

# Testing Higgs Self-Couplings at $e^+e^-$ Linear Colliders

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Sitges

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- $HH$  Signals in the SM
- Background Studies
- $hh$  Signals in the MSSM

A. Djouadi, W.K., M. Muhlleitner, P.M. Zerwas: hep-ph/9903229

D. Miller, S. Moretti / P. Bambade, P. Gay, P. Lutz: ECFA/DESY WS

# Higgs Potential

To verify the standard Higgs mechanism, we have to

- find Higgs boson(s)
- establish mass generation via Higgs ( $g_{hXX} \propto m_X$ )
- measure the Higgs potential (responsible for SSB)

**SM:**  $V(\varphi) = \lambda(|\varphi|^2 - v^2/2)^2$   
 $\Rightarrow \lambda_{HHH} = 3M_H^2/M_Z^2$

**MSSM:**  $V(\varphi_1, \varphi_2) =$

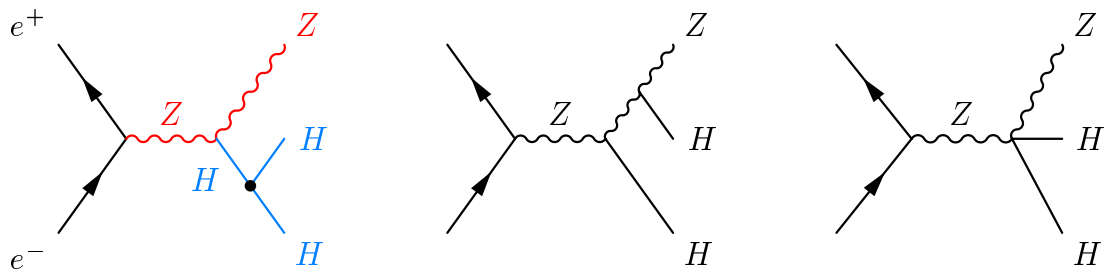
$$m_{11}^2 \varphi_1^\dagger \varphi_1 + m_{22}^2 \varphi_2^\dagger \varphi_2 - [m_{12}^2 \varphi_1^\dagger \varphi_2 + \text{h.c.}]$$
$$+ \frac{1}{2} \lambda_1 (\varphi_1^\dagger \varphi_1)^2 + \frac{1}{2} \lambda_2 (\varphi_2^\dagger \varphi_2)^2$$
$$+ \lambda_3 (\varphi_1^\dagger \varphi_1) (\varphi_2^\dagger \varphi_2) + \lambda_4 (\varphi_1^\dagger \varphi_2) (\varphi_2^\dagger \varphi_1)$$

$$\Rightarrow (\lambda_{hhh}, \lambda_{Hhh}, \dots) = f(M_Z, M_W, M_A, \tan \beta; m_t, m_{\tilde{q}}, \dots)$$

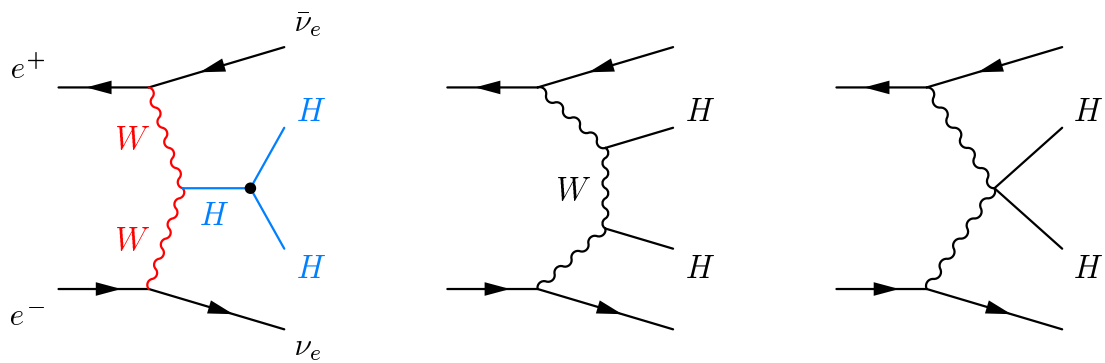
[ ... and quartic couplings]

# SM Processes

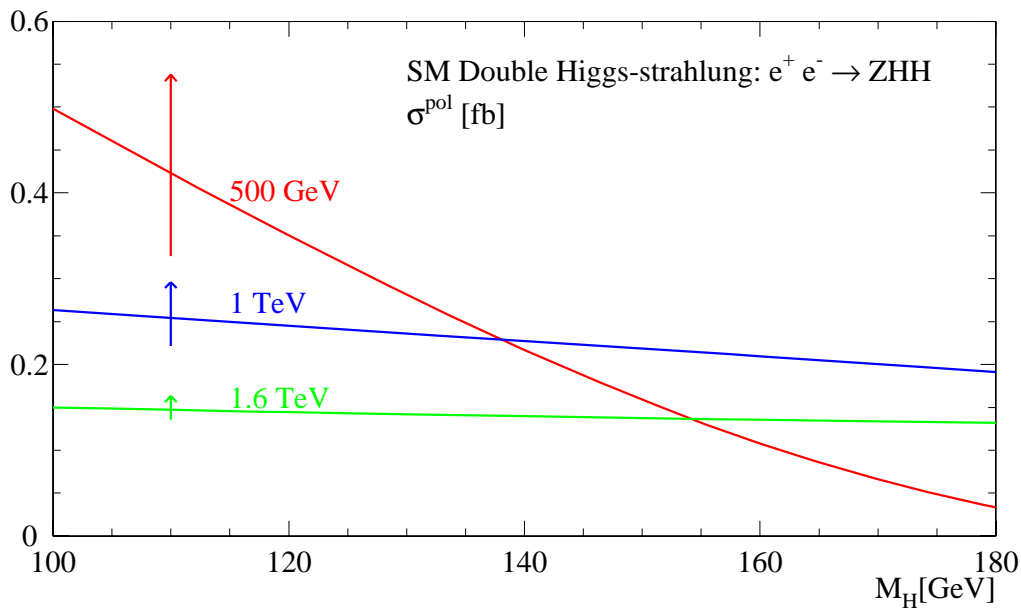
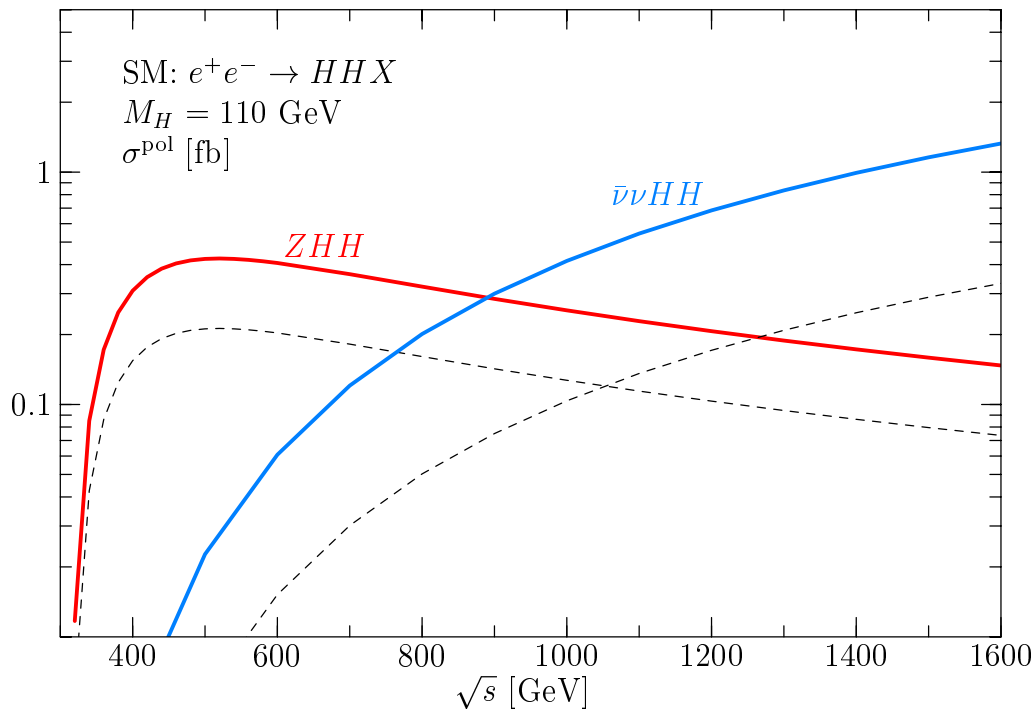
- Double Higgs-strahlung:  $ZHH$



- $WW$  fusion to Higgs pairs:  $\bar{\nu}\nu HH$



# SM Cross Sections



## Backgrounds to $ZHH$

### Intrinsic:

- Diagrams without  $hhh$  coupling

### Electroweak:

- $ZZH, WWH$
- $ZZZ, WWZ$
- other  $Zb\bar{b}b\bar{b}$
- $WW, ZZ, HZ$
- $t\bar{t}$

### QCD:

- multi-jets ( $b$ -jets!)

# Signal/Backgrounds $Zb\bar{b}b\bar{b}$

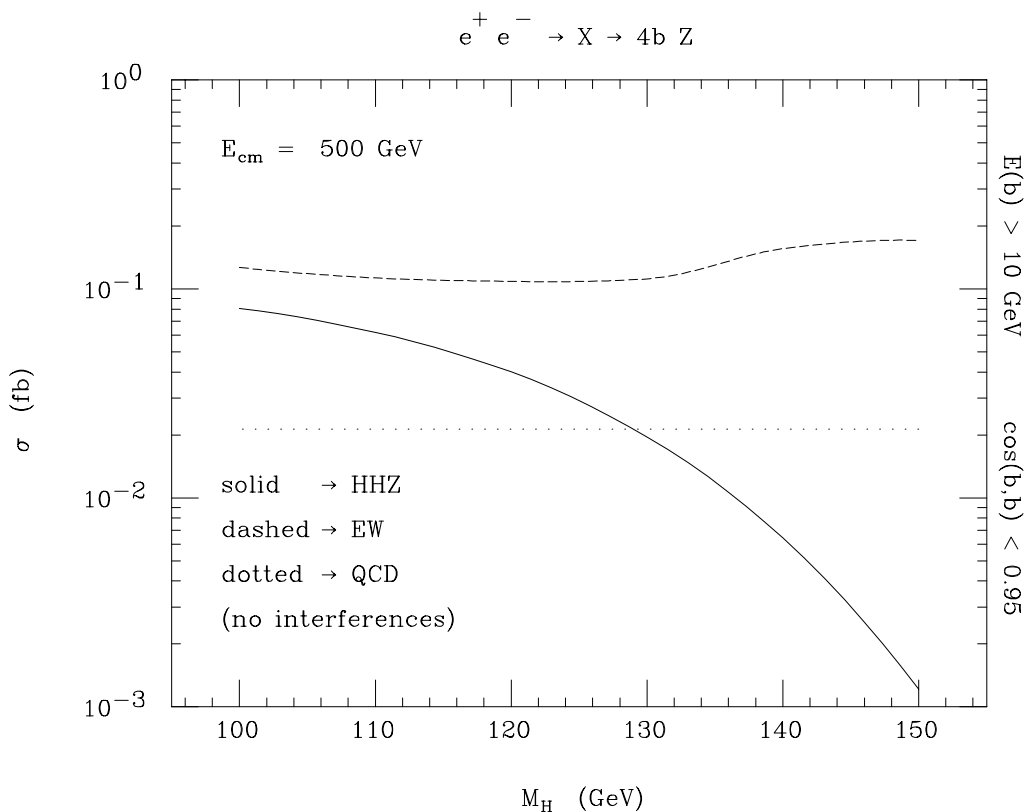
D. Miller, S. Moretti: **Calculation based on MADGRAPH**

**Cuts 1:** Acceptance:  $E_b, \cos(b, b)$

**Cuts 2:**  $|M(bb) - M(H)|, |M(bb) - M(Z)| / M(bbbb),$   
 $p_{\perp}(bbbb) / |\cos(2b, 3b, 4b, bZ)|$

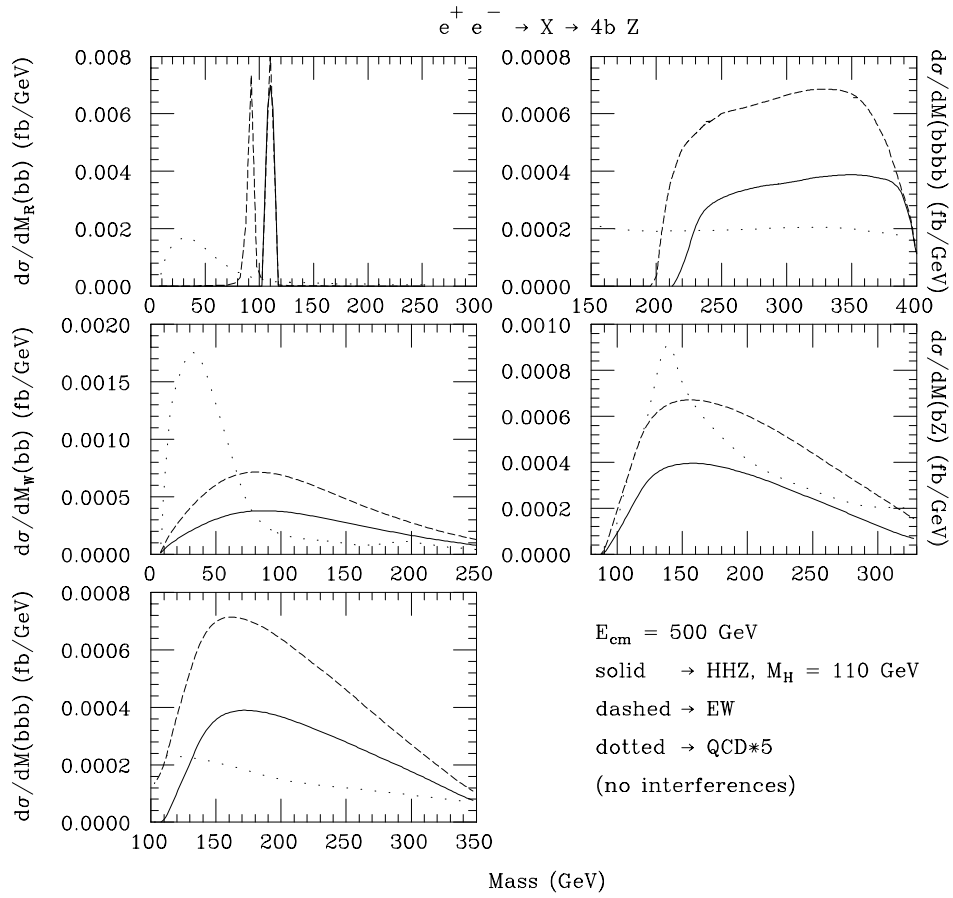
$\sigma$ [fb]	Acceptance cuts	Selection cuts	$\int \mathcal{L} = 2 \text{ ab}^{-1} : \# \text{evt}$
signal	0.081	0.0098	19.6
EW	0.192	0.0005	1.0
QCD	0.021	0.00002	0.04
total bkg.	0.213	0.0005	1.0

$\Rightarrow$  **BG under control, but signal very small ( $Z \rightarrow \ell^+ \ell^-$ )**



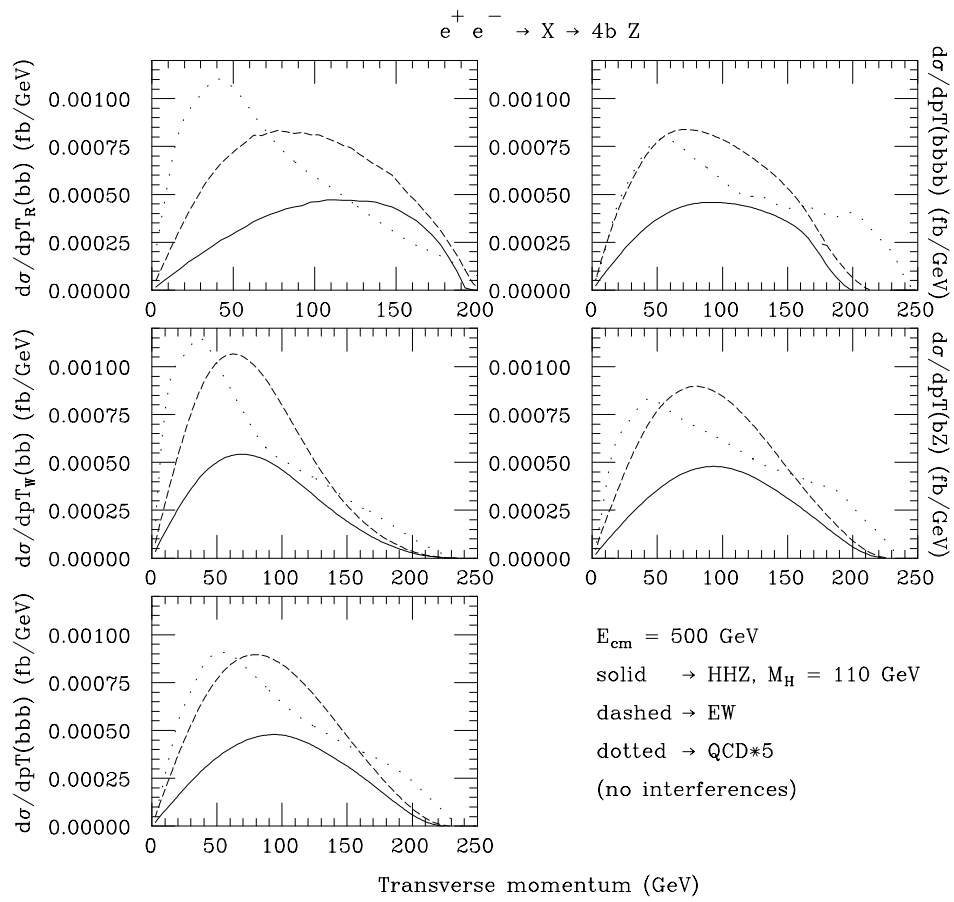
# Signal/Backgrounds $Zb\bar{b}b\bar{b}$

## Mass distributions



# Signal/Backgrounds $Zb\bar{b}b\bar{b}$

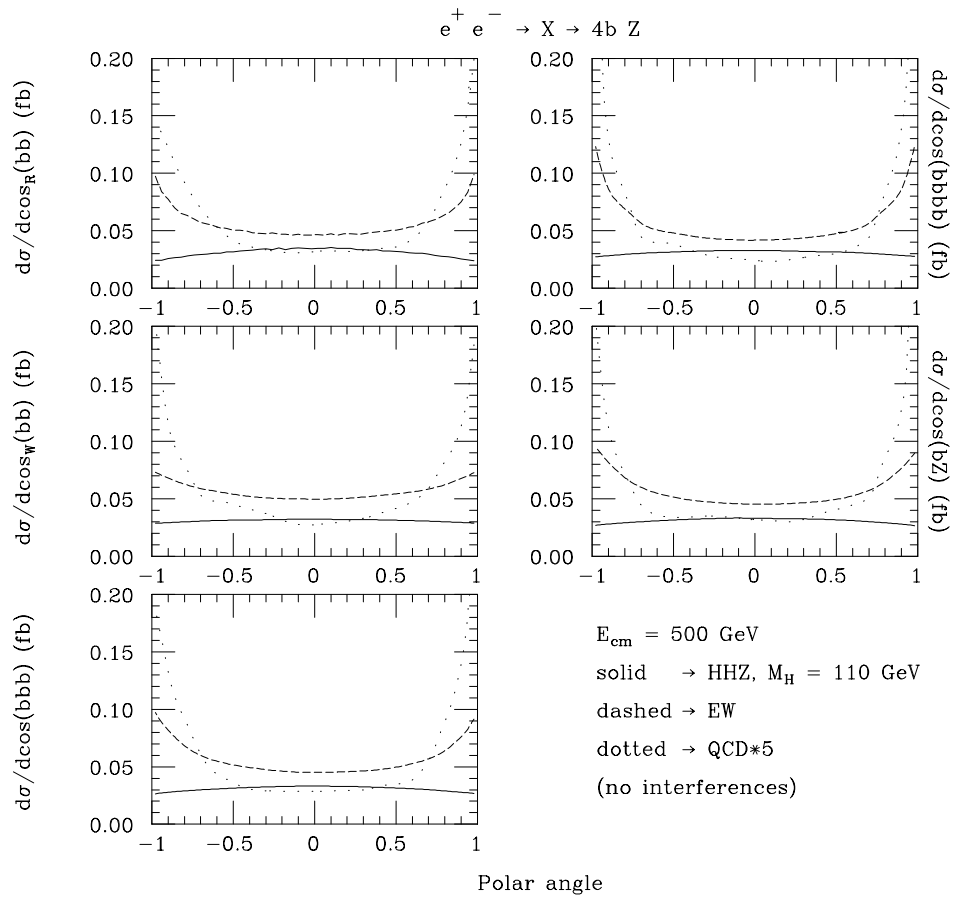
$p_{\perp}$  distributions





# Signal/Backgrounds $Zb\bar{b}b\bar{b}$

$\cos\theta$  distributions



## 6-jet signal/backgrounds

P. Bambade, P. Gay, P. Lutz: **generator-level analysis**

**Cut 1:** Anti-QCD cut: total charged multiplicity ( $> 35$ ),  $y_{34}$ , Fox-Wolfram moments order 2, 4.

**Cut 2:** Anti-4fermion cut: “distance” to  $WW$  or  $ZZ$

**Cut 3:** Rough kinematic compatibility with  $HHZ$

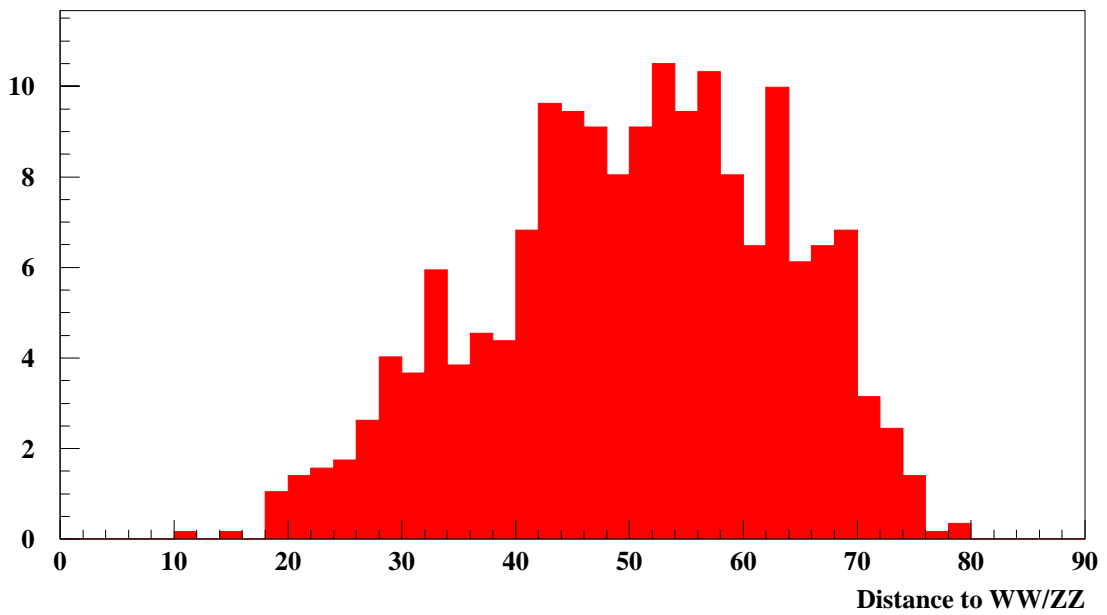
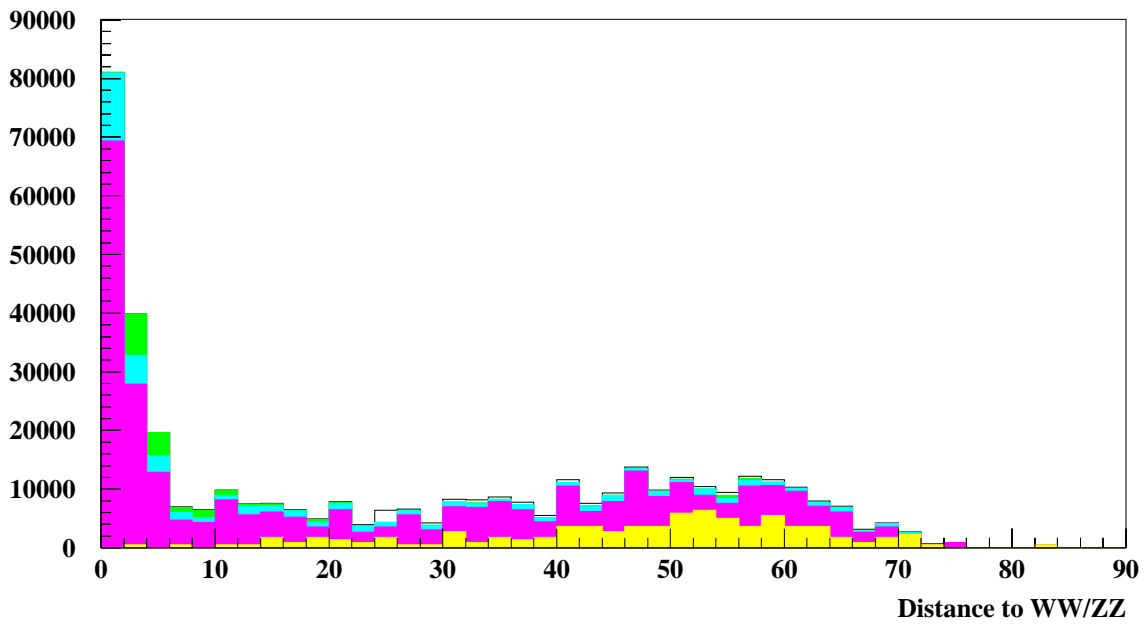
**Cut 4:** Count of  $b$ -tagged jets (require 5  $b$ -jets)

$\Rightarrow$  12–15% stat. error on  $\lambda_{HHH}$

$\sigma$ [fb]	Initial	cut 1	cut 2	cut 3	cut 4
		anti-QCD	anti- $WW/ZZ$	kine.	$b$ -tag
signal	0.175	0.170	0.168	0.132	0.016
QCD	8200	79	73	23	$0 \pm ?$
$WW$	7700	254	113	26	$0 \pm ?$
$ZZ$	550	46	19	0.2	$0 \pm ?$
other 4ferm.	12700	2	2	0	0
$HZ$	70	18	3	$0 \pm ?$	$0 \pm ?$
$WWZ$	14	9	8	4	$0 \pm ?$
$ZZZ$	0.182	0.175	0.170	0.137	$0.001 \pm 0.0005$
total bkg.	29000	410	218	59	0.001

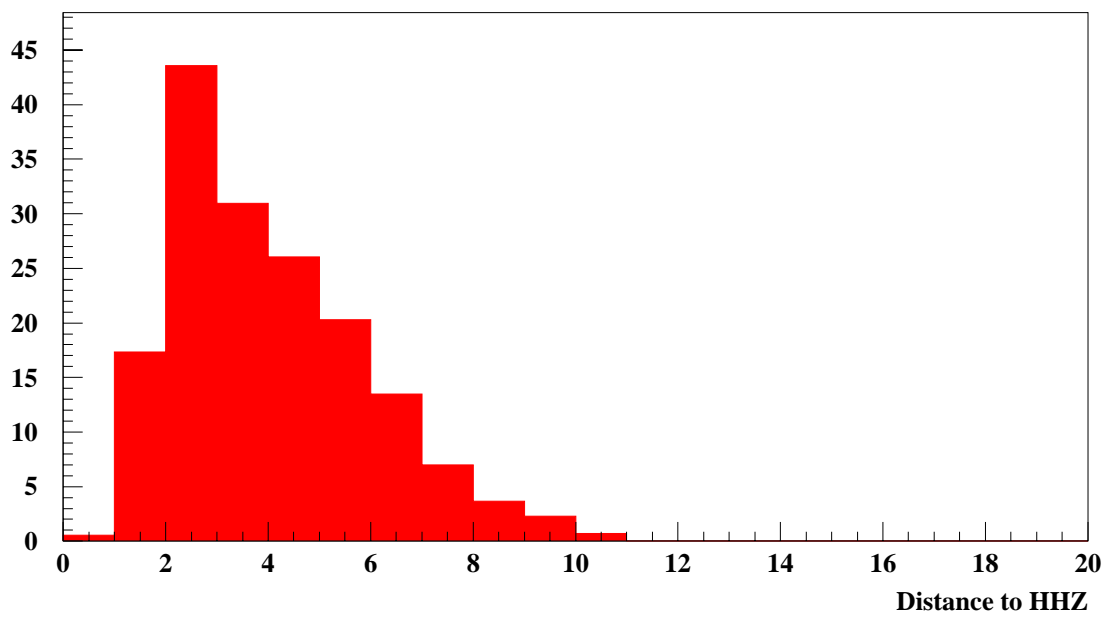
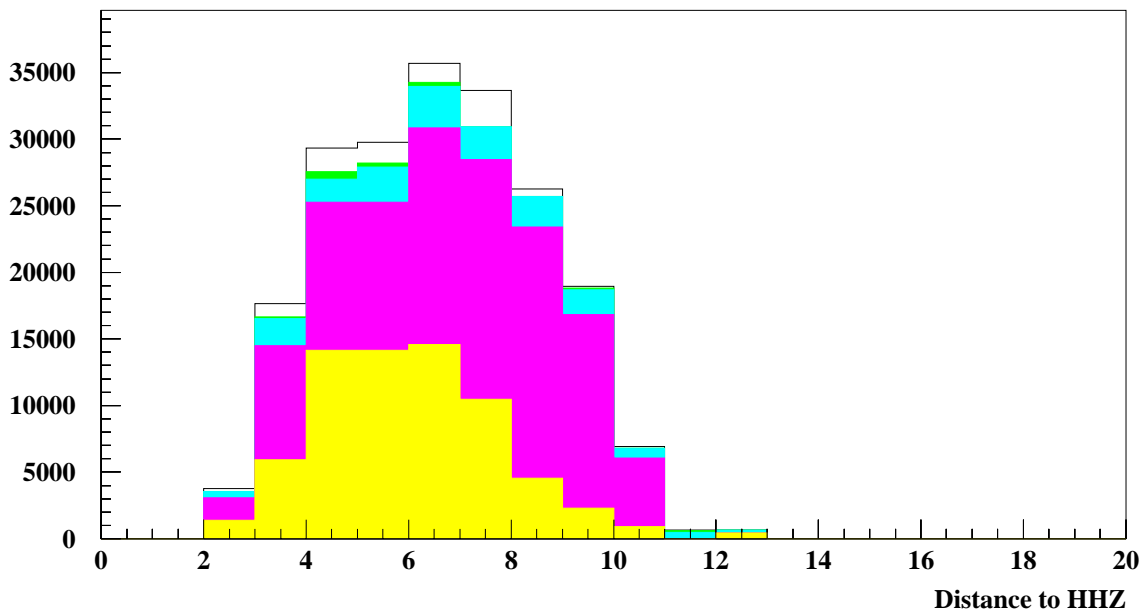
# 6-jet signal after cut 1

TESLA - HHZ analysis -  $\sqrt{s} = 500$  GeV



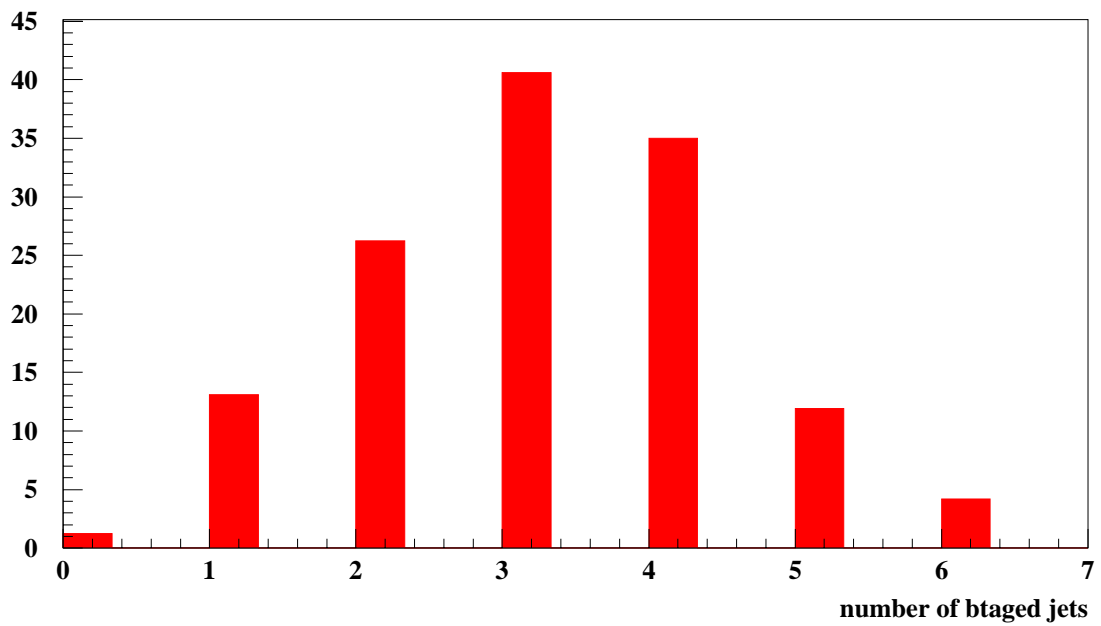
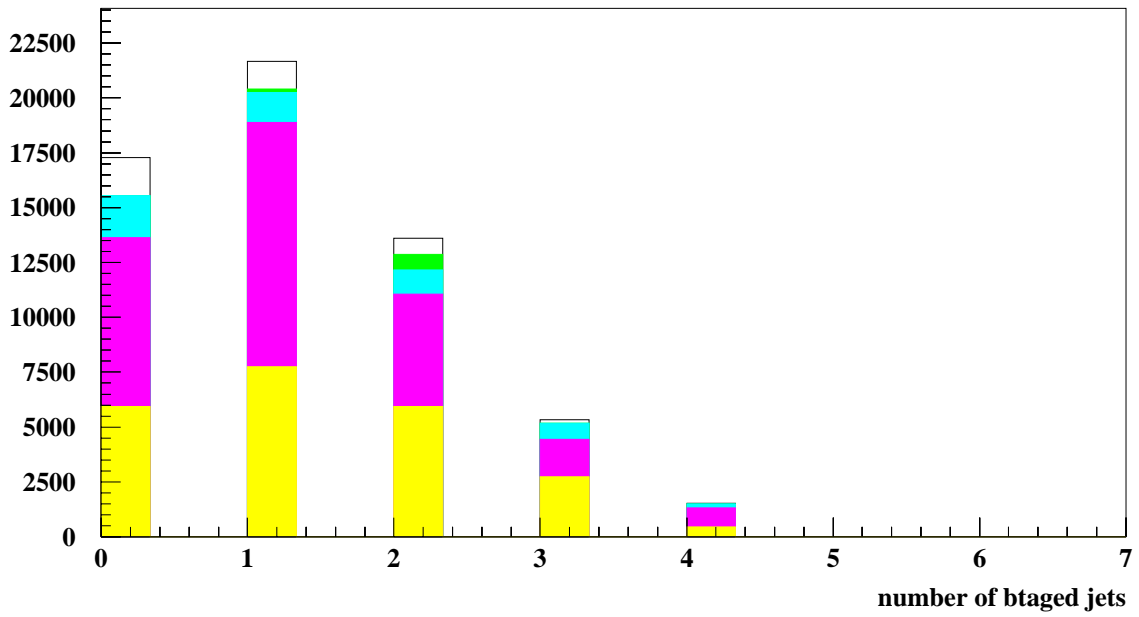
## 6-jet signal after cut 2

TESLA - HHZ analysis -  $\sqrt{s} = 500$  GeV



# 6-jet signal after cut 3

TESLA - HHZ analysis -  $\sqrt{s} = 500$  GeV



# MSSM

- Input:  $M_A, \tan \beta$
- SUSY Parameters:  $M_{\tilde{q}} = A = \pm \mu = 1 \text{ TeV}$
- Trilinear couplings:

$$hhh, Hhh, HHh, HHH, hAA, HAA$$

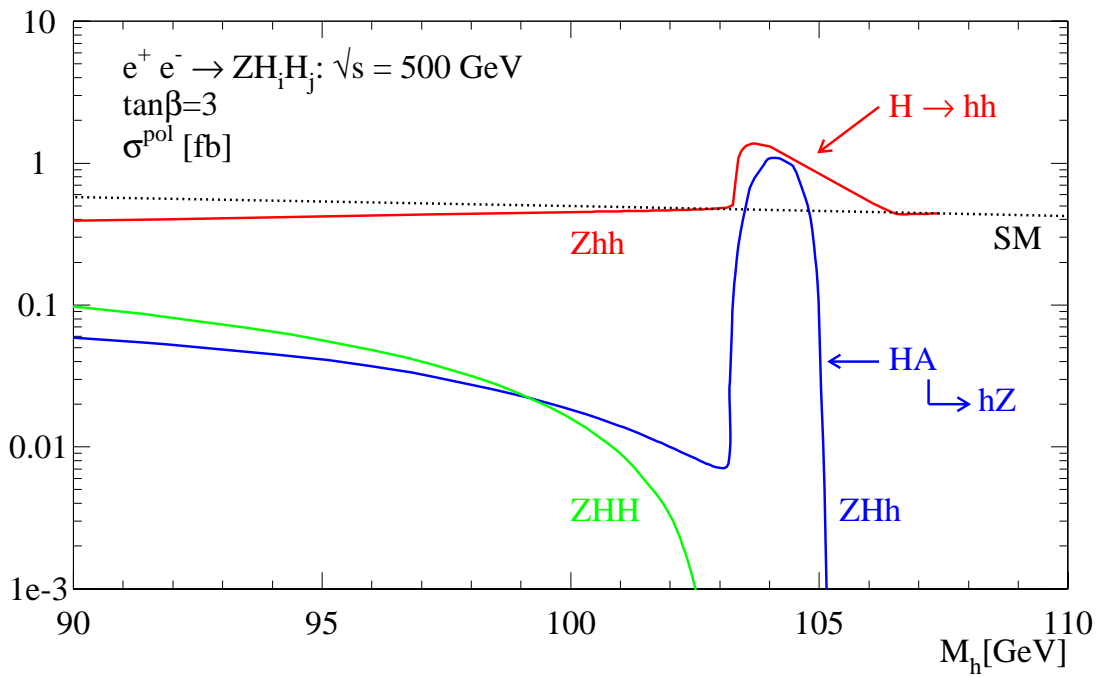
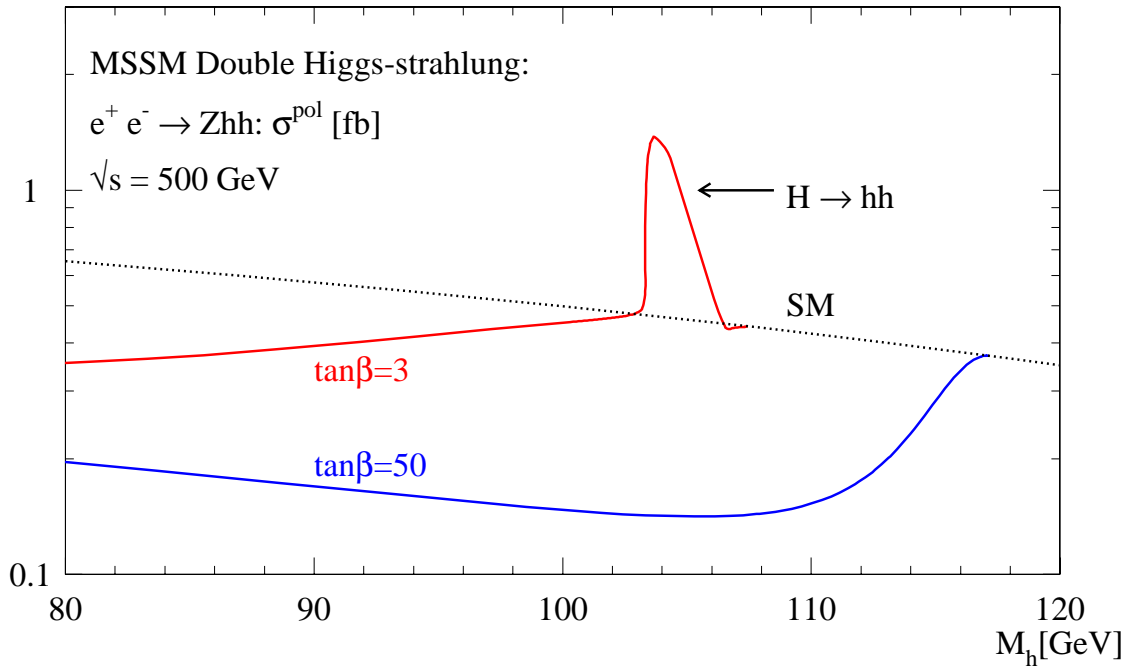
Used in analysis: full 1-loop and leading 2-loop corrections to masses and couplings

- Processes:

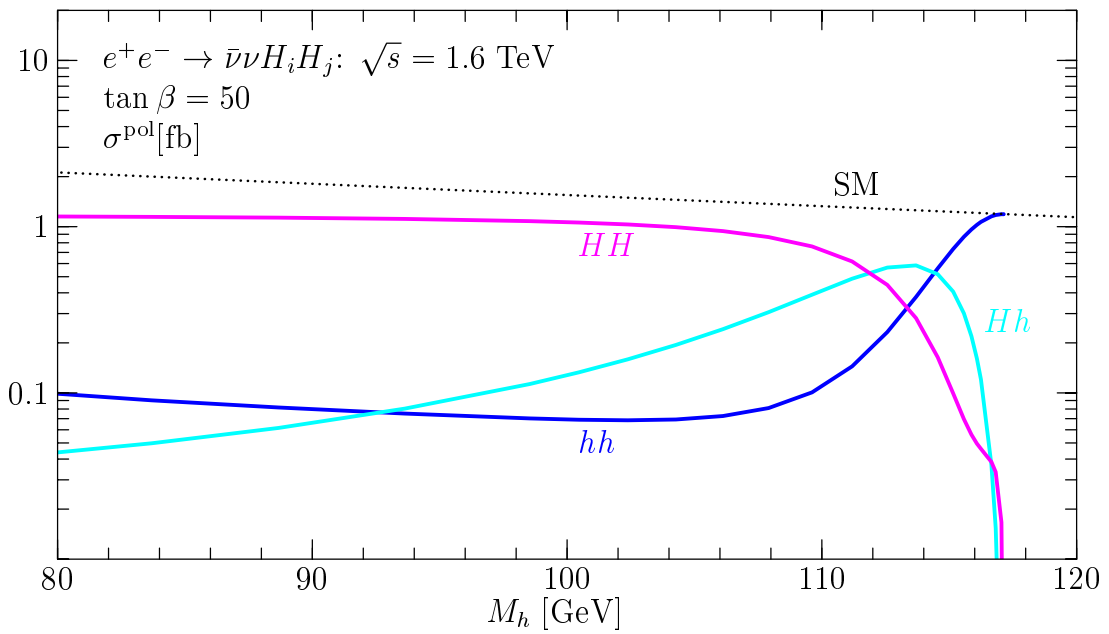
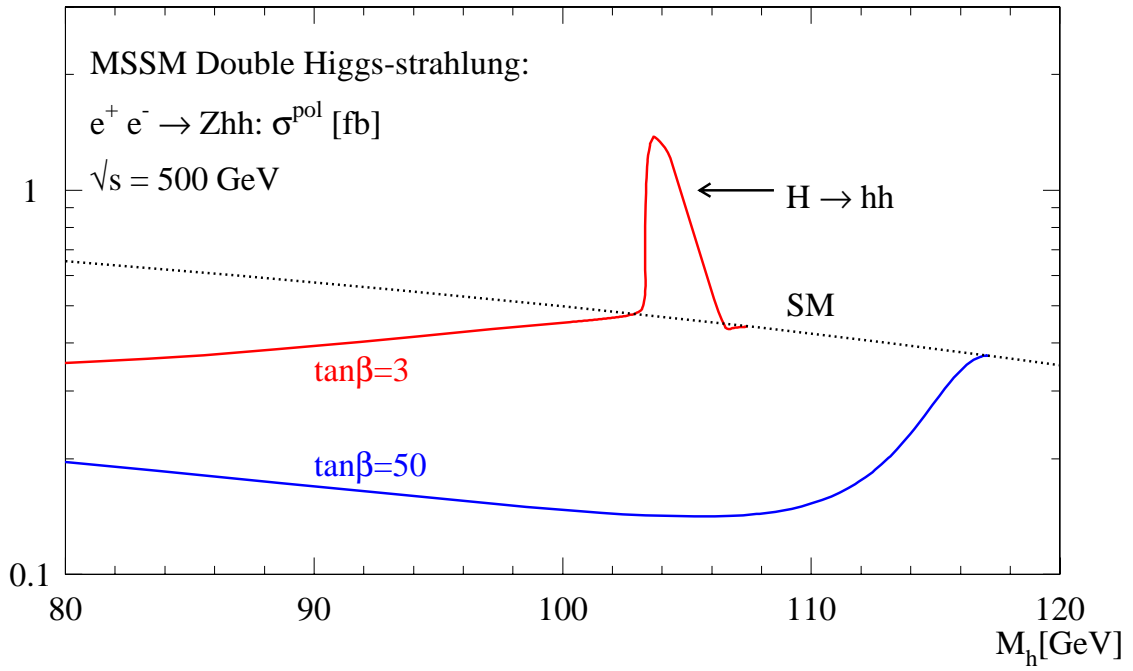
$\lambda$	double Higgs-strahlung				triple Higgs production			
	$Zhh$	$ZHh$	$ZHH$	$ZAA$	$Ahh$	$AHh$	$AHH$	$AAA$
$hhh$	×				×			
$Hhh$	×	×			×	×		
$HHh$		×	×			×	×	
$HHH$			×				×	
$hAA$				×	×	×		×
$HAA$				×		×	×	×

... and analogous  $WW$  fusion processes

# MSSM cross sections



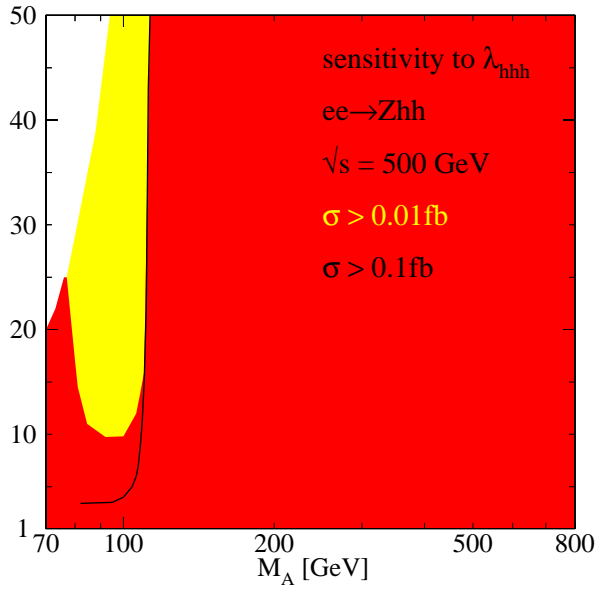
# MSSM cross sections



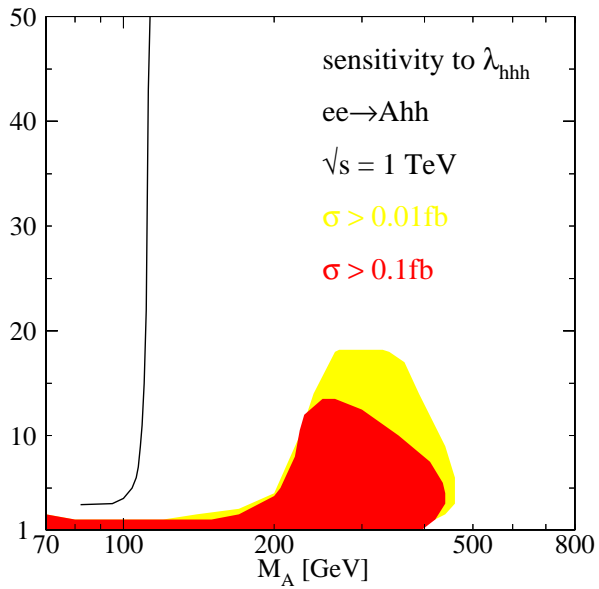


# Sensitivity: $hhh$ couplings

$Zhh$

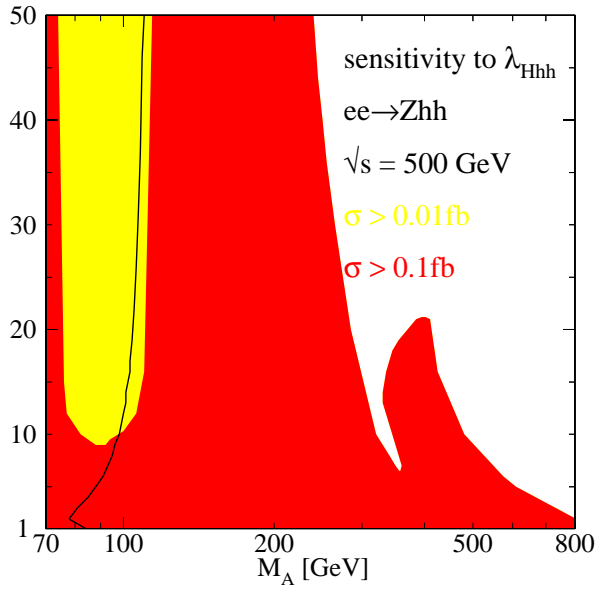


$Ahh$

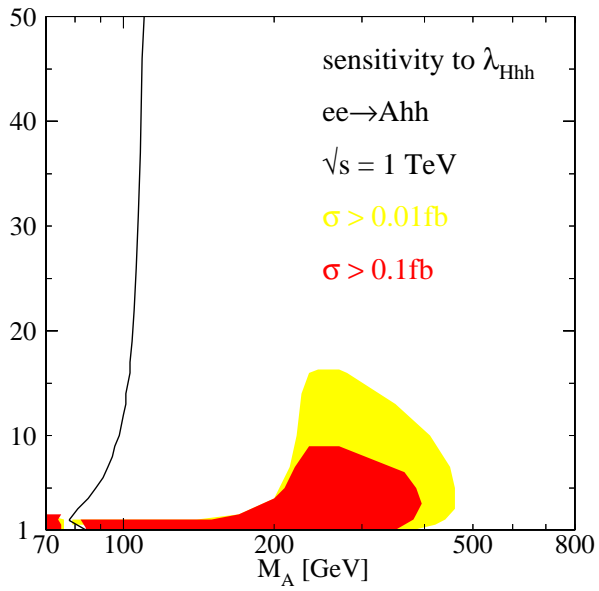


# Sensitivity: $Hhh$ couplings

$Zhh$



$Ahh$



## Conclusions

Trilinear Higgs couplings (SM, MSSM, etc.) are very likely to be measurable (15%?) at a linear collider

⇒ even at 500 GeV

Important:

- High Luminosity  $\int \mathcal{L} \sim 1 \text{ ab}^{-1}$
- Polarization of  $e^-$  and  $e^+$
- Detector: acceptance and  $b$  tagging in forward region

Higher energies ( $\sim 1 \text{ TeV}$ ):

- Large SM Higgs mass
- $WW$  fusion processes (more channels!)
- MSSM couplings for larger  $M_A$

Quartic couplings:  $\sigma(ZHHH) < 1 \text{ ab}$  [hopeless ... ]