

Top-Quark Pair Production and Decay in the Extended Higgs Sector

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Two-Higgs-Doublet Model

- Minimal extension: one additional scalar doublet
- Rich extended scalar spectrum:

$$h, H, A, H^\pm$$

- New CP and Yukawa structures
- Modified electroweak symmetry breaking:

$$\tan \beta = \frac{v_2}{v_1}$$

- Can support a strong first-order electroweak phase transition
- Appears naturally in BSM frameworks such as the MSSM
- Rich collider phenomenology, in particular

$$gg \rightarrow H/A \rightarrow t\bar{t}$$

Two-Higgs-Doublet Model

- A gauge-invariant, renormalisable 2HDM scalar potential can be written as

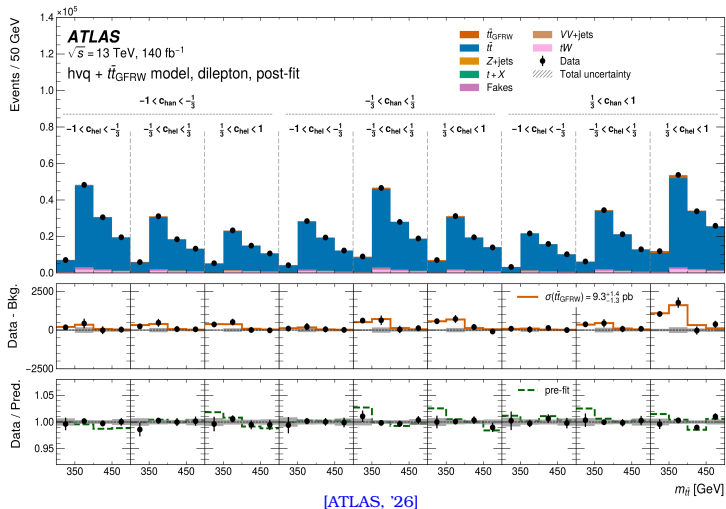
$$\begin{aligned} V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]. \end{aligned}$$

- $v^2 = v_1^2 + v_2^2$
- CP-conserving 2HDM with softly broken Z_2

$$h = \rho_1 \cos\alpha - \rho_2 \sin\alpha$$

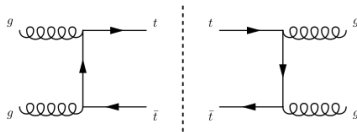
$$H = -\rho_1 \sin\alpha + \rho_2 \cos\alpha$$

$t\bar{t}$ at Threshold



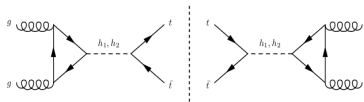
- CMS observed an excess near $t\bar{t}$ production threshold. This was later confirmed by ATLAS. [CMS, '25]

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



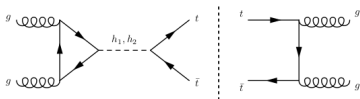
Representative LO contribution to QCD background

- Higgs Signal: $|\mathcal{M}_h|^2 + |\mathcal{M}_H|^2 + |\mathcal{M}_A|^2 + 2\text{Re}(\mathcal{M}_h^* \mathcal{M}_H)$

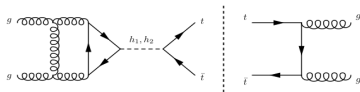


LO contribution to signal

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



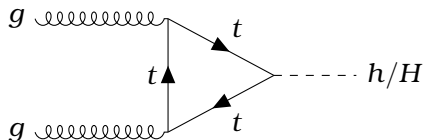
LO contribution to interference



Representative NLO contribution to interference

- Loop-squared and loop-tree squared amplitudes have been implemented in OpenLoops 2. [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller, '19]

One-Loop Form Factor



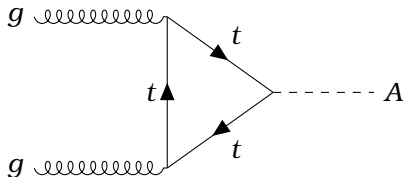
$$\mathcal{M}_{\mu\nu}^{ab} = \delta^{ab} [p_1 \cdot p_2 g_{\mu\nu} - p_{2\mu} p_{1\nu}] \times \mathcal{F}_{1/2}^{h/H}(\tau, s, m_t^2, \mu_R^2)$$

$$\mathcal{F}_{1/2}^{h/H} = -\frac{[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]}{\tau^2}, \quad \tau = \frac{M_H^2}{4m_t^2}$$

[Harlander, Kant, '05]

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau}, & \tau \leq 1, \\ -\frac{1}{4} \left[\log \frac{1 + \sqrt{1 - \tau^{-1}}}{1 - \sqrt{1 - \tau^{-1}}} - i\pi \right]^2, & \tau > 1. \end{cases}$$

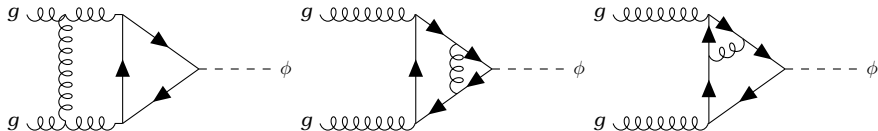
One-Loop Form Factor



$$\mathcal{L}_{Att} = -i \frac{m_t}{v} \kappa_t^A A \bar{t} \gamma^5 t, \quad \kappa_t^A = \cot \beta$$

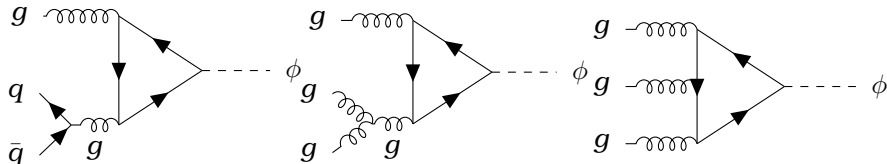
- The amplitude for its production in gluon-gluon fusion is $\mathcal{M}_{\mu\nu}^{ab}(gg \rightarrow A) = \delta^{ab} \epsilon_{\mu\nu\rho\sigma} p_1^\sigma p_2^\rho \times \mathcal{F}_{1/2}^A(s, m_t^2, \mu_R^2)$
- $\mathcal{F}_{1/2}^A(\tau) = -\frac{2f(\tau)}{\tau}$
- $M_A \ll m_t \implies \mathcal{F}_{1/2}^A \rightarrow 2$

Two-Loop Form Factor



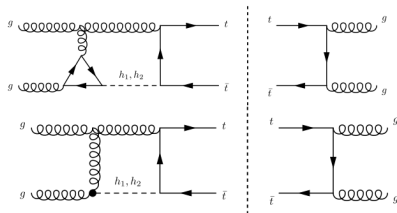
- Can be expressed analytically in terms of Harmonic Polylogarithms. [Aglietti, Bonciani, Degraasi, Vicini, '07]
- Implemented with CHAPLIN HPL library on OpenLoops 2. [Buehler and Duhr, '11]

Real Corrections



- Implemented with explicit loops on `OpenLoops 2`.
- A ' $ggg\phi$ Form Factor' does not currently exist in the literature.
- Using FF approximation for real emission diagrams ignores off-shell gluons and box diagrams.

Non-Factorisable Corrections

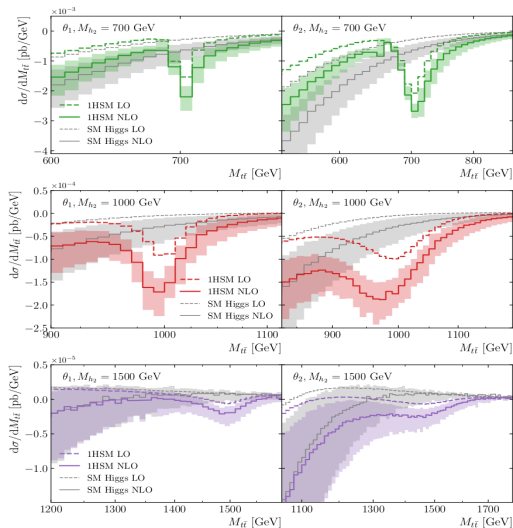


Non-factorisable correction and its EFT counterpart
[\[Banfi, Kauer, Lind, Lindert, Wood, '24\]](#)

- Rescaled in the EFT framework:

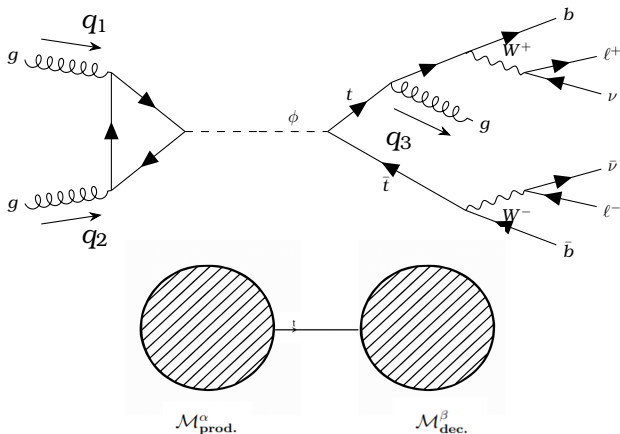
$$\sigma_{\text{Full Theory}}^{\text{NLO}} \approx \frac{\sigma_{\text{EFT}}^{\text{NLO}}}{\sigma_{\text{EFT}}^{\text{LO}}} \times \sigma_{\text{Full Theory}}^{\text{LO}}$$

Sensitivity to BSM Effects in 1HSM



Differential distributions in $M_{t\bar{t}}$ for the combined Higgs contribution (signal and interference) [Banfi, Kauer, Lind, Lindert, Wood, '24]

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.

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

- The phase space can be reweighted to include spin correlation.

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

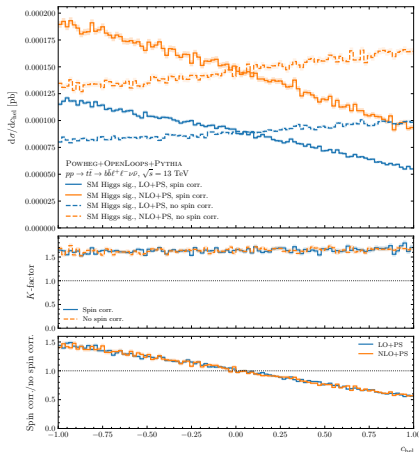
[Alioli, Moch, Uwer, '12]

- The top 'spin analysing power' κ_i quantifies the spin information passed along to a decay product i .

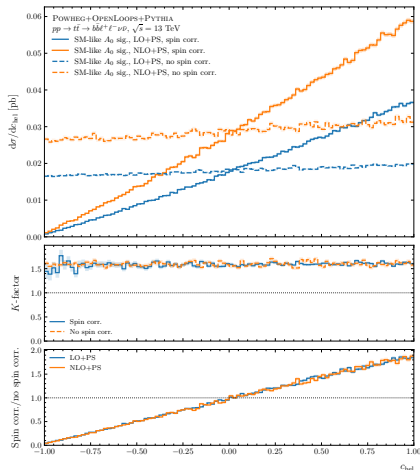
$$\frac{1}{\Gamma_t} \frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2} (1 + s_t \kappa_i \cos\theta_i)$$

- Top spin correlation effects in $Zt\bar{t}$ have been studied.
[Arco, Biekötter, Stylianou, Weiglein, '25].

Spin Correlation

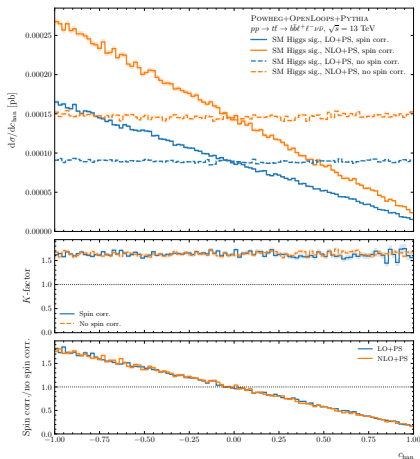


$$gg \rightarrow h \rightarrow t\bar{t} \rightarrow bbl^+ \ell^- \nu \bar{\nu}$$

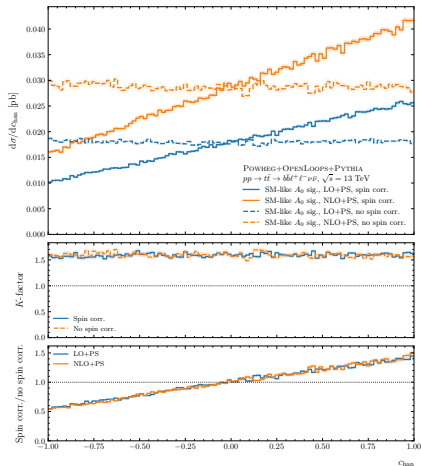


$$gg \rightarrow A \rightarrow t\bar{t} \rightarrow bbl^+ \ell^- \nu \bar{\nu}$$

Spin Correlation

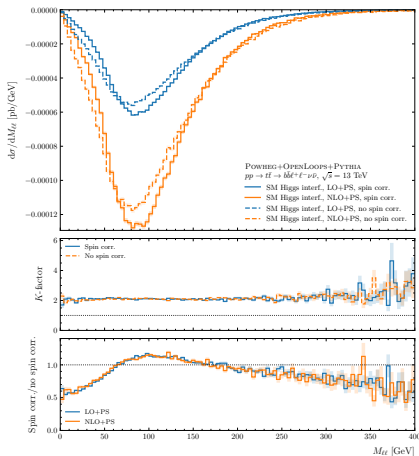


$$gg \rightarrow h \rightarrow t\bar{t} \rightarrow b\bar{b}\ell^+\ell^-\nu\bar{\nu}$$

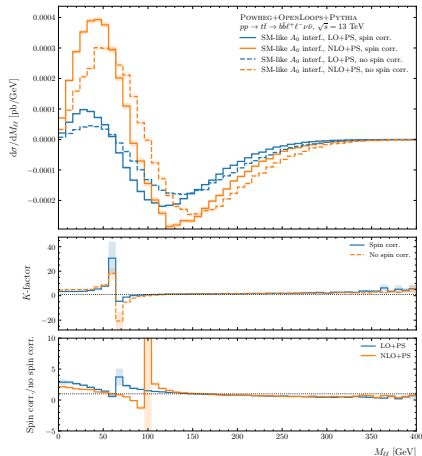


$$gg \rightarrow A \rightarrow t\bar{t} \rightarrow b\bar{b}\ell^+\ell^-\nu\bar{\nu}$$

Spin Correlation



$$gg \rightarrow h \rightarrow t\bar{t} \rightarrow b\bar{b}\ell^+\ell^-\nu\bar{\nu}$$



$$gg \rightarrow A \rightarrow t\bar{t} \rightarrow b\bar{b}\ell^+\ell^-\nu\bar{\nu}$$

Summary

- The Extended Higgs sector has very interesting cosmological implications and presents a rich collider phenomenology.
- We have included spin correlation effects in leptonic decaying of the top-quark pair in 2HDM at NLO+PS. Our results with an extra scalar singlet and a pseudoscalar have been validated against existing results. [Hespel, Maltoni, Vryonidou, '16], [Banfi, Kauer, Lind, Lindert, Wood, '24]
- Exclusion contours with detector effects and projections to future collider projects are on the way!

Thank you!



Sheldonian