Fourth Generation Quark
and
Vector Like Quark
with
the ATLAS detector

Léa Gauthier (CEA-Saclay / Montréal University)
on behalf of the ATLAS collaboration
Quark Confinement and the Hadron Spectrum X
Fourth Generation Quark:

- **new chiral generation**: SU(2) doublet (t',b') with the corresponding right-handed singlets under SU(2)
- **new CP violation** to explain matter dominated Universe
- **model disfavored** by $m_H \sim 126$ GeV (arXiv:1207.0438)
- **saved by extended 4\textsuperscript{th} generation**
- **latest results presented here**:
  - $m(Q) > 350$ GeV for up and down type Q
  - $m(t') > 656$ GeV    $m(b') > 670$ GeV
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Vector Like Quark:

- both right and left handed components transform the same way under the EW gauge groups
- VLQs have been introduced in many different models: Composite Higgs, Extra Dimension, SUSY
- VLQs fix the hierarchy problem and explain the observed $A_{FB}$ asymmetry of bottom quark
- VLQs mix with 3rd generation SM quarks (constraints from EWK precision and flavor observables)
- mixing to first generations is not excluded (in some models corrections to the quark mixings can cancel relaxing these constraints)
Events were studied in l+jets and dilepton channel (e and μ) @ 7 TeV between 1.98 fb$^{-1}$ and 4.7 fb$^{-1}$

**Events studied:**

- **Fourth generation quarks**: $QQ \rightarrow W^+qW^-\bar{q}$ for up and down type $Q$
  - $t' \bar{t} \rightarrow Wb\bar{Wb}$ and VLQ interpretation of $t' \rightarrow Wb$  $t' \rightarrow Zt$  $t' \rightarrow Ht$
  - $b'\bar{b'} \rightarrow Wt\bar{Wt}$

- **Vector Like Quarks**: VLQs with charge 5/3 for different coupling value $\lambda(T_{5/3}tW)$
  - VLQ interpretation of $b'\bar{b'} \rightarrow Zb+X$ (vector like singlet model)
  - single production of VLQ coupling to light generations
Searches

Events were studied in l+jets and dilepton channel (e and μ) @ 7 TeV between 1.98 fb⁻¹ and 4.7 fb⁻¹

Events studied:

- Fourth generation quarks: \( \bar{Q}Q \rightarrow W^+qW^-\bar{q} \) for up and down type Q
  \[ t' \bar{t} \rightarrow WbW\bar{b} \] and VLQ interpretation of \( t' \rightarrow Wb \ t' \rightarrow Zt \ t' \rightarrow Ht \)
  \[ b\bar{b} \rightarrow WtW\bar{t} \]

- Vector Like Quarks: VLQs with charge 5/3 for different coupling value \( \lambda(t_{5/3}tW) \)
  VLQ interpretation of \( b\bar{b}' \rightarrow Zb+X \) (vector like singlet model)
  single production of VLQ coupling to light generations

Events are selected based on top quark selection:

- Electrons:
  - \( P_T > 25 \text{ GeV} \)
  - \( |\eta| < 2.47 \) and not \( 1.37 < |\eta| < 1.52 \)
  - isolated

- Muons:
  - \( P_T > 20 \text{ GeV} \)
  - \( |\eta| < 2.50 \)
  - Isolated
  - cosmic rejection

- Jets:
  - anti-k\(_T\) \( \Delta R=0.4 \)
  - \( P_T > 25 \text{ GeV} \)
  - \( |\eta| < 2.50 \)
  - not inside an electron

Limits are extracted using Cls (except Bayesian for single production of VLQ coupling to light generations)
Background

★ For the dilepton final state:
- dibosons: WW, WZ and ZZ (Herwig or Alpgen + Jimmy)
- fake leptons (data-driven: matrix method)

★ for the opposite sign (OS) leptons:
- $t\bar{t}$ and single top (MC@NLO+Herwig)
- Z+jets (Alpgen + Jimmy or Sherpa)
- Drell-Yann events (data-driven technique that extrapolates from a control region)
★ for the same sign (SS) leptons:
- $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}WW$, WWjj (MadGraph + Pythia)
- charge flip (data-driven)

★ For the single lepton final state:
- dibosons: WW, WZ and ZZ (Herwig)
- $t\bar{t}$ (Alpgen+Herwig or MC@NLO+Herwig)
- single top (MC@NLO+Herwig or AcerMC+Pythia)
- W+jets, Z+jets (Alpgen + Herwig or Sherpa)
- $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}WW$, WWjj (MadGraph + Pythia for b' analysis with W only)
- multijets (data-driven)
Systematic uncertainties

- **For the Monte Carlo:**
  - object calibration, resolution and energy scale, missing energy
  - trigger and reconstruction efficiency
  - initial and final state radiations
  - luminosity
  - MC cross section
  - PDF
  - Modeling of b-tagging efficiency and fake rates
  - Modeling of the signal and background

- **For the data-driven techniques:**
  - fakes: estimated using variations on control region selection for the calculation of probability that a real or fake loose lepton passes the tight criteria
  - charge flip (for SS leptons): estimated by differences between the 3 methods used (tag-and-probe, direct extraction, likelihood)
**$Q\bar{Q} \rightarrow WqW\bar{q}$ in 2 leptons channel ($e$ or $\mu$)**

- Events $Q\bar{Q} \rightarrow W^+qW^-\bar{q}$  
  $q = d, s, b$ for up-type $Q$  
  $@ 1$ fb$^{-1}$  
  (arXiv: 1202.3389,  

- **Analysis:**
  - Mass reconstruction of heavy boosted $Q$ quark candidates is performed ($m_{\text{collinear}}$)
  - A cut $H_T, E_T^{\text{miss}}$ and $m_{\text{collinear}}$ dependent on the assumed signal mass is applied

- **Results:** a binned maximum-likelihood ratio technique is used to fit distributions of $m_{\text{collinear}}$ to the observed data

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**Graphs:**

- **ATLAS**
  - Events / 40 GeV
  - $m_{\text{collinear}}$ [GeV]
  - $L = 1.04$ fb$^{-1}$
  - $m(Q) > 335$ GeV (exp)
  - $m(Q) > 350$ GeV (obs)

- **$\sigma \times BR(Q\bar{Q} \rightarrow W^+qW^-\bar{q})$ [pb]**
  - $m_Q$ [GeV]
  - $95\%$ CL @ $4.7$ fb$^{-1}$
  - $m(Q) > 335$ GeV (exp)
  - $m(Q) > 350$ GeV (obs)

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**08/10/2012**

**Lea Gauthier**, (CEA-Saclay / Montréal University)  
**06/16**
$t't' \rightarrow WbWb$ in single lepton + jets channel (e or $\mu$)

- Events $t't' \rightarrow WbWb$ @ 4.7 fb$^{-1}$ (soon on arXiv)

- Only the range $m(t') < m(W) + m(b')$ is considered
  - events with exactly 3 jets or with 4 or more jets are analyzed separately

- Signal generated with Pythia and normalized to the approximate NNLO theoretical cross sections

- Event selection:
  - exactly 1 lepton
  - 2 definitions of $W_{\text{had}}$: $W_{\text{had}}^{\text{type I}}$ (single jet with $p_T > 250$ GeV and mass in [60-110] GeV) and $W_{\text{had}}^{\text{type II}}$ (dijet with $p_T > 150$ GeV, $\Delta R(j, j) < 0.8$ and $M_{ij}$ in [60-110] GeV)
  - $\geq 3$ jets and $\geq 1$ $W_{\text{had}}^{\text{type I}}$ candidates or $\geq 4$ jets and $\geq 1$ $W_{\text{had}}^{\text{type II}}$ candidates
  - $H_T$ ($\Sigma$lep, $E_T^{\text{miss}}$, 4(3) jets) $> 750$ GeV
  - $P_T$ (leading b-jet) $> 160$ GeV, $P_T$ (subleading b-jet) $> 60$ GeV,
  - $\Delta R(l, \nu) < 1.4$, $\min(\Delta R(W_{\text{had}}, b_{1,2})) > 1.4$, $\min(\Delta R(l, b_{1,2})) > 1.4$

- $t'$ mass reconstruction (built from $W_{\text{had}}$):
  - $m_{\text{reco}}$ built from $W_{\text{had}}$ and one of the two b-jet candidates
  - reconstruction of $W_{\text{lep}} \rightarrow$ two solutions and two possible ways to pair the b-jet candidates
  - the solution yielding the smallest $|\Delta M(t', \bar{t}')|$ is chosen
Results:

- $m_{\text{reco}}$ is analyzed using a log-likelihood ratio as test-statistic
- 95% C.L. upper limits on the $t' \bar{t}'$ production cross section are derived using the CLs method
- the uncertainties are taken into account

Previous limit @ 1 fb$^{-1}$: $m(t') > 394$ GeV (expected) @ 1 fb$^{-1}$ (arXiv: 1202.3076, Phys.Rev.Lett. 108 (2012) 261802)
$m(t') > 404$ GeV (observed)
Vector Like Quark interpretation of $t'\bar{t}' \rightarrow Wb\bar{W}b$

VLQ interpretation of $t' @ 4.7 \text{ fb}^{-1}$

→ soon on arXiv

the limit is interpreted in vector like quark model where $t' \rightarrow Wb$
$t' \rightarrow Zt$
$t' \rightarrow Ht$

the sum of the 3 BR is 1

$\sqrt{s} = 7 \text{ TeV}, \int L \, dt = 4.7 \text{ fb}^{-1}$
**Study:**
- \( b' \): pair production only (limit on cross-section)
- \( T_{5/3} \): pair + single production (limit on cross-section depending on the coupling \( T_{5/3} tW \))

**Signal** generated with Pythia and normalized to NNLO theoretical cross sections

**Event selection:**
- \( \geq 2 \) leptons (pair with highest \( P_T \) if multiple)
- at least 2 jets and at least 1 b-tagged
- \( E_T^{\text{miss}} > 40 \) GeV
- \( M_{ll} > 15 \) GeV and \( |M_{ll} - M_Z| > 10 \) GeV (ee, \( \mu \mu \) channels)
- \( H_T \) (lep, jets) > 550 GeV

**Results:**
- A cut and count method is used
- The CLs method is used to set 95% confidence level cross section upper limits for the pair production of fourth generation quarks

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\( b'b' / T_{5/3} T_{5/3} \to WtWt \) in same sign leptons channel (e or \( \mu \))

\( \text{Events } b'b' / T_{5/3} T_{5/3} \to WtWt \) \( @ 4.7 \) fb\(^{-1} \) for SS lepton channel

(ATALS-COM-CONF-2012-163)
\( \bar{b}'\bar{b}' / T_{5/3}^3 \bar{T}_{5/3} \rightarrow WtWt \) in same sign leptons channel (e or \( \mu \))

Other results:
- study done @ 1 fb\(^{-1}\) for single lepton channel \((arXiv: 1202.6540, Phys.Rev.Lett. 109 (2012) 032001)\)
- limit: \( m(b') > 480 \text{ GeV} \)

95% CL @ 4.7 fb\(^{-1}\)
- pair production: \( m(b'/T_{5/3}) > 670 \text{ GeV} \)
- pair+single coupling = 1: \( m(T_{5/3}) > 680 \text{ GeV} \)
- pair+single coupling = 3: \( m(T_{5/3}) > 700 \text{ GeV} \)
$b'b' \rightarrow Zb+X$ in single lepton and dilepton channel (e or $\mu$)

- Events $b'b' \rightarrow Zb+X$ @ 1.98 fb$^{-1}$ where $Z \rightarrow ee$ (arXiv : 1204.1265, Phys.Rev.Lett. 109 (2012) 071801)

- Signal generated with MadGraph + Pythia and normalized to NNLO theoretical cross sections

- At least one b' decay to $b' \rightarrow Z + b$

- The case of a vector-like singlet (VLS) mixing solely with the third SM generation is also considered (a SM Higgs of mass 125 GeV is assumed)

- Event selection:
  - at least 2 OS leptons
  - $|M_{ee} - M_Z| < 15$ GeV
  - at least 1 b-tagged jet

- Analysis:
  - the b' candidate is formed from the $e^+ e^-$ pair and the highest $p_T$ b-jet
  - the mass of the b' candidate, $m(Zb)$, is the discriminant variable
  - cut: $p_T(Zb) > 150$ GeV applied to increase the signal sensitivity
The limit is computed using a binned Poisson likelihood ratio test of the $m(Z_b)$ distribution for different $m(b')$ hypothesis.

The cross section limit is evaluated using the CLs modified frequentist approach.

$m(b') > 400$ GeV

vector-like singlet $b'$ mixing solely with the third SM generation: $m(b')$ for VLS > 358 GeV
**Single Production of VLQ Coupling to Light Generations**

- Events @ 4.64 fb⁻¹ with a \( W \rightarrow l\nu \) or \( Z \rightarrow l\nu \) boson produced in association with at least 2 high \( P_T \) jets (ATLAS-CONF-2012-137)

- Signal generated with MadGraph + Pythia

<table>
<thead>
<tr>
<th>charge</th>
<th>2/3</th>
<th>-1/3</th>
<th>5/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(400 \text{ GeV}).BR ) [pb]</td>
<td>0.849</td>
<td>5.47</td>
<td>7.78</td>
</tr>
<tr>
<td>( \sigma(2 \text{ TeV}).BR ) [pb]</td>
<td>0.305</td>
<td>1.32</td>
<td>3.64</td>
</tr>
</tbody>
</table>

- Event selection:
  - analysis divided into 4 channels: CC and NC, each with either e or \( \mu \) in the final state
  - the final event selection cuts are optimized independently for the CC and NC channels
  - CC channel: exactly 1 lepton and \( E_T^{\text{miss}} > 50 \text{ GeV} \rightarrow W \) reconstruction \([m_T(W) > 40 \text{ GeV}, |\eta(W)| < 2.5\] \( N_{\text{jets}} \geq 2 \) and \( p_T(\text{leading jet}) > 60 \text{ GeV} \)
    - cut optimization on: \( |\Delta \eta(W,\text{jet leading})|, |\Delta \eta(\text{jet leading,jet associated})|, |\Delta \Phi(W,\text{jet leading})|, |\Delta \Phi(1,E_T^{\text{miss}})| \)
  - NC channel: 2 OS and same-flavour leptons \((66 \text{ GeV} < M_{ll} < 116 \text{ GeV})\)
    - \( N_{\text{jets}} \geq 2 \)
    - cut optimization on: \( |\Delta \eta(l,l)|, |\Delta \eta(Z,\text{jet})|, |\Delta \eta(\text{jet leading,jet associated})|, |\Delta \Phi(l,l)|, |\Delta \Phi(Z,\text{jet leading})| \)
**Background**:  
- estimated in data by fitting the reconstructed VLQ mass  
- as a cross-check, data are compared to the simulated background model

**Results are consistent with a background-only hypothesis**:  
- limits are set on the production cross section and coupling (Bayesian limits)  
- stronger CC limits are obtained by requiring a negatively charged lepton in the final state  
  (background $(W^- + \text{jets}) = 1/3 \times \text{background (}W^+ + \text{jets})$)

95% CL @ 4.64 fb$^{-1}$ with $\tilde{\kappa}_{qQ} = 1$  
- $m(Q) > 1.12 \text{ TeV} \quad \text{charge} = 2/3$  
- $m(Q) > 1.08 \text{ TeV} \quad \text{charge} = -1/3$  
- $m(Q) > 1.42 \text{ TeV} \quad \text{charge} = 5/3$
The fourth generation quark model has been studied and the following results were obtained @ 95% CL:

- $m(Q) > 350$ GeV for up and down type $Q$
- $m(t') > 656$ GeV for $t' \rightarrow W+b$
- $m(b') > 670$ GeV for $b' \rightarrow W+t$

This model is now disfavored by $m_H \sim 126$ GeV.
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The Vector Like Model has also been studied
- a \textbf{VLQ interpretation of} \( t' @ 4.7 \text{ fb}^{-1} \) has been shown
- a \textbf{vector-like singlet} \( b' \) (with \( b' \rightarrow Z+b \)) \textbf{mixing solely with the third SM generation} has been studied
- limits on \textbf{VLQs with charge 5/3} has been shown for different coupling value \( \lambda(T_{5/3} tW) \)
- the \textbf{single production of VLQs coupling to light generations} has been studied for VLQs with charges \(-1/3, 2/3 \) and \( 5/3 \) and limits on the \textbf{production cross section and coupling} have been shown

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- a vector-like singlet $b'$ (with $b' \rightarrow Z+b$) mixing solely with the third SM generation has been studied
- limits on VLQs with charge $5/3$ has been shown for different coupling value $\lambda(T_{5/3} tW)$
- the single production of VLQs coupling to light generations has been studied for VLQs with charges = $-1/3$, $2/3$ and $5/3$ and limits on the production cross section and coupling have been shown

This model survives $m_H \sim 126$ GeV

We will continue to set limits on 4th generation at 8 TeV
The limits on the Vector Like Quark Model will be improved with data analysis at 8 TeV