Letter

Constraining $A \to ZH$ with $H \to t\bar{t}$ in the low-mass region

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The decay $A \to ZH$ is a characteristic signal of two-Higgs-doublet models (2HDMs), where A and H lie primarily within the same $SU(2)_L$ multiplet, leading to a coupling of order g_2 to the Z boson. The subsequent decay $H \to tt^{(*)}$ is particularly promising, as it gives rise to distinct final states involving multiple leptons and b-jets. The required splitting between m_A and m_H can naturally occur near the electroweak scale while being consistent with perturbative unitarity. Whereas dedicated ATLAS and CMS searches focused on the region with both top-quarks on-shell, we cover lower masses where one top quark is off-shell by recasting Standard Model $t\bar{t}Z$ measurements of ATLAS and CMS. The obtained limits on $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t})$ are between 0.12 pb and 0.62 pb. Interestingly, we observe these stringent limits despite a preference (up to 2.5σ) for a nonzero new physics signal, most pronounced around for $m_A \approx 450$–460 GeV and $m_H \approx 290$ GeV, with a best-fit value of $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t}) \approx 0.3$ pb. This cross section can be accommodated within a top-philic 2HDM for a top-Yukawa coupling of the second Higgs doublet of $0.16 \lesssim \mu_t \lesssim 0.33$.

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Introduction. With the observation of the Brout-Englert-Higgs boson [1–4] at the LHC [5,6], the particle content of the Standard Model (SM) has been confirmed. While the measured properties of this 125 GeV scalar boson are consistent with SM predictions [7,8], the existence of additional Higgs bosons is not excluded, provided their contribution in electroweak symmetry breaking is subdominant and their mixing with the SM Higgs is small. In fact, numerous extensions of the SM Higgs sector have been proposed, including $SU(2)_L$ singlets [9–11], doublets [12–18], triplets [19–29], and even higher representations.

The search for new Higgs bosons is a primary goal of the LHC program. Of particular interest are the cascade decays of heavy Higgs states (see Refs. [30,31] for an overview), such as the decay of a pseudoscalar Higgs boson A into a Z boson and a new scalar H ($A \to ZH$).Notably, this chain decay has been identified as a smoking gun signature for a strong first-order electroweak phase transition, which could explain the origin of the matter-antimatter asymmetry in the Universe [32–34]. While we focus on the decay $A \to ZH$, a strong first-order electroweak phase transition can also be realized when the channel $H \to ZA$ is kinematically open, even though parameter scans often favor the former [35,36]. From a collider perspective, both decay chains lead to very similar final states when followed by $A, H \to t\bar{t}$.[1] Furthermore, owing to their clean experimental signatures, these processes provide powerful probes of extended Higgs sectors. In particular, the decay $H \to t\bar{t}$ yields distinctive multilepton final states with b-jets, and

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[1] The two processes can nevertheless be distinguished using spin correlations [37].

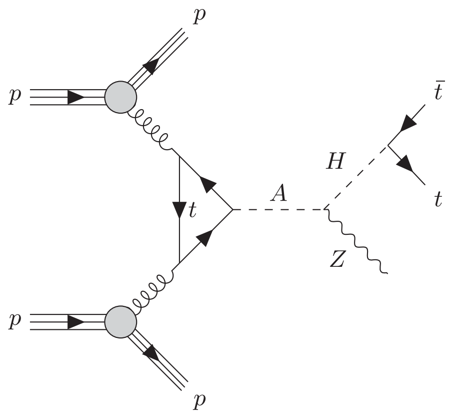

FIG. 1. Feynman diagram depicting the process $pp \to A \to ZH$ with $H \to t\bar{t}$, leading to a $t\bar{t}Z$-like signature.

has been searched for above the top threshold by ATLAS [38] and CMS [39].[2]

However, the low-mass region below the top threshold, where one of the top quarks is off-shell, remains essentially unexplored. In this paper, we close this gap by investigating the process $pp \to A \to ZH$ with $H \to t\bar{t}$ (see Fig. 1), focusing on the mass range where one top quark is on-shell while the other is virtual. For this, we recast the ATLAS and CMS analyses of SM $t\bar{t}Z$ production [40,41], which provide powerful experimental handles for such signatures [42].

From a theoretical perspective, the mass splitting among the components of an $SU(2)_L$ multiplet is governed by the electroweak (EW) vacuum expectation value (VEV) v: $m_A^2 = m_H^2 + \mathcal{O}(v^2)$. Consequently, for masses near the EW scale a gap exceeding the Z boson mass arises naturally while being consistent with perturbative unitarity, whereas for higher masses, such splittings are increasingly disfavored. This behavior is illustrated in Fig. 2, which shows the regions allowed by EW precision data and perturbative unitarity for different upper limits on the tree-level scattering amplitude. While a sizable part of the ATLAS search region does not satisfy these constraints, the low-mass region explored in this paper is fully populated by viable points in parameter space.

Analyses of $t\bar{t}Z$ differential distributions. We consider a CP-odd Higgs boson A produced via gluon fusion at the LHC with the subsequent decays $A \to ZH$ and $H \to t\bar{t}$, where one of the top quarks is off-shell. The resulting $t\bar{t}Z$-like signature enables us to exploit the measurements of the differential $t\bar{t}Z$ (and tWZ) cross sections by CMS [41] and ATLAS [40] to constrain this beyond-the-SM scenario.

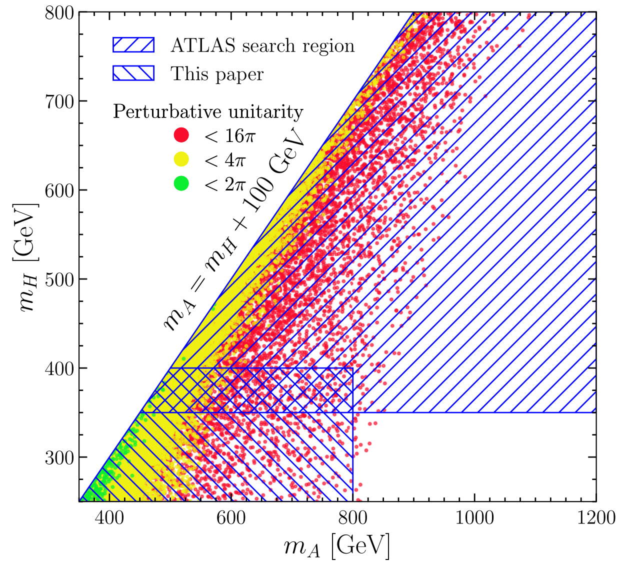

FIG. 2. Points allowed by EW precision data and perturbative unitarity for different upper limits on the tree-level scattering amplitudes: $< 16\pi$ (red), $< 4\pi$ (yellow) and $< 2\pi$ (green). The search region from ATLAS, as well as the one covered in this work, is hatched. One can see that while only part of the ATLAS region contains viable points, our region is fully populated and closes the gap for $A \to ZH$ with $H \to t\bar{t}$ searches.

The analysis targets final states with three or four leptons and at least one b-tagged jet, corresponding to $t\bar{t}Z$ (and tWZ) production in the SM. The CMS analysis provides results unfolded to the parton level (after radiation but before hadronization) and presents differential cross sections for five kinematic observables: the Z boson transverse momentum [$p_T(Z)$], the transverse momentum of the lepton from the W boson [$p_T(\ell_W)$], the azimuthal angle between the two Z leptons [$\Delta\phi(\ell^+, \ell^-)$], the angular separation between the Z boson and the W boson lepton [$\Delta R(Z, \ell_W)$], and the cosine of the angle between the Z boson and the negatively charged lepton from its decay ($\cos\theta_Z^*$). The ATLAS analysis reports only $t\bar{t}Z$ differential cross sections, applying a more stringent requirement on the invariant mass of the opposite-sign lepton pair, unfolded to both particle and parton levels, covering 15 observables listed in Table 15 of Ref. [40].

To validate our setup, we simulate the SM processes $pp \to t\bar{t}Z$ and tWZ using MADGRAPH5_AMC_V3.5.3 [43,44] with the `NNPDF31_nlo_as_0118_1000` parton distribution function [45] at next-to-leading order (NLO) in QCD.[3] The obtained parton-level events are interfaced with PYTHIA8.3 [47] using the `CMS-CUETP8S1-CTEQ6L1` tune

[2]ATLAS considers $m_H > 350$ GeV and CMS $m_H > 330$ GeV. Since CMS does not mention a $t\bar{t}$ threshold, it seems that they used the $\overline{\text{MS}}$ mass for the top quark, whereas for the decay width the on-shell mass would be more appropriate. We therefore show the ATLAS search region in our plots.

[3]At NLO, tWZ production interferes with the leading order ttZ process. To take this into account, we use the `MadSTR` plugin [46], which removes overlap at the amplitude level using the diagram removal approach.

[48] to simulate particle decays, parton showering, and radiation.[4]

For the reconstruction and selection of the leptons (electrons and muons) and jets (including b-tagged jets), we closely follow the CMS and ATLAS analyses; jets are clustered with the anti-k_T algorithm [49] implemented in FASTJET3.3.4 [50]. Events are required to contain at least three leptons, including a same-flavor opposite-sign pair with an invariant mass in the nominal Z boson window, and a third lepton consistent with a W boson decay. All additional selection requirements—jet and b-tagged jet multiplicities and kinematic thresholds on leptons and jets—are applied to reproduce the event selections used in the CMS and ATLAS signal regions, and are summarized explicitly in the Supplemental Material [51].

We then simulate our new physics (NP) signal $pp \to A \to ZH$ with $H \to t\bar{t}$ using the same setup. To have an on-shell Z boson, we require a mass splitting $m_A - m_H \geq 100$ GeV. Our scan covers m_H from 260 GeV to 400 GeV (such that one top quark and the W boson originating from the off-shell top quark are on-shell) and m_A from 360 GeV to 800 GeV. The resulting differential distributions for the benchmark point $(m_A, m_H) = (460, 290)$ GeV and $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t}) = 0.3$ pb are shown in the Supplemental Material [51].

Results and interpretation. The statistical model for the analysis is built from the binned data templates, SM predictions, and the NP contribution. The NP signal strength is extracted through a simultaneous χ^2 fit

$$\chi^2 = [\sigma_i^{\text{data}} - \sigma_i^{\text{theory}}]\Sigma_{ij}^{-1}[\sigma_j^{\text{data}} - \sigma_j^{\text{theory}}],$$

where i, j run over the bins across all observables, Σ_{ij} denotes the covariance matrix, σ_i^{data} is the measured cross section in bin i, and

$$\sigma_i^{\text{theory}} = \mu_{\text{SM}}\sigma_i^{\text{SM}} + \mu_{\text{NP}}\sigma_i^{\text{NP}},$$

represents the expected cross section in bin i, with SM and NP contributions weighted by the corresponding fit parameters; μ_{NP} is identified with $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t})$. Interference effects between the SM and NP contributions are neglected; given the narrow width of A in the parameter space considered, these effects are expected to be subleading compared to current experimental uncertainties. Correlations among the differential observables are obtained from our SM simulation, following Ref. [52].

For the CMS analysis, the theoretical uncertainties are given and incorporated by adding them in quadrature with the experimental ones, allowing us to fix $\mu_{\text{SM}} = 1$. In contrast, the ATLAS measurement does not include or provide theoretical uncertainties. We thus use the MG5_AMC@NLO+ PYTHIA8 SM prediction, which lies in between the two simulations obtained from SHERPA (without and with multileg merging of additional partons) and take into account the theory error by profiling over μ_{SM} by allowing a 5% deviation from 1, which corresponds approximately to the known uncertainty of the inclusive $t\bar{t}$ production cross section [53].

Using the global χ^2 (the sum of ATLAS and CMS), we extract model-independent limits on $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t})$ in the m_A–m_H plane at 95% confidence level (CL). The resulting exclusion is shown in the left panel of Fig. 3. Furthermore, as illustrated in the right panel, the fit exhibits a mild (up to 2.5σ) preference for a nonzero NP signal, most pronounced around for $m_A \approx 450$–460 GeV and $m_H \approx 290$ GeV, with a best-fit value of $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t}) \approx 0.3$ pb. Our limits are in good agreement with the dedicated ATLAS search for $A \to ZH$ with $H \to t\bar{t}$ in the overlap region, which demonstrates that reinterpretations of $t\bar{t}Z$ data can provide competitive sensitivity to heavy-Higgs signatures. For instance, at $m_A = 450(500)$ GeV and $m_H = 350(400)$ GeV, ATLAS reports a 95% CL limit of $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t}) \approx 0.13(0.14)$ pb in the narrow-width approximation[5] [38], while our combined fit yields $\approx$0.12 pb, consistent with the expected improvement from including the CMS data.

A. Interpretation

We now interpret these results in the top-philic realization of the two-Higgs-doublet model (2HDM). In 2HDMs, a second Higgs $SU(2)_L$ doublet, denoted Φ_1 [54], is added to the SM particle content. In the Higgs basis [55], Φ_1 does not acquire a VEV. The top-philic 2HDM constitutes a simplified realization within the general 2HDM with generic Yukawa couplings (Type III) [56,57], obtained by assuming that Φ_1 couples exclusively to the top quark. Normalizing the Yukawa interaction of the second doublet to the SM top Yukawa, the corresponding term reads $\mu_t Y_t \bar{Q}_3 \tilde{\Phi}_1 u_3$, where μ_t parametrizes the relative strength of the new interaction. For comparison, an approximately equivalent aligned 2HDM realization can be obtained by taking $\xi_u \neq 0$ while setting $\xi_d = \xi_\ell = 0$; we show results for both scenarios below.

In addition to the Higgs masses—$m_h = 125$ GeV, m_H (CP-even), m_A (CP-odd) and $m_{H^\pm}$ (charged)—the scalar sector is characterized by the mixing angle between the CP-even Higgs states (α), and the quartic coupling λ_5

[4]We previously applied the same strategy to constrain the WZ decay mode of a charged Higgs produced from top decays [42].

[5]In the ATLAS interpretation [38], results are provided for $\tan\beta = 0.5$, 1, and 5 and restricted to the narrow-width regime $\Gamma_A/m_A \leq 25\%$. Since our limits in Fig. 3 are derived in the narrow-width approximation without fixing $\tan\beta$, we compare them to the ATLAS results at $\tan\beta = 5$, which lies safely within this regime.

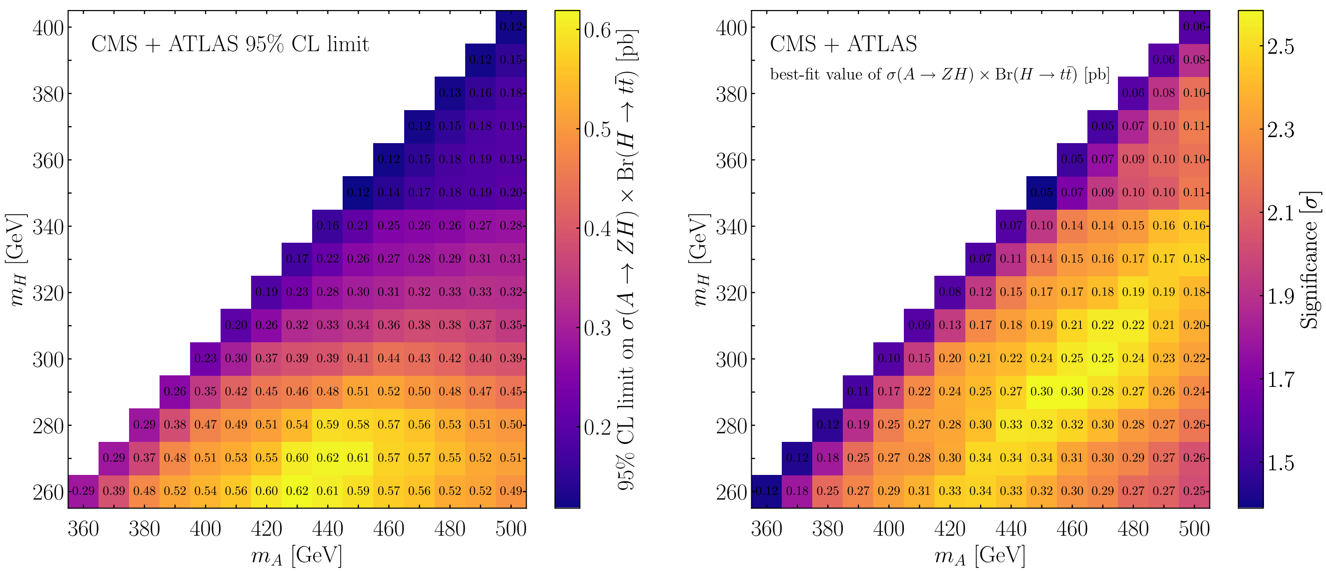

FIG. 3. 95% CL upper limit (left) and best-fit (right) value of $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t})$ in units of pb in the m_A–m_H plane with $m_A - m_H \geq 100$ GeV, obtained by combining the CMS and ATLAS analyses. The color bar in the left (right) plot indicates the 95% CL upper limit for the cross section (the preference for a nonzero NP signal in units of standard deviation). An extended region with $m_A < 800$ GeV is provided in the Supplemental Material [51].

associated with the term $(\Phi_1^\dagger \Phi_2)^2$. The decoupling limit is achieved for $\alpha \to 0$ and $m_A, m_H, m_{H^\pm} \to \infty$. Assuming $m_A < m_{H^\pm} + m_W$, such that the decay $A \to H^\pm W$ is not possible, the branching ratio of $A \to ZH$ is controlled by m_A, m_H and the couplings μ_t and $g_{AZH} \propto \cos\alpha$. The subsequent decay of H is governed by its couplings to fermions and gauge bosons, μ_t and $g_{HVV} \propto \sin\alpha$. Thus, the $H \to t\bar{t}$ mode dominates close to the alignment limit $\sin\alpha \approx 0$.

We show in the left panel of Fig. 4 the excluded regions in the m_A–m_H plane for different values of the top Yukawa rescaling parameter μ_t in the top-philic 2HDM. In the right panel, corresponding to the aligned 2HDM with $\xi_u \neq 0$, the opening of the $H \to c\bar{c}$ channel leads to slightly weaker exclusions, while the qualitative features remain similar to the purely top-philic case. Most of this parameter space was previously not covered by dedicated $A \to ZH$ searches and remains consistent with perturbative unitarity and vacuum stability, Higgs signal strength measurements [58], electroweak precision data [59], and bounds on the charged Higgs mass from inclusive weak radiative B-meson decays [60]. Furthermore, for $\mu_t \lesssim 0.5$, the existing bounds from $A, H \to t\bar{t}$ [61,62] and tb production with $H^\pm \to tb$ [63,64] are generally satisfied.

For the best-fit region around $m_A \simeq 450$–460 GeV and $m_H \simeq 290$ GeV (see right plot in Fig. 3), the preference for a nonvanishing NP contribution can be accommodated for $0.16 \lesssim \mu_t \lesssim 0.33$ and $\sin\alpha \sim 0$; see Fig. 5. The 1σ and 2σ regions (shaded in blue) are shown together with the exclusions from the CMS and ATLAS searches for $A \to t\bar{t}$ [61,62]. The corresponding best-fit line (purple) for the aligned realization is also displayed. The regions above the red and green lines are excluded by the ATLAS and CMS searches for $A \to t\bar{t}$ [61,62], respectively.

Conclusions and outlook. In this article, we derived novel limits on the cross section of the process $pp \to A \to ZH$ with $H \to t\bar{t}$ in the low-mass region where one of the top quarks is off-shell. This part of parameter space was previously not explored by dedicated ATLAS and CMS analyses, despite being well motivated: a sizable mass splitting between the neutral Higgs states is more naturally realized near the EW scale than for higher masses, i.e., the consistency with perturbative unitarity is better (see Fig. 2).

We obtained limits on $\sigma(A \to ZH) \times \mathrm{Br}(H \to t\bar{t})$ in the range 0.12–0.62 pb for $m_A > m_H + 100$ GeV and m_A between 360 GeV and 500 GeV, which are in good agreement with the dedicated ATLAS and CMS searches in the overlapping mass region. These strong bounds are obtained despite a preference (up to $\sim 2.5\sigma$) for an NP signal around $m_A \simeq 450$ GeV–460 GeV and $m_H \simeq 290$ GeV.

Interpreting the results within the top-philic 2HDM, novel constraints are derived. Furthermore, the observed preference for a nonzero NP signal can be accommodated in the top-philic 2HDM for $0.16 \lesssim \mu_t \lesssim 0.33$. Future high-luminosity LHC measurements of differential $t\bar{t}Z$ production and dedicated searches for $A \to ZH$ with $H \to t\bar{t}$ will allow this region to be probed with greater precision, providing a direct test of the top-philic Higgs scenario like the aligned 2HDM with $\xi_{d,\ell} \approx 0$ but $\xi_u \neq 0$. For completeness, we note that in 2HDMs with natural flavor conservation, the top Yukawa coupling is suppressed away from the low-$\tan\beta$ regime. As a consequence, in the mass region considered here, searches for $pp \to A \to ZH$ with

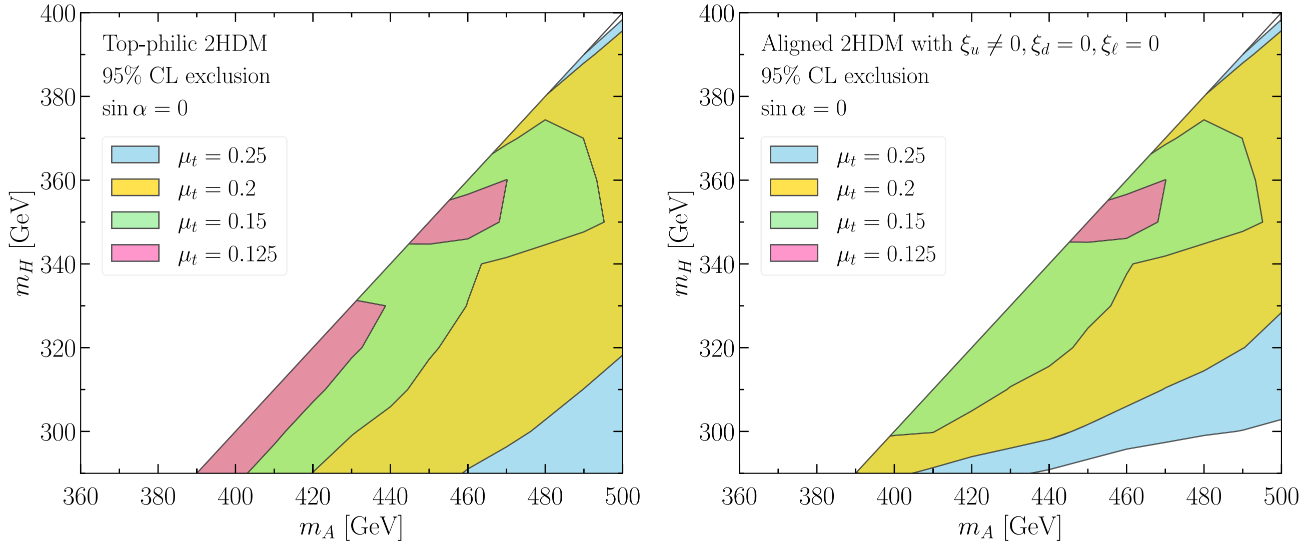

FIG. 4. Left: regions in the m_A–m_H plane for the top-philic 2HDM, assuming $\sin\alpha = 0$, that are excluded by our analysis for different values of the top Yukawa rescaling parameter μ_t. Right: corresponding exclusion in the aligned 2HDM realization with $\xi_u \neq 0$, i.e., both top and charm couplings. An extended version of this figure covering a larger m_A range up to 800 GeV is provided in the Supplemental Material [51].

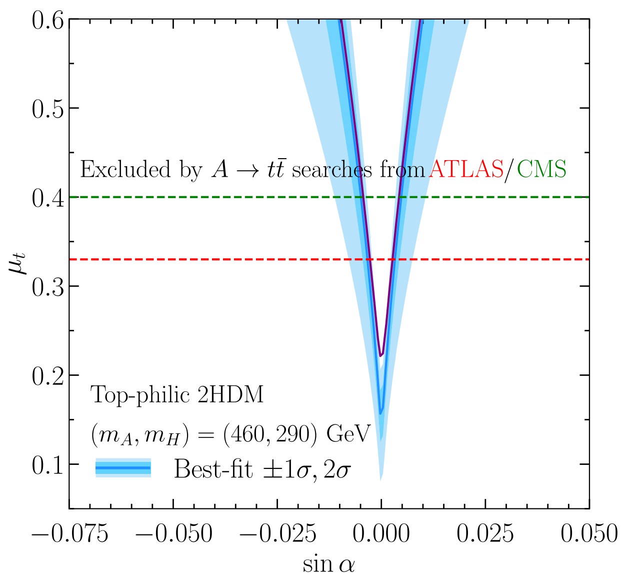

FIG. 5. Preferred 1σ and 2σ regions within the top-philic 2HDM for the best-fit point $(m_A, m_H) = (460, 290)$ GeV, where a 2.5σ preference is observed. The purple curve indicates the best-fit line for the aligned 2HDM with $\xi_u \neq 0$, $\xi_d = \xi_\ell = 0$. The regions above the red and green lines are excluded by the ATLAS and CMS searches for $A \to t\bar{t}$ [61,62].

$H \to b\bar{b}$ [65] typically provide stronger constraints than the $H \to t\bar{t}$ channel. Our results are therefore complementary and mainly relevant for scenarios with enhanced top couplings. In general, our analysis shows the importance and feasibility of searching for Higgs signals with off-shell top quarks in the final state.

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Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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