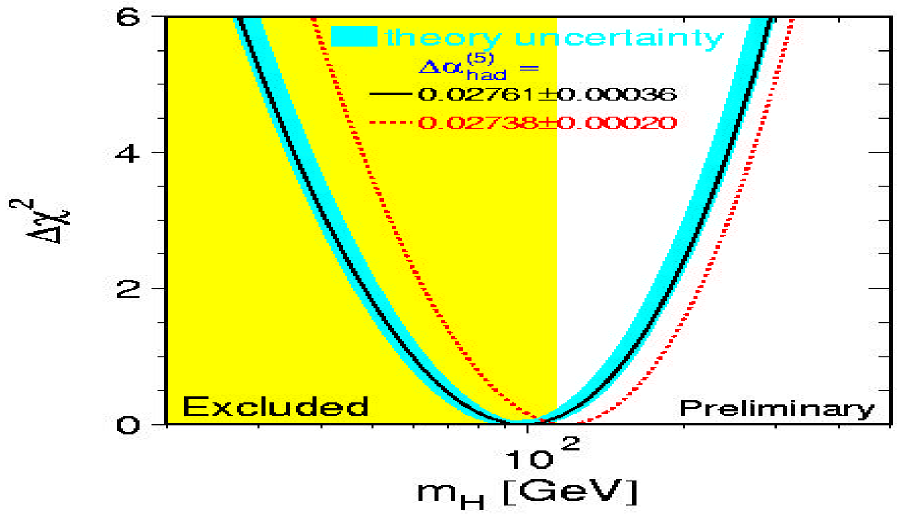
The Standard Model Higgs at the Linear Collider

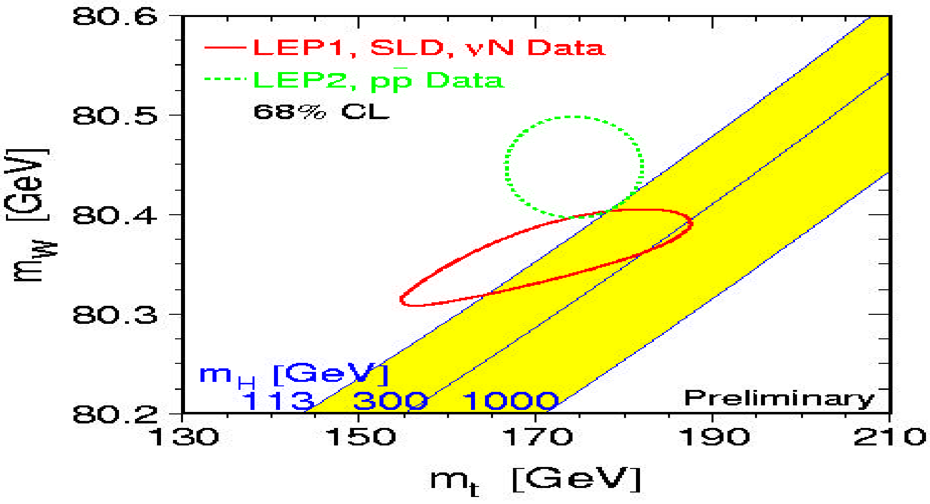
The LHC (or the Tevatron) should initiate the experimental measurement of the particle(s) associated with EWSB

These first discoveries will likely provide a limited view of the nature of the Higgs

A Linear Collider will be a crucial tool in advancing the understanding that the LHC / Tevatron begins

Indications for a Low Mass Standard Model Higgs





(SM) M_{higgs} < 190 GeV at 90% CL.
LEP2 limit M_{higgs} > 113.5 GeV.
Tevatron can discover up to 180 GeV

W mass (±34 MeV)
and top mass (±5 GeV)
agree with precision measures
and indicate low SM Higgs mass

LEP Higgs search – Maximum Likelihood for Higgs signal at m_H = 115.0 GeV with overall significance (4 experiments) = 2.9σ

Establishing <u>Standard Model</u> Higgs

precision **studies of the Higgs boson will be required to understand Electroweak Symmetry Breaking; just finding the Higgs is of limited value**

> **(we may learn at LHC that our precision measurements of the Z have anticipated the Higgs mass (as they did for the top),**
> **but what else?**
> **We need to measure the <u>full</u> nature of the Higgs to understand EWSB)**

The 500 GeV (and beyond) Linear Collider is the tool needed to complete these ***precision*** **studies**

References:

TESLA Technical Design Report
Linear Collider Physics Resource Book for Snowmass 2001
(contain references to many studies)

The next Linear Collider

The next Linear Collider proposals include plans to deliver a <u>few hundred fb^{-1}</u> of integrated lum. per year

		TESLA	JLC-C	NLC/JLC-X *
L_{design}	(10^{34})	3.4 → 5.8	0.43	2.2 → 3.4
E_{CM}	(GeV)	500 → 800	500	500 → 1000
Eff. Gradient	(MV/m)	23.4 → 35	34	70
RF freq.	(GHz)	1.3	5.7	11.4
Δt_{bunch}	(ns)	337 → 176	2.8	1.4
#bunch/train		2820 → 4886	72	190
Beamstrahlung	(%)	3.2 → 4.4		4.6 → 8.8

* US and Japanese X-band R&D cooperation, but machine parameters may differ

We can plan for 500 fb^{-1} in a few years, and 1000 fb^{-1} within about five years

The next Linear Collider

Standard Package:

e^+e^- **Collisions**

Initially at 500 GeV

Electron Polarization, ≥ 80%

Options:

Energy upgrades to ~ 1.0 -1.5 TeV

Positron Polarization

$\gamma\gamma$ **Collisions**

e^-e^- **and** $e^-\gamma$ **Collisions**

Giga-Z (precision measurements)

Special Advantages of Experimentation at the Linear Collider

Elementary interactions at known E_{cm}*

eg. $e^+e^- \rightarrow ZH$

Democratic Cross sections

eg. $\sigma(e^+e^- \rightarrow ZH) \sim 1/2\, \sigma(e^+e^- \rightarrow d\bar{d})$

Inclusive Trigger

total cross section

Highly Polarized Electron Beam

~ 80%

Exquisite vertex detection

eg. $R_{beampipe} \sim 1$ cm

$\sigma_{hit} \sim 3$ mm

Calorimetry with Jet Energy Flow

$\sigma_E/E \sim 30\text{-}40\%/\sqrt{E}$

*** beamstrahlung must be dealt with, but it's manageable**

The Higgs Physics Program of The next Linear Collider

Electroweak precision measurements suggest there should be a relatively light Higgs boson:

When we find it, we will want to study its nature.
The LC is capable of contributing significantly to this study.

- **Mass Measurement**
- **Total width**
- **Particle couplings**
  - **vector bosons**
  - **fermions (including top)**
- **Spin-parity-charge conjugation**
- **Self-coupling**

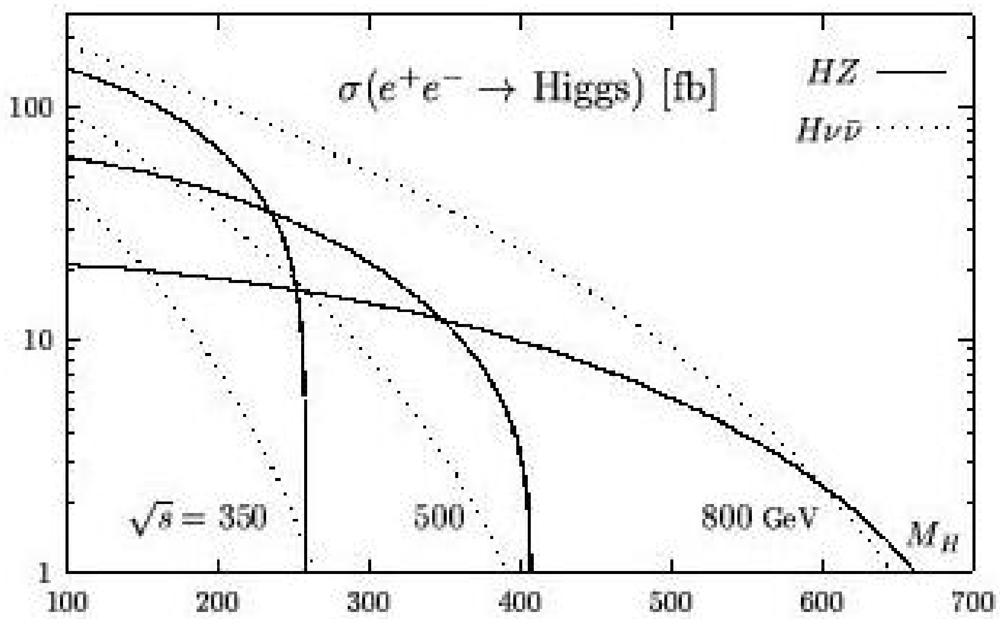
Example of Precision of Higgs Measurements at The next Linear Collider

For M_H = 140 GeV, 500 fb^{-1} @ 500 GeV

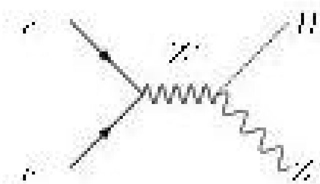
Mass Measurement	$\delta M_H \approx 60$ MeV $\approx 5 \times 10^{-4} M_H$
Total width	$\delta \Gamma_H / \Gamma_H \approx 3\,\%$
Particle couplings	
tt	(needs higher $\sqrt{s}$ for 140 GeV, except through $H \rightarrow gg$)
bb	$\delta g_{Hbb} / g_{Hbb} \approx 2\,\%$
cc	$\delta g_{Hcc} / g_{Hcc} \approx 22.5\,\%$
$\tau^+\tau^-$	$\delta g_{H\tau\tau} / g_{H\tau\tau} \approx 5\,\%$
WW^*	$\delta g_{Hww} / g_{Hww} \approx 2\,\%$
ZZ^*	**??**
gg	$\delta g_{Hgg} / g_{Hgg} \approx 12.5\,\%$
$\gamma\gamma$	$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} \approx 10\,\%$
Spin-parity-charge conjugation	establish $J^{PC} = 0^{++}$
Self-coupling	$\delta\lambda_{HHH} / \lambda_{HHH} \approx 32\,\%$ (statistics limited)

If Higgs is lighter, precision is often better

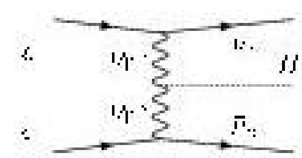
The Higgs Production Cross section at The next Linear Collider



Higgs-strahlung

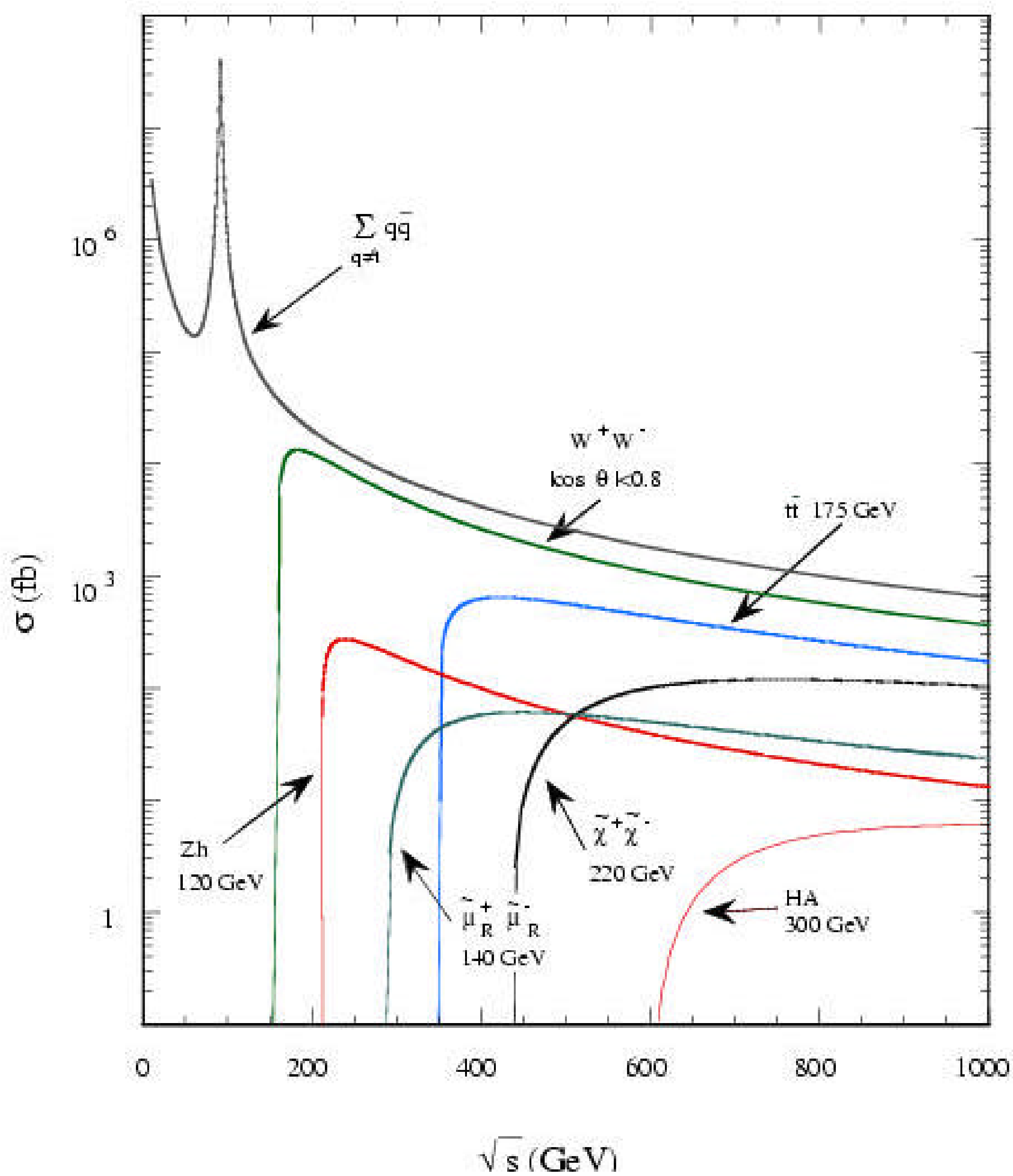


WW fusion



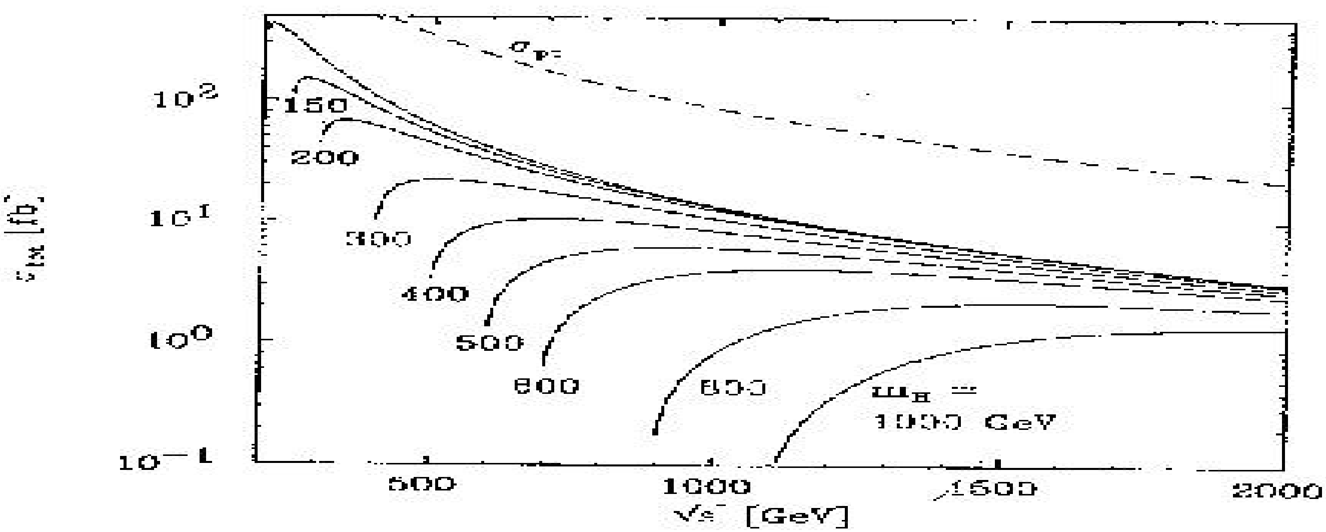
Recall, σ_{pt} **= 87** nb / $(E_{cm})^2$ ~ **350** fb @ 500 GeV

Cross sections at The next Linear Collider



The Higgs Production Cross section at The next Linear Collider

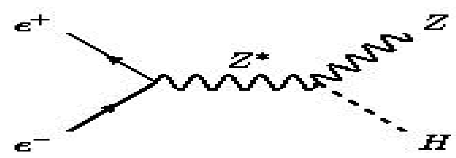
Higgs-strahlung



$e^+e^- \rightarrow ZH \rightarrow l^+ l^- X$ @ 500 GeV

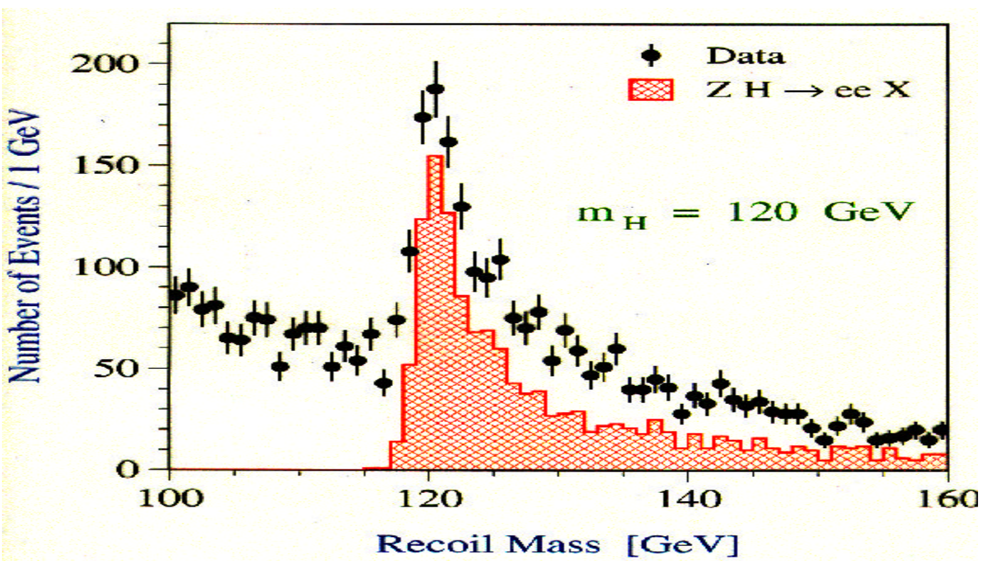
M_H (GeV)	events/ 500 fb^{-1}
120	2020
140	1910
160	1780
180	1650
200	1500
250	1110

Higgs studies -- The power of simple reactions



The LC can produce the Higgs recoiling from a Z, with known CM energy⇓, which provides a powerful channel for unbiassed tagging of Higgs events, allowing measurement of even invisible decays (⇓ - some beamstrahlung)

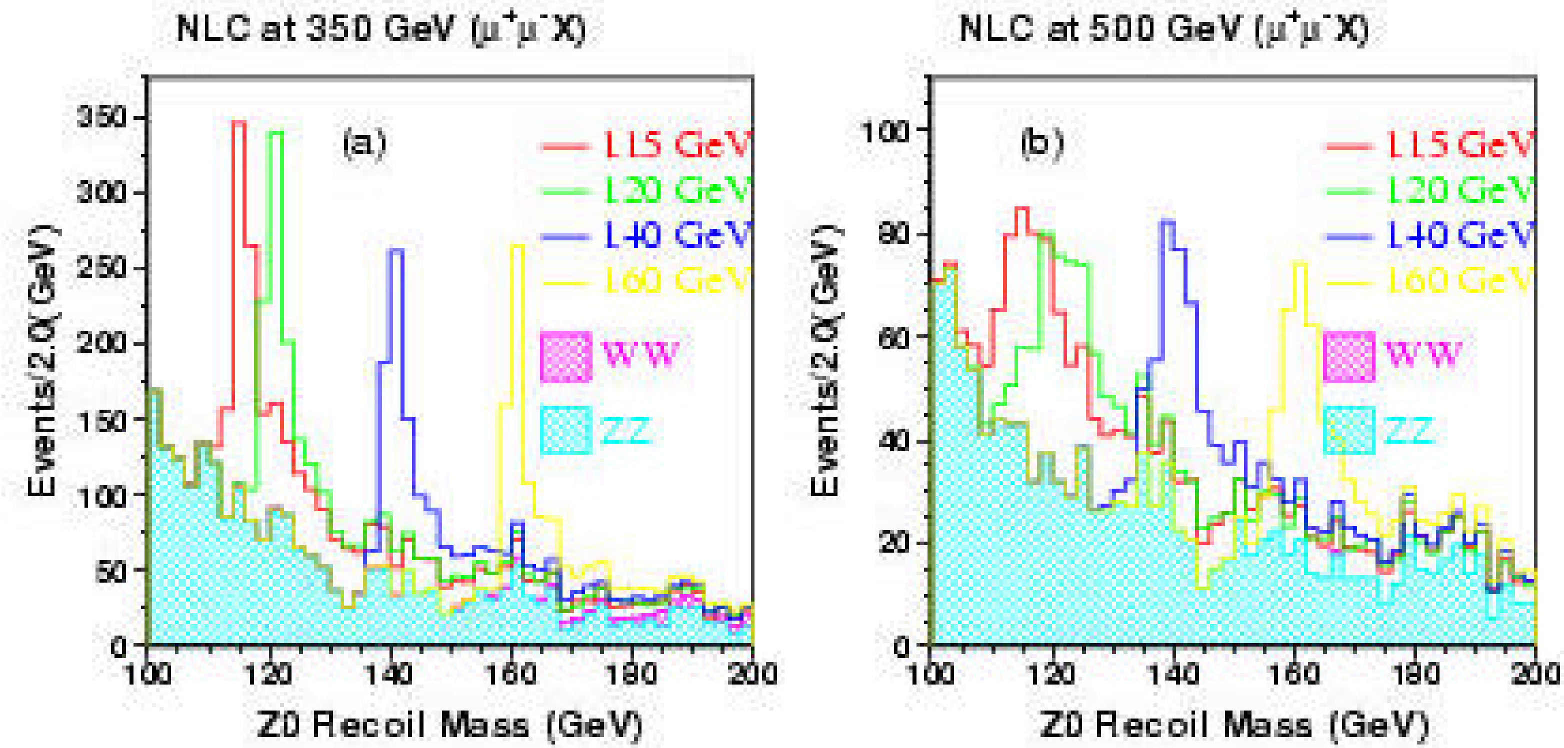
- Tag Z $l^+ l$
- Select $M_{recoil} = M_{Higgs}$



500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4

Invisible decays are included

Higgs studies -- The Mass Measurement



500 fb^{-1}, LC Physics Resource Book, Fig. 3.17

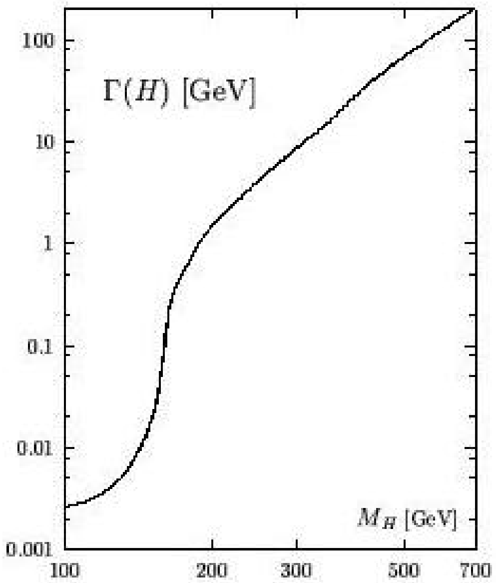
(m=120 GeV @ 500 GeV) $\delta M/M \sim 1.2\times10^{-3}$ from recoil alone (decay mode indep.), but reconstruction of Higgs decay products and fit does even better......

Higgs studies -- The Mass Measurement

M_H	δM_H(Recoil)	δM_H(Recon & fit)
120 GeV		40 MeV (3.3×10^{-4})
150 GeV	90 MeV	70 MeV (2×10^{-4})
180 GeV	100 MeV	80 MeV (4×10^{-4})

500 fb^{-1} @ 350 GeV, TESLA TDR, Table 2.2.1

Total width



$\Gamma_{TOT} = \Gamma_X / BR(H \rightarrow X)$

- $BR(H \rightarrow WW^*) = \Gamma_{WW} / \Gamma_{TOT}$
- Γ_{WW} from WW fusion cross section

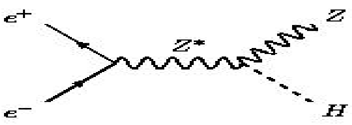
M_H	WW fusion	Higgs-strahlung
120 GeV	6.1%	5.6%
140 GeV	4.5%	3.7%
160 GeV	13.4%	3.6%

500 fb^{-1} @ 350 GeV, TESLA TDR, Table 2.2.4

Γ_{TOT} to few%

Higgs Z / W couplings

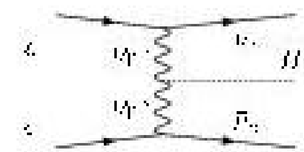
g_{HZZ} is measured through Higgs-strahlung cross section, or Higgs branching ratio



M_H	cross section	branching ratio
120 GeV	6.5%	
140 GeV	6.5%	
160 GeV	6 %	8.5%
200 GeV	7 %	4 %

500 fb^{-1} @ 500 GeV, LC Physics Resource Book, Table 3.2

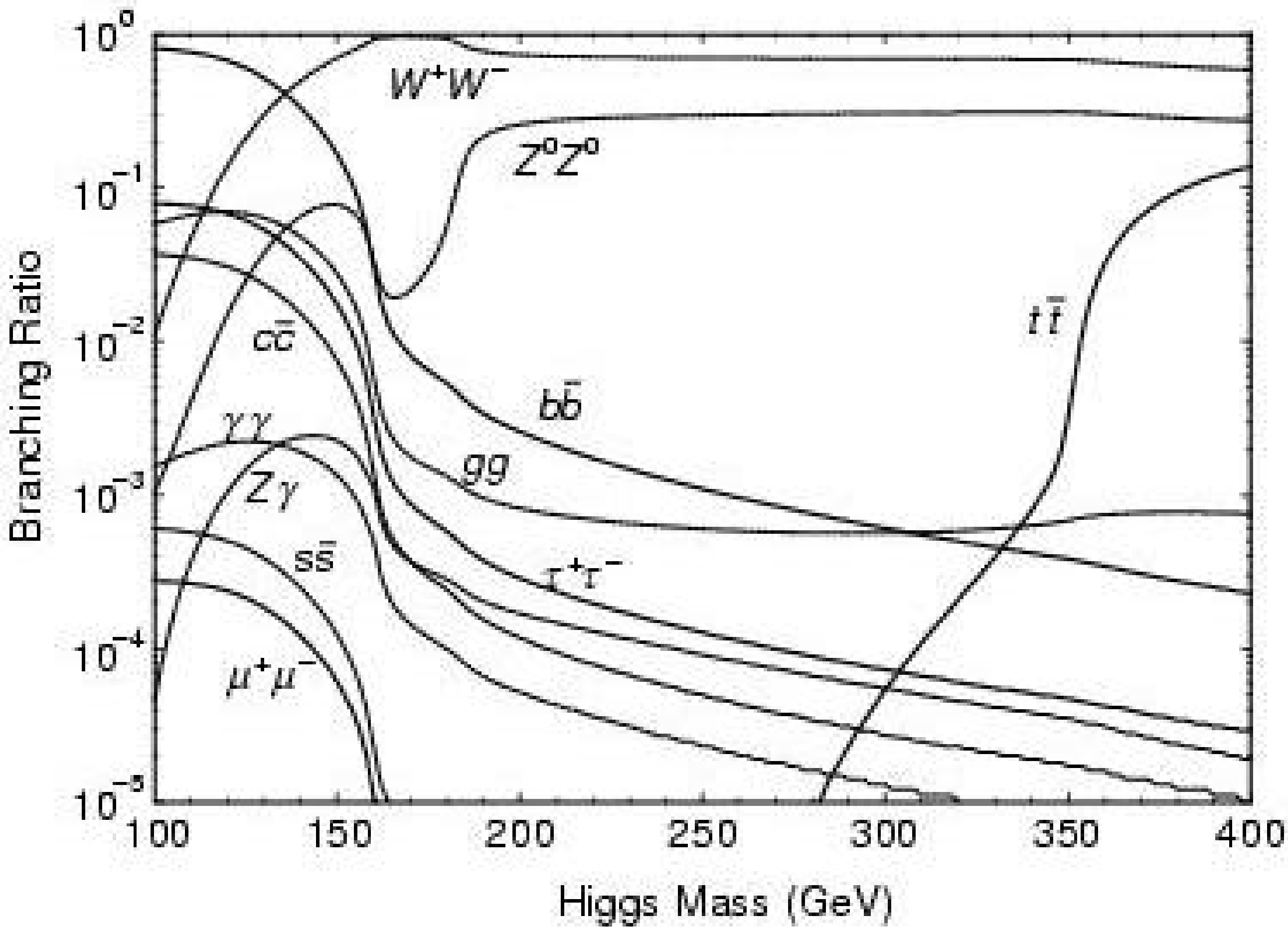
g_{HWW} is measured through the WW fusion cross section, or the Higgs branching ratio



M_H	cross section	branching ratio
120 GeV	3.5%	4.5 %
140 GeV	6 %	2 %
160 GeV	17 %	1.5 %
200 GeV		3.5 %

500 fb^{-1} @ 500 GeV, LC Physics Resource Book, Table 3.2

Higgs Couplings - the branching ratios



Higgs Couplings - the branching ratios

M_H	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to \tau^+ \tau^-$
120 GeV	2.9 %	39 %	18 %	7.9 %
140 GeV	4.1 %	45 %	23 %	10 %

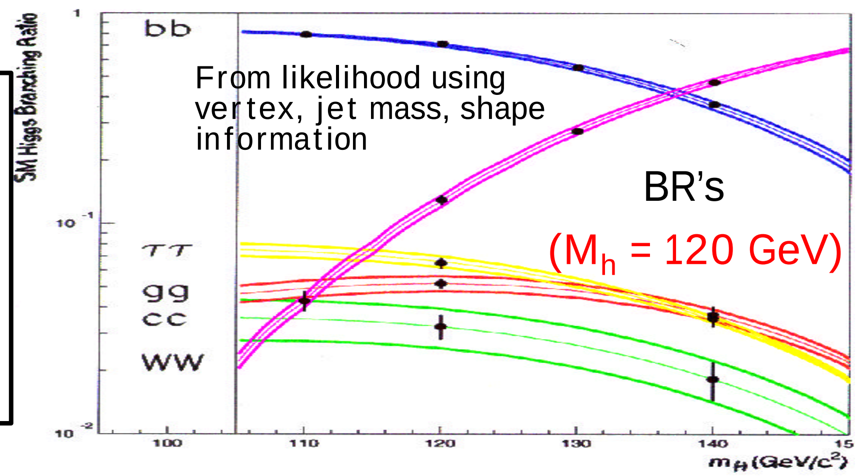
(through Higgs-strahlung, only)

500 fb^{-1} @ 500 GeV, LC Physics Resource Book, Table 3.1

At lower energy, including $e^+e^- \to H\nu\nu$, along with $e^+e^- \to ZH$

M_H	$H \to bb$	$H \to cc$	$H \to gg$	$H \to \tau^+ \tau^-$
120 GeV	2.4 %	8.3 %	5.5 %	5.0 %
140 GeV	2.6 %	19.0 %	14.0 %	8.0 %
160 GeV	6.5 %			

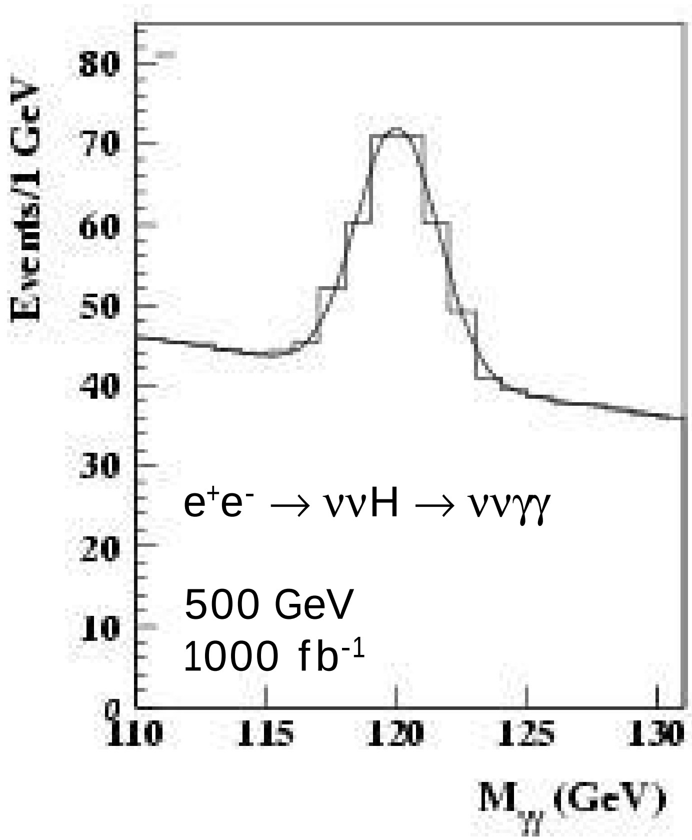
500 fb^{-1} @ 350 GeV, TESLA TDR, Table 2.2.5



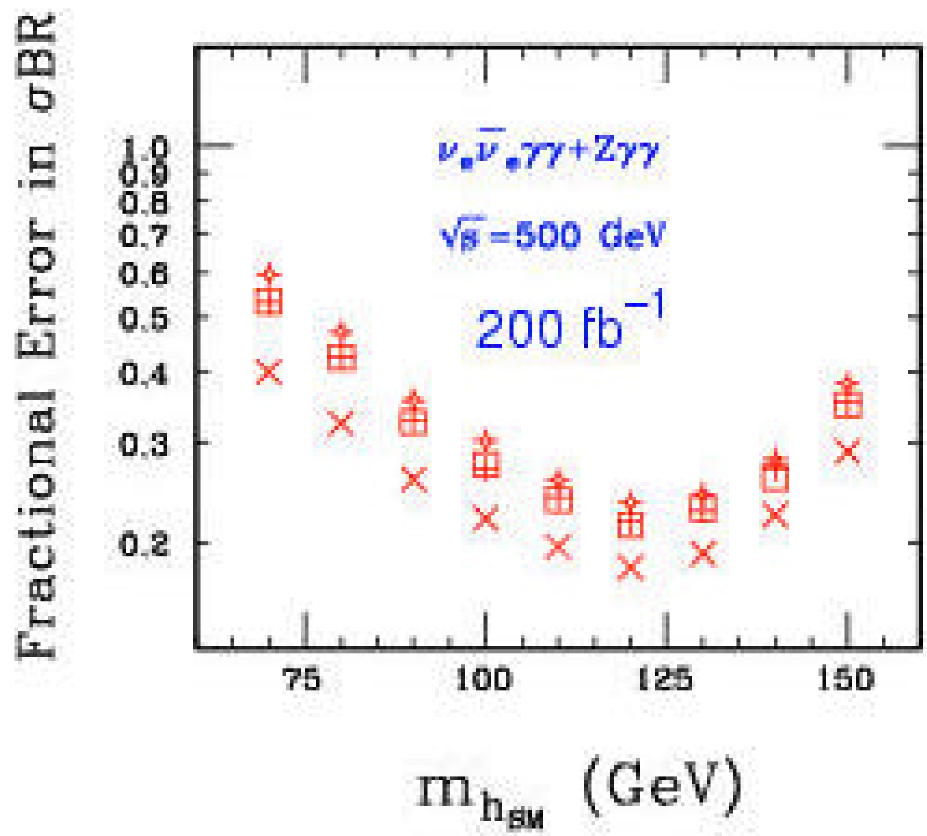
Measurement of BR's is powerful indicator of new physics

e.g. in MSSM, these differ from the SM in a characteristic way. Higgs BR must agree with MSSM parameters from many other measurements.

Higgs Couplings ($H \rightarrow \gamma\gamma$)



TESLA TDR, Fig 2.2.3(b)



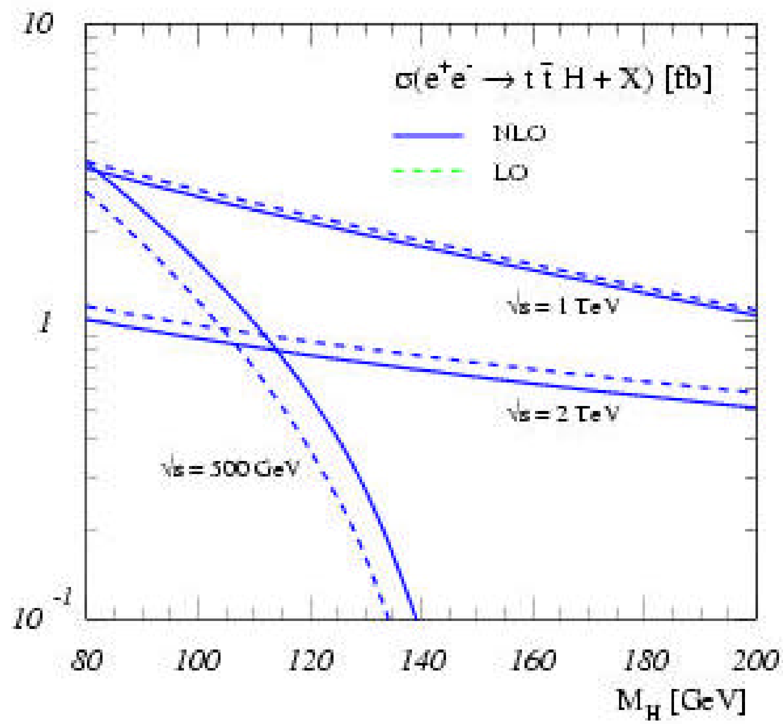
LC Physics Resource Book, Fig 3.21

With 500 fb^{-1} @ 500 GeV, expect 10% precision at 140 GeV

LC Physics Resource Book, Table 3.2

Higgs Couplings (top)

Due to the large top mass, the Higgs Yukawa coupling to top is very large: g^2_{ttH} 0.5

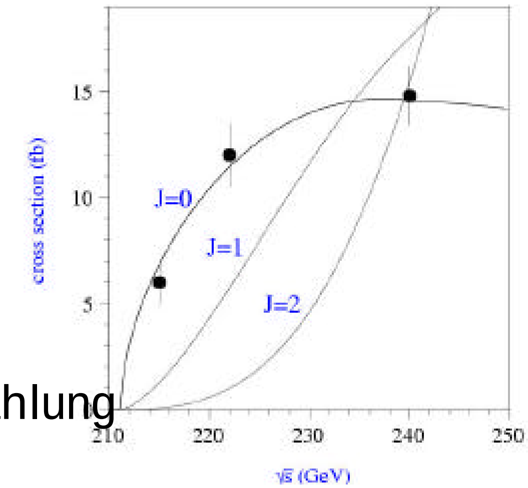


This measurement will require large luminosity, and probably high energy

Higgs spin parity and charge conjugation (J^{PC})

$H \to \gamma\gamma$ or $\gamma\gamma \to H$ rules out J=1 and indicates C=+1

Threshold cross section ($e^+e^- \to ZH$) for J=0
$\sigma \sim \beta$, while for J > 0, generally higher power of β (assuming n = $(-1)^J$ P)

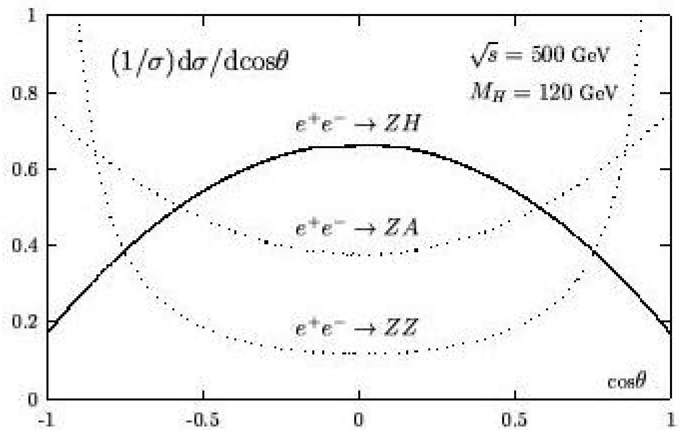


LC Physics Resource Book, Fig 3.23(a)

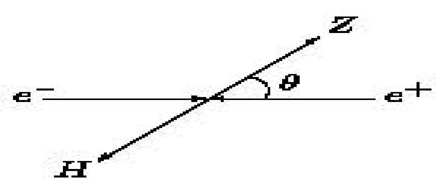
Production angle (θ) and Z decay angle in Higgs-strahlung reveals J^P ($e^+e^- \to ZH \to f\bar{f}H$)

	$J^P = 0^+$	$J^P = 0^-$
$d\sigma/d\cos\theta$	$\sin^2\theta$	$(1 - \sin^2\theta)$
$d\sigma/d\cos\phi$	$\sin^2\phi$	$(1 +/- \cos\phi)^2$

ϕ is angle of the fermion, relative to the Z direction of flight, in Z rest frame



TESLA TDR, Fig 2.2.8



Higgs self couplings

Measures Higgs potential λ

$V(\Phi)=\lambda(\Phi^2-\frac{1}{2}v^2)^2$ $\quad v \sim$ 246 GeV

$m_h^2=4\lambda v^2$

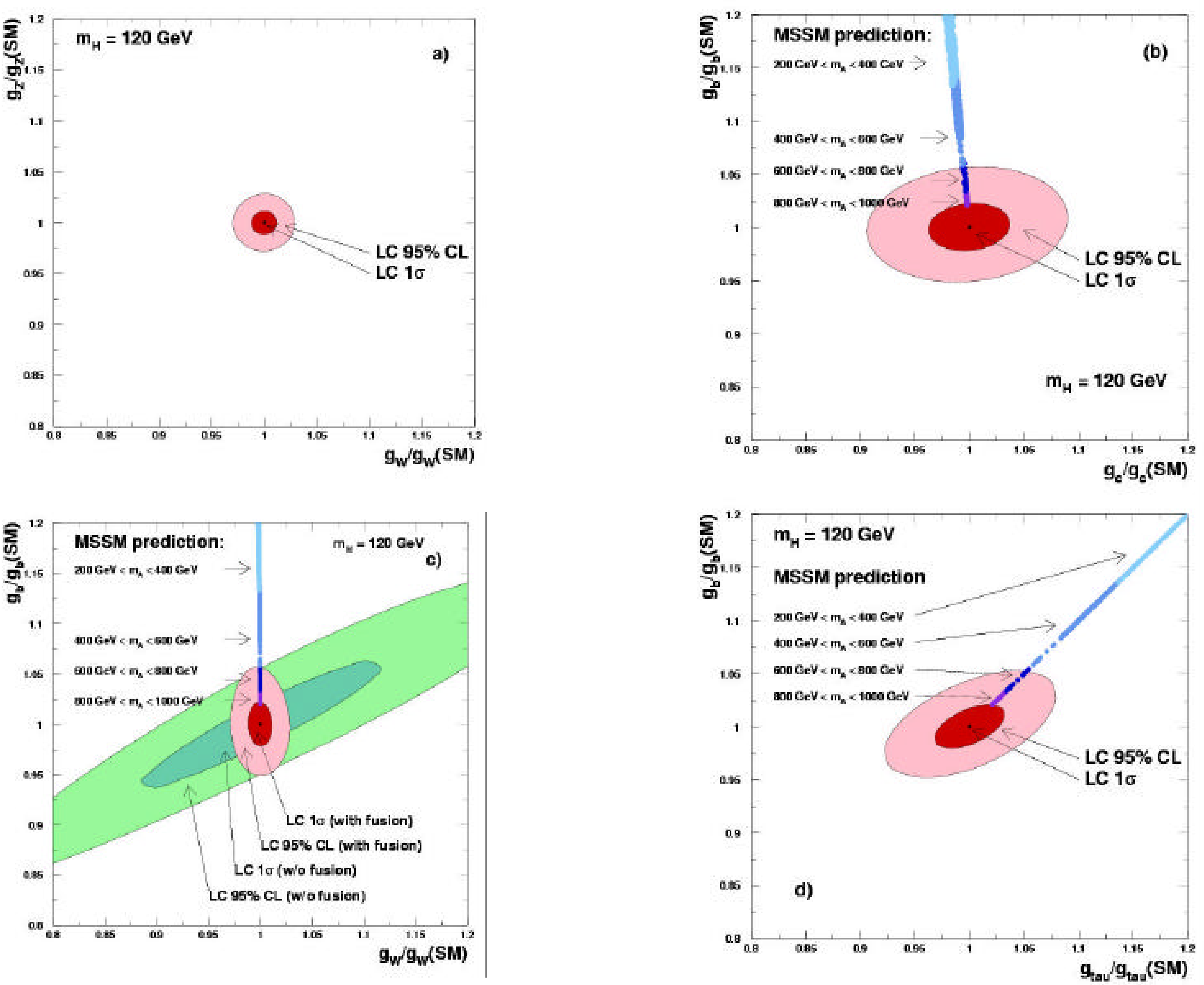
double Higgs-strahlung: $e^+e^- \rightarrow Zhh$

Study ZHH production and decay to 6 jets (4 b's). Cross section is small; premium on very good jet energy resolution. Can enhance x5 with positron polarization.

m_h (GeV/c²)	σ_{hhZ} (fb)	N_{hhZ}^{500}	ϵ_{hhZ}	$\mathcal{L}=500$ fb⁻¹	1000 fb⁻¹	2000 fb⁻¹
120	0.186	93.	43%	24.1%	17.3%	11.6%
130	0.149	74.	43%	26.6%	19%	17.7%
140	0.115	57.	39%	32%	23 %	17%

$\Delta\lambda/\lambda$ error 36% → 18%

Is it the Standard Model Higgs?



TESLA TDR, Fig 2.2.6

Complementarity with the LHC

	M_H (GeV)	$\delta(X)/X$ LHC $2 \times 300\,\mathrm{fb}^{-1}$	$\delta(X)/X$ LC $500\,\mathrm{fb}^{-1}$
M_H	120	9×10^{-4}	3×10^{-4}
M_H	160	10×10^{-4}	4×10^{-4}
Γ_{tot}	120-140	-	0.04 - 0.06
$g_{Hu\bar{u}}$	120-140	-	0.02 - 0.04
$g_{Hd\bar{d}}$	120-140	-	0.01 - 0.02
g_{HWW}	120-140	-	0.01 - 0.03
$\frac{g_{Hu\bar{u}}}{g_{Hd\bar{d}}}$	120-140	-	0.023-0.052
$\frac{g_{Hb\bar{b}}}{g_{HWW}}$	120-140	-	0.012-0.022
$\frac{g_{Ht\bar{t}}}{g_{HWW}}$	120	0.070	0.023
$\frac{g_{HZZ}}{g_{HWW}}$	160	0.050	0.022
CP test	120	-	0.03
λ_{HHH}	120	-	0.22

Table 2.5.1: *Comparison of the expected accuracy in the determination of the SM-like Higgs profile at the LHC and at TESLA. The mass, width, couplings to up-type and down-type quarks and to gauge bosons, several of the ratios of couplings, the triple Higgs coupling and the sensitivity to a CP-odd component are considered.*

TESLA TDR, Table 2.5.1

Giga-Z:
Precision studies at the Z^0

Some scenarios for the results of high energy measurements would motivate higher precision studies of the Z pole

> eg. A light Higgs is found, but nothing else. Given the mass of the higgs, its contribution to electroweak loop corrections would be known

SM Higgs mass could be confirmed through EW corrections to 7%

In MSSM or non-minimal Higgs context, EW corrections could narrow unknown

The Gamma-gamma collider

One option that a linear collider provides is the capability to do gamma-gamma collisions

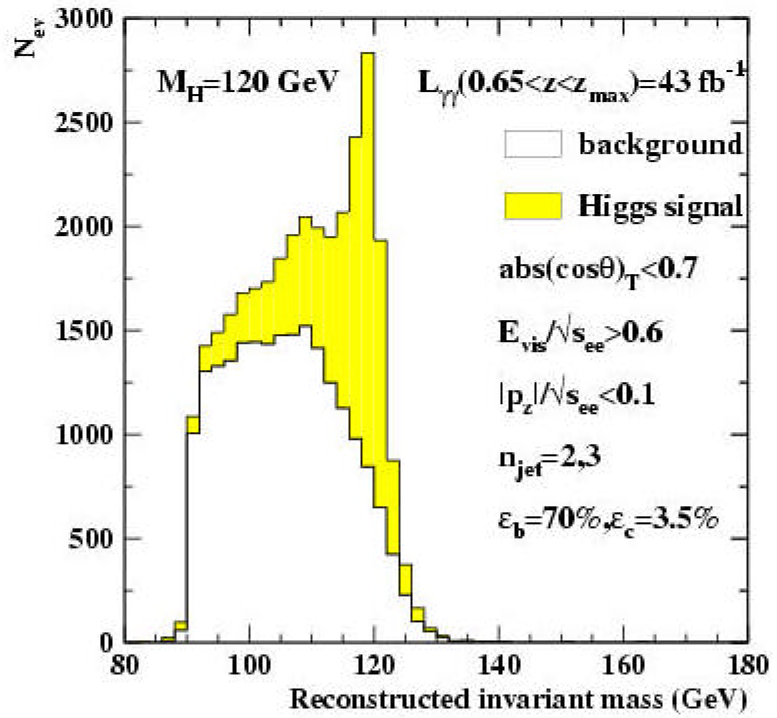
Measure $\gamma\gamma \rightarrow H \rightarrow X$

Also:

Production of Higgs at $\gamma\gamma$ collider establishes C to be positive
(and rules out J=1)

Can produce CP even and odd states **separately** using polarized
$\gamma\gamma$ collisions (Separate Susy H/A)
$\gamma\gamma \rightarrow$ H or A (can reach higher masses than e^+e^-)

The Gamma-gamma collider



TESLA TDR, Fig 2.2.3(a)

Expected precision for M_H = 120 GeV

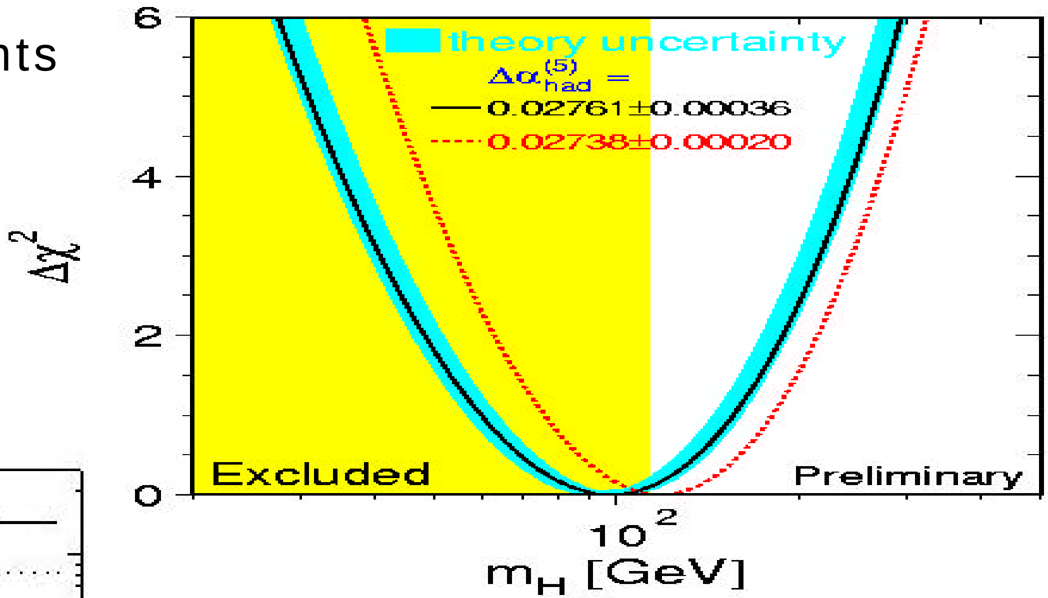
$\delta[\sigma(\gamma\gamma \rightarrow H)]$ = 2% for 43 fb^{-1} of hard spectrum (TESLA TDR)

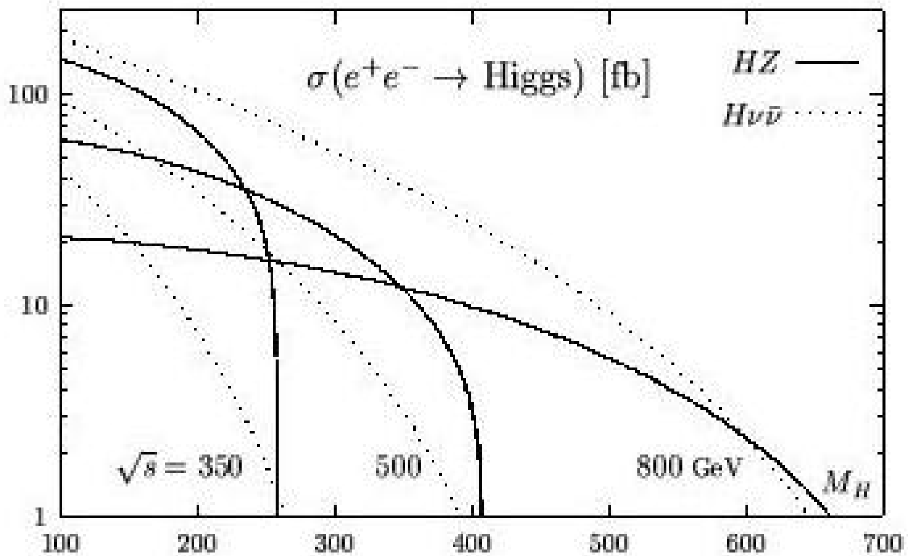
$\delta[\sigma(\gamma\gamma \rightarrow H)]$ = 5% for more conservative spectrum (LC Physics Res. Bk)

for M_H = 160 GeV 5% increases to 20%

Standard Model Heavy Higgs

Electroweak precision measurements strongly disfavor SM Heavy Higgs





Nevertheless, production is adequate to study to higher masses

Standard Model Heavy Higgs

Examples of some measurements that would be interesting:

If $M_H > 2M_T$ and if the couplings are found to be consistent with Standard Model, then EW precision measurements would demand some new physics. Therefore.......

1. Measure the cross section
for M_h = 500 GeV, 7% measurement could be done with 1000 fb^{-1} at 800 GeV

2. Measure the top Yukawa coupling
δG_{TTH} ~ 10% **FOR 1000 fb^{-1} at 800 GeV**

3. Measure the vector boson couplings
δG_{WWH} ~ 8.5% **FOR 500 fb^{-1} at 800 GeV**
δG_{ZZH} ~ 10% **FOR 500 fb^{-1} at 800 GeV**

Conclusions

The Linear Collider would be a powerful tool for studying a Standard Model-like Higgs.

Current status of Electroweak Precision measurements strongly suggest Nature will provide the opportunity.