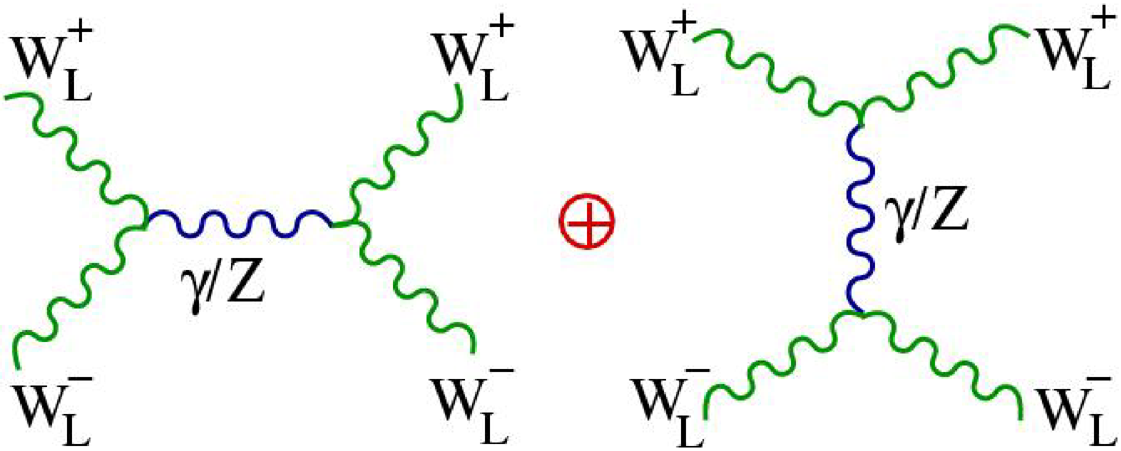
Quantum field theory with massive exchange particles fails at high energies:



cross section:
$\sigma \sim s^2$
violates unitarity at $\sqrt{s} \sim 1.3$ TeV

(if forces remain weak)

"if nothing happens, something must happen…"

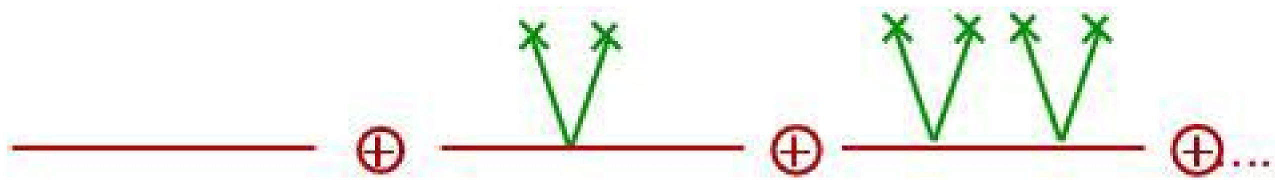
<u>The Standard Model Solution:</u>
(rescue plan for the gauge principle)
Introduction of a new scalar field with non-vanishing field strength in the vacuum: the Higgs field.

Paradigm:

All (elementary) particles are massless

⇨ gauge principle works
⇨ renormalizable theory (finite cross sections)

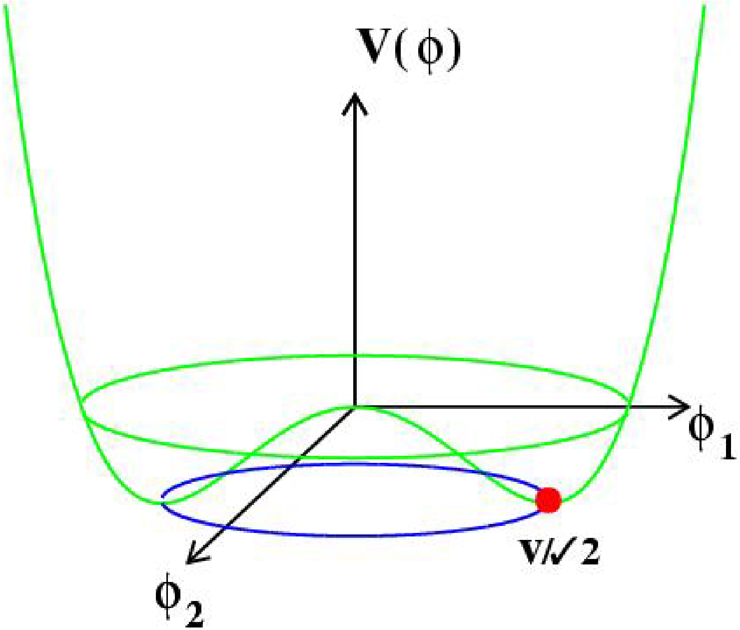
permanent interaction with the Higgs field acts, as if the particles had a mass (effective mass)



$$\left(\frac{1}{q^2}\right) \oplus \left(\frac{gv}{\sqrt{2}}\right)^2\left(\frac{1}{q^2}\right) \oplus \left(\frac{gv}{\sqrt{2}}\right)^4\left(\frac{1}{q^2}\right)^2 \oplus \ldots$$

$$= \frac{1}{q^2 - M^2} \; with \; M^2 = g^2\frac{v^2}{2}$$

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



"Mexican hat-Potential"

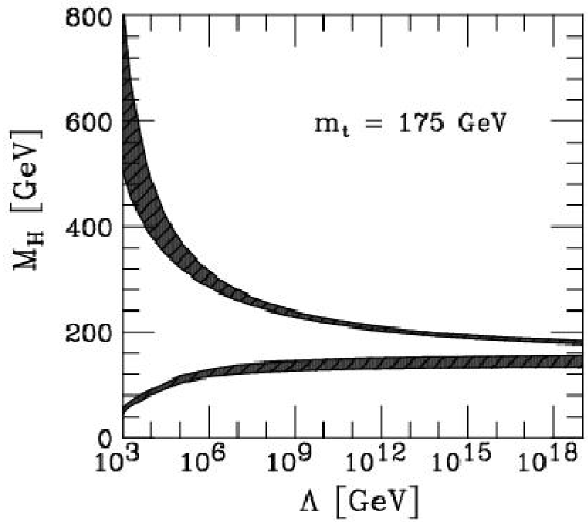
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

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,…

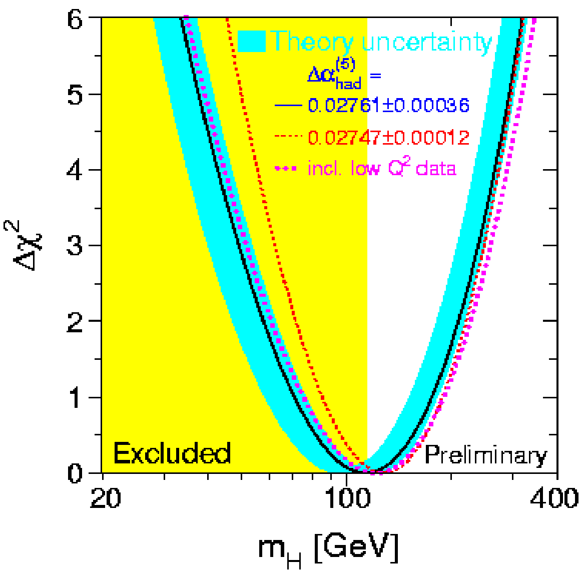
models with "true" and "effective" mass are not equivalent:

formulation with the help of Higgs mechanism:
- is gauge invariant
- postulates at least 1 scalar, massive Higgs boson



Theory:

Upper bound: perturbativity (λ<1)
Lower bound: vacuum stability
Models: minimal SUSY: m<135 GeV
GUT's : m<180 GeV

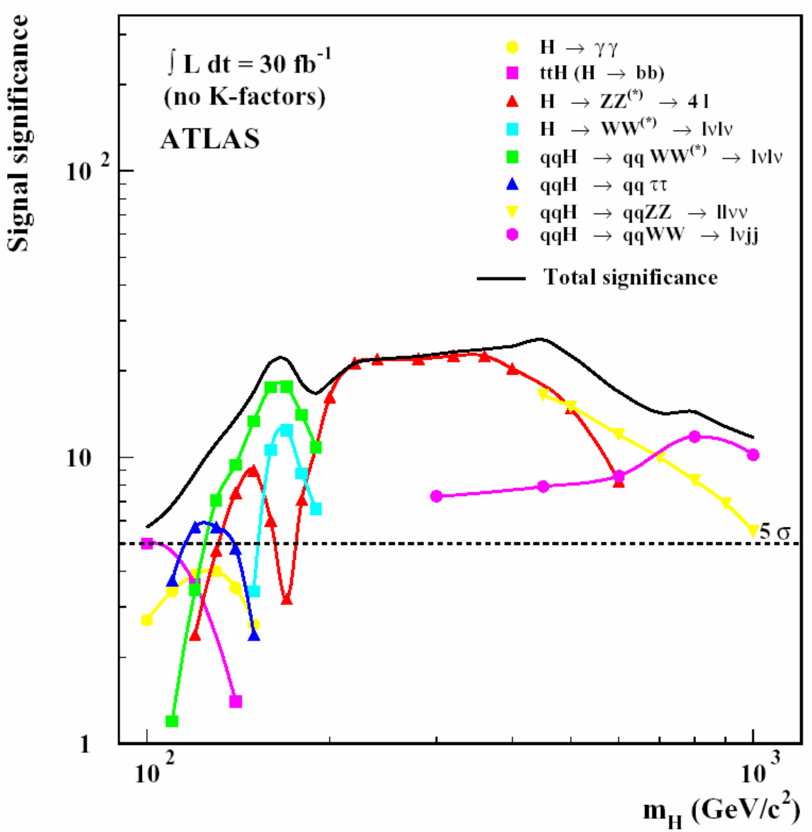


Experiment:

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

m<250 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 challenling
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/t: 10-20%
- model-independent measurements of absolute couplings impossible

Task of Linear Collider(s)

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

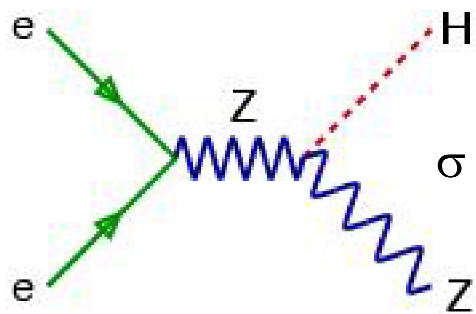
Precision Measurements must comprise:

- Mass
- Total Width
- Quantum numbers J^{PC} (Spin 0, CP-even?)
- Higgs-Fermion couplings (~ 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, …)

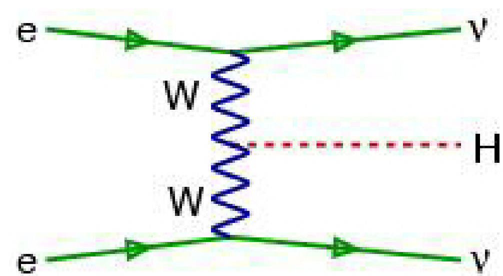
Aim at model-independence!

Dominant production processes at LC:



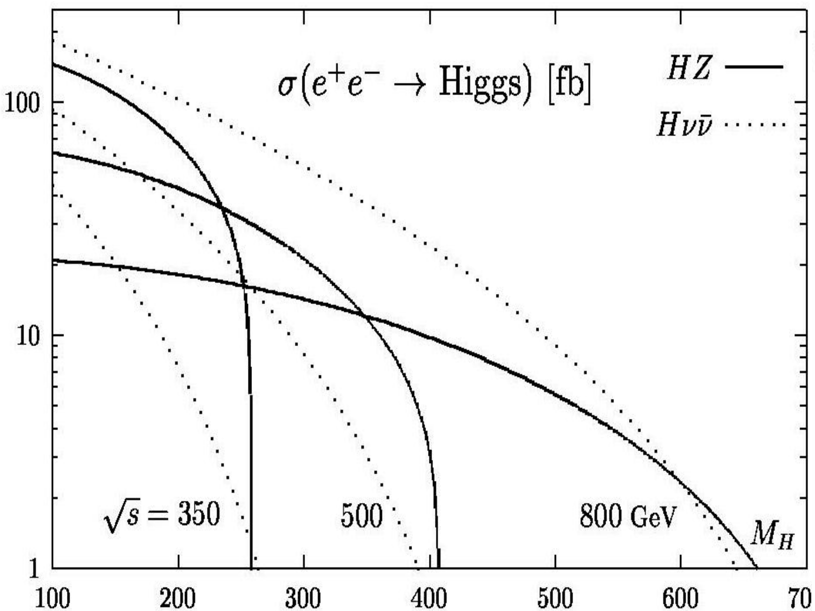
$\sigma \propto\sim 1/s$

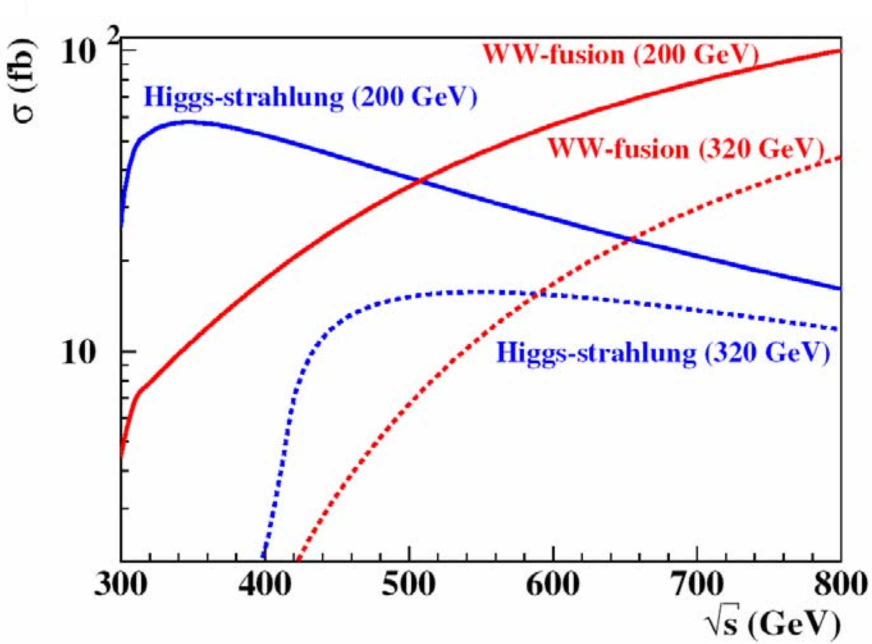
Higgs-strahlung



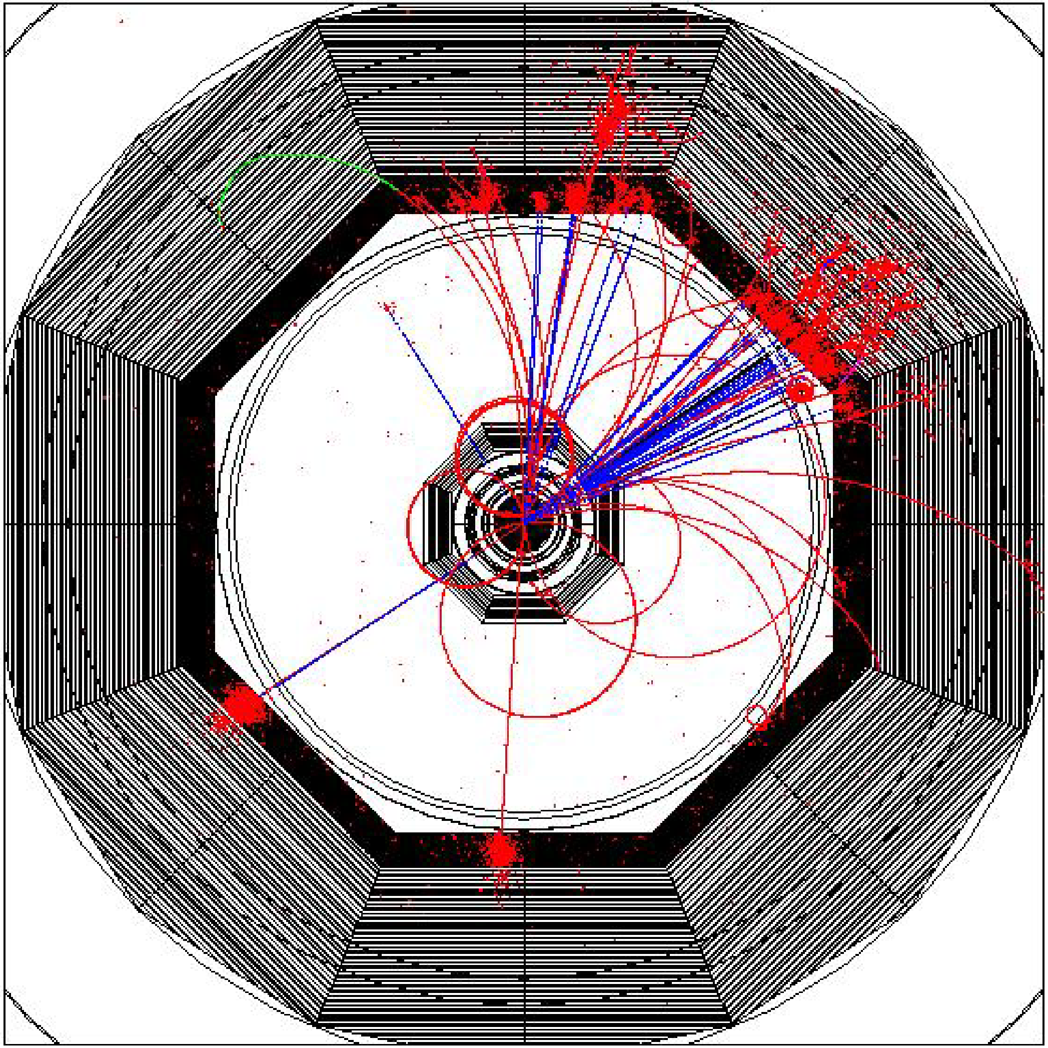
$\sigma \propto\sim \ln s$

WW fusion

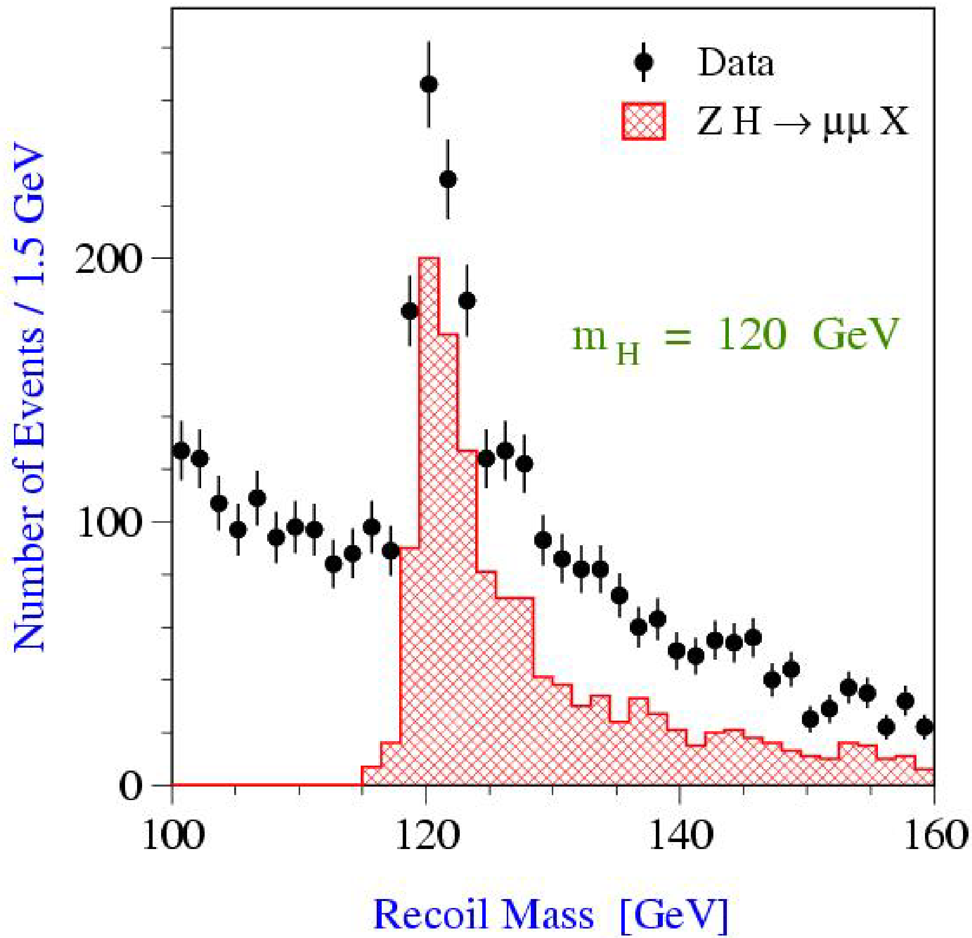


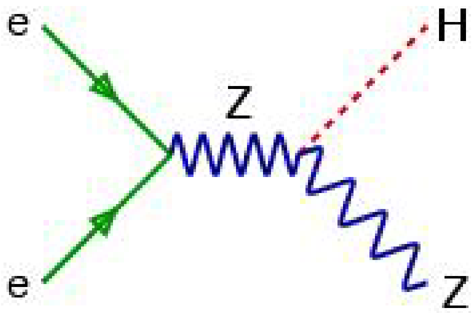


Fully simulated Higgs-strahlung event in TESLA detector ($Z \to ee, H \to bb$)



Anchor of LC Higgs physics:



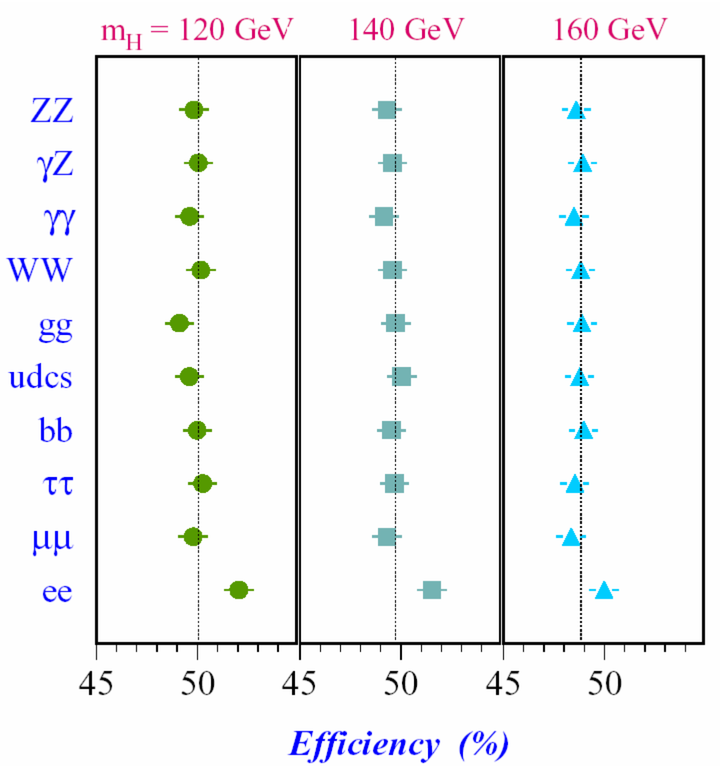


- select di-lepton events consistent with Z→ee/μμ
- calculate recoil mass:

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

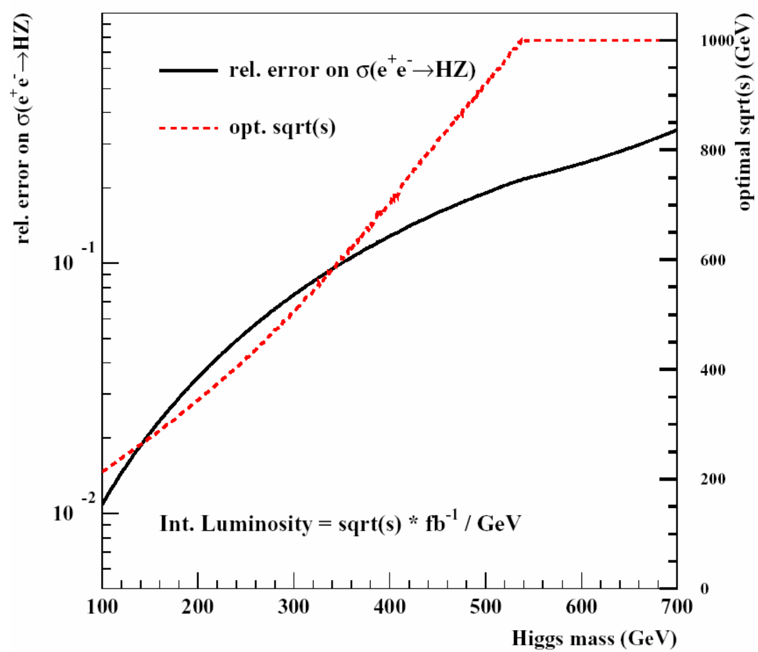
model independent, decay-mode independent measurement!

efficiency is ~independent of decay mode:



small differences can be corrected with MC

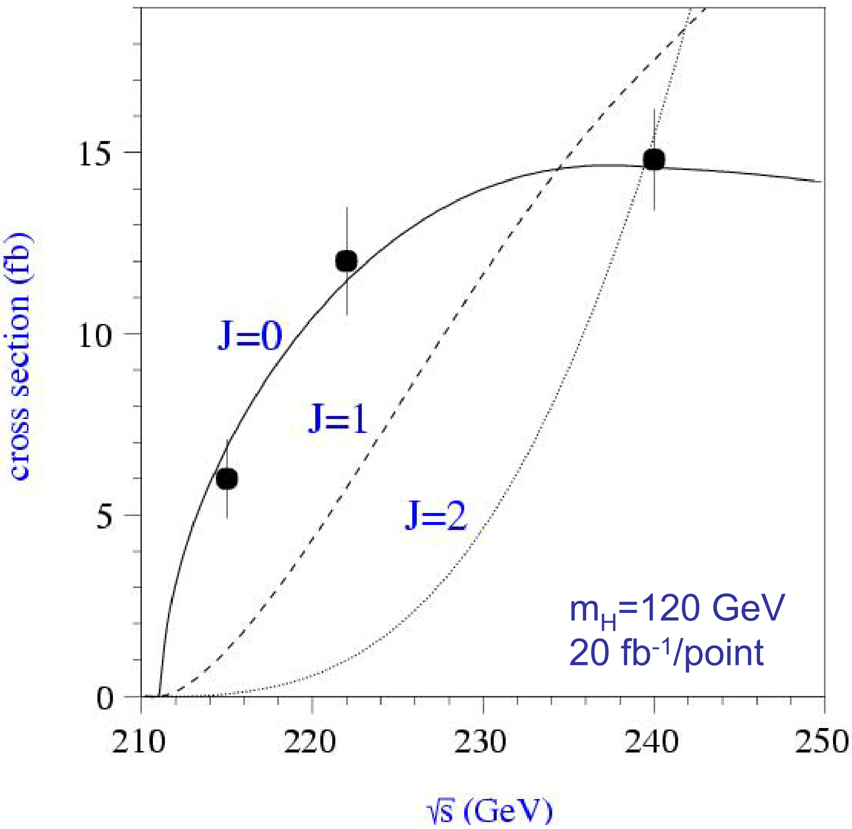
works over the whole range of possible Higgs masses:



precision on σ(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 ~ β
for J>0: rise ~ β^k ,k>1
(some cases for J=2 are also ~β but can be distinguished from J=0 through angular distributions)

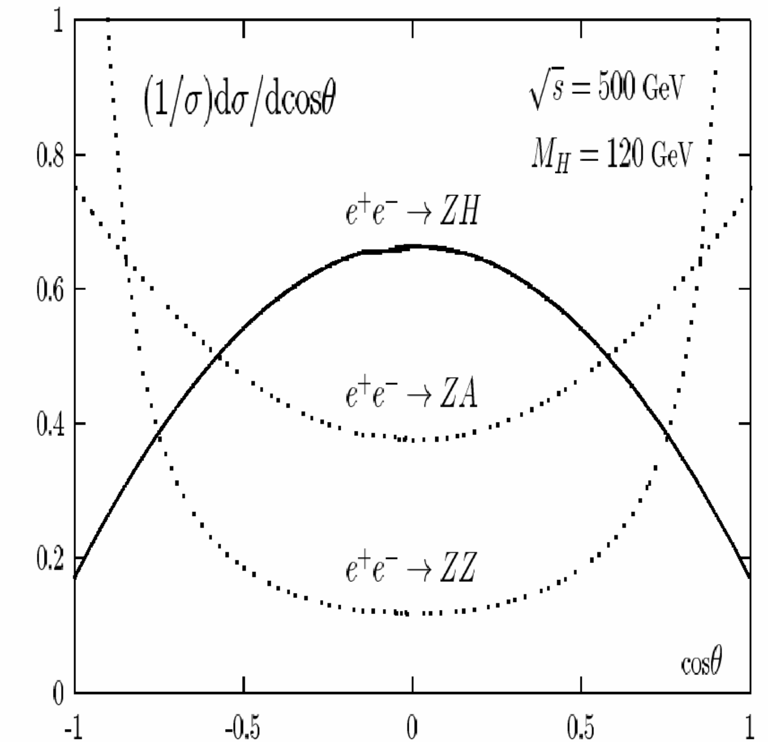
also:

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

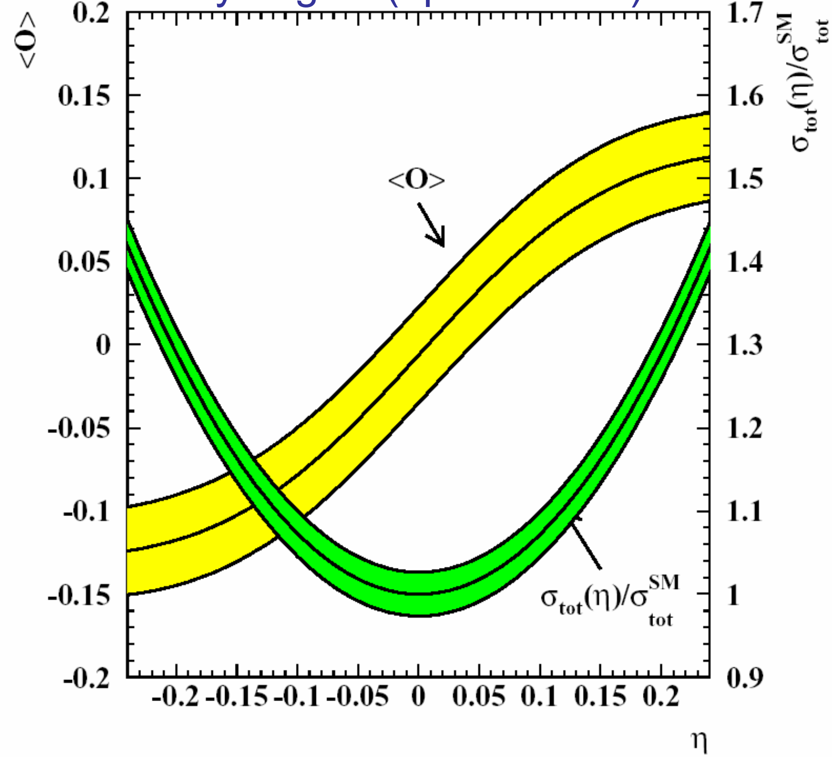
CP Quantum numbers:

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

production angle

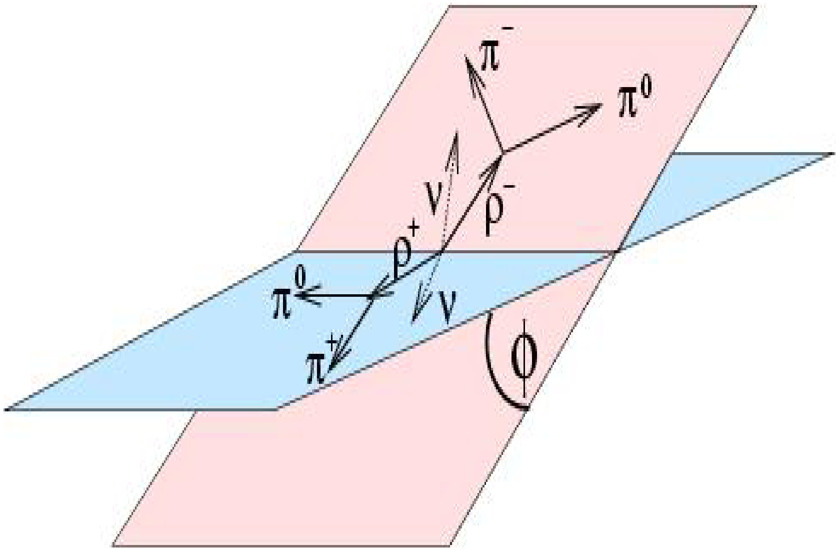


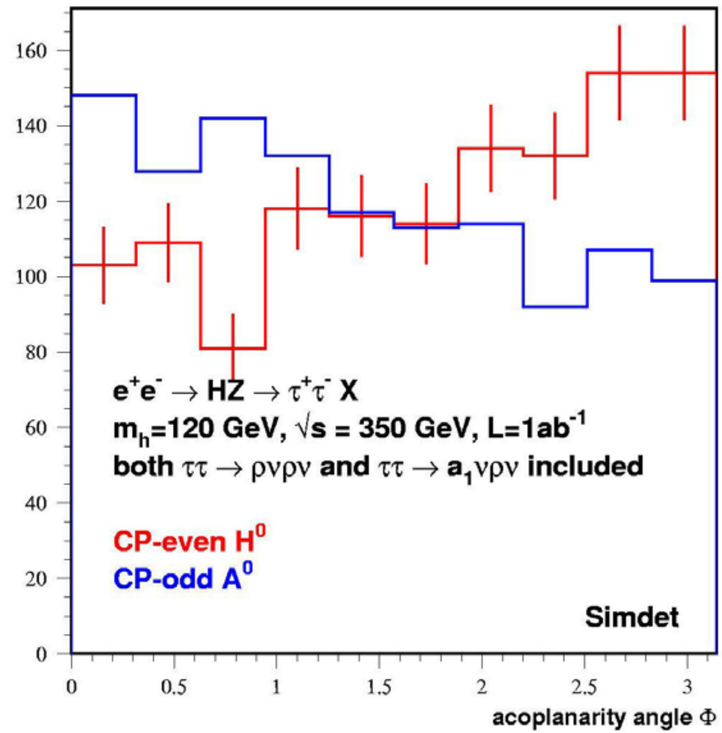
joint analysis of production and decay angles (optimal obs.)



η = CP-odd admixture to CP even amplitude: $\mathcal{M} = \mathcal{M}_{HZ} + i\eta\, \mathcal{M}_{ZA}$

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





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

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

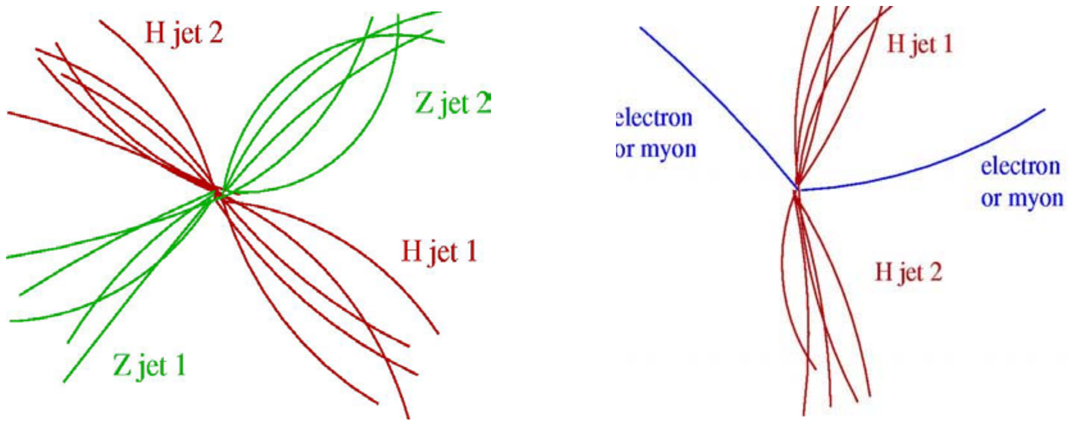
Model-independent HZ analysis only uses a fraction of the events (Z→ll)

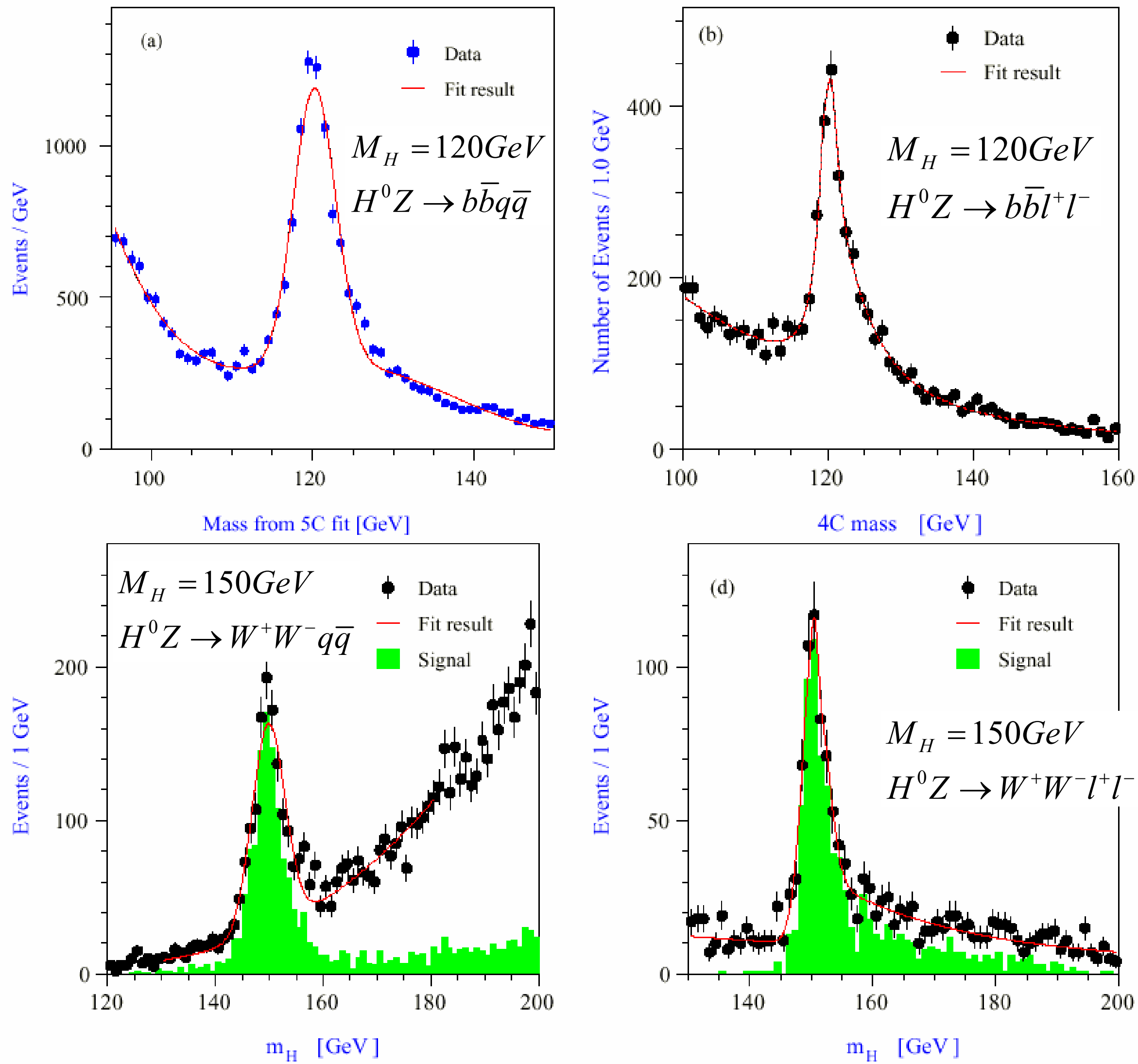
For a precise mass determination further statistics can be gained if hadronic Z-decays are used.

For mass measurement, explicit Higgs final states (e.g. H→bb) may be used

Highest sensitivity to Higgs mass comes from purely hadronic events

Kinematic fits improve the mass resolution

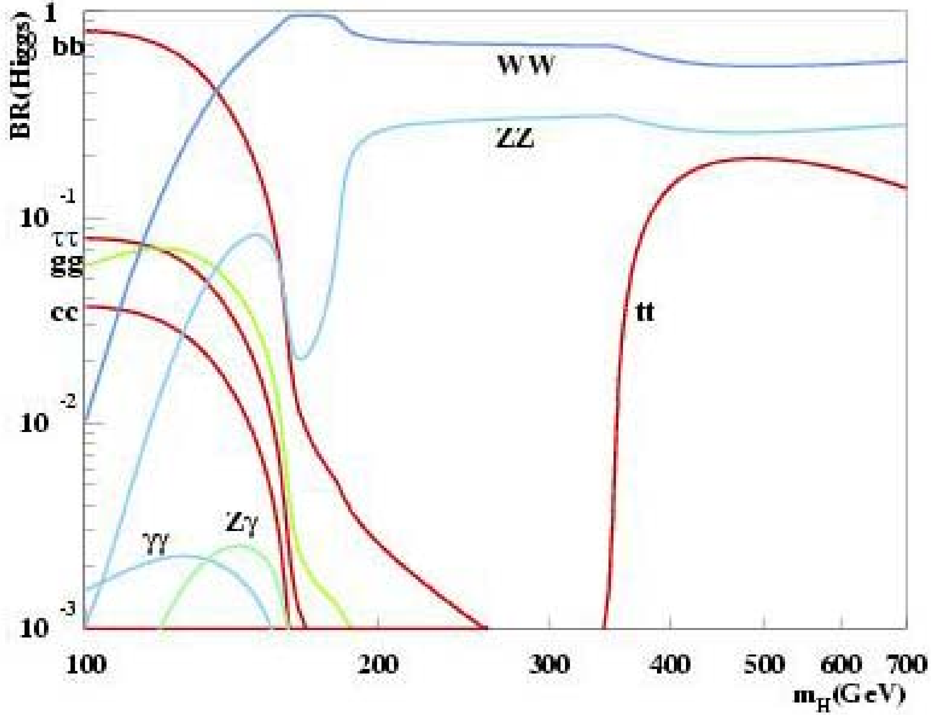




M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	±70
120	$qqbb$	±50
120	Combined	±40
150	$\ell\ell$ Recoil	±90
150	$qqWW$	±130
150	Combined	±70
180	$\ell\ell$ Recoil	±100
180	$qqWW$	±150
180	Combined	±80

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:

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

Most challenging: disentangle the hadronic Higgs decays

H→bb   H→cc   H→gg

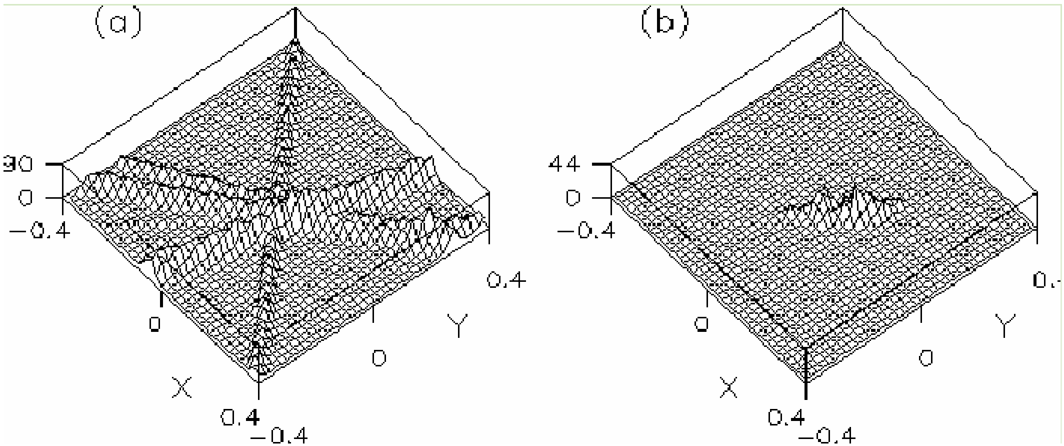
H→bb	68.2%
H→cc	3.0 %
H→gg	6.7 %

for m_H=120 GeV

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

Tracks interpreted as 3D probability tubes

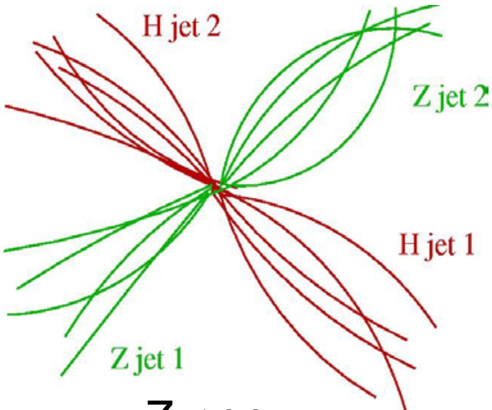
Vertices = overlapping tubes



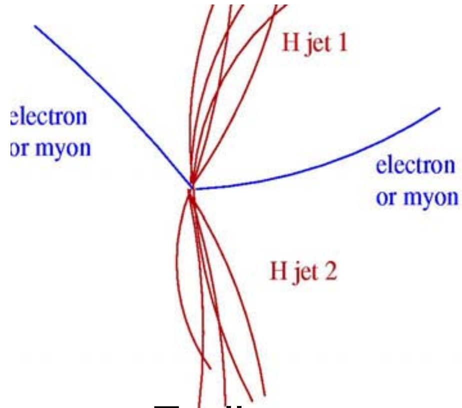
After vertex reconstruction, use ANN's with vertex+track information to obtain b- and c-likeness for each jet

2. Higgs Physics | Branching Ratios

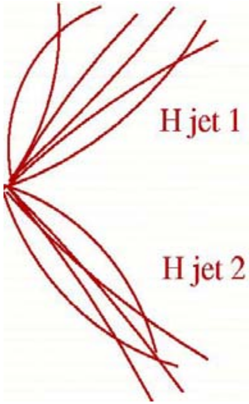
BR analysis performed for all HZ events, categorized acc. to Z decay



Z→qq

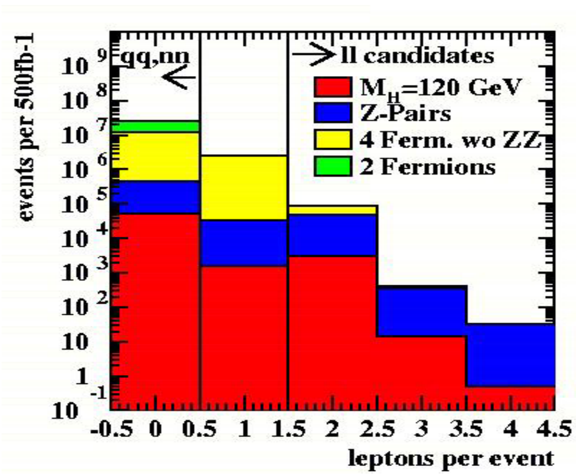


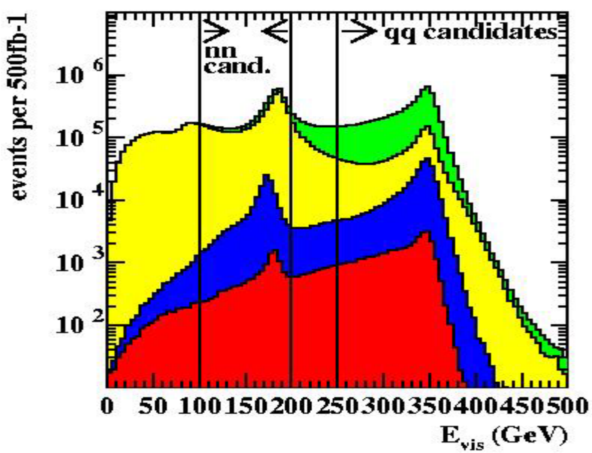
Z→ll



Z→νν

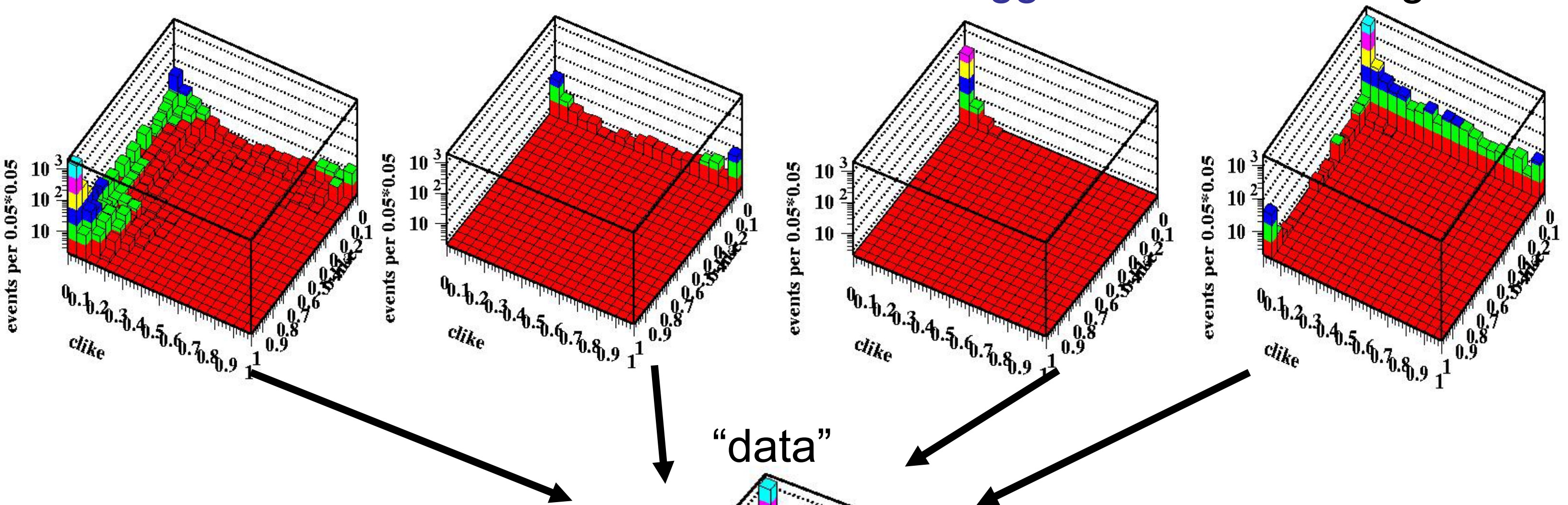
Classify according to #leptons and visible energy



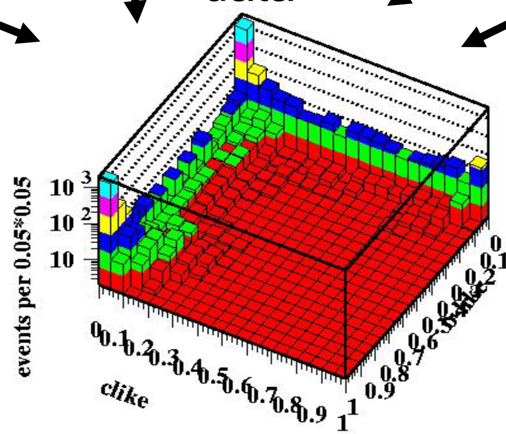


Then for each Z-channel fit the b- and c-likeness distributions

H→bb + H→cc + H→gg + background



"data"



Simultaneous fit of Z→qq,ll,νν distributions

Result on Δ(σxBR)/ (σxBR)

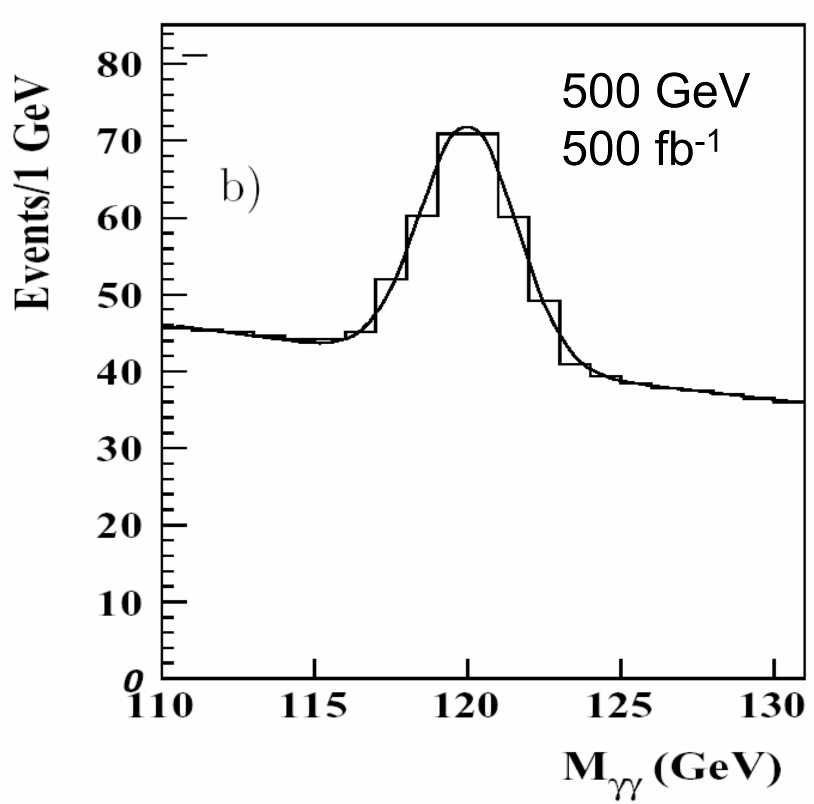
H→bb 1%

H→cc 12%

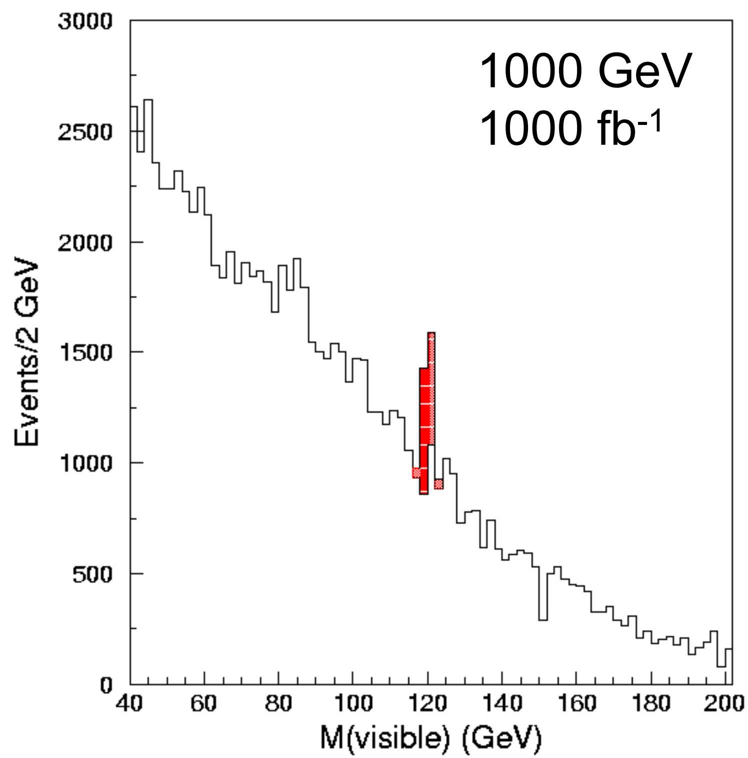
H→gg 8%

for m_H=120 GeV at 350 GeV 500 fb^{-1}

Rare decays: $H \to \gamma\gamma$
best in $\nu\nu H$
take advantage of huge event rate in WW-fusion at high energies

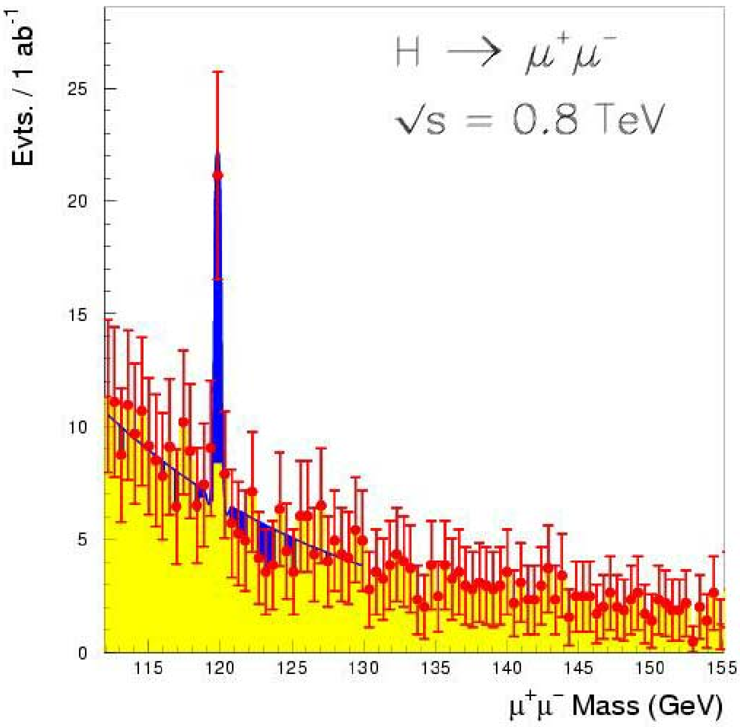


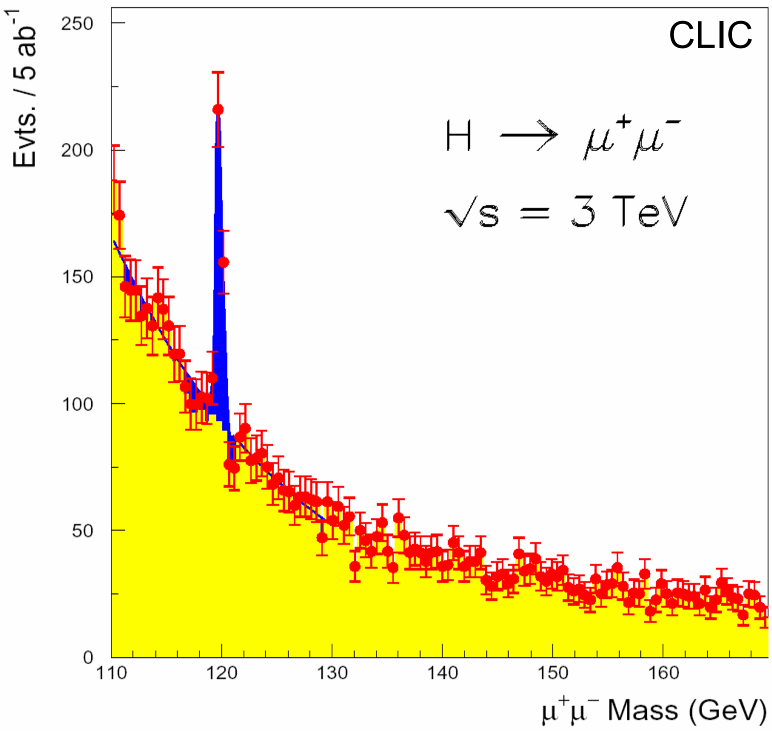
ΔBR/BR = 23%



ΔBR/BR = 5%

Rare decays: H→μμ

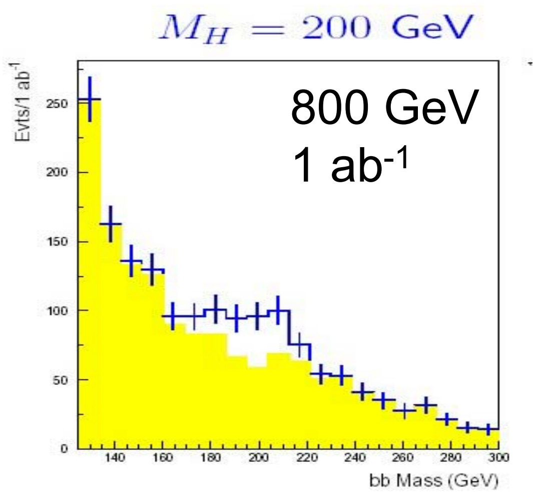


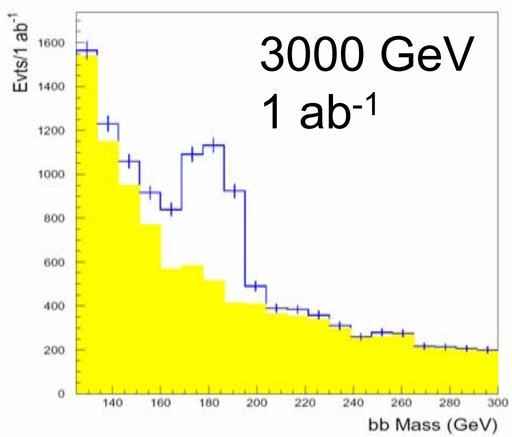


$\Delta BR/BR = 32\%$
at 800 GeV / 1ab^{-1}

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

Rare decays: H→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→bb? Use large rate of WW-fusion processes.



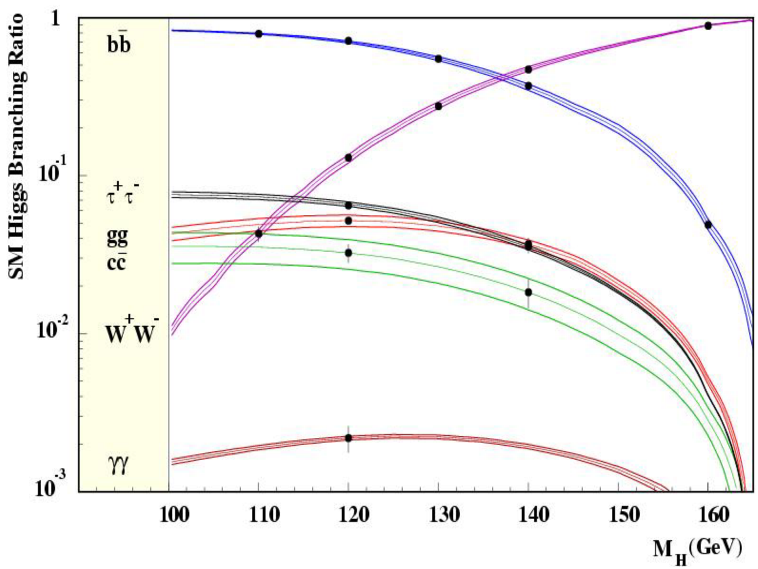


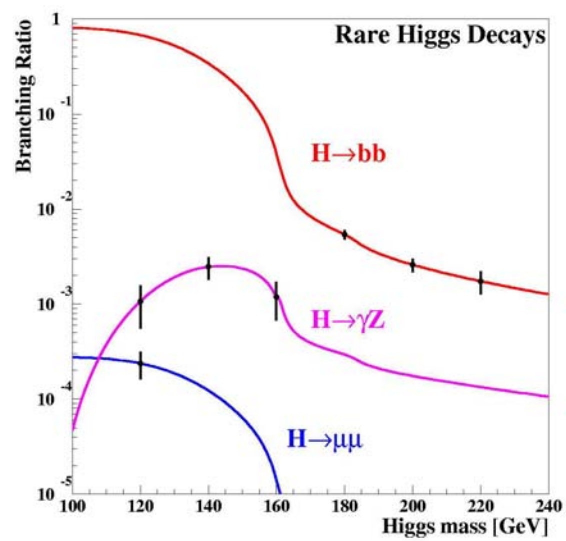
Results for 1ab^{-1}@800 GeV		
m_H(GeV)	S/sqrt(B)	ΔBR(bb)/BR(bb)
180	10.5	11.5%
200	7.5	16.5%
220	4.1	27.5%

improvement to 2-6% at CLIC

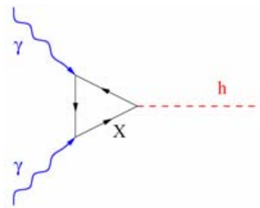
Summary on Branching ratios (state-of-the-art, expect improvements)

	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 $\gamma\gamma \to H$ production

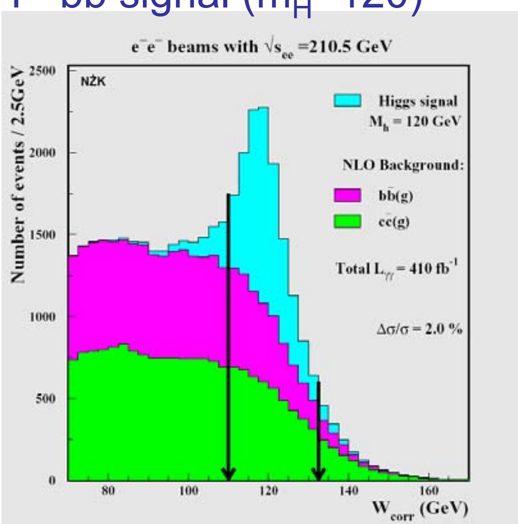


$$\sigma(\gamma\gamma \to H \to X) = \frac{4\pi^2}{m_H^3}\Gamma(H \to \gamma\gamma)\cdot BR(H \to X)(1+\lambda_1\lambda_2)$$

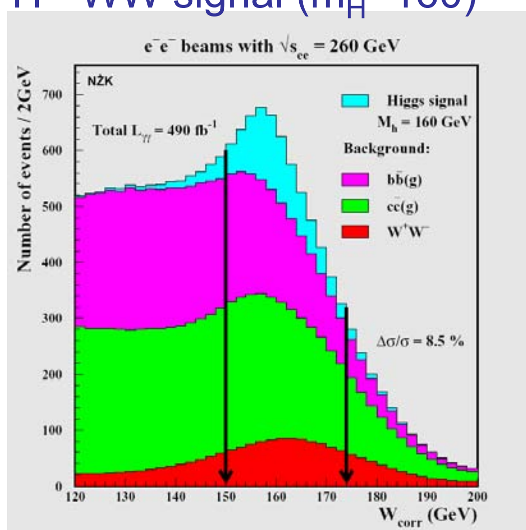
$$(\lambda_i = \text{helicity of photon } i)$$

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

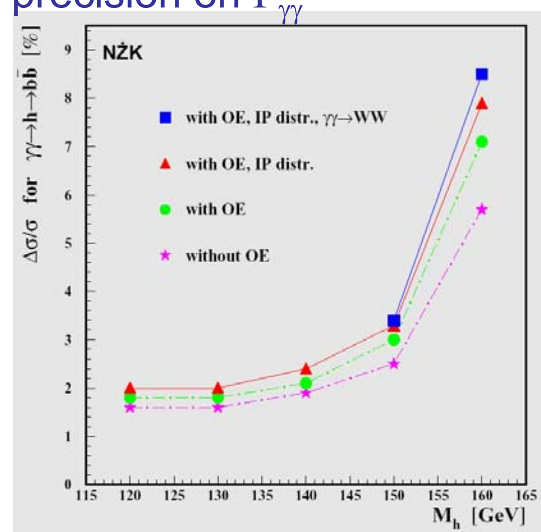
H→bb signal (m_H=120)

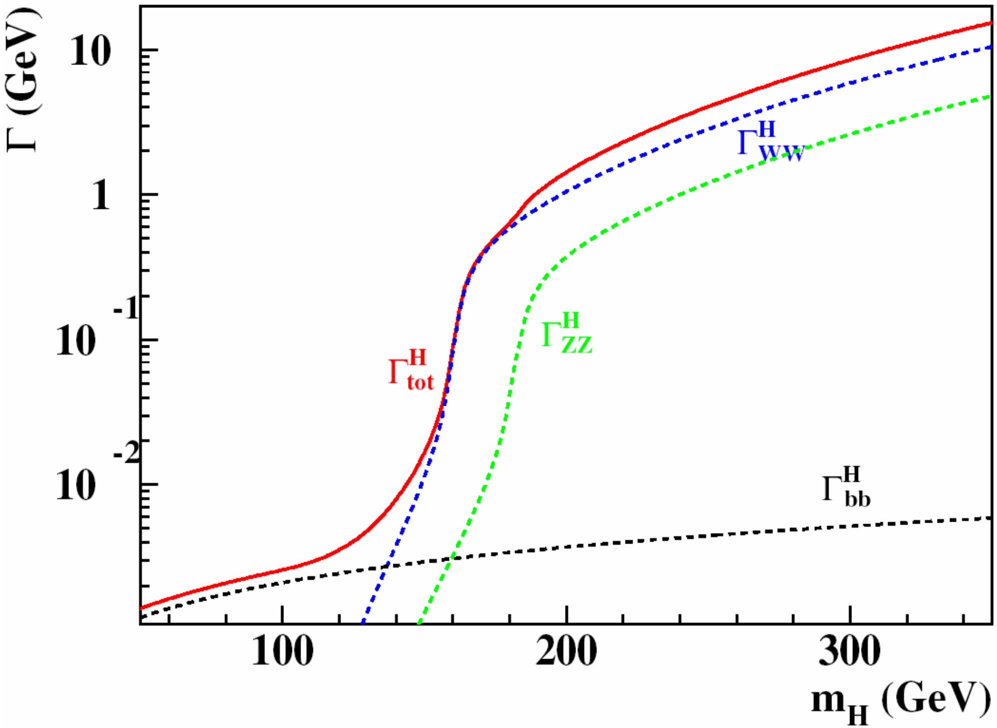


H→WW signal (m_H=160)



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



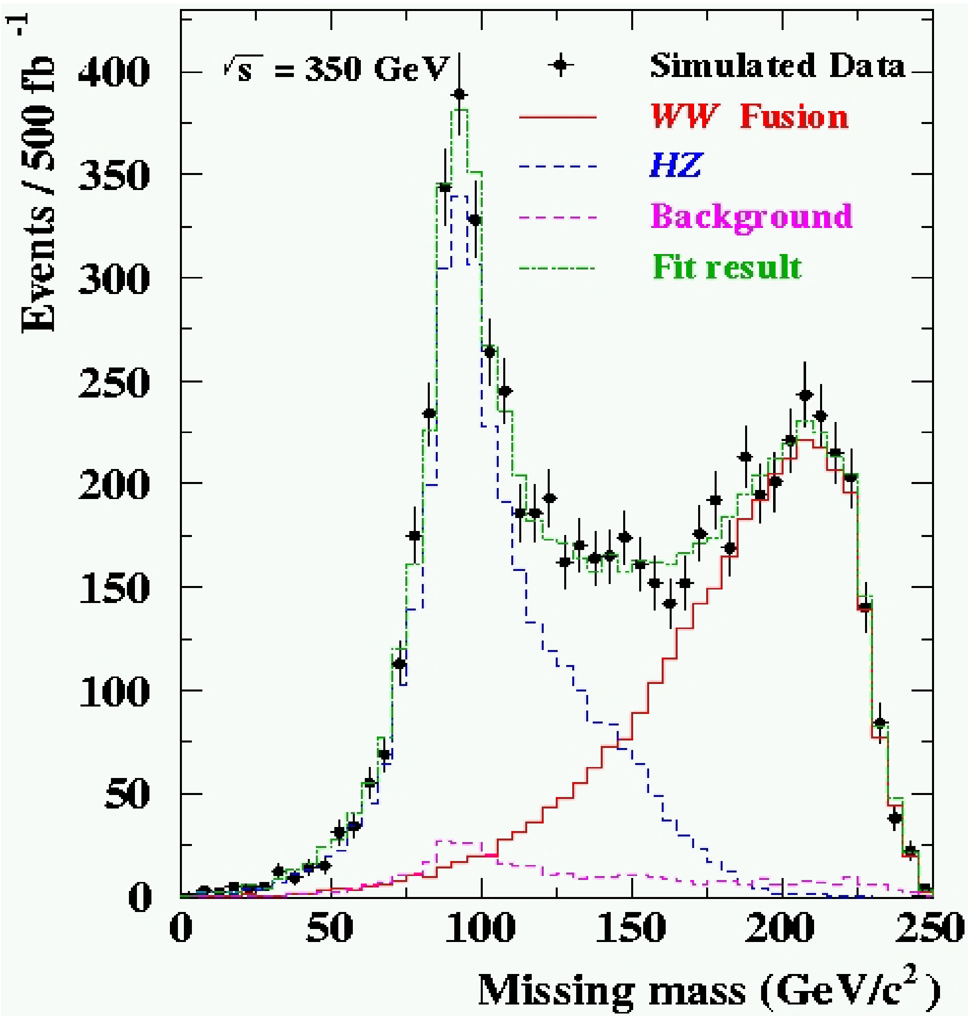


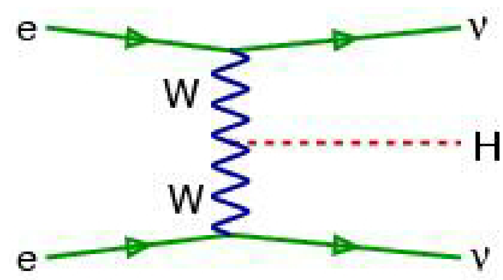
Measurement of the total Higgs decay width

m_H< 160 GeV: Γ too small to resolve in line-shape → 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→WW):

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

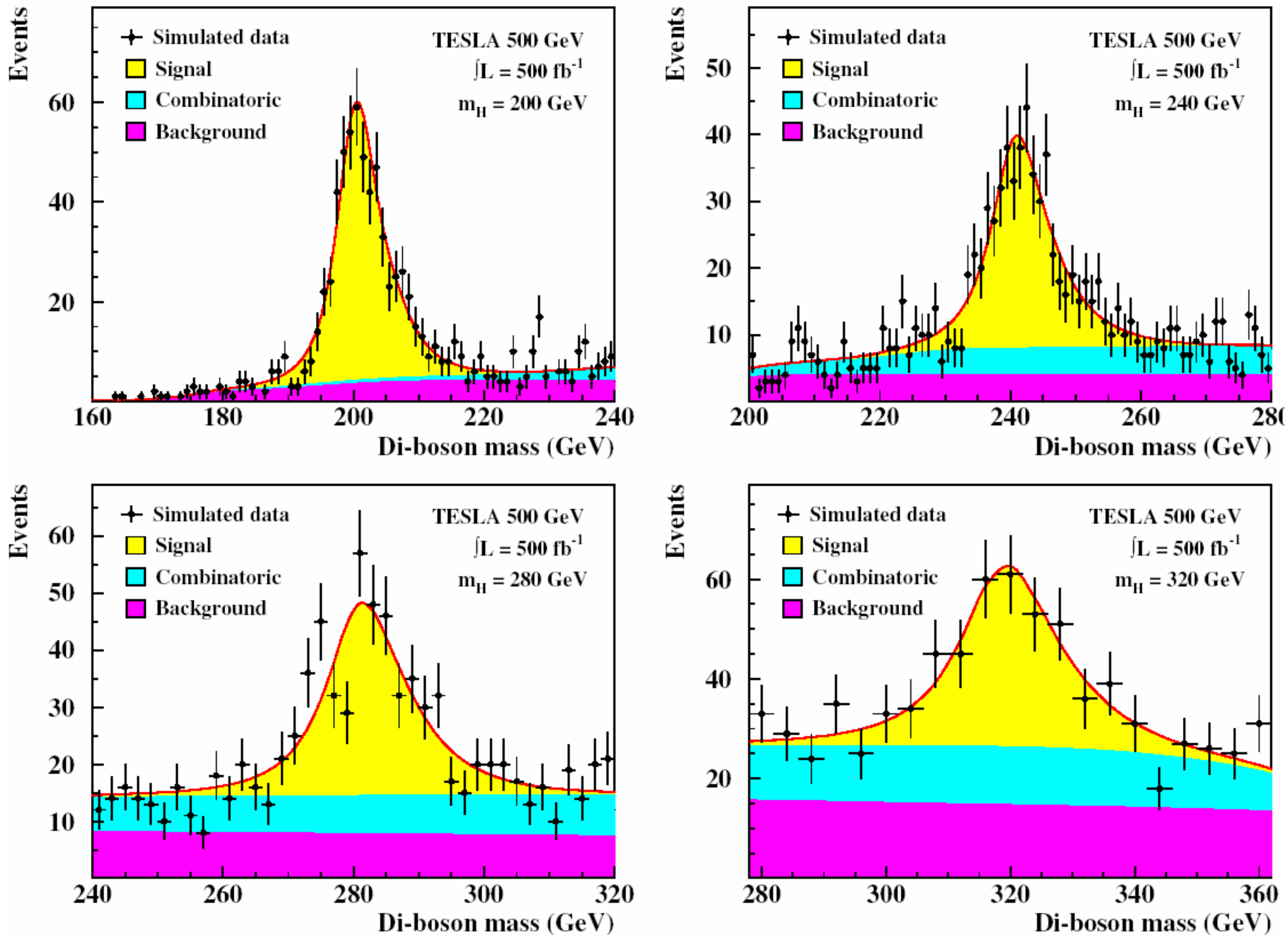
$$\Delta\Gamma_{tot} \cong 5\%$$

Alternative: use

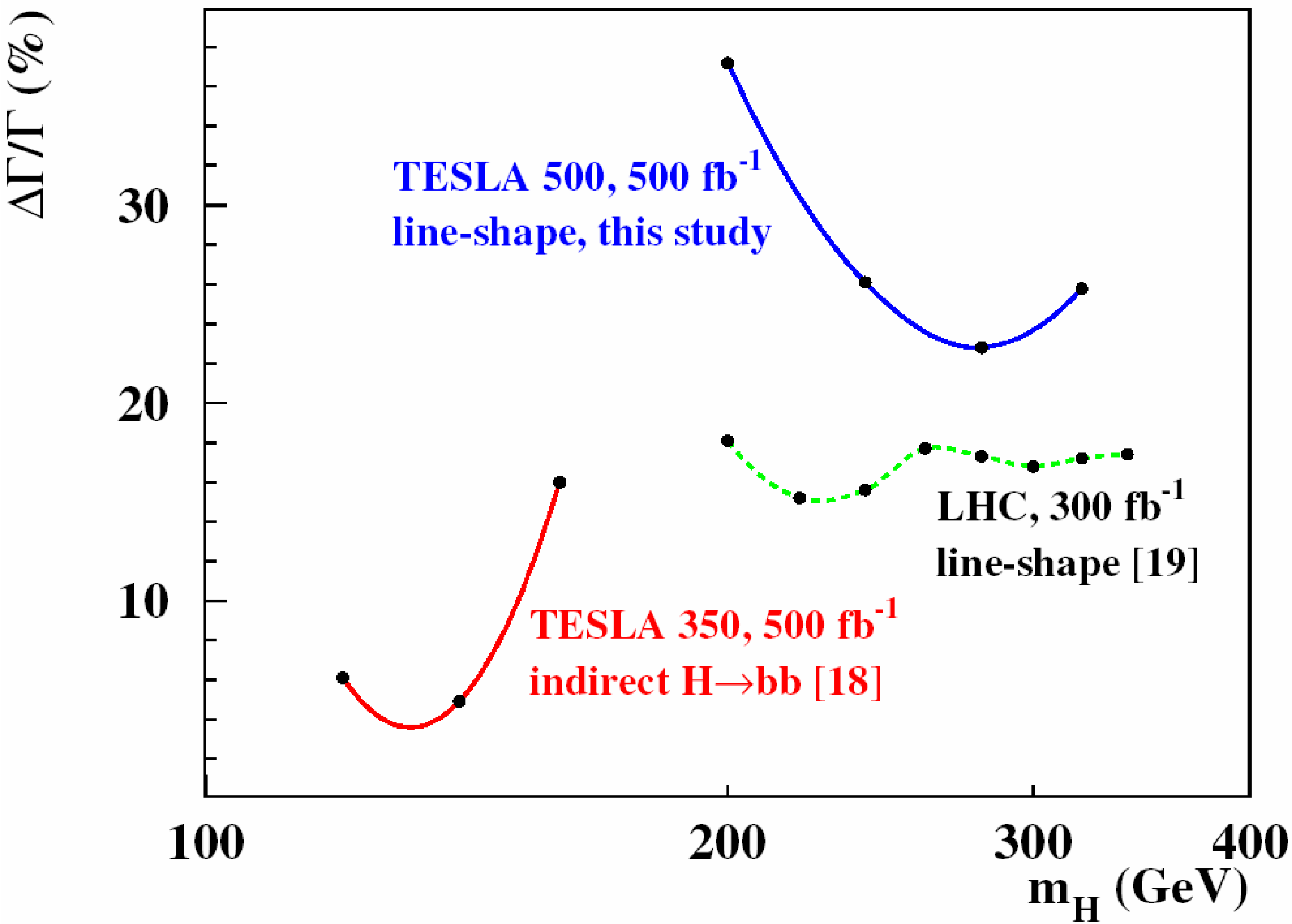
$$\Gamma_{tot} = \frac{\Gamma_{\gamma\gamma}}{BR(H \rightarrow \gamma\gamma)}$$

Precision determined by precision on BR(H→γγ)

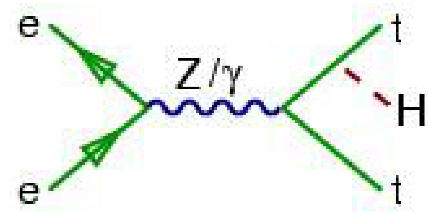
If m_H is above WW threshold, width can be reconstructed from lineshape



Summary on total width – more improvements to come…

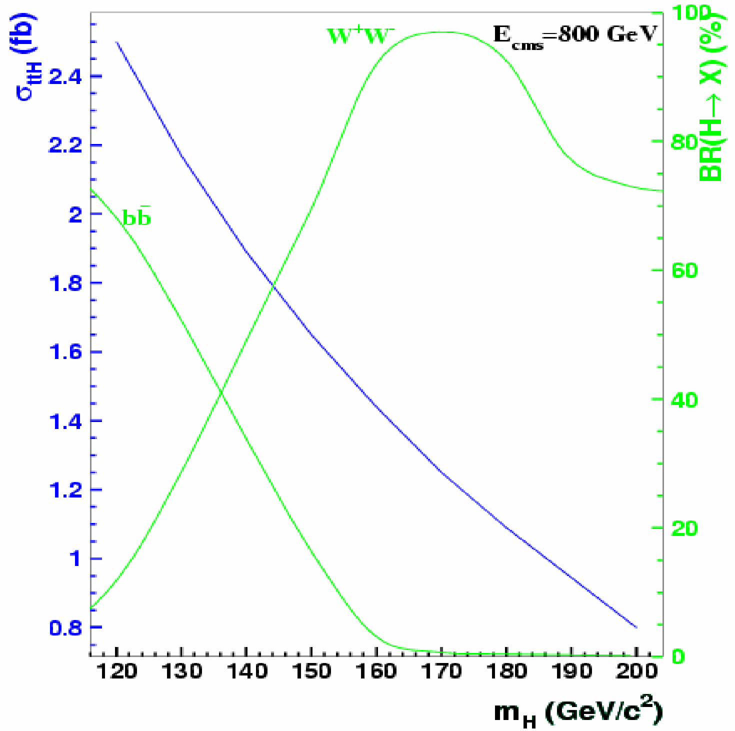


Top quark Yukawa coupling:

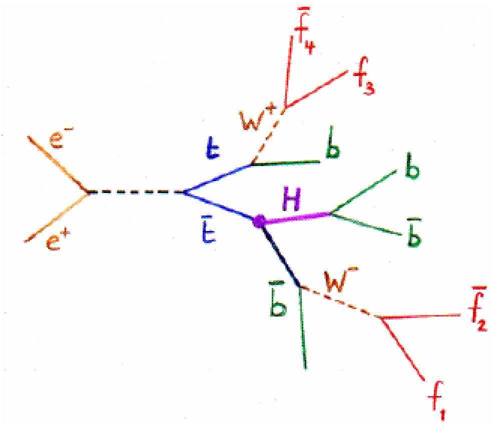


$\sigma \sim g^2_{ttH}$

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

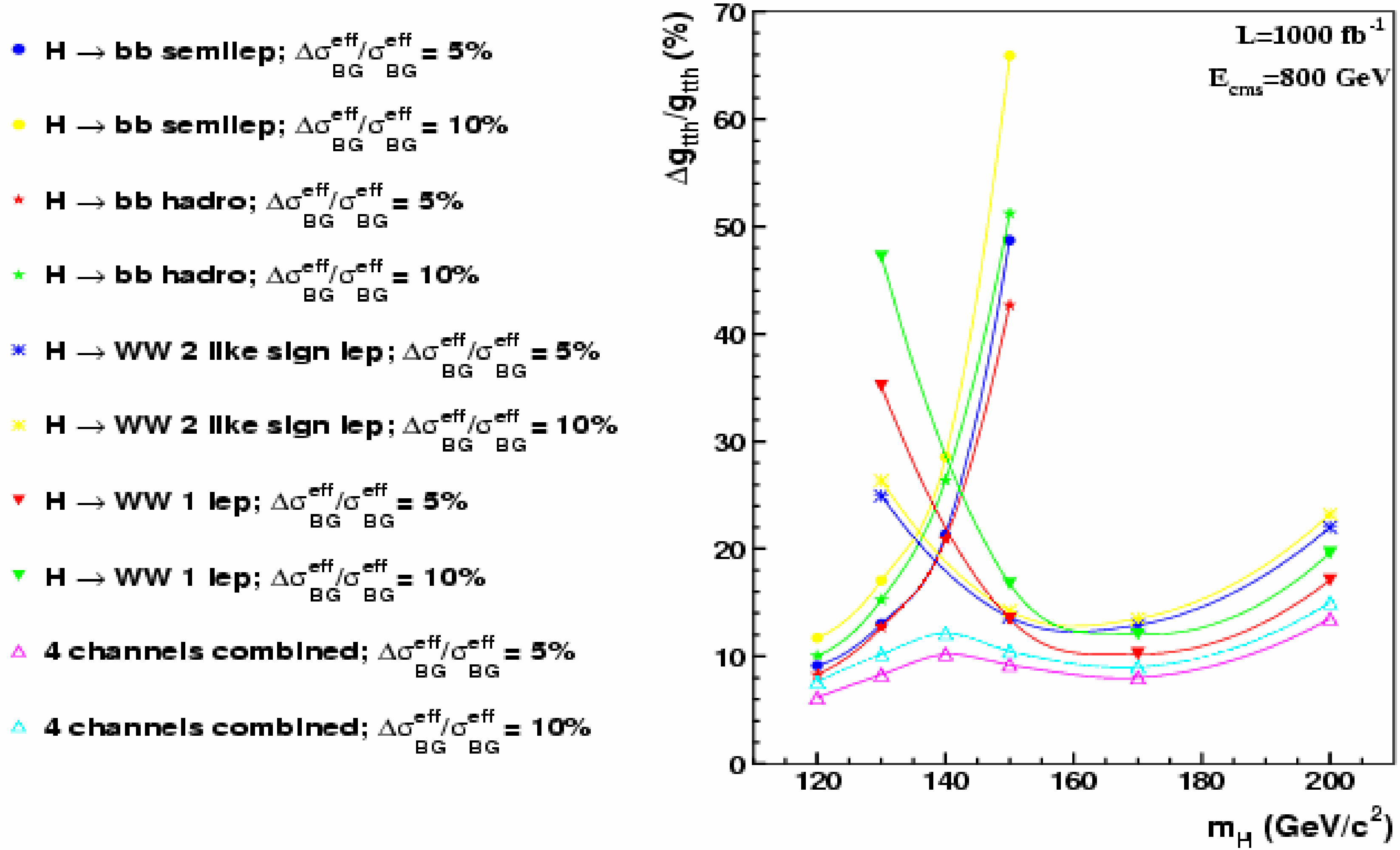


- analysis in bb and WW decay
- huge and complicated backgrounds (ttWW is a 10-fermion final state)
- b-tagging crucial to suppress bkg. and reduce combinatorial bkg.

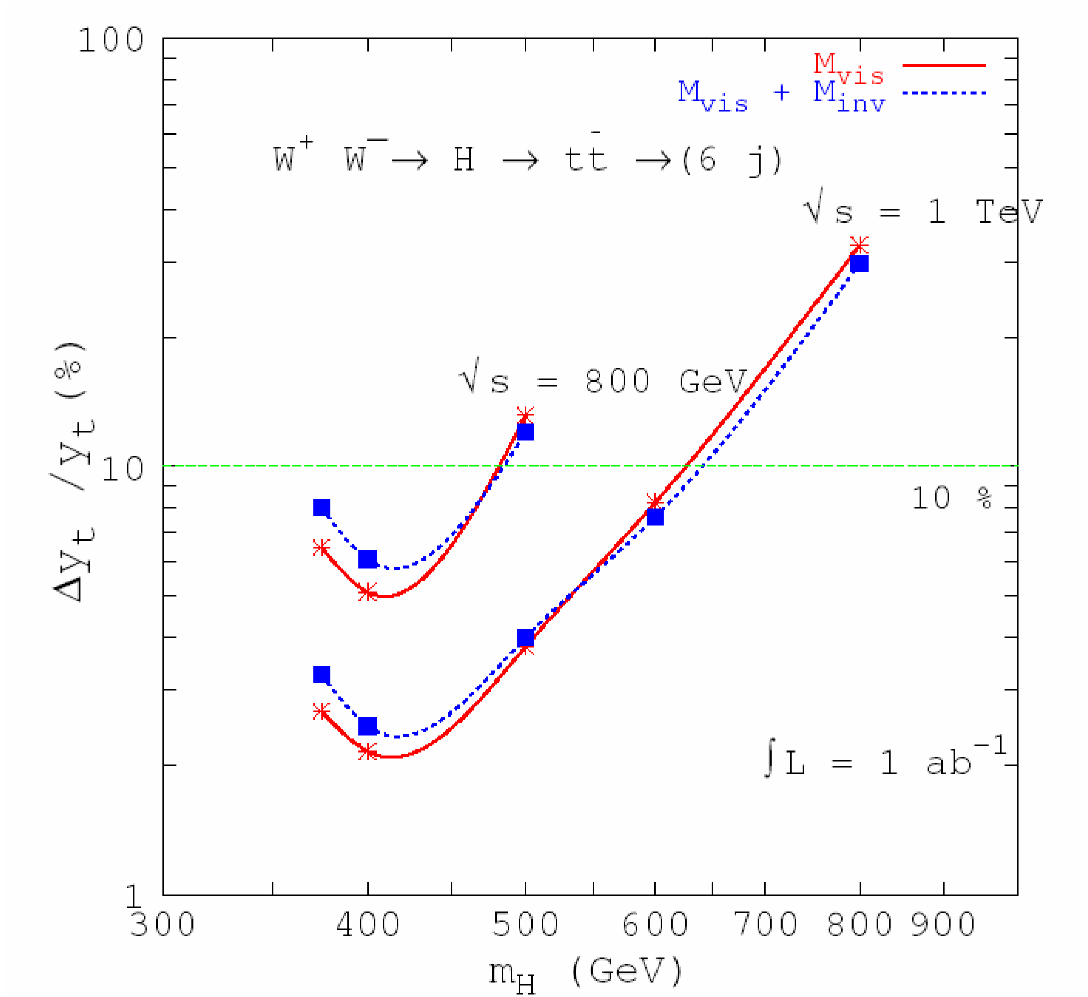


2. Higgs Physics | Top Yukawa Coupling

Result:

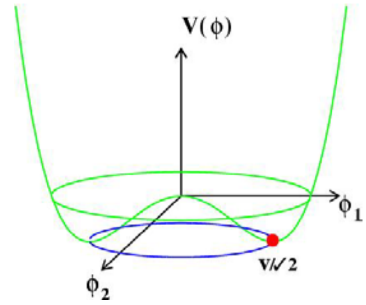


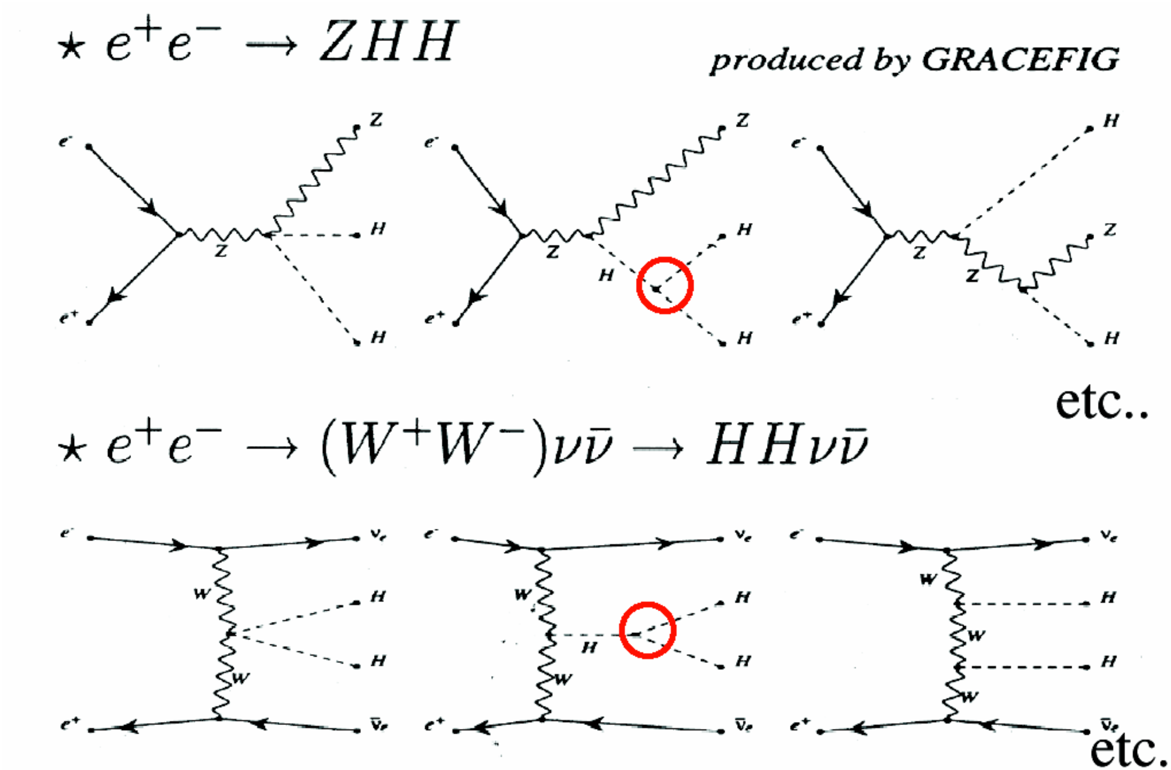
If m_H>350 GeV, study decay H→tt in ννH events



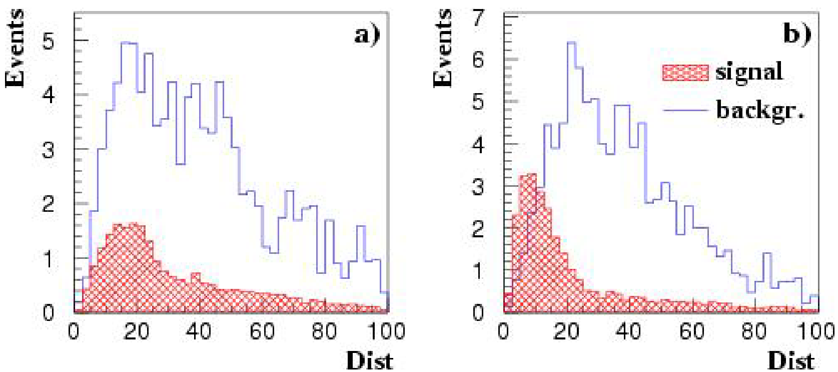
Higgs self-coupling (‘the holy grail’):

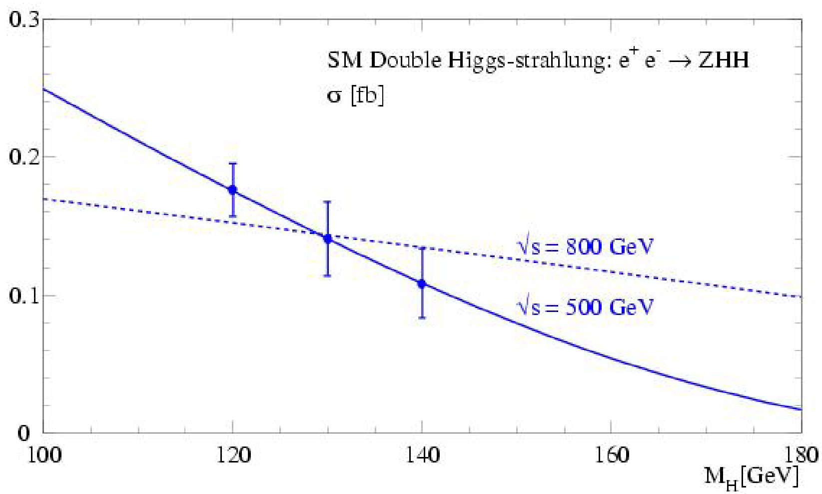
Close connection to the shape of the Higgs potential
→ essential test of the mechanism of
spontaneous symmetry breaking



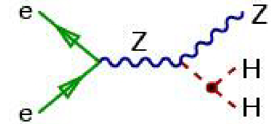


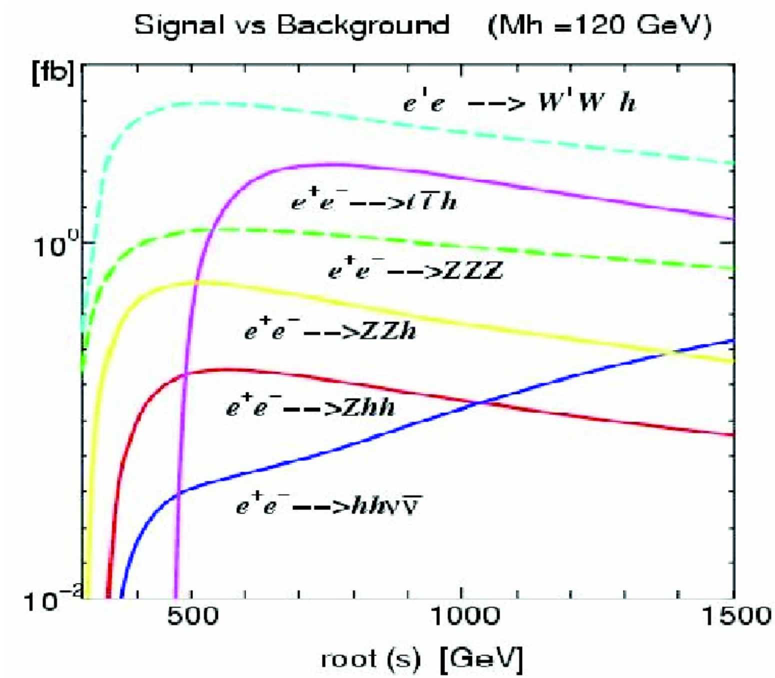
Tiny cross section
Complicated multi-jet final state
→ detector design: energy flow





Difficult backgrounds



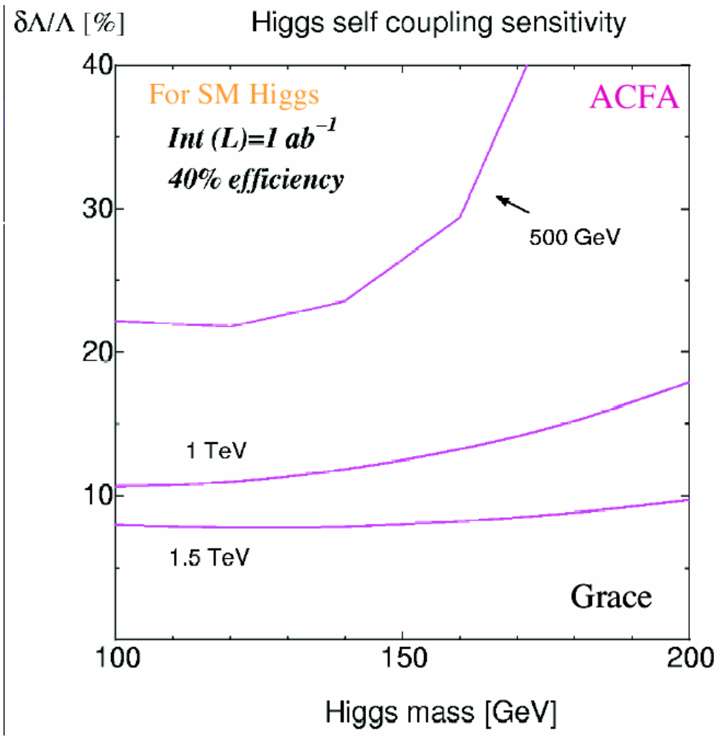


Need highest luminosity
Precision for 1 ab^{-1} :

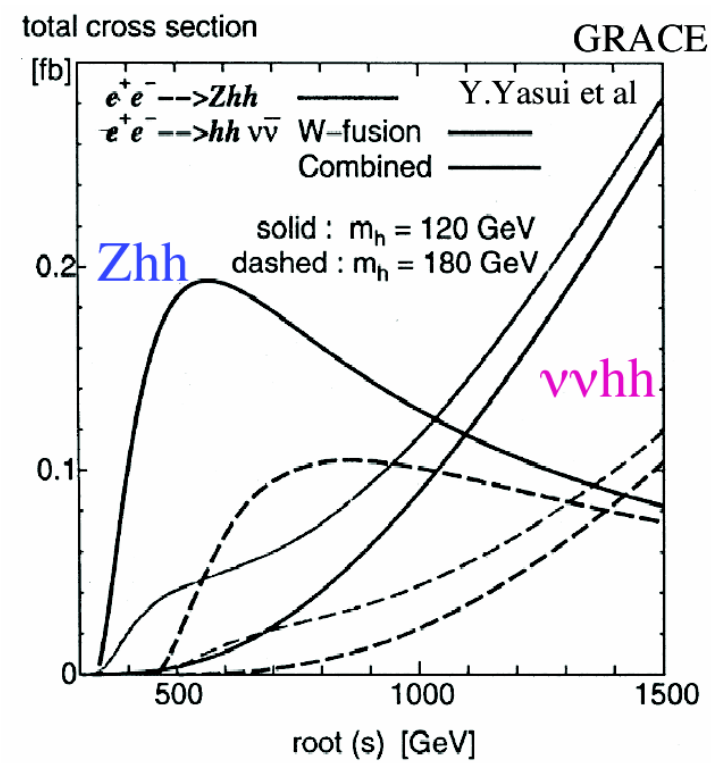
$$\Delta\lambda / \lambda \simeq 20\%$$

More sensitivity at higher energy?
Two competing effects:

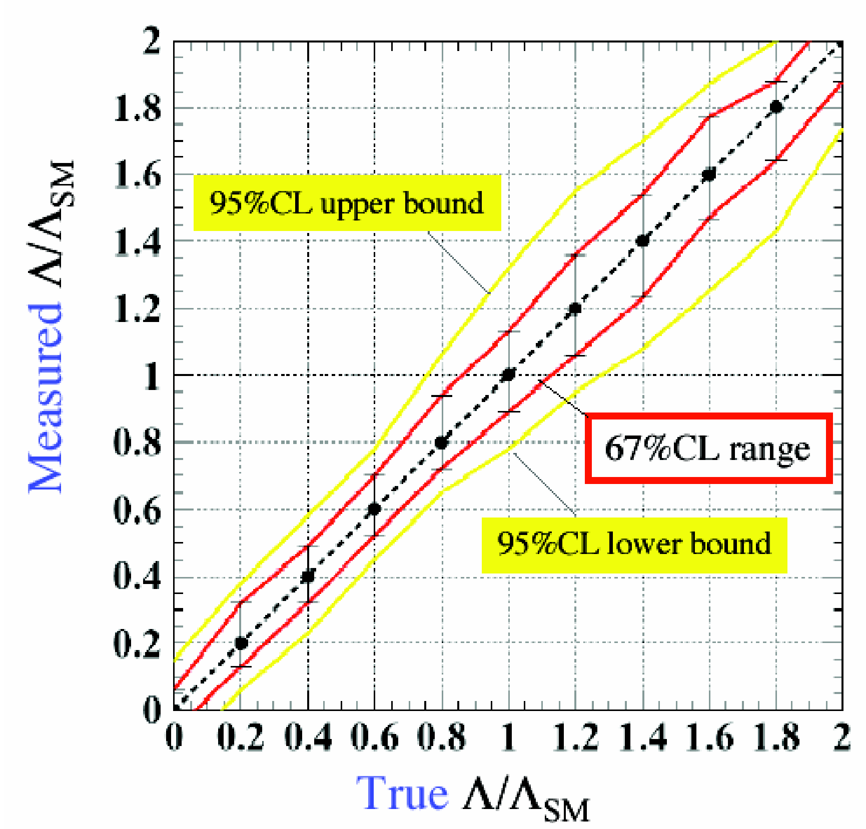
Larger dilution due to non-HHH diagrams



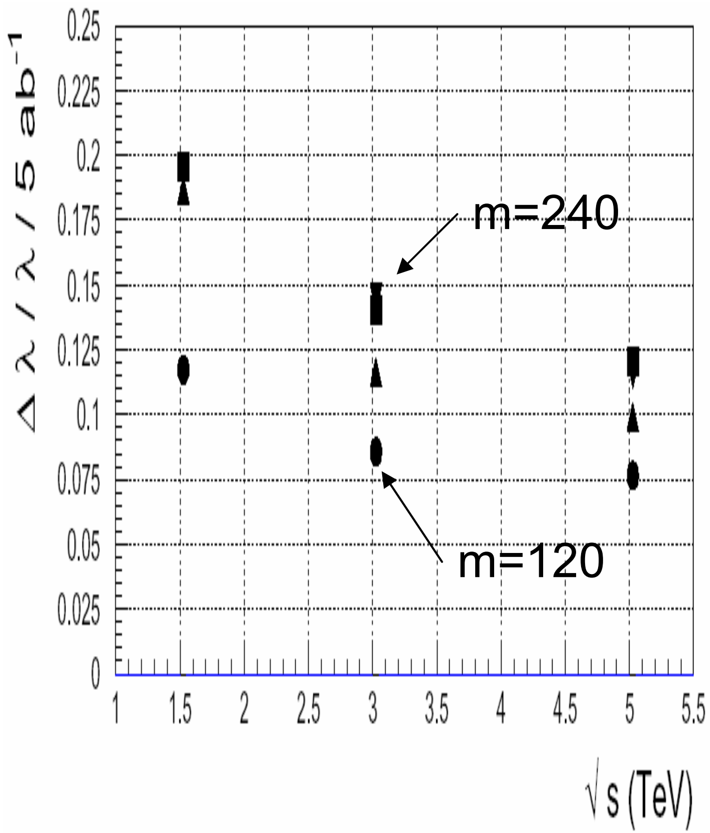
But large number of events due to contribution from WW-fusion:



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



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

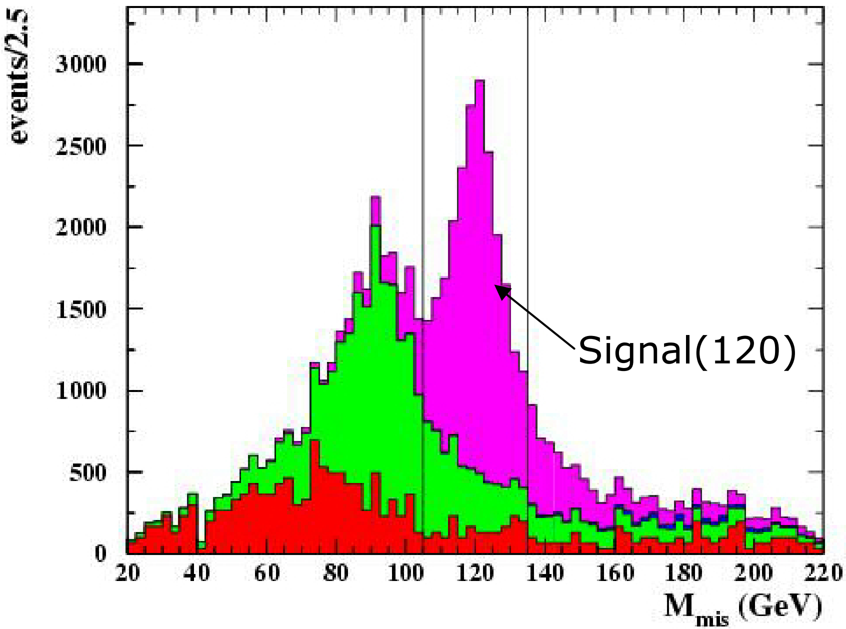


Many SM extensions predict invisible Higgs decays, e.g.:

- MSSM $H \rightarrow \chi^0_1 \chi^0_1$
- Extra Dimensions
- Model with new singlets (NMSSM,Majoron Models)
- Stealthy Higgs

Estimate sensitivity from 1 = BR(vis) + BR(invis)

or explicit reconstruction in

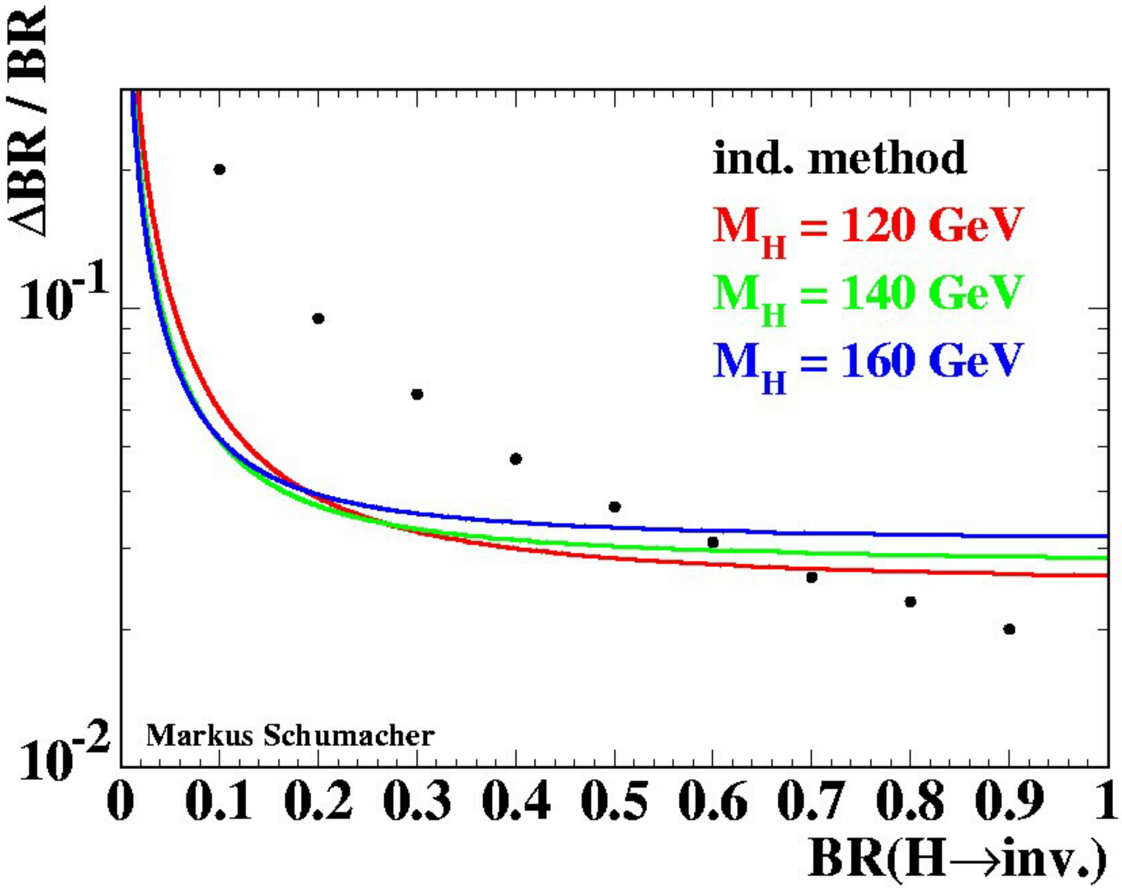


Assumptions:

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

$$m_H = 120, 140, 160\,GeV$$

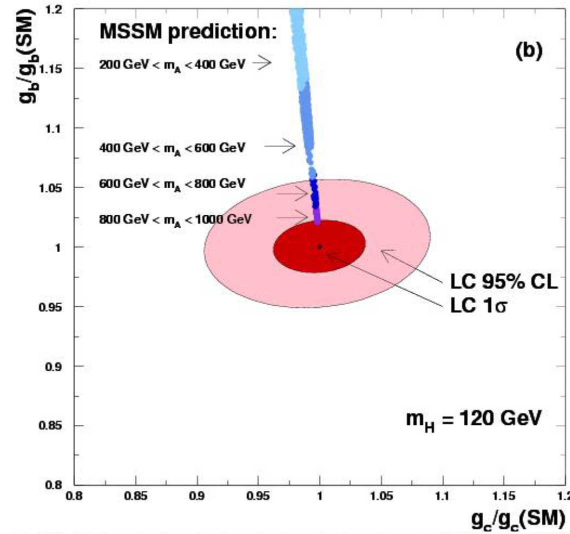
Result:

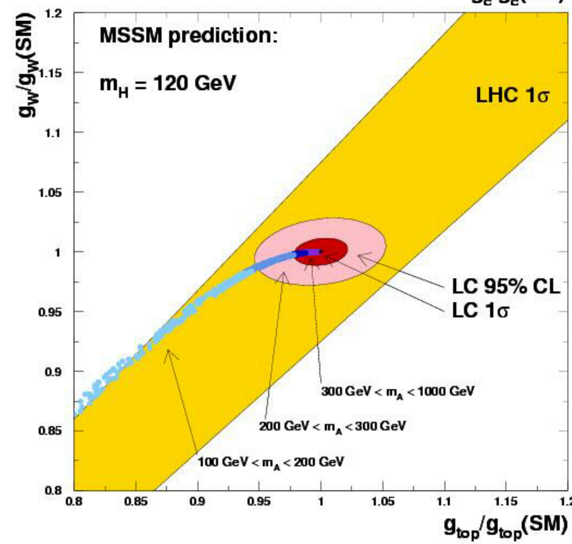


Result for 500 fb^{-1}@350 GeV (m_H=120 GeV):
ΔBR/BR(invis) = 10% for BR(invis) = 5%
5σ observation down to BR = 2%

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

Coupling	$M_H = 120\,\text{GeV}$	$140\,\text{GeV}$
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}	$\pm\,0.041$	$\pm\,0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\,0.027$	$\pm\,0.042$





%-level accuracy – sensitivity beyond SM

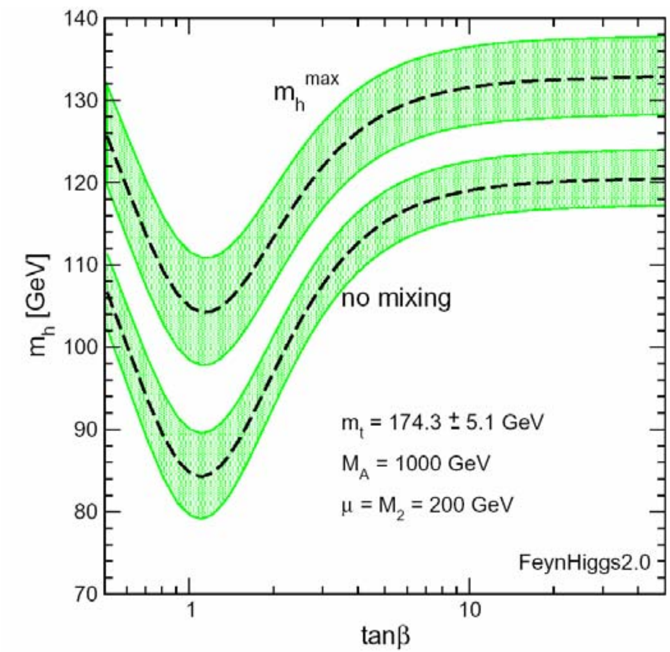
In MSSM two complex Higgs doublet fields needed

(cancellation of triangale anomalies)

Minimal possibility: two doublets (weak isospin ±1)

→ 5 physical Higgs bosons:

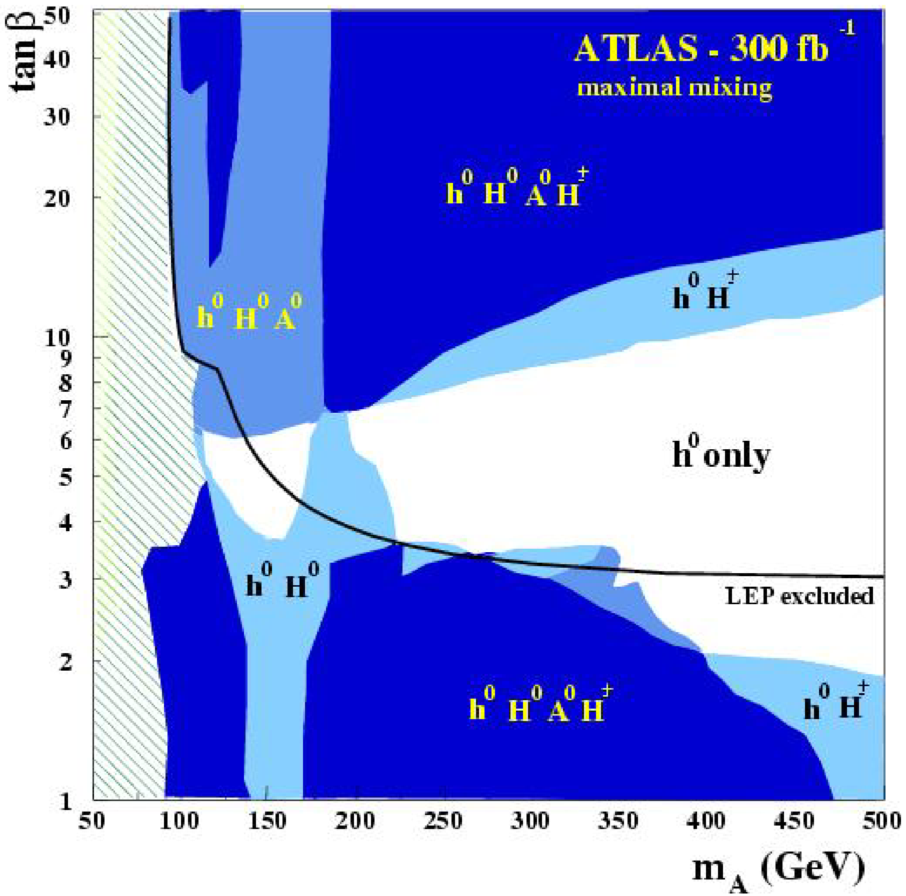
h,H	neutral, CP-even
A	neutral, CP-odd
$H^\pm$	charged



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

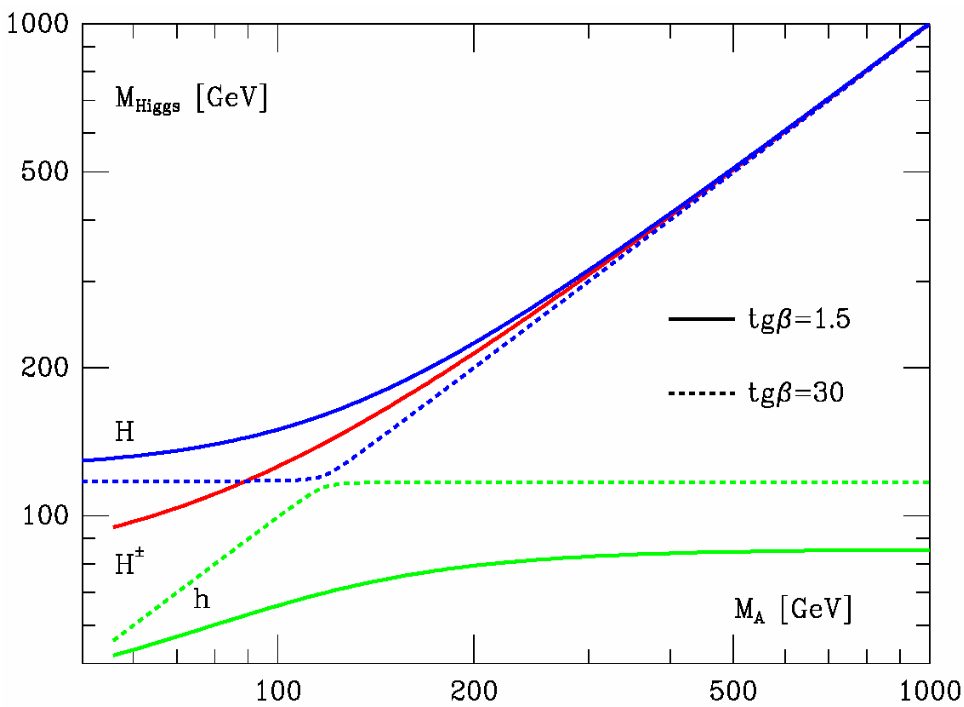
$m_h < 135$ GeV

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?

SUSY Higgs Production at ILC



Production processes:

$e^+e^- \to hZ$, $e^+e^- \to HA$ $\propto\sim \sin^2(\beta-\alpha)$

$e^+e^- \to HZ$, $e^+e^- \to hA$ $\propto\sim \cos^2(\beta-\alpha)$

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

$\gamma\gamma \to h, H, A$

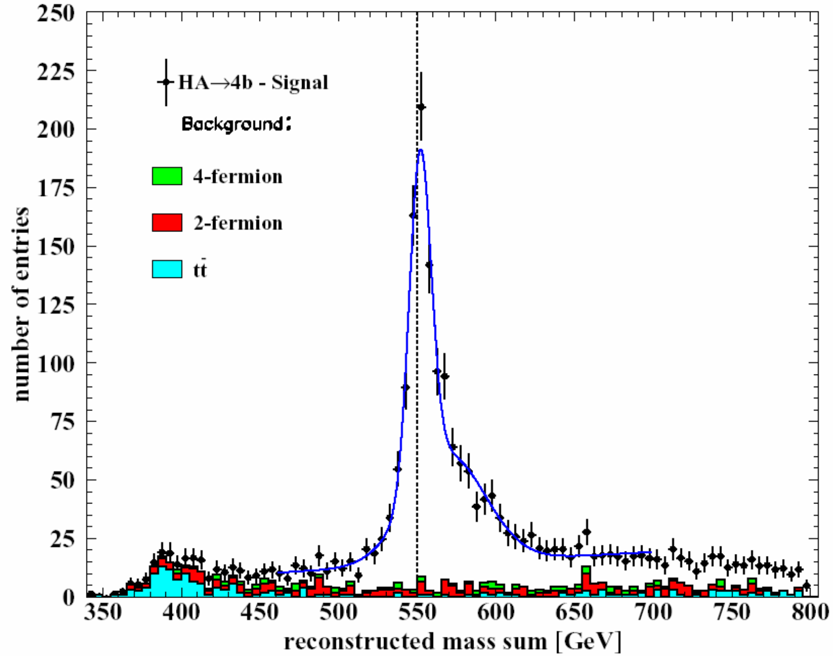
$\gamma\gamma \to H^+H^-$

Most challenging: 'decoupling limit'
$\sin^2(\beta-\alpha) \to 1$, m_A large
h becomes SM like
$H/A/H^{\pm}$ heavy and mass degenerate

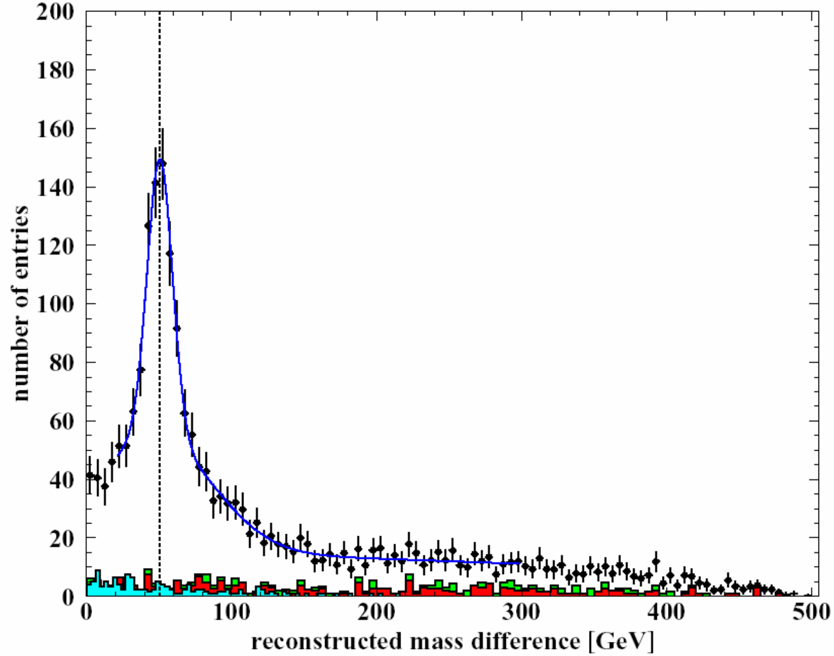
Very clear signal in HA → bbbb
100 – 1000 MeV mass precision due to kinematic fit
drawback: pair production → mass reach ~ √s / 2

Example for m_H=250 GeV / m_A=300 GeV at √s = 800 GeV:

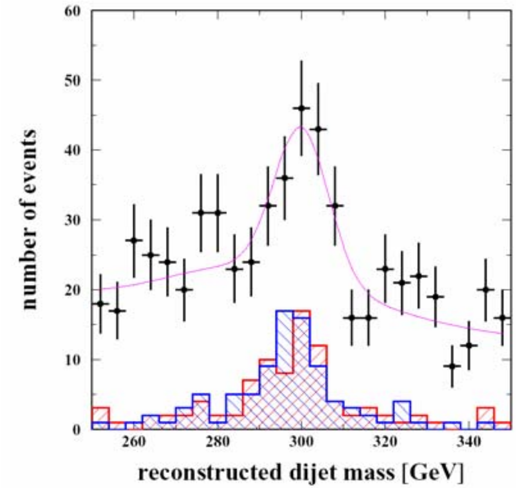
reconstructed mass sum

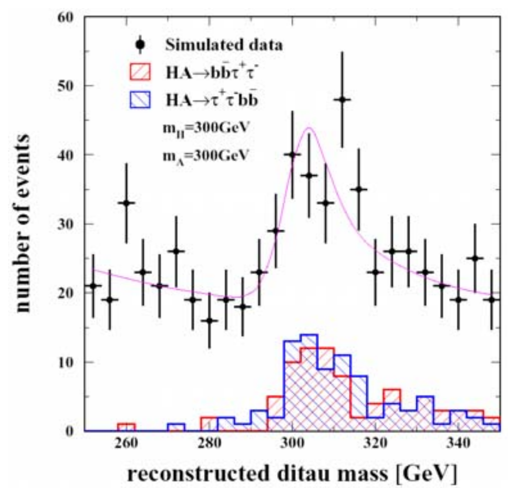


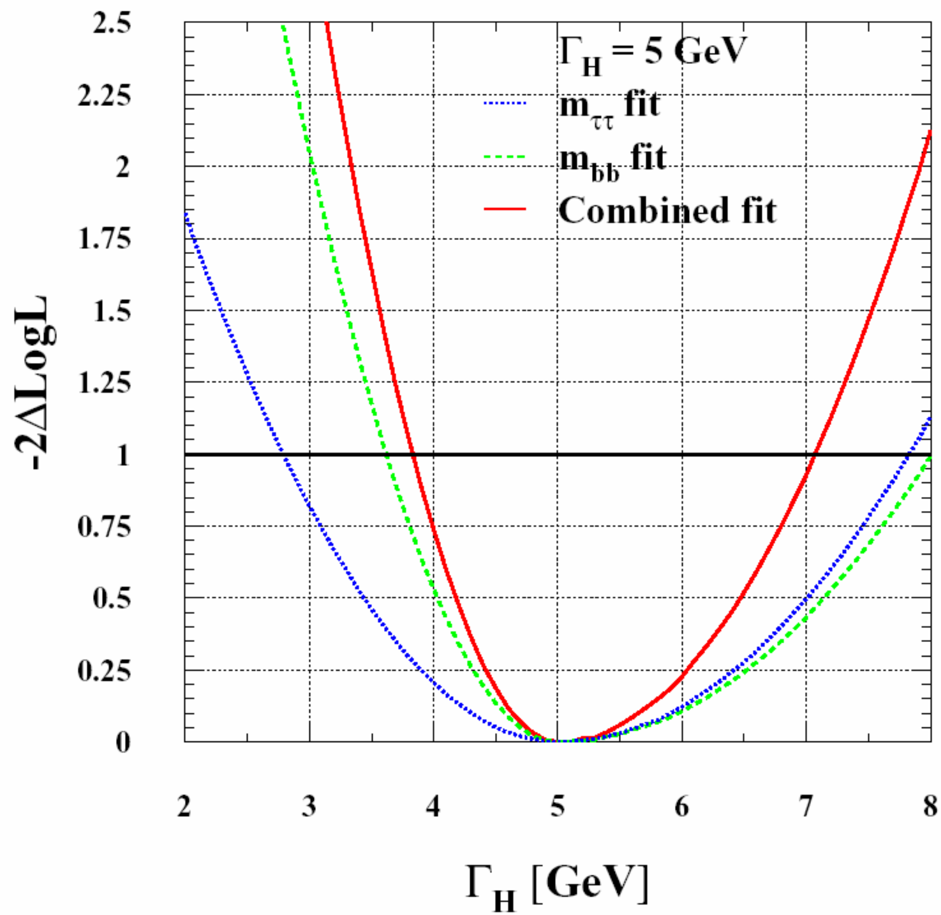
reconstructed mass difference



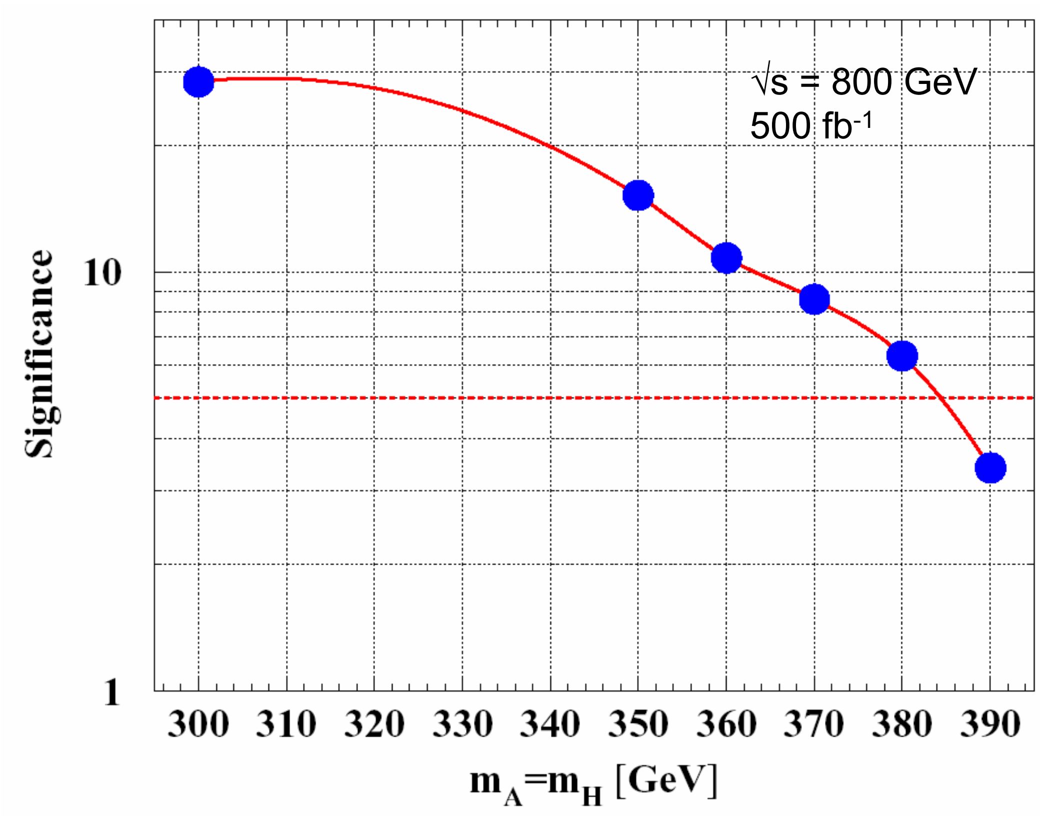
H/A → bbττ more difficult due to low BR(H/A→ττ) but allows for distinction of H and A and reconstruction of decay width to o(1 GeV)







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

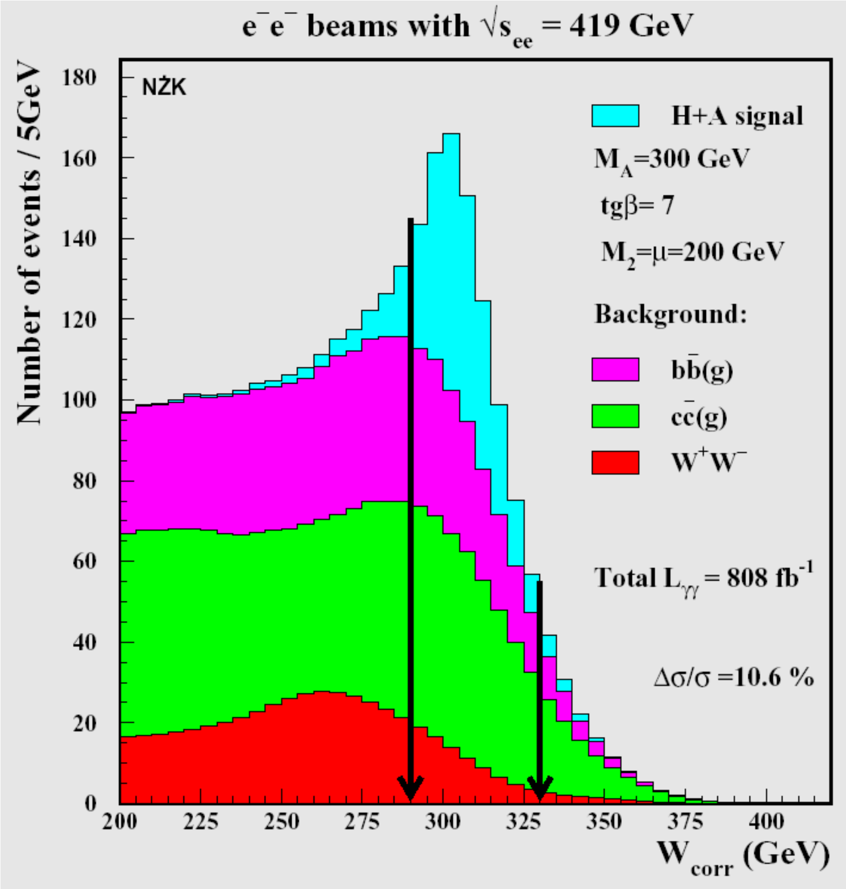


precision on
m_H / m_A

100 – 1000 MeV

SUSY Higgs at Photon Collider

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



Summary of Day 2

- 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

- Heavy SUSY Higgses can be seen if $m<\sqrt{s_{ee}}/2$ or $m<\sqrt{s_{\gamma\gamma}}$

- CLIC: improve on very rare decays + (maybe) self-coupling
  larger mass reach for heavy SUSY Higgses in decoupling limit