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Searching for a Charged Higgs Boson in Top-Quark Decays via the WZ Mode

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Top-quark decays are sensitive probes of light charged Higgs bosons ($H^\pm$) due to the sizable $t\bar{t}$ production cross section at the LHC in conjunction with their distinct experimental signatures. While dedicated ATLAS and CMS searches considered only $H^\pm$ decays into $\tau\nu$, cs, or cb for $m_{H^\pm} < m_t$, the WZ channel remains unexplored, despite being the dominant mode in $SU(2)_L$ triplet models. Since, top-quark pair production with $t \to H^\pm b$ and $H^\pm \to WZ$ gives rise to $t\bar{t}Z$-like signatures, we recast existing $t\bar{t}Z$ analyses to search for signs of charged Higgs bosons and set novel limits on the product of branching fractions $\mathrm{Br}(t \to H^\pm b)\times\mathrm{Br}(H^\pm \to WZ)$. These constraints turn out to be at the sub-permille level, despite the observed 2σ preference for a non-zero value. Interpreted within the hypercharge $Y = 0$ Higgs triplet model, this translates into a stringent constraint on the triplet Higgs vacuum expectation value of $v_\Delta \lesssim 2\,\mathrm{GeV}$, which is stronger than those from the $cs, \tau\nu$ modes and even surpasses electroweak precision constraints from the ρ parameter. Moreover, the 2σ preference for a non-zero cross section further strengthens the cumulative case for a $\approx 152\,\mathrm{GeV}$ boson as suggested, in particular, by di-photon excesses.

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I. INTRODUCTION

With the discovery of the Brout-Englert-Higgs boson [1–4] at the LHC [5, 6], the particle content of the Standard Model (SM) has been confirmed experimentally. Although the measured properties of this 125 GeV Higgs are consistent with the SM expectations [7, 8], this does not exclude the existence of additional scalar bosons provided their role in electroweak symmetry breaking is small. In fact, a plethora of extensions of the SM Higgs sector have been proposed, introducing $SU(2)_L$ singlets [9–11], doublets [12–18], and triplets [19–29], and even higher representations.

The search for such new Higgs bosons is a major component of the LHC program, resulting in many dedicated analyses [30, 31]. In particular, charged Higgses are probed via several production mechanisms and decay channels [30, 32]. For masses smaller than the top-quark ($m_{H^\pm} < m_t$), they can be produced from top decays, $t \to H^\pm b$ [33–35]—a promising avenue given the large $t\bar{t}$ production cross section at the LHC and the distinctive high-multiplicity final states involving leptons and (b-)jets. For this production mechanism, searches have used the cs [36, 37], cb [38], and $\tau\nu$ [39, 40] decay modes of $H^\pm$. The corresponding upper limits on the product of branching fractions $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to XY)$ ranges from 0.47%–0.11% ($XY = cs$), 0.15%–0.42% ($XY = cb$), and 0.16%–0.02% ($XY = \tau\nu$) at 95% confidence level (CL) for $m_{H^\pm}$ between 100 GeV and 160 GeV.[1] Moreover, LEP experiments set a lower limit of about 80 GeV on $m_{H^\pm}$ for cs and/or $\tau\nu$ decays [43].

In contrast, the decay $H^\pm \to WZ$ (denoting both off-shell cases $H^\pm \to W^*Z$ and $H^\pm \to WZ^*$) has not been subjected to any dedicated ATLAS or CMS searches in the low mass region ($m_{H^\pm} < m_t$). While being loop-induced in $SU(2)_L$-doublet models, it can be the dominant decay mode in $SU(2)_L$-triplet scenarios [26, 44–48]. In this Letter, we focus on charged Higgs bosons with masses between 100 GeV and 160 GeV, produced in top-quark decays and subsequently decaying via $H^\pm \to WZ$ (see Fig. 1) [49]. This shares its experimental signatures with $t\bar{t}Z$ and tWZ production, namely final states with b-jets and three or four leptons. Therefore, we can constrain charged Higgs bosons by recasting existing $t\bar{t}Z$ analyses done within the SM context [50, 51].

Note that this mass region is particularly interesting in light of the indications for a new Higgs boson at 152 GeV in associated di-photon production [52–54] and multi-lepton final states [55–59]. Furthermore, the $SU(2)_L$ triplet is a prime candidate to be involved in the explanation of these anomalies [60–64] and predicts not only a charged Higgs close in mass, but also that it decays dominantly to WZ [62].

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[1] Notably, in the cb channel, a moderate excess with a global significance of 2.5σ has been observed near a mass of 130 GeV, which, however points towards a non-minimal flavour structure [41, 42].

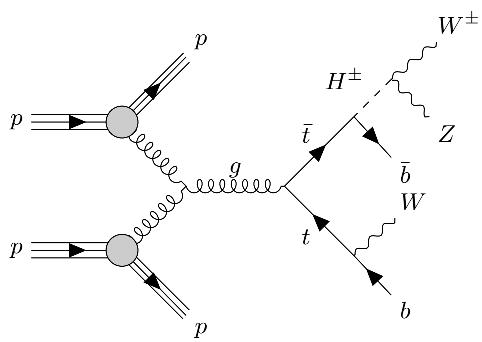

FIG. 1. Representative Feynman diagram for $pp \to t\bar{t}$ with $t \to H^\pm b$ and $H^\pm \to W^\pm Z$, leading to a $t\bar{t}Z$-like signature.

II. ANALYSES OF $t\bar{t}Z$ DIFFERENTIAL DISTRIBUTIONS

We consider a charged Higgs boson produced via top-quark decay at the LHC. Thus, its production cross section from top-quark decays is approximately

$$\sigma(H^\pm + 2b + W) \approx 2\sigma(pp \to t\bar{t}) \times \mathrm{Br}(t \to H^\pm b)\,, \quad (1)$$

with $\sigma(pp \to t\bar{t}) = 832^{+46}_{-51}\,\mathrm{fb}$ for $m_t = 172.5\,\mathrm{GeV}$ at the 13 TeV LHC within the SM [65].[2] We then consider the decay $H^\pm \to WZ$, where one of the vector bosons is off-shell.[3] This $t\bar{t}Z$-like signature enables us to use the measurements of differential $t\bar{t}Z$ and tWZ cross sections by CMS [51] and ATLAS [50].

The CMS analysis provides differential cross sections for the sum of $t\bar{t}Z$ and tWZ production (within the SM), unfolded to the parton level (after radiation but before hadronization), as functions of 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-lepton ($\Delta R(Z, \ell_W)$), and the cosine of the angle between the Z boson and the negatively charged lepton ($\cos\theta^*_Z$). The ATLAS analysis, on the other hand, reports $t\bar{t}Z$ differential cross sections unfolded to both particle and parton levels covering 15 observables (see Table 15 of Ref. [50]).

For the validation of our setup, we simulate the SM processes $pp \to t\bar{t}Z$ and tWZ using `MadGraph5_aMC_v3.5.3` [66, 67] with the `NNPDF31_nlo_as_0118_1000` parton distribution function [68] at next-to-leading order (NLO) accuracy in QCD.[4] The obtained parton-level events are interfaced with `Pythia 8.3` [70] containing the `CMS-CUETP8S1-CTEQ6L1` tune [71] to model particle decays, parton showering, and radiation. The new physics (NP) signal process $pp \to t\bar{t} \to W^\mp b H^\pm b$ is simulated analogously for 22 benchmark values of $m_{H^\pm}$ in the 100 GeV–160 GeV range. For the reconstruction and selection of physics objects, namely leptons (electrons and muons) and jets (including b-tagged jets), we closely follow the respective CMS and ATLAS analyses. Jets are clustered with the anti-k_T algorithm [72] implemented in `FastJet 3.3.4` [73], and the same reconstruction, isolation, and identification criteria are applied. Finally, we select events with at least three leptons, including a same-flavor oppositely charged lepton pair with invariant mass within the nominal Z-boson window and a third lepton consistent with originating from a W-boson (not from radiation). In addition, all further analysis-specific requirements, such as jet and b-tagged jet multiplicities and kinematic cuts on leptons and jets, are applied to ensure that the event samples match the signal regions defined by the CMS and ATLAS analyses.

III. RESULTS AND INTERPRETATION

The statistical model for the analysis is built from binned templates from data, SM predictions, and the NP contribution (see appendix for details). The NP signal strength is extracted via a simultaneous χ^2 fit

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

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

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

represents the expected cross section in bin i, with SM and NP contributions weighted by fit parameters. The correlations among the differential observables are obtained from our SM simulation. The NP signal strength μ_{NP} is identified with $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to W^\pm Z)$. For the CMS analysis, the theoretical uncertainty is included in the total uncertainty by adding it in quadrature to the experimental one, so we fix $\mu_{\mathrm{SM}} = 1$. In the ATLAS case, where theory uncertainties are not included in the reported errors, we use the one based on `MG5_aMC@NLO+Pythia 8`, whose predictions lie in between the two simulations obtained from `SHERPA` (without and with mult-leg merging of additional partons). To account for this uncertainty, we profile over μ_{SM}, allowing a 5% variation around 1, which corresponds to the uncertainty on the total $t\bar{t}$ production cross section [65].

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[2] Note that the cross section for $t\bar{t}$ production with both top quarks decaying to $H^\pm b$ is negligible, as seen from the bounds we later obtain on $\mathrm{Br}(t \to H^\pm b)$.

[3] The main contribution to the signal region originates from W^*Z. However, we also included WZ^* in our simulation since the ratio of the two modes can be calculated model-independently.

[4] At NLO, tWZ production interferes with the leading order ttZ process. We use the `MadSTR` plugin [69], which removes overlap at the amplitude level using the diagram removal approach.

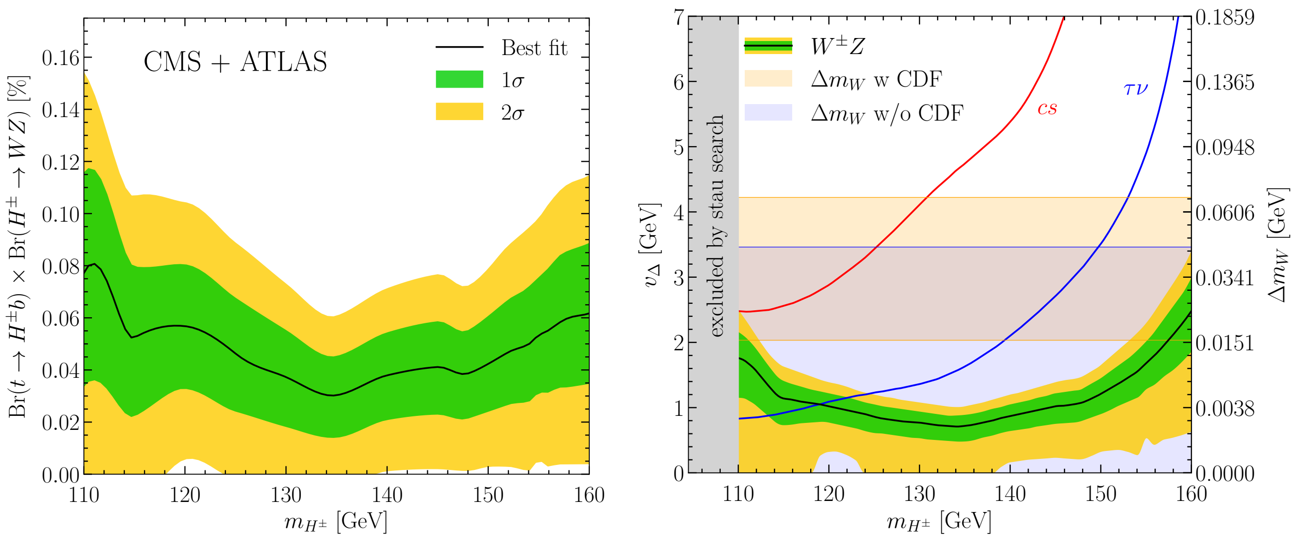

FIG. 2. Left: Preferred 1σ (green) and 2σ (yellow) range for $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to W^\pm Z)$ as a function of $m_{H^\pm}$. Right: Preferred range for v_Δ from $t\bar{t}Z$ measurement interpreted within the ΔSM model as a function of $m_{H^\pm}$. The gray band is excluded by stau searches and the area above the blue (red) line by LHC searches for $t \to H^\pm$ with $H^\pm \to \tau\nu(cs)$ at 95% CL. The light orange (blue) region shows the preferred shift in the W-mass from the global electroweak fit, including (excluding) the CDF-II measurement at 2σ.

Minimizing the global χ^2 (ATLAS plus CMS), we extract model-independent bounds on $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to WZ)$, with $\chi^2 - \chi^2_{\rm min} \leq 1$ (4) defining the 1σ (2σ) interval. The combined result is shown in the left panel of Fig. 2 as a function of $m_{H^\pm}$ (the individual results for CMS and ATLAS are shown in Fig. 5 in the appendix). Note that the lower edge of the 2σ band lies very close to $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to WZ) = 0$, indicating a mild ($\sim 2\sigma$) preference for a NP contribution.

Next, we interpret these results within the real Higgs triplet model, the ΔSM. In this model, $H^\pm$ is the charged component of the $SU(2)_L$-triplet Higgs with $Y = 0$ [19, 26–29]. The branching fractions of $H^\pm$ depend primarily on its mass, with the WZ mode being dominant.[5] Interestingly, the vacuum expectation value (VEV) of the neutral component of this field (v_Δ) contributes constructively to the W mass [29, 74], in agreement [75–78] with the CDF II measurement [79], which lies above the SM prediction [80, 81]. Moreover, this field remains largely unconstrained by LHC searches [62, 82, 83], so that its charged component can be lighter than the top quark, enabling the decay $t \to H^\pm b$ with the width

$$\Gamma(t \to H^\pm b) = \frac{g_2^2}{64\pi m_W^2 m_t} \sin^2\beta |V_{tb}|^2 \lambda^{1/2}\left(\frac{m_b^2}{m_t^2}, \frac{m_{H^\pm}^2}{m_t^2}\right) \times \left[(m_t^2 + m_b^2 - m_{H^\pm}^2)(\bar{m}_t^2 + \bar{m}_b^2) + 4m_t^2 m_b^2\right],$$

where $\beta = \tan^{-1}(-2v_\Delta/v_\Phi)$ denotes the charged Higgs mixing angle, with v_Φ being the SM Higgs VEV; $m_t = 172.5$ GeV and $m_b = 5.37$ GeV are the pole masses [84, 85], and $\bar{m}_b(m_t) \approx 2.6$ GeV is the $\overline{\rm MS}$ mass at scale m_t [86] and $\lambda(x, y) = (1 - x - y)^2 - 4xy$ is the usual kinematic function. While we provide the leading-order decay rate here, we apply a QCD correction of up to -7% depending on $m_{H^\pm}$, following Ref. [87]. The top-quark width in the SM is $\Gamma(t)_{\rm SM} = 1.326\,$GeV at next-to-next-to-leading order [84].

In the right panel of Fig. 2, we show the limit on v_Δ obtained from our recast and compare it to those from the searches for $t \to H^\pm b$ in the cs [37] (red) and $\tau\nu$ [40] modes (blue), together with the constraints from the world W-mass fit with and without the CDF-II measurement [84, 88] (light orange and light blue). The recast limit from the stau searches [89] (gray) excludes charged Higgs masses below 110 GeV [62]. We see that our limits from the WZ channel are stronger than those from the dedicated cs and $\tau\nu$ searches and surpass the electroweak precision constraints across the entire mass range.

IV. CONCLUSIONS AND OUTLOOK

We have recast the latest LHC measurements of $t\bar{t}Z$ differential cross-section measurements to probe charged Higgs bosons produced in top-quark decays in the previously unexplored $H^\pm \to WZ$ decay mode. This results in stringent bounds on $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to WZ)$ at the sub-permille level. Interpreted within the ΔSM, this yields a novel constraint on its VEV of $v_\Delta \lesssim 2\,$GeV. Intriguingly, our limits are stronger than those from ATLAS searches in the cs and $\tau\nu$ modes. Furthermore, they

[5] For example, in the $Y = 0$ triplet Higgs model, for $m_{H^\pm} \approx 150\,$GeV, the branching fractions to WZ^* and W^*Z are approximately 46% and 29%, respectively [62].

surpass the bounds from electroweak precision observables in the entire mass range.

Moreover, CMS and ATLAS data exhibit a combined $\sim 2\sigma$ preference for a NP signal. While not significant in isolation, it further strengthens the cumulative case for a $152 \pm 1\,\mathrm{GeV}$ boson, seen in di-photon and other measurements [52–54] (and predicated by the multi-lepton anomalies [55–58]), being the neutral component of an $SU(2)_L$ triplet with $Y = 0$ [60–62]. In fact, the ΔSM not only predict the charged and the neutral component to be close in mass, but the $Y = 0$ triplet can play a crucial role in explaining the tensions in differential $t\bar{t}$ distributions [63, 64]. Future high-luminosity LHC runs and dedicated analyses targeting the $H^\pm \to WZ$ mode in top decays could decisively test this scenario, potentially uncovering Higgs bosons beyond the SM.

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Appendix A

The differential cross sections for the considered observables are shown in Fig. 3 and Fig. 4, corresponding to the CMS and ATLAS analyses, respectively. The data and SM predictions are taken from each analysis, while the NP predictions correspond to $m_{H^\pm} = 150\,\mathrm{GeV}$ and to the respective best-fit values of $\mathrm{Br}(t \to H^\pm b) \times \mathrm{Br}(H^\pm \to W^\pm Z)$: 0.1% for CMS and 0.04% for ATLAS. Interestingly, the CMS measurement exhibits a small deviation from the SM prediction, while the ATLAS results are more consistent with the SM expectations.

The individual fits to ATLAS and CMS data are shown in Fig. 5.

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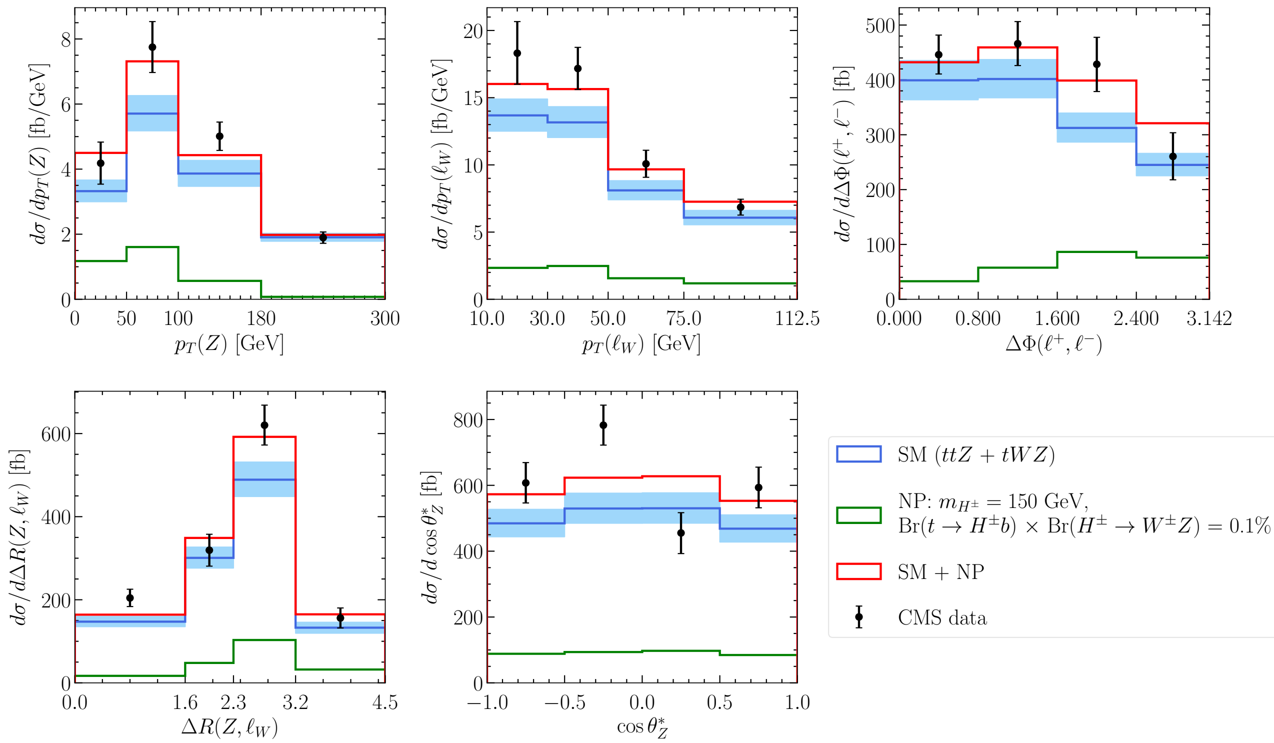

FIG. 3. The $ttZ + tWZ$ differential cross sections for different observables measured by CMS. The error bars indicate the total experimental uncertainties, while the shaded blue area corresponds to the uncertainty of the theory prediction. The NP contributions are shown for $m_{H^\pm} = 150\,\text{GeV}$ and $\text{Br}(t \to H^\pm b) \times \text{Br}(H^\pm \to W^\pm Z) = 0.1\%$, corresponding to the best-fit to CMS data (see the left plot in Fig. 5).

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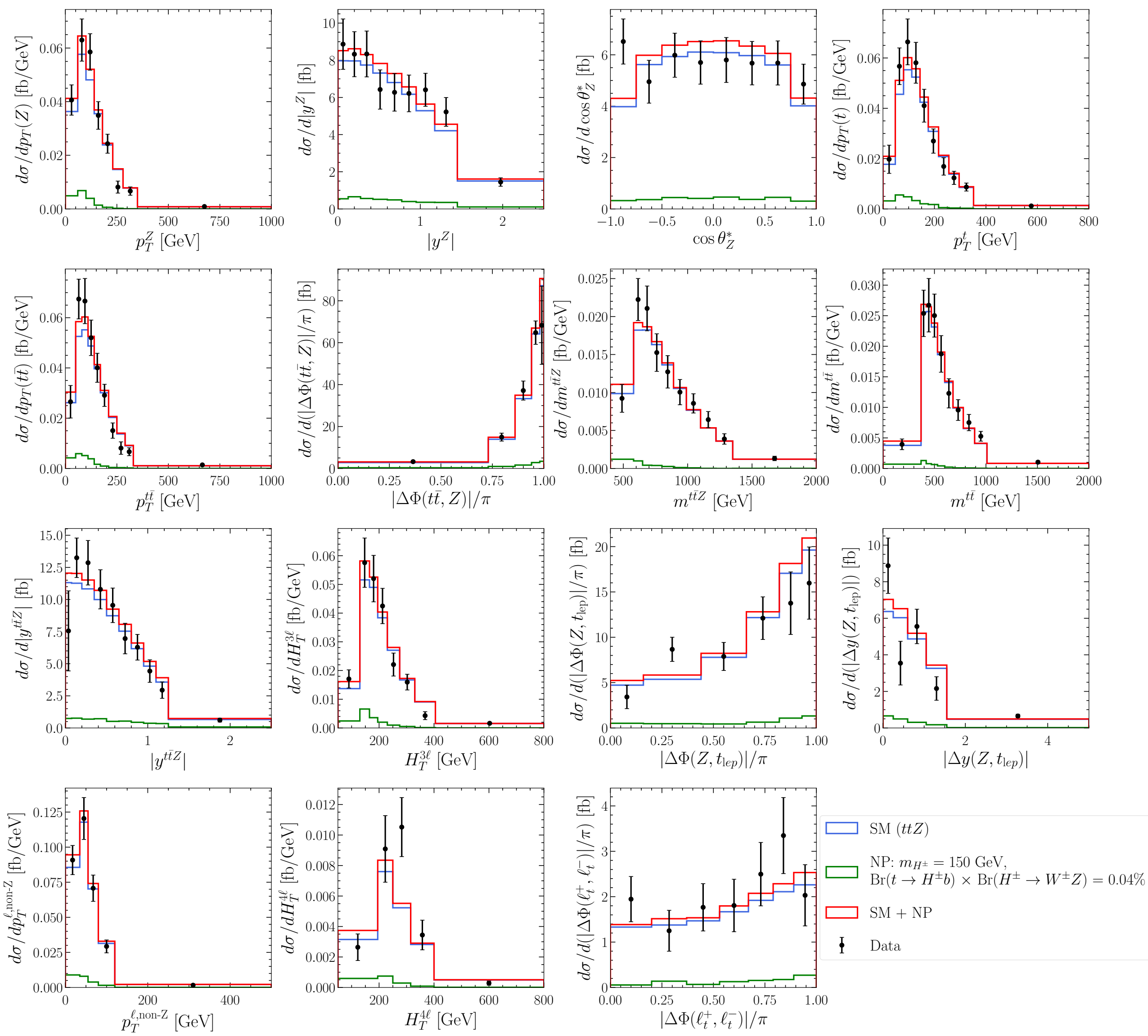

FIG. 4. Differential ttZ cross sections unfolded to particle level for different observables measured by ATLAS. The error bars indicate the total experimental uncertainties. The NP contributions are shown for $m_{H^\pm} = 150\,\text{GeV}$ and $\text{Br}(t \to H^\pm b) \times \text{Br}(H^\pm \to W^\pm Z) = 0.04\%$, corresponding to the best-fit to ATLAS data (see the right plot in Fig. 5).

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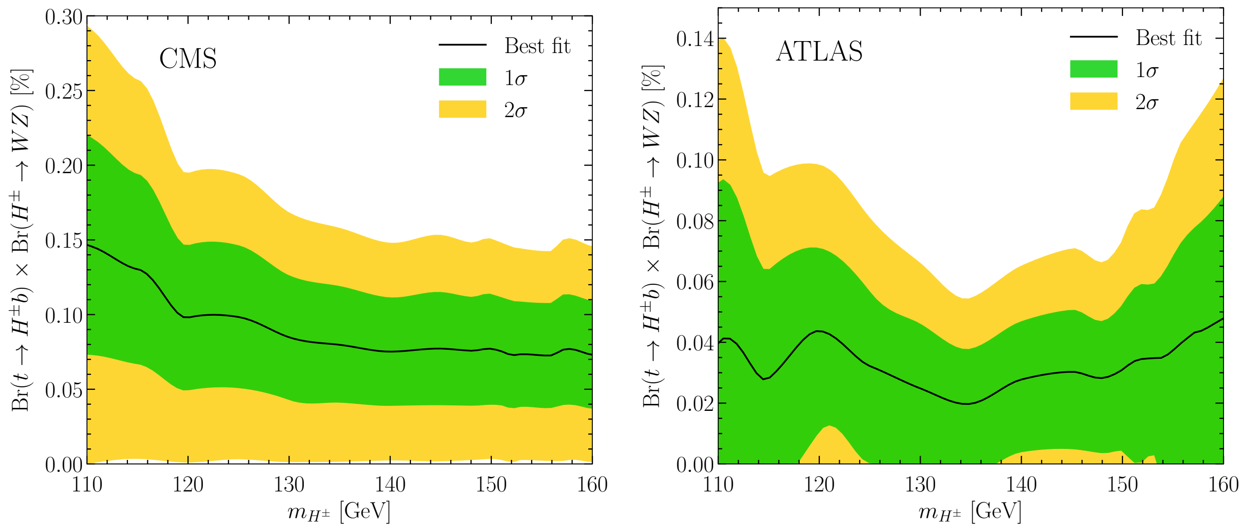

FIG. 5. Preferred 1σ (green) and 2σ (yellow) range for $\mathrm{Br}(t \to H^{\pm}b) \times \mathrm{Br}(H^{\pm} \to W^{\pm}Z)$ as a function of $m_{H^{\pm}}$, obtained from the CMS (left) and ATLAS (right) analyses.

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