Measuring the branching ratio of $h \rightarrow \mu^+ \mu^-$ at the ILC

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Introduction

Discovery of Higgs-like boson at the LHC
--> Last particle of SM? Or beyond SM?

Goal: model-independent determination of EWSB sector with precise measurements
- mass-coupling relation
- any deviation shows the existence of BSM

ILC

JHEP 08 (2016) 045

arXiv: 1506.05992 [hep-ex]
The International Linear Collider

- $e^+ e^-$ collider, $E_{CM} = 250 - 500$ GeV (upgradable to 1 TeV)
- polarized beam ($e^- : 0.8$, $e^+ : \geq 0.3(0.6)$)
- clean environment, known initial state
Key Point

LHC: all measurements are $\sigma \times BR$
ILC: $\sigma \times BR$ measurements + $\sigma$ measurement
Detector Concept at the ILC

ILD (International Large Detector)

Tracker: Vertex, TPC
Calorimeter: ECAL, HCAL
3.5T magnetic field
Yoke for muon, Forward system

Requirements:
- Impact parameter resolution
  \[ \sigma_{r\phi} < 5 \oplus \frac{10}{p \sin^{3/2} \theta} \text{ \mu m} \]
- Momentum resolution
  \[ \sigma_{1/p_T} < 2 \times 10^{-5} \text{ GeV}^{-1} \]
- Energy resolution
  \[ \sigma_E/E = 3 \text{ - } 4\% \]
In This Talk: $h \to \mu^+\mu^-$

- Challenging analysis: tiny branching ratio \( \text{BR}(h \to \mu^+\mu^-) = 2.2 \times 10^{-4} \) at \( M_h = 125 \text{ GeV} \)
- Can be used for testing:
  - \( y_f \propto m_f \)
  - mass generation mechanism between 2nd/3rd leptons (\( \kappa_\mu / \kappa_\tau \)) and 2nd lepton/quark (\( \kappa_\mu / \kappa_c \))
- Today I will show the first results at \( E_{\text{CM}} = 250/500 \text{ GeV} \)
- HL-LHC prospects (3000 fb\(^{-1}\)): \( \sim 14\% \) precision for cross section times branching ratio \( \frac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} \)
## Previous Studies

### Everything performed at $\geq 1$ TeV

<table>
<thead>
<tr>
<th>Reference</th>
<th>$E_{CM}$</th>
<th>$P(e^-, e^+)$</th>
<th>$\int Ldt$</th>
<th>$\Delta(\sigma \times BR)$</th>
<th>$\sigma \times BR$</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC-REP-2013-006</td>
<td>1 TeV</td>
<td>(-0.8, +0.2)</td>
<td>500 fb$^{-1}$</td>
<td>44%</td>
<td></td>
<td>ILC/ILD</td>
</tr>
<tr>
<td>arXiv:1306.6329 [hep-ex]</td>
<td>1 TeV</td>
<td>(-0.8, +0.2)</td>
<td>1000 fb$^{-1}$</td>
<td>32%</td>
<td></td>
<td>ILC/SiD</td>
</tr>
<tr>
<td>arXiv:1603.04718 [hep-ex]</td>
<td>1 TeV</td>
<td>(-0.8, +0.2)</td>
<td>500 fb$^{-1}$</td>
<td>36%</td>
<td></td>
<td>ILC/ILD used TMVA</td>
</tr>
<tr>
<td>Eur. Phys. J. <strong>C73</strong>(2), 2290 (2013)</td>
<td>3 TeV</td>
<td>unpol.</td>
<td>2000 fb$^{-1}$</td>
<td>15%</td>
<td></td>
<td>CLIC_SiD $M_h = 120$ GeV used TMVA</td>
</tr>
<tr>
<td>Eur. Phys. J. <strong>C75</strong>, 515 (2015)</td>
<td>1.4 TeV</td>
<td>unpol. (-0.8, 0)</td>
<td>1500 fb$^{-1}$</td>
<td>38%</td>
<td>25%</td>
<td>CLIC_ILD used TMVA</td>
</tr>
</tbody>
</table>
ILC Running Scenario
optimized scenario with considering
- Higgs precise measurements
- Top physics
- New physics search
20 years running with
energy range [250-500] GeV,
beam polarization sharing
--- then possible 1 TeV upgrade

preferred scenario:
2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV

※staging scenario will start from 250 GeV,
but total luminosities are the same
Single Higgs Production

$\sqrt{s} = 250$ GeV
Higgs-strahlung (Zh) dominant

$\sqrt{s} = 500$ GeV
WW-fusion dominant

<table>
<thead>
<tr>
<th>$E_{CM}$</th>
<th>process</th>
<th>beam pol.</th>
<th>$\int Ldt$</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>$\nu\bar{\nu}h$</td>
<td>L</td>
<td>1600</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>1600</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}h$</td>
<td>L</td>
<td>1600</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>1600</td>
<td>16</td>
</tr>
<tr>
<td>250</td>
<td>$q\bar{q}h$</td>
<td>L</td>
<td>1350</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>450</td>
<td>14</td>
</tr>
</tbody>
</table>

L: (e-, e+) = (-0.8, +0.3)
R: (e-, e+) = (+0.8, -0.3)
Analysis Settings

- Geant4-based full detector simulation with ILD model
- Included all possible SM backgrounds
  - Still some processes have not enough statistics, need more MC statistics (under production)

<table>
<thead>
<tr>
<th>Process</th>
<th># total MC events</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV</td>
<td>$1.4 \times 10^7$</td>
</tr>
<tr>
<td>250 GeV</td>
<td>$7.1 \times 10^7$</td>
</tr>
</tbody>
</table>
General Event Reconstruction

PandoraPFOs

IsolatedLeptonTagger

※ isolated electrons are included in “remained PFO”

isolated muons

remaining PFOs

$h \rightarrow \mu^+\mu^-$ candidate

$Z \rightarrow q\bar{q}, \ell^+\ell^-$ or nothing (neutrinos)

dedicated analysis for each channel
General Event Selection

Selections at 500(250) GeV:

- \# \mu^+ == 1, \# \mu^- == 1
- 0.5 < \chi^2(\mu^{\pm})/Ndf < 1.5  only select
- \sigma(M_{\mu^+\mu^-}) < 1(0.5) GeV  well-measured muons
- 100 < M_{\mu^+\mu^-} < 130 GeV  $h \to \mu^+\mu^-$ candidate
- \cos \theta_{\mu^+\mu^-} < 0.55(-0.4)

other colors: SM background plots from nnh500-L
$e^+ e^- \rightarrow \nu \bar{\nu} h$

nnh500-L/R
Precuts

- $N_{P_t > 5 \text{ GeV}} \leq 1$
- $125 < E_{\text{vis}} < 320 \text{ GeV}$
- missing $P_t > 5 \text{ GeV}$
- $|\cos \theta_{\text{miss}}| < 0.99$
TMVA (BDTG) Analysis

5 input variables: missing $P_t$, $M_{\mu^+\mu^-}$, charge * $\cos \theta_{\mu^\pm}$, $E_{\text{subleading}}$

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>11.66</td>
<td>2.69</td>
</tr>
<tr>
<td>$N_{\text{bkg}}$</td>
<td>1.39</td>
<td>0.01</td>
</tr>
<tr>
<td>$S$</td>
<td>3.2</td>
<td>1.6</td>
</tr>
<tr>
<td>$\sqrt{S + B}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{S}{\sqrt{S + B}}$</td>
<td>31%</td>
<td>61%</td>
</tr>
</tbody>
</table>

※still overtrained
need more MC (under production)
$e^+ e^- \rightarrow q\bar{q}h$

qqh500-L/R
Event Reconstruction

remaining PFOs

IsolatedLeptonTagger  kT clustering

use for veto  3 jets

$\gamma\gamma \rightarrow \text{low } P_t \text{ hadron backgrounds are overlaid on average at 500 GeV}$
Precuts

- veto: no isolated lepton in “remaining PFO”
- exactly 3 jets
- $60 < M_{jets} < 180$ GeV
- number of tracks should be greater or equal to 8
- thrust < 0.95
TMVA Analysis

7 input variables:
- thrust, $M_{\mu^+\mu^-}$, charge * $\cos \theta_{\mu^\pm}$,
- $E_{\text{subleading}}$, $M_{\text{jets}}$, $M_{\text{recoil}} = M_h$

※still overtrained
need more MC (under production)
$e^+ e^- \rightarrow q \bar{q} h$

qqh250-L/R
Event Reconstruction / Precuts

- remaining PFOs
- Durham clustering
- 2 jets

\( \gamma \gamma \rightarrow \) low \( P_t \) hadron backgrounds are overlaid 0.4 / bunch crossing on average at 250 GeV

- exactly 2 jets
- \( 60 < M_{\text{jets}} < 140 \) GeV
- \( \cos \theta_{\text{jets}} < -0.1 \)
- number of tracks should be greater or equal to 8
TMVA Analysis

7 input variables:
- \( \cos \theta_{\text{miss}} \)
- \( M_{\mu^+\mu^-} \)
- \( |p_{\mu^+\mu^-}| \)
- charge \( \times \) \( \cos \theta_{\mu^\pm} \)
- \( E_{\text{subleading}} \)
- \( M_{\text{jets}} \)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{sig}} )</td>
<td>22.18</td>
<td>5.81</td>
</tr>
<tr>
<td>( N_{\text{bkg}} )</td>
<td>20.13</td>
<td>1.03</td>
</tr>
<tr>
<td>( S )</td>
<td>3.4</td>
<td>2.2</td>
</tr>
<tr>
<td>( \frac{\sqrt{S+B}}{S+B} )</td>
<td>29%</td>
<td>45%</td>
</tr>
</tbody>
</table>

※still overtrained
need more MC (under production)
### Comparison with Extrapolation

<table>
<thead>
<tr>
<th>∫ L dt at √s</th>
<th>250 fb⁻¹ at 250 GeV</th>
<th>330 fb⁻¹ at 350 GeV</th>
<th>500 fb⁻¹ at 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(e⁻, e⁺)</td>
<td></td>
<td>(-80%, +30%)</td>
<td></td>
</tr>
<tr>
<td>production</td>
<td>Zh</td>
<td>ννh</td>
<td>Zh</td>
</tr>
<tr>
<td></td>
<td>ννh</td>
<td></td>
<td>ννh</td>
</tr>
<tr>
<td></td>
<td>Zh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>decay</td>
<td></td>
<td>Δ(σ · BR)/(σ · BR)</td>
<td></td>
</tr>
<tr>
<td>h → μ⁺μ⁻ [45]</td>
<td>72%</td>
<td>76%</td>
<td>140%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>88%</td>
<td>72%</td>
</tr>
</tbody>
</table>


- Scale to 1350 fb⁻¹: 31%
- My results: 29%, only qqh250-L
- Scale to 1600 fb⁻¹: 49%/40%
- My results: 26%/31%

(for Zh, only qqh500-L)

Everything is similar/better than extrapolation!
Impact of Momentum Resolution

• In this analysis, momentum resolution ($P_t$ resolution) is most important.
  • For high $P_t$ muons
  • This affects $M_{\mu^+\mu^-}$ which is most important variable for physics analysis.

• Checked what happens if we change momentum resolution artificially.
  • Used smearing to MCParticle (MC information)
  • Only signal process
$M_{\mu^+\mu^-}$ Spectrum

Effect of momentum resolution

- PFO
- MC
- $1 \times 10^{-3}$
- $5 \times 10^{-4}$
- $1 \times 10^{-4}$
- $5 \times 10^{-5}$
- $2 \times 10^{-5}$
- $1 \times 10^{-5}$

# MC Events / 0.1 GeV

- Overview

- Zoom up

※not luminosity weighted

MCParticle is smeared with artificial $P_t$ resolution
 Ratio Spectrum

Effect of momentum resolution

Ratio \equiv \frac{\text{smeared histogram}}{\text{PFO histogram}}

Clearly worse in bad momentum resolutions

※not luminosity weighted
Summary

Showed first results of $h \rightarrow \mu^+ \mu^-$ at 250/500 GeV based on ILD full simulation for the first time

<table>
<thead>
<tr>
<th></th>
<th>500 GeV</th>
<th>250 GeV</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$q\bar{q}h$</td>
<td>$\nu\bar{\nu}h$</td>
</tr>
<tr>
<td>left-handed</td>
<td>26% (1600 fb$^{-1}$)</td>
<td>31% (1600 fb$^{-1}$)</td>
</tr>
<tr>
<td>right-handed</td>
<td>36% (1600 fb$^{-1}$)</td>
<td>61% (1600 fb$^{-1}$)</td>
</tr>
</tbody>
</table>

Everything is better than extrapolation results
Combine everything gives 14% precision: almost same precision expected at the HL-LHC