STUDY OF CHARGED HIGGS BOSONS
SEARCH AT THE ILC FOR A COLLISION
ENERGY OF 1 TEV

Presentation by Christian Drews

Academic advisors:  Professor Hitoshi Yamamoto (Tohoku Uni.)
                     Professor Arno Straessner (TU Dresden)
Overview

• Full simulation study of ILC/ILD
• $m_{H^{\pm}} = 350$ GeV
• $e^+e^- \rightarrow H^+H^- \rightarrow tb\,tb \rightarrow Wbb\,Wbb$  
  $W\rightarrow 2\,\text{jets}$  
  8 jets (hadronic)

  $W\rightarrow 2\,\text{jets}$  
  6 jets + lepton

• Major background:
  • $ttH/ttZ/ttg \rightarrow ttbb$
  • $tt \rightarrow bWbW$
  • $HA \rightarrow bbbb$ (SUSY)
  • $H/A \rightarrow tt$ at resonance
  • Ignoring SUSY background

• Goal: $m_{H^{\pm}}$ measurament
Cross section

- $\sigma \approx 9$ fb with $P = (-80\%, 20\%)$ 10.4 fb
- $\mathcal{L} = 1000$ 1/fb
- $N = 9000$ $H^\pm$ events
- Assuming $\text{BR}(H^\pm \to t\bar{b}) = 90\%$
- $\text{BR}(t \to bW) = 100\%$
- $\text{BR}(W \to 2\text{jets}) = 67.6\%$
- $\text{BR}(W \to e\nu) = 10.75$
- $\text{BR}(W \to e\nu) = 10.57$
- Hadronic: 5100 events
- Semileptonic: 3200 events

Analysis Overview

- Isolated Lepton selection
- Reduce beam background by $kt$-Algorithm
- Jet-clustering and flavor tagging (LCFIplus)
- Calculating neutrino four-momentum (only semi-leptonic)
- Jet-pairing
- Extracting signal and background mass shape
- Added fit to find Higgs-mass
kt Algorithm
(beam background removal)

• Calculate the distance between to all tracks
  \[ d_{ij} = \min(p_{T_i}^2, p_{T_j}^2) \frac{\Delta R_{ij}}{R} \]
  
  with \( \Delta R_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \)
  
  \( \eta \) pseudo rapidity, \( \phi \) azimuth

• Find smallest \( d_{ij} \)

• If \( d_{ij} < d_{iB} = p_{T_i}^2 \) merge tracks, if not remove Track (B: Beam)
  – Remove particles that are closer to the beam than to the closest track \( i \)

• Continue to step one until there are only the requested number of jets
Find R for kt-Algorithm

Reconstructed $H^+$ and $H^-$ mass with realistic clustering and pairing with generator information
Reconstructed $H^+$ and $H^-$ mass with realistic clustering and pairing with generator information
Chi$^2$ - Jet Pairing (hadronic)

<table>
<thead>
<tr>
<th></th>
<th>w/o overlay</th>
<th>R: 1.3</th>
<th>with overlay</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-tag efficiency</td>
<td>44.6</td>
<td>42.5</td>
<td>38.0</td>
</tr>
<tr>
<td>Clustering works well</td>
<td>50.7</td>
<td>49.4</td>
<td>40.2</td>
</tr>
<tr>
<td>Pairing works</td>
<td>27.8</td>
<td><strong>25.0</strong></td>
<td>17.2</td>
</tr>
</tbody>
</table>

$$
\chi^2 = \left| \frac{(m_{j1j2j3j4})^2 - (m_{j5j6j7j8})^2}{2\sigma^2_{H^+}} \right| + \left( \frac{m_{j2j3j4} - M_t}{\sigma_t} \right)^2 \\
+ \left( \frac{m_{j6j7j8} - M_t}{\sigma_t} \right)^2 + \left( \frac{m_{j3j4} - M_W}{\sigma_W} \right)^2 + \left( \frac{m_{j7j8} - M_W}{\sigma_W} \right)^2
$$
Lepton Selection

- Using the IsolatedLeptonTaggingProcessor
  - From MarilnReco
  - Based on MVA

- Open task: reduce false Lepton Tag in hadronic Channel
  - With event shape or b-tag
  - But actually the pairing efficiency is not affected

<table>
<thead>
<tr>
<th></th>
<th>Total (%)</th>
<th>w/o tau (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Tag</td>
<td>60.3</td>
<td>90.4</td>
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<tr>
<td>Correct Tag</td>
<td>60.0</td>
<td>90.0</td>
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<tr>
<td>False Lepton Tagged</td>
<td>0.3</td>
<td>0.4</td>
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<tr>
<td>Electron</td>
<td>29.5</td>
<td>89.4 (w/o tau and myon)</td>
</tr>
<tr>
<td>Myon</td>
<td>30.3</td>
<td>90.5 (w/o tau and electron)</td>
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<tr>
<td>False Lepton Tag in hadronic</td>
<td>2.1</td>
<td></td>
</tr>
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</table>
Neutrino Four-vector

- **Method 1: Missing-Energy-Method (MEM)**

  \[ p_{\text{vis}} = \sum_{i=1}^{N_{\text{PF}}\text{O}} p_i \quad p_{\text{CMS}} = (1000, 0, 0, 1000 \cdot \sin(0.014/2)) \]

  \[ p_{\nu,\text{MEM}} = (p_{\text{CMS}} - p_{\text{vis}}) \]

- **Should I Sum pfos or jets? LCFIplus doesn't cluster all particles to jets?**

- **Method 2: Neutrino-Direction-Method (NDM)**

  - Using the Direction of Missing-Energy-Method and calculation the Energy by fixing W-Mass

  \[ E_{\nu,\text{NDM}} = \frac{m_W^2}{E_i(1 - \alpha)} \quad \alpha = \frac{p_{\nu,\text{MEM}} \cdot p_i}{|p_{\nu,\text{MEM}}| |p_i|} \]

  \[ p_{\nu,\text{NDM}} = \left( E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{p_{\nu,\text{MEM}}}{|p_{\nu,\text{MEM}}|} \right) \]
Neutrino Four-vector

• Method 1: Missing-Energy-Method (MEM)
  
  \[ p_{\text{vis}} = \sum_{i=1}^{N_{PFO}} p_i \quad p_{\text{CMS}} = (1000, 0, 0, 1000 \cdot \sin(0.014/2)) \]
  
  \[ p_{\nu,\text{MEM}} = (p_{\text{CMS}} - p_{\text{vis}}) \]

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  \[ E_{\nu,\text{NDM}} = \frac{m_W^2}{E_i (1 - \alpha)} \quad \alpha = \frac{\vec{p}_{\nu,\text{MEM}} \cdot \vec{p}_i}{||\vec{p}_{\nu,\text{MEM}}|| ||\vec{p}_i||} \]

  \[ p_{\nu,\text{NDM}} = (E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{\vec{p}_{\nu,\text{MEM}}}{||\vec{p}_{\nu,\text{MEM}}||}) \]

  Better Idea: only use missing transversal Energy and direction
Higgs mass reconstructed with Jet pairing

- Chi² minimization method

\[
\chi^2 = \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_{H^+}^2} \right| + \left( \frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2 \\
+ \left( \frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + \left( \frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + \left( \frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2
\]

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Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV

H1 (hadronic) and H2 (leptonic) mass

\[E_{\nu,\text{MEM}}\]

- \(m_{\text{H2}}\)
- \(m_{\text{H1}}\)

H1 and H2 mass (8 jets)

Hadronic / 8 jets

- \(m_{\text{H2}}\)
- \(m_{\text{H1}}\)
Before optimizing Chi^2 pairing

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Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV

H1 (hadronic) and H2 (leptonic) mass (ny 4-momentum from gen)

- $E_{\nu,\text{gen}}$
- $m_{H1}$
- $m_{H2}$

H1 (hadronic) and H2 (leptonic) mass (ny E from $M_W$)

- $E_{\nu,\text{NDM}}$
- $m_{H1}$
- $m_{H2}$

H1 (hadronic) and H2 (leptonic) mass

- $E_{\nu,\text{MEM}}$
- $m_{H1}$
- $m_{H2}$

H1 and H2 mass (8 jets)

- Hadronic / 8 jets
- $m_{H1}$
- $m_{H2}$
Neutrino Four-vector

Neutrino direction from Generator

\[ E_{\nu,\text{MEM}} \]

\[ E_{\nu,\text{NDM}} \]

\[ E_{\nu,\text{NDM}}' \]
### Cuts (leptonic)

<table>
<thead>
<tr>
<th>Cut</th>
<th>Signif</th>
<th>Effi</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest 4 b-tags &gt; 2.45</td>
<td>13.66</td>
<td>0.80</td>
<td>0.05</td>
</tr>
<tr>
<td>evis6 &lt; 1000.0</td>
<td>14.65</td>
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<td>evis6 &gt; 560.0</td>
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<td>0.06</td>
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<tr>
<td>chi2H &lt; 31.0</td>
<td>15.50</td>
<td>0.78</td>
<td>0.06</td>
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<tr>
<td>y45 &gt; 0.001</td>
<td>19.80</td>
<td>0.77</td>
<td>0.10</td>
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<tr>
<td>chi2t1 + chi2t2 &lt; 11.0</td>
<td>19.76</td>
<td>0.77</td>
<td>0.10</td>
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<tr>
<td>principleThrust &lt; 0.825</td>
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<td>0.77</td>
<td>0.10</td>
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<tr>
<td>minorThrust &gt; 0.12</td>
<td>27.83</td>
<td>0.71</td>
<td>0.22</td>
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<tr>
<td></td>
<td>cosThrustAxis</td>
<td>&lt; 0.915</td>
<td>27.83</td>
</tr>
<tr>
<td>missMass &gt; -160.0</td>
<td>28.58</td>
<td>0.69</td>
<td>0.24</td>
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<tr>
<td>missPt &lt; 240.0</td>
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<td>missPz &lt; 200.0</td>
<td>28.98</td>
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<td>0.26</td>
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<tr>
<td>One Isolated Lepton</td>
<td>35.30</td>
<td>0.40</td>
<td>0.63</td>
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### Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV

<table>
<thead>
<tr>
<th>Cuts (hadronic)</th>
<th>h2dm_h</th>
<th>2f_h</th>
<th>ttz</th>
<th>ttbb</th>
<th>6f_ttbar_sl</th>
<th>6f_ttbar_h</th>
<th>4f_h</th>
<th>tth_sl</th>
<th>tth_h</th>
<th>tth_hnobb</th>
<th>h2dm_slwp</th>
<th>h2dm_slwm</th>
<th>Signif</th>
<th>Effi</th>
<th>Purity</th>
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<td>56666668</td>
<td>8355</td>
<td>2059</td>
<td>219456</td>
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<td>2457</td>
<td>2.06</td>
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<td>Highest 4 b-tags&gt;2.7</td>
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<td>18533</td>
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<td>677</td>
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<tr>
<td>evis8&lt;1080.0</td>
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<td>4450</td>
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<td>52</td>
<td>1776</td>
<td>1765</td>
<td>18.50</td>
<td>0.76</td>
<td>0.09</td>
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<tr>
<td>evis8&gt;770.0</td>
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<td>791</td>
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<td>6870</td>
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<td>357</td>
<td>609</td>
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<td>1335</td>
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<td>chi2H&lt;23.0</td>
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<td>693</td>
<td>781</td>
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<td>6707</td>
<td>885</td>
<td>354</td>
<td>608</td>
<td>42</td>
<td>1338</td>
<td>1322</td>
<td>22.39</td>
<td>0.75</td>
<td>0.13</td>
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<tr>
<td>chi2t&lt;8.0</td>
<td>3804</td>
<td>9941</td>
<td>691</td>
<td>781</td>
<td>3220</td>
<td>6701</td>
<td>885</td>
<td>352</td>
<td>607</td>
<td>42</td>
<td>1330</td>
<td>1316</td>
<td>22.41</td>
<td>0.75</td>
<td>0.13</td>
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<tr>
<td>y67&gt;0.00025</td>
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<td>538</td>
<td>570</td>
<td>618</td>
<td>969</td>
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<td>245</td>
<td>595</td>
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<td>1013</td>
<td>1004</td>
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<td>principleThrust&lt;0.82</td>
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<td>372</td>
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<td>325</td>
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<td>47</td>
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<tr>
<td>minorThrust&gt;0.13</td>
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<td>&lt;0.925</td>
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<td>missMass&gt;-130.0</td>
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<td>239</td>
<td>770</td>
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<td>138</td>
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<td>880</td>
<td>875</td>
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<td>234</td>
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<td>760</td>
<td>47</td>
<td>115</td>
<td>372</td>
<td>25</td>
<td>741</td>
<td>746</td>
<td>40.94</td>
<td>0.67</td>
<td>0.49</td>
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<tr>
<td>Isolated Lepton Veto</td>
<td>3380</td>
<td>97</td>
<td>231</td>
<td>204</td>
<td>96</td>
<td>753</td>
<td>47</td>
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<td>306</td>
<td>291</td>
<td>44.37</td>
<td>0.66</td>
<td>0.58</td>
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</tbody>
</table>

27.06.2017
Boosted Decision Tree (Input)

- For further Background reduction
- Here for hadronic
- Trained only on main background after static cuts

27.06.2017  Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV
Boosted Decision Tree

- For further Background reduction
- Here for hadronic
- Trained only on main background after static cuts
- About 1.5σ gain
- Its quite difficult to apply result of TMVA to cuts

![Cut efficiencies and optimal cut value](image)

- For 1000 signal and 1000 background events the maximum $S/(S+B)$ is 23.96 when cutting at -0.37
- About 1.5σ gain
- Its quite difficult to apply result of TMVA to cuts
Mass distribution of Background

- BG and Signal with failed pairing has similar shape
- Fitting with Gauß-distribution
Mass fit

- Fit correctly paired Signal with Breit-Wigner or Gauß-distribution
- Gauß – good tail agreement
- Breit-Wigner – good agreement at the tip
- For mass extraction tip is essential -> Breit-Wigner in favor
Mass fit for different Higgs-mass
Mass fit for different Higgs-mass

- Linear regression for 5 different Higgs-masses
- Calculation the generated mass for a testing sample
- Problem: Is it linear or dominated by fitting effects?
- Expected Resolution < 1 GeV
Plan

• Toy Monte Carlo Study
• Add pt Method for neutrino four momentum
• Do fitting for semi-leptonic mode
• Goal:
  • mass fit -> mass resolution measurement
  • Detection efficiency
    -> cross section times branching ratio
• Bonus: (most probable imposibale)
  • Research how to distinguish H+ and H-
  • Study of CP-violation measurement
Backup
Cross section

- $\sigma(\tan\beta)$ const. on tree-level
- 1 TeV below maximum of $\sigma$

| Scen. | $\sqrt{s}$ | $t_\beta$ | $\mu$ | $M_{H^\pm}$ | $M_{Q,U,D}$ | $M_{L,E}$ | $|A_{t,b,\tau}|$ | $M_1$ | $M_2$ | $M_3$ |
|-------|-------------|-------------|-------|-------------|-------------|-------------|-----------------|-------|-------|-------|
| S1    | 1000        | 7           | 200   | 300         | 1000        | 500         | 1500 + $\mu/t_\beta$ | 100   | 200   | 1500  |
| S2    | 800         | 4           | 200   | 300         | 1000        | 500         | 1500 + $\mu/t_\beta$ | 100   | 200   | 1500  |

Source: Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis
Cross section

\[ e^+e^- \rightarrow H^+H^- \]

| Scen. | $\sqrt{s}$ | $t_\beta$ | $\mu$ | $M_{H^\pm}$ | $M_{Q, U, D}$ | $M_{L, E}$ | $|A_{t, b, \tau}|$ | $M_1$ | $M_2$ | $M_3$ |
|-------|------------|-----------|------|------------|--------------|-----------|--------|------|------|------|
| S1    | 1000       | 7         | 200  | 300        | 1000         | 500       | 1500 + $\mu/t_\beta$ | 100  | 200  | 1500 |
| S2    | 800        | 4         | 200  | 300        | 1000         | 500       | 1500 + $\mu/t_\beta$ | 100  | 200  | 1500 |

Source: **Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis**
Boosted Decision Tree (Input)

Input variable: cosHH_reco

Input variable: cosThetabb

Input variable: costt

Input variable: m_HH

Input variable: principleThrust

Input variable: majorThrust

Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV
Boosted Decision Tree

- **Input variable: m_{tt}**
  - Signal
  - Background

- **Input variable: m_{bb}**

- **Input variable: \text{costhrustAxis}**

- **Input variable: \chi^2**

- **Input variable: dEHH**

- **Input variable: dpbb**

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27.06.2017

Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV
Boosted Decision Tree

**Input variable: minorThrust**

<table>
<thead>
<tr>
<th>minorThrust</th>
<th>0.15</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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</tbody>
</table>

**Input variable: b_jet0+b_jet1**

<table>
<thead>
<tr>
<th>b_jet0+b_jet1</th>
<th>1.55</th>
<th>1.6</th>
<th>1.65</th>
<th>1.7</th>
<th>1.75</th>
<th>1.8</th>
<th>1.85</th>
<th>1.9</th>
<th>1.95</th>
<th>2</th>
</tr>
</thead>
</table>

**Input variable: b_jet2+b_jet3**

<table>
<thead>
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<th>b_jet2+b_jet3</th>
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<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2</th>
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**Input variable: y34**

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</table>
Analysis Strategy – Beam Background

• In average 2.7 beam background events per bunch crossing
• In these samples old number of 4.1 events per bunch crossing
• Has major influence on jet clustering
• Use kt-algorithm from fastjet package to reduce background
  • R: Generalized radius of jets
  • Vary R to optimal mass resolution
• Use Satoru Jetfinder for clustering
Fastjet Finder – kt Algorithm (beam background removal)

• Calculate the distance between to all tracks

\[ d_{ij} = \min(p_{T_i}^2, p_{T_j}^2) \frac{\Delta R_{ij}}{R} \]

\[ \Delta R_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]

\( \eta \) pseudo rapidity, \( \phi \) azimuth

• Find smallest \( d_{ij} \)

• If \( d_{ij} < d_{iB} = p_{Ti}^2 \) merge tracks, if not remove Track (B: Beam)
  – Remove particles that are closer to the beam than to the closest track

• Continue to step one until there are only the requested number of jets
Choose R for $k_t$ algorithm

Durham_8: w/o correction
Durham_8_WoOL: overlay removed by generator information
Durham_8_13: $R = 1.3$
Choose R for kt algorithm

- For W mass R = 1.0 seems best
- For H mass R = 1.3 seems best
- Maybe b-jets have a wider spread
- I will continue with 1.3
Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV
Analysis Strategy - Chi\(^2\)

- Choose \(\sigma\) from pairing with generator information
- Optimize for \(c\) for maximal pairing efficiency

\[
\chi^2 = c_H \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma^2_{H^+}} \right| + c_t \left( \frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2
+ c_t \left( \frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + c_w \left( \frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + c_w \left( \frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2
\]

\(\sigma_H = \sigma_t = 80\text{ GeV}, \ \sigma_W = 48\text{ GeV}\)
Analysis Strategy - Chi$^2$

- Choose $\sigma$ from pairing with generator information
- Optimize for $c$ for maximal pairing efficiency

$$\chi^2 = c_H \left| \frac{(m_{j1j2j3j4})^2 - (m_{j5j6j7j8})^2}{2\sigma_{H+}^2} \right| + c_t \left( \frac{m_{j2j3j4} - M_t}{\sigma_t} \right)^2$$

$$+c_t \left( \frac{m_{j6j7j8} - M_t}{\sigma_t} \right)^2 + c_w \left( \frac{m_{j3j4} - M_W}{\sigma_W} \right)^2 + c_w \left( \frac{m_{j7j8} - M_W}{\sigma_W} \right)^2$$

$$+c_{\cos \theta_{HH}} \left( \frac{1 - \cos \theta_{HH}}{\sigma_{\cos \theta_{HH}}} \right)^2 + c_{\theta_{HH}} \left( \frac{\theta_{HH}}{\sigma_{\theta_{HH}}} \right)^2 + c_E \left( \frac{E_{H-} - E_{H+}}{\sigma_E} \right)^2 + c_p \left( \frac{p^2 - p_{H+}^2}{\sigma_p} \right)^2$$
Analysis Strategy - Chi$^2$

- First test optimization for $c_H$ and $c_{\cos}$
- $c_H \sim 0.2 / c_{\cos} \sim 30 \ (\sigma_{\cos} = 1)$
- Pairing efficiency 25 -> 27.5 %

$$\chi^2 = c_H \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_{H+}^2} \right| + c_t \left( \frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2
+ c_t \left( \frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + c_w \left( \frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + c_w \left( \frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2
+ c_{\cos \theta_{HH}} \left( \frac{1 - \cos \theta_{HH}}{\sigma_{\cos \theta_{HH}}} \right)^2$$
Analysis Strategy - $\chi^2$