Interference Effect in Di-Higgs Production in SUSY models (MSSM with Gauge Extensions)

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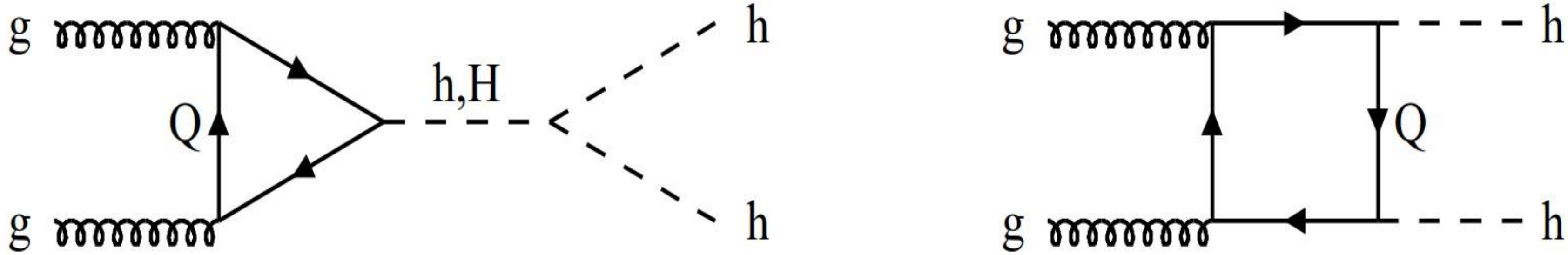
Motivation



(a) (b)

$$|\mathcal{M}|^2 = |\mathcal{M}_{Res} + \mathcal{M}_{NR}|^2$$

Interference term: $|\mathcal{M}|^2_{int} = 2Re[\mathcal{M}_{Res} \times \mathcal{M}^*_{NR}]$

- Where in the parameter space ($\tan\beta$, m_A) does the interference term is large?
- Why?

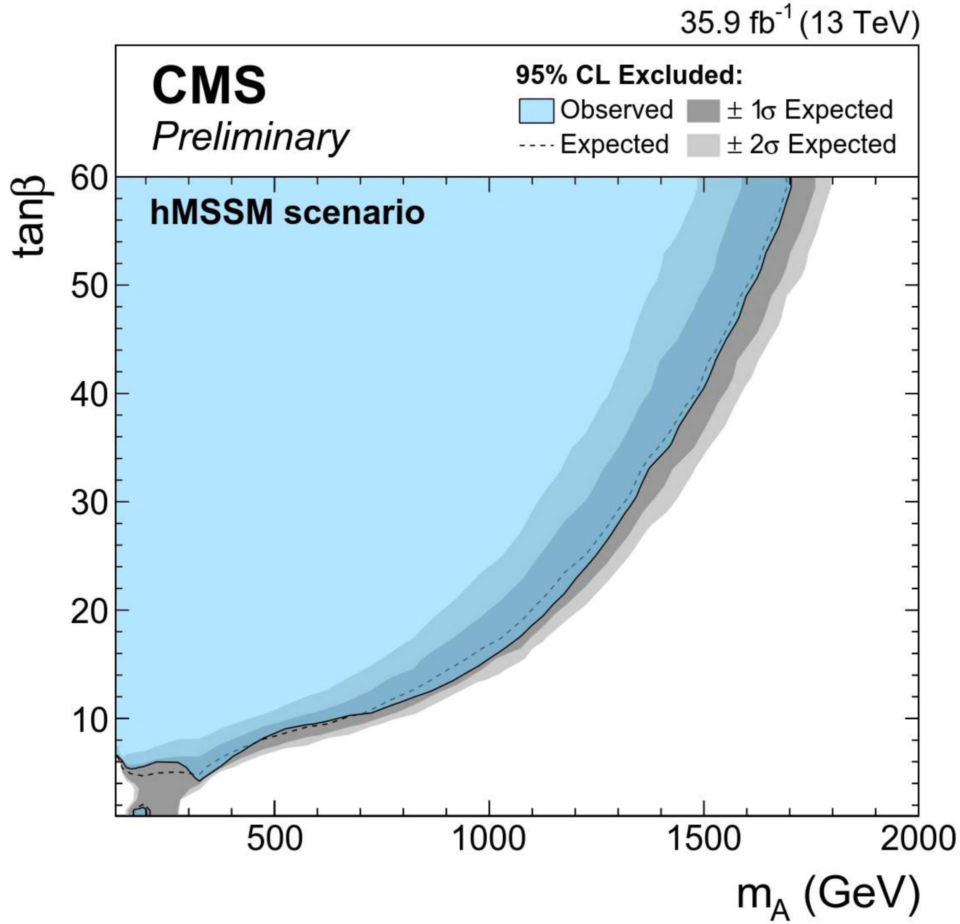
Choosing Region of Parameter Space

- Experimental Constraint:

1. Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $s^{1/2}$ = 13 TeV [1]
2. Precision measurement of Higgs Couplings [2]

- Obtained upper Bound of $\tan\beta$ from (1).
- Obtained lower Bound of m_A by comparing $\kappa_i = \frac{g_i^{MSSM}}{g_i^{SM}}$ calculated using FeynHiggs program with the experimental data from (2). (~220 GeV)

[1], Fig. 9



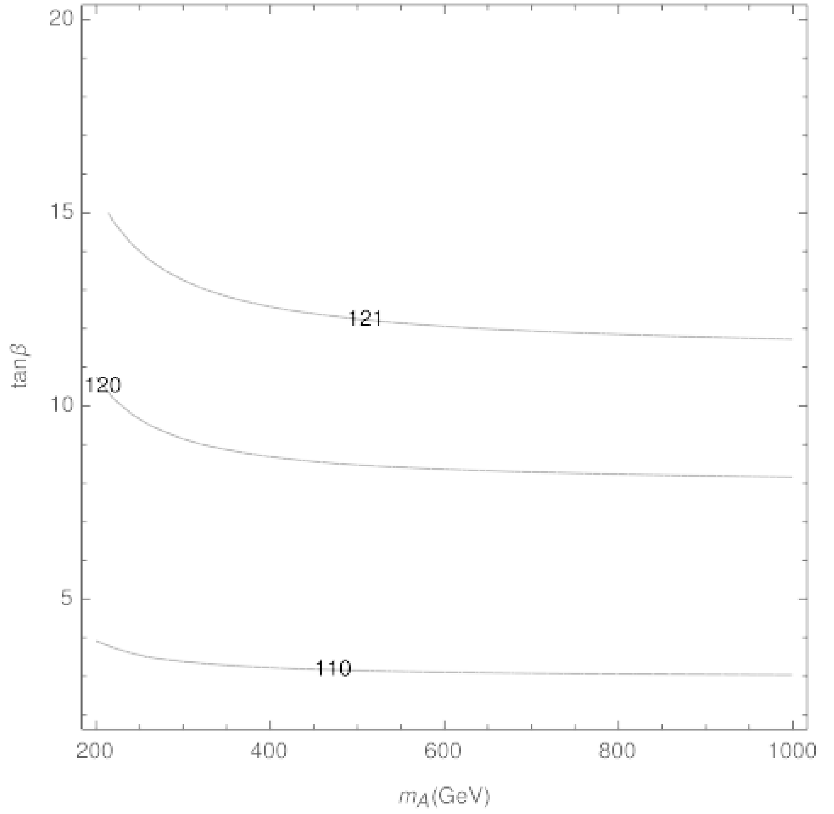
[2],Table 8

Parameter											
κ_W				κ_Z				κ_t			
Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.
1.09	$^{+0.12}_{-0.17}$	$^{+0.08}_{-0.16}$	$^{+0.09}_{-0.04}$	0.99	$^{+0.11}_{-0.12}$	$^{+0.09}_{-0.10}$	$^{+0.07}_{-0.07}$	1.11	$^{+0.12}_{-0.11}$	$^{+0.08}_{-0.07}$	$^{+0.09}_{-0.08}$
	$\left(^{+0.11}_{-0.10}\right)$	$\left(^{+0.08}_{-0.08}\right)$	$\left(^{+0.06}_{-0.06}\right)$		$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.06}_{-0.06}\right)$		$\left(^{+0.11}_{-0.12}\right)$	$\left(^{+0.07}_{-0.08}\right)$	$\left(^{+0.09}_{-0.09}\right)$

Parameter											
κ_b				κ_τ				κ_μ			
Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.
−1.10	$^{+0.33}_{-0.24}$	$^{+0.29}_{-0.16}$	$^{+0.15}_{-0.17}$	1.01	$^{+0.16}_{-0.20}$	$^{+0.11}_{-0.17}$	$^{+0.12}_{-0.10}$	0.82	$^{+0.50}_{-0.82}$	$^{+0.49}_{-0.82}$	$^{+0.11}_{-0.00}$
	$\left(^{+0.23}_{-0.22}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.16}_{-0.16}\right)$		$\left(^{+0.17}_{-0.15}\right)$	$\left(^{+0.12}_{-0.10}\right)$	$\left(^{+0.12}_{-0.11}\right)$		$\left(^{+0.45}_{-1.01}\right)$	$\left(^{+0.44}_{-1.00}\right)$	$\left(^{+0.07}_{-0.11}\right)$

Fixing m_h by $SU(2)\otimes SU(2)$ Gauge Extensions of MSSM

Reason: m_h is not around 125 GeV in the chosen region of parameter space.



Fixing m_h by SU(2)⊗SU(2) Gauge Extensions of MSSM

- The effect of SU(2)⊗SU(2) Gauge Extensions is : [3]

$$g^2 \to g^2\Delta,$$

where $\Delta = \dfrac{1+\frac{4m_\Sigma^2}{u^2}\frac{1}{g_1^2}}{1+\frac{4m_\Sigma^2}{u^2}\frac{1}{g_1^2+g_2^2}}$, $\dfrac{1}{g^2} = \dfrac{1}{g_1^2} + \dfrac{1}{g_2^2}$

$$m_h^2 = \frac{1}{2}\left[m_A^2 + {m'_Z}^2 - \sqrt{\left(m_A^2 + {m'_Z}^2\right)^2 - 4m_A^2 {m'_Z}^2 \cos^2 2\beta}\ \right]$$

$${m'_Z}^2 = \frac{1}{4}(\mathrm{g}^2\Delta + g_Y^2)\mathrm{v}^2$$

($m_\Sigma^2 = M_{\widetilde{\Sigma}}^\dagger M_{\widetilde{\Sigma}} + {m'_\Sigma}^2$; m'_Σ is soft mass term corresponds to scalar component of Σ supermultiplet; $M_{\widetilde{\Sigma}}$ is the mass corresponds to fermionic component of Σ. Σ is bidoublet chiral supermultiplet that links the two SU(2) gauge groups.)

Fixing m_h by SU(2)⊗SU(2) Gauge Extensions of MSSM

- Other consequences:

1. modified ghhh, gHhh

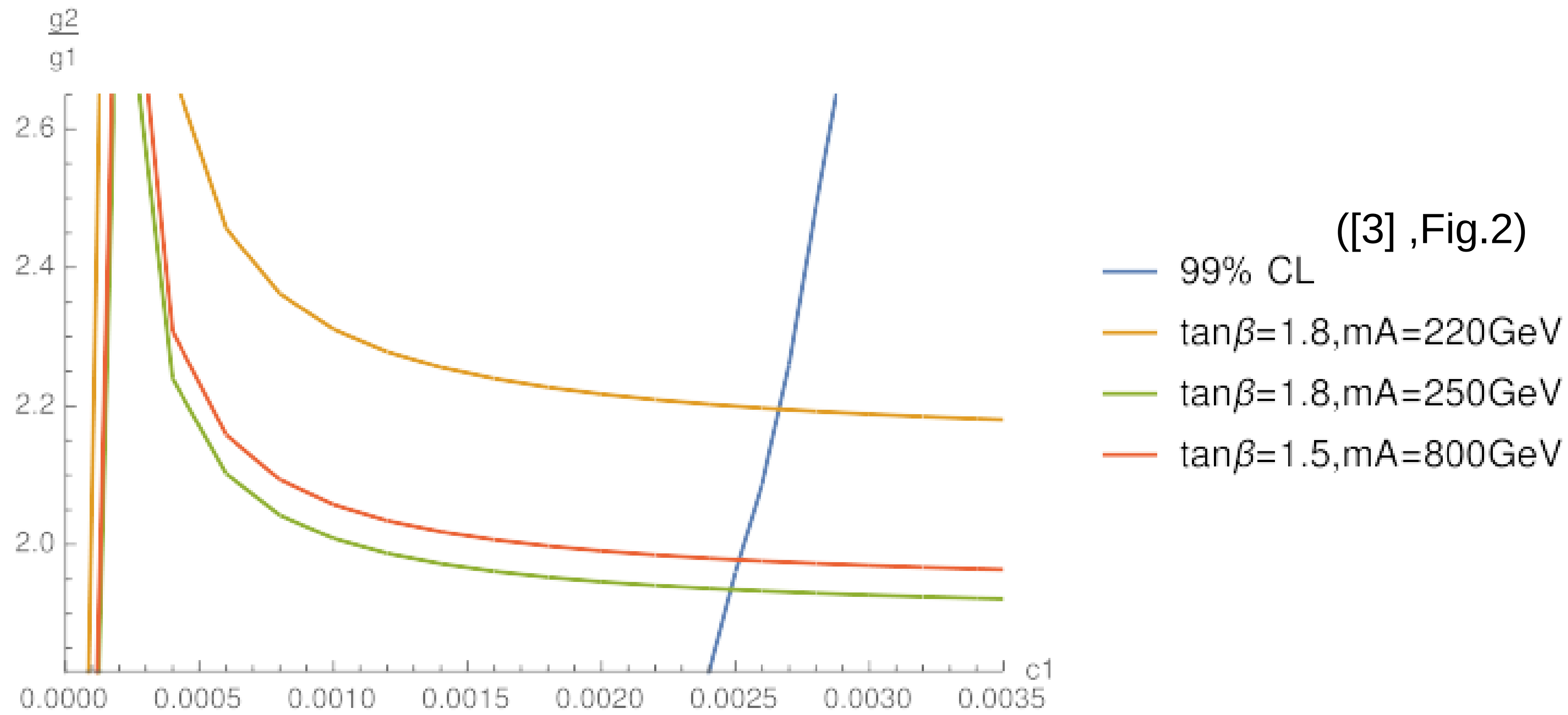
$$ghhh = \frac{-3i}{2}\cos 2\alpha \sin(\beta+\alpha)\frac{gm_z}{\cos\theta_w}$$

$$gHhh = \frac{-i}{2}[2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha)]\frac{gm_z}{\cos\theta_w}$$

$$\frac{gm_z}{\cos\theta_w} = \frac{v}{2}(g^2+g_Y^2) \rightarrow \frac{v}{2}(g^2\Delta + g_Y^2)$$

2. EW observables (since they are related to structure of gauge symmetry)

Precision EW Constraints



([3] ,Fig.2)

$m_\Sigma = 10TeV,\ c_1 = \frac{1}{2}\left(\frac{g}{g_1}\right)^4\left(\frac{v}{u}\right)^2$,and required m_h=125GeV

Understanding Interference Term

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15}\pi M_w^4 \hat{s}^2}\left(|gauge1|^2 + |gauge2|^2\right)$$ [4]

$$gauge1 = gauge1(\triangle) + gauge1(\square)$$

$$-gauge1(\triangle) = \mathrm{A}^{H}{}_{\triangle} + \mathrm{A}^{h}{}_{\triangle}$$

$$-gauge1(\square) = \mathrm{A}^{h}{}_{\square}$$

(Form factors in [5], App. A)

$$\mathrm{A}^{H}{}_{\triangle} = -6m_h^2 C_{Hhh} C_{Htt} F_{\triangle} \frac{\hat{s}}{\hat{s} - m_H^2 + i\Gamma_H m_H}$$

$$\mathrm{A}^{h}{}_{\triangle} = -6m_h^2 C_{hhh} C_{htt} F_{\triangle} \frac{\hat{s}}{\hat{s} - m_h^2 + i\Gamma_h m_h} \approx -6m_h^2 C_{hhh} C_{htt} F_{\triangle} \frac{\hat{s}}{\hat{s} - m_h^2}$$

$$\mathrm{A}^{h}{}_{\square} = -4C_{htt}^2 F_{\square}\, \hat{s}$$

$$a_{Res} = -6m_h^2 C_{Hhh} C_{Htt} F_{\triangle}$$

Understanding Interference Term

$$|gauge1|^2 = |\mathrm{A^H}_\triangle + \mathrm{A^h}_\triangle + \mathrm{A^h}_\square \Big|^2$$

$$= |\mathrm{A^H}_\triangle|^2 + |\mathrm{A^h}_\triangle + \mathrm{A^h}_\square|^2 + 2\mathrm{Re}[\mathrm{A^H}_\triangle \times (\mathrm{A^h}_\triangle + \mathrm{A^h}_\square)^*]$$

$$2\mathrm{Re}[\mathrm{A^H}_\triangle \times (\mathrm{A^h}_\triangle + \mathrm{A^h}_\square)^*] = 2\mathrm{Re}[\mathrm{A^H}_\triangle \times \mathrm{A^h}_\triangle{}^*] + 2\mathrm{Re}[\mathrm{A^H}_\triangle \times \mathrm{A^h}_\square{}^*]$$

Let $\mathrm{A^H}_\triangle = |a_{Res}|e^{i\delta_{Res}} \frac{\hat{s}}{\hat{s}-m_H^2+i\Gamma_H m_H} = |a_{Res}|e^{i\delta_{Res}}\hat{s}\,\frac{\hat{s}-m_H^2-i\Gamma_H m_H}{\left(\hat{s}-m_H^2\right)^2+(\Gamma_H m_H)^2}$,

$\mathrm{A^h}_\triangle = |\mathrm{A^h}_\triangle|e^{i\delta_{NR,\triangle}}$, $\quad \mathrm{A^h}_\square = |\mathrm{A^h}_\square|e^{i\delta_{NR,\square}}$

$$2\mathrm{Re}[\mathrm{A^H}_\triangle \times \mathrm{A_{NR}}^*] = 2\mathrm{Re}[|a_{Res}|\hat{s}|A_{NR}|e^{i(\delta_{Res}-\delta_{NR})}\frac{\hat{s}-m_H^2-i\Gamma_H m_H}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}]$$

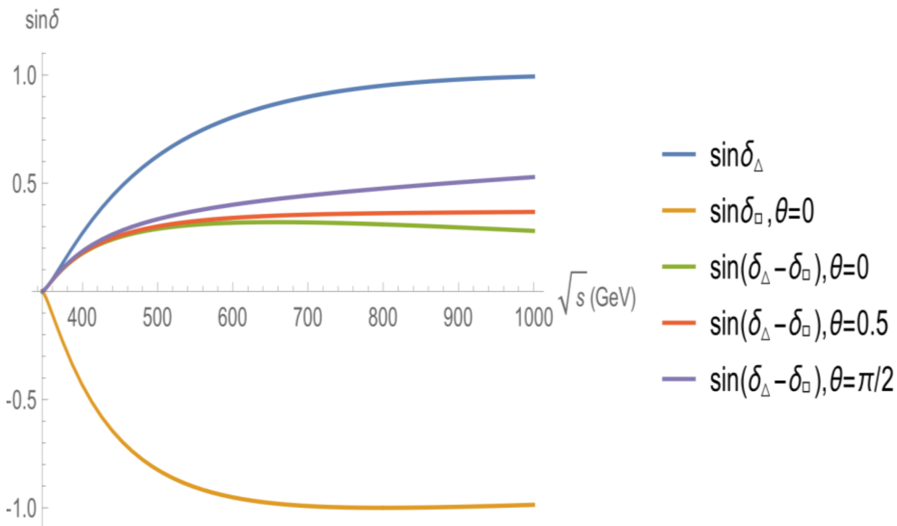
$$= 2(\mathrm{R_{int}} + \mathrm{I_{int}})$$

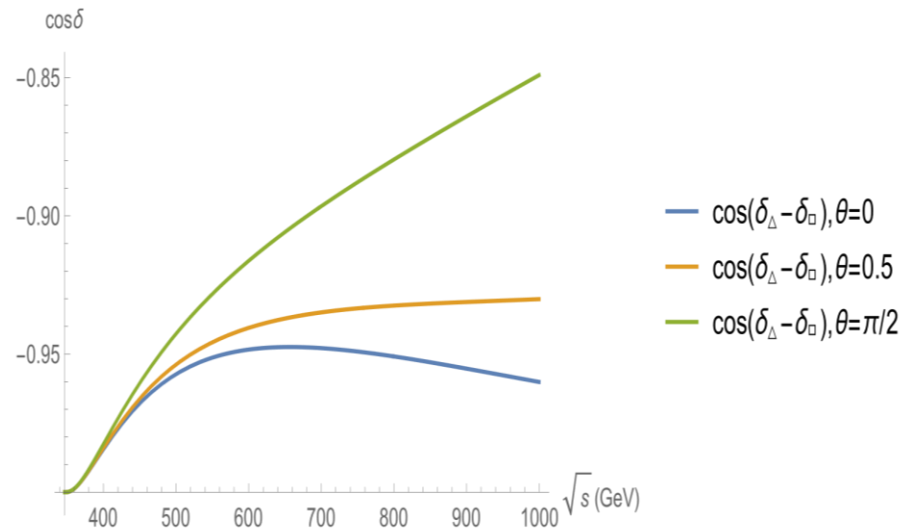
$$R_{int} = |A_{NR}||a_{Res}|\hat{s}\frac{\hat{s}-m_H^2}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}\cos(\delta_{Res}-\delta_{NR})$$

$$I_{int} = |A_{NR}||a_{Res}|\hat{s}\frac{\Gamma_H m_H}{(\hat{s}-m_H^2)^2+(\Gamma_H m_H)^2}\sin(\delta_{Res}-\delta_{NR})$$

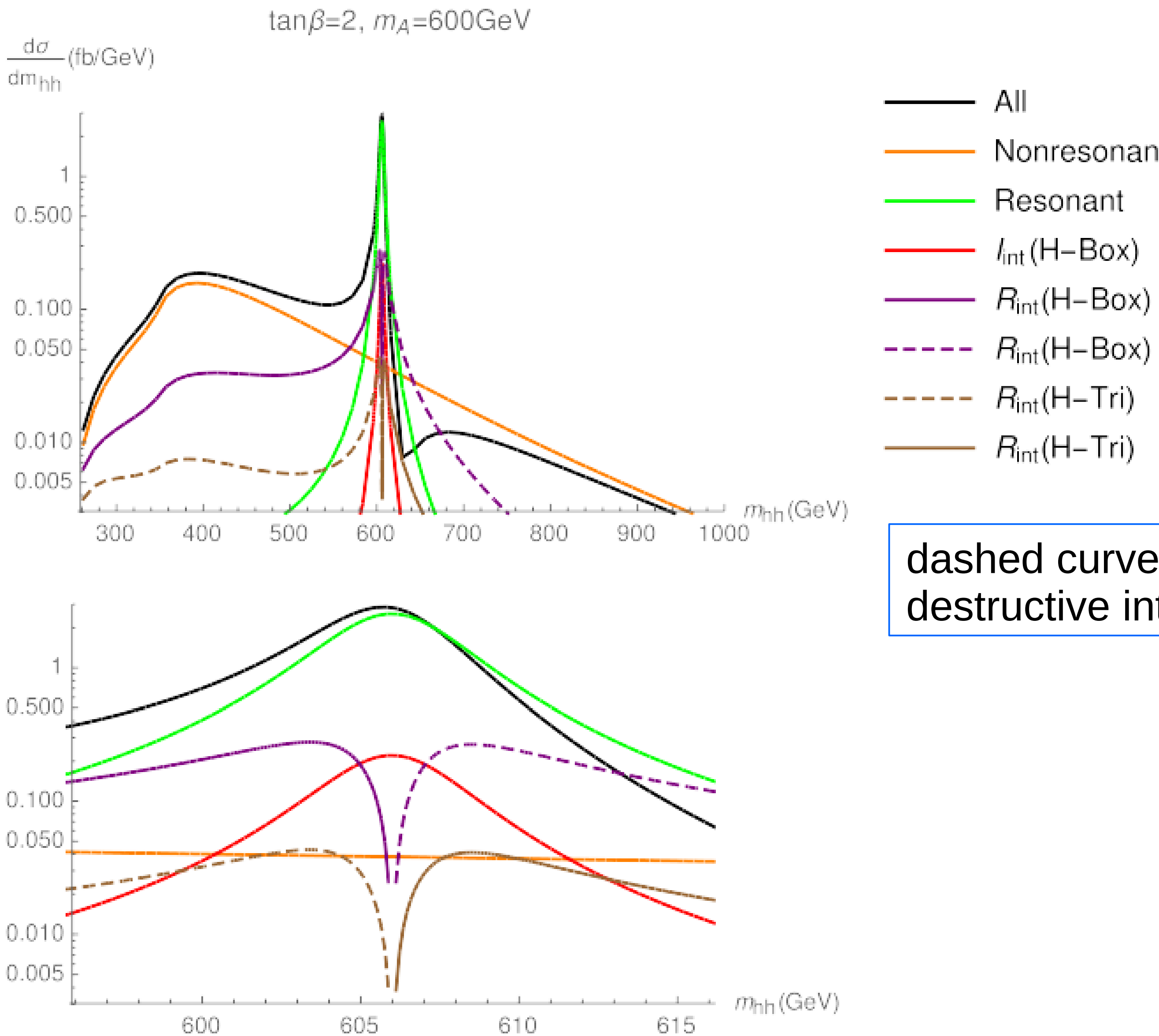
Understanding Interference Term

Interference Term		δ_{Res}	δ_{NR}	δ_{Res}-δ_{NR}		Interference Sign
$A^{H}_{\triangle}$ --$A^{h}_{\triangle}$	R_{int}	$\delta_{\triangle}+\pi$	$\delta_{\triangle}+\pi$	0	$\cos(\delta_{Res}-\delta_{NR})=1$	-/+
	I_{int}				$\sin(\delta_{Res}-\delta_{NR})=0$	0
$A^{H}_{\triangle}$ --$A^{h}_{\square}$	R_{int}		$\delta_{\square}+\pi$	$\delta_{\triangle}-\delta_{\square}$	$\cos(\delta_{Res}-\delta_{NR})=\cos(\delta_{\triangle}-\delta_{\square})<0$	+/-
	I_{int}				$\sin(\delta_{Res}-\delta_{NR})=\sin(\delta_{\triangle}-\delta_{\square})>0$	+



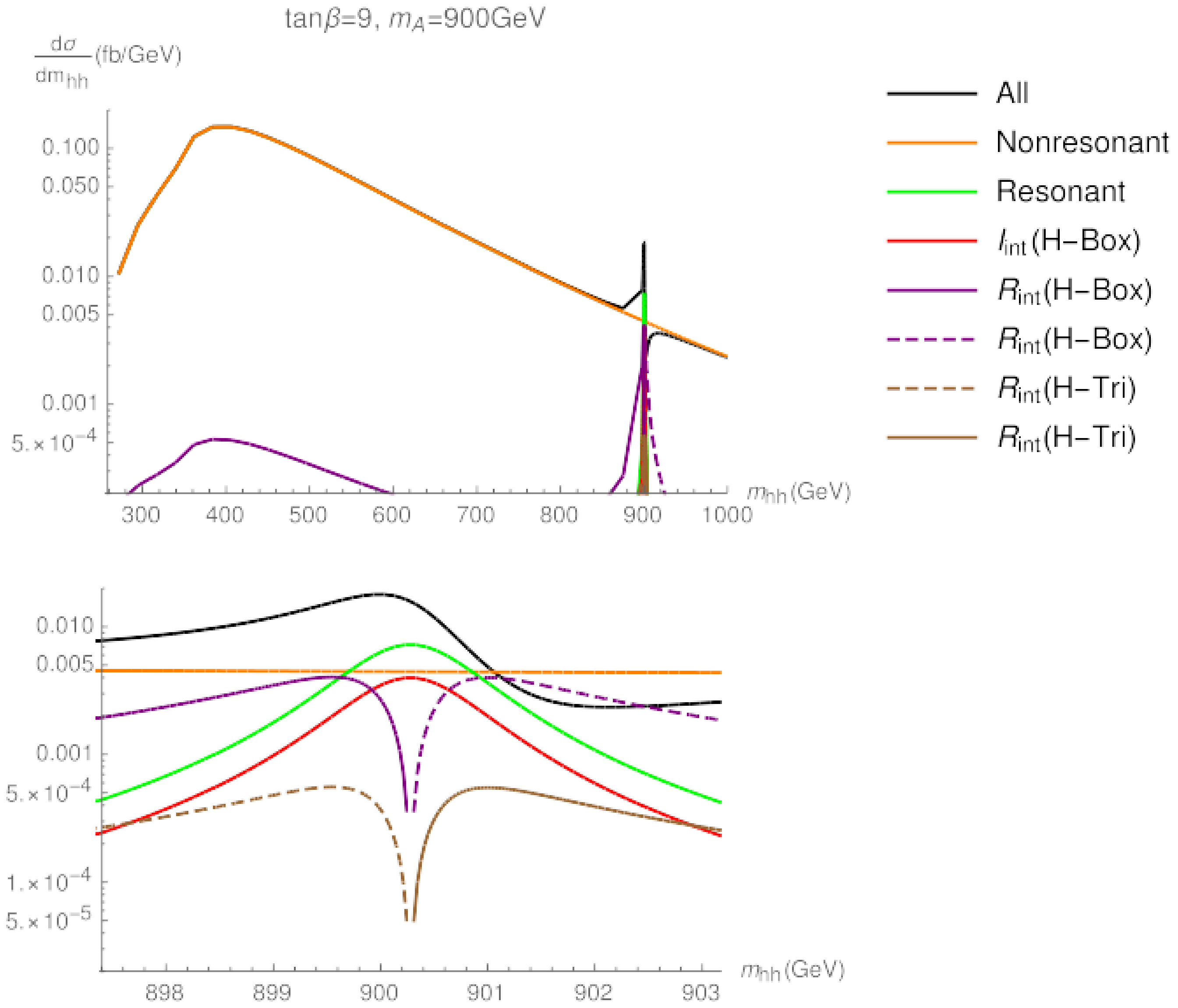


Results

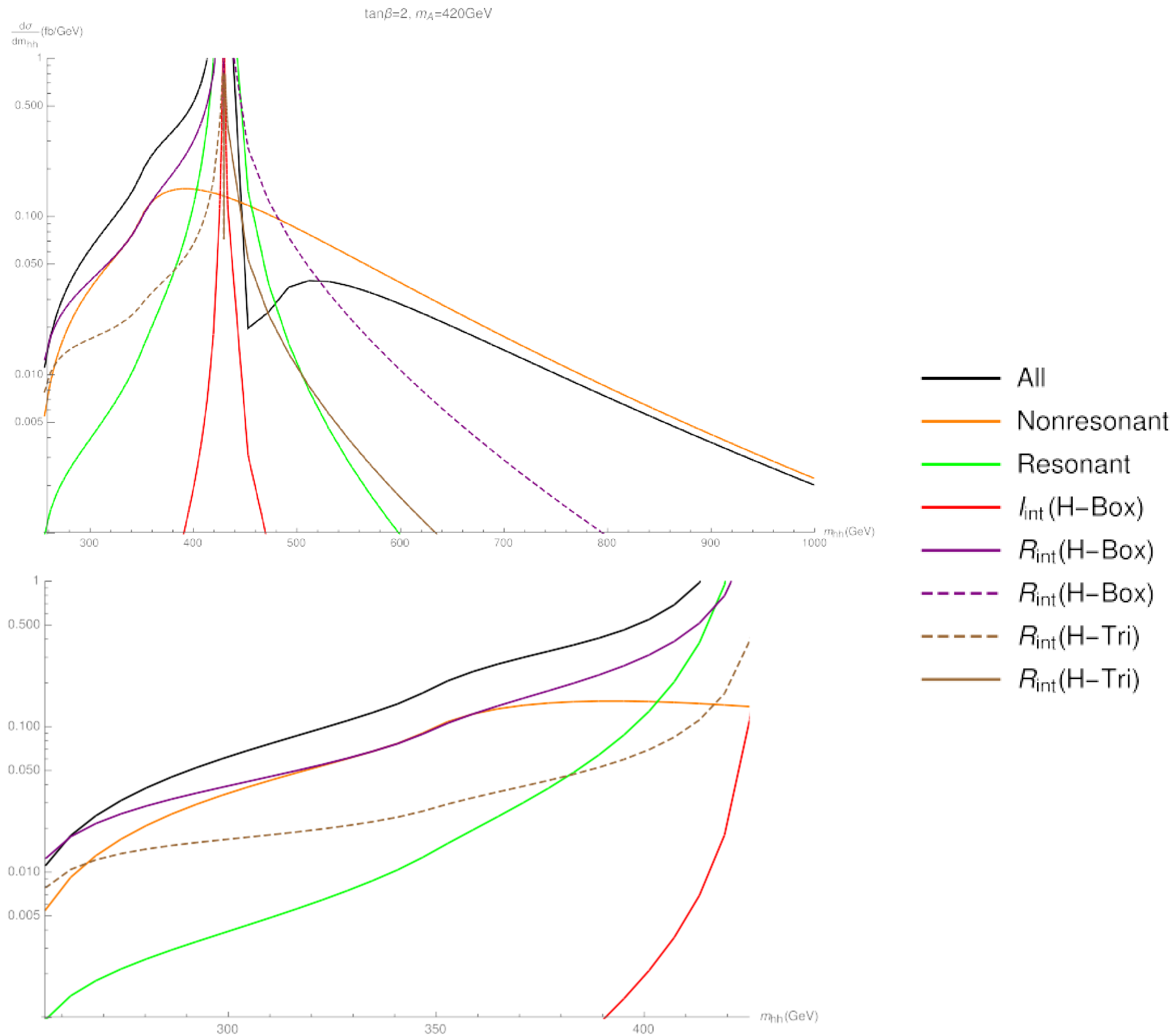


dashed curves represents destructive interferences

Results

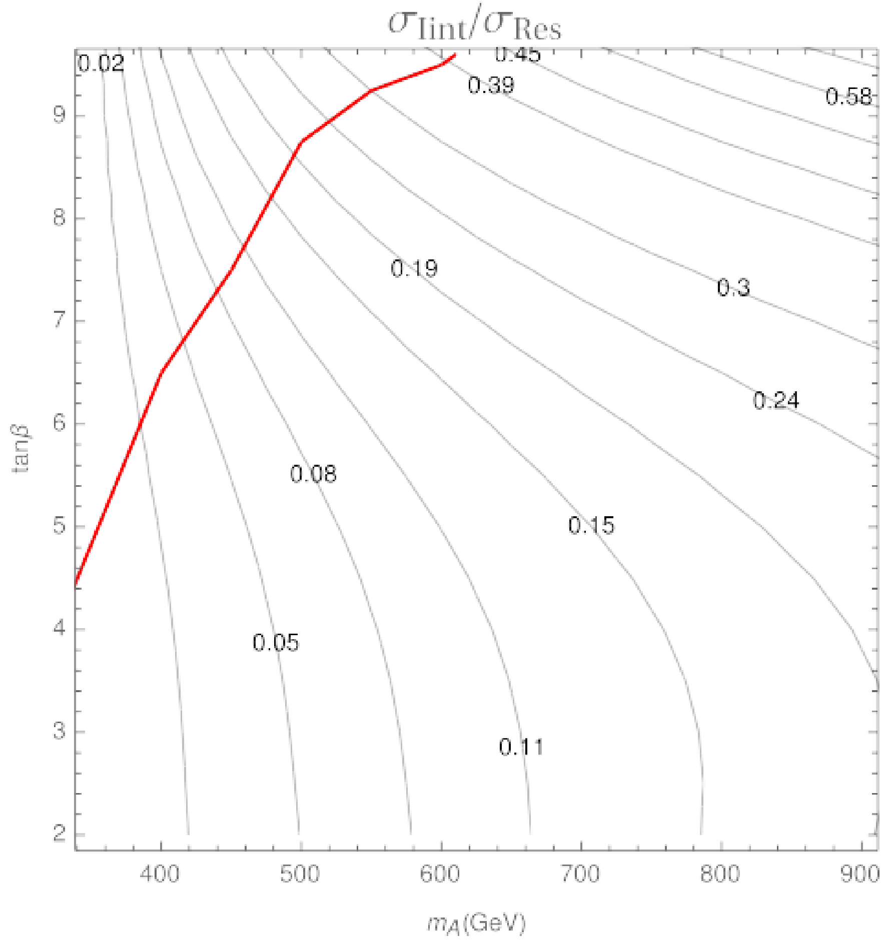


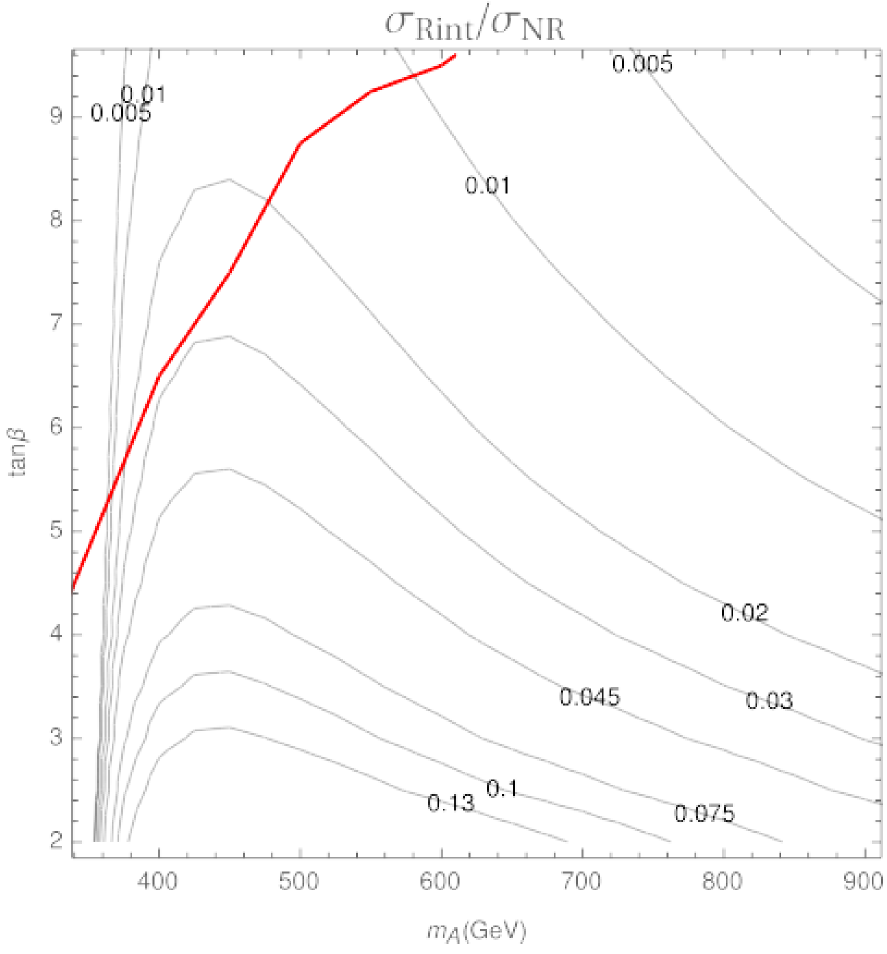
tanβ=9, m_A=900GeV
$\frac{d\sigma}{dm_{hh}}$(fb/GeV)
0.100
0.050
0.010
0.005
0.001
5.×10⁻⁴
300
400
500
600
700
800
900
1000
m_{hh}(GeV)
All
Nonresonant
Resonant
I_{int}(H–Box)
R_{int}(H–Box)
R_{int}(H–Box)
R_{int}(H–Tri)
R_{int}(H–Tri)
0.010
0.005
0.001
5.×10⁻⁴
1.×10⁻⁴
5.×10⁻⁵
898
899
900
901
902
903
m_{hh}(GeV)



tanβ=2, m_A=420GeV
$\frac{d\sigma}{dm_{hh}}$(fb/GeV)
m_{hh}(GeV)
All
Nonresonant
Resonant
I_{int}(H–Box)
R_{int}(H–Box)
R_{int}(H–Box)
R_{int}(H–Tri)
R_{int}(H–Tri)

Results





The region above the red line is excluded, according to [1].

Summary

- I_{int} is responsible for enhancing the total differential cross section around the $s^{1/2}=m_H$.
- $I_{int}=I_{int}$(H-Box)
- Differential cross section corresponds to R_{int}(H-Box) is larger than R_{int}(H-Tri), so the total interference is always constructive when $s^{1/2} < m_H$, and the total interference is destructive when $s^{1/2} > m_H + 2\Gamma_H$.

Summary

- $\sigma_{Iint}/\sigma_{Res}$ increases as tanβ increases or m_A increases.
- $\sigma_{Rint}/\sigma_{NR}$ are not small when the value of m_A is around the nonresonant peak.

Future Work

- Collider phenomenology study

(Which region is already excluded by current experimental data? How the study of interference effect will change the sensitivity of High Luminosity- and High Energy- LHC searches?)

- Consider influences of other SUSY particles.

References

[1]CMS PAS HIG-17-020

[2]CMS PAS HIG-17-031

[3]arXiv:1212.0560v2[hep-ph]

[4]E.W.N.Glover and J.J.van der Bij, *Higgs Boson Pair Production via Gluon Fusion*, Nucl. Phys. **B309** (1988) 282-294

[5]arXiv:hep-ph/9603205v1

[6]arXiv:1801.00794v2[hep-ph]