Search for vector-like quarks in ATLAS

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Vector like quark (VLQ): the quark that left- and right-handed chirality have the same transition components under weak SU(2).
  - SM quarks: left- is SU(2) doublet and right- is singlet.

Many BSM theories introduce VLQ existence.
  - composite Higgs, Little Higgs, and others.

4 possible VLQ are introduced.
  - X(+5/3), T(+2/3), B(-1/3), Y(-4/3)

3 possible SU(2) transitions are taken into account.
  - singlet, doublet, triplet
2 VLQ production channels exist.

(1) **pair production**
- Via QCD
- The cross section depends only on VLQ mass.

(2) **single production**
- Via Electro-Weak
- The cross section depends on VLQ mass and mixing with SM particles.
- Can be dominant if both VLQ mass and mixing is large.
ATLAS collaborators search for VLQs using the LHC Run2 data (\(\sqrt{s} = 13\) TeV).

- **2015 data only (I do not introduce details today):**
  - pair production, b + same sign leptons channel, 3.2 fb\(^{-1}\) (ATLAS-CONF-2016-032)
  - single production, W+b channel, 3.2 fb\(^{-1}\) (ATLAS-CONF-2016-072)

- **2015+2016 data:**
  - pair production, Zt+X channel, 36.1 fb\(^{-1}\) (ATLAS-CONF-2017-015)
  - pair production, Ht+X channel, 13.3 fb\(^{-1}\) (ATLAS-CONF-2016-104)
  - pair production, Wb channel, 13.3 fb\(^{-1}\) (ATLAS-CONF-2016-102)
Results of 2015 data

No signal excess over the background was observed. Cross section limit was set.

W+same sign channel
Results of 2015 data

No signal excess over the background was observed. Cross section limit was set.

W+b channel
Zt+X channel

- Target:
  - TT -> Zt + X
  - Z decays into a pair of neutrinos
  - t or the other T produces exactly 1 charged lepton.

- The final state contains
  - large missing transverse momentum($E_T^{\text{miss}}$) mainly due to the invisibly decaying Z.
  - multiple jets.
  - exactly 1 charged lepton.
  - at least 1 b-tagged jet.
First, events are required to pass the pre-selection.

- At least 4 jets are reconstructed
- Exactly 1 charged lepton is reconstructed
- $E_T^{\text{miss}} > 200$ GeV

Then, events are categorised into control regions (CRs), validation regions (VRs), and signal region (SR).

**CRs**
- WCR: enriched in $W+b$
- TCR: enriched in $t\bar{t}$

**VRs**
- WVR: enriched in $W+b$
- TVR: enriched in $t\bar{t}$
- SRVR: enriched in single top
The main background process in the SR is $t\bar{t}$ and $W$+jets, and single top.

$t\bar{t}$, $W$+jets contribution is estimated using the data in TCR, single top contribution is estimated based on MC, and then validated using the data in VRs.
The main background process in the SR is \( t\bar{t} \) and \( W+jets \), and single top. \( t\bar{t} \), \( W+jets \) contribution is estimated using the data in TCR, single top contribution is estimated based on MC, and then validated using the data in VRs.

Figure 3: Comparison of data and prediction in the \( E_T \) distribution (left) and the \( H_{miss} \), sig distribution (right) in the TCR (top) and the WCR (bottom). The \( t\bar{t} \) and \( W+Njets \) normalisations are derived from the simultaneous fit, as indicated in the legend. The lower panels show the ratio of the data to the prediction. The error bands include statistical and systematic uncertainties. The last bin contains the overflow.

6 Systematic uncertainties

Systematic uncertainties from experimental sources and from the theoretical predictions affect the signal and background estimates. They are included as nuisance parameters with Gaussian constraints and are profiled in the likelihood fits that determine the background normalisation factors and the possible signal contribution. The uncertainties are not constrained further in the fits as the analysis has as many bins as free parameters. In general the systematic uncertainties are smaller than the statistical ones.

Dominant experimental uncertainties come from the imperfect knowledge of the jet mass and jet energy scale and resolution, as well as the modelling of the \( b \)-tagging efficiency for \( b \), \( c \) and light flavour jets.

The relative uncertainty on the estimated background yields in the SR from these sources is 1%–5%.
Figure 4: Comparison of data and prediction in the statistical and systematic uncertainties. The last bin contains the overflow.
Figure 4: Comparison of data and prediction in the Data / Pred. ATLAS, ATLAS Preliminary $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Good agreement within uncertainty

- Data/MC comparison in CRs (after estimation)
- W+jets, Diboson, Others
- $m_T^{\ell\ell}$ [GeV]
- $E_T^{\text{miss}}$ [GeV]

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After the background estimation, data in SR was compared to MC expectation.

- **MC expectation**: 6.1 ± 1.9 events
- **Data**: 7 events

**No excess was observed.**
Since no excess was observed, the cross section times branching ratio limit was calculated.

2 VLQ models (SU(2) singlet and doublet) were taken into account.

Exp: 0.89 TeV  
Obs: 0.87 TeV

Exp: 1.06 TeV  
Obs: 1.05 TeV
• Limits on T branching ratio was also calculated.
• Assuming that $\text{BR}(T\rightarrow Ht) + \text{BR}(T\rightarrow Wb) + \text{BR}(T\rightarrow Zt)=1$

![Expected and Observed 95% CL upper limit on the cross-section times branching ratio for VLQ T pair production as a function of the T mass for BR$(T\rightarrow Zt)$=100% (top) and for branching ratios according to the singlet model (bottom left) and the doublet model (bottom right). Contributions from the X or B quark in the $(X/3, T)$ or $(T, B)$ doublet models are neglected, leading to very conservative limits. The thickness of the theory curve represents the theoretical uncertainty from PDFs, scale and the strong coupling constant.]

![Expected and Observed 95% CL lower limit on the VLQ T mass as a function of the decay branching ratios into Wb and Ht. The markers indicate the branching ratios in the singlet and doublet models for masses above about 0.8 TeV, where they are approximately independent of the VLQ T mass.]

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Ht+X channel

- Target:
  - TT -> Ht + X
  - H decays into a pair of b quarks

- The final state contains
  - large missing transverse momentum
  - multiple jets.
  - 0 or exactly 1 charged leptons.
  - at least 2 b-tagged jet.
Signal and background are estimated using 0-lepton and 1-lepton channel independently.

- **1-lepton:**
  - background is estimated using 8 search regions and validated using 6 validation regions.

- **0-lepton:**
  - background is estimated using 12 search regions and validated using 9 validation regions.
Ht+X: Data/MC in search regions

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

Search regions
Post-fit (Bkg-only)

Events

Data
$tt + \text{light-jets}$
$tt + \geq 1c$
$tt + \geq 1b$
Non-$tt$
Total Bkg unc.

Data / Bkg

11, 0.1, $x \geq 1$, 30
11, 0.1, 30, $x \geq 20$
11, 0.1, 30, 40, 40, 40
11, 0.1, $x \geq 1$, 30, 40, 40, 40
11, 0.1, 30, 40, 40, 40
11, 0.1, $x \geq 1$, 30, 40, 40, 40
11, 0.1, 30, 40, 40, 40
11, 0.1, 30, 40, 40, 40
11, 0.1, 30, 40, 40, 40
Good agreement within uncertainty
No signal excess over the background was observed in neither 0-lepton nor 1-lepton. 0- and 1-lepton results are combined to set limits.

Exp: 1.10 TeV  
Obs: 1.16 TeV

Exp: 0.96 TeV  
Obs: 1.02 TeV
Limits on $T$ branching ratio was also calculated.
Assuming that $\text{BR}(T\rightarrow Ht) + \text{BR}(T\rightarrow Wb) + \text{BR}(T\rightarrow Zt) = 1$
Wb channel search was done using 14.7 fb\(^{-1}\) LHC data.

**Target:**
- TT $\rightarrow$ Wb+Wb
- One of W decays leptonically, the other hadronically

The final state contains
- large missing transverse momentum ($E_T^{\text{miss}}$) mainly due to the neutrino from W.
- at least 1 jet.
- exactly 1 charged lepton.
- at least 2 b-tagged jet.
Boosted and non-boosted (resolved) hadronic W have quite different topology.

- **Resolved**
  - Hadrons are reconstructed as 2 small-R (R=0.4) jets.

- **Boosted**
  - Hadrons are reconstructed as 1 large-R (R=1.0) jet.

2 signal regions are defined to use both topology.
The dominant background in the Wb channel is $t\bar{t}$. Other background $W+$jet, single top, Diboson, $t\bar{t}+V$, $Z+$jets, and multi-jets are taken into account.

- $t\bar{t}$: Estimated by MC.
  Dedicated control regions are used in order to constrain the systematic uncertainty.


- Others: Estimated with MC.
The dominant background in the Wb channel is tt. Other background W+jet, single top, Diboson, tt+V, Z+jets, and multi-jets are taken into account. 

- tt: Estimated by MC.
- Dedicated control regions are used in order to constrain the systematic uncertainty.
- Others: Estimated with MC.
The dominant background in the Wb channel is tt.

Other background W+jet, single top, Diboson, tt+V, Z+jets, and multi-jets are taken into account.

- tt: Estimated by MC.
- Dedicated control regions are used in order to constrain the systematic uncertainty.
- Others: Estimated with MC.

Data/MC comparison in CRs (after estimation)

Good agreement within uncertainty
Wb: Event yields in the SRs

SR boosted
- MC: 3246±81
- Data: 3160

SR resolved
- MC: 3690±100
- Data: 3777

No excess was observed.
Since no excess was observed, the cross section times branching ratio limit was calculated.

SU(2) singlet model and BR(T->Wb)=1 model are taken into account.

Exp: 0.98 TeV
Obs: 1.09 TeV

Exp: 0.87 TeV
Obs: 0.81 TeV
Limits on T branching ratio was also calculated. Assuming that $BR(T\rightarrow Ht) + BR(T\rightarrow Wb) + BR(T\rightarrow Zt) = 1$.
Summary

- ATLAS VLQ search was done using the LHC 13TeV data.
- Search was done using many channels.
- No excess over MC expectation was observed.

- 95% CL limit was set:
  - 0.87 TeV (Zt+X channel, SU(2) singlet)
  - 1.05 TeV (Zt+X channel, SU(2) doublet)
  - 1.02 TeV (Ht+X channel, SU(2) singlet)
  - 1.16 TeV (Ht+X channel, SU(2) doublet)
  - 1.09 TeV (Wb channel, BR(T->Wb)=1)
  - 0.81 TeV (Wb channel, SU(2) singlet)
VLQ production cross section

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