2024-10-24

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

Romal Kumar (DESY) [ROMAL.KUMAR @ DESY.DE]
(in collaboration with Henning Bahl and Georg Weiglein)

O U T L I N E

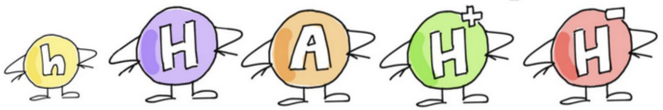
- Simplified model framework
- Monte-Carlo implementation
- Results with mixing between the scalars

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
  - . . .

Beyond the SM physics!

- Various extensions to the SM
  - supersymmetry (SUSY) → MSSM
  - **extended Higgs sector** (2HDM, C2HDM, …)



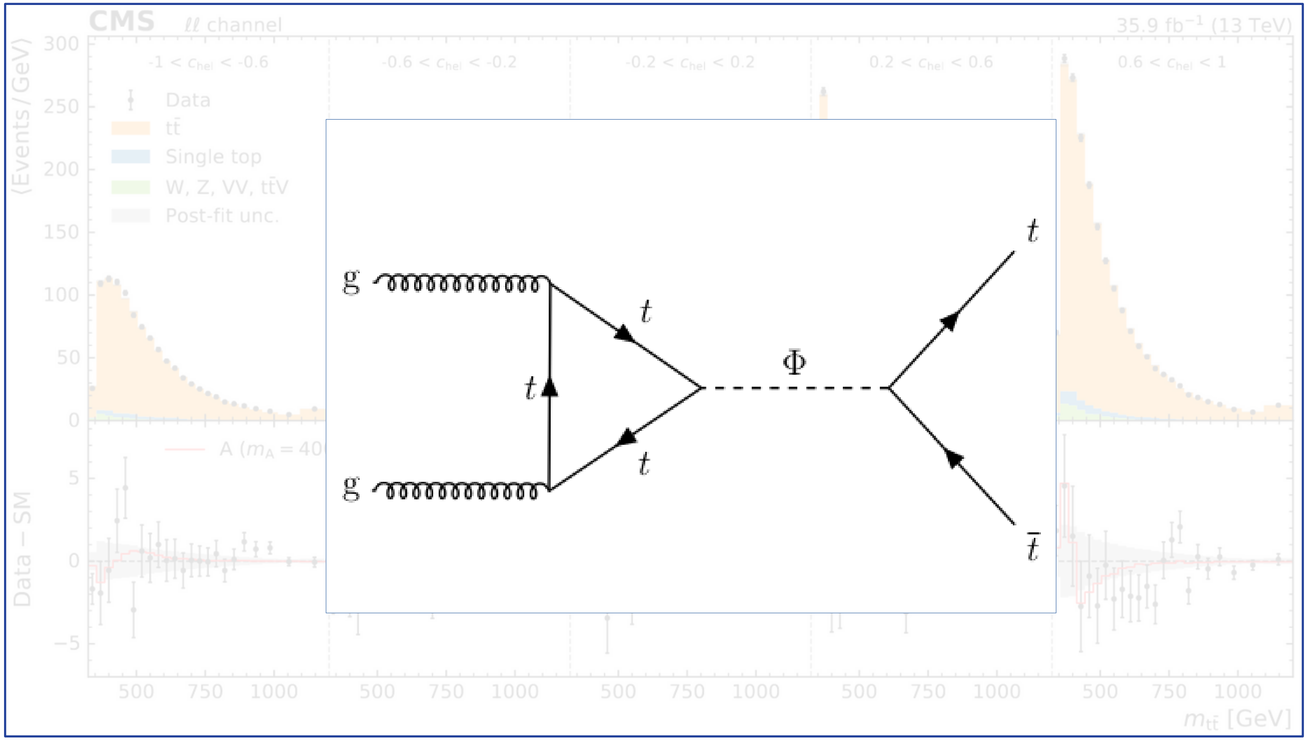
Physical states in two-Higgs doublets

Illustration by K. Radchenko

Motivation

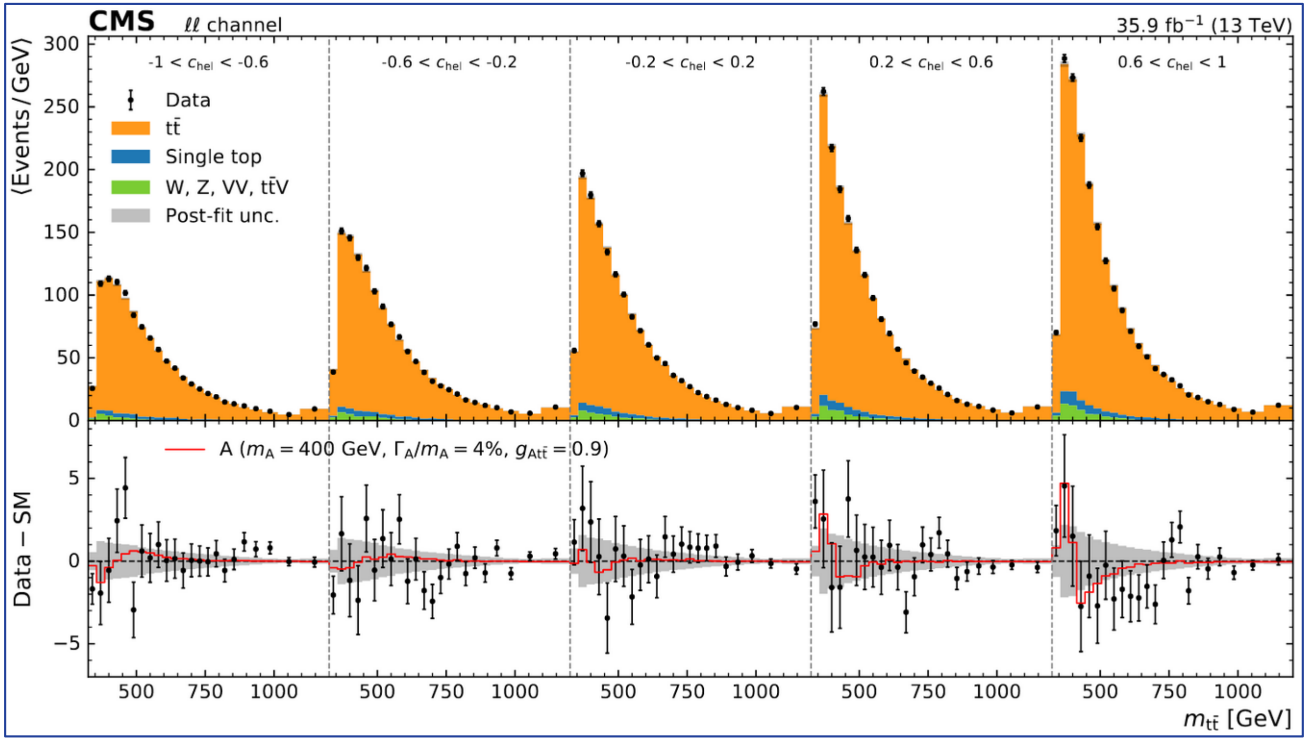
- Many BSM extensions feature heavy scalar(s) that decay to top pairs

- Heavy scalars predicted to have large couplings to third generation fermions



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]



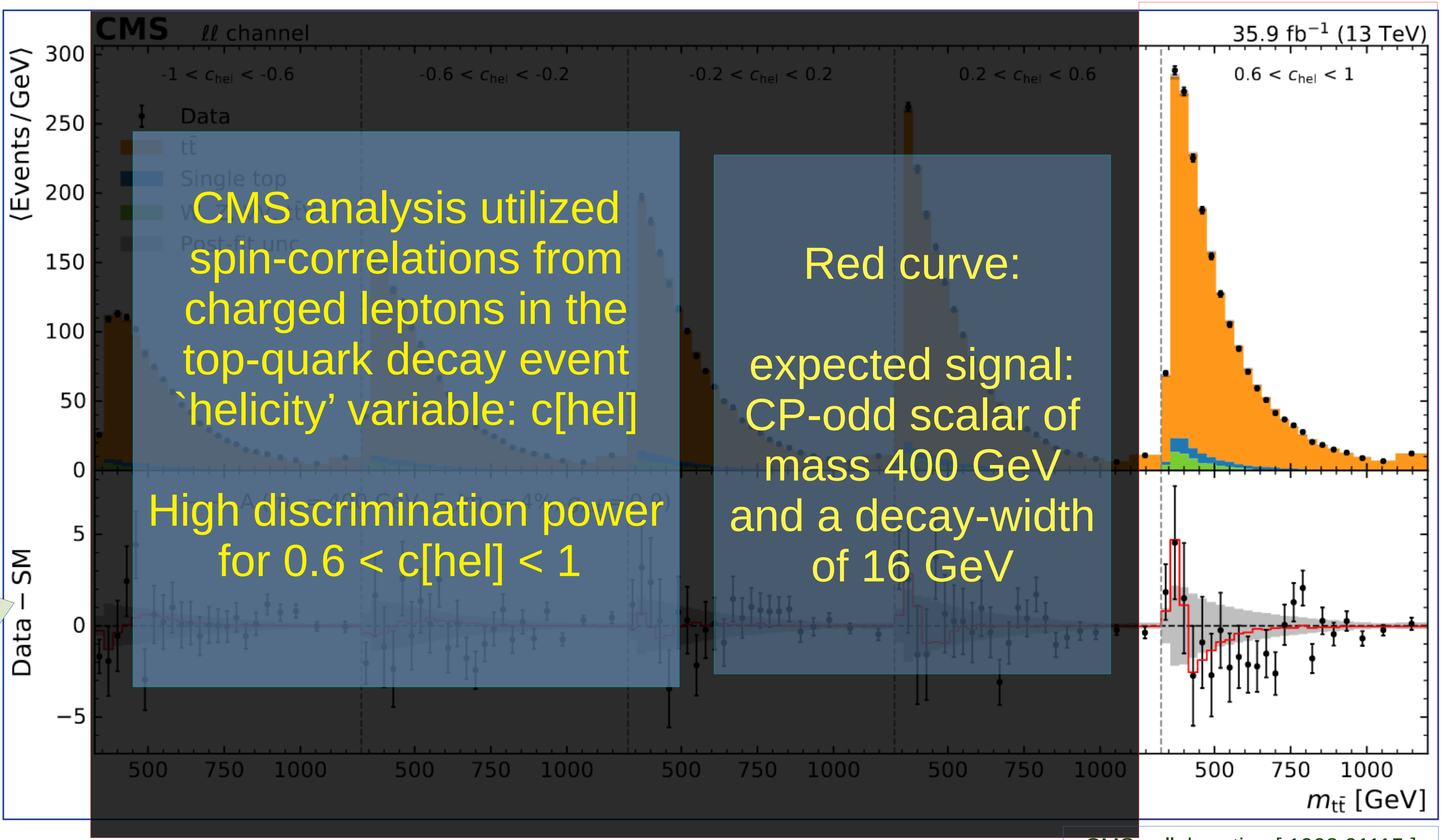
CMS collaboration [1908.01115]

CMS analysis utilized spin-correlations from charged leptons in the top-quark decay event `helicity’ variable: c[hel]

High discrimination power for 0.6 < c[hel] < 1

Red curve:

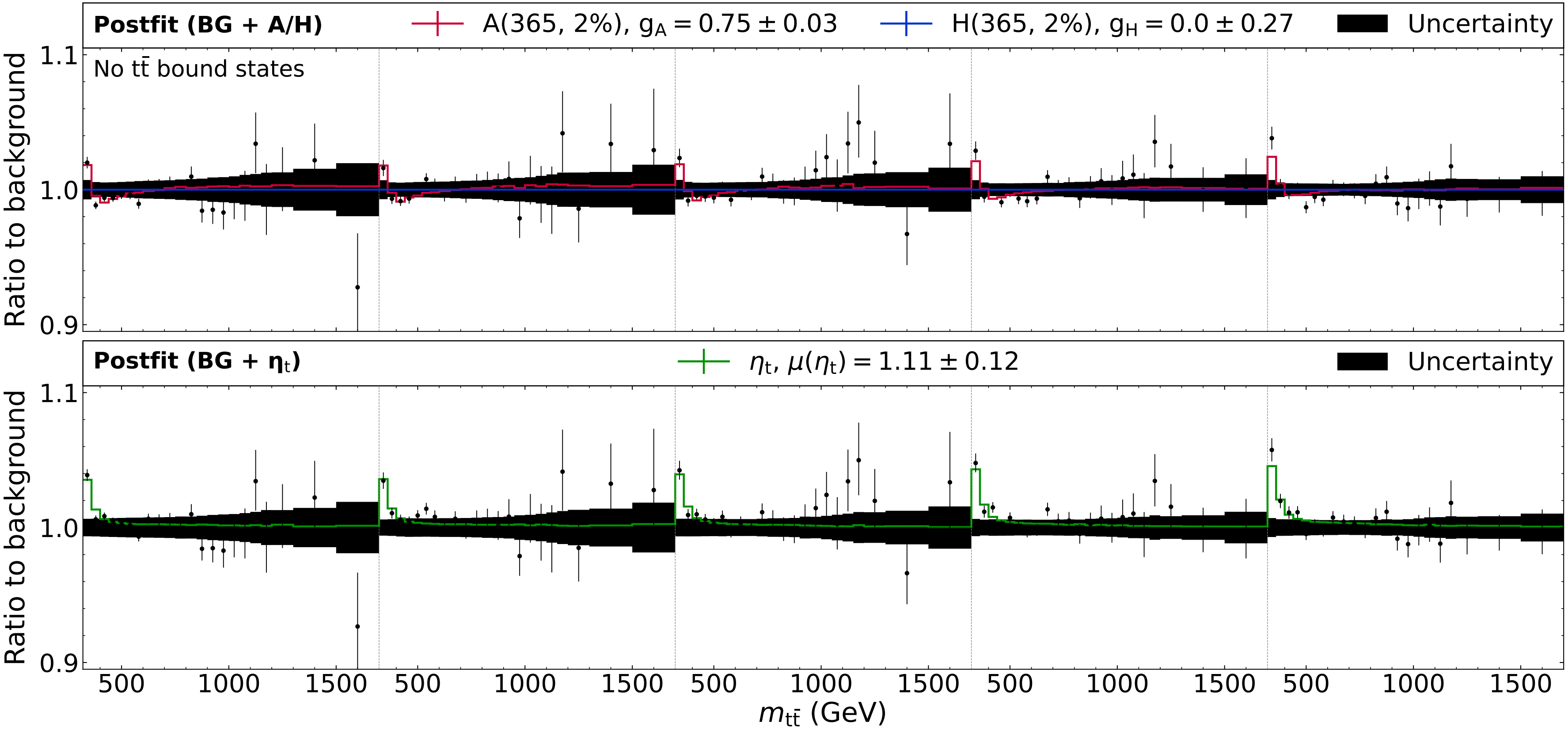
expected signal: CP-odd scalar of mass 400 GeV and a decay-width of 16 GeV



CMS collaboration [1908.01115]

Search for heavy scalars and pseudoscalar bosons decaying to top quark pairs; full Run-2 analysis by CMS

More than 5-sigma deviation in m(tt) expectation (!)



Best day of Romal's life (2024)

see also: Halil Saka's talk

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

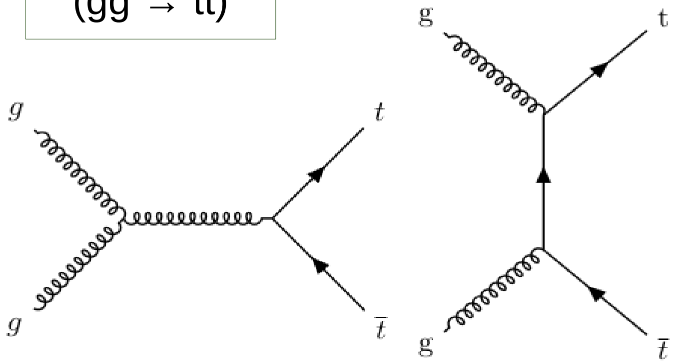
$$\propto \mathrm{Re}[\mathcal{A}(gg \to \Phi \to t\bar{t})\mathcal{A}^*(gg \to t\bar{t})]$$

large destructive contribution

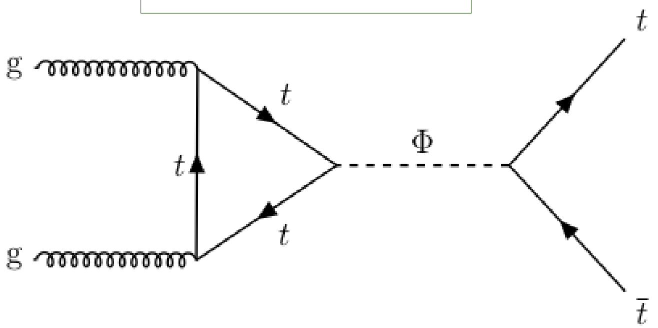
- Invariant mass distribution of the top quarks ($m_{t\bar{t}}$) significantly distorted → peak-dip structure

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

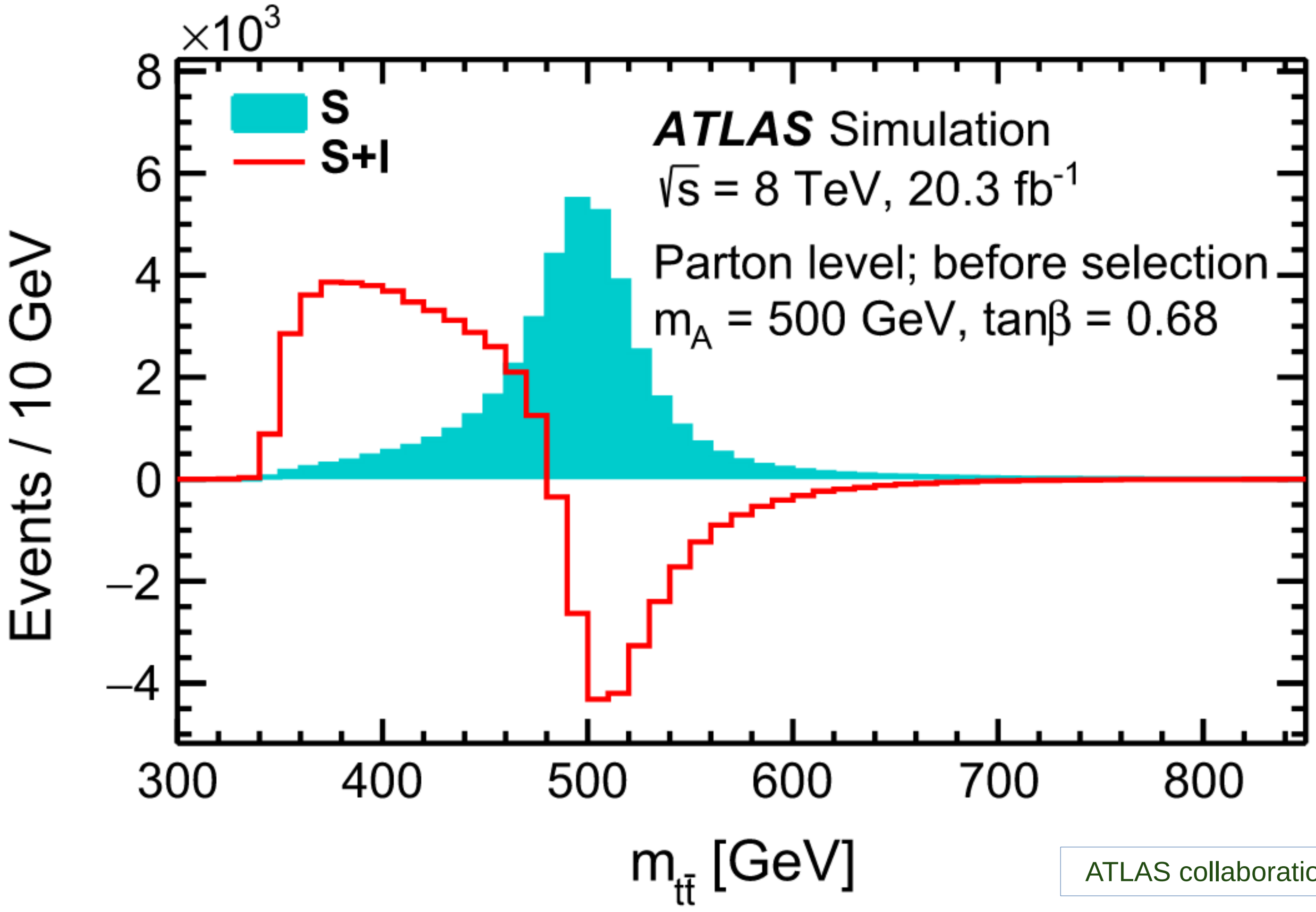
QCD background (gg → tt)



Signal (gg → Φ → tt)



One additional scalar



ATLAS collaboration [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

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

CP-even (→ $c_{t,j}$)

CP-odd (→ $\tilde{c}_{t,j}$)

Yukawa-coupling modifiers

Simplified model framework

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CP-even CP-odd

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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
- Signal-Signal interference terms contains (including fermion-loop functions)

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

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

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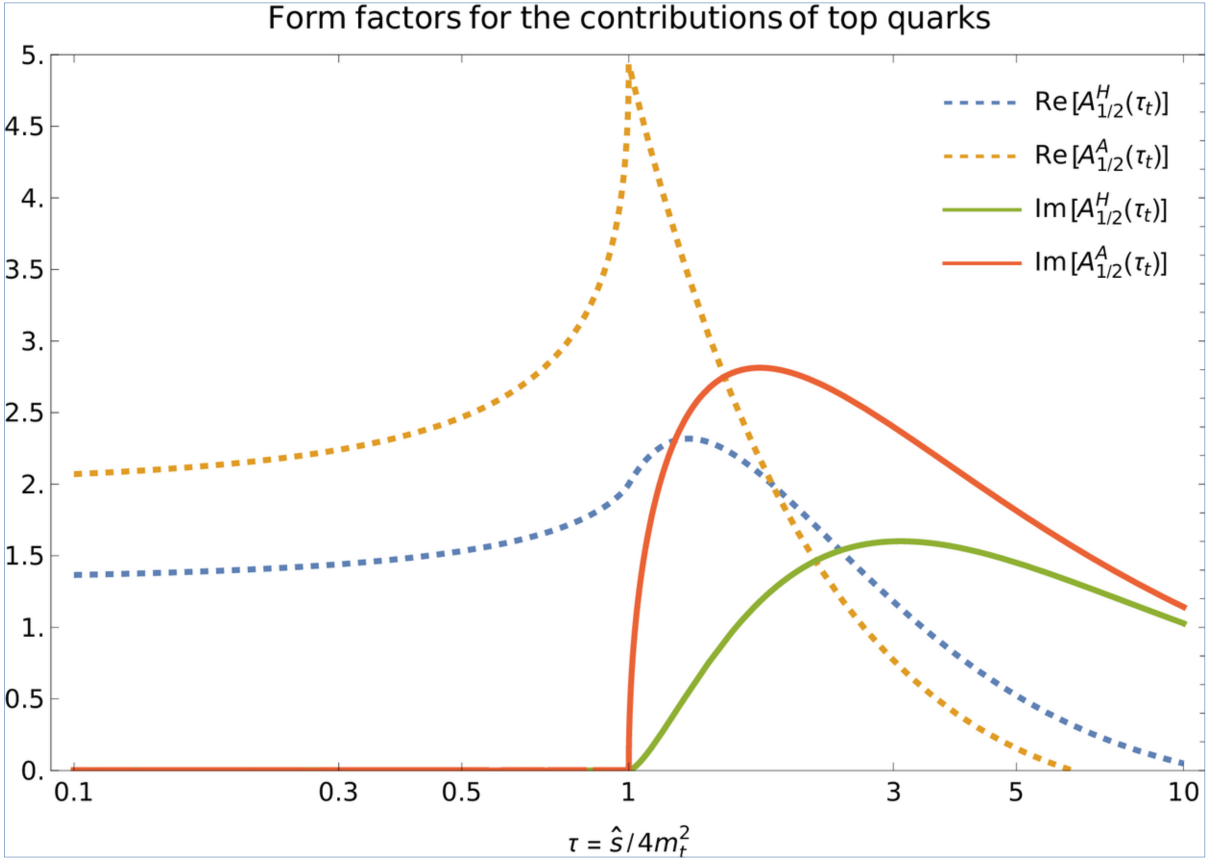
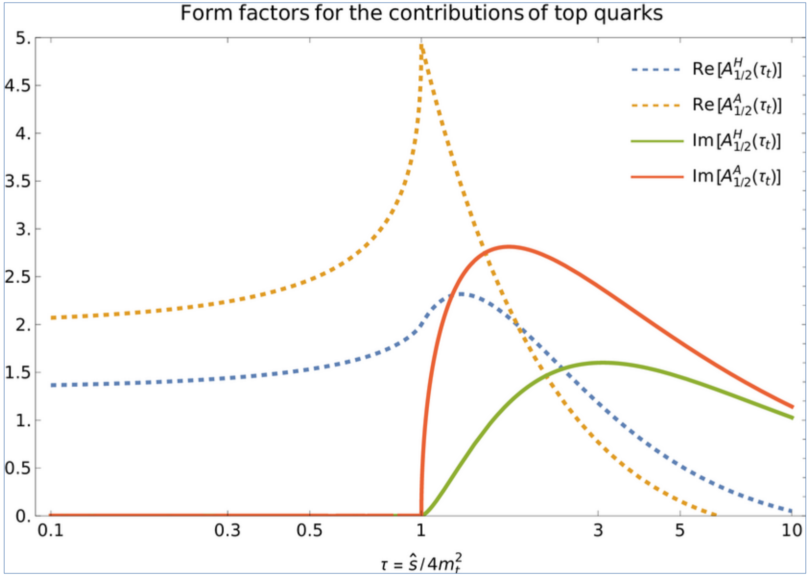
- No signal-signal interference between CP-even and CP-odd
- Sign of Yukawa-coupling modifiers can be relevant



For heavy scalars, effective Higgs-gluon coupling is a poor approximation

Need to incorporate the full top-quark loop in Monte-Carlo simulations



For heavy scalars, effective Higgs-gluon coupling is a poor approximation

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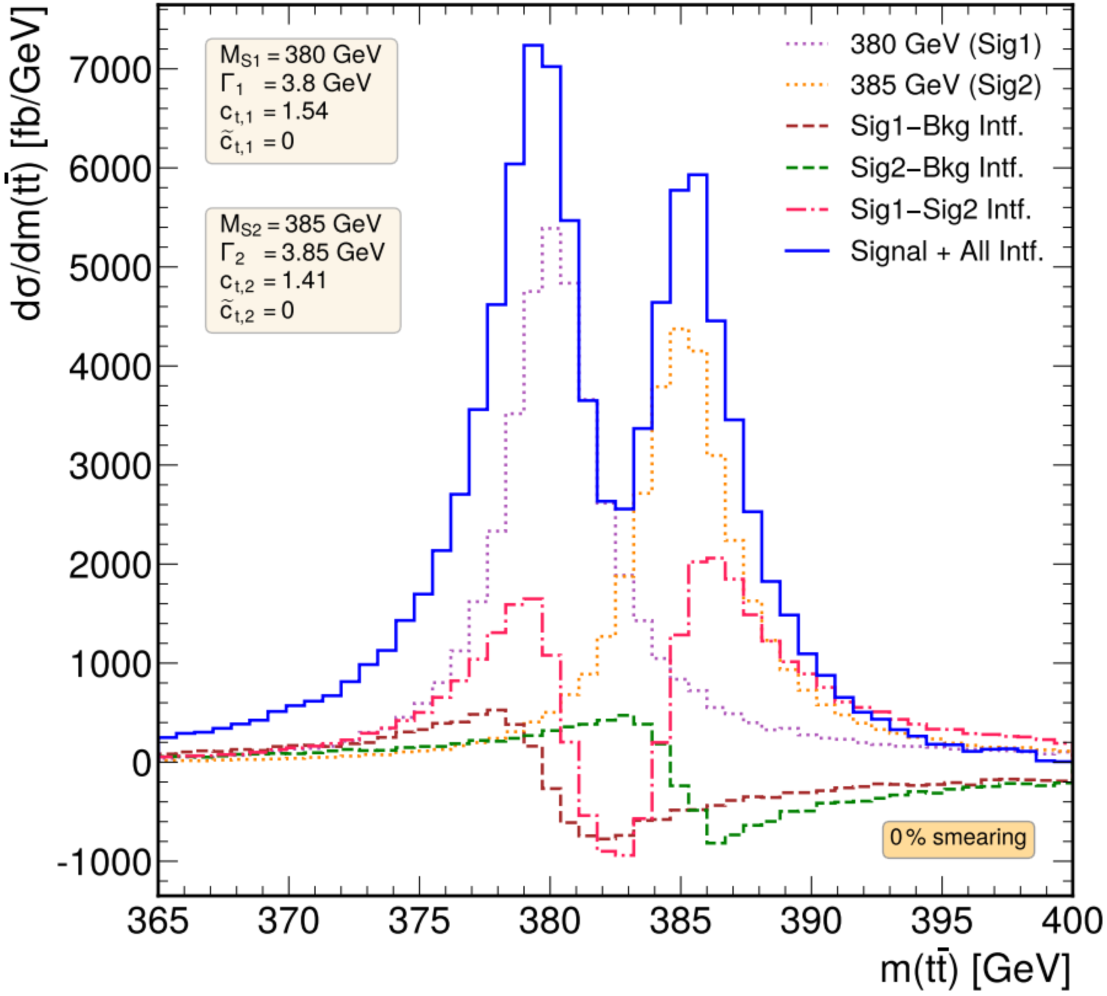
Illustrative plot for various interference effects [idealistic, no smearing; smearing discussed later]



Monte-Carlo

However, things change when there is mixing between the scalars

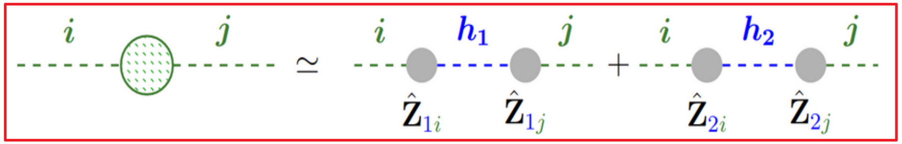
Investigation with loop-level mixing

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

- (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”, crucial for proper normalization of S-matrix, UV-finite) and the Breit-Wigner (BW) propagators

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

Z-factor formalism



Propagator matrix involves tree-level parameters of the scalars and (renormalized, MS) 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

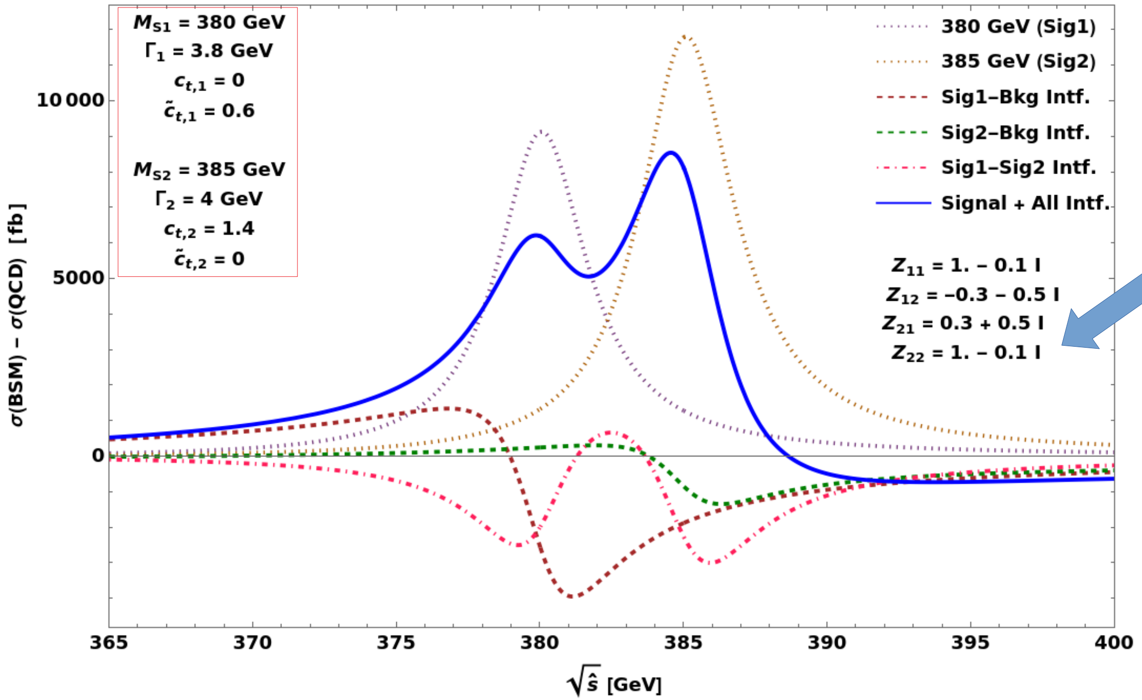
- Z-factors rearranged in matrix $\rightarrow \hat{Z}$–matrix, non-unitary and complex elements!
- Upshot: use Z-factors to write propagator-mixing in terms of separate Breit-Wigner propagators involving loop-corrected masses and widths

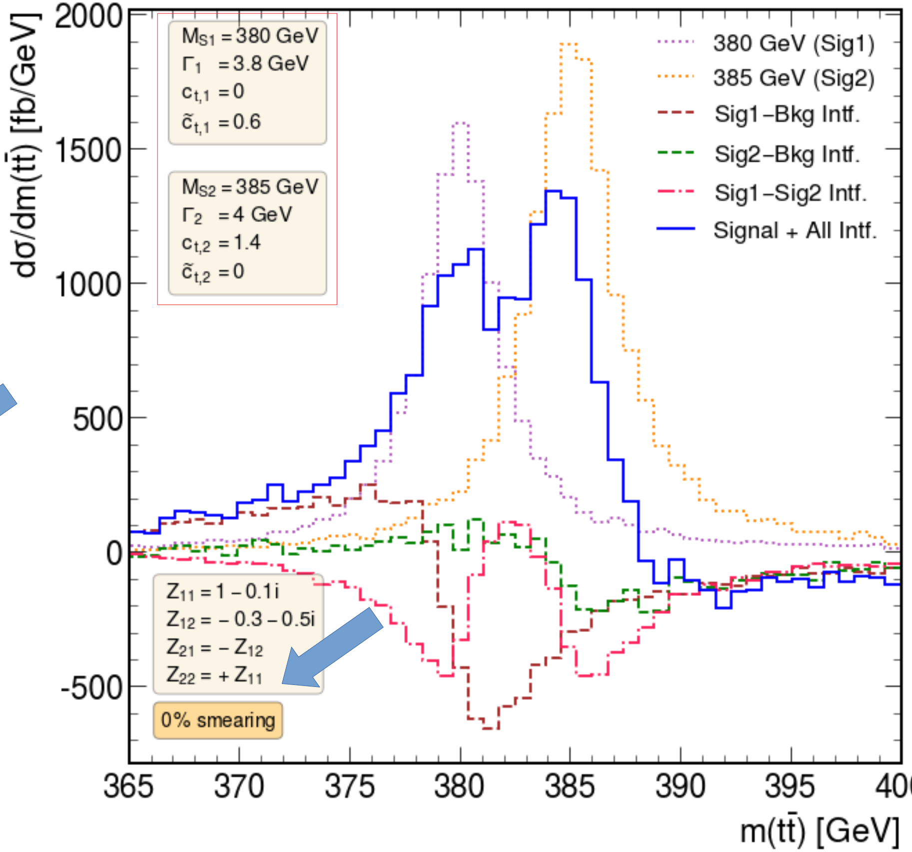
Z-factors can be complex numbers

Additional phases!

Affects the amplitudes and cross-sections, and eventually the m(tt)-distribution


Results

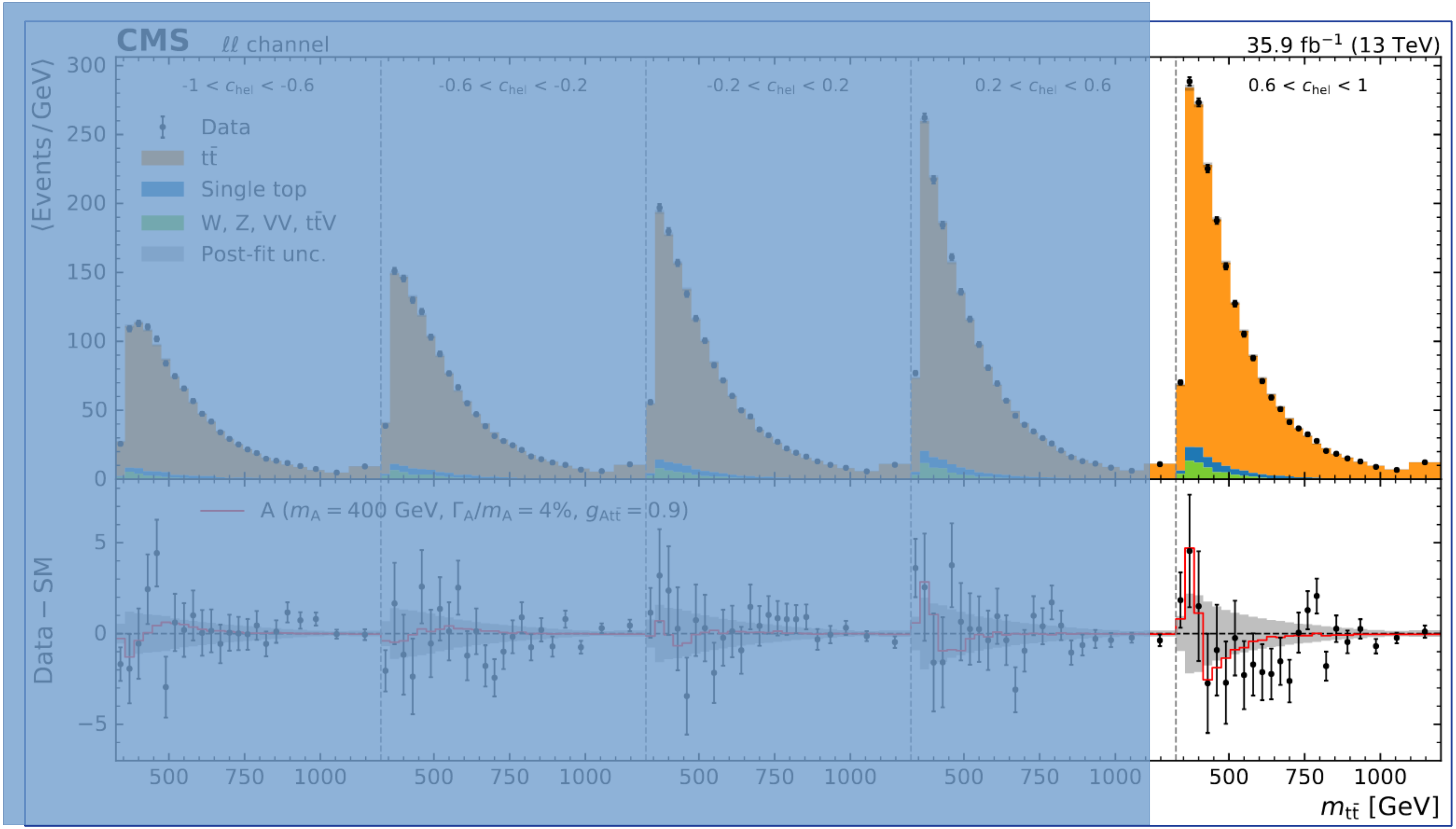




Good agreement between analytical
and Monte-Carlo results


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

LHC sensitivity



Prospects at the LHC

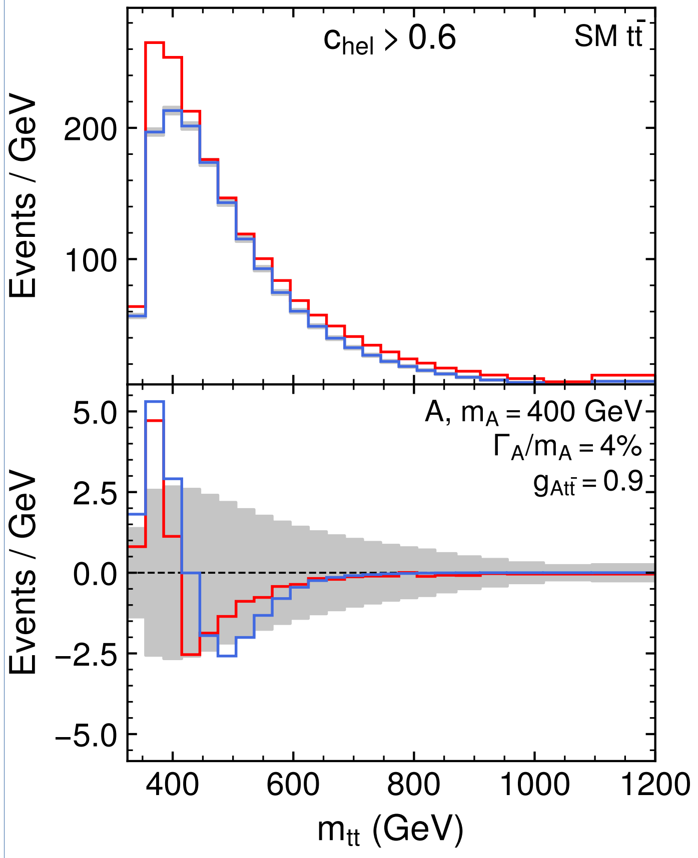
- Grey band: statistical uncertainty band, derived from the expected SM di-top events at NLO in QCD

➔ Within experimental reach: region outside grey band

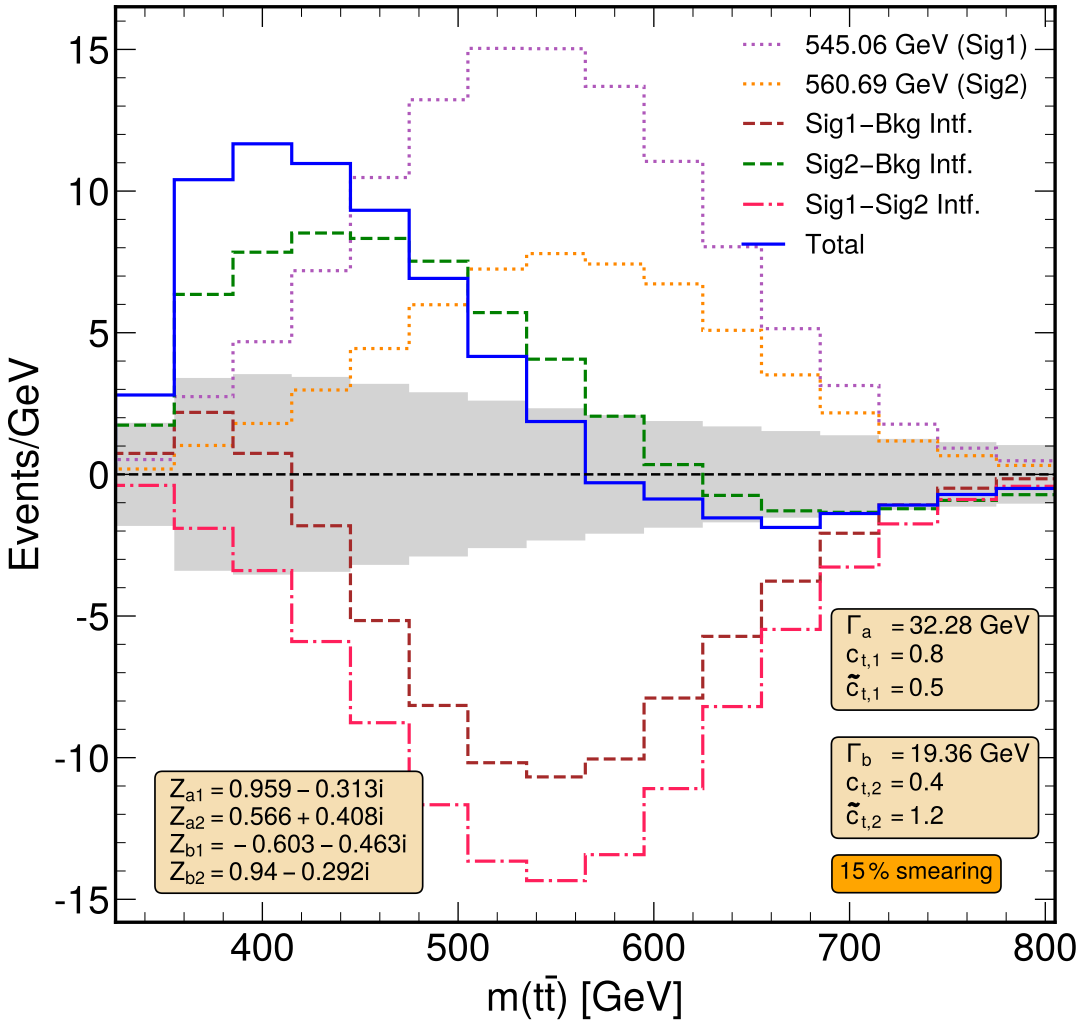
- Comparison with experimental sensitivity at Run-3 of the LHC using [2404.19014] (detector simulation not public)

➔ Gaussian smearing of 15% on the m(tt)-variable to incorporate detector-effects

- ++ other technical details: see backup slides or ask later ;)

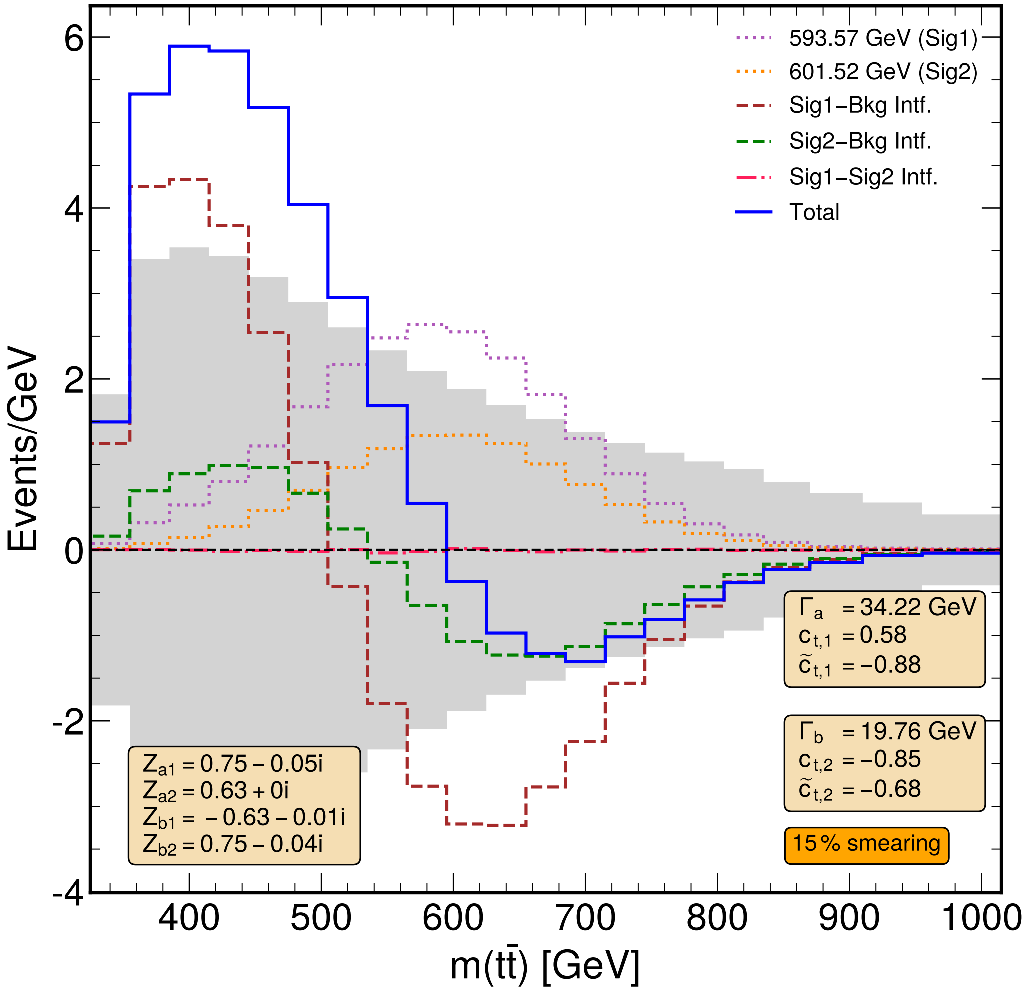


Anuar et al. [2404.19014]



M(S1) = 550 GeV
M(S2) = 580 GeV

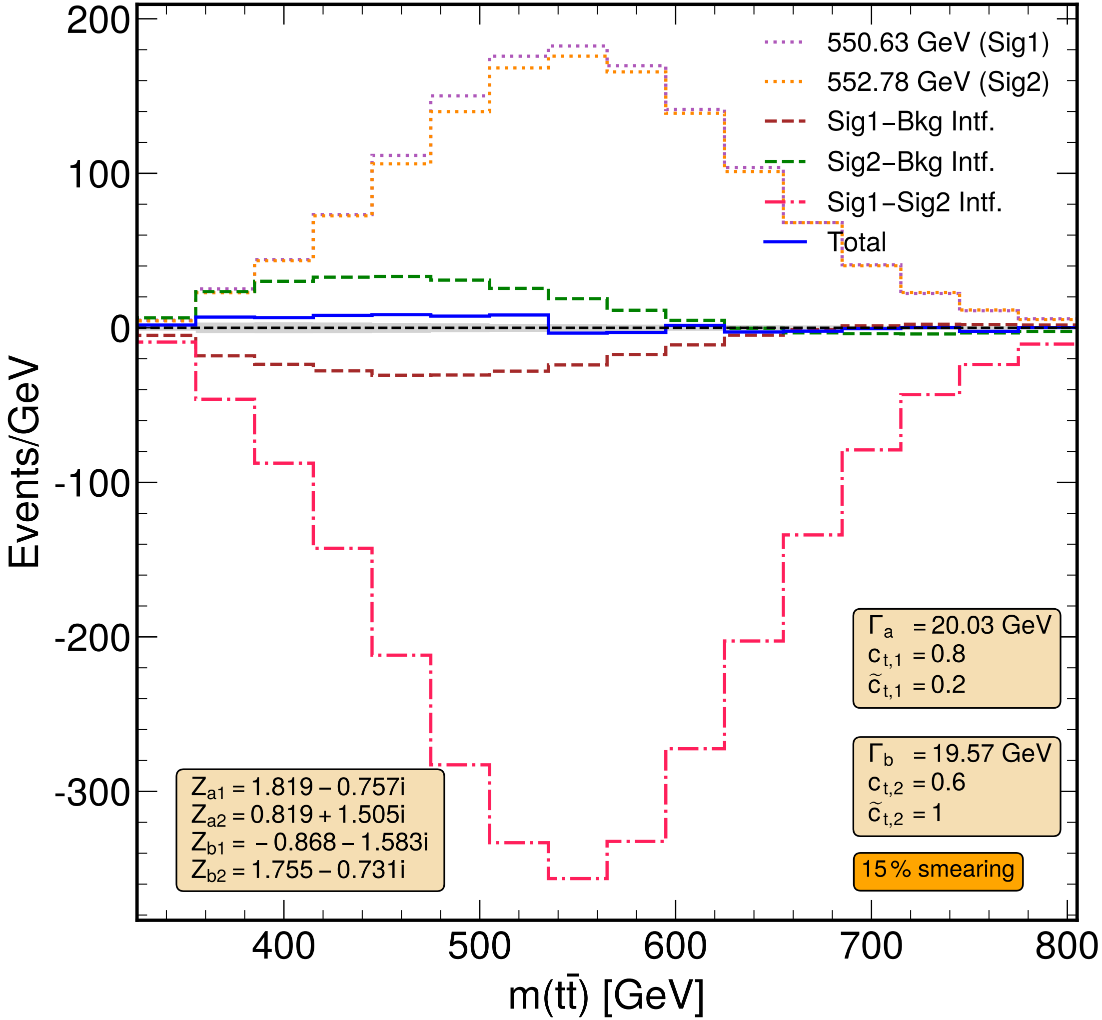
Total result resembles shape for a single particle at lower mass (!)



Benchmark point–3 of
Basler et al. [1909.09987]
in a C2HDM scenario

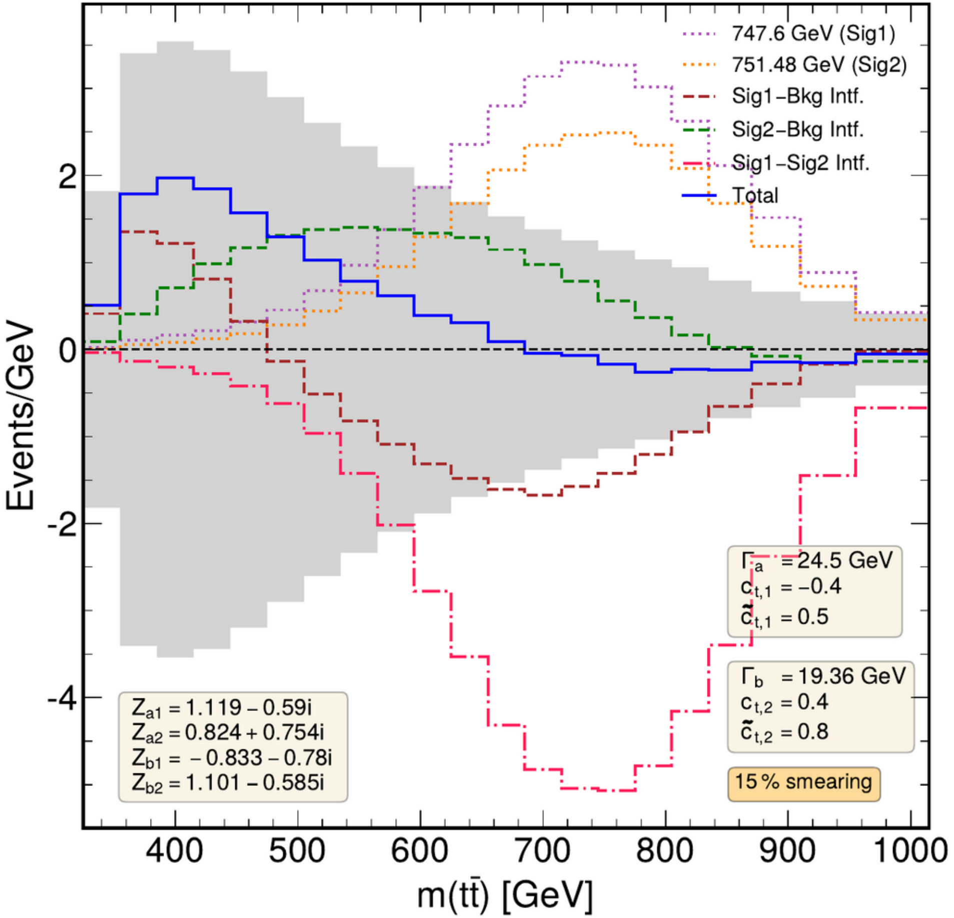
M(S1) = 608.6 GeV
M(S2) = 609.4 GeV

BSM effects: a low-mass resonance, in a physically realizable model;
also recall the recent CMS excess (2024) at the di-top threshold



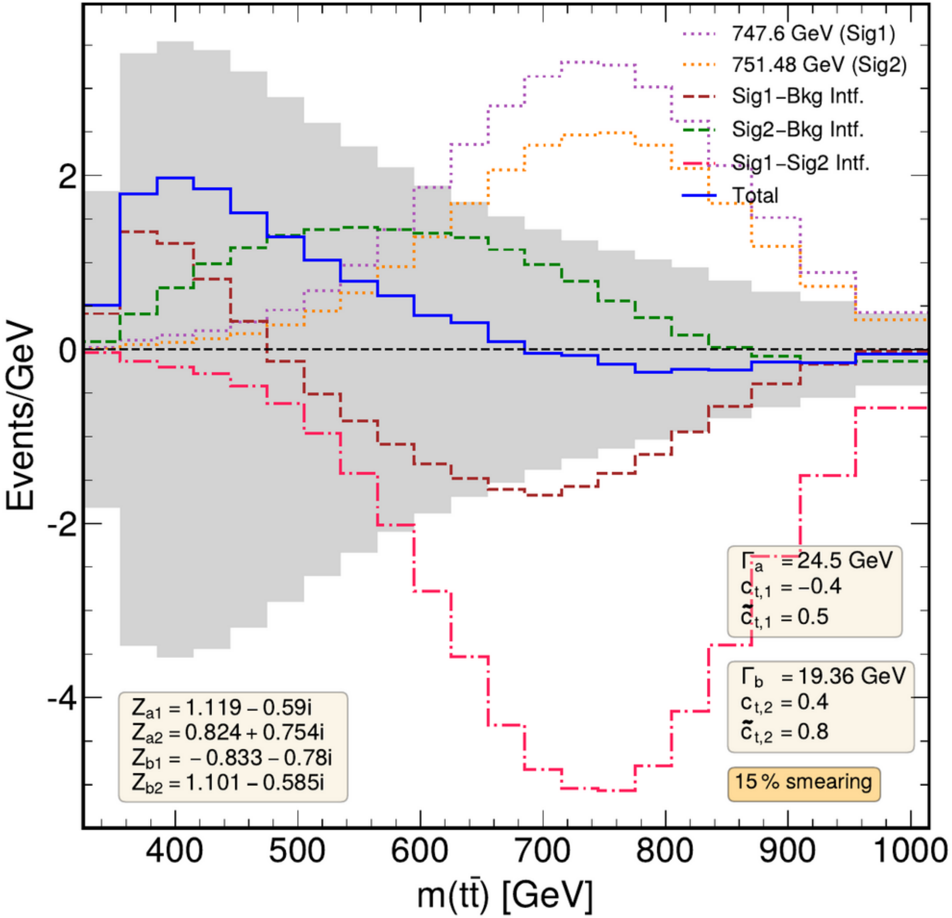
M(S1) = 550 GeV
M(S2) = 571 GeV

Large cancellations between resonances and interferences (!)



M(S1) = 750 GeV
M(S2) = 766 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)



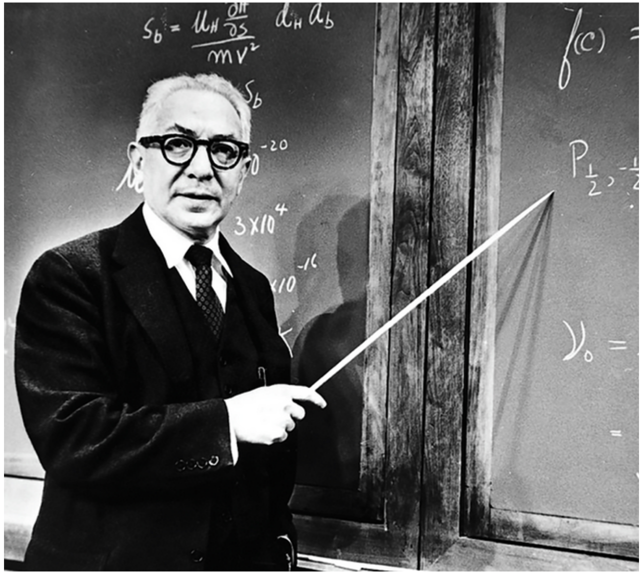
gives motivation to look into other decay channels (e.g. four-tops) to establish complementarity!

M(S1) = 750 GeV
M(S2) = 766 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)


HOW TO OPEN A BOTTLE
OF CHAMPAGNE OR SPARKLING WINE
GLASS of BUBBLY.com
1 Make sure the bottle is chilled.
2 Remove the foil around the top of the bottle.
3 Undo the wire cage (muselet) by turning the wire while keeping your thumb over the top of the bottle.
4 Hold the cork (bouchon) in the palm of your hand.
Hisss...
5 Hold the bottle at a 45 degree angle, making sure it is not pointing at anyone and twist the bottle at the bottom.
6 You should hear a gentle hiss not a pop.
Be careful when opening your bottle of bubbly.
Remember more people die from a Champagne cork than a bite from a poisonous spider!
© glassofbubbly.com

Takeaways!



Nobel laureate, Isidor Isaac Rabi (1898–1988)

- Complete Monte-Carlo implementation to simulate different processes including support for the Z-factors
- Mixing between scalars can lead to highly non-trivial distribution profiles
- Signatures can emerge that are unexpected and/or difficult to interpret
- (+ Mathematica solver to calculate Z-factors)

Who ordered all of that?

ROMAL.KUMAR@DESY.DE

Toolbox for experimental analysis to support investigation of “interesting” signatures that emerge in Higgs searches

Thank you for your attention :)

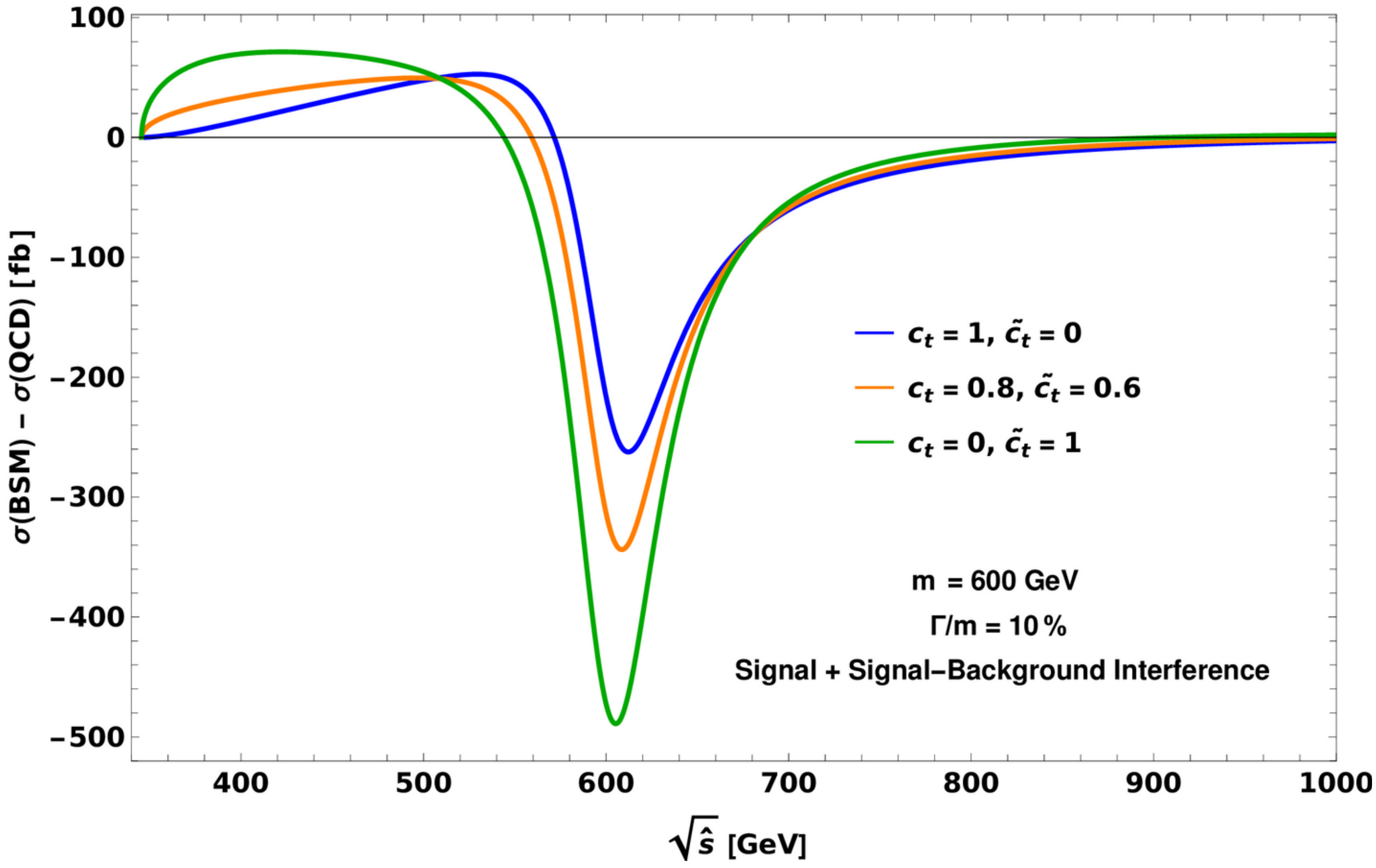
Backup/Extra slides

Summary

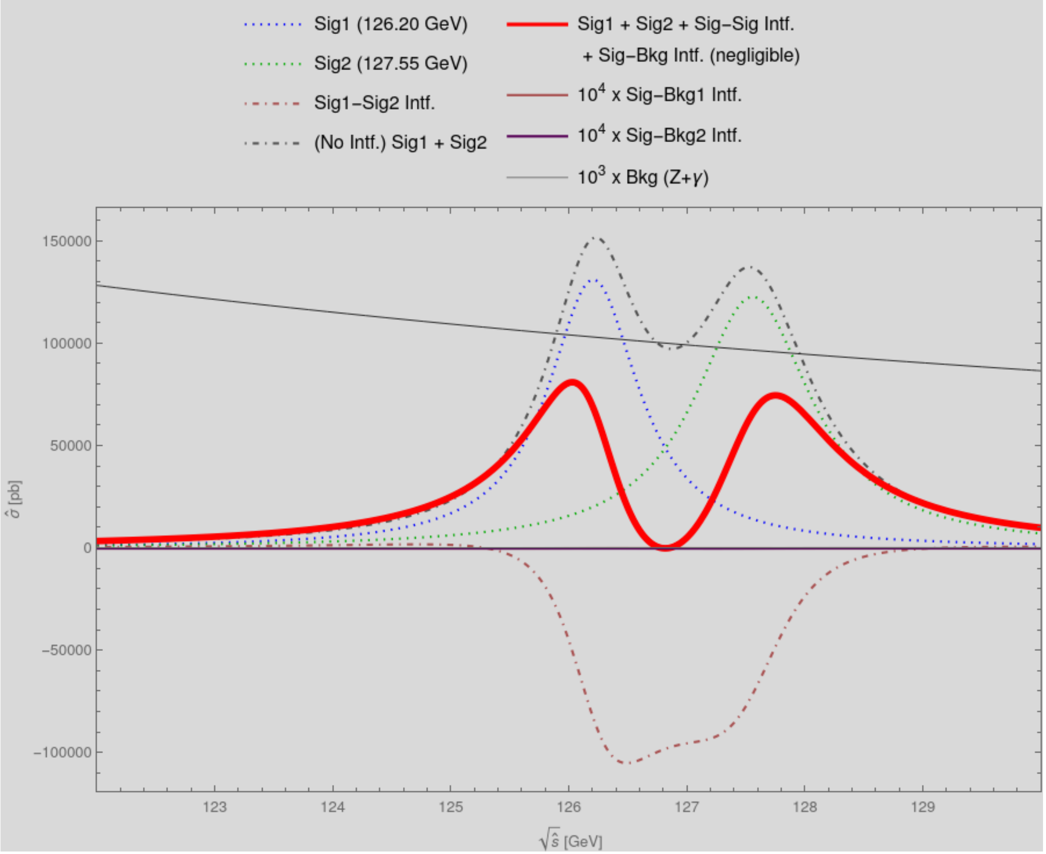
- **A search for a scalar or pseudoscalar has been peformed** in the dileptonic and semileptonic final states of $t\bar{t}$ using the full Run2 dataset of CMS
- The analysis targets the $m_{t\bar{t}}$ distribution along with angular and spin observables
- **An excess, of more than 5 standard-deviations, has been observed** that fits best with a **pseudoscalar** with a mass of 365 GeV
- Excess also fits a model of **the $t\bar{t}$ bound state η_t**, a cross section has been determined
- **Stringent limits have been set** on the scalar and pseudoscalar signal models, with a floating normalisation of η_t included

Reference: CMS-PAS-HIG-22-013

https://indico.ijclab.in2p3.fr/event/10259/contributions/35240/attachments/23869/34632/Higgs_Hunting_Samuel_Baxter_v7_2.pdf



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



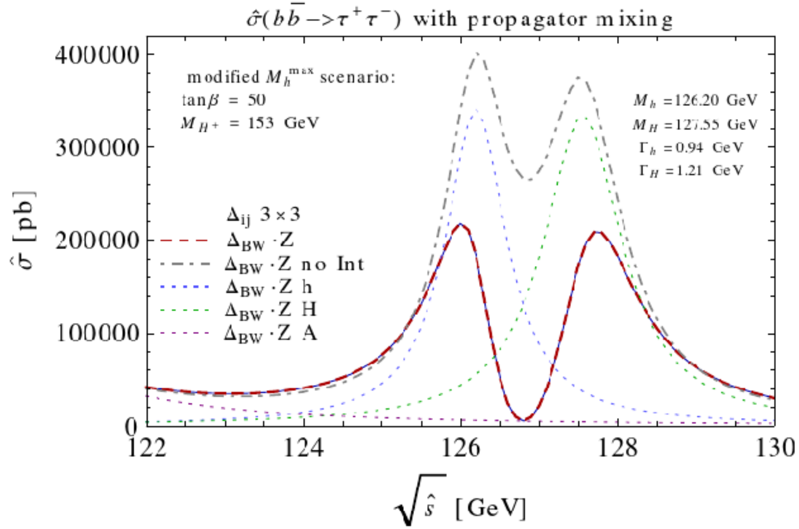
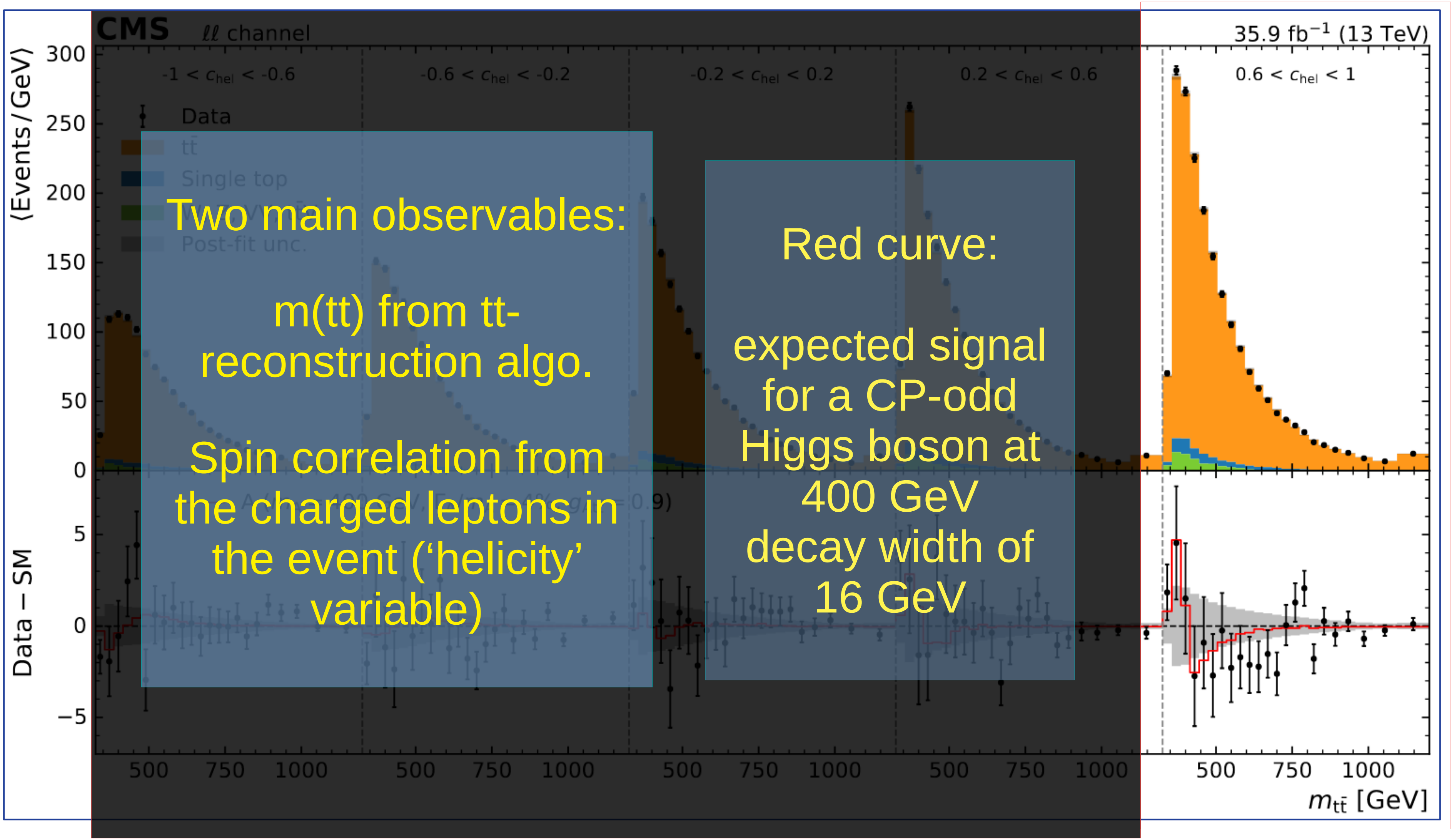


Figure 11: The partonic cross section $\hat{\sigma}(b\bar{b} \to \tau^+\tau^-)$ in a modified $M_h^{\max}$-scenario with $\tan\beta = 50$ and $M_{H^\pm} = 153\,\text{GeV}$. The cross section is calculated with the full mixing propagators (blue, solid), approximated by the coherent sum of Breit–Wigner 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.



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

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

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

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

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

quark-loop function

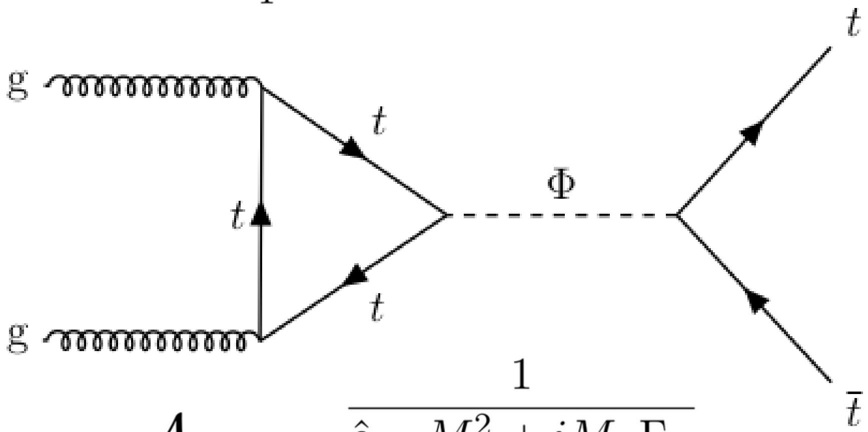
$$\tau_t = \frac{\hat{s}}{4m_t^2}$$

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

Two CP-mixed scalar(s)

- The total amplitude can be written as

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



$$\mathcal{A}_{gg\Phi} \qquad \frac{1}{\hat{s} - M_{\Phi}^2 + iM_{\Phi}\Gamma_{\Phi}} \qquad \hat{s}\,\mathcal{A}_{\Phi t\bar{t}}$$

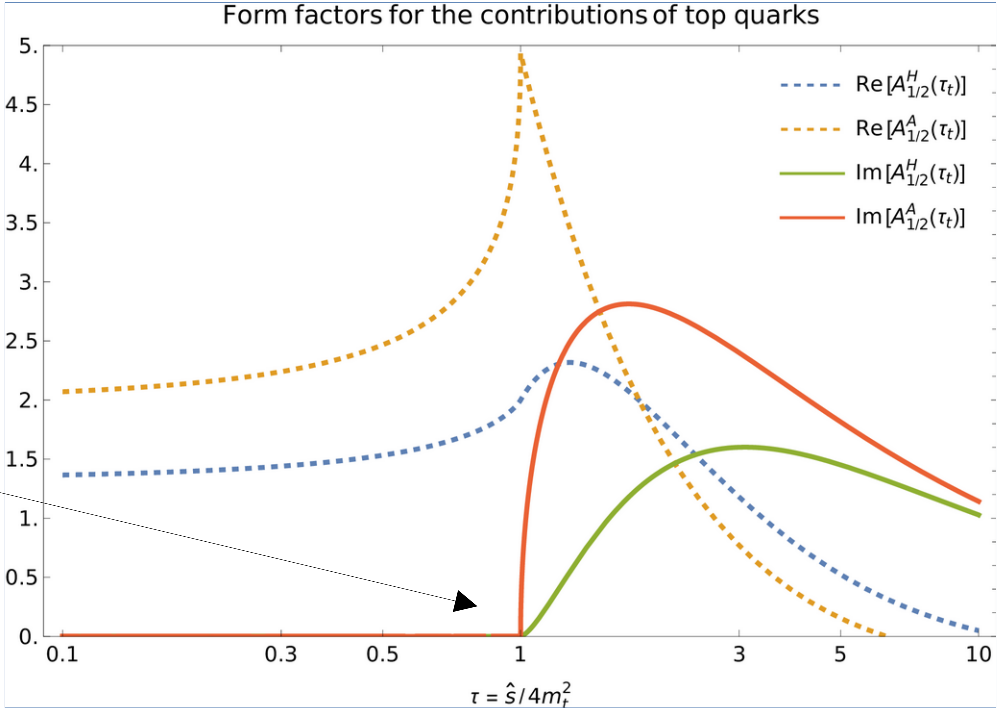
Production Amplitude | Propagator | Decay amplitude

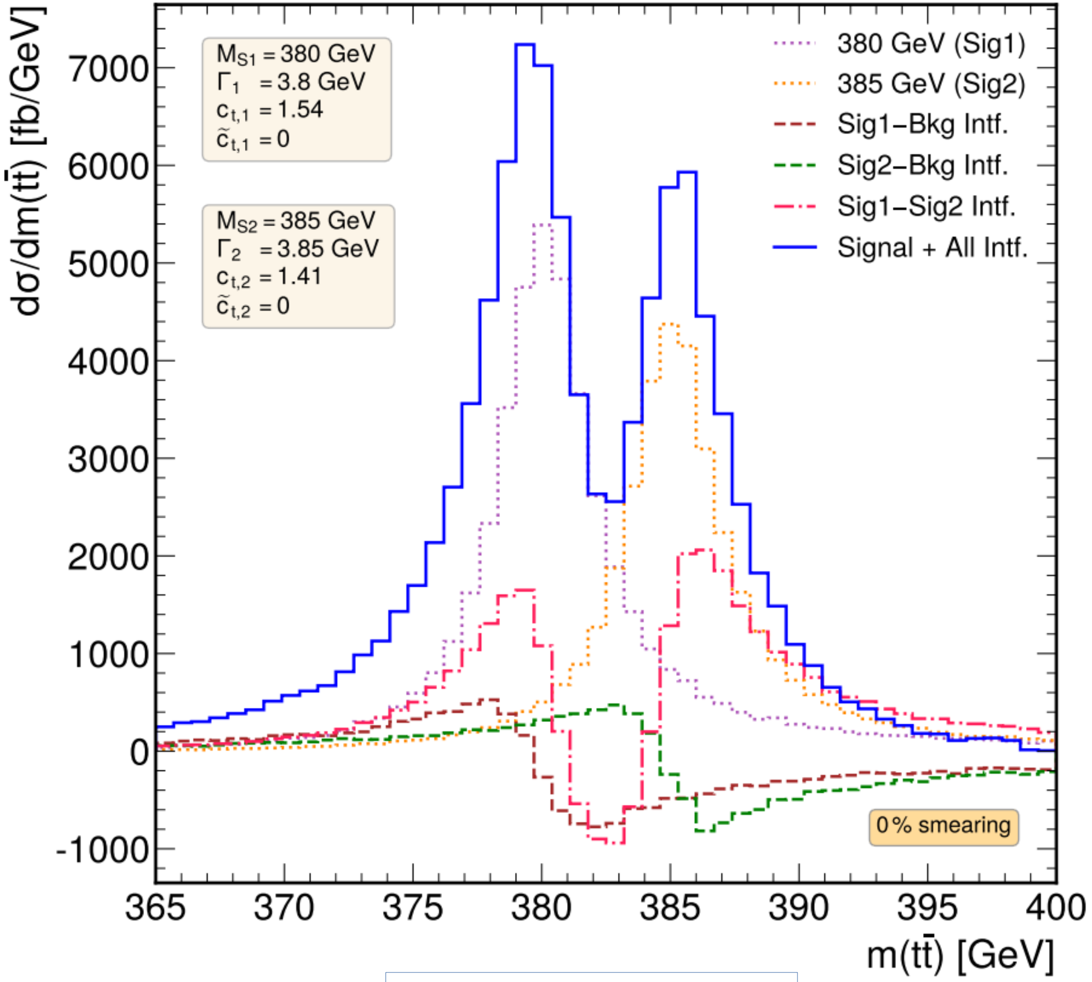
Monte-Carlo: treatment of imaginary parts

- Heavy-top approx. (effective Higgs-gluon) works well for SM-like Higgs
- But effective Higgs-gluon coupling: poor approximation for heavy scalars
- 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





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

Monte-Carlo

Aside: Neutrino or quark mixing

- Neutrino or quark flavours mix
- Reason: misalignment of mass (d’) and flavour (d, s, b) eigenstates

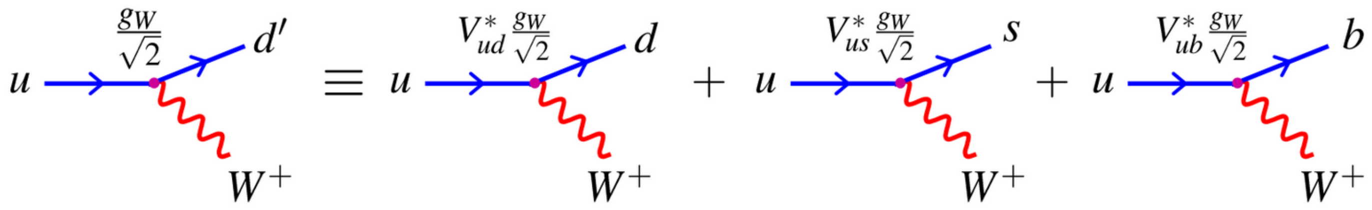


Image from a handout by Dr. A. Mitov [2012]

Flavour basis

- Propagators mix flavours
- Interactions are pure

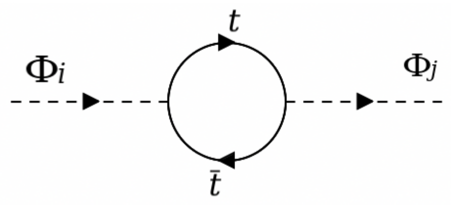
Change of basis

Mass basis

- Propagators are flavour-diagonal
- Interactions mix flavours

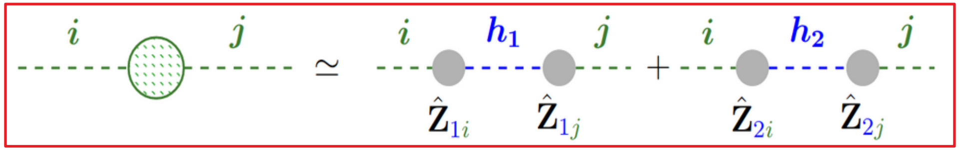
Investigation with loop-level mixing

- 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)



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

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

Z_{11} **Z_{12}**

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

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

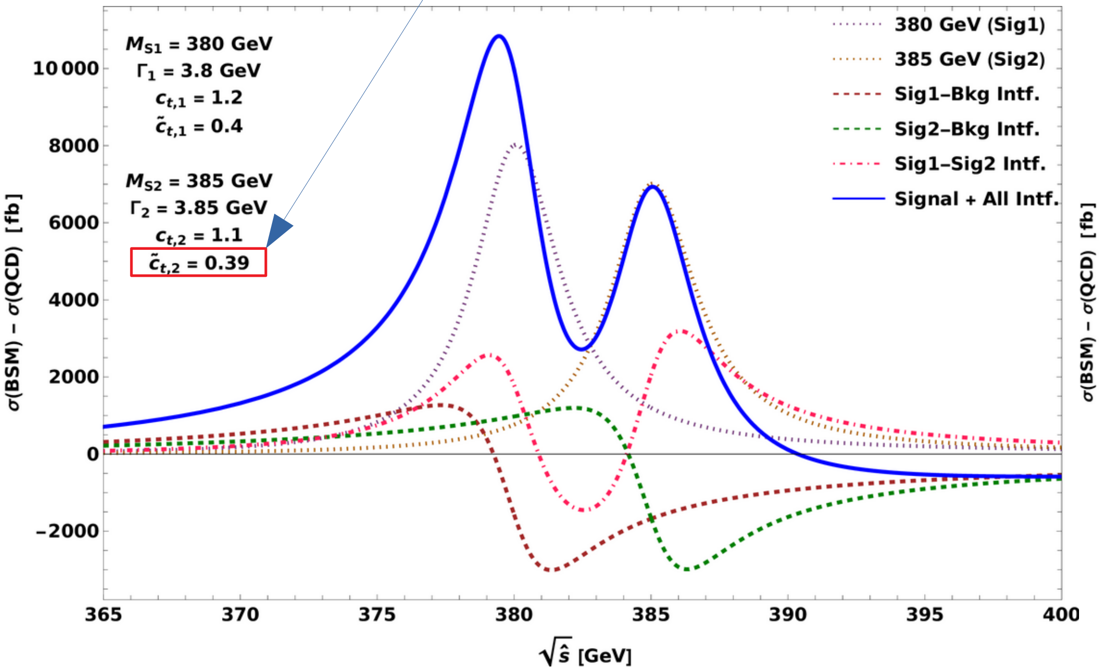
Additional phases!

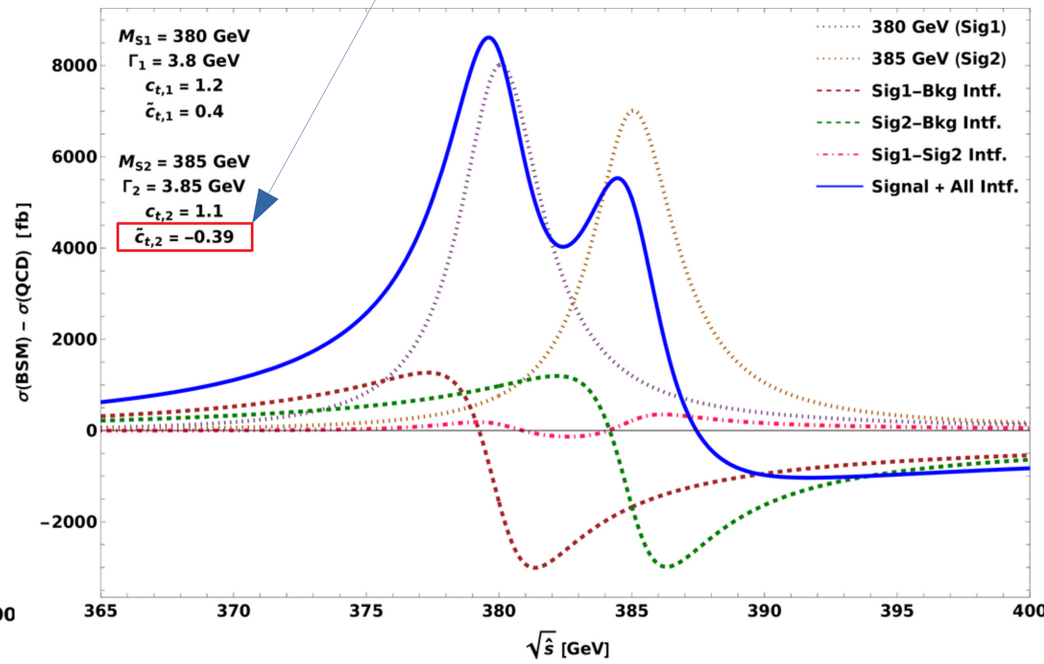
Approximately

$Z_{11} = Z_{22}$

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

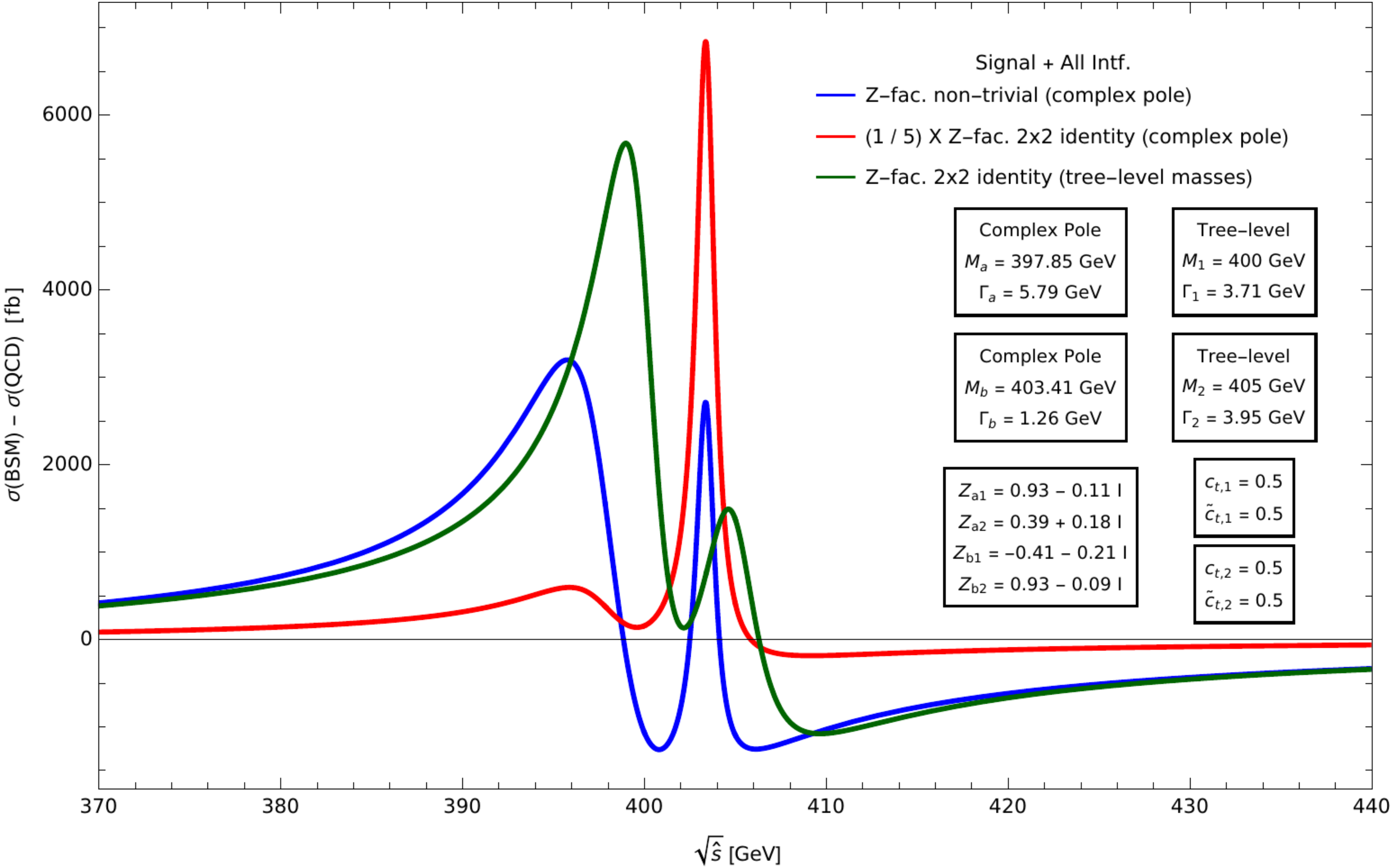
Some illustrative plots showing various processes





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

Analytical


Signal + All Intf.
Z–fac. non–trivial (complex pole)
(1 / 5) X Z–fac. 2x2 identity (complex pole)
Z–fac. 2x2 identity (tree–level masses)
Complex Pole
M_a = 397.85 GeV
Γ_a = 5.79 GeV
Tree–level
M_1 = 400 GeV
Γ_1 = 3.71 GeV
Complex Pole
M_b = 403.41 GeV
Γ_b = 1.26 GeV
Tree–level
M_2 = 405 GeV
Γ_2 = 3.95 GeV
Z_{a1} = 0.93 – 0.11 I
Z_{a2} = 0.39 + 0.18 I
Z_{b1} = –0.41 – 0.21 I
Z_{b2} = 0.93 – 0.09 I
$c_{t,1}$ = 0.5
$\tilde{c}_{t,1}$ = 0.5
$c_{t,2}$ = 0.5
$\tilde{c}_{t,2}$ = 0.5
σ(BSM) – σ(QCD) [fb]
6000
4000
2000
0
370
380
390
400
410
420
430
440
$\sqrt{\hat{s}}$ [GeV]

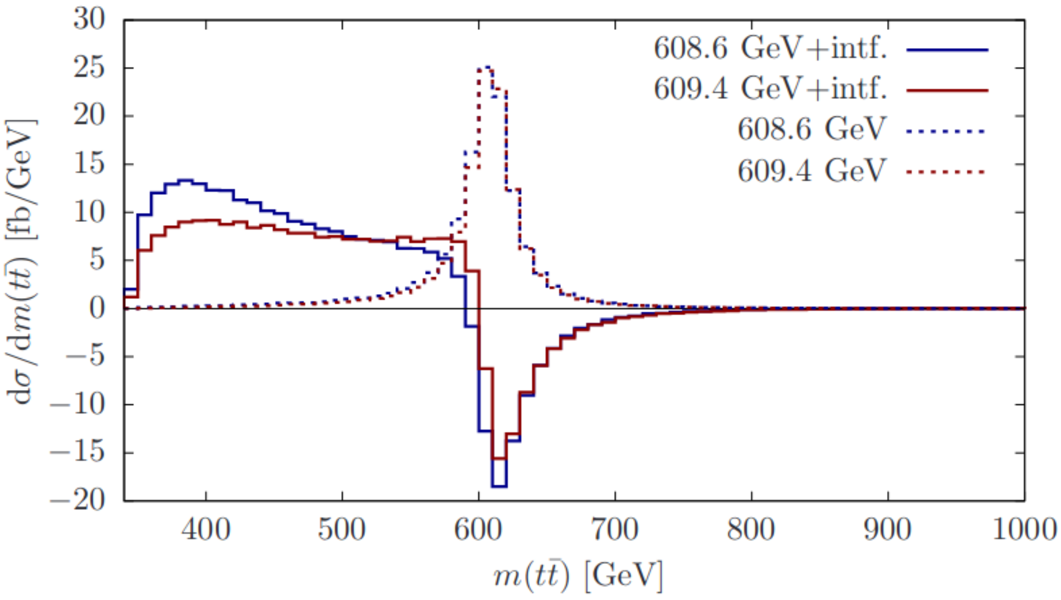
Application to the C2HDM

- 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

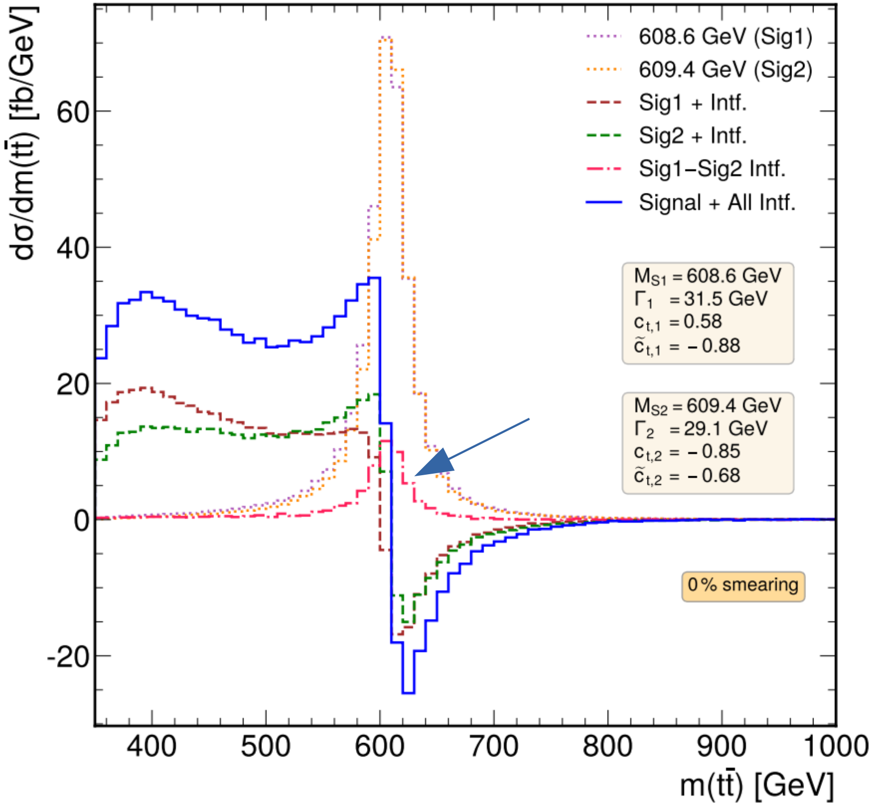
$$\{R_{i,j}\} \equiv R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

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

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



arXiv:1909.09987v2



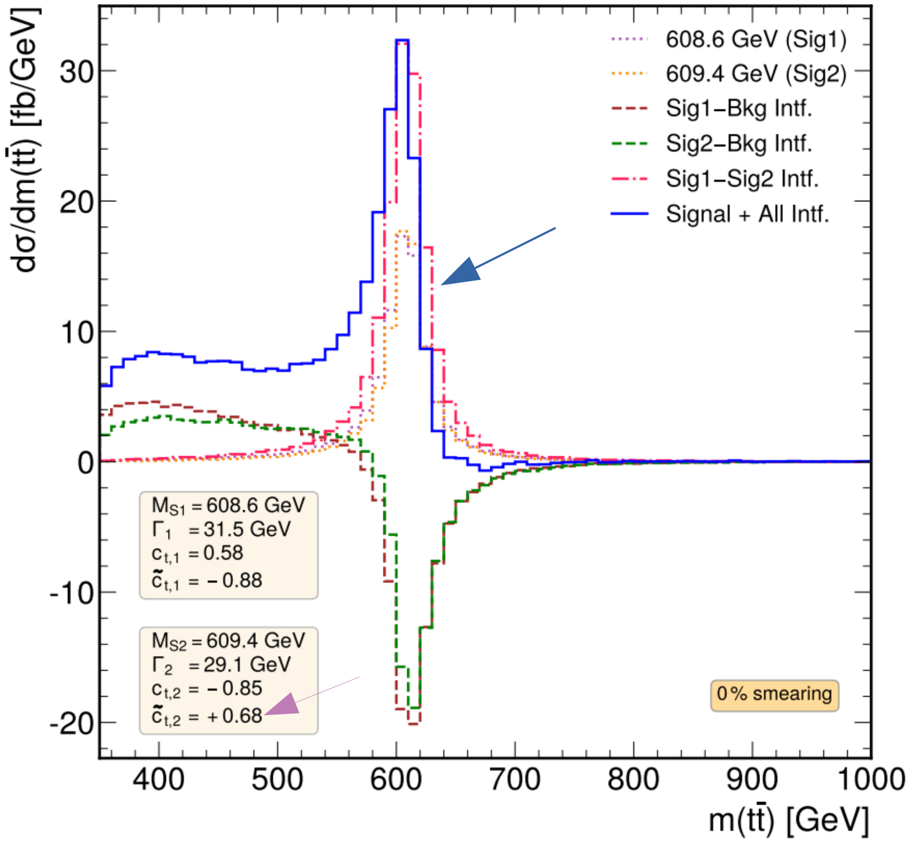
- Signal-Signal interference can be significant (not considered previously)

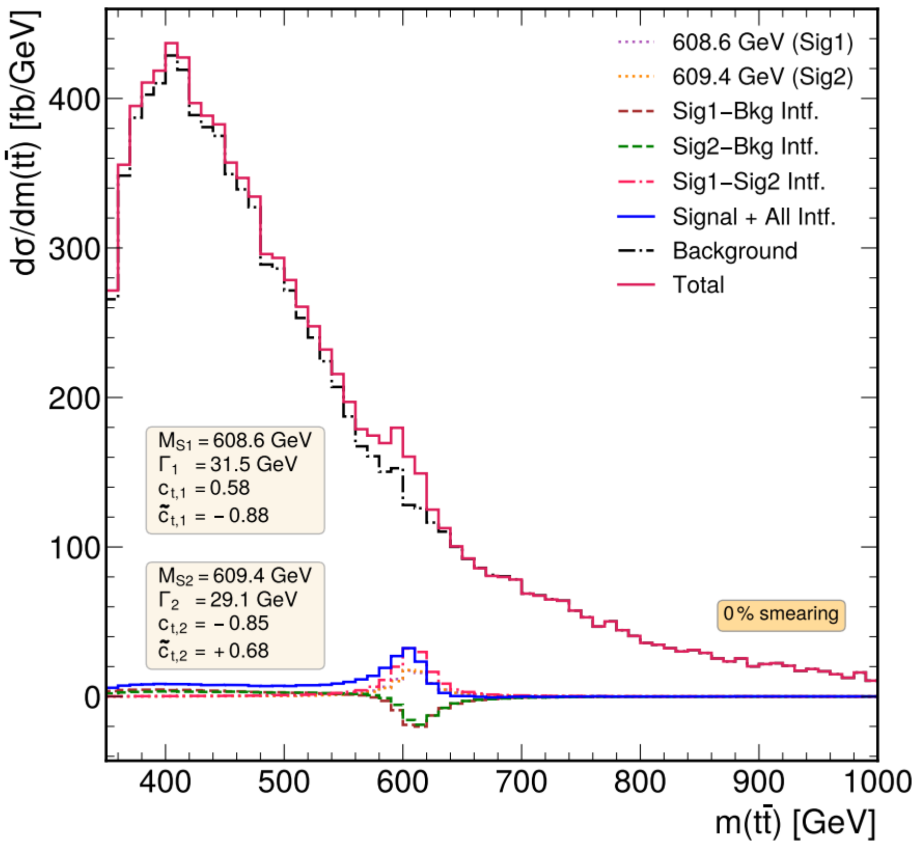
Prospects at the LHC

- 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

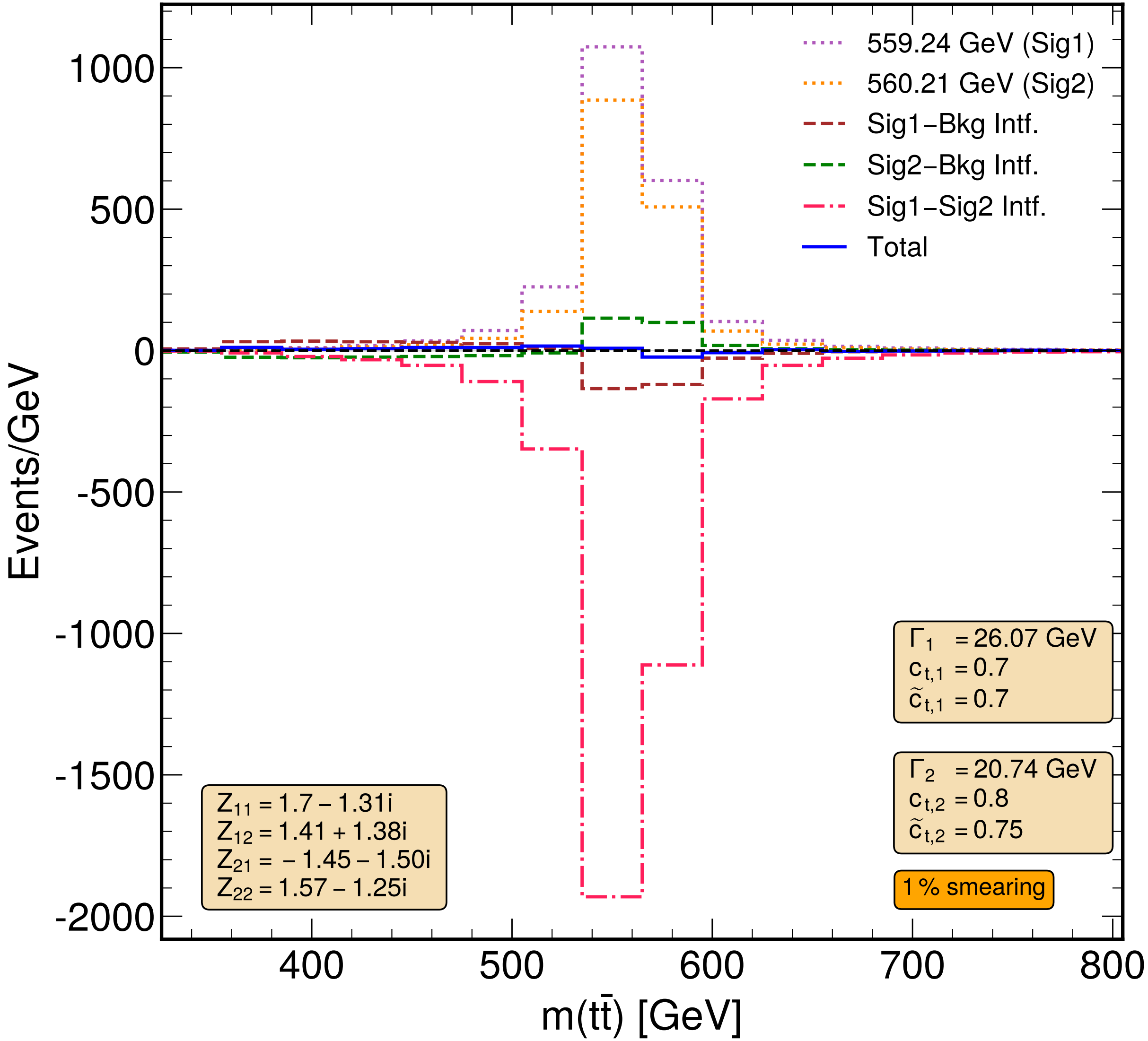
2404.19014

Sign of
ctt2 flipped





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



559.24 GeV (Sig1)
560.21 GeV (Sig2)
Sig1−Bkg Intf.
Sig2−Bkg Intf.
Sig1−Sig2 Intf.
Total
Events/GeV
m(tt̄) [GeV]
$\Gamma_1 = 26.07$ GeV
$c_{t,1} = 0.7$
$\tilde{c}_{t,1} = 0.7$
$\Gamma_2 = 20.74$ GeV
$c_{t,2} = 0.8$
$\tilde{c}_{t,2} = 0.75$
1 % smearing
$Z_{11} = 1.7 - 1.31i$
$Z_{12} = 1.41 + 1.38i$
$Z_{21} = -1.45 - 1.50i$
$Z_{22} = 1.57 - 1.25i$