Higgs Potential

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LHC, ILC, PLC

Higgs particle(s)

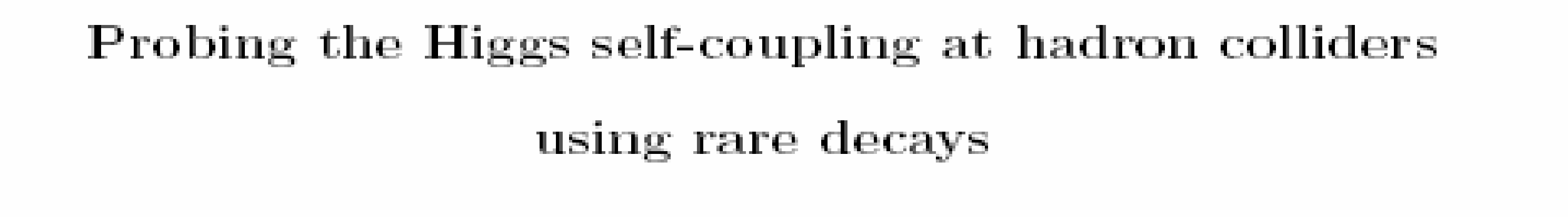
- Mass
- Couplings to gauge bosons, fermions
- Selfcouplings
- Loop couplings
- Total width
- Quantum numbers

Higgs potential:

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4,$$

direct measurements of trilinear and quartic couplings in multi Higgs production $\tilde{\lambda} \leq 8\pi/3$

$$\tilde{\lambda} = \lambda = \lambda_{SM} = \frac{m_H^2}{2v^2} .$$



Probing the Higgs self-coupling at hadron colliders using rare decays

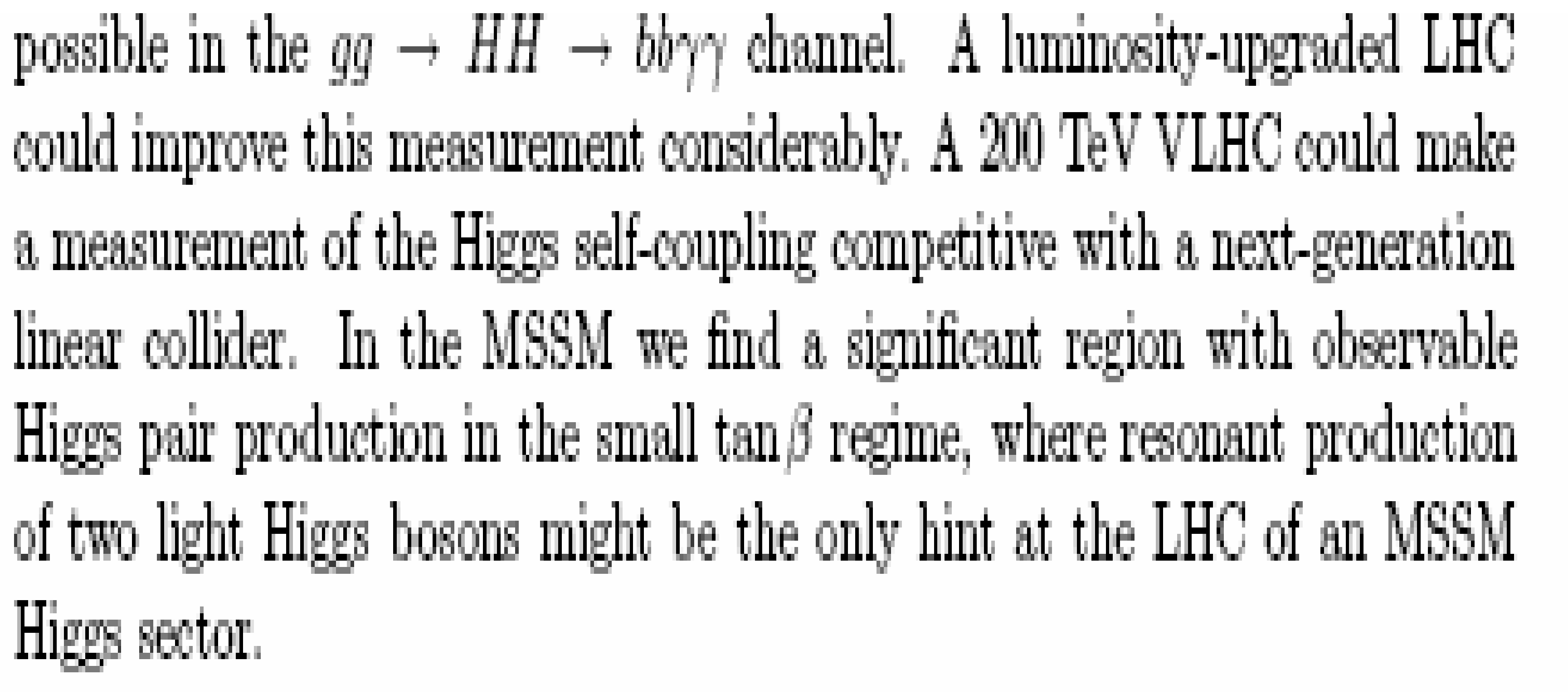
U. Bauer, T. Plehn, D. Rainwater 2004

Mass below 140 GeV

Rare decay of one or two Higgs bosons

- For SM number of events small
- gg -> HH -> b b gamma gamma (with upgrade of Luminosity)

LHC



possible in the $gg \to HH \to bb\gamma\gamma$ channel. A luminosity-upgraded LHC could improve this measurement considerably. A 200 TeV VLHC could make a measurement of the Higgs self-coupling competitive with a next-generation linear collider. In the MSSM we find a significant region with observable Higgs pair production in the small $\tan\beta$ regime, where resonant production of two light Higgs bosons might be the only hint at the LHC of an MSSM Higgs sector.

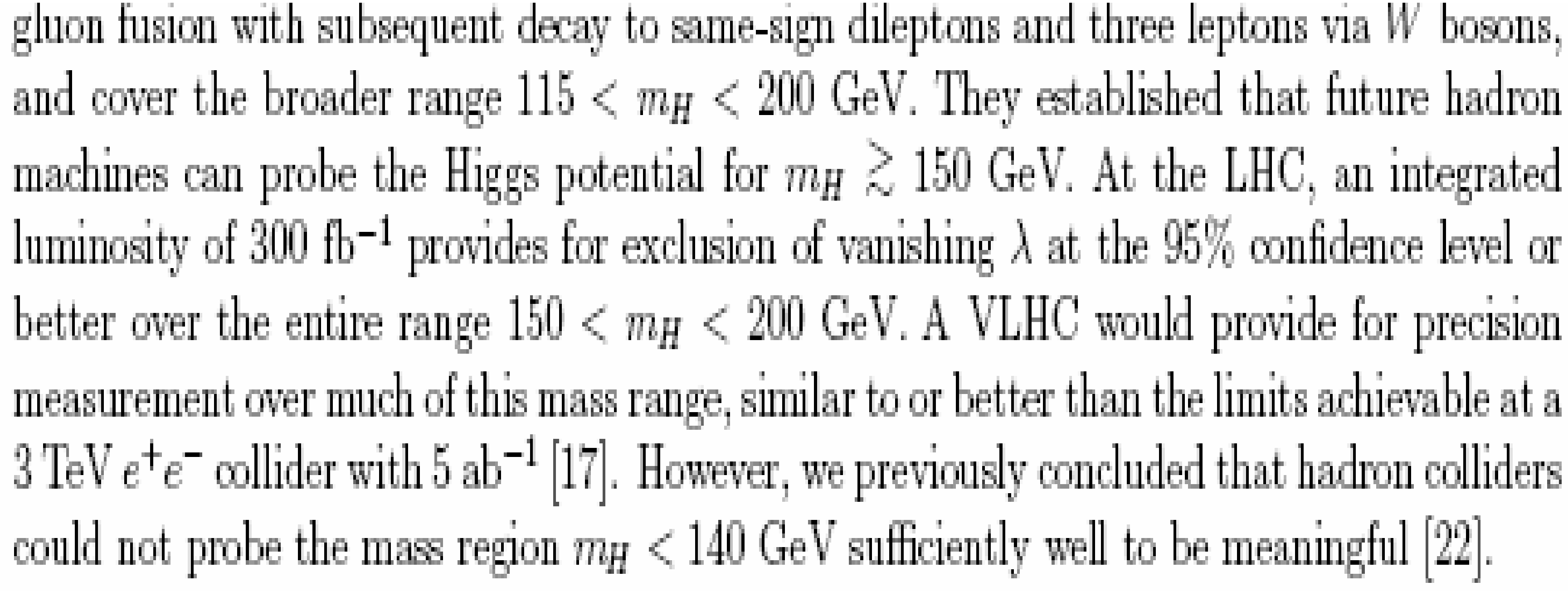
Corrections to lambda

- In SM – rad cor decrease lambda by 11 %
- 2HDM – may increase by 100 %
- MSSM – decrease by 8 % for light stop
- Anomalous couplings in many models

Remark on ILC

- Neural net-based study shows that ILC with integrated Luminosity 1 ab-1 could measure the trilinear Higgs coupling for mass 120 GeV (bb channel) at 20 %, what about mass above 140 GeV? (WW decay channel)

Study for SLHC (10 times LHC first run) and VLHC (200 TeV) Bauer, Plehn,Rainwater'04



gluon fusion with subsequent decay to same-sign dileptons and three leptons via W bosons, and cover the broader range $115 < m_H < 200$ GeV. They established that future hadron machines can probe the Higgs potential for $m_H \gtrsim 150$ GeV. At the LHC, an integrated luminosity of 300 fb^{-1} provides for exclusion of vanishing λ at the 95% confidence level or better over the entire range $150 < m_H < 200$ GeV. A VLHC would provide for precision measurement over much of this mass range, similar to or better than the limits achievable at a 3 TeV e^+e^- collider with 5 ab^{-1} [17]. However, we previously concluded that hadron colliders could not probe the mass region $m_H < 140$ GeV sufficiently well to be meaningful [22].

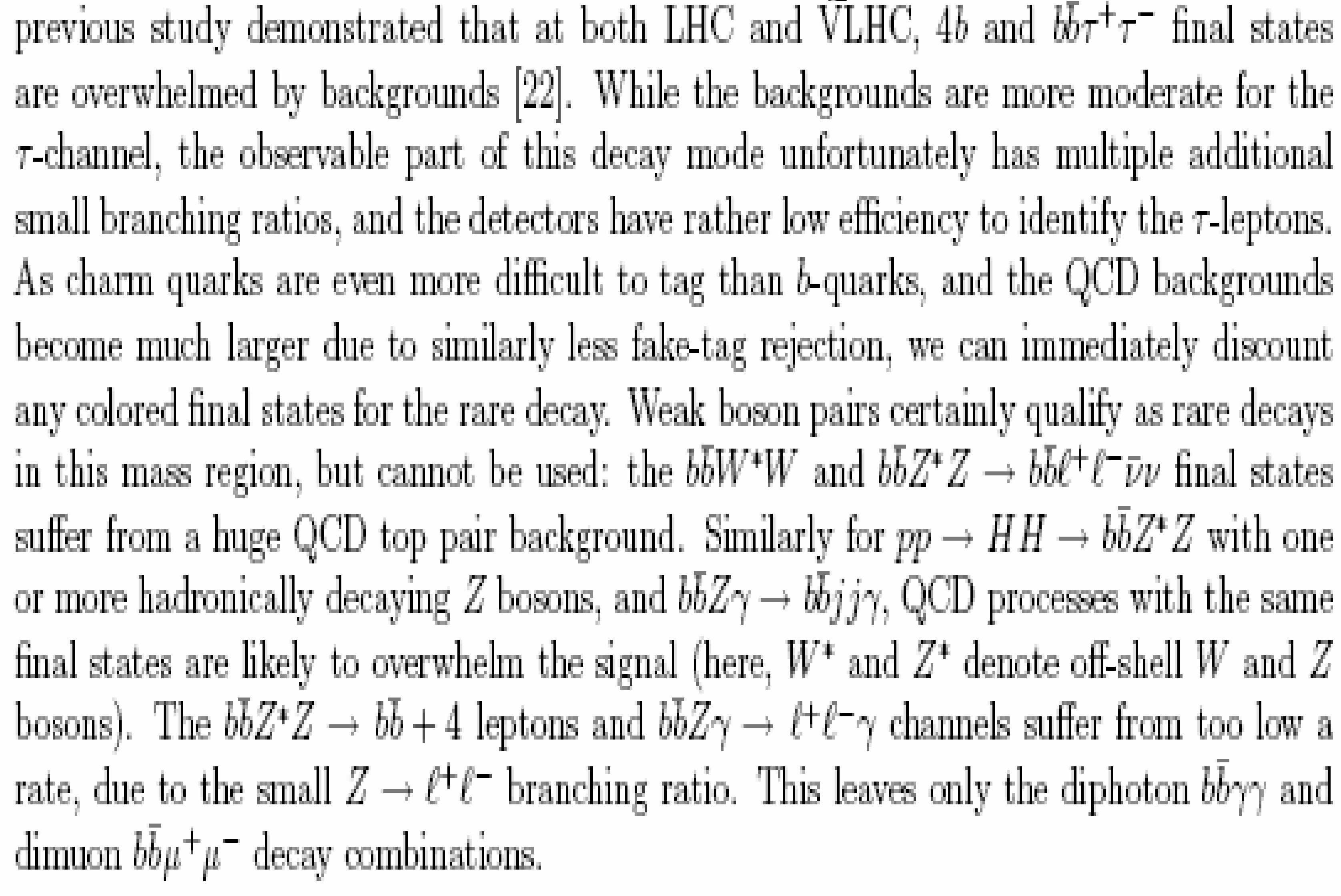
New conclusion using rare decays

- For mass below 140 GeV

- Only gg-> HH relevant
- Only final states containing one b quark

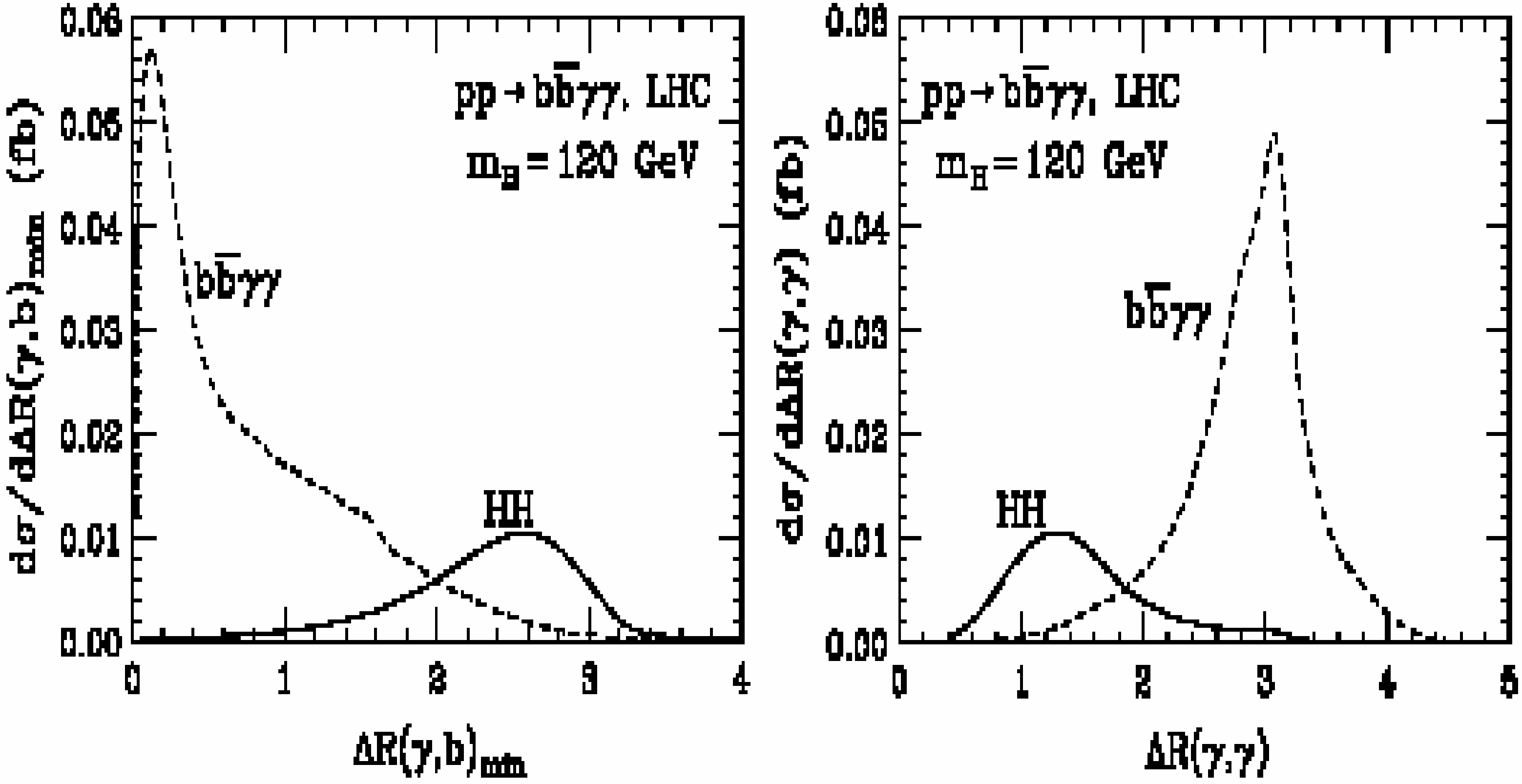
For all our calculations we assume an integrated luminosity of 600 fb^{-1} for the LHC, 6000 fb^{-1} [19] for the SLHC. For the VLHC, we consider both 600 fb^{-1} and 1200 fb^{-1}

Rare decays…

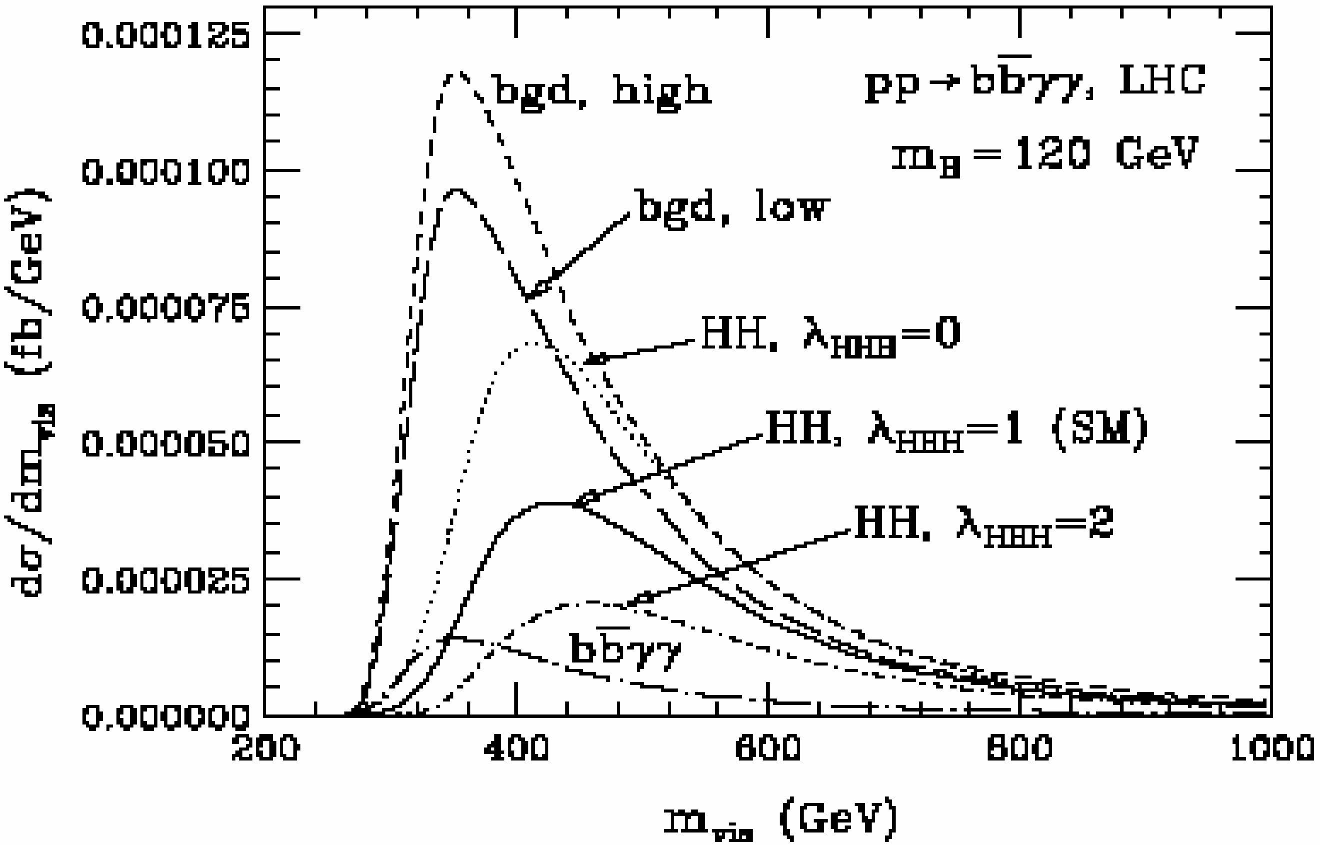


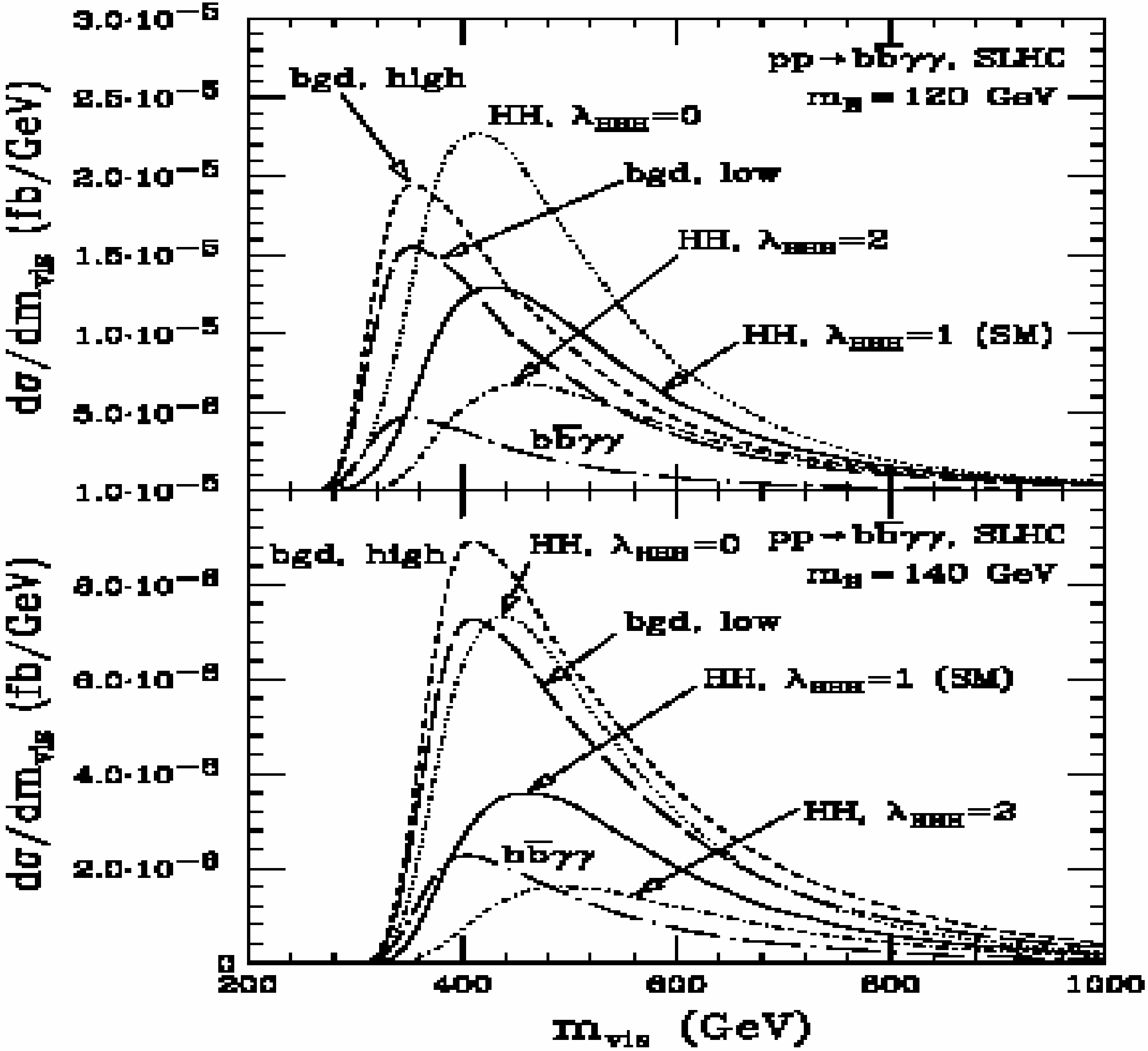
previous study demonstrated that at both LHC and VLHC, $4b$ and $b\bar{b}\tau^+\tau^-$ final states are overwhelmed by backgrounds [22]. While the backgrounds are more moderate for the τ-channel, the observable part of this decay mode unfortunately has multiple additional small branching ratios, and the detectors have rather low efficiency to identify the τ-leptons. As charm quarks are even more difficult to tag than b-quarks, and the QCD backgrounds become much larger due to similarly less fake-tag rejection, we can immediately discount any colored final states for the rare decay. Weak boson pairs certainly qualify as rare decays in this mass region, but cannot be used: the $b\bar{b}W^*W$ and $b\bar{b}Z^*Z \to b\bar{b}\ell^+\ell^-\bar{\nu}\nu$ final states suffer from a huge QCD top pair background. Similarly for $pp \to HH \to b\bar{b}Z^*Z$ with one or more hadronically decaying Z bosons, and $b\bar{b}Z\gamma \to b\bar{b}jj\gamma$, QCD processes with the same final states are likely to overwhelm the signal (here, W^* and Z^* denote off-shell W and Z bosons). The $b\bar{b}Z^*Z \to b\bar{b} + 4$ leptons and $b\bar{b}Z\gamma \to \ell^+\ell^-\gamma$ channels suffer from too low a rate, due to the small $Z \to \ell^+\ell^-$ branching ratio. This leaves only the diphoton $b\bar{b}\gamma\gamma$ and dimuon $b\bar{b}\mu^+\mu^-$ decay combinations.

Figure 2. Distributions of the minimum lego plot (pseudorapidity – transverse plane) separation between (a) b-jets and photons, and (b) the photons, for a SM signal of $m_H = 120$ GeV and the QCD $b\bar{b}\gamma\gamma$ background; using the cuts of Eq. (3) but no minimum $b-\gamma$ separation. We include the NLO K-factor for the signal and a factor 1.3 for the QCD background.



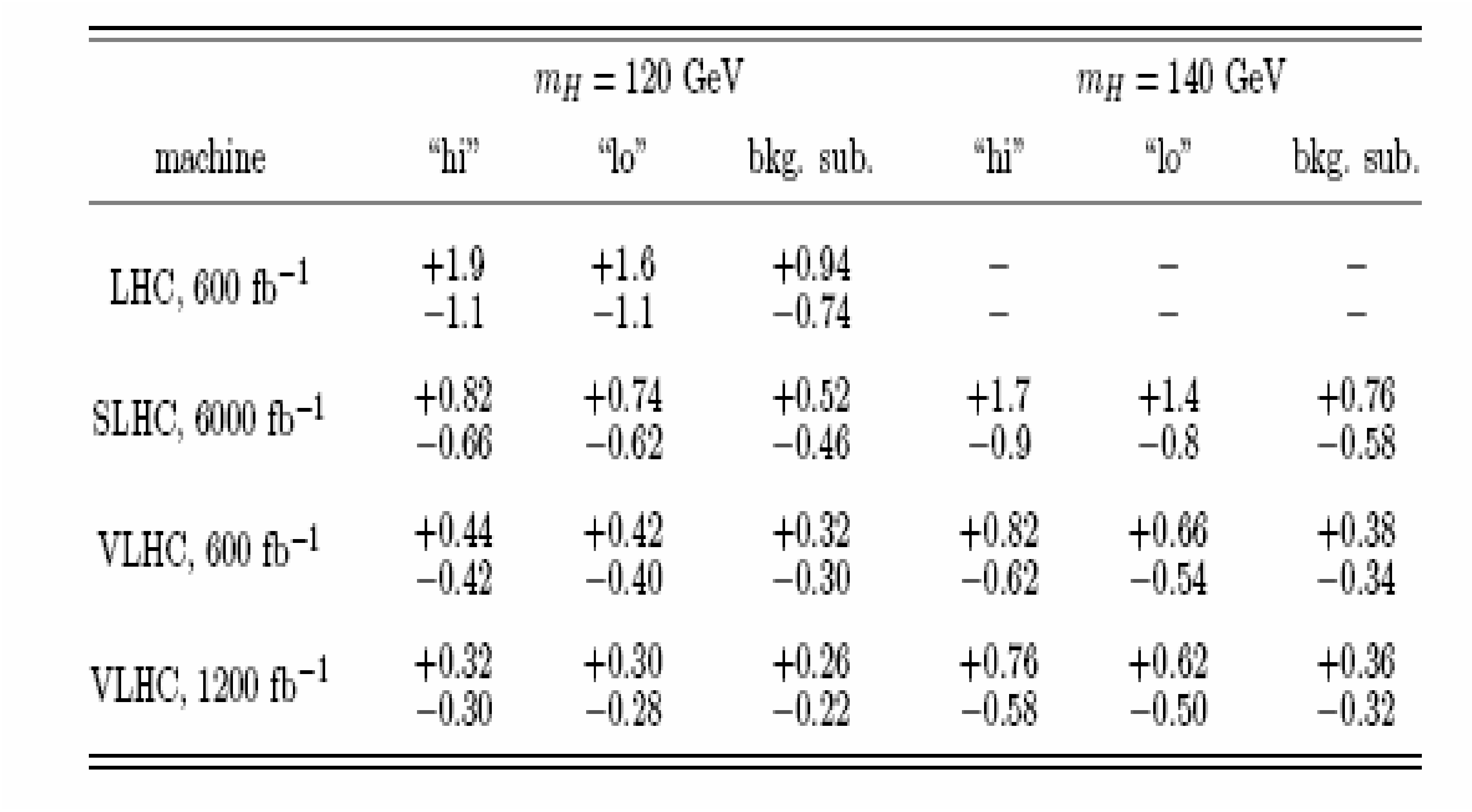
Optimistic and pesimistic cuts




3.0·10^{-5}
2.5·10^{-5}
2.0·10^{-5}
1.5·10^{-5}
1.0·10^{-5}
5.0·10^{-6}
1.0·10^{-5}
$d\sigma/dm_{vis}$ (fb/GeV)
pp → $b\bar{b}\gamma\gamma$, SLHC
m_H = 120 GeV
bgd, high
HH, λ_{HHH}=0
bgd, low
HH, λ_{HHH}=2
HH, λ_{HHH}=1 (SM)
$b\bar{b}\gamma\gamma$
pp → $b\bar{b}\gamma\gamma$, SLHC
m_H = 140 GeV
bgd, high
HH, λ_{HHH}=0
bgd, low
HH, λ_{HHH}=1 (SM)
HH, λ_{HHH}=2
$b\bar{b}\gamma\gamma$
8.0·10^{-6}
6.0·10^{-6}
4.0·10^{-6}
2.0·10^{-6}
0
$d\sigma/dm_{vis}$ (fb/GeV)
200
400
600
800
1000
m_{vis} (GeV)

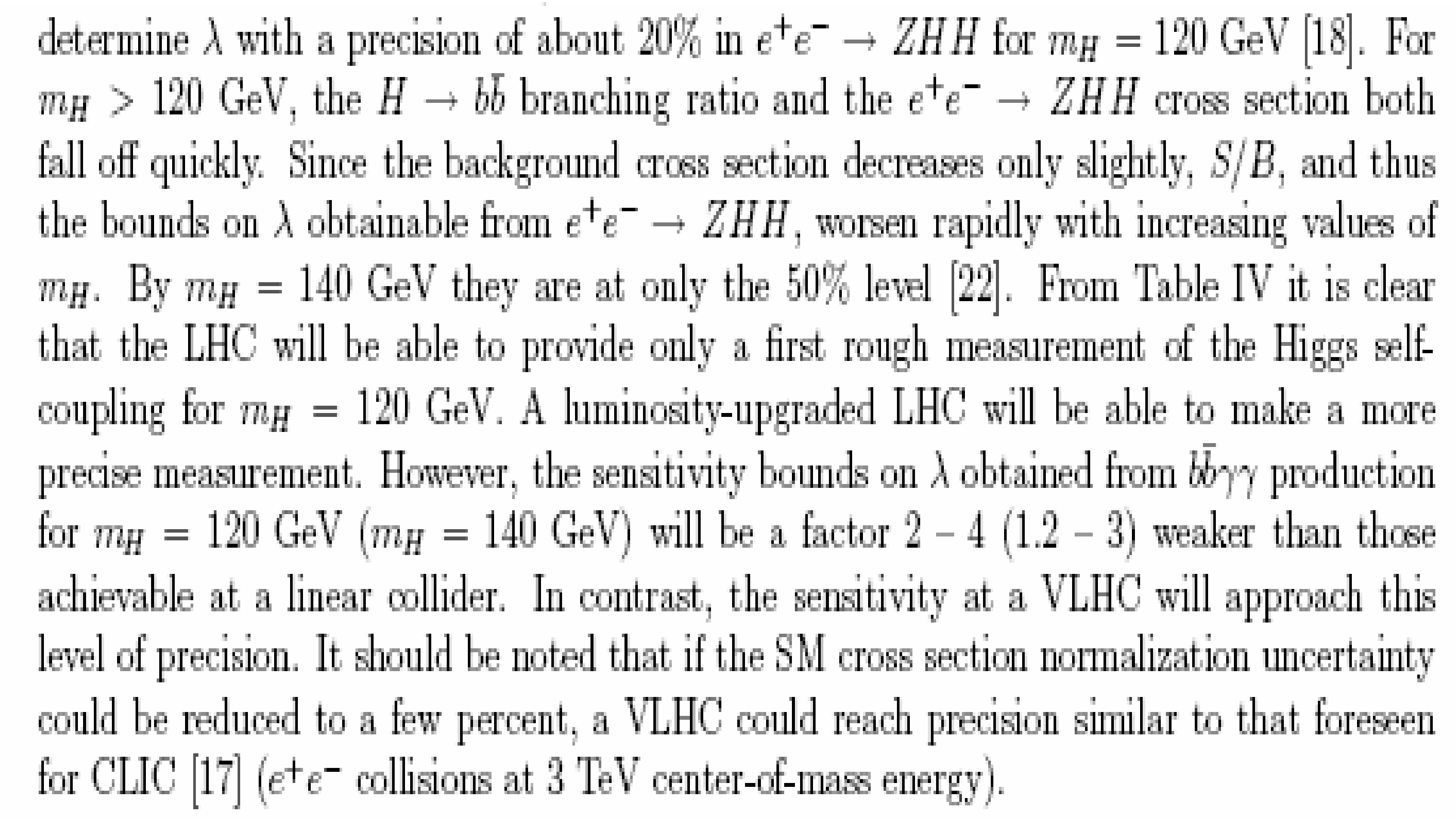
Deviation from SM: $\Delta\lambda=\lambda/\lambda_{SM}-1$

1 sigma limits



	$m_H = 120$ GeV			$m_H = 140$ GeV		
machine	"hi"	"lo"	bkg. sub.	"hi"	"lo"	bkg. sub.
LHC, 600 fb^{-1}	$+1.9$ -1.1	$+1.6$ -1.1	$+0.94$ -0.74	– –	– –	– –
SLHC, 6000 fb^{-1}	$+0.82$ -0.66	$+0.74$ -0.62	$+0.52$ -0.46	$+1.7$ -0.9	$+1.4$ -0.8	$+0.76$ -0.58
VLHC, 600 fb^{-1}	$+0.44$ -0.42	$+0.42$ -0.40	$+0.32$ -0.30	$+0.82$ -0.62	$+0.66$ -0.54	$+0.38$ -0.34
VLHC, 1200 fb^{-1}	$+0.32$ -0.30	$+0.30$ -0.28	$+0.26$ -0.22	$+0.76$ -0.58	$+0.62$ -0.50	$+0.36$ -0.32

Comparison with ILC (500 GeV, 1ab-1)

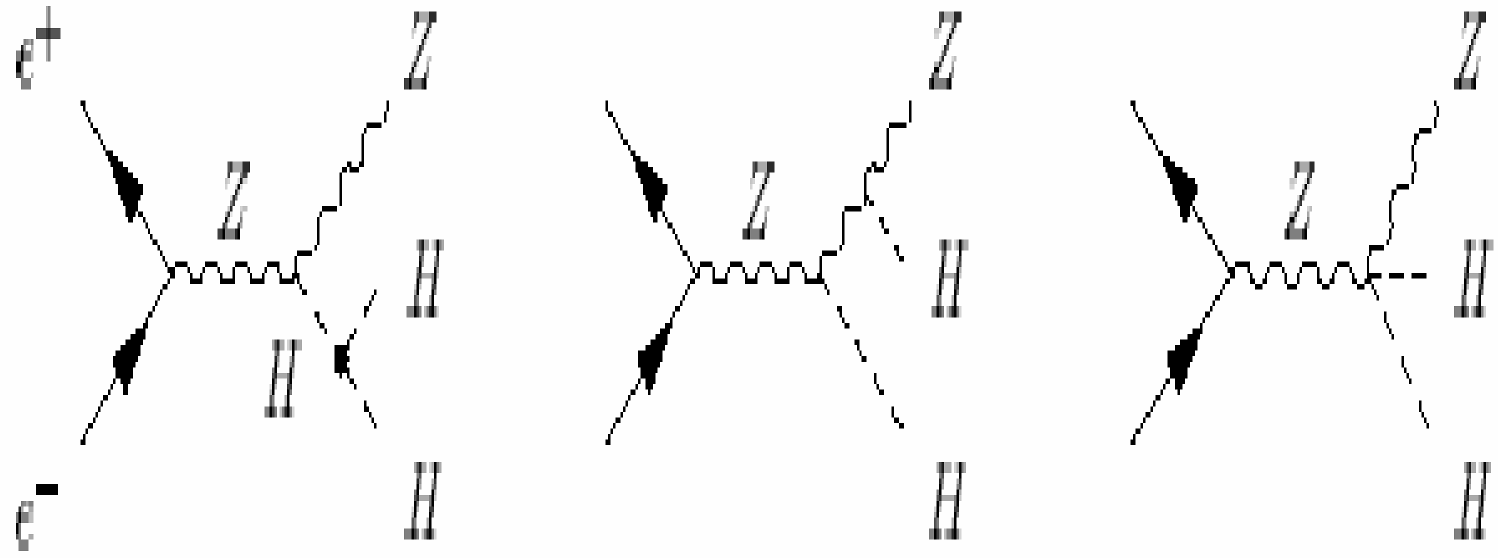


determine λ with a precision of about 20% in $e^+e^- \to ZHH$ for $m_H = 120$ GeV [18]. For $m_H > 120$ GeV, the $H \to b\bar{b}$ branching ratio and the $e^+e^- \to ZHH$ cross section both fall off quickly. Since the background cross section decreases only slightly, S/B, and thus the bounds on λ obtainable from $e^+e^- \to ZHH$, worsen rapidly with increasing values of m_H. By $m_H = 140$ GeV they are at only the 50% level [22]. From Table IV it is clear that the LHC will be able to provide only a first rough measurement of the Higgs self-coupling for $m_H = 120$ GeV. A luminosity-upgraded LHC will be able to make a more precise measurement. However, the sensitivity bounds on λ obtained from $b\bar{b}\gamma\gamma$ production for $m_H = 120$ GeV ($m_H = 140$ GeV) will be a factor $2-4$ ($1.2-3$) weaker than those achievable at a linear collider. In contrast, the sensitivity at a VLHC will approach this level of precision. It should be noted that if the SM cross section normalization uncertainty could be reduced to a few percent, a VLHC could reach precision similar to that foreseen for CLIC [17] (e^+e^- collisions at 3 TeV center-of-mass energy).

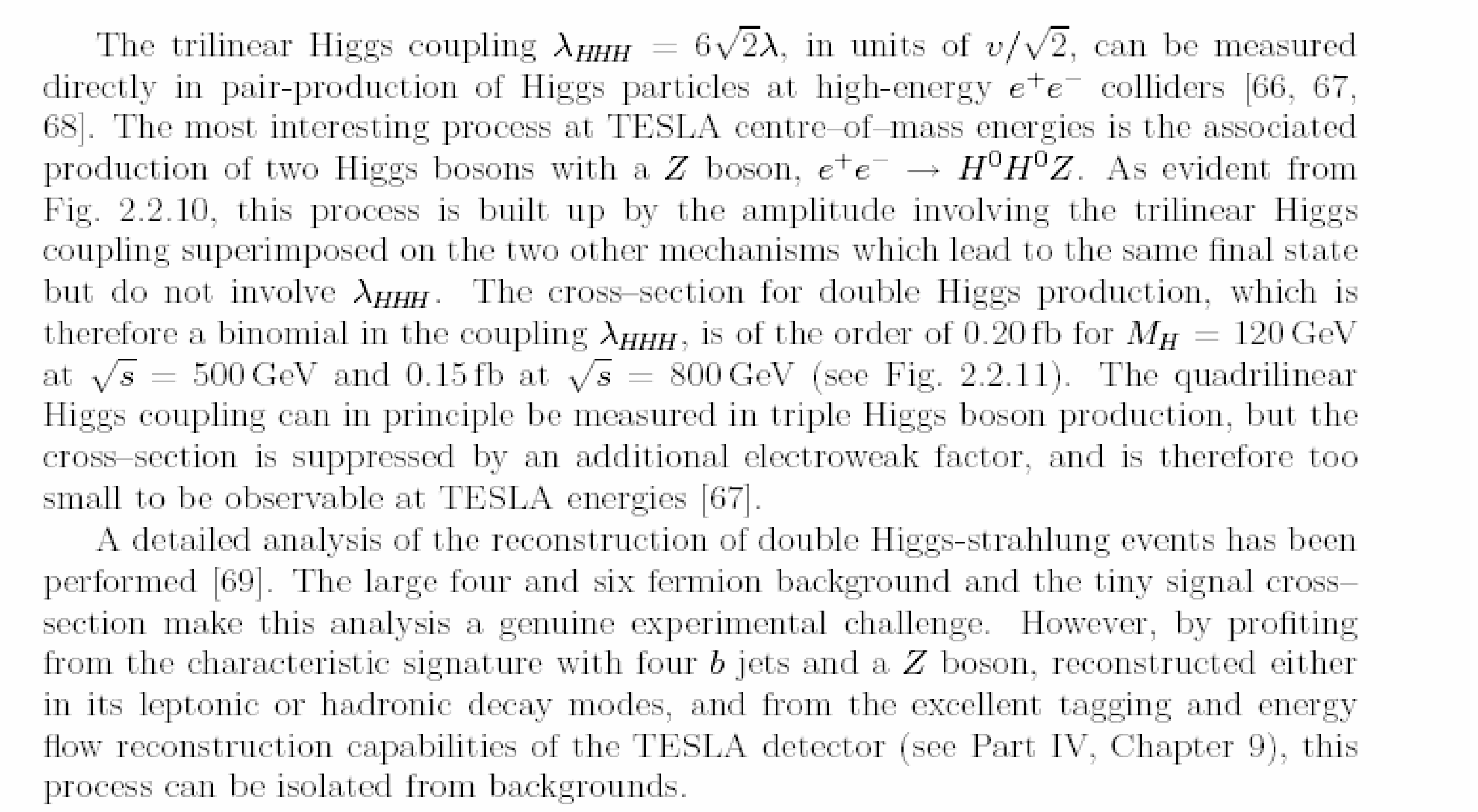
Table 2.2.6: *Relative accuracy on Higgs couplings and their ratios obtained from a global fit (see text). An integrated luminosity of 500 fb*$^{-1}$ *at* $\sqrt{s} = 500$ *GeV is assumed except for the measurement of* g_{Htt}*, which assumes 1000 fb*$^{-1}$ *at* $\sqrt{s} = 800$ *GeV in addition.*

Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
g_{HWW}	± 0.012	± 0.020
g_{HZZ}	± 0.012	± 0.013
g_{Htt}	± 0.030	± 0.061
g_{Hbb}	± 0.022	± 0.022
g_{Hcc}	± 0.037	± 0.102
$g_{H\tau\tau}$	± 0.033	± 0.048
g_{HWW}/g_{HZZ}	± 0.017	± 0.024
g_{Htt}/g_{HWW}	± 0.029	± 0.052
g_{Hbb}/g_{HWW}	± 0.012	± 0.022
$g_{H\tau\tau}/g_{HWW}$	± 0.033	± 0.041
g_{Htt}/g_{Hbb}	± 0.026	± 0.057
g_{Hcc}/g_{Hbb}	± 0.041	± 0.100
$g_{H\tau\tau}/g_{Hbb}$	± 0.027	± 0.042

HH production at ILC



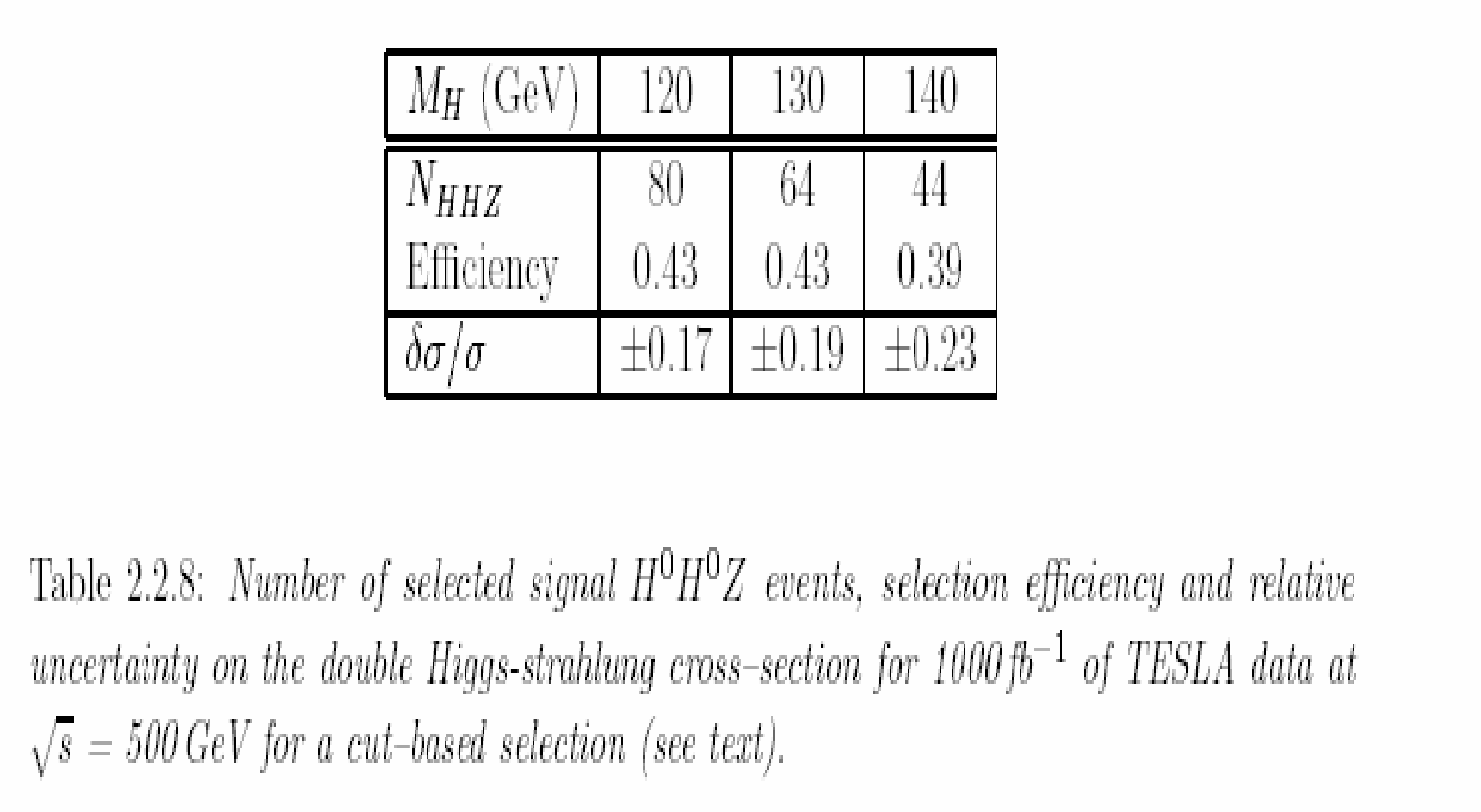
ILC – HHH coupling



The trilinear Higgs coupling $\lambda_{HHH} = 6\sqrt{2}\lambda$, in units of $v/\sqrt{2}$, can be measured directly in pair-production of Higgs particles at high-energy e^+e^- colliders [66, 67, 68]. The most interesting process at TESLA centre–of–mass energies is the associated production of two Higgs bosons with a Z boson, $e^+e^- \rightarrow H^0H^0Z$. As evident from Fig. 2.2.10, this process is built up by the amplitude involving the trilinear Higgs coupling superimposed on the two other mechanisms which lead to the same final state but do not involve λ_{HHH}. The cross–section for double Higgs production, which is therefore a binomial in the coupling λ_{HHH}, is of the order of 0.20 fb for $M_H = 120$ GeV at $\sqrt{s} = 500$ GeV and 0.15 fb at $\sqrt{s} = 800$ GeV (see Fig. 2.2.11). The quadrilinear Higgs coupling can in principle be measured in triple Higgs boson production, but the cross–section is suppressed by an additional electroweak factor, and is therefore too small to be observable at TESLA energies [67].

A detailed analysis of the reconstruction of double Higgs-strahlung events has been performed [69]. The large four and six fermion background and the tiny signal cross–section make this analysis a genuine experimental challenge. However, by profiting from the characteristic signature with four b jets and a Z boson, reconstructed either in its leptonic or hadronic decay modes, and from the excellent tagging and energy flow reconstruction capabilities of the TESLA detector (see Part IV, Chapter 9), this process can be isolated from backgrounds.

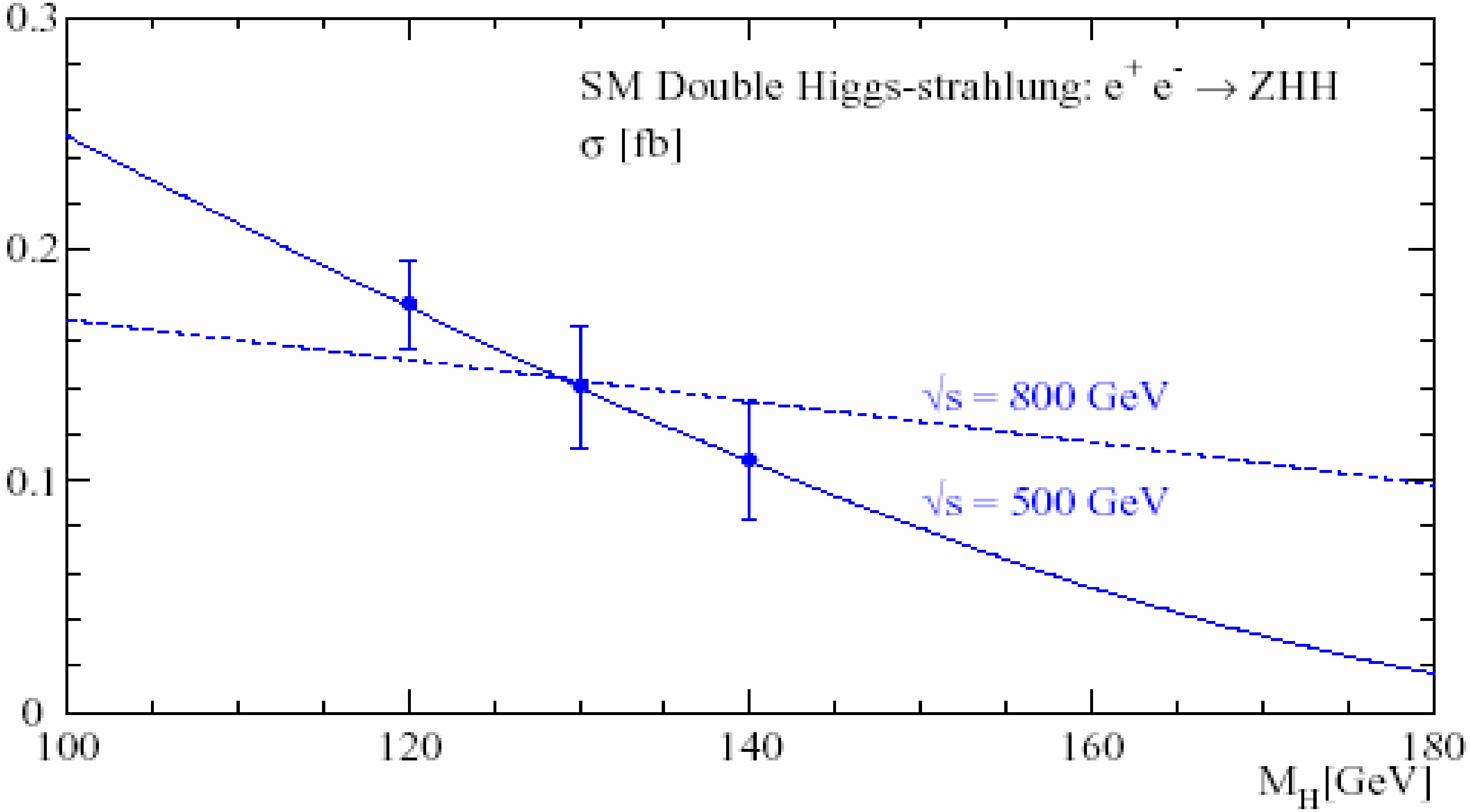
Number of events



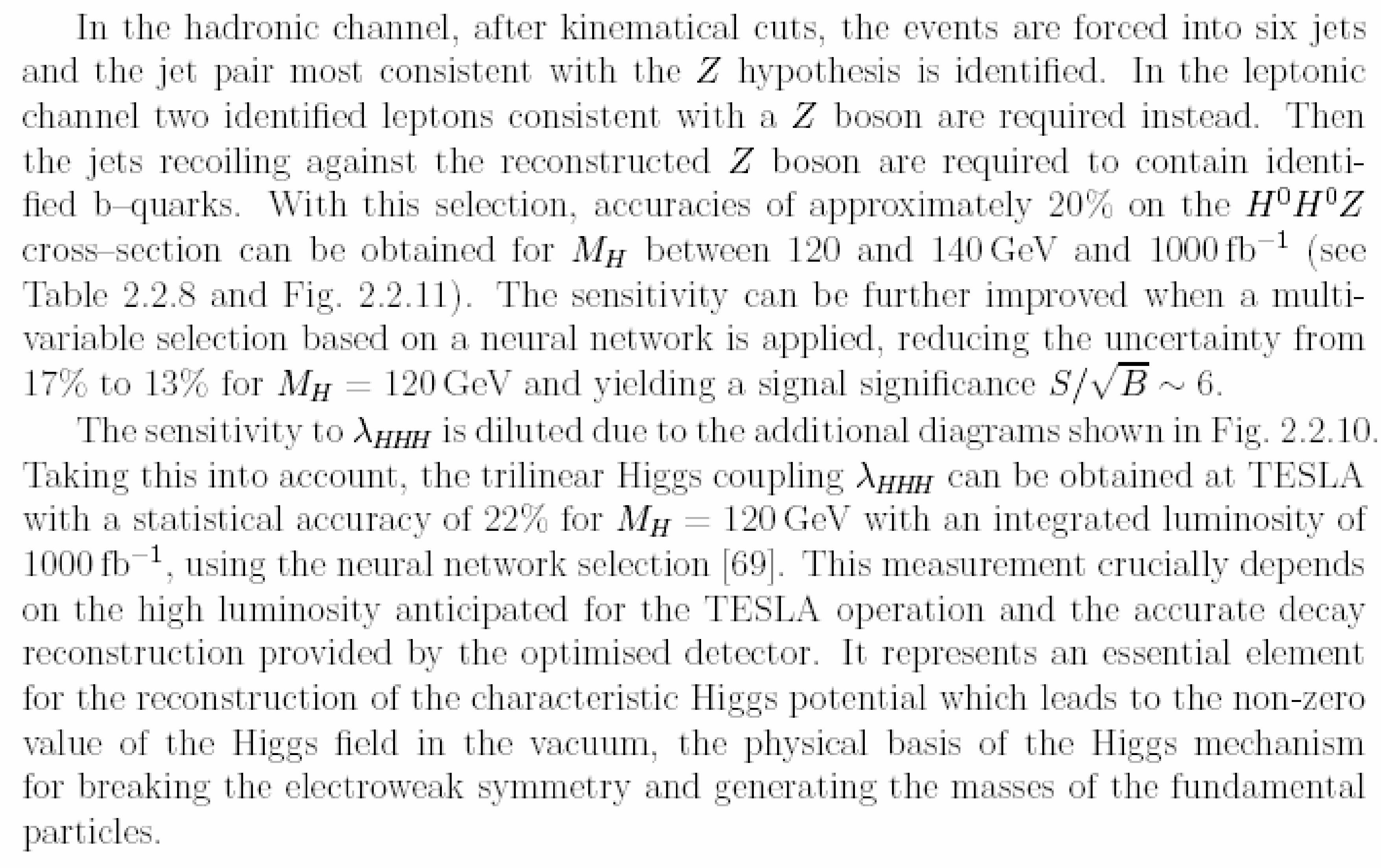
M_H (GeV)	120	130	140
N_{HHZ}	80	64	44
Efficiency	0.43	0.43	0.39
$\delta\sigma/\sigma$	±0.17	±0.19	±0.23

Table 2.2.8: *Number of selected signal H^0H^0Z events, selection efficiency and relative uncertainty on the double Higgs-strahlung cross–section for $1000\,fb^{-1}$ of TESLA data at $\sqrt{s} = 500\,GeV$ for a cut–based selection (see text).*

Figure 2.2.11: *The cross–section for double Higgs-strahlung $e^+e^- \to ZHH$ in the Standard Model at two collider energies: $\sqrt{s} = 500\,GeV$ and $800\,GeV$. The dots with error bars show the achievable experimental accuracies for $1000\,fb^{-1}$ (see text).*



ILC - conclusions

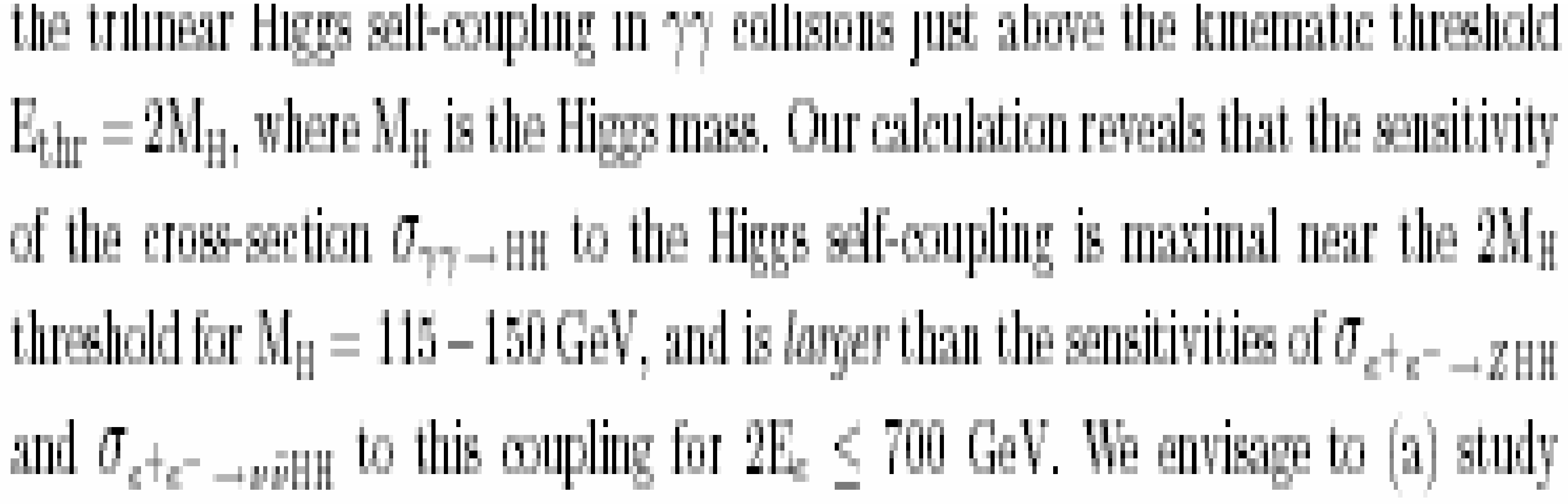


In the hadronic channel, after kinematical cuts, the events are forced into six jets and the jet pair most consistent with the Z hypothesis is identified. In the leptonic channel two identified leptons consistent with a Z boson are required instead. Then the jets recoiling against the reconstructed Z boson are required to contain identified b–quarks. With this selection, accuracies of approximately 20% on the H^0H^0Z cross–section can be obtained for M_H between 120 and 140 GeV and $1000\,\mathrm{fb}^{-1}$ (see Table 2.2.8 and Fig. 2.2.11). The sensitivity can be further improved when a multi-variable selection based on a neural network is applied, reducing the uncertainty from 17% to 13% for $M_H = 120\,\mathrm{GeV}$ and yielding a signal significance $S/\sqrt{B} \sim 6$.

The sensitivity to λ_{HHH} is diluted due to the additional diagrams shown in Fig. 2.2.10. Taking this into account, the trilinear Higgs coupling λ_{HHH} can be obtained at TESLA with a statistical accuracy of 22% for $M_H = 120\,\mathrm{GeV}$ with an integrated luminosity of $1000\,\mathrm{fb}^{-1}$, using the neural network selection [69]. This measurement crucially depends on the high luminosity anticipated for the TESLA operation and the accurate decay reconstruction provided by the optimised detector. It represents an essential element for the reconstruction of the characteristic Higgs potential which leads to the non-zero value of the Higgs field in the vacuum, the physical basis of the Higgs mechanism for breaking the electroweak symmetry and generating the masses of the fundamental particles.

Higgs selfcouplings at PLC

R. Belusevic and G. Jikia, **Phys.Rev.D70:073017,2004**.



the trilinear Higgs self-coupling in $\gamma\gamma$ collisions just above the kinematic threshold $E_{\rm thr} = 2M_H$, where M_H is the Higgs mass. Our calculation reveals that the sensitivity of the cross-section $\sigma_{\gamma\gamma\to HH}$ to the Higgs self-coupling is maximal near the $2M_H$ threshold for $M_H = 115 - 150$ GeV, and is *larger* than the sensitivities of $\sigma_{e^+e^-\to ZHH}$ and $\sigma_{e^+e^-\to\nu\bar{\nu}HH}$ to this coupling for $2E_e \leq 700$ GeV. We envisage to (a) study

$$\bar{\lambda}_{HHH} = (1 + \delta\kappa)\lambda_{HHH}$$

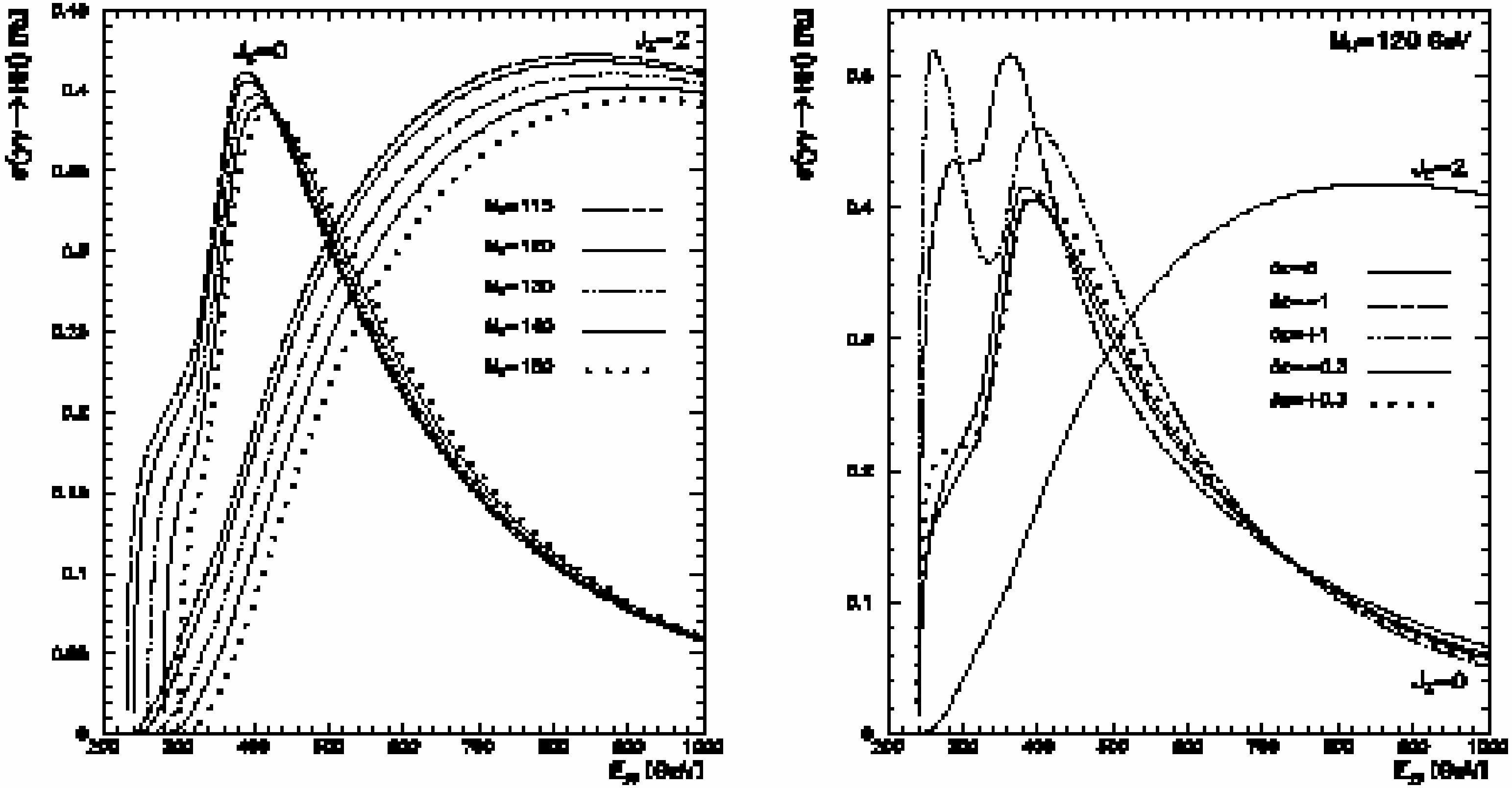
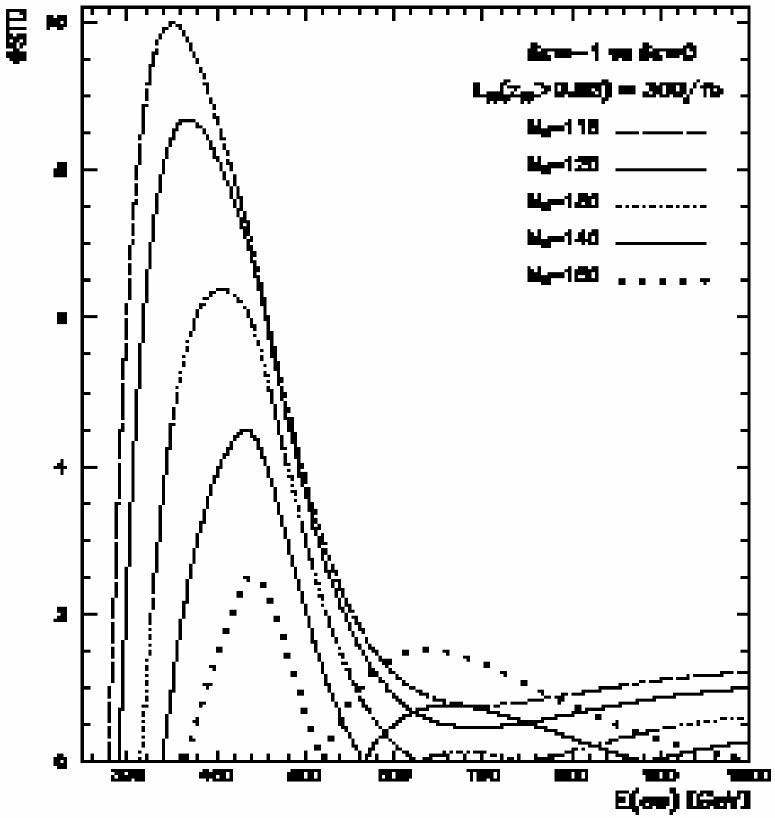
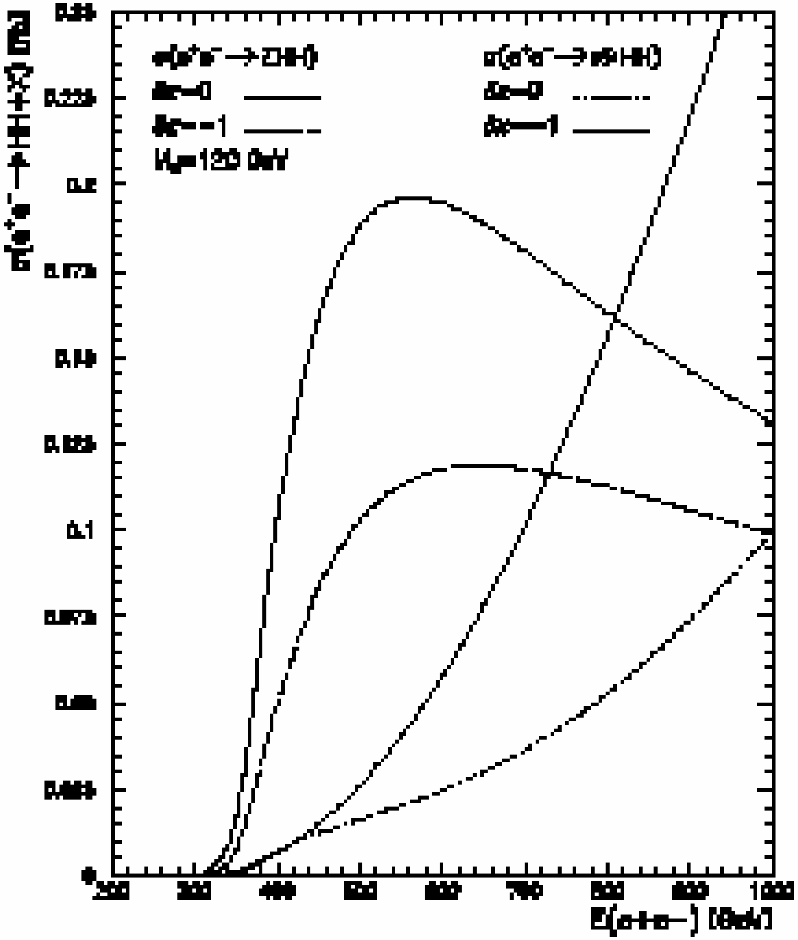


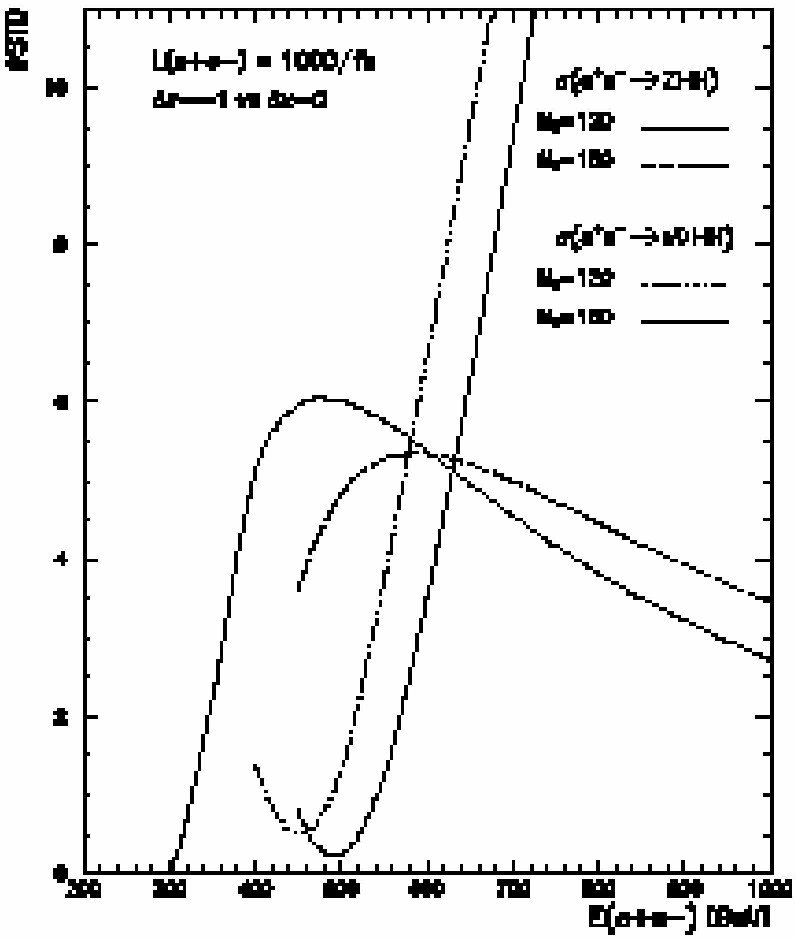
Figure 1: (a) The total $\gamma\gamma \to HH$ cross-section as a function of the $\gamma\gamma$ centre-of-mass energy for M_H=115, 120, 130, 140 and 150 GeV. Contributions for equal ($J_z = 0$) and opposite ($J_z = 2$) photon helicities are shown separately.
(b) The cross-sections for HH production in $\gamma\gamma$ collisions for anomalous trilinear Higgs self-couplings $\delta\kappa = 0, \pm 1, \pm 0.3$.

Figure 2: For the process $\gamma\gamma \to HH$, the number of standard deviations from the SM prediction for event rates, defined by Eq. (28), is plotted as a function of the e^-e^- centre-of-mass energy assuming a $\gamma\gamma$ luminosity $L_{\gamma\gamma} = 300$ fb^{-1}.

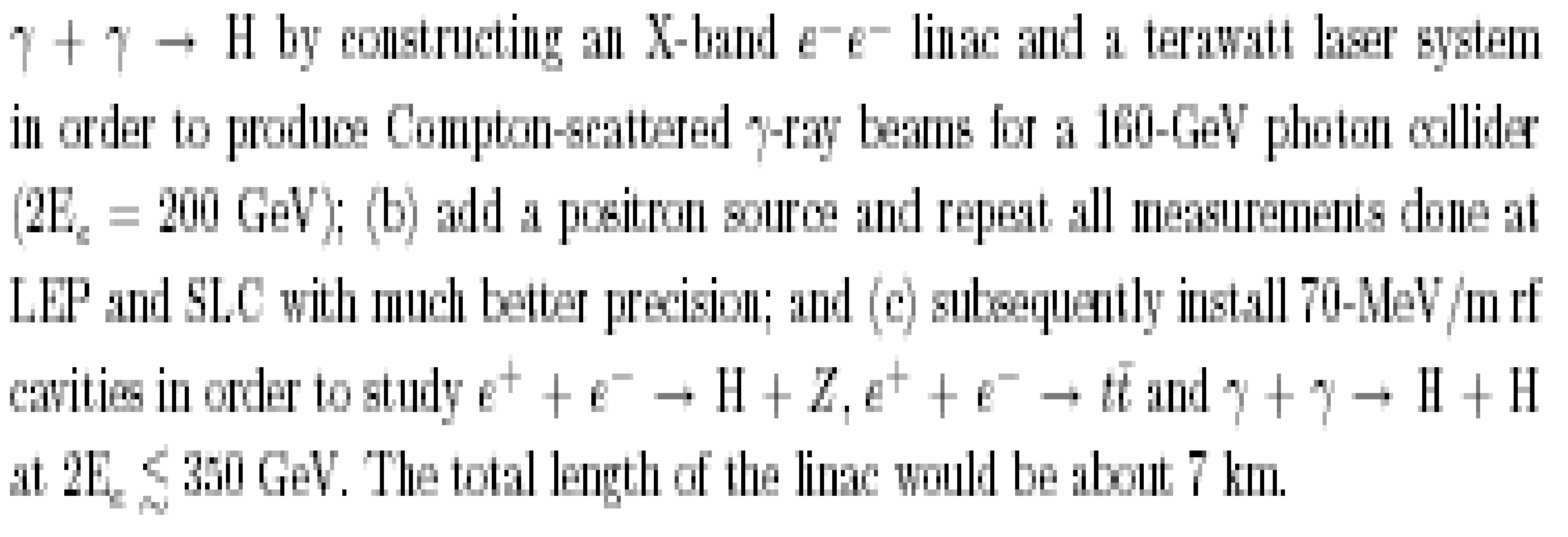


e+e→ZHH and nu nu HH for mass 120 GeV (d=0,-1) Lumi=1000fb-1





Proposal: 160 GeV PLC



$\gamma + \gamma \rightarrow$ H by constructing an X-band $e^- e^-$ linac and a terawatt laser system in order to produce Compton-scattered γ-ray beams for a 160-GeV photon collider ($2E_e = 200$ GeV); (b) add a positron source and repeat all measurements done at LEP and SLC with much better precision; and (c) subsequently install 70-MeV/m rf cavities in order to study $e^+ + e^- \rightarrow H + Z$, $e^+ + e^- \rightarrow t\bar{t}$ and $\gamma + \gamma \rightarrow H + H$ at $2E_e \lesssim 350$ GeV. The total length of the linac would be about 7 km.

Higgs Potential

- Further studies needed

- For PLC – one ongoing analysis
- For LHC ?