Improved jet clustering algorithm with vertex information for multi-b final states

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TeV physics in ILC/LHC/…

Higgs  \(\rightarrow\) \(bb\) (2-jet), \(WW\) (up to 4-jet)

SUSY  \(\rightarrow\) ex. missing + \(W\) (2-jet): 4-jet in pair production

exotics

Final states with many jets (4/6/8/…)

Jet clustering is a major performance driver
Example: ZHH in ILC

HHH coupling: a key to prove Higgs mechanism

Double Higgs-strahlung: largest xsec around 500 GeV

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR.</th>
<th># events in 1 ab⁻¹</th>
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<tbody>
<tr>
<td>qqbbbbbb</td>
<td>32%</td>
<td>73</td>
</tr>
<tr>
<td>ννbbbbbb</td>
<td>9%</td>
<td>21</td>
</tr>
<tr>
<td>qqbbWW*-&gt;qqbbqqqq</td>
<td>6%</td>
<td>14</td>
</tr>
<tr>
<td>llbbbb</td>
<td>4%</td>
<td>10</td>
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<tr>
<td>qqbbWW*-&gt;qqbbqqνν</td>
<td>3%</td>
<td>7</td>
</tr>
<tr>
<td>qqbbWW*-&gt;qqbbllνν</td>
<td>3%</td>
<td>7</td>
</tr>
<tr>
<td>others</td>
<td>43%</td>
<td>97</td>
</tr>
<tr>
<td>tt -&gt; bbqqqq</td>
<td></td>
<td>~400,000</td>
</tr>
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</table>

Extremely small cross section of 0.2 fb

Background (esp. top-pair) must be very strongly suppressed

Excellent b-tag in 6-jet environment
`# of b jets’ in ZHH

# of b-jets is reduced due to mis-jet-clustering

Major problem in counting b-quarks
New idea: use vertices in jet clustering

ex. \( bbqq \) with a hard gluon with 4-jet configuration
New idea: use vertices in jet clustering

ex. \( bbqq \) with a hard gluon with 4-jet configuration

Standard jet clustering:
A and B might be combined while E separated

Jet E
(gluon jet from D)
New idea: use vertices in jet clustering

ex. $bbqq$ with a hard gluon with 4-jet configuration

Standard jet clustering:
A and B might be combined while E separated

Vertex clustering:
Two b-jets can be separated with vertex information
New idea: use vertices in jet clustering

ex. bbqq with a hard gluon with 4-jet configuration

Standard jet clustering:
A and B might be combined while E separated

Vertex clustering:
Two b-jets can be separated with vertex information
Sample in MC (2D extraction)

Red circle: MC b (before gluon emission), Star: vertex found
Triangle: Durham jets, Square: Our jet clustering
Details (a bit) of our method

1. Vertex finder
2. Secondary Muon ID
3. Vertex combination
4. Jet clustering using vertices
5. Jet flavor tagging
1. A new build-up vertex finder

High-purity vertex finder is critical in this method
Fake vertices significantly degrade performance!

Problem:
Usual vertex finders assume jet clustering is correct
... and use the jet direction to improve purity

We cannot use jet direction since we search for vertices first

Original vertex finder

- Build-up method (pairing tracks -> association)
- Not include new idea; main effort on optimization
  - mass based cuts, track combination order, etc.

For implementation details, see backup slides
2. Secondary muon ID

Secondary muons can also be used to identify heavy-flavor jets
- Secondary electrons are currently not used (because of non-trivial separation from pions)

Secondary muon criteria:
- Require hit in muon detector
- Impact parameter $> 5 \sigma, < 5 \text{ mm}$
- ECAL, HCAL energy deposit

Secondary muons are treated similarly to vertices (with muon direction as vtx. direction)
3. Vertex combination

Our jet clustering strategy:

- **Identify** heavy flavor jets using vertices
- **Separate** heavy flavor jets using vertices

  \[ \text{b \& c vertices must be combined} \]
  \[ \text{others must remain separated} \]

- **Simple combination criteria**
  - Opening angle to IP < 0.2 rad.
  - In muon case; < 0.3 rad.

---

**Wrong combination**

**True combination**
1. Combined vertices are listed as ‘jet core’
2. All particles within 0.2 rad. to the jet core are associated to the core
3. All associated jet cores and residual particles are associated with Durham y criteria

\[ y = \frac{2 \min(E_1, E_2)^2 (1 - \cos \theta_{ij})}{Q^2} \]

* Jet cores with vertices are never combined to each other (y value is set to +inf.)
4. Jet clustering using vertices

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4. Jet clustering using vertices

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y = \frac{2 \min(E_1, E_2)^2(1 - \cos \theta_{ij})}{Q^2}
\]

* Jet cores with vertices are never combined to each other (\( y \) value is set to \(+\infty\))
5. Jet flavor tagging (LCFIVertex)

Neural-net based flavor tagging package of standard ILC analysis (now improving also by us, but new version not available yet)

LCFI Collaboration: NIM A 610 (573) [arxiv:0908.3019]
Performance

1. MC number of b-jets
2. MC number of tracks from b-hadrons
3. ZHH vs. top-pair b-tagging performance
4. Effect on b-tag cut in ZHH analysis
1. MC number of b-jets

Quick view of the vertex effect

Using ZHH -> bbbbbbb events (# b-jets should be 6)

Procedure:

1. Jet clustering (Durham / Vertex)

2. Listing b-hadrons (MC information)

   Listing tracks from b-hadrons

3. Associate b-hadrons to reconstructed jets

   Jet including largest # of tracks from a b-hadron
   is associated to the b-hadron

4. Counting jets associated to b-hadrons
1. MC number of b-jets

All jets including b – 52% -> 66%
Significant improvement!
2. MC number of tracks from b-hadrons

Using

- $ZHH \rightarrow qqHH$ (H-$\rightarrow bb$: 68%, Z decays to every flavor)
- $tt \rightarrow bbcssc$ (each W decays to c and s quarks)

Effect on b-tagging at MC level

Procedure:
1. Listing b-hadron tracks with MC information
2. Counting b-hadron tracks in each jet
3. Sort jets by number of b-hadron tracks
4. See 3$^{rd}$ and 4$^{th}$ jets:
   - $qqHH$: #b=4; # b-hadron tracks should be > 0
   - $tt$: #b=2; # b-hadron tracks should be 0
2. MC number of tracks from b-hadrons

**qqhh (should be non-zero)**

**3rd jet**

**tt (should be zero)**

**3rd jet**

- **4th jet**
- **Vertex**

- **4th jet**

**tt rejection improved**

**qqHH acceptance improved**
3. ZHH vs. top-pair b-tagging performance

Study with realistic b-tagging

Using ZHH -> qqHH & tt -> bbcssc (same as 2.)

Procedure:
1. Jet clustering (Durham / Vertex)
2. Flavor tagging by LCFIVertex
   - obtain b-likeness value (0 to 1) for each jet
3. Check qqHH vs bbcssc acceptance with varying b-likeness threshold
   - Both 3rd and 4th jets and sum b-likeness over all jets are examined
3. ZHH vs. top-pair b-tagging performance

- Improvements seen in all criteria
- Improvements are particularly significant for high-purity region (signal eff. < 60%)
4. Effect on b-tag cut in ZHH analysis

Practical impact on the physics study

Using ZHH -> qqHH & tt -> bbcssc (same as 2. & 3.)

1. Jet clustering & flavor tagging
2. Determine cut value of b-likeness
   at signal efficiency = 50%
   - High purity is needed
     to suppress enormous tt background
3. Count the remaining number of events
   and scale to 1 ab$^{-1}$ luminosity
4. Effect on b-tag cut in ZHH analysis

### Vertex jet clustering

<table>
<thead>
<tr>
<th></th>
<th>No cut</th>
<th>4&lt;sup&gt;th&lt;/sup&gt; jet cut</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; jet cut</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; &amp; 4&lt;sup&gt;th&lt;/sup&gt; jet cut</th>
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</thead>
<tbody>
<tr>
<td>qqHH (H -&gt; bb)</td>
<td>8352 (73)</td>
<td>4233 (37)</td>
<td>4367 (38)</td>
<td>3163 (28)</td>
</tr>
<tr>
<td>bbcscssc</td>
<td>9930 (100000)</td>
<td>95 (960)</td>
<td>113 (1140)</td>
<td>20 (201)</td>
</tr>
</tbody>
</table>

Numbers in parentheses are at 1 ab<sup>-1</sup>

### Durham jet clustering

<table>
<thead>
<tr>
<th></th>
<th>No cut</th>
<th>4&lt;sup&gt;th&lt;/sup&gt; jet cut</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; jet cut</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; jet cut</th>
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<tbody>
<tr>
<td>qqHH (H -&gt; bb)</td>
<td>8352 (73)</td>
<td>4277 (37)</td>
<td>4382 (38)</td>
<td>3116 (27)</td>
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<tr>
<td>bbcscssc</td>
<td>9930 (100000)</td>
<td>145 (1460)</td>
<td>137 (1380)</td>
<td>29 (292)</td>
</tr>
</tbody>
</table>

30% improvement!
Summary

Vertex clustering can improve jet clustering performance for counting b-jets

Simple analysis with ZHH shows 30% improvement in reducing tt background
Backup

- ILD detector
- ZHH analysis by J. Tian
- Vertex finder details
- LCFIIVertex input variables
ILD Detector

- muon detector
- em calorimeter
- hadron calorimeter
- TPC
- vertex detector
- beam pipe

**Vertex Detector**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>inner radius</td>
<td>15 mm</td>
</tr>
<tr>
<td>outer radius</td>
<td>60 mm</td>
</tr>
<tr>
<td>impact parameter resolution</td>
<td>&lt; 5 mm (high momentum)</td>
</tr>
</tbody>
</table>

TPC + VXD are critical for flavor tagging!
Measurement of the trilinear Higgs self-coupling @ ILC

- double Higgs-strahlung (dominate at lower energy)
- WW fusion (dominate at higher energy)

\[ \sigma = 0.2 \text{ fb} \]

Only 100 events in 500 fb\(^{-1}\)
### Reduction Table

**$E_{cm} = 500$GeV, $M_H = 120$GeV**

$$\int Ldt = 2ab^{-1}$$

<table>
<thead>
<tr>
<th>normalized</th>
<th>expected</th>
<th>MC</th>
<th>pre-selection</th>
<th>probZ1+probZ2&gt;0.9</th>
<th>Emiss&gt;400</th>
<th>MissPit&lt;0.5</th>
<th>(Pimax&gt;20&amp;$\Delta$Econe&gt;10)</th>
<th>MLP_bbggqg &gt;0.2</th>
<th>MLP_bbggqgg &gt;0.3</th>
<th>MLP_qgggbb &gt;0.6</th>
<th>Bmax3&lt;0.75</th>
<th>Bmax4&lt;0.33</th>
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<tr>
<td>qqhh(qqbbbb)</td>
<td>313(138)</td>
<td>117173</td>
<td>82.0(65.1)</td>
<td>15.5(13.8)</td>
<td>13.9(13.0)</td>
<td>13.1(12.3)</td>
<td>12.7(11.9)</td>
<td>12.1(11.4)</td>
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<td>2.01</td>
<td>1.75</td>
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<td>qqbbbb</td>
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<td>qqqqH(ZZH)</td>
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</table>

$qqhh$ (with Z-like pair)
<table>
<thead>
<tr>
<th></th>
<th>normalized</th>
<th>expected</th>
<th>pre-selection</th>
<th>probZ1+probZ2&lt;0.9</th>
<th>Plmax&lt;20</th>
<th>Ecore&gt;10</th>
<th>Eva&gt;400</th>
<th>MissPt&lt;60</th>
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<tbody>
<tr>
<td>qqhh(qqqb)</td>
<td>313(138)</td>
<td>82.0(65.1)</td>
<td>66.4(51.3)</td>
<td>63.0(50.9)</td>
<td>57.6(48.7)</td>
<td>54.9(47.1)</td>
<td>33.1(29.1)</td>
<td>16.6(15.1)</td>
<td></td>
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<td>1298</td>
<td>129</td>
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</table>
put all together  
(preliminary)

\[ e^+ + e^- \rightarrow ZHH \quad m(H) = 120 \text{GeV} \quad \int Ldt = 2 \text{ab}^{-1} \]

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Modes [ZHH \rightarrow (ll)(bb)(bb)]</th>
<th>signal</th>
<th>background</th>
<th>excess (I)</th>
<th>measurement (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>[ZHH \rightarrow (ll)(bb)(bb)]</td>
<td>6.4</td>
<td>6.7</td>
<td>2.1\sigma</td>
<td>1.7\sigma</td>
</tr>
<tr>
<td>500</td>
<td>[ZHH \rightarrow (\nu\bar{\nu})(bb)(bb)]</td>
<td>5.2</td>
<td>7.0</td>
<td>1.7\sigma</td>
<td>1.4\sigma</td>
</tr>
<tr>
<td>500</td>
<td>[ZHH \rightarrow (qq)(bb)(bb)]</td>
<td>8.5</td>
<td>11.7</td>
<td>2.2\sigma</td>
<td>1.9\sigma</td>
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<tr>
<td></td>
<td></td>
<td>16.6</td>
<td>129</td>
<td>1.4\sigma</td>
<td>1.3\sigma</td>
</tr>
</tbody>
</table>

we are interested in:

A. the combined significance of ZHH excess.
B. the combined precision of measured ZHH cross section.

Overall signal excess: 3.9\sigma in 2 ab\(^{-1}\) -> not enough??
1. Vertex finding (1)

- Original jet finder based on “build-up” method
  - ZVTOP cannot be used without tuning
    - It’s designed to be used after jet clustering
    - Too many fakes – without “jet-direction” parameter

- IP tracks are firstly removed (tear-down)
- Vertices are calculated for every track-pair
  - Calculate nearest points of two helices
    - Geometric calculation for the start point
    - Minuit minimization using track error-matrices
1. Vertex finding (2)

- **Pre-selection**
  - Mass < 10 GeV (B: ~5 GeV)
  - Momentum & vertex pos: not opposite to IP
  - Vertex mass < energy of either track
    - This selection is very effective for dropping fakes
  - Vertex distance to IP > 0.3 mm
  - Track chi2 to the vertex < 25

- **Associate more tracks to passed vertices**
  - Using same criteria as above

- **Sort & select obtained vertices by probability**
  - Associated (# tracks >=3) vertices are prioritized
  - Example in next slide…
1. Vertex finding (3)

- Example: 5 vertices are found

<table>
<thead>
<tr>
<th>Vertex #</th>
<th>Tracks included</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2,3</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>2,4,5</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>3,4</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>5,6</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>6,7</td>
<td>0.5</td>
</tr>
</tbody>
</table>
### 1. Vertex finding (3)

- Example

<table>
<thead>
<tr>
<th>Vertex #</th>
<th>Tracks included</th>
<th>Probability</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1,2,3</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>4,5</td>
<td>0.4 -&gt; 0.6</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>5,6</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
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- Adopted!
- Removed!
1. Vertex finding (3)

- Example

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</tr>
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## 1. Vertex finding (3)

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Adopted!  Adopted!  Adopted!

Finally, three vertices are adopted.
In 347 bbbbbbb events:
Good = 2040, bad (not from B-semistable) = 90
2. Vertex selection & muons

• Vertex selection
  – K0 vertices are removed (mass +/- 10 GeV)
  – Vertex position > 30 mm are removed
    • Mostly s-vertices

• Secondary muons
  – Following tracks are treated as same as vertices
    • With muon hit
      – Currently > 50 MeV energy deposit
    • Impact parameter (> 5 sigma & not too much)
    • Ecal, Hcal energy deposit
Selection performance

• Vertex selection (347 bbbbbbb events)

<table>
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<tr>
<th></th>
<th>Good vtx</th>
<th>Bad vtx</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>2040</td>
<td>90</td>
<td>96%</td>
</tr>
<tr>
<td>K0 and pos cut</td>
<td>1960</td>
<td>61</td>
<td>97%</td>
</tr>
</tbody>
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Optimized for efficiency (bad contains partially bad)

• Lepton selection (347 bbbbbbb events)

<table>
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<tr>
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<th>Secondary μ</th>
<th>Other μ</th>
<th>Others</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>430</td>
<td>585</td>
<td>23168</td>
<td>1.8%</td>
</tr>
<tr>
<td>Muon hit &gt; 50 MeV</td>
<td>267</td>
<td>23</td>
<td>49</td>
<td>79%</td>
</tr>
<tr>
<td>All cuts</td>
<td>178</td>
<td>4</td>
<td>5</td>
<td>95%</td>
</tr>
</tbody>
</table>

Optimized for purity (not so good efficiency)
LCFI input variables

- LCFI input variables:
  - three categories, trained independently:
    - # vertex = 0
      - d₀ impact parameter (1)
      - d₀ impact parameter (2)
      - z₀ impact parameter (1)
      - z₀ impact parameter (2)
      - track momentum (1)
      - track momentum (2)
      - d₀ joint probability
      - z₀ joint probability
    - for # vertex = 1, >=2 (8 variables):
      - d₀ joint probability
      - z₀ joint probability
      - vertex decay length
      - vertex decay length significance
      - vertex momentum
      - pt-corrected vertex mass
      - vertex multiplicity
      - vertex probability from the fitter
  (1) and (2) indicate the most and second most significant track.

“joint probability” – probability that a track comes from the IP, computed *a priori* using the distribution of impact parameter significance (separately for d₀ and z₀), multiplied for all tracks in the jet.