Outline:

• Why 4 generations?
• Phenomenology at the LHC
• Searches at ATLAS
• Conclusions and Outlook
• 4th generation not excluded by the electroweak precision data.
  – small mass splitting between the 4th generation quarks is preferred: $|m_t - m_{b'}| < m_W$.

• Measurement from LEP: $N_\nu = 2.92 \pm 0.05$
  – but $N(\text{gen}) > 3$ if heavy neutrino mass $> 0.5 m_Z$

• BAU: 4th generation could enhance CP violation

• Many interesting phenomena may occur at the LHC
  – presence of 4th generation affects Higgs production rate and decay modes
• Main production through strong interaction
  – single $t'$ production in the $t$-channel suppressed if 3-4 CKM mixing element is negligible
• Decay channel
  – $t'$: assuming $|m_{t'} - m_b'| < m_W$, $t'$ predominantly decays in W boson and down type quarks
  – $b'$: if $m_{b'} > m_t + m_W$ $b'$ decay mostly as $b' \rightarrow Wt \rightarrow WWb$
• Analysis presented here:
  – $t't' \rightarrow WbWb \rightarrow bbbq'lv$
  – $b'b' \rightarrow WtWt \rightarrow bbWWWW \rightarrow bbbq'qq'qq'lv$
  – $QQ \rightarrow WqWq \rightarrow qqlvlv$ [where $Q$ denotes a generic heavy quark]
• 4th generation quarks can also originated more exotic signatures
  – See talk on Vector-Like-Quarks by M. Davies
Exactly one lepton in the event
Muon: $p_T > 20$ GeV, $|\eta| < 2.5$
Electron: $p_T > 25$ GeV, $|\eta| < 2.47$

Neutrino detected as missing transverse energy
MET > 35 GeV [electron channel]
MET > 20 GeV [muon channel]

At least one jet is $b$-tagged
$\varepsilon(b) \sim 70\%$, rejection $\sim 100$

Jet multiplicity
At least 3 jets $p_T > 25$, $|\eta| < 2.5$
At least one jet $p_T > 60$

MET + $m_T > 60$ GeV, where $m_T$ is transverse mass lepton and MET
• Signal is modeled using PYTHIA 6.421
  – masses generated between 200 GeV to 600 GeV in steps of 50 GeV

• Main Background after pre-selection
  – top quark: estimated using simulated events with MC@NLO
  – W+Jets shape from simulation ALPGEN v2.13 and normalization from data
  – multi-jet events estimated from data using matrix method (normalization and shape)
Discriminant

- Reconstructed heavy quark mass $m_{\text{reco}}$ is the discriminating variable
  - in the case of events with $\geq 4$ jets combination minimizing a kinematic fit is taken

- Systematic uncertainties:
  - large contribution from $tt$
    - theoretical cross section, fragmentation models
  - $W$+jets systematics derived in 2 jet bin
    - associated to extrapolation to higher multiplicity and heavy flavor content
  - other major sources are $b$-tagging and QCD multi-jet evaluation

- Profile likelihood
  - per bin signal and background predictions are parameterized using 12 nuisance parameters representing major sources of systematic uncertainties
  - after the fit $m_{\text{reco}}$ is shown in the right
Assuming BR(\(t' \to Wb\))=1 observed (expected) 95% CL limit \(m_{t'} > 404 \, (394) \, \text{GeV}\)
Exactly one lepton in the event
Muon: $p_T > 20$ GeV, $|\eta| < 2.5$
Electron: $p_T > 25$ GeV, $|\eta| < 2.47$

Neutrino detected as missing transverse energy
MET > 35 GeV [electron channel]
MET > 20 GeV [muon channel]

Jet multiplicity
At least 6 jets $p_T > 25$ GeV, $|\eta| < 2.5$

MET + $m_T > 60$ GeV,
where $m_T$ is transverse mass lepton and MET

pre-selection

arXiv:1202.6540
Agreement after pre-selection

- Signal is modeled using PYTHIA 6.421
  - masses generated between 300 to 600 GeV cross section for $b'$ production \( \sim 3.2 \) pb at \( m_b' = 350 \) GeV and 0.33 pb at 500 GeV
  - signal efficiency of 11.2\% and 13.5\% for \( m_b' \) of 350 GeV and 500 GeV respectively
- Main Background after preselection
  - \( tt \) simulated using ALPGEN
    - rate from data in low jet multiplicity region
      - \( W+\text{jets} \) shape from simulation ALPGEN v2.13 and normalization from data
      - diboson ALPGEN normalized to NLO calculation
      - \( tt+\text{vector boson} \) production is modeled with MADGRAPH
      - \( \text{multi-jet events} \) estimated from data using matrix method (normalization and shape)
Events where a $b'$ is produced are identified by the large number of hadronic “semi-boosted” $W$ bosons

- medium energy $b'$ regime these can be identified by two jets having $\Delta R < 1.0$ and mass compatible with $W$ boson
- goodness of simulation checked on signal depleted samples (low jet multiplicity)

- 9 exclusive bins of different jet and hadronic $W$ multiplicity used
- Profile likelihood used to fit signal and background contribution within systematic uncertainties
Assuming $\text{BR}(t' \rightarrow Wb)=1$ observed (expected) 95% CL limit $m_b > 480$ (470) GeV
Exactly two leptons in the event
Muon: $p_T > 20 \text{ GeV}$, $|\eta| < 2.5$
Electron: $p_T > 25 \text{ GeV}$, $|\eta| < 2.47$

Neutrino detected as missing transverse energy
same flavor events (ee, $\mu\mu$) MET $> 60 \text{ GeV}$
different flavor ($e\mu$) HT $> 130 \text{ GeV}$

Dilepton invariant mass for same flavor events must be $> 15 \text{ GeV}$ and outside the Z mass peak 81 GeV to 101 GeV
Jet multiplicity
At least 2 jets $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
**Signal is modeled using PYTHIA 6.421**
- cross section for QQ’ NNLO ranges from 0.3 pb to 8.0 pb depending on the mass

**Main Background after pre-selection**
- top production simulated using MC@NLO
- Z/γ* + jets from ALPGEN
  - normalization factor from same flavor lepton events inside Z mass window
- multi-jet events
  - matrix method using electron and muon loose to tight efficiency for real electrons and fakes:
    - Fakes muons: b/c decays
    - Fake electrons: b/c decays, ϒ conversions, π0’s
• Discriminating variable $m_{\text{Collinear}}$
  – mass for heavy quarks reconstructed
  – collinear approximation for neutrinos taken into account when fitting masses using same mass constraint for heavy quark and real W mass
  – higher correlation for heavy quark production w.r.t. background events
    – $|m_{\text{collinear1}}-m_{\text{collinear2}}|< 25$ GeV
• Final Event Selection
  • pre-selection used to discriminate against $Z+\text{jet}$ production
  • additional signal mass dependent cuts, HT+MET and leading jet $p_T$’s, are put in place to discriminated against top quark production.
Sources of systematic uncertainty come from lepton reconstruction efficiencies, jet energy scale and pile up effect (particularly true for MET estimation)

- acceptance for signal and background from simulation carry associated uncertainty on choice of generator and either theoretical calculation or data driven rate estimation

Assuming $\text{BR}(Q \rightarrow Wq)=1$ observed (expected) 95% CL limit $m_Q>350$ (335) GeV
ATLAS actively searched for 4th generations quarks

Analyses with 1 fb-1 data have excluded at 95% CL the following new heavy quarks:

- observed (expected) limit for $t'$: $m_{t'} < 404 (394)$ GeV
  - Assuming $\text{BR}(t' \rightarrow Wb) = 1$
- observed (expected) limit for $b'$: $m_{b'} < 480 (470)$ GeV
  - Assuming $\text{BR}(b' \rightarrow Wt) = 1$
- observed (expected) limit for $Q$: $m_Q < 350 (335)$ GeV
  - Assuming $\text{BR}(Q \rightarrow Wq) = 1$

More results in the pipeline with full 2011 dataset

Sequential 4th generation can be ruled out using full 2012 dataset
  - constraints from Higgs production and decay rates

Direct Searches more challenging in the high mass region or in case of small 3-4 mixing angle
  - unexplored phase space could exists even after 2012 data taking