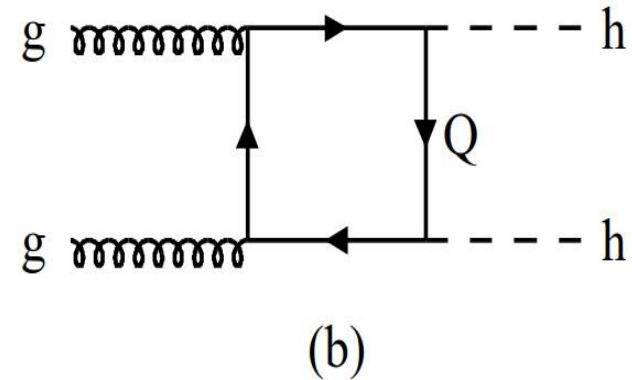
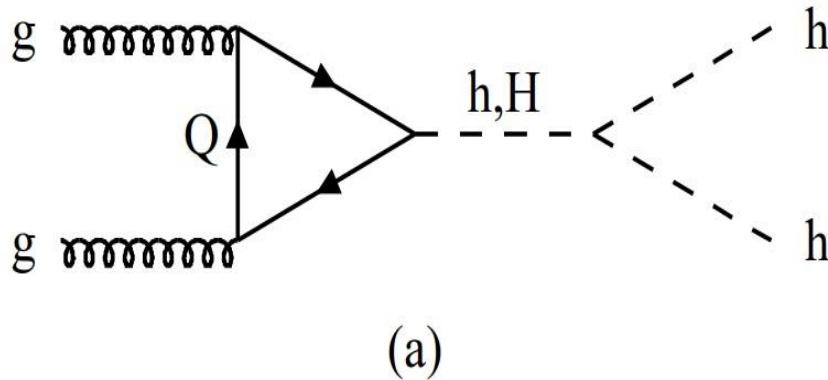


Interference Effect in Di-Higgs Production in SUSY models (MSSM with Gauge Extensions)

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Motivation



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

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

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

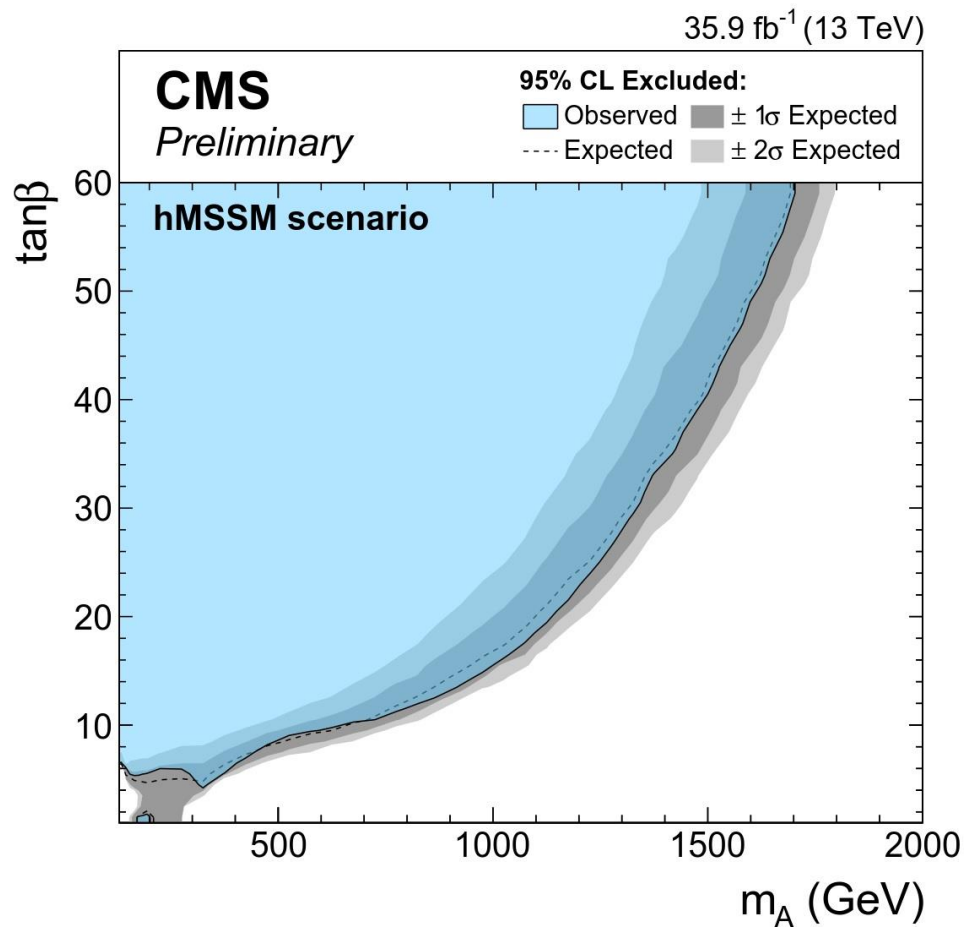
Choosing Region of Parameter Space

- 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] CMS PAS HIG-17-020

[2] CMS PAS HIG-17-031

[1], Fig. 9

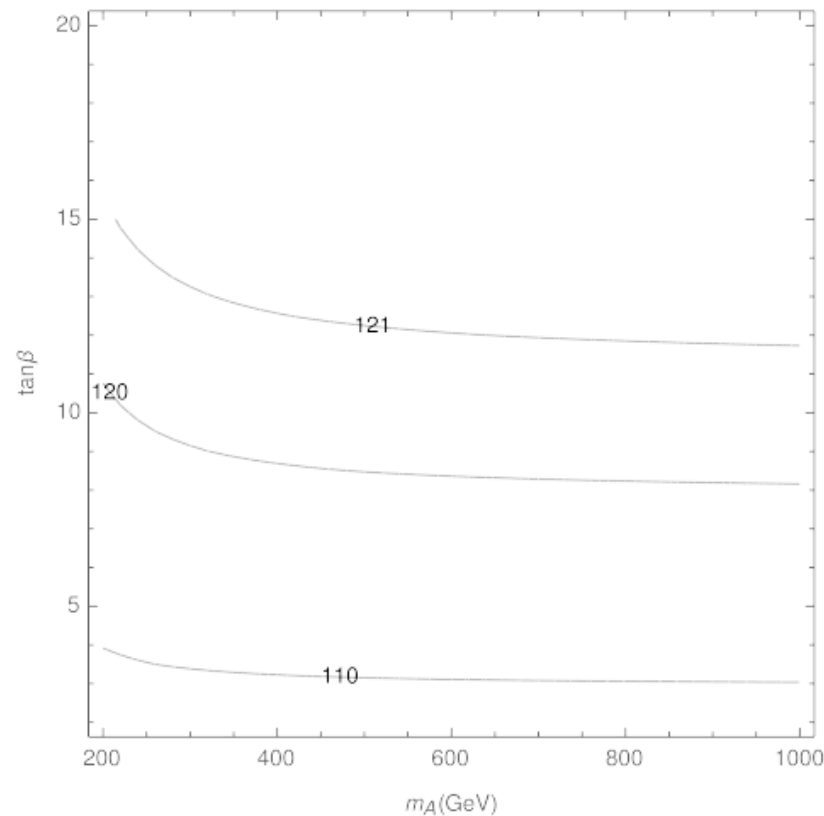


[2], Table 8

Parameter																							
κ_W				κ_Z				κ_t				κ_b				κ_τ				κ_μ			
Best fit		Uncertainty		Best fit		Uncertainty		Best fit		Uncertainty		Best fit		Uncertainty		Best fit		Uncertainty		Best fit		Uncertainty	
value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.	value	Stat.	Syst.
1.09	+0.12	+0.08	+0.09	0.99	+0.11	+0.09	+0.07	1.11	+0.12	+0.08	+0.09	-1.10	+0.33	+0.29	+0.15	1.01	+0.16	+0.11	+0.12	0.82	+0.50	+0.49	+0.11
	-0.17	-0.16	-0.04		-0.12	-0.10	-0.07		-0.11	-0.07	-0.08		-0.24	-0.16	-0.17		-0.20	-0.17	-0.10		-0.82	-0.82	-0.00
	(+0.11)	(+0.08)	(+0.06)		(+0.11)	(+0.09)	(+0.06)		(+0.11)	(+0.07)	(+0.09)		(+0.23)	(+0.16)	(+0.16)		(+0.17)	(+0.12)	(+0.12)		(+0.45)	(+0.44)	(+0.07)
	(-0.10)	(-0.08)	(-0.06)		(-0.11)	(-0.09)	(-0.06)		(-0.12)	(-0.08)	(-0.09)		(-0.22)	(-0.15)	(-0.16)		(-0.15)	(-0.10)	(-0.11)		(-1.01)	(-1.00)	(-0.11)

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 $SU(2) \otimes SU(2)$ Gauge Extensions of MSSM

- The effect of $SU(2) \otimes SU(2)$ Gauge Extensions is : [3]

$$g^2 \rightarrow g^2 \Delta,$$

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

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

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

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

[3]Huo, Lee, Thalapillil, Wagner, *SU(2) \otimes SU(2) Gauge Extensions of the MSSM Revisited* (2012)

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

Other Consequences:

1. modified $ghhh$, $gHhh$

$$\begin{aligned}ghhh &= \frac{-3i}{2} \cos 2\alpha \sin(\beta + \alpha) \frac{gm_z}{\cos \theta_w} \\gHhh &= \frac{-i}{2} [2 \sin 2\alpha \sin(\beta + \alpha) - \cos 2\alpha \cos(\beta + \alpha)] \frac{gm_z}{\cos \theta_w} \\ \frac{gm_z}{\cos \theta_w} &= \frac{v}{2} (g^2 + g_Y^2) \rightarrow \frac{v}{2} (g^2 \Delta + g_Y^2)\end{aligned}$$

2. Contributions to EWPO, but the constraints are weak. [3]

Understanding Interference Term

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

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

$$-gauge1(\Delta) = A_{\Delta}^H + A_{\Delta}^h$$

$$-gauge1(\square) = A_{\square}^h$$

$$A_{\Delta}^H = -6m_h^2 C_{Hhh} C_{Htt} F_{\Delta} \frac{\hat{s}}{\hat{s} - m_H^2 + i\Gamma_H m_H}$$

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

$$A_{\Delta}^h = -6m_h^2 C_{hhh} C_{htt} F_{\Delta} \frac{\hat{s}}{\hat{s} - m_h^2 + i\Gamma_h m_h} \approx -6m_h^2 C_{hhh} C_{htt} F_{\Delta} \frac{\hat{s}}{\hat{s} - m_h^2}$$

$$A_{\square}^h = -4C_{htt}^2 F_{\square} \hat{s}$$

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

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

[5]T. Plehn, M. Spira, P.M. Zerwas, *Pair Production of Neutral Higgs Particles in Gluon--Gluon Collisions*.(1996)

Understanding Interference Term

$$\begin{aligned}
 |gauge1|^2 &= |A^H_{\Delta} + A^h_{\Delta} + A^h_{\square}|^2 \\
 &= |A^H_{\Delta}|^2 + |A^h_{\Delta} + A^h_{\square}|^2 + 2\text{Re}[A^H_{\Delta} \times (A^h_{\Delta} + A^h_{\square})^*] \\
 2\text{Re}[A^H_{\Delta} \times (A^h_{\Delta} + A^h_{\square})^*] &= 2\text{Re}[A^H_{\Delta} \times A^{h*}_{\Delta}] + 2\text{Re}[A^H_{\Delta} \times A^{h*}_{\square}]
 \end{aligned}$$

$$\text{Let } A^H_{\Delta} = |a_{Res}|e^{i\delta_{Res}} \frac{\hat{s}}{\hat{s} - m_H^2 + i\Gamma_H m_H} = |a_{Res}|e^{i\delta_{Res}} \hat{s} \frac{\hat{s} - m_H^2 - i\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2},$$

$$A^h_{\Delta} = |A^h_{\Delta}|e^{i\delta_{NR,\Delta}}, \quad A^h_{\square} = |A^h_{\square}|e^{i\delta_{NR,\square}}$$

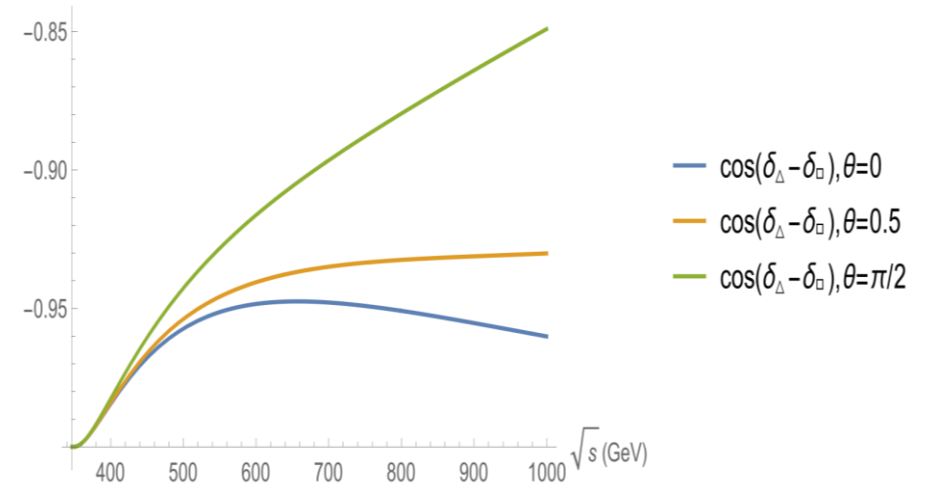
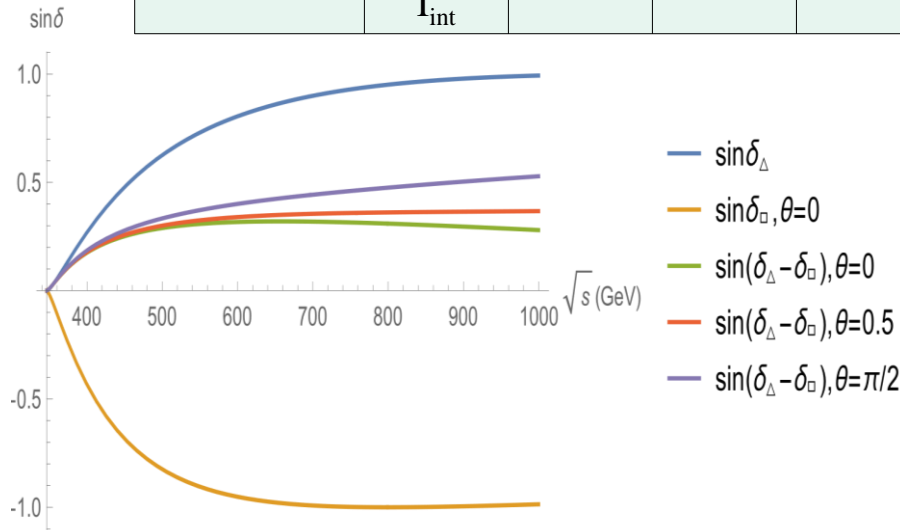
$$\begin{aligned}
 2\text{Re}[A^H_{\Delta} \times A_{NR}^*] &= 2\text{Re}[|a_{Res}|\hat{s}|A_{NR}|e^{i(\delta_{Res} - \delta_{NR})} \frac{\hat{s} - m_H^2 - i\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2}] \\
 &= 2(R_{int} + I_{int})
 \end{aligned}$$

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

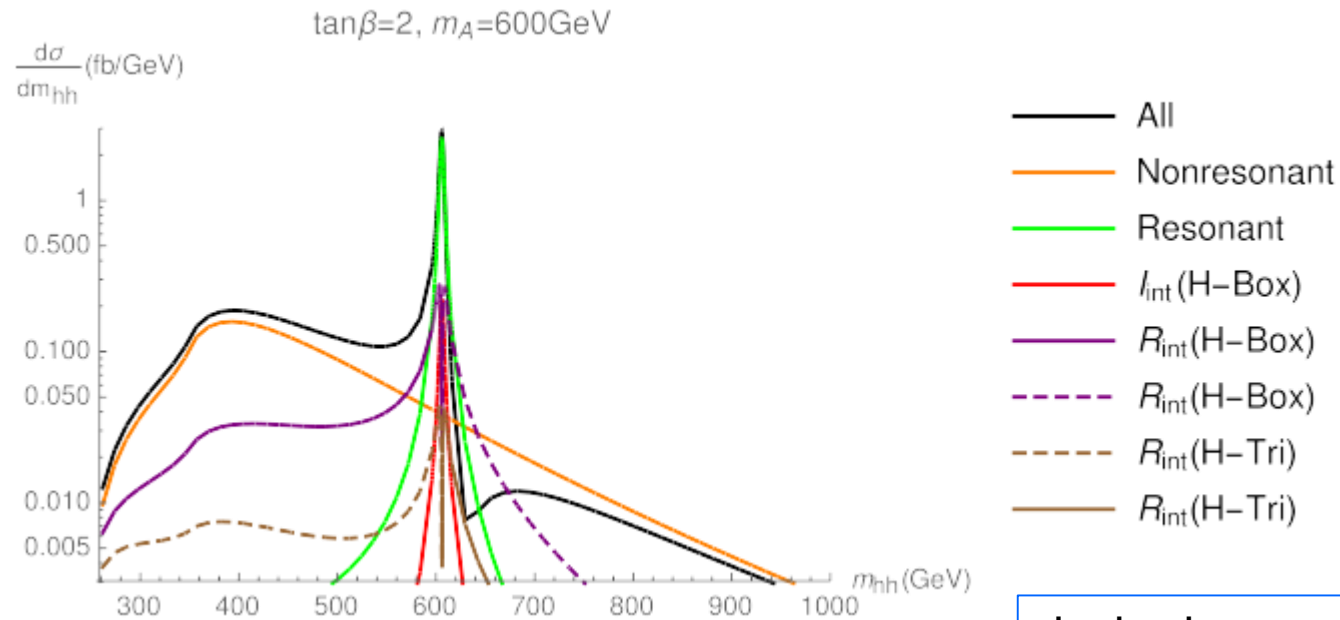
$$I_{int} = |A_{NR}||a_{Res}|\hat{s} \frac{\Gamma_H m_H}{(\hat{s} - m_H^2)^2 + (\Gamma_H m_H)^2} \sin(\delta_{Res} - \delta_{NR})$$

Understanding Interference Term

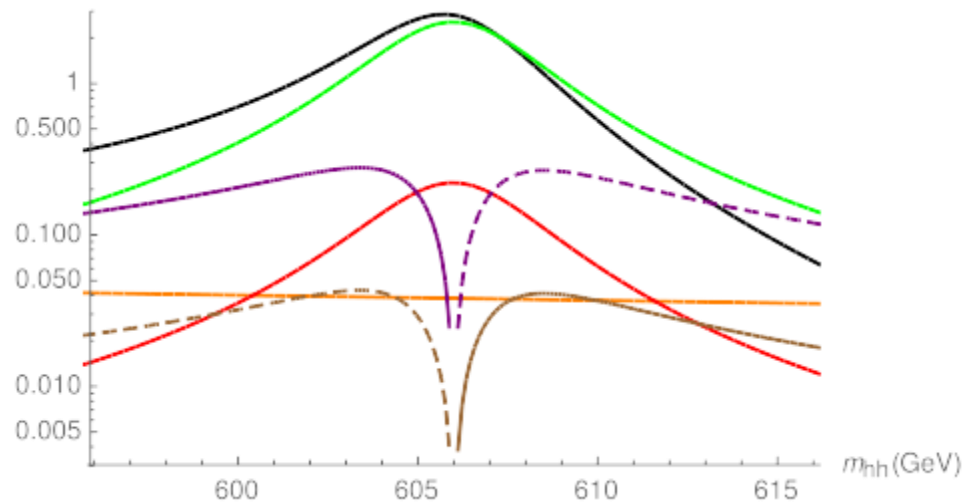
Interference Term		δ_{Res}	δ_{NR}	$\delta_{\text{Res}} - \delta_{\text{NR}}$		Interference Sign
$A_{\Delta}^H \leftrightarrow A_{\Delta}^h$	R_{int}	$\delta_{\Delta} + \pi$	$\delta_{\Delta} + \pi$	0	$\cos(\delta_{\text{Res}} - \delta_{\text{NR}}) = 1$	-/+
	I_{int}				$\sin(\delta_{\text{Res}} - \delta_{\text{NR}})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



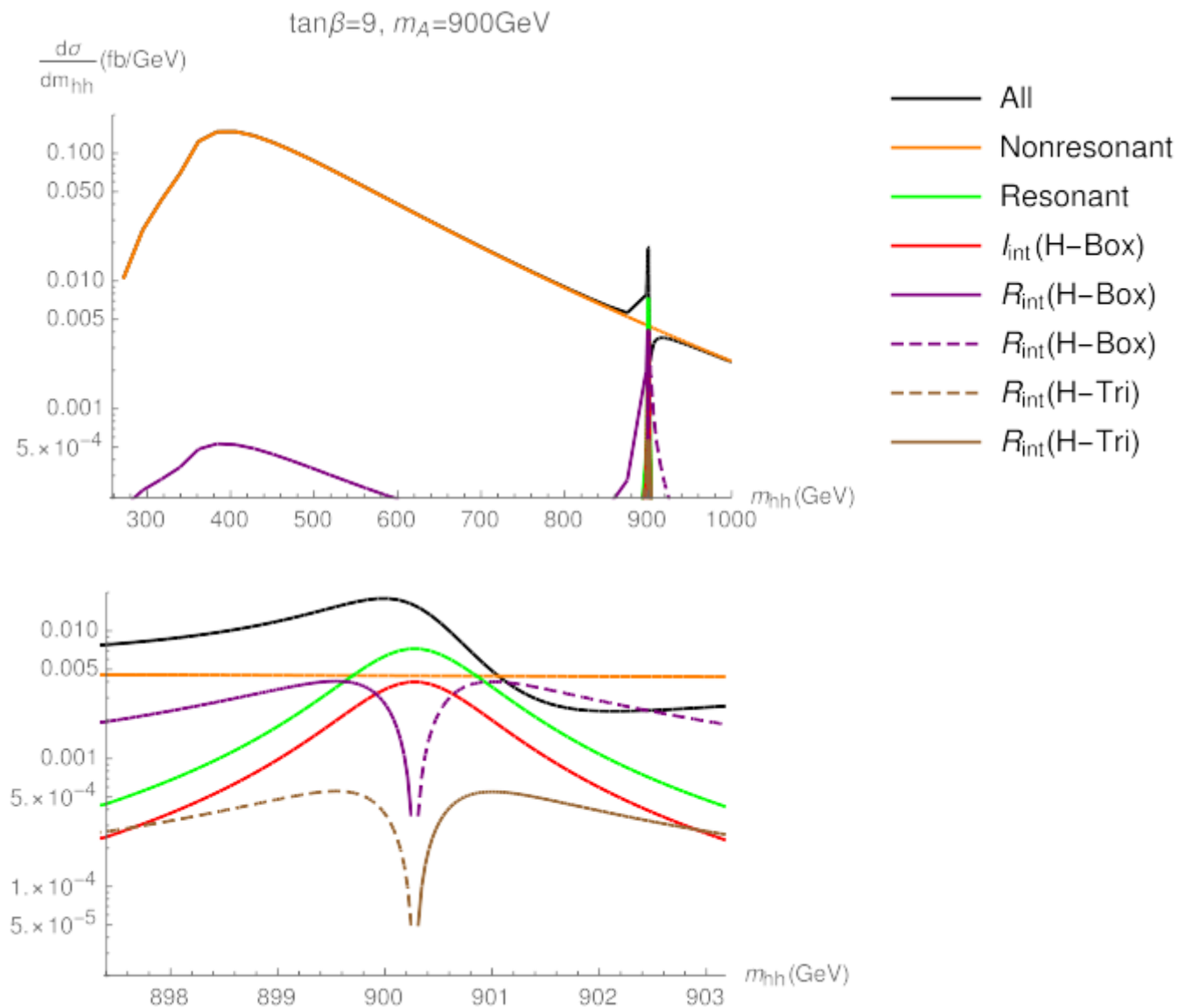
Results

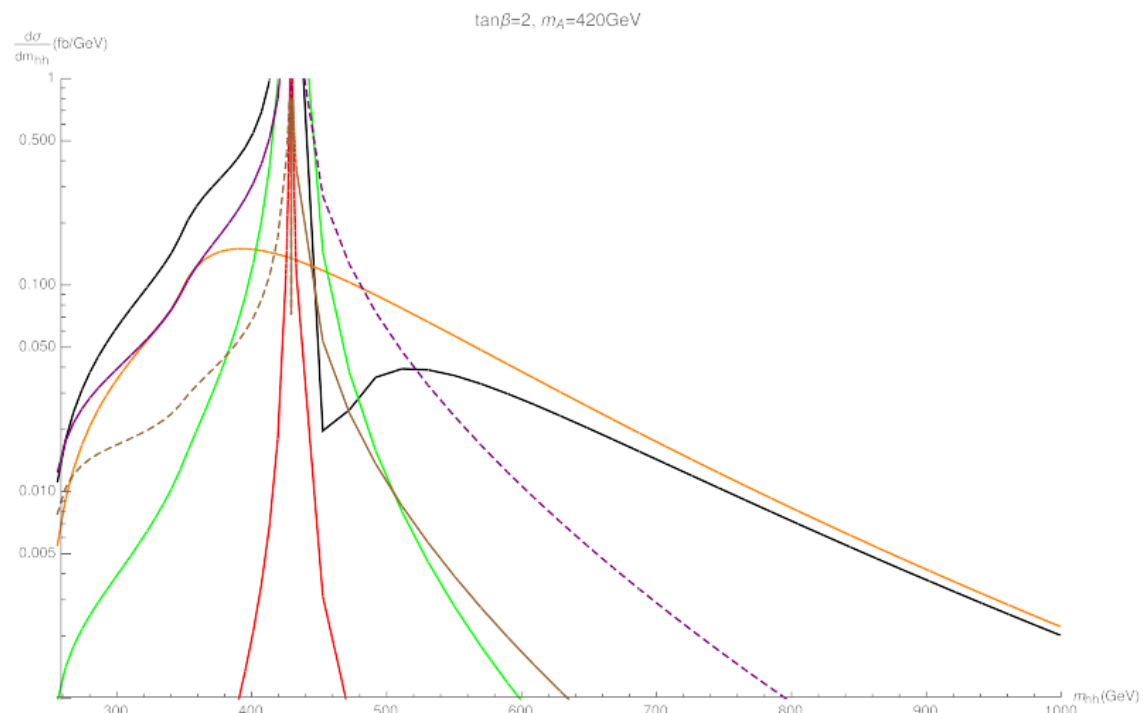


dashed curves represents destructive interferences

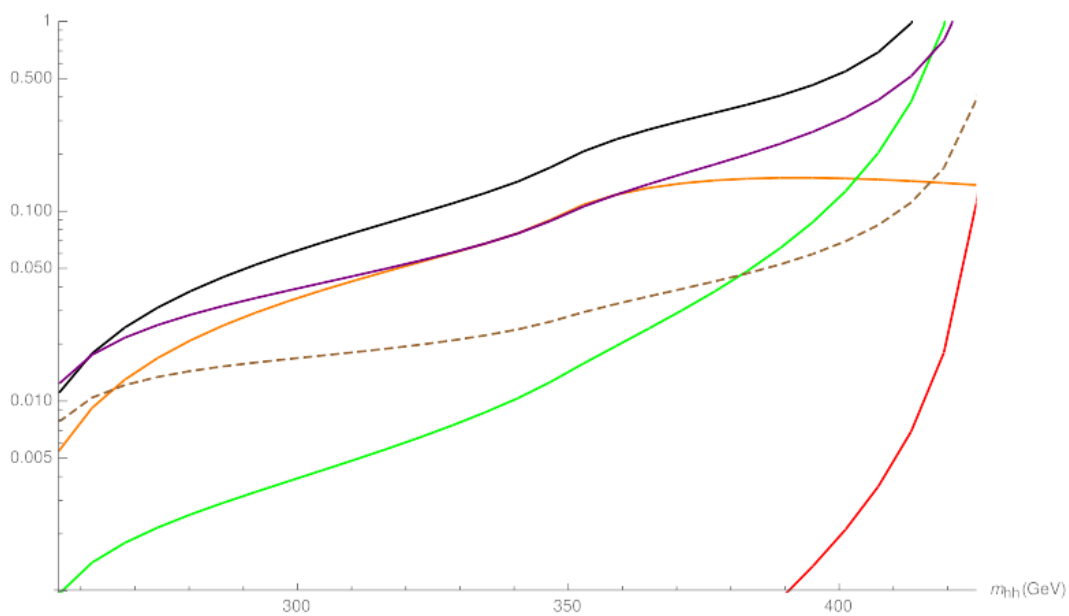


Results

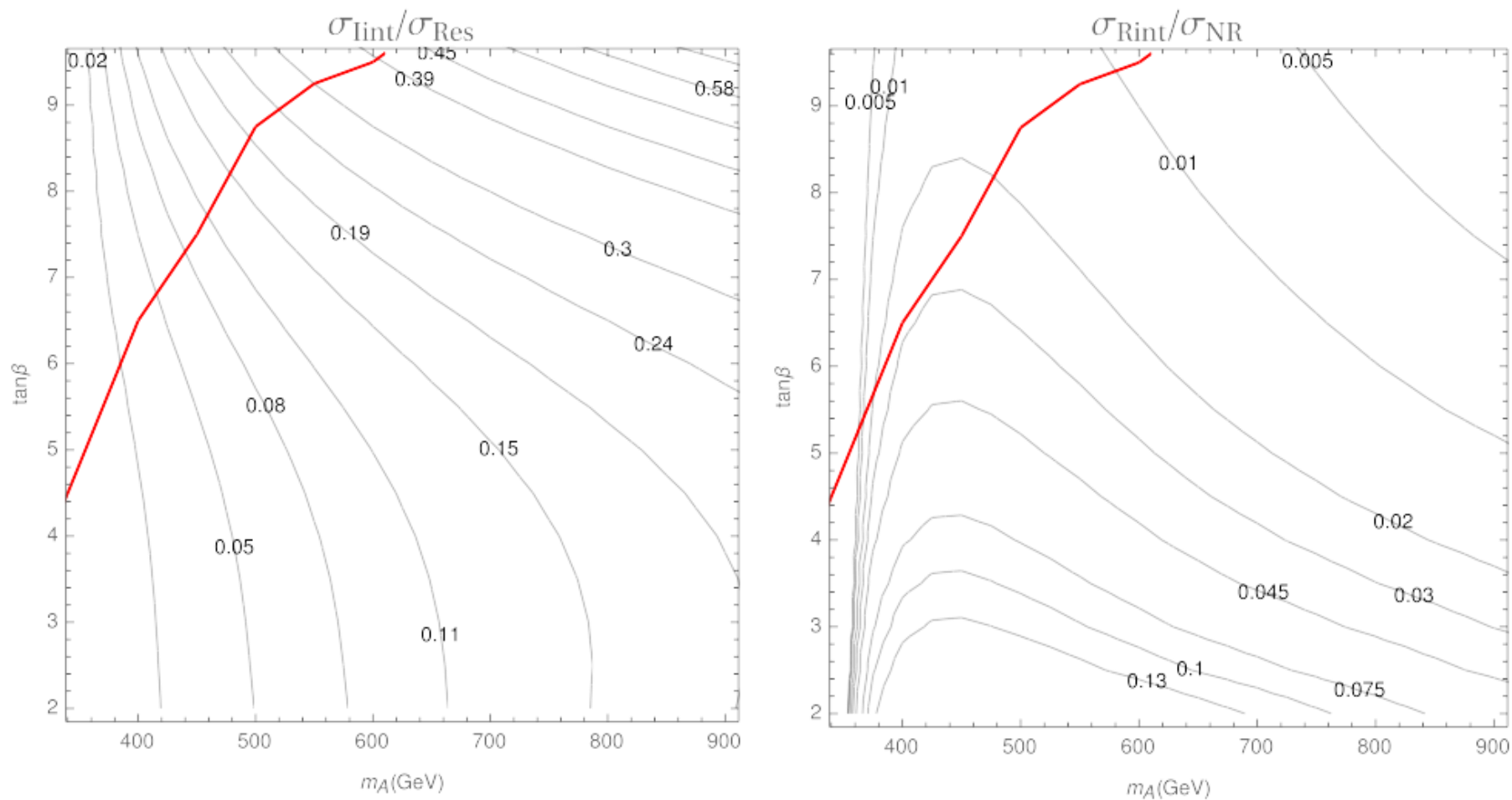




- All
- Nonresonant
- Resonant
- $I_{\text{int}}(\text{H-Box})$
- $R_{\text{int}}(\text{H-Box})$
- - $R_{\text{int}}(\text{H-Box})$
- - $R_{\text{int}}(\text{H-Tri})$
- $R_{\text{int}}(\text{H-Tri})$



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 $s^{1/2} = m_H$.
- $I_{\text{int}} = I_{\text{int}}(\text{H-Box})$
- Differential cross section corresponds to $R_{\text{int}}(\text{H-Box})$ is larger than $R_{\text{int}}(\text{H-Tri})$, 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

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

Future Work

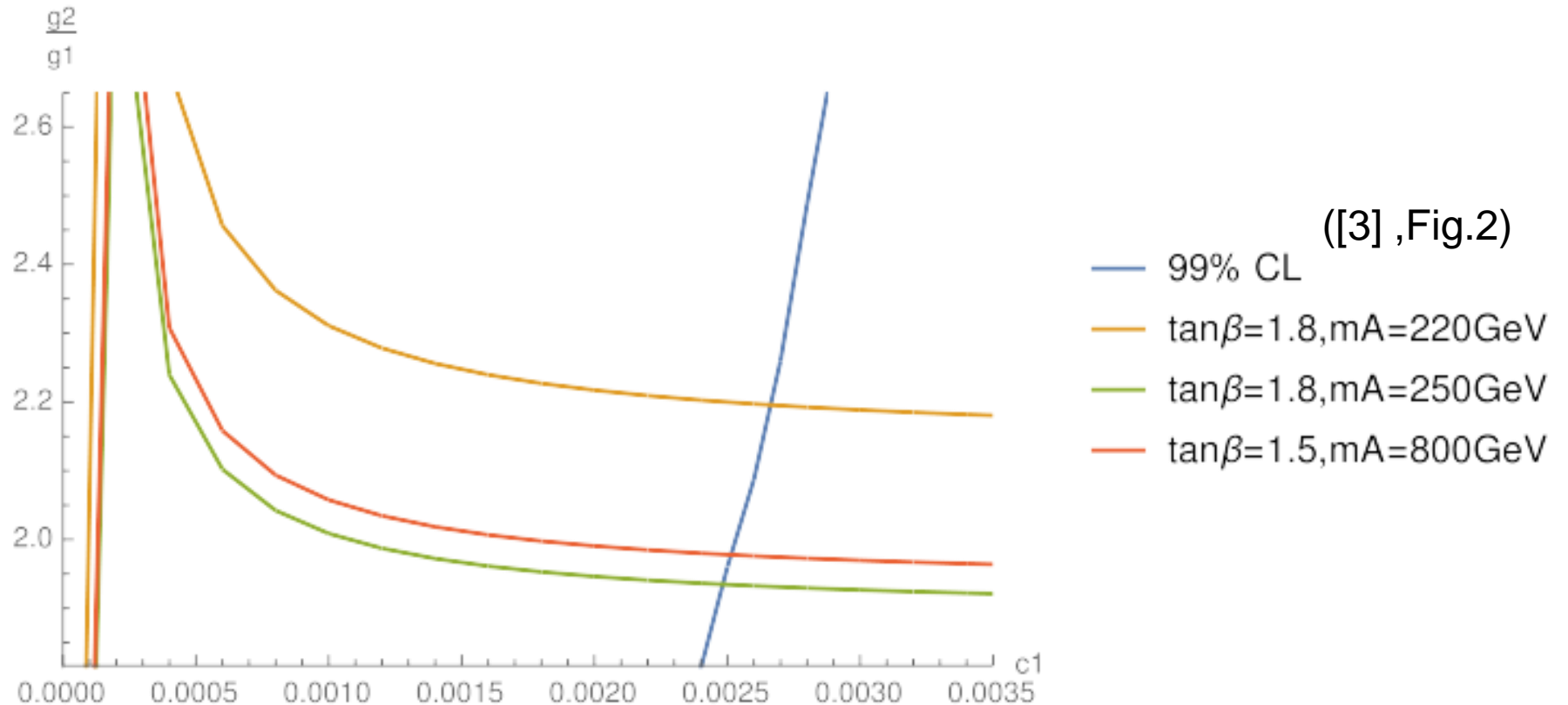
- Collider phenomenology study
 - to estimate the sensitivity for LHC
- Consider influences of other SUSY particles.

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]

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Precision EW Constraints



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