Measurement of Top Quark Properties @ LHC

Alison Lister
On behalf of the ATLAS and CMS Collaborations
Goal is to
• Get a complete picture of the heaviest known quark
• Look for signs of weakness of the SM

Behave as predicted by the SM?
• Spin, charge, correlation, lifetime, ...
  • Mass and Xs: see other talks today
• Produced as expected?
  • Resonances: See talk Tue (E. Moyse)
• Decay as expected?
• Only top or something similar?
MEASUREMENTS OF PROPERTIES

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
**CHARGE**

What

- Is the charge
  - SM: 2/3e
  - Exotic test: 4/3e

How

- Charge of W through charge of lepton
- Charge of b-jet through soft lepton tagger
  - Charged track weighting
  - Semi-leptonic b-decay: use lepton charge

Charge 4/3e excluded at >5σ

16/03/2012 Moriond QCD Alison Lister

ATLAS-CONF-2011-141 CMS-PAS-TOP-11-031
What
• Measurement of spin correlations in $t\bar{t}$ events
  • Check $\tau_t <$ strong interaction
  • Measure fraction of SM-like events ($f^{SM}$)

How
• Dilepton
• $\Delta\Phi$ between 2 leptons in lab frame
  • Binned Likelihood fit to two templates

$f^{SM} = 1.06 \pm 0.21\,(\text{stat.})^{+0.40}_{-0.27}\,(\text{syst.})$

Excludes no-correlation at $> 3 \sigma$
What

- Rapidity difference between top and anti-top
- Investigate Tevatron (CDF) excess
  - CDF larger excess for $m_{tt} > 450$ GeV
  - Not same observable at LHC!

How

- l+jets channel, b-tagged
- Subtract background
- Correct (particle level) for detector and acceptance effects

\[ A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \]

\[ \Delta |y| = |y_t| - |y_{\bar{t}}| \]

\[ A_C^{(MC@NLO)} = 0.006 \pm 0.002 \]

CMS: $A_C = 0.004 \pm 0.010$(stat) ± 0.012(syst)

ATLAS: $A_C = -0.018 \pm 0.028$(stat) ± 0.023(syst)
CHARGE ASYMMETRY

ATLAS Preliminary

CMS (new)

SM subtracted (both axes)

ATLAS Preliminary

CMS-PAS-TOP-11-030
W-BOSON POLARIZATION

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{8} (1 + \cos \theta^*)^2 F_R + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{4} (1 - \cos^2 \theta^*) F_0
\]

How

- \( \theta^* \): Angle between \( \vec{p}(\text{lep}) \) in W rest-frame and \( \vec{p}(W) \) in top rest-frame
- Kinematic fit to event
- Remove background
- Unfold to particle-level

<table>
<thead>
<tr>
<th>Polarisation</th>
<th>Predicted NNLO</th>
<th>ATLAS Measured</th>
<th>CMS Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_R )</td>
<td>0.0017 ± 0.0001</td>
<td>0.09 ± 0.04(stat) ± 0.09(syst)</td>
<td>0.040 ± 0.035(stat) ± 0.044(syst)</td>
</tr>
<tr>
<td>( F_L )</td>
<td>0.311 ± 0.005</td>
<td>0.35 ± 0.04(stat) ± 0.04(syst)</td>
<td>0.393 ± 0.045(stat) ± 0.029(syst)</td>
</tr>
<tr>
<td>( F_0 )</td>
<td>0.687 ± 0.005</td>
<td>0.57 ± 0.07(stat) ± 0.09(syst)</td>
<td>0.567 ± 0.074(stat) ± 0.047(syst)</td>
</tr>
</tbody>
</table>
ANOMALOUS WTB

What

• Assume scale of new physics >> observable region
  • Modeled as effective field theory
  • Add dimension 6 operators to modify Wtb
  • New physics parametrised as effective Lagrangian
    • \( V_L, V_R, g_L, g_R \): dimensionless constants (related to couplings and scale of new physics)

\[
\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \frac{i \sigma^{\mu\nu} q_v}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.,}
\]

How

• ATLAS uses asymmetry \( A_\pm \) of \( \cos \theta^* \) > or < \( \pm (2^{2/3} - 1) \)

Assume: \( V_R = 0, V_L = 1 \)
$t\bar{t} + $ JET VETO

\[ f(Q_0) = \frac{n(Q_0)}{N} = \frac{\sigma(Q_0)}{\sigma} \]

\[ f(Q_{sum}) = \frac{n(Q_{sum})}{N} = \frac{\sigma(Q_{sum})}{\sigma} \]

**What**
- $t\bar{t}$ production with a veto on central jet activity
- Fraction of events that do NOT contain jet activity with $p_T > Q$
  - Leading $p_T$ emissions from $t\bar{t}$ ($Q_0$)
  - All hard emissions from $t\bar{t}$ ($Q_{sum}$)

**How**
- High purity: dilepton +2 b-tags
- No extra jet with $p_T > Q$ in 4 $|\eta|$ regions
- Correct for detector effects
BRANCHING RATIO

\[ R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} \]

BR_{SM \, const}(t \rightarrow Wq) = 0.999152^{+0.000030}_{-0.000045}

What
- Look for decays other than t→Wb
  - Limit on: t→Wq

How
- Dilepton channel

\[ R = 0.98 \pm 0.03 \, (\text{stat} + \text{sys}) \]
FCNC IN $tt$}

**What**
- Look for decays other than $t \rightarrow Wb$
  - One top: $t \rightarrow Zq$
  - Other top: $t \rightarrow Wb$

**How**
- 3 leptons (2 form a $Z$)
- CMS: use $b$-tagging

CMS: $BR(t \rightarrow qZ) < 0.34\%$
ATLAS: $BR(t \rightarrow qZ) < 1.1\%$
FCNC IN SINGLE TOP

What
- Looking for FCNC in production

How
- Look for $t \rightarrow gq$
  - Leptonic decays + btagging

$BR(t \rightarrow ug) < 5.7 \cdot 10^{-5}$
$BR(t \rightarrow cg) < 2.7 \cdot 10^{-4}$

arXiv:1203.0529
SEARCHES FOR NEW PHYSICS IN TOP-LIKE FINAL STATES

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
<table>
<thead>
<tr>
<th>Mass Limit [GeV]</th>
<th>Channel</th>
<th>Exp.</th>
<th>Lumi [fb^{-1}]</th>
<th>Published</th>
<th>Variable</th>
<th>Comments</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>( t' \to Wb )</td>
</tr>
<tr>
<td>560</td>
<td>l+jets, btag</td>
<td>CMS</td>
<td>4.6(7)</td>
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<td>( H_T ) vs ( M_{reco} )</td>
<td>( S/B ) bin merging</td>
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<tr>
<td>404</td>
<td>l+jets, btag</td>
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<td>1.0</td>
<td>arXiv:1202.3076</td>
<td>( M_{reco} )</td>
<td>profiling</td>
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<tr>
<td>550</td>
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<td>CMS</td>
<td>4.7</td>
<td>?</td>
<td>counting</td>
<td>cutting hard</td>
</tr>
<tr>
<td>350</td>
<td>dilepton, no tag</td>
<td>ATLAS</td>
<td>1.0</td>
<td>arXiv:1202.3389</td>
<td>( M_{reco} )</td>
<td>( S/\sqrt{S+B} ) cut optimistion</td>
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<td></td>
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<td>( b' \to Wt )</td>
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<td>495</td>
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<td>CMS</td>
<td>1.0</td>
<td>CMS PAS EXO-11-036</td>
<td>( N_{jets} )</td>
<td>SS dil + trilepton</td>
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<td>480</td>
<td>l+jets</td>
<td>ATLAS</td>
<td>1.0</td>
<td>arXiv:1202.6540</td>
<td>( N_{jets} ) ( N_W )</td>
<td>semi-boosted ( W )</td>
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<tr>
<td>450</td>
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<td>MET and ( H_T )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( T \to tA_0 )</td>
</tr>
<tr>
<td>~400 (( A_0 &lt; 150 ))</td>
<td>l+jets</td>
<td>ATLAS</td>
<td>1.0</td>
<td>Phys.Rev.Lett.108 (2012) 041805</td>
<td>counting limits in ( A_0 ) vs ( m_T )</td>
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</tr>
<tr>
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<td></td>
<td></td>
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<td></td>
<td>( T \to Zt (FCNC) )</td>
</tr>
<tr>
<td>475</td>
<td>( \geq 3 ) lep</td>
<td>ATLAS</td>
<td>1.0</td>
<td>Phys.Rev.Lett.107 (2011) 271802</td>
<td>energy excl. leading 2 jets+ 2 lep</td>
<td></td>
</tr>
</tbody>
</table>
NO EXCESSES... LIMIT PLOTS

ATLAS
Approx. NNLO pred. ± 1 s.d.
- 68% C.L. observed limit
- 95% C.L. expected limit
- Expected limit ± 1 s.d.
- Expected limit ± 2 s.d.

CDF excluded
\( t' \) mass [GeV]
10 250 300 350 400 450 500

\( \int L dt = 1.04 \text{ fb}^{-1} \)
\( \sqrt{s} = 7 \text{ TeV} \)

CMS preliminary
CL_{10}+jets (4.6 fb^{-1}), e+jets (4.7 fb^{-1})
\( \sqrt{s} = 7 \text{ TeV} \)

- observed 95% C.L.
- expected
- a̸(1) expected
- a̸(2) expected
- σ_{T} Theory

\( \sigma \times Br(\tau \rightarrow \ell \nu) [pb] \)
\( \sigma (pp \rightarrow t\bar{t}) [pb] \)
\( \sigma (pp \rightarrow \tau \ell) [pb] \)

ATLAS Preliminary
L dt = 1.04 \text{ fb}^{-1} 95% C.L.
- NNLO from HATHOR
- and ± 1 s.d. uncertainty
- Median Expected Limit
- Observed Limit

σ × Br(t→Wtq)[pb]
σ (pp→tTB)[pb]

ATLAS
\( M_{T} \) [GeV/c^2]
300 320 340 360 380 400 420 440 460 480 500

ATLAS Preliminary
L dt = 1.04 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}
15% C.L. Exclusions:
- Expected: \( m_{\tau} = 460 \pm 80 \text{ GeV/c}^{2}, \sigma_{\tau \rightarrow b \bar{b}} = 0.5 \pm 0.05 \text{ pb} \)
- Observed: \( m_{\tau} = 460 \pm 80 \text{ GeV/c}^{2}, \sigma_{\tau \rightarrow b \bar{b}} = 0.47 \) pb

CMS Preliminary
1.14 fb^{-1} \sqrt{s} = 7 \text{ TeV}

\( L dt = 1.04 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV} \)

CMS 2011 Preliminary
1.14 fb^{-1} \sqrt{s} = 7 \text{ TeV}

\( \int L dt = 1.04 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV} \)

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### t’t’ → WbWb

**1 fb⁻¹**

**How**
- L+jets + ≥1 b-tag
- Reconstruct ‘top’ mass
  - Merge bins (<5% uncert.)
- 1D fit to 4 distributions
  - =3 jet as control region
  - 13 ‘profiled’ parameters
- Total of 35 nuisance parameters

**m_{t’} > 404 GeV**

### CMS preliminary

**4.7 fb⁻¹**

**How**
- L+jets + ≥1 b-tag
- Reconstruct ‘top’ mass + HT
- Fit each variable as 1D PDF
  - Extract S/B for bin
- Sort by S/B + merge (<20% uncert.)
- 1D fit
  - 5 ‘profiled’ parameters

**m_{t’} > 460 GeV**
\[ t't' \rightarrow Wq\bar{W}\bar{q} \]

- **Dilepton**
- **Reconstruct ‘top’ mass**
  - Solve 2ν assuming boosted W
- **Cut in** \( M_\text{reco} \) vs \( H_T \)
  - Best S/B (per \( t' \) mass point)
- **1D fit**
- **No ‘profiling’**

\[ m_{t'} > 350 \text{ GeV} \]

\[ m_{t'} > 552 \text{ GeV} \]

**How**

**1 fb^{-1}**

**4.7 fb^{-1}**

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**arXiv:1202.3389**

**No note**
How

• 1 lepton + MET + ≥6 jets
• Reconstruct ‘top’ mass
  • Solve $2\nu$ assuming boosted $W$
• Use semi-boosted $W$-boson
  • Decay products become collimated ($\sim M_W$)
• Count # $W$ and # jets

$m_{b'} > 480$ GeV

How

• SS dilepton + trilepton
• Low background
• Cut & count in signal region

$m_{b'} > 495$ GeV

CMS-PAS-EXO-11-036
SAME-SIGN TOP + 4^{TH} GEN B QUARKS

What
• Look for $tt$ or $\bar{tt}$ production
  • Low mass $Z'$ production
• Look for $BB\rightarrow WtWt$

How
• 2 Same-sign leptons + ≥2 jets + large MET
• Use MET and HT distributions

$m_{b'} > 450$ GeV

$\sigma(Z' = 100 \text{ GeV}) < 2.0$ pb @95%CL
$\sigma(Z' = 200 \text{ GeV}) < 1.4$ pb @95%CL

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**What**
- $\bar{t}t + \text{MET}$
- $\bar{t}t \rightarrow tA_0 \bar{t}A_0$
- $A_0$ escapes detector so seen as MET

**How**
- $L+\text{jets}$ selection
- Higher MET cut

---

*ATLAS*

**Events/30 GeV**

<table>
<thead>
<tr>
<th>Events/30 GeV</th>
<th>$E^\text{miss}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
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<tr>
<td>150</td>
<td>0</td>
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<tr>
<td>200</td>
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<tr>
<td>250</td>
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<tr>
<td>300</td>
<td>0</td>
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<tr>
<td>350</td>
<td>1</td>
</tr>
<tr>
<td>400</td>
<td>2</td>
</tr>
</tbody>
</table>

*ATLAS*

**$A_0$ Mass [GeV]**

<table>
<thead>
<tr>
<th>$A_0$ Mass [GeV]</th>
<th>$m(T)$, $m(A_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>350</td>
<td>550</td>
</tr>
<tr>
<td>400</td>
<td>600</td>
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</table>

---

FCNC 4\textsuperscript{th} GENERATION TOP

What
• $\text{Tt}\to\text{ZtZt}\to\text{ZZWbWb}$
• At least one leptonic $Z$

How
• $\geq 3$ leptons ($2$ OS make a $Z$) + $\geq 2$ jets
• $R_T = \text{Total transverse energy jets + leptons (excluding highest 2 j and 2 l)} > 80 \text{ GeV}$

$m_T > 475 \text{ GeV}$

We have come a long way in 2 years of LHC running! Many precision top measurements (and direct searches) Most results constrain the phase-space of new physics But there is a lot more space to explore…
BACKUP
CDF $A_{FB}$
CDF $A_{FB}$
What
• T (or t’) and B (or b’)
  • Prime usually refers to sequential SM
• Pair production or single production
• Mechanism and cross section depend on nature of quarks (scalar, vector-like, charge, ...)
• Searches for
  • T->Wb, T->Zt, T->tA_0
  • B->Wt, B->Zb

How
• Complicated final states
• Mostly with bosons
$t't' \rightarrow Wb\bar{W}b$

What
- Same as ATLAS search

How
- L+jets channel
- Use 2D: Mass vs HT
  - Sort by S/B (fitted with 1D PDFs)
  - Merge bins until uncertainties < 20%

$m_{t'} > 560 \text{ GeV} \@ 95\% \text{ CL}$
SAME-SIGN TOP + 4\textsuperscript{TH} GEN B QUARKS

What
• Look for \(tt\) or \(tb\overline{t}b\overline{t}\) production
• Low mass \(Z'\) production
• Look for \(BB\rightarrow WtWt\)

How
• 2 Same-sign leptons + \(\geq 2\) jets + large MET
• Use MET and HT distributions

\[ \sigma (Z' = 100 \text{ GeV}) < 2.0 \text{ pb} \ @ 95\% \text{ CL} \]

\[ \sigma (Z' = 200 \text{ GeV}) < 1.4 \text{ pb} \ @ 95\% \text{ CL} \]

\(m_{b'} > 450 \text{ GeV} @ 95\% \text{ CL}\)
SYSTEMATIC UNCERTAINTIES IN TOP PHYSICS

Many

• ~35 total
• Example of 4th generation t’ search

<table>
<thead>
<tr>
<th>Source</th>
<th>Normalization</th>
<th>Shape</th>
<th>Fitted</th>
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<tbody>
<tr>
<td>tt cross section</td>
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<td>NO</td>
<td>YES</td>
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<tr>
<td>tt fragmentation model</td>
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<td>Jet reconstruction efficiency</td>
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<td>$b$-quark jet energy scale</td>
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