6. Higgs Physics at LHC

On July 4th of this year ATLAS & CMS announced the discovery of a new particle with a mass around 126 GeV. While it is too early to be sure that the new particle is indeed the Higgs boson H, the pattern of its decays fits (so far) perfectly with the behavior of the SM Higgs.

The July announcement was the culmination of a long and ever intensifying search for this particle which is an important part of the SM, which was postulated 45 years ago.

We will not review the Higgs mechanism (Brout, Englert, Higgs, ... 1964), but focus on its signatures at LHC and the theoretical and experimental challenges one has to face to study it.

Two things made the search difficult:

1.) The SM does not predict the H-mass.

2.) The H-boson coupling to other particles is proportional to their mass, i.e. it couples to heavy particles.

While 1.) is an inconvenience, 2.) poses severe challenges since we only collide light particles and also only detect light particles.

In practice 2.) translates into tiny H cross sections, competing against huge backgrounds.
Only about 1 in 10^{10} proton collisions* results in a Higgs boson. Taking into account that we are only able to see the signal in selected channels, the rate drops to 1 in every $2 \cdot 10^{12}$ collisions.

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* → about 5/minute !

6.1. Higgs couplings in the SM

Parametrize $\quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = U(x) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

vacuum exp. value $\qquad$ physical Higgs.

$U(x)$ is a $SU(2)$ matrix, containing the massless excitations of the Higgs field. These would-be Goldstone bosons get eaten by the $W^\pm$ and Z bosons. The simplest way to see this is to make a gauge transformation which eliminates $U(x)$ from $\mathcal{L}_{SM}$: unitary gauge.

The electron mass arises from

$$\Delta\mathcal{L} = -\lambda_e \overline{E}_L \phi\, e_R + \text{h.c.} = -\frac{\lambda_e}{\sqrt{2}} \overline{e}_L e_R (v+h) + \text{h.c.}$$

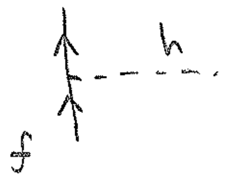
$$\begin{pmatrix} \overline{\nu}_e \\ \overline{e}_L \end{pmatrix}^T$$

$$= - m_e \overline{e}_L e_R \left(1 + \frac{h}{v}\right) + \text{h.c.}$$

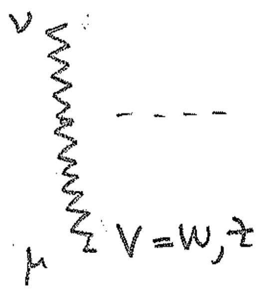
$$= - m_e \overline{e} e \left(1 + \frac{h}{v}\right)$$

So the coupling is proportional to the electron mass.

Going through the rest of $\mathcal{L}_{SM}$, one reads off the following Feynman rules:



$$= -i\,\frac{m_f}{v}$$

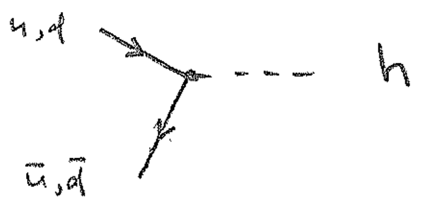


$$= 2i\,\frac{m_V^2}{v}\,g^{\mu\nu}$$

$$= -3i\,\frac{m_h^2}{v}$$

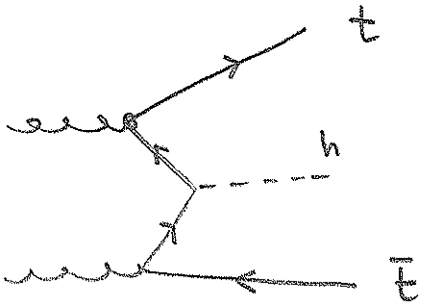
6.2. Higgs production

The direct production



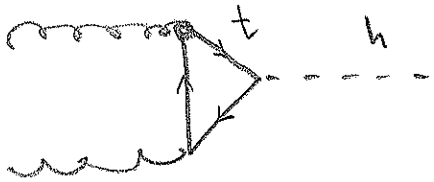
$\propto m_{u,d}$

is completely negligible. Since $m_t^2/m_{u,d}^2 \sim 10^9$ it is more efficient to couple to top quark:



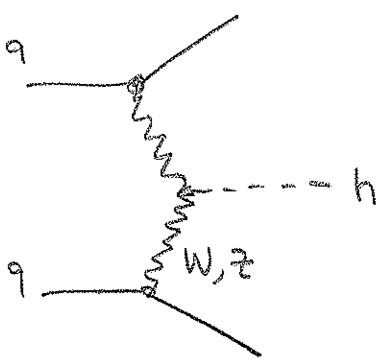
"$t\bar{t}$ - fusion"

but this needs gg with high energy, i.e. high x (momentum fraction)
⇝ suppression from PDF. It is more efficient to keep the top virtual



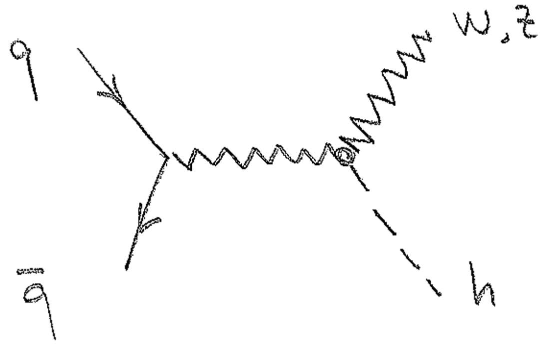
"gluon fusion"

This is the largest production cross section
~10 * larger than



"vetor-boson fusion"

which is ~ 6x larger than



"associated production"

(main production channel at e^+e^- colliders.)

which, in turn, is about twice as large as the $\bar{t}t$ fusion discussed above.

Let us look at gluon fusion in more detail. At leading order, one obtains

$$x_t = \frac{4m_t^2}{m_H^2} \approx 8$$

$$|\mathcal{M}(gg \to H)|^2 = \frac{\alpha_s^2(\mu_f)\, m_H^4}{576\pi^2\, v^2} \cdot |A(x_t)|^2$$

$$A(x) = 3x\,(2 + (4x-1) f(x)) = 1 + \frac{1}{4x} + \mathcal{O}\left(\frac{1}{x^2}\right)$$

$$f(x) = \arcsin^2 \frac{1}{\sqrt{x}}$$

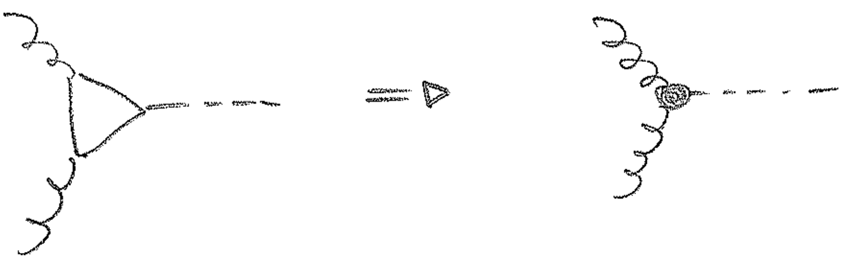
We can expand around $m_t \to \infty$ / $x_t \to \infty$.

The cross section in this limit can be obtained from the effective Lagrangian

$$\mathcal{L}_{eff} = C_t \cdot \frac{\alpha_s(\mu)}{12\pi} \cdot \frac{H}{v} G^a_{\mu\nu} G^{\mu\nu,a}$$

$$\uparrow$$

$$C_t = 1 + \mathcal{O}(\alpha_s)$$



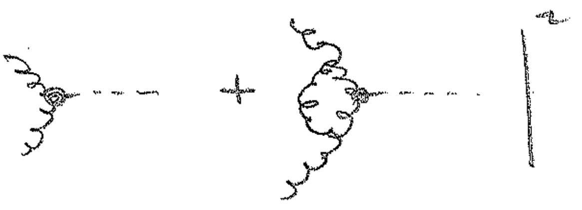
The Higgs production cross section at LO is obtained as

$$\sigma = \int dx_1 \int dx_2 \; f_g(x_1, \mu_F) f_g(x_2, \mu_F) \cdot \hat{\sigma}_{gg \to H}(\hat{s}, \mu_F)$$

where $\hat{\sigma} = \frac{\pi}{\hat{s}} \delta(\hat{s} - m_H^2) \, |M|^2$

Let us now write down all diagrams needed for NLO accuracy:

<u>virtual:</u> $\sigma_{gg \to H} \sim$



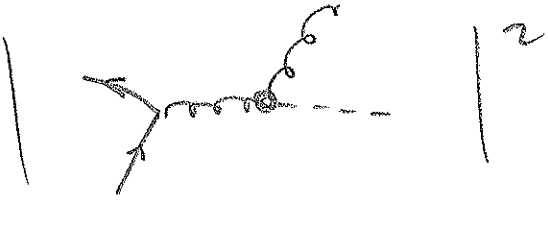
(all other loops vanish)

<u>real:</u>

$\sigma_{gg \to H+g} \sim$

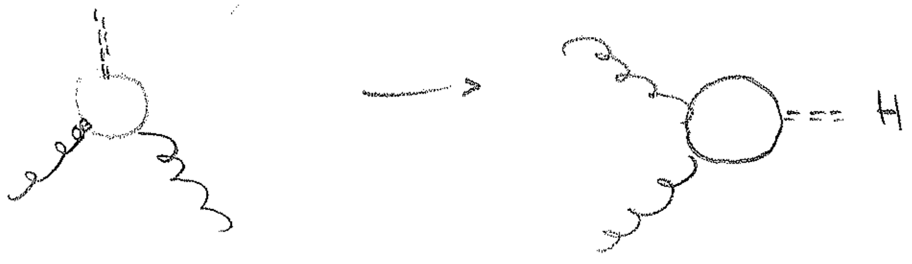
$\sigma_{gq \to H+q} \sim$

$\sigma_{q\bar{q} \to H+g} \sim$



It turns out that these corrections are huge: 130% if the PDFs are held fixed. Also the NNLO corrections are known and are 80% of the LO result! (see figures.)

The increase is mostly due to virtual corrections. In 0808.3008, we have identified the source of the corrections. They arise when the scalar form factor is continued from space-like to time-like momenta and can be resummed to all orders.



$C_V(q^2) \qquad\qquad C_V(-m_H^2)$

The relevant terms are $C_A \frac{\alpha_s}{2\pi} \ln^2(-1) \sim C_A \alpha_s \pi/2$

$\sim 0,6.$

6.3. Higgs decay

Again, the Higgs likes to decay into the heaviest available final states. The branching ratios are: (for $m_H = 126\,GeV$)

$h^0 \to \bar{b}b$ 56%

$h^0 \to WW^*$ 23%

$h^0 \to gg$ (via top loop) 8.5%

$h^0 \to \tau^+\tau^-$ 6.2%

(*) $h^0 \to ZZ^*$ 2,9%
$\hookrightarrow e^+e^-e^+e^-$ 0,125%

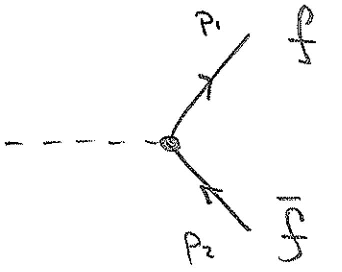
$h^0 \to c\bar{c}$ 2,6%

(*) $h^0 \to \gamma\gamma$ 0,23%

Because of the large backgrounds the two (*) decay modes were most important for the discovery.

Let us compute the decay to fermions *

$\mathcal{M}$ =



$$= -\frac{m_f}{v}\,\bar{u}(p_1)\,v(p_2)$$

$$\mathcal{M}^{+} = -\frac{m_f}{v}\,\bar{u}(p_1)\,u(p_2)$$

$$\sum_{\text{spins}} \mathcal{M}\mathcal{M}^{+} = \frac{m_f^2}{v^2}\sum_{\text{spins}} \bar{u}(p_1)\,v(p_2)\,\bar{v}(p_2)\,v(p_1)$$

$$= \frac{m_f^2}{v^2}\,\mathrm{tr}\left\{(\not{p}_2 - m_f)(\not{p}_1 + m_f)\right\}$$

$$= \frac{4m_f^2}{v^2}\left(p_1\cdot p_2 - m_f^2\right) = \frac{2m_f^2}{v^2}\left((p_1+p_2)^2 - 4m_f^2\right)$$

$$= \frac{2m_f^2}{v^2}\,m_H^2\left(1 - \frac{4m_f^2}{m_H^2}\right)$$

Decay rate: $\Gamma(h \to \bar{f}f) = \frac{1}{2m_H}\int dPS_2\,|\mathcal{M}|^2$

↑ two-body phase space.

$$\int dPS_2 = \frac{1}{8\pi}\left(1 - \frac{4m_f^2}{m_H^2}\right)^{1/2}.$$

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* It is somewhat problematic to work with Higgs bosons in the initial or final state. Since it is unstable, there is, strictly speaking, no Higgs particle.

%

The rate is then

$$\Gamma(h \to \bar{f} f) = \frac{1}{8\pi} \frac{m_f^2}{v^2} m_H \left(1 - \frac{4 m_f^2}{m_H^2}\right)^{3/2}$$

Note: for quarks there are 3 colors; multiply the above result by 3!

Branching ratio: $Br(h \to f\bar{f}) = \dfrac{\Gamma(h \to f\bar{f})}{\Gamma_{tot}}$

6.4. Higgs measurement

Because of the large QCD background from QCD production of $b\bar{b}$ pairs, the main channel $gg \to H \to \bar{b}b$ cannot be used. The discovery was ~~based~~ on the two decays

$$h^\circ \to \gamma\gamma$$

$$h^\circ \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$$

Our treatment is OK in the limit $\Gamma/m_h \to 0$. Since $\Gamma_{tot} = 4{,}18 \cdot 10^{-3}$ GeV the narrow-width treatment is appropriate.

which are rare, but have the advantage that the Higgs mass can be fully reconstructed: the signal gives rise to a mass peak and the background can be obtained from a side-band fit.

These chanels also open the possibility to study the spin of the boson. The cross section for $h^0 \to \gamma\gamma$ is isotropic, while a spin 2 resonance would give

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

(Gao et. al. 1001.3396)

At HCP, CMS presented results from a $h \to ZZ^* \to 4\ell$ study, which wants to discriminate between the CP even h^0 and a pseudoscalar A^0 which would couple as

$$\Delta\mathcal{L} = \frac{A^0}{v}\,\varepsilon^{\mu\nu\rho\sigma} Z_{\mu\nu} Z_{\rho\sigma}.$$

By now ATLAS and CMS also see signals in a series of other chanels. These include

* $\underline{h^0 \to W^+W^- \to \ell^+\nu\, \ell^-\bar{\nu}}$

This chanel has much more events than $\gamma\gamma$ or ZZ but suffers from missing energy (neutrinos).

It also suffers from $t\bar{t} \to bW^+\bar{b}W^-$ background. The background can be reduced by imposing a jet veto ($t\bar{t}$ will have two b-jets).

* $\underline{pp \to Z + h^0 \to e^+e^-\, b\bar{b}}$

Background nontrivial. Tevatron saw an excess of events in this chanel. Not confirmed by LHC.

* $\underline{h^0 \to \tau\tau}$

Challenging because of the τ reconstruction. Decay

$\tau \to \mu\,\bar{\nu}_\mu\,\nu_\tau$; $\tau \to e\,\bar{\nu}_e\,\nu_\tau$; $\tau \to$ hadrons $+ \nu_\tau$

involve missing energy.

It is interesting to consider many decay modes. As we have seen, all the Higgs couplings are fixed in the SM. To make sure that the particle is indeed the Higgs boson, one wants to check the coupling strengths.

The results (see Figures) are all consistent with the SM, but the precision is low. That the orders of magnitude of the couplings are of SM size indicates that the boson is a Higgs boson. On the other hand 50% deviations from the SM are in many cases still allowed. So there is room for New Physics.