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

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2309.16759 [hep-ph]

LNF Theory Seminar
Laboratori Nazionali di Frascati
4 June 2024

Who am I?

BSc, MSc	Niels Bohr Institute, University of Copenhagen, Denmark
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Research interests:

- Collider phenomenology
- Higgs physics, BSM
- Jets
- Monte Carlo event generator development

What is the landscape?

Higgs sector of the SM is still not well-understood

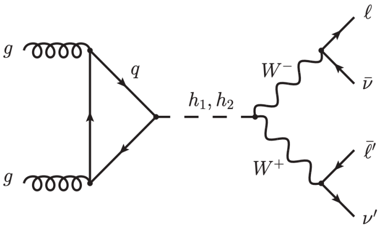
Collider physics is in a precision era

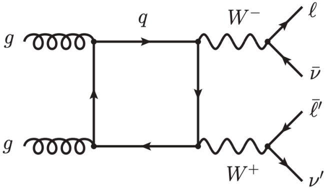
Theoretical precision predictions for Higgs extensions

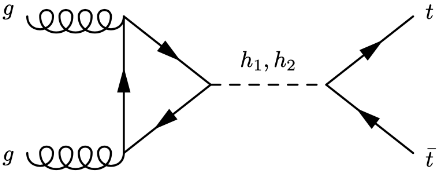
Heavy resonance searches

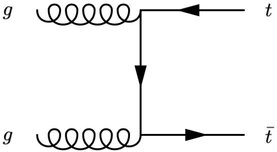
Search for New Physics:

Distinguishing effects of heavy resonance from continuum background



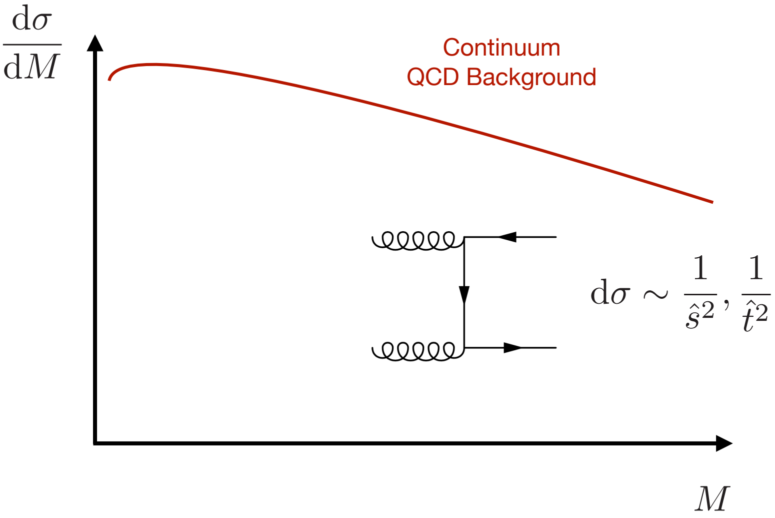






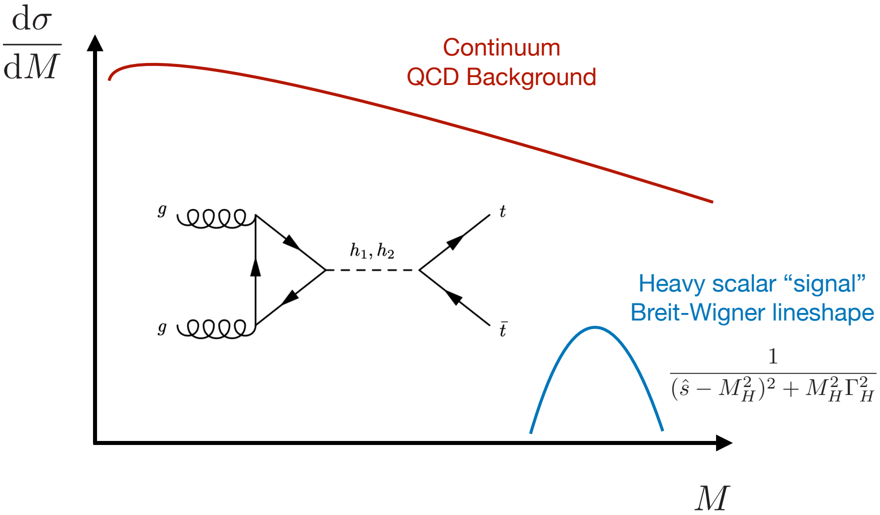
"Bump hunting"

Invariant mass spectrum:



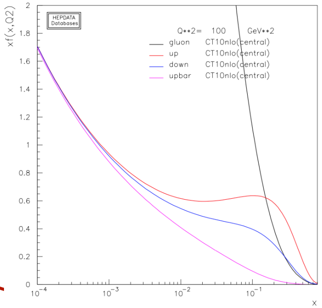
"Bump hunting"

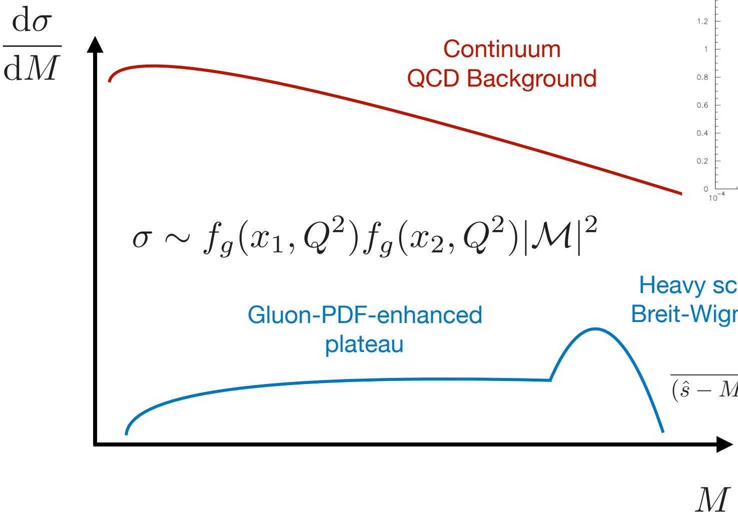
Invariant mass spectrum:



Alternative to "bump hunting"

Invariant mass spectrum:



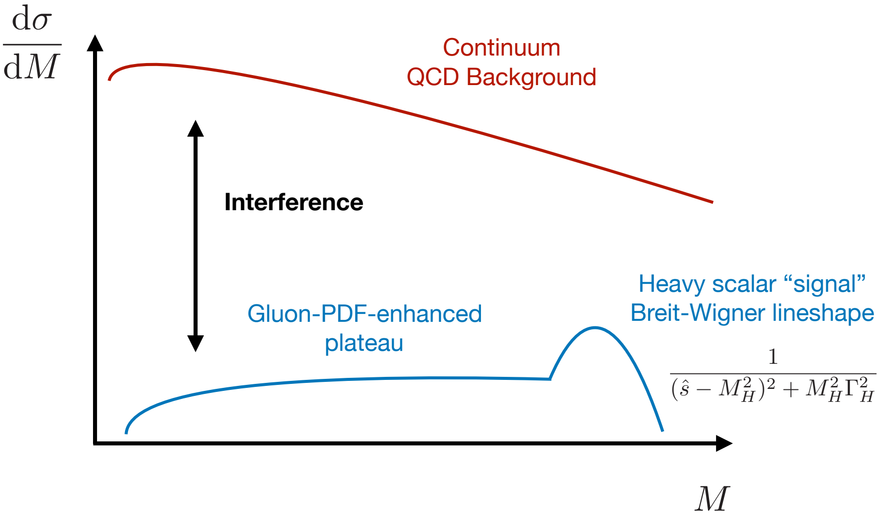


$$\sigma \sim f_g(x_1, Q^2) f_g(x_2, Q^2) |\mathcal{M}|^2$$

$$\frac{1}{(\hat{s} - M_H^2)^2 + M_H^2 \Gamma_H^2}$$

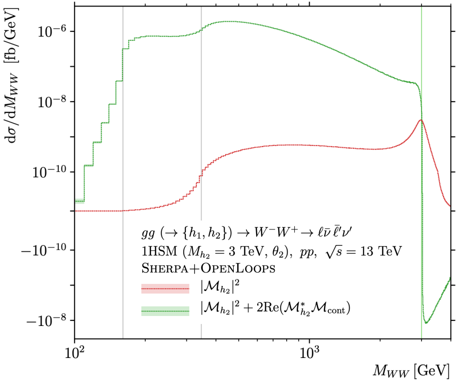
Alternative to "bump hunting"

Invariant mass spectrum:

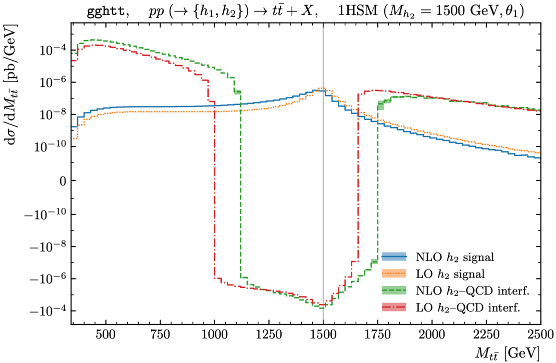


Alternative to “bump hunting”

Invariant mass spectrum:



$$\mathrm{d}\sigma \sim \frac{1}{\hat{s}^2}$$



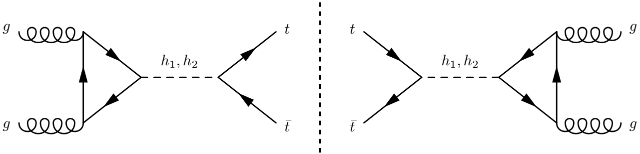
$$\mathrm{d}\sigma \sim \frac{1}{(\hat{s} - M_H^2)^2} \sim \frac{1}{M_H^4}$$

Process of interest

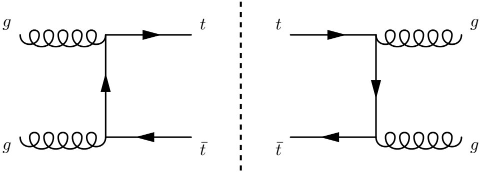
$pp\,(\to \{h_1, h_2\}) \to t\bar{t} + X$

Leading-order contributions:

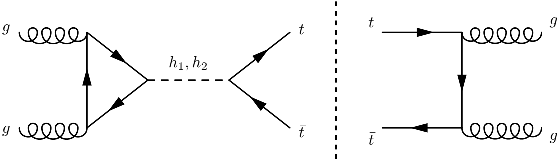
Signal



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, $\qquad \mu_1 = \lambda_1 = \lambda_2 = 0$

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

Precision

Large datasets

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

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

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

Lepton colliders (FCC-ee)

Large reduction in experimental uncertainties

- Electron/muon uncertainties: permille level
- JES: sub-percent level
- B-tagging uncertainty: sub-percent level

+ Machine Learning

$\Rightarrow$ Need for more precision in theory predictions and event generators

Precision: NLO QCD

$$\sigma_{\text{LO}} = \int_m \mathrm{d}\sigma_{\text{B}}$$

$$\sigma_{\text{NLO}} = \sigma_{\text{LO}} + \int_m \mathrm{d}\sigma_{\text{V}} + \int_{m+1} \mathrm{d}\sigma_{\text{R}}$$

NLO particularly important for Higgs production

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

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

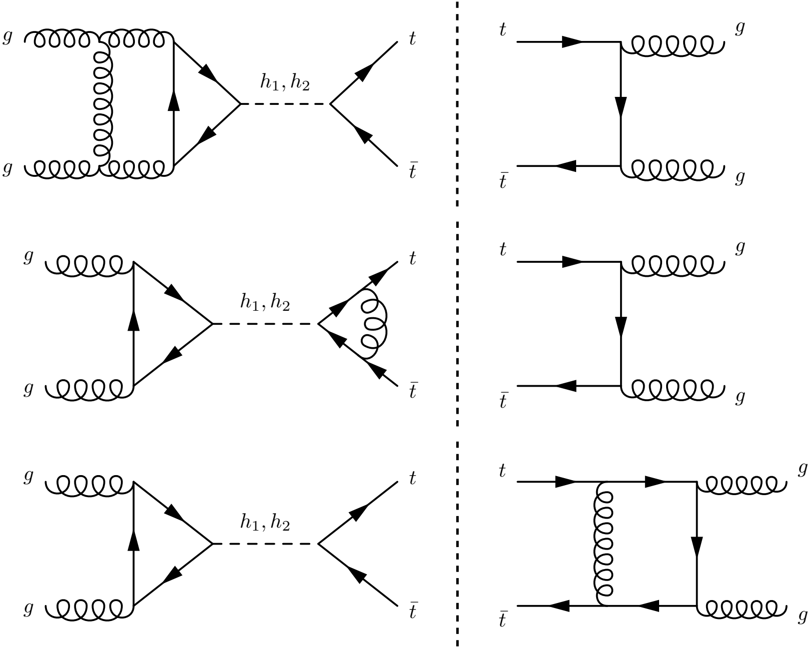
Infrared (soft/collinear) divergences $\Rightarrow$ Subtraction of dipoles

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

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

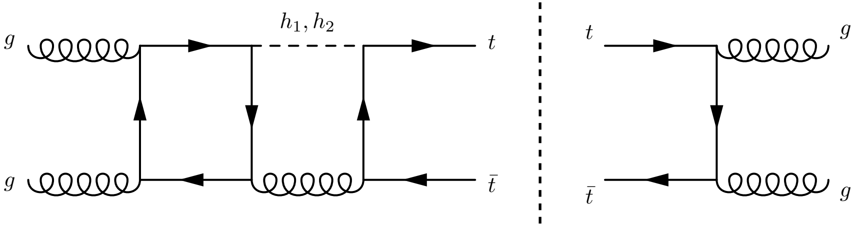
Interference effects also very important — and has large K-factors!

NLO QCD Corrections to the Interference



Non-Factorisable Corrections

Non-factorisable two-loop virtual corrections



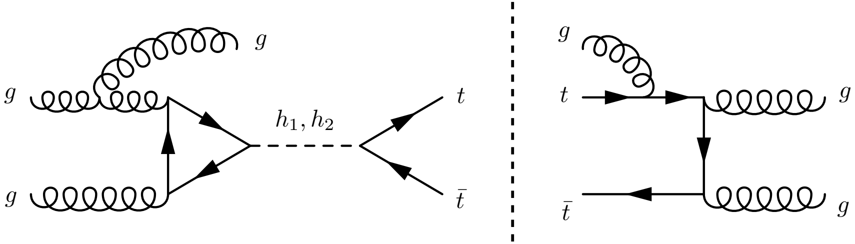
Non-zero for a (heavy) Higgs of finite width

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

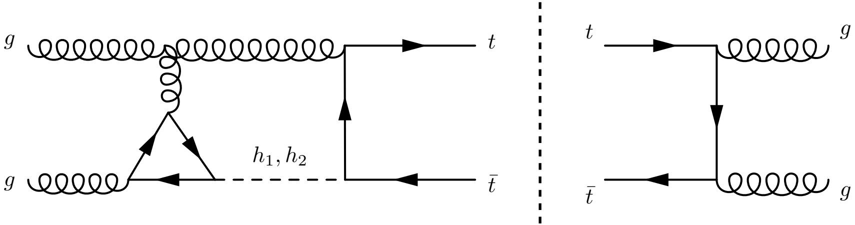
Could be calculated by expansions in $\frac{\Gamma_{h_i}}{M_{h_i}}$

Non-Factorisable Corrections

IR divergent non-factorisable **real** contribution

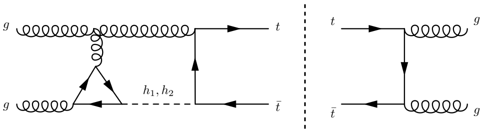


IR divergent non-factorisable **virtual** contribution

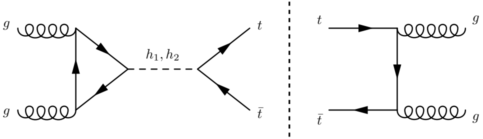


Non-Factorisable Corrections

However, in the soft limit:

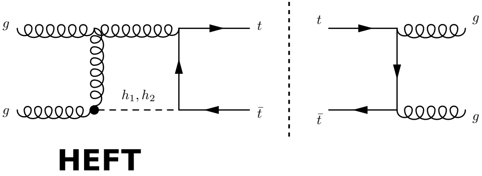


$$= C \times$$

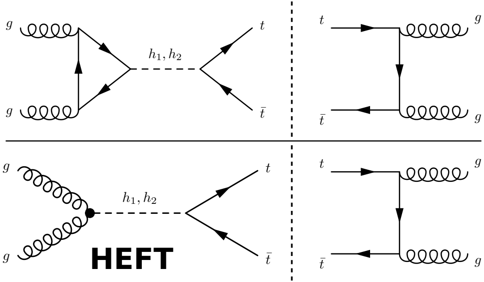


↑ Singular term

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

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

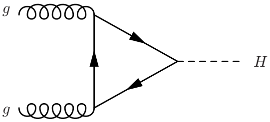
Davies, Herren, Steinhauser [1911.10214]

The one-loop form factor is

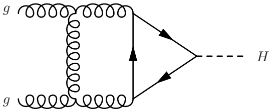
$$F_1 = -\sum_q \frac{2}{\tau_q^2}\left[\tau_q + \frac{1}{4}(1-\tau_q)\ln^2 x_q\right]$$

Harlander, Kant [hep-ph/0509189]

F_1:



F_2:

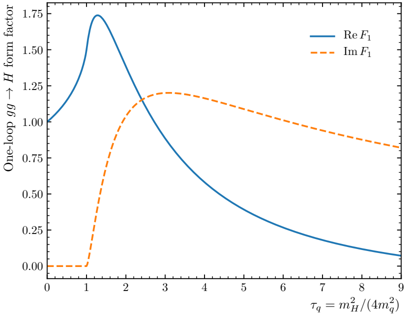


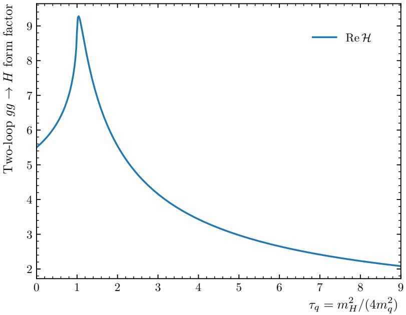
Form Factors for $gg \to H$

The two-loop form factor is

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

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

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

$pp\ (\to \{h_1\}) \to t\bar{t} + X$ 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 $K^{\text{interf}} = 2.01$

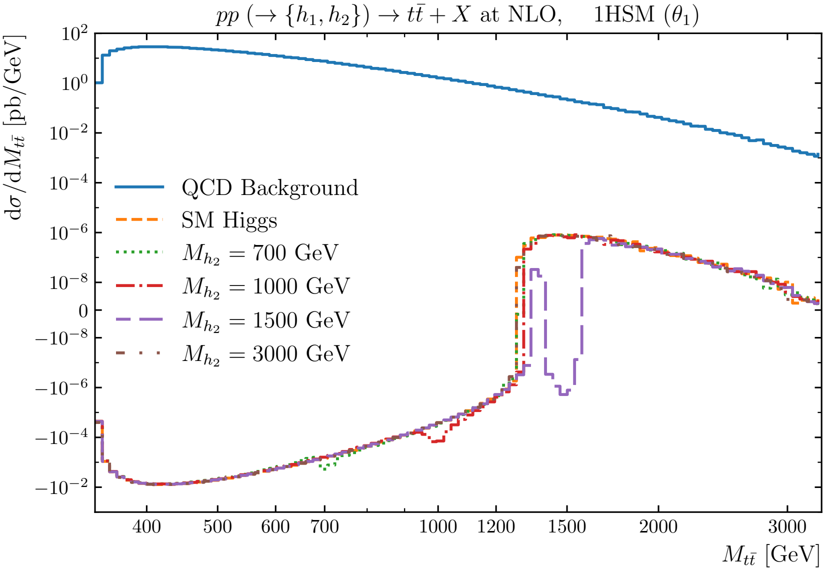
Results: Integrated Cross Sections

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)

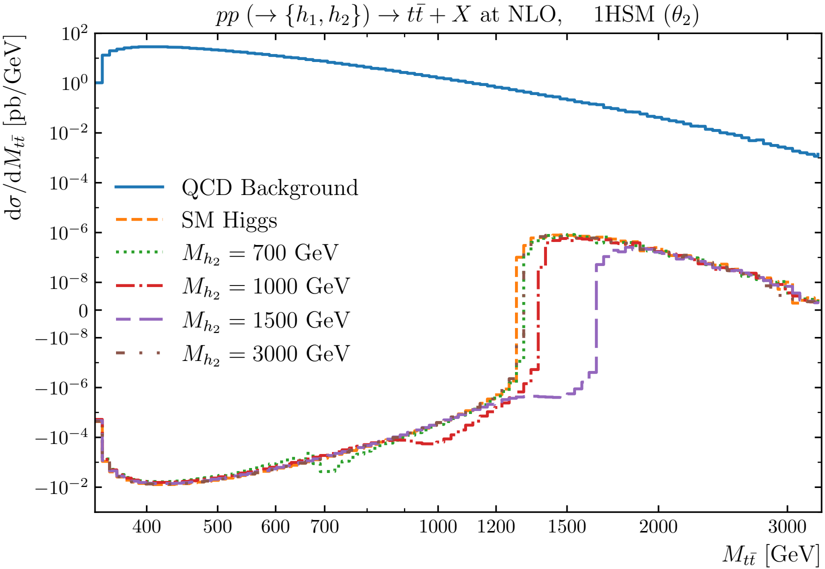
Results: Differential Distributions

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



Results: Differential Distributions

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

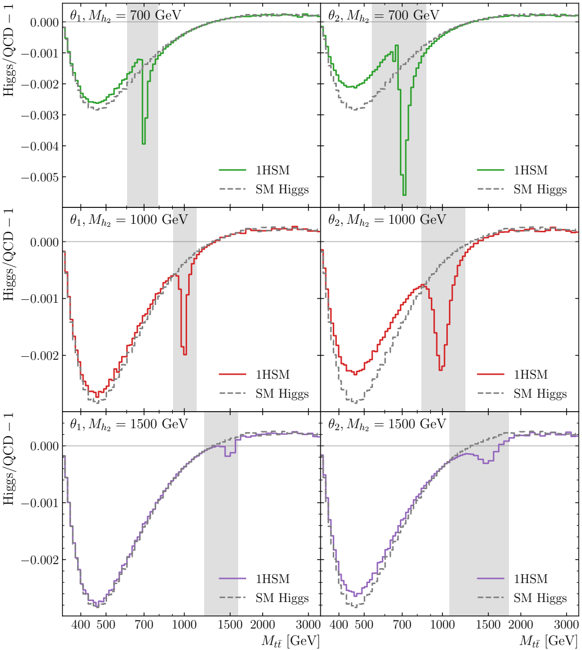


Results: Differential Distributions

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

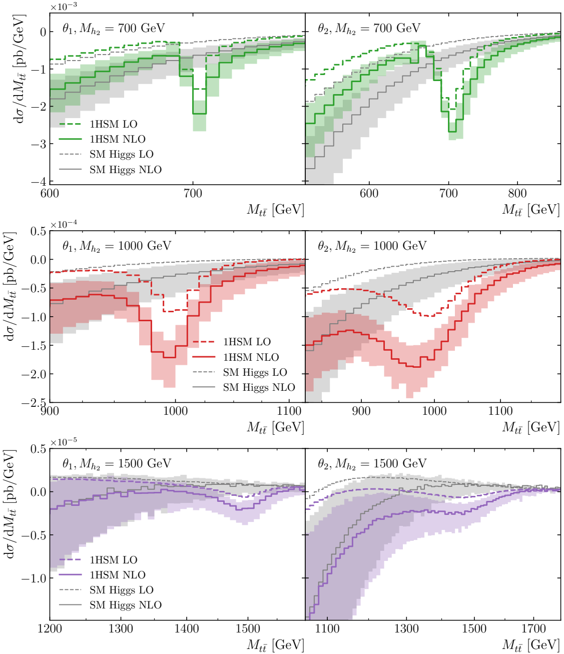
Results: Differential Distributions

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

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

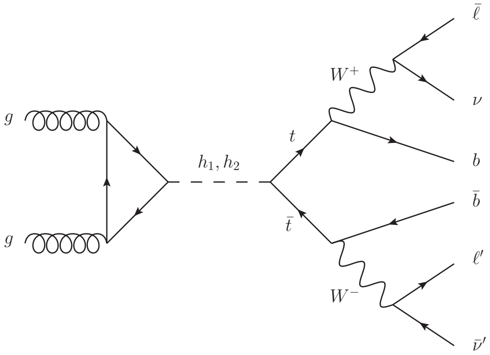
	M_{h_2} [GeV]	Invariant mass window	Excludable Run 2	Excludable Run 3	Excludable HL-LHC
θ_1	700	600–790 GeV	✓	✓	✓
	1000	900–1115 GeV	–	✓	✓
	1500	1200–1600 GeV	–	–	–
θ_2	700	530–870 GeV	✓	✓	✓
	1000	830–1200 GeV	✓	✓	✓
	1500	1050–1800 GeV	–	–	–

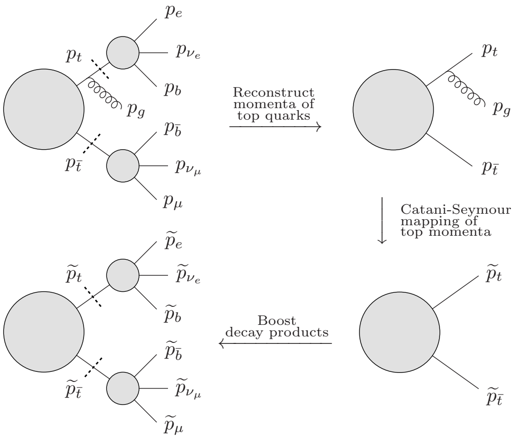
Outlook: Top Decays

Can consider the full $2 \to 6$ top decay amplitudes

$$pp\,(\to \{h_1, h_2\}) \to t\bar{t} \to W^+W^-b\bar{b} \to \bar{\ell}\nu\ell'\bar{\nu}'b\bar{b}$$

with spin correlations in the double pole approximation



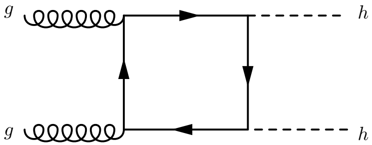


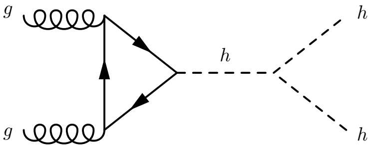
Bevilacqua, Hartanto, Kraus, Weber, Worek [1912.09999]

Outlook: Generalisation of the Code

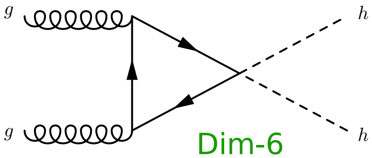
The code can be generalised to work for any loop-induced process, e.g.

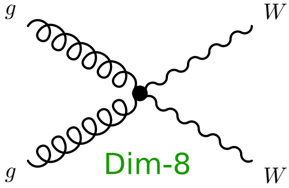
Double Higgs production



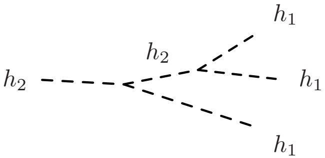


Effective field theories



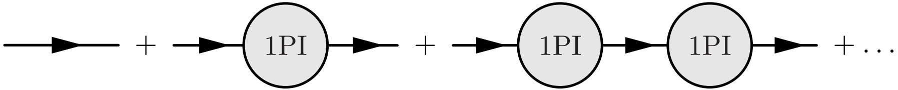


For one of our benchmark points: $\frac{\Gamma_{h_2}}{M_{h_2}} \sim 0.18$



Cascaded decays:
$h_2 \to 3 \times h_1$
Circular dependence on decay width

$\Pi(p^2) =$



$$= \frac{i}{p^2 - m_0^2} + \frac{i}{p^2 - m_0^2}\left[-i\Sigma(p^2)\right]\frac{i}{p^2 - m_0^2} + \ldots = \frac{i}{p^2 - m_0^2 - \Sigma(p^2)}$$

Exact scalar propagator:

$$\Pi(p^2) = \frac{i}{p^2 - m_0^2 - \Sigma(p^2)}$$

Optical theorem
On-shell approx.

$\xrightarrow{\hspace{2cm}}$

$\mathrm{Im}\,\Sigma(p^2{=}m^2){=}{-m\Gamma}$

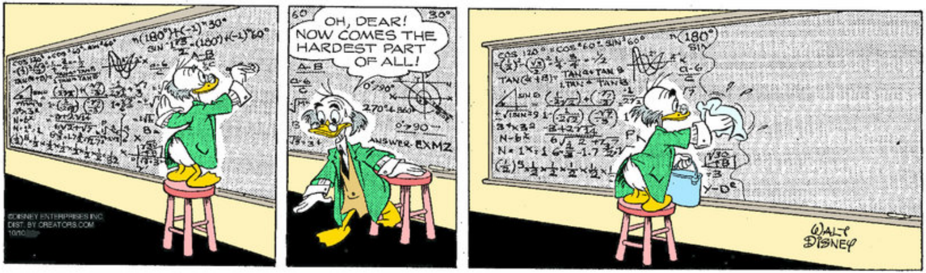
Breit-Wigner:

$$\Pi(p^2) \sim \frac{i}{p^2 - m^2 + im\Gamma}$$

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

Thank you very much for your attention! :)



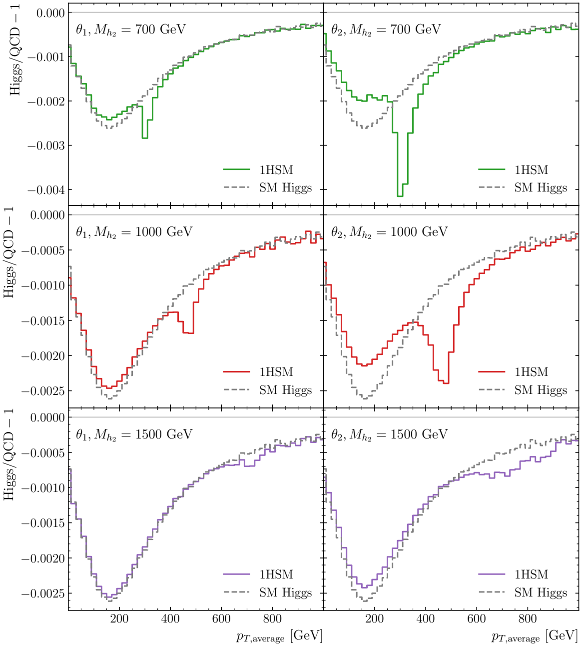
Backup Slides

Results: Additional Differential Distributions

Peak/dip structure in the BSM scenarios

Higgs/QCD-1
vs. $p_{T,\text{average}}$

$$p_{T,\text{average}} = \frac{p_{T,t} + p_{T,\bar{t}}}{2}$$



M_{h_2}

700 GeV

1000 GeV

1500 GeV

A second project:

H1JET

arXiv:2011.04694 [hep-ph]

with Andrea Banfi

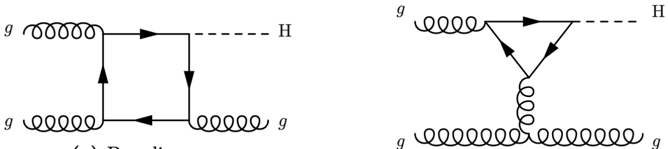
h1jet.hepforge.org

Motivation

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

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

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



(a) Box diagram. **(b)** Triangle diagram.

Loops: SM top + BSM top partner

The method

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

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

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

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

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

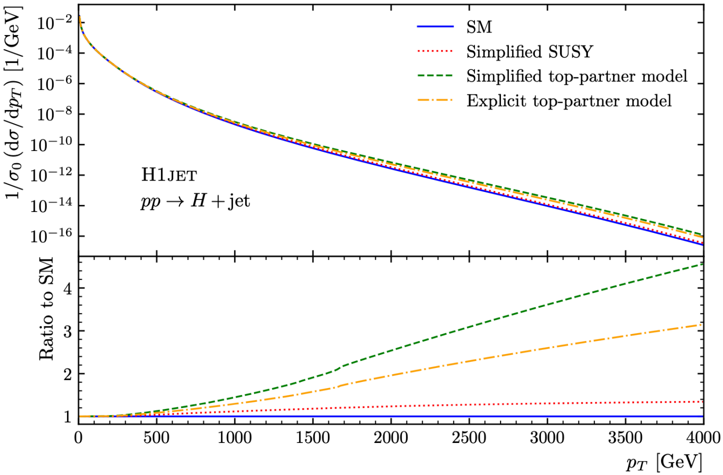
$$\hat{t} = -p_T e^{-\eta}\sqrt{\hat{s}}$$

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

1D integration done using adaptive Gaussian quadrature

Code interfaced with CHAPLIN and HOPPET

Built-in models



Provided user-interface allows for a custom process given a user-provided amplitude, $|\mathcal{M}(\hat{s}, \hat{t}, \hat{u})|^2$

Live demonstration

A live demonstration:

h1jet.hepforge.org/online