Top quarks in ATLAS: bridging measurements and searches

Stephanie Majewski, University of Oregon
on behalf of the ATLAS Collaboration

50th Rencontres de Moriond EW, March 14-21, 2015
Introduction

- The interplay between top quark measurements and searches is essential to fully explore avenues for new physics

1. "Classic" SM top cross-section measurements have played a key role to understanding $t\bar{t}$ backgrounds

2. The top Yukawa coupling can be measured at tree-level in $t\bar{t}H \rightarrow$ important for understanding EW symmetry breaking & sensitive to new physics

3. Strong motivation (naturalness) for top partner searches: vector-like quarks, SUSY stop (including “stealth” stop)
Measurements → Searches

Rapidity Gap in $\bar{t}t$ events

- Study the fraction of dilepton $\bar{t}t$ events that do not contain an additional central rapidity jet

![Graph showing the measured gap fraction as a function of $Q_0$ and $|y|$ for $\bar{t}t$ events.]

Updated: ATL-PHYS-PUB-2014-005

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Moriond EW 2015
Measurements → Searches

Rapidity Gap in $\bar{t}t$ events

- Study the fraction of dilepton $\bar{t}t$ events that do not contain an additional central rapidity jet

$\bar{t}t$ differential cross sections

- Jet multiplicity dependence


Updated: ATL-PHYS-PUB-2014-005

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Measurements → Searches

Rapidity Gap in $\bar{t}t$ events

- Study the fraction of dilepton $\bar{t}t$ events that do not contain an additional central rapidity jet

$t\bar{t}$ differential cross sections

- Jet multiplicity dependence
  
  JHEP 01 (2015) 020

- Dependence on $p_T(t\bar{t})$
  

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Updated: ATL-PHYS-PUB-2014-005

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Measurements → Searches

Rapidity Gap in $\bar{t}t$ events

- Study the fraction of dilepton $\bar{t}t$ events that do not contain an additional central rapidity jet

$t\bar{t}$ differential cross sections

- Jet multiplicity dependence
  JHEP 01 (2015) 020
- Dependence on $p_T(t\bar{t})$

**Essential** for constraining radiation in top production

**Important** for modeling of $t\bar{t}$ backgrounds in searches for new physics, $t\bar{t}H$

Updated: ATL-PHYS-PUB-2014-005
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see also talk by A. Loginov
Measurements → Searches

Boosted $\bar{t}t$ differential cross section

ATLAS-CONF-2014-057

- lepton+jets $\bar{t}t$ events, unfolded to particle & parton level
Measurements → Searches

**Boosted $t\bar{t}$ differential cross section**

- lepton+jets $t\bar{t}$ events, unfolded to particle & parton level

**New! $t\bar{t}$ resonance search**

- combined boosted+resolved $(\sigma \times B) < 0.03$ pb for 3 TeV $Z'$
- excludes narrow leptophobic $Z' < 1.8$ TeV

*ATLAS* Preliminary $1\sigma$=8 TeV, 20.3 fb$^{-1}$

**ATLAS-CONF-2014-057**

- ATLAS
- $20.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}$
- anti-$k_t$ R=1.0 jets, $\ell$+jets channel (hadronic)

**ATLAS-CONF-2015-009**

- Data / MC
- $d\sigma(t\bar{t})/dp_T$ [fb/GeV]
- $\sigma(t\bar{t}) \times B$ < 0.03 pb for 3 TeV $Z'$$
- $Z' < 1.8$ TeV

*see also talk by J. Stupak*
Top Yukawa Coupling

- SM Higgs predicted to have a large Yukawa coupling to tops
- can be probed through Higgs production in association with top quark(s): tH and ttH
- Three channels explored:
  - $H \rightarrow b\bar{b}$
  - $t\bar{t} \rightarrow \ell + \text{jets, dilepton}$
  - $H \rightarrow \gamma\gamma$
  - $t\bar{t} \rightarrow \ell + \text{jets, dilepton, all-had}$
  - Multi-lepton final states (including $\tau$s)

$\sigma_{t\bar{t}H}(\sqrt{s} = 8 \text{ TeV}) = 129.3^{+4.9}_{-12.0} \text{ (scale)} \pm 10.5 \text{ (PDF)} \text{ fb}$
Top Yukawa Coupling

- Events categorized according to jet and b-jet multiplicities into signal-rich & bkg-rich regions
- Most sensitive regions:

Single lepton
≥ 6 j, 3 b
≥ 6 j, ≥ 4 b

Dilepton
≥ 4 j, 3 b
≥ 4 j, ≥ 4 b

ATLAS Simulation
m_H = 125 GeV
\sqrt{s} = 8 TeV
- tf+light
- tf+c\bar{c}
- tf+b\bar{b}
- tf+V
- non-t\bar{t}
Top Yukawa Coupling

- Events categorized according to jet and b-jet multiplicities into signal-rich & bkg-rich regions
- Most sensitive regions:

  ![](Image)

<table>
<thead>
<tr>
<th>Single lepton</th>
<th>Dilepton</th>
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<tbody>
<tr>
<td>≥ 6 j, 3 b</td>
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<tr>
<td>m_H = 125 GeV</td>
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</tr>
<tr>
<td>s = 8 TeV</td>
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</tr>
<tr>
<td>Data</td>
<td>Data</td>
</tr>
<tr>
<td>Non-tt</td>
<td>Non-tt</td>
</tr>
<tr>
<td>tt + light</td>
<td>tt + light</td>
</tr>
<tr>
<td>tt + cbar</td>
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</tr>
<tr>
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<td>tt + V</td>
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Top Yukawa Coupling

$H \rightarrow b\bar{b}$

$t\bar{t} \rightarrow \ell + \text{jets, dilepton}$

- Main background: $t + X$, 2000 times higher cross section
- Very challenging final state, with high jet and $b$-tag multiplicity, large systematic uncertainties, both theoretical and experimental
- Search for $H$ targeting the decay $H \rightarrow b\bar{b}$ in the lepton+jets and dilepton channels

- Production:
  - $\sigma(tH)$ is known at NLO QCD
  - Suppressed compared to other Higgs production modes
  - $\approx 2600$ events in 20.3 fb$^{-1}$ at 8 TeV

- Decay:
  - Targeting the decay $H \rightarrow b\bar{b}$
  - Highest branching ratio (58%) but large backgrounds

Dominant systematics:
- $t\bar{t} + b\bar{b}$ background modeling, jet energy scale
Top Yukawa Coupling

- $m_{\gamma\gamma}$ mass spectrum provides discrimination 1.42 GeV (1.56 GeV) resolution for 7 TeV (8 TeV) data
- Best fit value ($m_H = 125.4$ GeV): $\mu_{ttH} = 1.3^{+2.5}_{-1.7}(\text{stat})^{+0.8}_{-0.4}(\text{syst})$

\[ H \rightarrow \gamma\gamma \]
\[ ttH \rightarrow \ell + \text{jets}, \text{dilepton, all-had} \]
Top Yukawa Coupling

Multi-lepton final states (including $\tau$ s)

- Five different multi-lepton final states ($2\ell$ are same-sign):
  
<table>
<thead>
<tr>
<th>Category</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\ell0\tau_{\text{had}}$</td>
<td>80%</td>
<td>15%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>$3\ell$</td>
<td>74%</td>
<td>15%</td>
<td>7%</td>
<td>4%</td>
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<tr>
<td>$2\ell1\tau_{\text{had}}$</td>
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<tr>
<td>$1\ell2\tau_{\text{had}}$</td>
<td>4%</td>
<td>93%</td>
<td>0%</td>
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</table>

- Main backgrounds:
  - $t\bar{t}Z$, $t\bar{t}W$ (all categories)
  - Diboson ($3\ell$)
  - $t\bar{t}$+jets, $Z$+jets (e charge mis-id)
  - $t\bar{t}$ with non-prompt leptons

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Top Yukawa Coupling

Multi-lepton final states (including $\tau$ s)

- Five different multi-lepton final states ($2\ell$ are same-sign):
  
  Higgs decay mode fraction

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- Main backgrounds:
  ttZ, ttW (all categories)
diboson ($3 \ell$)
$\tau$+jets, Z+jets ($e$ charge mis-id)
tt with non-prompt leptons

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Top Yukawa Coupling

Combined Results

ATLAS-CONF-2015-007

\[ \text{Input measurements} \]

\[ \pm 1\sigma \text{ on } \mu \]

\[ m_H = 125.36 \text{ GeV} \]

\[ \text{signal strength (}\mu\text{)} \]

\[ \sqrt{s} = 7 \text{ TeV, } 4.5-4.7 \text{ fb}^{-1} \]

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

\[ \mu_{\text{ttH}} < 3.2 \text{ (obs), } 1.4 \text{ (exp)} \]

\[ \mu_{\text{bb}}: \mu = 1.5^{+1.1}_{-1.1} \]

\[ \mu_{\text{Multilepton}}: \mu = 2.1^{+1.4}_{-1.2} \]

\[ \mu_{\gamma\gamma}: \mu = 1.3^{+2.8}_{-1.9} \]

\[ \text{see also talk by M. Duehrssen} \]

\[ \text{3 channels combined: } >2\sigma \text{ from 0} \]
Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin
- flavor-changing neutral current decays allowed: $T \rightarrow Wb, Zt, Ht$

Four search channels:

**ATLAS** Preliminary
Status: March 2015

$\sqrt{s} = 8$ TeV, \[ \int L dt = 20.3 \text{ fb}^{-1} \]
95% CL exp. excl. \hspace{1cm} 95% CL obs. excl.

New! $Ht+X$

SU(2) (T,B) doub. \hspace{1cm} SU(2) singlet

$\sigma_{\ell\ell}$

$\mathbf{Ht+X}$

$\mathbf{ATLAS}$ Preliminary
20.3 fb$^{-1}$, \( \sqrt{s} = 8 \text{ TeV} \)
\( \geq 6 \text{jets}, \geq 4 \text{b} \), \( M_{bb}^{\text{min}} > 100 \text{ GeV} \)
Post-fit

$\mathbf{T \bar{T} \rightarrow Ht+X}$

Data
- $t\bar{t}$+light jets
- $t\bar{t}+c\bar{c}$
- $t\bar{t}+b\bar{b}$
- $t\bar{t}V$
- $t\bar{t}H$
- Non-$t\bar{t}$
- Total Bkg unc.

$\mathbf{Ht+X}$

$\mathbf{Ht+X}$

$\mathbf{Ht+X}$

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Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin

- flavor-changing neutral current decays allowed: $T \rightarrow Wb, Zt, Ht$

Four search channels:

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

\[ \text{ATLAS} \quad \text{Preliminary} \]

\[ \text{Status: March 2015} \]

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

\[ 95\% \text{ CL exp. excl.} \quad \text{95\% CL obs. excl.} \]

\[ \text{ATLAS-CONF-2015-012} \]

\[ \text{Ht+X} \quad \text{Preliminary} \]

\[ \text{Same-Sign ll} \quad \text{(Wb) → BR(T→Ht)} \quad \text{(T→Wb)} \]

\[ \text{color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin} \]

\[ \text{flavor-changing neutral current decays allowed: } T \rightarrow Wb, Zt, Ht \]

\[ \text{Same-Sign Dilepton/Trilepton (+b-jets)} \]

\[ \text{ATLAS} \quad \text{Preliminary} \]

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

\[ \text{BR}(T \rightarrow Ht) \quad \text{BR}(T \rightarrow Wb) \]

\[ m_T = 600 \text{ GeV} \]

\[ \text{BR}(T \rightarrow Ht) \quad \text{BR}(T \rightarrow Wb) \]

\[ \text{Data} \quad \text{Q Miso-id} \quad \text{Fake/non-prompt leptons} \quad \text{Dibosons} \quad \text{Other} \quad \text{Uncertainties} \]

\[ 2.2\sigma \quad 2.4\sigma \]
Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin

- flavor-changing neutral current decays allowed: $T \rightarrow W b, Z t, H t$

**Four search channels:**

- $T \bar{T} \rightarrow Z t + X$

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**ATLAS Preliminary**

Status: March 2015

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

95% CL exp. excl.

95% CL obs. excl.

- $Ht+X$ [ATLAS-CONF-2015-012]
- Same-Sign $ll$ [Preliminary]
- $Zb/t+X$ [JHEP11 (2014) 104]

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

---

New! New!

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Moriond EW 2015
Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin

- flavor-changing neutral current decays allowed: $T \to W b$, $Z t$, $H t$

**Four search channels:**

**ATLAS-CONF-2015-012**

**$T\bar{T} \to Wb+X$**

**ATLAS Preliminary**

Status: March 2015

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

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

**New!**

 SU(2) (T,B) doub.

 ● SU(2) singlet

**ATLAS Preliminary**

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

$T\bar{T}$

- (600) Chiral
- (600) Singlet

- $t\bar{t}$
- Non-t$\bar{t}$
- Total Bkg unc.

**Data / Bkg**

**m$_{\text{reco}}$ [GeV]**

**m$_{T}$ = 600 GeV**

Unphysical

**BR($T \to H t$)**

**BR($T \to Wb$)**

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Morioka EW 2015
Vector-Like Quarks

See the full set of summary plots: ExoticsPublicResults

New results also available for vector-like B searches!

(submitted to arxiv yesterday)
As of ICHEP 2014, direct stop searches provided impressive phase space coverage.

But detailed $t\bar{t}$ measurements were needed to investigate the region $m_{\tilde{t}} \sim m_t$. 
Precise $t\bar{t}$ Cross Sections

- 7 TeV and 8 TeV $t\bar{t}$ cross sections measured in $e^{\pm}\mu^{\mp}$ events
- Reduced systematic uncertainties due to simultaneous fit and extraction of b-tagging efficiency

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3 \text{ pb (}\sqrt{s} = 7 \text{ TeV})$$
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2 \text{ pb (}\sqrt{s} = 8 \text{ TeV})$$
Precise $t\bar{t}$ Cross Sections

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$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2 \text{ pb (}\sqrt{s} = 8 \text{ TeV})$$

Total uncertainties:
- 7.1 pb (3.9%)
- 10.3 pb (4.3%)
Precise $t\bar{t}$ Cross Sections

- 7 TeV and 8 TeV $t\bar{t}$ cross sections measured in $e^{\pm}\mu^{\mp}$ events

- Reduced systematic uncertainties due to simultaneous fit and extraction of b-tagging efficiency

- Also constrains "stealth" stop pair production
  
  for $m_{\tilde{t}} = 175$ GeV,
  
  $\sigma_{\tilde{t}\tilde{t}^*} (8 \text{ TeV}) = 40 \text{ pb}$

- Results sensitive to top polarization in stop decays

\[ \text{EPJC 74 (2014) 3109} \]
**tt \text{ Spin Correlation}**

- Top—antitop spin correlation extracted from dilepton tt events using $\Delta \Phi(\ell^+, \ell^-)$
- Analysis sensitive to changes in yield and shape $\rightarrow$ can detect admixture of $tt + \bar{t}\bar{t}^*$

![Graph showing ATLAS results for $\Delta \Phi$ distribution for events with $\ell^+\ell^-$ pairs, comparing $tt$ (A=SM), $tt$ (A=0), and $\bar{t}\bar{t}$ with $m_1 = 180$ GeV.]

*arxiv:1412.4742, accepted by PRL*
**tt Spin Correlation**

- Top—antitop spin correlation extracted from dilepton $t\bar{t}$ events using $\Delta\Phi(\ell^+,\ell^-)$

- Analysis sensitive to changes in yield and shape → can detect admixture of $t\bar{t} + \tilde{t}\tilde{t}^*$

### Table

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>54000 ± 3400</td>
</tr>
<tr>
<td>$Z/\gamma^* +\text{jets}$</td>
<td>2800 ± 300</td>
</tr>
<tr>
<td>$tV$ (single top)</td>
<td>2600 ± 180</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
<td>80 ± 11</td>
</tr>
<tr>
<td>$WW, WZ, ZZ$</td>
<td>180 ± 65</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>780 ± 780</td>
</tr>
<tr>
<td>Total non-$tt$</td>
<td>6400 ± 860</td>
</tr>
<tr>
<td>Expected</td>
<td>60000 ± 35000</td>
</tr>
<tr>
<td>Observed</td>
<td>60424</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}_1$</td>
<td>7100 ± 1100</td>
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</tbody>
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$(m_{\tilde{t}_1} = 180 \text{ GeV}, m_{\tilde{\chi}_1^0} = 1 \text{ GeV})$

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Moriond EW 2015

arxiv:1412.4742, accepted by PRL
**tt Spin Correlation**

- Top—antitop spin correlation extracted from dilepton $t\bar{t}$ events using $\Delta\Phi(\ell^+,\ell^-)$

- Analysis sensitive to changes in yield and shape → can detect admixture of $t\bar{t} + \tilde{t}\tilde{t}^*$

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$\tilde{t}_1\tilde{t}_1$ | $7100 \pm 1100$ ($m_{\tilde{t}_1} = 180 \text{ GeV}$, $m_{\chi_1^0} = 1 \text{ GeV}$)

---

**limits set on “stealth” stops**

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arxiv:1412.4742, accepted by PRL
Stealth stop region ($m_{\tilde{t}} \sim m_t$) nearly closed by precision $t\bar{t}$ measurements!
Summary & Outlook

- On the 20th anniversary of its discovery, the massive top quark plays a central role in searching for new physics at the LHC.
- Measurements have improved our background estimates and increased our sensitivity to new physics in challenging regions of phase space.
- Looking forward to continued synergy between measurements and searches in Run 2!
Additional Material
Top Yukawa Coupling

\( H \rightarrow b\bar{b} \)
\( t\bar{t} \rightarrow \ell + \text{jets}, \text{ dilepton} \)

- Impact of reweighting Powheg+Pythia based on p_T(tt):

**ATLAS**
\( s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
Single lepton
4 j, 2 b

**Before reweighting**

**After reweighting**
Top Yukawa Coupling

\[ H \rightarrow b\bar{b} \]
\[ t\bar{t} \rightarrow \ell + \text{jets, dilepton} \]

- full set of signal-rich and background-rich regions:

**ATLAS** Simulation
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

- Single lepton
  - \( m_H = 125 \text{ GeV} \)
  - 4 j, 2 b
    - S/B < 0.1%
  - 4 j, 3 b
    - S/B = 0.2%
  - 4 j, 4 b
    - S/B = 1.4%

- \( \geq 6 j, 2 b \)
  - S/B = 0.2%

**ATLAS** Simulation
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

- Dilepton
  - \( m_H = 125 \text{ GeV} \)
  - 2 j, 2 b
    - S/B < 0.1%
  - 3 j, 2 b
    - S/B = 0.1%
  - 3 j, 3 b
    - S/B = 0.6%

- \( \geq 4 j, \geq 4 b \)
  - S/B = 5.9%
Decay

Very challenging final state, with high jet and b-tag multiplicity, large systematics production modes.

(ttH production) at 8 TeV

\(H \rightarrow \gamma\gamma\)

\(tt \rightarrow \ell + \text{jets, dilepton, all-had}\)

Table 2
Expected numbers of \(H \rightarrow \gamma\gamma\) events \((N_H)\) from an SM Higgs boson with \(m_H = 125.4\) GeV after the event selection. These combined yields are normalized to 4.5 fb\(^{-1}\) for the 7 TeV data and to 20.3 fb\(^{-1}\) for the 8 TeV data, and are listed in the table along with the percent contribution of each Higgs boson production process with respect to the sum of all Higgs boson production processes. The numbers of fitted continuum background events \((N_B)\) for the 7 TeV and 8 TeV data are also shown, where \(N_B\) is the integral of the continuum background in the \(m_{\gamma\gamma}\) range 120–130 GeV, which is determined by an unbinned signal-plus-background fit to all categories with one common scale factor for the \(H \rightarrow \gamma\gamma\) normalization. The uncertainty on \(N_B\) is the statistical uncertainty calculated from \(\delta N_B = \delta N_{tot} N_B / N_{tot}\), where \(N_{tot}\) is the total number of background events in the full \(m_{\gamma\gamma}\) range 105–160 GeV estimated from an unbinned signal-plus-background likelihood fit, and \(\delta N\) denotes the Poisson uncertainty on \(N\).

<table>
<thead>
<tr>
<th>Category</th>
<th>(N_H)</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>(t\bar{t}H)</th>
<th>(tHq\bar{b})</th>
<th>(WtH)</th>
<th>(N_B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV leptonic selection</td>
<td>0.10</td>
<td>0.6</td>
<td>0.1</td>
<td>14.9</td>
<td>4.0</td>
<td>72.6</td>
<td>5.3</td>
<td>2.5</td>
<td>0.5(^{+0.5})(^{-0.3})</td>
</tr>
<tr>
<td>7 TeV hadronic selection</td>
<td>0.07</td>
<td>10.5</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
<td>80.9</td>
<td>2.6</td>
<td>1.9</td>
<td>0.5(^{+0.5})(^{-0.3})</td>
</tr>
<tr>
<td>8 TeV leptonic selection</td>
<td>0.58</td>
<td>1.0</td>
<td>0.2</td>
<td>8.1</td>
<td>2.3</td>
<td>80.3</td>
<td>5.6</td>
<td>2.6</td>
<td>0.9(^{+0.6})(^{-0.4})</td>
</tr>
<tr>
<td>8 TeV hadronic selection</td>
<td>0.49</td>
<td>7.3</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
<td>84.2</td>
<td>3.4</td>
<td>2.1</td>
<td>2.7(^{+0.9})(^{-0.7})</td>
</tr>
</tbody>
</table>

5 candidate events observed in \(120 < m_{\gamma\gamma} < 130\) GeV, consistent with 1.3 expected from ttH + 4.6 from bkg

S. Majewski, University of Oregon  Moriond EW 2015
**Top Yukawa Coupling**

**Multi-lepton final states**  
*(including $\tau$ s)*

- **Expected and observed yields in each channel**

<table>
<thead>
<tr>
<th>Category</th>
<th>$q$ mis-id</th>
<th>Non-prompt</th>
<th>$t\bar{t}W$</th>
<th>$t\bar{t}Z$</th>
<th>Diboson</th>
<th>Expected Bkg.</th>
<th>$t\bar{t}H (\mu = 1)$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee + \geq 5j$</td>
<td>1.1 ± 0.5</td>
<td>2.3 ± 1.2</td>
<td>1.4 ± 0.4</td>
<td>0.98 ± 0.32</td>
<td>0.47 ± 0.42</td>
<td>6.5 ± 2.0</td>
<td>0.73 ± 0.11</td>
<td>10</td>
</tr>
<tr>
<td>$e\mu + \geq 5j$</td>
<td>0.85 ± 0.35</td>
<td>6.7 ± 2.4</td>
<td>4.8 ± 1.4</td>
<td>2.1 ± 0.7</td>
<td>0.38 ± 0.32</td>
<td>15 ± 4</td>
<td>2.13 ± 0.31</td>
<td>22</td>
</tr>
<tr>
<td>$\mu\mu + \geq 5j$</td>
<td>–</td>
<td>2.9 ± 1.4</td>
<td>3.8 ± 1.1</td>
<td>0.95 ± 0.31</td>
<td>0.69 ± 0.63</td>
<td>8.6 ± 2.5</td>
<td>1.41 ± 0.21</td>
<td>11</td>
</tr>
<tr>
<td>$ee + 4j$</td>
<td>1.8 ± 0.7</td>
<td>3.4 ± 1.7</td>
<td>2.0 ± 0.4</td>
<td>0.75 ± 0.25</td>
<td>0.74 ± 0.58</td>
<td>9.1 ± 2.3</td>
<td>0.44 ± 0.06</td>
<td>9</td>
</tr>
<tr>
<td>$e\mu + 4j$</td>
<td>1.4 ± 0.6</td>
<td>12 ± 4</td>
<td>6.2 ± 0.9</td>
<td>1.5 ± 0.2</td>
<td>1.9 ± 1.2</td>
<td>24.0 ± 4.5</td>
<td>1.16 ± 0.14</td>
<td>26</td>
</tr>
<tr>
<td>$\mu\mu + 4j$</td>
<td>–</td>
<td>6.3 ± 2.6</td>
<td>4.7 ± 0.9</td>
<td>0.80 ± 0.26</td>
<td>0.53 ± 0.30</td>
<td>12.7 ± 3.0</td>
<td>0.74 ± 0.10</td>
<td>20</td>
</tr>
<tr>
<td>$3\ell$</td>
<td>–</td>
<td>3.2 ± 0.7</td>
<td>2.3 ± 0.9</td>
<td>3.9 ± 0.9</td>
<td>0.86 ± 0.59</td>
<td>11.4 ± 3.1</td>
<td>2.34 ± 0.32</td>
<td>18</td>
</tr>
<tr>
<td>$2\ell1\tau_{had}$</td>
<td>–</td>
<td>0.4 ±0.6</td>
<td>0.38 ± 0.15</td>
<td>0.37 ± 0.09</td>
<td>0.12 ± 0.15</td>
<td>1.4 ± 0.6</td>
<td>0.47 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>$1\ell2\tau_{had}$</td>
<td>–</td>
<td>15 ± 5</td>
<td>0.17 ± 0.07</td>
<td>0.37 ± 0.10</td>
<td>0.41 ± 0.42</td>
<td>16 ± 6</td>
<td>0.68 ± 0.07</td>
<td>10</td>
</tr>
<tr>
<td>$4\ell Z$-enr.</td>
<td>–</td>
<td>$\leq 10^{-3}$</td>
<td>$\leq 3 \times 10^{-3}$</td>
<td>0.43 ± 0.13</td>
<td>0.05 ± 0.02</td>
<td>0.55 ± 0.17</td>
<td>0.17 ± 0.01</td>
<td>1</td>
</tr>
<tr>
<td>$4\ell Z$-dep.</td>
<td>–</td>
<td>$\leq 10^{-4}$</td>
<td>$\leq 10^{-3}$</td>
<td>0.002 ± 0.002</td>
<td>$\leq 2 \times 10^{-5}$</td>
<td>$0.007 \pm 0.005$</td>
<td>$0.03 \pm 0.00$</td>
<td>0</td>
</tr>
</tbody>
</table>

**Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\ell0\tau_{had}$ non-prompt muon transfer factor</td>
<td>+0.38</td>
</tr>
<tr>
<td>$t\bar{t}W$ acceptance</td>
<td>+0.26</td>
</tr>
<tr>
<td>$t\bar{t}H$ inclusive cross section</td>
<td>+0.28</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>+0.24</td>
</tr>
<tr>
<td>$2\ell0\tau_{had}$ non-prompt electron transfer factor</td>
<td>+0.26</td>
</tr>
<tr>
<td>$t\bar{t}H$ acceptance</td>
<td>+0.22</td>
</tr>
<tr>
<td>$t\bar{t}Z$ inclusive cross section</td>
<td>+0.19</td>
</tr>
<tr>
<td>$t\bar{t}W$ inclusive cross section</td>
<td>+0.18</td>
</tr>
<tr>
<td>Muon isolation efficiency</td>
<td>+0.19</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.18</td>
</tr>
</tbody>
</table>

S. Majewski, University of Oregon  
Moriond EW 2015  
35
Top Yukawa Coupling

Combined Results

ATLAS-CONF-2015-007 New!

$\neg$ative solution disfavored at 3.1$\sigma$

only SM particles in loops, no invisible or undetected Higgs decays

$\kappa_t \equiv \frac{Y_t}{Y_t^{\text{SM}}}$
Vector-Like Quarks

**$T \bar{T} \rightarrow Ht + X$**

Common preselection:

1 e or 1 $\mu$, ≥ 4 jets

$E_T^{\text{miss}} > 20$ GeV

$E_T^{\text{miss}} + m_T^W > 60$ GeV

<table>
<thead>
<tr>
<th>$T \bar{T}$ ($m_T = 600$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 j, 2 b</td>
</tr>
<tr>
<td>Singlet</td>
</tr>
<tr>
<td>Doublet</td>
</tr>
<tr>
<td>$\sigma\sigma \rightarrow t\bar{t}t\bar{t}$ ($m_{\sigma\sigma} = 800$ GeV)</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}X$ (Tier (1,1), $m_{KK} = 800$ GeV)</td>
</tr>
<tr>
<td>$t\bar{t}$+light jets</td>
</tr>
<tr>
<td>$t\bar{t} + c\bar{c}$</td>
</tr>
<tr>
<td>$t\bar{t} + b\bar{b}$</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td>$W$+jets</td>
</tr>
<tr>
<td>$Z$+jets</td>
</tr>
<tr>
<td>Single top</td>
</tr>
<tr>
<td>Diboson</td>
</tr>
<tr>
<td>Multijet</td>
</tr>
<tr>
<td>Total background</td>
</tr>
<tr>
<td>Data</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\bar{T}T$ ($m_T = 600$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 j, 2 b</td>
</tr>
<tr>
<td>Singlet</td>
</tr>
<tr>
<td>Doublet</td>
</tr>
<tr>
<td>$\sigma\sigma \rightarrow t\bar{t}t\bar{t}$ ($m_{\sigma\sigma} = 800$ GeV)</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}X$ (Tier (1,1), $m_{KK} = 800$ GeV)</td>
</tr>
<tr>
<td>$t\bar{t}$+light jets</td>
</tr>
<tr>
<td>$t\bar{t} + c\bar{c}$</td>
</tr>
<tr>
<td>$t\bar{t} + b\bar{b}$</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td>$W$+jets</td>
</tr>
<tr>
<td>$Z$+jets</td>
</tr>
<tr>
<td>Single top</td>
</tr>
<tr>
<td>Diboson</td>
</tr>
<tr>
<td>Multijet</td>
</tr>
<tr>
<td>Total background</td>
</tr>
<tr>
<td>Data</td>
</tr>
</tbody>
</table>
Vector-Like Quarks

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

<table>
<thead>
<tr>
<th>Selection</th>
<th>Requirements</th>
<th>Loose selection</th>
<th>Tight selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>One electron or muon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( E_T^{\text{miss}} &gt; 20 \text{ GeV}, E_T^{\text{miss}} + m_T &gt; 60 \text{ GeV} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \geq 4 ) jets, ( \geq 1 ) ( b )-tagged jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose selection</td>
<td>Preselection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \geq 1 ) ( W_{\text{had}} ) candidate (type I or type II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( H_T &gt; 800 \text{ GeV} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( p_T(b_1) &gt; 160 \text{ GeV}, p_T(b_2) &gt; 110 \text{ GeV} ) (type I) or ( p_T(b_2) &gt; 80 \text{ GeV} ) (type II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta R(\ell,\nu) &lt; 0.8 ) (type I) or ( \Delta R(\ell,\nu) &lt; 1.2 ) (type II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tight selection</td>
<td>Loose selection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>min((\Delta R(\ell,b_{1,2}))) &gt; 1.4, min((\Delta R(W_{\text{had}},b_{1,2}))) &gt; 1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta R(b_1,b_2) &gt; 1.0 ) (type I) or ( \Delta R(b_1,b_2) &gt; 0.8 ) (type II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta m &lt; 250 \text{ GeV} ) (type I)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( T\bar{T}(m_T = 600 \text{ GeV}) )</th>
<th>Loose selection</th>
<th>Tight selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiral fourth-generation</td>
<td>115 ( \pm ) 10</td>
<td>58.9 ( \pm ) 5.9</td>
</tr>
<tr>
<td>Vector-like singlet</td>
<td>60.3 ( \pm ) 5.1</td>
<td>24.5 ( \pm ) 2.3</td>
</tr>
<tr>
<td>( tt )</td>
<td>390 ( \pm ) 110</td>
<td>10.7 ( \pm ) 4.3</td>
</tr>
<tr>
<td>( t\bar{t}V )</td>
<td>6.5 ( \pm ) 2.5</td>
<td>0.4 ( \pm ) 0.2</td>
</tr>
<tr>
<td>W+jets</td>
<td>38 ( \pm ) 19</td>
<td>11.4 ( \pm ) 6.2</td>
</tr>
<tr>
<td>Z+jets</td>
<td>1.5 ( \pm ) 1.2</td>
<td>0.4 ( \pm ) 0.4</td>
</tr>
<tr>
<td>Single top</td>
<td>36 ( \pm ) 17</td>
<td>2.2 ( \pm ) 1.5</td>
</tr>
<tr>
<td>Diboson</td>
<td>5.6 ( \pm ) 1.4</td>
<td>1.5 ( \pm ) 0.6</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.3 ( \pm ) 1.6</td>
<td>0.8 ( \pm ) 0.7</td>
</tr>
<tr>
<td>Total background</td>
<td>480 ( \pm ) 120</td>
<td>27.5 ( \pm ) 8.6</td>
</tr>
<tr>
<td>Data</td>
<td>478</td>
<td>34</td>
</tr>
</tbody>
</table>
Vector-Like Quarks

Same-sign dilepton/trilepton

SR4t3: $H_T > 700 \text{ GeV}$, $N_{b\text{-}jets} = 2$, $E_T^{\text{miss}} > 100 \text{ GeV}$

SR4t4: $H_T > 700 \text{ GeV}$, $N_{b\text{-}jets} \geq 3$, $E_T^{\text{miss}} > 40 \text{ GeV}$

6/18 events in common with ttH multilepton analysis

$\sigma = 2.2 \sigma$ $\sigma = 2.4 \sigma$
5.2. Four-top-quark production

- SM $\sigma_{tttt} \sim 1$ fb @ 8 TeV
- Same channels as vector-like quark searches: Ht+X, ss dilepton/trilepton
  - Ht+X limit: 23 fb (obs), 32 fb (exp)
  - ss dilepton/trilepton limit: 27 fb (exp)