12 Higgs Boson Decays: Theoretical Status

Author: Michael Spira [Michael.Spira@psi.ch]

12.1 Introduction

The discovery of a Standard-Model-like Higgs boson at the LHC [1, 2] completed the theory of electroweak and strong interactions. The measured Higgs mass of (125.09 ± 0.24) GeV [3] ranges at the order of the weak scale. The existence of the Higgs boson [4–9] allows the Standard Model (SM) particles to be weakly interacting up to high-energy scales. This, however, is only possible for particular Higgs-boson couplings to all other particles so that with the knowledge of the Higgs-boson mass all its properties are uniquely fixed. The massive gauge bosons and fermions acquire mass through their interaction with the Higgs field that develops a finite vacuum expectation value in its ground state. The minimal model requires the introduction of one isospin doublet of the Higgs field and leads after spontaneous symmetry breaking to the existence of one scalar Higgs boson.

Since all Higgs couplings are fixed within the SM any meaningful approach to introduce variations requires to introduce effects beyond the SM (BSM). There two major branches pursued for this purpose: *(i)* the introduction of higher-dimension operators in terms of a general effective Lagrangian with dimension-6 operators providing the leading contributions for energy scales sufficiently below the novel cut-off scale of these operators and *(ii)* the introduction of specific BSM models with extended Higgs, gauge and fermion sectors. The extraction of BSM effects, however, strongly relies on the accuracy of the SM part as e.g. sketched in the basic decomposition of the SM-like Higgs boson decay widths as

$$\Gamma = \Gamma_{SM} + \Delta\Gamma_{BSM} \tag{12.105}$$

Any potential to extract the BSM effects $\Delta\Gamma_{BSM}$ is limited by the uncertainties $\delta\Gamma_{SM}$ of the SM part.

12.2 SM Higgs Boson Decays

The determination of the branching ratios of Higgs-boson decays thus necessitates the inclusion of the available higher-order corrections (for a recent overview see e.g. [10]) and a sophisticated estimate of the theoretical and parametric uncertainties.

(i) $H \to f\bar{f}$: The Higgs decay $H \to b\bar{b}$ is the dominant Higgs boson decay with a branching ratio of about 58%. The subleading fermionic decays $H \to \tau^+\tau^-$ and $H \to c\bar{c}$ reach branching ratios of about 6% and 3%, respectively. The rare decay $H \to \mu^+\mu^-$ will become visible at the HL-LHC and happens with about 0.02% probability [11]. The present status of the partial decay widths can be summarized in terms of the (factorized) expression

$$\Gamma(H \to f\bar{f}) = \frac{N_c G_F M_H}{4\sqrt{2}\pi}\, m_f^2\, (1 + \delta_{\rm QCD} + \delta_t + \delta_{mixed})\,(1 + \delta_{elw}) \tag{12.106}$$

where $N_c = 3(1)$ for quarks (leptons), G_F denotes the Fermi constant, M_H the Higgs mass and m_f the fermion mass. In general the pure QCD corrections $\delta_{\rm QCD}$ to the Higgs boson decays into quarks are known up to NLO including the full quark mass dependence [12–16] and up to N^{4}LO for the leading corrections with the leading mass effects [17–23]. The dominant part of the QCD corrections can be absorbed in the running quark mass evaluated at the scale of the Higgs mass. The top-induced QCD corrections, which are related to interference effects between $H \to gg$ and $H \to q\bar{q}$, are known at NNLO in the limit of heavy top quarks and light bottom quarks [24–26]. In the case of leptons there are no QCD corrections ($\delta_{\rm QCD} = \delta_t = \delta_{mixed} = 0$). The electroweak corrections δ_{elw} are known at NLO exactly [27–30]. In addition the mixed QCD-elw. corrections range at the one-per-mille level if the factorized expression with respect to QCD and elw. corrections is used [31–35]. The public tool `Hdecay` [36, 37] neglects these mixed QCD-elw. corrections but includes all other corrections. The partial decay width of $H \to b\bar{b}$ is also known fully differential at N^{3}LO QCD [38–41].

(ii) $H \to W^{(*)}W^{(*)}, Z^{(*)}Z^{(*)}$: The branching ratios of SM Higgs boson decays into (off-shell) W and Z bosons amount to about 21% and 3%, respectively. Off-shell effects of the W and Z are important [42–44] and lead to the $H \to Z^*Z^{(*)} \to 4\ell^\pm$ decay as one of the discovery modes of the SM Higgs boson [1, 2]. The electroweak corrections to the full decay modes $H \to V^{(*)}V^{(*)} \to 4f$ $(V = W, Z)$ have been calculated [27, 45–48]. The public tool `Prophecy4f` [47, 48] calculating the exclusive decay processes has been used in the experimental analyses. An improvement beyond the pure elw. corrections has been made by the proper matching to parton showers at NLO [49]. However, shower effects have not been relevant for the analyses performed so far.

(iii) $H \to gg$: The loop-induced Higgs decay into gluons reaches a branching ratio of about 8%. The decay is dominantly mediated by top and bottom-quark loops with the latter providing a 10%-contribution. The charm quark contributes at the level of about 2%. The two-loop QCD corrections are known including the exact quark mass dependences [50–52]. They enhance the partial decay width by about 70% and thus cannot be neglected in the decay profile of the Higgs boson. The NNLO, N^{3}LO and recently the N^{4}LO QCD corrections have been obtained for the top loops in the limit of heavy top quarks, i.e. the leading term of a heavy top-mass expansion [53–55]. The QCD corrections beyond NLO amount to less than 20% of the NLO QCD corrected partial decay width thus signaling perturbative convergence in spite of the large NLO corrections. The residual theoretical uncertainties have been estimated at the level of about 3% from the scale dependence of the QCD corrected partial decay width. The NLO elw. corrections have been calculated for the top-loop contributions first in the limit of heavy top quarks [33,56,57], then the electroweak corrections involving light fermion loops exactly [58–60] and finally the full electroweak corrections involving W, Z and top-loop contributions including the full virtual mass dependences by means of a numerical integration [61, 62]. They amount to about 5% for the SM Higgs mass value. The public tool `Hdecay` [36, 37] includes the NLO QCD results with the full quark mass dependences, the NNLO and N^{3}LO QCD corrections in the heavy-top limit and the full NLO elw. corrections in terms of a grid in the Higgs and top masses used for an interpolation.

(iv) $H \to \gamma\gamma$: The rare loop-induced Higgs decay into photons reaches a branching ratio of about 0.2%. The decay is dominantly mediated by W and top-quark loops with the W loops being dominant. The two-loop QCD corrections are known including the exact top mass dependences [52, 63–72]. They correct the partial decay width by a small amount of about 2%. The QCD corrections beyond NLO have been estimated in the limit of heavy top quarks to be in the per-mille range [73–75]. The NLO elw. corrections to the W and top-induced

contributions have been obtained by a numerical integration of the corresponding two-loop diagrams [62, 76–78]. They decrease the partial photonic branching ratio of the SM Higgs boson by about 2% thus nearly canceling against the QCD corrections by accident. The public tool `Hdecay` [36,37] includes the NLO QCD results with the full quark mass dependences and the full NLO elw. corrections in terms of a grid in the Higgs and top masses used for an interpolation, but neglects all corrections beyond NLO.

(v) $H \to Z\gamma$ and Dalitz decays: The rare loop-induced Higgs decay into a Z boson and photon reaches a branching ratio of less than 0.2%. The decay is dominantly mediated by W and top-quark loops with the W loops being dominant. The two-loop QCD corrections are known including the exact top mass dependences [79–81]. They correct the partial decay width by a small amount in the per-mille range and thus can safely be neglected. The electroweak corrections to this decay mode are unknown. However, the decay mode $H \to Z\gamma \to f\bar{f}\gamma$ is part of the more general Dalitz decays $H \to f\bar{f}\gamma$ [82–88]. The latter are described by the diagrams in Fig. B.37 where the Z-boson exchange appears in a part of the triangle diagrams. The resonant Z-boson exchange corresponds to the $H \to Z\gamma$ decay mode. The separation of

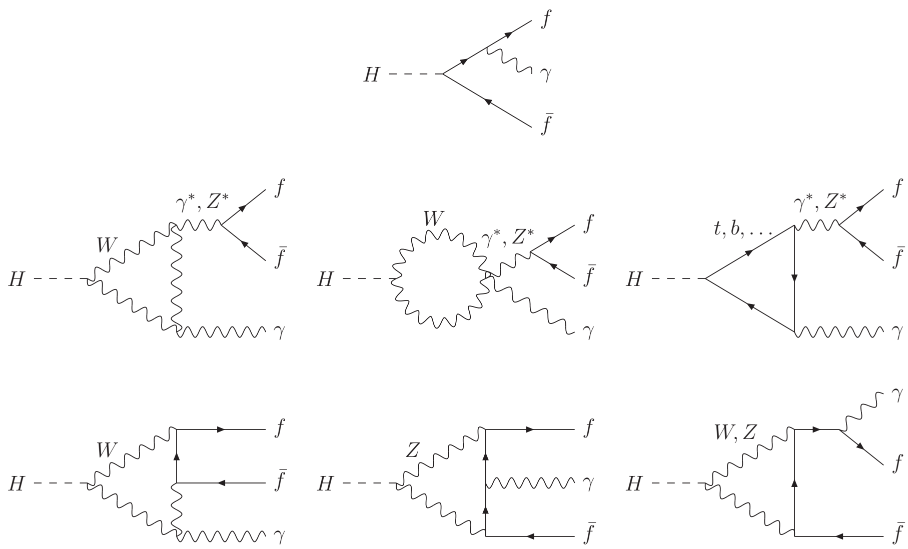

Fig. B.37: *Generic diagrams contributing to the Dalitz decays $H \to \gamma f\bar{f}$.*

this part, however, depends on the experimental strategy to reconstruct the Z boson in the final state. A first step for the reconstruction of the Z boson is to cut on the invariant mass of the final-state fermion pair. The corresponding distributions of the Dalitz decays are shown in Fig. B.38 for the three charged-lepton final states normalized to the partial width into photons with a cut $E_\gamma > 1$ GeV on the photon energy. For small invariant masses the photon conversion $H \to \gamma\gamma^* \to \gamma\ell^+\ell^-$ provides the dominant contribution, while for invariant masses around the Z-boson mass the Z-boson contribution $H \to \gamma Z^* \to \gamma f\bar{f}$ takes over the dominant role. At the end-point $q^2 \lesssim M_H^2$ of the spectrum the direct contribution determines the distributions. This rises with growing Yukawa coupling, i.e. it is largest for $H \to \gamma\tau^+\tau^-$ (where it dominates in the whole q^2-range)[‡]. For a clean separation of the $H \to \gamma\gamma$, $H \to \gamma\gamma^* \to \gamma\ell^+\ell^-$, $H \to Z\gamma$

[‡]It should be noted that the end point in the $e^+e^-\gamma$ case is 4–5 orders of magnitude smaller than the photon

and $H \to \ell^+\ell^-$ contributions appropriate cuts have to be implemented for the Dalitz decays. The low-q^2 part has to be attributed to $H \to \gamma\gamma$, the q^2-part around M_Z^2 to $H \to Z\gamma$ and the end-point region close to M_H^2 to the QED corrections to $H \to \ell^+\ell^-$. The public code `Hdecay` [36, 37] does not include the full Dalitz decays.

12.3 Uncertainties

The parametric errors are dominated by the uncertainties in the top, bottom and charm quark masses as well as the strong coupling α_s. We have used the $\overline{\mathrm{MS}}$ masses for the bottom and charm quark, $\overline{m}_b(\overline{m}_b) = (4.18 \pm 0.03)$ GeV and $\overline{m}_c(3\text{ GeV}) = (0.986 \pm 0.026)$ GeV, and the top quark pole mass $m_t = (172.5 \pm 1)$ GeV according to the conventions of the LHC Higgs Cross Section WG (HXSWG) [11]. The $\overline{\mathrm{MS}}$ bottom and charm masses are evolved from the input scale to the scale of the decay process with 4-loop accuracy in QCD. The strong coupling α_s is fixed by the input value at the Z-boson mass scale, $\alpha_s(M_Z) = 0.118 \pm 0.0015$. The total parametric uncertainty for each branching ratio has been derived from a quadratic sum of the individual impacts of the input parameters on the decay modes.

The theoretical uncertainties from missing higher orders in the perturbative expansion are summarized in Table B.9 for the individual partial decay processes along with the perturbative orders of the included QCD/elw. corrections [10, 11]. In order to be conservative the total parametric uncertainties are added linearly to the theoretical uncertainties. The final result for the branching ratios is shown in Fig. B.39 for the leading Higgs decay modes with branching ratio larger than 10^{-4} for the Higgs-mass range between 120 and 130 GeV. They have been obtained with `Prophecy4f` [47,48] for the decays $H \to WW, ZZ$ and `Hdecay` [36,37] for the other decay modes. The bands represent the total uncertainties of the individual branching ratios. For a Higgs mass $M_H = 125$ GeV the total uncertainty of the leading decay mode $H \to b\bar{b}$ amounts to less than 2%, since the bulk of it cancels out within the branching ratio. The uncertainty of $\Gamma(H \to b\bar{b})$, however, generates a significant increase of the uncertainties for the subleading decay modes. The total uncertainties of $BR(H \to WW/ZZ)$ and $BR(H \to \tau^+\tau^-/\mu^+\mu^-)$ amount to $\sim 2\%$, while the uncertainties of $BR(H \to gg)$ and $BR(H \to c\bar{c})$ range at $\sim 6-7\%$, of $BR(H \to \gamma\gamma)$ at $\sim 3\%$ and of $BR(H \to Z\gamma)$ at $\sim 7\%$. The total decay width of ~ 4.1 MeV can be predicted with $\sim 2\%$ total uncertainty.

and Z-exchange contributions thus making it impossible to determine the electron Yukawa coupling. The same conclusion is also valid for the reverse process $e^+e^- \to H\gamma$ so that the s-channel line-shape measurement proposed in Ref. [89] will not be sensitive to the electron Yukawa coupling but dominated by the loop-induced contribution with an additional photon.

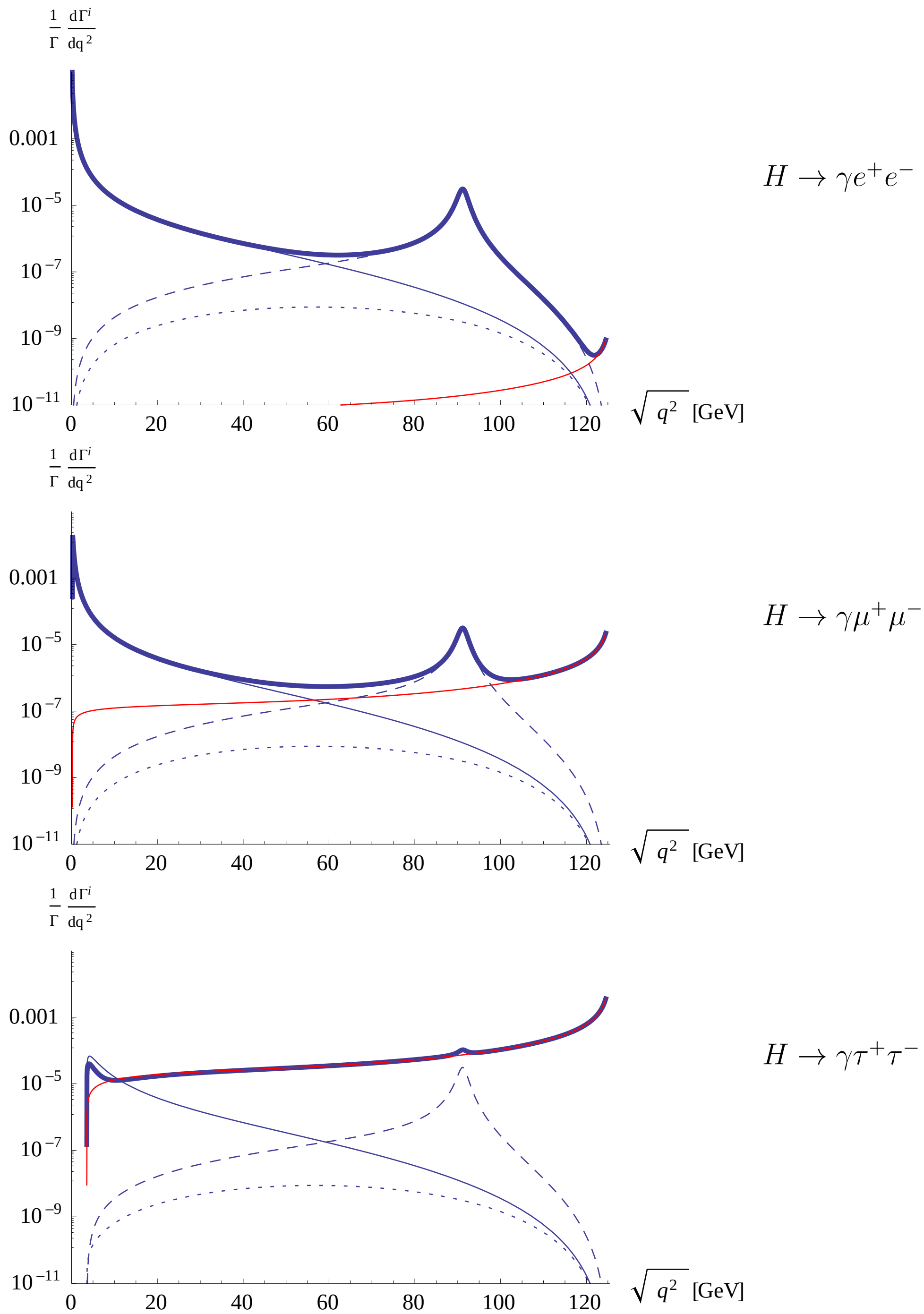

Fig. B.38: *The invariant mass distributions in* $\sqrt{q^2} = M_{\ell^+\ell^-}$ *of the Dalitz decays* $H \to \gamma + e^+e^-/\mu^+\mu^-/\tau^+\tau^-$ *normalized to* $\Gamma(H \to \gamma\gamma)$ *with a cut* $E_\gamma > 1$ *GeV on the photon energy. The red lines show the contribution of the tree diagrams, the thin solid lines denote the contribution of the photon conversion* $H \to \gamma\gamma^* \to \gamma\ell^+\ell^-$*, and the dashed line the contribution from the* Z^* *exchange diagrams, while the thick lines present the total contributions. The dotted lines denote the contribution from the box diagrams (in 't Hooft–Feynman gauge). From Ref. [88].*

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	N^{4}LO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$	—	$\sim 0.5\%$	$\sim 0.5\%$	— / NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	N^{3}LO / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	NLO/NLO

Table B.9: *Estimated theoretical uncertainties from missing higher orders and the perturbative orders (QCD/elw.) of the results included in the analysis.*

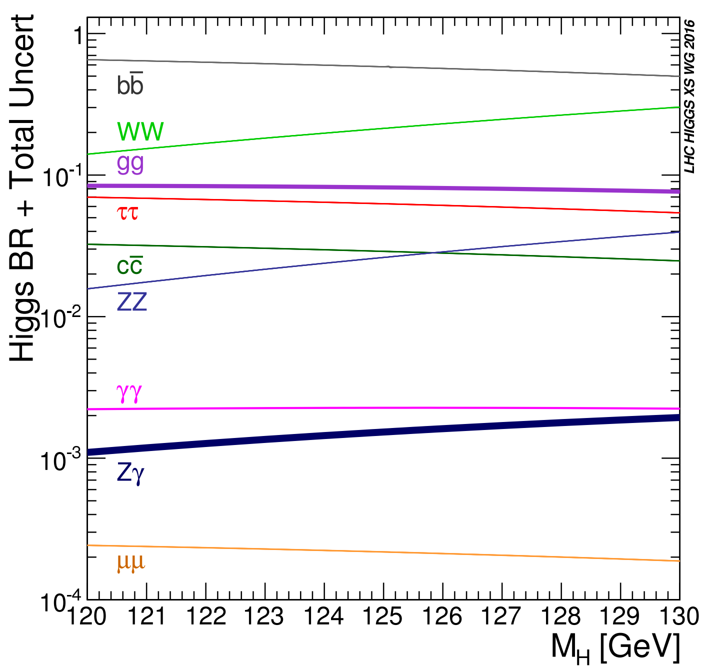

Fig. B.39: *Higgs boson branching ratios and their uncertainties for Higgs masses around 125 GeV. From Ref. [11].*

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