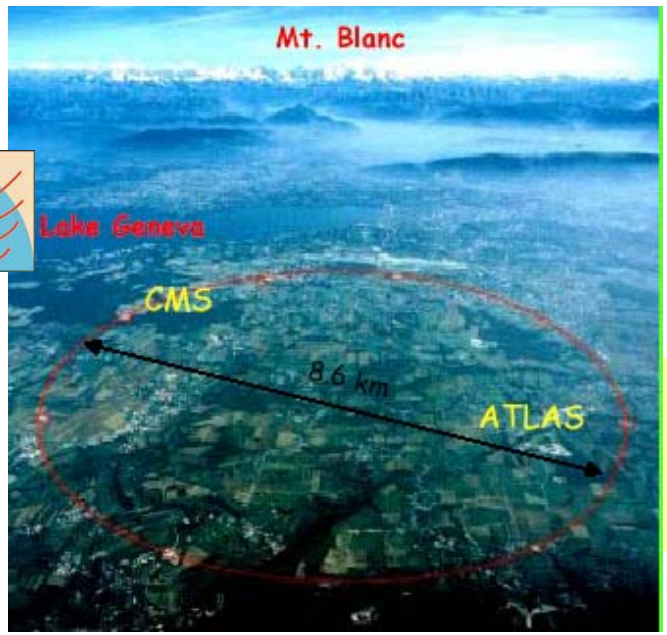
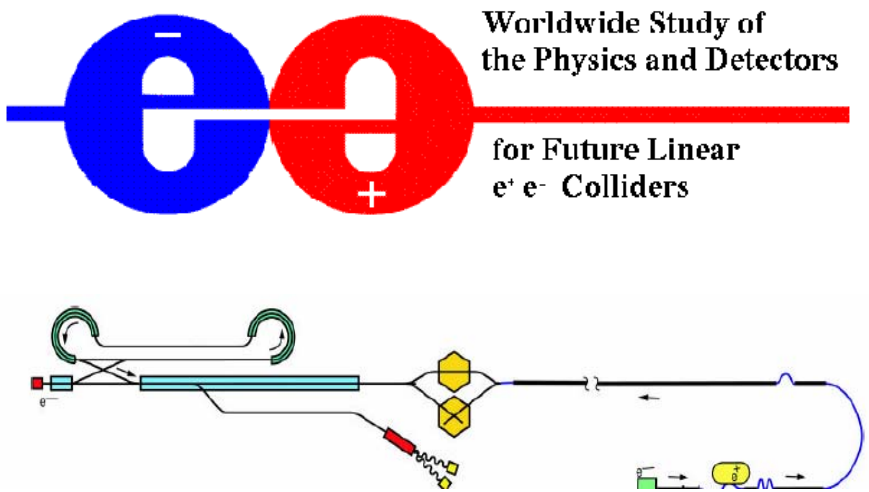
Higgs studies at the LHC and a Linear Collider

Albert De Roeck CERN
SLAC Summer Institute 06/08/04





High Energy Frontier in HEP

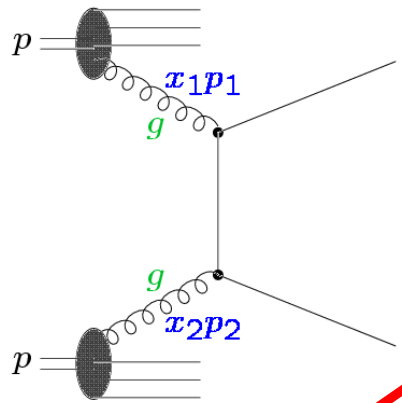
Next projects on the HEP roadmap(*)

- Large Hadron Collider LHC at CERN
  - Approved, budget in place and under construction
  - Expected turn on in middle of 2007
- Linear Collider (LC) ?
  - Strong world-wide effort to start construction around 2009/2010, if approved and budget established
  - Expected turn on 2015(+)
  - Study groups in Europe, Americas and Asia (+World Wide Study)

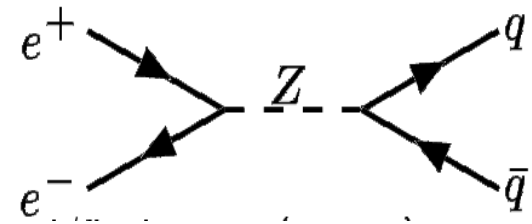
Quest for the Higgs particle is a major motivation for these new machines

(*) other projects like muon collider or VLHC on longer time scale

LHC/LC



Different characteristics of the two machines
⇒ Different virtues



LHC pp collisions √s = at 14 TeV

⇒ Strong point: larger mass reach for direct discoveries

- Kinematics: can use conservation of p_t
- Composite nature of colliding protons ⇒underlying event
- √s of the hard interaction not fixed
- Strongly interacting particles ⇒ huge QCD cross sec. (background)

e+e- collisions at √s = 0.5-1.0 TeV

⇒Strong point: high precision physics

- Kinematics: mom. conservation used to analyze the decays,...
- Well defined initial state, beam polarization, √s,...
- Backgrounds smaller than LHC
- Options: γγ, eγ, e-e- colliders.

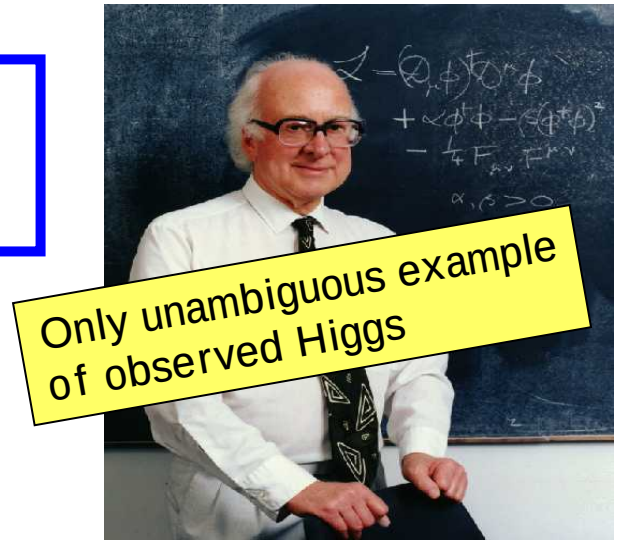
Where is the Higgs?

- Higgs mass :

-- 114.4 GeV $< m_H <$ 1000 GeV ← from theory

↑ from direct searches at LEP

-- from fit to the electroweak data
(LEP, Tevatron, SLC, etc.):
indirect limit $m_H <$ 237 GeV at 95% C.L.
→ present data favour a light Higgs



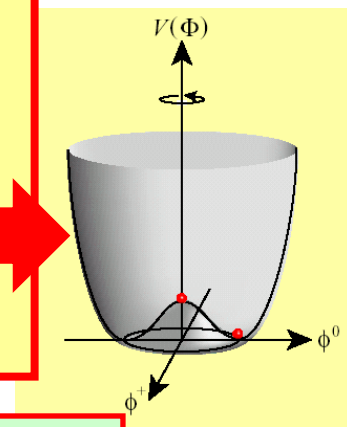
-- LEP " hint " (~ 2σ excess) for m_H ~ 115 GeV ?

Suspect that there may be a light Higgs but do not know for sure

- LHC will discover the SM Higgs or exclude it --unless Tevatron sees it first...
- LHC will measure mass and (mostly) ratios of couplings, spin,...
- LC will determine precisely the couplings and measure all its quantum numbers

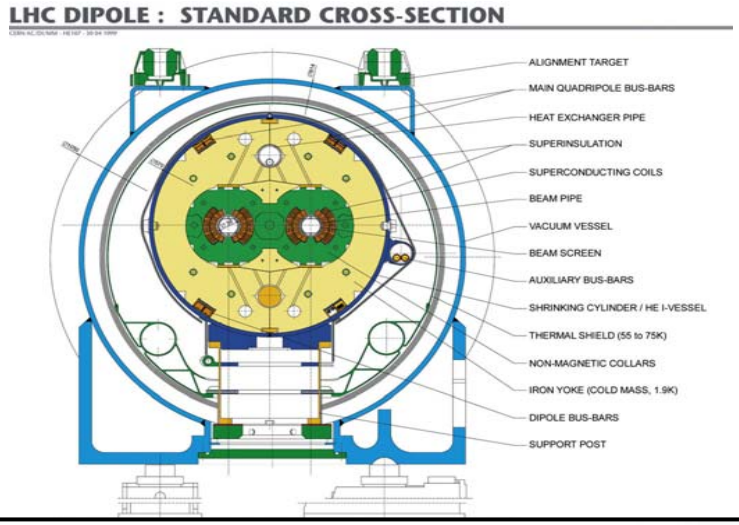
"Higgs Roadmap"

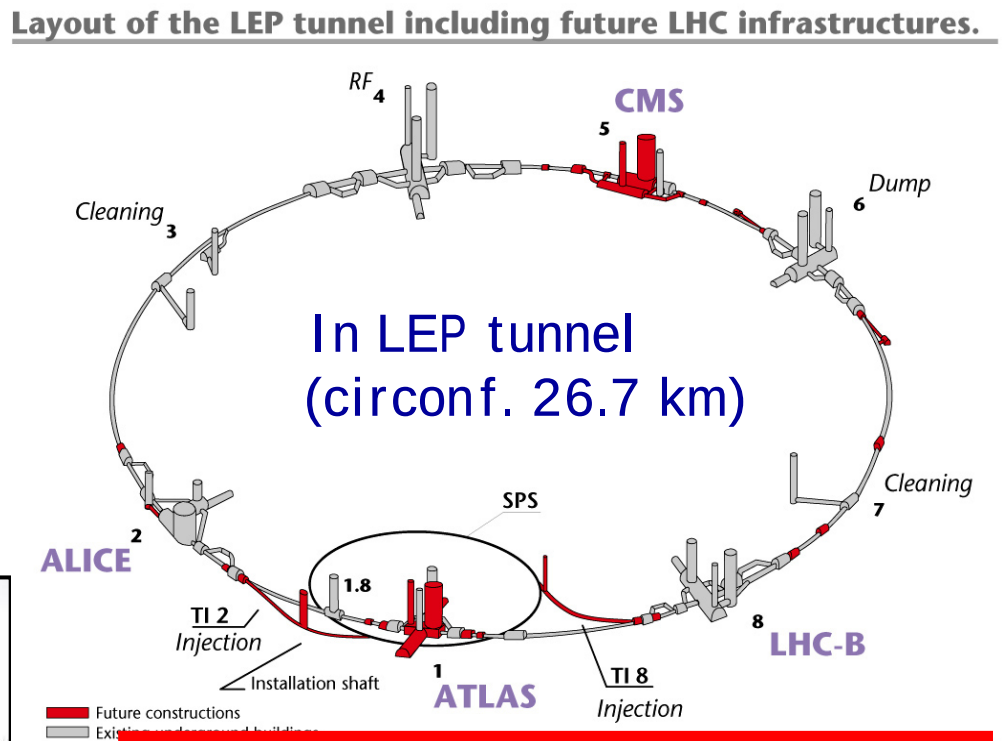
- Discover the Higgs
- Determine its properties/profile
  - The mass
  - Spin and parity quantum numbers
  - How does it decay?
    - Measure Yukawa like patterns
    - Measure relations between fermion and gauge boson couplings
    - Observe rare decay modes
    - Observe unexpected decay modes? (new particles?)
    - Measure total width
- Reconstruction of the Higgs potential by determination of the Higgs self coupling
- Its nature: is it standard, supersymmetric, composite.



BOTH LHC and LC will be crucial in establishing Higgs Dynamics

The LHC





~1100 Super conducting dipoles needed
~300 dipoles delivered

25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

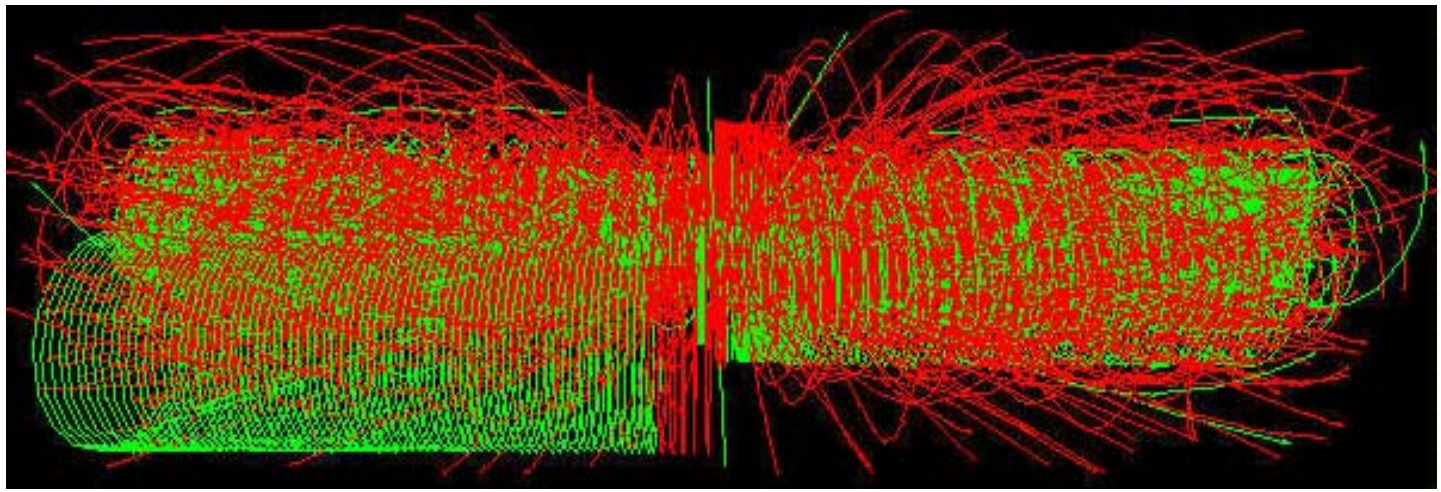
Design Luminosity:
$10^{34} cm^{-2} s^{-1}$ ⇒100 fb^{-1}/year

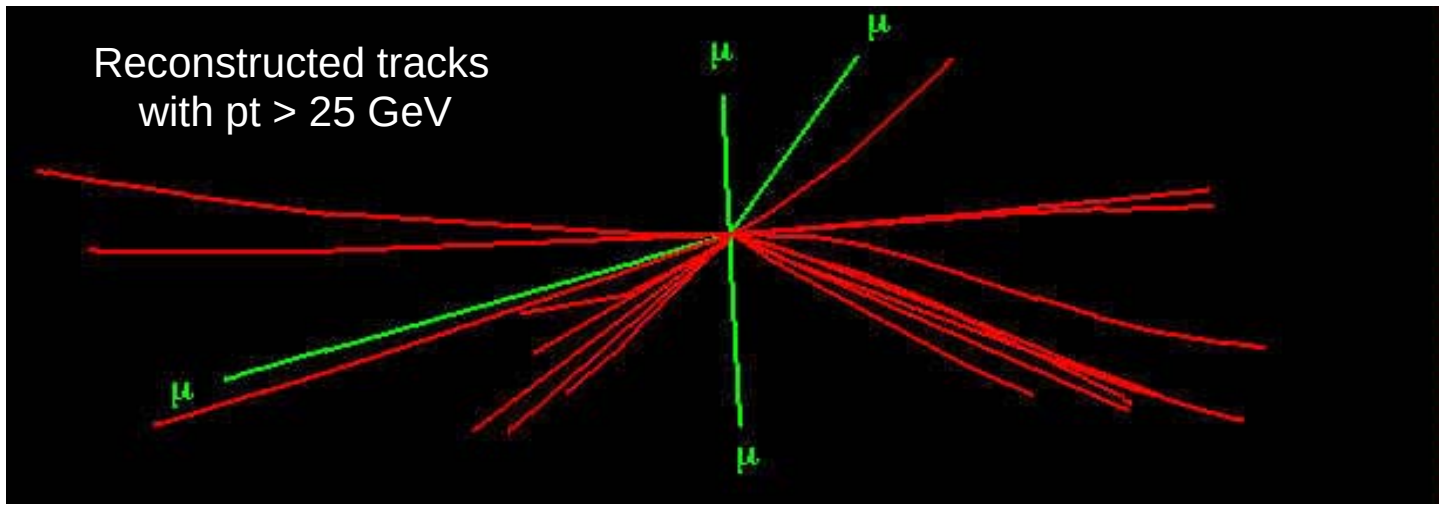
23 events per bunch crossing

pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

- 23 min bias events overlap at $10^{34} cm^{-2} s^{-1}$
- $H \rightarrow ZZ$
  $Z \rightarrow \mu\mu$
  $H \rightarrow$ 4 muons: the cleanest ("golden") signature

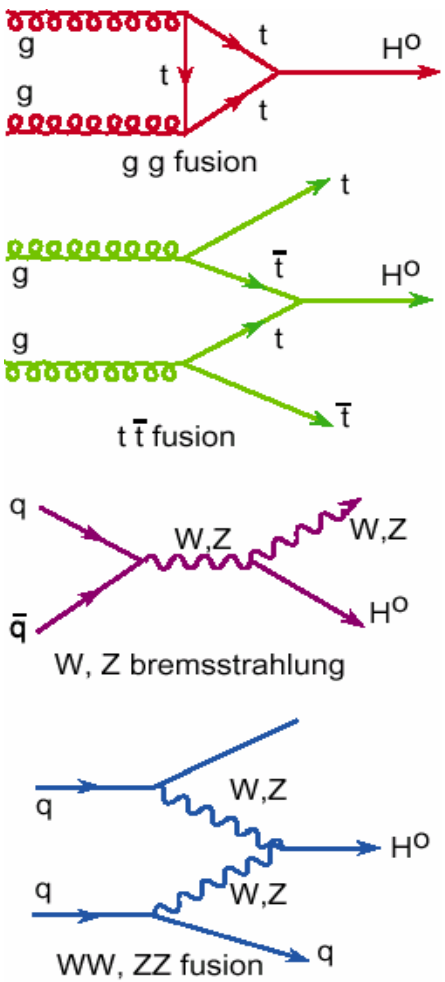
This (not the H !!) repeats every 25 ns…

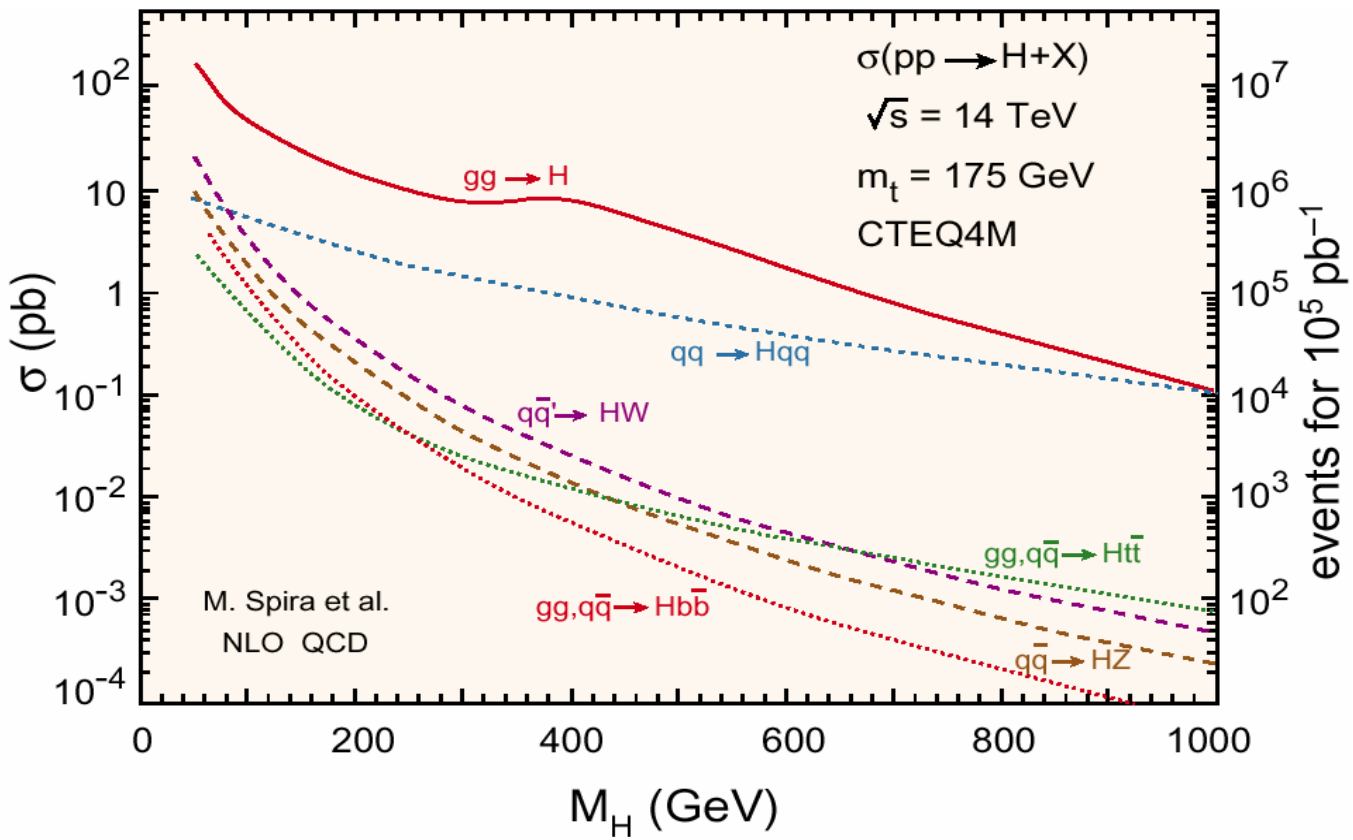




SM Higgs production at LHC

Production mechanisms & cross section





SM Higgs search

$H < 2M_Z$

H -> γγ, inclusive, in ttH and WH

H -> ZZ* -> 4 leptons

H -> WW* -> $l\nu l\nu$

H -> $b\bar{b}$ in $t\bar{t}$H and WH

qqH, H -> WW* -> $l\nu l\nu$

qqH, H -> ττ -> l+τ jet, ll

Recent!

$H > 2M_Z$

H -> ZZ -> 4 leptons ⇐golden channel

qqH, H -> WW -> $l\nu jj$,

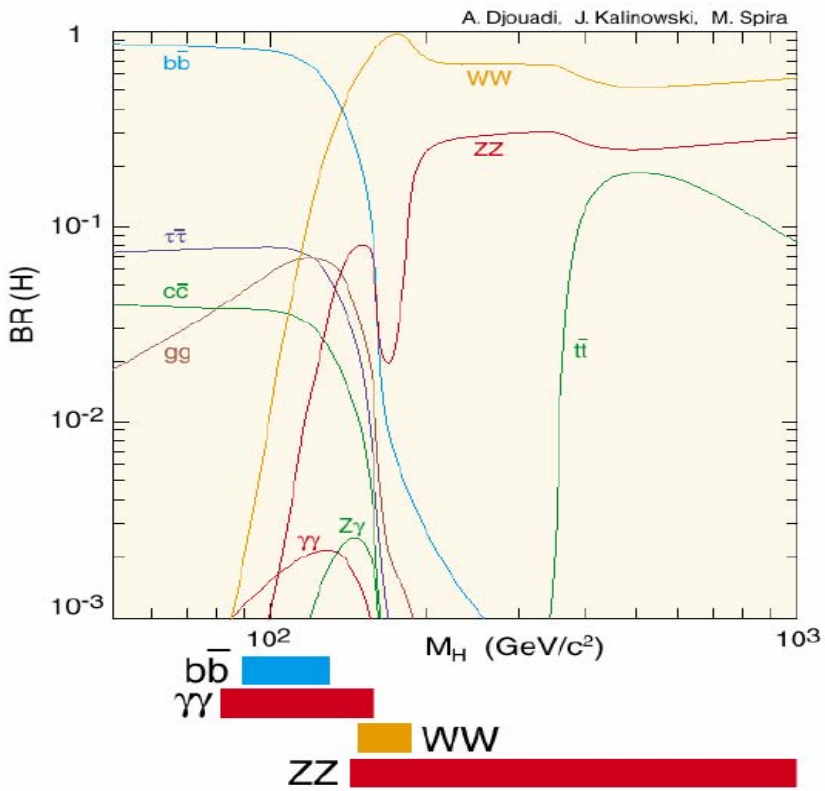
qqH, H -> ZZ -> $ll\nu\nu$,

qqH, H -> ZZ -> lljj

H -> $b\bar{b}$

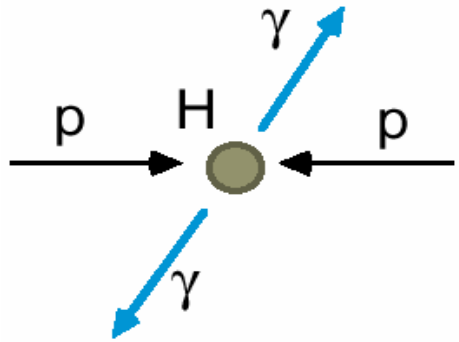
- Background 10^7 larger than signal
- Mass resolution 10-15%

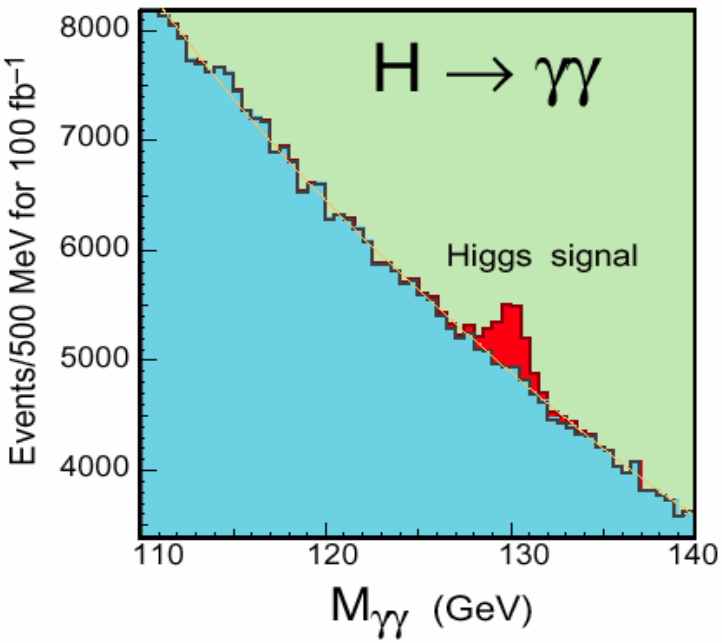
decay modes:

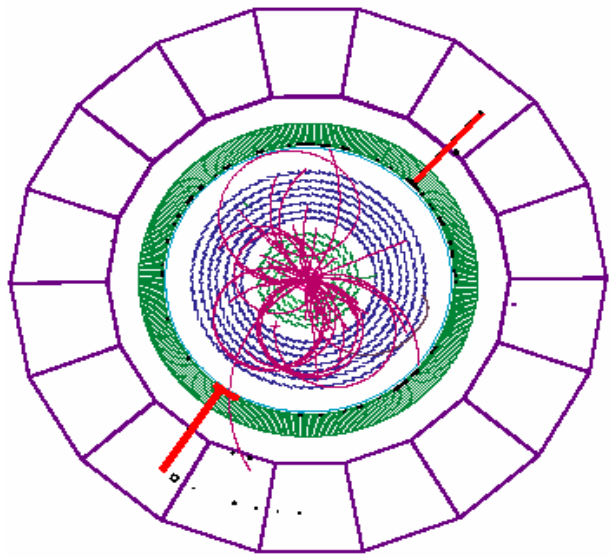


Examples: Low mass Higgs (M_H<140 GeV/c^2)

- $H \rightarrow \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)
  - But with good resolution, one gets a mass peak
  - Motivation for LAr/$PbWO_4$ calorimeters
  - CMS example: at 100 GeV, $\sigma \approx 1$GeV
    - S/B ≈ 1:20

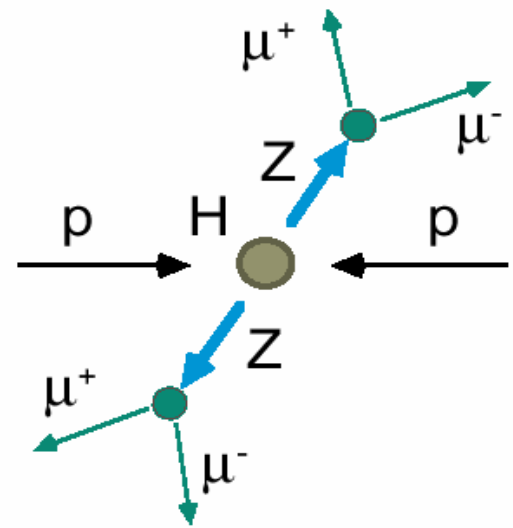


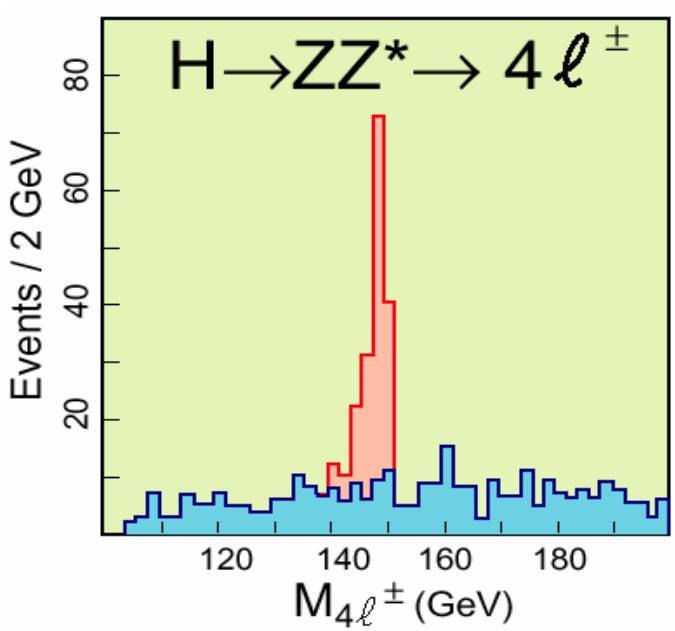


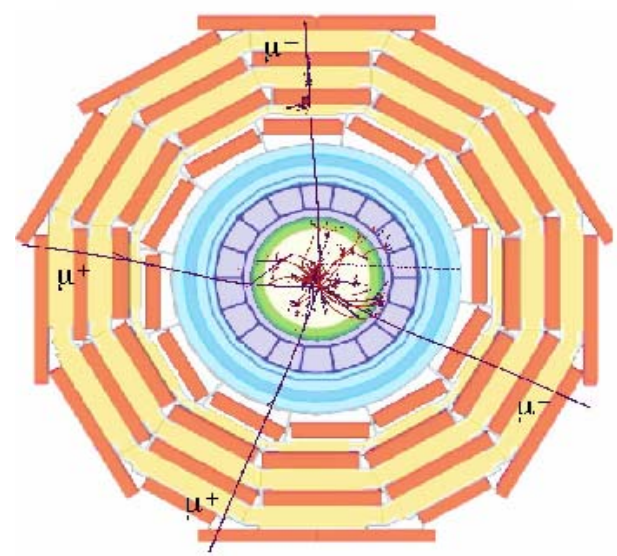


Example: Intermediate mass Higgs: $ZZ^{(*)}$

- $H \rightarrow ZZ \rightarrow \ell^+\ell^- \ell^+\ell^-$ (ℓ =e,μ)
  - Very clean
    - Resolution: around 1 GeV (around 100 GeV mass)
  - Valid for the mass range $130 < M_H < 500$ GeV/c^2

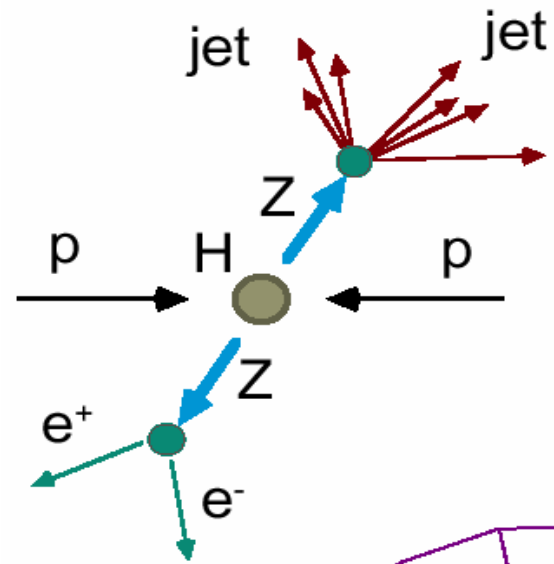


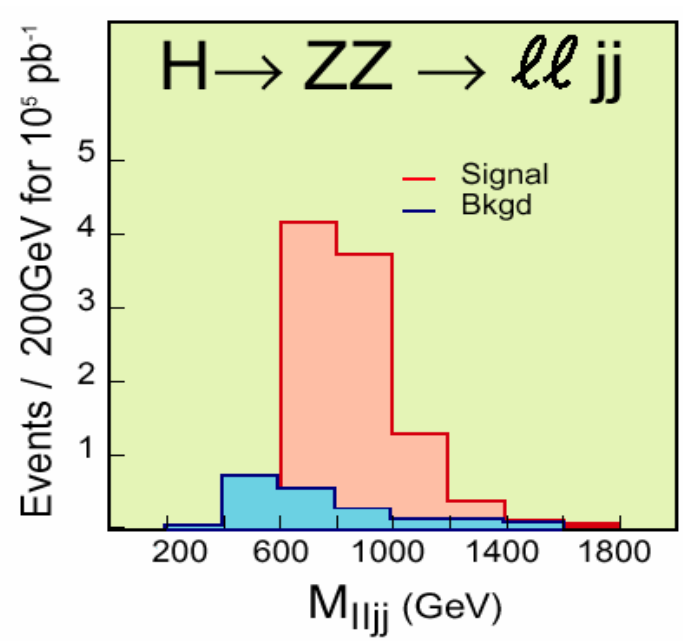


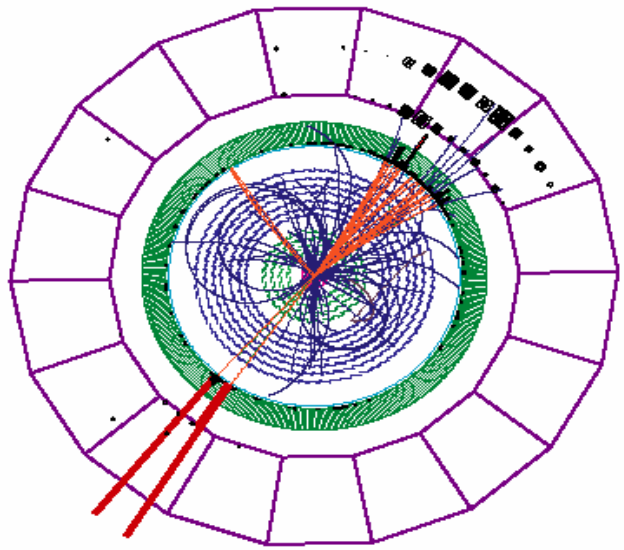


Example: (Very) High mass Higgs

- $H \rightarrow ZZ \rightarrow \ell^+\ell^-$ jet jet
  - Need higher Branching fraction (also $\nu\nu$ for the highest masses ~ 800 GeV/c^2)
  - At the limit of statistics

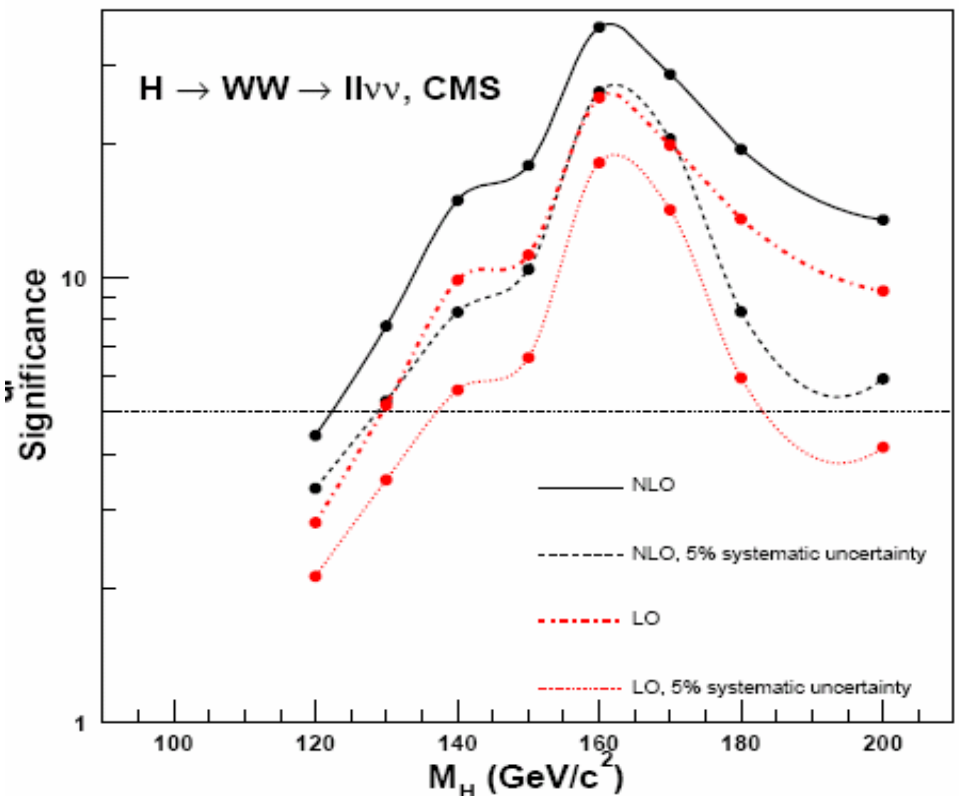




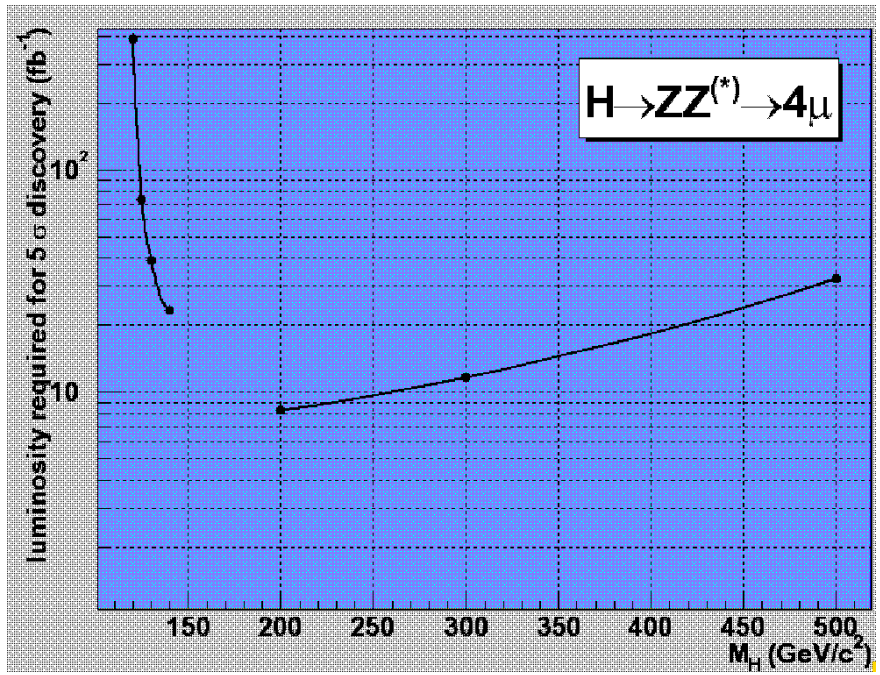


Examples: $H \to WW \to ll\nu\nu$; $H \to ZZ^{(*)} \to 4\mu$

Significance for 30 fb^{-1}



Luminosity needed for 5σ discovery



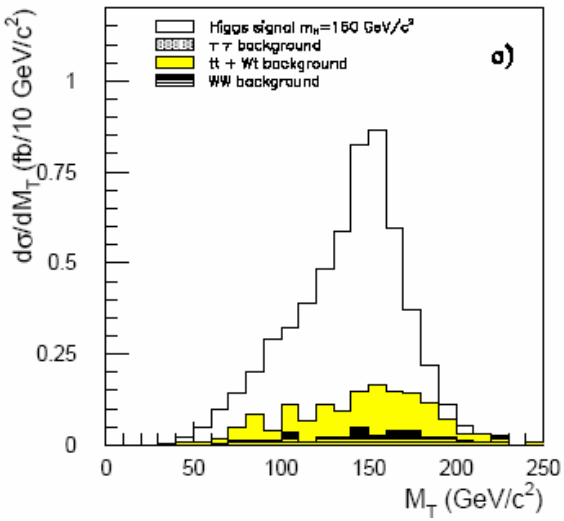
Note: Higher order corrections/systematics important
Low Higgs mass region challenging

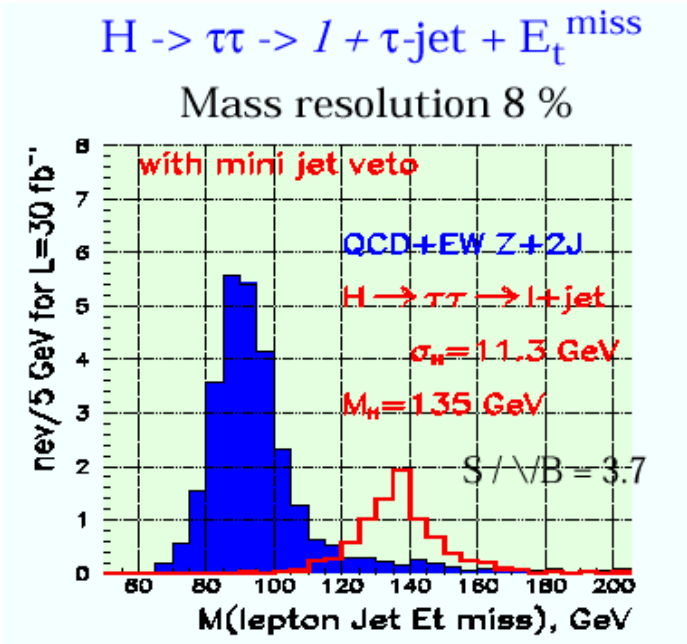
New channels

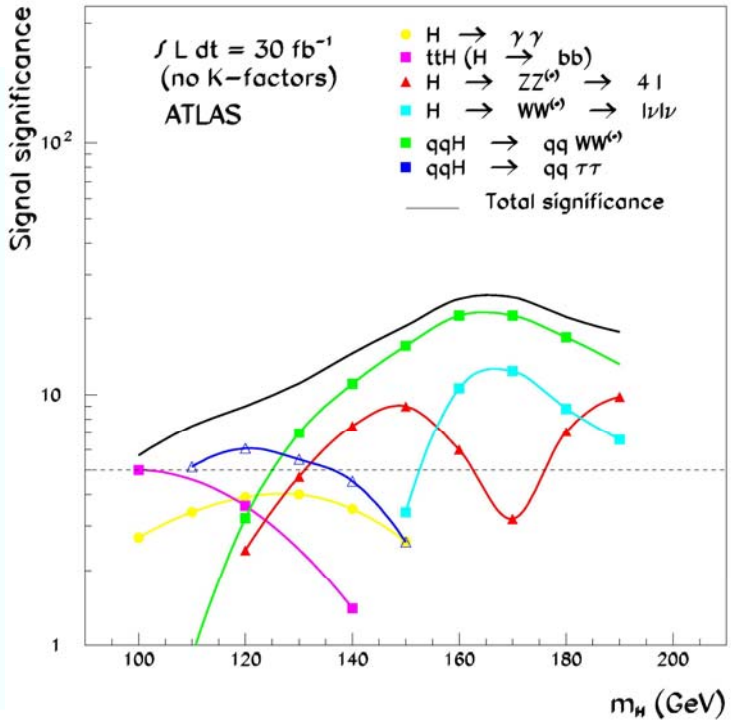
qqH, H -> WW* -> $l\nu l\nu$

qqH, H -> ττ -> l+τ jet, ll

Results

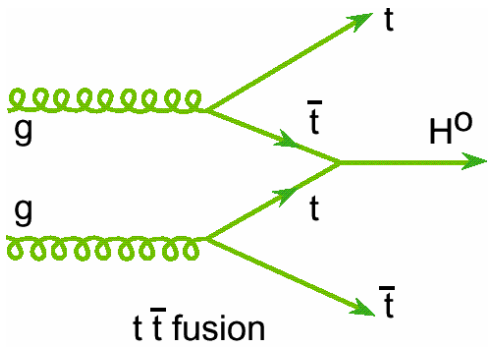


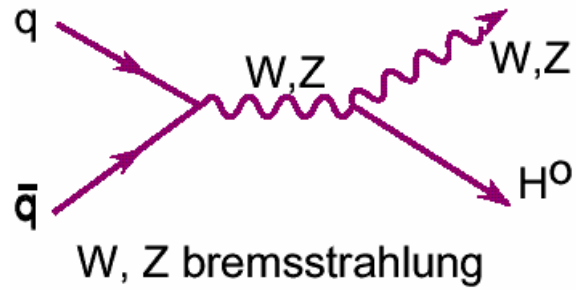


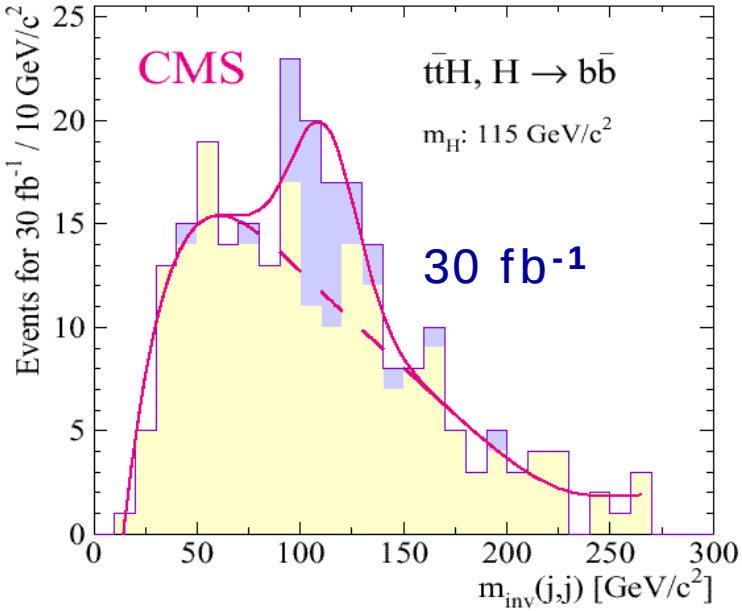


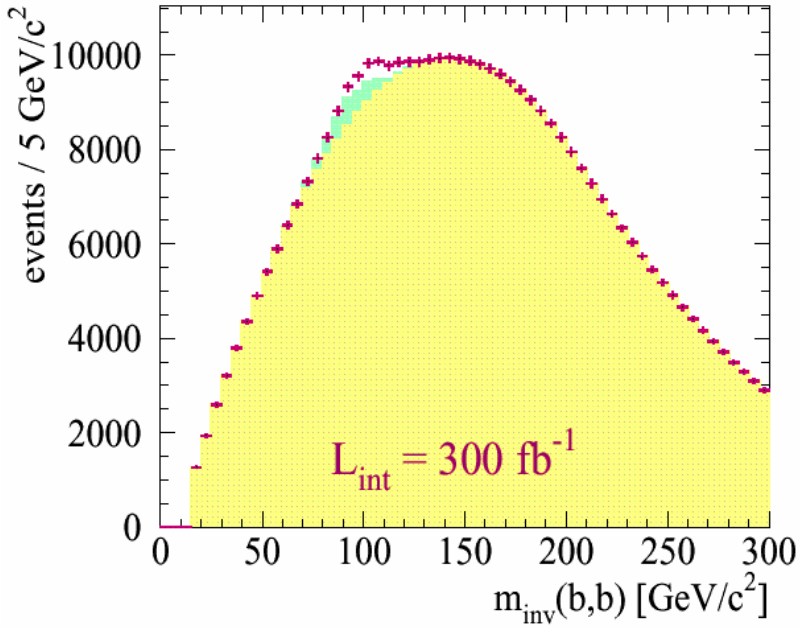
With these new channels each experiment can discover the Higgs with 5σ with 30 fb^{-1}

Other channels (H→bb)



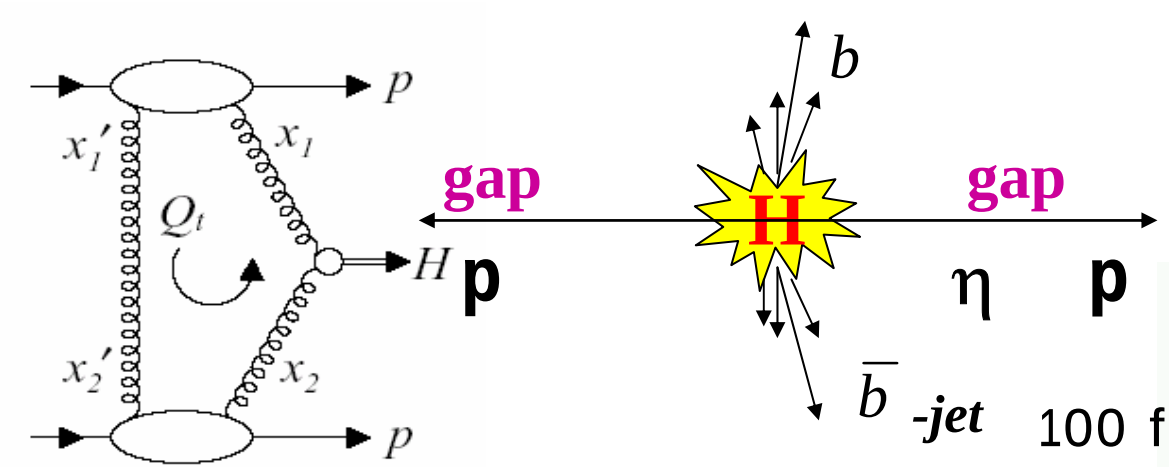




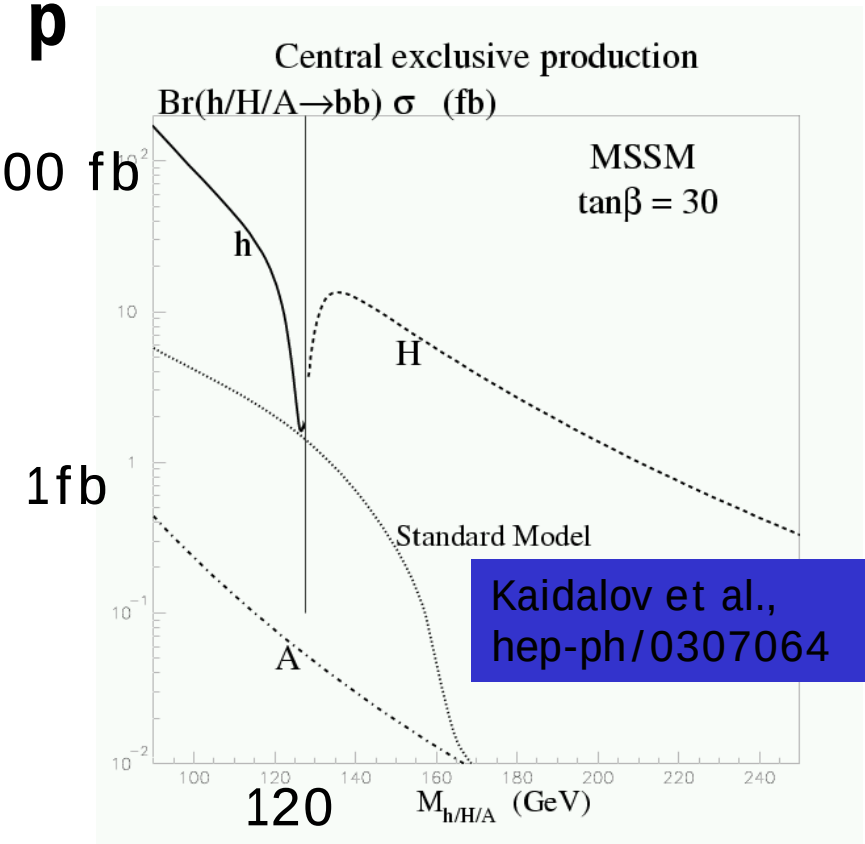


Not discovery channels but can be used to confirm/measure couplings

Diffractive Higgs production



SM Higgs: (30fb^{-1})
11 signal vs 12 bkg events
MSSM: s ~ x10 larger (tanβ)



Kaidalov et al., hep-ph/0307064

Exclusive production:

- J_z=0 suppression of gg→bb bkg
- Higgs mass via missing mass

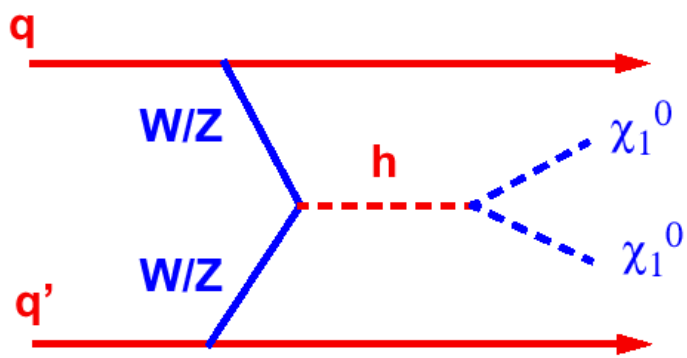
$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

ΔM = O(1.0 - 2.0) GeV

- CP structure of the Higgs from angular distribution of the protons
- Of course, need Roman pots

Invisible Higgs Decays

Non SM Higgs
e..g in SUSY



2 tag. J + miss E_T

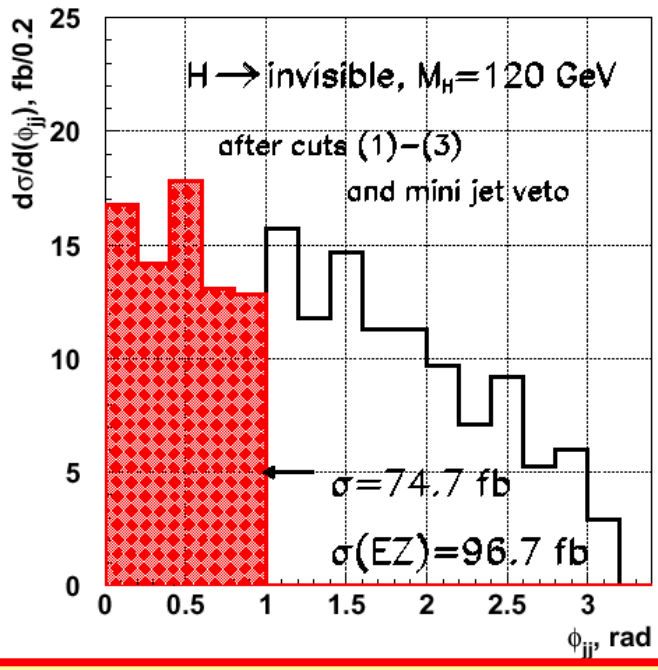
$$\xi^2 = \frac{\sigma(\mathrm{Hjj})}{\sigma(\mathrm{Hjj})_{\mathrm{SM}}} \times \mathrm{Br}(\mathrm{H} \to \mathrm{inv})$$

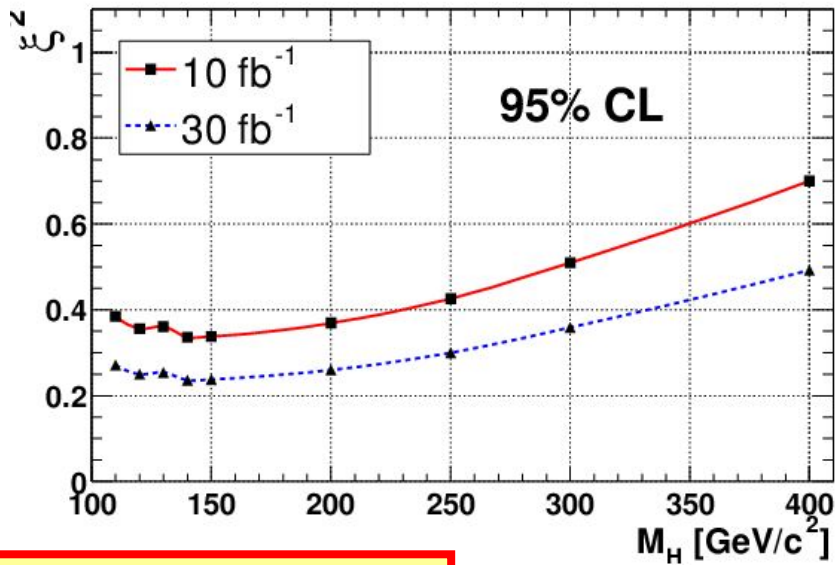
Search region in
$\Delta\phi_{JJ}$ < 1 rad

event counting

background can be predicted from data of Z->2*l* and W->*l* ν with accuracy ~ 3%

set up limit on σ Br(H->inv)

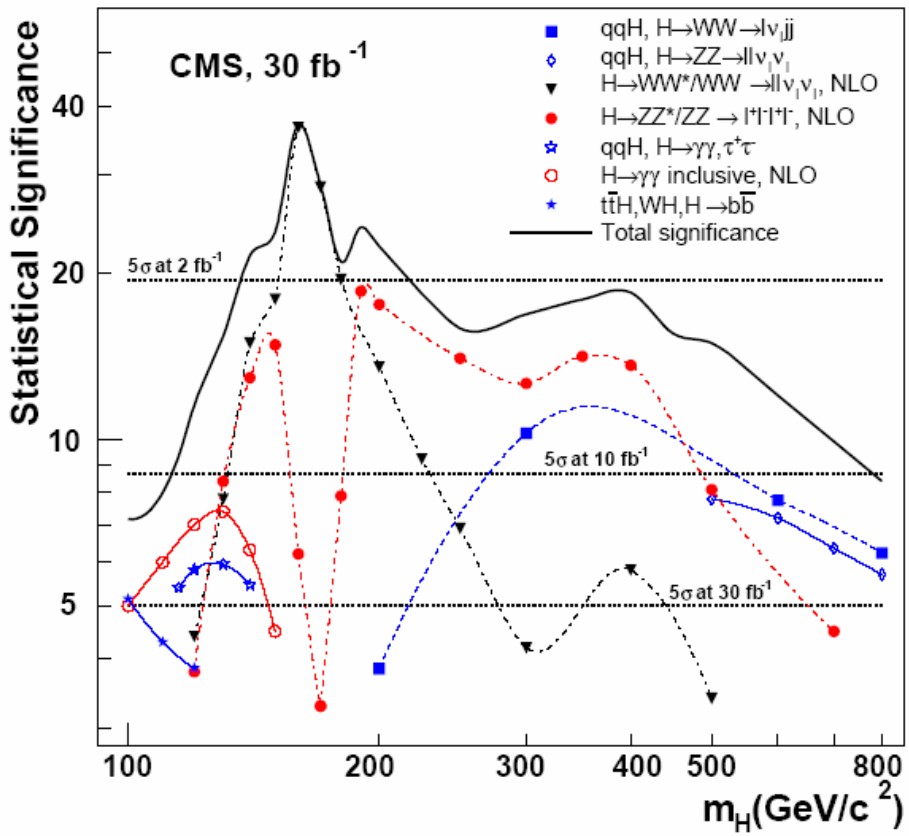




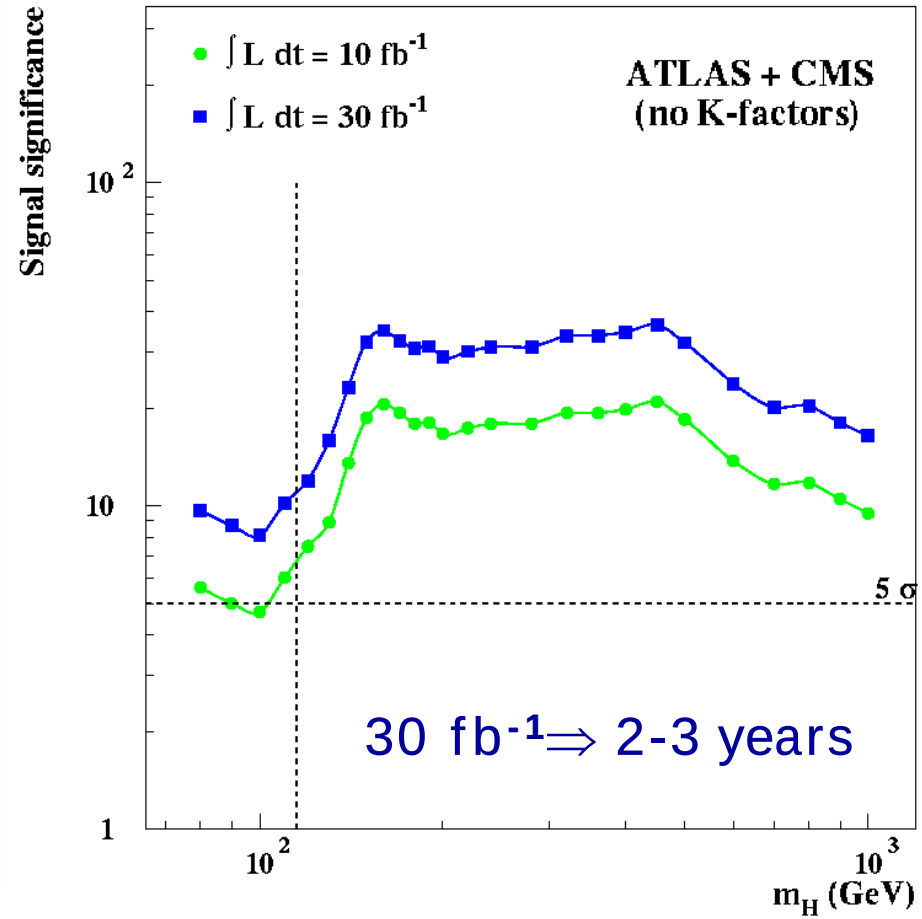
LHC has the potential to see invisible Higgs decays

LHC Reach for a Higgs Discovery

Different channels



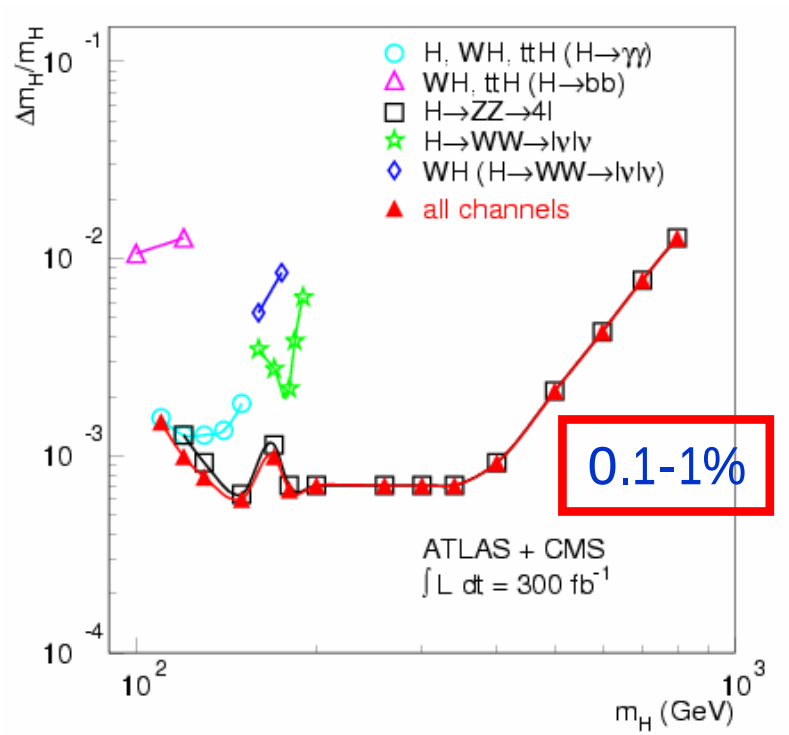
Total sensitivity

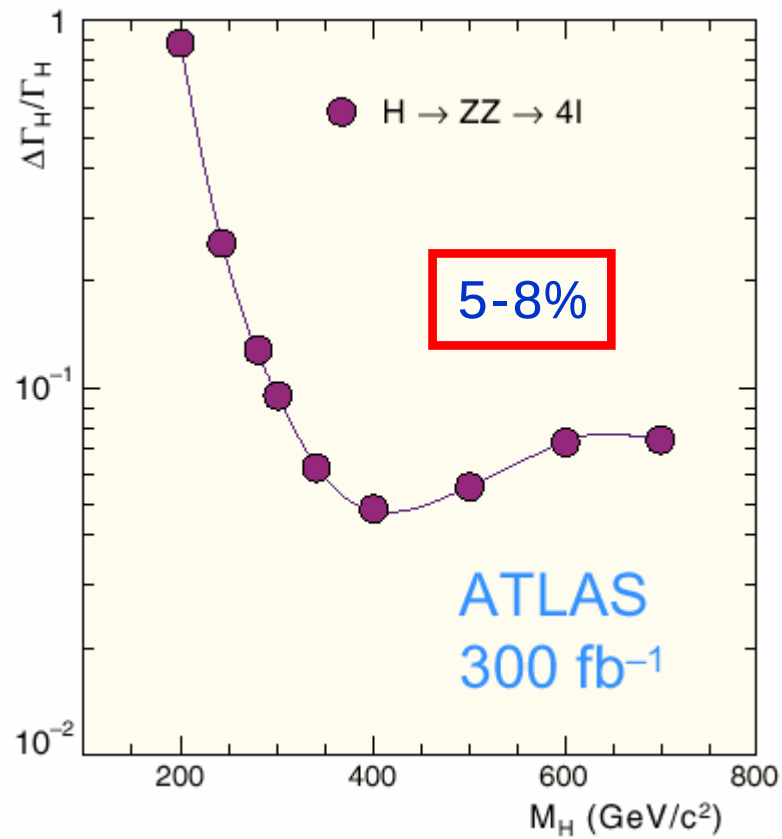


30 fb^{-1}⇒ 2-3 years

LHC can cover the whole region of interest with 10 fb^{-1}

Mass and width resolution





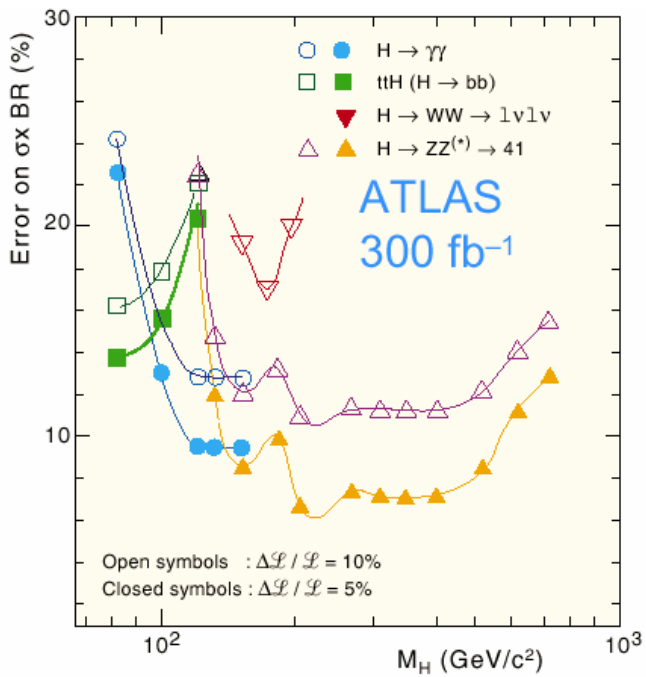
MSSM Higgs	Δm/m (%) 300 fb^{-1}
h, A, H → γγ	0.1–0.4
H → 4 ℓ	0.1–0.4
H/A → μμ	0.1-1.5
h → bb	1–2
H → hh → bb γγ	1-2
A → Zh → bb ℓℓ	1–2
H/A → ττ	1-10

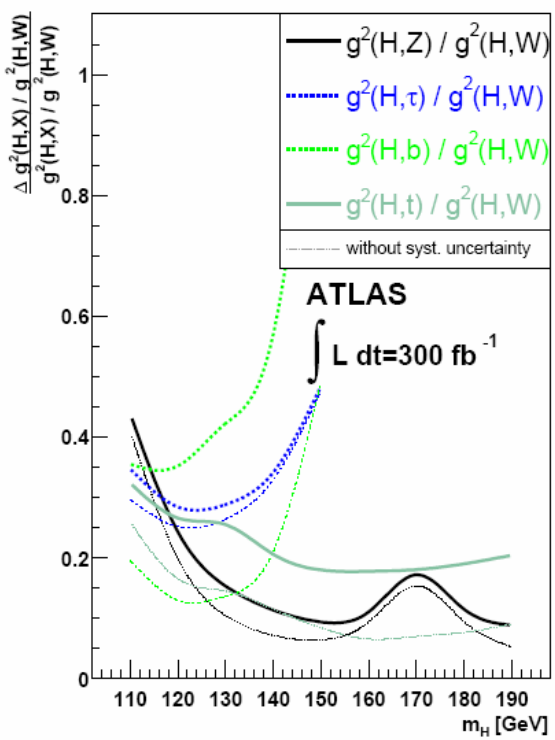
Analysis of indirect widths for mass range below 200 GeV:
10-20% precision

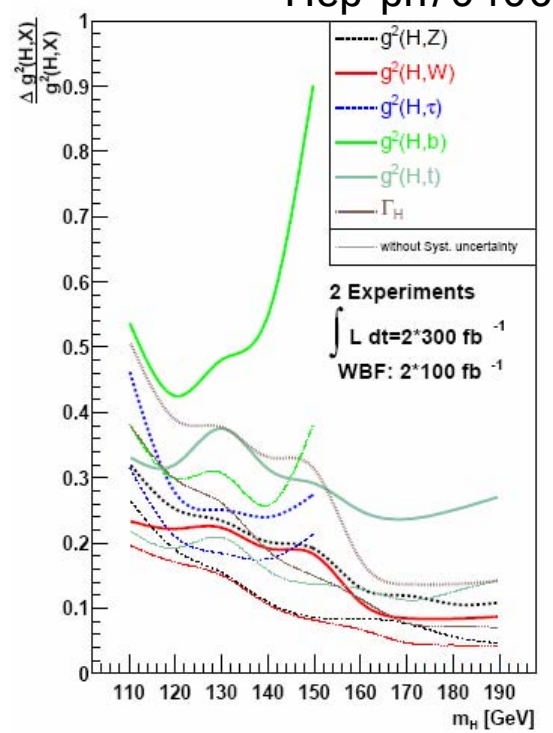
Branching Ratios and Couplings

Precision on σ•BR → Ratios of couplings → With "mild" theoretical assumptions→ couplings

Hep-ph/0406323





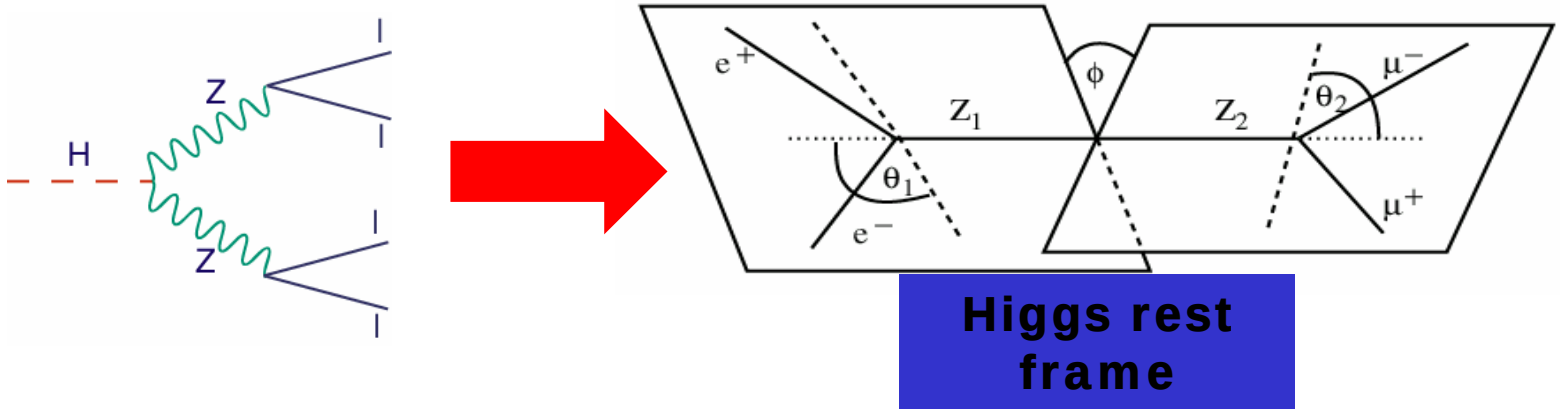


Dominated by luminosity uncertainty

Precision 10-40%

Precision 10-40(20)%
Assume $g(H,Z) \leq g(H,Z)_{SM}$
Also measurement of Γ_H

Spin and CP-quantum numbers: H → ZZ→4l

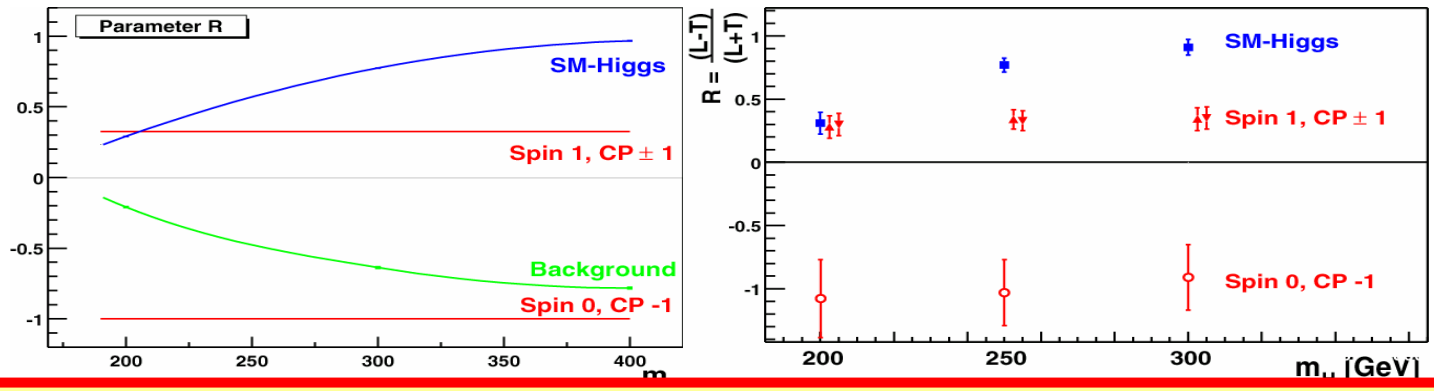


$$F(\phi) = 1 + \alpha \cos\phi + \beta \cos 2\phi$$

$$G(\theta) = L \sin^2\theta + T\left(1 + \cos^2\theta\right)$$

$$R = \frac{L - T}{L + T}$$

ATLAS
100 fb^{-1}

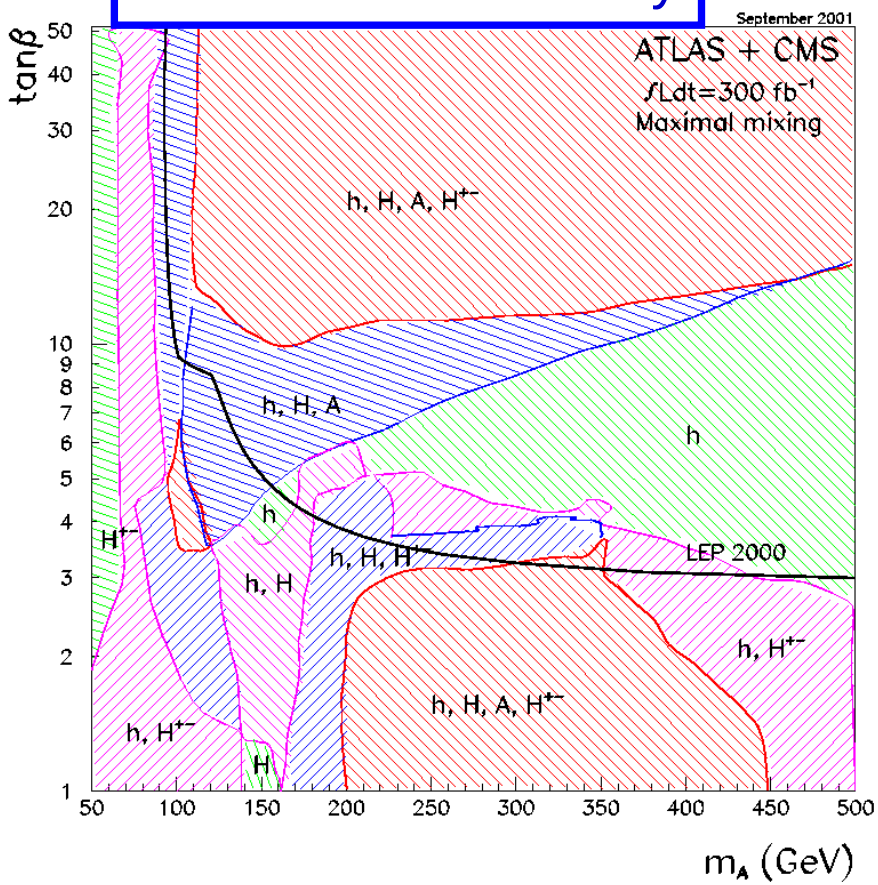


- MH>250 GeV: distinguish between S=0,1 and CP even.odd
- MH<250 GeV: only see difference between SM-Higgs and S=0, CP=-1
- α,β less powerful

Heavy MSSM Higgs search

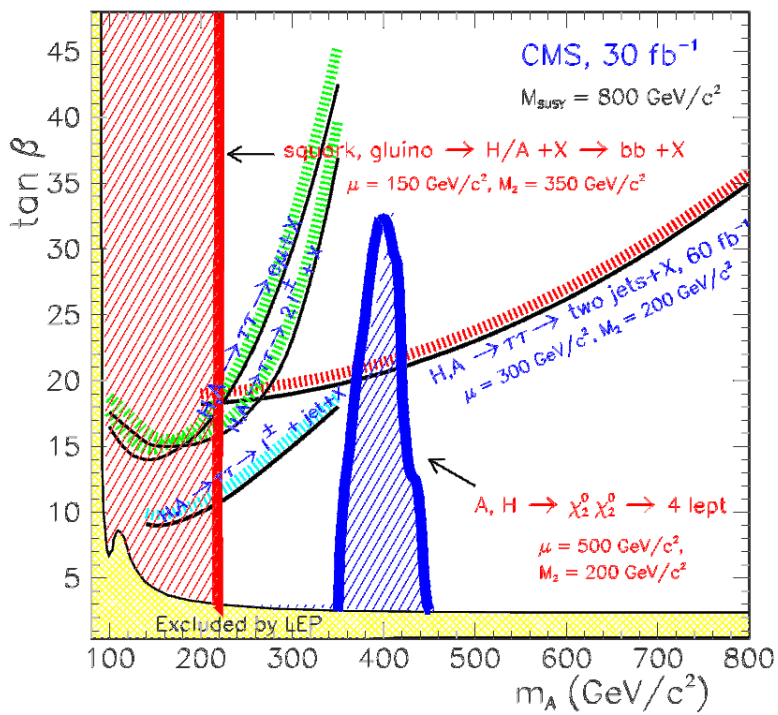
- $A/H \to \tau\tau$
- $A/H \to \mu\mu$
- $A/H \to bb$ in bb H/A (New studies)
- $H^{\pm} \to \tau\nu$
- $H^{\pm} \to tb$

Plot for 5 σ discovery



NEW: at low tan β, we may expl
the sparticle decay modes:

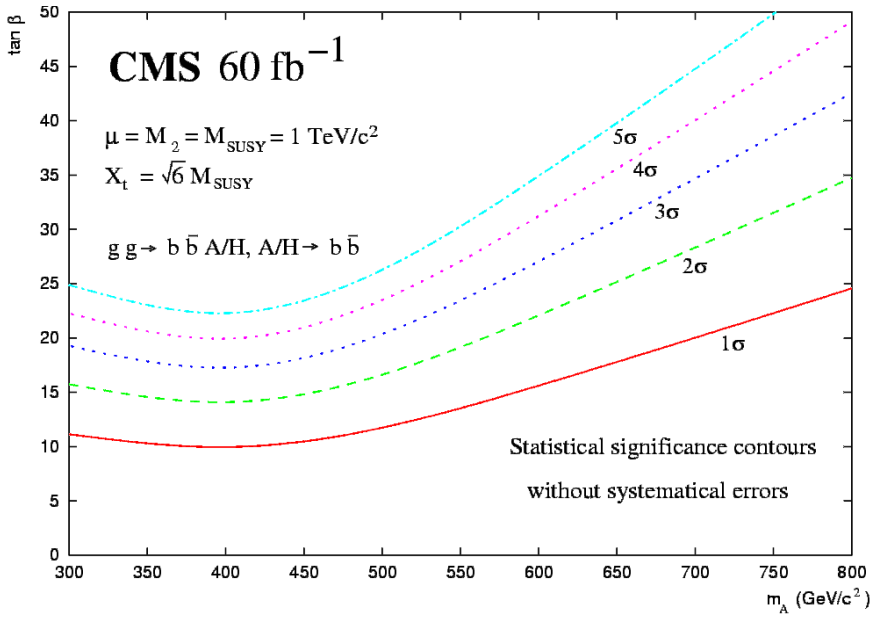
- A, H $\to \chi_2^0 \chi_2^0 \to 4l + E_T^{miss}$
- A, H in cascade decays of sparticles



Expected tanβ accuracy 5-25% (300 fb^{-1})

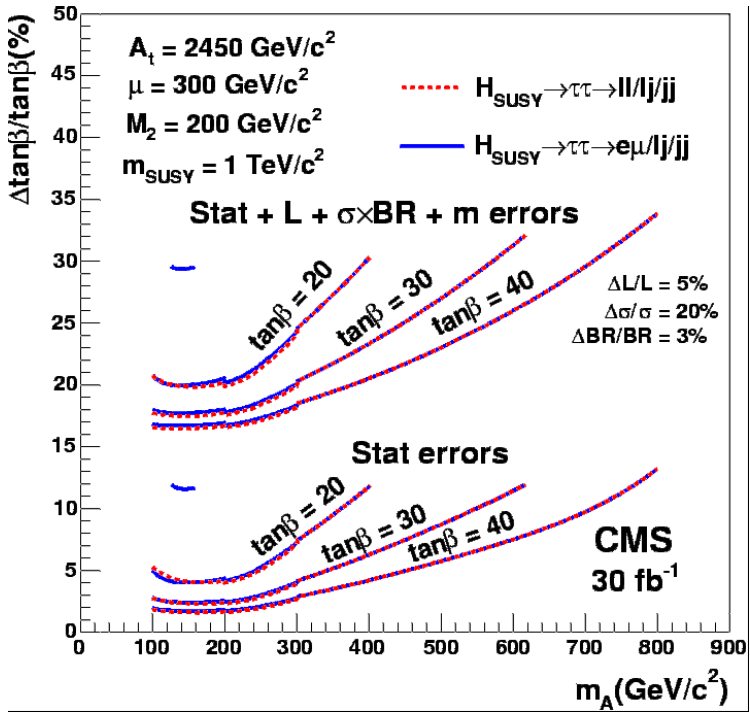
New: MSSM Higgs Studies

Observability of the channel gg→bb A/H with A/H→bb



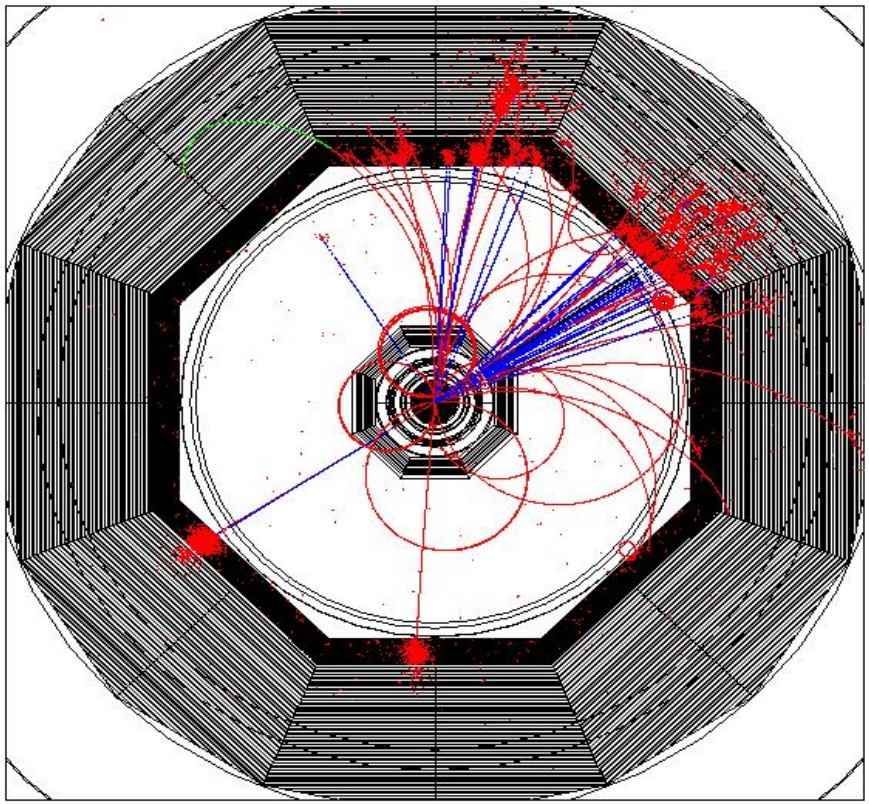
Difficult, but can be used as a confirmation channel

Extracting tanβ from measurement of gg→bb h/A/H with h/A/H→ττ



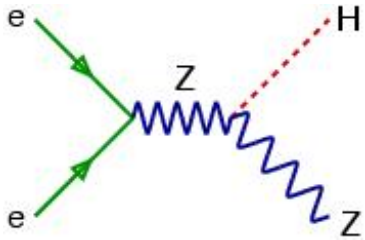
Precision dominated by the theoretical uncertainties!

Higgs studies at a e+e- linear Collider

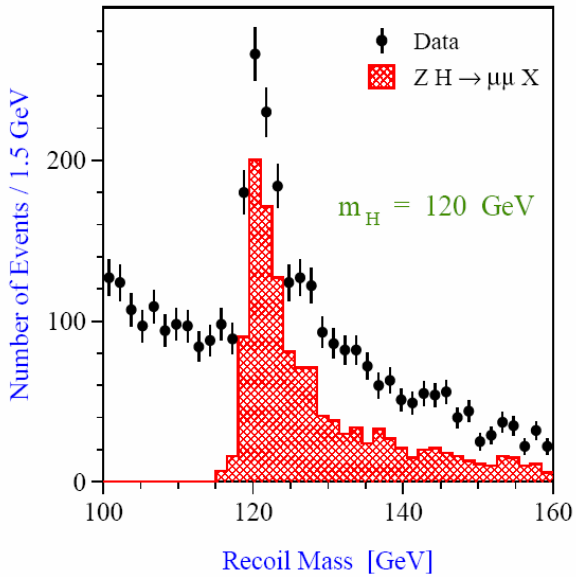


Fully simulated+reconstructed HZ event
Very clean compared to events at LHC

Precision measurements!



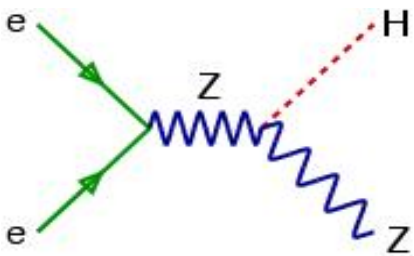
Can detect the Higgs via the recoil to the Z

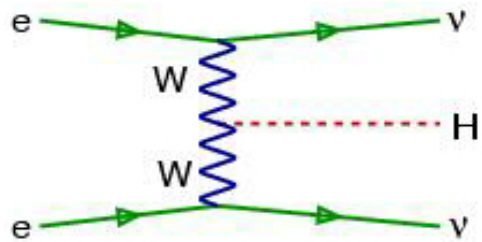


Observation of the Higgs independent of decay modes
Mass determination ~ 50 MeV

Higgs Production at a e+e- linear Collider

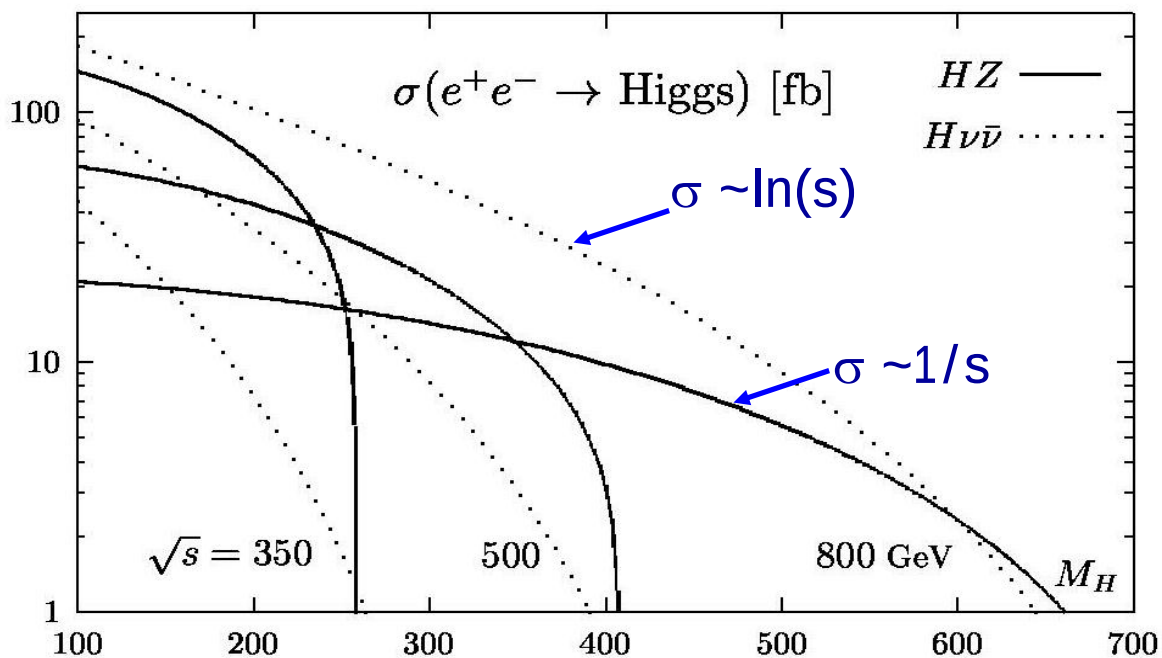
Dominant production processes at LC:





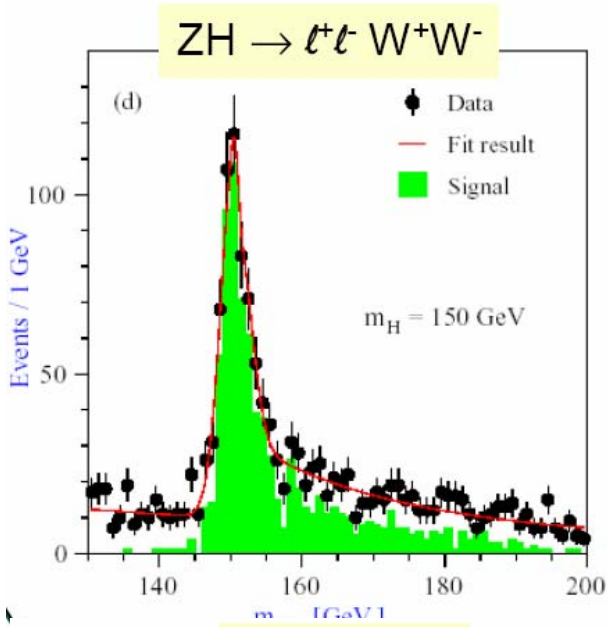
ZH Hνν

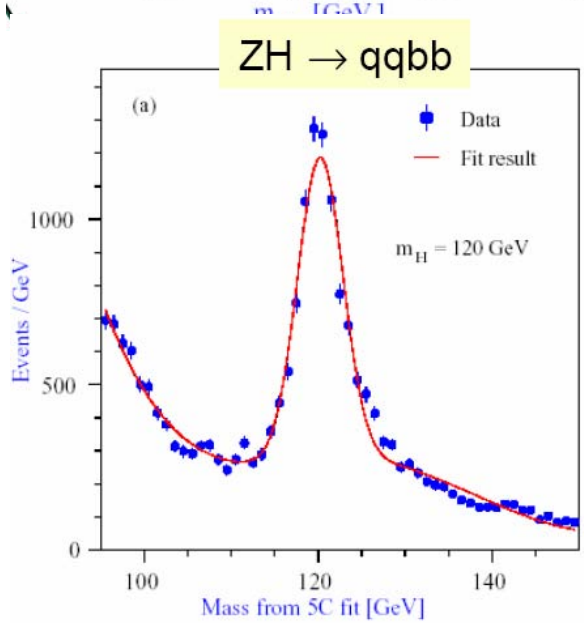
Luminosity	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
√s (GeV)/ m_H (GeV)	350	500	800
120	74k / 15.5k	35k / 37.5k	27k / 158k
160	52k / 7.5k	29k / 25k	24k / 126k
250	5.5k / 6.5k	16.5k / 8k	19k / 71k



Example: √s=350 GeV
m_H = 120 GeV
L= 500 fb^{-1} (~2 years)
~90 K Higgs events produced

Higgs Mass Measurement





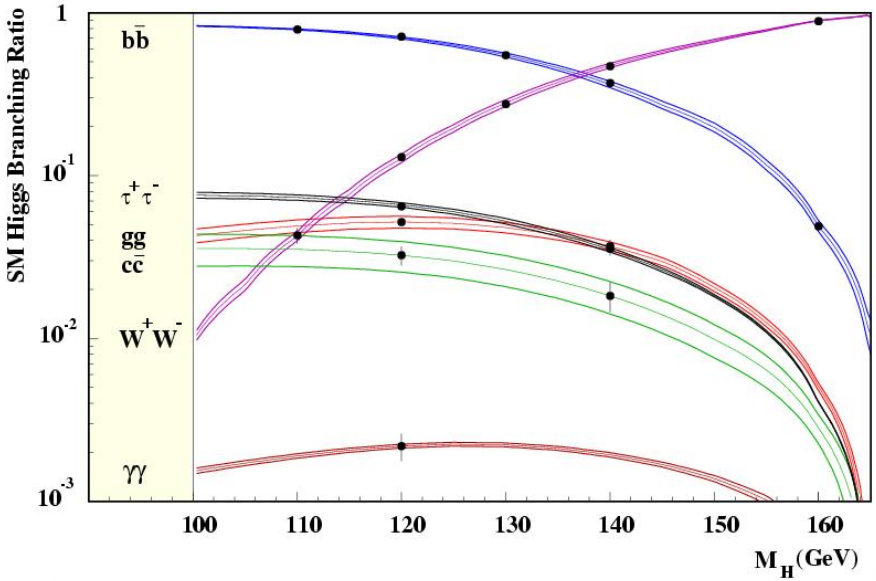
	δM_h in MeV		
Decay mode	TESLA $\delta E/E=0$	TESLA $\delta E/E=0.1\%$	NLC $\delta E/E=0.3\%$
recoil mass	110	117	143
$ZH \to l^+l^- q\bar{q}$	70	72	76
$ZH \to q\bar{q}b\bar{b}$	45	46	48
Combined	38	39	40

Several methods
Includes anticipated beam energy smearing

Determine the Higgs mass to better than 50 MeV

How much can theory handle/does theory want?

Higgs Branching Ratios



TDR 2001

- Model independent
- Absolute branching ratios!
- Precise measurements: few to 10%..
- Special options to improve further

e.g. $\Delta BR(H\rightarrow\gamma\gamma) \sim 2\%$ at photon collider

Table 1: Summary of expected precisions on Higgs boson branching ratios from existing studies within the ECFA/DESY workshops. (a) for 500 fb^{-1} at 350 GeV; (b) for 500 fb^{-1} at 500 GeV; (c) for 1 ab^{-1} at 500 GeV; (d) for 1 ab^{-1} at 800 GeV; (e) as for (a), but method described in [35] (see text).

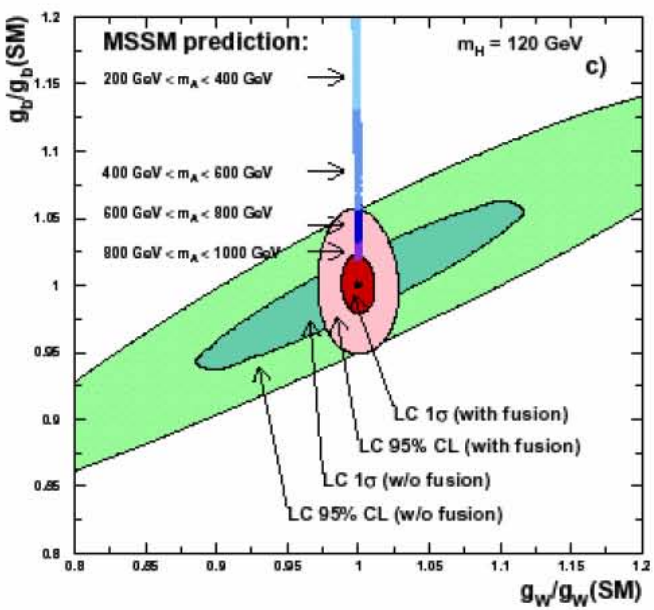
Updates since TDR

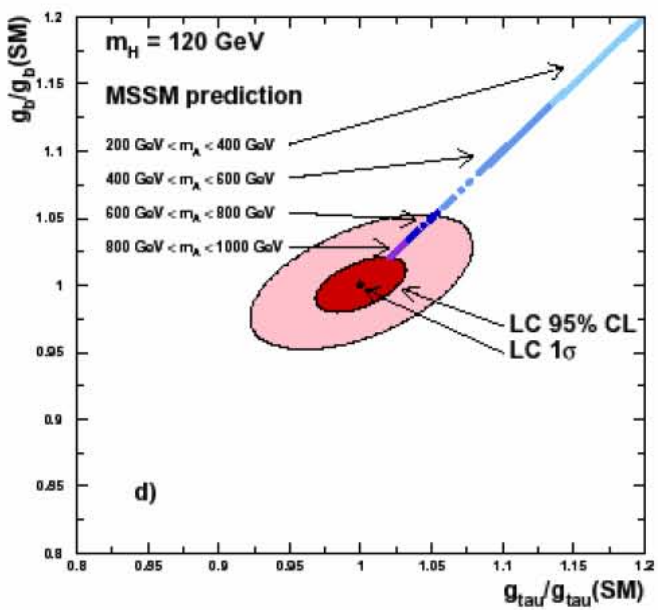
Mass(GeV)	120	140	160	180	200	220	240	280	320
Decay	Relative Precision (%)								
$b\bar{b}$	2.4 (a) / 1.9 (e)	2.6 (a)	6.5 (a)	12.0 (d)	17.0 (d)	28.0 (d)			
$c\bar{c}$	8.3 (a) / 8.1 (e)	19.0 (a)							
$\tau\tau$	5.0 (a) / 7.1 (e)	8.0 (a)							
$\mu\mu$	30. (d)								
gg	5.5 (a) /4.8 (e)	14.0 (a)							
WW	5.1 (a) / 3.6 (e)	2.5 (a)	2.1 (a)		3.5 (b)		5.0 (b)	7.7 (b)	8.6 (b)
ZZ			16.9 (a)		9.9 (b)		10.8 (b)	16.2 (b)	17.3 (b)
$\gamma\gamma$	23.0 (b) / 35.0 (e)								
$Z\gamma$		27.0 (c)							

Extraction of Higgs couplings

- Use measured branching ratios to extract Higgs couplings to fermions and bosons
- Global fit to all observables & take into account correlations

- The precise determination of the effective couplings opens a window of the sensitivity to the nature of the Higgs Boson





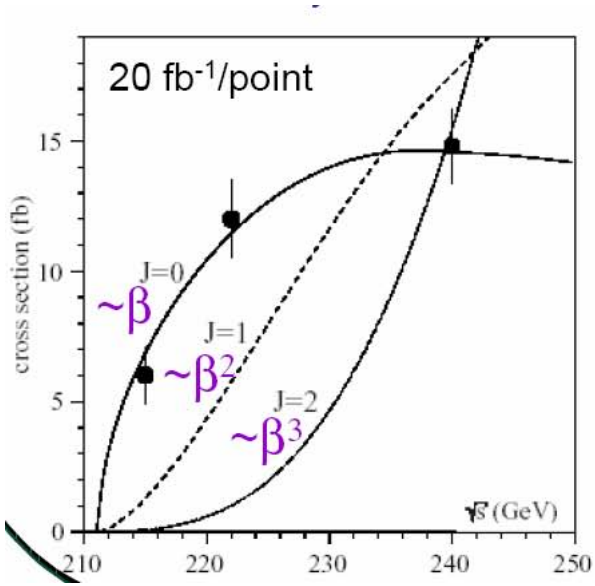
Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
g_{HWW}	$\pm\ 0.012$	$\pm\ 0.020$
g_{HZZ}	$\pm\ 0.012$	$\pm\ 0.013$
g_{Htt}	$\pm\ 0.030$	$\pm\ 0.061$
g_{Hbb}	$\pm\ 0.022$	$\pm\ 0.022$
g_{Hcc}	$\pm\ 0.037$	$\pm\ 0.102$
$g_{H\tau\tau}$	$\pm\ 0.033$	$\pm\ 0.048$
g_{HWW}/g_{HZZ}	$\pm\ 0.017$	$\pm\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

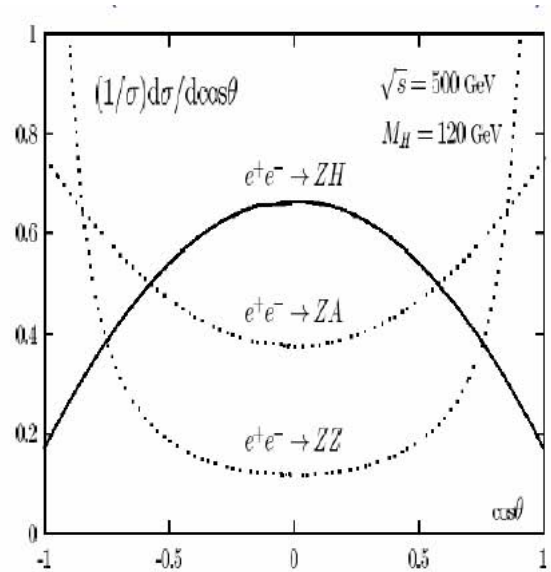
Spin and CP quantum numbers

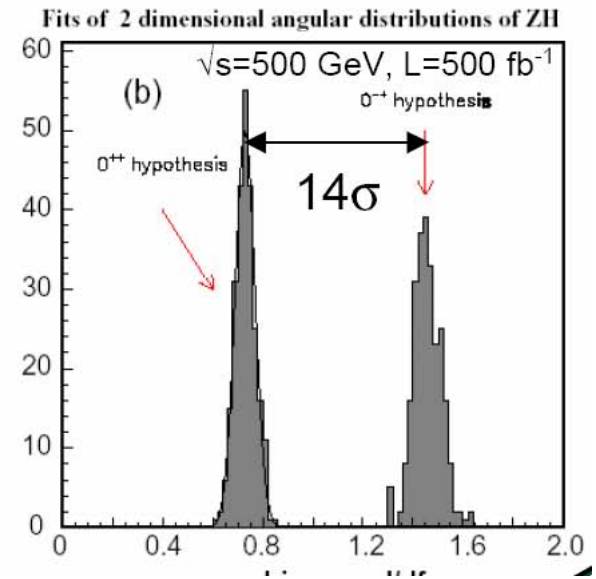
- At threshold: determine J from the β dependence of σ_{ZH}
- At continuum: use angular distributions to determine CP composition

CP-even Interference CP-odd

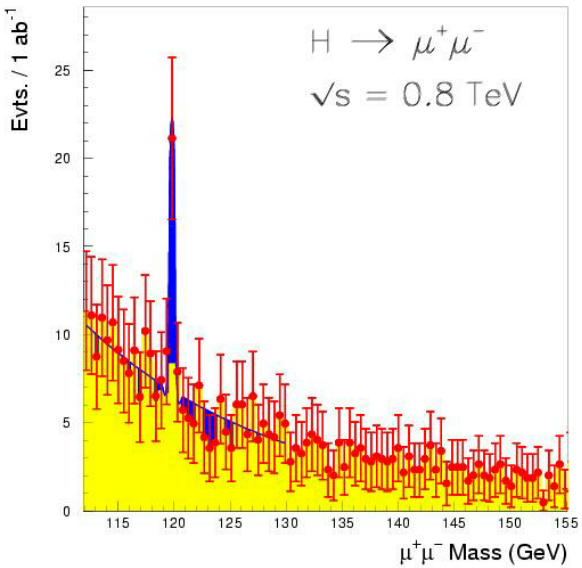
$$\frac{d\sigma}{d\cos\theta_Z} \propto 1+\frac{p_Z^2}{m_Z^2}\sin^2\theta_Z - 4\,\mathrm{Im}\left[\frac{\tilde{b}}{a}\right]\frac{v_e a_e}{v_e^2+a_e^2}\frac{p_Z\sqrt{s}}{m_Z^2}\cos\theta_Z + \left|\frac{\tilde{b}}{a}\right|^2\frac{p_Z^2 s}{2m_Z^4}(1+\cos^2\theta_Z)$$





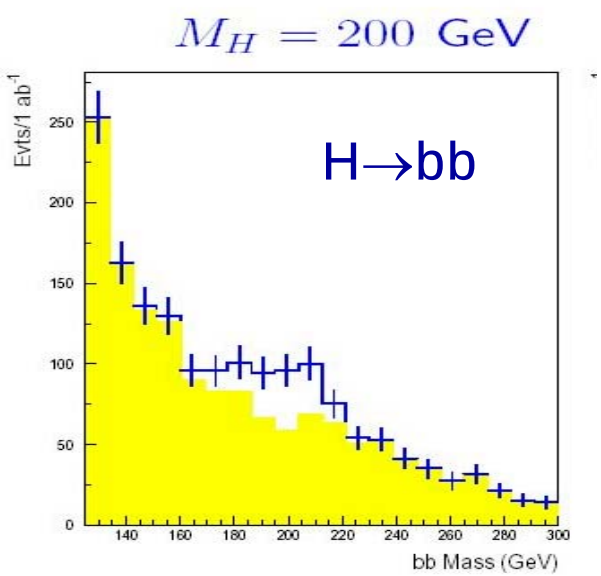


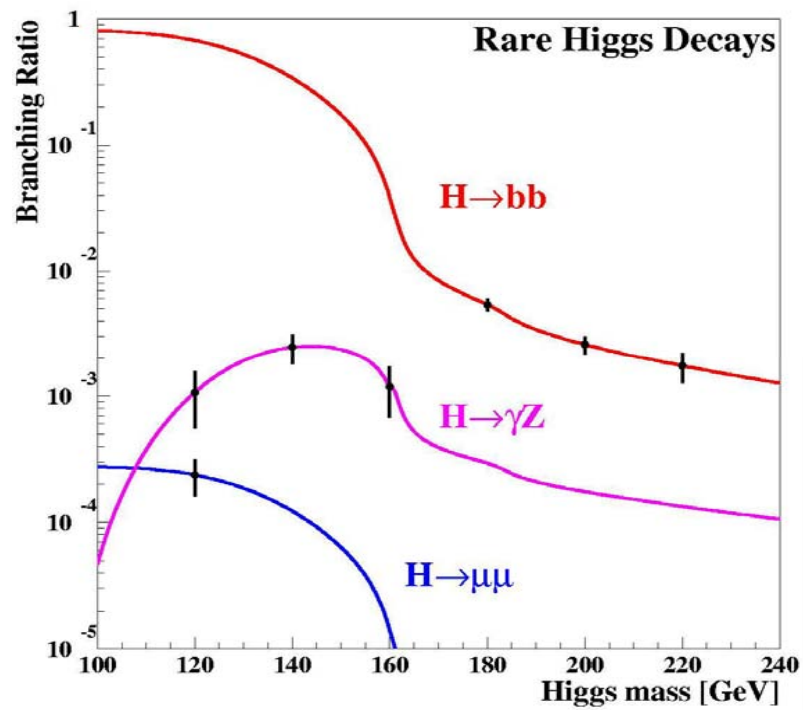
Rare Higgs decay modes



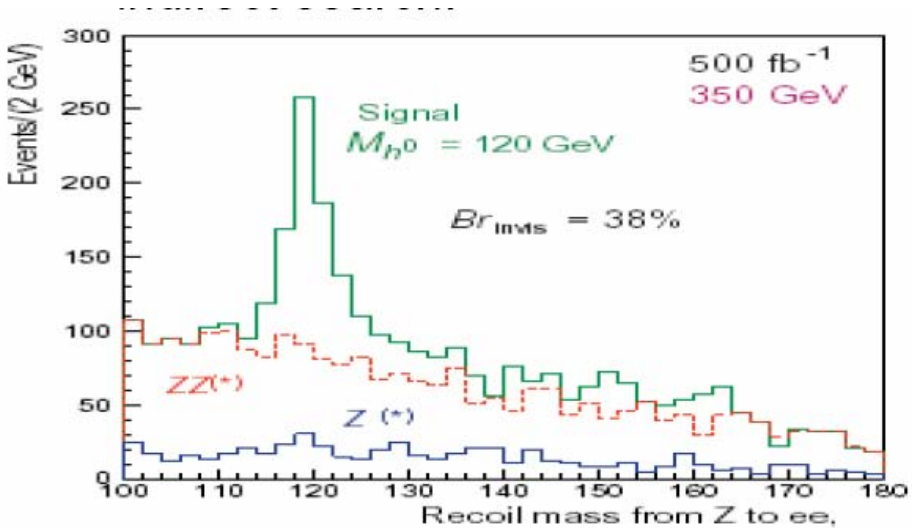
Rare Higgs decay modes become accessible eg

- H→bb at higher masses
- H→μμ
- H→γZ



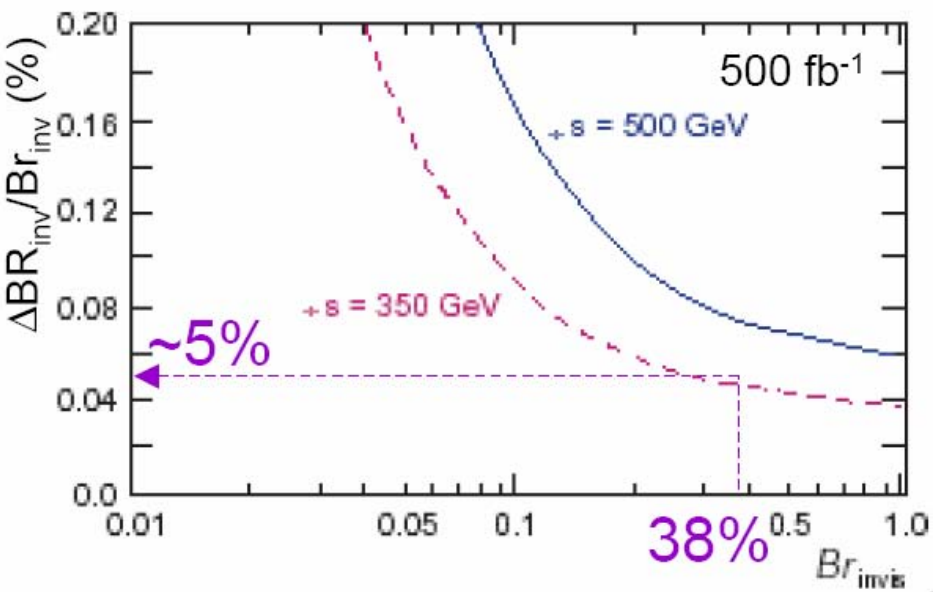


Invisible Higgs Decays



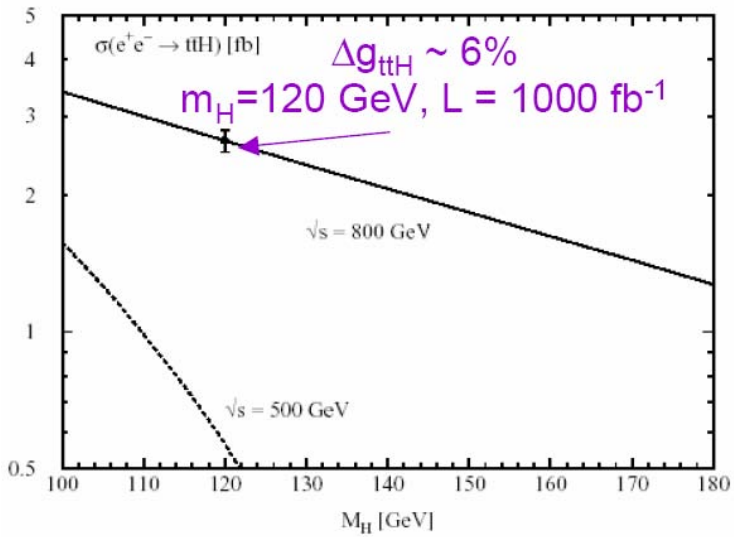
Invisible Higgs decays can be detected directly in ZH events

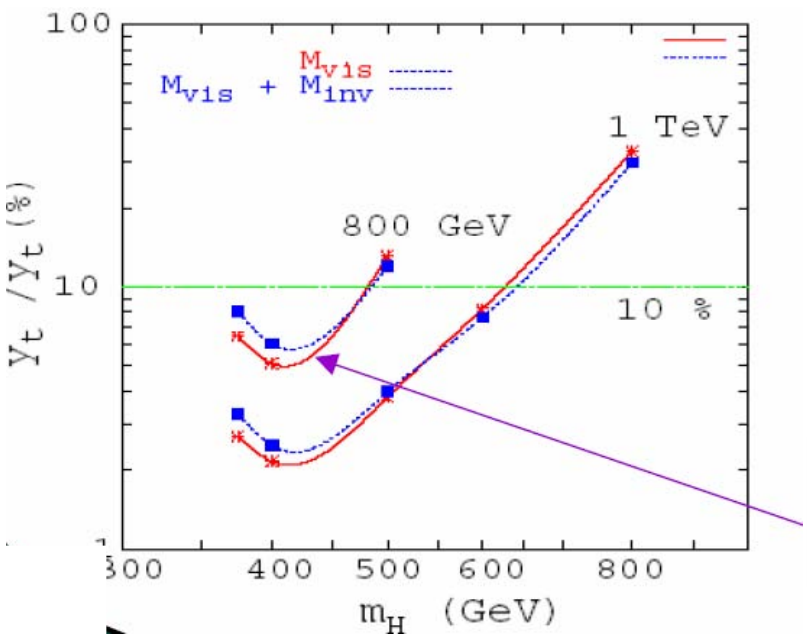
⇒ Observe a peak in the recoil mass of ZH events



Branching ratio can be determined with good precision:
Better than 5% for large enough Branching ratios

Top-Higgs Yukawa coupling





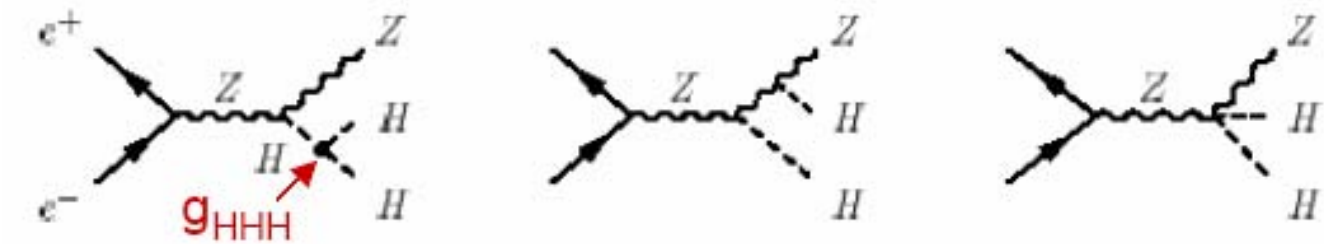
- The top-Higgs Yukawa coupling is very large (g_{ttH} ~ 0.7 while g_{bbH} ~ 0.02). Precise measurements important since could could show largest deviations to new physics
- Needs 0.8-1.0 TeV collider and large luminosity

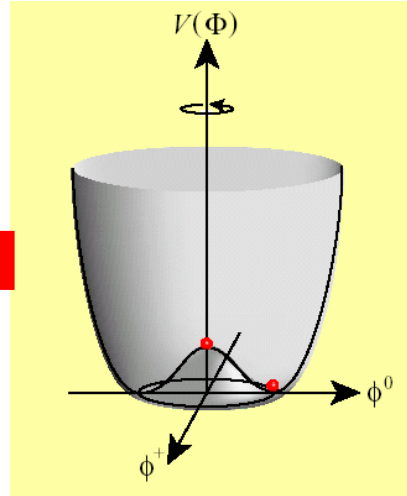
- If $m_H < 2m_t$ ⇒ e+e- → ttH
- If $m_H > 2m_t$ ⇒ measure BR(H→tt)

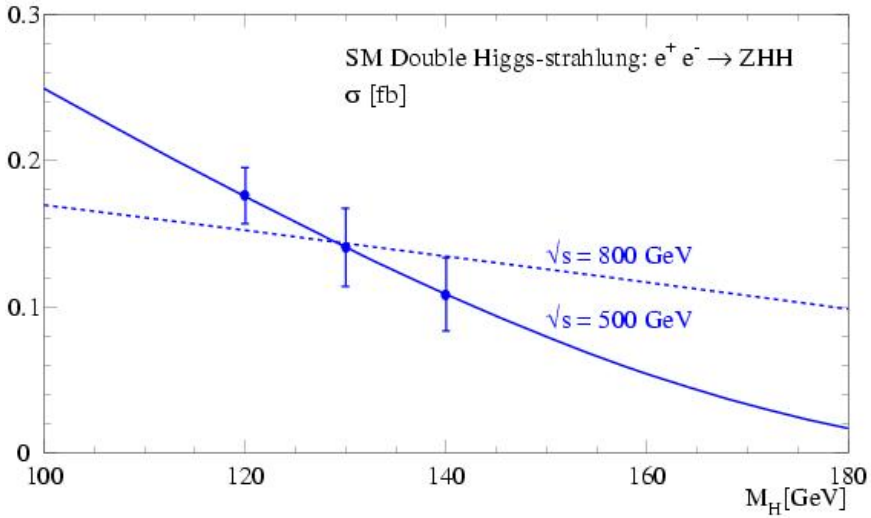
Δg_{ttH} ~ 5% (12%)
m_H=400 (500) GeV, L = 1000 fb^{-1}

Measuring the Higgs Potential

⇒ Measure the Higgs self-coupling: HH production

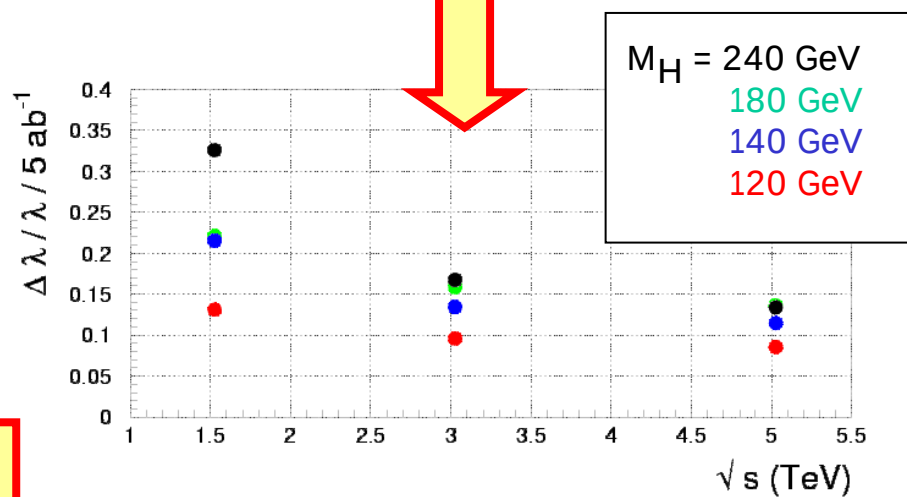






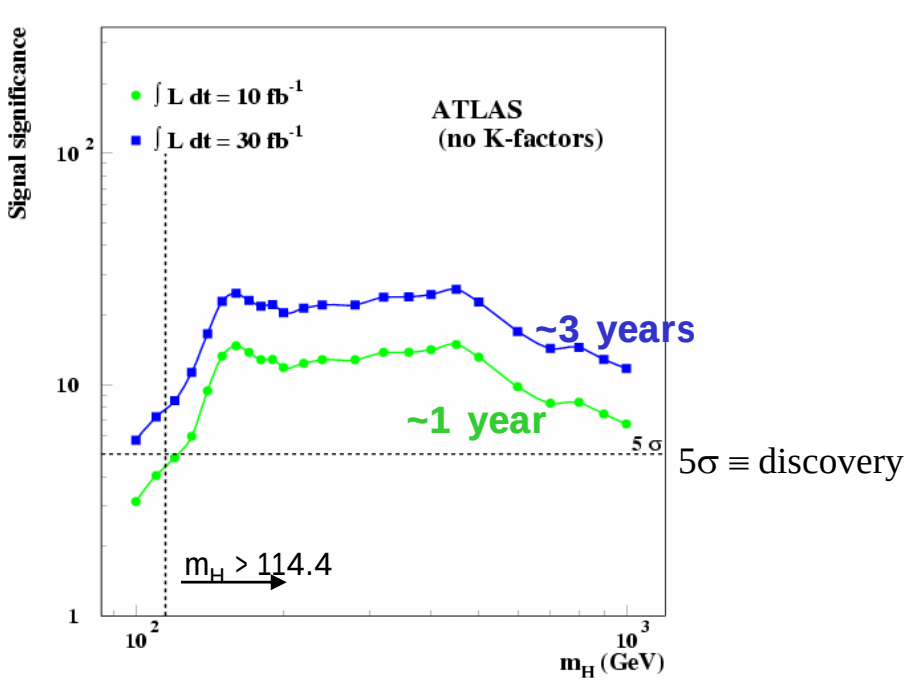
m_H (GeV)	120	130	140
N_{ZHH}	186	149	115
$\Delta g_{HHH}/g_{HHH}$	~23%	~25%	~29%

⇒Larger precision at higher energies
Eg CLIC: a 3 to 5 TeV LC



LHC: g_{HHH} (3000 fb^{-1}) for $150<M_H<200$ GeV

Summary: Higgs at the LHC and LC



- Higgs can be discovered over full allowed mass range in 1 year of (good) LHC operation

  → final word about SM Higgs mechanism
- However: it will take time to understand and calibrate ATLAS and CMS
- If Higgs found, mass can be measured to 0.1% up to mH~ 500 GeV
- A LC will provide precision measurements on absolute couplings, quantum numbers, the Higgs potential → tests at the quantum level