Unraveling the secrets of Electroweak Symmetry Breaking at an e+e- linear collider

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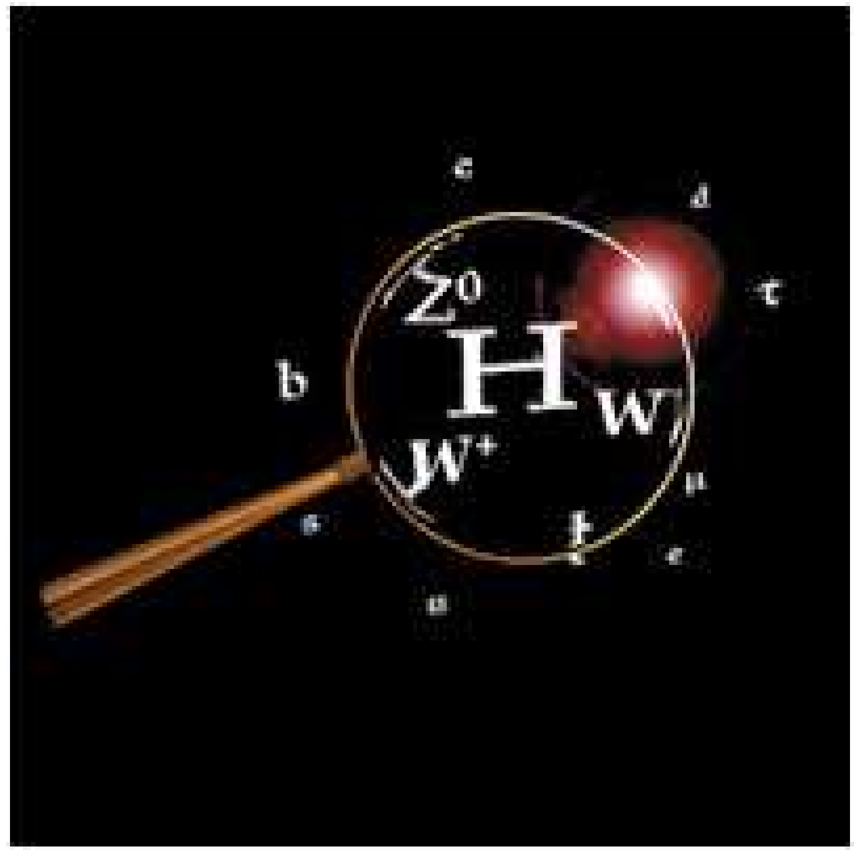
OUTLINE

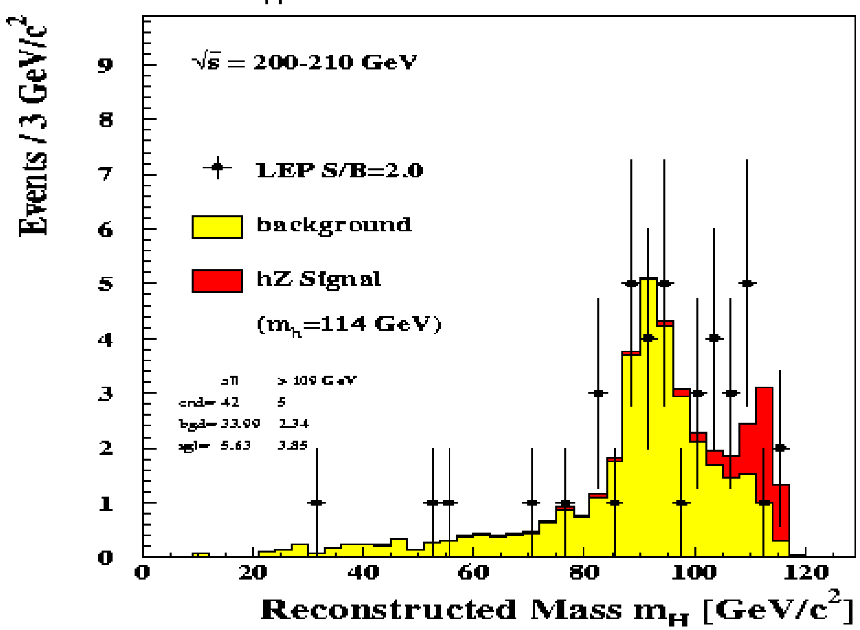
- Current experimental knowledge on EWSB
- Why an e^+e^- LC?
- Measurements on the EWSB sector at an e^+e^- LC
- Conclusions



Current experimental “knowledge” on EWSB

Direct

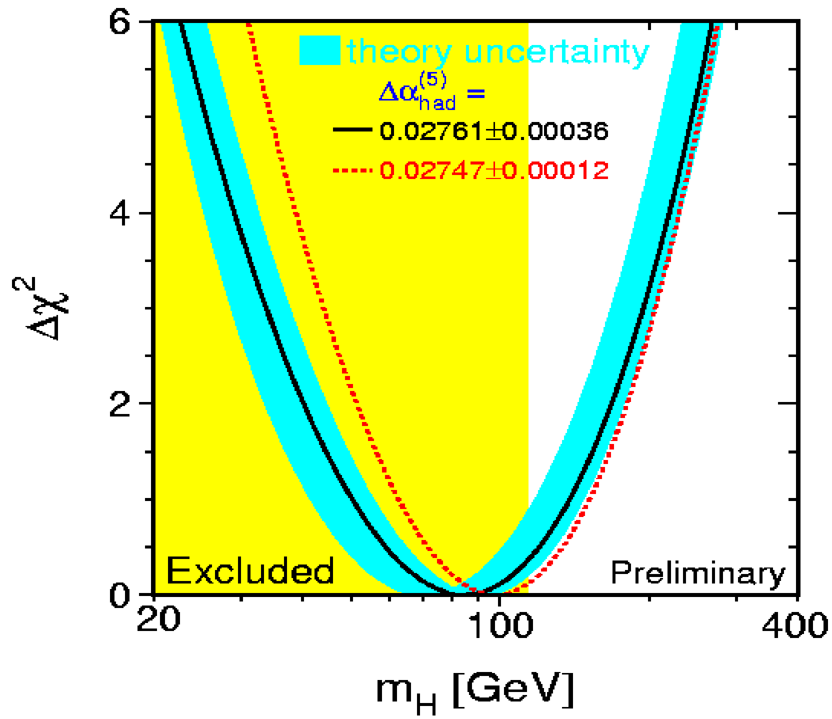
- Searches at LEP2 yielded tantalizing hints (2.9σ) of a SM-like Higgs boson with m_H~115 GeV:



- Will have to wait for further confirmation at the Tevatron or the LHC.

Indirect

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



m_h> 113.5 GeV (95% CL)

m_h< 196 GeV (95% CL)

m_h< 205-230 GeV (95% CL)

Why an e^+e^- linear collider?

In general, experimental access to the EWSB dynamics requires:

- High luminosity ➔ precision measurements (disentangle between different models, exploration of scales not accessible directly, etc).
- Polarization: above Λ_{EW}, left- and right-handed fermions are fundamentally different.
- Flexibility: in some unfavorable scenarios, it is not only desirable, but crucial to be able to drastically improve precision measurements by running at the Z resonance (Giga-Z: ~10^9 Z bosons) and WW threshold => point to the relevant energy scales to be explored by future accelerators.
- Upgradability: the TeV scale does not stop at $\sqrt{s}$ = 1 TeV. Multi-TeV operation will likely be needed in order to directly study the whole EWSB sector (e.g. produce the full SUSY spectrum, or ~TeV resonances responsible for strongly coupled EWSB).

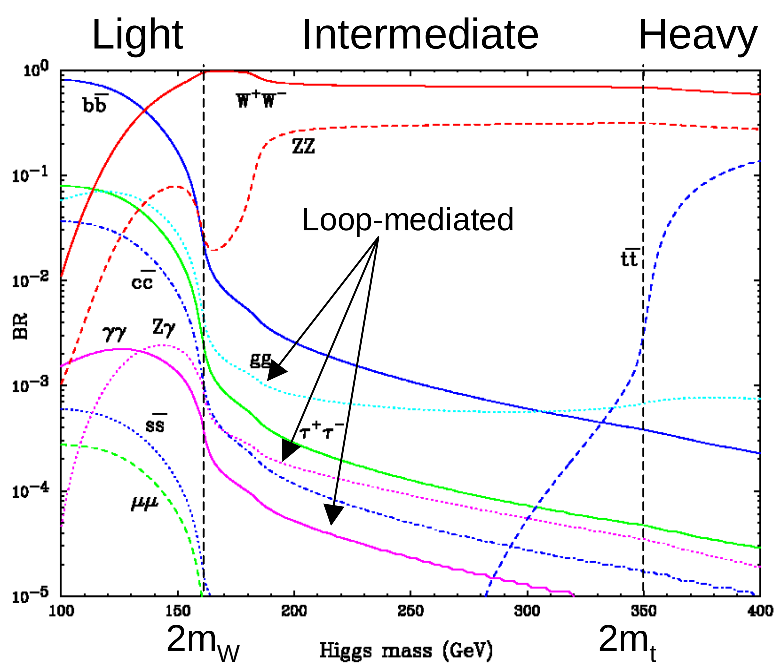
From the experimental point of view:

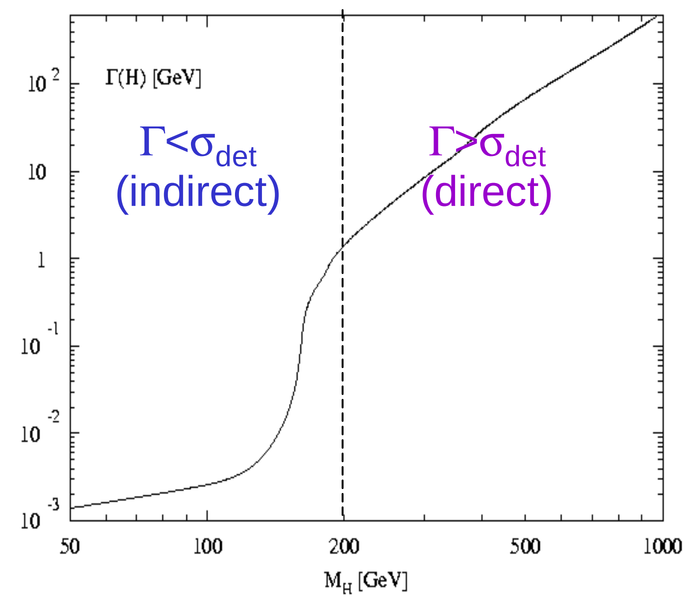
- Large production rate
- Various production processes
- Observability in all decay modes
- Well defined initial state
- Low backgrounds
- Good theoretical accuracy
- Excellent experimental accuracy

All these requirements are easily satisfied by a high luminosity e^+e^- linear collider operating at $\sqrt{s} \geq 500$ GeV

Standard Higgs

- The neighborhood of the decoupling limit is a good starting point: significant regions of parameter space for many extended models of EWSB.
- The decay properties of the nearly-standard Higgs are a strong function of its mass:

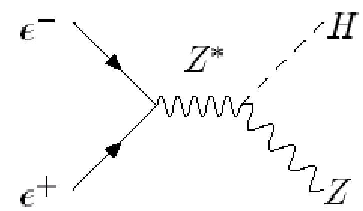




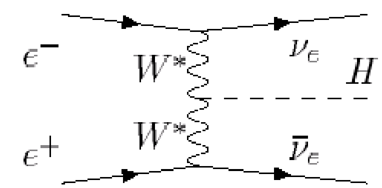
- Since $g_{HXX} \propto m_X$, the phenomenology is governed primarily by the couplings to W, Z and 3rd generation fermions.
- Subdominant decay modes important to establish a complete phenomenological profile of the Higgs boson as well as to check consistency with the SM
- Rare decay modes, e.g. $H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

Higgs boson production at a LC

- Within the SM (and nearly decoupled extensions), two main production mechanisms in e^+e^- collisions:
  - Higgsstrahlung: 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 $\sqrt{s} \gg m_H$



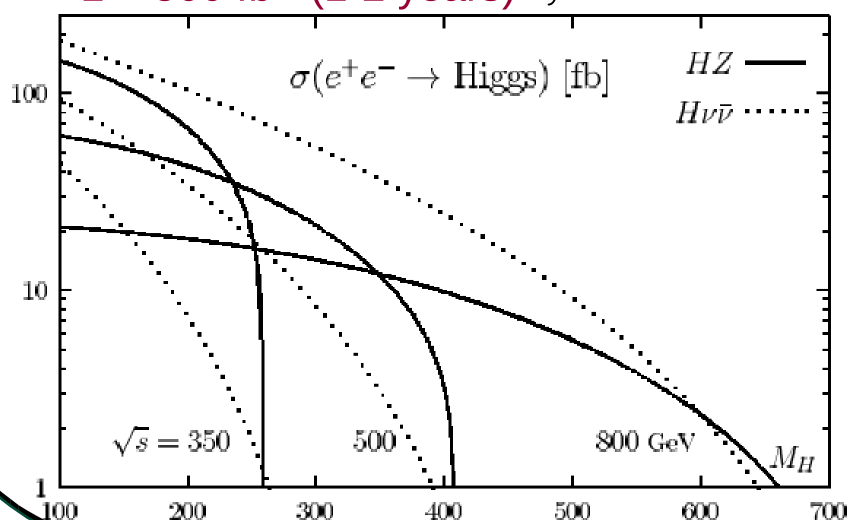
Higgsstrahlung



WW-fusion

- Main background processes are ZZ and WW.
- $\sqrt{s}$ = 350 GeV
  m_H = 120 GeV
  L = 500 fb^{-1} (1-2 years)

  ~ 80k Higgs evens produced (ZH + Hνν)



ZH Hνν

Luminosity	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
$\sqrt{s}$ (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

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?

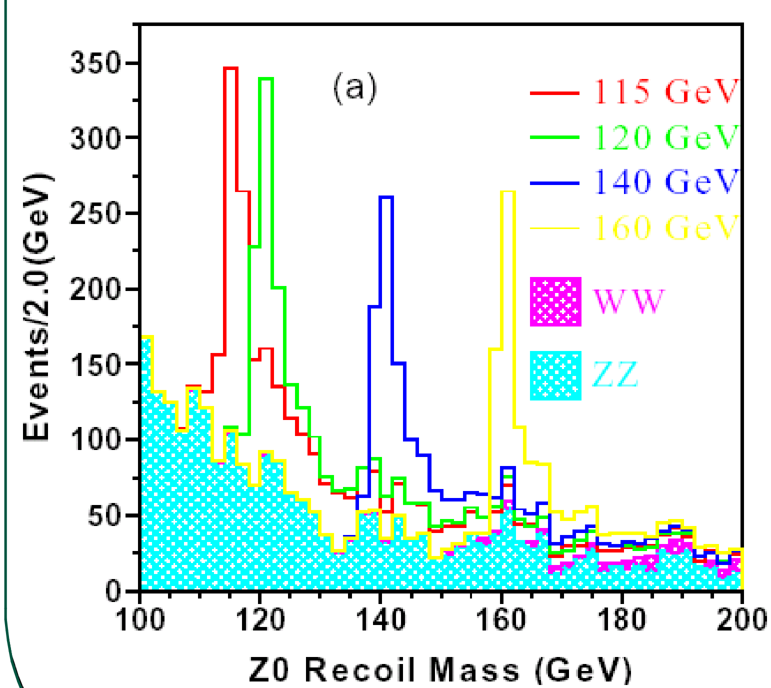
$$g_{ffH} = \frac{m_f}{v} \qquad \text{e.g.} \quad \frac{BR(H \to b\bar{b})}{BR(H \to \tau^+\tau^-)} \approx \frac{3m_b^2(m_H^2)}{m_\tau^2}$$

  - 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, 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: $e^+e^- \to ZH \to \ell^+\ell^- X \quad (\ell = e, \mu)$

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

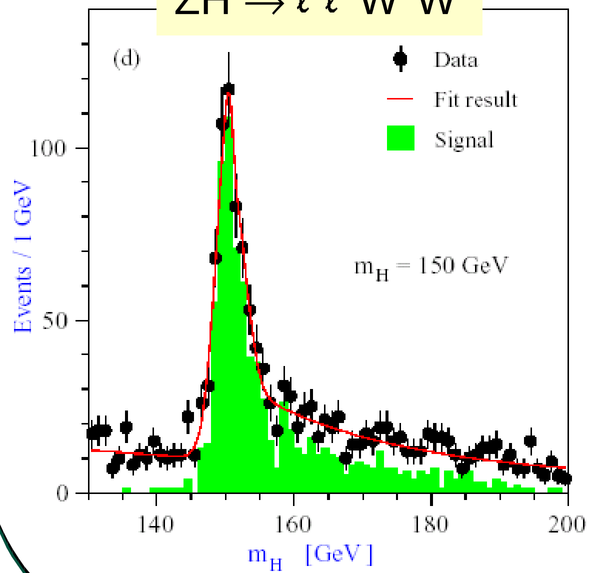
With # Higgs events ≥ 50

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:

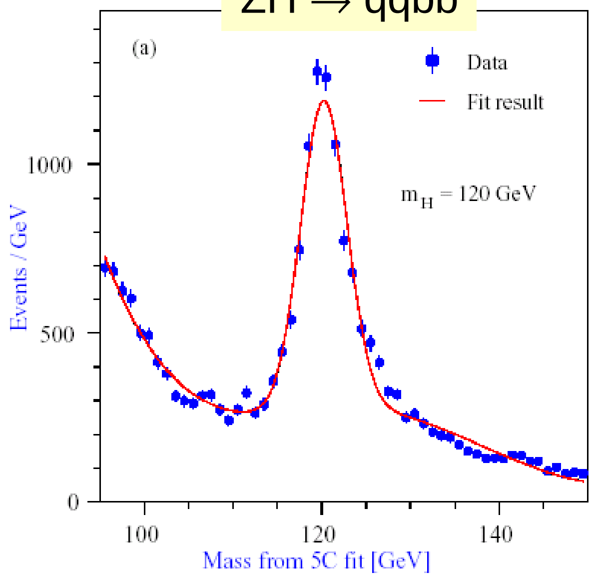
Inclusive Higgs decays
(recoil mass method)

$ZH \to \ell^+\ell^- W^+W^-$



Exclusive Higgs decays
(constrained kinematic fitting)

$ZH \to qqbb$



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

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

Spin and CP quantum numbers

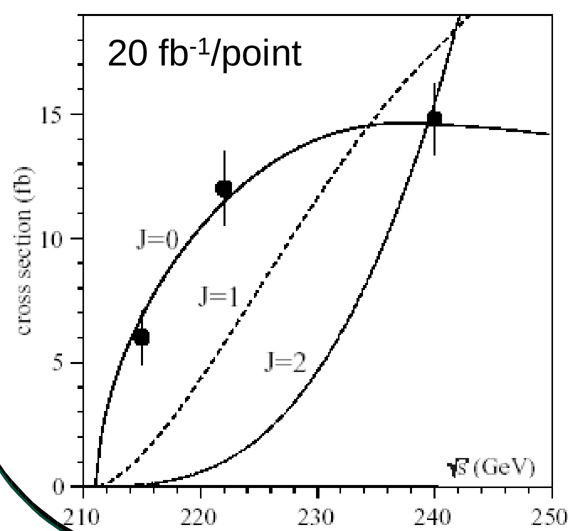
- J^{PC} of a Higgs boson can potentially be determined in a model-independent way.
- Observation of decay process $H \rightarrow \gamma\gamma$ or production process $\gamma\gamma \rightarrow H$ rules out J=1 and sets C=+1 (Landau-Yang Theorem).
- At threshold: determine J from β-dependence of σ_{ZH}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

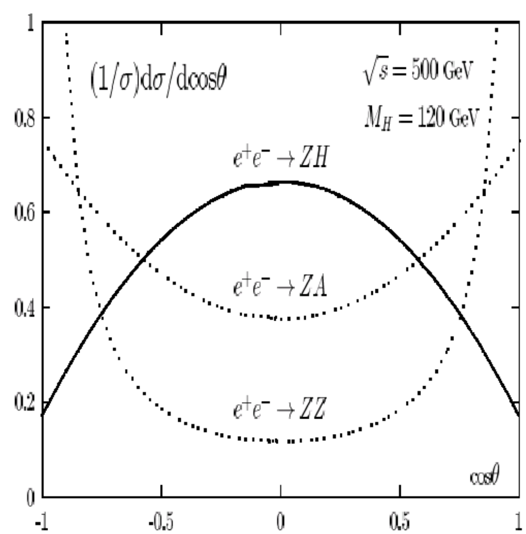
  - angular distribution of Z in ZH;

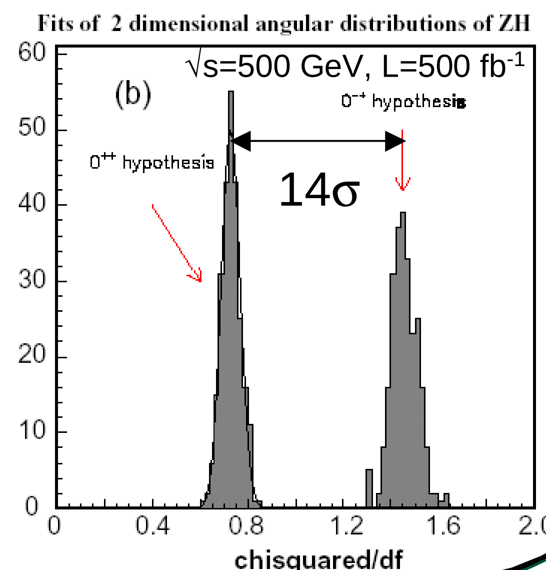
CP-even Interference CP-odd

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

  - 2D angular distribution of fermions in ZH $\rightarrow$ 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

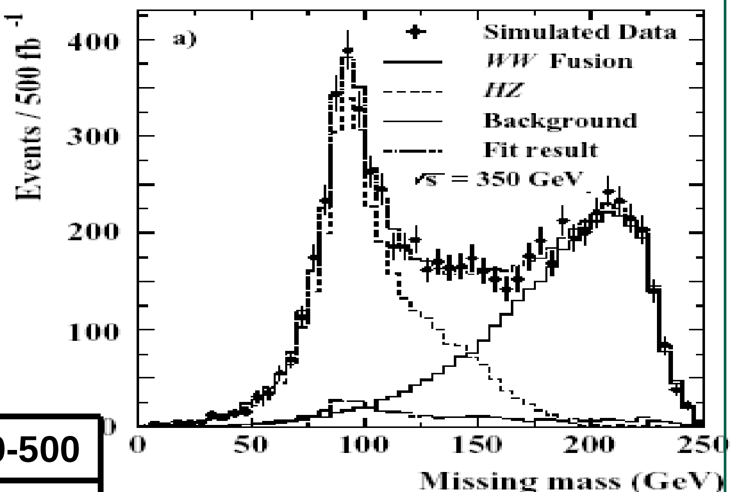
g_{ZZH}

- 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 $\sqrt{s}$ = 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$\rightarrow$WW*)
     - Select exclusive decay ZH $\rightarrow$ 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 WW, ZZ and tt backgrounds. Also useful e^- polarization to remove WW.



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

L=500 fb-1
$\sqrt{s}$ = 350 GeV
= 500 GeV
= 800 GeV

Higgs couplings to gauge bosons: γ

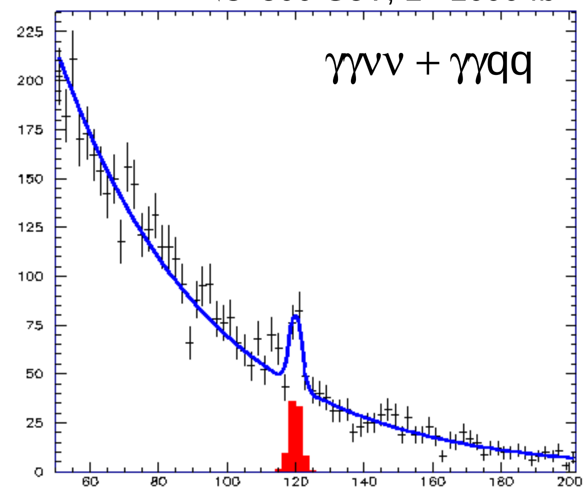
- $H\to\gamma\gamma$ mediated by loop and therefore sensitive to any particle directly coupled to H and γ. Within the SM, dominant contribution comes from W, followed by t.
- Several methods to determine the effective $g_{H\gamma\gamma}$ coupling.

e^+e^--collider

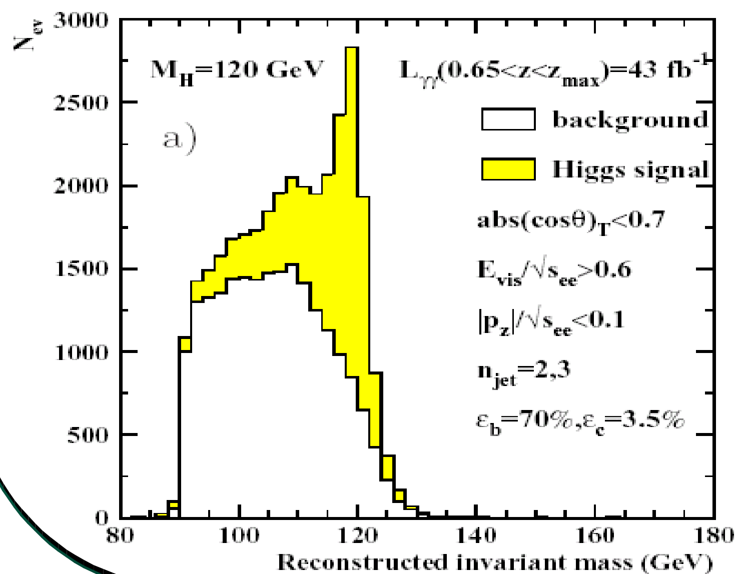
- BR($H\to\gamma\gamma$) from σ x BR($H\to\gamma\gamma$) in $\gamma\gamma\nu\nu$ events (ZH and $H\nu\nu$) and $\gamma\gamma qq$ events (only ZH).
- Challenging: large background from double-bremsstrahlung $Z\gamma\gamma$ events + smallness of BR($H\to\gamma\gamma$).

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

$\sqrt{s}$=500 GeV, L= 1000 fb^{-1}



$m_{\gamma\gamma}$ (GeV)



$\gamma\gamma$-collider

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

$\Delta\Gamma(H\to\gamma\gamma)/\Gamma(H\to\gamma\gamma)$~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.

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

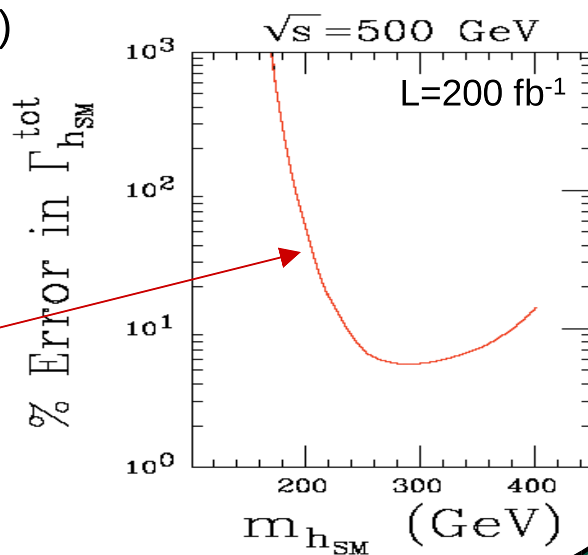
- Indirect methods:
  1) $\Gamma(H \to WW^*)$ from WW-fusion with final state $bb\nu\nu$. $BR(H \to WW^*)$ from $ZH \to qqWW$ through recoil mass method.
  2) compute $\Gamma(H \to WW^*)$ by imposing SU(2) relationship $g_{HWW} = g_{HZZ} \cos\theta_W$ (g_{HZZ} from ZH) and $BR(H \to WW^*)$ as in 1).
  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%		

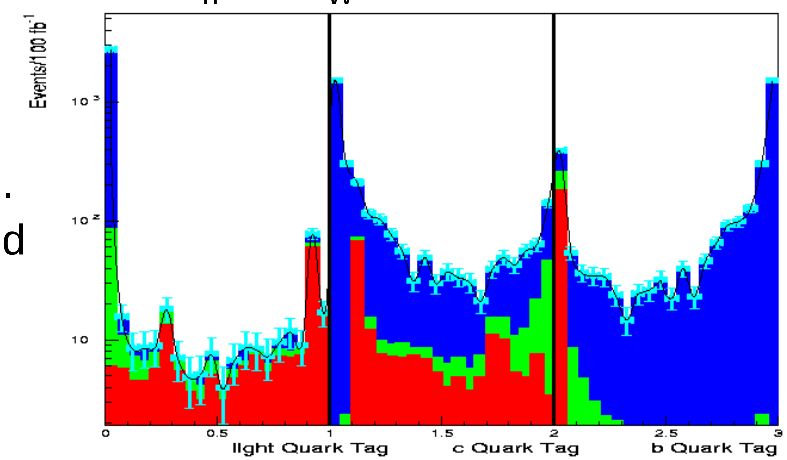
$m_H > 200$ GeV

- $\Gamma_H > 2$ 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($H \to ff$).



H→ bb, cc

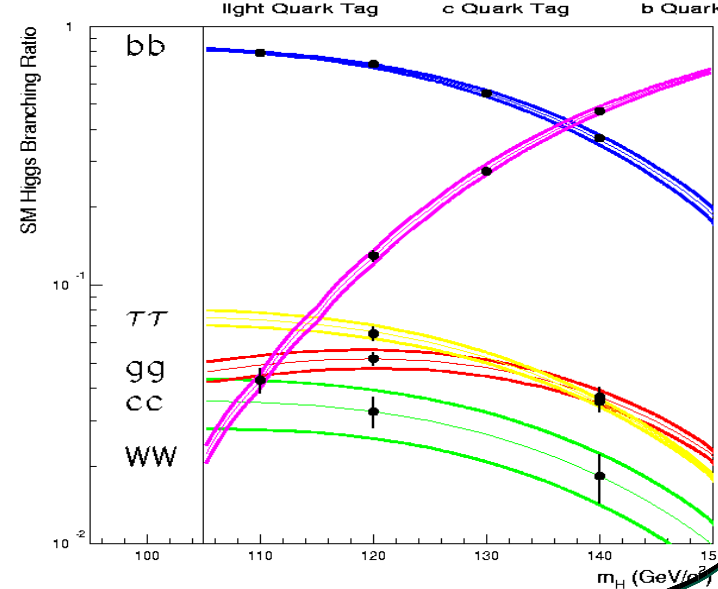
- Select hadronic Higgs boson decay channels.
- Fraction of bb, cc and gg final states extracted from binned-likelihood fit to jet flavor tagging probabilities.
- Background subtracted from Higgs mass distribution sidebands.

H→ $\tau\tau$

- From global $\tau\tau$ likelihood.

L=500 fb^{-1}, $\sqrt{s}$ = 350 GeV, 500 GeV

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

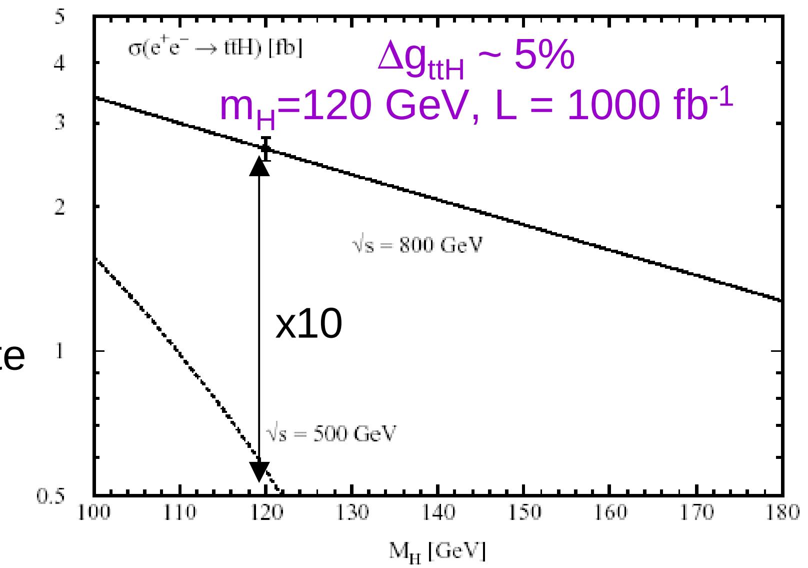


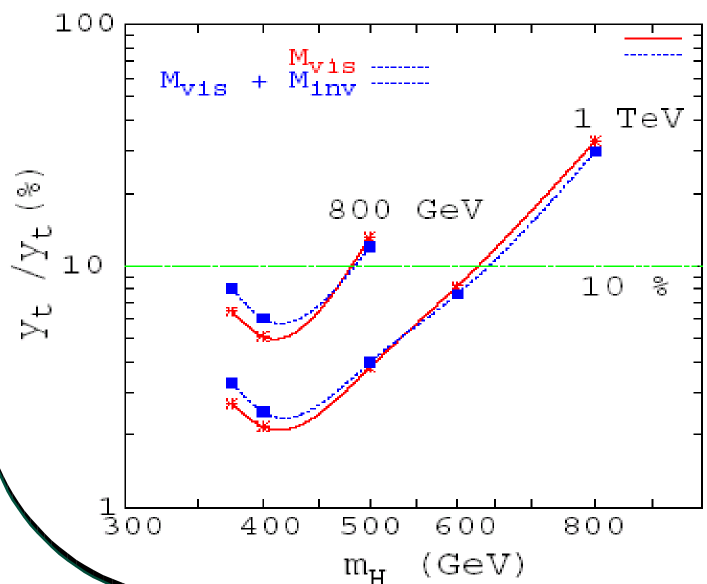
Higgs couplings to fermions: t

- 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.

$m_H < 2\, m_t$

- The process $e^+e^- \to ttH$ 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 ($\sqrt{s}$=800 GeV) and luminosity (L=1000 fb^{-1}).
- Use of b-tagging and sophisticated multivariate selections crucial.





$m_H > 2\, m_t$

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

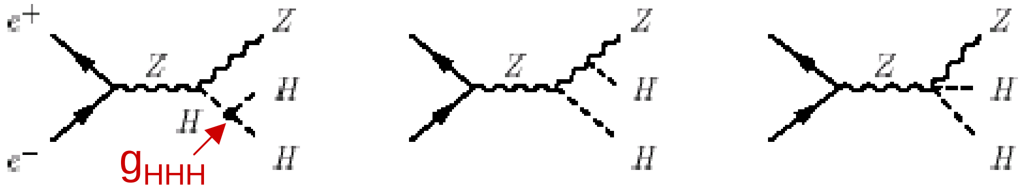
Δg_{ttH} ~ 5% (12%)
m_H=400 (500) GeV, L = 1000 fb^{-1}

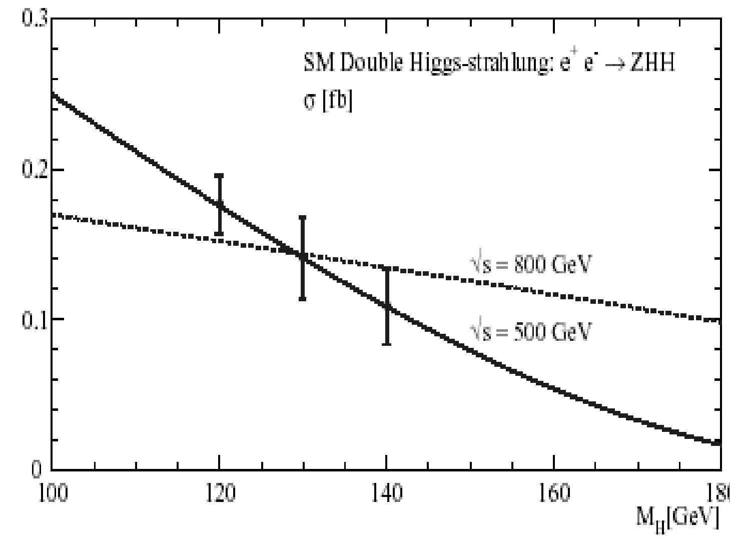
Higgs self-couplings

- 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 $\sqrt{s}$=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.

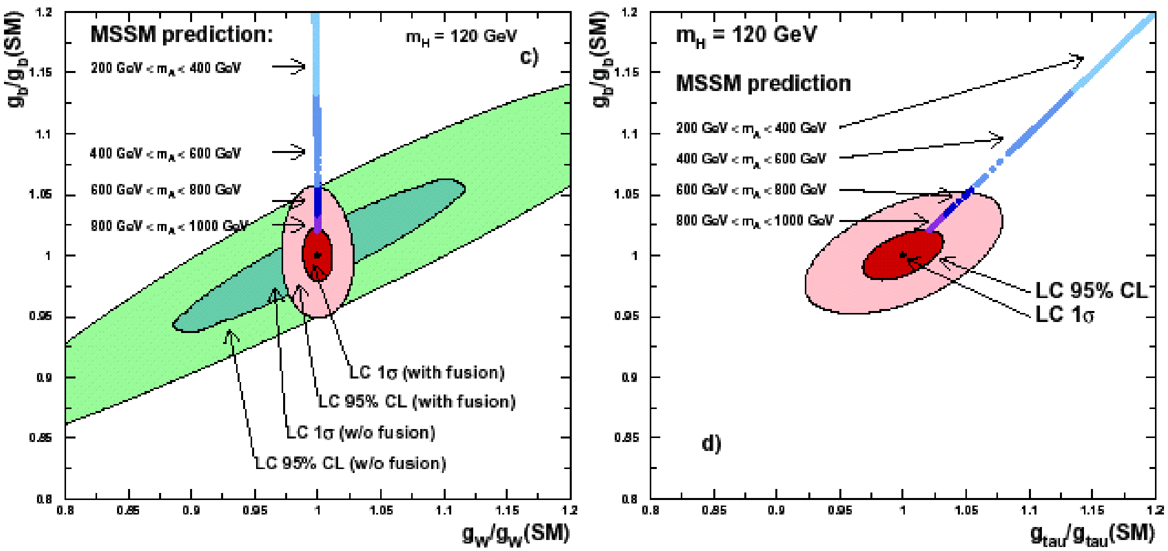
$$\left(\frac{\Delta g_{HHH}}{g_{HHH}}\right) \sim 1.75 \times \left(\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}}\right)$$

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.



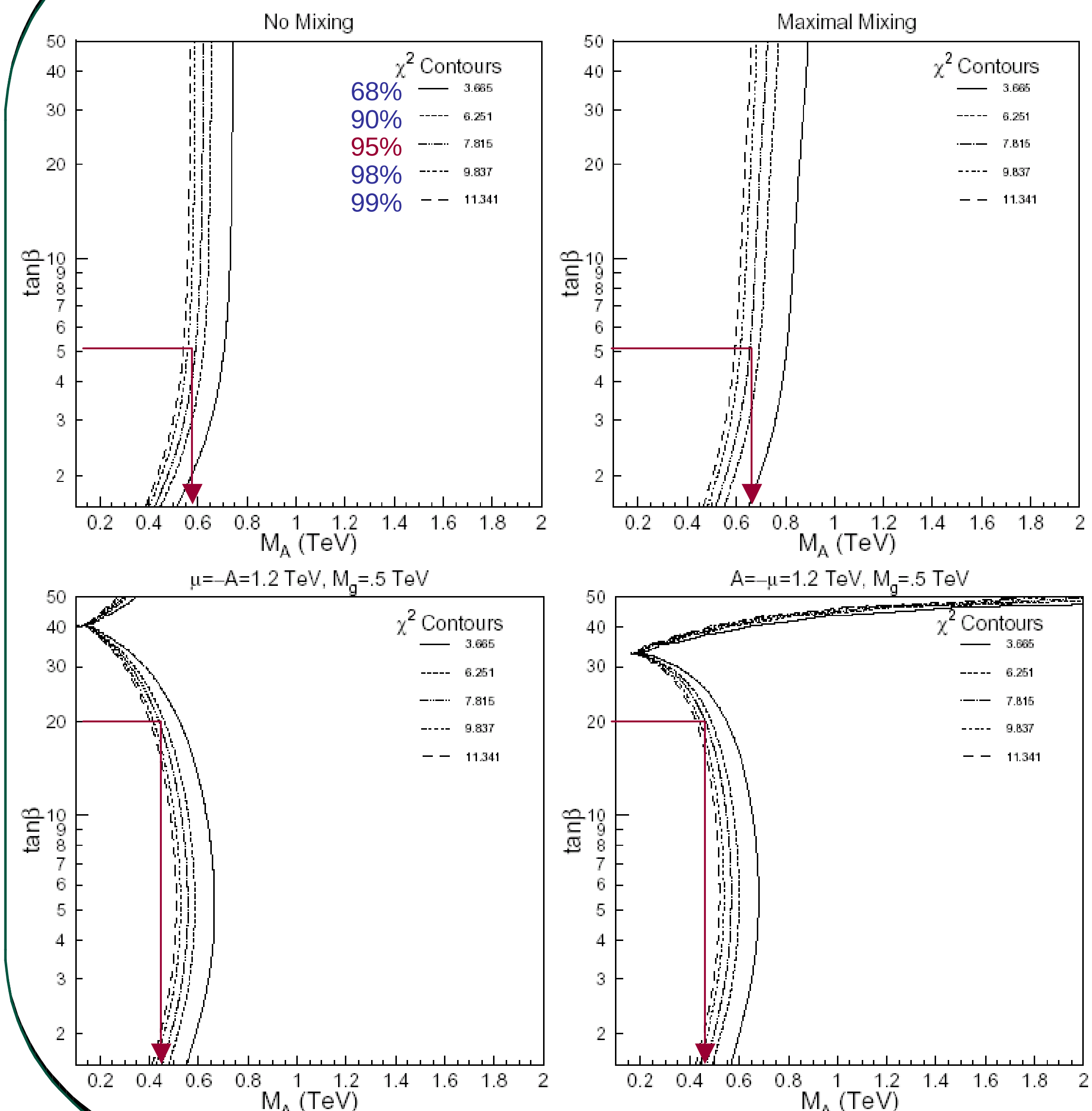
$L = 500\ fb^{-1}$

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

- 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:

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

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.
- 118 GeV<m_h<129 GeV.
- 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%

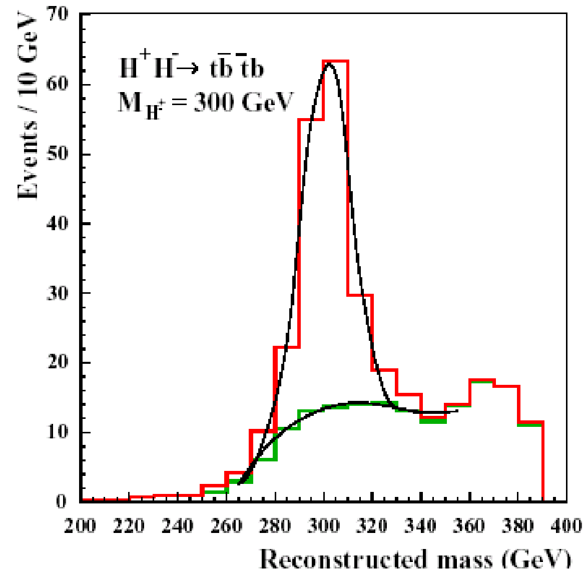
- 3 benchmark scenarios: radiative corrections make the reach on m_A depend on the SUSY parameters.
- There are regions of parameter space where a "m_A-independent" decoupling is obtained.

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 $m \sim 0.7\sqrt{s_{ee}}$

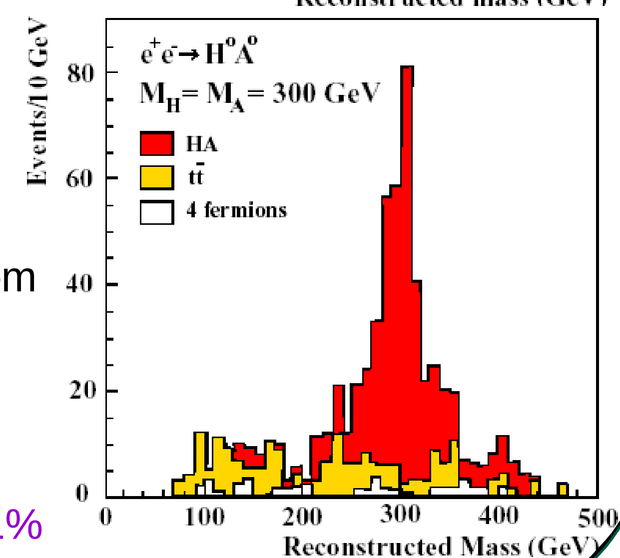
$e^+e^- \rightarrow H^+H^- \rightarrow tbtb$

- 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 fb^{-1}: 120 (50) signal (bckg) events
  $\Delta m_H \sim 1$ GeV, $\Delta(\sigma_{HH} \times BR^2) \leq 15\%$



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

- 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 fb^{-1}:
  $\Delta m_{H,A} / m_{H,A}$ = 0.2-0.4%,
  $\Delta(\sigma_{HA} \times BR(H \rightarrow bb) \times BR(A \rightarrow bb))$ = 5-11%
  for 260 GeV < $m_{H,A}$ < 340 GeV



Strong WW scattering and technicolor

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

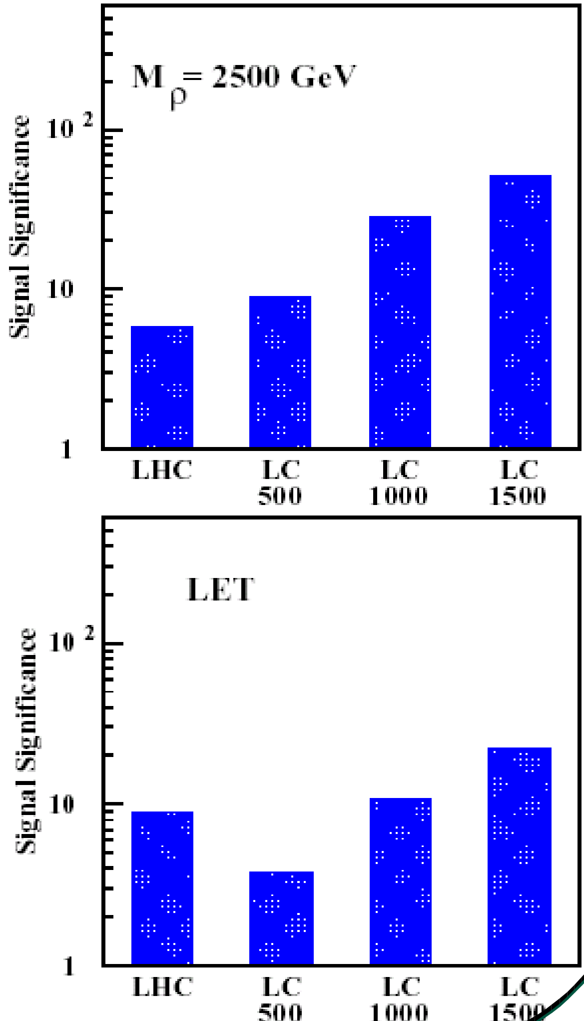
$e^+e^- \to \nu\nu WW$, $\nu\nu ZZ$
$e^+e^- \to WW$
$e^+e^- \to \nu\nu tt$

Example: Technicolor

- New chiral fermions 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 and QGCs at high energy. Sensitivity < 10^{-3} ➔ but not unambiguous.
- Search for vector resonance effects in $e^+e^- \to W^+W^-$ ➔ sensitivity even to LET limit.

L = 300, 500, 1000, 1000 fb^{-1}



Composite Higgs models

- 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.
- Approximate well SM at low energy.

Example: Top-quark seesaw model:

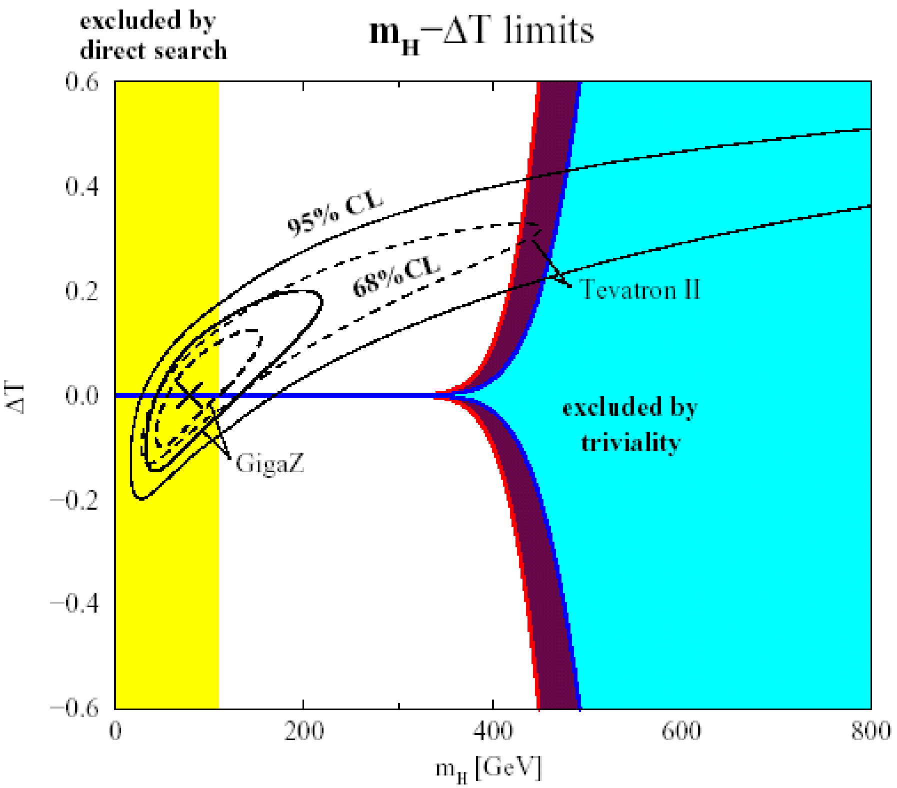
$H \sim \langle t_L \Psi_R \rangle$, $m_H \sim 500$ GeV

Ψ: new heavy (~ few TeV) vector-like quark

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 $e^+e^- \to f\bar{f}$.

Chivukula et al, hep-ph/0002022



Tevatron II: $\Delta m_W = 30$ MeV, $\Delta m_t = 2$ GeV
GigaZ : $\Delta m_W = 6$ MeV, $\Delta m_t = 200$ MeV

Conclusions

- Elucidation of the dynamics responsible for electroweak symmetry breaking 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 electroweak symmetry breaking 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 electroweak symmetry breaking "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.

- In order to fully exploit the potential of this experimental program, the existence of precise theoretical predictions will be mandatory (see L. Reina's talk).

References

- TESLA Technical Design Report
- Linear Collider Physics Resource Book for Snowmass 2001