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Impact of interference effects on Higgs searches in the di-top final state at the LHC

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O U T L I N E

- **Simplified model framework**
- **Loop-level mixing**
- **Results with mixing between the scalars**

Introduction

- heavy scalars with large couplings to top quarks appear in various extensions to the SM
- in particular, extended Higgs sector (2HDM, C2HDM, . . .)

Physical states in two-Higgs doublets

Illustration by K. Radchenko

→ searches in the di-top final state

- existing experimental searches see excesses [CMS-PAS-HIG-22-013]
- focused on single BSM scalar or two non-mixing scalar
- What happens for two mixing scalars?

Di-top final state for one additional scalar

- Total amplitude:

$$\mathcal{A} = \mathcal{A}(gg \to t\bar{t}) + \mathcal{A}(gg \to \Phi \to t\bar{t})$$

- Signal-background interference

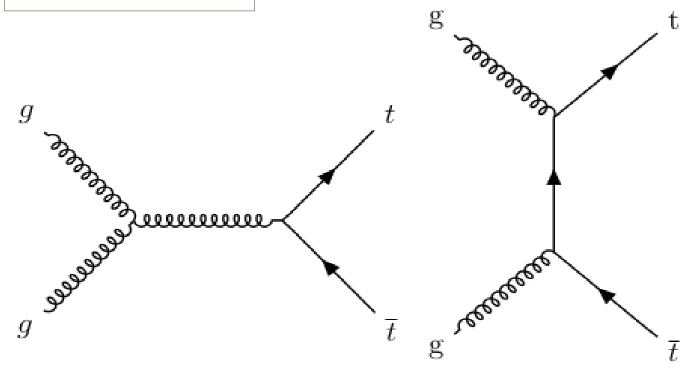
$$\propto \mathrm{Re}[\mathcal{A}(gg \to \Phi \to t\bar{t})\mathcal{A}^*(gg \to t\bar{t})]$$

large destructive contribution

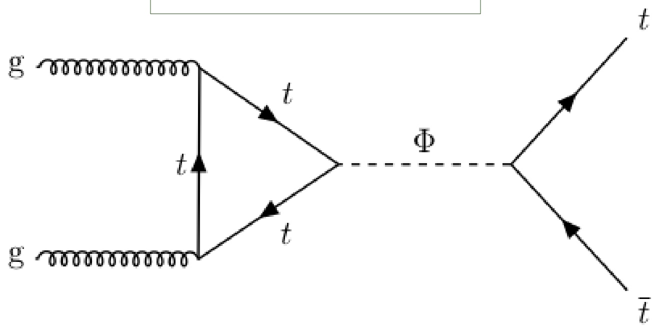
- Invariant mass distribution of the top quarks significantly distorted → peak-dip structure

Gaemers & Hoogeveen (1984)
Dicus et al. [hep-ph/9404359]
+ several others

QCD background ($gg \to t\bar{t}$)



Signal ($gg \to \Phi \to t\bar{t}$)



Simplified model framework for two BSM scalars

- Motivated by complex 2HDM with two heavy mixing BSM scalars
- Consider two scalars $\Phi_j \, \{j = 1, 2\}$ with
  - mass above di-top threshold ($M_{\Phi_j} > 2\, m_t$)
  - general complex top-Yukawa coupling
  - produced via gluon fusion, decay to top quarks

CP-even

CP-odd

$$\mathcal{L}_{\text{yuk}} = -\sum_{j=1}^{2} \frac{y_t^{\text{SM}}}{\sqrt{2}} \, \bar{t} \left(c_{t,j} + i\gamma_5 \tilde{c}_{t,j} \right) t \Phi_j$$

Yukawa-coupling modifiers

Analytical implementation
(Mathematica)

Monte-Carlo implementation
(MadGraph 3.4.0)

Note: SM-like Higgs boson at 125 GeV
CP-even coupling = 1
CP-odd coupling = 0

Two CP-mixed scalar(s)

Bernreuther et al. [1511.05584]
Carena & Liu [1608.07282]

- trivial to extend the signal-background interference contribution
- signal-signal interference terms contains

$$2 \times \frac{3\alpha_s^2 G_F^2 m_t^2}{8192\pi^3}\hat{s}^2 \times$$

$$\mathrm{Re}\left[\frac{\left(c_{t,1}A_{1/2}^{H}(\tau_1)c_{t,2}A_{1/2}^{H,*}(\tau_2)+\tilde{c}_{t,1}A_{1/2}^{A}(\tau_1)\tilde{c}_{t,2}A_{1/2}^{A,*}(\tau_2)\right)\cdot\left(c_{t,1}c_{t,2}\hat{\beta}_t^3+\tilde{c}_{t,1}\tilde{c}_{t,2}\hat{\beta}_t\right)}{(\hat{s}-M_1^2+iM_1\Gamma_1)(\hat{s}-M_2^2-iM_2\Gamma_2)}\right]$$

- no signal-signal interference between CP-even and CP-odd
- sign of Yukawa-coupling modifiers can be relevant

Loop-level mixing

Fuchs & Weiglein [1610.06193]
see also:
Dabelstein [hep-ph/9409375]
Frank et al. [hep-ph/0611326]

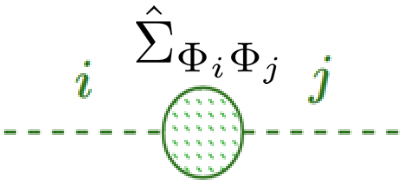
- lowest-order mass states will in general mix at the loop-level

$$\{\Phi_1, \Phi_2\} \xrightarrow{\text{mix at loop-level}} \{h_1, h_2\}$$

- loop-corrected masses and widths can be found by finding poles of the propagator matrix

$$\Delta_{\Phi_i\Phi_j}(p^2) = \begin{pmatrix} \Delta_{\Phi_1\Phi_1} & \Delta_{\Phi_1\Phi_2} \\ \Delta_{\Phi_2\Phi_1} & \Delta_{\Phi_2\Phi_2} \end{pmatrix} = -\left(\hat{\Gamma}_{\Phi_i\Phi_j}(p^2)\right)^{-1}$$

with $\hat{\Gamma}_{\Phi_i\Phi_j}(p^2) = i\left[(p^2 - m_i^2)\delta_{ij} + \hat{\Sigma}_{\Phi_i\Phi_j}(p^2)\right]$



Loop-level mixing

Fuchs & Weiglein [1610.06193]
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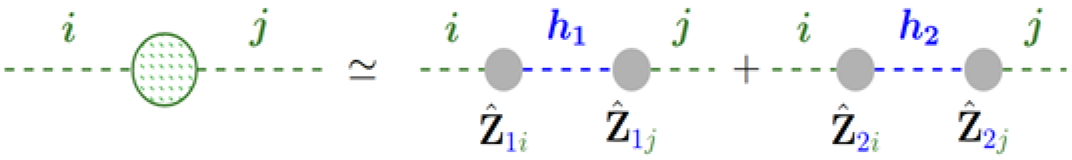
- in addition to shifting mass and widths, loop-level mixing also affects couplings

- approximate propagator matrix using wavefunction normalization factor — called “Z-factors” — and Breit-Wigner (BW) propagators

$$\Delta_{\Phi_i \Phi_j}(p^2) \simeq \sum_{a=1,2} Z_{h_a \Phi_i} \Delta^{\mathrm{BW}}_{h_a}(p^2) Z_{h_a \Phi_j}$$

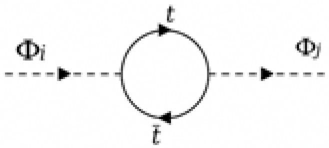


Loop-level mixing for $gg \to t\bar{t}$

- use this to approximate BSM $t\bar{t}$ amplitude

$$\mathcal{A}_{\rm BSM} \simeq \sum_{a=1,2} \left[\left(\sum_{i=1,2} Z_{h_a \Phi_i} \hat{\Gamma}_i^{gg\Phi_i} \right) \Delta_{h_a}^{\rm BW}(p^2) \left(\sum_{j=1,2} Z_{h_a \Phi_j} \hat{\Gamma}_j^{\Phi_j \to t\bar{t}} \right) \right]$$

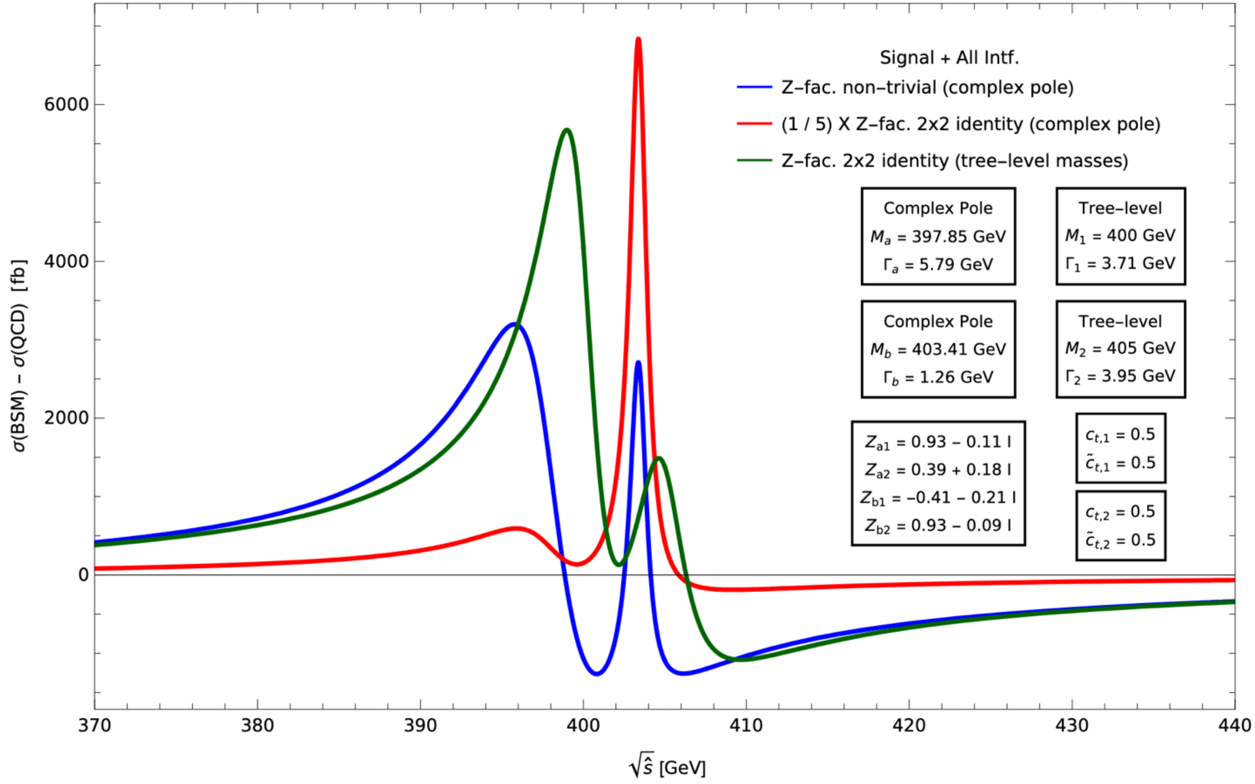
- calculate Z-factors within simplified model
- Z-factors rearranged in matrix $\to \hat{\mathbf{Z}}$ –matrix,
- $\hat{\mathbf{Z}}$ –matrix non-unitary and complex



→ Additional phases affecting interference patterns

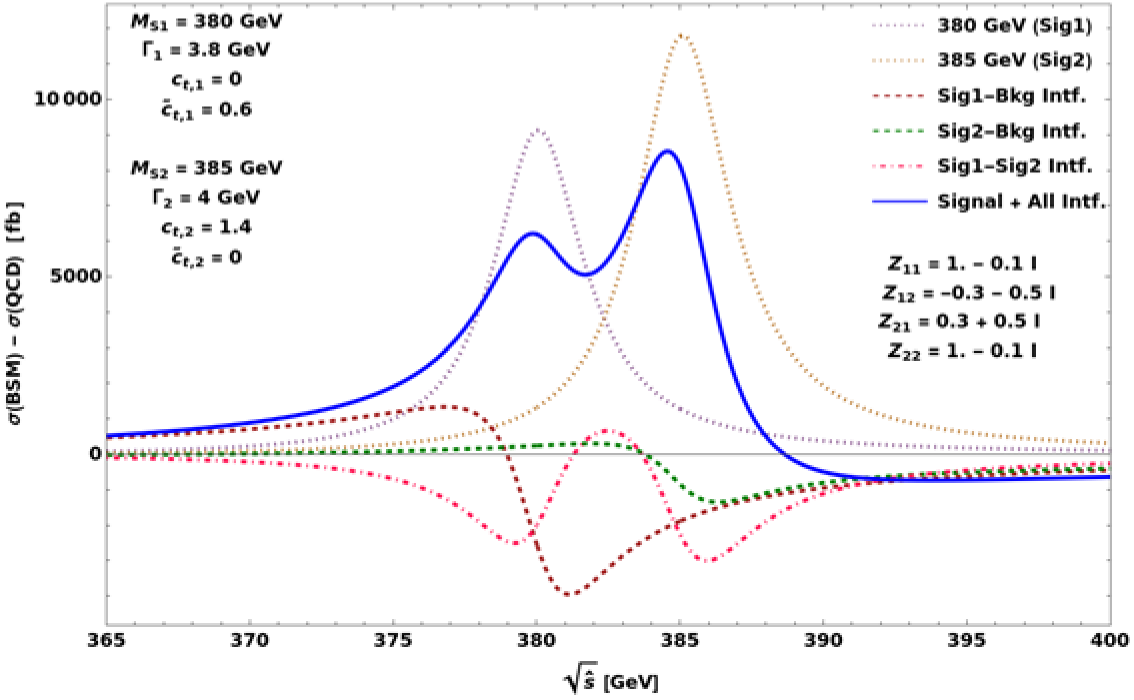

Results

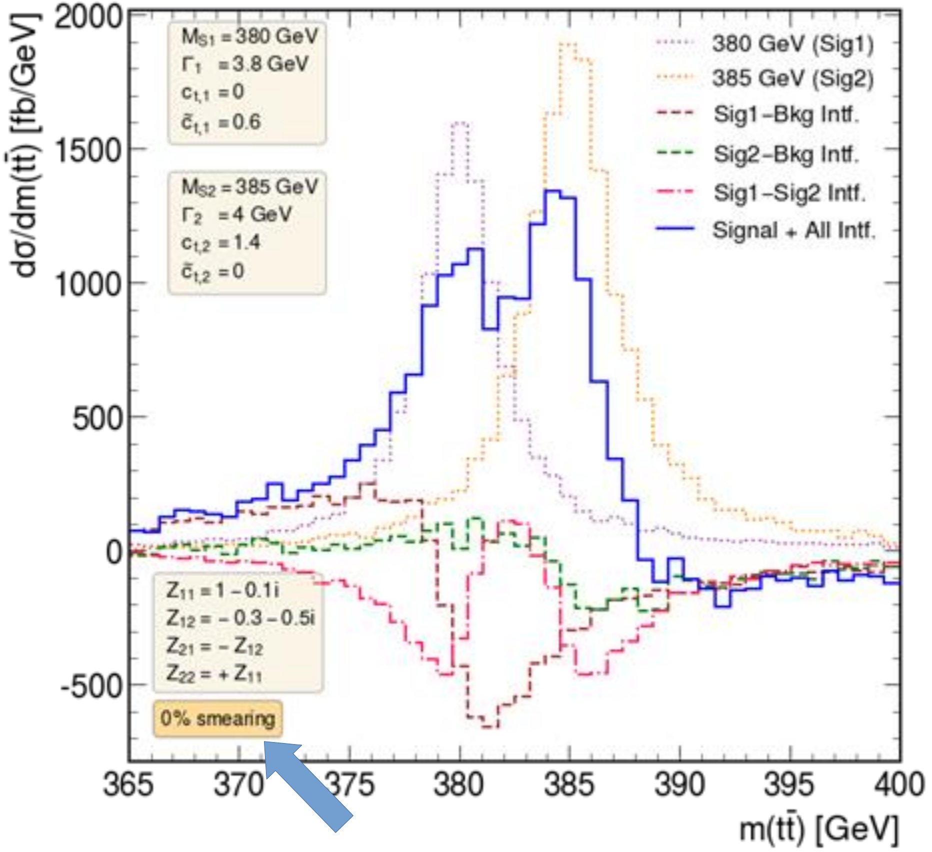
Impact of loop-level mixing



loop-level mixing has significant impact on $m_{t\bar{t}}$ distribution

MC implementation

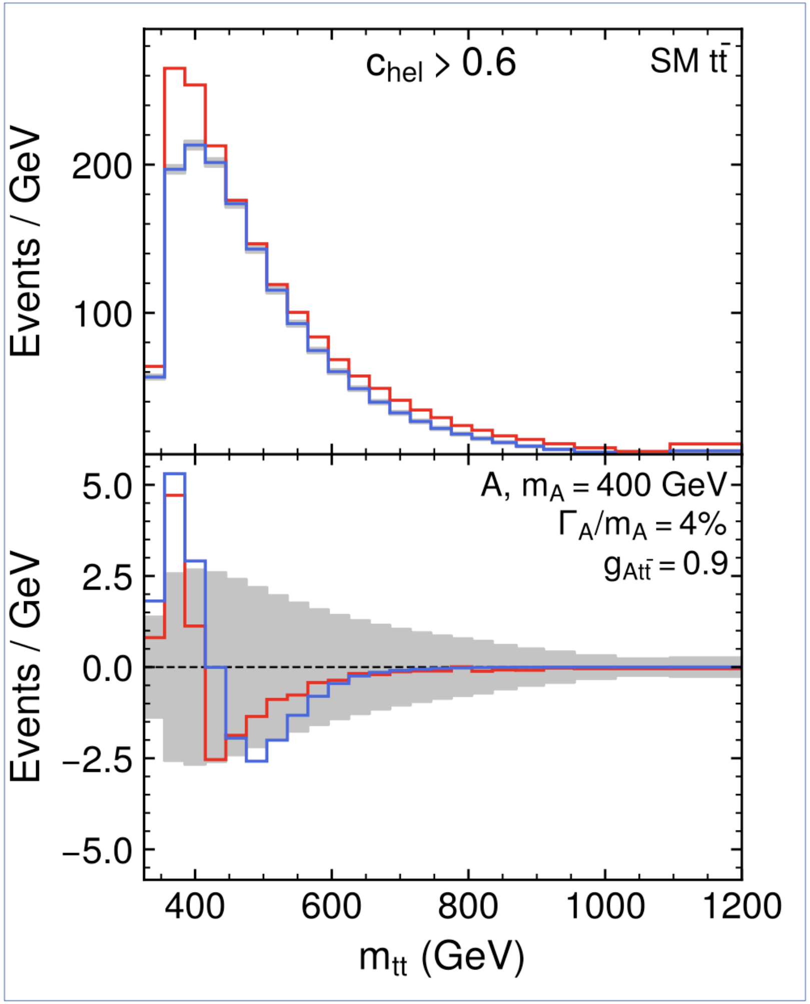




good agreement between analytical and Monte-Carlo results

Prospects at the LHC

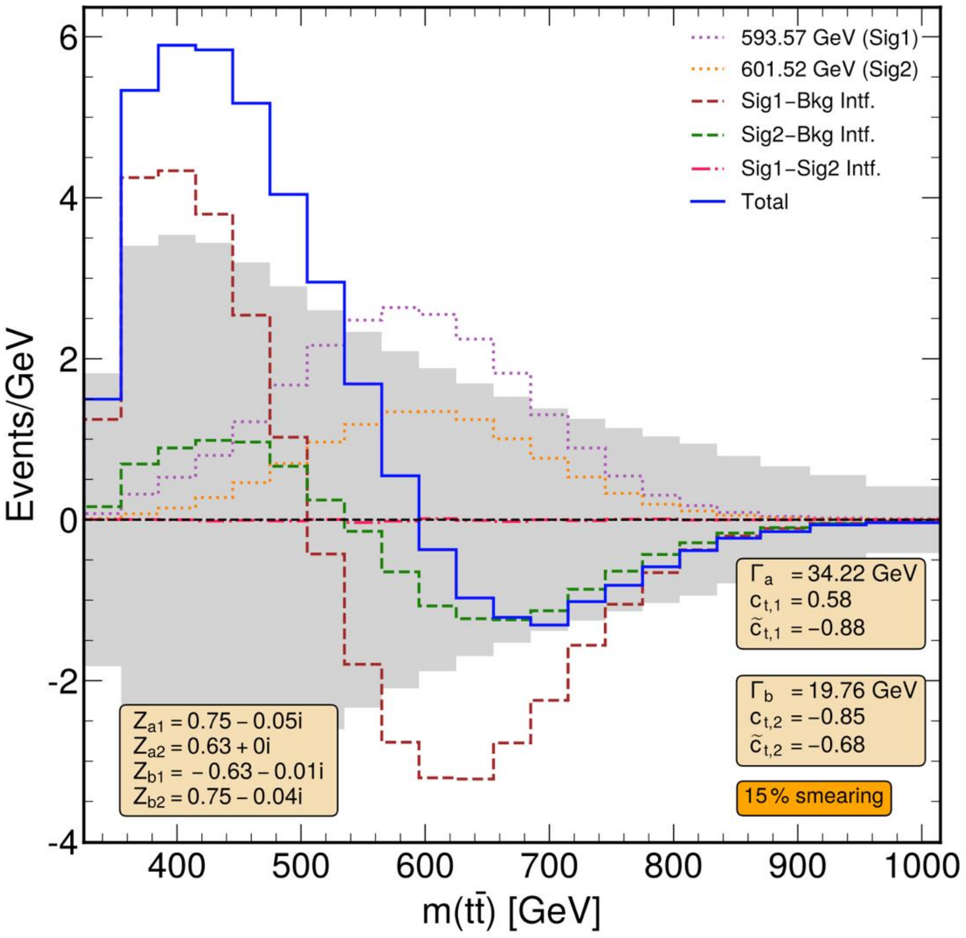
- comparison with experimental sensitivity at Run-3 of the LHC based on [Anuar et al.,2404.19014]
- Gaussian smearing of 15% on the $m_{t\bar{t}}$ variable to incorporate detector-effects
- grey band: statistical uncertainty band
- within experimental reach: region outside grey band



Anuar et al. [2404.19014]

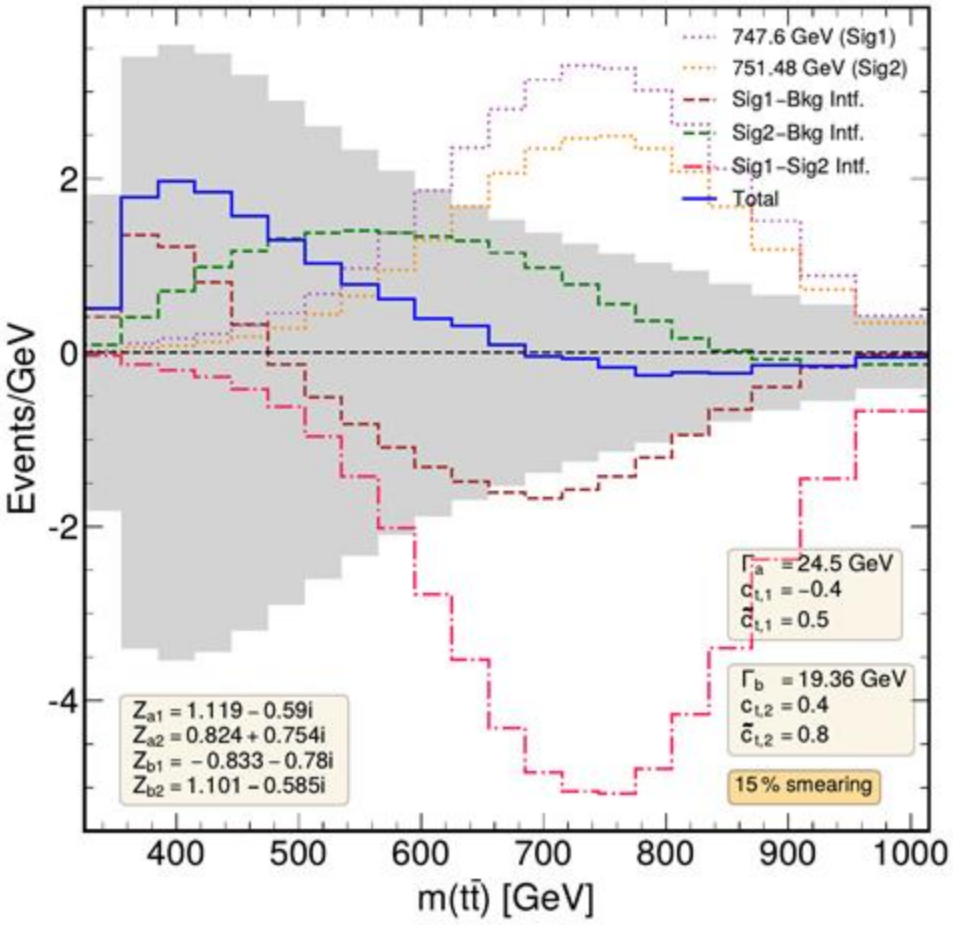
Complex 2HDM scenario

- benchmark point taken from [Basler et al., 1909.09987]
- peak at low $m_{t\bar{t}}$ even though scalars at ~ 600 GeV



“Nightmare” scenario

- large destructive signal-signal interference cancels the sum of the two signal resonances
- motivation to investigate complementary 4-top and 3-top channels



Takeaways!

- complete Monte-Carlo implementation to simulate $t\bar{t}$ production including support for the loop-level scalar mixing

- (loop-level)-mixing between scalars can significantly alter $m_{t\bar{t}}$ distribution

- unexpected and difficult-to-interpret signatures can emerge
  → correlate with 4-top and 3-top production

Takeaways!

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- (loop-level)-mixing between scalars can significantly alter $m_{t\bar{t}}$ distribution
- unexpected and difficult-to-interpret signatures can emerge
  $\rightarrow$ correlate with 4-top and 3-top production

Thank you for your attention!