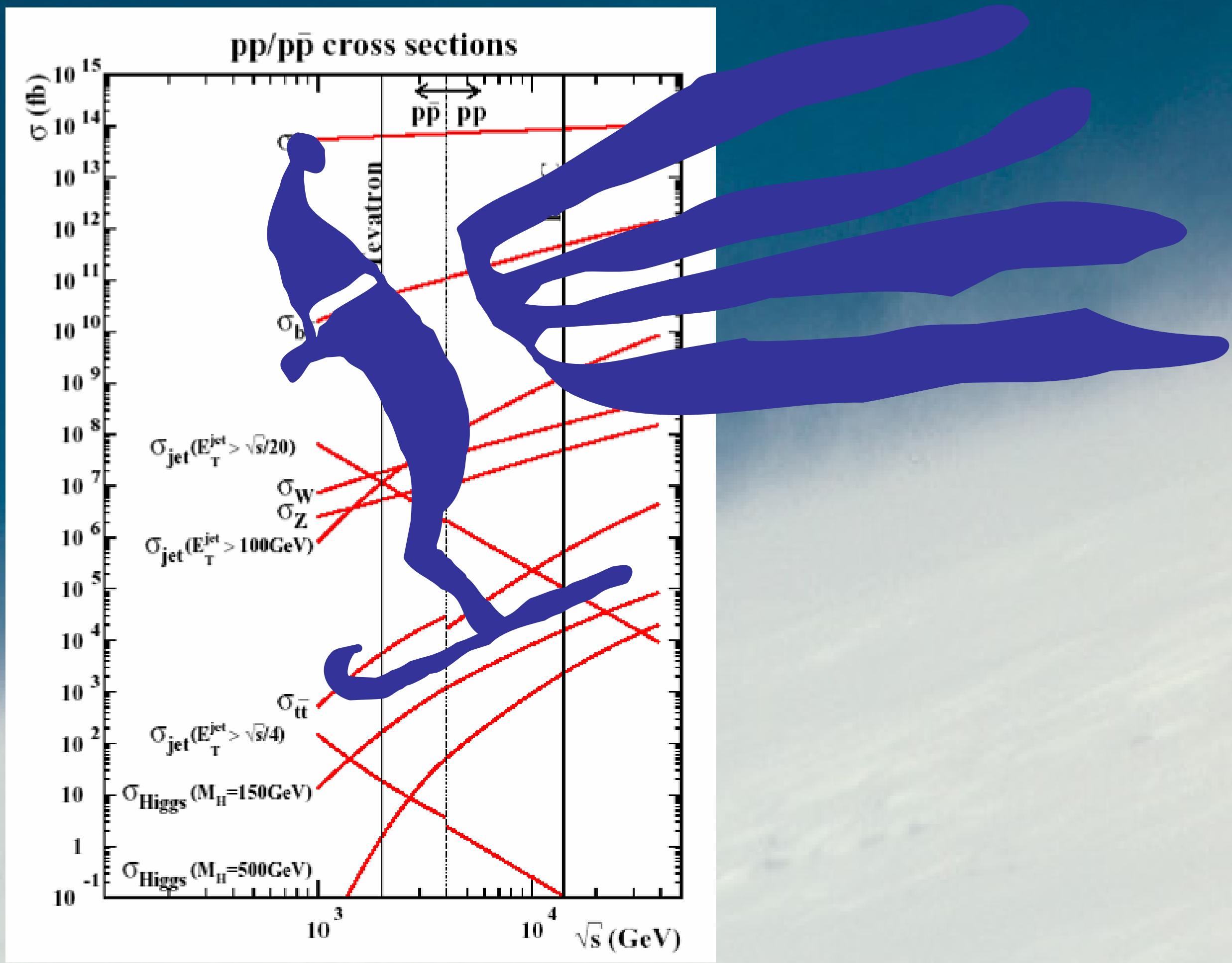
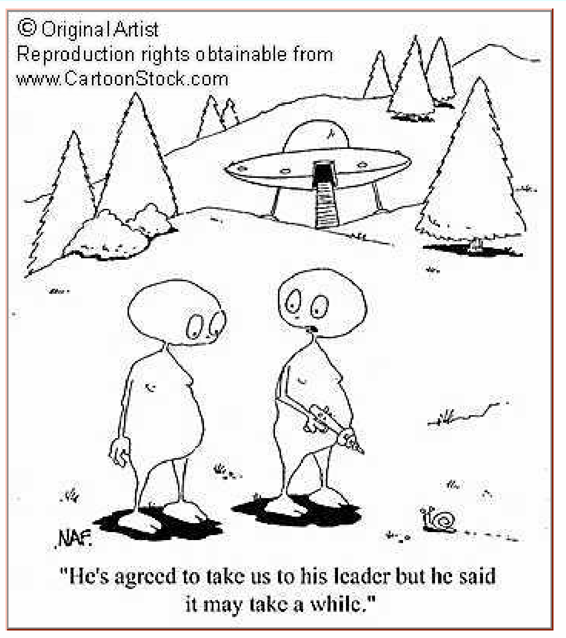
Prospects for measuring Higgs properties at the LHC



New particle discovery at the LHC depends on…

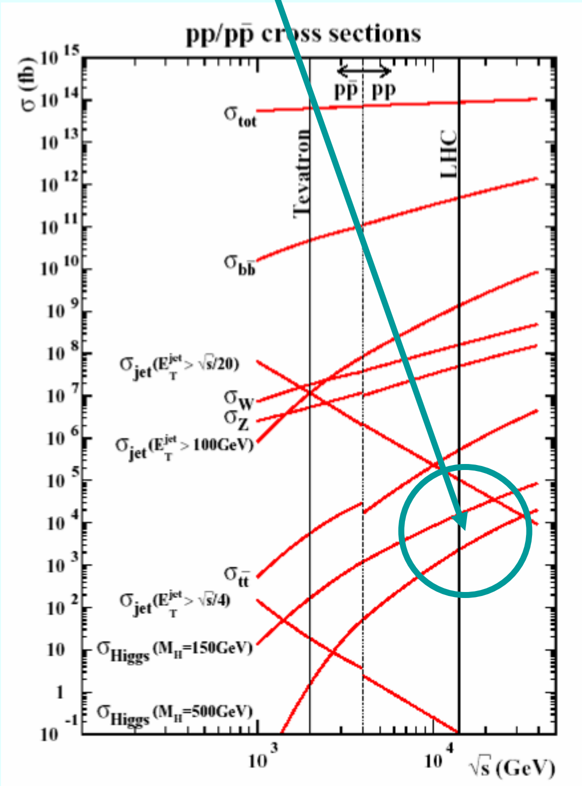
nature, LHC machine, readinous of our detectors.
Need to commission detectors and trigger.
Only then can we look for new physics potentially accessible the first year of $10^{33}cm^{-2}s^{-1}$

LHC startup in 2007…

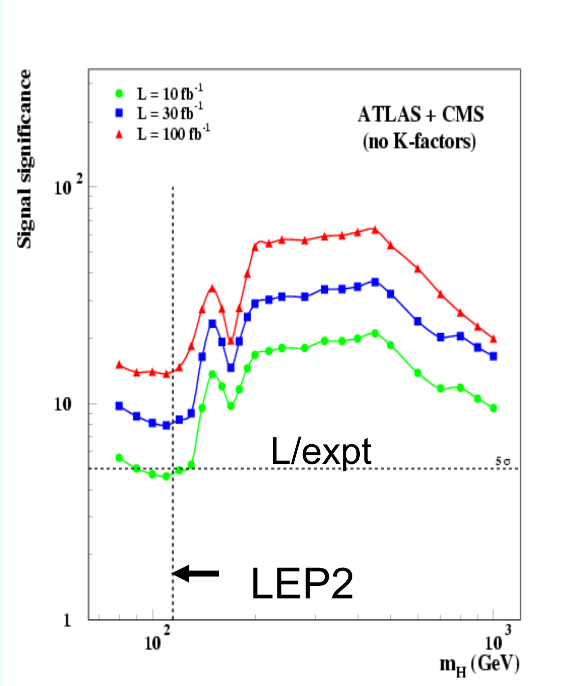


…detector performance
fairly good
at starting point

Small Higgs Xsection



Nonetheless we'll see the SM Higgs if it exists



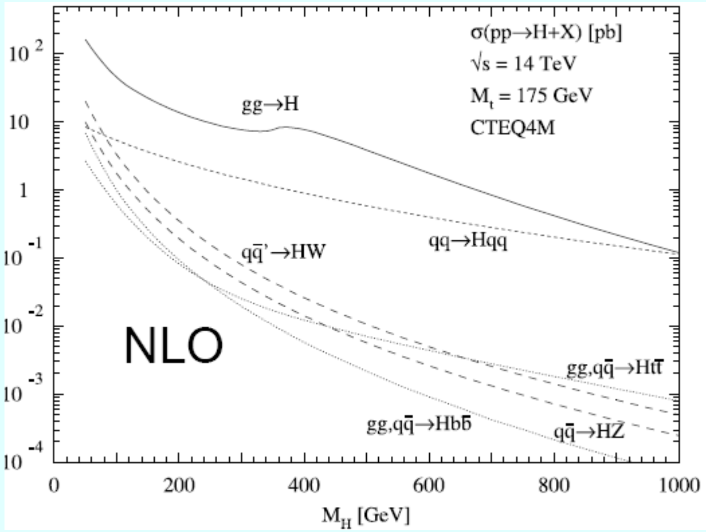
Measure its properties

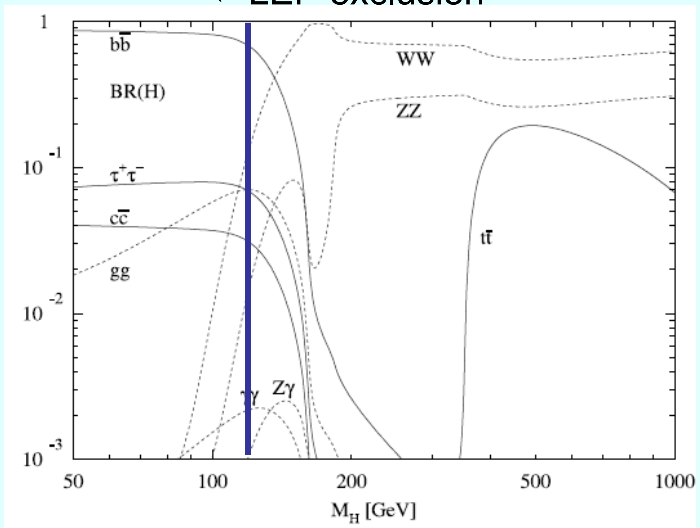
- mass
- width
- spin
- CP quantum numbers
- couplings to SM fermions and gauge bosons
- self couplings

Measurements need a lot of theoretical input.

Higgs boson production cross sections and BRs

←LEP exclusion

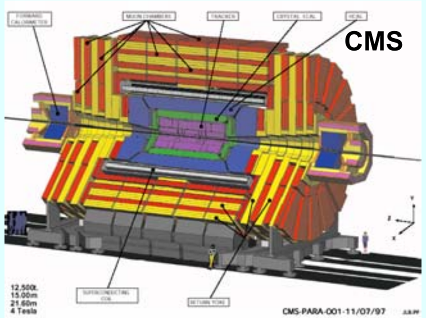




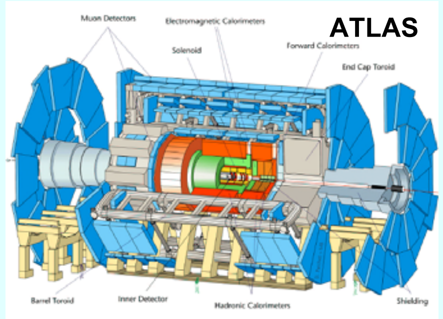
gluon fusion (GF)
weak vector boson fusion (WBF)
associated production (W, top, Z)

$\gamma\gamma$ (in GF and WBF)
$\tau\tau$ (in WBF)
ZZ, WW

Mass and width



Mass : CMS+ATLAS combined



Direct:

$H \rightarrow \gamma\gamma$, tt,W($H \rightarrow bb$), $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, WBF $H \rightarrow \tau\tau \rightarrow \ell$+hadr

Indirect:

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$, W($H \rightarrow WW$)$\rightarrow \ell\nu(\ell\nu\ell\nu)$, WBF $H \rightarrow \tau\tau \rightarrow \ell\ell$,…

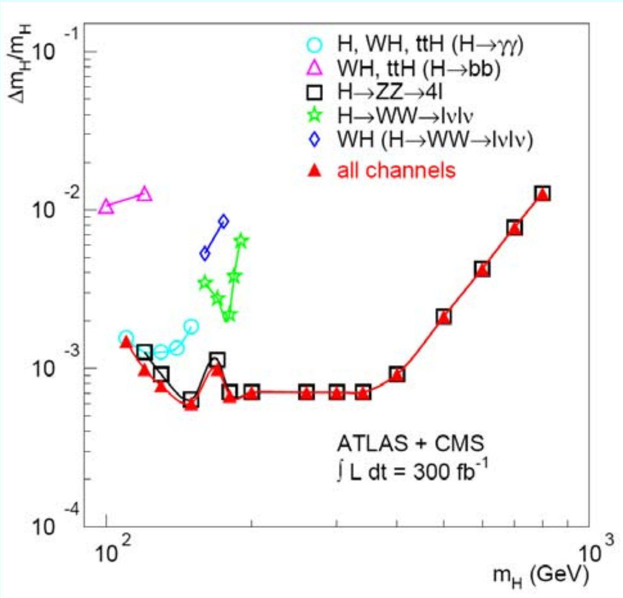
300 fb^{-1}, m^{direct}_H precision of 0.1% for m_H=100-400 GeV/c^2.

For m_H>400 GeV/c^2 precision degrades, however,

for m_H~ 700 GeV/c^2 ~1% precision.

Systematics dominated by knowledge of absolute E_{scale}:

for ℓ/γ~0.1% absolute goal 0.02%, for jets ~1%



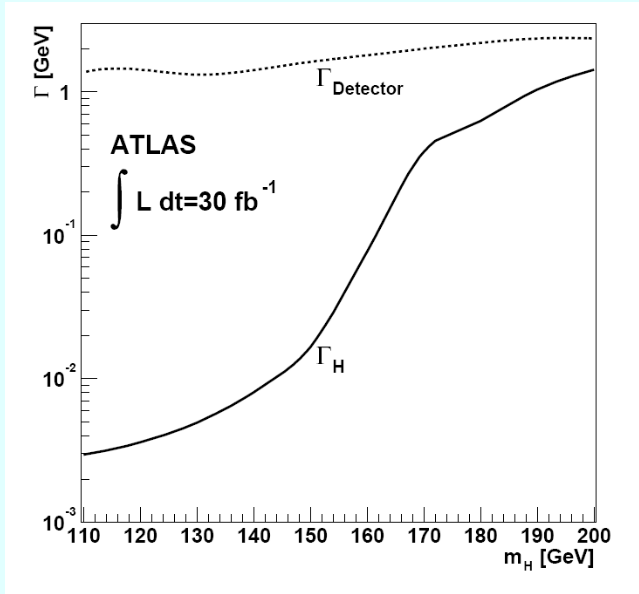
Width

Measured directly

from fit to mass peak,

for m_H>200 GeV/c^2, σ_{Γ_H} ~ 6%;

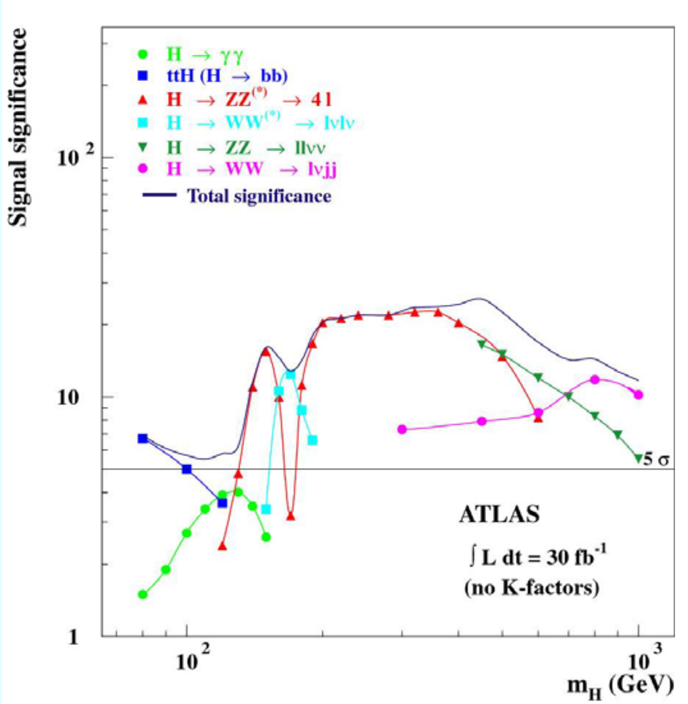
indirect extraction discussed later



Spin and CP eigenvalues

Spin and CP eigenvalues : ATLAS study (SN-ATLAS-2003-025)

i.e. Is it the $J^{CP}=0^{++}$ SM Higgs ?



Study angular distributions and correlations

$H \to ZZ \to 4\ell$ (μ or e) for m_H>200 GeV/c^2.

2 angular distributions

- cosθ polar angle of leptons relative to Z boson in H rest frame
- φ angle between decay planes of 2 Zs in H rest frame.

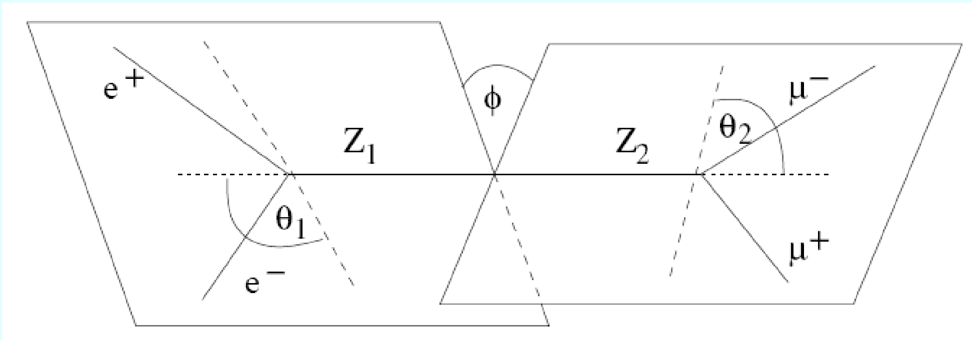
4 cases considered:

SM as well as

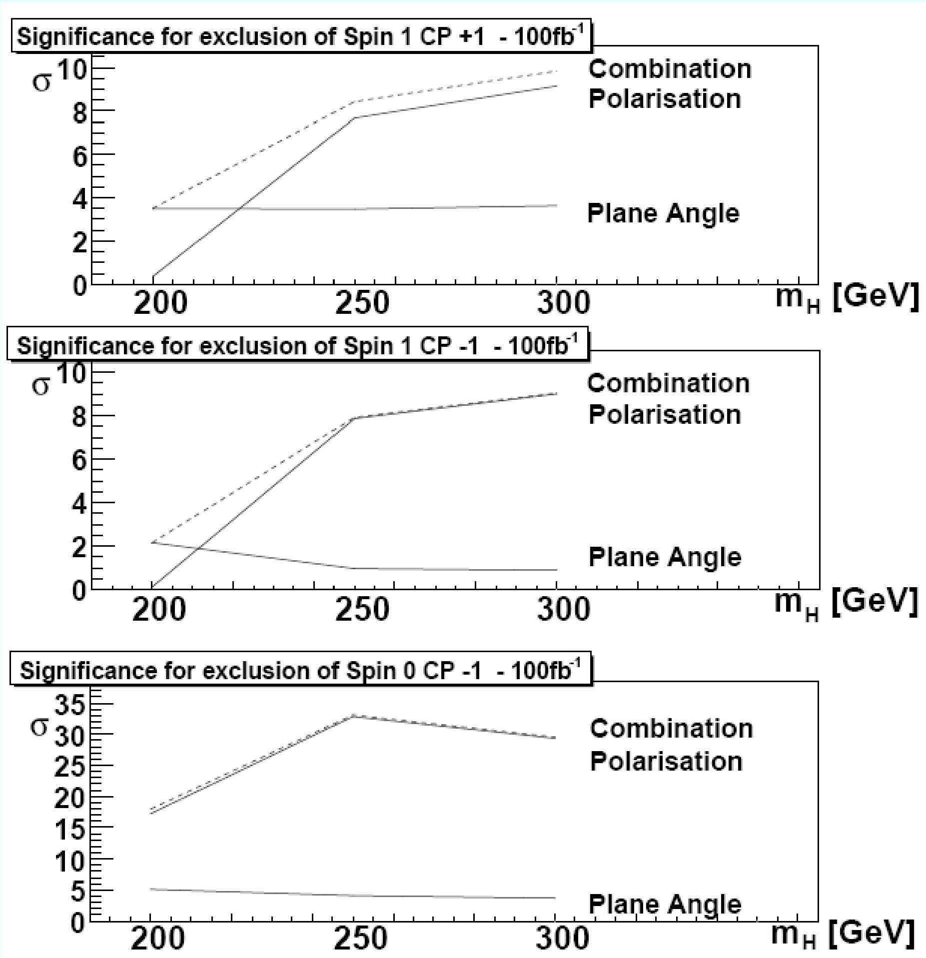
(J,CP) = (0,-1), (1,1), (1,-1)

(pseudo scalar, vector and axial vector)

hypothetical particle distributions



Spin and CP eigenvalues: angular distribution parametrisation



Comparing the SM angular distributions
with hypothetical particles distributions
extract significance of a SM Higgs

For 100 fb^{-1},
θ leads to good exclusion of non-SM (J,CP) values
for m_H>250 GeV/c^2.
As well, for m_H=200 GeV/c^2 with 300 fb^{-1}
(1,+1) can be ruled out with 6.4σ, and (1,-1) 3.9σ.

(J,CP)=(1,-1), (1,+1), (0,1) can be ruled out
for m_H>200 GeV/c^2 with 300 fb^{-1} or less

Systematics dominated by background subtraction.

N.B. For lower m_H,
use azimuthal separation of ℓ in WBF $H \rightarrow WW \rightarrow \ell\nu\ell\nu$
but has not yet been done.

N.B.bis. As well,
observation of non-zero Hγγ and Hgg couplings
rules out J=1 particles
and all odd spin particles in general
(see C.N.Yang Phys.Rev. 77,242 (1950) and
M.Jacob and G.C.Wick, Ann. Phys. 7 (1959) 404.)

Coupling parameters

Coupling parameters

By measuring rates of many (many) Higgs production and decay channels, various combinations of couplings can be determined.

Coupling constants for weak bosons and for fermions are given by

$g_W = 2m^2_W/v$ $\quad$ $g_Z = 2m^2_Z/v$ $\quad$ $|g_f| = \sqrt{2}\, m_f/v$

ATLAS study (ATL-PHYS-2003-030; Dührssen)

Maximum Likelihood for $110 < m_H < 190$ GeV/c^2.

Channels combined to determine

$g_W,\ g_Z,\ g_t,\ g_b,\ g_\tau$

For all signal channels determine (in narrow width approximation)

$\sigma_H \times BR(H \rightarrow yy)_i(x) = (\sigma^{SM}_H / \Gamma^{SM}_{prod})(\Gamma_{prod}\Gamma_{H\rightarrow yy}/\Gamma^{total}$

x : vector containing Higgs coupling parameters
and quantities with systematic uncertainties e.g.luminosity, detector effects, theoretical uncertainties, …

$\sigma \times BR_j(x)$ for bgd is treated as a systematic uncertainty.

Signals considered :
GF $H \rightarrow ZZ, WW, \gamma\gamma$;
WBF $H \rightarrow ZZ, \gamma\gamma, \tau\tau$ (2ℓ or 1ℓ + 1 hadr),WW ;
ttH with $H \rightarrow WW, t \rightarrow Wb$ (3ℓ + 1 hadr. or 2ℓ + 2 hadr.), $H \rightarrow \gamma\gamma$, $H \rightarrow bb$;
WH with $H \rightarrow WW$ (3ℓ or 2ℓ + 1 hadr.), $H \rightarrow \gamma\gamma$; ZH($H \rightarrow \gamma\gamma$) :
+ bgds

Coupling parameters: progressive assumptions

1. CP-even and spin-0 (can be more than one Higgs, degenerate in mass):
   only rate measurements are possible.

+2. Only one Higgs:
   any additional Higgs separated in mass and may not contribute to channels considered here
   relative BRs BR($H \to XX$)/BR($H \to WW$) equivalent to Γ_X/Γ_W.

+3. Only dominant SM couplings (no extra particles or extremely strong couplings to light fermions):
   measurement of squared ratios of Higgs couplings g^2_X/g^2_W,
   and lower limit on Γ_H obtained from sum of visible decay modes.

+4. Sum of all visible BRs ~ SM sum:
   absolute couplings and total width measurements.

Absolute couplings (4)

Γ_H fixed assuming fraction of non detectable Higgs decay modes as small as in SM.

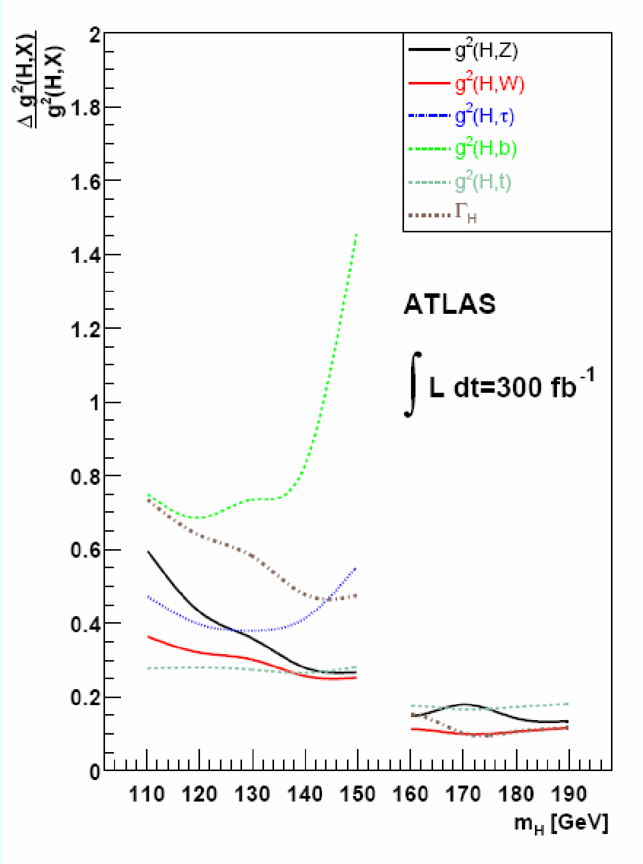
300 fb^{-1} and $110 < m_H < 190$ GeV/c^2

$\Delta g^2/g^2$ ~ 10%-60% (except for b)

$\Delta\Gamma_H/\Gamma_H$ ~ 10%-75%

Main systematics: expt. eff, bgd norm and σ, pdfs.

N.B. Discontinuity at $m_H > 150$ GeV/c^2 originates from change in assumption for sum of all BRs.



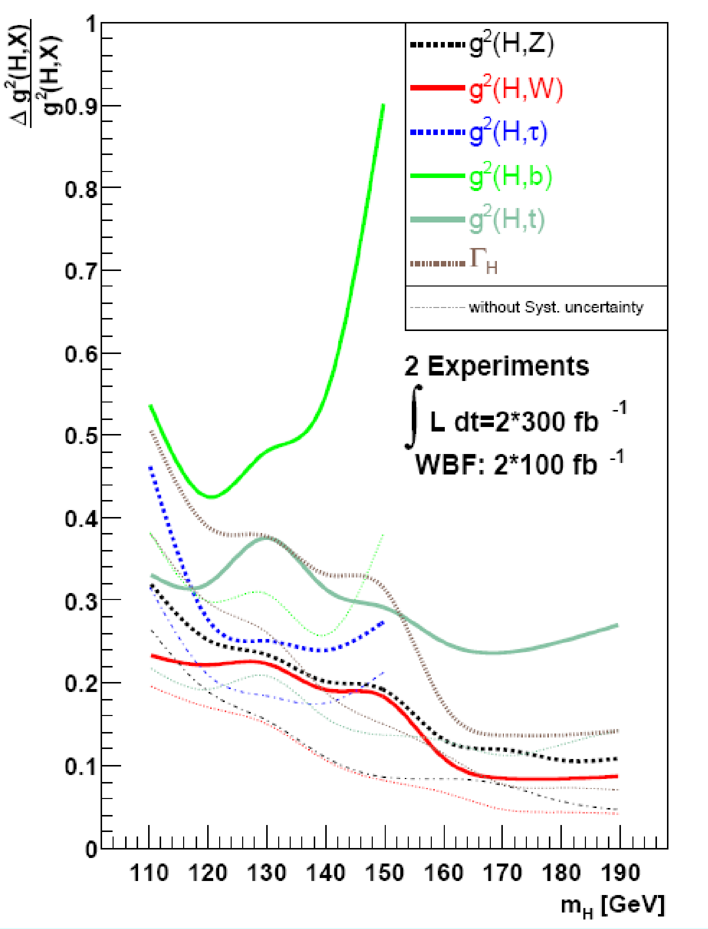
But also, hep-ph/0406323

Dührssen, with a little help from his theorist friends
Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld

Only one assumption :
strength of Higgs couplings to weak bosons does not exceed SM value
$\Gamma_V \leq \Gamma^{SM}_V$ V=W,Z
justified in any model with arbitrary number of Higgs doublets
e.g. MSSM.

Absolute determination of remaining Higgs couplings
as well as for Γ_H
is then possible.

300 fb^{-1} and 110<m_H<190 GeV/c^2
$\Delta g^2/g^2$ ~ 10%-45% (except for b)
$\Delta\Gamma_H/\Gamma_H$ ~ 10%-50%



Self coupling

Self coupling

To establish Higgs mechanism experimentally, reconstruct Higgs potential

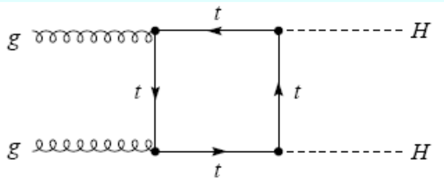
$V= (m^2_H/2)\, H^2 + (m^2_H/2v)\, H^3 + (m^2_H/8v^2)\, H^4$

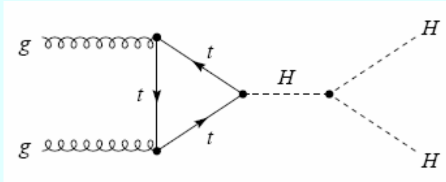
hence measure trilinear and quadrilinear (hopeless) Higgs self-couplings

uniquely determined by $m_H=\sqrt{(2\lambda)}v$.

Same sign dilepton final state hep-ph/0211224

Baur,Plehn,Rainwater





$gg\rightarrow HH\rightarrow(W^+W^-)(W^+W^-)\rightarrow(jj\ell^{\pm}\nu)\ (jj\ell'^{\pm}\nu)\ (\ell = e,\mu)$

for m_H>150 GeV/c^2.

$\sigma_{Signal} \rightarrow$ 1 loop ME with finite m_{top}. $\sigma_{Bgd} \rightarrow$ LO ME.

Only channel not swamped by bgd or with too low σ

Main backgrounds : WWWjj, ttW

but also: WWjjjj, WZjjjj, ttZ,ttj,tttt,WWWW, WWZjj and overlapping evts and double parton scattering.

σ(fb) after cuts:

$p_T(j)$>30,30,20,20 GeV, $p_T(\ell)$>15,15 GeV, $|\eta(j)|$<3.0, $|\eta(\ell)|$<2.5, $\Delta R(jj)$>0.6, $\Delta R(j\ell)$>0.4, $\Delta R(\ell\ell)$>0.2

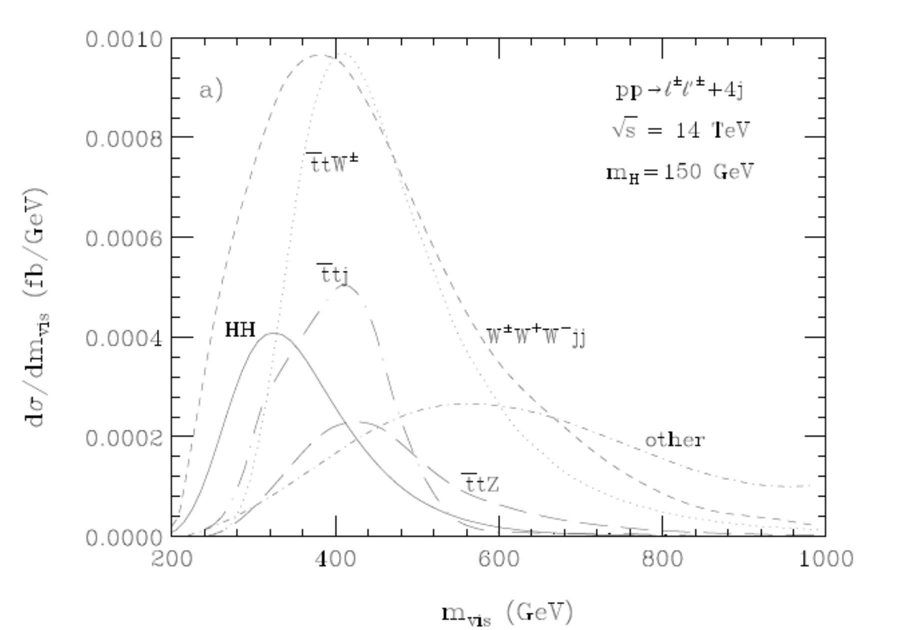
m_H	HH	$WWWjj$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}j$	$WZjjjj$	$WWjjjj$	$t\bar{t}t\bar{t}$	pileup	$\mathcal{B}_{tot}$
150	0.07	0.36	0.22	0.05	0.08	0.15	0.005	0.002	$\sim$ 0.03	0.90
160	0.19	0.49	0.22	0.05	0.08	0.15	0.005	0.002	$\sim$ 0.03	1.03
180	0.18	0.40	0.22	0.05	0.08	0.15	0.005	0.002	$\sim$ 0.03	0.94
200	0.08	0.29	0.22	0.05	0.08	0.15	0.005	0.002	$\sim$ 0.03	0.83

$\leq$ 50 signal events with 300 fb^{-1} for 150<m_H<200 GeV/c^2

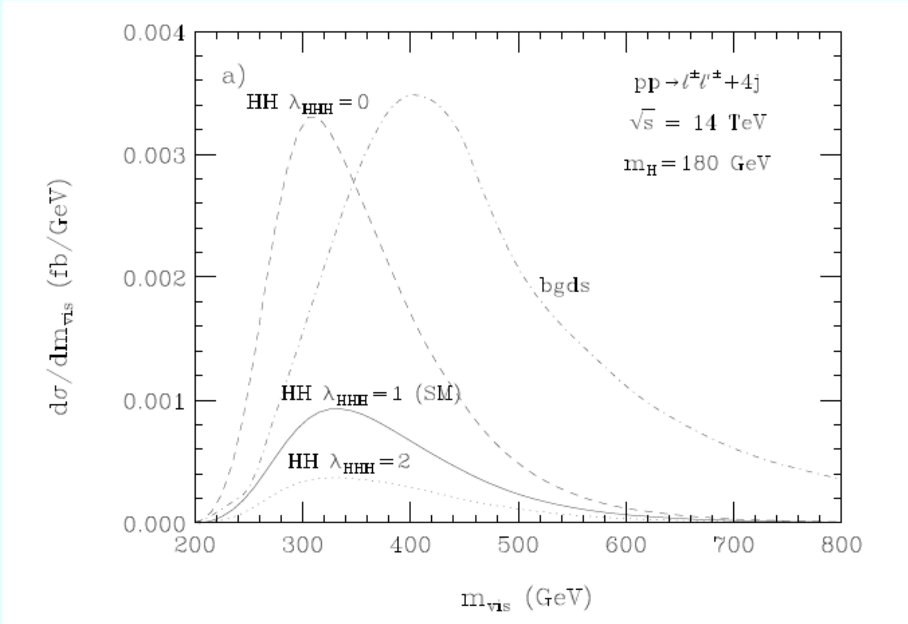
Self coupling: invariant mass distribution (Baur etal.)

Backgrounds are multi body production processes,
$\rightarrow m^{system}_{invariant}$ distribution peaks at values significantly above threshold.
Signal is 2 body : m_{inv} exhibits sharper threshold behavior,
but cannot be reconstructed due to 2 ν,
however m_{vis} will retain most of expected behavior.

M_{vis} after all cuts (50GeV<m(jj)<110GeV;ΔR(jj)>1.0)
for m_H=150 GeV/c^2



2 non-standard values of $\lambda_{HHH}=\lambda/\lambda_{SM}$ (0 and 2)
Box and triangle diagrams interfere destructively
$\rightarrow \sigma(gg\rightarrow HH)<\sigma_{SM}$ for $1<\lambda_{HHH}<2.7$.
Absence of self coupling (λ_{HHH}=0) $\rightarrow$ $\sigma(gg\rightarrow HH)>3\times\sigma_{SM}$.



Self coupling: χ^2 fit results

Derive 95%CL bounds from χ^2 fit to m_{vis} shape

SM assumed to be valid except for self coupling.

Assume m_H precisely known, and BR($H \rightarrow WW$) known to 10% or better.

Limits at 95%CL

With 300 fb^{-1},

$\Delta\lambda_{HHH}=(\lambda-\lambda_{SM})/\lambda_{SM} = -1$

(vanishing self-coupling)

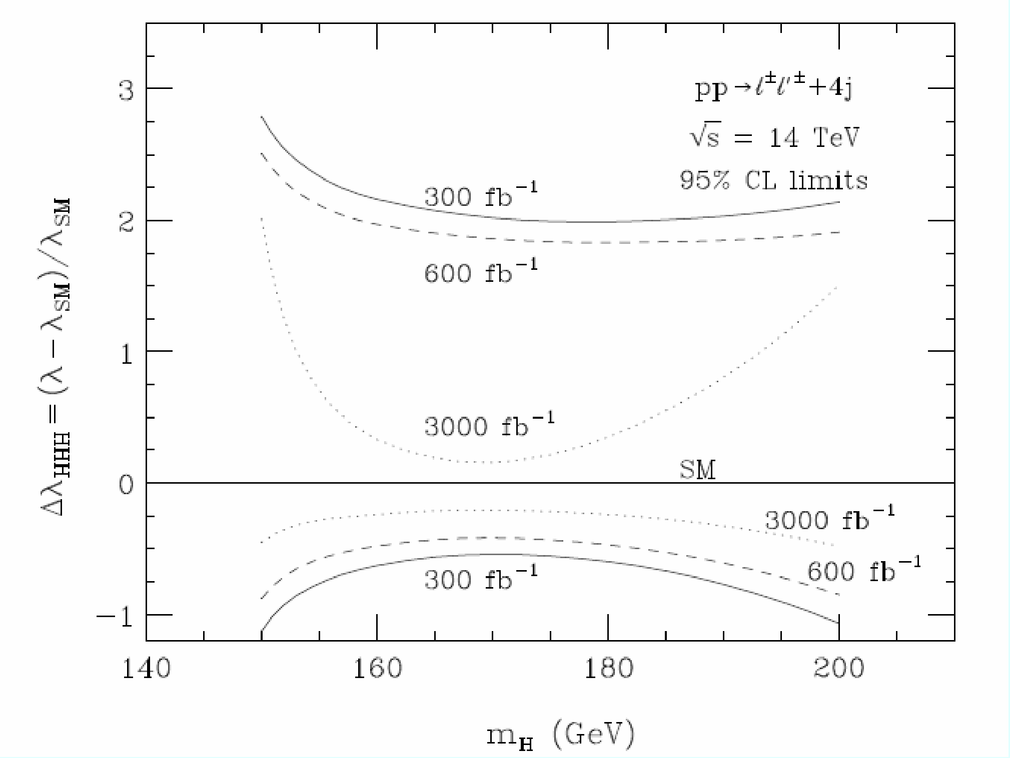
excluded at 95%CL or better;

λ determined to -60% to +200%.

Significance of SM signal for 300fb^{-1}

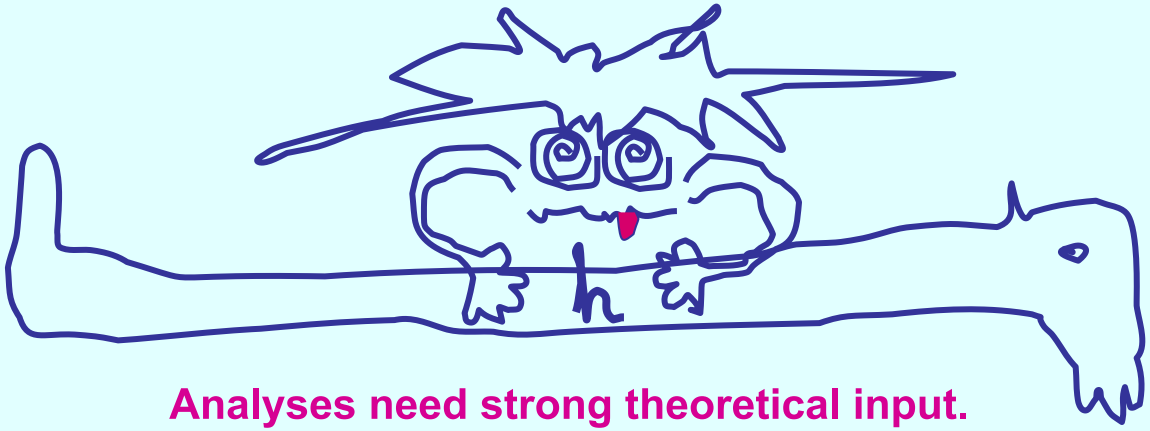
~ >1σ for $150<m_H<200$ GeV/c^2

~ 2.5σ for $160<m_H<180$ GeV/c^2.



Fit to m_{vis} improves accuracy of λ by a factor 1.2 to 2.5 compared to σ analysis.

Conclusion



Analyses need strong theoretical input.
Experimentalists and theorists working together.

→ Mass 0.1%-1% precision over whole mass range

→ Spin-CP can be ruled out

J=1

for m_H>230 GeV/c^2 - 100 fb^{-1} and for m_H=200 GeV/c^2 - 300 fb^{-1}.

(J,CP)=(0,-1)

for $m_H \geq$200 GeV/c^2 - <100fb^{-1}.

→ Couplings (depending on assumptions)

10%-45% precision on g^2_Z, g^2_W, g^2_τ, g^2_t and 10%-50% on Γ_H

for 110<m_H>190 GeV/c^2 and 300 fb^{-1}

→ Self-coupling

$\Delta\lambda_{HHH}=(\lambda-\lambda_{SM})/\lambda_{SM}$.= -1 excluded with at least 95%CL

with 300 fb^{-1},

λ determined to -60% to +200%.

Tree level couplings of Higgs to SM fermions/gauge bosons
uniquely determined and proportional to their masses.

BR calculations including HO QCD corrections are available
but m_h completely undetermined but linearly related to scalar field self coupling.
The self coupling behaviour determined by field theory which puts bounds on m_h.
$\lambda>0$ (vacuum remains stable under radiative corrections) $\rightarrow$ lower bound on m_h for a given value of m_{top}.
m_H also bounded from above by triviality considerations:
by considering only contributions of the scalar loops to radiative corrections to λ,
it can be shown that $m_h < 893 / (\Lambda/v)^{½}$ GeV/c^2
Theory must be valid at large Λ and yet non trivial at scale v $\rightarrow$ upper limit on λ and hence on m_H.
But as λ becomes large, perturbative methods used above fail.
m_H bounds depend on m_{top} (lower bound) and on uncertainties in non perturbative dynamics (upper bound).

These measurements still need a lot of theoretical input,
since signal and bgd cross sections are needed to extract the results.
One must aim to be most model independent as possible.

One of the main tasks of the LHC will be to probe the mechanism of EW gauge symmetry,
which is strongly dependent on the (Prout-Engelrt???)-Higgs boson son mass.

In SM, Higgs boson necessary to bring about EW symmetry breaking
which gives masses to the fermions and gauge bosons.
For the SB to happen, the mass^2 term for the complex scalar doublet Φ has to be negative i.e. the potential

$$V(\Phi)=(\lambda/4!)\,(\Phi^\dagger\Phi)^2 - \mu^2\,(\Phi^\dagger\Phi)$$

with μ^2 positive.
After the SB, out of the four scalar fields which comprise Φ, only the physical scalar h is left, with a mass

$$m_h^2 = \lambda\, v^2$$

The tree level couplings of the Higgs boson to the SM fermions and the gauge bosons are uniquely determined and proportional to their masses.

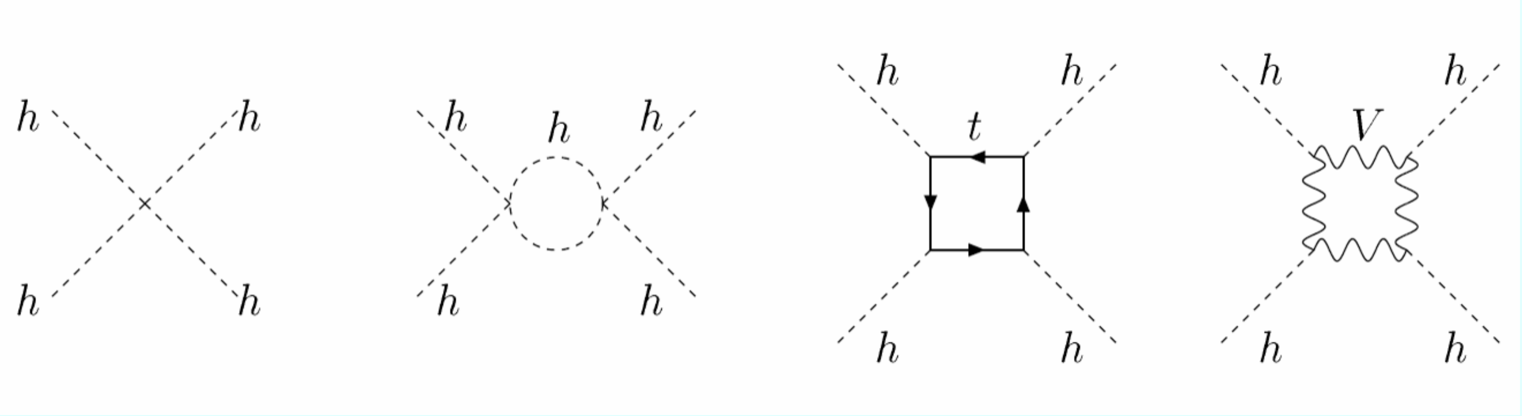
$h\to gg$, $\gamma\gamma$ for $m_h<2m_W$ and $h\to bb$ for $m_h<140$ GeV

The couplings of a Higgs to a pair of gluons/photons is induced at one loop level
through dominantly a top (for γ or gluon) or a W (for γ) loop.
This coupling, as with the other couplings,
is completely calculable to a given order in the strong and electromagnetic coupling.
The QCD corrections for $h\to gg$ are significant (order of 65%).

Γ_H is < 10 MeV, $\Gamma(h\to bb)$=68% for m_h=120 GeV
Γ_H is 1 GeV for m_h=300 GeV
$\Gamma_H \sim m_h$ for m_h>500 GeV

Calculations of various branching ratios,
including higher order QCD effects, are available.
The couplings and hence branching fractions of the Higgs are well determined,
once m_h and various other parameters such as m_{top} and α_s are specified.
On the other hand, m_h is completely undetermined.
Still, it is linearly related to the self coupling of the scalar field.
Nonetheless, the behaviour of the self coupling λ is determined by field theory,
and this then puts bounds on m_h.
The self coupling receives radiative corrections from the diagrams below.

Scalar and gauge boson loops on one hand,
and fermion loop on the other, are opposite in sign.
The requirement that λ stay positive (vacuum remains stable under radcorrs)
puts a lower bound on m_h is for a given value of m_{top}.
This bound depends on the htt coupling.



m_h is also bounded from above by triviality considerations.
This can be understood by considering only the contributions of the scalar loops, for simplicity, to the radcorrs to λ.
It can be shown that
$m_h < 893 / (\Lambda/v)^{1/2}$ GeV/c^2
The theory must be valid at large Λ and yet non trivial at a scale v.
This puts an upper limit on $\lambda(v)$ and hence on m_h.
But of course, as λ becomes large, perturbative methods used above must fail.

The m_h bounds depend on the value of m_{top} (lower bound) and the uncertainties in the non perturbative dynamics (upper bound).

The SM is in excellent agreement with all the experimental measurements.
However the EW mechanism remains a mystery.
The Higgs mechanism is one possible solution but to be confirmed, the Higgs boson must be observed.
ATLAS and CMS have the ability to discover a SM Higgs of mass 115GeV/c^2 to 1TeV/c^2 with 10fb^{-1} (ATLAS+CMS).

Search channels - mass range 100 – 1000 GeV

Production	Decay	Mass range	measures
Gluon fusion	$H \rightarrow gg$ $H \rightarrow ZZ^{(*)} \rightarrow 4l$ $H \rightarrow WW^{(*)} \rightarrow ln\ ln$	110 – 150 GeV 120 – 700 GeV 110 – 190 GeV	mass, WWH, ttH mass, ZZH, ttH, spin mass, WWH
Vector Boson Fusion	$H \rightarrow bb$ $H \rightarrow gg$ $H \rightarrow tt$ $H \rightarrow WW^{(*)} \rightarrow ln\ ln$	110 – 140 GeV 110 – 150 GeV 110 – 150 GeV 110 – 190 GeV	mass, bbH, WWH mass, WWH mass, WWH,ttH WWH, spin
ttH	$H \rightarrow gg$ $H \rightarrow bb$ $H \rightarrow tt$ $H \rightarrow WW^{(*)} \rightarrow ln\ ln$	110 – 120 GeV 110 – 140 GeV 110 – 130 GeV 120 – 200 GeV	mass, WWH, ttH mass, ttH, bbH ttH, ttH WWH, ttH
WH, ZH	$H \rightarrow gg$ $H \rightarrow bb$ $H \rightarrow WW^{(*)} \rightarrow ln\ ln$	110 – 150 GeV 110 – 150 GeV 110 – 190 GeV	mass, WWH mass, bbH, WWH WWH

Search channels - mass range 100 – 1000 GeV

Production	Decay	Mass range
Gluon fusion	$H \rightarrow \gamma\gamma$ $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110 – 150 GeV 120 – 700 GeV 110 – 190 GeV
Weak Boson Fusion	$H \rightarrow bb$ $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ $H \rightarrow \gamma\gamma$ $H \rightarrow \tau\tau$ $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110 – 140 GeV 110 – 200 GeV 110 – 150 GeV 110 – 150 GeV 110 – 190 GeV
ttH	$H \rightarrow \gamma\gamma$ $H \rightarrow bb$ $H \rightarrow \tau\tau$ $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110 – 120 GeV 110 – 140 GeV 110 – 150 GeV 120 – 200 GeV
WH	$H \rightarrow \gamma\gamma$ $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110 – 120 GeV 150??? – 190 GeV
ZH	$H \rightarrow \gamma\gamma$	110 – 120 GeV

LHC Higgs etal. factory

The expected signal event rates at low luminosity ($L=10^{33}\ cm^{-2}\ s^{-1}$)

Process	Event rate (Hz)	Events for 10 fb^{-1} (one year low L)	Total stats collected elsewhere by 2007
$W \rightarrow e\nu$	30	10^8	10^4 LEP/10^7 Tevatron/
$Z \rightarrow ee$	3	10^7	10^6 LEP
Top	2	10^7	10^4 Tevatron
Beauty	10^6	10^{12}-10^{13}	10^9 Belle/BaBar
H (m=130GeV)	0.04	10^5	
Gluino (m=1TeV)	0.002	10^4	
Black holes (m>3TeV)	0.0002	10^3	we won't be there anymore to say

Pile-up at high luminosity

Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus.

Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- a precise (and if possible fast detector response) minimises pile-up in time
    → very challenging for the electronics in particular
    → typical response times achieved are 20-50 ns (!)
- a highly granular detector minimises pile-up in space
    → large number of channels i.e. ATLAS: 100 Mpixels, 200k EMcalo cells

Annexe
Experiments
ATLAS-CMS performance requirements

- Lepton measurement p_T ~ GeV $\rightarrow$ 5TeV !!
- Mass resolution (m~100GeV)
  - ~1% (H $\rightarrow \gamma\gamma$, 4l)
  - ~10% (W $\rightarrow$ jj,H $\rightarrow$ bb)
- Calorimeter coverage $|\eta|<5$
  E_t^{miss} ,forward jet tag for heavy Higgs
- Particle identification
  ε_b~60% R_j~100 (H $\rightarrow$ bb, SUSY)
  ε_τ~50% R_j~100 (A/H $\rightarrow \tau\tau$)
  ε_γ~80% $R_j>10^3$ (H $\rightarrow \gamma\gamma$)
  ε_e>50% $R_j>10^5$ e/jet~10^{-3} $\sqrt{s}$=2TeV
  e/jet~10^{-5} $\sqrt{s}$=14TeV
- Trigger 40MHz $\rightarrow$ 100 Hz reduction
  bunch crossing id.

Annexe
Electromagnetic Calorimetry

In several scenarios moderate mass narrow states decaying into photons or electrons are expected:

SM intermediate mass H g gg, H g Z Z* g 4e

MSSM h g gg, H g gg, H g Z Z* g 4e

In all cases the observed width will be determined by the instrumental mass resolution. We need:

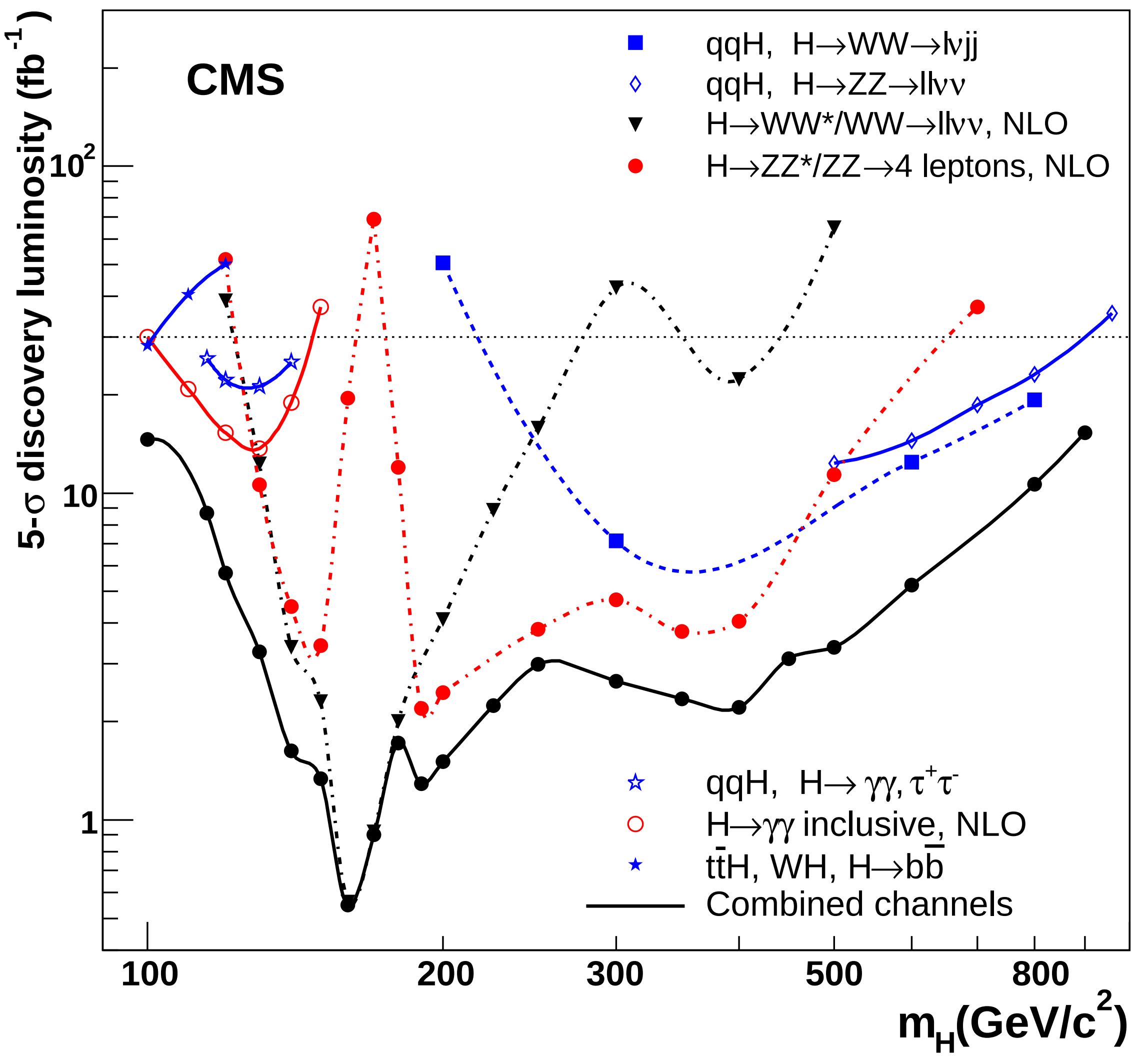
good e.m. energy resolution, good photon angular resolution and good 2-shower separation capability.

Hadronic Calorimetry

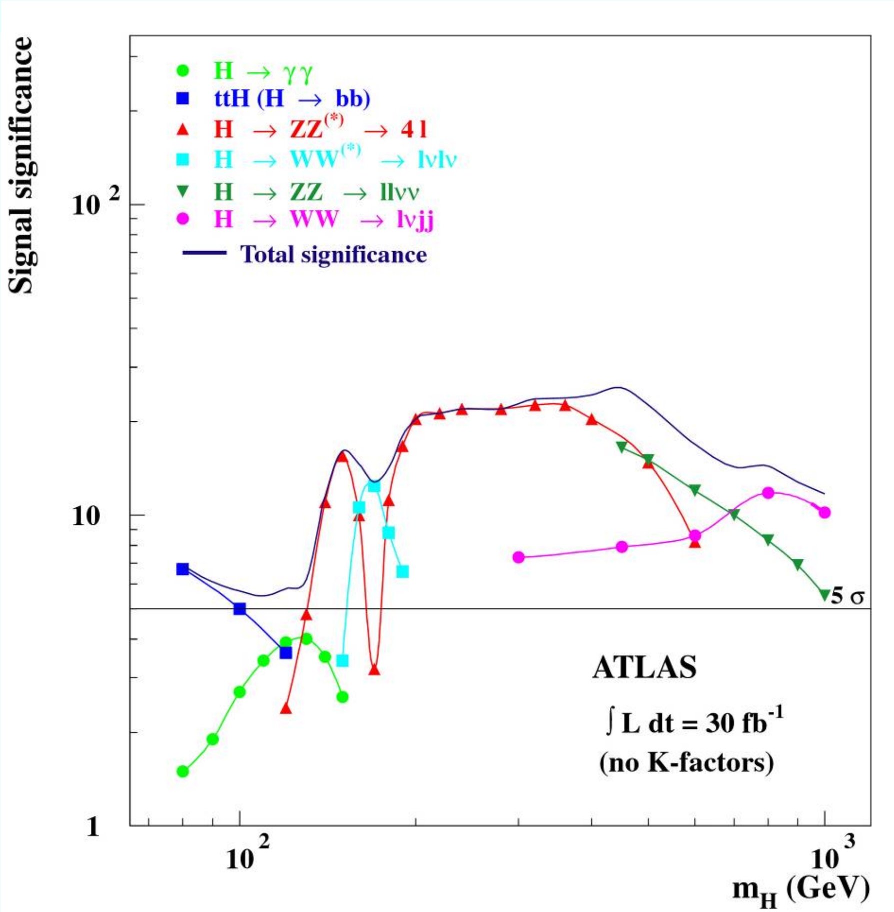
- **Jet energy resolution**
  - Limited by jet algorithm, fragmentation, magnetic field and energy pileup at high luminosity
  - Can use the width of jet-jet mass distribution as a figure of merit
    - Low p_t jets: W, Z → Jet-Jet, e.g. in top decays
    - High p_t jets: W', Z' → Jet-Jet
  - Fine lateral granularity (≤ 0.1) high p_t W's, Z's

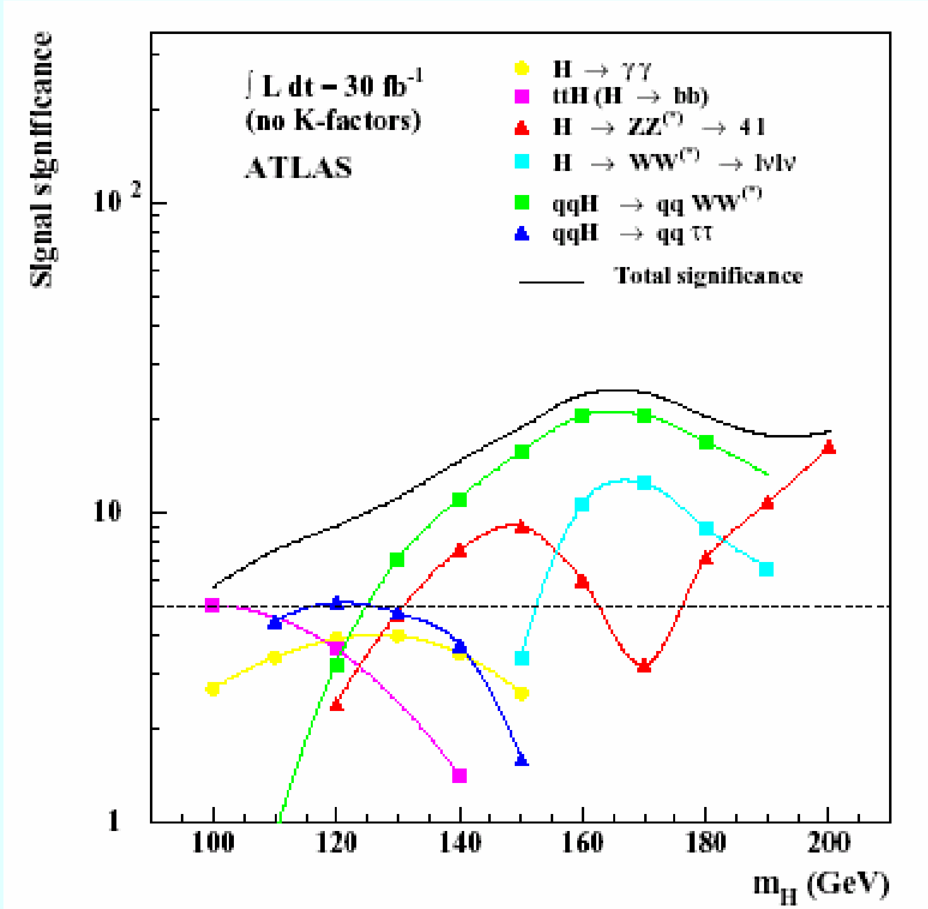
- **Missing transverse energy resolution**
  - Gluino and squark production
    - Forward coverage up to $|\eta| = 5$
    - Hermeticity - minimize cracks and dead areas
    - Absence of tails in the energy distribution is more important than a low value for the stochastic term
  - Good forward coverage is also required to tag processes initiated vector boson fusion

Annexe Discovery:
CMS 5σ discovery luminosity



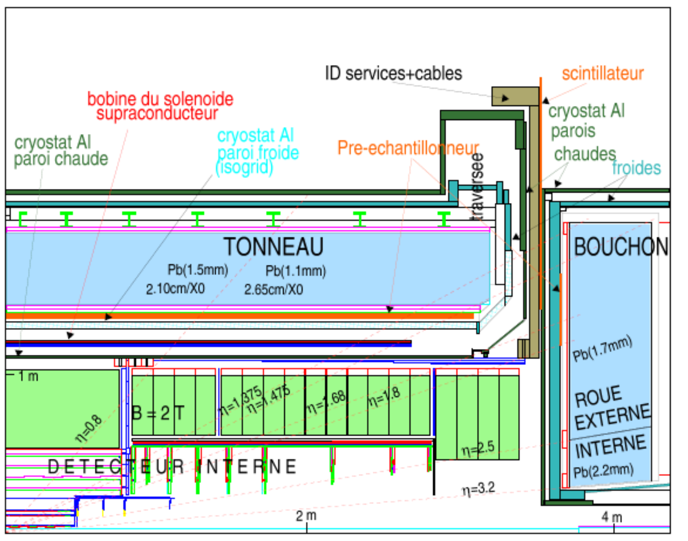
Discovery:
ATLAS probable signal significance S/√B





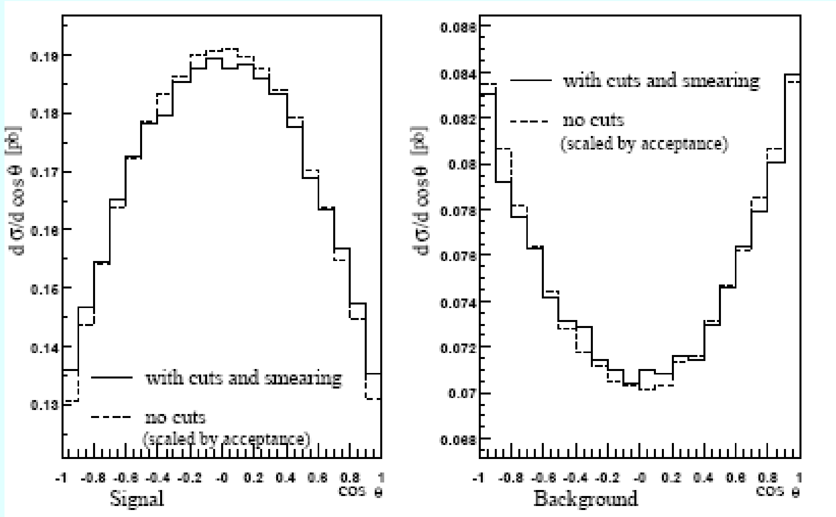
Spin and CP eigenvalues : analysis cuts

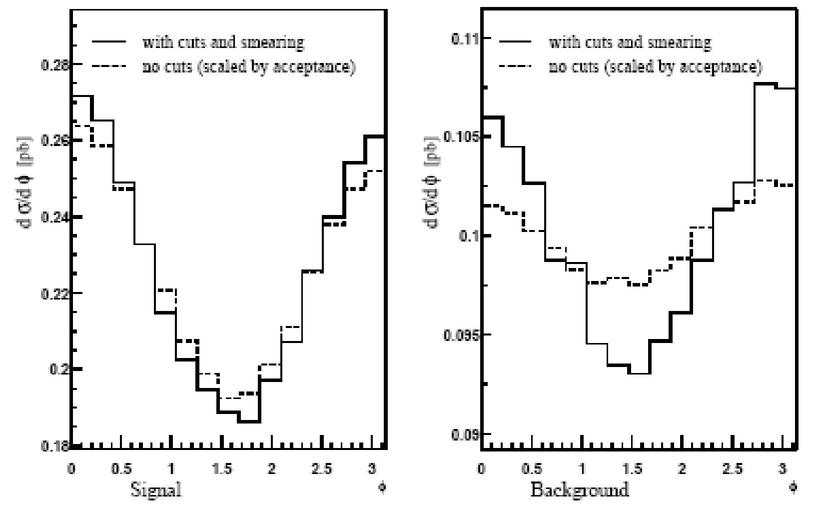
- 4ℓ with $|\eta|=|\ln\tan(\theta_{beam}/2)|<2.5$
- 2ℓ with $p_T>20$ GeV
- 2 other ℓ $p_T>7$GeV
- $Eff_{\ell id}=90\%$
- Zs using matching flavor - opposite charge ℓs.
  If all same flavor, minimize $(m_{\ell\ell 1}-m_Z)^2+(m_{\ell\ell 2}-m_Z)^2$
- $m_H-2\sigma_H<m_{ZZ}<m_H+2\sigma_H$



Polar (cosθ) and decay plane (φ) angles for H->ZZ->μ+μ-μ+μ-. Similar plots for other decay channels.
tt or Zbb bgds negligible for $m_H>200$ GeV/c^2.

BEWARE: Detector acceptance and efficiency effects can mock correlations.





Spin and CP eigenvalues : angular distributions

Complete differential Xsections for H→ZZ→4f calculated at tree level.
Two angular distributions :

- cosθ polar angle of decay leptons relative to Z boson.

H decays mainly into longitudinally polarized vector bosons and so the Xsection shows a max at cosθ=0.

- φ angle between decay planes of 2 Zs in H rest frame.

In the SM, it is 1+βcos2φ but flattened in the decay chain because of the small vector coupling of the leptons.

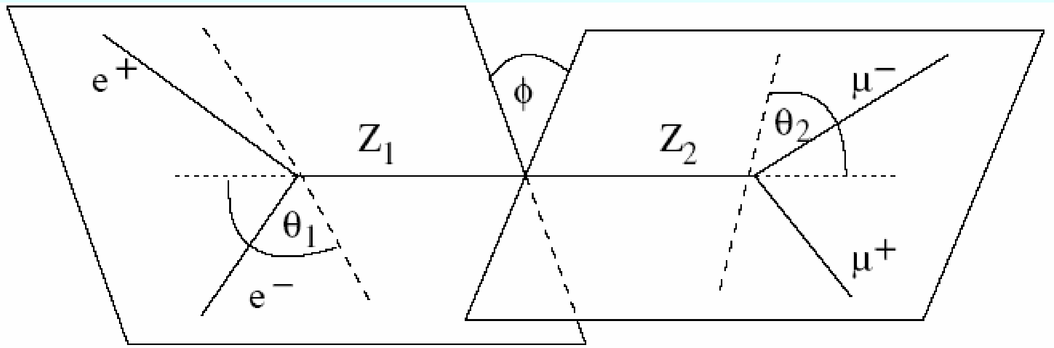


Figure 1: The decay plane angle ϕ is measured between the two planes defined by the leptons from the decay of the two Z bosons in the rest frame of the Higgs, using the charge of the leptons to fix the orientation of the planes. The dashed lines represent the direction of motion of the leptons in the rest frame of the Z Boson from which they originate. The angles θ_1 and θ_2 are measured between the negatively charged leptons and the direction of motion of the corresponding Z in the Higgs boson rest frame. ϕ=0 correspond to $p_{e^+} \times p_{e^-}$ and $p_{\mu^+} \times p_{\mu^-}$ being parallel. ϕ=π correspond to $p_{e^+} \times p_{e^-}$ and $p_{\mu^+} \times p_{\mu^-}$ being antiparallel.

Spin and CP eigenvalues : MC generators

3 MC generators:

• SM: complete differential $\sigma(H\rightarrow ZZ\rightarrow 4f)$ at tree level
• irreducible ZZ bgd (Matsuura and van der Bij)
• alternative particles (A.Nelson and J.R.Dell'Aquilla)

Irreducible $gg\rightarrow ZZ\rightarrow 4\ell$ and $qqbar\rightarrow ZZ\rightarrow 4\ell$ bgd considered
while $gg\rightarrow HH$ and other contribs neglected.
Polarizations of bgd Z boson kept.
$gg\rightarrow ZZ$ (~ 30% of total bgd) has different angular distribs from other bgds.
No K factors.
Narrow width approximation: results only valid for $m_H>2m_Z$.

3 generators use
CTEQ4M structure functions,
HDECAY for Higgs BRs and width,
narrow width approx.

Spin and CP eigenvalues: background subtraction

Subtraction of bgd angular distributions → source of systematic errors.
Number of bgd evts estimated using the sidebands (see Fig5).
Checking the shape of the bgd distrib can be done using bins below and above the signal region.
Fig 6 shows how R varies and Table 3 as well, for various bgd configurations.

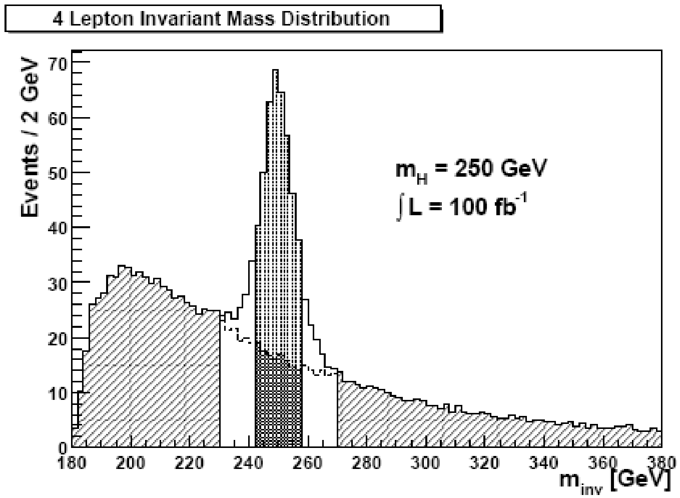


Figure 5: The invariant mass distribution of a 250 GeV/c^2 Higgs boson and the ZZ Background. The vertically hatched region is the signal region used in the analysis. The diagonally hatched regions are the sidebands used to determine the expected number of background events (hatched horizontally) inside the signal region. The dotted line indicates the shape of the background in the transition region between the sidebands and signal which is not used at all.

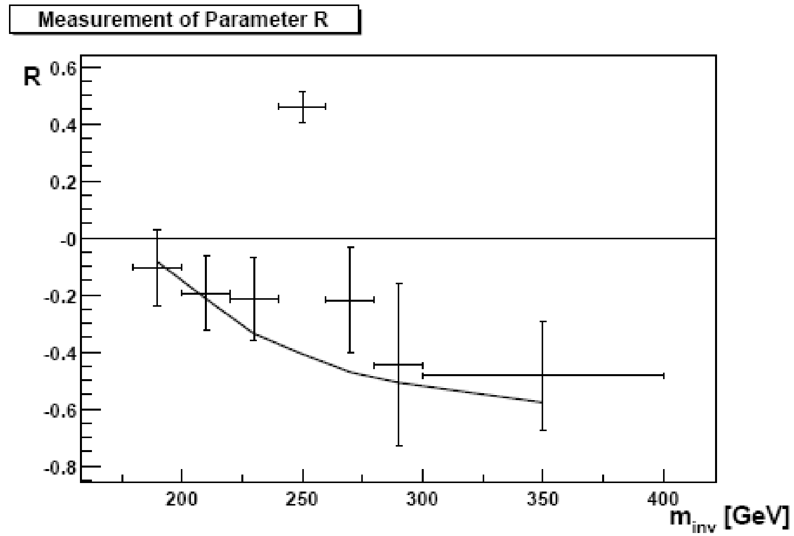


Figure 6: The parameter R (defined in (3)) as obtained by a fit to different mass regions of the background only (solid line) and by a fit to the same mass regions to signal plus background distributions (points with errorbars). The horizontal errorbars indicate the regions from which the distributions where taken.

ΔR	-0.2	-0.1	0.0	0.1	0.2
R_{signal}	0.747	0.758	0.770	0.782	0.796

Table 3: The measured Parameter R for five different distributions that have been used to subtract the expected background distribution. ΔR is the difference between the value of R from the background as produced by the Monte Carlo and the value of R of the subtracted distribution.

Spin and CP eigenvalues: angular distribution parametrisation

To distinguish between spins J=0,1 and/or CP-eigenvalues γCP=-1,+1 $\rightarrow$ 4 different distributions:
SM as well as (J,CP) = (0,-1), (1,1), (1,-1) hypothetical particle distributions

Plane correlation parametrized as

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

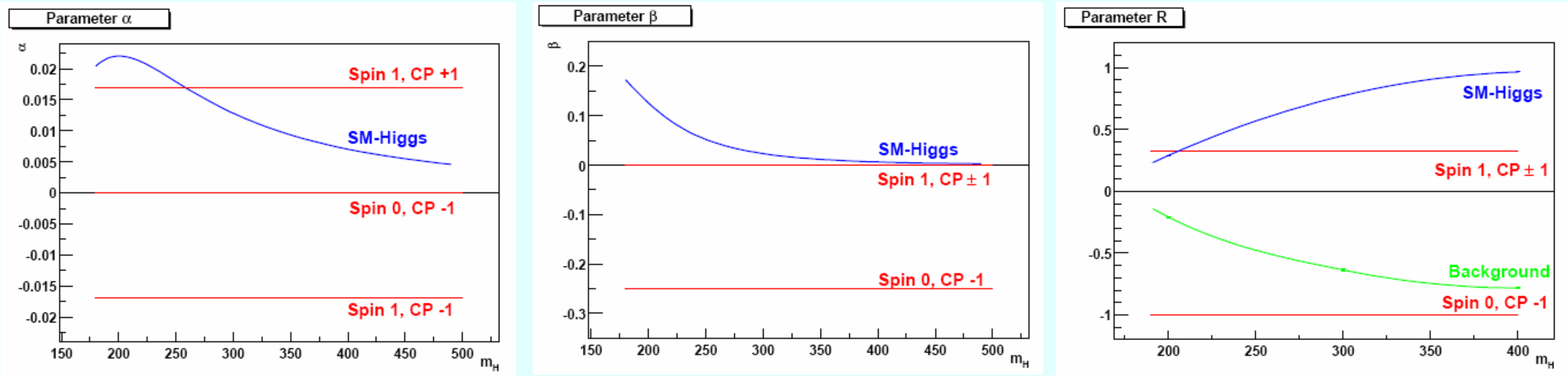
where α and β depend on m_H in the SM, but are constant over whole mass range for (J,CP)=(0,-1),(1,+1),(1,-1).

Polar angle described by

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

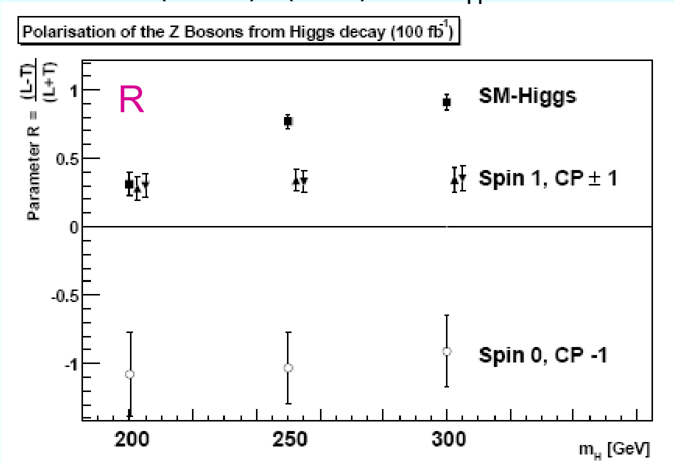
for Z Longitudinal or Transverse polarization, with R=(L-T)/(L+T).

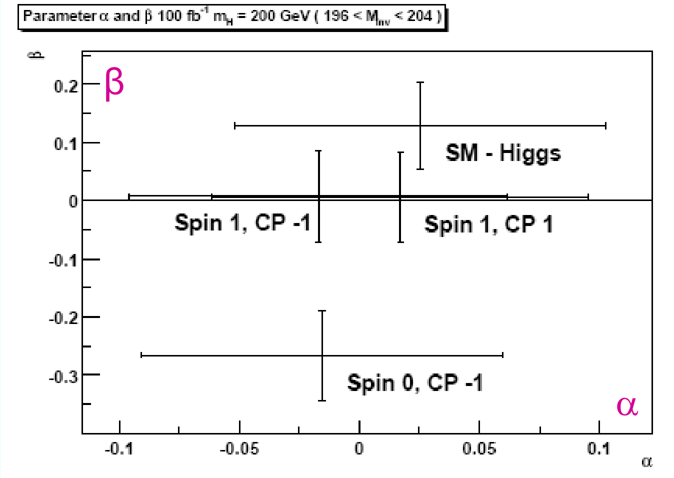
Dependence of α, β and R on m_H is shown below.
(0-) shows largest deviation from SM. (1,1) and (1,-1) excluded through R parameter for most m_H but for m_H~200GeV/c², main difference lies in β.
α can only discriminate between scalar and axialvector but difference is very small.



Spin and CP eigenvalues: Results

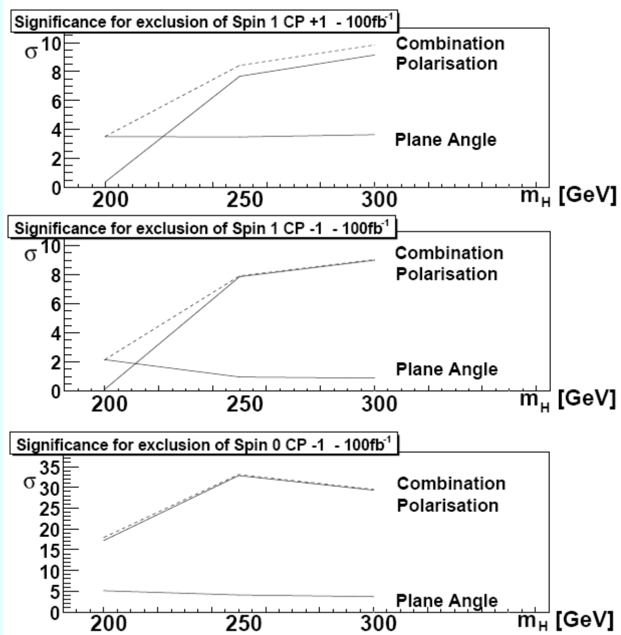
For 100 fb $^{-1}$
R can distinguish 4 hyp. for m_H>250 GeV/c^2,
and exclude (J,CP)=(0,-1) for m_H~200 GeV/c^2.





For m_H=200 GeV/c^2,
α can distinguish (1,-1) from SM (0,+1),
β can rule out (0,-1), but both stats limited

Significance (Δexpected values/$\sigma_{expected}$) of SM H.
Higher m_H, θ leads to good J and CP measurement.
For 300 fb $^{-1}$ and m_H=200 GeV/c^2
(1,+1) ruled out with 6.4σ, and (1,-1) 3.9σ.



Conclusions

J=1 ruled out
for m_H>230 GeV/c^2 with 100 fb $^{-1}$
and for m_H=200 GeV/c^2 with 300 fb $^{-1}$.
J=1 also ruled out if non-zero H$\gamma\gamma$ and Hgg couplings.
(J,CP)=(0,-1) ruled out
for $m_H\geq$200 GeV/c^2 with <100fb^{-1}.

Systematics dominated by background subtraction.

Spin and CP eigenvalues

Results

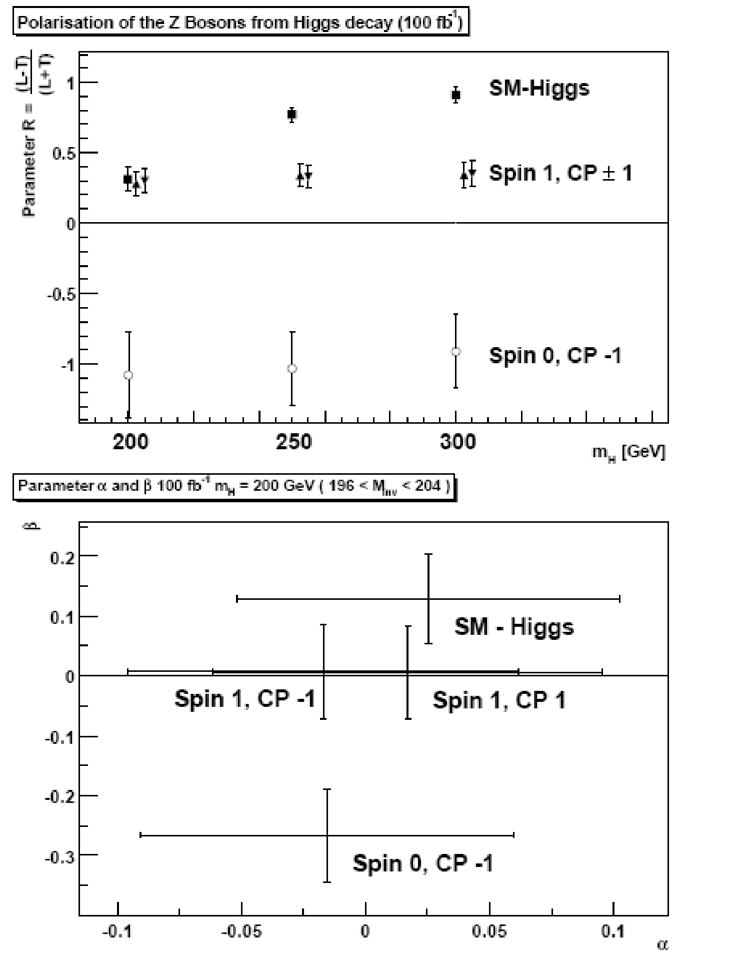


Figure 7: The parameter R for different Higgs massses (top) and α and β (bottom) for m_H = 200 GeV/c^2 using 100 fb^{-1}. The error scales with the integrated luminosity as expected.

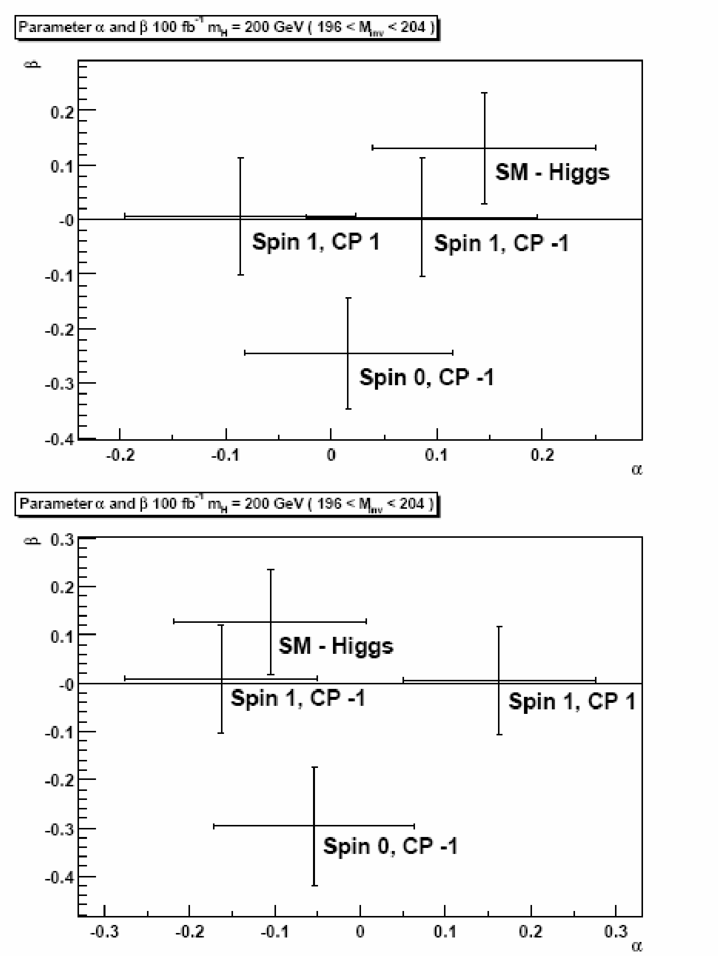


Figure 8: The parameter α depends on the signs of the $\cos(\theta)$ of the two Z bosons. The events where the signs are equal are used for the upper plot, those where the signs are different are used for the lower plot.

Spin and CP eigenvalues

Results

Fig9 shows the significance, the difference of the expected values divided by the expected error of the SM H.

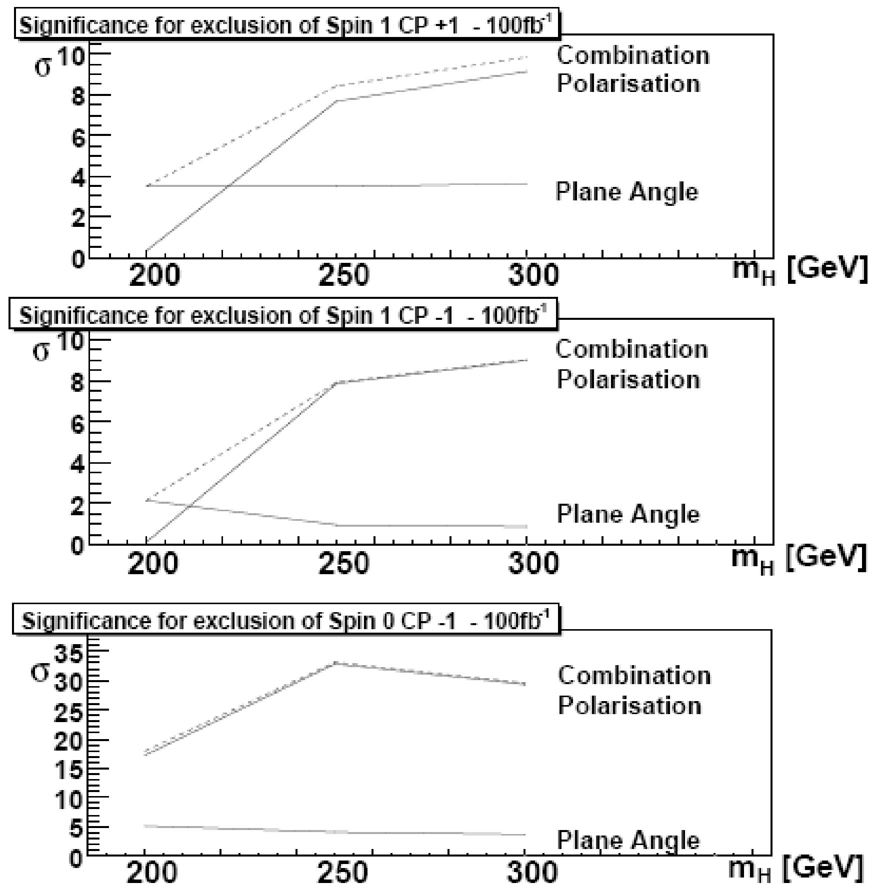


Figure 9: The overall significance for the exclusion of the non standard spin and CP-eigenvalue. The significance from the polar angle measurement and the decay-plane-correlation are plotted separately.

Spin and CP eigenvalues

For m_H<200 GeV/c^2
information on spin and CP can be extracted from the azimuthal separation of leptons
in the VBF process $qq \rightarrow qqH \rightarrow qqWW \rightarrow qq\ell\nu\ell\nu$
(see Asai etal article on VBF).

But also, hep-ph/0406323

Dührssen, with a little help from his theorist friends
Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld

Only one assumption :

strength of Higgs couplings to weak bosons does not exceed SM value

$\Gamma_V \leq \Gamma^{SM}_V$ V=W,Z

justified in any model with arbitrary number of Higgs doublets

e.g. MSSM.

Mere observation of Higgs
$\rightarrow$lower bound on couplings
thereby on Γ^{total}_H.

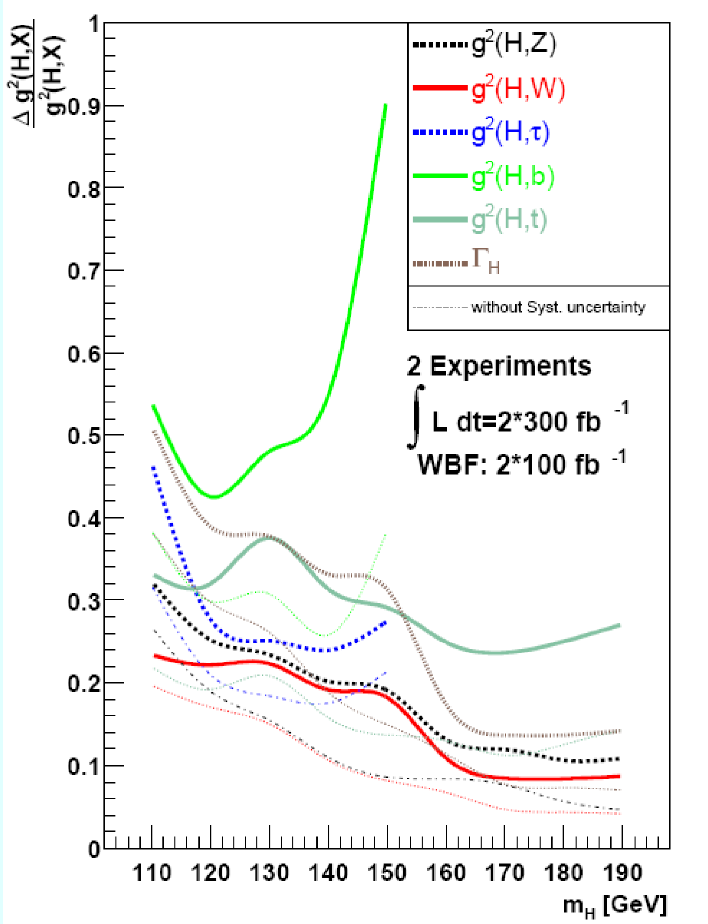
$\Gamma_V \leq \Gamma^{SM}_V$ assumption
combined with measurement of
$\Gamma^2_V/\Gamma^{total}$
in WBF production $\times$ $H \rightarrow VV$ decay
$\rightarrow$ upper bound on Γ_H

Absolute determination of remaining Higgs couplings
as well as for Γ_H
is then possible.

300 fb^{-1} and $110 < m_H < 190$ GeV/c^2

$\Delta g^2/g^2 \sim$ 10%-45% (except for b)

$\Delta\Gamma_H/\Gamma_H \sim$ 10%-50%



Coupling parameters
Tesla

Higgs couplings at TESLA 500 fb^{-1} $\sqrt{s}$=500 GeV
$\delta g_h / g_h$~. 2-10%

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_{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}	$\pm\ 0.041$	$\pm\ 0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\ 0.027$	$\pm\ 0.042$

Coupling parameters

By measuring rates of many (many) Higgs production and decay channels, various combinations of couplings can be determined.

At LHC, no clean way to determine σ^{total}_{Higgs}
+ some Higgs decay modes cannot be observed at LHC
$\rightarrow$ Only ratios of couplings (or partial widths) can be determined if no additional theoretical assumptions.

Coupling parameters: ATLAS study (ATL-PHYS-2003-030; Duehrssen)

For 300 fb^{-1}, ratios measurement with precision of 10% $\rightarrow$30%.
With an assumption on the upper limit for the W and Z couplings and on the lower limit for Γ_H,
absolute measurement of coupling parameters is possible,
where expected accuracy is 10%$\rightarrow$40%.

N.B. At an e^+e^- linear collider with $E_{cm}\geq$350GeV and 500 fb^{-1}
measurements would be improved by a factor 5.

Coupling parameters: counting events

Count $N_{signal}+N_{background}$
extrapolating $N_{background}$ from regions where only a few signal events are expected.

For signal channels determine
$\sigma \times BR_i(x)$
where x is a vector containing Higgs coupling parameters
and all quantities with systematic uncertainty (luminosity, detector effects, theoretical uncertainties, …).

For background channels, $\sigma \times BR_j(x)$ is treated as a systematic uncertainty.

Number of events for each channel and each m_H value
is the SM expectation value i.e. LO MC simulations without K factors.

Systematics:
efficiencies (ℓ and γ reconstruction, b and τ-tagging, WBF jets tag, jet veto, lepton isolation)
bgd norm.: N_{bgd} estimate by extrapol. meas. rate from bgd dominated region into signal region.
bgd Xsections
QCD/PDF and QED uncertainties for signal processes

Coupling parameters: signal and background channels

gg→H→ZZ and qqH→qqZZ	ZZ, tt and Zbb
gg→H→WW	WW,WZ,Wt and tt
qqH→qqWW	WW, WW (ew), Wt and tt
WH→WWW (3ℓ)	WZ,ZZ and tt
WH→WWW (2ℓ and 1 hadronic W-decay)	WZ,ZZ,W,Wt,t and tt
ttH(H→WW,t→Wb) (3ℓ and 1 hadronic W-decay)	tt,ttZ,ttW,tttt and ttWW
ttH(H→WW,t→Wb) (2ℓ and 2 hadronic W-decays)	tt,ttZ,ttW,tttt and ttWW
H→γγ	γγ,γ-jet and 2jets
qqH→qqγγ	γγ-2jets,γ-3jets,4jets
ttH(H→γγ)	ttγγ,tt and bb
WH(H→γγ)	Wγγ,γγ-jet,W γ-j, W-2j, γ-2j and 3j
ZH(H→γγ)	Zγγ
qqH→qqττ (2ℓ)	Z,WW and tt
qqH→qqττ (1ℓ and 1 hadronic τ decay)	Z and tt
ttH(H→bb)	ttbb and tt

Coupling parameters (Duhrssen ATLAS note)

The SM Higgs can be observed in a variety of channels,
in particular if its mass lies in the intermediate mass region 114 $< m_h <$ 250 GeV/c^2,
as suggested by direct searches and electroweak precision data.
The situation is similar for Higgs bosons in this mass range in many extensions of the SM.
Once a Higgs-like state is discovered, a precise measurement of its couplings will be
mandatory in order to experimentally verify (or falsify) the Higgs mechanism.

The couplings determined Higgs production cross sections and decay branching fractions.
By measuring the rates of multiple channels, various combinations of couplings can be determined.
There is no clean technique to determine the total Higgs production cross section,
such as a mssing mass spectrum at a linear collider (HZ-> X $\mu\mu$ recoil mass measurement???).
In addition, some Higgs decay modes cannot be observed at the LHC
e.g. $H \rightarrow gg$ or decays to light quarks will remain hidden below the overwhelming QCD dijet backgrounds.
e.g.2. $H \rightarrow bb$ suffers from large experimental uncertainties???

Hence only ratios of couplings (or partial widths) can be determined
if no additional theoretical assumptions are made.

The couplings of the Higgs boson to the weak bosons ($W^{\pm}$ and Z) are directly given by the mass of these bosons.
The coupling constants g_W and g_Z are

$g_W = 2m^2_W/v$

$g_Z = 2m^2_Z/v$.

Fermion masses are generated by introducing the Yukawa couplings of the fermions to the Higgs field.
This automatically implies couplings g_f negative for up type Yukawa couplings.

$|g_f| = \sqrt{2}\, m_f/v$

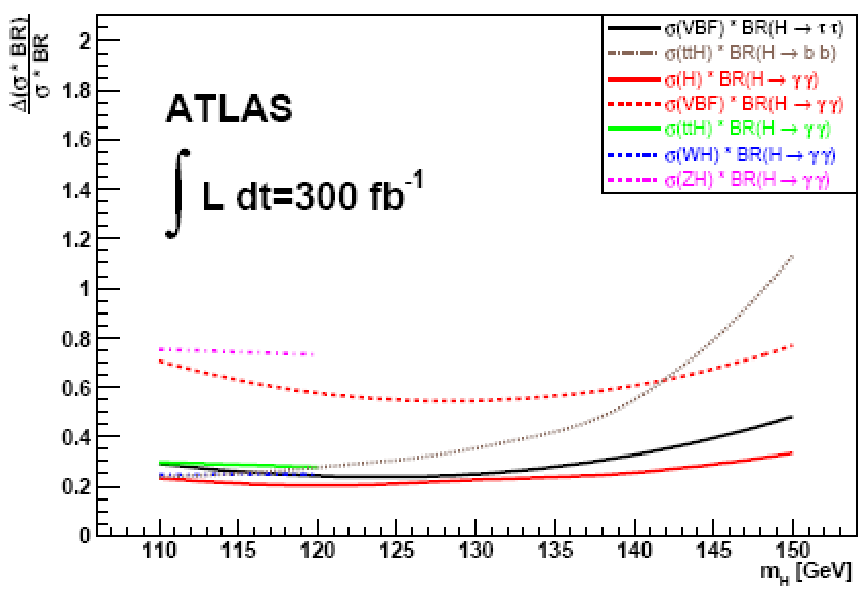
The discovery potential has been studied in a large number of channels using different prod. and decay modes.
Combining all these studies one can access and measure the couplings
g_W, g_Z, g_t, g_b, g_τ

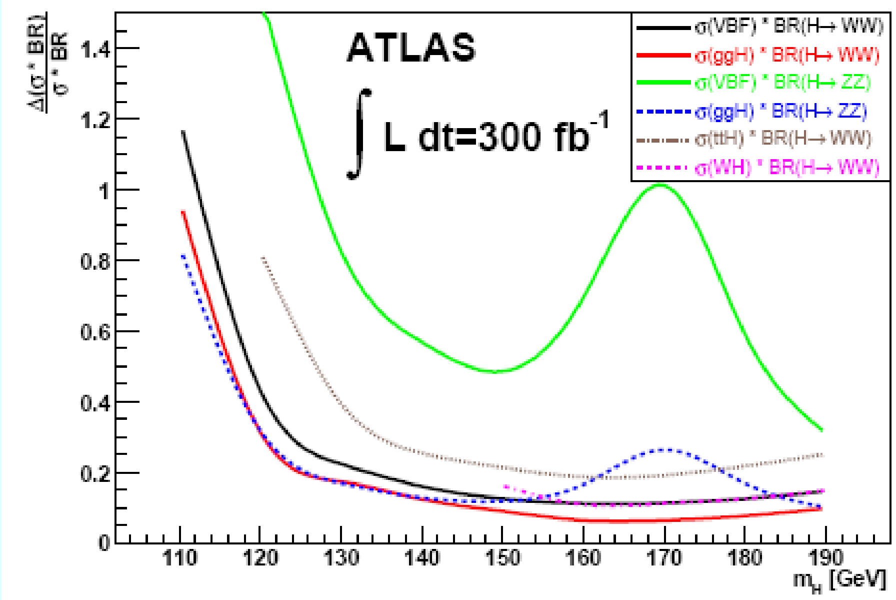
Coupling parameters: progressive assumptions

1. CP-even and spin-0 (can be more than one Higgs, degenerate in mass):
   only rate measurements are possible.
2. Only one Higgs:
   any additional Higgs separated in mass and may not contribute to channels considered here
   relative BRs BR(H→XX)/BR(H→WW) equivalent to Γ_X/Γ_W.
3. Only dominant couplings of SM are present (no extra particles or extremely strong couplings to light fermions):
   measurement of squared ratios of Higgs couplings g^2_X/g^2_W,
   and lower limit on Γ_H obtained from sum of visible decay modes.
4. Sum of all visible BRs ~ SM sum:
   absolute couplings and total width measurements.

Rates

from $H\to\gamma\gamma$, $H\to\tau\tau$ and $H\to bb$ for m_H<160 GeV/c², $H\to WW$ for m_H>160 GeV/c², $H\to ZZ$ for m_H>180 GeV/c².





Coupling parameters : relative BRs (2)

Reduce relative errors by reducing number of parameters to be fitted.
Not possible without additional assumptions i.e. only 1 Higgs boson.

$\sigma_j \times BR(H \to WW)$ and $BR(H \to XX)/BR(H \to WW)$ are fitted.
$H \to WW$ is used as normalisation : smallest error for most production modes and for $m_H > 120$ GeV/c^2.

For 30fb^{-1}, $\sigma(BR(H \to bb)/BR(H \to WW)) > 140\%$ (not shown).
All other relative BRs measured to better than 60% (for $m_H > 120$ GeV/c^2).

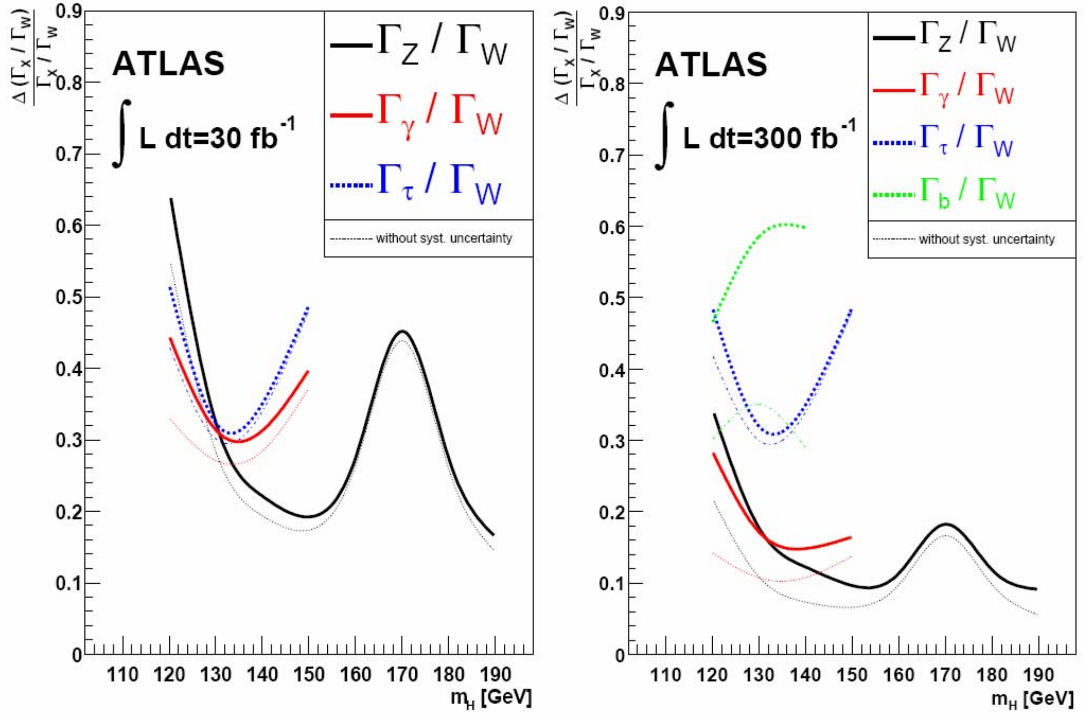


Figure 4: Relative error for the measurement of relative branching ratios. The dashed lines give the expected relative error without systematic uncertainties.

Coupling parameters : relative squared couplings (3)

Assuming only SM particles couple to Higgs, and no extremely enhanced couplings to light fermions,

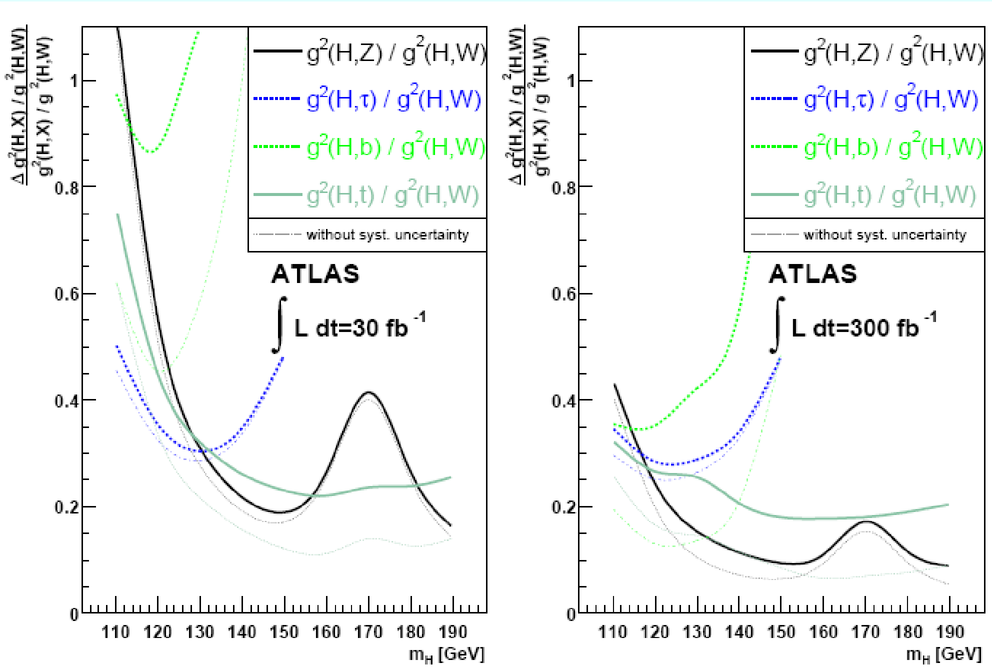
x: squared ratios of couplings as well as scale $g^2_W/\sqrt{\Gamma_H}$.
$\sigma_{\text{production}}$ and BRs expressed in terms of couplings and Γ_H :

$$
\begin{aligned}
\sigma_{ggH} &= \alpha_{ggH} \cdot g_t^2 \\
\sigma_{\mathrm{WBF}} &= \alpha_{\mathrm{WF}} \cdot g_W^2 + \alpha_{\mathrm{ZF}} \cdot g_Z^2 \\
\sigma_{t\bar{t}H} &= \alpha_{t\bar{t}H} \cdot g_t^2 \\
\sigma_{WH} &= \alpha_{WH} \cdot g_W^2 \\
\sigma_{ZH} &= \alpha_{ZH} \cdot g_Z^2 \quad .
\end{aligned}
$$

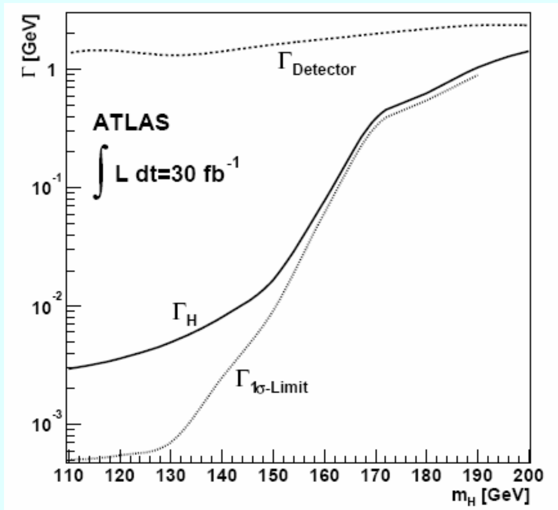
α and β from theory

$$
\begin{aligned}
\mathrm{BR}(H \to WW) &= \beta_W \frac{g_W^2}{\Gamma_H} \\
\mathrm{BR}(H \to ZZ) &= \beta_Z \frac{g_Z^2}{\Gamma_H} \\
\mathrm{BR}(H \to \gamma\gamma) &= \frac{\left(\beta_{\gamma(W)} \cdot g_W - \beta_{\gamma(t)} \cdot g_t\right)^2}{\Gamma_H} \\
\mathrm{BR}(H \to \tau\tau) &= \beta_\tau \frac{g_\tau^2}{\Gamma_H} \\
\mathrm{BR}(H \to b\bar{b}) &= \beta_b \frac{g_b^2}{\Gamma_H} \quad .
\end{aligned}
$$

Due to high rates of gluon fusion and ttH, top coupling ratio measured quite accurately even with only 30fb^{-1}.



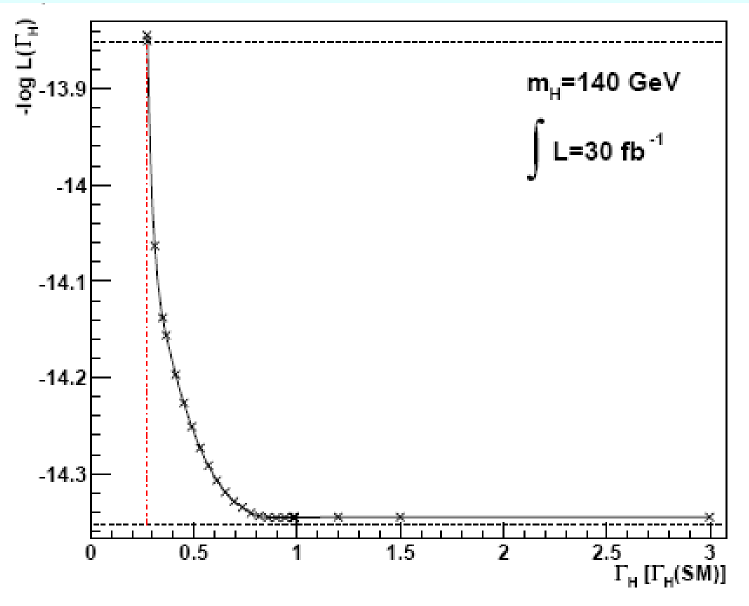
1 σ lower limit on Γ_H
$\to$ sum of all detectable Higgs decays.
Upper limit from direct meas. + SM expectation.



Coupling parameters : lower limit on Γ_H (3)

Based on fit of relative squared couplings,
extract a lower limit on Γ_H given by sum of all detectable Higgs decays.
Scale $g^2_W/\sqrt{\Gamma_H}$ split into 2 parameters g^2_W and Γ_H.

Without extra constraints,
no upper bound on Γ_H likelihood function
except upper limit Γ_H<1-2 GeV,
can be obtained from direct width measurements
for $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ$.



Lower 1σ limit
obtained from observable Higgs decays
and upper limit from direct measurement
together with the SM expectation.

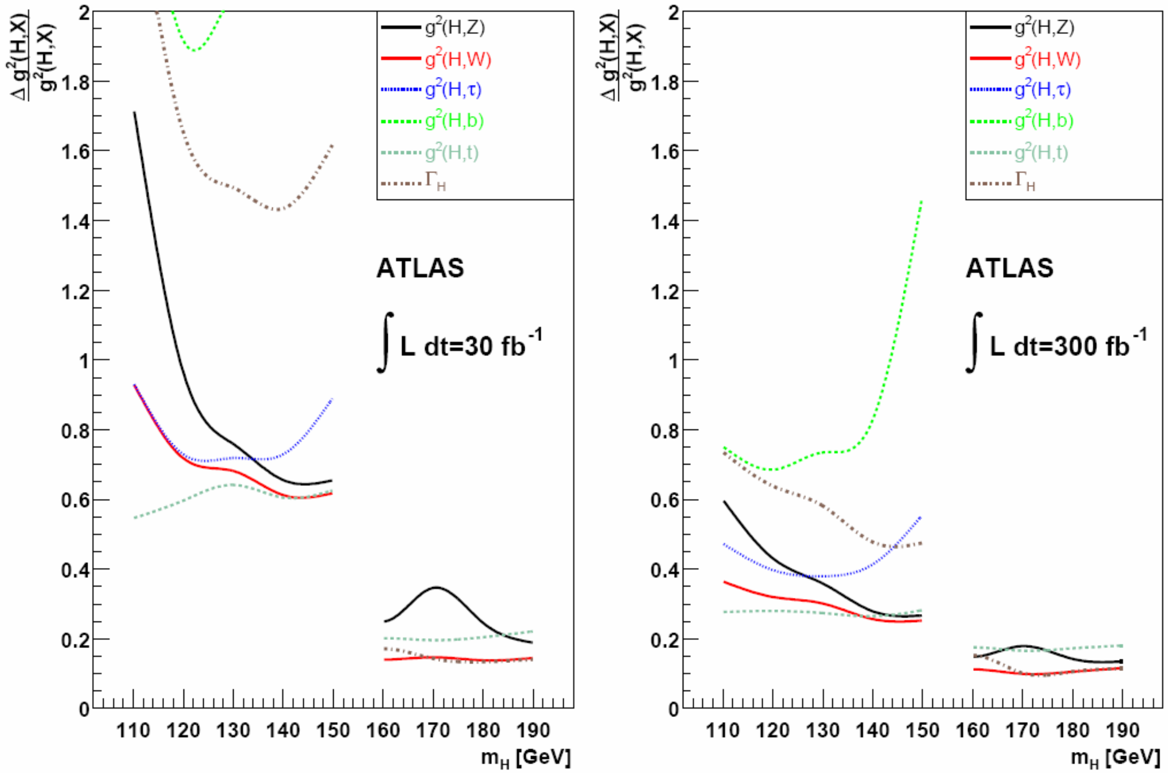


Figure 9: Relative error for the measurement of absolute couplings. The discontinuity at $m_H \approx 150$ GeV originates from the change in the assumption for the sum of all branching ratios. For $m_H \leq 150$ GeV the branching ratios into b and τ are included, above 150 GeV they are not added to the sum.

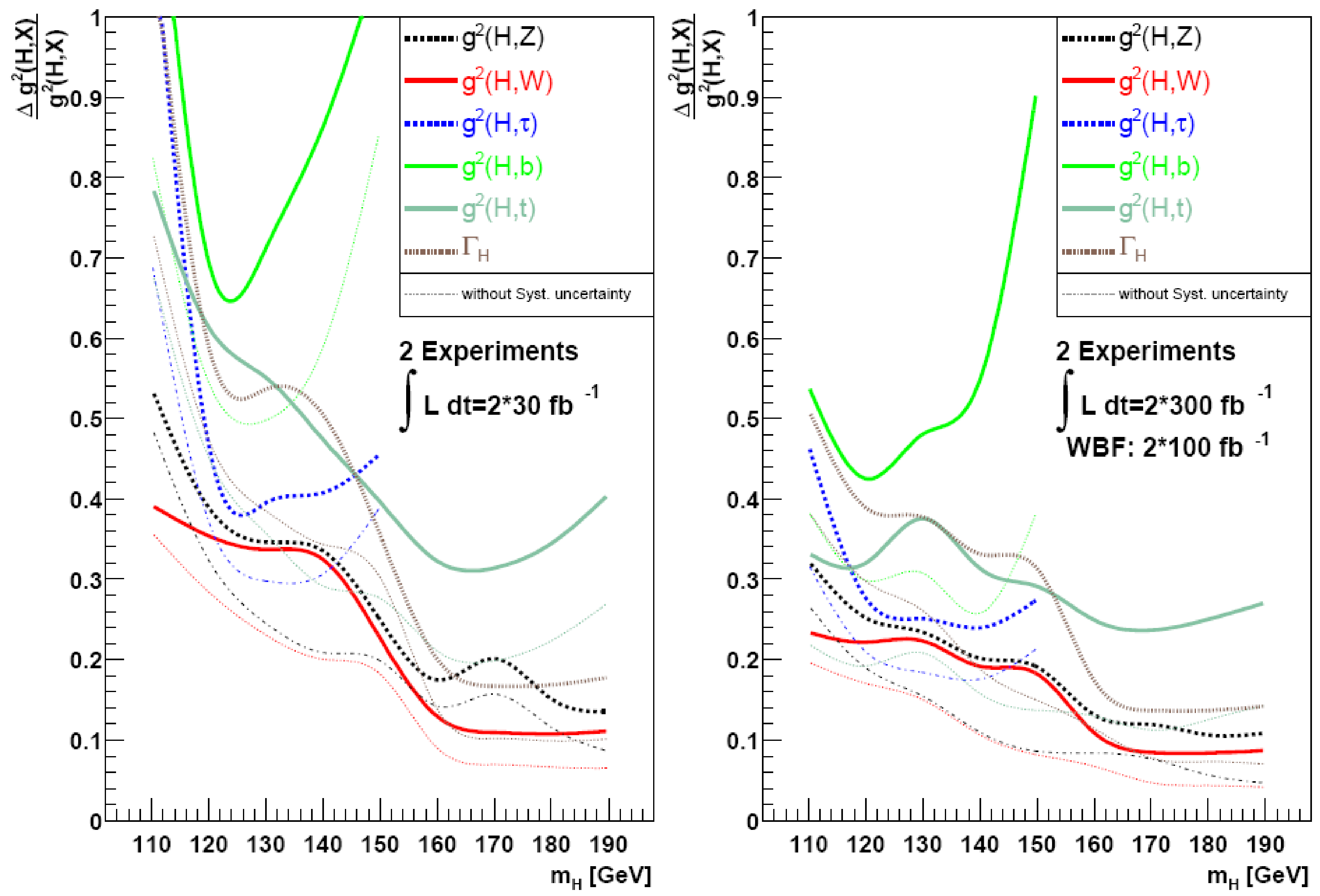
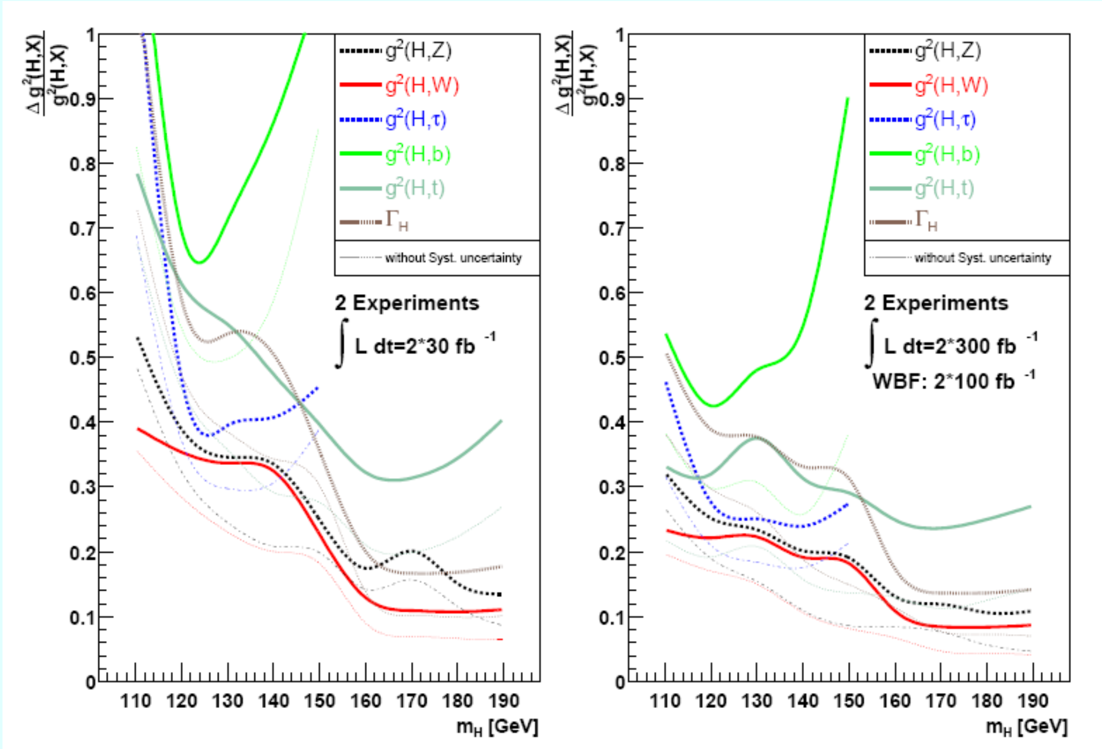


Figure 2: Relative precision of fitted Higgs couplings-squared as a function of the Higgs mass for the 2×30 fb^{-1} (left) and the $2 \times 300 + 2 \times 100$ fb^{-1} (right) luminosity scenarios. We make the weak assumption that $g^2(H,V) < 1.05 \cdot g^2(H,V,SM)$ $(V = W,Z)$ but allow for new particles in the loops for $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ and for unobservable decay modes. See text for details.

But also, hep-ph/0406323 (Dührssen etal)

Only assumption :
strength of Higgs couplings
does not exceed SM value
$\Gamma_V \leq \Gamma^{SM}_V$ V=W,Z.
Justified in any model
with arbitrary number of Higgs doublets
and true for MSSM in particular.
Observation of Higgs
puts lower bound on couplings and Γ_H,
combined with
Γ^2_V/Γ measurement from WBF H→VV
puts upper bound on Γ_H
→ absolute determination of Γ_H possible
and hence of
H couplings to gauge bosons and fermions.



Coupling parameters : conclusions

Γ_Z/Γ_W, Γ_γ/Γ_W and Γ_τ/Γ_W with 15%-60% precision for m_H>120 GeV/c^2 and 30 fb^{-1}.
If only SM particles couple to Higgs g^2_Z/g^2_W, g^2_τ/g^2_W and g^2_t/g^2_W to 15%-50% for m_H>125 GeV/c^2 and 30 fb^{-1}.
For 300 fb^{-1} g^2_t/g^2_W with 30% precision.
Lower limit on Γ_H

Systematics:
reco.+id.+tag. efficiencies (ℓ, γ, b, τ, WBF jets, jet veto, lepton isolation),
bgd norm. (N_{bgd} estimate by sideband extrapolation),
bgd Xsections, QCD/PDF and QED uncertainties for signal processes

Coupling parameters : conclusions

Systematics: eff, bgd norm and σ, pdfs and QED uncert. for signal

- Efficiencies: reconstruction (ℓ and γ) , tagging (b, τ, WBF jets, jet veto), lepton isolation
- Bgd normalization: N_{bgd} estimate by sideband extrapolation.
- Bgd Xsections
- QCD/PDF and QED uncertainties for signal processes

Coupling parameters : conclusions

For 300 fb^{-1}, ratios measurement with precision of 10% $\rightarrow$30%.
With an assumption on the upper limit for the W and Z couplings and on the lower limit for Γ_H,
absolute measurement of coupling parameters is possible,
where expected accuracy is 10%$\rightarrow$40%.

N.B. At an e^+e^- linear collider with $E_{cm} \geq 350$GeV and 500 fb^{-1}
measurements would be improved by a factor 5.

Coupling parameters (Duhrssen ATLAS note): measurement of rates

Rates $\sigma \times BR$ are measured for different channels.

$H \to WW$ measured with best accuracy :
for m_H>160 GeV/c², $H \to WW$ dominant.
$H \to \gamma\gamma$, $H \to \tau\tau$ and $H \to bb$ visible only for m_H<160 GeV/c²,
and error on rate measurement for the $H \to ZZ$ is 2X for 160 < m_H < 180 GeV/c².
At m_H=180 GeV/c², two on-shell Zs, reducing error on $H \to ZZ$ rate again.

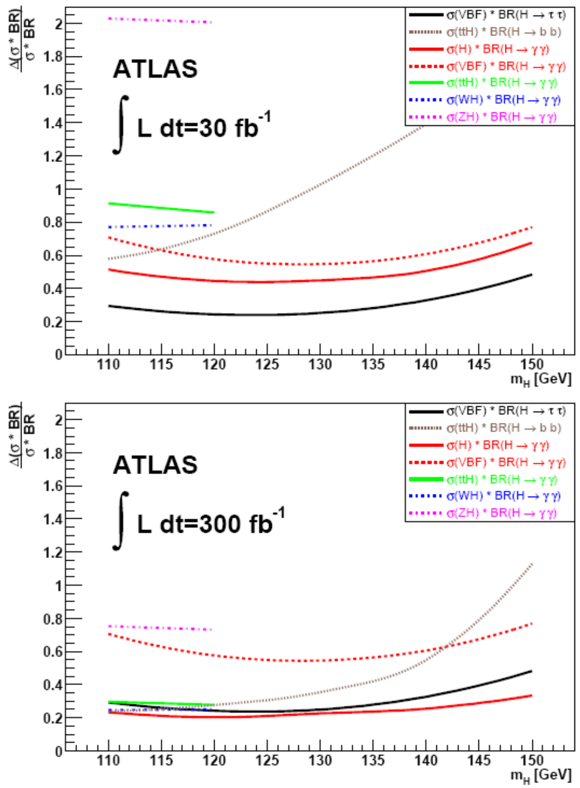


Figure 1: Relative error for the measurement of rates $\sigma \cdot$ BR for those channels that can be seen only for Higgs boson masses below 150 GeV.

Coupling parameters : relative BRs measurements

Reduce number of parameters to be fitted to reduce relative errors.
Not possible without additional assumptions: only 1 Higgs boson.

Two kinds of parameters are fitted:
$\sigma_j \times BR(H \to WW)$ and $BR(H \to XX)/BR(H \to WW)$.

$H \to WW$ is used as normalisation :
for most production modes and for $m_H > 120$ GeV/c^2, it has the smallest error.

For 30fb^{-1}, the error on $BR(H \to bb)/BR(H \to WW)$ > 140% (not shown).
This meas. depends entirely on the channel ttH(H->bb)
which has very low S/B and the total error is dominated by the syst. uncert. on the bgd.
All other relative BRs can be measured with an accuracy better tan 60% (for mH>120GeV).
For mH<120GeV, a normalis. to BR(H->gamgam) would ne more appropriate.

Higgs boson production times decay $H \to WW$	relative branching ratio	Higgs boson mass
$(\sigma \cdot \mathrm{BR})_{gg \to H(H \to WW)}$	$\frac{\mathrm{BR}(H \to ZZ)}{\mathrm{BR}(H \to WW)} \equiv \frac{\Gamma_Z}{\Gamma_W}$	110 GeV - 190 GeV
$(\sigma \cdot \mathrm{BR})_{qqH(H \to WW)}$	$\frac{\mathrm{BR}(H \to \gamma\gamma)}{\mathrm{BR}(H \to WW)} \equiv \frac{\Gamma_\gamma}{\Gamma_W}$	110 GeV - 150 GeV
$(\sigma \cdot \mathrm{BR})_{t\bar{t}H(H \to WW)}$	$\frac{\mathrm{BR}(H \to \tau\tau)}{\mathrm{BR}(H \to WW)} \equiv \frac{\Gamma_\tau}{\Gamma_W}$	110 GeV - 150 GeV
$(\sigma \cdot \mathrm{BR})_{WH(H \to WW)}$	$\frac{\mathrm{BR}(H \to b\bar{b})}{\mathrm{BR}(H \to WW)} \equiv \frac{\Gamma_b}{\Gamma_W}$	110 GeV - 140 GeV
$(\sigma \cdot \mathrm{BR})_{ZH(H \to WW)}$		

Coupling parameters : relative squared couplings

Assuming only SM particles couple to Higgs, and no extremely enhanced couplings to light fermions, all Higgs production and decay modes expressed by the Higgs couplings

g_W, g_Z, g_t, g_b and g_τ

Higgs total width cannot be measured $\rightarrow$ only ratios, or rather squared ratios, of couplings determined.
As well, scale which combines the coupling g_W and the total width

$g^2_W/\sqrt{\Gamma_H}$.

coupling parameter		Higgs boson mass
coupling ratio	$\frac{g_Z^2}{g_W^2}$	110 GeV - 190 GeV
coupling ratio	$\frac{g_\tau^2}{g_W^2}$	110 GeV - 150 GeV
coupling ratio	$\frac{g_b^2}{g_W^2}$	110 GeV - 140 GeV
coupling ratio	$\frac{g_t^2}{g_W^2}$	110 GeV - 190 GeV
scale	$\frac{g_W^2}{\sqrt{\Gamma_H}}$	110 GeV - 190 GeV

where all Higgs prod Xsections can be expressed by the couplings as
(α are proportionality constants between the coupl. squared and Xsections and are from theory

$$
\begin{aligned}
\sigma_{ggH} &= \alpha_{ggH} \cdot g_t^2 \\
\sigma_{\mathrm{WBF}} &= \alpha_{\mathrm{WF}} \cdot g_W^2 + \alpha_{\mathrm{ZF}} \cdot g_Z^2 \\
\sigma_{t\bar{t}H} &= \alpha_{t\bar{t}H} \cdot g_t^2 \\
\sigma_{WH} &= \alpha_{WH} \cdot g_W^2 \\
\sigma_{ZH} &= \alpha_{ZH} \cdot g_Z^2 \quad .
\end{aligned}
$$

The gluon fusion prod is not strictly propto the top coupling squared but has additional contribs from the interf. of a b-loop (SM: 7% at 110 GeV and 4% at 190 GeV) and from bb->H. But these add. contribs are ignored, so it is assumed that the b-coupling is not extremely enhanced (by factor of 10 or more compared to SM).

Coupling parameters **(Duhrssen ATLAS note): measurement of the relative squared couplings**

All Higgs BRs can be expressed in terms of the couplings and the total width.
The H->gamgam decay proceeds either by a W or a t loop with destructive interference between both loops.
The β coeffs relate the coupling strength to the appropriate H partial width.

$$\begin{aligned}
\mathrm{BR}(H \to WW) &= \beta_W \frac{g_W^2}{\Gamma_H} \\
\mathrm{BR}(H \to ZZ) &= \beta_Z \frac{g_Z^2}{\Gamma_H} \\
\mathrm{BR}(H \to \gamma\gamma) &= \frac{\left(\beta_{\gamma(W)} \cdot g_W - \beta_{\gamma(t)} \cdot g_t\right)^2}{\Gamma_H} \\
\mathrm{BR}(H \to \tau\tau) &= \beta_\tau \frac{g_\tau^2}{\Gamma_H} \\
\mathrm{BR}(H \to b\bar{b}) &= \beta_b \frac{g_b^2}{\Gamma_H} \quad .
\end{aligned}$$

As an example, one can write

$$\begin{aligned}
(\sigma \cdot \mathrm{BR})_{WH(H\to WW)}(\vec{x}) &= \sigma_{WH} \cdot \mathrm{BR}(H \to WW) \\
&= \alpha_{WH} \cdot \frac{g_W^2}{\sqrt{\Gamma_H}} \cdot \beta_W \cdot \frac{g_W^2}{\sqrt{\Gamma_H}}
\end{aligned}$$

$$\begin{aligned}
(\sigma \cdot \mathrm{BR})_{ggH(H\to ZZ)}(\vec{x}) &= \sigma_{ggH} \cdot \mathrm{BR}(H \to ZZ) \\
&= \alpha_{ggH} \cdot \frac{g_t^2}{g_W^2} \cdot \frac{g_W^2}{\sqrt{\Gamma_H}} \cdot \beta_W \cdot \frac{g_Z^2}{g_W^2} \cdot \frac{g_W^2}{\sqrt{\Gamma_H}}
\end{aligned}$$

Coupling parameters (Duhrssen ATLAS note): measurement of the relative squared couplings

The meas. of the top coupling ratio if no restriction on the b-coupling is applied and what is possible if the b-coupling ratio is restricted to be within a factor of 10 or 50 of the SM value.

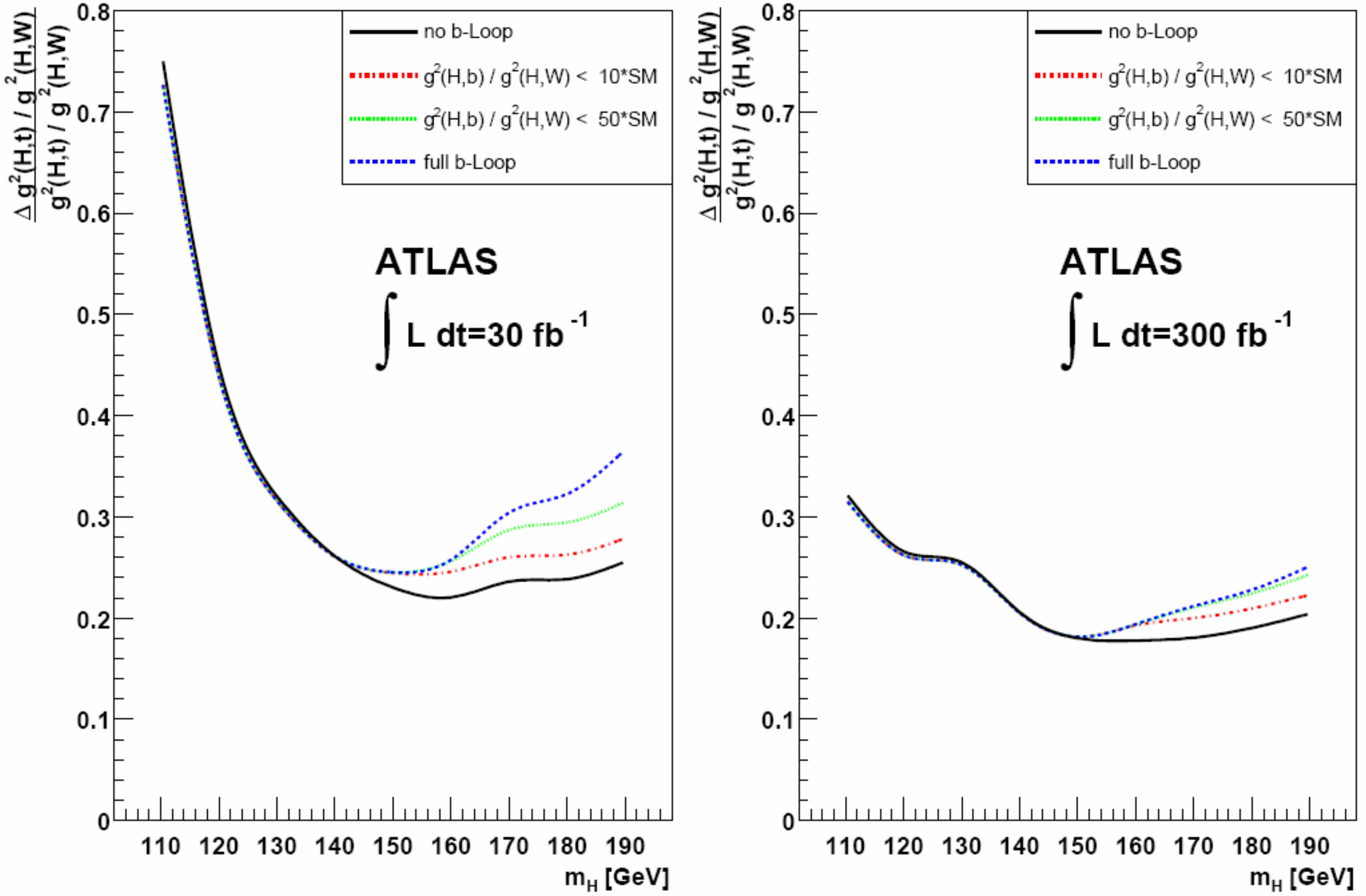


Figure 6: Relative error of $\frac{g_t^2}{g_W^2}$, if b-coupling effects are taken into account for the GF production. The black line corresponds to the result shown in Figure 5.

Coupling parameters (Duhrssen, Heinemeyer…)

In this analysis, only a very mild theoretical assumption is made which is valid in general multi HIggs doublet models. In this class of models, the strength of the Higgs-gauge-boson couplings does not exceed the SM value.
The existence of such an upper bound is already sufficient to allow the extraction of absolute couplings rather than coupling ratios.
It is assumed that the weak boson fusion channels are to suffer substantially from pile-up problems under high lumi running conditions (making forward jet tagging and central jet veto fairly inefficient).

In order to determine the properties of a physical state such as a Higgs boson, one needs at least as many separate meas. as properties to be measured.
Although the Higgs is expected to couple to all SM particles, not all these decays would be observable.
Very rare recays (e.g. electrons) would have no observable rate, and other modes are unidentifiable QCD final states at the LHC (gluons or quarks lighter than bottom).
The LHC will however be able to observe H decays to photons, weak bosons, tau leptons and b quarks, in the range of H masses where the BR is not too small.

For a Higgs in the intermediate mass range (114-250), the total width is small enough to use the narrow width approximation in extracting couplings. The rate is to good approximation given by:

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

where Γ_p is the H partial width.
The LHC will have access to or provide upper limits on combinations of
Γ_g, Γ_W, Γ_Z, Γ_γ, Γ_τ and Γ_b

and the square of the top Yukawa coupling.

The question in this article is how well LHC measurements of a single Higgs resonance can determine the various Higgs boson couplings or partial widths.

Coupling parameters : hep-ph/0406323

The ratios of couplings or partial widths can be extracted in a fairly model-independent way,
further theoretical assumptions are necessary in order to determine absolute values of the couplings
to fermions and bosons and of the total width.
We assume here that the strength of the Higgs-gauge-boson couplings does not exceed the SM value.

$\Gamma_V \leq \Gamma^{SM}_V$, V=W,Z

This assumption is justified in any model with an arbitrary number of Higgs doublets
(with or without additional Higgs singlets), and it is true for the MSSM in particular.
Hence there is an upper bound on the H coupling to weak bosons,
and the mere observation of H prod. puts a lower bound on the prod. couplings and thereby total width of H.
The upper contraint,
combined with a meas. of Γ^2_V/Γ from observation of H->VV in WBF
then puts an upper bound on the width.
Thus an absolute determination of the Higgs total width is possible in this way.
Using this result, an absolute determination also becomes possible for H couplings to gauge bosons and fermions.

Coupling parameters (Duhrssen, Heinemeyer…):

Precision of partial widths for multi-Higgs-doublet models

???Γγ(W,t): H->γγ through qqH and ttH???

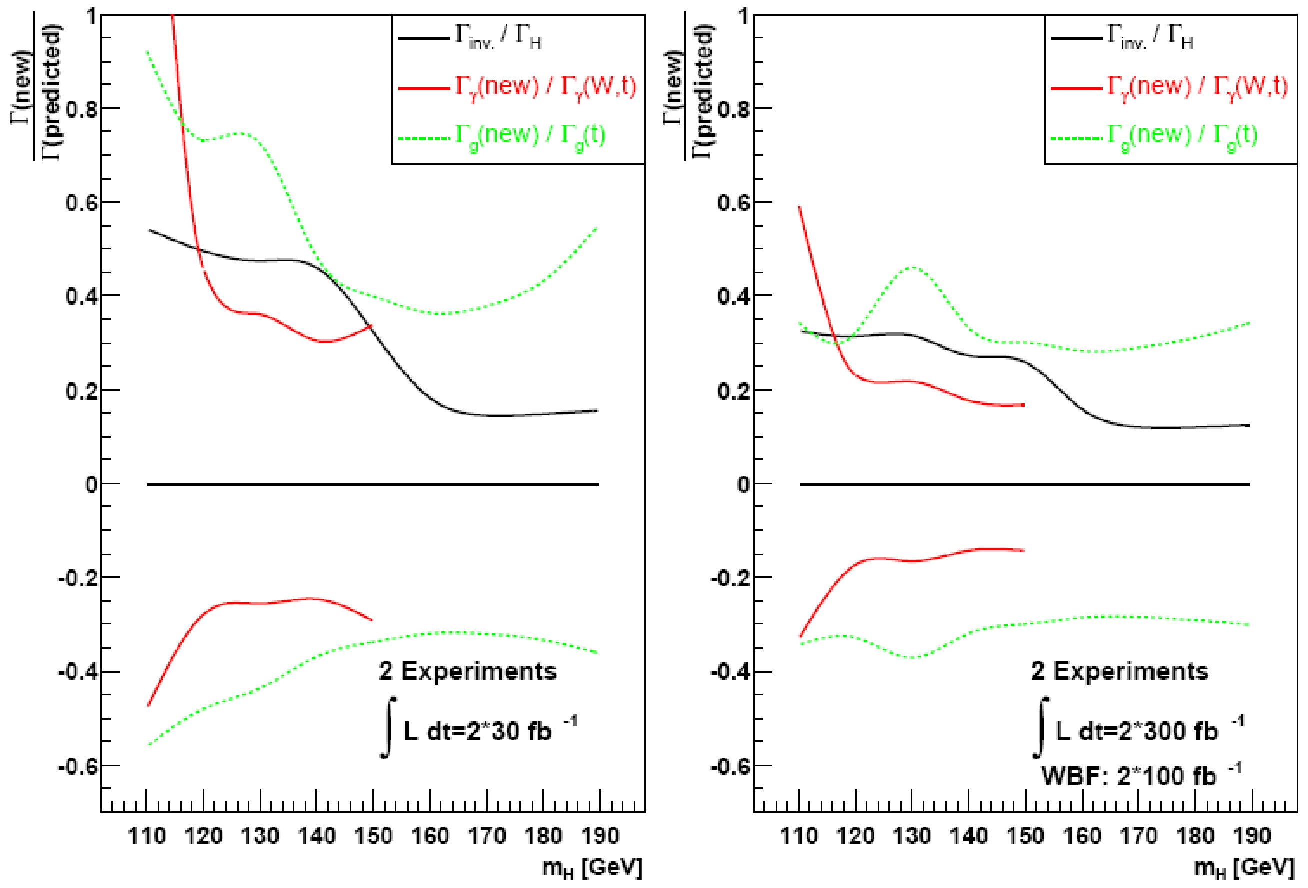


Figure 1: Relative precisions of fitted new partial widths as a function of the Higgs mass assuming that SM rates are observed with 30 fb^{-1} at each of two experiments (left) and 300 fb^{-1} at each of two experiments for all channels except WBF, for which 100 fb^{-1} is assumed (right). The new partial width can be due to new particles in the loops for $H \to \gamma\gamma$ and $gg \to H$ or due to unobservable decay modes. See text for details. Here we make the weak assumption that $g^2(H,V) < 1.05 \cdot g^2(H,V,SM)$ $(V = W,Z)$.

Coupling parameters (Duhrssen, Heinemeyer…):

Precision of couplings for multi-Higgs-doublet models

Systematic erros contribute up to half the total error, especially at high luminosity.
For mH<140 GeV the main contrib to the syst. uncert. is the bgd normalization from sidebands.
The largest contrib. is from H→bb for which 1/10<S/B<1/4. For the bgd norm, a syst.error of 10% is assumed, leading to a huge syst. error on Γ_b which is the main contrib to the total width Γ_H (BR(H→bb)=30-80%).
But a meas. of absolute couplings needs Γ_H as input
so all measurements of couplings share the large syst. uncert. on H->bb.

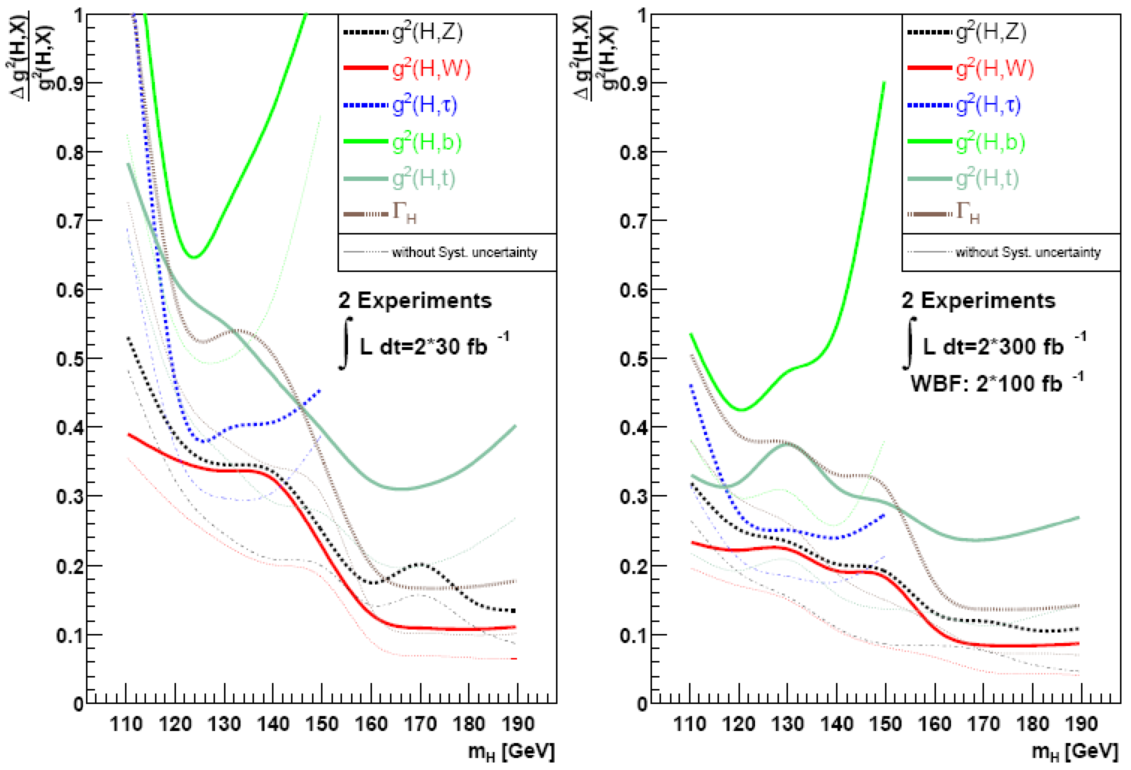


Figure 2: Relative precision of fitted Higgs couplings-squared as a function of the Higgs mass for the 2×30 fb^{-1} (left) and the $2 \times 300 + 2 \times 100$ fb^{-1} (right) luminosity scenarios. We make the weak assumption that $g^2(H,V) < 1.05 \cdot g^2(H,V,SM)$ $(V = W,Z)$ but allow for new particles in the loops for $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ and for unobservable decay modes. See text for details.

Coupling parameters (Duhrssen, Heinemeyer…):
Precision of couplings for multi-Higgs-doublet models

For mH>150 GeV two dominant contribs to the syst. error: bgd norms in GF, WBF
and ttH and QCD uncert. in GF and ttH Xsections,
especially evident in meas. of top coupling based on ttH channel.
Here the syst. uncert. contribute to half the error.
The precision of extracted couplings improves if more restrictive th. assumptions are applied.
hep-ph/0406323 and hep-ph/0406152.

If the values obtained for the H couplings differ from the SM predictions,
one can investigate at which significance the SM can be excluded from LHC meas. in the H sector alone.
e.g. if susy partners of the SM particles were detected at the LHC, this would of course rule out the SM.

Within the MSSM significant devaitions in the H sector could be observable at the LHC,
provided that the charged and the pseudoscalar Higgs masses are not too heavy
i.e. that decoupling is not completely realized.
Within the no-mixing benchmark scenario and with 300 fb-1, the LHC can distinguish the MSSM and the SM
at the 3sigma level up to mA~350 GeV and with 5sigma up to mA~250 GeV with the Higgs data alone.
The LHC will provide us a surprisingly sensitive first look at the Higgs sector
even though it cannot match the precision and model independence of analyses which are expected at the ILC.

Self coupling

Within Higgs mechanism, EW gauge bosons and fermions acquire mass through interaction with a scalar field.
Self interaction of scalar field induces, via non-vanishing field strength $v=(\sqrt{2}\,G_F)^{-1/2}$~246 GeV,
spontaneous breaking of EW $SU(2)_L \times U(1)_Y$ symmetry down to $U(1)_{EM}$ symmetry.
To establish Higgs mechanism experimentally, must reconstruct self-energy potential of SM

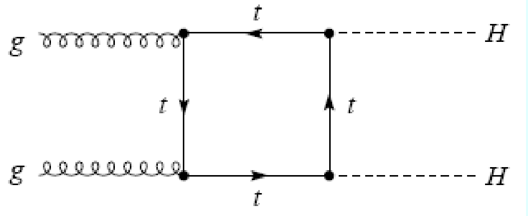
$$V=\lambda(\Phi^\dagger\Phi - v^2/2)^2,$$

with a minimum at $\langle\Phi\rangle_0 = v/\sqrt{2}$.
Measurement of the Higgs self-couplings of the Higgs boson, which can be read off from the potential

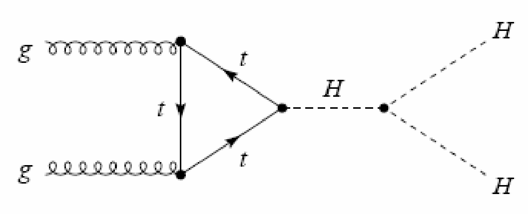
$$V= (m^2_H/2)\, H^2 + (m^2_H/2v)\, H^3 + (m^2_H/8v^2)\, H^4$$

In the SM, trilinear and quadrilinear vertices are uniquely determined by $m_H=\sqrt{(2\lambda)}v$.

At LHC, search for HH: concentrate on GF $gg \rightarrow HH$.
WBF $qq \rightarrow qqHH$, W/Z ass. prod. $qq \rightarrow VHH$, ass tt prod. $gg,qq \rightarrow ttHH$.
N.B. For HHH, Xsections >10 (10^3) smaller than for HH at the LHC (LC).



For m_H<140 GeV/c^2, dominant BR($H \rightarrow bb$) swamped by QCD bbbb bgd.
For m_H<140 GeV/c^2, BR($H \rightarrow WW$) dominates:
fully hadronic decays $\rightarrow$ QCD multi jets dwarf the signal.
1 or 2 leptonic decays $\rightarrow$ large W+multijets and WW+multijets bgds.
all leptonic decays : $(\ell'^+\nu\ell''^-\nu)\,(\ell'^+\nu\ell''^-\nu)$ $\rightarrow$ large suppression due to small BRs.
3 leptonic decays : $(jj\ell^\pm\nu)\,(\ell'^+\nu\ell''^-\nu)$ $\rightarrow$ σ too small at LHC (8 evts at best)



Channel investigated (ℓ = e,μ)
(hep-ph/0211224 Baur,Plehn,Rainwater: signal $\rightarrow$ 1 loop ME with finite m_{top}, bgd $\rightarrow$ LO ME) :
2 leptonic decays same sign dilepton : $gg \rightarrow HH \rightarrow (W^+W^-)(W^+W^-) \rightarrow (jj\ell^\pm\nu)\,(jj\ell'^\pm\nu)$
N.B. $gg \rightarrow HH \rightarrow (W^+W^-)(ZZ)$ could also be considered in the future.
Main backgrounds
WWWjj, ttW but also: WWjjjj, WZjjjj, ttZ,ttj,tttt,WWWW and WWZjj
As well, overlapping evts and double parton scattering.

Self coupling: same sign dilepton final state

$\leq$ 50 signal events with 300 fb^{-1} for $150<m_H<200$ GeV/c^2
BR($H\rightarrow WW^*$) too small for $m_H<150$ GeV/c^2, $\sigma(gg\rightarrow HH)$ too small for $m_H>200$ GeV/c^2.
Backgrounds:
WWWjj and ttW largest bgd, ttZ moderate, WZjjjj can be separated from the signal,
WWjjjj and tttt negligible: tttt suppressed by m_{top} and WWjjjj small,
ttj extremely sensitive $p_T(\ell)$ cut: warning of caution by Baur etal. for ME calc.
hadronization, evt pileup, extra jets from ISR or FSR, detector resolution effects negligible.

Discrepancy with ATLAS analysis (ATL-PHYS-2002-029):
Baur etal. and ATLAS overall normalization of signal, WWWjj, ttW and tttt bgds agree reasonably,
but Baur etal. σ(WZjjjj) 10 $\times$ ATLAS σ $\rightarrow$ virtual photon exchange not taken into account by ATLAS,
and no ttZ in ATLAS.
Comparison of ttj ME with ATLAS PYTHIA not possible $\rightarrow$ strong dependence of σ on $p_T(\ell)$ cut.

Invariant mass distribution (Baur etal.)

Backgrounds are multi body production processes,
$\rightarrow m^{system}_{invariant}$ distribution peaks at values significantly above threshold.
Signal is 2 body : m_{inv} exhibits sharper threshold behavior, but with 2 ν, m_{inv} cannot be reconstructed.
However m_{vis} will retain most of expected behavior especially for lower m_H.
m_{vis} allows for a χ^2 test, strengthening self-coupling extraction
(not used in ATLAS study).

Self coupling: invariant mass distribution (Baur etal.)

Backgrounds are multi body production processes,

$\rightarrow m^{system}_{invariant}$ distribution peaks at values significantly above threshold.

Signal is 2 body : m_{inv} exhibits sharper threshold behavior, but with 2 ν, m_{inv} cannot be reconstructed.

However m_{vis} will retain most of expected behavior especially for lower m_H.

m_{vis} allows for a χ^2 test, strengthening self-coupling extraction

Self coupling: extracting Higgs self-coupling

Gluon fusion production process through fermion triangle and box diagrams
Non-standard self couplings affect only triangle diagram, contribute only to J=0 partial wave
$\rightarrow$ affect m_{vis} mostly at small values.

Figure:
2 non-standard values of $\lambda_{HHH}=\lambda/\lambda_{SM}$.
Box and triangle diagrams interfere destructively $\rightarrow$ $\sigma(gg\rightarrow HH) < \sigma(gg\rightarrow HH)_{SM}$ for $1<\lambda_{HHH}<2.7$.
Absence of self coupling ($\lambda_{HHH}=0$) $\rightarrow$ $\sigma(gg\rightarrow HH) > 3 \times \sigma(gg\rightarrow HH)_{SM}$.
m_{vis} of signal peaks at smaller value than that of combined bgd for $m_H<200$ GeV/c^2

m_{vis} shape change induced by non-standard λ_{HHH} $\rightarrow$ derive 95%CL bounds on self-coupling by performing a χ^2 test.

Self coupling

Direct experimental investigation of Higgs potential
$\rightarrow$ test of EW symmetry breaking and mass generation mechanism
proof that fermion and weak boson masses generated by spontaneous symmetry breaking.

Signal:
exact one loop matrix elements (ME) for finite m_{top}.
Final state spin correlations for $H \rightarrow WW \rightarrow 4f$ fully taken into account, together with finite Γ_W and Γ_H effects.
Backgrounds:
exact LO ME, except for WWjjjj and WZjjjj
and simple order of magnitude for overlapping and double parton scattering.
Uncertainties in derivation estimated to be O(20%).

At an LC, $\sqrt{s}$=500-800 GeV, λ can only be determined for m_H<140 GeV/c^2.
For m_H=120 GeV/c^2 $\sqrt{s}$=500 GeV and 1ab^{-1}, λ determined to ±0.2 (1σ).
LHC and LC thus complement each other in their abilities to determine λ.
For m_H=180 GeV/c^2 $\sqrt{s}$=3 TeV and 5ab^{-1}, λ determined to ±0.08 (1σ).

More detailed simulations taking into account detector effects,
as well as higher order QCD corrections are needed.

Self coupling

Inclusive SM H pair prod. at LHC in order to determine λ
reminding ourselves of the H field potential
$V(\Phi)=(\lambda/4!)\,(\Phi^\dagger\Phi)^2 - \mu^2\,(\Phi^\dagger\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda\,(\Phi^\dagger\Phi)^2$???
and, after SB, the physical scalar mass
$m_h^2 = \lambda\, v^2$.
with $v=(\sqrt{2}G_F)^{-1/2}$
Regarding the SM as an effective theory, the H boson self-coupling λ is per se a free parameter.
S-matrix unitarity gives the constraint $\lambda \leq 8\pi/3$.
Anomalous H self-coupling appears in various BSM scenarios such as models with a composite H,
or in 2 H doublet models e.g. in the MSSM.
To measure λ and thus determine the H potential, experiments must at a minimum observe the H boson!

Both the trilinear coupling gHHH and the quartic coupling g_{HHHH} have to be measured separately
in order to fully determine the H potential.
While g_{HHH} can be meas. in H pair prod., triple H prod. is needed to probe g_{HHHH}.
Since the Xsections for HHH prod processes are more than a factor 10^3 smaller than for pairs at ILCs
and about an order of magnitude smaller at LHC,
the quartic coupling will likely remain elusive even at the highest collider energies and luminosities
considered so far.
So in the following only $g_{HHH}=3\lambda v$ is considered.

For an e+e- linear collider Ecm=500 GeV and 1ab-1, λ could be measured with a precision of 20% if mH=120GeV.
And there are many of these studies that have been performed.
In contrast, only since ~2000 have the LHC potential for such a meas. been studied.
An SLHC study has also been performed. With 6000fb-1, a precision of 25% (stats only) can be obtained.

Self coupling

Several mechanisms for pair prod of H.
Via GF gg→HH, WBF qq→qqHH, W or Z associated prod. qq→VHH,
and associated tt prod. gg,qq→ttHH.

Studies have concentrated on the dominant GF prod.
For mH<140GeV, H→bb dominates the BR but the QCD bbbb bgd swamps the signal.
For mH>140 GeV, H→WW dominates.
If all Ws decay hadronically, QCD multi jet prod. dwarfs the signal.
The same goes for one or two Ws decaying leptonically + respectively 6 or 4jets,
where the bgds W+multijet and WW+multijet are very large.
This leaves the same sign dilepton final states : $(jj\ell^{\pm}\nu)$ $(jj\ell'^{\pm}\nu)$,
modes where 3 Ws decay leptonically : $(jj\ell^{\pm}\nu)$ $(\ell'^{+}\nu\ell''^{-}\nu)$
and the all leptonic decay modes : $(\ell'^{+}\nu\ell''^{-}\nu)$ $(\ell'^{+}\nu\ell''^{-}\nu)$.
The last suffer from a large suppression due to small BRs.
Hence the two other modes are considered.

The channels investigated by Baur,Plehn,Rainwater are:
$gg\to HH\to(W^+W^-)(W^+W^-)\to(jj\ell^{\pm}\nu)$ $(jj\ell'^{\pm}\nu)$???why???
and
$gg\to HH\to(W^+W^-)(W^+W^-)\to(jj\ell^{\pm}\nu)$ $(\ell'^{+}\nu\ell''^{-}\nu)$???why???
where ℓ and ℓ' = e,μ
but $gg\to HH\to(W^+W^-)(ZZ)$ could also be considered in the future???.

main sources of bgd: WWWjj and ttW
but also: WWjjjj, WZjjjj, ttZ,ttj,tttt,WWWW and WWZjj
One also to worry about bgds from overlapping evts and double parton scattering (multiple hard interactions).

Self coupling: same sign dilepton final state

The total Xsections calculated by Baur, Plehn, Rainwater

TABLE II. Higgs pair signal and background cross sections (fb) for $pp \to \ell^{\pm}\ell'^{\pm} + 4j$ ($\ell, \ell' = e, \mu$) at (a) the LHC ($\sqrt{s} = 14$ TeV) and (b) at the VLHC ($\sqrt{s} = 200$ TeV), imposing the cuts listed in Eqs. (5) – (7), and as a function of the Higgs boson mass (GeV). The background labeled "pileup" represents a rough estimate of the combined $WWWjj$, $t\bar{t}W$, $t\bar{t}Z$, $WZjjjj$, $WWjjjj$ and $t\bar{t}t\bar{t}$ cross section from overlapping events and double parton scattering. Cross sections at the SLHC are identical to those in the LHC case with the exception of the pileup cross section, which is about a factor 3.7 larger than at the LHC. The last column, labeled $\mathcal{B}_{tot}$, shows the total background cross section.

(a) LHC										
m_H	HH	$WWWjj$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}j$	$WZjjjj$	$WWjjjj$	$t\bar{t}t\bar{t}$	pileup	$\mathcal{B}_{tot}$
150	0.07	0.36	0.22	0.05	0.08	0.15	0.005	0.002	~ 0.03	0.90
160	0.19	0.49	0.22	0.05	0.08	0.15	0.005	0.002	~ 0.03	1.03
180	0.18	0.40	0.22	0.05	0.08	0.15	0.005	0.002	~ 0.03	0.94
200	0.08	0.29	0.22	0.05	0.08	0.15	0.005	0.002	~ 0.03	0.83
(b) VLHC										
m_H	HH	$WWWjj$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}j$	$WZjjjj$	$WWjjjj$	$t\bar{t}t\bar{t}$	pileup	$\mathcal{B}_{tot}$
140	2.2	14.9	5.8	7.4	7.7	8.1	0.13	6.13	~ 20	70.2
150	6.5	17.0	5.8	7.4	7.7	8.1	0.13	6.13	~ 20	72.3
160	15.8	20.4	5.8	7.4	7.7	8.1	0.13	6.13	~ 20	75.7
180	16.0	17.9	5.8	7.4	7.7	8.1	0.13	6.13	~ 20	73.2
200	8.7	14.3	5.8	7.4	7.7	8.1	0.13	6.13	~ 20	69.6

Self coupling: same sign dilepton final state

At most 50 signal events with 300 fb^{-1} :
BR($H \rightarrow WW^*$) too small for m_H<150 GeV/c^2, $\sigma(gg \rightarrow HH)$ too small for m_H>200 GeV/c^2.

• WWWjj and ttW largest bgd
• ttZ moderate
• WZjjjj can be separated from the signal
• WWjjjj and tttt negligible:
tttt suppressed by m_{top} while σ(WWjjjj) small because qg and gg do not contribute to same sign W pair prod.
• ttj Xsection is extremely sensitive to the lepton pT cut,
but the authors warn that the ME calc. should be viewed with some caution.
• effects from hadronization, evt pileup, extra jets from ISR or FSR, as well as det. resoln effects
may significantly affect the Xsection.

A full detector simulation needs to be performed…

Our numerical (Baue, Plehn, Rainwater) results for the overall norm of the signal, the WWWjj, ttW and tttt bgds
agree resonably well with the ATLAS analysis.
For WZjjjj, we find a Xsection which is about a factor 10 larger.
The discrepancy can be traced to the contribution from virtual photon exchange
which was not taken into account in the ATLAS analysis.
No results for ttZ prod. is given in the ATLAS an.
A meaningful comparison of our matrix element based calc. of the ttj bgd and the pythia based estimate in
the ATLAS an. is not possible due to the strong dependence of the Xsection on the lepton pT.

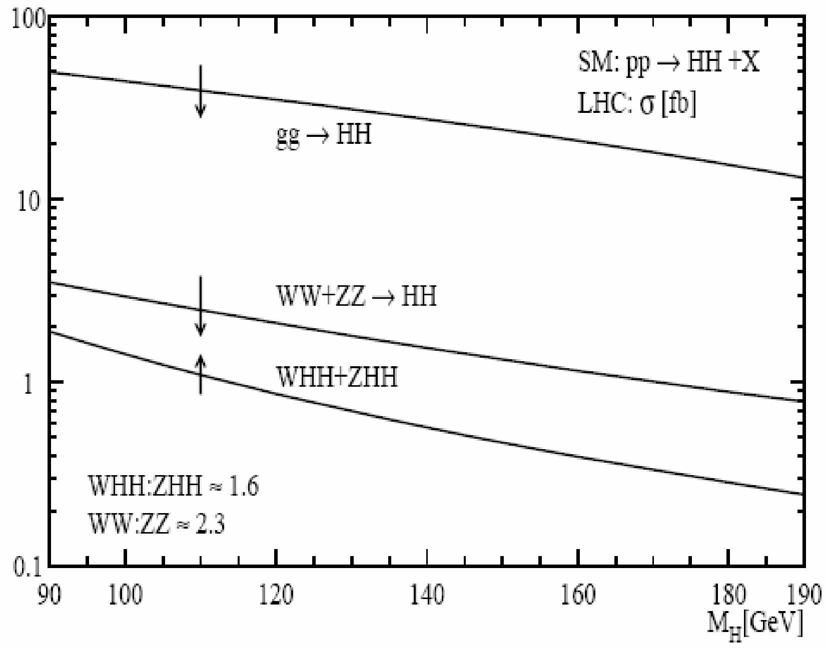


Figure 4: NLO cross section for Higgs pair production as a function of the Higgs mass. The contributions of the various production channels are shown. The vertical arrows show the effect on the cross section of a variation in the self-coupling strength from 0.5 to 1.5 with respect to the SM value.

Self coupling: VLHC

At a pp collider with Ecm=200 TeV, the Xsections of processes dominated by gluon fusion (gg->HH, tttt,ttZ,ttj) are about a factor 100-3000 larger than that at the LHC.
In contrast, the Xsections of processes dominated by q-g fusion or qq scatt such as WWWjj,ttW and WWjjjj prod. increase by only a factor 25-45. As a result, the ttZ,ttj and ttttbgds are relatively more important at the VLHC.
The Xsections due to overlapping events and double parton scatt increase by almost 3 orders of magnitude and thus may well compete insize with WWWjj prod,
unless the vertex positions of the overlapping events are resolved.
Since the signal is purely gluon induced,
the overall S/B ratio at the VLHC is about a factor 2 better than at the LHC.

Self coupling: invariant mass distribution (Baur etal.)

Backgrounds are multi body production processes,
$\rightarrow m^{system}_{invariant}$ distribution peaks at values significantly above threshold.
Signal is 2 body : m_{inv} exhibits sharper threshold behavior, but with 2 ν, m_{inv} cannot be reconstructed.
However m_{vis} will retain most of expected behavior especially for lower m_H.
This distribution

$$m_{vis}^2 = \left[\sum_{i=\ell,\ell',\text{jets}} E_i \right]^2 - \left[\sum_{i=\ell,\ell',\text{jets}} \mathbf{p}_\mathbf{i} \right]^2$$

was not considered in the atlas analysis and is what makes possible a chi2 based test to improve extraction of the Higgs boson self-coupling.

All Baur, Plehn, Rainwater calcs consistently performed at LO i.e. precisely 4 jets (partons) in the final state.
In practice, one expects a significant fraction of signal events to contain some ISR jets.
It is thus natural to construct the vis.mass from the 4 highest pT jets.
Nonetheless, a full calculation of the NLO QCD corrections to gg->HH with finite top mass is needed.
Insight may also be gained from performing a calc. where the gg->HH matrix elements are interfaced with an evt generator such as pythia.

In using pythia for the additional jet rad., one has to be careful.
the radiation of soft and collinear jets from ISR is the main source of the large QCD corrections to the total signal Xsection. the ISR modeled by pythia effectively resums the leading effects of precisely this rad. and includes it in the topology of the final state.
Normalizing the rate to the leading order total Xsection is therefore inconsistent and the result arbitrary and not as often as claimed, a conservative estimate,

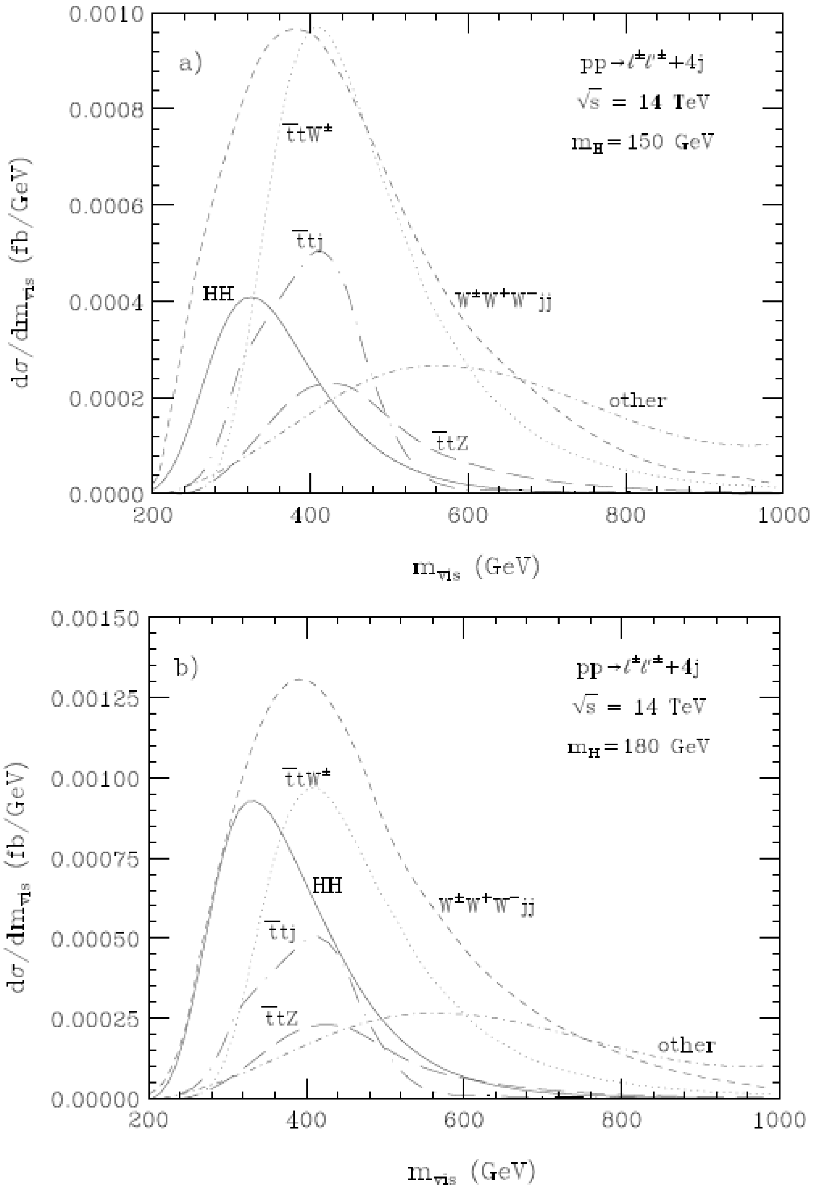


FIG. 4. Distribution of the invariant mass of the observable final state particles, m_{vis}, after all cuts, in $pp \to \ell^\pm \ell'^\pm + 4j$ for the signal with a) $m_H = 150$ GeV and b) $m_H = 180$ GeV, and all backgrounds (except for the contributions from overlapping events and double parton scattering) at the LHC. The dot-dashed curve shows the combined cross section of $WZjjjj$, $WWjjjj$ and $t\bar{t}t\bar{t}$ production.

Self coupling: extracting Higgs self-coupling

Gluon fusion production process through fermion triangle and box diagrams
Non-standard self couplings affect only triangle diagram, contribute only to J=0 partial wave
$\rightarrow$ affect m_{vis} mostly at small values.

Fig7 : 2 non-standard values of $\lambda_{HHH}=\lambda/\lambda_{SM}$.
Box and triangle diagrams interfere destructively $\rightarrow$ $\sigma(gg\rightarrow HH) < \sigma(gg\rightarrow HH)_{SM}$ for $1<\lambda_{HHH}<2.7$.
Absence of self coupling ($\lambda_{HHH}=0$) $\rightarrow$ $\sigma(gg\rightarrow HH) > 3 \times \sigma(gg\rightarrow HH)_{SM}$.
m_{vis} of signal peaks at smaller value than that of combined bgd for $m_H<200$ GeV/c^2

m_{vis} shape change induced by non-standard λ_{HHH} used to derive quantitative sensitivity bounds on self-coupling.
Baur etal calculate 95% CL performing a chi2 test.
The stat sign. is calculated by splitting the mvis distrib. into a number of bins
each with more than 5 evts.
Channels are combined, lepton id eff. of 85% are used.
Except for the self coupling, the SM is assumed to be valid.
By the time a Lambda meas. will be performed, mH will be precisely known,
and the H->WW BR will have been measured with a precision of 10% or better at the LHC or ILC.
All bgd processes are included except for overlapping evts and double parton scatt.
The challenge of including HO effects is considerably more complicated for the bgd than for the signal,
where at least the physics interpretation is clear???
The aim for the bgds is not to capture the bulk of evts after cuts.
Instead, one tries to cut the tails of the distribs.

Self coupling: χ^2 test

Except for self coupling, SM assumed to be valid.
Assume m_H precisely known, and BR($H \rightarrow WW$) known to 10% or better (LHC or ILC).
Overlapping evts and double parton scattering not included in fit.

Including HO effects in bgd considerably more complicated than for the signal.
Aim for bgds is not to capture bulk of evts after cuts, but rather to cut distribution tails,
where the impact of the HO corrs. might be very different.
Baur etal perform 2 separate calcs of sensitivity limits:
1. K=1 for the mvis distrib of the bgd with norm uncert. of 30% of the SM Xsection
2. K=1.3 for bgd mvis and norm uncert of 10% of SM Xsection.
The results are compared and the more conservative bound is selected.
For 300 fb-1, a vanishing self coupling (DeltaLambda_HHH=(Lambda-Lambda_SM)/Lambda_SM=-1)
is exclude at 95%CL or better,
and Lambda can be determined with a precision of up to -60% to +200%.
600fb-1 improves the sensitivity by 10-25%.
For 300 and 600 fb-1, the bounds for positive values of DeltaLambda_HHH are significantly weaker than
for negative values, due to the limited number of signal events.
At the SLHC, for 3000 fb-1,
the self coupling can be determined with an accuracy of 20-30% for 160<mH<180.
The significance of the SM signal for 300 (3000 fb-1) is slightly more than 1sigma (3sigma)
for mH=150GeV and 200 GeV,
and about 2.5 sigma (10sigma) for 160<mH<180.
Baur etal results are 5-10% weaker than old 2002 Baur etal article
where only WWWjj and ttW bgds were taken into account
while the effect of all other bgds was simulated by multiplying the combined WWWjj and ttW inv mass
distrib. by 1.1.

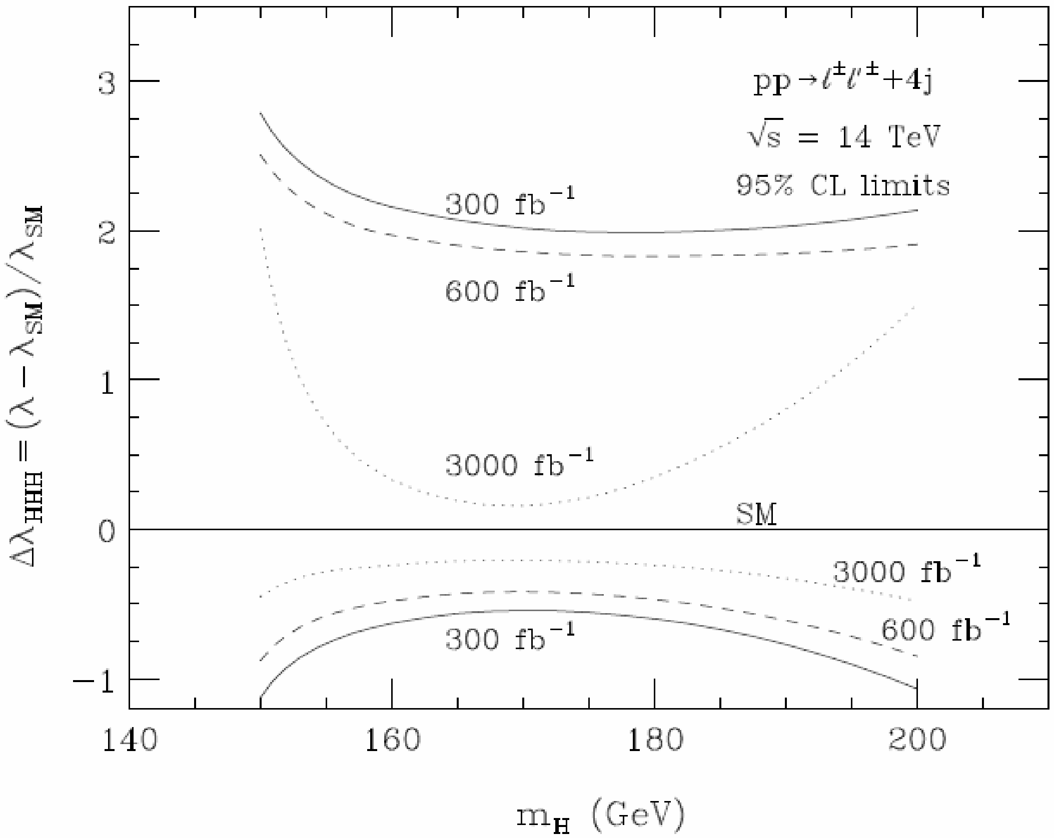


FIG. 8. Limits achievable at 95% CL for $\Delta\lambda_{HHH} = (\lambda - \lambda_{SM})/\lambda_{SM}$ in $pp \to \ell^{\pm}\ell'^{\pm} + 4j$ at the LHC. Bounds are shown for integrated luminosities of 300 fb^{-1} (solid lines), 600 fb^{-1} (dashed lines) and 3000 fb^{-1} (dotted lines). The allowed region is between the two lines of equal texture. The Higgs boson self-coupling vanishes for $\Delta\lambda_{HHH} = -1$.

Self coupling: determining the higgs boson self-coupling

For the VLHC, both channels are considered.
For Ecm=200TeV and 300 fb-1, the self coupling can be meas. with 8-25% precision at 95%CL for 150<mH<200 GeV.
For 1200fb-1, the bounds improve to 4-11%.

Uncertainties in this study:

-overlapping evts and double parton scatt have been ignored.
at the SLHC (VLHC) limits weaken by at most 5% (15%) if taken into account.

- contribs from WWZjj and WWWW prod ignored in their calcs. differences of up to 5% could be observed

- simple chi2 but more powerful tools could be used like NN

Exotic scenarios

Extra dimensions Randall-Sundrum model (derived version of it) predicts existence of scalar radion Φ
if heavy enough can decay into a pair of Higgs bosons.
m_Φ and m_h, ξ and Λ_Φ model parameters:
radion and Higgs masses, amount of Φ-h mixing, and radion field vev.
For m_Φ=300 GeV/c^2 and m_h =125 GeV/c^2 and $\Phi \to hh \to bb\gamma\gamma$
a 5σ discovery potential as a function of ξ and Λ_Φ is shown.