H→bb Tagging in ATLAS

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On behalf of the ATLAS Collaboration
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Introduction

Motivation

- SM decay \( H \rightarrow bb \): largest branching ratio
- Boosted topology provides various handles to suppress dominant multi-jet background
- Boosted \( H \rightarrow bb \) tagger becomes an essential tool for new physics search in ATLAS

Contents

- Boosted \( H \rightarrow bb \) tagger in Run-II
- Modeling in high-\( p_T \) \( g \rightarrow bb \) enriched sample using 8TeV data
Boosted H→bb Tagging in Run-II

ATL-PHYS-PUB-2015-035
Tagging Boosted $H \rightarrow bb$

- Reconstruct $H \rightarrow bb$ topology with trimmed anti-$k_t$ $R=1.0$ jet ($f_{cut}=0.05$, $R_{sub}=0.2$)

- Major backgrounds considered:
  - Multi-jet events
  - Boosted hadronically decaying top quarks

- Three handles for background rejection:
  - $b$-Tagging
  - Large-$R$ jet mass
  - Large-$R$ jet substructure
Small-R Track Jet $b$-Tagging

- Use small radius (R=0.2) track jets to resolve close-by $b$-hadrons
- Ghost association of track jets to ungroomed large-R jets to provide $b$-tagging

Advantage of track jets
- Better estimate $b$-hadron flight direction
- Pile-up resistant
- $b$-tagging independent of calorimeter jets

ATLAS Simulation Preliminary

Welcome to the page with information about Small-R Track Jet $b$-Tagging. The diagram illustrates the arrangement of large and small-radius jets, highlighting the advantage of using small-radius track jets for better estimation of $b$-hadron flight direction, being pile-up resistant, and independent of calorimeter jets.
Small-R Track Jet $b$-Tagging

- Large improvement in efficiency to find boosted Higgs jet from small radius
- Flexible in track jet $b$-tagging
  - Independent of calorimeter jets
  - Single / double / one-tight-one-loose schemes

**ATLAS** Simulation Preliminary

$\sqrt{s} = 8$ TeV, $k_{T\text{, initial}} = 1.0$

- anti-$k_t$ track jets
- $k_t$ calor jets

4b efficiency in
RSG$\rightarrow$hh$\rightarrow$4b

**ATLAS** Simulation Preliminary

anti-$k_t$ R=1.0 jets

Trimmed ($f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$)

$p_T > 250$ GeV, $|\eta_{\text{jet}}| < 2.0$

4b efficiency vs. Graviton Mass [GeV]

Higgs-jet efficiency vs. Multi-jet rejection
Large-R Jet Mass and Substructure

- Improve large-R jet mass resolution by:
  - Trimming with $f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$
  - Muon-in-b-jet correction correcting for semi-leptonic b hadron decays

- Substructure information considered in addition to mass cut and b-tagging:
  - Similar performance across $D_2^\beta=1$, $C_2^\beta=1$ and $\tau_{w^+a}$
  - $D_2^\beta=1$ is chosen due to better modeling in data

**ATLAS** Simulation Preliminary

- anti-$k_t$, $R=1.0$ jets
- Trimmed ($f_{\text{cut}}=0.05$, $R_{\text{sub}}=0.2$)
- $|\eta_{\text{det}}| < 2.0$
- Double b-tagged @ 70% WP

**ATLAS** Simulation Preliminary

- anti-$k_t$, $R=1.0$ jets
- Trimmed ($f_{\text{cut}}=0.05$, $R_{\text{sub}}=0.2$)
- $350 < p_T < 500$ GeV
- $|\eta_{\text{det}}| < 2.0$
- 68% mass window

- $\tau_{w^+a}$
H→bb Tagger Performance

- Three working points (WP) defined
- Systematic uncertainties:
  - $b$-tagging largest for loose selection
  - Jet energy/mass scale & resolution larger for tight selection

### Table 1: Criteria used for the different Higgs-jet tagging selections.

<table>
<thead>
<tr>
<th>Selection</th>
<th>double $b$-tagging</th>
<th>large-$R$ jet Mass</th>
<th>$D_2^{(\beta=1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose</td>
<td>70% WP</td>
<td>90% window, $m \in [76, 146]$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>Medium</td>
<td>70% WP</td>
<td>68% window, $m \in [93, 134]$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>Tight</td>
<td>70% WP</td>
<td>68% window, $m \in [93, 134]$ GeV</td>
<td>$p_T$-dependent cut</td>
</tr>
</tbody>
</table>

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**ATLAS Simulation Preliminary**

- anti-$k_t$, $R=1.0$ jets
- Trimmed ($f_{\text{cut}}=0.05$, $R_{\text{sub}}=0.2$)
- $|\eta_{\text{sel}}| < 2.0$
- Loose Selection

- Efficiency
- Jet Scale
- Jet Resolution
- $b$-tagging
- Total

Uncertainty: ~17%
Application in 13 TeV New Physics Search

Higgs tagger has been widely used in ATLAS 13TeV analysis, in particular the new physics search:

- A selected list of examples here
- More details in C. Pollard’s talk on Thursday

Di-Higgs 4b [EXOT-2015-11]:
- Require 3 or 4 \(b\)-tagged track jets
- 77% WP is used
- Customized jet mass requirement
Application in 13 TeV New Physics Search (Continued)

VH resonance search [ATLAS-CONF-2015-074]:
- Loose WP
- Additional 1 $b$-tag WP

mono-Higgs [ATLAS-CONF-2016-019]:
- 1 or 2 $b$-tagged track jets
- Full mass distribution used in likelihood fit

Lessons learnt from analysis:
- $b$-Tagging contributes the most to sensitivity
- Analysis benefits more from efficiency than rejection in boosted topology
  - Alternative: Single $b$-tagging (+ substructure)
  - Alternative: Looser $b$-tagging WP (especially high pT)
Updates of $H \rightarrow bb$ Tagger in 2016: $b$-Tagging

- In 2016, we are following the similar tagging strategy as previous $H \rightarrow bb$ tagger

- Improvement in $b$-tagging:
  - Algorithm optimization in impact parameter based tagging (IP3D) and secondary vertex finder (SV)
  - Optimization of final multivariable $b$-tagging discriminant (MV2)

- Various discriminants available for $b$-tagging
  - Suitable for various background composition
  - Improved rejection against light/c-jet in anti-$k_T$ $R=0.4$ calorimeter jets
  - Similar improvement expected in track jet $b$-tagging
Modeling in $g \rightarrow bb$ Enriched Data

ATLAS-CONF-2016-002
Challenges

• Not enough $H \rightarrow bb$ in data — not even found yet :)

• Solution: $g \rightarrow bb$ provides a copious sample of close-by b-jets
  ‣ Double b-tagging systematics for track jets
  ‣ Check modeling of large-R jet substructure variables
  ‣ Cross-check large-R jet energy scale (JES) / jet mass scale (JMS) / $D_2^{\beta=1}$ uncertainty

• We check these using 2012 8TeV data
Strategy

• Goal: Increase $g \rightarrow bb$ purity
• Key: At least one of small radius track jets should be matched to muon
  ‣ Select semi-leptonic $b$-hadron decays
  ‣ Enrich events with jets containing $b$-hadrons
• Further double $b$-tagging on small-$R$ track jets to obtain high purity $g \rightarrow bb$ samples
Flavor Fraction Correction

- **Issue:** MC does not model the heavy flavor content in data
- **Method:** Fit variable sensitive to flavor composition to data
- **Discriminant:** Largest track impact parameter significance inside track jet
- **Fit procedure:**
  - Build $S_{d_0}$ template for each flavor component
  - Simultaneous binned likelihood fit on 1-D $S_{d_0}$ distribution for muon and non-muon track jet

$$S_{d_0} = \text{sgn}(d_0) \times \frac{d_0}{\sigma(d_0)}$$
Flavor Fraction Correction

- A clear discrepancy between data/MC on flavor fraction can be seen for large-R jet, especially when $p_T < 500$ GeV
  → Flavor correction becomes essential
- Double $b$-tagging rate very well modeled after flavor correction
Results: Double b-Tagging

- Data/MC agrees well within the uncertainties

- It is noticeable that same level of agreement is seen at low $\Delta R$ in which jets are not isolated from each other
Results: Large-R Jet $p_T$ Modeling

- Large-R jet $p_T$ well modeled within uncertainties
- Large-R jet JES uncertainty cross-check
  - We use data and MC ratio of variable $\frac{p_T^{trk}}{p_T^{calo}}$ for in-situ calibration
  - Existing JES uncertainty derived from inclusive sample is large enough to cover topology dependence
- Same cross-check on JMS / $D_2^{\beta=1}$ uncertainty
Results: Large-R Jet Mass / Substructure Modeling

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### ATLAS Preliminary

- **$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**
- Anti-$k_t$, $R=1.0$ jet after b-tagging
- Trimmed ($R_{\text{sub}}=0.3$, $f_{\text{cut}}=0.05$)
- Flavor fraction corrected

#### Data / MC

- Total Uncertainty
- Fit Uncertainty
- b-tagging Uncertainty

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### ATLAS Preliminary

- **$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**
- Anti-$k_t$, $R=1.0$ jet after b-tagging
- Trimmed ($R_{\text{sub}}=0.3$, $f_{\text{cut}}=0.05$)
- Flavor fraction corrected

#### Data / MC

- Total Uncertainty
- Fit Uncertainty
- b-tagging Uncertainty

---

### ATLAS Preliminary

- **$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**
- Anti-$k_t$, $R=1.0$ jet after b-tagging, $|\eta| > 1.2$
- Trimmed ($R_{\text{sub}}=0.3$, $f_{\text{cut}}=0.05$)

#### Data / MC

- Data
- Pythia 8 MC

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### ATLAS Preliminary

- **$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**
- Anti-$k_t$, $R=1.0$ jet after b-tagging
- Trimmed ($R_{\text{sub}}=0.3$, $f_{\text{cut}}=0.05$)

#### Data / MC

- Pythia 8 MC
Concluding Remarks

Boosted $H \rightarrow bb$ tagger is highly successful in ATLAS for new physics search with 13TeV data

Pushing the physics search limits in ATLAS through
  ‣ Jet substructure techniques
  ‣ Small-R track jet $b$-tagging

Modeling of $b$-tagging performance and large-R jet properties studied in $g \rightarrow bb$ topology for the first time in ATLAS using 8TeV data
  ‣ Useful to cross-check flavor dependency of existing calibrations
  ‣ Modeling is in good agreement within uncertainties
Back Up
H→bb: Number of Track Jets

**ATLAS Simulation Preliminary**

- anti-$k_t$ $R=1.0$ jets
- Trimmed ($f_{cut}=0.05$, $R_{sub}=0.2$)
- $p_T > 250$ GeV, $|\eta_{det}| < 2.0$

Number of track-jets vs. Arbitrary Units

- Higgs-jet $M_{RSG}=500$ GeV
- Higgs-jet $M_{RSG}=1000$ GeV
- Higgs-jet $M_{RSG}=1500$ GeV
- Multi-jet
- Hadronic top
H→bb: b-Tagging

**ATLAS Simulation Preliminary**

anti-$k_t$ R=1.0 jets
Trimmed ($f_{cut} = 0.05$, $R_{sub} = 0.2$)
$p_T > 250 \text{ GeV}, |\eta_{jet}| < 2.0$

**ATLAS Simulation Preliminary**

anti-$k_t$ R=1.0 jets
Trimmed ($f_{cut} = 0.05$, $R_{sub} = 0.2$)
$p_T > 250 \text{ GeV}, |\eta_{jet}| < 2.0$

**ATLAS Simulation Preliminary**

anti-$k_t$ R=1.0 jets
Trimmed ($f_{cut} = 0.05$, $R_{sub} = 0.2$)
$p_T > 250 \text{ GeV}, |\eta_{jet}| < 2.0$
H→bb: Large-R Jet Mass and Substructure
H→bb Taggers

**ATLAS Simulation Preliminary**

- **Higgs-jet efficiency**
  - anti-κ, R=1.0 jets
  - Trimmed (\(f_{cut}=0.05, R_{sub}=0.2\))
  - \(|\eta_{jet}| < 2.0\)
  - b-tagging at 70% WP

- **Multi-jet rejection**
  - anti-κ, R=1.0 jets
  - Trimmed (\(f_{cut}=0.05, R_{sub}=0.2\))
  - \(|\eta_{jet}| < 2.0\)
  - b-tagging at 70% WP

- **Hadronic top rejection**
  - anti-κ, R=1.0 jets
  - Trimmed (\(f_{cut}=0.05, R_{sub}=0.2\))
  - \(|\eta_{jet}| < 2.0\)
  - b-tagging at 70% WP
H→bb Taggers

**ATLAS Simulation Preliminary**

- anti-\( k_{t} \), \( R=1.0 \) jets
- Trimmed (\( f_{\text{cut}}=0.05, R_{\text{sub}}=0.2 \))
- \( |\eta_{dij}| < 2.0 \)
- Medium Selection

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**ATLAS Simulation Preliminary**

- Trimmed (\( f_{\text{cut}}=0.05, R_{\text{sub}}=0.2 \))
- \( |\eta_{dij}| < 2.0 \)
- Tight Selection

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**Relative Uncertainty**

- Efficiency
- Jet Scale
- Jet Resolution
- b-tagging
- Total
H→bb Taggers

**ATLAS Simulation Preliminary**

- Anti-κ, $R=1.0$ jets
- Trimmed ($f_{cut} = 0.05, R_{sub} = 0.2$)
- $|\eta_{det}| < 2.0$
- Medium Selection
- Rejection
- Jet Scale
- Jet Resolution
- b-tagging
- Total

**ATLAS Simulation Preliminary**

- Anti-κ, $R=1.0$ jets
- Trimmed ($f_{cut} = 0.05, R_{sub} = 0.2$)
- $|\eta_{det}| < 2.0$
- Tight Selection
- Rejection
- Jet Scale
- Jet Resolution
- b-tagging
- Total
H→bb Taggers

ATLAS Simulation Preliminary

- anti-k, R=1.0 jets
- Trimmed \( f_{\text{cut}} = 0.05, R_{\text{sub}} = 0.2 \)
- \( |\eta_{\text{det}}| < 2.0 \)

Medium Selection

- Rejection
- Jet Scale
- Jet Resolution
- b-tagging
- Total

Hadronic top rejection

400 600 800 1000 1200 1400
\( p_T \) [GeV]

Relative Uncertainty

0.5 1 1.5
# H→bb Taggers

<table>
<thead>
<tr>
<th></th>
<th>Loose</th>
<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.41 ±0.07</td>
<td>0.32 ±0.06</td>
<td>0.25 ±0.05</td>
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<tr>
<td><strong>Multi-jet rejection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive</td>
<td>260 ±50</td>
<td>460 ±90</td>
<td>800 ±210</td>
</tr>
<tr>
<td>Light-flavor</td>
<td>O(10⁵)</td>
<td>O(10⁵)</td>
<td>O(10⁶)</td>
</tr>
<tr>
<td>cl</td>
<td>O(10³)</td>
<td>O(10³)</td>
<td>O(10⁴)</td>
</tr>
<tr>
<td>bl</td>
<td>O(10²)</td>
<td>O(10²)</td>
<td>O(10³)</td>
</tr>
<tr>
<td>bc</td>
<td>O(10)</td>
<td>O(10)</td>
<td>O(10²)</td>
</tr>
<tr>
<td>cc</td>
<td>250 ±150</td>
<td>480 ±310</td>
<td>1200 ±900</td>
</tr>
<tr>
<td>bb</td>
<td>11 ±2</td>
<td>19 ±4</td>
<td>31 ±9</td>
</tr>
<tr>
<td><strong>Hadronic top rejection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive</td>
<td>67 ±17</td>
<td>110 ±30</td>
<td>160 ±50</td>
</tr>
<tr>
<td>bl</td>
<td>360 ±230</td>
<td>660 ±460</td>
<td>810 ±600</td>
</tr>
<tr>
<td>bc</td>
<td>24 ±6</td>
<td>39 ±11</td>
<td>53 ±16</td>
</tr>
</tbody>
</table>
Large-R Jet Modeling before $b$-tagging
Large-R Jet Other Substructure Variables

**ATLAS Preliminary**

- **s=8 TeV, 20.3 fb⁻¹**
- Anti-kₜ R=1.0 jet before b-tagging
- Trimmed \( R_{\text{sub}}=0.3, f_{\text{cut}}=0.05 \)
- Flavor fraction corrected

**ATLAS Preliminary**

- **s=8 TeV, 20.3 fb⁻¹**
- Anti-kₜ R=1.0 jet after b-tagging
- Trimmed \( R_{\text{sub}}=0.3, f_{\text{cut}}=0.05 \)
- Flavor fraction corrected

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**Data**

- LL
- CL
- CC
- BL
- BC
- BB

**Total Uncertainty**

- **Fit Uncertainty**

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**Data**

- LL
- CL
- CC
- BL
- BC
- BB

**Total Uncertainty**

- **Fit Uncertainty**

- **b-tagging Uncertainty**
Variable-R Jets in $H \rightarrow bb$

**ATLAS Preliminary**
Simulation, $\sqrt{s} = 13$ TeV
$1.0 < p_{T}^\text{jet} < 1.5$ TeV
$G_{KK} \rightarrow hh$

**ATLAS Preliminary**
Simulation, $\sqrt{s} = 13$ TeV
$m_{jet}$ scan (lower bound)
$1.0 < p_{T}^\text{jet} < 1.5$ TeV
$G_{KK} \rightarrow hh$

**ATLAS Preliminary**
Simulation, $\sqrt{s} = 13$ TeV
AKT10 trim
AKT10 trim ISR Tagged
VR600 trim
VR600 trim ISR Tagged
$1.0 < p_{T}^\text{jet} < 1.5$ TeV
$G_{KK} \rightarrow hh$