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Analysis of interference effects in the di-top final state for CP-mixed scalars in extended Higgs sectors

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(in collaboration with Henning Bahl and Georg Weiglein)

O U T L I N E

- **Simplified model framework**
- **Monte-Carlo implementation**
- **Results with mixing between the scalars**

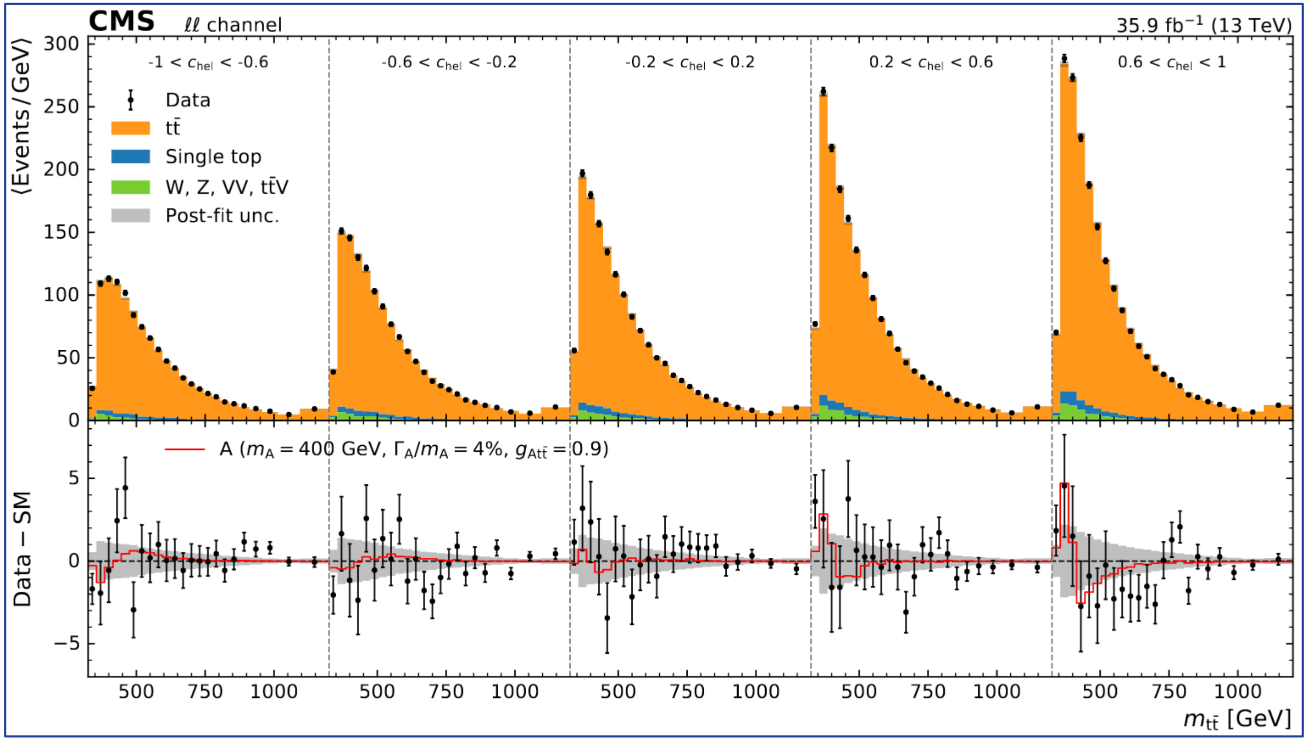
Introduction

- Standard Model (SM) – remarkably successful
- Discovery of a Higgs boson at 125 GeV (at LHC, 2012)
- Understanding of the universe is far from complete
  - hierarchy problem
  - baryon asymmetry of the universe
  - neutrino masses
  - . . .
- Various extensions to the SM
  - supersymmetry (SUSY) → MSSM
  - **extended Higgs sector** (2HDM, C2HDM, ...)

→ Beyond the SM physics!

Motivation

- Many BSM extensions feature heavy scalar(s) that decay to top pairs
- Heavy scalars predicted to have large couplings to third generation fermions
- Recent excess in tt-final state at 400 GeV by CMS [local: 3.5 ± 0.3 σ global: 1.9 σ]



arXiv:1908.01115

Di-top final state

- Total amplitude:

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

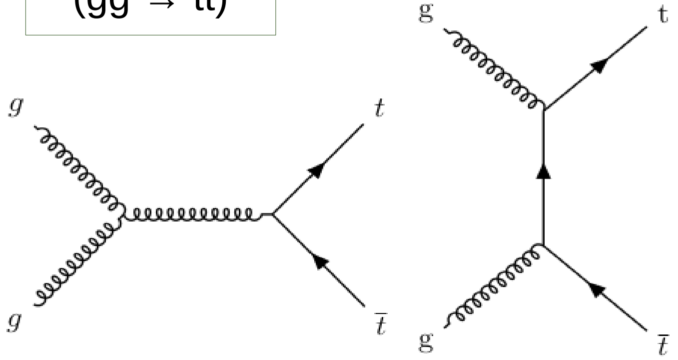
- Signal-background interference

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

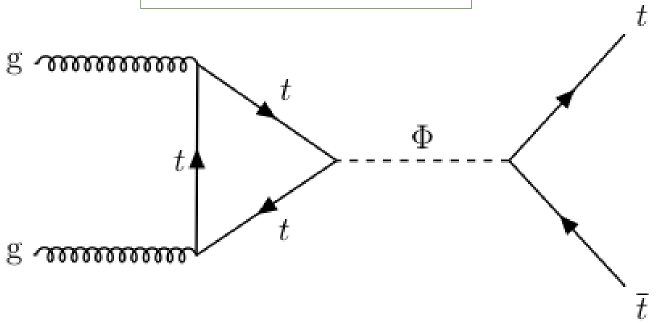
large destructive contribution

- Invariant mass distribution of the top quarks ($m_{t\bar{t}}$) significantly distorted → peak-dip structure

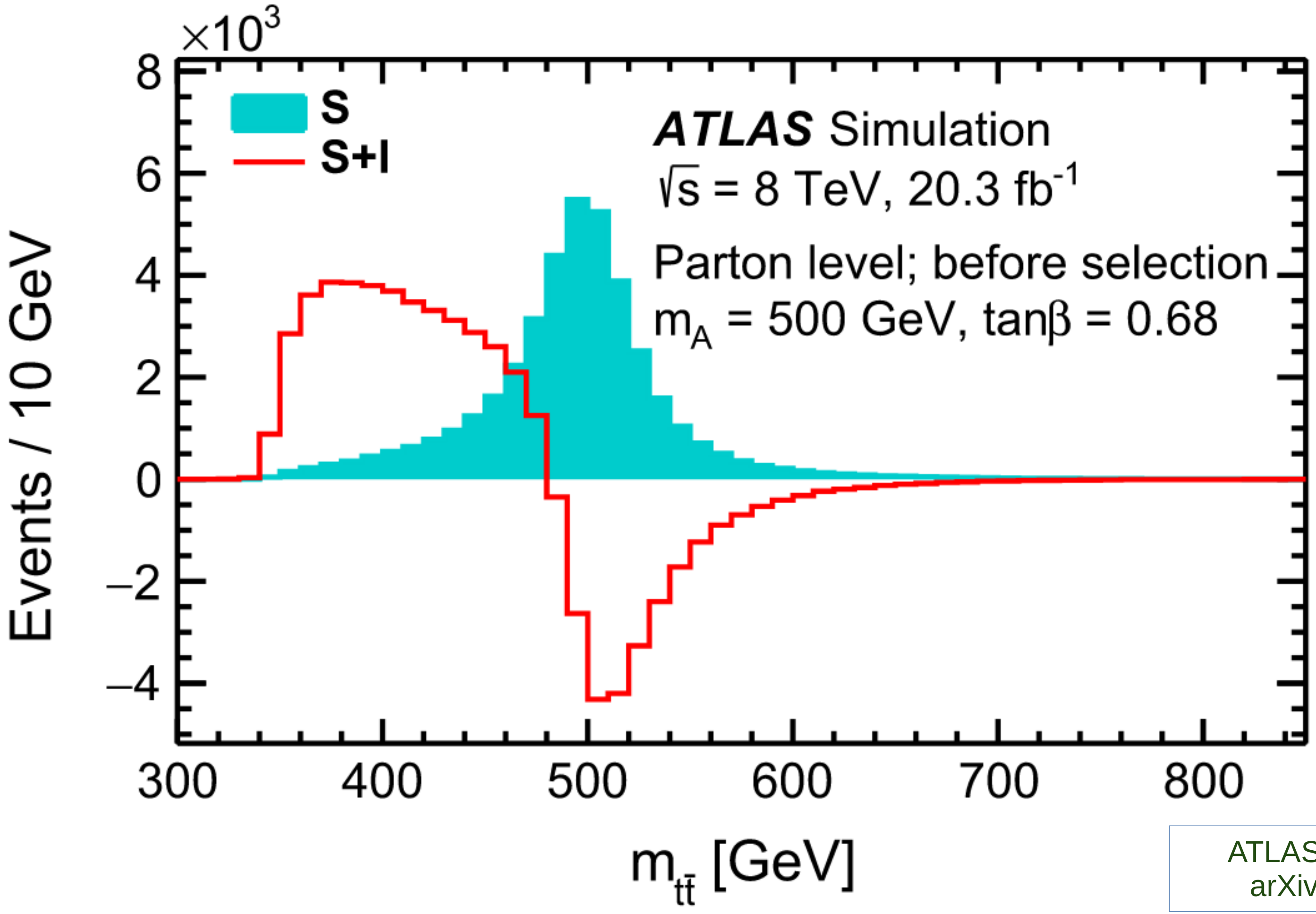
QCD background (gg → tt)



Signal (gg → Φ → tt)



One additional scalar



ATLAS collaboration, arXiv:1707.06025

Simplified model framework

- Extended Higgs sector (theoretically well motivated)
- Consider two scalars $\Phi_j\,\{j=1,2\}$ such that
  - mass above di-top threshold $(M_{\Phi_j} > 2\,m_t)$
  - produced via gluon fusion with top-triangle loop
  - CP-mixed character
  - decay to top quarks

CP-even CP-odd

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

Yukawa-coupling modifiers

Analytical implementation
(Mathematica)

Monte-Carlo implementation
(MadGraph 3.4.0)

Two CP-mixed scalar(s)

- The total amplitude can be written as

$$\mathcal{A}_{gg\to t\bar{t}} = -\sum_{\Phi} \frac{\mathcal{A}_{gg\Phi}\,\hat{s}\,\mathcal{A}_{\Phi t\bar{t}}}{\hat{s} - M_\Phi^2 + iM_\Phi\Gamma_\Phi} + \mathcal{A}_{ggt\bar{t}}$$

- Trivial to extend the Signal-Background interference
- Signal-Signal interference terms contains

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

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

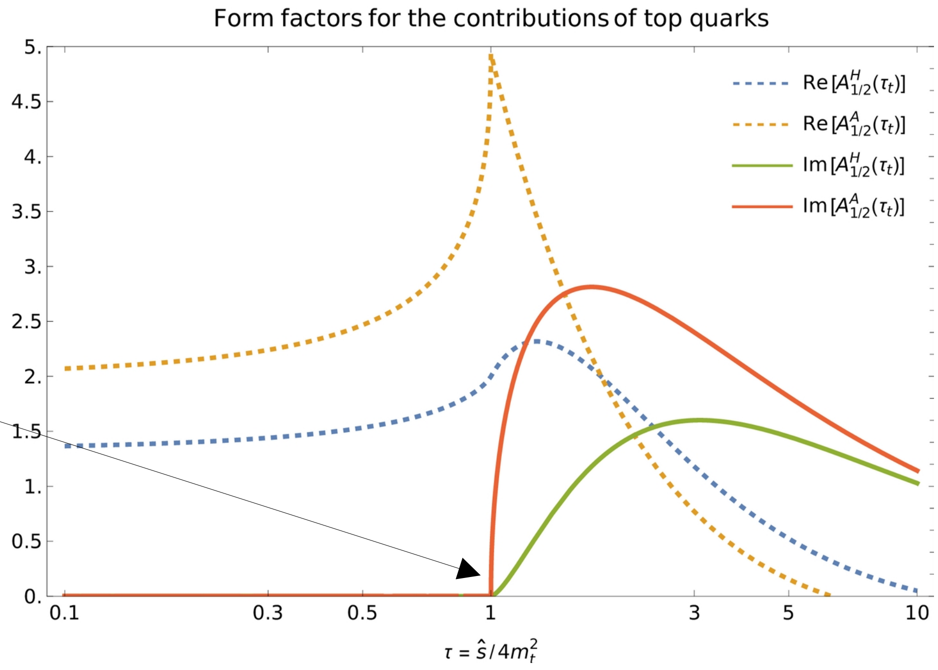
- No signal-signal interference between CP-even and CP-odd
- Sign of Yukawa-coupling modifiers can be relevant

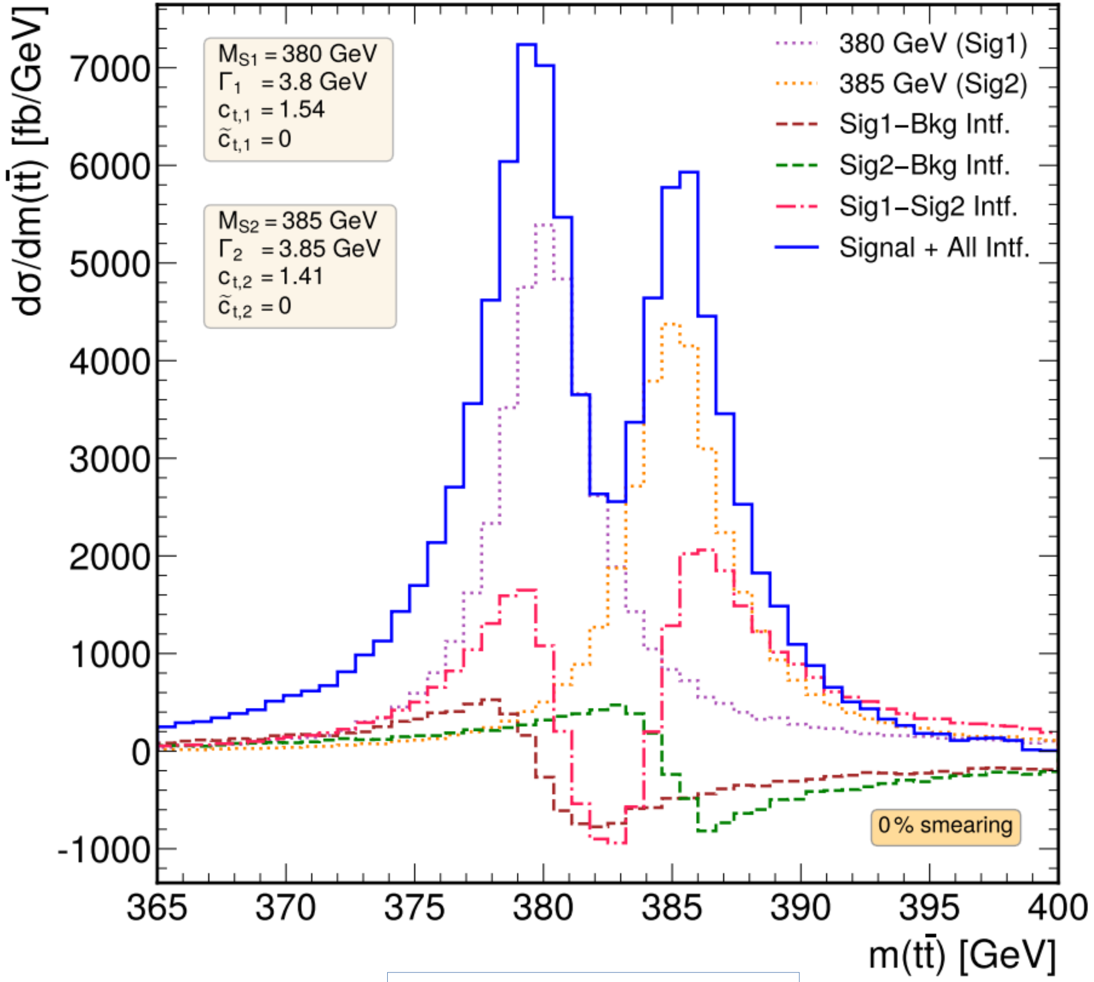
Monte-Carlo: treatment of imaginary parts

- Effective Higgs-gluon coupling – poor approximation
- Sizeable imaginary parts above the di-top threshold

➔ Need to incorporate the full top-quark loop

- Adapted python files in the FeynRules output files, Fortran routine for the top-loop





Monte-Carlo

Illustrative plot for various interference effects [idealistic, no smearing; smearing discussed later]

However, things change when there is mixing between the scalars

Investigation with loop-level mixing

- (lowest-order interaction states) $\{\Phi_1, \Phi_2\} \xrightarrow{\text{mix at loop-level}} \{h_a, h_b\}$ (loop-corrected mass eigenstates)

- For particles that mix, the total amplitude can be written using wavefunction normalization factor ("Z-factors", needed for proper normalization of S-matrix, UV-finite) and the Breit-Wigner (BW) propagators [1610.06193]

$$\mathcal{A} = \sum_{i,j=\Phi_1,\Phi_2} \hat{\Gamma}_i^X \Delta_{ij}(p^2) \hat{\Gamma}_j^Y$$

Z-factor formalism

$$\mathcal{A} \simeq \sum_{i,j=\Phi_1,\Phi_2} \hat{\Gamma}_i^X \left[\sum_{k=1}^{2} \hat{\boldsymbol{Z}}_{ki} \Delta_k^{\mathrm{BW}}(p^2) \hat{\boldsymbol{Z}}_{kj} \right] \hat{\Gamma}_j^Y$$

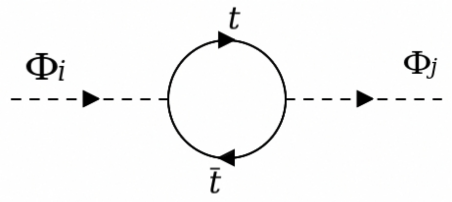
Propagator matrix that involves tree-level parameters of the scalars and (renormalized) self-energies

$$\Delta_k^{\mathrm{BW}}(p^2) = \frac{i}{p^2 - M_k^2 + i\, M_k \Gamma_k}$$

Containing loop-corrected mass

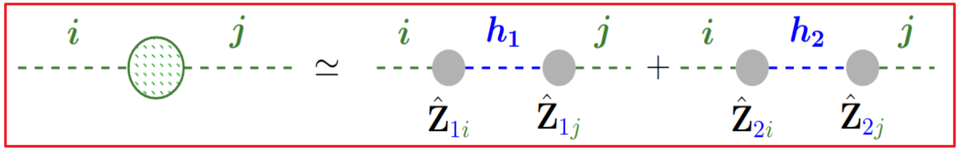
Investigation with loop-level mixing

- Z-factors rearranged in matrix → $\hat{Z}$–matrix, non-unitary and complex elements!
- Upshot: use Z-factors to write propagator-mixing in terms of separate Breit-Wigner propagators involving loop-corrected masses and widths



Z-factors calculated from self-energies contributions

Large mixing effects can be possible (large off-diagonal terms in the Z-matrix)



$$\mathcal{A} = \sum_{k=h_a,h_b} \left(\sum_{i=\Phi_1,\Phi_2} \hat{\boldsymbol{Z}}_{ki} \hat{\Gamma}_i^X \right) \Delta_k^{\mathrm{BW}}(p^2) \left(\sum_{j=\Phi_1,\Phi_2} \hat{\boldsymbol{Z}}_{kj} \hat{\Gamma}_j^Y \right)$$

$$\hat{\Gamma}^{(X,Y)}_{\Phi_1} \propto \left(c_{t,1} + i\gamma_5 \tilde{c}_{t,1}\right)$$
$$\hat{\Gamma}^{(X,Y)}_{\Phi_2} \propto \left(c_{t,2} + i\gamma_5 \tilde{c}_{t,2}\right)$$

$$\mathcal{A} \propto \left(\hat{Z}_{h_a\Phi_1}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + \hat{Z}_{h_a\Phi_2}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})\right) \Delta^{\mathrm{BW}}_{h_a}(p^2) \left(\hat{Z}_{h_a\Phi_1}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + \hat{Z}_{h_a\Phi_2}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})\right)$$
$$+ \left(\hat{Z}_{h_b\Phi_1}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + \hat{Z}_{h_b\Phi_2}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})\right) \Delta^{\mathrm{BW}}_{h_b}(p^2) \left(\hat{Z}_{h_b\Phi_1}(c_{t,1} + i\gamma_5\tilde{c}_{t,1}) + \hat{Z}_{h_b\Phi_2}(c_{t,2} + i\gamma_5\tilde{c}_{t,2})\right)$$

Z_{11} **Z_{12}** **Z_{21}** **Z_{22}**

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

Z-factors can be complex numbers

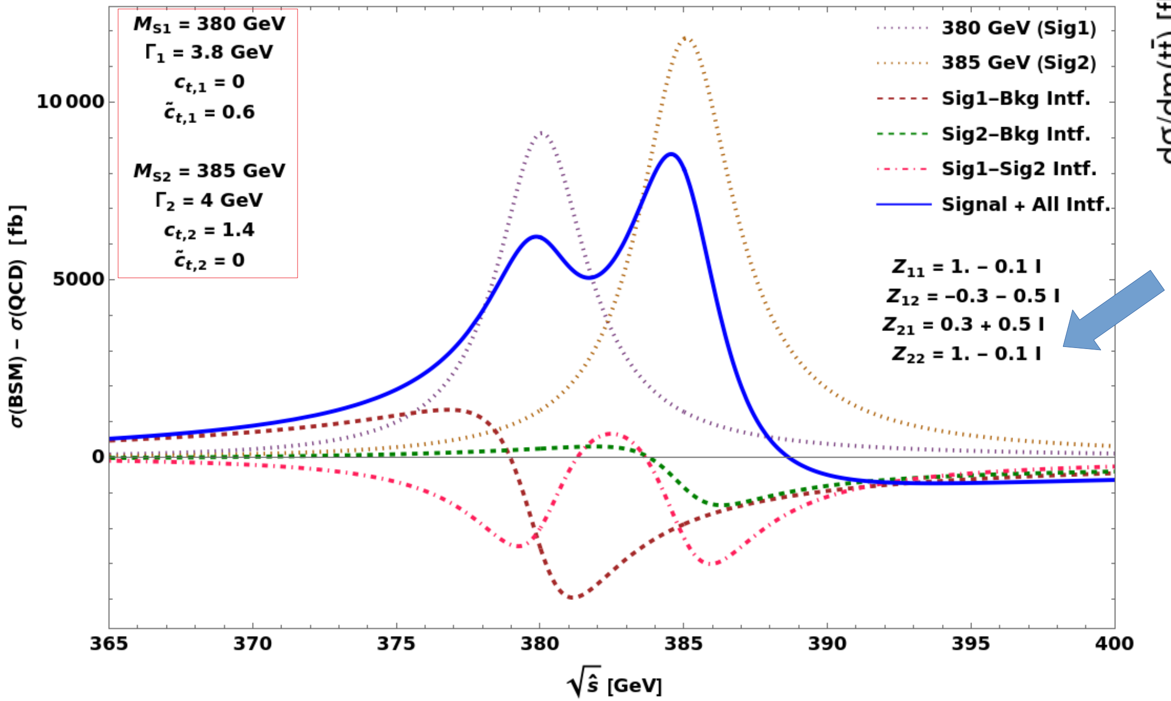
Additional phases!

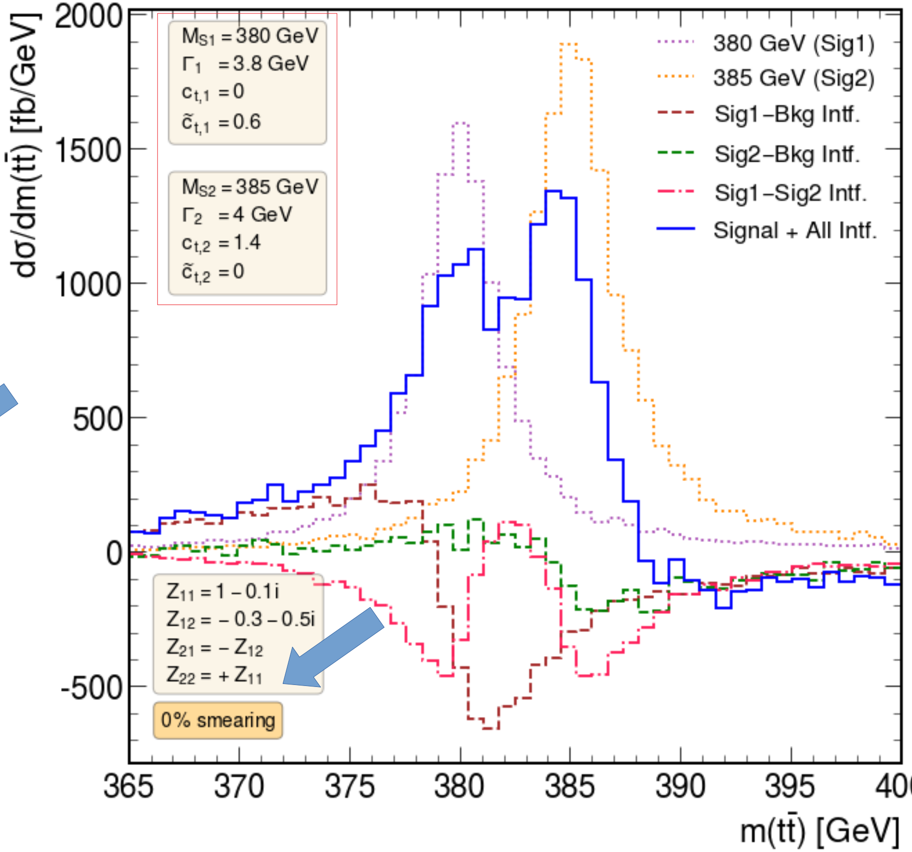
Approximately

$Z_{11} = Z_{22}$

$Z_{12} = -Z_{21}$


Results

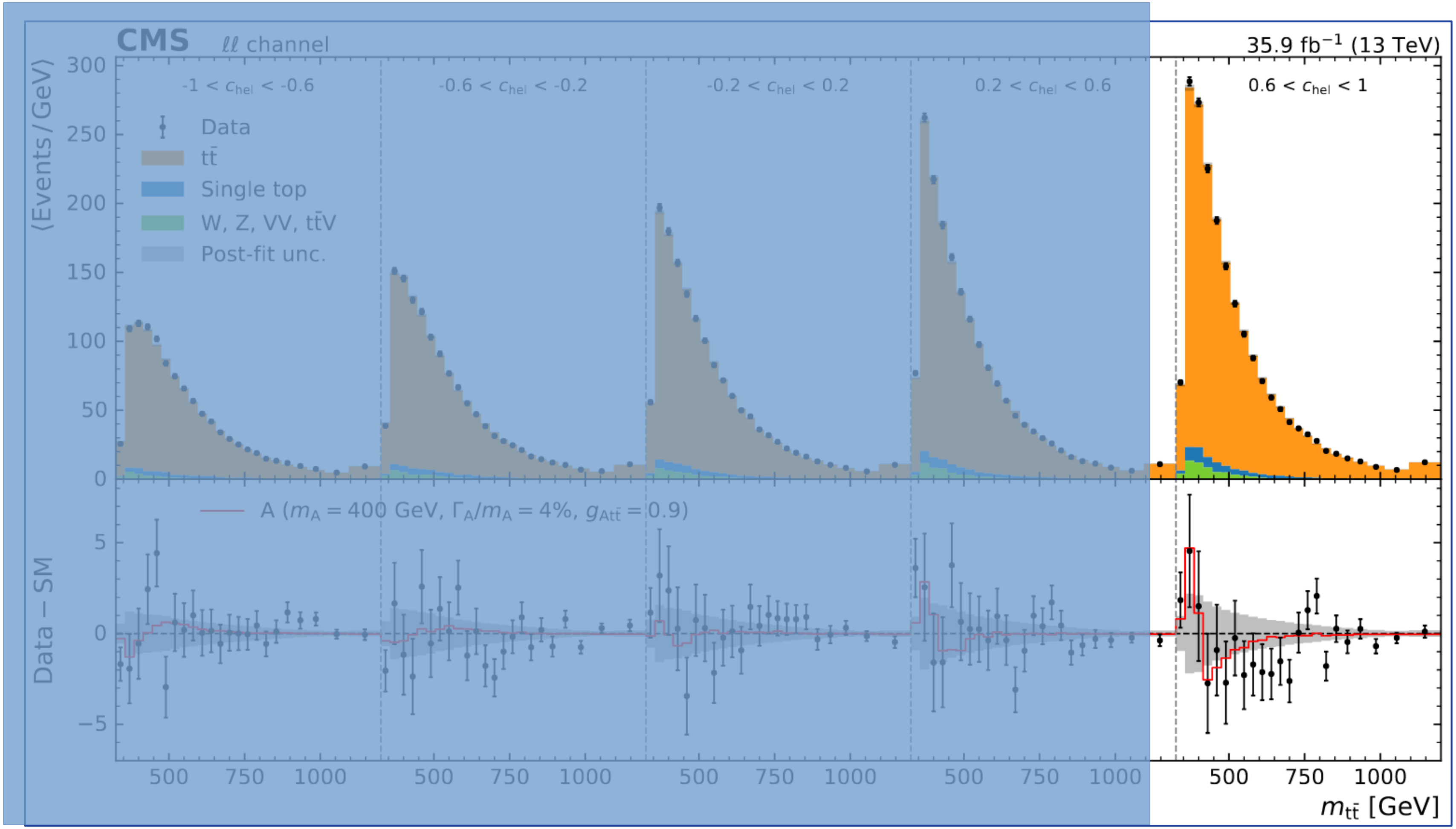




Good agreement between analytical and Monte-Carlo results

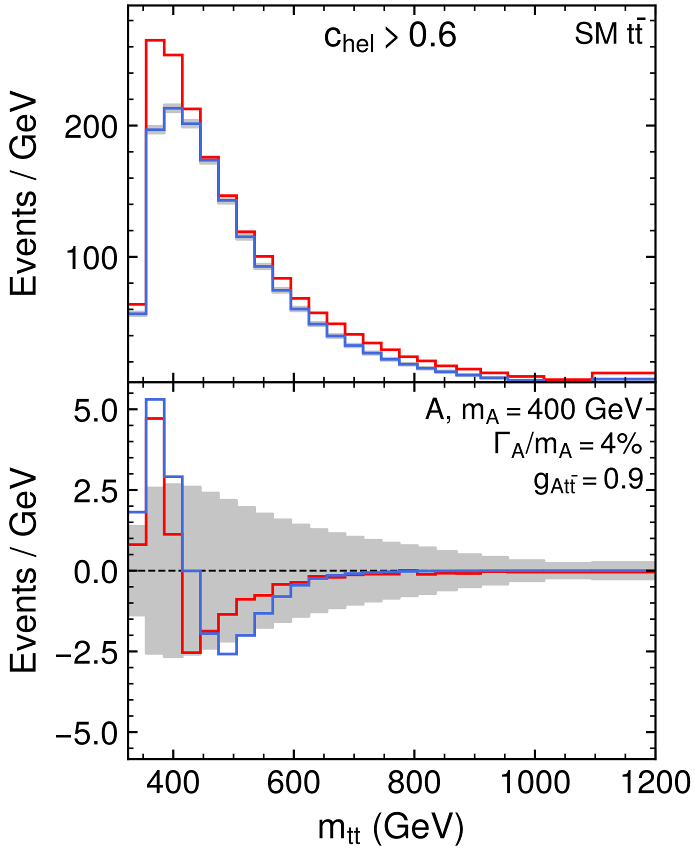

Ideal scenarios,
perfect everything
Realistic
scenarios,
detector effects
YOU
JAKE-CLARK.TUMBLR
imgflip.com

LHC sensitivity

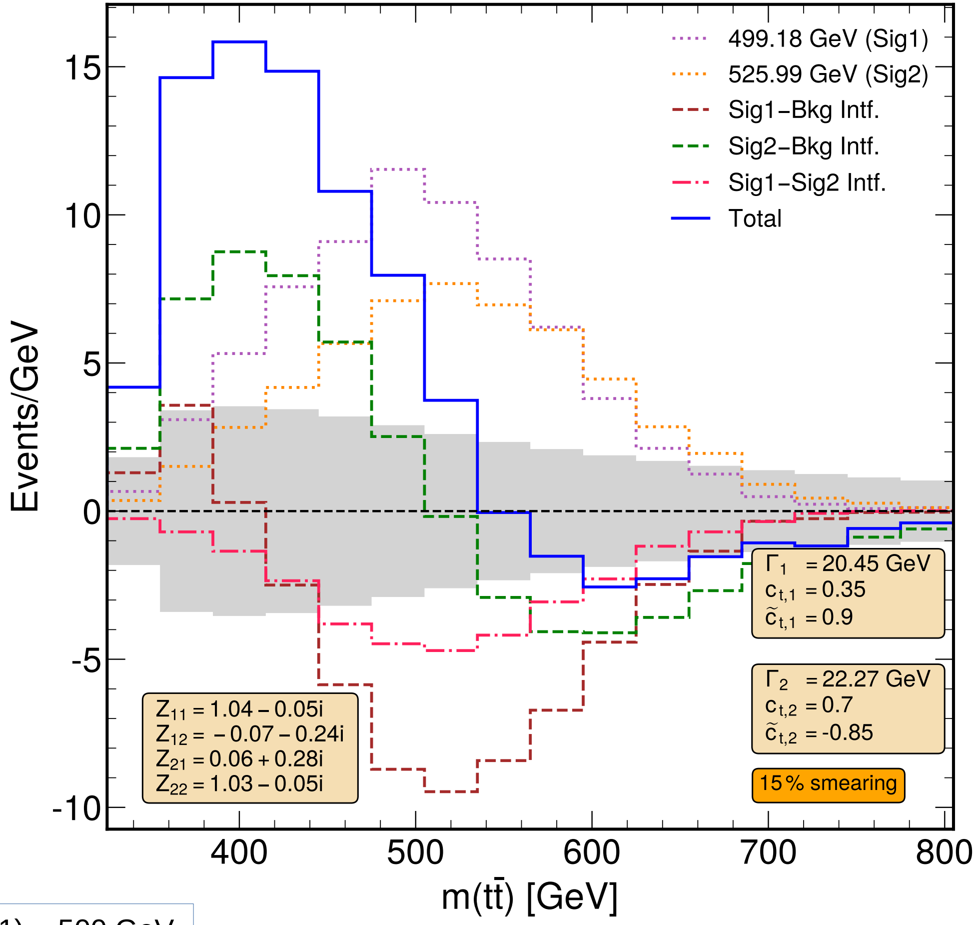


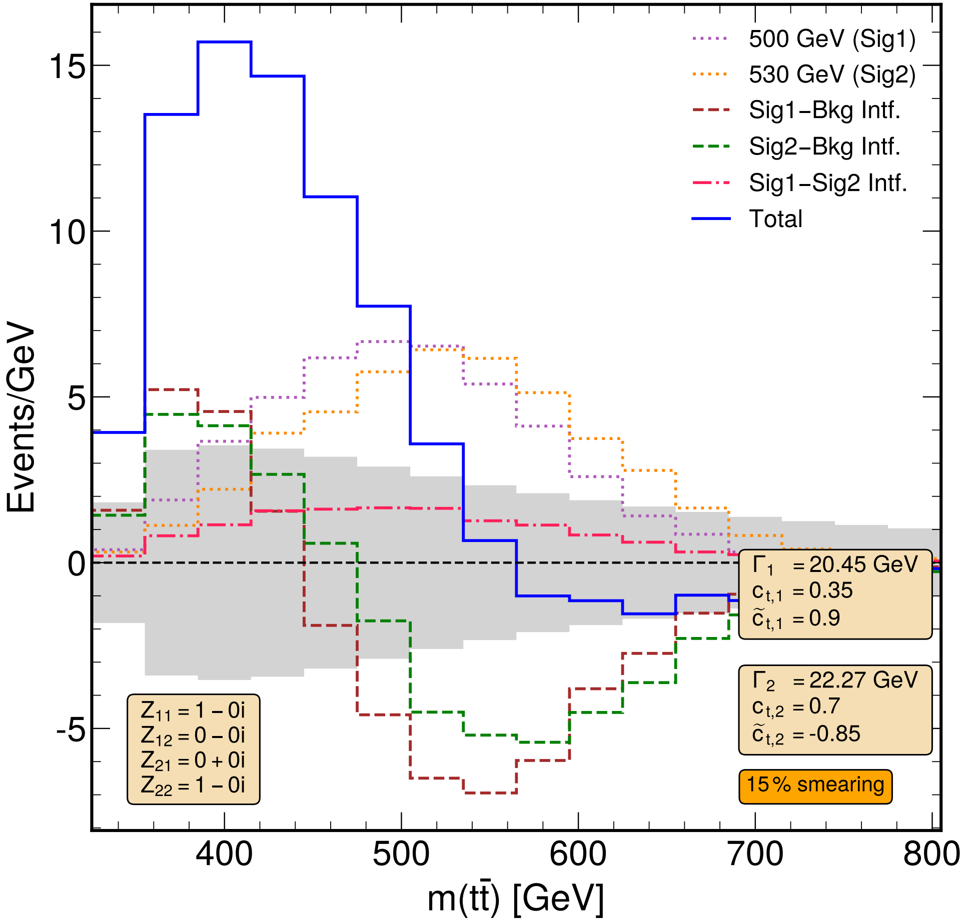
Prospects at the LHC

- Grey band → statistical uncertainty band, calculated from the square root of the expected SM top anti-top background events at NLO in QCD
- Branching ratio of the heavy scalar into leptons: ~11%
- Smearing of 15% and Acceptance of 6.5% to match the most sensitive helicity bin in the published CMS analysis (and also in comparison with results from 2404.19014)
- For the results shown in this presentation, the Monte-Carlo simulation events are scaled to the expected number of events at 300 fb^{-1} integrated luminosity and 13 TeV center of mass energy
- K-factors applied; 1.6 for the QCD background, ~2.5 for the signal process, and geometric mean for the K-factors of interference process



2404.19014



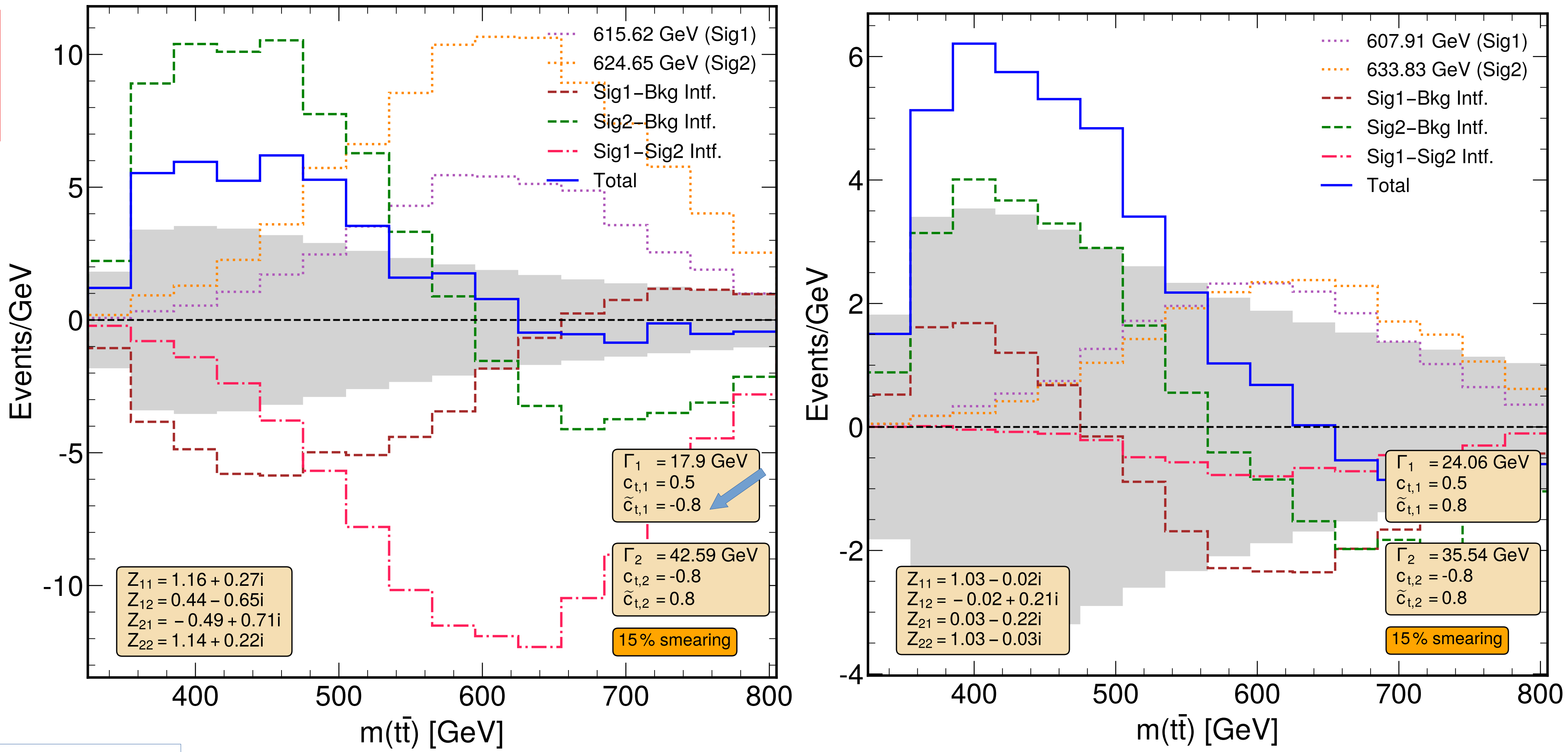


M(S1) = 500 GeV
M(S2) = 530 GeV

With Z-factors

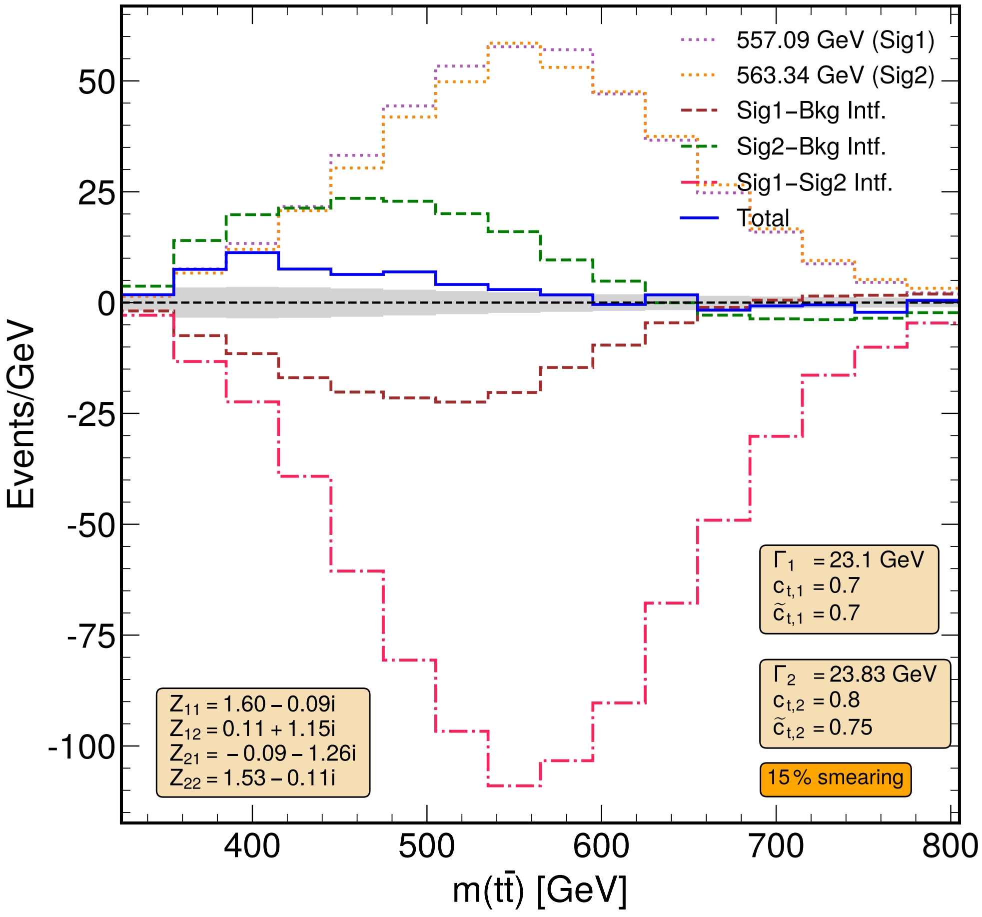
Without Z-factors

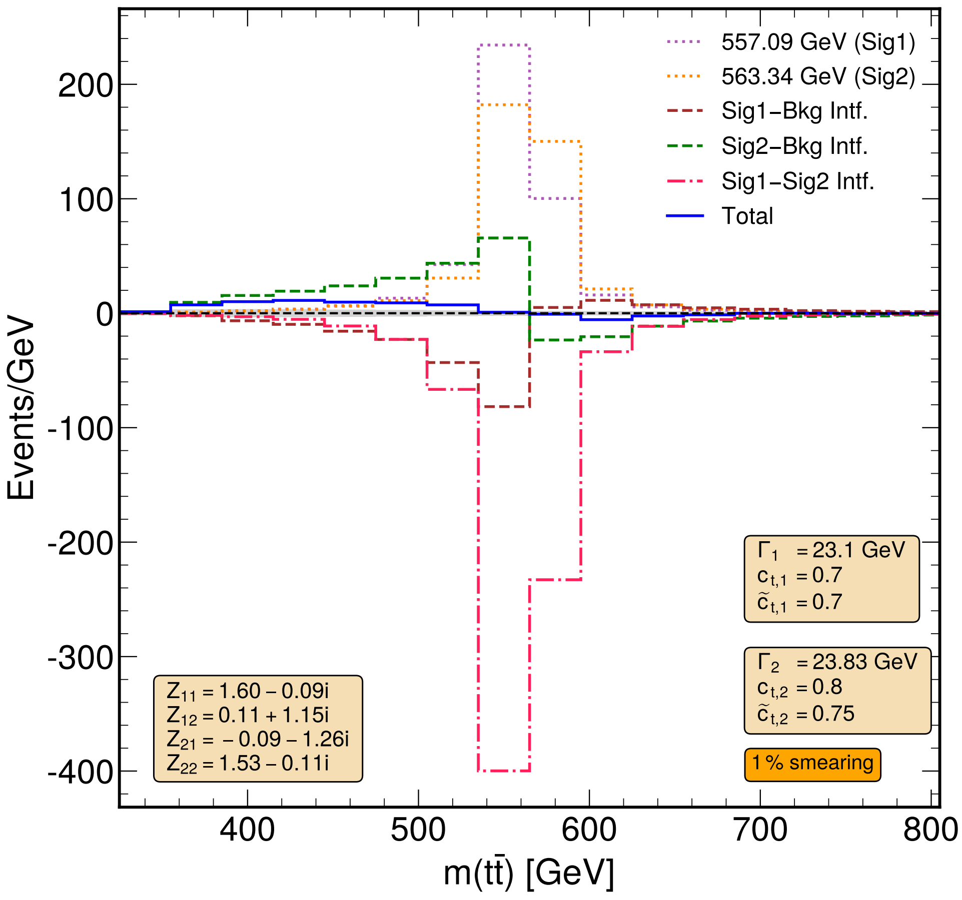
Different number of expected events and behaviour of interference contributions.
Marginal peak-dip-like structure with Z-factors.



M(S1) = 607 GeV
M(S2) = 635 GeV

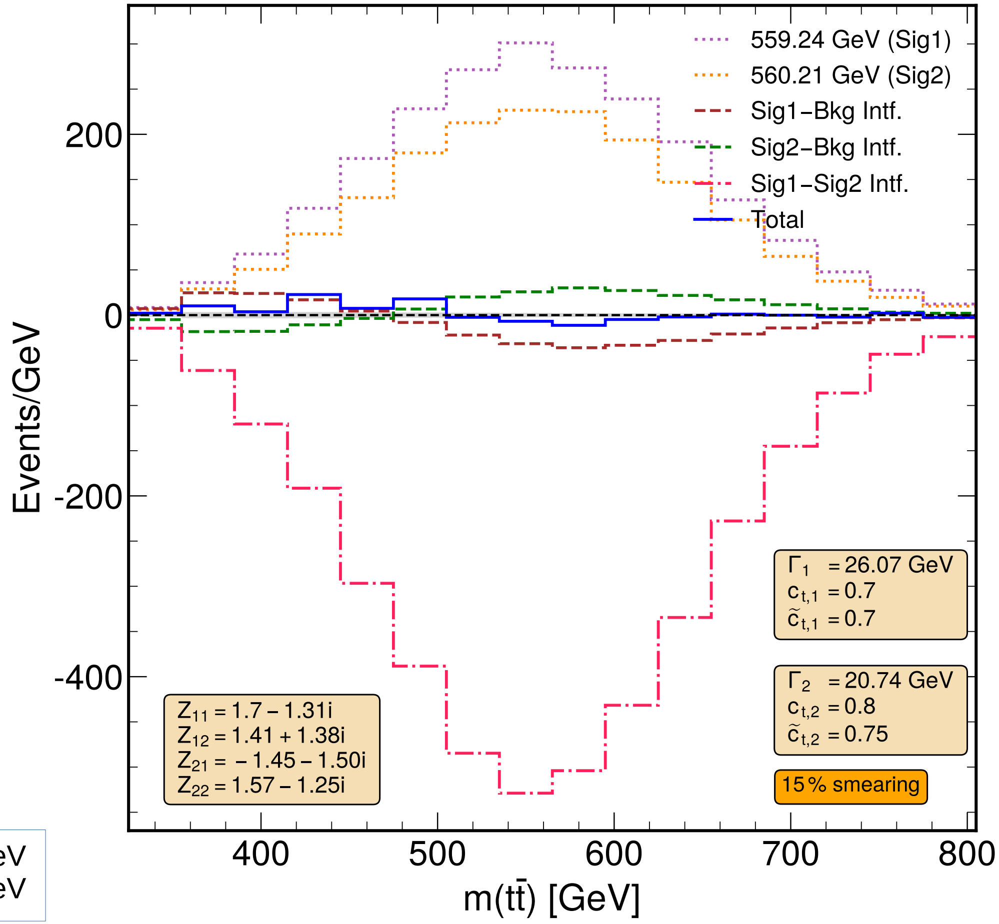
Dependence on the sign of the Yukawa-coupling modifiers.
Determining/Fitting the loop-corrected mass could be challenging.

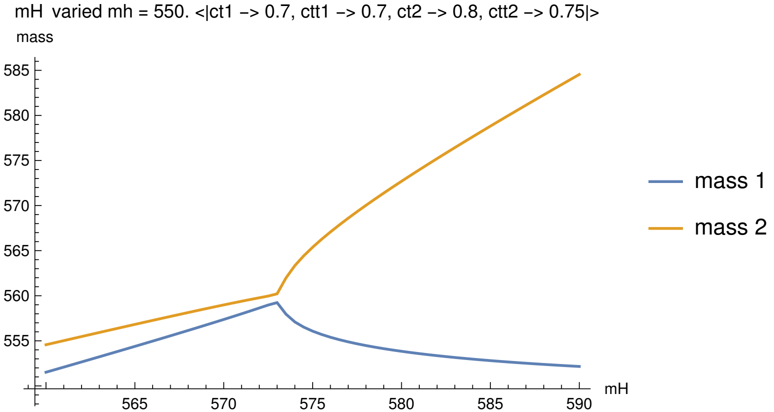


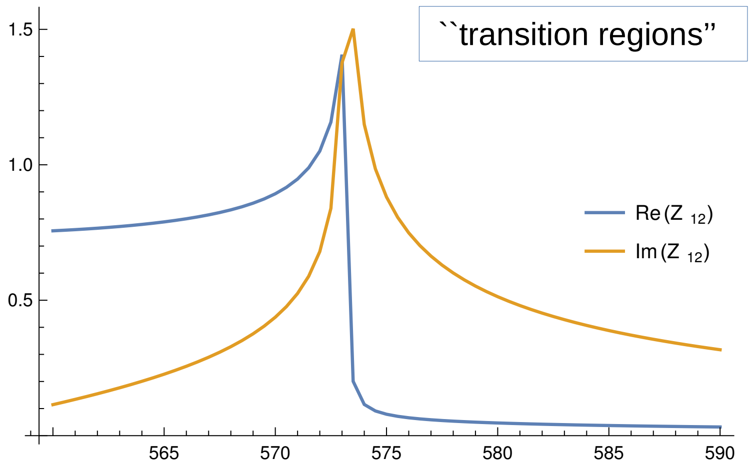


M(S1) = 550 GeV
M(S2) = 573 GeV

The two signal resonances nearly cancel the large destructive signal-signal interference. Interpretation of one scalar at 420 GeV? That would be wrong!



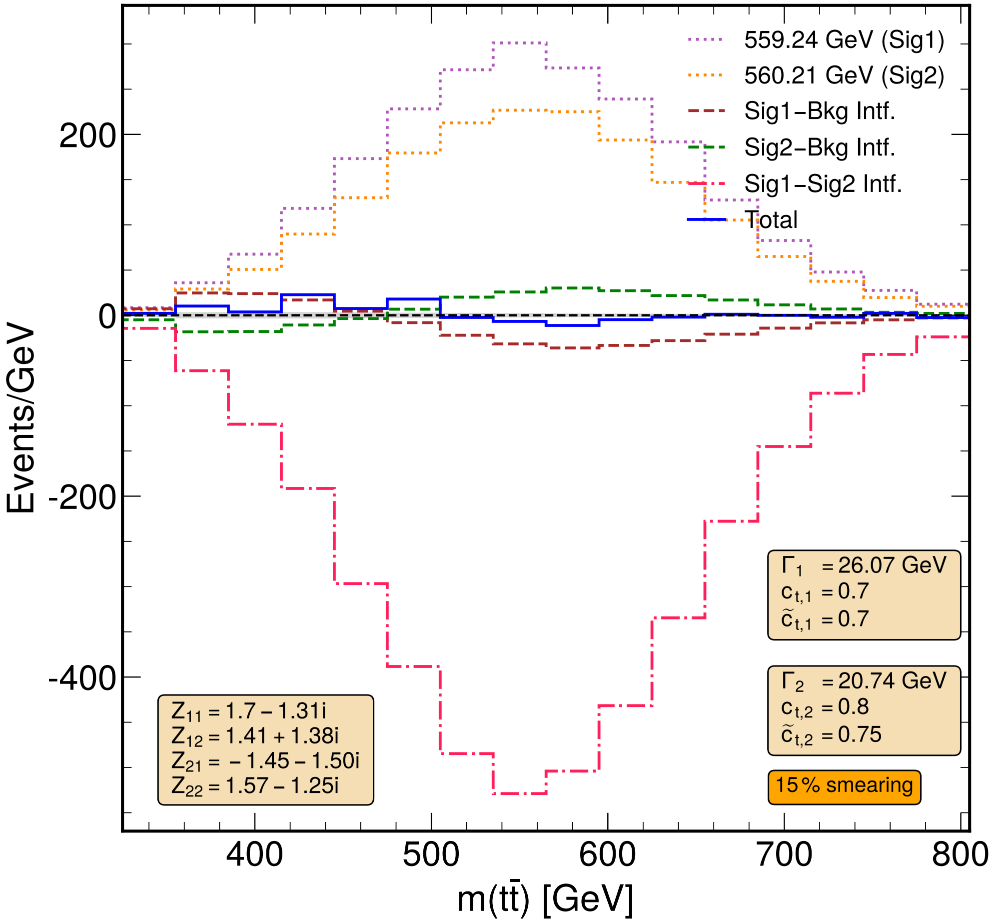




``transition regions''

M(S1) = 550 GeV
M(S2) = 574 GeV

"Nightmare" scenario, the large destructive signal-signal interference cancels the sum of the two signal resonances
(+ the two individual signal-background interferences almost cancel each other)



M(S1) = 550 GeV
M(S2) = 574 GeV

gives motivation to look into other decay channels (e.g. four-tops) to establish complementarity!

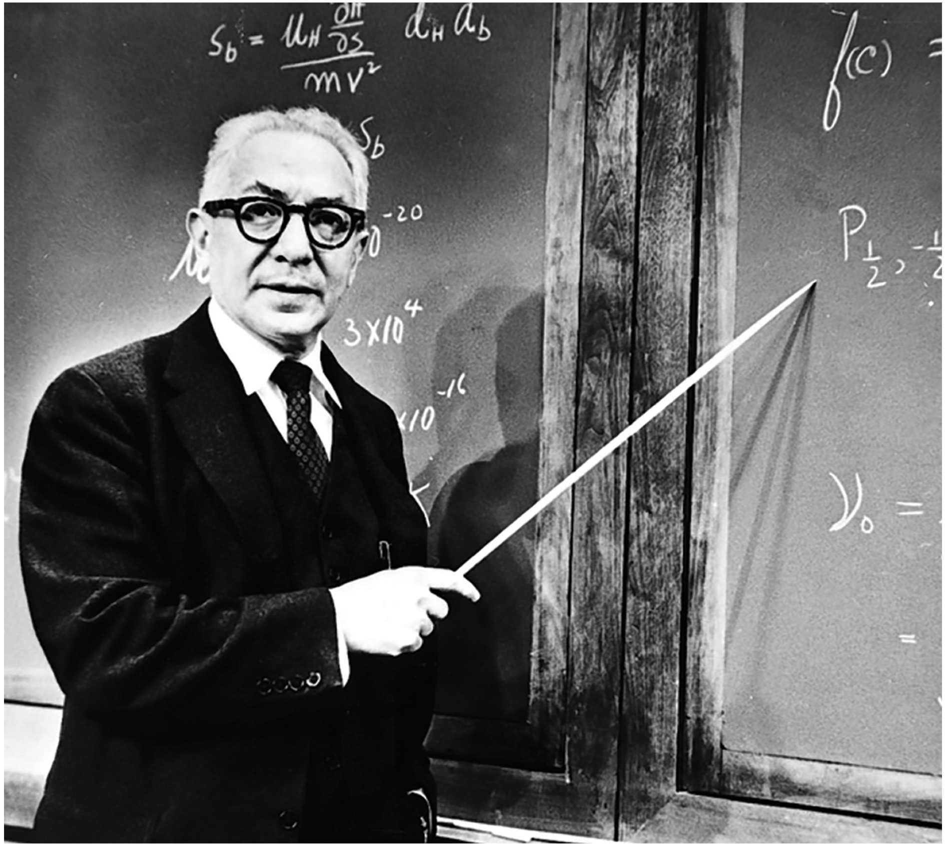
"Nightmare" scenario, the large destructive signal-signal interference cancels the sum of the two signal resonances
(+ the two individual signal-background interferences almost cancel each other)

Takeaways!

- Monte-Carlo (and analytical) implementation of individual signal-background and signal-signal interference contributions considering mixing between the scalars
  - ➔ Complete top-quark loop function used in Monte-Carlo results

- Mixing between scalars can lead to highly non-trivial distribution profiles → rich phenomenology to explore, including signatures unexpected/difficult to interpret

Summary



Nobel laureate, Isidor Isaac Rabi (1898–1988)

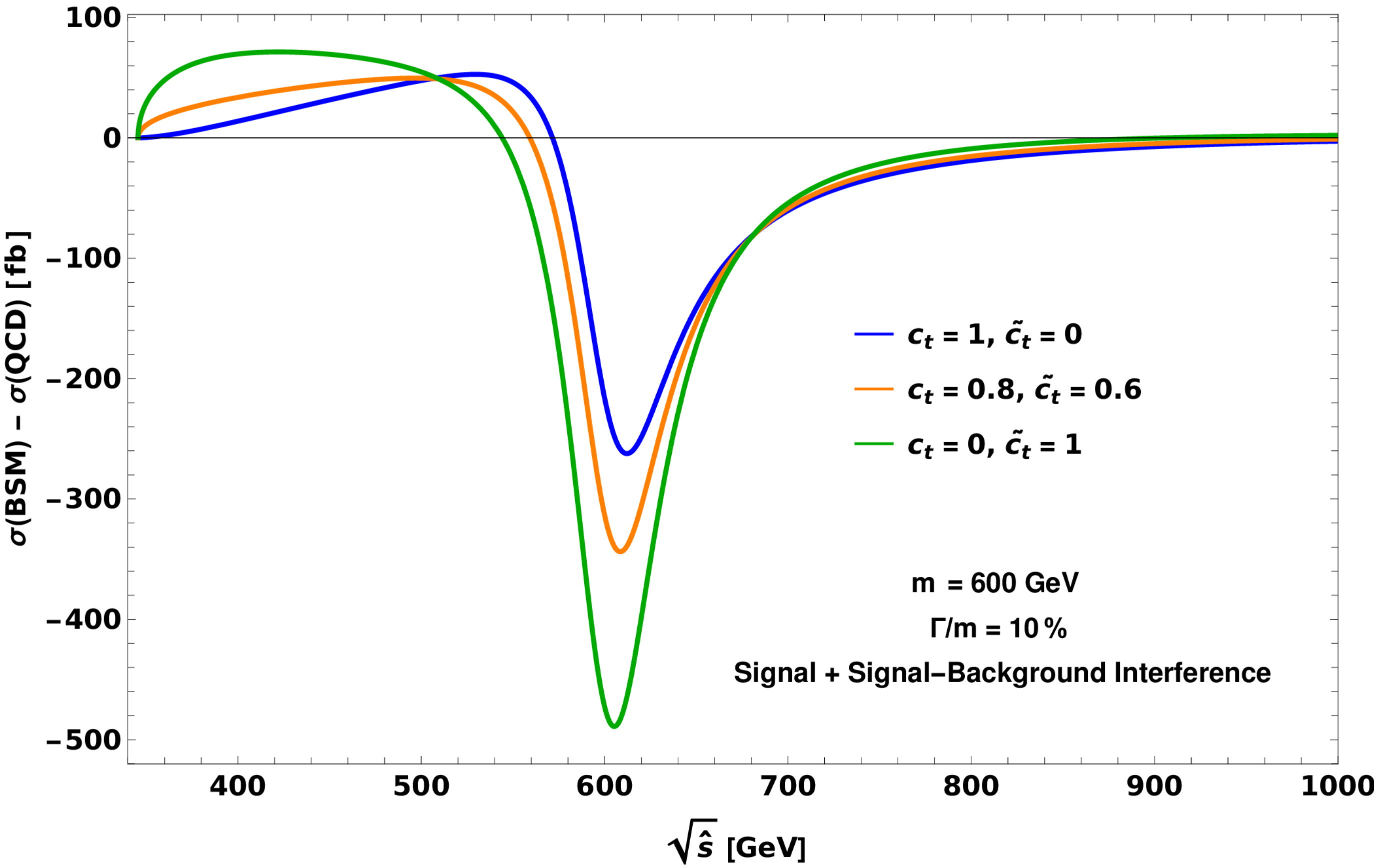
- Mathematica solve to calculate complex-valued Z-factors with two CP-mixed scalars
- Complete Monte-Carlo implementation to simulate different processes including support for the Z-factors
- Signatures can emerge that are difficult to interpret

Who ordered all of that?

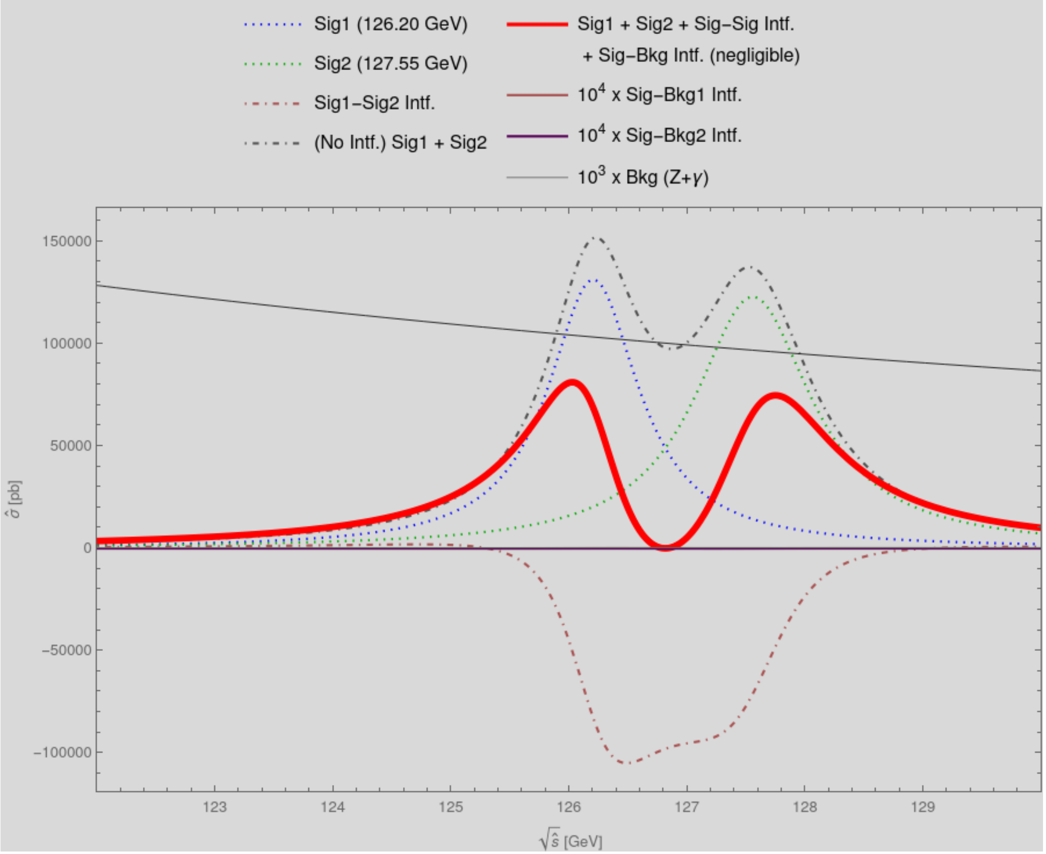
A toolbox for experimental analysis to fit excesses in the di-top distribution and subsequently fit parameters to a specific, realizable model

Thank you for your attention :)

Backup/Extra slides



CP-mixed scalar “intermediate” to a CP-even and a CP-odd scalar



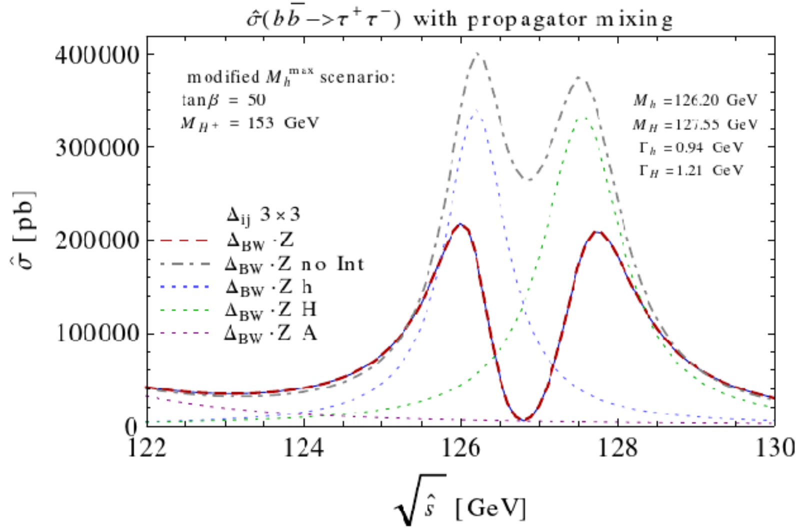
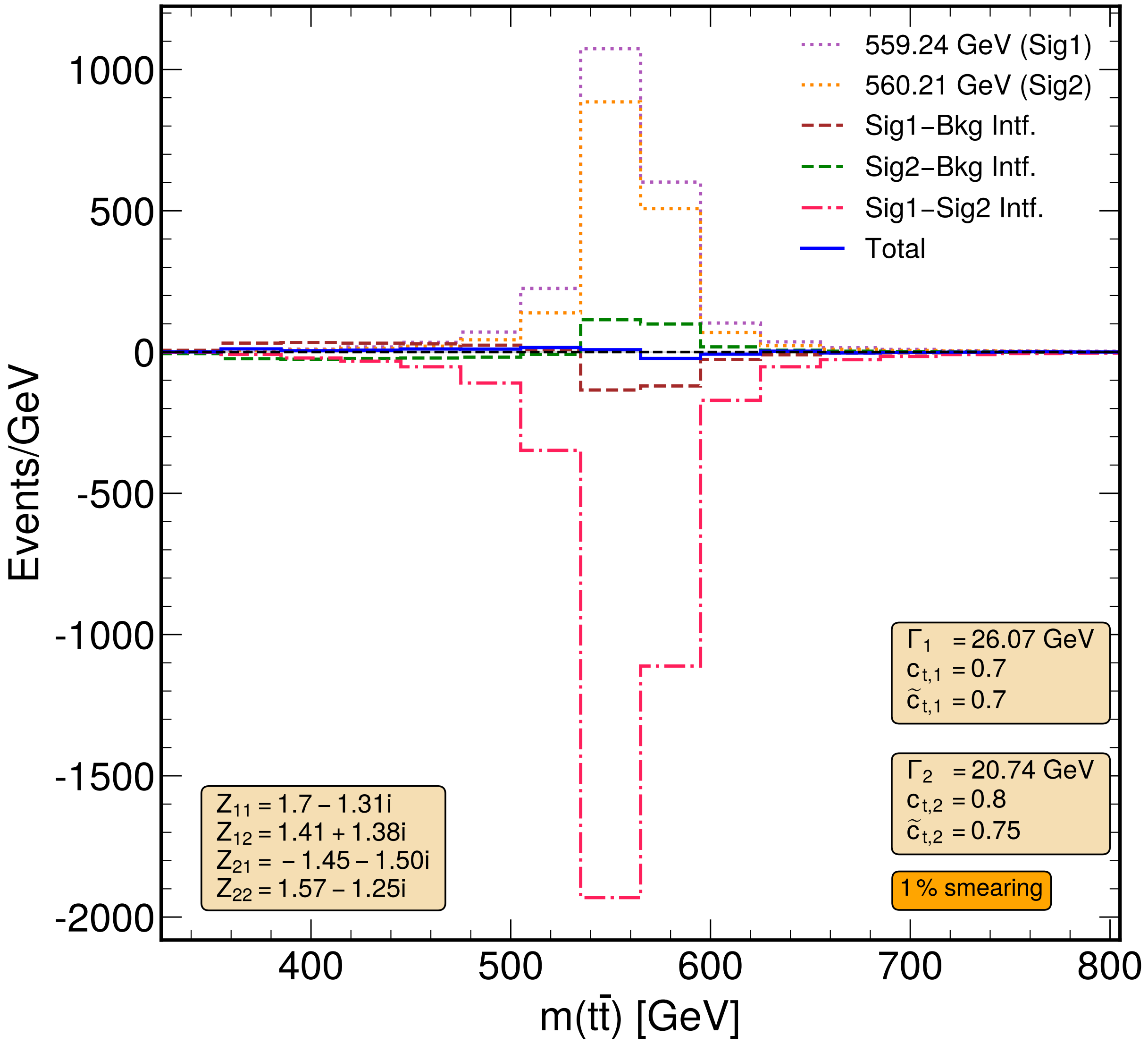
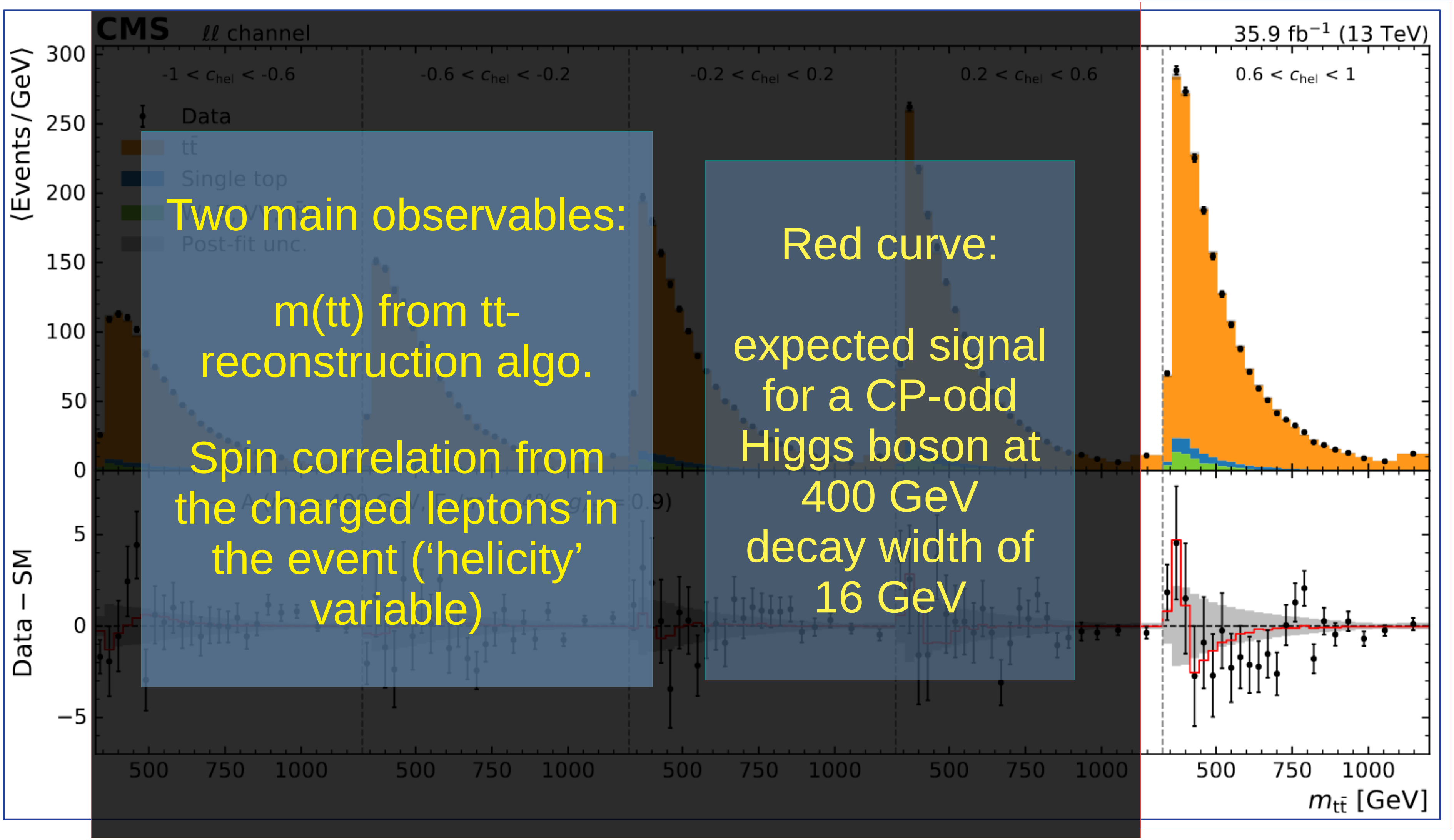


Figure 11: The partonic cross section $\hat{\sigma}(b\bar{b} \to \tau^+\tau^-)$ in a modified $M_h^{\max}$-scenario with $\tan\beta = 50$ and $M_{H^\pm} = 153\,\text{GeV}$. The cross section is calculated with the full mixing propagators (blue, solid), approximated by the coherent sum of Breit–Wigner propagators times $\hat{\mathbf{Z}}$-factors with the interference term (red, dashed) and the incoherent sum without the interference term (grey, dot-dashed). The individual contributions mediated by h_1 (light blue), h_2 (green) and h_3 (purple) are shown as dotted lines.



559.24 GeV (Sig1)
560.21 GeV (Sig2)
Sig1−Bkg Intf.
Sig2−Bkg Intf.
Sig1−Sig2 Intf.
Total
Events/GeV
m(tt̄) [GeV]
Γ1 = 26.07 GeV
c t,1 = 0.7
c̃ t,1 = 0.7
Γ2 = 20.74 GeV
c t,2 = 0.8
c̃ t,2 = 0.75
1 % smearing
Z11 = 1.7 − 1.31i
Z12 = 1.41 + 1.38i
Z21 = − 1.45 − 1.50i
Z22 = 1.57 − 1.25i



Two main observables:

m(tt) from tt-reconstruction algo.

Spin correlation from the charged leptons in the event (‘helicity’ variable)

Red curve:

expected signal for a CP-odd Higgs boson at 400 GeV decay width of 16 GeV

arXiv:1908.01115

Key points from one scalar analysis

- With the signal amplitude $\mathcal{A}(gg \to \Phi \to t\bar{t}) = -\frac{\mathcal{A}_{gg\Phi}\,\hat{s}\,\mathcal{A}_{\Phi t\bar{t}}}{\hat{s} - M_\Phi^2 + i\,M_\Phi\,\Gamma_\Phi}$

- The total differential cross-section:

  Background + Signal + Interference $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}z} = \frac{\mathrm{d}\hat{\sigma}_B}{\mathrm{d}z} + \frac{\mathrm{d}\hat{\sigma}_S}{\mathrm{d}z} + \frac{\mathrm{d}\hat{\sigma}_I}{\mathrm{d}z}$

- The absolute-value squared amplitudes for production and decay of scalar

$$|\mathcal{A}_{gg\Phi}|^2\Big|_{\mathcal{CP}\text{-mixed}} \propto \left(|c_t A_{1/2}^H(\tau_t)|^2 + |\tilde{c}_t A_{1/2}^A(\tau_t)|^2\right)$$

$$|\hat{s}\mathcal{A}_{\Phi t\bar{t}}|^2\Big|_{\mathcal{CP}\text{-mixed}} \propto \left(|c_t^2|\hat{\beta}_t^3 + |\tilde{c}_t^2|\hat{\beta}_t\right)$$

CP-even and CP-odd components can be independently treated

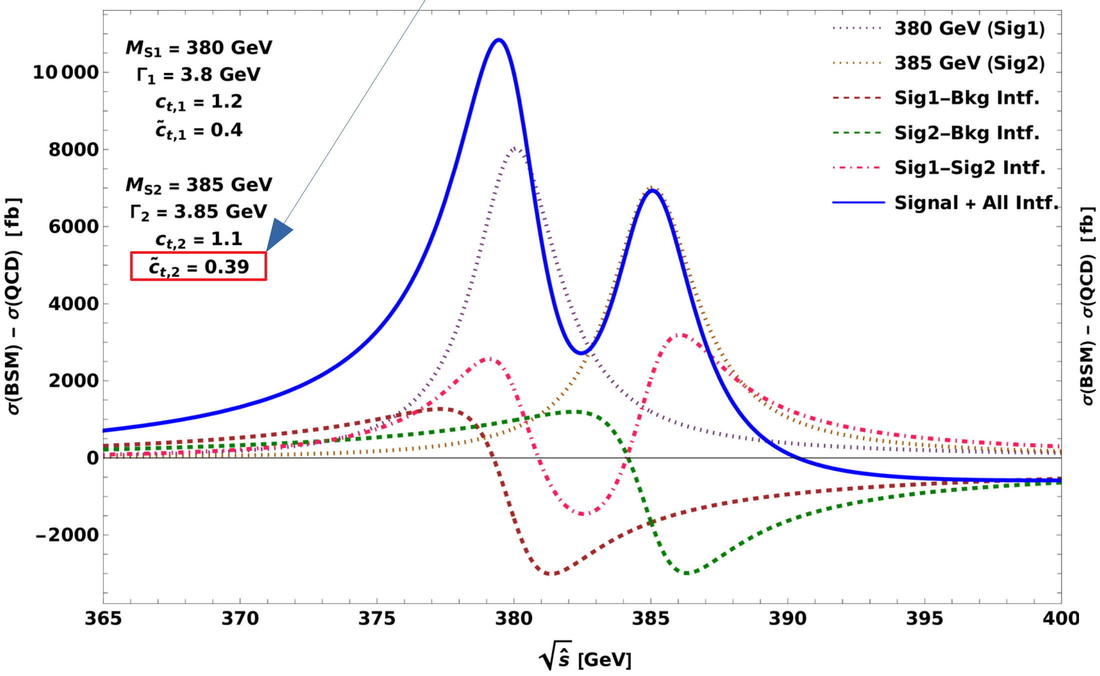
$A_{1/2}^H(\tau)$ $A_{1/2}^A(\tau)$

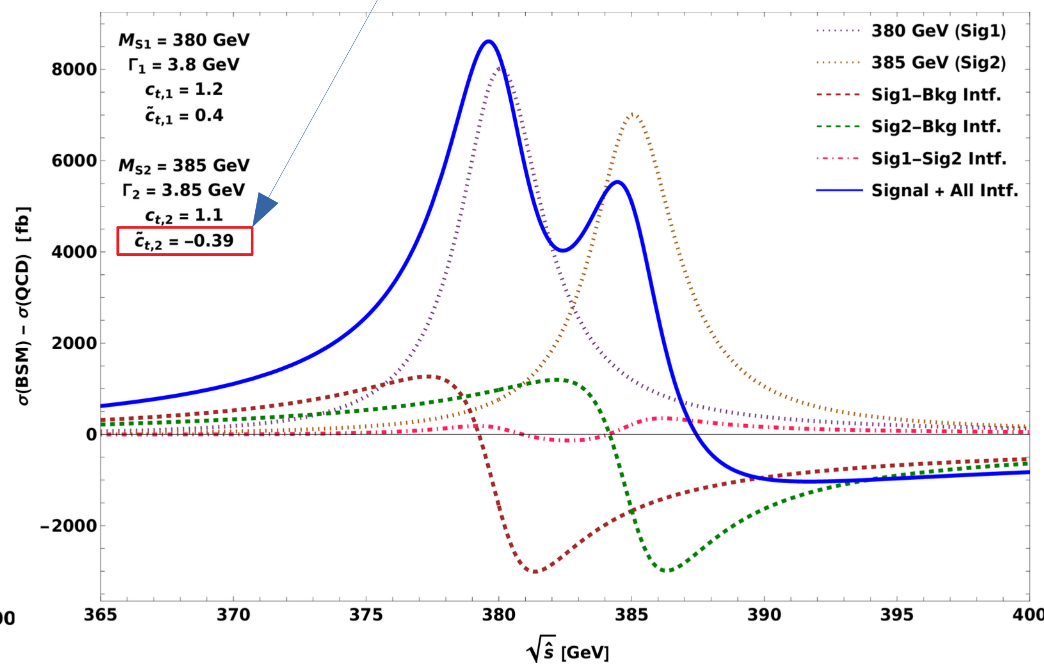
quark-loop function

$$\tau_t = \frac{\hat{s}}{4m_t^2}$$

$$\hat{\beta}_t \equiv \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

Some illustrative plots showing various processes





- Sign of Yukawa-coupling modifiers affects the contribution of signal-signal interference!

Analytical

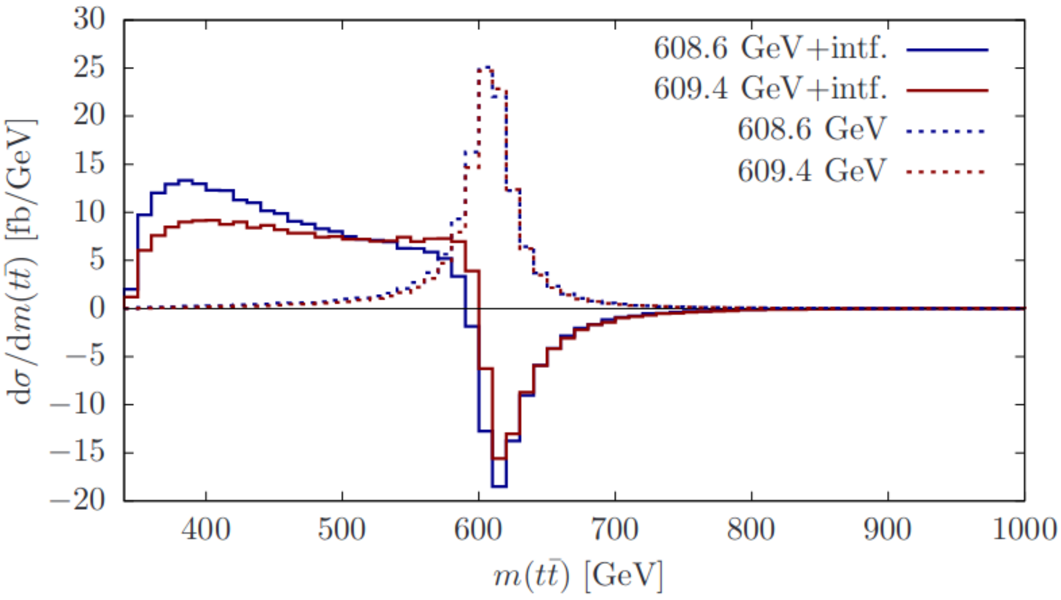
Application to the C2HDM

- Compare results with existing 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

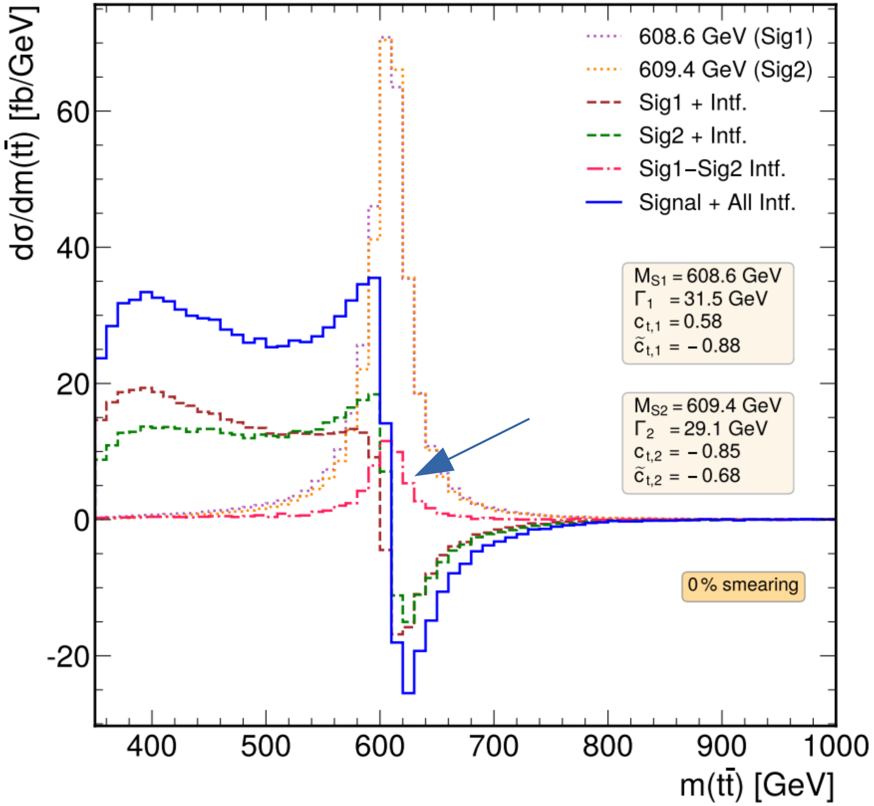
$$\{R_{i,j}\} \equiv R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

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

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

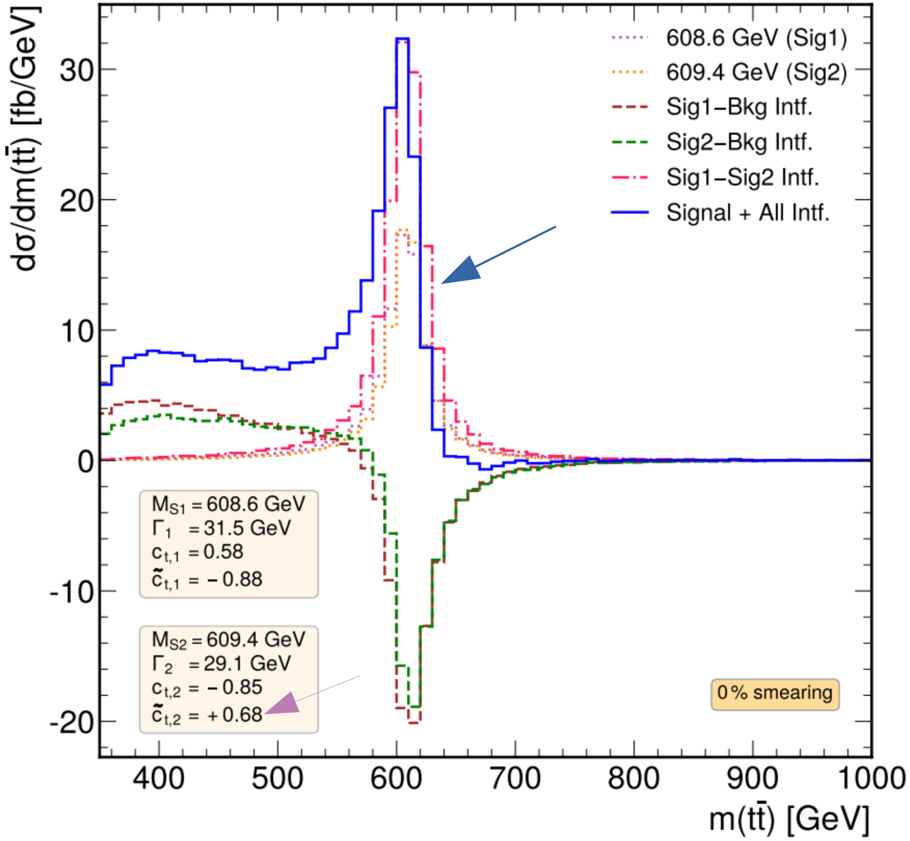


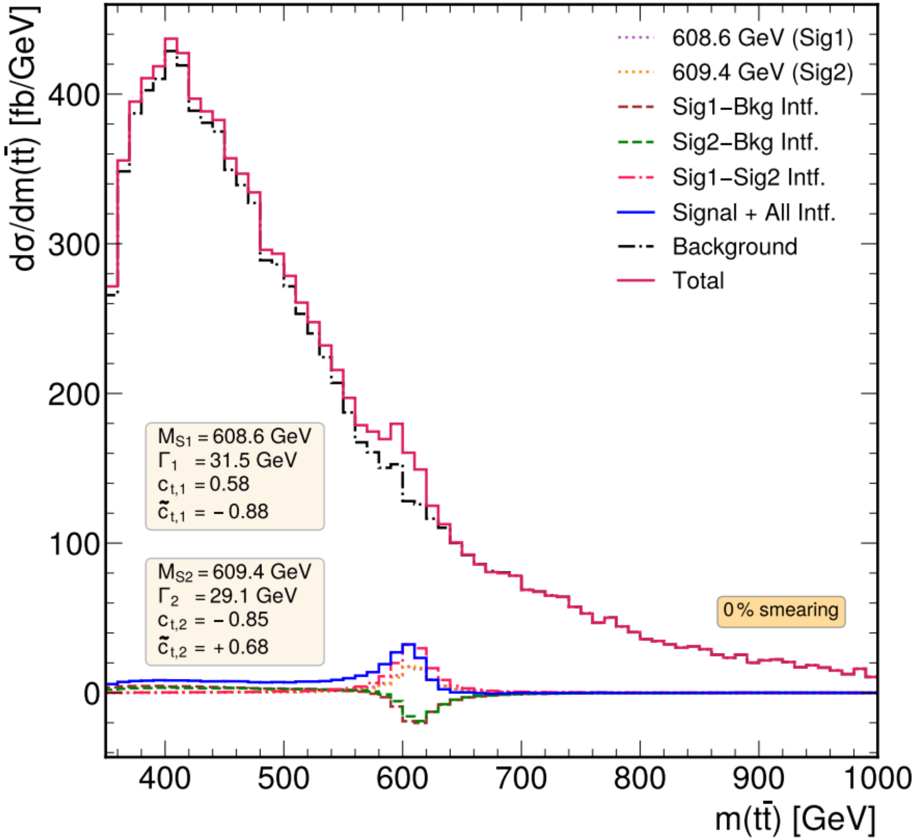
arXiv:1909.09987v2



- 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!