Prospects for a Heavy Vector-Like Charge 2/3 Quark $T$ search at the LHC with $\sqrt{s} = 14$ TeV and 33 TeV
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Abstract We present the prospects for the discovery or exclusion of heavy vector-like charge 2/3 quarks, $T$, in proton-proton collisions at two center-of-mass energies, 14 and 33 TeV at the LHC. In this note, the pair production of $T$ quark and its antiparticle, with decays to $W$ boson and a $b$ quark ($Wb$), a top quark and the Higgs boson ($tH$), and a top quark and $Z$ boson ($tZ$) are investigated. Higgs boson decays to $bb$ and $W^+W^-$ final states are selected for this study.
I. INTRODUCTION

The standard model comprises of three generations of chiral quarks. Many theoretical extensions of physics beyond the standard model posit the existence of vector-like quarks. Such quarks occur in models like the Little Higgs, extra dimensions or the minimally supersymmetric standard model. These quarks have the same left and right quantum numbers. They could be an SU(2) singlet or a doublet with the same left and right couplings. This condition on the couplings makes the interactions of these quarks purely vector-like. We look at a minimal extension of the standard model by introducing a vector-like top-like (of charge 2/3) heavy quark that couples to the third generation \[1\]. The model we consider has only two parameters: the mass of the new heavy quark and the mixing with the third generation, parametrized as an angle (set to \(\arcsin 0.02\) during signal generation).

The non-chiral nature of these fermions makes considerations of anomaly cancellations redundant. Such vector-like fermions have been studied as part of the Little Higgs model where the new heavy fermion is introduced to cancel the Higgs mass quadratic divergence which results from the interaction with the top quark. We consider decays of the this heavy vector-like quark \(T\) into three possible decay modes: \(T \rightarrow bW\), \(T \rightarrow tH\) and \(T \rightarrow Z t\). In the asymptotic region, where the mass of \(T\) is large, the model decouples from the standard model and the decay modes are equally shared by the Goldstone modes following the principle of Goldstone equivalence. The decay topology of the the \(T\) quark leads to the presence of multiple \(W\) and \(Z\) bosons in the final state that produce leptons and multiple \(b\)-jets. The Higgs (at 125 GeV) is forced to decay into either \(b\bar{b}\) or \(W^+W^-\) since these are the modes that have the highest branching fraction and lead to final states that are sensitive to the analysis strategy.

II. SIGNAL AND BACKGROUND SAMPLES

The model for production and decay of the \(T\) quark signal samples is implemented using the MadGraph \[2\] event generator. The PYTHIA \[3\], Monte Carlo generator was used to perform parton fragmentation and hadronization of quarks and gluons. Forty eight samples (six decay modes and eight mass points) corresponding to values of the \(T\) mass from 500 to 1900 GeV were generated for the analysis at \(\sqrt{s} = 14\) TeV, while sixty samples between \(T\) mass of 700 to 3500 GeV were generated for the analysis at \(\sqrt{s} = 33\) TeV. The production cross section for \(T\) quark signal are calculated using HATHOR \[4\] and corresponds to an (approximate) next-to-leading order calculation. The dominant Standard Model (SM) background processes for this analysis are \(t\bar{t}, V + jets\), Drell Yan, \(W^+W^\pm\), WWW, \(tW\) and \(t\bar{t}Z\). These were simulated with MADGRAPH event generator as described in the snowmass SM background generation whitepaper \[5\] and PYTHIA is used to take care of the parton fragmentation and hadronization. The background cross sections were obtained from the snowmass twiki \[6\] and snowmass background whitepaper \[5\]. For both background and signal samples, the events were processed through the the Snowmass detector using the snowmass Delphes fast simulation and object reconstruction software \[7, 8\]. The large statistics background samples were generated using the Open Science Grid infrastructure for snowmass \[9\].

III. ANALYSIS STRATEGY

A. Single lepton Channels

For the “single lepton channel”, the study is performed in events in which one of the \(W\) bosons (originating either from the decay of the heavy quark, or from the subsequent decay of a top quark) decays leptonically, while the other bosons decay into quark-antiquark pairs. These events have a large number of jets originating from \(b\)-quarks and hadronic \(W, Z, or H\) boson decays. For large \(T\) masses it is likely that the jets from one or more boson decay are not resolved which gives rise to jets that have substructure and a large invariant mass. In particular, we use “top-tagging” and “W-tagging” variables. The jets from highly boosted top quarks and \(W/Z\) bosons are clustered using the Cambridge-Aachen algorithm \[12\] with a distance parameter
of $R=0.8$. We call jets that are consistent with originating from boosted $W$ or $Z$ boson decays as $W - jets$ and those consistent with a top quark as top-jets.

Selected events are required to have exactly one charged lepton (electron or muon) with $p_T > 30$ GeV, large missing transverse energy $MET > 20$ GeV, and at least three jets with $|\eta| < 2.5$ and $p_T > 200, 90, 50$ GeV. The dominant standard-model (SM) background is $t\bar{t}$ production that results in the same signature. Other SM background contributions include electroweak processes: $W +$ jets, $Z +$ jets, single top quark, and diboson production, as well as multijet events. These background processes are characterized by smaller lepton and jet transverse momenta and lower jet multiplicities than those in heavy quark decays.

The search for heavy quark is performed by classifying selected events based on the number of final-state jets.

- **3-jets**: $p_T^{jet1} > 200$ GeV, $p_T^{jet2} > 90$ GeV, and $p_T^{jet3} > 50$ GeV. At least one jet with being consistent with $W - jet$ is required. If there is $b$-jet in the event, the highest $p_T$ $b$-jet should have $p_T > 150$ GeV.

- **4-jets**: at least 4 jets with $p_T^{jet1} > 200$ GeV, $p_T^{jet2} > 90$ GeV, $p_T^{jet3} > 50$ GeV, and $p_T^{jet4} > 35$ GeV. If there is $b$-jet in the event, the highest $p_T$ $b$-jet should have $p_T > 150$ GeV.

These events are further subdivided into categories based on multiplicity of b-jets: (a) no b-jet, (b) 1 b-jet, (c) 2 b-jets, and (d) at least 3 b-jets. The analysis thus considers a total of sixteen channels split into the two leptonic final states which differ in their selection criteria. With the combination of electron and muon channels, we have eight different categories. For each of these categories, the scalar sum ($H_T$) of the transverse momenta of the jets is used to test for the presence of the signal.

- **$e + \mu$**: at least 3 jets with $p_T^{jet1} > 200$ GeV, $p_T^{jet2} > 90$ GeV, and $p_T^{jet3} > 50$ GeV. At least one jet with being consistent with $W - jet$ is required. These events are further subdivided into four categories:
  - $e + \mu_3, 0b$: No b-jet in the event.
  - $e + \mu_3, 1b$: One b-jet in the event.
  - $e + \mu_3, 2b$: Two b-jets in the event.
  - $e + \mu_3, 3b$: $\geq$ 3 b-jets in the event.

- **$e + \mu$**: at least 4 jets with $p_T^{jet1} > 200$ GeV, $p_T^{jet2} > 90$ GeV, $p_T^{jet3} > 50$ GeV, and $p_T^{jet4} > 35$ GeV, but no jet consistent with being a $W$-jet. These events are further subdivided into four categories:
  - $e + \mu_4, 0b$: No b-jet in the event.
  - $e + \mu_4, 1b$: One b-jet in the event.
  - $e + \mu_4, 2b$: Two b-jets in the event.
  - $e + \mu_4, 3b$: $\geq$ 3 b-jets in the event.

The above mentioned event selections are valid for the 14 TeV analysis. The analysis based on $\sqrt{s} = 33$ TeV employs similar strategy with some of the object selections optimized for better signal versus background discrimination. The 33 TeV analysis uses significantly tighter selections on the jet kinematics and missing transverse energy. The selections which are different from the 14 TeV analysis are the following.

- $p_T^{jet1} > 350$ GeV, $p_T^{jet2} > 200$ GeV
- In the presence of $b$-tagged jet(s) in the event, the highest $p_T$ $b$-jet should have $p_T > 200$ GeV
- Missing transverse energy $> 75$ GeV
B. Multi-lepton Channels

We look at final states that contain at least two leptons in four mutually exclusive event categories (defined later in the section).

In order to suppress backgrounds from SM processes, and enhance the signal discrimination power, we use a few kinematic variables, defined as follows:

- \( H_T \): is defined as the scalar sum of the transverse momenta of all the selected AK5 jets.
- \( S_T \): is the scalar sum of the \( H_T \), leptons and missing transverse energy.
- \( \text{minM}_{lb} \): is the minimum invariant mass of a lepton and a b-jet and sensitive to the mass of the \( T \) quark.

In addition, we use jet substructure variables to enhance the signal yield. In the following sections, we use the phrase jet-constituent to designate the number of constituents from any given jet. Therefore, an AK5 jet (a jet clustered using the anti-\( K_T \) algorithm with a distance parameter, \( R \) of 0.5) has one constituent and a “W-jet” has two constituents while a “top-jet” has three constituents. Our selection criteria involves the requirement of a minimum number of jet constituents, instead of requiring a certain number of independent AK5 or \( W \)-tagged or a top-tagged jet.

The details of the selection criteria for each category are given below.

- Opposite signed (OS) leptons: Here we require specifically two leptons with an opposite sign. The major irreducible background is from \( t \bar{t} \) and Drell-Yan processes. In this channel, we further sub-divide final states into two categories:
  - OS23: This category is constructed to be solely sensitive to the \( TT \rightarrow bWbW \) mode. In this category, we require 2 or 3 jets constituents, veto on events within the Z-boson mass window and require at least 1 b-tagged jet. In addition to the above requirements, we make additional restrictive cuts on the following event variables: \( S_T \), \( H_T \), and \( \text{minM}_{lb} \) which is sensitive to the mass of the \( T \) quark. We require \( \text{minM}_{lb} > 180 \text{ GeV} \), \( H_T > 700 \text{ GeV} \) and \( S_T > 900 \text{ GeV} \).
  - OS5+: This category is constructed to be sensitive to modes that have multiple jets in the final state (from \( T \rightarrow tH \) decay modes). We do not require a Z-boson mass veto in this category so as to be sensitive to final states that arise from \( T \rightarrow tZ \) decays. We require at least two b-tagged jets and a minimum of 5 jet constituents in this category to minimize the Drell-Yan background. We find that the variables that give us the best discriminating power between signal and background are \( H_T \) and \( S_T \). We require \( H_T > 900 \text{ GeV} \) and \( S_T > 1000 \text{ GeV} \).

- Same signed (SS) leptons: Here we specifically require two leptons with the same sign. The dominant background in this channel is from fake leptons that arise due to misidentification of jets as leptons. CMS searches at 7TeV and 8TeV show that these instrumental backgrounds are non-negligible and in fact are the dominant backgrounds in this channel \[10,11\]. Other sources of same signed leptons are from rare standard model processes like \( t \bar{t}Z \), \( t \bar{t}W \), diboson and triboson processes. In this category, we require, at least one btagged jet, missing \( E_T > 30 \text{ GeV} \) and a minimum of 2 jet constituents. We further make stringent requirements on \( H_T \) and \( S_T \). We require \( H_T > 600 \text{ GeV} \) and \( S_T > 800 \text{ GeV} \).

- Multi-leptons: Here we specifically require three or more leptons. The dominant backgrounds are standard model processes that lead to three-lepton final states, such as diboson decays and contributions from fake leptons. We require at least one b-tagged jet, missing \( E_T >30 \text{ GeV} \) and a minimum of 2 jet constituents. We put harsh requirements on \( H_T \) and \( S_T \) in this category as well. We require \( H_T > 800 \text{ GeV} \) and \( S_T > 900 \text{ GeV} \).

Since these studies are solely based on simulated events, we do not account for instrumental backgrounds at this stage. The backgrounds estimated for an analysis carried out at 8TeV \[11\] could, in principle, be scaled
but the pitfall associated with such a scaling is that it is not a good indicator of the relative contribution of
the background, given that different sets of cuts were applied at different center of mass energies.

The cuts in each category were optimized by computing Signal/$\sqrt{\text{Background}}$ and calculating efficiencies
for particular sets of cuts and comparing these efficiencies to the published results at 8TeV [11].

In the multilepton channel, the following changes were made to optimize the analysis for $\sqrt{s}=33$ TeV:

- OS23: In the OS23 category, the 4 constituent bin is used. We require $\text{minM}_{lb}>220$ GeV, $H_T>1000$
  and $S_T>1200$ GeV.
- OS5+: Here $H_T$ and $S_T$ are set to 1800 GeV and 2000 GeV respectively.
- SS: We require $H_T>900$ GeV and $S_T>1000$ GeV.
- Multi-leptons: We require $H_T>900$ GeV and $S_T>1000$ GeV.

**IV. EVENT YIELDS AT $\sqrt{s}=14$ TeV**

- **Single-lepton Channels** Table I shows expected signal and background event yields determined
  assuming an integrated luminosity of 300 fb$^{-1}$ of data at $\sqrt{s}=14$ TeV and no additional pileup events
  for the different event categories. The background contributions from different electroweak processes are
  combined into a single background category. In tables II and III the expected signal and background
  yields for two different run scenarios are quoted: (a) 300 fb$^{-1}$ with an average $<\mu_{PU}>$ of 50 additional
  pileup interactions per crossing (LHC run 2, Phase 2) and (b) 3000 fb$^{-1}$ with an average $<\mu_{PU}>$ of
  140 additional pileup interactions per crossing (HL-LHC).
- **Multiple-lepton channels** In table V the expected signal and background event yields are tabulated,
  for the different event categories, assuming an integrated luminosity of 300 fb$^{-1}$ of data accumulated at
  $\sqrt{s}=14$ TeV and no additional pileup events. In tables VI and VII the expected signal and background
  yields for two different run scenarios: (a) LHC run 2, Phase 2, with 300 fb$^{-1}$ dataset and $<\mu_{PU}>=50$,
  and (b) HL-LHC with 3000 fb$^{-1}$ dataset with $<\mu_{PU}>=140$. The background events are summed
  and reflect the contribution of various backgrounds in the different event categories as described in
  Section III B.

| Mass (GeV) | $e^+\mu^+\nu\bar{\nu}$ ($e^3\mu^3,0$) | $e^+\mu^+\nu\bar{\nu}$ ($e^3\mu^3,1$) | $e^+\mu^+\nu\bar{\nu}$ ($e^3\mu^3,2$) | $e^+\mu^+\nu\bar{\nu}$ ($e^3\mu^3,3$) | $e^+\mu^+\nu\bar{\nu}$ ($e^4\mu^4,0$) | $e^+\mu^+\nu\bar{\nu}$ ($e^4\mu^4,1$) | $e^+\mu^+\nu\bar{\nu}$ ($e^4\mu^4,2$) | $e^+\mu^+\nu\bar{\nu}$ ($e^4\mu^4,3$) |
|-----------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 500       | 4709                                | 9809                                | 11419                               | 4901                                | 11828                               | 26439                               | 34885                               | 16800                               |
| 700       | 1295                                | 3333                                | 4168                                | 1857                                | 1520                                | 4074                                | 5579                                | 3148                                |
| 900       | 329.6                               | 1016                                | 1246                                | 586                                 | 249                                 | 757                                 | 1036                                | 568                                 |
| 1100      | 92.0                                | 301                                 | 376                                 | 173.4                               | 54.1                                | 183                                 | 241                                 | 127                                 |
| 1300      | 27.7                                | 95.6                                | 120.5                               | 53.7                                | 15.2                                | 51.6                                | 69.0                                 | 34.7                                 |
| 1500      | 9.03                                | 31.1                                | 39.0                                | 16.9                                | 4.5                                 | 16.9                                | 22.4                                 | 10.6                                 |
| 1700      | 2.89                                | 10.4                                | 13.1                                | 5.66                                | 1.67                                | 6.21                                | 8.02                                 | 3.73                                 |
| 1900      | 0.99                                | 3.62                                | 4.49                                | 1.94                                | 0.63                                | 2.34                                | 2.98                                 | 1.35                                 |

| Mass (GeV) | $\tau\tau$ | $\ell\ell$ | $\ell\ell$ | $\ell\ell$ |
|------------|-------------|-------------|-------------|-------------|
| 500        | 69251       | 84075       | 72516       | 11219       |
| 700        | 146485      | 16193       | 2581        | 161         |
| 900        | 215736      | 100268      | 75097       | 11380       |

| Mass (GeV) | $t\bar{t}$ | Electroweak | Total Background |
|------------|-------------|-------------|------------------|
| 500        | 69251       | 146485      | 215736          |
| 700        | 84075       | 16193       | 100268          |
| 900        | 72516       | 2581        | 75097           |
| 1100       | 11219       | 161         | 11380           |
| 1300       | 418164      | 1104532     | 1522696         |
| 1500       | 375164      | 80507       | 455671          |
| 1700       | 331133      | 15173       | 346306          |
| 1900       | 52361       | 1236        | 53597           |

**TABLE I** Number of expected signal and background events for 300 fb$^{-1}$ of pp collisions at 14 TeV for
$<\mu_{PU}>=0$ in different event categories.
### TABLE II: Number of expected signal events for 300 fb$^{-1}$ of pp collisions at 14 TeV for $<\mu_{PU}>$=50 in different event categories.

| Mass (GeV) | $e^{3+}\mu^{3,0}$ | $e^{3+}\mu^{3,1}$ | $e^{3+}\mu^{3,2}$ | $e^{3+}\mu^{3,3}$ | $e^{4+}\mu^{4,0}$ | $e^{4+}\mu^{4,1}$ | $e^{4+}\mu^{4,2}$ | $e^{4+}\mu^{4,3}$ |
|-----------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 500       | 4908             | 10400            | 12532            | 5204             | 11450            | 26134            | 33489            | 16010            |
| 700       | 1293             | 3484             | 4291             | 1938             | 1568             | 4079             | 5458             | 3024             |
| 900       | 340.4            | 1014             | 1273             | 587              | 246              | 773              | 1011             | 559              |
| 1100      | 92.8             | 304              | 380              | 174.3            | 57.6             | 181              | 238              | 127              |
| 1300      | 28.6             | 96.2             | 120.8            | 54.0             | 15.6             | 53.5             | 68.5             | 35.1             |
| 1500      | 8.92             | 31.4             | 39.0             | 17.3             | 4.99             | 17.5             | 22.6             | 10.9             |
| 1700      | 2.89             | 10.6             | 13.2             | 5.78             | 1.77             | 6.39             | 8.31             | 3.72             |
| 1900      | 1.01             | 3.63             | 4.53             | 1.96             | 0.64             | 2.42             | 3.14             | 1.39             |

### TABLE III: Number of expected signal events for 3000 fb$^{-1}$ of pp collisions at 14 TeV for $<\mu_{PU}>$=140 in different event categories.

| Mass (GeV) | $e^{3+}\mu^{3,0}$ | $e^{3+}\mu^{3,1}$ | $e^{3+}\mu^{3,2}$ | $e^{3+}\mu^{3,3}$ | $e^{4+}\mu^{4,0}$ | $e^{4+}\mu^{4,1}$ | $e^{4+}\mu^{4,2}$ | $e^{4+}\mu^{4,3}$ |
|-----------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 500       | 67927            | 143746           | 166297           | 69421            | 102273           | 235739           | 288660           | 118514           |
| 700       | 16281            | 41406            | 49359            | 22018            | 15007            | 38205            | 47904            | 24971            |
| 900       | 3830             | 11370            | 13987            | 6356             | 2541             | 7428             | 9617             | 4786             |
| 1100      | 1050             | 3325             | 4025             | 1878             | 549              | 1856             | 2362             | 1150             |
| 1300      | 313              | 1044             | 1248             | 554              | 167              | 562              | 708              | 330              |
| 1500      | 100              | 332              | 408              | 176              | 52.1             | 188              | 239              | 105              |
| 1700      | 32.2             | 112              | 138              | 58.5             | 19.0             | 70.2             | 88               | 37.6             |
| 1900      | 10.5             | 38.5             | 47.4             | 20.1             | 7.31             | 27.3             | 34.0             | 14.1             |

### V. EXPECTED SIGNIFICANCE AND EXCLUSION LIMITS

The signal significance and exclusion limits were computed using a Bayesian approach with the “theta statistical analysis package” [13]. For the single lepton channel, the signal significance and exclusion limits were computed using 16 independent categories, to account for eight classifications based on $H_T$ and number of bjets, and two channels ($e$+jets and $\mu$+jets). The signal significance and exclusion limits for the multilepton channels were computed using a 12 binned histogram, as there are four categories (OS23, OS5+, SS, and trileptons) each for the three channels (eee, $e\mu$ + $ee\mu$ and $\mu\mu\mu$). The final combined limits and signal significances as a function of the expected luminosity and pileup scenarios were also computed. The mutually exclusive categories constructed in the lepton+jets channel and the multi-lepton channel were used to obtain the combined significance and exclusion limits. The lepton+jets templates and the multi-lepton templates were fed as independent models to “theta”.

TABLE II: Number of expected signal events for 300 fb$^{-1}$ of pp collisions at 14 TeV for $<\mu_{PU}>$=50 in different event categories.

TABLE III: Number of expected signal events for 3000 fb$^{-1}$ of pp collisions at 14 TeV for $<\mu_{PU}>$=140 in different event categories.
### TABLE IV: Number of expected signal events for 3000 fb$^{-1}$ of pp collisions at 33 TeV for $<\mu_{PU}>$=140 in different event categories.

| Mass (GeV) | $c3 + \mu3.0b$ | $c3 + \mu3.1b$ | $c3 + \mu3.2b$ | $c3 + \mu3.3b$ | $c4 + \mu4.0b$ | $c4 + \mu4.1b$ | $c4 + \mu4.2b$ | $c4 + \mu4.3b$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 500        | 148256          | 369044          | 444898          | 185027          | 78789           | 235132          | 285382          | 115089          |
| 700        | 1773            | 5922            | 7046            | 2928            | 1189            | 4036            | 4907            | 2048            |
| 900        | 810             | 2846            | 3344            | 1401            | 651             | 2153            | 2694            | 1064            |
| 1100       | 410             | 1383            | 1646            | 708             | 337             | 1246            | 1534            | 618             |
| 1300       | 198             | 713             | 849             | 364             | 199             | 730             | 900             | 345             |
| 1500       | 103             | 371             | 451             | 192             | 117             | 428             | 538             | 210             |
| 1700       | 53.7            | 200             | 239             | 103             | 71.3            | 265             | 327             | 127             |
| 1900       | 16.0            | 62.0            | 75.3            | 33.6            | 26.3            | 103             | 128             | 49.0            |
| 2100       | 9.4             | 35.3            | 43.3            | 19.3            | 17.0            | 64.3            | 80.9            | 30.9            |
| 2300       | 5.5             | 20.5            | 25.3            | 11.3            | 10.5            | 41.8            | 52.2            | 19.8            |

### TABLE V: Number of expected signal and background events for 300 fb$^{-1}$ of pp collisions at 14 TeV in different event categories for $<\mu_{PU}>$=0 pileup scenario.

| Mass (GeV) | OS23 | OS5+ | SS | Multi-leptons ($\geq3$) |
|------------|------|------|----|------------------------|
| 500        | 691.8| 1311.6| 772.6| 629.3                  |
| 700        | 323.5| 576.9| 213.1| 242.5                  |
| 900        | 143.3| 170.6| 50.6 | 87.4                   |
| 1100       | 54.0 | 47.8 | 12.3 | 27.6                   |
| 1300       | 19.9 | 13.7 | 3.3  | 7.8                    |
| 1500       | 7.0  | 4.1  | 1.0  | 2.2                    |
| 1700       | 2.6  | 1.2  | 0.3  | 0.7                    |
| 1900       | 9.8  | 0.4  | 0.1  | 0.2                    |
| Total Background | 197.5 | 1467.1 | 399.7 | 67.4                  |

### TABLE VI: Number of expected signal and background events for 300 fb$^{-1}$ of pp collisions at 14 TeV in different event categories for $<\mu_{PU}>$=50 pileup scenario.

| Mass (GeV) | OS23 | OS5+ | SS | Multi-leptons ($\geq3$) |
|------------|------|------|----|------------------------|
| 500        | 629.3| 1857.8| 911.6| 640.8                  |
| 700        | 243.4| 780.6| 228.9| 242.8                  |
| 900        | 119.9| 232.1| 53.7 | 86.7                   |
| 1100       | 46.4 | 63.8 | 14.4 | 26.5                   |
| 1300       | 17.1 | 18.2 | 3.7  | 7.6                    |
| 1500       | 5.8  | 5.4  | 1.2  | 2.3                    |
| 1700       | 2.1  | 1.7  | 0.4  | 0.7                    |
| 1900       | 8.3  | 0.6  | 0.1  | 0.2                    |
| Total Background | 235.3 | 1804.0 | 421.2 | 69.4                  |
TABLE VII: Number of expected signal and background events for 3000 fb$^{-1}$ of pp collisions at 14 TeV in different event categories for $<\mu_{PU}>$=140 pileup scenario.

| Mass (GeV) | OS23 | OS5+ | SS | Multi-leptons ($\geq 3$) |
|------------|------|------|----|--------------------------|
| 500        | 3622.5 | 19168.6 | 10348.1 | 6005.0 |
| 700        | 1738.9 | 8619.7 | 2716.8 | 2381.7 |
| 900        | 777.5  | 2875.6 | 665.8  | 881.8  |
| 1100       | 297.5  | 867.2  | 168.1  | 275.7  |
| 1300       | 109.1  | 256.5  | 46.8   | 78.9   |
| 1500       | 38.4   | 79.3   | 14.8   | 22.7   |
| 1700       | 14.7   | 25.9   | 4.8    | 6.9    |
| 1900       | 5.6    | 8.7    | 1.7    | 2.2    |
| **Total Background** | 1378.6 | 23473.7 | 4403.2 | 691.4 |

TABLE VIII: Number of expected signal and background events for 3000 fb$^{-1}$ of pp collisions at 33 TeV in different event categories for $<\mu_{PU}>$=140 pileup scenario.

| Mass (GeV) | OS23 | OS5+ | SS | Multi-leptons ($\geq 3$) |
|------------|------|------|----|--------------------------|
| 700        | 17451.9 | 12970.1 | 17225.9 | 30396.1 |
| 1700       | 1022.0  | 1033.7 | 257.2  | 352.0  |
| 1900       | 552.6   | 532.4  | 125.8  | 154.0  |
| 2100       | 320.7   | 386.6  | 81.4   | 99.7   |
| 2300       | 171.0   | 157.4  | 34.8   | 30.5   |
| 2500       | 97.5    | 88.7   | 19.5   | 17.5   |
| 2700       | 54.5    | 50.5   | 11.4   | 8.6    |
| 3100       | 20.5    | 17.8   | 4.4    | 2.3    |
| 3300       | 12.4    | 10.5   | 2.3    | 1.3    |
| 3500       | 8.0     | 6.6    | 1.4    | 0.7    |
| **Total Background** | 7154.6 | 30150.3 | 13655.9 | 6400.4 |

A. $\sqrt{s}$=14 TeV

Figures 1, 2, and 3 show the expected 95% C.L. limit, the $5\sigma$ and $3\sigma$ discovery reaches respectively for $\sqrt{s}$=14 TeV.

FIG. 1: Expected 95% C.L. limits for $T$ quark pair production in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right).
FIG. 2: Expected sensitivity for a $5\sigma$ $T$ quark pair production signal in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right).

FIG. 3: Expected sensitivity for a $3\sigma$ $T$ quark pair production signal in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right).
B. $\sqrt{s}=33$ TeV

Figures 4, 5 and 6 show the expected 95% C.L. limit, the $5\sigma$ and $3\sigma$ discovery reaches respectively for $\sqrt{s}=33$ TeV.

FIG. 4: Expected 95% C.L. limits for $T$ quark pair production in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right) for $\sqrt{s}=33$ TeV.

FIG. 5: Expected sensitivity for a $5\sigma$ $T$ quark pair production signal in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right) for $\sqrt{s}=33$ TeV.

FIG. 6: Expected sensitivity for a $3\sigma$ $T$ quark pair production signal in the the $l+$ jets channel (left), multilepton channel (middle) and combined (right) for $\sqrt{s}=33$ TeV.

In table IX, the expected mass sensitivity is summarized. The expected 95% C.L. limit, the $5\sigma$ and $3\sigma$ discovery reaches for both $\sqrt{s}=14$ and 33 TeV LHC runs are listed.
| Collider     | Luminosity | Pileup | 3σ evidence | 5σ discovery | 95% CL  |
|--------------|------------|--------|--------------|--------------|---------|
| **Single lepton+jets** |            |        |              |              |         |
| LHC 14 TeV   | 300 fb⁻¹   | 0      | 1280 GeV    | 1150 GeV     | 1390 GeV |
| LHC 14 TeV   | 300 fb⁻¹   | 50     | 1260 GeV    | 1140 GeV     | 1410 GeV |
| LHC 14 TeV   | 3 ab⁻¹     | 140    | 1560 GeV    | 1430 GeV     | 1730 GeV |
| **Multi-lepton analyses** |        |        |              |              |         |
| LHC 14 TeV   | 300 fb⁻¹   | 0      | 1350 GeV    | 1225 GeV     | 1450 GeV |
| LHC 14 TeV   | 300 fb⁻¹   | 50     | 1340 GeV    | 1200 GeV     | 1420 GeV |
| LHC 14 TeV   | 3 ab⁻¹     | 140    | 1475 GeV    | 1375 GeV     | 1575 GeV |
| **Combination of single lepton+jets and multi-lepton analyses** |        |        |              |              |         |
| LHC 14 TeV   | 300 fb⁻¹   | 0      | 1410 GeV    | 1300 GeV     | 1525 GeV |
| LHC 14 TeV   | 300 fb⁻¹   | 50     | 1415 GeV    | 1300 GeV     | 1525 GeV |
| LHC 14 TeV   | 3 ab⁻¹     | 140    | 1620 GeV    | 1525 GeV     | 1780 GeV |
| **Single lepton+jets** |            |        |              |              |         |
| LHC 33 TeV   | 3 ab⁻¹     | 140    | 2800 GeV    | 2420 GeV     | 3200 GeV |
| **Multi-lepton analyses** |        |        |              |              |         |
| LHC 33 TeV   | 3 ab⁻¹     | 140    | 2450 GeV    | 2250 GeV     | 2600 GeV |
| **Combination of single lepton+jets and multi-lepton analyses** |        |        |              |              |         |
| LHC 33 TeV   | 3 ab⁻¹     | 140    | 2900 GeV    | 2600 GeV     | 3400 GeV |

TABLE IX: Expected mass sensitivity for a top-partner $T$ pair production in the lepton + jets and multi-lepton signatures for all three decay modes $bW$, $tH$ and $Zt$. 
VI. DISTRIBUTIONS ($\sqrt{s} = 14$ TeV)

FIG. 7: Distributions of leading electron, leading b-jet, b-jet multiplicity and W-jet multiplicity in the $l+$jets channel.
FIG. 8: Distributions of $H_T$ in different event categories with $l^+ \geq 3$ jets with 1 $W$-jet and 0 b-jet (top left), 1 b-jet (top right), 2 b-jet (bottom left) and at least 3 b-jets (bottom right).
FIG. 9: Distributions of $H_T$ in different event categories with $l^+ \geq 4$ jets with no $W$-jet and 0 b-jet (top left), 1 b-jet (top right), 2 b-jet (bottom left) and at least 3 b-jets (bottom right).
FIG. 10: Distributions of $H_T$, $\text{min}M_{f\bar{f}}$, $S_T$ and the number of jet constituents for the OS category. The signal is scaled by 5000.
FIG. 11: Distributions of $H_T$, $S_T$ and the number of jet constituents for the SS category. The signal is scaled by 5000.

FIG. 12: Distributions for $H_T$, $S_T$ and the number of jet constituents for events with $\geq 3$ leptons. The signal is scaled by 5000.
VII. DISTRIBUTIONS ($\sqrt{s}=33$ TeV)

FIG. 13: Distributions of leading electron, leading b-jet, b-jet multiplicity and W-jet multiplicity in the $l+$jets channel.
FIG. 14: Distributions of $H_T$ in different event categories with $l^+ \geq 3$ jets with 1 $W -$jet and 0 b-jet (top left), 1 b-jet (top right), 2 b-jet (bottom left) and at least 3 b-jets (bottom right).
FIG. 15: Distributions of $H_T$ in different event categories with $l+\geq 4$ jets with no $W$-jet and 0 b-jet (top left), 1 b-jet (top right), 2 b-jet (bottom left) and at least 3 b-jets (bottom right) .
FIG. 16: Distributions of $H_T$, $\min M_{fb}$, $S_T$ and the number of jet constituents for the OS category. The signal is scaled by 5000.
FIG. 17: Distributions of $H_T$, $S_T$ and the number of jet constituents for the SS category. The signal is scaled by 5000.

FIG. 18: Distributions for $H_T$, $S_T$ and the number of jet constituents for events with $\geq 3$ leptons. The signal is scaled by 5000.
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