

Optimization of a search for pair produced vector-like quark in pp collision at $\sqrt{S} = 13$ TeV with the ATLAS detector at the LHC

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Abstract

We present an optimization study of a search for vector-like top quark that decays into a W boson and a b quark. The analysis is performed using Monte Carlo simulation.

Introduction

Standard Model is the theory of fundamental particles and the interaction between them. The Standard Model (SM) includes electromagnetic, weak, and strong interactions. Thus far, all its predictions have been experimentally verified.

Although it provides a good explanation of many experimental results and is self-consistent, it doesn't explain other many mysteries of the universe. So it is not quite regarded as the complete theory of nature. The SM has no mechanism to explain the observed matter-antimatter asymmetry in the Universe. It cannot explain the generational structure of fundamental fermions and the mass hierarchy among those generations. Some additional phenomena that the SM doesn't explain are neutrino oscillation, dark matter, dark energy, and gravitation.

To resolve the inadequacies of the SM, many new theoretical models have been proposed. Some of the popular extensions of the SM are super-symmetry (SUSY), Composite Higgs, Extra dimensions etc. A feature common to several of these models is the existence of 'vector-like' quarks. Vector like quarks are hypothetical spin $\frac{1}{2}$ particles that transform as triplet under the color gauge group and whose left- and right-handed components have the same color and electroweak quantum numbers, which could possibly be pair produced at the Large Hadron Collider, and could then be detected as they decay into the SM gauge bosons and quarks.

We present an optimization study of a search for pair production of vector-like top quark (T) that decays into a W and a b quark. The Feynman diagram for the signal process is as shown in Figure 1. We consider the channel in which one of the W bosons decays leptonically (to an electron or muon plus a neutrino) and the other W boson decays hadronically (into two light quarks). The study is performed using Monte Carlo simulation samples produced in the Data Challenge Campaign 2014 (DC14).

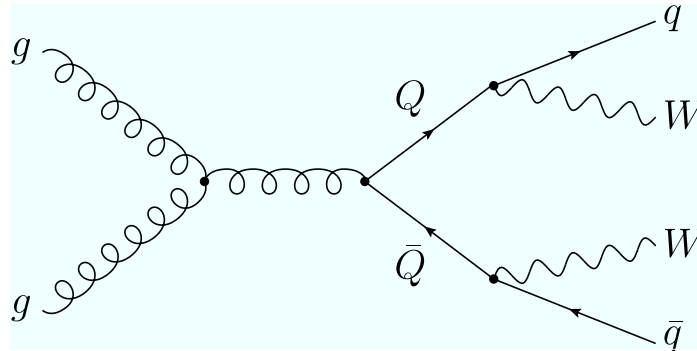


Figure 1: Leading order Feynman diagram for VLQ pair production at the LHC.

ATLAS detector

The ATLAS detector at the LHC covers nearly the entire solid angle around the interaction point. It consists of inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and muon spectrometer incorporating three large superconducting toroid magnets. The inner tracker is used to measure the momentum of the charged particles. The electromagnetic calorimeter measured the energy deposited by photons and electrons. The hadronic calorimeters measures the energy deposited by hadrons. The muon spectrometer measured the energy of muons. The final state particles of the signal of interest can all be detected by the ATLAS detector, except the neutrino which escapes the detector. However, its momentum in the direction transverse to the beam can be inferred from the missing momentum information. A schematic the ATLAS detector is shown in Fig. 2.

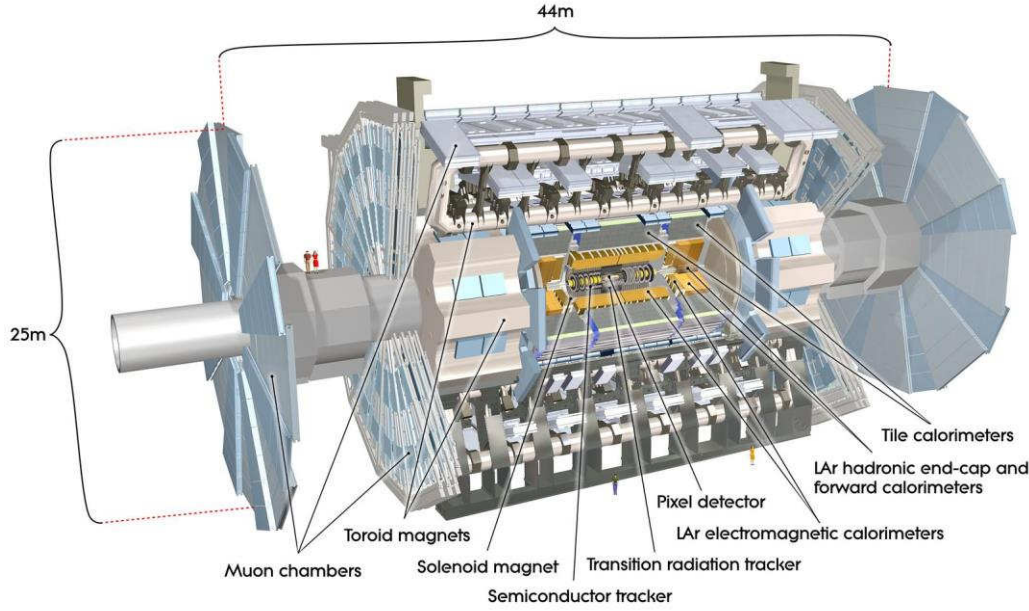


Figure 2. The ATLAS detector and its components.

Pre-selection and Analysis Strategy

In a search for new physics signature, we have to understand the background processes that can mimic the signal. For the search of T quark pair production in the lepton+jets channel, the main background is $t\bar{t}$ because the decay products of T quark and the standard model top quark (t) are similar, assuming that the T quark decays into a W boson and a b quark.

The physics objects used in this study are standard physics objects reconstructed by the Top Working Group in the ATLAS collaboration. The basic object selection, often simply called pre-selection, that we have adopted is exactly the same as recommended by the Top group. The pre-selection, in addition to requiring a lepton trigger, requires exactly one charged lepton, at least four jets, and large missing transverse momentum.

VLQ has been extensively studied by the ATLAS and CMS collaborations at the LHC. And these studies have set lower limit on the T quark mass, which falls in the range 715 GeV to 950 GeV, at 95% confidence level. Therefore, in our study, we have taken the signal to be a VLQ produced with the mass of 1100 GeV.

We use a boosted analysis strategy. Since the T quark is very heavy, its decay products are boosted (very high transverse momentum, p_T). We can distinguish the signal from the background using H_T (scalar sum of transverse momenta of the lepton, neutrino, hadronic W and two b -jet candidates) as H_T of the signal is much greater than that of the background. Additionally, we also consider the reconstructed mass of vector-like top as one of the discriminants between the SM top and T quark.

Reconstructed Heavy Quark Mass

In our case, we considered the first two leading jets as two b -jet candidates and the third and fourth leading jets in the event as the jets coming from hadronic W . We construct the mass of hadronic W from the third and fourth leading jets and combine it with one of the b -jets to get the reconstructed mass of top on the hadronic side. This gives us two solutions for hadronic T mass. The z -component of the neutrino momentum, is solved for up to two-fold ambiguity using the W mass constrain. Of the four permutations, the one that gives the smallest mass difference between the leptonic T and hadronic T , is kept as the best solution. Reconstructed mass of the T quark on the hadronic side, labeled m_{recoHad} , is considered as one of the discriminants.

Final Selection

By studying the various kinematic distributions of the signal and main background, we have chosen the following selection requirements. In the first selection (cutc), we require events to have more than 3 jets because in our final state there are 4 quarks. In the second selection (cut2), we constrained the mass of W_{had} within 65 GeV to 105 GeV. Third and fourth selections (cut3 and cut4) require the leading jet to have p_T greater than 200 GeV and the second leading jet to have p_T greater than 80 GeV. H_T of $t\bar{t}$ system peaks around 500 GeV while the signal has a peak at much higher value, so at cut5, we require $H_T > 800$ GeV. Then we require ΔR between lepton and neutrino < 1.0 , cut6. Since W is boosted the decay products of W must have small angular separation, therefore we require ΔR between third and fourth leading jet be smaller than 1.0 (cut7), and finally we require p_T of $W_{\text{had}} > 200$ GeV (cut8).

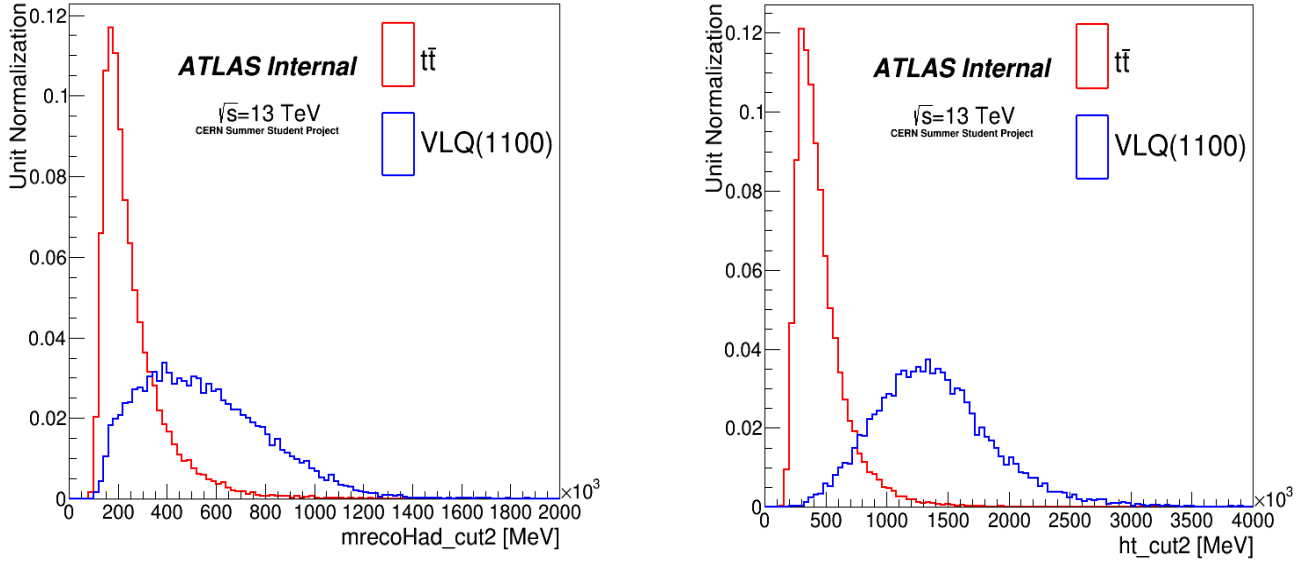


Figure 3: m_{recoHad} (left) and H_T (right) distribution after cut2.

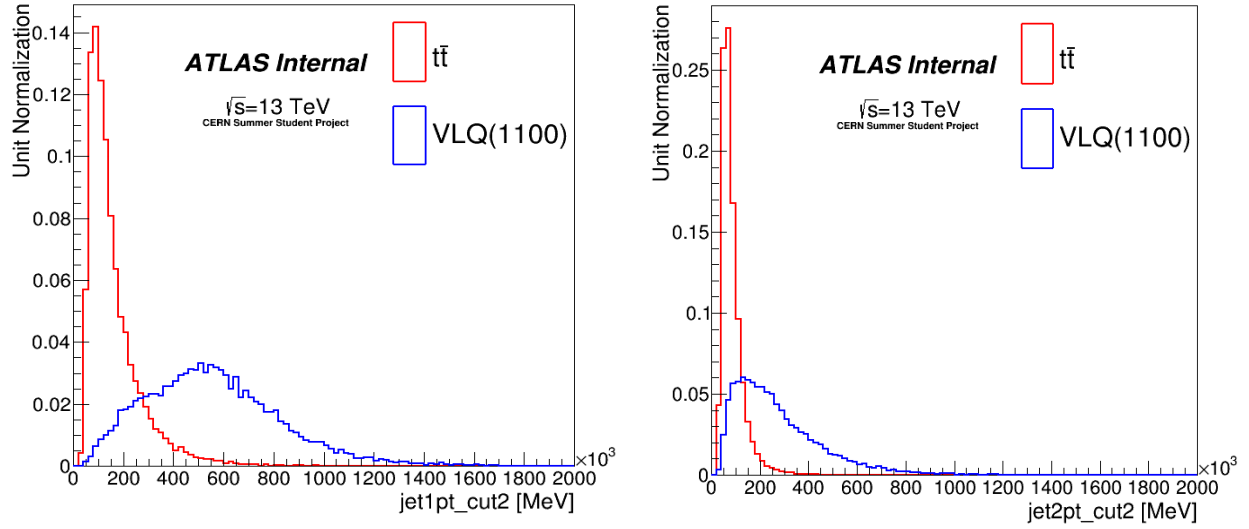


Figure 4: p_T distribution for first (left) and second (right) leading jets after cut2.

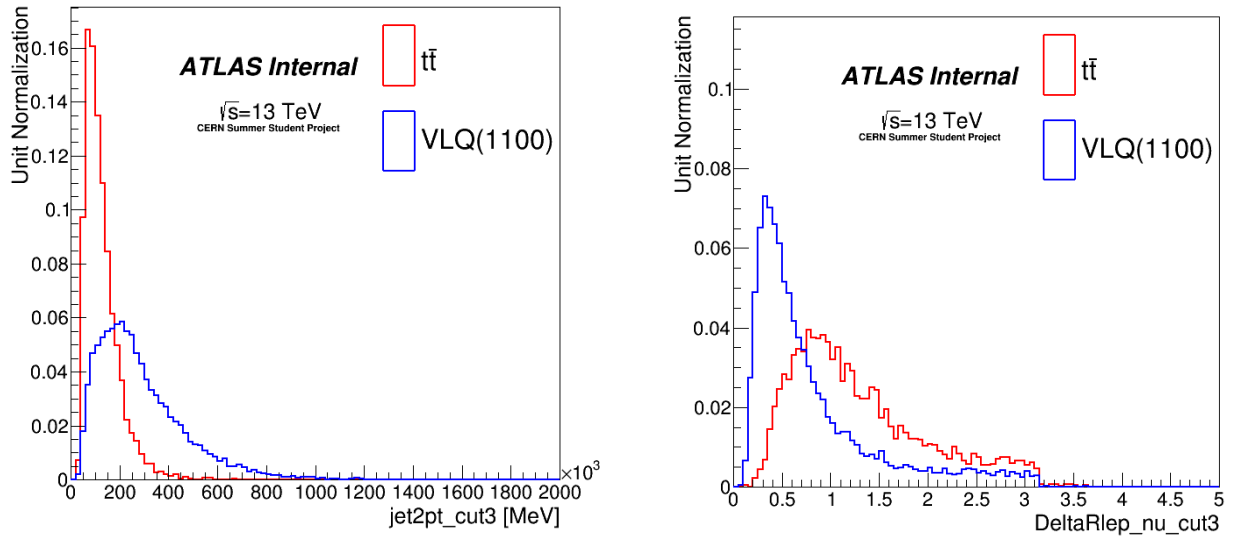


Figure 5: p_T of the second leading jet (left) and ΔR distribution between lepton and neutrino (right) after cut3.

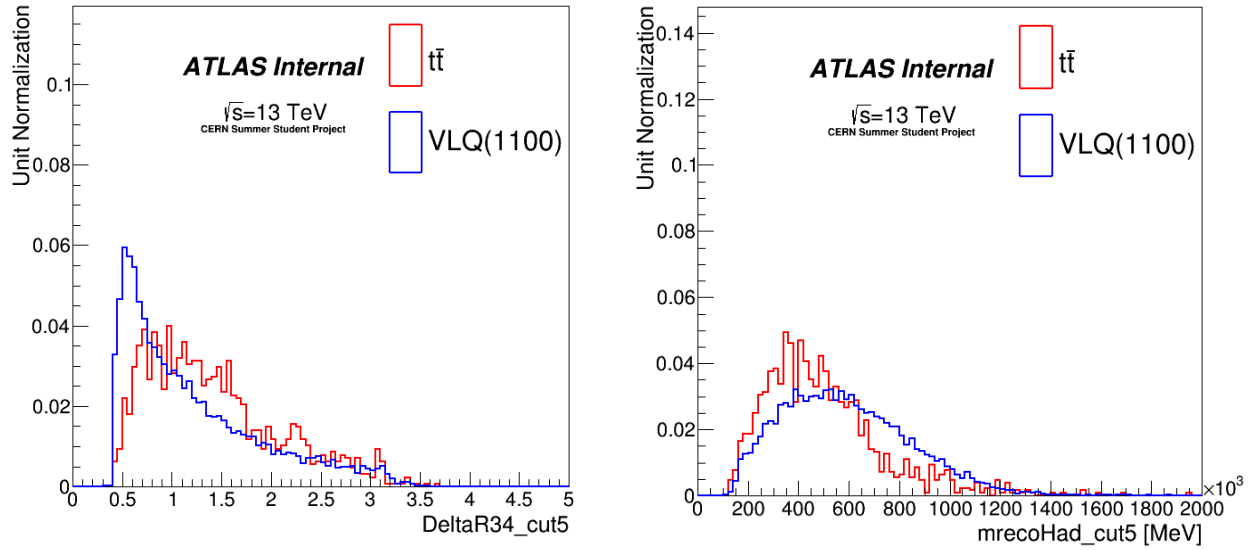


Figure 6: DeltaR distribution between third and fourth leading jets and m_{recoHad} after cut5 ($H_T > 800\text{GeV}$).

Results & Outlook

We note that with each selection the significance, defined as $\text{signal}/\sqrt{\text{Background}}$, increases. Due to limited statistics in the available Monte Carlo samples, requiring very tight cuts gave highly unreliable m_{recoHad} and H_T distributions. However, from Figure 3 it can be seen that H_T distribution can be a good discriminant against background.

We also show that with the given selection it is possible to reconstruct the mass of the VLQ. However, the reconstructed mass doesn't quite peak around 1100 GeV as one would expect for a VLQ of that mass. A potential problem we identified in the reconstructed mass may be due to the mixture of decay modes. In the VLQ sample, the vector-like top can decay through different modes such as, $T \rightarrow Wb$, $T \rightarrow Zt$, and $T \rightarrow Ht$ while we are only considering the Wb decay mode. An improvement for the future can be distinguishing the different decay modes and to optimize by picking only signals that decay to a W boson and a b quark.

References

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