Determination of Higgs Boson Couplings at the LHC

Georg Weiglein

IPPP Durham

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Based on collaboration with M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, D. Zeppenfeld

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Need to determine the nature of the detected particle in order to experimentally verify the Higgs mechanism:

- Higgs mass(es), spin, $\mathcal{CP}$ properties
- Higgs couplings to different particles:
  $Hb\bar{b}$, $Ht\bar{t}$, $H\tau^+\tau^-$, HW^+W^-, HZZ, Hgg, $H\gamma\gamma$, HHH, $HHHH$, ...

Higgs couplings

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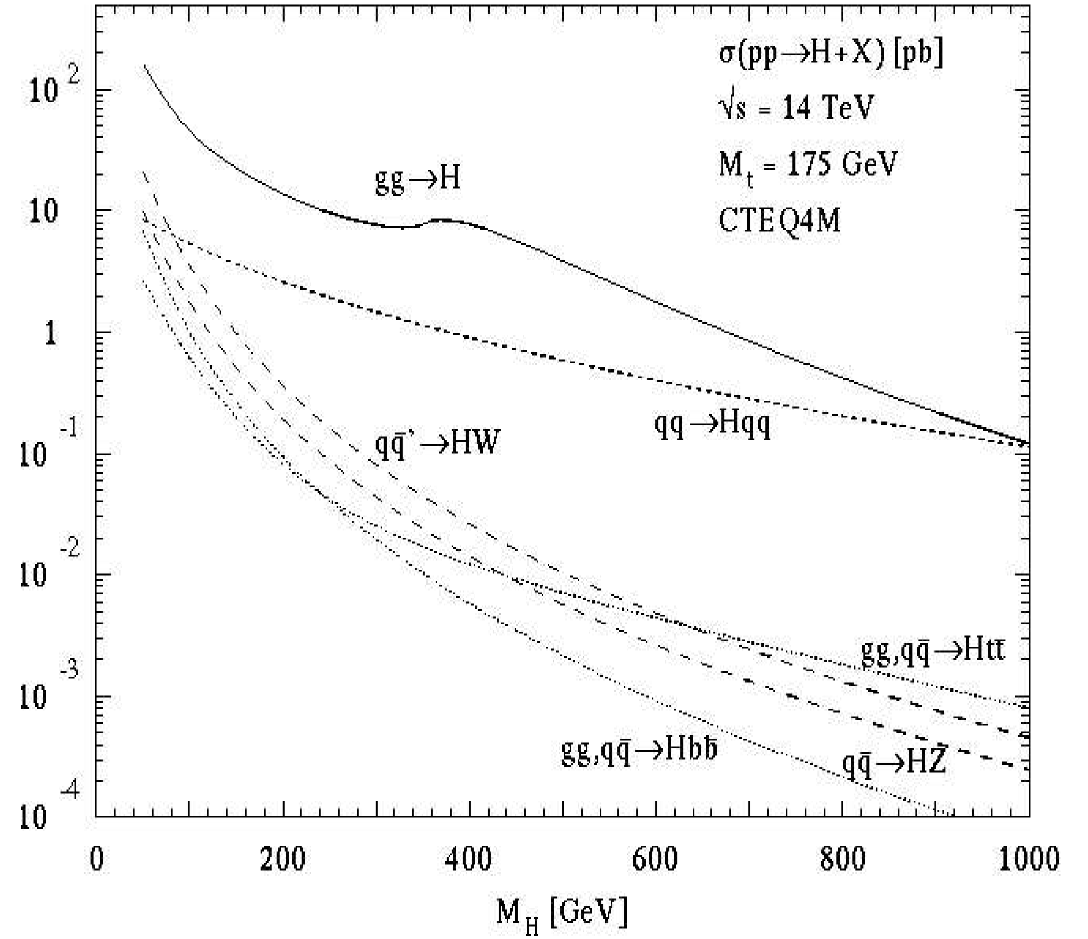
Precise knowledge of Higgs couplings crucial for

- experimentally establishing the Higgs mechanism
- revealing the structure of the underlying model

Higgs production at the LHC

Relevant production processes for SM-like Higgs:



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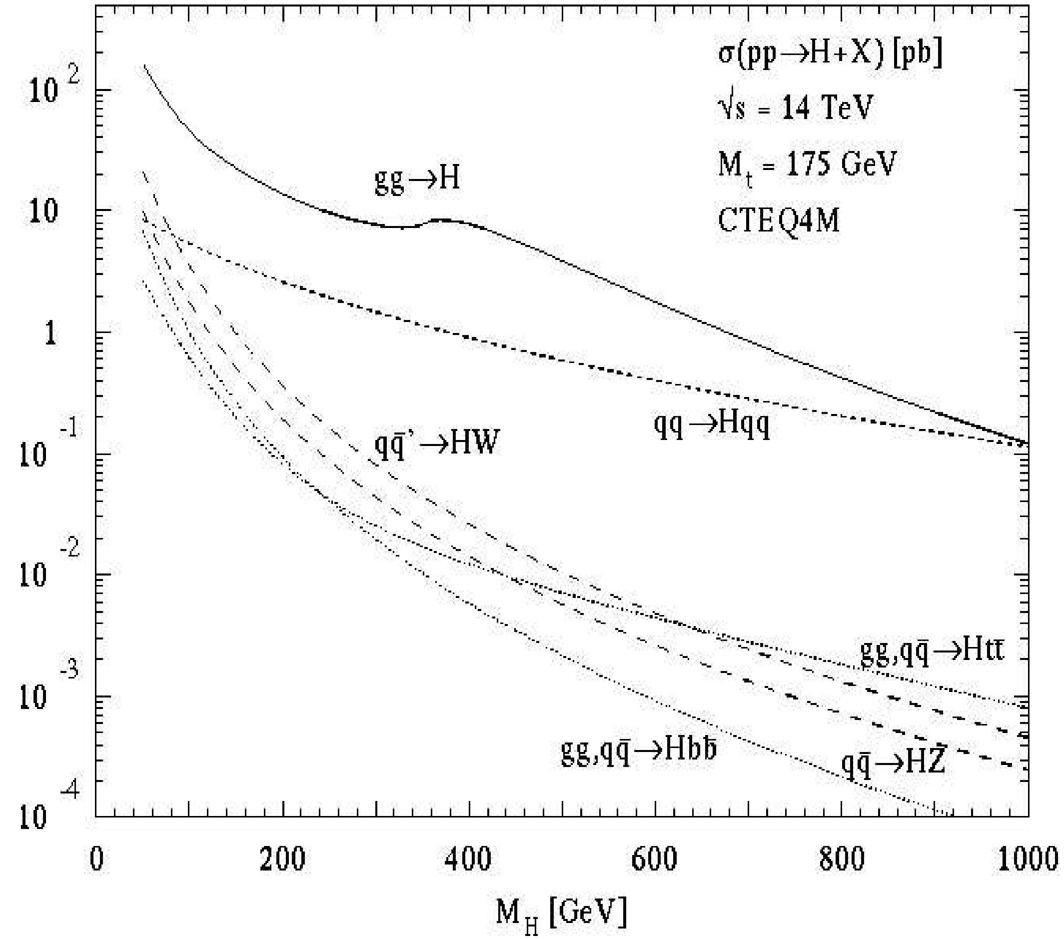

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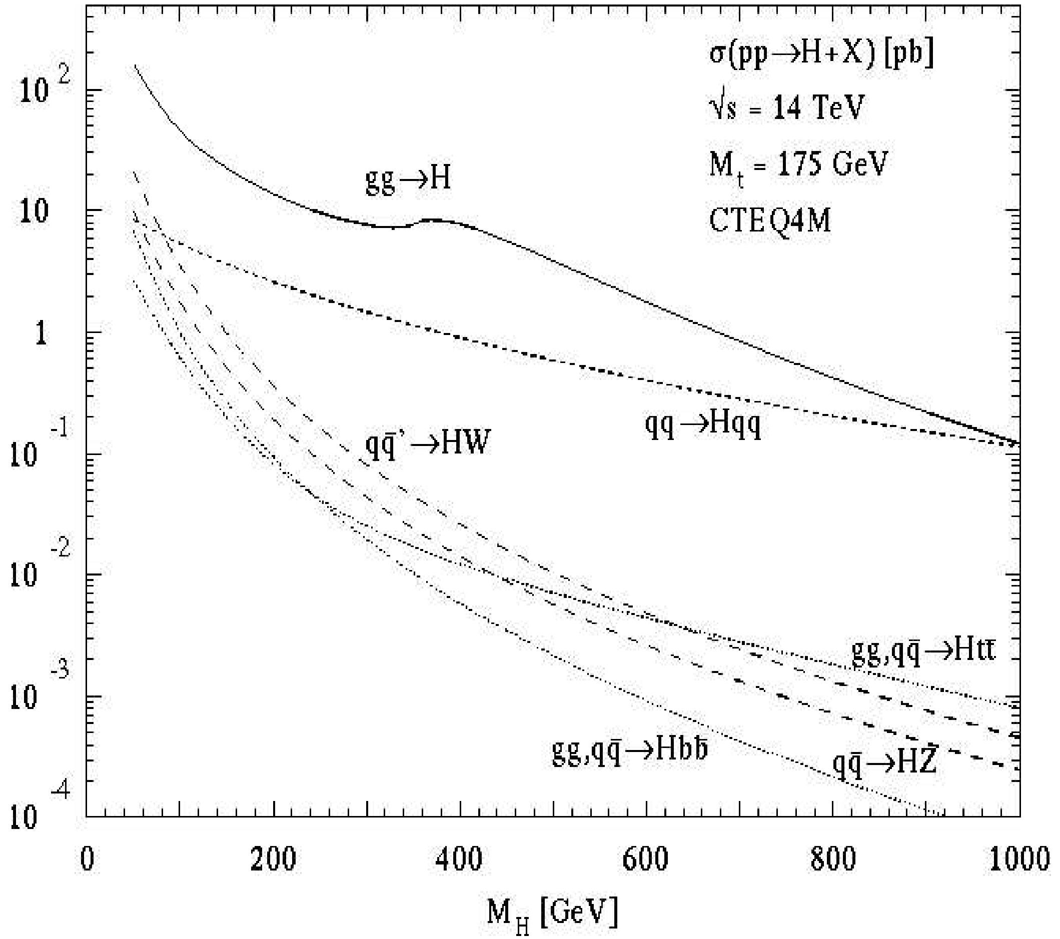

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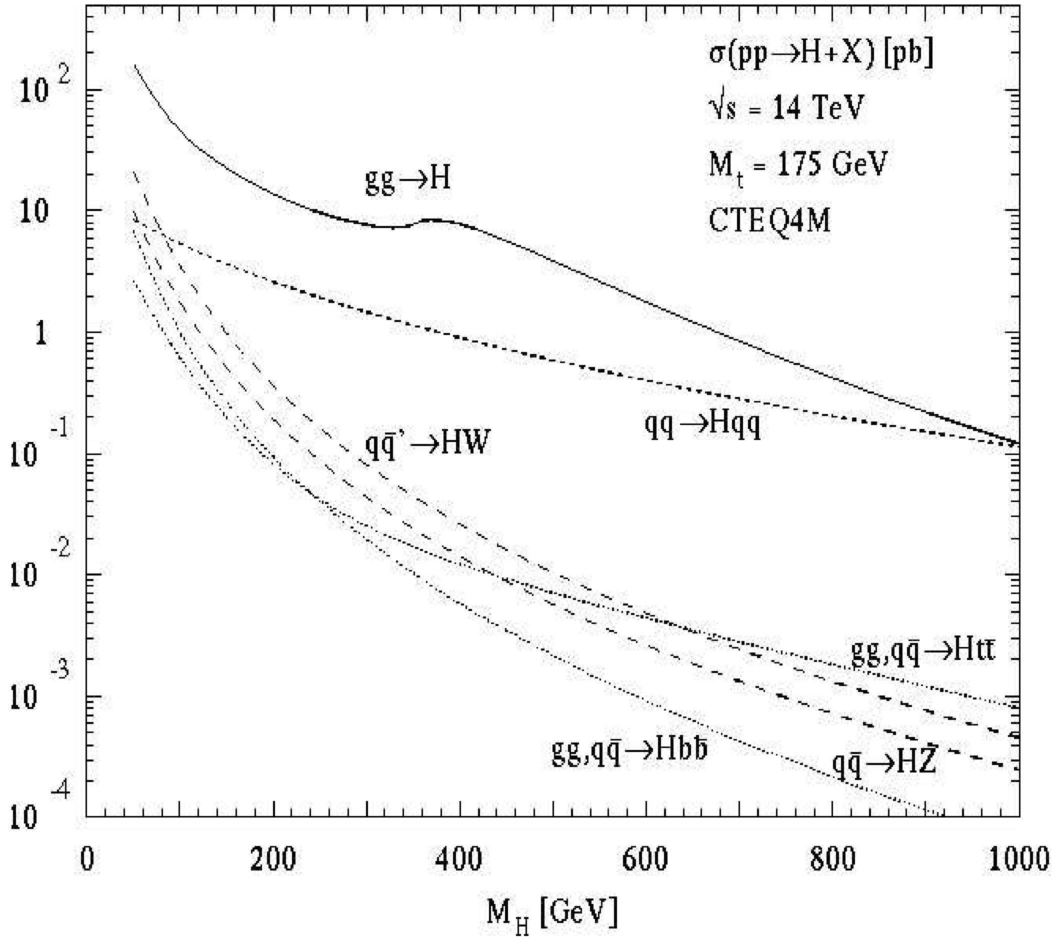

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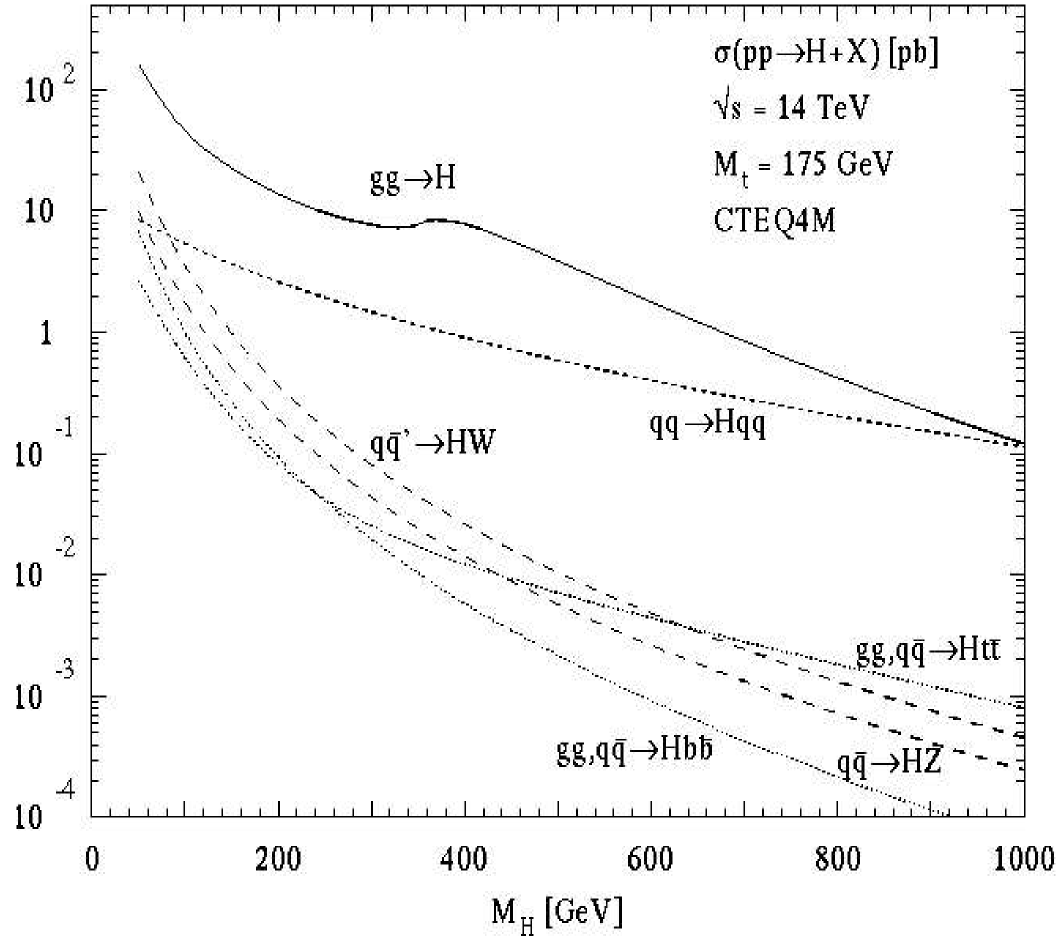

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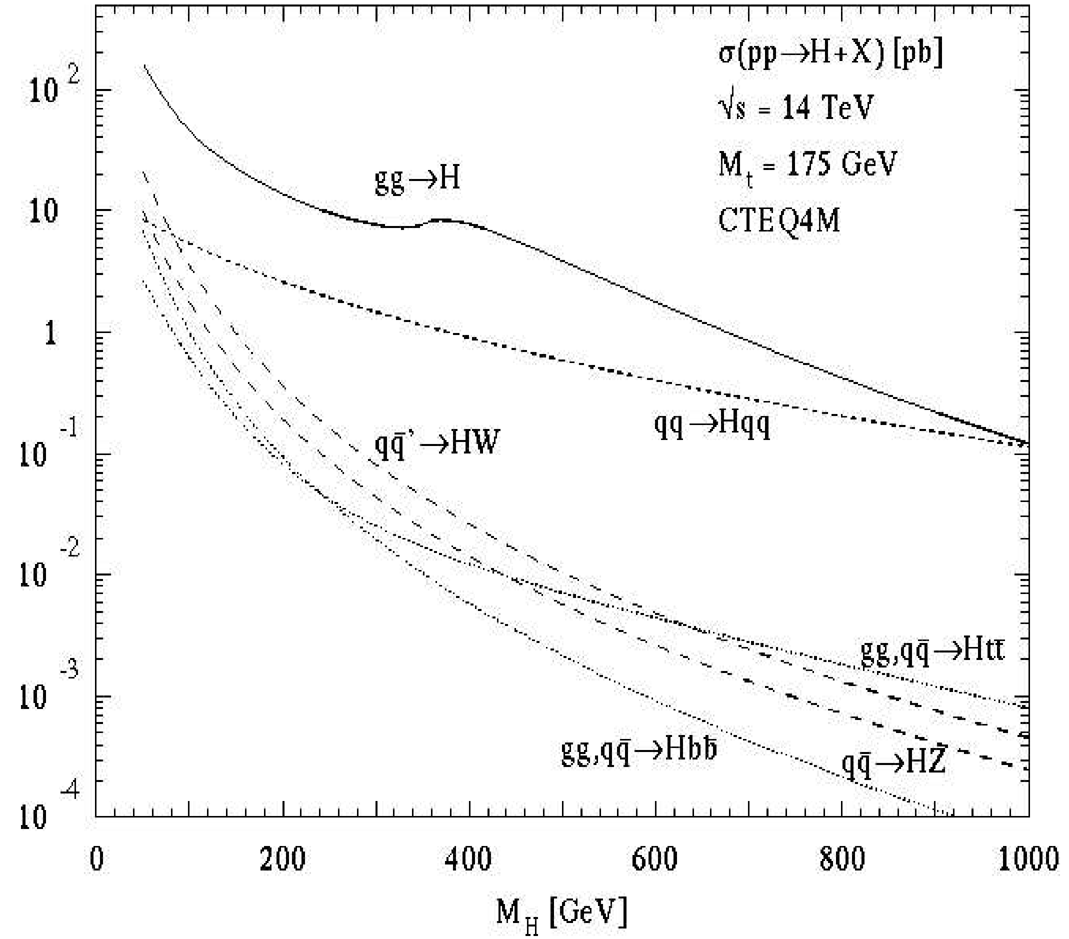

How well does WBF channel work at high luminosity?

Higgs production at the LHC

No LHC analogue to recoil method at LEP and LC:
$e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ no absolute measurement of total Higgs production cross section

QCD backgrounds $\Rightarrow$ not all decay modes accessible,
large uncertainty on $H \to b\bar{b}$, ...

Measurement of $\sigma \times \mathrm{BR}$:

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Measurement of $\sigma \times \mathrm{BR}$: Narrow-width approximation

$$\Rightarrow \quad \sigma(H) \times \mathrm{BR}(H \to a + b) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_{\mathrm{prod}}^{\mathrm{SM}}} \cdot \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}$$

Determination of ratios of couplings

Observation of different channels (or upper bound from non-observation) provides information on combinations of $\Gamma_g, \Gamma_W, \Gamma_Z, \Gamma_\gamma, \Gamma_\tau, \Gamma_b, Y_t^2$

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$\Rightarrow$ Determination of ratios of partial widths

E.g.: global fit [*M. Dührssen '03*]

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$\Rightarrow$ Additional theoretical assumptions needed for absolute determination of partial widths

Theoretical assumptions: earlier approach

[*D. Zeppenfeld, R. Kinnunen, A. Nikitenko, E. Richter-Was '00*]

- SM ratio of $H \to b\bar{b}$, $H \to \tau^+\tau^-$ partial widths
- SM ratio of $H \to W^{(*)}W^{(*)}$, $H \to Z^{(*)}Z^{(*)}$ partial widths
- No large unexpected decay modes

Questionable in various scenarios of new physics, e.g. SUSY

2. Strategy

Consider general multi-Higgs-doublet models (with or without additional Higgs singlets), includes e.g. MSSM

$\Rightarrow$ HVV couplings bounded by SM values: $\Gamma_V \leq \Gamma_V^{\mathrm{SM}}$ ($V = W, Z$)

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$\Rightarrow$ Absolute determination of $\Gamma_{\rm tot}$ and remaining Higgs couplings

Strategy, luminosity scenarios

Couplings determined from a global fit

Three luminosity scenarios considered:

- 30 fb^{-1} at each of two experiments
- 300 fb^{-1} at each of two experiments, of which only 100 fb^{-1} is usable for WBF channels at each experiment (assume significant degradation of WBF channels in high luminosity environment)
- 300 fb^{-1} at each of two experiments (full luminosity usable for WBF channels)

Use SM rates in the fits $\Rightarrow$ statistical errors

Estimate of systematic errors:

5% luminosity error

uncertainties on reconstruction/identifi cation of leptons (2%), photons (2%), b-quarks (3%), forward tagging / veto jets (5%)

error propagation for background determination from side-band analyses (from 0.1% for $H \to \gamma\gamma$ to 5% for $H \to WW$ and $H \to \tau\tau$)

theoretical and parametric uncertainties on Higgs boson production (20% ggH, 15% ttH, 7% WH/ZH, 4% WBF) and decays (1%, as a future expectation)

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Analysis repeated with more restrictive theoretical constraints
$\Rightarrow$ investigate possible improvements

Considered channels

- $H \to Z^{(*)} Z^{(*)} \to 4\ell$
- $H \to \gamma\gamma$
- $H \to W^{+(*)} W^{-(*)} \to \ell^+ \ell^- + p_{T,\text{miss}}$
- $H \to \tau^+ \tau^-$
- $t\bar{t}H$, $H \to b\bar{b}$

3. Results for general multi-Higgs-doublet models

Assume

$$g^2_{HWW} < 1.05\, g^2_{HWW,\mathrm{SM}}, \quad g^2_{HZZ} < 1.05\, g^2_{HZZ,\mathrm{SM}}$$

5% margin to allow for theoretical uncertainties in translation between g^2_{HVV} and partial widths and for small admixtures of exotic states

Allow for possibility of additional particles running in the loops for $H \to \gamma\gamma$ and $gg \to H$

fitted by positive/negative new partial width to $H \to \gamma\gamma$, $gg \to H$

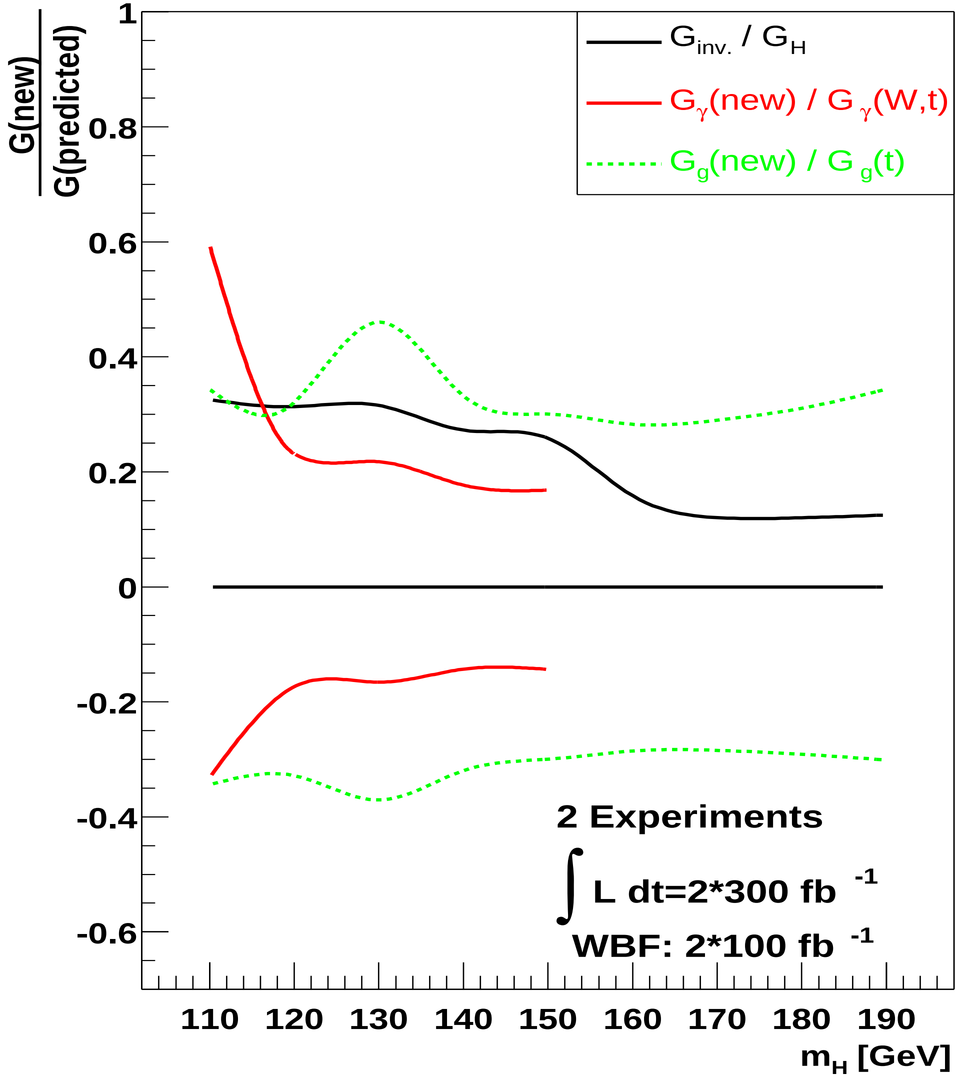
Allow for additional Higgs decays

fitted with extra partial width

Constraints on extra partial widths

Detection of SM rates

$\Rightarrow$ Constraints on additional partial widths



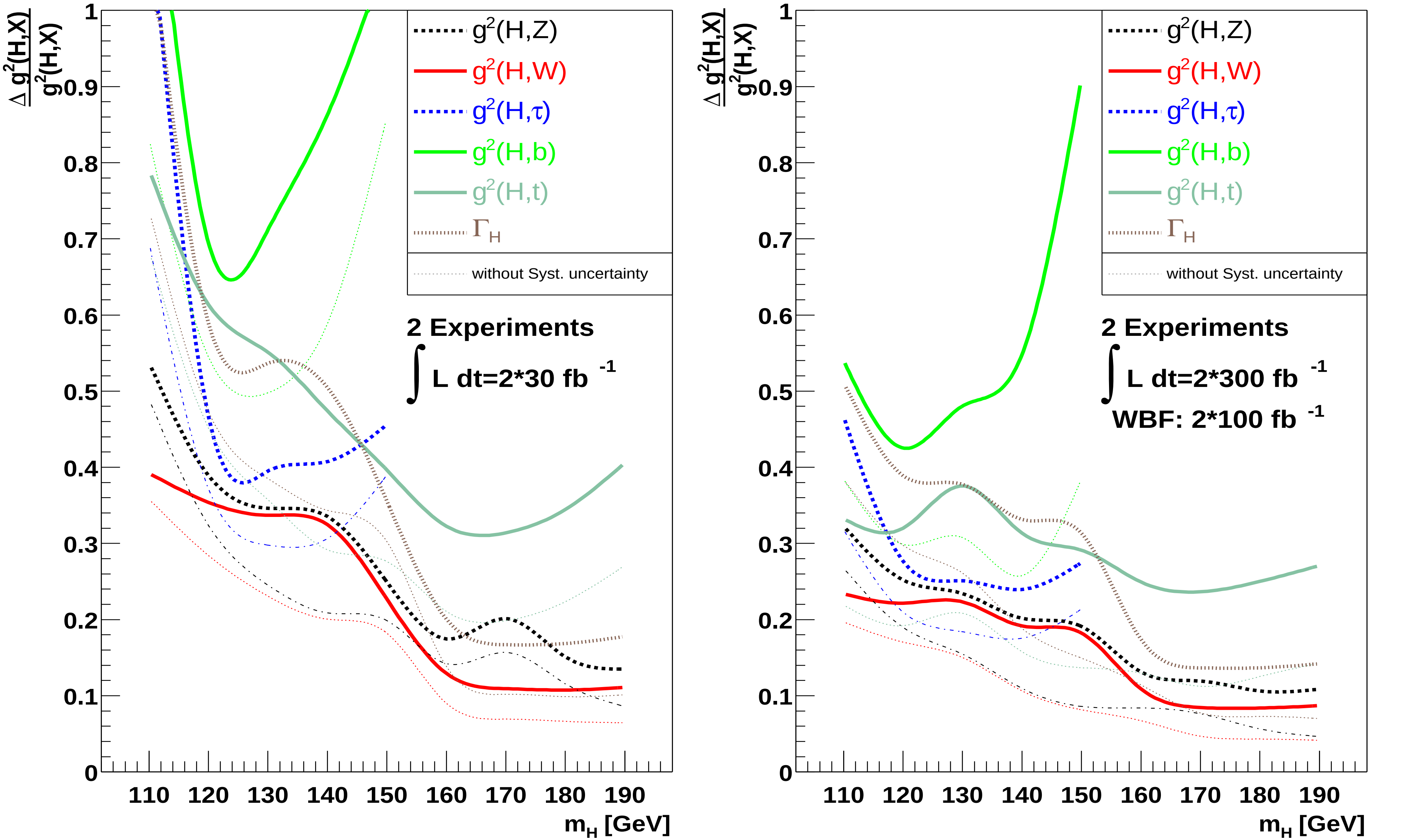
For $2 \times 300 + 2 \times 100$ fb^{-1}:

$$\Gamma_\gamma \lesssim 0.2\,\Gamma_\gamma^{\rm SM}$$

$$\Gamma_g \lesssim 0.4\,\Gamma_g^{\rm SM}$$

$$\Gamma_{\rm inv} \lesssim 0.2\,\Gamma_{\rm tot}^{\rm SM}$$

Results for the couplings and the total Higgs width, relative precisions



Results for the couplings and total Higgs width

For $2 \times 300 + 2 \times 100$ fb^{-1}:

typical accuracies of 20–30% for $m_H \lesssim 150$ GeV

10% accuracy for HWW, HZZ couplings above W-pair threshold

Accuracy significantly worse in low luminosity case (2×30 fb^{-1}) for light Higgs

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Systematic errors contribute up to half the total error, especially at high luminosity

Results with more restrictive theoretical constraints

Additional assumption: HWW, HZZ couplings close to their SM values

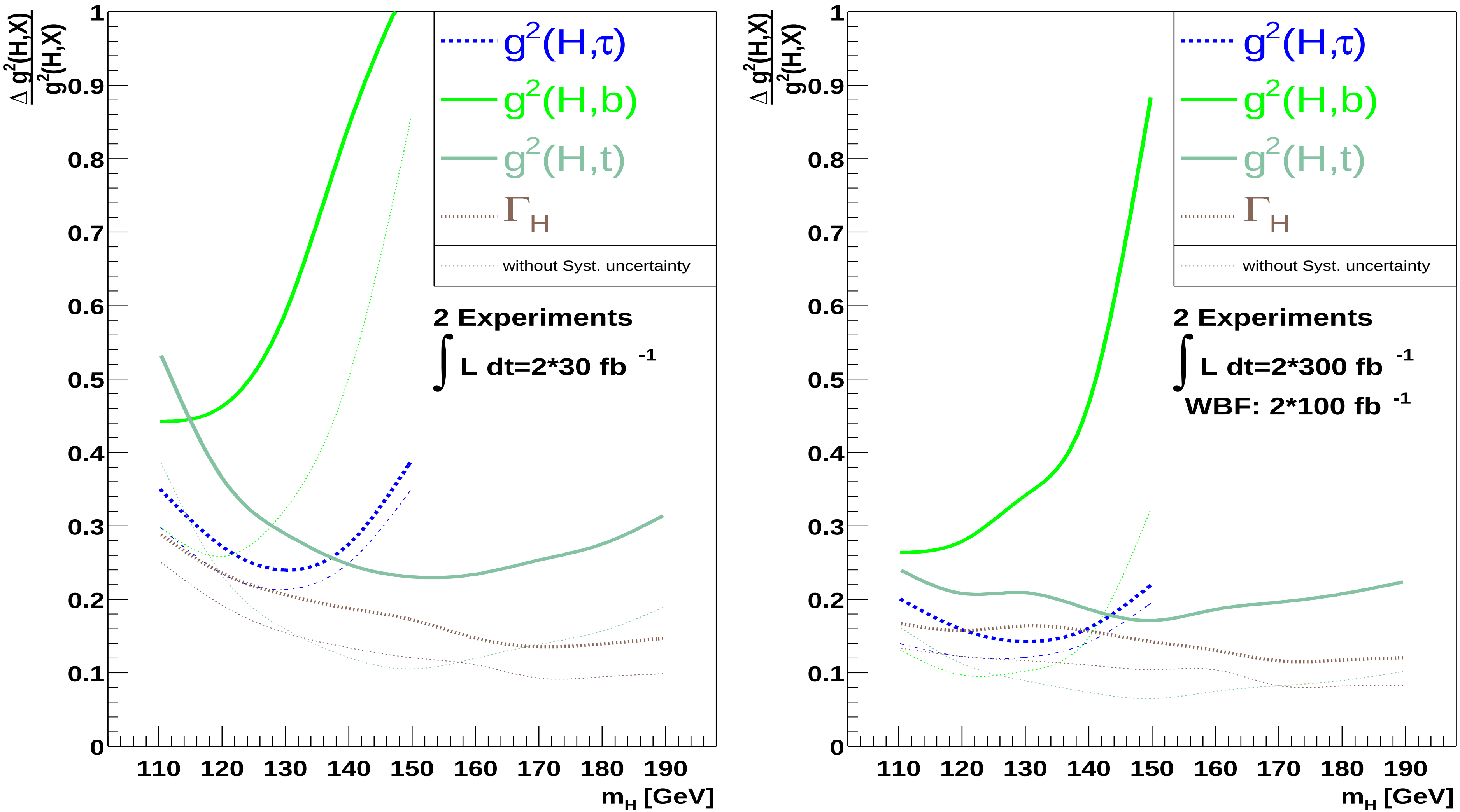
$$g^2_{HWW} = g^2_{HWW,\mathrm{SM}} \pm 5\%, \quad g^2_{HZZ} = g^2_{HZZ,\mathrm{SM}} \pm 5\%$$

Realised for the light $\mathcal{CP}$-even Higgs of the MSSM over wide part of SUSY parameter space (decoupling region, $m_A \gtrsim 200$ GeV)

Further assumption (has only small impact on accuracies):
No new particles in loops of $H \to \gamma\gamma$, $gg \to H$, i.e. couplings fixed in terms of couplings of SM particles in the loops

Additional Higgs decays allowed

Results with more restrictive theoretical constraints



$\Rightarrow$ 10–20% accuracies over entire intermediate Higgs mass range for $2 \times 300 + 2 \times 100$ fb^{-1}

4. Sensitivity to the structure of the underlying physics scenario

Higgs coupling measurements

$\Rightarrow$ sensitivity to deviations from the SM

Example: MSSM, $m_h^{\max}$ benchmark scenario

In decoupling region ($m_A \gtrsim 200$ GeV): SM-like Higgs sector, small deviations in couplings of $\mathcal{CP}$-even Higgs h from SM predictions

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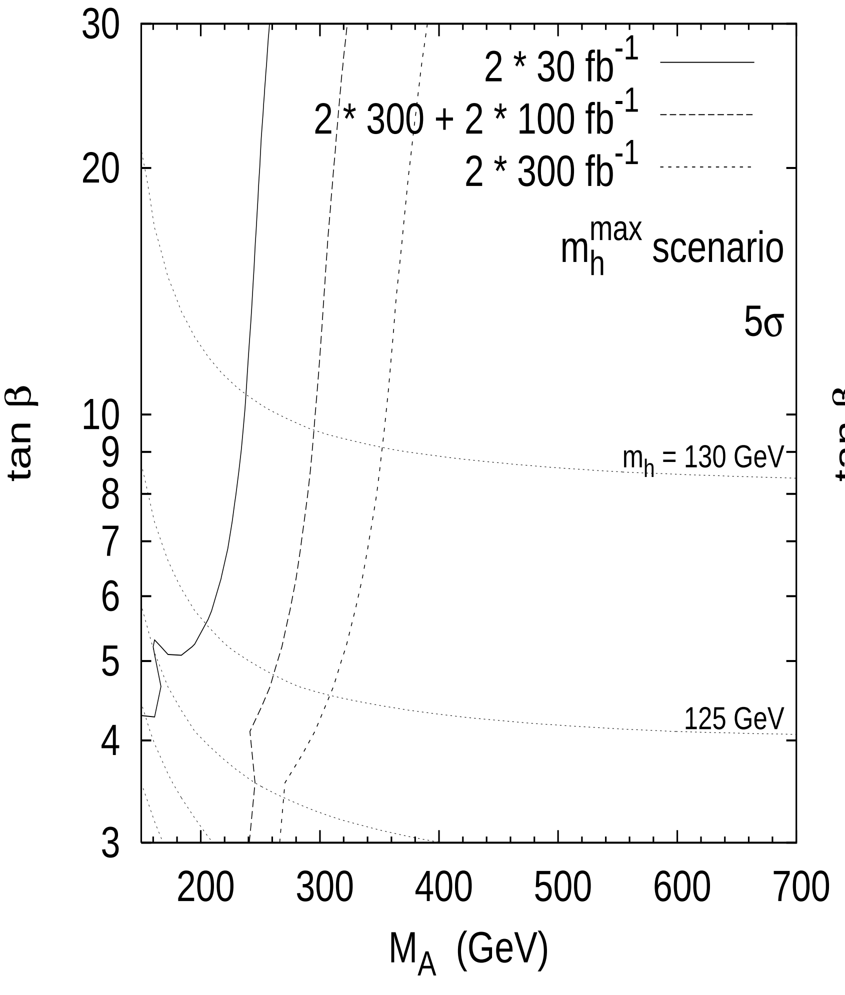
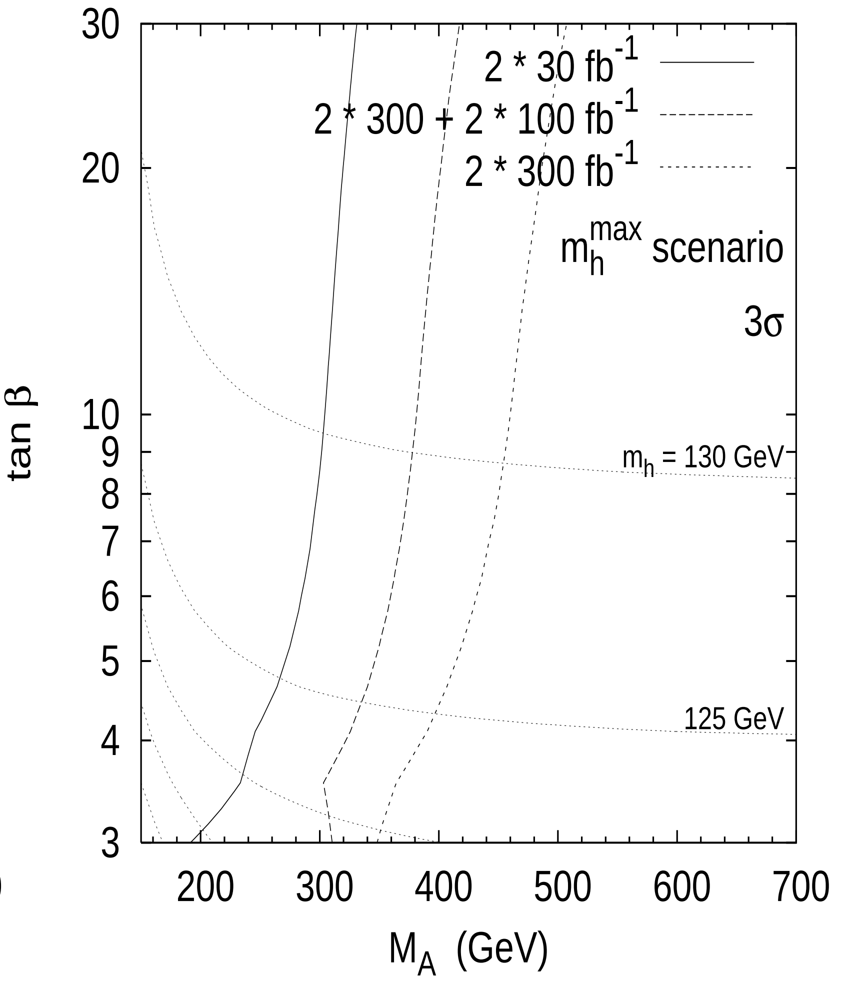
Question: at what significance can the SM be ruled out from h measurements at the LHC alone?

MSSM example: 3 σ and 5 σ deviations from the SM





$\Rightarrow$ For $2 \times 300 + 2 \times 100$ fb^{-1}:

5 σ discrepancy from SM up to $m_A \approx 300$ GeV

Indirect constraints on m_A

Note:

Deviations from the SM cannot directly be translated into indirect bounds on m_A

Relation between m_h, m_A, $\tan\beta$ and Higgs couplings affected by all other SUSY parameters

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Relation between m_h, m_A, $\tan\beta$ and Higgs couplings affected by all other SUSY parameters

$\Rightarrow$ Need precision measurements of Higgs couplings $+$ detailed information on SUSY spectrum

Indirect bounds on m_A: LHC + LC

Precision measurement of

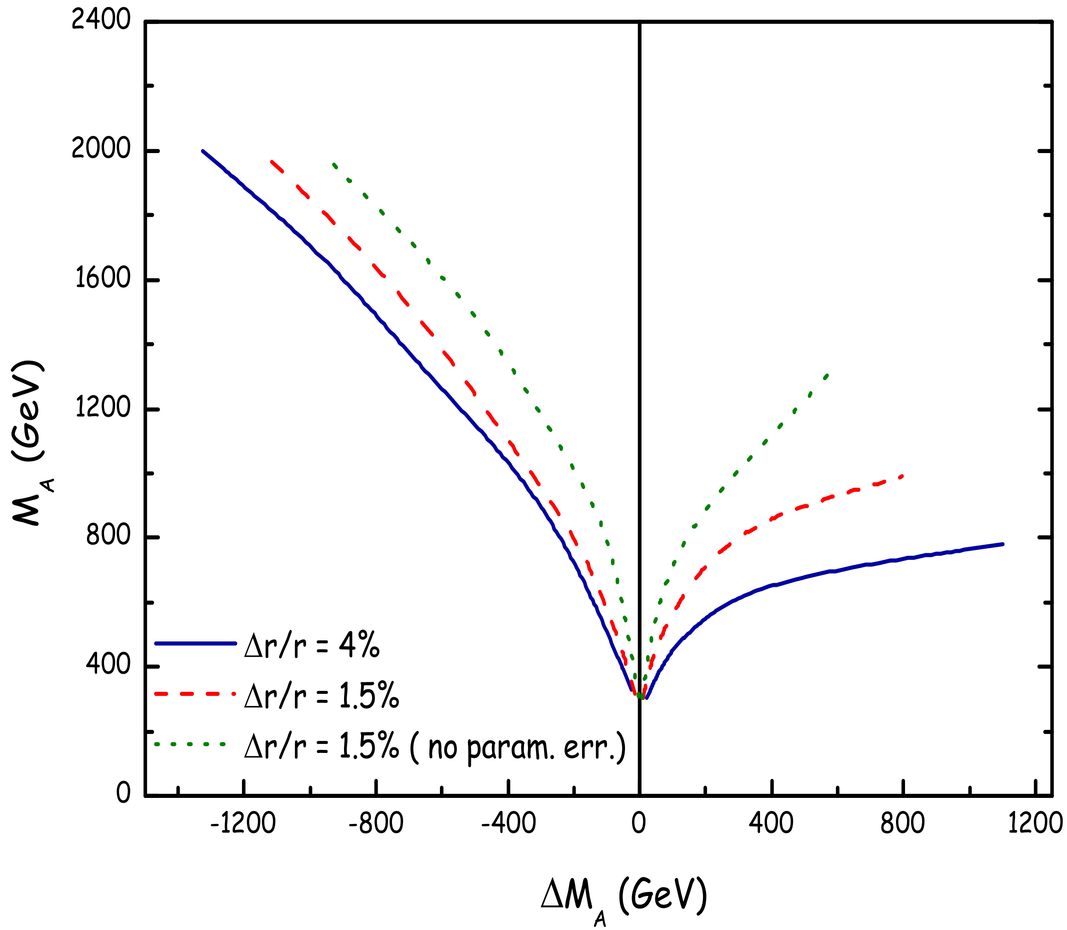
$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

at the LC

and

LHC + LC information on SUSY spectrum (SPS1a scenario)

[*K. Desch, E. Gross, S. Heinemeyer, G. W., L. Zivkovic '04*]



⇒ Sensitive indirect bounds on m_A only with high-precision measurements, LHC + LC information

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- Determination of Higgs couplings

  $\Rightarrow$ Significant deviations in the Higgs sector observable in many models of physics beyond the SM