Estimated Sensitivity for New Particle Searches at the HL-LHC

The CMS Collaboration

Abstract

Sensitivity projections for new physics searches with 3000 fb$^{-1}$ of data anticipated at the high-luminosity LHC (HL-LHC) are presented. These results were obtained from dedicated studies performed for the ECFA 2016 upgrade workshop. Projections for heavy vector bosons ($Z'$ and $W'$) decays containing top quarks are obtained by extrapolating Run-2 results assuming scenarios with varying systematic uncertainties. Results for the dark matter and weak production of single vector-like quark searches are obtained by implementing detector performance specifications from the CMS Phase-2 technical proposal in the DELPHES simulation package.
1 Introduction

The High Luminosity LHC (HL-LHC) run, which is due to start in 2025, is expected to collect an integrated luminosity of approximately 3000 fb$^{-1}$ at $\sqrt{s} = 14$ TeV. During the entire operation prior to this run, a dataset of only 10% of this size is expected, namely 300 fb$^{-1}$. The discovery and study of physics beyond the standard model will remain one of the major goals of the CMS collaboration during the HL period. Such physics can yield exotic signatures, the observation of which will require high demands on the performance and capabilities of the detector. For a few selected physics models, we present studies of potential for new physics using CMS data during the HL-LHC run. The goal of these studies is to estimate the sensitivity for key channels at the HL-LHC either via a projection from $\sqrt{s} = 13$ TeV analyses or via dedicated studies. This document summarizes new physics studies performed in preparation for the ECFA 2016 HL-LHC workshop in October 2016 [1] complementing similar high luminosity studies for the Higgs sector [2] and for standard model processes [3].

Two of these searches, $W' \rightarrow tb$ and $Z' \rightarrow t\bar{t}$, are projections extrapolated from current searches. These projections are based on present 2015/2016 $\sqrt{s}$=13 TeV analyses, referred to as Run-2 baseline analyses. Signal and background samples are taken from the corresponding 2015/2016 analysis and scaled to $\sqrt{s}$=14 TeV by the ratio of their production cross sections at 13 and 14 TeV. The sensitivity after accumulating 3000 fb$^{-1}$ is estimated in terms of discovery potential and in terms of exclusion at the 95% confidence level (C.L.). The impact of systematic uncertainties is studied by considering different scenarios with the two extreme cases: (1) no improvement, keeping the systematic uncertainties at their Run-2 levels, (2) all systematics assumed to be negligible, corresponding to the detection limit. Systematic uncertainties have theoretical and experimental origins. For the former, improvements from higher order calculations are expected but hard to quantify at this time. On the experimental side, the Phase-2 detector will have better performance while pileup conditions will be much more severe. Uncertainties related to data-driven methods will decrease with larger datasets. Such considerations also apply to measurements of cross sections, lepton and trigger efficiencies, jet energy and tagging performances.

A second class of analyses simulates aspects of the upgraded CMS detector based on the documentation in the CMS Phase-2 Technical Proposal [4]. The studies target the physics reach with 3000 fb$^{-1}$ but now include a parameterization of the expected detector performance. Different systematic scenarios are investigated using reasonable assumptions regarding their improvements in the future. More analyses of this type, including the Phase-2 detector performance, were performed previously [5], e.g. $W' \rightarrow ev$ and $Z' \rightarrow ee$, mono-$W$ dark matter, heavy stable charged particles (HSCP) and long-lived signatures. The following two searches include detector performance in the parametrized detector simulation package DELPHES [6], dark matter (DM) in the jet+MET final state and single vector-like quarks (VLQ) in the $T \rightarrow tH$ channel.

This document is organized as follows. Sections 3 and 4 contain the projections for the heavy vector bosons ($Z'$ and $W'$) in decay channels with top quarks. Both projections are based on Run-2 results and take into account the impact of different scenarios for systematic uncertainties. Sections 5 and 6 follow with the summaries of upgrade analyses using the parametrized simulation package DELPHES with a performance parameterization according to the CMS Phase-2 Technical Proposal.

2 The CMS Phase-2 upgrade

In the Phase-2 CMS Technical Proposal [4], the performance of the CMS Phase-1 detector under the conditions of HL-LHC has been studied, considering the higher instantaneous luminosities leading to high pileup (PU) and high radiation levels. These studies show that the tracker and
the endcap calorimetry will need to be replaced for Phase-2. With these changes, the performance issues due to high PU that are expected to be most pronounced in the inner and forward detector regions can be addressed. The new tracker and pixel vertex detector will have an extended forward acceptance. New endcap calorimeter detectors have higher segmentation and improve the energy resolution measurement. Additional improvements are foreseen for barrel calorimeters where the readout will be upgraded along with the electronics to handle higher event rates and larger trigger latencies which are necessary to accommodate the new track trigger. The forward muon system will be augmented with additional detectors in the region $|\eta| > 2.1$ which is the only region in the Phase-1 muon system without redundancy.

The performance parameters of this Phase-2 upgraded detector has been studied with simulations and is also documented in the “Technical Proposal for the Phase-2 Upgrade of the CMS Detector” [4]. Performance studies are not described in this document, which concentrates on physics sensitivity with the 3000 fb$^{-1}$ of HL-LHC data. These performance studies do provide the input for the parameterized detector simulation based on DELPHES (version 3.3.16) [6] which is used in the simulation for the mono-X and VLQ search projections.

The SM background samples are based on samples generated for Snowmass [7] with the generator information being reprocessed through the DELPHES version mentioned above. Dedicated trigger studies were not performed for these sensitivity estimates.

## 3 Sensitivity projections for $W' \rightarrow tb$ in leptonic final states

Many SM extensions require additional heavy gauge bosons. For example, the sequential standard model (SSM) [8] predicts the existence of a new massive charged boson, $W'$, exhibiting the same couplings as the SM W boson with the additional decay channel $W' \rightarrow tb$ opening up if the new boson is sufficiently massive. The benchmark analysis with maximum discovery sensitivity is the decay to a single lepton ($\ell = e, \mu$) and neutrino. In a scenario where a right-handed $\nu_R$ is heavier than a right-handed $W'_R$ boson, the decay to leptons is forbidden, leaving only the $tb$ final state open for discovery.

The projection in this section is based on an analysis performed with 12.9 fb$^{-1}$ collected in 2016 at $\sqrt{s}=13$ TeV [9] and is referred to as the “baseline analysis”. The analysis uses leptonic W boson decays, like $W'_R \rightarrow t(\rightarrow W(\ell \nu) + b)b$ with $\ell = e, \mu$. In this final state, we perform the search in four event categories in terms of lepton ($\ell = e, \mu$) and the number of b-tagged jets $N_{b\text{-tags}}$:

- electron plus one b-tagged jet, labeled “e+jets $N_{b\text{-tags}}=1$”
- electron plus two b-tagged jets, labeled “e+jets $N_{b\text{-tags}}=2$”
- muon plus one b-tagged jet, labeled “$\mu$+jets $N_{b\text{-tags}}=1$”
- muon plus two b-tagged jets, labeled “$\mu$+jets $N_{b\text{-tags}}=2$”

The simulated samples from the baseline analysis are scaled to the cross sections at 14 TeV. Details of the analysis strategy itself can be found in [9], while this note contains information relevant to the procedure used to extrapolate from 12.9 fb$^{-1}$ at $\sqrt{s}=13$ TeV to a projection for 3000 fb$^{-1}$ at $\sqrt{s}=14$ TeV.

### 3.1 Extrapolation details

The signal and background simulation is identical to the one used in the baseline analysis from 2016 [9] and scaled to $\sqrt{s}=14$ TeV by their cross section ratio. For signal samples, a ded-
icated calculation of the 14 TeV cross sections for all signal masses of interest was performed using CompHEP (the same generator used for the 13 TeV samples). The resulting signal scaling factors are a function of the boson mass, and range from 1.16 for $m(W'_R) = 1$ TeV to 1.48 for $m(W'_R) = 4$ TeV. The lower limit of $m(W'_R) = 1$ TeV is driven by the trigger thresholds. For the projection studies, additional mass points from 3.1 to 4 TeV in 100 GeV steps are included in order to better understand the analysis behavior in the region of interest for the projected luminosities. No correction is made for shape differences which may arise at 14 TeV from a slightly lower off-shell component.

The backgrounds are taken from simulation for this analysis, and then the modeling is checked in dedicated control regions enriched in the dominant background processes. For each background source extrapolations for the sample cross sections from 13 to 14 TeV are performed depending on the sample. All objects and efficiencies are similar to the baseline analysis.

### 3.2 Event selection and resulting distributions

The four search categories have been defined in Sec. 3.1. The discriminating variable is the invariant $tb$ mass, $M(tb)$, reconstructed the following way: we first reconstruct a $W$ boson from the lepton and $E_T^{\text{miss}}$ in the event using the $W$ mass to constrain the $z$-component of the neutrino momentum. Subsequently a top quark candidate is reconstructed using the jet in the event which gives a candidate mass closest to the top mass, and then combine the top quark candidate with the highest $p_T$ jet remaining in the event to give the $W'_R$ candidate and compute $M(tb)$. The corresponding $M(tb)$ distributions are shown in Fig. 1.

Here we briefly repeat the selection steps from the baseline analysis for 2016 data. It is expected that trigger thresholds and some specific selection steps will have to be adapted when performing this analysis at HL conditions where pileup is larger and the Phase-2 detector acceptance is larger. The triggers are the lowest unprescaled single lepton triggers, with trigger thresholds of 105 GeV and 45 GeV for electrons and muons, respectively. The following physics objects definitions are used in the analysis:

- **Electron** candidates are selected using a multivariate technique based on the shower-shape information, the quality of the track, the match between the track and electromagnetic cluster, the fraction of total cluster energy in the hadronic calorimeter, the amount of activity in the surrounding regions of the tracker and calorimeters and the probability of the electron originating from a converted photon.

- **Muon** candidates are required to be associated to a track with hits in the pixel and muon detectors, a good quality fit and transverse and longitudinal impact parameters close to the primary vertex.

- **Jets** are reconstructed within $|\eta| < 2.4$ with the anti-$k_T$ algorithm [10, 11] with a size parameter of 0.4 and a transverse momentum requirement $p_T > 25$ GeV. The $b$ jets are identified with a $b$-tagging working point corresponding to 10% misidentification probability and 80% efficiency for $b$ jets.

The kinematics selections in the analysis are:

- Events must contain one lepton with $p_T > 180$ GeV and excluded in the presence of an additional lepton with $p_T > 35$ GeV.

- Lepton and jet are required either to be well separated, quantified as $\Delta R(\text{lepton, closest jet}) > 0.4$, or have a relative difference between the lepton and jet transverse momentum, $p_T(\text{rel})$, above 60 (50) GeV for electrons (muons). The quantity $p_T(\text{rel})$ is defined as the magnitude of the lepton momentum orthogonal to the jet axis.
3 Sensitivity projections for $W' \rightarrow tb$ in leptonic final states

- The leading jet is required to have $p_T$ greater than 350 (450) GeV for the electron (muon) channel with the subleading jet showing $p_T$ greater than 30 GeV.
- $E_T^{miss}$ has to be greater than 120 (50) GeV in the electron (muon) channel.
- $\Delta \phi$ between $E_T^{miss}$ and the electron has to be below 2.
- The vector sum of both jets is required to be $p_T (\text{jet1} + \text{jet2}) > 350$ GeV and $p_T (\text{top}) > 250$ GeV.
- In the muon channel, the top mass is required to be between 100 and 250 GeV, in order to suppress background.

![Graphs showing invariant mass distributions for different categories.](image)

Figure 1: The reconstructed $tb$ invariant mass distributions in the 1 b-tag (top) and 2 b-tag (bottom) categories.

### 3.3 Systematic uncertainties

All systematic uncertainty estimates are taken from the baseline analysis. We disregard systematics affecting lepton efficiencies and photon identification that were specific to 2016 data. In addition a 15% (10%) uncertainty on the theoretical cross section of the top (bosonic) background is added. We then consider three scenarios for extrapolating systematics to 3000 fb$^{-1}$.

- **Current systematics** - We do not perform any adjustment to the magnitude of the systematics and keep the values from the Run-2 baseline analysis [9].
Table 1: Systematic uncertainties in two scenarios used for extrapolating from results using 12.9 fb$^{-1}$ of data collected at $\sqrt{s} = 13$ TeV [9]. The “current systematic” scenario assumes no change in systematics from their nominal values in the 12.9 fb$^{-1}$ dataset used for projection. The “reduced systematic” scenario assumes a realistic reduction in the magnitude of systematic uncertainties from their nominal values, based on improvements in dataset size, detector performance, and theoretical accuracy among others. For systematics which affect the shape of the invariant mass distribution, the value quoted for the rate uncertainty is approximate.

<table>
<thead>
<tr>
<th>Source</th>
<th>Current systematics</th>
<th>Reduced systematics</th>
<th>Shape?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.2%</td>
<td>1.5%</td>
<td>No</td>
</tr>
<tr>
<td>Trigger Efficiency ($e/\mu$)</td>
<td>2%/5%</td>
<td>1%/1%</td>
<td>No</td>
</tr>
<tr>
<td>Lepton ID Efficiency ($e/\mu$)</td>
<td>5%/2%</td>
<td>1%/1%</td>
<td>No</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>3.8%</td>
<td>1%</td>
<td>Yes</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>1%</td>
<td>0.07%</td>
<td>Yes</td>
</tr>
<tr>
<td>$b/c$-tagging</td>
<td>2.7%</td>
<td>1%</td>
<td>Yes</td>
</tr>
<tr>
<td>light quark mis-tagging</td>
<td>1.2%</td>
<td>1.2%</td>
<td>Yes</td>
</tr>
<tr>
<td>$W+$jets Heavy Flavor Fraction</td>
<td>2.3%</td>
<td>1.1%</td>
<td>Yes</td>
</tr>
<tr>
<td>Top $p_T$ Reweighting</td>
<td>18%</td>
<td>6%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.3%</td>
<td>0.09%</td>
<td>Yes</td>
</tr>
<tr>
<td>PDF</td>
<td>6.1%</td>
<td>3%</td>
<td>Yes</td>
</tr>
<tr>
<td>Matrix element $Q^2$ scale</td>
<td>18.9%</td>
<td>9.5%</td>
<td>Yes</td>
</tr>
<tr>
<td>$t\bar{t}$ Parton matching $Q^2$ scale</td>
<td>1.7%</td>
<td>0.9%</td>
<td>Yes</td>
</tr>
<tr>
<td>Theoretical top cross section</td>
<td>15%</td>
<td>7.5%</td>
<td>No</td>
</tr>
<tr>
<td>Theoretical bosonic cross section</td>
<td>10%</td>
<td>5%</td>
<td>No</td>
</tr>
</tbody>
</table>

- **Reduced systematics** - We scale theoretical cross section, PDF, and $Q^2$ scale uncertainties down by a factor of 2. The top $p_T$ uncertainty scaled down by a factor of 3 and the luminosity uncertainty is reduced to 1.5%. The magnitude of the jet energy scale uncertainty and the b-tag uncertainty is set to 1%. The mis-tag uncertainty stays unchanged. All other uncertainties are scaled down by a factor of $\sqrt{L}$.

- **No systematics** - No systematics at all, corresponding to the best possible limit.

The systematic uncertainties and their sizes in the two scenarios in which systematics are considered are shown in Table 1. The leading uncertainties are not of experimental nature (e.g. $Q^2$, top and diboson cross sections, PDF) and should improve in the coming ten years when more data are recorded and theoretical calculations are refined, hence a factor two improvement is assumed in the scenario of “reduced systematics”. Experimental uncertainties (e.g. efficiencies, scale factors, tagging efficiencies or luminosity) will be different with the real Phase-2 detector and expected to improve as well when this upgraded detector has been sufficiently studied. The last column in the Table indicates whether the source of systematics has an impact on the shape of the distribution. For these cases the value quoted for the rate uncertainty is approximate.

### 3.4 Projected exclusion reach

Exclusion limits for right-handed $W'_R$ bosons are shown in Fig. 2, with all four event categories combined. Theoretical $W'$ cross sections times branching ratios for two different theoretical assumptions on the right-handed neutrino mass are shown in red. On the top-left, the current
Sensitivity projections for $W' \rightarrow tb$ in leptonic final states scenario which assumes no change in systematics from their nominal values in the 12.9 fb$^{-1}$ dataset used for projection. $W'_R$ masses up to 4 TeV can be excluded. The reduced systematic scenario assumes a realistic reduction in the magnitude of systematic uncertainties from their nominal values based on improvements in dataset size, detector performance, and theoretical accuracy among others and is shown on the top-right. Not surprisingly, the sensitivity increases beyond 4 TeV. The selection was optimized for signal masses between 2-3 TeV corresponding to the reach of the 2016 baseline analysis. For masses beyond 4 TeV, where the off-shell part starts to become important, the selection should be re-optimized, which was not done for this projection. On the bottom-left in Fig. 2 the exclusion limit is displayed for the case without any systematics, exceeds significantly beyond 4 TeV.

Figure 2: Projection of expected and observed Bayesian 95% C.L. upper limits on the production cross section times branching ratio of right-handed $W'$ bosons for an integrated luminosity of 3000 fb$^{-1}$. The projection combines electron/muon+jets channel and 1 or 2 b-tags. The “current systematic” scenario (top-left) assumes no change in systematics from the 12.9 fb$^{-1}$ dataset [9] used for projection. The “reduced systematic” scenario (top-right) assumes a realistic reduction from their nominal values. For the graph on the bottom-left, no systematic uncertainties are included. Theoretical $W'$ cross sections times branching ratios for two different theoretical assumptions on the right-handed neutrino mass are shown in red. Bottom-right: the three different uncertainty scenarios in the same figure.
3.5 Projected discovery reach

We also make projections for the discovery sensitivity for a range of signal masses and cross sections. A quasi-model-independent method is used where projections are performed for arbitrary cross sections and resonance mass. Toy datasets with different amounts of injected signal are studied. The p-values for these hypothesized datasets compared to the null-signal hypothesis yield significances which are reported in units of standard deviations in Fig. 3. Three exemplary values of $2\sigma$, $3\sigma$ (corresponding to ”evidence”) and $5\sigma$ (corresponding to discovery) are given. These projections are performed for the three systematic scenarios discussed previously.

Figure 3: Expected discovery sensitivity for an integrated luminosity of 3000 fb$^{-1}$ as a function of the signal mass and the production cross section times branching ratio of right-handed $W'$ bosons in the combined electron/muon+jets channel, for combined 1 or 2 b-tags. Three scenarios for systematic are shown as explained in the legend. Theoretical $W'$ cross sections times branching ratios for two different theoretical assumptions on the right-handed neutrino mass are shown in grey (solid and dashed lines).

4 Sensitivity projection for $Z' \rightarrow t\bar{t}$

Additional neutral heavy vector bosons (denoted $Z'$) are also predicted. This section concentrates on the physics potential with 3000 fb$^{-1}$ in the decay channel $Z' \rightarrow t\bar{t}$. The $Z' \rightarrow t\bar{t}$ search comprises of two event categories:

- The lepton+jets channel as described in Ref. [12].
- The all-hadronic channel as described in Ref. [13].

The individual analyses use the 2015 LHC dataset corresponding to an integrated luminosity of 2.6 fb$^{-1}$. A combination of the baseline analyses is not publicly available, the results here are shown separately for the two event categories.
The projections are performed for two signal models: a narrow $Z'$ signal hypothesis [14], where the width of the resonance is set to 1% of the resonance mass, and a Randall-Sundrum Kaluza-Klein gluon resonance [15], where the resonance width is approximately 16% of the resonance mass. We use simulated events with masses up to, but not exceeding, 4 TeV, for both the $Z'$ and RS KK gluon signal models. Analysis above 4 TeV is challenging due to the large off-shell component important at high masses for wide-width signals.

4.1 Methodology of the extrapolation

The extrapolation is based on the analysis using 2.6 fb$^{-1}$ of 2015 LHC data, projecting to the planned 3000 fb$^{-1}$ of HL-LHC. The projection uses the existing Run-2 signal and background expectations, scaled by the 14-to-13 TeV luminosity ratio. The theta software framework [16] is used to compute expected cross section limits with these scaled templates. Table 2 lists the six all-hadronic and six lepton+jet channels that are considered. The $m_{t\bar{t}}$ distribution in each category is used for signal discrimination, as a peak on a falling background spectrum.

<table>
<thead>
<tr>
<th>Semileptonic Channel</th>
<th>All-Hadronic Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + 0 b-tag + 0 top-tag</td>
<td>0 subjet b-tag + $</td>
</tr>
<tr>
<td>e + 1 b-tag + 0 top-tag</td>
<td>1 subjet b-tag + $</td>
</tr>
<tr>
<td>e + 1 top-tag</td>
<td>2 subjet b-tag + $</td>
</tr>
<tr>
<td>$\mu$ + 0 b-tag + 0 top-tag</td>
<td>0 subjet b-tag + $</td>
</tr>
<tr>
<td>$\mu$ + 1 b-tag + 0 top-tag</td>
<td>1 subjet b-tag + $</td>
</tr>
<tr>
<td>$\mu$ + 1 top-tag</td>
<td>2 subjet b-tag + $</td>
</tr>
</tbody>
</table>

4.2 Systematic uncertainties

Two projections are made based on assumptions about the systematic uncertainties:

- **Current systematics** - same as in Run-2 baseline analysis, without scaling of the uncertainties.
- **Without any systematics** - only statistical uncertainties are included and scaled appropriately with the background and signal yield estimates.

The first projection uses the current uncertainties, with no improvements added. For example, the non-top multijet (NTMJ) background component for the all-hadronic channel is estimated using a data-driven approach, and improvements in the associated errors are expected when performing future analyses with larger datasets. Contributions to uncertainties from cross section measurements will also improve, as well as other contributions from components like jet energy scale, resolution, and lepton identification efficiency.

The dominant source of uncertainty in the all-hadronic channel is in the non-top multijet background. This is determined using a mistag rate which carries a momentum-dependent uncertainty of 5–100% depending on the b-tag content of the event. A corresponding mistag rate uncertainty of 19% is also applied in the semileptonic channel. Other important uncertainties include those applied to the simulated $t\bar{t}$ events, including uncertainties related to the choice of parton distribution functions as well as the scales used for the matrix element generation and parton shower evolution, which can be of order 10–20%. See the individual analysis documentation [12, 13] for further details on each of the uncertainty components.
In the second scenario, all systematic uncertainties are ignored, assuming only statistical uncertainties. This scenario yields the best possible limit with the existing analysis techniques. It assumes perfect knowledge of all the background components and associated modeling effects.

### 4.3 Projected exclusion reach

The projections in terms of $95\%$ C.L. exclusion are shown in Fig. 4. In the first scenario of "current systematics", the expectation is to exclude the narrow $Z'$ model up to 3.3 TeV masses, and the RS KK Gluon model up to 4 TeV. For the second case where only statistical uncertainties are considered, signal models are excluded to well beyond the 4 TeV limit of this analysis. However, for the highest resonance masses, off-shell production of the $Z'$ becomes important, and the reconstructed $m_{tt}$ does not peak at the resonance mass value. The analysis as presently designed will lose sensitivity quickly to the 5 TeV and higher-mass $Z'$ bosons. Therefore, a different analysis strategy should be designed and optimized for the off-shell decays of high mass resonances, which generally have less-boosted top quarks in the final state. Cross section limits of less than 1 fb and a few fb are obtained from the narrow $Z'$ and the RS KK gluon analysis, respectively.

### 4.4 Projected discovery reach

In addition to projections of exclusion limits, we also project expected discovery sensitivities in the possible presence of a new physics signal. The discovery sensitivities are estimated by using toy datasets with different amounts of injected signal. The p-values for these hypothesized datasets, compared to the null-signal hypothesis, are used to compute expected significances, reported as the number of standard deviations. The same two scenarios are examined regarding the systematic uncertainties, reusing the two channels. Figure 5 shows these results for the lepton+jets and all-hadronic channels. The significances are reported in the range of resonance cross section and resonance mass, for two width scenarios. This allows the estimation of sensitivities for arbitrary models with similar widths, if the mass and cross section are known.
Figure 4: Projected ranges of cross section limits expected for 3000 fb$^{-1}$ of HL-LHC running, shown individually for the lepton+jets (blue) and all-hadronic event (green) categories. The short-dashed line shows the median expected limits using full systematics from the Run-2 analyses [17] assuming no improvements in systematic uncertainties. The long-dashed line shows the same when applying no systematic uncertainties.
4.4 Projected discovery reach

Figure 5: Discovery sensitivities for the lepton+jets channel (left column) and all-hadronic channel (right column), for 3000 fb\(^{-1}\). The results are presented in the plane of the cross section versus the resonance mass, with the color contours representing the boundaries of areas with significances larger than 2, 3, or 5 standard deviations. The results are shown for the narrow-width signal hypothesis (top row) and RS KK gluon signal hypothesis (bottom row), with the “current systematic” uncertainties scenario from the Run-2 analysis [17] shown by the dashed lines and the “no systematic uncertainties” scenario shown by the solid lines.
5 Dark matter analysis

The search and/or characterization of dark matter (DM) in the form of Weakly Interacting Massive Particles (WIMPs) will be one of the top priorities of the HL-LHC. This section discusses the projected constraints on certain benchmark simplified dark matter models using the mono-jet search employing the signature of jets and missing transverse momentum.

This analysis uses Delphes simulated signal and background samples and performs a full signal event selection which follows the actual Run-2 analysis described in Ref. [18] as closely as possible.

The simplified models of dark matter considered for these projections are the following with the corresponding Feynman diagrams for both processes in Fig. 6:

- s-channel DM pair production with an axial vector mediator with the couplings of the mediator to DM \((g_{DM}) = 1.0\) and to the SM \((g_{SM}) = 0.25\).
- s-channel production via a pseudoscalar mediator with the couplings of the mediator to DM \((g_{DM}) = 1.0\) and to the SM \((g_{SM}) = 1.0\).

Figure 6: Feynman diagrams of DM pair production for an axial vector and pseudoscalar mediated interaction.

Constraints on the axial vector (AV) interaction can be translated to limits on spin-dependent DM-nucleon interactions and compared to those from the direct detection experiments. The results of searches for DM at the LHC so far have shown that colliders can place competitive constraints on spin-dependent interactions for this simplified model. For the pseudoscalar mediated model (PS) shown in Fig. 6, the LHC is uniquely placed to probe this interaction as it leads to velocity suppressed scattering cross sections for the direct detection experiments and is effectively inaccessible to them. Both models thus represent well-motivated benchmarks to study the projections of the HL-LHC.

5.1 Analysis strategy and event selection

Before the projection, the Delphes implementation has been validated with respect to the Run-2 analysis with 13 fb\(^{-1}\) at 13 TeV [18]. Details of the event selection for are presented in Tab. 3. The jet collection of AK4 jets is used for the validation study as well as for the ECFA projection in the 0 pileup (PU) scenario. Because the sensitivity of the analysis is dominated by events with very large MET, the effects from high pileup are not expected to cause a significant decrease in the expected sensitivity. Studies with the upgraded Phase-2 detector including the track trigger indicate that the Phase-2 trigger algorithms will allow to keep the thresholds around this value even in an environment with 200 PU events.

Signal samples are simulated with Powheg [19, 20] and subsequently passed through the Delphes simulation with Phase-2 detector performance. A signal would manifest itself as an excess in
Table 3: Summary of the event selection criteria used to select monojet events for this analysis.

<table>
<thead>
<tr>
<th>Event selection</th>
<th>p_{T}(j_1) &gt; 250 for AV (200 for PS),</th>
<th>\Delta \phi &gt; 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>AK4 jets</td>
<td>\Delta \phi(jet, E_{T}^{miss})</td>
<td>\Delta \phi &gt; 0.5</td>
</tr>
<tr>
<td>\Delta \phi(jet, E_{T}^{miss})</td>
<td>\Delta \phi &gt; 0.5</td>
<td>\Delta \phi &gt; 0.5</td>
</tr>
<tr>
<td>veto electrons</td>
<td>p_{T} &gt; 10,</td>
<td>\eta</td>
</tr>
<tr>
<td>veto muons</td>
<td>p_{T} &gt; 10,</td>
<td>\eta</td>
</tr>
<tr>
<td>veto taus</td>
<td>p_{T} &gt; 18,</td>
<td>\eta</td>
</tr>
<tr>
<td>b-jet veto (‘Loose’)</td>
<td>p_{T} &gt; 15,</td>
<td>\eta</td>
</tr>
<tr>
<td>E_{T}^{miss}</td>
<td>E_{T}^{miss} &gt; 200 GeV</td>
<td></td>
</tr>
</tbody>
</table>

the E_{T}^{miss} distribution after requiring large E_{T}^{miss} and a jet. This E_{T}^{miss} distribution is the discriminating variable, displayed in Fig. 7 after the full event selection from Tab. 3. Also shown are signal examples for the scenario of an axial vector interaction for the example DM and mediator masses given in the legend. The signal-to-background ratio improves with increasing E_{T}^{miss}. The dominant background is due to Z(\nu\nu) and W(\ell\nu)+j and is taken from simulation. It is labeled V+jets in Fig. 7.

![Figure 7: Distribution of the discriminating variable, E_{T}^{miss}, after full event selection. The V+jets background is taken from simulation. Two signal examples are shown for the axial vector model with the model parameters given in the legend.](image)

5.2 Systematic uncertainties

The region of E_{T}^{miss} dominating sensitivity to the two signal models chosen for the ECFA projections are different and hence the sources of systematic uncertainties. For the axial vector model, the tail of the E_{T}^{miss} distribution plays the dominant role while for the pseudoscalar model it is bulk/low E_{T}^{miss} region that provides the greatest sensitivity.

- For the axial vector model, the E_{T}^{miss} range is extended to 2.4 TeV while presently the maximum E_{T}^{miss} bin is at 1.2 TeV. The “current systematic” scenario is where the same systematic uncertainties on the E_{T}^{miss} distribution in the current monojet analysis are used for the ECFA analysis with the extended E_{T}^{miss} range, so the uncertainty
in the last bin of the $E_T^{\text{miss}}$ is 10%. Other scenarios considered are, reducing the current uncertainties by a factor of 2 and a factor of 4.

- To address the variation in systematic error, the $E_T^{\text{miss}}$ distribution is divided into a low and high $E_T^{\text{miss}}$ region, where low $E_T^{\text{miss}}$ is $<500$ GeV and high $E_T^{\text{miss}}$ is $>500$ GeV. The dominant systematic uncertainty in the low $E_T^{\text{miss}}$ region comes from the uncertainty on the lepton identification/isolation efficiency via the selection of the dilepton control sample which provides the dominant contribution to the estimation of the Z($\nu\nu$) background and also the single muon control sample which predicts the W($\ell\nu$) background. The low $E_T^{\text{miss}}$ region is hence systematics dominated and a systematic uncertainty of 1% per leg is taken for the ECFA $3000\,\text{fb}^{-1}$ projection, compared to the current uncertainty of 2% per leg. The uncertainty in the high $E_T^{\text{miss}}$ region is dominated by the size of the control samples used for estimating the $V+$jets background. The uncertainty in this region is taken from the current monojet analysis and scaled by luminosity. The above-mentioned scenario is the “current systematics extrapolated to HL-LHC” scenario for the PS model. Other systematic scenarios studied are: the current systematics scaled down by a factor of 2, and, the uncertainties in the full $E_T^{\text{miss}}$ region taken from the CMS monojet analysis and scaled by luminosity.

5.3 Projected exclusion reach

Following the simplified model parametrization, the sensitivity is studied in terms of mediator mass, $M_{\text{med}}$, and dark matter mass, $M_{\text{DM}}$. The coupling values were given previously and are kept constant. The projected exclusion reach for $3000\,\text{fb}^{-1}$ for both studied DM models is depicted in Fig. 8. The limits at 95% confidence level derived with the CLs method are shown for three systematic scenarios. They have a large impact on the reach in mediator mass. With the present knowledge one would reach $2.5\,\text{TeV}$ for the AV-model and $600\,\text{GeV}$ for the PS-model, while the limit with the best “scaled” uncertainty scenario corresponds to $3\,\text{TeV}$ (AV) and $900\,\text{GeV}$ (PS), respectively. The reach in DM mass improves accordingly for high mediator masses.
Figure 8: Projected exclusion limits at 95% C.L. for 3000 fb$^{-1}$ of HL-LHC statistics for two simplified dark matter models using the monojet analysis. On top the axial vector mediated simplified DM model ($g_{\text{DM}}=1$, $g_{\text{SM}}=0.25$), on the bottom the pseudoscalar mediated model ($g_{\text{DM}}=1$, $g_{\text{SM}}=1$). The limits are shown for three systematic scenarios. For the AV model: a “current” scenario assumes that the level of systematic control in the high $E_T^{\text{miss}}$ region is the same as the Run-2 analysis [18], while the “current/2” scenario scales it down by a factor of 2, and the “current/4” scenario by a factor of 4. For the PS model: a “current” scenario where the low $E_T^{\text{miss}}$ region is dominated by systematic uncertainties and the uncertainties in the high $E_T^{\text{miss}}$ region are taken from the Run-2 analysis and scaled by luminosity, the “current/2” scenario is the nominal systematics scaled down by a factor of 2, and the “luminosity scaled” scenario takes the uncertainties from the current analysis and scales by luminosity for the full $E_T^{\text{miss}}$ range.
6 Single vector-like quark T decaying to tH

Many SM extensions contain vector-like quarks (VLQ) which preferably mix with third generation quarks [21]. Such a particle could have a role in stabilizing the Higgs mass, and thus offers a potential solution to the hierarchy problem.

The analysis searches for the electroweak production of a vector-like partner of the top quark (T) decaying to a top quark and a Higgs boson (T → tH) assuming 3000 fb$^{-1}$ of proton-proton collision data at 14 TeV. Much like the top quark itself, a vector-like top quark can be produced either in pairs dominantly through the strong interaction, or singly in association with additional quarks through the electroweak interaction via diagrams such as those depicted in Fig. 9. For pair production, lower limits at 95% C.L. on the mass between 720 and 920 GeV have been set depending on decay mode [22]. For very massive VLQs above TeV range, the pair-production cross section rapidly decreases as the phase space for producing two massive particles is limited. Hence, in this regime the single production via the electroweak process is expected to dominate over pair production [21]. In this search, the single T can be produced through the processes $qg \rightarrow Tbq'$ and $qg \rightarrow Tq'$, and their charge conjugates. The production cross sections of single T quark and the branching fraction of $B(T \rightarrow tH)$ depends on the strength of the electroweak couplings at the production vertex, i.e, $c_{bW}^{L/R}$ for charged and $c_{bZ}^{L/R}$ for neutral current interactions up to a factor of the electroweak coupling constant $g_W$. In this search we consider the simplest Simplified Model [23] for a singlet and a doublet T quark, where only the LH coupling $c_{bW}^{L}$ is allowed for the singlet case, and RH coupling $c_{bZ}^{R}$ for the doublet case. Therefore, we only focus on these two models in this search.

Figure 9: Example production diagrams. Charged-current (left) and neutral current (right).

The $qg \rightarrow Tbq'$ process, where a T decays into a semileptonically decaying top quark and Higgs boson, decaying into two b-quarks leading to the final state $qg \rightarrow (\ell \nu b)(b\bar{b})q'$ consisting of a lepton, missing energy from the neutrino, and possibly 4 b jets. The event signature has a very forward jet which can benefit from the plans to increase the acceptance of the tracker to $|\eta| = 4$. The forward tracking should distinguish primary vertices from a very high pileup of 200, hence reducing the fake background in forward region. For high values of the T mass, it is expected that the large boost from the decay, will lead to the decay products from the top quark, and the jets from the Higgs to become progressively more and more merged.

6.1 Analysis strategy

This study is a full analysis based on DELPHES using the Phase-2 performance from the technical proposal [4]. Samples for the process $pp \rightarrow T b$, $T \rightarrow tH$ were generated using the leading order event generator MADGRAPH 5.2.3.30. [24]. The benchmark T quark masses used for the final result are 1, 1.5, 2.0, 2.5, and 3.0 TeV. The MADGRAPH samples are generated with an additional parton and interfaced with PYTHIA8 [25]. The NNPDF parton distribution function (PDF) was used [26]. The samples have the t decaying inclusively and H decaying 100% to b$\bar{b}$, with the mass of the Higgs set to 125 GeV. The mean pileup was set to 200 interactions per
events. Separate samples were generated for left-handed (right-handed) couplings of the $c_L^{bW}$ ($c_R^{bW}$) vertices for the $T \rightarrow tH$ decay using narrow width of 10 GeV.

The main SM backgrounds are: $t\bar{t} +$jets, $V+$jets, single top and diboson events. The backgrounds are binned in $H_T$ and simulated using MADGRAPH interfaced with PYTHIA8. The backgrounds are normalized using the NLO cross sections, except for $t\bar{t} +$jets and $V+$jets, where a k-factor of 1.68 and 1.23 is used respectively to normalize them to NNLO cross sections.

6.2 Event Selection

The event selection assumes the Phase-2 detector geometry including the increased acceptance. The object selection largely follows the present selection steps adapted to the Phase-2 detector performance. One requires events with one electron or muon with $p_T > 40$ GeV and $|\eta| < 4.0$. Jets and $E_T^{\text{miss}}$ are reconstructed with a new algorithm (denoted PUPPI) targeting high PU scenarios, which is an extension of the particle flow algorithm with charged hadron subtraction giving weights to particles based on the probability that they come from pileup or the primary vertex. Jets overlapping with leptons are removed if their separation within a cone $\Delta R(AK4, \ell)$ is greater than 0.4 and $\Delta p_T$ (rel) exceeds 40 GeV. This selection is assumed to suppress any QCD backgrounds in events. In addition at least one forward jet within the acceptance $2.4 < |\eta| < 5.0$ and $p_T > 30$ GeV is required. Also at least two central jets with $|\eta| < 2.4$, where the first leading jet has $p_T > 200$ GeV, the second leading jet has $p_T > 80$ GeV. At least one jet has to be identified as a b-jet with a tagging efficiency of around 70% and mistag rate of 5%. The $E_T^{\text{miss}}$ has to be greater than 20 GeV.

Higgs candidates are identified using boosted AK8 jets, where AK8 jets are defined as jets clustered within a cone size of radius 0.8. The AK8 jets with $p_T > 300$ GeV and $|\eta| < 2.4$ are first cleaned to the non-prompt leptons such as jets are rejected if they overlap with leptons within a cone $\Delta R(AK8, \ell) < 0.4$ radius, and $\Delta p_T$ (rel) > 40. The soft drop algorithm is used to identify subjets in a AK8 jet that are compatible with two body decay. Therefore to tag a Higgs boson, exactly two soft drop subjets are required with jet shape N-subjettiness variable $\tau_21 < 0.6$ [27] and the soft drop jet mass within 90-160 GeV. Due to unavailability of the b-tagging on the subjets in DELPHES, no subjet b-tagging is applied to the subjets. To avoid the ambiguity between a Higgs candidate and a prompt lepton from a top quark decay of a T quark, the Higgs candidates are rejected if $\Delta R(H, \ell) < 1$.

The T mass is reconstructed by first identifying a top quark candidate and then combining it with a Higgs boson candidate using a $\chi^2$ minimization. To identify a top quark candidate decaying into a semileptonically decaying W boson and a b-quark, first the neutrino $p_\nu$ solution is obtained by solving a quadratic equation using the following kinematic constraints $m(\ell\nu) = m(W) = 80.399$ GeV. Out of the two solutions, the smaller is kept. In case of solely one imaginary solution, its real part is used. Therefore using the neutrino and lepton four momentum, a top candidate is formed by combining them with one or two AK4 jets, and keeping the combination that results from the minimization the following $\chi^2$ function

$$\chi^2 = \left(\frac{M_{t,H,MC} - M_{t,H,rec}}{\sigma_{M_{t,H,MC}}}\right)^2 + \left(\frac{M_{t,MC} - M_{t,rec}}{\sigma_{M_{t,MC}}}\right)^2 + \left(\frac{dR(t,H)_{MC} - dR(t,H)_{rec}}{\sigma_{dR,MC}}\right)^2.$$ 

Here $M_{t,H}$ is defined as Higgs mass, $M_t$ as top mass, and $\Delta R(t, H)$ as separation between a top quark and a Higgs boson candidate. The mean and widths for $\chi^2$ event are taken from generator level studies [28]. Only combinations that pass the requirement of $\Delta R(AK4$ jet, $H) > 1.0$ and $\Delta R(t,H) > 2$ are considered for the statistical analysis.
Figure 10 show the reconstructed mass distribution ($M_{T,\text{reco}}$) along with signal examples for various $T$ masses as given in the legend. Signal efficiencies are about 4% for $T_bq$ and about 3% for $T_tq$ with only a light dependence on the $T$ mass.

Figure 10: Distributions of the reconstructed mass of the $T$ quark decaying into a top quark and a Higgs boson. The top quark further decays leptonically and the Higgs boson into a pair of $b\bar{b}$ quarks, leading to the final state of $qg \rightarrow (\ell \nu b)(b\bar{b})(bq'/tq')$. Selected signal samples of $T$ masses of 1, 2, and 3 TeV from the processes $pp \rightarrow T_bq$ ($T_tq$), with left-handed (right-handed) couplings to the SM third generation quarks are overlaid on the total estimated background.

6.3 Systematic uncertainties

The main SM background in this search are $t\bar{t} + \text{jets}$ events, which are normalized to the NNLO cross section. We consider a total of 27% uncertainty on $t\bar{t} + \text{jets}$ normalization, which is 1/2 of the total uncertainty on $t\bar{t}$ theory cross section due to PDF and QCD scale, and top quark mass. We keep the same uncertainty on the single top quark background, since for the limit setting procedure, we combine the two samples and treat them as one template. Another large background is $V + \text{jets}$, where $V$ can be a W or a Z boson. This background is combined with the smaller diboson backgrounds and a total of 20% conservative uncertainty is assigned on their normalization.

The largest shape uncertainties comes from b-tagging. To estimate them, we vary the nominal b-tagging SF at medium efficiency working point by scaling it up and down by 1% for b jets, 2% for c jets, and 5% for the light jet, and use the resultant shape template in our statistical analysis. For the jet energy scale an estimated flat uncertainty of 3.8% is applied. In Run-2 for Higgs-tagging, the measured uncertainty on jet mass and N-subjettiness selection scale factors are found to be $1.03\pm0.13$, and we expect the uncertainty to improve with new tagging tools and hence do not apply any uncertainty due to these sources. Other uncertainties include 1% on jet energy resolution, 1.5% on luminosity, 1% on presumed trigger scale factor, 1% on lepton reconstruction and identification.

Without available QCD simulation, it is very difficult to estimate the QCD contribution, one does not expect QCD backgrounds in the signal region after the full event selection though. However, we checked the impact on expected limits by constraining the normalization of total background to 0%, 10%, 50% and 100% and found the median of the limits on cross section
times branching ratio varies around 1%. Due to this observation and the analysis being shape based, we decided to drop any additional uncertainty due to QCD background.

6.4 Results

The Higgs combine package [29] has been used for the limit-setting procedure. A simultaneous fit of the background and the signal $M_T$ distributions is performed, with the systematic uncertainties treated as nuisance parameters with log-normal priors. A binned likelihood fit with Bayesian algorithm (asymptotic) is used to obtain a 95% C.L. upper limit on the signal strength. The expected limits for different mass hypotheses of the T quark are computed using the $M(tH)$ distributions for the background and the signal. The results are shown in Fig. 11 and Tab. 4. The two scenarios are considered for signal interpretation. First is the singlet T quark production through $pp \rightarrow Tbq$ process, where only left-handed coupling ($c_{L}^{bW}$) of T quark to the third generation quark is allowed, and the second is production of doublet T quark through $pp \rightarrow Ttq$ process, where only right-handed coupling ($c_{R}^{tZ}$) is allowed. According to the equivalence theorem [30–32], a T quark can decay into $bW$, $tZ$ or $tH$ channels with the benchmark branching fraction of $B(T \rightarrow bW) : B(T \rightarrow tZ) : B(T \rightarrow tH) = 0.5 : 0.25 : 0.25$. However, considering the simplest Simplified Model, this is only valid for a singlet T quark with $c_{L}^{bW}$ coupling. For the doublet T quark with $c_{R}^{tZ}$ coupling, we considered the benchmark branching fraction of $B(T \rightarrow bW) : B(T \rightarrow tZ) : B(T \rightarrow tH) = 0.0 : 0.50 : 0.50$. The couplings $c_{L}^{bW}$ and $c_{R}^{tZ}$ are chosen as 0.5 due to the fact that signal simulations were performed with a fixed width of 10 GeV under the narrow width approximation, and the theoretical width of the VLQs is negligible compared to the experimental mass resolution for values, equal to or below 0.5. In future studies coupling values higher than 0.5 will be considered as signal simulations with wider width of around 20% and 30% of the T quark mass will be studied. In addition, with improved analysis methods such as the usage of subject b-tagging in Higgs identification, the sensitivity to smaller couplings is expected to improve for T production through both the $pp \rightarrow Tbq$ and $pp \rightarrow Ttq$ processes.

Figure 11: The expected limits at 95% C.L. on the $\sigma \times B(T \rightarrow tH)$ of a T quark for different mass assumption of 1, 1.5, 2, 2.5, and 3 TeV, at an integrated luminosity of 3000 fb$^{-1}$. The left (right) plot shows the results for the process $pp \rightarrow Tbq$ ($pp \rightarrow Ttq$) with left-handed (right-handed) coupling to the third generation SM quarks as described in models in Refs. [23, 33]. The dotted blue line in left (right) plot is the theory cross section assuming 0.5 coupling strength of the T quark to a $W$ ($Z$) boson, and $B(T \rightarrow tH = 0.25 (0.50))$, and is obtained by scaling the NLO cross sections at 13 TeV to the k-factor obtained at 14 TeV with CTEQ6L PDF.
Table 4: The median expected upper limits at 95% C.L. on the cross section $\times B(T \rightarrow TH)$ of the T quark for the models $pp \rightarrow Tbq$ ($Tbq$) with $B(T \rightarrow TH = 0.25)$ and $pp \rightarrow Ttq$ ($Ttq$) with $B(T \rightarrow TH = 0.50)$ for different mass hypotheses and left-handed or right-handed couplings respectively. An integrated luminosity of 3000 fb$^{-1}$ at proton-proton collision at $\sqrt{s} = 14$ TeV is assumed.

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7 Summary and conclusion

The physics reach with 3000 fb$^{-1}$ of HL-LHC data is studied in a number of searches for new physics. The projections described here demonstrate the gain from high-luminosity.

Discovering the nature of DM is an important problem in physics. The LHC is performing collider searches for dark matter and its mediators. One of the most common searches is the monojet search with j+MET in the final state. Based on the Run-2 event selection, the analysis for the two interesting couplings scenarios, namely the axial vector and pseudoscalar coupling, is performed. The precise knowledge of systematic uncertainties has a significant impact on the reach in mediator mass which corresponds to 2.5 TeV without any improvement of the present understanding of the systematic uncertainties. If, on the contrary, the systematics improves by 1/4 the sensitivity increases by 20% to 3 TeV.

Projections of searches are performed for new heavy vector bosons ($Z'$ and $W'$) at the HL-LHC. Analyses performed on the 13 TeV data are projected to the HL-LHC data set of 3000 fb$^{-1}$ to determine the maximum reach of excluded boson masses as well as the discovery reach. The projections are performed under different scenarios considering systematic uncertainties. A promising search is for a right-handed $W'_R$ in the decay channel to tb yielding final states of an electron or muon together with one or two b-tagged jets. The maximum reach in terms of boson mass is 4 TeV with present systematics and above with improved systematics. In addition, model independent discovery sensitivities are presented. The projected $Z' \rightarrow t\bar{t}$ exclusion limits are also around 3-4 TeV, depending on the widths of the new resonance and the knowledge of systematics. Two different widths are studied, $\Gamma=1\%$ for a SSM $Z'$ and 16% for a RS KK gluon. The expectation is to exclude the narrow $Z'$ model up to 3.3 TeV masses, and the RS KK Gluon model up to 4 TeV in the scenario of Run-2 systematics. In the best case scenario of only statistical uncertainties, the reach extends for both models beyond 4 TeV pushing into a region where the analysis strategy has to be adapted to accommodate the increasing off-shell component for high resonance masses.

The discovery of the Higgs boson provided theoretical constraints to physics beyond the SM and also opens new decay channels for searches. As one example, this document presents a search for weakly produced single vector like quarks (T) decaying to a t-quark and a Higgs boson. Since both particles decay further, this challenging analysis has to reconstruct them from the final state consisting of a lepton, $E_{T}^{miss}$ and up to four b-quarks. Due to the forward going jets an increased sensitivity is expected from the extended acceptance of the Phase-2 detector. Considering simplest Simplified Model for a singlet and a doublet T quark, two scenarios are
considered for signal interpretation: LH coupling $c_{\text{L}}^{bW}$ with $\mathcal{B}(T \rightarrow bW) : \mathcal{B}(T \rightarrow tZ) : \mathcal{B}(T \rightarrow tH) = 0.5 : 0.25 : 0.25$ for the singlet $T$ quark, and RH coupling $c_{\text{R}}^{bW}$ with $\mathcal{B}(T \rightarrow bW) : \mathcal{B}(T \rightarrow tZ) : \mathcal{B}(T \rightarrow tH) = 0.0 : 0.5 : 0.5$ for the doublet $T$ quark. The expected upper cross section limits range from 85.9 fb (54.7 fb) for a $T$ mass of 1 TeV to 4.7 fb (4.1 fb) for a $T$ mass of 3 TeV for the singlet (doublet) $T$ quark.

References


References


[17] CMS Collaboration, “Search for \( t\bar{t} \) resonances in highly-boosted lepton+jets and fully hadronic final states in proton-proton collisions at \( \sqrt{s} = 13 \) TeV”, arXiv:1704.03366.


