Di-Higgs production in Composite Models

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in collaboration with

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Introduction

The standard model for elementary particles is very successful in describing high energy phenomena. However, the details of Higgs sector are still unknown part of the Standard Model. The Higgs mechanism will be tested by determining the coupling constants of the Higgs boson to the weak gauge boson. The measurement of the Yukawa coupling constants will clarify the mass generation mechanism of quarks and charged leptons.

It is also important to measure the Higgs pair production processes at LHC and ILC.

Test for the SM (Reconstruction of Higgs potential)
Search for New Physics effect

In the minimal Composite Higgs model (MCHM):

Global symmetry f $\langle H \rangle = \frac{v}{2}$

$$SO(5) \Rightarrow SO(4) \simeq SU(2)_L \times SU(2)_R \Rightarrow SU(2)_V$$

Number of broken generators $N_{NGB} = \frac{5(5-1)}{2} - \frac{4(4-1)}{2} = 4$

Higgs boson emerges as a pseudo-Nambu-Goldstone boson from a global symmetry.

Higgs couplings to gauge bosons in MCHM

In composite models, the EWSB can be written as

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

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

We parametrize the W mass Lagrangian

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

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

These results are universal. (same couplings in all models)

The mass of W is given by

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

The couplings of the composite Higgs to WW

$$g_{WWh} = \frac{1}{f}\frac{\partial m_W^2(\theta)}{\partial\theta} = \frac{2m_W^2}{v}\cos\theta\,;$$

$$g_{WWhh} = \frac{1}{f^2}\frac{\partial^2 m_W^2(\theta)}{\partial\theta^2} = \frac{2m_W^2}{v^2}\cos 2\theta\,;$$

Higgs couplings to SM Fermions in MCHM

In the composite Higgs model, the effective Lagrangian can be written as

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

$\Sigma = exp(i\sigma_a \pi^a / v)$, $v = 246$ GeV, i, j are integers (quark family index)

Assuming that there is no tree level flavor violation, $i = j$. $m_f = \frac{v}{\sqrt{2}}\lambda_{ii}$ and $\xi = v^2/f^2$

The Higgs couplings to the SM fermions can be written as

For MCHM4 (spinorial representation)

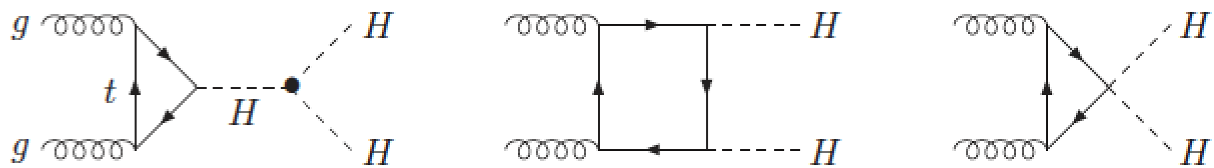
$$m_t(\theta) = \frac{\lambda f}{\sqrt{2}} \sin\theta \quad \Rightarrow \quad \begin{cases} g_{ffh} = \frac{m_t}{v}\cos\theta\,, \\ g_{ffhh} = -\frac{m_t}{v^2}\sin^2\theta\,. \end{cases}$$

For MCHM5 (fundamental representation)

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

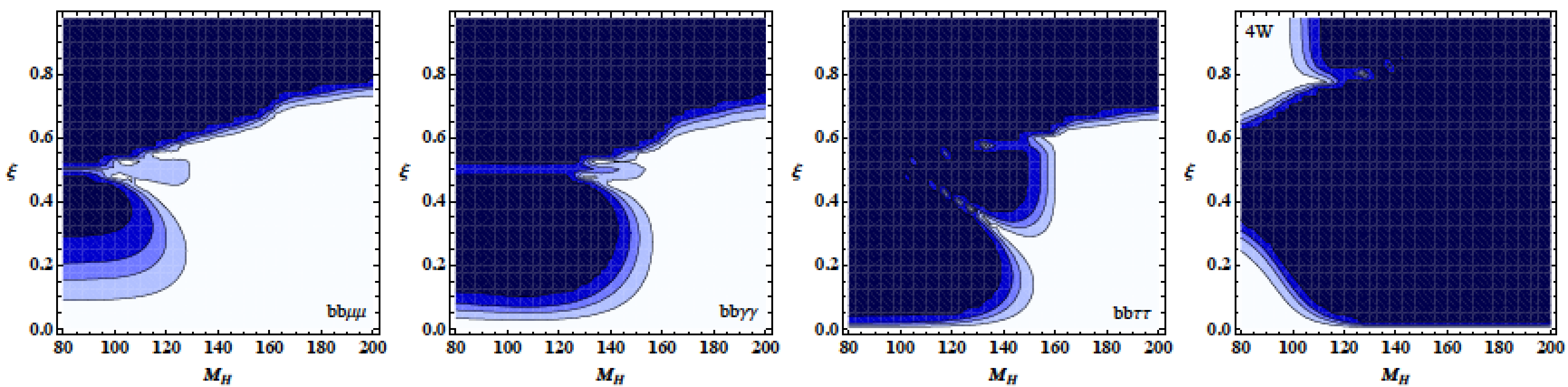
Higgs pair production at LHC in MCHM5

Grober and Muhlleitner 1012.1562



Sensitivity @300 fb^-1

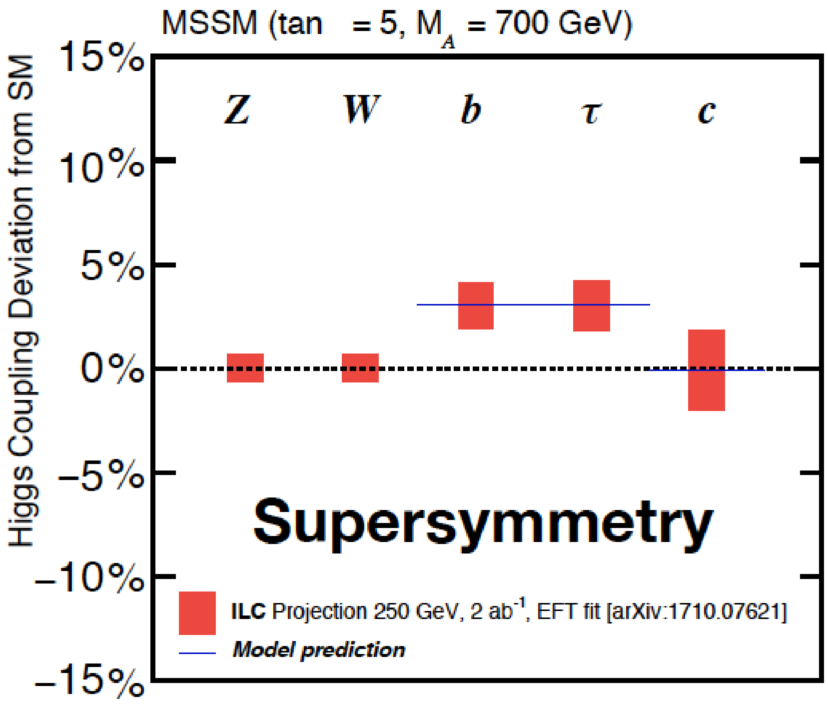
$$S^{\mathrm{SM}} + \beta\sqrt{S^{\mathrm{SM}}} > S^{\mathrm{MCHM}} \quad \text{or} \quad S^{\mathrm{SM}} - \beta\sqrt{S^{\mathrm{SM}}} < S^{\mathrm{MCHM}} \qquad (\beta = 1, 2, 3, 5)$$

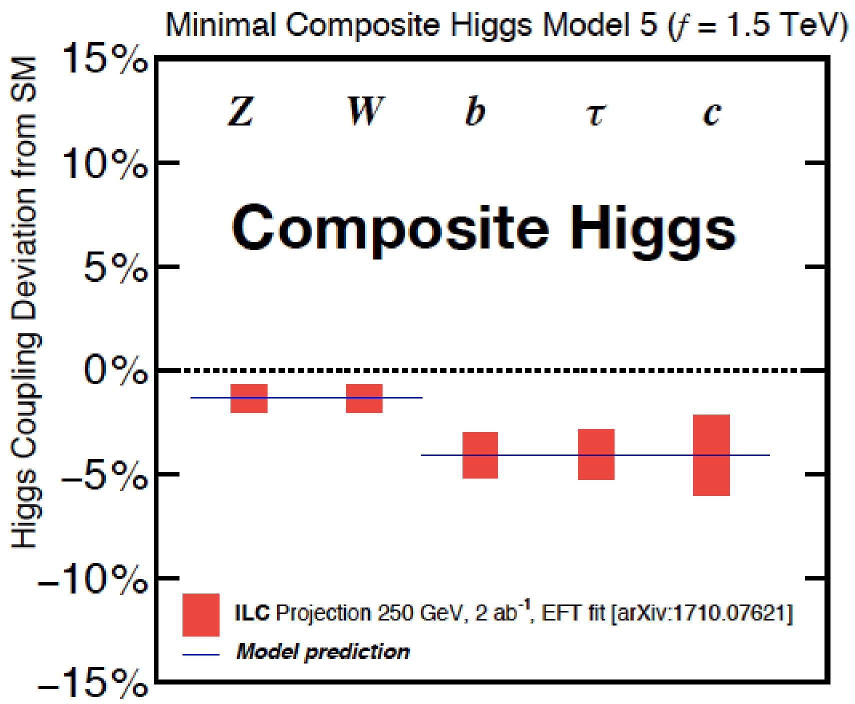


However, Higgs pair production process at LHC is challenging because large QCD backgrounds.

Higgs coupling deviation in MCHM5

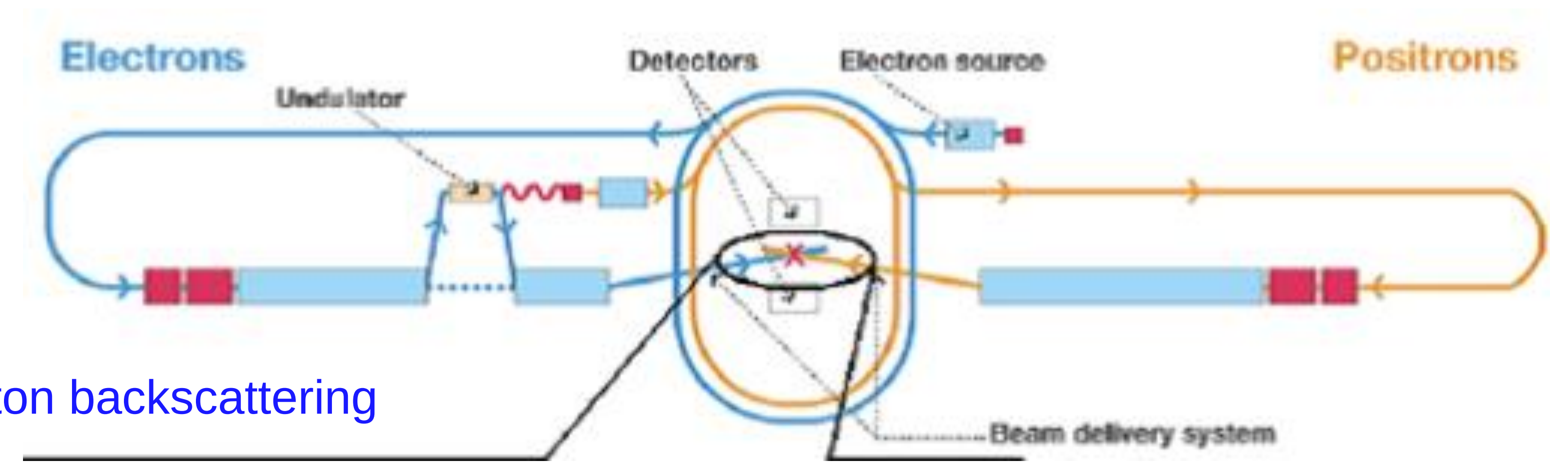
Model	$hf\bar{f}(c_f)$	$hhf\bar{f}(c_{2f})$	$hW^+W^-(c_V)$	$hhW^+W^-(c_{2V})$	c_{3h}
MCHM4 [2]	$\sqrt{1-\xi}$	$-\xi$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5 [3]	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-\xi}{\sqrt{1-\xi}}$





The pattern of the deviation can be specific to certain models. The precision Higgs coupling measurements at the ILC with 250 GeV at the 1% level enable us to fingerprint the different model. In MCHM, deviation from SM is negative, 1-10 % for f = 1.5 TeV.

Photon Linear Collider (PLC)



Compton backscattering

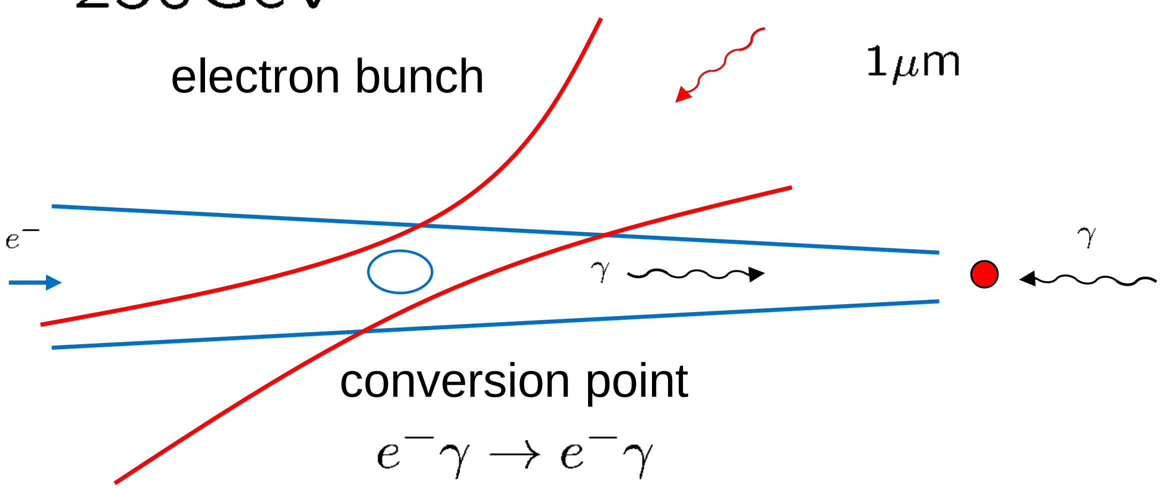
Electron beam energy
$\sim 250\text{GeV}$

laser wavelength

$1\mu\text{m}$

Photon Linear Collider (PLC) is an optional experiment for ILC.

electron bunch



conversion point

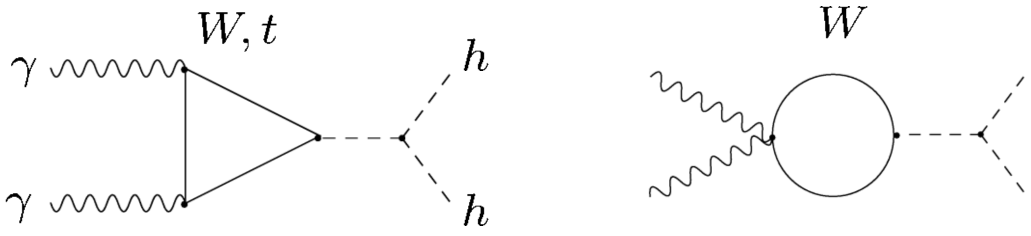
$$e^-\gamma \to e^-\gamma$$

Differences from Zhh and W fusion

$$\gamma\gamma \to hh$$

Two body final state

There is kinematical advantage.

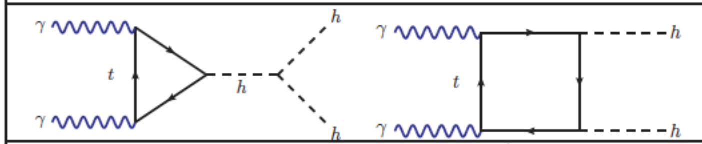
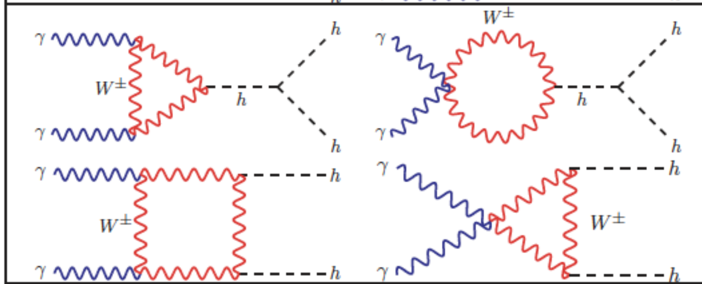
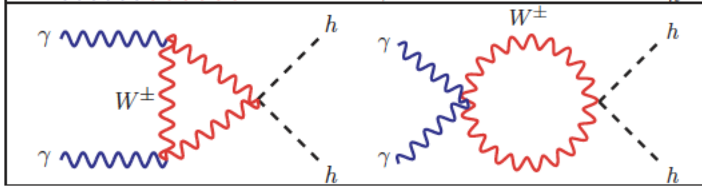


Loop induced process

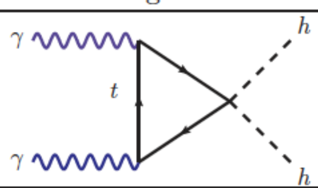
This process would be sensitive to the New loop diagrams (tthh).

Higgs pair production process at PLC in MCHM

SM contributions

Diagrams	Amplitude
	$\mathcal{M}_{c_f}$
	$\mathcal{M}_{c_v}$
	$\mathcal{M}_{c_{2v}}$

New contribution

Diagrams	Amplitude
	$\mathcal{M}_{c_{2f}}$

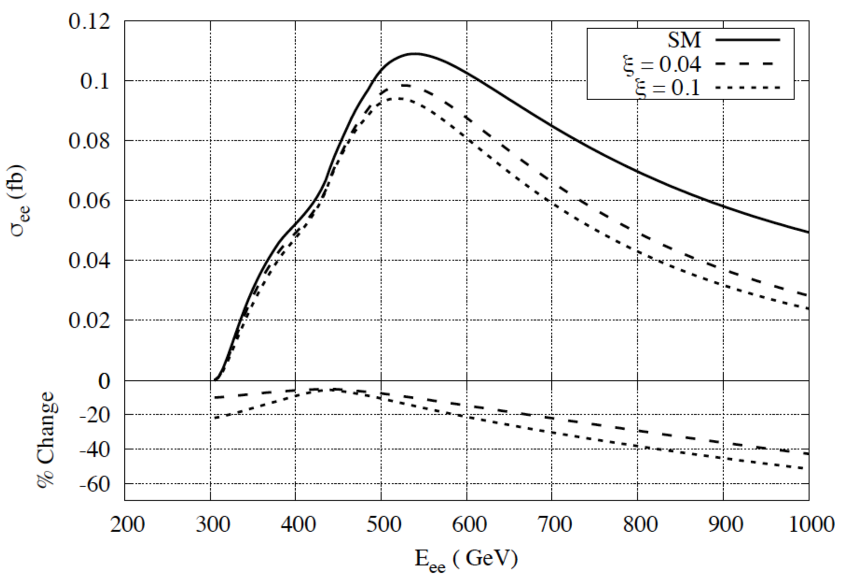
In this work, we specially focus on the tthh coupling.

The cross section of γγ → hh in MCHM

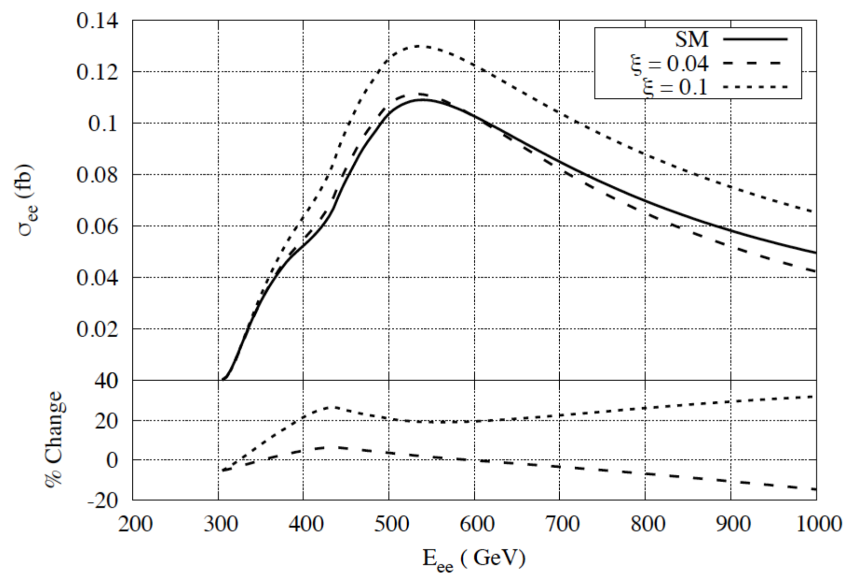
Model	$hf\bar{f}(c_f)$	$hhf\bar{f}(c_{2f})$	$hW^+W^-(c_V)$	$hhW^+W^-(c_{2V})$	c_{3h}
MCHM4 [2]	$\sqrt{1-\xi}$	$-\xi$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5 [3]	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-\xi}{\sqrt{1-\xi}}$

$$\xi = v^2/f^2$$

MCHM4



MCHM5



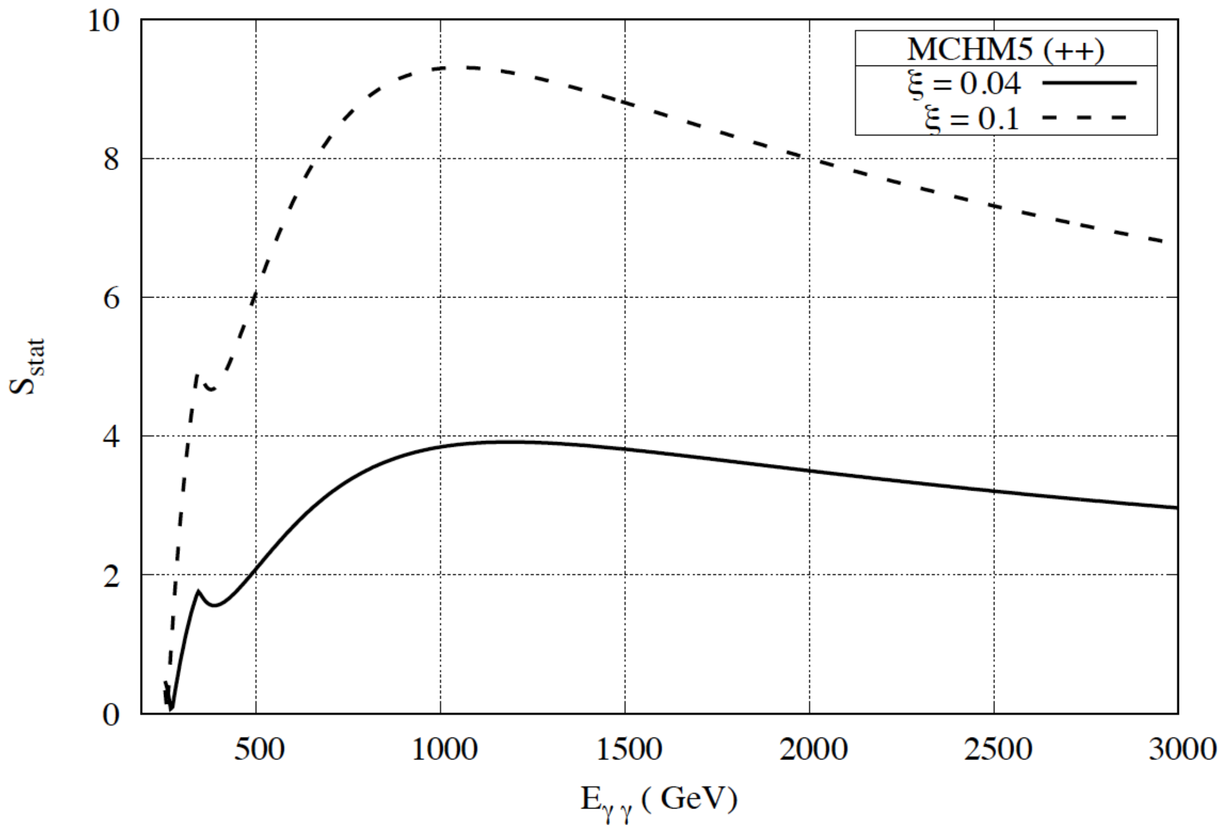
In the MCHM4, we observe a systematic decrease in the total cross-section, with sizeable effects emerging for center-of-mass energies above 500 GeV. Thus, this scenario can only be tested at a high-energy version of the collider. On the other hand, the MCHM5 can feature an increase in the cross-section compared to the SM one, driven by the tthh coupling c2f.

Statistical sensitivity in MCHM5

$$S_{stat} = \sqrt{\mathcal{L}}\frac{|\sigma - \sigma_{SM}|}{\sqrt{\sigma}}$$

work in progress

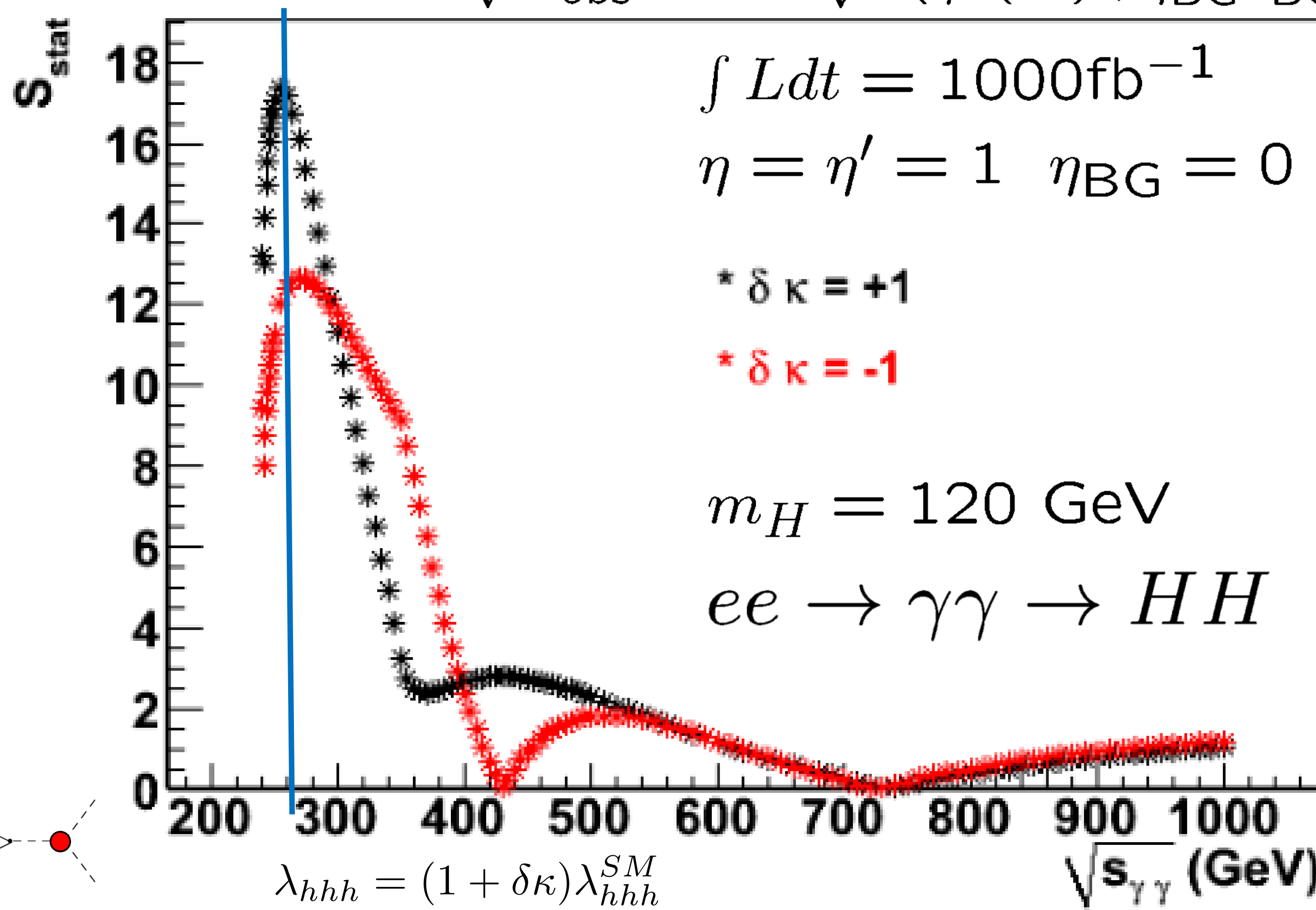
$$\xi = v^2/f^2$$

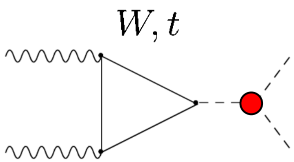


Statistical sensitivity ~ 5 around 300 GeV for xi=0.1 at L=1 fb^-1.

Statistical sensitivity in SM with hhh

$$\text{sensitivity} \equiv \frac{|N(\delta\kappa) - N_{\text{SM}}|}{\sqrt{N_{\text{obs}}}} = \frac{L|\eta\sigma(\delta\kappa) - \eta\sigma_{\text{SM}}|}{\sqrt{L(\eta\sigma(\delta\kappa) + \eta_{\text{BG}}\sigma_{\text{BG}})}}$$





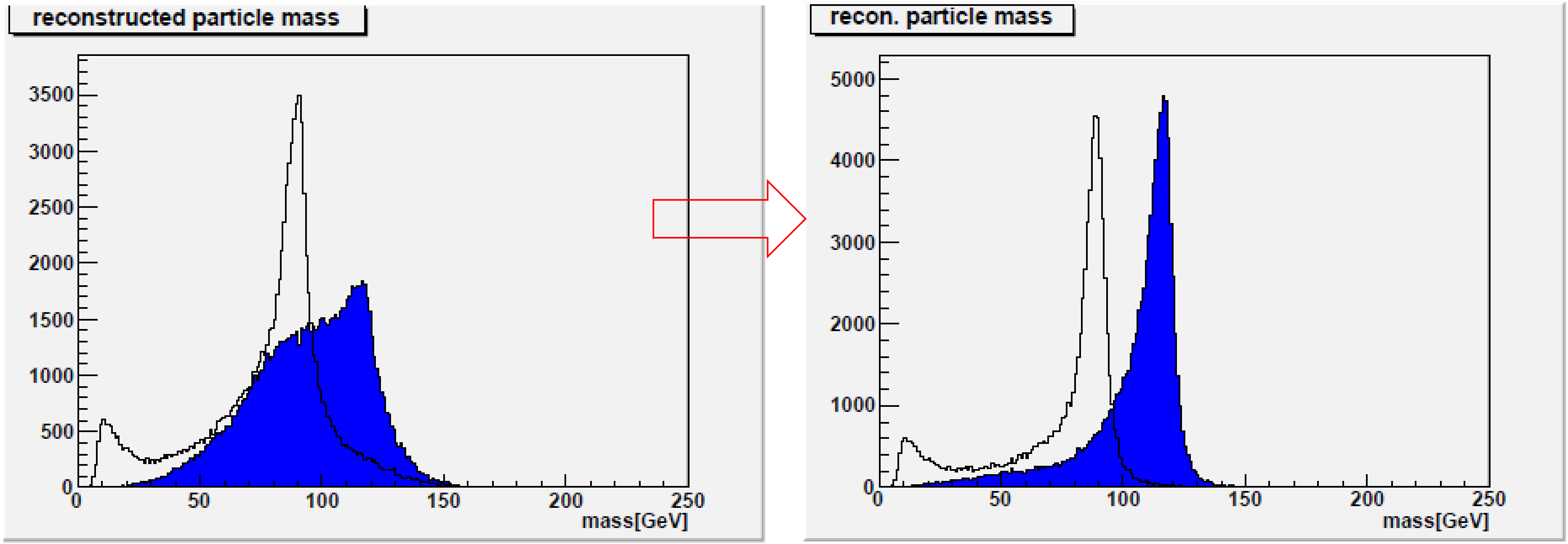
$\lambda_{hhh} = (1 + \delta\kappa)\lambda_{hhh}^{SM}$

Improved mass resolution

Mass distribution of HH and ZZ BG

S. Kawada, T. Takahashi, K. Fujii and ILC physics working group

JADE clustering | Ideal jet clustering



$$\text{significance} = \frac{N_{signal}}{\sqrt{N_{signal}+N_{BG}}} = 0.922\sigma$$

$$\text{significance} = 4.87\sigma$$

$$(\int L dt = 2\text{ab}^{-1})$$

Large backgrounds can be suppressed If each track could be successfully assigned to parent partons is achieved.

Introducing a heavy scalar

Franzosi, Cacciapaglia, Deandrea Eur. Phys. J. C 80(2020)28

The presence of a rather light scalar resonance in the spectrum of CHMs has been shown to help in reducing the constraints on the misalignment angle.
We add a heavy scalar H.
The couplings to gauge bosons and tops resemble the SM Higgs ones, and can be parametrised as:

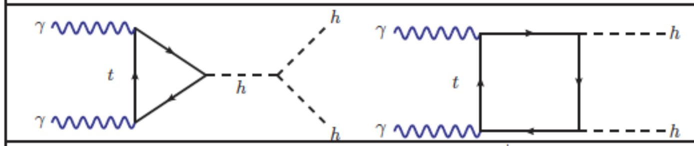
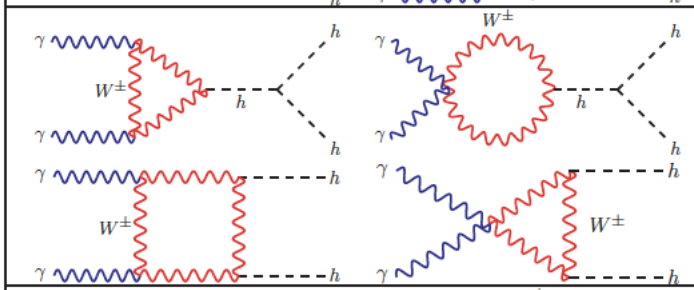
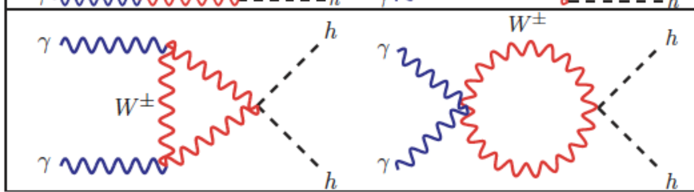
$$\mathcal{L} \supset m_W^2 W_\mu^+ W^{-,\mu} \left(1 + 2c_v \frac{h}{v} + 2c_v^H \frac{H}{v} + c_{2v} \frac{h^2}{v^2} + \dots \right) + m_t \bar{t}t \left(1 + c_f \frac{h}{v} + c_t^H \frac{H}{v} + \frac{c_{2t}}{2} \frac{h^2}{v^2} + \dots \right)$$

There is also a derivative coupling of H to two Higgses, which is relevant for di-Higgs pair production, that can be parametrised as:

$$\mathcal{L} \supset c_{Hhh}\, H \partial_\mu h \partial^\mu h \to -\frac{1}{2} c_{Hhh} \frac{\hat{s} - 2m_h^2}{v}\, Hhh\,.$$

Introducing a heavy scalar

SM contributions

<table>
<tr><th>Diagrams</th><th>Amplitude</th></tr>
<tr><td>
</td><td>$\mathcal{M}_{c_f}$</td></tr>
<tr><td>
</td><td>$\mathcal{M}_{c_v}$</td></tr>
<tr><td>
</td><td>$\mathcal{M}_{c_{2v}}$</td></tr>
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Heavy scalar

New contribution

<table>
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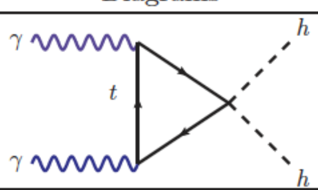
<tr><td>
</td><td>$\mathcal{M}_{c_{2f}}$</td></tr>
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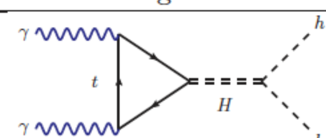
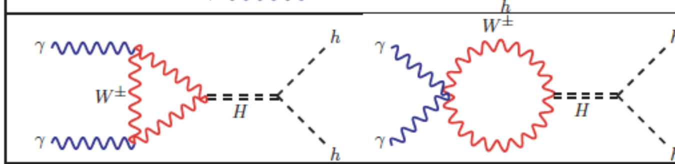
<tr><td>
</td><td>$\mathcal{M}_{c_f^H}$</td></tr>
<tr><td>
</td><td>$\mathcal{M}_{c_v^H}$</td></tr>
</table>

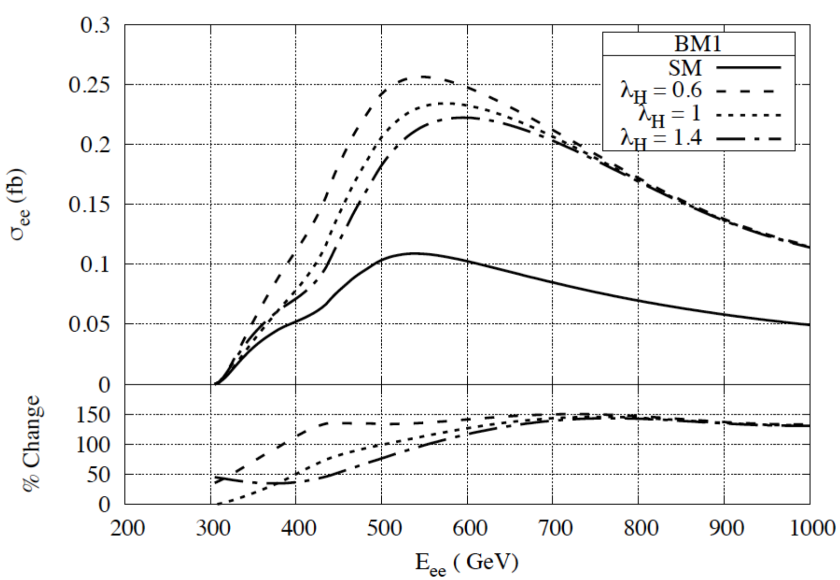
Introducing a heavy scalar

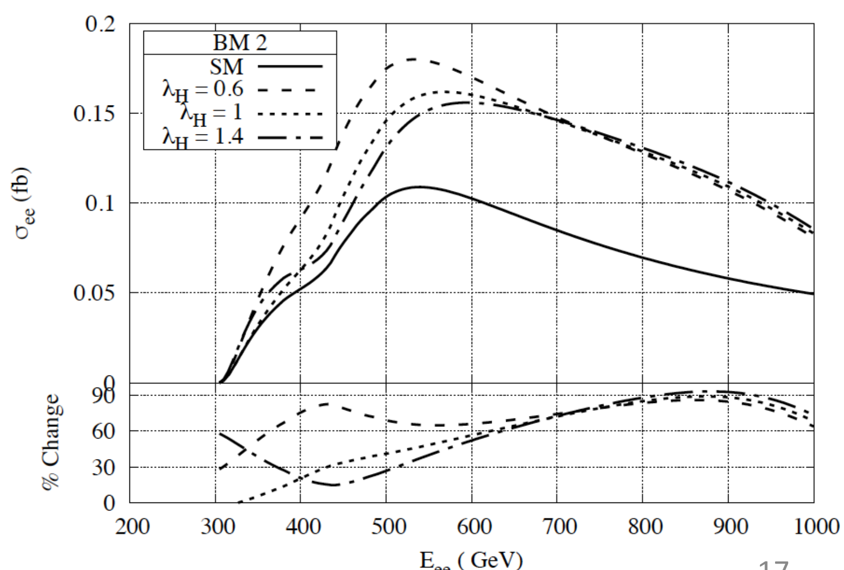
Eur. Phys. J. C 80(2020)28

Benchmark 1	$m_H = 610$ GeV, $\xi = 0.306$, $\Gamma_H = 498$ GeV, $k'_G = 1.5$					
	c_f/c_f^H	c_{2f}	c_v/c_v^H	c_{2v}	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/c_f^H	c_{2f}	c_v/c_v^H	c_{2v}	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/c_f^H	c_{2f}	c_v/c_v^H	c_{2v}	c_{3h}	c_{Hhh}
h	0.9572	−0.1498	0.9741	0.9038	λ_h	–
H	0.6896	...	0.0511	...	–	0.1270

Table 5. Couplings of the Higgs h and of the heavier state H, for 3 benchmark points. The parameter k'_G characterises the coupling of the heavy resonance to the gauge bosons (see Ref. [39] for more details).

For BM1 and BM2, sizeable enhancements are expected at low energies, where the cross section can even double with respect to the SM one.





Summary

We considered the Higgs pair production process in Composite Models at the Photon Linear Collider (PLC).

Especially, we are interesting in the MCHM5. The cross section of gamma gamma->hh is enhanced by New diagram (tthh coupling) below the center of mass energy 500 GeV.

ILC working group has already done the gamma gamma -> hh process including BG.
(5 sigma signifinicance@2ab^-1)
tthh coupling would be also tested at PLC in MCHM5.

In MCHM, we plan to study more details of this model in collaboration with ILC working group.

The presence of an additional scalar resonance H opens up a new s-channel diagram. This results in large enhancements of up to 450%, accentuated for lower value of mH and depending on the width ΓH
.

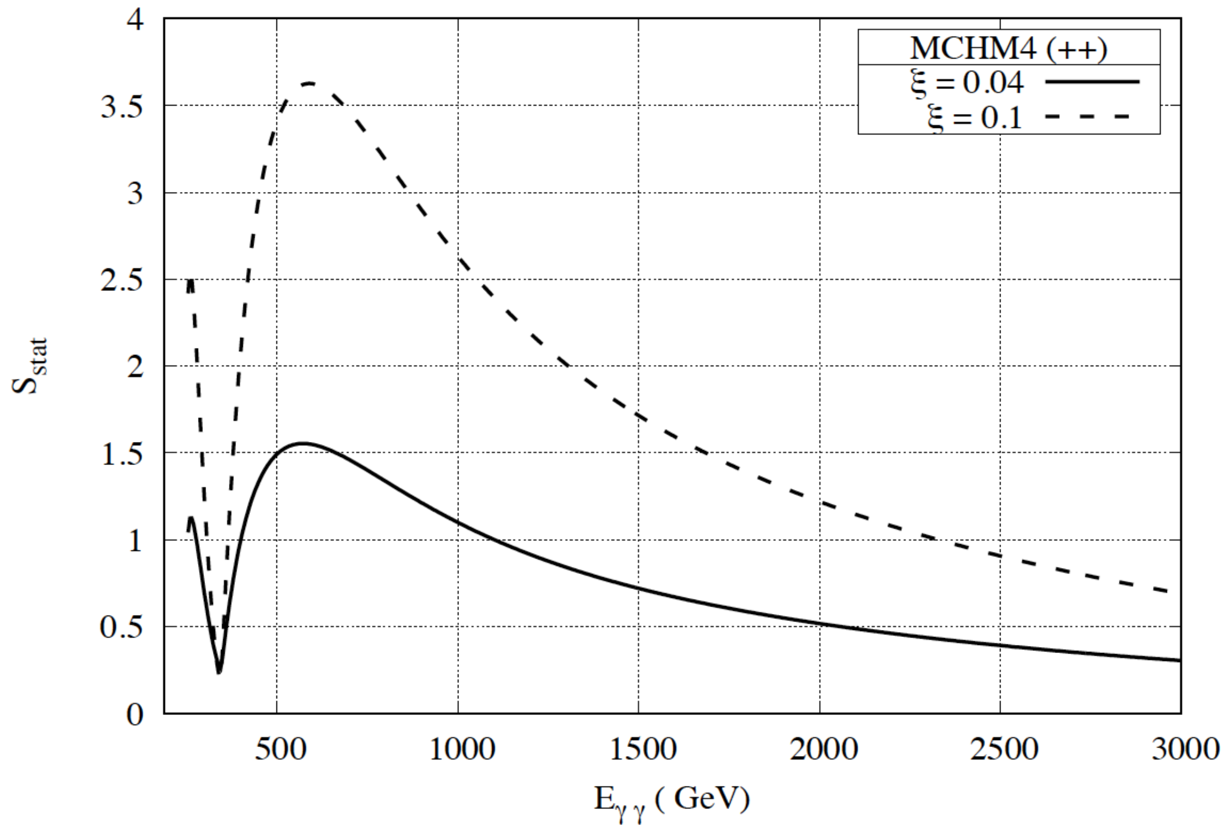
Backup slide

Statistical sensitivity in MCHM4

$$S_{stat} = \sqrt{\mathcal{L}}\frac{|\sigma - \sigma_{SM}|}{\sqrt{\sigma}}$$

work in progress

$$\xi = v^2/f^2$$



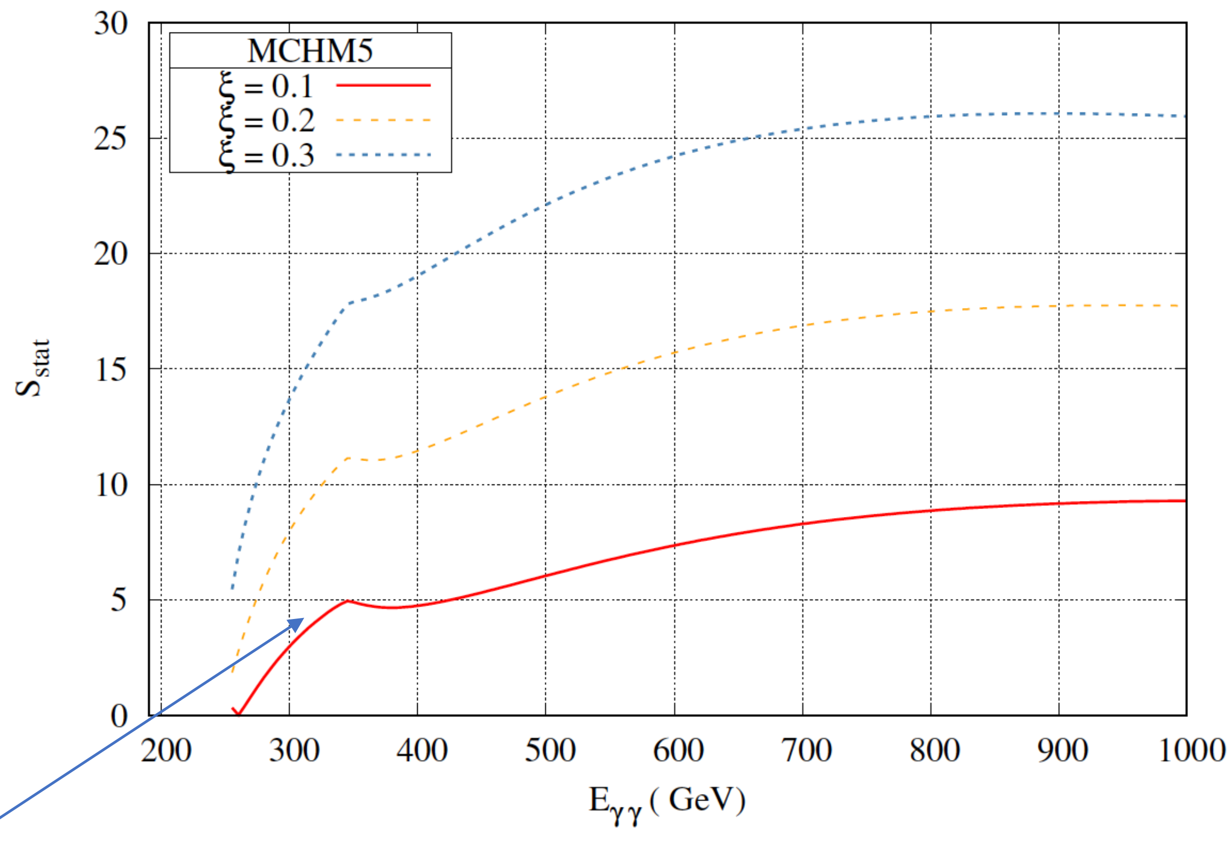
Statistical sensitivity ~ 3.5 around 500 GeV for xi=0.1.

Statistical sensitivity in MCHM5

$$S_{stat} = \sqrt{\mathcal{L}}\frac{|\sigma - \sigma_{SM}|}{\sqrt{\sigma}}$$

work in progress

$$\xi = v^2/f^2$$



Statistical sensitivity ~ 5 around 300 GeV for xi=0.1.

Back grounds

Dominant back ground

$$\sigma(\gamma\gamma \to WW) \sim 90\text{pb}$$

$$\sigma(\gamma\gamma \to ZZ) \sim 60\text{pb}$$

$$\int Ldt = 400\text{fb}^{-1}/\text{year}$$

Signal

$\gamma\gamma \to HH \to 4j$ 16 events/yea r

Back grounds

$\gamma\gamma \to WW \to 4j$

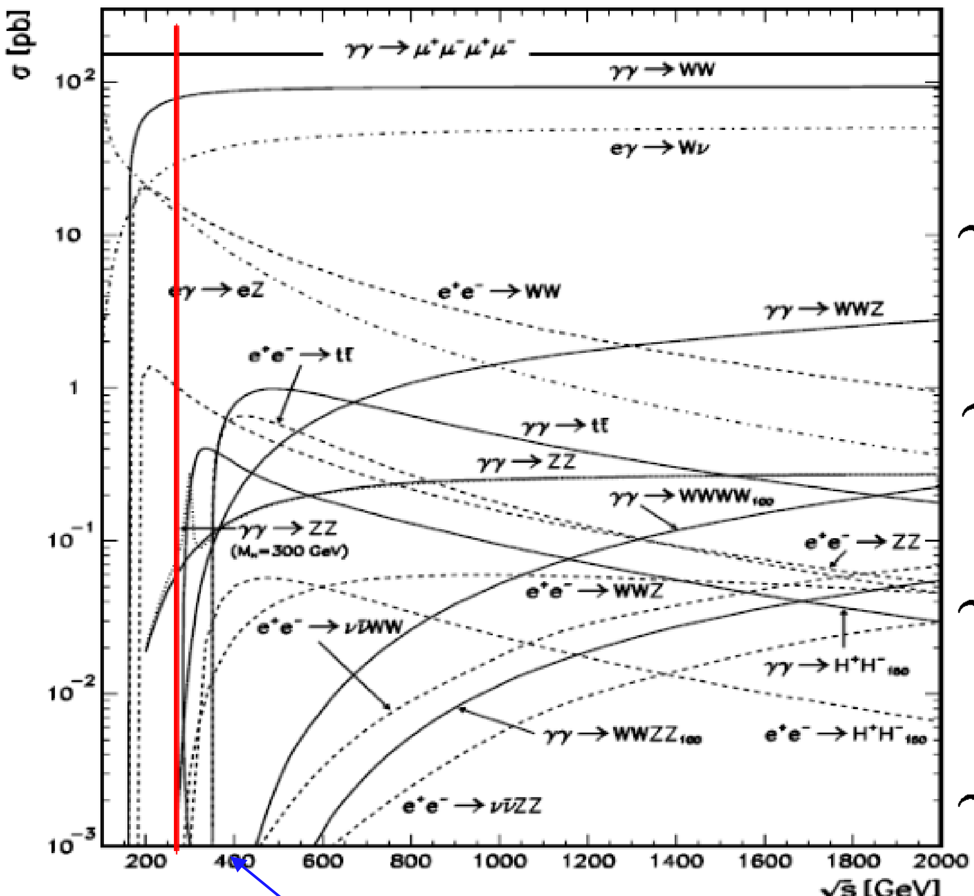
1.5×10^{7} events/yea r

$\gamma\gamma \to ZZ \to 4j$

1.2×10^{4} events/yea r

$\gamma\gamma \to b\bar{b}b\bar{b} \to 4j$

5.2×10^{4} events/yea r



270 GeV

$\gamma\gamma \to t\bar{t}$ threshold