$\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{C}$oupling and $\mathcal{H}$iggs $\mathcal{P}$otential

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SYMPOSIUM

Collider Physics at the Tera-Scale

May 29, 2007

Outline

* $\mathcal{M}$otivation
* $\mathcal{I}$nternational $\mathcal{L}$inear $\mathcal{C}$ollider
  - Self-Couplings of the SM Higgs Boson
  - Self-Couplings of the MSSM Higgs Bosons
* $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$ouplings at the $\mathcal{L}$arge $\mathcal{H}$adron $\mathcal{C}$ollider
* $\mathcal{C}$onclusions

Motivation

$\mathcal{H}$iggs $\mathcal{M}$echanism

$\mathcal{P}$roduction of $\mathcal{M}$asses via $\mathcal{S}$pontaneous $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{SSB}$)

- $\mathcal{P}$articles acquire $\mathcal{M}$asses through $\mathcal{I}$nteraction with a $\mathcal{S}$calar Field.
- $\mathcal{S}$elf-Interaction of the $\mathcal{S}$calar Field $\rightsquigarrow$
  $\mathcal{N}$on-Zero Field Strength in the $\mathcal{G}$round State $\rightsquigarrow$ $\mathcal{SSB}$.
- $\mathcal{V}$eV $v = 246$ GeV $\neq 0$ $\mathcal{I}$nduced by the typical $\mathcal{F}$orm of the $\mathcal{H}$iggs Potential.
- $\mathcal{W}$eak iso-doublet $\mathcal{S}$calar Field via $\mathcal{SSB}$ $\rightsquigarrow$ $\mathcal{H}$iggs Particle.

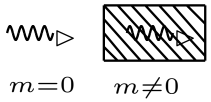
Motivation

$\mathcal{H}$iggs $\mathcal{M}$echanism

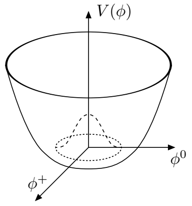
$\mathcal{H}$ow establish experimentally?

Test of the Higgs mechanism

- Discovery – m
- Spin and CP properties – J^{PC}
- Interaction with the scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X^{(2)}$



- EWSB requires Higgs potential $\leftrightarrow$ $\lambda_{HHH}, \lambda_{HHHH}$



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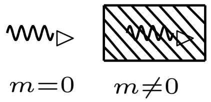

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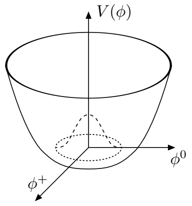
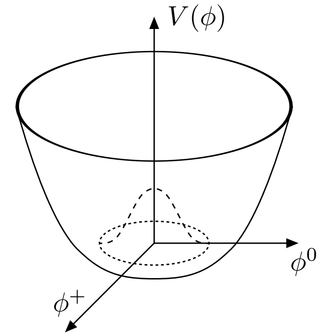


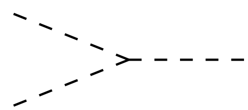
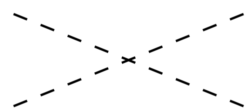
The SM Higgs Sector

The Higgs potential: $[v = 246$ GeV]



$$V(\Phi) = \lambda[\Phi^\dagger\Phi - \frac{v^2}{2}]^2 \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightarrow$$

$$\boxed{V(H) = \frac{1}{2!}\lambda_{HH} H^2 + \frac{1}{3!}\lambda_{HHH} H^3 + \frac{1}{4!}\lambda_{HHHH} H^4}$$

$\mathcal{H}$iggs boson mass	$\lambda_{HH} = M_H^2 = 2\lambda v^2$	
$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

$\mathcal{M}$easurement of the Higgs Self-Couplings
and
$\mathcal{R}$econstruction of the Higgs Potential

} $\mathcal{E}$stablish the Scalar
$\mathcal{S}$ector of the Higgs Mechanism
$\mathcal{E}$xperimentally

Determination of the Higgs Self-Couplings

Determination of the Higgs self-couplings at future colliders:

$\boldsymbol{\lambda_{HHH}}$ via Higgs pair production

$\boldsymbol{\lambda_{HHHH}}$ via triple Higgs production

Higgs-strahlung, WW/ZZ fusion, gg fusion

Also, but not treated here

$*$ At Photon Collider Ginzburg et al. Ilyin et al.;Telnov et al. in $\gamma\gamma$ fusion Boudjema,Chopin La-Zhen,Yao-Yang;Zhu et al. Gounaris,Layssac,Porfyriadis,Renard; Belusevic,Jikia;...

$*$ At ILC: $e^+e^- \to b\bar{b}HH, t\bar{t}HH$ Gutiérrez-Rodriguez et al.

Determination of the Higgs Self-Couplings

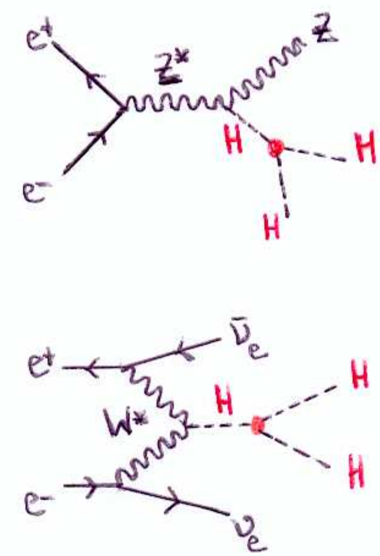
Determination of the Higgs self-couplings at future colliders:

λ_{HHH}	via Higgs pair production	Higgs-strahlung, WW/ZZ fusion, gg fusion
λ_{HHHH}	via triple Higgs production	

Main HH production processes at the ILC

$e^+e^- \to Z^* \to ZHH$ @ LE

$e^+e^- \to W^*W^* \to HH\nu_e\bar{\nu}_e$ @HE

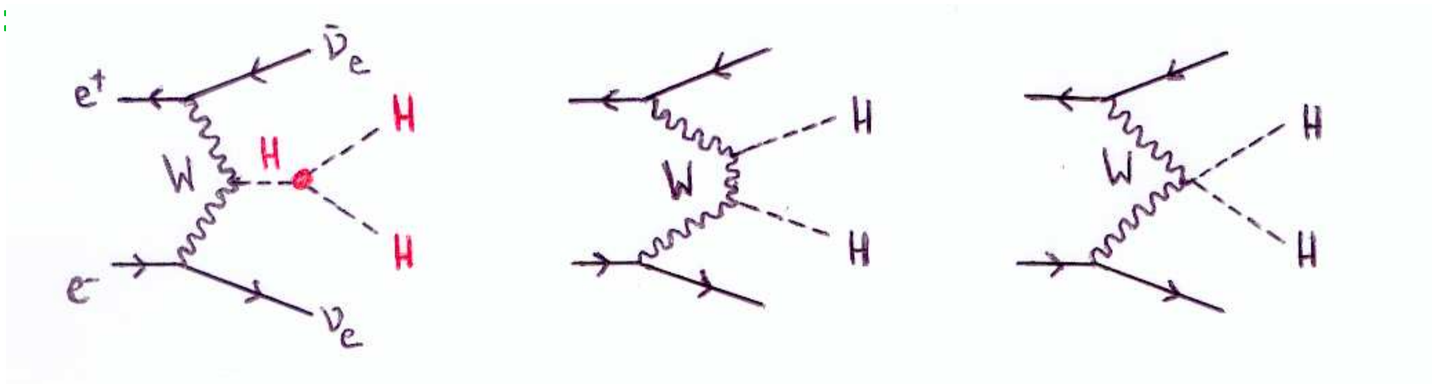


Gounaris,Schildknecht,Renard;
Barger,Han,Phillips;
Ilyin et al;
Boudjema,Chopin;
Djouadi,Kilian,MM,Zerwas;
Bélanger et al;
Zhang et al;
Dobado,Herrero,Hollik,Penaranda;
Kanemura et al.;...

Barger,Han;
Dicus,Kallianpur,Willenbrock;
...

WW Fusion in e^+e^- Collisions

Contributing diagrams:



Dominant Production Amplitude: $W_L W_L \to HH$

$$\hat{\mathcal{M}}_{LL} = \frac{G_F \hat{s}}{\sqrt{2}} \left\{ \frac{\lambda_{HHH}}{(\hat{s}-M_H^2)/M_Z^2}(1+\beta_W^2) + \frac{1}{\beta_W \beta_H}\left[\frac{1-\beta_W^4+(\beta_W-\beta_H x)^2}{x-x_W} + (x \to -x)\right] + (1+\beta_W^2)\right\}$$

$$x=\cos\theta_W,\ \ x_W=(1-2M_H^2/\hat{s})/(\beta_W\beta_H),\ \ \beta_x=(1-4M_x^2/\hat{s})^{1/2}$$

Process $e^+e^- \to W^+W^- \to \bar{\nu}_e \nu_e HH$

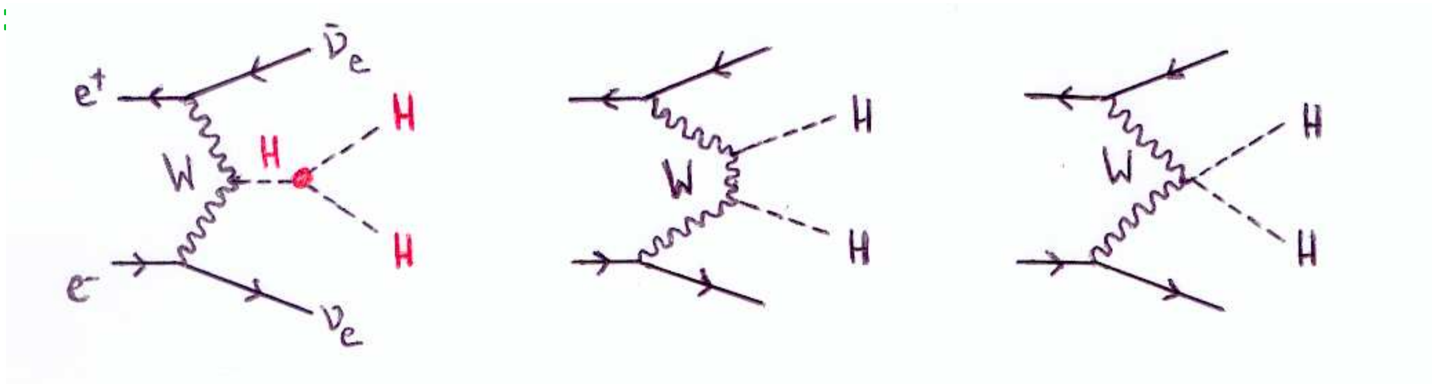
Rough estimate: Equivalent particle approximation: W bosons partons in $e^\pm$, on-shell

Kane et al.
Dawson

$$\sigma = \int_{4M_H^2/s_{ee}}^1 d\tau \left(\frac{d\mathcal{L}}{d\tau}\right)_{WW/ee} \hat{\sigma}_{WW\to HH}(\hat{s}=\tau s_{ee})$$

WW Fusion in e^+e^- Collisions

Contributing diagrams:



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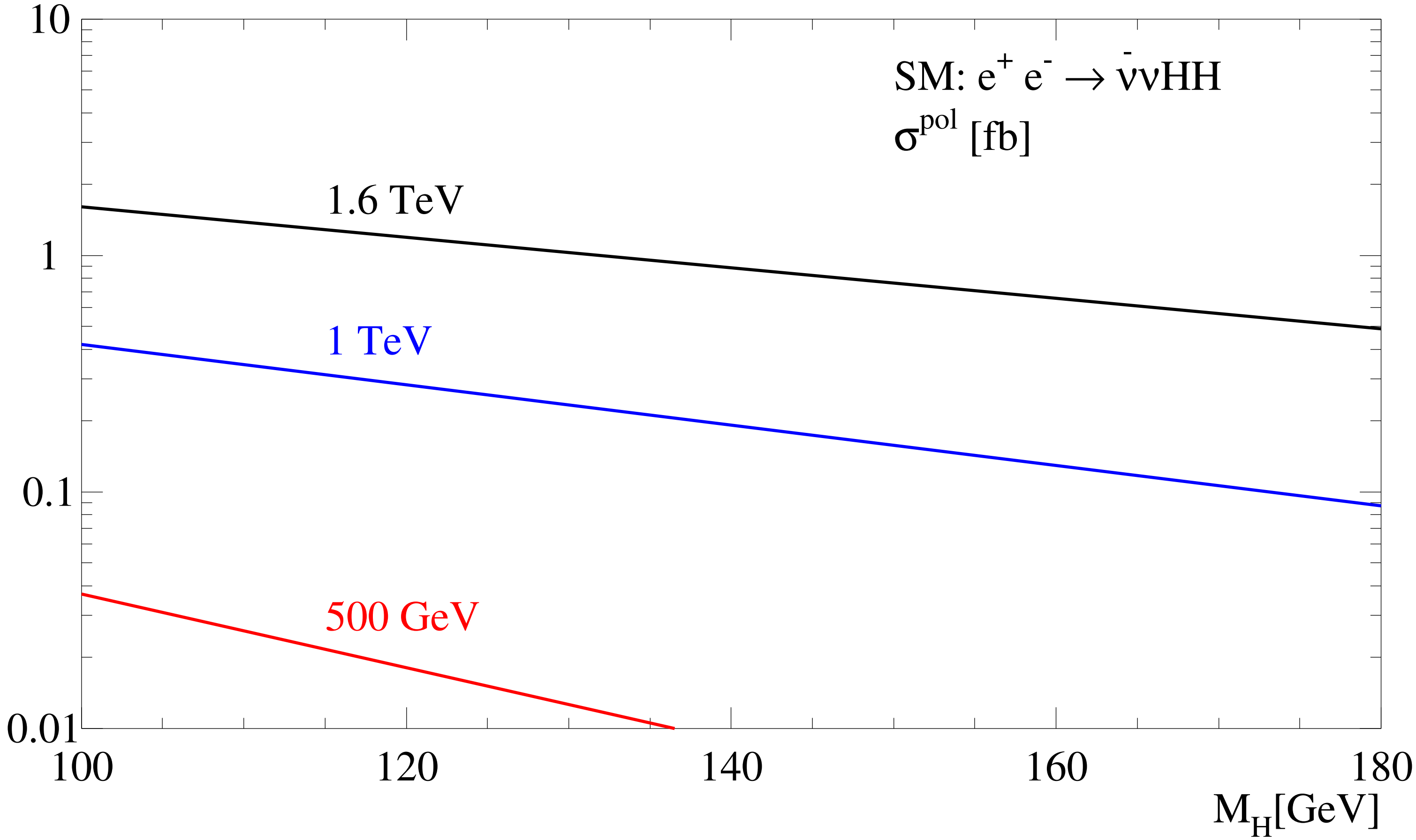
Process $e^+e^- \to W^+W^- \to \bar{\nu}_e \nu_e HH$

High-enery limit:

$$\sigma_\infty(e^+e^- \to \bar{\nu}_e \nu_e HH) \approx \left(\frac{\alpha}{4\pi \sin^2\theta_W}\right)^2 \left[\frac{1}{2}\ln^2\left(\frac{4M_H^2}{s_{ee}}\right) + 2\ln\left(\frac{4M_H^2}{s_{ee}}\right) + 3\right] \frac{M_W^2 G_F^2}{2\pi}$$

SM WW Double Higgs Fusion

CompHEP: Boos et al.



- polarized $e^{\pm}$ beams

Why Polarisation?

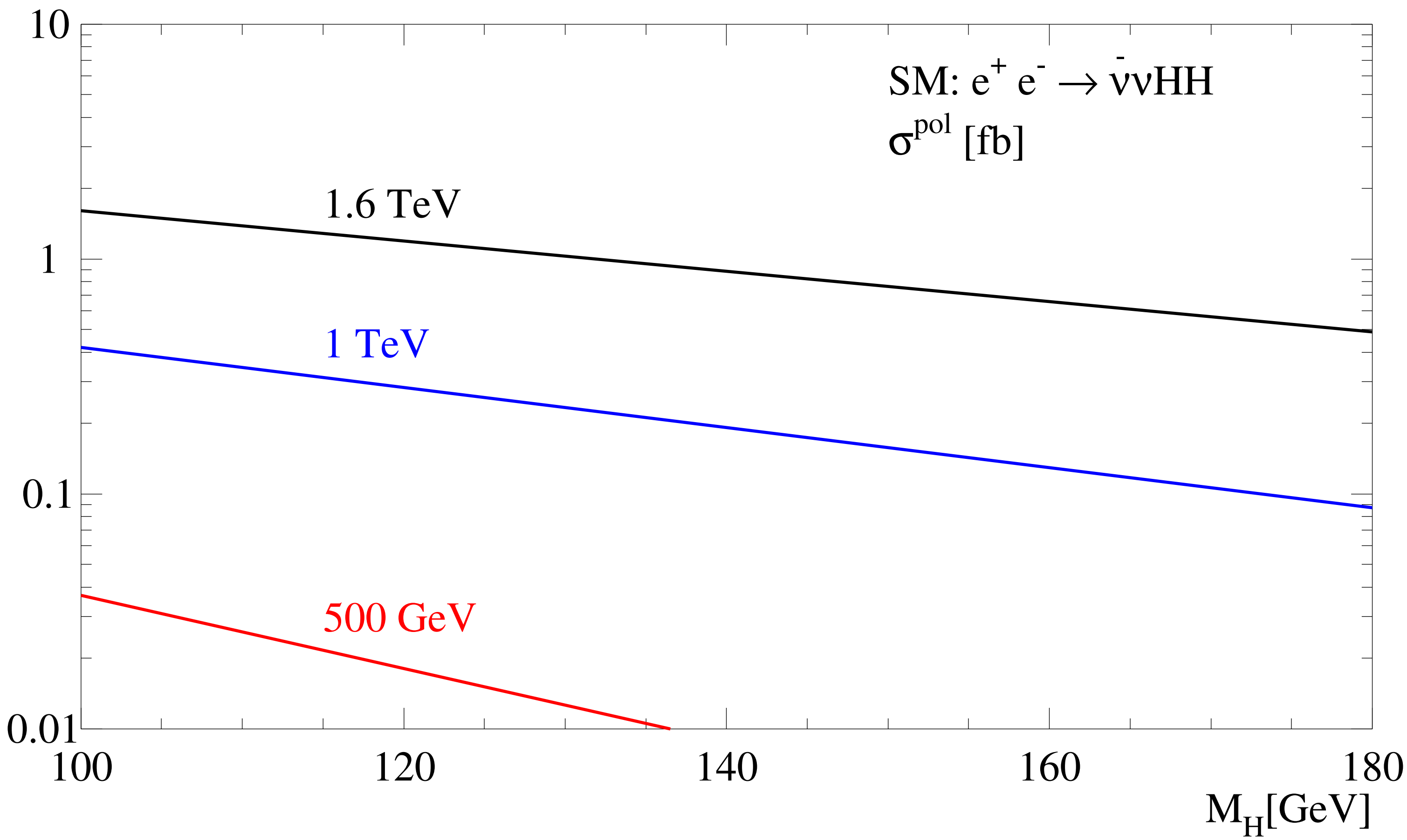
Polarisation of e^+, e^- beams:

W^- bosons only couple to left-handed e^- $\rightsquigarrow$

$$\sigma_{WW}^{\text{pol}} = 4\,\sigma_{WW}^{\text{unpol}}$$

SM WW Double Higgs Fusion

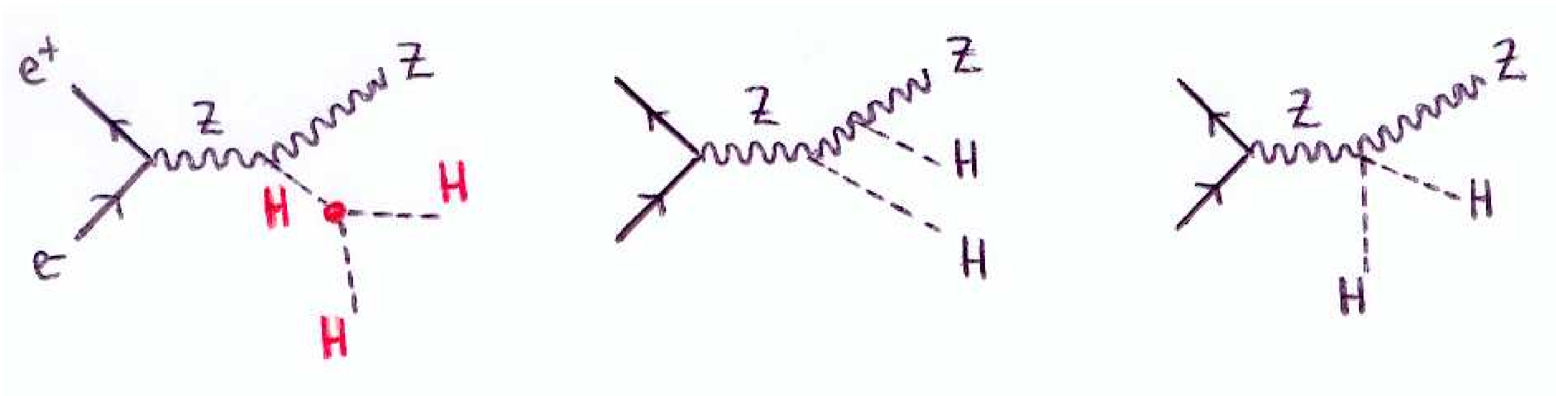
CompHEP: Boos et al.



- polarized $e^{\pm}$ beams $\rightsquigarrow \sigma^{\text{pol}} = 4\sigma^{\text{unpol}}$
- cross sections increase with higher energy

Double Higgs-strahlung in e^+e^- Collisions

Contributing diagrams:



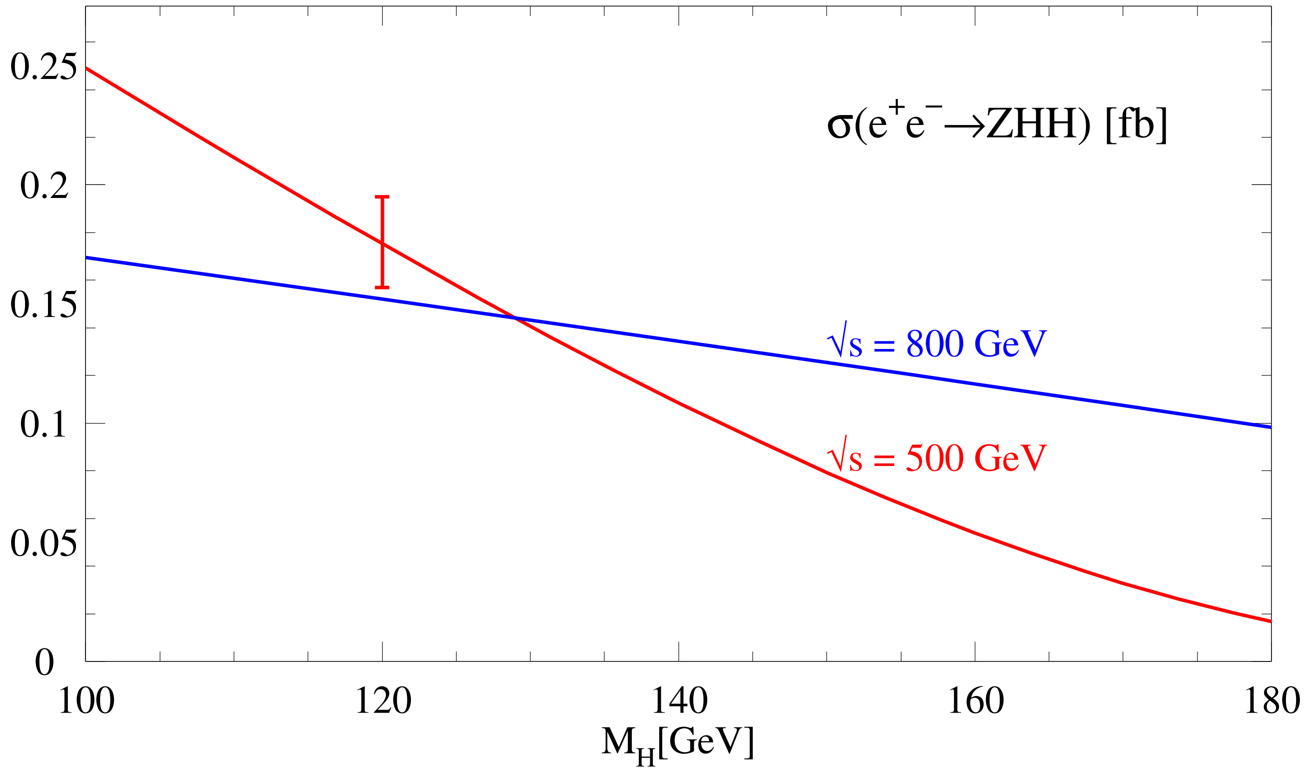
Double differential cross section

$$\frac{d\sigma(e^+e^-\to ZHH)}{dx_1 dx_2} = \frac{G_F^3 M_Z^6 (v_e^2+a_e^2)}{384\sqrt{2}\pi^3} \frac{1}{s(1-\mu_Z)^2} \left\{ \frac{M_Z^2[(y_1+y_2)^2+8\mu_Z]}{4s[-1+x_1+x_2+\mu_Z-\mu_H]^2} \lambda_{HHH}^2 + \ldots \right\}$$

scaled energies: $x_i = E_i/\sqrt{s}$
reduced masses: $\mu_i = M_i^2/s$

SM Double Higgs-strahlung at $\sqrt{s} = 500$ GeV, 800 GeV

Djouadi,Kilian,MM,Zerwas



- σ small; polarisation of $e^\pm \rightsquigarrow \sigma^{\text{pol}} = 2\sigma^{\text{unpol}}$
- σ shows scaling behaviour
- $\sqrt{s} = 500$ GeV good choice for $M_H = 120$ GeV: σ large, sensitivity to λ_{HHH} large
- I: $\Delta\sigma_{ZHH}$ for $\delta\lambda/\lambda_{SM} = 20\%$

Expected Accuracies

Intermediate Higgs mass range $M_H = 120$ GeV

$\sqrt{s} = 500$ GeV, $\int \mathcal{L} = 2$ ab^{-1} $ZHH \to q\bar{q}b\bar{b}b\bar{b}, l^+l^-b\bar{b}b\bar{b}$ $\delta\lambda/\lambda = 18\%$ Castanier,Gay, Lutz,Orloff; Miller,Moretti

$\sqrt{s} = 800$ GeV, $\int \mathcal{L} = 2$ ab^{-1} $ZHH, HH\nu\bar{\nu}$ combined $\delta\lambda/\lambda = 12\%$ Badaud,Gay

$\left.\begin{array}{l}\sqrt{s} = 500 \text{ GeV} \\ \sqrt{s} = 1 \text{ TeV}\end{array}\right\} \int \mathcal{L} = 1$ ab^{-1} $\left.\begin{array}{l} ZHH \\ HH\nu\bar{\nu}\end{array}\right\} M_H \leq 150$ GeV $\delta\lambda/\lambda \approx 20\%$, $\delta\lambda/\lambda \lesssim 10\%$ Yasui et al.

Higher Higgs masses

$HH\nu\bar{\nu}$ @ $\sqrt{s} = 3$ TeV, $\int \mathcal{L} = 5$ ab^{-1} $M_H = 120...180$ GeV $\delta\lambda/\lambda = 8\%$ Battaglia,Boos,Yao

$HH\nu\bar{\nu}$ @ $\sqrt{s} \gtrsim 1.5$ TeV, $\int \mathcal{L} = 5$ ab^{-1} $M_H = 180...240$ GeV $\delta\lambda/\lambda \approx 20...30\%$ Battaglia, de Roeck

The Quartic Coupling λ_{HHHH}

Processes involving λ_{HHHH}

triple Higgs-strahlung $e^+e^- \to ZHHH$

WW triple Higgs fusion $e^+e^- \to \nu_e \bar{\nu}_e HHH$

Size of the cross section $\sigma_{HHH} \approx 10^{-3} \sigma_{HH}$

λ_{HHHH} is suppressed with respect to λ_{HHH}

One more particle in the final state

CompHep/Boos et al.

	$\sigma(e^+e^- \to ZHHH)$ [ab]
$\sqrt{s} = 1$ TeV $M_H = 110$ GeV	0.44
$\sqrt{s} = 1.6$ TeV $M_H = 110$ GeV	0.30

The quartic coupling is not measurable for the time being. [idem LHC/$gg \to HHH$:Plehn,Rauch]

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The MSSM Higgs Sector

MSSM Higgs sector – SUSY & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets $\rightarrow$ 5 Higgs states

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;...

6 CP-invariant neutral trilinear Higgs couplings

$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta+\alpha) \quad +3\frac{\epsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha$$
$$\lambda_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha) \quad +3\frac{\epsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha$$
$$\lambda_{HHh} = -2\sin 2\alpha \cos(\beta+\alpha) - \cos 2\alpha \sin(\beta+\alpha) \quad +3\frac{\epsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\sin^2\alpha$$
$$\lambda_{HHH} = 3\cos 2\alpha \cos(\beta+\alpha) \quad +3\frac{\epsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\sin^2\alpha$$
$$\lambda_{hAA} = \cos 2\beta \sin(\beta+\alpha) \quad +\frac{\epsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\beta$$
$$\lambda_{HAA} = -\cos 2\beta \cos(\beta+\alpha) \quad +\frac{\epsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\beta$$

Radiative Corrections one-loop leading m_t^4 approximation parametrized by

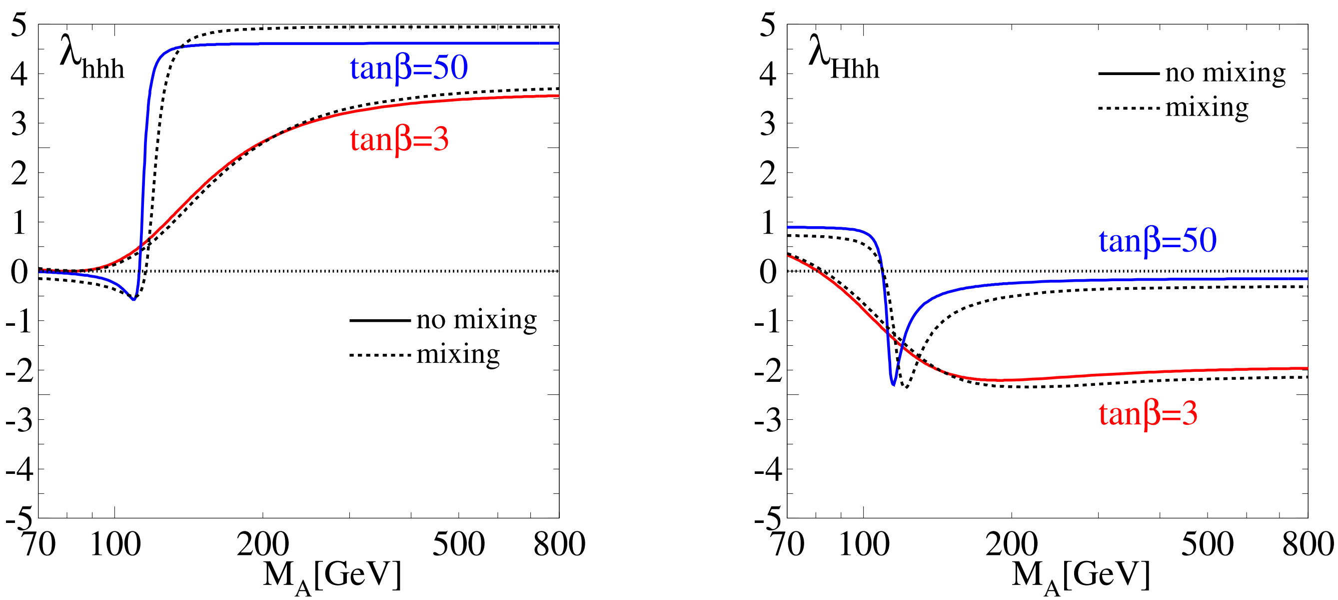
$$\epsilon = \frac{3G_f m_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\ln\left(1+\frac{M_S^2}{m_t^2}\right) \qquad \tan\beta = \frac{v_2}{v_1}$$

The Trilinear Couplings $\lambda_{hhh}, \lambda_{Hhh}$

Subsequent analysis:

Carena,Espinosa,Quiros,Wagner
Djouadi,Kalinowski,Spira

- ∗ Dominant one-loop and two-loop corrections to MSSM Higgs masses and couplings included.
- ∗ Corrections involve mixing paramters A and μ.



- ○ Mixing: $A = \mu = 1$ TeV.
- ○ $\lambda_{hhh}, \lambda_{Hhh}$ can become zero.
- ○ Couplings not strongly affected by mixing effects when evaluated for the physical Higgs masses.

The MSSM Higgs Self-Couplings

6 CP-invariant couplings between the neutral Higgs bosons

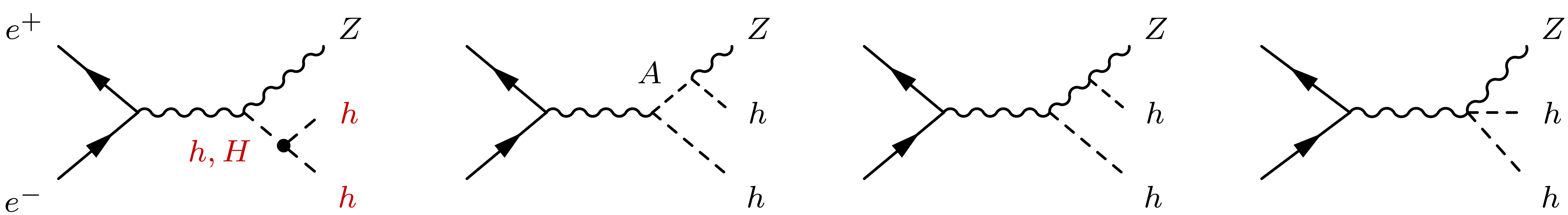
Djouadi,Kilian,MM,Zerwas;Pandita,Osland; Boudjema,Semenov;(exts: Kanemura ea; Barger,Han,Langacker,McElrath,Zerwas)

λ_{hhh}	λ_{Hhh}	λ_{HHh}
λ_{HHH}	λ_{hAA}	λ_{HAA}

Determination of $\lambda_{3\Phi}$ at e^+e^- Colliders

- ⋆ WW/ZZ fusion
- ⋆ double Higgs-strahlung
- ⋆ triple Higgs production

For example $e^+e^- \to Zhh$



sensitive to $\lambda_{hhh}, \lambda_{Hhh}$

The Sensitivity Areas

Processes sensitive to $\lambda_{3\Phi}$

	double Higgs−strahlung				triple Higgs−production			
λ	Zhh	ZHh	ZHH	ZAA	Ahh	AHh	AHH	AAA
hhh	×				×			
Hhh	×	×			×	×		
HHh		×	×			×	×	
HHH			×				×	
hAA				×	×	×		×
HAA				×		×	×	×

System solvable for all λ's up to discrete ambiguities

Sensitivity Areas

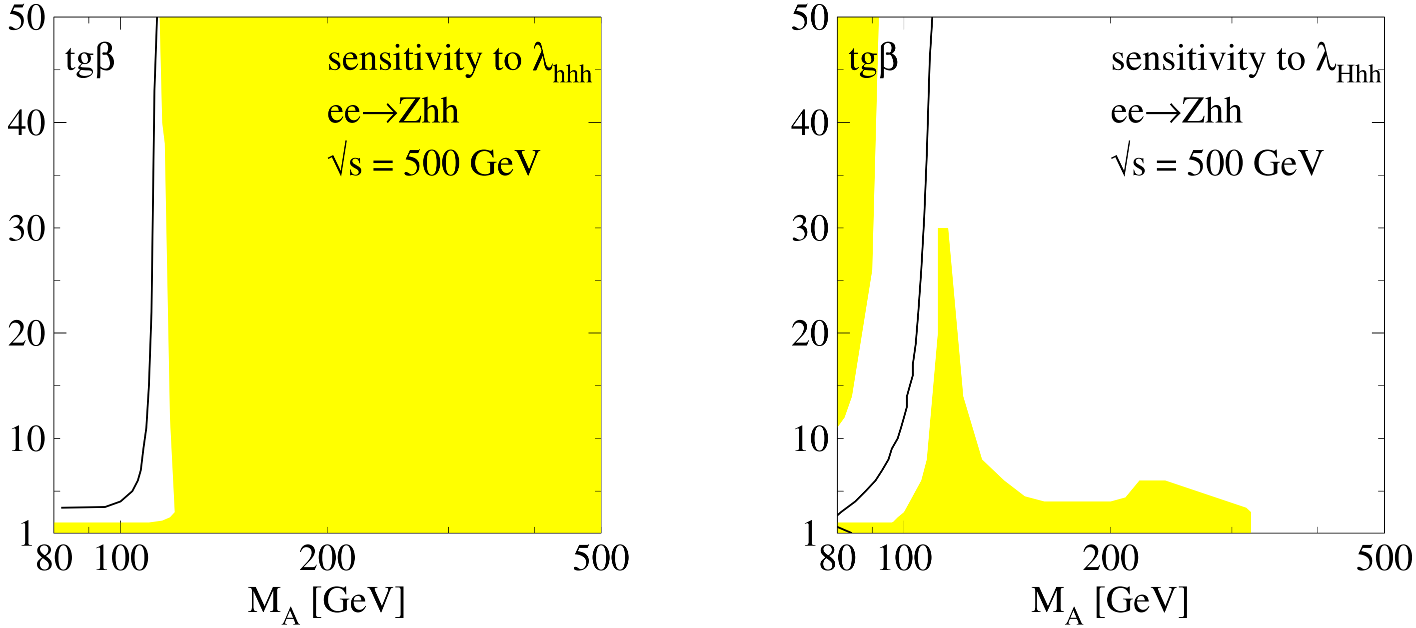
Djouadi, Kilian, MM, Zerwas

(i) $\sigma[\lambda] > 0.01$ fb [and relaxed to 0.1 fb]

(ii) $\text{eff}\{\lambda \to 0\} > 2$ st.dev. for $\int \mathcal{L} = 2$ ab^{-1}

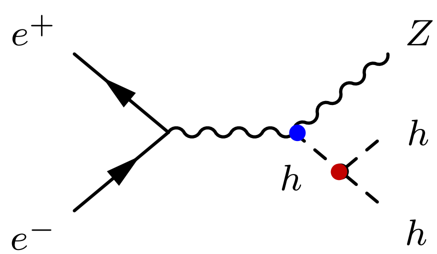
Sensitivity Areas for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: λ_{hhh} : Zhh, Ahh λ_{Hhh} : Zhh, ZHh, Ahh



Regions of no sensitivity: $\lambda \sin(\beta - \alpha), \lambda \cos(\beta - \alpha)$ small

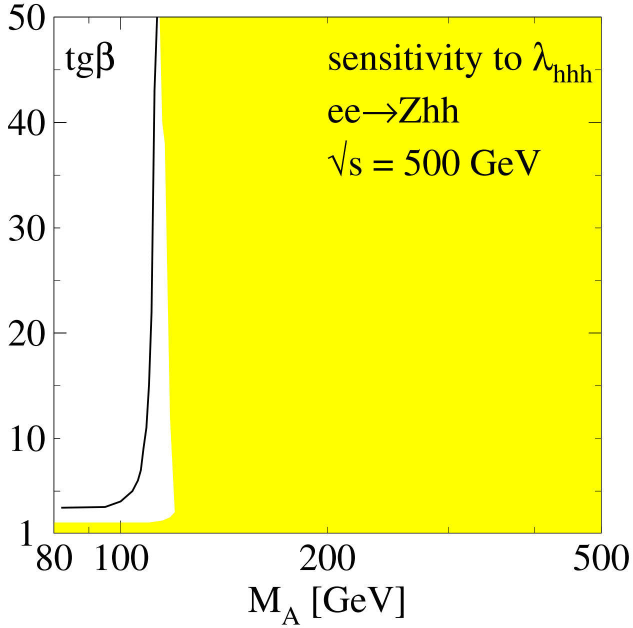
For example:

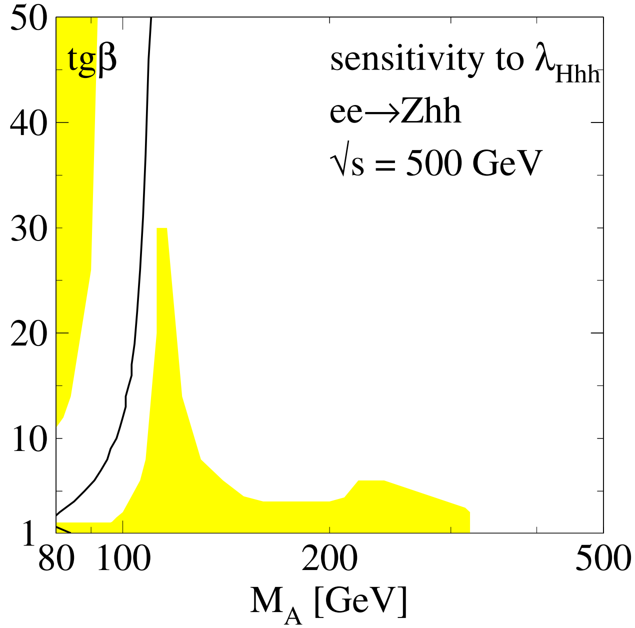


$\sim \lambda_{hhh} \sin(\beta - \alpha)$

Sensitivity Areas for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: λ_{hhh} : Zhh, Ahh $\quad$ λ_{Hhh} : Zhh, ZHh, Ahh





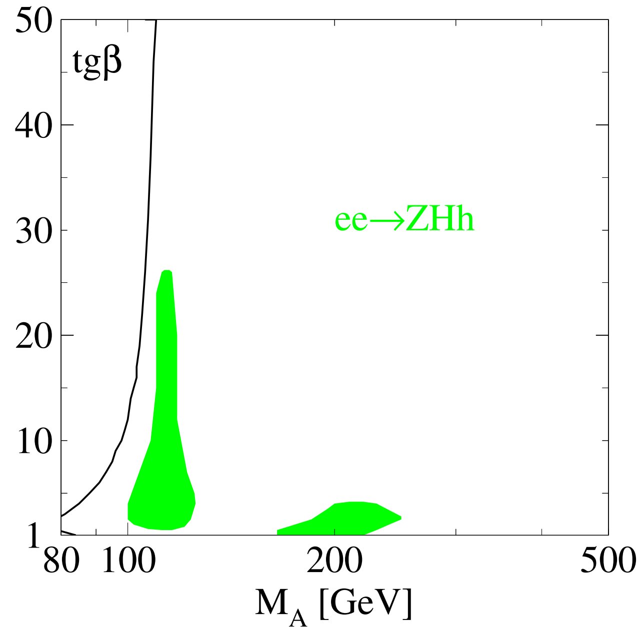
Regions of no sensitivity: $\lambda \sin(\beta - \alpha), \lambda \cos(\beta - \alpha)$ small

large M_A: sensitivity criteria not fulfilled due to

- ∘ phase space effects
- ∘ suppression of the H, A propagators for large masses

Sensitivity Areas for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: λ_{hhh} : Zhh, Ahh $\quad$ λ_{Hhh} : Zhh, ZHh, Ahh



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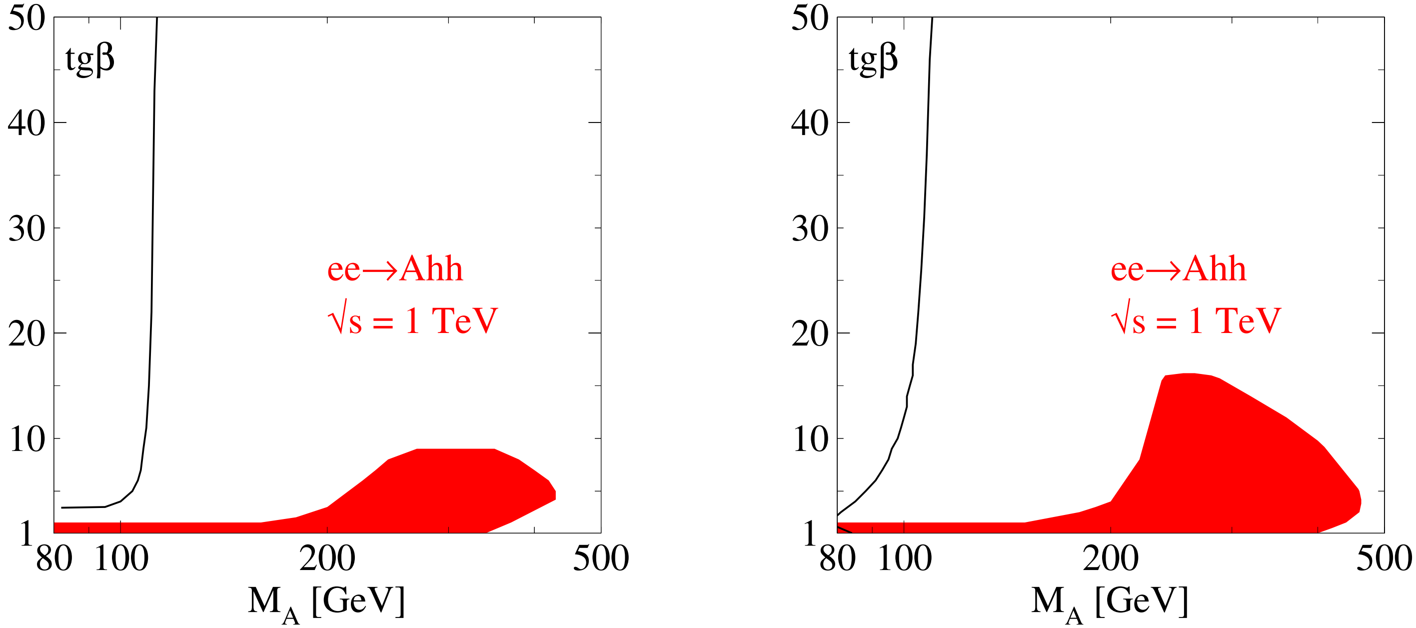

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The Trilinear Higgs Self-Coupling at the LHC

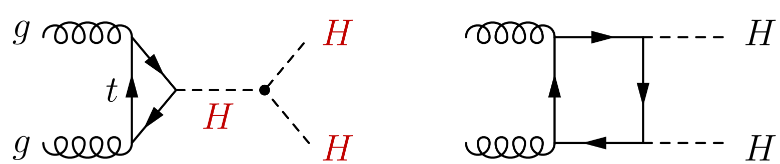
Determination of λ_{HHH} at the LHC

Djouadi,Kilian,MM,Zerwas

In processes analogous to those at e^+e^- colliders and in gluon gluon fusion

double Higgs-strahlung:	$q\bar{q}$	$\to$	$W/Z + HH$	Barger,Han,Phillips
WW/ZZ fusion:	qq	$\to$	$qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale
gluon gluon fusion:	gg	$\to$	HH	Glover,van der Bij Plehn,Spira,Zerwas Dawson,Dittmaier,Spira

Gluon Gluon Fusion - dominant process

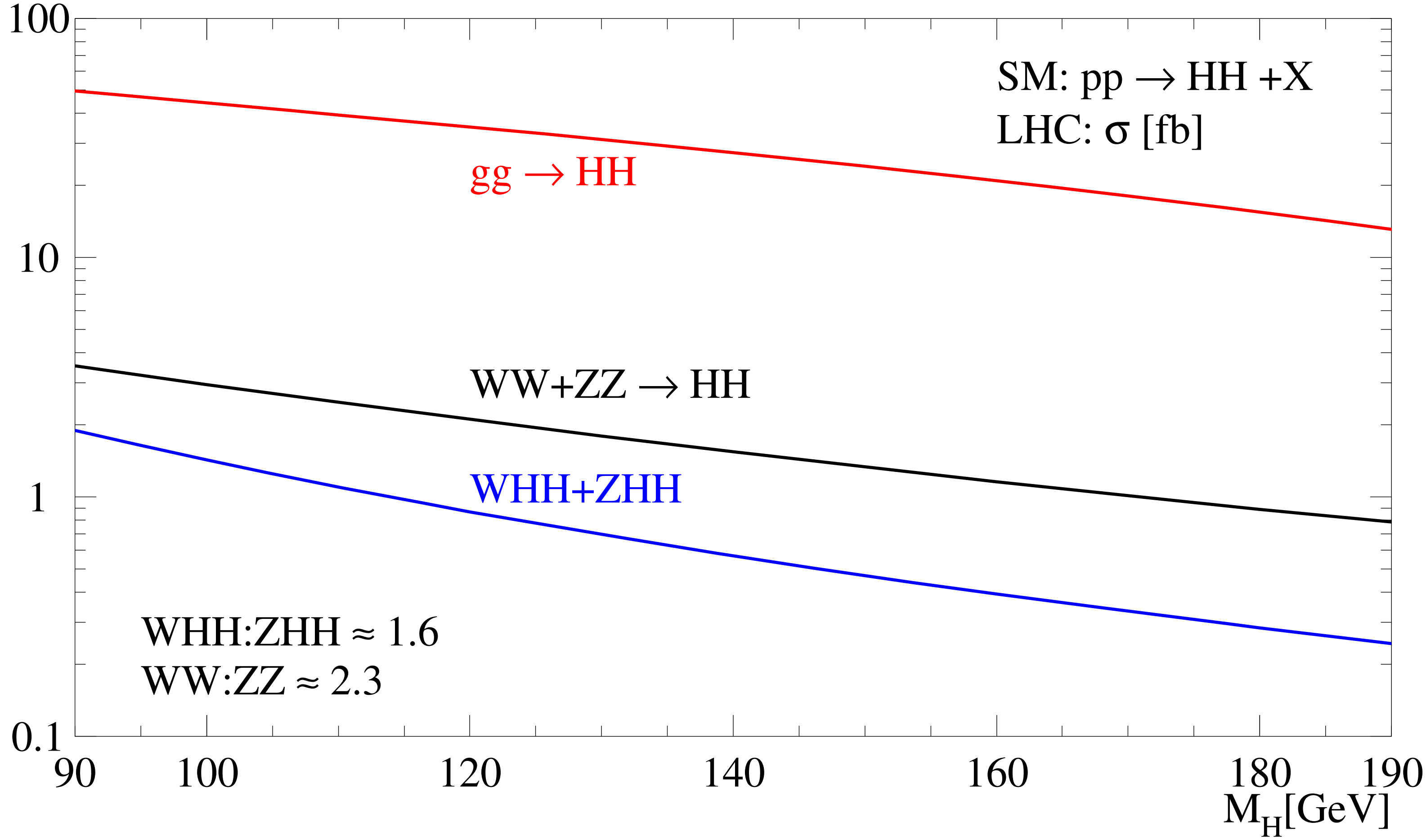


Comments:

- 2-loop QCD corrections known for $m_t \to \infty$: $K \sim 1.9$ — Dawson,Dittmaier,Spira
- Single Higgs production $\rightsquigarrow K \to K \pm 10\%$ for large M_H — Spira,Djouadi,Graudenz,Zerwas

SM Double Higgs Production at the LHC

Djouadi,Kilian,MM,Zerwas



Expected Accuracies on λ_{HHH} at the LHC

Smallness of the signal + large QCD backgrounds $\rightsquigarrow$ challenging!

Baur,Plehn,Rainwater

$M_H < 140$ GeV: $gg \to HH \to b\bar{b}\gamma\gamma$:

- SLHC [$\int \mathcal{L} = 6$ ab^{-1}]:

  $M_H = 120$ GeV — rule out $\lambda_{HHH} = 0$ — at 90% CL

- VLHC [$\sqrt{s} = 200$ TeV]:

  $M_H = 120$ GeV: — $\delta\lambda_{HHH}/\lambda_{HHH} = 20 - 40\%$ — at 1 σ

Gianotti et al.;Blondel,Clark,Mazzucato
Baur,Plehn,Rainwater
Dahlhoff

$M_H > 140$ GeV: $gg \to HH \to W^+W^-W^+W^-$:

- LHC [$\int \mathcal{L} = 300$ fb^{-1}]:

  $150 \lesssim M_H \lesssim 200$ GeV: — rule out $\lambda_{HHH} = 0$ — at 95% CL

- SLHC [$\int \mathcal{L} = 3$ ab^{-1}]:

  $150 < M_H < 200$ GeV — $\delta\lambda_{HHH}/\lambda_{HHH} = 10 - 30\%$ — at 1 σ

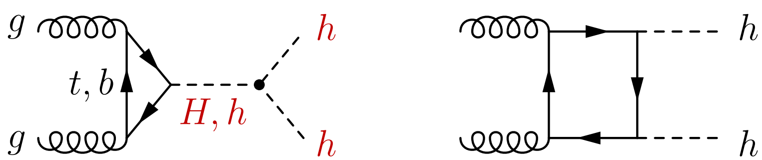
MSSM Higgs Self-Couplings at the LHC

Determination of $\lambda_{3\Phi}$

Dawson,Dittmaier,Spira; Plehn,Spira,Zerwas
Belyaev,Drees,Eboli,Mizkoshi,Novaes; Djouadi,Kilian,MM,Zerwas

* gluon gluon fusion
* double Higgs-strahlung
* VV double Higgs fusion
* triple Higgs production

Example $gg \longrightarrow hh$

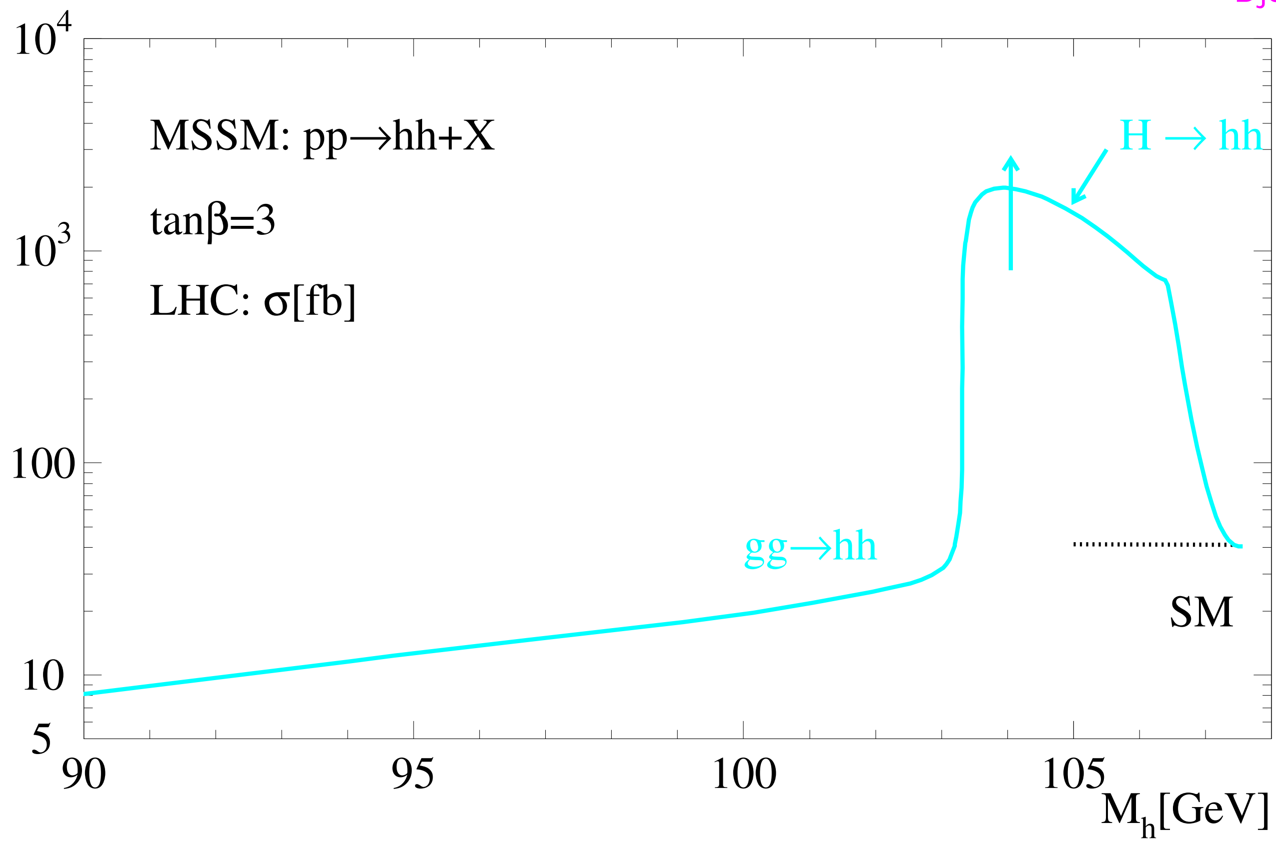


Comments:

- Involves the Higgs self-couplings $\lambda_{hhh}, \lambda_{Hhh}$.
- 2-loop QCD corrections (large m_t limit) included. Dawson,Dittmaier,Spira

MSSM hh Production in gg Fusion at the LHC

Djouadi,Kilian,MM,Zerwas



- Enhancement: resonant H production & $H \to hh$.
- $\uparrow$ variation: $0.5\lambda_{Hhh}...1.5\lambda_{Hhh}$.
- Parton/Hadron level analysis (LO): signal feasible in resonant region.

Miller,Moretti,MM;Lafaye
Baur,Plehn,Rainwater

Conclusions

Standard Model λ_{HHH} at the ILC

- Double Higgs-strahlung & WW double Higgs fusion are sensitive to λ_{HHH}.
- For $M_H = 120$ GeV $\sqrt{s} = 500$ GeV is a good choice: sensitivity to λ_{HHH} is large.
- Accuracy at ILC: $\delta\lambda_{HHH}/\lambda_{HHH} \lesssim 20$ %.

$\lambda_{HHH}^{SM} = 3\frac{M_H^2}{v} \rightsquigarrow$ Measurement of λ_{HHH} allows for a first consistency check.

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MSSM trilinear Higgs self-couplings at the ILC

* Zhh, ZHh, Ahh sensitive to $\lambda_{hhh}, \lambda_{Hhh}$ in parts of the parameter space $\tan\beta - M_A$.

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Higgs self-couplings at the LHC

* Larger cross sections face large QCD background.
* May rule out $\lambda^{SM}_{HHH} = 0$.
* λ^{MSSM}_{Hhh} might be accessible in resonance region.

Conclusions

Trilinear Higgs self-couplings are accessible at e^+e^- Linear Colliders [and the LHC] ⇝
First step in order to establish the scalar sector of the Higgs mechanism experimentally.