A model-independent analysis of interference effects in the $t\bar{t}$ final state at the LHC involving two CP-mixed Higgs bosons

Romal Kumar (DESY)
(in collaboration with Henning Bahl and Georg Weiglein)

02.03.2023

Outline

- **Introduction + Simplified model framework**
- **Summary of the Monte-Carlo implementation**
- **Results with mixing between the scalars**
- **(time permitting) Application to the C2HDM**

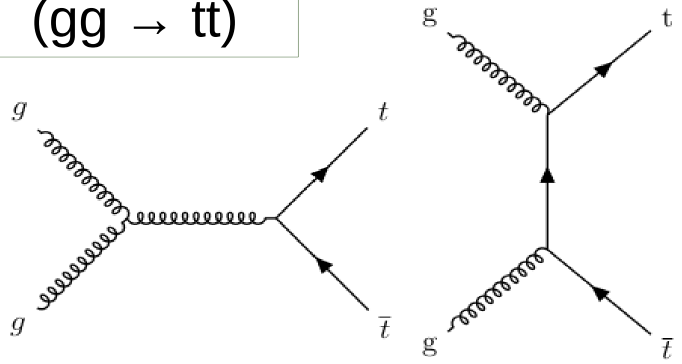
Di-top final state

- Total amplitude:

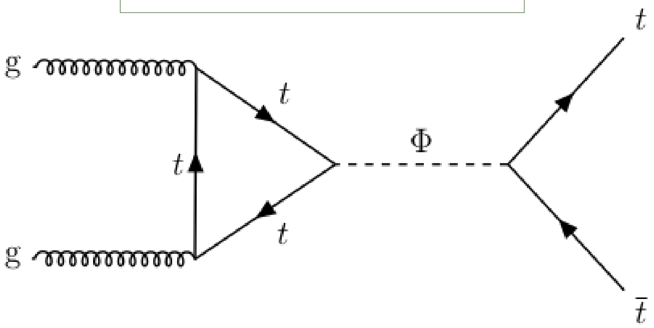
$$\mathcal{A} = \mathcal{A}(gg \to t\bar{t}) + \mathcal{A}(gg \to \Phi \to t\bar{t})$$

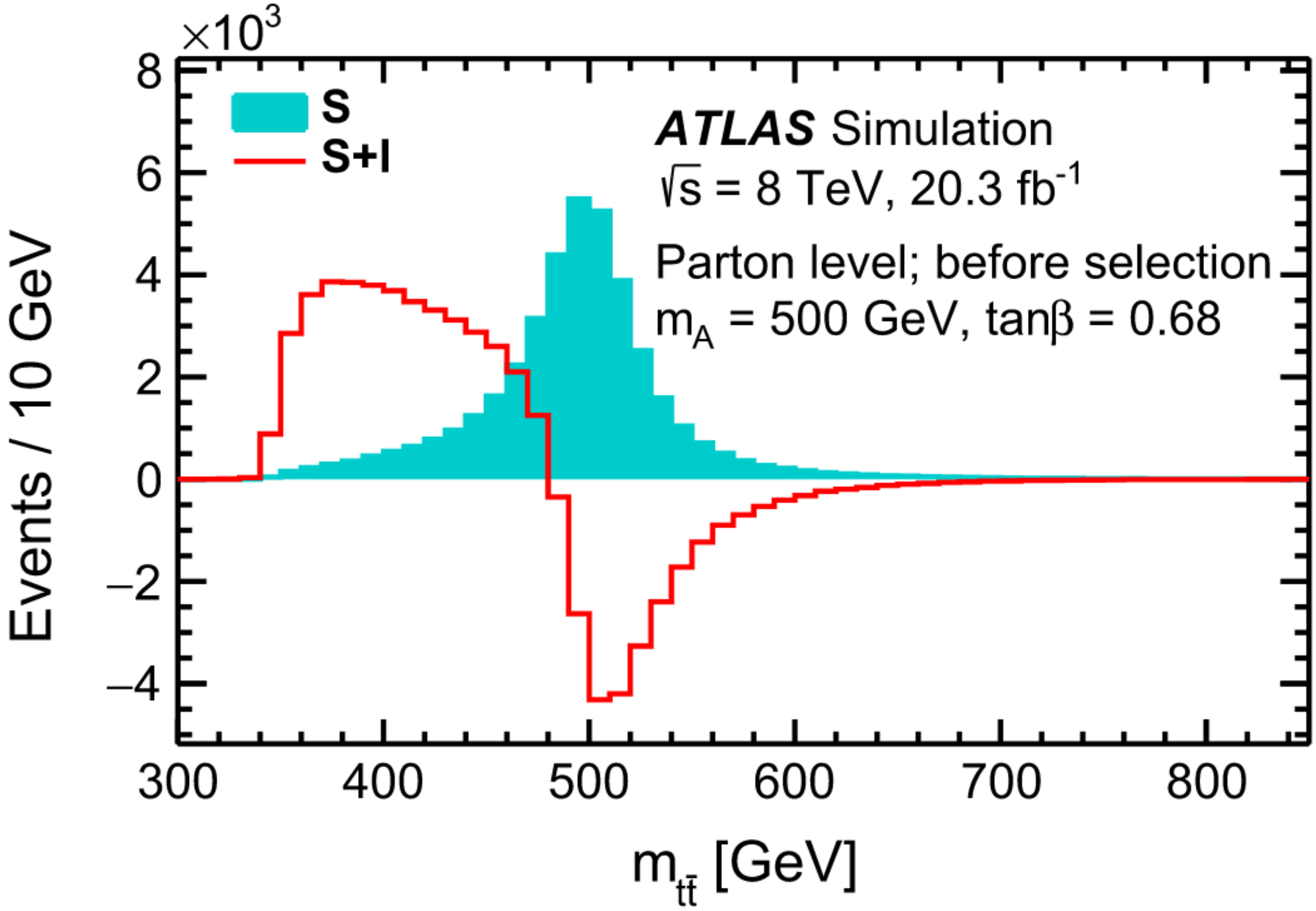
- Interference between the amplitudes in the cross-section!
- Signal-background interference: large destructive contribution
- Invariant mass distribution of the top quarks significantly distorted → peak-dip structure

QCD background
(gg → tt)



Signal
(gg → Φ → tt)





arXiv:1707.06025

Simplified model framework

- Extended Higgs sector
- Consider two scalars (Φ_1, Φ_2) such that
  - massive than di-top threshold ($M_\Phi > 2\, m_t$)
  - produced via gluon fusion with top-triangle loop
  - CP-mixed character
  - decay to top quarks

CP-even CP-odd

$$\mathcal{L}_{\text{yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\, \bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\, tH$$

Yukawa-coupling modifiers

- Analytical implementation (Mathematica)
- Monte-Carlo implementation (MadGraph 3.4.0)

- Investigate impact of interference effects on the distribution profiles
- With two scalars: signal-signal interference possible

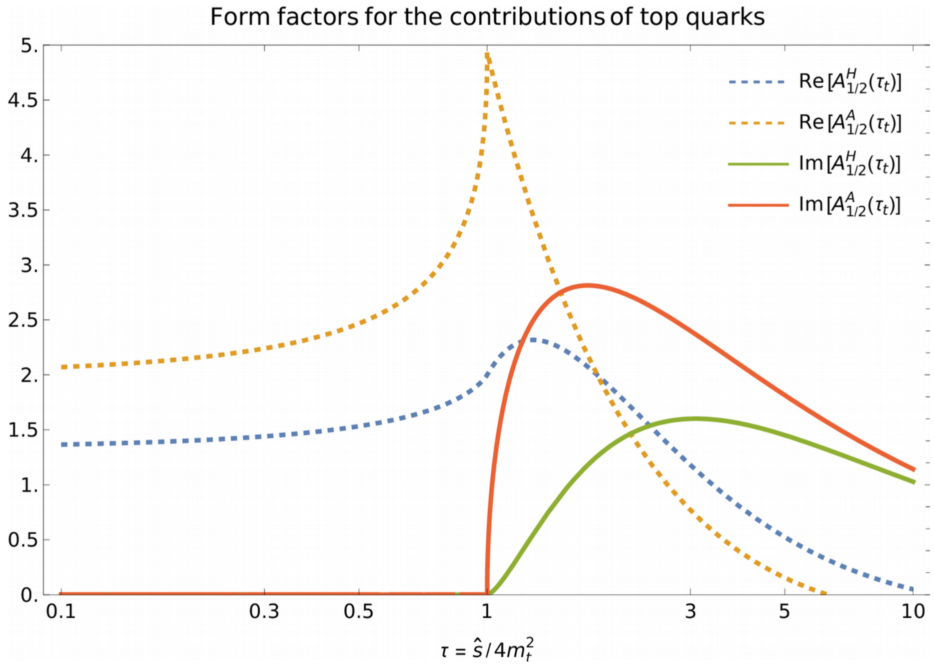
- Contribution of signal-signal interference
- Conditions? $|M_{H_1} - M_{H_2}| < \Gamma_{H_1} + \Gamma_{H_2}$
- Possible distribution profiles? Modifications to the usual peak-dip?

- Scalars mixing at loop-level → Z-factors (complex numbers) → modify distribution profiles?
- Followed by Monte-Carlo simulations

- Investigate impact of interference effects on the distribution profiles
- With two scalars: signal-signal interference possible
- Contribution of signal-signal interference
- Conditions? $|M_{H_1} - M_{H_2}| < \Gamma_{H_1} + \Gamma_{H_2}$
- Possible distribution profiles? Modifications to the usual peak-dip?
- **Scalars mixing at loop-level → Z-factors (complex numbers) → modify distribution profiles?**
- **Followed by Monte-Carlo simulations**

Summary of the Monte-Carlo implementation

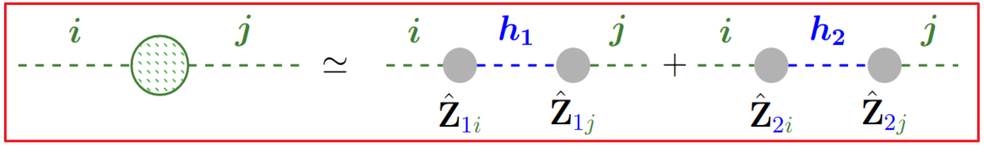
- Sizeable imaginary parts above the di-top threshold, effective coupling – poor approximation
- Incorporate the full top-triangle loop
- Two scalars, Yukawa-coupling modifiers, internal bookkeeping variables, and the Z-factors in the FeynRules file
- “hacked” python files in the FeynRules output files, Fortran routine for the top-loop



+ MadGraph caveats! (for e.g., internal parameters vs external parameters, etc)

Investigation with Z-factors

Allow the scalars to mix at the loop-level → Z-factors (complex numbers) → modify distribution profiles?



- Lowest-order interaction states H_1, H_2 → mix at loop-level → h_a, h_b loop-corrected mass eigenstates
- Following arxiv:1610.06193, for particles that mix, the total amplitude (gg → Φ → tt) can be written using Z-factors and the Breit-Wigner propagators as

$$\mathcal{A} = \sum_{a=1,2} \left(\sum_{i=H_1,H_2} \hat{Z}_{ai} \hat{\Gamma}_i^X \right) \Delta_a^{\mathrm{BW}}(p^2) \left(\sum_{j=H_1,H_2} \hat{Z}_{aj} \hat{\Gamma}_j^Y \right)$$

- $\hat{Z}$-matrix complex elements! [finite wave function normalisation factor (proper normalisation of the S-matrix)]

- In our case, we have,

$$\hat{\Gamma}^{(X,Y)}_{H_1} \propto (c_{t,1} + i\gamma_5 \tilde{c}_{t,1})$$

$$\hat{\Gamma}^{(X,Y)}_{H_2} \propto (c_{t,2} + i\gamma_5 \tilde{c}_{t,2})$$

$$\begin{aligned}\mathcal{A} \propto & \left(\hat{\boldsymbol{Z}}_{h_a H_1}(c_{t,1} + i\gamma_5 \tilde{c}_{t,1}) + \hat{\boldsymbol{Z}}_{h_a H_2}(c_{t,2} + i\gamma_5 \tilde{c}_{t,2})\right) \Delta^{\mathrm{BW}}_{h_a}(p^2) \\ & \left(\hat{\boldsymbol{Z}}_{h_a H_1}(c_{t,1} + i\gamma_5 \tilde{c}_{t,1}) + \hat{\boldsymbol{Z}}_{h_a H_2}(c_{t,2} + i\gamma_5 \tilde{c}_{t,2})\right) \\ & + \left(\hat{\boldsymbol{Z}}_{h_b H_1}(c_{t,1} + i\gamma_5 \tilde{c}_{t,1}) + \hat{\boldsymbol{Z}}_{h_b H_2}(c_{t,2} + i\gamma_5 \tilde{c}_{t,2})\right) \Delta^{\mathrm{BW}}_{h_b}(p^2) \\ & \left(\hat{\boldsymbol{Z}}_{h_b H_1}(c_{t,1} + i\gamma_5 \tilde{c}_{t,1}) + \hat{\boldsymbol{Z}}_{h_b H_2}(c_{t,2} + i\gamma_5 \tilde{c}_{t,2})\right)\end{aligned}$$

- With

$$\hat{\boldsymbol{Z}}_{h_a H_1} = Z_{11}\,,\ \hat{\boldsymbol{Z}}_{h_a H_2} = Z_{12}\,,\ \hat{\boldsymbol{Z}}_{h_b H_1} = Z_{21}\,,\ \hat{\boldsymbol{Z}}_{h_b H_2} = Z_{22}$$

- The amplitude can be written as

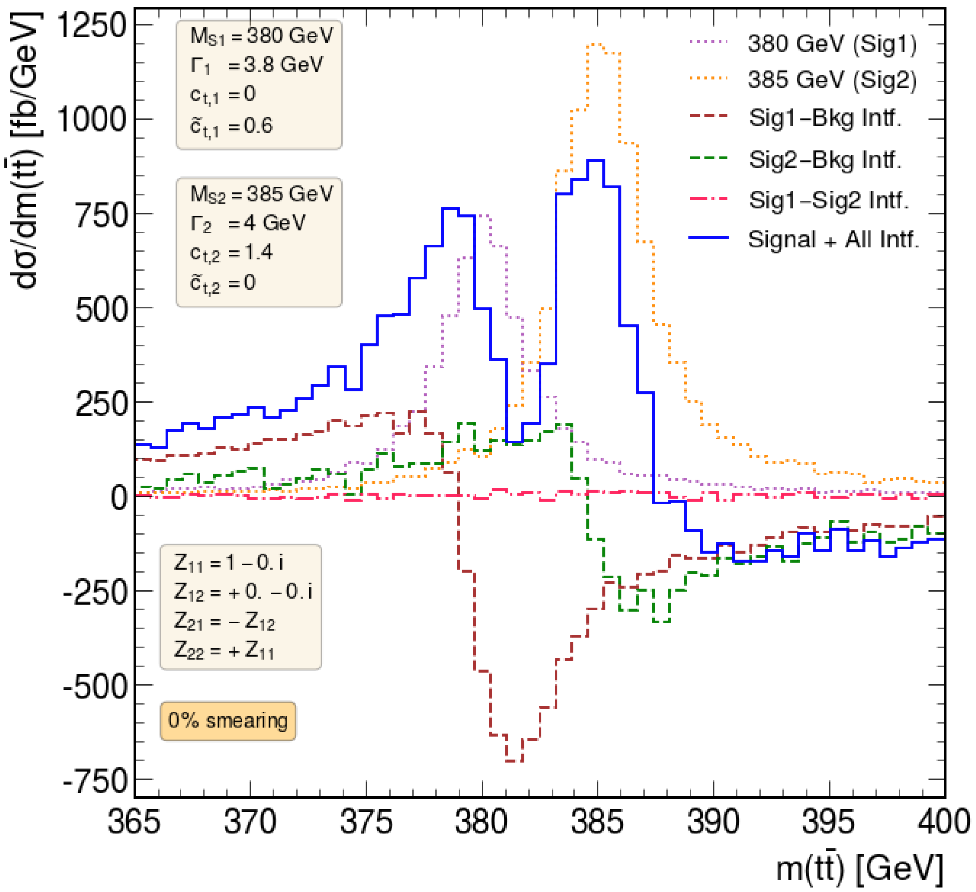
$$\mathcal{A} \propto \Bigg(\underbrace{Z_{11}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + Z_{12}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})}_{\text{Production side}}\Bigg)\,\Delta^{\rm BW}_{h_a}(p^2)\,\Bigg(\underbrace{Z_{11}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + Z_{12}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})}_{\text{Decay side}}\Bigg)$$
$$+\Bigg(\underbrace{Z_{21}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + Z_{22}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})}_{\text{Production side}}\Bigg)\,\Delta^{\rm BW}_{h_b}(p^2)\,\Bigg(\underbrace{Z_{21}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + Z_{22}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})}_{\text{Decay side}}\Bigg)$$

- Identifying

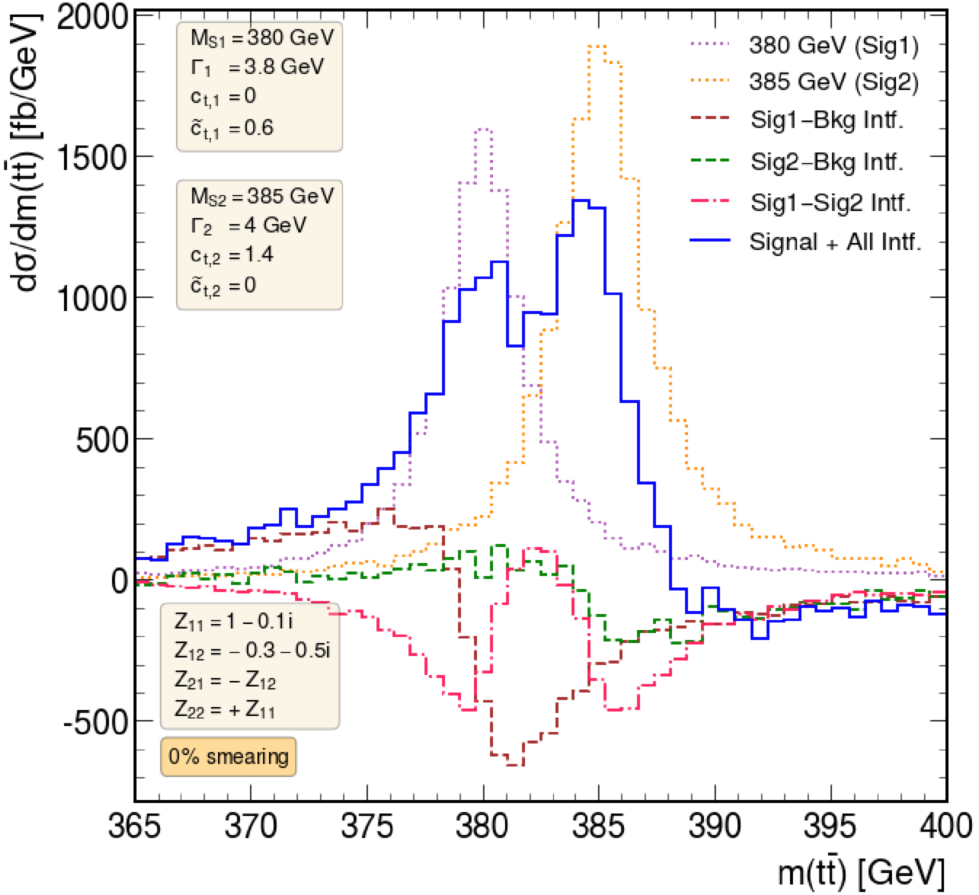
$$c_{t,1} \to Z_{11}c_{t,1} + Z_{12}c_{t,2}$$
$$\tilde{c}_{t,1} \to Z_{11}\tilde{c}_{t,1} + Z_{12}\tilde{c}_{t,2}$$
$$c_{t,2} \to Z_{22}c_{t,2} + Z_{21}c_{t,1}$$
$$\tilde{c}_{t,2} \to Z_{22}\tilde{c}_{t,2} + Z_{21}\tilde{c}_{t,1}$$

→ **Z-factors can be complex numbers** → **Complex Yukawa-coupling modifiers!**

Additional phases!

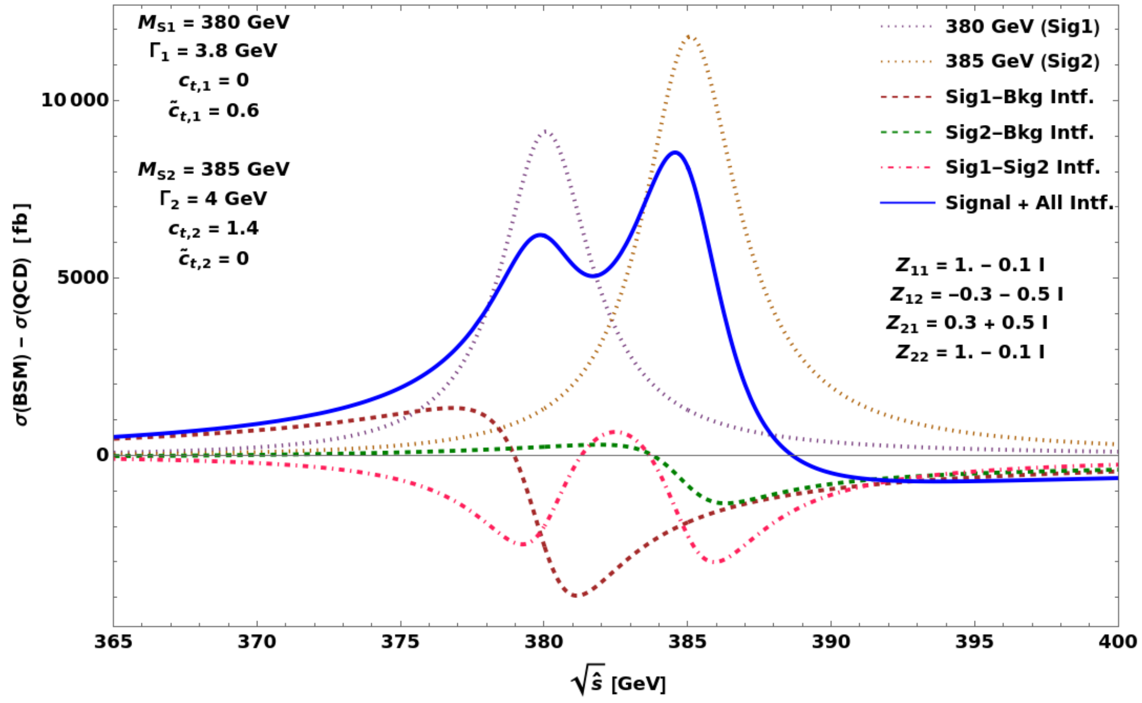


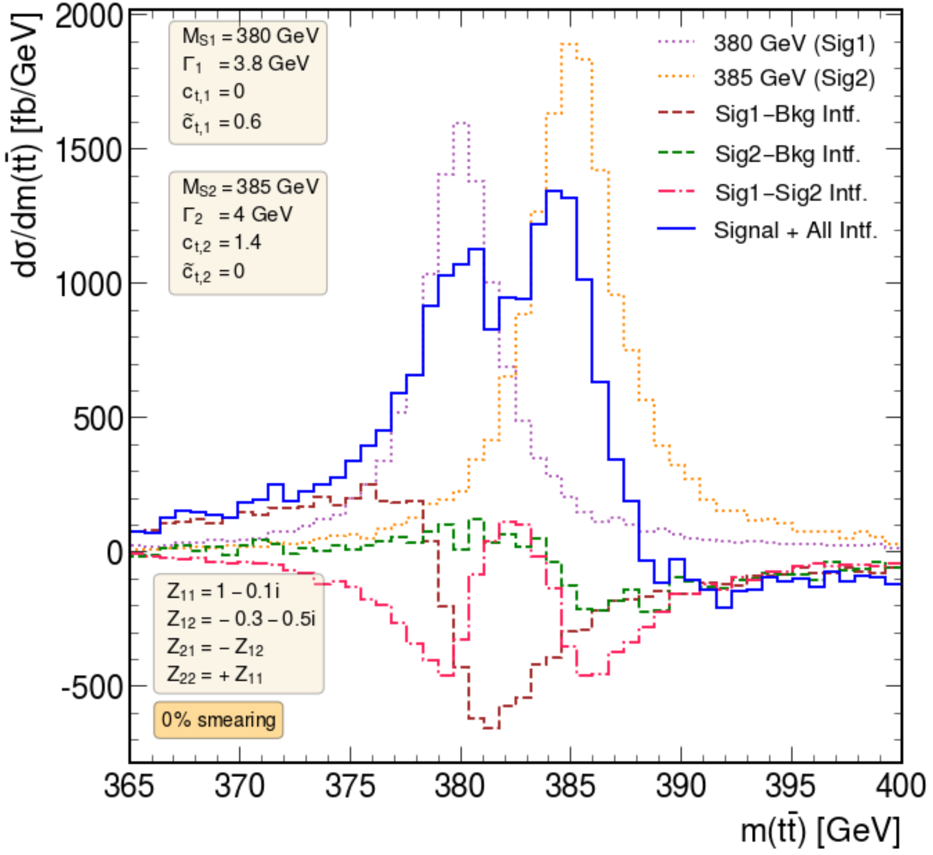
Without mixing



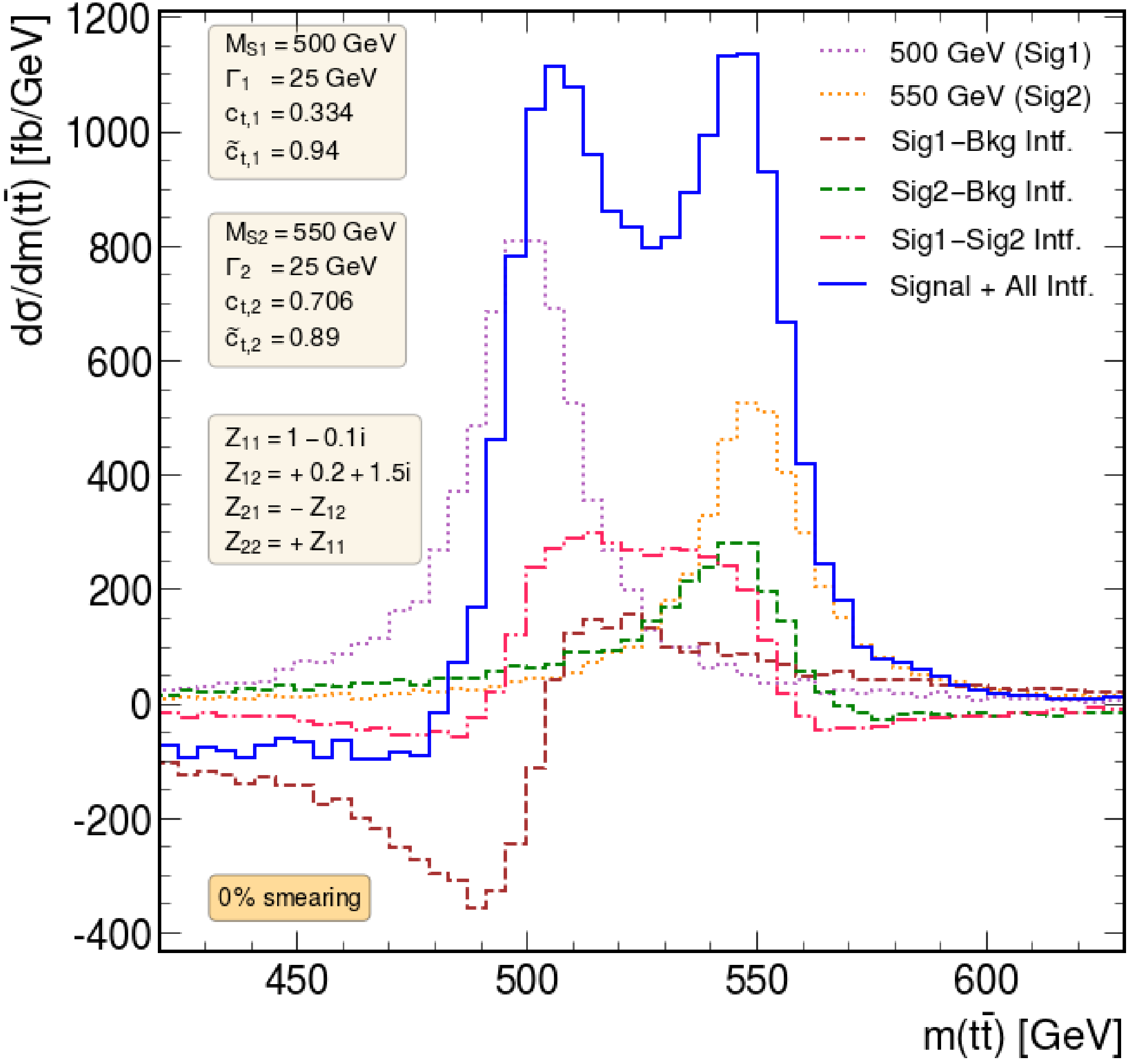
With mixing

With mixing

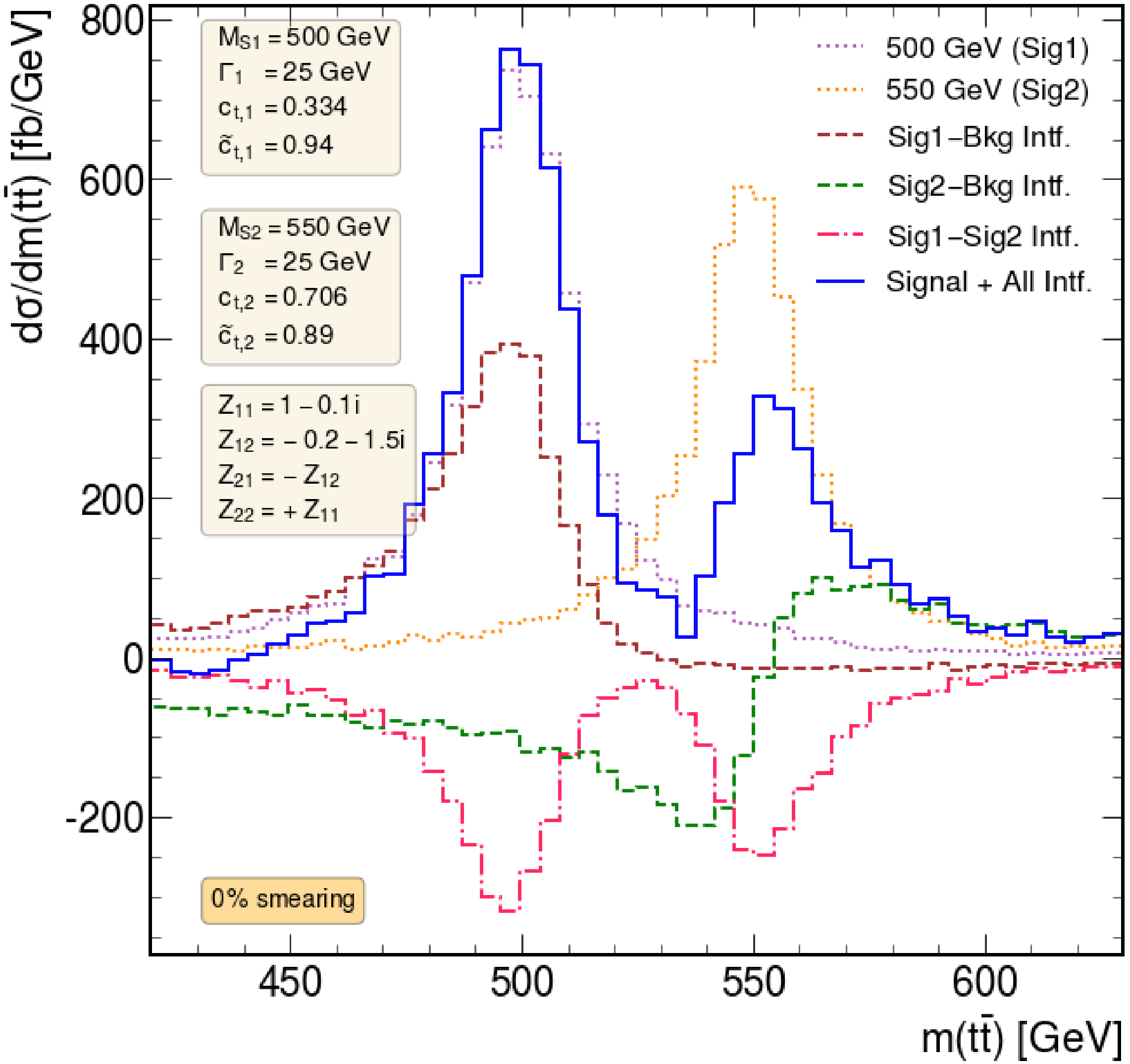




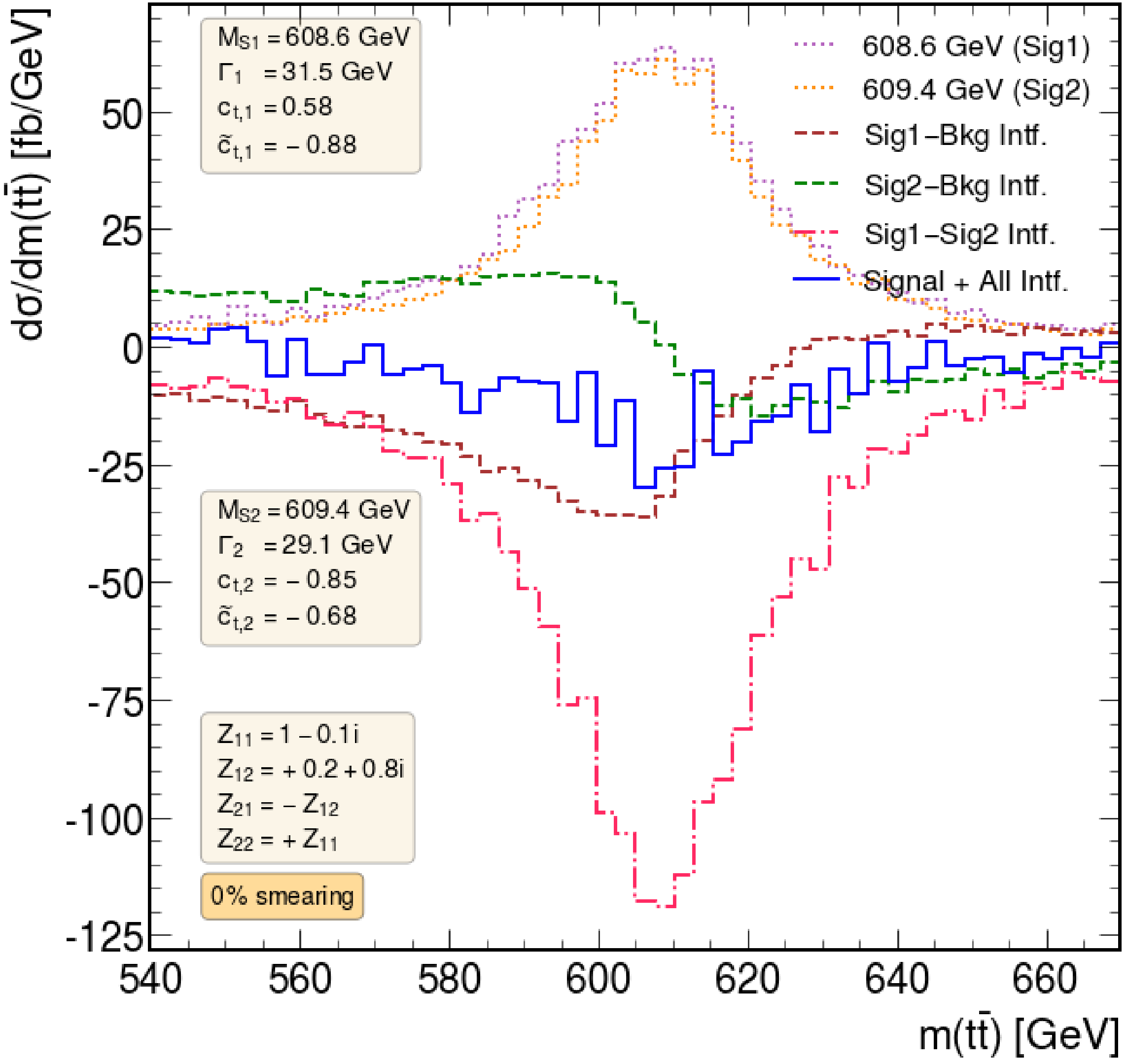
Good agreement between analytical
and Monte-Carlo results



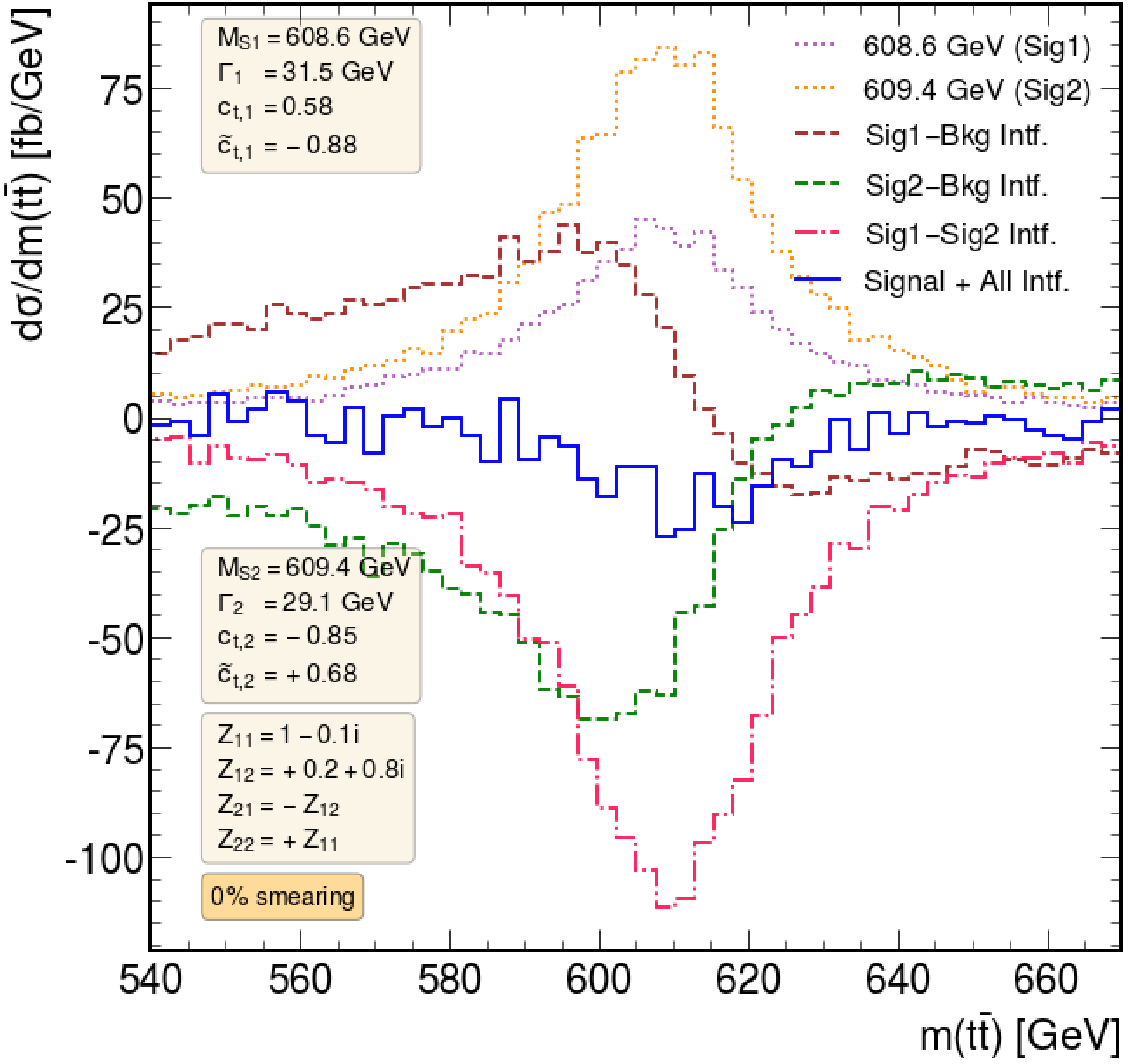
Large mixing between the scalars



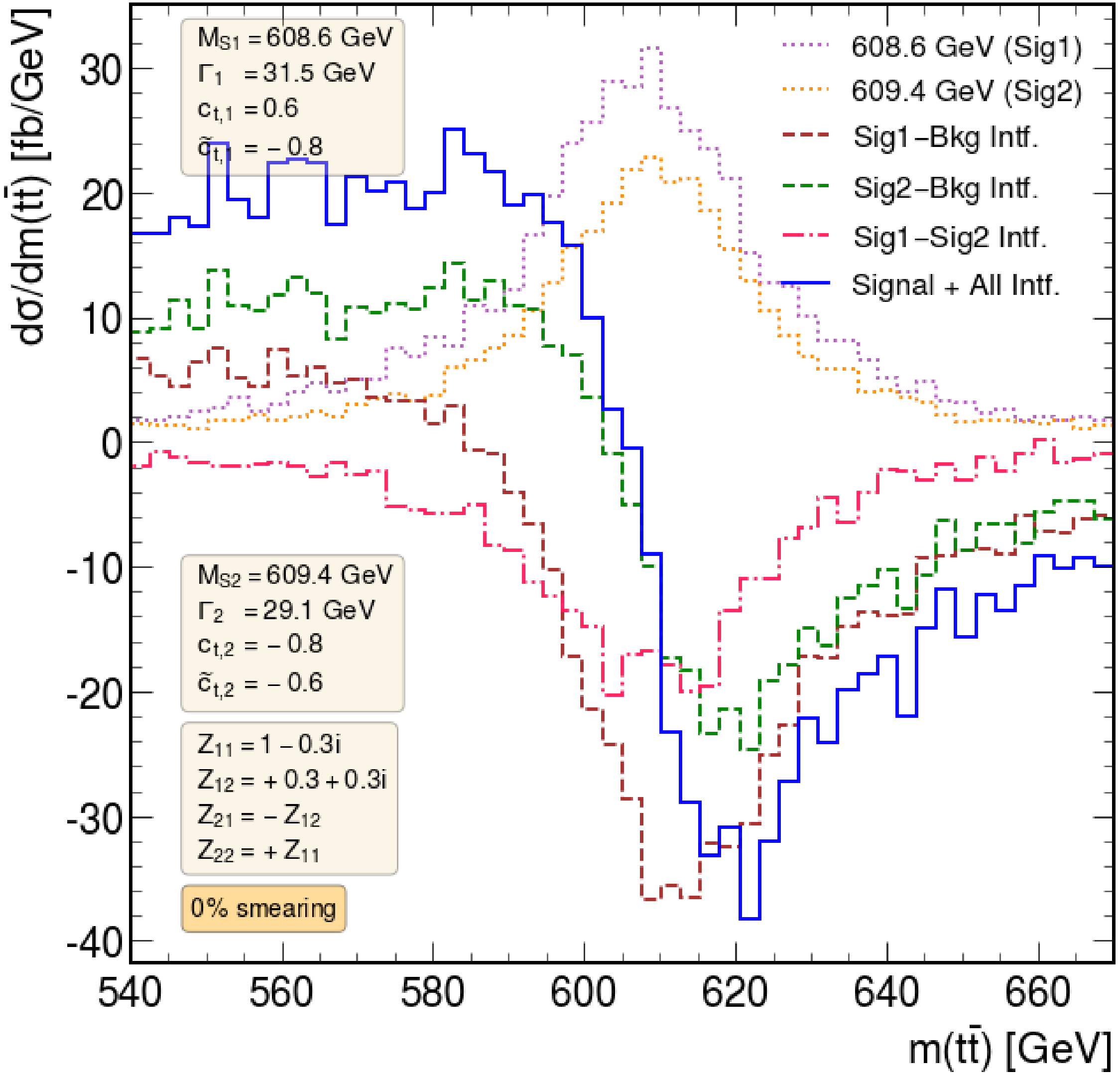
Large mixing between the scalars, different sign for off-diagonal term



Large destructive signal-signal interference



ct2 flipped, different behaviour of signal-background interferences



Slightly smaller values of Yukawa-coupling modifiers and mixing

Takeaways!

- Monte-Carlo (and analytical) implementation of individual signal and interference contributions considering mixing between the scalars

- Mixing between scalars can lead to highly non-trivial distribution profiles, rich phenomenology

- One needs precise estimation of the Z-factors

Backup/Extra slides

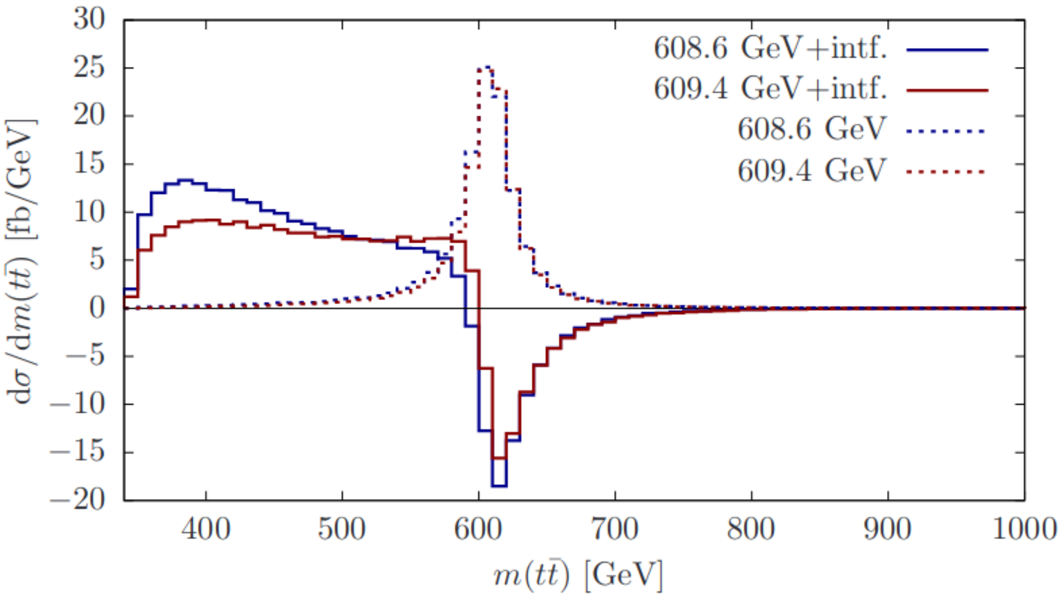
Application to the C2HDM

- Compare results with exisiting literature in arXiv:1909.09987v2
- 2HDM with a CP-violating scalar sector
- The Yukawa-coupling modifiers can be calculated using the elements of the rotation matrix that diagonalizes the 3x3 mass matrix to give a diagonal matrix with mass eigenstates
- We consider the lower-right 2x2 submatrix

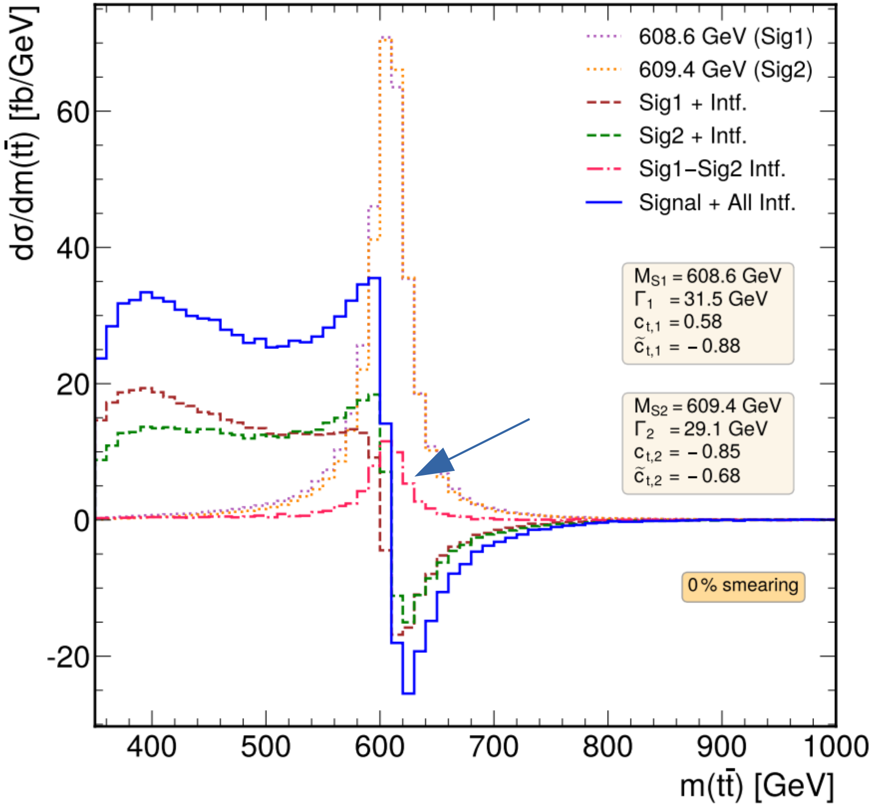
$$\{R_{i,j}\} \equiv R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

$$\text{Type I}: \quad c_t = \frac{R_{i2}}{s_\beta} \quad , \quad \tilde{c}_t = -i\frac{R_{i3}}{t_\beta}$$

$$\text{Type II}: \quad c_t = \frac{R_{i2}}{s_\beta} \quad , \quad \tilde{c}_t = -i\frac{R_{i3}}{t_\beta}$$

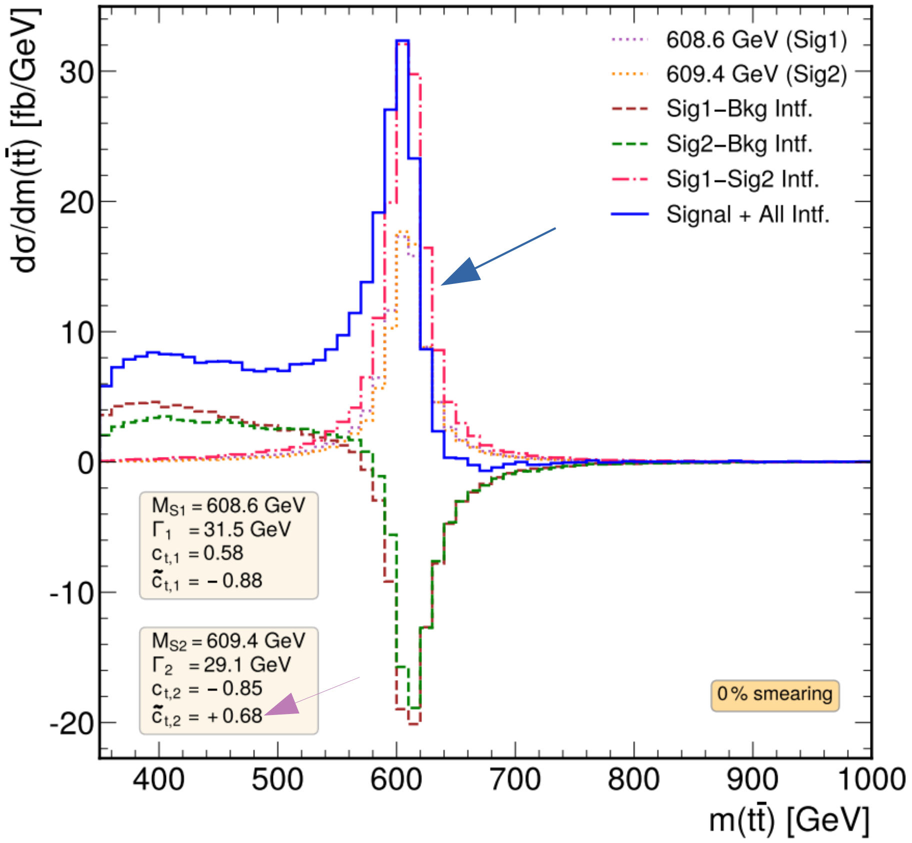


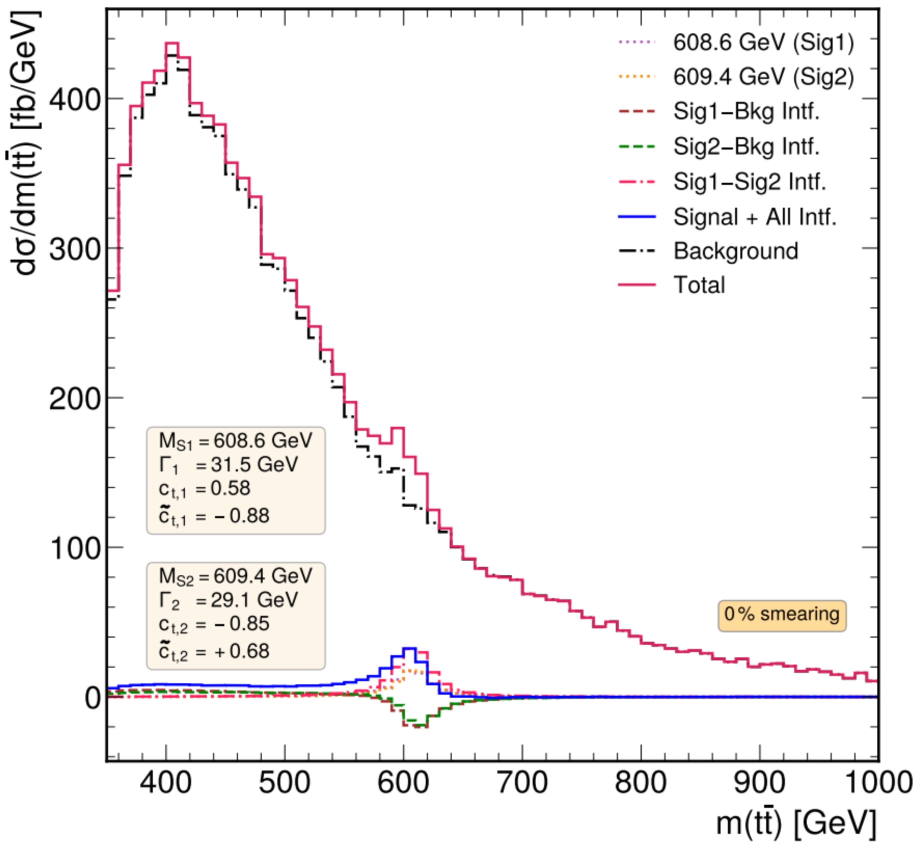
arXiv:1909.09987v2



- Signal-Signal interference can be significant (not considered previously)

Sign of
ctt2 flipped





- Signal-Signal could be as large as one of the pure signals!