Searches for new physics with third generation quarks using the ATLAS detector at the LHC

J. Ferrando
on behalf of the ATLAS Collaboration

University of Glasgow

DIS 2016
Hamburg, 13/04/2016
Why search for new physics with third generation quarks?
Searches for new heavy bosons
Searches for new heavy fermions
Summary

Searches from two different datasets are presented in this talk:
- Run 1: 20 fb$^{-1}$ of $\sqrt{s} = 8$ TeV data
- Run 2: 3 fb$^{-1}$ of $\sqrt{s} = 13$ TeV data
Why 3rd Gen?

The third generation quarks are particularly interesting for new-physics searches, especially the top quark:

- The heaviest fundamental particle
- The only fermion with mass around the EW breaking scale
- The only quark with yukawa coupling of order unity

Many BSM models place the top in a special role:

- **2 Higgs-doublet models**: Large coupling to the top
- **Extra dimensions**: Kaluza-Klein excitations of gauge bosons and the graviton with strong coupling to the top in 'Bulk RS' scenarios
- **Composite Higgs**: Fermionic 'Top partners’

These models predict new heavy bosons and/or fermions decaying to final states involving top quarks
New heavy bosons

Searching for new heavy bosons that decay to $t\bar{t}$, possible candidate bosons include:

- New Scalar, such as heavy higgs
- New Spin 1 resonances (color singlet), such as $Z'$ (usually narrow), from e.g. topcolor, Bulk-RS
- New Spin 1 resonances (color octet) such as $g_{KK}$ (broad) from e.g. Compositeness, bulk RS
- New Spin 2 resonances (color singlet): such as $G_{KK}$ (narrow) from e.g. Compositeness, bulk RS

Strategy: Select $t\bar{t}$ events then reconstruct $m(t\bar{t})$ and look for a mass peak
Run-2 searches for new particles at masses over 2 TeV expected to quickly surpass sensitivity of Run-1 searches
Introduction

Why third gen?

New bosons

New fermions

Summary

Search at 13 TeV

Comparison with 8 TeV

Low Energy tops

\[ t \rightarrow bW, \ W \rightarrow qq' \] gives three distinct “jets”:

- b-jet
- Light Jets

High Energy tops

top decay system is highly boosted and reconstructed as only one jet:

- Top Monojet

Run 1 search JHEP 1508 (2015) 148 combined both regimes

First ATLAS Run-II search for \( X \rightarrow t\bar{t} \):

ATLAS-CONF-2016-014 targets highly-boosted case
Run-2 search uses the single lepton plus jets $t\bar{t}$ decay channel

- Much larger branching ratio than dileptonic $t\bar{t}$
- Much better $t\bar{t}$ selection purity than all-hadronic $t\bar{t}$

Simple requirements:

- Hadronic top candidate:
  - Large-radius jet, top-tagged (ATL-PHYS-PUB-2015-053)

- Semi-leptonic top candidate:
  - Charged lepton
  - Missing transverse momentum
  - Small-radius jet
Selection efficiency good for masses above 1.5 TeV
Looser $p_T$-dependent overlap removal between $\mu$ and jets allows higher selection efficiency
No evidence for new particles decaying to $t\bar{t}$
Search at 13 TeV
Comparison with 8 TeV

Limit on new physics

Introduction
Why third gen?
New bosons
New fermions
Summary

Searches with third generation quarks

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

$\sigma_Z \times BR(Z' \rightarrow t\bar{t})$ [pb]

- Observed 95% CL limit
- Expected 95% CL limit
- Exp. 1 $\sigma$ uncertainty
- Exp. 2 $\sigma$ uncertainty
- $Z'_{TC2}(\Gamma/m=1.2\%)$ (LO $\times 1.3$)
- $Z'_{TC2}(\Gamma/m=3\%)$ (LO $\times 1.3$)
With 3.2 fb\(^{-1}\) new physics reach in \(m(Z')\) already surpasses Run 1

Run 1 search also has limits on scalars, \(g_{KK}\) and \(G_{KK}\)

Run 1 includes the resolved regime
New heavy vector-like quarks predicted in compositeness/extra dimension scenarios:

- No yukawa coupling to the higgs
- Can decay to $qW$, $qZ$, $qH$
- Natural masses $\lesssim 1$ TeV
- Pair produced via the strong-interaction
- Limited parameter space: mass and branching ratios
- Can also be singly produced

Depending on weak coupling single production rate can exceed pair production at high-masses
New heavy vector-like quarks predicted in compositeness/extra dimension scenarios:

- No yukawa coupling to the higgs
- Can decay to $qW$, $qZ$, $qH$
- Natural masses $\lesssim 1$ TeV
- Pair produced via the strong-interaction
- Limited parameter space: mass and branching ratios
- Can also be singly produced
- Depending on weak coupling single production rate can exceed pair production at high-masses
ATLAS has several searches for pair production of B quarks, each sensitive to different decay modes:

- $Zb + X$ for large $\mathcal{BR}(B \to bZ)$:
  JHEP 1411 (2014) 104

- $l^\pm l^\pm + b$ for large $\mathcal{BR}(B \to tW)$:
  JHEP 1510 (2015) 150

- $Hb + X$ for large $\mathcal{BR}(B \to bH)$:
  JHEP 1508 (2015) 105

the latter search is discussed here
Select sample dominated by $t\bar{t}$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^\pm$, $E^\text{miss}_T$
- Subdivide into 8 categories by $n_{\text{jets}}$, $b$ multiplicity and mass of closest two $b$ jets
- Background rich regions have low $b$-multiplicity
- Signal rich regions have high $b$-multiplicity
- Search using distribution of scalar sum of transverse momentum of jets, $l^\pm$ and $E^\text{miss}_T (H_T)$
Select sample dominated by $t\bar{t}$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^\pm$, $E_T^{miss}$
- Subdivide into 8 categories by $n_{jets}$, $b$ multiplicity and mass of closest two $b$ jets
- Background rich regions have low $b$-multiplicity
- Signal rich regions have high $b$-multiplicity
- Search using distribution of scalar sum of transverse momentum of jets, $l^\pm$ and $E_T^{miss}$ ($H_T$)
Select sample dominated by $t\bar{t}$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^{\pm}$, $E_T^{\text{miss}}$
- Subdivide into 8 categories by $n_{\text{jets}}$, $b$ multiplicity and mass of closest two $b$ jets
- Background rich regions have low $b$-multiplicity
- Signal rich regions have high $b$-multiplicity
- Search using distribution of scalar sum of transverse momentum of jets, $l^{\pm}$ and $E_T^{\text{miss}} (H_T)$
Pair production

Why third gen?
New bosons
New fermions

Summary

searching for $B$
searching for $T$

Cross-section limits dependent on mass and BR set
Exclusion in BR plane for given hypothetical $B$ masses
Pair production

Introduction
Why third gen?
New bosons
New fermions
Summary

Add Same-sign lepton limits to the plot
Add $bZ + X$ limits to the same plot
ATLAS has several searches for pair production of $T$ quarks, each sensitive to different decay modes:

- $Zt + X$ for large $\mathcal{BR}(T \rightarrow tZ)$:
  JHEP 1411 (2014) 104
- $l^\pm l^\mp + b$ for large $\mathcal{BR}(T \rightarrow tZ, tH)$:
  JHEP 1510 (2015) 150
- $Wb + X$ for large $\mathcal{BR}(T \rightarrow Wb)$:
  JHEP 1508 (2015) 105
- $Ht + X$ for large $\mathcal{BR}(T \rightarrow tH)$:
  ATLAS-CONF-2016-013

the latter search is discussed here
Similar strategy to $Hb + X$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^{\pm}$, $E_T^{\text{miss}}$
- 20 categories by $n_{\text{jets}}$, $n_b$
  - mass of closest two $b$ jets,
  - number of large-radius jets with mass $> 100$ GeV

- Background rich regions have low $b$-multiplicity
- Signal rich regions have high $b$-multiplicity
- Use distribution of scalar sum of transverse momentum of jets, $l^{\pm}$ and $E_T^{\text{miss}}$, $m_{\text{eff}}$
Similar strategy to $Hb + X$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^\pm$, $E_T^{\text{miss}}$
- 20 categories by $n_{\text{jets}}$, $n_b$ mass of closest two $b$ jets, number of large-radius jets with mass $> 100$ GeV
- Background rich regions have low $b$-multiplicity
- Signal rich regions have high $b$-multiplicity
- Use distribution of scalar sum of transverse momentum of jets, $l^\pm$ and $E_T^{\text{miss}}$ ($m_{\text{eff}}$)
Similar strategy to $Hb + X$:

- Require $\geq 5$ jets $\geq 2$ b-jets, $l^\pm$, $E^\text{miss}_T$
- 20 categories by $n_{\text{jets}}$, $n_b$
  - mass of closest two $b$ jets,
  - number of large-radius jets with mass $> 100$ GeV
- Background rich regions have low $b$ - multiplicity
- Signal rich regions have high $b$ - multiplicity
- Use distribution of scalar sum of transverse momentum of jets, $l^\pm$ and $E^\text{miss}_T (m_{\text{eff}})$
Some $m_{\text{eff}}$ distributions from signal-sensitive regions before/after a background-only hypothesis fit.
- Observed limits slightly weaker than expected above 700 GeV
- Sensitivity to physical BRs up to around 900 GeV mass
Compared to 8 TeV

**Introduction**

Why third gen?

New bosons

New fermions

**Summary**

Searching for $B$

Searching for $T$

\[ \text{ATLAS} \]

$\sqrt{s} = 8 \text{ TeV}$, \[ L dt = 20.3 \text{ fb}^{-1} \]

- 95% CL exp. excl.
- 95% CL obs. excl.

$H_t + X$ limits from Run 1
Expected mass reach exceeds that of Run-1 but fluctuations in data lead to weaker observed limits
Compared to 8 TeV

Add same-sign limits
Introduction

Why third gen?

New bosons

New fermions

Summary

Compared to 8 TeV

ATLAS

$\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$

95% CL exp. excl. – 95% CL obs. excl.

$Ht+X$ [arXiv:1505.04306]

Same-Sign dil. [arXiv:1504.04605]

$Zb/t+X$ [JHEP11 (2014) 104]

$\rightarrow$ BR($T_Ht$) → BR($T_Ht$)

Add $Zt + X$ limits to Run 1 limits
Compared to 8 TeV

**Introduction**

Why third gen?

New bosons

New fermions

**Summary**

**Compared to**

searching for $B$

searching for $T$

ATLAS

$\sqrt{s} = 8$ TeV,

\[ L \text{ dt} = 20.3 \text{ fb}^{-1} \]

$95\% \text{ CL exp. excl.}$

$95\% \text{ CL obs. excl.}$

\[ \int \]

\[ SU(2) \text{ singlet} \]

\[ SU(2) \text{ (T,B) doub.} \]

\[ JFerrando \]

\[ JHEP11 (2014) 104 \]

$90\% \text{ CL exp. excl.}$

$90\% \text{ CL obs. excl.}$

\[ JFerrando \]

\[ JHEP11 (2014) 104 \]

$90\% \text{ CL exp. excl.}$

$90\% \text{ CL obs. excl.}$

\[ JFerrando \]

\[ JHEP11 (2014) 104 \]
Single production of $T$ has also recently been studied in the $T \rightarrow Wb$ finale state (arXiv:1602.05606):

- Sensitive to $TWb$ coupling for given masses
- Signature: $l^{\pm}$, $E_T^{\text{miss}}$, isolated $b$-jet, forward jet
- Large $t\bar{t}$ background suppressed by matching a low-mass large-$R$ jet to the $b$-jet as proposed in: Phys. Rev. D 90, 075009 (2014)
- $b$-jet, lepton and $E_T^{\text{miss}}$ used to reconstruct candidate $T$ mass
**Introduction**

Why third gen?

New bosons

New fermions

Summary

---

**Searches with third generation quarks**

---

**Single Production**

**Why third gen?**

**New bosons**

**New fermions**

**Summary**

---

**Remainder SM prediction dominated by \( W + \text{jets} \)**
Cross-section limits set and translated to coupling limits
For large couplings, extends mass limit beyond pair production searches
Final states with top quarks are an excellent way to probe new physics.

Run-2 sensitivity to heavy bosons and fermions that decay to top quarks already surpasses Run-1 in phenomenologically interesting mass ranges.

Exclusion limits on VLQ production pushing close to natural size of masses.

Single VLQ Production searches shown to extend sensitivity to higher masses for larger coupling values.
Additional related searches which could not be covered in the time allotted to this talk:

- Single $b^*$ production: JHEP 1602 (2016) 110