Rise and Fall of Light Top Squarks in the LHC Top-Quark Sample

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We discuss the possibility that light new physics in the top-quark sample at the LHC can be found by investigating with greater care well-known kinematic distributions, such as the invariant mass $m_{b\ell}$ of the b-jet and the charged lepton in fully leptonic $t\bar{t}$ events. We demonstrate that new physics can be probed in the rising part of the already measured $m_{b\ell}$ distribution. To this end, we analyze a concrete supersymmetric scenario with a light right-handed top-squark, chargino and neutralino. The corresponding spectra are characterized by small mass differences, which make them not yet excluded by current LHC searches and give rise to a specific end point in the shape of the $m_{b\ell}$ distribution. We argue that this sharp feature is general for models of light new physics that have so far escaped the LHC searches and can offer a precious handle for the implementation of robust searches that exploit, rather than suffer from, soft bottom quarks and leptons. Recasting public data on searches for new physics, we identify candidate models that are not yet excluded. For these models, we study the $m_{b\ell}$ distribution and derive the expected signal yields, finding that there is untapped potential for discovery of new physics using the $m_{b\ell}$ distribution.

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Introduction—Despite the great efforts put in new physics searches, no signs of new physics have been spotted at the LHC yet. In light of these results, the widespread attitude today is to favor physics scenarios with new physics characterized by a mass scale beyond the reach of the LHC, but possibly accessible to future larger machines [1–4]. For this reason, it has become customary to parametrize new physics using contact operators than encode microphysics in a similar fashion to how the Fermi four-fermion contact interaction preluded to the SU(2) weak interactions [5].

In spite of the general trend, in this Letter we take a complementary attitude and investigate the possibility of light new physics in the top-quark sector still not excluded at the LHC. We find that it is still possible for new physics to appear in signals that are quite similar to the simplest manifestations that one can imagine in the minimal supersymmetric standard model (MSSM). Furthermore, we provide new methods to probe this enticing possibility and show that there is a significant potential to make a discovery in the current LHC dataset.

The majority of searches have so far concentrated on signals characterized by large energy releases in new physics events, in the TeV range, giving rise to beyond the standard model (BSM) signals that appear in regions of the phase space where the standard model (SM) has a scarce rate. Much less activity has been devoted to searches in SM-rich signal regions. To fill this gap, it is necessary to pursue a search method that confronts the SM backgrounds where they are largest, that is to say, in events where the energy release is in the range of tens or a few hundreds of GeV. In this region of phase space, thanks to the enormous progress in SM high-precision calculations, it is possible to carry out measurements with exquisite precision; e.g., [6–14]. Therefore, in this Letter we propose to carry out new searches for BSM in regions of phase space and in physical observables that were previously used only for SM measurements. Following our novel use of the data acquired for these measurements, we demonstrate that it is possible to obtain sensitivity to new physics scenarios that have not been probed yet by current searches or suffer from large uncertainty in the reach of these searches.

To ascertain what new physics scenarios are currently probed by the present results of the LHC, we will recast publicly available data using a simplified-model approach [15,16]. This method offers a reproducible and relatively reliable procedure to determine what new physics models, beyond those explicitly tested by the experiments, can be considered as excluded. This recast allows us to focus our

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attention on the models that are likely still experimentally allowed. Our search for new physics models not yet excluded by recast of public information also has value as a stress test of the present strategy for the publication of experimental results and their reinterpretation. We believe this is a valuable contribution to the assessment of the quality of the reinterpretation effort carried out by the LHC community.

Elusive new physics in top-quark samples—New physics in the top-quark sector has been searched for in a large number of final states (see, e.g., Ref. [17] for a recent review). Generally, these searches are sensitive to new physics that results in large energy release, because of large mass differences between the new states themselves and between new states and SM ones. Unfortunately, this search strategy hits a blind spot when the spectrum has small mass differences.

The issue of possible blind spots in LHC searches, due to small mass differences in the new physics spectrum and possible closeness of the new physics masses with the SM ones, has emerged early on in the exploitation of the LHC data [18,19]. The solutions that have been suggested involved the precision measurement of the total cross section for $t\bar{t}$ production [20,21], possible disagreement in the extraction of m_t [21], and angular distributions [22,23] that may be sensitive to new physics, as well as features in the kinematic distributions of very high-p_T top quarks [24].

Despite these proposals, the status of weak-scale supersymmetry, including that of superpartners charged under QCD, remains unset. To fill in this gap, we propose a new method to identify new physics hidden in the top-quark sample. Our method leverages the notable feature of the candidate new physics models to involve energy releases in the decay of the new physics particles that are typically smaller than those of the SM $t\bar{t}$ production and other SM background processes.

As a consequence of this feature, the range of the Lorentz invariants that can be used to characterize the kinematics of the events involving new physics is different from that of the SM processes. In particular, the maximum of the invariant mass of the b-jet and the lepton, such as the ones that arise from top-quark decay, denoted by $m_{b\ell}$, turns out to be significantly smaller than in SM $t\bar{t}$ production for models that have not been excluded from present searches. This gives rise to a notable rise-and-fall shape of the new physics signal in the low energy part of the $m_{b\ell}$ spectrum. This rise-and-fall shape changes for each new physics model spectrum, but it is generic of the whole class of new physics models not presently excluded. Some examples of $m_{b\ell}$ spectra that arise for MSSM parameter choice not presently excluded by the recast of public data are presented in Fig. 1 for illustration. The softest spectra are those from benchmark points with the smallest mass differences between new particles. The shape of new physics spectra has a distinctive rise from the lowest possible $m_{b\ell}$ value up to the end point that can be calculated for this kind of decay chain [25,26].

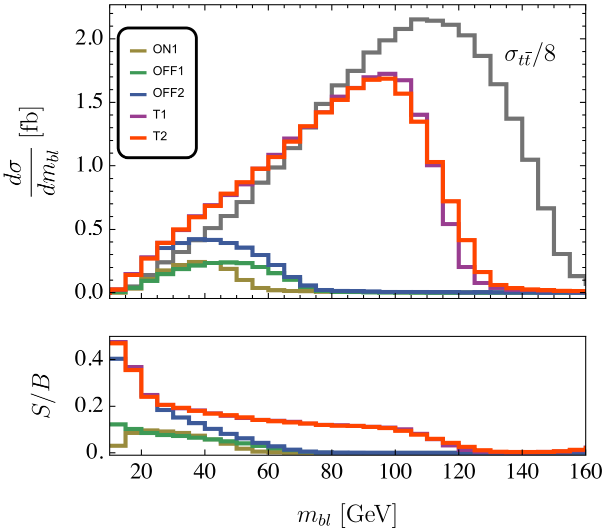

FIG. 1. The $m_{b\ell}$ distribution of the SM (gray line, rescaled by 1/8) and MSSM signals (colored lines) for the benchmark points ON1, OFF1, OFF2, T1, T2. The signal distribution has a characteristic rise-and-fall shape, which makes it easier to observe. In the bottom panel, we display the ratio of the signals over the SM contribution.

Remarkably, the quantity $m_{b\ell}$ is routinely measured by the LHC experiments; thus, our observation can be readily applied to measurements already carried out, with no required new measurements to be performed to search for new physics. (We stress that, in principle, other quantities can be used to test new physics following the same logic that led us to $m_{b\ell}$. E.g., the spectrum of the energy of the b-jets is sensitive to new physics [27,28], but there is no published data on this quantity except a preliminary CMS measurement [29].)

Based on the $m_{b\ell}$ spectrum of each new physics model, we derive an estimate for the sensitivity to new physics of precision $m_{b\ell}$ measurements carried out at the LHC. We take ATLAS [12] and CMS [30] recent results on the $m_{b\ell}$ spectrum (and its uncertainty in each bin) to compute the expected statistical significance that a new physics signal from the MSSM would have. The obtained expected significance is given in Fig. 2 from which we can see that our method has the potential to probe large areas of the MSSM parameter space. In particular, it is sensitive to mass spectra that are not currently probed by reinterpretation of LHC searches. In addition, the sensitivity of our method depends on a different combination of the new physics masses with respect to standard searches. Thus, our method can probe new physics in previously unexplored corners of the models' space and also provide independent information on models that can be studied with already proposed strategies. This is particularly useful in view of the complexity to set bounds with traditional methods due

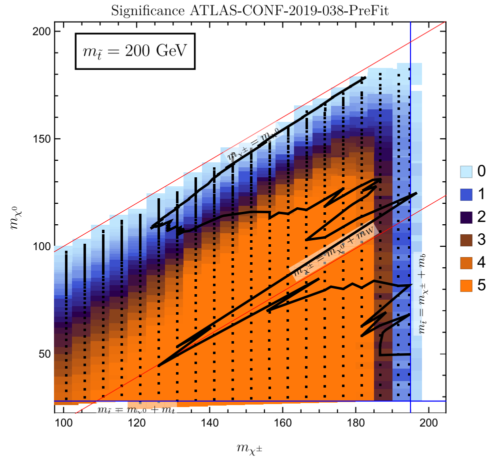

FIG. 2. MSSM signal significance Eq. (3) versus $\chi_1^\pm$ and χ_1^0 at fixed $m_{\tilde t_1} = 200$ GeV evaluated from the $m_{b\ell}$ spectrum and its uncertainty in ATLAS [12] (before the fit of SM backgrounds). The black dots correspond to the points in the plane we have explicitly generated. The colored shades are stepwise interpolations of the generated points. The color scale is saturated at $z = 5$. The black line is the approximate contour for the exclusion from present searches. The full result of our recast is presented in Fig. 3. The region of the plane at the left of the black line is deemed as excluded from our recast.

to systematics and modeling difficulties, e.g., related to the transition from on- to off-shell intermediate resonances.

Methodology—We consider the decay of $t\bar t$ to a double lepton final state, which leads to a final state containing two b-jets, two oppositely charged leptons, and their corresponding neutral partners which manifest as missing transverse momentum at the LHC. In this sample, we carefully study a well-known observable $m_{b\ell}$, the invariant mass of the lepton and the b-jet. This quantity has been used to extract the mass of the top quark [31,32] and its width [33,34], demonstrating the great control that the experiments can achieve on this observable.

As argued above, the observable $m_{b\ell}$ can show deviations from the SM prediction if it gets contaminated by a new particle which has mass close to m_t and can mimic the final state of fully leptonic $t\bar t$ events. Referring to the MSSM as a case study, such final states are given by events with pair production of the lightest top squark $\tilde t_1$ decaying into the lightest chargino $\chi_1^\pm$ and a b quark, followed by $\chi_1^\pm$ decay into the lightest neutralino χ_1^0 and lepton pair via a real or a virtual W:

$$\tilde t_1 \to \chi_1^\pm b \to b\ell\nu\chi_1^0. \tag{1}$$

The lightest neutralino and the neutrino manifest themselves as a missing transverse momentum, so that this signal leads to the same final state as fully leptonic $t\bar t$ pairs. An analogous final state could be achieved in the MSSM if the lightest top squark $\tilde t_1$ decays into a (leptonically decaying) t quark and χ_1^0. In this case, the dominant decay ($\tilde t_1 \to t\chi_1^0$) suffers much stronger bounds from specific searches [35], and therefore it is not the focus of our Letter.

To root our study in a concrete and reproducible setup, we consider a large set of points in the MSSM parameter space and study the signal in the $m_{b\ell}$ spectrum for each MSSM point. For concreteness, we consider three possible values for the lightest stop mass: $m_{\tilde t_1} = 180$, 200, and 220 GeV. For each value of $m_{\tilde t_1}$ we scan the parameter space to get different values of $m_{\chi_1^\pm}$ and $m_{\chi_1^0}$. In order to obtain our reference points, we make use of SPheno 4.0.3 [36] interfaced with SARAH 4.15.1 [37]. The SPheno input parameters are set at a high-scale Q and then run down to the weak scale by means of renormalization group equations. The description of the inputs used is provided in the Appendix.

Each of these points has been checked against searches available for recast using SModelS [38]. In particular, we check the value of the metric r computed by SModelS. Points for which $r > 1$ are deemed to be excluded by the recast, while for $r < 1$ we consider the present public data to be insufficient to exclude that model. Clearly, it is possible that the full dataset held by the experiment collaborations, as well as combinations of signal regions not taken into account by SModelS, can still exclude the points where we find $r < 1$.

Next, we simulate the contribution to $m_{b\ell}$ for each parameter space point using Pythia 8.3 [39] in the region of phase space identified by the following selection:

$$\begin{aligned} p_T(\ell) &\geq 25\ \text{GeV}, \qquad |\eta(\ell)| < 2.5, \\ p_T(j) &\geq 25\ \text{GeV}, \qquad |\eta(j)| < 2.5 \end{aligned} \tag{2}$$

for jets made with an anti-kT [40] algorithm with $R = 0.4$ and separations between jets and leptons $\Delta R(\ell, j) > 0.2$, $\Delta R(j, j) > 0.4$, and $\Delta R(\ell, \ell) > 0.1$. This is a selection closely following that of the experimental collaborations, e.g., [12,14,33], except for minor differences in the selection for $\ell = e$ and $\ell = \mu$ that we do not pursue. We remark that Pythia 8.3 decays stop squarks and their decay products according to mere phase-space density. Thus, angular correlations in the decay chains are not taken into account in our treatment of Eq. (1). This inaccuracy should not change our results, because, as we will discuss below, the shape of the signal is mostly given by energy considerations. We have considered variations of the cuts and found that, if attainable, softer selections on the transverse momenta would magnify the signal in the $m_{b\ell}$ distribution even further, but we limit ourselves to the conservative choice of cuts as in Eq. (2). The $m_{b\ell}$ spectra that we obtain are compared with those measured by ATLAS [12] and CMS [30] for 139 fb^{-1} integrated luminosity. The two experiments have dealt with the problem of associating the bottom-tagged jets and the leptons to compute the $m_{b\ell}$ variable in different ways, each specific to the selection and reconstruction methods of the experiment. For simplicity, we will show our result for the correct pairing of bottom and leptons, which highlights most transparently the effect we want to describe in this Letter. As the experiment results are endowed with an uncertainty on each bin of the measured differential cross section $d\sigma/dm_{b\ell}$, we can use the expected rate of the MSSM signal to compute a significance

$$z = \sqrt{\sum_i \left(\frac{S_i}{\delta B_i}\right)^2}, \tag{3}$$

where S_i is the MSSM signal yield expected in the ith bin of the published histogram, and δB_i is the uncertainty on each bin as published by the experiments. In the absence of more precise information from the experiments, the uncertainty in each bin is assumed to be uncorrelated with the others.

We note that both experiment collaborations provide two sets of uncertainties: One is obtained with nominal Monte Carlo predictions and uncertainties, while a second one is provided after the measured $m_{b\ell}$ spectrum is used as a constraint on the sum of the Monte Carlo predictions for several SM processes contributing to the relevant region of phase space. These two results are indicated by the experiments as "prefit" and "postfit" measurements of the $m_{b\ell}$ distribution. The postfit one has smaller uncertainties and leads to stronger bounds on new physics. For reference, we note that the smallest uncertainty in a single bin for the prefit ATLAS result we use is about 5%. Using the postfit result would give even stronger exclusions, as the smallest uncertainty in a single bin would be reduced to 0.8% in that scenario. However, we argue that it should be used with care, because it is obtained assuming that the $m_{b\ell}$ spectrum is due solely to the SM and no new physics.

In Fig. 2, we show the more conservative prefit result of the significance Eq. (3) from the ATLAS result [12]. Points for which $z > 2$ can be excluded at 95% confidence level with the new proposed analysis of $m_{b\ell}$. Strikingly, the region excluded by our proposal covers a large area of the chargino-neutralino mass plane not excluded by the recast of the present searches.

We observe that the contours of z in the chargino-neutralino mass plane closely follow those of the maximal $m_{b\ell}$ value that can be obtained for a cascade decay [25,26]. This finding corroborates the intuition that the sensitivity of our proposal is mostly dictated by energy considerations in the expected signal from new physics. In addition, we remark that our sensitivity depends on a different combination of masses compared to the present searches. This is apparent comparing the contours of r in Fig. 3 and the contours of z in Fig. 2.

TABLE I. Chargino and neutralino masses, input parameters μ, M_1, and A_t, all given in GeV for a few benchmarks (BM). The resulting value of r was computed from SModelS, and the range of the significance Eq. (3) was expected from the $m_{b\ell}$ spectrum analysis using ATLAS [12] or CMS [30] measurements. The low (high) end significance range corresponds to uncertainties on the $m_{b\ell}$ spectrum before (after) a fit using SM predictions for the known backgrounds.

BM	μ	M_1	A_t	m_{χ^+}	m_{χ^0}	z [30]	z [12]	r
				$m_{\tilde t} = 200$ GeV				
ON1	185	115	2820.5	186.7	102.8	[0.85,1.7]	[2.7,15.4]	0.5
OFF1	155	160	2857.5	156.4	123.3	[0.9,1.8]	[2.6,14.8]	0.7
OFF2	175	125	2829.5	176.6	109.1	[1.7,3.45]	[5.6,27.75]	0.8
T1	135	65	2895.5	136.2	54.	[4.,7.7]	[10.7,61.3]	0.8
T2	135	60	2895.5	136.2	49.9	[4.1,7.9]	[10.8,60.6]	0.8
				$m_{\tilde t} = 220$ GeV				
OFF3	155	150	3140.5	156.4	118.6	[0.7,1.4]	[1.9,10.9]	0.8
OFF4	170	160	3122	171.5	130.8	[0.9,1.8]	[2.5,13.7]	0.6
ON2	190	95	3104	191.7	86.1	[2.1,4.3]	[6.1,32.8]	0.8
OFF5	190	165	3094	191.7	141.7	[1.15,2.34]	[3.5,18.4]	0.7
ON3	190	60	3104	191.7	54.3	[1.9,3.9]	[5.5,29.6]	0.9
				$m_{\tilde t} = 180$ GeV				
OFF6	165	140	2560.5	166.5	116.9	[0.95,1.96]	[4.2,18.74]	0.9
OFF7	160	145	2570	161.5	118.1	[1.4,2.8]	[5.3,24.4]	0.9
OFF8	160	170	2570	161.5	130.3	[0.6,1.2]	[2.4,11.2]	0.6
OFF9	155	150	2579.5	156.4	118.5	[1.6,3.2]	[5.3,27.2]	0.8
OFF10	145	175	2598.5	146.3	122.2	[0.8,1.6]	[2.4,12.7]	0.8

For greater detail, in Table I we present the results for several points that are not excluded by the recast of present searches; i.e., the SModelS gives $r < 1$ We note that in several cases one expects deviations from the SM in the $m_{b\ell}$ distribution much larger than the uncertainties published by the experiments. These include cases for chargino-neutralino mass differences close to m_W, where the present searches have a marked blind spot. We note that CMS results tend to give a weaker sensitivity: This is due to the coarser binning of the data published by CMS with respect to ATLAS. The table presents results for the three masses $m_{\tilde t}$ considered. The complementarity of the proposed search using $m_{b\ell}$ is evident for all $m_{\tilde t}$, so as to testify to the general validity of the point that we make in this Letter.

Summary and outlook—The presently available public information from LHC searches for new physics can be reinterpreted to test models for which the LHC experiments have not provided explicit results. The MSSM is the model for which the majority of the efforts to provide data reinterpretation has been carried out so far. In our Letter, we have used the publicly available information and assembled it to the extent that it is possible with a standard tool such as SModelS. We have investigated the bounds on weak-scale supersymmetry spectra featuring light SU(2)-singlet stops squarks and light bino and Higgsino states with masses close to the top-quark mass. We have found that the LHC search results reinterpreted by using the most recent data still cannot exclude a large part of the models we have tested.

At face value, this result implies that the LHC experiments, even after years of efforts, have not yet reached a level at which weak-scale supersymmetry can be said to be ruled completely, not even in the case of colored superpartners.

Exclusion of supersymmetric models with light stops, binos, and Higgsinos may be possible using the full power of the data that are held by the experiment collaborations, but this cannot be deduced either from publicly available information on search results or from a recast of the public material. Therefore, we urge the experiment collaborations to present data for these models in a similar fashion to our results in Fig. 3, so as to provide results for these specific types of models. We also advise that they should do all that is in their power to release and maintain public information suitable to obtain exclusions on new physics models in a systematic and reproducible way. We have explained that the generation of spectra of this type in the MSSM may require a very focused setting of MSSM spectrum generators; thus, a specific effort, beyond the "wide-net" studies in the context of the phenomenological MSSM, may be needed to tackle this issue.

In addition to raising a flag about the actual reach of the LHC searches for new physics and their reinterpretability, we have provided an example of search strategy that would cover the gaps that we have highlighted. The novel strategy leverages the precision in top-quark measurements and in particular the spectrum of the b-jet + lepton invariant mass $m_{b\ell}$ that is used to measure the top-quark mass and its width with high precision. Relying on publicly available data on the measured $m_{b\ell}$ spectrum, we have identified the sensitivity contours in the chargino-neutralino mass plane at various representative values of the stop mass. Remarkably, the sensitivity of our search strategy depends on a different combination of masses from that relevant for the other searches. In particular, it seems to cope well with the transition between on- and off-shell intermediate resonances, such as $\chi^\pm \to \chi^0 W^\pm \mapsto \chi^\pm \to \chi^0 \ell^\pm \nu$. Therefore, the novel search strategy that we have proposed offers a very valuable complementary constraint that can fill the gaps and extend the reach of the searches for weak-scale supersymmetry that have been devised so far.

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[1] M. Mangano *et al.*, Eur. Phys. J. C **79**, 474 (2019).
[2] J. de Blas *et al.*, CERN Yellow Rep. Monogr., 10.23731/CYRM-2018-003 (2018).
[3] ALEGRO Collaboration, arXiv:1901.10370v2.
[4] C. Accettura *et al.*, Eur. Phys. J. C **83**, 864 (2023).
[5] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, J. High Energy Phys. 10 (2010) 085.
[6] ATLAS Collaboration, Improved W boson mass measurement using 7 TeV proton-proton collisions with the ATLAS detector, CERN Technical Report No. ATLAS-CONF-2023-004, 2023.
[7] ATLAS Collaboration, Prospects for the measurement of the W-boson mass at the HL- and HE-LHC, CERN Technical Report No. ATL-PHYS-PUB-2018-026, 2018.
[8] ATLAS Collaboration, W mass measurement, CERN Technical Report No. ATL-PHYS-PROC-2017-051, 2017.
[9] ATLAS Collaboration, Eur. Phys. J. C **78**, 110 (2018).
[10] CMS Collaboration, Projection of the top quark spin correlation measurement and search for top squark pair production at the HL-LHC, CERN Technical Report No. CMS-PAS-FTR-18-034, 2022.
[11] CMS Collaboration, Phys. Lett. B **758**, 321 (2016).
[12] ATLAS Collaboration, Measurement of the top-quark decay width in top-quark pair events in the dilepton channel at $\sqrt{s} = 13$ TeV with the ATLAS detector, CERN Technical Report No. ATLAS-CONF-2019-038, 2019.
[13] ATLAS Collaboration, arXiv:1709.04207.
[14] CMS Collaboration, Bounding the top quark width using final states with two charged leptons and two jets at $\sqrt{s} = 13$ TeV, CERN Technical Report No. CMS-PAS-TOP-16-019, 2016.
[15] S. Kraml, S. Kulkarni, U. Laa, A. Lessa, W. Magerl, D. Proschofsky-Spindler, and W. Waltenberger, Eur. Phys. J. C **74**, 2868 (2014).
[16] M. Mahdi Altakach, S. Kraml, A. Lessa, S. Narasimha, T. Pascal, and W. Waltenberger, SciPost Phys. **15**, 185 (2023).
[17] R. Franceschini, Annu. Rev. Nucl. Part. Sci. **73**, 397 (2023).
[18] J. Fan, M. Reece, and J. T. Ruderman, J. High Energy Phys. 11 (2011) 012.
[19] J. Fan, R. Krall, D. Pinner, M. Reece, and J. T. Ruderman, J. High Energy Phys. 07 (2016) 016.
[20] T. Eifert and B. Nachman, Phys. Lett. B **743**, 218 (2015).
[21] T. Cohen, S. Majewski, B. Ostdiek, and P. Zheng, J. High Energy Phys. 06 (2020) 019.
[22] T. Cohen, W. Hopkins, S. Majewski, and B. Ostdiek, J. High Energy Phys. 07 (2018) 142.
[23] Z. Han, A. Katz, D. Krohn, and M. Reece, J. High Energy Phys. 08 (2012) 083.
[24] S. Macaluso, M. Park, D. Shih, and B. Tweedie, J. High Energy Phys. 03 (2016) 151.
[25] R. Franceschini, D. Kim, K. Kong, K. T. Matchev, M. Park, and P. Shyamsundar, Rev. Mod. Phys. **95**, 045004 (2023).
[26] A. J. Barr and C. G. Lester, J. Phys. G **37**, 123001 (2010).
[27] K. Agashe, R. Franceschini, and D. Kim, Phys. Rev. D **88**, 057701 (2013).
[28] R. Franceschini, Nuovo Cimento Soc. Ital. Fis. **39C**, 340 (2017).
[29] CMS Collaboration, CERN Report No. CMS-PAS-TOP-15-002, 2015.
[30] CMS Collaboration), Eur. Phys. J. C **79**, 368 (2019).
[31] CMS Collaboration, CERN Report No. CMS-PAS-TOP-14-014, 2014.

[32] CMS Collaboration, CERN Report No. CMS-PAS-TOP-09-002, 2009.
[33] ATLAS Collaboration, Eur. Phys. J. C **78**, 129 (2018).
[34] CMS Collaboration, Phys. Lett. B **736**, 33 (2014).
[35] CMS Collaboration, J. High Energy Phys. 03 (2019) 101.
[36] W. Porod and F. Staub, Comput. Phys. Commun. **183**, 2458 (2012).
[37] F. Staub, Comput. Phys. Commun. **185**, 1773 (2014).
[38] G. Alguero, J. Heisig, C. K. Khosa, S. Kraml, S. Kulkarni, A. Lessa, H. Reyes-González, W. Waltenberger, and A. Wongel, J. High Energy Phys. 08 (2022) 068.
[39] C. Bierlich *et al.*, SciPost Phys. Codebases **2022**, 8 (2022).
[40] M. Cacciari, G. P. Salam, and G. Soyez, J. High Energy Phys. 04 (2008) 063.
[41] ATLAS Collaboration, Eur. Phys. J. C **81**, 1118 (2021).
[42] CMS Collaboration, Eur. Phys. J. C **73**, 2677 (2013).
[43] CMS Collaboration, J. High Energy Phys. 03 (2018) 166.
[44] CMS Collaboration, J. High Energy Phys. 06 (2014) 055.
[45] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, LEP TGC Working Group, A combination of preliminary results on gauge boson couplings measured by the LEP experiments, CERN Technical Reports No. LEPEWWG-TGC-2003-01, No. DELPHI-2003-068-PHYS-936, No. L3-Note-2826. LEPEWWG-2006-01, No. OPAL-TN-739, No. ALEPH-2006-016-CONF-2003-012, 2003.
[46] H. Bahl, T. Biekötter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, and J. Wittbrodt, Comput. Phys. Commun. **291**, 108803 (2023).

End Matter

Appendix A: Sensitivity of present searches—The full result on the exclusion metric r computed by SModelS is given in Fig. 3. The most constraining searches identified by SModelS are ATLAS $3\ell + \not{E}_T$ [41], CMS leptons $+ \not{E}_T$ [42,43], and jets $+ \not{E}_T$ [44]. These searches have one or more signal regions dedicated to the search of compressed spectra, thus indicating that SModelS does contain at least part of the most important searches for the scenario under study. We conclude that the results from SModelS can serve as good guidance to deem a specific model as excluded or not. In any case, we iterate that the results from SModelS are no substitute for a dedicated search. Unfortunately, results for supersymmetry (SUSY) simplified spectra so far have not been presented in a way that can be readily applied to our scenario; thus, SModelS emerges as the next best thing.

A notable drop of the strength of the bounds from the searches appears along the line diving the on-shell and off-shell intermediate W in the $\tilde{\chi}^+$ decay. Similar plots can be obtained for other values of $m_{\tilde{t}_1}$. The overall look is quite similar; thus, we do not display these figures here for brevity. The general trend is that for lighter $m_{\tilde{t}_1}$ larger parts of the chargino-neutralino mass plane are constrained. As is clear from Table I, there are regions unconstrained by the recast of the present searches for all the three masses $m_{\tilde{t}_1}$ we have tested. It should be recalled that the approach of SModelS does not allow us to combine exclusions from different signal regions, as this requires us to account for correlations that are in general not available. Hence, it is possible that a more complete analysis that can only be carried out by the experiments may find that larger regions of the chargino-neutralino mass plane are excluded.

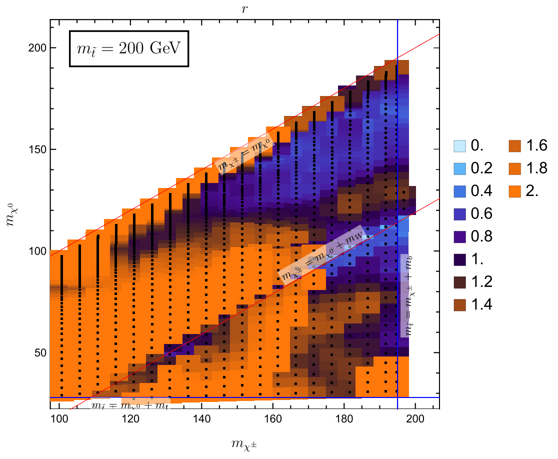

FIG. 3. Values of r for different masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ at fixed $m_{\tilde{t}_1} = 200$ GeV calculated using SModelS. A value of $r > 1$ implies the model is excluded. The color scale is saturated at $r = 2$.

Appendix B: MSSM points generation—We focused our generation on spectra in which the decay via chargino is prominent, so as to pursue this elusive decay mode. For the reproducibility of our Letter, we list all the relevant inputs of the spectrum generator. At $Q = 1.6$ TeV, we set the following: (i) $m_{\tilde{u}}(1,1)^2 = m_{\tilde{u}}(2,2)^2 = m_{\tilde{q}}(i,i)^2 = m_{\tilde{l}}(i,i)^2 = m_{\tilde{e}}(i,i)^2 = m_{\tilde{d}}(i,i)^2 = 1.2 \times 10^7\ \text{GeV}^2$ for $i = 1, 2, 3$, where $\tilde{q}$, $\tilde{l}$ are charged under SU(2), while $\tilde{d}$, $\tilde{u}$, $\tilde{e}$ are charged only under hypercharge. All the off-diagonal squark and slepton mass terms are set to zero. (ii) $m_{\tilde{u}}(3,3)^2 = 1.7 \times 10^5\ \text{GeV}^2$, which governs the lightest stop eigenstate and results in a $\tilde{t}_1$ almost pure SU(2) singlet state. (iii) $M_1 \in [5, 1000]$ GeV, $M_2 = 1$ TeV, $M_3 = 3.5$ TeV. (iv) $M_A^2 = 2 \times 10^6\ \text{GeV}^2$, $\tan\beta = 10$. (v) $\mu \in [100\ \text{GeV}, m_{\tilde{t}_1}]$. (vi) $A(3,3)$: The trilinear scalar soft SUSY breaking interaction for the stop in the range $X_t + \mu \times \cot\beta + [-100, 100]$ GeV where the exact value is obtained by trial and error to get the desired $m_{\tilde{t}_1}$. All other trilinear couplings are set to zero. In order to optimize our effort, we did not consider M_1 below 5 GeV as it tends to make the decay channel $\tilde{t}_1 \to t\chi_1^0$ very copious, and the spectrum is typically excluded by dedicated searches; e.g., Ref. [35]. The lower limit on μ takes into account limits from LEP-II experiments [45].

As the stop sector plays an important role in the MSSM Higgs phenomenology, we have studied two issues which may be considered necessary conditions for a realistic MSSM scenario, namely, the predicted Higgs boson mass and the couplings of the Higgs boson to the fermions and gauge bosons of the SM. These issues are very specific to the MSSM; thus, the following results may or may not be relevant for other new physics scenarios that appear in top-quark-like events. Nevertheless, for the sake of completeness, we note that the benchmarks in Table I all give a predicted value for the Higgs boson mass in the range [123.5,126.6] GeV using the Higgs boson mass calculation from SPheno 4.0.3. This needs to be taken with a grain of salt, as the input parameters we employ are not in the typical range where MSSM radiatively corrected Higgs boson mass can be easily applied. Nevertheless, we note that the predicted values are compatible with the measured one within the theory uncertainty of about 2 GeV. In addition, we have checked that the points in Table I are not excluded by loop contributions of light stops to Higgs coupling to photons and gluons. We have ensured this by testing each of these points using the module HiggsSignals of the package HiggsTools [46] and found that all points are statistically compatible with the current SM measurements.