

Top Quark Pair Production and Decay: The 1-Higgs-Singlet Model and Pseudoscalar Decay

Andrea Banfi¹, Jonas Lindert¹, Vishakha Lingadahally² and Alexander Lind³

¹University of Sussex, ²Royal Holloway, University of London, ³INFN, Frascati

May 11, 2026
Pheno 2026

1-Higgs-Singlet Model

- 1HSM is a minimal extension of the Standard Model with one extra scalar Higgs.
- Minimal extension of SM with two physical scalar bosons.

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

- s is the additional real singlet scalar with mass M , which mixes with the Higgs doublet ϕ
- λ , λ_1 and λ_2 are quartic couplings.
 $\lambda > 0$, $\lambda_1 > 0$ and $\lambda_2 = -2\sqrt{\lambda\lambda_1}$.
- Trilinear couplings μ_1 and μ_2 can be either positive or negative.

1-Higgs-Singlet Model

- After EW symmetry-breaking (unitary gauge),

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

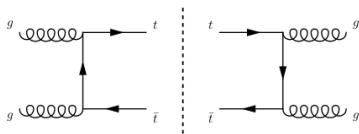
$$V = \frac{\lambda}{4} H^4 + \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{2} M^2 s^2 + \lambda_1 s^4 + \frac{\lambda_2}{2} H^2 s^2 + \lambda_2 v H s^2 + \mu_1 s^3 + \frac{\mu_2}{2} H^2 s + \mu_2 v H s$$

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

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

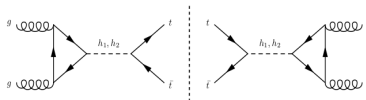
M_{h_2} [GeV]	700	1000	1500	3000
$\theta = \theta_1$	$\frac{\pi}{15}$	$\frac{\pi}{15}$	$\frac{\pi}{22}$	$\frac{\pi}{45}$
$\theta = \theta_2$	$\frac{\pi}{8}$	$\frac{\pi}{8}$	$\frac{\pi}{12}$	$\frac{\pi}{24}$

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



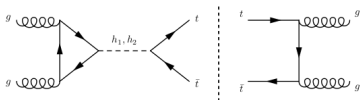
Representative LO contribution to QCD background

- Higgs Signal: $|\mathcal{M}_{h_1}|^2 + |\mathcal{M}_{h_2}|^2 + 2\text{Re}(\mathcal{M}_{h_1}^* \mathcal{M}_{h_2})$

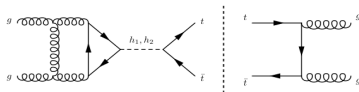


LO contribution to signal

- Higgs-QCD Interference: $2\text{Re} ((\mathcal{M}_{h_1}^* + \mathcal{M}_{h_2}^*)\mathcal{M}_{\text{QCD}})$

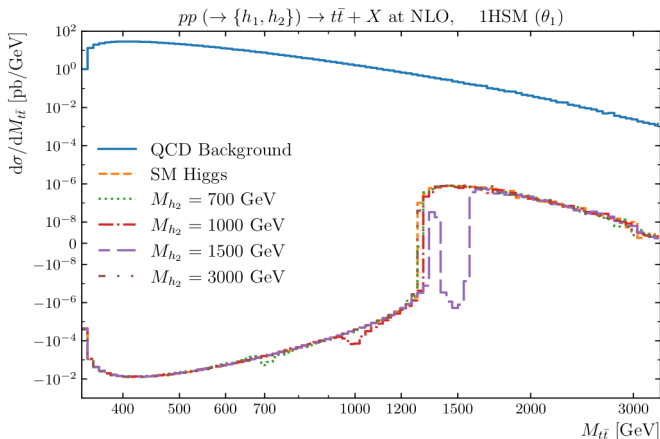


LO contribution to interference



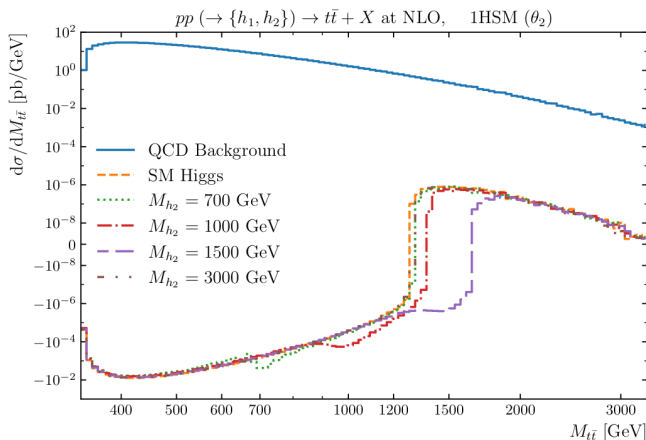
Representative NLO contribution to interference

Differential Cross Section



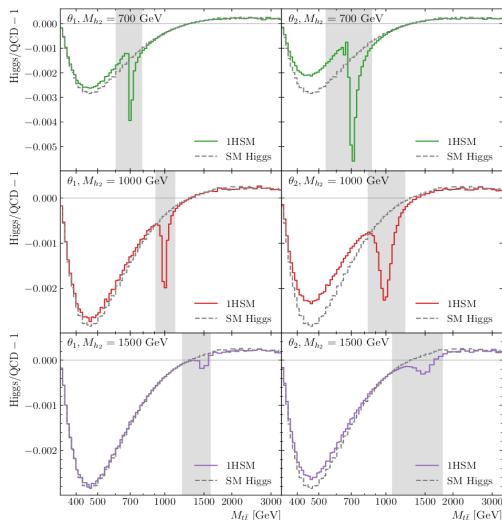
Differential cross section of $pp (\rightarrow h_1, h_2) \rightarrow t\bar{t} + X$ as a function of $M_{t\bar{t}}$ at NLO (θ_1) [Banfi et al., '23]

Differential Cross Section



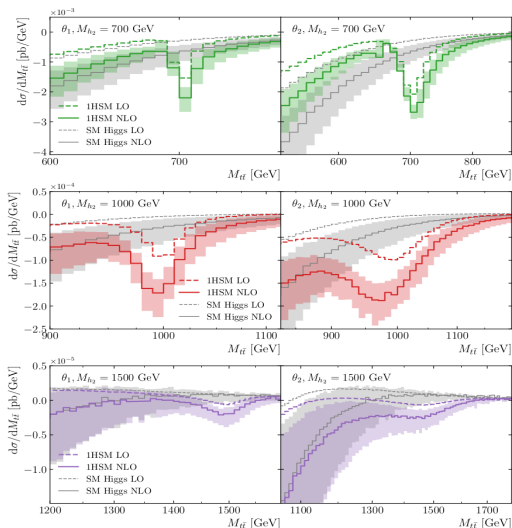
Differential cross section of $pp (\rightarrow h_1, h_2) \rightarrow t\bar{t} + X$ as a function of $M_{t\bar{t}}$ at NLO (θ_2) [Banfi et al., '23]

Sensitivity to BSM Effects



Ratio of Higgs contribution (signal and interference) to the QCD continuum background [Banfi et al., '23]

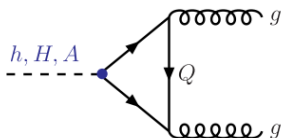
Sensitivity to BSM Effects



Differential distributions in $M_{t\bar{t}}$ for the combined Higgs contribution (signal and interference) [Banfi et al., '23]

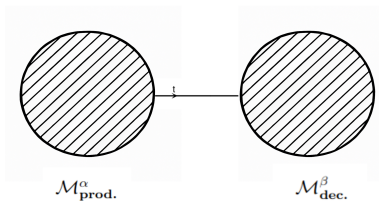
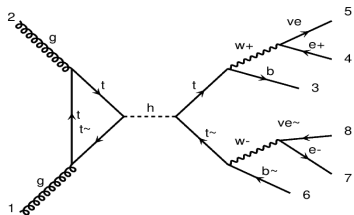
The Pseudoscalar

- $CP : A(t, x) \rightarrow -A(t, -x)$
- The 2-Higgs-Doublet Model (2HDM) and the Minimal Supersymmetric Standard Model (MSSM) require five scalar Higgs Bosons, H , h , A and H^\pm .



- Its fermion coupling has the form $\mathcal{L} \supset iy_A \bar{f} \gamma^5 f$ (as opposed to $\mathcal{L} \supset -y_H H \bar{f} f$ in case of the Higgs).
- The amplitude for its production in gluon-gluon fusion is
$$\mathcal{M}_{\mu\nu}^{ab}(gg \rightarrow A) = \delta^{ab} \epsilon_{\mu\nu\rho\sigma} p_1^\sigma p_2^\rho \times \mathcal{F}_{1/2}^A(s, m_t^2, \mu_R^2)$$
- $\mathcal{F}_{1/2}^A(\tau) = -\frac{2f(\tau)}{\tau}$
- $M_A \ll m_t \implies \mathcal{F}_{1/2}^A \rightarrow 2$

Decays



$$i\mathcal{M} = \mathcal{M}_{\text{dec.}}^{\beta} \left[\frac{i(p_t + m_t)_{\beta\alpha}}{p_t^2 - m_t^2 + im_t\Gamma_t} \right] \mathcal{M}_{\text{prod.}}^{\alpha} = \mathcal{M}_{\text{dec.}}^{\beta} \left[\frac{i \sum_s u^s(p_t) \bar{u}^s(p_t)}{p_t^2 - m_t^2 + im_t\Gamma_t} \right] \mathcal{M}_{\text{prod.}}^{\alpha}$$

Spin Correlation

- Spin-density matrices can be constructed from spin-correlated matrix elements.

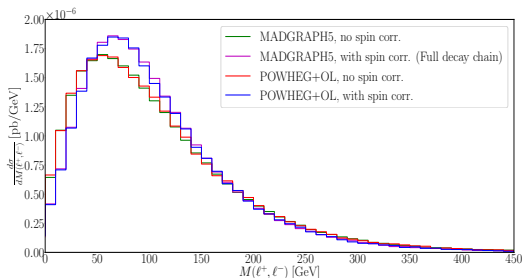
$$|\mathcal{M}|^2 = [\text{C.F.}] \times \frac{1}{(p_t^2 - m_t^2)^2 + (m_t \Gamma_t)^2} \times \sum_{\alpha, \beta, \alpha', \beta'} \sum_{s_t, s'_t = \pm 1} \left[\mathcal{M}_{\text{dec.}}^\alpha \frac{(p_t + m_t)_{\alpha\beta} (1 + s_t \gamma^5 \not{p}_t)}{2} \mathcal{M}_{\text{prod.}}^\beta \right] \\ \times \left[\mathcal{M}_{\text{dec.}}^{\alpha'} \frac{(p_t + m_t)_{\alpha'\beta'} (1 + s'_t \gamma^5 \not{p}_t)}{2} \mathcal{M}_{\text{prod.}}^{\beta'} \right]^*$$

- $\rho_{\text{prod.}}^{ss'} = \mathcal{M}_{\text{prod.}} (\mathcal{M}_{\text{prod.}})^*$, $\rho_{\text{dec.}}^{ss'} = \mathcal{M}_{\text{dec.}} (\mathcal{M}_{\text{dec.}})^*$
- The phase space can be reweighted to include spin correlation.

$$dP(\Phi_{\text{full dec.}} | \Phi_{\text{prod.}}) = \frac{1}{\text{BR}(t \rightarrow b\bar{\ell}\nu) \times \text{BR}(\bar{t} \rightarrow \bar{b}\bar{\ell}\bar{\nu})} \frac{|\mathcal{M}_{\text{full dec.}}(\Phi_{\text{prod.}}, \Phi_{t \rightarrow b\bar{\ell}\nu}, \Phi_{\bar{t} \rightarrow \bar{b}\bar{\ell}\bar{\nu}})|^2}{|\mathcal{M}_{\text{prod.}}(\Phi_{\text{prod.}})|^2} d\Phi_{t \rightarrow b\bar{\ell}\nu} d\Phi_{\bar{t} \rightarrow \bar{b}\bar{\ell}\bar{\nu}}$$

[Alioli, Moch, Uwer, '12]

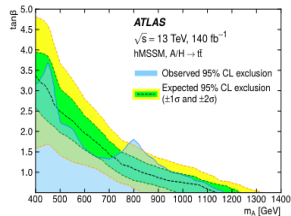
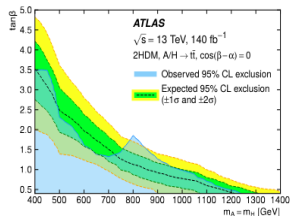
Spin Correlation



Differential cross section of $pp \rightarrow H \rightarrow t\bar{t} + \text{Decays}$ at LO in a function of $M(\ell^+, \ell^-)$

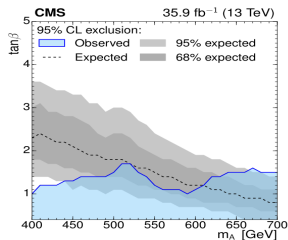
- The SM signal at LO has been validated against MadGraph5_aMC@NLO at the differential level.
- Currently working on producing results at NLO in 1HSM as well as with A .
- Would love to receive inputs regarding observables that are of special experimental interest!

Exclusion Contours



Type-II 2HDM [ATLAS, '24]

hMSSM [ATLAS, '24]



hMSSM [CMS, '16]

- Phenomenological predictions for top-quark pair production in 1HSM at LO and NLO have been made in [Banfi et al., 2023].
- Inclusion of decays and parton showers gets us closer to a ‘full simulation’ of the real-world collider phenomena.
- We have validated $gg \rightarrow A \rightarrow t\bar{t}$ at LO as well as the two-loop form factor for the process against existing results.
- We are working on including spin correlation in decays at NLO as well as non-factorisable corrections.
- We aim to produce exclusion contours that provide inputs to experimental searches of the heavy Higgs Boson and A .

Thank you!

