1-loop effects of MSSM particles in Higgs productions at the ILC

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OUTLINE

• Introduction (What)
• How (GRACE/SUSY)
• Results
• Summary
Introduction
SUSY indirect detection in Higgs production at the ILC

Graph 1

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

Graph 7

$e^- \rightarrow W \rightarrow e^+ \nu_e \bar{\nu_e}$
Is the 1-loop effect of virtual MSSM particles statistically significant?
SUSY indirect detection in Higgs production at the ILC

Tree level total cross section

\[ e^+ e^- \rightarrow \nu \bar{\nu} h \text{ (sum of 3 generation)} \]

\[ e^+ e^- \rightarrow \nu_e \bar{\nu}_e h (W \text{ fusion}) \]

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

\[ e^+ e^- \rightarrow Zh \rightarrow \nu \bar{\nu} h \]
The cross section of $Zh$ is large at low energy region.
The cross section of $Zh$ is large at low energy region.

The cross section of $\nu\bar{\nu}h$ is large at high energy region.

Tree level total cross section

- $e^+e^- \rightarrow \nu\bar{\nu}h$ (sum of 3 generation)
- $e^+e^- \rightarrow v_e\bar{v}_eh (W$ fusion $)$
- $e^+e^- \rightarrow Zh$
- $e^+e^- \rightarrow Zh \rightarrow \nu\bar{\nu}h$
The cross section of $Zh$ is large at low energy region.

The cross section of $v\bar{v}h$ is large at high energy region.

The accurate measurement of SM Higgs is expected.

SUSY indirect detection in Higgs production at the ILC
The cross section of $Zh$ is large at low energy region.

The cross section of $\nu\bar{\nu}h$ is large at high energy region.

The accurate measurement of SM Higgs is expected.

At the same time, we want to focus on the effect of MSSM.
Selection of sets (Zh)

- Higgs mass: $m_h(\text{exp}) = 125.09 \pm 0.24$ GeV
- B physics constraint: $b \to s\gamma, B_s \to \mu\mu$
  \[ a_\mu(\text{exp}) - a_\mu(\text{SM}) = (25.9 \pm 8.1) \times 10^{-10} \]
- muon g-2 constraint
- DM thermal relic density: (Planck data of $\Omega h^2$)
- LHC direct search of sparticles

<table>
<thead>
<tr>
<th>light stop $\approx 300$ GeV</th>
<th>heavy stop $\approx 1000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>The DM abundance is explained by Co-annihilation of stau and LSP</td>
<td>set 1</td>
</tr>
<tr>
<td>The DM abundance is explained by Co-annihilation of stop and LSP</td>
<td>set 3</td>
</tr>
</tbody>
</table>

SuSpect2 (A.Djouadi, J.Kneur and G.Moultaka)
micrOMEGAs (G. Belanger, F. Boudjema, A. Pukhov, A. Semenov)

We have selected the set neutralino pair is \textbf{not} produced.

\((\tilde{\chi}_1^0 \geq 500\text{GeV})\)

We pay attention to the case

\textit{“only the effects of virtual MSSM particles are statistical significant”}

\textbf{Selection of sets (W fusion)}

\begin{align*}
\text{SM} & \quad e^+e^- \rightarrow \nu\nu h \\
\text{MSSM} & \quad e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 h
\end{align*}

(This study does not focus on this)
the set (W fusion)

Higgs (consistent with the observed mass)

ElectroWeak particles (Only these contribution don’t explain muon g-2)

QCD particles

<table>
<thead>
<tr>
<th>set 10</th>
<th>h</th>
<th>H</th>
<th>A</th>
<th>H⁺</th>
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<tbody>
<tr>
<td>h</td>
<td>125.2</td>
<td>2000</td>
<td>2000</td>
<td>2002</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>(\chi'^{±}_{1})</th>
<th>(\chi'^{±}_{2})</th>
<th>(\tilde{\chi}^{0}_{1})</th>
<th>(\tilde{\chi}^{0}_{2})</th>
<th>(\tilde{\chi}^{0}_{3})</th>
<th>(\tilde{\chi}^{0}_{4})</th>
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<tbody>
<tr>
<td>mass</td>
<td>583.3</td>
<td>1376</td>
<td>552.8</td>
<td>588.2</td>
<td>614.8</td>
<td>1376</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>(\ell_{1})</th>
<th>(\ell_{2})</th>
<th>(\tilde{\nu}_{\ell})</th>
<th>(\tilde{\tau}_{1})</th>
<th>(\tilde{\tau}_{2})</th>
<th>(\tilde{\nu}_{\tau})</th>
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</thead>
<tbody>
<tr>
<td>mass</td>
<td>601.5</td>
<td>651.7</td>
<td>646.9</td>
<td>589.5</td>
<td>662.5</td>
<td>646.9</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>(\tilde{\nu}_{1})</th>
<th>(\tilde{\nu}_{2})</th>
<th>(d_{1})</th>
<th>(d_{2})</th>
<th>(\tilde{t}_{1})</th>
<th>(\tilde{t}_{2})</th>
<th>(b_{1})</th>
<th>(b_{2})</th>
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</thead>
<tbody>
<tr>
<td>mass</td>
<td>5000</td>
<td>5000</td>
<td>4800</td>
<td>5000</td>
<td>1798</td>
<td>2508</td>
<td>2200</td>
<td>2501</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\theta_{\tau})</th>
<th>(\theta_{b})</th>
<th>(\theta_{t})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.164</td>
<td>1.539</td>
<td>1.481</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(M_{1})</th>
<th>(M_{2})</th>
<th>(M_{3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>585.0</td>
<td>1370</td>
<td>2500</td>
</tr>
</tbody>
</table>

\(\mu=586, \tan \beta=30\)
How (GRACE/SUSY) (before and after the discovery of Higgs)
The system that can automatically calculate cross sections or decay widths in SM and MSSM

* GRACE/SUSY [tree version (opened to public)]

* GRACE/SUSY-loop [1-loop version(unopened to public)]

1. Feynman diagrams
2. Physical amplitudes
3. Phase space Integration
4. Event generation
5. Various Self-checks

We can check the validity of numerical calculation
Before the discovery of Higgs, GRACE have been used with Higgs mass as a free parameter.

Higgs mass was final free parameter in SM.

SM full 1-loop correction of $e^+e^- \rightarrow \nu\bar{\nu}h$ have calculated with using GRACE in 2003.


Denner et al., NPB660(2003)289
After the discovery of Higgs, GRACE is used with Higgs mass as a fixed parameter for the search of MSSM that have many free parameters. For example, in this way,

**step 1**, we can generate all diagrams.

\[ e^+ e^- \rightarrow \nu_e \bar{\nu}_e h \]  
full 1-loop MSSM diagrams • • • 13793 diagrams

**step 2**, we can select diagrams.

By selecting diagrams that WW fusion in internal line, they are reduced to 239 diagrams.

**step 3**, we can check whether a renormalization works well.

we have confirmed(self-check)
the cancelation of ultraviolet or infrared divergence

and

independence on the cut off energy between hard and soft photon

**step 4**, actual calculations
Results
(ZH,W fusion)
Angular distribution (1-loop level)

- $\theta$ is the Z generation angle.
- The 1-loop correction for the tree level is negative.
- The correction of MSSM for SM is positive.
MSSM 1-loop effect

- We have defined the correction ratio $\delta$
- We have compared with the statistical error (assumed the luminosity that planned in the ILC).

H. Baer et al,

- The 1-loop effect is 11% in the entire region.
- The 1-loop effect for SM is larger than the error.
- The difference among sets is larger than the error.

$\delta_{\text{SUSY}} = \frac{\frac{d\sigma_{\text{SUSY 1-loop}}}{d\cos\theta} - \frac{d\sigma_{\text{SM}}}{d\cos\theta}}{\frac{d\sigma_{\text{tree}}}{d\cos\theta}}$

correction ratio ($\sqrt{s}=250$ GeV)

$\int L dt = 250 \text{fb}^{-1}$

$\delta_{\text{SUSY}}$ (%)
1-loop correction for the tree level is negative.
MSSM correction for SM is positive.
The correction of SM total cross section for the tree level is -37%.
The correction of MSSM total cross section for the tree level is -19%.
We have defined the correction ratio $\delta$.

We have compared with Monte Carlo integration error.

The correction ratio is 15% in the entire region.

The 1 loop effect is larger than the error.

\[
\delta_{\text{SUSY}} = \frac{\frac{d\sigma_{\text{SUSY,loop}}}{dE_h} - \frac{d\sigma_{\text{SM}}}{dE_h}}{\frac{d\sigma_{\text{tree}}}{dE_h}}
\]

$\sqrt{s} = 500\,(\text{GeV})$
summary
We select sets that consistent with Higgs mass, B physics, DM relic density, LHC direct search of sparticles, and muon g-2(in Zh)

We have probed statistical significance at the ILC.

In W fusion calculation, We have considered a set neutralino is not produced, and investigate whether only one loop effect is statistically significant.

GRACE/SUSY is very Useful for the search of MSSM particles!!
back up
The part compared in the $\delta_{\text{susy}}$ canceled each other, because they are common in SM and MSSM.
Sfermion co-annihilation scenario in Bino Dark Matter

Stop that consistent with Higgs mass

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- DM thermal relic density: (Planck data of \(\Omega h^2\))
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Our sets have almost pure Bino DM (No mix with Higgsino or Wino)

Then, the stop1 or the stau1 mass are constrained (sfermion co-annihilation scenario)

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<td>set 1</td>
<td>set 2</td>
</tr>
<tr>
<td></td>
<td>set 3</td>
<td>inconsistent with muon g-2 (LSP is too heavy)</td>
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The DM abundance is explained by Co-annihilation of stau and LSP

The DM abundance is explained by Co-annihilation of stop and LSP

G. Bélanger LAPTH-Annecy