Probing the EWSB dynamics at an e+e- linear collider

WIN'03, 6-11 October, 2003

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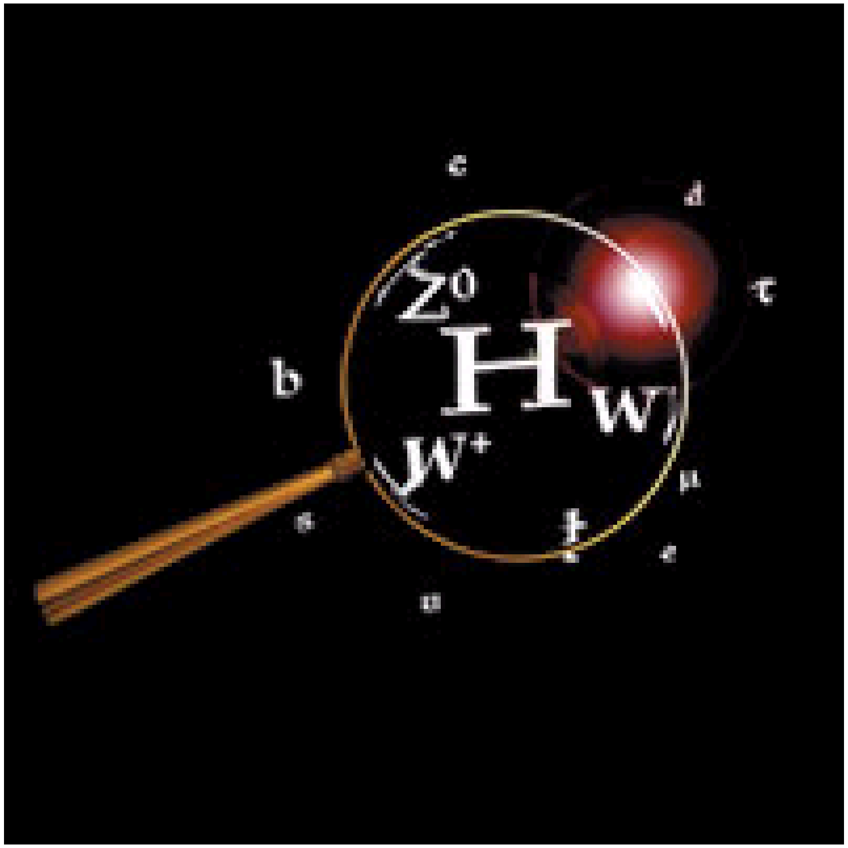
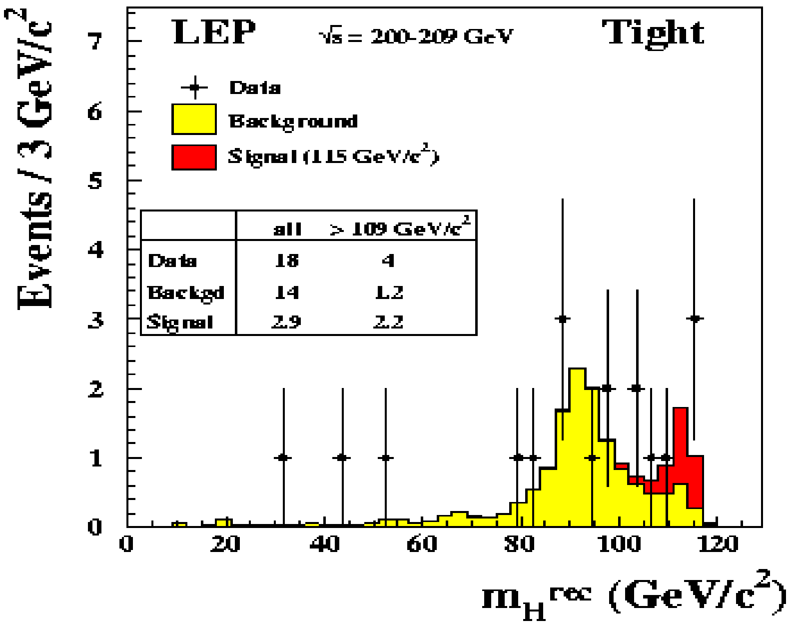
OUTLINE

- ➢ Introduction
- ➢ EWSB program at a LC
- ➢ Conclusions



Current experimental “knowledge” on EWSB

- During the last decade the SM has been confirmed experimentally beyond reproach (some “3σ anomalies” remain). However, the dynamics for EWSB still awaits direct experimental verification.
- Searches at LEP2 yielded tantalizing hints (1.7σ) of a SM-like Higgs boson with m_H~115 GeV:

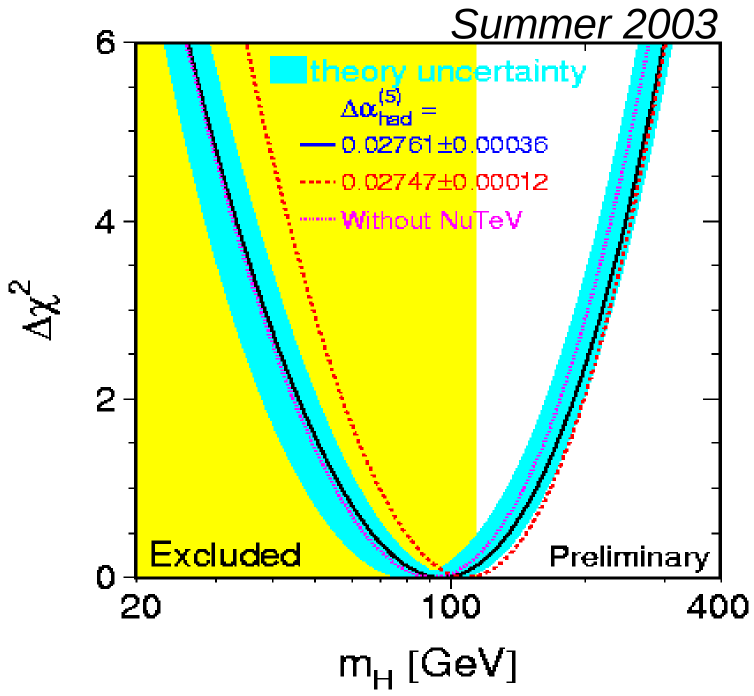


m_h> 114.4 GeV (95% CL)

- The high accuracy achieved (both experimental and theoretical) allows to perform tests at the quantum level:

➔Precision EW observables ~log(m_H) at the 1-loop level.

➔Some sensitivity to the EWSB sector (requires careful interpretation)



m_h< 219 GeV (95% CL)

What is the significance of all this?

- The upper limit on m_h from precision EW data is under the assumption that new physics beyond the SM makes a negligible contribution.
- Present experimental data not sufficient to identify with certainty the dynamics responsible for EWSB, which will likely require ingredients beyond the SM
  - More complex Higgs sector
  - New particles affecting EW observables

  } May considerably weaken upper bound from fits to EW data

  After all, the self-interacting scalar field is only one model of EWSB; other approaches, based on very different dynamics are also possible…

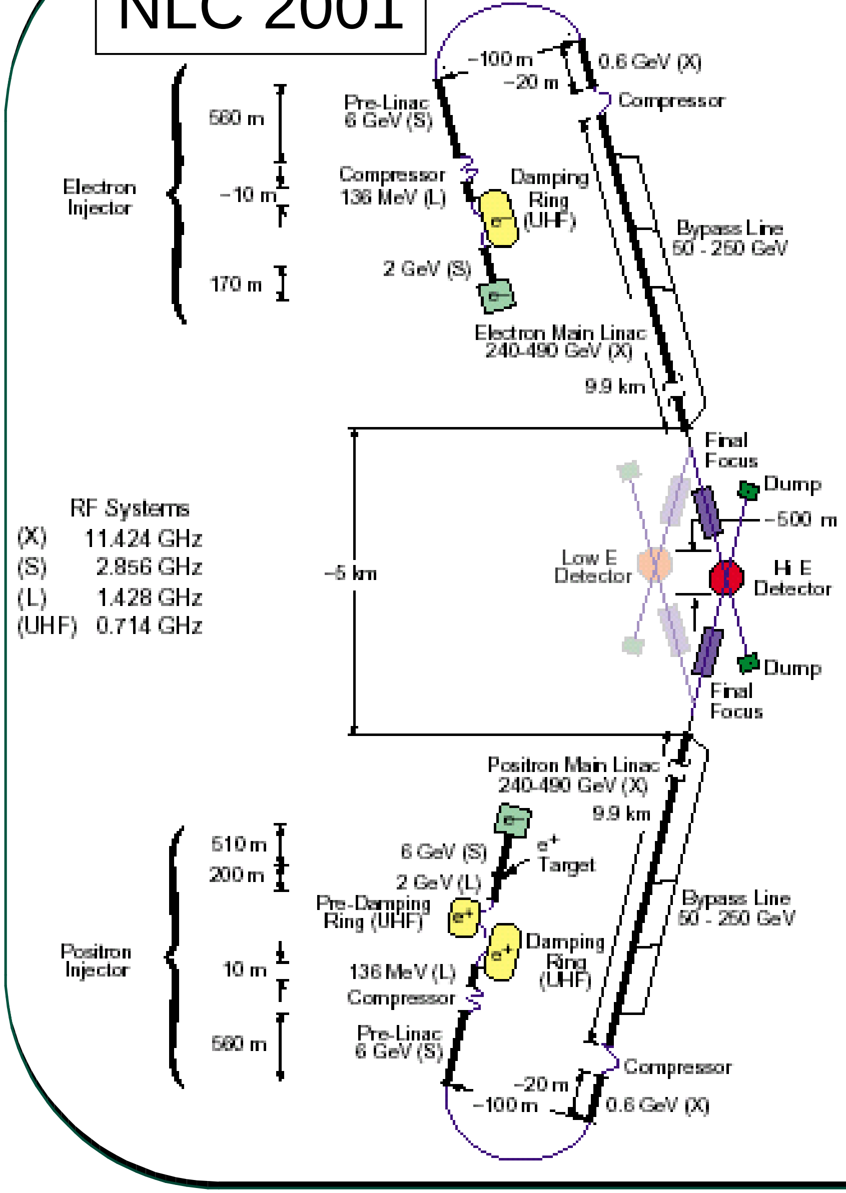
General Model of EWSB

- Underlying $SU(2)_L \times U(1)_Y$ symmetry
- New fields which:
  - spontaneously break $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$
  - couple to the W and Z ➔ contribute to EW radiative corrections
- There is not necessarily a light narrow Higgs resonance (but a compensation mechanism needed to recover agreement with EW precision data).

- Decoupling limit: many extended models of EWSB posses a limit in which they are experimentally almost indistinguishable from the SM:
  - Usually predict a weakly coupled Higgs boson with $m_h \leq$ 200-300 GeV.
  - Agree with precision EW data equally well.

The machine (baseline design)

NLC 2001



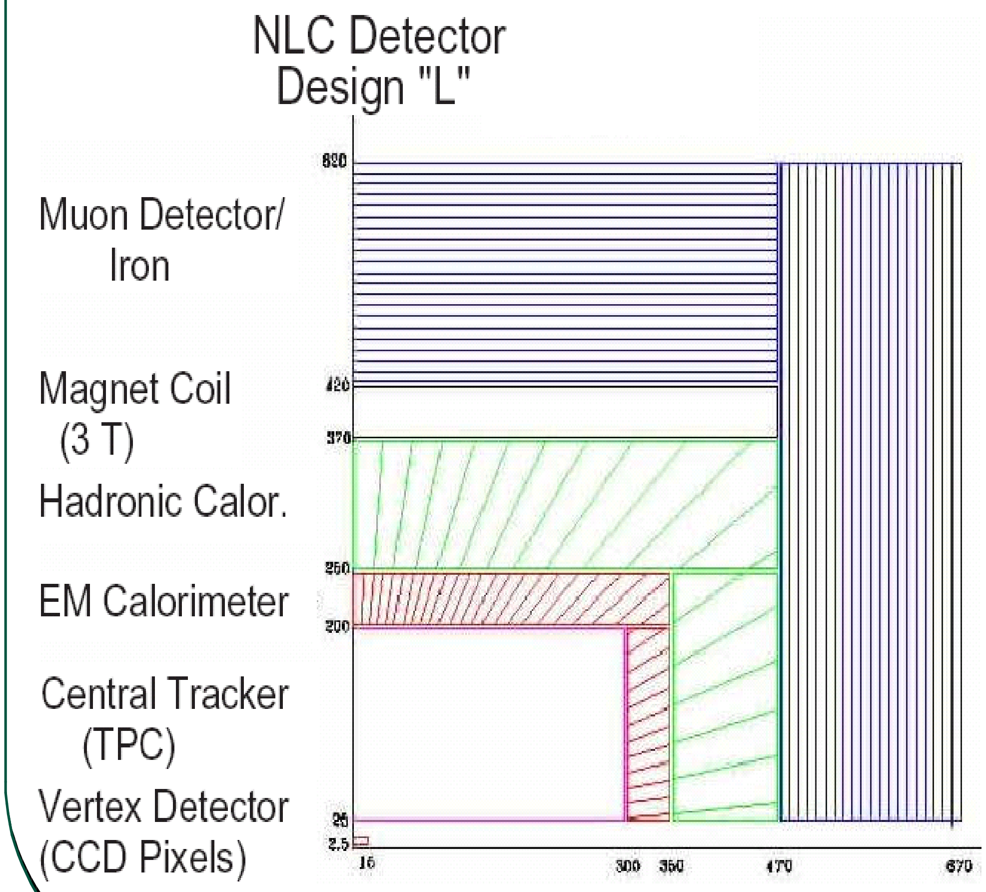
	TESLA	NLC
Technology	Supercond.	Warm Cu
Max √s (GeV)	500…800++	500…1000
$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	3.4…5.0	2.2…3.4
	Parameters at 500 GeV	
Linac length (km)	31	10.8
Gradient (MV/m)	22	50.2
RF (GHz)	1.3	11.4
Repetition rate (Hz)	5	120/60+60
#Bunches/train	2800	190
Bunch separation (ns)	337	1.4
σ_x/σ_y @ IP (nm)	553/5	?
Beamstrahlung (%)	3.3	4.6
e^- polarization	80%	
# IR	1	2
Xing angle @ IP (mrad)	30	20/20-40

OPTIONS

- ➢ energy upgrades to ~1.0-1.5 TeV
- ➢ e^+ polarization (40-60%)
- ➢ γγ collisions
- ➢ e^-e^- and $e^-\gamma$ collisions
- ➢ low energy running ($\sqrt{s} = m_Z$ and $2m_W$)

The generic detector

- ➢ High resolution detectors, based on the experience from LEP/SLD and R&D for the LHC.
- ➢ Several designs (in the case of the NLC) under consideration.



Detector design largely driven by performance optimization for Higgs physics:

- ➢ Precise vertexing (1 cm beampipe):

$$\Delta(\mathrm{IP}_{r\phi,z}) \le 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m\,GeV/c}}{p\sin^{3/2}\vartheta}$$

- ➢ Excellent global tracking (B=3-5 T):

$$\Delta(1/p_T) \le 5\times10^{-5}\ (\mathrm{GeV/c})^{-1}$$

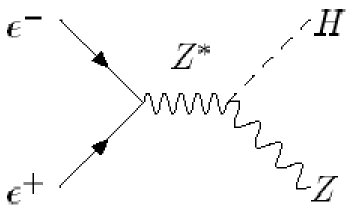
$$\text{systematics} \le 10\,\mu\mathrm{m}$$

- ➢ Highly granular calorimetry (EM transverse segmentation < 3 x 3 cm^2) for optimal energy flow.
- ➢ Energy flow jet energy resolution:

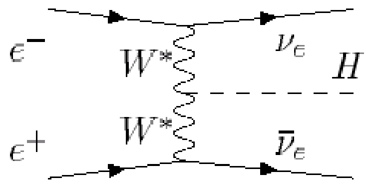
$$\frac{\Delta E}{E} \approx \frac{0.3}{\sqrt{E/\mathrm{GeV}}}$$

Higgs boson production at a LC

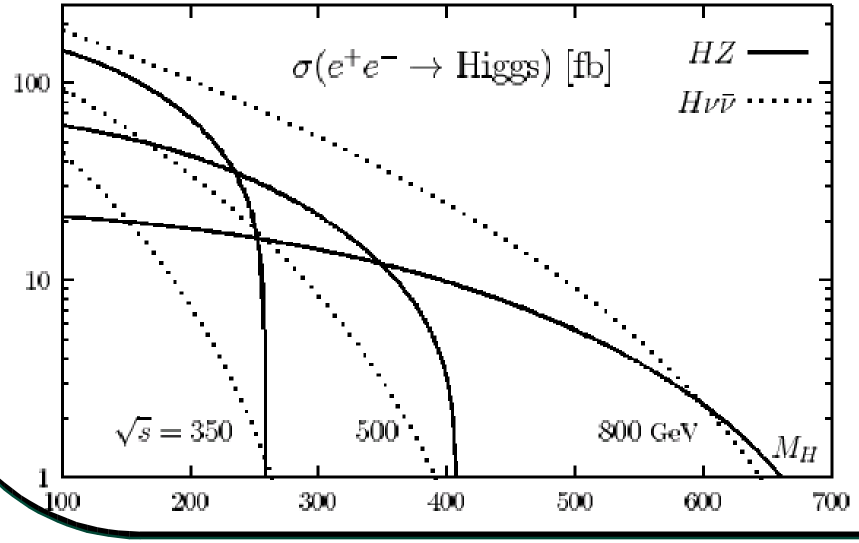
- Within the SM (and nearly decoupled extensions), two main production mechanisms in e^+e^- collisions:
  - Higgstrahlung: on-shell Z boson provides important trigger.
    σ_{max} at $\sqrt{s} \sim m_Z + m_H + 20$ GeV, then $\sigma \sim 1/s$
  - Weak boson fusion: dominated by WW-fusion.
    $\sigma \sim \ln(s)$, therefore dominant production mechanism for $\sqrt{s} \gg m_H$
- Main background processes are ZZ and WW.
- $\sqrt{s} = 350$ GeV
  $m_H = 120$ GeV
  $L = 500\ \text{fb}^{-1}$ (~2 years)
  } ~ 90k Higgs evens produced (ZH + Hνν)



Higgstrahlung



WW-fusion

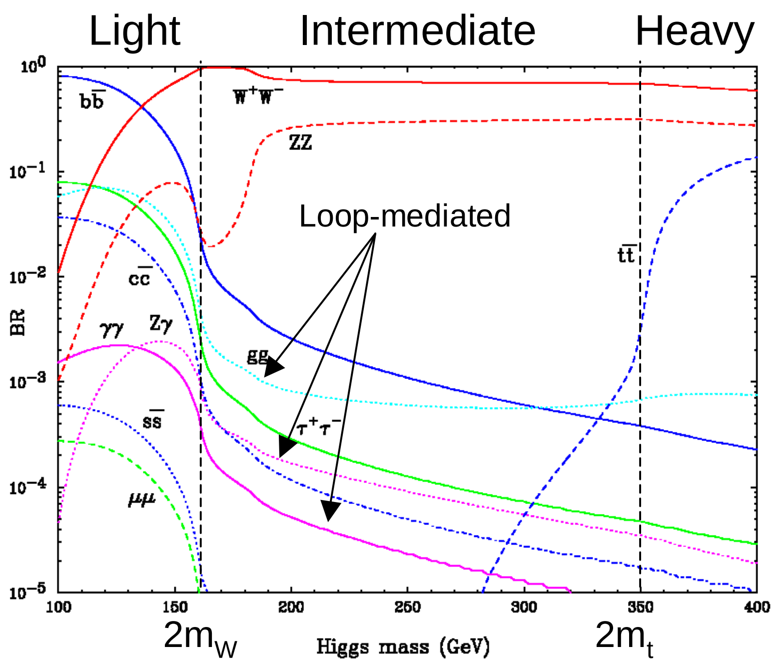


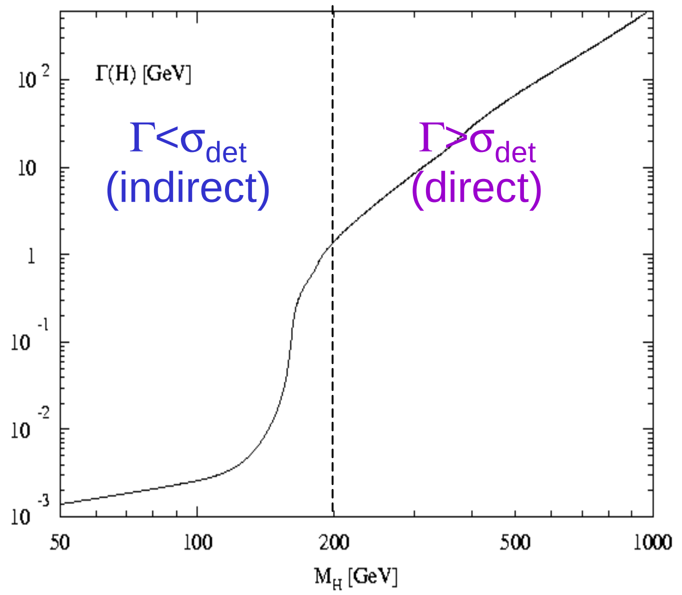
ZH Hνν

Luminosity	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
√s (GeV)/ m_H (GeV)	350	500	800
120	74k / 15.5k	35k / 37.5k	27k / 158k
160	52k / 7.5k	29k / 25k	24k / 126k
250	5.5k / 6.5k	16.5k / 8k	19k / 71k

Standard Higgs

- The decay properties of the nearly-standard Higgs are a strong function of its mass:





- Since $g_{HXX} \propto m_X$, the phenomenology is governed primarily by the couplings to W, Z and 3rd generation fermions.
- Subdominant decay modes important to establish a complete phenomenological profile of the Higgs boson as well as to check consistency with the SM
- Rare decay modes, e.g. $H \rightarrow \gamma\gamma$ also very important (LHC in low-mass region, $\gamma\gamma$-collider)

Outlining the Higgs boson profile

- Necessary steps for an experimental verification of the Higgs mechanism as the responsible for electroweak symmetry breaking and the generation of mass of the fundamental Standard Model particles:

  - Discovery of the Higgs particle(s)
  - Determination of mass, total width and quantum numbers
  - Accurate determination of the couplings to fermions and gauge bosons.
    - What fraction of the W,Z mass the observed Higgs boson(s) contributes to?
    - Are the coupling to fermions scaling with the fermion masses?

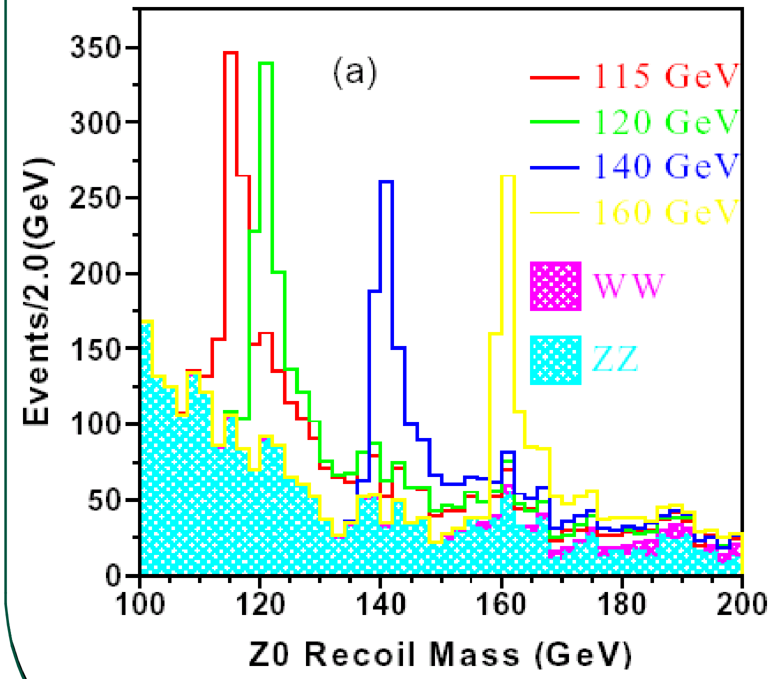
$$g_{ffH} = \frac{m_f}{v} \qquad \text{e.g.} \quad \frac{BR(H \to b\bar{b})}{BR(H \to \tau^+\tau^-)} \approx \frac{3m_b^2(m_H^2)}{m_\tau^2}$$

  - Reconstruction of the Higgs potential by determination of the Higgs self-couplings: is it a “Mexican hat”?
  - Finally, determination of its nature: is it standard, supersymmetric, composite, etc?

Higgs boson(s) observation

- Unless the lightest Higgs boson has very non-standard couplings, it is expected to be discovered at the LHC.
- The LC can (re)discover any relatively narrow resonance which couples to the Z boson, independently of its decay modes ➔ even invisible!!
- Golden channel: $e^+e^- \rightarrow ZH \rightarrow \ell^+\ell^- X \quad (\ell = e, \mu)$

NLC at 350 GeV ($\mu^+\mu^-X$)



- The Z is produced monochromatic (modulo initial state radiation effects)
- Make use of the missing mass recoiling against the Z: $m_H^2 = s - 2\sqrt{s}\,E_Z + m_Z^2$
- The rates are sufficiently large to detect Higgs particles up to ~0.7√s.

L = 500 fb^{-1}

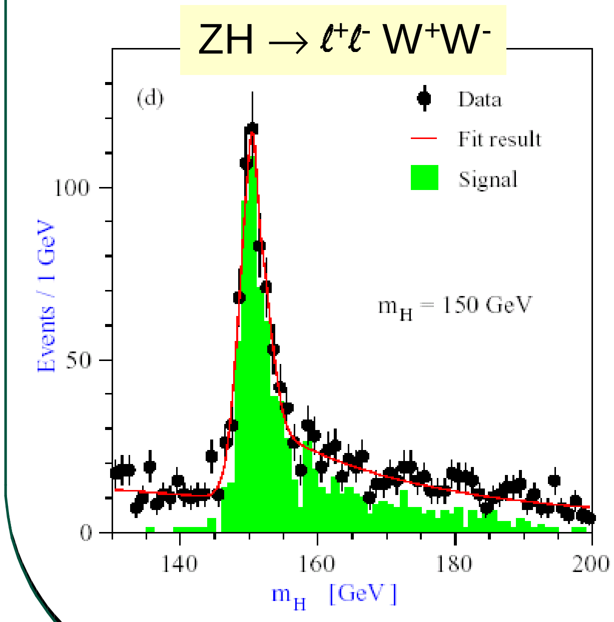
M_H (GeV)	$\sqrt{s} = 350$ GeV	500 GeV	800 GeV
120	4670	2020	740
140	4120	1910	707
160	3560	1780	685
180	2960	1650	667
200	2320	1500	645
250	230	1110	575
Max M_H (GeV)	258	407	639

With # Higgs events ≥ 50

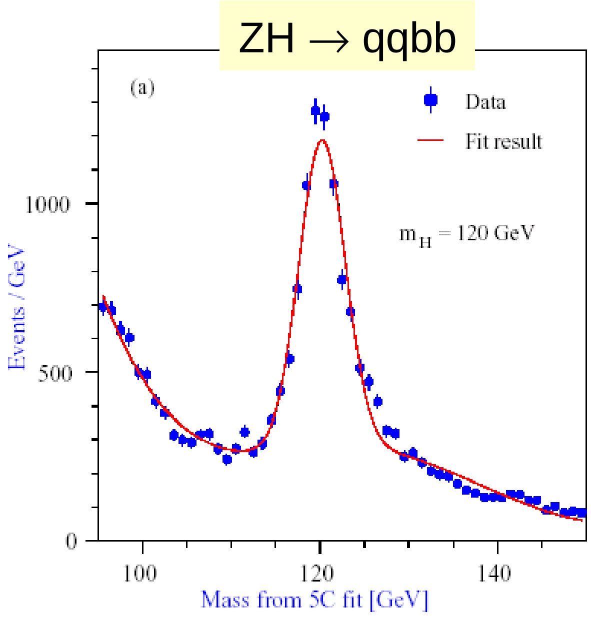
Higgs mass measurement

- In the SM, m_H is a free parameter of the theory, which fully determines all other Higgs properties.
- Very important to measure it as accurately as possible (global fits within the SM, important input determining underlying model parameters in theories with extended Higgs sectors, etc)
- Take advantage of the ZH kinematics:

Inclusive Higgs decays
(recoil mass method)



Exclusive Higgs decays
(constrained kinematic fitting)



Uncertainties for:
$\sqrt{s}$ = 350 GeV, L = 500 fb^{-1}
(*) 500 GeV

M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	± 70
120	$qqbb$	± 50
120	Combined	± 40
150	$\ell\ell$ Recoil	± 90
150	$qqWW$	± 130
150	Combined	± 70
180	$\ell\ell$ Recoil	± 100
180	$qqWW$	± 150
180	Combined	± 80
(*) 240	$\ell\ell VV \rightarrow \ell\ell 4j$	±400

Spin and CP quantum numbers

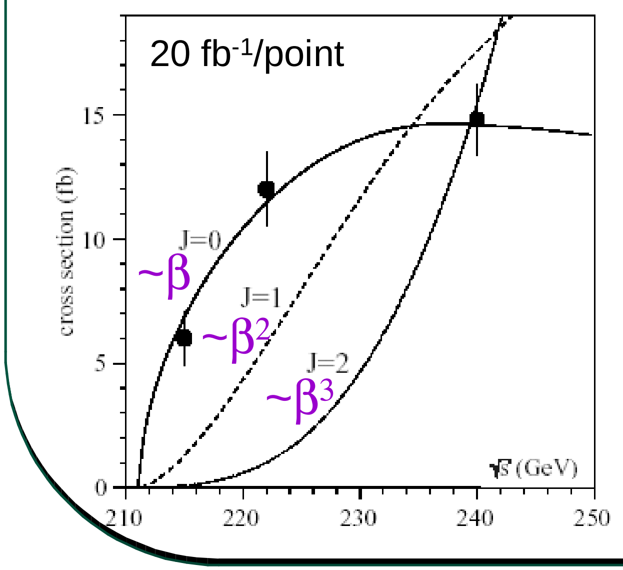
- J^{PC} of a Higgs boson can potentially be determined in a model-independent way.
- Observation of decay process $H \to \gamma\gamma$ or production process $\gamma\gamma \to H$ rules out J=1 and sets C=+1 (Landau-Yang Theorem).
- At threshold: determine J from β-dependence of σ_{ZH}
- In the continuum: use angular distributions to determine CP-composition

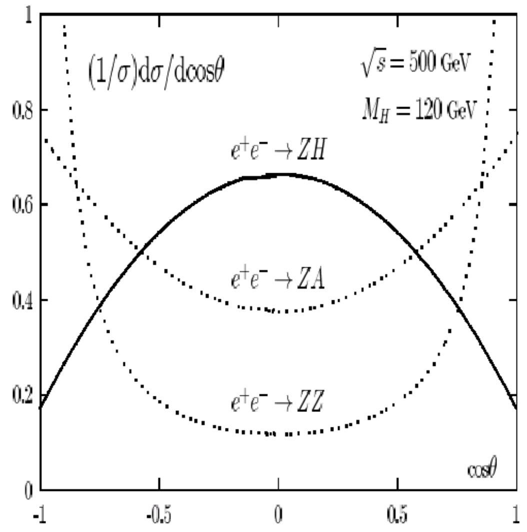
  - angular distribution of Z in ZH;

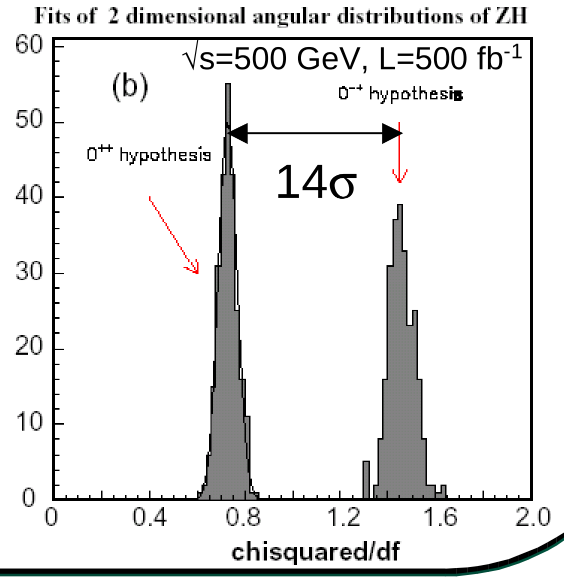
$$\frac{d\sigma}{d\cos\theta_Z} \propto 1 + \overset{\text{CP-even}}{\frac{p_Z^2}{m_Z^2}\sin^2\theta_Z} - \overset{\text{Interference}}{4\,\mathrm{Im}\left[\frac{\tilde{b}}{a}\right]\frac{v_e a_e}{v_e^2 + a_e^2}\frac{p_Z\sqrt{s}}{m_Z^2}\cos\theta_Z} + \overset{\text{CP-odd}}{\left|\frac{\tilde{b}}{a}\right|^2 \frac{p_Z^2 s}{2m_Z^4}(1+\cos^2\theta_Z)}$$

  - 2D angular distribution of fermions in ZH → f f H
  - 3D angular distribution: also sensitivity to general anomalous couplings.

  Sensitivity to CP-odd admixture ($\sqrt{s}$=500 GeV, L=500 fb^{-1}) ~ 3%.







Higgs couplings to gauge bosons: W and Z

g_{ZZH}

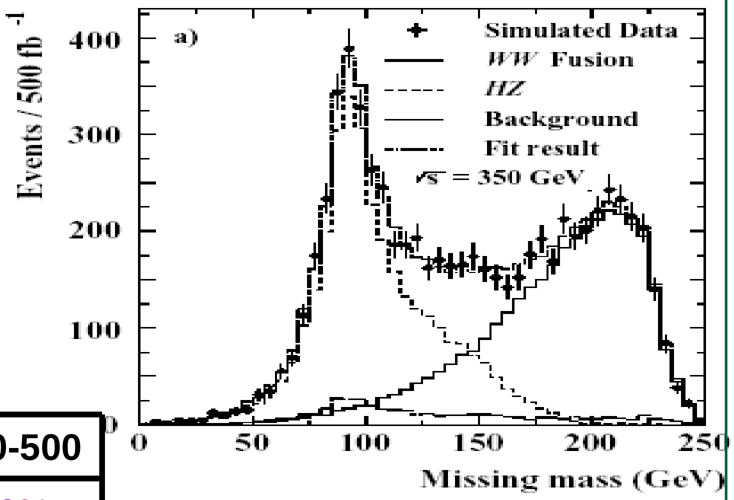
- Recoil mass method allows for a model-independent determination via σ_{ZH}
  $\Rightarrow$ test whether the observed Higgs boson generates the complete mass of the Z (saturation of the sum rule)

$$\sum_i g^2_{ZZh_i} = \frac{4m_Z^2}{v^2}$$

g_{WWH}

- Two methods:
  1) Direct determination via $\sigma_{H\nu\nu}$ at √s = 350 GeV or 500 GeV (ZH contribution small)
    - Select b-tagged hadronic events with large missing mass ($bb\nu\nu$ final state)
    - Extract $\sigma_{H\nu\nu}$ from χ^2 fit to missing mass distribution.
    - Systematics can be reduced by using different beam polarizations.

  2) Measurement of BR(H→WW*)
    - Select exclusive decay ZH → qqWW, with both semileptonic and fully hadronic W decays.
    - Cuts: $M_{JJ} \sim M_Z$, $M_{recoil} \sim m_H$, anti-b tag to remove large ZZ and tt backgrounds. Also useful e^- polarization to remove WW.



m_H (GeV) =	120	140	160	200	400-500
$\sigma(e^+e^- \to HZ)$	2.5%	2.7%	3.0%	7%	10%
$\sigma(e^+e^- \to H\nu\nu)$	2.8%	3.7%	13%		
BR(H →WW*)	5.1%	2.5%	2.1%	7%	17%
BR(H →ZZ*)			17%	8%	20%

L=500 fb-1
√s = 350 GeV
= 500 GeV
= 800 GeV

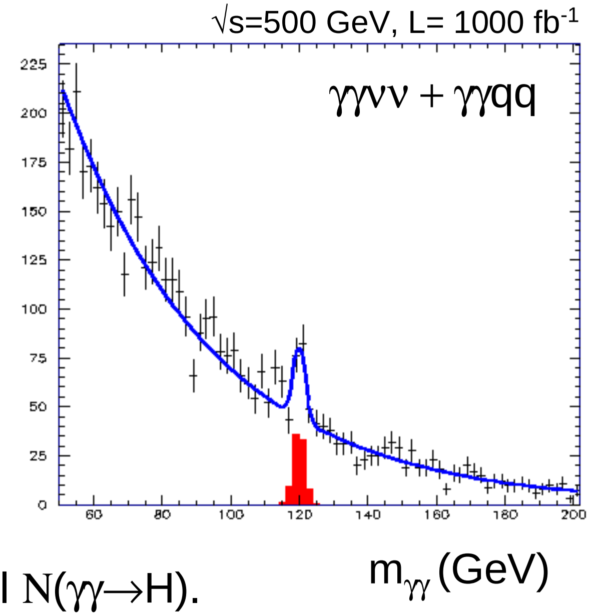
Higgs couplings to gauge bosons: γ

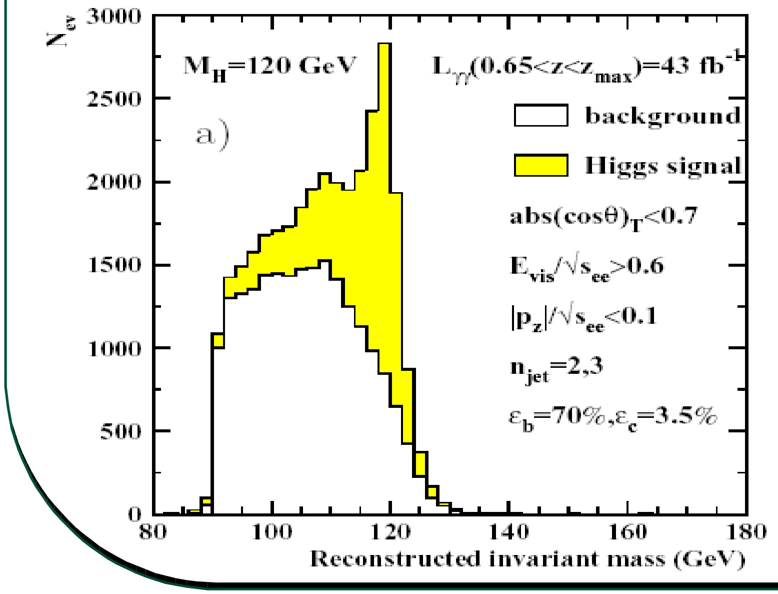
- $H \rightarrow \gamma\gamma$ mediated by loop and therefore sensitive to any particle directly coupled to H and γ. Within the SM, dominant contribution comes from W, followed by t.
- Several methods to determine the effective $g_{H\gamma\gamma}$ coupling.

e^+e^--collider

- BR($H \rightarrow \gamma\gamma$) from σ x BR($H \rightarrow \gamma\gamma$) in $\gamma\gamma\nu\nu$ events (ZH and $H\nu\nu$) and $\gamma\gamma qq$ events (only ZH).
- Challenging: large background from double-bremsstrahlung $Z\gamma\gamma$ events + smallness of BR($H \rightarrow \gamma\gamma$).

ΔBR($H \rightarrow \gamma\gamma$)/BR($H \rightarrow \gamma\gamma$)~14%
for √s=500 GeV, L= 1000 fb^{-1}





$\gamma\gamma$-collider

- Rather substantial N($\gamma\gamma \rightarrow H$).
- Use exclusive Higgs decay channel $H \rightarrow bb$.
- Relatively large background from non-resonant $\gamma\gamma \rightarrow$hadrons efficiently removed with b/c flavor discrimination.

$\Delta\Gamma$($H \rightarrow \gamma\gamma$)/$\Gamma$($H \rightarrow \gamma\gamma$)~2%
for m_H=120 GeV, L=43 fb^{-1} $\gamma\gamma$-luminosity
in the hard part of the spectrum

Higgs total width

- A measured Γ_H inconsistent with SM prediction would indicate new physics effects.

$m_H < 2M_W$

- Γ_H extremely small and only measurable indirectly. Nearly model-independent determination from the combination of Higgs couplings to gauge bosons with the corresponding BR.

$$\Gamma_H = \frac{\Gamma(H \to X)}{BR(H \to X)}, \quad X = WW^*, \gamma\gamma$$

from production

- Indirect methods:

1) $\Gamma(H \to WW^*)$ from WW-fusion with final state bb$\nu\nu$. BR($H \to WW^*$) from ZH $\to$qqWW through recoil mass method.

2) compute $\Gamma(H \to WW^*)$ by imposing SU(2) relationship $g_{HWW} = g_{HZZ} \cos\theta_W$ (g_{HZZ} from ZH) and BR($H \to WW^*$) as in 1).

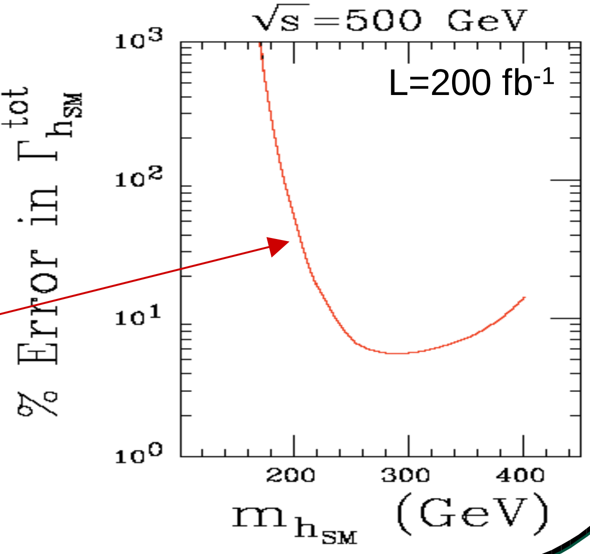
3) $\Gamma(H \to \gamma\gamma)$ from $\gamma\gamma$-collider. BR($H \to \gamma\gamma$) from $e^+e^- \to \gamma\gamma\nu\nu$, $\gamma\gamma$qq. Error on BR($H \to \gamma\gamma$) dominates.

L= 500 fb^{-1}

m_H (GeV)/ Method	120	140	160
1	6.1%	4.5%	13.4%
2	5.6%	3.7%	3.6%
3	23%		

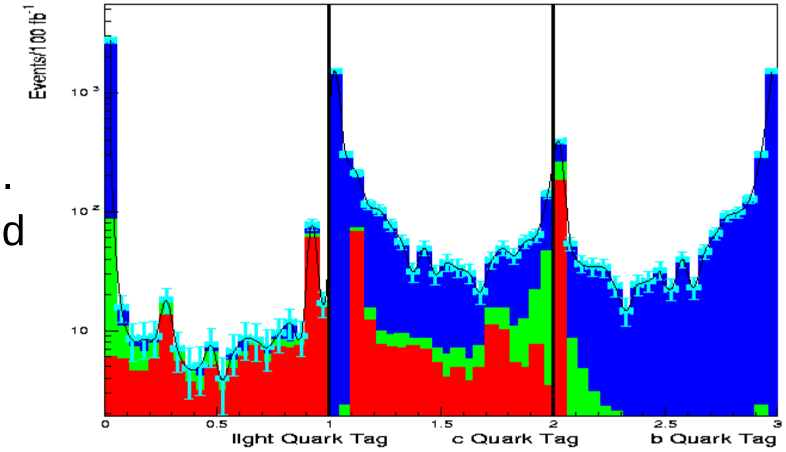
$m_H > 200$ GeV

- $\Gamma_H > 2$ GeV and directly resolvable.
- Use ZH with recoil mass method or direct reconstruction of $H \to$bb,WW* final state.
- Can also use indirect method.



Higgs couplings to fermions: b, c, τ

- Accurate determination very important as a proof of the Higgs mechanism ($g_{Hff} \propto m_f$) and to establish the nature of the Higgs boson (e.g. SM vs MSSM).
- Within SM, precision measurements only possible for $m_h < 2M_W$.
- What is measured is $\sigma_{ZH,\, H\nu\nu}$ x BR(H→ff).

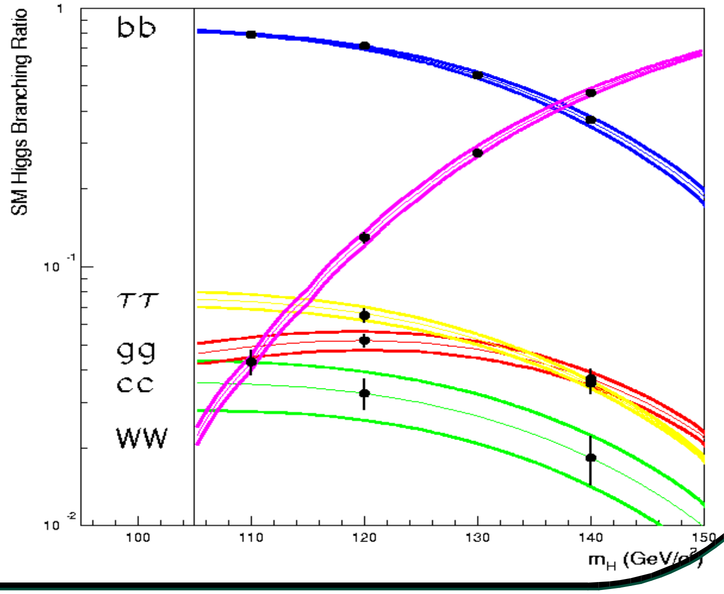


H→ bb, cc

- Select hadronic Higgs boson decay channels.
- Fraction of bb, cc and gg final states extracted from binned-likelihood fit to jet flavor tagging probabilities.
- Background subtracted from Higgs mass distribution sidebands.

H→ ττ

- From global ττ likelihood.



L=500 fb^{-1}, √s = 350 GeV, 500 GeV

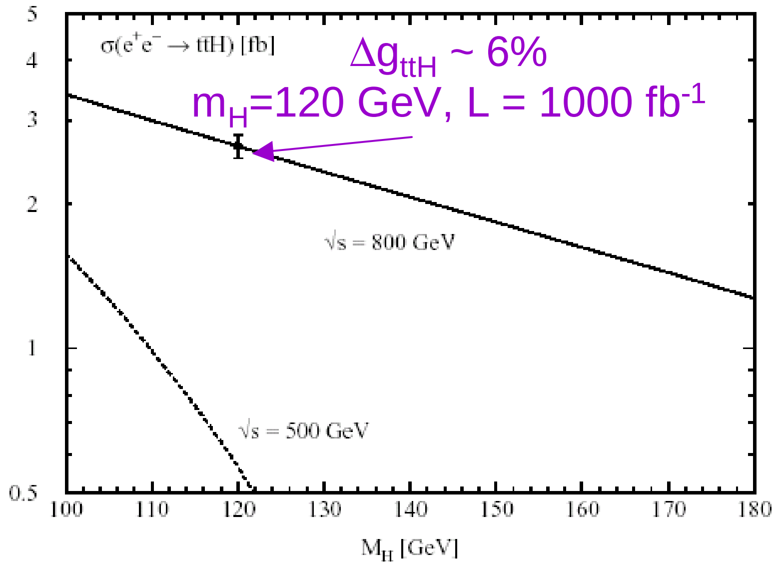
m_H (GeV)/ Channel	120	140	160	200
BR(H→bb)	2.4%	2.6%	6.5%	~25%
BR(H→cc)	8.3%	19%		
BR(H→ττ)	5.0%	8.0%		
BR(H→gg)	5.5%	14%		

Higgs couplings to fermions: t

- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions (g_{ttH} ~ 0.7 vs g_{bbH} ~ 0.02). Precise measurement important since the top quark is the only "natural" fermion from the EWSB standpoint.

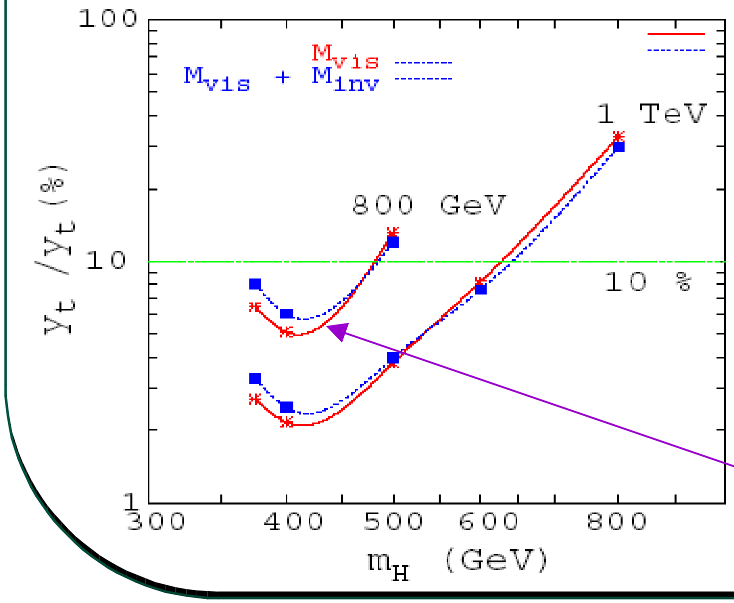
$\underline{m_H < 2\ m_t}$

- The process $e^+e^- \rightarrow ttH$ allows for a direct determination of g_{ttH} via σ_{ttH}.
- Spectacular signature: 4b+4q, 4b+2q+ℓ+ν.
- A precise measurement requires high energy (√s=800 GeV) and luminosity (L=1000 fb^{-1}).
- Use of b-tagging and sophisticated multivariate selections crucial.



Δg_{ttH} ~ 6%

m_H=120 GeV, L = 1000 fb^{-1}



$\underline{m_H > 2\ m_t}$

- Determination of BR(H →tt) from the process $e^+e^- \rightarrow H\nu\nu \rightarrow tt\nu\nu$
- Signature: 4q+2b+missing energy.
- Visible mass distribution to discriminate against dominant backgrounds: $e^+e^- \rightarrow tt$, $e^+e^- \rightarrow e^+e^-tt$.

Δg_{ttH} ~ 5% (12%)

m_H=400 (500) GeV, L = 1000 fb^{-1}

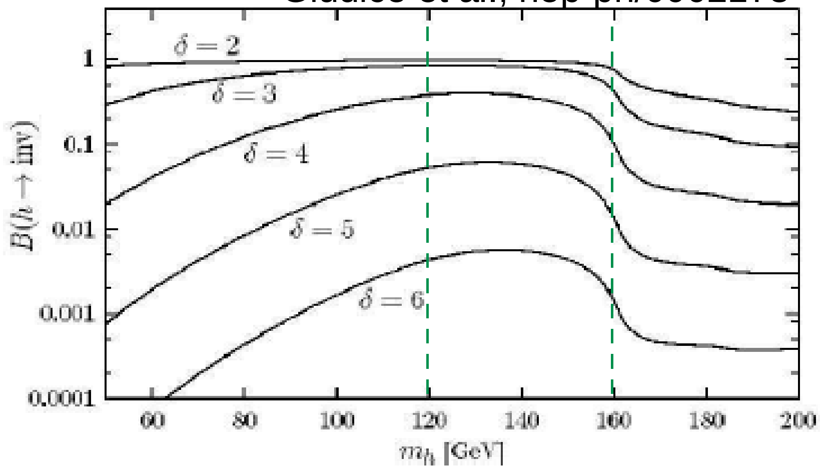
Non-standard Higgs decays: h→invisible

- Some possible invisible final states:
  - LSPs: h→ $\tilde{\chi}^0_1\tilde{\chi}^0_1$
  - Heavy neutrinos
  - Radion-Higgs mixing

    Large possible variation of BR_{inv}

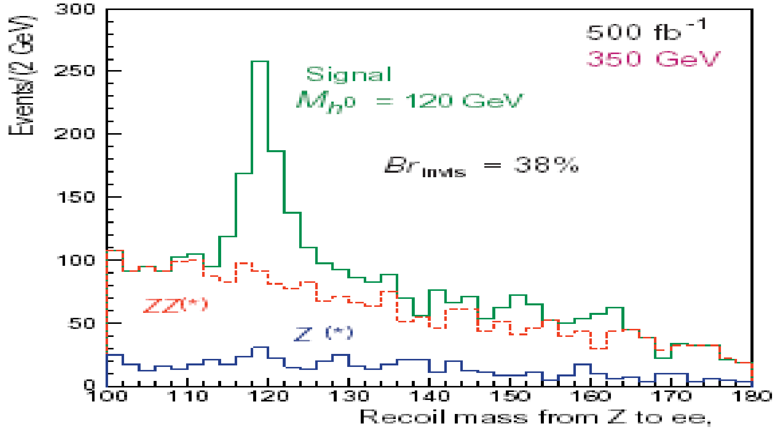
    e.g. $\delta=4$, $m_h=120$ GeV ➔ $BR_{inv}\sim38\%$

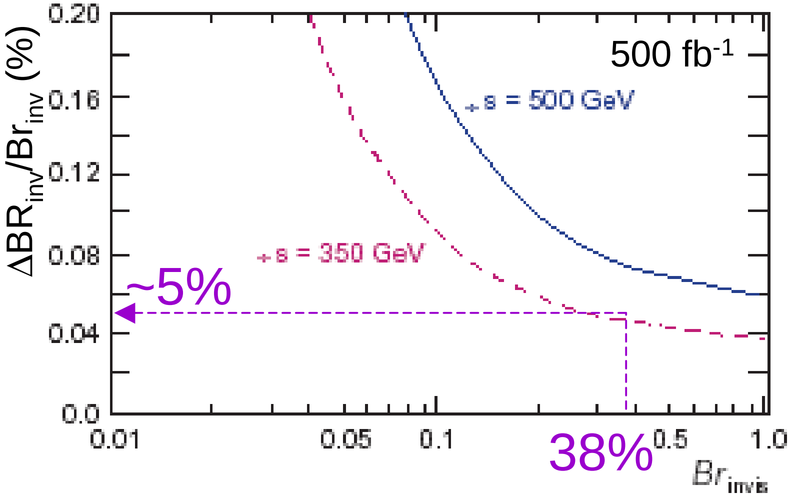
    Giudice et al., hep-ph/0002178



  - Stealth Higgs model
  - …
- At LHC: very challenging.
- At LC: make use of the recoil mass method in ZH events.

- Backgrounds: WW(-fusion), ZZ, Z/γ
- Direct search for h→inv (narrow resonance). Comparable sensitivity to indirect search.



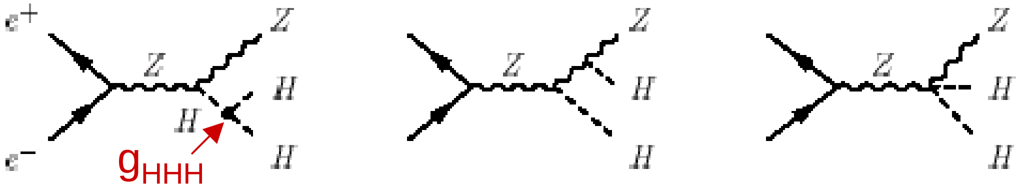


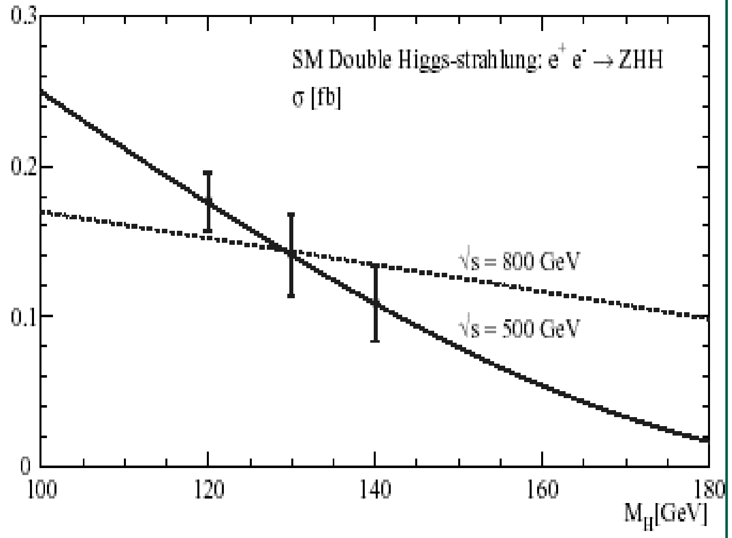
Higgs self-couplings

- Unambiguous experimental verification of the Higgs mechanism as responsible for EWSB requires reconstruction of the Higgs self-energy potential.

$$V=\lambda\left(|\varphi|^2-\tfrac{1}{2}v^2\right)^2 \;\Rightarrow\; V=\underbrace{\lambda v^2}_{m_H^2/2}H^2+\underbrace{\lambda v}_{g_{HHH}}H^3+\underbrace{\tfrac{1}{4}\lambda}_{g_{HHHH}}H^4$$

- Within the SM, m_H, g_{HHH} and g_{HHHH}, are related to λ, at tree level.
  - Determination of m_H provides indirect information on λ.
  - The cross-section for double (triple) Higgs production is sensitive to g_{HHH} (g_{HHHH}).





- Triple Higgs coupling determined from ZHH events at √s=500 GeV with L=1000 fb^{-1}.
- Signature: qqbbbb, $\ell^+\ell^-$bbbb.
- Challenging analysis: tiny signal and huge 4- and 6-fermion backgrounds (S/B~10^{-5}).
- Benefit from excellent flavor tagging and reconstruction detector capabilities as well as from multivariate analysis.

$$\left(\frac{\Delta g_{HHH}}{g_{HHH}}\right)\sim \underset{\uparrow}{1.75}\times\left(\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}}\right)$$

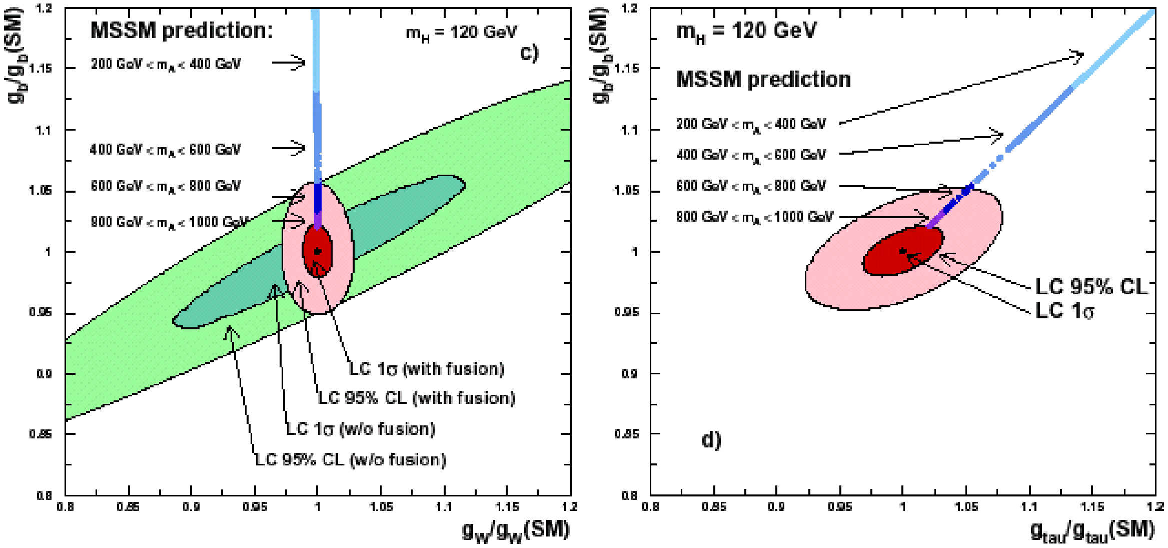
Dilution factor

m_H (GeV)	120	130	140
N_{ZHH}	186	149	115
$\Delta g_{HHH}/g_{HHH}$	~23%	~25%	~29%

Extraction of Higgs couplings

- The measured branching ratios and rates can be used to extract the Higgs couplings to fermions and gauge bosons.
- A dedicated program (HFITTER) has been developed based on the HDECAY program for the calculation of Higgs boson branching ratios.
- A global fit to all observables allows to make optimal use of the information taking into account the existing correlations.

L = 500 fb^{-1}

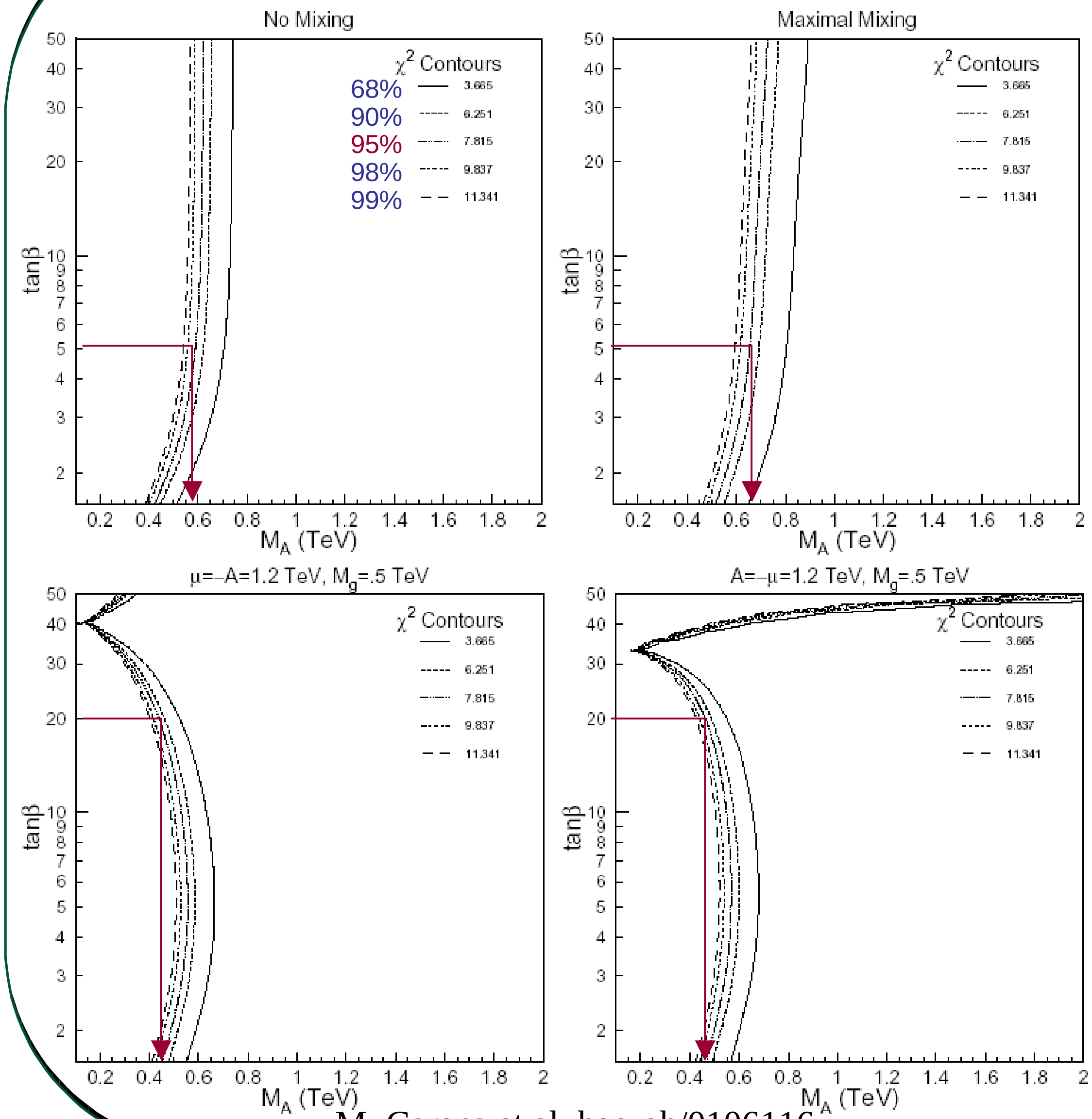


Coupling	M_H = 120 GeV	140 GeV
g_{HWW}	± 0.012	± 0.020
g_{HZZ}	± 0.012	± 0.013
g_{Htt}	± 0.030	± 0.061
g_{Hbb}	± 0.022	± 0.022
g_{Hcc}	± 0.037	± 0.102
$g_{H\tau\tau}$	± 0.033	± 0.048
g_{HWW}/g_{HZZ}	± 0.017	± 0.024
g_{Htt}/g_{HWW}	± 0.029	± 0.052
g_{Hbb}/g_{HWW}	± 0.012	± 0.022
$g_{H\tau\tau}/g_{HWW}$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

- The precise determination of the Higgs effective couplings opens a window of sensitivity to the nature of the Higgs boson, even near the decoupling limit:
  - $g_{ZZH} < (g_{ZZH})_{SM}$ indicates the existence of an extended Higgs sector.
  - Ratios of BRs give sensitivity to m_A:

$$\text{e.g.}\quad \frac{\mathrm{BR}(h \to c\bar{c})}{\mathrm{BR}(h \to b\bar{b})} \propto \frac{1}{\tan^2\alpha\ \tan^2\beta} \approx \frac{(m_h^2 - m_A^2)^2}{(m_Z^2 + m_A^2)^2}$$

Telling the SM from the MSSM



M. Carena et al, hep-ph/0106116

- Determine regions of parameter space where, based on BR measurements, one can distinguish the SM and MSSM at different CLs.
- 4 benchmark scenarios: radiative corrections make the reach on m_A depend on the SUSY parameters.
- χ^2 combination of bb, $\tau^+\tau^-$ and gg squared couplings:

	$\Delta g_{hbb}^{\;2}$	$\Delta g_{h\tau\tau}^{\;2}$	$\Delta g_{hgg}^{\;2}$
Exp.(*)	4.4%	6.6%	7.4%
Theor.	3.5%	-	3.9%

(*) $\sqrt{s}$=500 GeV, L=500 fb^{-1}

- Note sensitivity to m_A extended beyond the kinematically allowed region for ZA production.

Heavy Higgs sector

- In the decoupling limit, $H^{\pm}$, H^0 and A^0 expected to be heavy and decay predominantly to 3rd generation quarks.
- e^+e^--collider: pair production; discovery up to $m \sim \sqrt{s}/2$

  $\gamma\gamma$-collider: single resonance; discovery up to $m \sim 0.7\sqrt{s_{ee}}$

$e^+e^- \to H^+H^- \to tbtb$

- $m_H = 300$ GeV, $\sqrt{s} = 800$ GeV.
- Signature: 8 jets (4 b-jets).
- Backgrounds suppressed by using b-tagging and multijet invariant mass constraints.
- For $L = 500\ \text{fb}^{-1}$: 120 (50) signal (bckg) events

  $\Delta m_H \sim 1$ GeV, $\Delta(\sigma_{HH} \times BR^2) \leq 15\%$

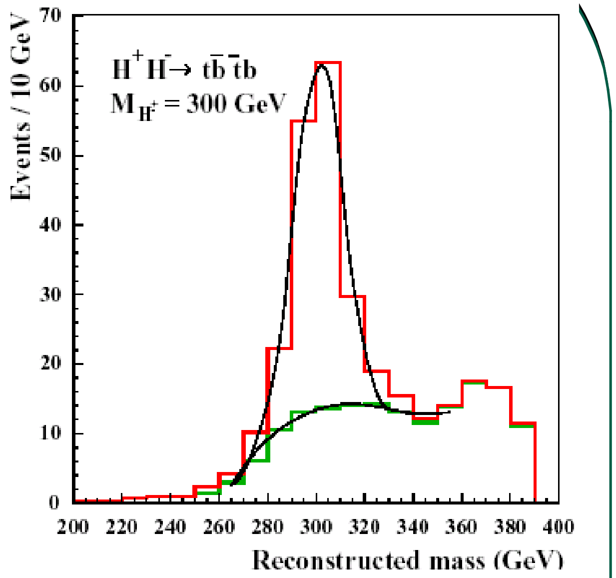
$e^+e^- \to H^0A^0 \to bbbb$

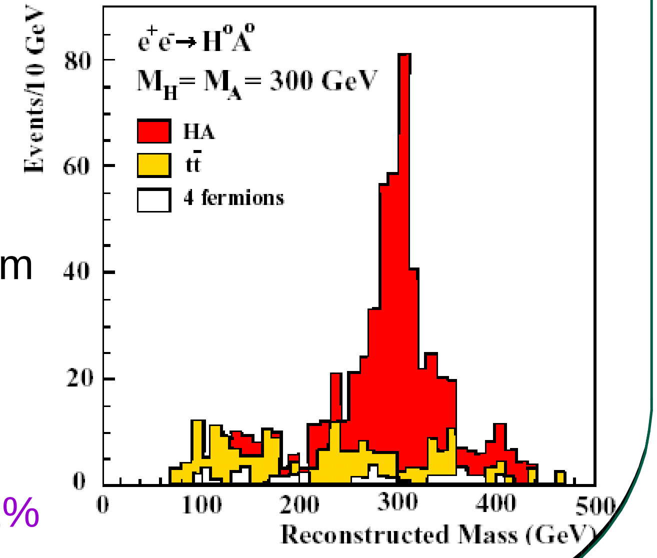
- Assume $m_H \approx m_A$, $\sqrt{s} = 800$ GeV.
- Requiring 4 b-jets significantly reduces backgrounds from qqgg and tt.
- With 50 fb^{-1} can be discovered up to $m_{H,A} = 340$ GeV.
- For $L = 200\ \text{fb}^{-1}$:

  $\Delta m_{H,A} / m_{H,A} = 0.2\text{-}0.4\%$,

  $\Delta(\sigma_{HA} \times BR(H \to bb) \times BR(A \to bb)) = 5\text{-}11\%$

  for 260 GeV $< m_{H,A} <$ 340 GeV





Strongly Coupled EWSB: No Higgs

- Without a Higgs boson with m_H< 1 TeV, cross-section for $V_L V_L$ scattering violates unitarity at ~3 TeV ➔ weak bosons required to interact strongly.

  $e^+e^- \to \nu\nu WW$, $\nu\nu ZZ$ (best for I=J=0)
  $e^+e^- \to WW$ (best for I=J=1)
  $e^+e^- \to \nu\nu tt$

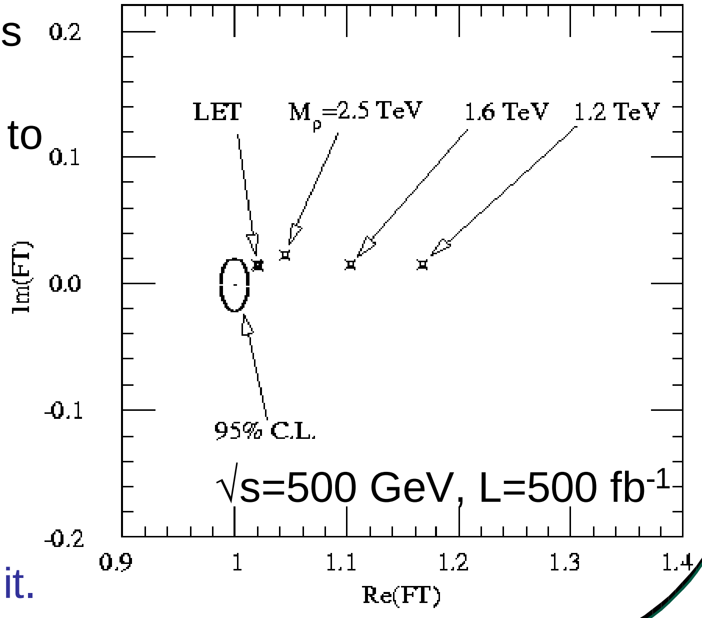
Example: Technicolor (and extensions)

- New chiral fermions (“technifermions”) generate EWSB by forming pair-condensates (new asymptotically free interaction that becomes strong at ~TeV).
- Substantial corrections to precision EW observables (no decoupling limit) ➔ severely constrained.
- Difficult to make quantitative predictions. Important to perform model-independent searches.

  Signatures:
  - New relatively light (< TeV) pseudoscalars.
  - New heavy (~2 TeV) vector resonance which couples to J=1 WW amplitude.
- Perform accurate measurement of TGCs at high energy. Sensitivity < 10^{-3} ➔ but not unambiguous.
- Search for vector resonance effects (complex form factor) in $e^+e^- \to W^+W^-$ ➔ sensitivity even to LET limit.

CP-conserving TGCs

	error $\times 10^{-4}$			
	$\sqrt{s} = 500$ GeV		$\sqrt{s} = 1000$ GeV	
TGC	Re	Im	Re	Im
	500 fb^{-1}		1000 fb^{-1}	
g_1^γ	15.5	18.9	12.8	12.5
κ_γ	3.5	9.8	1.2	4.9
λ_γ	5.4	4.1	2.0	1.4
g_1^Z	14.1	15.6	11.0	10.7
κ_Z	3.8	8.1	1.4	4.2
λ_Z	4.5	3.5	1.7	1.2



$\sqrt{s}$=500 GeV, L=500 fb^{-1}

Strongly Coupled EWSB: Composite Higgs

- Short-range strong interactions give rise to bound states, which include Higgs boson(s).
  - Heavy Higgs (~500 GeV) but new interactions modify precision observables to compensate for it.
  - Binding interactions generate an extended composite Higgs sector, where mixing produces a light and weakly coupled SM-like Higgs.
  - Binding interaction can originate from:

    - Breaking of a symmetry (gauge, family or flavor)

    - Propagation of SM particles in extra spatial dimensions.
- Approximate well SM at low energy.

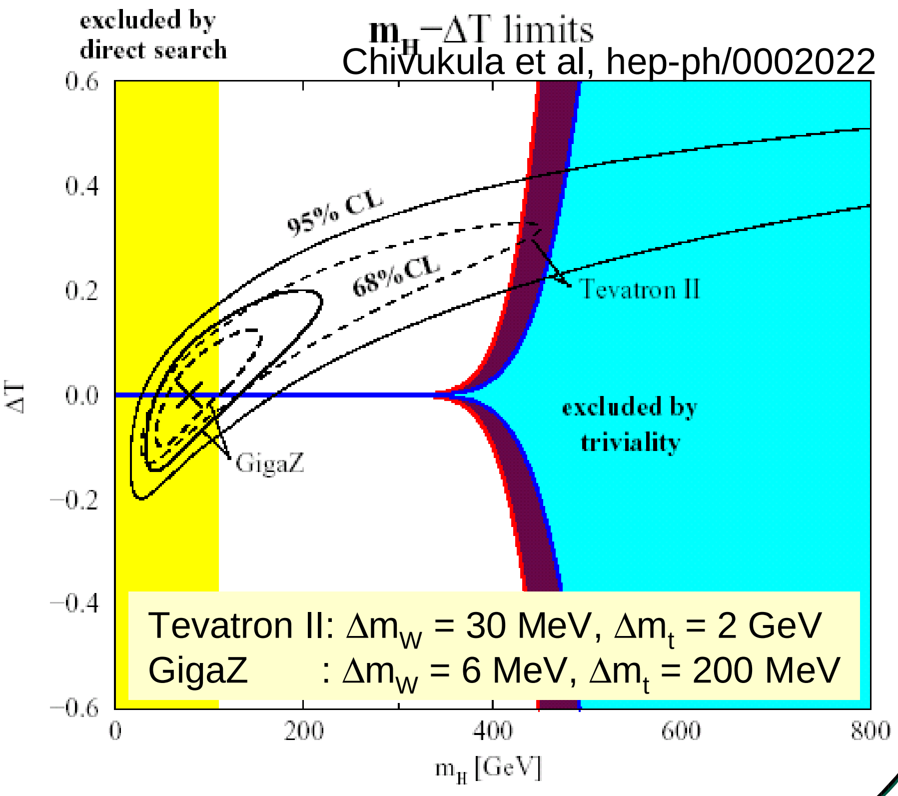
Signatures:

- Additional composite scalar states: precision measurement of masses and BRs.
- Extra (~TeV) fermions: affect precision electroweak data
- New heavy vector bosons: contact interactions in $e^+e^- \rightarrow f\bar{f}$.

- Example: Top-Quark Seesaw model

  $H \sim \langle t_L \Psi_R \rangle$, $m_H \sim 500$ GeV

  Ψ: new heavy ($m_\Psi \sim$ few TeV) vector-like quark



Chivukula et al, hep-ph/0002022

Low energy running

- The possibility to measure EW observables very precisely at low energy (< 500 GeV) opens new areas for high precision tests of EW theories.

	now	Run II	LHC	LC	Giga-Z
$\delta \sin^2\theta_w^{\text{eff}} (\times 10^5)$	17	50	21	(6)	1.3
δm_W [MeV]	37	30	15	15	6
δm_t [GeV]	5.1	4.0	2.0	0.2	0.2
δm_h [MeV]	—	—	100	50	50

$\mathcal{L}$~ 5x10^{33} cm^{-2}s^{-1} (~50 fb^{-1}/year) at √s = m_Z

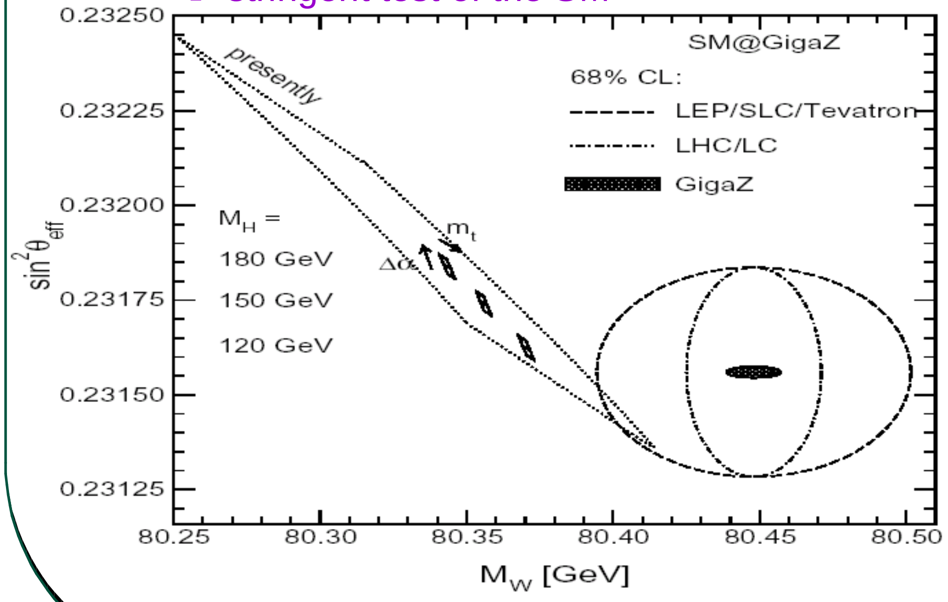
➔ from A_{LR} at Z peak (1/2 year = ~10^9 Zs)

➔ from WW-threshold scan (100 fb^{-1} = ~10^6 WWs)

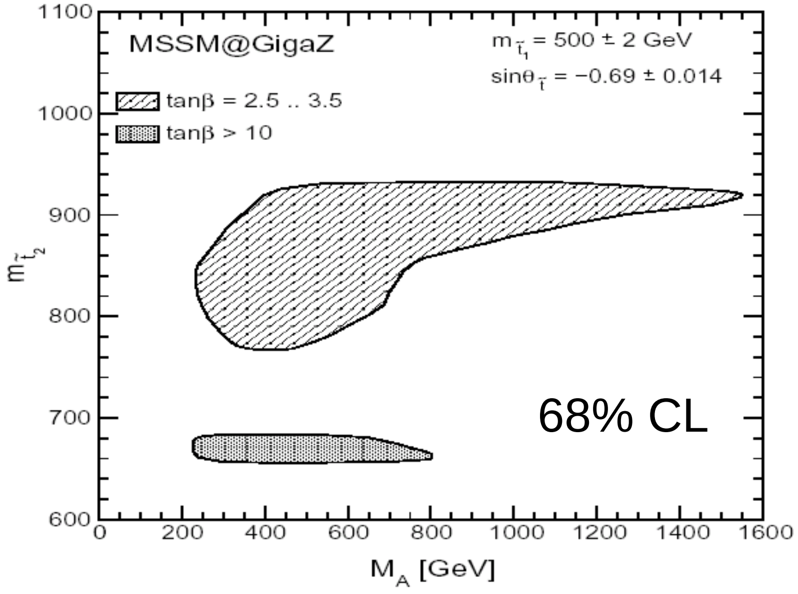
➔ from tt-threshold scan (100 fb^{-1})

Within SM: $\Delta m_H/m_H$ ~ 8%

➔ stringent test of the SM



Within MSSM: obtain information about new heavy states beyond direct reach.



⇒ In general, place constraints on extensions of the SM (e.g. S,T parameters).

Conclusions

- Elucidation of the dynamics responsible for EWSB constitutes the main goal for particle physics research in the next 20 years.
- The LHC will be probing the relevant energy scale and should definitely discover signs of the EWSB dynamics. In (currently favored) weakly-coupled theories, the LHC will discover at least one Higgs boson and measure some of its properties.
- An e^+e^- Linear Collider operating at $\sqrt{s} \geq 500$ GeV will complement the LHC by providing essential information to interpret and exploit these discoveries.
- In particular, the Higgs boson's profile will be outlined, determining its nature and establishing the mechanism of EWSB "sui generis".
- If Nature turns out to be more complicated than the simplest models, its precision will be crucial to point to the relevant energy scales and to possible extensions of the Standard Model.