Determination of $\tan \beta$

at a Future $e^+e^-\text{LC}$

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Outline

• Introduction

• $b\bar{b}A \rightarrow b\bar{b}b\bar{b}$ simulation

• High luminosity: 2000 fb$^{-1}$

• $HA \rightarrow b\bar{b}b\bar{b}$ event rate

• $H$ and $A$ width from $HA \rightarrow b\bar{b}b\bar{b}$

• New aspect: $H^+H^- \rightarrow t\bar{t}b\bar{b}$

• Conclusions
Introduction

- Framework:
  Two-Higgs Doublet Model or MSSM.

- Production and Decay of A, h, H, and H±.

- Considered reactions for TESLA:
  strong dependence on $\tan \beta$.

- Extrapolation $b\bar{b}A \rightarrow b\bar{b}b\bar{b}$ for $100 < m_A < 200$ GeV.

- Estimate of $HA \rightarrow b\bar{b}b\bar{b}$ event rate.

- Estimate of H and A width determination.

- Estimate of charged Higgs bosons branching ratio and decay width.
**b-tagging**

Experimental potential depends strongly on the b-tagging performance.

Hadronic events $e^+e^- \rightarrow q\bar{q}$ (5 flavors).

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Efficiency: Ratio of simulated $b\bar{b}$ events after the selection to all simulated $b\bar{b}$ events.

Purity: Ratio of simulated $b\bar{b}$ events after the selection to all selected $q\bar{q}$ events.

A. Sopczak
Simulated Higgs boson mass: 100 GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>bbA</th>
<th>qq</th>
<th>WW</th>
<th>eWν</th>
<th>tt</th>
<th>ZZ</th>
<th>eeZ</th>
<th>hA</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in 1000)</td>
<td>50</td>
<td>6250</td>
<td>3500</td>
<td>2500</td>
<td>350</td>
<td>300</td>
<td>3000</td>
<td>50</td>
<td>16000</td>
</tr>
<tr>
<td>After Presel.</td>
<td>73%</td>
<td>20991</td>
<td>7481</td>
<td>0</td>
<td>89983</td>
<td>10278</td>
<td>145</td>
<td>12665</td>
<td>141544</td>
</tr>
</tbody>
</table>

Simulated hA rate corresponds to twice the luminosity (maximum cross section in general Two-Higgs Doublet Model).

A. Sopczak
Signal and Background

Events/ 500 fb$^{-1}$ vs Efficiency

A. Sopeczak
Interference: $b\overline{b}A \ hA \rightarrow b\overline{b}b\overline{b}$

Expectation before event selection:

$\sigma_{bbA} \equiv \sigma(e^+e^- \rightarrow bbA \rightarrow b\overline{b}b\overline{b})$

$\sigma_{hA} \equiv \sigma(e^+e^- \rightarrow hA \rightarrow b\overline{b}b\overline{b})$

$\sigma_{bbA+hA} \equiv \sigma(e^+e^- \rightarrow bbA, hA \rightarrow b\overline{b}b\overline{b})$

$\sigma_{\text{interf}} = \sigma_{bbA+hA} - \sigma_{bbA} - \sigma_{hA}$.

For $m_b = 4.62$ GeV:

$\sigma_{bbA} = 1.83 \pm 0.01$ fb

$\sigma_{hA} = 36.85 \pm 0.10$ fb

$\sigma_{bbA+hA} = 39.23 \pm 0.12$ fb

$\sigma_{\text{interf}} = 0.55 \pm 0.16$ fb

Positive interference,

reduction in statistical error.

A. Sopczak
**Interference: b¯bA hA → b¯b¯b**

Expectation after event selection:

100 b¯bA → b¯b¯b events

2 ± 1 hA → b¯b¯b events.

Maximum interference magnitude:

\[(10 + 1.4)^2 - 100 - 2 \approx 28\]

Similar ratio of interference to signal 30% before and after event selection.

Interference events:

background-like: small systematic error.
signal-like: large systematic error.

Solution: fit signal and background to data for various \(\tan \beta\).

Another systematic error is the running b-mass.

Higher-order corrections should be very precisely known by the time the LC is constructed.

A. Sopczak
b\bar{b}A Results for 500 fb$^{-1}$

For $\tan \beta = 50$ and $m_A = 100$ GeV:

$\Delta \tan \beta / \tan \beta = 0.07$.

$$\Delta \tan^2 \beta / \tan^2 \beta = \Delta N_{\text{signal}} / N_{\text{signal}}$$

$$= \sqrt{N_{\text{signal}} + N_{\text{background}} / N_{\text{signal}}} = 0.14.$$  

Smaller values of $\tan \beta$, the sensitivity decreases rapidly. $5\sigma$ signal detection for $\tan \beta = 35$.

MSSM: $b\bar{b}h$ would double the number of signal events and have the same $\tan \beta$ dependence:

$$\Delta \tan^2 \beta / \tan^2 \beta \sim \sqrt{300/200} \approx 0.085$$

For $\tan \beta = 50$ and $m_A = m_h = 100$ GeV:

$\Delta \tan \beta / \tan \beta = 0.04$.

(For heavier A, $b\bar{b}H$ will contribute).

Experimental challenge:

at 10% efficiency, $\Delta \tan \beta / \tan \beta < 0.05$

requires $\Delta \epsilon / \epsilon < 0.1$, thus $\Delta \epsilon < 1\%$.

A. Sopczak
$e^+e^- \rightarrow b\bar{b} \rightarrow b\bar{b}A$ Rate

At 100 GeV: 1000 events.
At 200 GeV: 200 events.

A. Sopczak
b\bar{b}A Results for 2000 fb$^{-1}$

\[ \Delta \tan\beta / \tan\beta \]

\[ m_A = 200 \text{ GeV} \]

\[ 150 \text{ GeV} \]

\[ 100 \text{ GeV} \]

L = 2000 fb$^{-1}$

bbA

A. Sopczak
HA → b¯b b¯b Event Rate

Assume b-tagging purity 80% per b¯b pair, thus 40% signal efficiency.
For b¯b b¯b: 16% efficiency.

Further reduction: kinematic event selection:
final efficiency 10%, and negligible background.

Small tan β: constant MSSM cross section and large variation of branching fraction.

Typical expected signal rate for 2000 fb⁻¹ and \( m_A = m_H = 200 \) GeV
for \( \tan \beta = 5 \): 500 events.
\[ \Delta \tan \beta / \tan \beta \approx 0.01 \]

Nice overlap with b¯bA results.
H and A width from

\[ \text{HA} \rightarrow b\bar{b}b\bar{b} \]

Assumption: \( 5 \pm 0.5 \) GeV detector resolution.

Reconstruction of mean H and A widths from \( b\bar{b} \)-mass.

There are two \( b\bar{b} \) masses per event.

Wrong jet-jet pairings: 25%.

Available statistics for mass reconstruction:

1.5 \( \text{HA} \rightarrow b\bar{b}b\bar{b} \) rate.

Determination of intrinsic Higgs width by convolution with detector resolution.

\[ 0.5(\Gamma_H + \Gamma_A) = 12.5 \pm 0.54 \text{ GeV}, \]

dominated by error on detector resolution.

\[ \Delta \tan \beta / \tan \beta < 0.02 \text{ for } \tan \beta = 55. \]

A. Sopczak
\[
e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}
\]

- 500 GeV and 10 fb\(^{-1}\),
  the charged Higgs can be reconstructed


- 800 GeV and 1000 fb\(^{-1}\),
  high precision reconstruction,

  M. Battaglia, A. Ferrari, A. Kiiskinen, T.M. Ki,

- Sensitivity for 500 GeV and 1000 fb\(^{-1}\),
  for a 200 GeV charged Higgs boson mass:
  uncertainty about 0.5 GeV.

- Very similar uncertainty as for the HA.

- Similar precision on tan \(\beta\)
  as from HA production
  \[
  \Delta \tan \beta / \tan \beta \approx 0.02 \text{ for } \tan \beta = 5.
  \]

A. Sopczak
Further information on $\tan \beta$

- $tbH^\pm \rightarrow tb\tau\nu$
  

- A width from $b\bar{b}A \rightarrow b\bar{b}b\bar{b}$

- Scalar taus (E. Boos et al.)
Conclusions

Experimental challenges:

• High luminosity needed.

• Best possible b-tagging performance.

• Precision detector resolution measurement.

• Combined analyses, e.g. Fit of all b$\bar{b}$b$\bar{b}$ processes as function of tan $\beta$.

• Precision determination of signal efficiency.

• Precision cross section and decay width meas.

• b$\bar{b}$A $\rightarrow$ b$\bar{b}$b$\bar{b}$

• HA $\rightarrow$ b$\bar{b}$b$\bar{b}$

• H$^+$H$^-$ $\rightarrow$ t$\bar{t}$b$\bar{t}$

TESLA: Precision determination of tan $\beta$ with different independent complementary methods.

A. Sopczak