Higgs Boson Parameter Measurements at the LHC

Michael Dührssen

University of Freiburg, Germany

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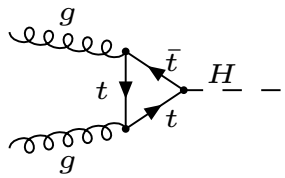
- **Introduction / Motivation**
- **Determining Higgs Boson Parameters**
  - Mass
  - Spin / CP
  - Measurement of Coupling Parameters
- **Summary**

Introduction

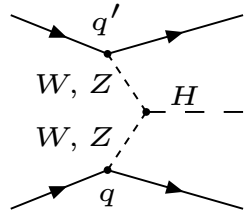
Higgs Boson Production and Decays

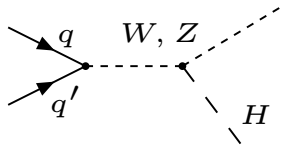
Higgs Production

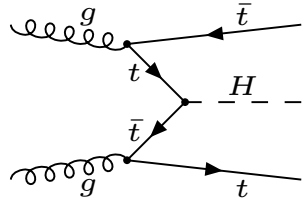
GF:

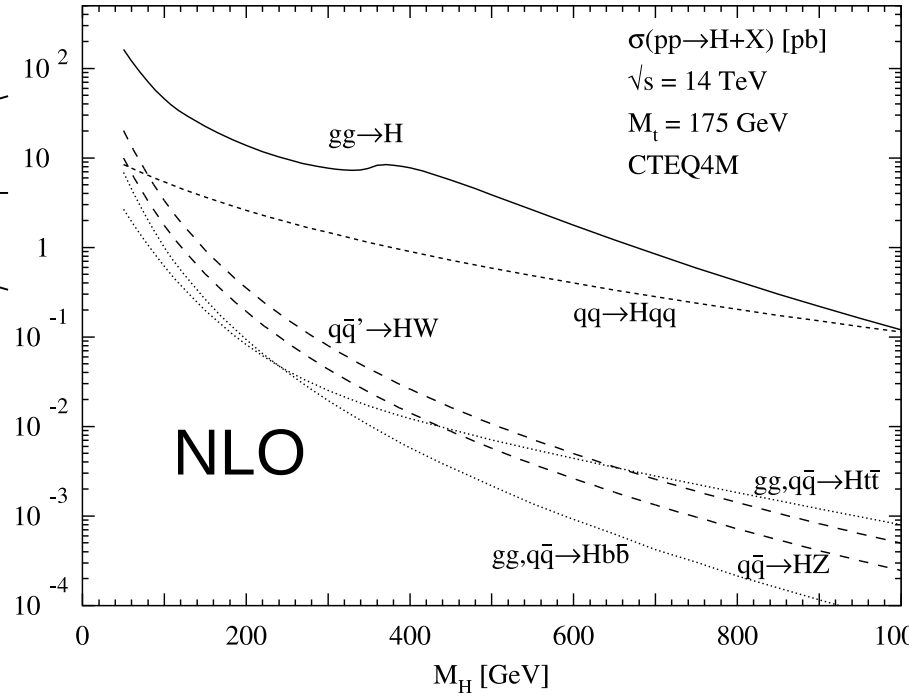


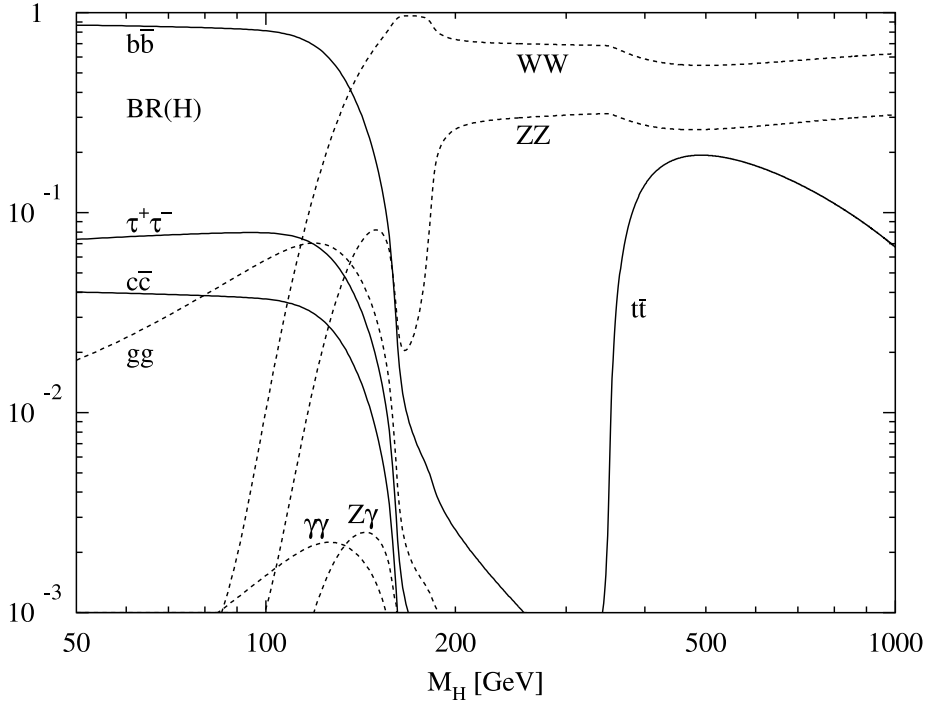
WBF:



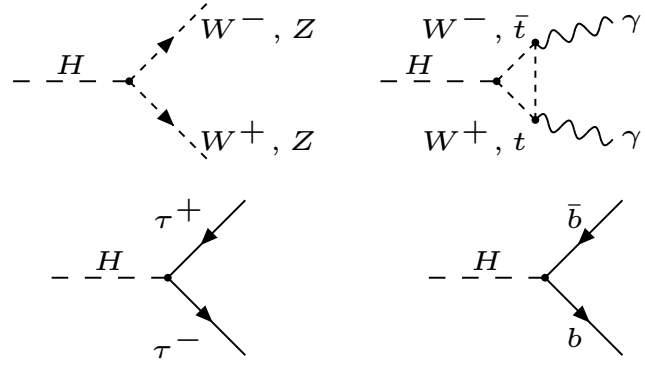








Higgs Decays



Motivation

If there is a SM-like Higgs Boson, it will be discovered !

BUT

Is it really a Higgs Boson or something else ?

Is it a SM Higgs Boson ?

Can we verify the Higgs Mechanism ?

For a SM Higgs Boson:

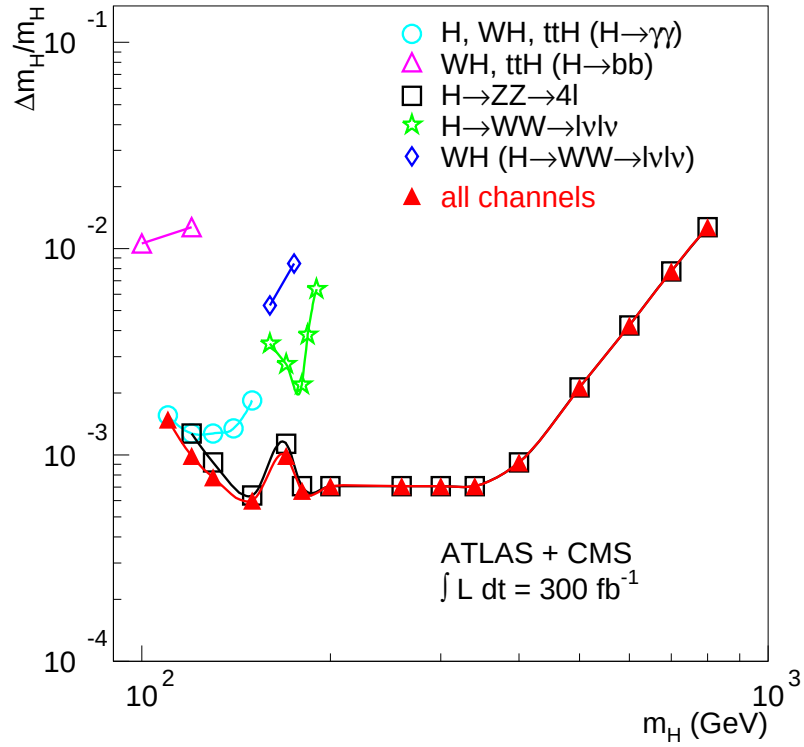
- Mass $\longrightarrow$ $m_H > 114.4$ GeV (LEP)
- Spin / CP $\longrightarrow$ Spin 0, CP even
- Couplings $\longrightarrow$ Proportional to mass
- Self-Couplings $\longrightarrow$ Observable? $\longrightarrow$ Measurement of Higgs potential!

Resolution of Mass Measurement

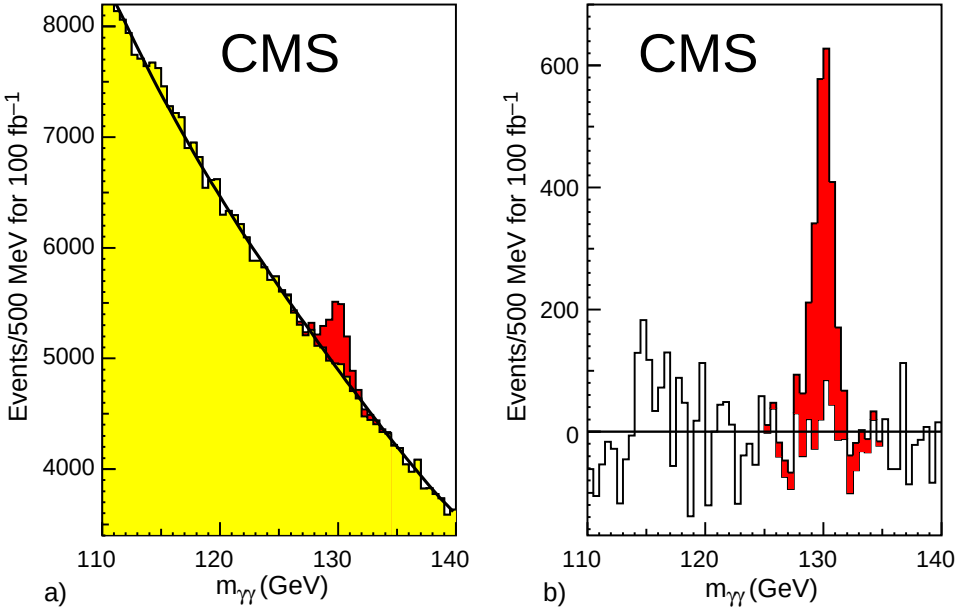
Possible channels:

- **Direct:** $H \longrightarrow ZZ \longrightarrow 4l$, $H \longrightarrow \gamma\gamma$
- **Indirect** (from Likelihood fit):

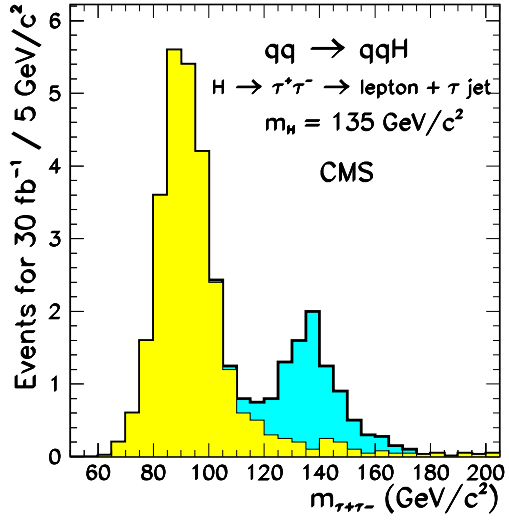
  GF $H \longrightarrow WW$, WH ($H \longrightarrow WW$)



Mass resolution in $H \longrightarrow \gamma\gamma$:



$\sigma_H \approx$ **0.8 GeV**



τ final state may contribute:

WBF

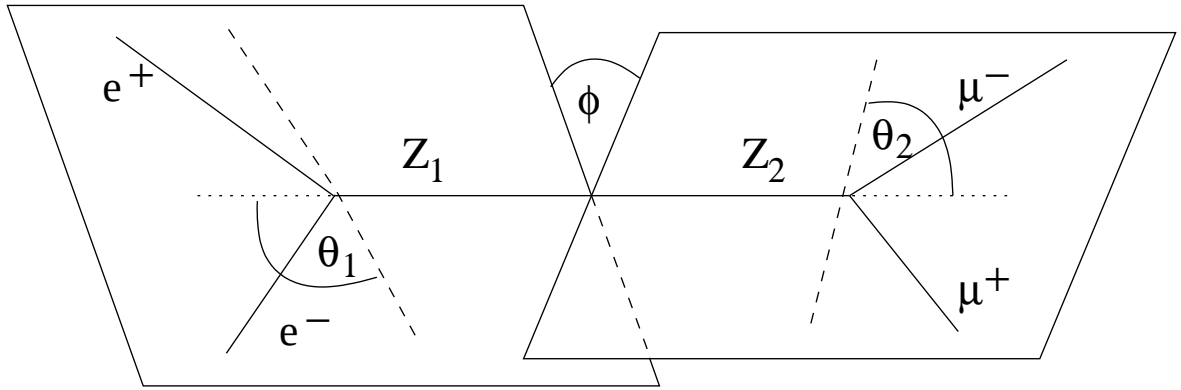
$H \longrightarrow \tau\tau$

$\sigma_H \approx$ 12 GeV

Determination of Spin / CP

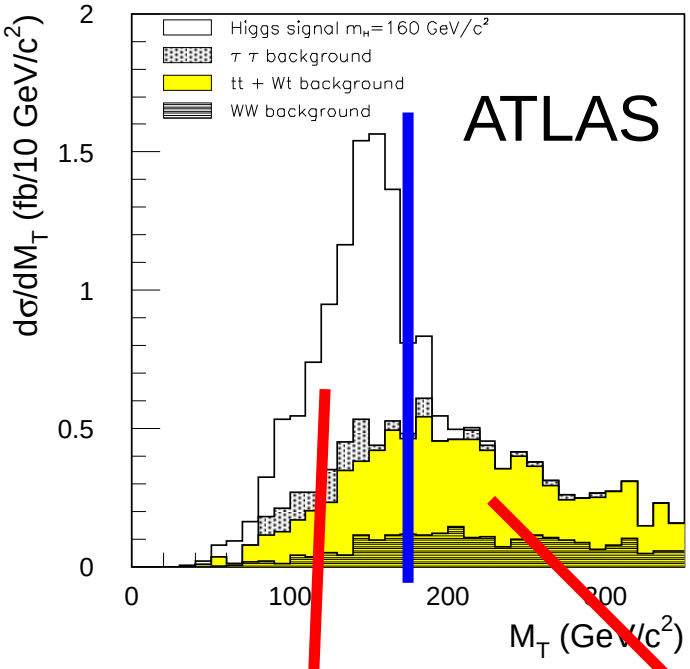
Possible observables:

- Spin 1: no decays H $\longrightarrow \gamma\gamma$ or GF-Production (gg $\longrightarrow$ H)
- Discrimination of Spin 0 / Spin 1 in WBF H $\longrightarrow$ WW $\longrightarrow$ lν lν
- H $\longrightarrow$ ZZ $\longrightarrow$ 4l : polarisation correlations of decay products



- Still under study: angular correlations in WBF and $t\bar{t}$ H / $t\bar{t}$ A

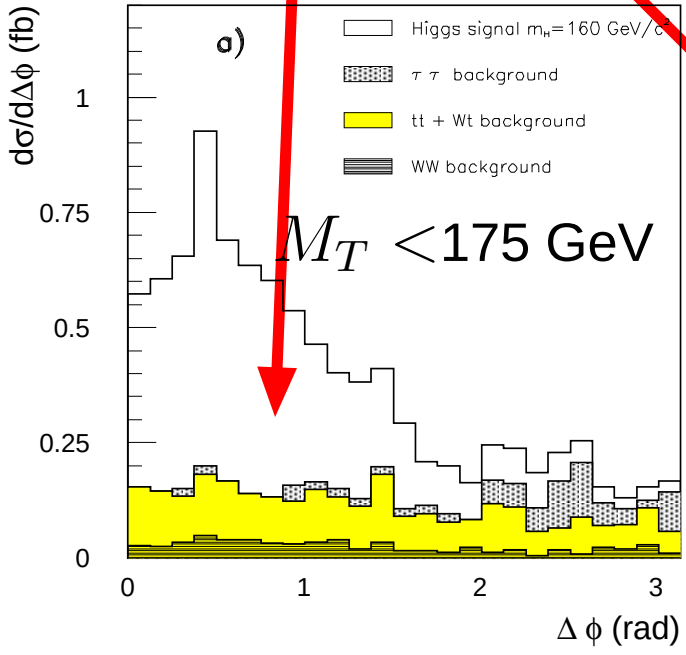
Determination of Spin in WBF H $\rightarrow$ WW $\rightarrow$ lν lν

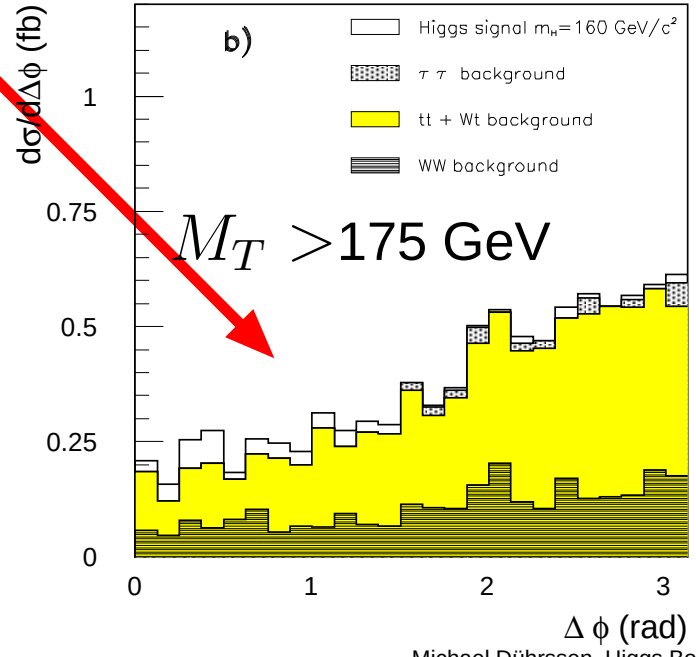


Spin correlation of W-Bosons:

$\rightarrow$ For a Spin 0 Higgs Boson leptons tend to go in the same direction.

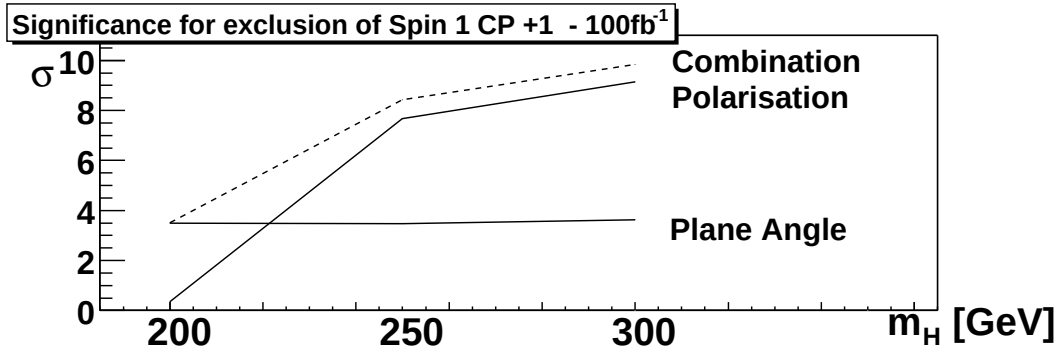
$\rightarrow$ Evidence in distribution of transverse opening angle $\Delta\phi$ for signal and background.

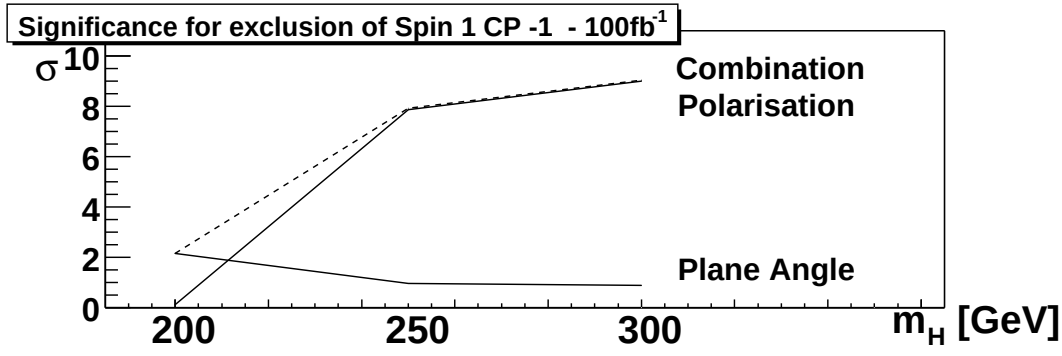


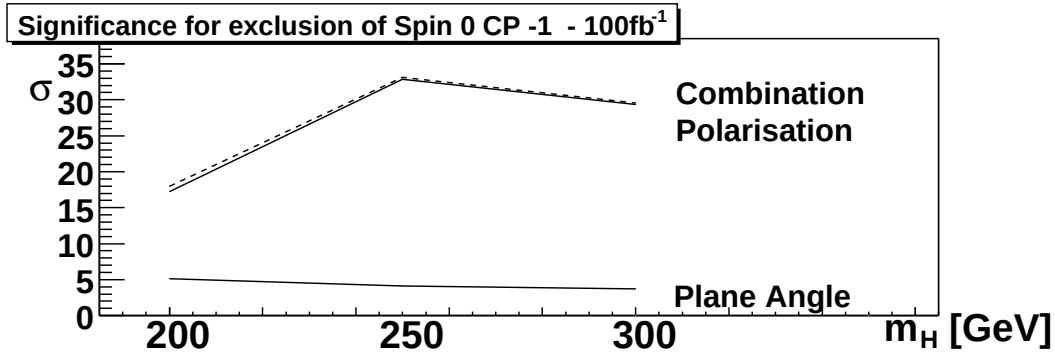


Determination of Spin / CP in H → ZZ → 4l

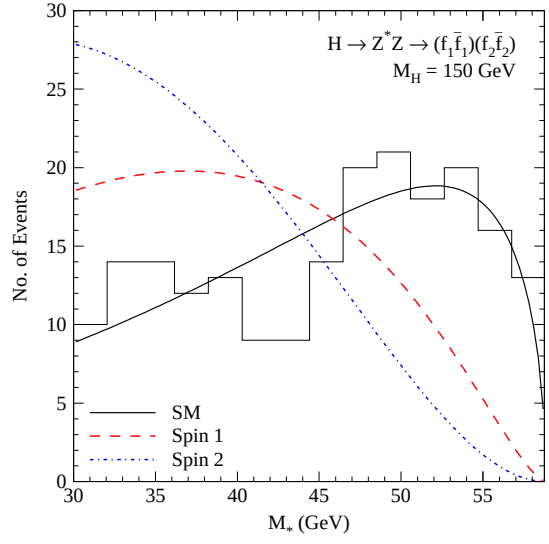
ATLAS:







- Good discrimination for $m_{\mathrm{H}} \gtrsim 250$ GeV
- Does not work for $m_{\mathrm{H}} \lesssim 2\,m_Z$
- Alternative for $m_{\mathrm{H}} \lesssim 2\,m_Z$: Distribution of virtual Z-Boson mass $m_{Z'}$ (⟶ hep-ph/0210077)



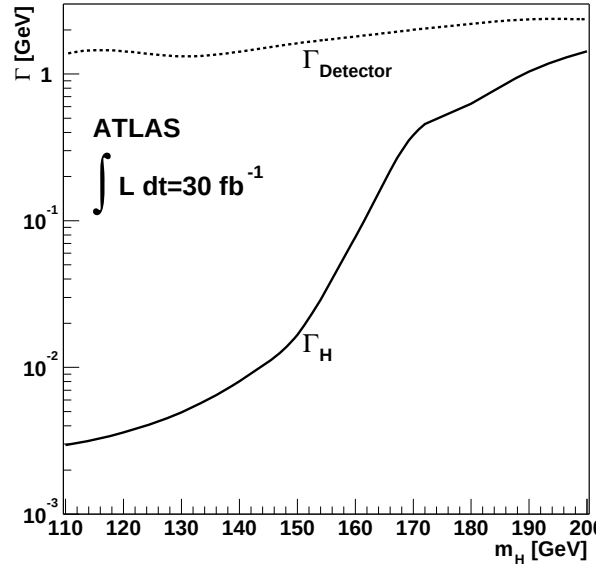
Determination of Coupling Parameters

Region $m_H \lesssim 2\,m_Z$: 110 GeV $\leq m_H \leq$ 190 GeV

Main problem :

Total width Γ_H not directly observable

$\longrightarrow$ impossible to separate Higgs Boson production from Higgs Boson decays



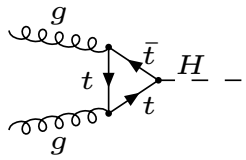
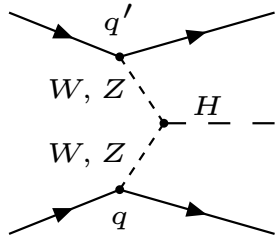
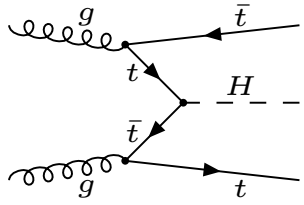
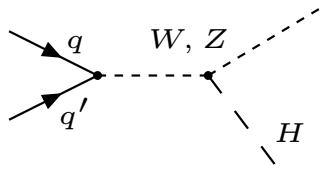
Theoretical assumptions needed:

increasing level of assumptions

- **CP-even, Spin 0 (used in H $\longrightarrow$ WW, can be checked $\longrightarrow$ Spin / CP)**
  $\longrightarrow$ measurement of rates $\sigma \cdot \mathrm{BR}(\mathrm{XX} \longrightarrow \mathrm{H} \longrightarrow \mathrm{YY})$
- **only one Higgs boson**
  $\longrightarrow$ measurement of ratios of partial decay widths Γ_X / Γ_W
- **no extra particles in loops, no strong couplings to light fermions**
  $\longrightarrow$ measurement of ratios of couplings g(H,X) / g(H,W) and limit on Γ_H
- **Assumptions on some couplings or Γ_H**
  $\longrightarrow$ measurement of absolute couplings g(H,X) and total width Γ_H

Determination of Coupling Parameters

Overview of signal channels

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

Determination of Coupling Parameters

Measurement of ratios of partial decay widths Γ_X/Γ_W

Assumption: Only one light Higgs boson

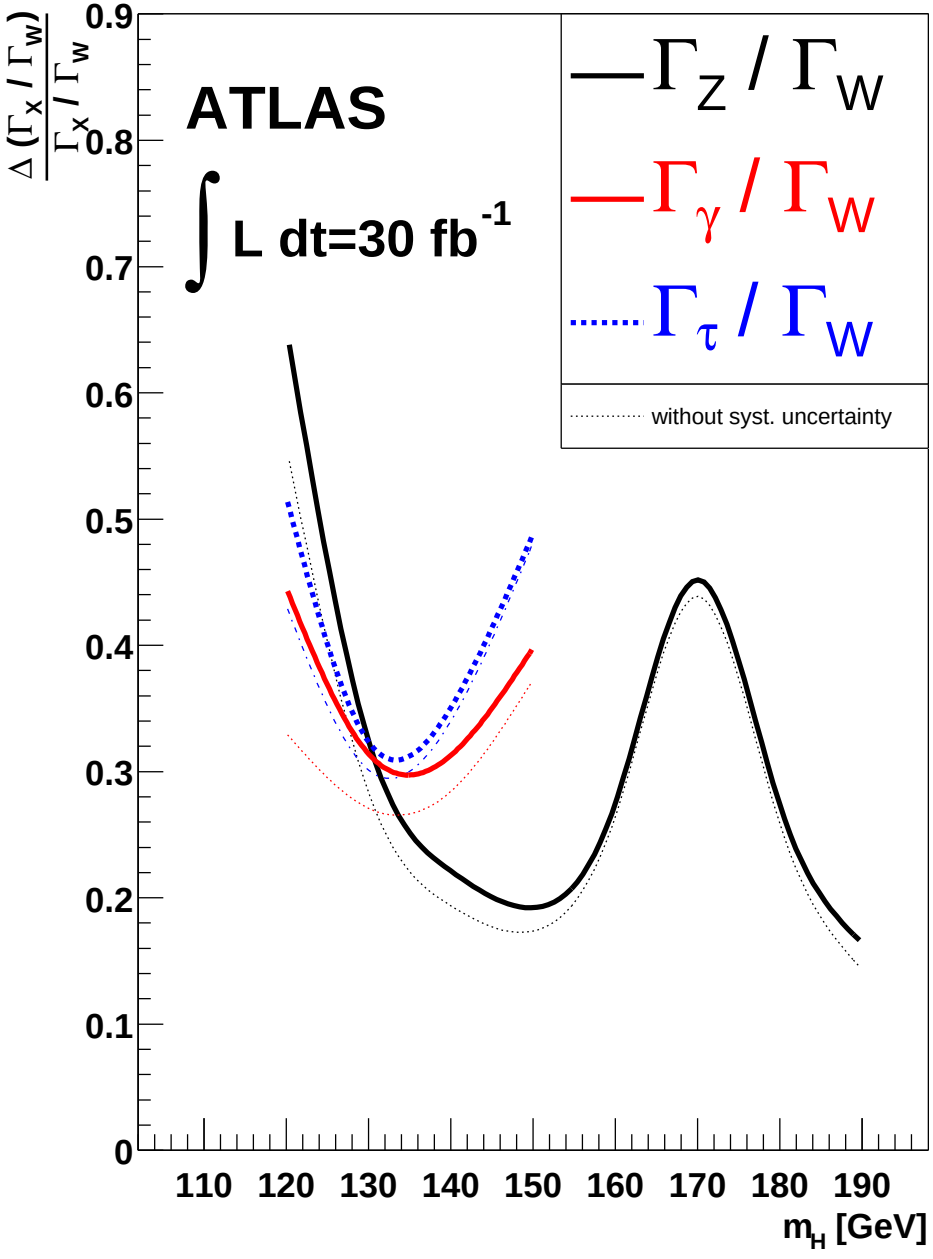
Perform global maximum likelihood fit to all signal channels, taking into account :

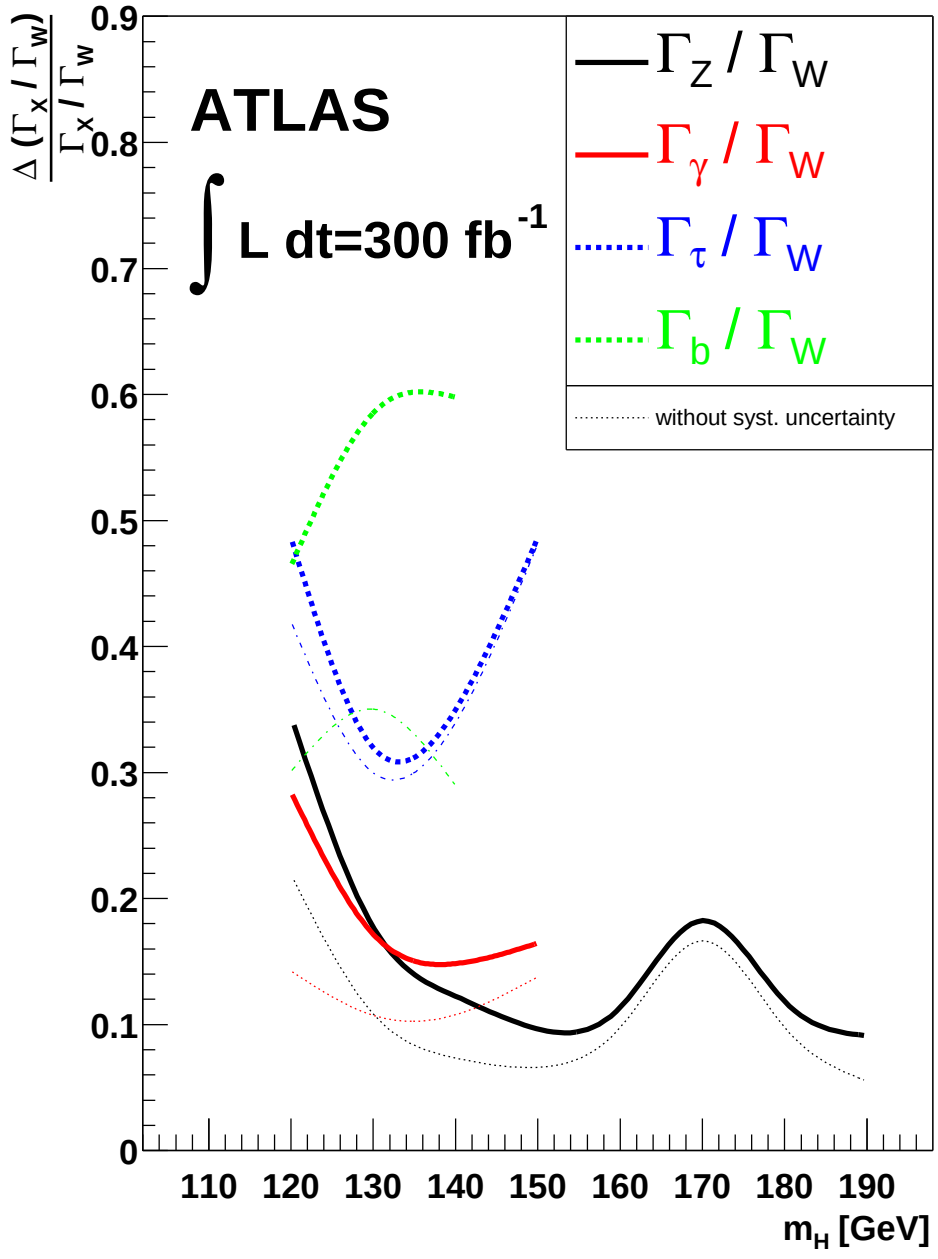
- Statistical fluctuations
- Cross talk between signal channels
- Systematic uncertainties (luminosity, reconstruction efficiencies)
- Statistical and systematic uncertainties on the backgrounds

Fit 4 ratios of Higgs Boson partial decay widths:

$\frac{\Gamma_Z}{\Gamma_W}$, $\frac{\Gamma_\gamma}{\Gamma_W}$, $\frac{\Gamma_\tau}{\Gamma_W}$ **and** $\frac{\Gamma_b}{\Gamma_W}$ (Γ_W is best measured for m_H <200 GeV)

Measurement of Ratios of Partial Decay Widths





Determination of Coupling Parameters

Extracting Higgs Boson couplings information

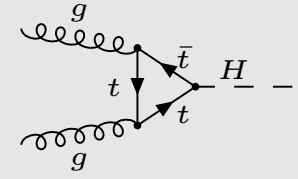
Problem : GF and H $\longrightarrow \gamma\gamma$ are loop-induced. What is the coupling ?

Assumption : Only SM particles couple to Higgs boson

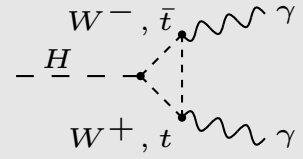
$\longrightarrow$ Express all Higgs Boson production and decay modes by couplings

Higgs Boson production	Higgs Boson decay
$\sigma_{ggH} = \alpha_{\mathrm{GF}} \cdot g_t^2$ (no b-loop)	$\mathrm{BR}(\mathrm{H} \to \mathrm{WW}) = \beta_W \cdot \frac{g_W^2}{\Gamma_H}$
$\sigma_{WBF} = \alpha_{\mathrm{WF}} \cdot g_W^2 + \alpha_{\mathrm{ZF}} \cdot g_Z^2$	$\mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) = \beta_Z \cdot \frac{g_Z^2}{\Gamma_H}$
$\sigma_{t\bar{t}H} = \alpha_{t\bar{t}H} \cdot g_t^2$	$\mathrm{BR}(\mathrm{H} \to \tau\tau) = \beta_\tau \cdot \frac{g_\tau^2}{\Gamma_H}$
$\sigma_{WH} = \alpha_{WH} \cdot g_W^2$	$\mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}}) = \beta_b \cdot \frac{g_b^2}{\Gamma_H}$
$\sigma_{ZH} = \alpha_{ZH} \cdot g_Z^2$	$\mathrm{BR}(\mathrm{H} \to \gamma\gamma) = \frac{(a\, g_W - b\, g_t)^2}{\Gamma_H}$

Gluon-Fusion

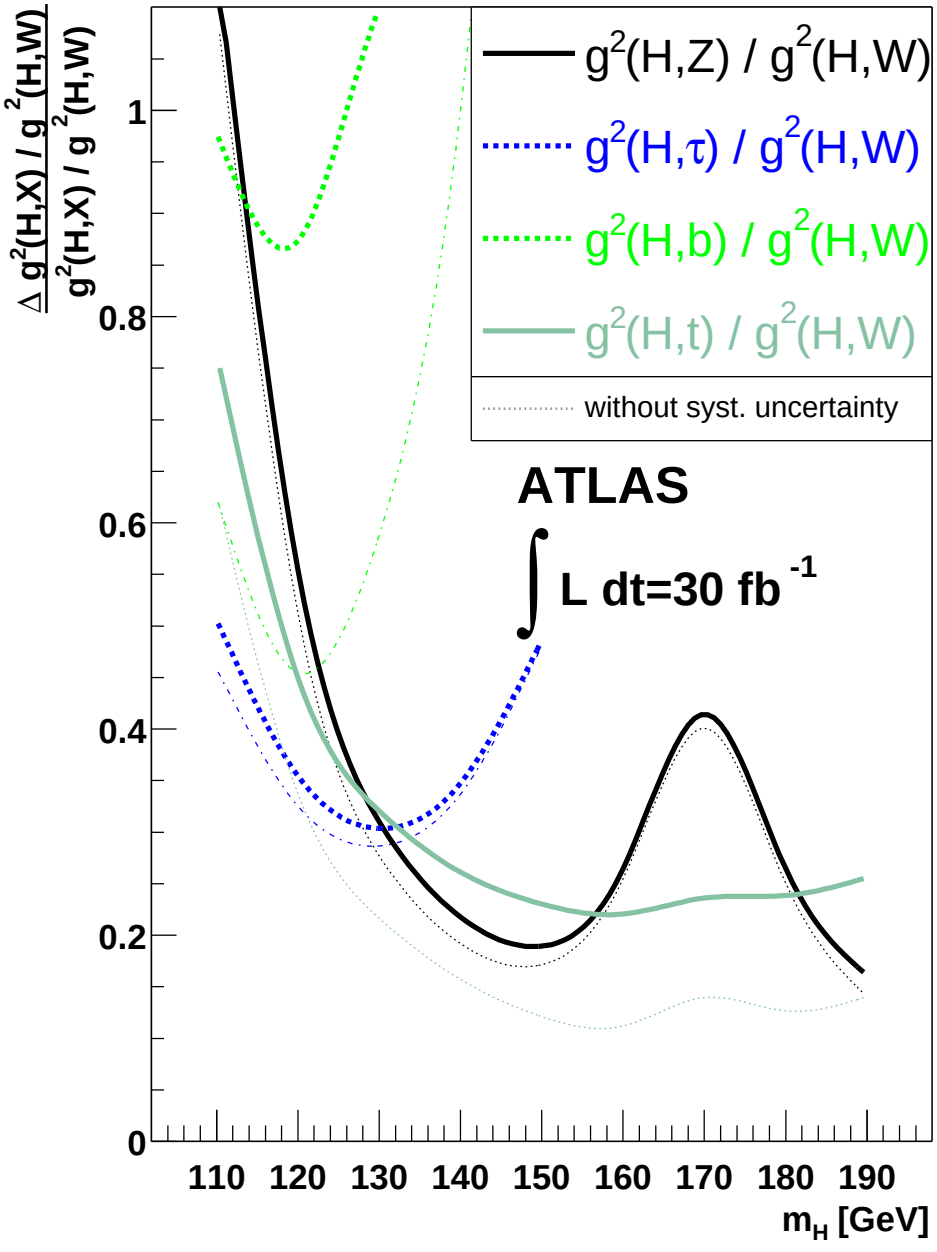


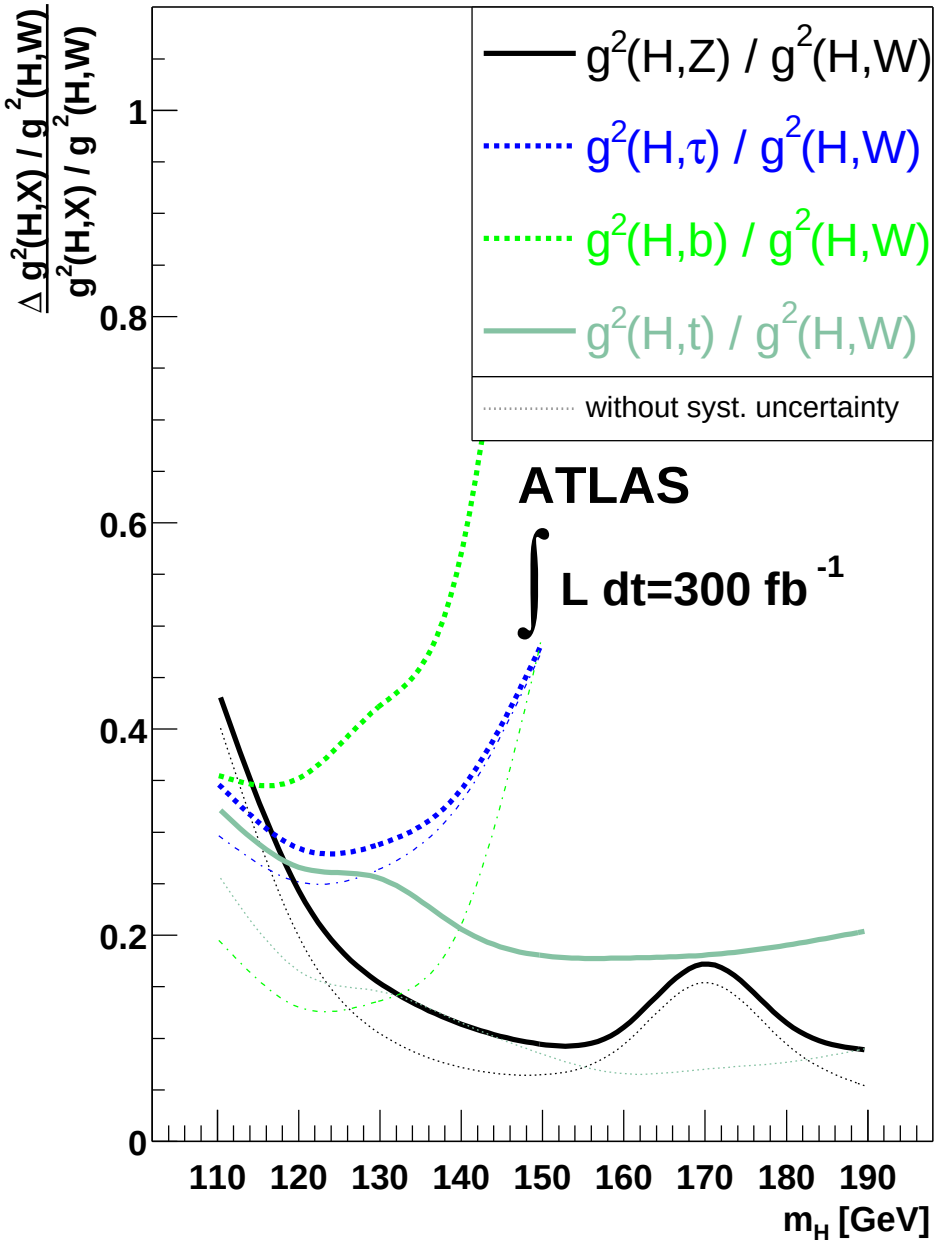
H $\longrightarrow \gamma\gamma$



Γ_H not known $\longrightarrow$ Measurement of $\frac{g_Z^2}{g_W^2}$, $\frac{g_\tau^2}{g_W^2}$, $\frac{g_b^2}{g_W^2}$, $\frac{g_t^2}{g_W^2}$ **and** $\frac{g_W^2}{\sqrt{\Gamma_H}}$

Measurement of Ratios of Higgs Boson Couplings



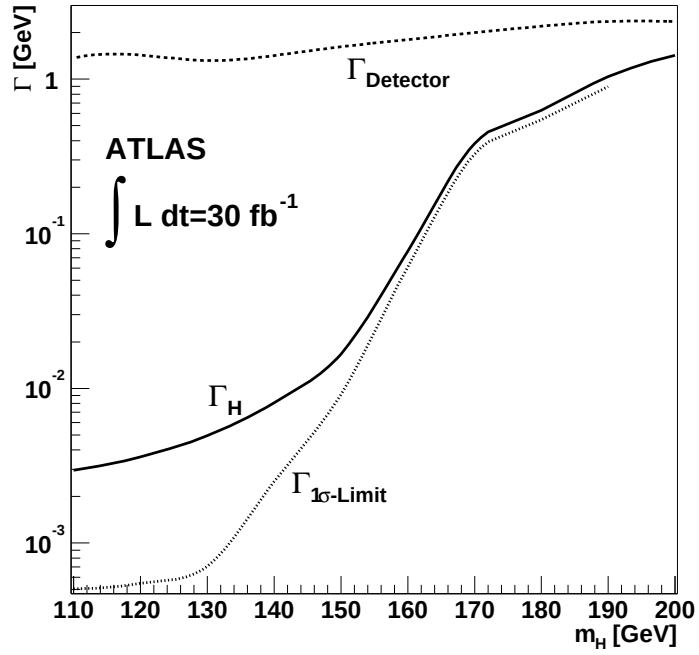


Determination of Coupling Parameters

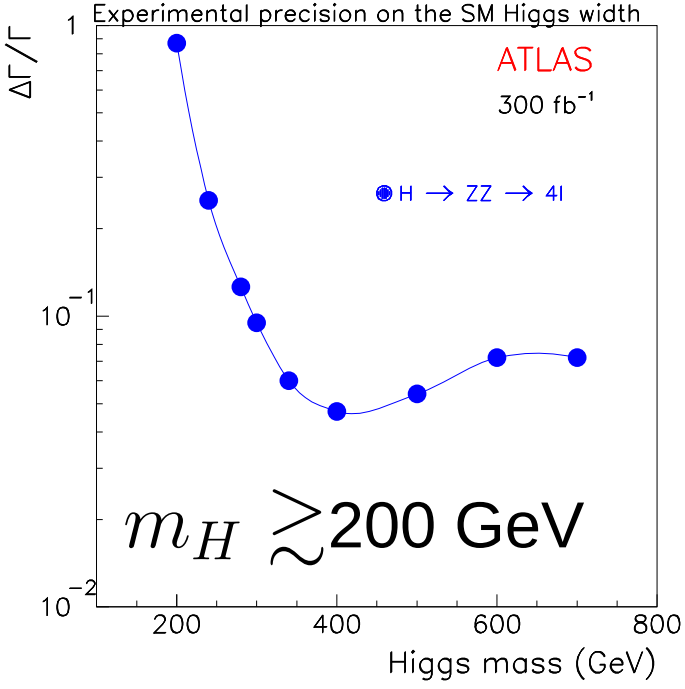
A lower limit on Γ_H

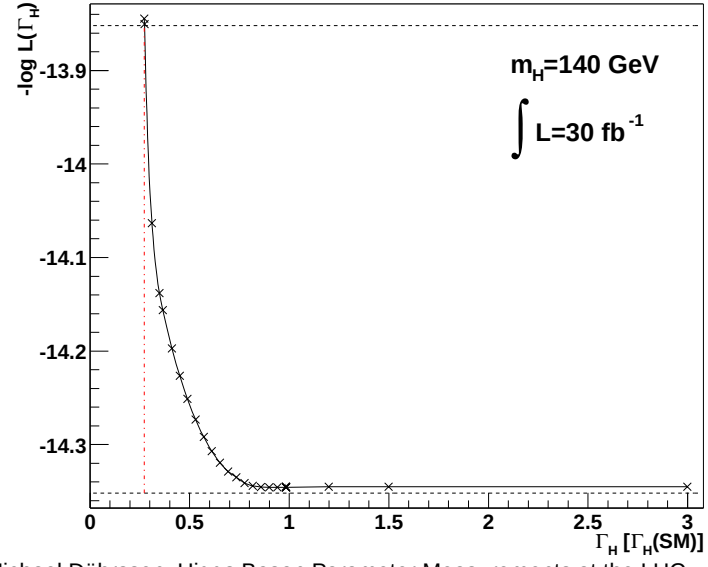
The sum of all visible decay widths gives a lower limit on Γ_H :

$\longrightarrow$ Split $\frac{g_W^2}{\sqrt{\Gamma_H}}$ into g_W^2 and Γ_H



Direct Measurement in H $\longrightarrow$ ZZ :





Determination of Coupling Parameters

Measurement of absolute couplings

To measure absolute couplings, an upper limit for either a coupling or the total width is needed:

$\longrightarrow$ Input from observation outside the Higgs sector

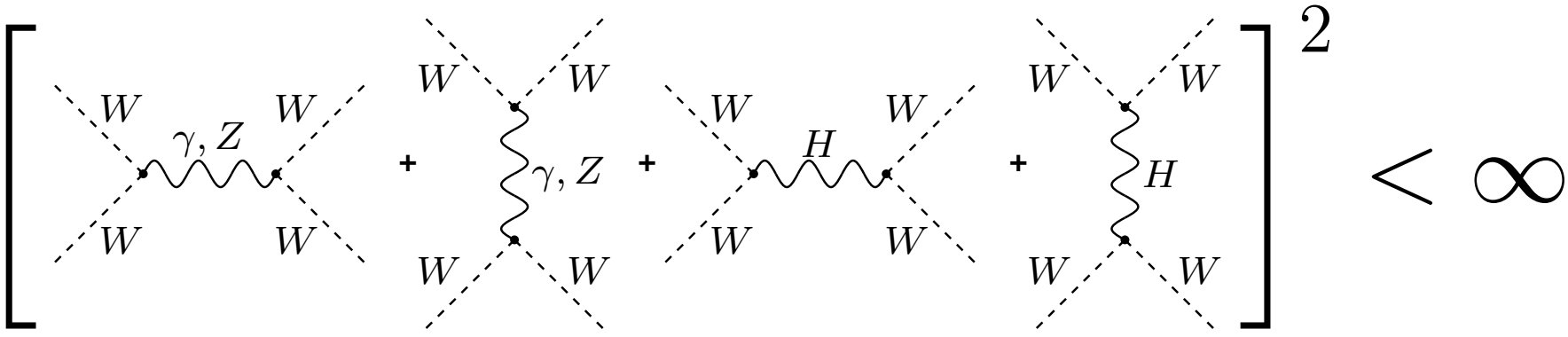
Possible assumptions:

- The sum of the visible BRs is close to unity (as in SM)
- **Unitarity limit 1 : the coupling to W and Z are not stronger than in the SM**
- **Unitarity limit 2 : the coupling to W and Z are as in the SM**
- **. . .**

Determination of Coupling Parameters

Measurement of absolute couplings (Unitarity limit 1)

Motivation: Unitarity limit for W-scattering



Assume:

- Limit on g_W^2 and g_Z^2:

  $\frac{g_W^2}{g_W^2(\mathrm{SM})}$, $\frac{g_Z^2}{g_Z^2(\mathrm{SM})} < 1 + 5\%$

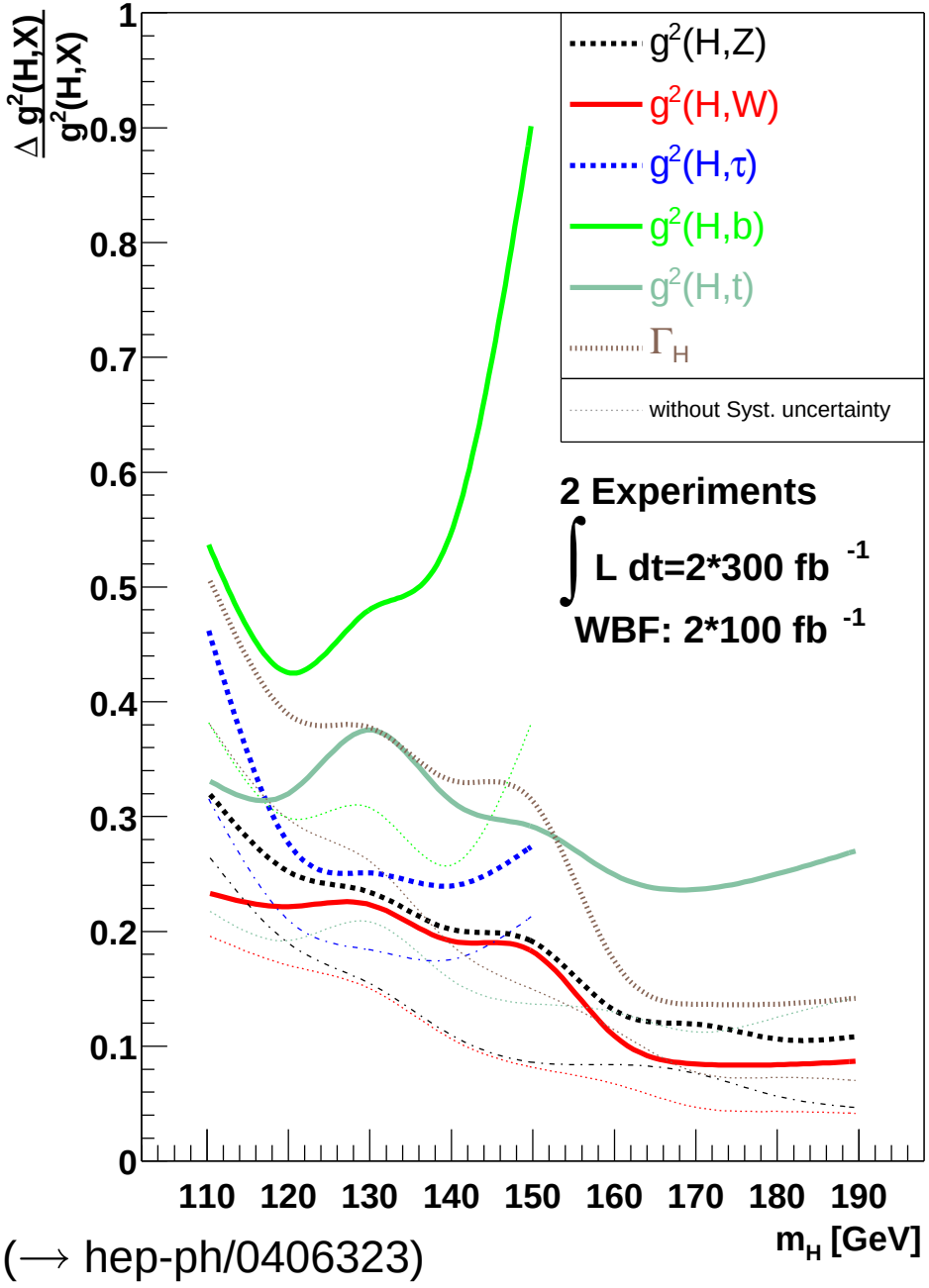
- Loops for H $\longrightarrow \gamma\gamma$ and GF: new particles may be present

  $\longrightarrow$ additional partial width Γ_γ(new) and Γ_g(new)

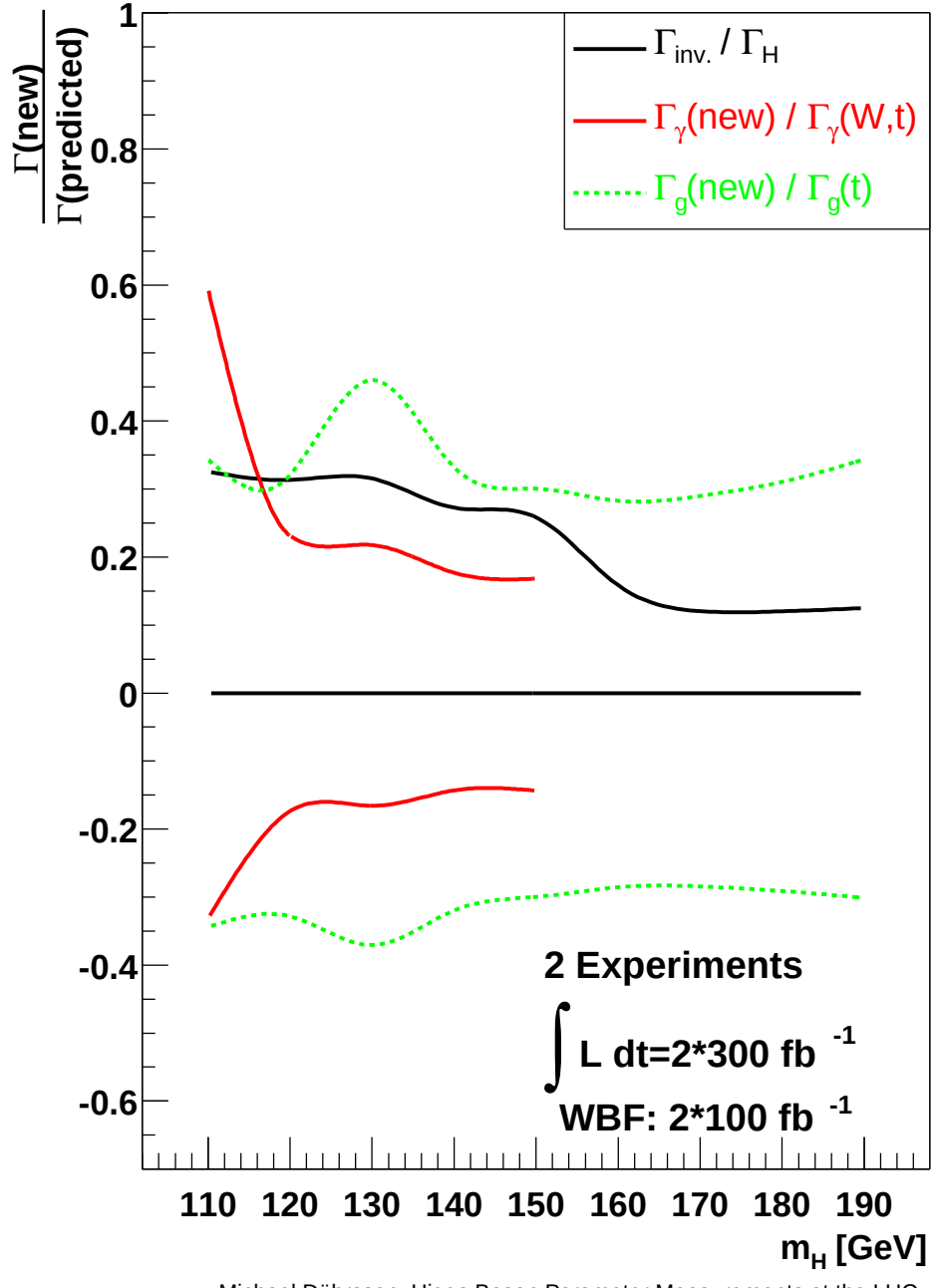
- Invisible / undetectable Higgs Boson decays may be present

  $\longrightarrow$ additional partial width $\Gamma_{\text{inv.}}$

Measurement of Absolute Couplings (Unitarity limit 1)



(⟶ hep-ph/0406323)



Determination of Coupling Parameters

Measurement of absolute couplings (Unitarity limit 2)

Assume:

- g_W^2 and g_Z^2 as in SM:

  $\frac{g_W^2}{g_W^2(\mathrm{SM})}$, $\frac{g_Z^2}{g_Z^2(\mathrm{SM})} = 1 \pm 5\%$

  (e.g. MSSM, $m_A \gtrsim 200$ GeV)

- Loops for H $\longrightarrow \gamma\gamma$ and GF:

  no new particles present

  $\longrightarrow$ described by couplings to W and t

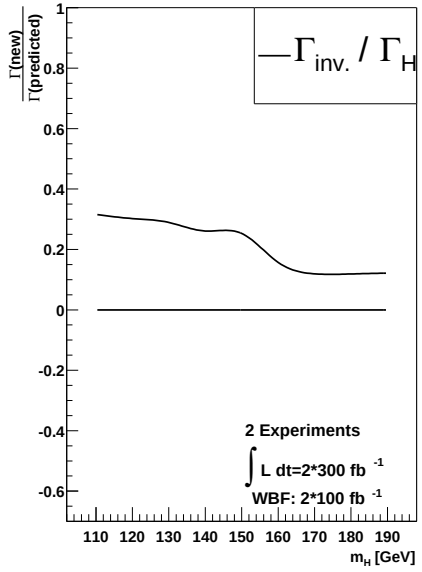
- Invisible/undetectable Higgs Boson

  decays may

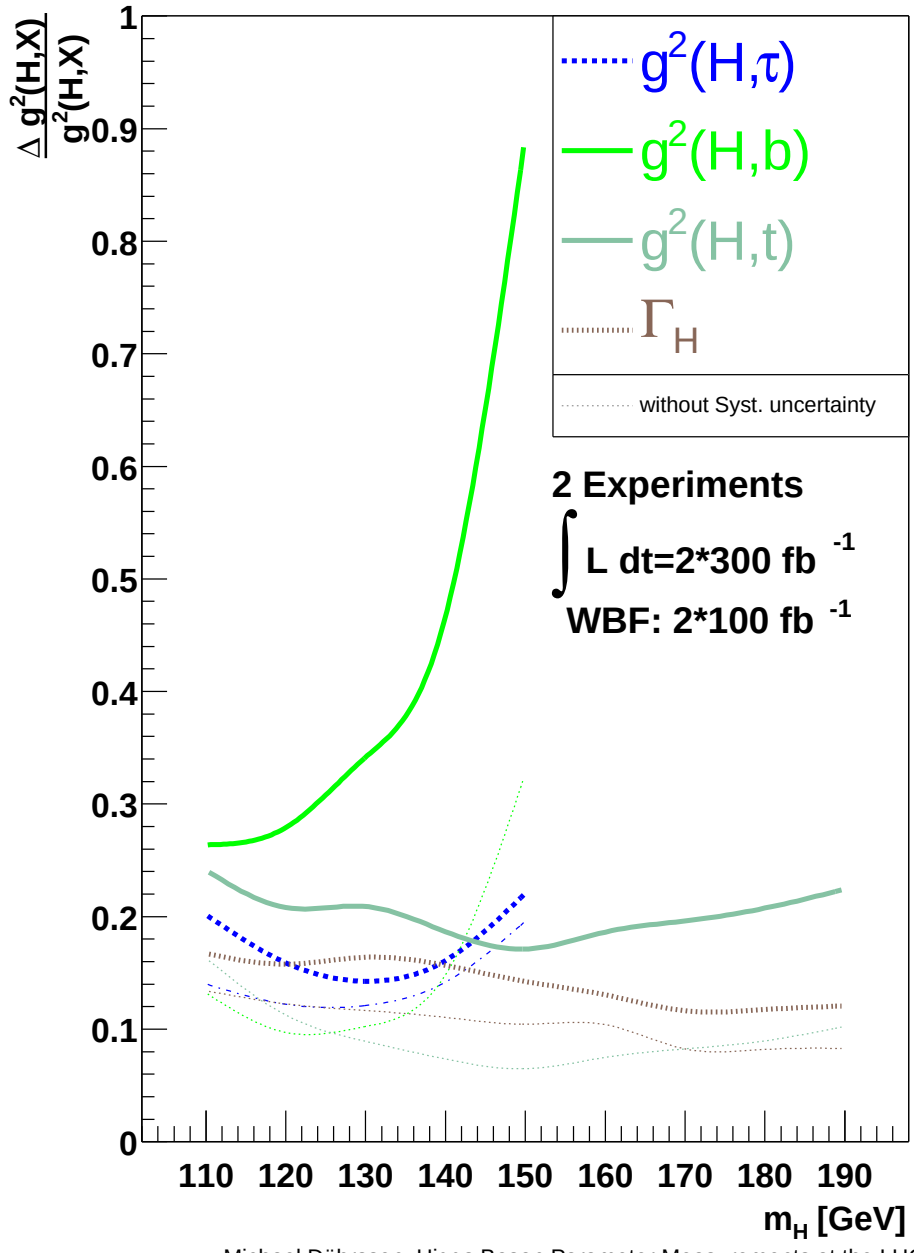
  be present

  $\longrightarrow$ additional

  width $\Gamma_{\mathrm{inv.}}$



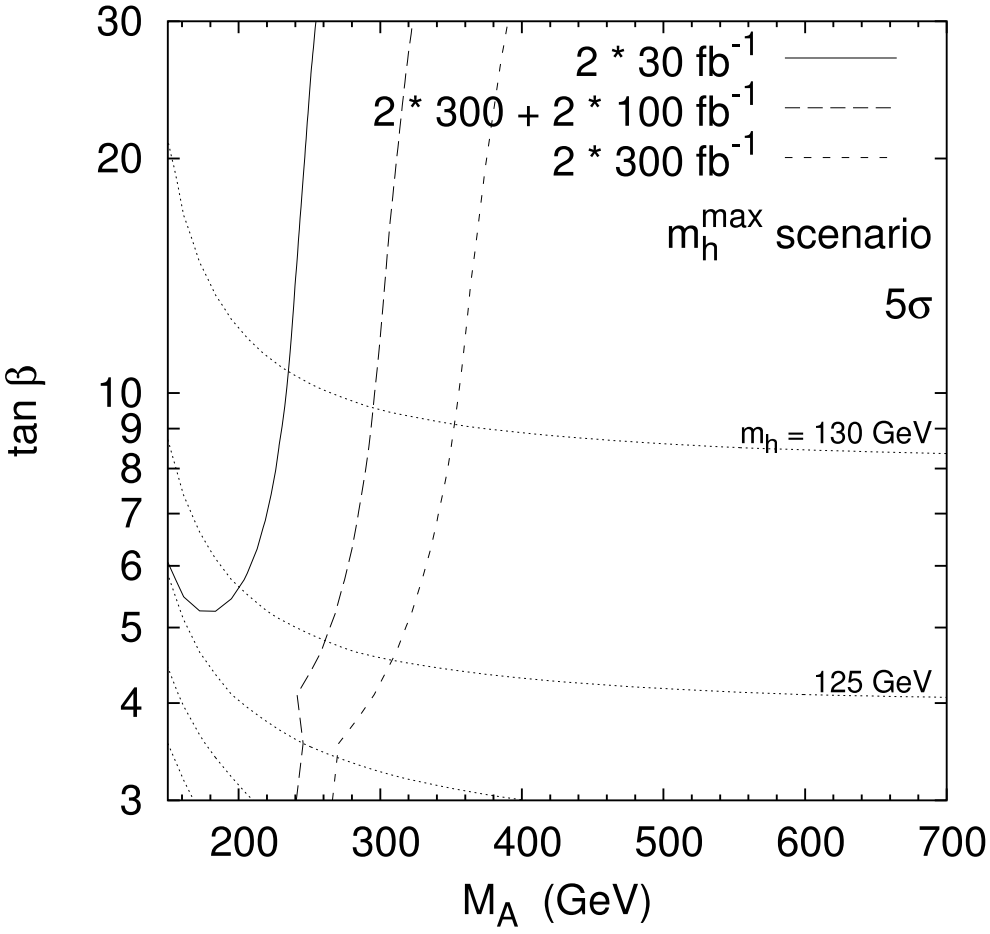
(⟶ hep-ph/0406323)



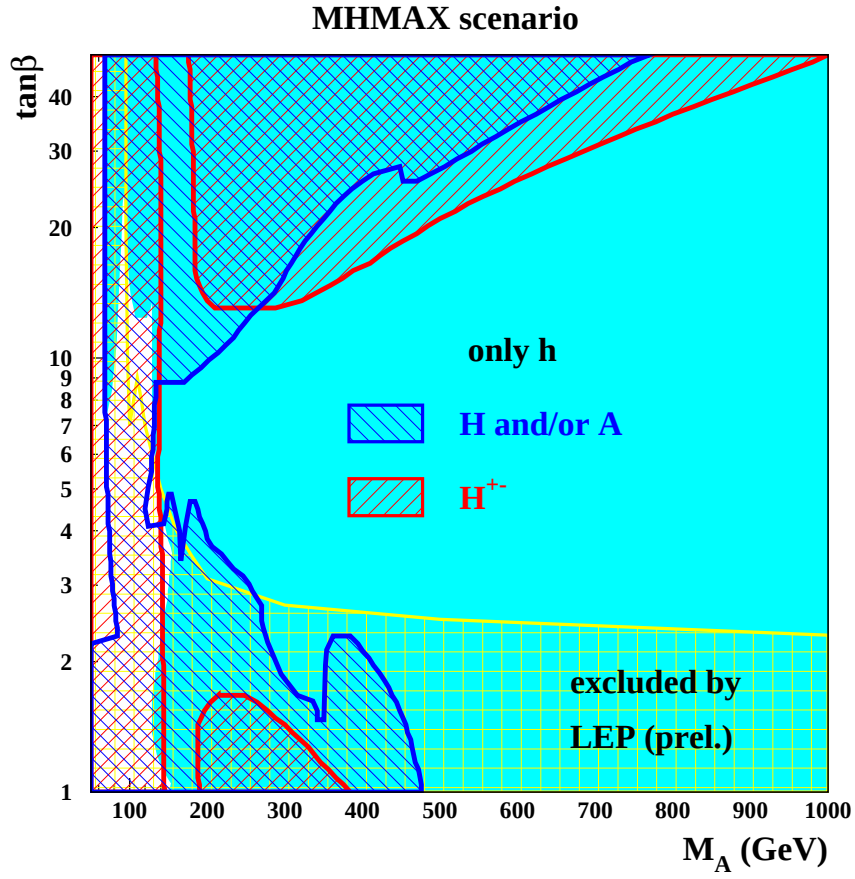
Determination of Coupling Parameters

Discriminating SM and MSSM ($m_h^{\max}$ scenario)

χ^2-Fit using the same channels and assumptions to find the discrimination power between SM and a specific MSSM scenario (⟶ hep-ph/0406323)



SM exclusion (5σ)



Number of observable Higgs (5σ)

Summary

Higgs Boson Parameter Measurements

- A measurement of the mass is possible at 1% level or better
- There are several ways of determining Spin / CP
- Combination of all visible channels allows relative coupling measurements (10% -50% precision)
- Moderate theoretical assumptions allow absolute coupling measurements
- Coupling measurements might help to discriminate between SM and MSSM in difficult regions