PROCEEDINGS OF SCIENCE

# Searches for heavy quarks and other signatures with the ATLAS detector at the LHC

**Xiaowen Lei***
*On behalf of the ATLAS Collaboration*
*E-mail:* Xiaowen.Lei@CERN.CH

The Standard Model is very successful in describing nature but is thought to be an approximation to a more complete theory. Given that no clue has been found on the scale of new physics, signature-based search covering a wide range of final states and topologies is very important nowadays. Searches for fermionic top/bottom quark partners, referred to as vector-like quarks, are performed in various final states with leptons, jets, and missing transverse momentum ($p_T$). Searches in final states with a high $p_T$ jet or boson recoiling against large missing energy are quite powerful for detecting dark matter production. Long-lived, weakly-interacting particles predicted by various beyond-Standard-Model theories often lead to a signature with displaced decay vertices in ATLAS detector. This talk highlights recent ATLAS results on searches for vector-like quarks, dark matter, and long-lived particles in LHC Run 1 data at a center-of-mass energy of 8 TeV.

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## 1. Introduction

The Standard Model (SM) has been repeatedly confirmed experimentally. Despite its tremendous success, it is however an incomplete theory, with missing ingredients such as dark matter candidate particles and a mechanism to naturally stabilize the Higgs boson mass. The substantial dataset of around 20 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV collected by the ATLAS detector [1] during Run 1 of the LHC [2] provided an unprecedented opportunity to search for phenomena beyond the SM. A thorough signature-driven search program targeting non-supersymmetry extensions to the SM was executed to cover many different theories. This conference proceeding highlights recent results from the ATLAS Collaboration on searches for vector-like quarks, dark matter, and long-lived particles.

## 2. Vector-like quark searches

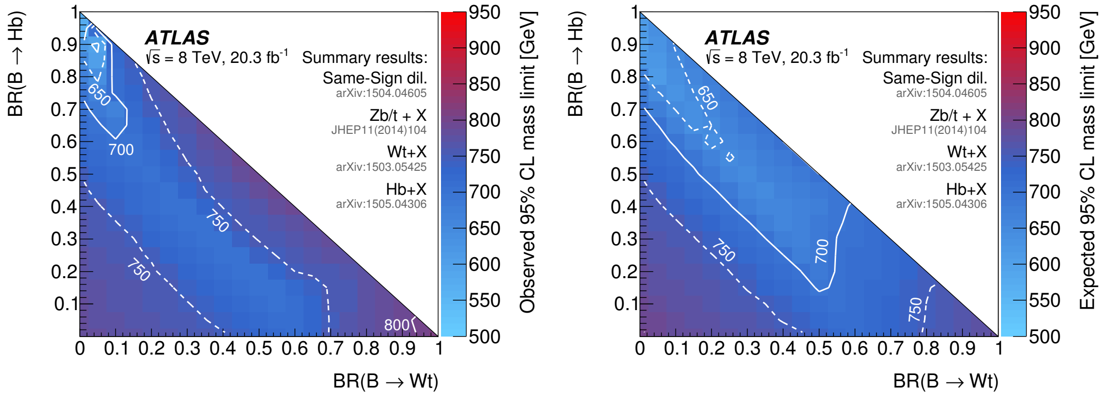
Vector-like quarks (VLQ's) are predicted by many theories beyond the Standard Model that stabilize the Higgs mass without invoking supersymmetry. These exotic quarks can decay via the neutral or the charged current. At ATLAS, several complementary searches are carried out, targeting different decay modes [3, 4, 5, 6]. There are two single lepton analyses, one targeting $BB \to Wt + X$ and the other targeting $TT \to W_{had}b + X$, $TT \to Ht + X$, and $BB \to Hb + X$). And there are two multilepton analyses, one looks for events with a leptonically decaying $Z$ boson and the other searches for events with a same-sign lepton pair and $b$ jets.

There are several possible varieties of VLQ. Besides the $B$ and $T$ quarks, which carry the same charge as the SM $b$ and $t$ quarks respectively, there are also $X$ and $Y$ quarks that carry exotic charges of +5/3 and -4/3 respectively. All of the different types can be produced either in pairs via the QCD interaction or singly via the electroweak interaction. Pair production of $T$ and $B$ are considered by all four ATLAS analyses. Some of these analyses also consider single production of T and B, and/or $X$.

Figures 1 and 2 summarize the mass limits on pair-produced vector-like $B$ and $T$ from the four ATLAS analyses. Figure 1 shows the expected and observed 95% CL limits for production of vector-like $BB$ for all possible decay branching ratios (BR's). Figure 2 shows the corresponding limits for vector-like $TT$. The expected mass exclusion reaches close to 750 GeV for $B$ and 800 GeV for $T$, pushing near the naturalness limit of around 1 TeV []. The observed limits are overall more stringent than the expected limits, meaning the background expectation over-predicts data. However, this doesn't hold true for all regions in the decaying ratio plane, and also not for all analyses. For example, the same-sign lepton pair analysis observed an excess in data with significance up to 2.5 $\sigma$ [6].

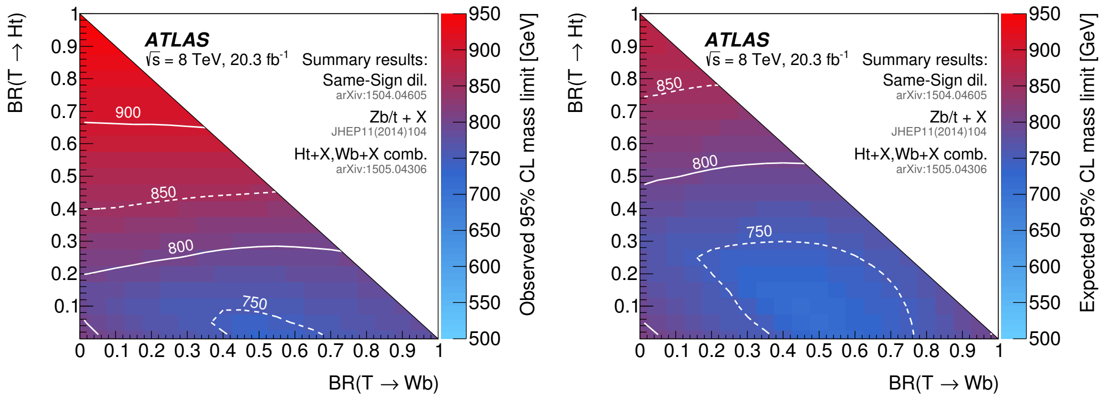
## 3. Dark matter searches

The existence of dark matter (DM) is firmly established on the basis of cosmological and astrophysical observations, but little is known about its composition. One DM candidate is called Weakly Interacting Massive Particle (WIMP), which only interact weakly with SM particles. The annihilation rates of WIMPs with masses in the GeV-TeV range are consistent with the thermal




(a) (b)

Figure 1: Expected (a) and observed (b) lower limits on the vector-like $B$ quark mass at 95% CL [4]. Mass exclusions are drawn sequentially for the different analyses in each of the figures. For a given bin in the BR plane, the strongest of all limits considered is shown.

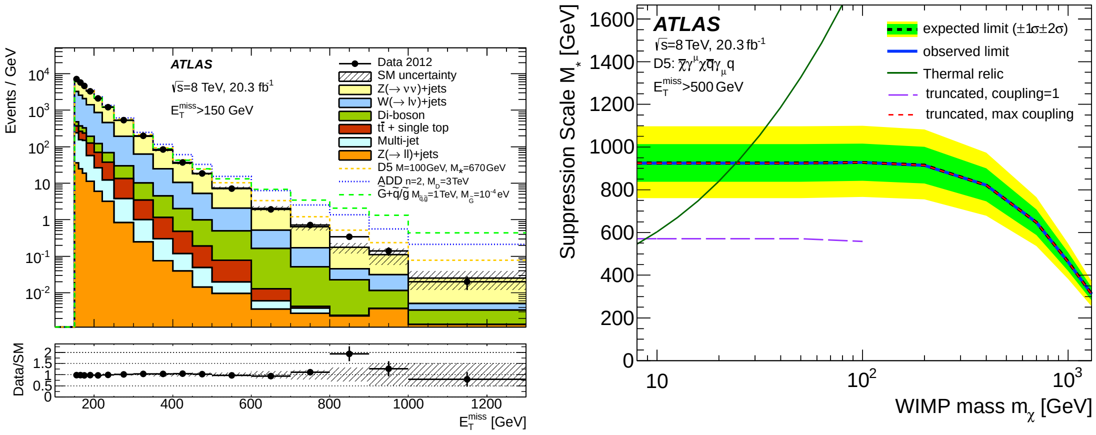



(a) (b)

Figure 2: Expected (a) and observed (b) lower limits on the vector-like $T$ quark mass at 95% CL [4]. Mass exclusions are drawn sequentially for the different analyses in each of the figures. For a given bin in the BR plane, the strongest of all limits considered is shown.

relic density, making them a promising candidate for dark matter. Most dark matter searches at colliders exploit the recoil of undetected pair-produced WIMPs against an object typically radiated in the initial state. These signatures are referred to as mono-X signatures. The ATLAS experiment performs searches for DM final states such as mono-jet, mono-$\gamma$, mono-HF (heavy flavor), mono-$Z(ll)$, mono-Z/W$(jj)$, and mono-top [7, 8, 9, 10, 11, 12]. Among these, the mono-jet search is one of the most promising because of the large cross-section for initial state radiation of a jet at the LHC.

The most recent ATLAS mono-jet analysis considers nine inclusive signal regions with increasing $E_T^{miss}$ thresholds from 150 to 700 GeV, labeled SR1 to SR9 [7]. Figure 3a shows the distribution of $E_T^{miss}$ in data compared to the SM expectations in SR1. The number of events in data agrees well with the SM expectations in the different signal regions. The results are translated into exclusion limits using several different signal models including WIMP's. Figure 3b shows the limit on the suppression scale $M_*$ as a function of the DM particle mass for for one of EFT (effective field theory) operators that describe the interaction between SM and DM particles.



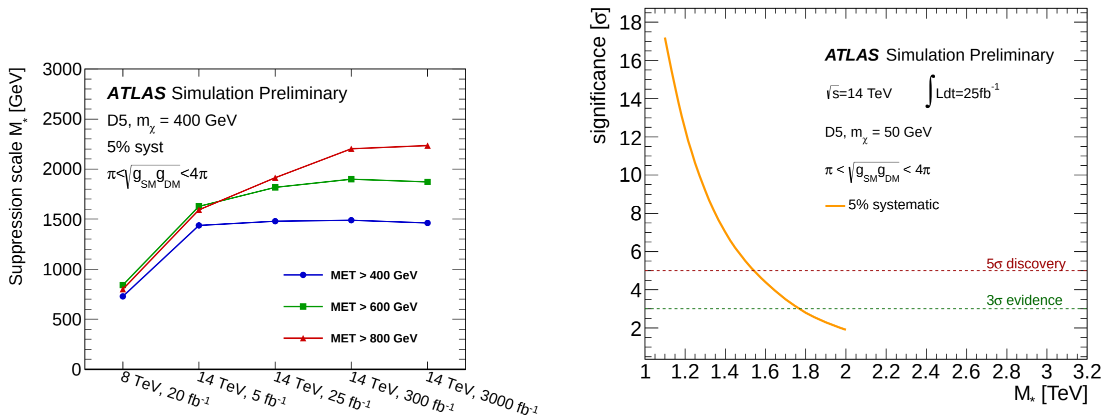

(a) (b)

Figure 3: DM searches, the mono-jet final state [7]: (a) Measured distribution of $E_T^{miss}$ for the SR1 selection compared to the SM expectations. For illustration purposes, the distributions of several signal scenarios are also shown. (b) Lower limits at 95% CL on the suppression scale $M_*$ shown as a function of the WIMP mass for the D5 operator in the most sensitive signal region for this operator, SR7.

The EFT description was adopted as the main benchmark model for DM in Run 1 of the LHC. It provides a simple, convenient benchmark for DM searches, without being dependent on details of a specific theory. However, the EFT approach becomes invalid when the momentum transfer of the collision approaches the mass of the mediator particle. The reliability of the EFT framework has been discussed in detail in [13], in which a study of the sensitivity of the ATLAS mono-jet search at $\sqrt{s} = 14$ TeV was presented considering both the EFT model and simplified models with an explicit light mediator. As shown in Figure 4, the sensitivity at 14 TeV will surpass the sensitivity using the final 8 TeV dataset within first year of data taking, assuming the EFT is a valid approach.

## 4. Long-lived particle searches

Many beyond-Standard-Model theories, including supersymmetry (SUSY), predict new massive particles with relatively long lifetimes. These theories include Split SUSY models, Hidden Valley models, Gauge mediated SUSY breaking, Stealth SUSY models, Anomaly mediated SUSY breaking, and SUSY with weak R-parity violation. Long-lived particles lead to unique experimental signatures such as late decaying, displaced vertices, and high ionization. ATLAS has a




(a) (b)

Figure 4: Sensitivity to WIMP in the mono-jet final state at 14 TeV [13]: (a) The 95% CL lower limits on the suppression scale $M^*$ at $\sqrt{s} = 8$ TeV and 14 TeV for three signal regions defined by $E_{\mathrm{T}}^{\mathrm{miss}} > 400$, 600 and 800 GeV. The limits are shown for the D5 operator with $M_\chi = 400$ GeV. (b) Discovery potential for dark matter signal with D5 operator and $M_\chi = 50$ GeV with 25 fb$^{-1}$ of data. These results assume that the EFT is a valid approach.

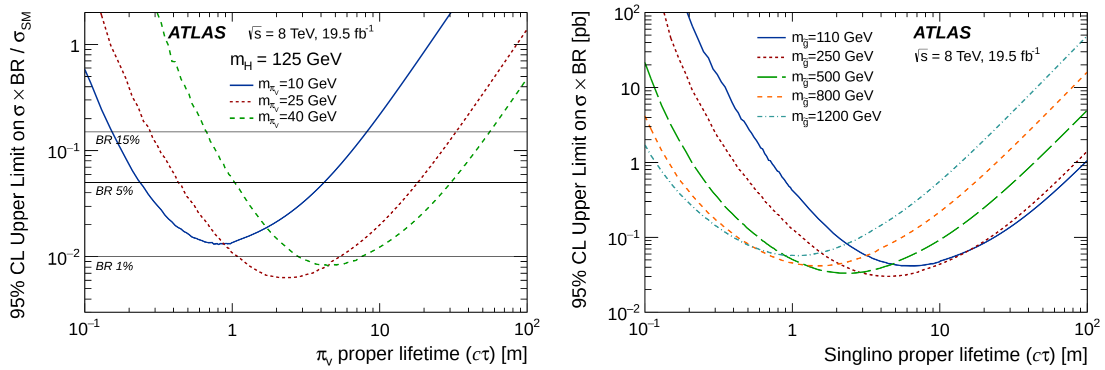
comprehensive search program covering almost all possible experimental signatures with innovative analysis techniques. In this proceeding two recent analyses that target non-SUSY signals are presented.

The first analysis employs techniques for reconstructing decay vertices of long-lived particles decaying to jets in the inner detector and the muon spectrometer [14]. Analysis is done in two separate channels defined by triggers: either passing muon RoI (Region of Interest) trigger or jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. Different topologies are considered for the two different channels targeting different benchmark models. No significant excess over the SM prediction is observed, and limits as a function of proper lifetime are reported for the long-lived particles in each benchmark model. Figure 5 presents results for two of the models considered.

The second analysis searches for heavy long-lived multi-charge particles [15]. These particles are predicted by many theories including models that implicate composite dark matter and a model that predicts a doubly charged Higgs. This analysis searches for particles producing anomalously high ionisation consistent with long-lived massive particles of electric charges from $|q| = 2e$ to $|q| = 6e$. Signal regions are defined using discriminating variables such as $dE/dx$ significances in the muon and inner detectors. Figure 6a shows an example distribution of the discriminating variables. For this analysis, no signal candidate events are observed, and the result is interpreted as 95% CL lower mass limits for a Drell-Yan production model, as shown in Figure 6b.

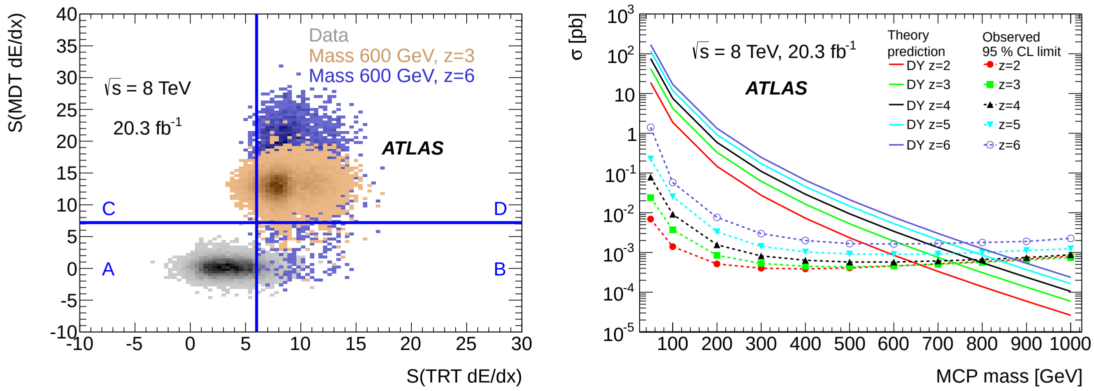
## 5. Conclusion

Using data collected in Run 1 of the LHC, the ATLAS Collaboration has produced impressive results on searches for VLQ, for dark matter candidates, and for long-lived particles. While no new




(a) (b)

Figure 5: Displaced jets in inner and muon detectors [14]: (a) Observed 95% CL limits on $\sigma \times \mathrm{BR}/\sigma_{\mathrm{SM}}$ for the scalar boson samples with $m_H = 125$ GeV. (b) Observed 95% CL limits on $\sigma \times \mathrm{BR}$ for the Stealth SUSY samples.




(a) (b)

Figure 6: Heavy long-lived multi-charge particles [15]: (a) $S(\mathrm{MDT}\ \mathrm{d}E/\mathrm{d}x)$ versus $S(\mathrm{TRT}\ \mathrm{d}E/\mathrm{d}x)$ after the $z \geq 3$ tight selection. The distributions of the data and the simulated signal samples (here for a mass of 600 GeV) are shown. (b) Observed 95% CL cross-section upper limits and theoretical cross-sections as functions of the MCP's mass for values of $z$ between 2 and 6.

physics beyond the Standard Model has been reached, stringent limits have been set on production cross section and parameters of new physics models. Additionally, interesting excess has been observed in some analyses. The increased center-of-mass energy and luminosity expected for Run 2 of the LHC will provide a tremendously exciting opportunity to discover new phenomena. In many instances, Run 1 sensitivity are expected to be surpassed within the first year of data taking.

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