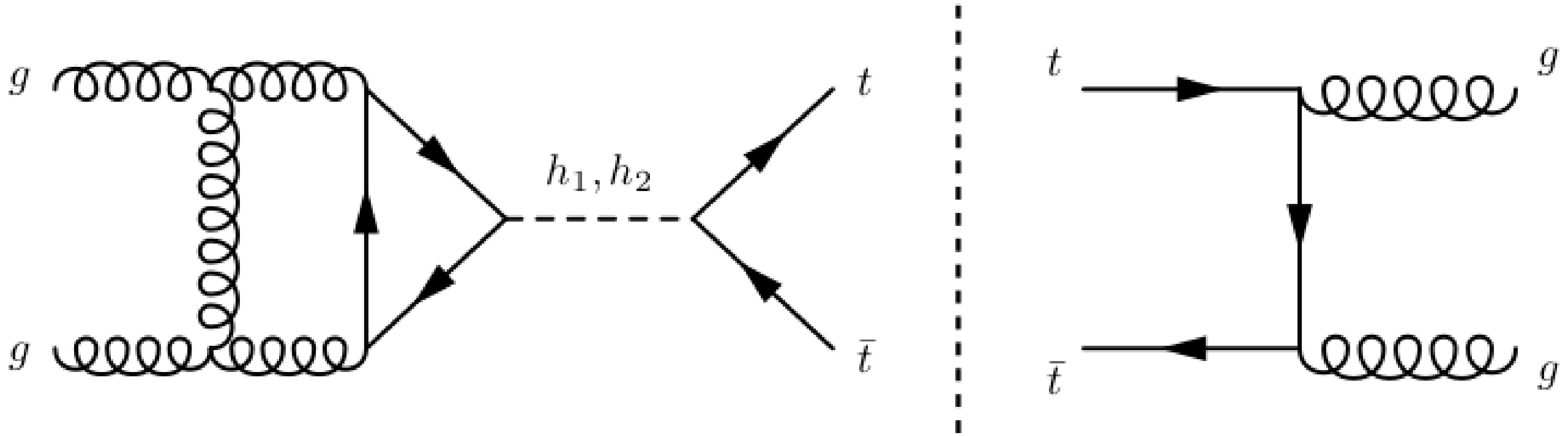
Higgs interference effects in top-quark pair production in the 1HSM



Andrea Banfi

LHCP 2024 – Boston – 6 June 2024

University of Sussex

Based on 2309.16759, in collaboration with
Nikolas Kauer, Alexander Lind, Jonas Lindert and Ryan Wood

Outline

- Overview of the 1-Higgs singlet model
- Higgs interference effects at NLO
- Treatment of non-factorisable corrections
- Sensitivity to BSM effects

The 1-Higgs singlet model

Add a real scalar field s, with the following potential

[Chen Dawson Lewis1410.5488]

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

After spontaneous symmetry breaking, the new scalar field mixes with the SM Higgs doublet to give two neutral spin-0 particles

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

$$h_1 = H \cos\theta - s \sin\theta$$

$$h_2 = H \sin\theta + s \cos\theta$$

The 1-Higgs singlet model

Add a real scalar field s, with the following potential

[Chen Dawson Lewis1410.5488]

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

After spontaneous symmetry breaking, the new scalar field mixes with the SM Higgs doublet to give two neutral spin-0 particles

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

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

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

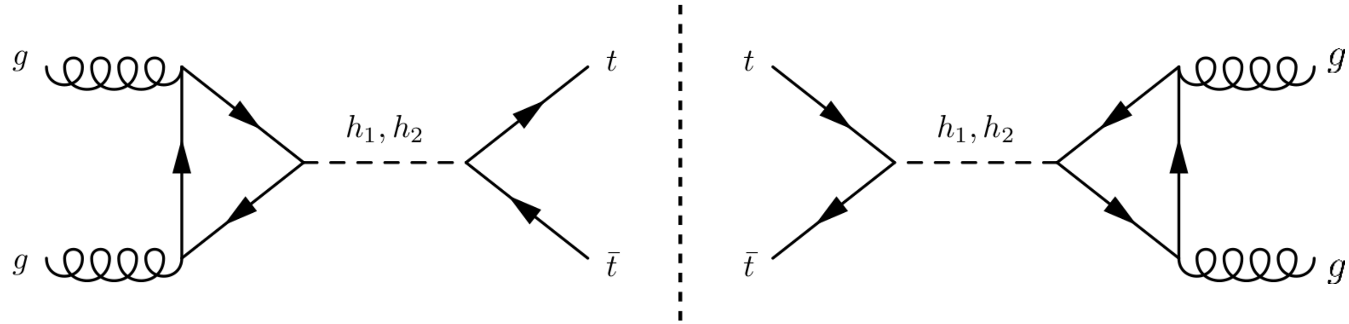
Free parameters: M_{h_2}, θ , with 8 benchmark points

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

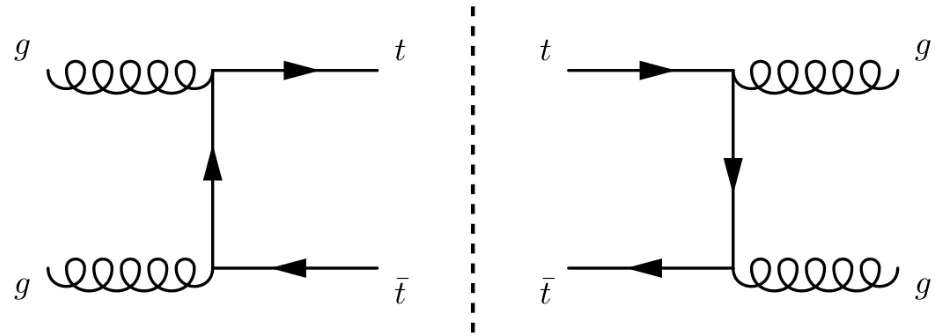
Higgs effects in top-antitop production

A heavy Higgs boson can decay into a top-antitop pair

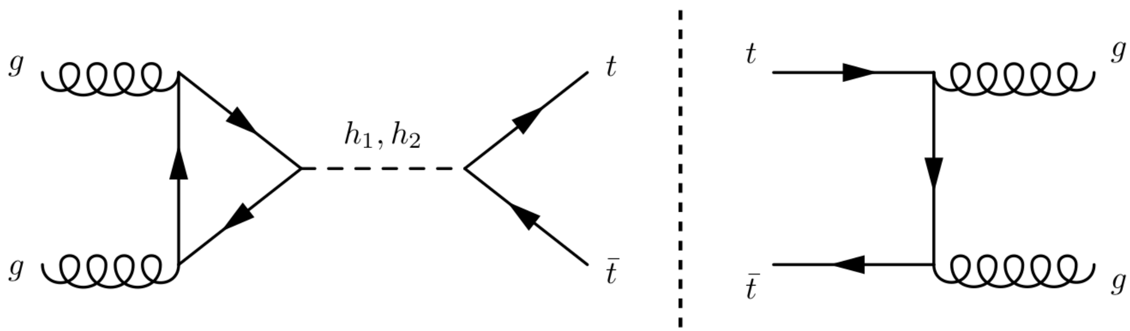
Signal



Background

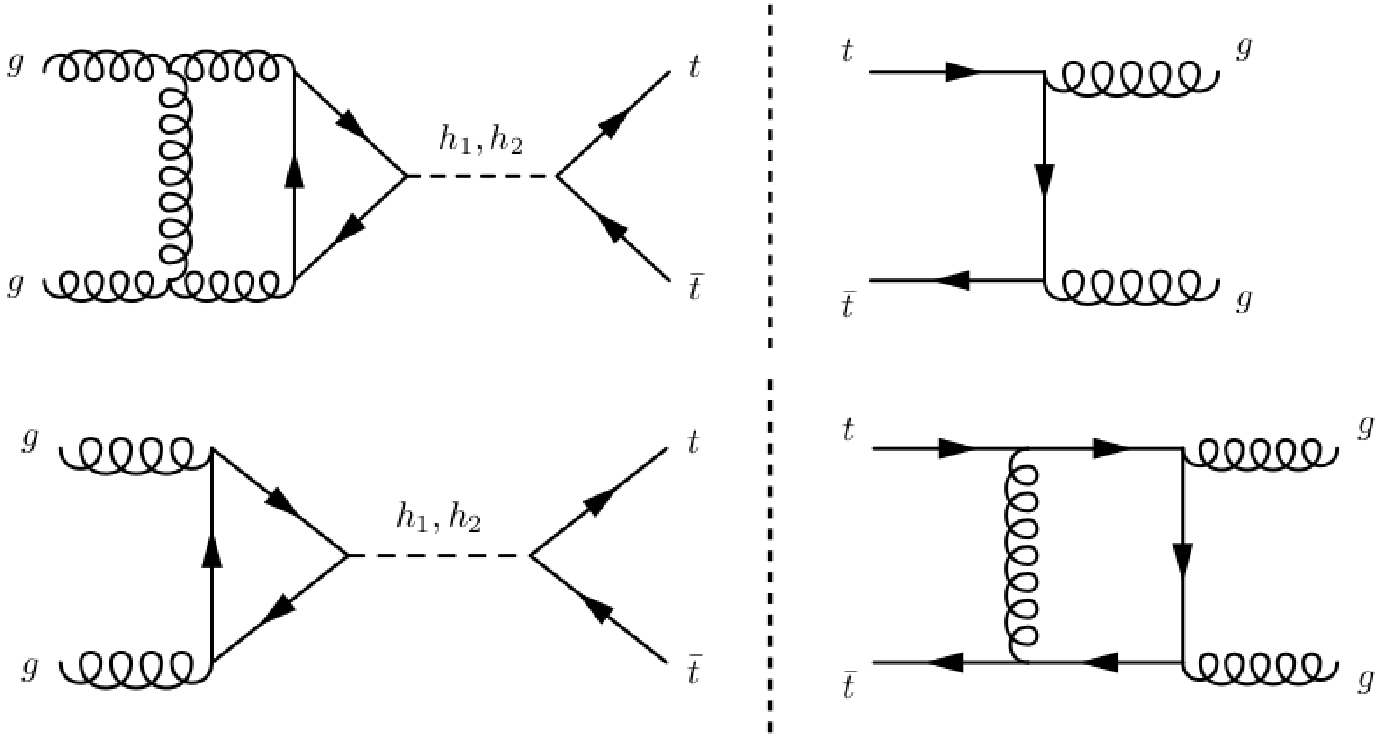


Interference



NLO QCD corrections

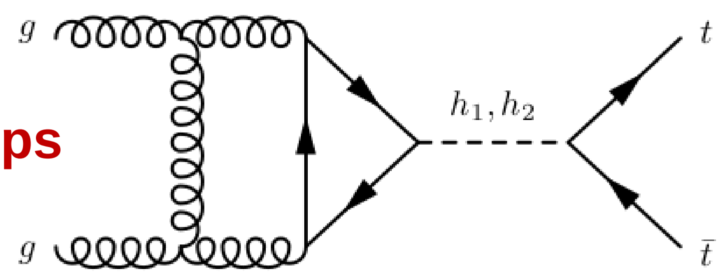
- Both Higgs and top production are affected by large K-factors, therefore the first reliable perturbative order is NLO
- Examples of virtual corrections to the interference

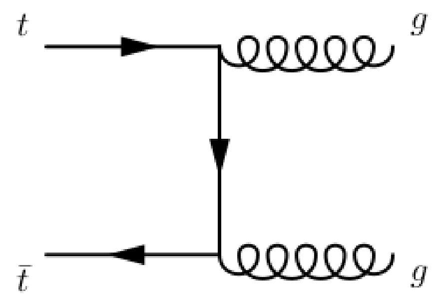


NLO QCD corrections

- Both Higgs and top production are affected by large K-factors, therefore the first reliable perturbative order is NLO
- Examples of virtual corrections to the interference

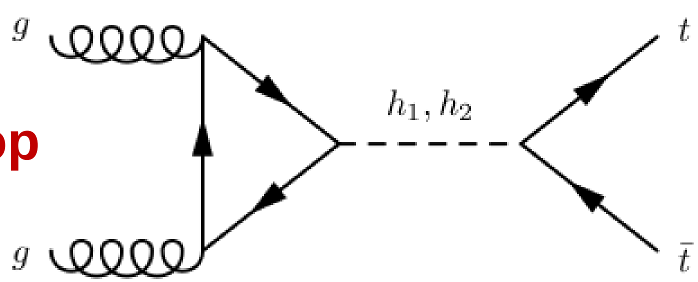
2 loops

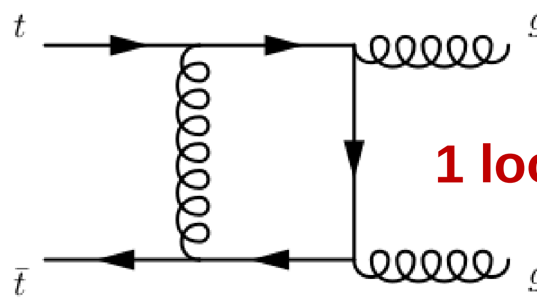




0 loops

1 loop





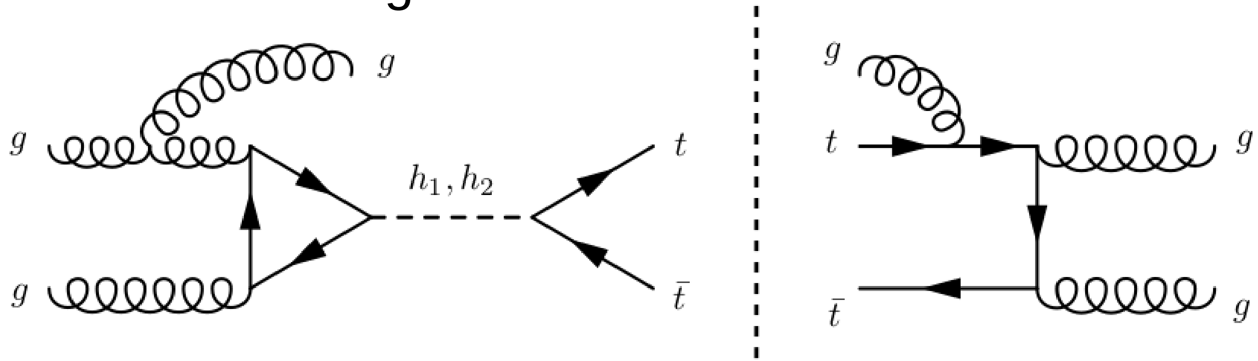
1 loop

NLO corrections for our process of interest involve combinations of contributions at different loop orders $\Rightarrow$ not available in automated tools

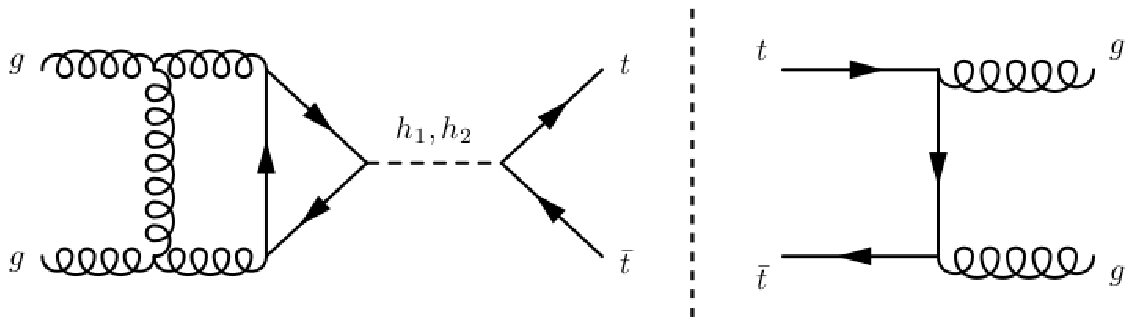
NLO QCD calculation

Ingredients for the NLO calculation

- Emission of an additional gluon



- Interference of virtual corrections and LO amplitude

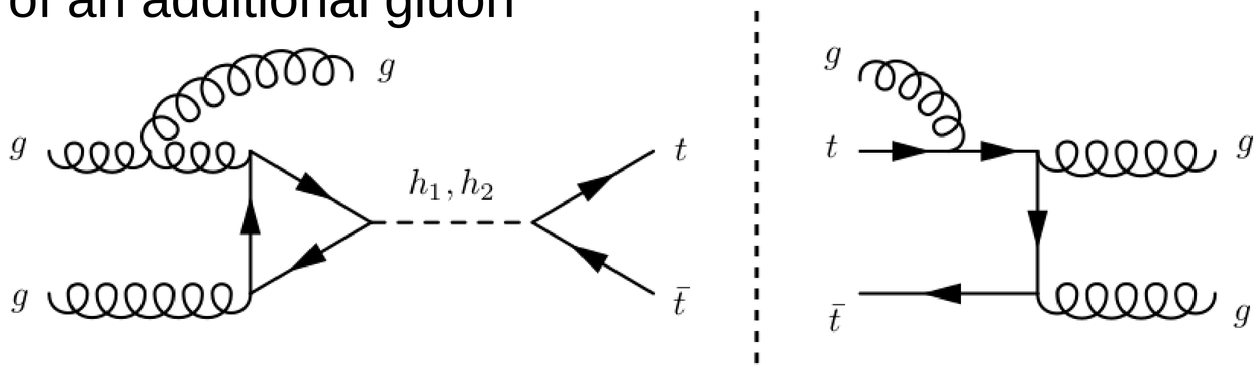


- Subtraction counterterms to ensure the cancellation of infrared and collinear divergences in real and virtual contributions

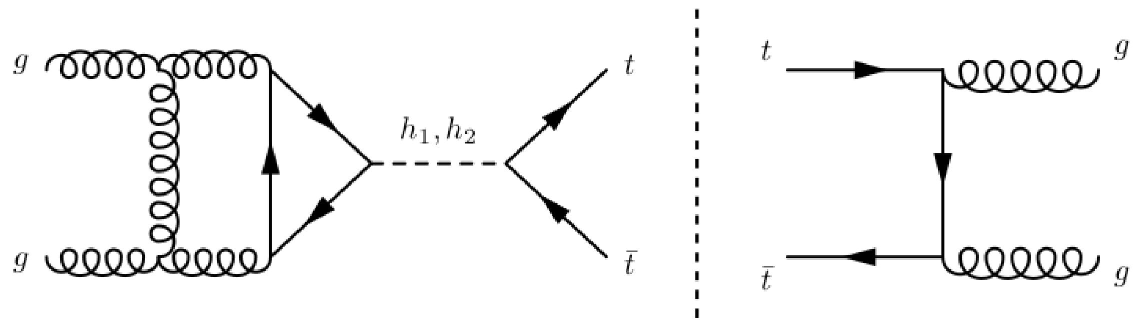
NLO QCD calculation: Helac+OpenLoops

Ingredients for the NLO calculation

- Emission of an additional gluon



- Interference of virtual corrections and LO amplitude



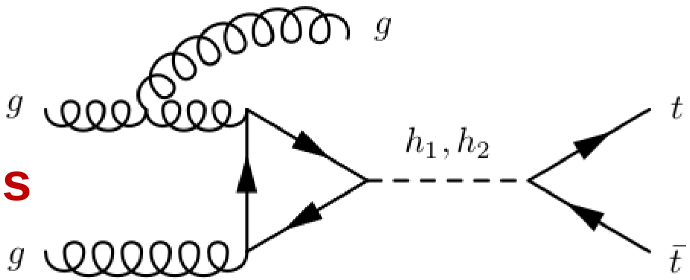
- Subtraction counterterms to ensure the cancellation of infrared and collinear divergences in real and virtual contributions

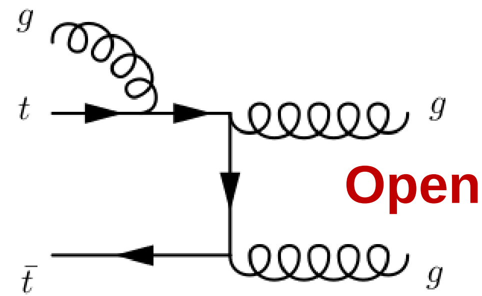
NLO QCD calculation: Helac+OpenLoops

Ingredients for the NLO calculation

- Emission of an additional gluon

OpenLoops



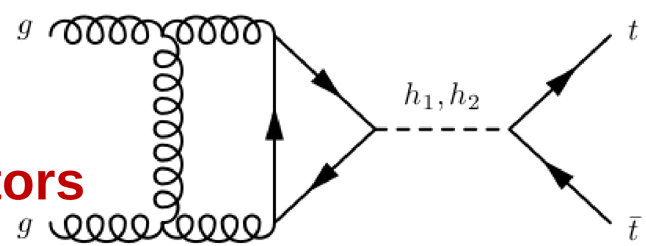


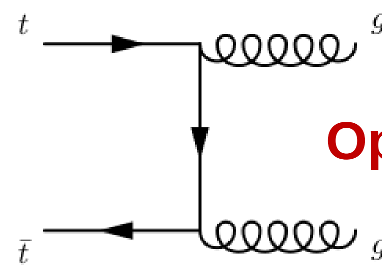
OpenLoops

[Buccioni Lang Lindert Maierhöfer Pozzorini Zhang Zoller 1907.13071]

- Interference of virtual corrections and LO amplitude

OpenLoops
+
2-loop form factors





OpenLoops

[Aglietti Bonciani Degrassi Vicini hep-ph/0611266]

- Subtraction counterterms to ensure the cancellation of infrared and collinear divergences in real and virtual contributions **Helac-Dipoles**

[Czakon Papadopoulos Worek 0905.0883]

Total cross-sections: SM

NLO predictions with stable tops

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\mathrm{QCD}}|^2}_{\text{QCD background}} + \underbrace{|\mathcal{M}_{h_1}|^2}_{\text{Higgs signal}} + \underbrace{2\mathrm{Re}(\mathcal{M}_{h_1}^* \mathcal{M}_{\mathrm{QCD}})}_{\text{Higgs-QCD interference}}$$

$pp\ (\to \{h_1\}) \to t\bar{t} + X$ in the SM					
QCD background $\lvert\mathcal{M}_{\mathrm{QCD}}\rvert^2$		Higgs signal $\lvert\mathcal{M}_{h_1}\rvert^2$		Higgs-QCD Interference $2\mathrm{Re}(\mathcal{M}_{h_1}^* \mathcal{M}_{\mathrm{QCD}})$	
$\sigma_{\mathrm{NLO}}^{\mathrm{QCD}}$ [pb]	K^{QCD}	$\sigma_{\mathrm{NLO}}^{\mathrm{Higgs}}$ [pb]	K^{Higgs}	$\sigma_{\mathrm{NLO}}^{\mathrm{interf}}$ [pb]	K^{interf}
675.23(4)	1.5965(1)	0.030971(3)	1.6512(2)	−1.4625(1)	2.0101(2)

- Large K-factors for all contributions ⇒ NLO needed
- Our results can be compared to the ansatz by Hespel, Maltoni, Vryonidou

[Hespel Maltoni Vryonidou 1606.04149]]

$$K_{\mathrm{estimate}}^{\mathrm{interf}} = \sqrt{K^{\mathrm{Higgs}} \cdot K^{\mathrm{QCD}}} = 1.62$$

Total cross-sections: BSM

NLO predictions with stable tops

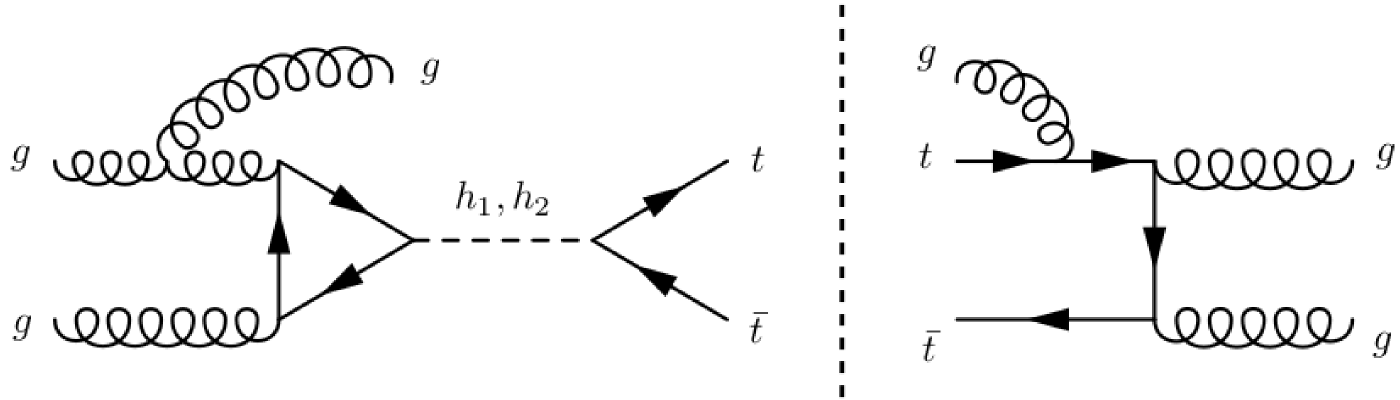
$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{QCD}}|^2}_{\text{QCD background}} + \underbrace{|\mathcal{M}_{h_1} + \mathcal{M}_{h_2}|^2}_{\text{Higgs signal}} + \underbrace{2\text{Re}((\mathcal{M}^*_{h_1} + \mathcal{M}^*_{h_2})\mathcal{M}_{\text{QCD}})}_{\text{Higgs-QCD interference}}$$

$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM

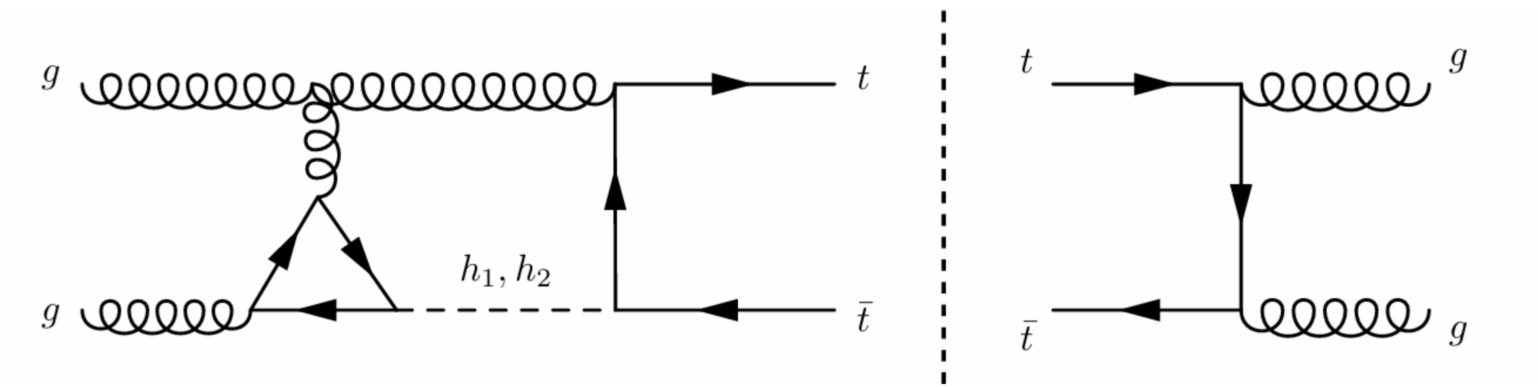
		Higgs signal $|\mathcal{M}_{h_1} + \mathcal{M}_{h_2}|^2$		Higgs–QCD interference $2\text{Re}\left((\mathcal{M}^*_{h_1} + \mathcal{M}^*_{h_2})\mathcal{M}_{\text{QCD}}\right)$	
	M_{h_2} [GeV]	$\sigma^{\text{Higgs}}_{\text{NLO}}$ [pb]	K^{Higgs}	$\sigma^{\text{interf}}_{\text{NLO}}$ [pb]	K^{interf}
θ_1	700	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)

Non-factorisable corrections

Non-factorisable **real** contributions $\Rightarrow$ OpenLoops

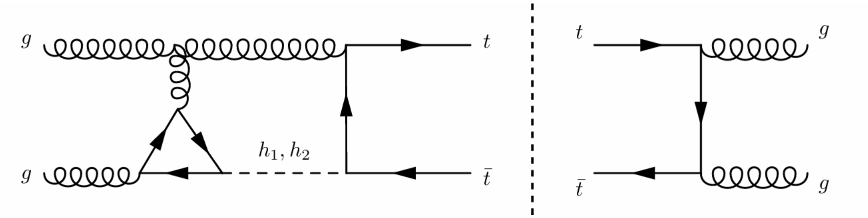


Non-factorisable **virtual** contributions $\Rightarrow$ two-loop integrals with different masses in the propagators, beyond today's technology

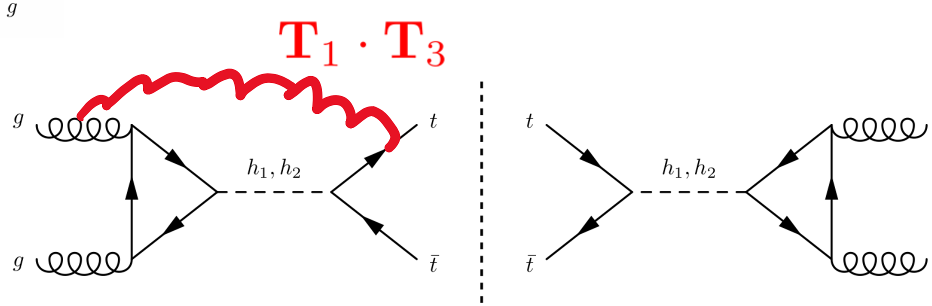


Non-factorisable corrections

IR divergent virtual contributions can be approximated in the soft limit



$\sim$



$$\sim \int [dk] \left(J^{(13)}_{\text{eik}}(k) \right)^2 \times$$

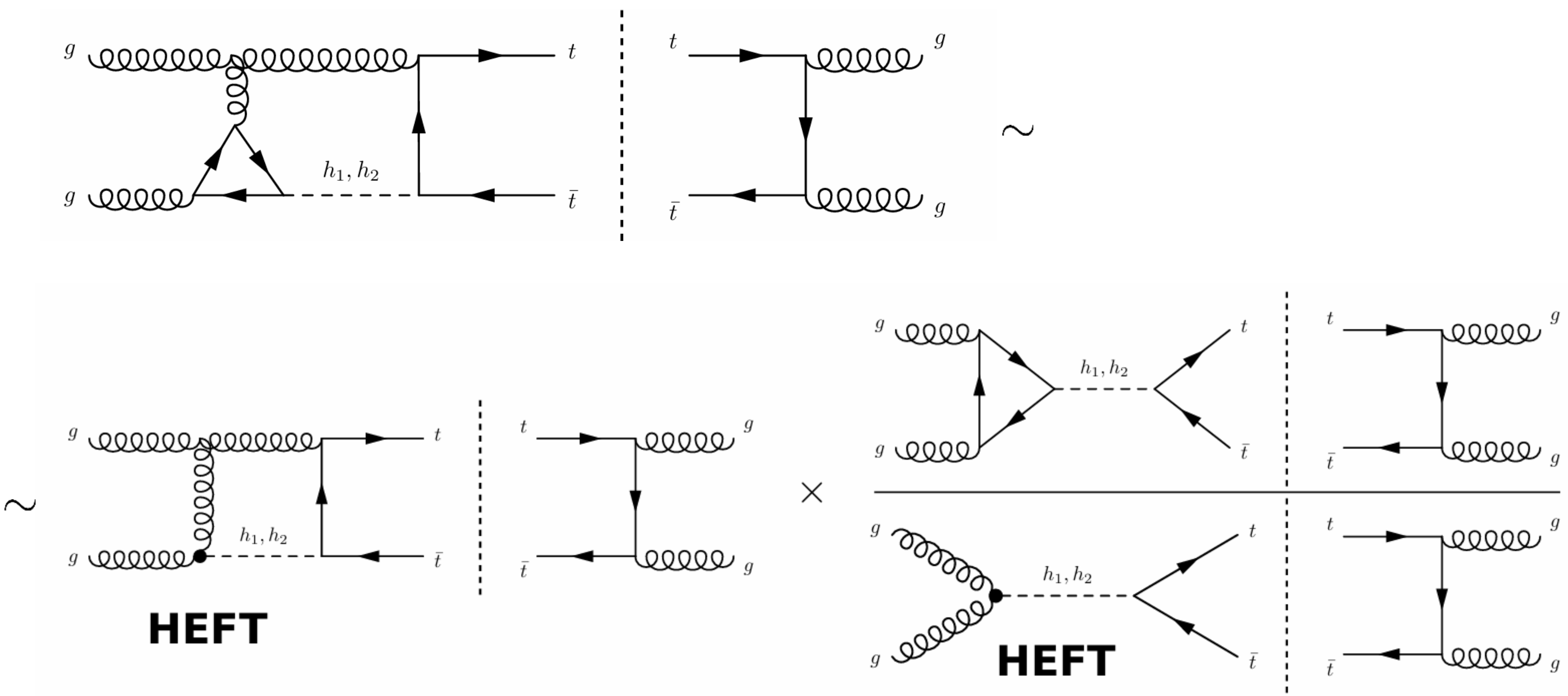
IR divergences must cancel against integrated countertems, as per the famous NLO formula

$$\sigma_{\text{NLO}} = \underbrace{\int_m d\sigma_B}_{\sigma_{\text{LO}}}$$

$$+ \int_{m+1} \Big[d\sigma_R - \underbrace{d\sigma_B \otimes \mathbf{V}}_{\text{local counterterms}} \Big] + \int_m \Big[d\sigma_V + d\sigma_B \otimes \underbrace{\int_1 \mathbf{V}}_{\text{integrated counterterms}} \Big]$$

Non-factorisable corrections

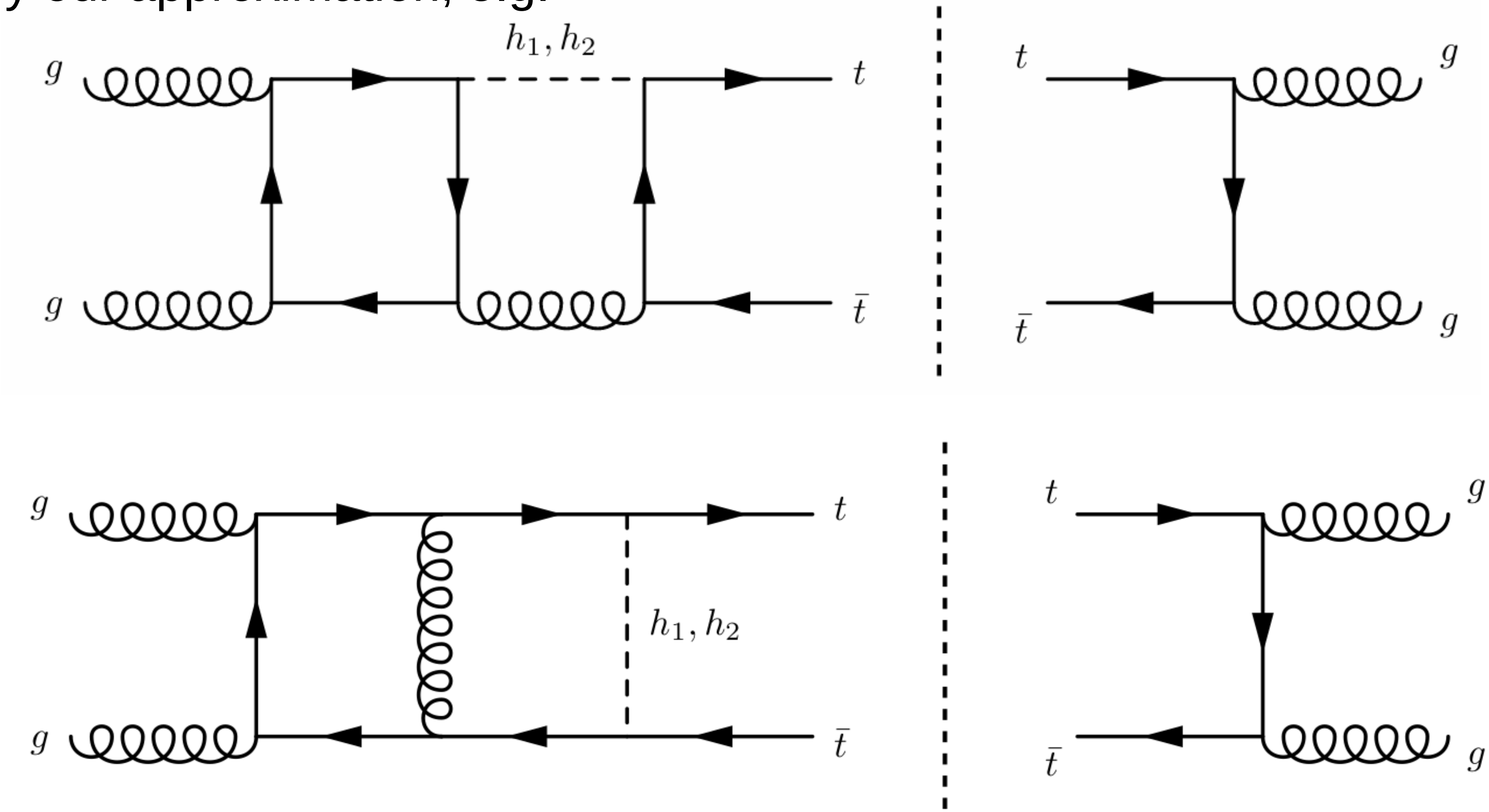
The soft limit of non-factorisable corrections is preserved by the approximation below



IR divergences are correctly cancelled against the integrated counterterms

Non-factorisable corrections

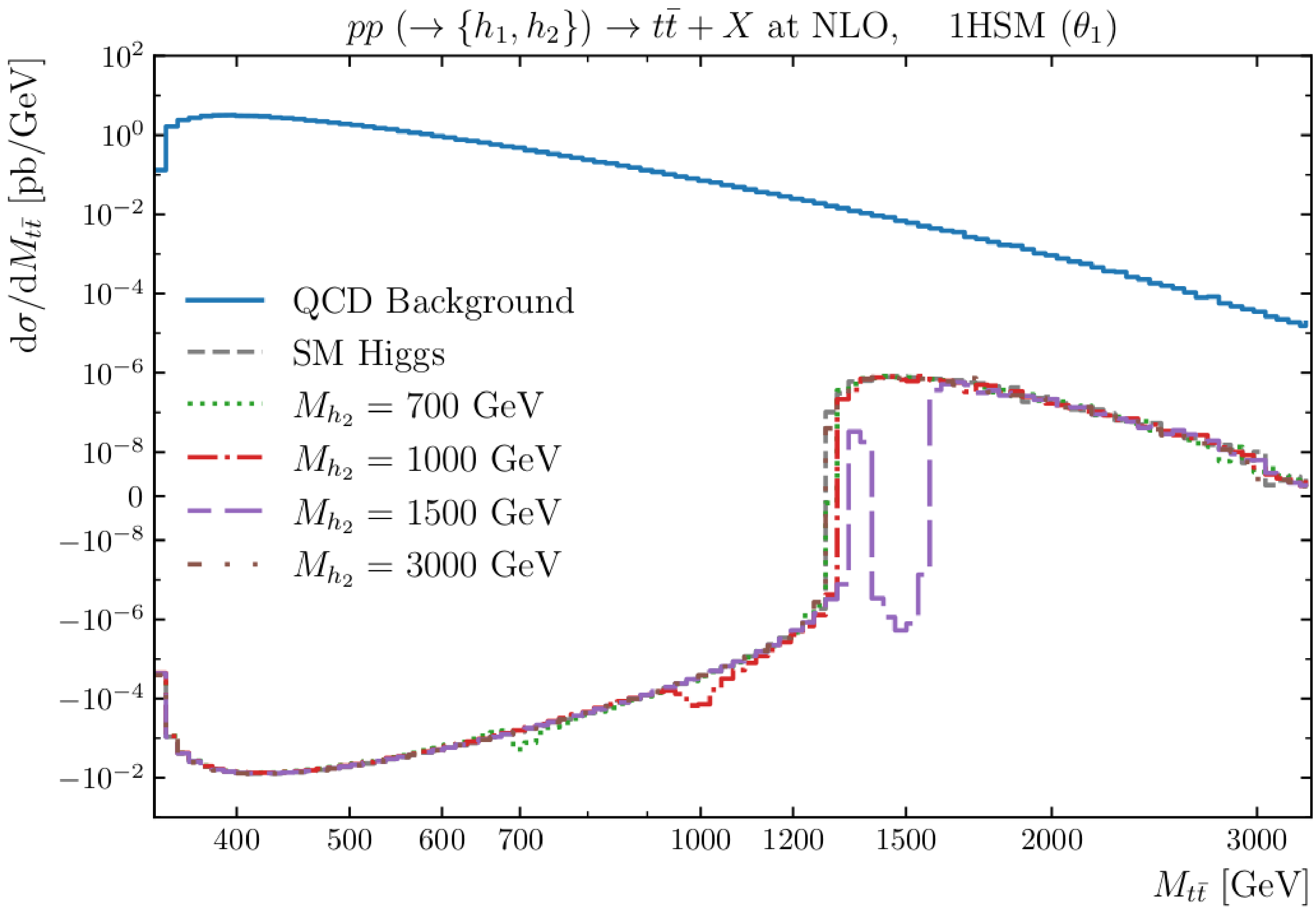
There are non-singular non-factorisable corrections that are not captured by our approximation, e.g.



These contributions are beyond today’s two-loop technology and require dedicated studies exploiting suitable approximations

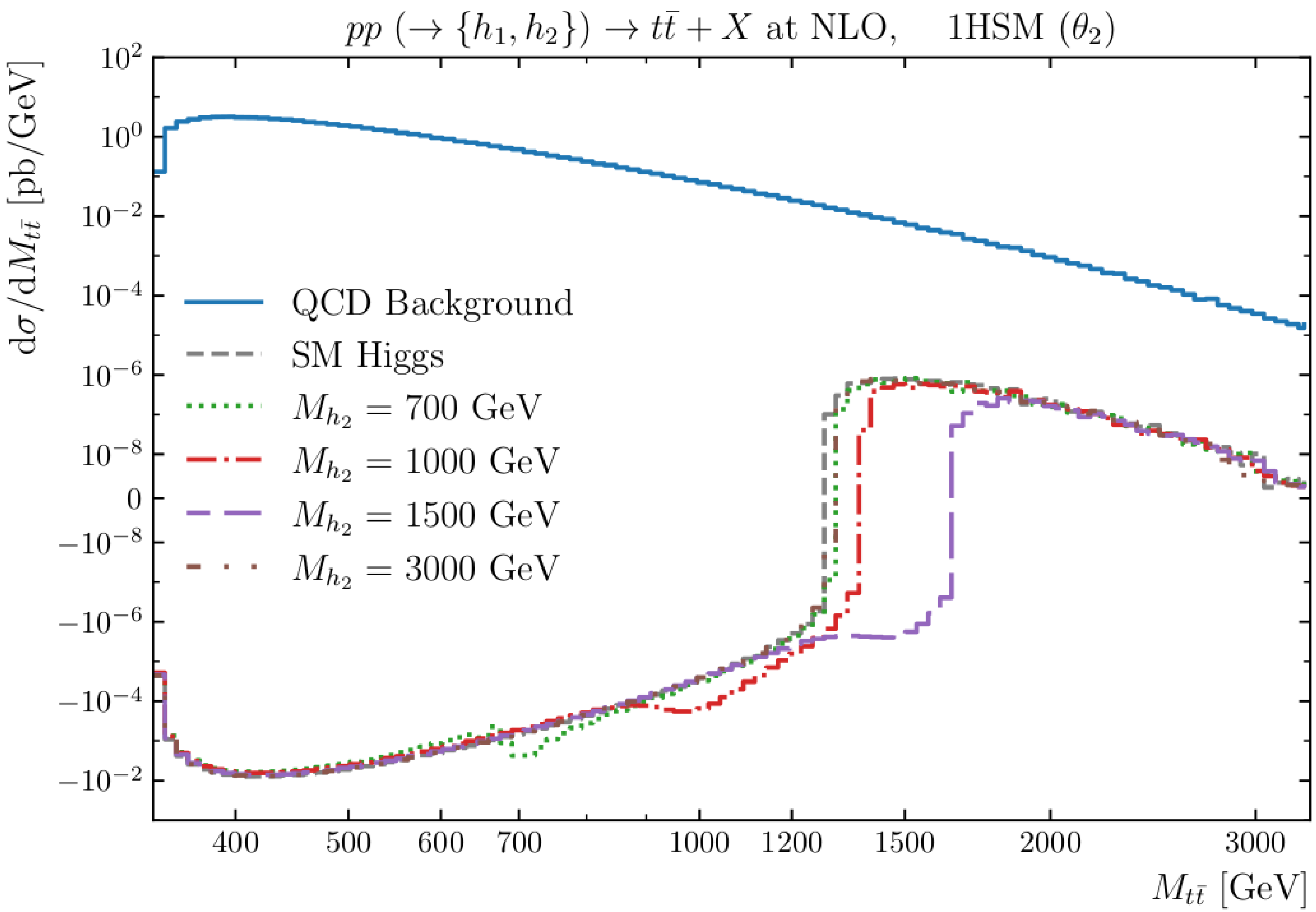
Differential distributions

Benchmark scenarios with $\theta = \theta_1$



Differential distributions

Benchmark scenarios with $\theta = \theta_2$

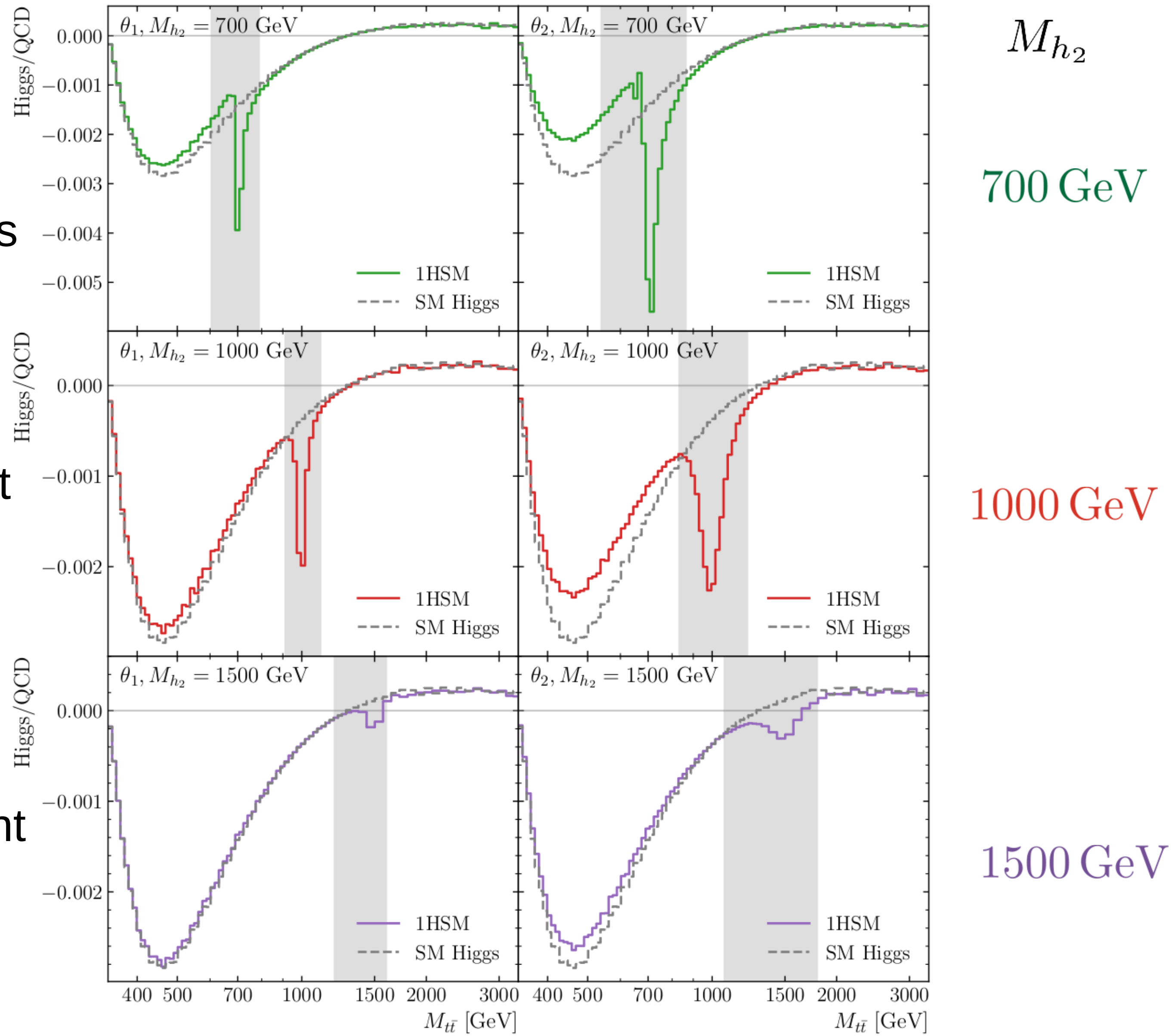


Impact of BSM effects

Peak-dip structure in all BSM scenarios

Small deviations, at most at 0.5% level

Grey band: invariant mass window for sensitivity studies



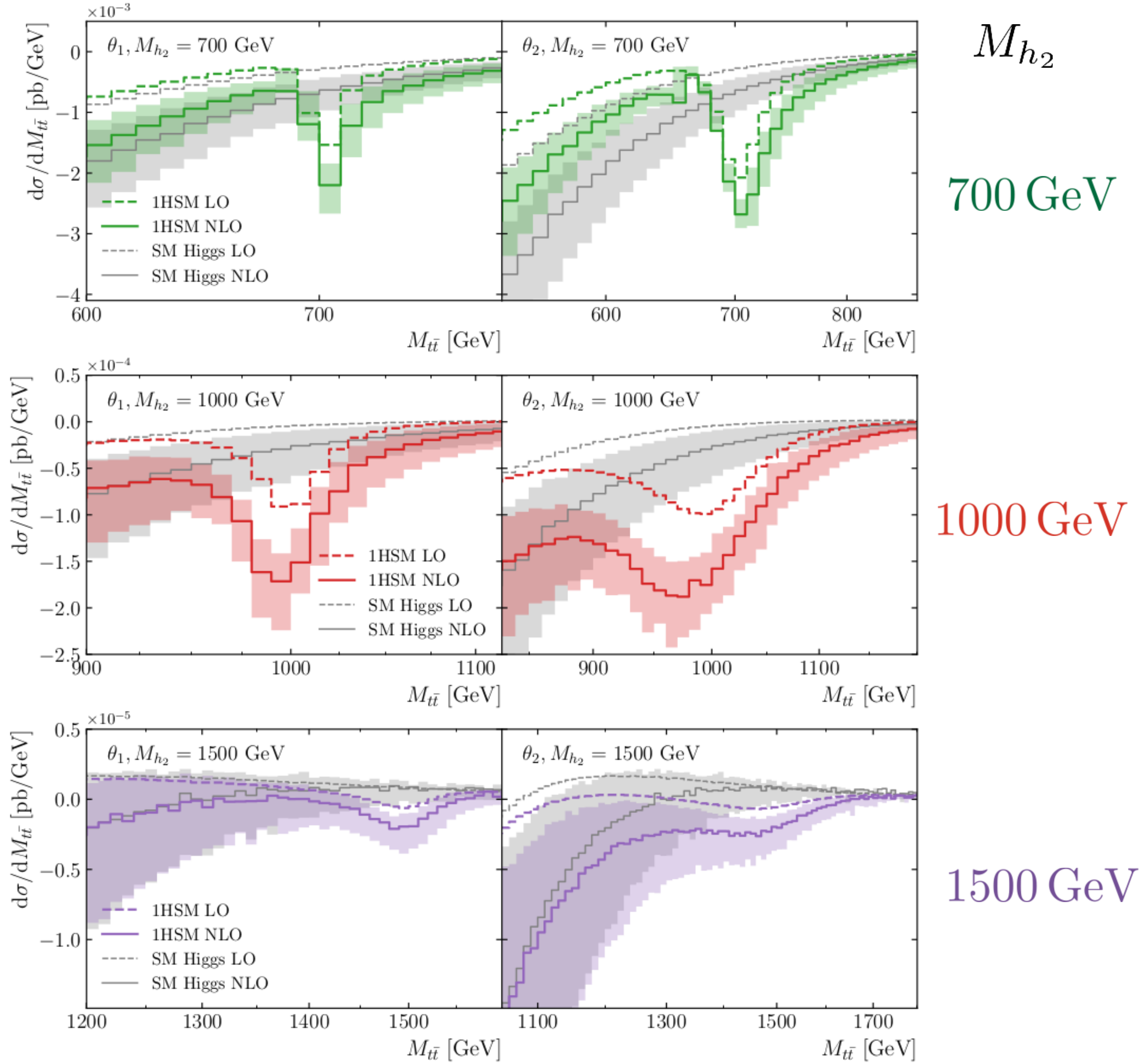
Impact of BSM effects

LO vs NLO: note large K-factors

Zooming in at the mass window

Estimation of theory uncertainties

- 7-scale variations
- 20-30%@NLO



Sensitivity estimates to BSM effects

Naïve estimate for the significance from Poisson statistcs

$$\frac{|S|}{\sqrt{B}} = \sqrt{\mathcal{L}}\,\frac{\sigma_{\text{interf}} + \sigma_{\text{Higgs}}}{\sigma_{\text{QCD}}}$$

Improvement considering

- fully leptonic top decays
- estimate of systematic uncertainties

[Snowmass White Paper 2205.02140]

Exclusion limit: $\frac{|S|}{\sqrt{B}}\,\frac{\Delta\sigma_{\text{stat}}}{\Delta\sigma_{\text{tot}}}\sqrt{\text{BR}_{2\ell 2\ell'}} > 2$

	M_{h_2} [GeV]	invariant mass window	$\lvert S\rvert/(\sqrt{B}\,\Delta\sigma_{\text{tot}}/\Delta\sigma_{\text{stat}})\sqrt{\text{BR}_{2\ell 2\ell'}}$ Run 2	Run 3	HL-LHC
θ_1	700	600–790 GeV	0.66(3)	0.97(5)	**3.1(2)**
	1000	900–1115 GeV	0.186(1)	0.274(2)	0.866(5)
	1500	1200–1600 GeV	–	–	–
θ_2	1500	1050–1800 GeV	–	–	–

PRELIMINARY

Conclusions

- A heavy Higgs decaying into a top-antitop pair interferes with QCD induced top-antitop production
- This interference can induce a peak-dip structure in top quark differential distributions
- We have constructed a framework to compute such effects at NLO QCD
- In the 1HSM, BSM effects are small and point to the need for dedicated cut-based or BDT analysis, including top decays

Outlook

- Top decays using POWHEG $\Rightarrow$ improved sensitivity studies
- CP-odd Higgs
- Full explorations of models with additional scalars, e.g. 2HDM

Extra slides

Form factors for $\mathbf{gg} \rightarrow \mathbf{H}$

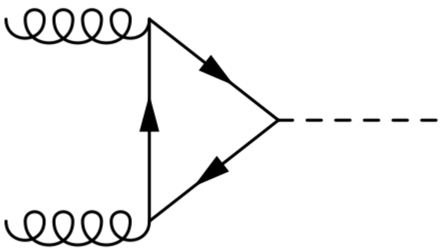
Coupling of a Higgs to two on-shell gluons of momenta q_1, q_2

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

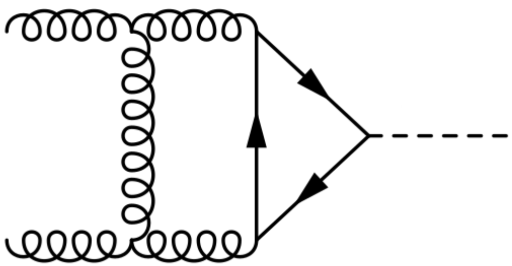
The form factor F has a series expansion in powers of α_s

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

F_1 :



F_2 :



One-loop form factor in terms of $\tau_q \equiv (q_1 \cdot q_2)/(2m_q^2)$

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

Form factors for $\mathbf{gg \to H}$

Two-loop form factor in $4-2\epsilon$ dimensions

$$F_2 = \left(\frac{4\pi\mu_R^2}{-2(q_1\cdot q_2)-i0}\right)^{\epsilon}\frac{1}{\Gamma(1-\epsilon)}\times$$
$$\times\left\{-\left(\frac{C_A}{\epsilon^2}+\frac{\beta_0}{\epsilon}+\beta_0\ln\left(\frac{2(q_1\cdot q_2)}{\mu_R^2}\right)+\mathcal{H}\right)F_1\right\}$$

[Aglietti Bonciani Degrassi Vicini hep-ph/0611266]