ATLAS + CMS: Boosted Topologies

John Stupak III
On behalf of the ATLAS and CMS collaborations
Introduction

- What is meant by boosted? $p_T \gtrsim 2m$
- Collimated decay products: $\Delta R \approx 2m/p_T$
- Non-isolated leptons + challenging/rich hadronic topologies*

Why the boosted regime?
- No sign yet of BSM physics at the LHC $\rightarrow$ probe higher mass scales
- Hadronic decays often have large BRs
  - Recover significant signal cross section
  - Reject QCD background with jet substructure

*This talk focuses on hadronic decays of boosted particles

Use “fat jet” to capture all daughters

$BR(H \rightarrow \text{hadrons}) \approx 84\%$
$BR(Z \rightarrow \text{hadrons}) \approx 70\%$
$BR(W \rightarrow \text{hadrons}) \approx 68\%$

3/17/15
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• Jet substructure techniques
  • Grooming
  • Additional substructure
  • Subjet b-tagging
  • V/top/Higgs tagging
• Boosted analyses
  • Fermion+fermion resonances
  • Fermion+boson resonances
  • Diboson resonances
  • SUSY
  • SM measurements
• Run II considerations
Boosted Techniques
Jet Mass / Grooming

• Jet mass
• Powerful tool to identify merged jets from heavy particle decays
• Generated perturbatively for jets from light quarks/gluons ("QCD jets")
• Highly sensitive to UE and PU

Grooming
• Remove soft / wide angle radiation
• Examples: pruning, trimming, filtering, …

NB: jet mass resolution insufficient to separate W jets from Z jets

Grooming improves background rejection, energy/mass resolution, and PU stability
Additional Observables

- **$k_T$-splitting scale**
  \[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \Delta R_{12} \]
  Exploit symmetric nature of heavy particle decays

- **Mass drop**
  \[ \mu_{1,2} = \frac{\max(m_1, m_2)}{m_{12}} \]
  Characterize "clumpyness"

- **N-subjettiness**
  \[ \tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\Delta R_{1k}, \Delta R_{2k}, ..., \Delta R_{Nk}) \]
Additional Observables

- $k_T$-splitting scale
  \[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \Delta R_{12} \]
  Exploit symmetric nature of heavy particle decays

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- Energy correlation functions

- Quark/gluon likelihood

- Jet width
  \[ w = \frac{\sum_i \Delta R_{i,\text{jet}} p_{Ti}}{\sum_i p_{Ti}} \]

- Jet charge
  \[ q = \sum_i q_i \left( \frac{p_{Ti}}{p_{T,\text{jet}}} \right)^\kappa \]

- Pull angle
  \[ \vec{t} = \sum_i \frac{p_{Ti} |r_i|}{p_{T,\text{jet}}} \vec{r}_i \]

- Q-jets volatility
  \[ \nu_{Q-jets} = \sqrt{\langle m^2 \rangle - \langle m \rangle^2} / \langle m \rangle \]

- Planar flow
  \[ P = 4 \times \det(I) / \Tr(I)^2 \]

- ...
Boosted B-tagging

- Many variables from the previous slide are correlated
- B-tagging of subjets is largely orthogonal
- Difficult in boosted regime due to density of environment
- Strong efforts ongoing within both collaborations to further improve performance

**Figure 13:** B-tagging efficiencies of the MV1, MVb and MVbCharm algorithms as a function of the minimal distance of a b-jet to the quarks originating from the hadronic decay of a W boson and the jet axis shift are shown. As both quantities are very sensitive to a jet overlap they are perfect candidates to display the improvement from the MVb and MVbCharm taggers compared to the current ATLAS tools when they are applied to dense environments. It can be seen that the performance of the different taggers is very similar for a given working point if the alignment between the b-hadron and the jet is perfect. Indeed the b-tagging efficiency of the MVb and MVbCharm taggers decreases as well for increasing values of the angular separation between the b-hadron and the jet. The loss of efficiency is however less significant and an improvement by a factor of up to 1.5 is shown for the various ∆R values.

In a comparison between the Figures 13 (a) and 4 a difference in the efficiency loss can be observed, which is mainly due to the different kinematics of the top quarks and their decay products. The same holds for the results presented in the Figures 13 (b) and 5.

**Figure 14 (a):** B-tagging efficiency of the MVb, MVbCharm and the current ATLAS default b-tagger, MV1, is presented in Figures 13 (a) and (b), where the efficiency dependence on the minimal distance of a b-jet to the quarks originating from the hadronic decay of a W-boson and the jet axis shift are shown. As both quantities are very sensitive to a jet overlap they are perfect candidates to display the improvement from the MVb and MVbCharm taggers compared to the current ATLAS tools when they are applied to dense environments. It can be seen that the performance of the different taggers is very similar for a given working point if the alignment between the b-hadron and the jet is perfect. Indeed the b-tagging efficiency of the MVb and MVbCharm taggers decreases as well for increasing values of the angular separation between the b-hadron and the jet. The loss of efficiency is however less significant and an improvement by a factor of up to 1.5 is shown for the various ∆R values.
V/top/Higgs Tagging

- Putting all available information together
  - Typically groomed mass window + substructure (+ + b tagging)
  - Alternatively, groomed mass window can be replaced with a more sophisticated tagging algorithm
    - CMS/HEP Top Tagger, BDRS, …

See talk by Chris Malena Delitzsch for more details on ATLAS V tagging

[ATLAS PHYS-PUB-14-004]

CMS/HEP Top Tagger
- Groom to find subjets
- Require:
  - \( N_{\text{subjets}} \geq 3 \)
  - \( m_{\text{jet}} \approx m_{\text{top}} \)
  - \( \min(m_{ij}) \approx m_W (\text{CMS}) \)
  - \( m_{ij} \approx m_W (\text{HEP}) \)

[CMS PAS JME-13-007]
See talks by Mario Pelliccioni and Eduardo Navarro De Martino

Higgs

- High mass searches
  - $H \rightarrow WW \rightarrow \ell νqq$ [CMS PAS HIG-14-008] Brand New!
  - $H \rightarrow ZZ \rightarrow \ell \ell qq$ [CMS PAS HIG-14-007] Brand New!
Fermion+Fermion Resonances

- Additional searches in the backup
  - $W' \rightarrow tb$ [ATLAS arXiv:1408.0886]
  - $W' \rightarrow tb$ [CMS PAS HIG-14-007]
• Combination of searches for tt resonance in 0, 1, 2 lepton events
  • Hadronic channel
  • Dijet topology w/ 2 top tags
  • Separate high and low mass optimizations
  • QCD mistag rate measured in data

<table>
<thead>
<tr>
<th>Top Tagger</th>
<th>b-tagging</th>
<th>N-subjettiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mass</td>
<td>HEP (R = 1.5)</td>
<td>sub-jet</td>
</tr>
<tr>
<td>High Mass</td>
<td>CMS (R = 0.8)</td>
<td>$\tau_{32} = \tau_3 / \tau_2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>19.7 fb$^{-1}$ (8 TeV)</th>
</tr>
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<tbody>
<tr>
<td>95% CL observed</td>
<td>m &gt; 2.4 TeV for $\Gamma / m = 1.2%$</td>
</tr>
</tbody>
</table>

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(Extended gauge sectors, colorons, axigluons, pseudoscalar Higgs, extra dimensions)
• Lepton + jets (resolved and merged analyses)
  • Merged channel
    • Event selection
      • 1 $\ell$ (mini-isolation) + $\geq$1 b jet + $\geq$1 top jet + MET + $m_T$
    • Trimmed R=1.0 jet with $m > 100$ GeV + $k_T$-splitting scale
  • Categorize events based on $\Delta R$-matching of b-jets to top candidates
  • W+jets normalization and heavy flavor corrections taken from data
Fermion+Boson Resonances

- $T' \rightarrow t(b jj) H(bb)$ [CMS arXiv:1503.01952]
  - Brand New!
- Additional searches in the backup
  - $\ell^* \rightarrow \ell \gamma/ \ell Z$ [CMS PAS EXO-14-015]
    - Brand New!
  - $B' \rightarrow b H(bb)$ [CMS PAS B2G-14-001]
Search for pair production of $tH$ resonances
- First vector-like quark search in an all hadronic final state
- First use of Higgs tagger exploiting substructure + subjet $b$-tagging
- Require $\geq 1$ top jet and $\geq 1$ Higgs jet
  - Top tag - HEP Top Tagger + subjet $b$-tag
  - Higgs tag - Filtered $R=1.5$ jet with $m > 60$ GeV + double subjet $b$-tag
    - Efficiencies validated in boosted semileptonic $tt$ data

$T' \rightarrow t(bjj)H(bb)$

CMS
- Events

$H_T = \sum_i p_T^i$

Likelihood($H_T, m_{bb}$)

$19.7 fb^{-1}$ (8 TeV)

Observed

$BR(T' \rightarrow tH) = 100\%$

CMS

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Diboson Resonances

- $V(qq)H(bb/WW)$ [CMS PAS EXO-14-009]  
  
- $Z(qq)H(\tau\tau)$ [CMS arXiv:1502.04994]  
  
- Additional searches in the backup  
  - $V(qq)W(\ell\nu)$ [ATLAS arXiv:1503.04677]  
  
- $V(qq)Z(\ell\ell)$ [ATLAS EPJC 75:69 (2015)]  
  
- $V(qq)V(qq)$ [CMS JHEP 08 (2014) 173]  
  
- $V(qq)V(\ell\nu/\ell\ell)$ [CMS JHEP 08 (2014) 174]  

See talk by Katharine Leney
VH Resonance

- First search for VH resonance in all hadronic final state
  - With $H \rightarrow bb/H \rightarrow WW^* \rightarrow 4q$ and $V \rightarrow qq$
- First attempt to reconstruct boosted $H \rightarrow 4q$ decays
- Pruned $R=0.8$ jets used for $H \rightarrow bb/4q$ and $V \rightarrow qq$ tagging
  - + N-subjettiness ($H \rightarrow 4q$: $\tau_{42}$, $V \rightarrow qq$: $\tau_{21}$)
  - + Sub-jet/fatjet b-tagging ($H \rightarrow bb$)
- Categorize events based on $H$ decay mode and $H/V$ purity
- Background model:
  $$P(m_{jj}) = \frac{p_0(1 - m_{jj}/\sqrt{s})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

**High purity selection**

**Low purity selection**

Heavy Vector Triplet model

$m > 1.7$ TeV

(Little Higgs, composite Higgs, 2HDM)

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Z\(\rightarrow\)H resonance

- Search for boosted \(Z\rightarrow qq\) recoiling against \(H\rightarrow \tau\tau\)
  - Consider all possible \(\tau\) decays: \(\tau_e\tau_e, \tau_e\tau_\mu, \tau_\tau\tau_\mu, \tau_h\tau_e, \tau_h\tau_\mu, \tau_h\tau_h\)
  - \(Z\) tagging - Pruned \(R=0.8\) jet with \(70 < m < 110\) GeV + N-subjettiness
  - \(\tau_h\tau_h\): Novel reconstruction of boosted \(H\rightarrow \tau\tau\)
  - Pruned (\(R=0.8\)) subjets with large mass drop serve as seeds to the “hadron-plus-strips” algorithm
  - Likelihood fit to reconstruct \(H\rightarrow \tau\tau\) from MET and visible daughters (SVfit)
  - \(105 < m_{\tau\tau} < 180\) GeV

\[
\mu_{1,2} = \frac{\max(m_1,m_2)}{m_{12}}
\]

Heavy Vector Triplet model

- [CMS arXiv:1502.04994]
SUSY


- Additional searches in the backup
  - Stop (all hadronic) [ATLAS JHEP 09 (2014) 015]
  - Stop (single lepton) [ATLAS JHEP 11 (2014) 118]
RPV SUSY

- Jet multiplicity and total-jet-mass based searches
  - Jet counting analysis
    - ≥6/7 jets ⊗ ≥0/1/2 b tags (R=0.4)
  - Total jet mass analysis
    - Relies on “accidental substructure”
      - Trimmed R=1.0 jets formed from unrelated hadronic activity
      - Large masses generated “accidentally”
    - Signal region - 4 fat jets with small |Δn_{12}|

Signal Event (M_{JΣ} = 705 GeV):

\[ W_{Rp} = \frac{1}{2} \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i D_j D_k + \kappa_i L_i H^2 \]

Primary observable: \[ M_{JΣ}^\Sigma = \sum_{j=1}^{4} m_{jet} \]

ATLAS Simulation

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RPV SUSY

- Jet multiplicity and total-jet-mass based searches
  - Jet counting analysis
    - ≥6/7 jets ⊕ ≥0/1/2 b tags (R=0.4)
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$\phi$ [radians]

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SM Measurements

- tt differential cross section [ATLAS-CONF-2014-057]
- V + jets cross section [ATLAS 2014 NJP 16 113013]
Differential $tt$ Cross Section

- Extension of leptonic results with $p_T(t) < 800$ GeV
- Lepton + jets channel
  - Trimmed $R=1.0$ jets with $m > 100$ GeV + $k_T$ splitting scale
    - $p_T > 300$ GeV and $|\eta| < 2.0$
- MC predictions overestimate the data, especially at high $p_T(t)$
- Dominated by JES (particle level) and signal modeling (parton level) uncertainties

### Data and MC Comparison at Detector-Level

<table>
<thead>
<tr>
<th>Process</th>
<th>$t\bar{t}$ $\ell$+jets</th>
<th>$t\bar{t}$ dilepton</th>
<th>$W$+jets</th>
<th>single top</th>
<th>Multijet</th>
<th>$Z$+jets</th>
<th>Dibosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction</td>
<td>$4790 \pm 130\times 10^3$</td>
<td>$227 \pm 35\times 10^3$</td>
<td>$252 \pm 48\times 10^3$</td>
<td>$134 \pm 25\times 10^3$</td>
<td>$18 \pm 9\times 10^3$</td>
<td>$18 \pm 9\times 10^3$</td>
<td>$3604\times 10^3$</td>
</tr>
<tr>
<td>Data</td>
<td>$4148 \pm 18\times 10^3$</td>
<td>$27 \pm 18\times 10^3$</td>
<td>$23 \pm 8\times 10^3$</td>
<td>$18 \pm 9\times 10^3$</td>
<td>$18 \pm 9\times 10^3$</td>
<td>$18 \pm 9\times 10^3$</td>
<td>$3604\times 10^3$</td>
</tr>
</tbody>
</table>

$\sim 85\%$ purity
V + Jets Cross Section

- Challenging measurement extending leptonic result with $p_T(V) < 300$ GeV
  - Based on $L = 4.6$ fb$^{-1}$ at $s^{1/2} = 7$ TeV
- $R = 0.6$ jets with $p_T > 320$ GeV and $|\eta| < 1.9$
- $50 < m < 140$ GeV
- Likelihood constructed from jet shape variables in the jet rest frame
- Extract V + jets cross section with binned maximum fit to $m_{\text{jet}}$

$\sigma_{W+Z}: 8.5 \pm 0.8 \text{ (stat)} \pm 1.5 \text{ (syst)} \text{ pb}$

$\text{MCFM (NLO): } 5.1 \pm 0.5 \text{ pb}$

~20% precision

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\sigma_{W+Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC modelling</td>
<td>4.4%</td>
</tr>
<tr>
<td>Background pdf</td>
<td>8.8%</td>
</tr>
<tr>
<td>Signal pdf</td>
<td>5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3.7%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>2.2%</td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td>12.6%</td>
</tr>
<tr>
<td>$tt$ contribution</td>
<td>2.8%</td>
</tr>
<tr>
<td>Single-top and diboson contrib.</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>$W$ and $Z$ relative yield</td>
<td>2.9%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.8%</td>
</tr>
<tr>
<td>Total</td>
<td>18%</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV, $4.6$ fb$^{-1}$

Jet Mass / 2 GeV

Data 2011
Signal + Background fit
Background fit component
Signal fit component

\(\text{ATLAS}\)

\(\sqrt{s} = 7\) TeV, 4.6 fb$^{-1}$

$\rho_T > 320$ GeV $|\eta| < 1.9$

$L > 0.15$

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• Challenging measurement extending leptonic result with $p_T(V) < 300 \text{ GeV}$
  • Based on $L = 4.6 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
• $R = 0.6$ jets with $p_T > 320 \text{ GeV}$ and $|\eta| < 1.9$
• $50 < m < 140 \text{ GeV}$
• Likelihood constructed from jet shape variables in the jet rest frame
• Extract $W/Z + \text{jets}$ cross section with binned maximum fit to $m_{\text{jet}}$

[ATLAS 2014 NJP 16 113013]
Run II Considerations
• With increase to 13 TeV, large increase in cross section for heavy particle production
  • Boosted techniques essential
• New challenges as well
  • Triggering in hadronic final states
  • Pileup mitigation

[W.J. Stirling]

ratios of LHC parton luminosities: 13 TeV / 8 TeV

M_{X} (GeV)

luminosity ratio

\sigma_{13} \approx 20 \times \sigma_{8} \text{ for } m(Z') = 2.9 \text{ TeV}

WJS2013

MSTW2008NLO

3/17/15

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Triggering will be a serious challenge in Run II, especially for all hadronic analyses.

Substructure based triggers being deployed which incorporate grooming + mass cut.

Maybe even something more sophisticated - top tagging?
Pileup Mitigation

- More extreme pileup expected during Run II (w/ 25ns bunch spacing)
- New techniques being developed to cope
  - Cleansing
  - Constituent subtraction
  - Shape subtraction
  - Soft Killer
  - PileUp Per Particle Identification (PUPPI)
    - Correct for pileup at the particle level
    - Jet vertex tagger / pileup jet ID
      - Likelihoods constructed from tracking information and jet shape variables
- … See https://indico.cern.ch/event/306155 for details on these and other methods
Conclusion

• The boosted regime and jet substructure significantly enhanced the sensitivity to new physics during Run I
  • Many strong analyses published, in addition to those presented here
  • Virtually all physics groups within ATLAS and CMS exploited boosted topologies
• With the increased energy in Run II, the boosted regime will be vital
  • Also many new challenges
    • The community is working hard to mitigate pileup effects and improve existing algorithms to maximize performance
Backup
Jet Constituents

- Inputs to sequential, Iterative clustering algorithms
  - ATLAS - topological clusters
  - 3D clustering with built-in noise and pileup suppression
  - CMS - particle flow + charged hadron subtraction
  - Stable particles (e, μ, γ, π±, π⁰) reconstructed and identified with an optimized combination of all sub-detectors
Jet Reconstruction

- Jet constituents
- CMS - particle flow + charged hadron subtraction
  - Reconstruct and identify all particles with an optimized combination of all sub-detectors (e, μ, γ, π⁺, π⁻)
- ATLAS - topological clusters
- 3D clustering with built-in noise and pileup suppression
- Sequential, Iterative clustering algorithms
- Calculate the “distance” between all constituents
  \[ d_{ij} = \min(p_{T_i}^2, p_{T_j}^2) \Delta R_{ij}^2 / R^2 \]
  \[ d_{iB} = p_{T_i}^{2n} \]
- Merge nearest constituents
- If for a given constituent i all \( d_{ij} > d_{iB} \), classify i as a jet
- Repeat until all constituents are clustered

<table>
<thead>
<tr>
<th>n</th>
<th>Algorithm</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>kₜ</td>
</tr>
<tr>
<td>0</td>
<td>Cambridge-Aachen</td>
</tr>
<tr>
<td>-1</td>
<td>anti-kₜ</td>
</tr>
</tbody>
</table>

[Image 1]: jet constituents and their methods of reconstruction using CMS and ATLAS techniques. The figure illustrates the clustering process and the impact of different algorithms on jet reconstruction.

[Image 2]: The above properties of the anti- jets translate into concrete results for various algorithms, illustrating the “active” catchment areas of different jets algorithms, as described in [4]. The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.

[Image 3]: The most concrete context in which to quantitatively discuss the properties of jets, as we outline below.

[Image 4]: Two definitions were given for jet areas in [4]: the passive area (\( p_T^2 \)) and a soft one (\( \Delta R_{ij}^2 / R^2 \)). The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.

[Image 5]: The above properties of the anti- jets translate into concrete results for various algorithms, illustrating the “active” catchment areas of different jets algorithms, as described in [4]. The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.

[Image 6]: The above properties of the anti- jets translate into concrete results for various algorithms, illustrating the “active” catchment areas of different jets algorithms, as described in [4]. The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.

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[Image 8]: The above properties of the anti- jets translate into concrete results for various algorithms, illustrating the “active” catchment areas of different jets algorithms, as described in [4]. The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.

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[Image 10]: The above properties of the anti- jets translate into concrete results for various algorithms, illustrating the “active” catchment areas of different jets algorithms, as described in [4]. The left-hand one is much softer than the right-hand one. SISCone (and Cam/Aachen) place the boundary between the jets roughly midway between them.
V tagging

- The combination of grooming and substructure variables to identify hadronic W/Z
- Studied by both ATLAS and CMS
  - Many combinations of jet algo, groomer, and substructure techniques
Jet Core Tracking Improvements

- Additional iterative tracking step targeting the core of jets
- Pattern recognition is performed testing in parallel a large number of possibilities
- Merged pixel cluster splitter
- Exploit the information of the jet direction to predict the expected cluster shape and charge

https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighPtTrackingDP
CMS Top Tagger

- Optimized for jets with \( p_T \gtrsim 350 \text{ GeV} \)
- CA R=0.8 jets
- Reverse clustering sequence
  - Find \( \leq 4 \) well-separated, high \( p_T \) subjets
- Require:
  - \( N_{\text{subjets}} \geq 3 \)
  - \( m_{\text{jet}} \approx m_{\text{top}} \)
  - \( \min(m_{ij}) \approx m_{W} \)

\[
\Delta R_{ij} > 0.4 - 0.0004 \times p_T
\]

\[
p_{T_{\text{cluster}}} > 0.05 \times p_{T_{\text{jet}}}
\]
HEP Top Tagger

- Optimized for jets with $p_T \geq 200$ GeV
- CA $R=1.5$ jets $\max(m_i, m_j) < 0.8m_j$
- Mass drop decomposition + filter

Require:
- $N_{\text{subjets}} \geq 3$
- $m_{\text{jet}} \approx m_{\text{top}}$
- $m_{ij} \approx m_W$

CMS Simulation $\sqrt{s} = 8$ TeV

[CMS PAS JME-13-007] [ATLAS CONF-2013-084]
• Semi-leptonic channel (boosted analysis)

• CMS Top Tagger + N-subjettiness + subjet b-tagging

• Categorize events based on CMS top-tag and b-jet multiplicity

• $\chi^2$ based event reconstruction

• W+jets bkgd

• Apply SF for top mistag rate from W+jets enriched SB

$\epsilon_{\text{data}} = 1.2\%$

$\epsilon_{\text{MC}} = 0.83 \pm 0.21$
W' → tb

- Search for high mass tb resonance
- Top tagging
  - CMS - CMS top tagger + N-subjettiness + subjet b-tag
  \[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \Delta R_{12} \]
  - ATLAS - Trimming + k_{T} scale + N-subjettiness
- Well separated b jet

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<thead>
<tr>
<th>Mass Limits [TeV]</th>
<th>CMS</th>
<th>ATLAS</th>
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<tbody>
<tr>
<td>( W_{R} )</td>
<td>2.02</td>
<td>1.76</td>
</tr>
<tr>
<td>( W_{L} )</td>
<td>1.94</td>
<td>1.68</td>
</tr>
</tbody>
</table>

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• Search for pair production of bH resonance

• Higgs tagging - Pruned R=0.8 jet with $90 < m < 140$ GeV + N-subjettiness + double subjet b-tag

• Categorize events based on the number of additional b jets

• Test for presence of signal with $H_T$

$m > 846$ GeV for

$\text{BR}(B' \rightarrow bH) = 100\%$
**Search for excited leptons through contact interactions**

**Production:**

\[ \mathcal{L}_{CI} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu \]

**Decay:**

\[ \mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left( g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{\gamma}{2} B_{\mu\nu} \right) f_L + h.c. \]

- \(2\ell+\gamma, 4\ell,\) and \(2\ell+J\) final states
- \(2\ell+J\) search
  - Trigger - double electron or double muon trigger
  - Z tag
    - Pruned R = 0.8 jet with \(70 < m < 110\) GeV + N-subjettiness
      - Data/MC scale factor of \(0.9 \pm 0.1\)
    - \(m_{\ell\ell} > 200\) GeV
  - Background modeled with ABCD method
    - \(m_{\ell\ell}\) and \(\tau_{21}\)
Search for excited leptons through contact interactions

2\ell+J search

Pair Z with remaining leptons to form 2 \ell* candidates

Apply mass-dependent L-shaped cut

\ell* → \ell\gamma/\ell Z

<table>
<thead>
<tr>
<th>Search channel</th>
<th>( M_\ell^2 = \Lambda ), values in TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee' → ee'γ</td>
<td>( f = f' = 1 )</td>
</tr>
<tr>
<td>ee' → ee'Z → 2e2j</td>
<td>2.45 (2.45)</td>
</tr>
<tr>
<td>ee' → ee'Z → 4e</td>
<td>2.10 (2.10)</td>
</tr>
<tr>
<td>ee' → ee'Z → 2e2\mu</td>
<td>1.55 (1.55)</td>
</tr>
<tr>
<td>ee' → ee'Z → 2e2\ell</td>
<td>1.60 (1.60)</td>
</tr>
<tr>
<td>\mu\mu' → \mu\mu'γ</td>
<td>2.48 (2.40)</td>
</tr>
<tr>
<td>\mu\mu' → \mu\mu'Z → 2\mu2j</td>
<td>2.10 (2.05)</td>
</tr>
<tr>
<td>\mu\mu' → \mu\mu'Z → 4\mu</td>
<td>1.65 (1.65)</td>
</tr>
<tr>
<td>\mu\mu' → \mu\mu'Z → 2\mu2\ell</td>
<td>1.60 (1.60)</td>
</tr>
<tr>
<td>\mu\mu' → \mu\mu'Z → 2\mu2\ell</td>
<td>1.75 (1.75)</td>
</tr>
</tbody>
</table>

Table 9: Summary of the observed (expected) limits on \( M_\ell^2 = \Lambda \).
RPV SUSY

- Total jet mass analysis
  - Background modeling - “template method”
    - $p_T$- and $\eta$-dependent $m_j$ probability density functions derived in 3-jet CR
    - Convolve PDFs with data in the SR $\rightarrow m_\Sigma^j$ background prediction
  - Validate in 4-jet CR with large $|\Delta\eta_{12}|$


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Stop

- Searches in fully hadronic and single lepton final states
- Each contains 1 SR targeting boosted regime
- Fully hadronic
  - \( \geq 5/6 \) \( R=0.4 \) jets
  - \( \geq 2 \) b-tagged
- MET > 150 GeV

---

<table>
<thead>
<tr>
<th></th>
<th>SRB1</th>
<th>SRB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-( k_t ), ( R = 0.4 ) jets</td>
<td>4 or 5, ( p_T &gt; 80, 35, 35, (35) ) GeV</td>
<td>5, ( p_T &gt; 100, 100, 35, 35, 35 ) GeV</td>
</tr>
<tr>
<td>( p_T^{\text{jet}, R=1.2} )</td>
<td>(&lt; 0.5 )</td>
<td>( &gt; 0.5 )</td>
</tr>
<tr>
<td>( m_T^{\text{jet}, R=1.2} )</td>
<td>( &gt; 80 ) GeV</td>
<td>[140, 500] GeV</td>
</tr>
<tr>
<td>( m_T^{\text{jet}, R=0.8} )</td>
<td>[60, 200] GeV</td>
<td>( = )</td>
</tr>
<tr>
<td>( m_T^{\min} )</td>
<td>( &gt; 50 ) GeV</td>
<td>[70, 300] GeV</td>
</tr>
<tr>
<td>( m_T (\text{jet}^3, \text{p}_{T\min}^{\text{miss}}) )</td>
<td>( &gt; 175 ) GeV</td>
<td>( &gt; 125 ) GeV</td>
</tr>
<tr>
<td>( E_T^{\text{miss}} / \sqrt{H_T} )</td>
<td>( &gt; 280 ) GeV for 4-jet case</td>
<td>( = )</td>
</tr>
<tr>
<td>( E_T^{miss} )</td>
<td>( &gt; 325 ) GeV</td>
<td>( &gt; 17 \sqrt{\text{GeV}} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( &gt; 400 ) GeV</td>
</tr>
</tbody>
</table>
• Searches in fully hadronic and single lepton final states
  • Each contains 1 SR targeting boosted regime
• Single lepton
  • ≥4 R=0.4 jets
    • ≥1 b-tagged
• MET > 350 GeV

<table>
<thead>
<tr>
<th>tN_boost</th>
<th>e</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>No requirements</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Trigger</td>
<td>95.31%</td>
<td>95.31%</td>
</tr>
<tr>
<td>Event DQ</td>
<td>94.07%</td>
<td>94.07%</td>
</tr>
<tr>
<td>Lepton (exactly 1 baseline)</td>
<td>33.75%</td>
<td>33.75%</td>
</tr>
<tr>
<td>Lepton (exactly 1 signal)</td>
<td>11.41%</td>
<td>11.41%</td>
</tr>
<tr>
<td>≥4 jets (75, 65, 40, 25) GeV</td>
<td>7.74%</td>
<td>7.74%</td>
</tr>
<tr>
<td>Δφ(jet1,2, Ptmiss) &gt; 0.5, 0.3</td>
<td>7.36%</td>
<td>7.36%</td>
</tr>
<tr>
<td>≥1 b-tag in 4 leading jets</td>
<td>5.81%</td>
<td>5.81%</td>
</tr>
<tr>
<td>Etmiss &gt; 315 GeV</td>
<td>2.92%</td>
<td>2.92%</td>
</tr>
<tr>
<td>mt &gt; 175 GeV</td>
<td>2.65%</td>
<td>2.65%</td>
</tr>
</tbody>
</table>

≥1 large-R jet, Pr > 270 GeV and jet mass > 75 GeV

Trimmed R=1 jets

$\sqrt{s} = 8$ TeV, $\int L dt = 20$ fb$^{-1}$

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Stop

- Searches in fully hadronic and single lepton final states
- Each contains 1 SR targeting boosted regime

Single lepton analysis
(similar results in hadronic channel)

Hadronic analysis sensitivity

\[ \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \]

\[ m_{\text{stop}} \geq 675 \text{ GeV} \]

@ \( m_{\text{neutralino}} = 0 \)

\[ \text{ATLAS} \]

\[ \int L dt = 20 \text{ fb}^{-1}, \, \sqrt{s} = 8 \text{ TeV} \]

1-lepton + jets + \( E_T^{\text{miss}} \)

All limits at 95% CL

\[ \text{Observed limit (} \pm 1 \sigma_{\text{SUSY}} \text{)} \]

\[ \text{Expected limit (} \pm 1 \sigma_{\text{exp}} \text{)} \]
VH Resonance

- First search for VH resonance in all hadronic final state
  - With $H \rightarrow bb / H \rightarrow WW^* \rightarrow 4q$ and $V \rightarrow qq$
- First attempt to reconstruct boosted $H \rightarrow 4q$ decays
- $H_T$ and dijet mass triggers
- Pruned R=0.8 jets used for $H \rightarrow bb / 4q$ and $V \rightarrow qq$ tagging
  - + N-subjettiness ($H \rightarrow 4q$: $\tau_{42}$, $V \rightarrow qq$: $\tau_{21}$)
  - + Sub-jet/fatjet b-tagging ($H \rightarrow bb$)
- Categorize events based on $H$ decay mode and $V$ purity

High purity selection
Low purity selection

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VW Resonance

- Search in $\ell\nu qq$ final state
  - Low $p_T$ resolved, high $p_T$ resolved, and merged analyses
- Merged channel
  - Momentum balance filtered $R=1.2$ jets with $65 < m < 105$ GeV
  - Neutrino $p_z$ determined from $W$ mass constraint

\[
\sqrt{y_f} = \min(p_T^{j1}, p_T^{j2}) \Delta R_{12}/m_{12} > 0.45
\]
VV Resonance

- Search for VV resonance
  - JJ, ℓνJ, and ℓℓJ final states
  - Pruned R=0.8 jets with 70 ≤ m ≤ 105 GeV + N-subjettiness
  - Categorize events based on τ_21 and single/double tag (JJ)

- Semileptonic analyses: take normalization and shape of V+jets background from m_{JJ/jj} sideband (with shape corrections from MC)
- Fully-hadronic: Model multijet background as smoothly falling distribution
- Bump hunt in m_{JJ}/m_{ℓνJ}/m_{ℓℓJ}/m_{ℓℓjj}

- ℓℓJ and ℓℓjj final states
- BRDS-A R=1.2 jets with 70 < m < 110 GeV

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**VV Resonance**

**signal region results**

CMS, $L = 19.7 \, fb^{-1}$, $\sqrt{s} = 8 \, TeV$

- High-purity doubly W/Z-tagged data
- Fit
- $G_W$ $\rightarrow$ WW (1.5 TeV)

**Additional limits in papers**

- CMS [JHEP 08 (2014) 173]
- CMS [JHEP 08 (2014) 174]
- ATLAS [EPJC 75:69 (2015)]

**Best limit on W' → WZ**

$m > 1.58 \, TeV$

**m > 1.7 \, TeV**

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ABCDD Method in T'→tH

- QCD normalization:
  \[ N_D = N_B \frac{N_C}{N_A} \]

- QCD shape:
  - Taken from region B
  - Validated with QCD MC and data

![Diagram](attachment:image.png)

Table 3: Predicted background contributions in the signal region for the two event categories with one and with multiple H tags. Statistical uncertainties in the background estimates are also shown.

<table>
<thead>
<tr>
<th></th>
<th>single H tag category</th>
<th>multi H tag category</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD (predicted from data)</td>
<td>917 ± 11</td>
<td>127 ± 4</td>
</tr>
<tr>
<td>t(t) (from simulation)</td>
<td>486 ± 8</td>
<td>55 ± 3</td>
</tr>
<tr>
<td>total background</td>
<td>1403 ± 14</td>
<td>182 ± 5</td>
</tr>
<tr>
<td>data</td>
<td>1355 ± 205</td>
<td></td>
</tr>
</tbody>
</table>

[CMS arXiv:1503.01952]
Top Tagging Performance

- Techniques validated in data

![ATLAS Preliminary](image)

- Optimal performance
  - Obtained by combining tagger with additional jet substructure info
  - Analysis dependent
Example: CMS Top Tagger decomposition

Primary decomposition

\[ \Delta R(A,B) > D_{\text{cut}} \]

Decomposition fails

\[ p_T^A < 0.05 \times p_T^{\text{jet}} \text{ and } p_T^B < 0.05 \times p_T^{\text{jet}} \]

Decomposition fails

\[ p_T^A > 0.05 \times p_T^{\text{jet}} \text{ and } p_T^B > 0.05 \times p_T^{\text{jet}} \]

Decomposition succeeds

\[ p_T^A < 0.05 \times p_T^{\text{jet}} \text{ and } p_T^B < 0.05 \times p_T^{\text{jet}} \]

Decomposition fails

Remove B. Try to decluster A.

Secondary decomposition

Individually decluster A and B

\[ A' \text{ and } A'' \text{ pass criteria} \]

3 final subjets

\[ B' \text{ and } B'' \text{ are too close} \]
HEP Top Tagger

Step 1:
Mass drop decomposition

Step 2:
Loop over all combinations of 3 mass drop subjets

Step 3:
Recluster with $R_{\text{filt}} = \min(0.3, \Delta R_{\text{min}}/2)$

Step 4:
Filtering: keep only the 5 leading subjets

Step 5:
Repeat reclustering and filtering procedure for all combinations of 3 mass drop subjets

Step 6:
Pick the combination with filtered mass closest to the top mass. Recluster to force 3 subjets
HEP Top Tagger

\[ R_{\text{min}}^2 \left( 1 + \left( \frac{m_{12}}{m_{13}} \right)^2 \right) < 1 - \left( \frac{m_{23}}{m_{123}} \right)^2 < R_{\text{max}}^2 \left( 1 + \left( \frac{m_{12}}{m_{13}} \right)^2 \right) \]

\[ R_{\text{min}}^2 \left( 1 + \left( \frac{m_{13}}{m_{12}} \right)^2 \right) < 1 - \left( \frac{m_{23}}{m_{123}} \right)^2 < R_{\text{max}}^2 \left( 1 + \left( \frac{m_{13}}{m_{12}} \right)^2 \right) \]

\[ R_{\text{min}} < \frac{m_{23}}{m_{123}} < R_{\text{max}} \]

\[ R_{\text{max}} = (1 + f_W) \times m_W/m_t \]

\[ R_{\text{min}} = (1 - f_W) \times m_W/m_t \]

\[ \frac{m_{23}}{m_{123}} > 0.35 \]

HEP Top Tagger
CA R=1.5 \(|\eta|<2.4\)
\(p_T > 200\) GeV/c
\(t\bar{t}\) simulated with MADGRAPH

CMS Simulation \(\sqrt{s} = 8\) TeV

\[ 0.2 < \arctan \frac{m_{13}}{m_{12}} < 1.3 \]
Top Tagging Performance

CMS Simulation, $\sqrt{s} = 8$ TeV

Matched parton $p_T > 400$ GeV/c

Matched parton $p_T > 600$ GeV/c

Matched parton $p_T > 800$ GeV/c

CMS Top Tagger

subjet b-tag

N-subjettiness ratio $\tau_3/\tau_2$

CMS + subjet b-tag

$\tau_3/\tau_2 +$ subjet b-tag

HEP Top Tagger

$\tau_3/\tau_2 +$ subjet b-tag

HEP WP0

HEP Comb. WP1

HEP Comb. WP2

HEP Comb. WP3

CMS WP0

CMS Comb. WP1

CMS Comb. WP2

CMS Comb. WP3

CMS Comb. WP4

HEP Comb. WP3

ATLAS Simulation Preliminary

$\sqrt{s} = 8$ TeV

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[CMS PAS JME-12-009] [ATLAS CONF-2013-084]