Phenomenology of Higgs Bosons in QCD at the LHC

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Subatech

A first project…

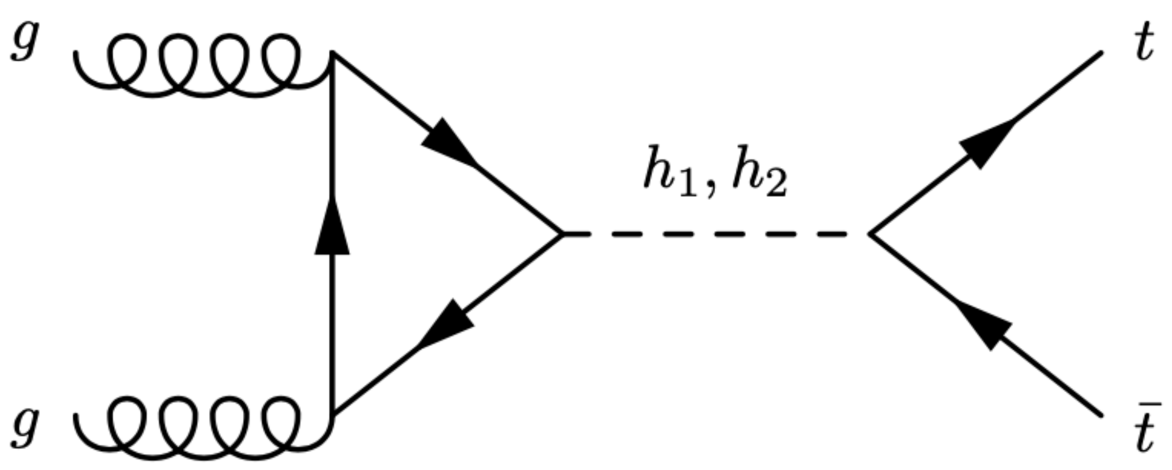
Higgs interference effects in top pair production at NLO QCD

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

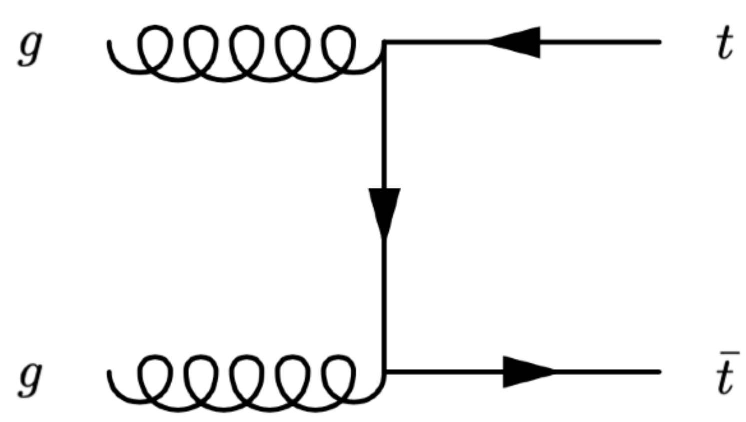
Process of Interest

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

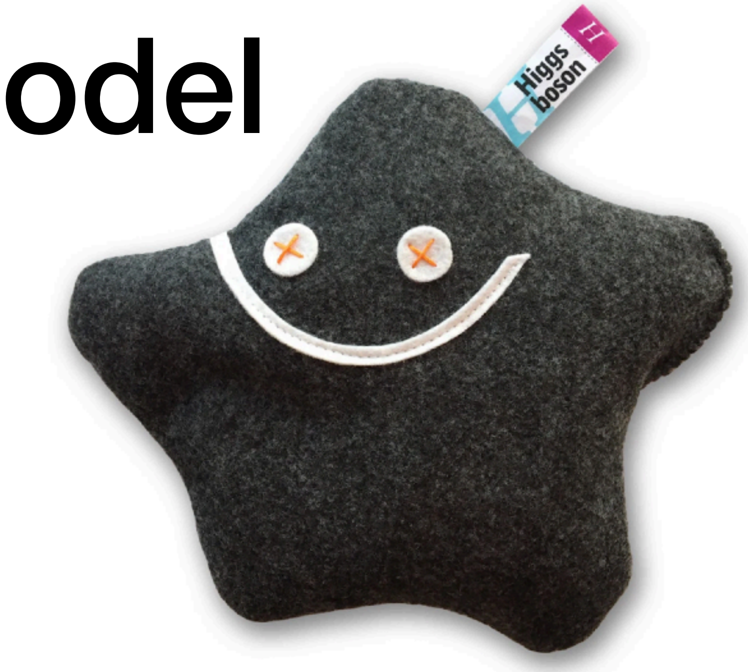
Higgs signal



QCD background



The 1-Higgs-Singlet model



Add a real singlet scalar field

Potential after EW symmetry breaking:

$$V = \frac{\lambda}{4}H^4 + \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \frac{\lambda_2}{2}H^2 s^2 + \lambda_2 v H s^2 + \mu_1 s^3 + \frac{\mu_2}{2}H^2 s + \mu_2 v H s$$

Mixing:

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

Free parameters:
M_{h_2}, θ

$$M_{h_1} = 125 \text{ GeV}$$

$$\mu_1 = \lambda_1 = \lambda_2 = 0$$

8 benchmark points:

M_{h_2} [GeV]	700	1000	1500	3000
θ_1	$\pi/15$ ≈ 0.21	$\pi/15$ ≈ 0.21	$\pi/22$ ≈ 0.14	$\pi/45$ ≈ 0.07
θ_2	$\pi/8$ ≈ 0.39	$\pi/8$ ≈ 0.39	$\pi/12$ ≈ 0.26	$\pi/24$ ≈ 0.13

NLO QCD

NLO necessary for most processes — in particular Higgs production

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

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

Infrared (soft/collinear) divergences
Subtraction of dipoles
(Catani-Seymour)

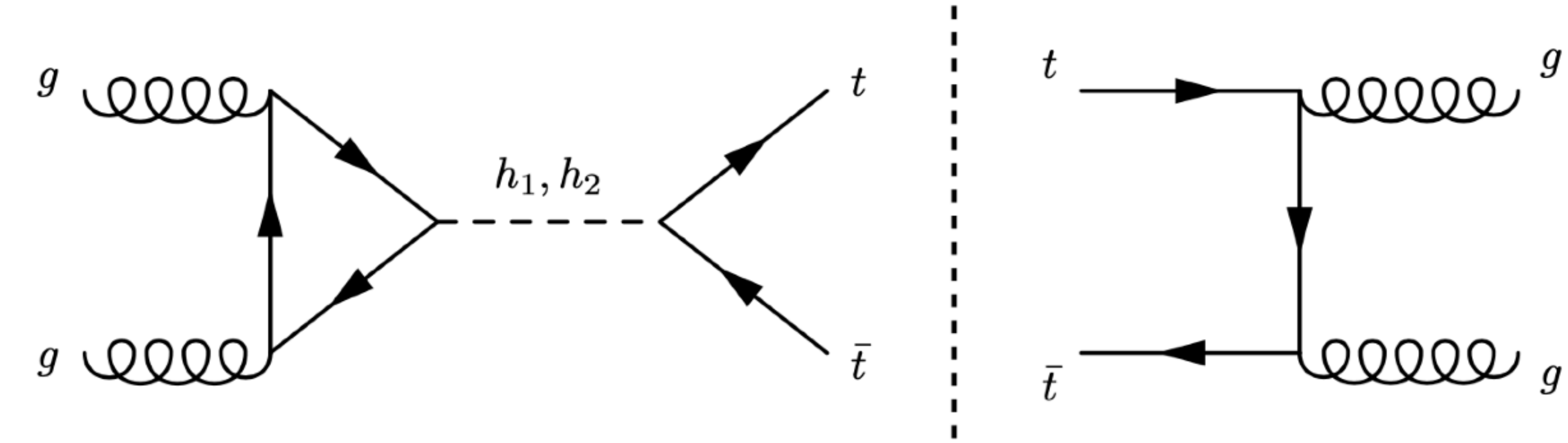
$$\sigma_{\mathrm{LO}} = \int_m \mathrm{d}\sigma_B$$
$$\sigma_{\mathrm{NLO}} = \sigma_{\mathrm{LO}} + \int_m \left[\mathrm{d}\sigma_V + \mathrm{d}\sigma_B \otimes \mathbf{I}\right] + \int_{m+1} \left[\mathrm{d}\sigma_R - \sum_{\mathrm{dipoles}} \mathrm{d}\sigma_B \otimes V\right]$$

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

Gap in current event generator landscape: Loop-induced x tree interference at NLO

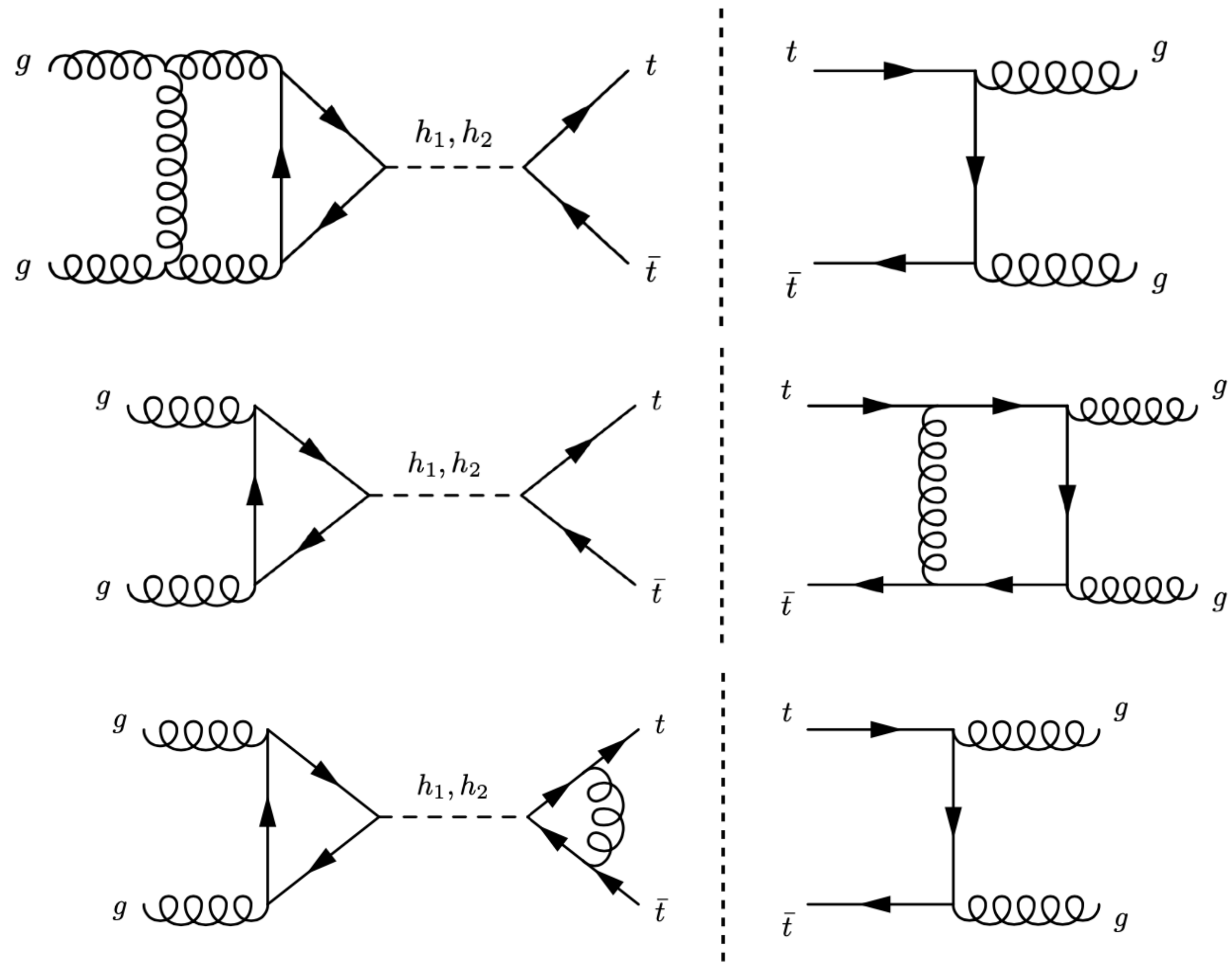
NLO QCD Corrections to Interference

LO



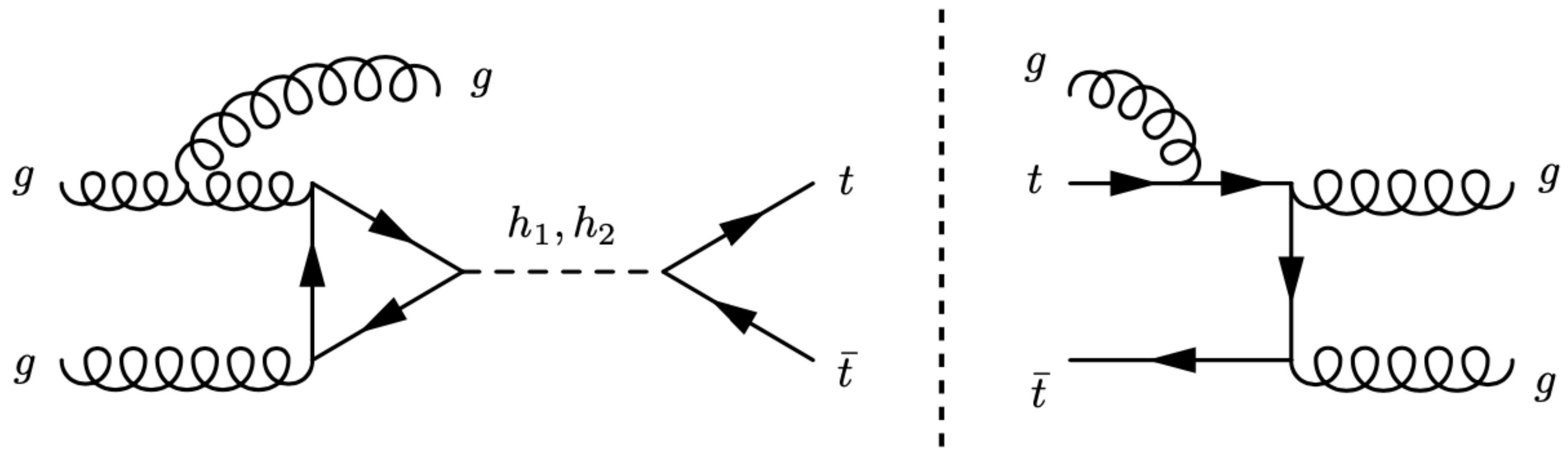
NLO

Virtual Contributions

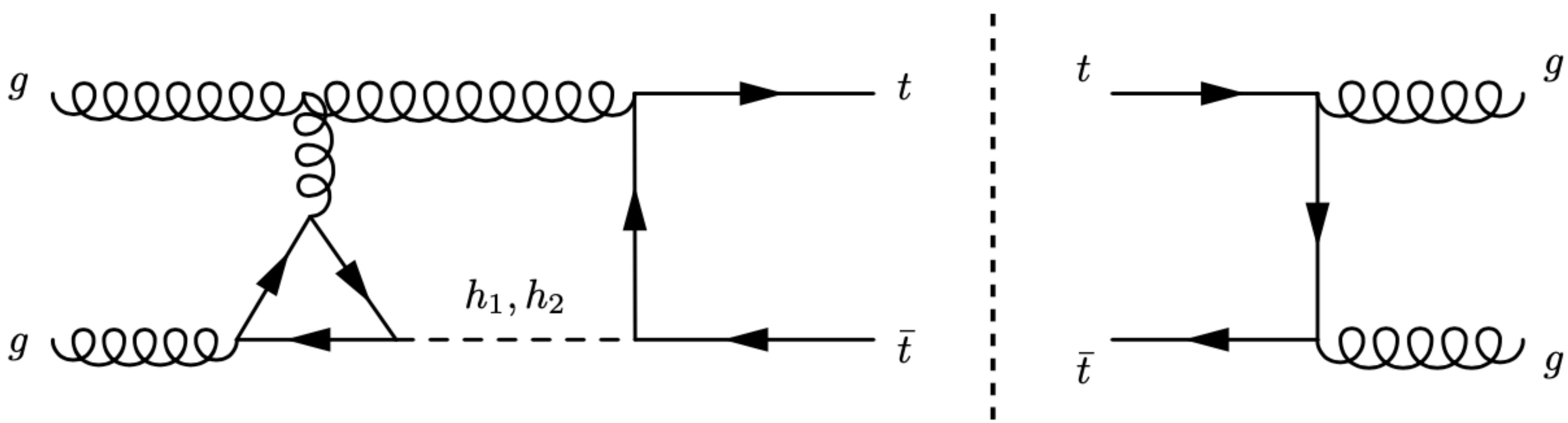


Non-Factorisable Corrections

IR divergent non-factorisable **real** contribution

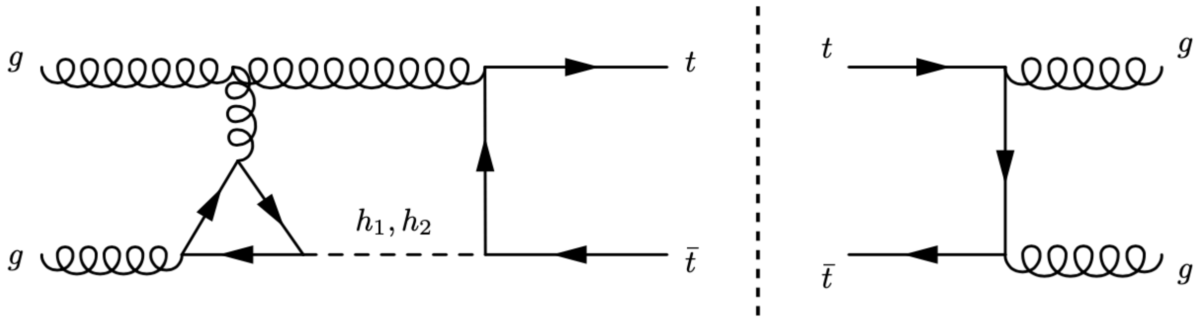


IR divergent non-factorisable **virtual** contribution

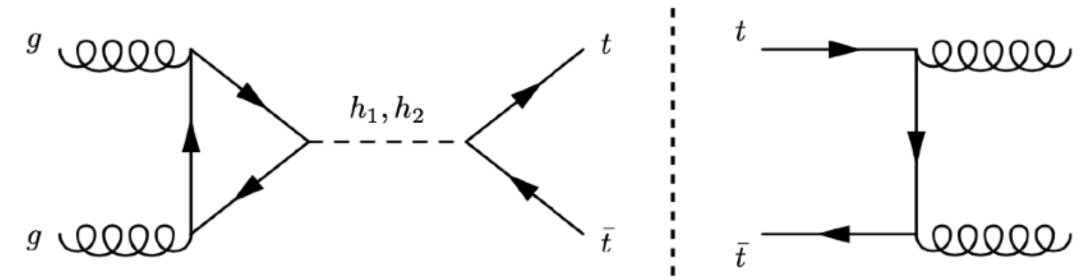


Non-Factorisable Corrections

However, in the soft limit:

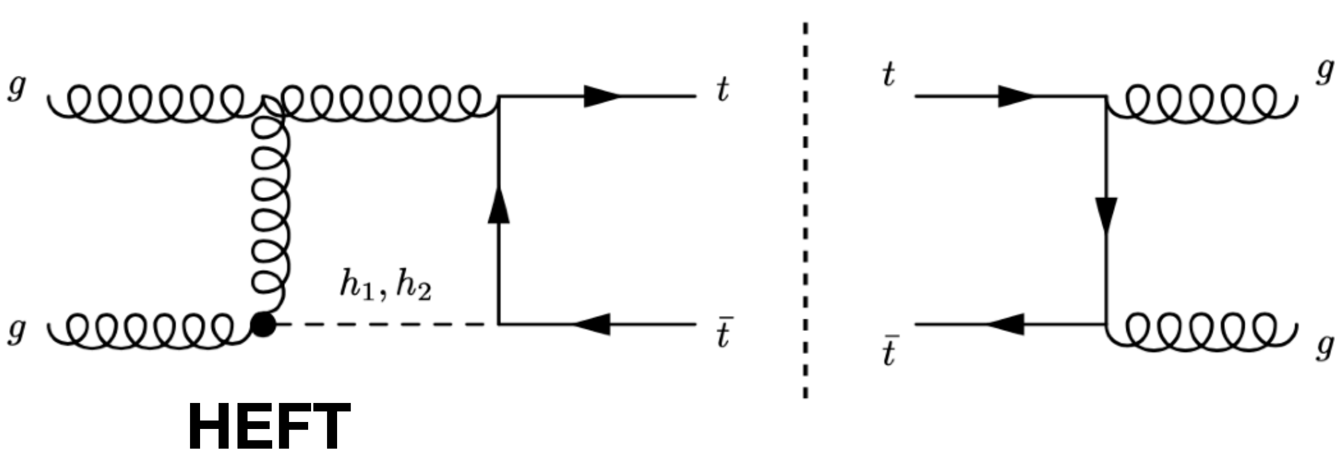


$= C \times$

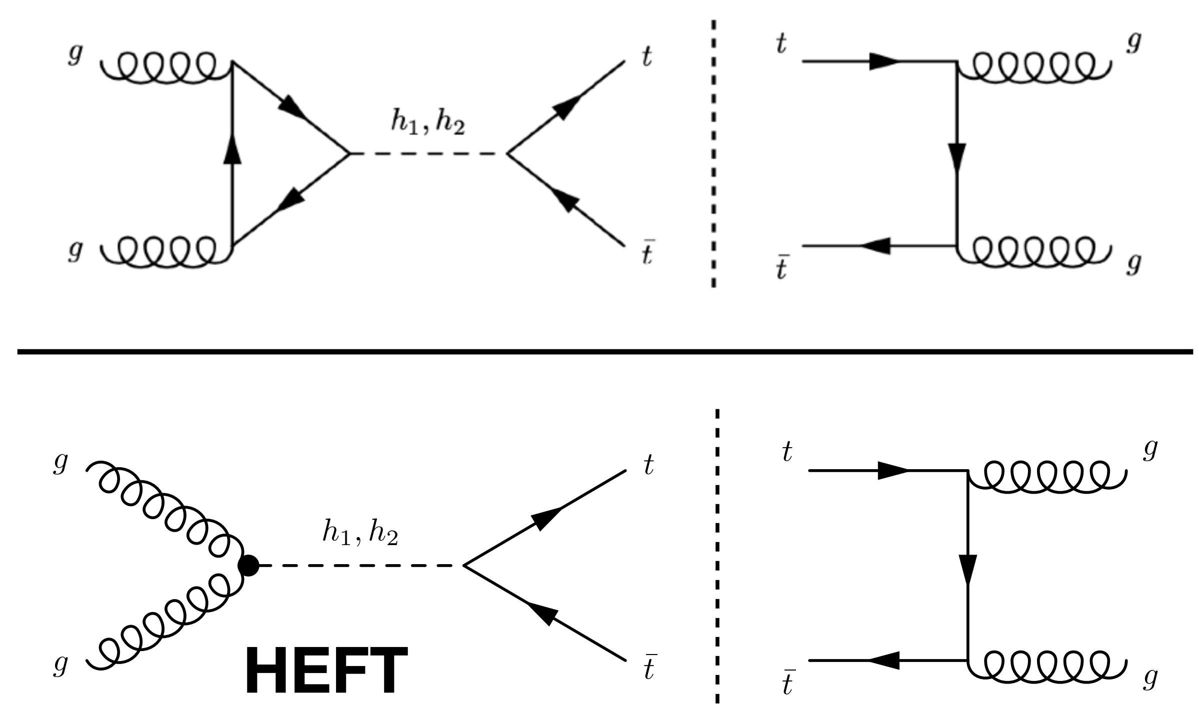


Singular term

Reweighting:



$\times$



HELAC+OpenLoops

Need to develop our own NLO Monte Carlo framework

But no need to reinvent the wheel

→

Kaleu: Phase space generation

HELAC: Dipole subtraction

OpenLoops: Tree and loop amplitudes

Modified OpenLoops with:

- Form factor interface for $gg \to H$

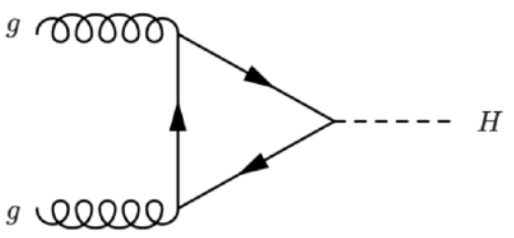
$$F = F_1 + \frac{\alpha_s}{\pi} F_2 + \mathcal{O}(\alpha_s^2)$$

$$F_2 = \frac{1}{2} F_1 \left[\mathrm{Re}\,(\mathcal{H}) + \frac{C_A}{2}\pi^2 - \frac{C_A}{2} \ln^2\left(\frac{m_H^2}{\mu_R^2}\right) \right]$$

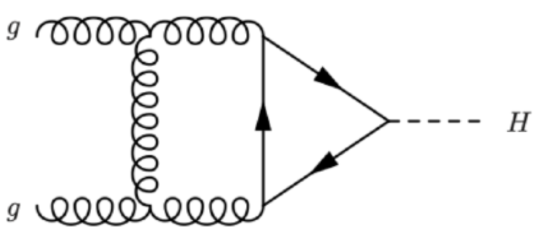
- BSM extensions
- Interface to get colour correlated helicity amplitudes:

$$\mathrm{d}\sigma_B \sim \langle \mathcal{M}_B | \mathcal{M}_B \rangle$$

$$\mathcal{D}_{ij,k} \sim \langle \mathcal{M}_B | \frac{\mathbf{T}_k \cdot \mathbf{T}_{ij}}{\mathbf{T}_{ij}^2} \mathbf{V}_{ij,k} | \mathcal{M}_B \rangle$$



(a) One-loop contribution.



(b) Two-loop contribution.

Results

Integrated cross-sections

SM

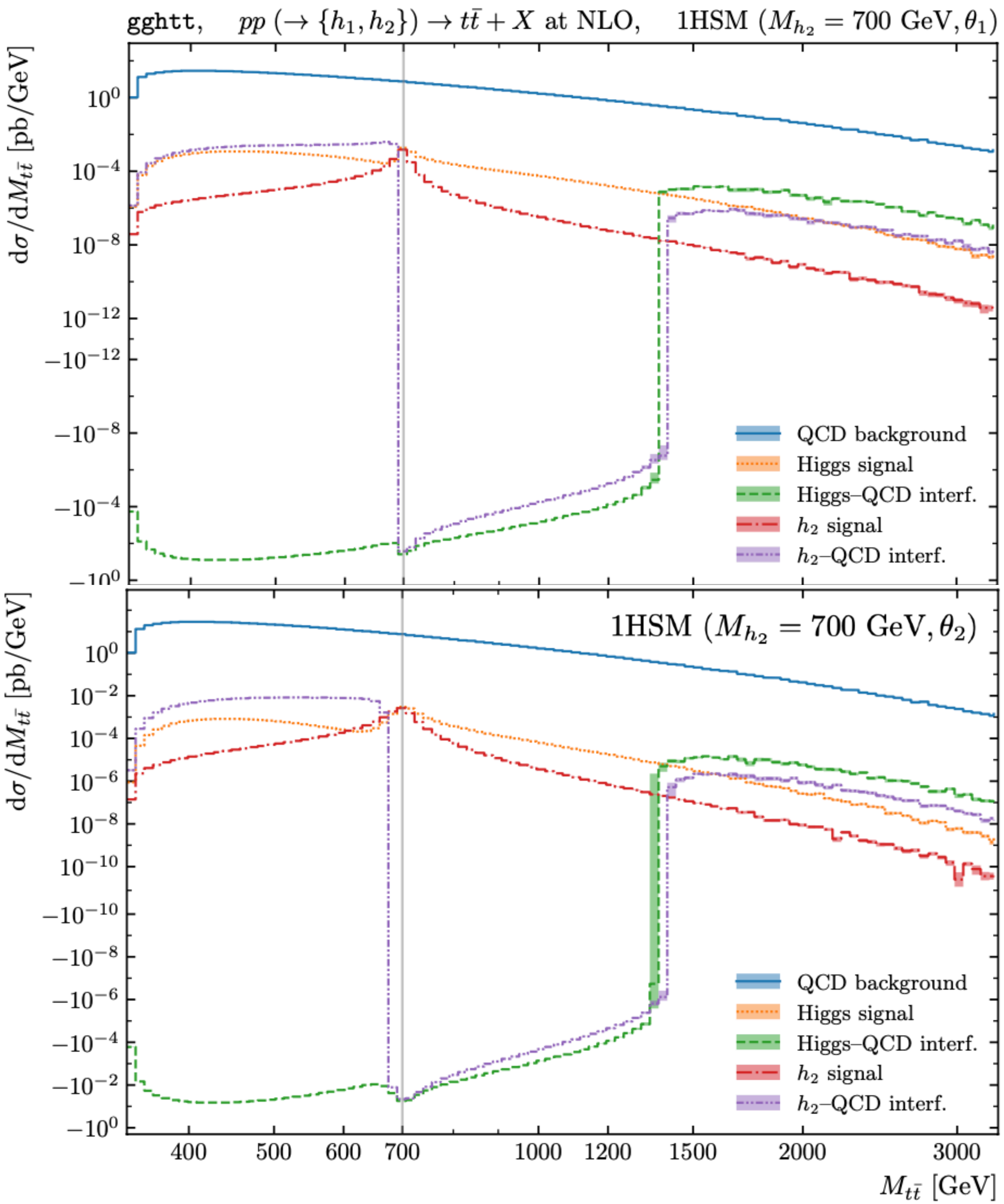
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the SM, pp, $\sqrt{s} = 13$ TeV					
Higgs signal		QCD background		Interference	
σ_{NLO} [pb]	K	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
0.030971(3)	1.6512(2)	675.23(4)	1.5965(1)	−1.5865(2)	2.1807(2)

1HSM

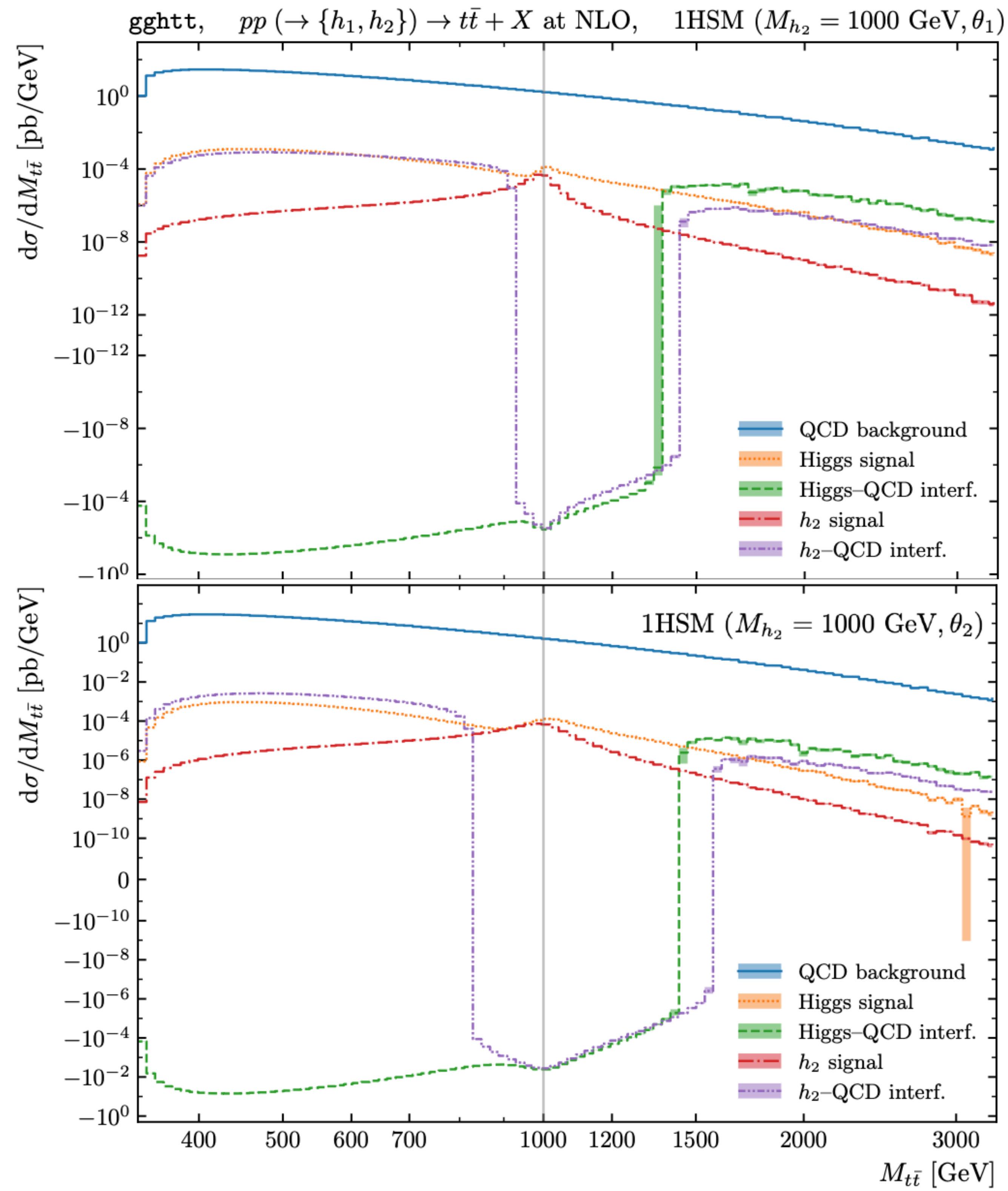
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM, pp, $\sqrt{s} = 13$ TeV					
		Higgs signal		Higgs–QCD interference	
	M_{h_2} [GeV]	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
θ_1	700	0.029108(2)	1.6234(2)	−1.5169(2)	2.1743(3)
	1000	0.027334(2)	1.6459(2)	−1.49132(9)	2.1579(2)
	1500	0.029932(3)	1.6745(2)	−1.5601(2)	2.1926(2)
	3000	0.030933(3)	1.6661(2)	−1.5724(1)	2.1719(2)
θ_2	700	0.027231(2)	1.5689(2)	−1.3487(2)	2.1383(3)
	1000	0.020114(2)	1.6442(2)	−1.30744(8)	2.1458(2)
	1500	0.026519(2)	1.6617(2)	−1.4796(2)	2.1903(2)
	3000	0.029772(2)	1.6452(2)	−1.5673(2)	2.1924(2)

Results

700 GeV

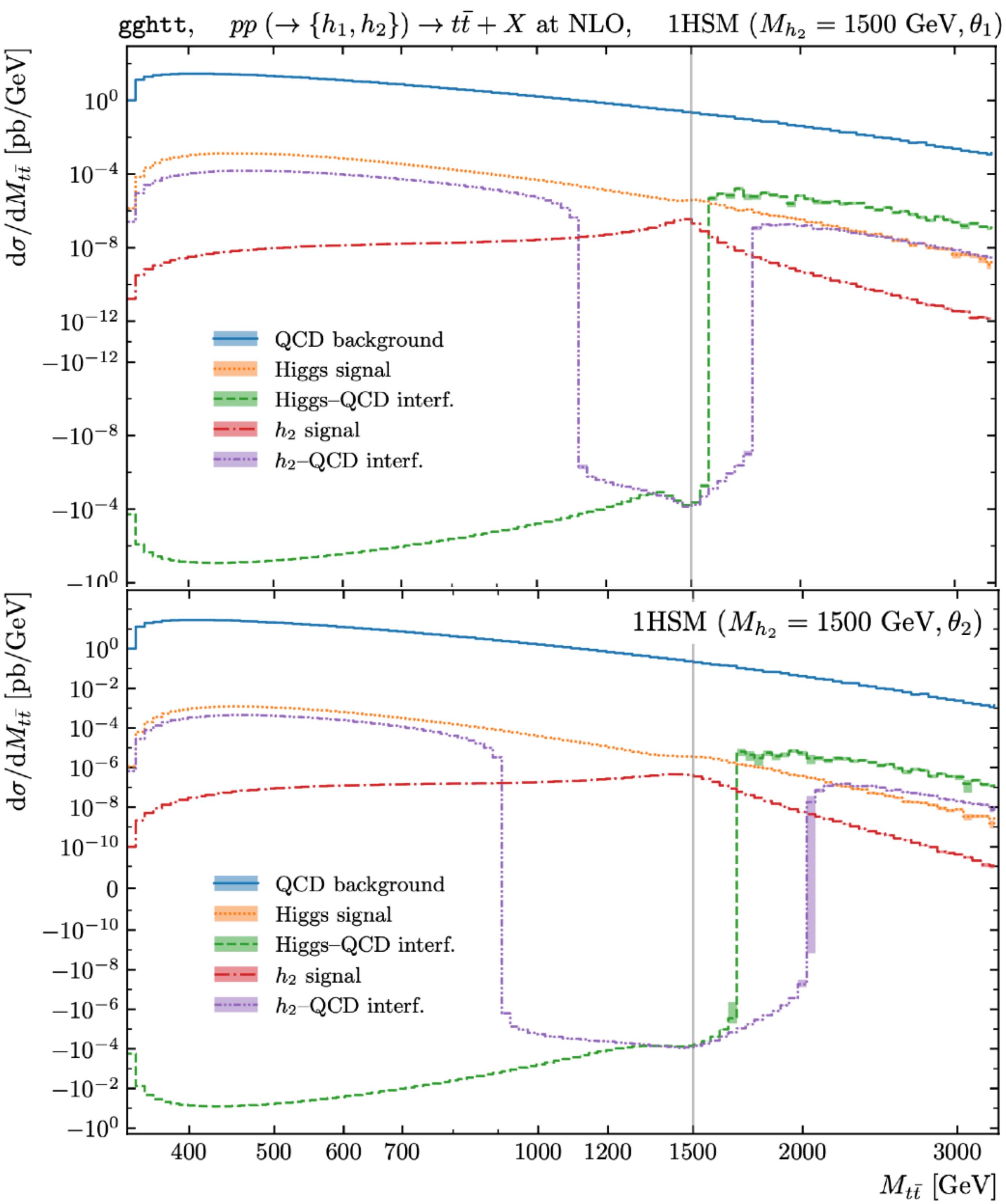


1 TeV

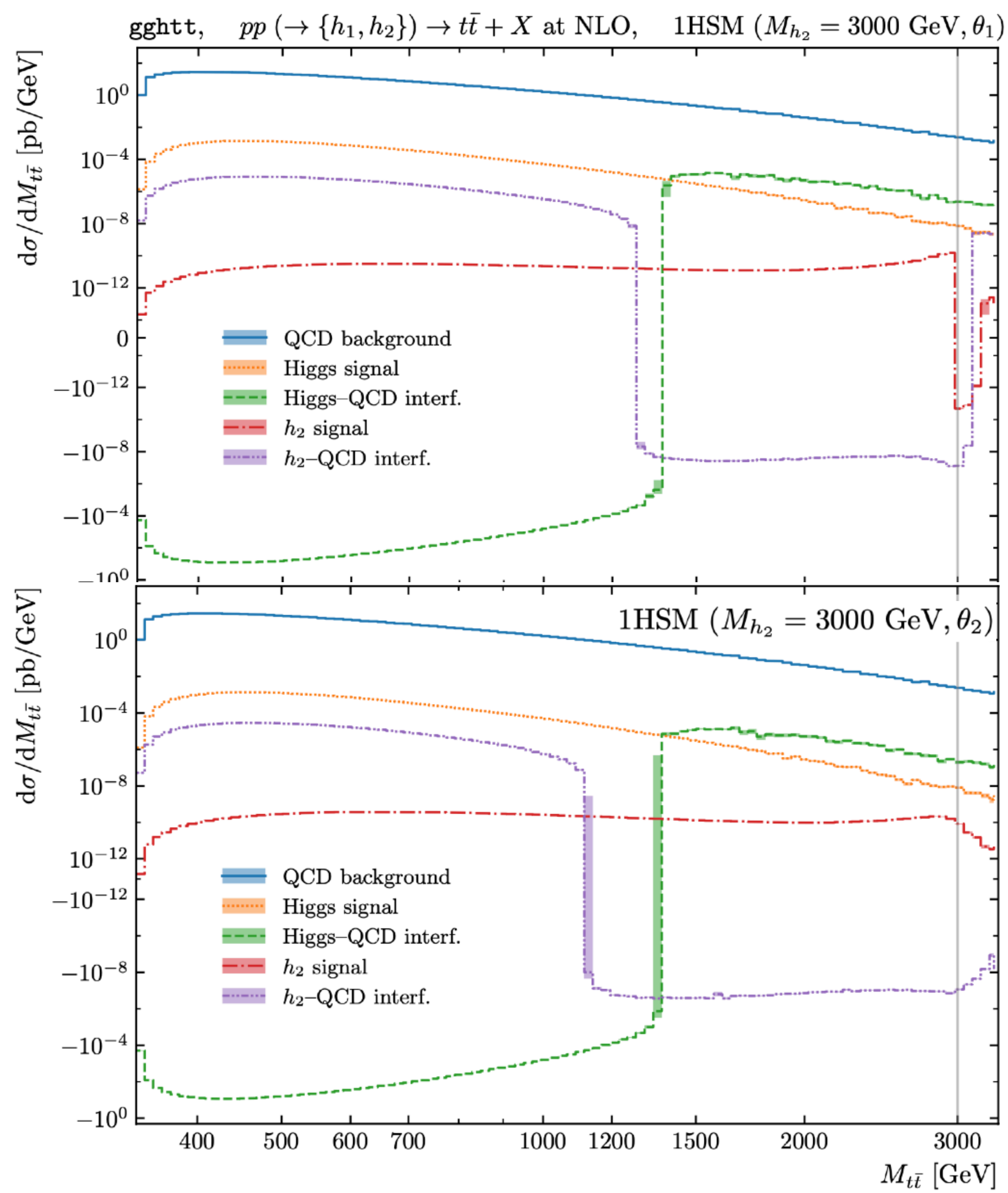


Results

1.5 TeV



3 TeV



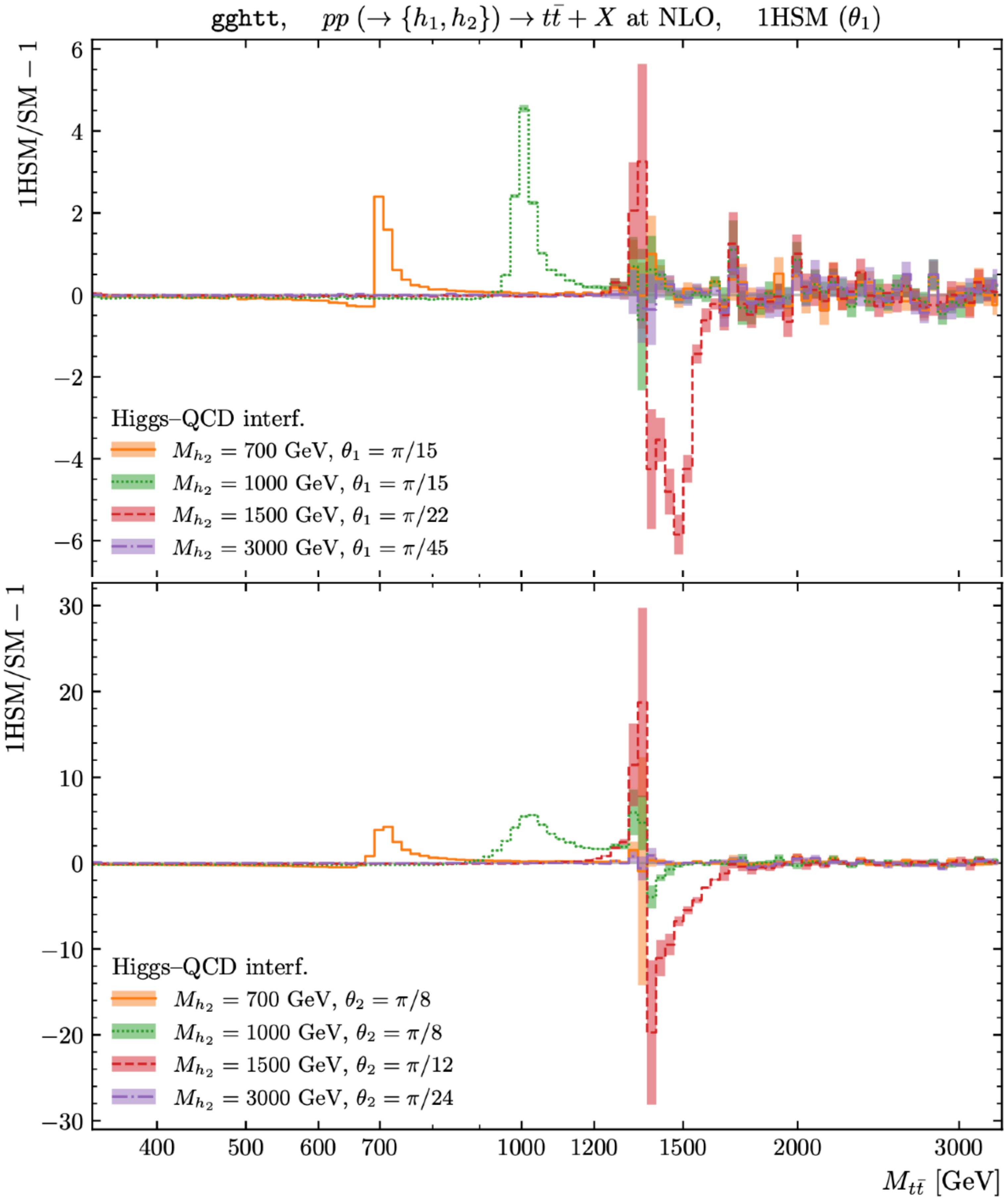
Results

Observed dip structures around heavy resonance mass when considering the 1HSM

Consider mass windows around dips

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

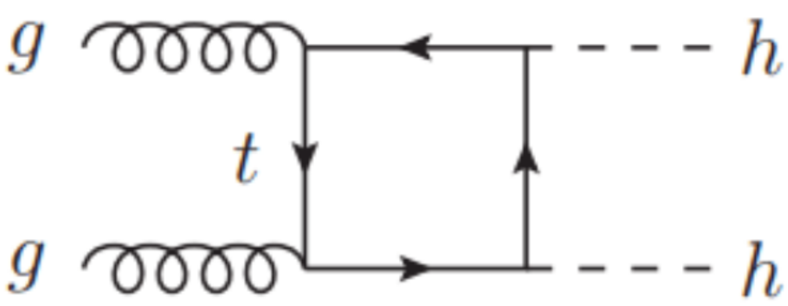
	M_{h_2} [GeV]	Invariant mass window	Excludable Run 2	Run 3	HL-LHC
θ_1	700	600–790 GeV	✓	✓	✓
	1000	900–1115 GeV	–	–	✓
	1500	1200–1600 GeV	–	–	–
	3000	2500–3340 GeV	–	–	–
θ_2	700	530–870 GeV	✓	✓	✓
	1000	830–1200 GeV	–	✓	✓
	1500	1050–1800 GeV	–	–	–
	3000	2100–3340 GeV	–	–	–

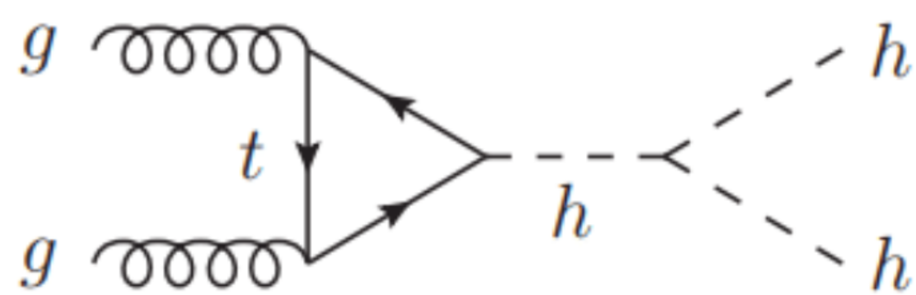


Generalisation

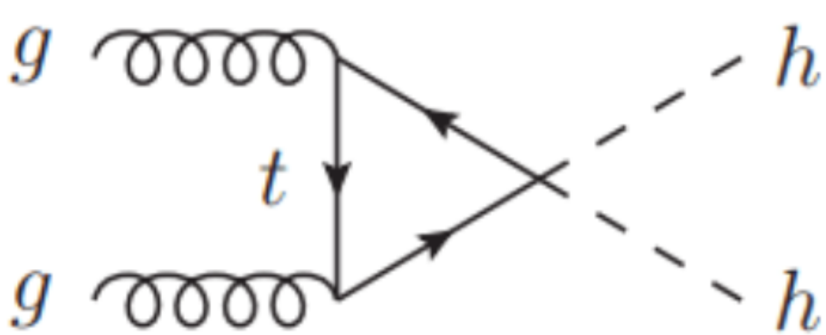
The code be generalised to work for any loop-induced process

Double Higgs production

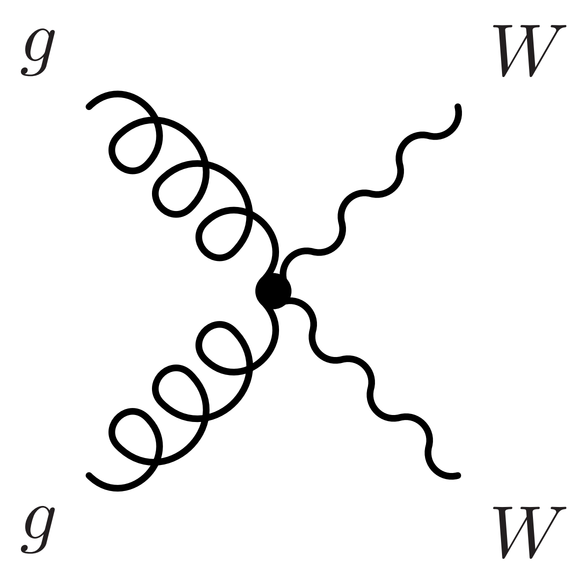




Effective field theories



dim-6



dim-8

Summary

- We studied the interference of a heavy Higgs with the continuum QCD background at NLO QCD

- This is loop-induced x tree-level at LO and has a complicated structure at NLO

- This required a specially built Monte Carlo — which can now be used for other loop-induced processes

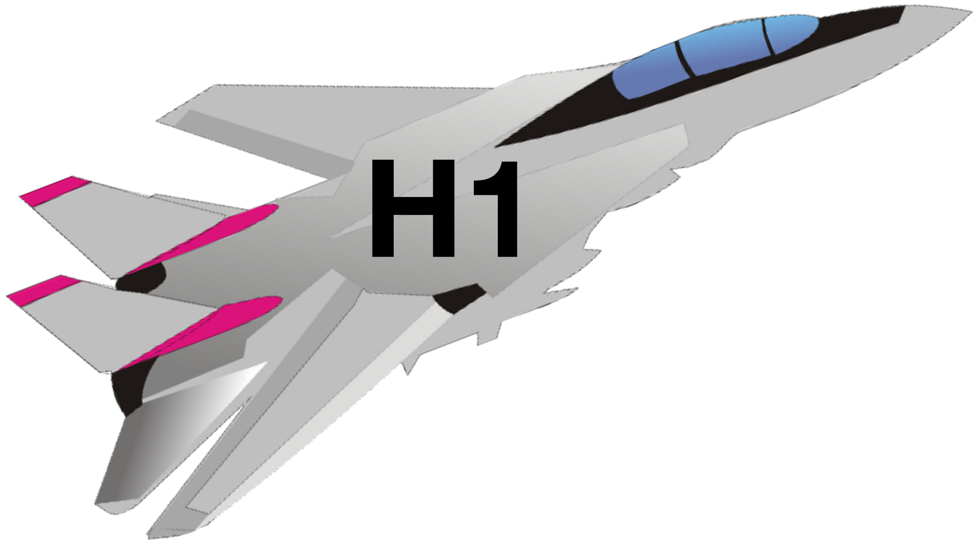
A second project…

H1JET

[arXiv:2011.04694 [hep-ph]](https://arxiv.org/abs/2011.04694)

with Andrea Banfi

h1jet.hepforge.org

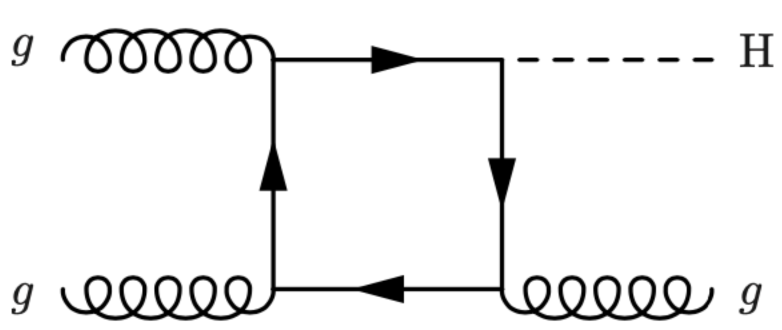


Motivation

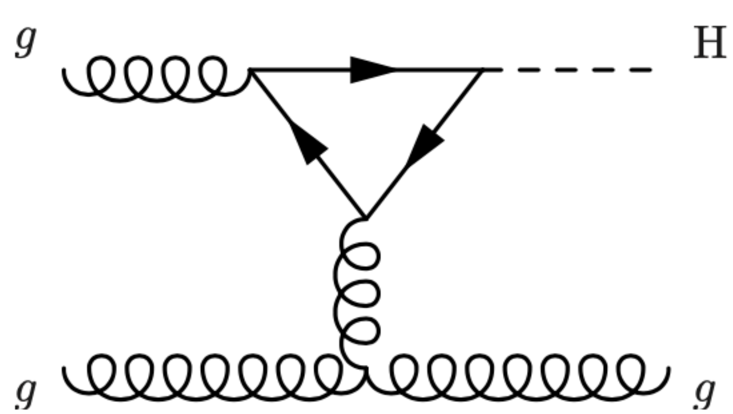
A fast and easy-to-use tool to compute transverse momentum distributions

$$\mathcal{L}_{\text{eff.}} \supset -\kappa_t \frac{m_t}{v} t\bar{t}H + \kappa_g \frac{\alpha_s}{12\pi} \frac{H}{v} G^a_{\mu\nu} G^{\mu\nu\, a}$$

$$\frac{\sigma(\kappa_t, \kappa_g)}{\sigma^{\text{SM}}} \propto (\kappa_t + \kappa_g)^2$$



(a) Box diagram.



(b) Triangle diagram.

Loops:
SM top + BSM top partner

The Method

$2 \to 1$ and $2 \to 2$ but can be extended

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \frac{p_T}{8\pi} \int_{-\eta_M}^{\eta_M} \mathrm{d}\eta \sum_{i,j} \left[\frac{M_{ij}^2\left(\hat{s}, \hat{t}, \hat{u}\right)}{E_X \hat{s}^{3/2}} \mathcal{L}_{ij}\left(\frac{\hat{s}}{s}, \mu_F\right) \right]$$

$$\eta_M = \ln\left(x_M + \sqrt{x_M^2 - 1}\right)$$

$$x_M = \frac{s - m_X^2}{2p_T\sqrt{s}}$$

$$\hat{s} = \left(p_T \cosh\eta + \sqrt{m_X^2 + p_T^2 \cosh^2\eta}\right)^2$$

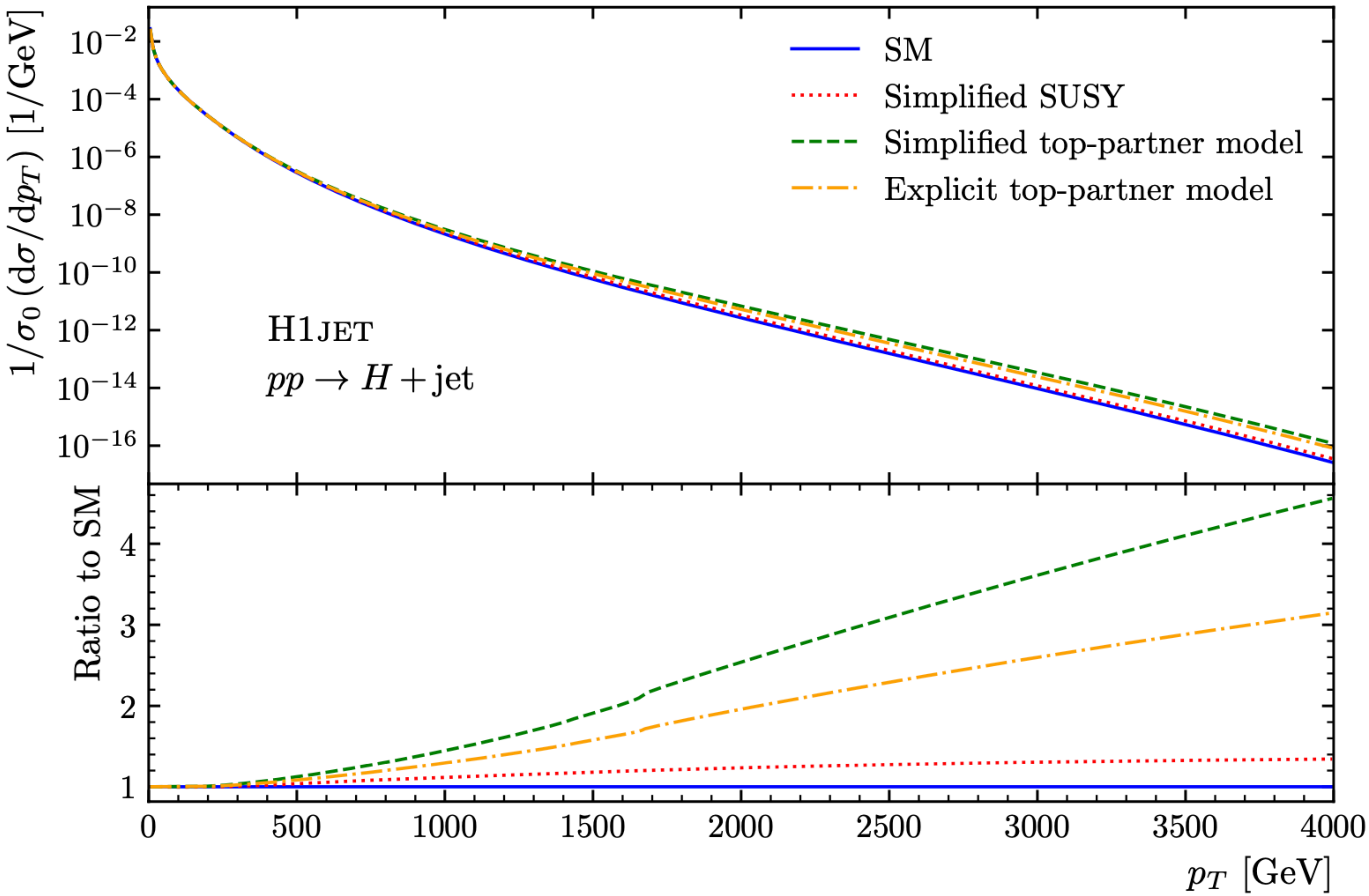
$$\hat{t} = -p_T e^{-\eta}\sqrt{\hat{s}}$$

$$\hat{u} = -p_T e^{\eta}\sqrt{\hat{s}}$$

1-dimensional integration done using adaptive Gaussian quadrature → super fast

Written in Fortran 95, interfaced with CHAPLIN and HOPPET

Built-In Models



Provided user-interface allows for
a custom process given a user-provided amplitude

$$|\mathcal{M}(\hat{s}, \hat{t}, \hat{u})|^2$$

h1jet.hepforge.org/online

H1jet Online

This is an online interface for H1jet, which allows you to run H1jet in your browser to quickly compute the total cross-section and differential transverse momentum distribution of a colour singlet.

See the manual or hover/click the tooltips ⓘ for more information on each parameter.

General Settings:

Process: pp/ppbar → H + jet ⓘ

Collider: pp ⓘ

Centre-of-mass energy, sqrt(s) [GeV]: 13000 ⓘ

Scale strategy: muR = muF = pT + sqrt(pT^2 + M^2) ⓘ

Factor for the renormalization scale, muR = muR * xmur: 0.5 ⓘ

Factor for the factorisation scale, muF = muF * xmuf: 0.5 ⓘ

PDF set: MSTW2008nlo68cl ⓘ

The desired integration accuracy: 0.001

Histogram Settings:

Number of histogram bins in the output: 100

☐ Enable logarithmic x-axis of histogram, i.e. logarithmic bins and pT

Minimum pT value [GeV]: 0

Maximum pT value [GeV]: 4000

Physics Parameters:

These parameters are process-dependent. Note that H1jet uses the Gmu scheme, so that the VEV is given by the Fermi coupling constant and the Weinberg angle by mW and mZ.

☐ Toggle for CP-odd Higgs

Higgs mass, mH [GeV]: 125

Z boson mass, mZ [GeV]: 91.1876

W boson mass, mW [GeV]: 80.385

Fermi coupling constant, G_F [GeV^(-2)]: 0.0000116638

Top quark mass, mt [GeV]: 173.5

On-shell bottom quark mass, mb [GeV]: 4.65

Top Yukawa factor, yt: 1

Bottom Yukawa factor, yb: 1

Additional Model Parameters:

Choose physics model: Standard Model ⓘ

No additional parameters necessary for the Standard Model.

☐ Do not reset graph, i.e. plot subsequent results in the same graph in order to compare results

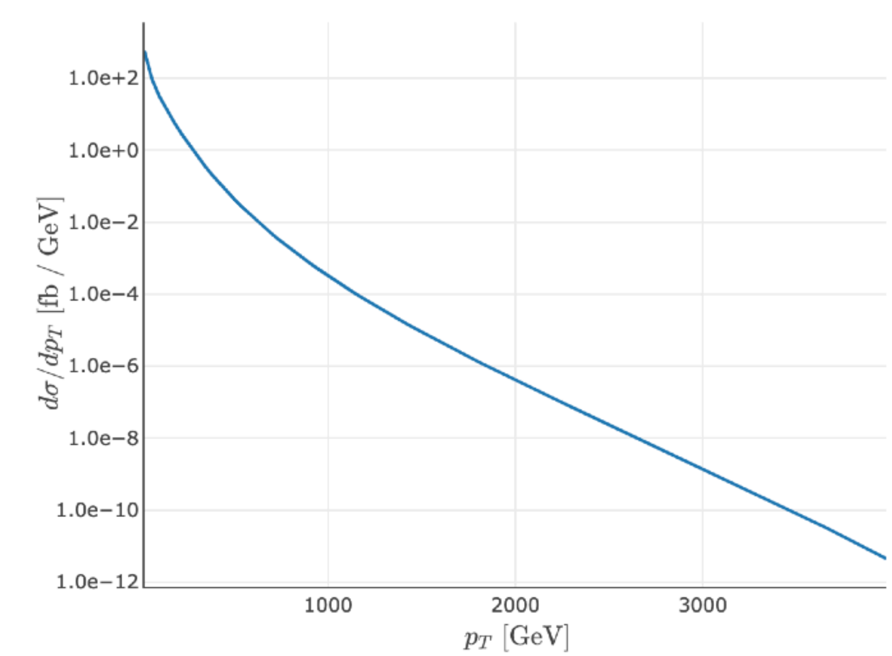
Run H1jet

Reset All Parameters

Copy Output to Clipboard

Output:

$\sigma_0 = 0.015163$ nb

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============================================================
H1jet version 1.0.0
Tool for the fast and accurate calculation of the pT
distribution in Higgs + jet production at hadron colliders

Written by Alexander Lind and Andrea Banfi
arXiv:2011.04694 [hep-ph]
============================================================

Provided command options:
# h1jet --proc H --collider pp --roots 13000 --scale_strategy HT --xmur 0.5 --xmuf 0.5 --pdf_

LHAPDF 6.3.0 loading LHAPDF/MSTW2008nlo68cl/MSTW2008nlo68cl_0000.dat
MSTW2008nlo68cl PDF set, member #0, version 2; LHAPDF ID = 21100

collider = pp
roots(GeV) = 13000.000000000000
process = H
model = SM
mass = 125.00000000000000
muR = 62.500000000000000
muF = 62.500000000000000
```

h1jet.hepforge.org/online

Additional Model Parameters:

Choose physics model: Multiple top-partners ⓘ

This interface allows you to specify multiple top-partners running in the loops in the table below. Note that you have to specify the SM top and bottom quarks as well if you wish to include them (they are already added to the table by default).

Mass [GeV]	CP-even Yukawa factor	CP-odd Yukawa factor	Loop approximation	
173.5	1	0	Fermion - full mass effects	Remove
4.65	1	0	Fermion - full mass effects	Remove
300	1	0	Fermion - full mass effects	Remove

Add new top-partner

$\sigma_0 = 0.062745$ nb (for latest run)