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Interference effects in Higgs decays to heavy gauge bosons at the LHC and their relevance for heavy Higgs searches

LHC physics discussion - DESY

Hamburg - May 2016

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

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Relevance of off-shell SM Higgs decays to heavy gauge bosons $H \to VV^{(*)}$:

- First discussion: Off-shell contributions in $H \to VV^{(*)}$

[1206.4803; Kauer Passarino]

[1305.2092, 1310.7011; Kauer]

- Access to the Higgs width Γ_H

[1307.4935; Caola Melnikov]

[1311.3589, 1312.1628, 1408.1723; Campbell Ellis Williams]

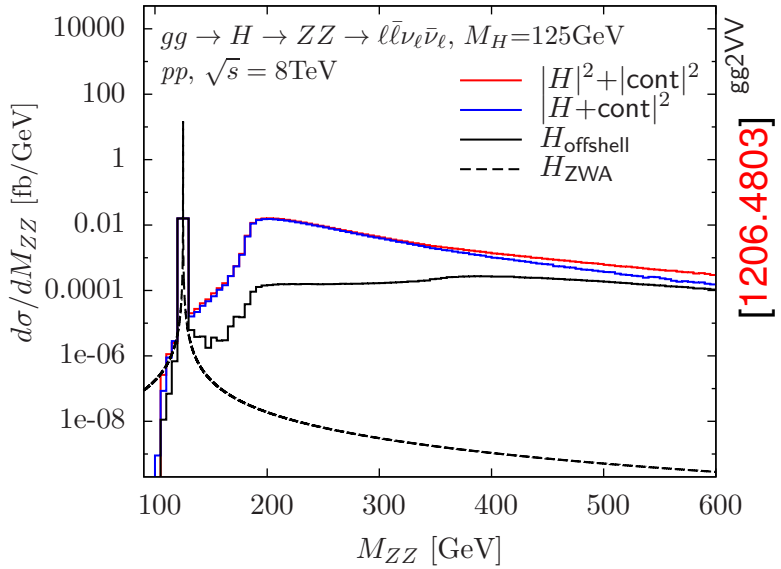
Application: ATLAS [1503.01060], CMS [1405.3455, 1507.06656]

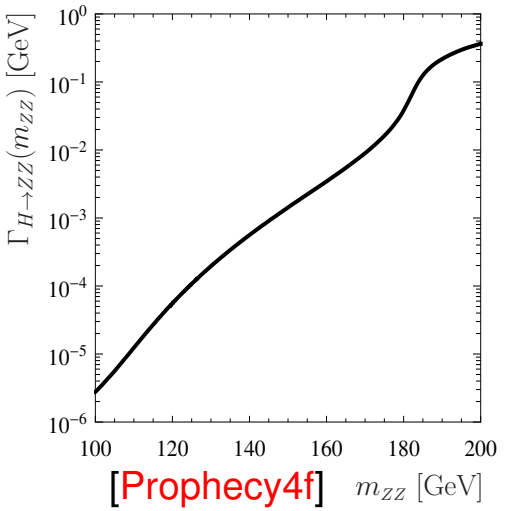
$$\sigma^{VV}_{\rm OS} \propto \frac{(g^{\rm OS}_{ggH} g^{\rm OS}_{HVV})^2}{\Gamma_H}$$

$$\frac{d\sigma^{VV}}{dm_{VV}} \propto (g^{\rm OFF}_{ggH}\, g^{\rm OFF}_{HVV})^2$$

- Limitations of Higgs width constraint and opportunities:

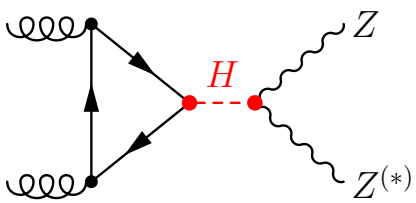
[1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338, 1410.5440, 1410.5806, 750GeV?]

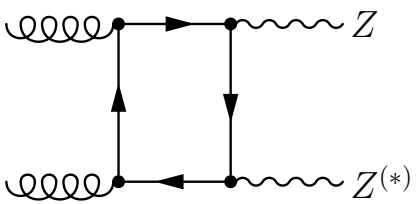




Relevant processes at the LHC: Have in mind $Z/Z^{(*)} \to l^+l^-/\nu\bar{\nu}$!

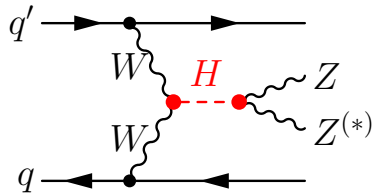
ggF:

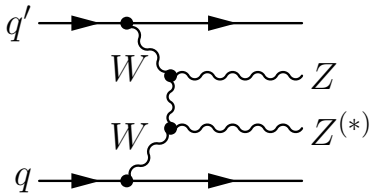
S: 

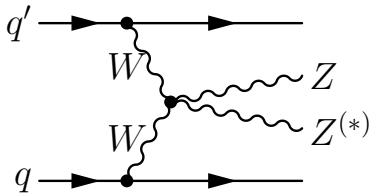
B: 

$+\ldots$

VBF:

S: 

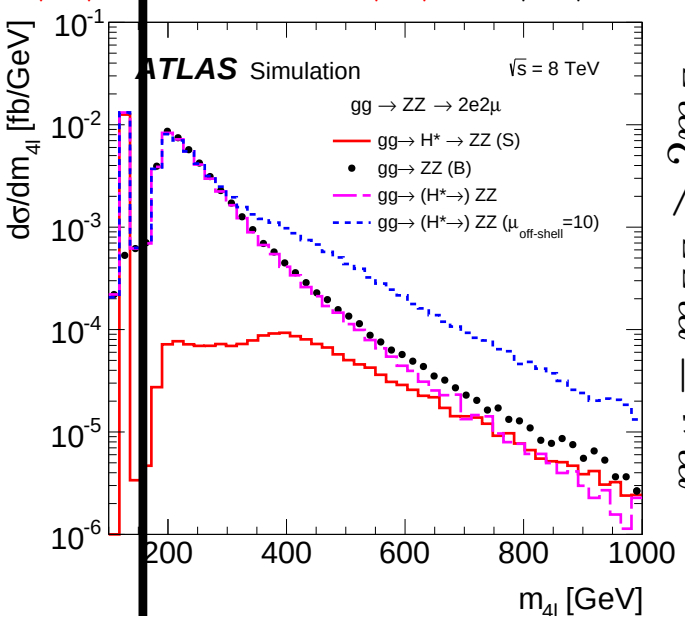
B: 

$+$ 

$+\ldots$

$HZZ^{(*)}$:$|S|^2$ | $H^{(*)}ZZ$:$|S|^2 + |B|^2 + 2\mathrm{Re}(SB)$

$m_{4l} = m_{ZZ} < 2m_Z$



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[1503.01060]

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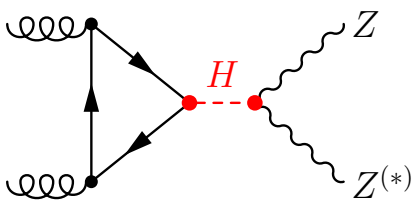
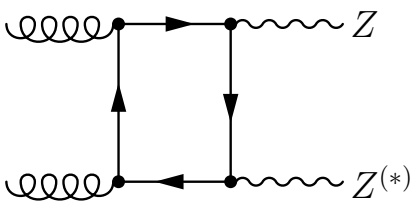
S: 

B: 

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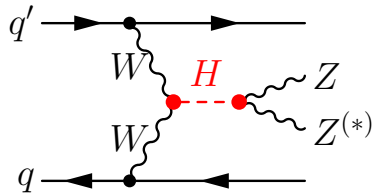
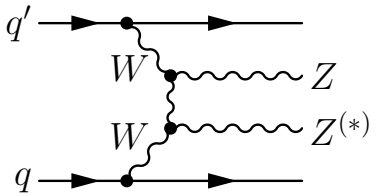
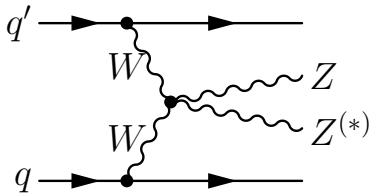
S: 

B: 

$+$ 

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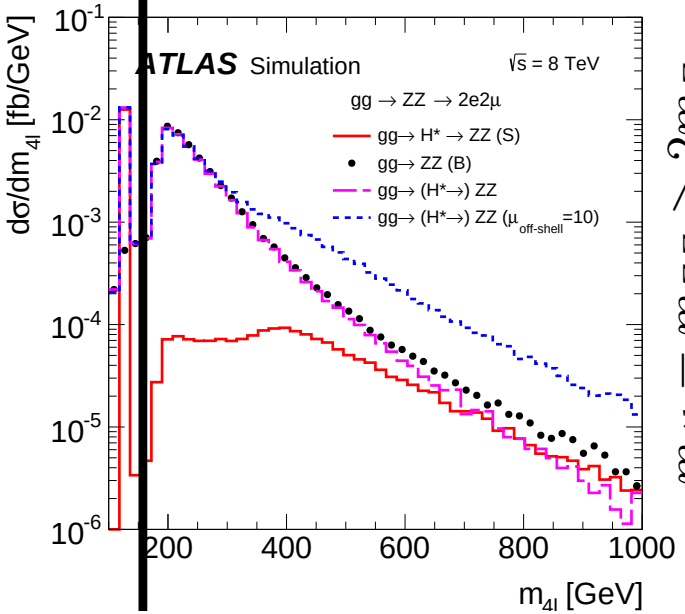

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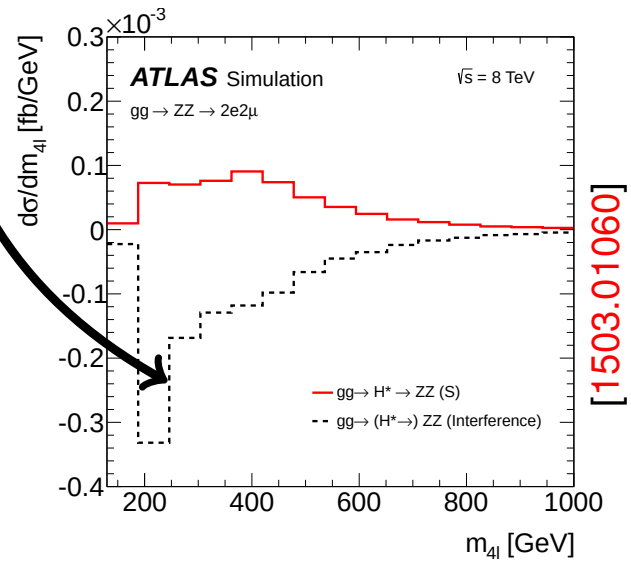
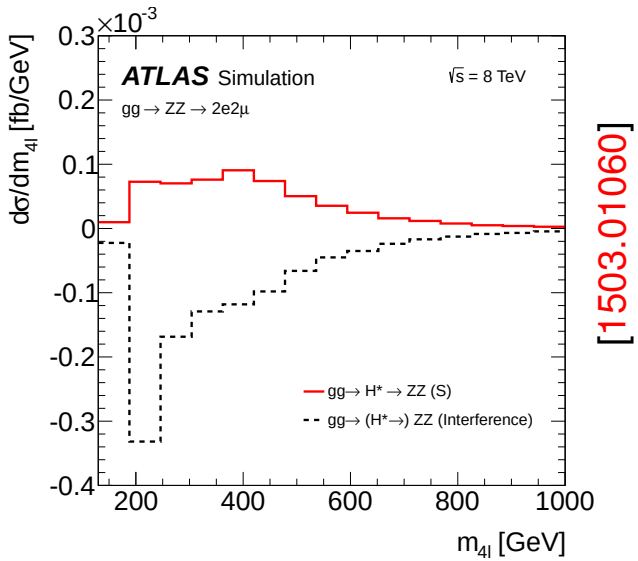


[1503.01060]

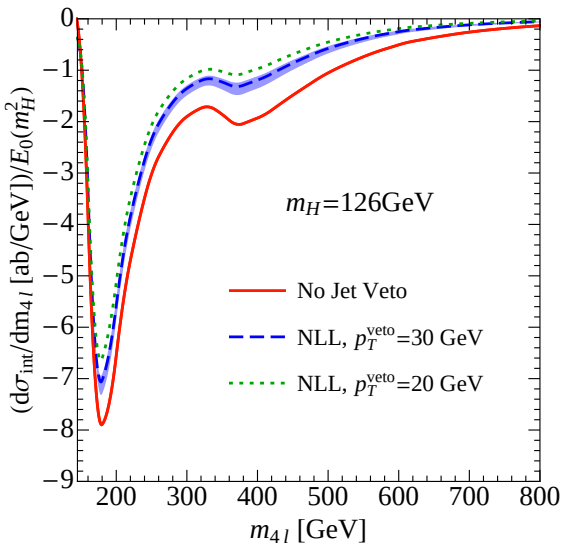
Theoretical issues:

- Interference I is negative.

I restores unitarity in $W_L W_L \to W_L W_L$.
($\to$ Negative I affects sensitivity to Γ_H!)



[1503.01060]



Interference dependent on jet vetos for $H \to WW$: [1405.5534; Moult Stewart]

Interference effects for ZZ+jet production: similar behaviour [1409.1897; Campbell Ellis et al.]

Theoretical issues:

▷ Precision for gluon fusion ($gg \to VV$):

S: meanwhile known at N^{3}LO QCD (since 2016) (applicable as fct. of m_{VV})

B: meanwhile known at NLO QCD (since 2014+2015)!

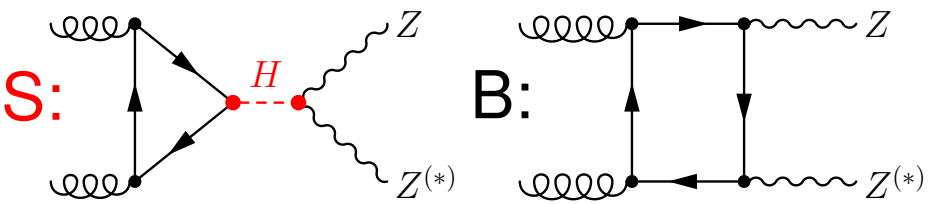
[1404.4853; Gehrmann von Manteuffel Tancredi Weihs: Master integrals]
[1503.08759; Caola Henn Melnikov Smirnov Smirnov: Helicity amplitudes]
[1503.08835; von Manteuffel Tancredi: Helicity amplitudes]
towards pheno predictions in the heavy top-limit:
[1503.01274; Melnikov Dowling]
[1509.06734, 1511.08617; Caola Melnikov Röntsch Tancredi (ZZ/WW)]
[1605.01380; Campbell Ellis Czakon Kirchner: interference + top-quark mass effects]
Related work on $q\bar{q} \to VV$: [1408.6409, 1503.04812]

Previously K-factor

$$R_H^B = \frac{K(gg \to ZZ)}{K(gg \to H^{(*)} \to ZZ)}$$

in ATLAS bound on Γ_H!
[1503.01060]

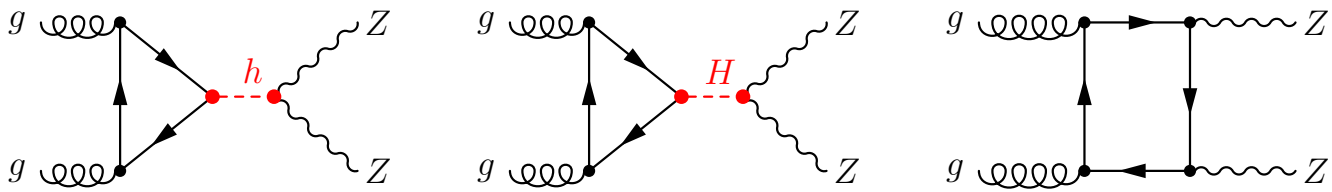
S: B:



▷ Other issues:

Dominant background $q\bar{q} \to VV$ known at NNLO QCD [Grazzini et al.]
Interference of $WW \to 2l2\nu$ and $ZZ \to 2l2\nu$ known (e.g. `gg2VV` [Kauer et al.])

How does this discussion interfere with the searches for heavy Higgs bosons in ZZ and WW channels?
Studies in the context of SM+Singlet: [1501.02139, 1502.04113, 1506.02257]
Answer in a Two-Higgs-Doublet Model (2HDM): [1512.07232; Greiner Liebler Weiglein]



$\rightarrow$ The heavy Higgs H (mass m_H) can interfere with h and background B.
▷ Higgs mixing angle α from (H_1^0, H_2^0) to (h, H) and $\tan\beta = v_2/v_1$ defines

$$g_V^h = \sin(\beta-\alpha) = s_{\beta-\alpha} \qquad \text{and} \qquad g_V^H = \cos(\beta-\alpha) = c_{\beta-\alpha} \quad .$$

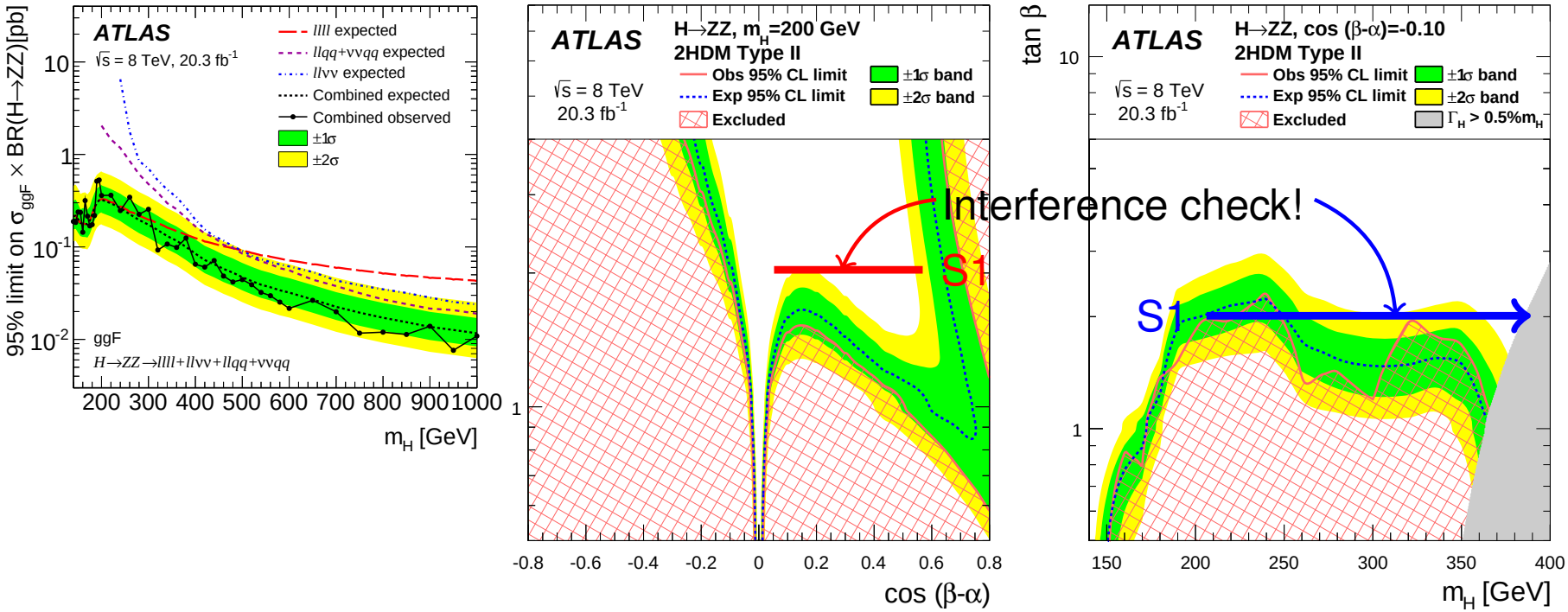
$\rightarrow$ The combination $(g_V^h)^2 + (g_V^H)^2 = 1$ guarantees unitarization!
$\rightarrow$ If $g_V^h \rightarrow 1$, then $g_V^H \approx 0$. Expect weak signal with large interferences!

Experimental analyses in heavy Higgs boson searches $H \rightarrow WW/ZZ$:
▷ ATLAS ($H \rightarrow ZZ$ in Singlet+2HDM): No interference! [1507.05930]
▷ CMS ($H \rightarrow WW/ZZ$ in Singlet): Rescaled SM $H \cdot B$ interference! [1504.00936]

Is the assumption of no interference justified?

- ▷ In Run I it was indeed ok.
- ▷ In Run II experiments are getting sensitive to interferences in H searches.

Check of the 8 TeV ATLAS analysis (result of various channels): [1507.05930]



Implementation of $gg \to ZZ$ in a 2HDM in `vh@nnlo` [1210.5347, 1307.8122]

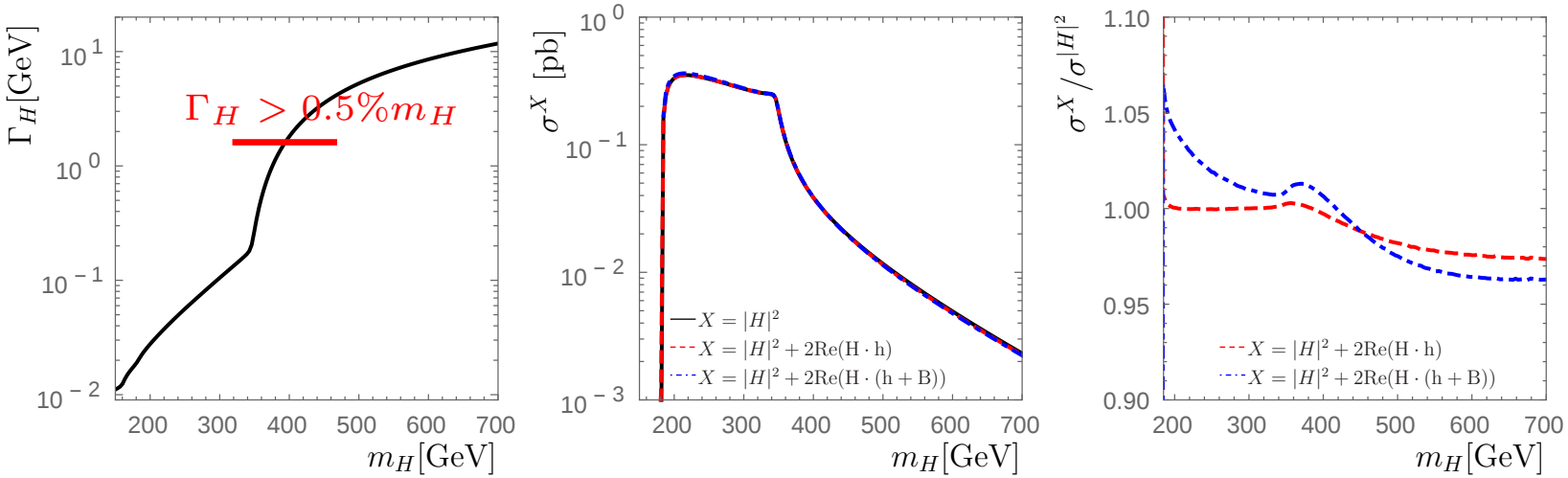
Implementation of $gg \to e^+e^-\mu^+\mu^-/e^+e^-\nu_l\bar{\nu}_l$ in a 2HDM

with `GoSam` [1111.2034, 1404.7096]

with link to `2HDMC` [0902.0851] for the calculation of the Higgs width Γ_H

Scenario S1: 2HDM type II with $\tan\beta = 2$,
$\sin(\beta-\alpha) = -0.995 \leftrightarrow \cos(\beta-\alpha) = -0.10$, $m_H = 200\,\text{GeV}$, $\Gamma_H = 0.0277\,\text{GeV}$
Relevant parameters for variation: m_H, $\cos(\beta-\alpha)$ and $\tan\beta$
Let's start with the previously mentioned m_H variation (for $\sqrt{s} = 8\,\text{TeV}$):

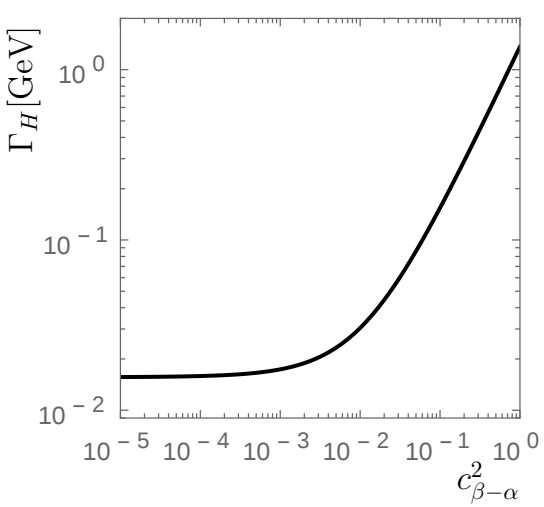
$$\sigma^X = \int_{m_H-15\text{GeV}}^{m_H+15\text{GeV}} dm_{ZZ} \frac{d\sigma^X(gg \to ZZ)}{dm_{ZZ}}$$

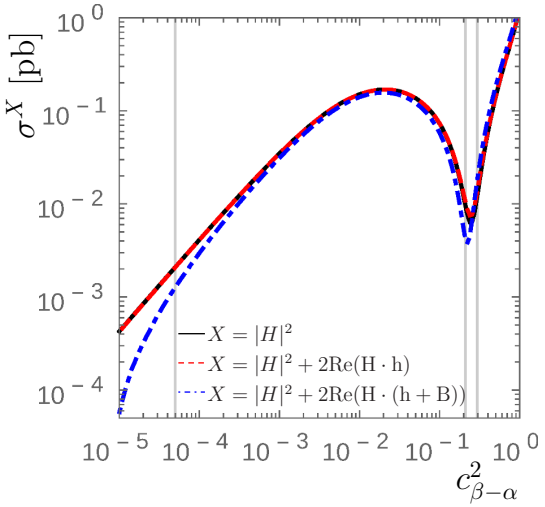


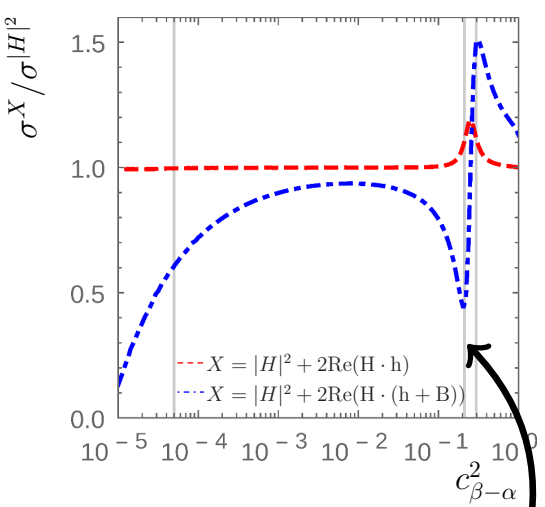
$\rightarrow$ Relevance of the interferences remains below 10%.
It's not so much the mass m_H and width Γ_H which determine the relevance of the interferences.

We continue with a variation of $\cos(\beta-\alpha)$ (for $\sqrt{s}=8\,\text{TeV}$):

- Decay $H \to ZZ$ is determined by $g_V^H = \cos(\beta-\alpha) = c_{\beta-\alpha}$.





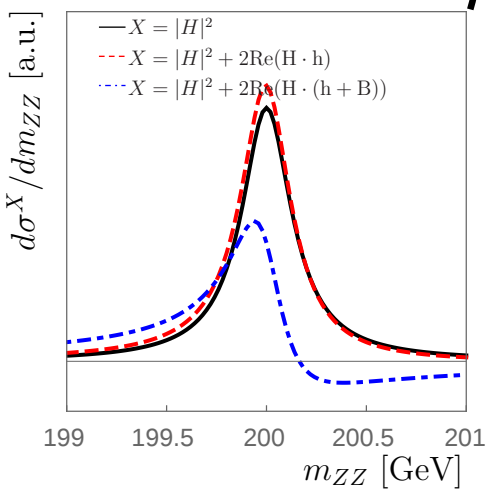


- Production $gg \to H$ involves g_t^H and g_b^H with

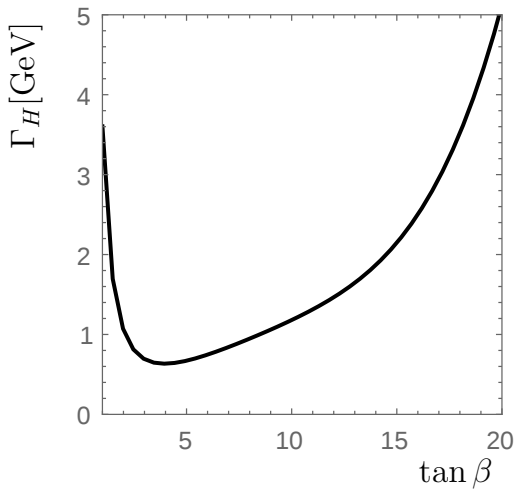
$$g_t^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{\tan\beta} + c_{\beta-\alpha} \approx 0$$

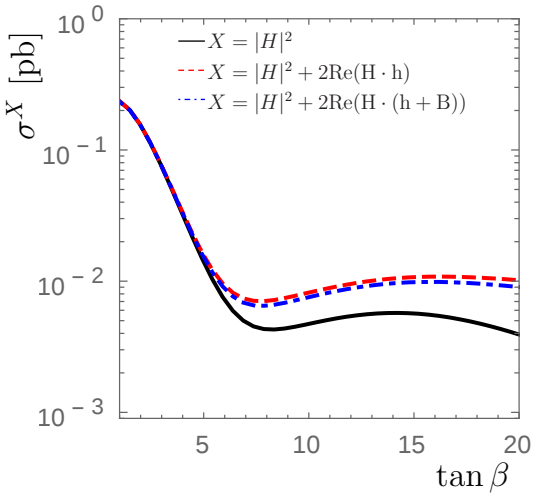
at $\quad c^2_{\beta-\alpha} = 0.2,\ \tan\beta = 2\,.$

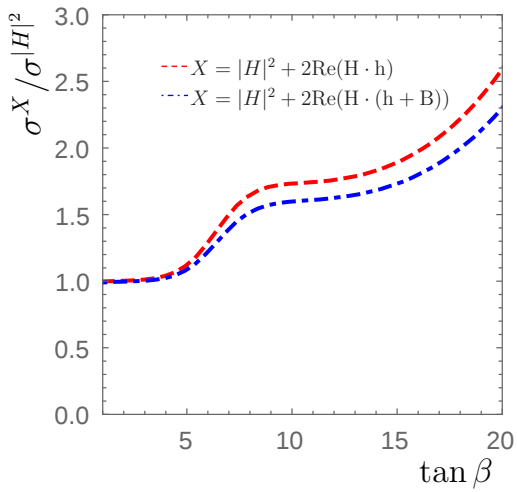
$\to$ Where couplings are small (in production or decay) interferences are large.



We are left with a variation of $\tan\beta$ (for $\sqrt{s} = 13\,\text{TeV}$):
Scenario S2: 2HDM type II with $\tan\beta = 1$,
$\sin(\beta-\alpha) = 0.990$, $m_H = 400\,\text{GeV}$, $\Gamma_H = 3.605\,\text{GeV}$

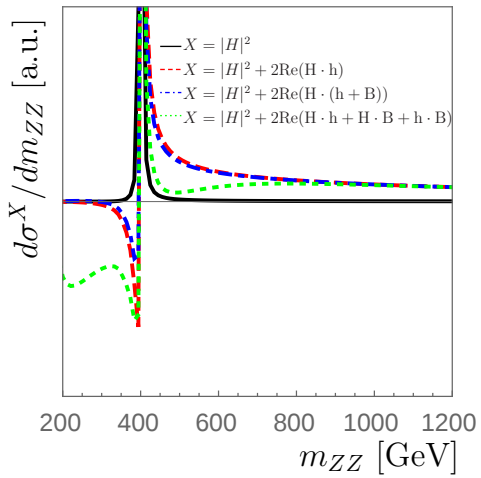




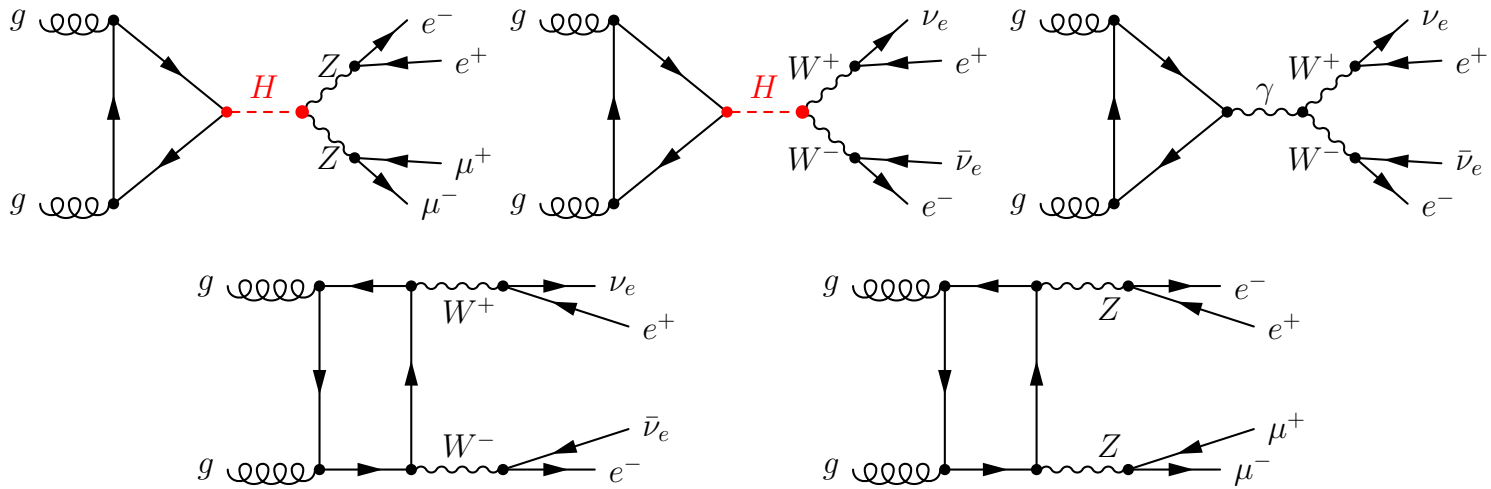


$\rightarrow$ Pushing the bottom Yukawa g_b^H through $\tan\beta$ enhances interferences.

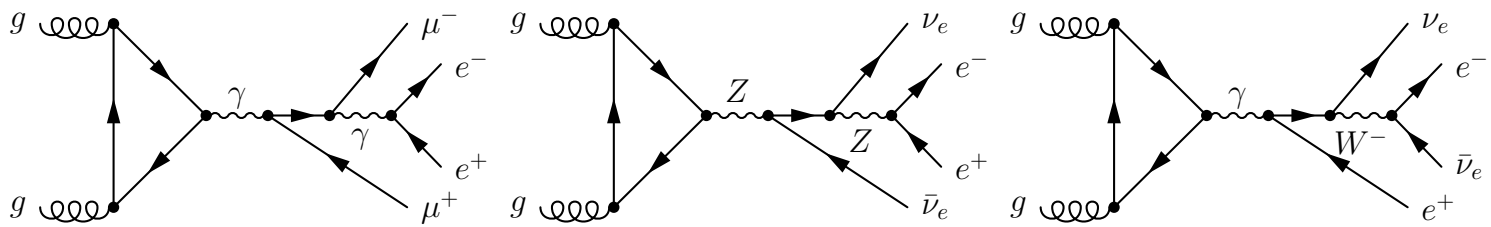
Not to forget at high invariant masses:
All interferences are of relevance:
$h \cdot B$ and $H \cdot B \leftrightarrow$ negative.
$h \cdot H$ can be large and have either sign!
Another effect: Sum of interferences can mimic
a broad peak-like structure beyond m_H.



We did our study also for the full process with GoSam:
Double-resonant W and Z contributions:

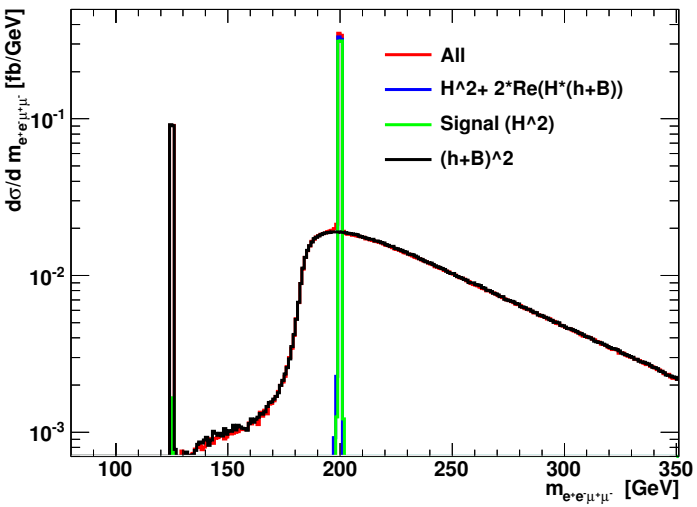


Single- and non-resonant W and Z contributions:

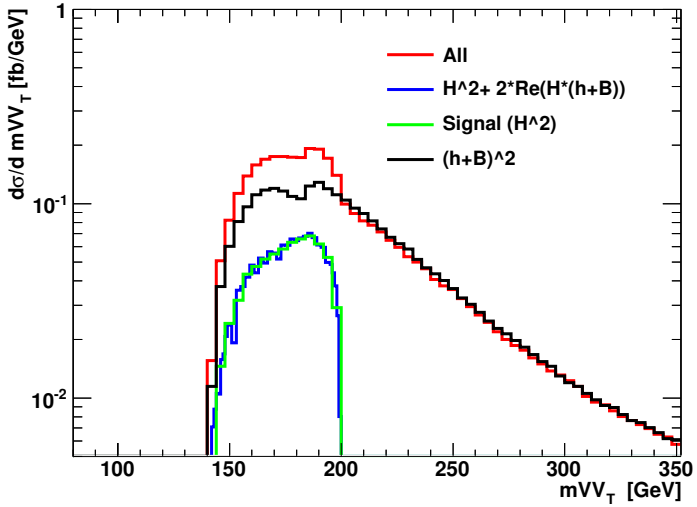


Implementation can be used for studies including all interferences, e.g. S1:

$gg \to e^+e^-\mu^+\mu^-$



$gg \to e^+e^-\nu_l\bar{\nu}_l$



Employed cuts inspired by the ATLAS analysis:

$p_T^l > 10\,\text{GeV}$, $|\eta_l| < 2.7$, $\Delta R^{ll'} > 0.1$,

$m_{ll} > 5\,\text{GeV}$, $E_T^{\text{miss}} > 70\,\text{GeV}$

▷ Conclusions in the SM:
Off-shell SM Higgs boson decays $H \to VV$ at $m_{VV} \geq 2m_V$ are large!
$\to$ Interferences are even larger and guarantee unitarity.
$\to$ Recent progress in the description of $gg \to VV$ incl. interferences at NLO.
Application: Constraint on the Higgs boson width,
however under strong theoretical assumptions only!

▷ Conclusions for heavy Higgs searches:
Basic guideline: Model interpretations should include all interferences.
1. Ideal solution:
Run a generator for the considered model taking into account all interferences
[only way to get the lineshape correct, tedious e.g. for $gg \to l^+l^- q\bar{q}$ and beyond LO].
2. Simplest option (well-defined and usable!):
Provide ($\sigma \cdot$ BR) limit in the narrow width approximation (NWA).
3. More refined option:
Apply correction factor to NWA for H with narrow width [1510.03450, see above].
4. Option to include in addition:
Provide a fiducial cross section e.g. in bins of m_{VV}, e.g. in [1509.07844; ATLAS].
$\leftrightarrow$ Allows for model interpretation in your favorite model.
[using the newest N^{4}LO generator on your smart watch in 15 years].