Searches for resonances in the $t\bar{t}b\bar{b}$ final state at the LHC with ATLAS and CMS

Craig Buttar
University of Glasgow
On behalf of ATLAS & CMS
CKM16
Outline

• Introduction
  – Physics
  – Low and high mass topologies
  – backgrounds

• Analyses
  – ATLAS 8TeV resonance searches
  – ATLAS 8TeV search for heavy Higgs updated to include interference
  – CMS 8TeV resonance searches
  – ATLAS & CMS searches at 13TeV

• Projections for the HL-LHC

• Summary
Physics

- Many BSM predict high mass particles decaying to ttbar because of its yukawa coupling $\sim 1$
- Experiments search for resonances on top of non-resonant standard model backgrounds
  - Analysis is a generic bump-hunt looking for significant deviations from the SM
- Interpret in terms of physics models to establish limits:
  - Techicolour $Z'$ - spin-1 colour singlet
  - Extra dimension models Kaluza-Klein gluons – spin -1 colour octet
  - Extra dimensions Kaluza-Klein gravitons – spin-2 colour singlets
  - Heavy Higgs – spin-0 scalar
- In general interference is not implemented in the models, except for search for heavy Higgs’ bosons
A tale of two topologies

• Two topologies: high mass and low mass

• High mass:
  – jets from hadronic decays of highly boosted top quarks merge and are treated as single large-R jets

• Low mass:
  – Match jets to t-decay using $\chi^2$-function

• Lepton isolation is $p_t$ dependent

• Handling Large-R (fat) jets
• Identify jets using anti-$k_t$ algorithm
• Recluster using $k_t$ or Cambridge-Aachen (CA) algorithms to measure jet substructure
• Use substructure within jets to tag as t-jets and/or reject jets not associated with a top
  – $\tau 32$ subjettness: measures whether a jet is well described by 2-subjets or 3-subjets: a value $\rightarrow 1$ indicated two subjets, lower indicates 3 jets
  – $d12$, last splitting: large value indicates two high mass jets, small value indicated light quark/gluon jets with radiation.
  – Pairwise jet mass
  – Mass drop

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
General comments on the analyses

• Search for resonances in non-resonant SM ttbar-mass spectrum
• Backgrounds:
  – SM ttbar
  – W+jets
  – Single top
  – Z+jets
  – QCD
• In general, backgrounds are simulated using MC
• QCD background is significantly reduced by using leptonic decay channels of the top
• QCD background determined from data
  – Both normalisation and shape can be determined
• W+jets normalisation from data
Semi-leptonic channel at 8TeV

- Exactly one isolated electron or muon with $p_t > 25$GeV
- $E_T^{miss} > 20$GeV and $E_T^{miss} + M_{T,W} > 60$GeV
- $\geq 1$ b-tagged jet (anti-kt R=0.4 calorimeter jet)
- Anti-kt R=0.4 jets with $p_t > 25$GeV and $|\eta| < 2.5$
- Test even against boosted selection, if not boosted $\rightarrow$ resolved selection
  - If boosted and resolved $\rightarrow$ boosted

**Resolved channel**

- $\geq 4$ anti-$k_t$ calorimeter $R = 0.4$ jets required.

**Boosted channel**

- $\geq 1$ anti-$k_t$ calo. $R = 0.4$ jet ($p_T > 25$ GeV) that has $\Delta R(\text{jet, } \ell) < 1.5$ ($j_{sel}$).
- $\geq 1$ top-tagged anti-$k_t$ calo. $R = 1.0$ jet ($p_T > 300$ GeV, $|\eta| < 2.0$) with $\Delta \phi(\ell, \text{jet}) > 2.3$ and $\Delta R(\text{jet, } j_{sel}) > 1.5$.
- Top-tagging: $m > 100$ GeV, $\sqrt{s} > 40$ GeV.
Semi-leptonic channel at 8TeV

- For resolved analysis, assign jets to the t-quarks using $\chi^2$ function

$$\chi^2 = \left[ \frac{m_{jj} - m_W}{\sigma_W} \right]^2 + \left[ \frac{m_{jj} - m_j - m_t}{\sigma_{j \rightarrow t}} \right]^2 + \left[ \frac{m_{j\ell\nu} - m_{\ell\nu}}{\sigma_{\ell\nu}} \right]^2$$

Principal systematics:
- Common to both boosted and resolved
  - Paron distribution function and luminosity
  - ttbar background normalization
- Boosted channel
  - JES & JMS of large-R jets
  - b-tagging
- Resolved channel
  - JES of small-R jets

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
Semi-leptonic channel at 8TeV

- Reconstruct ttbar system mass
  - 3 categories: b-tag matched in dR to: leptonic $t$, hardonic $t$, leptonic & hadronic $t$

- No significant deviation from the standard model is found

Resolved channel

Boosted channel:

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
Semi-leptonic channel at 8TeV

- No deviations $\rightarrow$ set limits using models
  - $Z'_\text{TC2}$ and Bulk RS Kaluza-Klein gluon

$Z'_\text{TC2}$: A narrow resonance with mass below 2.0TeV (expected) is excluded

KK-gluon: A broader resonance with mass below 2.3TeV (expected) is excluded

Searches for resonances in the $t\bar{t}$ final state at the LHC with ATLAS and CMS, CKM16
Revisiting the search for heavy scalars: including interference

- Interference between gluon initiated signal and background
- Previous analyses assume no interference, but processes with gluon initial state will interfere with SM top production
- New analysis reinterprets in terms of 2HDM type-II $H/A \rightarrow t\bar{t}$
- Probe mass range $400 < M < 800$ GeV and low $\tan\beta$
  - Events are tested against boosted and resolved categories, if both treat as resolved
Effect of interference

- Modify Madgraph5_aMC@NLO to generate events without SM ttbar background i.e. generate signal+interference only
  - Keep good description of background at NLO (Powheg+Pythia)
  - Efficient generation
  - Cross check with full S+I+B generation

Parton level simulation

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
Effect of interference

- S+I for $e$ and $\mu$ channels after reconstruction and event selection
- Effect of interference remains but distorted relative to parton level.
  - In some cases strong or even completely negative component
Interference

- Add signal+interference to Powheg+Pythia ttbar SM background
- No deviation from SM observed
- Set limits on Scalar model
Scalar limits

- Limits are set parameterising $S+I$ and $S$ as function of $\sqrt{\mu}$
  
  $\mu S + \sqrt{\mu} I + B = \sqrt{\mu}(S + I) + (\mu - \sqrt{\mu})S + B$

- ($\mu=1$ for 2HDM type II)

$M_{H/A}=500\text{GeV}$
Excluded region for pseudoscalar: $\tan\beta<0.85$
For scalar $\tan\beta<0.45$

No limit on $\tan\beta$ for $M_{H/A}=750\text{GeV}$

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
Di-leptonic analysis at 8TeV

*Phys. Rev. D 93 (2016) 012001*

- 2 opposite charged leptons
  - No isolation
  - \( ee: p_t > 85 \text{ GeV} \& 20 \text{ GeV} |\eta| < 2.5 \)
  - \( e\mu: p_t^m > 45 \text{ GeV} \& p_t^e > 20 \text{ GeV} \& 20 \text{ GeV} |\eta| < 2.5 \)
  - \( \mu\mu: p_t > 45 \text{ GeV} \& 2.1 \& 20 \text{ GeV} |\eta| < 2.4 \)
- \( \geq 2 \) Anti-\( k_t \) \( R=0.5 \) (AK5) jets
- Lepton isolation
  - \( \Delta R(l,\text{jet}) > 0.5 \) or \( \Delta p_t^{\text{rel}}(l,\text{jet}) > 15 \text{ GeV} \)
  - \( \Delta R(l^{\text{leading}},\text{jet}) < 1.2 \) and \( \Delta R(l^{\text{subleading}},\text{jet}) < 1.5 \)
- \( E_T^{\text{miss}} > 30 \text{ GeV} \)
  - Veto \( Z+\text{jet} \) \& multi-jet backgrounds
- Approximate \( M_{ttbar} \) reconstructed
  - Assign \( E_T^{\text{miss}} \) to total \( E_T^{\text{miss}} \) of neutrinos
  - \( p_z \) of neutrino = 0
Semi-leptonic at 8TeV

- Exactly 1 electron or muon
  - Avoid overlap with dilepton channel
  - $p_T^{\mu}>45\text{GeV}$ | $|\eta|<2.1$ or $p_T^e>35\text{GeV}$ | $|\eta|<2.5$
- $\geq 2$ jets
  - $p_T^{\text{leading}}>150\text{GeV}$ and $p_T^{\text{subleading}}>50\text{GeV}$
  - AK5 and Cambridge-Aachen jets with $R=0.8$ (CA8) for boosted top-quark decays
  - Events with $\geq 2$ CA $R=0.8$ jets are rejected to prevent overlap with all-hadronic analysis
- Lepton isolation
  - $\Delta R(l,\text{jet})>0.5$ or $\Delta p_T^{\text{rel}}(l,\text{jet})>25\text{GeV}$
- $E_T^{\text{miss}}>50\text{GeV}$
  - Multi-jet backgrounds
- $M_{tt\bar{t}}$ reconstructed
  - Minimise $\chi^2(M_{t\bar{t}}, M_{th}, M_{WW}, p_{t\bar{t}})$ to select and assign correct jets
  - If event has a single CA8 t-tagged, this is taken as the hadronic jet
- Split into different tagging categories for each lepton flavour
  - 1 CA8 t-tagged jet
  - 0 CA8 t-tagged jet, 1 b-tagged jet
  - 0 CA8 t-tagged jet, 0 b-tagged jets
All-hadronic at 8TeV

• Determine if high mass, if not treat as low mass event
• High mass
  – 2CA8 jets t-tagged $p_t>400\text{GeV}$, $|\eta|<2.4$, $\Delta\phi < 2.1$
  – Consider two regions: $\Delta|y|<1.0$ and $\Delta|y|>1.0$ (dominated by multi-jets)
• Low mass
  – 2CA15 jets t-tagged $p_t>200\text{GeV}$
  – Split in $H_T=\sum|p_T|<800\text{GeV}$ and $H_T>800\text{GeV}$
• Multi-jet background calculated from data
• Categorised according to number of b-tagged sub-jets
All-hadronic at 8TeV

High mass
No significant deviations from standard model observed

Low mass
Results at 8TeV

95% CL upper limits on cross-section $X$ branching ratio for $Z'$ and KK gluon
Combined Results at 8TeV

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
Run-2 at 13TeV

- 2015 very successful for rebooting LHC at 13TeV, and ATLAS & CMS after long shutdowns
  - 2016 luminosities:
    - ATLAS: 36 fb$^{-1}$
    - CMS: 32.87 fb$^{-1}$ (preliminary)
- Significant increase in parton luminosity of heavy particles
  - >10 increase for ~3 TeV mass object
Semi-leptonic channel at 13TeV

- Focus on highly boosted top quarks with 3.2fb\(^{-1}\) at 13TeV (2015 data)
- Similar analysis to 8TeV
  - Improved b-tagging
  - Use Anti-kt R=0.2 track jets as higher efficiency at heavier masses
Semi-leptonic channel at 13TeV

- No significant deviations from SM found
- Use $Z'_\text{TC2}$ to set limits
  - $\Gamma/M_{Z'}=1.2\%$: $0.7\text{TeV} < M < 2.1\text{TeV}$ expected
    $(0.7\text{TeV} < M < 2.0\text{TeV}$ observed)$
  - $\Gamma/M_{Z'}=3\%$: $0.7\text{TeV} < M < 2.5\text{TeV}$ expected
    $(0.7\text{TeV} < M < 3.2 \text{ TeV}$ observed)
Semi-leptonic channel at 13TeV


- 2.6fb$^{-1}$ (2015 data)
- Highly boosted analysis to focus on high $M_{tt}$
- No significant deviation from SM is found

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
All-hadronic channel at 13TeV

- All-hadronic final state
- Identify two large-R jets (Anti-kt R=0.8) as top candidates
- Tag t-quark jets using
- Event categories:
  - 0,1,2-b-tags
  - $\Delta n(j_1,j_2)>0.1$ and $\Delta \nu(j_1,j_2)<0.1$
CMS 13TeV: all-hadronic

- No significant deviations from SM found
- Set limits for $Z'_{TC2}$ and KK-gluon

### Signal Model

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

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
HL-LHC projections

- Performance extrapolations for 3000fb\(^{-1}\) at HL-LHC
- Extrapolate with current systematics
- Extrapolate with no systematics
- Project semi-leptonic
- Limits extended to 3 TeV for \(Z'\) and 3.5Tev for KK-gluon

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
HL-LHC projections

- Performance extrapolations for 3000 fb$^{-1}$ at HL-LHC
- Extrapolate with current systematics and with no systematics (most optimistic results)
- Project all hadronic
- Limits extended to 3 TeV for Z’ and 3.5 TeV for KK-gluon
### Summary of results at 8 and 13 TeV

<table>
<thead>
<tr>
<th></th>
<th>Mass limit (95% CL upper limit on σxBr)</th>
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<tr>
<td><strong>13TeV</strong></td>
<td></td>
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<tr>
<td>ATLAS 3.2fb⁻¹ semi-leptonic</td>
<td>Z’ 1.2% width</td>
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<tr>
<td>CMS 2.6fb⁻¹ all-hadronic</td>
<td>Z’ 1% width</td>
</tr>
<tr>
<td>RS KK-gluon</td>
<td>1.0&lt;M&lt;2.5 TeV (17pb @ 1TeV– 0.25pb @ 4TeV)</td>
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<tr>
<td><strong>CM 2.6fb⁻¹ semi-leptonic</strong></td>
<td>Z’ 1% width</td>
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<tr>
<td>RS KK-gluon</td>
<td>0.5&lt;M&lt;2.9 TeV (73.4pb @ 0.5TeV– 0.22pb @ 4TeV)</td>
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<tr>
<td><strong>8TeV</strong></td>
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<tr>
<td>ATLAS 20.3fb⁻¹ semi-leptonic</td>
<td>Z’ 1.2% width</td>
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<td>RS KK-gluon</td>
<td>M&lt;2.3TeV (4.8pb @ 0.4TeV – 0.09 pb @ 3TeV)</td>
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<tr>
<td>CMS 19.7fb⁻¹ (Combined)</td>
<td>Z’ 1% width</td>
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<tr>
<td>RS KK-gluon</td>
<td>M&lt;2.7 TeV (17pb @ 0.7TeV– 0.059pb @ 3TeV)</td>
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</table>

CMS result at 8TeV, combination of di-leptonic, semi-leptonic, all-hadronic channels
Summary

• Results on ttbar resonance searches at 8TeV and 13TeV from ATLAS & CMS
  – Complementary analyses covering all decay channels of ttbar events
• Search for resonances on non-resonant SM background show no significant deviations from the Standard Model
• Limits are set using specific physics models: up to ~2TeV for $Z'$ (colour singlets) and ~2.7TeV for RS KK-gluons (colour octet)
• 13TeV limits using 2015 data only, ~3fb$^{-1}$, agree with current 8TeV limits
  – Expect full 13TeV dataset with ~20fb$^{-1}$, to significantly extend mass limits
• Watch this space for new results from LHC run 2
• In the future HL-LHC will allow limits to be extended
Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS, CKM16
References

- ATLAS 8-TeV analysis: *JHEP 1508 (2015) 148*
- ATLAS 8-TeV H/A re-interpretation: *ATLAS-CONF-2016-073*
- CMS 8-TeV analysis: *Phys. Rev. D 93 (2016) 012001*

- ATLAS 13-TeV analysis: *ATLAS-CONF-2016-014*
### ATLAS 8TeV systematics on the yield

<table>
<thead>
<tr>
<th>Systematic Uncertainties</th>
<th>Resolved selection yield impact [%]</th>
<th>Boosted selection yield impact [%]</th>
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<td>Luminosity</td>
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<td>tt top quark mass</td>
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