ALPs vs. CP-odd Higgs bosons at the LHC

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based on work in collaboration with Afiq Anuar, Anke Biekötter, Thomas Biekötter, Alexander Grohsjean, Sven Heinemeyer, Laurids Jeppe, Christian Schwanenberger

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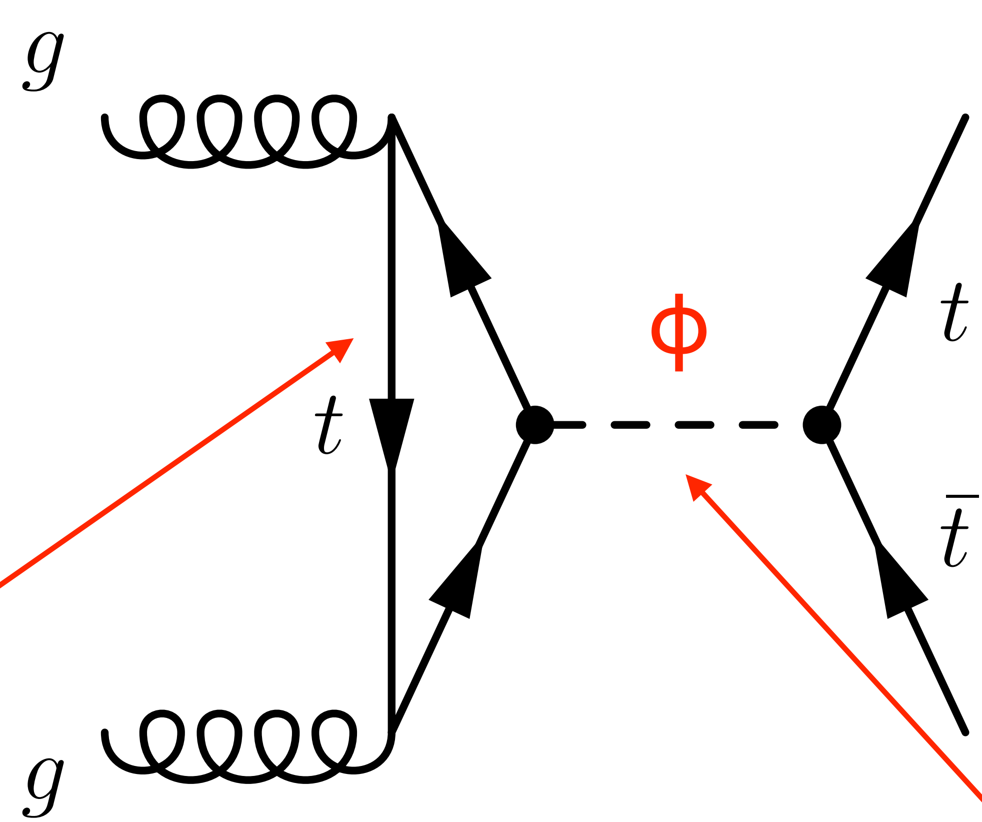
Introduction

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

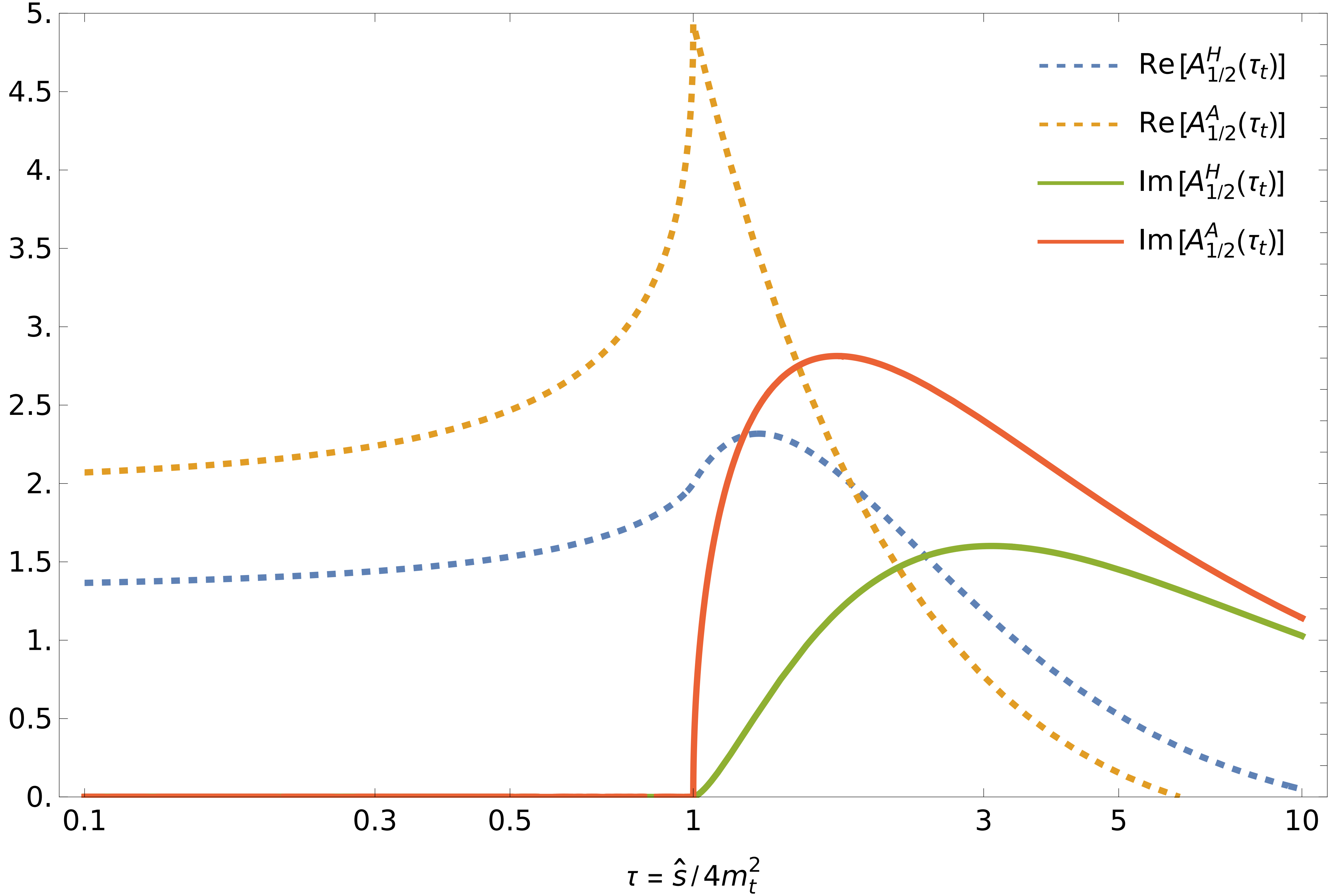
Example:



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

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

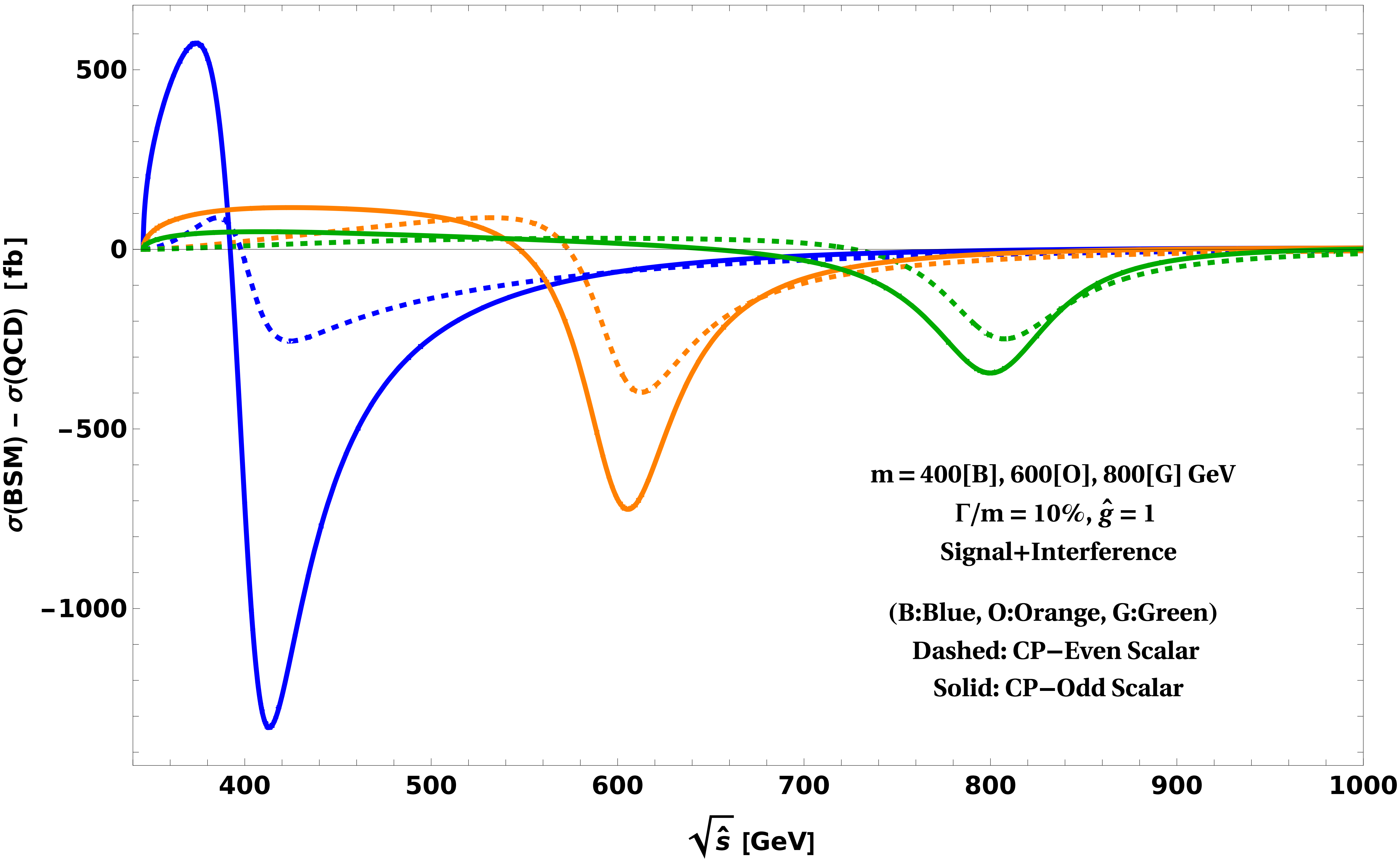
Loop function Aᶲ(τ)



⇒ Interference contribution ~ Im[$A^\Phi(\tau)$] $m_\Phi\, \Gamma_\Phi$

Interference patterns for background-subtracted cross section, parton level

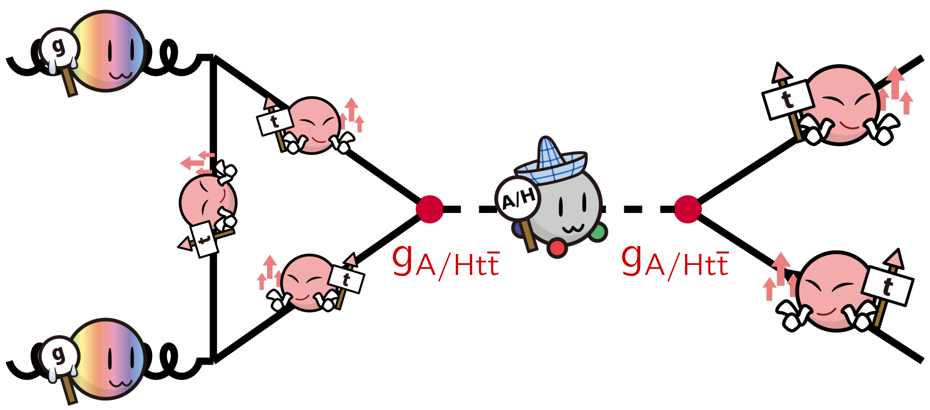
[H. Bahl, R. Kumar, G. W. '22]



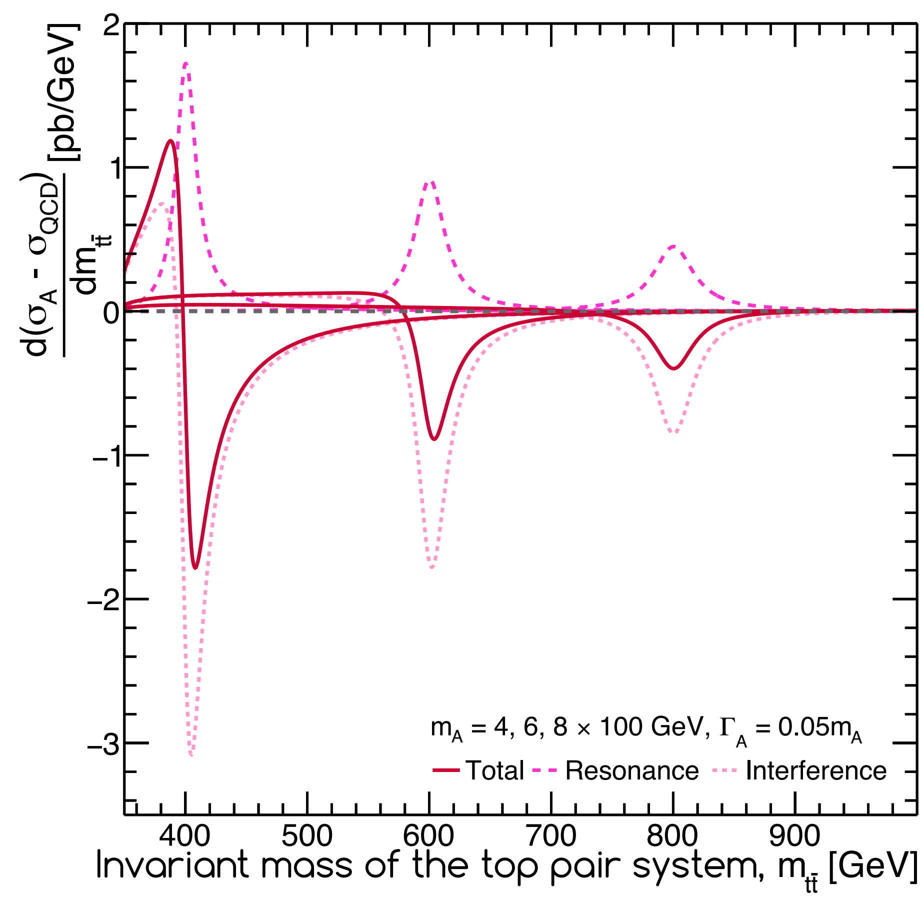
Sensitivity to BSM physics in di-top final states

Example: H, A → tt search in CMS

[A. Anuar ’21]



Interference ⇒

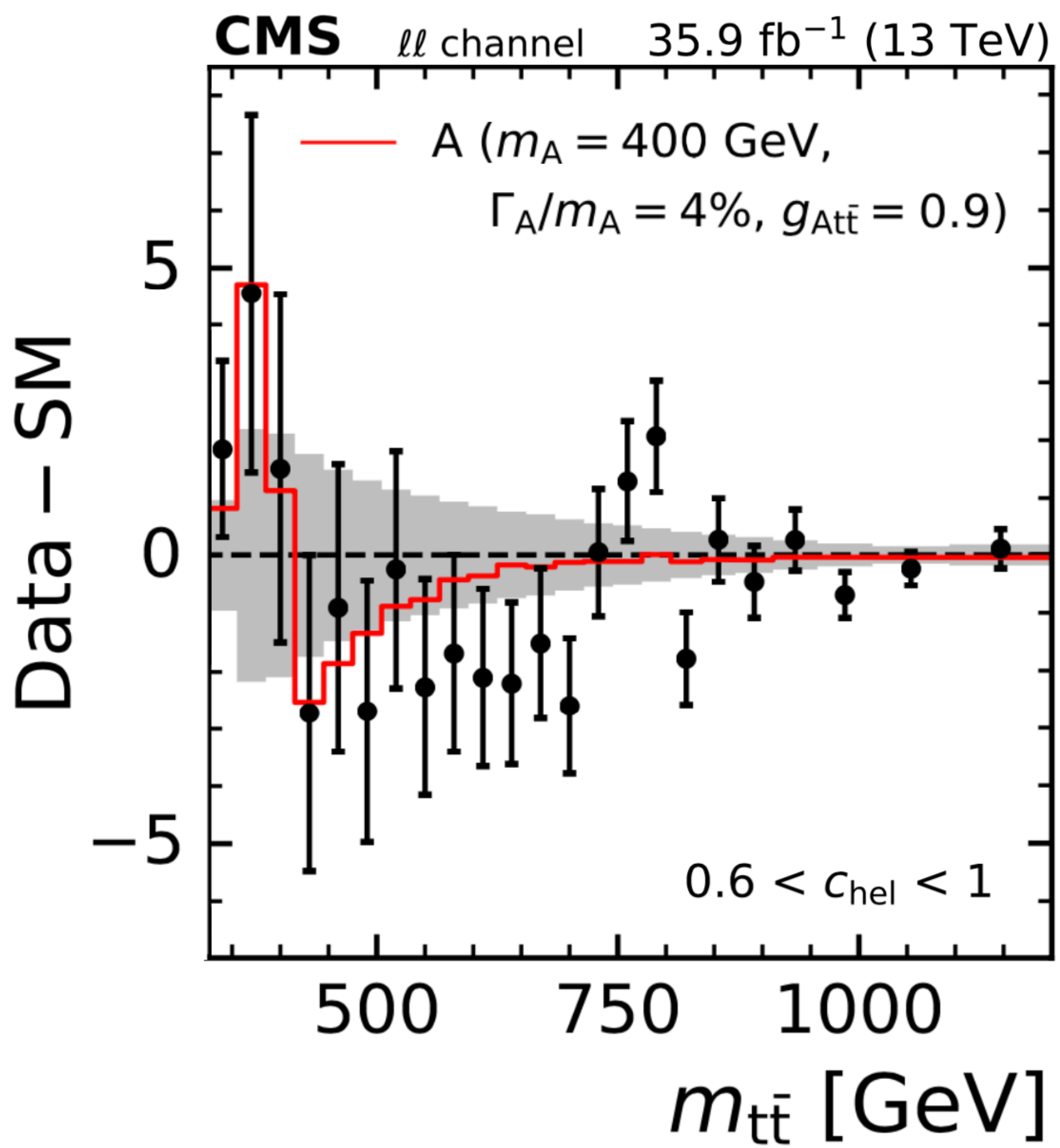


Signal-background interference yields peak-dip structure

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

H, A → tt search in CMS

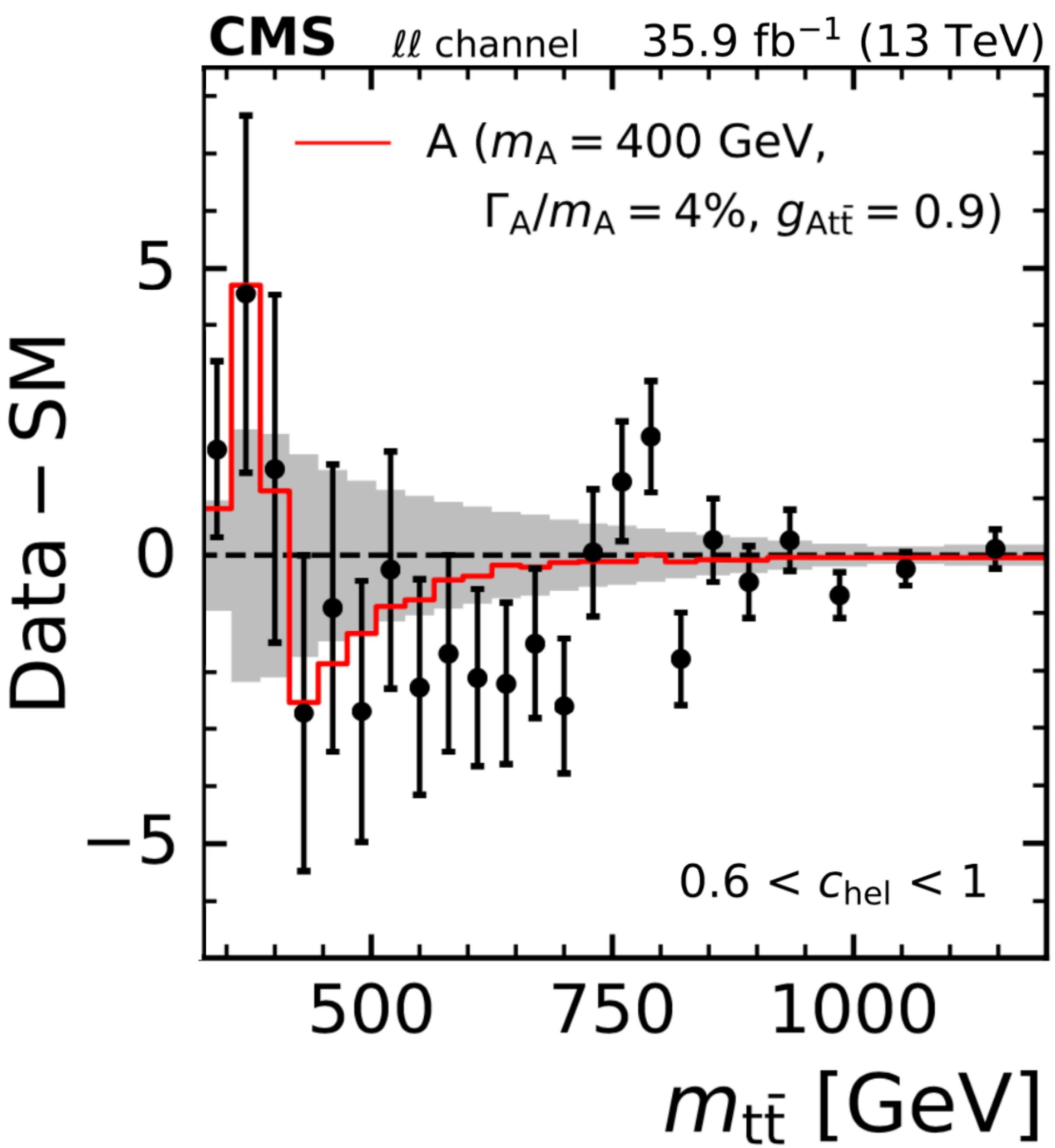
[CMS Collaboration '19]

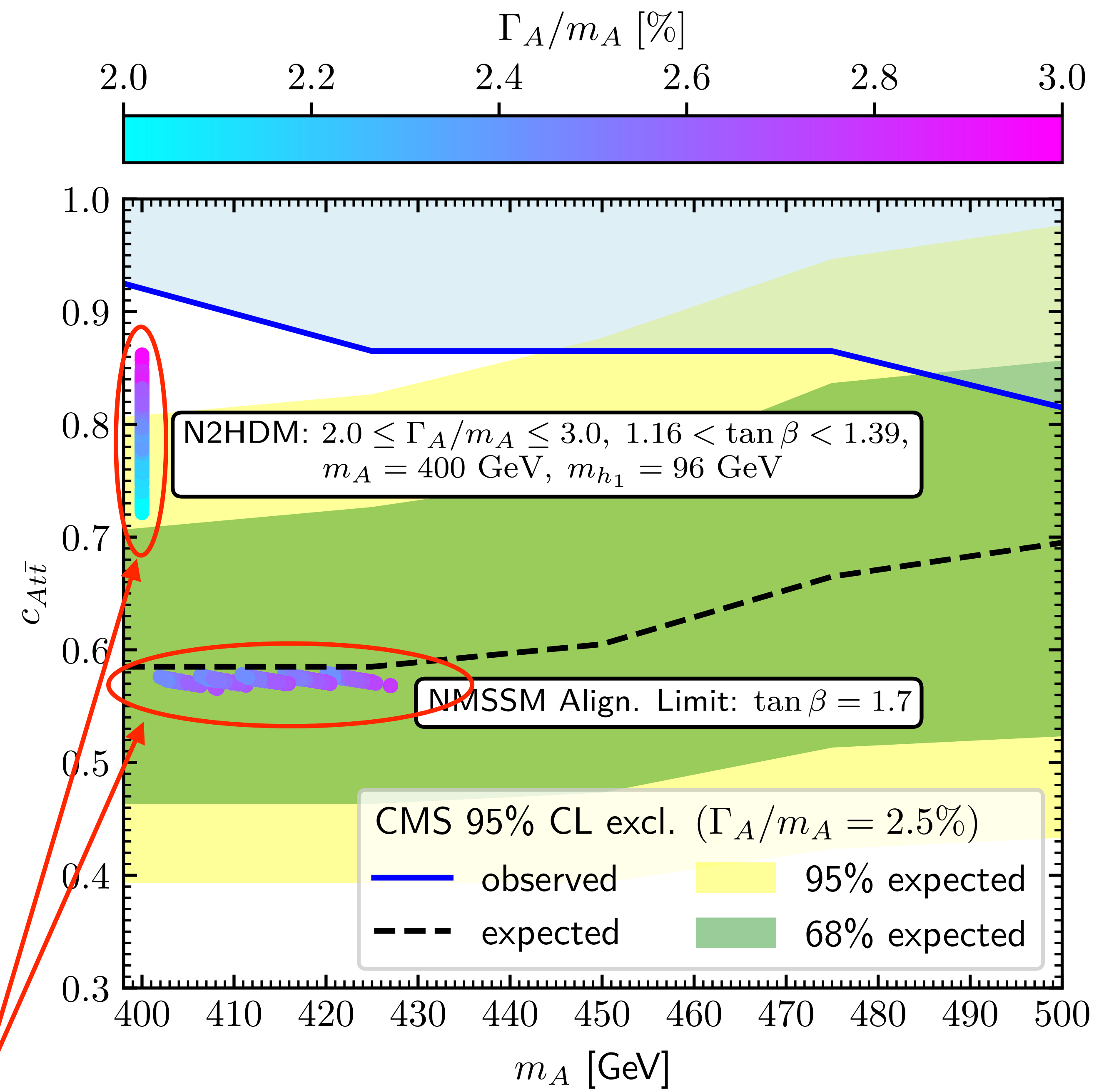


⇒Excess in CMS search, compatible with CP-odd Higgs at about 400 GeV

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

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



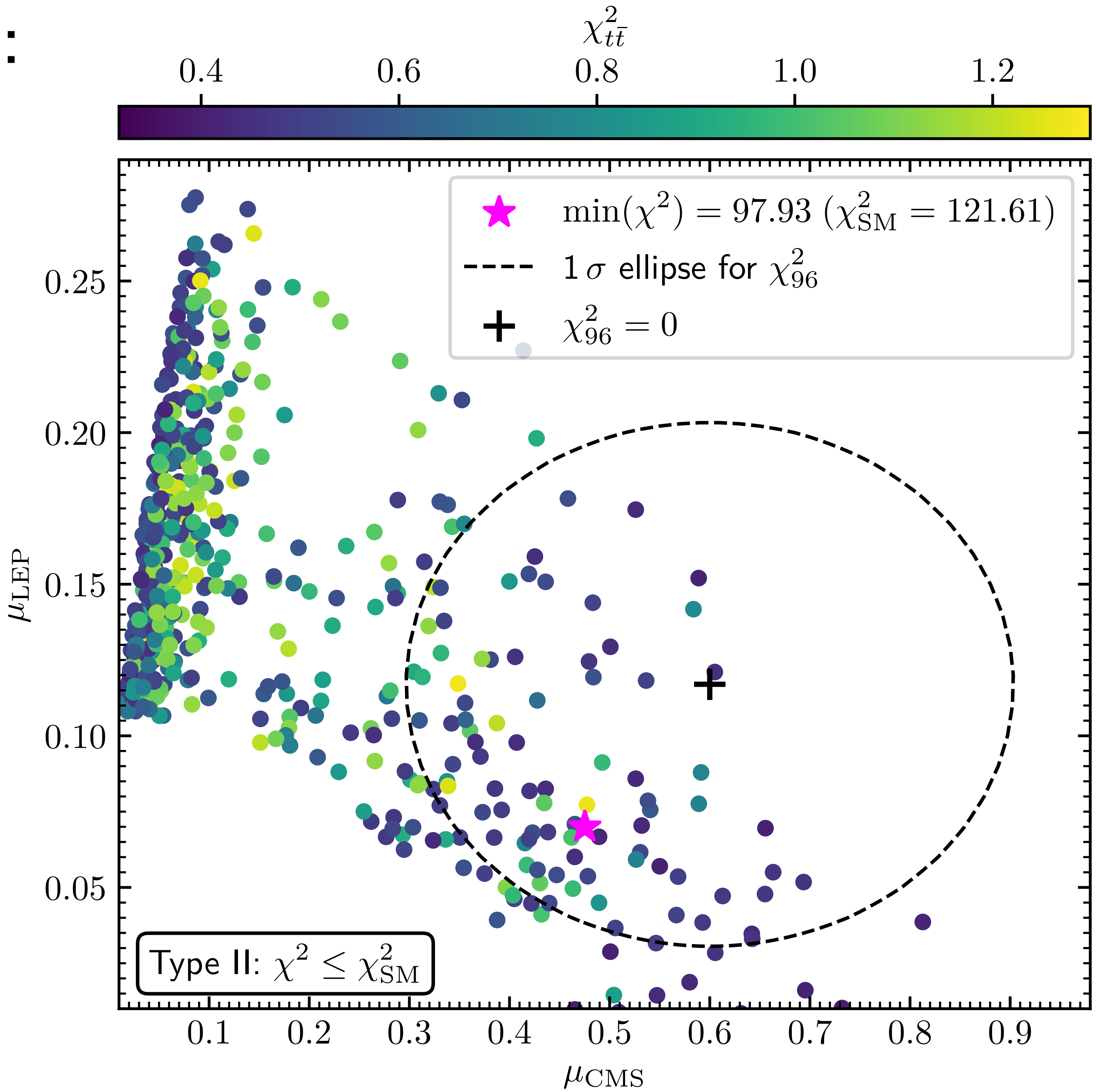


Good description of A → tt excess at 400 GeV, simultaneously with excess at 95 GeV, in models with extended Higgs sectors (N2HDM, NMSSM)

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

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

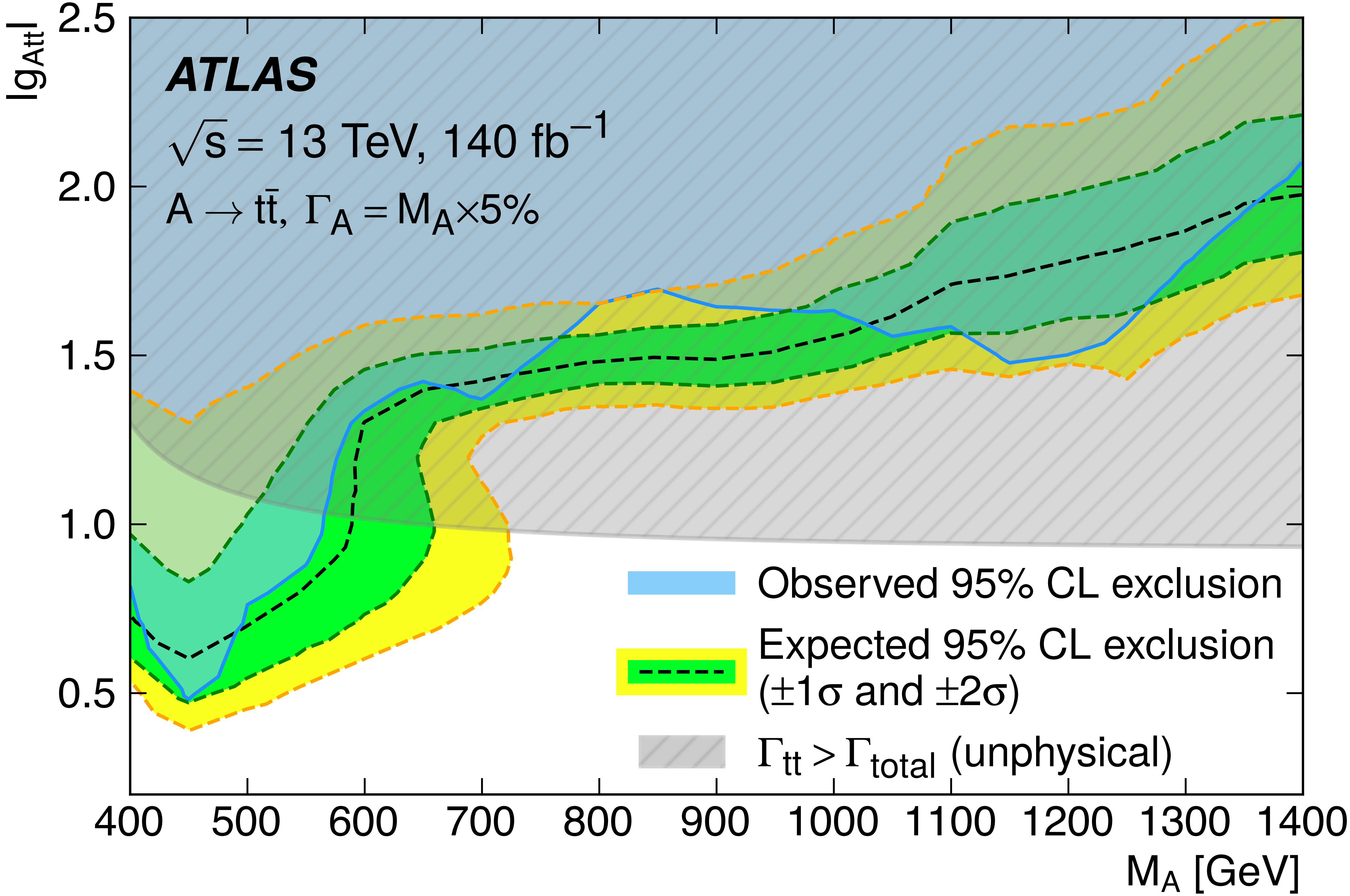
N2HDM, type II:



⇒ 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!

New ATLAS result

[ATLAS Collaboration '24]



⇒No significant excess at 400 GeV

Sensitivity to the BSM nature of a possible signal

Is there sensitivity for distinguishing a CP-odd Higgs from an ALP?

Axion-like particles (ALPs):

[L. Jeppe '23]

- Strong CP problem: no observation of CP violation in QCD although it would be allowed from first principles
- Solved by axions – BSM particles that exhibit U(1) shift symmetry
- In general: axion-like particles = particles with the same symmetry
  - Arise in many high-energy theories
  - Promising candidates for dark matter or dark matter mediators

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

CP-violating!
Obs.: $\theta < 10^{-10}$

↓

Promote to particle: $\theta \to a$
Absorb CP-violating term in

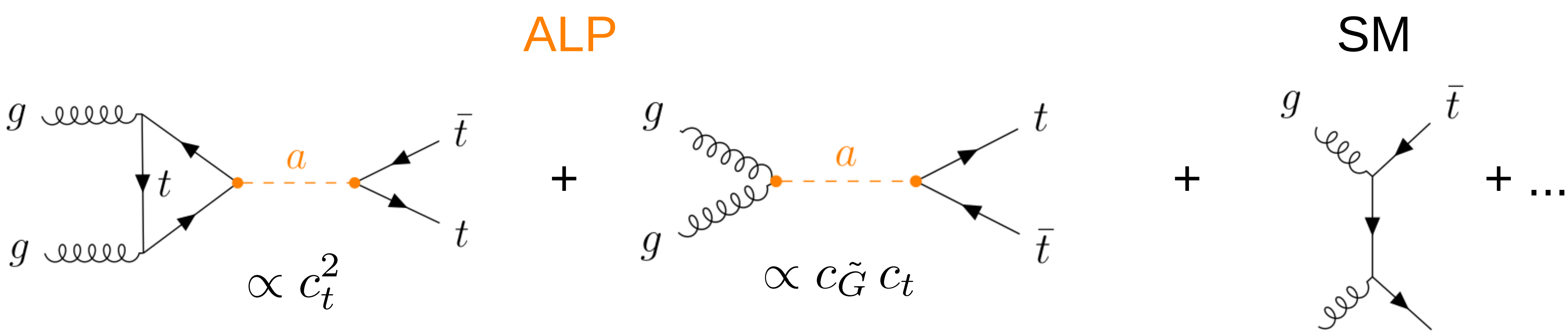
$$\mathcal{L}_{ax} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_G \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + \ldots$$

Here: heavy axion-like particles at the LHC (not dark matter candidates)

Coupling to top quarks like for CP-odd Higgs, but additional effective coupling to gluons

[L. Jeppe '23]

- ALP couplings: photons, EW bosons, gluons, massive fermions (usual models: Yukawa-like ~ m_f)
- Produce at the LHC via gluon fusion
- If $m_a > 2m_t$: decay to top quarks $\rightarrow$ interferes with SM final state:



$O(m_a) \approx m_t$
→ top quark loop explicitly considered

Explicit gluon coupling - physics at high scales integrated out

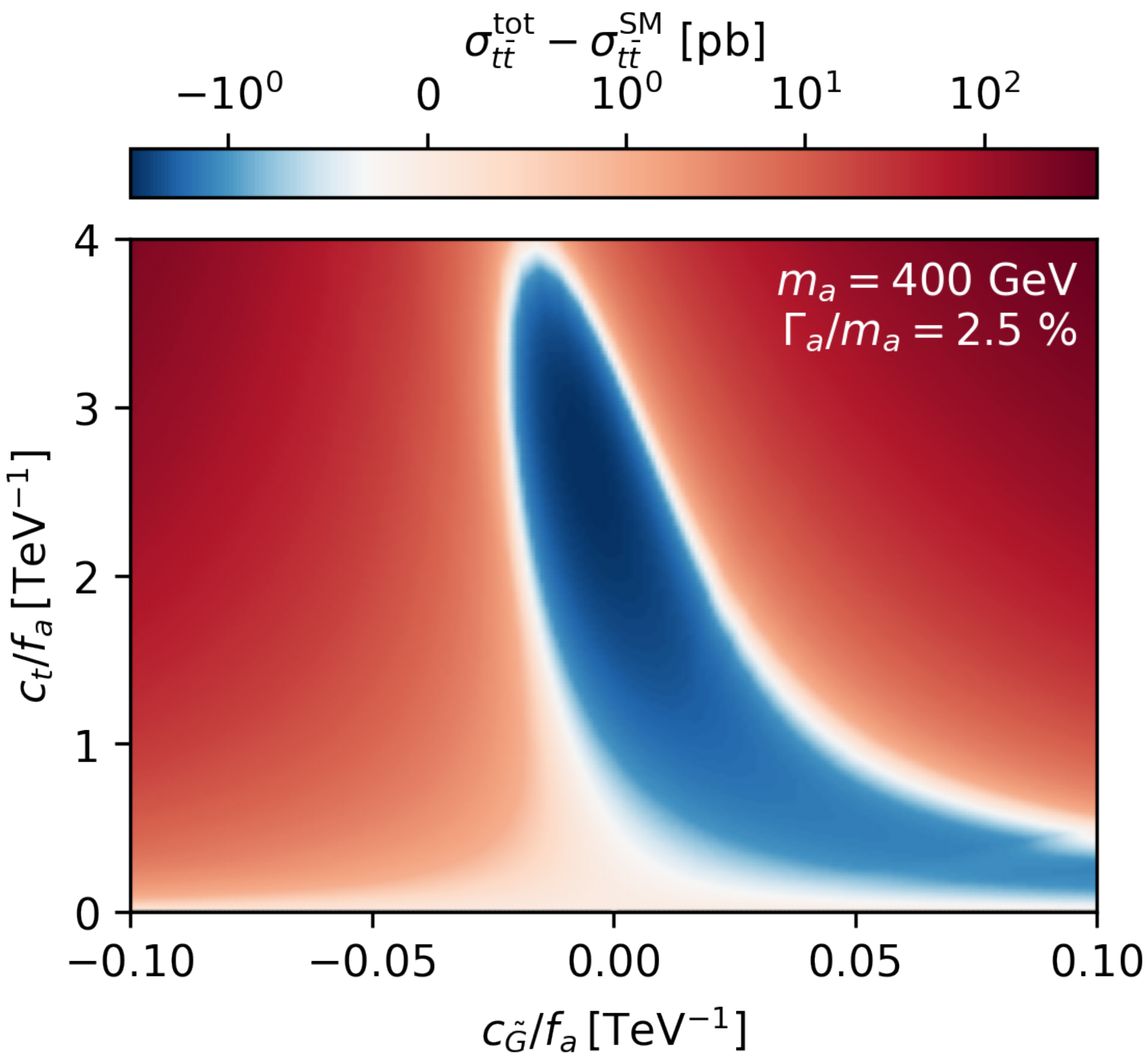
Effective ALP Lagrangian:

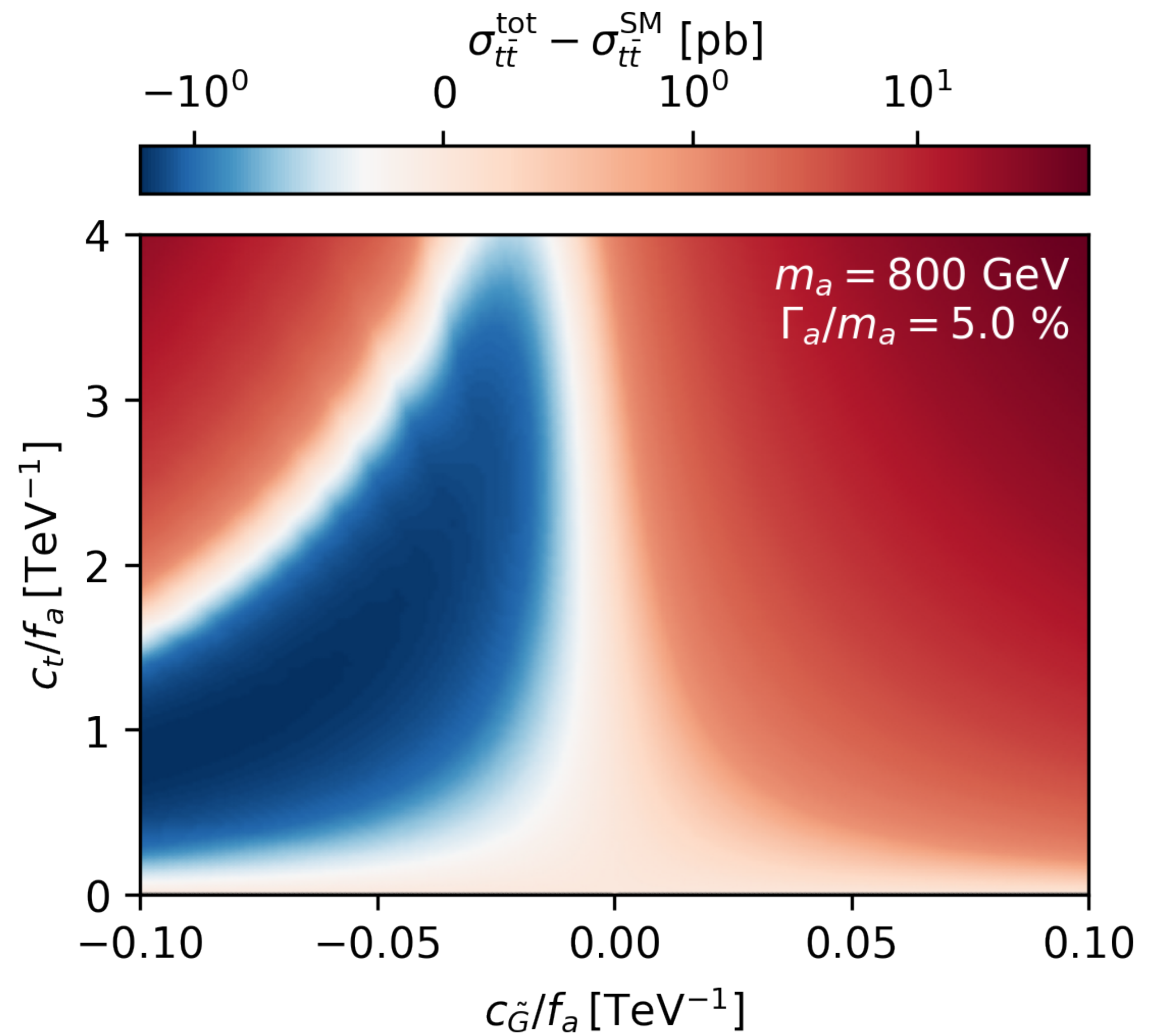
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{m_a^2}{2} a^2 - \frac{a}{f_a} c_{\tilde{G}}\, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + i c_t\, \frac{a}{f_a} \left(\bar{q}\, Y_t\, \tilde{H}\, t_R + \text{h.c.} \right)$$

ALP couplings

Background-subtracted cross section

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

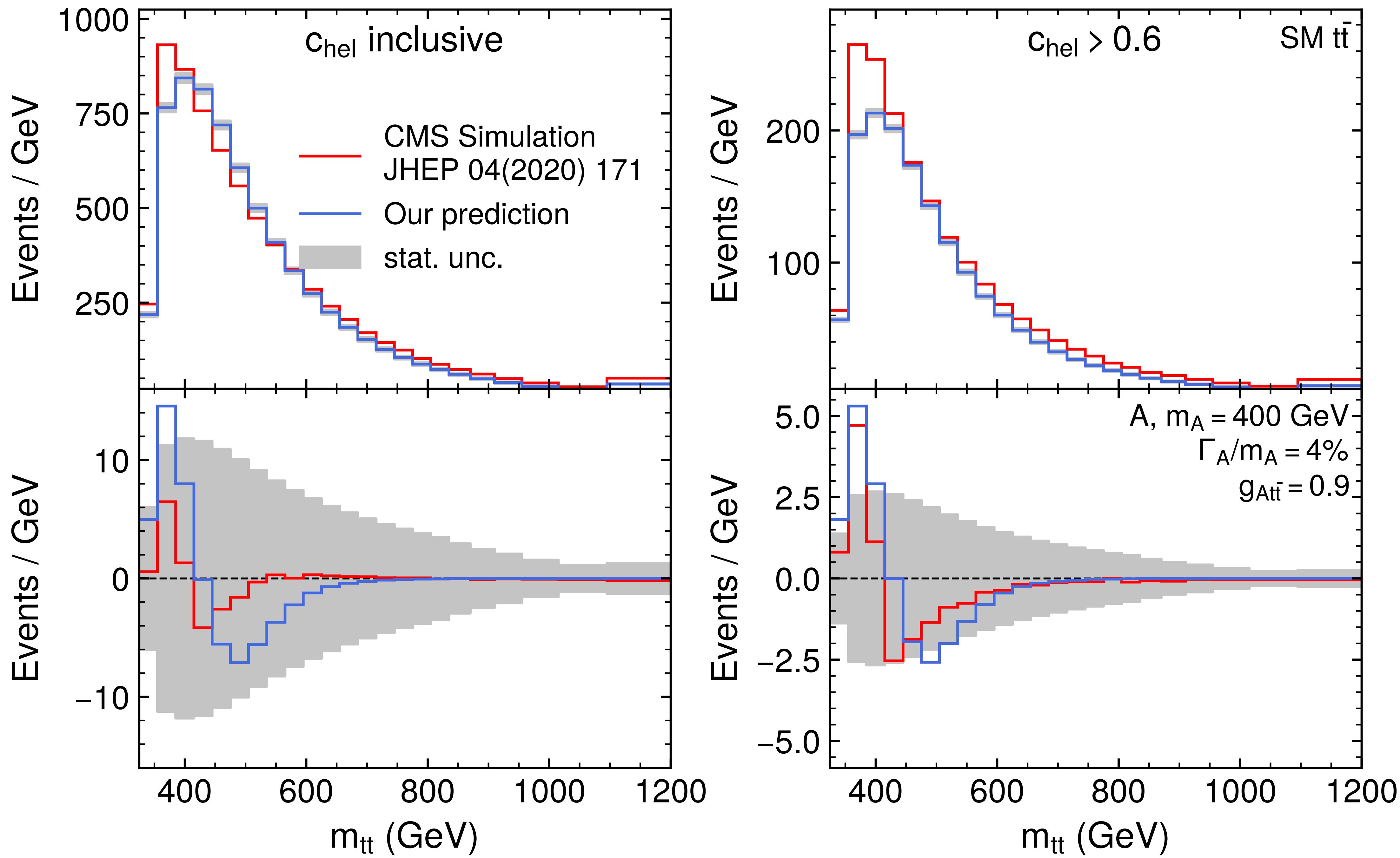




⇒ Large interference effects

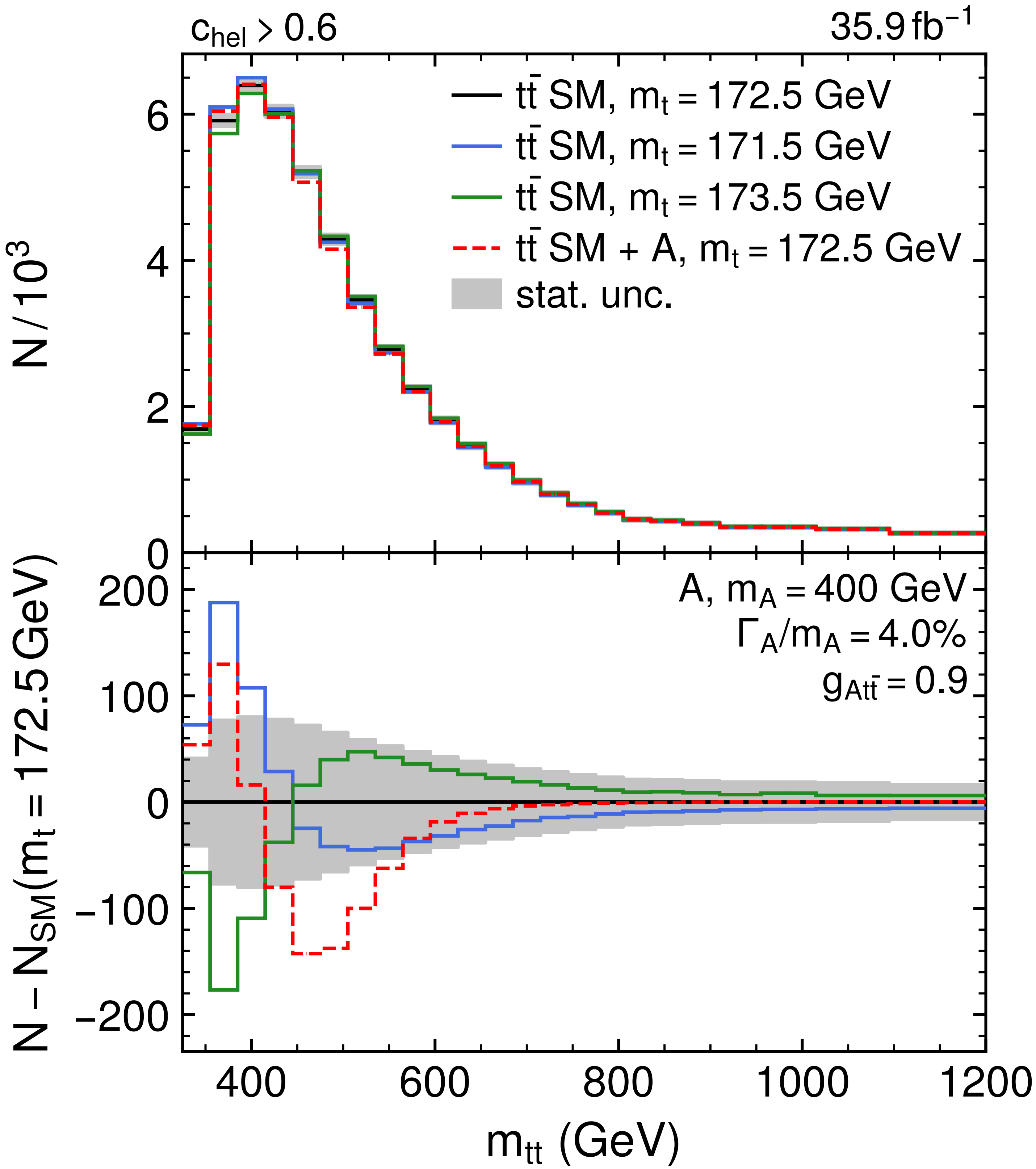
Generator-level analysis, 15% Gaussian smearing: comparison with CMS result

Impact of helicity variable c_{hel}:



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

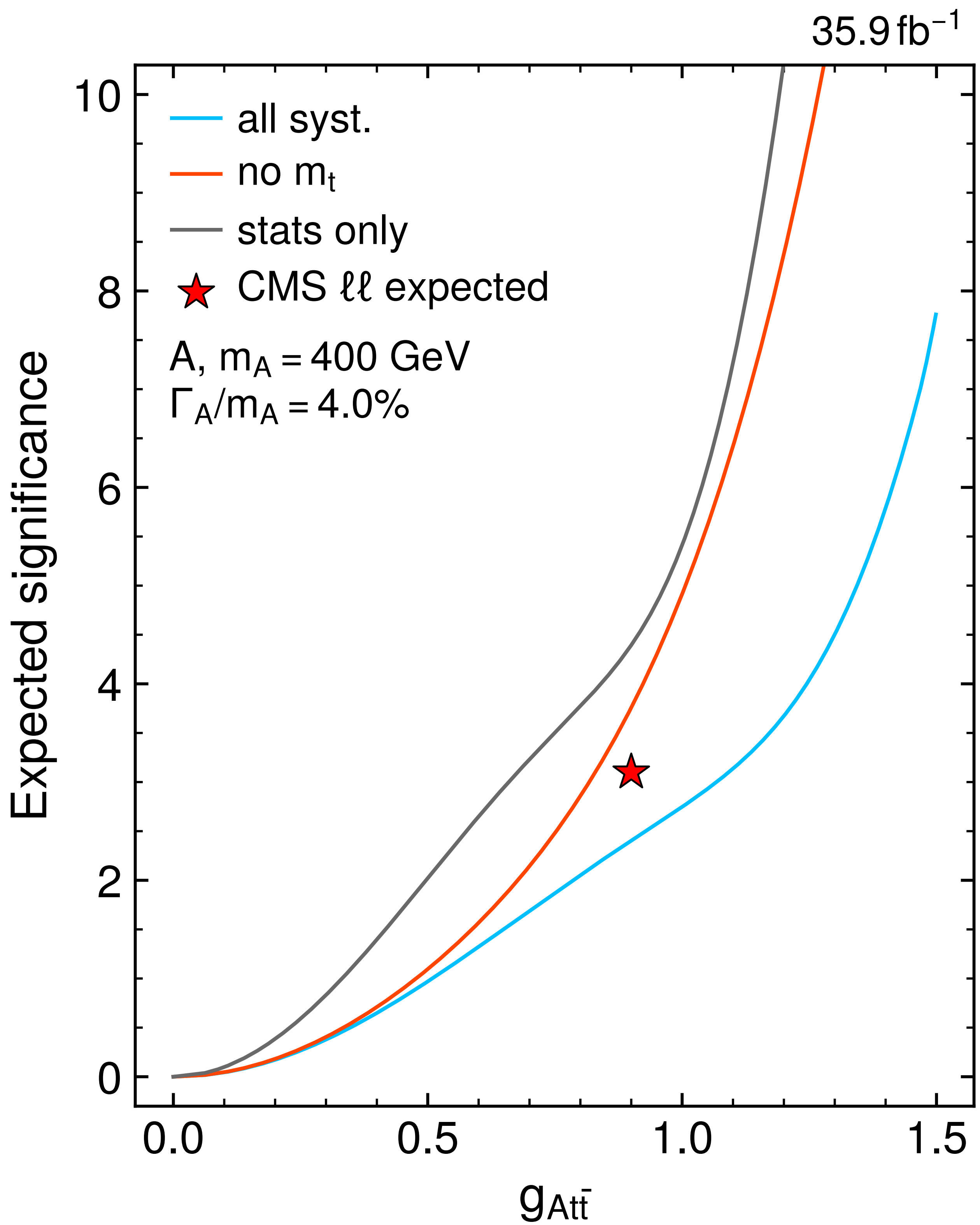
Systematic uncertainties: impact of variation of top-quark mass by ±1 GeV



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

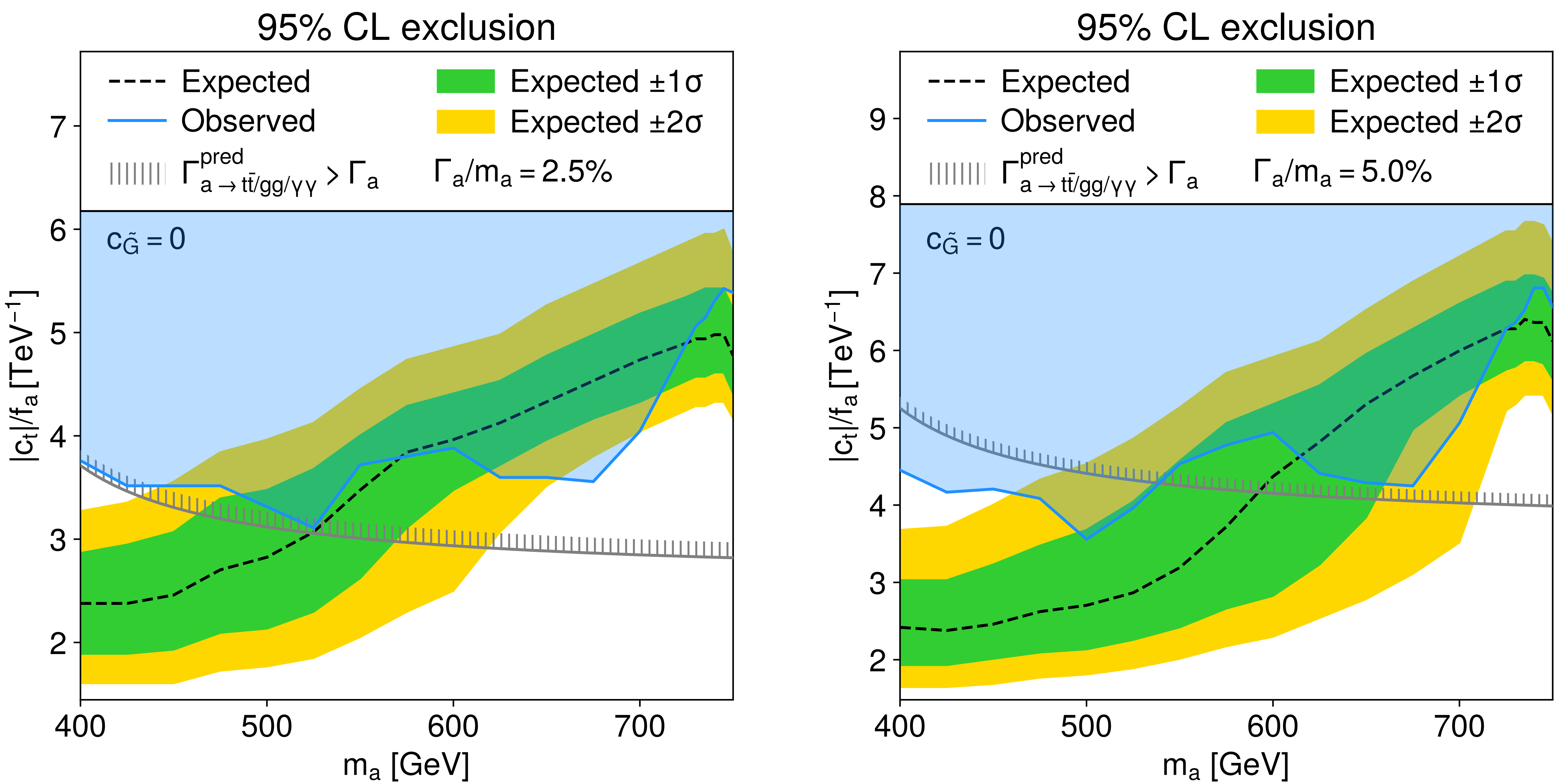
Effects expected to be smaller in experimental analysis

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



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

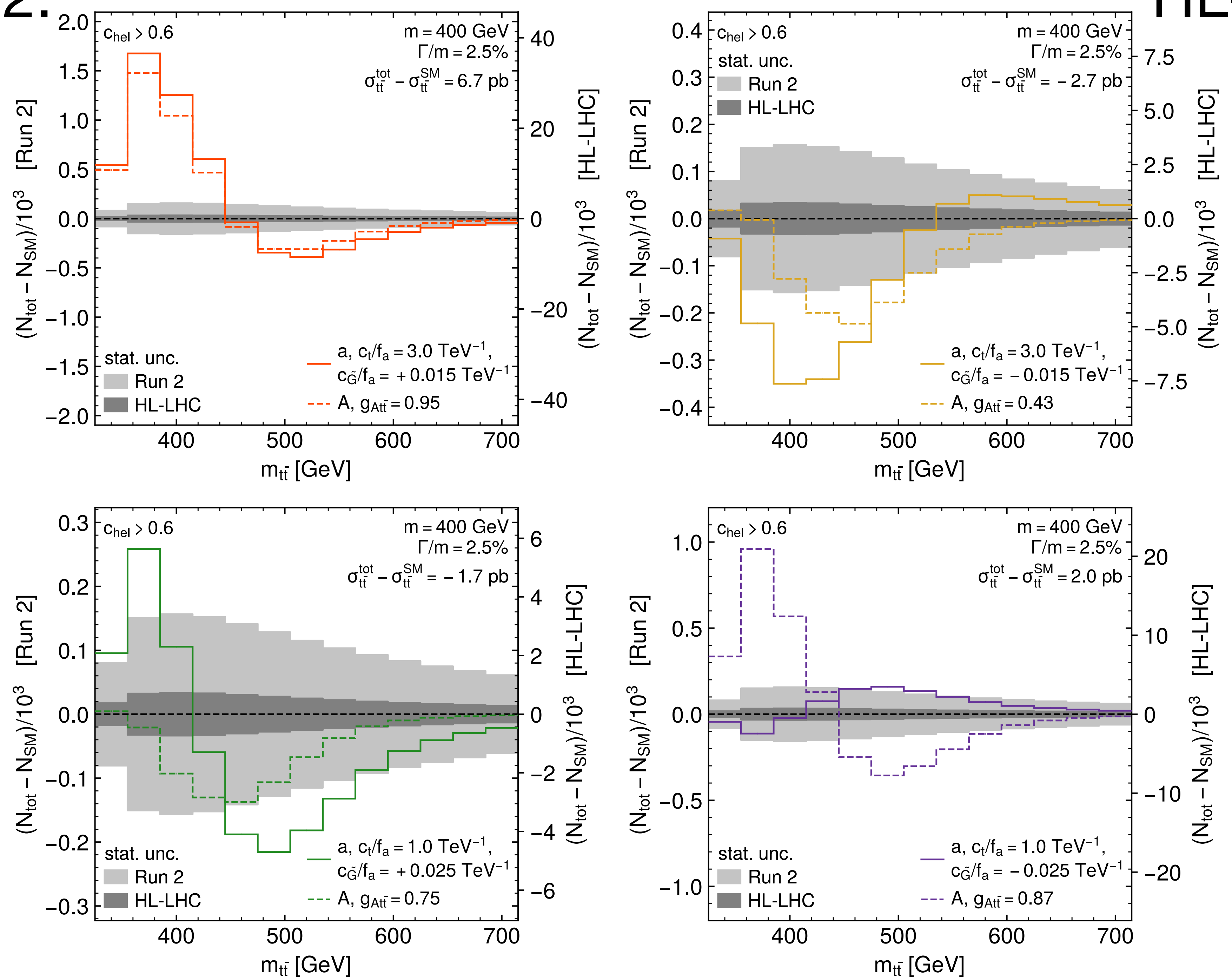
Reinterpretation of existing limits for the case $c_{\tilde{G}} = 0$



⇒Constraints on $| c_t |/f_a$

Expected sensitivity for an ALP ($c_{\tilde{G}} \neq 0$) and a CP-odd Higgs boson with same total cross section

LHC Run 2: HL-LHC:



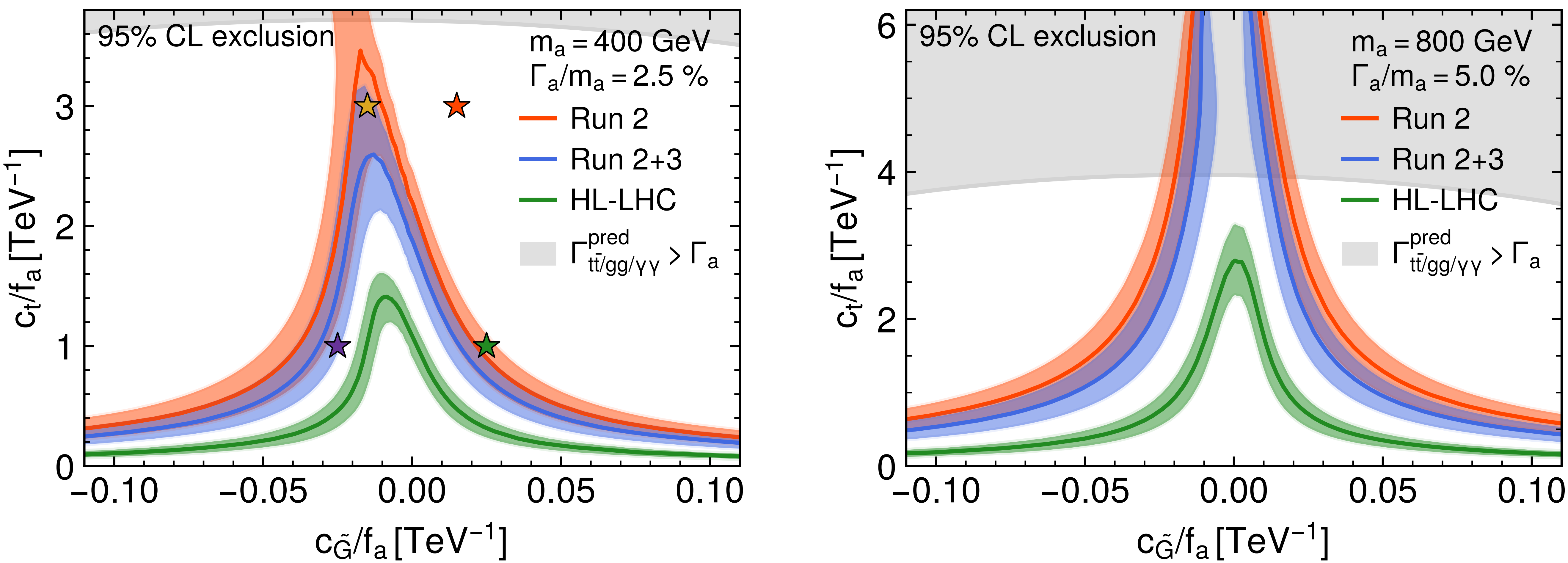
⇒High sensitivity for detecting a signal, good prospects for distinguishing ALP from CP-odd Higgs

Significances for discriminating between an ALP and a CP-odd Higgs (mass: 400 GeV, width: 2.5%)

a		A		Significance (a vs. A)		
c_t/f_a [TeV^{-1}]	$c_{\tilde{G}}/f_a$ [TeV^{-1}]	$g_{At\bar{t}}$	Luminosity	all syst.	no m_t	stats only
3.0	$+0.015$	0.95	Run 2	1.3	1.9	3.3
			Run 2+3	1.8	2.3	4.9
			HL-LHC	5.3	5.7	> 10
3.0	-0.015	0.43	Run 2	1.2	1.9	3.3
			Run 2+3	1.7	2.4	4.9
			HL-LHC	5.0	6.0	> 10
1.0	$+0.025$	0.75	Run 2	1.5	2.3	2.7
			Run 2+3	2.0	3.1	3.9
			HL-LHC	5.8	8.8	> 10
1.0	-0.025	0.87	Run 2	3.7	9.0	> 10
			Run 2+3	4.6	> 10	> 10
			HL-LHC	> 10	> 10	> 10

Projected expected limits on ALP couplings: without systematic uncertainty from m_t

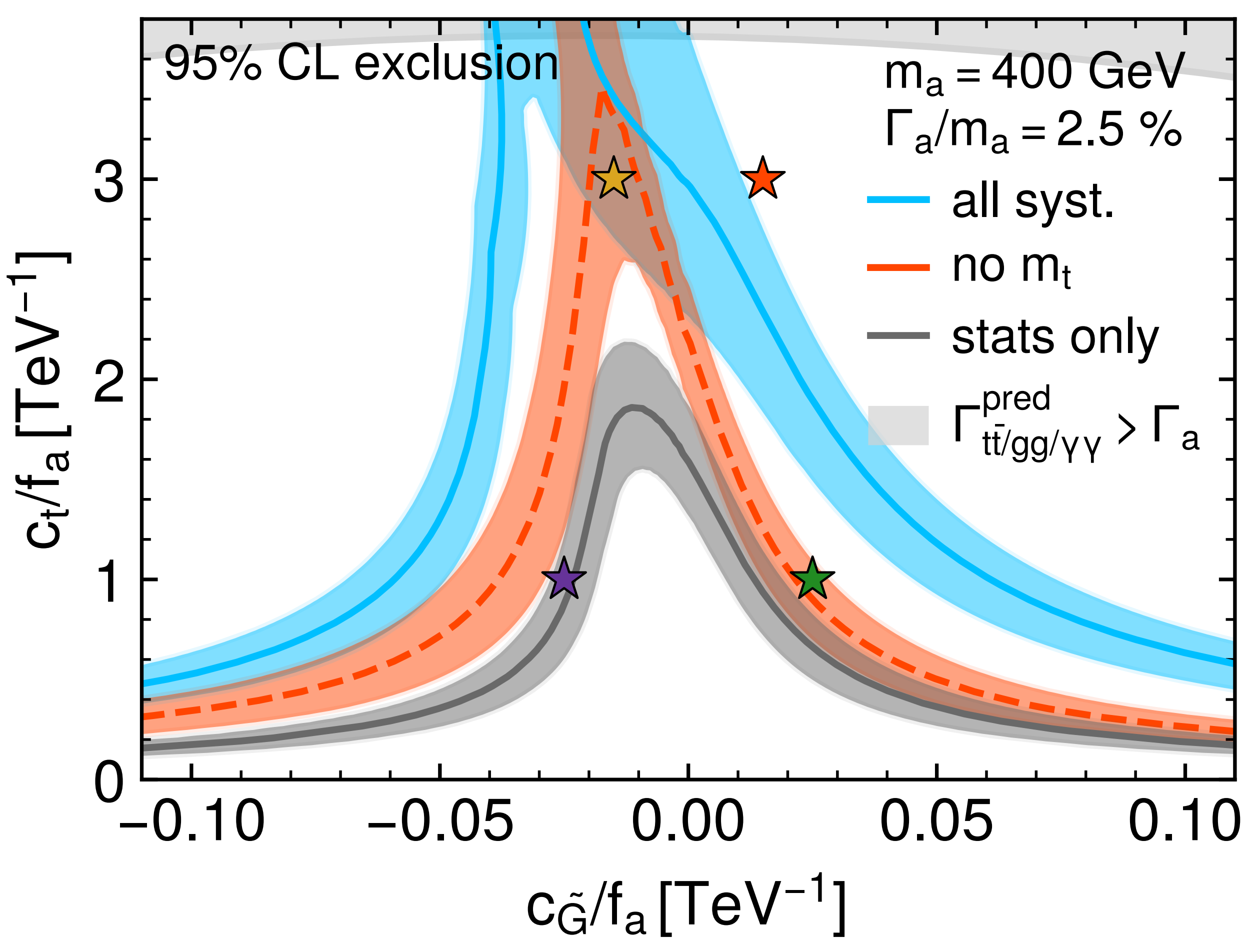
Run 2, Run 2+3, HL-LHC:

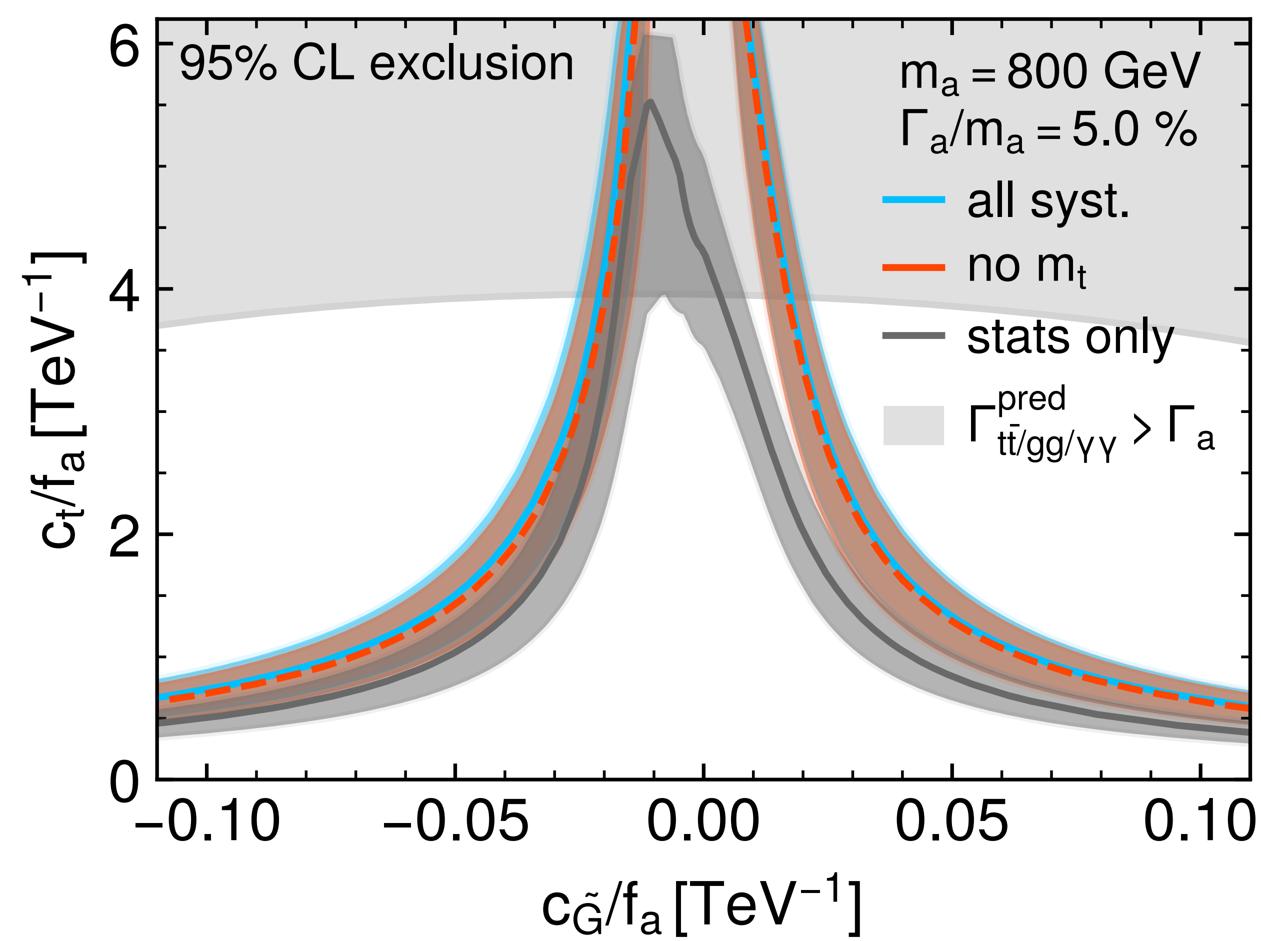


⇒HL-LHC provides sensitivity for all studied benchmark points, some scenarios can already be probed with Run 2 data

Projected expected limits on ALP couplings: impact of systematic uncertainties

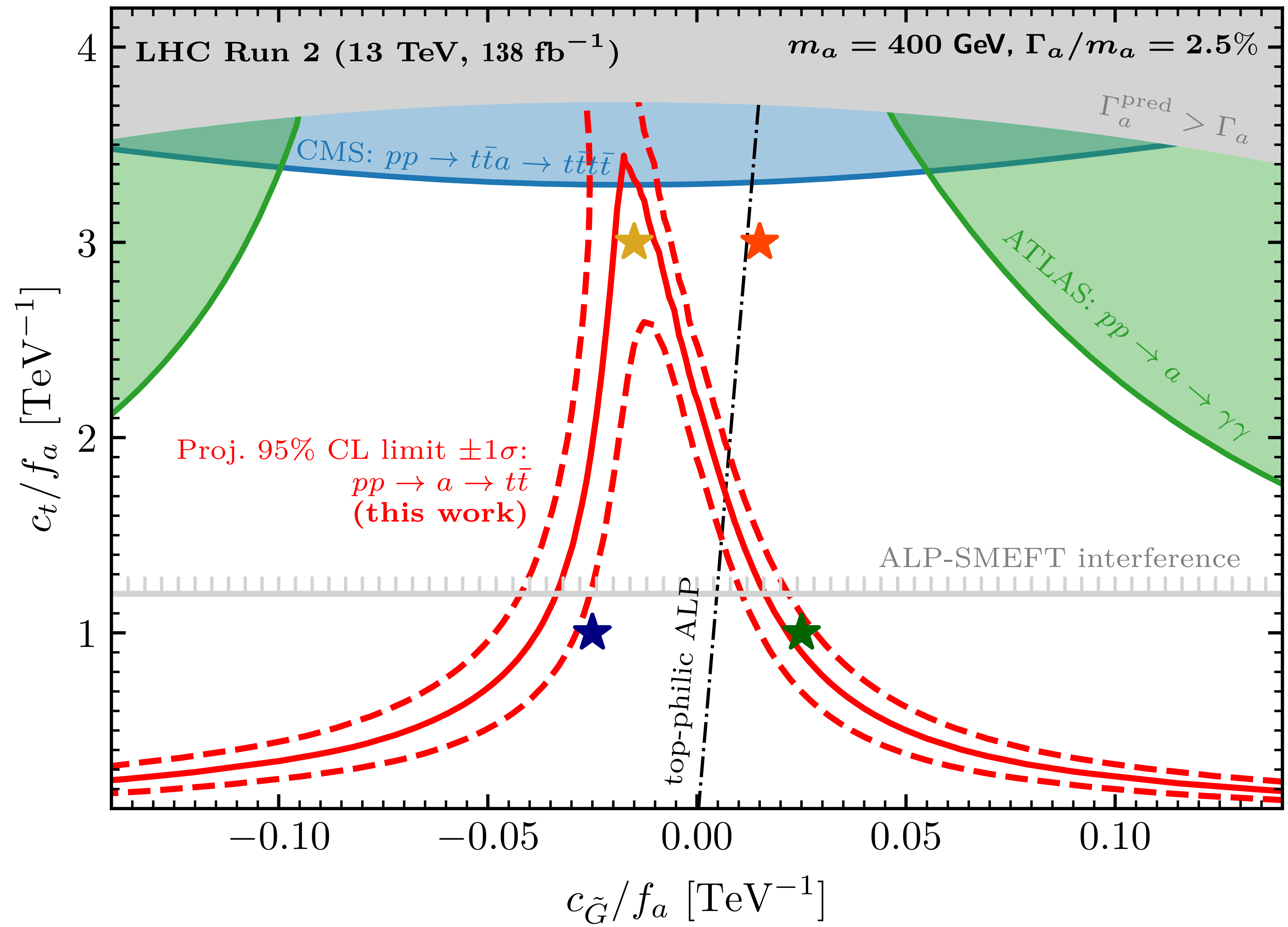
Run 2:





⇒ m_t uncertainty has significant impact for m_a = 400 GeV (expected to be smaller in exp. analysis)
Small effect for m_a = 800 GeV

Comparison with other experimental limits



Direct search limits for di-top final state yield stringent constraints, comparable or stronger than indirect limits from ALP-SMEFT interference

Conclusions

Production of a BSM particle in di-top final state: high discrimination power of spin correlations, top-mass uncertainty can be important

Expected sensitivity at Run 2, Run 2+3, HL-LHC: high sensitivity for a possible signal, good prospects for discrimination between CP-odd Higgs boson and axion-like particle

Projected limits: direct limits from searches in di-top final state are comparable or stronger than indirect limits and stronger than other direct limits

⇒ Looking forward to experimental analyses from ATLAS and CMS!

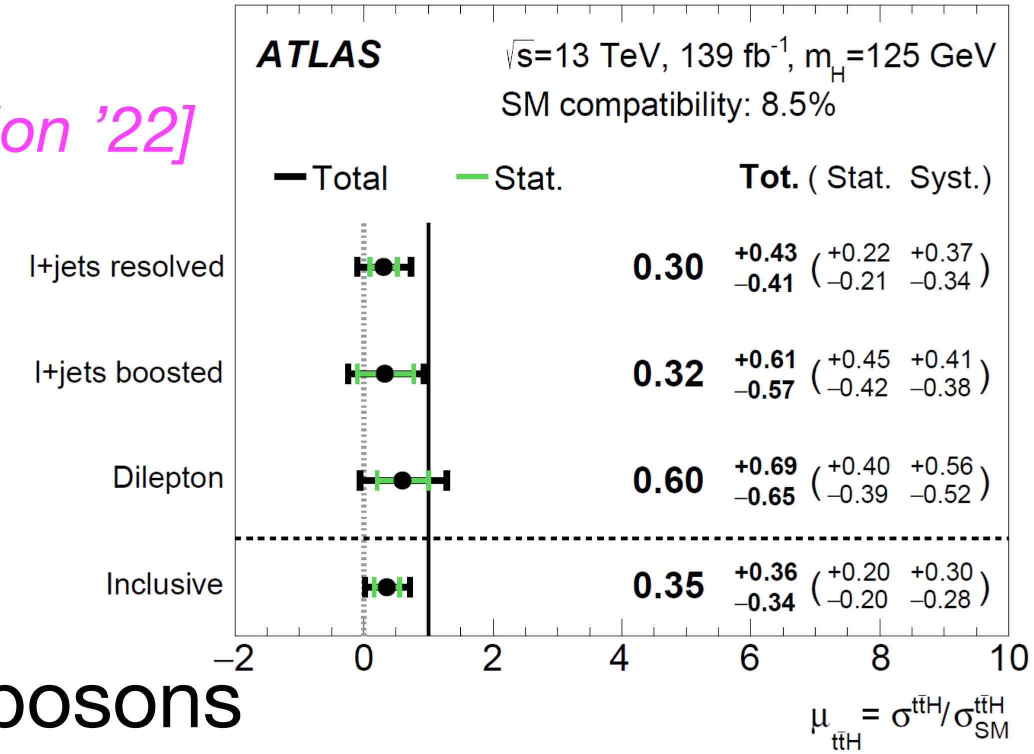
Backup

Higgs physics, current situation

Some deviations in the properties of h125

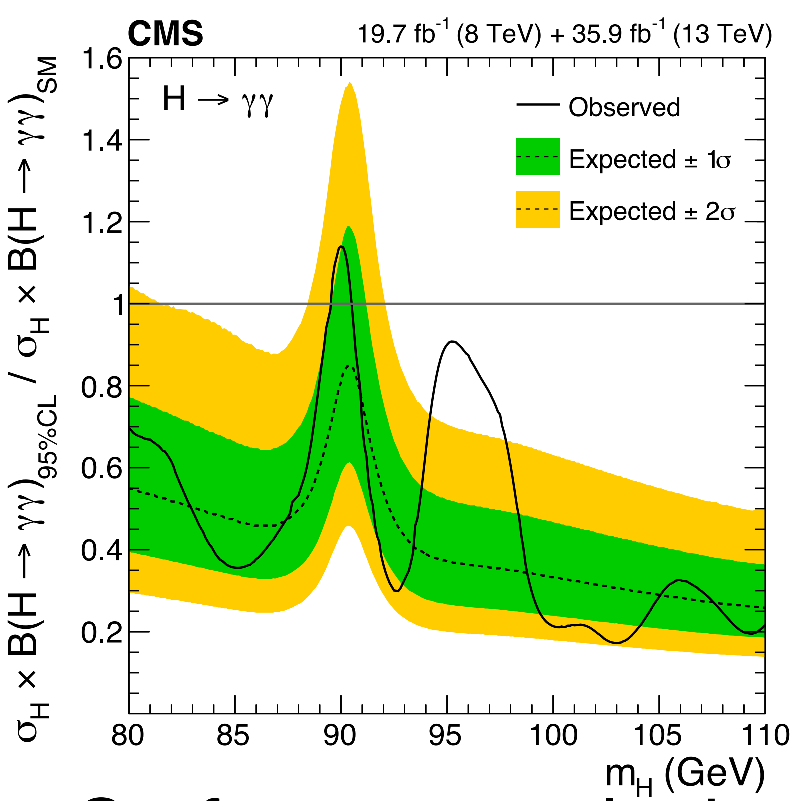
[ATLAS Collaboration '22]

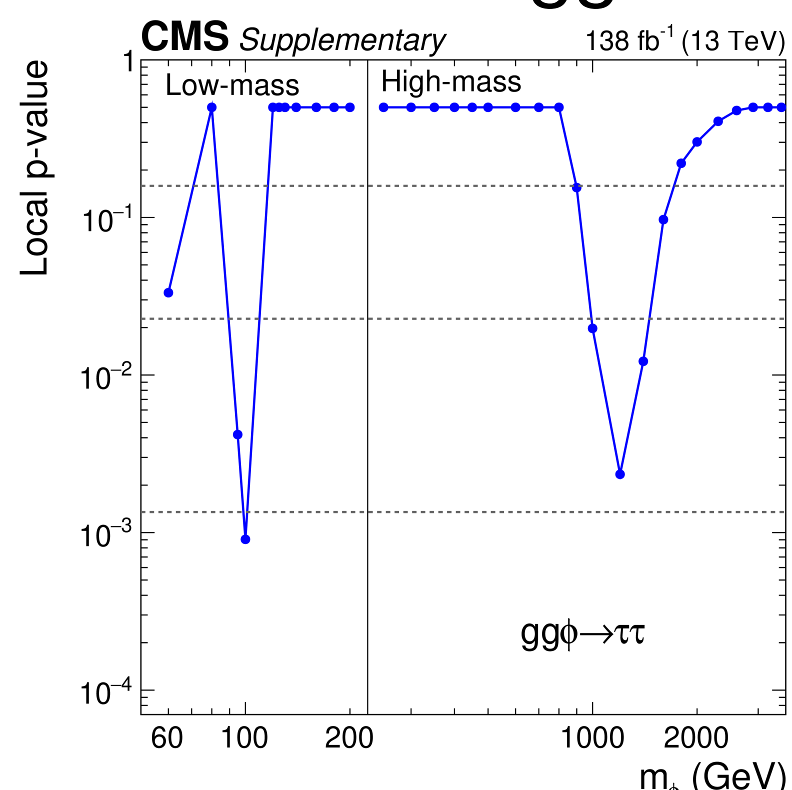
ttH, H → bb

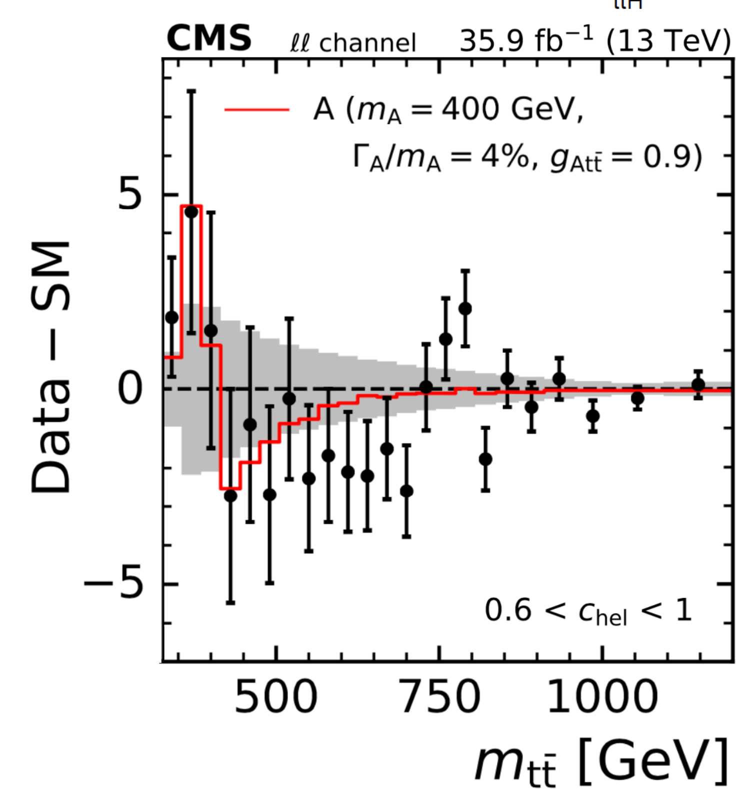


[CMS Collaboration '18, 19, 22]

Excesses in searches for additional Higgs bosons







So far no conclusive evidence for BSM Higgs physics

Significances for detecting an ALP or CP-odd Higgs (mass: 400 GeV, width: 2.5%)

a		A		Significance (a/A vs. SM)		
$c_t/f_a\,[\mathrm{TeV}^{-1}]$	$c_{\tilde{G}}/f_a\,[\mathrm{TeV}^{-1}]$	$g_{At\bar{t}}$	Luminosity	all syst.	no m_t	stats only
3.0	+0.015	0.95	Run 2	3.9/3.3	$>10/8.9$	$>10/>10$
			Run 2+3	5.2/4.3	$>10/>10$	$>10/>10$
			HL-LHC	$>10/>10$	$>10/>10$	$>10/>10$
3.0	−0.015	0.43	Run 2	2.1/1.2	2.2/1.5	4.4/2.9
			Run 2+3	3.0/1.5	3.0/2.0	6.5/4.3
			HL-LHC	8.7/4.2	8.8/5.7	$>10/>10$
1.0	+0.025	0.75	Run 2	1.1/2.4	2.6/4.7	4.0/6.3
			Run 2+3	1.4/3.1	3.2/6.0	5.9/9.4
			HL-LHC	3.9/8.4	$8.2/>10$	$>10/>10$
1.0	−0.025	0.87	Run 2	0.7/2.8	1.7/6.9	2.8/9.8
			Run 2+3	0.9/3.6	2.2/8.6	$4.1/>10$
			HL-LHC	2.3/9.9	$5.5/>10$	$>10/>10$