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

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based on work in collaboration with Henning Bahl and Romal Kumar

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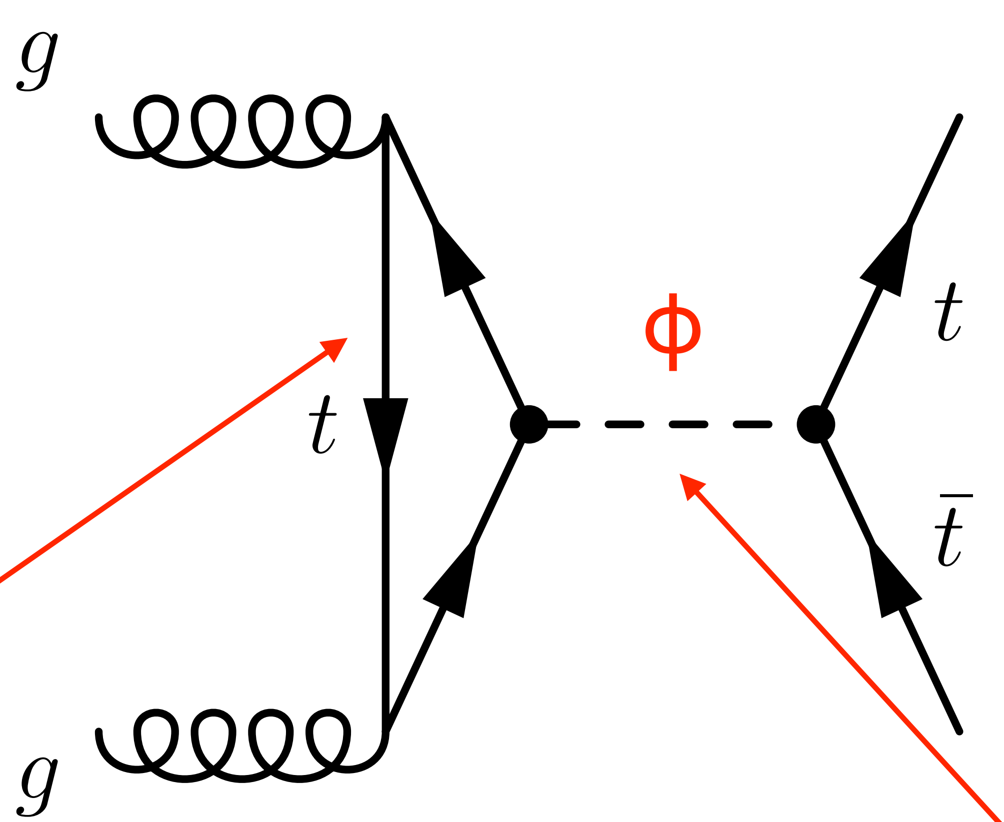
Outline

- Introduction
- Case of two BSM states that can mix with each other
- Comparison with the sensitivity at Run 3 of the LHC
- Conclusions

Introduction

Characteristic feature of LHC searches for an s-channel resonance in gluon fusion: large signal-background interference possible above the di-top threshold

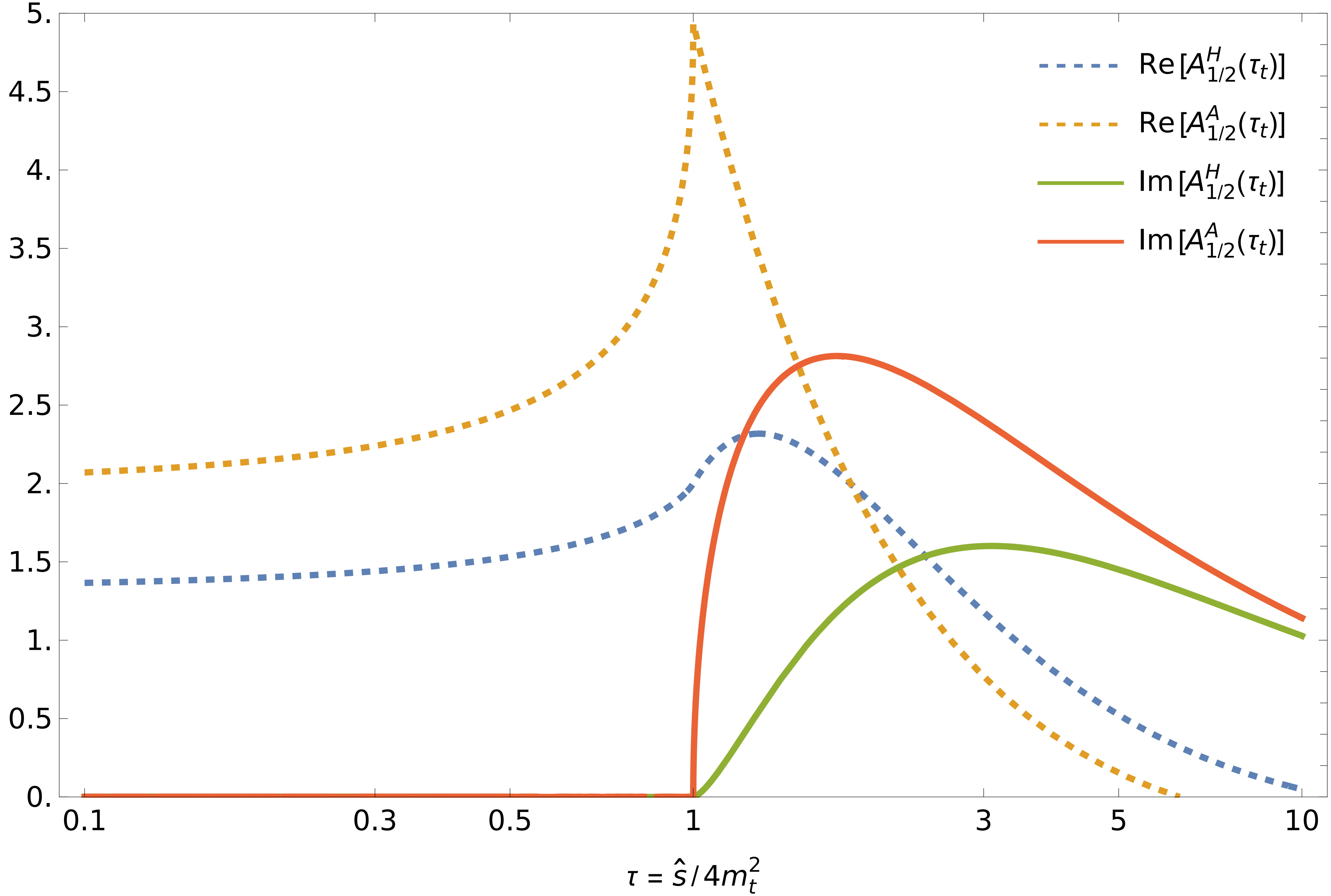
Example:



Loop function AΦ(τ) develops imaginary part above the threshold $\tau \equiv \frac{\hat{s}}{4m_t^2} \geq 1$

propagator $\sim \frac{1}{\hat{s} - m_\Phi^2 + i m_\Phi \Gamma_\Phi}$

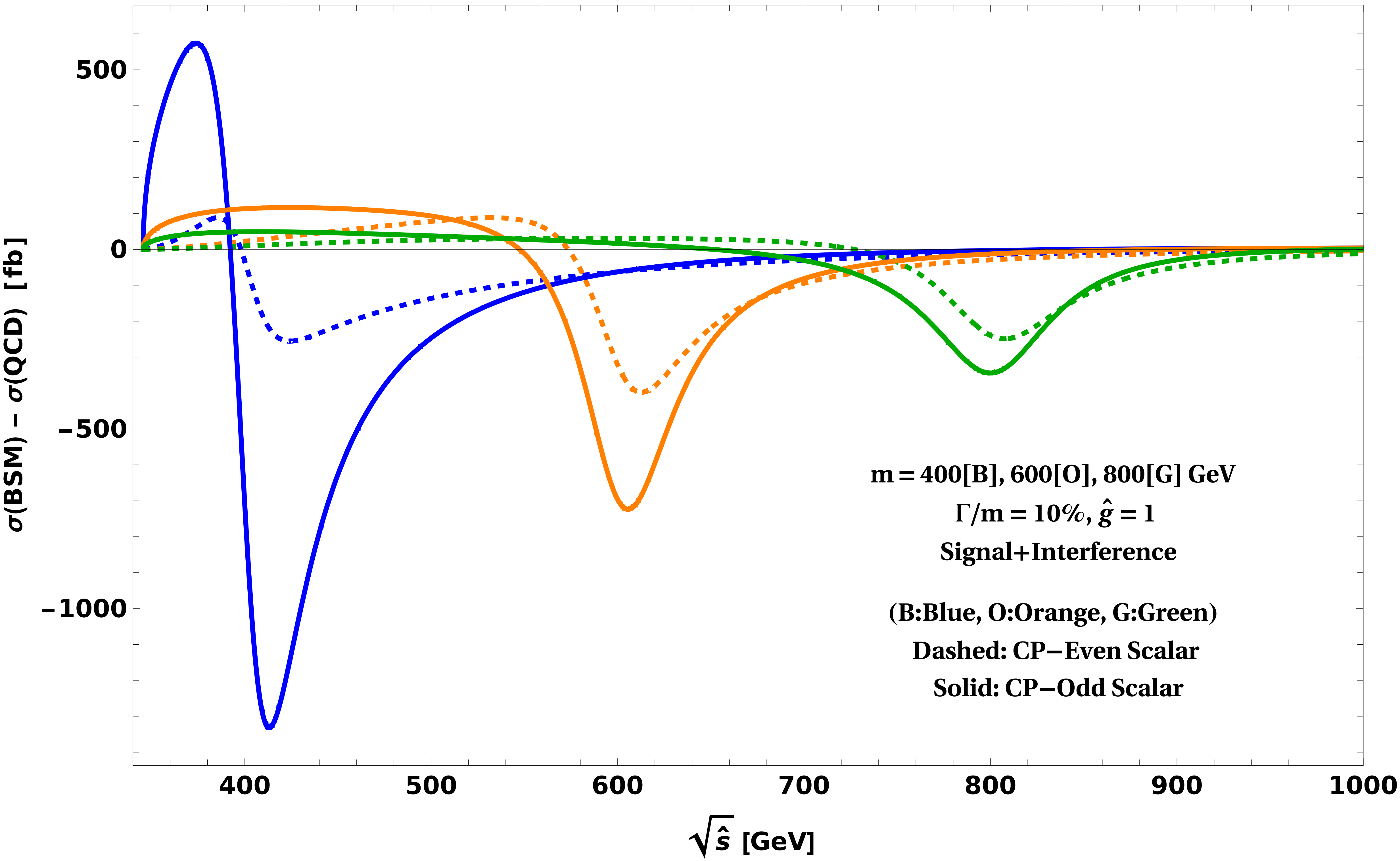
Loop function AΦ(τ)



⇒ Interference contribution ~ Im[AΦ(τ)] $m_\Phi\,\Gamma_\Phi$

Interference patterns for background-subtracted cross section, parton level

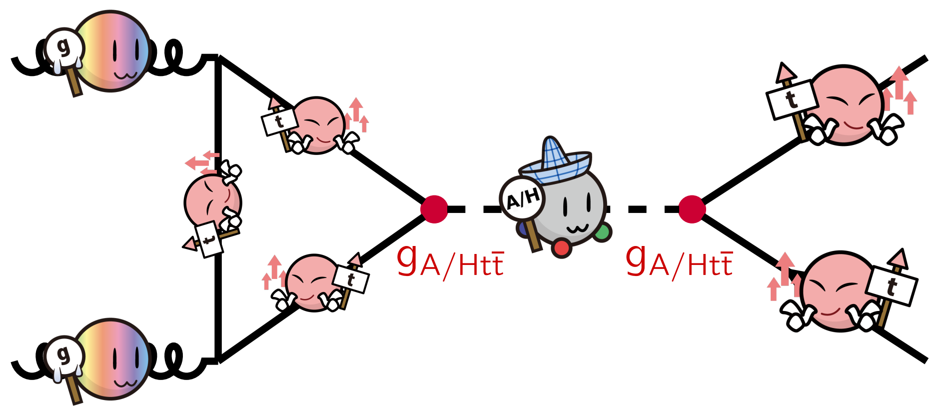
[H. Bahl, R. Kumar, G. W. '22]



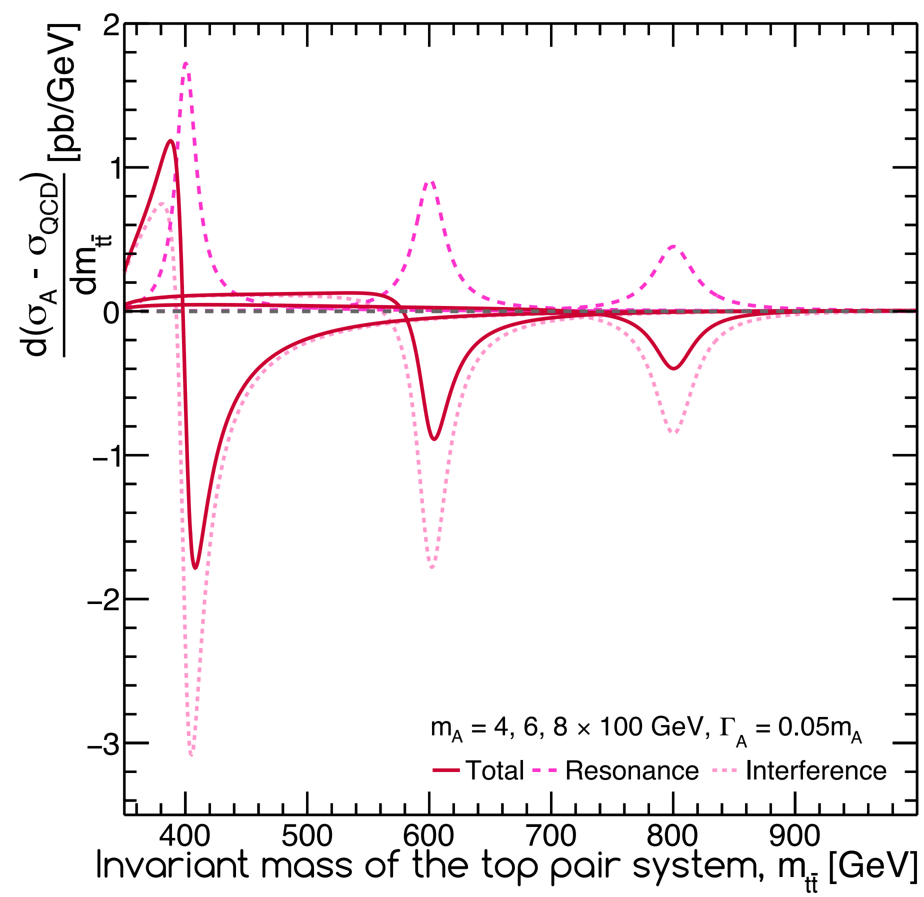
Sensitivity to BSM physics in di-top final states

Example: H, A → tt search in CMS

[A. Anuar '21]



Interference ⇒

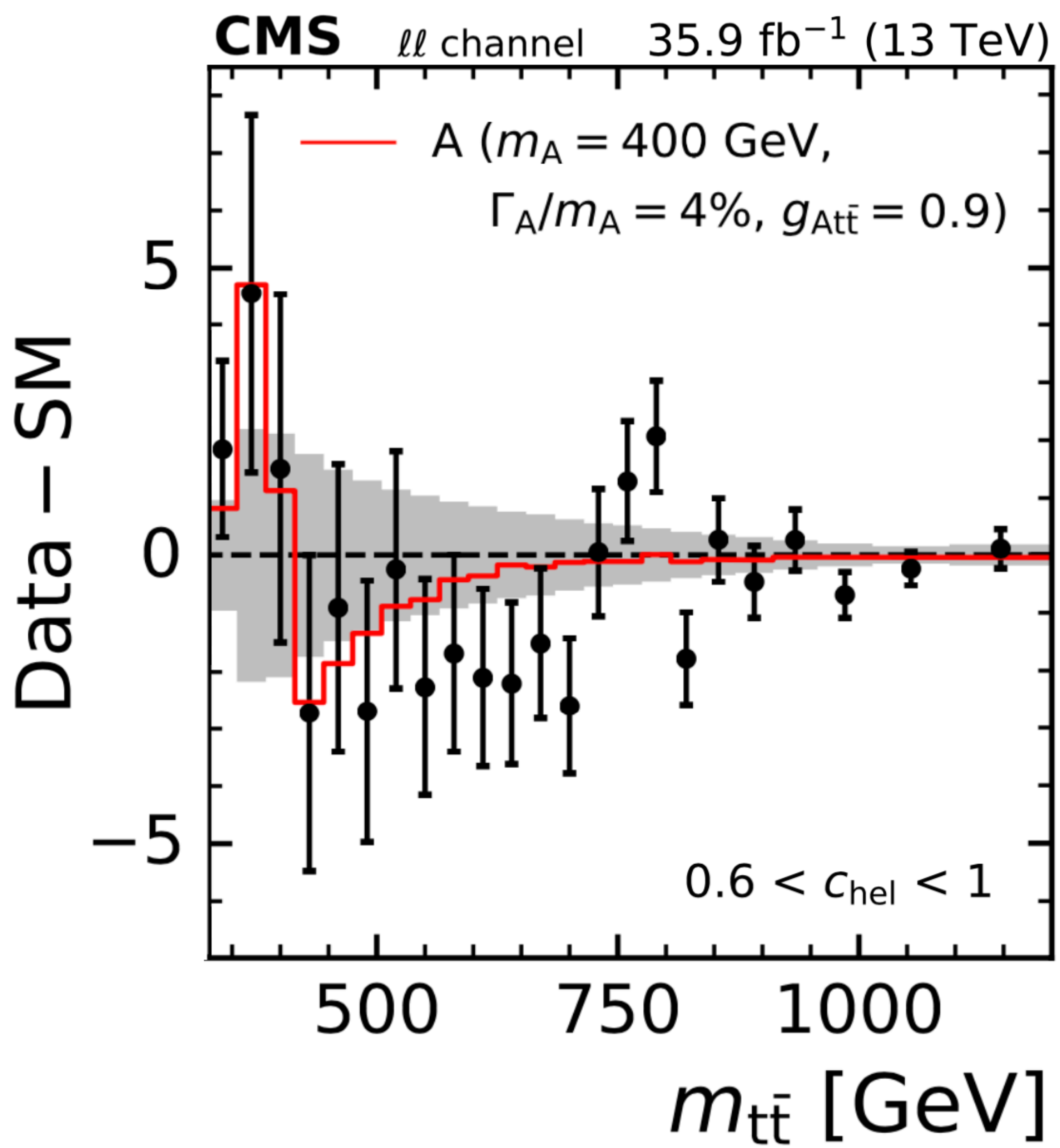


Signal-background interference yields peak-dip structure

Analysed using angular correlations of the top and anti-top decay products

H, A → tt search in CMS

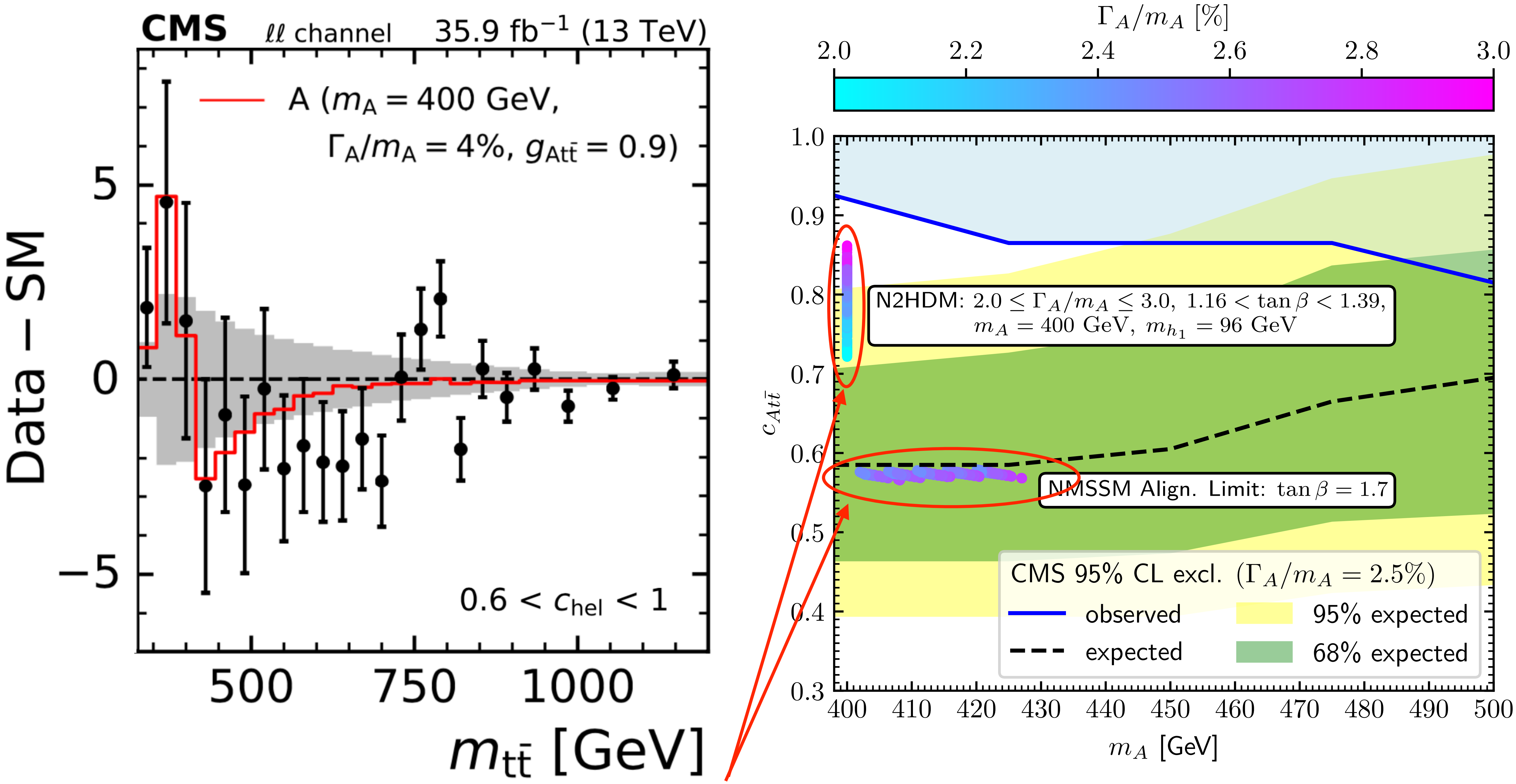
[CMS Collaboration '19]



⇒Excess in CMS search, compatible with CP-odd Higgs at about 400 GeV

Excess (3 σ local) in CMS search at about 400 GeV

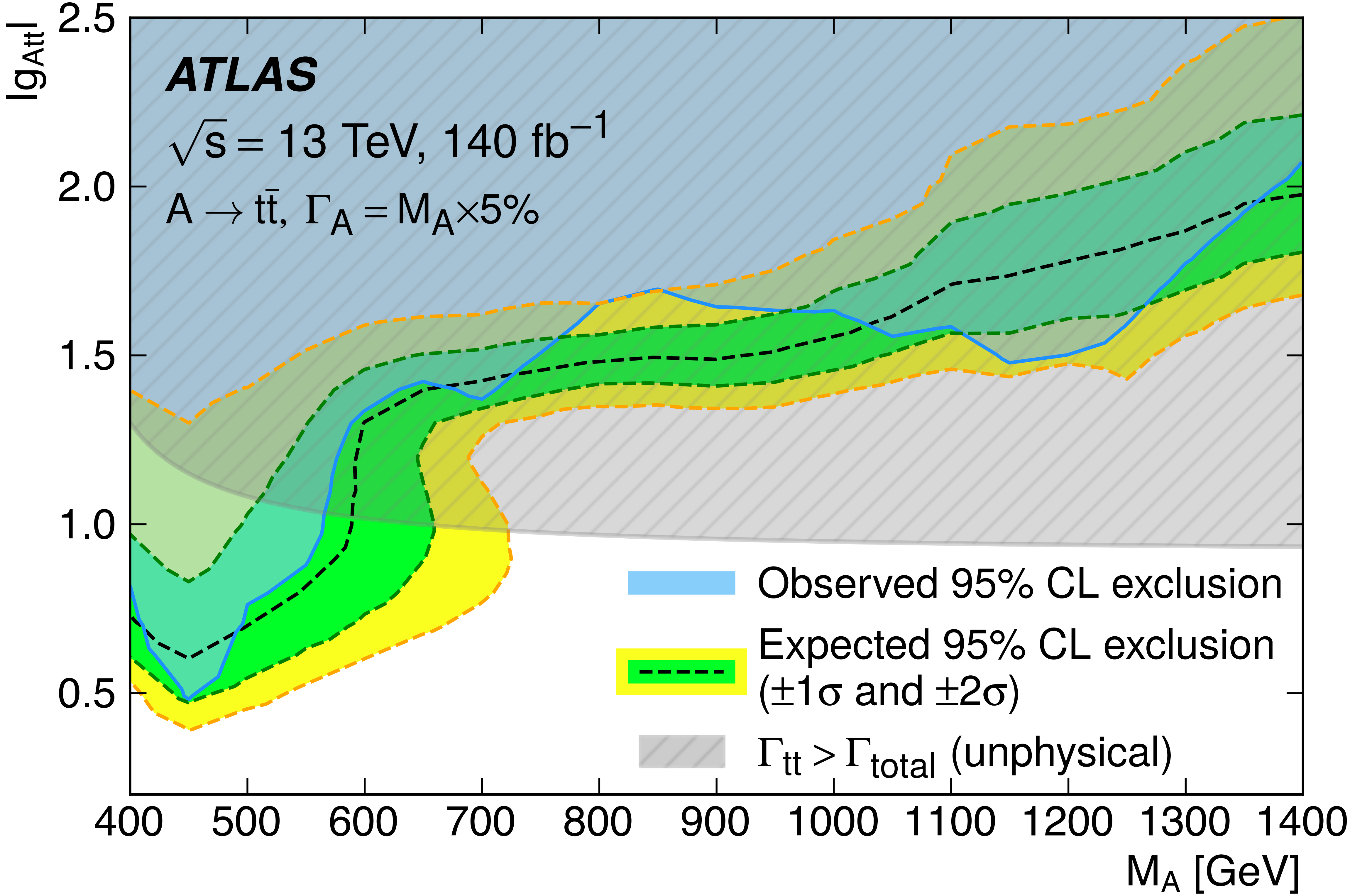
[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. ’21]



Good description of A → tt excess at 400 GeV, simultaneously with excess at 95 GeV, in models with extended Higgs sectors (N2HDM, NMSSM)

New ATLAS result

[ATLAS Collaboration '24]



⇒ No significant excess at 400 GeV

Typical situation in extended Higgs sectors

SM-like Higgs boson at 125 GeV, other Higgs states are significantly heavier and close together in mass

CP-conserving case (e.g. 2HDM, …): signals of CP-even Higgs boson H and CP-odd Higgs boson A may overlap, but there is no interference between the two signal contributions

General case with CP-mixing (e.g. C2HDM, …): mass eigenstates differ from the CP eigenstates, large signal-signal interference effects possible

Case of two BSM states that can mix with each other

Example: extended Higgs sector with two heavy Higgs bosons that are CP-mixed states

$$
\begin{aligned}
\left|\mathcal{A}^{\Phi}_{gg\to t\bar{t}}\right|^2 \supset & \left| -\frac{\mathcal{A}_{gg,1}\hat{s}\mathcal{A}_{1,t\bar{t}}}{\hat{s}-M_1^2+iM_1\Gamma_1} - \frac{\mathcal{A}_{gg,2}\hat{s}\mathcal{A}_{2,t\bar{t}}}{\hat{s}-M_2^2+iM_2\Gamma_2}\right|^2 \\
= & \underbrace{\left|\frac{\mathcal{A}_{gg,1}\hat{s}\mathcal{A}_{1,t\bar{t}}}{\hat{s}-M_1^2+iM_1\Gamma_1}\right|^2}_{\text{signal}-1} + \underbrace{\left|\frac{\mathcal{A}_{gg,1}\hat{s}\mathcal{A}_{1,t\bar{t}}}{\hat{s}-M_1^2+iM_1\Gamma_1}\right|^2}_{\text{signal}-2} + \\
& \underbrace{\left(\frac{\mathcal{A}_{gg,1}\hat{s}\mathcal{A}_{1,t\bar{t}}\mathcal{A}^*_{2,t\bar{t}}\hat{s}\mathcal{A}^*_{gg,2}}{(\hat{s}-M_1^2+iM_1\Gamma_1)(\hat{s}-M_2^2-iM_2\Gamma_2)} + \frac{\mathcal{A}_{gg,2}\hat{s}\mathcal{A}_{2,t\bar{t}}\mathcal{A}^*_{1,t\bar{t}}\hat{s}\mathcal{A}^*_{gg,1}}{(\hat{s}-M_2^2+iM_2\Gamma_2)(\hat{s}-M_1^2-iM_1\Gamma_1)}\right)}_{\text{Signal-Signal Interference}}
\end{aligned}
$$

⇒ Signal-signal interference contribution in addition to the interferences of both Higgs bosons with the background

Simplified model framework

Effective Yukawa couplings with CP-even and CP-odd components

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

Loop-level mixing (complex) between lowest-order states ϕ_1, ϕ_2 and loop-corrected mass eigenstates h_a, h_b

Loop-corrected masses: poles of the propagators

For an unstable particle:

$\Sigma(\mathcal{M}^2)$ is complex $\Rightarrow$ Pole in the complex plane

$$\mathcal{M}^2 - m^2 + \Sigma(\mathcal{M}^2) = 0, \quad \mathcal{M}^2 = M^2 - iM\Gamma$$

M: physical mass, Γ: decay width of the unstable particle

$\Rightarrow$ The mass of an unstable (elementary) particle is defined according to the real part of the complex pole

Mixing between two Higgs bosons:

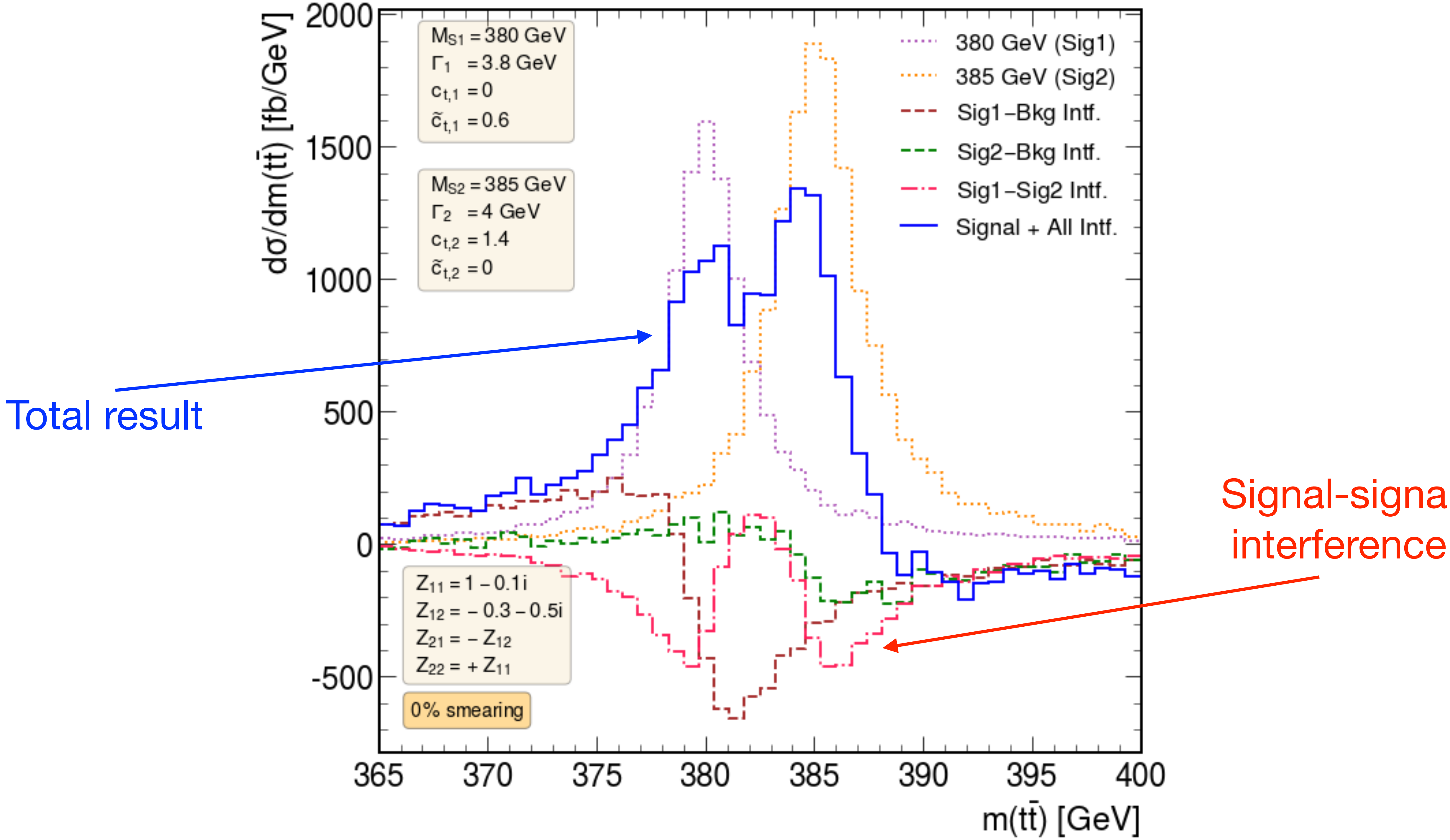
Complex pole $\mathcal{M}^2$ of each propagator is determined from

$$\mathcal{M}_i^2 - m_i^2 + \hat{\Sigma}_{ii}^{\text{eff}}(\mathcal{M}_i^2) = 0,$$

$$\hat{\Sigma}_{ii}^{\text{eff}}(p^2) = \hat{\Sigma}_{ii}(p^2) - \frac{\hat{\Sigma}_{ij}^2(p^2)}{D_j(p^2) + \hat{\Sigma}_{jj}(p^2)}, \quad D_i(p^2) = p^2 - m_i^2$$

Total result for (signal – background)

Idealised case, no experimental smearing: *[H. Bahl, R. Kumar, G. W. '24]*

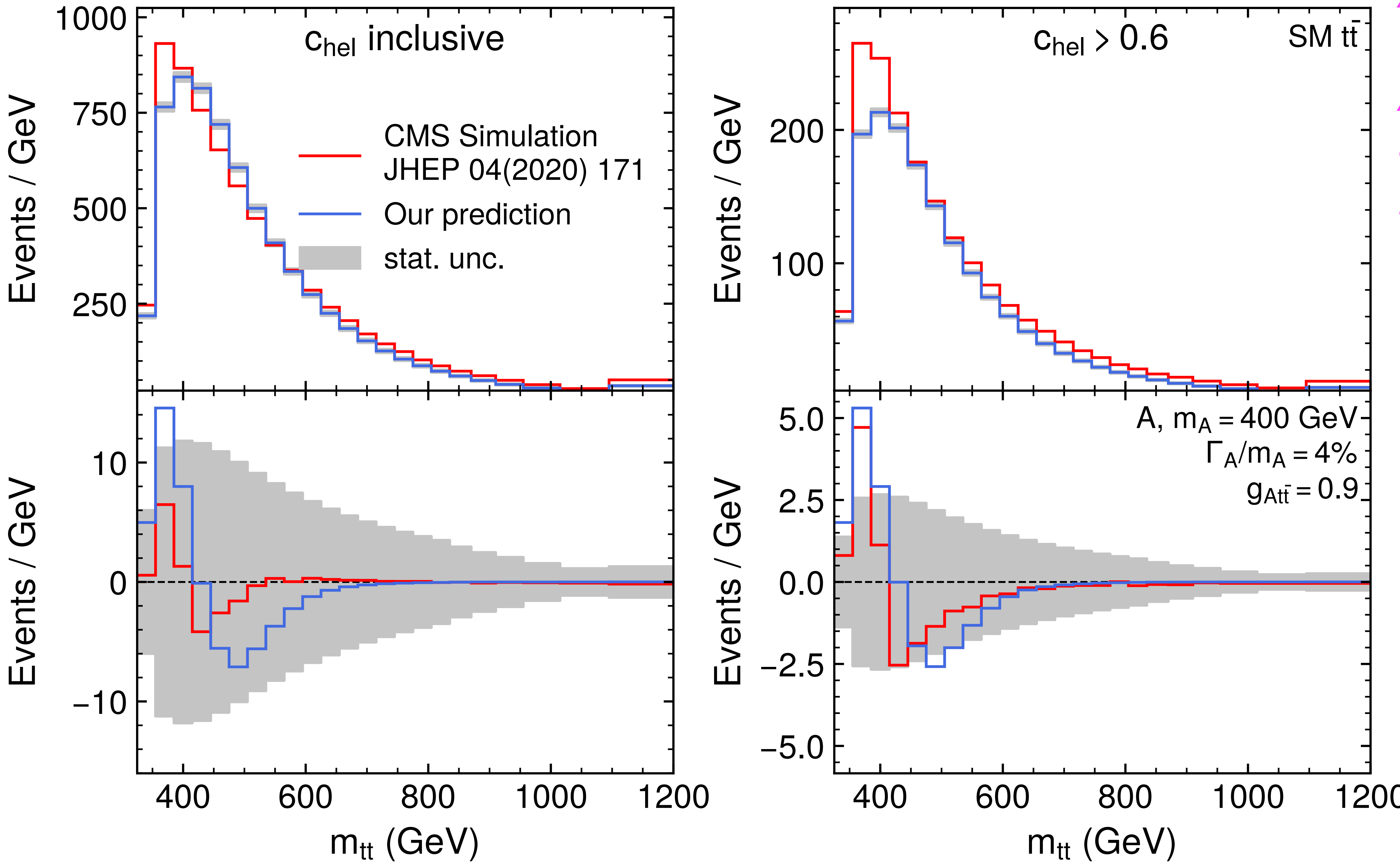


⇒ Different patterns possible for the total result

Comparison with expected LHC sensitivity

Impact of helicity variable c_{hel}:

[A. Anuar, A. Biekötter, T. Biekötter, A. Grohsjean, S. Heinemeyer, L. Jeppe, C. Schwanenberger, G. W. '24]



⇒ High discrimination power for $c_{hel} > 0.6$, good agreement with CMS analysis

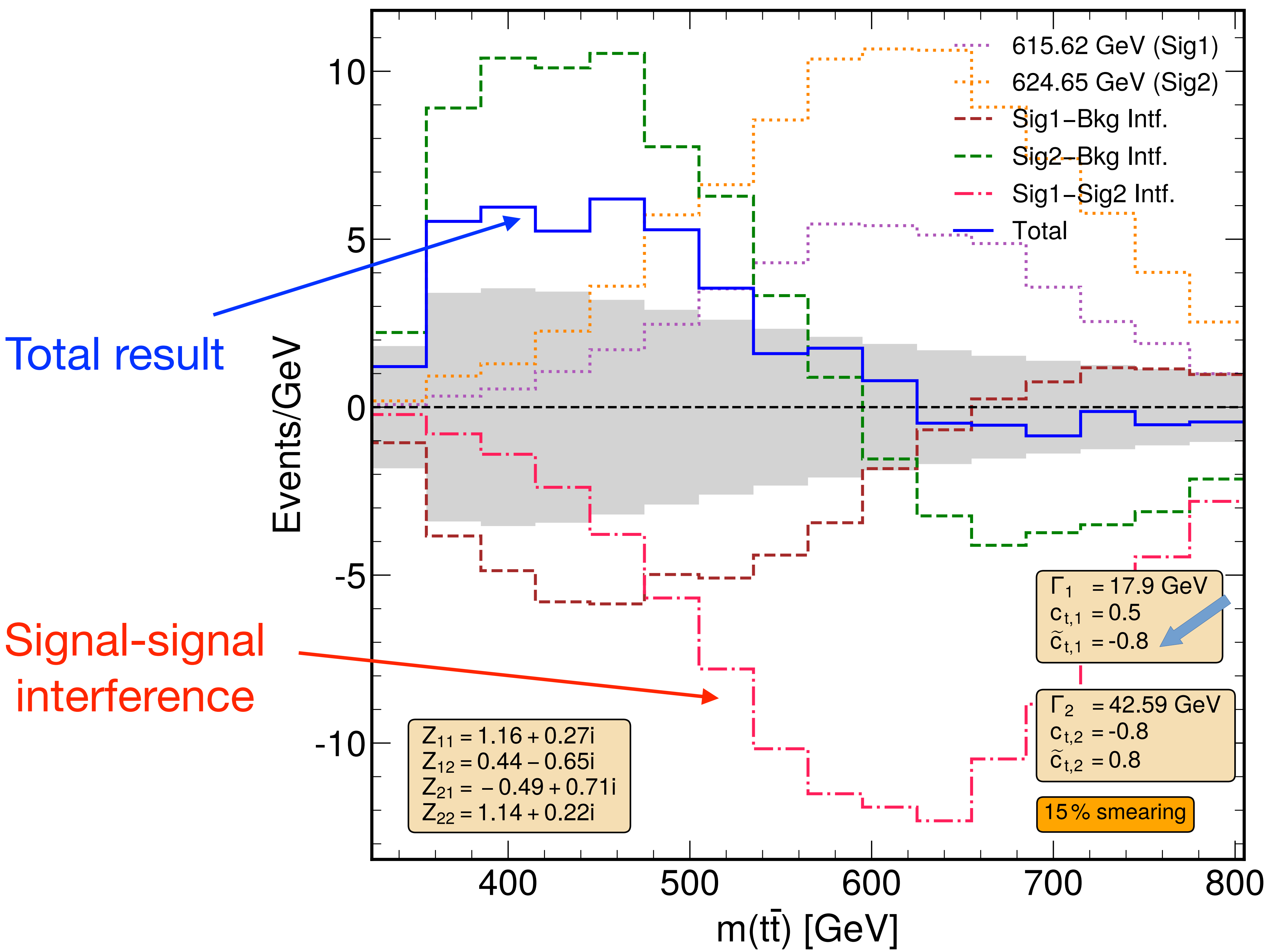
Generator-level analysis, 15% Gaussian smearing

- 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

⇒In the following analysis: comparison with the experimental sensitivity at Run 3 of the LHC using the results from [A. Anuar et al. '24]

Comparison with the sensitivity at Run 3 of the LHC

Example: two CP-mixed states at ≈620 GeV



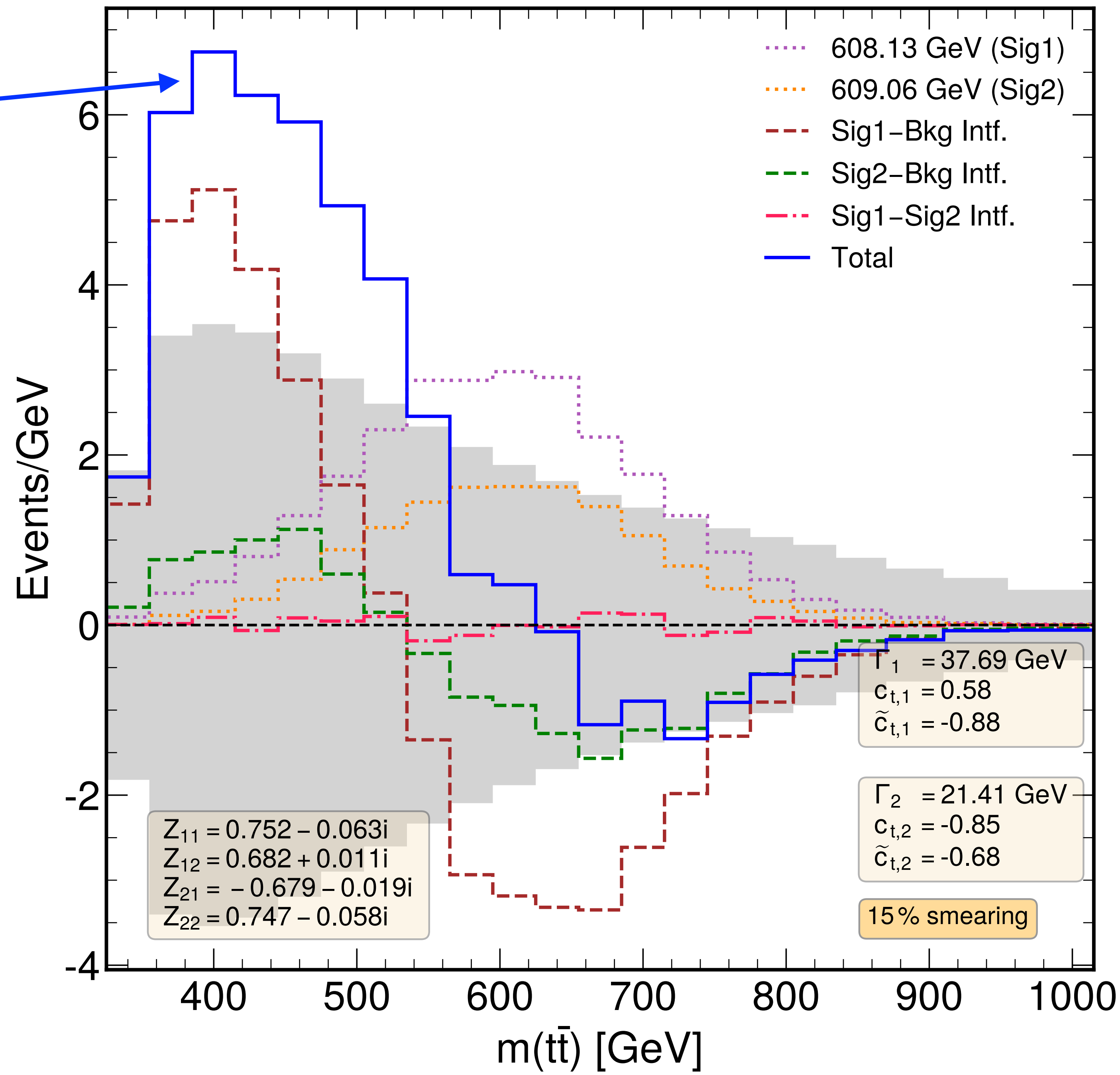
⇒ Signal-signal interference effects can have large impact on distribution

C2HDM example: two CP-mixed states at ≈600 GeV

Result for BP 3 of *[P. Basler, S. Dawson, C. Englert, M. Mühlleitner '20]*

[H. Bahl, R. Kumar, G. W. '24]

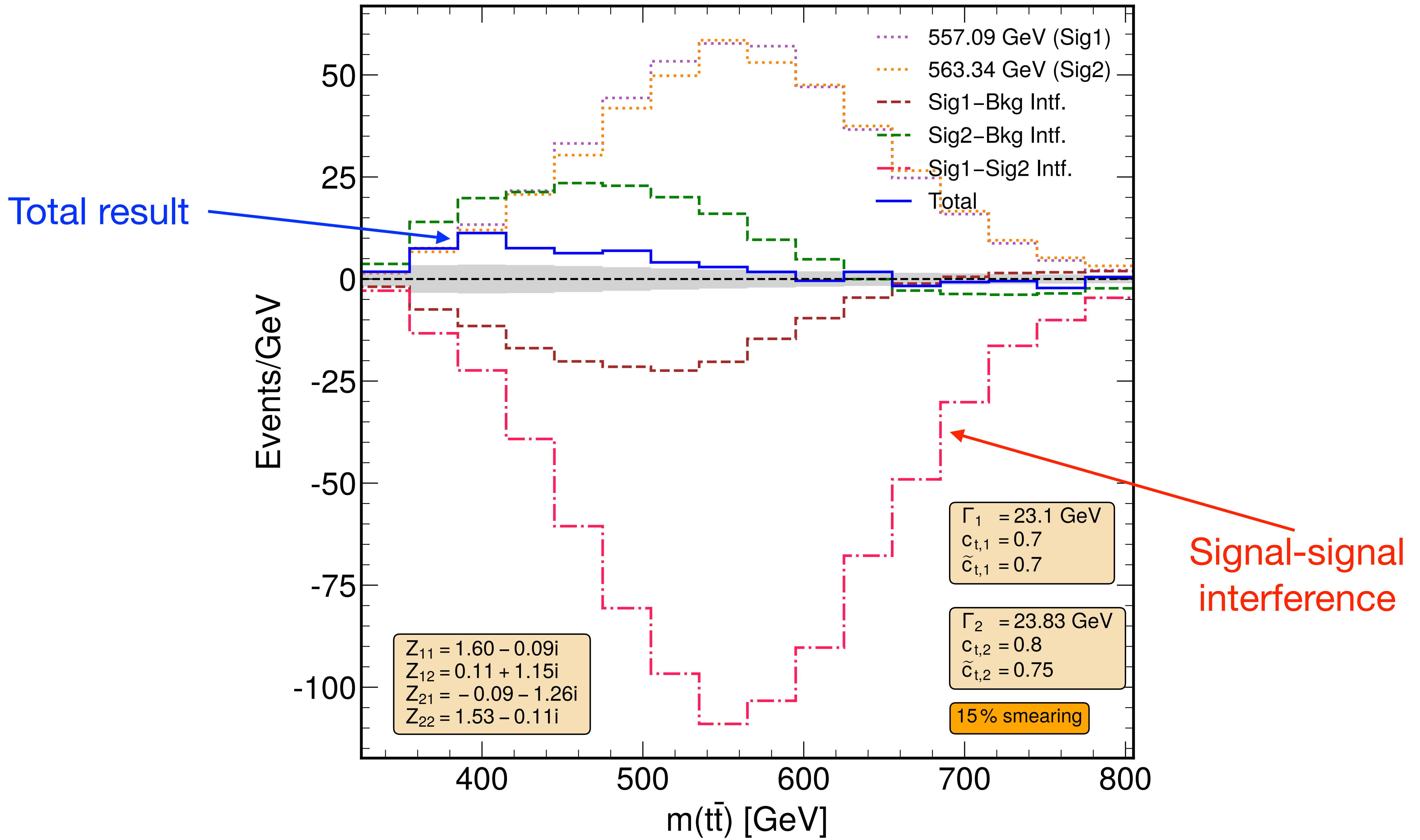
Total result



⇒ Total result resembles shape for a single particle at lower mass
Highest sensitivity in the region just above the tt threshold!

"Nightmare scenario" with large destructive signal-signal interference

[H. Bahl, R. Kumar, G. W. '24]



⇒ Experimental results can be difficult to interpret!

Conclusions

Production of BSM Higgs bosons (or other scalar particles) in di-top final state: high sensitivity, large signal-background interference contributions

If the BSM states can mix with each other (typical situation in extended Higgs sector with additional source of CP violation): additional signal-signal interference contributions, can be very large

Comparison with the sensitivity at Run 3 of the LHC: interference patterns can mimic the case of a single new particle or give rise to unexpected shapes; ``nightmare" scenarios possible; highest sensitivity in the region just above the tt threshold

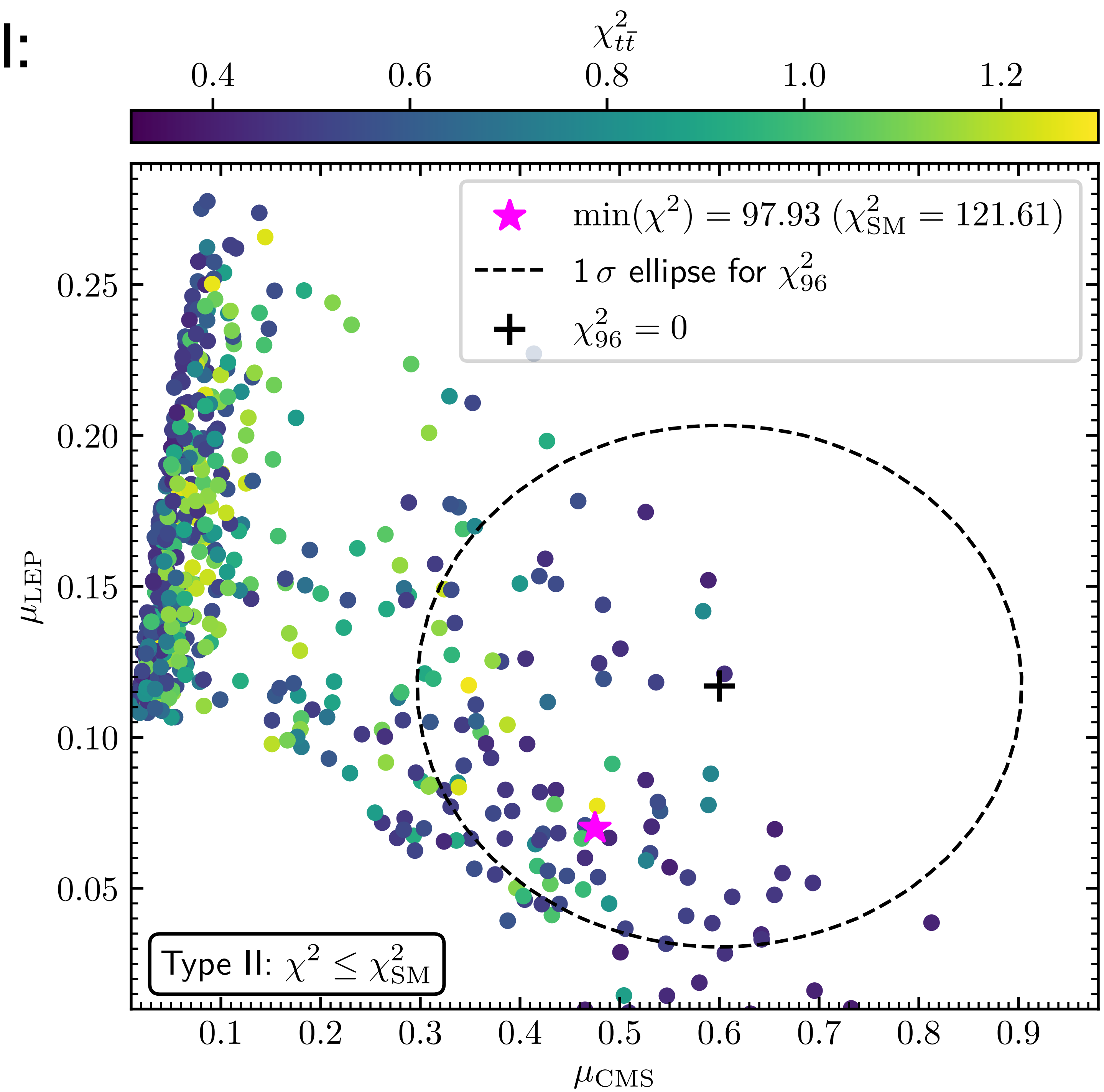
⇒ Experimental results may be difficult to interpret!

Backup

Combined interpretation of excesses at 400 GeV (tt) + 95 GeV

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

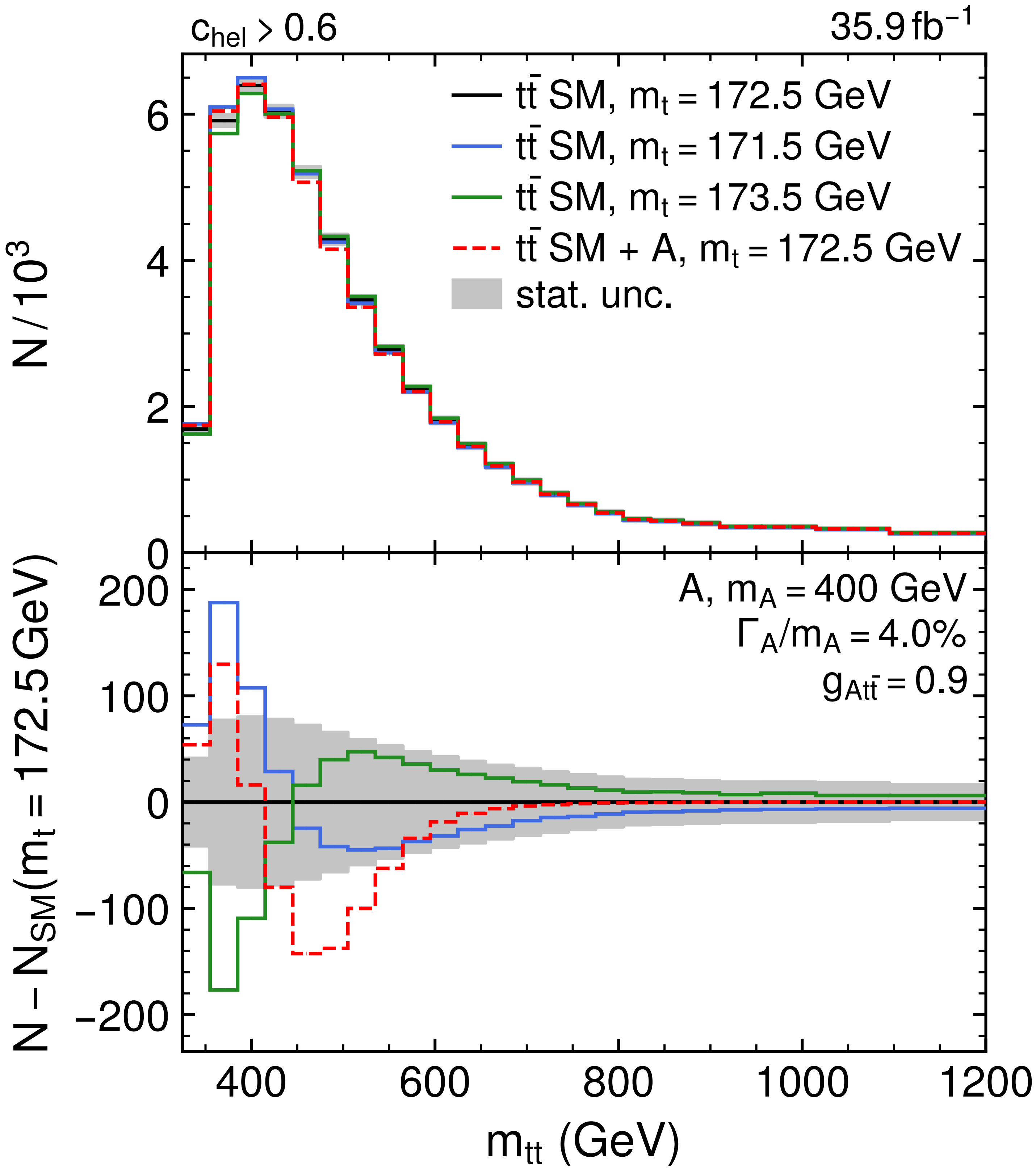
N2HDM, type II:



⇒ The A → tt excess at 400 GeV and the CMS $\gamma\gamma$ and LEP excesses at about 95 GeV can be described very well simultaneously!

Systematic uncertainties: impact of variation of top-quark mass by ±1 GeV

[A. Anuar et al. ’24]

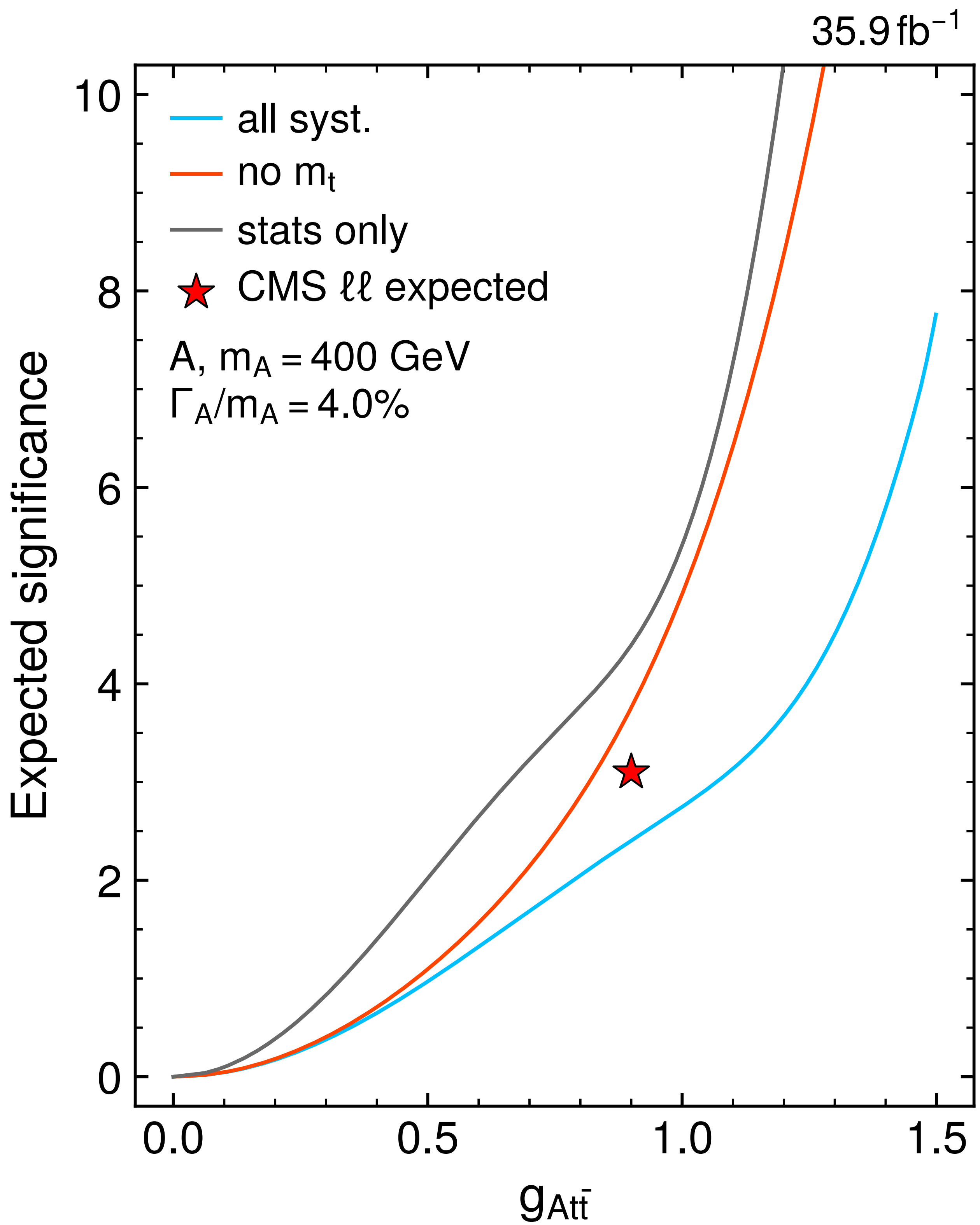


⇒ Variation of m_t can mimic peak-dip-like structure as expected from a signal

Effects expected to be smaller in experimental analysis

Systematic uncertainties: impact of variation of top-quark mass by ±1 GeV

[A. Anuar et al. ’24]



⇒ Sensitivity of CMS analysis lies between the projections with and without the systematic uncertainty induced by m_t