Higgs interference effects in top-quark pair production in the 1HSM

Alexander Lind

with Andrea Banfi, Nikolas Kauer, Jonas Lindert, and Ryan Wood

2309.16759 [hep-ph]

LHC Higgs Working Group WG3 (BSM) – Extended Higgs Sector subgroup meeting
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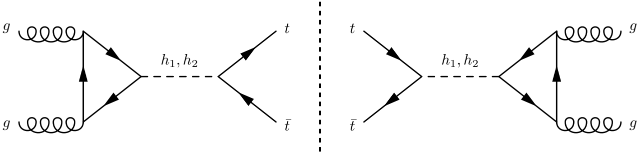
Process of interest

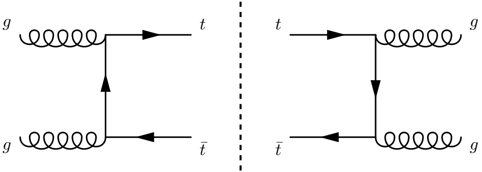
$pp\,(\to \{h_1, h_2\}) \to t\bar{t} + X$

Leading-order contributions:

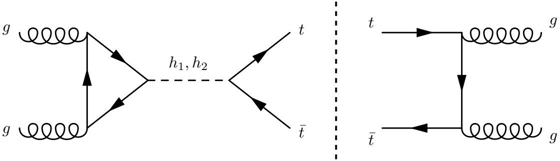
Signal



Background



Interference



The 1-Higgs Singlet Model

Add a real singlet scalar field

Potential after symmetry breaking:

$$V = \lambda\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2\left(\phi^\dagger\phi - \frac{v^2}{2}\right) + \mu_1 s^3 + \mu_2 s\left(\phi^\dagger\phi - \frac{v^2}{2}\right)$$

Mixing: $h_1 = H\cos\theta - s\sin\theta \qquad h_2 = H\sin\theta + s\cos\theta$

Fixed parameters: $M_{h_1} = 125$ GeV, $\mu_1 = \lambda_1 = \lambda_2 = 0$

Free parameters: M_{h_2}, θ, with 8 benchmark points:

M_{h_2} [GeV]	700	1000	1500	3000
$\theta = \theta_1$	$\pi/15$ ≈ 0.21	$\pi/15$ ≈ 0.21	$\pi/22$ ≈ 0.14	$\pi/45$ ≈ 0.07
$\theta = \theta_2$	$\pi/8$ ≈ 0.39	$\pi/8$ ≈ 0.39	$\pi/12$ ≈ 0.26	$\pi/24$ ≈ 0.13

NLO QCD

NLO particularly important for Higgs production

$$\sigma_{\text{LO}}(pp \to H + X) = 14.541(7) \text{ pb}$$
$$\sigma_{\text{NLO}}(pp \to H + X) = 35.11(2) \text{ pb}$$

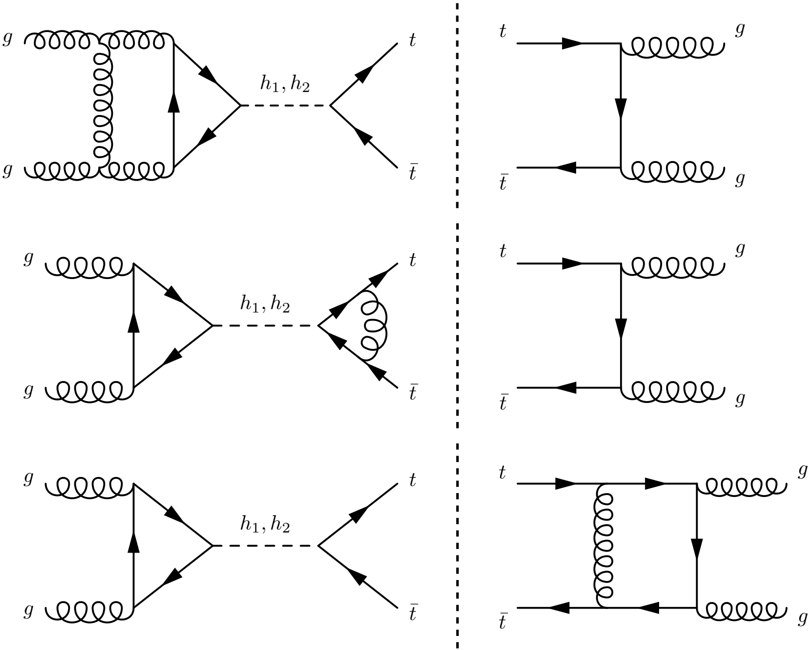
Infrared (soft/collinear) divergences $\Rightarrow$ Subtraction of dipoles

$$\sigma_{\text{LO}} = \int_m \mathrm{d}\sigma_{\text{B}}$$
$$\sigma_{\text{NLO}} = \sigma_{\text{LO}} + \int_m \left[\mathrm{d}\sigma_{\text{V}} + \mathrm{d}\sigma_{\text{B}} \otimes \mathbf{I}\right] + \int_{m+1} \left[\mathrm{d}\sigma_{\text{R}} - \sum_{\text{dipoles}} \mathrm{d}\sigma_{\text{B}} \otimes \mathbf{V}\right]$$

Even NNLO can give sizable corrections but 2-loop is highly non-trivial

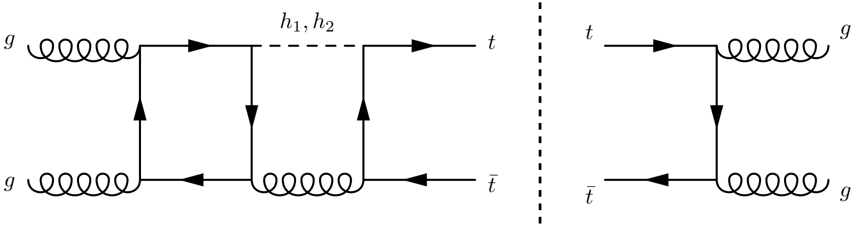
Interference effects also very important — and has large K-factors!

NLO QCD Corrections to the Interference



Non-Factorisable Corrections

Non-factorisable two-loop virtual corrections



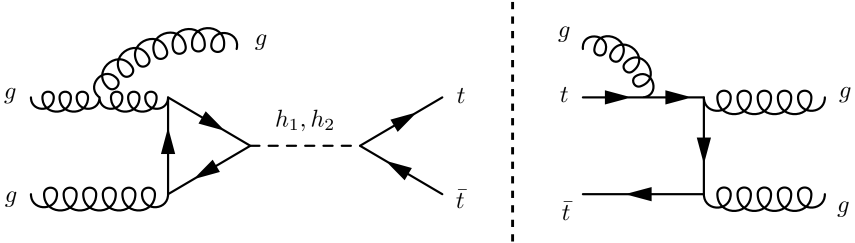
Non-zero for a (heavy) Higgs of finite width

Three different masses in internal propagators
$\Rightarrow$ Beyond today's loop technology

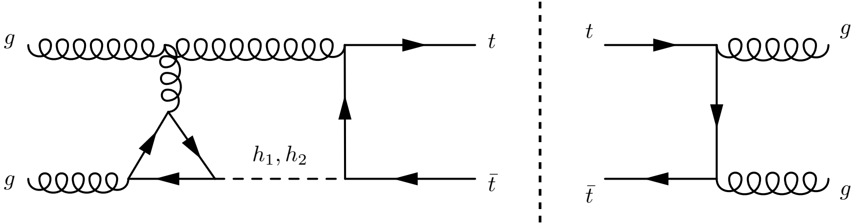
Could be calculated by expansions in $\frac{\Gamma_{h_i}}{M_{h_i}}$

Non-Factorisable Corrections

IR divergent non-factorisable **real** contribution

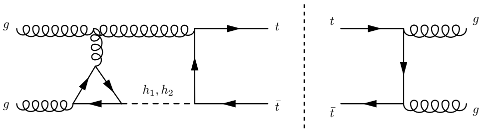


IR divergent non-factorisable **virtual** contribution

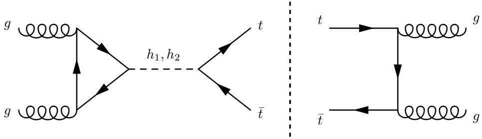


Non-Factorisable Corrections

However, in the soft limit:

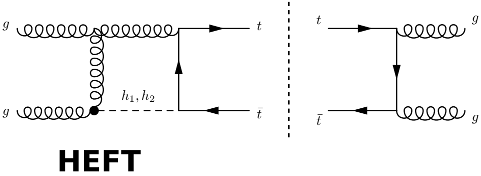


$= C \times$

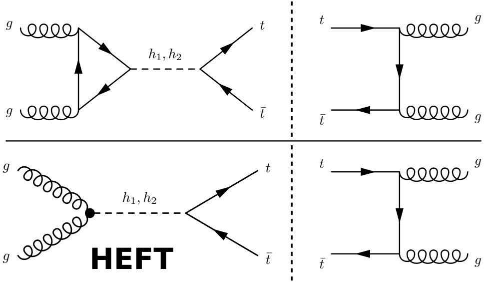


Singular term

Reweighting:



$\times$



HELAC+OpenLoops

Gap in current MC landscape: Loop-induced $\times$ tree interference at NLO
$\Rightarrow$ Need to develop our own NLO Monte Carlo framework

But no need to reinvent the wheel

- **Helac-Dipoles**
  Dipole subtraction
- **Kaleu**
  Phase space generation
- **OpenLoops**
  Tree-level and loop amplitudes

Modify OpenLoops with:

- BSM extension
- Interface to get colour correlated helicity amplitudes

$$\mathrm{d}\sigma_{\mathsf{B}} \sim \langle \mathcal{M}_{\mathsf{B}} | \mathcal{M}_{\mathsf{B}} \rangle \qquad \mathcal{D}_{ij,k} \sim \langle \mathcal{M}_{\mathsf{B}} | \frac{\mathbf{T}_k \cdot \mathbf{T}_{ij}}{\mathbf{T}_{ij}^2} \mathbf{V}_{ij,k} | \mathcal{M}_{\mathsf{B}} \rangle$$

- One- and two-loop $gg \to H$ form factors (see next slides)

Form Factors for $gg \to H$

Coupling of a Higgs doublet to two on-shell gluons

$$\mathcal{V}^{\mu\nu,ab}(q_1, q_2) = \frac{\alpha_s}{4\pi v} F \, \delta^{ab} \left((q_1 \cdot q_2) \, g^{\mu\nu} - q_1^{\nu} \, q_2^{\mu} \right)$$

Form factor F can be represented as a series expansion in powers of α_s

$$F = F_1 + \frac{\alpha_s}{2\pi} F_2 + \mathcal{O}(\alpha_s^2)$$

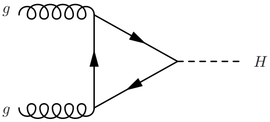
Davies, Herren, Steinhauser [1911.10214]

The one-loop form factor is

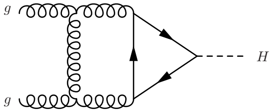
$$F_1 = -\sum_q \frac{2}{\tau_q^2} \left[\tau_q + \frac{1}{4}(1 - \tau_q) \ln^2 x_q \right]$$

Harlander, Kant [hep-ph/0509189]

F_1:



F_2:

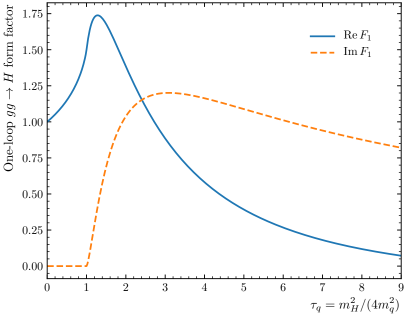


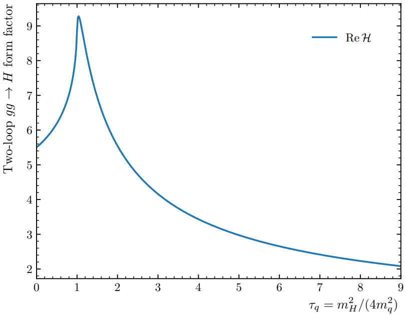
Form Factors for $gg \to H$

The two-loop form factor is

$$F_2 = \left(\frac{4\pi\mu_R^2}{-2(q_1\cdot q_2) - i0}\right)^{\epsilon} \frac{1}{\Gamma(1-\epsilon)} \left\{ -\left(\frac{C_A}{\epsilon^2} + \frac{\beta_0}{\epsilon} + \beta_0 \ln\left(\frac{2(q_1\cdot q_2)}{\mu_R^2}\right)\right) F_1 \right.$$
$$\left. + 2\sum_q \left[C_F \left(\mathcal{F}_{1/2}^{2l,a}(x_q) + \frac{4}{3}\mathcal{F}_{1/2}^{2l,b}(x_q)\right) + C_A \mathcal{G}_{1/2}^{2l}(x_q)\right] \right\}$$

Aglietti, Bonciani, Degrassi, Vicini [hep-ph/0611266]





Results: Integrated Cross Sections

NLO predictions with stable tops

QCD background: $|\mathcal{M}_{\text{QCD}}|^2$

Higgs signal: $|\mathcal{M}_{h_1}|^2 + |\mathcal{M}_{h_2}|^2 + 2\,\mathrm{Re}\left(\mathcal{M}^*_{h_1}\mathcal{M}_{h_2}\right)$

Higgs–QCD interference: $2\,\mathrm{Re}\left(\left(\mathcal{M}^*_{h_1} + \mathcal{M}^*_{h_2}\right)\mathcal{M}_{\text{QCD}}\right)$

$pp\ (\to \{h_1\}) \to t\bar{t} + X$ in the SM

QCD background		Higgs signal		Higgs-QCD Interference	
$\sigma^{\text{QCD}}_{\text{NLO}}$ [pb]	K^{QCD}	$\sigma^{\text{Higgs}}_{\text{NLO}}$ [pb]	K^{Higgs}	$\sigma^{\text{interf}}_{\text{NLO}}$ [pb]	K^{interf}
$675.23(4)$	$1.5965(1)$	$0.030971(3)$	$1.6512(2)$	$-1.4625(1)$	$2.0101(2)$

Ansatz from Hespel, Maltoni, Vryonidou, [1606.04149]:

$$\sigma^{\text{interf}}_{\text{NLO}} = \sqrt{K^{\text{Higgs}} \cdot K^{\text{QCD}}}\,\sigma^{\text{interf}}_{\text{LO}}$$

This ansatz yields $K^{\text{interf}}_{\text{estimate}} = \sqrt{K^{\text{Higgs}} \cdot K^{\text{QCD}}} = 1.62$ vs. ours $K^{\text{interf}} = 2.01$

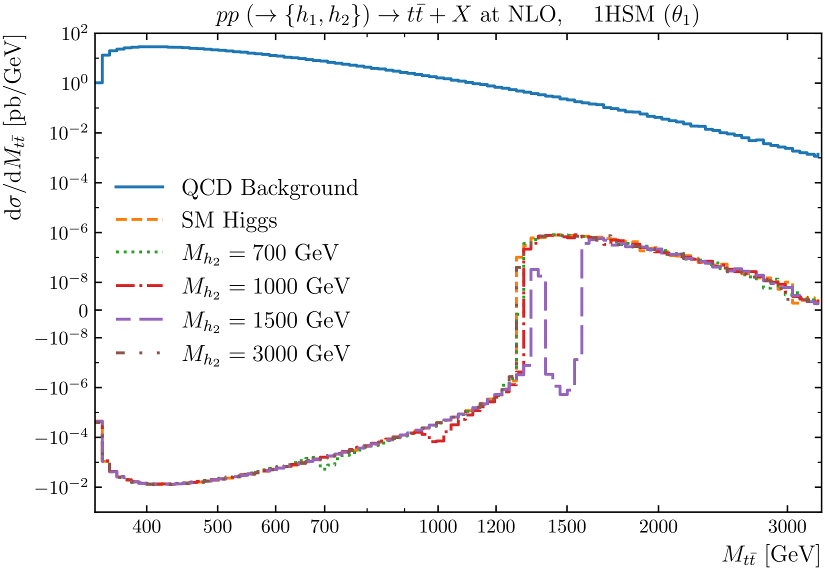
Results: Integrated Cross Sections

Same story for our considered BSM model

$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM					
		Higgs signal		Higgs–QCD interference	
	M_{h_2} [GeV]	$\sigma_{\text{NLO}}^{\text{Higgs}}$ [pb]	K^{Higgs}	$\sigma_{\text{NLO}}^{\text{interf}}$ [pb]	K^{interf}
θ_1	700	$0.029108(2)$	$1.6234(2)$	$-1.388(8)$	$1.99(2)$
	1000	$0.027334(2)$	$1.6459(2)$	$-1.3924(2)$	$2.0151(2)$
	1500	$0.029932(3)$	$1.6745(2)$	$-1.4369(2)$	$2.0194(2)$
	3000	$0.030933(3)$	$1.6661(2)$	$-1.4781(2)$	$2.0414(2)$
θ_2	700	$0.027231(2)$	$1.5689(2)$	$-1.186(8)$	$1.88(2)$
	1000	$0.020114(2)$	$1.6442(2)$	$-1.21053(9)$	$1.9867(2)$
	1500	$0.026519(2)$	$1.6617(2)$	$-1.34853(9)$	$1.9958(2)$
	3000	$0.029772(2)$	$1.6452(2)$	$-1.4365(2)$	$2.0097(2)$

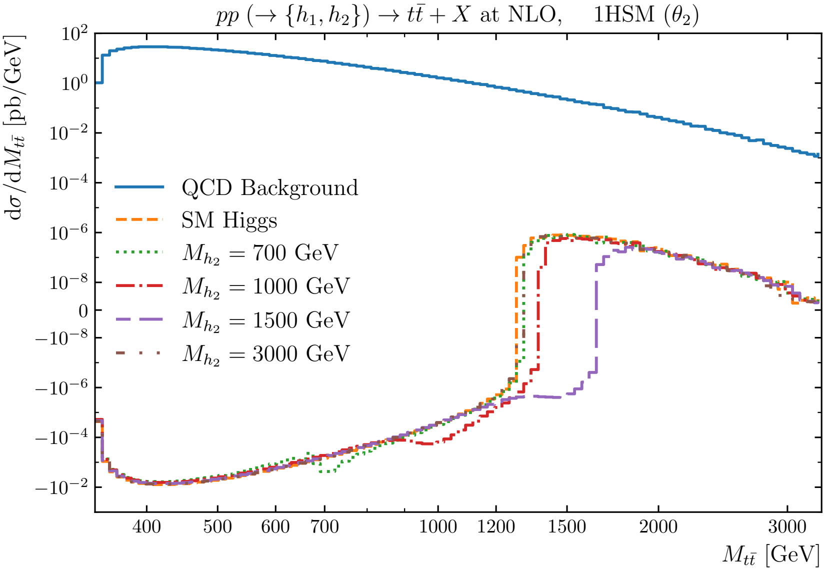
Results: Differential Distributions

$M_{t\bar{t}}$ distribution for benchmark points with $\theta = \theta_1$



Results: Differential Distributions

$M_{t\bar{t}}$ distribution for benchmark points with $\theta = \theta_2$

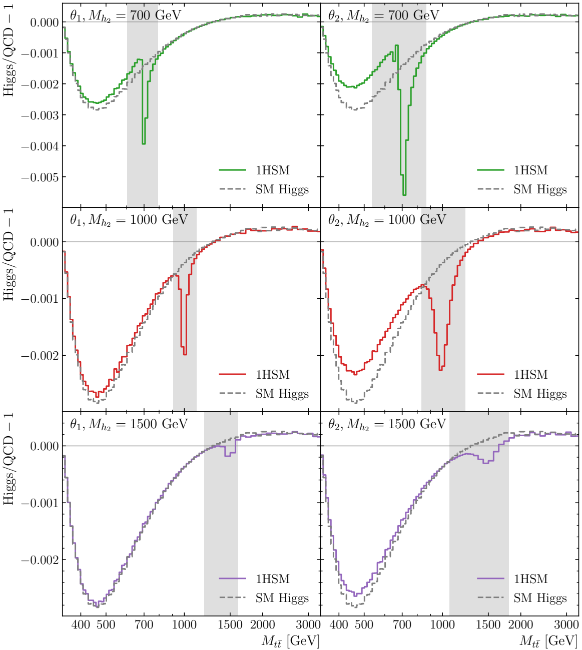


Results: Differential Distributions

Peak/dip structure in the BSM scenarios

Higgs/QCD-1 vs. $M_{t\bar{t}}$

Grey bands: Invariant mass windows



M_{h_2}

700 GeV

1000 GeV

1500 GeV

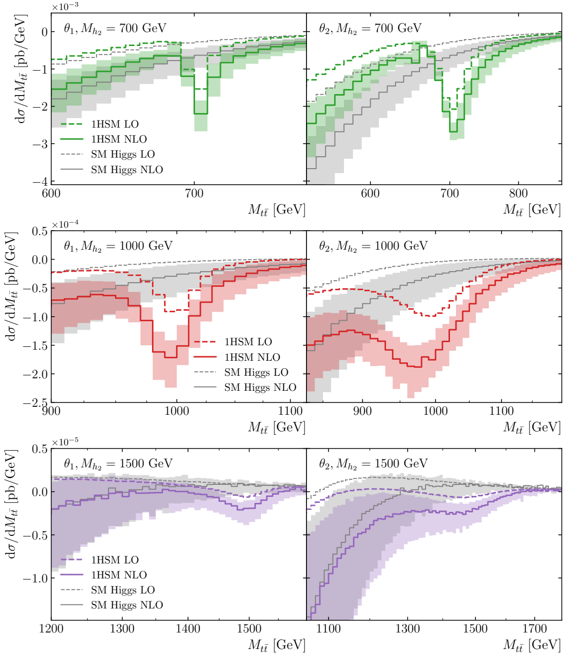
Results: Differential Distributions

NLO vs. LO

Zoomed in at the invariant mass windows

Estimation of theoretical uncertainties:

- 7-point scale variation
- 20–30%



M_{h_2}

700 GeV

1000 GeV

1500 GeV

Results: Sensitivity Estimates to BSM Effects

Naive estimate for the significance from Poisson statistics

$$\frac{|S|}{\sqrt{B}} = \sqrt{\mathcal{L}}\,\frac{|\sigma_S|}{\sqrt{\sigma_B}}$$

Run 2: $\mathcal{L} = 139$ fb^{-1}

Run 3: $\mathcal{L} \approx 300$ fb^{-1}

HL-LHC: $\mathcal{L} \approx 3000$ fb^{-1}

Excludable if

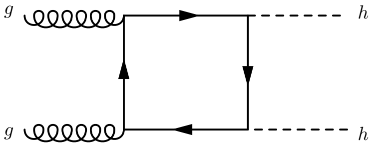
$$\frac{|S|}{\sqrt{B}} > 2$$

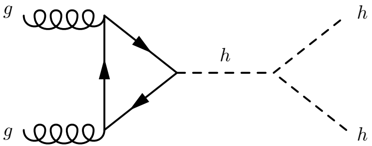
	M_{h_2} [GeV]	Invariant mass window	Excludable Run 2	Excludable Run 3	Excludable HL-LHC
θ_1	700	600–790 GeV	✓	✓	✓
	1000	900–1115 GeV	–	✓	✓
	1500	1200–1600 GeV	–	–	–
θ_2	700	530–870 GeV	✓	✓	✓
	1000	830–1200 GeV	✓	✓	✓
	1500	1050–1800 GeV	–	–	–

Outlook

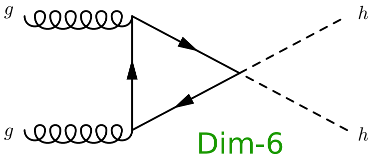
The code can be generalised to work for any loop-induced process, e.g.

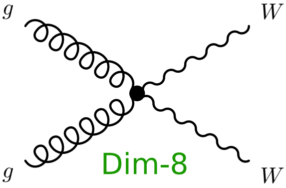
Double Higgs production





Effective field theories





Summary

- We have studied the interference of a heavy Higgs with the continuum QCD background at NLO QCD
- The interference is loop-induced $\times$ tree-level at LO, and has a complicated structure at NLO
- This has required a specially built Monte Carlo – which can be now be used for other loop-induced processes