Searches for new heavy quarks

Aurelio Juste
(ICREA/IFAE, Barcelona)

On behalf of the ATLAS and CMS Collaborations
The LHC represents an extremely powerful instrument to search for new heavy quarks:

- **Direct searches** in a plethora of kinematic regions and final state signatures.
- Broad program of **precise measurements** of SM processes and parameters.
  - Higgs boson cross section measurements exclude chiral 4\(^{th}\) generation of quarks.

A more compelling possibility: **Vector-Like Quarks** (VLQs)

- Present in many BSM extensions: e.g. Composite Higgs, extra dimensions.
- Colored spin-1/2 fermions whose left and right components transform the same under SU(2)\(_L\).
- Can mix with their SM counterparts and regulate the Higgs mass-squared divergence.
  - attractive solution to the Hierarchy Problem.
Vector-Like Quarks: Production and Decay

Production:
- **Pair production**: via QCD, “universal” production mode (just depends on $m_Q$).  
  ➔ Focus of Run 1 searches
- **Single production**: via EW interaction, depends on coupling strength, but potentially important at high $m_Q$.

Decay: $Q \rightarrow Wq, Zq, Hq$, all with sizable BR

**VLQs assumed to mix preferentially with 3rd generation quarks.**
Pair Production Strategy

- Very rich phenomenology, depending on VLQ mass and quantum numbers.
- Goal is to probe full BR plane in as model independent possible way.
  - Searches specialized on particular heavy quark decay modes, but also able to probe part of the plane.
  - Multiple searches required, ideally overlapping on the plane.
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Run 1 excludes T-quark (B-quark) masses below ~720 (740) GeV for any combination of BRs
Run 2 Status and Plans
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
  - Large increase in production cross section at high masses
    - Continue to exploit pair production above 1 TeV
    - Add single production above 1 TeV

Pair production
model independent, relevant at low mass

Single production
model dep. coupling, PDF-favored at high mass
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
  - Large increase in production cross section at high masses
- Optimize strategy at high mass

SM resonances are often boosted!
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity

2015: 3.9 fb\(^{-1}\) recorded
First results exceeding Run 1 sensitivity!

2016: \(~36\) fb\(^{-1}\) recorded
Exceed design inst. lumi of \(~10^{34}\) cm\(^{-2}\)s\(^{-1}\).
Record daily delivered luminosity of \(~0.6\) fb\(^{-1}\).

Results shown today:
up to \(36\) fb\(^{-1}\)

2017: \(~47\) fb\(^{-1}\) recorded
Record inst. lumi of \(~2.1\times10^{34}\) cm\(^{-2}\)s\(^{-1}\).

2018: Ongoing (started on April 17, 2018).
Inst. lumi regularly at \(~2\times10^{34}\) cm\(^{-2}\)s\(^{-1}\).
Expect 60 fb\(^{-1}\) delivered in 2018.

Full Run 2: \(~130\) fb\(^{-1}\)
Pair Production: $TT \rightarrow Wb + X$

- Search targeting high BR($T \rightarrow W^+b$), but also sensitive to other decay modes.
- Most sensitive searches exploit the lepton+jets final state.
- Strategy:
  - Presel: 1 lepton, high $E_T^{\text{miss}}$, $\geq 4$ jets/$\geq 1$ b-tags.
  - Reconstruct boosted hadronic $W$ boson.
  - Tight cuts: high $H_T$ (*), additional cuts to exploit boosted topology for $W$ bosons.
  - Analyze reconstructed $T$-quark mass spectrum.

$\text{BR}(T \rightarrow W^+b) = 1$: $m_T > 1.28$ (1.30) TeV

Limits also apply to $Y_{-4/3}$.

$\text{BR}(T \rightarrow W^+b) = 1$: $m_T > 1.35$ (1.31) TeV

$Y_{-4/3}$: $m_T > 1.17$ (1.08) TeV
Pair Production: $TT \rightarrow Zt + X$

- Most sensitive searches exploit $Z \rightarrow ll$ decays, giving OS dileptons or trilepton final states (coming soon).
- **Search targeting high BR($T \rightarrow Zt$), with $Z \rightarrow \nu \nu$.**
- **Strategy:**
  - Presel: 1 lepton, $E_T^{\text{miss}} > 300$ GeV, $\geq 4$ jets, $\geq 1$ b-tag.
  - Signal region defined through tight cuts to suppress $tt$ background (on $m_{T,W}$, $am_{T^2}$, $\geq 2$ large-$R$ jets, etc).
  - Control regions used to normalize $tt$ and $W+jets$ bkgs in signal region. Background prediction checked in dedicated validation regions.

95% CL obs (exp) limits:

$\text{BR}(T \rightarrow Zt) = 1:$ $m_T > 1.16$ (1.17) TeV

**Doublet:** $m_T > 1.05$ (1.06) TeV

**Singlet:** $m_T > 0.87$ (0.89) TeV
Pair Production: $TT \rightarrow Ht+X$

- Search targeting high BR($T \rightarrow Ht$), with $H \rightarrow bb$, but designed as broad-band search.
- Strategy:
  - Consider lepton+jets and high-$E_T^{\text{miss}}$+jets channels.
  - Top and Higgs tagging via mass cut on large-$R$ jets.
  - Categorize events according to b-tag, top-tag and Higgs-tag multiplicities (a total of 34 regions).
  - Analyze effective mass spectrum.
  - Signal-depleted regions used to constrain in-situ bkg uncert. through likelihood fit to data.

95% CL obs (exp) limits:
- BR($T \rightarrow Ht$)=1: $m_T > 1.43$ (1.34) TeV
- Doublet: $m_T > 1.31$ (1.26) TeV
- BR($T \rightarrow Zt$)=1: $m_T > 1.17$ (1.18) TeV
- Singlet: $m_T > 1.19$ (1.11) TeV
Pair Production: $BB, X_{5/3}X_{5/3} \rightarrow WtWt$

- Searches targeting $B \rightarrow Wt$ or $X_{5/3} \rightarrow W^+t$.
- Consider SS dilepton+jets and lepton+jets signatures, both with comparable sensitivity.
- Strategy (lepton+jets):
  - Presel: 1 lepton, high $E_T^{\text{miss}}$, $\geq 4$ jets/$\geq 1$ b-tags.
  - Multiple event categories depending on the presence of boosted hadronic $W$ bosons.
- Analyze $B$-quark mass or BDT output (ATLAS), or $\min[M(l,b)]$ (CMS) spectra.

$BR(X_{5/3} \rightarrow Wt)=1$: $m_T > 1.30$ (1.33) TeV
  - Left-Handed: $m_T > 1.30$ (1.33) TeV
  - Right-Handed: $m_T > 1.28$ (1.30) TeV

$BR(B, X_{5/3} \rightarrow Wt)=1$: $m_T > 1.35$ (1.33) TeV
  - Singlet: $m_T > 1.17$ (1.14) TeV

$\sim 36$ fb$^{-1}$
Inclusive search for $T\bar{T}$ and $B\bar{B}$ production focused on final states with leptons.

Three channels considered:

1-lepton:
- W and Higgs tagging based on large-$R$ jets via jet substructure variables and b-tagging requirements.
- 16 event categories based on $W$, $H$ and b-tag multiplicities.
- Analyze $S_T$ distribution.

Same-sign 2-leptons:
- Counting experiment.

3-leptons:
- Analyze $S_T$ distribution.
### Vector-like T BR Hypothesis

<table>
<thead>
<tr>
<th>BR Hypothesis</th>
<th>ATLAS 95% CL Limit on $m_T$ (TeV)</th>
<th>CMS 95% CL Limit on $m_T$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Wb (chiral, Y)</td>
<td>1.35 (1.31)</td>
<td>1.28 (1.30)</td>
</tr>
<tr>
<td>T singlet</td>
<td>1.19 (1.11)</td>
<td>1.20 (1.16)</td>
</tr>
<tr>
<td>T in (T, B) doublet</td>
<td>1.31 (1.26)</td>
<td>1.28 (1.24)</td>
</tr>
</tbody>
</table>

VLT masses below ~1.14 TeV excluded for any possible combination of BRs

(*) Inclusive search (1l, 2l, 3l)

(*) Not including latest $Ht+X$ results

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Most restrictive single bounds to date
Pair Production Summary: Vector-Like Bottom

(*) Several new results imminent

VLB masses below ~0.91 TeV excluded for any possible combination of BRs

<table>
<thead>
<tr>
<th>Vector-like B BR Hypothesis</th>
<th>ATLAS 95% CL Limit on $m_B$ (TeV) obs (exp)</th>
<th>CMS 95% CL Limit on $m_B$ (TeV) obs (exp)</th>
</tr>
</thead>
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<tr>
<td>100% Wt (chiral, X)</td>
<td>1.35 (1.33)</td>
<td>1.24 (1.24)</td>
</tr>
<tr>
<td>B singlet</td>
<td>1.17 (1.14)</td>
<td>1.17 (1.13)</td>
</tr>
<tr>
<td>B in (B, Y) doublet</td>
<td>0.76 (0.76) [Run 1]</td>
<td>0.94 (0.92)</td>
</tr>
</tbody>
</table>

Most restrictive single bounds to date
Many channels (w/ and w/o leptons) to be exploited.

**Powerful handles against backgrounds:**
- Forward jet tagging
- Boosted techniques
- VLQ mass reconstruction

Beware of:
- Signal/background interference
- Helicity propagation in decay
Single Production: $T(\rightarrow Zt)+X$

Strategy:
- Presel: $Z(\rightarrow ll)+$jets, $\geq 1$ b-tags, small $\Delta R(ll)$.
- Top-tagging and $W$-tagging on AK8 jets.
- 10 event categories depending on lepton flavor, top kinematics (fully-merged/semi-merged/resolved) and presence of forward jets.
- Use heavy quark mass built from reconstructed $Z$-boson and top candidates.
- Main background: $Z+\text{jets}$. Estimated using dedicated control regions.

*PLB 781 (2018) 574*
Single Production: $B(\rightarrow Hb) + X$

Strategy:

• Trigger based on scalar sum of jet $p_T$.
• Presel: $\geq 3$ small-R jets/$\geq 1$ b-tag, $\geq 1$ large-R jet tagged as Higgs boson. Additional kinematic cuts to suppress multijet background.
• Higgs tagging based on large-R jets via jet substructure variables and b-tagging requirements.
• Events categorized according to forward jet multiplicity.
• Main background: $tt$ and multijet. Multijet estimated using data-driven techniques.
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Increased use of simplified models
  - Combination of pair and single production
  - Take into account effect of extra resonances in some cases

\[
\Delta m^2 \sim y^2 v^2 \quad B \\
\Delta m^2 \sim y^2 f^2 \quad T \\
\Delta m^2 = 0 \quad X_{2/3} \\
\Delta m^2 = 0 \quad X_{5/3} \\
\Delta m^2 = 0 \quad t
\]
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches

- Make sure we don’t miss a signal!
  - Non-standard production
    E.g. via heavy gluon: $G^* \rightarrow TT \ (m_{G^*} \geq 2m_T)$,
    $G^* \rightarrow Tt \ (m_T + m_t < m_{G^*} < 2m_T)$
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don’t miss a signal!**
  - **Non-standard decays**
    \[ \text{BR} (Q \rightarrow Wq) + \text{BR} (Q \rightarrow Zq) + \text{BR} (Q \rightarrow Hq) < 1 \]
    
    Example: \( Q \rightarrow q + \eta \), \( \eta \) CP-odd scalar
    - If exotic BRs dominant, signal may be picked by existing searches.
    - For comparable BRs, it becomes difficult as signal split into challenging channels. But also promising channels: \( TT \rightarrow W^+ bttt! \)
Summary and Outlook

• Run 2 program of searches for vector-like quarks in full swing
  • First round of publications with up to 36 fb\(^{-1}\) of data at \(\sqrt{s}=13\) TeV becoming available.
  • Pair production searches significantly extend the Run 1 sensitivity, excluding VLQ masses up to 1.3 TeV (depending on scenario).
  • Broad program of single production searches being developed.
  • Starting to target non-standard production/decay modes.

• More sophisticated searches being developed with the full Run 2 dataset, capitalizing on the experience gained and improvements in object reconstruction algorithms.

Exciting times ahead!
Extra
Recent VLQ Searches

For more information see:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Plan for Run 2 Analyses

- Capitalize on Run 1 experience
  - Most sensitive channels
  - Complementary channels
  - Missing channels
  - Most powerful experimental strategies
  - Improved background estimation techniques
  - Reducing the impact of systematic uncertainties
  - …
Searches performed in lepton+jets and all-hadronic final states, with comparable sensitivity.

Basic strategy (all-hadronic):
- Trigger based on scalar sum of jet $p_T$.
- Presel: $\geq 4$ small-$R$ jets, $\geq 1$ large-$R$ jets, $H_T > 1100$ GeV.
- Top and Higgs tagging based on large-$R$ jets via jet substructure variables and $b$-tagging requirements.
- Main background: $t\bar{t}$ and multijet. Multijet estimated using data-driven techniques.

See also: PLB 771 (2017) 80
Basic strategy:

- Presel: 1 lepton, high $E_T^{\text{miss}}$, ≥1 hard central jet b-tagged, 1 forward jet.
- Additional tight kinematic requirements.
- Kinematic reconstruction of leptonic $W$ candidate and pairing with b-tagged central jet to estimate heavy quark mass.
- Main backgrounds: tt and W+jets. Estimated using dedicated control regions.

Comparable limits between ATLAS and CMS
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity

**Improved interpretation of searches**

So far:

- Renormalizable extension of the SM including mixing term between SM quarks and VLQs (e.g. arXiv:1306.0572).
- Phenomenological (non-renormalizable) Lagrangian parameterized with coupling terms.

<table>
<thead>
<tr>
<th>partner (MG name)</th>
<th>( Q )</th>
<th>( W^\pm )</th>
<th>( Z )</th>
<th>( h )</th>
<th>( W^\pm W^\pm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{2/3} ) (T23)</td>
<td>2/3</td>
<td>( c_{LW} ), ( c_{RW} )</td>
<td>( c_{LZ} ), ( c_{RZ} )</td>
<td>( c_{Lh} ), ( c_{Rh} )</td>
<td>( -- )</td>
</tr>
<tr>
<td>( B_{1/3} ) (B13)</td>
<td>-1/3</td>
<td>( c_{LW} ), ( c_{RW} )</td>
<td>( c_{LZ} ), ( c_{RZ} )</td>
<td>( c_{Lh} ), ( c_{Rh} )</td>
<td>( -- )</td>
</tr>
<tr>
<td>( X_{3/3} ) (X33)</td>
<td>5/3</td>
<td>( c_{LW} ), ( c_{RW} )</td>
<td>( c_{LZ} ), ( c_{RZ} )</td>
<td>( c_{Lh} ), ( c_{Rh} )</td>
<td>( -- )</td>
</tr>
<tr>
<td>( Y_{4/3} ) (Y43)</td>
<td>-4/3</td>
<td>( c_{LW} ), ( c_{RW} )</td>
<td>( c_{LZ} ), ( c_{RZ} )</td>
<td>( c_{Lh} ), ( c_{Rh} )</td>
<td>( -- )</td>
</tr>
<tr>
<td>( V_{8/3} ) (V83)</td>
<td>8/3</td>
<td>( c_{LW} ), ( c_{RW} )</td>
<td>( c_{LZ} ), ( c_{RZ} )</td>
<td>( c_{Lh} ), ( c_{Rh} )</td>
<td>( -- )</td>
</tr>
</tbody>
</table>

\[ L = \frac{g_W}{2} \left[ c_{LR}^{\nu R} \overline{X}_R \nu^R + c_{LR}^{\nu L} \overline{X}_L \nu_L \right] + \frac{g_W}{2} \left[ c_{LR}^{\nu R} \overline{X}_L \nu_R + c_{LR}^{\nu R} \overline{X}_R \nu_R \right] + \left[ c_{LR}^{h R} \overline{X}_L \nu_R + c_{LR}^{h R} \overline{X}_R \nu_R \right] + \left[ c_{LR}^{h R} \overline{X}_L \nu_R + c_{LR}^{h R} \overline{X}_R \nu_R \right] + \text{h.c.} \]

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