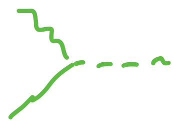
Lecture 18:

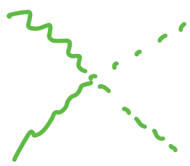
V. Higgs phenomenology

coupling to gauge bosons

$V = W, Z$

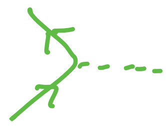


$$g_{HVV} = \frac{2M_V^2}{v}$$



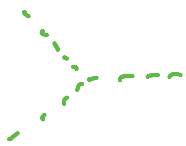
$$g_{HHVV} = \frac{2M_V^2}{v^2}$$

Yukawa coupl.



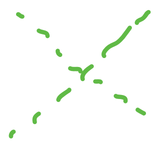
$$g_{Hff} = \frac{m_f}{v}$$

trilinear coupl.



$$\lambda_{HHH} = 3\frac{m_h^2}{v}$$

quartic coupl.



$$\lambda_{H^4} = 3\frac{m_h^2}{v^2}$$

V.1 Higgs decays

Higgs bosons mainly decay into pair of heavy particles X,

$$H \to XX$$

for which decay kinematically allowed. $(\Rightarrow m_h > 2m_X)$

Branching ratios

$$BR\,(H \to XX) = \frac{\Gamma(H \to XX)}{\Gamma_{tot}(H)}$$

← partial decay width

← total "

give probabilities of decays $H \to XX$.

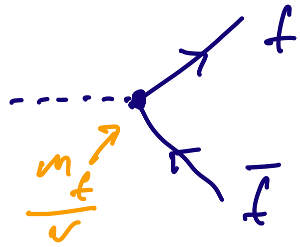
total decay width

$$\Gamma_{tot}(H) = \sum_X \Gamma(H \to XX) \approx 4\ \mathrm{MeV}$$

The branching ratios and decay widths can be calculated with e.g. the program HDECAY

Mühlleitner et al.

Decays into fermions



$$\Gamma\,(h \to f\bar{f}) = \frac{1}{2m_h} \int d\Phi_2 \quad |\mathcal{M}|^2$$

$$|\mathcal{M}|^2 = \left|\, \bar{u}(p_f)\, i\,\frac{m_f}{v}\, v(p_{\bar{f}}) \right|^2 = \frac{m_f^2}{v^2}\, \mathrm{tr}\left[(\not{p}_f + m_f)(\not{p}_{\bar{f}} - m_f) \right]$$

$$= \frac{m_f^2}{v^2} \cdot 4\,\left(p_f \cdot p_{\bar{f}} - m_f^2 \right) = \frac{m_f^2}{v^2} \cdot 4 \left(\frac{1}{2} m_h^2 - 2 m_f^2 \right)$$

$$\int d\Phi_2 = \frac{1}{32\pi^2 m_h^2} \cdot \underbrace{\lambda(m_h^2, m_f^2, m_f^2)}_{= m_h^2 \cdot \sqrt{1 - \frac{4m_f^2}{m_h^2}}} \underbrace{\int d\Omega_2}_{4\pi}$$

→ sheet 6

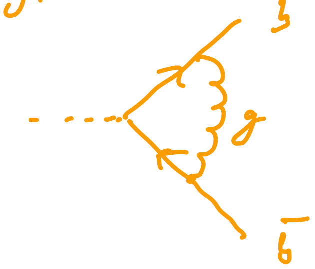
$$v^{-2} = \sqrt{2}\, G_F \qquad\qquad \text{velocity } \beta$$

$$\Rightarrow \Gamma(h \to f\bar{f}) = \frac{G_F\, m_h}{4\sqrt{2}\,\pi}\, m_f^2\, \beta^3 \cdot N_{cf}$$

color factor
$N_{cf} = 3$ for quarks
$N_{cf} = 1$ for leptons

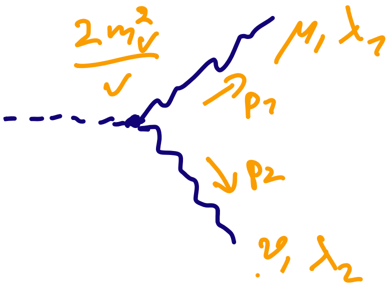
$$\Rightarrow BR(H \to b\bar{b}) = 0.58$$
$$BR(H \to \tau^+\tau^-) = 0.063$$
$$BR(H \to c\bar{c}) = 0.029$$
$$BR(H \to s\bar{s}) = 2.2 \cdot 10^{-4}$$
$$BR(H \to \mu^+\mu^-) = 2.2 \cdot 10^{-4}$$

including higher order corrections,
e.g.



Decays into vector bosons

The (on-shell) decays $H \to WW$, $H \to ZZ$ would be possible if $\frac{1}{2} m_H > m_W, m_Z$



$$\mathcal{M} = \frac{2 m_V^2}{v} \cdot g_{\mu\nu}\, \varepsilon^{*\mu}_{\lambda_1}(p_1)\, \varepsilon^{*\nu}_{\lambda_2}(p_2)$$

polarization sum for massive vector bosons:

$$\sum_{\lambda=1}^{3} \varepsilon^{\mu}_{\lambda}(p)\, \varepsilon^{\nu *}_{\lambda}(p) = -g^{\mu\nu} + \frac{p^\mu p^\nu}{m_V^2}$$

$$\Rightarrow \Gamma(H \to VV) = \delta_V \frac{G_F\, m_H^3}{8\sqrt{2}\,\pi} \sqrt{1-4x}\,\left(1 - 4x + 12x^2\right)$$

$$\delta_Z = \frac{1}{2}, \quad \delta_W = 1 \qquad\qquad x = \frac{m_V^2}{m_H^2}$$

↳ 2 identical particles in final state (→ sect. IV.4)

The vector bosons further decay into leptons or quarks:

$$BR(W \to \ell \nu_\ell) = 33\%$$ (split equally into $\ell = e, \mu, \tau$)

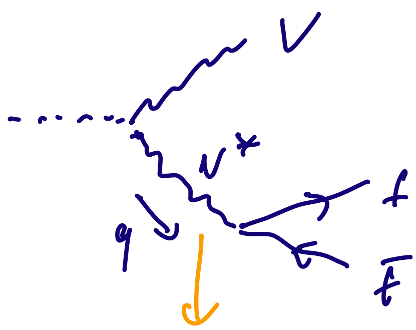
$$BR(W \to q \bar{q}') = 67\%$$

$$BR(Z \to \ell \bar{\ell}) = 10\%$$

$$BR(Z \to \nu \nu) = 20\%$$

$$BR(Z \to q \bar{q}) = 70\%$$

Also for $m_H < 2 m_V$, decays into vector bosons is possible, if one of the vector bosons is off-shell



$$H \to V V^* \to V f \bar{f}$$

with $q^2 = (p_f + p_{\bar{f}})^2 < m_V^2$

propagator factor & phase space integration

$$\to \Gamma(H \to V V^*) = \frac{1}{\pi} \int_0^{m_H^2} dq^2 \frac{m_V \Gamma_V}{\underbrace{(q^2 - m_V^2)}_{\text{↳ suppression for large } |q^2 - m_V^2|} + m_V^2 \Gamma_V^2} \cdot \Gamma(H \to V V^*(q^2))$$

q^2 of V^* fixed

full expressions for $\Gamma(H \to VV^*)$ given e.g. in arXiv: 1612.07651

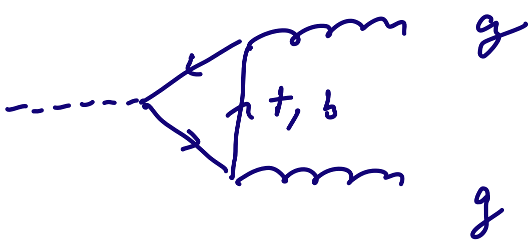
$BR(H \to WW^*) = 0.22$

$BR(H \to ZZ^*) = 0.026$

Loop-induced decays

Higgs decays into massless particles possible via loop diagrams with massive particles

$H \to gg$



$$\Gamma_{LO}(H \to gg) = \frac{G_F \alpha_s^2 m_H^2}{36\sqrt{2}\pi^3} \left| \sum_{Q=t,b} A_Q(\tau_Q) \right|^2$$

leading order

$\tau_t > 1$
$\tau_b < 1$

with $A(\tau) = \frac{3}{2}\tau\left(1 - (1-\tau) f(\tau)\right)$ $\qquad \tau_Q \mathrel{\dot=} \frac{4m_i^2}{m_H^2}$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left(\log \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right)^2 & \tau < 1 \end{cases}$$

Including the next-to-leading order (NLO) in α_s, the decay width increases by $\sim 90\%$. Γ known up to N^3LO in α_s using the heavy top limit.

$$BR(H \to gg) = 0{,}082$$

comment: <u>heavy top limit (HTL)</u>

In the limit $m_t \to \infty$, we obtain $A(\tau \to \infty) = 1$ and we can approximate the Hgg interaction with an effective vertex

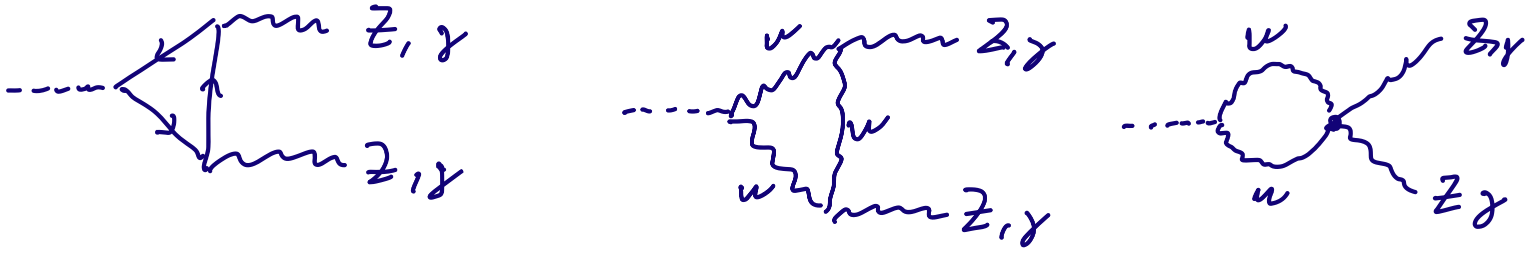
$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} \frac{H}{v} G^a_{\mu\nu} G^{a\,\mu\nu}$$

$\Rightarrow$ huge simplification, since number of loops reduced by 1

$\Rightarrow$ often used for calculation of higher-order corrections, justified since $\frac{m_H^2}{4 m_t^2} = \frac{1}{\tau_t} \approx \frac{1}{8}$ small

$$\Rightarrow \quad \Gamma \approx \Gamma_{LO}(m_t) \frac{\Gamma_{NLO}(m_t \to \infty)}{\Gamma_{LO}(m_t \to \infty)}$$

$H \to \gamma\gamma$, $H \to Z\gamma$



$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2 M_H^3}{128\sqrt{2}\,\pi^3} \left| \sum_f N_{c,f}\, e_f^2\, A_f(\tau_f) + A_W(\tau_W) \right|^2$$

3 or 1

with $A_f(\tau) = 2\tau\left(1 + (1-\tau) f(\tau)\right)$

$$A_W(\tau) = -\left(2 + 3\tau + 3\tau(2-\tau) f(\tau)\right)$$

For $m_H = 125$ GeV , $m_W = 80$ GeV , $m_t = 173$ GeV

$\to$ $\tau_t = 1.66$ $\qquad$ $\tau_W = 1.64$

$A_t(\tau_t) = 1.38$ $\qquad$ $A_W = -8.34$

$N_c e_t^2 A_t(\tau_t) = 1.8$

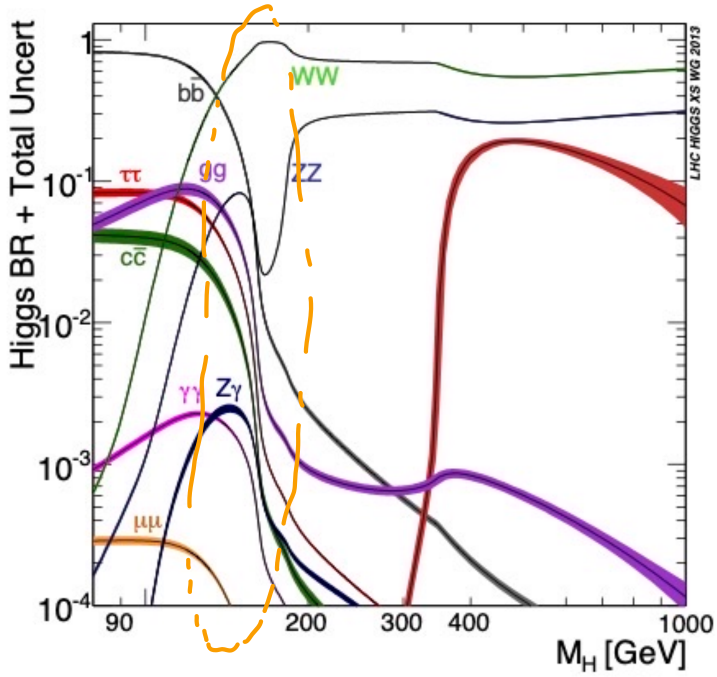
$\to$ Dominant contributions from W loops, destructive interference with top-quark loop.

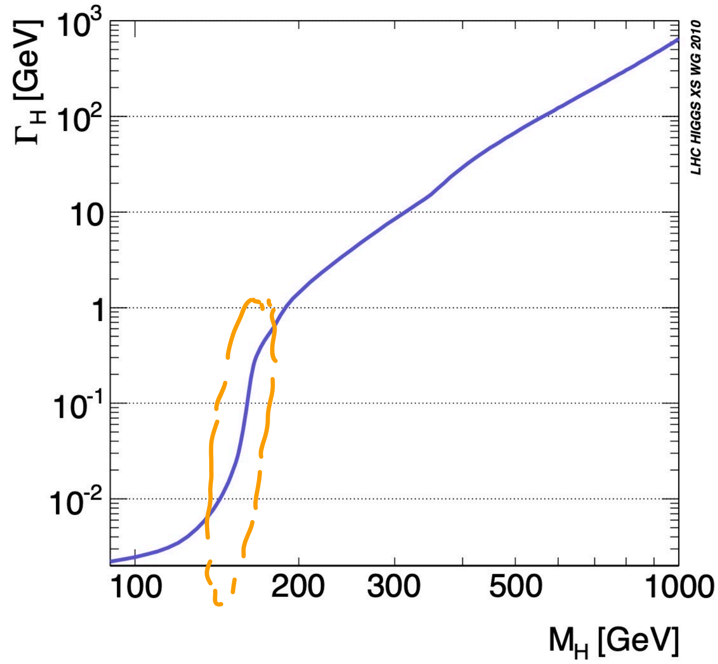
$$\Gamma(H \to Z\gamma) = \frac{G_F^2 m_W^2\, \alpha\, m_H^3}{64\pi^4} \left(1 - \frac{m_Z^2}{m_H^2}\right) \left| \sum_f A_f(\tau_f, \lambda_f) + A_W(\tau_W, \lambda_W) \right|^2$$

$A_f(\tau_f, \lambda_f)$, $A_W(\tau_W, \lambda_W)$ given in arXiv: 1612.07651 $\qquad$ $\lambda_i = \frac{4 m_i^2}{m_Z^2}$

$\Gamma(H \to \gamma\gamma) = 2.3 \cdot 10^{-3}$

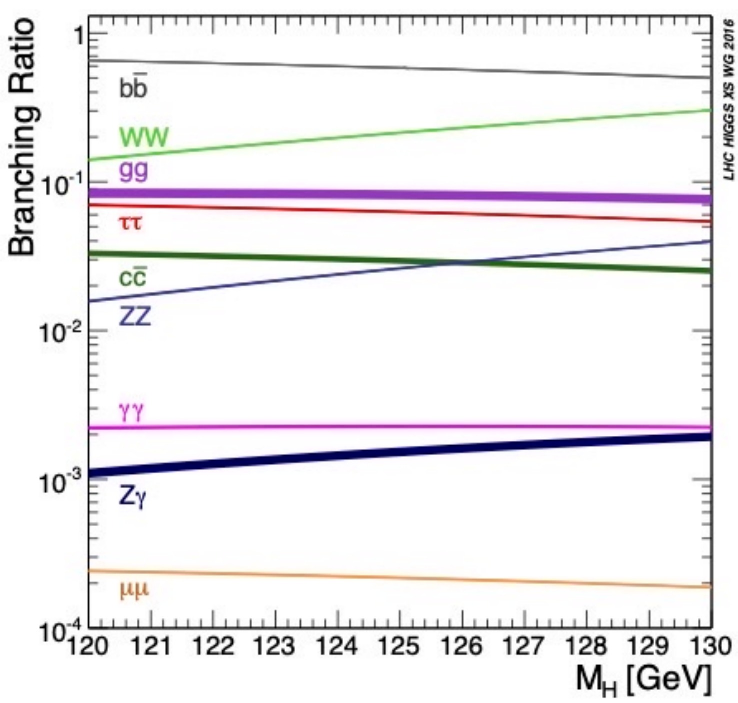
$\Gamma(H \to Z\gamma) = 1.5 \cdot 10^{-3}$





rapid increase of $\Gamma(H \to WW)$ and $\Gamma(H \to ZZ)$ with m_H in region $m_H \gtrsim 2 m_V$

$\to$ other branching ratios drop, even though the partial decay widths increase with m_H.



$\to$ main decay channels: $b\bar{b}$, WW

$\left.\begin{array}{l} ZZ \to 4\ell \\ \gamma\gamma \\ Z\gamma \to \ell\bar{\ell}\gamma \\ \mu\mu \end{array}\right\}$ small branching fractions, but clear detector signal