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).

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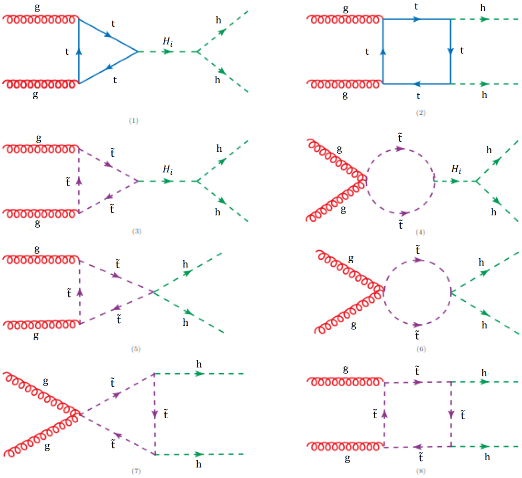
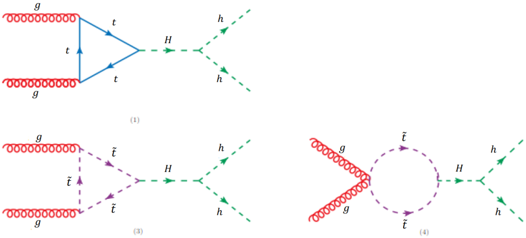
  - allow us to study the interference between resonant and nonresonant amplitudes
- Includes both quark and squark loop contributions
- Separate the cross section into resonant, nonresonant, and interference parts
  - To better understand how SUSY Higgs pair production cross section is enhanced as compared to SM case

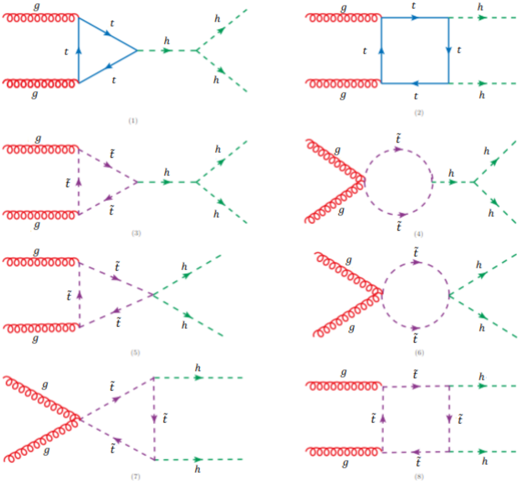
Leading order Feynman diagrams for Higgs pair production in MSSM:



Resonant amplitude:



Nonresonant amplitude:



VALID PARAMETER SPACE

- Require mass of light CP-even Higgs boson to be 125 ± 0.5 GeV
  - Stop mixing parameter X_t can be determined by m_A and $\tan\beta$ (μ, M_1, M_2, M_3, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$ are fixed)
  - X_t satisfies the vacuum stability bound:

$$(X_t + \frac{\mu}{\tan\beta})^2 \leq (3.4(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + 0.5|m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2|) + 60(\frac{m_Z^2}{2}\cos 2\beta + m_A^2 \cos^2\beta)$$

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m_A and tanβ are restricted by:

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

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- Precision measurement of Higgs Couplings
  - ref: CMS PAS HIG-17-031
  - checked coupling modifiers: κ_t, κ_b, κ_τ, κ_γ, κ_g
  - Lower bound of m_A

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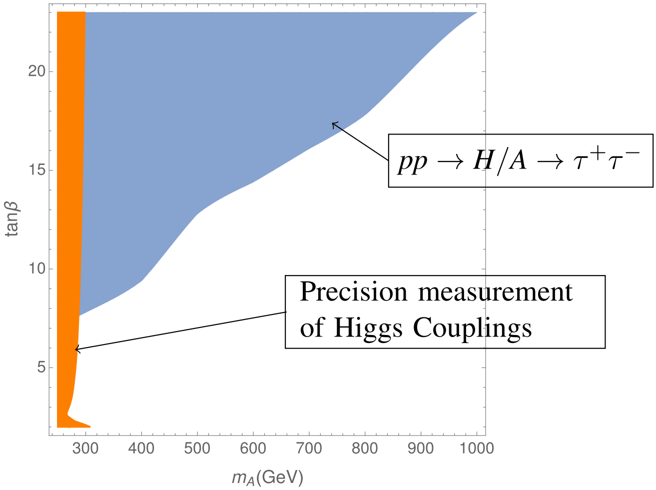

UNDERSTANDING INTERFERENCE TERM

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 $\quad A^{nr} = |A^{nr}| e^{i\delta_{nr}}$,

$$A^H_\triangleright = a_{res} \frac{\hat{s}}{\hat{s} - m_H^2 + i\Gamma_H m_H} \ , \qquad a_{res} = |a_{res}| e^{i\delta_{res}} \ .$$

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

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

$$\mathcal{I}_{int} = |a_{res}||A^{nr}| \sin(\delta_{res} - \delta_{nr}) \hat{s} \frac{\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2}$$

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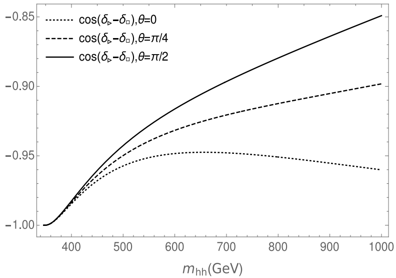
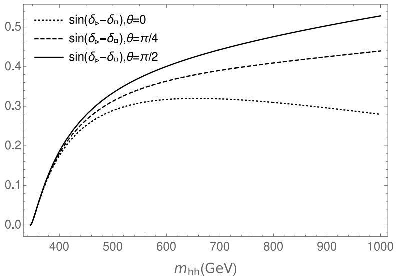
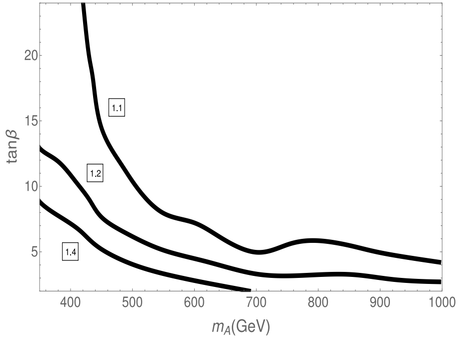




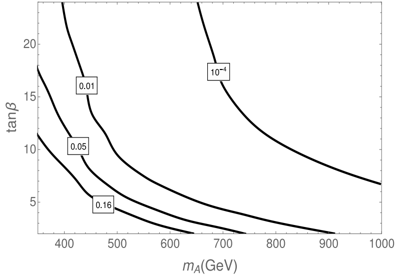
Interference Term		δ_{res}	δ_{nr}	$\delta_{res} - \delta_{nr}$	Relative phase	Interference Sign
$\mathrm{Re}(A^H_\triangleright \times A^{h*}_\triangleright)$	$\mathcal{R}_{int}$	$\delta_\triangleright$	$\delta_\triangleright$	0	$\cos 0 = 1$	$-/+$
	$\mathcal{I}_{int}$				$\sin 0 = 0$	0
$\mathrm{Re}(A^H_\triangleright \times A^{h*}_\square)$	$\mathcal{R}_{int}$		$\delta_\square$	$\delta_\triangleright - \delta_\square$	$\cos(\delta_\triangleright - \delta_\square) < 0$	$+/-$
	$\mathcal{I}_{int}$				$\sin(\delta_\triangleright - \delta_\square) > 0$	$+$

RESULTS

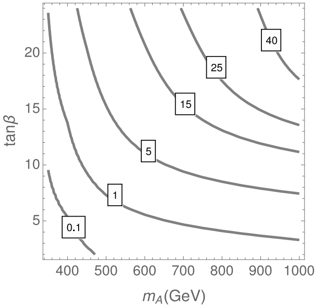


- $\sigma^{LO}_{MSSM} / \sigma^{LO}_{SM}$ (σ^{LO}_{SM}=21.7 fb)
- Always larger than SM cross section (10% $\sim$ 40% enhancement)

RESULTS

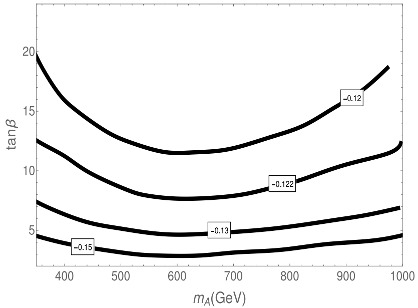


- $\sigma_{res} / \sigma_{SM}^{LO}$
- σ_{res} is largest when tanβ and m_A are small
- σ_{nr} dominates when tanβ and m_A are large



- $\sigma_{I_{int}} / \sigma_{res}$
- When tanβ and m_A are small, $\sigma_{I_{int}}$ can be as large as σ_{res}

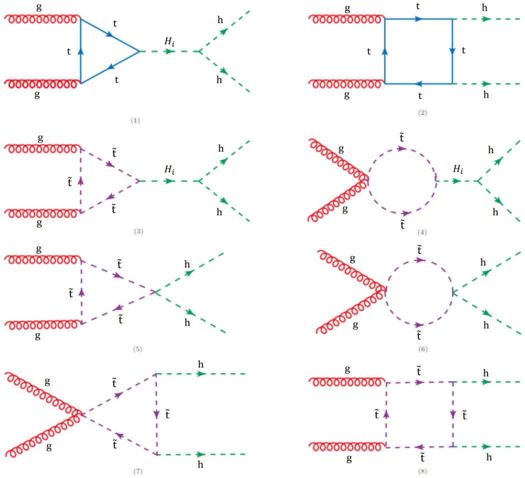
RESULTS



- $\delta_3 = \frac{g_{hhh}^{MSSM} - g_{hhh}^{SM}}{g_{hhh}^{SM}}$
- Always smaller than SM value

  $(-12\% \sim -15\%)$
- $\kappa_t \approx 1$
- δ_3 is the main factor that increases σ_{nr} by about $8\% \sim 10\%$

Leading order Feynman diagrams for Higgs pair production in NMSSM:



PARAMETER SPACE SCAN RANGES

	$\tan\beta$	λ	κ	A_λ	A_κ	μ_{eff}	M_1	M_2	M_3	A_t	A_b	A_τ	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$
				(in TeV)										
min	1	0	-0.7	-1	-1	-0.5	0.1	0.2	1.3	-6	-6	-3	0.6	0.6
max	10	0.7	0.7	1	1	0.5	1	2	7	6	6	3	4	4

- 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

$\sigma^{LO}_{SM} = 22.3$ fb

σ^{LO} (fb)	42.60	41.34	29.31
σ^{LO}_{res} (fb)	5.70	9.77	1.74×10^{-3}
σ^{LO}_{nr} (fb)	35.08	29.42	29.22
σ^{LO}_{int} (fb)	1.82	2.15	0.0857
$\sigma^{LO}/\sigma^{LO}_{SM}$	1.91	1.86	1.32
m_{H_1} (GeV)	124.8	124.9	44.2
m_{H_2} (GeV)	424.6	290.2	124.9
m_{H_3} (GeV)	1564.7	660.3	719.9
$\tan\beta$	7.0	1.73	3.90
λ	0.15	0.47	0.42
κ	-0.46	0.27	0.11
A_λ (GeV)	964.7	-391.8	-679.9
A_κ (GeV)	981.7	322.4	197.2
μ_{eff} (GeV)	291.1	-326.0	-178.6

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

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- NMSSM:
  - σ_{NMSSM} can be larger than σ_{SM} by 90%
  - m_{H_1} can be as small as 44 GeV

INTERFERENCE TERM

$$|\mathcal{M}|^2 \propto |A_{\triangleright}^{H} + A_{\triangleright}^{nr} + A_{\square}^{nr}|^2$$
$$= |A_{\triangleright}^{H}|^2 + |A_{\triangleright}^{nr} + A_{\square}^{nr}|^2 + 2Re[A_{\triangleright}^{H} \times (A_{\triangleright}^{nr} + A_{\square}^{nr})^*]$$

The interference term is
$2Re[A_{\triangleright}^{H} \times (A_{\triangleright}^{nr} + A_{\square}^{nr})^*] = 2Re[A_{\triangleright}^{H} \times A_{\triangleright}^{nr\,*}] + 2Re[A_{\triangleright}^{H} \times A_{\square}^{nr\,*}]$.
Let $A^{nr} = |A^{nr}|e^{i\delta_{nr}}$, $a_{res} = C_{Hhh}C_{Htt}F_{\triangleright}$, then

$$A_{\triangleright}^{H} = a_{res}\frac{\hat{s}}{\hat{s} - m_H^2 + i\Gamma_H m_H}$$
$$= |a_{res}|e^{i\delta_{res}}\hat{s}\frac{\hat{s} - m_H^2 - i\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2}$$

INTERFERENCE TERM

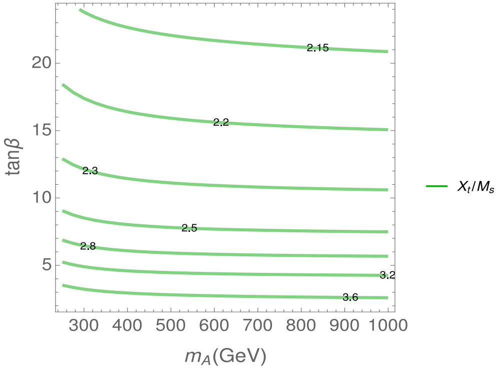
$$2Re[A_{\triangleright}^{H} \times A^{nr\,*}] = 2Re[|a_{res}||A^{nr}|e^{i(\delta_{res}-\delta_{nr})}\hat{s}\frac{\hat{s}-m_H^2-i\Gamma_H m_H}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}]$$

$$= 2(R_{int}+I_{int})$$

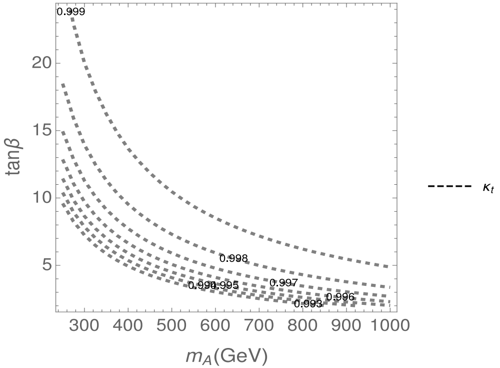
$$R_{int} = |a_{res}||A^{nr}|cos(\delta_{res}-\delta_{nr})\hat{s}\frac{\hat{s}-m_H^2}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}$$

$$I_{int} = |a_{res}||A^{nr}|sin(\delta_{res}-\delta_{nr})\hat{s}\frac{\Gamma_H m_H}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}$$

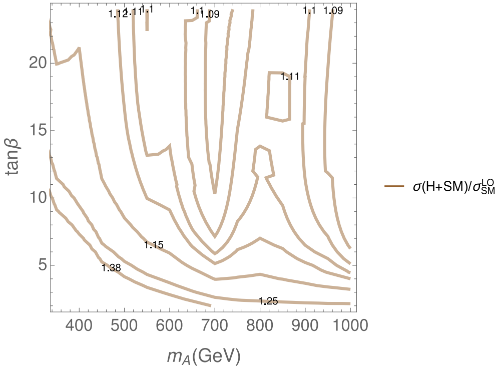
X_t/M_S contour plot



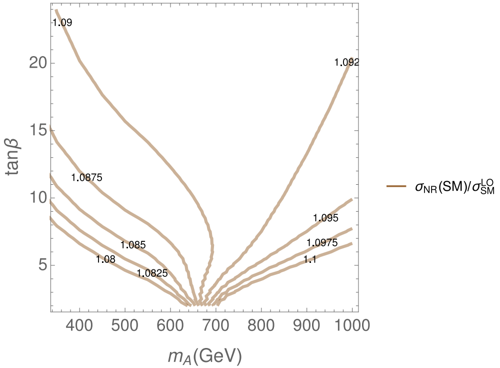
κ_t CONTOUR PLOT



$\sigma^{LO}_{MSSM}(no\ \tilde{t})/\ \sigma^{LO}_{SM}$ CONTOUR PLOT



$\sigma_{nr}/\ \sigma_{SM}^{LO}$ contour plot



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 » Msusy
PROB(30) excluded by DM relic density (checked only if OMGFLAG=/=0)

PROB(31) excluded by DM SI WIMP-nucleon xs (checked if |OMGFLAG| =2 or 4)
PROB(32) b->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->mu+mu- more than 2 sigma away
PROB(36) B+-> tau+ν_τ more than 2 sigma away
PROB(37) $(g-2)_\mu$ more than 2 sigma away
PROB(38) excluded by Upsilon(1S) -> A gamma
PROB(39) excluded by $\eta_b(1S)$ mass measurement
PROB(40) BR(B–>X_s mu+ mu-) more than 2 sigma away
PROB(41) excluded by ee -> hZ, h -> AA -> 4taus (ALEPH analysis)
PROB(42) excluded by top -> b H+, H+ -> c s (CDF, D0)
PROB(43) excluded by top -> b H+, H+ -> τ ν_τ (D0)
PROB(44) excluded by top -> b H+, H+ -> W+ A1, A1 -> 2taus (CDF)
PROB(45) excluded by t -> 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

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M_1 (GeV)	642	520	605
M_2 (GeV)	1239	722	1678
M_3 (GeV)	3636	1566	3421
A_t (GeV)	-4608	5234	5580
A_b (GeV)	-1342	-2602	-2033
A_τ (GeV)	1589	-1153	1742
$m_{\tilde{Q}_3}$ (GeV)	1827	3047	3671
$m_{\tilde{L}_3}$ (GeV)	2136	654	3508