Future Circular Collider

PUBLICATION

Higgs Physics Potential of FCC-hh Standalone

Mangano, Michelangelo (CERN) *et al.*

05 July 2019

The research leading to this document is part of the Future Circular Collider Study

Higgs Physics Potential of FCC-hh Standalone

M.L. Mangano

CERN TH

ABSTRACT

We complement the Higgs studies presented in the FCC-hh CDR with a preliminary assessment of the reach for the couplings to the W boson, and to the bottom and tau fermions.

1 Introduction

We start this note by recalling the underlying principles of the Higgs studies presented so far in the FCC-hh CDR and in the accompanying documentation. Targeting the (sub)percent precision, systematics becomes very delicate, particularly in consideration of the pileup conditions, which at the FCC-hh will be even more extreme than at the HL-LHC. Repeating the HL-LHC analyses, which for the prominent channels and couplings lead to systematics-limited precision, requires assumptions about detector performance and theoretical progress that cannot be reliably estimated today. This is particularly true for final states like WW, $\tau\tau$ or bb, for which observables like $\not{E}_T$, or like the final state invariant mass, are particularly sensitive to pileup and detector performance. To provide CDR results that we claim are reliable and robust, we focused on observables for which we believe the systematics can be trusted. For example:

- we used fully reconstructed H final states, exploiting therefore an ideal mass resolution to reduce backgrounds ($\gamma\gamma$, 4ℓ, $\mu\mu$, $\gamma Z[\to \ell\ell]$). These are also the decays for which an e^+e^- Higgs factory has limited statistics, making the hadronic collider essential.
- We used boosted Higgses, to reduce experimental systematics on the lepton/photon trigger, isolation and identification efficiencies, but also to have the Higgs signal stand out more clearly from the huge pileup, due to the large p_T and "simplicity" of the individual decay objects
- In the case of ttH, where we considered the $H \to b\bar{b}$ decay, we used boosted Higgses, but also focused on the ratio ttH[$\to b\bar{b}$]]/ttZ[$\to b\bar{b}$]. In this case, pileup systematics related to the b-tagging, the fat-jet tagging, etc, as well as theory systematics, will cancel due to the closeness in mass of H and Z.
- In the case of the $HH \to b\bar{b}\gamma\gamma$ channel, the precision target is not %, it is 5-10%, so systematics that would arise at the % level are not a concern here. The study of HH final states is by and large still statistics limited even at the FCC.

It turns out that, with the inputs from the ee collider, the results we generated for the CDR provide a complete picture, which optimizes the FCC-hh Higgs output: rare BRs to sub-% (using absolute BR(H→ZZ) from ee), ttH coupling to % (using ttZ couplings and BR(H→bb) from ee), H selfcoupling from bb+$\gamma\gamma$ to 7% (using ttH at the % level). If we take out any of these ee inputs, we need to extend the set of hadron-collider measurements, along the lines of what is done with HL-LHC, and with the same eventual limitations (eg lack of an absolute model independent Γ(H)).

So to attempt a kappa-framework fit (let alone a global EFT fit) we need to add at least measurements of H→ $\tau\tau$, WW and bb possibly separating production channels, at least along the lines of gg→H, VBF, VH. The problem with absolute measurements of these final states is that we don't have a sharp signal, so backgrounds and impact of pileup are potentially much larger. Statistically, we can easily achieve the per mille precision, but systematics is harder to defend without solid studies, considering that to improve over the HL-LHC projections we need to push to the level of 1% or less.

In the spirit of the existing studies, we aim to identify observables that could remove as much as possible the systematics, whether production systematics (luminosity, cross sections, PDF, ...) or experimental systematics (eg tau or b tagging efficiencies, mass reconstruction efficiencies, background systematics, etc). In doing that, we cannot use observables required to extract other couplings. For example, we cannot use ttH[bb]/ttZ[bb] since this is needed to extract g_{ttH}, assuming BR(H→bb). We cannot use ttH[bb]/ttH[$\gamma\gamma$] (which statistically is a great channel) since the detection systematics of bb and $\gamma\gamma$ do not cancel in the ratio, etc.

We therefore propose to consider the 3 following ratios (σ here does not refer to total cross sections, but to fiducial rates obtained after various cuts on the final states, typically at large p_T(H), and consistent between numerators and denominators):

1. σ(WH[→γγ]) / σ(WZ[→ e$^+$e$^-$]). This will give:

$$G_W = g^2_{HWW} \times BR(H \to \gamma\gamma) \tag{1}$$

and therefore g_{HWW} as a function of BR(H→γγ), where the systematics of luminosity, production dynamics, and of the trigger and identification efficiencies of electrons and photons will greatly cancel.

2. σ(WH[→ττ]) / σ(WZ[→ττ]). This will give:

$$G_\tau = g^2_{HWW} \times BR(H \to \tau\tau) \tag{2}$$

leading to $g_{H\tau\tau}$ as a function of g_{HWW} or, using (1), of BR(H→γγ).

3. σ(WH[→bb]) / σ(WZ[→ bb]). This will give:

$$G_b = g^2_{HWW} \times BR(H \to bb) \tag{3}$$

providing g_{Hbb} as a function of g_{HWW} (or BR(H→γγ).

For simplicity, we apply the following general cuts to all final state objects in all decay channels:

$$p_T(X) > 40\,\mathrm{GeV}, \quad |\eta_X| < 2.5, \quad (X = e,\ \mu,\ \tau,\ \gamma,\ b) \tag{4}$$

and study the results as a function of minimum p_T cut, p_T^{min}, for the Higgs boson. When the Higgs boson p_T cannot be measured precisely (as in the case of tau or b decays), the presence of the same final state in both numerator and denominator ensures that the reconstructed p_T of the decay system is a good proxy for the Higgs p_T: the decay BR's of the objects in the numerator or denominator of our ratios are independent of p_T, and therefore the precise knowledge of p_T is not necessary in the estimate of the ratios, provided both numerator and denominator are measured within the same range of this proxy p_T.

2 σ(WH[→γγ]) / σ(WZ[→ e$^+$e$^-$])

Table 1 gives the individual event rates for these processes and the statistical uncertainties on their ratios, for different values of p_T^{min}. In this and following tables we shall use the short-hand notation of W[e] to define the process W→eν, W[ℓ] for W→ ℓν with ℓ =e,μ, and a similar notation for the Z boson.

When the two photons in the final state are required to reconstruct the Higgs mass to within the standard resolution of a couple of GeV, there is no significant background. For each value of p_T^{min}, the WZ final state has a statistics much larger than WH, and therefore the statistical uncertainty in the ratio is dominated by the uncertainty of the Higgs decays. The WH and WZ final states have a very similar production dynamics; each process is known already today at the NNLO level, with a theoretical systematics, including PDF, at the percent level. The systematics of the ratio is further reduced, due to the almost complete correlation of the respective scale and PDF uncertainties. It is reasonable to expect that, by the time of the measurements, this production systematics will be totally negligible, and well below the percent level. All the input parameters of the denominator (the couplings of the W and the Z to the initial state quarks, and the leptonic decay branching ratios) are precisely known. The only remaining parameters are the Higgs coupling to the W (entering with a square in the WH production rate), and the H→γγ branching ratio. Their product can therefore be extracted from the ratio measurement, with a statistical precision indicated in the last column of the table. The uncertainty on the product of the couplings $g_{HWW} \times g_{H\gamma\gamma}$ is given by half those values, giving a result well below the percent level.

For information, we show in Table 2 the equivalent results for the ratio σ(Z[νν]H[→γγ]) / σ(Z[νν]Z[→ e$^+$e$^-$]). This channel does not directly probe any new coupling, but is statistically rather powerful. Considering that the q$\bar{\text{q}}$ → ZH[γγ] is theoretically well understood, and can be also monitored via the measurement of q$\bar{\text{q}}$ → WH[γγ] we just discussed, the ratio σ(Z[νν]H[→γγ]) / σ(Z[νν]Z[→ e$^+$e$^-$]) could be used to single out the gg→ZH contribution, which, at 100 TeV, represents a non-negligible fraction of the ZH production.

3 σ(WH[→ττ]) / σ(WZ[→ττ])

The individual rates for these final states are shown in Table 3. We assume that the separate Z[ττ] and H[ττ] rates can be extracted through a global fit of the ττ invariant mass spectrum, for some optimized definition of "invariant mass", which will depend on the selected τ decay modes. The MC modeling of the cross-talk between Z and H decays (τ pairs from Z decays feeding into the H signal, and viceversa) can be validated and precisely tuned by using the mass spectrum of $\ell\ell$ (ℓ=e,μ) pairs in WZ*[$\ell\ell$], folded with the modeling of individual τ decays. The Higgs p_T spectrum can likewise be precisely modeled using the measured shape of WH[γγ] spectrum, and then folded with the kinematically trivial H[ττ] decay, and subsequent τ decays. For the production systematics of the ratio WH/WZ, the same considerations of the previous section apply.

The results of Table 3 include an overall identification efficiency for the tau pairs of 10%. Using a 4% efficiency leads to the results of Table 4.

Table 1. First two columns: rates (in pb) for the WZ and WH final states, with W→eν and Z→ee. Third and fourth columns: event rates for L=30 ab^{-1}, considering the W decays to both electron and muons, and including the BR(H→γγ). The uncertainty on the ratio, statistically equivalent to the WH uncertainty, is given in the last column.

p_T^{min} (GeV)	W[e]Z[e] (pb)	W[e]H (pb)	W[ℓ]Z[e] × L	W[ℓ]H[γγ] × L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E6	1.4E4	8.5E−3
150	1.0E-2	6.3E-2	6.0E5	8.7E3	1.1E−2
200	5.6E-3	3.8E-2	3.4E5	5.2E3	1.4E−2
300	2.1E-3	1.6E-2	1.3E5	2.2E3	2.1E−2

Table 2. First two columns: rates (in pb) for the ZZ and ZH final states, with one Z→νν and the second Z→ee. Third and fourth columns: event rates for L=30 ab^{-1}, including the BR(H→γγ). The uncertainty on the ratio, statistically equivalent to the ZH uncertainty, is given in the last column.

p_T^{min} (GeV)	Z[ν]Z[e] (pb)	Z[ν]H (pb)	Z[ν]Z[e] × L	Z[ν]H[γγ] × L	$\delta R\ R$
100	6.6E-2	1.5E-1	2.0E6	1.0E4	9.8E−3
150	3.2E-2	8.1E-2	9.6E5	5.6E3	1.3E−2
200	1.7E-3	4.7E-2	5.1E5	3.2E3	1.8E−2
300	6.2E-3	1.9E-2	1.9E5	1.3E3	2.8E−2

Table 3. First two columns: rates (in pb) for the WZ and WH final states, with W→eν and Z→ττ. Third and fourth columns: event rates for L=30 ab^{-1}, considering the W decays to both electron and muons, including the BR(H→ττ), and adding an overall tau pair identification efficiency $\varepsilon_\tau = 10\%$, for both Z and H decays. The uncertainty on the ratio $\delta R/R$ is given in the last column.

p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\varepsilon_\tau$ L	W[ℓ]H[ττ] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2	1.3E4	6.0E3	1.6E−2
400	9.8E-4	7.9E-3	5.9E3	3.0E3	2.2E-2

Table 4. Same as table 3, but with a 4% identification efficiency for the tau pairs.

p_T^{min} (GeV)	W[e]Z[ττ] (pb)	W[e]H (pb)	W[ℓ]Z[ττ] $\times\varepsilon_\tau$ L	W[ℓ]H[ττ] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	5.0E4	1.5E4	9.3E−3
150	1.0E-2	6.3E-2	2.4E4	9.5E3	1.2E−3
200	5.6E-3	3.8E-2	1.3E4	5.7E3	1.6E−2
300	2.1E-3	1.6E-2	5.0E3	2.4E3	2.5E−2

4 σ(WH[$\to$bb]) / σ(WZ[$\to$ bb])

This is clearly the most challenging observable, due to the large QCD background from W+b$\bar{b}$. The Z[bb] and H[bb] signals can be extracted by requesting the invariant mass of the bb system to satisfy $|m[bb]-m_X| < 15$ GeV, for X=Z,H, respectively. As shown in Table 5, this reduces the QCD background to a level comparable to the signal rates.

The production systematics for the ratio of the WZ and WH signals is assumed negligible, as discussed above. The production systematics for the QCD background Wbb is assumed also to be negligible, as the absolute background rate could be extracted from the analysis of the sidebands in the m[bb] distribution, with a possible MC guidance in the modeling of the shape. One also expects that the purely theoretical modeling of the Wbb process will have greatly improved with future higher-order calculations. The uncertainties in the b-tagging efficiency, and in the reconstruction of the bb system, are strongly correlated in the case of Z[bb] and H[bb], due to the closeness in mass of Z and H. For the sake of extracting the rates in Table 5 we assign a 50% overall tagging efficiency for the b pair.

We notice that the statistical uncertainty remains below the % level up to p_T(H)=800 GeV, leaving plenty of room for the introduction of more refined analysis requirements required to further purify the signals.

Table 5. The first four columns give the rates (in pb) for the relevant signal and background processes. The 1st and 3rd column, in particular, refer to the QCD Wbb background, subject to the constraint $|m[bb]-m_X| < 15$ GeV, for X=Z,H, respectively (defined here by $m[bb] \in X$). The second set of columns gives the rates, including the relevant Higgs branching ratio and a total tagging efficiency of 50% for the two b's. The final uncertainty, in the last column, is obtained combining in quadrature the statistical uncertainties of the WZ[bb] and WH[bb] signals, each of them given by $\sqrt{S+B}/S$, with B representing the QCD Wbb background.

p_T^{min} (GeV)	W[e]+bb (pb) $m[bb] \in m_Z$	W[e]Z[bb] (pb)	W[e]+bb (pb) $m[bb] \in m_H$	W[e]H (pb)	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_Z$	W[ℓ]Z[bb] $\times\varepsilon_b$ L	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_H$	W[ℓ]H[bb] $\times\varepsilon_b$ L	$\delta R/R$
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

5 Conclusions

We summarize in Table 6 possible precision targets for the various combinations of couplings that can be obtained from the observables considered here. Compiling this table, we selected values of p_T^{min} that have a chance of optimizing the balance between statistics and systematics.

We do not claim that the above estimates of the $\delta G/G$ are robust. This should be seen as a first assessment of the potential statistical relevance of these observables. If there were no statistical power, no point discussing the systematics! The proposed observables are designed to minimize the key systematics, but more detailed studies are obviously needed. As a start, at least some DELPHES-based analyses of the full final states and backgrounds must be done, to identify the required detector performance targets, compare them with those of the existing FCC-hh detector design, and place a first judgement on the actual value of the proposed measurements. The generic sub-% precision can could be achievable for these "clean" observables gives some hope that the % level can be reached once more thorough analyses are in place. The large statistics and p_T reach of

Table 6. Summary of the statistical precisions, assuming $\Gamma_{tot} = \Gamma_{tot}^{SM}$.

Coupling G	Ref Table	$p_T^{min}(GeV)$	$\delta G/G$
$g_{HWW}g_{H\gamma\gamma}$	1	200	0.7E−2
$g_{HWW}g_{H\tau\tau}$	3	300	0.8E−2
$g_{HWW}g_{Hbb}$	5	800	0.5E−2

100 TeV provide very powerful handles to pin down backgrounds and systematics in a data-driven way, following the inspiring examples given by the LHC experiments.

The examples given here could be of relevance even under the highly desirable assumption that FCC-ee will be realized, and provide extremely accurate measurements of the couplings to W, b and τ. For example, they highlight the power of FCC-hh to extend to large p_T(H) the precise measurements of Higgs production, to test its basic couplings in the high-Q^2 region.

On the other hand, it remains true that FCC-hh alone cannot easily fill in the shoes of the ee collider. There is no evidence as yet that one can achieve a precision for the Hcc coupling comparable to that promised by FCC-ee, or a robust and precise, model-independent measurement of Γ_{tot}(H). We are also aware of the fact that the combination of couplings outlined here is not enough to remove possible degeneracies in the extraction of EFT constraints. Work is in progress to propose measurements for additional coupling combinations, for example directly probing the g_{HWW} coupling using H$\rightarrow$WW decays.