ATLAS Note
ANA-HDBS-2020-09-INT1
18th January 2023
Draft version 0.1

Search for tb resonance using boosted top-quark topology in the lepton+jets final state at $\sqrt{s}$ = 13 TeV with the ATLAS detector

De La Torre Perez, Hector[a], Gombas, Jason Peter[a], Schwienhorst, Reinhard[a], Sato, Koji[b], Hirose, Shigeki[b], Yamauchi, Hiroki[b], Salvador Salas, Adrian[c], Riu, Imma[c], Mir Martinez, Lluisa Maria[c]

[a]*Michigan State University (US)*
[b]*University of Tsukuba (JP)*
[c]*The Barcelona Institute of Science and Technology (BIST) (ES)*

A search for tb resonances with a boosted top tagging technique is presented, focusing on a final state consisting of a single charged lepton and multiple jets as well as a top-tagged large-R jet. The analysis is based on the pp collision data at the centre-of-mass energy of 13 TeV collected with the ATLAS detector with an integrated luminosity of 139 fb^{-1}. As a hypothetical particle with spin-0(1), a charged Higgs boson (a W' boson) scenario is searched in the mass range from 1 TeV up to 5 TeV.

Contents

List of contributions

De La Torre Perez, Hector	W' vs H+ comparisons, W' generation
Gombas, Jason Peter	W' NLO model, W' vs H+ comparisons, W'generation
Schwienhorst, Reinhard	W' NLO model, Jason supervision
Sato, Koji	Analysis contact, supervision of Hiroki
Hirose, Shigeki	Analysis contact, ntuple production, BDT training, MC production, supervision of Hiroki
Yamauchi, Hiroki	Main analyser: ntuple production, fit studies and limits extraction
Salvador Salas, Adrian	Main analyser of resolved analysis, providing technical support; ntuple production
Riu, Imma	Signal AODs and TOPQ1s production; provision of other technical support from resolved analysis
Mir Martinez, Lluisa Maria	Monte Carlo production

Remaining to do

The reweighting method: A complete proposal is to be discussed at the EB request (HBSM meeting) on 21st July, and incorporate comments and discussions there for the method, summarize them in the note in 1-2 weeks after the meeting.

***W′* MC production:** Validations are to be finalized by the end of July so that the MC generator can be implemented into the ATLAS official software. We aim for finishing the MC production as well as limit evaluations by the end of September. This is to be done in parallel to EB review, as agreed with the HBSM / HDBS conveners.

Theoretical interpretation: Interpret limits in terms of the theoretical H+/W' scenarios, such as hMSSM and XXX. This will be done by the end of September.

Version log with major updates:

v1.1:

- Filled the Section **??** that describes the reweighting technique.
- Added the Figures **??** to **??** in Appendix **??** to show BDT output distributions of events used for derivating reweighting factors.
- Updated the Table **??** and the Section **??** with the systematics source of $t\bar{t}$ + jets reweighting included. (The original Section 5.4 that describes the reweighting systematics sources was put into the Section **??**)

1 Introduction

The discovery of a neutral boson with a measured mass around 125 GeV at the Large Hadron Collider (LHC) in 2012 [1–3] ~~,~~opens the question whether this is the Higgs boson of the Standard Model (SM) or part of an extended scalar sector. Indeed, charged Higgs bosons [1] are predicted in several extensions of the SM, which add a second doublet [4–7] or triplets [7–11] to its scalar sector. In CP-conserving Two-Higgs-Doublet Models (2HDMs) H^+ production and decay at tree level depend on its mass and two parameters: the mixing angle α of the neutral CP-even Higgs bosons, and the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$).

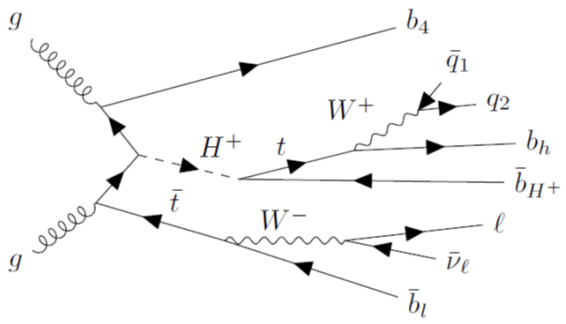

Figure 1: Feynman diagram for $pp \to tbH^+ \to tb(tb)$

For H^+ masses above the top-quark mass the leading production mode is $gg \to tbH^+$ and, close to the alignment limit when $\cos(\beta-\alpha) \approx 0$, the dominant decay mode is $H^+ \to tb$. For lower H^+ masses, the dominant decay mode is $H^+ \to \tau\nu$, as well as for large values of $\tan\beta$ irrespective of the charged Higgs mass. Therefore, the two decay modes naturally complement each other in searches for charged Higgs bosons.

The ATLAS and CMS collaborations have searched for charged Higgs bosons in pp collisions at $\sqrt{s} = 7, 8$ and 13 TeV, probing the mass range below the top-quark mass in the $\tau\nu$ [12–17], cs [18, 19], and cb [20] decay modes, as well as above the top-quark mass in the $\tau\nu$ and tb decay modes [14, 16, 17, 21–27]. In addition, $H^+ \to WZ$ was searched for in the vector-boson-fusion production mode [28, 29]. No evidence for charged Higgs bosons was found in any of these searches.

This note presents a search for H^+ production in the $H^+ \to tb$ decay mode using pp collisions at $\sqrt{s} = 13$ TeV. Events with one charged lepton ($l = e, \mu$) and jets in the final state are considered. Compared with the previous analysis using the same final state and the dataset [24] (so-called 'resolved analysis'), boosted top tagging technique is used to identify a hadoronically decaying top quark originated from the decay of the heavy H^+. This technique allows to improve sensitivities in the high mass regions, where all top decay products are merged into a single ~~large~~ large-R jet, and therefore cannot be reconstructed in the resolved analysis [24]. To separate signal from SM background, multivariate discriminants are employed in the regions where the signal rate is expected to be the largest. Limits on the $H^+ \to tb$ production cross-section are set by a simultaneous fit of BDT distributions.

[1] Charge-conjugate is implied elsewhere in this note.

Furthermore, the analysis technique is extended to a search for the $W' \to tb$ decay, where W' is produced in association with tb.

The analysis replies on ATLAS official background as well as requested H^+ and W' signal samples, as detailed in Section 2, with the TOPQ1 derivation. The ntuples are produced using the TTHbbAnalysis software package.[2] These ntuples are used as inputs to TRExFitter to perform statistical analysis.[3]

[2] https://gitlab.cern.ch/atlasHTop/TTHbbAnalysis/-/tree/user/hyamauch/pflow_dev_HplusBoosted
[3] https://gitlab.cern.ch/hyamauch/TRExFitter

2 Data and MonteCarlo Simulated Events

2.1 Data Sample

This analysis uses pp collision data collected from 2015 to 2018 by the ATLAS detector at $\sqrt{s}$ = 13 TeV. Selected events are recorded using unprescaled triggers, as detailed in Table 1. Only runs with stable colliding beams and all ATLAS subsystems oprerational are used. These are summarized in the Good Run Lists (GRL) shown in Table 2, together with the integrated luminosity collected each year. The total integrated luminosity is 139 fb^{-1} [30].

Year	Single-electron triggers
2015	e24_lhmedium_L1EM20VH_OR_e60_lhmedium_OR_e120_lhloose
2016-2018	e26_lhtight_nod0_ivarloose_OR_e60_lhmedium_nod0_OR_e140_lhloose_nod0

(a)

Year	Single-muon triggers
2015	mu20_iloose_L1MU15_OR_mu50
2016-2018	mu26_ivarmedium_OR_mu50

(b)

Table 1: Single-electron (a) and single-muon (b) trigger menus used depending on the year of data-taking.

Year	Luminosity (pb^{-1})	GRL
2015	3219.6	data15_13TeV/20170619/physics_25ns_21.0.19.xml
2016	32988.1	data16_13TeV/20180129/physics_25ns_21.0.19.xml
2017	44307.4	data17_13TeV/20180619/physics_25ns_Triggerno17e33prim.xml
2018	58450.1	data18_13TeV/20190318/physics_25ns_Triggerno17e33prim.xml

Table 2: Integrated luminosity for each year of data-taking, computed with the OflLumi-13TeV-010 luminosity tag [31], together with the corresponding GRLs [32].

2.2 Signal Samples

This paragraph describes MC samples used for each signal event's estimation. The summary is shown in Table 3.

Physics process	Generator	PS generator	Normalisation	PDF set
tbH^+ ($M_{H^+} \leq 3.0$ TeV)	MG5_aMC 2.6.2	Pythia 8.212	NLO	NNPDF2.3NLO
tbH^+ ($M_{H^+} = 4.0, 5.0$ TeV)	MG5_aMC 2.8.1	Pythia 8.244	NLO	NNPDF3.0NLO
tbW'	MG5_aMC 2.9.9	Pythia 8.307	NLO	NNPDF3.0NLO

Table 3: Nominal simulated signal event samples. The generator, parton shower generator and cross-section used for normalisation are shown together with the applied PDF set.

2.2.1 $\bar{t}bH^+$ Samples

The H^+ signal samples are generated with MadGraph5_aMCatNLO (MG5_aMC) [33], which is a generator based on a four-flavor scheme (4FS) next-to-leading order (NLO) in QCD [34]. The NNPDF2.3NLO [35] parton distribution function (PDF) set is used. [4] The width of the H^+ is set to zero. Dynamic QCD factorisation and renormalisation scales (μ_f and μ_r) are set to $\frac{1}{3}\sum_i \sqrt{m(i)^2 + p_T(i)^2}$, where i runs over the final state particles (H^+, t and b) used in the generation. The events are showered with Pythia 8.212 [37] with the A14 [38] set of underlying-event related parameters tuned to ATLAS. Ten different H^+ mass points between 1000 and 5000 GeV are generated as detailed in Table 4. The table also shows cross sections from MG5_aMC and Santander-matched cross sections for 2HDM type-II (a la MSSM), but without SUSY QCD corrections [33, 39–41]. All samples are fully simulated with the proportions of mc16a, mc16d and mc16e corresponding to the amount of data recorded in the 2015-2016, 2017 and 2018 data-taking years.

DSID	H^+ mass [GeV]	Size	$\sigma^{\text{MG5\_aMC}}$ [fb]	$\sigma^{\text{MSSM}}_{\tan\beta=1}$ [fb]	$\sigma^{\text{MSSM}}_{\tan\beta=60}$ [fb]
450004	1000	1.0M	3.28	40.9	37.8
450598	1200	1.0M	1.31	16.4	15.1
450599	1400	1.0M	5.62×10^{-1}	7.1	6.5
450600	1600	1.2M	2.54×10^{-1}	3.2	3.0
450601	1800	1.3M	1.21×10^{-1}	1.5	1.4
450602	2000	1.9M	5.90×10^{-2}	0.8	0.7
451490	2500	1.9M	1.11×10^{-2}	*Not available*	
451491	3000	1.9M	2.34×10^{-3}	*Not available*	
508710	4000	1.9M	9.75×10^{-5}	*Not available*	
508711	5000	1.9M	4.28×10^{-6}	*Not available*	

Table 4: Generated H^+ samples. All samples are simulated with FullSim and available in the appropriate proportions of mc16a, mc16d and mc16e. The cross-section values for $\tan\beta = 1$ or $\tan\beta = 60$ take into account the production of $H^\pm$.

[4] The samples with masses of 4 and 5 TeV are generated using NNPDF3.0NLO [36] PDF set.