Introduction to Higgs Physics (2nd Lesson)

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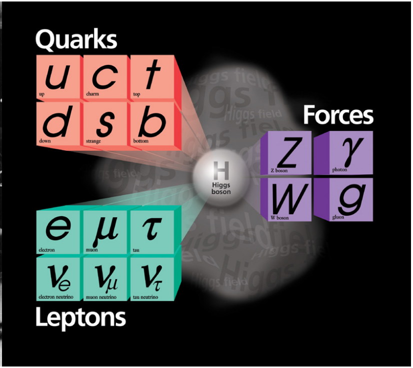
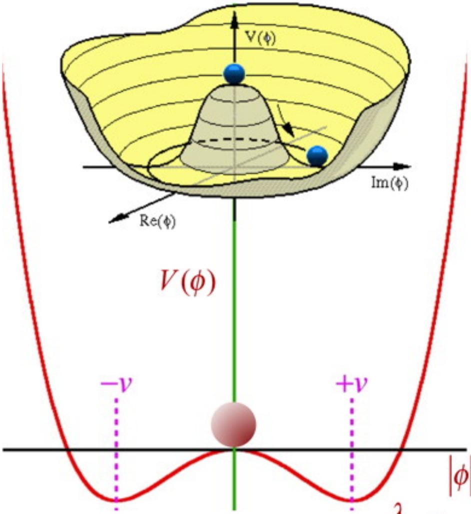
The Standard Model (SM)

- Matter is made of quarks and leptons,
- Forces are associated with gauge symmetries,
- Masses arise from spontaneous symmetry breaking (SSB),



In the SM a Higgs doublet can work (Minimal)



$$V(\phi) = \tfrac{1}{2}\mu^2\phi^\dagger\phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$

$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$$

$$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$$

SM Higgs interactions

SM lagrangian for a Higgs doublet $\Phi = (\phi^+, \phi^0)$ includes:

- Gauge ints. $\rightarrow$ Gauge boson masses,

  i.e. $\mathcal{L}_{HV} = (D^\mu \Phi)^\dagger (D_\mu \Phi)$

- Yukawa sector $\rightarrow$ fermion masses,

  i.e. $\mathcal{L}_Y = Y_u Q_L \Phi u_R$, etc.

- Higgs potential $V(\Phi) \rightarrow$ SSB and Higgs mass,

  i.e. $V(\Phi) = \lambda(|\Phi|^2 - v^2)^2$,

- One unknown parameter λ,
  - it determines Higgs mass: $m_h \simeq \lambda v$

SM Yukawa lagrangian - 1 family

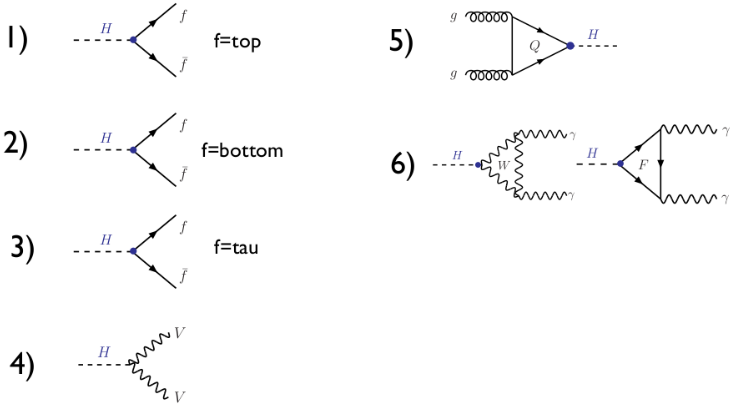
$$\mathcal{L}_Y = y_d \bar{Q}_L \Phi d_R + y_u \bar{Q}_L \Phi u_R + h.c. \quad (1)$$

- $\bar{Q}_L = (\bar{u}_L, \bar{d}_L)$, $\quad \Phi = (\phi^+, \phi^0)^T$,
- After SSB: $\quad \phi^0 = \frac{1}{\sqrt{2}}(v + h + iG_z)$
- $\bar{Q}_L \Phi = (\bar{u}_L, \bar{d}_L)(\phi^+, \phi^0)^T = \bar{u}_L \phi^+ + \bar{d}_L \phi^0$
- $\bar{Q}_L \Phi d_R = \bar{u}_L d_R \phi^+ + \bar{d}_L d_R \phi^0$
- $y_d \bar{Q}_L \Phi d_R = (\bar{d}_L d_R) y_d \frac{1}{\sqrt{2}}(v + h + iG_z)$

$$\mathcal{L}_Y = \frac{1}{\sqrt{2}}(y_d v + y_d h)\bar{d}_L d_R + ... \quad (2)$$

$\rightarrow m_d = \frac{1}{\sqrt{2}} y_d v \quad$ and $\quad (hdd) = \frac{m_d}{v}$

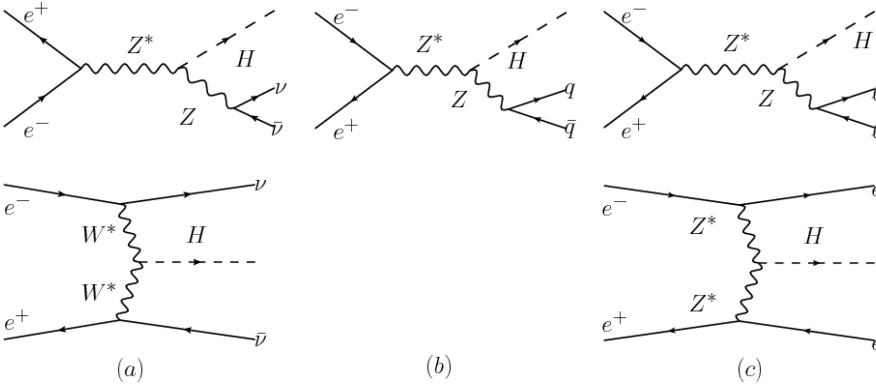
Higgs couplings



- $(hVV): \quad \frac{2m_V^2}{v}, \qquad (hff): \quad \frac{m_f}{v}$
- $(hhh): \quad \frac{3}{2}\lambda v, \qquad (hhhh): \quad \frac{3}{2}\lambda$

Busqueda de efectos directos del Higgs

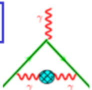
- Busqueda en LEP2: $e^+e^- \to Z + h \to m_h > 115\text{GeV}$



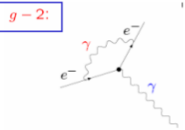
- Busqueda en Tevatron

Efectos indirectos del boson de Higgs

Precision Physics in the SM



QED: $g-2$:

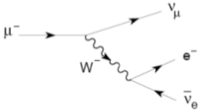


$a = \frac{1}{2}(g-2)$

$a_{\text{exp}} = 1\,159\,652\,188(\pm 4)\times 10^{-12}$

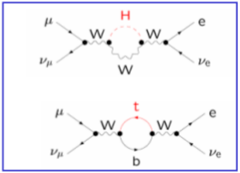
$a_{\text{theo}} = 1\,159\,652\,157(\pm 28)\times 10^{-12}$

EW: $\begin{cases} G_F \\ M_Z,\, \Gamma_Z,\, g_V,\, g_A,\, \sin^2\theta_{\text{eff}},\, \ldots \\ M_W,\, m_t \end{cases}$

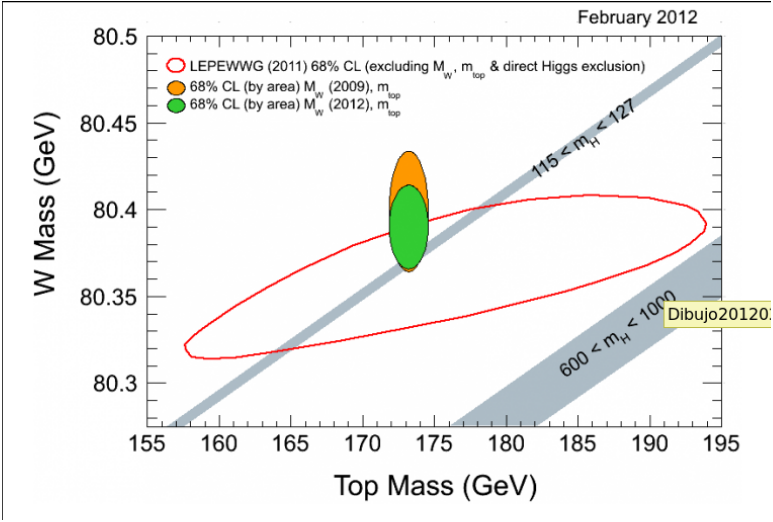


$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}(1+\Delta r)$$

$$\Delta r = \Delta r(m_t, M_H)$$



Radiative Constraints on m_h:



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→ light Higgs, i.e. with a mass of order of EW scale, ($m_{\phi_{SM}} \simeq v$).

SM Higgs Phenomenology

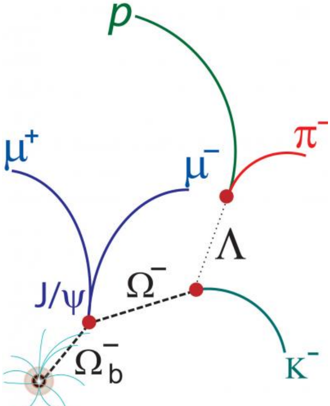
First, one need to study decay modes for a light Higgs:

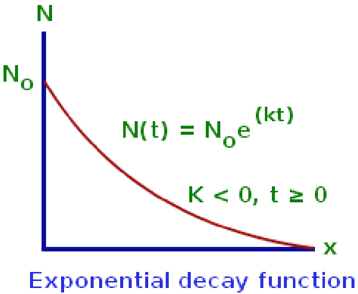
- $h \to b\bar{b}$,
- $h \to \tau^+\tau^-$,
- $h \to \gamma\gamma$ (top and W loops) (Ellis, Gaillard, Nanopoulos),
- $h \to gg$ (top loop) (Georgi, Glashow, Machacek, Nanopoulos)
- $h \to WW^*, ZZ^*$ (Keung, Marciano)
- $h \to t\bar{t}$

$$B.R.(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma_{total}} \tag{3}$$

The decay Width?

- Schroedinger equation: $H|\psi>= i\frac{d}{dt}|\psi>$
- The Hamiltonian for an unstable particle at rest: $H = M - i\frac{\Gamma}{2}$,
- $\psi(t) = \psi(0)e^{-iHt} = \psi(0)e^{-iMt}e^{-\Gamma t/2}$
- $|\psi|^2 = |\psi(0)|^2 \, e^{-\Gamma t}$





SM Higgs decay into fermion pairs

For the decay: $h(p) \to f(p_1)\bar{f}(p_2)$

$$M(h \to f\bar{f}) = \frac{-igm_f}{2m_W}\bar{u}(p_1)(1)v(p_2), \quad (4)$$

Kinematics:

- Energy-momentum conservation: $p = p_1 + p_2$,
- In rest frame of Higgs: $p = (m_h, 0)$,
- $p^2 = m_h^2$, $p_1^2 = m_f^2 = p_2^2$,
- $p.p_1 = m_h E_1$, $p.p_2 = m_h E_2$, $2p_1.p_2 = m_h^2 - 2m_f^2$,

SM Higgs decay into fermion pairs

$$d\Gamma(h \to f\bar{f}) = \frac{1}{8\pi^2 m_h}|M(h \to f\bar{f})|^2 d_2(PS) \tag{5}$$

Then,

$$\Gamma(h \to f\bar{f}) = N_c \frac{g^2}{32\pi}\frac{m_f^2}{m_W^2}[1 - 4\frac{m_f^2}{m_h^2}]^{3/2} \tag{6}$$

where:

- $N_c = 3\,(1)$ for quarks (leptons),
- The exponent 3/2 signals that the Higgs is an SCALAR (would be 1/2 if it were a pseudoscalar),
- $m_f = m_f(Q^2)$ (RGE), ex. $m_b(M_Z) \simeq 3.5$ GeV,

Higgs Decay widths

$$\Gamma(h \to f\bar{f}) = N_c \frac{g^2}{32\pi} \frac{m_f^2}{m_W^2} [1 - 4\frac{m_f^2}{m_h^2}]^{3/2} \quad (7)$$

$$\Gamma(h \to gg) = \frac{\alpha_s^2 g^2 m_h^3}{128\pi^3 m_W^2} |I_g(r_x)|^2 \quad (8)$$

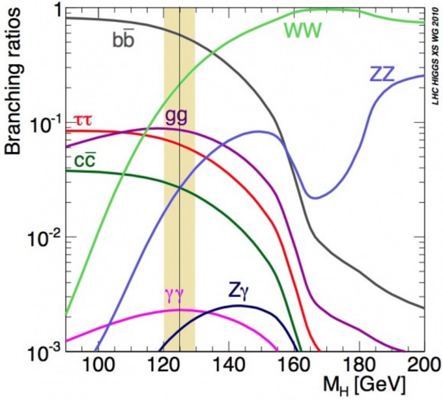
$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 g^2 m_h^3}{1024\pi^3 m_W^2} |I_\gamma(r_x)|^2 \quad (9)$$

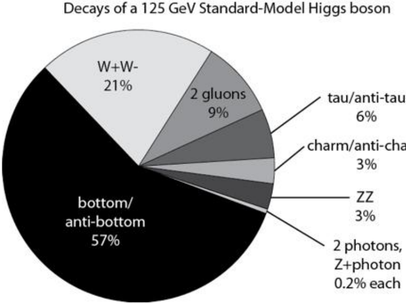
$$\Gamma(h \to WW^*) = \frac{3g^4 m_h}{512\pi^3} F_{3b}(m_W/m_h) \quad (10)$$

where $r_x = 4m_x^2/m_h^2$, and analogous expression can be written for: $\Gamma(h \to \gamma Z)$ and $\Gamma(h \to ZZ^*)$

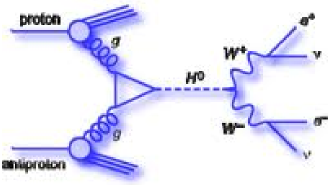
Tarea: 2) Estimate: $BR(h \to \tau\tau)$,

Higgs B.R.'s


Branching ratios
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
180
200
M_H [GeV]
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
LHC HIGGS XS WG 2010


Decays of a 125 GeV Standard-Model Higgs boson
W+W-
21%
2 gluons
9%
tau/anti-tau
6%
charm/anti-cha
3%
ZZ
3%
2 photons,
Z+photon
0.2% each
bottom/
anti-bottom
57%

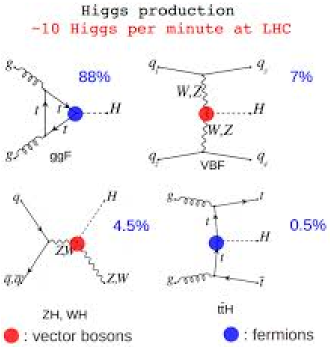
Higgs production at $pp/p\bar{p}$ colliders (LHC/Tevatron)



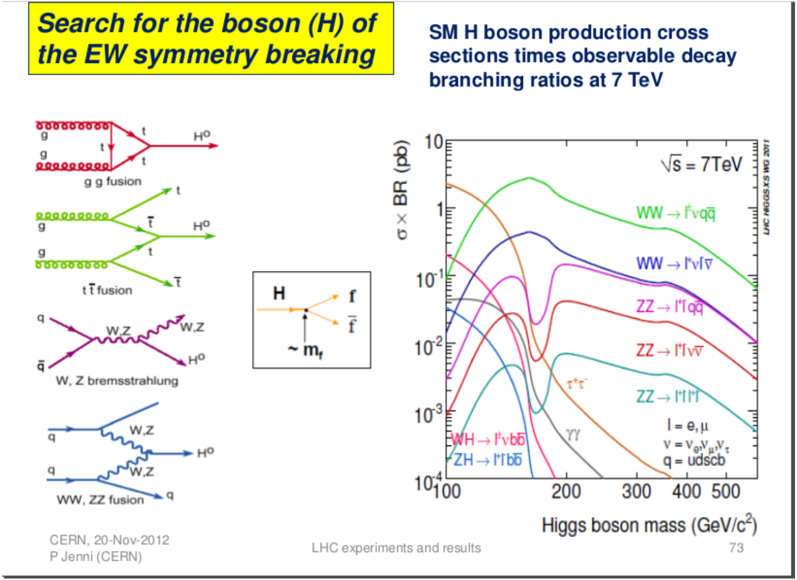
$$\sigma_{had} = \sum_{ij} \int f_i(x_1, Q^2)\, f_i(x_2, Q^2)\, dx_1 dx_2\, \hat{\sigma}_{parton} \tag{11}$$

$$\sigma_{gg} = \int f_g(x_1, Q^2)\, f_g(x_2, Q^2)\, dy\, \frac{\pi^2 \Gamma(h \to gg)}{8m_h^2} \tag{12}$$

Higgs cross sections



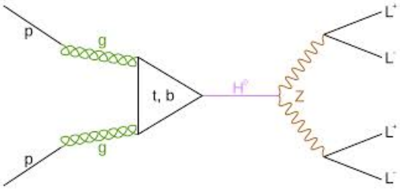
Higgs cross sections → No. ef events

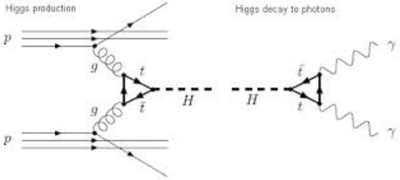


Higgs cross sections → No. ef events

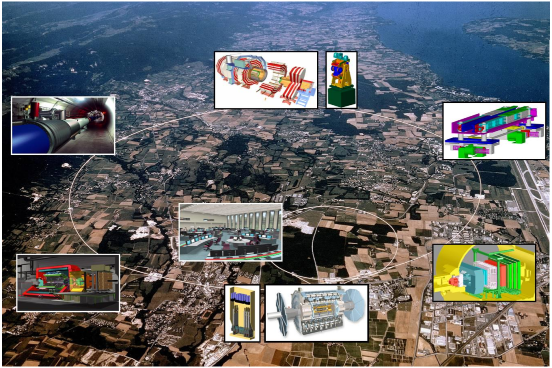
- Total Production cross section
  $\sigma * Br = \sigma(pp \to h + X) \times BR(h \to YY)$
- Need to look for interesting modes,
- No. of events= $\sigma * Br * I.L.$
- Integrated Luminosity= No. of colisions per unit area,
- ex. With $IL(LHC) = 13\, fb^{-1} = 13 \times 10^3 pb^{-1}$ and
  $\sigma(pp \to h \to \gamma\gamma) = 4 \times 10^{-2}$ pb for $m_h = \simeq 125$ GeV
  $\to 520$ Events!
- Signal vs Background: only a fraction of those 500's events will be detected,

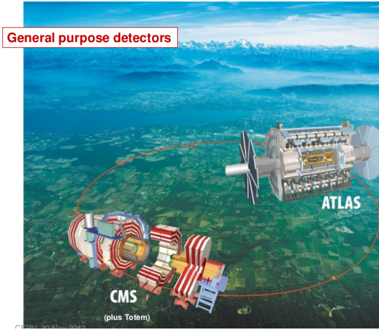
Higgs cross sections



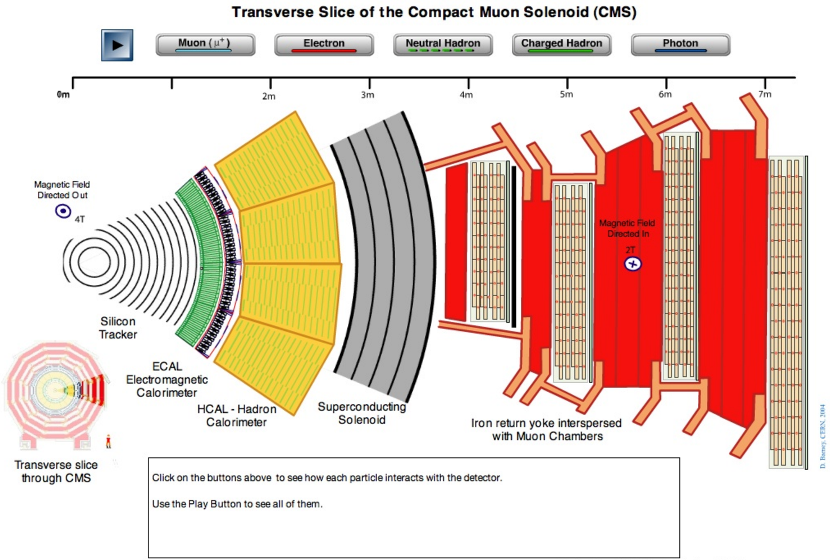


Higgs search- LHC



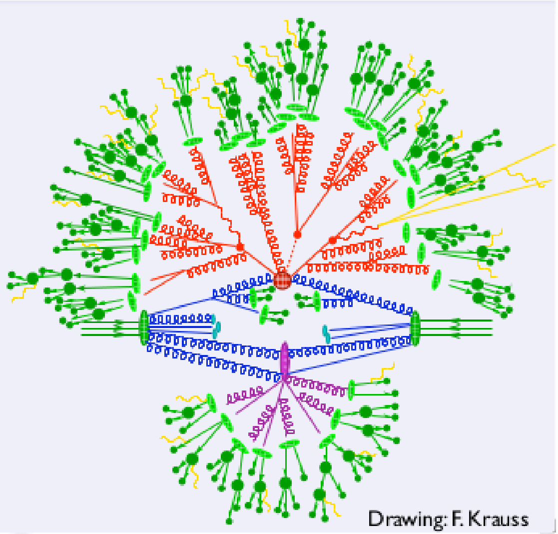


Higgs search- LHC

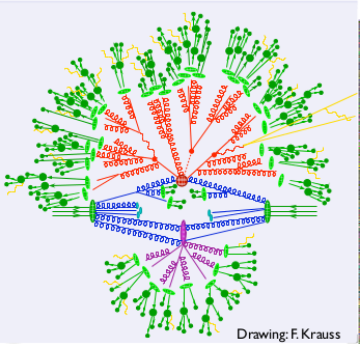


Derived from CMS Detector Slice from CERN

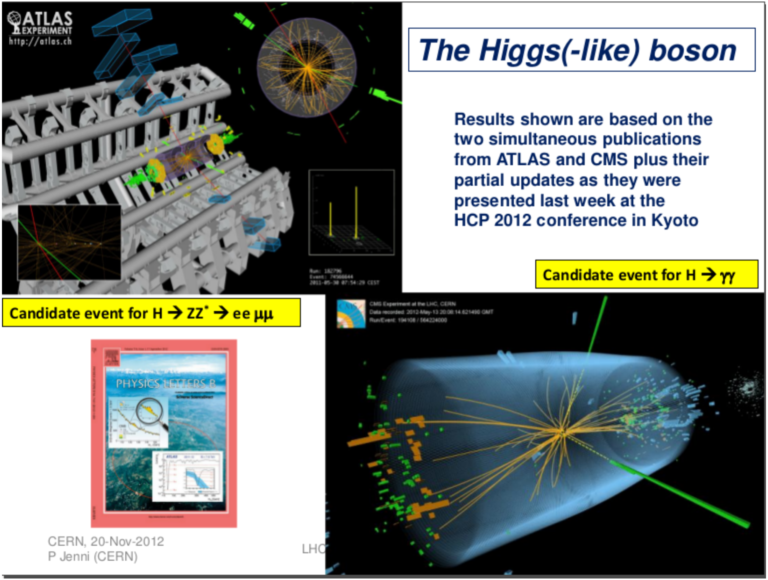
Higgs search- LHC



Higgs search- LHC



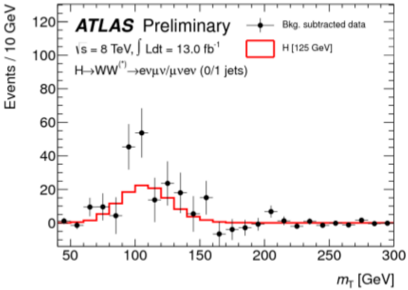
The Higgs-dependence day



The Higgs-dependence day

Higgs search- LHC

To get a feeling for the number of events, and of the background-subtracted distributions (example ATLAS)



	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* + \text{jets}$	$W + \text{jets}$	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

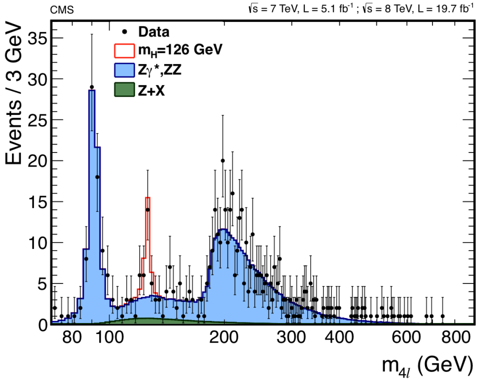
Updated: ATLAS-CONF-2012-158

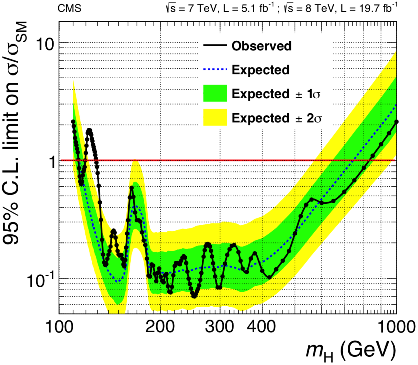
CERN, 20-Nov-2012
P Jenni (CERN)

LHC experiments and results

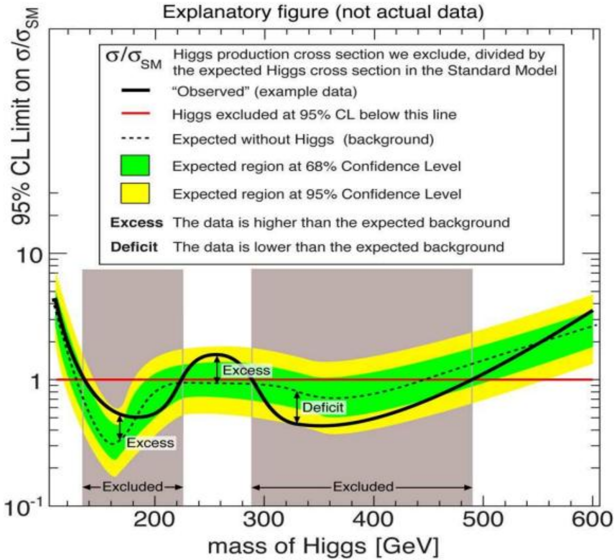
80

Higgs search- CMS -ZZ Channel

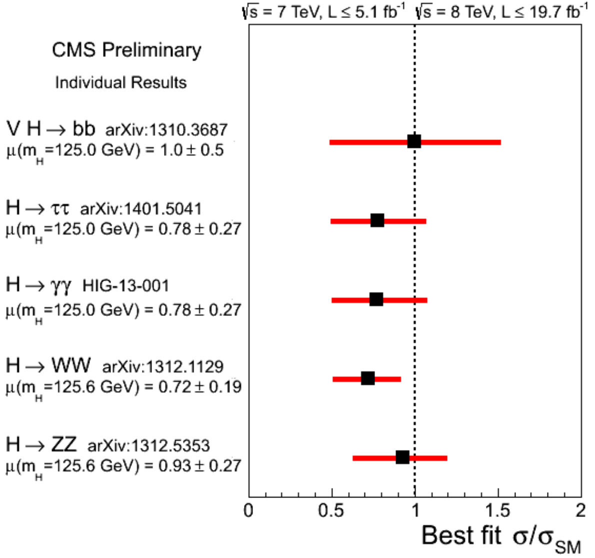


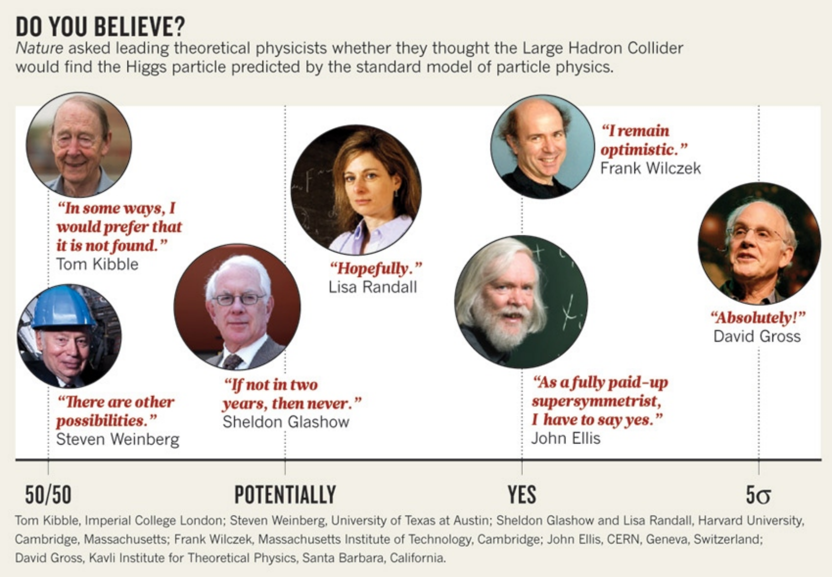


Higgs search- LHC

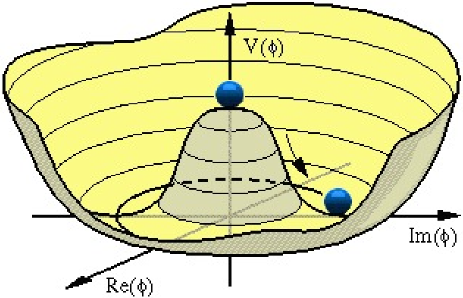


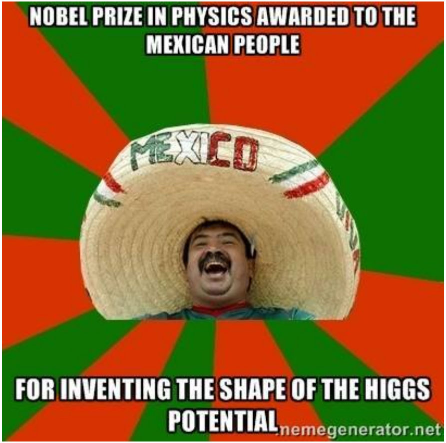
Higgs search- LHC




DO YOU BELIEVE?
Nature asked leading theoretical physicists whether they thought the Large Hadron Collider would find the Higgs particle predicted by the standard model of particle physics.
"In some ways, I would prefer that it is not found."
Tom Kibble
"There are other possibilities."
Steven Weinberg
"If not in two years, then never."
Sheldon Glashow
"Hopefully."
Lisa Randall
"I remain optimistic."
Frank Wilczek
"As a fully paid-up supersymmetrist, I have to say yes."
John Ellis
"Absolutely!"
David Gross
50/50
POTENTIALLY
YES
5σ
Tom Kibble, Imperial College London; Steven Weinberg, University of Texas at Austin; Sheldon Glashow and Lisa Randall, Harvard University, Cambridge, Massachusetts; Frank Wilczek, Massachusetts Institute of Technology, Cambridge; John Ellis, CERN, Geneva, Switzerland; David Gross, Kavli Institute for Theoretical Physics, Santa Barbara, California.

Mexican hat and BEH mechanism

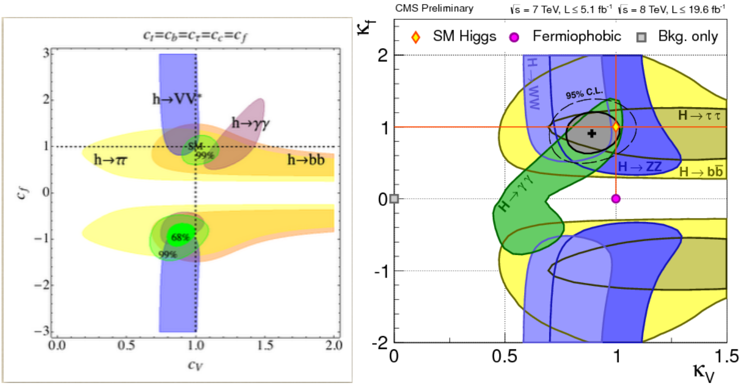




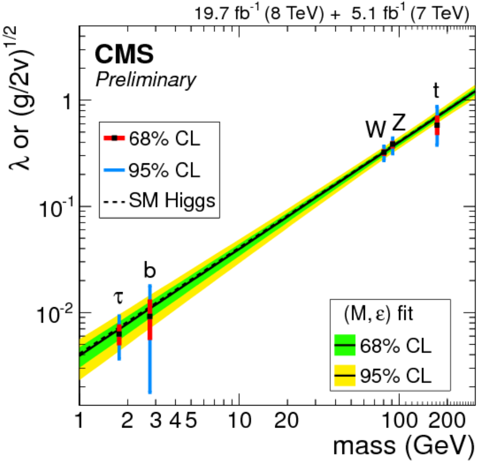
Then what?

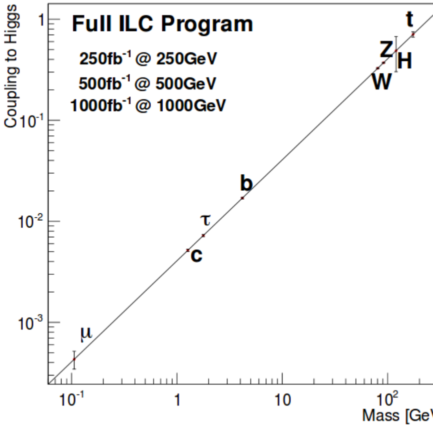
Higgs identity: $g_{hXX} = c_X \, g^{sm}_{hXX}$

In the SM: $c_X = 1$,

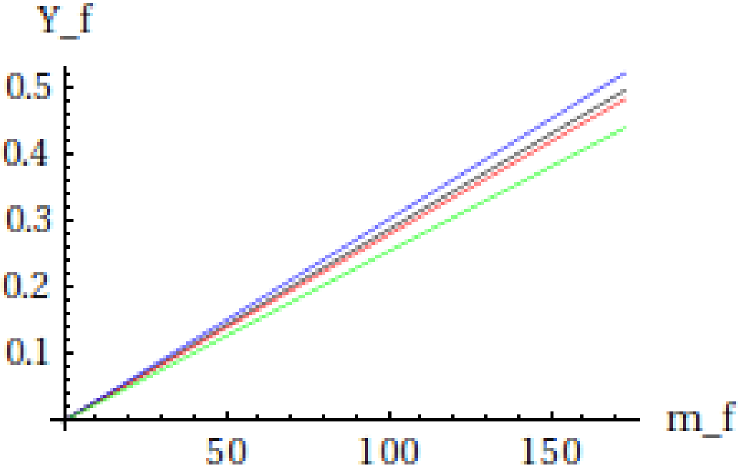


SM Higgs identity: $g^{sm}_{hXX} = \frac{M_X}{v}$





Higgs Couplings in 3+1 HDM (JLDC)



The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{13}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ ($\epsilon_W = -0.15 \pm 0.14$),
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

4. Higgs Physics Beyond the SM

5. Higgs Physics on the far UV