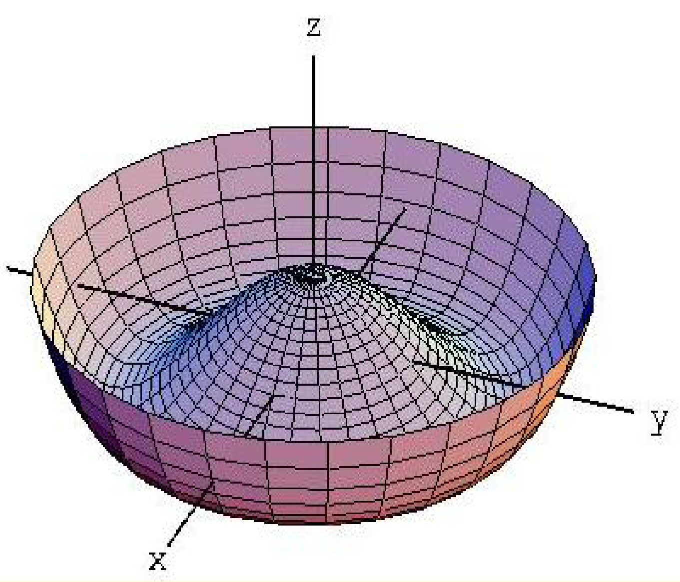
The determination of Higgs boson parameters at the LHC



- Experimental Input

- How well can the LHC determine
  - Higgs boson mass
  - Couplings to fermions and bosons
  - Spin and CP quantum numbers, tensor coupling
  - Higgs boson self coupling

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Important remarks / disclaimer:

- The focus of the experimental collaborations is at present in the areas of commissioning and understanding of the experimental signatures / reconstruction;
  (and rightly so, since otherwise there will be no understanding of early data !)

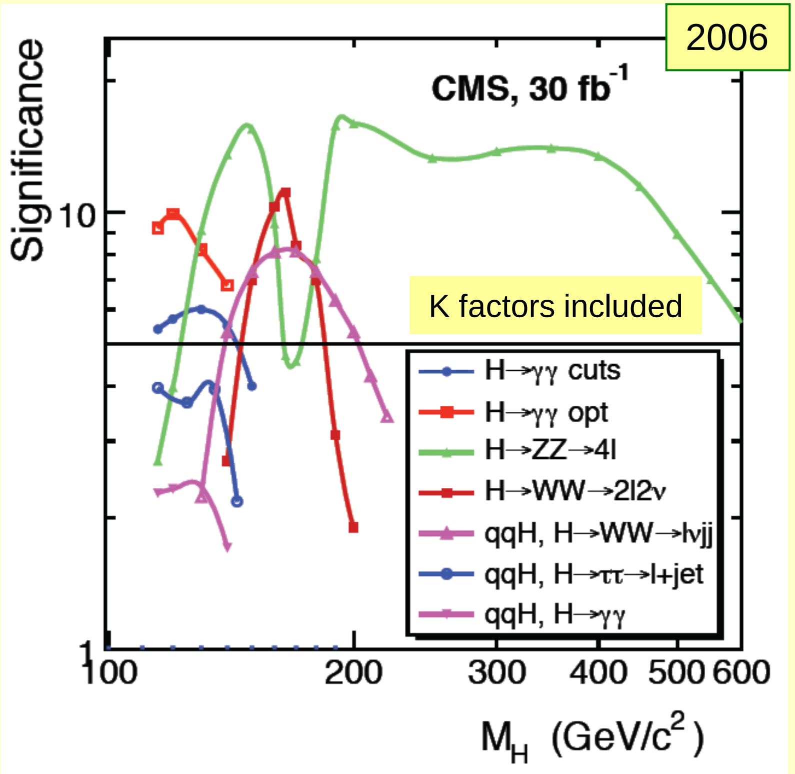
  ⇒ The new / updated results from ATLAS (CSC-Studies, arxiv:09010512) and CMS (TDR, J. Phys. G 34 (2006) 995) are not yet included in all studies shown in the following;
  Important differences will be pointed out !

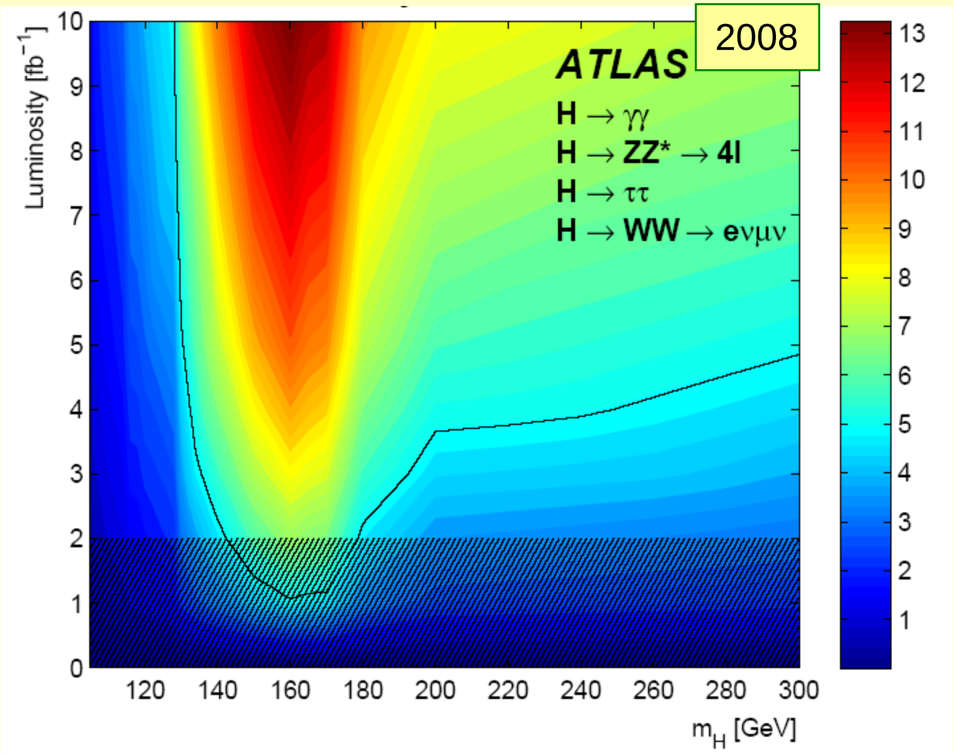
- Studies on the Higgs boson self coupling are very preliminary, and we know that they are optimistic !!
  (fast simulations, even for sLHC, missing backgrounds, ……)
  To be trustable, they will need to be repeated using a more detailed simulation and more realistic assumptions on the sLHC performance.

- Vector boson fusion channels have been assumed to scale with luminosity;
  (relevant for results given for integrated luminosities above 30 fb^{-1})

- For Jochum (and others): All estimates of measurement uncertainties given in the following are based on the assumption of Standard Model counting rates;
  (no diluted and washed-out Higgs bosons have been considered so far)

The experimental situation



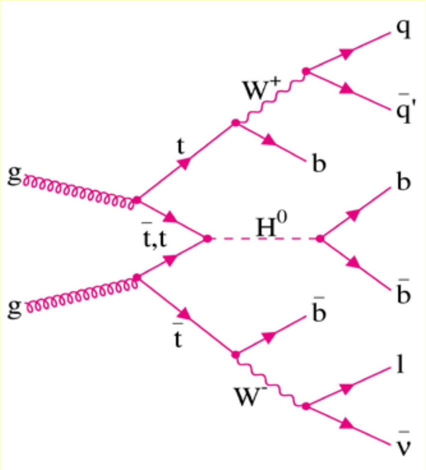


- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)

Important changes w.r.t. previous studies:

- **H → γγ** sensitivity of ATLAS and CMS comparable
- **ttH → tt bb** disappeared in both ATLAS and CMS studies from the discovery plot

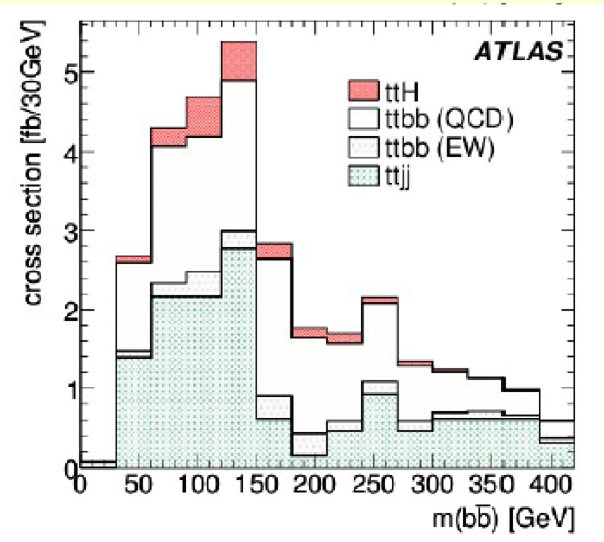
$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$



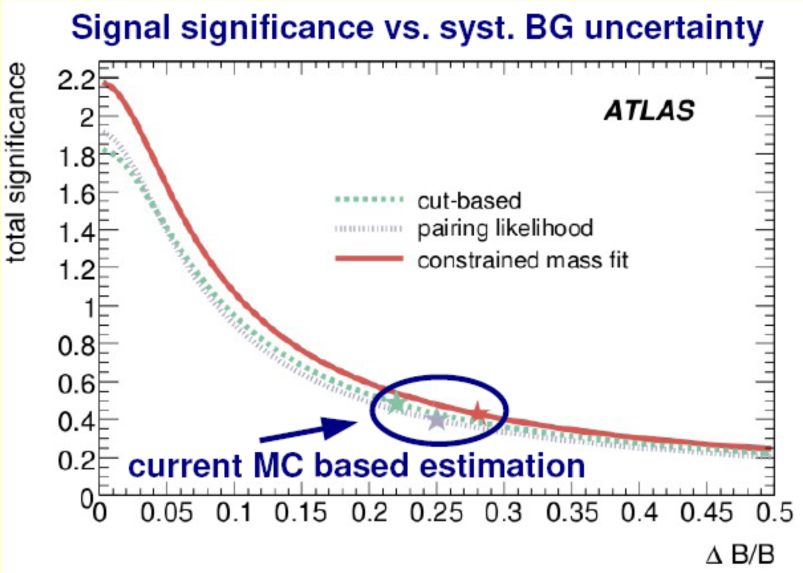
- Complex final states: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$
  $t \rightarrow b\ell\nu$, $t \rightarrow b\ell\nu$
  $t \rightarrow bjj$, $t \rightarrow bjj$

- Main backgrounds:
  - combinatorial background from signal (4b in final state)
  - ttjj, ttbb, ttZ,…
  - Wjjjjjj, WWbbjj, etc. (excellent b-tag performance required)

- Updated ATLAS and CMS studies: matrix element calculations for backgrounds
  $\rightarrow$ larger backgrounds (ttjj and ttbb)



M (bb) after final cuts, 30 fb^{-1}



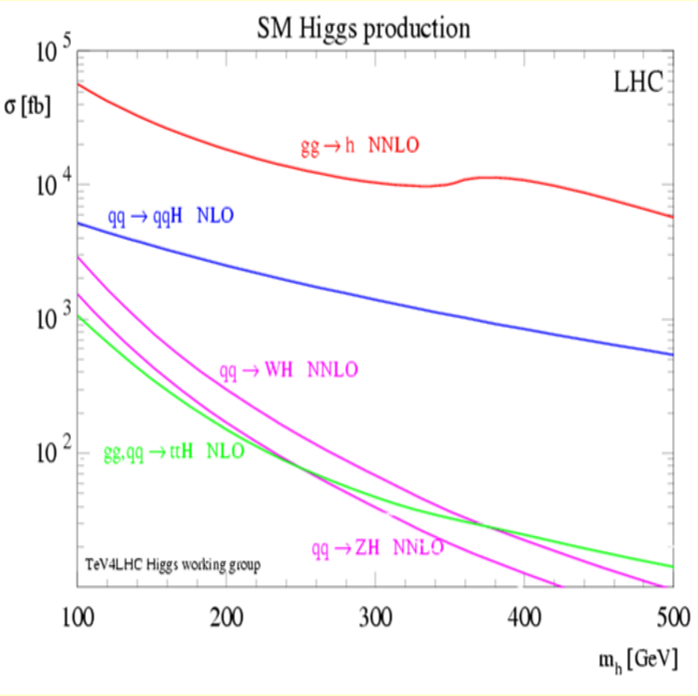
estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))
⇒ Normalization from data + precise calculations needed to reduce this (non trivial,…)

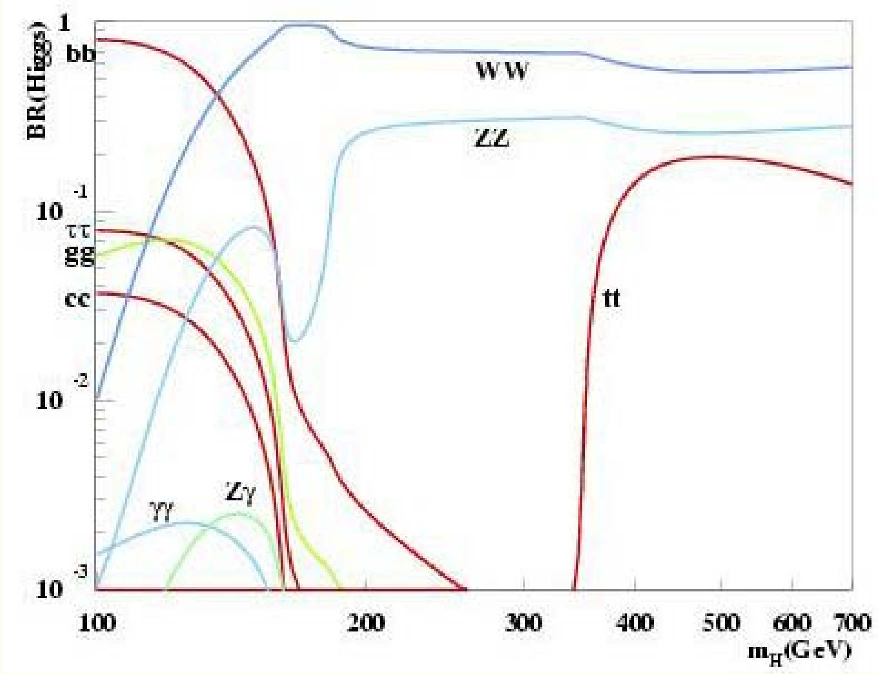
(i) Measurement of the Higgs boson mass

- The mass value itself is important for precision tests of the Standard Model, but moderate precision seems to be adequate; (as compared to the anticipated m_t and m_W uncertainties)

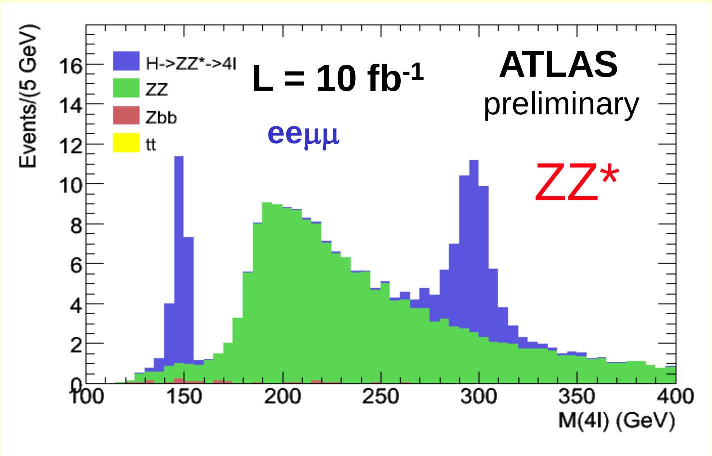
- In addition: the Higgs mass value is important for the parameter measurements (in particular for the extraction of ratios of couplings) …..

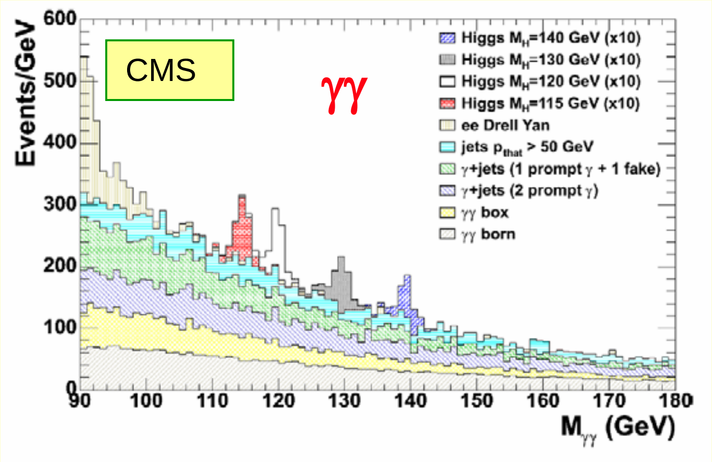
  … as many experimental observables / input values need to be compared to the theoretical predictions, which in turn depend -sometimes rather strongly- on m_H





Precision on mass is achieved in el.magn. final states



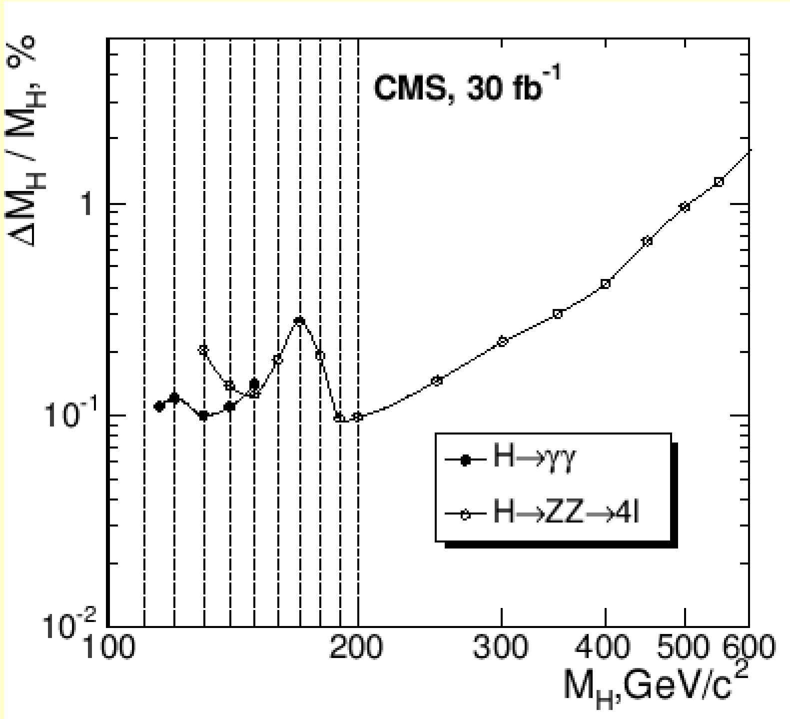


Dominant systematic uncertainty:

γ / ℓ energy scale.

assumed: 1‰ (goal 0.2‰)

Scale from Z $\rightarrow \ell\ell$ (close to light Higgs)



Precision below 1% can be achieved over a large mass range for 30 fb^{-1};

syst. limit can be reached for higher integrated luminosities $\rightarrow$ 100 fb^{-1}

Note: no theoretical errors, e.g. mass shift for large Γ_H (interference resonant/non-resonant production) taken into account

Higgs boson mass (cont.)

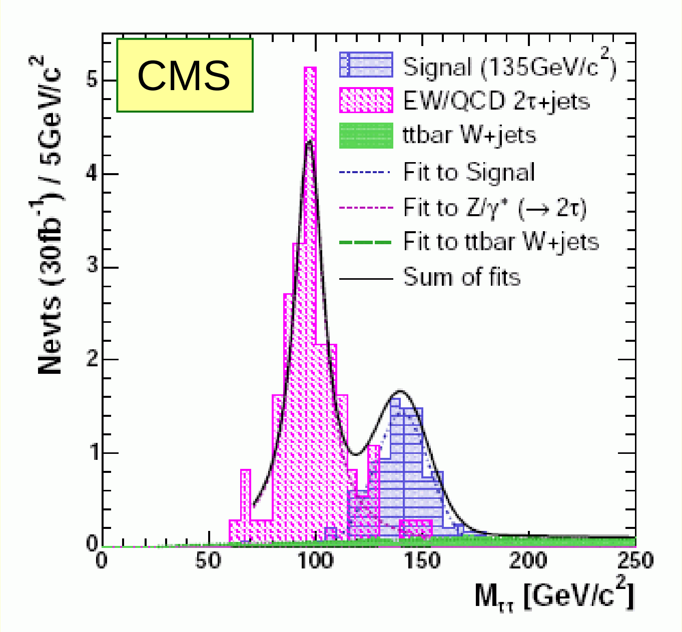
In case of exotic Higgs boson couplings (e.g. suppressed $H \to WW / ZZ$ couplings) the situation is more difficult

(even the $\gamma\gamma$ decay mode would be affected, since the WW loop contribution is dominant)

Remaining channels at low mass: $H \to \tau\tau$

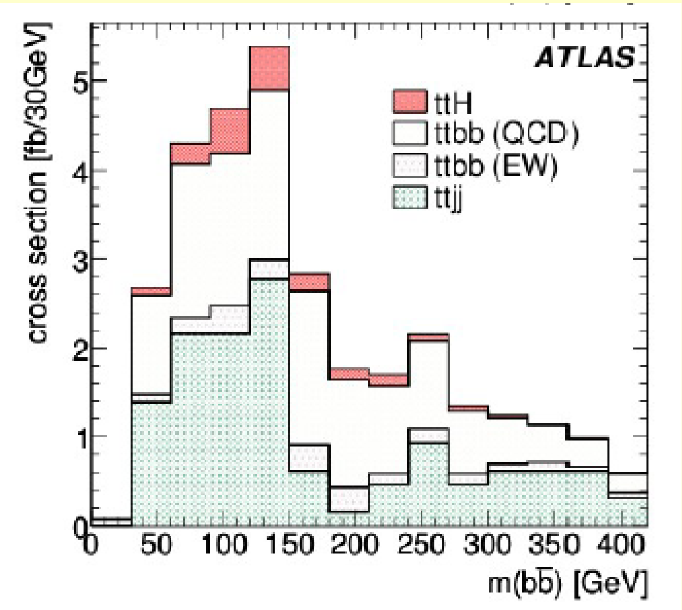
$H \to bb$ (difficult S:B situation, difficult as a discovery channel; mass value is most likely needed to extract a signal, if background and mass known, it might be useful and add to coupling measurements)

$qq\,H \to qq\,\tau\tau \to qq\ \ell\nu\nu\ \text{had}\ \nu$

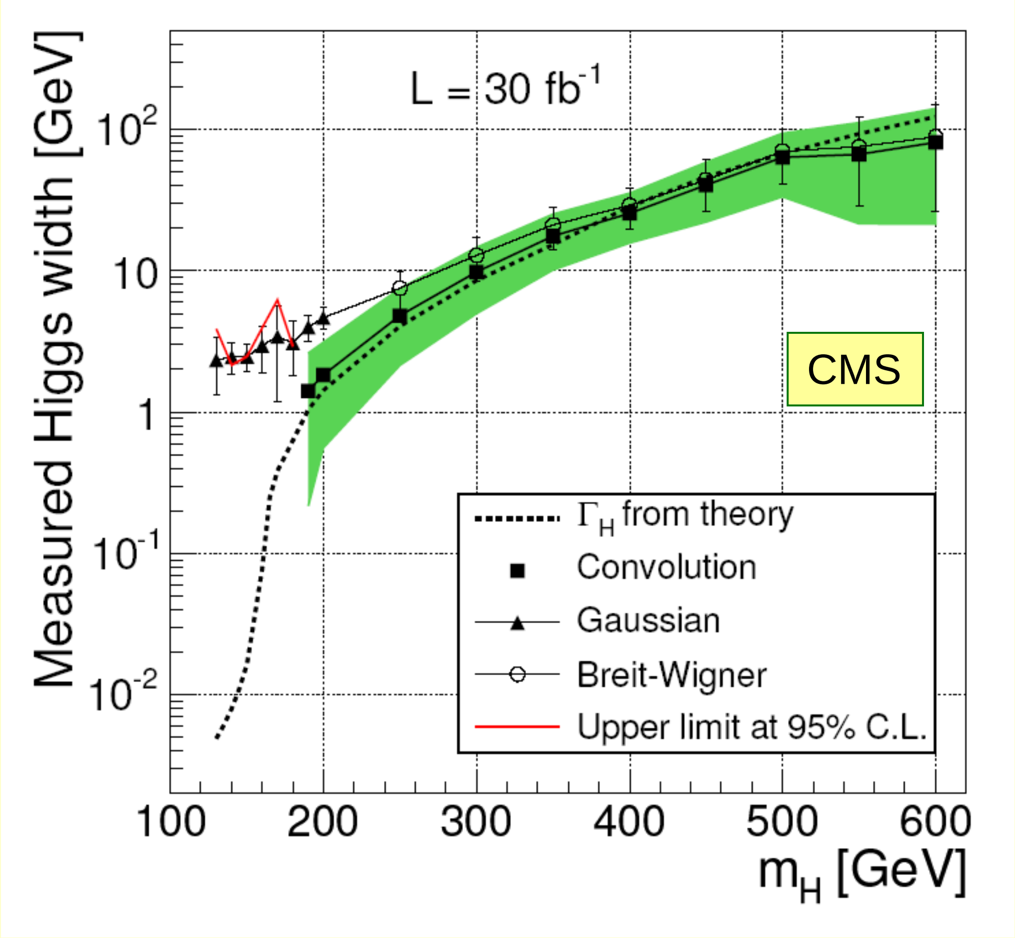


Requires good understanding of the detector (τ, E_T^{miss}), resolution limited

$tt\,H,\ H \to bb$



Direct extraction of the Higgs boson width:



(ii) Higgs boson couplings to fermions and bosons

The Higgs boson couplings can in principle be extracted from rate measurements,

$$\sigma_{yy \to H} \cdot BR(H \to xx) \sim \Gamma_y \cdot \Gamma_x / \Gamma_H$$

however, Γ_H is needed, which cannot be directly measured at the LHC for $m_H < 200$ GeV.

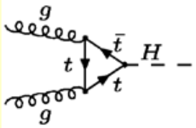
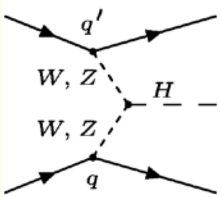
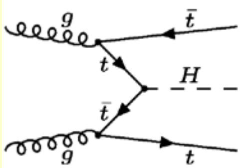
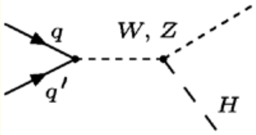
Two options:

(i) Measure ratios of couplings
Systematic uncertainties taken into account;
M. Dührssen, ATLAS-PHYS-2003-030.

(ii) Include more theoretical assumptions and measure absolute couplings
M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld, Phys. Rev. D70 (2004) 113009.

→ For both options, the information from all visible Higgs boson production and decay modes can be combined into one global maximum likelihood fit

Experimental input:

Production		Decay	mass range	
	Gluon-Fusion $(gg \to H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 200 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	WBF $(qq\, H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 190 GeV	
		$H \to \tau\tau \to l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV	
		$H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$	110 GeV - 150 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	$t\bar{t}H$	$H \to WW \to l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV	optimistic assumptions
		$H \to b\bar{b}$	110 GeV - 140 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	WH	$H \to WW \to l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV	

Mass range is restricted to $m_H < 200$ GeV
Based on „old ATLAS studies"
Most significant differences: ttH channels with $H \to bb$ and $H \to WW$

Higgs-Boson Couplings (cont.)

Global fit

(all channels at a given mass point)

Analysis is done with increasing level of theoretical assumptions

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2} \quad \frac{g_W^2}{\sqrt{\Gamma_H}}$$

Production cross-sections

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$

$$\sigma_{VBF} = \alpha_{WF} \bullet g_W^2 + \alpha_{ZF} \bullet g_Z^2$$

$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$

$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$

$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

(b loop neglected so far in ggH)

Branching ratios

$$BR(H \to WW) = \beta_W \frac{g_W^2}{\Gamma_H}$$

$$BR(H \to ZZ) = \beta_Z \frac{g_Z^2}{\Gamma_H}$$

$$BR(H \to \gamma\gamma) = \frac{\left(\beta_{\gamma(W)} g_W - \beta_{\gamma(t)} g_t\right)^2}{\Gamma_H}$$

$$BR(H \to \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H}$$

$$BR(H \to bb) = \beta_b \frac{g_b^2}{\Gamma_H}$$

α,β from theory with assumed Uncertainties:

$$\Delta\alpha_{ggH} = 20\%$$

$$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$$

$$\Delta\alpha_{ttH} = 15\%$$

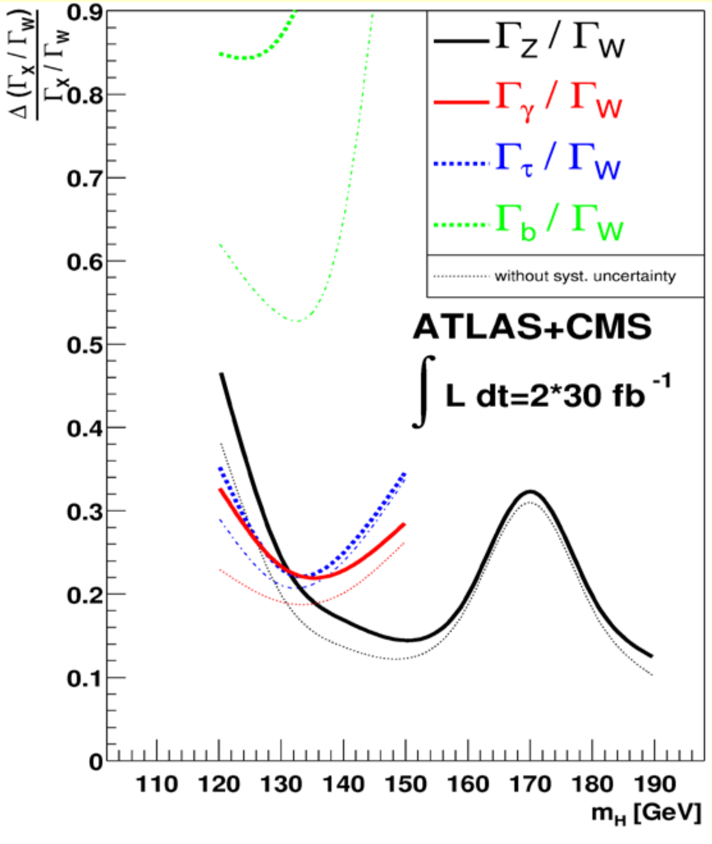
$$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$$

$$\Delta\beta = 1\%$$

Step 1: measurement of ratios of partial decay width:

Assumption: only one light Higgs boson

To cancel Γ_H, normalization to Γ_W is made
(suitable channel, measurable over a large mass range ~120–200 GeV)

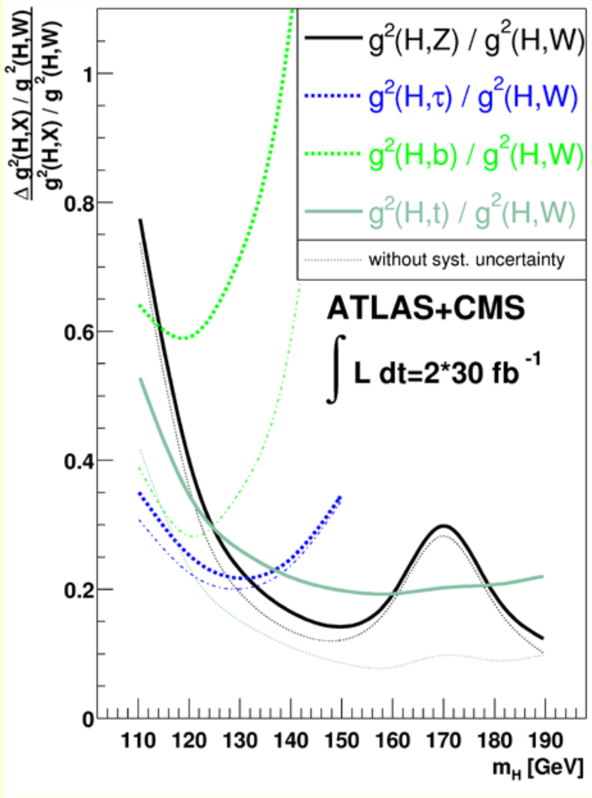


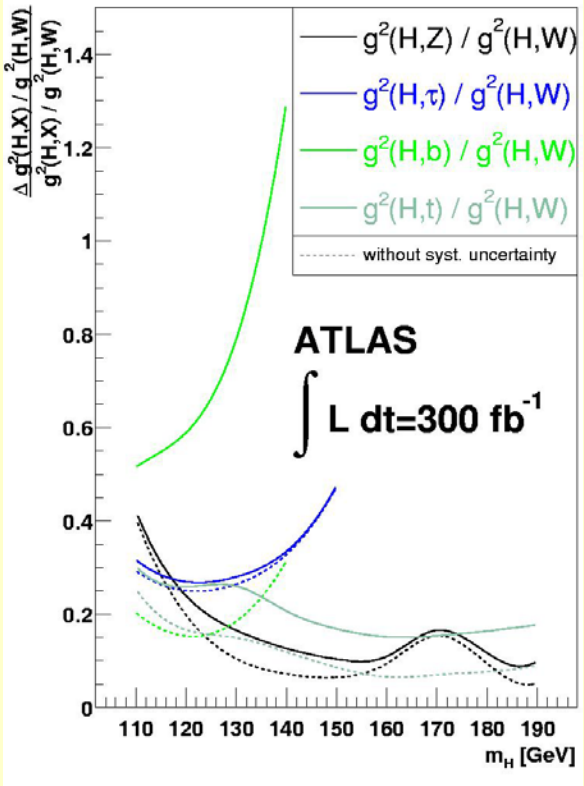
Note: optimistic assumptions for H → bb (based on old studies)

Step 2: measurement of ratios of couplings:

Additional assumption: particle content in the gg- and $\gamma\gamma$-loops are known;

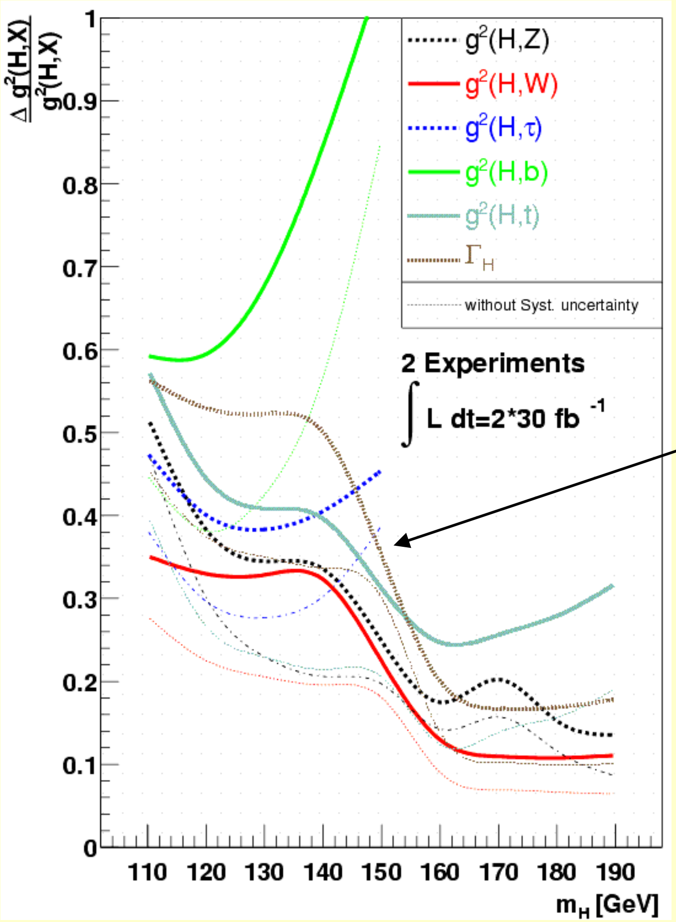
Information from Higgs production is now used as well;
Important for the determination of the top-Yukawa coupling



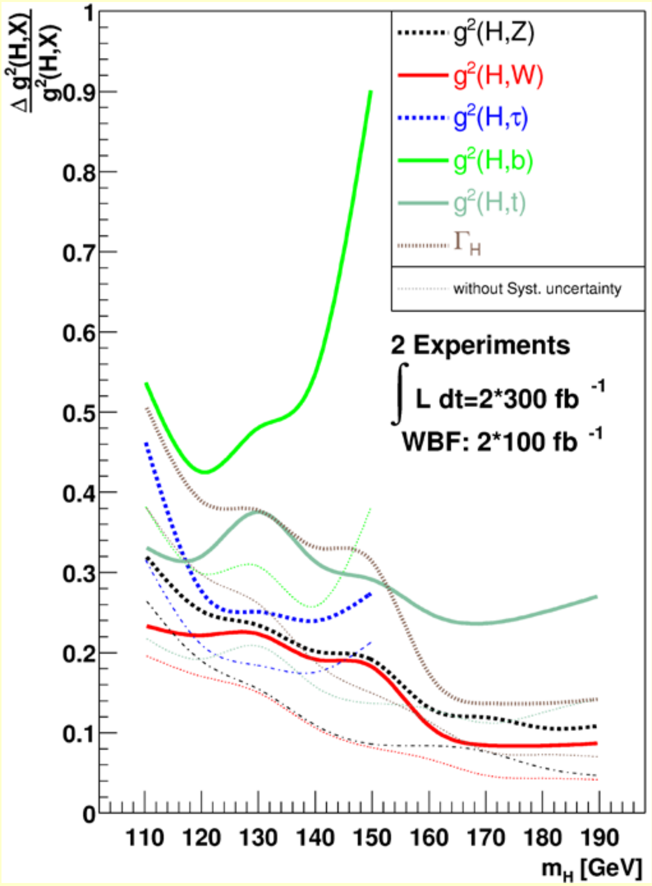


Step 3: measurement of couplings (absolute values):

Needs additional *("mild")* theoretical assumptions:
- use lower limit on Γ_H from visible decay modes
- assume that g (H,W) are bound from above by the Standard Model value:
  $g^2(H,W) \leq g^2(H,W,SM)$; (valid for any model that contains only Higgs doublets and singlets)
  (upper value is motivated from WW scattering unitarity arguments)



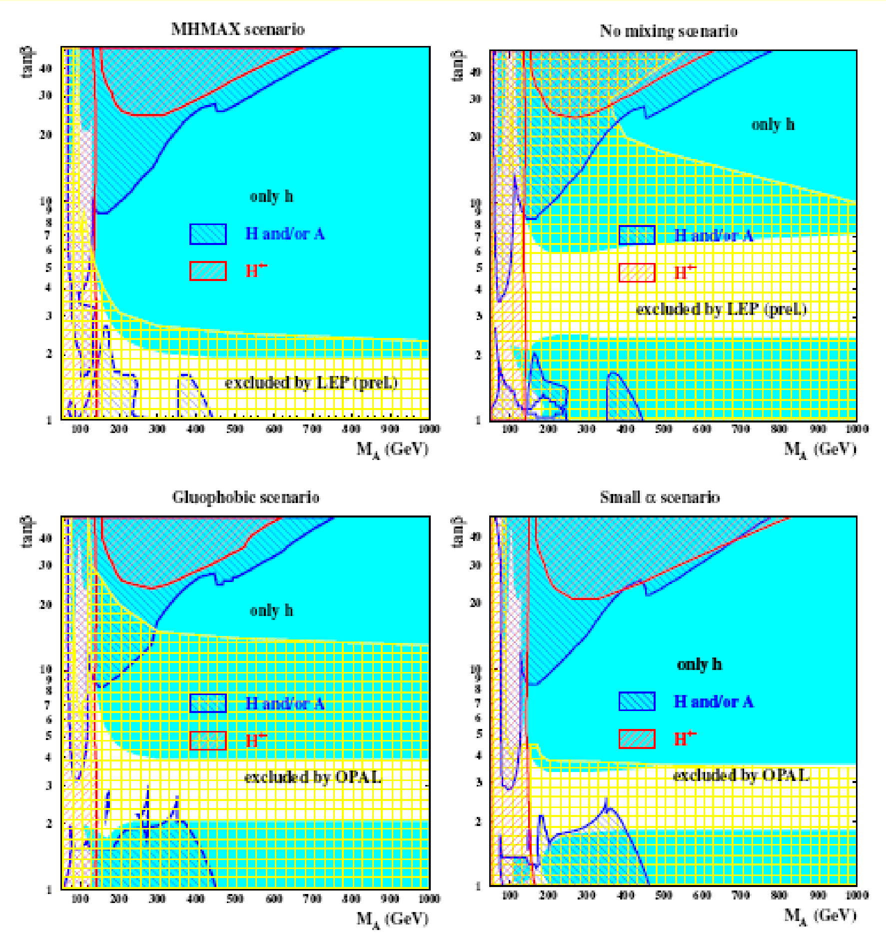
Total width is "measured" as well



Discrimination between MSSM and SM Higgs ?
Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ $\gamma\gamma$ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for
large tan β and M_A 100 to 500 GeV/c^2

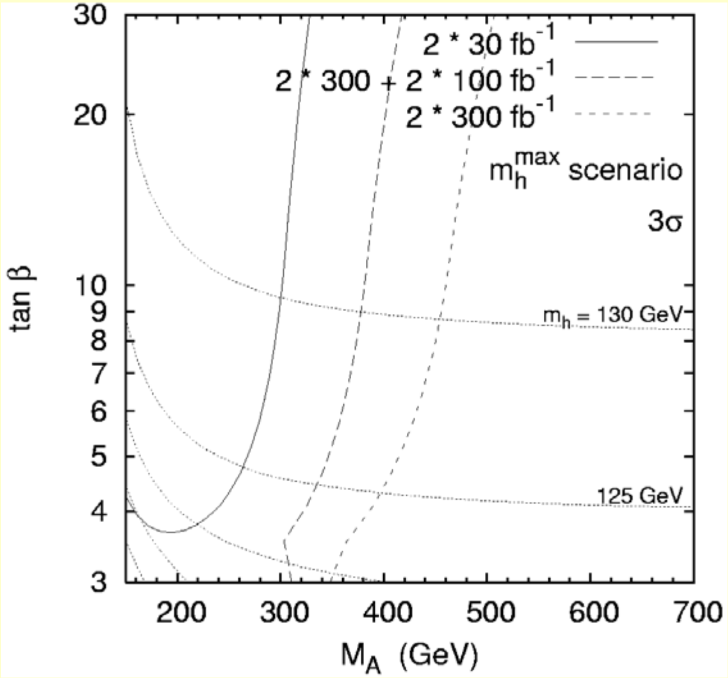
The full parameter space is covered for all scenarios

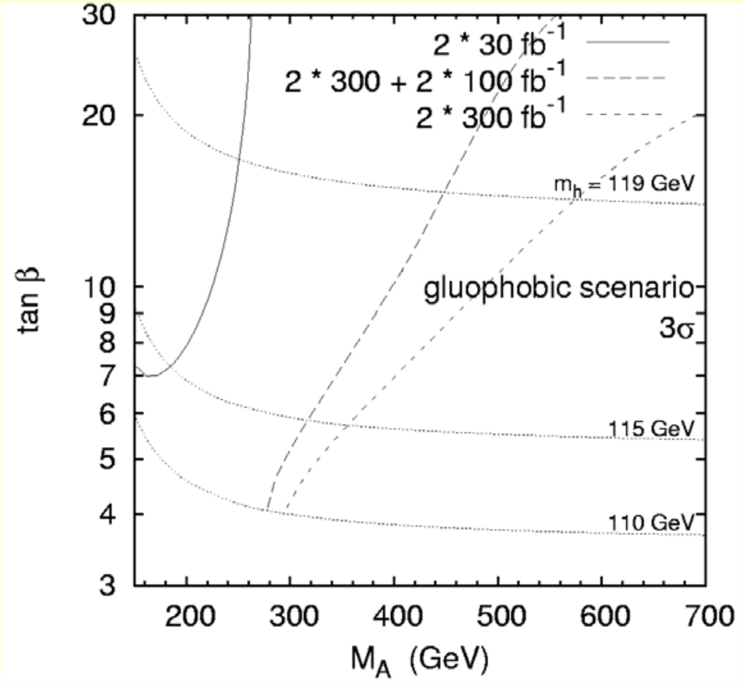
Discrimination between a SM or MSSM Higgs

In some regions of MSSM parameter space only one light Higgs boson is visible

⇒ Try to exclude MSSM using a χ^2 analysis of coupling fits

M. Dührssen et al., Phys. Rev. D70 (2004) 113009.





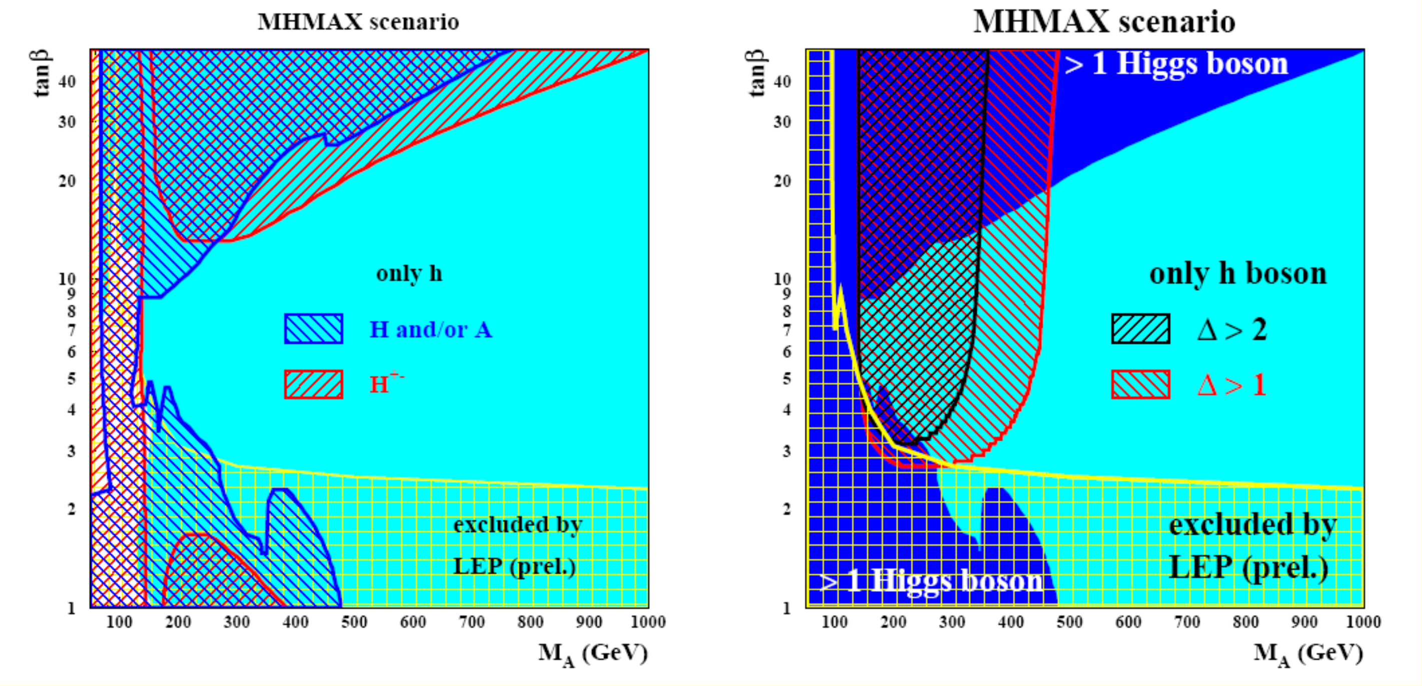
Discrimination between a SM or MSSM Higgs (cont.)

Similar analysis based on direct comparison of ratios of rates in different final states, using VBF production

M. Schumacher et al., hep-ph/0410112

Consider variables R: = BR ($h \to \tau\tau$) / BR ($h \to WW$)

Δ: = ($R_{MSSM} - R_{SM}$) / σ_{exp}



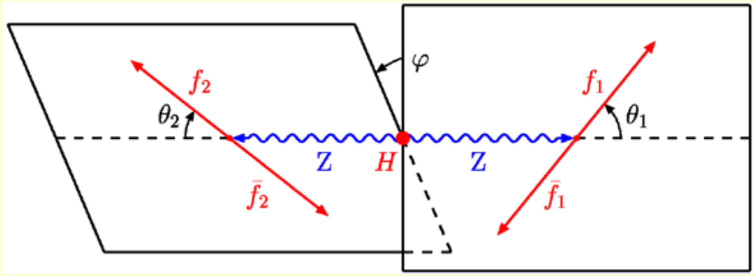
30 fb^{-1}

(only stat. errors considered so far, m_H assumed to be known with high precision)

(iii) Spin and CP quantum numbers

Spin:

- Spin 1: no H → γγ decay
- Spin 0: angular correlations in H → WW → ℓν ℓν decays
- More general: Angular distributions in the decay channel H → $ZZ^{(*)}$ → 4 ℓ are sensitive to spin and CP eigenvalues



- Azimuthal angle φ
- Polar angle θ

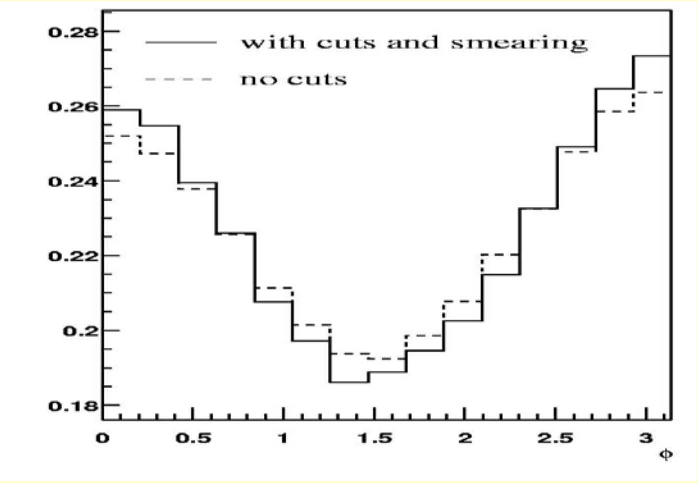
J.R. Dell'Aquila and C.A. Nelson Phys.Rev.D33:101,1986
S.Choi,D.Miller,M.Mühlleitner and P.Zerwas Phys.Lett.B553 (2003)
C.P.Buszello,I.Fleck,P.Marquard and J.J. van der Bij, Eur Phys J C32,209,2004
C.P. Buszello, P. Marquard, J. van der Bij, hep-ph/0406181.
CMS TDR - M.Bluj CMS NOTE 2006/094
R.Godbole,D.Miller and M.Mühlleitner JHEP 0712:031,2007

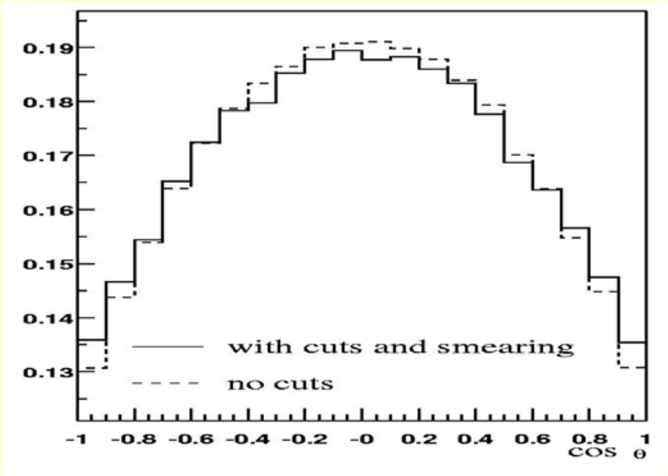
CP information:

- Angular distributions in the decay channel H → ZZ(*) → 4 ℓ
- Angular correlation of tagging jets in vector boson fusion production
- Angular correlations in ttH decays

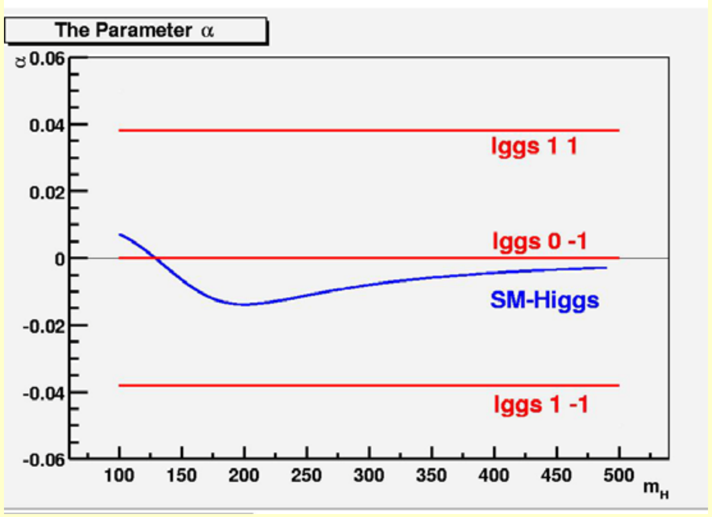
J. Gunion and X.G. He, Phys. Rev. Lett. 76 (1996) 4468.
T. Plehn, D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801, 2002
T. Figy and D.Zeppenfeld Phys. Lett. B 591 (2004) 297-303
V. Hankele,G. Klamke,D. Zeppenfeld and T. Figy, Phys.Rev.D74:095001,2006
C. Ruwiedel,M. Schumacher and N. Wermes, Eur.Phys.J.C51:385-414,2007

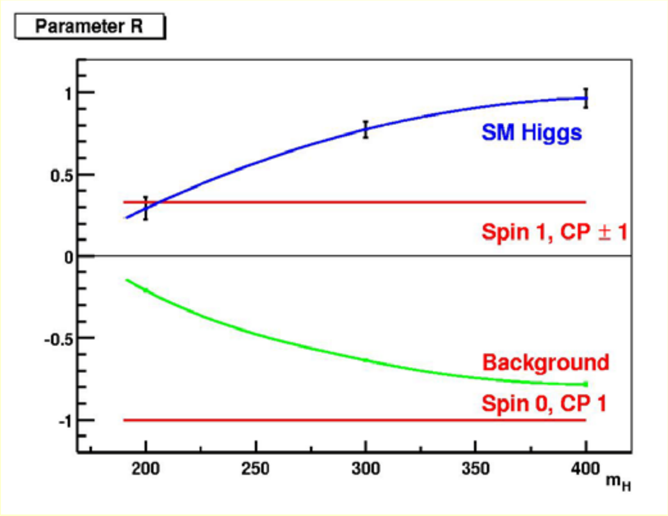
Exploiting angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ decays:





Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$
$F(\theta) = T\,(1+\cos^2\theta) + L \sin^2\theta$ $\qquad R = (L-T) / (L+T)$

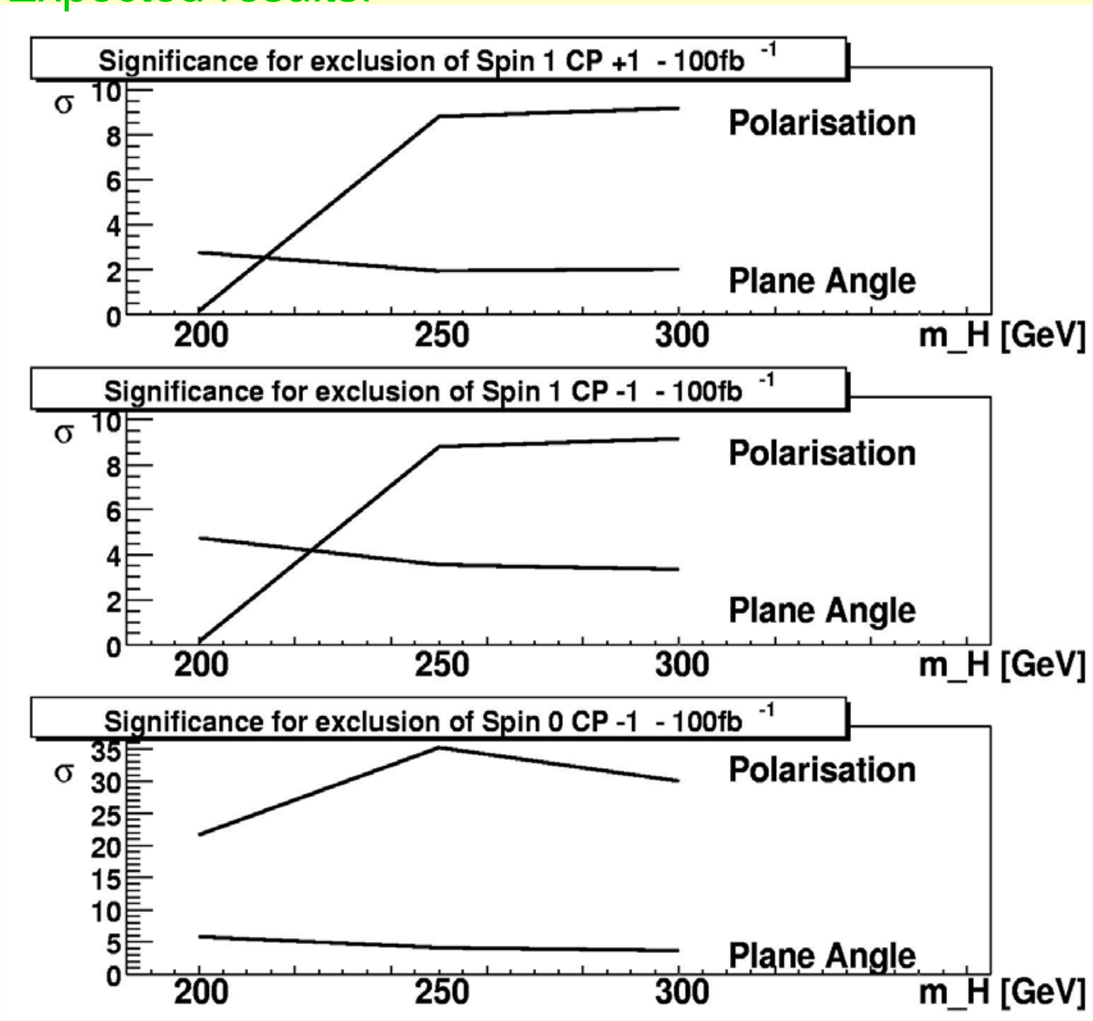




J.R. Dell´Aquila and C.A. Nelson, Phys. Rev. D33 (1986) 101

Exploiting angular correlations in $H \to ZZ^{(*)} \to 4\ell$ decays:

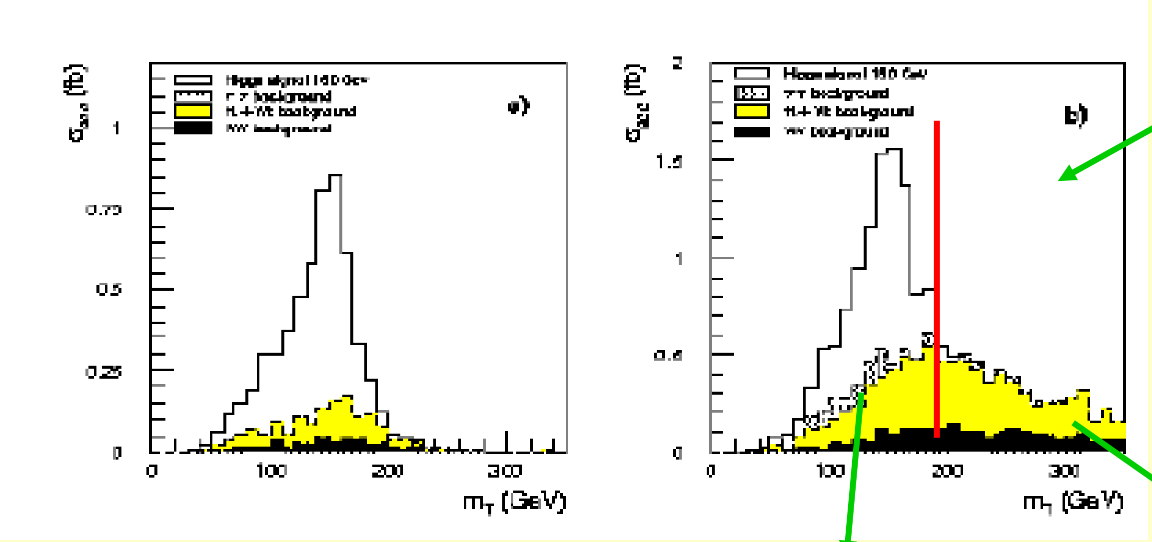
Expected results:



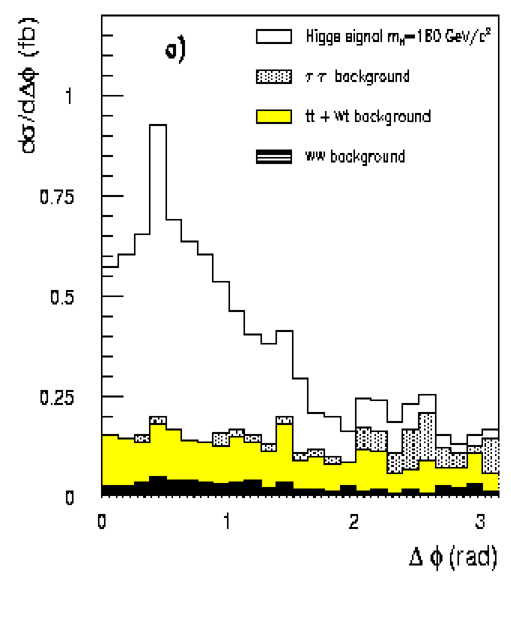
C.P. Buszello, P. Marquard, J. van der Bij et al., SN-ATLAS-2003-025 and Eur. Phys. J C32 (2004) 209.
method extended in: C.P. Buszello, P. Marquard, J. van der Bij, hep-ph/0406181.

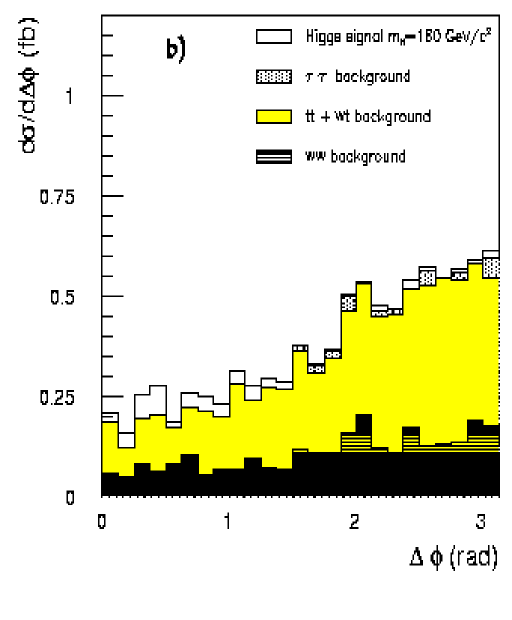
Evidence for spin-0 in H → WW → ℓν ℓν

- Cuts can be relaxed, to get background shape from the data + Monte Carlo:



No kinematical cuts on leptons applied: (ATLAS study)





Evidence for spin-0 of the Higgs boson, Δφ distribution

Spin-0 → WW → ℓνℓν expect leptons to be close by in space

S. Asai et al., Eur. Phys. J. C32, (2003) 209.

Tensor structure of Higgs couplings in VBF events

- General parametrization of the coupling of a scalar to vector bosons:

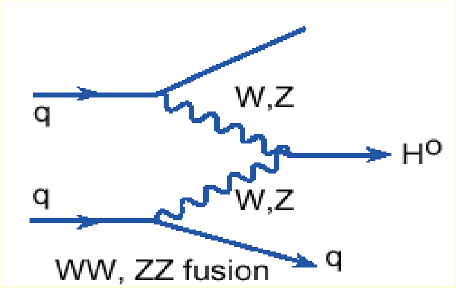
$$\begin{aligned} T^{\mu\nu}(q_1,q_2) = {} & a_1(q_1,q_2) g^{\mu\nu} \\ & + a_2(q_1,q_2)\left[q_1\cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}\right] \\ & + a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}. \end{aligned}$$

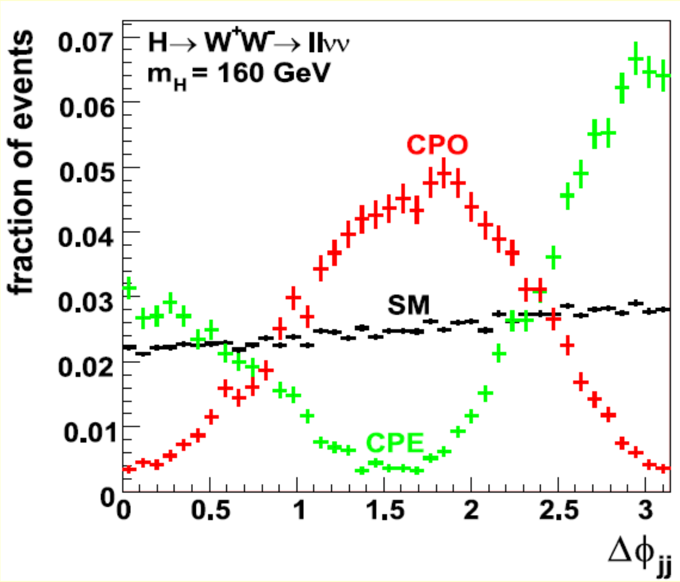
CP even Standard Model term

anomalous CPE term

anomalous CPO term

- Contributions and admixtures can be determined in VBF using the $\Delta\phi$ distribution between the two tag jets





Shapes of $\Delta\phi$ distributions
(no backgrounds, large statistics)

T. Plehn, D.Rainwater and D.Zeppenfeld, Phys. Rev. Lett. 88, (2002) 051801

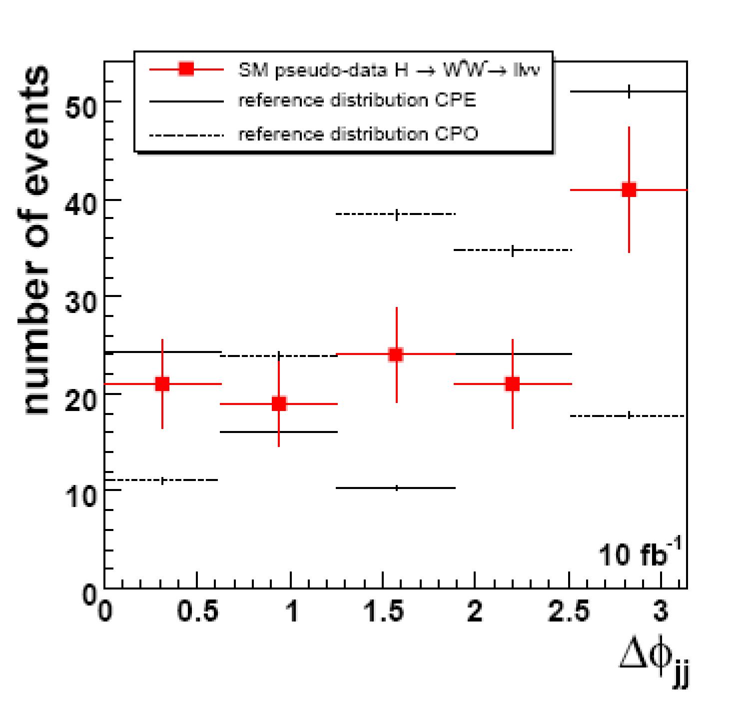
Tensor structure of Higgs couplings in VBF events (cont.)

- ATLAS study using the qqH → qqWW and qqH → qq $\tau\tau$ channels:
  C.Ruwiedel, M.Schumacher and N.Wermes, Eur. Phys. J. C51 (2007) 385

- Apply typical VBF selection cuts: central leptons
  two tag jets: M_{jj}, P_T

After (fast) detector simulation

ATLAS, qqH → qqWW, L = 10 fb^{-1}



Expectations:

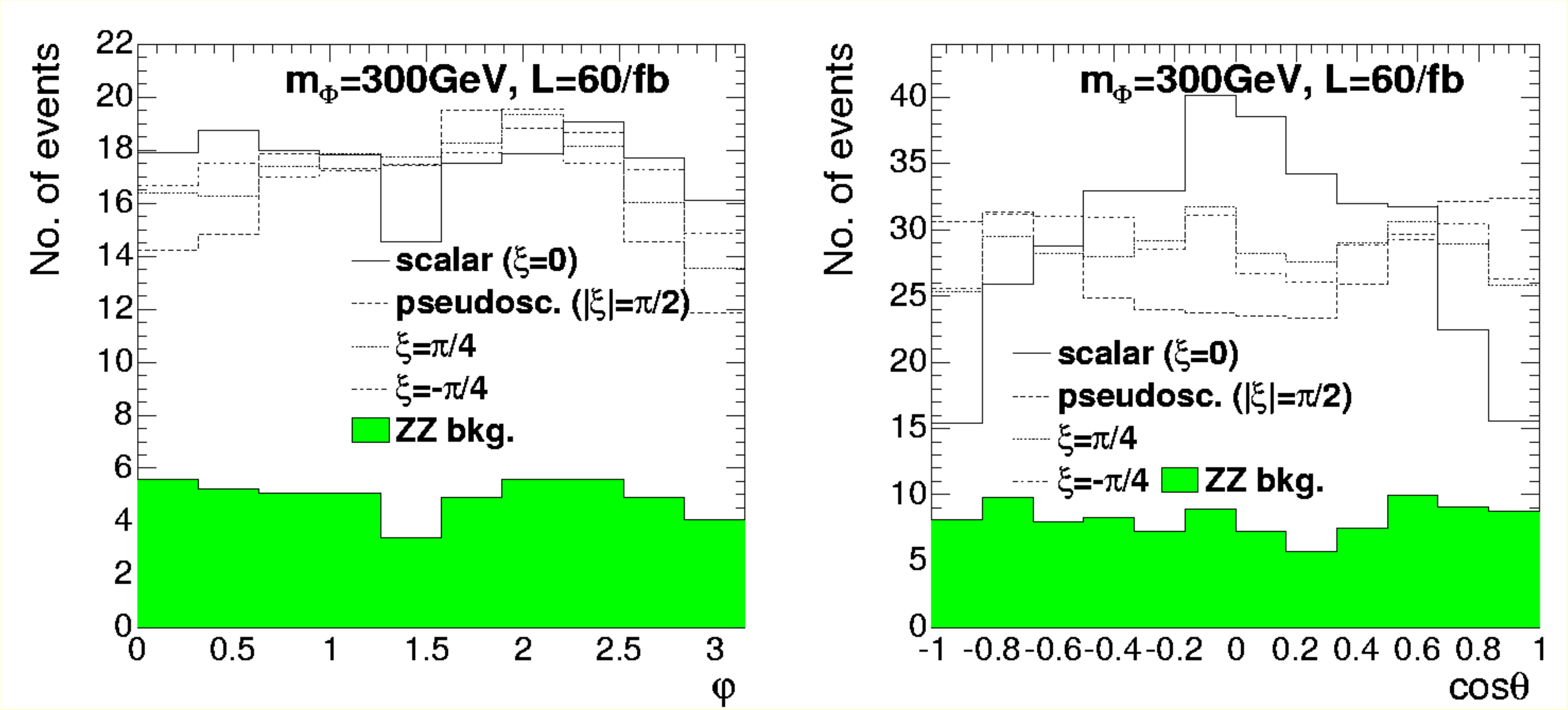
WW decay mode: m_H = 160 GeV
Anomalous CP-even and CP-odd couplings can be excluded with 5σ, for 10 fb^{-1}

$\tau\tau$ decay mode: m_H = 120 GeV
Exclusion with a 2σ significance requires 30 fb^{-1}

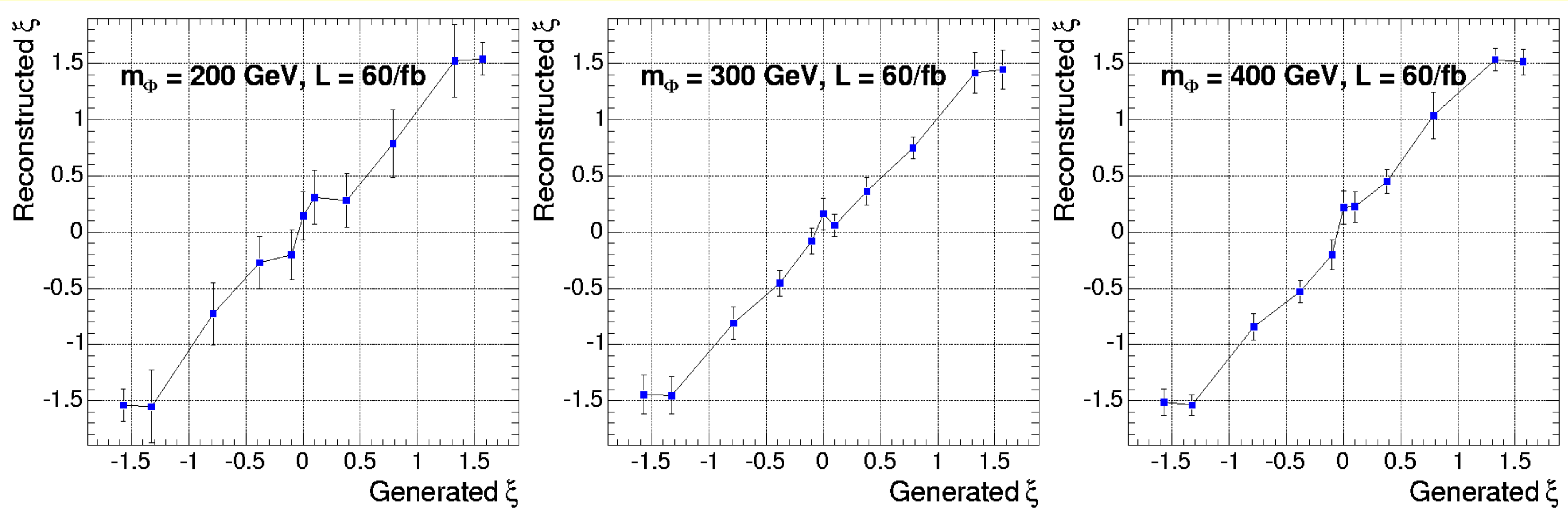
CMS analysis: search for a pseudoscalar admixture

- Use again the angular correlations in $H \to ZZ \to 4\ell$ decays
- Assume Spin-0 Higgs boson and allow for a pseudoscalar admixture $\phi = H + \xi A$

(Standard Model (scalar) case: $\xi = 0$)



Results from Monte Carlo experiments for a maximum likelihood fit to the angular distributions and the 4-lepton invariant mass (including signal and background)

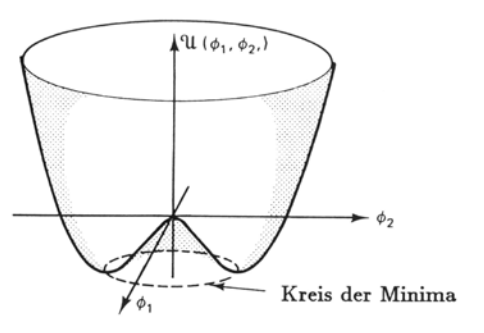


Allows precise measurement of pseudoscalar admixture for 60 fb^{-1}

CMS Collaboration, J. Phys. G 34 (2006) 995

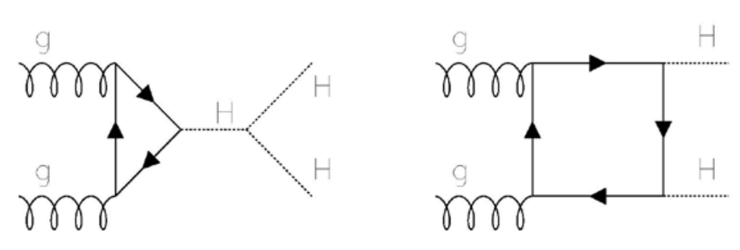
(iv) Higgs boson self-coupling ?

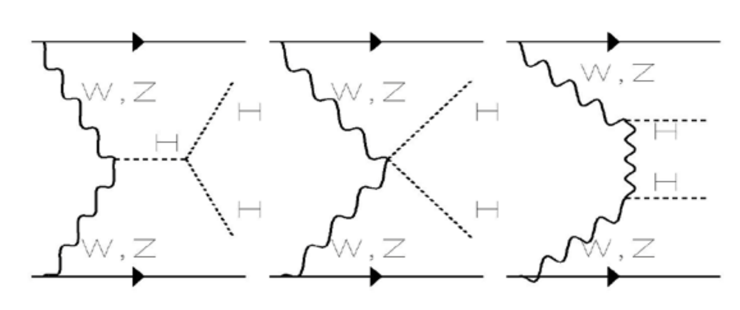
To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

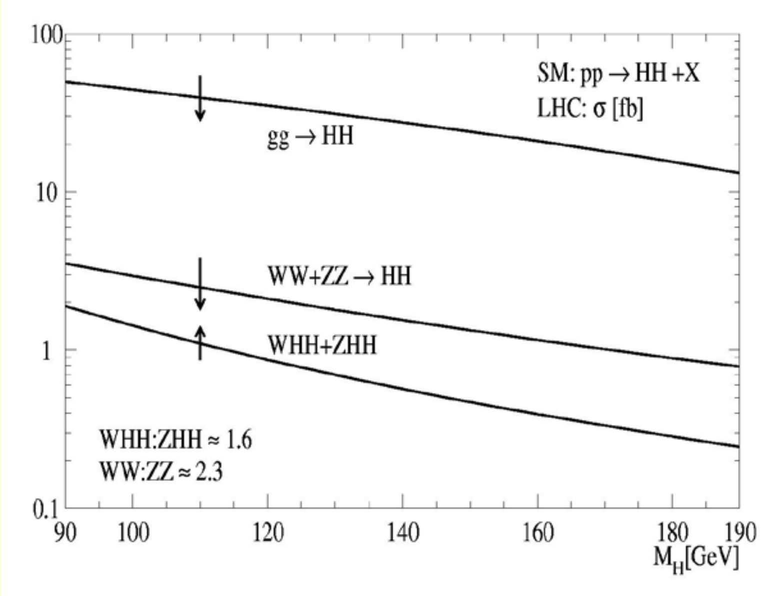


$$\lambda_{HHH}^{SM} = 3\,\frac{m_H^2}{v}\ , \qquad \lambda_{HHHH}^{SM} = 3\,\frac{m_H^2}{v^2}$$

Cross sections for HH production:







small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

$\Rightarrow$ no significant measurement possible at the LHC

need Super LHC $L = 10^{35}$ cm^{-2} sec^{-1}, 6000 fb^{-1}

Most sensitive channel: **$gg \rightarrow HH \rightarrow WW\ WW \rightarrow \ell\nu\ jj\ \ \ell\nu\ jj$**

- accessible in mass range around 160 GeV
- bb- or $\gamma\gamma$ decay modes at lower masses are hopeless

Selection (old analysis):

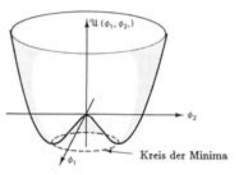
- 2 isolated, high P_T, like sign leptons (from different Higgs bosons)
- 4 high P_T jets, compatible with W-mass

m_H	Signal	$t\bar{t}$	$W^{\pm}Z$	$W^{\pm}W^{+}W^{-}$	$t\bar{t}W^{\pm}$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8

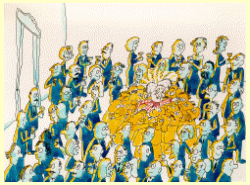
6000 fb $^{-1}$ $\Rightarrow$ $\Delta\lambda_{HHH}/\lambda_{HHH}$ = 19 % (stat.) (for m_H = 170 GeV)
$\Delta\lambda_{HHH}/\lambda_{HHH}$ = 25 % (stat.) (for m_H = 200 GeV)

Note: - background contributions (tt and WWW) underestimated
- Estimates are based on fast detector simulation
- No pile-up effects and no realistic sLHC performance assumed

$\Rightarrow$ Study needs to be updated with more realistic simulations, before more reliable estimates can be given



Summary: Is it a Higgs Boson ?



1. Mass

Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ resonances

2. Couplings to bosons and fermions

- Ratios of major couplings can be measured with reasonable precision;
- Absolute coupling measurements need further theory assumptions
  (Methods established, exp. Updates are needed, in particular for VBF channels at high luminosity)

3. Spin and CP

Angular correlations in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $\Delta\phi_{jj}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling

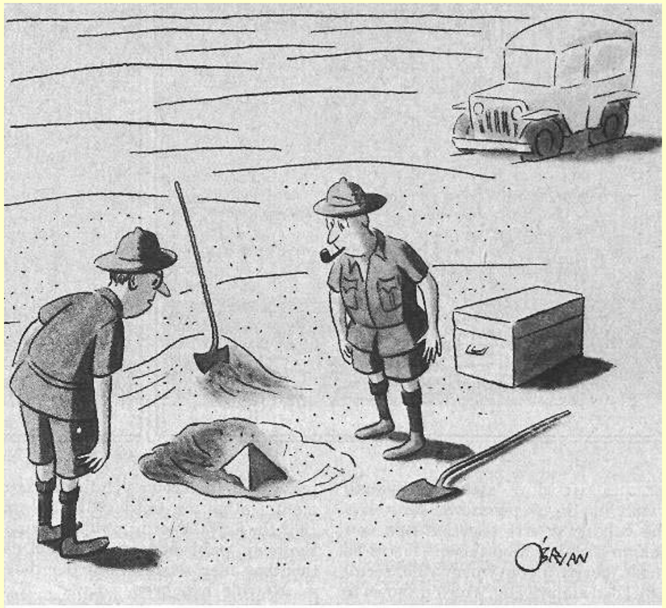
No measurement possible at the LHC;
Very difficult at the sLHC, there might be sensitivity in $HH \rightarrow WW\,WW$ for $m_H \sim 160$ GeV
Situation needs to be re-assessed with more realistic simulations, timescale unknown

Motivation:

- After a discovery of a significant excess of "Higgs-like" events at the LHC one has to measure its parameters and consolidate the evidence for a Higgs boson

- As many parameters as possible have to be measured in as many different production and decay channels as possible ! (global fit, see later)

- Discriminate between: SM Higgs boson
  MSSM like Higgs boson
  "Exotic" Higgs boson



"This could be the discovery of the century. Depending, of course, on how far down it goes."