Extraction of Higgs parameters at the LHC

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Workshop on the Future of Higgs Physics

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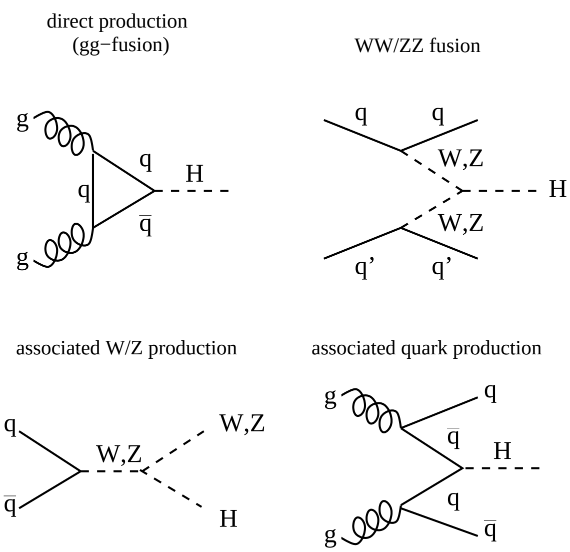
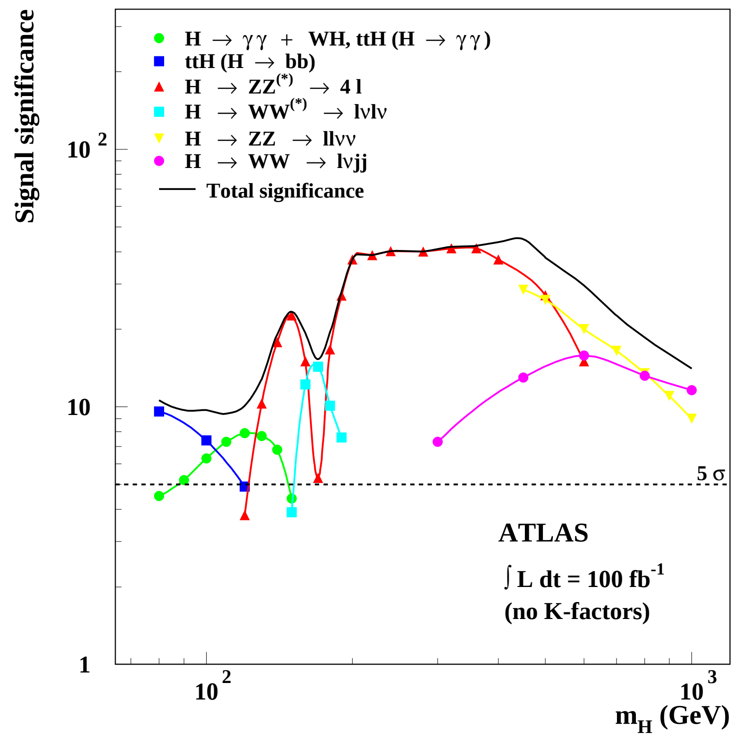
- Introduction
- Measurement of the Higgs boson mass
- Couplings to bosons and fermions
- Measurement of the width
- First approach of a spin determination
- Summary

Higgs discovery in ATLAS

Higgs production at LHC



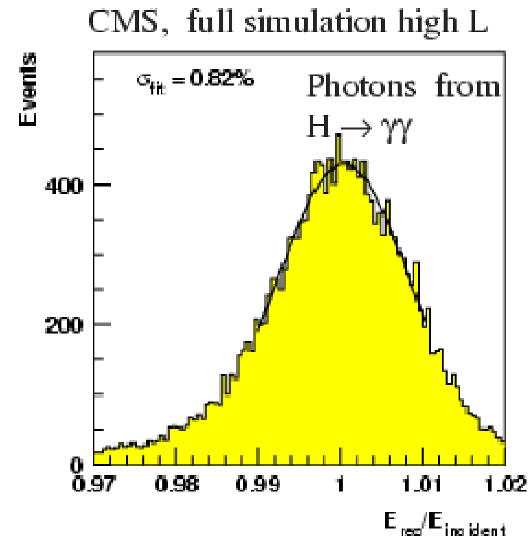


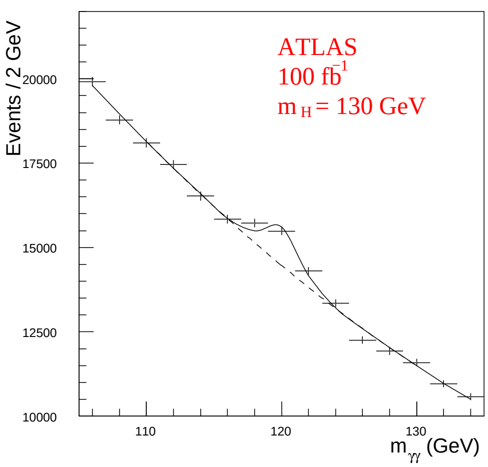
Production process	Decay Channel	Mass Range
direct prod.	$H \to \gamma\gamma$	80 GeV–150 GeV
	$H \to ZZ^* \to 4l$	120 GeV–2 m_Z
	$H \to ZZ \to 4l$	2 m_Z–600 GeV
	$H \to WW \to l\nu l\nu$	150 GeV–190 GeV
	$H \to WW \to l\nu jj$	300 GeV–1000 GeV
	$H \to ZZ \to ll\nu\bar{\nu}$	500 GeV–1000 GeV
WW fusion	$H \to WW \to e\nu e\nu$	120 GeV–200 GeV
	$H \to \tau\tau \to llp_T^{miss}$	110 GeV–150 GeV
ass. W prod.	$WH \to WWW \to l\nu l\nu l\nu$	150 GeV–190 GeV
	$WH \to WWW \to l\nu l\nu jj$	150 GeV–190 GeV
ass. quark prod.	$H \to b\bar{b}$	80 GeV–100 GeV
	$H \to \gamma\gamma$	80 GeV–140 GeV

$H\rightarrow \gamma\gamma$, $H\rightarrow ZZ^{(*)} \rightarrow 4l$

$H\rightarrow \gamma\gamma$ results for ATLAS and 100 fb^{-1}

m_H (GeV)	110	130	150
S	1110	1110	617
B	47300	33700	23350
$S/\sqrt{B}$	5.6	6.5	4.3
σ_m	1.37	1.55	1.74



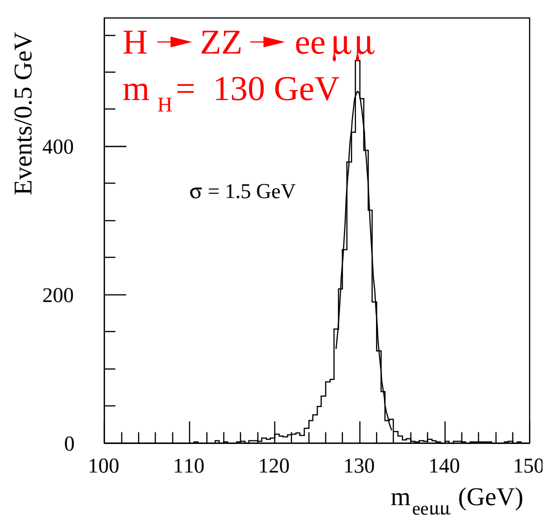


- CMS mass resolution better due to better performance of crystal calorimeter in comparison with ATLAS LAr calorimeter
- Acceptance loss bigger for CMS due to rejection of converted photons
- Assuming same K-factors and kinematic cuts, signal significances for ATLAS and CMS are within 10%

$H\rightarrow ZZ\rightarrow 4l$ results for ATLAS and 100 fb^{-1}

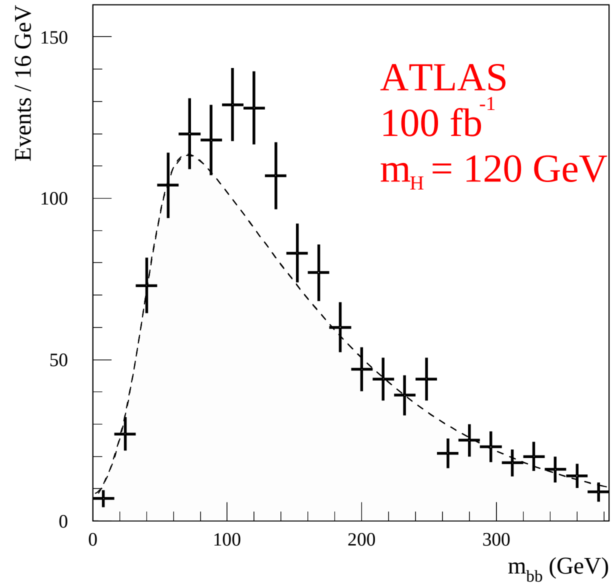
m_H (GeV)	120	130	150	180
S	10.3	28.7	67.6	49.7
B	4.39	7.76	8.92	8.81
$S/\sqrt{B}$	4.9	10.3	15.5	11.2
σ_m (GeV)	1.60	1.65	1.82	2.28
m_H (GeV)	200	300	400	600
S	445	352	285	76
B	246	129	96	49
$S/\sqrt{B}$	28.4	31.0	29.1	10.8

1 experiment
(full detector simulation)

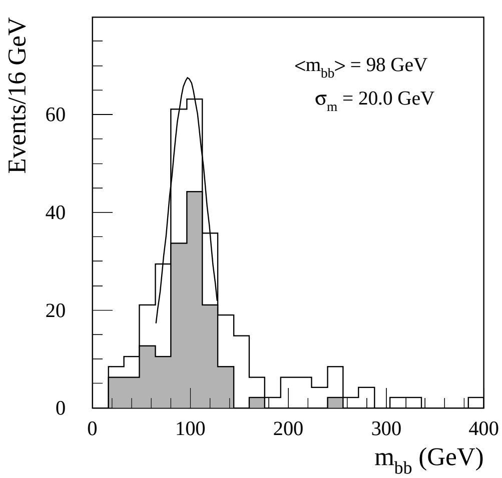


$t\bar{t}H \to t\bar{t}b\bar{b}$, $t \to bjj$, $t \to be/\mu\nu$

- Major backgrounds
  - combinatorial from signal
  - Wjjjjjj, WWbbjj, etc.
  - ttjj (dominant, non–resonant)



- Background not flat under the peak
  $\Rightarrow$ Uncertainty of 10% assumed for background subtraction
  $\Rightarrow$ This error is included in determination of rate and coupling

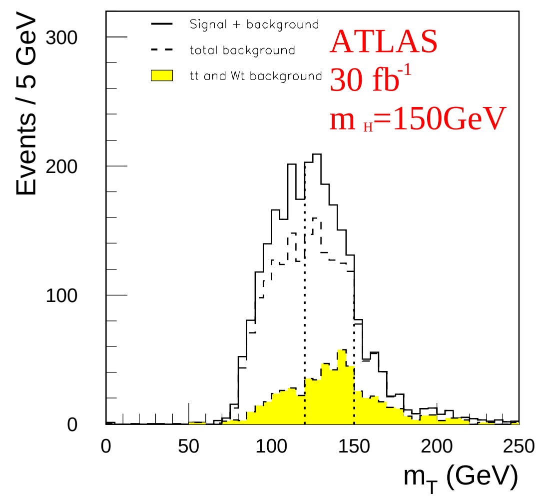


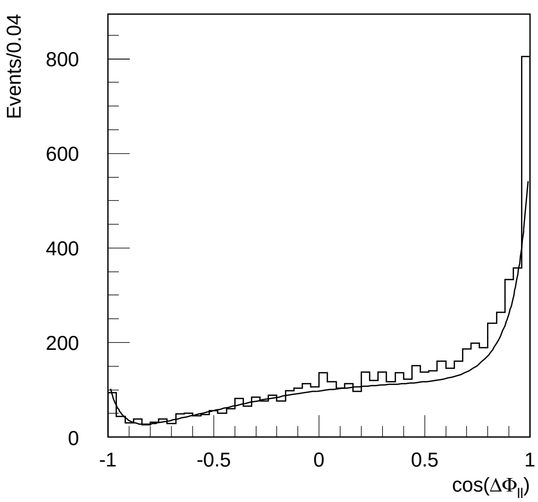
fully simulated events

m_H (GeV)	100	120
S	107	62
B	278	257
$S/\sqrt{B}$	6.4	3.9

$H \to WW \to l\nu l\nu$

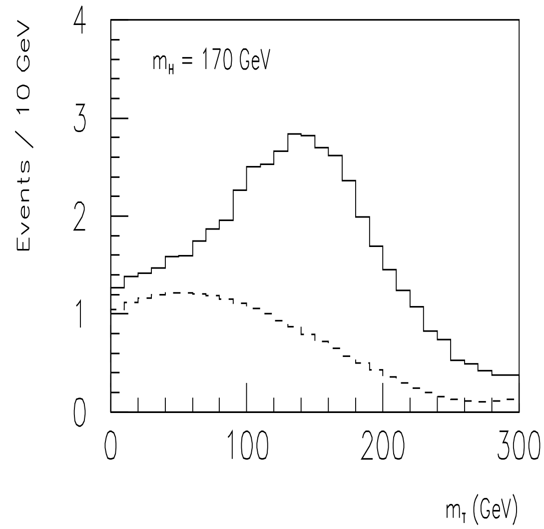
- No mass peak due to neutrinos in final state
- Transverse mass:
  $m_H = \sqrt{2 \cdot p_T \cdot E_T^{miss}(1 - \cos\Delta\phi)}$
- Signal appears as excess above background (WW and $t\bar{t}$)
- Shape similar, sidebands cannot be used to determine background below signal





- Better signal to background separtion in $\cos(\Delta\Phi)$ due to spin correlations
- Normalization of background in low signal region ($\cos(\Delta\Phi) < 0.2$)
  $\Rightarrow$ Allows background estimate with uncertainty of $\pm 3.5\%$ (result from MC study)
  $\Rightarrow$ Included in determination of rates and couplings

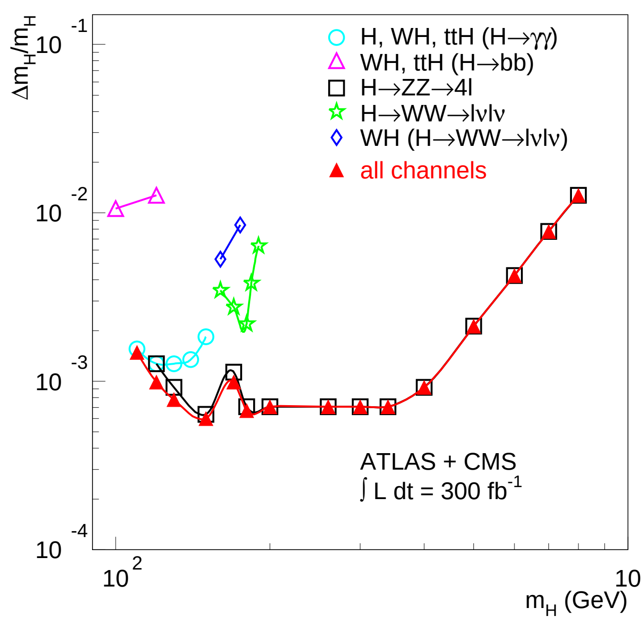
- Associated channel:
  $WH \to WWW \to l\nu l\nu l\nu$
- Similar uncertainty on background subtraction assumed as for WW channel
- Important for determination of couplings

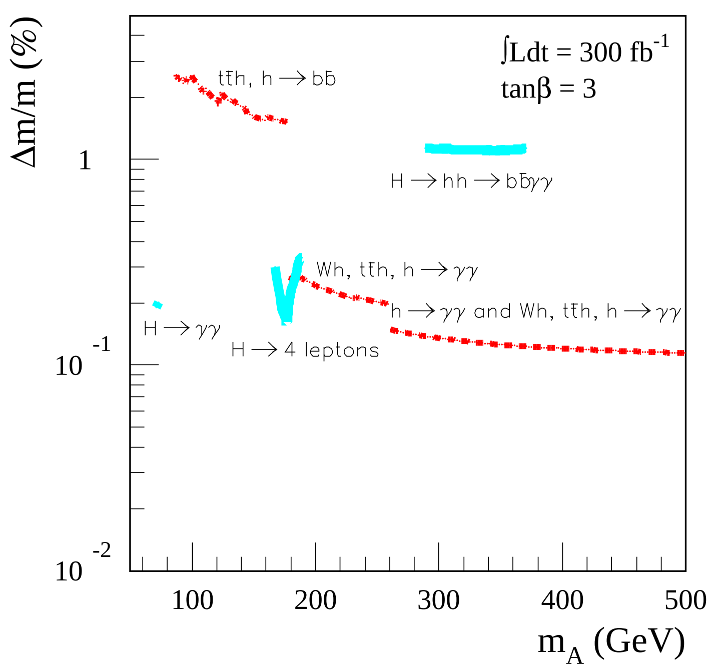


Results for the mass reconstruction

- Precision includes statistical error due to limited number of signal events and background subtraction
- Systematic error:
  - Leptonic E scale (assumed to be 0.1%, goal 0.02%)
  - 1% error on energy scale for hadronic channels
- No theoretical error included:
  - Interference of signal and background not included $\Rightarrow$ shift of m_H for large m_H and Γ_H
  - Uncertainty from structure functions expected to be small
- Expected mass resolution combining rates of ATLAS and CMS and assuming 300 fb^{-1}/experiment:

  $\Delta m_H/m_H \approx 0.06\%$ ($m_H < 400$ GeV)
  $\Delta m_H/m_H \approx 1\%$ ($m_H = 700$ GeV)





MSSM

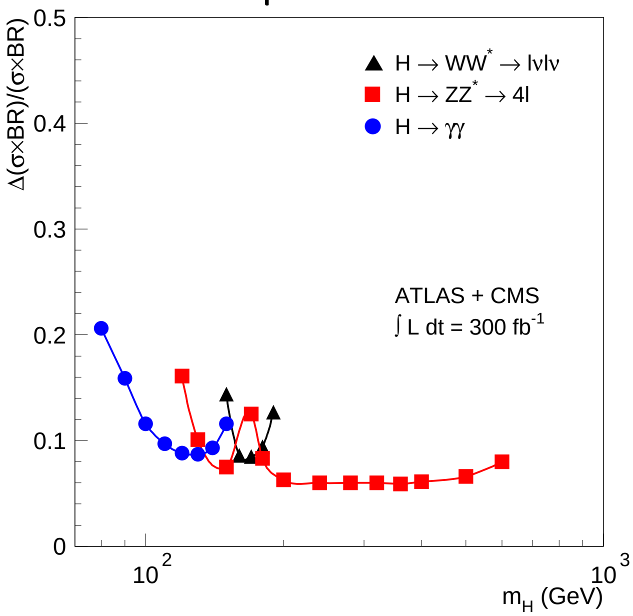
Channel	$\Delta m/m$ (%)
h,A,H→ $\gamma\gamma$	0.1–0.4
H→ ZZ* →4l	0.1–0.4
H/A→ $\mu\mu$	0.1–1.5
h→ b$\bar{b}$	1–2
H→hh→ b$\bar{b}\gamma\gamma$	1–2
A→Zh→ b$\bar{b}$	1–2
H/A→ $\tau\tau$	1–10

Measurement of the rate

- Measurement of production cross-section times decay branching ratio

$$\sigma \times \mathrm{BR} = \frac{N_{S+B} - \langle N_B \rangle}{\epsilon \cdot \eta \cdot \int \mathcal{L} dt}$$

direct production



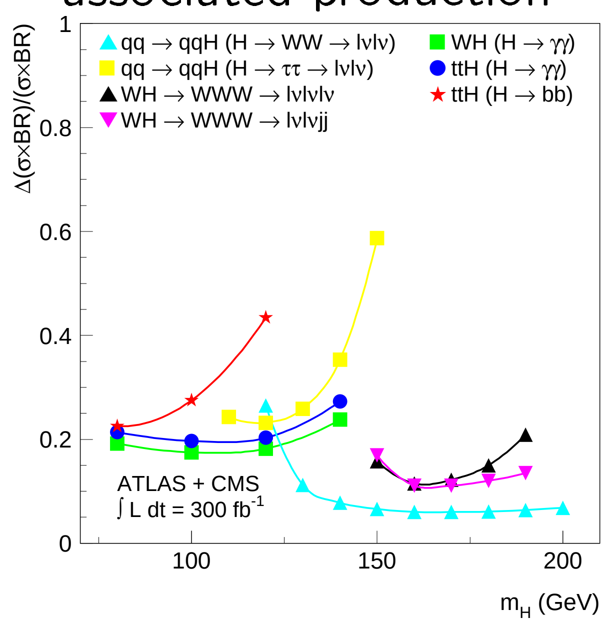
- Included errors:
  Luminosity: $\Delta L/L$=5%
  Efficiency and acceptance: $\Delta(\epsilon \cdot \eta)/(\epsilon \cdot \eta)$=2%
  Uncertainty of background:
  - 5% for H→WW
  - 10% for H→ $b\bar{b}$

Typical precision for ATLAS+ CMS and 300 fb^{-1}/experiment:

- Direct production:
  6%–20% in mass range
  $120 < m_H < 600$ GeV

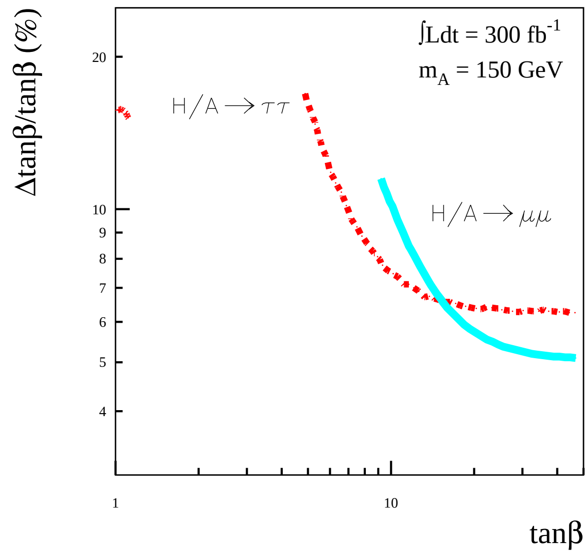
- Associated production:
  6%–30% in mass range
  $100 < m_H < 200$ GeV

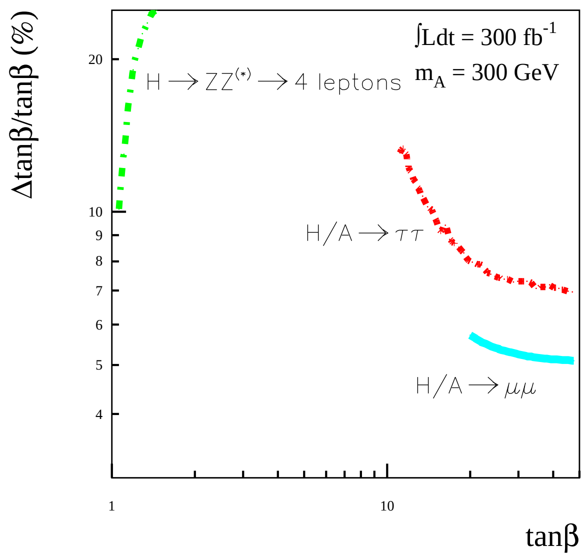
associated production



Measurement of $\tan\beta$

- Measurement of the signal rate of heavy Higgs H provides good sensitivity to $\tan\beta$
- Accuracy for $\tan\beta$ assuming 300 fb^{-1} and m_A=150GeV
- H/A$\to\tau\tau$ channel:
  $\Delta(\tan\beta)/\tan\beta$ = 6–15%
- H/A$\to\mu\mu$ channel:
  $\Delta(\tan\beta)/\tan\beta$ = 5–12%
- H$\to ZZ^{(*)}\to$4l channel:
  $\Delta(\tan\beta)/\tan\beta$ = 10–25%





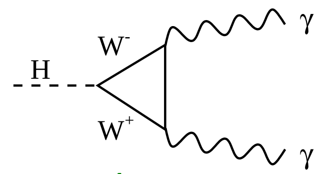
- Systematic error is dominated by luminosity (assumed here to be 10%)
- H$\to ZZ^*\to$4l channel is rate limited

- Compared to the SM the rate in the H$\to ZZ^{(*)}\to$4l channel is supressed by an order of magnitude in the MSSM
  $\Rightarrow$ Distinction between SM and MSSM may be feasible

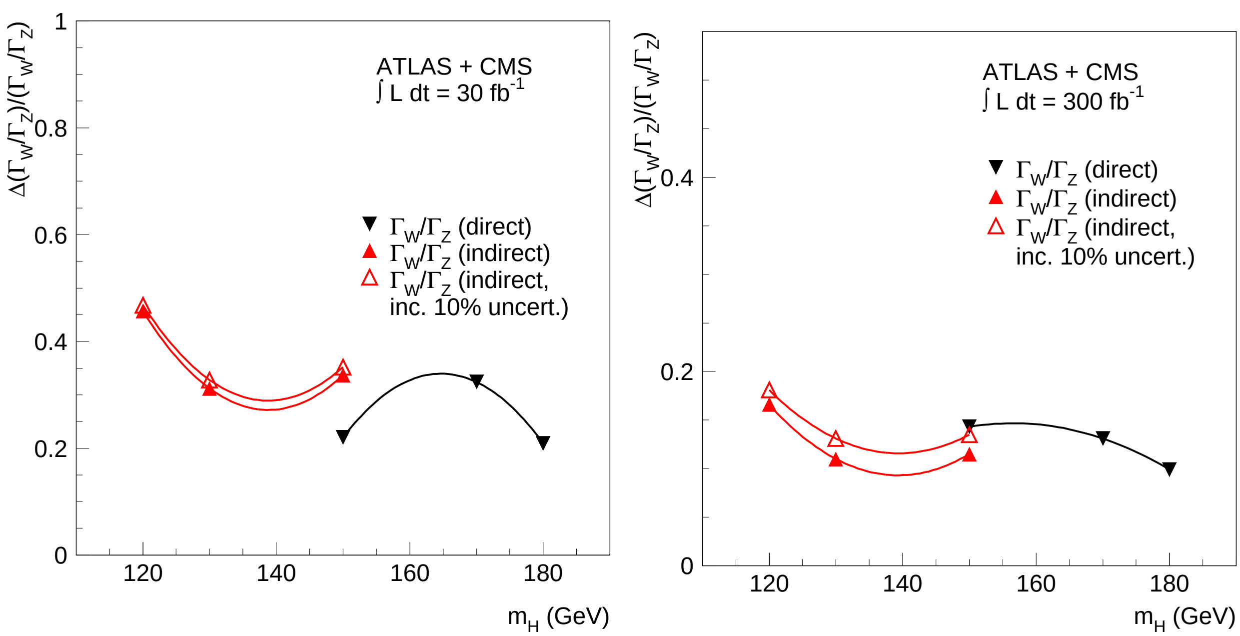
Coupling to bosons

- Without theoretical input only measurement of coupling ratios possible
- Direct measurement
  - $$\frac{\sigma\times BR(H\to WW^*)}{\sigma\times BR(H\to ZZ^*)} = \frac{\Gamma_g\Gamma_W}{\Gamma_g\Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$
  - QCD corrections cancel (in first order)
- Indirect measurement
  - $$\frac{\sigma\times BR(H\to\gamma\gamma)}{\sigma\times BR(H\to ZZ^*)} = \frac{\Gamma_g\Gamma_\gamma}{\Gamma_g\Gamma_Z} \sim \frac{\Gamma_W}{\Gamma_Z}$$
- Indirect measurements ⇒ Proportionalities are used

  $\Gamma_W = \alpha\ \Gamma_\gamma$
  $\Gamma_t = \beta\ \Gamma_g$
  Error of 10% assumed for α resp. β



Results for 30 fb^{-1} and 300 fb^{-1} per experiment

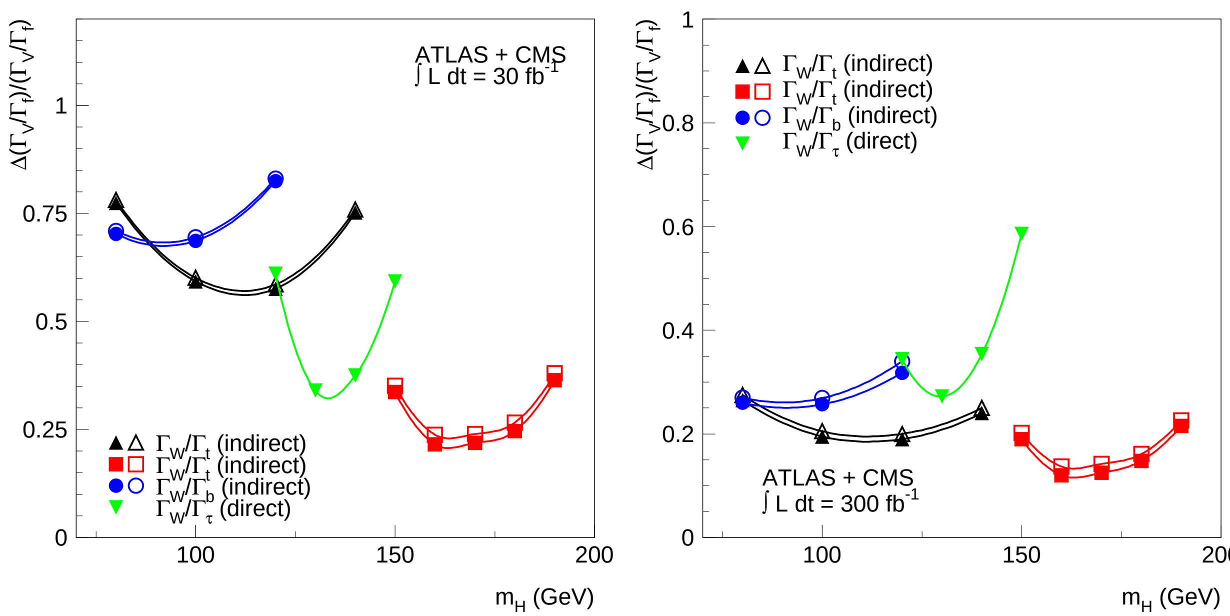


- No theoretical errors included:
  Different K-factors for gg-Fusion (K_g=1.7–1.8) and WW-Fusion (K_W=1.06–1.08)
  ⇒ Additional uncertainty, if channels with different production processes are compared

Ratio of boson/fermion coupling

- Direct measurement
  - $\frac{\sigma \times BR(qq \to qqH(H \to WW))}{\sigma \times BR(qq \to qqH(H \to \tau\tau))} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$
- Indirect measurement
  - $\frac{\sigma \times BR(WH(H \to \gamma\gamma))}{\sigma \times BR(H \to \gamma\gamma)} = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_g \Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  - $\frac{\sigma \times BR(WH(H \to WW))}{\sigma \times BR(H \to WW^*)} = \frac{\Gamma_W \Gamma_W}{\Gamma_g \Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  - $\frac{\sigma \times BR(ttH(H \to bb))}{\sigma \times BR(ttH(H \to \gamma\gamma))} = \frac{\Gamma_t \Gamma_b}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_W}$
    - * Uncertainties on the ratio arising through different production processes are not included

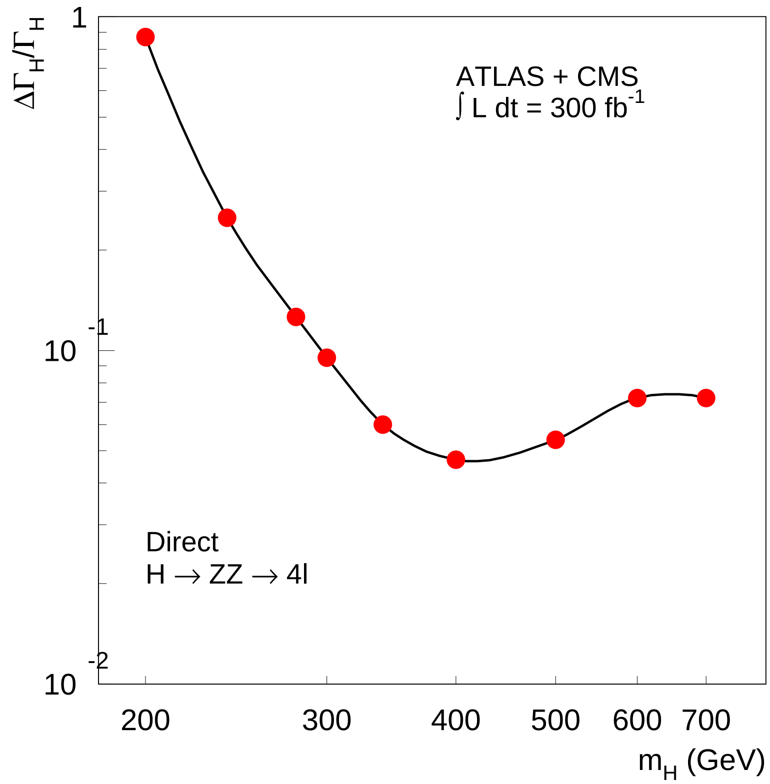
Results for 30 fb^{-1} and 300 fb^{-1} per experiment



Measurement of the total width

- Determined from reconstructed width of reconstructed mass peak
- Direct measurement only possible for $m_H > 200$ GeV
  - $\Gamma_H^{tot} < 0.1$ GeV for $m_H < 2M_Z$
  - expected detector resolution 1.2–1.4 GeV
- mostly covered by H→ZZ→4l decays

Result for ATLAS and CMS and 300 fb^{-1} per experiment



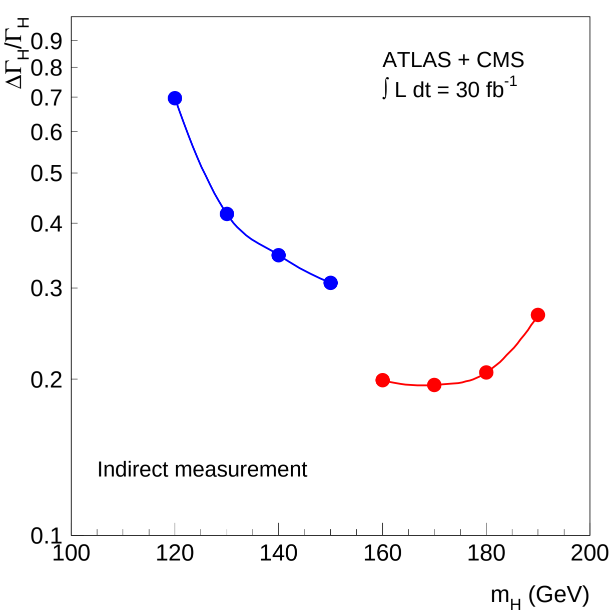
- sytematic error dominated by uncertainty of radiative decays, assumed to be 1.5%

Indirect measurement for $m_H < 200$ GeV

- Proposed by D. Zeppenfeld et al., Phys. Rev. **D 62** (2000) 013009/1–10
  - Computation of partial width $\tilde{\Gamma}_W$
    $[\Gamma_b + \Gamma_\tau + \Gamma_W + \Gamma_Z + \Gamma_g]\frac{\Gamma_W}{\Gamma} = \Gamma_W(1-\epsilon) = \tilde{\Gamma}_W$
  - Using SU(2)-symmetry
    $\Gamma_Z = z \cdot \Gamma_W \qquad \Gamma_b = y \cdot \Gamma_\tau$
  - Computation of total width $\tilde{\Gamma}$
    $\tilde{\Gamma} = \Gamma(1-\epsilon)^2 = \frac{\Gamma_W^2}{X_W}$
- Important channels: Weak Boson Fusion
  qq→qqH (H→WW→lνlν): 120 GeV $\leq m_H \leq$ 190 GeV
  (Detector simulation)

  qq→qqH (H→ $\tau\tau$ →llp_T^{miss}): 110 GeV $\leq m_H \leq$ 150 GeV
  (Detector simulation, statistics corresponding to 30fb^{-1}/experiment)
- $\epsilon < 5\%$ over whole mass range

Results for 30fb^{-1} and 300fb^{-1} per experiment



Decay correlation function for $H \rightarrow ZZ^{(*)} \rightarrow 4l$

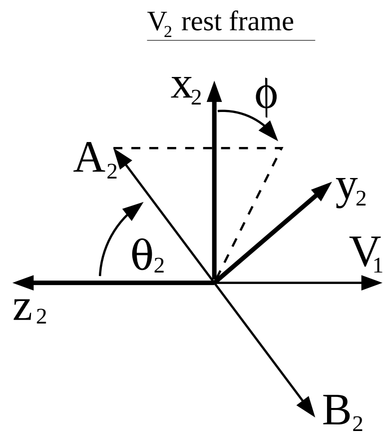
- From C.A. Nelson, Phys. Rev. **D 37** (1988) 1220

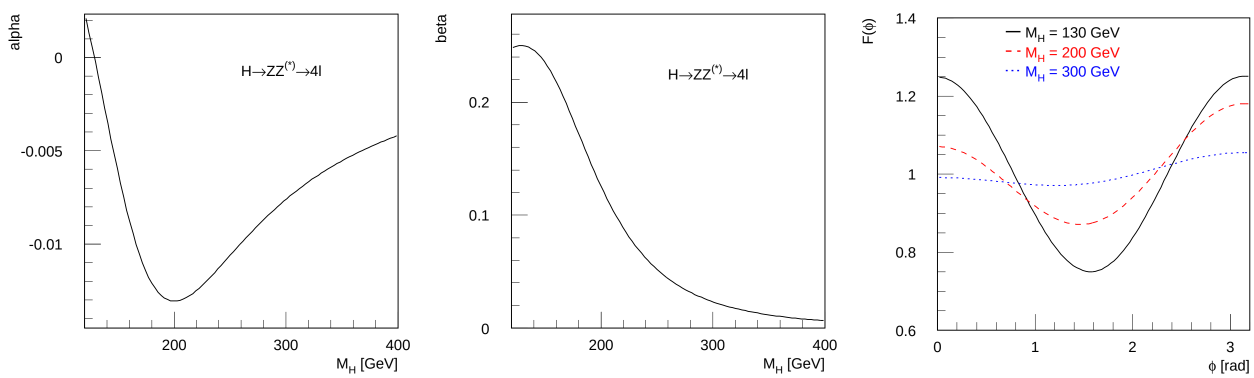
$$F(\Phi) = 1 + \alpha cos\Phi + \beta cos2\Phi$$

$$\alpha = \left(\frac{3\pi}{8}\right)^2 \frac{\gamma}{(1+\gamma^2/2)}$$

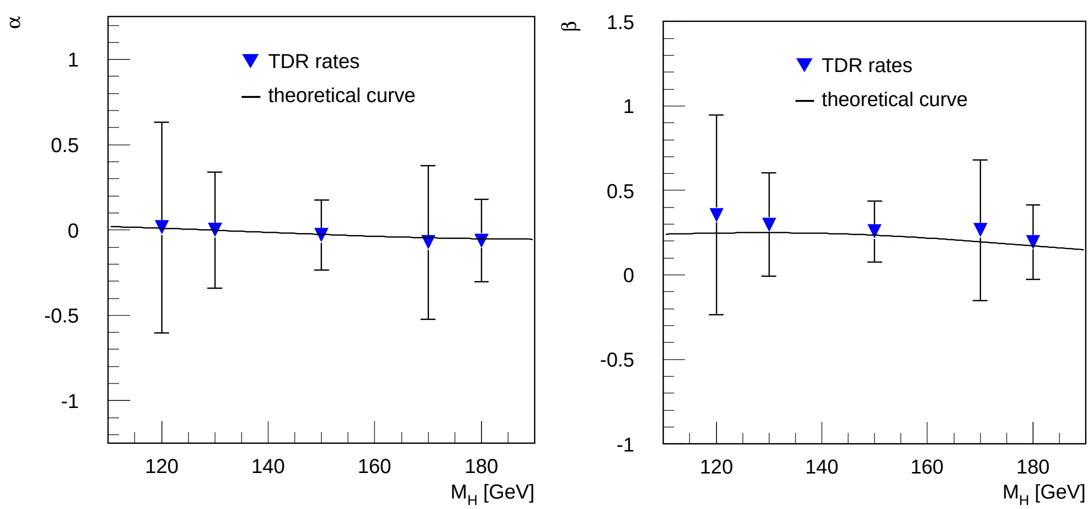
$$\beta = \frac{1}{4}\frac{1}{(1+\gamma^2/2)}$$

$$\gamma = \frac{(M_H^2 - 2m_V^2)}{2m_V^2}$$





Sensitivity for α and β for 100 fb^{-1} and $m_H < 2m_Z$



- Similar results for mass range 200 GeV $< m_H <$ 400 GeV

Summary

- Mass:
  - Mass resolution around 0.06 % for $m_H < 400$ GeV
  - Interference of signal and background must be included in further studies
- Rates:
  - In various channels the rate can be determined with a relative precision of 6%
  - Good rate measurement desirable for determination of couplings and width
- Couplings:
  - The ratio of the coupling to W and Z bosons can measured with a relative precision of 10–20%
  - The ratio of boson and fermion coupling can be determined with an accuracy of 10–35%
- Width:
  - In the mass range above 200 GeV a direct measurement of the width is possible with a relative precision of 5–20% for $m_H > 220$ GeV
  - In the intermediate mass range the width can be determined indirectly with an accuracy of 13–45%
- Spin:
  - Consistency with spin 0 over the whole mass range 120 to 400 GeV can be demonstrated
  - Comparison with particle with spin $S \neq 0$ necessary