Di-Higgs production at Photon Collider in composite models

Naveen Gaur

Department of Physics,
Dyal Singh College (University of Delhi), Delhi - 110003

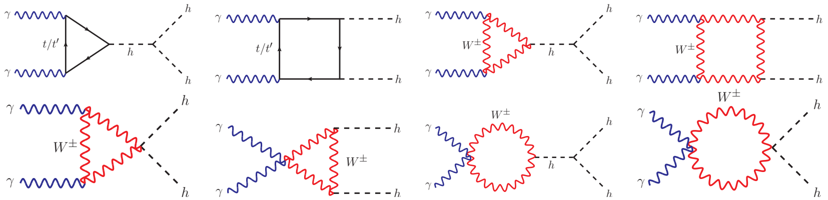
A. Barucha, G. Cacciapaglia, A. Deandrea, N. Gaur, D. Harada, F. Mahmoudi, K. Sridhar

LIO International conference on Composite connections of Higgs, Dark Matter and Neutrinos

Table of contents

.

$$\gamma\gamma \to hh$$



$$\frac{d\hat{\sigma}(l_1,l_2)}{d\hat{t}} = \frac{1}{2!}\frac{1}{16\pi\hat{s}^2}\frac{\alpha^2\alpha_W^2}{(4\pi)^2}\left|\mathcal{M}(l_1,l_2)\right|^2$$

$l_i = +,-$ helicities of photons.

$$\sigma = \int_{4m_h^2/s}^{y_m^2} d\tau \frac{dL_{\gamma\gamma}}{d\tau}\left[\frac{1+\xi_1^\gamma\xi_2^\gamma}{2}\hat{\sigma}_{++}(\hat{s}) + \frac{1-\xi_1^\gamma\xi_2^\gamma}{2}\hat{\sigma}_{+-}(\hat{s})\right],$$

where $\xi^\gamma_{(1,2)}$ are the mean photon helicities and the differential luminosity

$$\frac{dL_{\gamma\gamma}}{d\tau} = \int_{\tau/y_m}^{y_m}\frac{dy}{y}f(x,y)f(x,\tau/y),$$

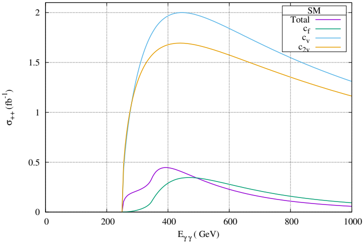
where $\tau = \hat{s}/s$, $y = E_\gamma/E_b$ with E_γ and E_b being the energy of photon and electron beams respectively, and the maximal energy fraction of photon $y_m = x/(1+x)$ with $x = 4E_b\omega_0/m_e^2$ where ω_0 is the laser photon energy and m_e is the electron mass. The photon luminosity spectrum is given by

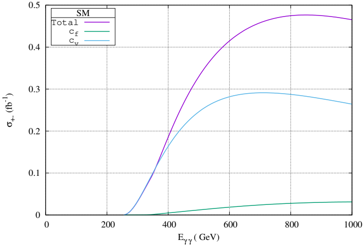
$$\begin{aligned} f_\gamma(x,y) &= \frac{1}{D(x)}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) - 2\lambda_e\lambda_\gamma rx(2r-1)(2-y)\right], \\ D(x) &= \left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(1+x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1+x)^2} \\ &\quad + 2\lambda_e\lambda_\gamma\left[\left(1+\frac{2}{x}\right)\ln(1+x) - \frac{5}{2} + \frac{1}{1+x} - \frac{1}{2(1+x)^2}\right], \end{aligned}$$

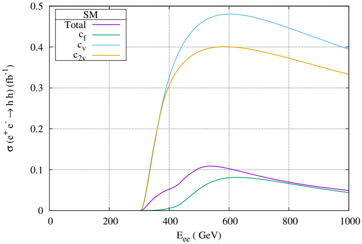
where $r = \frac{y}{x(1-y)}$ and $\lambda_e(\lambda_\gamma)$ is the helicity of the electron (photon).

Standard Model

.







$$\mathcal{M}(+,+) = \mathcal{M}^{f}_{c_{2f}} + \sum_{i=t,W} \left(\mathcal{M}^{i}_{tri} + \mathcal{M}^{i}_{box}(+,+) \right) ,$$

$$\mathcal{M}(+,+) = \mathcal{M}_{c_f} + \mathcal{M}_{c_{2f}} + \mathcal{M}_{c_V} + \mathcal{M}_{c_{2V}} + \sum_{i=t,W} \mathcal{M}^{i}_{box}(+,+) ,$$

$$\mathcal{M}(+,-) = \sum_{i=t,W} \mathcal{M}^{i}_{box}(+,-) ,$$

Composite Models

In composite models the scale of EWSB (Electro Weak Symmetry Breaking) can be written as :

$$v = f \ sin(\theta)$$

$$m_W^2(\theta) = \frac{g^2 f^2}{4} \sin^2\theta \equiv \frac{g^2 v^2}{4}$$

θ is the mis-alignment of vacuum and f is the spontaneous symmetry breaking scale.

$$\begin{aligned} g_{WWh} &= \frac{1}{f}\frac{\partial m_W^2(\theta)}{\partial\theta} = \frac{2m_W^2}{v}\cos\theta \\ g_{WWhh} &= \frac{1}{f^2}\frac{\partial^2 m_W^2(\theta)}{\partial\theta^2} = \frac{2m_W^2}{v^2}\cos 2\theta \end{aligned}$$

$$\mathcal{L} = m_W^2 W_\mu^+ W^{-,\mu}\left(1 + c_V\frac{h}{v} + \frac{c_{2V}}{2}\frac{h^2}{v^2} + \dots\right),$$

$$c_V = \cos\theta = \sqrt{1-\xi}, \qquad c_{2V} = \cos 2\theta = 1 - 2\xi\,;$$

where $\xi = v^2/f^2 \equiv \sin^2\theta$.

$$g_{ffh} = \frac{1}{f}\frac{\partial m_t^\theta}{\partial\theta}, \qquad g_{ffhh} = \frac{1}{f^2}\frac{\partial^2 m_t^\theta}{\partial^2\theta}, \qquad g_{ffhhh} = \frac{1}{f^3}\frac{\partial^3 m_t^\theta}{\partial^3\theta}$$

Composite Models

For MCHM4:

$$m_t(\theta) = \frac{\lambda f}{\sqrt{2}} \sin\theta \quad \Rightarrow \quad \begin{cases} g_{ffh} = \frac{m_t}{v} \cos\theta \,, \\ g_{ffhh} = -\frac{m_t}{v^2} \sin^2\theta \,. \end{cases}$$

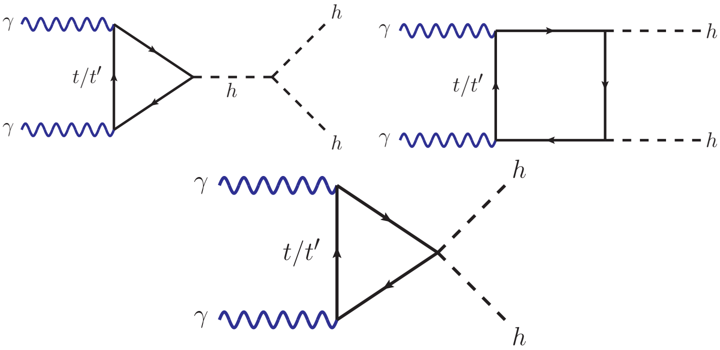
For MCHM5:

$$m_t(\theta) = \frac{\lambda f}{\sqrt{2}} \sin 2\theta \quad \Rightarrow \quad \begin{cases} g_{ffh} = \frac{m_t}{v} \frac{\cos 2\theta}{2\cos\theta} \,, \\ g_{ffhh} = -\frac{m_t}{v^2} 4\sin^2\theta \,. \end{cases}$$

$$\mathcal{L} = \frac{v}{\sqrt{2}} \lambda_{ij} \left(\bar{\psi}^i \Sigma \psi^j\right) \left(1 + c_f \frac{h}{v} + \frac{1}{2} c_{2f} \frac{h^2}{v^2}\right) + h.c.$$

Model	$hf\bar{f}(c_f)$	$hhf\bar{f}(c_{2f})$	$hW^+W^-(c_V)$	$hhW^+W^-(c_{2V})$	c_{3h}
MCHM4	$\sqrt{1-\xi}$	$-\xi$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
MCHM5 Higgs	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	$\sqrt{1-\xi}$	$1-2\xi$	λ_H

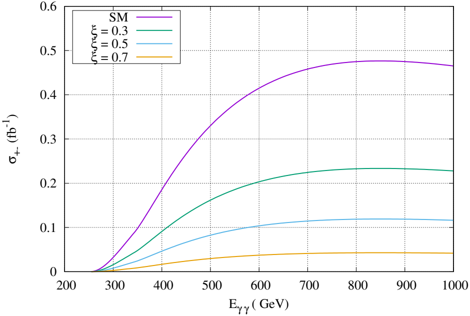
$\gamma\gamma \rightarrow hh$



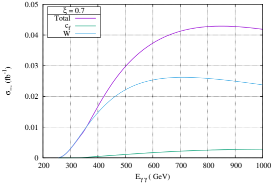
MCHM4

.

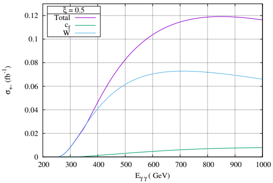
σ_{+-}



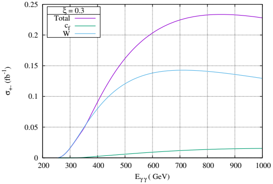
SM
ξ = 0.3
ξ = 0.5
ξ = 0.7
σ+- (fb-1)
0.6
0.5
0.4
0.3
0.2
0.1
0
200
300
400
500
600
700
800
900
1000
Eγγ (GeV)



ξ = 0.7
Total
cf
W
σ+- (fb-1)
Eγγ (GeV)



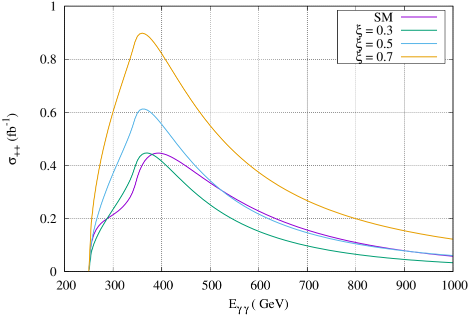
ξ = 0.5
Total
cf
W
σ+- (fb-1)
Eγγ (GeV)

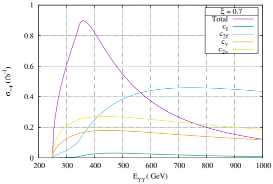


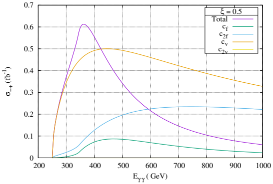
ξ = 0.3
Total
cf
W
σ+- (fb-1)
Eγγ (GeV)

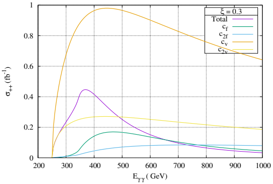
·

σ_{++}


SM
ξ = 0.3
ξ = 0.5
ξ = 0.7
σ++ (fb-1)
Eγγ (GeV)
0
0.2
0.4
0.6
0.8
1
200
300
400
500
600
700
800
900
1000

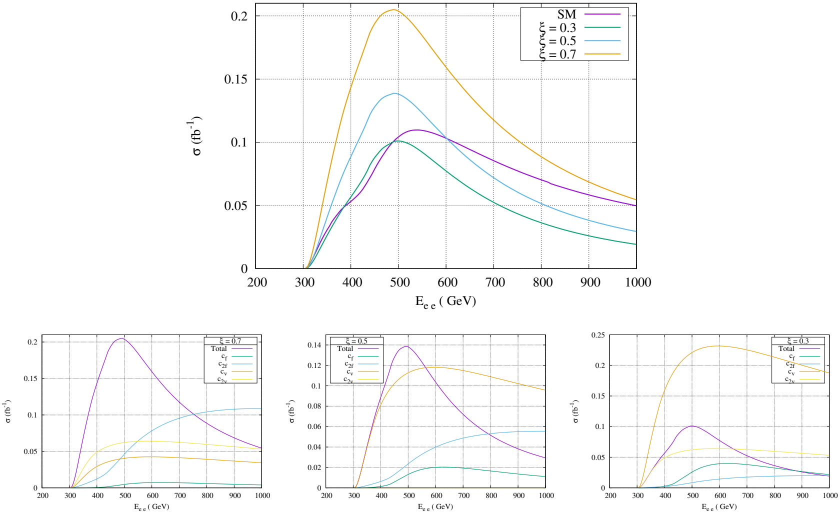

ξ = 0.7
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)


ξ = 0.5
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)


ξ = 0.3
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)

·

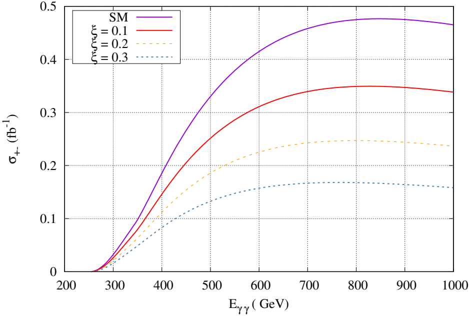
σ_{ee}

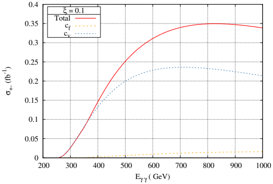


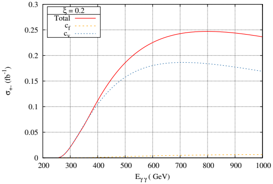
MCHM5

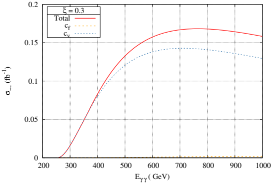
.

σ_{+-}


SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ+- (fb-1)
Eγγ (GeV)


ξ = 0.1
Total
cf
cv
σ+- (fb-1)
Eγγ (GeV)

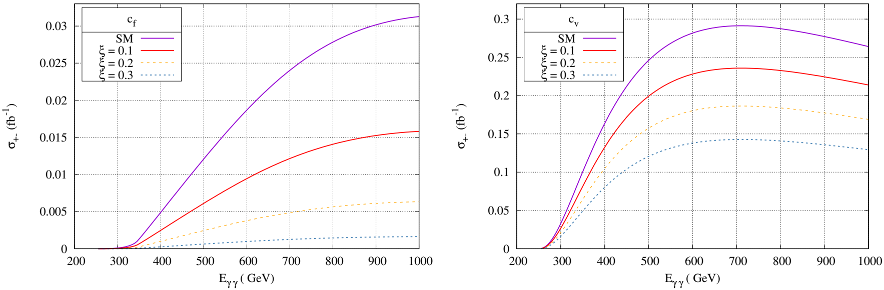

ξ = 0.2
Total
cf
cv
σ+- (fb-1)
Eγγ (GeV)


ξ = 0.3
Total
cf
cv
σ+- (fb-1)
Eγγ (GeV)

MCHM5

.

σ_{+-}

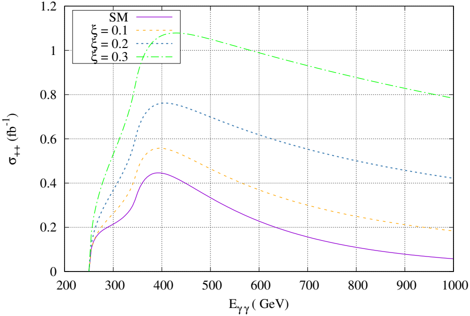


c_f
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ+- (fb-1)
E_γγ (GeV)
0
0.005
0.01
0.015
0.02
0.025
0.03
200
300
400
500
600
700
800
900
1000
c_v
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ+- (fb-1)
E_γγ (GeV)
0
0.05
0.1
0.15
0.2
0.25
0.3

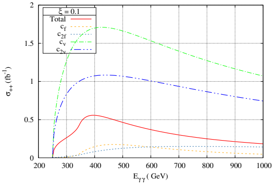
MCHM5

.

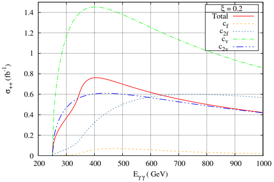
σ_{++}



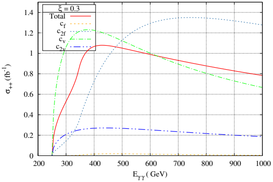
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ++ (fb-1)
Eγγ (GeV)



ξ = 0.1
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)



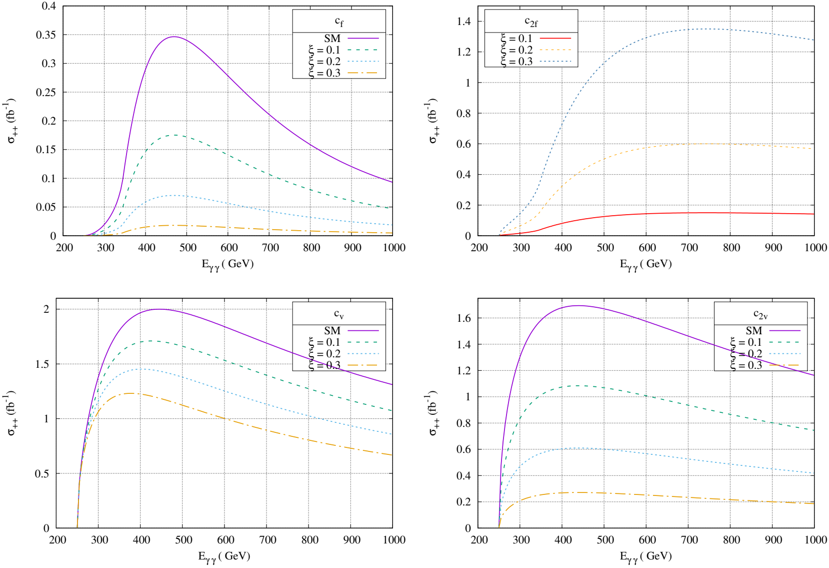
ξ = 0.2
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)



ξ = 0.3
Total
cf
c2f
cv
c2v
σ++ (fb-1)
Eγγ (GeV)

σ_{++}

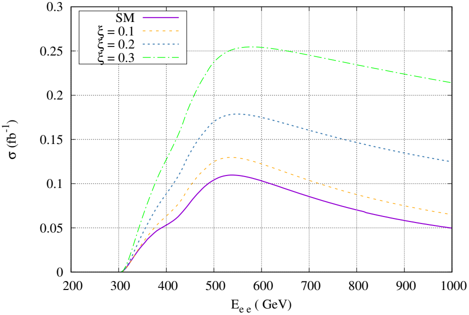
.

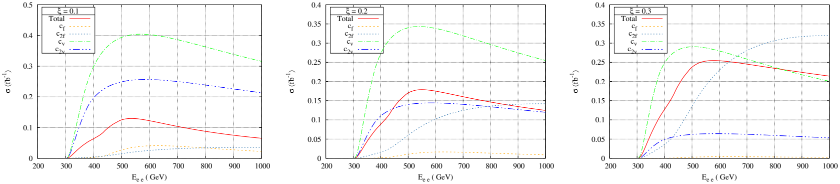

c_f
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ++ (fb-1)
Eγγ (GeV)
c_2f
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ++ (fb-1)
Eγγ (GeV)
c_v
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ++ (fb-1)
Eγγ (GeV)
c_2v
SM
ξ = 0.1
ξ = 0.2
ξ = 0.3
σ++ (fb-1)
Eγγ (GeV)

MCHM5

·

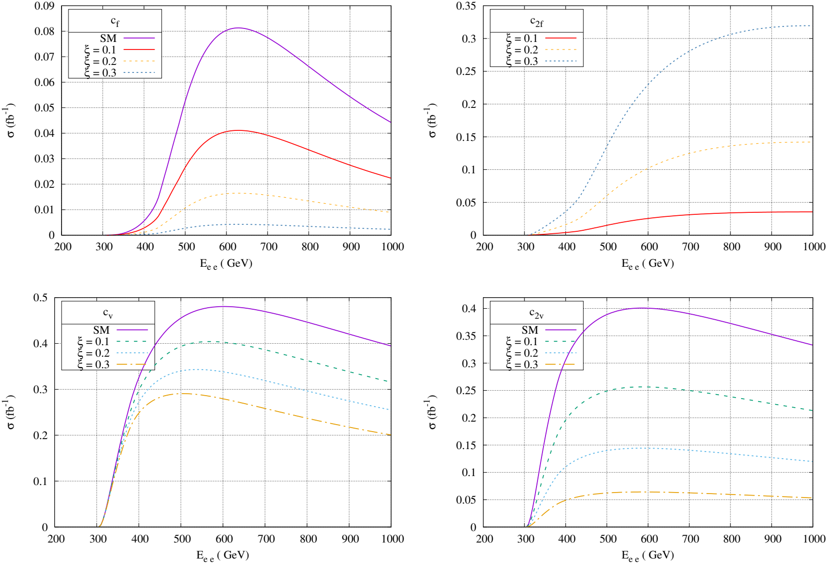
σ_{ee}





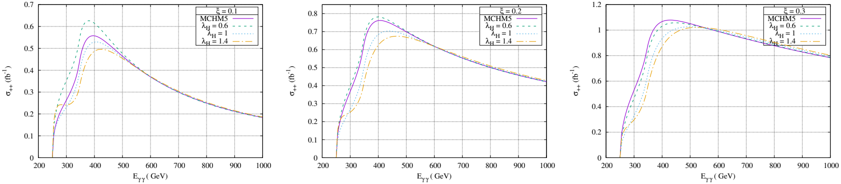
MCHM5

σ_{ee}

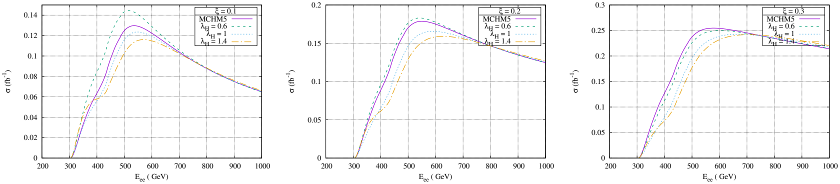


.

σ_{++}



σ_{ee}



Singlet Scalar

.

$$\mathcal{L} \supset m_W^2 W_\mu^+ W^{-,\mu} \left(1 + 2c_V^h \frac{h}{v} + 2c_V^H \frac{H}{v} + c_{2V} \frac{h^2}{v^2} + \dots\right)$$
$$+ m_t \bar{t} t \left(1 + c_f^h \frac{h}{v} + c_t^H \frac{H}{v} + \frac{c_{2t}}{2} \frac{h^2}{v^2} + \dots\right),$$

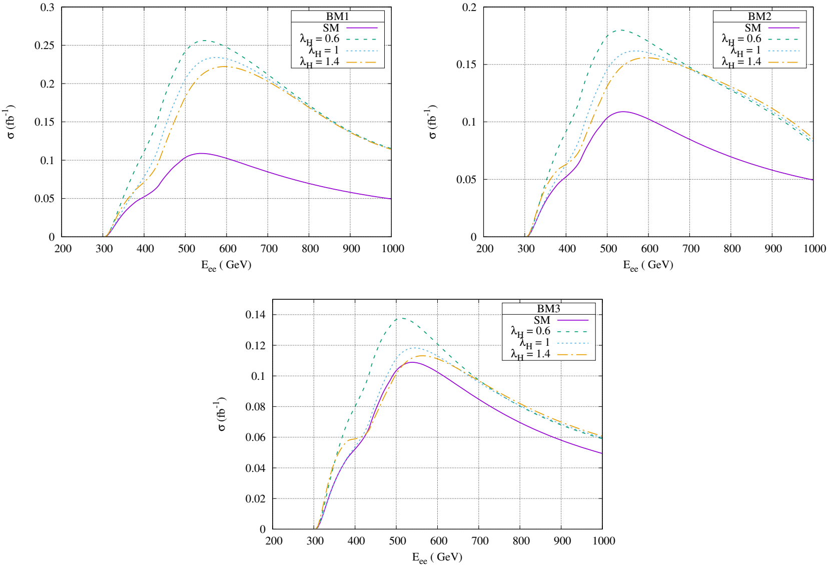
$$\mathcal{L}_{\rm eff} = \frac{1}{2} c_{Hhh} \frac{\hat{s} - 2m_h^2}{v} Hhh,$$

h = SM Higgs, H = Heavy Higgs

Benchmark 1	$m_H = 610$ GeV, $\xi = 0.306$, $\Gamma_H = 498$ GeV, $k'_G = 1.5$					
	$c_f^{h,H}$	$c_{2f}^{h,H}$	$c_V^{h,H}$	$c_{2V}^{h,H}$	c_{3h}	c_{Hhh}
h	0.9199	−0.7814	0.8791	0.5562	λ_h	–
H	3.507	…	0.3054	…	–	0.4149
Benchmark 2	$m_H = 800$ GeV, $\xi = 0.197$, $\Gamma_H = 350$ GeV, $k'_G = 1.8$					
	$c_f^{h,H}$	$c_{2f}^{h,H}$	$c_V^{h,H}$	$c_{2V}^{h,H}$	c_{3h}	c_{Hhh}
h	0.9102	−0.4627	0.9305	0.7381	λ_h	–
H	2.368	…	0.3109	…	–	0.4001
Benchmark 3	$m_H = 1000$ GeV, $\xi = 0.0646$, $\Gamma_H = 47.6$ GeV, $k'_G = 1.$					
	$c_f^{h,H}$	$c_{2f}^{h,H}$	$c_V^{h,H}$	$c_{2V}^{h,H}$	c_{3h}	c_{Hhh}
h	0.9572	−0.1498	0.9741	0.9038	λ_h	–
H	0.6896	…	0.0511	…	–	0.1270

Singlet Scalar

.



.

$$
\begin{aligned}
-\mathcal{L}_{TP} \quad = \quad & M_Q \left(\bar{U}_L U_R + \bar{U}_R U_L + \bar{D}_L D_R + \bar{D}_R D_L\right) + M_S \left(\bar{S}_L S_R + \bar{S}_R S_L\right) + \\
& y_L f \cos\theta \, \left(\bar{t}_L U_R + \bar{b}_L D_R\right) + y_R f \cos\theta \, \bar{S}_L t_R + \text{h.c.} \\
& -y_L' f \sin\theta \, \bar{t}_L S_R - y_R' f \sin\theta \, \bar{T}_L t_R + \text{h.c.}
\end{aligned}
$$

As the Higgs h is associated to the the angle θ, the coupling of the Higgs can be extracted by taking derivatives with respect to θ, as follows:

$$
\mathcal{L}_{h+h^2} = \frac{\partial \mathcal{L}_{TP}}{\partial \theta} \frac{h}{f} + \frac{1}{2} \frac{\partial^2 \mathcal{L}_{TP}}{\partial \theta^2} \frac{h^2}{f^2} \, .
$$

$$-\mathcal{L}_S = M_S\,\bar{S}_L S_R + y_R f\cos\theta\,\bar{S}_L t_R - y_L' f\sin\theta\,\bar{t}_L S_R + \text{h.c.}$$

We can first define an angle, α_R, characterising the degree of compositeness of the right-handed top, as follows:

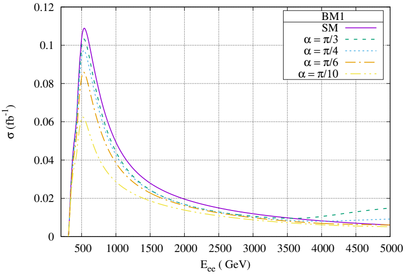
$$\sin\alpha_R = \frac{y_R f}{M}\,, \quad M = \sqrt{M_S^2 + y_R^2 f^2}\,.$$

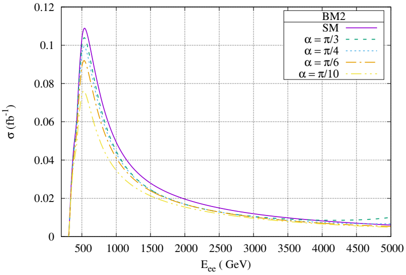
$$\begin{aligned}\mathcal{L} &= -m_t\left\{\left(1 + c_f\frac{h}{v} + \frac{1}{2}c_{2f}\frac{h^2}{v^2}\right)\bar{t}_L t_R + \left(c_T\frac{h}{v} + \frac{1}{2}c_{2T}\frac{h^2}{v^2}\right)\bar{T}_L T_R + \right.\\ &\left.\left(c_{tT}\frac{h}{v} + \frac{1}{2}c_{2tT}\frac{h^2}{v^2}\right)\bar{t}_L T_R + \left(c_{Tt}\frac{h}{v} + \frac{1}{2}c_{2Tt}\frac{h^2}{v^2}\right)\bar{T}_L t_R\right\} + \text{h.c.}\end{aligned}$$

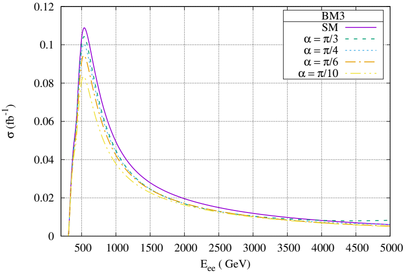
Benchmark 1	$M = 1500$ GeV, $\theta = 0.2$, $m_{\text{top}} = 173$ GeV								
	M_T	c_f	c_{2f}	c_T	c_{2T}	c_{tT}	c_{2tT}	c_{Tt}	c_{2Tt}
$\alpha_R = \pi/3$	1480	0.965	−0.0497	−0.212	−0.250	−0.603	0.006	−0.220	−0.146
$\alpha_R = \pi/4$	1496	0.945	−0.0596	−0.0427	−0.167	−1.034	0.0211	−0.291	−0.166
$\alpha_R = \pi/6$	1525	0.906	−0.0685	0.293	−0.0923	−1.77	0.0542	−0.347	−0.137
$\alpha_R = \pi/10$	1608	0.810	−0.0709	1.204	−0.0749	−3.123	0.0115	−0.430	−0.0795
Benchmark 2	$M = 2000$ GeV, $\theta = 0.2$, $m_{\text{top}} = 173$ GeV								
	M_T	c_f	c_{2f}	c_T	c_{2T}	c_{tT}	c_{2tT}	c_{Tt}	c_{2Tt}
$\alpha_R = \pi/3$	1973	0.967	−0.0497	−0.309	−0.334	−0.599	0.00608	−0.253	−0.196
$\alpha_R = \pi/4$	1988	0.951	−0.0596	−0.132	−0.222	−1.028	0.0209	−0.319	−0.223
$\alpha_R = \pi/6$	2014	0.926	−0.0689	0.165	−0.117	−1.762	0.0536	−0.348	−0.188
$\alpha_R = \pi/10$	2075	0.869	−0.0729	0.845	−0.0729	−3.11	0.114	−0.388	−0.117
Benchmark 3	$M = 2500$ GeV, $\theta = 0.2$, $m_{\text{top}} = 173$ GeV								
	M_T	c_f	c_{2f}	c_T	c_{2T}	c_{tT}	c_{2tT}	c_{Tt}	c_{2Tt}
$\alpha_R = \pi/3$	2465	0.968	−0.0497	−0.400	−0.417	−0.598	0.006	−0.292	−0.245
$\alpha_R = \pi/4$	2481	0.954	−0.0596	−0.208	−0.277	−1.025	0.0207	−0.359	−0.280
$\alpha_R = \pi/6$	2506	0.934	−0.0691	0.0793	−0.143	−1.757	0.0533	−0.368	−0.238
$\alpha_R = \pi/10$	2556	0.896	−0.0738	0.643	−0.0766	−3.103	0.1136	−0.374	−0.153
Benchmark 4	$M = 5000$ GeV, $\theta = 0.2$, $m_{\text{top}} = 173$ GeV								
	M_T	c_f	c_{2f}	c_T	c_{2T}	c_{tT}	c_{2tT}	c_{Tt}	c_{2Tt}
$\alpha_R = 0.518$	4985	0.9455	−0.0695	−0.164	−0.273	−1.773	0.0540	−0.554	−0.481
$\alpha_R = \pi/10$	5020	0.932	−0.0749	0.233	−0.117	−3.093	0.113	−0.4405	−0.323

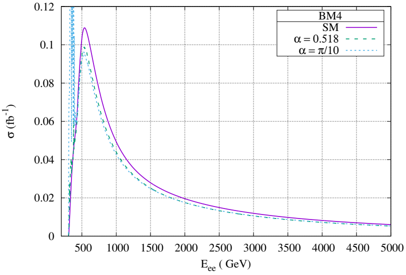
Singlet

.


BM1
SM
α = π/3
α = π/4
α = π/6
α = π/10
σ (fb⁻¹)
E_ee (GeV)


BM2
SM
α = π/3
α = π/4
α = π/6
α = π/10
σ (fb⁻¹)
E_ee (GeV)


BM3
SM
α = π/3
α = π/4
α = π/6
α = π/10
σ (fb⁻¹)
E_ee (GeV)


BM4
SM
α = 0.518
α = π/10
σ (fb⁻¹)
E_ee (GeV)

Doublet

$$-\mathcal{L}_Q = M_Q\left(\bar{U}_L U_R + \bar{D}_L D_R\right) + y_L f\cos\theta\,\left(\bar{t}_L U_R + \bar{b}_L D_R\right) - y_R' f\sin\theta\,\bar{T}_L t_R + \text{h.c.}$$

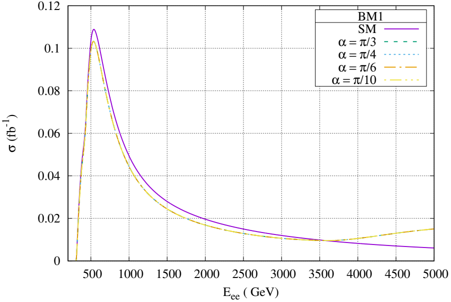
$$\sin\alpha_L = \frac{y_L f}{M}\,,\quad M = \sqrt{M_Q^2 + y_L^2 f^2}\,.$$

$$\begin{aligned}\mathcal{L} \;=\; & -m_t\left\{\left(1 + c_f\frac{h}{v} + \frac{1}{2}c_{2f}\frac{h^2}{v^2}\right)\bar{t}_L t_R + \left(c_T\frac{h}{v} + \frac{1}{2}c_{2T}\frac{h^2}{v^2}\right)\bar{T}_L T_R + \right.\\ & \left.\left(c_{tT}\frac{h}{v} + \frac{1}{2}c_{2tT}\frac{h^2}{v^2}\right)\bar{t}_L T_R + \left(c_{Tt}\frac{h}{v} + \frac{1}{2}c_{2Tt}\frac{h^2}{v^2}\right)\bar{T}_L t_R\right\} + \text{h.c.}\\ & -m_t\left\{\left(c_B\frac{h}{v} + \frac{1}{2}c_{2B}\frac{h^2}{v^2}\right)\bar{B}_L B_R + \left(c_{bB}\frac{h}{v} + \frac{1}{2}c_{2bB}\frac{h^2}{v^2}\right)\bar{b}_L B_R + \left(c_{Bb}\frac{h}{v} + \frac{1}{2}c_{2Bb}\frac{h^2}{v^2}\right)\right.\end{aligned}$$

Benchmark 1	$M = 1500$ GeV, $\theta = 0.2$, $m_{\text{top}} = 173$ GeV								
	M_X	c_f	c_{2f}	c_X	c_{2X}	c_{xX}	c_{2xX}	c_{Xx}	c_{2Xx}
$\alpha_R = \pi/3$	T: 1481	0.965	-0.0497	-0.212	-0.250	-0.220	-0.146	-0.603	0.006
	B: 1478	0	0	-0.255	-0.250	-0.150	-0.147	0	0
$\alpha_R = \pi/4$	T: 1496	0.945	-0.0596	-0.0427	-0.167	-0.291	-0.166	-1.034	0.0211
	B: 1485	0	0	-0.169	-0.166	-0.173	-0.169	0	0
$\alpha_R = \pi/6$	T: 1525	0.906	-0.0685	0.293	-0.0923	-0.347	-0.137	-1.77	0.0543
	B: 1493	0	0	-0.0843	-0.0826	-0.149	-0.146	0	0
$\alpha_R = \pi/10$	T: 1608	0.810	-0.0709	1.204	-0.0749	-0.430	-0.0795	-3.123	0.0115
	B: 1497	0	0	-0.0321	-0.0314	-0.101	-0.0988	0	0

Doublet

.



Process	CM Energy	SM ($\times 10^{-2}$)	BP 1 ($\times 10^{-2}$)	BP 2 ($\times 10^{-2}$)	BP 3 ($\times 10^{-2}$)
$\sigma(e^+e^- \to \ell^+\ell^- hh)$ (fb^{-1})	1 TeV	1.49	1.42	1.45	1.44
$\sigma(e^+e^- \to \ell^+\ell^- hh)$ (fb^{-1})	500 GeV	1.52	1.48	1.42	1.45
$\sigma(e^+e^- \to \nu\nu hh)$ (fb^{-1})	1 TeV	8.79	10.84	10.9	9.96
$\sigma(e^+e^- \to \nu\nu hh)$ (fb^{-1})	500 GeV	3.41	3.37	3.39	3.32

Conclusion

.

- The most significant contribution comes from quartic fermionic term (c_{2f})
- Trilinear Higgs coupling (c_{3h}) could change the predictions by 10-20% at ILC@500GeV.
- Additional scalars can also give substantial contributions.
- The contributions from Vector Like quark multiplets is expected to be small.