Prospects of measuring Higgs boson decays into muon pairs at the ILC

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Introduction

Discovery of SM-like Higgs boson at the LHC

But, still many open questions:
- SM Higgs? BSM Higgs?
- dark matter, dark energy
- BSM (SUSY, composite...)
- ...

Precise measurement of Higgs boson would be a key to answer the questions
- mass-coupling relation
- any deviation shows the existence of BSM
- typically small deviation

One example: Supersymmetry

\[
\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2
\]

arXiv:1306.6352
The **International Linear Collider (ILC)**

- $e^+e^-$ collider, $E_{CM} = 250$ GeV (upgradable to 500 GeV, 1 TeV)
- polarized beam ($e^-: \pm 80\%, e^+: \pm 30\%$)
- clean environment, known initial state

under in-depth consideration by the Japanese government
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
\[ \sigma_E/E = 3 - 4\% \]
In This Talk: $h \rightarrow \mu^+ \mu^-$

- 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 ($\kappa_\mu/\kappa_c$)

- Challenging: tiny branching ratio ($\text{BR}(h \rightarrow \mu^+ \mu^-) = 2.2 \times 10^{-4}$)
## Previous Studies

### Everything performed at >= 1 TeV, or not realistic

| Reference                                  | $E_{\text{CM}}$ | beam pol. $P(e^-, e^+)$ | $\int L dt$ | $\frac{\Delta(\sigma \times BR)}{(\sigma \times BR)}$ | comment                                |
|--------------------------------------------|-----------------|--------------------------|-------------|---------------------------------------------------|----------------------------------------|
| LC-REP-2013-006                            | 1 TeV           | (-0.8, +0.2)             | 500 fb$^{-1}$ | 44%                                               | ILC/ILD                               |
| arXiv:1306.6329 [hep-ex]                   | 1 TeV           | (-0.8, +0.2)             | 1000 fb$^{-1}$ | 32%                                               | ILC/SiD                                |
| arXiv:1603.04718 [hep-ex]                  | 1 TeV           | (-0.8, +0.2)             | 500 fb$^{-1}$ | 36%                                               | ILC/ILD used TMVA                      |
| Eur. Phys. J. **C73**(2), 2290 (2013)       | 3 TeV           | unpol.                   | 2000 fb$^{-1}$ | 15%                                               | CLIC_SiD $M_h = 120$ GeV used TMVA     |
| Euro. Phys. J. **C75**, 515 (2015)          | 1.4 TeV         | unpol.                   | 1500 fb$^{-1}$ | 38%                                               | CLIC_ILD used TMVA                     |
|                                           |                 | (-0.8, 0)                |              | 25%                                               |                                        |
| arXiv:0911.0006 [physics.ins-det]          | 250 GeV         | (-0.8, +0.3)             | 250 fb$^{-1}$ | 91%                                               | ILC/SiD $M_h = 120$ GeV                |
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
Single Higgs Production

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

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

| $E_{CM}$ | process | beam pol. | $\int L\,dt$ (fb$^{-1}$) | # events |
|----------|---------|-----------|-----------------|----------|
| 500      | $\nu\bar{\nu}h$ | L         | 1600            | 57.5     |
|          |         | R         | 1600            | 7.9      |
| 500      | $q\bar{q}h$   | L         | 1600            | 24.6     |
|          |         | R         | 1600            | 16.5     |
| 250      | $\nu\bar{\nu}h$ | L         | 900             | 15.0     |
|          |         | R         | 900             | 8.4      |
| 250      | $q\bar{q}h$   | L         | 900             | 41.1     |
|          |         | R         | 900             | 28.1     |

$P(e^-, e^+) = (-0.8, +0.3)$, $M_h = 125$ GeV

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 available SM backgrounds
  • (for specialist) Used DBD-world samples
  • Performed toy MC in the end to estimate the precision

| $E_{CM}$  | # total MC events |
|-----------|------------------|
| 500 GeV   | $1.4\times10^7$  |
| 250 GeV   | $7.1\times10^7$  |
1. select $h \rightarrow \mu^+ \mu^-$ candidate
2. channel-specific analysis
3. multivariate analysis
4. modeling and toy MC with $M_{\mu^+ \mu^-}$
   - extract final precision
   - (for experts) Crystal Ball + Gaussian (CBG) for signal, pol1 for background

Analysis is structured in the same way for all channels.
## Results

**ILC250 combined** = 24.9% (“theoretical limit” = 10.4%)

ILC250+500 combined = 17.5% (“theoretical limit” = 7.1%)

HL-LHC: 10-13%

※theoretical limit = 100% efficiency, no backgrounds, no detector effects

| Energy | \(q\bar{q}h\) | \(\nu\bar{\nu}h\) |
|--------|----------------|------------------|
| **250 GeV** | L | 36.2% | 122.4% |
|        | R | 38.0% | 105.1% |

\[
\text{precision for } \frac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})}
\]

| Energy | \(q\bar{q}h\) | \(\nu\bar{\nu}h\) |
|--------|----------------|------------------|
| **500 GeV** | L | 43.8% | 37.9% |
|        | R | 54.2% | 108.8% |
Impact of Momentum Resolution

• The variable $M_{\mu^+ \mu^-}$ is most important and essential for this analysis. Thus, the momentum resolution ($P_t$ resolution) has a crucial role.

• Studied what will happen when we change the momentum resolution artificially
  • 13 benchmark points

| Resolution (GeV$^{-1}$) |
|-------------------------|
| $1 \times 10^{-3}$  |
| $5 \times 10^{-4}$  |
| $5 \times 10^{-5}$  |
| $5 \times 10^{-6}$  |
| $3 \times 10^{-4}$  |
| $3 \times 10^{-5}$  |
| $3 \times 10^{-6}$  |
| $2 \times 10^{-4}$  |
| $2 \times 10^{-5}$  |
| $2 \times 10^{-6}$  |
| $1 \times 10^{-4}$  |
| $1 \times 10^{-5}$  |
| $1 \times 10^{-6}$  |
Impact of Momentum Resolution

• smeared MCParticle momentum of $h \rightarrow \mu^+ \mu^-$ candidate
  • Gaussian-smeared with constant number
    • no momentum/angular dependencies
    • Not 100% correct, but muons will fly everywhere and rather high momentum. On average, this is still good approximation.
  • replace $M_{\mu^+ \mu^-}$ to $M_{\mu^+ \mu^-}^{\text{smeared}}$ in toy MC

Studied the impact to final number:
$$\frac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})}$$ in this study

arXiv:1306.6329
Results (Major Channel)

qqh250-L
full: 36.2%

nnh500-L
full: 37.9%
Combined Results

- better resolution gives better result
- relative improvement is ~20% when resolution is factor 10 better
- relative ~40% worse when resolution is factor 10 worse

ILC250: ~18-23%
ILC250+500: ~14-18%
Summary

• Precise measurements and extracting absolute Higgs couplings are possible at the ILC
• Studied $h \rightarrow \mu^+ \mu^-$ channel with $E_{\text{CM}} = 250/500$ GeV at the ILC
  • Can reach 17.5% combined precision for $\frac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})}$
• Studied the impact of momentum resolution
• Now summarizing into a full paper: ongoing
• (for specialist) IDR analysis has just started