THE Higgs BOSON (see the PDG review)

- The SM gauge group $SU(2)_L \times U(1)_Y$ is spontaneously broken by $\varphi = \begin{pmatrix} \varphi^+ \\ \frac{v+h+i\varphi^3}{\sqrt{2}} \end{pmatrix}$

- The presence of $v \neq 0$ suppresses the strength of the weak interactions and gives masses to

$$M_W,\ M_Z,\ m_h,\ m_f \quad = \text{everyone}$$

- How do we <u>test</u> this mass generation mechanism?

$$M^2_{AB} = \frac{v^2}{4}\begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & -gg' \\ & & -gg' & g'^2 \end{pmatrix} \begin{matrix} \\ \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} Z \,\&\, A \quad m_A = 0 \end{matrix}$$

$g^2 \to W$

SU(2) inv.

actually an SO(3) (custodial) symmetry suffices

$M_Z = \frac{M_W}{c_W}$ prediction @ tree level $\frac{M_W}{M_Z c_W} \simeq 1$

- The doublet preserves the custodial symmetry and gives $\rho = \left(\frac{M_W}{M_Z c_W}\right)^2 \simeq 1$ and sets constraints on other reps of SU(2) to carry a part of the vev.

- Yukawa interactions and longitudinal enhancements

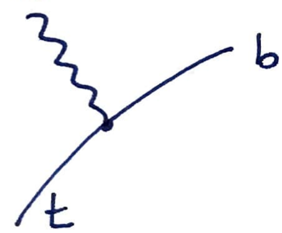
$$2\times 2 = 1 + 3$$

$$\mathcal{L}_Y = y\,(\bar{\Psi}_L\,\varphi)\,\psi_R + \text{h.c.}$$

e.g. for the heaviest top $\quad m_t = \underbrace{\frac{y_t}{\sqrt{2}}}_{\text{coupling to } \varphi\ \mathcal{O}(1)} \cdot v$

- The presence of longitudinal Goldstones in e.g. Ws can be seen in top decays

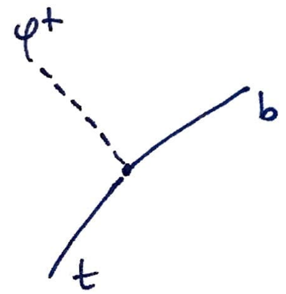
W^+, all polarizations



$$\mathcal{L}_{gauge} = \frac{g}{\sqrt{2}}\, W^-_\mu\, b_L^\dagger\, \bar{\sigma}^\mu\, t_L$$

$$\Downarrow$$

- $$\Gamma_t = \underbrace{\frac{\alpha_w}{16}}_{\text{expected}}\, m_t\, \underbrace{\left(\frac{m_t}{M_W}\right)^2}_{\text{enhanced} > 1} \left(1 + 2\left(\frac{M_W}{m_t}\right)^2\right)\left(1 - \left(\frac{M_W}{m_t}\right)^2\right)^2$$



$$\Gamma_t = \frac{1}{32\pi}\, y_t^2\, m_t\,, \quad y_t^2 = \frac{2 m_t^2 g^2}{g^2 v^2} = \frac{g^2}{2}\frac{m_t^2}{M_W^2}$$

$$\alpha_w 4\pi = g^2$$

$$= \frac{\cancel{2\pi}\,\alpha_w}{\cancel{32\pi}\,16}\, m_t \left(\frac{m_t}{M_W}\right)^2$$

$\hookrightarrow$ GOLDSTONE BOSON EQUIVALENCE

21.2. PROPERTIES OF THE HIGGS BOSON

$$\varphi = \begin{pmatrix} \varphi^+ \\ \frac{v + h + i\varphi^3}{\sqrt{2}} \end{pmatrix}$$

$\to$ Goldstones, become the longitudinal parts of $W^\pm, Z$

h: the only remaining real scalar d.o.f.

- Couplings to the Higgs @ tree level ($v = 246$ GeV from G_F)

$$\mathcal{L}_{Higgs} = -\sum m_f \bar{f} f \frac{h}{v} + 2 M_W^2 W^+ W^- \frac{h}{v}$$

$$+ \frac{2}{2} M_Z^2 ZZ \frac{h}{v} - 3 m_h^2 \frac{h}{v} + \mathcal{O}(h^4)$$

- Conserves P and C $\Rightarrow$ Higgs $= S=0$, $\underbrace{P=+1}_{\text{scalar}}$

- DECAYS : to fermion $\propto m_f^2$

$$\Gamma_{h\to f\bar{f}} = \frac{1}{32\pi} y_f^2 m_h$$

- A bit more precisely, with phase space & m_f, M_W

$$\Gamma_{h\to f\bar{f}} = N_c \frac{\alpha_W}{8} \left(\frac{m_f}{M_W}\right)^2 m_h \left(1 - \frac{4 m_f^2}{m_h^2}\right)^{3/2}$$

$\times$ QCD corrections

$$\Gamma_{h\to b\bar{b}} \simeq 2\,\text{MeV} \ll m_h$$

- Decays to $c\bar{c}$ are $(m_c/m_b)^2 \sim 10^{-1}$ suppressed
$(1\,\text{GeV}/4\,\text{GeV}) \sim 1/16$

- Decays to WW, ZZ

$\delta_Z = 1$
$\delta_W = 2$

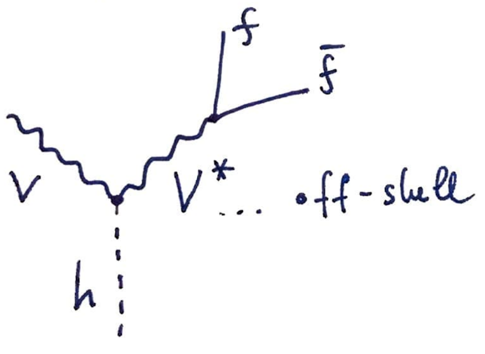
$$\Gamma_{h\to VV} = \frac{G_F m_h^3}{16\sqrt{2}\pi}\,\delta_V\sqrt{1-4x_h}\,(1-4x_h+12x_h^2), \quad x_h = \left(\frac{M_V}{m_h}\right)^2$$

$$\Gamma_L \propto 1-4x_h+4x_h^2 \quad , \quad \Gamma_T \propto 8x_h^2$$

- For a very heavy Higgs, the L dominates $x_h \ll 1$

&
$$\frac{\Gamma_L}{\Gamma_L+\Gamma_T} = \frac{1-4x_h+4x_h^2}{1-4x_h+8x_h^2} \longrightarrow 1 + O(x_h^2)$$

- Of course finally $m_h \sim 125$ GeV so no 2-body decays to VV, however 3 body are ok



$$h \to VV^*$$

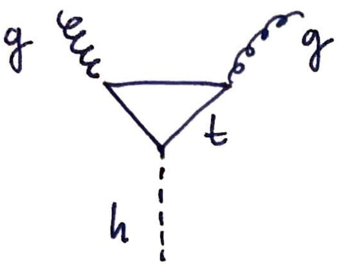
$$\Gamma_{h\to VV^*} \sim \frac{3\,G_F^2 M_V^4}{16\pi^3}\, m_h\, \delta_V'\, R_T(x)$$

$\delta_{W'} = 1$

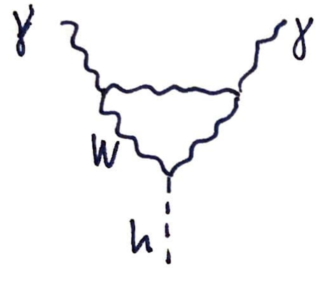
$\delta_{Z'} = \frac{7}{12} - \frac{10}{9}s_W^2 + \frac{40}{9}s_W^4$, $R_T(x) =$ (see Djouadi et al. SM Higgs review) (2.31)

• Loop suppressed Radiative Decays

• to gluons



• to photons



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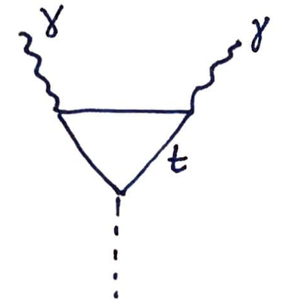


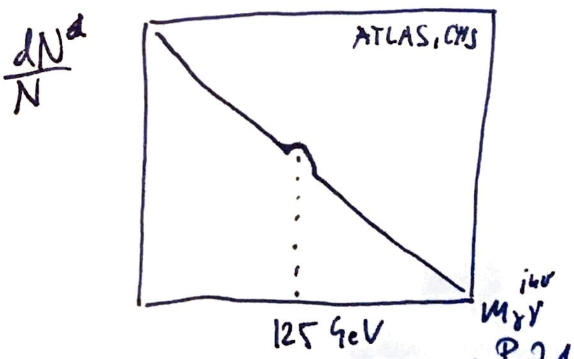
, $Z\gamma$

$$\Gamma_{h\to\gamma\gamma} = \frac{G_F\,\alpha^2}{128\sqrt{2}\,\pi^3}\cdot m_h^3 \left|\sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W)\right|^2$$

$$A_f = \frac{2}{\tau^2}\left(\tau + (\tau-1) f(\tau)\right),\quad A_V = -\frac{1}{\tau^2}\left(2\tau^2+3\tau + 3(2\tau-1) f(\tau)\right)$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} \\ -\frac{1}{4}\left(\ln\frac{1+\sqrt{1-1/\tau}}{1-\sqrt{1-1/\tau}} - i\pi\right)^2 \end{cases},\quad \tau_i = \frac{m_h^2}{4 m_i^2}.$$

• The di-photon channel gives a very clean measurement of m_h and the coupling strength



• It is also sensitive to the presence of charged BSM particles running in the loop.

BRANCHING RATIO SUMMARY $m_h = 125$ GeV

$b\bar{b}$	WW	ZZ	$\tau^+\tau^-$
58 %	21 %	2.6 %	6.3 %

$\gamma\gamma$	$Z\gamma$	$\mu^+\mu^-$
2 ‰	1.5 ‰	$2\cdot10^{-4}$

SM predictions

- $h(125)$ has been observed in $\gamma\gamma$, WW, ZZ channels ~~almost~~ very quickly (leptons and photons are cleaner, less QCD background at the LHC)

- It has also been observed ~~in~~ $b\bar{b}$ and $\tau\tau$ modes, the rest are challenging and need more data (in $\mu^+\mu^-$, $Z\gamma$) or new strategies : $c\bar{c}$, light quarks, and gg.

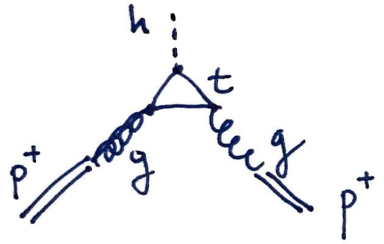
- Finally because of $\Gamma_h \sim$ MeV (very narrow width) and a significant # of Higgses produced (next section), we may be sensitive to BSM physics in EXOTIC, RARE Higgs decays.

Higgs Boson Production

- pp colliders, e^+e^- colliders, (muon, ...)

- at the LHC, the dominant production channels are given by

1) $gg \to h$ (GGF ... gluon fusion channel)



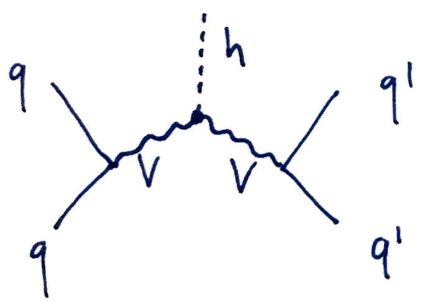
$$\sigma^{\sqrt{s}=14\,TeV}_{pp\to gg\to h} \sim 40\ pb$$

$$\#\,\text{events} = \sigma \cdot \overbrace{\text{Lumi}}^{300\,fb^{-1}}$$

$$\sim 40\ \cancel{pb} \cdot 3 \cdot 10^5\ \cancel{pb^{-1}}$$

$$\sim 12 \cdot 10^6 \text{ Higgses}$$

2) qqh (VBF = vector boson fusion)



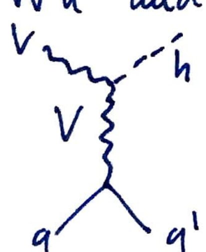
$$\sigma^{\sqrt{s}=14\,TeV}_{hqq} = 5\ pb$$

NOTE

$\sigma_{pp\to pp} \sim 100\ mb$

$\times 10^9$ suppressed

3) Wh and Zh



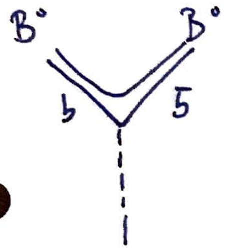
$$\sigma_{Wh} = 2pb$$

$$\sigma_{Zh} = 1pb$$

- We cannot measure the total $\sigma_{pp\to h}$. What we observe are specific final states, thus

$$\sigma(pp \to h) \times Br(h \to XY)$$

- $h \to b\bar{b}$ search



$m_{BB} \sim 125$ GeV

- the B mesons are hard to ID, they give off radiation and produce the so-called b-jets.

- QCD : $pp \to qq, qg, gg$ gives many hard jets with $m_{qq} \sim 125$ GeV

$pp \to W+Z,\ Z \to bb$; $pp \to W+g,\ g \to b\bar{b}$

- a similar issue exists for the hadronic W and Z decays, – $h \to VV^* \to 4q$'s , $m_{qq} \sim M_W$

$m_{4q} \sim m_h$

- best chance are the photons and e^-, μ^- (τ also decays hadronically, giving a τ-jet)

- Spin / parity of the Higgs.

  $J^P = 0^+$ prediction vs $0^-, 2, 1 \dots$

- If $X \to \gamma\gamma \Rightarrow$ not spin 1

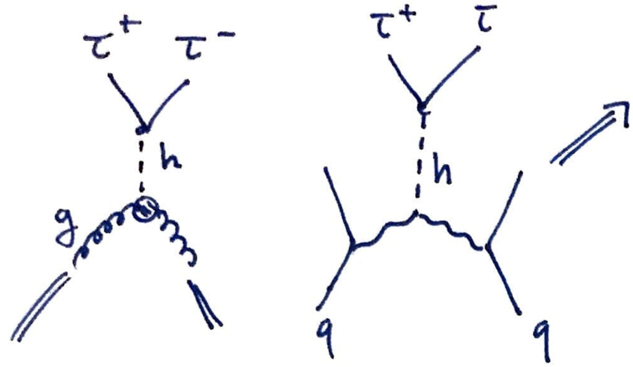
  (Landau - Yang theorem)

- From $h \to ZZ^* \to 4\ell$ we get a rather clean final state where 0^+ v 0^- can be tested (also $J^P = 1^\pm$ and $2^\pm$, etc.)

- Similarly for $h \to WW \to \ell\nu\, \ell\nu$, however this is more difficult, $\nu = \cancel{E}$.

  so : no jets, $\cancel{E}$ and two opposite sign ℓ's, vs. the DY background and $\underbrace{WW}_{\text{on-shell}}$, WZ, ZZ processes.

- The $\tau^+\tau^-$ channel



$\Rightarrow$ VBF channel has two forward VBF jets that can be used for tagging such events

SM backgrounds

$pp \to Z \to \tau\tau$, $W + j \to \tau\nu$ + fake τ

$Z \to jj$, j fakes τ's

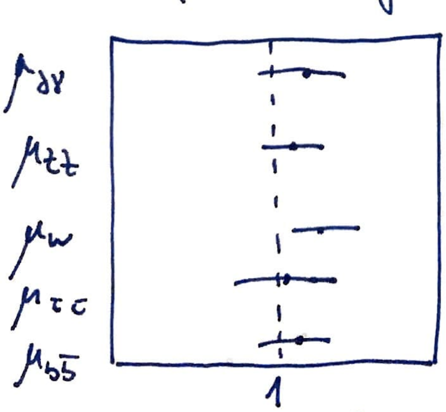
Discovery in 2018 : $\boxed{6.4\,\sigma}$ 1811.08856

in both GGF and VBF channels

$\sigma = 3.1\,\text{pb}$ $\sigma = 0.3\,\text{pb}$

- Finally, we can measure $\mu_i = \dfrac{\sigma \cdot Br(\text{obs.})}{\sigma \cdot Br(\text{SM})} = K_i^2$

HIGGS COUPLING strengths



all agree with the SM

see e.g. CMS PAS HIG-19-005