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Higgs pair production in Composite Higgs models

Ramona Gröber in coll. with Margarete Mühlleitner | 09.02.2012

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

- Hierarchy problem
  $\rightarrow$ in Composite Higgs models: Higgs mass generated dynamically through loops of SM fermions and gauge bosons
  $\rightarrow$ Higgs mass is naturally light

- To reconstruct Higgs potential $\rightarrow$ measurement of Higgs self couplings is necessary
  $\rightarrow$trilinear coupling can be measured in Higgs pair production
  $\rightarrow$ quartic Higgs coupling is accessible in Three-Higgs-production, but: Cannot even be measured at ILC/CLIC [CLIC Physics working group] or VLHC [Plehn, Rauch]

The Composite Higgs model

- Higgs boson is a bound state from a strongly-interacting sector [Kaplan, Georgi, Galison, Dugan; Dimopoulos, Preskill; Banks]
- Higgs boson emerges as a pseudo-Nambu-Goldstone boson from a global symmetry

$$G \xrightarrow{f} H \supset H_0 = SU(2)_L \times U(1)_Y$$

- G is explicitely broken by couplings of SM fields to strong sector $\rightarrow$ loops of SM fermions and gauge bosons generate Higgs potential
- Higgs boson is naturally separated by a mass gap from the other usual resonances
- In an effective low-energy description only the Higgs couplings to the SM fields are modified and depend on $\xi = \frac{v^2}{f^2}$ with $\xi \in [0, 1]$ [Giudice,Grojean,Pomarol,Rattazzi]

Minimal Composite Higgs models [Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol]

- Realized as 5D theory on AdS spacetime $\rightarrow$ holographic interpretation in terms of 4D strongly coupled field theories
- Global symmetry $G = SO(5) \times U(1)_X$ broken down to
  - $SO(4) \times U(1)_X$ on IR-brane
  - $SU(2)_L \times U(1)_Y$ on UV-brane
- Higgs-fermion and Higgs self-couplings depend on the representation of the fermions:
  - spinorial representation: MCHM_4
  - fundamental representation: MCHM_5

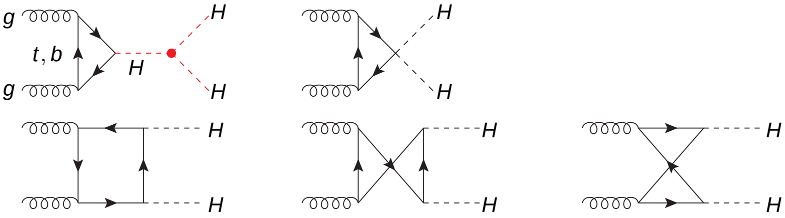
Feynman rules

	MCHM_4	MCHM_5
HVV	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$HHVV$	$1-2\xi$	$1-2\xi$
HHH	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
$Hf\bar{f}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

New couplings appear from operators with dim>4
(e.g $g_{HHf\bar{f}}$ which is important for Higgs pair production via gluon fusion)

What about the LHC? [RG, Mühlleitner]

- Dominating process: Gluon fusion ($\sim$ 1 order larger than cross section of vector boson fusion for SM)
- New coupling $g_{HH\bar{f}f} \sim \frac{1}{v^2}\xi$



- Cxn increases with ξ
- The dominant background processes do not depend on $\xi \Rightarrow$ prospects of extracting the signal are better than in SM
- In SM: λ_{HHH} can be measured with accuracy of $50 - 80\%$ for $\int \mathcal{L} = 6000\,\text{fb}^{-1}$ on 1σ level for $M_H = 120$ GeV [Baur, Plehn, Rainwater].

What about the LHC?

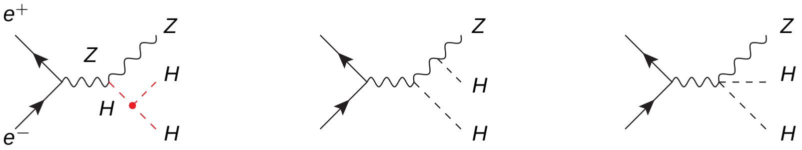
- If there are any new fermions (top partners) below the cutoff, they can influence the cross section [Espinosa, Gillioz, RG, Grojean, Mühlleitner, Salvioni; in preparation]
- New parameters come into play, which have to be measured.
- They don't affect single Higgs production [Low, Vichi; Azatov, Galloway]. $\longrightarrow$ Accessible in Higgs pair production or direct production of heavy top partners.
- If the top partners are very heavy and cannot be directly produced, a measurement of the triple Higgs coupling might not be possible anymore.

$\Longrightarrow$ The triple Higgs coupling can only be measured at another collider.

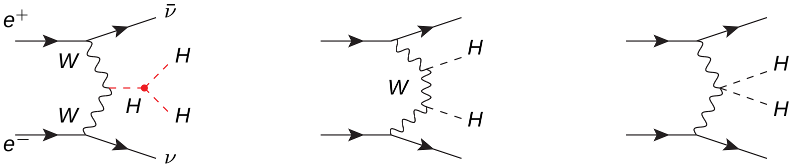
Higgs pair production at the ILC

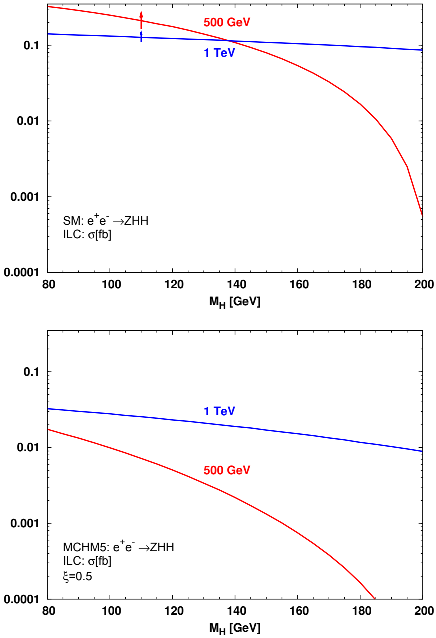
- The trilinear Higgs self coupling can be measured in Higgs pair production.
- Most important processes in SM at the ILC:
  - For low energies: Double Higgs-strahlung
  - For large energies: W fusion

Double Higgs-strahlung:



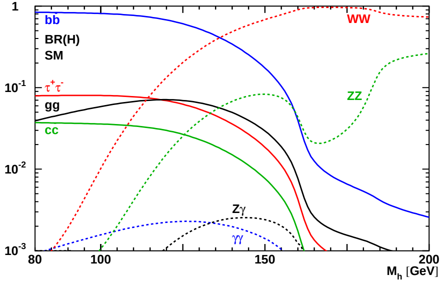
W fusion:




500 GeV
1 TeV
SM: $e^+e^- \to ZHH$
ILC: σ[fb]
MCHM5: $e^+e^- \to ZHH$
ILC: σ[fb]
ξ=0.2
x3
ξ=0.5
ξ=0.8
M_H [GeV]
0.1
0.01
0.001
0.0001
80
100
120
140
160
180
200

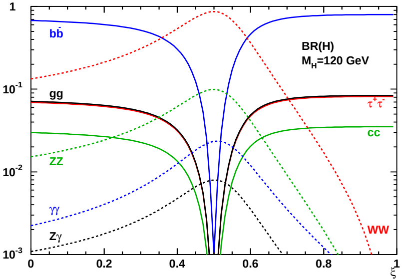
Branching ratios [Espinosa, Grojean, Mühlleitner]

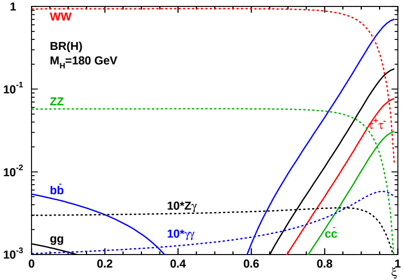
$MCHM_4$:



	$MCHM_4$	$MCHM_5$
HVV	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$Hf\bar{f}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

$MCHM_5$:





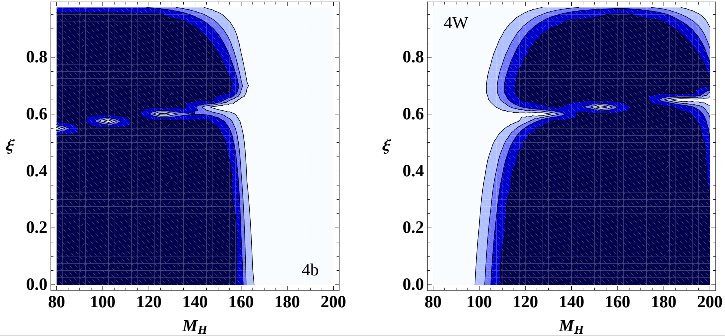
Sensitivities to $\lambda_{HHH} \neq 0$ in double Higgs-strahlung

Assumption: EWSB is realized in the framework of MCHM (ξ can be measured with accuracy of $\sim$ 20% at the LHC [Bock, Lafaye, Plehn, Rauch, Zerwas, Zerwas]; for anomolous Higgs couplings cf. [Barger, Han, Langacker, McElrath, Zerwas])

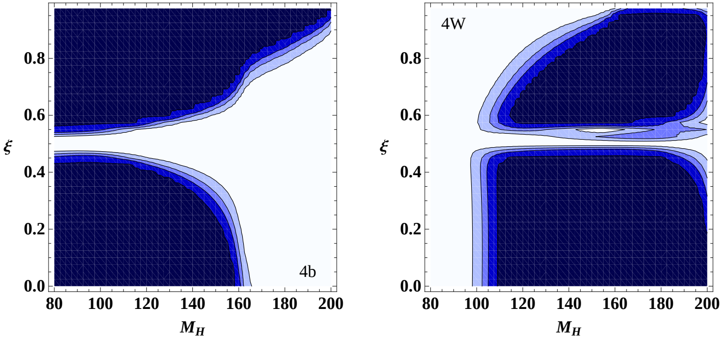
Criterion:

$$S + \beta\sqrt{S} < S_{\lambda_{HHH}=0} \quad \text{or} \quad S - \beta\sqrt{S} > S_{\lambda_{HHH}=0} \quad (\beta = 1, 2, 3, 5)$$

$MCHM_4$ for $\int \mathcal{L} = 500\,\text{fb}^{-1}$ and $\sqrt{s} = 500$ GeV:

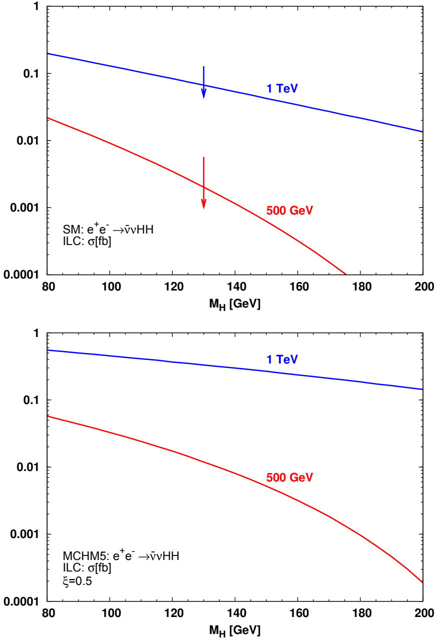


MCHM$_5$ for $\int \mathcal{L} = 500\,\mathrm{fb}^{-1}$ and $\sqrt{s} = 500$ GeV:



Feasibility

- Our analysis represents only the ideal case – for a realistic study detector properties and background processes have to be taken into account
- In the SM, the triple Higgs coupling can be measured with a precision of 22% for $\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$ [Castanier, Gay, Lutz, Orloff; Djouadi, Kilian, Mühlleitner, Zerwas; Baur; talk by Junping Tian]
- In the MCHM the cross sections are reduced but not the dominant background processes- prospects are worse than in the SM


1
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M_H [GeV]
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SM: e+e- →ν̄νHH
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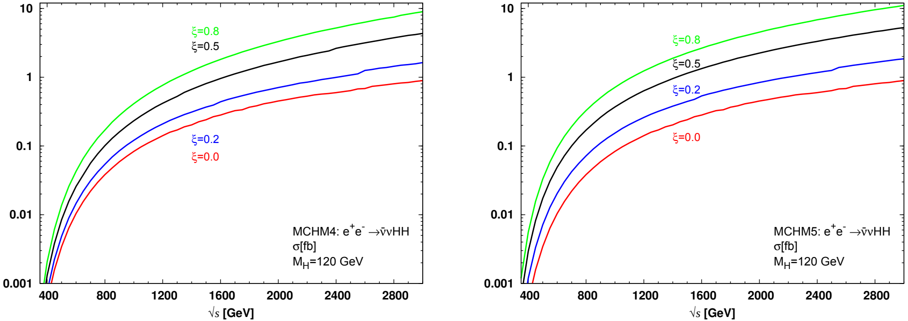
ILC: σ[fb]
ξ=0.2
MCHM5: e+e- →ν̄νHH
ILC: σ[fb]
ξ=0.5
MCHM5: e+e- →ν̄νHH
ILC: σ[fb]
ξ=0.8
x2

Energy behaviour in W fusion

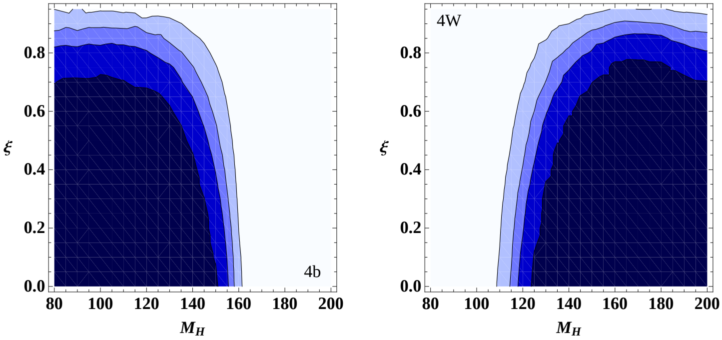
For high energies: $\mathcal{M} \sim \xi s$
Modified couplings to vector bosons$\rightarrow$ no complete cancellation of s-dependence



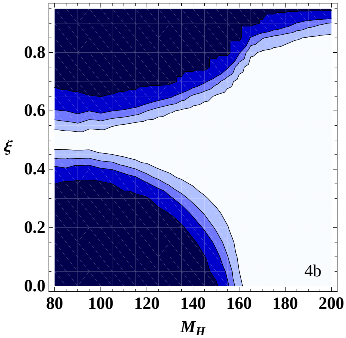
Partial wave unitarity: Theory is only valid up to cutoff of effective description, which should be smaller than unitarity bound.
The diagram involving λ_{HHH} is not $\sim s \Rightarrow$ Irreducible background (of the other diagrams) becomes dominating for high energies.

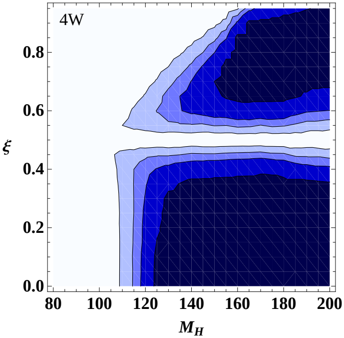
Sensitivities on $\lambda_{HHH} \neq 0$ in W fusion

MCHM$_4$ for $\int \mathcal{L} = 500\,\text{fb}^{-1}$, $\sqrt{s} = 1$ TeV and polarized beams (factor 4 for cross section, but realistically $P(e^-) \approx 80\%,\ P(e^+) \approx 60\%$ [Moortgat-Pick et al.]):



MCHM$_5$ for $\int \mathcal{L} = 500\,\text{fb}^{-1}$, $\sqrt{s} = 1$ TeV and polarized beams:





Feasibility

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- The W fusion cross section increases with rising ξ
- λ_{HHH} can be measured with a precision of $\sim$ 10% in the SM [Boos, Battaglia, Yau; Yasui, Kanemura, Kiyoura, Odagiri, Okada, Seneha, Yamashita; Baur]
- Similar results can be expected in a some parts of the parameter region in W fusion

Conclusion

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- Measurement of Higgs self couplings necessary to reconstruct Higgs potential
- A measurement of λ_{HHH} at the LHC is very difficult.
- In MCHM cross sections in double Higgs-strahlung are reduced compared to the SM $\rightarrow$ prospects of extracting λ_{HHH} look worse.
- The W boson fusion cross section increases with rising ξ and the energy.
- Large parameter regions where λ_{HHH} seems to be measurable in W-fusion and double Higgs-strahlung.

Constraints from electroweak data

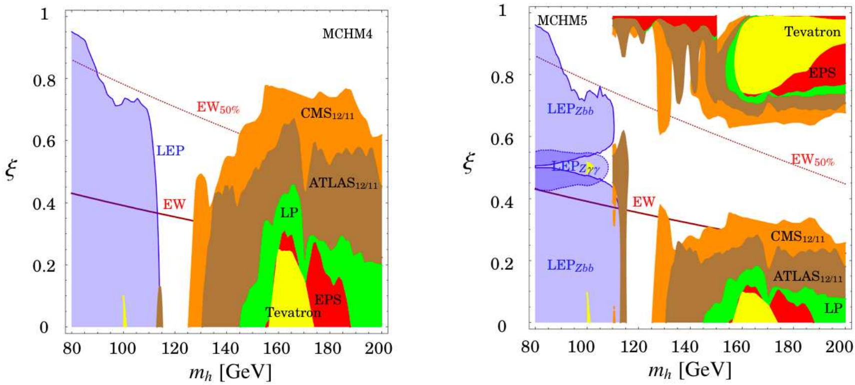


Figure: See [Espinosa,Grojean, Mühlleitner]

SILH [Giudice, Grojean, Pomarol, Rattazzi]

New kinetic terms → field redefinition

$$\Phi = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \frac{1}{v}\left(H - \frac{c_H \xi}{2}\left(H + \frac{H^2}{v} + \frac{H^3}{3v^2}\right)\right) + 1 \end{pmatrix}$$

→ redefinition of Higgs and fermion masses and vacuum expectation value

$$\frac{v^2}{2} = \frac{\mu^2}{2\lambda}\left(1 - \frac{3}{4} c_6\, \xi\right) = \frac{(246\,\text{GeV})^2}{2} \; .$$

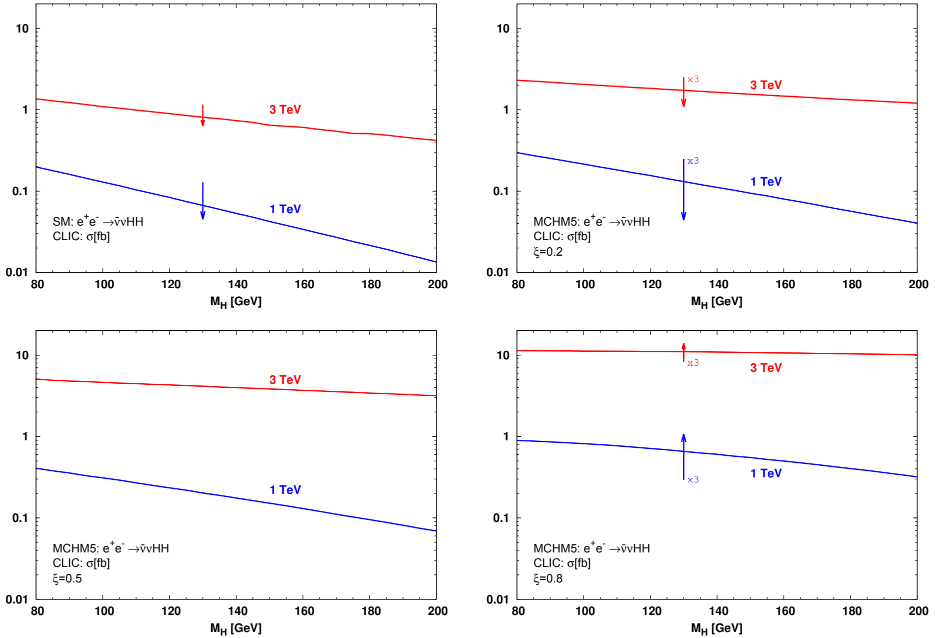
$$m_f = \frac{1}{\sqrt{2}} y_f v \left(1 + \frac{\xi}{2} c_y\right) \; ,$$

$$\frac{M_H^2}{2} = \frac{\left(\sqrt{2\lambda} v\right)^2}{2}\left(1 - c_H\, \xi + \frac{3}{4} c_6\, \xi\right) \; .$$

$$g_{HVV} = g_{HVV}^{SM}\left(1 - \frac{c_H}{2}\xi\right) \qquad \text{with } g_{HWW}^{SM} = g\,M_W \text{ and } g_{HZZ}^{SM} = \frac{g\,M_Z}{2}$$

$$g_{Hff} = g_{Hff}^{SM}\left(1 - \xi\frac{c_H}{2} + \xi c_y\right) \qquad \text{with } g_{Hff}^{SM} = \frac{g\,m_f}{2\,M_W}$$

$$g_{HHH} = g_{HHH}^{SM}\left(1 + \xi c_6 - \xi\frac{3\,c_H}{2}\right) \qquad \text{with } g_{HHH}^{SM} = \frac{3\,g\,M_H^2}{2\,M_W}$$



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M_H [GeV]
3 TeV
1 TeV
SM: e+e- →ν̄νHH
CLIC: σ[fb]
x3
MCHM5: e+e- →ν̄νHH
CLIC: σ[fb]
ξ=0.2
MCHM5: e+e- →ν̄νHH
CLIC: σ[fb]
ξ=0.5
MCHM5: e+e- →ν̄νHH
CLIC: σ[fb]
ξ=0.8

Measurement of $\lambda_{HHH} \neq 0$ in W-fusion

MCHM$_5$ for $\int \mathcal{L} = 500\,\text{fb}^{-1}$, $\sqrt{s} = 1$ TeV and unpolarized beams: