Searches for vector-like quarks and ttbar resonances with the ATLAS detector

PASCOS 2013, Taipei (Taiwan)

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on behalf of the ATLAS Collaboration

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24th November, 2013
**Motivation**

- Standard Model of particle physics well confirmed
- Unanswered questions remaining
  - Dark Matter
  - Fermion generations
  - Mass hierarchy
  - Matter-Antimatter asymmetry
  - Fine tuning
  - ...and more...
- Hint for new physics!?
- Several beyond standard model (BSM) theories predict new physics in the heavy quark and top sector
  - Little / Composite Higgs
  - Randall-Sundrum (with warped extra dimensions)
  - Technicolor / Topcolor
  - ...and more...

Tobias Heck (JGU Mainz, ATLAS)

vector-like quarks and ttbar resonances

24th November, 2013
Presenting several searches for new physics using

- 14.3 fb$^{-1}$ of data @ $\sqrt{s} = 8$ TeV
- recorded by ATLAS experiment at the LHC from April to October 2012

$t\bar{t}$ resonances searches

- $t\bar{t} \rightarrow$ lepton + jets [ATLAS-CONF-2013-052]

Heavy vector like quark pair searches

- $T \bar{T} \rightarrow Ht + X$ [ATLAS-CONF-2013-018]
- $T \bar{T} \rightarrow Wb + X$ [ATLAS-CONF-2013-060]
- $T \bar{T} \rightarrow Zt + X$ and $B\bar{B} \rightarrow Zb + X$ [ATLAS-CONF-2013-056]

Same sign dilepton + b-jets

- $t\bar{t} t\bar{t}$, $tt$, Chiral quarks [ATLAS-CONF-2013-051]
**Search for heavy resonance decaying into $t\bar{t}$ pair**

- Top quark has $\approx 99.9\%$ BR for $t \rightarrow W + b$
- Three different decay channels, classified via $W$-decay modes
  - All-hadronic (alljets), di-leptonic (dileptons), semi-leptonic (lepton+jets)

### Top Pair Branching Fractions

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<th>Decay</th>
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<th>e+jets</th>
<th>μ+μ-</th>
<th>μ+jets</th>
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</table>

### Top Pair Decay Channels

- All-hadronic (alljets), di-leptonic (dileptons), semi-leptonic (lepton+jets)
$t\bar{t} \rightarrow \text{LEPTON + JETS}$

- Benchmark models
  - Narrow width leptophobic topcolor $Z'$
    \(\Gamma/m = 1.2\%\) [Model IV von Harris et al.]
  - Broad width Kaluza-Klein gluon
    \(g_{KK} \ (\Gamma/m = 15.3\%)\) [R.S., warped extra-dim.]

- Resolved and boosted topologies

- Reconstruction of hadronic top
  - Resolved: 2-3 Anti-$k_T$ \((R = 0.4)\) jets
  - Boosted: one large radius Anti-$k_T$ \((R = 1.0)\) jet
    \(p_T \geq 300\ \text{GeV}, \ m_{\text{jet}} \geq 100\ \text{GeV}, \ \sqrt{d_{12}} \geq 40\ \text{GeV}\)

- Reconstruction of leptonic top
  - 1 Anti-$k_T$ \((R = 0.4)\) jet, 1 isolated lepton, $E_T^{\text{miss}}$
  - At least one b-tag
  - Clear separation of leptonic and hadronic objects: \(\Delta\Phi(\text{fatjet, lepton}) > 2.3\)
    and \(\Delta R(\text{fatjet, leptonic jet}) > 1.5\)

- Resolved orthogonal to boosted channel
\( t\bar{t} \rightarrow \text{LEPTON} + \text{JETS} \)

- **Benchmark models**
  - Narrow width leptophobic topcolor \( Z' \) 
    \( (\Gamma/m = 1.2\%) \) [Model IV von Harris et al.]
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- **At least one b-tag**

- **Clear separation of leptonic and hadronic objects**
  - $\Delta\Phi(\text{fatjet, lepton}) > 2.3$
  - $\Delta R(\text{fatjet, leptonic jet}) > 1.5$

- **Resolved orthogonal to boosted channel**

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**Diagram:**
- Proton interactions
- $t\bar{t}$ resonance searches
- Leptonic and hadronic objects
- Clear separation criteria

**Graphs:**
- Event distribution
- Data vs. Background
- $m_T^{\text{had}}$ vs. $m_T^{\text{had}}$
- $t\bar{t}$ vs. $t\bar{t}$

**ATLAS Preliminary**
- $\mathbb{L} dt = 14.2$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV
- Distributions for different processes

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**References:**
- [Model IV von Harris et al.]
- [R.S., warped extra-dim.]
\( t\bar{t} \rightarrow \text{LEPTON + JETS EVENT RECONSTRUCTION} \)

- Combine hadronic and leptonic top for reconstruction of \( t\bar{t} \) system
- Boosted channel
  - Use highest \( p_T \) fat jet passing selection as hadronic top candidate
- Resolved channel
  - Pick combination of jets using \( \chi^2 \) algorithm (constraints on \( W \)-mass and top-mass)
  \[
  \chi^2 = \left( \frac{m_{jj} - m_W}{\sigma_W} \right)^2 + \left( \frac{m_{jjb} - m_{jj} - m_W}{\sigma_{\text{th-W}}} \right)^2 + \left( \frac{m_{ll\nu} - m_{tl}}{\sigma_{\text{tl}}} \right)^2 + \left( \frac{(p_{T}^{jjb} - p_{T}^{ll\nu}) - (p_{T}^{\text{th}} - p_{T}^{tl})}{\sigma_W} \right)^2
  \]
- Discriminant: reconstructed mass \( m_{t\bar{t}}^{\text{reco}} \) of the full \( t\bar{t} \) system
Absence of any significant excess in the $m_{t\bar{t}}$ distributions

Set (95% CL) Bayesian limits on $\sigma_{Z'\rightarrow t\bar{t}} \times BR_{Z'\rightarrow t\bar{t}}$ and $\sigma_{g_{KK}\rightarrow t\bar{t}} \times BR_{g_{KK}\rightarrow t\bar{t}}$

- narrow $Z'$: excluded within $0.5 - 1.8$ ($0.5 - 1.9$) TeV range observed (expected)
- broad $g_{KK}$: excluded within $0.5 - 2.0$ ($0.5 - 2.1$) TeV range observed (expected)

**Graphs:**
- Plot of $\sigma_{Z'\rightarrow t\bar{t}} \times BR_{Z'\rightarrow t\bar{t}}$ vs. $Z'$ mass [TeV]
- Plot of $\sigma_{g_{KK}\rightarrow t\bar{t}} \times BR_{g_{KK}\rightarrow t\bar{t}}$ vs. $g_{KK}$ mass [TeV]
Heavy vector like quark pair searches

Introduction

New weak isospin singlet, doublet or triplet, preferred coupling to 3\textsuperscript{rd} gen. quarks

Heavy top quark partner T plays role in Higgs mass regulation in many models

Three decay modes

- $T \rightarrow Wb$, $T \rightarrow Zt$, $T \rightarrow Ht$
- $B \rightarrow Wt$, $B \rightarrow Zb$, ($B \rightarrow Hb$)

Two production regimes

- Pair (QCD), dominant for $m_{B,T} < 1$ TeV
- Single (weak), dominant for $m_{B,T} > 1$ TeV
\( T \bar{T} \rightarrow Ht + X \)

- **Signature**
  - Lepton+jets channel (at least one \( W \rightarrow l\nu \))
  - Exactly one isolated lepton, \( E_{\text{miss}}^{\text{T}} \)
  - \( \geq 6 \) Anti-\( k_T \) (\( R=0.4 \)) jets and \( \geq 4 \) b-tags
  - \( H \rightarrow b\bar{b} \) (\( m_H = 125 \) GeV)

- **Sensitive to multiple decay modes**
  - \( T \bar{T} \rightarrow Ht + H\bar{t} \)
  - \( T \bar{T} \rightarrow Ht + Z\bar{t} \)
  - \( T \bar{T} \rightarrow Ht + W\bar{b} \)

- 2 and 3 b-tag events used as control region
- 4 b-tag events used as signal region

- **Discriminant:** \( H_T = \sum_{\text{jet}} p_T^{\text{jet}} + p_T^{\text{lepton}} + E_{\text{miss}}^{\text{T}} \)

- \( H_T \) distribution peaks around \( 2m_T \) for signal

- 2 b-tag events with \( H_T < 700 \) GeV rejected, to obtain orthogonality to \( T \bar{T} \rightarrow Wb + X \) searches
Absence of any significant data excess in the $H_T$ spectra

Set (95% CL) $CL_s$ limits on $\sigma_{T\bar{T}}$

- Weak isospin doublet: $m_T > 790 \ (745) \text{ GeV}$ observed (expected)
- Weak isospin singlet: $m_T > 640 \ (615) \text{ GeV}$ observed (expected)
Heavy vector like quark pair searches

\( T \bar{T} \rightarrow Wb + X \)

**Signature**
- Lepton+jets channel
  - Exactly one isolated lepton, \( E_T^{\text{miss}} \)
  - \( \geq 4 \) Anti-\( k_T \) (\( R=0.4 \)) jets and \( \geq 1 \) b-tag
  - Two W-Bosons, \( BR(T \rightarrow Wb) = 1 \)
  - b-jets: 1 b-tagged jet, 2\(^{nd} \) highest b-tag weight jet

**Leptonically decaying W-boson**
- Lepton + \( E_T^{\text{miss}} \)

**Hadronically decaying W-boson**
- Type 1: boosted W-Boson, single merged jet
  - \( 60 < m_{jj} < 120 \ \text{GeV}, \ p_T^{jj} > 250 \ \text{GeV} \)
- Type 2: semi-boosted W-Boson, 2 separated jets
  - \( 60 < m_{jj} < 120 \ \text{GeV}, \ p_T^{jj} > 200 \ \text{GeV}, \ \Delta R(j,j) < 0.8 \)
  - Excluding b-jet candidates from reconstruction
  - Type 2 excluded if type 1 successfully reconstructed

**Reject events with \( \geq 6 \) jets and \( \geq 3 \) b-tags to obtain orthogonality to \( T \bar{T} \rightarrow Ht + X \) searches**
$\bar{T}T \rightarrow Wb + X$ MASS RECONSTRUCTION

- $H_T > 800$ GeV
- separation $\min(\Delta R(W_{\text{had}}/\text{lepton}, b\text{jet}_{1,2})) > 1.4$
- Discriminant: Reconstructed $T$ mass $m_{\text{reco}}$ ($T = W_{\text{had}} + b\text{jet}$)
  - Two possibilities to assign b-jet candidates
  - $W_{\text{lep}}$ with two solutions (due to two neutrino solutions)
  - Choose the one possibility minimizing difference between $T$ masses $\min(|m_{T}^{\text{lep}} - m_{T}^{\text{had}}|)$

ATLAS Preliminary

Events / 0.2

Data ($\sqrt{s} = 8$ TeV)

TT (600) Chiral

$tt$(600) Chiral

$tt$(600) Singlet

Non-tt

Total BG uncert.

$\int L dt = 14.3$ fb$^{-1}$

Data / BG

1

2

3

0

5

10

15

20

25

30

35

40

45

0

0.5

1

1.5

2

2.5

3

3.5

min $\Delta R(l,b)$

Events / 150 GeV

Data ($\sqrt{s} = 8$ TeV)

TT (600) Chiral

TT (600) Singlet

$tt$(600) Chiral

Non-tt

Total BG uncert.

$\int L dt = 14.3$ fb$^{-1}$

Data / BG

1

2

3

0

5

10

15

20

25

30

35

40

45

100 200 300 400 500 600 700 800 900 1000

$m_{\text{reco}}$ [GeV]
Absence of any significant data excess in the $m_{\text{reco}}$ spectra

Set (95% CL) $CL_s$ limits on $\sigma_{T\bar{T}}$

- Chiral 4th generation $T$ quark: $m_T > 740 \ (770) \ \text{GeV}$ observed (expected)
- Vector-like singlet $T$ quark: $m_T > 505 \ (630) \ \text{GeV}$ observed (expected)
Heavy vector like quark pair searches

$T \bar{T} \rightarrow Zt + X$ AND $B \bar{B} \rightarrow Zb + X$

- Sensitive to $T$ and $B$ vector-like heavy quarks
- Signature
  - 2 same flavor leptons with opposite charge
  - $\geq 2$ jets and $\geq 2$ b-tags
  - high $p_T > 150$ GeV Z-Boson candidate reconstructed from the two leptons
  - choose Z-Boson closest within $m_Z \pm 15$ GeV
- 0 and 1 b-tag events used as control region
- 2 b-tag events used as signal region
- $H_T(jets) = \sum_{jet} p_T^{jet} > 600$ GeV
- Discriminant: $m(Zb)$ sum of Z-Boson and highest $p_T$ b-jet candidate
Absence of any significant data excess in the $m(Zb)$ spectra

Set (95% CL) $CL_s$ limits on $\sigma_{T\bar{T}\rightarrow Zt + X}$ and $\sigma_{B\bar{B}\rightarrow Zb + X}$

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<th>type</th>
<th>obs.</th>
<th>(exp.)</th>
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<td></td>
<td>doublet</td>
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**SAME SIGN DILEPTON + B-JETS**

- **Very small cross section in the Standard Model**
- **Several production channels**
  - Chiral or vector like heavy quarks
    
    \[ B\bar{B} \rightarrow Wt + X, \ T\bar{T} \rightarrow Zt + X, \ T\bar{T} \rightarrow Ht + X \]
  
    - Enhanced production of four tops \( (\sigma_{SM}^{t\bar{t}t\bar{t}} \approx 1\,\text{fb}) \)
  
    - Production of two positively charged top quarks mediated through new heavy particle \( \tilde{g} \) or \( g_{KK} \)

- **Baseline selection**
  - 2 same flavor leptons with same electric charge \( m_{ll} > 15 \,\text{GeV}, \ Z \text{ veto } |m_{ll} - m_{Z}| > 10 \,\text{GeV} \)
  
    - \( \geq 2 \text{ jets and } \geq 1 \text{ b-tag} \)
  
    - \( E_{T}^{miss} > 40 \,\text{GeV} \) and \( H_T > 550 \,\text{GeV} \)

- **Signal specific selection**
  
    - Heavy Quark: \( H_T > 650 \,\text{GeV} \)
  
    - \( t\bar{t} t\bar{t} \) : \( H_T > 650 \,\text{GeV} \), 2 b-tagged jets
  
    - tt: positive leptons only
Absence of any significant data excess in the $H_T$ spectra

Set (95% CL) $CL_s$ limits on $T$, $B$ and $b'$ production

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<td>$m_{b'}$</td>
<td>chiral</td>
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<td>(770)</td>
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$[\text{GeV}]$ $[\text{GeV}]$
Absence of any significant data excess in the $H_T$ spectra

Set (95% CL) $CL_s$ limits on $\sigma_{G \rightarrow t\bar{t} t\bar{t}} \times BR_{G \rightarrow t\bar{t} t\bar{t}}$ and $\sigma_{g_{KK} \rightarrow t\bar{t} t\bar{t}} \times BR_{g_{KK} \rightarrow t\bar{t} t\bar{t}}$

- SGlueon $G$: $m_G > 800 (830) \text{ GeV}$ observed (expected)
- KK gluon $g_{KK}$: $m_{g_{KK}} > 900 (920) \text{ GeV}$ observed (expected)
HEAVY VECTOR LIKE $T$ QUARK PAIR SEARCHES SUMMARY

ATLAS Preliminary
Status: Lepton-Photon 2013
$\sqrt{s} = 8$ TeV, $\int L dt = 14.3$ fb$^{-1}$

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

SU(2) (T,B) doub.
SU(2) singlet

$\text{m}_T = 350$ GeV
$\text{m}_T = 400$ GeV
$\text{m}_T = 450$ GeV
$\text{m}_T = 500$ GeV
$\text{m}_T = 550$ GeV
$\text{m}_T = 600$ GeV
$\text{m}_T = 650$ GeV
$\text{m}_T = 700$ GeV
$\text{m}_T = 750$ GeV
$\text{m}_T = 800$ GeV
$\text{m}_T = 850$ GeV

BR($T \rightarrow Ht$) vs. BR($T \rightarrow Wb$)

ATLAS-CONF-2013-018
ATLAS-CONF-2013-051
ATLAS-CONF-2013-056
ATLAS-CONF-2013-060

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HEAVY VECTOR LIKE $B$ QUARK PAIR SEARCHES SUMMARY

**ATLAS** Preliminary

Status: Lepton-Photon 2013

$\sqrt{s} = 8$ TeV, $\int L dt = 14.3$ fb$^{-1}$

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

SU(2) (B,Y) doub.
SU(2) singlet

- Same-Sign $[\text{ATLAS-CONF-2013-051}]$
- $Zb/t+X$ $[\text{ATLAS-CONF-2013-056}]$

For $m_B = 350$ GeV, $m_B = 400$ GeV, $m_B = 450$ GeV, $m_B = 500$ GeV, $m_B = 550$ GeV, $m_B = 600$ GeV, $m_B = 650$ GeV, $m_B = 700$ GeV, $m_B = 750$ GeV, $m_B = 800$ GeV, $m_B = 850$ GeV

$\text{BR}(B \rightarrow Hb)$

$\text{BR}(B \rightarrow Wt)$
Conclusions

- Searching for answers to remaining questions in the SM
- Presented several searches for new physics beyond the SM with 14.3 fb$^{-1}$ 2012 Data @ $\sqrt{s} = 8$ TeV
- No significant deviations from SM found for any of the presented searches
- Limits set on masses for new particles of several models
  - Vector like heavy quarks (singlets, doublets)
  - Chiral heavy quarks
  - $t\bar{t}$ resonances ($Z'$ and $g_{KK}$)
  - Four top final states ($\tilde{g}$ and $g_{KK}$)
- Stay tuned for improvements and updates in the future!
  - New results with full 20 fb$^{-1}$ 2012 Data @ $\sqrt{s} = 8$ TeV
  - RUN II @ LHC with $\sqrt{s} = 13 - 14$ TeV from 2015 on

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Backup
TTBarRes lep+jets selections

ATLAS Preliminary Simulation

Resolved (excl.) $\sqrt{s}=8$ TeV
- $\mu$ + jets, $\geq 0$ b-tags
- $\mu$ + jets, $\geq 1$ b-tags
- $e$ + jets, $\geq 0$ b-tags
- $e$ + jets, $\geq 1$ b-tags

Efficiency [%]

ATLAS Preliminary Simulation

Boosted $\sqrt{s}=8$ TeV
- $\mu$ + jets, $\geq 0$ b-tags
- $\mu$ + jets, $\geq 1$ b-tags
- $e$ + jets, $\geq 0$ b-tags
- $e$ + jets, $\geq 1$ b-tags

Efficiency [%]

ATLAS Preliminary Simulation

Combined $\sqrt{s}=8$ TeV
- $\mu$ + jets, $\geq 0$ b-tags
- $\mu$ + jets, $\geq 1$ b-tags
- $e$ + jets, $\geq 0$ b-tags
- $e$ + jets, $\geq 1$ b-tags

Efficiency [%]
Backup

TTBarRes lep+jets event display

leptonic top candidate

hadronic top candidate

Muon missing $E_T$

leptonic top candidate

hadronic top candidate

hadronic top candidate

leptonic top candidate

vector-like quarks and ttbar resonances

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