# Higgs pair production in the Composite Higgs model

Ramona Gröber in coll. with Margarete Mühlleitner, see JHEP 06 (2011) 020 [arXiv: 1012.1562] | 29.07.2011

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# Motivation

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- Higgs pair production:
  Measurement of triple Higgs coupling $\rightarrow$ reconstruction of Higgs potential
- 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

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

- SILH: 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]
- Completion for large values of $\xi$: 5D theory on AdS spacetime $\rightarrow$ holographic interpretation in terms of 4D strongly coupled field theories
- Higgs boson as a pseudo Nambu-Goldstone boson [Kaplan, Georgi, Galison, Dugan; Dimopoulos, Preskill; Banks] of a global symmetry $G = SO(5) \times U(1)_X$ which is broken down to
  - $O(4) \quad \times U(1)_X$ on IR-brane
  - $SU(2)_L \times U(1)_Y$ on UV-brane
- G is explicitely broken by couplings of SM fields to strong sector $\rightarrow$ loops of SM fermions and gauge bosons generate Higgs potential
- MCHM$_5$: Fermions in fundamental representation of $SO(5)$

# Feynman rules

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

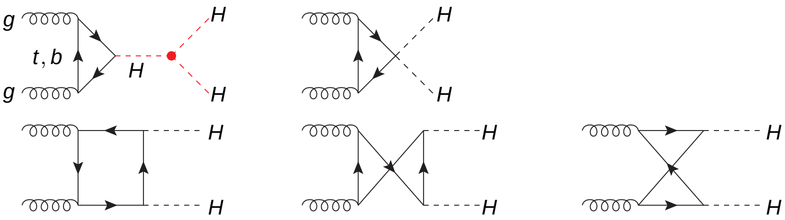
New coupling: $g_{HHf\bar{f}} = \frac{m_f}{v^2} 4\xi$

In SM limit $\xi \to 0$ the new coupling vanishes.

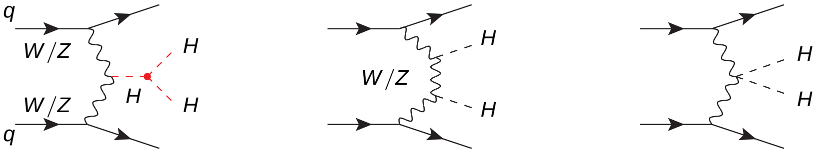
# Higgs pair production at the LHC

- Higgs self-couplings are necessary to investigate Higgs potential.
- In multi-Higgs-production Higgs self-couplings can be measured.
- Most important processes in SM at the LHC:
  - Gluon fusion
  - Vector boson fusion
  - Double Higgs-strahlung

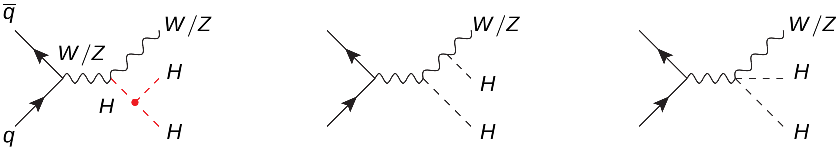
Gluon fusion:

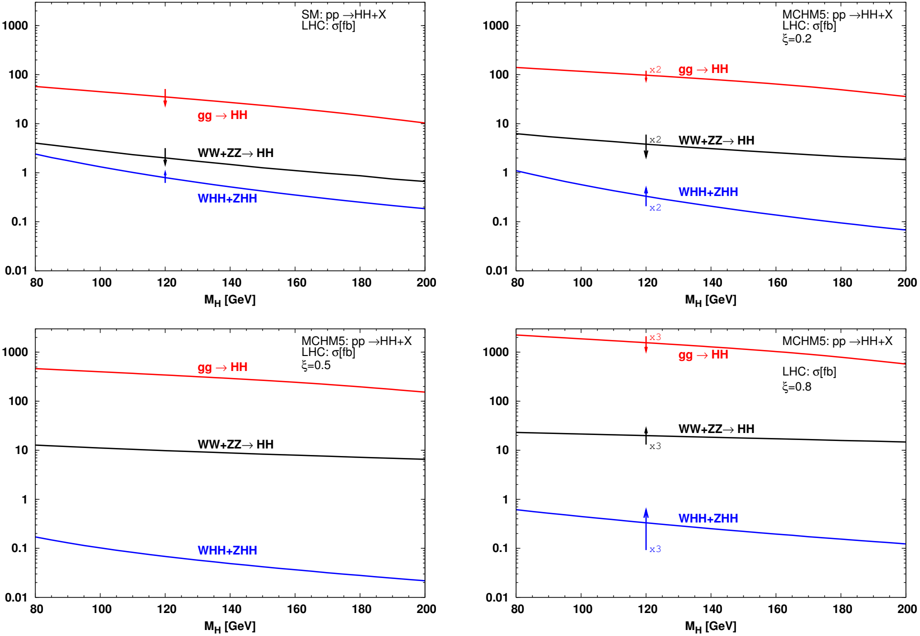


Vector boson fusion:

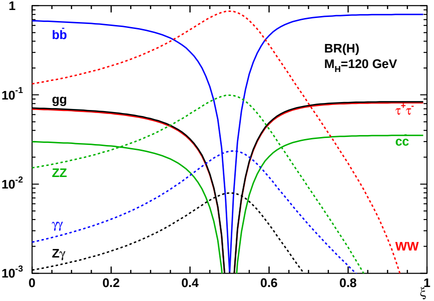


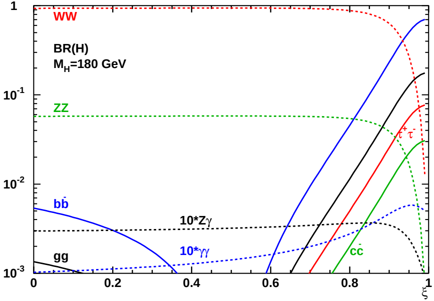

Double Higgs-strahlung:




SM: pp →HH+X
LHC: σ[fb]
gg → HH
WW+ZZ→ HH
WHH+ZHH
MCHM5: pp →HH+X
LHC: σ[fb]
ξ=0.2
x2
MCHM5: pp →HH+X
LHC: σ[fb]
ξ=0.5
MCHM5: pp →HH+X
LHC: σ[fb]
ξ=0.8
x3
1000
100
10
1
0.1
0.01
80
100
120
140
160
180
200
M_H [GeV]

# Branching ratios [Espinosa, Grojean, Mühlleitner]




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

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

In SM: $HH \to b\bar{b}\gamma\gamma$ for low Higgs masses and $HH \to W^+W^-W^+W^-$ for Higgs masses above the gauge boson threshold have best prospects

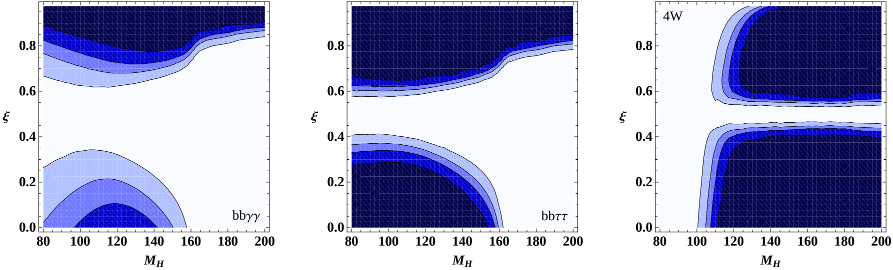
[Baur,Plehn,Rainwater]

Assumption: EWSB is realized in the framework of MCHM ($\xi$ can be measured with accuracy of $\sim$ 20% [Bock, Lafaye, Plehn, Rauch, Zerwas, Zerwas])

Criterion:

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

$\text{MCHM}_5$ for $\int \mathcal{L} = 300\,\text{fb}^{-1}$:

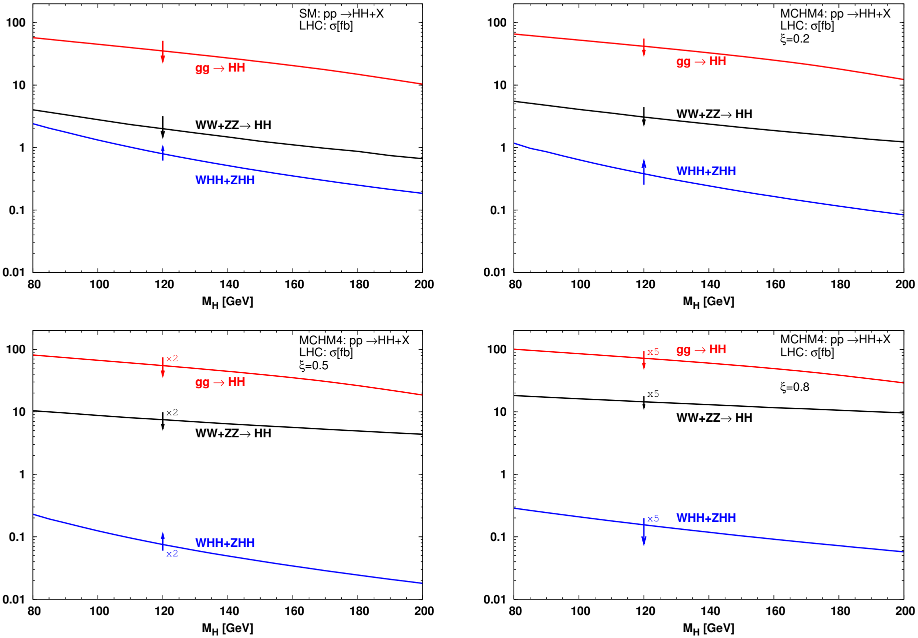


# Feasibility

- Sensitivity areas present ideal case $\rightarrow$ for a full analysis: Detector properties and background processes must be investigated
- But e.g. for the $4W$ final state with $W^+W^-W^+W^- \rightarrow (jjl^{\pm}\nu)(jjl^{\pm}\nu)$:
  In SM: For 150 GeV $\leq M_H \leq$ 200 GeV a vanishing triple Higgs coupling can be excluded at 95% C.L. for 300 fb$^{-1}$ [Baur,Plehn,Rainwater]
- Dominating background ($\mathcal{O}(\alpha_s \alpha^3)$)
  $\rightarrow$ no Higgs in intermediate state
  $\rightarrow$ leading background processes are the same as in SM
- But: Signal cross section is larger than in the SM!

# Conclusion

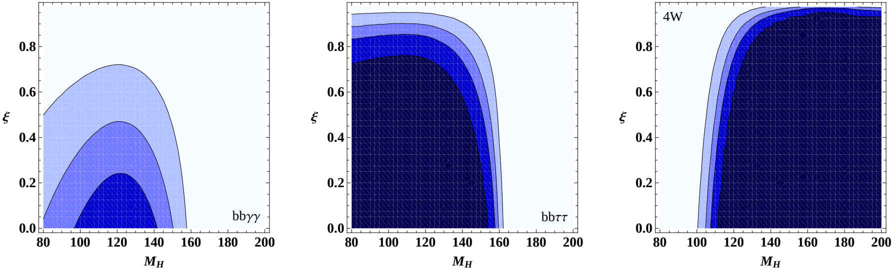
- Composite Higgs models are an interesting alternative to the SM
- Cross sections for Higgs pair production via gluon fusion and vector boson fusion are enhanced compared to the SM for all $\xi$
- Cross section for Higgs pair production via double Higgs-strahlung is reduced compared to the SM
- Branching ratios in $\mathrm{MCHM}_5$ are changed compared to the SM and depend on $\xi$.
- Prospects of measuring non-vanishing $\lambda_{HHH}$ for large Higgs masses in $W^+W^-W^+W^-$ decay channel good, for low Higgs masses $b\bar{b}\tau^+\tau^-$ might be possible
- Measuring $\lambda_{HHH}$ with higher precision might be possible for higher luminosities.



SM: pp →HH+X
LHC: σ[fb]
gg → HH
WW+ZZ→ HH
WHH+ZHH
MCHM4: pp →HH+X
LHC: σ[fb]
ξ=0.2
ξ=0.5
ξ=0.8
x2
x5
M_H [GeV]

# Sensitivity on $\lambda_{HHH} \neq 0$ in gluon fusion

MCHM$_4$ for $\int \mathcal{L} = 300\,\mathrm{fb}^{-1}$:



# Constraints from electroweak data

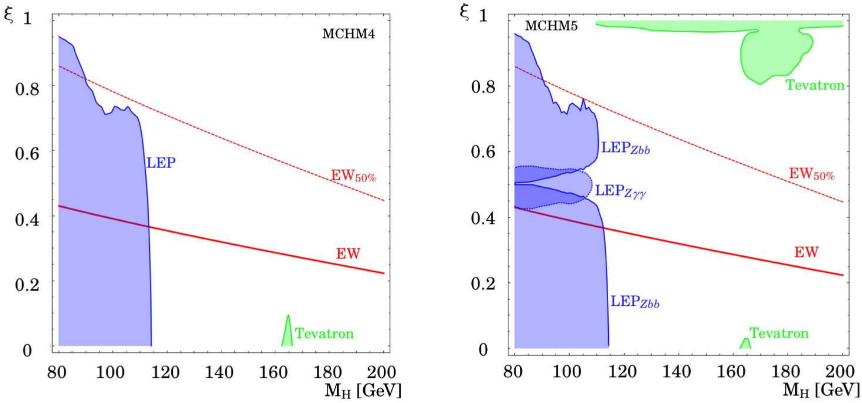



Figure: See [Espinosa,Grojean, Mühlleitner; arXiv:1003.3251]
For constraints in a model with partially composite top, see [Anastasiou, Furlan, Santiago; Gillioz]

# Total width

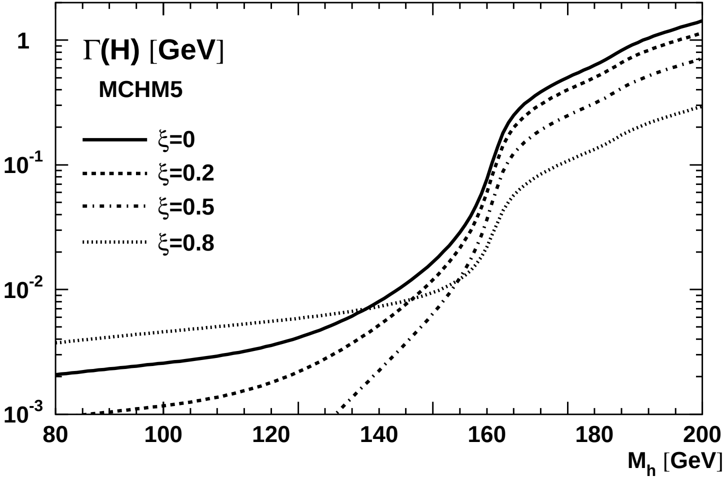
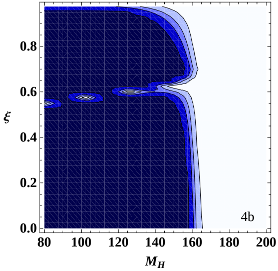
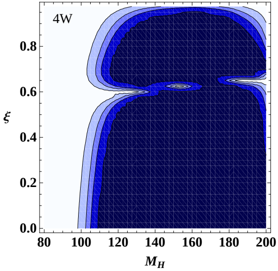



Figure: See [Espinosa, Grojean, Mühlleitner]

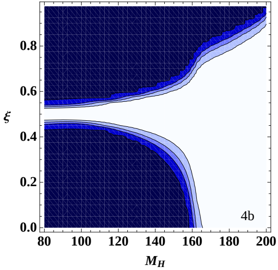
# Double Higgs-strahlung at the ILC ($\sqrt{s} = 0.5$ TeV, $\int \mathcal{L} = 500\,\mathbf{fb}^{-1}$)

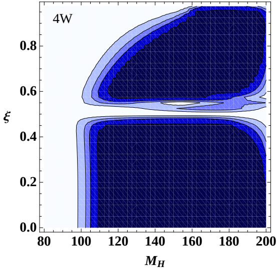
MCHM$_4$:



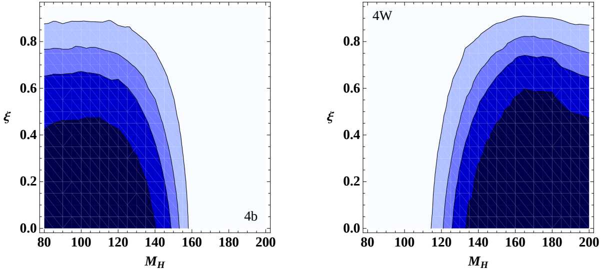

MCHM$_5$:



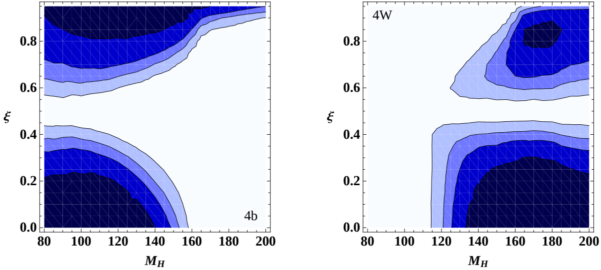



# W boson fusion at the ILC ($\sqrt{s} = 0.5$ TeV, $\int \mathcal{L} = 500\,\mathbf{fb}^{-1}$)

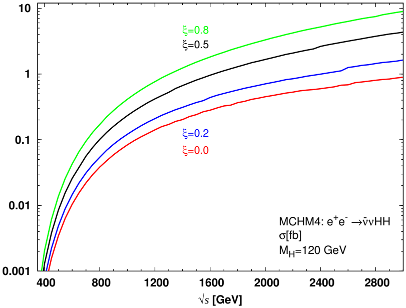
MCHM$_4$:

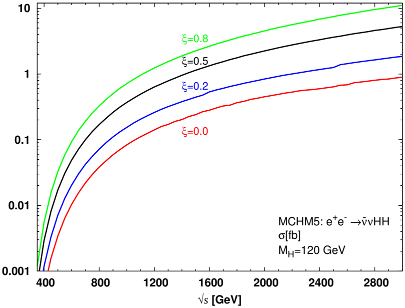



MCHM$_5$:



# Energy behaviour of W fusion at the ILC




$$\mathcal{M} \overset{s\to\infty}{\longrightarrow} -\sqrt{2}G_F s\,\xi$$

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New kinetic terms $\rightarrow$ field redefinition

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

$\rightarrow$ redefinition of Higgs and fermion masses and vacuum expectation value

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

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

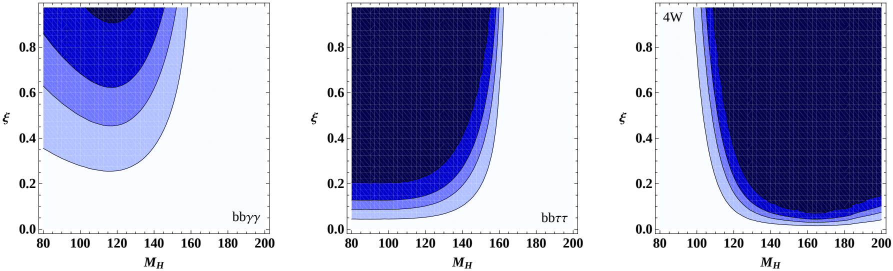
$$\frac{M_H^2}{2} = \frac{\left(\sqrt{2\lambda} v\right)^2}{2}\left(1 - c_H\, \xi + \frac{3}{4} c_6\, \xi\right) \,.$$

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

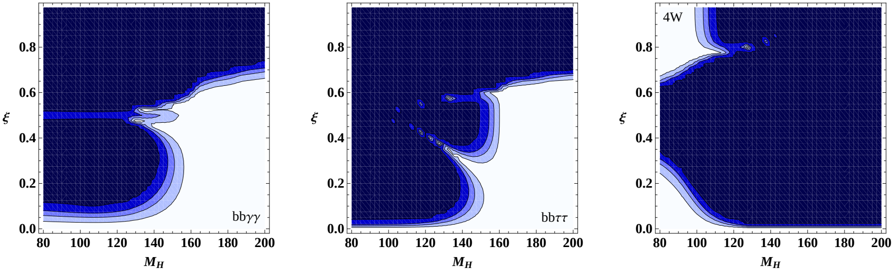
$$g_{Hff} = g_{Hff}^{SM}\left(1 - \xi\frac{c_H}{2} + \xi c_y\right) \qquad \text{with } g_{Hff}^{SM} = \frac{g\,m_f}{2\,M_W}$$

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

# Can the MCHM$_4$ be distinguished from the SM for $\int \mathcal{L} = 300\,\mathbf{fb}^{-1}$?

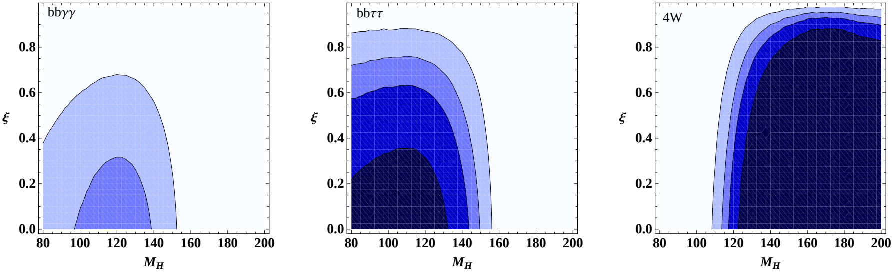


# Can the MCHM$_5$ be distinguished from the SM for $\int \mathcal{L} = 300\,\mathbf{fb}^{-1}$?



# Can $\lambda_{HHH}$ be measured with 30% precision in $\mathrm{MCHM}_4$?

$\int \mathcal{L} = 3000\,\mathrm{fb}^{-1}$ for $b\bar{b}\gamma\gamma$, $\int \mathcal{L} = 600\,\mathrm{fb}^{-1}$ for $b\bar{b}\tau^+\tau^-$ and $4W$



# Can $\lambda_{HHH}$ be measured with $30\%$ precision in MCHM$_5$?

$\int \mathcal{L} = 3000\,\text{fb}^{-1}$ for $b\bar{b}\gamma\gamma$, $\int \mathcal{L} = 600\,\text{fb}^{-1}$ for $b\bar{b}\tau^+\tau^-$ and $4W$