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Can the Triple Higgs Coupling be measured at Future Colliders?

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1. The Triple Higgs Coupling in the Standard Model:
   – At the LHC
   – At an e^+e^- Linear Collider

2. The Triple Higgs Couplings in the MSSM:
   – At the LHC
   – At an e^+e^- Linear Collider

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1. The Triple Higgs Coupling in the Standard Model

- SM Higgs potential:

$$V = \lambda \left\{ |\phi|^2 - \tfrac{1}{2}v^2 \right\}^2.$$

where $\phi = U^{-1}(\xi)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ H+v \end{pmatrix}$ gives,

$$V = \tfrac{1}{2}M_H^2 H^2 + \tfrac{1}{2}\frac{M_H^2}{v}H^3 + \frac{M_H^2}{8v^2}H^4.$$

- Mass term
- Triple Higgs coupling
- Quartic Higgs coupling

Depend only on M_H and v (or M_Z).

$\Rightarrow$ Must test these predictions in experiment.

$\Rightarrow$ Allows reconstruction of the Higgs potential from experiment.

Can they be measured?

- Higgs mass measured soon after discovery.

- Excitingly, the triple Higgs coupling may also be measurable at the next generation of colliders!

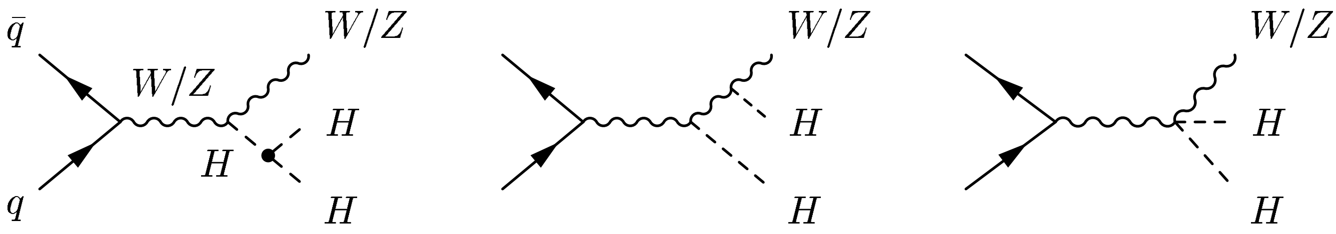
- Quartic coupling looks out of reach for some time to come.

$\Rightarrow$ Here I will discuss only the triple Higgs coupling.

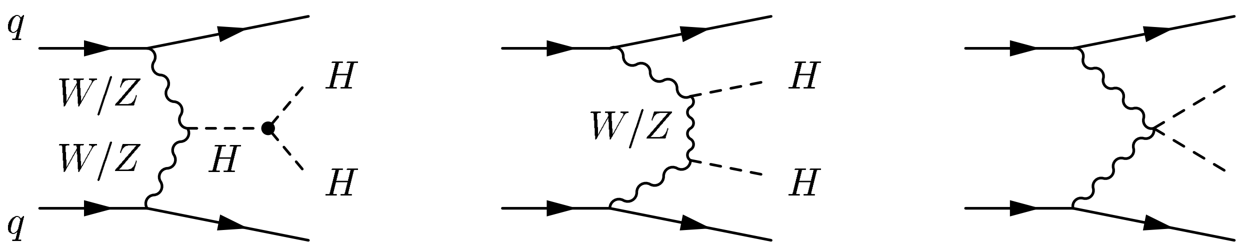
The SM triple Higgs coupling at the LHC

Processes involving a triple Higgs coupling:

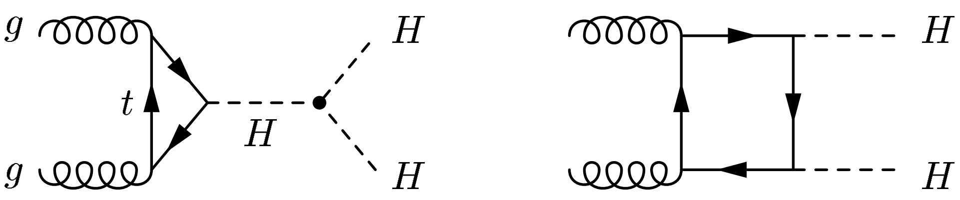
<u>double Higgs-strahlung: $q\bar{q} \to ZHH/WHH$</u>



<u>WW/ZZ double-Higgs fusion: $qq \to qqHH$</u>

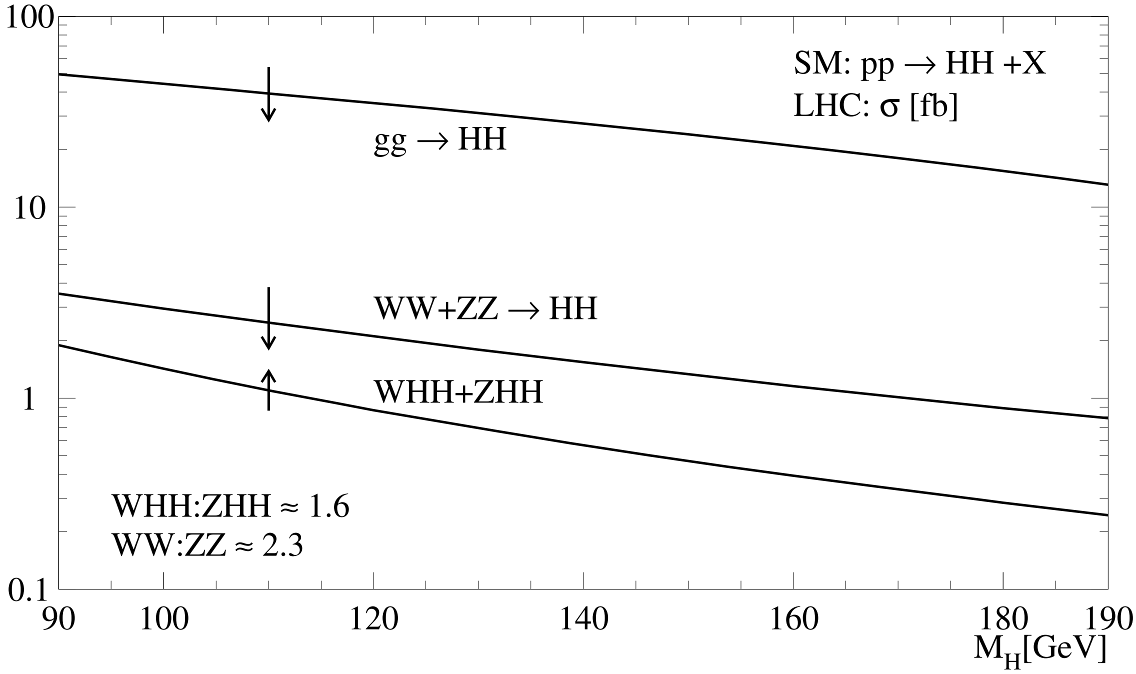


<u>gg double-Higgs fusion: $gg \to HH$</u>



- Rather low cross-sections, at most 50fb
- Messy QCD backgrounds at the LHC
- Extraction of triple Higgs coupling impractical

Plot curtesy of Djouadi, Kilian, Muhlleitner and Zerwas,
`hep-ph/9904287`.



- Require sensitivity to the triple Higgs coupling

(The arrows indicate change to signal when triple Higgs coupling is varied form 1/2 to 3/2 of its SM value.)

$\Rightarrow$ Measurement of the SM triple Higgs coupling at the LHC impractical.

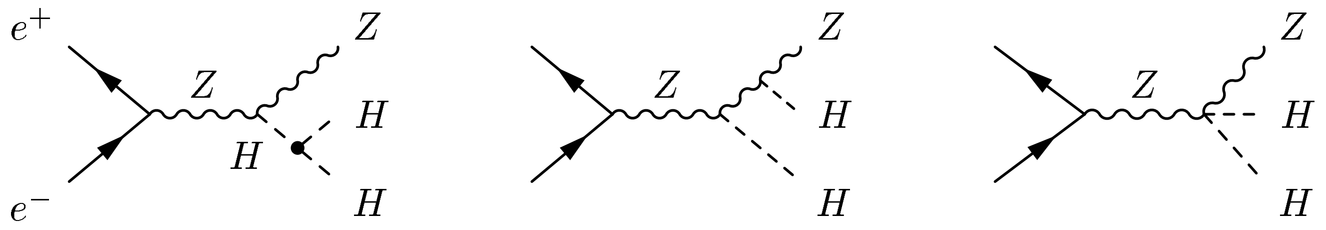
$\Rightarrow$ Turn to a future e^+e^- linear collider.

The SM triple Higgs coupling at a future linear collider

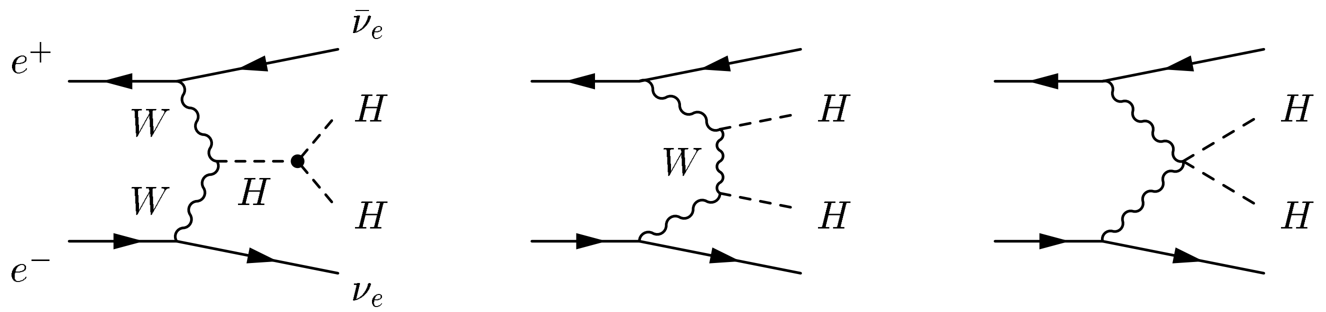
The signal:

Processes involving a triple Higgs coupling:

double Higgs-strahlung: $e^+e^- \to ZHH$



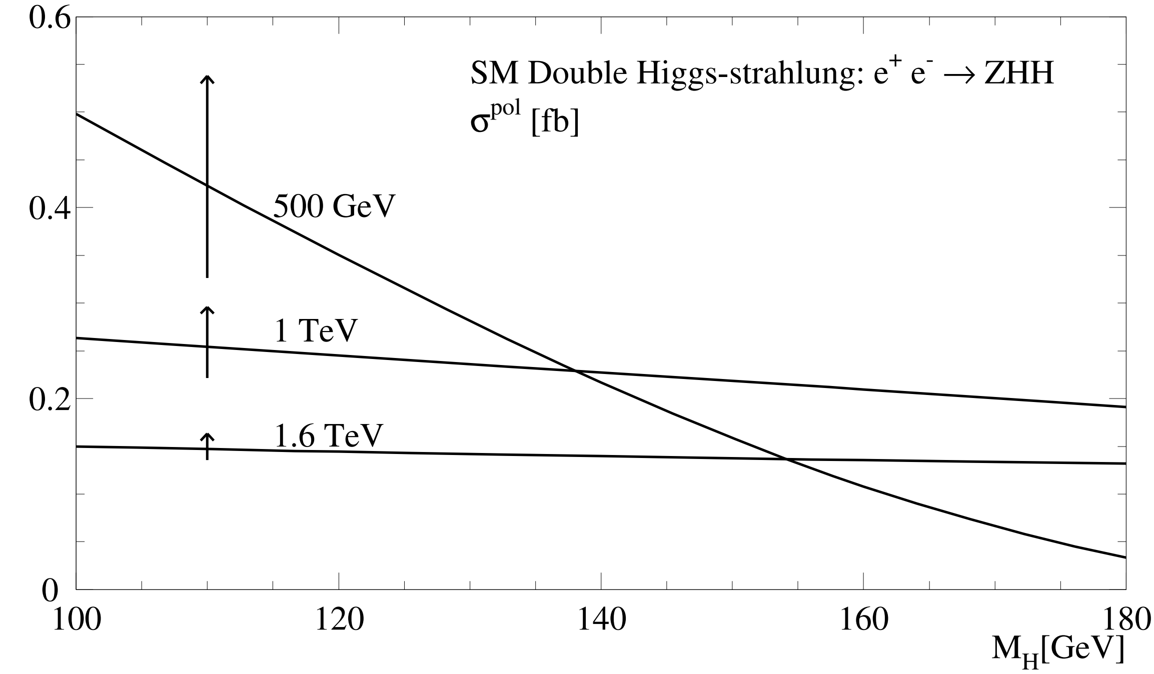
WW double-Higgs fusion: $e^+e^- \to \bar{\nu}_e \nu_e HH$

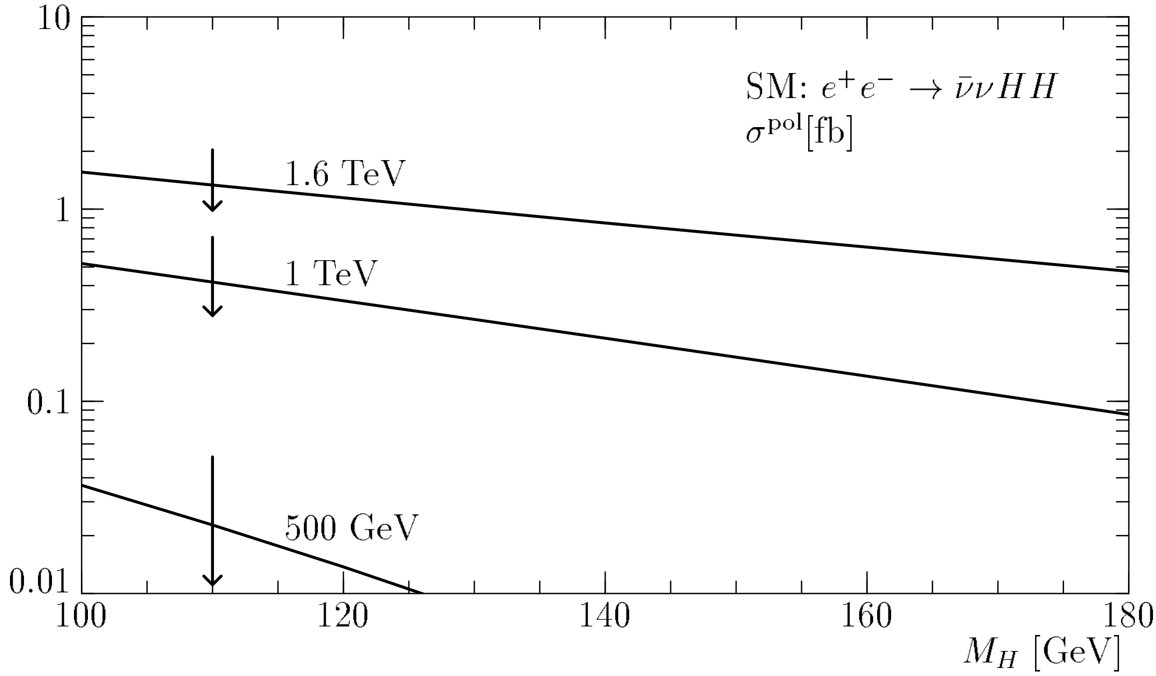


- Even smaller signal: always < 1fb at 500GeV.
- Linear Collider much cleaner than LHC

  $\Rightarrow$ Backgrounds smaller and easier to handle

Plots curtesy of Djouadi, Kilian, Muhlleitner and Zerwas, `hep-ph/9903229`.





Most promising signal for 500GeV collider:

double Higgs-strahlung, $e^+e^- \to ZHH$

Simplifications:

- Restrict to decay $H \to b\bar{b}$ for $M_H \le 140$GeV
(If $M_H \ge 140$GeV, $H \to W^{\pm(*)}W^{\mp}$ is important.)

- Do not decay the Z – keep on shell in final state, i.e. assume it can be easily reconstructed.

- Assume a very efficient tagging and high purity sampling of b quarks.

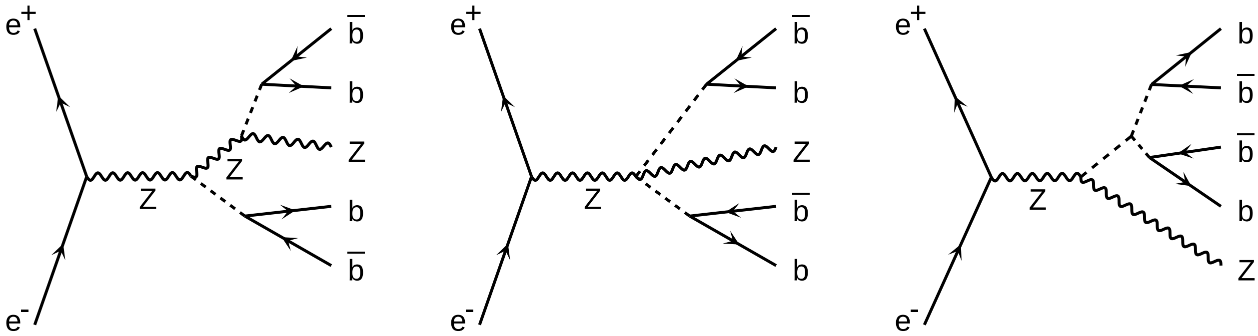
  $\Rightarrow$ Need only irreducible backgrounds, $e^+e^- \to b\bar{b}b\bar{b}Z$.

- Calculation performed at the parton level.

- No ISR is included.

Signal: $e^+e^- \to HHZ \to b\bar{b}b\bar{b}Z$

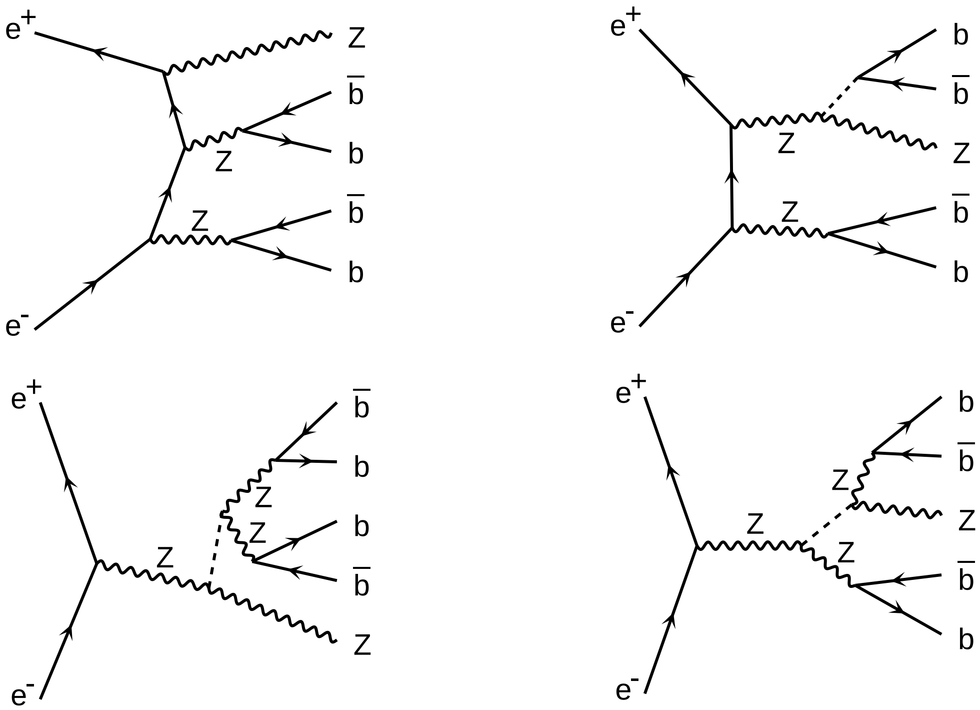
Generic Feynman diagrams –



- Only right-most diagram contains triple Higgs coupling

EW Background: $e^+e^- \to$ EW Graphs $\to b\bar{b}b\bar{b}Z$

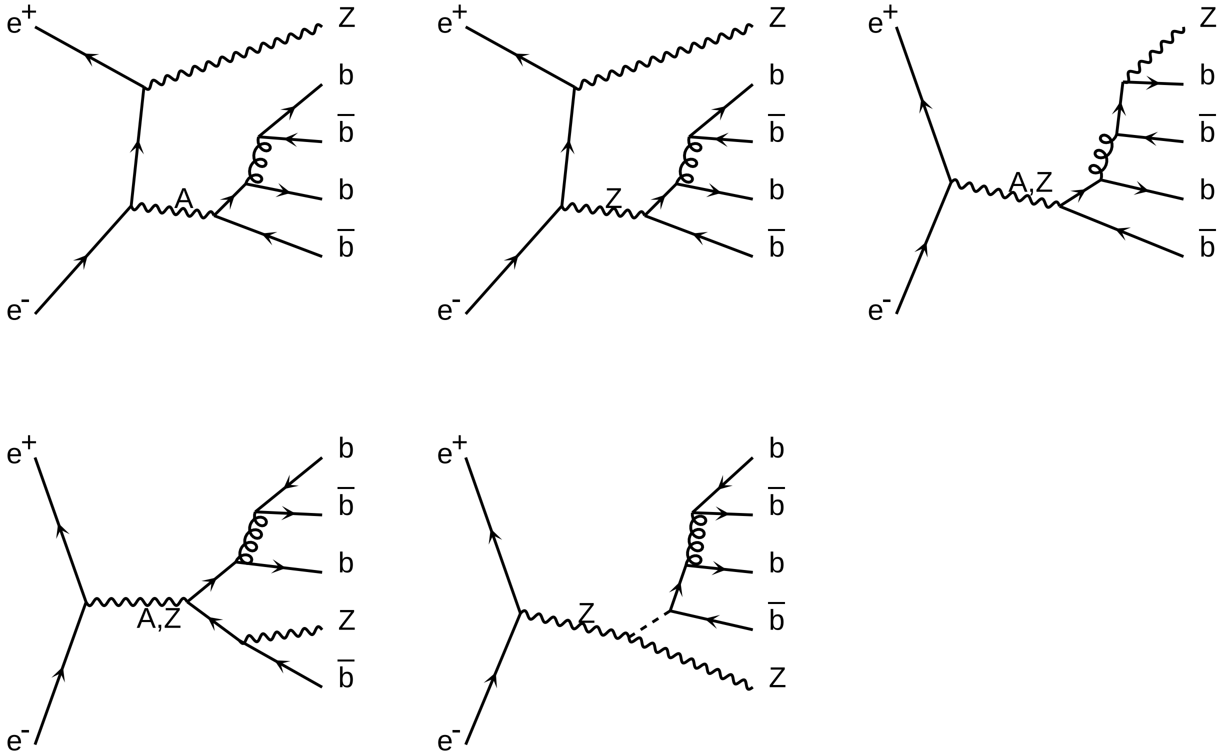
Generic Feynman diagrams for the dominant EW sub-processes –



- EW background is $O(\alpha_{em}^5)$ away form resonances
- Has both $Z \to b\bar{b}$ and $H \to b\bar{b}$ mimicking signal

$\Rightarrow$ Problematic

QCD Background: $e^+e^- \to$ QCD Graphs $\to b\bar{b}b\bar{b}Z$



(Feynman diagrams are generic)

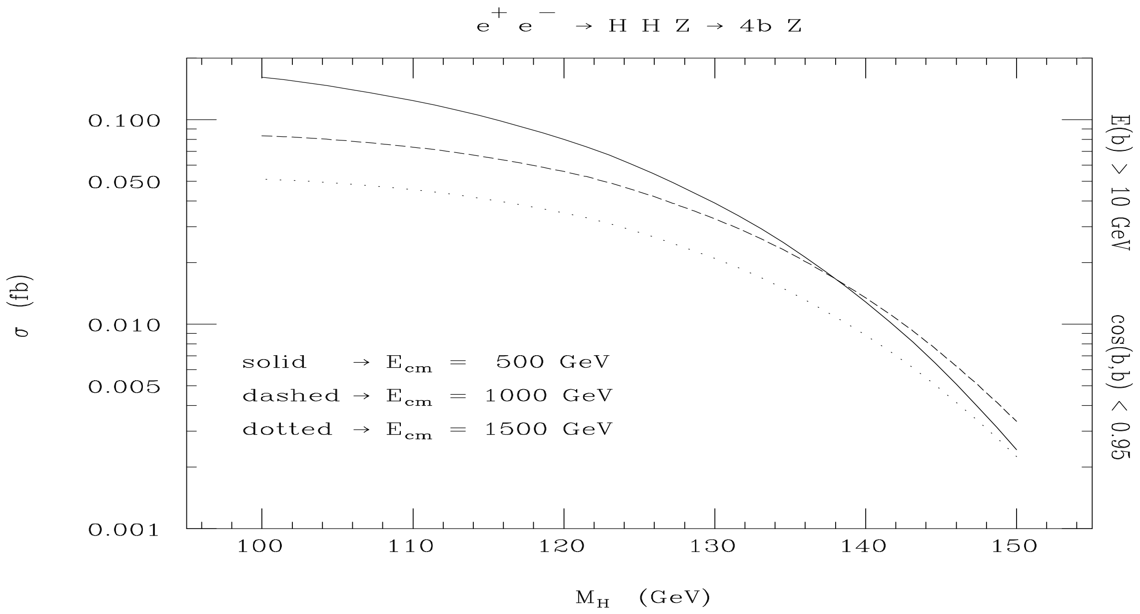
- No problematic resonances
- may be large due to the strong coupling constant.

Preliminary Cuts:

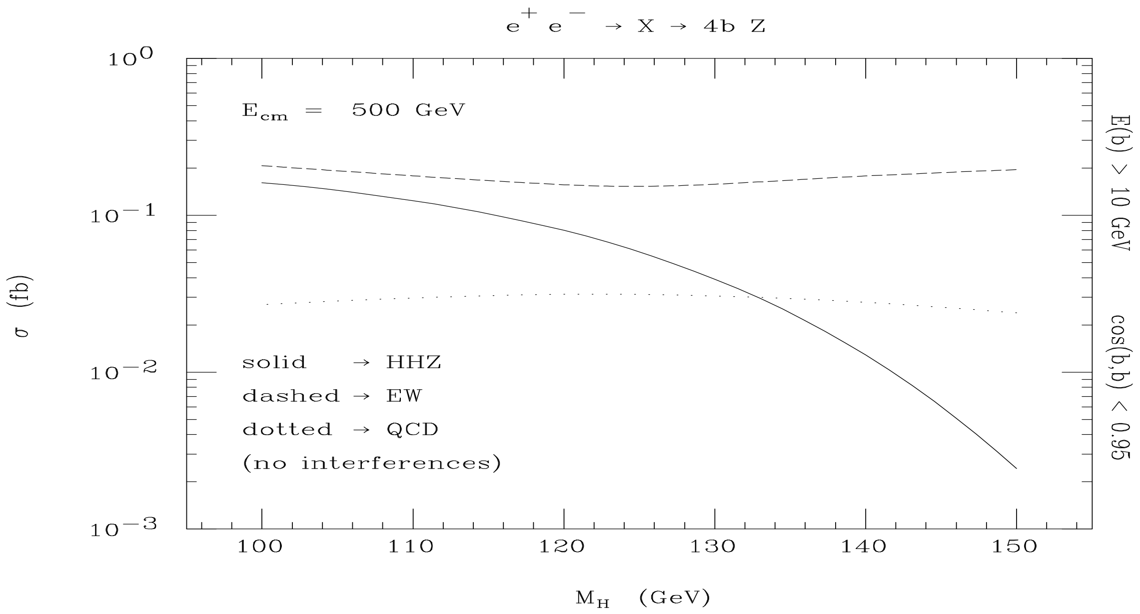
$E(b) > 10$GeV for each b (anti)quark

$\cos(b, b) < 0.95$ on the separation of all possible $2b$ combinations

Cross-sections with preliminary cuts



- Signal decreases with increasing Higgs mass (due to decrease of $H \to b\bar{b}$ branching ratio)
- $1/s$ suppression.

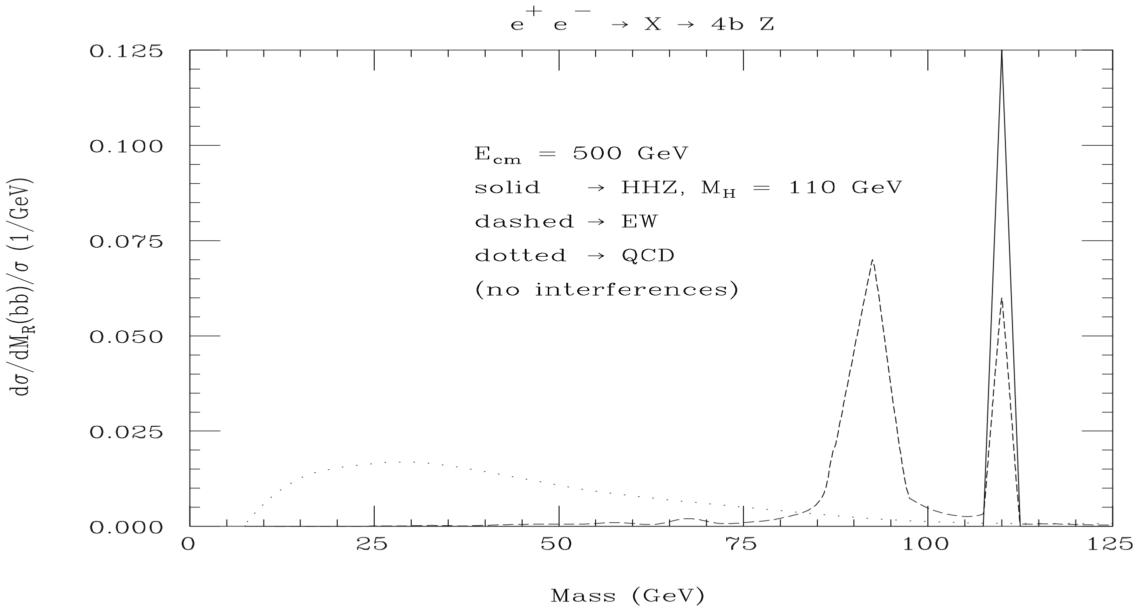


- Signal overwhelmed by EW background
- QCD background is not a problem.

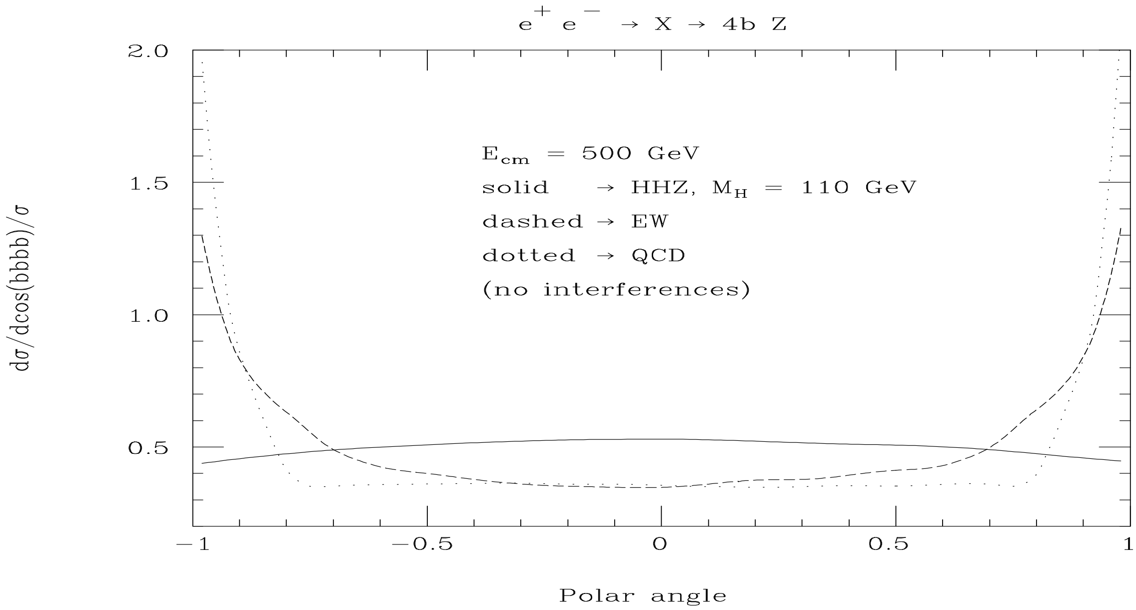
$\Rightarrow$ Need cuts which remove EW background without destroying the already small signal.

Some event shapes

- Most useful: invariant mass of the $b\bar{b}$ pairs must resonate at M_H



- Also exploit the s-channel nature of the signal compared to the t-channel nature of the background.



- Evidenced by the cosine of the angle of the $4b$-system (or alternatively the Z) with respect to the beam axis.

Selection cuts

With these event shapes in mind we introduce the following selection cuts:

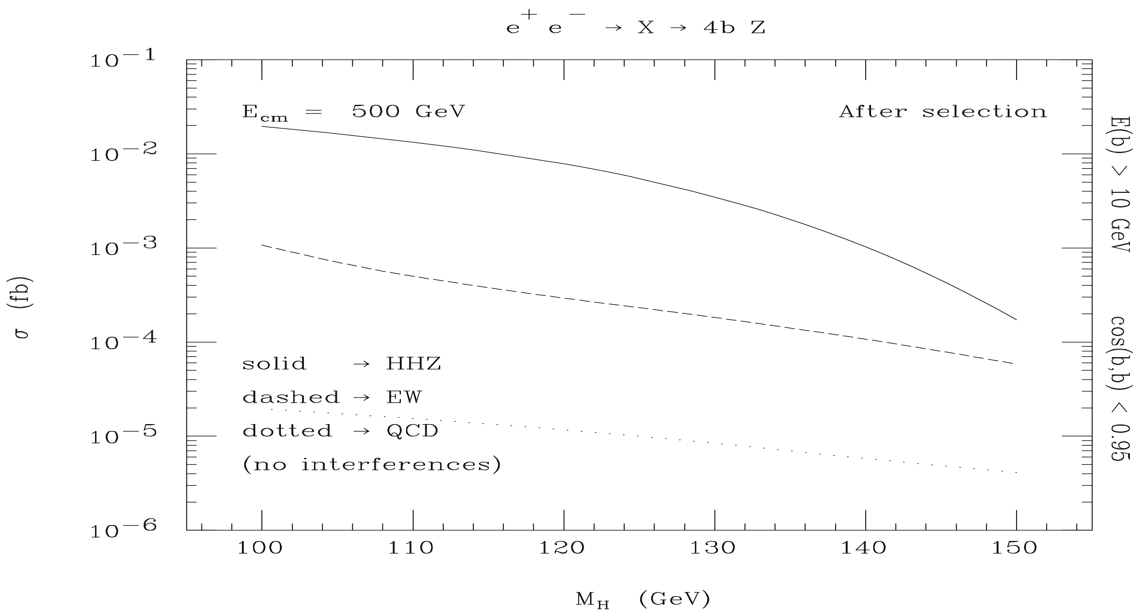
$|M(bb) - M_H| < 5\text{GeV}$ on exactly two combinations of $2b$-systems.

$|M(bb) - M_Z| > 5\text{GeV}$ for all combinations of $2b$-systems.

$$M(bbbb) > 2M_H\text{GeV}$$

$$\cos(2b, 3b, 4b) < 0.75\text{GeV}$$

Results with selection cuts



- The backgrounds have been effectively cut away while the signal has been maintained.

	Events per ab^{-1} after cuts		
	500 GeV	1000 GeV	1500 GeV
signal	26	40	34
Electroweak	1.0	0.6	0.3
Qcd	0.032	0.026	0.016

2. The triple Higgs coupling in the MSSM

- MSSM Higgs sector is much more complicated
- Two isodoublets of Higgs fields ϕ_1 and ϕ_2 $\Rightarrow$

$$V = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - (m_{12}^2\phi_1^\dagger\phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \left\{\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \Big(\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\Big)\,\phi_1^\dagger\phi_2 + h.c.\right\}$$

- Five physical Higgs bosons, h, H, A, $H^\pm$

$\Rightarrow$ Have many triple Higgs couplings!

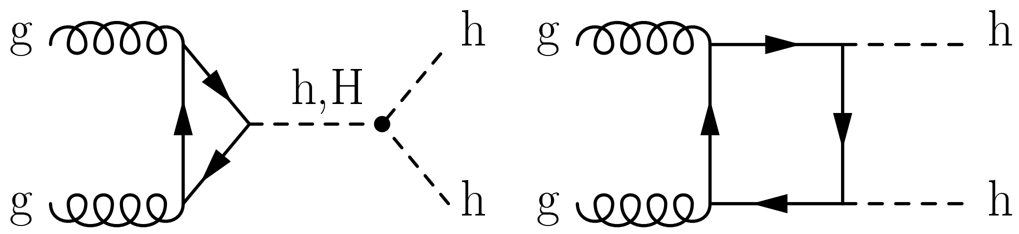
- Most of these couplings inaccessible at the next generation of colliders.
- Exception is the triple Higgs coupling λ_{Hhh}
- λ_{Hhh} can be enhanced by resonant heavy Higgs production with the subsequent decay $H \to hh$.

$$\lambda_{Hhh} = (2\sin 2\alpha \sin(\beta+\alpha)\cos 2\alpha \cos(\beta+\alpha) + 3\frac{\epsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha)\frac{M_Z^2}{v}$$

We must test this prediction.

The MSSM triple Higgs coupling at the LHC

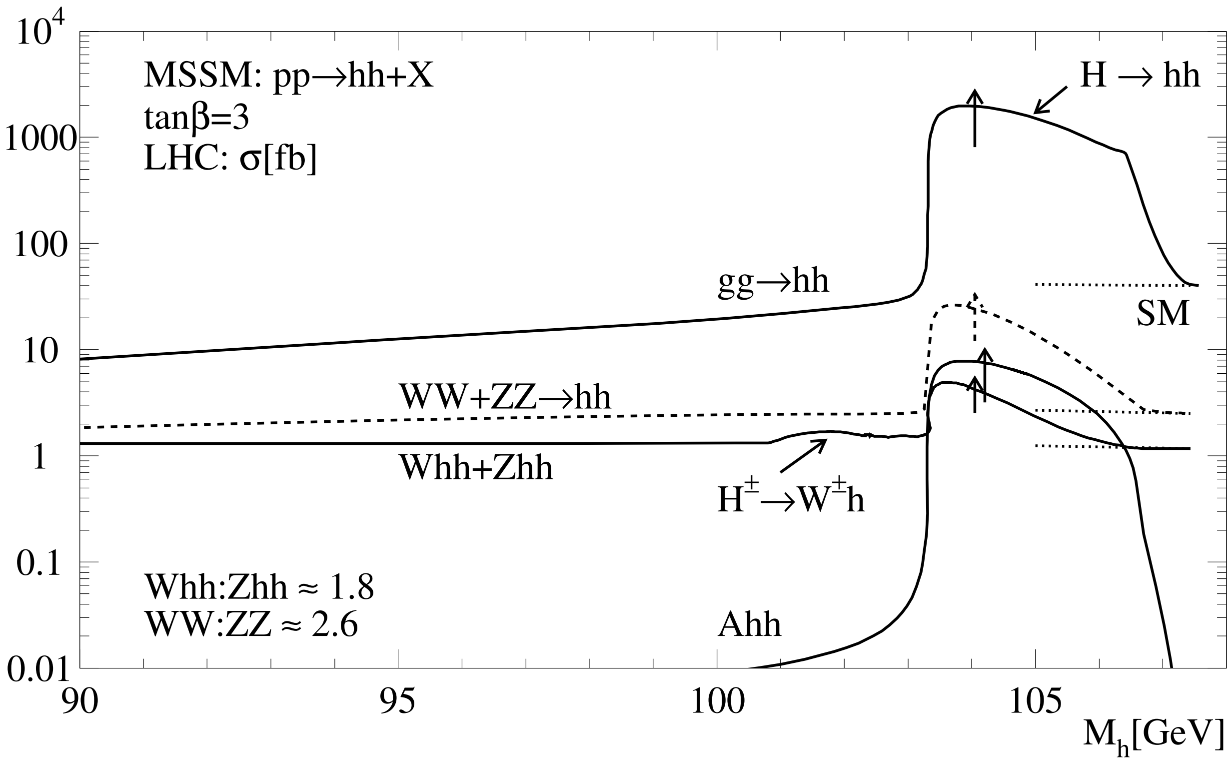
Gluon-gluon fusion:



- $\tan\beta = 3$

Sizable gg cross-sections for M_h around 105GeV.
Good sensitivity to λ_{Hhh}.

Plot curtesy of Djouadi, Kilian, Muhlleitner and Zerwas, `hep-ph/9904287`.

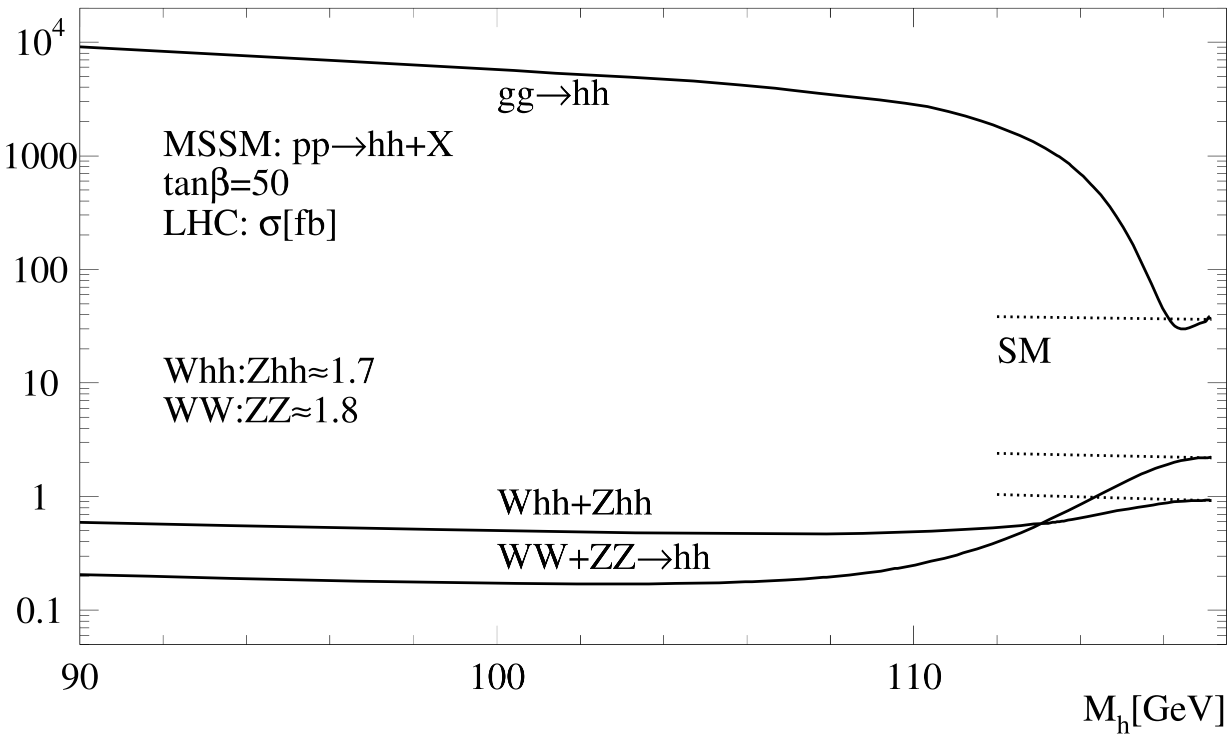


- $\tan\beta = 50$

Sizable gg cross-sections for entire mass region.
Box diagrams dominate

$\Rightarrow$ No sensitivity to λ_{Hhh}.

Plot curtesy of Djouadi, Kilian, Muhlleitner and Zerwas, `hep-ph/9904287`.



- Consider only gg fusion with

$$\tan\beta = 3,$$

$$M_A = 210\text{GeV}.$$

Backgrounds:

As before:

- Decay $h \to b\bar{b}$
- Assume very efficient b tagging.
- Perform the calculation at the parton level.
- No ISR included.

$\Rightarrow$ backgrounds are $q\bar{q}, gg \to b\bar{b}b\bar{b}$ via QCD, EW and QCD/EW processes.

Preliminary cuts:

$$p_T(b) > 30\text{GeV}$$

$$|\eta(b)| < 2.5$$

$$\Delta R(bb) > 0.4$$

(where $\Delta R(ij) = \sqrt{\Delta\eta(ij)^2 + \Delta\phi(ij)^2}$)

$$m(bbbb) \geq 3m_h - 40\text{GeV}$$

$$|m(bb) - m_h| < 20\text{GeV}$$

Find:

Signal: 0.16pb

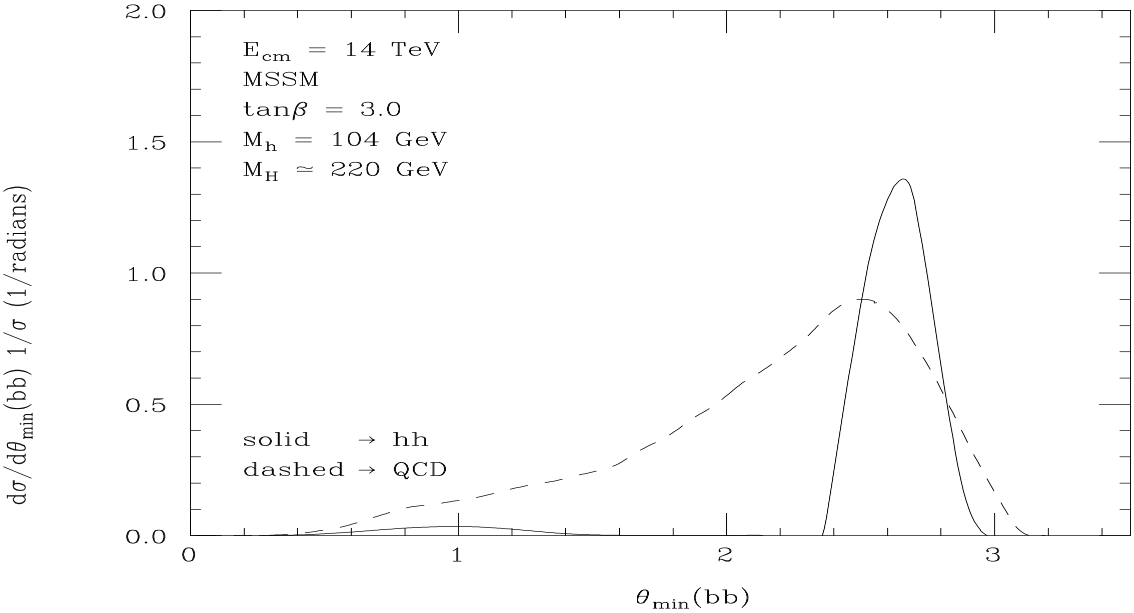
QCD: 7.85pb

EW and QCD/EW backgrounds are negligible.

Event shapes

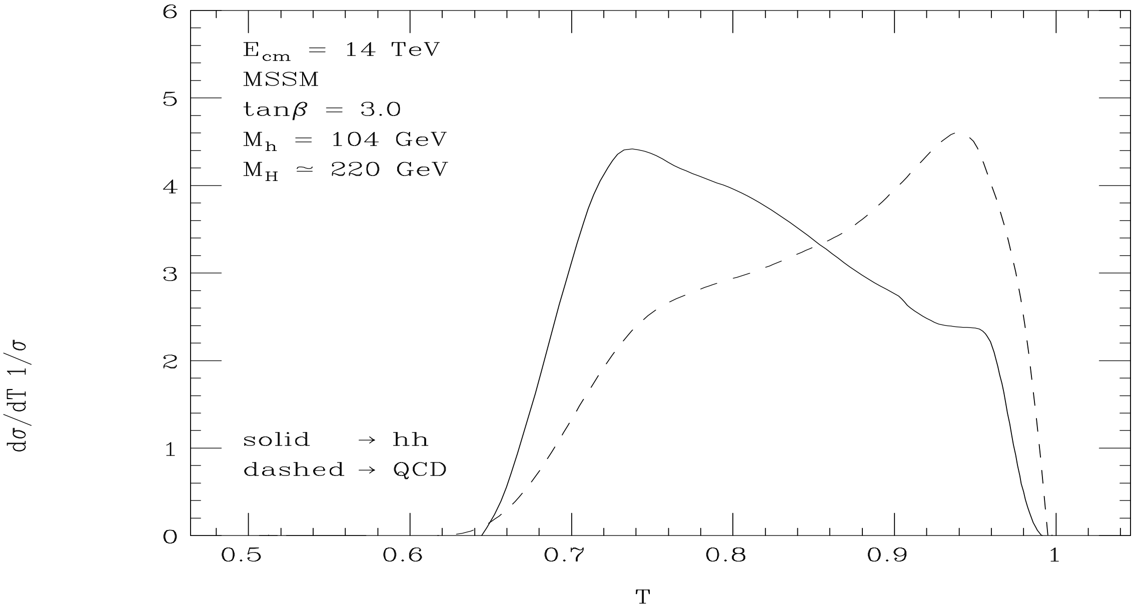
- All event shapes in $4b$ rest frame

Minimum angle between two b-jets reconstructing m_h.



$\Rightarrow$ Make cut $\theta(bb) < 2.5$ radians.

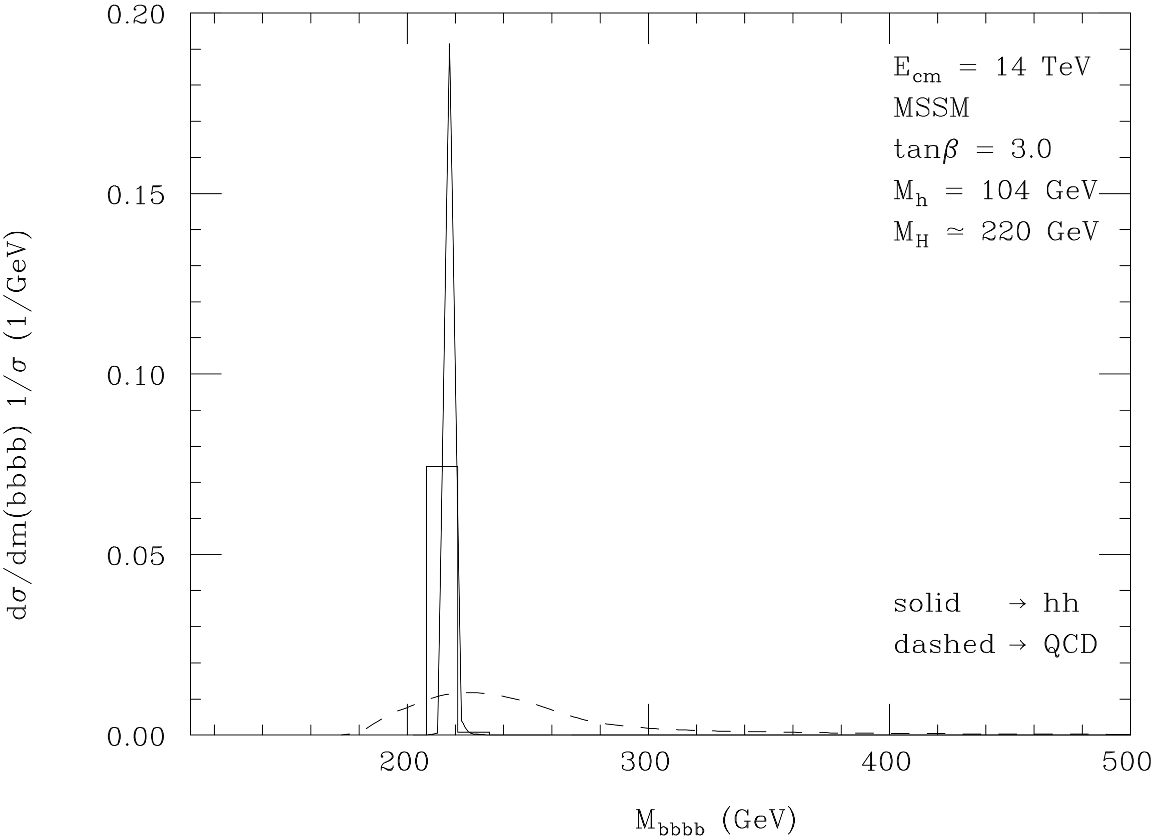
Thrust Distribution.



- b quarks in signal process produced by decaying heavy objects $\Rightarrow$ lower thrust

$\Rightarrow$ Make cut $T < 0.85$.

4b invariant mass



- Very good discriminator due to resonant heavy Higgs
- Histogram shows experimentally realistic 13GeV binning

$\Rightarrow$ Make cut $|m(bbbb) - m_H| < 40$GeV.

Results with selection cuts

Finally,

Signal: 102fb

QCD: 453fb

- If a 10% mass resolution can be achieved, cuts could be tightened to,

$$|m(bb) - m_h| < 10\text{GeV}$$

$$|m(bbbb) - m_H| < 20\text{GeV}$$

giving,

Signal: 126fb

QCD: 174fb

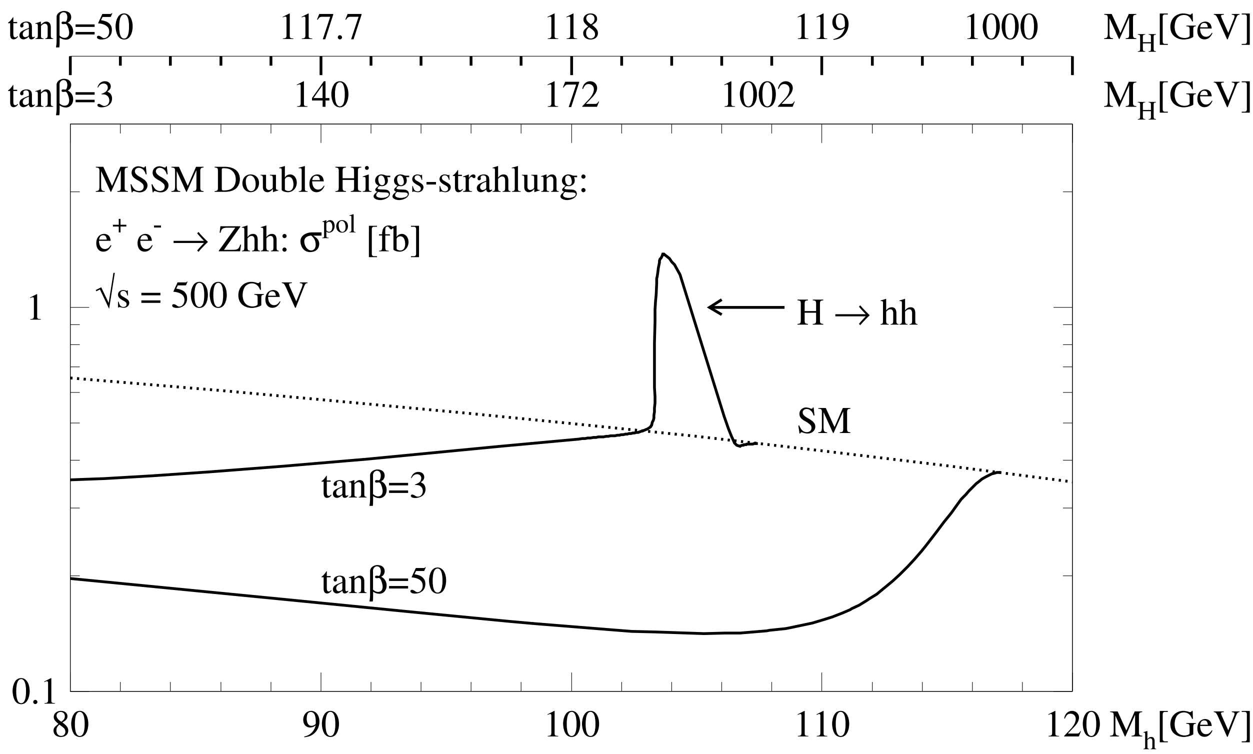
This would be visible at the LHC.

The MSSM triple Higgs coupling at a linear collider

- Very similar to SM

- Most promising channel is double Higgs-strahlung $e^+e^- \to Zhh$.

Plot curtesy of Djouadi, Kilian, Muhlleitner and Zerwas, `hep-ph/9903229`.



- Enhancement due to resonant heavy Higgs production.

- Backgrounds are same as SM case, ie. $e^+e^- \to b\bar{b}b\bar{b}$ via QCD and EW processes.

Make cuts:

Demand b quarks are resolvable:

$$E(b) > 10\text{GeV}.$$

$$\cos\theta(b,b) < 0.95.$$

The $4b$ could originate from a heavy Higgs:

$$m(bbbb) \geq 2m_H - 10\text{GeV}.$$

Exactly two $2b$ combinations reconstruct the light Higgs:

$$|m(bb) - m_h| < 5\text{GeV}.$$

No $2b$ combinations reconstructs the Z boson mass:

$$|m(bb) - m_Z| > 5\text{GeV}.$$

The polar angles of all $(2b, 3b, 4b)$ systems is sufficiently large:

$$|\cos\theta(2b, 3b, 4b)| < 0.75.$$

After these cuts EW and QCD backgrounds become negligible $O(10^{-3})$fb

Consider 2 points in MSSM parameter space:

- $\tan\beta = 3$ and $m_A = 210\text{GeV}$

Signal is 0.312fb yielding 156 events for 500fb^{-1} of data.

- $\tan\beta = 50$ and $m_A = 130\text{GeV}$

Signal is 0.030fb yielding 15 events for 500fb^{-1} of data.

Conclusions

SM conclusions

- The SM triple Higgs coupling will not be measurable at the LHC.

- However, the signal at a 500GeV linear collider will be measurable with very high luminosity.

- QCD and EW irreducible backgrounds at a linear collider can be removed by the kinematical cuts give above.

MSSM conclusions

- If $m_h \approx 105\text{GeV}$ then λ_{Hhh} will be easily measured at both the LHC and a future e^+e^- linear collider.

- Otherwise λ_{Hhh} can be measured at a future e^+e^- linear collider as for the SM provided it has very high luminosity.