Searches for new physics in the Top Sector at the LHC

Davide Gerbaudo
On behalf of the CMS and ATLAS collaborations

Fermilab, April 2015
LHC top searches and measurements entering the TeV-scale → **Boosted** top quarks

Efficient hadronic top-tagging:
- large $R$ jet as top candidate, less combinatorics
- jet **substructure** can be exploited for powerful discriminants
Several reasons for which final states containing top quarks are an excellent means to probe new physics:

- **the top quark decays** before hadronization
  - direct studies of top-quark properties
  - search for new physics in top decays
- **the top quark is heavy**
  - it plays a special role in many new physics models
  - large BR(heavy particle → t+X)
top quark

Vector-like-quarks
$Q \rightarrow t + X$ or
$Q \rightarrow Wb + X$

SUSY stop
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ or
$\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$

(à la $Z'$) $\tilde{t} \tilde{t}$ resonances

(à la $W'$) $tb$ resonances

Dark matter → monotop
Resolved + boosted selections:

- Resolved: $\bar{t}t$ with $\ell+u+4$ small R jets; choose kinematically best combination
- Boosted:
  - **leptonic top** = $\ell+u$+small R jet
  - **hadronic top** = large R jet with high mass, hard substructure

Wide mass range covered
- Resolution ~10%
- Narrow leptophobic $Z'$ excluded up to 1.8 TeV
CMS: $\bar{t}t$ resonances in all final states

CMS B2G-13-008 New!

Optimized for boosted tops, using jet substructure. Consider all three possible top-pair decays:
(à la $Z'$) $tt$ resonances

(à la $W'$) $tb$ resonances

Vector-like-quarks
$Q \rightarrow t + X$ or $Q \rightarrow Wb + X$

SUSY stop
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0$

Dark matter → monotop

top quark
CMS: $W' \rightarrow tb$

- **Single lepton** (e/µ) final state
- Missing $E_T$
- $\geq 2$ jets (small-R), at least 1 b-tag
- $p_T$ reweighting derived in control region
- Exclude $W'_R$ up to 2.03 TeV

JHEP 05 (2014) 108

- **All-hadronic** final state
- Focus on di-jet topology, with one b-jet and one large-R top-jet (substructure)
- Exclude $W'_R$ up to 2.0 TeV

PAS B2G-12-009
**ATLAS: W' → tb**

**Single-lepton** (e/µ) final state
- Missing $E_T$
- 2 or 3 jets (small-R), 2 b-tags
- BDT discriminant, inputs:
  - $m(tb)$, $p_T(t)$, etc.
- Exclude $W'_R \ (W'_L)$ as heavy as 1.92 (1.80) TeV

**All hadronic** final state, two jets with $\Delta R > 2.0$
- One b-tagged $R=0.4$ jet, one $R=1.0$ **t-tag** jet,
- Two categories based on b-tag of top candidate
- jet substructure, N-subjettiness

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- Unbinned lhoo fit on $m(tb)$
- Bkg estimation from data

Exclude:
- $W'_L$ up to 1.68 TeV
- $W'_R$ up to 1.76 TeV

1408.0886 [hep-ex]
Submitted to EPJC
(à la $Z'$) $t\bar{t}$ resonances

(à la $W'$) $tb$ resonances

Vector-like-quarks
$Q \rightarrow t+X$ or
$Q \rightarrow Wb+X$

SUSY stop
$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ or
$\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$

Dark matter
$\rightarrow$ monotop
CMS: all-hadronic monotop

WIMP probe complementary to monojet and monophoton DM searches
- Large missing $E_T$
- Three high-$p_T$ jets
- One b-tag
- Exclusion up to
  - 350 GeV (scalar)
  - 630 GeV (vector)
ATLAS: $\ell$+jets monotop

- $t \rightarrow Wb$ ($W \rightarrow \ell \nu$) + missing $E_T$
- $tt \rightarrow$ (dilepton) is the main background
- $m_T(\ell, \text{missing } E_T)$ and $\Delta\Phi(\ell, b)$ are the main discriminating variables

Interpretation: many theories predicting monotop → use effective models:
- resonant production of spin-0 → $t_R f_{1/2}$
- non-resonant production of spin-1 + $t_R$

ATLAS: Dark Matter + HF

Dark matter pair production with t or b:
- large missing $E_T$
- at least one high-$p_T$ jet
- four selections:
  - one or two b-jets
  - two top quarks, both with hadronic decays or one hadronic and one leptonic
- optimized selection with several advanced variables: razor, am$_{T2}$, topness


Strong limits in the **low mass region**, relevant to recent claims by DAMA/LIBRA, COGENT, CDMS, Fermi-LAT
(à la $Z'$) $tt$ resonances

(à la $W'$) $tb$ resonances

Vector-like-quarks
$Q \rightarrow t + X$
or
$Q \rightarrow Wb + X$

Dark matter $\rightarrow$ monotop

SUSY stop
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$ or
$\tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1$
VLQ production and decay

Possible final states for $T\bar{T}$

Decays:
- $T \rightarrow Wb/Zt/Ht$
- $B \rightarrow Wt/Zb/Hb$

Rich signatures:
- top quarks
- $b$ jets
- $V_{had} \rightarrow jj/J$
- $H \rightarrow b\bar{b}$. 

Possible signatures for $T\bar{T}$ ($\ell$+jets)
ATLAS: VLT

New! \( Ht+X \)
- dominant \( H \rightarrow bb \)
- \( N_{\text{jet}}>5, N_{b-jet}>2 \)
- 8 channels, largest s/b for \( N_{\text{jet}}>6, N_{b-jet}>4 \)

Same-sign dilepton/trilepton (+ b-jets)
- SS 2\( \ell \) or 3\( \ell \), \( N_{b-jet}>1 \), missing \( E_T \), \( H_T \)
- sensitive to VLQ and several other BSM models
- 11 SR based on charge, \( H_T \), \( N_{b-jets} \), missing \( E_T \)

ATLAS: VLT

$\bar{t}t \rightarrow Zt+X$:
- $\ell\ell$ consistent with a high-$p_T$ $Z$, allow 3rd $\ell$
- $N_{\ell\ell} > 2$, $N_{b\text{-jets}} > 1$
- selections optimized on $N_{\ell\ell}$, $N_{b\text{-jets}}$, $N_{fwd\text{-jets}}$
- discriminant $m_{Zb}$ or $H_T$

JHEP 11 (2014) 104

Wb+X New!
- optimized for $\bar{t}t \rightarrow WbWb$
- one $W \rightarrow \ell\nu$
- one $W_{\text{had}}$, boosted or resolved
- kinematic req. to suppress $t\bar{t}$

ATLAS-CONF-2015-012

D. Gerbaudo, UCI

Top@20, Fermilab, April 2015

17
1503.05425 [hep-ex] New!

- Assuming allowable decay modes are: $B \to Wt/Zb/Hb$
- Consider subsets with 1 or more reconstructed hadronic boson
- Do not measure charge
  → also set limits on $T_{5/3} \to Wt > 840$GeV

Combination VLT New!

For more summary plots, see the ExoticsPublicResults
CMS: inclusive VLT & VLB

Comprehensive searches for $T\bar{T}$ and $B\bar{B}$ in:

- Single lepton
- Multilepton
  - Opposite-sign, on/off-Z
  - Same-sign
  - Trilepton

CMS-PAS-B2G-12-019
- Single lepton
- $\geq 4$ jets, $\geq 1$ b-jet
- 0, 1, 2$\geq$ V-tags
CMS: VLQ $\ell+\text{jets}$

New!
CMS-PAS-B2G-12-017

- Assume $\text{BR}(T\rightarrow Wb) = \text{BR}(Q\rightarrow Wq) = 100\%$
- For the hadronic $W$, consider both
  - resolved decay
  - boosted decay
CMS: VLQ all-had

New! submitted to JHEP
1503.01952 [hep-ex]

- ≥2 high-$p_T$ CA jets (R=1.5)
- ≥1 top candidate (HEP top tagger)
- ≥1 Higgs candidate

For the first time: tagging boosted Higgs with a combination of jet substructure and b-tagging.
CMS: VLQ Ht+X, H → γγ

- One Higgs boson required to decay H → γγ
- Low BR, high purity
- Hadronic (W → qq) and leptonic (W → ℓν) channels
- Loose kinematic selection (H_T)

CMS Preliminary √s = 8 TeV L = 19.7 fb⁻¹

Hadronic Category
M_T = 700 GeV

Data
Bkg Model

TT → tHh(→ γ γ)

CMS-PAS-B2G-14003
(à la Z') tt resonances

(à la W') tb resonances

Vector-like-quarks
Q → t+X or
Q → Wb+X

SUSY stop
\tilde{t}_1 → t \tilde{\chi}_1^0 or
\tilde{t}_1 → W b \tilde{\chi}_1^0

Dark matter → monotop
Pair produced stop detected in all-hadronic top decays: JHEP 09 (2014) 015
Two decay modes considered:

Pair produced stop detected in $\ell+\text{jets}$ top decays: JHEP 11(2014)118
Several signal regions accounting for different mass hierarchies and decay modes

ATLAS: stop

Three categories considered:
• fully resolved (6 jets)
• partially resolved (2 jets reclustered with $R=1.2$)
• five jets
Most discriminating variable: missing $E_T$

Shape fits enhance sensitivity in challenging scenarios
Impressive coverage already reached last year. Detailed $t\bar{t}$ measurements made it possible to probe the stealth stop region ($m_{\tilde{t}} \sim m_t$)
→ see yesterday's talk by Frederic Deliot

$\tilde{t}\tilde{t}$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$
Outlook

- Top turns 20, and plays a **central role** in many searches for new physics at the LHC
- **New tools**, such as top tagging and reconstruction of boosted objects, are key in many of these searches
- Looking forward to the next 20 years of top physics; hopefully it will lead to the observation of new physics!
Extra
CMS B2G Summary

CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)

Vector-like $Q'$

Vector-like $T'$

Vector-like $B'$

Dark matter

Excluded Mass (TeV)

$Q'\rightarrow qW$ (semilep+M)
$T(3/3)$ (dilep, ss)
$T'\rightarrow tZ$ (semilep+lep)
$T'\rightarrow tH$ (semilep+lep)
$T'\rightarrow bW$ (semilep+lep)
$T'\rightarrow bH$ (semilep+M)
$T'\rightarrow tH (H \rightarrow \gamma\gamma)$
$T'\rightarrow tH$ (hadronic)
$B'\rightarrow bZ$ (multilep)
$B'\rightarrow bH$ (multilep)
$B'\rightarrow WZ$ (multilep)
$B'\rightarrow WZ$ (se-dilep)
$B'\rightarrow bZ$ (dilep)
$B'\rightarrow bZ$ (semilep)
$B'\rightarrow bH$ (semilep)
$B'\rightarrow tW$ (semilep)
$B'\rightarrow bH$ (hadronic)
t+MET, vectorial (had)
t+MET, scalar (had)
t+MET, scalar (dil)
t+MET, scalar (dil)
t+MET, scalar (dil)
# ATLAS Exotics Summary

## ATLAS Exotics Searches* - 95% CL Exclusion

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \mathcal{L} ) [fb]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD G0x + g/h</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>5.26 TeV</td>
</tr>
<tr>
<td>ADD non-resonant ( \ell \ell )</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD QCD (BR)</td>
<td>1, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>7.2 TeV</td>
</tr>
<tr>
<td>ADD QCD</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>8.82 TeV</td>
</tr>
<tr>
<td>ADD BH Higgs ( N_{\text{R}} )</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD BH Higgs ( \gamma \gamma )</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>5.8 TeV</td>
</tr>
<tr>
<td>ATLAS Preliminary</td>
<td></td>
<td></td>
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<td></td>
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### Extra dimensions

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \mathcal{L} ) [fb]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk RS ( G_{\text{R}} \to ZZ \to q\bar{q}q\bar{q} )</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>7.2 TeV</td>
</tr>
<tr>
<td>Bulk RS ( G_{\text{R}} \to WW \to q\bar{q}J )</td>
<td>1, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>6.8 TeV</td>
</tr>
<tr>
<td>Bulk RS</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>5.8 TeV</td>
</tr>
</tbody>
</table>

### Gauge bosons

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \mathcal{L} ) [fb]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM Z \to \ell \ell</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>2.8 TeV</td>
</tr>
<tr>
<td>SSM Z \to \ell \ell</td>
<td>2, 1</td>
<td>2 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>5.22 TeV</td>
</tr>
<tr>
<td>SSM W \to \ell \ell</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>3.24 TeV</td>
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</table>

### Photons

<table>
<thead>
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<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \mathcal{L} ) [fb]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRSM ( W_L \to b^+ b^- )</td>
<td>2, 1</td>
<td>2 b</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>5.97 TeV</td>
</tr>
<tr>
<td>LRSM ( W_L \to b^+ b^- )</td>
<td>2, 1</td>
<td>2 b</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>1.92 TeV</td>
</tr>
</tbody>
</table>

### Other

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \mathcal{L} ) [fb]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSTC ( g \to W_L )</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>7.2 TeV</td>
</tr>
<tr>
<td>LSTC triple ( H^+ \to \ell \ell )</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>Higgs triple ( H^+ \to \ell \ell )</td>
<td>2, 1</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_0 )</td>
<td>9.06 GeV</td>
</tr>
</tbody>
</table>

### References

- D. Gerbaudo, UC
- Top@20, Fermilab, April 2015
- ATLAS Exotics Summary - 95% CL Exclusion
- ATLAS Preliminary

*Only a selection of the available mass limits on new states or phenomena is shown.