

Higgs physics at the ILC

Klaus Desch
University of Bonn

LINEAR COLLIDER PHYSICS SCHOOL 2006

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Disclaimers + Announcements

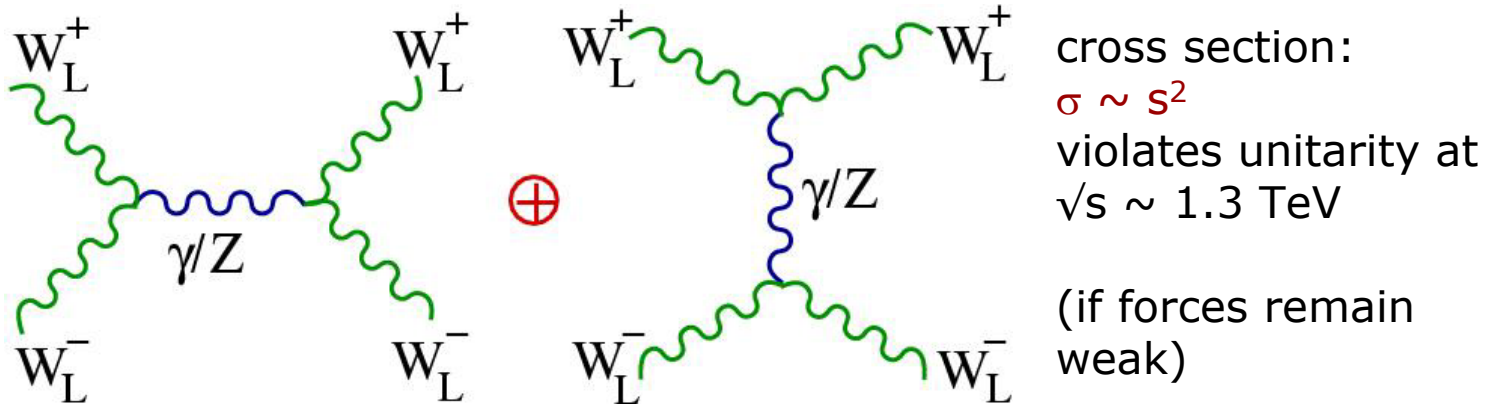
Focus will be on experimental possibilities + studies with detector simulation

Huge theoretical effort in the past decade will probably not be covered as it should – apologies!

I'm happy to answer questions at any time – we don't have to rush!

Any selection of topics is biased – in these lectures as well...

Quantum field theory with massive exchange particles fails at high energies:



“if nothing happens, something must happen...”

The Standard Model Solution:

(rescue plan for the gauge principle)

Introduction of a new scalar field with non-vanishing field strength in the vacuum: **the Higgs field.**

Paradigm:

All (elementary) particles are massless

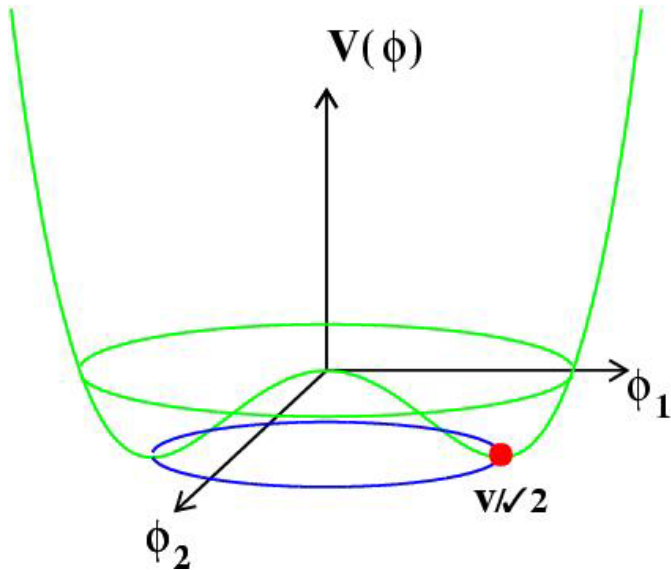
⇒ gauge principle works

⇒ renormalizable theory (finite cross sections)

permanent interaction with the Higgs field acts, as if the particles had a mass (**effective mass**)

$$\begin{aligned}
 & \left(\frac{1}{q^2} \right) + \left(\frac{gv}{\sqrt{2}} \right)^2 \left(\frac{1}{q^2} \right) + \left(\frac{gv}{\sqrt{2}} \right)^4 \left(\frac{1}{q^2} \right)^2 + \dots \\
 & = \frac{1}{q^2 - M^2} \quad \text{with } M^2 = g^2 \frac{v^2}{2}
 \end{aligned}$$

How to add such a field in a gauge invariant way?



“Mexican hat-Potential”

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

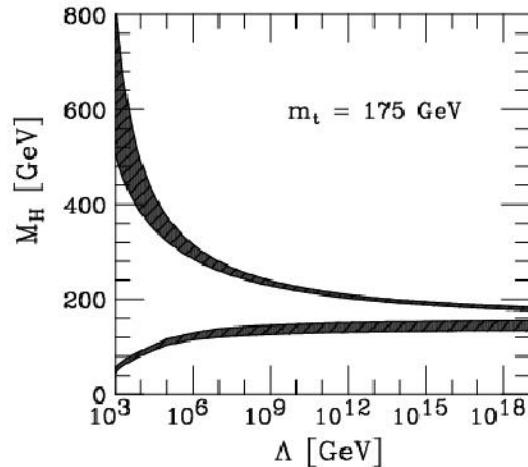
most simple case: Φ = complex doublet of weak isospin (=SM)

but this is a pure guess
many more possibilities, e.g.:
2 doublets (minimal SUSY),
triplets,...

models with “true” and “effective” mass are not equivalent:

formulation with the help of Higgs mechanism:

- is gauge invariant
- postulates at least 1 scalar, massive Higgs boson



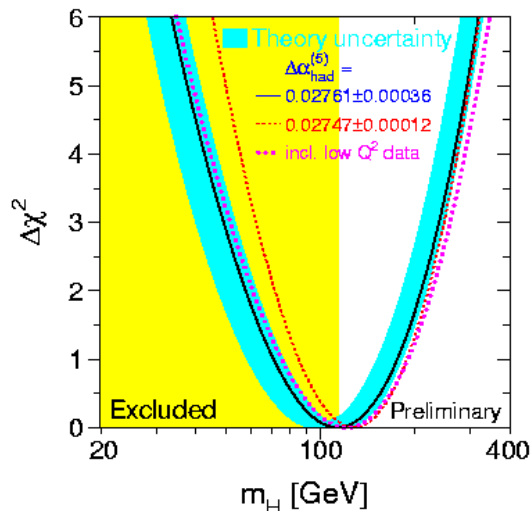
Theory:

Upper bound: perturbativity ($\lambda < 1$)

Lower bound: vacuum stability

Models: minimal SUSY: $m < 135 \text{ GeV}$

GUT's : $m < 180 \text{ GeV}$



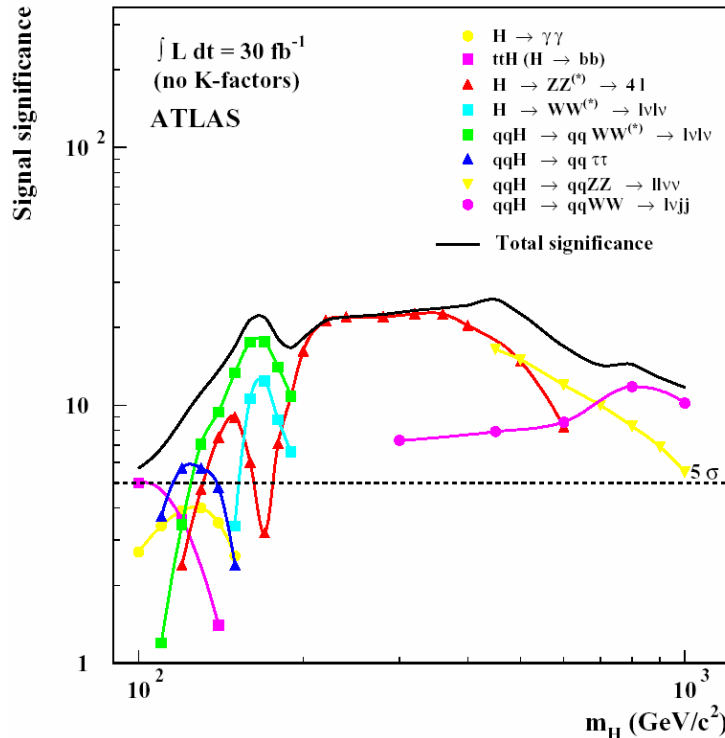
Experiment:

Precision measurements

(LEP, SLC, Tevatron) are sensitive to virtual corrections:

$m < 200 \text{ GeV}$ (95% CL) within SM

The Higgs boson is probably "light"!



SM-like Higgs discovery with 30 fb^{-1} in one experiment guaranteed

Light Higgs most challenging
Fusion channels help a lot

Unusual decay modes (invisible, purely hadronic more complicated)

First measurements of Higgs properties possible:

- Mass: 0.1 – 0.4%
- Production rates: 10-20%
- Ratios of couplings: W/Z , W/t , W/b : 10-20%
- model-independent measurements of absolute couplings impossible

After the discovery of a Higgs boson, the key task of ILC is to establish the Higgs mechanism in all elements as being responsible for EW symmetry breaking

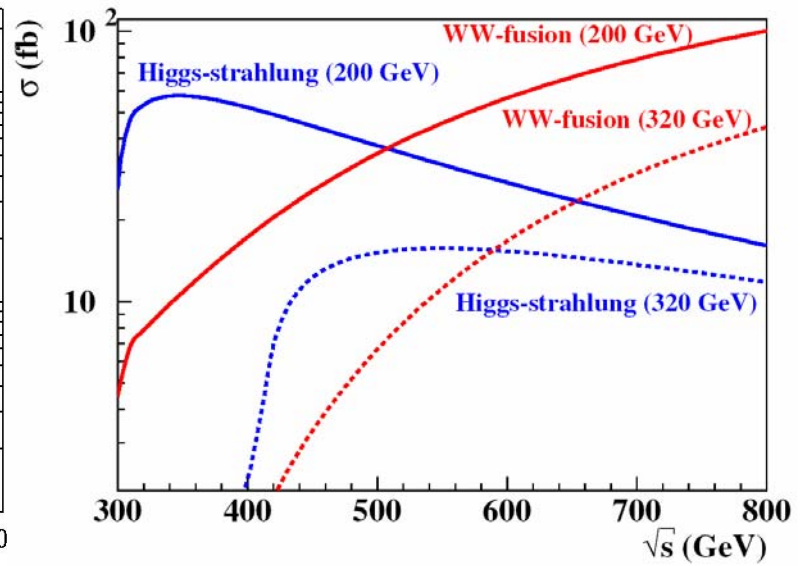
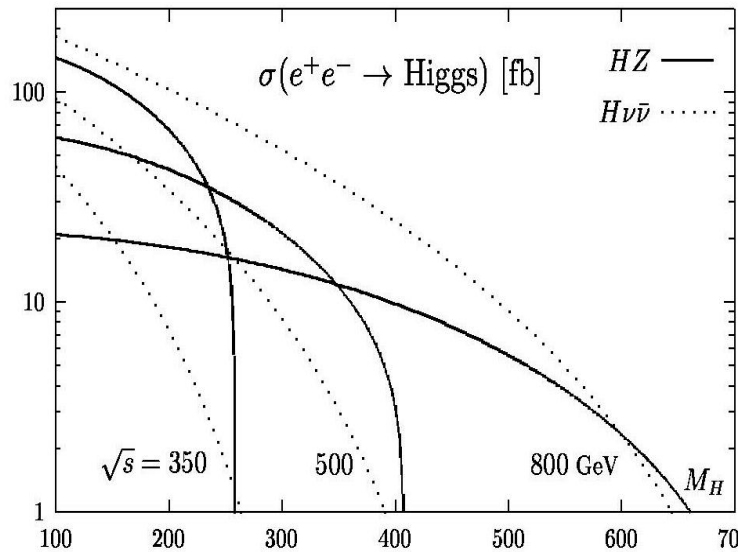
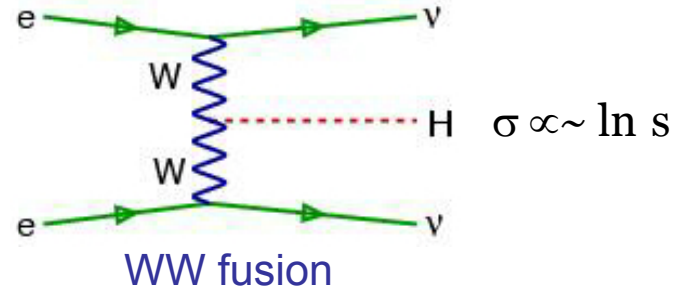
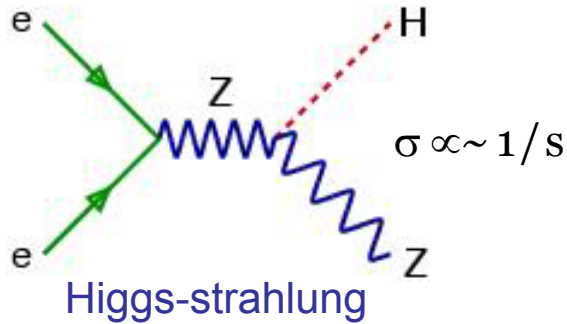
Precision Measurements must comprise:

- Mass
- Total Width
- Quantum numbers J^{PC} (Spin 0, CP-even?)
- Higgs-Fermion couplings (\sim mass ?)
- Higgs-Gauge-Boson couplings (W/Z masses)
- Higgs self coupling (spontaneous symmetry breaking)

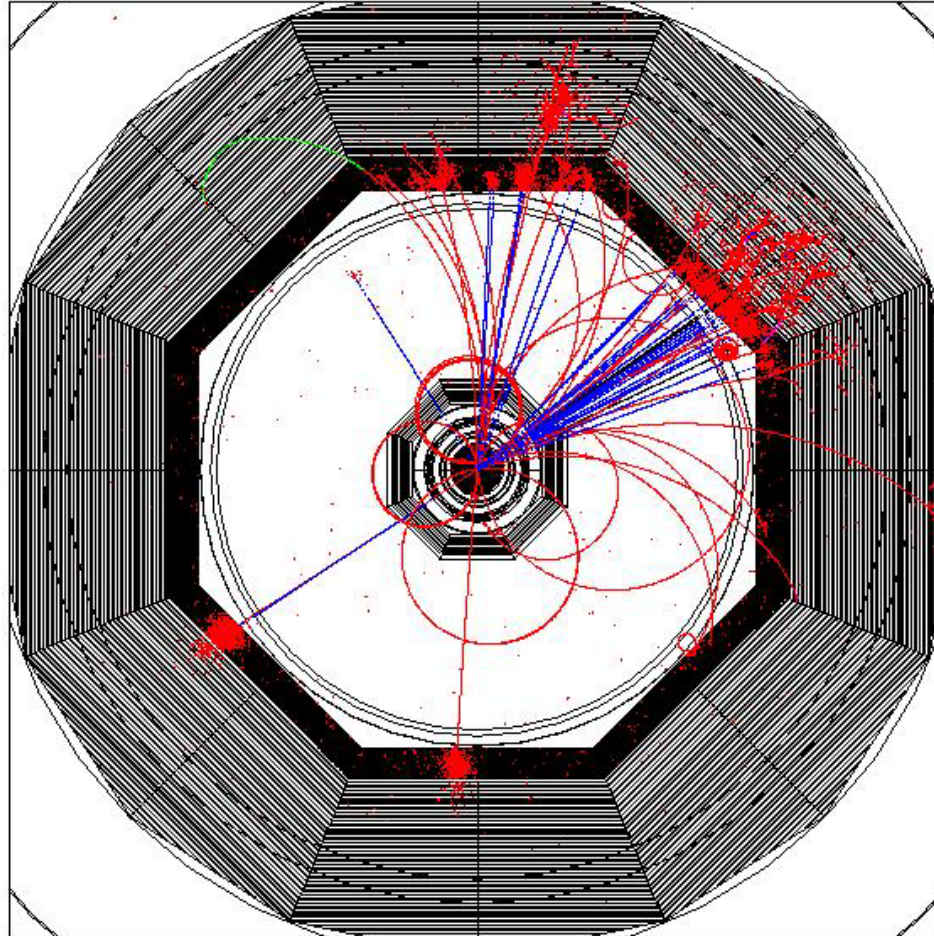
Measurements should be precise enough to distinguish between different models (e.g. SM/MSSM, effects from extra-dimensions, ...)

Aim at model-independence!

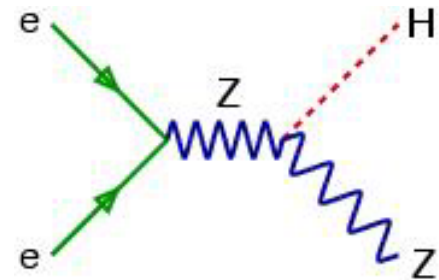
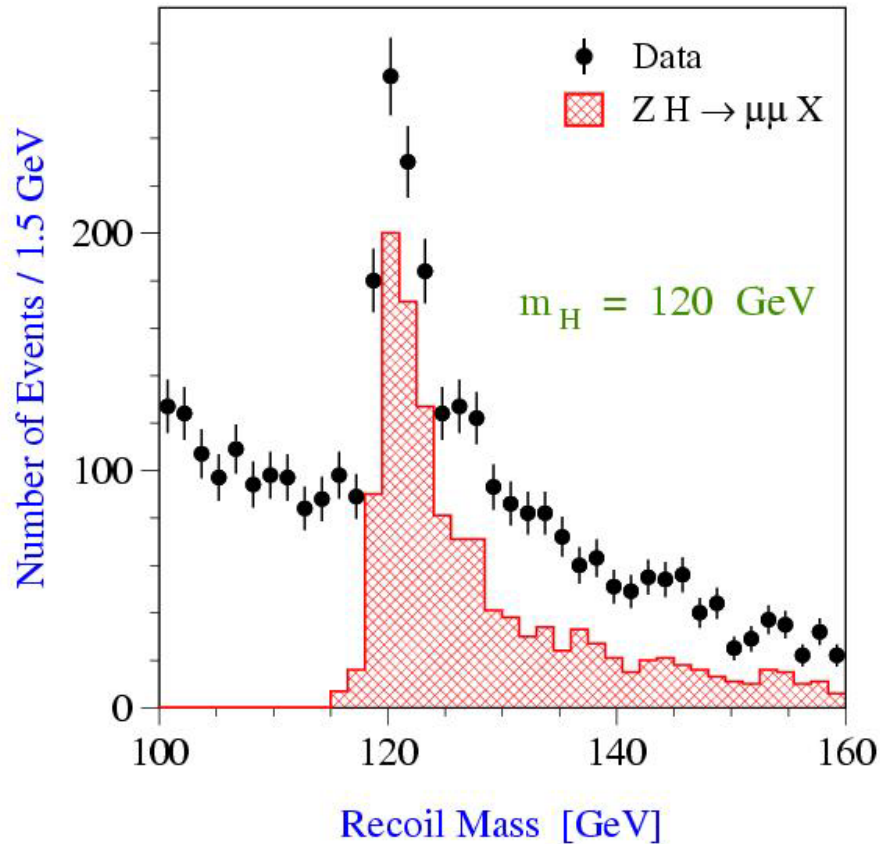
Dominant production processes at LC:



Fully simulated Higgs-strahlung event in TESLA detector ($Z \rightarrow ee, H \rightarrow bb$)



Anchor of LC Higgs physics:

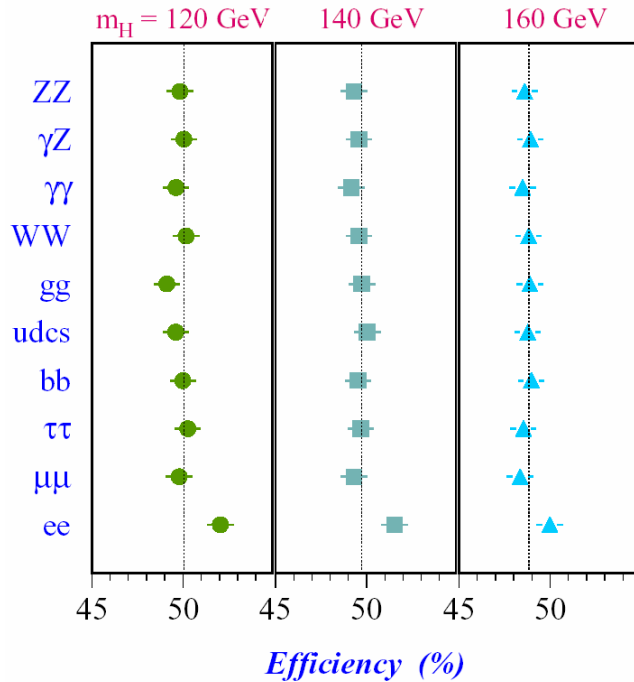


- select di-lepton events consistent with $Z \rightarrow ee/\mu\mu$
- calculate recoil mass:

$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

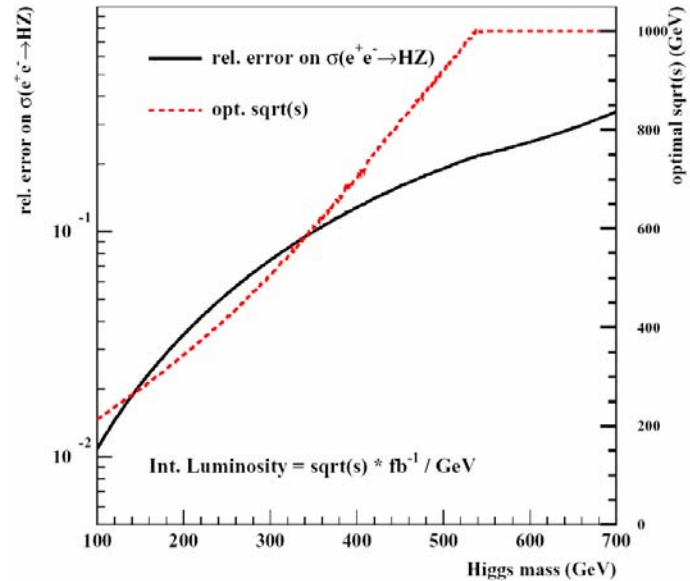
model independent,
 decay-mode independent
 measurement!

efficiency is ~independent of decay mode:



small differences can be corrected with MC

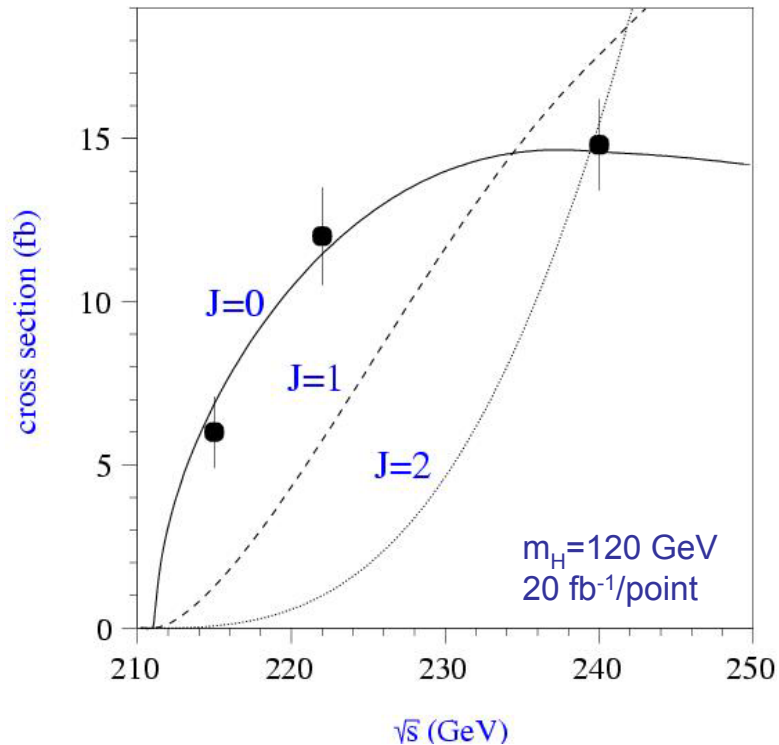
works over the whole range of possible Higgs masses:



precision on $\sigma(HZ)$:
 1-3% for $m_H < 200$ GeV
 3-20% for $m_H < 500$ GeV

Is it a Higgs boson ?

Rise of cross section near threshold is sensitive to Higgs Spin



for $J=0$: rise $\sim \beta$

for $J>0$: rise $\sim \beta^k$, $k>1$

(some cases for $J=2$ are also $\sim \beta$
but can be distinguished from $J=0$
through angular distributions)

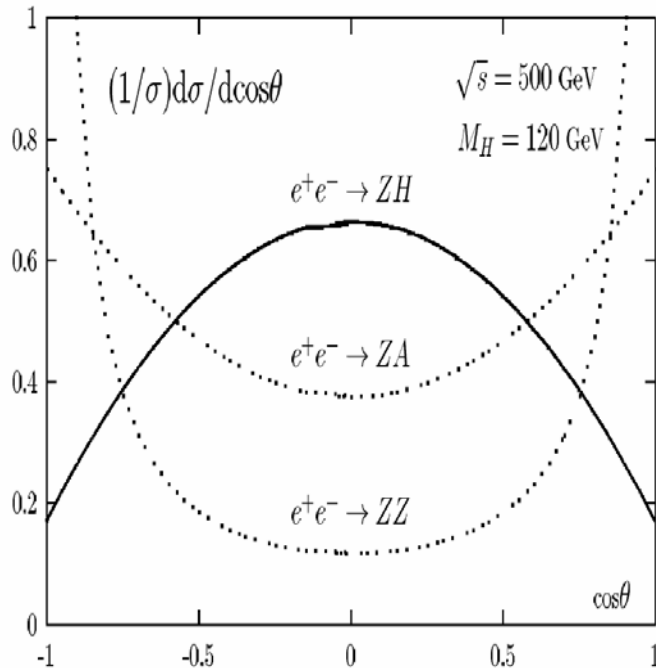
also:

observation of $H \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow H$
rule out $J=1$ and require $C = +$

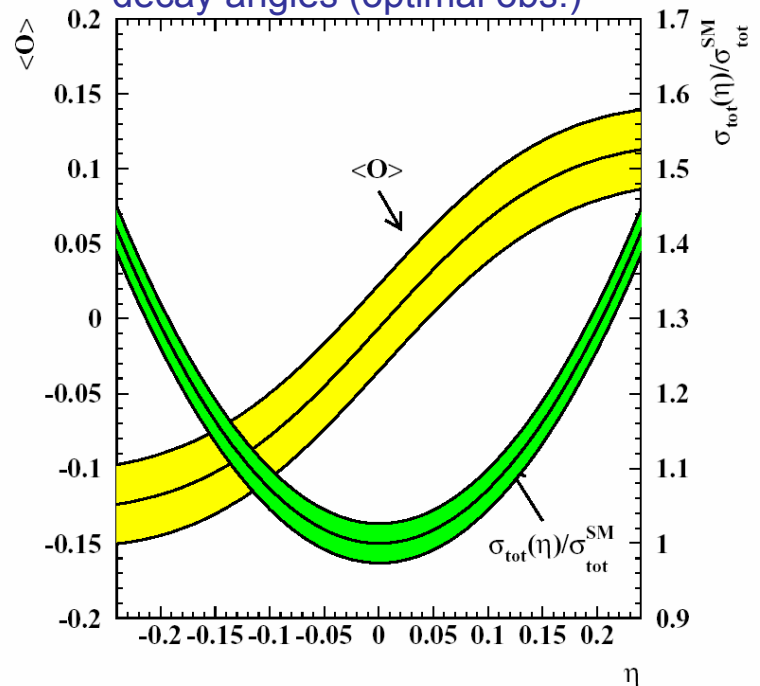
CP Quantum numbers:

Method A: Study production and decay angles of Z in Higgs-strahlung

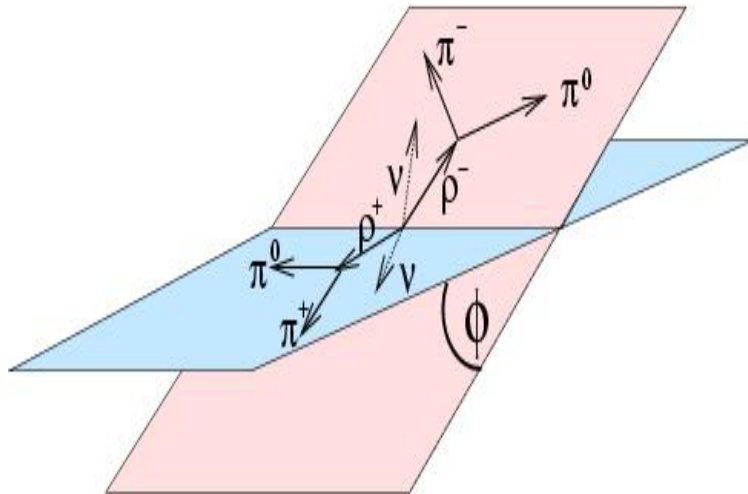
production angle



joint analysis of production and decay angles (optimal obs.)

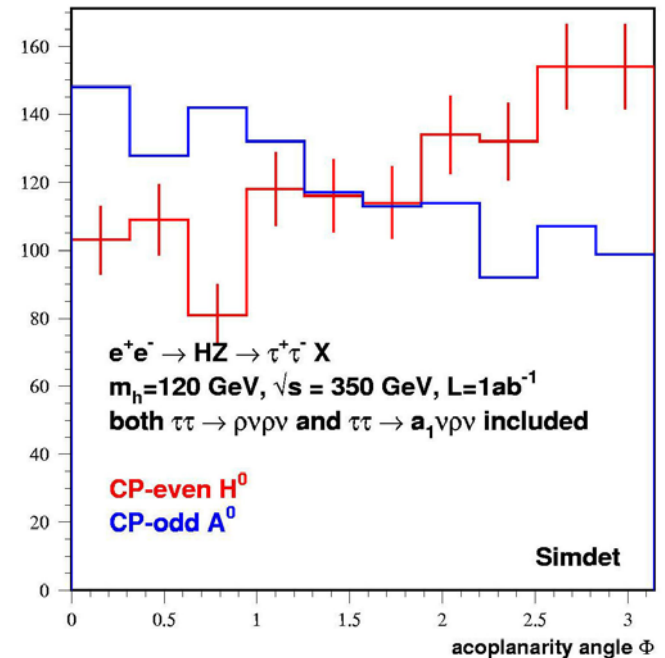


$\eta = \text{CP-odd admixture to CP even amplitude: } \lambda = \lambda_{\text{HZ}} + i\eta \lambda_{\text{ZA}}$

Method B: CP from transverse polarization correlations in $H \rightarrow \tau\tau$ 

Needs exclusive reconstruction
 $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$ decay modes

First estimate with detector simulation:
 $> 8\sigma$ separation between CP+ and CP-
 for 120 GeV Higgs (350GeV/1 ab^{-1})



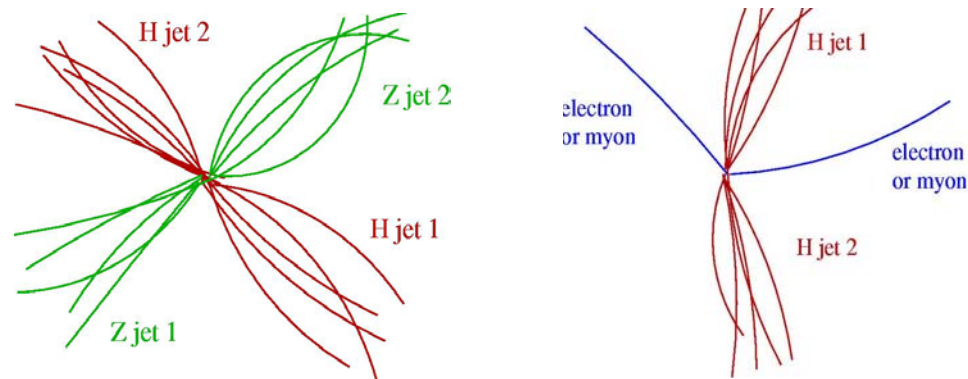
Model-independent HZ analysis only uses a fraction of the events ($Z \rightarrow \ell\ell$)

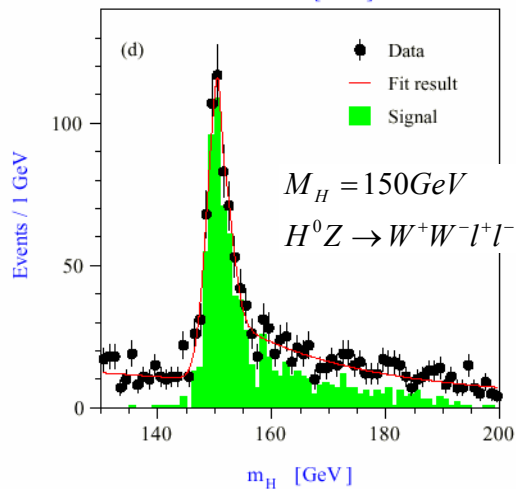
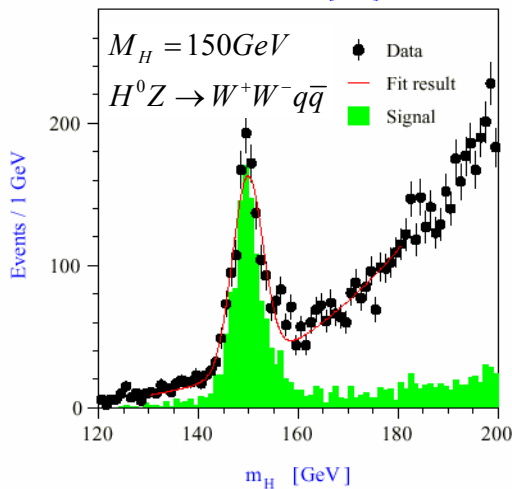
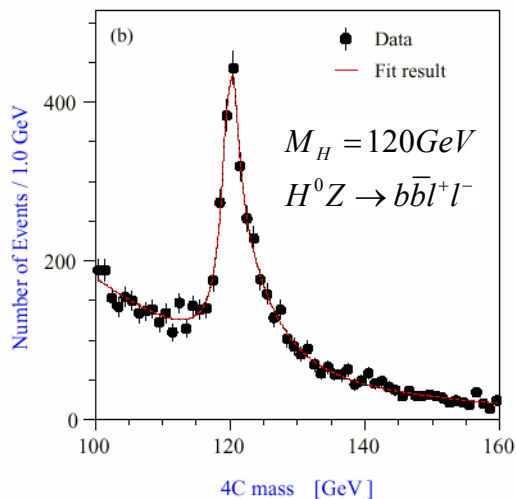
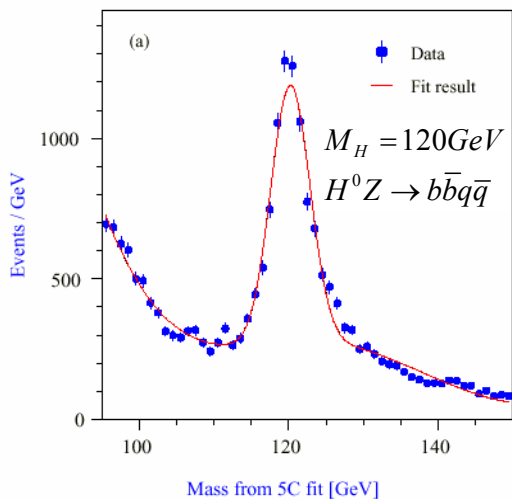
For a precise mass determination further statistics can be gained if hadronic Z-decays are used.

For mass measurement, explicit Higgs final states (e.g. $H \rightarrow b\bar{b}$) may be used

Highest sensitivity to Higgs mass comes from purely hadronic events

Kinematic fits improve the mass resolution

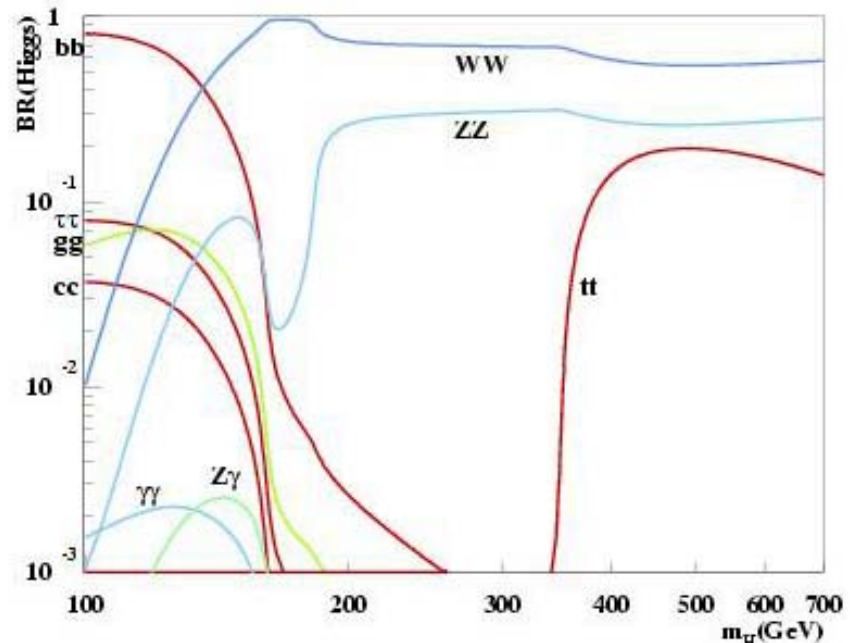




M_H GeV)	Channel	δM_H (MeV)
120	$llqq$	± 70
120	$qqbb$	± 50
120	Combined	± 40
150	ll Recoil	± 90
150	$qqWW$	± 130
150	Combined	± 70
180	ll Recoil	± 100
180	$qqWW$	± 150
180	Combined	± 80

Higgs Branching ratios best to study Higgs Yukawa couplings for a light H
 Exception: top (later)

Crucial test: $\Gamma(H \rightarrow ff) \sim m_f$?



At ILC measurement of >absolute< BR's is possible, because of decay-mode independent g_{HZZ} measurement:

$$BR(H \rightarrow X) = \frac{[\sigma(HZ) \square BR(H \rightarrow X)]^{\text{meas}}}{\sigma(HZ)^{\text{meas}}}$$

Most challenging: disentangle the hadronic Higgs decays

$H \rightarrow bb$ $H \rightarrow cc$ $H \rightarrow gg$

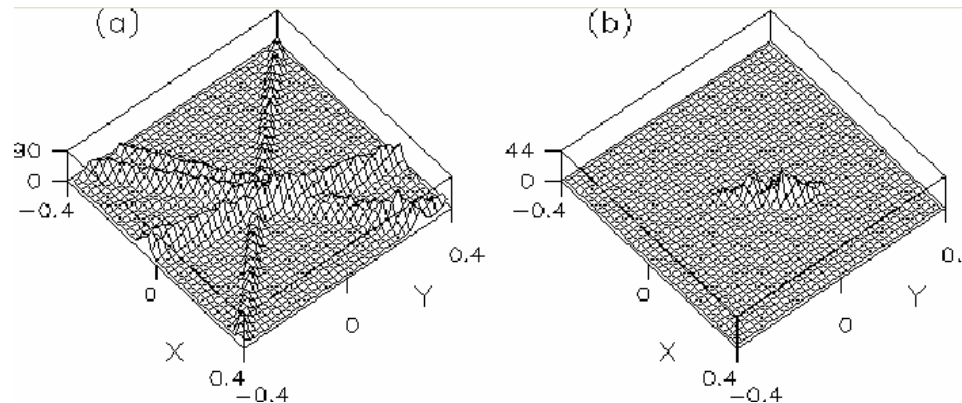
$H \rightarrow bb$	68.2%
$H \rightarrow cc$	3.0 %
$H \rightarrow gg$	6.7 %

for
 $m_H = 120 \text{ GeV}$

Need sophisticated flavour tagging:
Vertex reconstruction using ZVTOP algorithm (SLD)

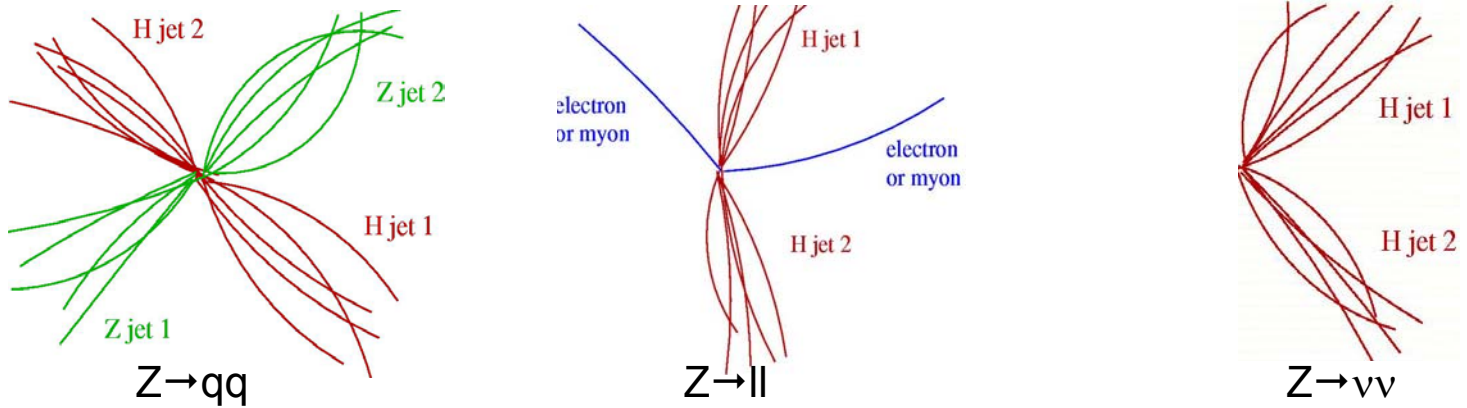
Tracks interpreted
as 3D probability tubes

Vertices = overlapping
tubes

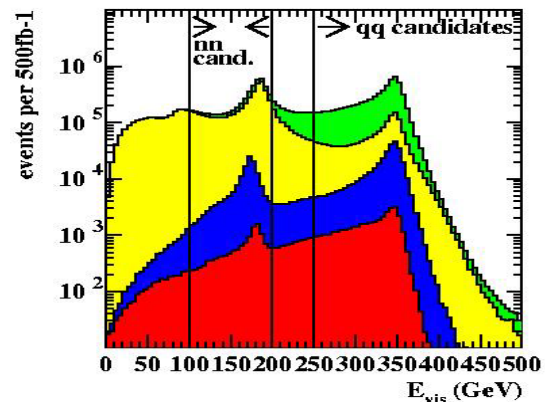
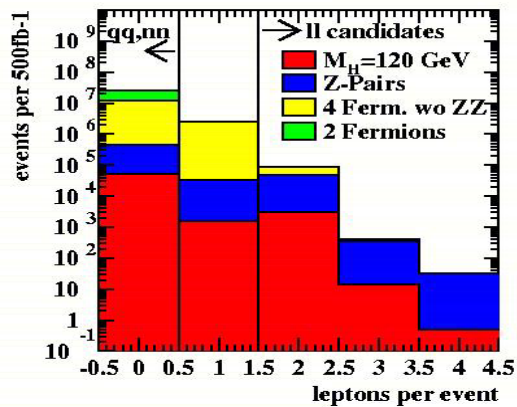


After vertex reconstruction, use ANN's with vertex+track information
to obtain b- and c-likeness for each jet

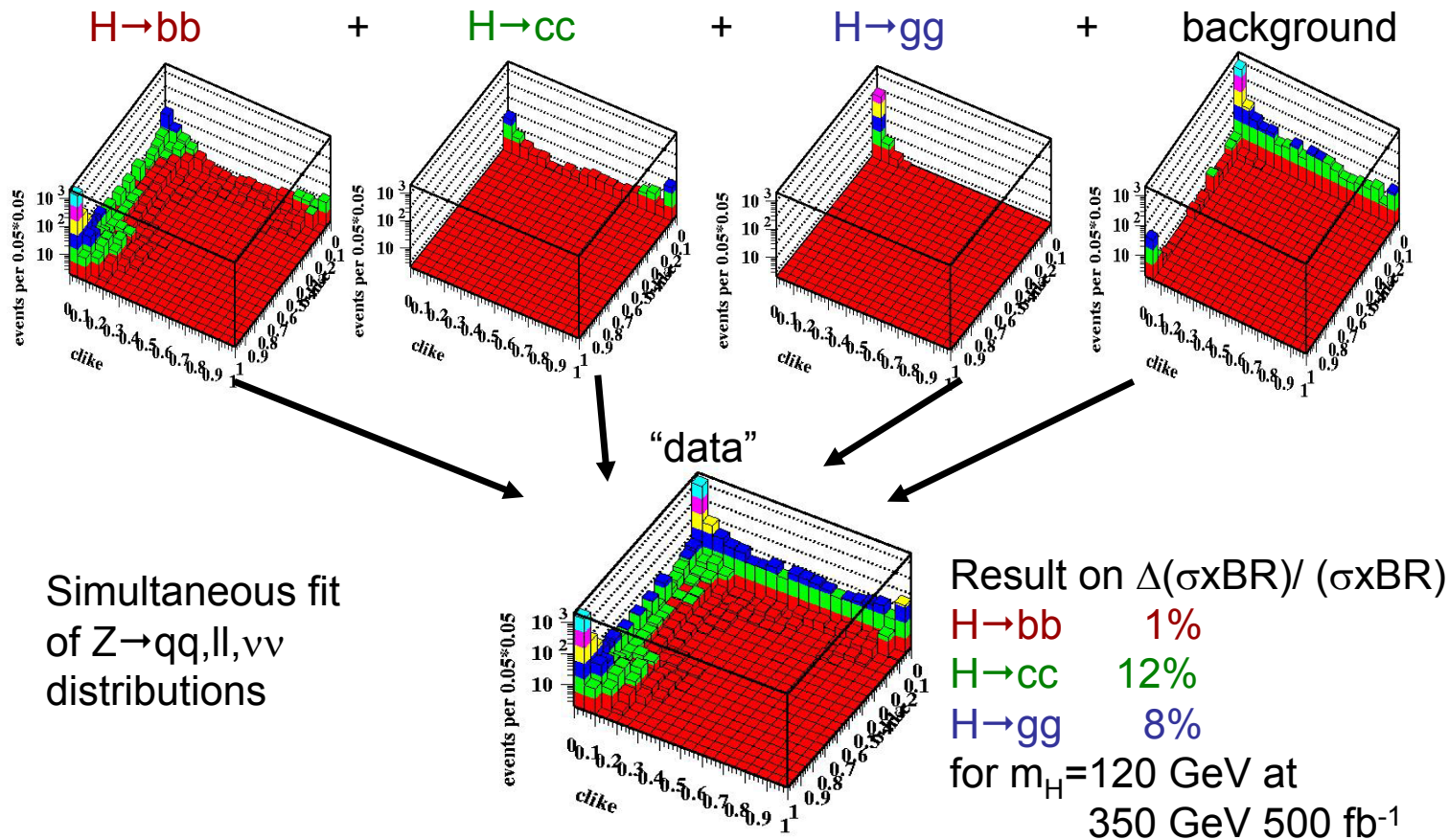
BR analysis performed for all HZ events, categorized acc. to Z decay



Classify according to #leptons and visible energy



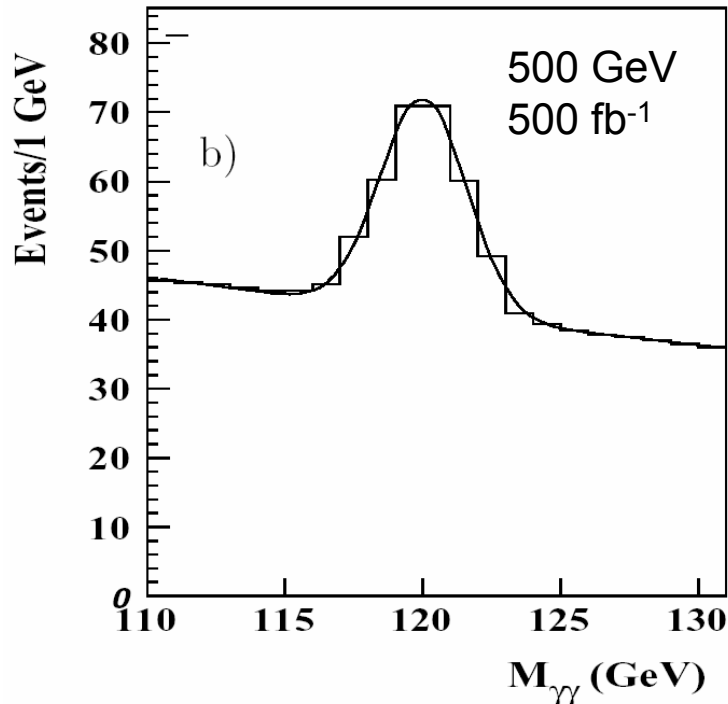
Then for each Z-channel fit the b- and c-likeness distributions



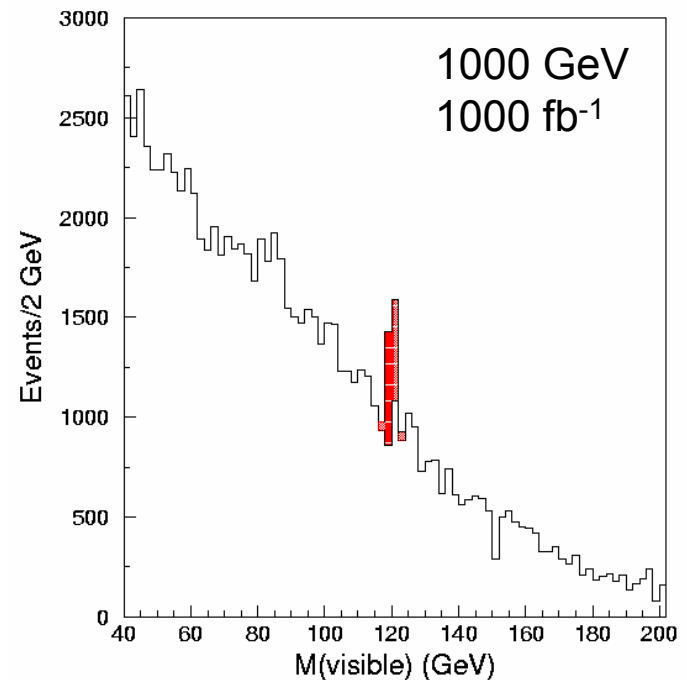
Rare decays: $H \rightarrow \gamma\gamma$

best in $\nu\nu H$

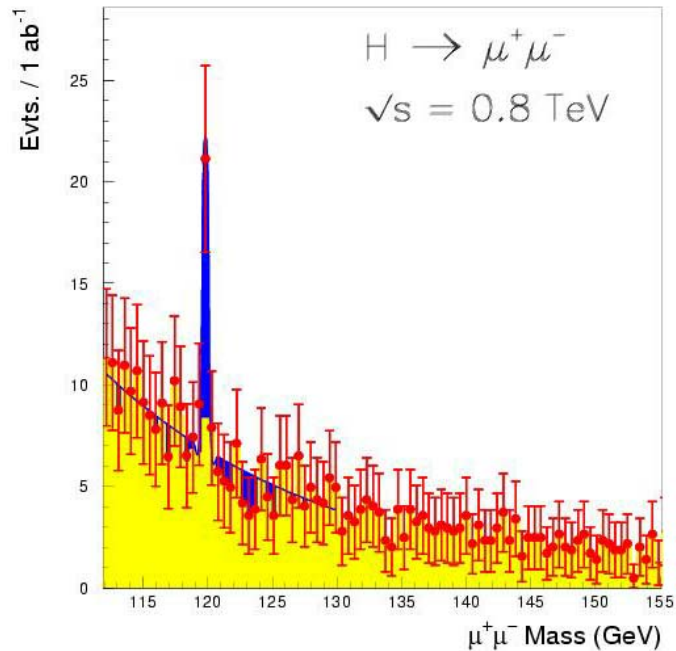
take advantage of huge event rate in WW-fusion at high energies



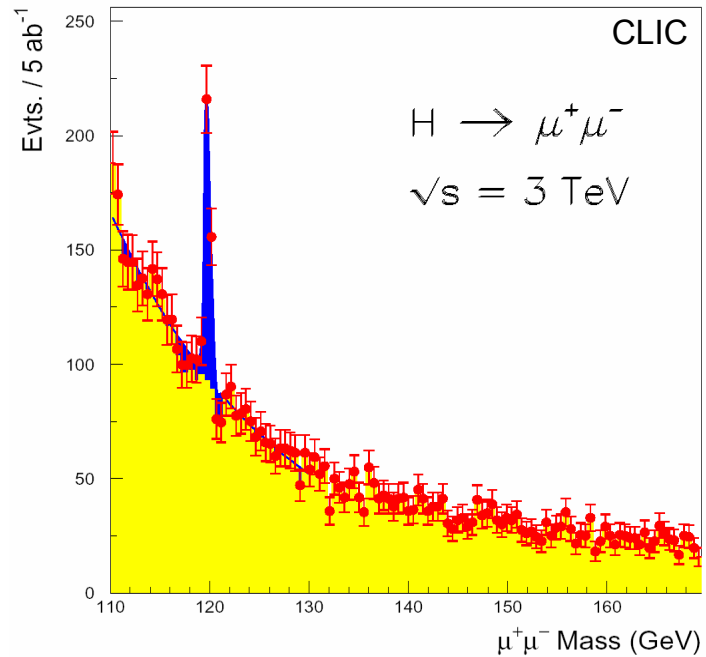
$$\Delta\text{BR}/\text{BR} = 23\%$$



$$\Delta\text{BR}/\text{BR} = 5\%$$

Rare decays: $H \rightarrow \mu\mu$ 

$\Delta\text{BR}/\text{BR} = 32\%$
 at $800 \text{ GeV} / 1\text{ab}^{-1}$

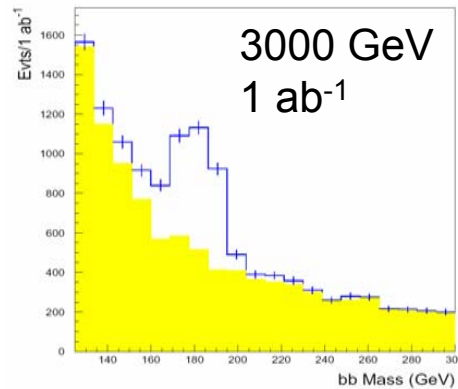
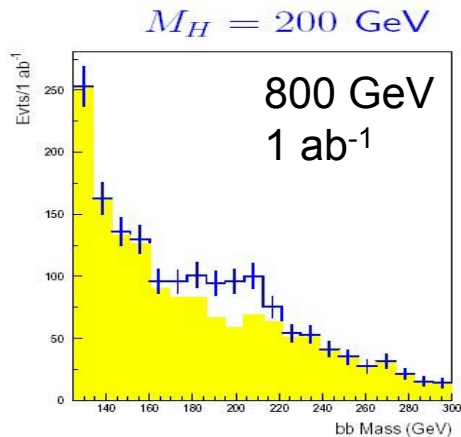


$\Delta\text{BR}/\text{BR} = 6\%$
 at $3000 \text{ GeV} / 5\text{ab}^{-1}$

Rare decays: $H \rightarrow bb$ at $m_H > 160$ GeV

hard to get any direct Yukawa coupling information if $200 < m_H < 350$ GeV!

How far can one go with $H \rightarrow bb$? Use large rate of WW-fusion processes.



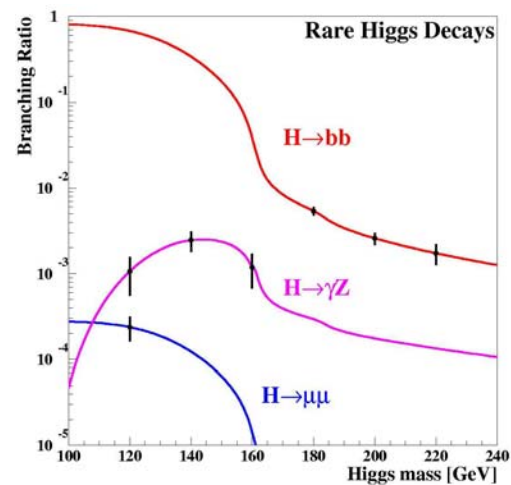
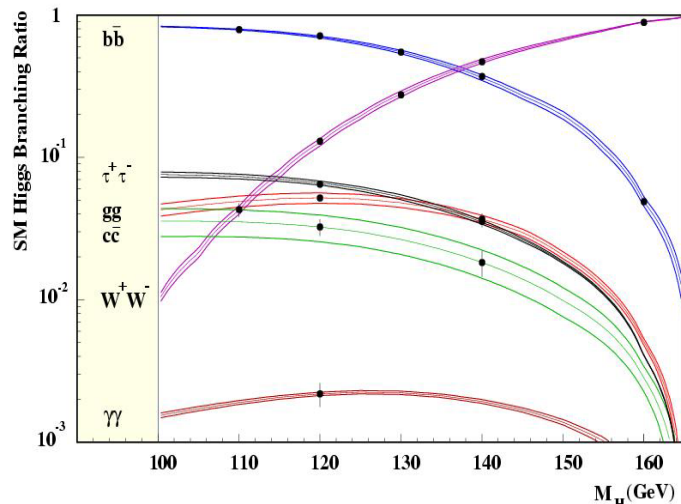
Results for $1ab^{-1}@800$ GeV

m_H (GeV)	S/sqrt(B)	$\Delta BR(bb)/BR(bb)$
180	10.5	11.5%
200	7.5	16.5%
220	4.1	27.5%

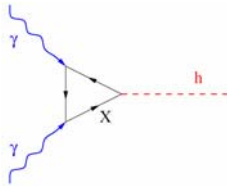
improvement to
2-6% at CLIC

Summary on Branching ratios (state-of-the-art, expect improvements)

	Higgs Mass (GeV)			
	120	140	160	200
$\Delta B_{bb}/B_{bb}$	0.016	0.018	0.020	0.090
$\Delta B_{WW}/B_{WW}$	0.020	0.018	0.010	0.025
$\Delta B_{gg}/B_{gg}$	0.023	0.035	0.146	
$\Delta B_{\gamma\gamma}/B_{\gamma\gamma}$	0.054	0.062	0.237	
$\Delta B_{\tau\tau}/B_{\tau\tau}$	0.050	0.080		
$\Delta B_{cc}/B_{cc}$	0.083	0.190		



Photon Collider: unique place to study Higgs $\gamma\gamma$ partial width in s-channel $\gamma\gamma \rightarrow H$ production

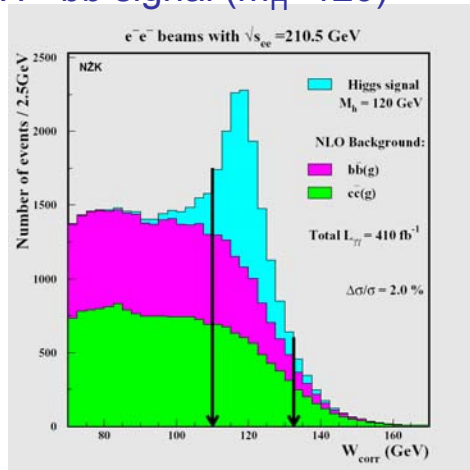


$$\sigma(\gamma\gamma \rightarrow H \rightarrow X) = \frac{4\pi^2}{m_H^3} \Gamma(H \rightarrow \gamma\gamma) \cdot \text{BR}(H \rightarrow X) (1 + \lambda_1 \lambda_2)$$

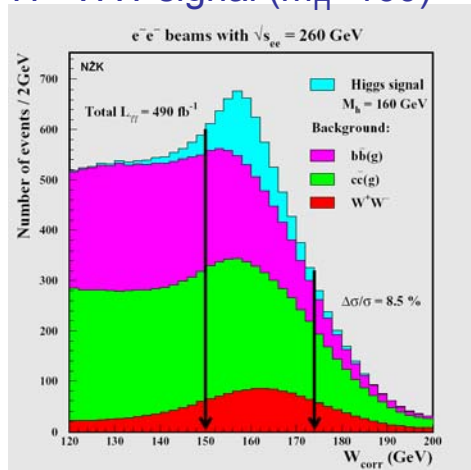
(λ_i = helicity of photon i)

Sensitive to any massive charged particle in the loop \rightarrow universal NP probe
 Combination with Higgs-BR's from e^+e^- can give total Higgs width (later)
 Assume Higgs mass known \rightarrow tune $\sqrt{s_{\gamma\gamma}}$ to peak position

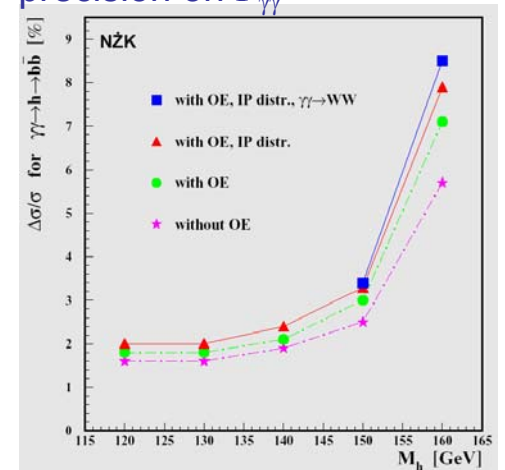
H \rightarrow bb signal ($m_H=120$)

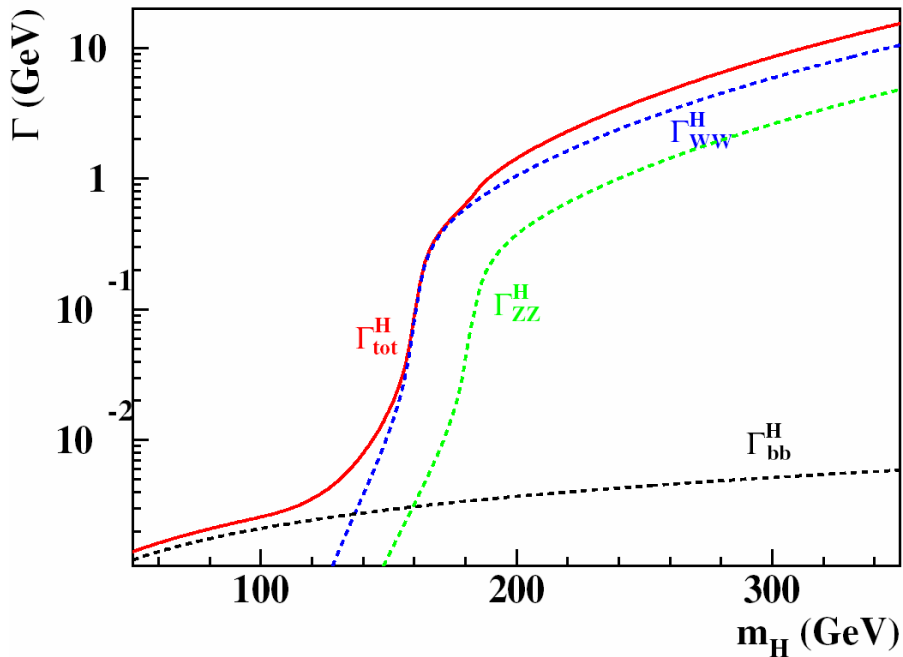


H \rightarrow WW signal ($m_H=160$)



precision on $\Gamma_{\gamma\gamma}$



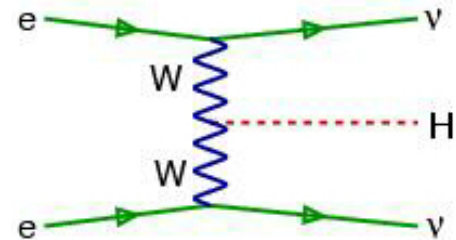
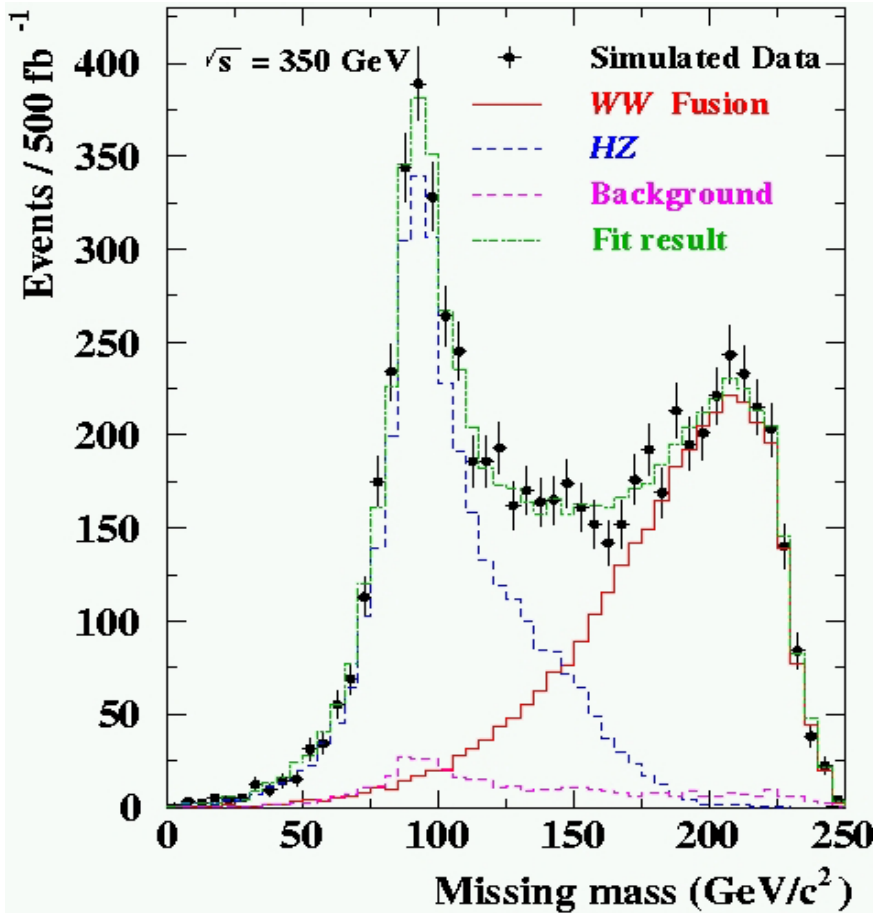


Measurement of the total Higgs decay width

$m_H < 160$ GeV: Γ too small to resolve in line-shape
 \rightarrow indirect method

$m_H > 160$ GeV: Γ from Higgs lineshape

WW-fusion process:



large cross section at large \sqrt{s}
 model independent handle
 on total width, when combined
 with $BR(H \rightarrow WW)$:

$$\Gamma_{\text{tot}} = \frac{\Gamma_{WW}}{BR(H \rightarrow WW)}$$

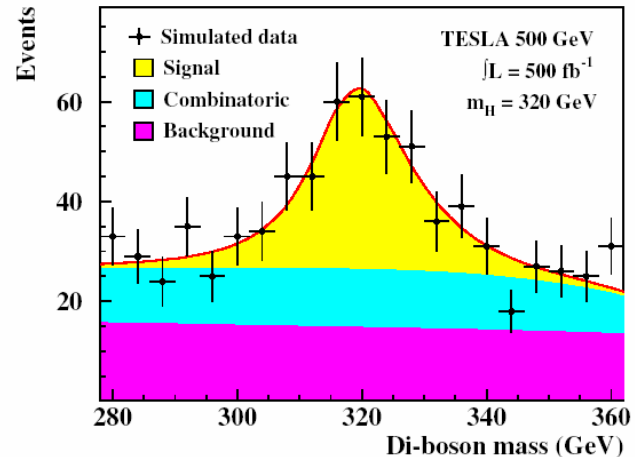
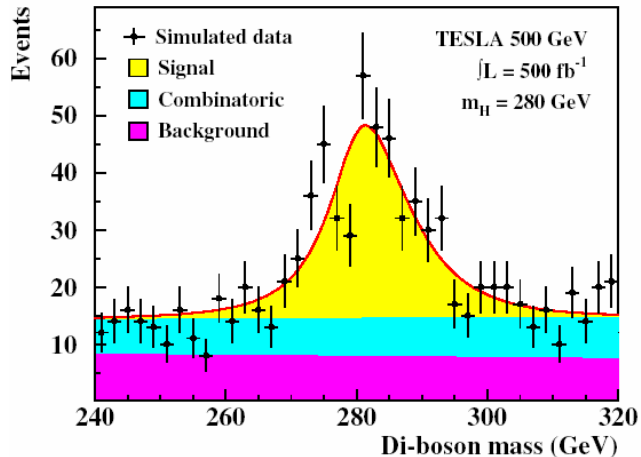
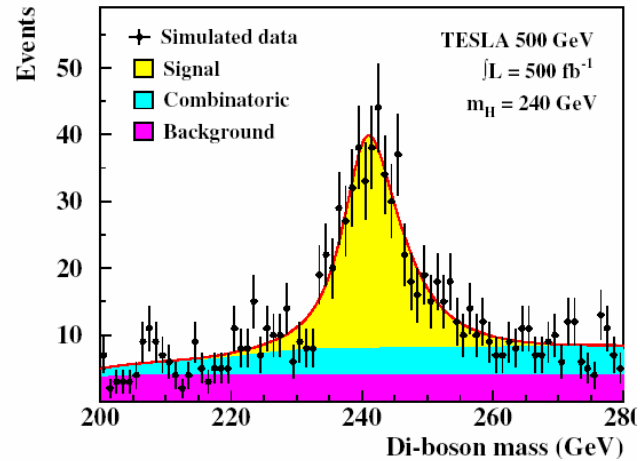
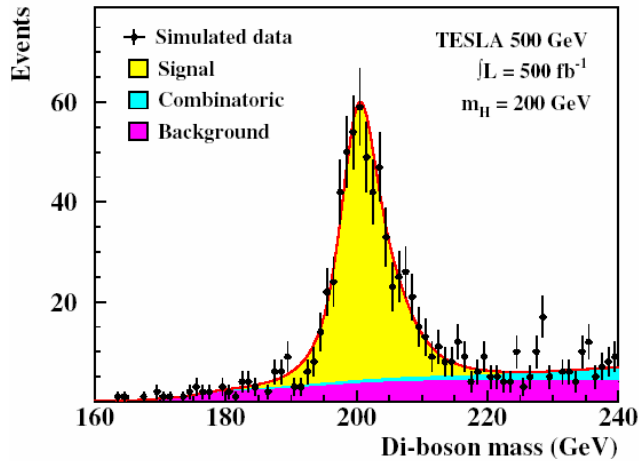
$\Delta\Gamma_{\text{tot}} \cong 5\%$

Alternative: use

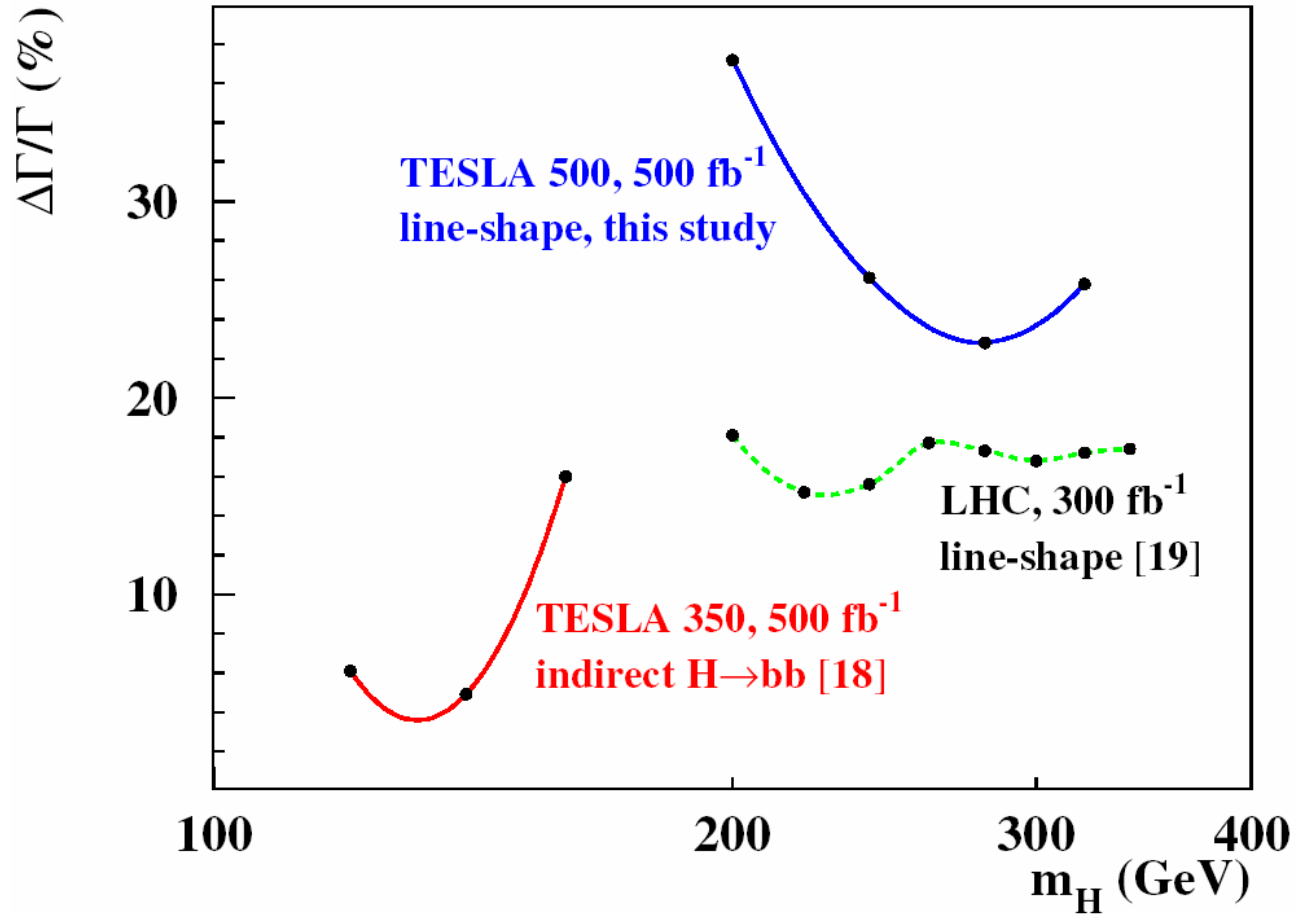
$$\Gamma_{\text{tot}} = \frac{\Gamma_{\gamma\gamma}}{BR(H \rightarrow \gamma\gamma)}$$

Precision determined by
 precision on $BR(H \rightarrow \gamma\gamma)$

If m_H is above WW threshold, width can be reconstructed from lineshape

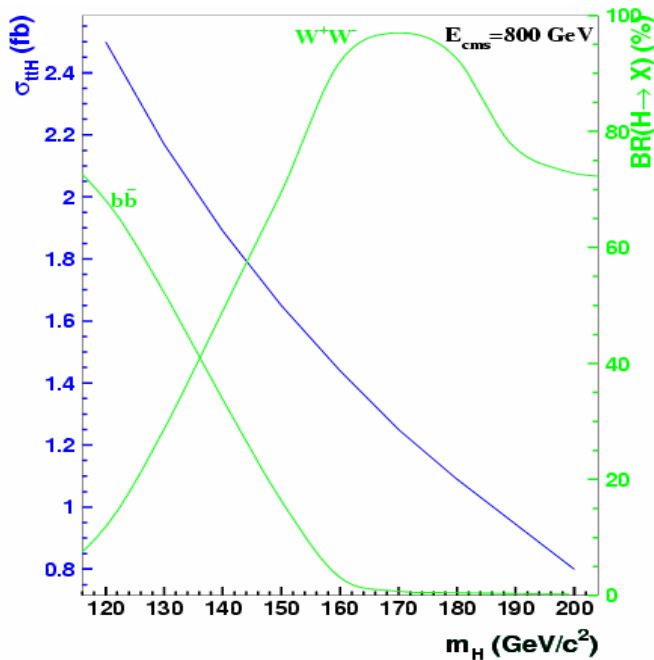
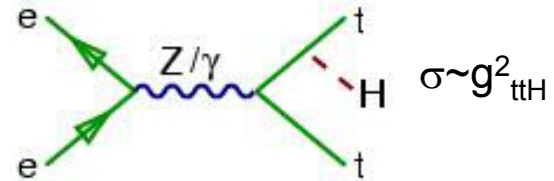


Summary on total width – more improvements to come...

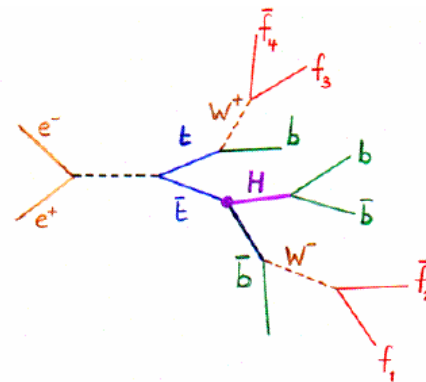


Top quark Yukawa coupling:

- need highest energy
- heaviest quark → surprises?
- small cross section
- complicated final state

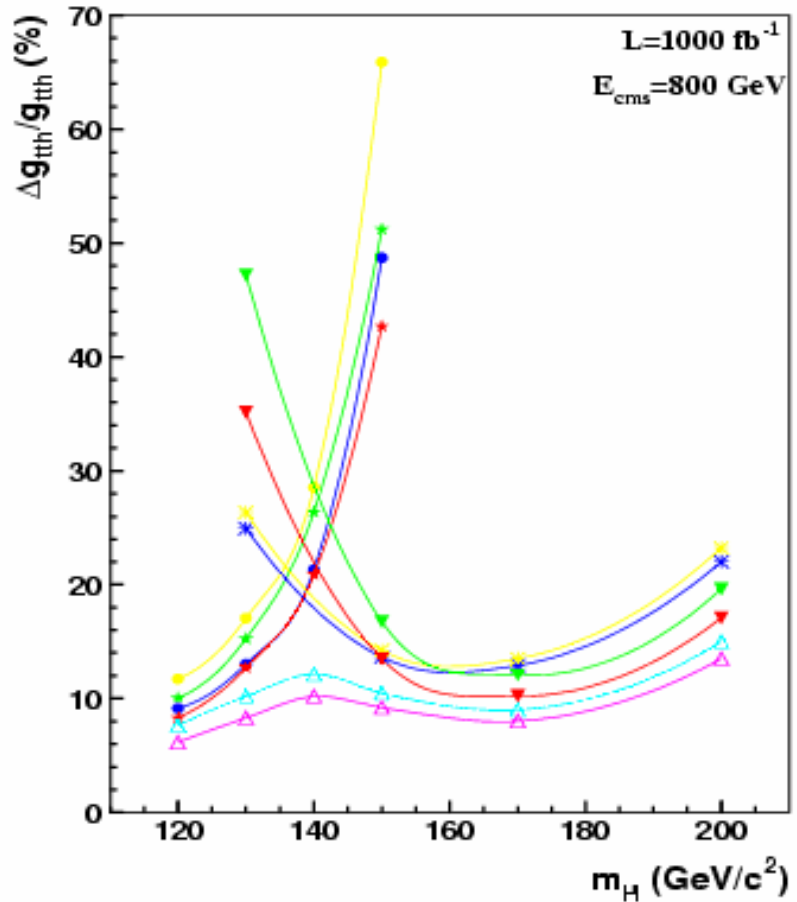


- analysis in bb and WW decay
- huge and complicated backgrounds (ttWW is a 10-fermion final state)
- b-tagging crucial to suppress bkg. and reduce combinatorial bkg.

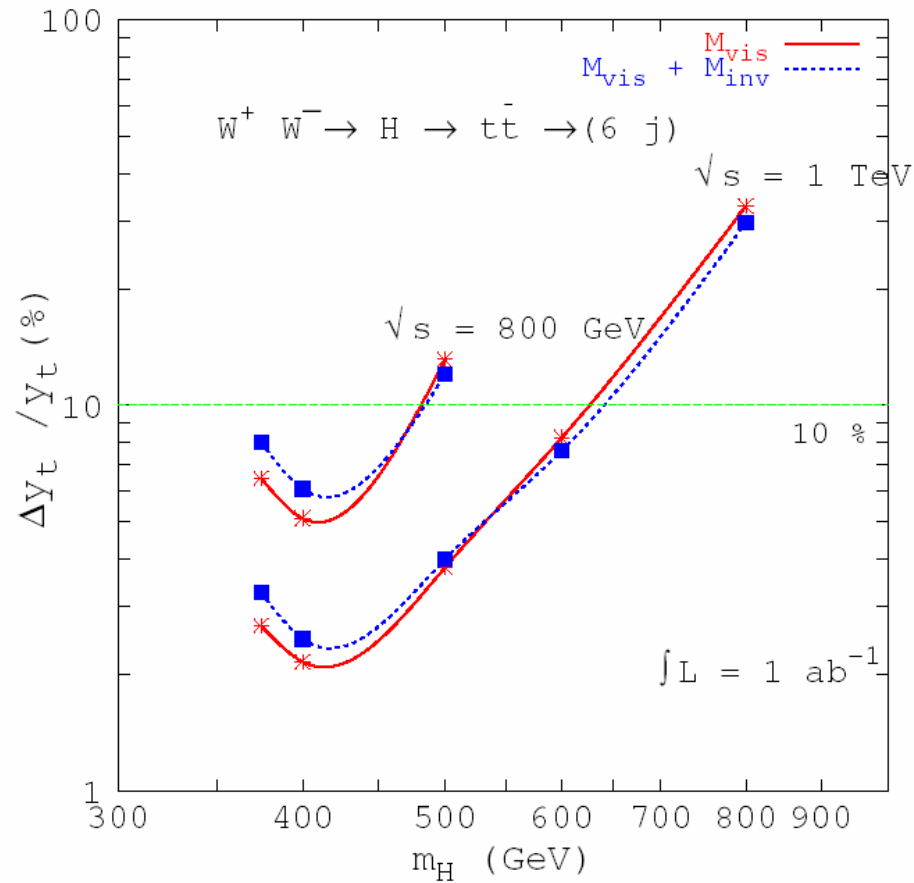


Result:

- **H → bb semilep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 5\%$**
- **H → bb semilep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 10\%$**
- **H → bb hadro; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 5\%$**
- **H → bb hadro; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 10\%$**
- **H → WW 2 like sign lep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 5\%$**
- **H → WW 2 like sign lep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 10\%$**
- **H → WW 1 lep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 5\%$**
- **H → WW 1 lep; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 10\%$**
- **4 channels combined; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 5\%$**
- **4 channels combined; $\Delta\sigma_{BG}^{eff}/\sigma_{BG}^{eff} = 10\%$**

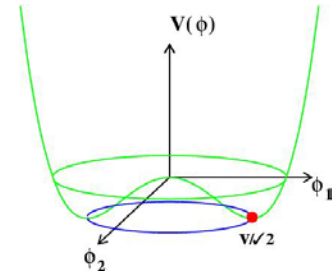


If $m_H > 350$ GeV, study decay $H \rightarrow tt$ in $\nu\nu H$ events



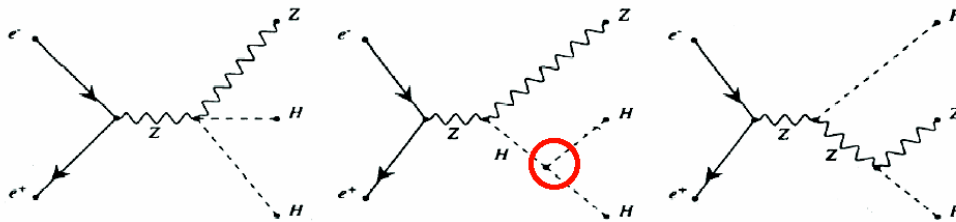
Higgs self-coupling ('the holy grail'):

Close connection to the **shape of the Higgs potential**
 → **essential test of the mechanism of spontaneous symmetry breaking**



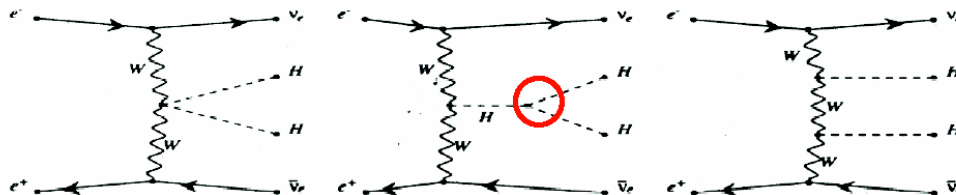
★ $e^+e^- \rightarrow ZHH$

produced by GRACEFIG



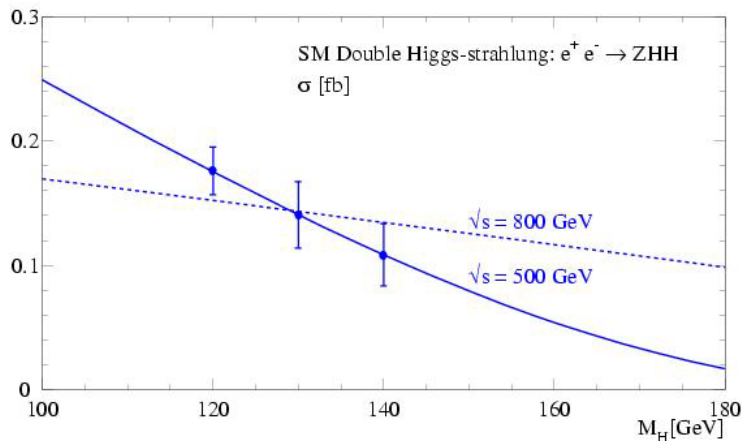
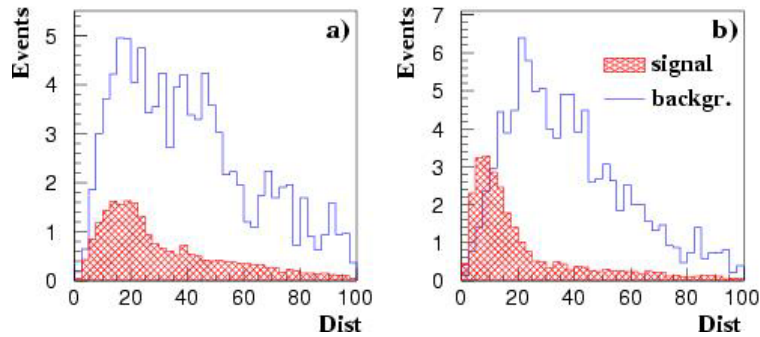
etc..

★ $e^+e^- \rightarrow (W^+W^-)\nu\bar{\nu} \rightarrow HH\nu\bar{\nu}$

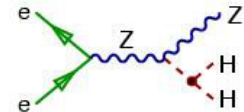


etc.

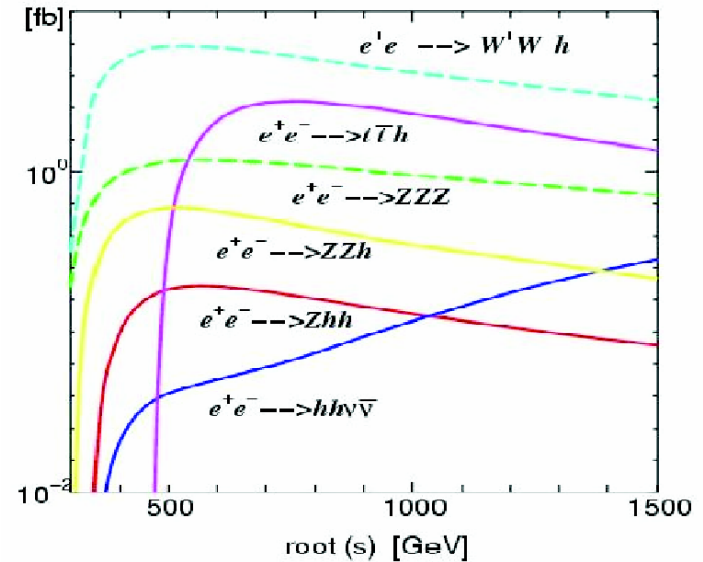
Tiny cross section
 Complicated multi-jet final state
 → detector design: energy flow



Difficult backgrounds

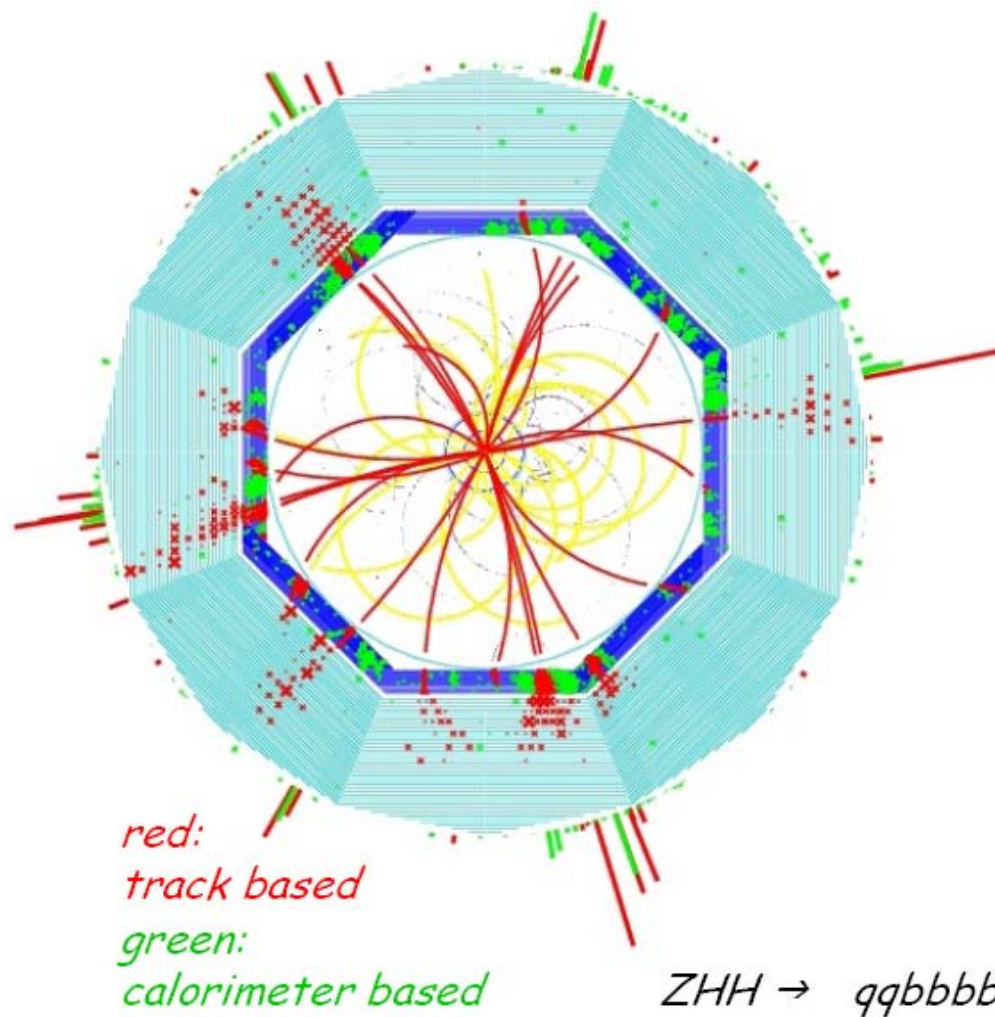


Signal vs Background (M_H = 120 GeV)



Need highest luminosity
 Precision for 1 ab⁻¹ :

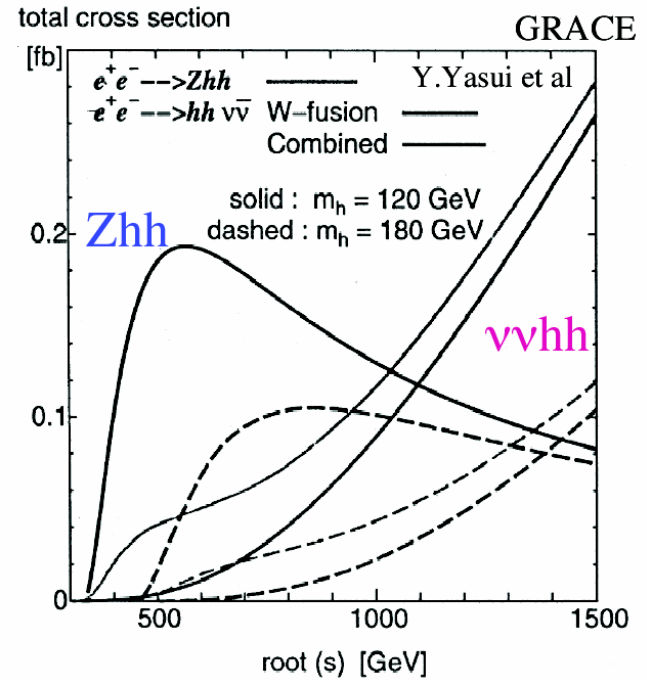
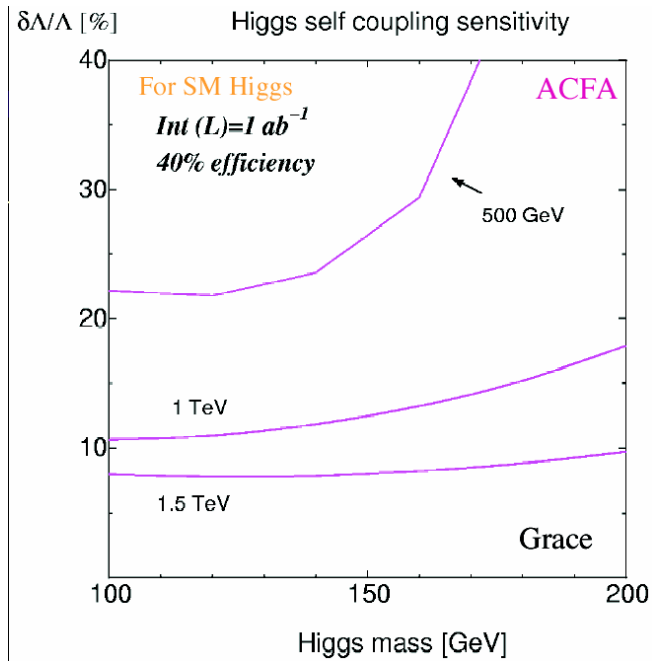
$$\frac{\Delta\lambda}{\lambda} \cong 20\%$$



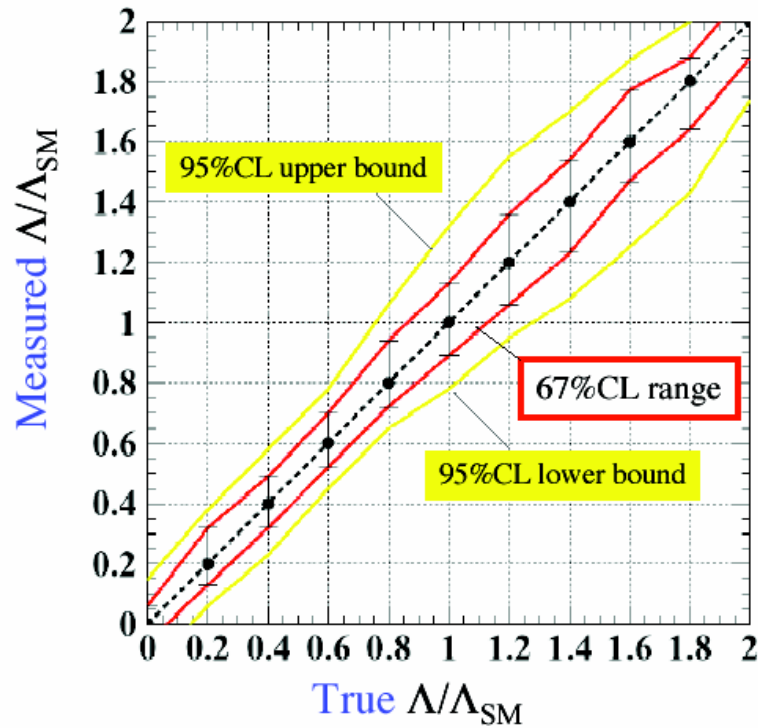
More sensitivity at higher energy?
Two competing effects:

Larger dilution due to non-HHH diagrams

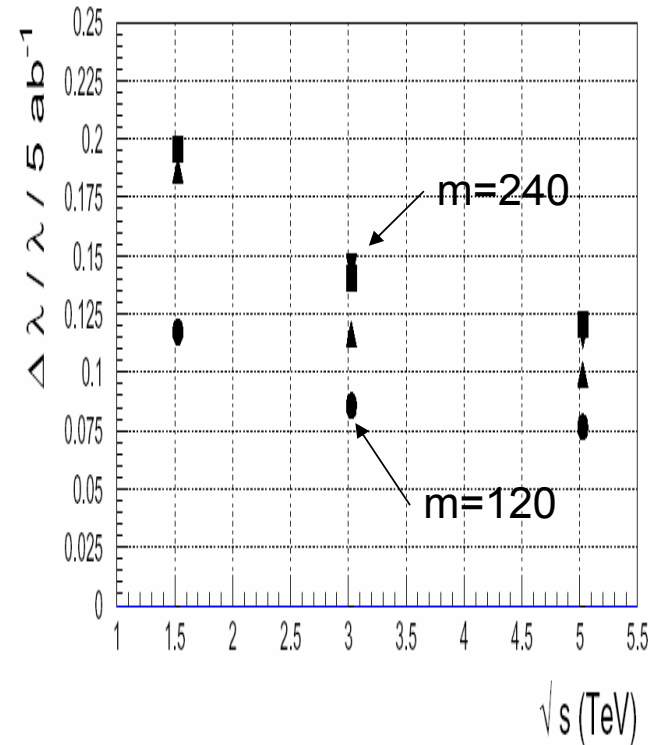
But large number of events due to contribution from WW-fusion:



Preliminary analysis at 1 TeV (1ab^{-1}) achieves $\Delta\lambda/\lambda = 12\%$ at $m_H=120$ GeV



Sensitivity at CLIC (for 5ab^{-1}):



Many SM extensions predict invisible Higgs decays, e.g.:

- MSSM $H \rightarrow \chi_1^0 \chi_1^0$
- Extra Dimensions
- Model with new singlets (NMSSM, Majoron Models)
- Stealthy Higgs

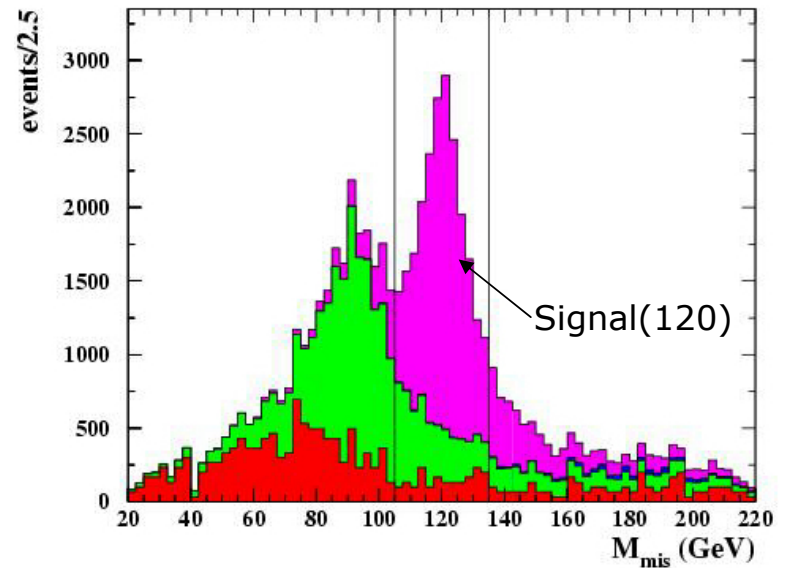
Estimate sensitivity from $1 = \text{BR}(\text{vis}) + \text{BR}(\text{invis})$

or explicit reconstruction in

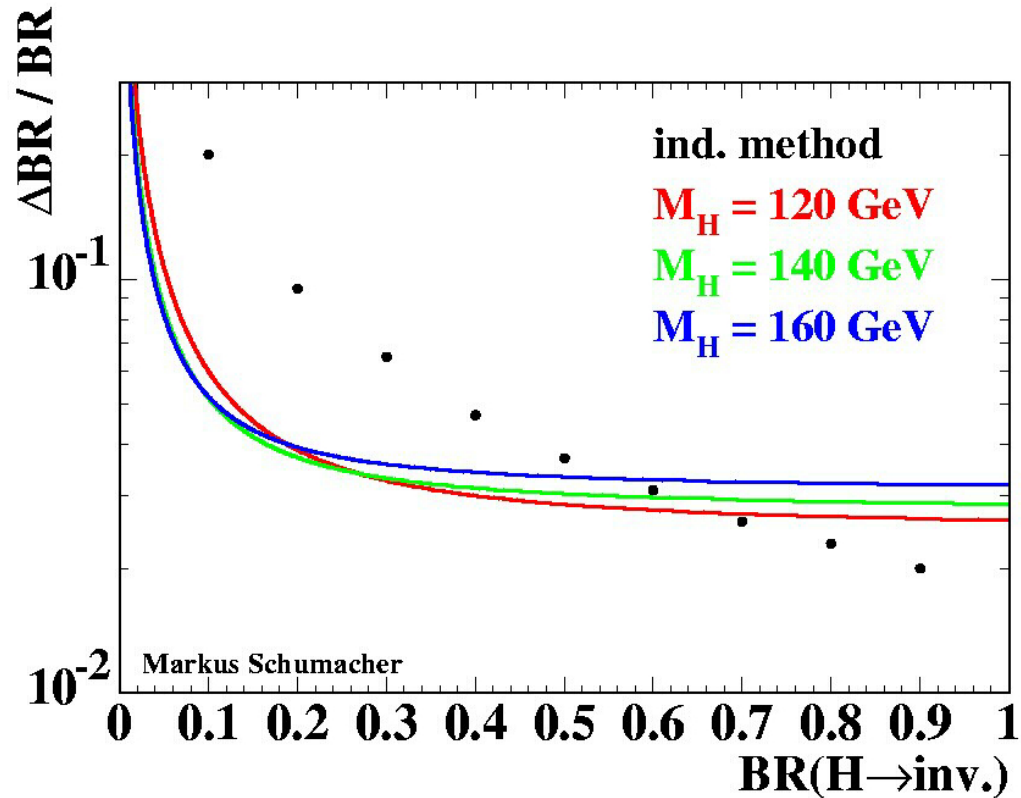
Assumptions:

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

$$m_H = 120, 140, 160 \text{ GeV}$$



Result:

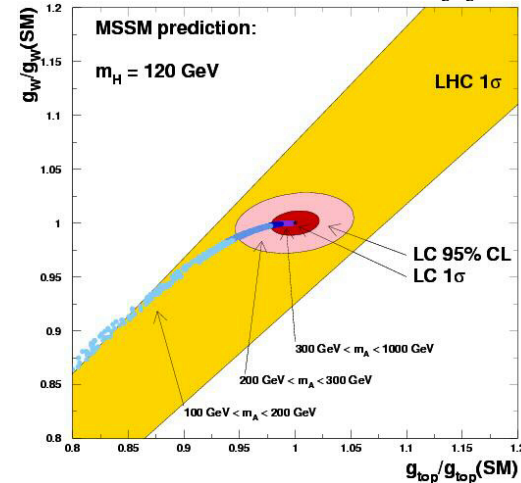
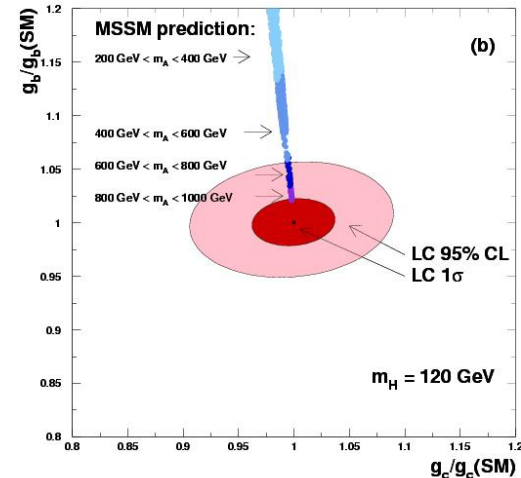


Result for 500 fb^{-1} @ 350 GeV ($m_H = 120 \text{ GeV}$):
 $\Delta\text{BR}/\text{BR}(\text{invis}) = 10\%$ for $\text{BR}(\text{invis}) = 5\%$
 5σ observation down to $\text{BR} = 2\%$

Interpretation of branching ratio and cross section measurements in global fits (HFITTER)

Coupling	$M_H = 120 \text{ GeV}$	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

%-level accuracy – sensitivity beyond SM

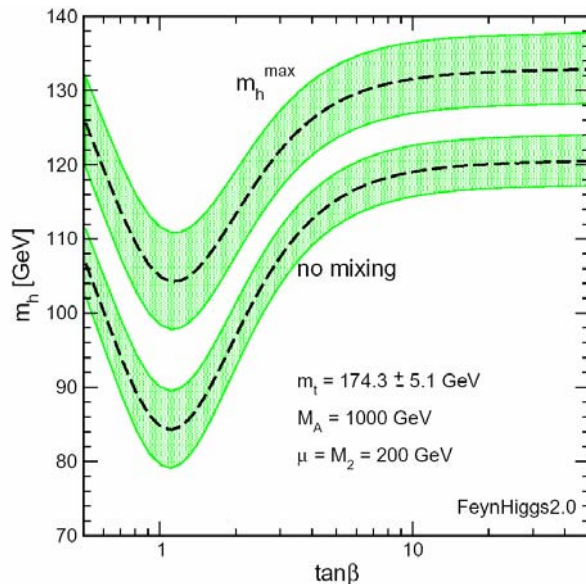


In MSSM two complex Higgs doublet fields needed
(cancellation of triangle anomalies)

Minimal possibility: two doublets (weak isospin ± 1)

→ 5 physical Higgs bosons:

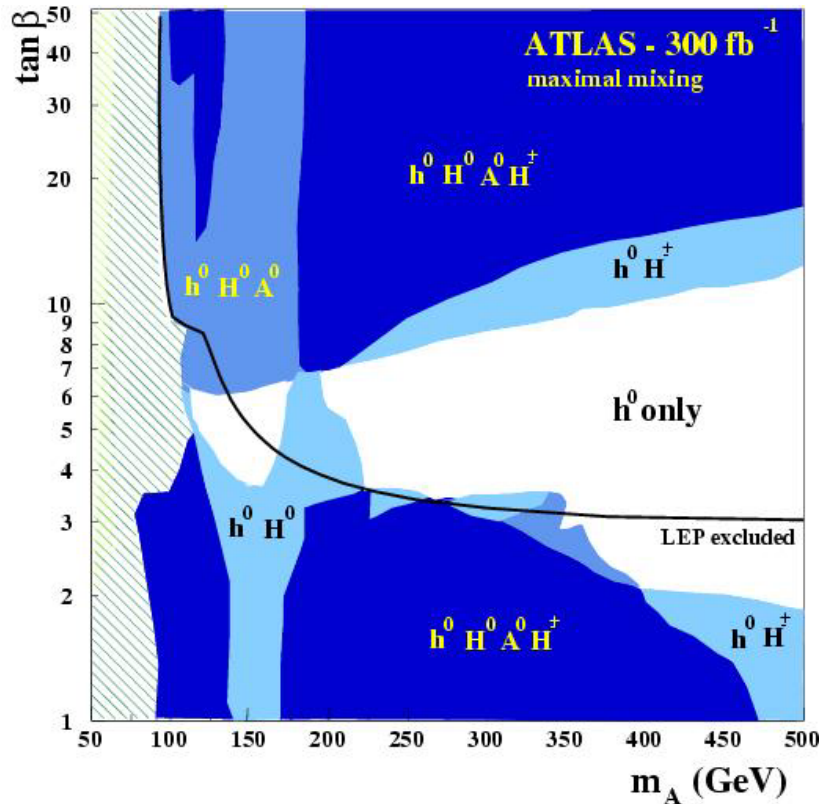
h, H	neutral, CP-even
A	neutral, CP-odd
H^\pm	charged



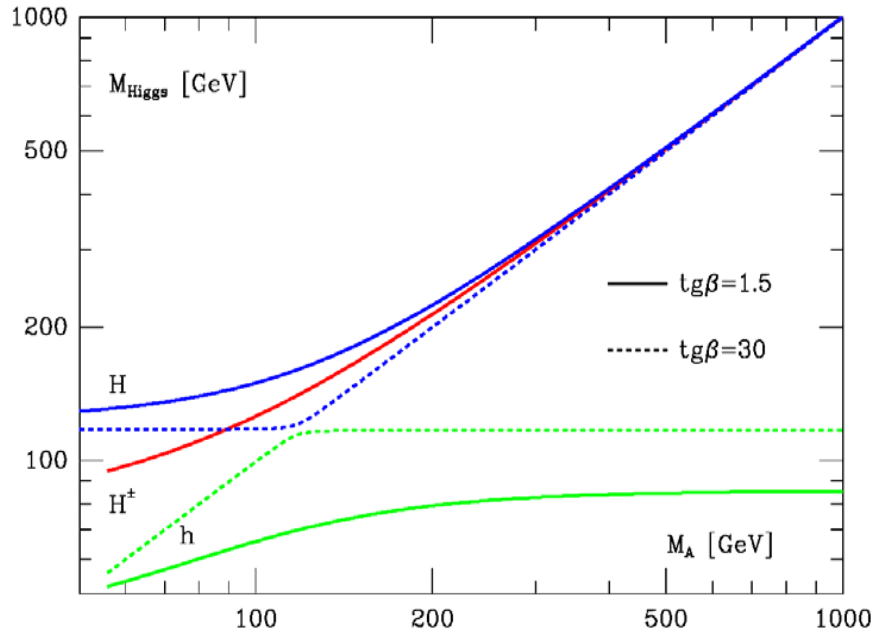
Masses at tree-level predicted as function
of m_A and $\tan\beta$
but large rad. corrections (top, stop)

$$m_h < 135 \text{ GeV}$$

To prove the structure of the Higgs sector, the heavier Higgs bosons have to be observed either directly or through loop-effects.
 Direct observation difficult in part of parameter space at LHC



What's possible at a
 Linear Collider?



Production processes:

$$\left. \begin{aligned} e^+e^- &\rightarrow hZ \\ e^+e^- &\rightarrow HA \end{aligned} \right\} \propto \sin^2(\beta - \alpha)$$

$$\left. \begin{aligned} e^+e^- &\rightarrow HZ \\ e^+e^- &\rightarrow hA \end{aligned} \right\} \propto \cos^2(\beta - \alpha)$$

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

$$\gamma\gamma \rightarrow h, H, A$$

$$\gamma\gamma \rightarrow H^+H^-$$

Most challenging: 'decoupling limit'
 $\sin^2(\beta - \alpha) \rightarrow 1$, m_A large
 h becomes SM like
 H/A/H[±] heavy and mass degenerate

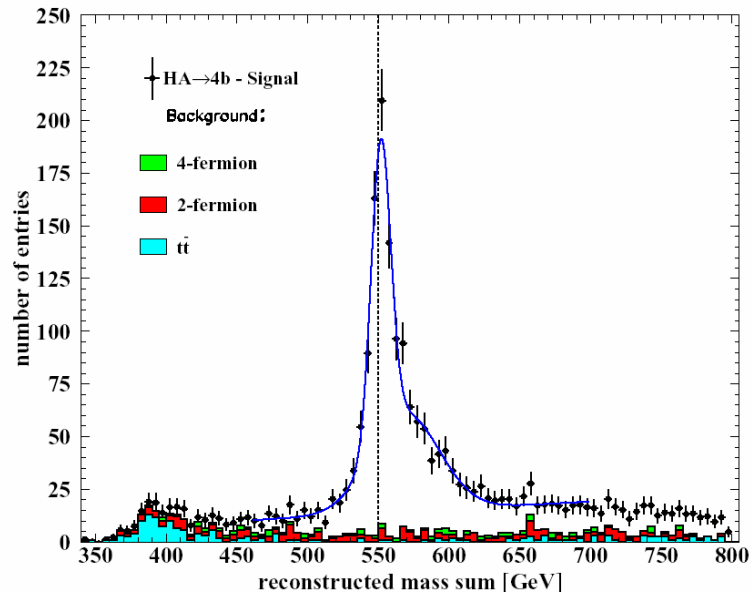
Very clear signal in $HA \rightarrow bbbb$

100 – 1000 MeV mass precision due to kinematic fit

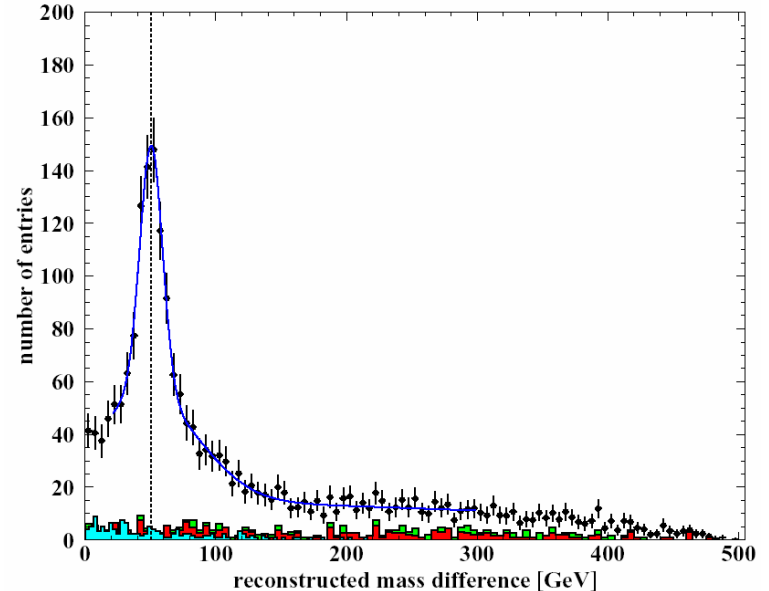
drawback: pair production \rightarrow mass reach $\sim \sqrt{s} / 2$

Example for $m_H=250$ GeV / $m_A=300$ GeV at $\sqrt{s} = 800$ GeV:

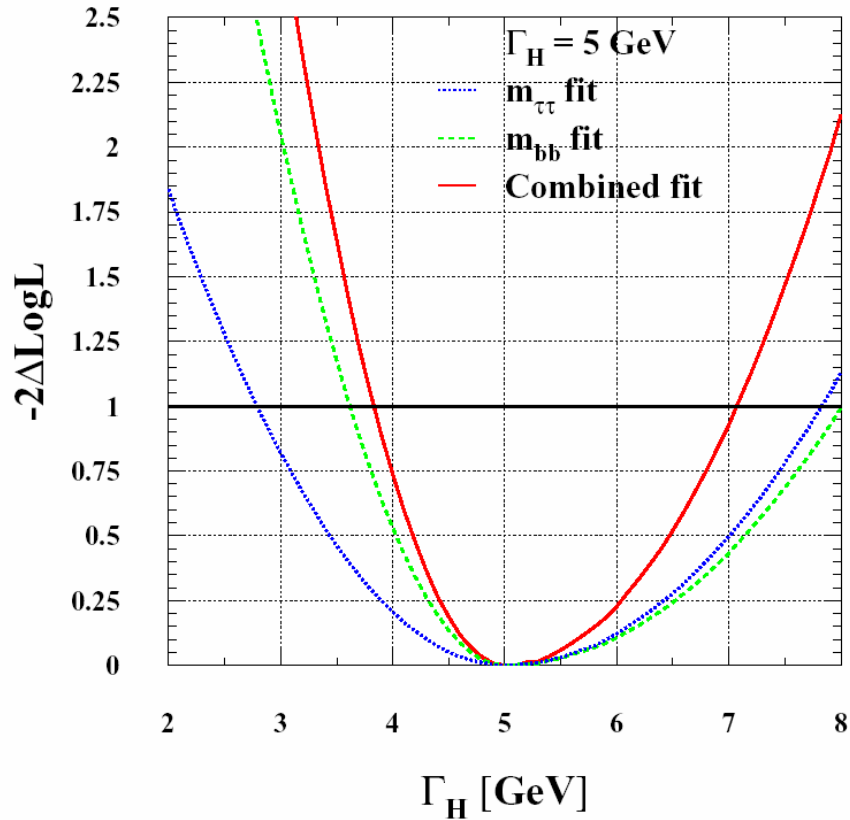
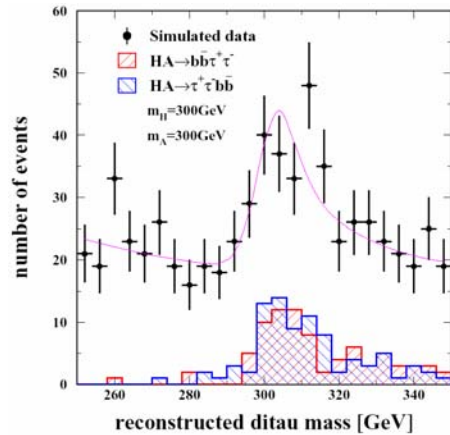
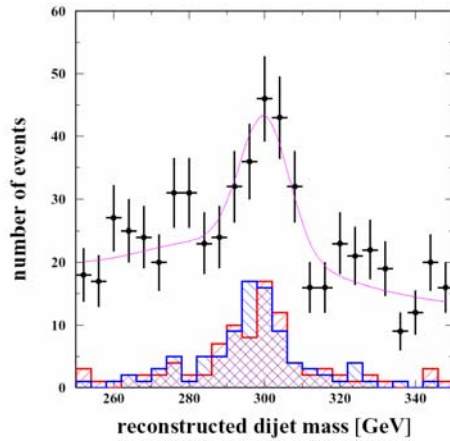
reconstructed mass sum



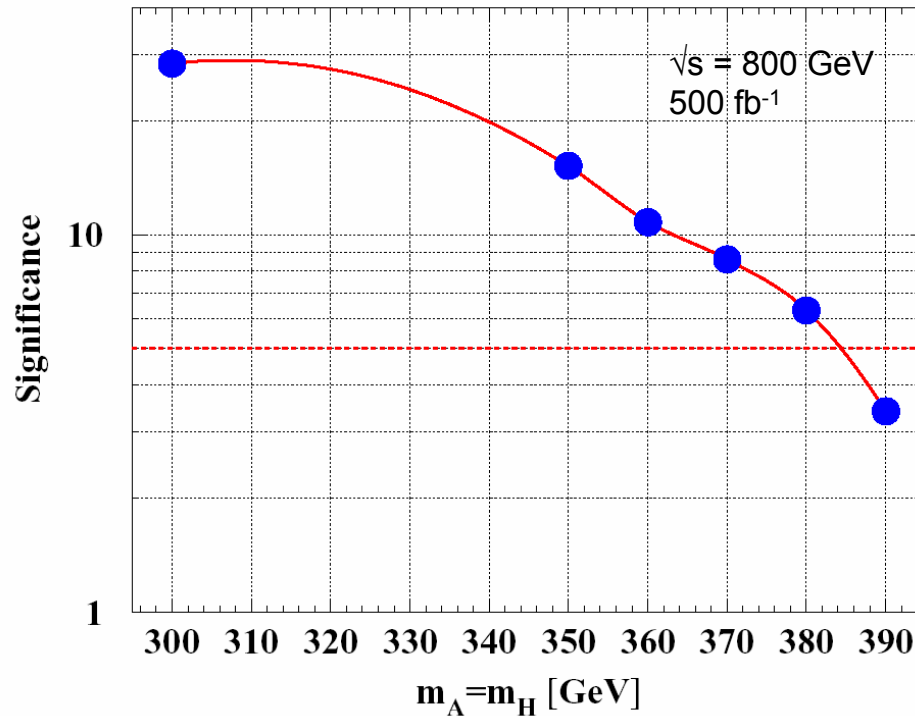
reconstructed mass difference



$H/A \rightarrow bb\tau\tau$ more difficult due to low $BR(H/A \rightarrow \tau\tau)$ but allows for distinction of H and A and reconstruction of decay width to $\mathcal{O}(1 \text{ GeV})$



Discovery reach almost up to $m_A = m_H = \sqrt{s} / 2$

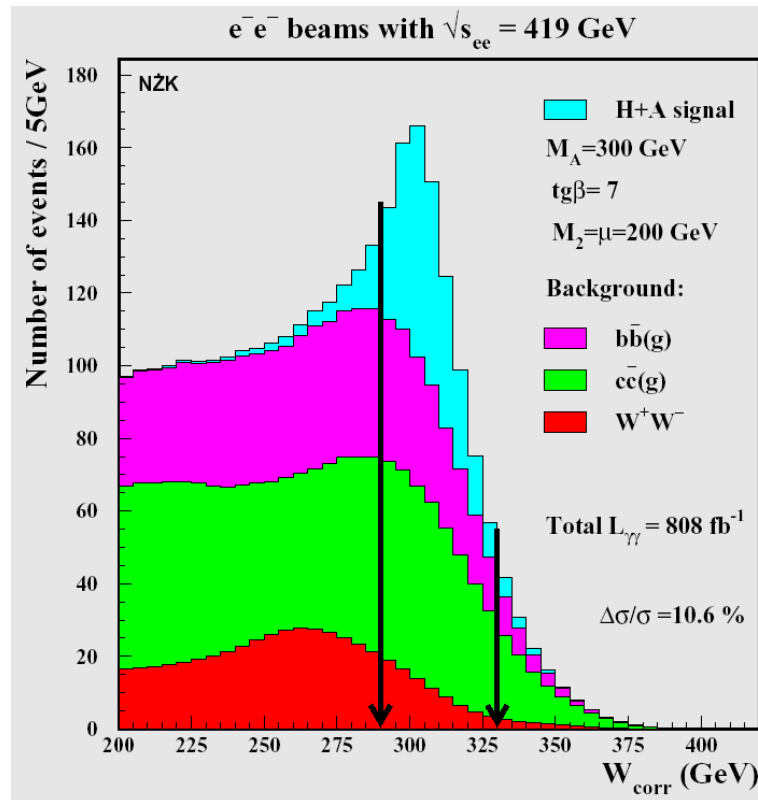


precision on
 m_H / m_A

100 – 1000 MeV

Advantage of photon collider: single production

Mass reach in principle up to $\sqrt{s_{\gamma\gamma}} = 0.8 \sqrt{s_{ee}}$ but very high luminosity required
 + need to have an estimate of m to use peaking photon spectrum



- Higgs mechanism (still) the only completely calculable model of electro-weak symmetry breaking
- Intriguing hints for light Higgs boson from experiment + theory
- LHC will find a SM-like Higgs if it's there
- ILC will be able to pin down the properties of the light Higgs at the quantum level and test details of the model