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Theoretical Uncertainty for the Higgs Boson Lineshape

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A summary of the theoretical uncertainty associated with the Higgs boson lineshape

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1. Introduction

In this work, following Independence Day [1, 2], we summarize the status of theoretical uncertainties (THU) associated with the Higgs boson lineshape. The recent observation of a new massive neutral boson by ATLAS and CMS opens a new era where characterization of this new object is of central importance. Interim recommendations to explore the coupling structure of a Higgs-like particle can be found in Ref. [3]. A recent note by ATLAS Collaboration [4], using data taken in 2011 and 2012, reports that, within the current statistical uncertainties, no significant deviations from the Standard Model couplings are observed. Nevertheless, this is only the beginning of the program of “identification”; we will assume that the new particle is a CP-even scalar. As shown in Ref. [5] one can classify the couplings of a neutral CP even scalar to W and Z bosons according to its properties under custodial symmetry. The possibilities are: the scalar is an electroweak (EW) singlet, is not an EW singlet (but is a custodial singlet), the scalar is the neutral member of a custodial 5-plet, mixtures of the above. The Higgs boson is the custodial singlet in the decomposition $(2_{\mathrm{L}}\,, 2_{\mathrm{R}}) = 1 \oplus 3$.

The search for the coupling structure of the light Higgs-like particle, as well as for new heavy states, will continue. The huge uncertainty used so far for the heavy Higgs searches [6] ($1.5\,(M_{\mathrm{H}}/\mathrm{TeV})^3$) was supposed to cover both the effect of the incorrect treatment of the lineshape and the missing interference. However, this uncertainty forced ATLAS and CMS to stop the search at 600 GeV, where the uncertainty is 30%.

In the following we will review recent improvements on estimating the THU. We do not discuss uncertainties coming from QCD scale variations and from PDF$+\alpha_{\mathrm{S}}$ [6].

2. Limits of Zero-width approximation for a light Higgs boson signal

In the mass range of the new Higgs-like state the width of the Standard Model (SM) Higgs boson is more than four orders of magnitude smaller than its mass. The zero-width approximation is hence expected to be an excellent approximation. the work of Ref. [7] has shown that this is not always the case. The inclusion of off-shell contributions is essential to obtain an accurate Higgs signal normalization at the 1% precision level. For $gg\ (\to H) \to VV$, $V = W, Z$, $\mathscr{O}(10\%)$ corrections occur due to an enhanced Higgs signal in the region $M_{\mathrm{VV}} > 2\,M_{\mathrm{V}}$, where also sizeable Higgs-continuum interference occurs.

It is worth noting again that the whole effect on the signal has nothing to do with $\Gamma_{\mathrm{H}}/M_{\mathrm{H}}$ effects; above the ZZ-threshold the lineshape is higher than expected (although tiny w.r.t. the narrow peak) and stays constant till the *bartt*-threshold after which we observe an almost linear decrease. This is why the total cross-section is affected (in ZZ final state) at the 10% level.

3. The Complex-Pole Scheme

Until recently, the Higgs boson invariant mass distribution (Higgs–boson-lineshape) has received little attention. In the work of Refs. [8, 9] we have made an attempt to resolve the problem by comparing different theoretical inputs to the off-shellness of the Higgs boson. There is no question at all that the zero-width approximation should be avoided, especially in the high-mass region

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where the on-shell width becomes of the same order as the on-shell mass, or higher. We have shown evidence that only the Dyson-resummed propagator should be used, leading to the introduction of the H complex pole, a gauge-invariant property of the S-matrix. It is convenient to describe the Complex-Pole scheme (CPS) as follows: the signal cross-section for the process $ij \to F$ can be written as

$$\sigma_{ij\to H\to F}(s) = \frac{1}{\pi}\,\sigma_{ij\to H}\,\frac{s^2}{\left|s - s_{\rm H}\right|^2}\,\frac{\Gamma_{\rm H}^{\rm tot}}{\sqrt{s}}\,{\rm BR}\big(H \to F\big), \quad \Gamma_{\rm H}^{\rm tot} = \sum_{f\in F}\Gamma_{H\to F}. \tag{3.1}$$

where s is the Higgs virtuality, $s_{\rm H}$ is the Higgs complex pole and we have introduced a sum over all final states.

Note that the complex pole describing an unstable particle is conventionally parametrized as $s_i = \mu_i^2 - i\,\mu_i\,\gamma_i$. It would we desirable to include two- and three-loop contributions in $\gamma_{\rm H}$ and for some of these contributions only on-shell results have been computed so far. Therefore, it is very useful to give a rough estimate of the missing orders. Following the authors of Ref. [10] (as explained in Sect. 7 of Ref. [9]) we can estimate that the first correction to $\gamma_{\rm H}$ is roughly given by

$$\delta_{\rm H} = 0.350119\,\frac{G_{\rm F}\,\mu_{\rm H}^2}{2\sqrt{2}\pi^2}. \tag{3.2}$$

Changes in $\gamma_{\rm H}$ range from 2.3% at 400 GeV to 9.4% at 750 GeV. In general, we do not see very large variations up to 1 TeV with a breakdown of the perturbative expansion around when 1.74 TeV. Therefore, using $\gamma_{\rm H}\,(1\pm\delta_{\rm H})$ we can give a rough but reasonable estimate of the remaining uncertainty on the lineshape. To summarize our estimate of the theoretical uncertainty associated to the signal: the remaining uncertainty on the production cross-section is typically well reproduced by $(\delta_{\rm H}+1)[\%]$, σ_{max} (the peak cross-section) changes approximately with the naive expectation, $2\,\delta_{\rm H}[\%]$.

The factor $\Gamma_{\rm H}^{\rm tot}(\sqrt{s})$ in Eq.(3.1) deserves a separate discussion. It represents the "on-shell" decay of an Higgs boson of mass $\sqrt{s}$ and we have to quantify the corresponding uncertainty. The staring point is $\Gamma^{\rm tot}$ computed by PROPHECY4F [11] which includes two-loop leading corrections in $G_{\rm F}M_{\rm H}^2$, where $M_{\rm H}$ is now the on-shell mass. Next we consider the on-shell width in the Higgs-Goldstone model, discussed in [10, 12]. We have

$$\frac{\Gamma_{\rm H}}{\sqrt{s}}\Big|_{\rm HG} = \sum_{n=1}^{3} a_n\,\lambda^n = X_{\rm HG}, \qquad \lambda = \frac{G_{\rm F}s}{2\sqrt{2}\pi^2}. \tag{3.3}$$

Let $\Gamma_{\rm p} = X_{\rm p}\sqrt{s}$ the width computed by PROPHECY4F, we redefine the total width as

$$\frac{\Gamma_{\rm tot}}{\sqrt{s}} = \big(X_{\rm p} - X_{\rm HG}\big) + X_{\rm HG} = \sum_{n=0}^{3} a_n\,\lambda^n, \tag{3.4}$$

where now $a_0 = X_{\rm p} - X_{\rm HG}$. As long as λ is not too large we can define a $p\% < 80\%$ credible interval as (following from $a_{2,3} < a_1$)

$$\Gamma_{\rm tot}(\sqrt{s}) = \Gamma_{\rm p}(\sqrt{s}) \pm \Delta\Gamma, \qquad \Delta\Gamma = \frac{5}{4}\max\{|\,a_0\,|, a_1\}\,p\%\,\lambda^4\sqrt{s}. \tag{3.5}$$

4. Interference signal - background

In the current experimental analysis there are additional sources of uncertainty, e.g. background and Higgs interference effects [13, 14, 15, 16, 17]. As a matter of fact, this interference is partly available and should not be included as a theoretical uncertainty; for a discussion and results we refer to Refs. [18, 19, 20].

Here we will examine the channel $gg \to ZZ$ and discuss the associated THU. The background (continuum $gg \to ZZ$) and the interference are only known at leading order (LO, one-loop) [21]. Here we face two problems, a missing NLO calculation of the background (two-loop) and the NLO or NNLO signal at the amplitude level, without which there is no way to improve upon the present LO calculation.

A potential worry, already addressed in Ref. [18], is: should we simply use the full LO calculation or should we try to effectively include the large (factor two) K-factor to have effective NNLO observables? There are different opinions since interference effects may be as large or larger than NNLO corrections to the signal. Therefore, it is important to quantify both effects. Let us consider any distribution D, i.e.

$$D = \frac{d\sigma}{dx} \quad x = M_{\rm ZZ} \quad \text{or} \quad x = p_{\perp}^{\rm Z} \quad \text{etc.} \tag{4.1}$$

where $M_{\rm ZZ}$ is the invariant mass of the ZZ-pair and $p_{\perp}^{\rm Z}$ is the transverse momentum. We introduce the following options, see Ref. [22] (S, B and I are shorthands for signal, background and interference):

- **additive** where one computes

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = \frac{d\sigma^{\rm NNLO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B) \tag{4.2}$$

- **multiplicative** where one computes

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\Big[\frac{d\sigma^{\rm LO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I)\Big] + \frac{d\sigma^{\rm LO}}{dx}(B), \qquad K_{\rm D} = \frac{\frac{d\sigma^{\rm NNLO}}{dx}(S)}{\frac{d\sigma^{\rm LO}}{dx}(S)}, \tag{4.3}$$

  where $K_{\rm D}$ is the differential K-factor for the distribution. Note that $K_{\rm D}$ accounts for both QCD and EW higher order effects in the production and in the decay.

- **intermediate** It is convenient to define

$$K_{\rm D} = K_{\rm D}^{gg} + K_{\rm D}^{\rm rest}, \qquad K_{\rm D}^{gg} = \frac{\frac{d\sigma^{\rm NNLO}}{dx}\big(gg \to H(g) \to ZZ(g)\big)}{\frac{d\sigma^{\rm LO}}{dx}\big(gg \to H \to ZZ\big)} \tag{4.4}$$

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\,\frac{d\sigma^{\rm LO}}{dx}(S) + \big(K_{\rm D}^{gg}\big)^{1/2}\,\frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B) \tag{4.5}$$

Oour recipe for estimating the theoretical uncertainty in the effective NNLO distribution is as follows: the intermediate option gives the *central value*, while the band between the multiplicative and the additive options gives the uncertainty. Note that the difference between the intermediate option and the median of the band is always small if not far away from the peak where, in any case, any option becomes questionable.

For an inclusive quantity the effect of the interference, with or without the NNLO K-factor for the signal, is almost negligible. For distributions this is radically different; referring to the ZZ invariant mass distribution we can say that, close to $M_{ZZ} = \mu_{\rm H}$, the uncertainty is small but becomes large in the rest of the search window $[\mu_{\rm H} - \gamma_{\rm H}\,, \mu_{\rm H} + \gamma_{\rm H}]$. The effect of the LO interference, w.r.t. LO $S+B$, reaches a maximum of $+16\%$ before the peak (e.g. at $\mu_{\rm H} = 700\,$GeV) while our estimate of the scaled interference (always w.r.t. LO $S+B$) is $86+7-3\,\%$ in the same region, showing that NNLO signal effects are not negligible[1].

5. EW corrections to $gg \to H$ and $H \to VV$

The NLO EW corrections to gluon fusion have been computed in Refs. [24, 25]. The original results have been produced up to a Higgs invariant mass of 1 TeV. If one is interested in the lineshape corresponding to a Higgs mass of 600 GeV - 1 TeV there will be some non-negligible fraction of events with invariant mass up to 2 TeV. In this case extrapolation will give wrong results; for this reason we have provided additional values: $\delta_{\rm EW} = +19.37\%(+34.53\%, +53.90\%)$ for $\mu_{\rm H} = 1.5\,{\rm TeV}(2\,{\rm TeV}, 2.5\,{\rm TeV})$[2]. Also $\Gamma_{\rm H}^{\rm tot}$ of Eq.(3.1) needs some attention. The best results available are from Ref. [6] where, however, tables stop at 1 TeV. If one wants go go above this value, it is better to include few additional points, e.g. $\Gamma_{\rm H}^{\rm tot} = 3.38(15.8)\,$TeV for $\mu_{\rm H} = 1.5(2)\,$TeV. Note that, at 2 TeV, one has $\Gamma(H \to ZZ) = 5.25\,$TeV and $\Gamma(H \to WW) = 10.52\,$TeV.

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[1] Complete set of results, including results for the THU discussed in Sect. 3, and a code for computing the SM Higgs complex pole can be found at [23].

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