

Search for top partners with charge $5e/3$

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Abstract

A feasibility study of searches for top partners with charge $5e/3$ at the upgraded Large Hadron Collider is performed. The discovery potential and exclusion limits are presented using integrated luminosities of 300 fb^{-1} and 3000 fb^{-1} at center-of-mass energies of 14 and 33 TeV.

1 Introduction

The recent discovery of a 125 GeV Higgs-like particle [1, 2] has been a resounding success for the Large Hadron Collider (LHC) and its experiments. The focus now shifts to fully understanding the nature of electroweak symmetry breaking by measuring the properties of the Higgs boson and discovering new physics to address the critical questions still facing particle physics today. What is the solution to the hierarchy problem? What is responsible for dark matter? Why is gravity so weak?

A number of extensions to the Standard Model (SM) attempt to solve the above problems by predicting new particles. In particular, heavy partners of the top quark (“top partners”) arise in many of these models for addressing the hierarchy problem [3, 4, 5, 6]. Because of the large Higgs-top Yukawa coupling, radiative corrections to the weak scale from the top loop are considered the most significant source of fine-tuning in the SM. Natural theories of the weak scale must, therefore, include top partners whose interactions with the Higgs cancel the top-loop contribution to the weak scale.

These top partners are predicted to have masses close to the electroweak symmetry breaking scale thus making them accessible at the LHC. In some cases they can also have exotic charge and contribute minimally to the coupling of the Higgs boson to gluons [7]. Searches for such top partners, therefore, continue to be viable despite the recent observation of a 125 GeV SM Higgs-like resonance.

We present a feasibility study for the $T_{5/3}$, an exotic top partner with charge $5e/3$ (where e is the charge of the electron) using simulated data with the Snowmass Combined LHC detector [8] at $\sqrt{s} = 14$ and 33 TeV. We assume that the $T_{5/3}$ is pair-produced and decays [see Fig. 1 (left)] via $T_{5/3} \rightarrow tW^+$ and $t \rightarrow W^+b$ (charge conjugate modes are implied throughout). We concentrate on the dilepton final state wherein the presence of same-sign leptons helps distinguish this process from the large $t\bar{t}$ background. Only contributions due to instrumental effects, QCD multijets and Z +jets remain along with backgrounds with much smaller cross sections: $t\bar{t}W$, $t\bar{t}Z$, WWW , and same-sign WW .

2 Signal and Background Samples

All samples used in this study are generated using MadGraph 5 [10] and simulated using Delphes 3.0.9 [11]. For the backgrounds, the MadGraph generation is done in bins of the sum of transverse energy of all MadGraph-level particles in the event as described in [12]. The detector used as input to the simulation of both signal and background samples is the Snowmass Combined LHC detector [8]. Two pileup scenarios are considered for each center-of-mass energy: one with 50 mean interactions per bunch crossing and one with 140 such interactions.

Signal samples are generated with the $T_{5/3}$ mass varied in intervals of 100 GeV. The mass in 14 TeV samples ranges from 0.7 TeV to 2.2 TeV while for 33 TeV samples, it varies from 0.7 TeV to

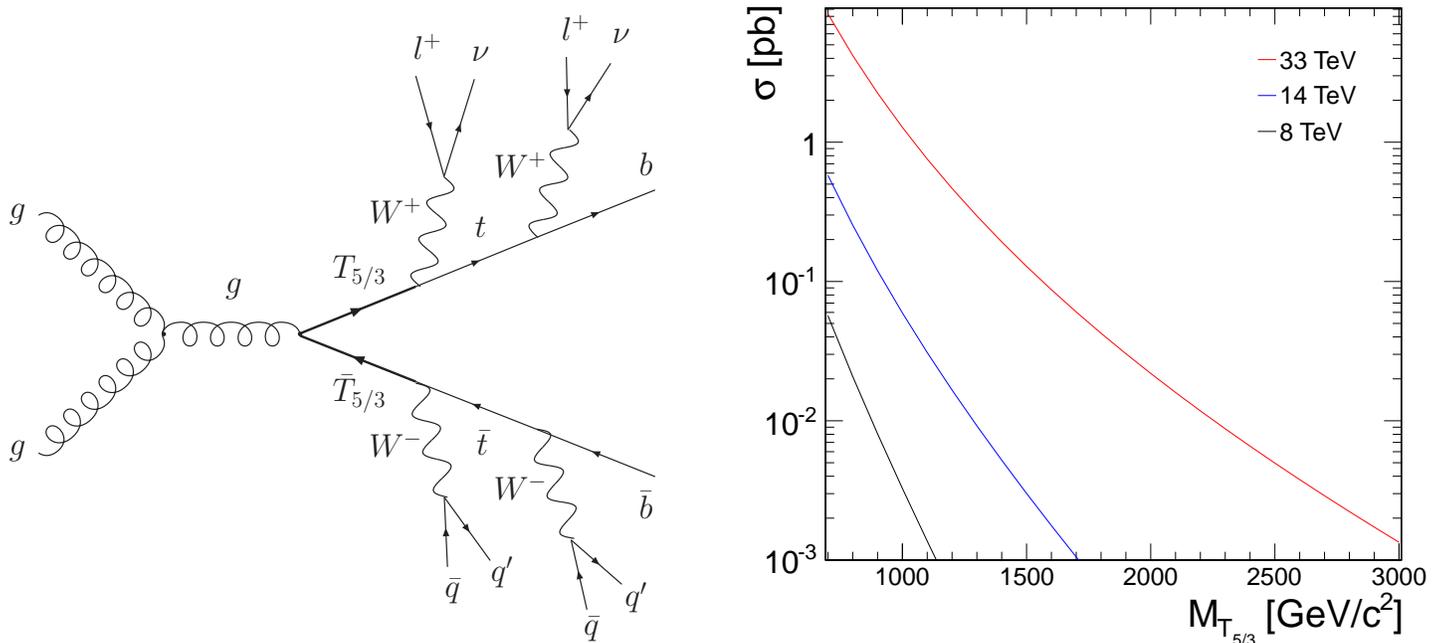


Figure 1: The pair production and decay into same-sign dileptons of the $T_{5/3}$ (left) and the cross-section of the $T_{5/3}$ for various center-of-mass energies (right). The Feynman diagram is from [6]. The cross-section is calculated using HATHOR [9].

3.0 TeV. The principal same-sign backgrounds are $t\bar{t}W$, $t\bar{t}Z$ and the various combinations of triboson backgrounds (e.g. $W^\pm W^\pm$, WZ , WWW , WWZ , etc.).

3 Event Selection

In addition to having same-sign leptons, the decay of a $T_{5/3}\bar{T}_{5/3}$ pair also typically results in many jets and missing transverse energy (\cancel{E}_T) from the neutrinos. At masses of the $T_{5/3}$ relevant at 14 and 33 TeV, all of the $T_{5/3}$ decay products have transverse momenta (p_T) that are significantly higher than similar objects from any of the backgrounds. Therefore, the event selection is based primarily on the p_T of the decay products and sums thereof. The requirements at 14 and 33 TeV are listed in Table 1. H_T is the scalar sum of all leptons and jets in the event with $p_T > 30$ GeV. S_T is the scalar sum of the H_T and the \cancel{E}_T .

Table 1: Event selection requirements as a function of center-of-mass collider energy.

Parameter	14 TeV Min [GeV]	33 TeV Min [GeV]
Leading lepton p_T	80	150
Second lepton p_T	30	50
Leading jet p_T	150	150
Second jet p_T	50	50
\cancel{E}_T	100	200
H_T	1500	2200
S_T	2000	3000

Aside from the p_T requirements, the number of decay products in the event is also a good discriminant between signal and background. However, it can be obscured by the fact that jets from highly boosted W bosons and top quarks tend to merge into a single jet. To recover this information, we

use the top and W tagging algorithms implemented in the Delphes output [8]. These algorithms use Cambridge-Aachen jets with a radius of 0.8 (CA8 jets). A CA8 jet is considered to be W -tagged if its mass is between 60 and 120 GeV and if the “mass drop” of the jet (the ratio of the leading sub-jet mass to that of the whole jet) is less than 0.4. Jets are top-tagged if their mass is between 140 and 230 GeV and if they have at least 3 sub-jets.

Given this implementation of jet substructure, the number of decay products is approximated by the number of “constituents” in the event. Each top-tagged CA8 jet counts as 3 constituents and each W -tagged jet counts as 2. All other jets in the event are reconstructed with the Anti- k_T algorithm with a radius of 0.5 and are hence called AK5 jets. These jets are required to be at least $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.8$ away from the W and top-tagged jets where $\Delta\phi$ is the difference in azimuthal angle between the jets and $\Delta\eta$ is the difference in pseudorapidity ($\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$). Each AK5 jet counts as one constituent and so does each lepton with $p_T > 30$ GeV except for the two leptons used for the same-sign requirement. A minimum of 5 constituents is required at both 14 and 33 TeV.

The signal and background yields of this selection are shown in Table 2 and 3 respectively.

Table 2: Background yields for 300 fb^{-1} .

	14 TeV		33 TeV	
	50 Pileup	Pileup 140	Pileup 50	Pileup 140
Tribosons	0.53	0.96	1.45	3.56
Dibosons	3.66	6.94	6.24	17.37
$t\bar{t}$ +Boson	5.70	6.80	8.57	12.43
Sum	9.88	14.70	16.26	33.36

4 Discovery Potential

Based on the event yields of the above selection, the significance as a function of $T_{5/3}$ mass is computed at the various integrated luminosity, pileup and center-of-mass energy scenarios. In the absence of a signal, limits on the $T_{5/3}$ mass are also computed. In agreement with other Snowmass top-related searches, the systematic uncertainty on all of the backgrounds is assumed to be 20%. The significances and limits are shown in Table 4.

5 Mass Reconstruction

In the event that the $T_{5/3}$ is discovered, it can be distinguished from models with similar signatures by using the mass distribution of the $T_{5/3}$. The mass can be fully reconstructed when the decay of one quark in the $T_{5/3}\bar{T}_{5/3}$ pair is fully leptonic while the decay of the other is fully hadronic. The hadronic decays result in 2 partons from the W boson and 3 partons from the top quark. The reconstruction proceeds by reconstructing the Lorentz vectors of the W boson and top quark and then combining them to construct the $T_{5/3}$. If the event has W -tagged or top-tagged CA jets, these are assumed to be the corresponding particle. If there are not enough tagged CA jets to reconstruct the $T_{5/3}$, the missing particles are reconstructed using AK5 jets. A W boson reconstructed from AK5 jets must be within 20 GeV of the W mass whereas a top quark reconstructing using AK5 jets must be within 30 GeV of the top quark mass. If there are more top quark or W boson candidates in an event than necessary to reconstruct the $T_{5/3}$, the ones closest to the expected mass are used and the rest are discarded.

The selection used prior to the mass reconstruction is the same as the full event selection, but without the \cancel{E}_T and S_T requirements. Instead of the latter, the $T_{5/3}$ mass is required to be greater than the transverse mass of the two leptonic W bosons. The possible jet combinations in the preferred order of reconstruction are shown in Table 5. The distributions of the reconstructed mass at 14

Table 3: Signal yields for 300 fb⁻¹.

	14 TeV		33 TeV	
	50 Pileup	Pileup 140	Pileup 50	Pileup 140
700	270.47	293.83	870.72	951.17
800	222.80	240.15	648.39	791.04
900	164.38	169.71	533.27	708.37
1000	120.48	131.80	466.74	536.83
1100	83.65	95.69	389.30	527.08
1200	56.77	64.44	414.78	518.18
1300	36.84	43.05	282.59	386.26
1400	21.31	25.14	253.73	319.38
1500	13.29	15.89	194.14	255.87
1600	8.12	9.59	139.97	197.43
1700	4.71	5.72	101.48	151.23
1800	2.81	3.48	73.96	108.77
1900	1.76	2.12	60.33	82.41
2000	0.99	1.24	42.03	63.76
2100	0.63	0.74	33.49	49.09
2200	0.36	0.43	22.56	37.72
2300	-	-	19.99	27.87
2400	-	-	13.97	21.60
2500	-	-	10.20	14.82
2600	-	-	8.36	13.08
2700	-	-	6.07	8.71
2800	-	-	4.53	7.01
2900	-	-	3.23	5.35
3000	-	-	2.76	4.28

TeV with 50 and 140 pileup are shown in Figure 2. For $T_{5/3}$ masses accessible at 33 TeV, the W bosons and top quarks are boosted beyond the p_T range of current W and top tagging algorithms. Reconstruction of the $T_{5/3}$ at 33 TeV would make use of improved detectors and improved tagging algorithms as described in [13].

6 Conclusion

We have performed a feasibility study of searches for top partners with charge 5e/3 at the upgraded Large Hadron Collider. At 14 TeV, it is possible to discover such top partners with masses up to 1.6 TeV or exclude masses below 1.8 TeV. At 33 TeV, the discovery potential increases to 2.4 TeV and the exclusion grows to 2.8 TeV.

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Collider	Luminosity	Pileup	3σ evidence	5σ discovery	95% CL
LHC 14 TeV	300 fb ⁻¹	50	1.51 TeV	1.39 TeV	1.57 TeV
LHC 14 TeV	300 fb ⁻¹	140	1.50 TeV	1.38 TeV	1.58 TeV
LHC 14 TeV	3 ab ⁻¹	50	1.67 TeV	1.57 TeV	1.76 TeV
LHC 14 TeV	3 ab ⁻¹	140	1.66 TeV	1.55 TeV	1.76 TeV
LHC 33 TeV	300 fb ⁻¹	50	2.36 TeV	2.13 TeV	2.48 TeV
LHC 33 TeV	300 fb ⁻¹	140	2.17 TeV	2.15 TeV	2.47 TeV
LHC 33 TeV	3 ab ⁻¹	50	2.61 TeV	2.40 TeV	2.77 TeV
LHC 33 TeV	3 ab ⁻¹	140	2.50 TeV	2.35 TeV	2.69 TeV

Table 4: Expected mass sensitivity for charge 5/3 pair production with decay into tW .

Table 5: Possible jet combinations used to reconstruct the $T_{5/3}$ in the order of preference used for the reconstruction.

top-tagged jets	W-tagged jets	AK5 jets
1	1	0
1	0	2
0	2	1
0	1	3
0	0	5

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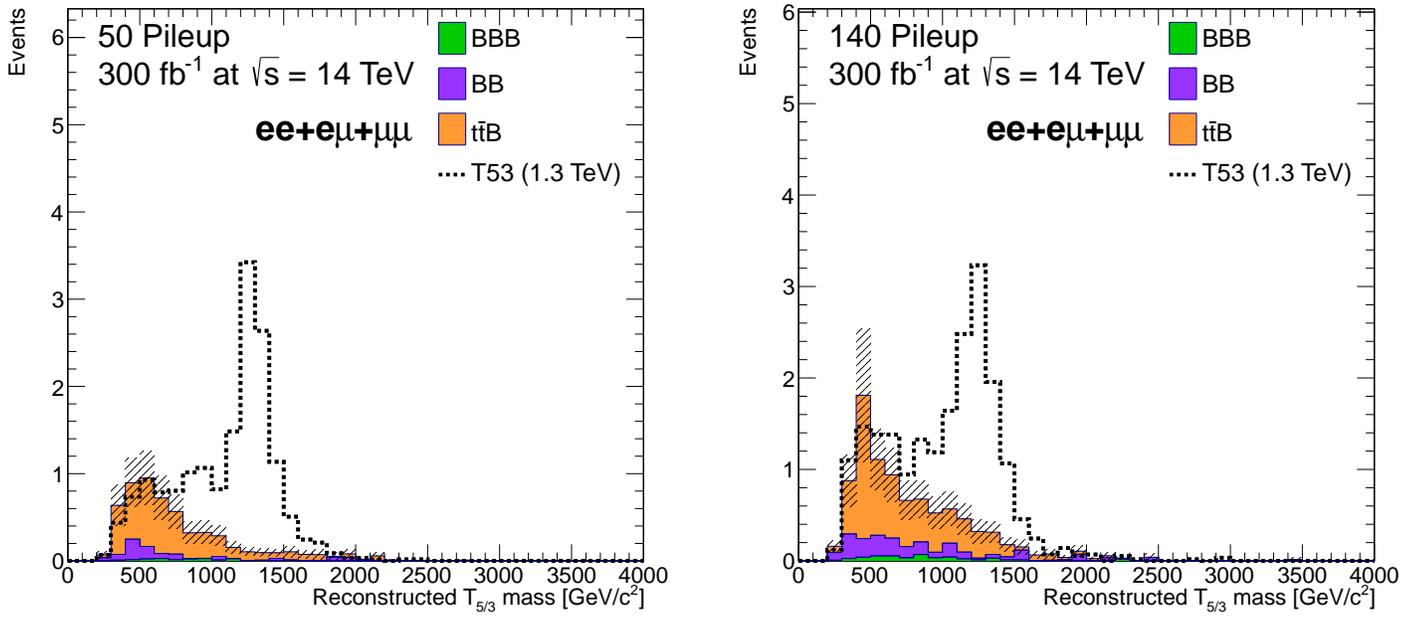


Figure 2: The reconstructed mass distribution at 14 TeV with 50 (left) and 140 (right) pileup.