Di-Higgs Production in SUSY Models

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INTRODUCTION

Di-Higgs production through gluon fusion at 14TeV collider energy in the framework of Minimal Supersymmetric Standard Model(MSSM) and Next-to-Minimal Supersymmetric Standard Model(NMSSM).
Higgs pair production cross section is calculated based on the analytical expression of the leading order Feynman amplitudes.
Introduction

- Higgs pair production cross section is calculated based on the analytical expression of the leading order Feynman amplitudes
  - allow us to study the interference between resonant and nonresonant amplitudes
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Includes both quark and squark loop contributions.
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- Separate the cross section into resonant, nonresonant, and interference parts
INTRODUCTION

- Higgs pair production cross section is calculated based on the analytical expression of the leading order Feynman amplitudes
  - allow us to study the interference between resonant and nonresonant amplitudes
- Includes both quark and squark loop contributions
- Separate the cross section into resonant, nonresonant, and interference parts
  - To better understand how SUSY Higgs pair production cross section is enhanced as compared to SM case
Leading order Feynman diagrams for Higgs pair production in MSSM:
Resonant amplitude:
Nonresonant amplitude:
Valid Parameter Space

- Require mass of light CP-even Higgs boson to be $125 \pm 0.5$ GeV
- Stop mixing parameter $X_t$ can be determined by $m_A$ and $\tan \beta$
  ($\mu$, $M_1$, $M_2$, $M_3$, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$ are fixed)
- $X_t$ satisfies the vacuum stability bound:
  $$(X_t + \frac{\mu}{\tan \beta})^2 \leq (3.4(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + 0.5|m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2|) + 60\left(\frac{m_Z^2}{2}\cos 2\beta + m_A^2 \cos^2 \beta\right)$$
Valid Parameter Space

- Require mass of light CP-even Higgs boson to be $125 \pm 0.5$ GeV
  - Stop mixing parameter $X_t$ can be determined by $m_A$ and $\tan\beta$ ($\mu, M_1, M_2, M_3, m_{\tilde{t}_1}, m_{\tilde{t}_2}$ are fixed)
  - $X_t$ satisfies the vacuum stability bound:
    $$\left( X_t + \frac{\mu}{\tan\beta} \right)^2 \leq 3.4(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + 0.5|m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2| + 60\left( \frac{m_Z^2}{2} \cos 2\beta + m_A^2 \cos^2 \beta \right)$$

$m_A$ and $\tan\beta$ are restricted by:

- Search for additional neutral MSSM Higgs Bosons in the di-tau final state in pp collision at $\sqrt{s} = 13$ TeV

- Precision measurement of Higgs Couplings
**Valid Parameter Space**

- Require mass of light CP-even Higgs boson to be $125 \pm 0.5$ GeV
- Stop mixing parameter $X_t$ can be determined by $m_A$ and $\tan \beta$
  - $(\mu, M_1, M_2, M_3, m_{\tilde{t}_1}, m_{\tilde{t}_2}$ are fixed)
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  $$ (x_t + \frac{\mu}{\tan \beta})^2 \leq (3.4(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + 0.5|m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2|) + 60(\frac{m_Z^2}{2} \cos 2\beta + m_A^2 \cos^2 \beta) $$

$m_A$ and $\tan \beta$ are restricted by:

- Search for additional neutral MSSM Higgs Bosons in the di-tau final state in pp collision at $\sqrt{s} = 13$ TeV
  - ref: CMS PAS HIG-17-020
  - Upper bound of $\tan \beta$
- Precision measurement of Higgs Couplings
**Valid Parameter Space**

- Require mass of light CP-even Higgs boson to be $125 \pm 0.5$ GeV
  - Stop mixing parameter $X_t$ can be determined by $m_A$ and $\tan\beta$
  - $(\mu, M_1, M_2, M_3, m_{\tilde{t}_1}, m_{\tilde{t}_2}$ are fixed)
  - $X_t$ satisfies the vacuum stability bound:
    $$ (X_t + \frac{\mu}{\tan\beta})^2 \leq (3.4(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) + 0.5|m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}|) + 60(\frac{m^2_Z}{2} \cos 2\beta + m^2_A \cos^2 \beta) $$

$m_A$ and $\tan\beta$ are restricted by:

- Search for additional neutral MSSM Higgs Bosons in the di-tau final state in pp collision at $\sqrt{s} = 13$ TeV
  - ref: CMS PAS HIG-17-020
  - Upper bound of $\tan \beta$

- Precision measurement of Higgs Couplings
  - ref: CMS PAS HIG-17-031
  - checked coupling modifiers: $\kappa_t, \kappa_b, \kappa_\tau, \kappa_\gamma, \kappa_g$
  - Lower bound of $m_A$
**Valid Parameter Space**

- **Precision measurement of Higgs Couplings**

\[ pp \rightarrow H/A \rightarrow \tau^+\tau^- \]
UNDERSTANDING INTERFERENCE TERM

The interference term is

\[ 2Re[A^{H}_\triangleright \times (A^{nr}_\triangleright + A^{nr}_\square)^*] = 2Re[A^{H}_\triangleright \times A^{nr}_\triangleright^*] + 2Re[A^{H}_\triangleright \times A^{nr}_\square^*] \]

Let \( A^{nr} = |A^{nr}|e^{i\delta_{nr}} \),

\[ A^{H}_\triangleright = a_{res}\frac{\hat{s}}{\hat{s} - m^2_H + i\Gamma_H m_H} , \quad a_{res} = |a_{res}|e^{i\delta_{res}} \]

\[ 2Re[A^{H}_\triangleright \times A^{nr}_\triangleright^*] = 2(\mathcal{R}_{int} + \mathcal{I}_{int}) \]

\[ \mathcal{R}_{int} = |a_{res}| |A^{nr}| \cos(\delta_{res} - \delta_{nr})\hat{s}\frac{\hat{s} - m^2_H}{(\hat{s} - m^2_H)^2 + (\Gamma_H m_H)^2} \]

\[ \mathcal{I}_{int} = |a_{res}| |A^{nr}| \sin(\delta_{res} - \delta_{nr})\hat{s}\frac{\Gamma_H m_H}{(\hat{s} - m^2_H)^2 + (\Gamma_H m_H)^2} \]
**Understanding Interference Term**

\[
\text{Re}(A^H \times A^{h^*}) = \mathcal{R}_{\text{int}} \delta_{\triangle} \quad \delta_{\triangle} = 0
\]

\[
\sin(\delta_{\triangle} - \delta_{\square}) < 0 +/-
\]

\[
\cos(\delta_{\triangle} - \delta_{\square}) < 0 +/-
\]
RESULTS

\[ \sigma_{\text{MSSM}}^{\text{LO}} / \sigma_{\text{SM}}^{\text{LO}} \]

\[ (\sigma_{\text{SM}}^{\text{LO}} = 21.7 \text{ fb}) \]

- Always larger than SM cross section
  
  \[ (10\% \sim 40\% \text{ enhancement}) \]
RESULTS

- $\sigma_{res}/\sigma_{SM}^{LO}$

- $\sigma_{res}$ is largest when $\tan\beta$ and $m_A$ are small

- $\sigma_{nr}$ dominates when $\tan\beta$ and $m_A$ are large

- $\sigma_{int}/\sigma_{res}$

- When $\tan\beta$ and $m_A$ are small, $\sigma_{int}$ can be as large as $\sigma_{res}$
RESULTS

\[ \delta_3 = \frac{g_{hhh}^{MSSM} - g_{hhh}^{SM}}{g_{hhh}^{SM}} \]

\[ \kappa_t \approx 1 \]

\[ \delta_3 \text{ is the main factor that increases } \sigma_{nr} \text{ by about } 8\% \sim 10\% \]

Always smaller than SM value

\[ ( -12\% \sim -15\% ) \]
Leading order Feynman diagrams for Higgs pair production in NMSSM:
PARAMETER SPACE SCAN RANGES

<table>
<thead>
<tr>
<th>$\tan \beta$</th>
<th>$\lambda$</th>
<th>$\kappa$</th>
<th>$A_\lambda$</th>
<th>$A_\kappa$</th>
<th>$\mu_{\text{eff}}$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$</th>
<th>$A_t$</th>
<th>$A_b$</th>
<th>$A_\tau$</th>
<th>$m_{\tilde{Q}_3}$</th>
<th>$m_{\tilde{L}_3}$</th>
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<tbody>
<tr>
<td>min</td>
<td>1</td>
<td>0</td>
<td>-0.7</td>
<td>-1</td>
<td>-1</td>
<td>-0.5</td>
<td>0.1</td>
<td>1.3</td>
<td>-6</td>
<td>-6</td>
<td>-3</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>max</td>
<td>10</td>
<td>0.7</td>
<td>0.7</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

- Scanned by NMSSMTools5.4.0
- Choose $\lambda^2 + \kappa^2 < 0.7^2$ to ensure perturbativity
- Various phenomenological and theoretical constraints are checked by NMSSMTools
BENCHMARKS FOR HIGGS PAIR PRODUCTION IN NMSSM

\[ \sigma_{LO}^{SM} = 22.3 \text{ fb} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NMSSM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{LO} )  (fb)</td>
<td>42.60</td>
<td>41.34</td>
</tr>
<tr>
<td>( \sigma_{LO} )  (fb)</td>
<td>5.70</td>
<td>9.77</td>
</tr>
<tr>
<td>( \sigma_{LO} )  (fb)</td>
<td>35.08</td>
<td>29.42</td>
</tr>
<tr>
<td>( \sigma_{LO} )  (fb)</td>
<td>1.82</td>
<td>2.15</td>
</tr>
<tr>
<td>( \sigma_{LO} )  (fb)</td>
<td>1.91</td>
<td>1.86</td>
</tr>
<tr>
<td>( \sigma_{LO}/\sigma_{LO}^{SM} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{H_1} ) (GeV)</td>
<td>124.8</td>
<td>124.9</td>
</tr>
<tr>
<td>( m_{H_2} ) (GeV)</td>
<td>424.6</td>
<td>290.2</td>
</tr>
<tr>
<td>( m_{H_3} ) (GeV)</td>
<td>1564.7</td>
<td>660.3</td>
</tr>
<tr>
<td>( \tan \beta )</td>
<td>7.0</td>
<td>1.73</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>0.15</td>
<td>0.47</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>-0.46</td>
<td>0.27</td>
</tr>
<tr>
<td>( A_{\lambda} ) (GeV)</td>
<td>964.7</td>
<td>-391.8</td>
</tr>
<tr>
<td>( A_{\kappa} ) (GeV)</td>
<td>981.7</td>
<td>322.4</td>
</tr>
<tr>
<td>( \mu_{\text{eff}} ) (GeV)</td>
<td>291.1</td>
<td>-326.0</td>
</tr>
</tbody>
</table>
SUMMARY

▶ MSSM:

σ_{nr} is about 8\% - 10\% larger than σ_{LO}.

σ_{res} is largest when \tan β and m_A are small.

σ_{MSSM} is largest when \tan β and m_A are small.

▶ NMSSM:

σ_{NMSSM} can be larger than σ_{SM} by 90\%.

m_{H_1} can be as small as 44 GeV.
SUMMARY

- **MSSM:**
  - $\sigma_{nr}$ is about 8% ~ 10% larger than $\sigma_{SM}^{LO}$
  - $\sigma_{res}$ is largest when $\tan\beta$ and $m_A$ are small
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- **MSSM:**
  - $\sigma_{nr}$ is about 8% ~ 10% larger than $\sigma_{LO}^{SM}$
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  - $\sigma_{MSSM}$ is largest when $\tan\beta$ and $m_A$ are small
SUMMARY

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  - $\sigma_{MSSM}$ is largest when $\tan\beta$ and $m_A$ are small

- **NMSSM:**
  - $\sigma_{NMSSM}$ can be larger than $\sigma_{SM}$ by $90\%$
SUMMARY

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  - $\sigma_{res}$ is largest when $\tan\beta$ and $m_A$ are small
  - $\sigma_{MSSM}$ is largest when $\tan\beta$ and $m_A$ are small

- **NMSSM:**
  - $\sigma_{NMSSM}$ can be larger than $\sigma_{SM}$ by 90%
  - $m_{H_1}$ can be as small as 44 GeV
**Interference Term**

\[ |\mathcal{M}|^2 \propto |A^H_\triangledown + A^{nr}_\triangledown + A^{nr}_\Box|^2 \]

\[ = |A^H_\triangledown|^2 + |A^{nr}_\triangledown + A^{nr}_\Box|^2 + 2\text{Re}[A^H_\triangledown \times (A^{nr}_\triangledown + A^{nr}_\Box)^*] \]

The interference term is

\[ 2\text{Re}[A^H_\triangledown \times (A^{nr}_\triangledown + A^{nr}_\Box)^*] = 2\text{Re}[A^H_\triangledown \times A^{nr}_\triangledown^*] + 2\text{Re}[A^H_\triangledown \times A^{nr}_\Box^*]. \]

Let \( A^{nr} = |A^{nr}|e^{i\delta_{nr}} \), \( a_{res} = C_{Hhh}C_{Htt}F_\triangledown \), then

\[ A^H_\triangledown = a_{res} \frac{\hat{s}}{\hat{s} - m^2_H + i\Gamma_H m_H} \]

\[ = |a_{res}|e^{i\delta_{res}} \hat{s} \frac{\hat{s} - m^2_H - i\Gamma_H m_H}{(\hat{s} - m^2_H)^2 + (\Gamma_H m_H)^2} \]
INTERFERENCE TERM

\[ 2\text{Re}[A_H^T \times A^{nr*}] = 2\text{Re}[|a_{res}| |A^{nr}| e^{i(\delta_{res} - \delta_{nr})} \hat{s} \frac{\hat{s} - m_H^2 - i\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2}] \]

\[ = 2(R_{int} + I_{int}) \]

\[ R_{int} = |a_{res}| |A^{nr}| \cos(\delta_{res} - \delta_{nr}) \hat{s} \frac{\hat{s} - m_H^2}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2} \]

\[ I_{int} = |a_{res}| |A^{nr}| \sin(\delta_{res} - \delta_{nr}) \hat{s} \frac{\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2} \]
$X_t/M_S$ CONTOUR PLOT
$\kappa_t$ CONTOUR PLOT
$$\frac{\sigma_{\text{MSSM}}^{\text{LO}}(\text{no } \tilde{t})}{\sigma_{\text{SM}}^{\text{LO}}} \text{ CONTOUR PLOT}$$
$\sigma_{nr}/\sigma_{SM}^{LO}$ CONTOUR PLOT

$\tan\beta$ vs $m_A (\text{GeV})$
NMSSM CONSTRAINTS

PROB(1) chargino too light
PROB(2) excluded by Z -> neutralinos
PROB(3) charged Higgs too light
PROB(4) excluded by ee -> hZ
PROB(5) excluded by ee -> hZ, h -> bb
PROB(6) excluded by ee -> hZ, h -> tautau
PROB(7) excluded by ee -> hZ, h -> invisible
PROB(8) excluded by ee -> hZ, h -> 2jets
PROB(9) excluded by ee -> hZ, h -> 2photons
PROB(10) excluded by ee -> hZ, h -> AA -> 4bs
PROB(11) excluded by ee -> hZ, h -> AA -> 4taus
PROB(12) excluded by ee -> hZ, h -> AA -> 2bs 2taus
PROB(13) excluded by Z -> hA (Z width)
PROB(14) excluded by ee -> hA -> 4bs
PROB(15) excluded by ee -> hA -> 4taus
PROB(16) excluded by ee -> hA -> 2bs 2taus
PROB(17) excluded by ee -> hA -> AAA -> 6bs
PROB(18) excluded by ee -> hA -> AAA -> 6taus
PROB(19) excluded by ee -> Zh -> ZAA -> Z + light pairs
PROB(20) excluded by stop -> b l sneutrino
PROB(21) excluded by stop -> neutralino c
PROB(22) excluded by sbottom -> neutralino b
PROB(23) squark/gluino too light
PROB(24) selectron/smuon too light
PROB(25) stau too light
PROB(26) lightest neutralino is not LSP or < 511 keV
PROB(27) Landau Pole in l, k, ht, hb below MGUT
PROB(28) unphysical global minimum
PROB(29) Higgs soft masses \(\gg\) Msusy
PROB(30) excluded by DM relic density (checked only if OMGFLAG=\/=0)
PROB(31) excluded by DM SI WIMP-nucleon xs (checked if $|\text{OMGFLAG}| = 2$ or 4)  
PROB(32) $b \rightarrow s \gamma$ more than 2 sigma away  
PROB(33) Delta $M_s$ more than 2 sigma away  
PROB(34) Delta $M_d$ more than 2 sigma away  
PROB(35) $B_s \rightarrow \mu^+\mu^-$ more than 2 sigma away  
PROB(36) $B^+ \rightarrow \tau^+\nu_\tau$ more than 2 sigma away  
PROB(37) $(g - 2)_\mu$ more than 2 sigma away  
PROB(38) excluded by Upsilon(1S) $\rightarrow A$ gamma  
PROB(39) excluded by $\eta_b(1S)$ mass measurement  
PROB(40) $\text{BR}(B \rightarrow X_s \mu^+\mu^-)$ more than 2 sigma away  
PROB(41) excluded by $ee \rightarrow hZ, h \rightarrow AA \rightarrow 4\text{taus}$ (ALEPH analysis)  
PROB(42) excluded by top $\rightarrow b H^+, H^+ \rightarrow c s$ (CDF, D0)  
PROB(43) excluded by top $\rightarrow b H^+, H^+ \rightarrow \tau \nu_\tau$ (D0)  
PROB(44) excluded by top $\rightarrow b H^+, H^+ \rightarrow W^+ A1, A1 \rightarrow 2\text{taus}$ (CDF)  
PROB(45) excluded by $t \rightarrow bH^+$ (LHC)
PROB(46) No Higgs in the MHmin-MHmax GeV range
PROB(47) chi2gam > chi2max
PROB(48) chi2bb > chi2max
PROB(49) chi2zz > chi2max
PROB(51) excluded by H/A->tautau
PROB(52) Excluded by H->AA->4leptons/2lept.+2b (LHC)
PROB(53) excluded by ggF->H/A->gamgam (65GeV < M < 122GeV, ATLAS)
PROB(55) b -> d gamma more than 2 sigma away
PROB(56) B_d -> mu+ mu- more than 2 sigma away
PROB(57) b -> s nu nubar more than 2 sigma away
PROB(58) b -> c tau nu more than 2 sigma away (as SM)
PROB(59) K -> pi nu nubar more than 2 sigma away
PROB(60) DMK / epsK more than 2 sigma away
PROB(61) excluded by DM SD WIMP-neutron xs (checked if |OMGFLAG| =2 or 4)
PROB(62) excluded by DM SD WIMP-proton xs (checked if |OMGFLAG| =2 or 4)
# All Input Parameters of NMSSM Benchmarks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{LO}$ (fb)</td>
<td>42.60, 41.34, 29.31</td>
</tr>
<tr>
<td>$\sigma^{LO}_{res}$ (fb)</td>
<td>5.70, 9.77, 1.74 x 10^{-3}</td>
</tr>
<tr>
<td>$\sigma^{LO}_{nr}$ (fb)</td>
<td>35.08, 29.42, 29.22</td>
</tr>
<tr>
<td>$\sigma^{LO}_{int}$ (fb)</td>
<td>1.82, 2.15, 0.0857</td>
</tr>
<tr>
<td>$\sigma^{LO}/\sigma^{LO}_{SM}$</td>
<td>1.91, 1.86, 1.32</td>
</tr>
<tr>
<td>$m_{H_1}$ (GeV)</td>
<td>124.8, 124.9, 44.2</td>
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<tr>
<td>$m_{H_2}$ (GeV)</td>
<td>424.6, 290.2, 124.9</td>
</tr>
<tr>
<td>$m_{H_3}$ (GeV)</td>
<td>1564.7, 660.3, 719.9</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>7.0, 1.73, 3.90</td>
</tr>
<tr>
<td>$\lambda$</td>
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<tr>
<td>$\kappa$</td>
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<td>$A_{\lambda}$ (GeV)</td>
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<td>$A_{\kappa}$ (GeV)</td>
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<tr>
<td>$m_{\tilde{Q}_3}$ (GeV)</td>
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</tr>
<tr>
<td>$m_{\tilde{L}_3}$ (GeV)</td>
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