The Higgs Mechanism and Electroweak Symmetry Breaking at e^+e^- Colliders

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Snowmass 2001
Workshop on the Future of High Energy Physics

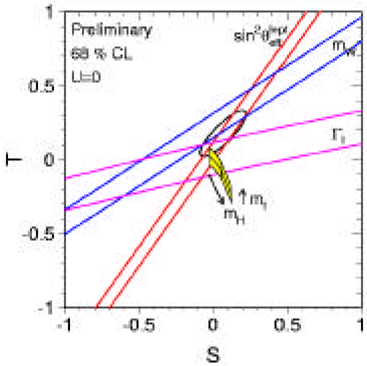
The Higgs Mechanism and Electroweak Symmetry Breaking at e^+e^- Colliders

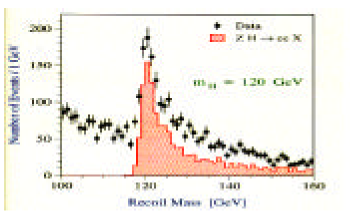
The LHC (or the Tevatron) should initiate the experimental measurement of the particle(s) associated with EWSB

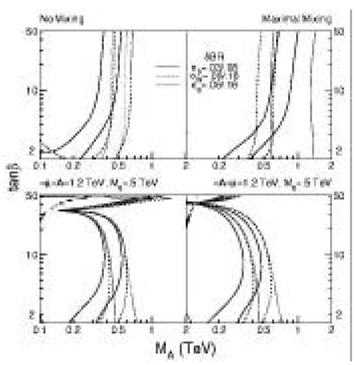
These first discoveries will likely provide a limited view of the nature of the Higgs mechanism

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

Outline







Present knowledge of Electroweak Symmetry Breaking

Parameters of the proposed future Linear Colliders

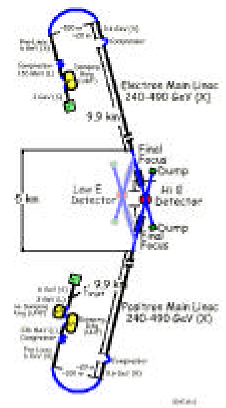
Standard Model Higgs

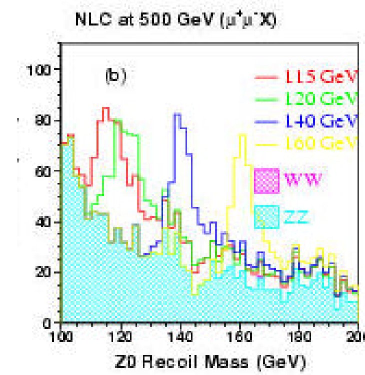
MSSM Higgs

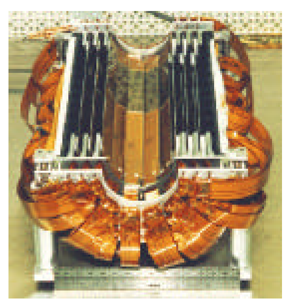
Strong coupling gauge models of EWSB

Other scenarios

Value added to LHC observations

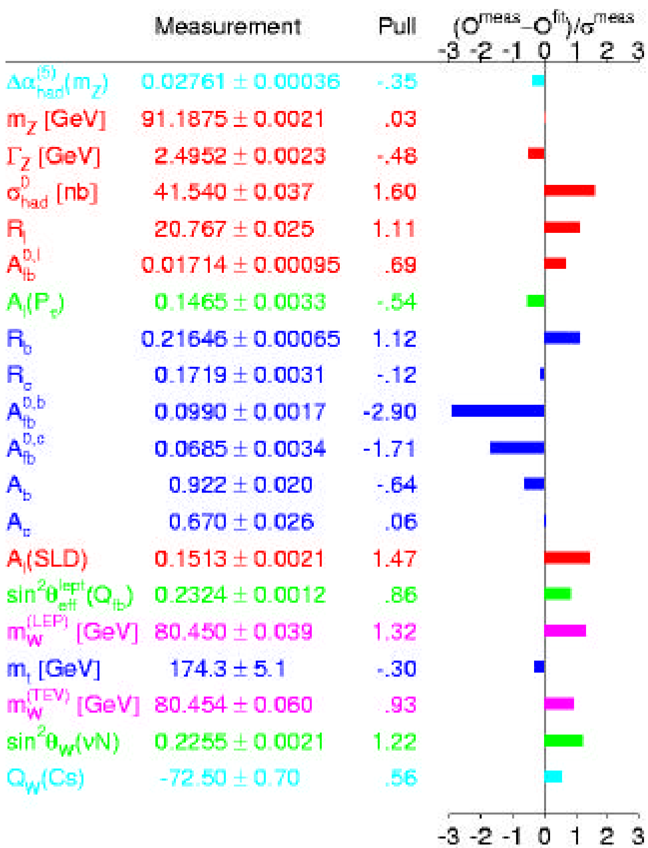


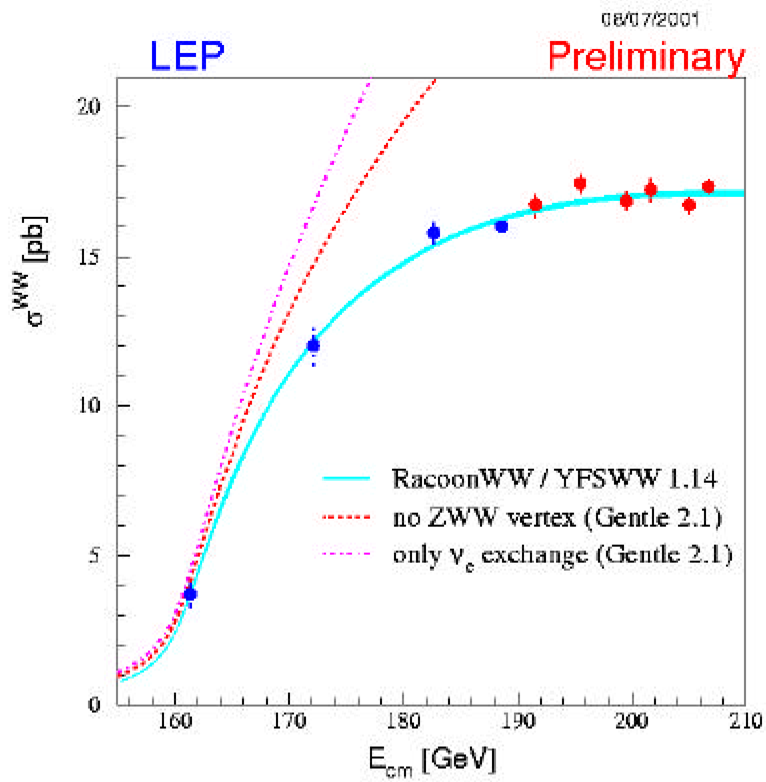




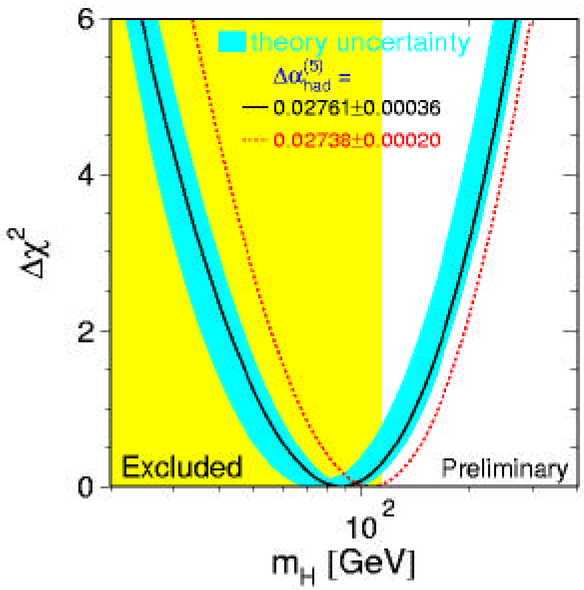
Electroweak Symmetry Breaking

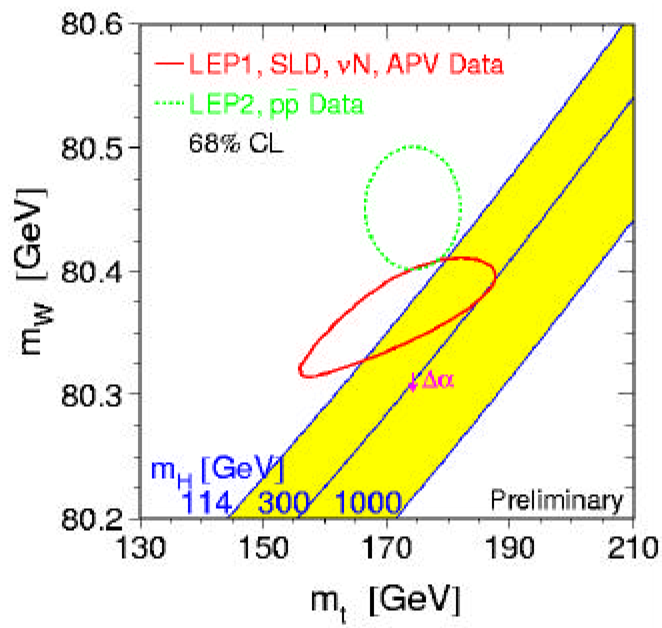
The Standard Model has been remarkably successful





Indications for a Light Standard Model-like Higgs





(SM) M_{higgs} < 195 GeV at 95% CL.
LEP2 limit M_{higgs} > 113.5 GeV.
Tevatron can discover up to 180 GeV

W mass (± 33 MeV)
and top mass (± 5 GeV)
agree with precision measures
and indicate low SM Higgs mass

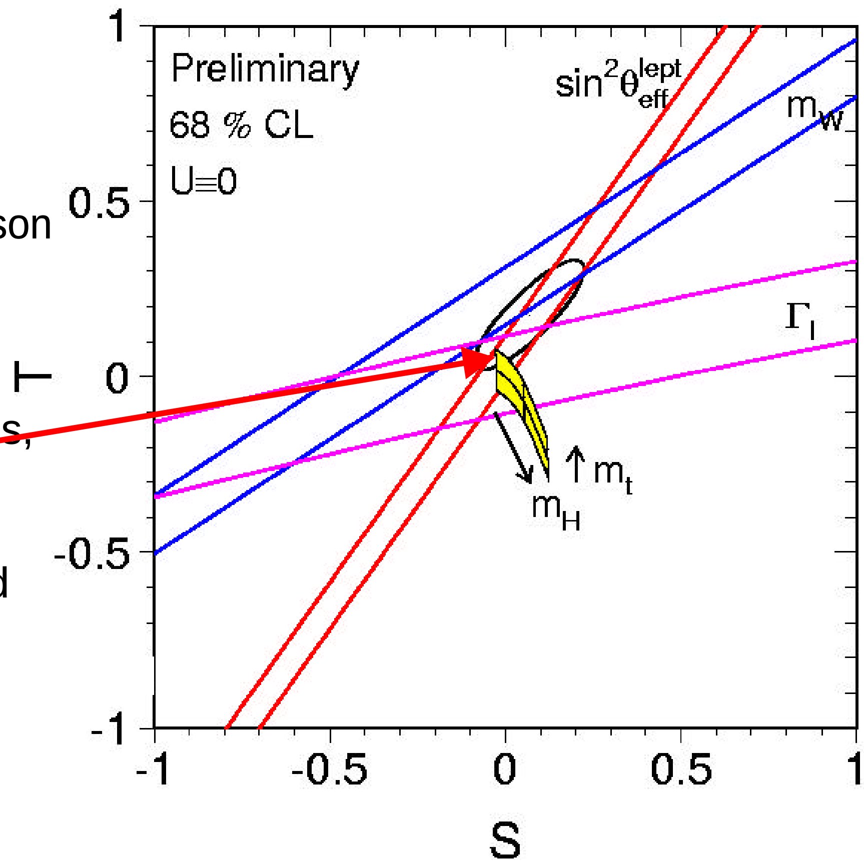
LEP Higgs search – Maximum Likelihood for Higgs signal at m_H = 115.0 GeV with overall significance (4 experiments) = 2.9σ

Indications for a Light Standard Model Higgs

S,T, and U parameters describe new physics which enters through vacuum-polarization (self-energy) to vector-boson propagators of the SM.

Light SM Higgs is in good agreement with measured EW radiative corrections, as expressed as S and T.

Sizeable contributions to S and T would be expected from many models of New Physics.



Establishing Standard Model Higgs

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

We expect the Higgs to be discovered at LHC (or tevatron) and the measurement of its properties will begin at the LHC

We need to measure the full 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 (~ 40 - 60% ?)

$\gamma\gamma$ **Collisions**

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

Giga-Z (precision measurements)

Special Advantages of Experiments 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 and $\sigma_{hit} \sim 3\ \mu m$

Calorimetry with Jet Energy Flow

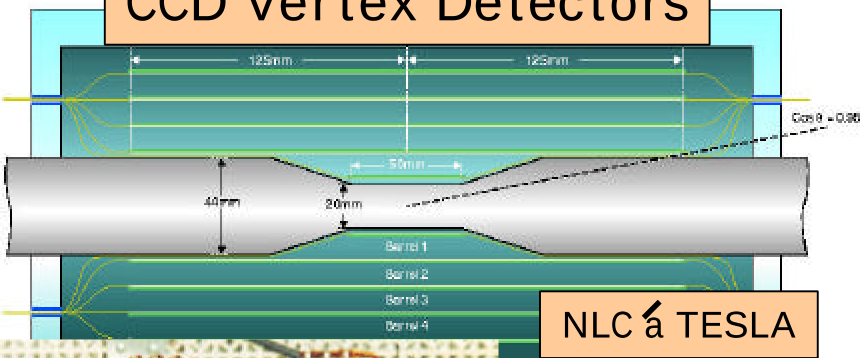
$\sigma_E/E \sim 30\text{-}40\%/\sqrt{E}$

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

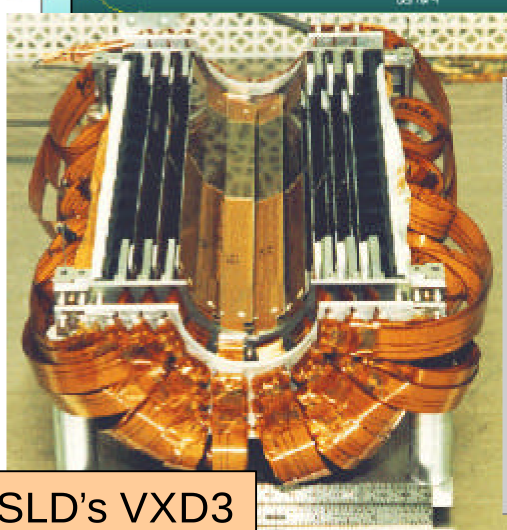
Linear Collider Detectors

The Linear Collider provides very special experimental conditions (eg. superb vertexing and jet calorimetry)

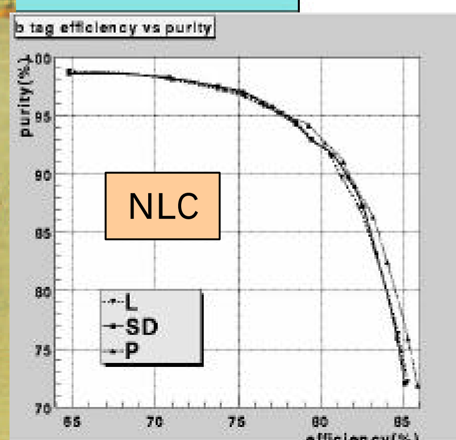
CCD Vertex Detectors



NLC à TESLA



SLD's VXD3



NLC

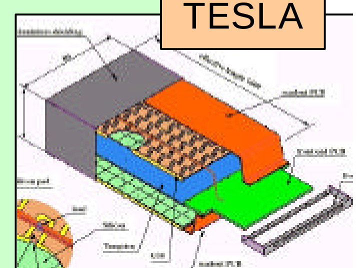
Silicon/Tungsten Calorimetry

SLD Lum (1990)
Aleph Lum (1993)
Opal Lum (1993)

Snowmass - 96 Proceedings

NLC Detector - fine gran. Si/W

Now TESLA & NLD have proposed Si/W as central elements in jet flow measurement



TESLA

Candidate Models for Electroweak Symmetry Breaking

Standard Model Higgs

excellent agreement with EW precision measurements

implies M_H < 200 GeV (but theoretically ugly - h'archy prob.)

MSSM Higgs

expect M_h< ~135 GeV

light Higgs boson (h) may be very "SM Higgs-like"

(de-coupling limit)

Non-exotic extended Higgs sector

eg. 2HDM

Strong Coupling Models

New strong interaction

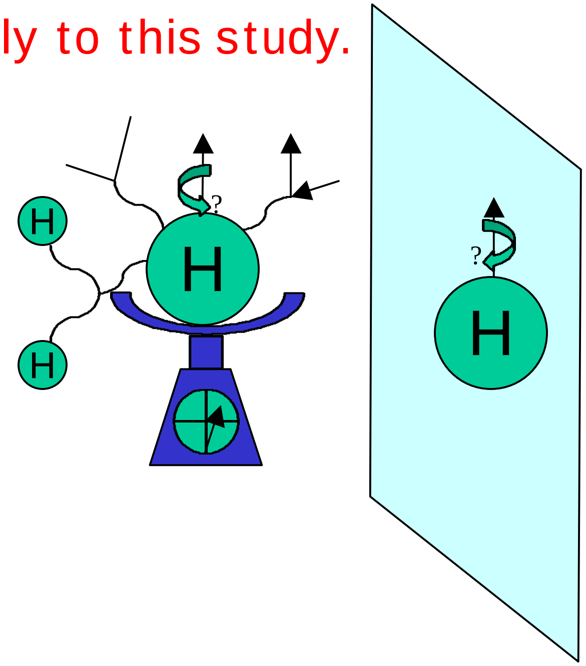
The Higgs Physics Program of the Next Linear Collider

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



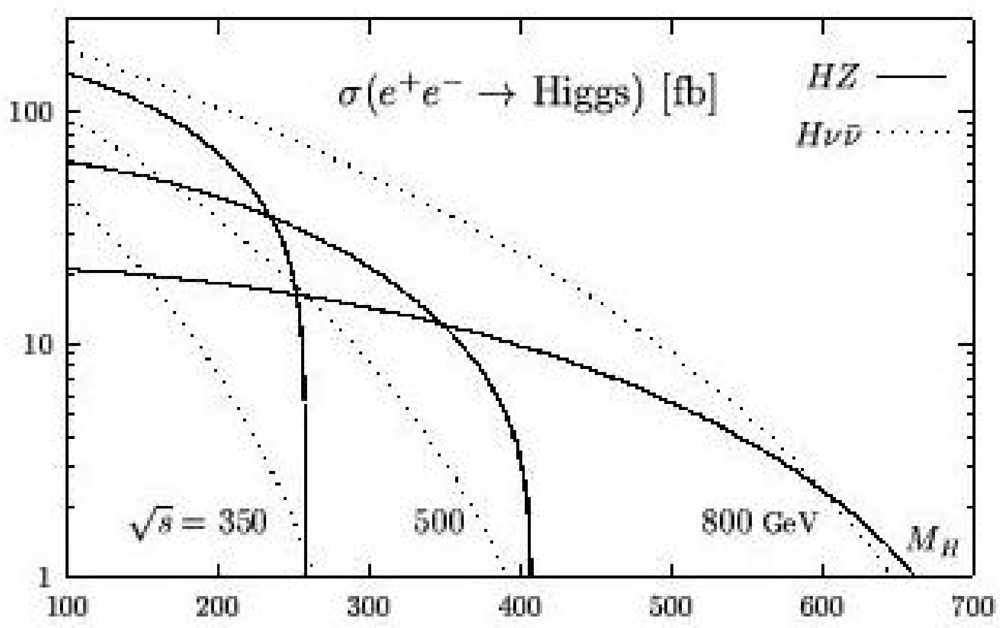
Example of Precision of Higgs Measurements at the Next Linear Collider

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

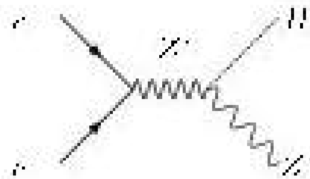
Mass Measurement	$\delta M_H \approx 60$ MeV $\approx 5 \times 10^{-4} M_H$
Total width	$\delta \Gamma_H / \Gamma_H \approx 3$ %
Particle couplings	
tt	(needs higher $\sqrt{s}$ for 140 GeV, except through $H \to gg$)
bb	$\delta g_{Hbb} / g_{Hbb} \approx 2$ %
cc	$\delta g_{Hcc} / g_{Hcc} \approx 22.5$ %
$\tau^+\tau^-$	$\delta g_{H\tau\tau} / g_{H\tau\tau} \approx 5$ %
WW*	$\delta g_{Hww} / g_{Hww} \approx 2$ %
ZZ	$\delta g_{HZZ} / g_{HZZ} \approx 6$ %
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

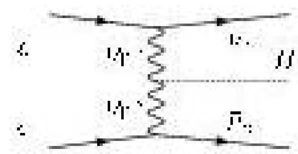
Higgs Production Cross-section at the Next Linear Collider



Higgs-strahlung

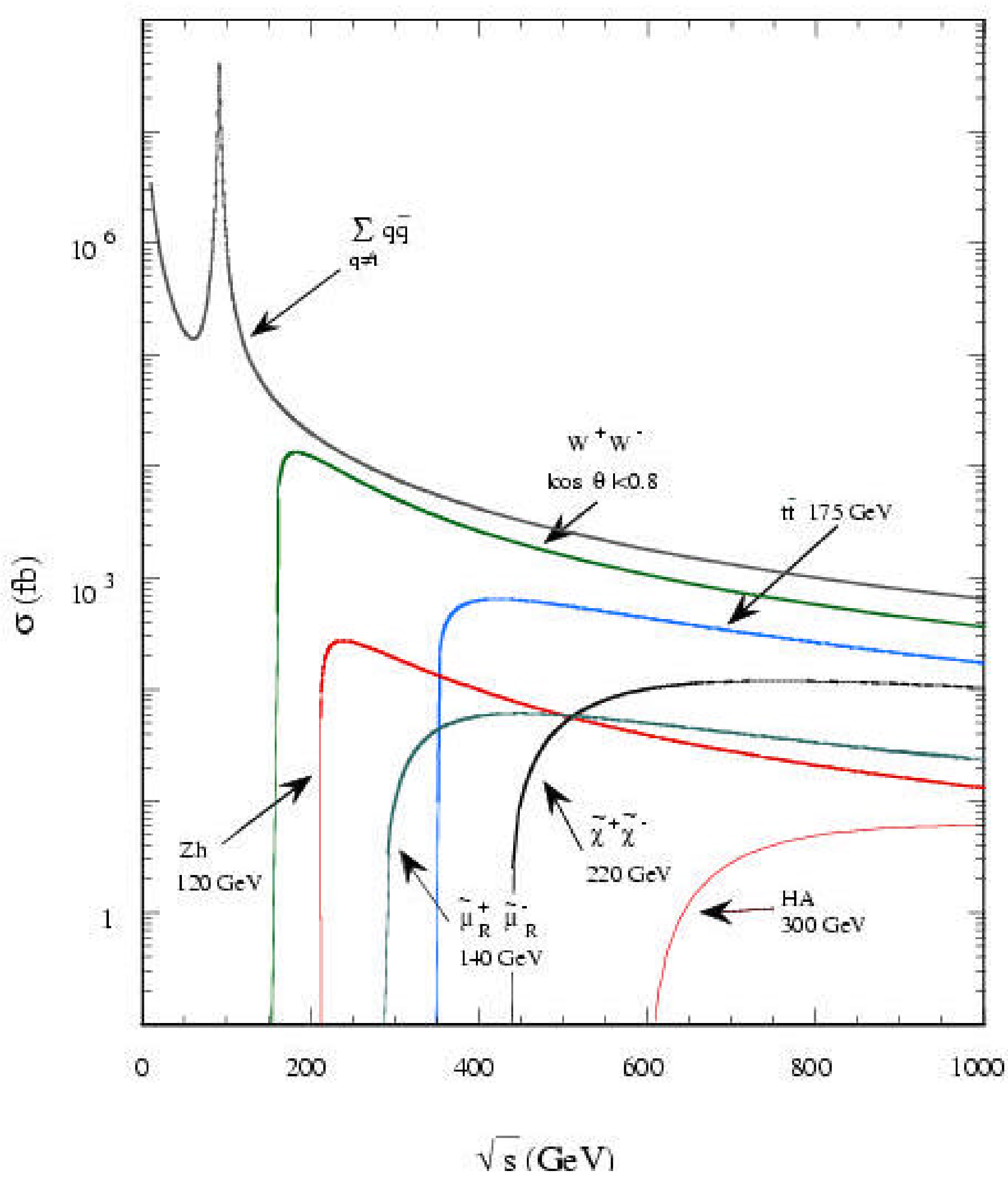


WW fusion



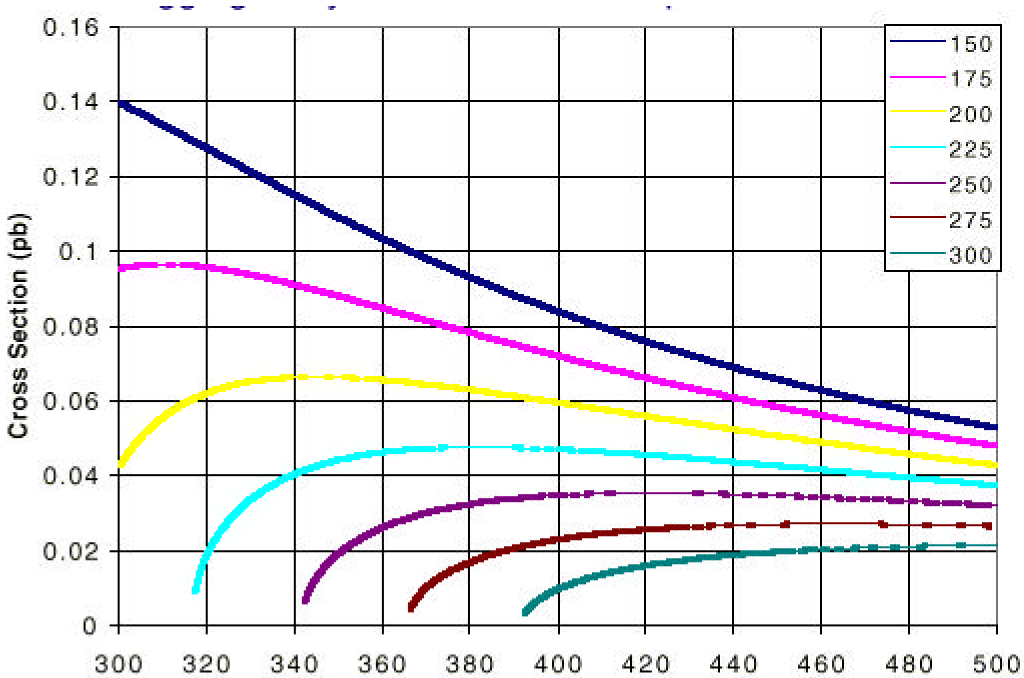
Recall, σ_{pt} **= 87** nb / $(E_{cm})^2$ ~ **350** fb @ 500 GeV

Cross-sections at the Next Linear Collider



Higgs Production Cross-section at the Next Linear Collider

Higgs-strahlung



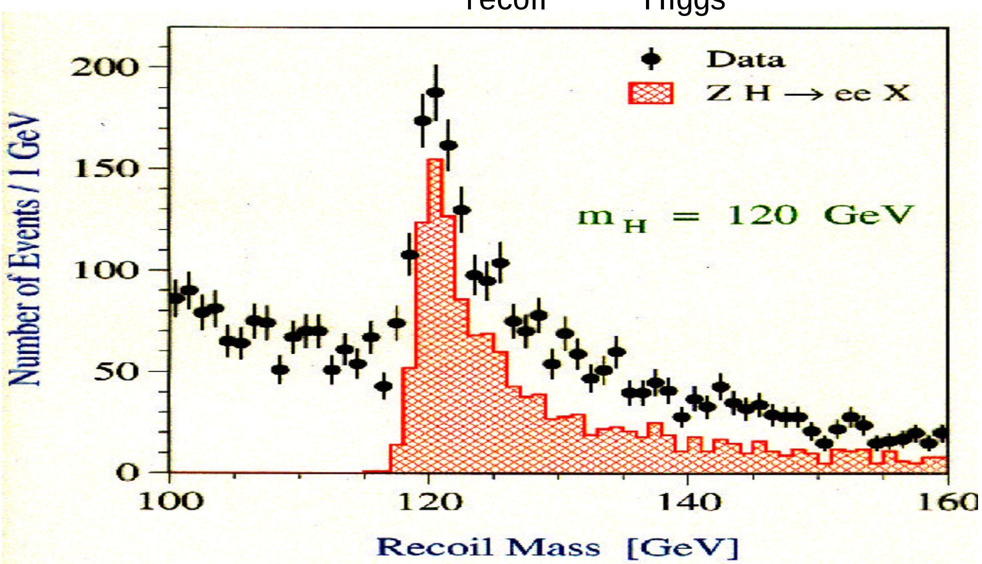
$e^+e^- \rightarrow ZH \rightarrow l^+ l^- X$ @ 500 GeV

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)

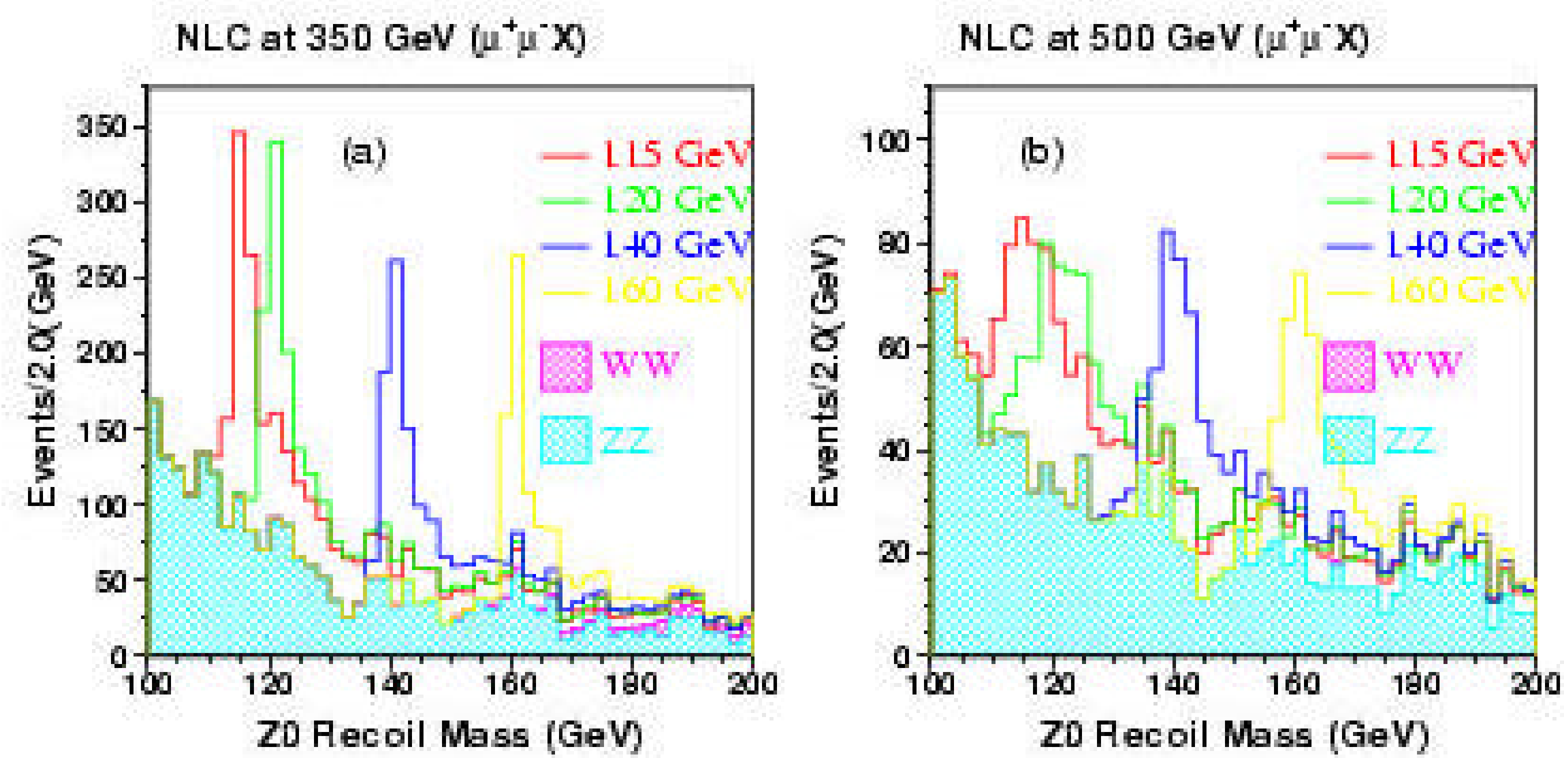
- Tag Z $l^+ l$
- Select $M_{recoil} = M_{Higgs}$



Invisible decays are included

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

Higgs Studies - the Mass Measurement



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

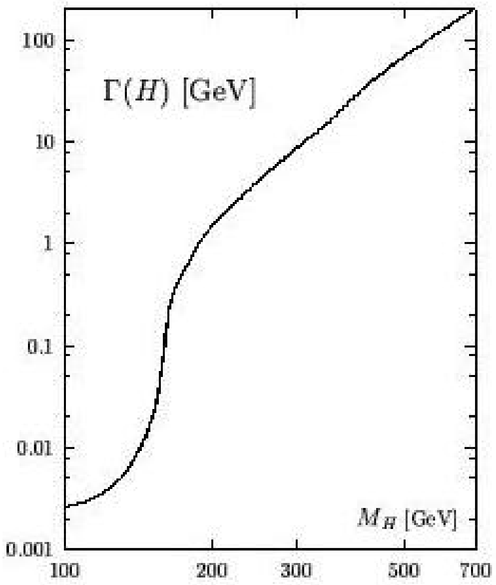
(m=120 GeV @ 500 GeV) $\delta M/M \sim 1.2 \times 10^{-3}$ from recoil alone (decay mode indep.), but reconstruction of Higgs decay products and fit does even better......

Higgs Studies - the Mass Measurement

M_H	$\delta\, M_H$(Recoil)	$\delta\, M_H$(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 of the Higgs



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

- $BR(H \to WW^*) = \Gamma_{WW} / \Gamma_{TOT}$
- 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%

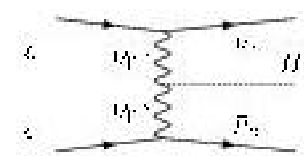
Higgs Z/W Couplings

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

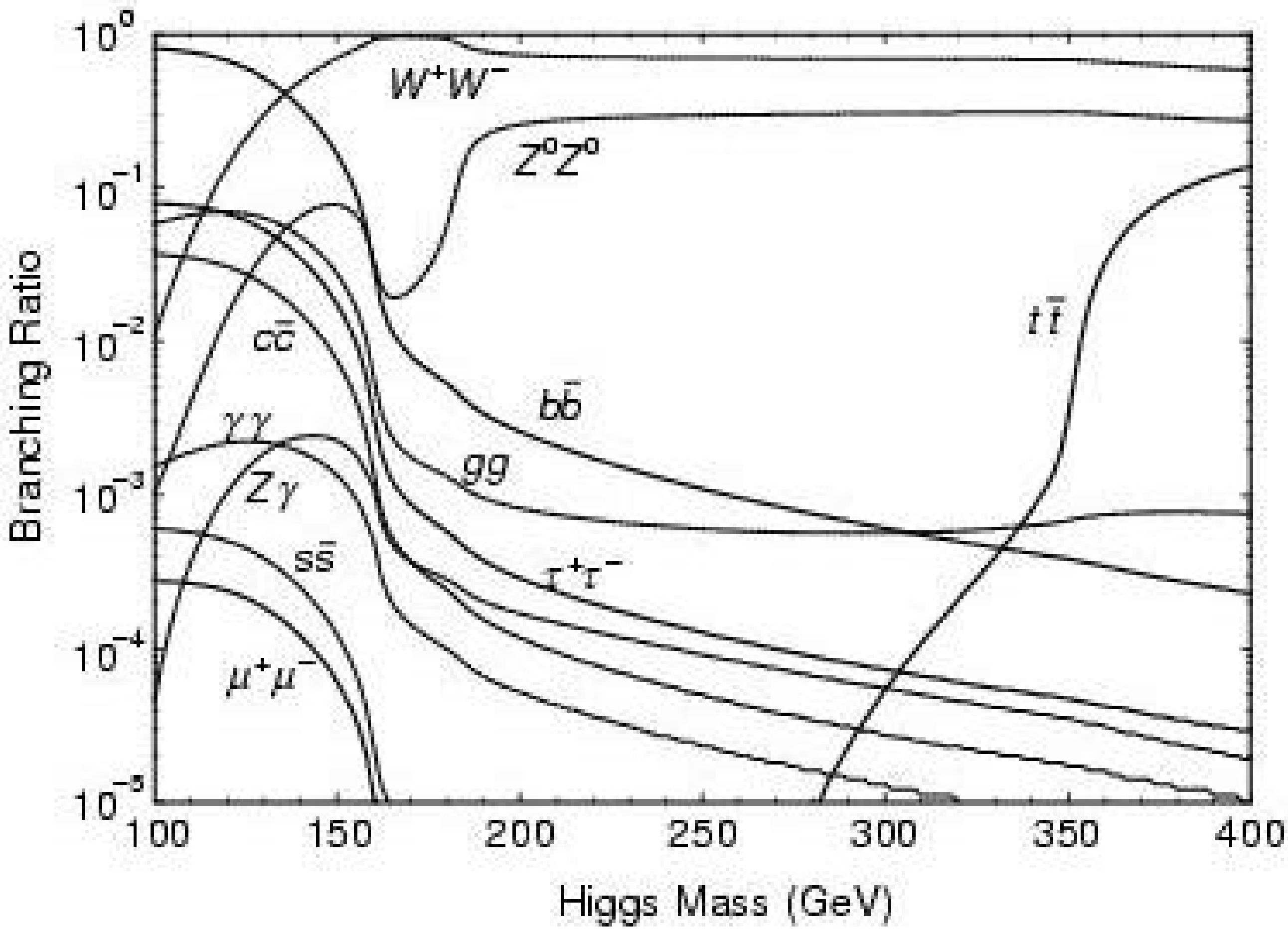
g_{HWW} is measured through the WW fusion cross section, or the Higgs branching ratio



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 %

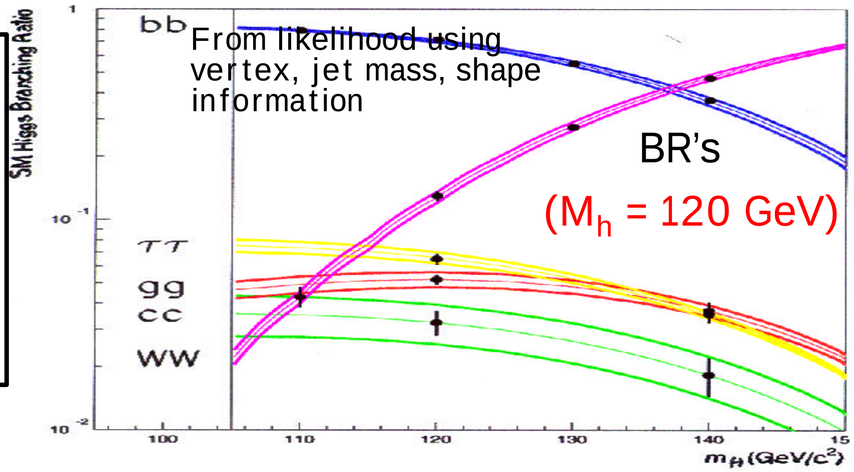
(through Higgs-strahlung, only)

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

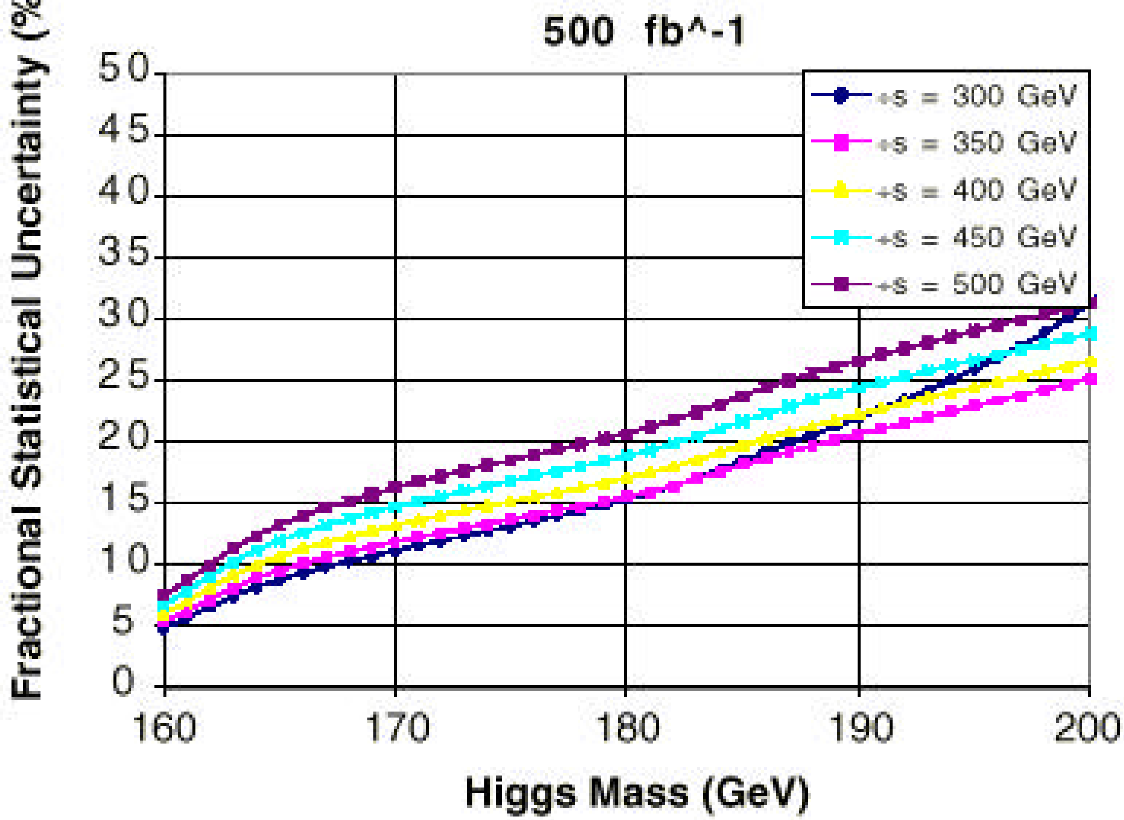


Measurement of BR's is powerful indicator of new physics

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

hbb coupling for Heavier Higgs

- $\delta Br(b\bar{b})/Br(b\bar{b})$



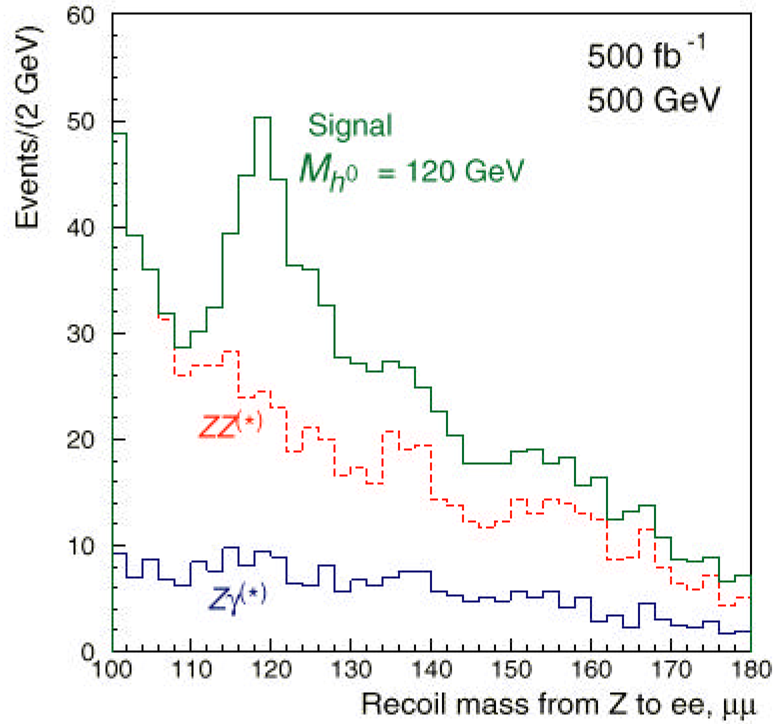
R. Van Kooten, Fermilab Line-Drive

Invisible Higgs Decays

Invisible Branching Ratio

Rick Van Kooten

- *hZ → all*, └→ *invisible* — Explicitly search for Z recoiling against "nothing" (previously, e.g., [1 -ΣBr's])
- PYTHIA, FastMC, Large NLC (ldmar01) detector, NLC beamst. $M_{h^0} = 120$ GeV
- Test case, e.g., Wells et al., hep-ph/002178, $\delta = 4$ extra dimensions, $Br(h \to invis) = 38\%$, $\Gamma_{inv} \sim 2$ MeV
- Recoil mass ± 10 GeV of M_{h^0}, thrust hemispheres, veto neutral clusters > 5 GeV and any track activity in "away" hemisphere

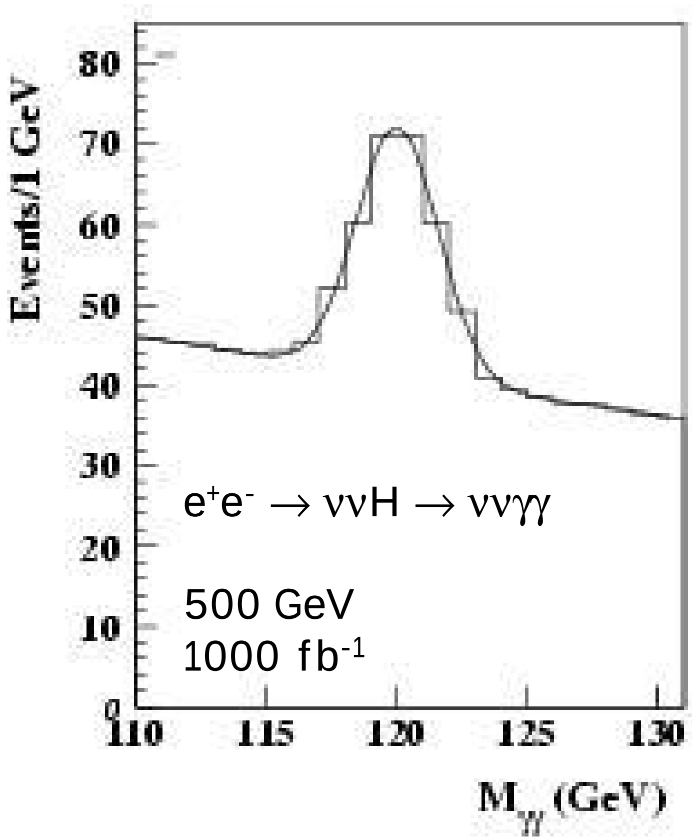


Snowmass Study

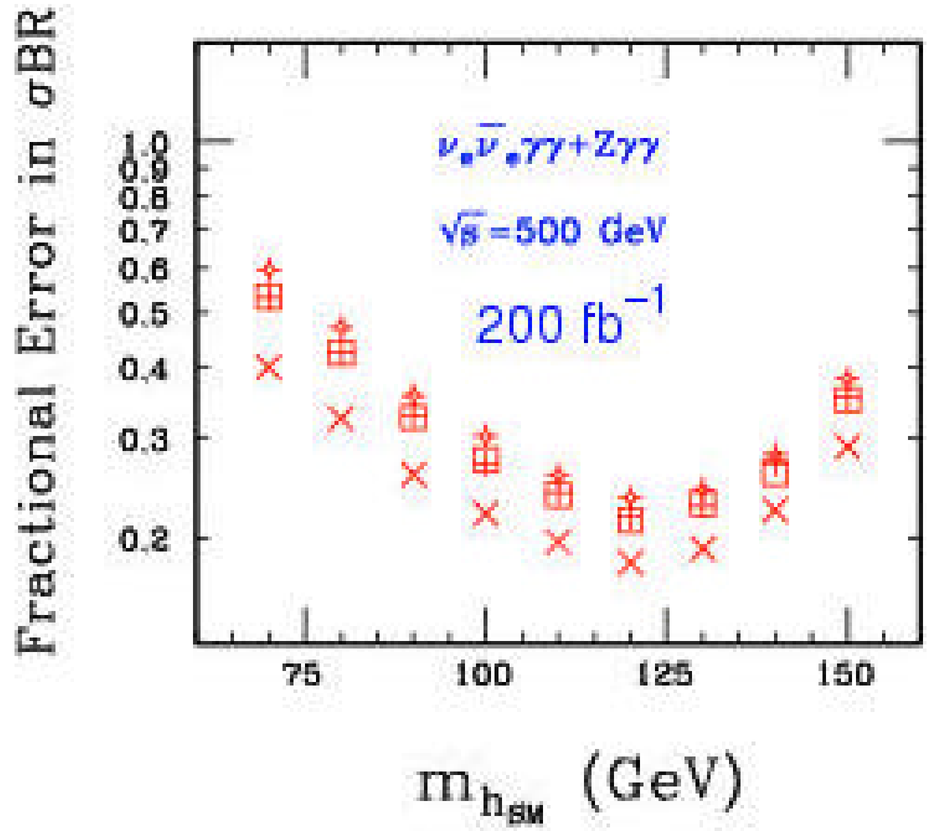
- *Preliminary*: Measure $\frac{\delta Br(h \to invis)}{Br(h \to invis)} \sim 12\%$

- Add hadronic *Z* decays! (should gain factor ~2 in above precision)

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



TESLA TDR, Fig 2.2.3(b)



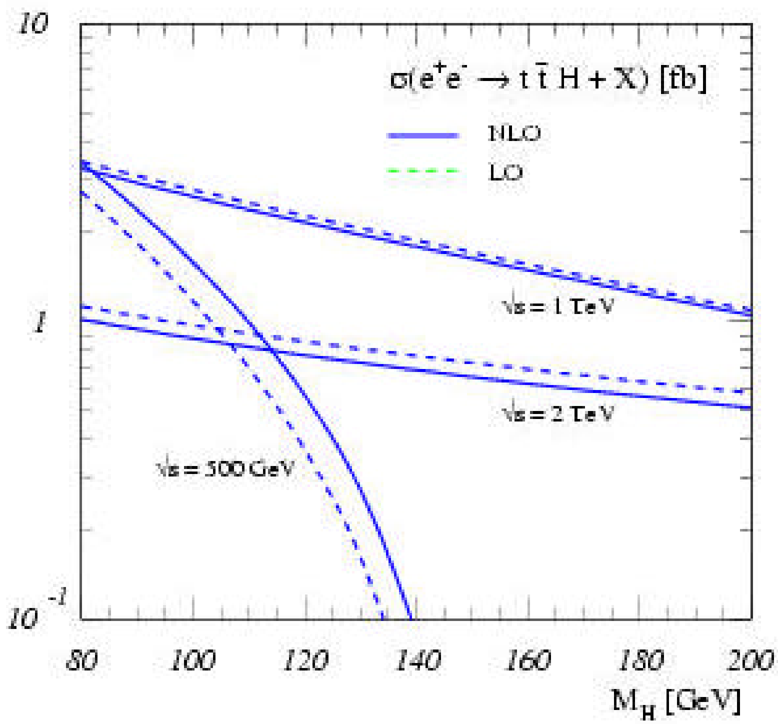
LC Physics Resource Book, Fig 3.21

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: $g^2_{ttH} \quad 0.5$

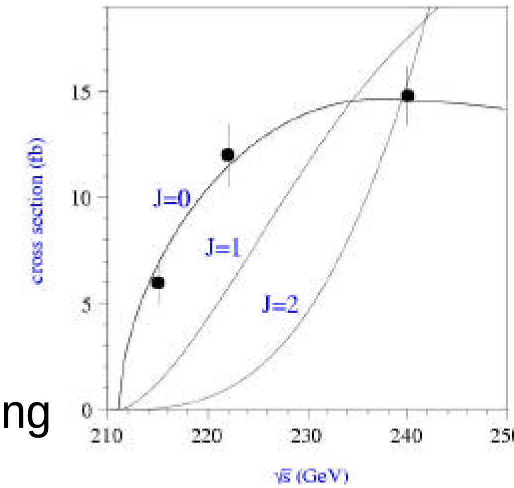


This measurement will require large luminosity, and probably high energy

Higgs Spin Parity and Charge Conjugation (J^{PC})

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

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

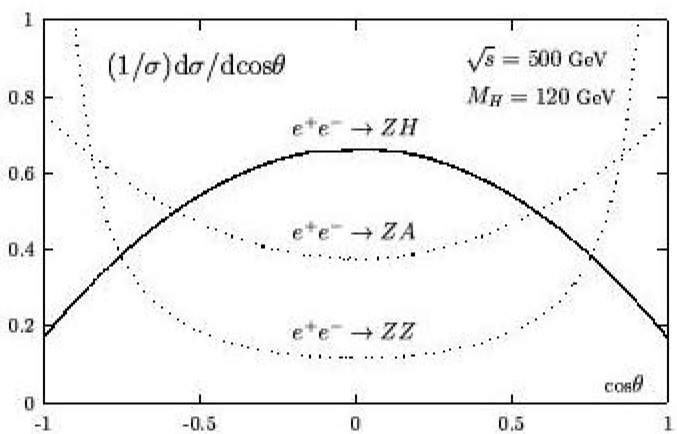


LC Physics Resource Book, Fig 3.23(a)

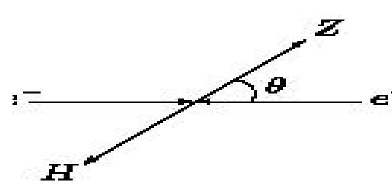
Production angle (θ) and Z decay angle in Higgs-strahlung reveals J^P ($e^+e^- \rightarrow ZH \rightarrow f\bar{f}H$)

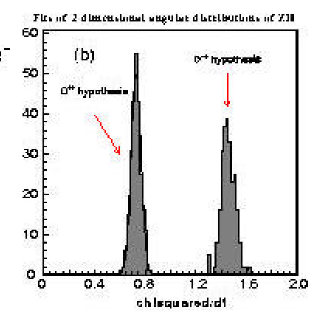
	$J^P = 0^+$	$J^P = 0^-$
$d\sigma/d\cos\theta$	$\sin^2\theta$	$(1 - \sin^2\theta)$
$d\sigma/d\cos\phi$	$\sin^2\phi$	$(1 +/- \cos\phi)^2$

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



TESLA TDR, Fig 2.2.8





Also $e^+e^- \rightarrow e^+e^-Z$
Han, Jiang

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: $e^+e^- \to Zhh$

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^{500}_{hhZ}	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 This the Standard Model Higgs?

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 $H \to gg$)
bb	$\delta g_{Hbb} / g_{Hbb} \approx 2$ %
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$\tau^+\tau^-$	$\delta g_{H\tau\tau} / g_{H\tau\tau} \approx 5$ %
WW	$\delta g_{Hww} / g_{Hww} \approx 2$ %
ZZ	$\delta g_{HZZ} / g_{HZZ} \approx 6$ %
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)

Is This the Standard Model Higgs?

1.) Does the hZZ coupling saturate the Z coupling sum rule?

$$\Sigma\, g_{hZZ} = M_Z^2\, g_{ew}^2 \;/\; 4 \cos^2 \theta_W$$

eg. $g_{hZZ} = g_Z M_Z \sin(\beta-\alpha)$
$g_{HZZ} = g_Z M_Z \cos(\beta-\alpha)$ $\qquad g_Z = g_{ew}/2 \cos\theta_W$

2.) Are the measured BRs consistent with the SM?

eg. $g_{hbb}^{MSSM} = g_{hbb}(-\sin\alpha \;/\; \cos\beta) \rightarrow -\, g_{hbb}(\sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta\,)$
$g_{h\tau\tau}^{MSSM} = g_{h\tau\tau}(-\sin\alpha \;/\; \cos\beta) \rightarrow -\, g_{h\tau\tau}(\sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta\,)$
$g_{htt}^{MSSM} = g_{htt}(-\cos\alpha \;/\; \sin\beta) \rightarrow g_{htt}(\sin(\beta-\alpha) + \cos(\beta-\alpha) \;/\; \tan\beta\,)$

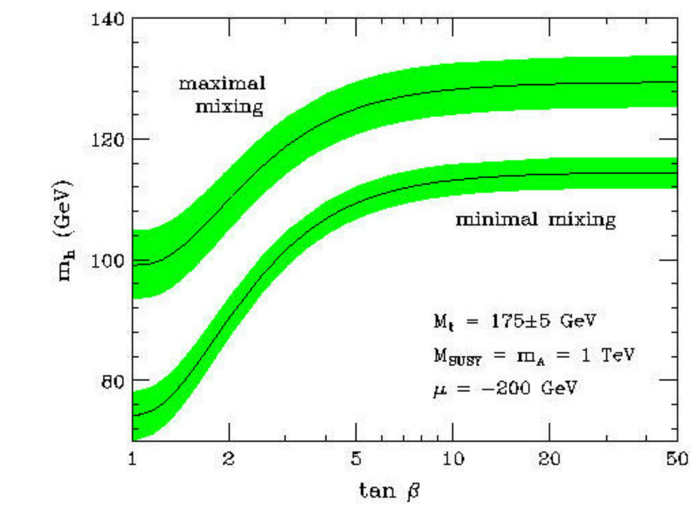
(in MSSM only for smaller values of M_A will there be sensitivity, since $\sin(\beta-\alpha) \rightarrow 1$ as M_A grows -decoupling)

3.) Is the width consistent with SM?

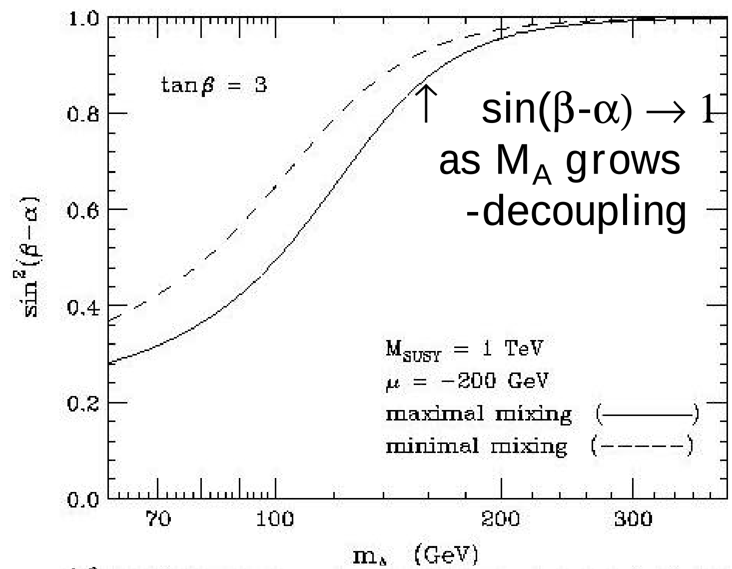
4.) Have other Higgs bosons or super-partners been discovered?

5.) etc.

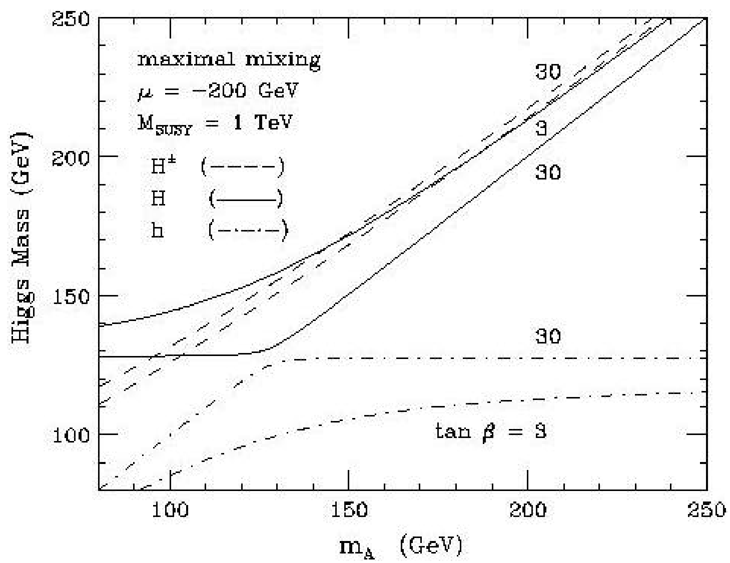
MSSM Higgs



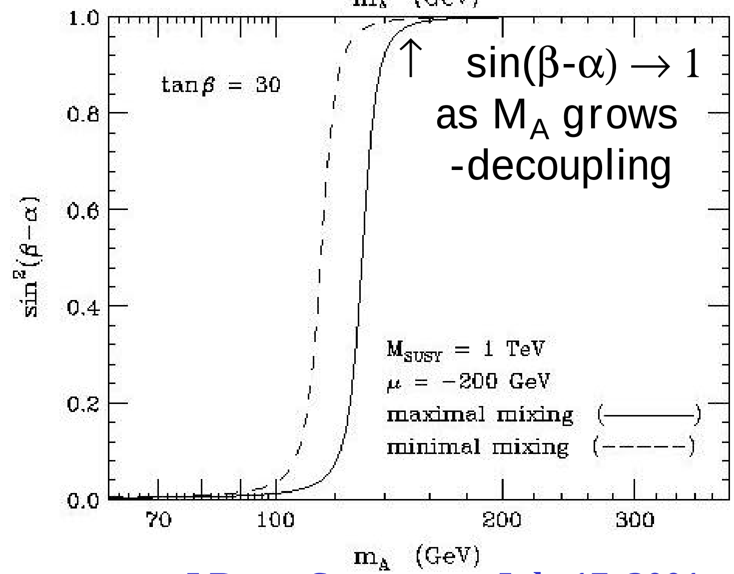
maximal mixing
minimal mixing
M_t = 175±5 GeV
M_{SUSY} = m_A = 1 TeV
μ = −200 GeV
m_h (GeV)
tan β



tan β = 3
sin(β-α) → 1
as M_A grows
-decoupling
M_{SUSY} = 1 TeV
μ = −200 GeV
maximal mixing (———)
minimal mixing (- - - - -)
$\sin^2(\beta-\alpha)$
m_A (GeV)



maximal mixing
μ = −200 GeV
M_{SUSY} = 1 TeV
$H^\pm$ (- - - - -)
H (———)
h (-·-·-)
tan β = 3
Higgs Mass (GeV)
m_A (GeV)



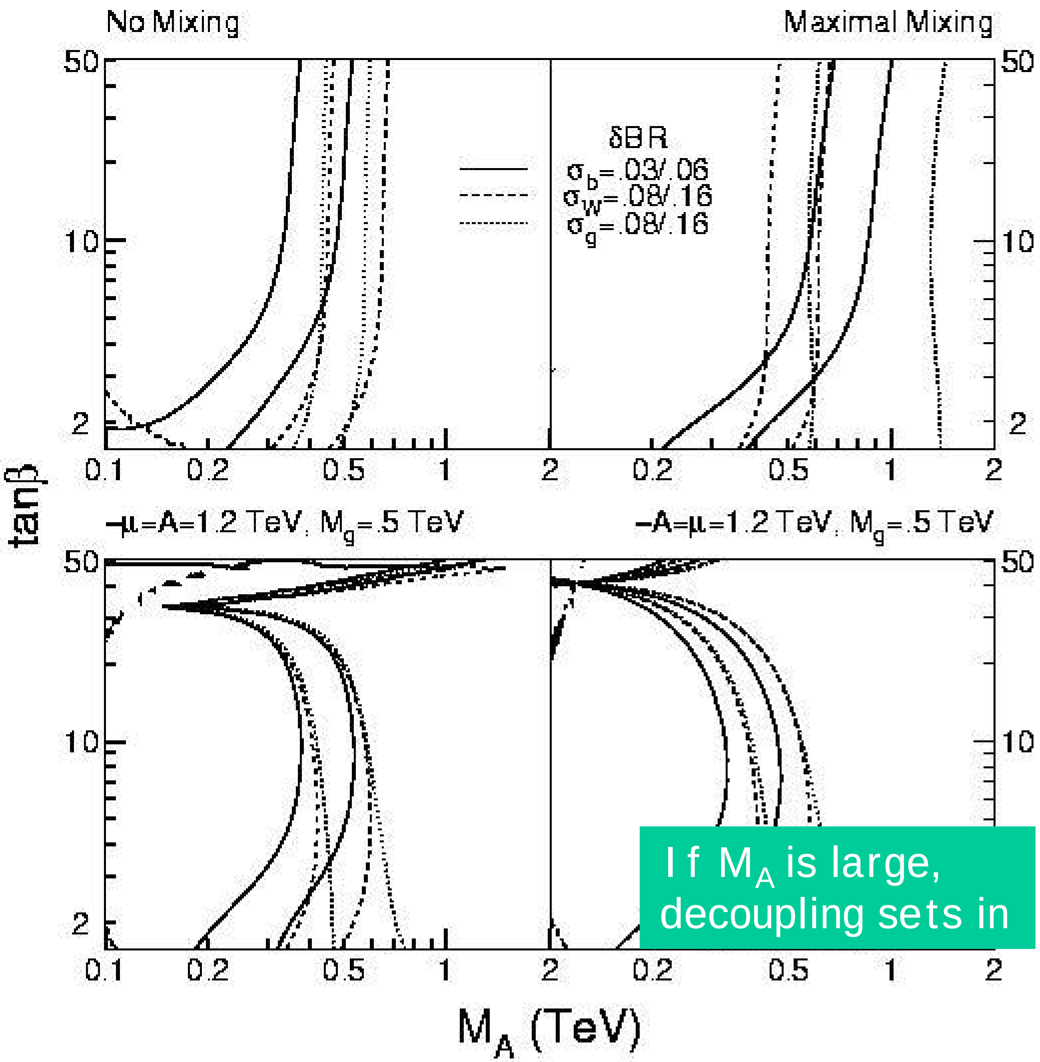
tan β = 30
sin(β-α) → 1
as M_A grows
-decoupling
M_{SUSY} = 1 TeV
μ = −200 GeV
maximal mixing (———)
minimal mixing (- - - - -)
$\sin^2(\beta-\alpha)$
m_A (GeV)

Is This the Standard Model Higgs?

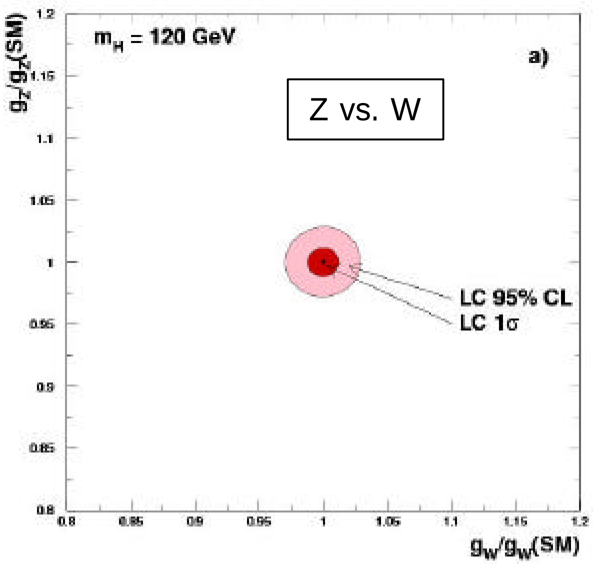
Are the measured BRs consistent with the SM?
(only for smaller values of M_A will there be sensitivity -decoupling)

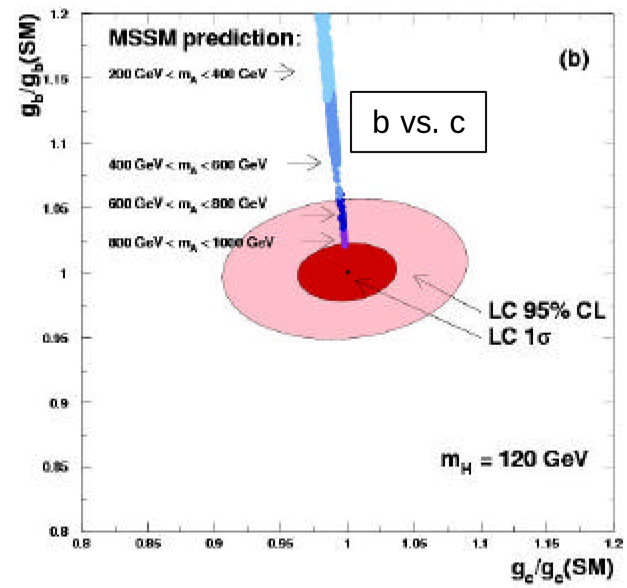
⇒

M. Carena, H.E. Haber, H.E. Logan, and S. Mrenna, FERMILAB-Pub-00/334-T



Is This the Standard Model Higgs?

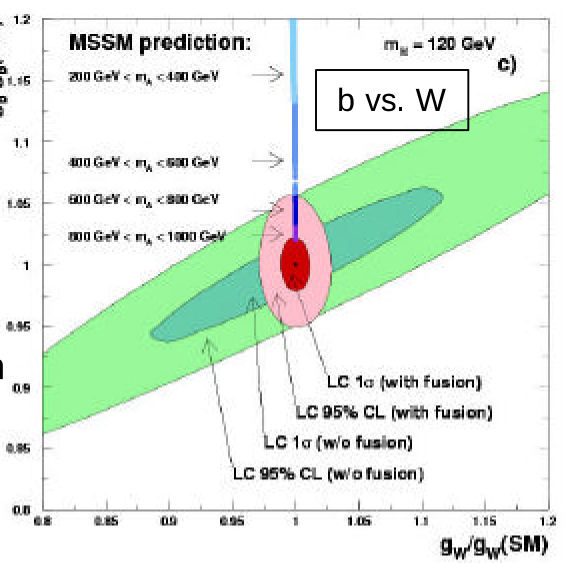


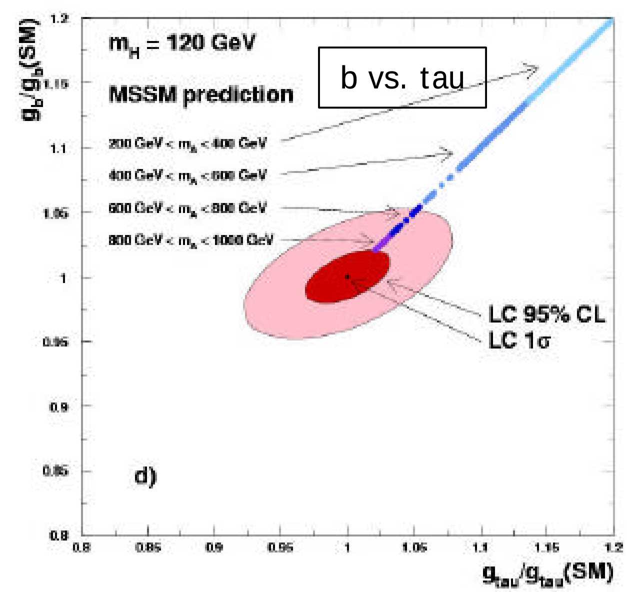


Arrows at:
M_A = 200-400
M_A = 400-600
M_A = 600-800
M_A = 800-1000

HFITTER output

conclusion:
for M_A < 600,
likely distinguish

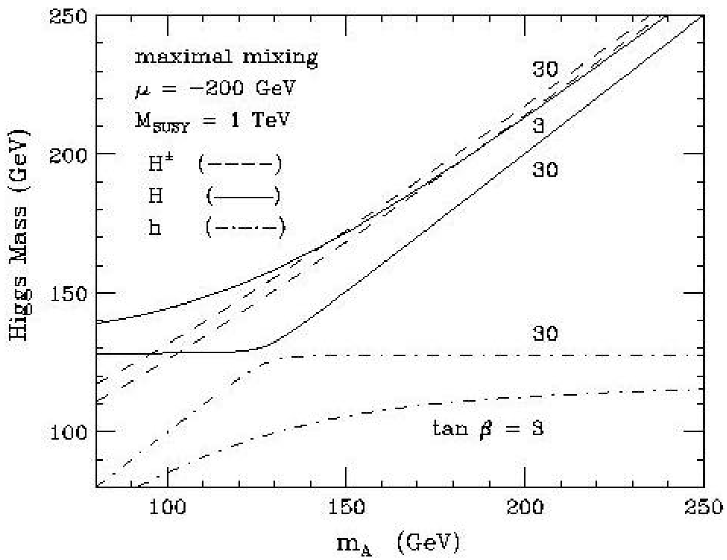




TESLA TDR, Fig 2.2.6

MSSM Higgs Bosons

For $M_A > 150$ GeV, MSSM Higgs sector approaches decoupling



Accessible production mechanisms for heavier MSSM Higgs':

$e^+ e^- \to Z^* \to H^0 A^0$ for $\sqrt{s} > M_A/2$

$e^+ e^- \to \gamma^* \to H^+ H^-$ for $\sqrt{s} > M_H/2$

$\gamma\gamma \to A^0$ $\gamma\gamma \to H^0$

Complementarity with LHC

The SM-like Higgs Boson

	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.*

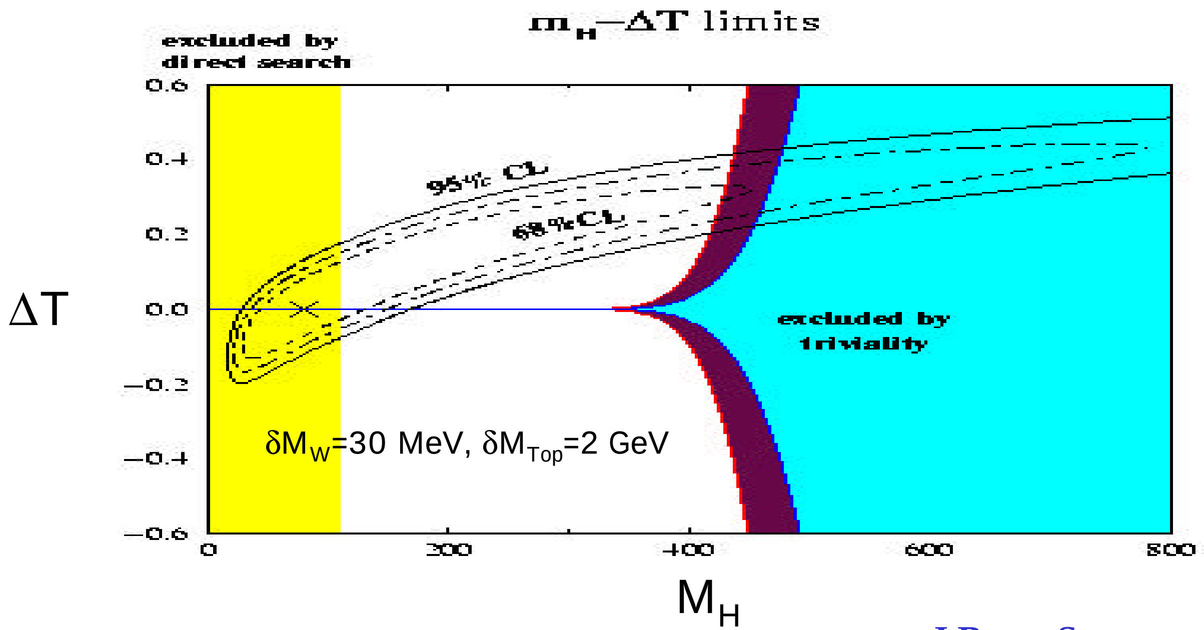
These precision measurements will be crucial in understanding the Higgs Boson

TESLA TDR, Table 2.5.1

Strong Coupling Gauge Models

Suppose EWSB is not explained by fundamental scalars.
Suppose a new strong interaction provides the Higgs mechanism for EWSB.

At the LC, strong coupling composite 'higgs' should be constrained to < 500 GeV with **Giga Z**.



Strong Coupling Gauge Models

Strong coupling Observables at LC:

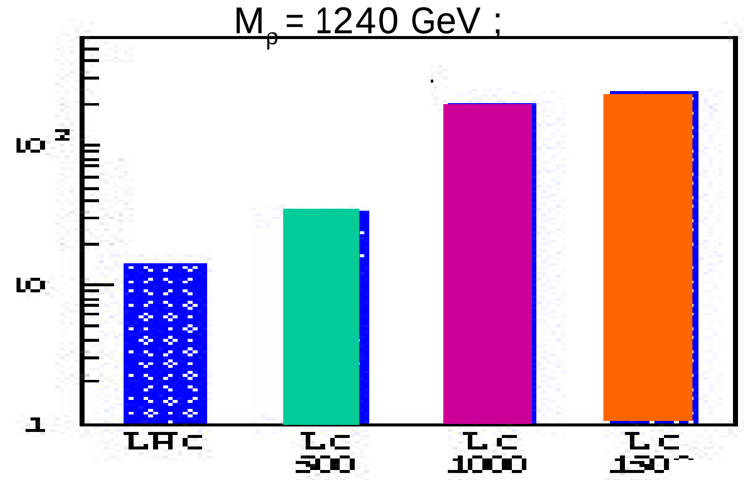
Bound states of new fermions should occur on the TeV scale.

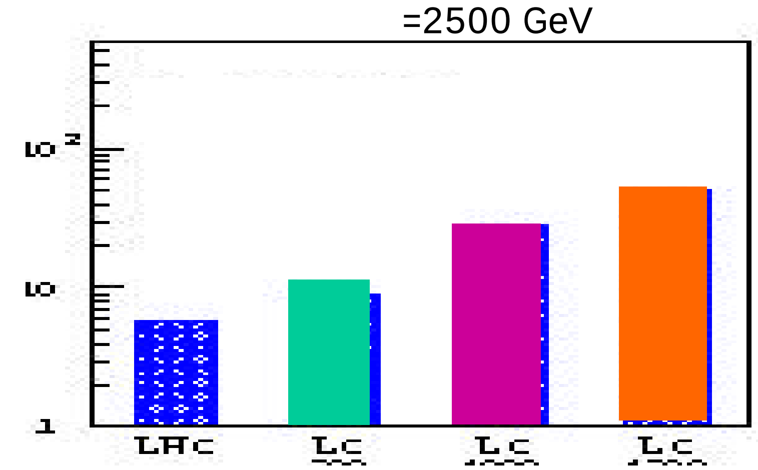
Since the longitudinal components of W/Z are primordial higgs particles, WW (ZZ) scattering is modified:

a broad resonance is seen at LHC

LC sees modification to $e^+ e^- \rightarrow$ WW cross section

Significance





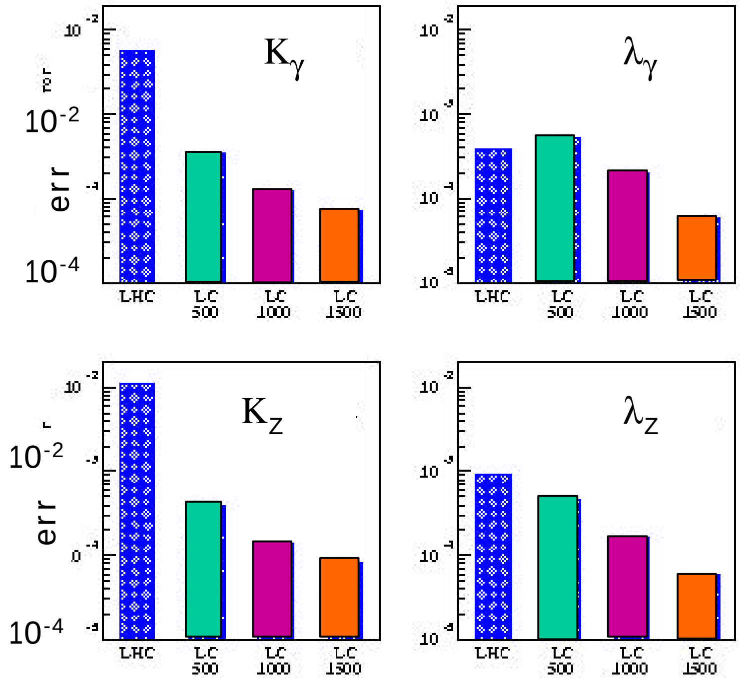
Technirho relative signal significance for **LHC** and **LC** at **500**, **1000**, **1500** GeV

Strong Coupling Gauge Models

Expect observable modifications to $WW\gamma$ coupling.

For $\Delta\kappa_{\gamma,Z}$, LC at 500 GeV has precision 10-20 times better than LHC – in the range expected in Strong Coupling models.

$\gamma\gamma \rightarrow WW$ gives orthogonal information of comparable precision.



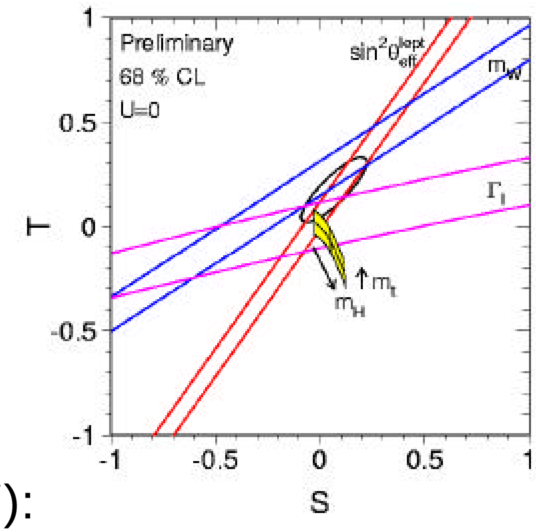
Errors on $WW\gamma$ / WWZ coupling for **LHC** and LC at **500** , **1000** , **1500** GeV

Discovery reach for **Z'** at **LC500** is better or comparable to **LHC** for different models; better for **LC1000** by factor ~2.

Anomalous top couplings to Z,γ are expected, only observable at LC.

Other Scenarios

Imagined other scenarios must introduce EWSB consistent with precision EW measurements.



Scenarios have been investigated.

(Peskin & Wells hep-ph/0101342)

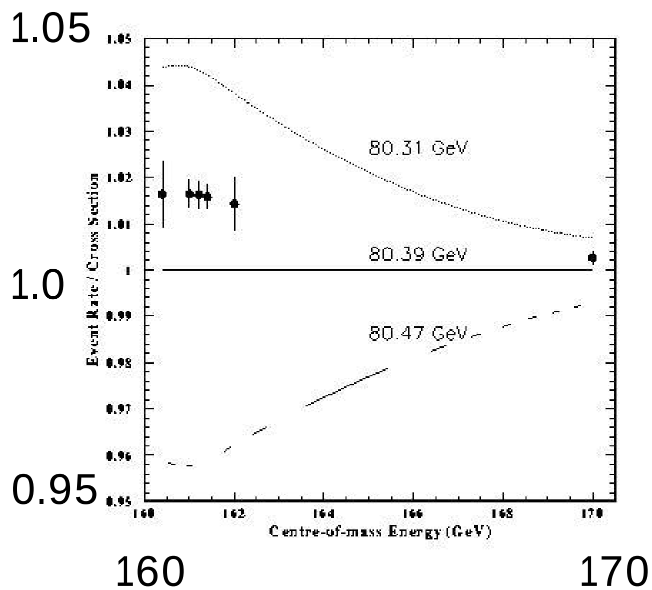
Generally, additional new physics emerges which the LC is able to detect.

Examples (these are highly selective, to match PrEW):

- Heavy Higgs (say 500 GeV) + light SU(2)xSU(2) **(observe new particles)**
- Heavy Higgs (say 500 GeV) + Z′ **(observable)**
- Heavy Higgs (say 500 GeV) + extra dimen. **(detectable)**
- Heavy Higgs (say 500 GeV) + new particles with large up/down flavor asymmetry **(Giga-Z effects)**

The Linear Collider Options

Energy upgrades to ~ 1.0 -1.5 TeV
Positron Polarization (~ 40 - 60%?)
$\gamma\gamma$ Collisions
$e^- e^-$ and $e^-\gamma$ Collisions
Giga-Z (precision measurements)
and WW threshold



δM_W = 6 MeV

(positron polarization, one year)

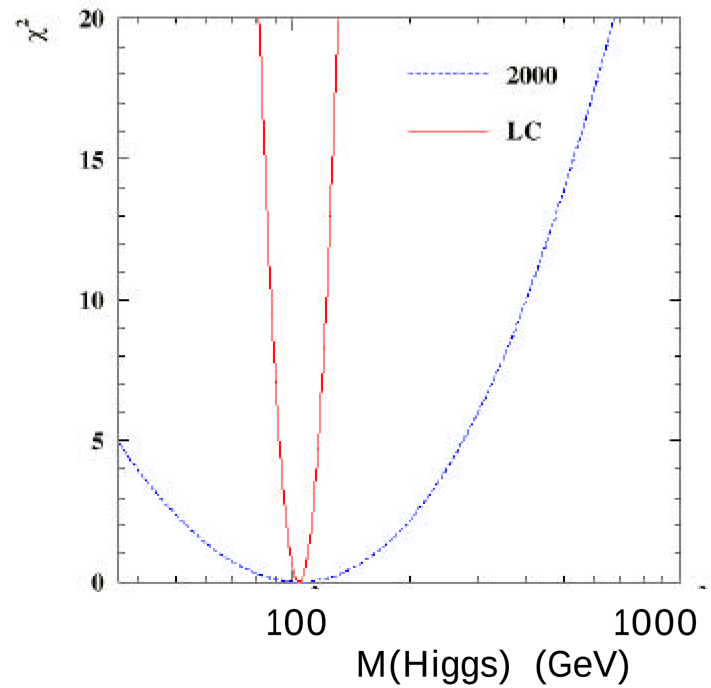
Giga-Z: Precision Studies at the Z

Some scenarios for the results of high energy measurements would motivate higher precision studies of the Z pole (100 days)

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%
($\delta\sin^2\theta_w$ = 0.000013, δm_W = 6 MeV,
δm_t = 100 MeV)

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

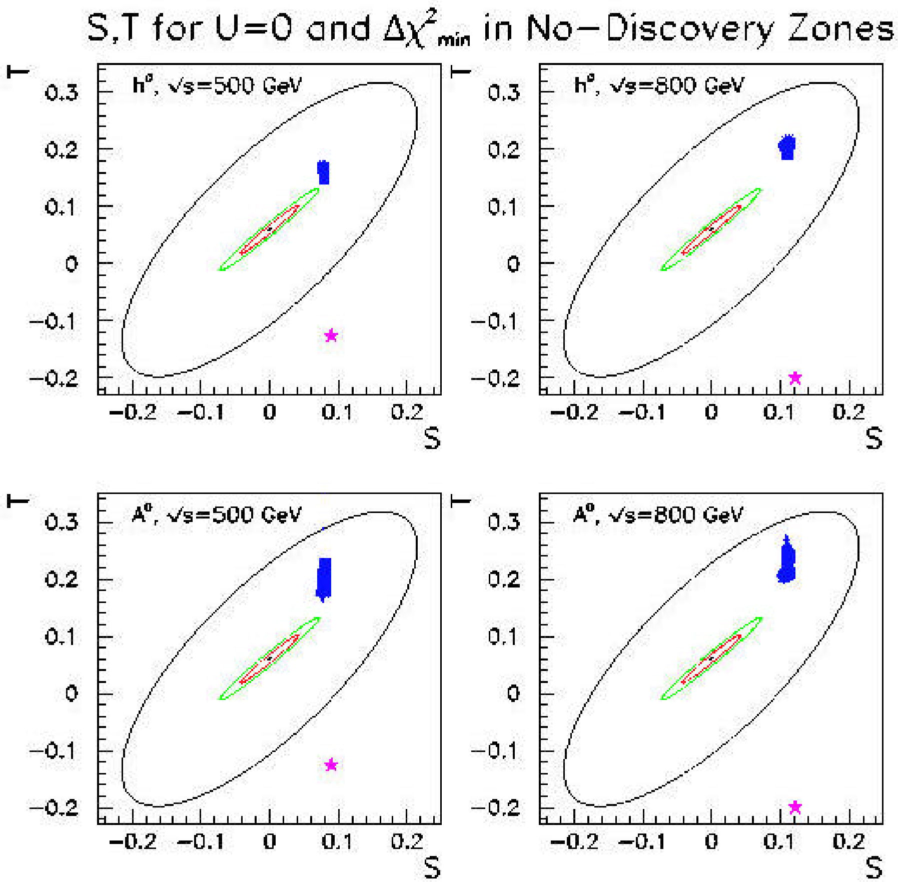


Giga-Z: Precision Studies at the Z

Blue blob is 2HDM for which no Higgs Boson is detected.

Inner ellipse for Giga-Z assuming M_H = 115 GeV.

☆ is expectation for $M_H = \sqrt{s}$



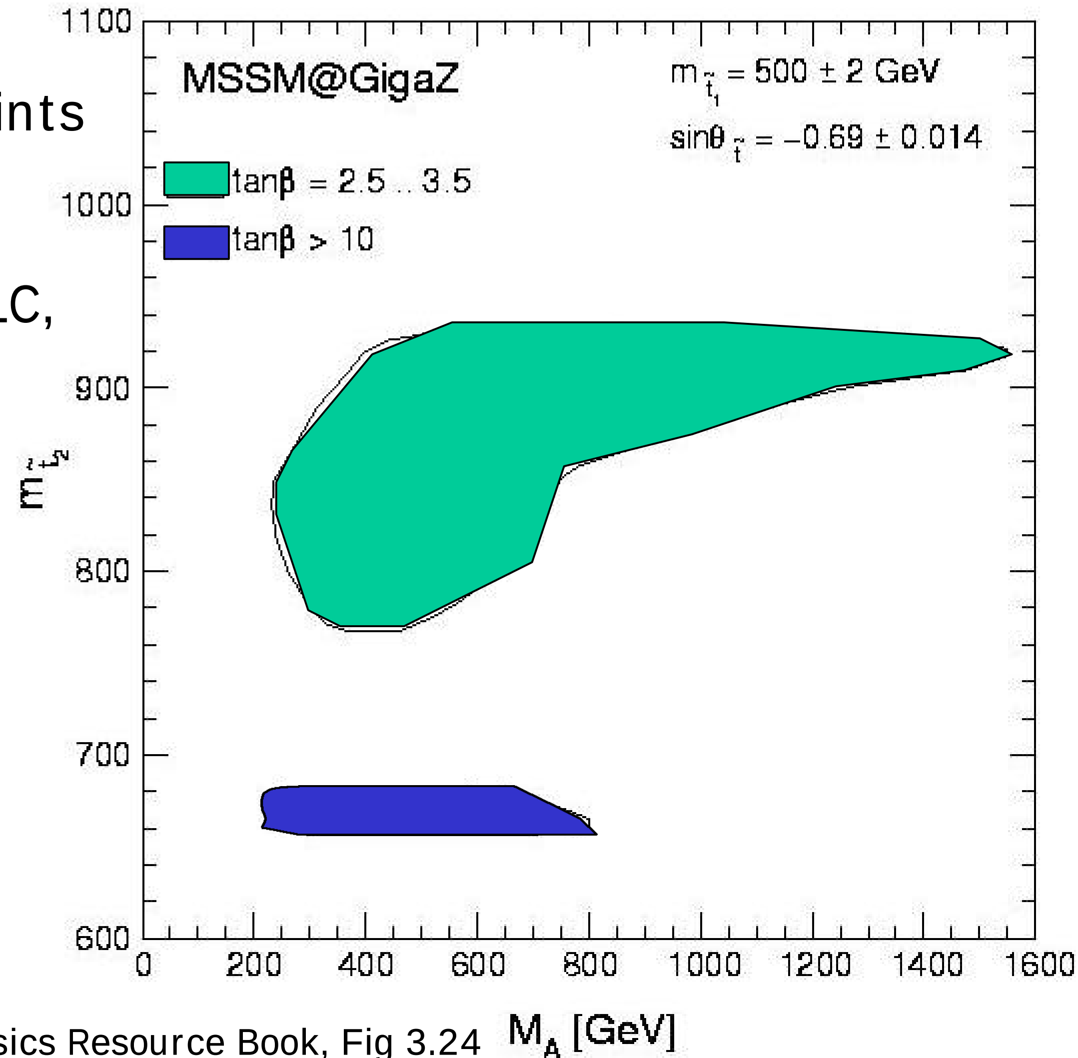
LC Physics Resource Book, Fig 3.15

Giga-Z: Precision Studies at the Z

Example of Giga-Z constraints on high mass:

$e^+ e^- \rightarrow \tilde{t}_1^+ \tilde{t}_1^-$ observed at LC,
$M_{\tilde{t}} = 500$ GeV

light higgs found:
$M_h = 120$ GeV



LC Physics Resource Book, Fig 3.24

Giga-Z: Precision Studies at the Z

"Topcolor" seesaw model (Dobrescu and Hill)

This model has little or no signatures of new physics at the LHC or the LC

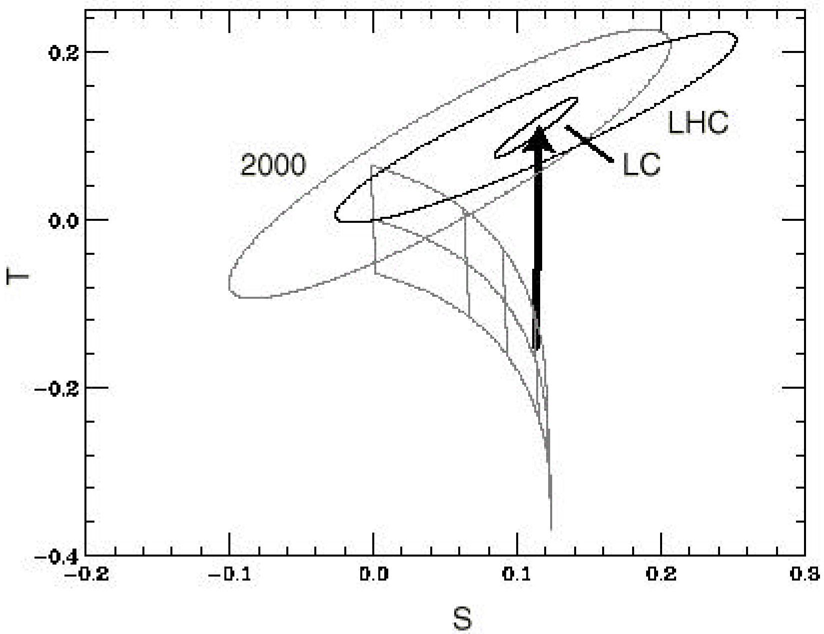
However, the Giga-Z run would be sensitive through the Giga-Z precision measurements

This model introduces a heavy, weak SU(2)-singlet fermion χ which adds positive ΔT to the EW measurements:

M_χ	ΔT
1 Tev	+7.2
5 TeV	+0.3

Giga-Z: Precision Studies at the Z

“Topcolor” seesaw model
$M_\chi = 5$ TeV



This is an example of a general principle:

If the electroweak measurements are to be explained by a “conspiracy” between a heavy SM Higgs and other new physics, that other new physics will generally be detectable at the LC

experimentalist paraphrase of Peskin and Wells hep-ph/0101342

The Gamma-Gamma Collider

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

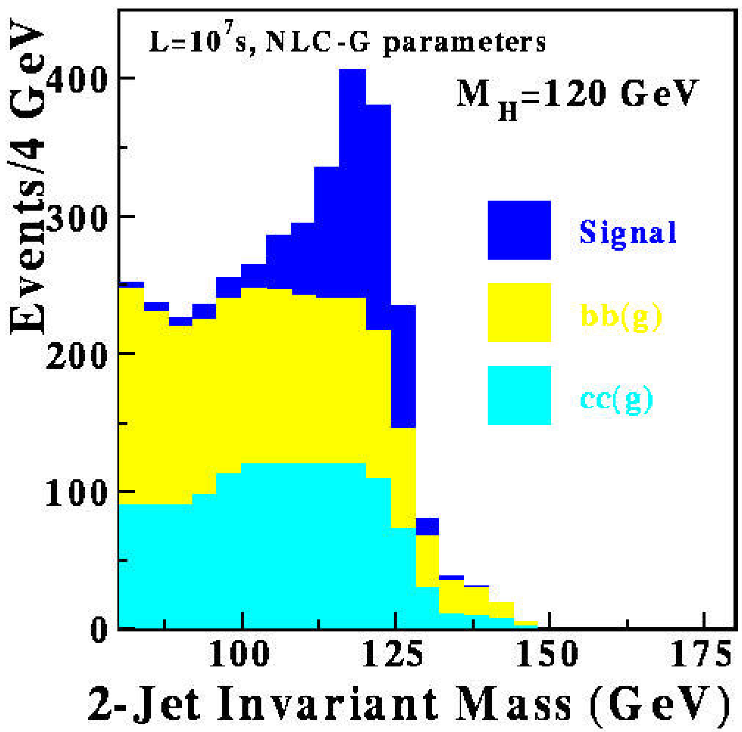
Measure $\gamma\gamma \rightarrow H \rightarrow X$

Also:

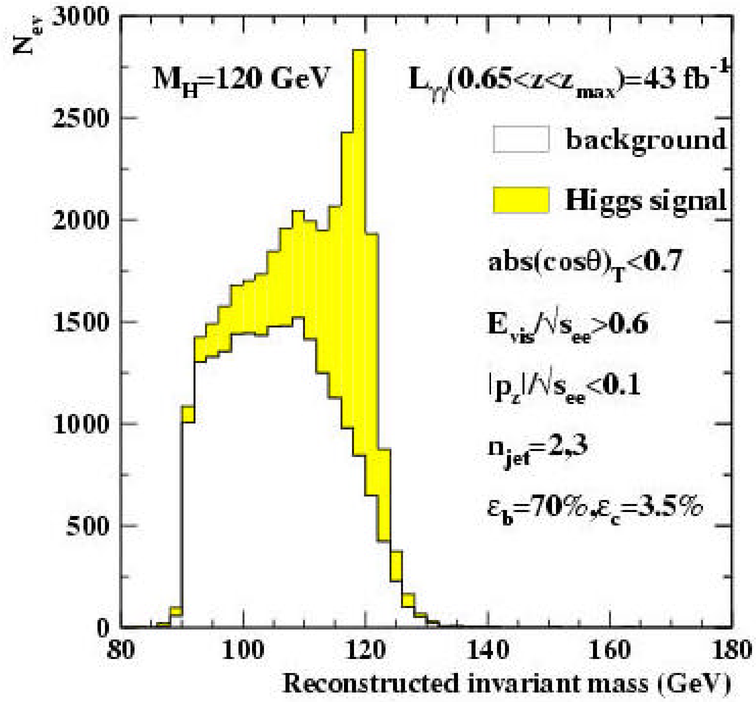
Production of Higgs at $\gamma\gamma$ collider establishes C to be positive
(and rules out J=1)

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



LC Physics Resource Book, Fig 3.26



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)

(however better as a result of Snowmass studies)

for M_H = 160 GeV 5% increases to 20%

Adding Value to LHC measurements

The Linear Collider will add value to the LHC measurements ("enabling technology")

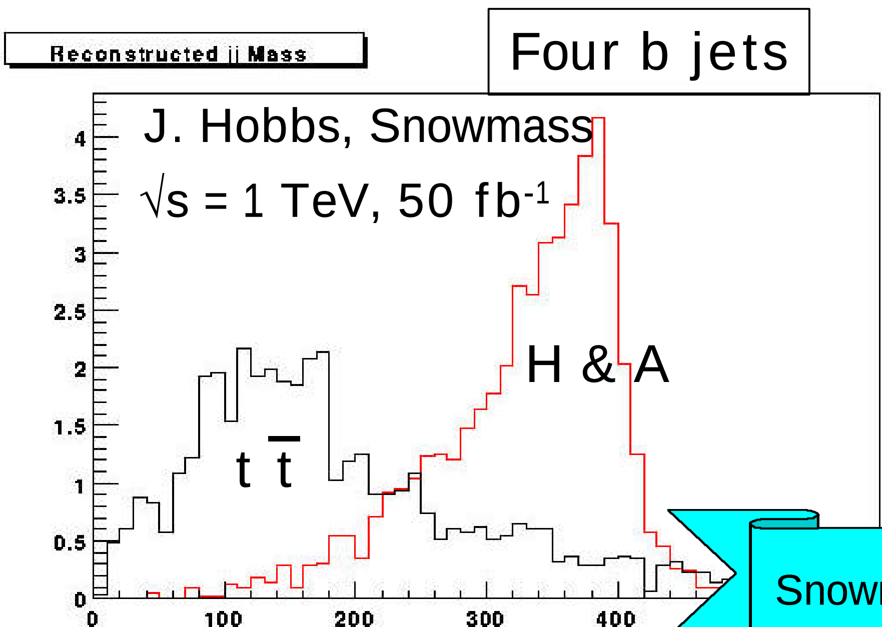
How this happens depends on the Physics:

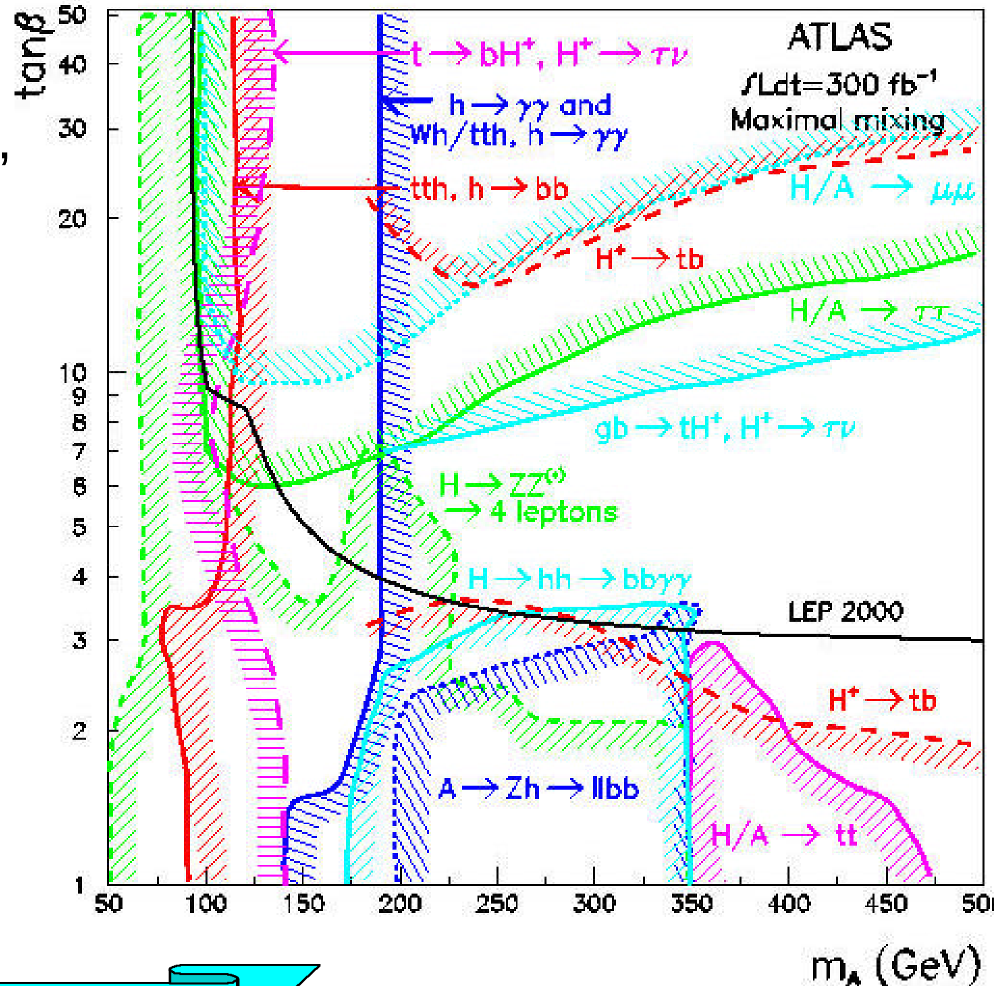
- Add precision to the discoveries of LHC
    - eg. light higgs measurements
- Susy parameters may fall in the tan β /M_A wedge.
- Directly observed strong WW/ZZ resonances at LHC are understood from asymmetries at Linear Collider
- Analyze extra neutral gauge bosons
- Giga-Z constraints

Complementing the LHC: the tanβ - M_A wedge

For tan β ~ 4-8 and M_A > 250 GeV, the LHC will have a difficult time detecting MSSM.

LC should add the detection.





Snowmass Study

Scheduling the Run Parameters

The Linear Collider has a broad role in elucidating the new physics:

- follow up on results of LHC
  - Higgs boson discovered?
  - Other new particles?
  - Evidence for strong coupling?
- measure details of light Higgs
- scan threshold of new particles
- W/top threshold scans
- Giga-Z

Can we devise a run plan that measures what we need to know in available time?

YES! Constrain time to that needed for 1000 fb^{-1} at 500 GeV.

Statistics for Higgs BRs equivalent to 700 fb^{-1} at 350 GeV

Example:
Light Higgs and superpartners seen at LHC

320 GeV	160 fb^{-1}	**sit**
500 GeV	245 fb^{-1}	**span**
255 GeV	20 fb^{-1}	**Chargino threshold scan**
265 GeV	100 fb^{-1}	**Slepton ($l_R^- l_R^+$) threshold scan**
310 GeV	20 fb^{-1}	**Slepton ($l_L^- l_R^+$) threshold scan**
350 GeV	20 fb^{-1}	**Top threshold scan**
450 GeV	100 fb^{-1}	**Neutralino($\chi_2^0 \chi_3^0$) threshold scan**
470 GeV	100 fb^{-1}	**Chargino($\chi_1^- \chi_2^+$) threshold scan**

Ref: Linear Collider Physics Resource Book, SM2001

Conclusion

The Linear Collider will be a powerful tool for studying the Higgs Mechanism and Electroweak Symmetry Breaking.

Current status of Electroweak Precision measurements strongly suggests that the physics will be rich and greatly advance our understanding of the elementary particles

If Nature turns out to be more complicated than the simplest models, its precision could be critical