_u \left( \bar{Q}^T i \sigma_2 \hat{H}_u \right) \hat{u}_R
\]

This leads to the following fermion masses,

\[
  m_e = \frac{1}{\sqrt{2}} h_e v_d, \quad m_d = \frac{1}{\sqrt{2}} h_d v_d, \quad m_u = \frac{1}{\sqrt{2}} h_u v_u
\]

Notice that the smaller the vev the larger the corresponding Yukawa coupling. This means that as \( \tan \beta \) grows, \( h_e \) and \( h_d \) grow and \( h_u \) decreases.

These interactions look the same as in the SM. The difference is in the numerical value of the Yukawa couplings, which introduce a strong dependency on the parameter \( \tan \beta \).
In Fig. 7-top we see the neutral CP-even Higgs boson branching ratios as a function of the corresponding Higgs boson mass for $\tan \beta = 30$. The range shown for $H$ is $90 < m_A < 130$ GeV, while for $h$ the range shown is $128 < m_A < 1000$ GeV.

In Fig. 7-bottom we have the same plot but now for $\tan \beta = 3$. At these smaller values of $\tan \beta$ the $B(h \rightarrow \tau \tau)$ grows up to $\sim 10^{-2}$, depending on $m_h$. In addition, since the couplings of the Higgs bosons to charged leptons and down type quarks decrease with smaller $\tan \beta$, the
decays into gauge bosons acquire more importance. Depending on $m_H$, the decay $H \rightarrow hh$ can be also large.

![FIG. 8: Total width of MSSM Higgs bosons.](image_url)
VI. TWO HIGGS DOUBLET MODELS

There are several different realizations of a two Higgs doublet model. The MSSM is one, where a different Higgs doublet gives mass to the up and down type of quarks, called 2HDM type II. Here as an example a 2HDM type I is introduced.

Consider two Higgs doublets $H_1$ and $H_2$ both with hypercharge $Y_H = 1$. The most general potential is,

$$V = m_1^2|H_1|^2 + m_2^2|H_2|^2 - \left( m_{12}^2 H_1^\dagger H_2 + h.c. \right)$$

$$+ \frac{1}{2} \lambda_1 |H_1|^4 + \frac{1}{2} \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left( H_1^\dagger H_2 \right) \left( H_2^\dagger H_1 \right)$$

$$+ \left\{ \frac{1}{2} \lambda_5 \left( H_1^\dagger H_2 \right)^2 + \left[ \lambda_6 |H_1|^2 + \lambda_7 |H_2|^2 \right] \left( H_1^\dagger H_2 \right) + h.c. \right\}$$

This potential spontaneously breaks the electroweak symmetry when the two Higgs fields acquire a vev,

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

with $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV and $\tan \beta = v_2/v_1$. The CP-odd mass matrix is

$$M_A^2 = \begin{pmatrix} m_{12}^2 t_\beta - \lambda_5 v^2 s_\beta^2 & -m_{12}^2 + \lambda_5 v^2 s_\beta c_\beta \\ -m_{12}^2 + \lambda_5 v^2 s_\beta c_\beta & m_{12}^2/t_\beta - \lambda_5 v^2 c_\beta^2 \end{pmatrix}$$

and it has a null eigenvalue which corresponds to the neutral Goldstone boson, and a physical CP-odd Higgs boson with mass,

$$m_A^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \lambda_5 v^2$$

The charged Higgs mass matrix is given by

$$M_{H^\pm}^2 = \begin{pmatrix} m_{12}^2 t_\beta - \frac{1}{2} \left( \lambda_4 + \lambda_5 \right) v^2 s_\beta^2 & -m_{12}^2 + \frac{1}{2} \left( \lambda_4 + \lambda_5 \right) v^2 s_\beta c_\beta \\ -m_{12}^2 + \frac{1}{2} \left( \lambda_4 + \lambda_5 \right) v^2 s_\beta c_\beta & m_{12}^2/t_\beta - \frac{1}{2} \left( \lambda_4 + \lambda_5 \right) v^2 c_\beta^2 \end{pmatrix}$$

which has a zero eigenvalue: the charged Goldstone boson, and a physical Higgs with mass,

$$m_{H^\pm}^2 = m_A^2 + \frac{1}{2} \left( \lambda_5 - \lambda_4 \right) v^2.$$
The neutral CP-even Higgs mass matrix is more complicated:

\[
M_{H^0}^2 = \begin{pmatrix}
m_A^2 s_\beta^2 + \lambda_1 v^2 c_\beta^2 + \lambda_5 v^2 s_\beta^2 \\
-m_A^2 s_\beta c_\beta + (\lambda_3 + \lambda_4) v^2 s_\beta c_\beta \\
-m_A^2 s_\beta c_\beta + (\lambda_3 + \lambda_4) v^2 s_\beta c_\beta + m_A^2 c_\beta^2 + \lambda_2 v^2 s_\beta^2 + \lambda_5 v^2 c_\beta^2
\end{pmatrix}
\]

(68)

and the two eigenvalues are the masses of the neutral CP-even Higgs bosons $h^0$ and $H^0$. It is diagonalized by an angle $\alpha$ defined by

\[
\sin 2\alpha = \frac{[-m_A^2 + (\lambda_3 + \lambda_4) v^2] s_2 b}{\sqrt{[(m_A^2 + \lambda_5 v^2) c_2 + \lambda_1 v^2 c_\beta^2 + \lambda_2 v^2 s_\beta^2]^2 + [m_A^2 - (\lambda_3 + \lambda_4) v^2]^2 s_2^2}}.
\]

(69)

The fermion masses are obtained in a similar way as in the SM, but with the Higgs field $\Phi$ replaced by $H_2$ for example. Thus, the fermion masses are

\[
m_e = \frac{1}{\sqrt{2}} h_e v_2, \quad m_d = \frac{1}{\sqrt{2}} h_d v_2, \quad m_u = \frac{1}{\sqrt{2}} h_u v_2
\]

(70)

and the Higgs couplings to fermions are proportional to $\cos \beta$.
VII. SM HIGGS MASS AND PRECISION DATA

The Gfitter Group has performed a global fit of the Standard Model to electroweak precision data, in particular to the Higgs boson mass, demonstrating an impressive predictive power of quantum loop corrections. The observables used are

- $Z$ resonance parameters: $Z$ mass $m_Z$ and width $\Gamma_Z$; hadron production cross section in $e^+e^-$ collisions $\sigma_{\text{had}}$.

- Partial $Z$ cross sections: Ratios of hadronic to leptonic $R_\ell$, and heavy-flavour hadronic to total hadronic $R_c, R_b$ cross sections.

- Neutral current couplings: Effective weak mixing angle $\sin^2 \theta_{\text{eff}}$; left-right and forward-backward asymmetries for universal leptons and heavy quarks $A_\ell, A_c, A_b, A_{FB}^c, A_{FB}^b$.

- $W$ boson parameters: $W$ mass $m_W$ and width $\Gamma_W$.

- Other parameters: running quark masses $\overline{m_c}, \overline{m_b}$, and top quark mass $m_t$; hadronic contribution to electromagnetic coupling $\Delta a_{\text{had}}^{(5)}(m_Z^2)$.

with numerical values shown in Table I.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_Z ) (GeV)</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>( \Gamma_Z ) (GeV)</td>
<td>2.4952 ± 0.0023</td>
</tr>
<tr>
<td>( \sigma_{had} ) (nb)</td>
<td>41.540 ± 0.037</td>
</tr>
<tr>
<td>( R_\ell )</td>
<td>20.767 ± 0.025</td>
</tr>
<tr>
<td>( R_c )</td>
<td>0.1721 ± 0.0030</td>
</tr>
<tr>
<td>( R_b )</td>
<td>0.21629 ± 0.00066</td>
</tr>
<tr>
<td>( \sin^2 \theta_{eff}^\ell )</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>( A_\ell )</td>
<td>0.1499 ± 0.0018</td>
</tr>
<tr>
<td>( A_c )</td>
<td>0.670 ± 0.027</td>
</tr>
<tr>
<td>( A_b )</td>
<td>0.923 ± 0.020</td>
</tr>
<tr>
<td>( A_{ FB}^\ell )</td>
<td>0.0171 ± 0.0010</td>
</tr>
<tr>
<td>( A_{ FB}^c )</td>
<td>0.0707 ± 0.0035</td>
</tr>
<tr>
<td>( A_{ FB}^b )</td>
<td>0.0992 ± 0.0016</td>
</tr>
<tr>
<td>( m_W ) (GeV)</td>
<td>80.399 ± 0.025</td>
</tr>
<tr>
<td>( \Gamma_W ) (GeV)</td>
<td>2.098 ± 0.048</td>
</tr>
<tr>
<td>( m_c ) (GeV)</td>
<td>1.25 ± 0.09</td>
</tr>
<tr>
<td>( m_b ) (GeV)</td>
<td>4.20 ± 0.07</td>
</tr>
<tr>
<td>( m_t ) (GeV)</td>
<td>172.4 ± 1.2</td>
</tr>
<tr>
<td>( \Delta \alpha_{had}^{(5)}(m_Z^2) \times 10^{-5} )</td>
<td>2768 ± 22</td>
</tr>
</tbody>
</table>
The main output is in table II.

Our concern here is with the Higgs boson mass: precision electroweak data and its fit to the SM including radiative corrections predicts a light Higgs boson!

![Graphs showing $\Delta \chi^2$ as a function of $m_H$ with and without direct Higgs boson searches.](image-url)
In Fig. 9-top we see the $\Delta \chi^2$ profile as a function of the Higgs boson mass. A similar plot is shown in Fig. 9-bottom but this time including the results from direct searches for Higgs bosons at LEP and Fermilab. We clearly see the preference for a light Higgs boson. The LEP exclusion is seen as a step rise of the $\Delta \chi^2$ at a value $m_h = 114$ GeV, while the data from Fermilab decreases $\Delta \chi^2$ between that value and $m_h \sim 140$ GeV.

In Fig. 10-top we find the 68%, 95% and 99% CL contours in the plane $m_t$ vs. $M_H$ (top) and $\Delta \alpha^{(5)}_{\text{had}}(m_Z^2)$ vs. $M_H$ (bottom).

In Fig. 10-top we find the 68%, 95% and 99% CL contours in the plane $m_t$ vs. $m_H$. The large blue contours exclude the information on the measurement of the top quark mass, while the smaller purple contours do include it. Similarly, the small green contours include the information on the direct non-observation of the Higgs boson by LEP. The horizontal band is the
1σ world average of the top quark mass. A clear preference for a low Higgs boson mass is observed, specially in the 99% CL contour.

A similar plot is found in Fig. 10-bottom, this time in the plane $\Delta \alpha_{\text{had}}^{(5)}(m_Z^2)$ vs. $m_H$, where $\Delta \alpha_{\text{had}}^{(5)}(m_Z^2)$ is the hadronic contribution of the five light quarks to the electromagnetic coupling constant at the scale $m_Z$. This parameter is used instead of $\alpha_s(m_Z^2)$ because it concentrates most of the theoretical uncertainties.
VIII. SM HIGGS PRODUCTION AND DECAY

The main production mechanisms of Higgs bosons at a hadron collider can be seen in Fig. 11, and they are based on couplings already studied: a Higgs boson with a pair of heavy fermions and a Higgs boson with a pair of gauge bosons. In order of importance these production mechanisms are: (a) Gluon fusion, where the Higgs boson is produced off a heavy quark in a loop, (b) Vector Boson fusion, where two quark-emitted vector bosons annihilate into a Higgs, (c) Higgs-strahlung, where a Higgs boson is emitted off a vector boson (either a $Z$ or a $W$), (d) $t\bar{t}$ emission, where a Higgs boson is emitted off a t-quark in the t-channel.

The cross sections at the LHC with a centre of mass energy $\sqrt{s} = 7$ TeV are shown in Fig. 12 as a function of the Higgs mass. Gluons are easily produced at high energy hadron colliders, such that the dominant production mechanism is gluon fusion by at least an order of magnitude over most of the Higgs mass range. Theoretical uncertainty can be large, of the order of 20 – 30%.

Vector boson fusion $pp \to qqH$ is the second largest Higgs production cross section at the LHC, and it approaches gluon fusion at $m_H \sim 1$ TeV. The Higgs-strahlung mechanism is comparable with VBF only at low Higgs masses, but rapidly becomes an order of magnitude smaller for Higgs masses near 300 GeV. Even smaller is the $pp \to ttH$ cross section [See Carena-Haber 2002 for example].
In Fig. 13 we see the product of cross section times branching ratio of the main SM Higgs decay modes. It can be seen the dominance of the Higgs decay into a pair of gauge bosons at
Higgs masses larger than about 160 GeV. Also seen is the importance of the one-loop generated decay mode $H \rightarrow \gamma\gamma$ at low Higgs masses.
IX. HIGGS DECAY INTO TWO PHOTONS

Since the neutral Higgs boson does not have electric charge, it does not couple directly to photons. The decay $H \rightarrow \gamma\gamma$ is possible thanks to quantum corrections,

The loops associated to gauge and scalar bosons include a second graph that involves a quartic coupling. In the case of a fermiophobic Higgs, the first graph is absent. If Higgs triplets are present, a loop involving a doubly charged Higgs boson maybe necessary.

The fermiophobic benchmark scenario does not include the fermion loop, and the Higgs couplings to bosons are kept at SM values. This means there is no charged Higgs loop, and the Higgs coupling to $WW$ has a magnitude given by $gm_W$. 

X. EXPERIMENTAL HIGGS SEARCHES: INTRODUCTION

FIG. 14: Explanation of the typical plot for Higgs boson mass exclusion limit. No real data is shown.

Atlas, CMS and other Collaborations use plots like the one in Fig. 14 to seek hints of the Higgs boson and to exclude regions of mass where it is very unlikely to be found. The example in this figure is not real.

The vertical axis shows, as a function of the Higgs mass, the Higgs boson production cross-section that is excluded, divided by the expected cross section for Higgs production in the Standard Model at that mass. This is indicated by the solid black line. This is shown at 95% confidence level, which in effect means the certainty that a Higgs particle with the given mass does not exist.
The dotted black line shows the median (average) expected limit in the absence of a Higgs. The green and yellow bands indicate the corresponding 68% and 95% certainty of those values.

If the solid black line dips below the value of 1.0 as indicated by the red line, then we see from the data that the Higgs boson is not produced with the expected cross section for that mass. This means that those values of a possible Higgs mass are excluded with a 95% certainty. In this example, two regions would be ruled out at 95% certainty: approximately 135-225 GeV and 290-490 GeV.

If the solid black line is above 1.0 and also somewhat above the dotted black line (an excess), then there might be a hint that the Higgs exists with a mass at that value. If the solid black line is at the upper edge of the yellow band, then there may be 95% certainty that this is above the expectations. It could be a hint for a Higgs boson of that mass, or it could be a sign of background processes or of systematic errors that are not well understood. In this example, there is an excess and the solid black line is above 1.0 between about 225 and 290 GeV, but the excess has not reached a statistically significant level.

The red-gray shaded regions show what is excluded. The ”bump” near a mass of 250 GeV could be a slight hint of a Higgs boson in this fictional example.
XI. FERMIOPHOBIC HIGGS BOSONS

A search for a fermiophobic Higgs boson with diphoton events produced in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV was performed using data corresponding to an integrated luminosity of 4.9 fb$^{-1}$ collected by the ATLAS experiment.

A specific benchmark model is considered where all the fermion couplings to the Higgs boson are set to zero and the bosonic couplings are kept at the Standard Model values.

The production is not via gluon fusion, but via Vector Boson Fusion and Higgs-strahlung. The Higgs is searched via the decay $h_f \rightarrow \gamma\gamma$ with only the $W$ loop and with SM coupling.

Previous searches:

- LEP: $m_{h_f} < 109$ GeV.
- Tevatron: $m_{h_f} < 119$ GeV.

To enhance the sensitivity of the analysis, the data sample is split into nine categories, each with different expected signal mass resolutions, signal yields, and signal over background ratios (S/B). The component of the diphoton transverse momentum orthogonal to the diphoton thrust axis in the transverse plane is called $p_Tt$, with the following sketchy definition:

![FIG. 15: Sketch of the $p_Tt$ definition.](image-url)
In Fig. 16 we have the diphoton invariant mass for two of these categories.

FIG. 16: Diphoton invariant mass spectra for the low (high) $p_T$ categories, overlaid with the sum of the background-only fits from the individual categories. The bottom plot shows the residual of the data with respect to the fitted background. The signal expectation for a Higgs boson with a mass of 120 GeV is shown on top of the background fit.
In Fig. 17 we see the largest excess with respect to the background-only hypothesis at around 125.5 GeV, with a significance of 3.0, which diminishes to 1.6 when the “look elsewhere effect” is included.

![Graph showing observed and expected 95% confidence level limits for a fermiophobic Higgs boson normalized to fermiophobic cross section times branching ratio expectation as a function of Higgs boson mass hypothesis (mH).]

**FIG. 17:** Observed (black line) and expected (red line) 95% confidence level limits for a fermiophobic Higgs boson normalized to the fermiophobic cross section times branching ratio expectation as a function of the Higgs boson mass hypothesis (mH).

A CMS analysis is in preparation.
XII. CHARGED HIGGS BOSONS

A search of a charged Higgs boson was made with the ATLAS detector with 4.6 fb\(^{-1}\) of pp collisions at \(\sqrt{s} = 7\) TeV. The search is made among \(t\bar{t}\) events, i.e., the charged Higgs is produced from the decay

\[
t \rightarrow H^+ b
\]

(71)

which contains the assumption that the charged Higgs mass is smaller than the top quark mass, so \(H^+\) can be produced on-shell. An example of a production and decay shown in Fig. 18.

FIG. 18: Example of a leading-order Feynman diagram for the production of \(t\bar{t}\) events arising from gluon fusion, where one top quark decays to a charged Higgs boson, followed by \(H^+ \rightarrow \tau \nu\).

With the assumption that \(B(H^+ \rightarrow \tau \nu) = 1\) (reasonable for \(\tan \beta > 3\)), no excess over background was observed, as shown in Fig. 19. This leads to upper limits of \(B(t \rightarrow H^+ b)\) between 5% and 1% for charged Higgs masses between 90 and 160 GeV respectively.
FIG. 19: Expected and observed 95% CL exclusion limits on \( \mathcal{B}(t \rightarrow H^+b) \) for charged Higgs boson production from top quark decays as a function of \( m_{H^+} \), assuming \( \mathcal{B}(H^+ \rightarrow \tau \nu) = 100\% \) (left frame). Also 95% CL exclusion limits on \( \tan \beta \) as a function of \( m_{H^+} \). Results are shown in the context of the MSSM scenario \( m_{h}^{\text{max}} \) for the combination. The blue dashed lines indicate the theoretical uncertainties on \( \mathcal{B}(t \rightarrow bH^+) \).

Previous results from LEP and Tevatron are shown in Fig. 20. There are talks by CMS on their analysis on charged Higgs bosons.

FIG. 20: Charged Higgs related limits from LEP, CDF, and D0 respectively.
The CDF and D0 Collaborations have combined their results on SM Higgs boson searches at the Tevatron. With $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, CDF analyzed $8.2 \, fb^{-1}$ and D0 $8.6 \, fb^{-1}$, obtaining the exclusion plot in Fig. 21. We see the LEP exclusion limit of 114.4 GeV, and the Tevatron exclusion limit at 95% c.l. given by $156 < m_H < 177$ GeV.

They see a small 1σ “excess” of data with respect to background in the mass range $125 < m_H < 155$ GeV. The production mechanisms considered are Higgs-strahlung $q\bar{q} \rightarrow W/ZH$, gluon-gluon fusion $gg \rightarrow H$, and vector boson fusion $q\bar{q} \rightarrow q'\bar{q}'H$. The decay modes studied are $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$, $H \rightarrow ZZ$, $H \rightarrow \tau^+\tau^-$, and $H \rightarrow \gamma\gamma$. 
XIV. HIGGS SEARCHES WITH ATLAS AND CMS AT THE LHC

FIG. 22: ATLAS Detector.

FIG. 23: CMS Detector.
A. \( H \to WW^* \to \ell^+\nu\ell^-\bar{\nu} \) channel.

A search for the SM Higgs boson was done with the ATLAS detector in the channel \( H \to WW^* \to \ell^+\nu\ell^-\bar{\nu} \) where the lepton can be electron or muon. This is done in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV, with an integrated luminosity of \( 2.05 \text{ fb}^{-1} \). The decay mode \( H \to WW^* \) is dominant for \( m_H \lesssim 135 \) GeV, as we can see in Fig. 4.

Electron candidates are selected from clustered energy deposits in the electromagnetic calorimeter, with an associated track reconstructed in the inner detector. They are identified with an efficiency of 71\% for electrons with transverse energy \( E_T > 20 \) GeV and \( |\eta| < 2.47 \). Muons are reconstructed by combining tracks from the inner detector and muon spectrometer, with an efficiency of 92\% for \( p_T > 20 \) GeV and \( |\eta| < 2.4 \). Electrons and muons should be produced at the primary vertex, which should have more than 3 tracks. Both leptons should be isolated within a cone
\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.2
\] (72)

One important parameter is the invariant mass of the pair of leptons \( m_{\ell\ell} \), defined as,
\[
m_{\ell\ell}^2 = (p_{\ell_1} + p_{\ell_2})^2
\] (73)
If the two leptons have different flavours their invariant mass is required to be \( m_{\ell\ell} > 10 \) GeV, otherwise \( m_{\ell\ell} > 15 \). This is to suppress the background from \( \Upsilon \). In addition, to suppress the background from \( Z \) production it is required \( |m_{\ell\ell} - m_Z| > 15 \) GeV.

A second important variable is the azimuthal angle between the two leptons \( \Delta \phi_{\ell\ell} \), calculated simply with the product of the two 3-vectors,
\[
\vec{p}_{1T} \cdot \vec{p}_{2T} = |\vec{p}_{1T}| |\vec{p}_{2T}| \cos \Delta \phi_{\ell\ell}
\] (74)
This angle is used to exploit differences in spin correlations between signal and background: \( \Delta \phi_{\ell\ell} < 1.3 \) for \( m_H < 170 \) GeV, and \( \Delta \phi_{\ell\ell} < 1.8 \) for \( m_H < 120 \) GeV.
FIG. 24: $m_T$ distribution shown after all cuts for $m_H = 150$ GeV, except for the $m_T$ cut itself. The top graph shows the selection for the $H + (0 \text{ jet})$ channel and the bottom for the $H + (1 \text{ jet})$ channel. The background distributions are stacked, so that the top of the diboson background coincides with the Standard Model (SM) line which includes the statistical and systematic uncertainties on the expectation in the absence of a signal. The expected signal for $m_H = 150$ GeV is shown as a separate thicker line, and the final bin includes the overflow.

For the transverse mass $m_T$ we require $0.75m_H < m_T < m_H$ if $m_H < 220$ GeV, and $0.6m_H < m_T < m_H$ otherwise. These requirements reduce the $WW$ and top backgrounds.
TABLE III: The expected numbers of signal \((m_H = 150 \text{ GeV})\) and background events after the requirements listed in the first column, as well as the observed numbers of events in data. All numbers are summed over lepton flavor.

<table>
<thead>
<tr>
<th>(H + 0)-jet Channel</th>
<th>Signal</th>
<th>WW</th>
<th>(W + \text{ jets} Z/\gamma^* + \text{ jets})</th>
<th>(t\bar{t})</th>
<th>(tW/\bar{t}b/\bar{t}q)</th>
<th>(WZ/ZZ/W\gamma)</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Veto</td>
<td>99 ± 21</td>
<td>524 ± 52</td>
<td>84 ± 41</td>
<td>174 ± 169</td>
<td>42 ± 14</td>
<td>32 ± 8</td>
<td>15 ± 4</td>
<td>872 ± 182</td>
</tr>
<tr>
<td>(p_T^l &gt; 30 \text{ GeV})</td>
<td>95 ± 20</td>
<td>467 ± 45</td>
<td>69 ± 34</td>
<td>30 ± 12</td>
<td>39 ± 14</td>
<td>29 ± 8</td>
<td>13 ± 4</td>
<td>648 ± 60</td>
</tr>
<tr>
<td>(m_{\ell\ell} &lt; 50 \text{ GeV})</td>
<td>68 ± 15</td>
<td>118 ± 15</td>
<td>21 ± 8</td>
<td>13 ± 8</td>
<td>7 ± 4</td>
<td>5.8 ± 1.8</td>
<td>1.9 ± 0.6</td>
<td>166 ± 19</td>
</tr>
<tr>
<td>(\Delta\phi_{\ell\ell} &lt; 1.3)</td>
<td>58 ± 13</td>
<td>91 ± 12</td>
<td>12 ± 5</td>
<td>9 ± 6</td>
<td>6 ± 3</td>
<td>5.8 ± 1.8</td>
<td>1.7 ± 0.6</td>
<td>125 ± 15</td>
</tr>
<tr>
<td>(0.75 m_H &lt; m_T &lt; m_H)</td>
<td>40 ± 9</td>
<td>52 ± 7</td>
<td>5 ± 2</td>
<td>2 ± 4</td>
<td>2.4 ± 1.6</td>
<td>1.5 ± 1.0</td>
<td>1.1 ± 0.5</td>
<td>63 ± 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(H + 1)-jet Channel</th>
<th>Signal</th>
<th>WW</th>
<th>(W + \text{ jets} Z/\gamma^* + \text{ jets})</th>
<th>(t\bar{t})</th>
<th>(tW/\bar{t}b/\bar{t}q)</th>
<th>(WZ/ZZ/W\gamma)</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet</td>
<td>50 ± 9</td>
<td>193 ± 20</td>
<td>38 ± 21</td>
<td>74 ± 65</td>
<td>473 ± 124</td>
<td>174 ± 26</td>
<td>14 ± 2</td>
<td>967 ± 145</td>
</tr>
<tr>
<td>(b)-jet veto</td>
<td>48 ± 9</td>
<td>188 ± 19</td>
<td>35 ± 19</td>
<td>73 ± 61</td>
<td>174 ± 49</td>
<td>66 ± 11</td>
<td>14 ± 2</td>
<td>549 ± 83</td>
</tr>
<tr>
<td>(</td>
<td>p_T^{\ell\ell}</td>
<td>&lt; 30 \text{ GeV})</td>
<td>39 ± 7</td>
<td>154 ± 16</td>
<td>18 ± 9</td>
<td>38 ± 32</td>
<td>106 ± 30</td>
<td>50 ± 9</td>
</tr>
<tr>
<td>(Z \to \tau\tau \text{ veto})</td>
<td>39 ± 7</td>
<td>150 ± 17</td>
<td>18 ± 8</td>
<td>34 ± 23</td>
<td>102 ± 23</td>
<td>48 ± 8</td>
<td>9 ± 2</td>
<td>361 ± 38</td>
</tr>
<tr>
<td>(m_{\ell\ell} &lt; 50 \text{ GeV})</td>
<td>26 ± 6</td>
<td>33 ± 5</td>
<td>3.3 ± 1.4</td>
<td>8 ± 7</td>
<td>20 ± 7</td>
<td>11 ± 3</td>
<td>1.8 ± 0.5</td>
<td>77 ± 12</td>
</tr>
<tr>
<td>(\Delta\phi_{\ell\ell} &lt; 1.3)</td>
<td>23 ± 5</td>
<td>25 ± 4</td>
<td>2.1 ± 1.0</td>
<td>4 ± 6</td>
<td>17 ± 6</td>
<td>9 ± 3</td>
<td>1.5 ± 0.4</td>
<td>60 ± 10</td>
</tr>
<tr>
<td>(0.75 m_H &lt; m_T &lt; m_H)</td>
<td>14 ± 3</td>
<td>12 ± 3</td>
<td>0.9 ± 0.4</td>
<td>1.3 ± 1.9</td>
<td>8 ± 2</td>
<td>4.0 ± 1.6</td>
<td>0.7 ± 0.3</td>
<td>28 ± 4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control Regions</th>
<th>Signal</th>
<th>WW</th>
<th>(W + \text{ jets} Z/\gamma^* + \text{ jets})</th>
<th>(t\bar{t})</th>
<th>(tW/\bar{t}b/\bar{t}q)</th>
<th>(WZ/ZZ/W\gamma)</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WW 0)-jet ((m_H &lt; 220 \text{ GeV}))</td>
<td>1.7 ± 0.4</td>
<td>223 ± 30</td>
<td>20 ± 15</td>
<td>6 ± 8</td>
<td>25 ± 10</td>
<td>15 ± 4</td>
<td>8 ± 3</td>
<td>296 ± 36</td>
</tr>
<tr>
<td>(WW 0)-jet ((m_H \geq 220 \text{ GeV}))</td>
<td>10 ± 2</td>
<td>173 ± 23</td>
<td>24 ± 12</td>
<td>13 ± 19</td>
<td>15 ± 6</td>
<td>8 ± 3</td>
<td>3.3 ± 0.6</td>
<td>236 ± 33</td>
</tr>
<tr>
<td>(WW 1)-jet ((m_H &lt; 220 \text{ GeV}))</td>
<td>1.0 ± 0.3</td>
<td>76 ± 13</td>
<td>5 ± 5</td>
<td>5.6 ± 14</td>
<td>23 ± 3</td>
<td>5.3 ± 1.4</td>
<td>171 ± 21</td>
<td>184</td>
</tr>
<tr>
<td>(WW 1)-jet ((m_H \geq 220 \text{ GeV}))</td>
<td>5.8 ± 1.5</td>
<td>51 ± 9</td>
<td>3.9 ± 1.8</td>
<td>10 ± 10</td>
<td>35 ± 9</td>
<td>18 ± 4</td>
<td>2.8 ± 0.6</td>
<td>120 ± 17</td>
</tr>
<tr>
<td>(t\bar{t} 1)-jet</td>
<td>0.9 ± 0.3</td>
<td>3.9 ± 1.0</td>
<td>-</td>
<td>1 ± 17</td>
<td>184 ± 64</td>
<td>80 ± 19</td>
<td>0.2 ± 0.9</td>
<td>270 ± 69</td>
</tr>
</tbody>
</table>

In Table III we show the cutflow for these cuts for the two cases \(H + 0\)-jet and \(H + 1\)-jet. The expectations for background and signal compatible with a Higgs boson with \(m_H = 150 \text{ GeV}\) are compared to the data after successive applications of cuts.
In Fig. 25 we see a detail on the $m_T$ distribution. To the total background a signal corresponding to a SM Higgs with mass $m_H = 130$ GeV has been added.
FIG. 26: The expected (dashed) and observed (solid) 95% CL upper limits on the cross section, normalized to the Standard Model cross section, as a function of the Higgs boson mass. Expected limits are given for the scenario where there is no signal. The vertical lines in the curves indicate the points where the selection cuts change, and the bands around the dashed line indicate the expected statistical fluctuations of the limit.

No significant excess of events is observed, with the maximal deviation observed being $1.9\sigma$ at low Higgs mass. The Higgs boson is excluded at $145 < m_H < 206$ GeV.

FIG. 27: CMS limits.

No excess is observed by CMS neither.
B. $H \to ZZ^* \to 4\ell$ channel.

A search for the SM Higgs boson has been done with the ATLAS detector in the channel $H \to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$ with $\ell, \ell' = e, \mu$. The analysis was performed with $4.8 \text{fb}^{-1}$ of luminosity in $pp$ collisions at $\sqrt{s} = 7$ TeV. The decay mode $H \to ZZ$ is the second dominant for masses $m_H > 160$ GeV, and with a BR larger than $10^{-2}$ for $m_H > 120$ GeV, as seen in Fig. 4. In addition, in Fig 13 we see that the decay mode $H \to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$ has a $\sigma BR$ value between $10^{-3}$ and $10^{-2}$ pb in a very large range of Higgs masses, including the low mass region. This makes the decay mode very important.

![Graph showing the $m_{4\ell}$ distribution](image)

**FIG. 28:** $m_{4\ell}$ distribution of the selected candidates, compared to the background expectation. Error bars represent 68.3 % central confidence intervals. The signal expectation for several $m_H$ hypotheses is also shown.

The $m_{4\ell}$ distribution for the total background and several signal hypotheses is compared to the data in Fig. 28.
FIG. 29: The expected (dashed) and observed (full line) 95% CL upper limits on the Higgs boson production cross section as a function of the Higgs boson mass, divided by the expected SM Higgs boson cross section. The green and yellow bands indicate the expected sensitivity with ±1σ and ±2σ fluctuations, respectively.

Fig. 29 shows the expected and observed 95% c.l. cross sections upper limits as a function of $m_H$. The SM Higgs boson is excluded at 95% c.l. in the mass ranges $135 < m_H < 156$ GeV, $181 < m_H < 234$ GeV, and $255 < m_H < 415$ GeV.

The most significant deviations from the background-only hypothesis are observed for $m_H = 125$ GeV with 2.1σ, $m_H = 244$ GeV with 2.3σ, and $m_H = 500$ GeV with 2.2σ.
FIG. 30: Event display of a $4\mu$ candidate event with $m_{4\mu} = 124.6$ GeV. The masses of the lepton pairs are 89.7 GeV and 24.6 GeV.

In Fig. 30 we show an ATLAS $4\mu$ event. The pair of muons coming from the on-shell $Z$ has an invariant mass of 89.7 GeV, while the off-shell $Z$ has an invariant mass of 24.6 GeV. One of the muons is detected by a Thin Gap Chamber.
Small excesses are observed by CMS at 119 and 126 GeV.
C. \( H \rightarrow \gamma\gamma \) channel.

A search for the SM Higgs boson was done with the ATLAS Detector in the channel \( H \rightarrow \gamma\gamma \), with 4.9 fb\(^{-1}\) of integrated luminosity with \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. In Fig. 4 we see that the branching ratio \( B(H \rightarrow \gamma\gamma) \) is of the order \( 10^{-3} \), with a \( \sigma \times \text{BR} \) value between \( 10^{-2} \) and \( 10^{-1} \) pb, as seen in Fig 13. It is one of the most important decay modes in the low mass region.

Events are required to contain a primary vertex with at least three tracks with \( p_T > 0.4 \) GeV. The \( E_T \) of the leading and sub-leading photon is required to be larger than 40 and 25 GeV respectively. The photon identification efficiency ranges typically from 65\% to 95\% for \( E_T \) between 25 to 80 GeV.

![Inclusive diphoton sample](image)

**FIG. 32:** Invariant mass distribution for the inclusive data sample, overlaid with the sum of the background-only fit and the signal expectation for a mass hypothesis of 120 GeV corresponding to the SM cross section. The figure below displays the residual of the data with respect to the background-only fit sum.

In Fig. 32 we plot the di-photon mass distribution \( m_{\gamma\gamma} \) for the about 22500 events passing
the selection in the range $100 < m_{\gamma\gamma} < 160 \text{ GeV}$. The red solid line indicates the background only scenario. Also shown is the signal expectation for a SM Higgs boson with mass 120 GeV. Notice the excess of events near 125 GeV.

![Diagram](image)

**FIG. 33:** The observed and expected 95% confidence level limits, normalised to the SM Higgs boson cross sections, as a function of the hypothesized Higgs boson mass.

In Fig. 33 we see the 95% c.l. limits on the ratio of the inclusive production cross section of a SM-like Higgs boson relative to the SM model cross section. Very small Higgs mass regions are ruled out: $114 < m_H < 115 \text{ GeV}$ and $135 < m_H < 136 \text{ GeV}$. Over the di-photon mass range $110 < m_{\gamma\gamma} < 150 \text{ GeV}$ the maximum deviation from the background-only expectation is observed at 126 GeV, with a local significance of 2.8 standard deviations.
FIG. 34: CMS limits.

CMS sees an excess at 124 GeV.
D. ATLAS and CMS: all channels combined

A preliminary combination of SM Higgs searches with the ATLAS Experiment has been made, with a dataset corresponding to an integrated luminosity of up to $4.9 \text{ fb}^{-1}$ of $pp$ collisions collected at $\sqrt{s} = 7 \text{ TeV}$ at the LHC.

![Graph](image)

**FIG. 35:** The combined upper limit on the Standard Model Higgs boson production cross section divided by the Standard Model expectation as a function of $m_H$ is indicated by the solid line. This is a 95% CL limit using the CLs method in the entire mass range. The dotted line shows the median expected limit in the absence of a signal and the green and yellow bands reflect the corresponding 68% and 95% expected regions.
The combination, in terms of the observed and expected upper limits at the 95% c.l. on the Higgs boson production cross section, normalized to the SM value, of all channels is shown in Fig. 35. The observed 95% c.l. exclusion regions are $112.7 < m_H < 115.5$ GeV, $131 < m_H < 237$ GeV, and $251 < m_H < 468$ GeV.

An excess of events is observed at $m_H = 126$ GeV with a local significance of $3.6\sigma$, diminishing to $2.2\sigma$ with the look elsewhere effect in the interval $110 – 600$ GeV. This excess is observed by ATLAS in the three channels: $H \rightarrow \gamma\gamma$ with $2.8\sigma$, $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ with $2.1\sigma$, and $H \rightarrow WW^* \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ with $1.4\sigma$.

CMS Collaboration has also reported a smaller excess compatible with a SM Higgs boson with mass in the vicinity of 124 GeV and below, with a local significance of $3.1\sigma$, diminishing to $2.1\sigma$ if the mass interval is $110 – 145$ GeV, or to $1.5\sigma$ for the full interval $110 – 600$ GeV.

![Graph showing the 95% CL limit on the cross section normalized to the SM value.](image)

**FIG. 36**: CMS limit.
More data is needed to study this excess.

2012 is the year when the Higgs boson most likely will either be discovered or ruled out.

If the excess at 125 GeV is confirmed as a new particle consistent with the Higgs boson, we would have given the first step to understand the mechanism by which gauge bosons and elementary fermions acquire mass.