Study of

Higgs couplings to leptons
and
Higgs CP properties
at the ILC

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for the
International Large Detector
concept group
ICHEP 2018, Seoul
International Linear Collider

e^+ e^- collisions @ 250 GeV
beam polarisation:
  e^- 80%, e^+ 30%
luminosity \( \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  0.5 M Higgs in \( \sim 11 \) years

linear accelerator
  → future energy upgrades possible, if and when needed

talk by J. Reuter

presently under in-depth consideration by the Japanese Government
ILC 250 physics program

2 $\text{ab}^{-1}$ (0.5 ZH events) over ~11 years

electro-weak symmetry breaking

- comprehensive and precise study of Higgs sector
  talk by T. Ogawa
- electro-weak processes
  LEP2 + beam polarisation
  + higher energy
  + better detectors
  + 1000 times more data
  talk by S. Bilokhin

→ indirect probe of BSM physics

direct searches for BSM particles

- profit from trigger-less readout, efficiency for lower energy signatures
  talks by M. Berggren, Y. Wang

Phys. Rev. D94 (2016) no.11, 113002

D. Jeans @ ICHEP18
International Large Detector
one of two detector concepts being developed for ILC

high precision detector optimised for particle flow reconstruction

silicon, gaseous tracking systems
\[ \sigma_{d_0} \rightarrow 5 \, \mu m \]
\[ \sigma_{p_T/p_T} \rightarrow 2 \times 10^{-5} \, p_T \]

high granularity calorimetry
jet energy resolution 3-4%
test the lepton Yukawa – mass relation

Full ILC Program
250 fb\(^{-1}\) @ 250 GeV
500 fb\(^{-1}\) @ 500 GeV
1000 fb\(^{-1}\) @ 1000 GeV

arXiv:1310.0763

Phys. Rev. D 97, 053003

2HDM-X example

composite H example

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Higgs boson coupling to $\tau \tau$

*all studies with full simulation of ILD, all background processes, realistic reconstruction*

$$e^+ e^- \rightarrow H Z \rightarrow \tau \tau + (e e, \mu \mu, q q)$$

isolated narrow jets,

- 1 or 3 charged particles
- total jet charge $\pm 1$
- invariant mass $< 2 \text{ GeV/c}^2$

various cuts to reduce backgrounds

**colinear** approximation to estimate momenta of $\nu$ from $\tau$ decay

**final multivariate analysis** [BDT]

**expected precision at ILC on**

$$\sigma (h) \cdot \text{BR} (h \rightarrow \tau \tau):$$

- 1.2 % [ ILC250 / 2 ab$^{-1}$]
- 1.0 % [ + ILC500 / 4 ab$^{-1}$]
Higgs boson coupling to $\mu\mu$

**Challenge:** small sample due to tiny BR ($h \rightarrow \mu\mu$) $\sim 2 \times 10^{-4}$ [in SM]

$e^+ e^- \rightarrow H Z$

$\rightarrow \mu\mu q\bar{q}$

$\rightarrow \mu\mu \nu\nu$

Pair of prompt, isolated, oppositely charged, well-measured, $\mu$ candidates

cuts on “Z”, $\mu$ angles

Multivariate analysis to suppress backgrounds

**Key:** excellent momentum resolution

$dp_T/p_T \rightarrow 2 \times 10^{-5} p_T$

arXiv:1801.07966
$h \rightarrow \mu \mu :$ estimating sensitivity

expected relative precision on $\sigma (h) \cdot BR (h \rightarrow \mu \mu)$ at ILC:

- $20\% \ [ \text{ILC250 / 2 ab}^{-1}]$
- $15\% \ [ \text{+ ILC500 / 4 ab}^{-1}]$

some sensitivity even to this very rare decay mode
does Higgs $\to \tau \tau$ conserve CP?

*baryogenesis at E-W scale?*

\[ h_{125} = \cos \psi_{\text{CP}} h_{\text{CPeven}} + \sin \psi_{\text{CP}} A_{\text{CPodd}} \]

\[ g \bar{f} \left( \cos \psi_{\text{CP}} + i \gamma_5 \sin \psi_{\text{CP}} \right) f h_{125} \]

$h$ is a spin 0 state:

\[ |f \bar{f}| = |↑↓⟩ + e^{2i\psi_{\text{CP}}} |↓↑⟩ \]

\[ [\psi_{\text{CP}} = 0 \quad \text{CP even,} \quad \pi/2 \quad \text{CP odd}] \]

"polarimeter" - estimator of spin direction from $\tau$ decay products

\[ a \rightarrow b \]

$\Delta \phi = \phi^+ - \phi^-$

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full $\tau$ reconstruction

in Higgs-strahlung $e^+ e^- \rightarrow ZH, \ H \rightarrow \tau \tau$
  visible Z decay:
  $\rightarrow \tau$ production vertex
  $\rightarrow p_\tau$ of di-$\tau$ system

excellent vertex detector:
  $\rightarrow$ trajectory of $\tau$ decay products
  $\rightarrow$ plane of $\tau$ momentum

6 constraints to solve for
6 unknowns / event with hadronic $\tau$ decays
  $2 \times$ neutrino 3-momenta

$polarimeter$ $\rightarrow$ spin estimator from decay products’ momenta

optimal information on $\tau$ momentum and spin
relies on excellent detector performance:
impact parameter, tracking, photon and jet measurement
**CP in h → ττ: sensitivity**

\[ \tau^\pm \rightarrow \pi^\pm \nu \quad [\text{B.R. 11%}] \]
\[ \tau^\pm \rightarrow \pi^\pm \pi^0 \nu \quad [\text{B.R. 26%}] \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^+ \rightarrow \pi^+ \nu )</td>
<td>11%</td>
<td>4.3 deg</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \pi^0 \nu )</td>
<td>26%</td>
<td></td>
</tr>
</tbody>
</table>

**Golden events**

**Silver events**

**Signal:** Phases of \( \Delta \phi \) distribution sensitive to CP

**Backgrounds:** Consistent with flat distribution

**Pseudo-experiments:** Simultaneous likelihood fit to \( \Delta \phi \) distributions in all channels

10k pseudo-exps.

**Fitted phase**

**With 2 ab\(^{-1}\) @ ILC250,** measure \( \psi_{CP} \) to 75 mrad (4.3 deg)

Summary

International Linear Collider will enable comprehensive set of Higgs measurements, shining light on physics beyond the SM

ILC250 stage:
\[ \sigma ( h ) \cdot BR ( h \rightarrow \tau \tau ) \text{ with a precision of } 1.2\% \quad [1.0\% \text{ w/ ILC500}] \]
\[ \rightarrow \text{ several times more precise than HL-LHC projections} \]

\[ \sigma ( h ) \cdot BR ( h \rightarrow \mu \mu ) \text{ with a precision of } 20\% \quad [15\% \text{ w/ ILC500}] \]
\[ \rightarrow \text{ statistically limited} \]
\[ \rightarrow \text{ ILC250+500 similar level as HL-LHC projections} \]

CP mixing in \( h \rightarrow \tau \tau \) with a precision of 75 mrad
\[ \rightarrow \text{ baryogenesis at electro-weak scale?} \]
backup
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CP properties of HZZ coupling

decay distributions in
\(e^+ e^- \rightarrow H \ (Z \rightarrow f f)\)

\[ \mathcal{L}_{ZZH} \sim M_Z^2 \left( \frac{1}{v} + \frac{a_z}{\Lambda} \right) Z^\mu Z^\nu H + \frac{b_z}{2\Lambda} Z^{\mu\nu} H + \frac{\tilde{b}_z}{2\Lambda} \tilde{Z}^{\mu\nu} H \]

\(ZH \rightarrow l^+ l^- H\), \(\sqrt{s} = 250\text{GeV}\)

Full ILD simulation
reconstruct $Z \rightarrow (e e / \mu \mu / \text{jets}) + 2 \times (1\text{-prong tau jets})$

simple preselection

some distributions after reconstruction and pre-selection:

group events according to sensitivity to CP
quality of event reconstruction
background contamination
longitudinal polarimeter components