# Measurements of the Standard Model Higgs parameters at ATLAS

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# Measurements of the Standard Model Higgs parameters

- If there is a Higgs boson, it would be found at ATLAS (> 5σ) over the full mass range after a few months of physics run.
- Precision measurement of Higgs parameters will become a major goal
- Necessary for better understanding of Standard Model symmetry-breaking mechanism

- References for this talk:
  - Physics TDR
  - M. Hohlfeld, ATL-PHYS-2001-004
  - D. Zeppenfeld, et al., hep-ph/0002036
  - M. Dührssen, et al., note in preparation
  - E. Gross, L. Živković, A. Ito, note in preparation
  - C. P. Buszello, et al, SN-ATLAS-2003-025 (spin and CP)

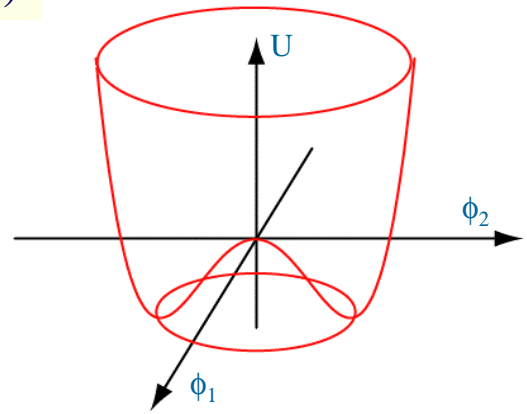
# The Higgs Mechanism

- Essential ingredient of the Standard Model:
  - complex scalar field with potential $U(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$
- Used to break the el. weak symmetry.....

$$M_{W^\pm} = \tfrac{1}{2} vg \qquad M_Z = \tfrac{1}{2} vg / \cos\theta_W = M_W / \cos\theta_W$$

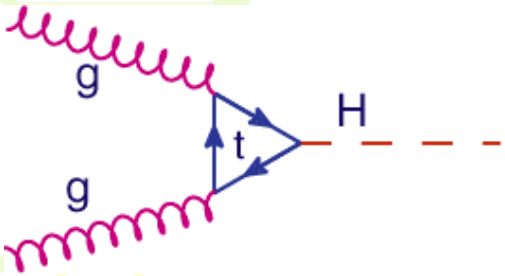
- ..... and to generate fermion masses:

$$m_f = g_f v / \sqrt{2} \qquad \Rightarrow g_f = m_f \sqrt{2} / v$$

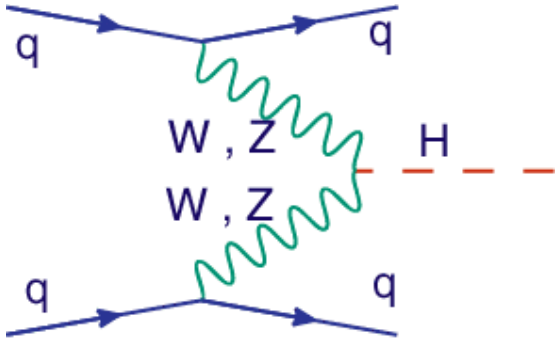



- Search for the Higgs Boson is a key issue for experiments at future colliders
- Experimental challenges:
  - Higgs boson discovery
  - Measurement of Higgs boson parameters (couplings to bosons and fermions)
  - Measurement of the Higgs self coupling $\Rightarrow$ Higgs potential
- Mass limits: lower 114.4 GeV/$c^2$ and upper up to 1 TeV from theory and ~200 GeV from precision measurement

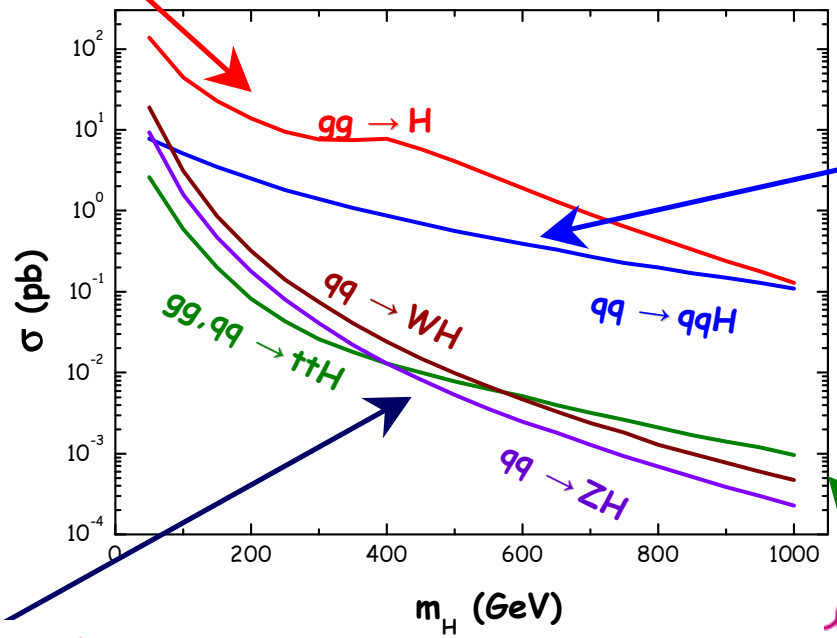
# Production …




The highest cross-section

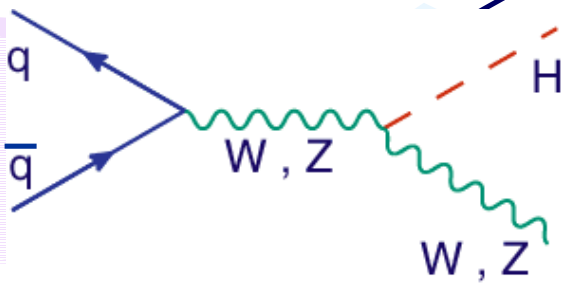



Two high-$p_T$ forward jets

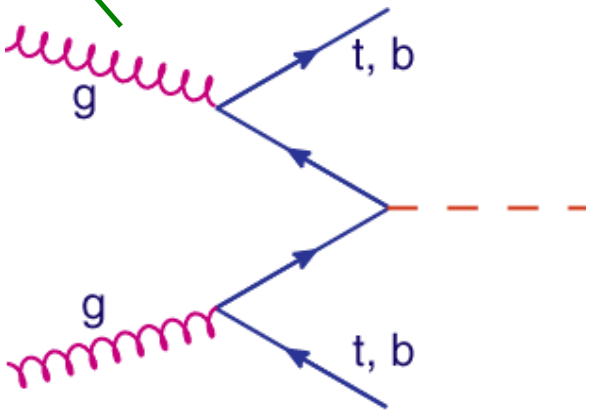



One or two high $p_T$ leptons for trigger

High $p_T$ lepton for trigger




Reconstruction of one or two top quarks



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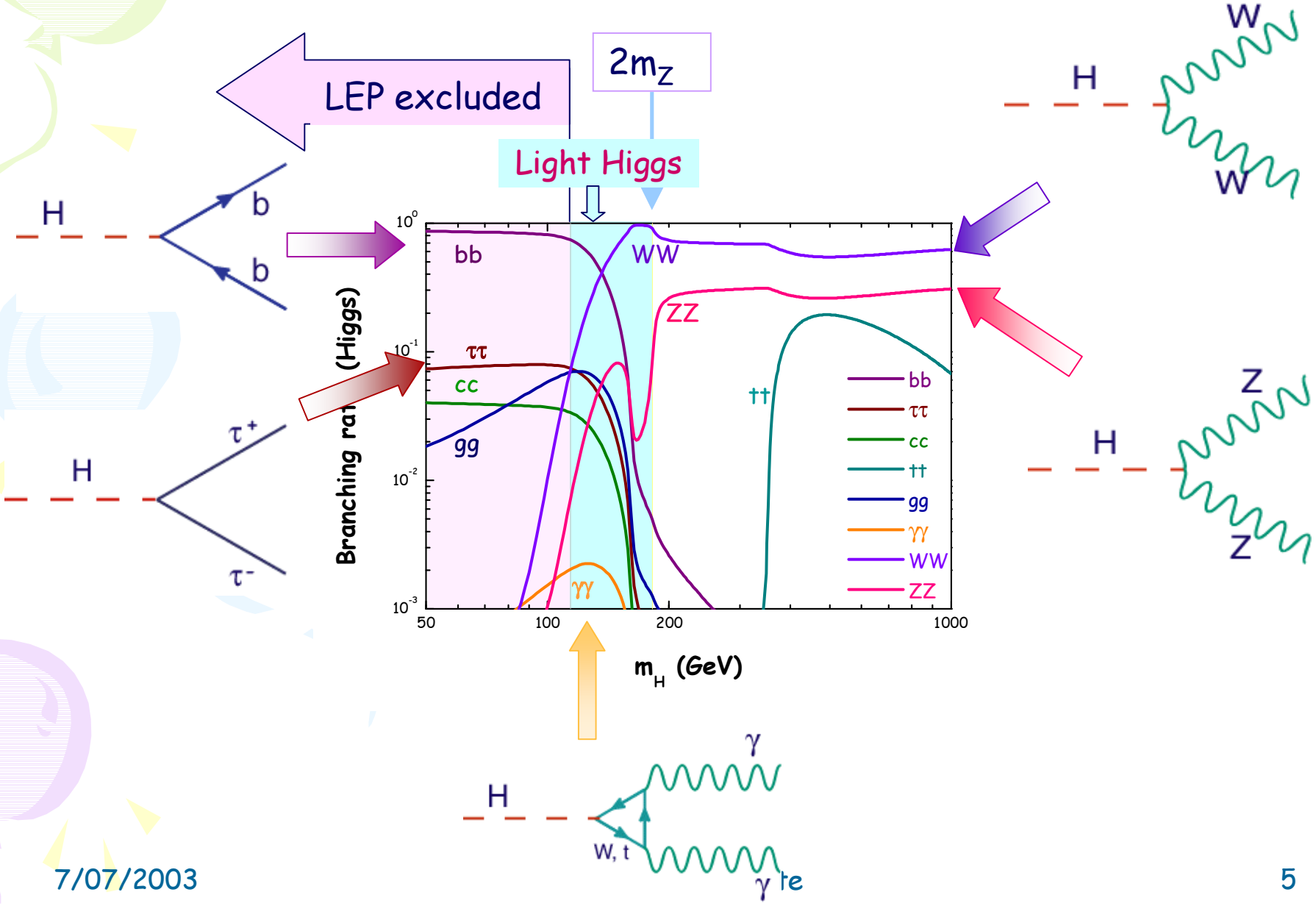
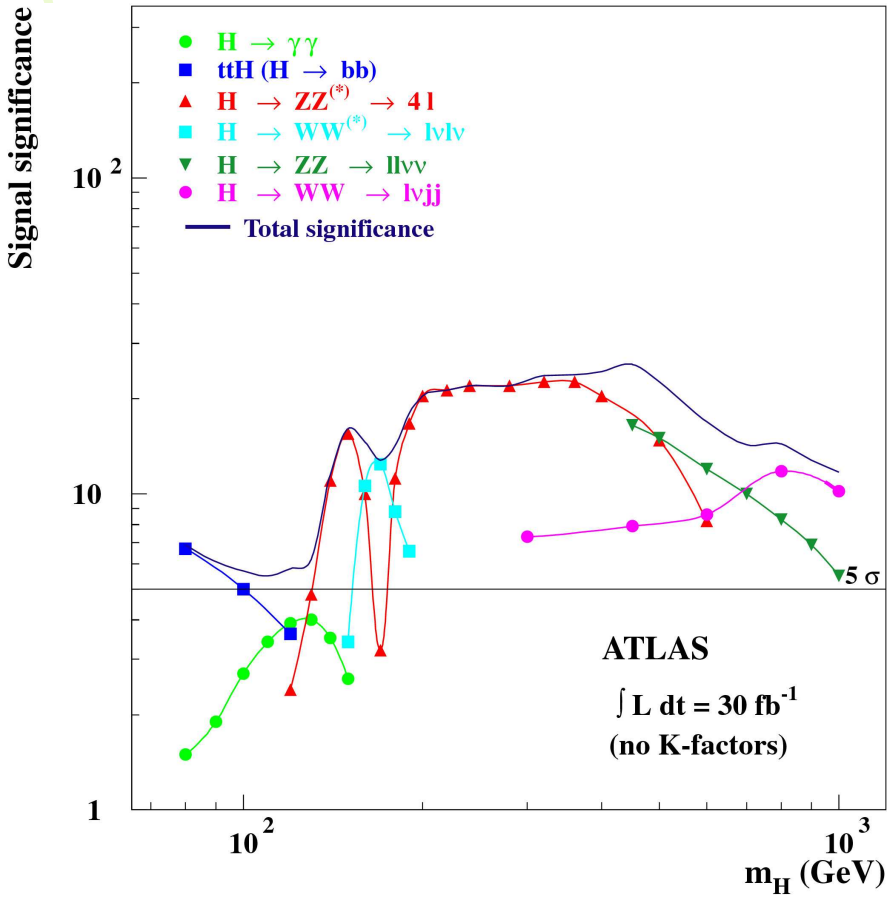
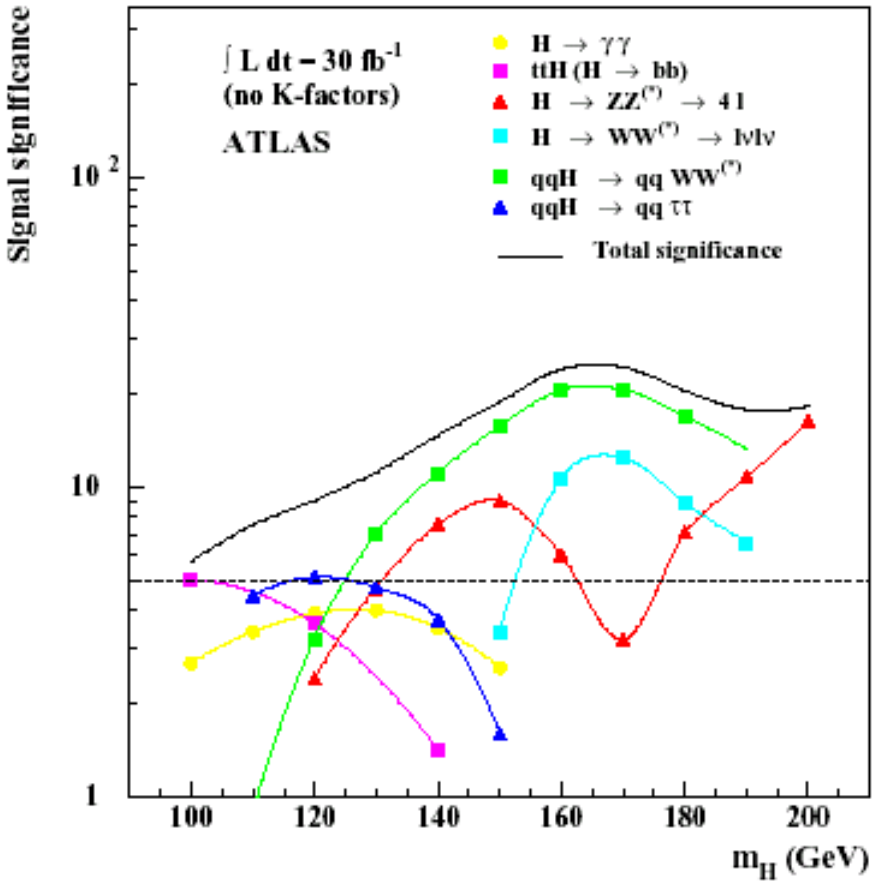
# … and Decays


LEP excluded
2m_Z
Light Higgs
H
b
b
H
τ+
τ-
W
W
H
Z
Z
H
H
γ
γ
W, t
Branching ratio (Higgs)
m_H (GeV)
bb
ττ
cc
gg
WW
ZZ
tt
γγ
50
100
200
1000

# SM Higgs




Physics TDR



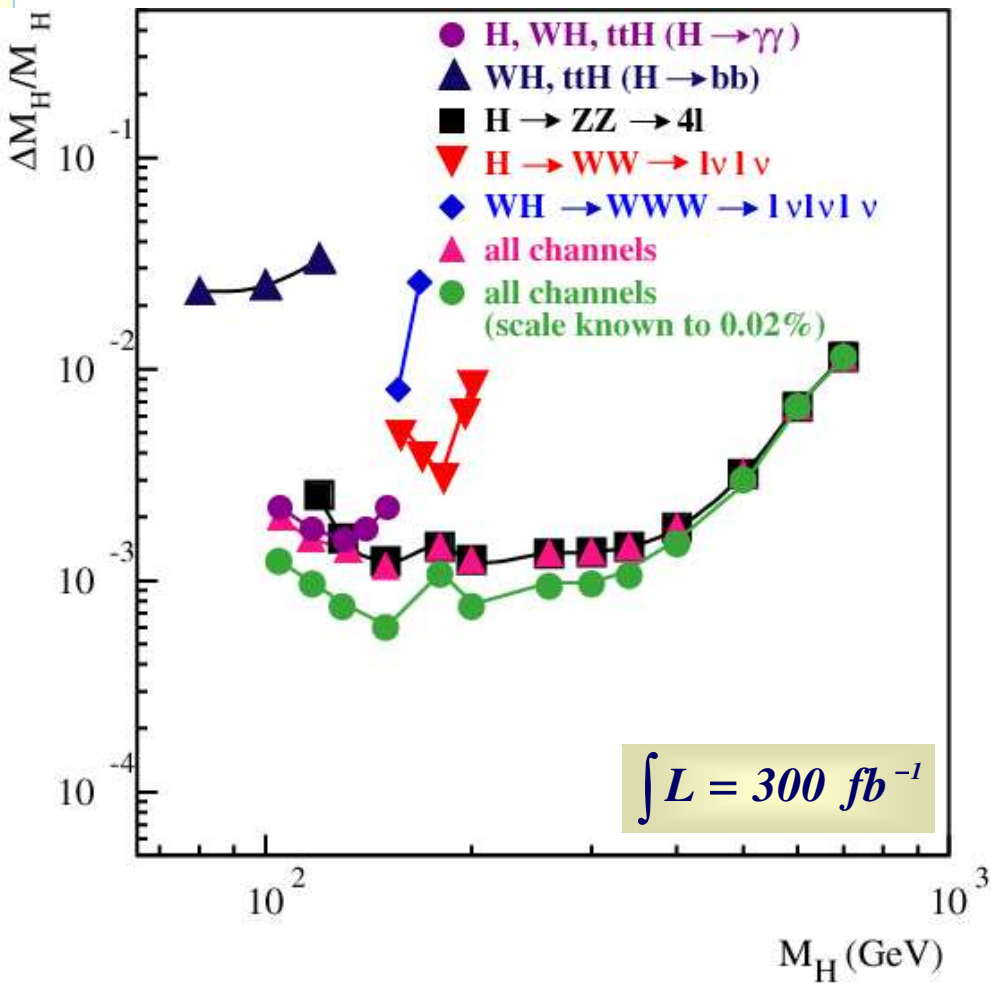

ATLAS-PHYS-2003-005

# Search channels - mass range 100 - 1000 GeV

| Production | Decay | Mass range | measures |
|---|---|---|---|
| Gluon fusion | $H \to \gamma\gamma$<br>$H \to ZZ^{(*)} \to 4l$<br>$H \to WW^{(*)} \to l\nu\ l\nu$ | 110 - 150 GeV<br>120 - 700 GeV<br>110 - 190 GeV | mass, WWH, ttH<br>mass, ZZH, ttH, spin<br>mass, WWH |
| Vector Boson Fusion | $H \to bb$<br>$H \to \gamma\gamma$<br>$H \to \tau\tau$<br>$H \to WW^{(*)} \to l\nu\ l\nu$ | 110 - 140 GeV<br>110 - 150 GeV<br>110 - 150 GeV<br>110 - 190 GeV | mass, bbH, WWH<br>mass, WWH<br>mass, WWH, ττH<br>WWH, spin |
| ttH | $H \to \gamma\gamma$<br>$H \to bb$<br>$H \to \tau\tau$<br>$H \to WW^{(*)} \to l\nu\ l\nu$ | 110 - 120 GeV<br>110 - 140 GeV<br>110 - 130 GeV<br>120 - 200 GeV | mass, WWH, ttH<br>mass, ttH, bbH<br>ttH, ττH<br>WWH, ttH |
| WH, ZH | $H \to \gamma\gamma$<br>$H \to bb$<br>$H \to WW^{(*)} \to l\nu\ l\nu$ | 110 - 150 GeV<br>110 - 150 GeV<br>110 - 190 GeV | mass, WWH<br>mass, bbH, WWH<br>WWH |

# Measurements of Higgs Mass

- Mass:
  - Direct in the channels where Higgs mass can be reconstructed:
    - $H \rightarrow \gamma\gamma$,
    - $H \rightarrow bb$,
    - $H \rightarrow ZZ^{(*)} \rightarrow 4l$
  - indirect elsewhere:
    - $H \rightarrow WW \rightarrow l\nu l\nu$
    - $WH \rightarrow WWW \rightarrow l\nu l\nu l\nu$
    - VBF channels ($\tau$ final states)
- Errors: statistical, systematic on absolute energy scale (assumed 0.1% for channels with leptons and photons and 1% for jets; goal 0.02% for channels with leptons and photons)
- Precission from 0.1% to 1%

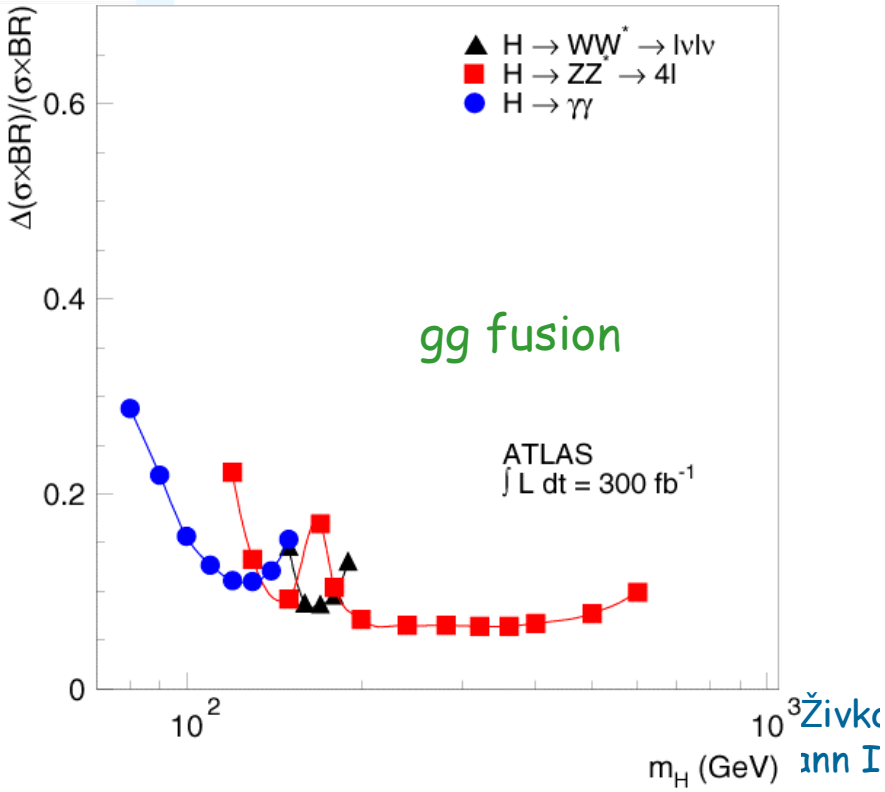


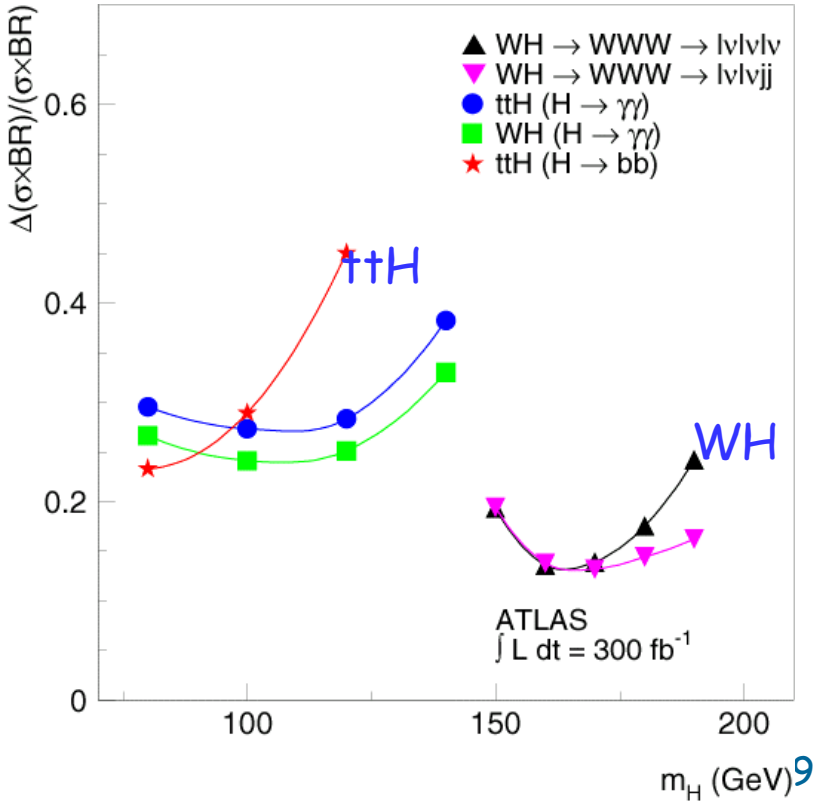

*Physics TDR and ATL-PHYS-2001-004*

# Measurements of Higgs Rates

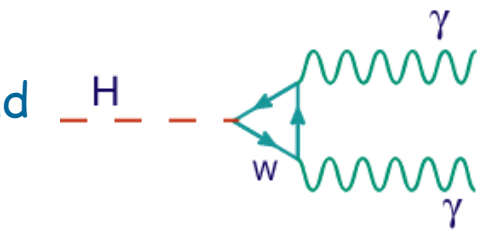
- The cross section times branching ratio: $\sigma \times BR = \frac{N_{S+B} - \langle N_B \rangle}{\epsilon \cdot \eta \cdot \int L dt}$ where Є is efficiency and η is acceptance.
- Errors: 5% on background where it can't be subtracted, neglected otherwise, 5% or 10% on luminosity' 2% on Є·η
- Relative error: $\frac{\Delta(\sigma \times BR)}{\sigma \times BR} = \frac{\sqrt{N_{S+B}^{\ 2} + N_S^{\ 2}(0.02^2 + \epsilon_{Lumi}^{\ 2}) + (\Delta\langle N_B \rangle)^2}}{N_{S+B} - \langle N_B \rangle}$

*ATL-PHYS-2001-004*



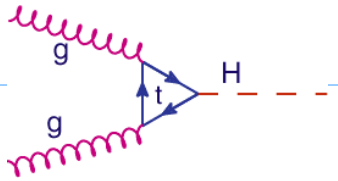



# Measurements of Higgs Couplings

- Couplings and branching ratios
  - Can be obtained from rate measurements if $\sigma(pp \to H + X)$ is known from the theory;
  - Otherwise: measure ratios of rates for different channels: (errors on the) cross sections, L, $\Gamma$ cancel $\Rightarrow$ get ratios of couplings
- Couplings to bosons ($m_H$ < 190 GeV considered so far):
  - directly from $\frac{H \to ZZ^{(*)}}{H \to WW^{(*)}}$ and the same production mode for $m_H$ > 150 GeV
  - indirectly using $\frac{H \to \gamma\gamma}{H \to ZZ^{*}}$ and 

$\Rightarrow \Gamma_W = \alpha\Gamma_\gamma$
    - the last one can be checked via $\frac{H \to \gamma\gamma}{H \to WW^{*}}$ with the same production mode (VBF, ttH)

# Measurements of Higgs Couplings




- Couplings to fermions:
  - ttH from $\frac{WH \to WWW}{H \to WW^{(*)}} = \frac{\Gamma_W \Gamma_W}{\Gamma_g \Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$ $\qquad \frac{ttH \to ttX}{qqH \to qqX} = \frac{\Gamma_t \Gamma_X}{\Gamma_W \Gamma_X} \sim \frac{\Gamma_t}{\Gamma_W}$

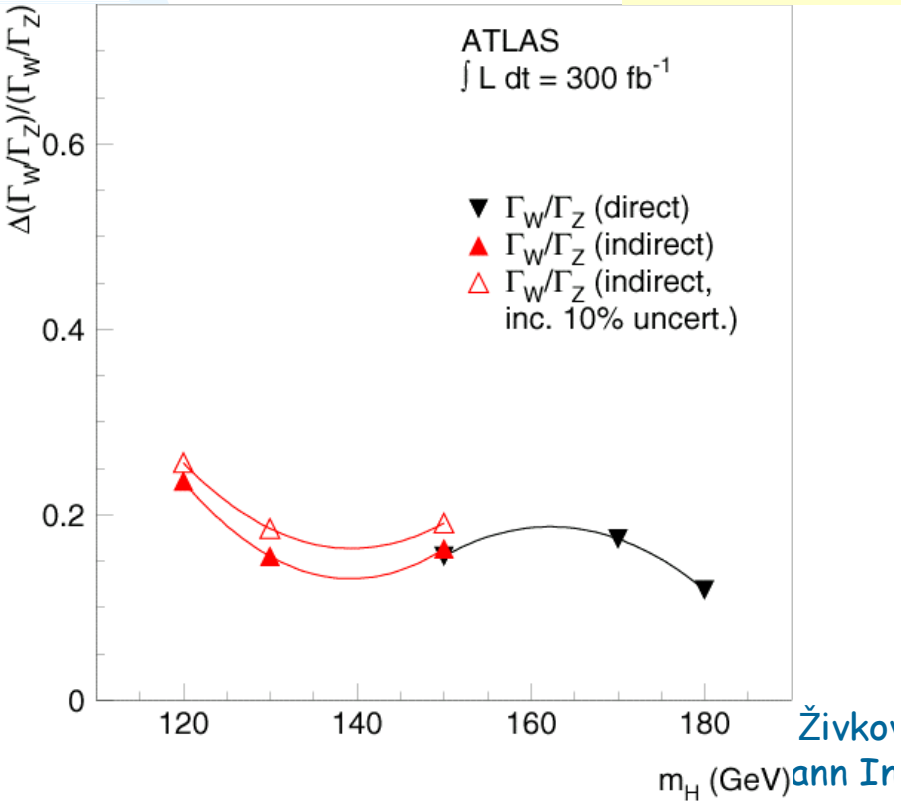
$$\frac{WH \to W\gamma\gamma}{H \to \gamma\gamma} = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_g \Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$$

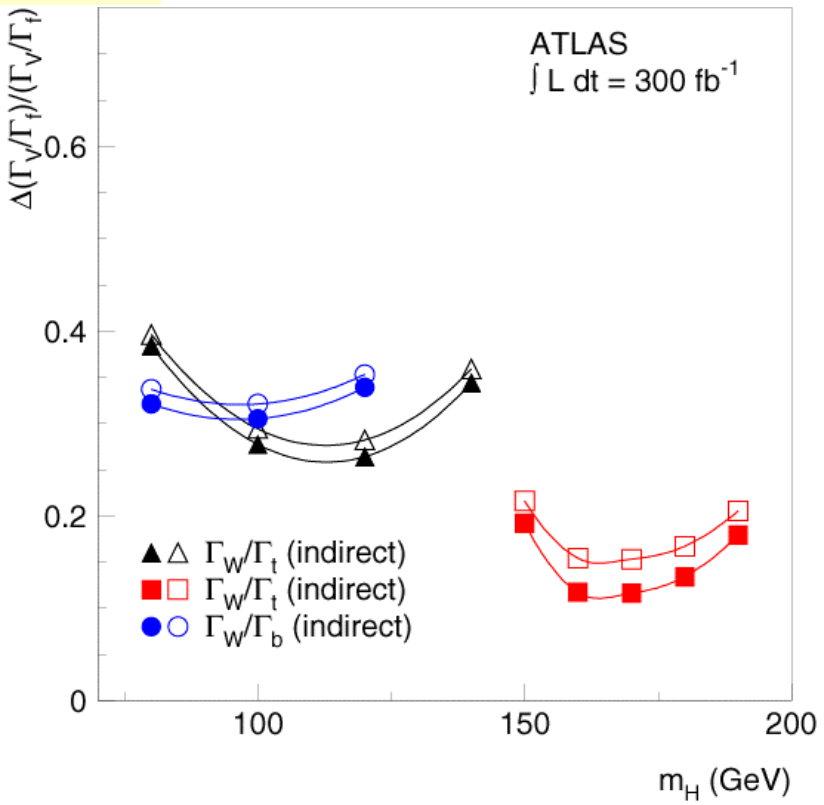
  - bbH from $\frac{ttH \to ttbb}{ttH \to tt\gamma\gamma} = \frac{\Gamma_t \Gamma_b}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_w}$ and $\frac{qqH \to qqbb}{qqH \to qqWW} = \frac{\Gamma_W \Gamma_b}{\Gamma_W \Gamma_W} \sim \frac{\Gamma_b}{\Gamma_w}$
  - ττH from $\frac{ttH \to tt\tau\tau}{ttH \to tt\gamma\gamma} = \frac{\Gamma_t \Gamma_\tau}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_\tau}{\Gamma_w}$ and $\frac{qqH \to qq\tau\tau}{qqH \to qqWW} = \frac{\Gamma_W \Gamma_\tau}{\Gamma_W \Gamma_W} \sim \frac{\Gamma_\tau}{\Gamma_w}$

# Measurements of Higgs Couplings

- Errors:
  - K-factors - 20% gluon fusion, 5% VBF
  - proportionality constant for Higgs decay to gg or γγ via loop – 10%
  - theoretical uncertainties from comparison of two different production modes

*ATL-PHYS-2001-004*

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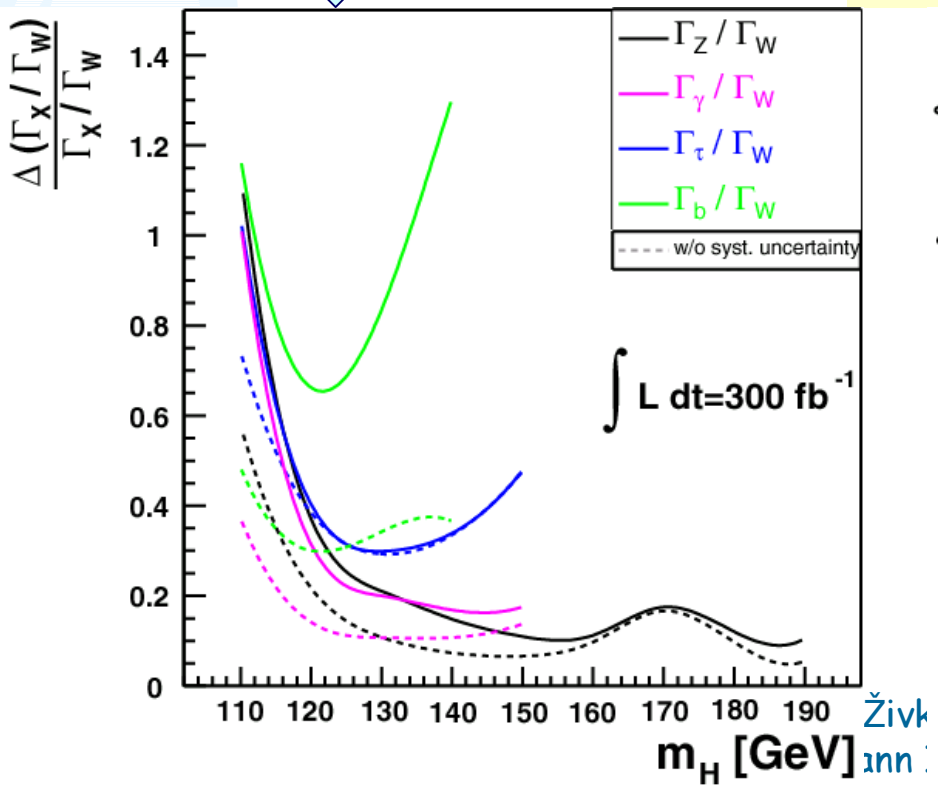
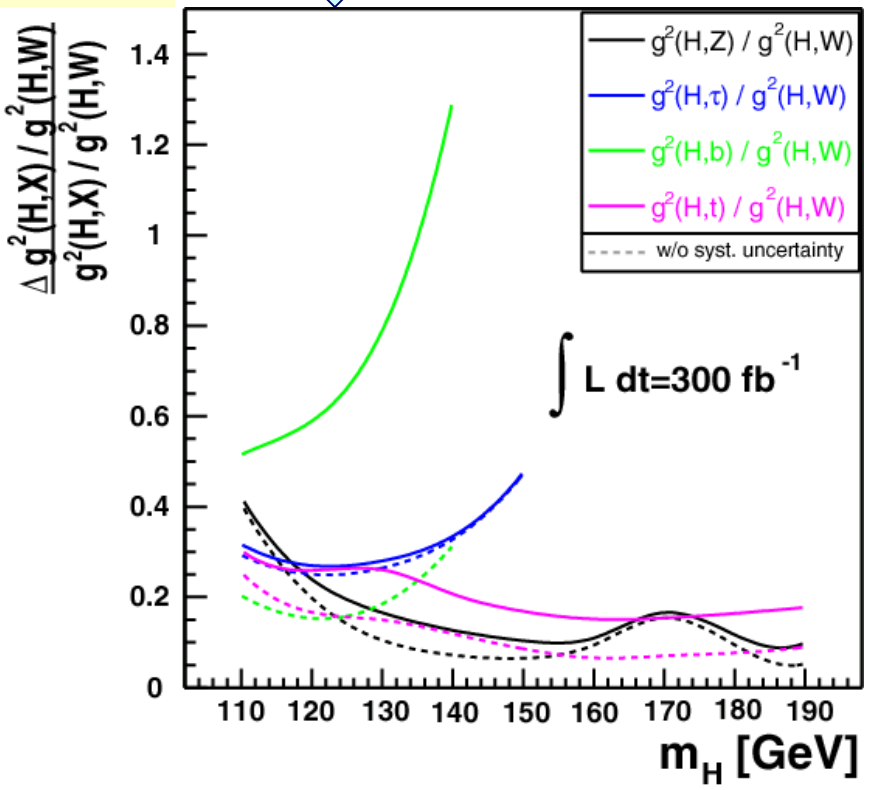
# Measurements of Higgs Couplings

## New results from Physics Workshop in Athens:

- Relative branching ratios:
  - Theoretical assumption : only one Higgs-Boson
- Relative couplings:
  - Additional assumption: only particles of Standard-Model

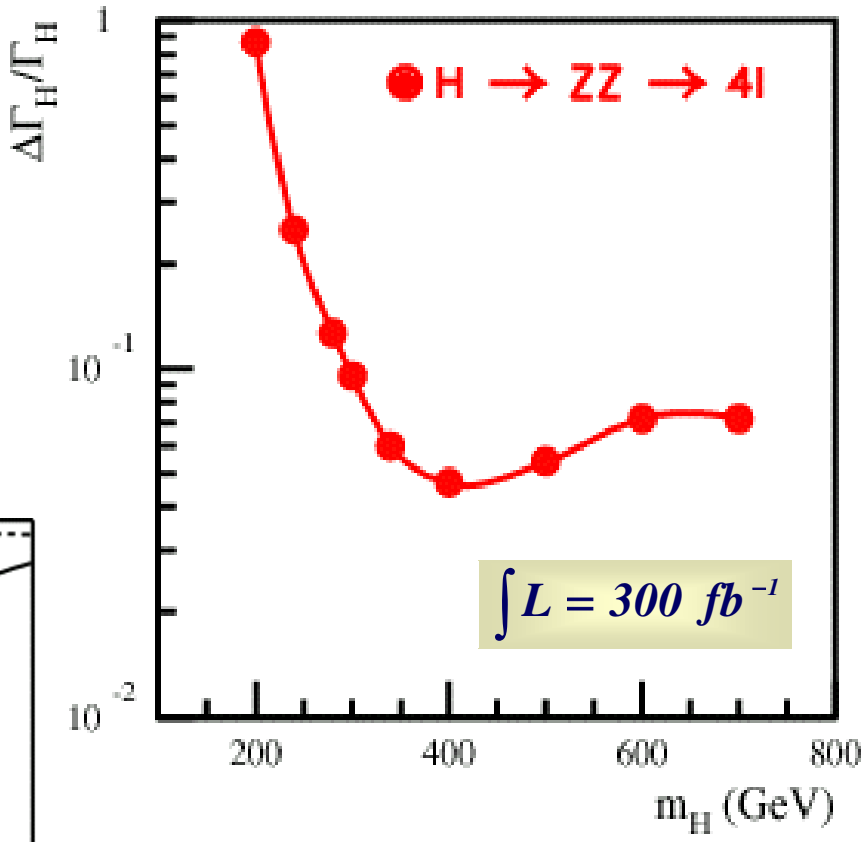
*M. Dührssen*

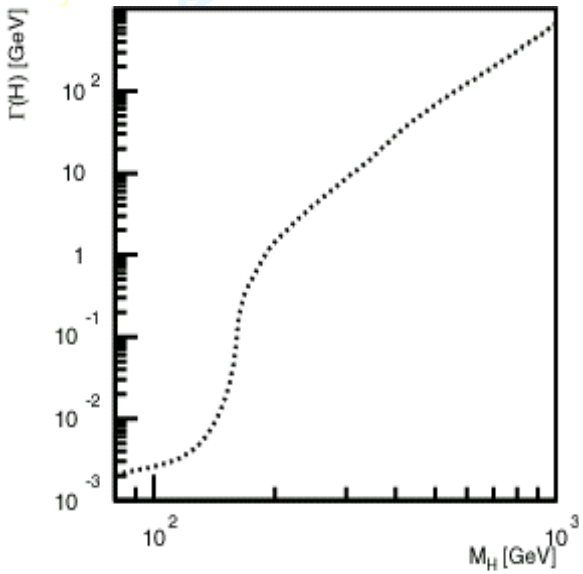


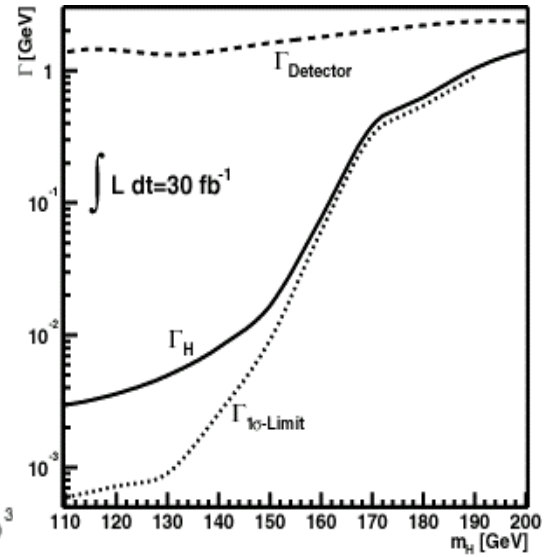



# Measurements of Higgs Width

- Width:
  - direct $H \rightarrow ZZ^{(*)} \rightarrow 4l$ just for $m_H >$ 200 GeV because total width, $\Gamma_H$ is smaller than $\Gamma_{Detector}$, detector resolution.
- Errors: statistical, systematic (detector energy and momentum resolution) ~ 1.5%




*Physics TDR*

# Measurements of Higgs Width

- Width:
  - Indirect measurement at lower masses $m_H < 200$ GeV.
- Method proposed by D. Zeppenfeld et al., hep-ph/0002036:
  - The total width is dominated by bb, cc, WW, ZZ, gg, γγ, ττ → most of them partially detectable in this mass range and the part that can't be measured taken into account by the parameter ε:

$$\varepsilon = 1 - [BR(H \to b\bar{b}) + BR(H \to WW) + BR(H \to ZZ) + BR(H \to gg) + BR(H \to \gamma\gamma) + BR(H \to \tau\bar{\tau})] << 1$$

  - The H → ZZ* and H → WW* partial widths are related by SU(2): $z = \frac{\Gamma_Z}{\Gamma_W}$
  - The ratio of b to τ partial widths is connected to their mass ratio:

$$y = \frac{\Gamma_b}{\Gamma_\tau} = 3c_{QCD}\frac{g_{Hbb}^{\ 2}}{g_{H\tau\tau}^{\ 2}} = 3c_{QCD}\frac{m_b^{\ 2}(m_H)}{m_\tau^{\ 2}}$$

# Measurements of Higgs Width

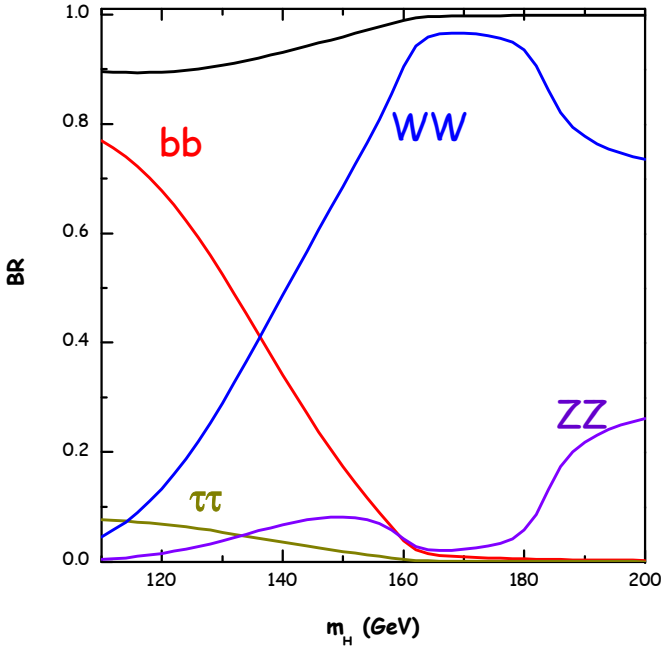
- Method proposed by D. Zeppenfeld et al., hep-ph/0002036 (continued):
  - Let us defined: $X_W = \frac{\Gamma_W \Gamma_W}{\Gamma}$ ($H \to WW$), $X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma}$ ($H \to \tau\tau$), $X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma}$ ($H \to \gamma\gamma$), $Y_g = \frac{\Gamma_g \Gamma_W}{\Gamma}$ ($gg \to H$, $H \to WW$)

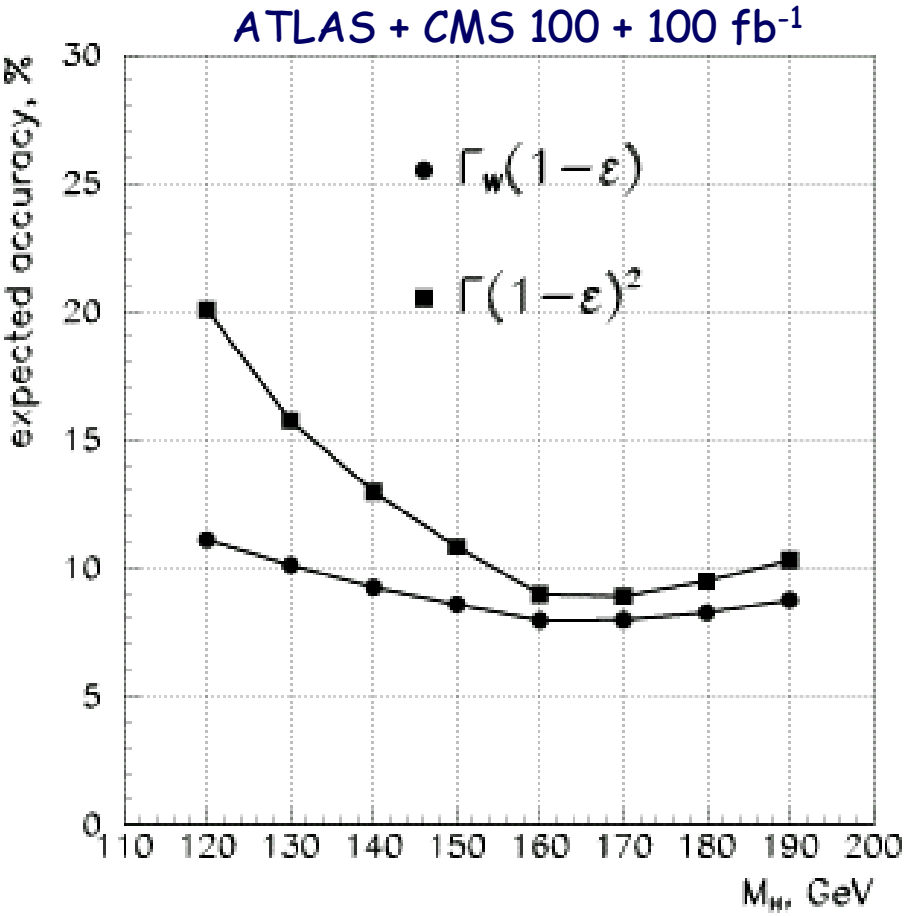
    $X_W, X_\tau, X_\gamma$: VBF or VH (V = Z or W)
  - Then $\tilde{\Gamma}_W = X_\tau(1+y) + X_W(1+z) + X_\gamma + Y_g$ provides lower limit on $\Gamma(H \to WW^{(*)}) = \Gamma_W$

    $= (\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g)\frac{\Gamma_W}{\Gamma} = (1-\varepsilon)\Gamma_W$
  - Then $\tilde{\Gamma} = \frac{\Gamma_W^2}{X_W} = \frac{1}{X_W}(X_\tau(1+y) + X_W(1+z) + X_\gamma + Y_g)^2 \frac{1}{(1-\varepsilon)^2}$
  - With a knowledge of $\Gamma_W$ and $\Gamma$, it is easy to obtain the other partial widths

# Measurements of Higgs Width

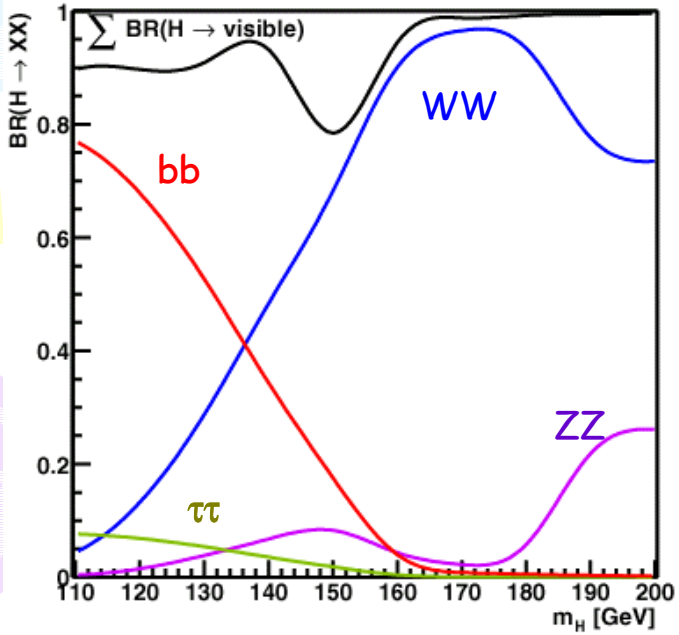
- Correct assumptions (small $\varepsilon$, SM ratios)
- Just prediction for VBF processes: D. Zeppenfeld et al., hep-ph/0002036



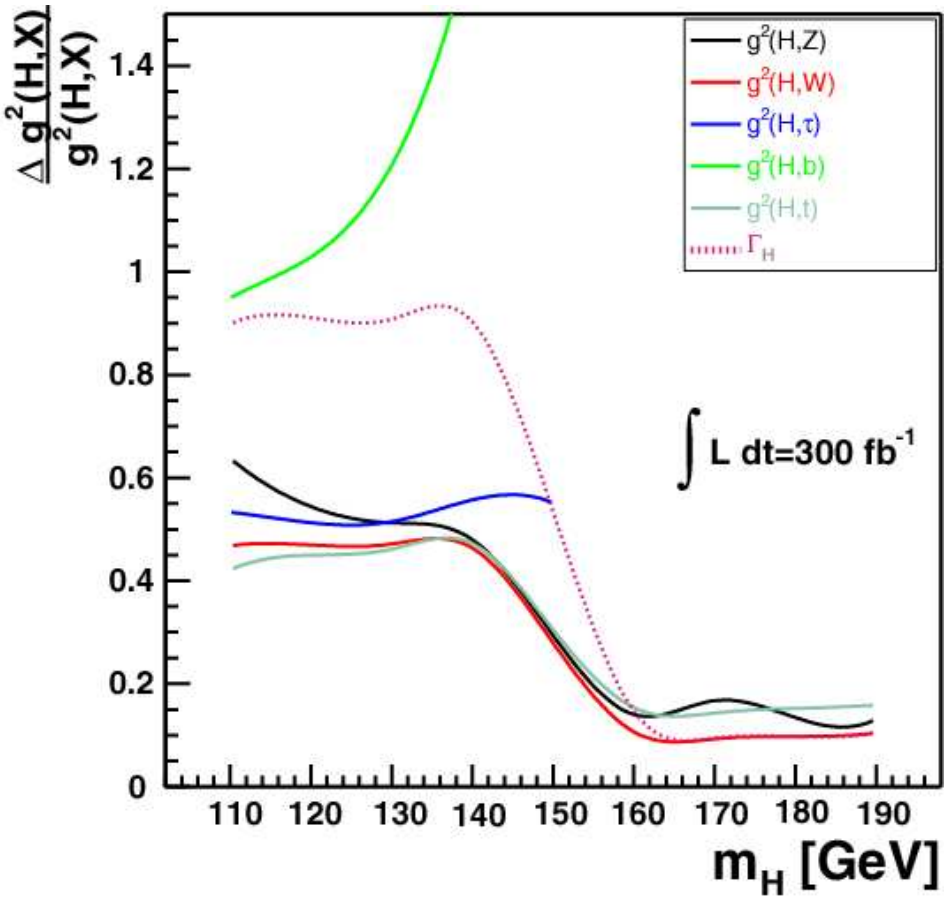



# Measurements of Higgs Width

- But $H \rightarrow bb$ can't really be measured at $m_H \sim 150$ GeV
  $\Rightarrow \varepsilon$ not so small (~20%)
  $\Rightarrow$ b to $\tau$ width ratio (y) can't really be checked
- Assumption: $\Sigma BR_{visible} = 1 - \varepsilon$, $\varepsilon$ from Standard Model



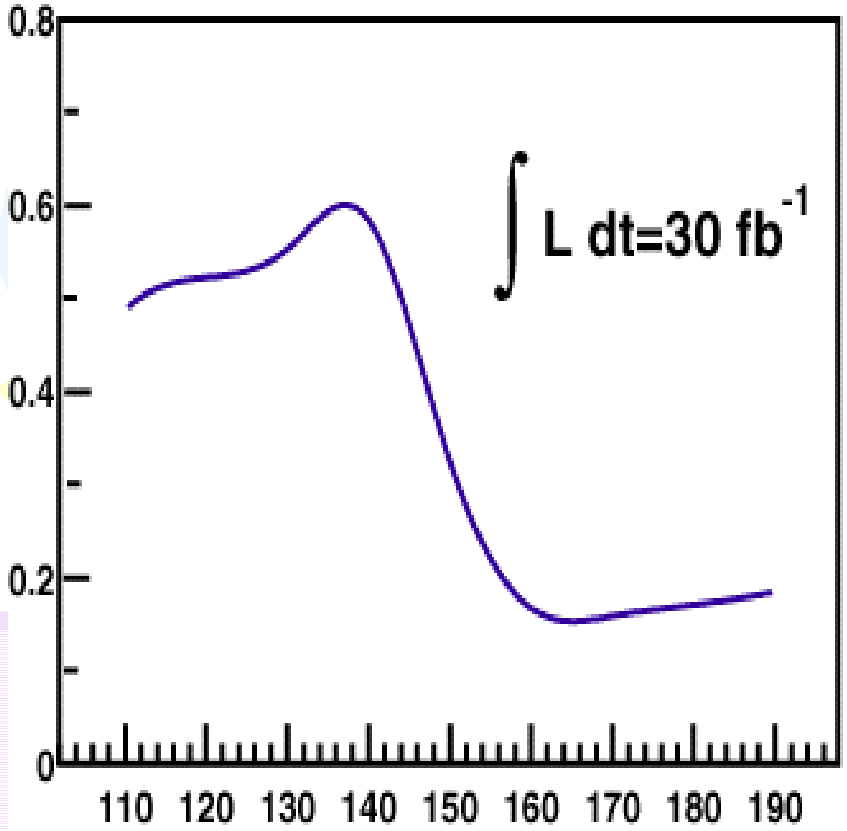

*M. Dührssen*



# top-Yukawa coupling

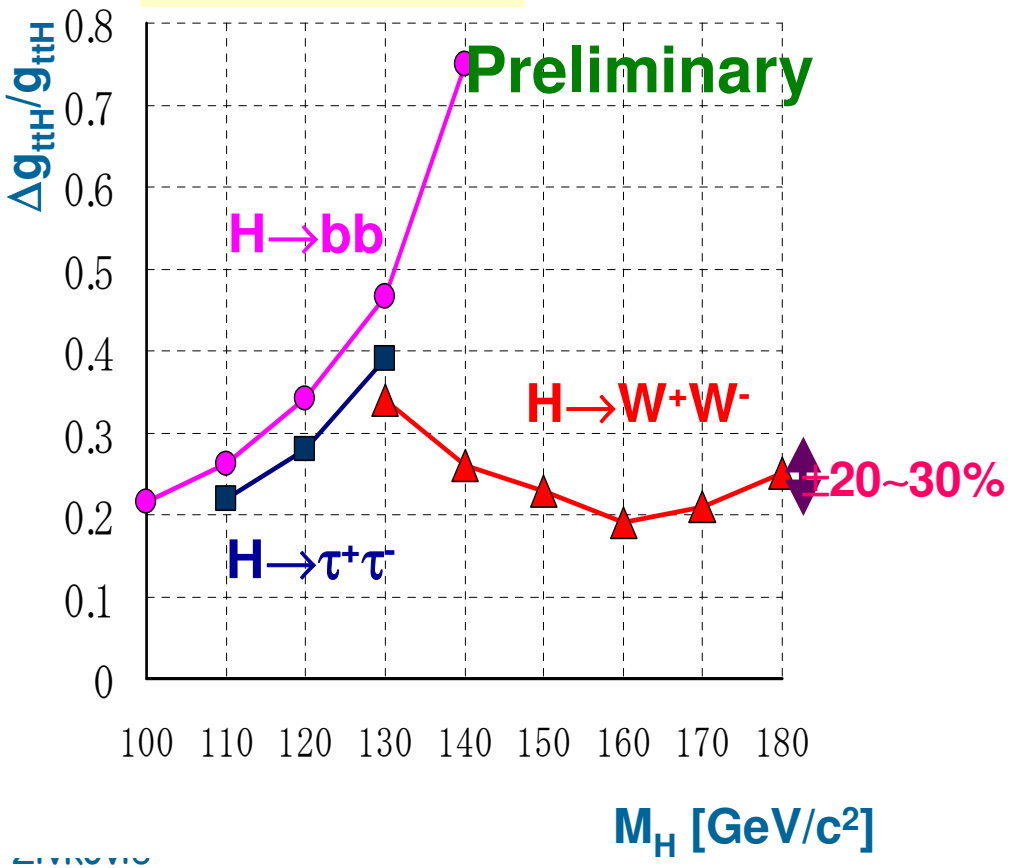
- $tt\mathrm{H} \rightarrow tt\,\tau\tau$ not included yet
- Can improve measurement of top Yukawa coupling

*M. Dührssen*

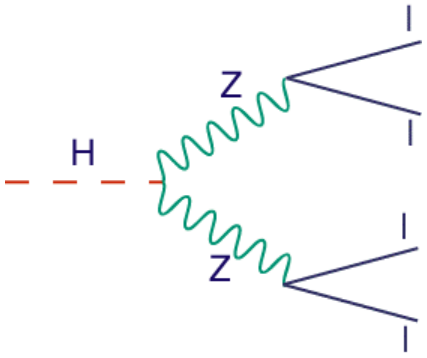


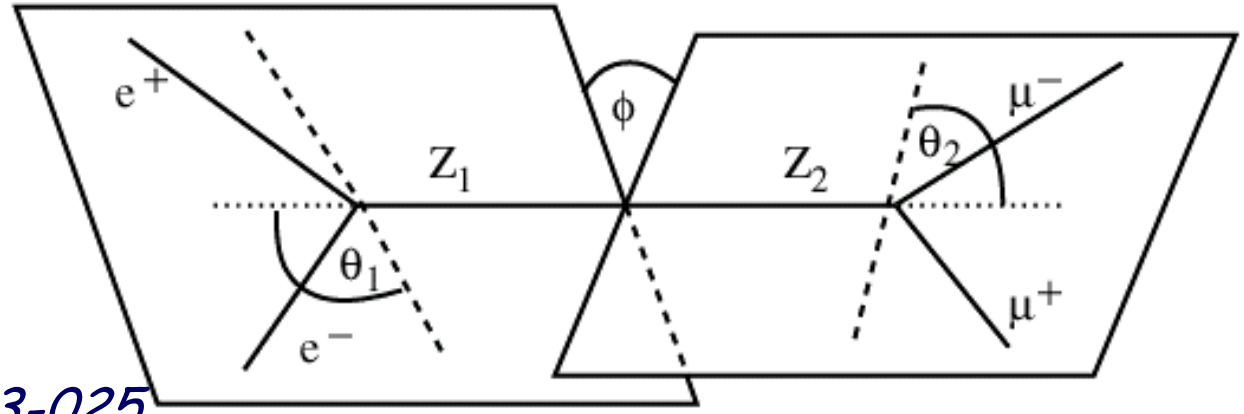

*E. Gross, et al.*

$\mathcal{L} = 30\ \mathrm{fb}^{-1}$



# Measurements of Spin




SN-ATLAS-2003-025

- ϕ - angle between decay planes in the rest frame of the Higgs.
- θ - angle between leptons and the momentum of the Z in the rest frame of the Z.

- Azimuthal angle ϕ:

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

- Polar angle θ:

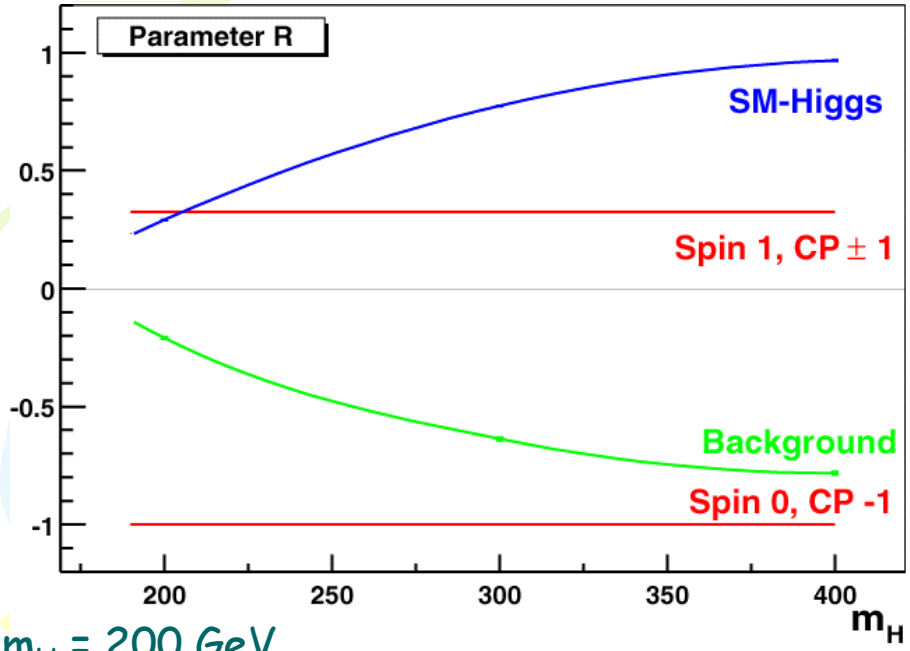
$$G(\theta) = L\sin^2(\theta) + T(1 + \cos^2(\theta))$$

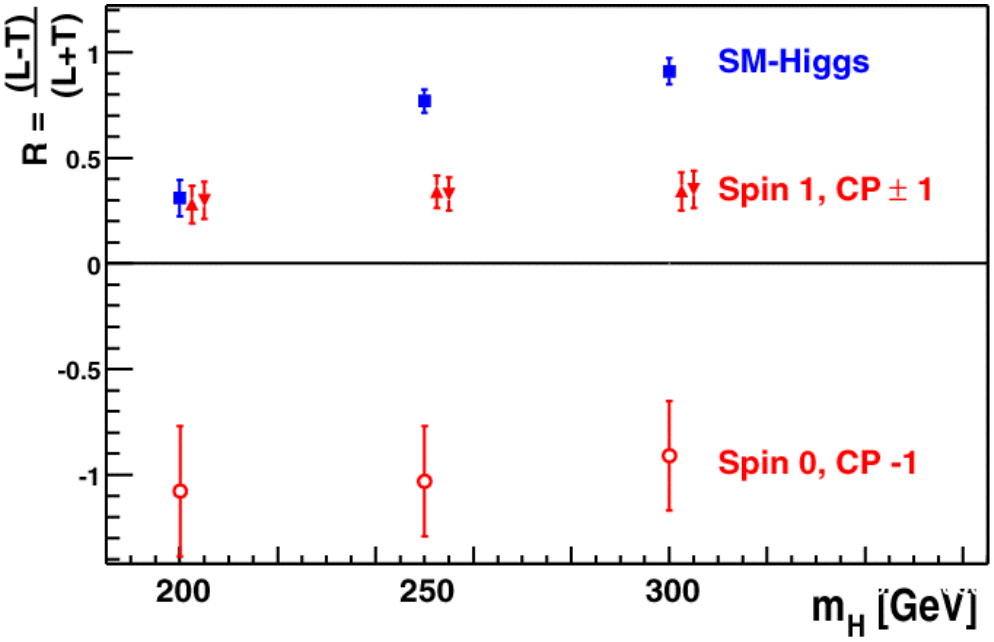
$$R = \frac{L - T}{L + T}$$

# Measurements of Spin

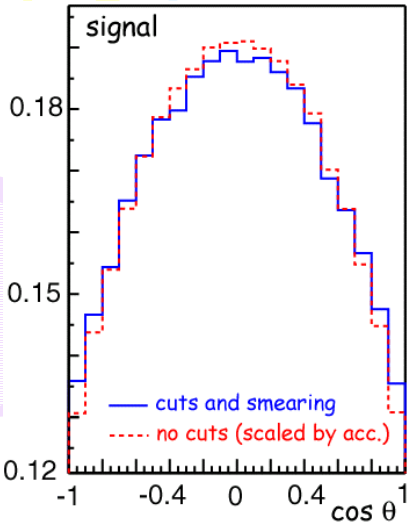
- Theoretical prediction

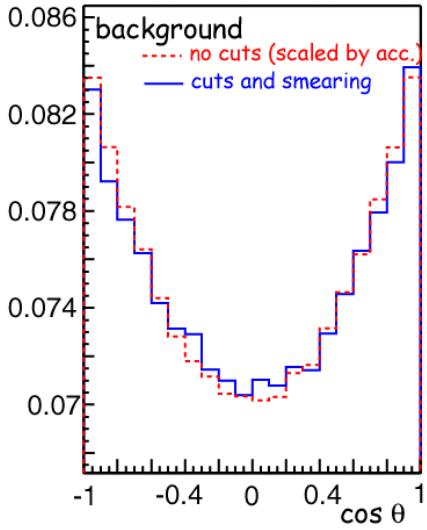
$\int L = 100\ fb^{-1}$




$m_H$ = 200 GeV

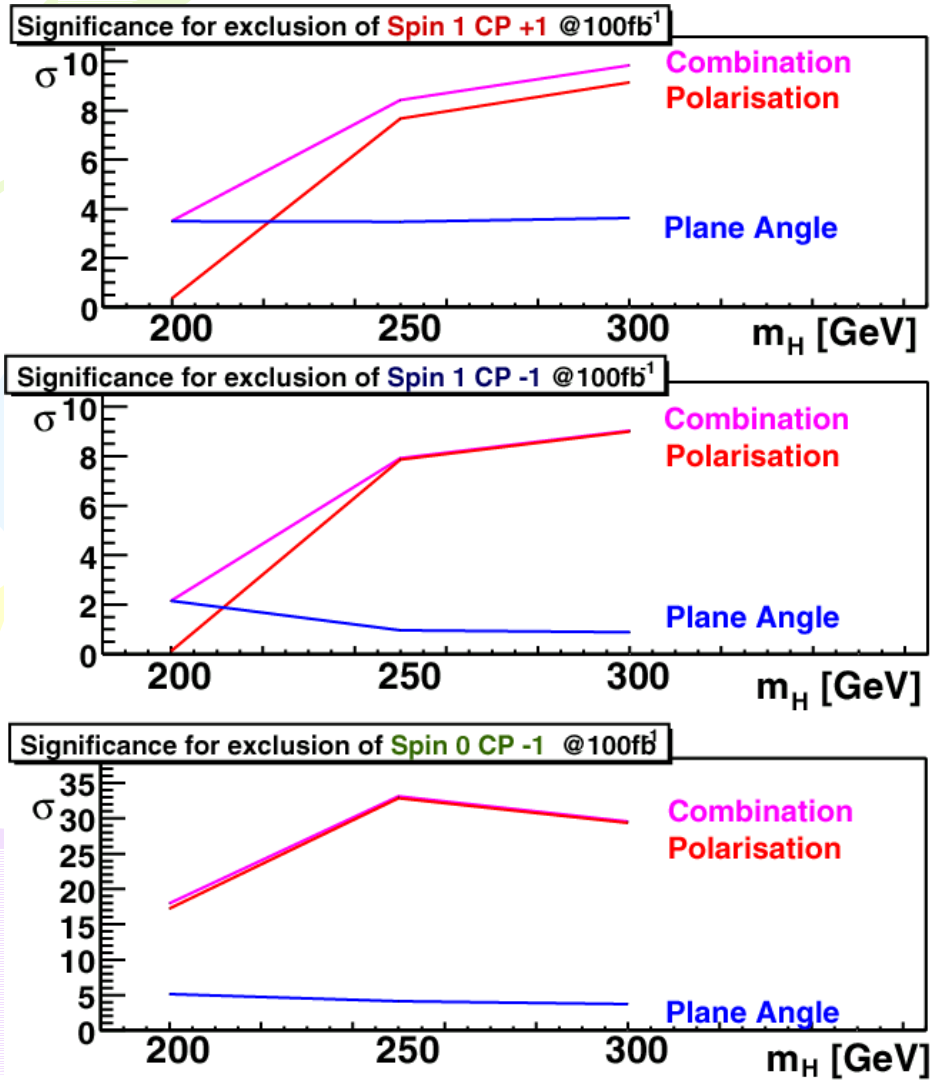



- Results after background subtraction
- For $m_H$ > 250 GeV all non Standard Model particles are excluded

*SN-ATLAS-2003-025*

# Measurements of Spin




- Exclusion of non Standard Model particles through polar angle for higher Higgs masses.
- For $m_H$ = 200 GeV pseudoscalar is excluded even at 100 $fb^{-1}$.
- The $m_H$ = 200 GeV spin 1, CP even can be excluded at 300 $fb^{-1}$ with significance 6.4σ, while for the CP odd case significance is only 3.9σ.

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# Conclusions

- Precision measurements:
  - masses $\Rightarrow$ 0.1% - 1%
  - production rates $\Rightarrow$ 10% - 20%
  - relative branching ratios $\Rightarrow$ 15% - 45%
  - relative coupling ratios $\Rightarrow$ 10% - 20%
  - width $\Rightarrow$ 10% - 30% for $m_H > 150$ GeV

  - For $m_H > 200$ (230) GeV a Spin-0 CP-odd and a Spin-1 (CP-even and CP-odd) Higgs-Boson can be ruled out at $2\sigma$ ($5\sigma$) -Level with 100 $fb^{-1}$