Fat jets

Tilman Plehn

Universität Heidelberg

Higgs Days, Santander 10/2010
Fat jets

Boosted particles at the LHC

1994 boosted $W \rightarrow 2$ jets from heavy Higgs [Seymour]
1994 boosted $t \rightarrow 3$ jets [Seymour]
2002 boosted $W \rightarrow 2$ jets from strongly interacting $WW$ [Butterworth, Cox, Forshaw]
2006 boosted $t \rightarrow 3$ jets from heavy resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]
2008 boosted $H \rightarrow b\overline{b}$ [Butterworth, Davison, Rubin, Salam]
2009 boosted $\tilde{\chi}_1^0 \rightarrow 3$ jets in $R$ parity violating SUSY [Butterworth, Ellis, Raklev, Salam]
2009 boosted $t \rightarrow 3$ jets from top partners [TP, Salam, Spannowsky, Takeuchi]

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Higgs to bottoms

New strategy for $H \rightarrow bb$ [Butterworth, Davison, Rubin, Salam]

- desperately needed [2/3 of all light Higgses; impact Dührssen & SFitter]

- $S$: large $m_{bb}$, boost-dependent $R_{bb}$
  - $B$: large $m_{bb}$ only for large $R_{bb}$
  - $S/B$: go for large $m_{bb}$ and small $R_{bb}$, so boost Higgs

- fat Higgs jet $R_{bb} \sim 2m_H/p_T \sim 0.8$

- $q\bar{q} \rightarrow V_ℓH_b$ sizeable in boosted regime [\(p_T \gtrsim 300\) GeV, few % of total rate]
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$\Rightarrow$ non-trivial challenge to jet algorithms  [details later]

<table>
<thead>
<tr>
<th>jet definition</th>
<th>$\sigma_S$/fb</th>
<th>$\sigma_B$/fb</th>
<th>$S/\sqrt{B_{30}}$</th>
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<tbody>
<tr>
<td>C/A, $R = 1.2$, MD-F</td>
<td>0.57</td>
<td>0.51</td>
<td>4.4</td>
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<tr>
<td>$k_\perp$, $R = 1.0$, $y_{cut}$</td>
<td>0.19</td>
<td>0.74</td>
<td>1.2</td>
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<tr>
<td>SISCone, $R = 0.8$</td>
<td>0.49</td>
<td>1.33</td>
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Higgs to bottoms

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⇒ non-trivial challenge to jet algorithms [details later]

Results and checks

- combined channels $V \rightarrow \ell\ell, \nu\nu, \ell\nu$
- NLO rates [bbV notorious, not from data alone]
- Z peak as sanity check
- checked by Freiburg [Piquadio]
  - subjet $b$ tag excellent [70%/1%]
  - charm rejection challenging
  - $m_H \pm 8$ GeV tough
⇒ confirmed at 20% level
Rescuing $t\bar{t}H$

**Traditional $t\bar{t}H$, $H \rightarrow b\bar{b}$** [Atlas-Bonn study, CMS-TDR even worse]

- trigger: $t \rightarrow bW^+ \rightarrow b\ell^+\nu$
  reconstruction and rate: $\bar{t} \rightarrow \bar{b}W^- \rightarrow bjj$
- continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [weighted by b-tag]
- no chance:
  1– combinatorics: $m_{bb}$ from $pp \rightarrow 4b_{tag} 2j \ell\nu$
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  3– systematics: $S/B \sim 1/9$
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**Fat jets analysis** [TP, Salam, Spannowsky]

- S: large $m_{bb}$, boost-dependent $R_{bb}$
  - B: large $m_{bb}$ only for large $R_{bb}$
  - S/B: large $m_{bb}$ and small $R_{bb}$; correct bottom pair boosted [solves 1]
- $pp \rightarrow t\ell t_H H_b$ even harder than $VH$
  - also boost different for S and B [solves 2]
- cool: fat Higgs jet + fat top jet
  - uncool: QCD [Dittmaier et al: $K = 2.3$ for $t\bar{t}b\bar{b}$]
- see how far we get... [watch $S/B$ for 3]
Rescuing $t\bar{t}H$

**Top tag**  [cf Johns Hopkins, Princeton, Washington]

- start with C/A jet \([R = 1.5]\)  [Johns Hopkins]
- uncluster one-by-one: \(j \rightarrow j_1 + j_2\)
  1– unbalanced \(m_{j_1} > 0.8m_j\) means QCD; discard \(j_2\)
  2– soft \(m_{j_1} < 30\) GeV means QCD; keep \(j_1\)
- top decay kinematics in relevant substructures
  reconstruct \(m_W = 60\ldots95\) GeV
  reconstruct \(m_t = 150\ldots200\) GeV
  helicity angle \(\cos \theta_{t,j_1} > 0.7\)  [changed later]
  no \(b\) tag needed
- underlying event scaling like \(R^4\)
  filter reconstruction jets  [Butterworth–Salam]
  decay plus one add’l jet at \(R_{\text{filt}} \sim R_{jj}/2\)
  reconstruct masses w/ QCD jet

⇒ HEPTopTagger
Rescuing $t\bar{t}H$

**Higgs tag**

- same as top tag  
  [stricter mass drop criterion, harder jets]
  but: Higgs mass unknown

- double $b$ tag  
  [$\mathcal{O}(10\%)$ from leptonic top]
  combinations ordered by $J = p_{T,1}p_{T,2}(\Delta R_{12})^4$
  three leading combinations vs $m_{bb}^{filt}$

⇒ like Butterworth-Salam for busy QCD

**Analysis**

- require tagged top and Higgs
trigger on lepton

- remove ‘Higgs’ as $t_\ell \rightarrow b$ plus QCD
  3rd $b$ tag in continuum
  $B = 3.8S \rightarrow 2.4S$  
  [costing $S/\sqrt{B}$]
  only continuum $t\bar{t}bb$ left

<table>
<thead>
<tr>
<th>per 1 fb$^{-1}$</th>
<th>signal</th>
<th>$t\bar{t}Z$</th>
<th>$t\bar{t}bb$</th>
<th>$t\bar{t}+$jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>events after acceptance</td>
<td>24.1</td>
<td>6.9</td>
<td>191</td>
<td>4160</td>
</tr>
<tr>
<td>events with one top tag</td>
<td>10.2</td>
<td>2.9</td>
<td>70.4</td>
<td>1457</td>
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<tr>
<td>events with $m_{bb} = 110 - 130$ GeV</td>
<td>2.9</td>
<td>0.44</td>
<td>12.6</td>
<td>116</td>
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<tr>
<td>corresponding to subjet pairings</td>
<td>3.2</td>
<td>0.47</td>
<td>13.8</td>
<td>121</td>
</tr>
<tr>
<td>subjet pairings two $b$ tags</td>
<td>1.0</td>
<td>0.08</td>
<td>2.3</td>
<td>1.4</td>
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<tr>
<td>including a third $b$ tag</td>
<td>0.48</td>
<td>0.03</td>
<td>1.09</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Rescuing $\bar{t}tH$

**Higgs tag**

- same as top tag  [stricter mass drop criterion, harder jets]
  but: Higgs mass unknown
- double $b$ tag  [$\mathcal{O}(10\%)$ from leptonic top]
  combinations ordered by $J = p_{T, 1} p_{T, 2} (\Delta R_{12})^4$
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- require tagged top and Higgs trigger on lepton
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<tr>
<th>$m_H$</th>
<th>$S$</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
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<tbody>
<tr>
<td>115</td>
<td>57</td>
<td>1/2.1</td>
<td>5.2 (5.7)</td>
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<tr>
<td>120</td>
<td>48</td>
<td>1/2.4</td>
<td>4.5 (5.1)</td>
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<tr>
<td>130</td>
<td>29</td>
<td>1/3.6</td>
<td>2.9 (3.0)</td>
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⇒ under experimental scrutiny
**Boosted top**

**Highly boosted top quarks**  
[Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

- identify hadronic tops with $p_T \gtrsim 800$ GeV isolation and $b$ tagging challenging
- C/A algorithm with $p_T$ drop criterion  
  all top decay jets identified  
  3 kinematic constraints: $m_W$, $m_t$, $\cos \theta_{\text{hel}}$  
  [no $b$ tag]
- top mass included, no sidebins
- general ATLAS studies  
  [ATLAS-2010-008]
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**Standard Model: HEPTopTagger**  [TP, Salam, Spannowsky, Takeuchi]

- extend lower $p_T \gtrsim 250$ GeV testable in Standard Model $t\bar{t}$
- start like Higgs tagger [mass drop, $R = 1.5$]
  kinematic selection: $m_{jjj}, m_j^{(1)}, m_j^{(2)}$  [no $b$ tag, filtered]
Fat jets

Tilman Plehn

Fat jets

VH, H → b̅b

t̅tH, H → b̅b

HEPTopTagger

Stop pairs

More Higgs

Boosted top

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- promising tests by ATLAS  [Kasieczka & Schätzel]

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![Efficiencies graph](https://via.placeholder.com/150)
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<th>QCD $W$+jets</th>
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<tr>
<td>$0$</td>
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<td>$200$</td>
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**HEPTopTagger: kinematic selection**

- kinematic criteria without boosts etc
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**HEPTopTagger: momentum reconstruction**

- top momentum reconstruction [\(p_T > 200, 300\) GeV]
Stops

Stop pairs  [TP, Spannowsky, Takeuchi, Zerwas]

- stop most important particle for hierarchy problem
- comparison to other top partners  [Meade & Reece]
- dark matter means difficult semi-leptonic channel
- purely hadronic:  \( \tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 \tilde{t}\tilde{\chi}_1^0 \)  [CMS TDR: leptons as spontaneous life guards]

<table>
<thead>
<tr>
<th>Events in 1 fb(^{-1})</th>
<th>( \tilde{t}_1\tilde{t}_1^* )</th>
<th>( \tilde{t}\tilde{t} )</th>
<th>QCD</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>( S/B )</th>
<th>( S/\sqrt{B} ) 10 fb(^{-1})</th>
</tr>
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<tbody>
<tr>
<td>( m_{\tilde{t}} [\text{GeV}] )</td>
<td>340 390 440 490 540 640</td>
<td>728 447 292 187 124 46</td>
<td>87850 2.4 \times 10^7 1.6 \times 10^5</td>
<td>n/a</td>
<td>3.0 \times 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p_T,j &gt; 200 \text{ GeV, } \ell \text{ veto} )</td>
<td>283 234 184 133 93 35</td>
<td>2245 2.4 \times 10^5 1710 2240</td>
<td>1.2 \times 10^{-3}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \not{E}_T &gt; 150 \text{ GeV} )</td>
<td>100 91 75 57 42 15</td>
<td>743 7590 90 114</td>
<td>1.2 \times 10^{-2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First top tag</td>
<td>15 12.4 11 8.4 6.3 2.3</td>
<td>32 129 5.7 1.4</td>
<td>8.3 \times 10^{-2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second top tag</td>
<td>8.7 7.4 6.3 5.0 3.8 1.4</td>
<td>19 2.6</td>
<td>n/a</td>
<td>0.40</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b \text{ tag} )</td>
<td>4.3 5.0 4.9 4.2 3.2 1.2</td>
<td>4.2 &lt; 0.6 &lt; 0.2 &lt; 0.05</td>
<td>0.88</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Stops

Stop pairs  [TP, Spannowsky, Takeuchi, Zerwas]

- stop most important particle for hierarchy problem
  comparison to other top partners  [Meade & Reece]
- dark matter means difficult semi-leptonic channel
- purely hadronic: \( \tilde{t}\tilde{t}^* \rightarrow t\tilde{X}_1^0 \tilde{t}\tilde{X}_1^0 \)  [CMS TDR: leptons as spontaneous life guards]
- stop mass from \( m_{T_2} \) endpoint  [like sleptons or sbottoms]
- not harder analysis than \( b\bar{b} + E_T \)
More Higgs

**Higgs in cascade decays**  [Kribs, Martin, Roy, Spannowsky]

- idea: find Higgs in cascade decays  [Cambridge]
- BSM sample after missing energy or hard $\gamma$ cut
- Higgs tag over the remaining event
- side bin analysis in $m_{bb}$

...
Outlook

Fat jets — Aspirin of LHC phenomenology

- $VH$: curing QCD backgrounds
- $t\bar{t}H$: curing combinatorics and backgrounds
- $\tilde{t}\tilde{t}^*$: curing backgrounds
- cascade Higgs: curing lack of strategy
- heavy resonances: curing calorimeter resolution
- try using it against your headache...
Fat jets

Tilman Plehn

Fat jets

$VH, H \rightarrow b\bar{b}$

$t\bar{t}H, H \rightarrow b\bar{b}$

HEPTopTagger

Stop pairs

More Higgs