Boosting Beyond: A Novel Approach to Probing Top-Philic Resonances at the LHC

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We introduce a novel search strategy for heavy top-philic resonances that induce new contributions to four-top production at the LHC. We capitalize on recent advances in top-tagging performance to demonstrate that the final state, that is expected to be boosted based on current limits, can be fully reconstructed and exploited. Notably, our approach promises bounds on new physics cross-sections that are 30 to 60 times stronger than those obtained through traditional searches, showcasing its unprecedented effectiveness in probing top-philic new physics.

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Introduction – With the third run of the LHC, both the ATLAS and CMS experiments are poised to make significant progress in the detection of heavy top-philic resonances with four-top probes. These resonances, prevalent in various new physics scenarios (see, *e.g.*, [1–7]), typically lead to an increased rate of four-top events through their QCD-induced pair production and associated production with a $t\bar{t}$ pair.

Previous LHC analyses focusing on four-top production [8–10] have yielded valuable insights, particularly enabling investigations of the top Yukawa coupling and serving to constrain new top-philic states. Building on this, our prior works [11–15] have demonstrated that slight modifications to existing four-top searches can provide a potent tool for probing top-philic new physics. Specifically, we have shown that new physics contributions to the four-top production cross section at 13 TeV are constrained to approximately 15 fb. Additionally, we anticipate modest improvements in sensitivity when scaling our predictions for the high-luminosity phase of the LHC (HL-LHC) due to the large background uncertainties, that arise when the four-top final state is not fully reconstructed.

In light of these constraints, it becomes evident that substantial improvements in sensitivity could only be achieved through a dedicated approach focusing on boosted top quarks. The present study pursues a dual objective within this context. First, we establish the feasibility of fully reconstructing a final state featuring four boosted top quarks with high efficiency, thereby enabling the potential observation of the corresponding new physics signal amidst the overwhelming Standard Model (SM) background. Secondly, we devise a novel search strategy capitalizing on recent advances in top-tagging techniques [16–18], aimed at improving bounds on top-philic new physics. Utilizing two illustrative scenarios with top-philic scalars, we showcase that our strategy can substantially strengthen cross-section limits by a factor of 30 to 60 compared to conventional methods, reaching sub-fb sensitivity.

Theoretical framework and analysis toolchain – To showcase the potential of our innovative search strategy for top-philic particles at the LHC in the four-top final state, we examine two categories of simplified models. In the first scenario, we augment the SM field content with a color-singlet scalar S_1, while in the second scenario, we introduce a color-octet scalar S_8. The new physics contributions to the Lagrangians of these respective models are [15]:

$$\mathcal{L}_{S_1} = \frac{1}{2}\partial_\mu S_1 \partial^\mu S_1 - \frac{1}{2}m_{S_1}^2 S_1^2 + y_{1S}\bar{t}\, S_1\, t\,, \tag{1}$$

$$\mathcal{L}_{S_8} = \frac{1}{2}D_\mu S_8^A D^\mu S_8^A - \frac{1}{2}m_{S_8}^2 S_8^A S_8^A + y_{8S}\bar{t}\, T^A S_8^A\, t\,. \tag{2}$$

The first two terms in these Lagrangians represent gauge-invariant kinetic and mass terms for the new fields, while the last term describes their interaction with the SM top quark via coupling parameters y_{1S} and y_{8S}. Additionally, the explicit indices A denote (summed) $SU(3)_c$ adjoint indices. For simplicity, we focus solely on scalar interactions, as the CP nature of the new interactions is not anticipated to impact our results.

The main phenomenological difference between these two models lies in the possibility for strong production of a pair of color-octet states ($pp \to S_8 S_8$), while the primary production channel for the color-singlet solely involves the "associated" production of the new state with a $t\bar{t}$ pair ($pp \to t\bar{t}S_1$), a production mode present in both model classes. Predictions related to the former process remain independent of y_{8S}, resulting in stringent model-independent constraints on moderately heavy color-octet states. This stands in contrast to the latter process, where the production rate can be suppressed by decreasing the new physics couplings. Nevertheless, in both scenarios the primary signature of the model in light of current bounds consists of LHC events featuring four boosted top quarks. Identifying and characterizing these events is the focus of the present study.

To achieve this, both models were implemented into FeynRules [19] to generate a UFO library [20] suitable for calculations at leading order (LO). Hard-scattering events were generated using MadGraph5_aMC@NLO [21], incorporating inclusive decays of unstable final-state particles via MadSpin [22] and MadWidth [23], and then matched with parton showers and hadronization modeled by Pythia 8 [24]. Additionally, we simulated the response of a typical LHC detector using the SFS framework [25] of MadAnalysis 5 [26], relying on the default ATLAS parameterization with updated performance [27–29]. The use of MadAnalysis 5 further facilitated event reconstruction using FastJet [30], and the implementation of the preliminary analysis cuts.

Signal events comprise four boosted top quarks, and their observation necessitates control over various sources of SM

Process	σ(LO)	Scale	PDF	σ(NLO)	Scale	PDF
$t\bar{t}jj$	354	$^{+62\%}_{-35\%}$	± 5.8%	352	$^{+3.7\%}_{-13\%}$	± 2.6%
$t\bar{t}W$	0.376	$^{+23\%}_{-17\%}$	± 3.9%	0.565	$^{+8.3\%}_{-8.3\%}$	± 1.8%
$t\bar{t}Wj$	0.329	$^{+39\%}_{-26\%}$	± 2.1%	0.452	$^{+8.1\%}_{-12\%}$	± 1.2%
$t\bar{t}Z$	0.563	$^{+31\%}_{-22\%}$	± 4.8%	0.756	$^{+9.2\%}_{-11\%}$	± 2.1%
$t\bar{t}Zj$	0.639	$^{+47\%}_{-30\%}$	± 6.5%	0.672	$^{+2.6\%}_{-9\%}$	± 2.5%
$t\bar{t}t\bar{t}$	0.00612	$^{+65\%}_{-37\%}$	± 13%	0.00920	$^{+28\%}_{-24\%}$	± 6.0%
$t\bar{t}t + t\bar{t}\bar{t}$	0.00155	$^{+22\%}_{-17\%}$	± 13%	0.00201	$^{+20\%}_{-19\%}$	± 7.5%

TABLE I. LO and NLO cross sections for the dominant SM background contributions relevant to our analysis, given at LO and NLO in QCD and for a center-of-mass energy of 13 TeV. Predictions rely on the NNPDF2.3NLO set of parton densities [31], and include theory errors (scale and parton density variations) with a central scale fixed to half the hadronic activity in the event ($H_T/2$). The transverse momentum for any parton-level jet must satisfy $p_T > 20$ GeV.

background. The primary contributions arise from the production of a top-antitop pair in association with additional bosons and/or jets. Specifically, the dominant background component consists of the production of a top-antitop pair in association with two extra jets ($pp \to t\bar{t}jj$), each jet mimicking a boosted top quark. Additionally, the processes $pp \to t\bar{t}V$ and $pp \to t\bar{t}Vj$ (with $V = W, Z$) contribute, albeit to a lesser extent.[1] The cross sections for the production of four tops ($pp \to t\bar{t}t\bar{t}$) and three tops ($pp \to t\bar{t}t/t\bar{t}\bar{t}$) are at least two orders of magnitude smaller. Despite their expected lower significance, we include these backgrounds in our analysis. Conversely, we have verified that the multijet and $t\bar{t}VV$ backgrounds are negligible after the selection cuts and top tagging procedure described below. Table I presents cross sections for the most relevant background contributions, both at LO and next-to-leading order (NLO) in QCD, at a center-of-mass energy of 13 TeV (a value used throughout this work). Background simulations are conducted with the toolchain introduced above.

Characterization of a boosted four-top system – To demonstrate the feasibility of reconstructing a final-state with four boosted top quarks and its utility in identifying new physics, we leverage significant recent advances in top-tagging [16–18].

Our analysis begins by selecting lepton candidates, requiring their transverse momentum p_T to exceed 20 GeV and their pseudo-rapidity to fall within the ranges $|\eta^e| < 2.74$ and $|\eta^\mu| < 2.5$ for electrons and muons, respectively. Additional isolation criteria are applied, ensuring that the sum of transverse momenta of all tracks within a cone of radius ΔR centered on the lepton direction remains below 6% (4%) of the electron (muon) transverse momentum, with a cone size determined by $\Delta R = \min[\Delta R^{\min}, 10~\text{GeV}/p_T]$ where $\Delta R^{\min} = 0.2$ (0.3). We reconstruct two classes of jets using the anti-k_T algorithm [32] with radius parameters $R = 0.4$ and 1.0, which we refer to as AK4 and AK10 jets, respectively. AK4 jet candidates must satisfy $p_T > 20$ GeV and $|\eta| < 2.5$, while AK10 jets are required to have $p_T > 350$ GeV, $|\eta| < 2.0$, and an invariant mass larger than 40 GeV after applying the soft-drop grooming procedure [33]. We address overlap between leptons and AK4 jets following the procedure of [34], and AK10 jets within a transverse distance $\Delta R < 1$ of a lepton are additionally removed.

We tag AK4 jets as either b-jets or non-b jets using a p_T-dependent performance similar to the MV2c10 ATLAS algorithm [29]. We select a working point that achieves an average tagging efficiency of 77%, with average mis-tagging rates for c-jets, τ-jets and lighter jets of 16.7%, 4.5% and 0.75%, respectively. AK10 jets overlapping with a parton-level top quark within $\Delta R < 0.75$ and containing a B-hadron are considered to originate from a top quark. Following the approach outlined in [17], these AK10 jets are uniformly top-tagged with an efficiency of 80%. Conversely, AK10 jets not consistent with a top quark are mis-top-tagged with a p_T-dependent rate of 5% (optimistic) or 10% (conservative) in average.

Our analysis is divided into several signal regions based on the number of top quarks decaying leptonically. In a first category, we select events with *at most* one lepton. This encompasses events with four top quarks decaying hadronically, as well as events with three hadronically-decaying top quarks and one leptonically-decaying top quark, constituting approximately two-thirds of all $t\bar{t}t\bar{t}$ events. In a second class of signal regions, we require events to feature two same-sign leptons, aiming to reduce contamination from the $t\bar{t}jj$ background.

In the first category, if an event contains a lepton, it must also feature one additional b-tagged AK4 jet that does not overlap with any top-tagged AK10 jets. This ensures the kinematic reconstruction of a leptonically-decaying top quark. The longitudinal momentum of the associated neutrino is determined by assuming that it originates from the decay of an on-shell W boson, which results in two solutions. We choose the one that yields a reconstructed top-quark invariant mass closest to the top pole mass. A first signal region SR1 is dedicated to events featuring three reconstructed top-like objects and one additional (top-tagged or not) AK10 jet. SR1 therefore includes events with either two top-tagged AK10 jets, one additional AK10 jet, and one leptonically-decaying top quark, or events with three top-tagged and one additional AK10 jets without an isolated lepton. Correspondingly, events with four reconstructed top-like objects are placed in a region SR2. It includes events with four top-tagged AK10 jets without a leptonically-decaying top quark, as well as events with three top-tagged AK10 jets and one leptonically-decaying top.

Moreover, we introduce a third signal region, SSL. It is populated by events featuring exactly two leptons with the same electric charge, assumed to originate from two leptonically-decaying top quarks. In addition, we require the presence of at least two AK10 jets and two b-tagged AK4 jets that do not overlap with them, along with missing transverse energy larger than 50 GeV. The reconstruction of the two associated neutrinos is performed by minimizing the maximum transverse masses of the two reconstructed W bosons (which corresponds to evaluating the m_{T2} variable for the di-leptonic system [35]), and enforcing that these W bosons are on-shell. Among the two

[1] We separately consider the $t\bar{t}V$ and $t\bar{t}Vj$ background contributions. This follows the analysis requirements, which dictate jets mistagged as tops to be very hard. Consequently, the generated samples do not overlap.

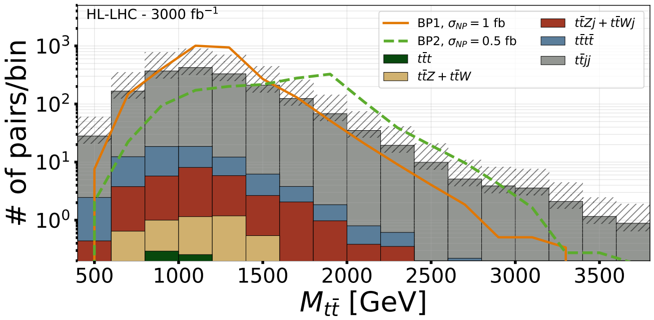

FIG. 1. Distribution of the reconstructed top pair invariant mass $M_{t\bar{t}}$, normalized to 3000 fb^{-1}, resulting from events passing the SR1 selection with conservative top-tagging performance. Predictions are provided for two signal scenarios (defined in the text) alongside all background contributions accounting for theory uncertainties stemming from scale variation. The last bin incorporates overflow events.

possible solutions for the longitudinal component of the neutrinos' momenta, we select the ones with the smallest absolute values. Finally, the reconstruction of the leptonically-decaying top quarks is achieved by pairing the two leading b-jets with the leptons and neutrinos, ensuring that the resulting tops have masses closest to the top pole mass.

At this stage, each selected event falls into at least one of the signal regions and features four top-candidate objects, some of which being top-like (*i.e.*, a reconstructed leptonically-decaying top quark or a top-tagged AK10 jet) and others not (a non-top-tagged AK10 jet). First, we apply an invariant-mass pairing tailored to the production of a pair of top-philic resonances, $pp \to XX \to t\bar{t}t\bar{t}$. For each possible pairing among the four top candidates, we compute the two di-top invariant masses and select the combination leading to the smallest difference between these values. If the relative difference satisfies a certain threshold, determined so that 80% of the signal events from the pair production mechanism meet this criterion, then the two invariant mass values are chosen as proxies for the mass of the X resonance. Otherwise, the event is considered compatible with the associated production mechanism, $pp \to t\bar{t}X \to t\bar{t}t\bar{t}$. Here, we use as a single proxy for the resonance mass the invariant mass of the top pair with the largest opening angle θ, defined by $\cos\theta = \vec{p}_1 \cdot \vec{p}_2 / (|\vec{p}_1|\,|\vec{p}_2|)$ where $\vec{p}_{1,2}$ are the three-momenta of the two top candidates.

Results and projections – Applying the procedure outlined above, we found that the SR1, SR2 and SSL selection efficiencies are respectively of about 10%, 2% and 1% for new physics states heavier than 1 TeV, regardless of whether they are produced in pairs or in association with top quarks. Moreover, the efficiency does not strongly depend on the optimistic or conservative scenarios for top-tagging performance, and it sharply decreases for smaller new physics masses. In Fig. 1, we present the distributions of the reconstructed top pair invariant mass $M_{t\bar{t}}$ resulting from the SR1 selection, both for the background and two representative benchmark scenarios featuring a scalar-octet state. For scenario BP1, characterized by $m_{S_8} = 1.3$ TeV and $y_{8S} = 0.25$, pair production dominates, whereas for BP2, with $m_{S_8} = 2$ TeV and $y_{8S} = 1$, both pair and

	BP1				BP2			
Top-tag.	Optimistic		Conservative		Optimistic		Conservative	
$\mathcal{L}$ [fb^{-1}]	400	3000	400	3000	400	3000	400	3000
SR1	1.35	0.52	1.69	0.64	0.68	0.24	0.82	0.30
SR2	0.64	0.26	0.75	0.36	0.51	0.14	0.61	0.20
SSL	0.97	0.27	0.97	0.27	1.13	0.29	1.12	0.28

TABLE II. Upper limits on the new physics cross section (in fb), considering the benchmark scenarios BP1 and BP2, derived from our analysis strategy and its three signal regions. The scenarios lead to a signal dominated by pair production of a new scalar (BP1), and made of an admixture of its pair and associated production (BP2). Results are shown for both optimistic and conservative top-tagging performance, with luminosities of 400 and 3000 fb^{-1}.

associated productions contribute due to the larger coupling value. In the figure, we normalize the production rate of new physics to 1 fb and 0.5 fb for the BP1 and BP2 scenarios, and rescale the predictions to a luminosity of 3000 fb^{-1}. The signal exhibits a peak at the resonance mass, with a resolution of a few hundred GeV. In contrast, the background, that is primarily driven by $t\bar{t}jj$ production after the mis-tagging of non-top AK10 jets as top candidates, displays a spectrum that smoothly decreases with increasing $M_{t\bar{t}}$ values. Notably, unlike in previous $t\bar{t}t\bar{t}$ analyses, contributions from the ttV background are suppressed due to our specific signal reconstruction which relies on four boosted top candidates.

We establish bounds at the 95% confidence level (C.L.) on the signal by leveraging the shape of the $M_{t\bar{t}}$ distribution, employed as input to the PyHF software [36] for limit setting. Given the substantial theoretical uncertainties on the dominant $t\bar{t}jj$ background contribution, we incorporate a correlated scale factor on the background predictions.

Our analysis commences with an examination of the two benchmark scenarios BP1 and BP2, our findings being summarized in Table II. Results are presented in terms of projected sensitivity for both the LHC run 3 (with a luminosity of 400 fb^{-1}) and its HL-LHC upgrade (with a luminosity of 3000 fb^{-1}). Sensitivity is expressed as an upper limit on the total signal production cross section (times branching ratios into top quarks). Remarkably, irrespective of the assumed top-tagging performance, we observe a dramatic enhancement of almost two orders of magnitude compared to projections from typical analyses currently conducted at the LHC [8–10]. To illustrate this, a straightforward extrapolation of the CMS-TOP-18-003 analysis [10] to 3000 fb^{-1} would constrain new physics contributions to the four-top production rate to approximately 10 fb [15]. In contrast, our proposed search strategy yields bounds that are 30 to 60 times stronger, ranging from 0.15 to 0.3 fb, with the exact improvement contingent on the assumptions made on top-tagging performance. This result therefore not only underscores the feasibility of conducting a search for new physics in events with four boosted top quarks, but it also emphasizes its unparalleled efficacy in exploiting the LHC's potential for probing physics beyond the SM.

To showcase the effectiveness of our approach, we examine the sensitivity in Fig. 2 to the color-octet (left) and color-singlet (right) simplified models under consideration. We delineate

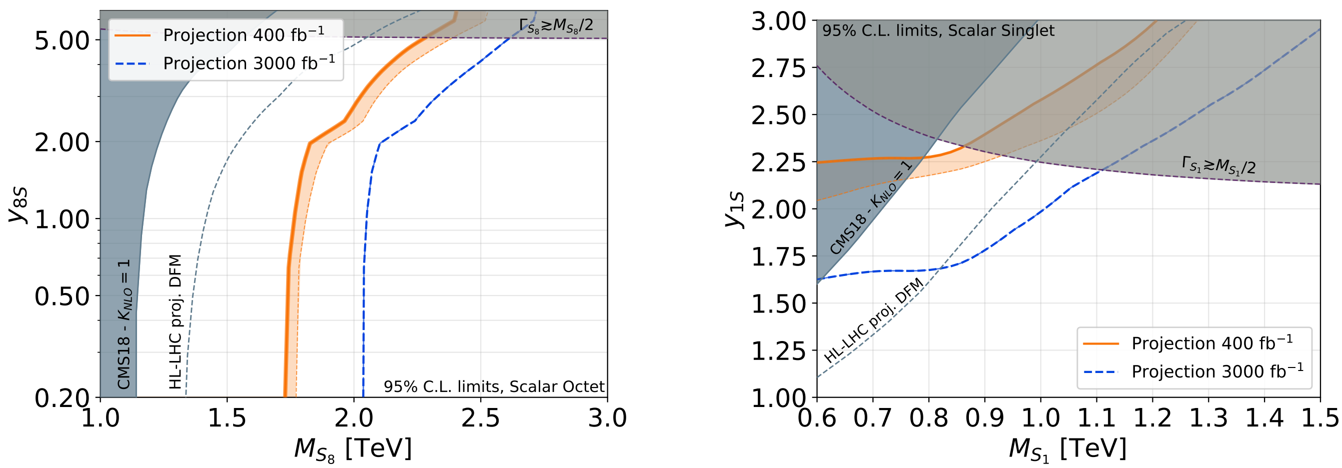

FIG. 2. Projected 95% C.L. exclusions for the scalar color-octet (left) and scalar color-singlet (right) simplified models, presented in mass *versus* coupling planes, considering luminosities of 400 (orange) and 3000 fb^{-1} (dashed blue). The solid orange lines represent exclusions obtained with conservative top-tagging performance, while the dashed orange lines refer to a more optimistic assumption. These limits are compared to the currently excluded region of the parameter space, obtained from a recast of the CMS-TOP-18-003 analysis (dark shades) [15], and its naive extrapolation for the HL-LHC (dashed gray). In addition, light gray regions in the top-right corners of the figures represent configurations in which the width of the new scalar is very large, rendering our approach unreliable.

its projected reach for the LHC run-3 (orange bands encompassing different choices for top-tagging performance), and for the HL-LHC and optimistic top tagging performance (dashed blue curves). These exclusions are juxtaposed with current limits derived from the recast of the results of LHC run 2's CMS-TOP-18-003 analysis (dark shaded regions on the left of the plots, sourced from [15, 37]), and their extrapolation for the HL-LHC luminosity (dashed gray curves, from [15, 37, 38]). Our strategy remarkably demonstrates a substantial enhancement in mass reach compared to traditional searches for new physics with four-top production. For instance, we have found that, from LO rates, heavy color-octet scalars could potentially be excluded for masses up to 2.1 TeV, even with moderately small Yukawa couplings y_{8S}. This consists of a significant improvement over current search strategies employed by the ATLAS and CMS collaborations, which currently reach only masses up to approximately 1.2 TeV. This corresponds to a region of the parameter space where new physics contributions to four-top production is induced by scalar-octet pair production.

Currently, color-singlet states face mass limits ranging from 600 to 800 GeV, given Yukawa couplings falling in the 1.5–2.5 regime. Extrapolating these limits to the HL-LHC luminosity extends them to 600–1000 GeV, possibly with slightly lower couplings. Consequently, new physics four-top events may not necessarily be highly boosted, posing a challenge for our analysis. Our findings confirm this limitation, although it additionally largely stems from large theory uncertainties on the background. While anticipated improvements in sensitivity by applying our approach to the LHC run 3 only marginally increase the reach for color-singlets with masses of 800–900 GeV, it yields exclusion limits substantially complementary to those obtained from traditional searches at the HL-LHC, particularly for singlet masses above 1 TeV. Although not as dramatic as in the case of scalar-octet states, our approach therefore still holds promise for improving searches for top-philic color-singlets with masses exceeding 1 TeV at the HL-LHC.

Furthermore, our findings exhibit minimal sensitivity to future top-tagging performance. This is exemplified at a luminosity of 400 fb^{-1}, where the reaches under optimistic and conservative top-tagging assumptions are delineated by the two edges of the orange band. With this band being relatively narrow, it is evident that the influence of top-tagging performance is modest. However, achieving sensitivity beyond the 2 TeV barrier at the HL-LHC may pose a challenge and require further improvements in top-tagging efficiency.

Conclusion – In this letter, we introduced a pioneering analysis strategy designed to explore new physics through four-top events at the LHC. Leveraging significant progress in top-tagging techniques, our method enables the efficient reconstruction of boosted four-top systems. Subsequently, it allows for the characterization of hypothetical top-philic particles by effectively controlling the associated SM background.

To demonstrate the effectiveness of our approach, we applied it to two scenarios with new top-philic scalars. Our results revealed a significant enhancement in sensitivity to these scalars at the LHC, with bounds on associated cross sections improving by a notable factor of 30 to 60 compared to conventional searches. This brings the bounds on these rates below the fb level, providing unprecedented insights into new top-philic resonances. Specifically, our analysis indicates that color-charged scalars could potentially be constrained beyond the 2 TeV barrier, while color-singlet scalars with substantial top Yukawa couplings may be restricted to the TeV regime.

Importantly, we emphasize that future improvements in top-tagging algorithms have the potential to further strengthen these limits, highlighting the promise of our approach in pushing the boundaries of new physics exploration at the LHC.

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