4th generation and heavy quarks at LHC

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KEK Tsukuba
New heavy quarks

- Over the past decades, Standard Model (SM) has been very successful in describing all the experimental measurements using “only” three generations of quarks and lepton family

- Many BSM models predict new heavy quarks: Extra-dimension, little higgs, new SM like generations, GUTs, etc...

- Can be vector like, can have flavor changing neutral current decays, etc...

- Initial searches at the LHC focus mainly on pair produced heavy quarks, decaying mostly like the top-quark

- **Benchmark model:**
  - Simplest extension of the SM: 4th sequential generation of fermions
Top Quark Pair Production

- $\sigma_{tt} (7 \text{ Tev LHC}) \sim 165 \text{ pb} \ (172.5 \text{ GeV}, \text{ Moch, Uwer, Langenfeld} \ (\text{Phys. Rev. D78 (2008) 034003, arXiv:0907.2527}) = 20 \sigma_{tt} (\text{Tevatron})$

- 5fb$^1$ @ 7 TeV already on tape
  → 825K ttbar pairs (~10 times Tevatron statistics)

Dominant at the LHC (80%)

Dominant at the Tevatron
Top Quark Event Topology

- Almost all top quarks decay to \( t \rightarrow Wb \)
- Final states classified by \( W \) decay modes:
  - \( W \rightarrow qq \) (2/3) or \( W \rightarrow 1\nu \) (1/3)
  - All hadronic (no \( W \rightarrow 1\nu \)) \( \rightarrow \) 4/9 (~45%)
  - Semi-leptonic (1 \( W \rightarrow 1\nu \)) \( \rightarrow \) 4/9 (only electron/muon considered \( \rightarrow \) ~31%)
  - Di-leptonic (2 \( W \rightarrow 1\nu \)) \( \rightarrow \) 1/9 (only electron/muon considered \( \rightarrow \) ~5%)
- The top-quark provides a virtual lab to search for new physics
  - Many tops have already been produced at LHC!!
  - Various properties of the top-quark have been measured
  - This helps us to provides procedures/tools to separate SM backgrounds from new physics
Top Quark Physic Status (cross sections only...)

- results now comparable with theoretical errors!!!

**ATLAS Preliminary**

19 March 2012

- Theory (approx. NNLO) for $m_t = 172.5$ GeV
- statistically
- total uncertainty

<table>
<thead>
<tr>
<th>Data 2011</th>
<th>$\sigma_{tt}$ (stat) = (syst) = (lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>0.70 fb$^{-1}$</td>
</tr>
<tr>
<td>Dilepton</td>
<td>0.70 fb$^{-1}$</td>
</tr>
<tr>
<td>All hadronic, 1.02 fb$^{-1}$</td>
<td>167 ± 18 ± 78 ± 6 pb</td>
</tr>
<tr>
<td>Combination</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>New measurements</th>
<th>$\sigma_{tt}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{had} +$ jets, 1.67 fb$^{-1}$</td>
<td>200 ± 19 ± 43 pb</td>
</tr>
<tr>
<td>All hadronic, 4.7 fb$^{-1}$</td>
<td>168 ± 12 ± 60 ± 57 ± 6 pb</td>
</tr>
</tbody>
</table>

**CMS Preliminary, $\sqrt{s}=7$ TeV**

- CMS e/μ+jets+btag TOP-11-003 (L=0.8-1.09/pb)
- CMS dilepton (ee,μμ,μμ) TOP-11-005 (L=1.14/ fb)
- CMS all-hadronic TOP-11-007 (L=1.09/ fb)
- CMS dilepton (μτ) TOP-11-006 (L=1.09/ fb)
- CMS 2010 combination arXiv:1108.3773 (L=36/pb)
- CMS e/μ+jets+btag arXiv:1108.3773 (L=36/pb)
- CMS dilepton (ee,μμ,μμ) arXiv:1105.5661 (L=36/pb)
- CMS e/μ+jets arXiv:1106.0902 (L=36/pb)

- MSTW2008(N)NLO PDF, scale PDF(90% C.L.) uncertainty

- $164 \pm 3 \pm 12 \pm 7$ (val ± stat. ± syst. ± lum)
- $170 \pm 4 \pm 16 \pm 8$ (val ± stat. ± syst. ± lum)
- $136 \pm 20 \pm 40 \pm 8$ (val ± stat. ± syst. ± lum)
- $149 \pm 24 \pm 26 \pm 9$ (val ± stat. ± syst. ± lum)
- $154 \pm 17 \pm 6$ (val ± tot. ± lum.)
- $150 \pm 9 \pm 17 \pm 6$ (val ± stat. ± syst. ± lum)
- $168 \pm 18 \pm 14 \pm 7$ (val ± stat. ± syst. ± lum)
- $173 \pm 14 \pm 36 \pm 7$ (val ± stat. ± syst. ± lum)
4\textsuperscript{th} generation quarks

- SM doesn’t predict number of fermion generations:
  - Upper bound from QCD asymptotic freedom: number of families < 9 (<16 quarks).
  - CKM constraints fairly weak.
- SM4 = SM + 4\textsuperscript{th} generation family of fermions with 100 GeV < M < 600 GeV. Above 600 GeV large Yukawa couplings render model non-perturbative.
- In this talk will focus on heavy quarks
- Who ordered that?
  - Consistent w/ precision EW data and allowing for a heavier Higgs boson (up to ~500 GeV).
  - Extended CKM matrix could provide enough CP-violation to explain matter-antimatter asymmetry.
  - Can explain some anomalies in CP-violation measurements in B-physics.
Vector like quarks

- Vector-like quarks: left and right components transform the same under SU(2)_L
- \( \rightarrow \) can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet need to be nearly degenerate in mass.
- Predicted by many models: extra-dimensions, Little Higgs, GUTs,…
- Since mixing with other quarks is \( \sim m/M \), they preferentially couple to the 3\textsuperscript{rd} generation.
- Quite a few possibilities to explore! BRs can be quite model-dependent.

<table>
<thead>
<tr>
<th>Label</th>
<th>Charge</th>
<th>Decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>T singlet</td>
<td>( T_S )</td>
<td>(+2/3)</td>
</tr>
<tr>
<td>B singlet</td>
<td>( B_S )</td>
<td>(-1/3)</td>
</tr>
<tr>
<td>(T,B) doublet</td>
<td>( TB_d )</td>
<td>(+2/3, -1/3)</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>(X,T) doublet</td>
<td>( XT_d )</td>
<td>(+5/3, +2/3)</td>
</tr>
<tr>
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<td></td>
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</tr>
<tr>
<td>(B,Y) doublet</td>
<td>( BY_d )</td>
<td>(-1/3, -4/3)</td>
</tr>
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</tbody>
</table>

"Democratic"
Vector like quarks

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<tbody>
<tr>
<td>$T$ singlet</td>
<td>$T_S$</td>
<td>$T \rightarrow W^+b, Zt, Ht$</td>
</tr>
<tr>
<td>$B$ singlet</td>
<td>$B_S$</td>
<td>$B \rightarrow W^+t, Zb, Hb$</td>
</tr>
<tr>
<td>(T,B) doublet</td>
<td>$TB_d$</td>
<td>$(+2/3, -1/3)$ $T \rightarrow W^+b, Zt, Ht$, $B \rightarrow W^+t, Zb, Hb$</td>
</tr>
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<td>(X,T) doublet</td>
<td>$XT_d$</td>
<td>$(+5/3, +2/3)$ $X \rightarrow W^+t$, $T \rightarrow Zt, Ht$</td>
</tr>
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<td>(B,Y) doublet</td>
<td>$BY_d$</td>
<td>$(-1/3, -4/3)$ $B \rightarrow Zb, Hb$, $Y \rightarrow W^+b$</td>
</tr>
</tbody>
</table>

"W-phobic"

Triplets not included

JHEP 11, 030 (2009)

PRD 81, 035004 (2010)

04/19/2012

Clément Helsens, IFAE Barcelona
Heavy quark production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
  - $\sqrt{s}=7$ TeV: $\sigma(QQ) \sim 1.5$ pb for $m_Q \sim 400$ GeV vs $\sigma(tt) = 160$ pb
  - $\sqrt{s}=14$ TeV: $\sigma(QQ) \sim 8$ pb for $m_Q \sim 400$ GeV vs $\sigma(tt) = 880$ pb
- Many models involving vector-like quarks also have new heavy spin-1 colored particles (e.g. $G'$) which can enhance significantly the cross section.
- For masses above ~1 TeV the dominant production mode is single via the EW interactions (model-dep, but also opportunity to measure weak couplings of heavy quarks!).

(Clément Helsens, IFAE Barcelona)

PREPRINT

PRD 81, 035004 (2010)
JHEP 11, 030 (2009) 14TeV

04/19/2012  Clément Helsens, IFAE Barcelona
Signatures: 4\textsuperscript{th} generation quarks

- 4\textsuperscript{th} Generation models have a restricted list of available signatures that simplify the search strategy: TT→WbWb, BB→tWtW → WbW WbW

<table>
<thead>
<tr>
<th></th>
<th>4 leptons</th>
<th>3 leptons</th>
<th>OS dileptons</th>
<th>SS dileptons</th>
<th>lepton+jets</th>
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<tr>
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<tr>
<td>4 leptons (0Z)</td>
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**Signatures: vector like quarks**

- If we consider VLQ models, there are many signatures that could be exploited, and which are ultimately needed to both enhance discovery potential and model discrimination.

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<th></th>
<th>$T_s$</th>
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<tr>
<td><strong>4 leptons</strong></td>
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</tr>
<tr>
<td>$4 \ell$ (2Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td>BB</td>
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<tr>
<td>$4 \ell$ (1Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td>BB</td>
</tr>
<tr>
<td>$4 \ell$ (0Z)</td>
<td>TT</td>
<td>BB</td>
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<td>TT,XX</td>
<td>BB</td>
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<tr>
<td>$\ell^\pm\ell^\mp$</td>
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<td>BB</td>
<td>BB</td>
<td>XX</td>
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<td><strong>lepton+jets</strong></td>
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<tr>
<td>$\ell^\pm$ (4j)</td>
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<td></td>
<td>TT</td>
<td>TT</td>
<td>YY</td>
</tr>
<tr>
<td>$\ell^\pm$ (≥6j)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT,XX</td>
<td></td>
</tr>
</tbody>
</table>

- Of course, some of them are more challenging or powerful than others…
Higgs and 4\textsuperscript{th} generations 1/3

- 4\textsuperscript{th} generation quarks can come with or without the Higgs boson
- If Higgs exist and considering SM4
  - Higgs couples to the new heavy quarks in the standard way
  - Substantial enhancement of the gg → H cross section
  - Leads to dramatic exclusion on the Higgs → 4\textsuperscript{th} family in big trouble
- Data seems to indicate that both fourth family and SM Higgs cannot both exist
- If 4\textsuperscript{th} family is discovered → SM Higgs is in deep troubles
- Also models of VLQ with a Higgs but suppression of SM branching ratio → Higgs only visible via heavy quark production

\[ \text{Ruan & Zhang (2011)} \]
Higgs and 4\textsuperscript{th} generations 2/3

- What ATLAS did → consider 4\textsuperscript{th} generation quarks/leptons with a mass of 600GeV
- Exclude Higgs boson with m(H) >119GeV and m(H)<593GeV
- If 125GeV excess is real → difficult to have a 4\textsuperscript{th} generation quarks

→ But, LHC limits not conservative
Higgs and 4\textsuperscript{th} generations 3/3

- But: Some room left for 4\textsuperscript{th} generations and SM Higgs boson
  - 4\textsuperscript{th} generation quarks also change the Higgs branching fractions
  - Heavy neutrino mass becomes a key parameter
  - SM4 with SM Higgs only possible
    - For very large Higgs masses > 600GeV
    - Small mass window $\rightarrow$ size depend on the heavy neutrino mass (Conservative limit from $Z$ lineshape: Bulanov, Rozanov & Vysotsky (2003) $m(\nu4)>46.7$GeV )
    - $\rightarrow$ need to recalculate LHC Higgs limits with 4\textsuperscript{th} generation for 46.7GeV heavy neutrino
Tevatron Results $t'$ (4\textsuperscript{th} gen)

- $t' \rightarrow Wb, L$+jets Channel
- No signal consistent with $t'$ pair production

$m(t') > 358\text{GeV (CDF')} @ 95\%\text{C.L.}$

$m(t') > 285\text{GeV (DO)} @ 95\%\text{C.L.}$
Tevatron Results $b'$ ($4^{th}$ gen)

- $b' \to Wt \to WWb, L+\text{jets Channel}$ and same-signed leptons
- No signal consistent with $b'$ pair production

$m(b') > 338\text{GeV} (CDF) @ 95\%\text{C.L.}$

$m(b') > 372\text{GeV} (CDF) @ 95\%\text{C.L.}$
Detectors and LHC Data

- Data collected in 2011 → up to 5.25 fb$^{-1}$
- Maximum instantaneous luminosity $3.5 \times 10^{-33}$ cm$^2$s$^{-1}$
- Pileup up to nvtx = 24 (depending on the LHC)
- Luminosity uncertainty down to 3.4(4.5)% in ATLAS(CMS)
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- Luminosity uncertainty down to 3.4(4.5)% in ATLAS(CMS)
Monte-Carlos

- Signal generated with Pythia or MadGraph (ATLAS/CMS)
- Signal cross-sections from HATHOR (NNLO approximation)

**Backgrounds:**
- ATLAS: MC@NLO for ttbar, single top, Alpgen for W/Z+jets, Herwig for dibosons
- CMS: Pyhtia, MadGraph
- For fake leptons: Obtained via data-driven techniques → loosening the lepton ID criteria and extracting tight vs loose efficiencies in control samples
Results Covered In This Talk

- **CMS results** → https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  
  - Search for a Heavy Bottom-like Quark (4.9 fb⁻¹, arXiv:1204.1088)
  
  - Search for a Heavy Top-like Quark in the Dilepton Final state (5 fb⁻¹, arXiv:1203.5410)
  
  - Search for the pair production of a fourth-generation up-type t’ quark in events with a lepton and at least four jets (4.6 fb⁻¹, PAS-EXO-11-099)
  
  - Inclusive search for a fourth generation of quarks (1.1 fb⁻¹, PAS-EXO-11-054)
  
  - Search for a Vector-like Quark with Charge 2/3 in t+Z Events from pp collisions at √s= 7 TeV (1.14fb⁻¹, arXiv:1109.4985)
Results Covered In This Talk

- **ATLAS results** → https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
  - Search for pair production of a heavy quark decaying to a W boson and a b quark in the lepton+jets channel with the ATLAS detector (1.04fb⁻¹, arXiv:1202.3076)
  - Search for pair-produced heavy quarks decaying to Wq in the two-lepton channel at sqrt(s) = 7 TeV with the ATLAS detector (1.04fb⁻¹, arXiv:1202.3389)
  - Search for same-sign top-quark production and fourth-generation down-type quarks in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector (1.04fb⁻¹, arxiv:1202.5520)
  - Search for down-type fourth generation quarks with the ATLAS Detector in events with one lepton and high transverse momentum hadronically decaying W bosons in sqrt(s)=7 TeV pp collisions (1.04fb⁻¹, arxiv:1202.6540)
  - Search for New Phenomena in ttbar Events With Large Missing Transverse Momentum (1.04fb⁻¹, arXiv:1109.4725)
  - Search for pair production of a new quark that decays to a Z boson and a bottom quark with the ATLAS detector (2.0fb⁻¹, approved plots)
  - Search for a heavy vector-like quark coupling to light quarks in proton-proton collision at √s= 7 TeV with the ATLAS detector (1.04 fb⁻¹, arXiv:1112.5755)
BB → WtWt 1/3

- b’b’ → tWtW → WbW WbW
  - 2 same sign or three isolated leptons (e/mu) in the final state → 7.3% of the decay
  - Dilepton triggers → 92% (mu/mu), 96% (e/mu), >99% (e/e)

- **Selection criteria:**
  - Muons: pT>20GeV, |η|<2.4; isolation ΣET(ΔR<0.3) – pileup < 0.15*pT
  - Electron: pT>20GeV, |η|<2.4 ≤ 1.44 < |η| < 1.57; isolation ΣET(ΔR<0.3) – pileup < 0.06*pT
    - Select event with 2 opposite sign leptons or three leptons (2 of them opposite charge)
  - For same flavor leptons → Z mass veto: |mll – mZ| > 10GeV
  - B-tagging based on IP significance → 50% b-tag efficiency; 1% mistag rate; nbjet≥1
  - Jets clustered using PF particles and Anti-kt with a cone of 0.5; pt > 25GeV; |η|<2.4
    - Same sign lepton → njets≥4; 3 lepton channel njets≥2
  - ST = scalar sum of jet pT, lepton pT, MET, should be > 500GeV

- **Signal selection efficiency:**

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</thead>
<tbody>
<tr>
<td>450</td>
<td>0.662</td>
<td>1.52 ± 0.13</td>
<td>49</td>
<td>0.47 ± 0.05</td>
<td>15</td>
</tr>
<tr>
<td>500</td>
<td>0.330</td>
<td>1.64 ± 0.14</td>
<td>26</td>
<td>0.51 ± 0.05</td>
<td>8.2</td>
</tr>
<tr>
<td>550</td>
<td>0.171</td>
<td>1.71 ± 0.14</td>
<td>14</td>
<td>0.56 ± 0.05</td>
<td>4.7</td>
</tr>
<tr>
<td>600</td>
<td>0.0923</td>
<td>1.69 ± 0.14</td>
<td>7.6</td>
<td>0.60 ± 0.06</td>
<td>2.7</td>
</tr>
<tr>
<td>650</td>
<td>0.0511</td>
<td>1.71 ± 0.15</td>
<td>4.3</td>
<td>0.63 ± 0.06</td>
<td>1.6</td>
</tr>
</tbody>
</table>
BB → WtWt 2/3

- **Backgrounds:**
  - Same sign 2 leptons → main contribution is from ttbar
  - 3 leptons; main contribution tt+W(Z)
- Good modeling of the data, no sign of any excess → set limits

- **Expected/observed yields:**

<table>
<thead>
<tr>
<th></th>
<th>Total BG in signal region</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SS</td>
<td>11.4 +/- 2.9</td>
<td>12</td>
</tr>
<tr>
<td>3 lepton</td>
<td>0.78 +/- 0.21</td>
<td>1</td>
</tr>
</tbody>
</table>

arXiv:1204.1088
Limits extracted using a cut and count method

Modified frequentist method used to extract limits

Observed limit: \( m(b') > 611 \text{GeV} @ 95\% \text{CL} \)

<table>
<thead>
<tr>
<th></th>
<th>Same-charge dilepton ( \Delta \varepsilon / \varepsilon ) [%]</th>
<th>Trilepton ( \Delta \varepsilon / \varepsilon ) [%]</th>
<th>( \Delta B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of control-sample method</td>
<td>-</td>
<td>2.63</td>
<td>-</td>
</tr>
<tr>
<td>Control sample statistics</td>
<td>-</td>
<td>0.76</td>
<td>-</td>
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<tr>
<td>b-tagging</td>
<td>6.7</td>
<td>0.35</td>
<td>6.7</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>3.3</td>
<td>0.03</td>
<td>4.9 – 5.1</td>
</tr>
<tr>
<td>Background normalization</td>
<td>-</td>
<td>0.74</td>
<td>-</td>
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<tr>
<td>Pile-up events</td>
<td>0.5</td>
<td>0.13</td>
<td>0.6</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.1 – 2.0</td>
<td>0.31</td>
<td>0.3 – 1.0</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.3 – 1.4</td>
<td>0.22</td>
<td>0.3 – 0.9</td>
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<tr>
<td>Missing energy resolution</td>
<td>0.1 – 0.7</td>
<td>0.38</td>
<td>0.1 – 2.2</td>
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<td>Trigger</td>
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<td>0.11</td>
<td>0.7</td>
</tr>
<tr>
<td>PDF</td>
<td>0.4 – 1.9</td>
<td>0.26</td>
<td>0.4 – 1.3</td>
</tr>
<tr>
<td>Simulated sample statistics</td>
<td>2.7 – 3.4</td>
<td>0.26</td>
<td>4.5 – 6.5</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.2</td>
<td>0.24</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Total BG in signal region Data

<table>
<thead>
<tr>
<th></th>
<th>Total BG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SS</td>
<td>11.4 +/- 2.9</td>
<td>12</td>
</tr>
<tr>
<td>3 lepton</td>
<td>0.78 +/- 0.21</td>
<td>1</td>
</tr>
</tbody>
</table>

Limit at 95% CL: \( M_{b'} > 600 \text{GeV}/c^2 \)
BB → WtWt (single lepton) 1/3

- Final state $b'b' \rightarrow WtWt \rightarrow WWbWWb \rightarrow 1\text{lep}+\text{MET}+\geq 6\text{jets}$
- **Event selection:**
  - Exactly 1 lepton (electron or muon) with tight selection criteria
  - Lepton $p_T > 20(25)\text{GeV}$ muon(electron); muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - $ET_{\text{Miss}} > 20(35)\text{ GeV}$; muon(electron)
  - $ET_{\text{Miss}} + MTW(\text{lep}) > 60\text{GeV}$
  - $\geq 6\text{jets}$ with $p_T > 25\text{GeV}$ and $|\eta| < 2.5$
- No b-tagging requirements
- High jet multiplicity → suppress background
- Identify high $p_T$ W bosons (close-by jets)

arXiv:1202.6540

1fb^{-1}
BB → WtWt (single lepton) 2/3

- Analysis based on high pT hadronic W (2 jets collimated)
- Pair jets if DR(j,j) < 1
- Count the number of W with 70<M_W<100GeV
  - → >75% efficient for pt(W)>250GeV
- Very good Background modeling in several signal free regions

arXiv:1202.6540
BB → WtWt (single lepton) 3/3

- Data in agreement with SM expectations → Set limits
- Number of hadronic W boson candidate (0,1, ≥2) for 3 jet bins (6, 7, ≥8)
- Mclimit used (Cls method with profile likelihood fit)
- Assuming BR(b' → tW ) = 1 → m(b') > 480GeV @ 95% C.L.

ArXiv:1202.6540

1fb⁻¹

Applicable to VLQ
B → W⁻ t (Q=-1/3) and
X → W⁻ t (Q=+5/3)
BB → WtWt (SS dileptons) 1/3

- Final state b'b' → WtWt → WWbWWb → 2SS leptons, MET, ≥2jets
- Search for two same sign leptons (ee/µµ/µµ)
- Signature: 2 SS leptons, MET, >=2jets
- **Pre-Selection:**
  - 2 same sign leptons with tight identification criteria
  - Single lepton trigger
  - Lepton pT > 20(25)GeV muon(electron); muon |η| < 2.5; electron |η| < 2.47 ≠ 1.37 < |η| < 1.52
  - ee/mumu → Mll > 15GeV and |Mll - MZ| > 10GeV
  - Jets: 2 Anti-kt 0.4, pt> 20GeV, |η| < 2.5
  - ETMiss > 40 GeV
- No b-tagging requirements
BB → WtWt (SS dileptons) 2/3

- **Background sources in the SM:**
  - Diboson (MC) → irreducible background (Real leptons)
  - Ttbar, Wjets → one fake lepton or charge flip → data driven

- **Dominant systematics:**
  - Jet energy scale and resolution
  - Fake lepton background
  - Charge flip background

- **Strategy:**
  - Signal region → HT > 350GeV (scalar sum of leptons and jets)
  - Low background search → accurate estimations
  - Cut and count analysis

arXiv:1202.5520

1fb⁻¹
BB → WtWt (SS dileptons) 3/3

- A single bin counting experiment is used to set limit
- Data in agreement with SM expectations
- Limits setting using Collie package
- Confidence level interval are build using a Likelihood ratio test statistic
- Assuming BR(b' → tW ) = 1 → m(b') > 450 GeV @ 95% C.L.

<table>
<thead>
<tr>
<th></th>
<th>$e^-e^-$</th>
<th>$\mu^-\mu^-$</th>
<th>$e^-\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake</td>
<td>$0.2 \pm 0.3 \pm 0.1$</td>
<td>$0.7 \pm 0.3 \pm 0.6$</td>
<td>$0.5 \pm 0.2 \pm 0.7$</td>
</tr>
<tr>
<td>Charge flip</td>
<td>$0.3 \pm 0.1 \pm 0.3$</td>
<td>$0 \pm 0 \pm 0.01$</td>
<td>$0.3 \pm 0.1 \pm 0.2$</td>
</tr>
<tr>
<td>Real</td>
<td>$0.8 \pm 0 \pm 0.3$</td>
<td>$1.0 \pm 0 \pm 0.4$</td>
<td>$2.3 \pm 0 \pm 0.8$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.4 \pm 0 \pm 0.4$</td>
<td>$1.7 \pm 0 \pm 0.7$</td>
<td>$3.1 \pm 0 \pm 1.1$</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$b'$ 450 GeV</td>
<td>$1.8 \pm 0 \pm 0.3$</td>
<td>$2.1 \pm 0 \pm 0.3$</td>
<td>$4.3 \pm 0 \pm 0.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^+$</th>
<th>$\mu^+\mu^+$</th>
<th>$e^+\mu^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake</td>
<td>$0.8 \pm 0 \pm 0.6$</td>
<td>$1.0 \pm 0 \pm 0.8$</td>
<td>$3.3 \pm 1.1 \pm 1.3$</td>
</tr>
<tr>
<td>Charge flip</td>
<td>$0.3 \pm 0 \pm 0.3$</td>
<td>$0 \pm 0 \pm 0.01$</td>
<td>$0.4 \pm 0 \pm 0.3$</td>
</tr>
<tr>
<td>Real</td>
<td>$2.9 \pm 0 \pm 0.7$</td>
<td>$1.6 \pm 0 \pm 0.9$</td>
<td>$4.4 \pm 0 \pm 1.3$</td>
</tr>
<tr>
<td>Total</td>
<td>$3.0 \pm 0 \pm 0.8$</td>
<td>$2.6 \pm 0 \pm 1.1$</td>
<td>$8.1 \pm 1.1 \pm 2.2$</td>
</tr>
<tr>
<td>Data</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>$b'$ 450 GeV</td>
<td>$1.8 \pm 0 \pm 0.3$</td>
<td>$2.7 \pm 0 \pm 0.4$</td>
<td>$5.0 \pm 0 \pm 0.7$</td>
</tr>
</tbody>
</table>

Applicable to VLQ
B → W-t (Q=-1/3) and
X → W+t (Q=+5/3)

Clément Helsens, IFAE Barcelona
• **Selection:**
  - 2 (or more) opposite sign leptons; pt>20GeV; |\(\eta\)| < 2.4
  - Dilepton triggers efficiency \(\rightarrow 100, 95, 90\%\) for ee, \(e\mu\), \(\mu\mu\), respectively
  - Lepton isolation \(\rightarrow \Sigma E_T(\Delta R<0.3) < 0.15*pT\)
  - Z mass veto for ee, \(\mu\mu\) \(\rightarrow \) removed event if 76 < Mll < 106GeV or Mll<12GeV
  - Jets: Anti-kt R=0.5; pT>30GeV; |\(\eta\)| < 2.5 (separated by \(\Delta R>0.4\) from selected leptons)
    - At least 2 jets and at least two of them b-tag
  - ETMiss > 50GeV
• **Signal region:**
  → after basics selection ttbar dominates...

• The invariant mass of lepton and b-jet is used as discriminant

• **At generator level:**
  → clear distinction between t’ and top

• **At reconstruction level:**
  → pairing done with min(ΔR) between lepton and b-jet

• M_{lb} > 170GeV is applied for the minimum
  → signal efficiency ~ 50%
  → ttbar very small...

<table>
<thead>
<tr>
<th>Sample</th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>t'W', M_ν = 400GeV/c^2</td>
<td>10.6 ± 0.9</td>
<td>13.9 ± 1.0</td>
<td>29.4 ± 1.5</td>
<td>53.9 ± 2.0</td>
</tr>
<tr>
<td>t'W', M_ν = 500GeV/c^2</td>
<td>3.0 ± 0.2</td>
<td>3.3 ± 0.2</td>
<td>6.7 ± 0.4</td>
<td>12.9 ± 0.5</td>
</tr>
<tr>
<td>t'W', M_ν = 600GeV/c^2</td>
<td>0.9 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>2.2 ± 0.1</td>
<td>4.1 ± 0.2</td>
</tr>
<tr>
<td>tt → ℓ⁺ℓ⁻</td>
<td>488 ± 11</td>
<td>615 ± 12</td>
<td>1472 ± 19</td>
<td>2575 ± 25</td>
</tr>
<tr>
<td>tt → other</td>
<td>7.2 ± 1.3</td>
<td>0.5 ± 0.3</td>
<td>10.5 ± 1.6</td>
<td>18.2 ± 2.1</td>
</tr>
<tr>
<td>W + jets</td>
<td>&lt; 1.9</td>
<td>&lt; 1.9</td>
<td>&lt; 1.9</td>
<td>&lt; 1.9</td>
</tr>
<tr>
<td>DY → ℓ⁺ℓ⁻</td>
<td>2.9 ± 1.5</td>
<td>1.6 ± 1.0</td>
<td>0.6 ± 0.5</td>
<td>5.1 ± 1.8</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.5 ± 0.1</td>
<td>1.1 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>3.6 ± 0.3</td>
</tr>
<tr>
<td>Single top quark</td>
<td>15.6 ± 1.0</td>
<td>19.5 ± 1.1</td>
<td>46.9 ± 1.7</td>
<td>82.0 ± 2.2</td>
</tr>
<tr>
<td>Total background</td>
<td>514 ± 11</td>
<td>637 ± 12</td>
<td>1532 ± 19</td>
<td>2683 ± 25</td>
</tr>
<tr>
<td>Data</td>
<td>510</td>
<td>615</td>
<td>1487</td>
<td>2612</td>
</tr>
</tbody>
</table>

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04/19/2012

arXiv:1203.5410

5fb⁻¹
TT $\rightarrow$ WbWb (OS dilepton) 3/3

- 1 event observed; 1.8 +/- 1.1 expected
- 95% CL Limits extracted using Cut and count
- Observed limit $m(t') > 552$ GeV @ 95%CL

<table>
<thead>
<tr>
<th>$t't'$ sample</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{t'} = 400$ GeV/c$^2$</td>
<td>$3.5 \pm 0.5$</td>
<td>$5.5 \pm 0.6$</td>
<td>$11.2 \pm 0.9$</td>
<td>$20.1 \pm 1.2$</td>
</tr>
<tr>
<td>$M_{t'} = 500$ GeV/c$^2$</td>
<td>$1.4 \pm 0.2$</td>
<td>$1.9 \pm 0.2$</td>
<td>$3.3 \pm 0.2$</td>
<td>$6.7 \pm 0.4$</td>
</tr>
<tr>
<td>$M_{t'} = 600$ GeV/c$^2$</td>
<td>$0.6 \pm 0.1$</td>
<td>$0.6 \pm 0.1$</td>
<td>$1.3 \pm 0.1$</td>
<td>$2.5 \pm 0.1$</td>
</tr>
</tbody>
</table>

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5fb$^{-1}$
TT → WqWq (OS dilepton) 1/3

- Final state t’t’ → WqWq → lνq lνq
- No assumption about the quark mixing t’ → Wq

**Baseline selection:**
- Exactly 2 leptons pT > 20GeV; muon |η| < 2.5; electron |η| < 2.47 ≠ 1.37 < |η| < 1.52
- Lepton isolation: ΣET(ΔR<0.2) < 3.5GeV
- Jets: Anti-kt 0.4, pt > 25GeV, |η| < 2.5 → at least 2 jets
- ETMiss > 60 GeV (ee/μμ); HT(MET+lep pt) > 130GeV (eμ)
- For ee/μμ → Mll > 15GeV; |Mll – MZ| > 10GeV

**Reconstruction of the heavy quark masses:**
- At high W pT → neutrino and lepton ~ collinear
- Reconstruct both neutrinos by assuming solely contribution to MET
- Reconstruct |Δη(l,ν)| and |ΔΦ(l,ν)| for each neutrino as a free parameter → range [0,1]
- Find the |Δη(l,ν)| and |ΔΦ(l,ν)| values and jet assignment that minimizes the differences between the two masses (collinear mass) and keep events with |m1-m2|<25GeV

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04/19/2012
Final state $t't' \rightarrow WqWq \rightarrow l\nu q l\nu q$

No assumption about the quark mixing $t' \rightarrow Wq$

Baseline selection:
- Exactly 2 leptons $p_T > 20\text{GeV}$; muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \not\in (1.37 < |\eta| < 1.52)$
- Lepton isolation: $\Sigma ET(\Delta R<0.2) < 3.5\text{GeV}$
- Jets: Anti-kt 0.4, $p_T > 25\text{GeV}$, $|\eta| < 2.5$ → at least 2 jets
- $ET_{\text{Miss}} > 60\text{ GeV}$ ($ee/\mu\mu$); $HT(MET+\text{lep pt}) > 130\text{GeV}$ ($e\mu$)
- For $ee/\mu\mu$ → $M_{ll} > 15\text{GeV}$; $|M_{ll} - M_Z| > 10\text{GeV}$

Reconstruction of the heavy quark masses:
- At high $W$ $p_T \rightarrow$ neutrino and lepton ~ collinear
- Reconstruct both neutrinos by assuming solely contribution to MET
- Reconstruct $|\Delta \eta(l,\nu)|$ and $|\Delta \phi(l,\nu)|$ for each neutrino as a free parameter → range [0,1]
- Find the $|\Delta \eta(l,\nu)|$ and $|\Delta \phi(l,\nu)|$ values and jet assignment that minimizes the differences between the two masses (collinear mass) and keep events with $|m_1-m_2|<25\text{GeV}$
\textbf{TT \rightarrow WqWq (OS dilepton) 2/3}

\begin{tabular}{|c|c|}
\hline
$m_Q$ (GeV) & Triangle Requirement (GeV) \\
\hline
300 & $H_T + E_T^{\text{miss}} > 610 - 0.4 \times m_{\text{Collinear}}$ \\
350 & $H_T + E_T^{\text{miss}} > 700 - 0.4 \times m_{\text{Collinear}}$ \\
400 & $H_T + E_T^{\text{miss}} > 790 - 0.4 \times m_{\text{Collinear}}$ \\
450 & $H_T + E_T^{\text{miss}} > 880 - 0.4 \times m_{\text{Collinear}}$ \\
500 & $H_T + E_T^{\text{miss}} > 970 - 0.4 \times m_{\text{Collinear}}$ \\
\hline
\end{tabular}

\begin{tabular}{|c|c|c|}
\hline
$m_Q$ (GeV) & Jet $p_T$ (GeV) & $E_T^{\text{miss}}$ (GeV) \\
\hline
300 & Leading jet $p_T > 80$ & $E_T^{\text{miss}} > 70$ \\
350 & Leading jet $p_T > 120$ & $E_T^{\text{miss}} > 70$ \\
400 & Leading jet $p_T > 130$ & $E_T^{\text{miss}} > 70$ \\
450 & Leading jet $p_T > 130$ & $E_T^{\text{miss}} > 70$ \\
500 & Leading jet $p_T > 130$ & $E_T^{\text{miss}} > 70$ \\
\hline
\end{tabular}

- **Final selection:**
  \rightarrow triangular cut in the $M_{\text{Collinear}} - H_T$ plane (\( = H_{\text{had}} + \text{lepton } p_T + \text{MET} \))

- **Optimized for each t' mass**
  \rightarrow improve the signal/background discrimination

- \rightarrow $M_{\text{Collinear}}$ after triangular cut is used to discriminate signal and background

04/19/2012

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**TT → WqWq (OS dilepton) 3/3**

- Binned maximum likelihood used to set limit on the production cross section; Template fit using the Mcoll distribution

- Observed limit m(t') > 350GeV @ 95%CL

<table>
<thead>
<tr>
<th>Source</th>
<th>+1σ Unc.</th>
<th>−1σ Unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton trigger</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Lepton ID and reconstruction</td>
<td>2 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>3 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>13 %</td>
<td>11 %</td>
</tr>
<tr>
<td>μ momentum resolution</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>μ momentum scale</td>
<td>1 %</td>
<td>2 %</td>
</tr>
<tr>
<td>e energy resolution</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>e energy scale</td>
<td>&lt; 1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>e isolation pileup term</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>e isolation pT term</td>
<td>&lt; 1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>E_T^miss uncertainties</td>
<td>1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>LAr readout problem</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>ISR/FSR: tt</td>
<td>8 %</td>
<td>5 %</td>
</tr>
<tr>
<td>MC generator: tt</td>
<td>1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>MC fragmentation/model: tt</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Drell-Yan model</td>
<td>7 %</td>
<td>7 %</td>
</tr>
</tbody>
</table>

Applicable to to VLQ

T → Wq(q=d,s,b) B → Wq(q=u,c) and Y → W-b

*04/19/2012*

Clément Helsens, IFAE Barcelona
**Final state** $t't' \rightarrow WbWb \rightarrow qqb l\nu b$

**Selection:**
- Isolated Electron $p_T > 35$ GeV $|\eta| < 2.4 \neq 1.44 < |\eta| < 1.57$
- Isolated Muon $p_T > 35 - 42$ GeV (depending on the running period) $|\eta| < 2.1$
- Jets: Anti-kt $R=0.5 \rightarrow 4$ jets 120, 90, 50(35), 35 GeV electron(muon)
- MET $> 20$ GeV
- At least 1 btag jet

<table>
<thead>
<tr>
<th>background process</th>
<th>$\mathcal{L}$</th>
<th>e+jets events</th>
<th>$\mu$+jets events</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>4683 pb$^{-1}$</td>
<td>4734</td>
<td>4601 pb$^{-1}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>165.8 pb</td>
<td>4000 $\pm$ 33</td>
<td>5536 $\pm$ 45</td>
</tr>
<tr>
<td>single $t$</td>
<td>33 pb</td>
<td>196 $\pm$ 3</td>
<td>316 $\pm$ 5</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>30 $\mu$b</td>
<td>434 $\pm$ 13</td>
<td>709 $\pm$ 48</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>2.9 $\mu$b</td>
<td>46 $\pm$ 5</td>
<td>51 $\pm$ 6</td>
</tr>
<tr>
<td>WW,WZ,ZZ</td>
<td>67 pb</td>
<td>–</td>
<td>14 $\pm$ 1</td>
</tr>
<tr>
<td>multijets</td>
<td>73 $\pm$ 3</td>
<td>5 $\pm$ 5</td>
<td>5 $\pm$ 5</td>
</tr>
<tr>
<td>total background</td>
<td>4749 $\pm$ 36</td>
<td>6631 $\pm$ 67</td>
<td></td>
</tr>
</tbody>
</table>
A kinematic fit is performed by minimizing a chi2 from the measured momenta of all the particles and their resolutions.

Fitted t' mass is used together with HT → 2D discriminant unfolded in a 1D.

Unfolding method:
- Order bins in a 1D S/B histogram
- Merge adjacent bins until the fractional statistical uncertainty is below 20% for both signal and background templates.
CLs method used to set limits on the t't' production cross section

Assuming BR(t' → Wb) = 1
→ m(t') > 550GeV @ 95%CL
TT → WbWb (single-lepton) 1/3

**Final state** $t't' \rightarrow WbWb \rightarrow jjb \ell \nu b$

**Strategy:** stay as close as possible to the top group selection → loose selection

**Event selection:**
- Single lepton triggers
- Exactly 1 lepton $p_T > 20$ GeV; muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin [1.37 < |\eta| < 1.52]$ (veto the other flavor)
- Jets: Anti-kt 0.4, $p_T > 25$ GeV, $|\eta| < 2.5$ → at least 3 jets; leading jet $p_T > 60$ GeV
- $E_T^{\text{Miss}} > 20$ (30) GeV muon (electron); $E_T^{\text{Miss}} + M_TW > 60$ GeV
- Using the btagging ($\geq 1$ bjet 70% efficiency, optimize to get best $S/\sqrt{B}$)

**1D kinematic Likelihood fit**
- Reconstructed top mass
- 3 jet bin: just the invariant mass of the 3 jets
- $\geq 4$ jets: using KLFitter
  - Using leading 4 jets only
  - Floating ‘top’ mass
  - No Btagging information used
  - Only constrain both ‘sides’ to be similar

Helps to constraint systematics with profiling

Clément Helsens, IFAE Barcelona

04/19/2012
TT → WbWb (single-lepton) 2/3

- Systematics treated as nuisance parameters
- Dominant systematics: Jet energy scale; ttbar modeling: ISR/FSR, NLO generator (*), fragmentation model (*) (*) = Not profiled
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet and electron and muon channels

<table>
<thead>
<tr>
<th>Source</th>
<th>e+3 jets</th>
<th>μ+3 jets</th>
<th>e+≥4 jets</th>
<th>μ+≥4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>2320 ± 460</td>
<td>3000 ± 630</td>
<td>4470 ± 920</td>
<td>5900 ± 1200</td>
</tr>
<tr>
<td>W+jets</td>
<td>1440 ± 790</td>
<td>2200 ± 1200</td>
<td>830 ± 580</td>
<td>1160 ± 790</td>
</tr>
<tr>
<td>Z+jets</td>
<td>92 ± 53</td>
<td>118 ± 62</td>
<td>86 ± 56</td>
<td>83 ± 46</td>
</tr>
<tr>
<td>Single top</td>
<td>382 ± 68</td>
<td>554 ± 94</td>
<td>262 ± 70</td>
<td>325 ± 79</td>
</tr>
<tr>
<td>Dibosons</td>
<td>28 ± 7</td>
<td>37 ± 11</td>
<td>12 ± 5</td>
<td>17 ± 5</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>520 ± 520</td>
<td>550 ± 550</td>
<td>320 ± 320</td>
<td>340 ± 340</td>
</tr>
<tr>
<td>Total prediction</td>
<td>4800 ± 1000</td>
<td>6500 ± 1500</td>
<td>6000 ± 1100</td>
<td>7800 ± 1400</td>
</tr>
<tr>
<td>Data</td>
<td>4533</td>
<td>6421</td>
<td>6145</td>
<td>8149</td>
</tr>
<tr>
<td>t#bar{t}(400 GeV)</td>
<td>20.0 ± 3.3</td>
<td>21.0 ± 3.6</td>
<td>102.0 ± 10.5</td>
<td>98.1 ± 11.1</td>
</tr>
</tbody>
</table>

04/19/2012

Clément Helsens, IFAE Barcelona

arXiv:1202.3076
TT → WbWb (single-lepton) 3/3

- No sign of excess → set limits (mclimit)
  - Combined limit: electron/muon =3/≥4jets → 4 orthogonal channels
  - Observed limit: $m_{t'} > 404\text{GeV} \at 95\% \text{ C.L.}$. Expected limit: 394GeV
  - Observed limit is within 1σ of the expected in the full mass range considered

Applicable to VLQ
$Y \rightarrow W-b \ (Q=-4/3)$
Inclusive search for a $4^{th}$ generation 1/3

PAS-EXO-11-054

• This analysis presents the inclusive search of $4^{th}$ generation up-down type quark from pair or single production ($t'b \rightarrow Wb \ b; \ b't \rightarrow WbW \ Wb; \ t't' \rightarrow WbWb; \ b'b' \rightarrow WbW \ WbW$)

• Search is performed in the muon channel:
  - 1 isolated muon $p_T > 40$ GeV; $|\eta| < 2.1$; veto other isolated muons $p_T > 10$ GeV, $|\eta| < 2.5$; veto electrons $p_T > 20$ GeV; $|\eta| < 2.5$
  - Jets $p_T > 30$ GeV; $|\eta| < 2.5$; $\geq 1$ to be a b-tag ($|\eta| < 2.4$ tracker acceptance)
  - MET $> 40$ GeV to reduce QCD multijet

• Search performed in 6 subsamples, based on nb-jet ($==1, \geq 2$); nWhad ($==0, ==1, ==2, \geq 3$)
  - 1B_0W $\rightarrow$ single $t'$ with 1 fwd/1central bjet; $==1$ forward jet ($2.4 < |\eta| < 5$) $p_T > 30$ GeV
  - 2B_0W $\rightarrow$ single $t'$ with 2central bjets; $==0$ forward jet ($2.4 < |\eta| < 5$) $p_T > 30$ GeV
  - 1B_1W $\rightarrow$ $t't'$ tt pair production with 1 b-jet failing ID; $\geq 3$ jets in addition of the btag
  - 2B_1W
  - 2B_2W $\rightarrow$ one additional bjet at least 2, 4, 6 additional jets
  - 2B_3W
Inclusive search for a 4\textsuperscript{th} generation 2/3

**PAS-EXO-11-054**

- HT discriminant is used = scalar sum of MET, muon pT, btag jets, Whad pT
- HT is sensitive to the presence of 4\textsuperscript{th} generation quark
- A 4\textsuperscript{th} generation quark would appear in the high tails of the HT distribution
- The 6 channels are combined into a single template histogram
- The 4 different signals processes are added into a single distribution for the signal
Different templates of signal are made for each value of $A$ and masses of the new quark.

The results are presented in the plane $(A, m_{q4})$, where $m_{q4}$ is the degenerate mass of the quarks, $A = |V_{tb}|^2$.

Using the CLs method is used to set limits together with a profile likelihood template fit.

For minimal off diagonal mixing, $(A \sim 1)$ between the third and the fourth generation, $m_{t'} = m_{b'} > 490\text{GeV} @ 95\%\text{CL}$.
Search for anomalous MET in tt (single lepton) events

Benchmark: TT pair with T → tA₀ → 0
- A₀ is a dark matter candidate
- Enhanced cross section due to spin states

Signal region:
- $E_T^{\text{miss}} > 100\text{GeV}$, $m_T > 150\text{GeV}$, dilepton veto,
- $p_T > 15\text{GeV}$, tracks, loose electrons
Assuming $\text{BR}(T \rightarrow tA_0) = 1$

- Cut and count method used to set limit using frequentist confidence intervals
- 95% CL limits on TT pair production cross section (depend on A0 and T masses)
  - $m(T) < 420 \text{ GeV}$ for $m(A_0) < 10 \text{ GeV}$
  - $330 < m(T) < 390 \text{ GeV}$ for $m(A_0) < 140 \text{ GeV}$

Could be applied to VLQ
- $TT \rightarrow WbZt, ZtZt$ (with $Z \rightarrow \nu\nu$)
- $TT \rightarrow Wb Ht$ ($H$ invisible)

Could be applied to VLQ

04/19/2012
Search for VLQ in $t+Z$ (pair prod.) \(1/2\)

- Search for a pair-produced heavy vector like quark T (VLQ) with charge 2/3
- 100% BR $T \rightarrow tZ$; $pp \rightarrow TT \rightarrow tZtZ \rightarrow WbZWbZ$
- Muon, $p_T > 15$ GeV and $|\eta| < 2.4$
- Electron $> 20$ GeV and $|\eta| < 2.5 \not\in [1.44 < |\eta| < 1.57]$
- Jets from particle flow, antikt 0.5; $p_T > 25$ GeV, $|\eta| < 2.4$
- One leptonic $Z \rightarrow 2$ OS, same flavored leptons (e or mu) $60 < M_{ll} < 120$ GeV
- At least 3 leptons and at least 2 jets
- $RT > 80$ GeV, with $RT = \Sigma p_T(jet\ i) + \Sigma p_T(lepton \ i)\ (i \neq 1,2)$

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Search for VLQ in t+Z (pair prod.)

- After full event selection two types of background remain:
  - Events with 2 prompt leptons and a non-prompt lepton from a jet ($B_{2l}$) → data driven
  - Events with 3 prompt leptons ($B_{3l}$) tt+Z, diboson → from MC

- Seven events observed in data, compatible with SM expectation → no evidence of VLQ
- Upper limit on the cross section calculated using a Bayesian method
- Assuming a BR of 100% T → tZ set limits on the cross section
- Exclude $m(VLQ) < 475 \text{GeV} @ 95\% \text{ C.L.}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee_{e}$</th>
<th>$ee_{\mu}$</th>
<th>$\mu e_{e}$</th>
<th>$\mu e_{\mu}$</th>
<th>$\mu \mu_{e}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{2l}$</td>
<td>$0.2^{+0.3}_{-0.2}$</td>
<td>$0.8 \pm 0.5$</td>
<td>$0.9 \pm 0.4$</td>
<td>$1.1 \pm 0.5$</td>
<td>$3.0 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>$B_{3l}$</td>
<td>$0.3 \pm 0.1$</td>
<td>$0.3 \pm 0.1$</td>
<td>$0.5 \pm 0.2$</td>
<td>$0.5 \pm 0.2$</td>
<td>$1.6 \pm 0.5$</td>
<td></td>
</tr>
<tr>
<td>$B_{\text{total}}$</td>
<td>$0.5 \pm 0.3$</td>
<td>$1.1 \pm 0.5$</td>
<td>$1.4 \pm 0.5$</td>
<td>$1.7 \pm 0.6$</td>
<td>$4.6 \pm 1.0$</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
• Final state $BB \rightarrow Zb + X \rightarrow llb + X$
• Focus on at least one $B \rightarrow Zb$
• Using only electron channel: $Z \rightarrow ee$
• Preselection:
  - Single electron trigger (95%)
  - $\geq 2$ OS electrons
  - electron $p_T > 25$ GeV $|\eta| < 2.47 \neq 1.37 < |\eta| < 1.52$
  - $\geq 1$ jet with $p_T > 25$ GeV (antikt04)
  - $\geq 1$ bjet (60% efficiency)
Exploit boosted configuration of the Zb system

Z candidate $\rightarrow$ 2OS electrons satisfying $|M_{ee} - M_Z| < 15\text{GeV}$ (take the closest to $M_Z$)

B $\rightarrow$ Zb formed with Z and highest pT b jet

Final selection:
- pT (Zb) $> 150$GeV $\rightarrow$ heavy quarks produced with large pT
BB → Zb+X (OS dileptons) 3/3

- Final discriminant M(Zb)
- 2 scenarios → maximal mixing β=1; Vector Like Singlet (VLS) solely mixing with 3rd generation (mass dependent β=0.9-0.5/200-700GeV)
- SM Higgs mass of 125GeV assumed
- Set limits with mclimit
- m(b') > 400 (358) GeV @ 95%C.L. For beta=1 (VLS)
Search for VLQ (single prod.) 1/3

- Search for vector like quarks (VLQ)Q singly produced both in
  - Charged Current (CC) \( pp \rightarrow Qq \rightarrow Wqq' \)
  - Neutral Current (NC) \( pp \rightarrow Qq \rightarrow Zqq' \)
- Assuming only leptonic decays of the gauge boson
- Both S and T channels contribute to the signal cross section
- Assume VLQ couples to first two generation only (2 degenerate VLQ doublets) → potentially strong signal at the LHC
- Couplings \( K_{qQ} = (\nu/m_Q)K'_{qQ} \)
  - \( q \) is any light quark; \( Q \) is VLQ, \( m_Q \) VLQ mass
  - \( \nu \) Higgs vev
  - \( K'_{qQ} \) → the model dependence of the \( qVQ \) vertex (\( V = W \) or \( Z \))
- Consider only VLQs U and D of charge +2/3 and -1/3
Search for VLQ (single prod.) 2/3

- Event selection, considering electron and muon leptons:
  - Single lepton triggers
  - Isolated electron, pT > 25GeV, |\eta| < 2.47 \neq 1.37 < |\eta| < 1.52
  - Isolated muon, pT > 25GeV, |\eta| < 2.5
  - Jets reconstructed with antiKT0.4
- Charge Current:
  - Exactly one lepton
  - $E_T^{\text{miss}} > 50$GeV
  - At least 2 jets with pT > 50, 25 GeV
  - $|\Delta \eta| > 1$ leading jet pT and 2nd or 3rd jet
  - $m_T(W) > 40$GeV
  - $\Delta \phi(l,E_T^{\text{miss}}) > 2.4$ (expect boosted Ws)
  - VLQ mass $\rightarrow m(W,\text{jet})$ with leading jet pT ($\nu$ pz chosen to give the largest $|\Delta \eta|$ between neutrino and leading jet pT)
- Neutral Current:
  - Exactly two opposite charged same-flavor leptons
  - $66 < M_{ll} < 116$GeV, pT(l,l) > 50GeV (expect boosted Zs)
  - At least 2 jets with pT> 25GeV
  - VLQ mass $\rightarrow m(l,l,\text{jet})$ with leading jet pT
Search for VLQ (single prod.) 3/3

- CLs method and binned maximum Likelihood
- Search performed by searching a signal peak on top of a smooth background
- No evidence of VLQ found
- Assuming $K'uU = K'uD = 1$ set limits $→ m_{VLQ} > 900(760) \text{ GeV for CC(NC) @95\%C.L.}$
- Tevatron limits $→ K'uU=1 690\text{GeV (100\% BR CC) ; K'uD=sqrt(2) 550\text{GeV (100\% BR NC)}}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{\pm}$jets</td>
<td>$14500\pm100\pm4400$</td>
<td>$16600\pm100\pm5000$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$2360\pm50\pm270$</td>
<td>$2530\pm50\pm290$</td>
</tr>
<tr>
<td>Single Top</td>
<td>$700\pm30\pm120$</td>
<td>$740\pm27\pm120$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$670\pm30\pm270$</td>
<td>$340\pm20\pm410$</td>
</tr>
<tr>
<td>$Z^{0}$jets</td>
<td>$128\pm11\pm90$</td>
<td>$432\pm21\pm170$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$174\pm13\pm53$</td>
<td>$198\pm14\pm62$</td>
</tr>
<tr>
<td>Expected Total Background</td>
<td>$18500\pm100\pm4400$</td>
<td>$20900\pm100\pm5100$</td>
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<tr>
<td>Data</td>
<td>$17302$</td>
<td>$20668$</td>
</tr>
<tr>
<td>Expected Signal, $D(225 \text{GeV})$</td>
<td>$2360\pm50\pm350$</td>
<td>$2380\pm50\pm400$</td>
</tr>
<tr>
<td>Expected Signal, $D(600 \text{GeV})$</td>
<td>$133\pm12\pm10$</td>
<td>$133\pm12\pm11$</td>
</tr>
<tr>
<td>Expected Signal, $D(1000 \text{GeV})$</td>
<td>$14\pm4\pm1$</td>
<td>$14\pm4\pm1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z^{0}$jets</td>
<td>$3250\pm60\pm430$</td>
<td>$5350\pm70\pm700$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$58\pm8\pm3$</td>
<td>$90\pm9\pm5$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$38\pm6\pm4$</td>
<td>$58\pm8\pm4$</td>
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<tr>
<td>Expected Total Background</td>
<td>$3350\pm60\pm430$</td>
<td>$5500\pm70\pm700$</td>
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<tr>
<td>Data</td>
<td>$3105$</td>
<td>$5070$</td>
</tr>
<tr>
<td>Expected Signal, $U(225 \text{GeV})$</td>
<td>$192\pm14\pm9$</td>
<td>$339\pm18\pm19$</td>
</tr>
<tr>
<td>Expected Signal, $U(600 \text{GeV})$</td>
<td>$15\pm3.9\pm0.6$</td>
<td>$23\pm4.8\pm0.7$</td>
</tr>
<tr>
<td>Expected Signal, $U(1000 \text{GeV})$</td>
<td>$1.9\pm1.4\pm0.1$</td>
<td>$2.7\pm1.6\pm0.1$</td>
</tr>
</tbody>
</table>
Summary of the results

- **4th generation:**
  - $b'b' \rightarrow Wt$ (100% BR) 611GeV
  - $t't' \rightarrow Wb$ (100% BR) 552GeV
  - Inclusive search ($mt' = mb'$) 490GeV

- **Vector like quarks:**
  - $TT \rightarrow tZ$ (100% BR) 475GeV
  - $TT \rightarrow tZ + X$ 358 - 400GeV
  - $T \rightarrow Wq$ (no coupling to 3rd generation) 900GeV
  - $T \rightarrow Zq$ (no coupling to 3rd generation) 750GeV
Producing model independent results

- For the most part LHC searches so far have been, not only model-dependent, but often in the context of unrealistic models, e.g.:
  - Assume BR=1 for particular heavy quark decay modes.
  - Neglect additional signals that would be present in any realistic model (e.g. in 4th gen models there are two quarks, not one which in principle can contribute in the signal region depending on the final event selection and observable used).

- Given the large number of possible signatures to explore, it’s hard to imagine we can in general design “model-indep” searches for VLQs, but we can sometimes alleviate some of the model assumptions by carefully designing the search.

- A good example: \( QQ \rightarrow Zb+X \)
  - Leptonic Z allows to focus on Q decay modes containing Z bosons with small contamination from other decay modes.
  - Reconstructed Zb system “enough” to suppress backgrounds and build a sensitive observable so don’t really need to look at the “rest of the event”.

Designing event selections which are very inefficient for most but a subset of decay modes may also be a way to have a “cleaner” interpretation (e.g. SS dileptons mainly sensitive to B/X quarks, \( l+6 \) b-tag searches only sensitive to \( T \rightarrow tH \), etc).

- In the case of 4th gen models, it’s possible to relax assumptions on the VQq elements (e.g. by not using b-tagging requirements or producing limits on BR vs mQ plane).
Conclusion and Outlook

- ATLAS and CMS have performed the search for new heavy quarks in several decay channels
  - Search for new heavy quarks made a lot of quick progress at LHC
  - LHC limits are now the most stringent ones
  - Unfortunately no sign of new physic yet :(
- Our program of heavy quark searches is barely covering the tip of the iceberg…
- We have a nice set of searches focusing on pair production but much territory remains to be explored (NC decay modes, boosted topologies, single production, etc).
- Very exciting prospects ahead!
  - Factor of 5 increase in statistics from analyses (2011 dataset).
  - Also reoptimized/broader scope analyses and new channels!
  - Up to 15 fb\(^1\) at \(\sqrt{s}=8\) TeV by then end of 2012.
- Apologies for any relevant topics omitted due to time limitations