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Interference effects in heavy Higgs searches

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

Geneva – November 2017

Karlsruhe Institute of Technology

HELMHOLTZ | GEMEINSCHAFT

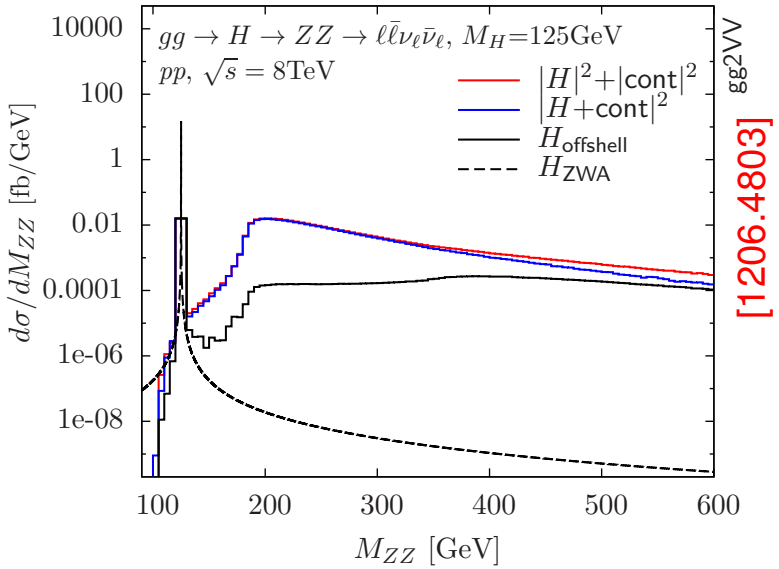
Outline

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

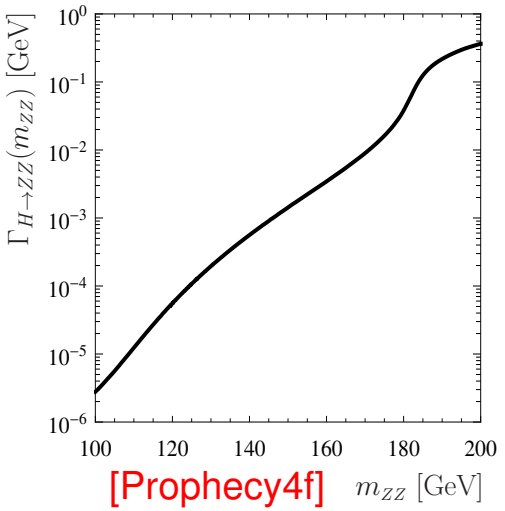
[1307.4935; Caola Melnikov]

[1311.3589, 1312.1628, 1408.1723; Campbell Ellis Williams]

Application: see Roberto's talk!

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

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

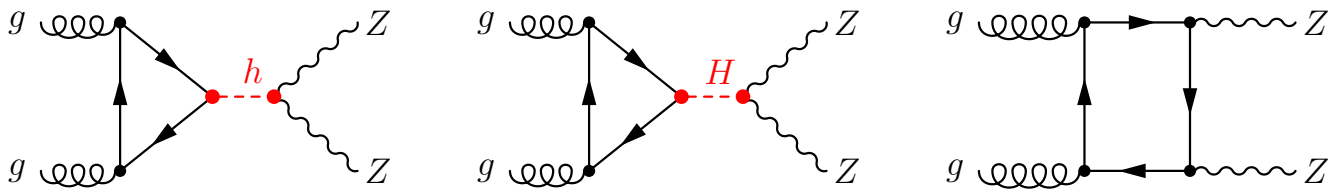


▷ A lot of effort went into the NLO description of the interferences!

▷ Limitations of Higgs width constraint and opportunities:

[1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338, 1410.5440, 1410.5806, 1710.02149, etc.]

How does this discussion interfere with the searches for heavy Higgs bosons in VV channels (with $V \in \{W, Z\}$)?
Example in a Two-Higgs-Doublet Model (2HDM): [1512.07232 Greiner SL Weiglein]



$\rightarrow$ The heavy Higgs H (mass m_H) can interfere with h and background B.

Classification of interferences depending on SM final state in $gg \rightarrow \Phi_i \rightarrow F$:
Heavy (CP-admixed) Higgs bosons ϕ_i, SM Higgs boson H, SM background B

$F =$	$b\bar{b}/\tau^+\tau^-$	$t\bar{t}$	$\gamma\gamma$	VV	HH	ZH
Int. between ϕ_i and ϕ_j	✓	✓	✓	✓	✓	✓
Int. between ϕ_i and B	(✓)	✓	✓	✓	✓	✓
Int. between ϕ_i and H			✓	✓	✓	✓

Similar tables can be produced for the other production mechanism, mainly VBF (NB ZH is listed as decay!)

Non-exhaustive list regarding interferences at the LHC (last 3 years):

- Final state $t\bar{t}/gg/\gamma\gamma$:

[1605.00542 Djouadi Ellis Quevillon]: $gg \to \phi \to t\bar{t}$ and $gg \to \phi \to \gamma\gamma$
[1608.07282 Carena Liu]: $gg \to \phi \to t\bar{t}$
[1606.04149 Hespel Maltoni Vryonidou]: $gg \to \phi \to t\bar{t}$ (2HDM, NLO)
[1707.06760 Franzosi Vryonidou Zhang]: $gg \to \phi \to t\bar{t}$ (NLO advanced)
[1606.03026 Martin]: $pp \to \phi \to gg$
[1511.05584 Bernreuther Galler Mellein Si Uwer]: $gg \to \phi \to t\bar{t}$
[1702.06063 Bernreuther Galler Mellein Si Uwer]: $gg \to \phi \to t\bar{t}$ (polarization, spin)
[1505.00291 Jung Song Yoon]: Generic discussion with complex phase (also $b\bar{b}$)

- Final state VV: (Consistent model due to unitarity needed!)

[1501.02139 Maina]: $gg \to \phi \to VV$ (SM+singlet)
[1502.04113 Kauer O'Brien]: $gg \to \phi \to VV$ (SM+singlet)
[1506.02257 Ballestrero Maina]: VBF$\to \phi \to VV$ (SM+singlet)
[1506.01694 Kauer O'Brien Vryonidou]: $gg \to \phi \to VV \to 4l$ (SM)
[1510.03450 Jung Song Yoon]: $gg \to \gamma\gamma/ZZ$ (2HDM)
[1512.07232 Greiner SL Weiglein]: $gg \to VV \to 4l$ (2HDM)

- Final state HH:

[1407.0281 Hespel Lopez-Val Vryonidou]: $gg \to \Phi \to HH$ (2HDM, NLO)
[1508.05397 Dawson Lewis]: $gg \to \Phi \to HH$ (SM+singlet, NLO)

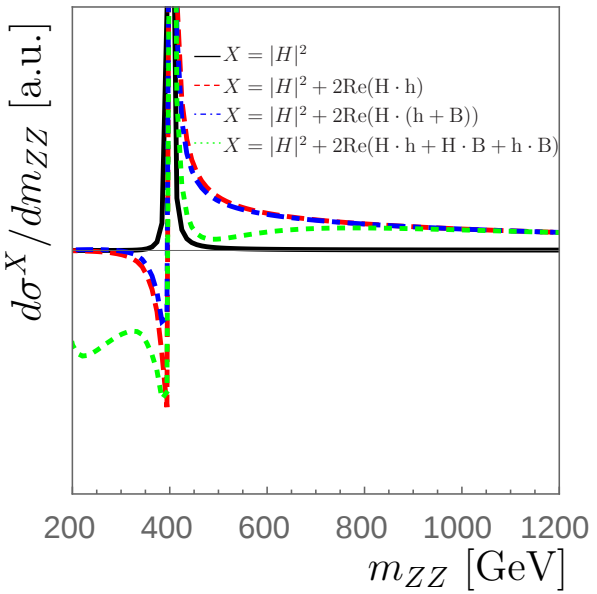
- Interferences among heavy Higgs bosons:

[1411.4652 1705.05757 Fuchs Weiglein]: ϕ's of the MSSM

Various works on Higgsstrahlung, not listed: $\gamma\gamma$ peak shift for light Higgs!
see the poster for m_t determination from $\gamma\gamma$ peak-dip structure by H. Yokoya

What happens at a high-energy LHC?
Consider the LHC running at $\sqrt{s} = 27$ rather than 13 TeV and exactly the same scenario of BSM physics:
The **relative** interference I among signal S and background B are mostly **identical**, since all contributions start with the same initial state (at a certain x of the PDFs). Thus, the overall cross section of S, B and I are different, but their relative fractions stay.
$\leftrightarrow$ Interference studies can be carried out at the partonic CMS energy $\sqrt{\hat{s}}$.

Effect at higher energies $\sqrt{s}$:
Probe different BSM scenarios with larger m_ϕ.
$\rightarrow$ Higher masses m_ϕ usually come with larger decay width Γ_ϕ and larger Γ_ϕ/m_ϕ.
$\rightarrow$ Tendency to increase the relevance of interference effects (following NWA $\Gamma_\phi/m_\phi \ll 1$).



[1512.07232 Greiner SL Weiglein]

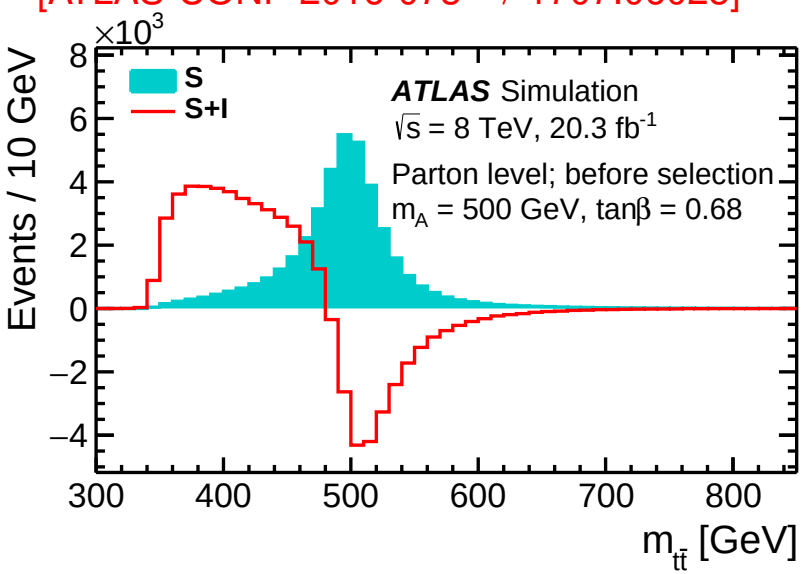
Of much larger relevance are high integrated luminosities, since they probe smaller signals S. Thus the relative fraction to the background S/B is smaller (B/S larger) and the interference I is larger. Rough estimate:

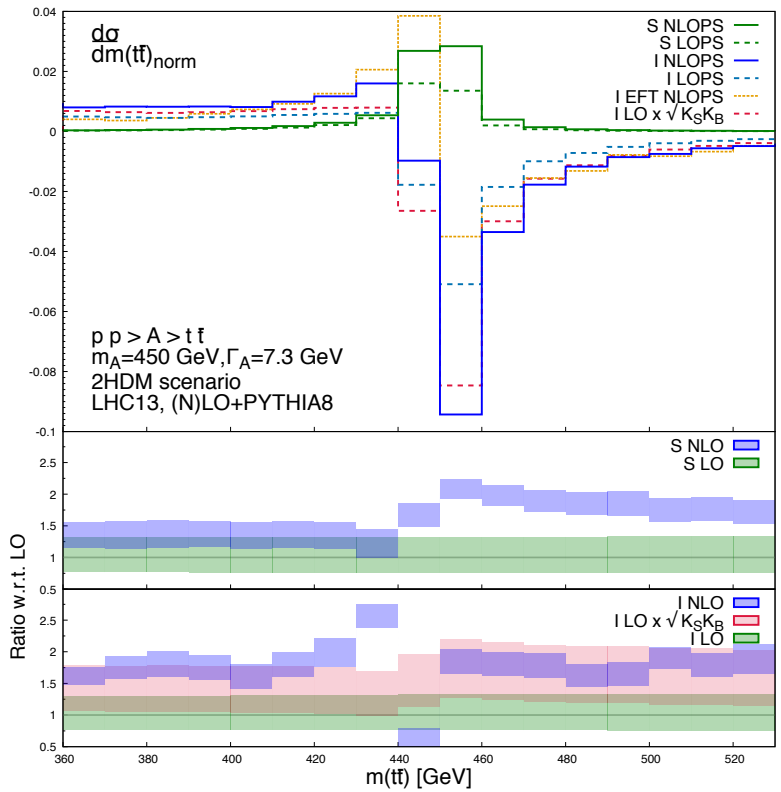
$$I \sim 2\mathrm{Re}(\mathcal{A}_S \cdot \mathcal{A}_B)$$

Fraction of interference over signal: $I/|\mathcal{A}_S|^2 \sim \mathcal{A}_B/\mathcal{A}_S$

Already of relevance and taken into account for $t\bar{t}$:

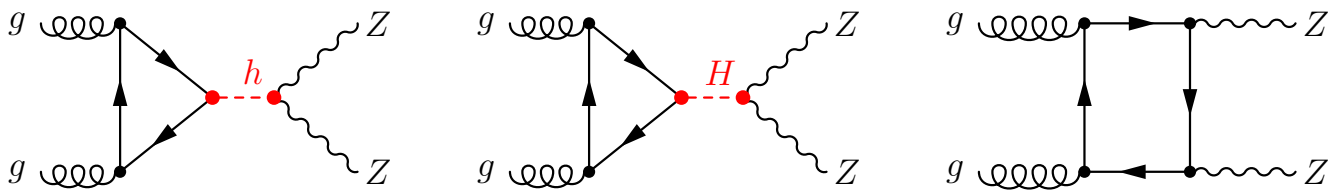
[ATLAS-CONF-2016-073 → 1707.06025]





[1707.06760 Franzosi Vryonidou Zhang]

At which level does the interference in VV play a role?
Consider again the 2HDM: [1512.07232 Greiner SL 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

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

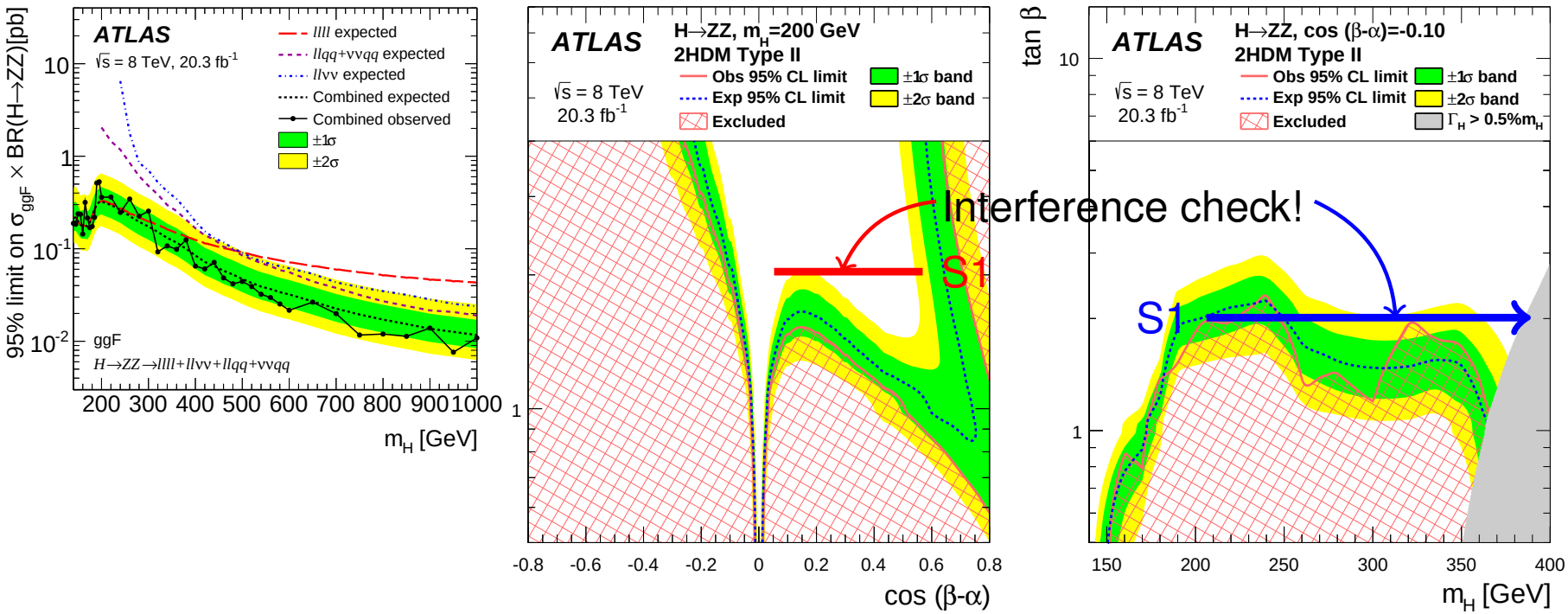
$\rightarrow$ The combination $(g_V^h)^2 + (g_V^H)^2 = 1$ guarantees unitarization!
$\rightarrow$ If $g_V^h \rightarrow 1$, then $g_V^H \approx 0$. Expect weak signal with large interferences!

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 (and partially Run II) it was indeed ok.
- ▷ At HL-LHC 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]

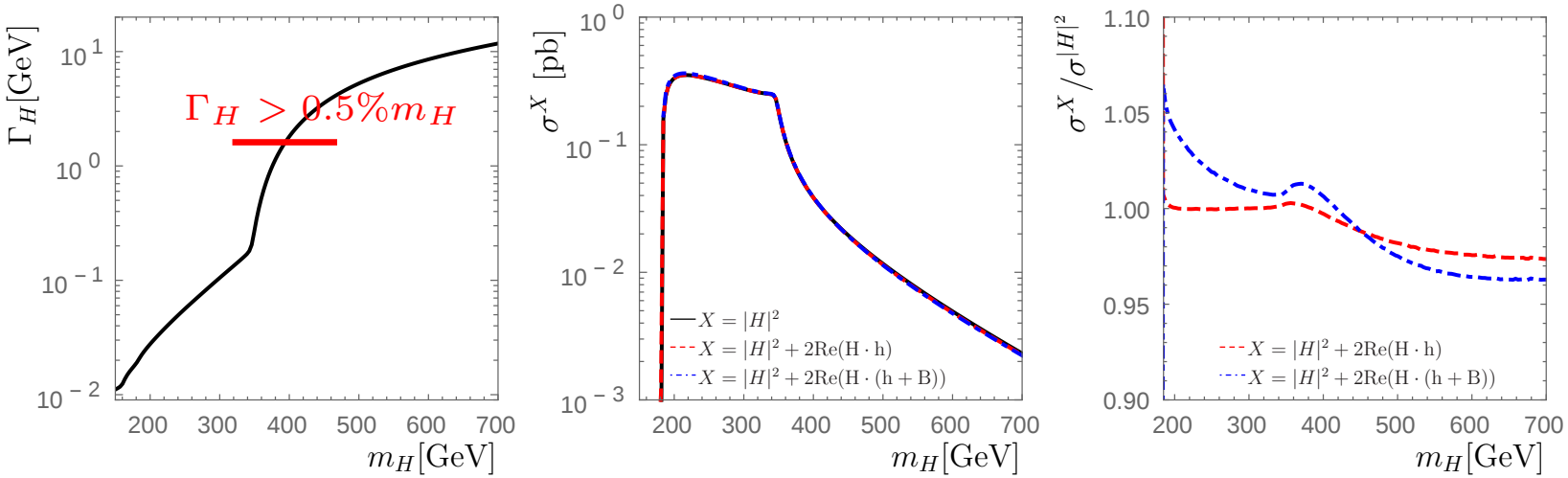
Implementation of $gg \to e^+e^-\mu^+\mu^-/e^+e^-\nu_l\bar{\nu}_l$ in a 2HDM

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 $\sqrt{s} = 8\,\text{TeV}$):

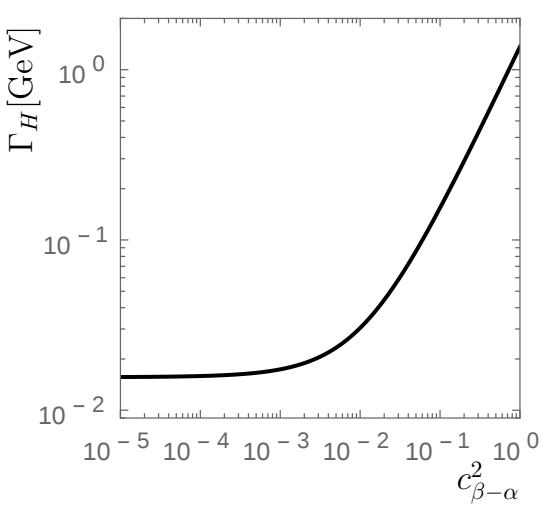
$$\sigma^X = \int_{m_H-15\text{GeV}}^{m_H+15\text{GeV}} dm_{ZZ} \frac{d\sigma^X(gg \to ZZ)}{dm_{ZZ}}$$

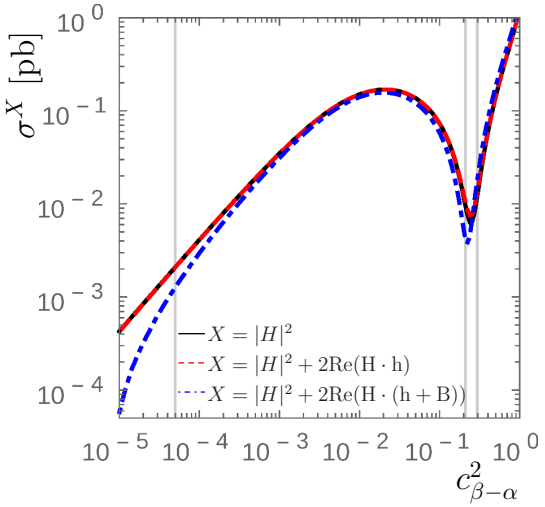


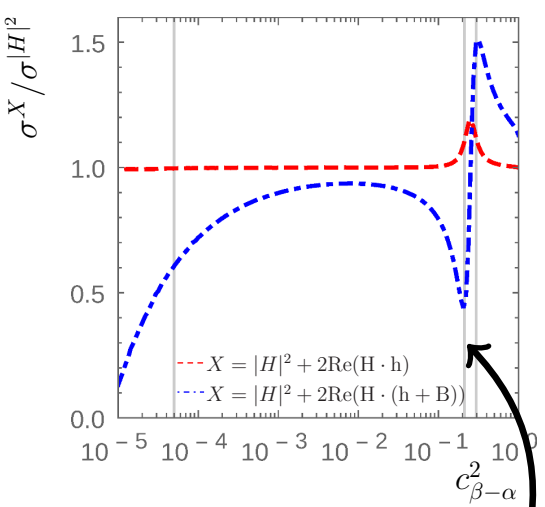
$\rightarrow$ Relevance of the interferences remains below 10%.
It's not so much the mass m_H and width Γ_H which determine the relevance of the interferences.

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

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





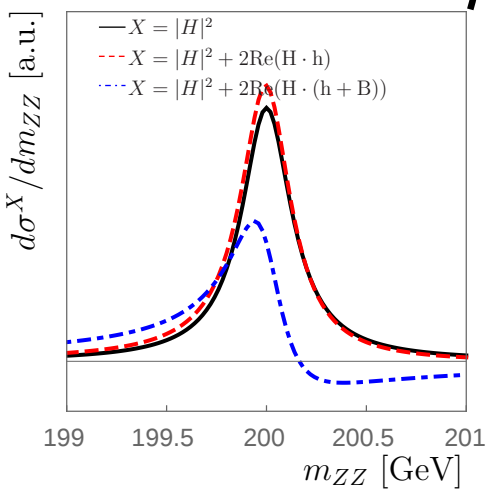


- Production $gg \to H$ involves g_t^H and g_b^H with

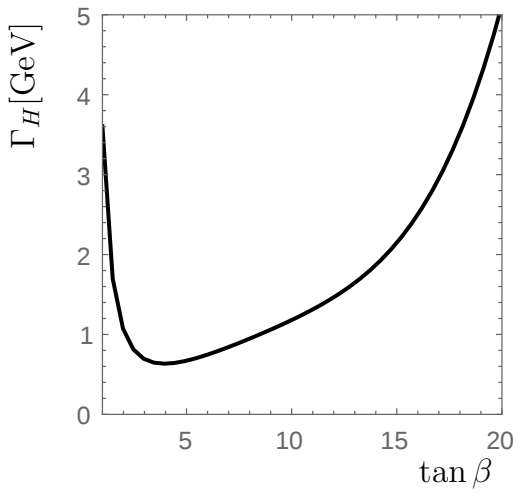
$$g_t^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{\tan\beta} + c_{\beta-\alpha} \approx 0$$

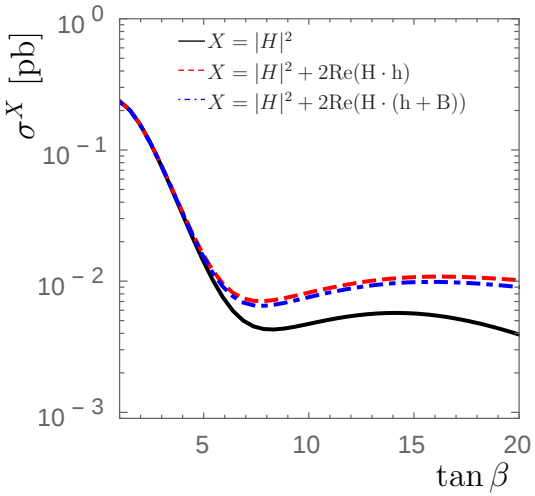
at $\quad c^2_{\beta-\alpha} = 0.2,\ \tan\beta = 2\,.$

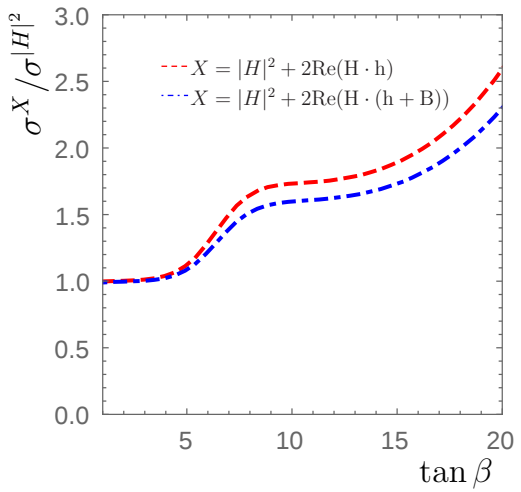
→ Where couplings are small (in production or decay) interferences are large.



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

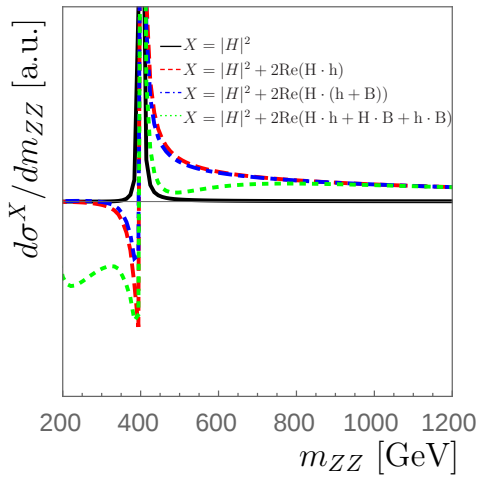






$\rightarrow$ Pushing the bottom Yukawa g_b^H through $\tan\beta$ enhances interferences.

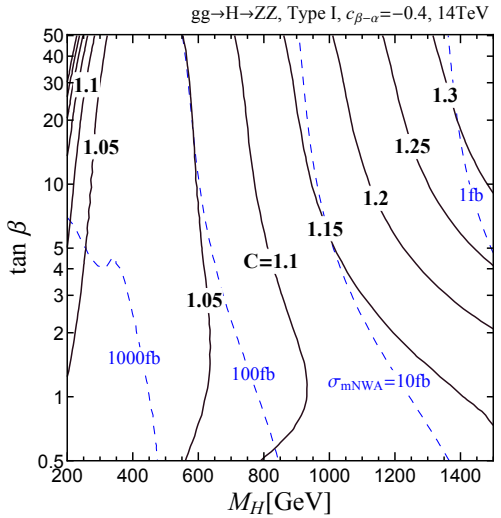
Not to forget at high invariant masses:
All interferences are of relevance:
$h \cdot B$ and $H \cdot B \leftrightarrow$ negative.
$h \cdot H$ can be large and have either sign!
Another effect: Sum of interferences can mimic
a broad peak-like structure beyond m_H.

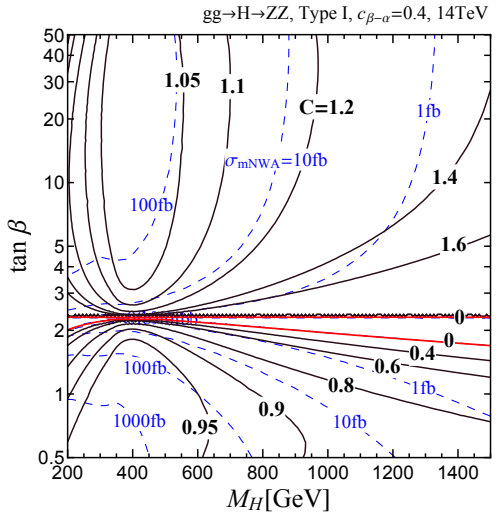


Similar conclusion for the 2HDM derived in: [1510.03450 Jung Song Yoon]

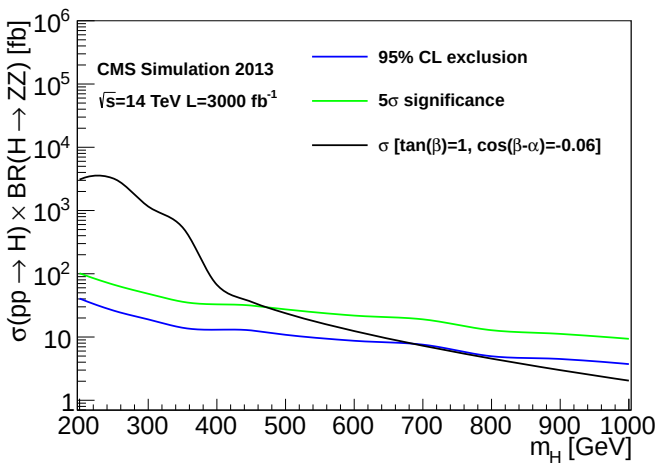
$$C = \frac{\sigma_{\mathrm{mNWA}}}{\sigma_{\mathrm{NWA}}}$$

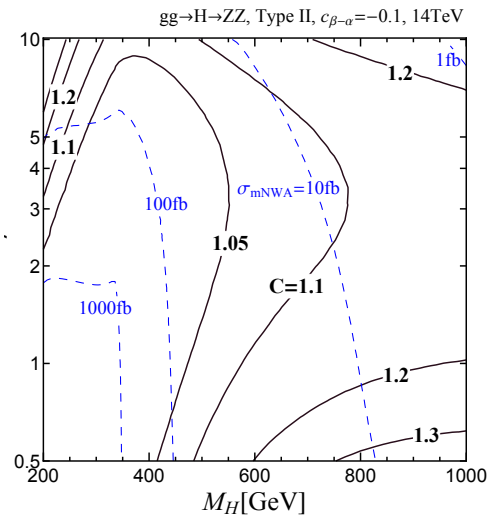
mNWA = modified NWA with interferences

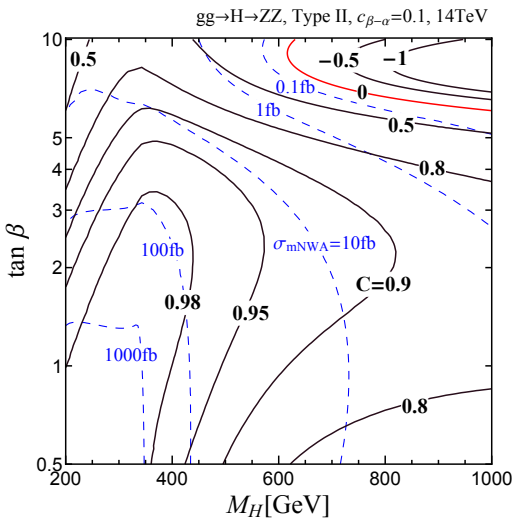




[CMS-PAS-FTR-13-024]



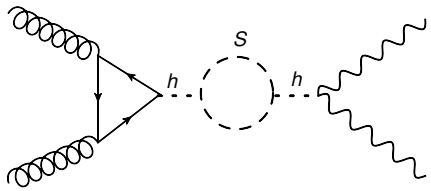




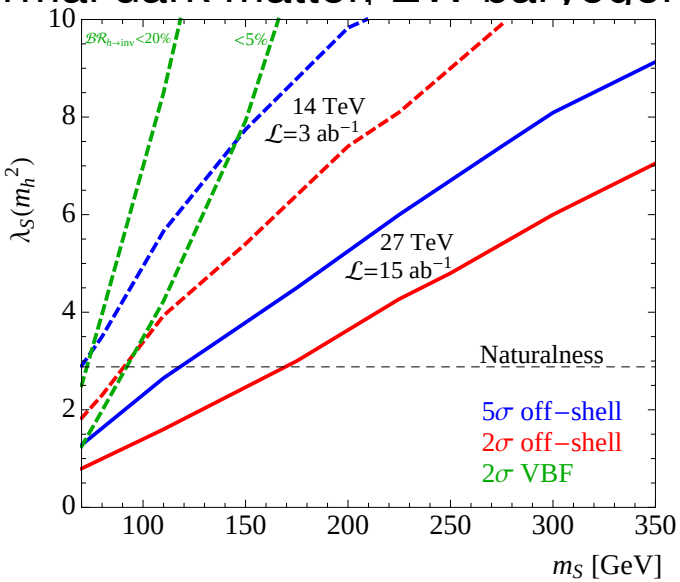
Coming back to the interference of the light Higgs H with the background:
Sensitivity to Higgs portal scenarios: [1710.02149 Gonçalves Han Mukhopadhyay]
Singlet S coupling only via the Higgs sector

$$\mathcal{L} \supset \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \lambda_S |S|^2 |H|^2$$

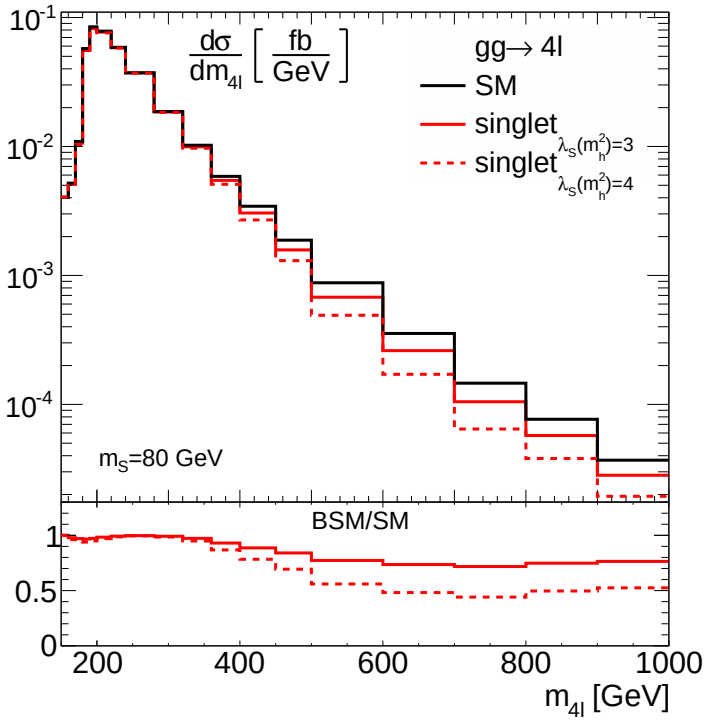
→ see Matthew Mccullough's talk



based on prospects in:
[ATL-PHYS-PUB-2015-024]
can address: naturalness,
Thermal dark matter, EW baryogenesis



→ typical in DM portals:
see Anne-Marie Magnan's talk



The relevance of interference contributions in the search for heavy Higgs bosons is process dependent. In the last years various publications looked at interferences at the LHC in different BSM models.

Two main points:

▷ Going to higher energies will not alter the relative interferences in a fixed BSM scenario. Though higher energies probe larger masses and thus Γ_ϕ/m_ϕ gets larger.

▷ Going to higher luminosities probes smaller signal cross sections and this has a profound effect on the relevance of interferences. Many processes will have to take into account interferences sooner (e.g. $t\bar{t}$) or later (VV).

Outlook:

▷ There is a LesHouches project ongoing to classify interferences in VV and HH (We are a bit behind schedule though...). We could add a higher mass scenario with a larger width.

▷ In the context of this group work out a summary of the interferences as a function of the integrated luminosity of a HL-LHC, if possible.

Thank you for your attention!

Theoretical issues:

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

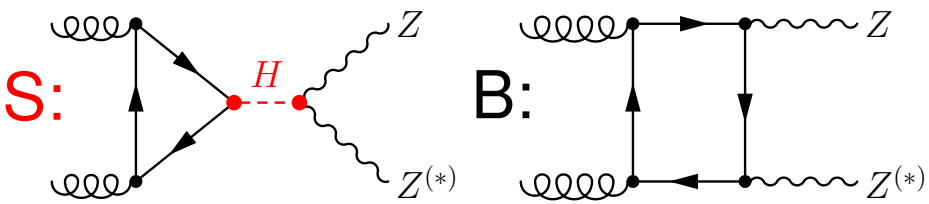
S: meanwhile known at $\mathrm{N^3LO\ QCD}$ (since 2016) (applicable as fct. of m_{VV})

B: meanwhile known at $\mathrm{NLO\ QCD}$ (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, 1605.04610; Caola (Dowling) Melnikov Röntsch Tancredi (ZZ/WW)]
[1605.01380; Campbell Ellis Czakon Kirchner: interference + top-quark mass effects]
[1609.09719; Alioli Caola Luisoni Röntsch (ZZ matched to parton shower)]
Related work on $q\bar{q} \to VV$: [1408.6409, 1503.04812]
[1710.06294; Heinrich Jahn Jones Kerner Pires (ZZ NNLO)]

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]

▷ Other issues:

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