

Higgs Interference Effects in $gg \rightarrow ZZ$ and their Uncertainty*

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Interference between the Standard Model Higgs boson and continuum contributions in $gg \rightarrow ZZ$ is considered in the heavy-mass scenario. Results are available at leading order for the background (the $gg \rightarrow ZZ$ box diagrams). It is discussed how to combine the result with the next-to-next-to-leading order Higgs production cross-section and a proposal for estimating the associated theoretical uncertainty is presented.

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1 Introduction

At the beginning of 2011 the status of the inclusive cross-section for Higgs-boson production in gluon fusion was summarized [1]. Corrections arising from higher-order QCD, electroweak effects, as well as contributions beyond the commonly-used effective theory approximation were analyzed. Uncertainties arising from missing terms in the perturbative expansion, as well as imprecise knowledge of parton distribution functions, were estimated to range from approximately 15–20%, with the precise value depending on the Higgs boson mass. For an updated study we refer to Ref. [2].

Recently the problem of going beyond the zero-width approximation has received new boost from the work of Refs. [3,4] and of Ref. [5] which implemented the complex-pole-scheme with an estimate of the residual theoretical uncertainty (see also the work of Ref. [6]). Here we only recall that the complex pole describing an unstable particle is conventionally parametrized as

$$s_i = \mu_i^2 - i \mu_i \gamma_i, \quad (1)$$

with $i = W, Z, H$ etc. (see Ref. [5,7,8]).

In the current experimental analysis there are additional sources of uncertainty, e.g. background and Higgs interference effects [9–13]. 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. [14–17]. In particular, from Refs. [14] we see that at $\mu_H = 600 \text{ GeV}$ (the highest value reported) the effect is about +40% in the window $\zeta = 440\text{--}560 \text{ GeV}$, where ζ is the Higgs virtuality; the effect is practically zero at the peak and reaches –50% after $\zeta = 680 \text{ GeV}$ (no cuts applied). For the total cross-section in $gg \rightarrow \text{lvl}'v'$ at $\mu_H = 600 \text{ GeV}$ the effect of including the interference is already +34% and rapidly increasing with μ_H .

We stress that setting limits without including the effects of the interference induces large variations in rate and shape that will propagate through to all distributions. Therefore, any attempt to analyze kinematic distributions which are far from the Standard Model (SM) shape may result in misleading limits.

The importance of a complete understanding of the shape of the background from non-resonant diagrams has been emphasised in Refs. [18,19]. It was shown in this work that a heavy Higgs boson with mass larger than 800 GeV does not lead to a pronounced peak structure in the lineshape and predictions for the non-resonant background must therefore be as accurate as possible in order to discriminate a heavy Higgs boson from a light one.

In the current experimental analysis for heavy Higgs searches, a theoretical uncertainty of $150 \mu_H^3 [\%]$ (μ_H in TeV) has been used for conservative estimate¹. For a Higgs boson of 700 GeV this amounts to $\pm 51\%$.

One might wonder why considering a Standard Model (SM) Higgs boson in such a high-mass range. There are classic constraints on the Higgs boson mass coming from unitarity, triviality and vacuum stability, precision electroweak data and absence of fine-tuning [20]. The situation is different if we consider extensions of the SM: in the THD model, even if the SM-like Higgs boson is found to be light ($< 140 \text{ GeV}$), there is a possible range of mass splitting in the heavy Higgs boson. In general, for a given Higgs boson mass, the magnitude of the mass splittings among different heavy scalar bosons can be determined to satisfy the electroweak precision data, see Ref. [21].

This paper is organized as follows. In Section 2 we discuss results available in the literature. In Section 3 we present and discuss numerical results. Conclusions are presented in Section 4.

2 Summary of available results

There are serious problems in including the signal/background interference in gluon-gluon fusion and very few examples of theoretical predictions, e.g. interference has been computed for the di-photon signal in Ref. [22]. Let us concentrate on the process $gg \rightarrow ZZ$, the whole cross-section can be written as follows (here, for simplicity, we neglect folding the partonic process with parton distribution functions):

$$\sigma_{gg \rightarrow ZZ} = \sigma_{gg \rightarrow ZZ}(S) + \sigma_{gg \rightarrow ZZ}(I) + \sigma_{gg \rightarrow ZZ}(B), \quad (2)$$

¹<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyHiggs>

where S, B and I stand for signal ($gg \rightarrow H \rightarrow ZZ$), background ($gg \rightarrow ZZ$, i.e. gluon initiated box contribution for all three quark doublets) and interference; the signal can be written as

$$\sigma_{gg \rightarrow ZZ}(S) = \sigma_{gg \rightarrow H \rightarrow ZZ}(\zeta) = \frac{1}{\pi} \sigma_{gg \rightarrow H} \frac{\zeta^2}{|\zeta - s_H|^2} \frac{\Gamma_{H \rightarrow ZZ}}{\sqrt{\zeta}}, \quad (3)$$

where we have introduced s_H , the Higgs boson complex pole [7,5]; furthermore, ζ is the Higgs boson virtuality. So far, most if not all theoretical prediction have been devoted to compute the signal with the highest possible precision, next-to-leading order (NLO) and beyond. Therefore, in Eq.(2), we have

- the production cross-section, $\sigma_{gg \rightarrow H}$, with next-to-next-to-leading logarithmic resummation (NNLL) [23], i.e. with NNLL + NNLO + EW + bottom quark contribution up to NLO + NLL (three loop level plus resummation), see Ref. [2]
- the partial decay width of an off-shell Higgs boson of virtuality ζ , $\Gamma_{H \rightarrow ZZ}$, which is known at NLO (one-loop) with leading NNLO effects in the limit of large Higgs boson mass, see Ref. [24,25].

However the background (continuum $gg \rightarrow ZZ$) and the interference are only known at leading order (LO, one-loop) [26]. 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. For low values of the Higgs boson mass the interference arises primarily from the imaginary part of the continuum background interfering with the real part of the signal. For $\mu_H < 2m_t$, where we can use the effective theory (i.e. large- m_t limit), it would be relatively easy to get the signal amplitude; however, what might be the tougher part is implementing it in the same program that contains the background. Above the $\bar{t}t$ -threshold, getting the signal amplitude becomes more difficult. We know that the effective theory misses imaginary parts in this region, and it is not clear how one would trust a calculation for the interference using it.

Of course, putting in the $\mathcal{O}(\alpha_s^n)$ corrections to the signal without the background can only be considered an approximation to the interference correction. It is difficult to believe that background NLO calculation will be done in a foreseeable future since not all basic master integral for the two-loop contribution are known, at least analytically.

We can also summarize the basic features of the LO interference, especially for high value of the Higgs boson mass where the contribution from the imaginary part of the signal is not negligible. The main issue is on unitarity cancellations at high energy. Of course, the behavior of both LO amplitudes (signal and background) for $M_{ZZ} \rightarrow \infty$ is known and simple and any correct treatment of perturbation theory (no mixing of different orders) will respect the unitarity cancellations. Since the Higgs boson decays almost completely into longitudinal Zs, for $M_{ZZ} \rightarrow \infty$ we have [26] (for a single quark q)

$$A_S \sim \frac{M_{ZZ}^2 m_q^2}{2M_Z^2} \Delta_H \ln^2 \frac{M_{ZZ}^2}{m_q^2} \quad A_B \sim -\frac{m_q^2}{2M_Z^2} \ln^2 \frac{M_{ZZ}^2}{m_q^2}, \quad (4)$$

where Δ_H is the Higgs propagator, showing cancellation in the limit ($M_{ZZ}^2 \Delta_H \rightarrow 1$). However, the behavior for $M_{ZZ}^2 \rightarrow \infty$ (unitarity) should not/cannot be used to simulate the interference for $M_{ZZ} < \mu_H$. The only relevant message to be derived here is that unitarity requires the interference to be destructive at large values of M_{ZZ} . The explicit LO calculation also shows that the interference is constructive below the Higgs peak. The higher-order correction in gluon-gluon fusion [27–33,23] have shown a huge K -factor (for updated cross-sections at 8 TeV see Ref. [34])

$$K = \frac{\sigma_{\text{prod}}^{\text{NNLO}}}{\sigma_{\text{prod}}^{\text{LO}}}, \quad \sigma_{\text{prod}} = \sigma_{gg \rightarrow H}. \quad (5)$$

A potential worry, already addressed in Ref. [14], 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. So far, two options have been introduced to account for the increase in the signal (*cf.* Ref. [35,36]). Let us consider any distribution D , i.e.

$$D = \frac{d\sigma}{dM_{ZZ}} \quad \text{or} \quad \frac{d\sigma}{dp_{\perp}^Z} \quad \text{etc.} \quad (6)$$

where M_{ZZ} is the invariant mass of the ZZ-pair and p_{\perp}^Z is the transverse momentum. Two possible options are:

- **additive** where one computes

$$D_{\text{eff}}^{\text{NNLO}} = D^{\text{NNLO}}(S) + D^{\text{LO}}(I) + D^{\text{LO}}(B) \quad (7)$$

- **multiplicative** where one computes

$$D_{\text{eff}}^{\text{NNLO}} = K_{\text{D}} [D^{\text{LO}}(S) + D^{\text{LO}}(I)] + D^{\text{LO}}(B), \quad K_{\text{D}} = \frac{D^{\text{NNLO}}(S)}{D^{\text{LO}}(S)}, \quad (8)$$

where K_{D} is the differential K -factor for the distribution.

In both cases the NNLO corrections include the NLO electroweak part, for production [37] and decay [25]. It is worth noting that the differential K -factor for the ZZ-invariant mass distribution is a slowly increasing function of M_{ZZ} , going (e.g. for $\mu_{\text{H}} = 700 \text{ GeV}$) from 2.04 at $M_{ZZ} = 210 \text{ GeV}$ to 2.52 at $M_{ZZ} = 1 \text{ TeV}$.

The two options, as well as intermediate ones, suffer from an obvious problem: they are spoiling the unitarity cancellation between signal and background for $M_{ZZ} \rightarrow \infty$, breakdown which is described in details in Ref. [26]. Therefore, our partial conclusion is that any option showing an early onset of unitarity violation should not be used for too high values of the ZZ-invariant mass.

Therefore, our first prescription in proposing an effective higher-order interference will be to limit the risk of overestimation of the signal by applying the recipe only in some restricted interval of the ZZ-invariant mass, e.g. $[\mu_{\text{H}} - \gamma_{\text{H}}, \mu_{\text{H}} + \gamma_{\text{H}}]$. This is especially true for high values of μ_{H} where the width is large.

Explicit calculations show that the *multiplicative* option is better suited for regions with destructive interference while the *additive* option can be used in regions where the effect of the interference is positive, i.e. we still miss higher orders from the background amplitude but do not spoil cancellations between signal and background.

Actually, there is an intermediate options that is based on the following observation: higher-order corrections to the signal are made of several terms (see Ref. [29] for a definition of $\Delta\sigma$),

$$\sigma^{\text{prod}} = \sum_{i,j} \int \text{PDF} \otimes \sigma_{ij \rightarrow \text{all}}^{\text{prod}} = \sum_{i,j} \int_{z_0}^1 dz \int_z^1 \frac{dv}{v} \mathcal{L}_{ij}(v) \sigma_{ij \rightarrow \text{all}}^{\text{prop}}(\zeta, \kappa, \mu_{\text{R}}, \mu_{\text{F}}), \quad (9)$$

where the sum is over incident partons; furthermore $\zeta = z s$ is the Higgs virtuality, z_0 is a lower bound on the invariant mass of the H decay products, $\kappa = v s$ is the invariant mass of the incoming partons (i, j) and the luminosity is defined by

$$\mathcal{L}_{ij}(v) = \int_v^1 \frac{dx}{x} f_i(x, \mu_{\text{F}}) f_j\left(\frac{v}{x}, \mu_{\text{F}}\right). \quad (10)$$

The partonic cross-section is defined by

$$\sum_{ij} \sigma_{ij \rightarrow \text{H}+\text{X}}(\zeta, \kappa, \mu_{\text{R}}, \mu_{\text{F}}) = \sigma_{\text{gg} \rightarrow \text{H}} \delta\left(1 - \frac{z}{v}\right) + \frac{s}{\kappa} (\Delta\sigma_{\text{gg} \rightarrow \text{Hg}} + \Delta\sigma_{\text{qg} \rightarrow \text{Hq}} + \Delta\sigma_{\text{q}\bar{\text{q}} \rightarrow \text{Hg}} + \text{NNLO}). \quad (11)$$

From this point of view it seems more convenient to define

$$K_{\text{D}} = K_{\text{D}}^{\text{gg}} + K_{\text{D}}^{\text{rest}}, \quad K_{\text{D}}^{\text{gg}} = \frac{D^{\text{NNLO}}(\text{gg} \rightarrow \text{H}(\text{g}) \rightarrow \text{ZZ}(\text{g}))}{D^{\text{LO}}(\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ})} \quad (12)$$

and to introduce a third option

- **intermediate**

$$D_{\text{eff}}^{\text{NNLO}} = K_{\text{D}} D^{\text{LO}}(S) + (K_{\text{D}}^{\text{gg}})^{1/2} D^{\text{LO}}(I) + D^{\text{LO}}(B) \quad (13)$$

which, in our opinion, better simulates the inclusion of K -factors at the level of amplitudes (although we are still missing corrections to the continuum amplitude).

Alternatively one could consider a different approach when $M_{\text{ZZ}} \gg \mu_{\text{H}}$; it is based on Eq.(4) and on the work of Ref. [38] and amounts to neglect the background (where NLO corrections are not available) while modifying the Higgs propagator,

$$\frac{1}{M_{\text{ZZ}}^2 - s_{\text{H}}} = \left(1 + i \frac{\bar{\Gamma}_{\text{H}}}{\bar{M}_{\text{H}}}\right) \left(M_{\text{ZZ}}^2 - \bar{M}_{\text{H}}^2 + i \frac{\bar{\Gamma}_{\text{H}}}{\bar{M}_{\text{H}}} M_{\text{ZZ}}^2\right)^{-1} \rightarrow \frac{\bar{M}_{\text{H}}^2}{M_{\text{ZZ}}^2} \left(M_{\text{ZZ}}^2 - \bar{M}_{\text{H}}^2 + i \frac{\bar{\Gamma}_{\text{H}}}{\bar{M}_{\text{H}}} M_{\text{ZZ}}^2\right)^{-1} \quad (14)$$

where we have introduced mass and width in the Bar-scheme [5] according to

$$\bar{M}_{\text{H}}^2 = \mu_{\text{H}}^2 + \gamma_{\text{H}}^2 \quad \mu_{\text{H}} \bar{\Gamma}_{\text{H}} = \bar{M}_{\text{H}} \gamma_{\text{H}}. \quad (15)$$

This recipe, Eq.(14), should be used only for $M_{\text{ZZ}} \gg \mu_{\text{H}}$ and should not be extended below the resonant peak.

In the following Section we present numerical results in the high Higgs-mass region.

3 Numerical results

In the following we will present numerical results obtained with the program HTO (G. Passarino, unpublished) that allows for the study of the Higgs-boson-lineshape, in gluon-gluon fusion (ggF), using complex poles. HTO is a FORTRAN 95 program that contains a translation of the subroutine HIGGSNNLO written by M. Grazzini for computing the total (on-shell) cross-section for Higgs-boson production (in ggF) at NLO and NNLO [39–41] and a translation of the program **ggzz** by E.W Glover and J.J. van der Bij for computing the LO interference in $gg \rightarrow ZZ$.

All results in this paper refer to $\sqrt{s} = 8 \text{ TeV}$ and are based on the MSTW2008 PDF sets [42]. They are implemented according to the OFFP - scheme, see Eq.(45) of Ref. [5]. Furthermore we use renormalization and factorization QCD scales that evolve with the Higgs virtuality (M_{ZZ}).

In Table 1 we present the effect of the interference w.r.t. signal + background for the total cross-section. We select a leptonic final state (the branching ratio for both Z bosons to decay into e or μ is $4.36 \cdot 10^{-3}$) and use $p_{\text{T}}^Z > 0.25 M_{\text{ZZ}}$ and $2 M_{\text{Z}} < M_{\text{ZZ}} < 1 \text{ TeV}$. As is evident the strong cancellations between the constructive and destructive interference below and above the peak result in a small effect on the total cross-section. However, the effect is drastically different on distributions. We present results for the M_{ZZ} -distribution

Table 1: Interference effect for the total cross-section at LO and NNLO with multiplicative (M) option of Eq.(8), additive (A) option of Eq.(7) and intermediate option of Eq.(13). Here $p_{\text{T}}^Z > 0.25 M_{\text{ZZ}}$ and $2 M_{\text{Z}} < M_{\text{ZZ}} < 1 \text{ TeV}$. In the table we show the percentage effect of the interference, i.e. interference/(signal + background).

$\mu_{\text{H}}[\text{GeV}]$	LO	NNLO(A)	NNLO(I)	NNLO(M)
400	0.80[%]	0.64[%]	1.05[%]	1.65[%]
600	0.98[%]	0.93[%]	1.57[%]	2.52[%]
800	0.66[%]	0.63[%]	1.12[%]	1.84[%]

(lineshape) with a cut $p_{\text{T}}^Z > 0.25 M_{\text{ZZ}}$, where M_{ZZ} is the invariant mass of the ZZ-pair.

In Figure 1 we show the lineshape for a Higgs mass of 600 GeV . The black line gives the full $gg \rightarrow ZZ$ process at LO; the cyan line gives signal plus background (LO) neglecting interference while the blue line includes both gg and $\bar{q}q$ initial states (LO). The red line gives the LO signal with different cuts on the Z transverse momentum.

In Figure 2 we present options for including higher-order effects. The black line is again full LO $gg \rightarrow ZZ$ result, the brown line gives the multiplicative option, the red line is the additive option while the blue line is the intermediate option. The cyan line gives signal plus background (LO) neglecting interference.

In Figure 3 we show the same set of results as in Figure 2 but for a Higgs boson mass of 700 GeV . There are different options for showing the effect of the interference, e.g.

$$R_{\text{eff}} = \frac{D_{\text{eff}}^{\text{NNLO}}}{D^{\text{LO}}(S) + D^{\text{LO}}(B)} - 1, \quad D = \frac{d\sigma}{dM_{ZZ}}. \quad (16)$$

However, our preferred way will be to use the following equation:

$$R'_{\text{eff}} = \frac{K_D D^{\text{LO}}(S) + (K_D^{\text{gg}})^{1/2} D^{\text{LO}}(I) + D^{\text{LO}}(B)}{K_D D^{\text{LO}}(S) + D^{\text{LO}}(B)} - 1, \quad D = \frac{d\sigma}{dM_{ZZ}}. \quad (17)$$

To summarize:

Eq.(17) is our recipe for estimating the theoretical uncertainty in the effective NNLO distribution: 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. The ratio K_D^{gg}/K_D can be greater than one in some region, e.g. for $M_{ZZ} \text{trsim} 316 \text{ GeV}$, almost μ_H -independent with a maximum of 1.024 at $M_{ZZ} = 1 \text{ TeV}$.

In Table 4 we show the estimated theoretical uncertainty for the fractional interference correction to the 700 GeV resonance, R'_{eff} defined in Eq.(17). The effect computed according to Eq.(17) is very similar to the one obtained by considering LO alone, shifted to the left and slightly less destructive for high values of M_{ZZ} . In Figure 4(Figure 5) we present R'_{eff} (Eq.(17)) for $\mu_H = 700 \text{ GeV}$ (800 GeV) summarizing the percentage effect of interference in the effective NNLO theory. The black line gives the central value while the two blue lines represent the estimated theoretical uncertainty in including the NNLO K -factor.

In Figure 6 we present the LO interference effect for $\mu_H = 600, 700, 800 \text{ GeV}$. In Figure 7 we present the effective NNLO invariant mass distribution $\mu_H = 400, 500, 600, 700, 800 \text{ GeV}$, including our estimate of the theoretical uncertainty. In Figure 8 we show the effective NNLO ZZ invariant-mass distribution for $\mu_H = 700 \text{ GeV}$ including theoretical uncertainty and a comparison between 7 TeV and 8 TeV .

In Figure 9 we present the sum signal + interference for $\mu_H = 400, 500, 600, 700, 800 \text{ GeV}$, including our estimate of the theoretical uncertainty. This quantity has no direct physical meaning but represents the pseudo-observable preferred by the experimental Collaborations.

In Table 2 we show the effect of the p_T^Z cut; from $p_T^Z > 0.25 M_{ZZ}$ to $p_T^Z > 0.15(0.05) M_{ZZ}$ the signal is reduced by only 10%(17%) while the background is reduced by a factor 1.98(3.06). Finally in Figure 10 we compare the interference effects with $p_T^Z > 0.25 M_{ZZ}$ and with $p_T^Z > 0.15 M_Z$; within the $\pm\gamma_H$ window the change is negligible and becomes larger for lower or higher values of M_{ZZ} , as expected.

Table 2: Effect of the p_T^Z cut on the total LO cross-section (Signal, Background and Total multiplied by $B = 4.36 \cdot 10^{-3}$, the BR for both Z bosons to decay into e or μ) for $2 M_Z < M_{ZZ} < 1 \text{ TeV}$.

	S fb	B fb	T fb	I/(S+B)[%]
$p_T^Z > 0.25 M_{ZZ}$	$1.091 \cdot 10^{-1}$	7.797	7.971	0.82
$p_T^Z > 0.20 M_{ZZ}$	$1.163 \cdot 10^{-1}$	11.491	11.683	0.65
$p_T^Z > 0.15 M_{ZZ}$	$1.216 \cdot 10^{-1}$	15.553	15.760	0.54
$p_T^Z > 0.05 M_{ZZ}$	$1.274 \cdot 10^{-1}$	24.139	24.366	0.41

3.1 Residual theoretical uncertainty

In our results we have not included uncertainties coming from QCD scale variations and from PDF + α_s ; due to the scaling of the LO result, these uncertainties are coming from the numerator in the K -factor and are the typical NNLO uncertainties in gluon-gluon fusion [1]. Also excluded is the residual electroweak uncertainty for the signal lineshape [5]. To give an example of the complete set of theoretical uncertainties we select $\mu_H = 700 \text{ GeV}$ and define maximum and half-maxima of the signal lineshape; they are given by

$$S(M_{ZZ}) = \frac{d\sigma^S}{dM_{ZZ}}, \quad S(M_1) = \max S(M_{ZZ}), \quad S(M_{1/2}^\pm) = \frac{1}{2} S(M_1). \quad (18)$$

We find $M_1 = 701 \text{ GeV}$ and $M_{1/2}^- = 565 \text{ GeV}$, $M_{1/2}^+ = 761 \text{ GeV}$. We define theoretical uncertainties (THU) according to the following sources: 1) intrinsic, the full band between multiplicative and additive options, 2) electroweak, due to THU on γ_H and $\Gamma_{H \rightarrow ZZ}(M)_{ZZ}$ and described in Sect. 7 of Ref. [5] and 3) QCD scales. THU arise from uncertainties in underlying theoretical paradigm. Results are shown in Table 3 for

Table 3: Theoretical uncertainty on $R'_{\text{eff}} = I/(S+B)$ for $\mu_H = 700 \text{ GeV}$.

M_{ZZ}	$R'_{\text{eff}}[\%]$	intrinsic[%]	EW[%]	QCD scales
M_1	+3.82	-1.28 +1.85	-0.34 +0.26	-0.38 +0.67
$M_{1/2}^-$	+17.19	-5.59 +8.02	-0.34 +0.44	< 0.1
$M_{1/2}^+$	-10.47	-5.18 +3.58	-0.56 +4.24	-1.58 +0.82

$R'_{\text{eff}} = I/(S+B)$. THU on M_1 is tiny, intrinsic THU is large for the half-maxima, electroweak THU remains small in the window between the two half-maxima. As far as QCD scale variation is concerned we observe that R'_{eff} is very stable when varying $M_{ZZ}/4 < \mu_R, \mu_F < M_{ZZ}$. The percentage correction R'_{eff} is the scaling factor that one has to apply to her/his own calculation of $S+B$. What it is meant in Table 3 is the following: the THU on I induced by QCD scale variation is between 5.39% $[S+B](M_{ssZZ}/4)$ and 6.44% $[S+B](M_{ZZ})$ at $M_{ZZ} = M_1 = 701 \text{ GeV}$, etc The largest uncertainty in scale variation is due to the background which is only known at LO; at $M_{ZZ} = M_1$ we observe a variation of 19% in $K_D S+B$ while the variation in $S+B$ is 89%. For this reason it would be difficult to work completely at LO.

4 Conclusions

In this paper we have addressed some issues concerning the inclusion of interference effects in gluon-gluon fusion, especially for high values of the Higgs boson mass.

The results of Figure 1 - Figure 3 suggest the following compromise for effectively including higher order effects in the interference between Higgs and continuum contributions in $gg \rightarrow ZZ$. For the heavy Higgs scenario, above the Higgs boson peak the *multiplicative* (or at least the *intermediate*) option is recommended while the *additive* (or the *intermediate*) one should be preferred below the peak. However, one should also provide an estimate of the corresponding theoretical uncertainty. For this reason a conservative assessment of interference effects is represented by a central value given by the *intermediate* option of Eq.(13) with remaining theoretical uncertainty given by the full band between the *additive* option of Eq.(7) and the *multiplicative* option of Eq.(8).

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 and we have shown our results for the ZZ invariant mass distribution: close to $M_{ZZ} = \mu_H$ the uncertainty is small but becomes large in the rest of the search window $[\mu_H - \gamma_H, \mu_H + \gamma_H]$. The effect of the LO interference, w.r.t. LO $S+B$, reaches a maximum of +16% before the peak (e.g. at $\mu_H = 700 \text{ GeV}$) 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.

The estimate of the uncertainty is certainly a conservative one; however, it would be unsave to select less-conservative choices since we are not able to properly quantify the NLO corrections for the background. The percentage effect of the interference is slightly distorted when we go from LO to effective NNLO (at least in the *intermediate* option), however the global effect on the complete distribution is sizable, as seen in Figure 3.

In summary, we have discussed options to simulate NNLO corrections for the continuum interference effects to the ZZ-signal for the Standard Model Higgs boson produced via gluon fusion. The effects are large in the heavy Higgs-mass scenario, depending on the ZZ invariant mass.

We can anticipate precisely what the likely criticism will be, therefore we must clearly state that LO kinematics is different from the NLO(NNLO) one and the K -factor will depend on aspects of kinematics that are not present in the LO background-interference, e.g. contribution to p_T^Z coming from emission of extra gluons etc. Therefore, there is absolutely no guarantee that different distributions will not be distorted by the procedure and we will need to check the effect of the NLO effects on the interference for the full kinematic distributions. However, one should remember that the band representing the theoretical uncertainty has no statistical meaning, at most a flat prior to represent maximal uncertainty. Note that the so-called *central value* also has no special meaning, although it is extremely useful for the experimental analysis where the MonteCarlo events are reweighted by using some analytical function. An alternative view considers the difference between multiplicative and additive options as a systematic uncertainty resulting in overall distortion of the shape. We can try to turn our three *measures* of the lineshape into a continuous estimate in each bin; there is a technique, called “vertical morphing” [43], that introduces a “morphing” parameter f which is nominally zero and has some uncertainty. If we define

$$D^0 = \frac{d\sigma}{dM_{ZZ}}, \quad \text{option I}, \quad D^+ = \max_{A,M} D \quad D^- = \min_{A,M} D, \quad (19)$$

the simplest “vertical morphing” replaces

$$D^0 \rightarrow D^0 + \frac{f}{2} (D^+ - D^-). \quad (20)$$

Of course, the whole idea depends on the choice of the distribution for f , usually Gaussian which is not necessarily our case; instead, one would prefer to maintain, as much as possible, the LO cancellations around the peak². We would like to elaborate on this with the following heuristic argument: how does the lineshape uncertainty band translate into uncertainty for the total cross-section? We define two curves

$$C_M(\lambda, M_{ZZ}) = \lambda D_I(M_{ZZ}) + (1 - \lambda) D_M(M_{ZZ}), \quad C_A(\lambda, M_{ZZ}) = \lambda D_I(M_{ZZ}) + (1 - \lambda) D_A(M_{ZZ}), \quad (21)$$

where $D_i, i = I, A, M$ is the lineshape according to I, A and M options. The parameter λ , with $0 \leq \lambda \leq 1$, parametrizes how far we are from the central value (we assume that λ has a flat distribution). The uncertainty on the total cross-section is obtained by integrating over M_{ZZ} , once along C_M and a second time along C_A ; the difference gives the uncertainty, maximal for $\lambda = 0$. The observation is not trivial since the two curves cross shortly after the peak and one should not integrate over $\min\{C_A, C_M\}$ and over $\max\{C_A, C_M\}$.

It is worth noting that even for the signal alone, $gg \rightarrow H \rightarrow VV$, the current generation of events is done with something like POWHEG [44] for the initial state kinematics plus PYTHIA [45,46] for the decay. The resulting events are rescaled in cross-section to NNLO for $gg \rightarrow H$ while the branching ratios are rescaled according to PROPHECY4F [24,25]. For the kinematics itself this means $gg \rightarrow H$ is NNLO while the H decay has the LO model of PYTHIA.

Further study is warranted of exact NLO background for all selected channels and there is not much we can add at this stage; phases in NLO(NNLO) corrections to the signal are not available as well as NLO corrections to the background. The typical example that we have in mind is the process $pp \rightarrow \gamma\gamma X$, as described in Ref. [47] for the full NNLO QCD corrections; in the gg -channel the box contribution was computed in Ref. [48] and the next-order gluonic corrections in Ref. [49]. This is a case where all contributions for the gg -channel have been included in a fully-consistent manner.

²We gratefully acknowledge S. Bolognesi for suggesting this alternative.

The options that have been introduced in the literature and that we have summarized and extended here can only give us a rough approximation of the true result. However, this solution improves upon the previous estimate of $150 \mu_H^3 [\%]$ (μ_H in TeV) made without any reference to the existing LO calculation of the interference.

The calculation described in this work refers to a SM Higgs boson; however, ATLAS and CMS quantify their analysis in terms of

$$\text{Hypothesis}(\mu) = \mu \sigma(S) + \sigma(B) \quad (22)$$

where interference is only included in the uncertainty; $\mu = 0$ is the null hypothesis, $\mu \neq 0$ is the alternate hypothesis (Neyman - Pearson lemma). Another issue, currently under discussion, is the following: should one define the cross-section for events containing a Higgs boson in terms of $\sigma(S) + \sigma(I)$ with $\sigma(B)$ defining the null hypothesis? The obvious criticism is that signal + interference is not positive defined. Therefore, it is not completely clear how the hypothesis should be modified to include the interference [50], a possibility being [51]

$$\text{Hypothesis}(\mu) = \mu \sigma(S) + \sqrt{\mu} \sigma(I) + \sigma(B), \quad (23)$$

which is reasonably good for $\mu \approx 1$, i.e. for analyzing the SM hypothesis. In general it would be better to start with an effective Lagrangian containing anomalous couplings [3] $\{\lambda\}$ (such that $\lambda_i = 0$ is the SM) and to define

$$\text{Hypothesis}(\{\lambda\}) = \sigma(S, \{\lambda\}) + \sigma(I, \{\lambda\}) + \sigma(B, \{\lambda\}), \quad (24)$$

which will respect, among other things, the unitarity cancellations requested by Eq.(4), i.e.

$$\text{Hypothesis}(\mu) \Big|_{M_{ZZ} \rightarrow \infty} = 0, \quad (25)$$

which proves that, in any consistent theory (not only the SM), the background *knows* the signal (at least asymptotically). Clearly, Eq.(25) imposes $\mu = 1$ in Eq.(23) if $\sigma(S)$ etc. are the SM cross-sections. A possibility in implementing Eq.(24) is to use the Buchmüller - Wyler basis [52].

If one does not have a clear idea of what the BSM signal is, it is difficult to optimize an analysis (Neyman - Pearson lemma cannot help). Alternative strategies require that, in absence of a signal, a C.L. limit is set on μ_H . Based on the observation that a ultra-heavy Higgs boson does not lead to a pronounced peak structure, Baur and Glover [18,19] made an alternative proposal for the null hypothesis: here the background corresponds to the minimum of $S + I + B$ for all Higgs masses. More precisely, in ZZ -production, they define

$$S_{\max} = \max S(m_0), \quad S^2(m_0) = \frac{[N(\mu_H, m_0) - N(\mu'_H, m_0)]^2}{N(\mu'_H, m_0)}, \quad (26)$$

where $M_{ZZ} > m_0$ and $N(\mu_H, m_0)$ is the number of signal events for a Higgs boson of mass μ_H . Therefore, S_{\max} gives a quantitative measure of how well the μ_H hypothesis can be discriminated from the μ'_H hypothesis. The background corresponds to $\mu'_H = 0$ but we could have $\mu_H = 125 GeV$ as well. The strength of the analysis should be in terms of the C.L. at which the μ_H hypothesis can be excluded. Note that model-independent searches have been addressed in Ref. [53,54] and recommendations have been made in Ref. [55].

If the signal for a light Higgs boson will be confirmed at LHC then any heavy scalar boson must be beyond-Standard-Model (BSM). As a prototype we can take a THD model; from the perspective of searching for the heavy partner(s) the light one is assimilable to the background (i.e. the two resonances do not interfere). Of course, the signal has to be rescaled according to the BSM model (couplings of the heavy partner(s), H, A, H^\pm , to fermions and gauge bosons) but we have not attempted a detailed analysis, e.g. taking into account the mass difference among the heavy bosons, related to the breaking of the custodial $SU(2)$ symmetry. Other possibilities include a heavy scalar singlet with a large vacuum expectation value that can evade the potential instability of the SM electroweak vacuum [56]. The qualitative aspects of this work will not change.

Finally, the interference effects for a light SM Higgs boson will follow the same pattern described in this work; the final state will contain four fermions (below the ZZ or WW thresholds) but the background/interference will always be at LO and we will be missing large K -factors. Numerics will change

but our recipe for estimating effective NNLO signal + background + interference and the corresponding theoretical uncertainty will remain the same. Only progress, i.e. new more accurate calculations will be able to produce more accurate estimates for the theoretical uncertainty.

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Table 4: Interference effect (percentage), R'_{eff} for $\mu_{\text{H}} = 700 \text{ GeV}$ with corresponding theoretical uncertainty. Here $p_{\text{T}}^Z > 0.25 M_{\text{ZZ}}$ and $2 M_{\text{Z}} < M_{\text{ZZ}} < 1 \text{ TeV}$.

Bin[GeV]	R'_{eff} [%]	minus error[%]	plus error[%]
210 – 212	0.24	–0.07	+0.11
230 – 232	0.31	–0.09	+0.13
250 – 252	0.38	–0.12	+0.17
270 – 272	0.47	–0.14	+0.20
290 – 292	0.56	–0.17	+0.24
310 – 312	0.73	–0.22	+0.32
330 – 332	0.96	–0.29	+0.41
350 – 352	1.47	–0.44	+0.63
370 – 372	2.21	–0.67	+0.96
390 – 392	2.82	–0.87	+1.25
410 – 412	3.67	–1.14	+1.64
430 – 432	4.72	–1.48	+2.13
450 – 452	6.00	–1.90	+2.74
470 – 472	7.49	–2.37	+3.41
490 – 492	9.24	–2.95	+4.24
510 – 512	11.30	–3.63	+5.21
530 – 532	13.49	–4.36	+6.27
550 – 552	15.87	–5.14	+7.37
570 – 572	17.75	–5.78	+8.30
590 – 592	19.12	–6.25	+8.97
610 – 612	19.43	–6.39	+9.19
630 – 632	18.16	–5.99	+8.62
650 – 652	15.39	–5.11	+7.36
670 – 672	11.29	–3.77	+5.42
690 – 692	6.43	–2.15	+3.10
710 – 712	1.28	–0.43	+0.62
730 – 732	–3.72	–1.82	+1.26
750 – 752	–8.34	–4.11	+2.84
770 – 772	–12.43	–6.18	+4.26
790 – 792	–16.05	–8.06	+5.55
810 – 812	–19.21	–9.73	+6.69
830 – 832	–21.98	–11.19	+7.69
850 – 852	–24.36	–12.54	+8.58
870 – 872	–26.52	–13.88	+9.45
890 – 892	–28.37	–14.98	+10.18
910 – 912	–30.06	–16.07	+10.88
930 – 932	–31.63	–17.18	+11.57
950 – 952	–33.01	–18.10	+12.16
970 – 972	–34.28	–19.17	+12.79
990 – 992	–35.50	–20.11	+13.36

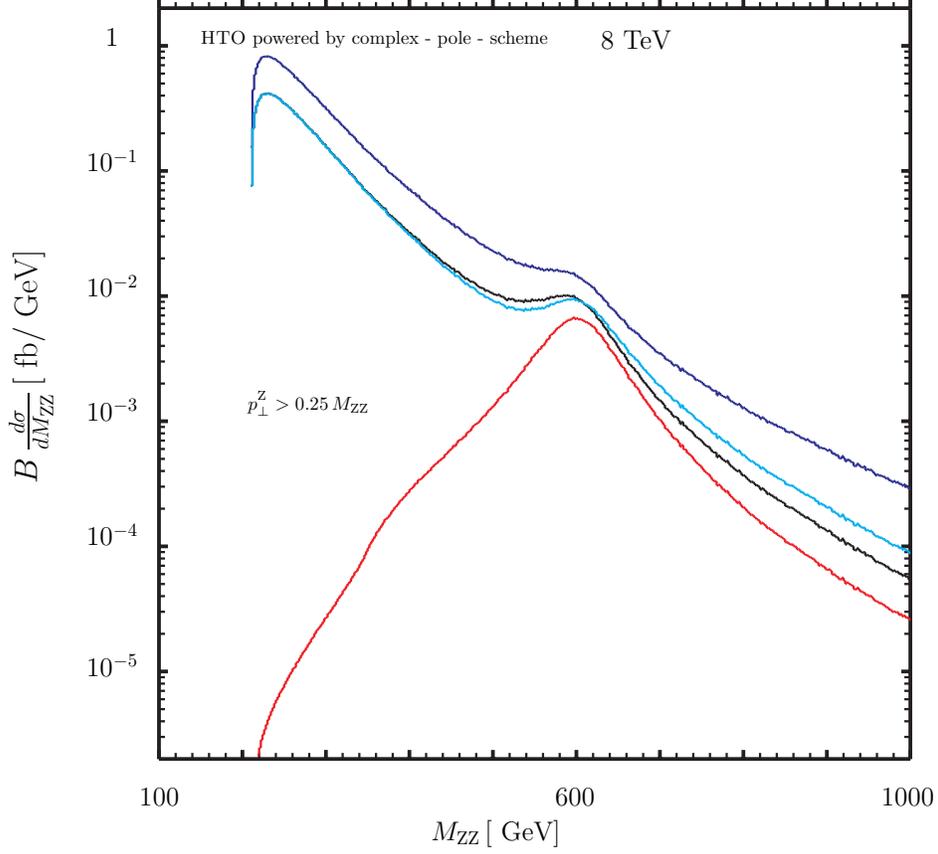


Figure 1: The ZZ invariant mass distribution in the OFFP-scheme of Ref. [5] with running QCD scales for $\mu_H = 600 \text{ GeV}$. $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ . The black line gives the full $gg \rightarrow ZZ$ process at LO; the cyan line gives signal plus background (LO) neglecting interference while the blue line includes both $gg \rightarrow ZZ$ and $\bar{q}q \rightarrow ZZ$ components (LO). The red line gives the LO signal.

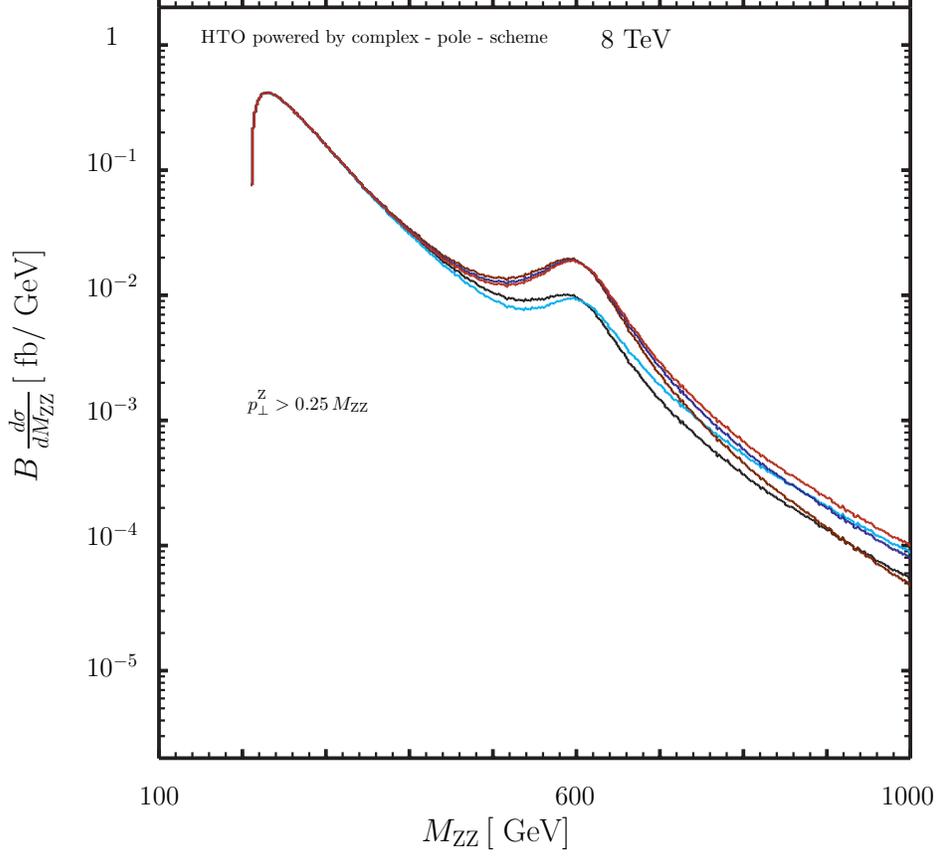


Figure 2: The ZZ invariant mass distribution in the OFFP-scheme of Ref. [5] with running QCD scales for $\mu_H = 600 \text{ GeV}$. $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ . The black line is the full LO $gg \rightarrow ZZ$ result, the brown line gives the multiplicative option of Eq.(8), the red line is the additive option of Eq.(7) while the blue line is the intermediate option of Eq.(13). The cyan line gives signal plus background (LO) neglecting interference.

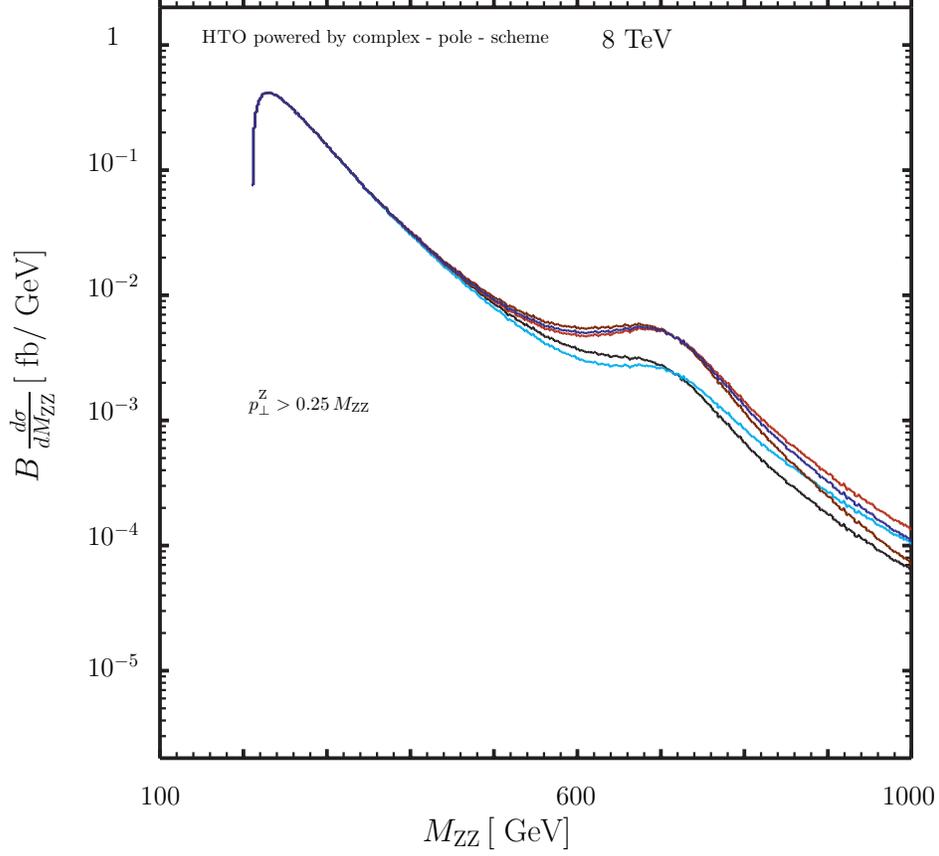


Figure 3: The ZZ invariant mass distribution in the OFFP-scheme of Ref. [5] with running QCD scales for $\mu_H = 700 \text{ GeV}$. $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ . The black line is the full LO $gg \rightarrow ZZ$ result, the brown line gives the multiplicative option of Eq.(8), the red line is the additive option of Eq.(7) while the blue line is the intermediate option of Eq.(13). The cyan line gives signal plus background (LO) neglecting interference.

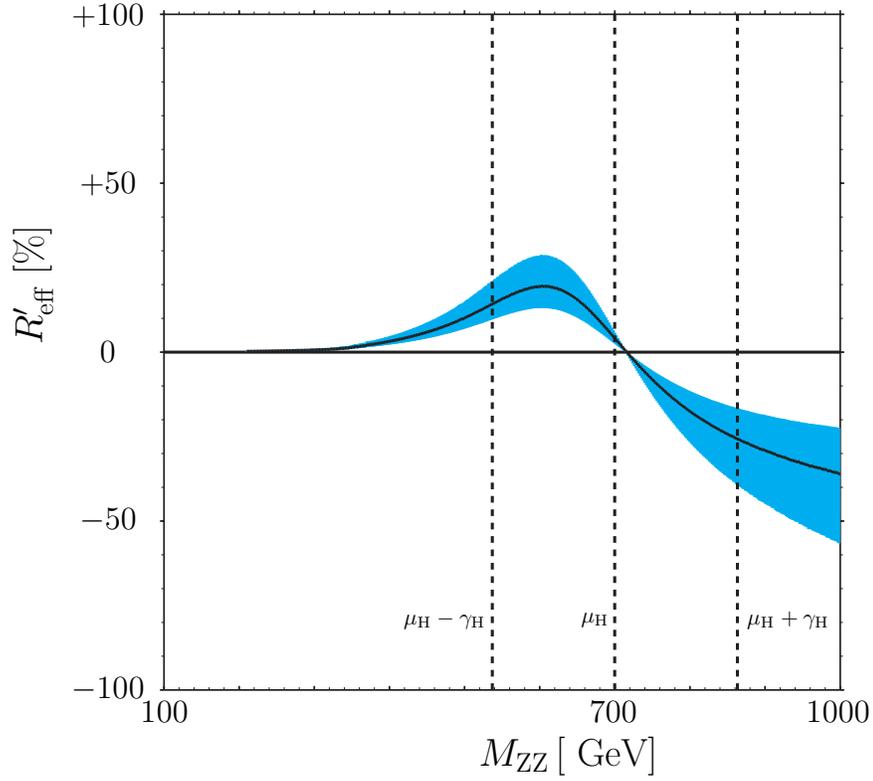


Figure 4: Interference effects (see Eq.(17)) in the ZZ distribution for $\mu_H = 700 \text{ GeV}$. The black line is the central value, the blue lines give the estimated theoretical uncertainty.

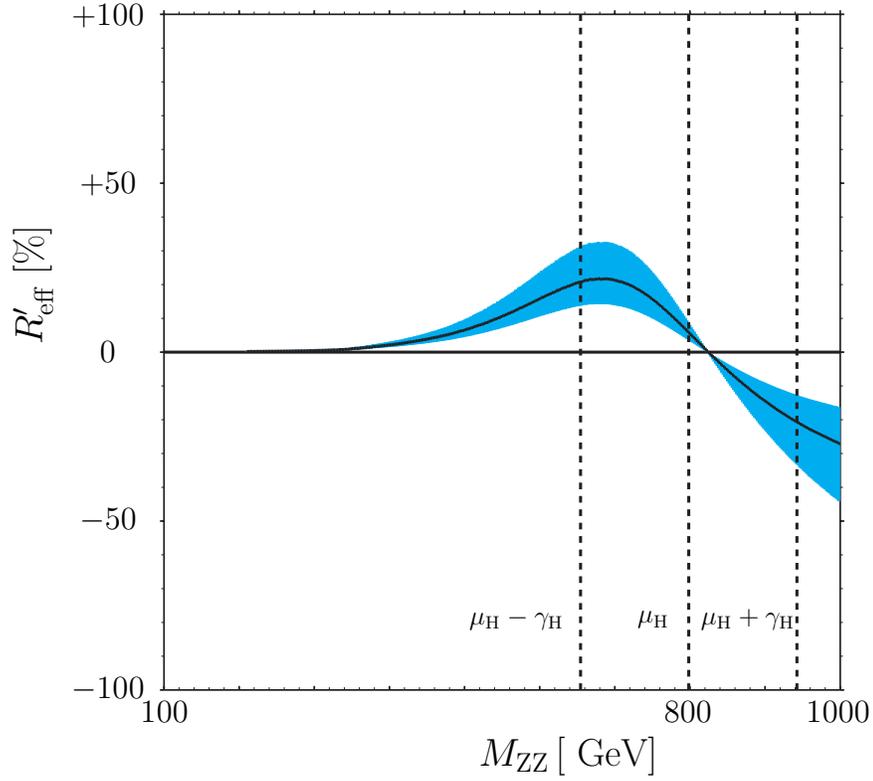


Figure 5: Interference effects (see Eq.(17)) in the ZZ distribution for $\mu_H = 800$ GeV. The black line is the central value, the blue lines give the estimated theoretical uncertainty.

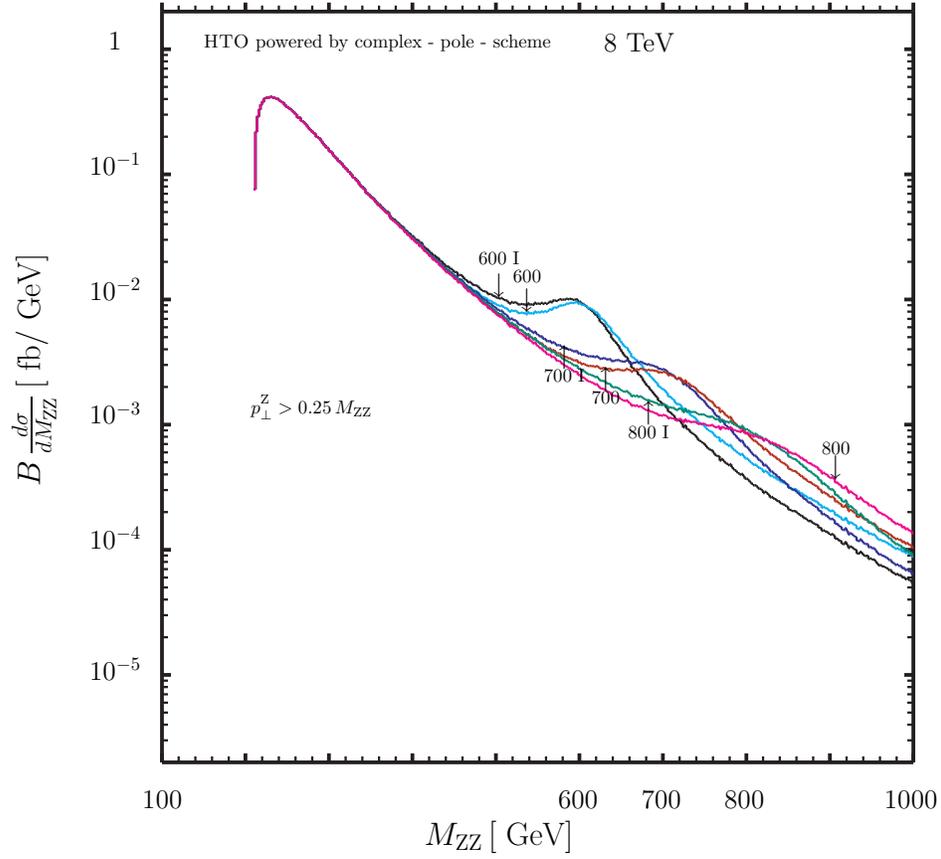


Figure 6: LO Interference effects [%] in the ZZ distribution for $\mu_H = 600, 700, 800 \text{ GeV}$.

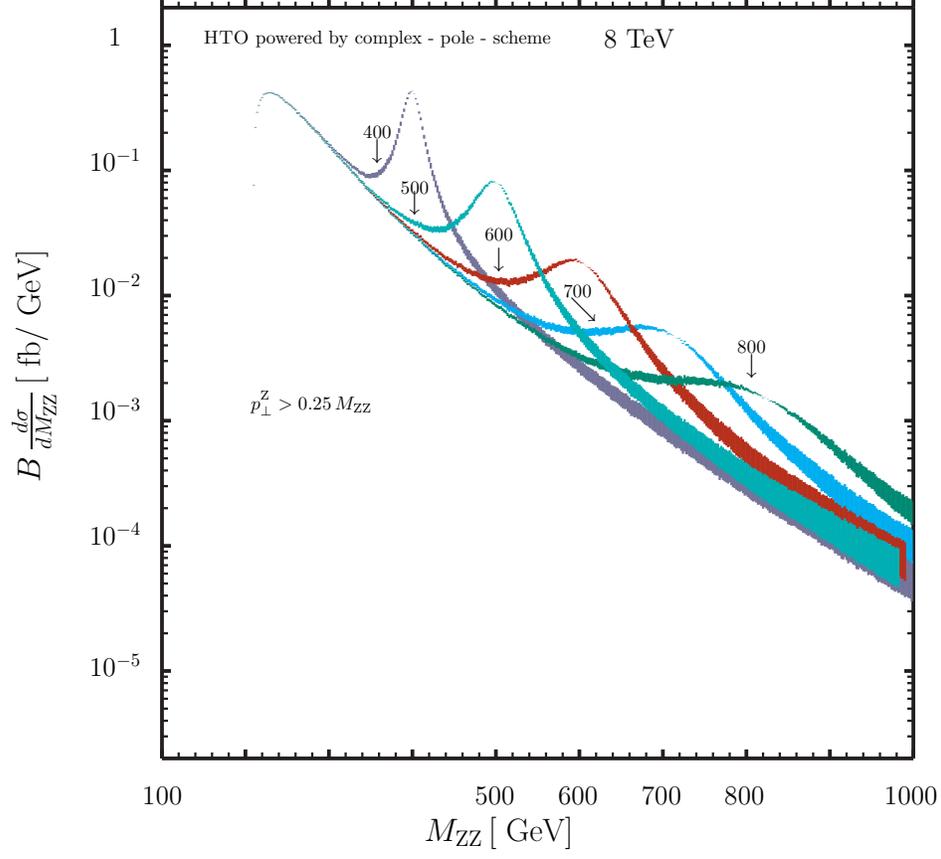


Figure 7: Effective NNLO ZZ invariant-mass distribution for $\mu_H = 400, 500, 600, 700, 800 \text{ GeV}$ including theoretical uncertainty. $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ .

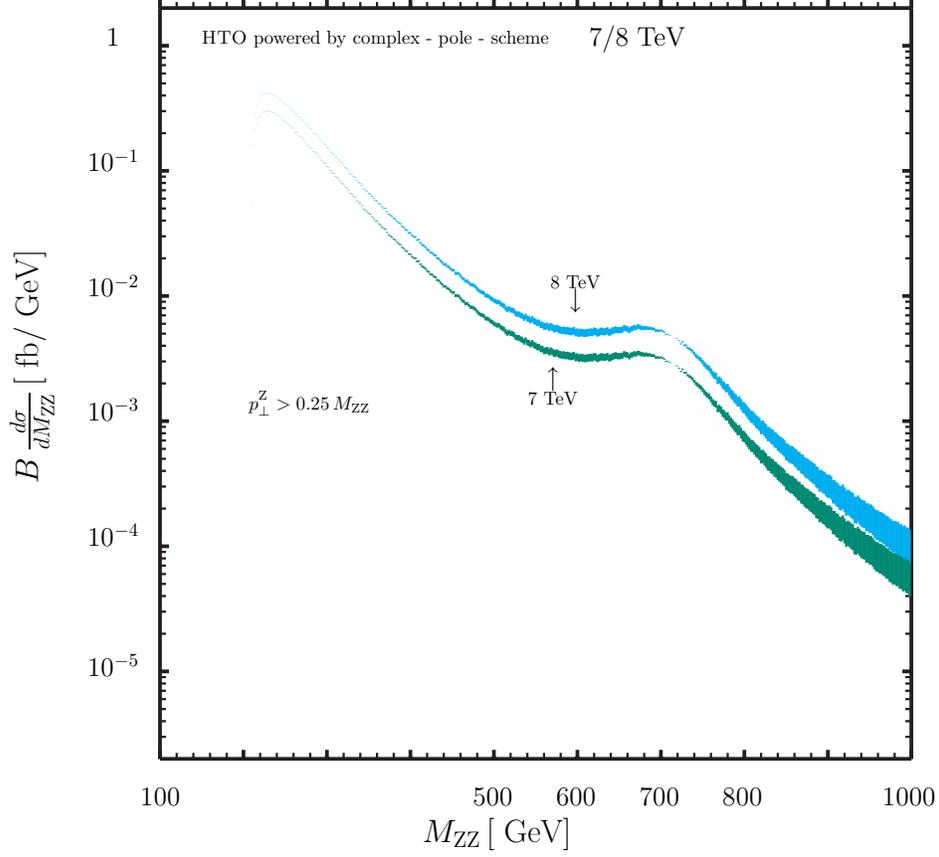


Figure 8: Effective NNLO ZZ invariant-mass distribution for $\mu_H = 700 \text{ GeV}$ including theoretical uncertainty and a comparison between 7 TeV and 8 TeV . $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ .

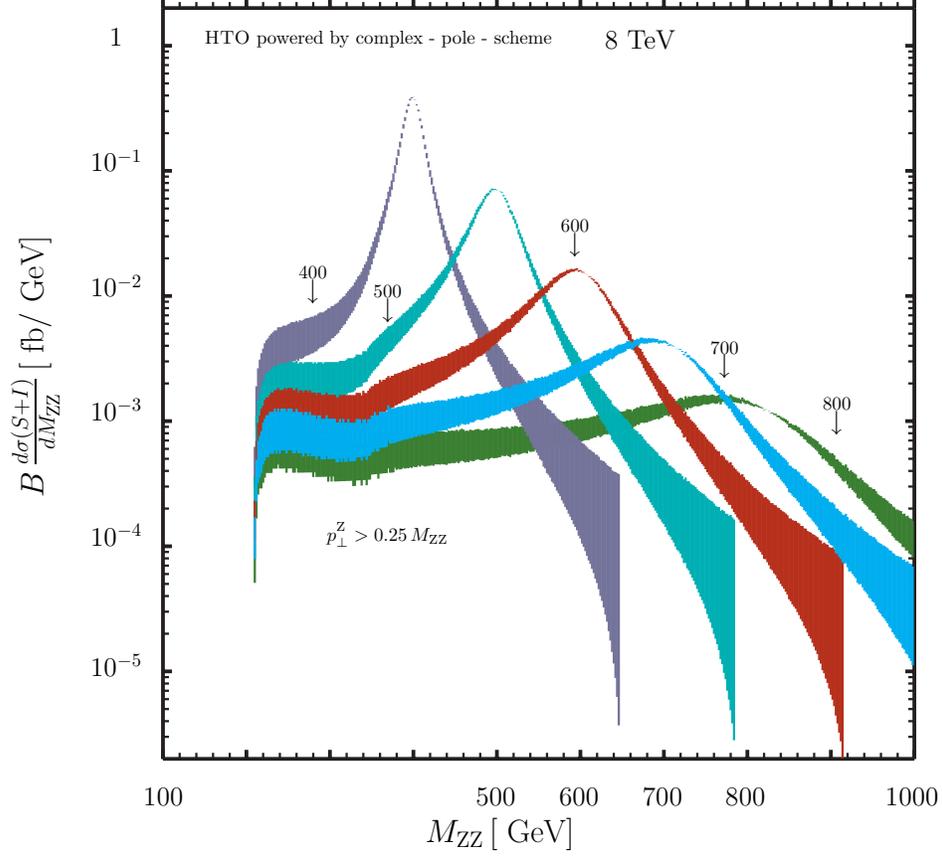


Figure 9: Effective NNLO ZZ invariant-mass distribution for $\mu_H = 400, 500, 600, 700, 800 \text{ GeV}$ including theoretical uncertainty. Only signal + interference is plotted. $B = 4.36 \cdot 10^{-3}$ represents the BR for both Z bosons to decay into e or μ .

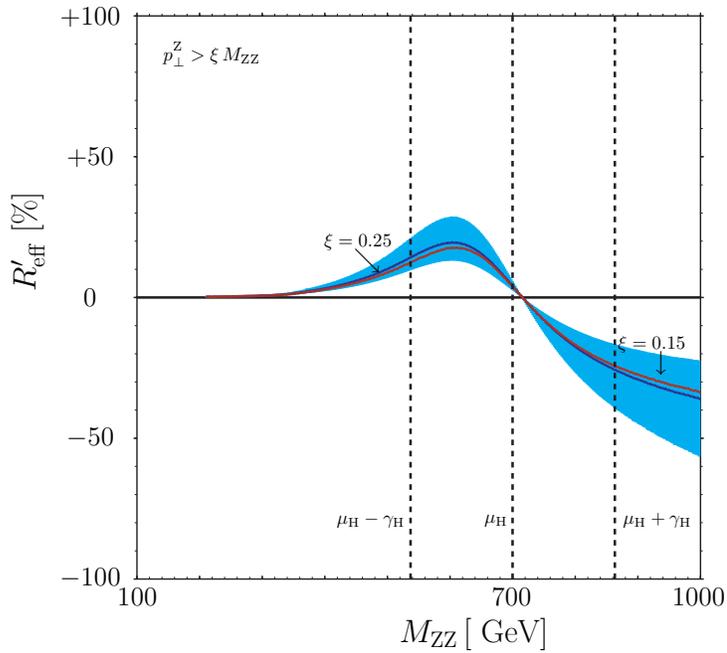


Figure 10: Interference effects (see Eq.(17)) in the ZZ distribution for $\mu_H = 700 \text{ GeV}$ comparing $p_T^Z > 0.25 M_{ZZ}$ (blue) with $p_T^Z > 0.15 M_{ZZ}$ (green).

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