4th generation and heavy quarks at LHC

Clément Helsens
IFAE Barcelona

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LPSC Grenoble
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

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

- $5 \text{ fb}^{-1} @ 7 \text{ TeV}$ already on tape
  $\rightarrow 825K \ \text{ttbar pairs} \ (\sim 10 \times \text{Tevatron statistics})$

- Dominant at the LHC (80%)
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 \( W \rightarrow l\nu \ (1/3) \)
  - All hadronic (no \( W \rightarrow l\nu \)) \( \rightarrow 4/9 \) (~45%)
  - Semi-leptonic (1 \( W \rightarrow l\nu \)) \( \rightarrow 4/9 \) (only electron/muon considered \( \rightarrow ~31\% \))
  - Di-leptonic (2 \( W \rightarrow l\nu \)) \( \rightarrow 1/9 \) (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...)

- Single lepton: (0.7fb-1) $\sigma(t\bar{t}) = 179.0 \pm 9.8 - 9.7$ (stat+syst) $\pm 6.6$(lumi.)pb
- Dilepton: (0.7fb-1) : $\sigma(t\bar{t}) = 177 \pm 6$ (stat.)$+17 - 14$ (sys.) $\pm 8$ (lumi.)pb
- Combination (L+jets 35pb-1 and DL 0.7fb-1 no btag): $\sigma(t\bar{t}) = 176 \pm 5$(stat.) $+13 - 10$(syst.) $\pm 7$ (lumi.)pb.
- CMS combine L+jets, dilepton, mu+tau, all hadronic (0.8-1.1fb-1) $\sigma(t\bar{t}) = 165.8 \pm 2.2$ (stat.) $\pm 10.6$ (syst.) $\pm 7.8$ (lumi.) pb.
- $\rightarrow$ results with more luminosity coming soon approaching theoretical errors!

- **ATLAS** Preliminary

  \[ \int Ldt = 35 \text{ pb}^{-1} \text{ (L+jets, 2010)} \]
  \[ \int Ldt = 0.70 \text{ fb}^{-1} \text{ (dilepton, 2011)} \]

  | L+jets w/ b-tagging     | 186 ± 10 $^{+21}_{-20}$ ± 6 |
  | Dilepton w/o b-tagging | 171 ± 6 $^{+16}_{-14}$ ± 8  |
  | **Combination**         | 176 ± 5 $^{+13}_{-19}$ ± 7  |

  | L+jets w/o b-tagging    | 171 ± 17 $^{+20}_{-17}$ ± 6  |
  | Dilepton w/ b-tagging  | 177 ± 6 $^{+17}_{-14}$ $^{+8}_{-7}$ (stat)$\pm$(syst)$\pm$(lumi) |

**CMS Preliminary, $s=7$ TeV**

- CMS 2011 combination TOP-11-024 (L=0.8-1.1fb) $\sigma(t\bar{t}) = 166 \pm 2 \pm 11 \pm 8$ (val. ± stat. ± syst. ± lumi.)
- CMS e$/\mu$+jets+btag TOP-11-003 (L=0.8-1.1fb) $\sigma(t\bar{t}) = 164 \pm 3 \pm 12 \pm 7$ (val. ± stat. ± syst. ± lumi.)
- CMS dilepton (ee,$\mu$,$\mu$,
  ee) TOP-11-005 (L=1.1fb) $\sigma(t\bar{t}) = 170 \pm 4 \pm 16 \pm 8$ (val. ± stat. ± syst. ± lumi.)
- CMS all-hadronic TOP-11-007 (L=1.1fb) $\sigma(t\bar{t}) = 136 \pm 20 \pm 40 \pm 8$ (val. ± stat. ± syst. ± lumi.)
- CMS dilepton ($\mu$,$\mu$) TOP-11-006 (L=1.1fb) $\sigma(t\bar{t}) = 149 \pm 24 \pm 26 \pm 9$ (val. ± stat. ± syst. ± lumi.)

Approx. NNLO QCD, Aliev et al., Comput.Phys.Commun. 182 (2011) 1034
Approx. NNLO QCD, Kidonakis, Phys.Rev.D 82 (2010) 114030
Approx. NNLO QCD, Aliev et al., JHEP 1009 (2010) 097
LNO QCD
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>( T \rightarrow W^+b, Zt, Ht )</td>
</tr>
<tr>
<td>B singlet</td>
<td>( B_s )</td>
<td>( B \rightarrow Wt, Zb, Hb )</td>
</tr>
<tr>
<td>(T,B) doublet</td>
<td>( TB_d )</td>
<td>( T \rightarrow W^+b, Zt, Ht ), ( B \rightarrow Wt, Zb, Hb )</td>
</tr>
<tr>
<td>(X,T) doublet</td>
<td>( XT_d )</td>
<td>( X \rightarrow W^+t ), ( T \rightarrow Zt, Ht )</td>
</tr>
<tr>
<td>(B,Y) doublet</td>
<td>( BY_d )</td>
<td>( B \rightarrow Zb, Hb ), ( Y \rightarrow Wb )</td>
</tr>
</tbody>
</table>

"Democratic"

JHEP 11, 030 (2009)  
Triplets not included

PRD 81, 035004 (2010)
Vector like quarks

- Vector-like quarks: left and right components transform the same under SU(2)\(_L\).
- 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.

\[\begin{array}{|c|c|c|}
\hline
\text{Label} & \text{Charge} & \text{Decay mode} \\
\hline
T \text{ singlet} & T_s & +2/3 \\
& T & \rightarrow W^+b, Zt, Ht \\
B \text{ singlet} & B_s & -1/3 \\
& B & \rightarrow Wt, Zb, Hb \\
(T,B) \text{ doublet} & TB_d & (+2/3, -1/3) \\
& T & \rightarrow W^+b, Zt, Ht \\
& B & \rightarrow Wt, Zb, Hb \\
(X,T) \text{ doublet} & XT_d & (+5/3, +2/3) \\
& X & \rightarrow W^+t \\
& T & \rightarrow Zt, Ht \\
(B,Y) \text{ doublet} & BY_d & (-1/3, -4/3) \\
& B & \rightarrow Zb, Hb \\
& Y & \rightarrow W^+b \\
\hline
\end{array}\]
Heavy quark production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
  - $\sqrt{s}=7$ TeV: $\sigma(QQ) \sim 1.5\text{ pb}$ for $m_Q \sim 400$ GeV vs $\sigma(tt) = 160\text{ pb}$
  - $\sqrt{s}=14$ TeV: $\sigma(QQ) \sim 8\text{ pb}$ for $m_Q \sim 400$ GeV vs $\sigma(tt) = 880\text{ pb}$
- 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!).

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Signatures: 4\textsuperscript{th} generation quarks

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

<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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$4l$ (0Z)</td>
<td>$3l$ (0Z)</td>
<td>$l^\pm l^\mp (0Z)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$BB$</td>
<td>$BB$</td>
<td>$TT,BB$</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th></th>
<th>$T_s$</th>
<th>$B_s$</th>
<th>$TB_d$</th>
<th>$XT_d$</th>
<th>$BY_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4l (2Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td>BB</td>
</tr>
<tr>
<td>4l (1Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td>BB</td>
</tr>
<tr>
<td>4l (0Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT,XX</td>
<td>BB</td>
</tr>
<tr>
<td>3 leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3l (1Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td></td>
</tr>
<tr>
<td>3l (0Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT,XX</td>
<td></td>
</tr>
<tr>
<td>OS dileptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l⁺l⁻ (1Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT</td>
<td>BB</td>
</tr>
<tr>
<td>l⁺l⁻ (0Z)</td>
<td>TT</td>
<td>BB</td>
<td>TT,BB</td>
<td>TT,XX</td>
<td>BB,YY</td>
</tr>
<tr>
<td>SS dileptons</td>
<td>l±l±</td>
<td>BB</td>
<td>BB</td>
<td>XX</td>
<td></td>
</tr>
<tr>
<td>lepton+jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l± (4j)</td>
<td>TT</td>
<td></td>
<td>TT</td>
<td>YY</td>
<td></td>
</tr>
<tr>
<td>l± (≥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

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

- What ATLAS did → consider a 4\textsuperscript{th} generation quark 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

\[\int Ldt = 1.0 - 2.3 \text{ fb}^{-1}\]

\[\sqrt{s} = 7 \text{ TeV}\]

- But, LHC limits not conservative
Higgs and 4th generations 3/3

- But: Some room left for 4th generations and SM Higgs boson
  - 4th 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 size depend on the heavy neutrino mass (Conservative limit from Z lineshape: Bulanov, Rozanov & Vysotsky (2003) m(ν4) > 46.7GeV)

- → need to recalculate LHC Higgs limits with 4th generation for
Tevatron Results $t'$ (4\textsuperscript{th} gen)

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

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

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

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

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

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

- Data collected in 2011 → up to 5.25 fb⁻¹
- Maximum instantaneous luminosity $3.5 \times 10^{-33} \text{ cm}^{-2} \text{s}^{-1}$
- Pileup up to $\text{nvtx} = 24$ (depending on the LHC)
- 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

- **ATLAS results** → [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/)
  - Search for Up-Type Fourth Generation Quarks in the Dilepton plus Jets Channel (37pb-1, ATLAS-CONF-2011-022)
  - 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 New Phenomena in ttbar Events With Large Missing Transverse Momentum (1.04fb-1, arXiv:1109.4725)
  - 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)
  - Search for Up-Type Fourth Generation Quarks in the Lepton plus Jets Channel (1.04fb-1, arXiv:1202.3076)

- **CMS results** → [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
  - Search for a Heavy Bottom-like Quark (1.14fb-1, CMS PAS EXO-11-036)
  - Search for a Heavy Top-like Quark in the Dilepton Final state (1-4.7fb-1, PAS-EXO-11-050)
  - Search for pair production of a fourth-generation t’ quark in the lepton-plus-jets channel (0.82-0.57 fb-1, PAS-EXO-11-051)
  - 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)
CMS – Search for b' 1/3

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

• **Selection criteria:**
  - Muons: \(p_T>20\text{GeV}, |\eta|<2.4;\) isolation \(\Sigma\text{ET}(\Delta R<0.3)\) – pileup < 0.15*pT
  - Electron: \(p_T>20\text{GeV}, |\eta|<2.4 \not\in 1.44<|\eta|<1.57;\) isolation \(\Sigma\text{ET}(\Delta R<0.3)\) – pileup < 0.06*pT
  - Select event with 2 opposite sign leptons or three leptons (2 of them opposite charge)
  - For same flavor leptons \(\to Z\) mass veto: \(|mll - mZ| > 10\text{GeV}\)
  - B-tagging based on IP significance \(\to 50\%\) b-tag efficiency; 1\% mistag rate; \(n\text{bjet} \geq 1\)
  - Jets clustered using PF particles and Anti-kt with a cone of 0.5; \(p_T > 25\text{GeV}; |\eta|<2.4\)
  - Same sign lepton \(\to n\text{jets} \geq 4; 3\) lepton channel \(n\text{jets} \geq 2\)
  - \(S_T = \text{scalar sum of jet } p_T, \text{lepton } p_T, \text{MET, should be } > 500\text{GeV}\)

• **Signal selection efficiency:**

<table>
<thead>
<tr>
<th>(M_{b'}) [GeV/(c^2)]</th>
<th>\text{cross section} [pb]</th>
<th>\text{same-sign dilepton efficiency} [%]</th>
<th>\text{yield}</th>
<th>\text{trilepton efficiency} [%]</th>
<th>\text{yield}</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>3.20</td>
<td>1.16 ± 0.15</td>
<td>42</td>
<td>0.33 ± 0.06</td>
<td>12</td>
</tr>
<tr>
<td>400</td>
<td>1.41</td>
<td>1.36 ± 0.17</td>
<td>22</td>
<td>0.42 ± 0.06</td>
<td>6.7</td>
</tr>
<tr>
<td>450</td>
<td>0.662</td>
<td>1.51 ± 0.18</td>
<td>11</td>
<td>0.45 ± 0.07</td>
<td>3.4</td>
</tr>
<tr>
<td>500</td>
<td>0.330</td>
<td>1.57 ± 0.19</td>
<td>5.9</td>
<td>0.48 ± 0.07</td>
<td>1.8</td>
</tr>
<tr>
<td>550</td>
<td>0.171</td>
<td>1.80 ± 0.22</td>
<td>3.5</td>
<td>0.57 ± 0.08</td>
<td>1.1</td>
</tr>
</tbody>
</table>
CMS – Search for b' 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>4.4 +/- 1.4</td>
<td>5</td>
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<tr>
<td>3 lepton</td>
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<td>1</td>
</tr>
</tbody>
</table>

23/02/2012

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CMS – Search for b' 3/3

- Limits extracted using a cut and count method
- Bayesian method with log-normal prior for integration over the nuisance parameters
- Observed limit: m(b') > 495 GeV @ 95%CL

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<td>1</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>same-sign dilepton</th>
<th>trilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of control-sample method</td>
<td>$\Delta \epsilon / \epsilon$</td>
<td>$\Delta B$</td>
</tr>
<tr>
<td>Control sample statistics</td>
<td>-</td>
<td>1.02</td>
</tr>
<tr>
<td>-</td>
<td>0.49</td>
<td>-</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>4.5%</td>
<td>0.03</td>
</tr>
<tr>
<td>Background normalization</td>
<td>-</td>
<td>0.39</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>4.4 – 4.5%</td>
<td>0.03</td>
</tr>
<tr>
<td>b-tagging</td>
<td>10%</td>
<td>0.07</td>
</tr>
<tr>
<td>Pile-up events</td>
<td>2.3%</td>
<td>0.35</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.4 – 3.2%</td>
<td>0.12</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.8 – 2.4%</td>
<td>0.51</td>
</tr>
<tr>
<td>Missing energy resolution</td>
<td>0.1 – 3.1%</td>
<td>0.10</td>
</tr>
<tr>
<td>Trigger</td>
<td>2.3%</td>
<td>0.07</td>
</tr>
<tr>
<td>PDF</td>
<td>0.3 – 0.7%</td>
<td>0.06</td>
</tr>
<tr>
<td>Simulated sample statistics</td>
<td>3.1 – 4.0%</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>12 – 13%</td>
<td>1.4</td>
</tr>
</tbody>
</table>

CMS 2011 Preliminary

Observed limit: $M_{b'} > 495$ GeV/c$^2$ at 95% CL
This analysis presents the search for two same sign leptons (ee/eμ/μμ).

Inclusive search for new physics \rightarrow limits on heavy Majorana neutrinos, UED, b'

Selection:
- 2 same sign leptons with tight identification criteria
- Single lepton trigger
- Lepton pt > 20GeV; muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
- Lepton isolation: $\Sigma ET(\Delta R<0.2) < 0.15*pT$
- Jets: Anti-kt 0.4, pt> 30GeV, $|\eta| < 2.5$
- ETMiss > 30 GeV
ATLAS – Same sign dileptons 2/3

- **Background sources in the SM:**
  - QCD $\rightarrow$ jets faking/creating isolated leptons
  - Charge Mis-Identification
  - Diboson $\rightarrow$ irreducible background

- **Data/Monte Carlos modeling is shown in the njet distribution:**
  - This is the variable used for limit setting
ATLAS – Same sign dileptons 3/3

- A 3 bin template is used for limit setting \( n_{\text{jet}} = 0, 1 \) and \( \geq 2 \)
- Limits are set using the Feldman-Cousins prescription
- Confidence level interval are build using a Likelihood ratio test statistic
- Assuming \( \text{BR}(b' \rightarrow tW) = 1 \rightarrow m(b') > 290\text{GeV} \) @ 95% C.L.

\[
\int L dt = 34 \text{ pb}^{-1}
\]
CMS – Search for t' dilepton 1/3

PAS-EXO-11-050

- **Search for heavy top-like**: \( t't' \rightarrow WbWb \rightarrow l\nu lb \) \((l=e/\mu)\)

- **Selection**:
  - 2 (or more) opposite sign leptons; \( p_T > 20\text{GeV}; |\eta| < 2.4 \)
  - Dilepton triggers efficiency \( \rightarrow 100, 95, 90\% \) for \( ee, e\mu, \mu\mu \), respectively
  - Lepton isolation \( \rightarrow \Sigma ET(\Delta R<0.3) < 0.15\times p_T \)
  - \( Z \) mass veto for \( ee, \mu\mu \rightarrow \) removed event if \( 76 < M_{ll} < 106\text{GeV} \) or \( M_{ll}<12\text{GeV} \)
  - Jets: Anti-kt \( R=0.5; p_T>30\text{GeV}; |\eta| < 2.5 \) (separated by \( \Delta R>0.4 \) from selected leptons)
    - At least 2 jets and at least two of them b-tag
  - \( ET_{\text{Miss}} > 30\text{GeV} \)
CMS – Search for t' dilepton 2/3

- **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 bjet

- **M_{lb} > 170GeV** is applied for the two masses
  - → signal efficiency ~ 40%
  - → 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′t′, M_{tt′} = 350 GeV/c²</td>
<td>5.63 ± 0.41</td>
<td>5.63 ± 0.38</td>
<td>13.43 ± 0.61</td>
<td>24.69 ± 0.83</td>
</tr>
<tr>
<td>t′t′, M_{tt′} = 400 GeV/c²</td>
<td>2.51 ± 0.18</td>
<td>2.92 ± 0.19</td>
<td>6.33 ± 0.28</td>
<td>11.76 ± 0.38</td>
</tr>
<tr>
<td>t′t′, M_{tt′} = 450 GeV/c²</td>
<td>1.45 ± 0.09</td>
<td>1.53 ± 0.09</td>
<td>3.27 ± 0.14</td>
<td>6.25 ± 0.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>t° → ℓ⁺ℓ⁻</td>
<td>167.46 ± 5.85</td>
<td>178.88 ± 5.71</td>
<td>445.45 ± 9.30</td>
<td>791.79 ± 12.38</td>
</tr>
<tr>
<td>tt → fake</td>
<td>3.35 ± 0.85</td>
<td>0.19 ± 0.19</td>
<td>5.81 ± 1.04</td>
<td>9.35 ± 1.36</td>
</tr>
<tr>
<td>W + jets</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>DY → ℓ⁺ℓ⁻</td>
<td>2.23 ± 1.39</td>
<td>2.15 ± 1.66</td>
<td>&lt; 1</td>
<td>4.38 ± 2.17</td>
</tr>
<tr>
<td>Dij-boson</td>
<td>0.04 ± 0.01</td>
<td>0.14 ± 0.07</td>
<td>0.14 ± 0.07</td>
<td>0.31 ± 0.10</td>
</tr>
<tr>
<td>Single top</td>
<td>2.63 ± 0.28</td>
<td>2.41 ± 0.26</td>
<td>7.03 ± 0.45</td>
<td>12.06 ± 0.59</td>
</tr>
<tr>
<td>Total simulated background</td>
<td>175.70 ± 6.08</td>
<td>183.76 ± 5.96</td>
<td>458.43 ± 9.37</td>
<td>817.88 ± 12.66</td>
</tr>
</tbody>
</table>

- Data                     | 184 | 182 | 512 | 878
CMS – Search for t' dilepton 3/3

- 1 event observed; 1.62 expected
- 95% CL Limits extracted using Cut and count
- Observed limit \( m(t') > 422 \text{GeV} @ 95\% \text{ CL} \)
- Analysis updated to 4.7 fb\(^{-1}\), \( m(t') > 552 \text{GeV} @ 95\% \text{CL} \)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( tt \rightarrow \ell^+\ell^- )</td>
<td>1.35 ± 0.67</td>
<td>Data</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>0.0±0.4</td>
<td>Data</td>
</tr>
<tr>
<td>DY( \rightarrow e^+e^- ) or ( \mu^+\mu^- )</td>
<td>0.07±0.13</td>
<td>Data</td>
</tr>
<tr>
<td>DY( \rightarrow \tau^+\tau^- )</td>
<td>0.11 ± 0.11</td>
<td>Simulation</td>
</tr>
<tr>
<td>Di-boson</td>
<td>0.02 ± 0.02</td>
<td>Simulation</td>
</tr>
<tr>
<td>Single top</td>
<td>0.07 ± 0.04</td>
<td>Simulation</td>
</tr>
<tr>
<td>Total prediction</td>
<td>1.62±0.80</td>
<td>1</td>
</tr>
</tbody>
</table>

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For this analysis, no assumption about the quark mixing in the final state $t' \rightarrow Wq$

**Baseline selection:**
- Exactly 2 leptons $p_T > 20$ GeV; muon $|\eta| < 2.5$; electron $|\eta| < 2.47$  
  $\not{E_T} (\Delta R < 0.2) < 3.5$ GeV
- Jets: Anti-kt 0.4, $p_T > 25$ GeV, $|\eta| < 2.5$  
  at least 2 jets
- $E_T^{\text{miss}} > 60$ GeV (ee/\(\mu\mu\)); $HT(MET+\text{lep } p_T) > 130$ GeV (e\(\mu\))
- For ee/\(\mu\mu\) -> $M_{ll} > 15$ GeV; $|M_{ll} - M_Z| > 10$ GeV

**Reconstruction of the heavy quark masses:**
- At high $W$ $p_T$ → 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)
**ATLAS – Search for t' dilepton 2/3**

1 fb$^{-1}$

<table>
<thead>
<tr>
<th>$m_Q$ (GeV)</th>
<th>Triangle Requirement (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$H_T + E_T^{miss} &gt; 610 - 0.4 \times m_{Collinear}$</td>
</tr>
<tr>
<td>350</td>
<td>$H_T + E_T^{miss} &gt; 700 - 0.4 \times m_{Collinear}$</td>
</tr>
<tr>
<td>400</td>
<td>$H_T + E_T^{miss} &gt; 790 - 0.4 \times m_{Collinear}$</td>
</tr>
<tr>
<td>450</td>
<td>$H_T + E_T^{miss} &gt; 880 - 0.4 \times m_{Collinear}$</td>
</tr>
<tr>
<td>500</td>
<td>$H_T + E_T^{miss} &gt; 970 - 0.4 \times m_{Collinear}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_Q$ (GeV)</th>
<th>Jet $p_T$ (GeV)</th>
<th>$E_T^{miss}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Leading jet $p_T &gt; 80$</td>
<td>—</td>
</tr>
<tr>
<td>350</td>
<td>Leading jet $p_T &gt; 120$</td>
<td>$E_T^{miss} &gt; 70$</td>
</tr>
<tr>
<td>400</td>
<td>Leading jet $p_T &gt; 130$</td>
<td>$E_T^{miss} &gt; 70$</td>
</tr>
<tr>
<td>450</td>
<td>Leading jet $p_T &gt; 130$</td>
<td>$E_T^{miss} &gt; 70$</td>
</tr>
<tr>
<td>500</td>
<td>Leading jet $p_T &gt; 130$</td>
<td>$E_T^{miss} &gt; 70$</td>
</tr>
</tbody>
</table>

- **Final selection:**
  → triangular cut in the $M_{coll} – HT$ plane ( = $H_{thad} + \text{lepton } p_T + \text{MET}$)

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

- → $M_{coll}$ after triangular cut is used to discriminate signal and background
Binned maximum likelihood used to set limit on the production cross section; Template fit using the Mcoll distribution

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

<table>
<thead>
<tr>
<th>Source</th>
<th>$+1\sigma$ Unc.</th>
<th>$-1\sigma$ 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>$\mu$ momentum resolution</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>$\mu$ 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 $p_T$ 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>
CMS – Search for t' single-lepton 1/3

PAS-EXO-11-051

- **Final state** \( t'\bar{t}' \rightarrow WbWb \rightarrow qqb l\nu b \)

- **Selection:**
  - Isolated Electron \( p_T > 30 - 45 \text{ GeV} \) (trigger threshold changed) \( |\eta| < 2.4 \neq 1.44 < |\eta| < 1.57 \)
  - Isolated Muon \( p_T > 35 \text{ GeV} \) \( |\eta| < 2.1 \)
  - Jets: Anti-kt \( R=0.5 \rightarrow 4 \) jets 120, 90, 35, 35 GeV
  - MET > 20 GeV
  - At least 1 btag jet

<table>
<thead>
<tr>
<th>process</th>
<th>cross section ( \mathcal{L} )</th>
<th>e+jets events</th>
<th>\mu+jets events</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>573 pb(^{-1}) 821 pb(^{-1})</td>
<td>520</td>
<td>1054</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>158 pb</td>
<td>456 ± 91</td>
<td>907 ± 114</td>
</tr>
<tr>
<td>single ( t )</td>
<td>33 pb</td>
<td>14.5 ± 3.5</td>
<td>30 ± 6</td>
</tr>
<tr>
<td>( W+jets )</td>
<td>30 ( \mu )</td>
<td>33.3 ± 8.2</td>
<td>106 ± 25</td>
</tr>
<tr>
<td>( Z+jets )</td>
<td>2.9 ( \mu )</td>
<td>4.5 ± 1.2</td>
<td>2.6 ± 2.6</td>
</tr>
<tr>
<td>( WW,WZ,ZZ )</td>
<td>67 pb</td>
<td>2.1 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>multijets</td>
<td>2.5 ± 1.2</td>
<td>5.7 ± 5.5</td>
<td></td>
</tr>
<tr>
<td>total background</td>
<td>510 ± 103</td>
<td>1054 ± 145</td>
<td></td>
</tr>
</tbody>
</table>

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CMS – Search for t' single-lepton 2/3

- Mass reconstruction → take four-jet combination out of the hardest 5 jets
- Use the W mass constraint and leptonic/hadronic t' mass should be equal
- 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

PAS-EXO-11-051

0.5-0.8fb^{-1}
CMS – Search for t' single-lepton 3/3

- CLs method used to set limits on the t't' production cross section

- Assuming BR(t' → Wb) = 1 → m(t') > 450GeV @ 95%CL

23/02/2012

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ATLAS – Search for t' single-lepton 1/3

As in CMS: Final state t't' → WbWb → jjb lνb

Strategy:
- Stay as close as possible to the top group selection
- Relatively low jet pT (60/25/25), and lepton pT (e/mu 25/20)
- Using the btagging (≥1bjet 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
- >=4 jets: using KLFitter (see many talks about performance)
  - Using leading 4 jets only
  - Floating ‘top’ mass
  - Only constrain both ‘sides’ to be similar

Use mclimit package to set CLs limits
- Modified package:
  - Extrapolation methods
  - Added functionality for running tests et
ATLAS – Search for t' single-lepton 2/3

- Systematics treated as nuisance parameters
- ATLAS list of systematics is very conservative respect to CMS (23 sources considered, 13 are profiled; CMS 7 systematics, no ttbar modeling )
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet and electron and muon channels

arXiv:1202.3076

23/02/2012

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• **No sign of excess → set limits**
  - Combined limit: electron/muon =3/≥4jets → 4 orthogonal channels
  - Observed limit: $m_{t'} > 404\text{GeV} @ 95\% \text{ C.L.}$
  - Expected limit: 394GeV
  - Observed limit is within 1σ of the expected in the full mass range considered
This analysis presents the inclusive search of 4th 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 pt > 40 GeV; |\(\eta\)| < 2.1; veto other isolated muons pt > 10 GeV, |\(\eta\)| < 2.5; veto electrons pt > 20 GeV; |\(\eta\)| < 2.5
- Jets pt > 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) pt > 30 GeV
- 2B_0W \(\rightarrow\) single t' with 2 central bjets; \(=0\) forward jet (2.4 < |\(\eta\)| < 5) pt > 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
CMS – Inclusive search for a 4th generation 2/3

- HT discriminant is used = scalar sum of MET, muon pT, btag jets, Whad pT

- HT is sensitive to the presence of 4th generation quark

- A 4th 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 $T \rightarrow tA_0$
- $A_0$ 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

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton $tt$</td>
<td>$62 \pm 15$</td>
</tr>
<tr>
<td>Single-lepton $t\bar{t}/W+\text{jets}$</td>
<td>$33.1 \pm 3.8$</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>$1.2 \pm 1.2$</td>
</tr>
<tr>
<td>Single top</td>
<td>$3.5 \pm 0.8$</td>
</tr>
<tr>
<td>$Z+jets$</td>
<td>$0.9 \pm 0.3$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$0.9 \pm 0.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$101 \pm 16$</td>
</tr>
<tr>
<td>Data</td>
<td>105</td>
</tr>
</tbody>
</table>
### ttbar + Anomalous $E_T^{\text{miss}}$ 2/2

- **Assuming** $\text{BR}(T \to tA_0) = 1$
- Cut and count method used to set limit using frequentist confidence intervals
- 95% CL limits on $TT$ pair production cross section (depend on $A_0$ and $T$ masses)
  - $m(T) < 420$ GeV for $m(A_0) < 10$ GeV
  - $330 < m(T) < 390$ GeV for $m(A_0) < 140$ GeV

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**arXiv:1109.4725**

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**23/02/2012**

Clément Helsens, IFAE Barcelona
Search for VLQ (single prod.) 1/3

- Search for vector like quarks (VLQ) singly produced both in
  - Charged Current (CC) pp → Qq → Wqq′
  - Neutral Current (NC) pp → Qq → 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 $K_{qQ}^q = (\frac{\nu}{mQ})K_{qQ}^\prime$
  - $q$ is any light quark; $Q$ is VLQ, $mQ$ VLQ mass
  - $\nu$ Higgs vev
  - $K_{qQ}^\prime$ → the model dependence of the $qVQ$ vertex ($V = W$ or $Z$)
- Consider only VLQs U and D of charge $+2/3$ and $-1/3
• Event selection, considering electron and muon leptons:
  • Single lepton triggers
  • Isolated electron, pT > 25GeV,  |η| < 2.47 6 1.37 < |η| < 1.52
  • Isolated muon, pT > 25GeV,  |η| < 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 2$^\text{nd}$ or 3$^\text{rd}$ jet
  − $m_T(W) > 40$GeV
  − $\Delta \phi(l,E_T^{\text{miss}}) > 2.4$ (expect boostedWs)
  − VLQ mass → m(W,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 < $M_{ll}$ < 116GeV , pT(l,l) > 50GeV (expect boosted Zs)
  − At least 2 jets with pT> 25GeV
  − VLQ mass → m(l,l,jet) with leading jet pT
• 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 $\rightarrow m_{VLQ} > 900(760) \text{ GeV for CC(NC) @95\% C.L.}$
• Tevatron limits $\rightarrow K'uU=1 \ 690\text{GeV} \ (100\% \text{ BR CC}) \ ; \ K'uD=\sqrt{2} \ 550\text{GeV} \ (100\% \text{ BR NC})$

<table>
<thead>
<tr>
<th>Process</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+\text{jets}$</td>
<td>14500 ± 100 ± 4400</td>
<td>16600 ± 100 ± 5000</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>2360 ± 50 ± 270</td>
<td>2530 ± 50 ± 290</td>
</tr>
<tr>
<td>Single Top</td>
<td>700 ± 30 ± 120</td>
<td>740 ± 27 ± 120</td>
</tr>
<tr>
<td>Multijet</td>
<td>670 ± 30 ± 270</td>
<td>340 ± 20 ± 410</td>
</tr>
<tr>
<td>$Z+\text{jets}$</td>
<td>128 ± 11 ± 90</td>
<td>432 ± 21 ± 170</td>
</tr>
<tr>
<td>Diboson</td>
<td>174 ± 13 ± 55</td>
<td>198 ± 14 ± 62</td>
</tr>
<tr>
<td>Expected Total Background</td>
<td>18500 ± 100 ± 4400</td>
<td>20900 ± 100 ± 5100</td>
</tr>
<tr>
<td>Data</td>
<td>17302</td>
<td>20668</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z+\text{jets}$</td>
<td>3250 ± 60 ± 430</td>
<td>5350 ± 70 ± 700</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>58 ± 8 ± 3</td>
<td>90 ± 9 ± 5</td>
</tr>
<tr>
<td>Diboson</td>
<td>38 ± 6 ± 4</td>
<td>58 ± 8 ± 4</td>
</tr>
<tr>
<td>Expected Total Background</td>
<td>3350 ± 60 ± 430</td>
<td>5500 ± 70 ± 700</td>
</tr>
<tr>
<td>Data</td>
<td>3105</td>
<td>5070</td>
</tr>
<tr>
<td>Expected Signal, $U(225 \text{GeV})$</td>
<td>192 ± 14 ± 9</td>
<td>339 ± 18 ± 19</td>
</tr>
<tr>
<td>Expected Signal, $U(600 \text{GeV})$</td>
<td>15 ± 3.9 ± 0.6</td>
<td>23 ± 4.8 ± 0.7</td>
</tr>
<tr>
<td>Expected Signal, $U(1000 \text{GeV})$</td>
<td>1.9 ± 1.4 ± 0.1</td>
<td>2.7 ± 1.6 ± 0.1</td>
</tr>
</tbody>
</table>
Search for VLQ in $t+Z$ (pair prod.)

- Search for a pair-produced heavy vector like quark $T$ (VLQ) with charge 2/3
- $100\% \text{ BR } T \rightarrow tZ; \ pp \rightarrow TT \rightarrow tZtZ \rightarrow WbZWbZ$
- Muon, $p_T > 15\text{GeV}$ and $|\eta| < 2.4$
- Electron $> 20\text{GeV}$ and $|\eta| < 2.5 \notin 1.44 < |\eta| < 1.57$
- Jets from particle flow, antikt 0.5; $p_T > 25\text{GeV}$, $|\eta| < 2.4$
- One leptonic $Z \rightarrow 2 \text{ OS}$, same flavored leptons (e or mu) $60 < M_{ll} < 120\text{GeV}$
- At least 3 leptons and at least 2 jets
- $R_T > 80\text{GeV}$, with $R_T = \Sigma p_T(\text{jet i}) + \Sigma p_T(\text{lepton i})$ ($i \neq 1,2$)

Clément Helsens, IFAE Barcelona

23/02/2012
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 ($B_{3l}$) $t\bar{t}+Z$, 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% $T \to tZ$ set limits on the cross section
- Exclude $m(VLQ) < 475$ GeV @ 95% C.L.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e\mu\mu$</th>
<th>$\mu\mu\mu$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{2l}$</td>
<td>$0.2^{+0.3}_{-0.2}$</td>
<td>$0.9 \pm 0.4$</td>
<td>$1.1 \pm 0.5$</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>
</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>
</tr>
<tr>
<td>Data</td>
<td>$0$</td>
<td>$2$</td>
<td>$2$</td>
</tr>
</tbody>
</table>
Summary of the results

- **4th generation:**
  - $b'b' \rightarrow Wt$ (100% BR) 495GeV
  - $t't' \rightarrow Wb$ (100% BR) 552GeV
  - Inclusive search ($mt' = mb'$) 490GeV

- **Vector like quarks:**
  - TT $\rightarrow tZ$ (100% BR) 475GeV
  - 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 :(
- Some analysis still based on 2010 dataset, but are being updated (in the pipeline for approval)
- Improvement expected for Moriond ~ factor of 4 in luminosity
- 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).
- Lots of fun coming soon :)
- Apologies for any relevant topics omitted due to time limitations
Bonus Slides