Searches for other heavy resonances with 13 TeV data
(boosted ttbar, vector-like quarks, ...)

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On behalf of ATLAS & CMS

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Introduction

Vector-like quarks (VLQs)
- could damp the unnaturally large corrections to $m_H$
- predominantly decaying via $t/b+V$, e.g. $T \rightarrow Wb / Zt / Ht$

Top partners from Composite Higgs models could also address naturalness

New heavy bosons with enhanced couplings to 3rd generation
- $Z'$ and $W'$ models, RS models with KK gluons
- Little Higgs models, 2HDM, and more

Jet substructure for largeR jets
- final states with several tops and V-bosons
- boosted tops/bosons can appear merged in the detector ($\Delta R \sim 2m/p_T$)
- different grooming algorithms and tagging approaches (see backup)
The searches in this talk

Vector Like Quarks

- Single VLT: $tZ(\ell\ell)+X$
- VLT pair: $tZ(\nu\nu)+X$ (1 $\ell$)
- VLT pair: $Wb+X$ (1 $\ell$)
- VLT pair: $tH(bb)+X$ (0 $\ell$, 1 $\ell$)

Top partners

- $X_{5/3}$ (same-sign $\ell\ell$)

New heavy bosons

- $W'\rightarrow bt\ell$
- $Z'\rightarrow t_3t_3$

and more in the backup
- Optimised for single $\text{VLT} \rightarrow \text{tZ}(\ell\ell)$
- $\ell\ell$ (small $\Delta R$)+jets ($\geq 1b$)
- Bkg from a CR with b-jet veto
  - $Z+$jets($>80\%$), $t\bar{t}V$, $t\bar{Z}q$, $tt$
- Use tagged $t$- and $W$-jets
- Categorise by leptons and top:
  - fully-/semi-merged/resolved
  - number of forward jets (0, $\geq 1$)
- 10%-45% uncertainty: low stat in the CR impact on the normalisation
tZ(νν)+X (1ℓ)

- Optimised for TT→Z(νν)t+X
- 1ℓ+≥4jets+≥2Jets+MET (≥1b)
- Bkg: tt, W+jets and single-t
- **Categorise** by object multiplicities, by kinematics and by
  - \( m_{T2} \) variants (generalised \( m_T \) for two undetected particles
  - \( MHT_{\text{sig}} = (MHT-100\text{GeV})/\sigma_{MHT} \)
  - \( MHT \): vector -\( \Sigma p_T(\text{leptons}+\text{jets}) \)
  - \( \sigma_{MHT} \) from per-event JER
- ~17% uncertainty from tt modelling (< stat uncertainty)
tZ(νν)+X (1ℓ)

Limits on m(T) [GeV]
- Pure T→Zt 1160 (1170)
- Singlet 870 (890)
- Doublet 1050 (1060)

m(T) below ~1 TeV excluded for:
- BR(T→Ht)<65% at BR(T→Wb)~0
- BR(T→Wb)<45% at BR(T→Ht)~0
- Optimised for $TT \rightarrow W(\ell)v b+WB/X$
- $1\ell+\text{jets}+\text{MET}, \geq 1b$
- Tagged W-jets are vetoed if they are also tagged as top-jets
- $W(\ell)v$: $m_W$ constraint to get $p_z(v)$
- Bkg: tt+jets, W+jets, single-t and multijet (from data, 100% uncert.)

- $TT$ reconstruction:
  - pair $W_h$ and $W_\ell$ with all signal jets to define $T_h$ and $T_\ell$
  - best configuration is the one minimising $\Delta m = |m(T_h) - m(T_\ell)|$

Categorise by $S_T$ and by the
  - hadronic $W \rightarrow J/jj$ decay (boosted/resolved)
  - $\Delta R(\ell,v)$
Wb+X ($1\ell$)

- **Final discriminant** is $m(T\ell)$ due to cleaner top reconstruction.

- **Limits:**
  - $\text{BR}(T\rightarrow Wb)=1$: $m(T)<1090$ GeV (980 GeV)
  - SU(2) singlet: $m(T)<810$ GeV (870 GeV)

$BR(T\rightarrow Wb)\sim 100\%$

Expected Observed

$BR(T\rightarrow Wb)=1$
tH(bb)+X (0\ell,1\ell)

- Optimised for \( TT \rightarrow tH(bb)+X \)
- \( 1\ell/0\ell+\text{jets+MET (\geq 2b)} \)
- Tagged \( t/H\)-jets with \( \geq 2 \) subjets
- Bkg: \( tt+\text{jets, single-top and V+jets} \)
- Categorise by multiplicities and by
  - \( m(bb,\Delta R_{\text{min}}) \) - signal peaks at \( m_H \)
  - \( m_T(b)_{\text{min}} \) - signal peaks at \( m_t \)
  - \( m_{\text{eff}} \) - signal peaks at \( \sim 2m(T) \)
- \( \sim 50\%\rightarrow 16\% \) uncertainty from \( tt \) modelling in the most sensitive SR

\[ m_{\text{eff}} = \Sigma p_T(\text{signal objects})+\text{MET} \]
H(bb)t+X (0ℓ,1ℓ)

More results for EFT 4t and 2HDM are in the conf note linked above
CMS-PAS-B2G-16-019
2016 data, ~35.9 fb⁻¹

**X₅/₃ (SS-ℓℓ)**

- Pair production of top-partners: \( X₅/₃ \rightarrow W^+t(bW^+) \)
- \( W^+W^- \rightarrow ℓ^+ℓ'^+νν' \) with the other \( W^-W^- \rightarrow \text{jets} \)
- \( ℓℓ+≥5(\text{jets} \& \text{leptons}), H_T>1.2 \text{ TeV} \)
- Stringent requirements on the electrons’ charge
- Bkg estimation:
  - **prompt SS**: mostly diboson (from simulation)
  - **prompt OS**: OS events reweighted by charge mis-id prob. (data driven, ~30% uncertainty)
  - **non-prompt SS**: heavy flavour, fakes etc. (data driven, ~50% uncertainty)

*2015 data analysis with both SS-ℓℓ and ℓ+jets final states: B2G-15-006*
W' could couple more strongly to 3rd generation quarks

- Heavy W' $\Rightarrow$ boosted top $\Rightarrow$ b+$\ell$ overlap
- $1\ell+\geq 2\text{jets+MET (\geq 1b)}$
- Bkg: tt+jets and W+jets from MC (& CRs)
- Best top in $m_t$: from $m_W$ constraint to get \( p_z(\nu) \), combined with $j_1$ or $j_2$
- W': the “best” top and highest $p_T$ jet
- \( \sim 15\% \) uncertainty due to each top $p_T$ reweighting and renorm’+factor’ scale

\[ \mathcal{L} = \frac{V_{q_iq_j}}{2\sqrt{2}} \delta_{W_{\mu}\gamma_{\mu}} (a_{q_iq_j}^R (1 + \gamma^5) + a_{q_iq_j}^L (1 - \gamma^5)) W'_{q_iq_j} + \text{h.c.} \]

Plots showing $m(t+b)$

Categorise by $\ell$ and by number of b-tags (1,2) and by Type A/B with Type A: $p_T(t) > 650$ and $p_T(j_1+j_2) > 700$ GeV (otherwise Type B)
SSM Z’ and RS KK gluons

- Test $\Gamma_{Z'}$ of 1%, 10%, 30%, i.e. $<\sigma_{\text{det}}$, $\sim\sigma_{\text{det}}$, $>\sigma_{\text{det}}$
- Heavy Z’ $\Rightarrow$ boosted tops $\Rightarrow$ bW(qq’) overlap $\Rightarrow$ 2 largeR, high $p_T$ t-jets
- Bkg: multijet and tt+jets
- multijet bkg: using mis-tag (top) rate from a CR
- $\sim$20% uncertainty on the top-jet tagging efficiency

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<table>
<thead>
<tr>
<th>Mass Exclusion Limits</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Model</td>
<td>Exclusion Ranges (TeV)</td>
<td></td>
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<tr>
<td>Z’ (1% Width)</td>
<td>1.2 – 1.6</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Z’ (10% Width)</td>
<td>1.0 – 3.1</td>
<td>1.0 – 3.3</td>
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<tr>
<td>Z’ (30% Width)</td>
<td>1.0 – 3.7</td>
<td>1.0 – 3.8</td>
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<tr>
<td>RS Gluon</td>
<td>1.0 – 2.5</td>
<td>1.0 – 2.4</td>
</tr>
</tbody>
</table>

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Plots showing m(t+t)

**Categorise** by $|\Delta y_{JJ}|$ and by the number of Jets having $\geq$1b-subjet (0,1,2 for the leading JJ only)

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Equivalent $Z'\rightarrow tt$ (boosted) searches in $\ell+$jets: ATLAS-CONF-2016-014 and B2G-15-006
Presented the newest searches data with 3rd generation final states

These searches are using advanced jet substructure & b-tagging techniques

No significant excess/deficit is observed by both experiments yet

**What’s next for the VLQs and naturalness relationship?**
- LHC $\sqrt{s}$ will not be improved dramatically soon
- Luminosity will increase significantly but…
  - mild gain in sensitivity to VLQ mass (while $\sigma B$ will scale as expected)
  - will it be enough for seeing VLQs at (or above) $m\sim1$ TeV?
- looking at more exotic cases with e.g. exotic productions

**New bosons may still hide at low masses due to weak couplings**
- various analyses are starting to look more carefully over there
- switching-on the SM interference may have interesting impact as well

I will not tell you to “stay tuned for more results in the coming months!”
Motivation

- Divergent contributions to the Higgs mass in the SM
- Cancellation may come from models beyond the SM

- **VLQs** appear in several SM extensions like SUSY, extra dimensions, composite Higgs, little Higgs etc
  - spin-½ coloured particles with L/R components that transform similarly under the SM
  - mixing predominantly with the 3\textsuperscript{rd} generation quarks of the SM (1\textsuperscript{st}/2\textsuperscript{nd} not excluded)
  - masses not generated by Yukawa coupling to Higgs
  - flavour-changing neutral current decays, as well as charged-current: T\rightarrow Wb,Zt,Ht, B\rightarrow Wt,Zb,Hb
  - small mass splitting in the same multiplet is required so e.g. T\rightarrow WB is kinematically forbidden

- **New heavy bosons** also appear in SM extensions like Z’ and W’, little Higgs models, 2HDM, Randall-Sundrum Kaluza Klein gluons etc
  - may have enhanced couplings to the 3\textsuperscript{rd} generation fermions of the SM
Decays of boosted massive particles (t, Z, W) appear merged in the detector
- we have much more of these topologies at 13 TeV compared to 8 TeV
- the average angular separation between the decay products is $\Delta R \sim 2m/p_T$

Must develop large R-Jet techniques with different grooming algorithms, input variables, tagging approaches etc.
- Jet grooming is used to remove soft contaminations from PU, UE and ISR

Jet grooming examples
- **Trimming**: Jets built with the anti-$k_t$ algorithm using $R \sim 1$, trimmed using $R \sim 0.2$ subjets, removing those whose $p_T$ fraction is e.g. <5% of the jet $p_T$
- **Soft-drop**: remove soft, wide-angle constituents. Degree of grooming is controlled by $z_{cut}$ and $\beta$ with $\beta \rightarrow \infty$ returning an ungroomed jet

Soft Drop Condition:
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left( \frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

**Soft-drop**: given a jet of radius $R_0$ with only 2 constituents. Can be extended to >2 constituents
Jet substructure 2

- **N-subjettiness, \( \tau_N \):** the degree to which a large \( R \) Jet is composed of \( N \) small \( R \) subjets
  - Using the distance from a jet constituent to the nearest subjet axis
  - Discriminate \( N \) from \((N-1)\)-body structures within jets using the ratio \( \tau_N/\tau_{N-1} \)
  - \( \tau_{21} (\tau_{32}) \) used to separate 2(3)-subjets from 1(2)-subjet structures for e.g. W’s (tops)

- **Jet mass:** the difference between the squared sums of the energies and momenta of the constituents

- **Energy correlation functions, \( e_n(\beta) \):**
  - The ratio, \( D_N(\beta) \), of the normalised \( n \)-point ECFs is used to identify boosted, \( N \)-prong jets
  - Promising **machine-learning** taggers will use these variables (and others) as inputs
b-tagging

ATLAS

- Jets containing b-hadrons are tagged via an algorithm that uses multivariate techniques to combine information from the impact parameters of displaced tracks as well as topological properties of secondary and tertiary decay vertices reconstructed within the jet.
- For each jet, a value for the multivariate b-tagging discriminant is calculated.
- The jet is considered b-tagged if this value is above a given threshold.
- The threshold used corresponds to an average 77% efficiency to tag a b-quark jet, with a light-jet rejection factor of ~126 and a charm-jet rejection factor of ~4.5, as determined for jets with $p_T > 20$ GeV and $|\eta| < 2.5$ in simulated $t\bar{t}$ events.

CMS

- Jets are clustered from objects reconstructed by the particle-flow algorithm.
- Simple Secondary Vertex (SSV) algorithms use the significance of the flight distance (the ratio of the flight distance to its estimated uncertainty) as the discriminating variable.
- Combined secondary vertex (CSV) algorithm involves the use of secondary vertices, together with track-based lifetime information.
- The threshold used results in a b-tagging efficiency of ~80% and misidentification rates from light flavour jets of about 1%.
- Can be applied both to AK4 jets and the subjets of AK8 jets.
### tt + HF jets (0ℓ,1ℓ)

#### 1ℓ

<table>
<thead>
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<th>Search regions (≥6 jets)</th>
<th>Channel name</th>
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<td>b-jet multiplicity</td>
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<tr>
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<tr>
<td>≥2</td>
<td>3</td>
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<td>≥2</td>
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#### Validation regions (5 jets)

<table>
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<tr>
<th>Mass-tagged jet multiplicity</th>
<th>b-jet multiplicity</th>
<th>$m_{bb}^{\min\Delta R}$</th>
<th>$m_{eff}$</th>
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<td>&gt; 400 GeV</td>
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<td>3</td>
<td>-</td>
<td>&gt; 400 GeV</td>
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<td>&gt; 700 GeV</td>
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#### 0ℓ

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#### Validation regions (6 jets)

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<th>b-jet multiplicity</th>
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</tr>
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<td>≥4</td>
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<td>2</td>
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</tr>
<tr>
<td>1</td>
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<tr>
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<td>-</td>
</tr>
<tr>
<td>≥2</td>
<td>≥4</td>
<td>-</td>
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</table>
tt + jets (1ℓ)

- Optimised for $\text{TT} \rightarrow \text{H(bb)t+X}$
- $1\ell + \geq 2\text{Jets} + \geq 3\text{jets} (\geq 1b)$
- **H-tagged jets**: with $\geq 1$ b-subjet
- Multijet bkg taken from simulation
- **Categorisation**:
  - $H2b$: $\geq 1$ H-tag with 2 sub-b-jets
  - $H1b$: $\geq 1$ H-tag with 1 sub-b-jets
  - $0H$: zero H-tags

Excluding T quarks with masses below 860 (870) GeV, assuming BR($T \rightarrow Ht$) = 1

Plots showing $S_T = \Sigma p_T$(all signal objects) + MET
Single VLT ($0\ell, 1\ell$)

**Focus on $T \rightarrow H(bb)t$**

- $\geq 1$ Jet + $\geq 4$ jets and $H_T > 1100$ GeV
- **H-tagged**: $\tau_2/\tau_1 < 0.6$, pruned mass in 105-135 GeV and $p_T > 300$ GeV
- **t-tagged**: $\tau_3/\tau_2 < 0.54$, soft-drop mass in 110-210 GeV, $p_T > 400$ GeV and subjet b-tag
- The $p_T$ leading H-jet + t-jet with $\Delta R(H,t) > 2$ are paired to form the T candidate
- Bkg: tt+jets, multijet(data), and W+jets
- Data/MC ratio in $H_T$ is fitted with a linear function after preselection.
- The $H_T$ distributions of MC backgrounds are reweighted using this fit

**0\ell**

- $\geq 2$ jets (could be forward, i.e. $|\eta| > 2.4$)
- $\geq 1$ H-tag, $90 < m_J < 160$ GeV, $\Delta R(J, \ell) > 1$
- Tops: $m_W$ constraint to get $p_z(\nu)$ with all jets (no b-tagging), $p_T(t) > 100$ GeV
- $T \rightarrow tH$ candidate: $X^2$ algorithm for all pairing combinations with $\Delta R(t, H) > 2$
- SR: H with 2b-subjets and $\geq 1$ fwd jet

$$
\chi^2 = \left( \frac{M_{H,MC} - M_H}{\sigma_{M_{H,MC}}} \right)^2 + \left( \frac{M_{t,MC} - M_t}{\sigma_{M_{t,MC}}} \right)^2 + \left( \frac{\Delta R(t, H)_{MC} - \Delta R(t, H)}{\sigma_{\Delta R,MC}} \right)^2
$$
Single VLT (0ℓ,1ℓ)

0ℓ

Assuming T quark width of 10 GeV. Analysis insensitive for this assumption up to \( \Gamma(T) \sim 10\% \)

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>pp → Tbq (LH)</th>
<th>pp → Tbq (RH)</th>
<th>pp → Ttq (LH)</th>
<th>pp → Ttq (RH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.93</td>
<td>1.36</td>
<td>0.66</td>
<td>0.96</td>
</tr>
<tr>
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<tr>
<td>1800</td>
<td>0.51</td>
<td>0.23</td>
<td>0.39</td>
<td>0.19</td>
</tr>
</tbody>
</table>

1ℓ

Signal efficiency:
including\( \text{BR}(t \rightarrow \ell + \text{jets}) \times \text{BR}(H \rightarrow bb) \sim 8\% \)

Excluded cross sections are ~order of magnitude higher than the predictions and the current data do not place constraints on this model.
The sensitivity of the 2 analyses is comparable.
W’ → bt

- W’ width is set to 3% of the W’ mass
- Heavy W’ → boosted top → b-jet and W→qq’ overlap → single, largeR jet (t-jet)
- ≥2Jets (≥1 b-tagged)
- Top-tagging (0.3% mis-tag rate working point):
  - soft-drop declustered Jets, 110<mJ<210 GeV
  - N-subjettiness with τ_{32}<0.61
  - subjet b-tagging
- The b-jet from the W’:
  - highest-p_T, loosely b-tagged jet
  - away from the t-jet in |\Delta\phi|>\pi/2 and |\Delta y|<1.3
  - soft-drop mass <70 GeV
    - for tt bkg, this jet has mass >m_W or even >m_t
- Bkg: tt+jets, single-top & multijet
- Multijet bkg is estimated using the average b-tagging rate measured in a QCD-enhanced CR
Focus on 2HDM $gg\rightarrow H/A$ production
- reinterpretation of JHEP 08 (2015) 148
- first analysis to include SM interference
- assume type-II 2HDM with $\sin(\alpha-\beta)=1$ and no mass degeneracy between H/A
- check $m_S=500/750$ GeV and low $\tan\beta$

1$\ell$+jets+MET resolved (and boosted)
- $m_W$ constraint to get $p_z(\nu)$
- $X^2$ algorithm for objects assignment
- Categorise by $\ell$ and number of b-tags
- $S+I$ shape@NLO: same k-factor as for $S$
- Scan $\sqrt{\mu}$ with $\mu=1$ being the exact model hypothesis while $\mu=0$ is the SM ttbar only

$\tan\beta>0.85$ (0.45) for $m_{A(H)}=500$ GeV
- no $\tan\beta$ value is excluded for $m_{A(H)}=750$

Scan $\sqrt{\mu}$ with $\mu=1$ being the exact model hypothesis while $\mu=0$ is the SM ttbar only