hhh Coupling in SUSY models after LHC run I

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Outline

- Introduction
- hhh coupling in MSSM & NMSSM under current constraints
- hhh coupling relation to the measurements in future colliders
- Conclusion

Motivation and *hhh* Coupling in SM

- In order to describe the full Higgs sector, we need to know the Higgs self-coupling.
- Multi-Higgs New Physics models always have very non-SM-like Higgs self-coupling
- It's important to show how large this deviation will be and whether the future colliders could detect such deviation

Motivation and *hhh* Coupling in SM

SM Higgs sector:

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \tag{1}$$

$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger \Phi)^2 - \mu^2 \Phi^\dagger \Phi, \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{2}$$

In Unitary gauge we have:

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}, v = 2\frac{\mu}{\sqrt{\lambda}} \tag{3}$$

Then the tree-level potential will yield:

$$m_h = \sqrt{\frac{\lambda}{2}}\, v,\ \lambda_{hhh} = \frac{3}{2}\lambda v = \frac{3m_h^2}{v} \tag{4}$$

Consider the one loop top correction, we get:

$$\lambda_{hhh} = \frac{3m_h^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \tag{5}$$

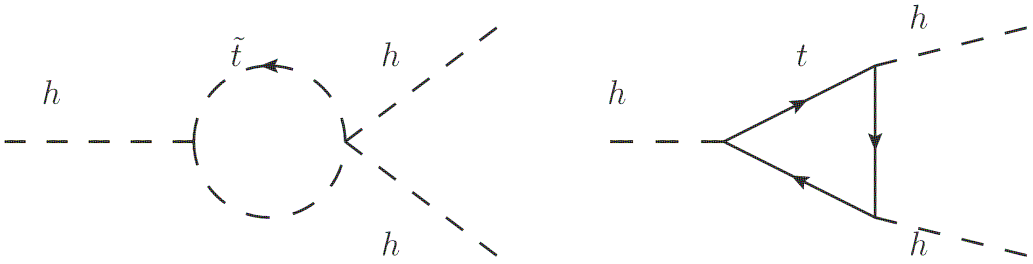
Effective Potential Method

$$\begin{aligned}\mathcal{V}_{tree} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.] \\ &+\frac{1}{8}(g_2^2+g_1^2)(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{8}(g_2^2+g_1^2)(\Phi_2^\dagger\Phi_2)^2 \\ &+\frac{1}{4}(g_2^2-g_1^2)(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - \frac{1}{2}g_2^2(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \qquad (6)\end{aligned}$$

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1^0 + iA_1^0) \end{pmatrix}, \Phi_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + H_2^0 + iA_2^0) \end{pmatrix} \qquad (7)$$

In SUSY models, for example the MSSM, m_H is not an input parameters but a calculable quantity that mainly controlled by top and stop sector, and the tree-level couplings are fixed by gauge couplings constants. So one may expect a very different *hhh* coupling in SUSY. Let's perform a simple estimation first.

Effective Potential Method



Correction to triple coupling is(simplified stop sector):

$$\Gamma_{hhh}^{t,\tilde{t}} = \frac{3m_t^4}{2\pi^2 v^3}\left(3\ln\frac{m_{\tilde{t}}^2}{m_t^2} - 2\right) \tag{8}$$

So it seems we get a very large corrections from top/stop sector. But the top/stop correction to Higgs mass is:

$$\Delta m_h^2 = \frac{3m_t^4}{2\pi^2 v^2}\ln\frac{m_{\tilde{t}}^2}{m_t^2} \tag{9}$$

So if we shift the tree level Higgs mass to the one-loop level Higgs mass, the relationship we found in SM still hold.

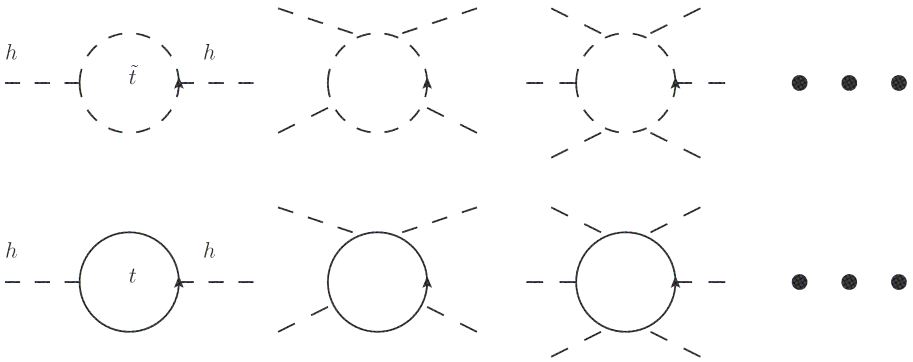
W. Hollik, S. Penaranda. Eur. Phys. J. C 23, 163 - 172 (2002)

Effective Potential Method

As we've seen, the loop correction to *hhh* coupling may have a corresponding part in the loop correction to Higgs mass. So the key point in here is to **treat the *hhh* coupling and Higgs mass in a consistent way**.

A convenient way to perform such a consistent calculation is the **effective potential** method. The effective potential method can absorb the dominant loop contribution into the effective couplings in low energy scale and deal with the Higgs mass and coupling in the same accuracy.

Effective Potential Method



These infinity Feynman graphs series can be summed to a elegant expression:

$$\mathcal{V}^{(1)} = \frac{3}{16\pi^2}\left\{m_{\tilde{t}}^4\left(\ln\frac{m_{\tilde{t}}^2}{\mu^2} - \frac{3}{2}\right) - m_t^4\left(\ln\frac{m_t^2}{\mu^2} - \frac{3}{2}\right)\right\} \tag{10}$$

$$\left\{\begin{array}{r} \textit{expand the effective potential in SUSY scale} \\ \textit{ignore the high dimensional operators} \end{array}\right\} \Rightarrow \left\{\begin{array}{r} \textit{effective couplings in} \\ \textit{low energy scale} \end{array}\right\}$$

M. Carena, J.R. Espinosa, M. Quiros and C.E.M. Wagner. Phys.Lett. B355 (1995) 209-221
Howard E. Haber and Ralf Hempfling.Phys.Rev. D48 (1993) 4280-4309
Ellis J, Ridolfi G, Zwirner F. Physics Letters B, 1991, 257(1): 83-91.
Okada Y, Yamaguchi M, Yanagida T.Progress of Theoretical Physics, 1991, 85(1): 1-5.

We use too loop result.

hhh Coupling in MSSM and NMSSM

In order to illustrate the genuine SUSY effect on *hhh* coupling, it's convenient to define:

$$\delta_{hhh} = \frac{\lambda_{hhh}^{SM} - \lambda_{hhh}^{SUSY}}{\lambda_{hhh}^{SM}} = (\frac{3m_h^2}{\sqrt{2}v} - \lambda_{hhh}^{SUSY})/\frac{3m_h^2}{\sqrt{2}v} \tag{11}$$

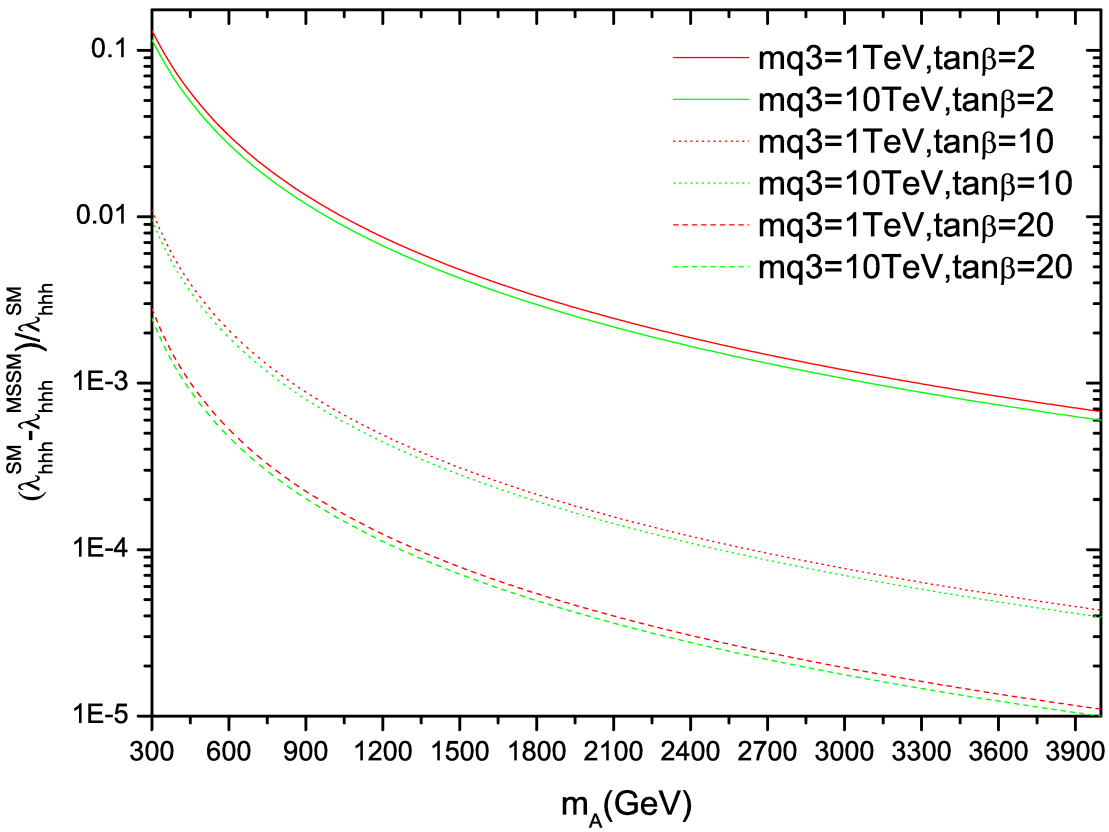
We will call the quantity "triple coupling deviation". This triple coupling deviation is more suitable than the absolute value of triple coupling, because the uncertainty in Higgs mass calculation have little impact to this deviation.

$$\left\{ all\ non-SM\ particles\ mass \to \infty \right\} \Rightarrow \left\{ \delta_{hhh} \to 0 \right\}$$

(for conciseness, we don't write m_t^4 term in here)

hhh Coupling in MSSM and NMSSM

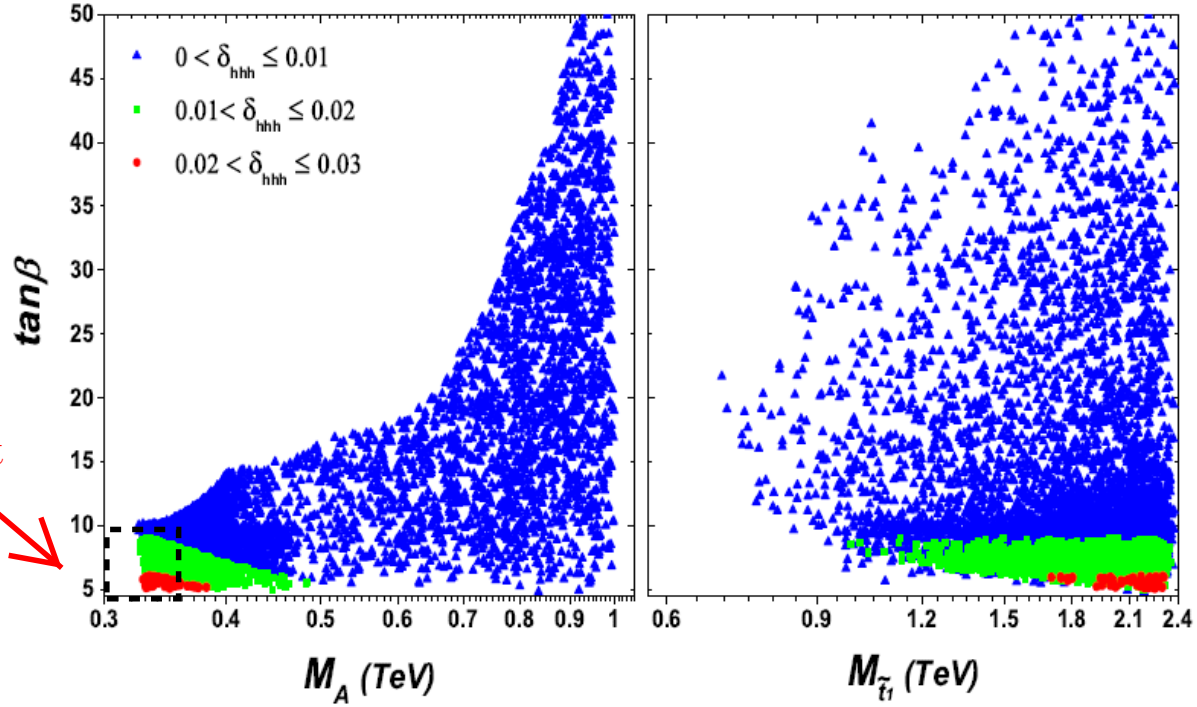
MSSM Higgs sector dominantly decided by m_A and $\tan\beta$. δ_{hhh} dependency on m_A and $\tan\beta$ is the under graph (other parameters: all the other soft mass and A_t are equal to m_{q3}, and other A-terms are zero):



small tanb and light mA are wanted

hhh Coupling in MSSM and NMSSM

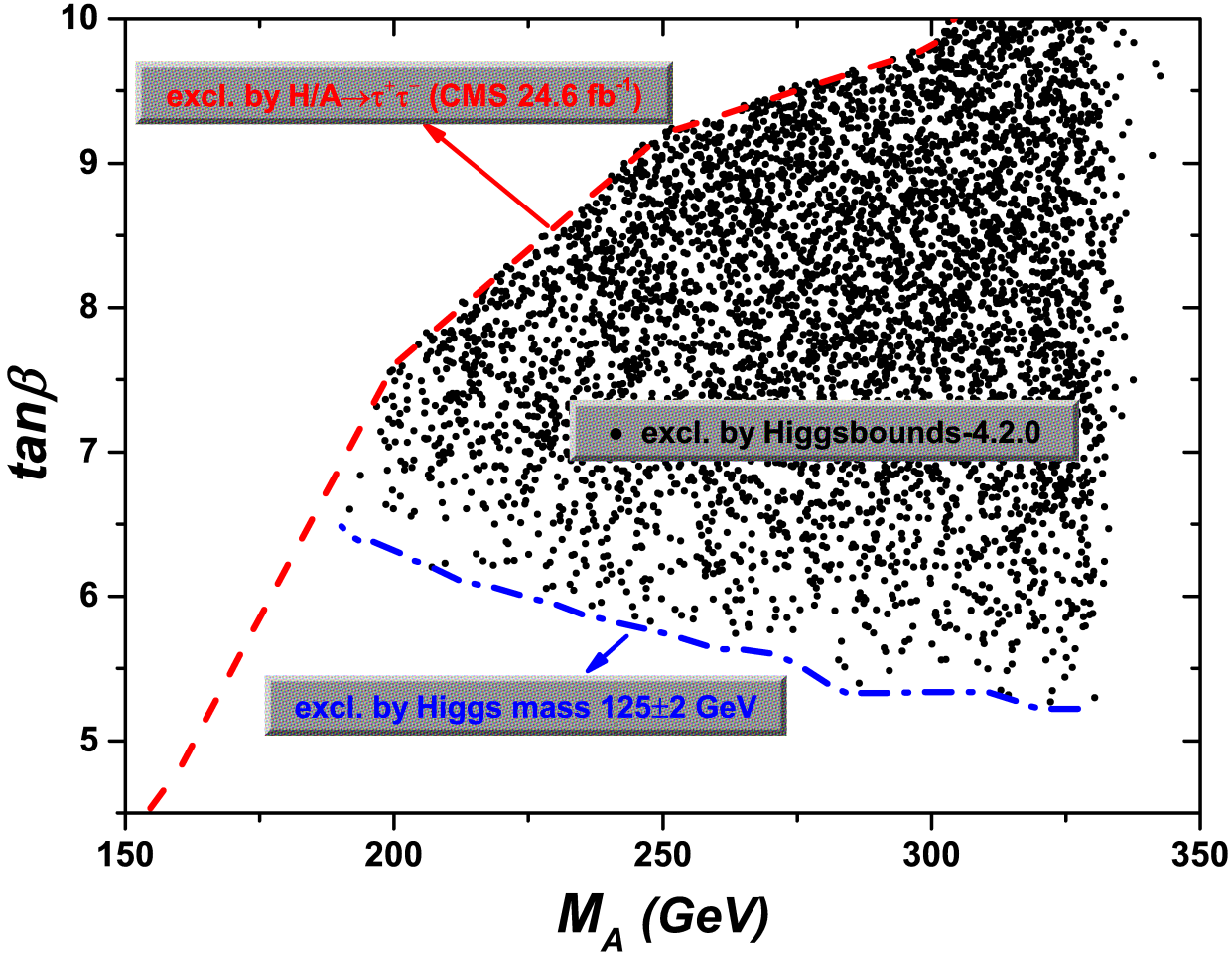
important part



Scan range: $1 < \tan\beta < 50, 100GeV < m_A < 1TeV, |\mu| < 1TeV, |A_t = A_b| < 6TeV, 500GeV < m_{u3} = m_{d3} = mq3 < 2.5TeV$.

Other soft mass are equal to 2TeV and other A-terms are equal to zero.

hhh Coupling in MSSM and NMSSM



Similar to:
Marcela Carena, Howard E. Haber, Ian Low, Nausheen R. Shah, Carlos E. M. Wagner. Phys.Rev. D91 (2015) 035003

hhh Coupling in MSSM and NMSSM

NMSSM give a solution of the μ-problem in MSSM by introducing a Singlet Field. The Higgs part super potential of NMSSM is:

$$W_{Higgs} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \tag{12}$$

and the corresponding Higgs soft term is:

$$\begin{aligned} -\mathcal{L}_{soft} &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ &+ (\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3} \kappa A_\kappa S^3 + h.c.) \end{aligned} \tag{13}$$

In order to describe the NMSSM Higgs sector, we need six parameters:

$\lambda, \kappa, A_\lambda, A_\kappa, \tan\beta, \mu_{eff} = \lambda s$.($s$ is the vev of singlet Higgs field)

Such couplings can be very large:

$$\lambda_{sss} = \sqrt{2}\kappa \left(\frac{6\kappa\mu_{eff}}{\lambda} + \sqrt{2} A_\kappa \right), \lambda_{uds} = -\frac{\lambda A_\lambda}{\sqrt{2}} - \sqrt{2}\kappa\mu_{eff}. \tag{14}$$

and the mixing between singlet and SM-like Higgs – O_{HS} is the most relevant quantity.

hhh Coupling in MSSM and NMSSM

The new couplings in NMSSM are not fixed by gauge coupling and can vary in a large range, so significant mixing O_{HS} will induce a very different Higgs triple coupling.

We use NMSSMTools to scan the parameter space.

Scan range:

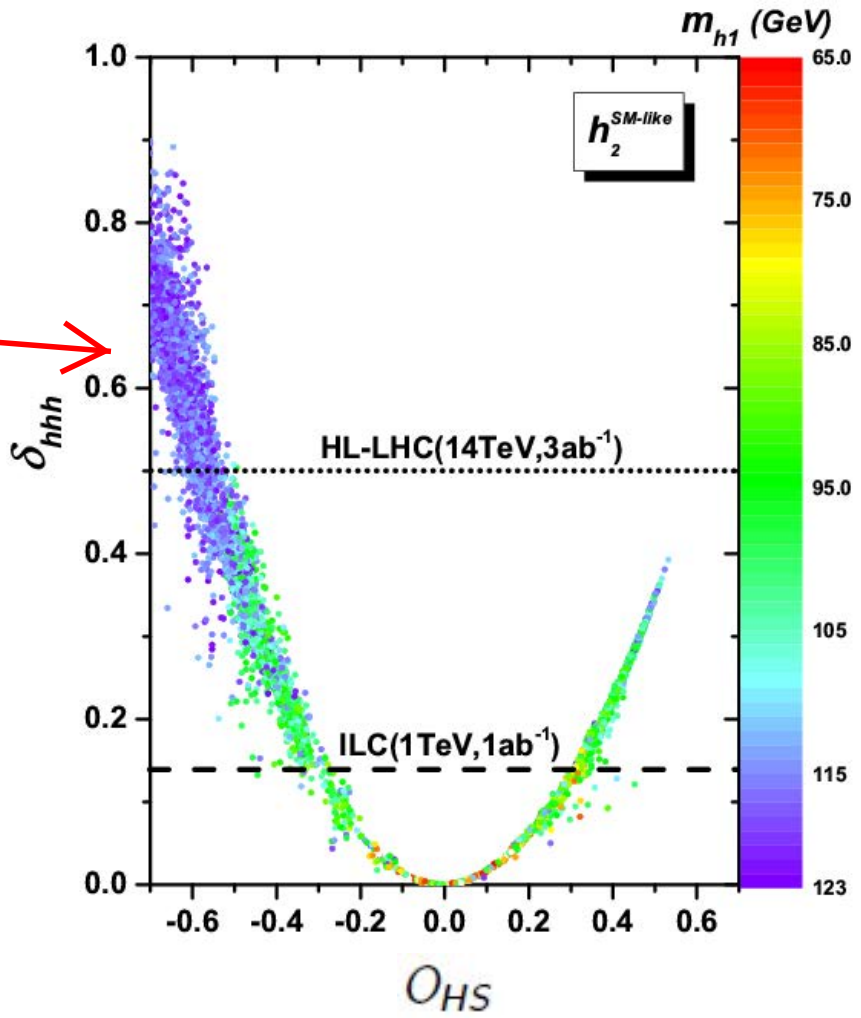
$0 < \lambda < 0.7, -0.7 < \kappa < 0.7, 200\,GeV < A_\lambda < 1\,TeV, -500\,GeV < A_\kappa < 500\,GeV, 1 < \tan\beta < 20, 100\,GeV < \mu < 500\,GeV, 500\,GeV < m_{q3} = m_{u3} = m_{d3} < 2.5\,TeV, |A_t = A_b| < 6\,TeV$.

Other soft mass are equal to 2TeV and other A-terms are equal to zero.

Most relevant constrains: Higgs mass and Higgs signal strength in 2σ region. Higgs mass will strongly limit Higgs sector parameters and Higgs signal strength will restrict O_{HS} directly.

hhh Coupling in MSSM and NMSSM

huge deviation is a hint of another scalar in the neighbor



hhh Coupling Measurement in Future Colliders

$$\left\{\begin{array}{r} mixing\ between\ SM-like\ Higgs \\ and\ non-SM\ Higgs \end{array}\right\} \Rightarrow \begin{array}{r} C_{hbb}, C_{h\gamma\gamma}\ldots\ deviation \\ \lambda_{hhh}\ deviation \end{array}$$

So there is a close relationship between $C_{hbb}, C_{h\gamma\gamma}\ldots$ and λ_{hhh}.

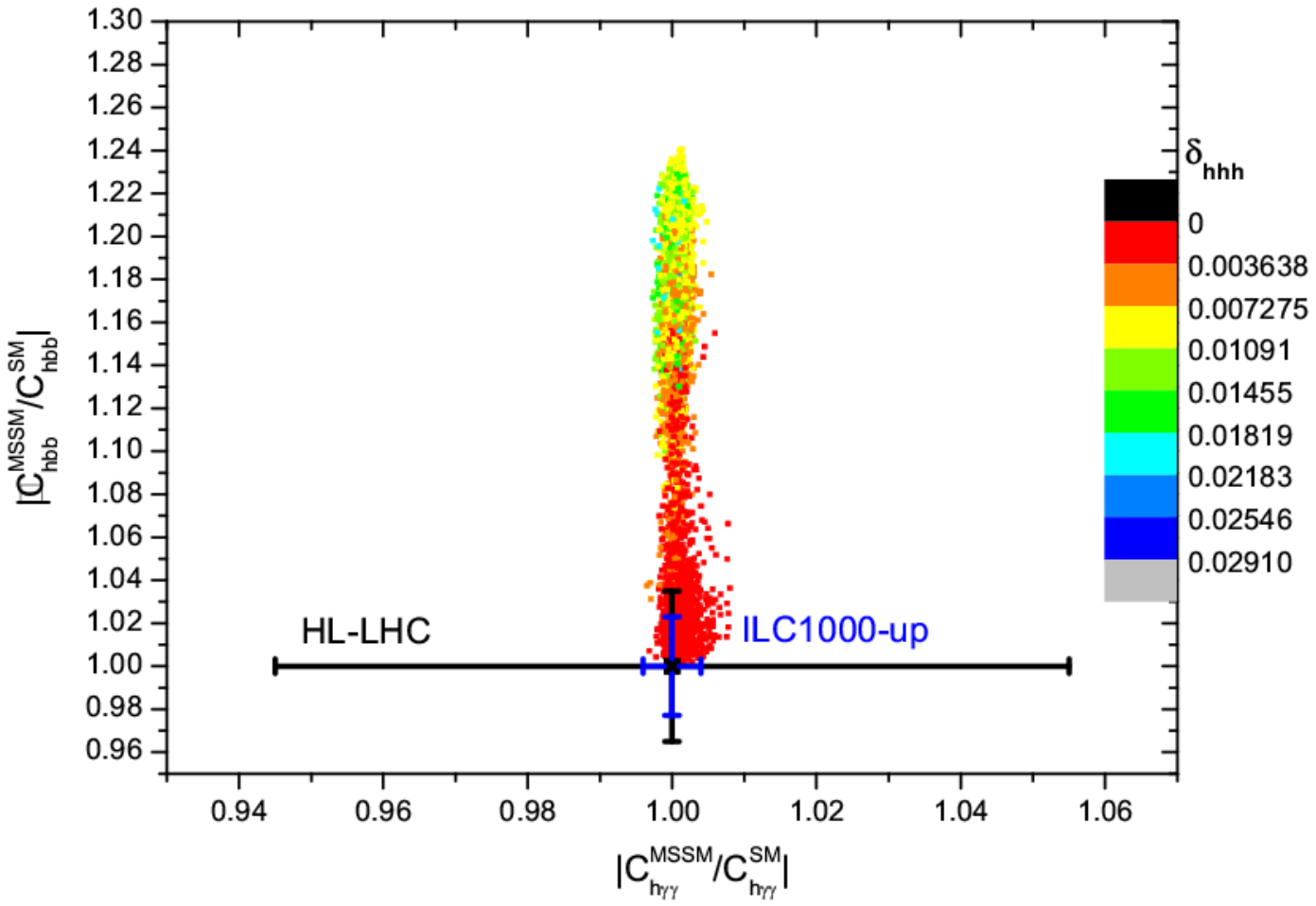
Precise measurement on Higgs couplings will confine λ_{hhh}.

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

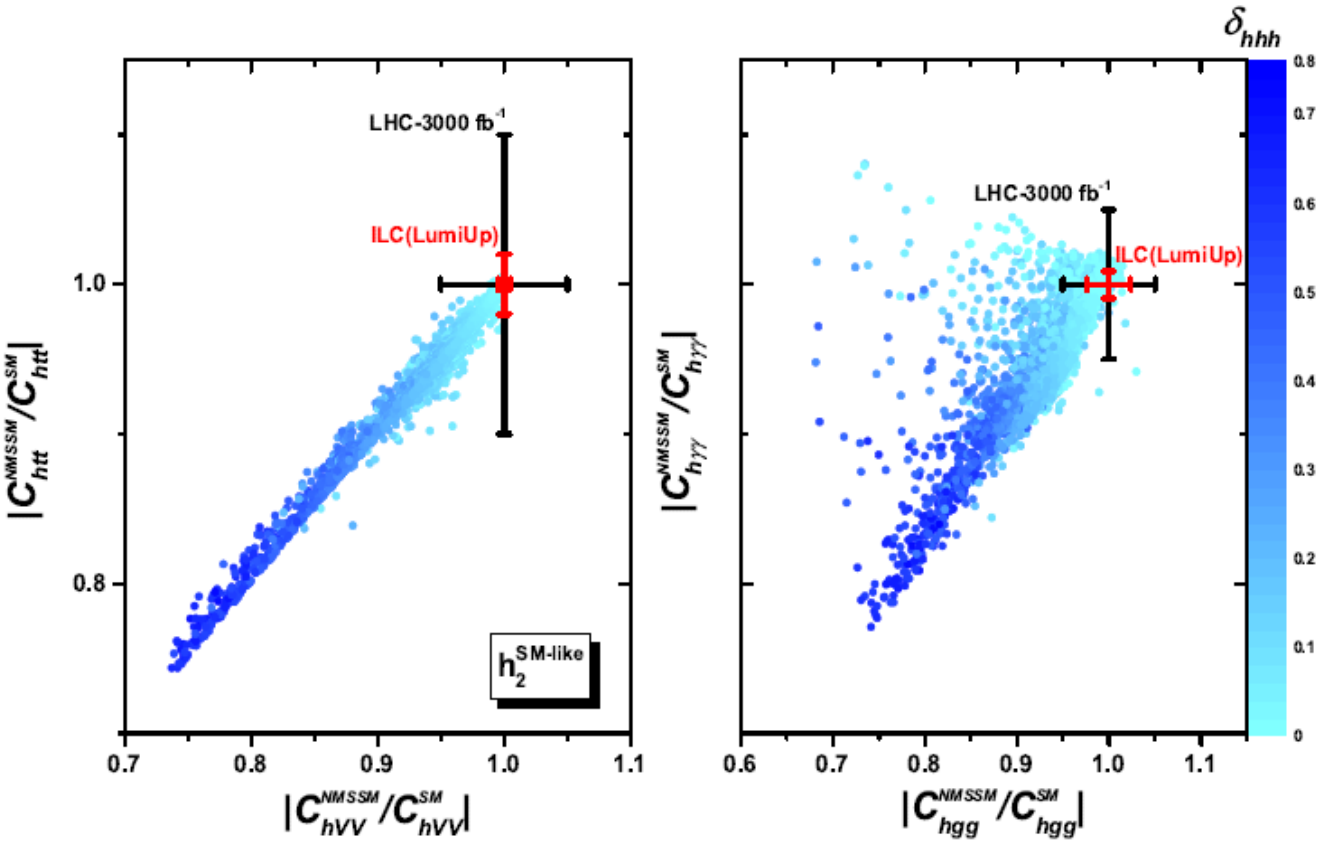
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Higgs working group report:1310.8361

hhh Coupling Measurement in Future Colliders



hhh Coupling Measurement in Future Colliders



Conclusions

hhh coupling deviation in MSSM: $< 3\%$

hhh coupling deviation in NMSSM: $> 50\%$

ILC(LumUp) measurement constraint to hhh coupling deviation in MSSM: $< 0.3\%$

ILC(LumUp) measurement constraint to hhh coupling deviation in NMSSM: $< 1.0\%$