Determination of Higgs Couplings at LHC $\oplus$ ILC

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based on collaboration with

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1. Motivation

Higgs field in the SM:

$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

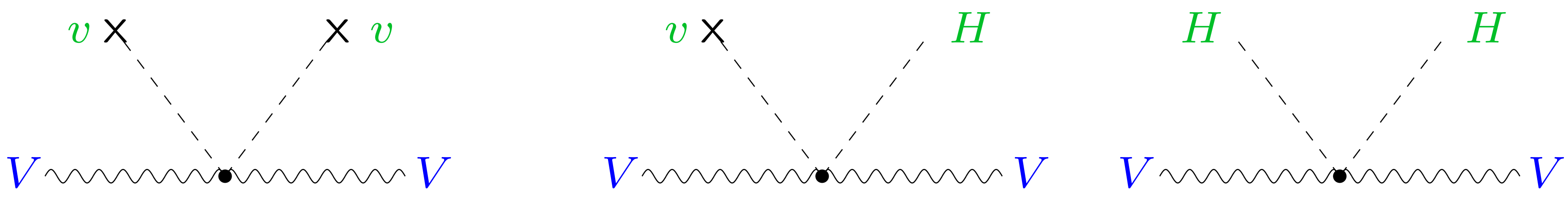
H: elementary scalar field, Higgs boson

Lagrange density: $\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

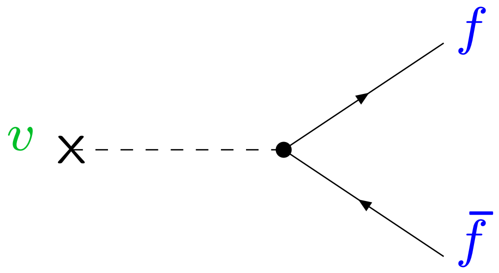
1.) $VV\Phi\Phi$ coupling:

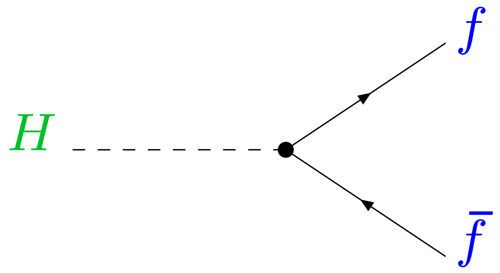


$\Rightarrow$ VV mass terms $\qquad$ $\Rightarrow$ triple/quartic couplings to gauge bosons

$g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$ $\Rightarrow$ coupling $\propto$ masses

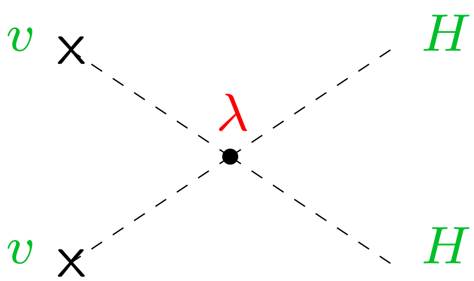
2.) fermion mass terms: Yukawa couplings





$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



...

$\lambda = M_H^2/v$

$M_H = v\sqrt{\lambda}$ free parameter

$\rightarrow$ last unknown parameter of the SM

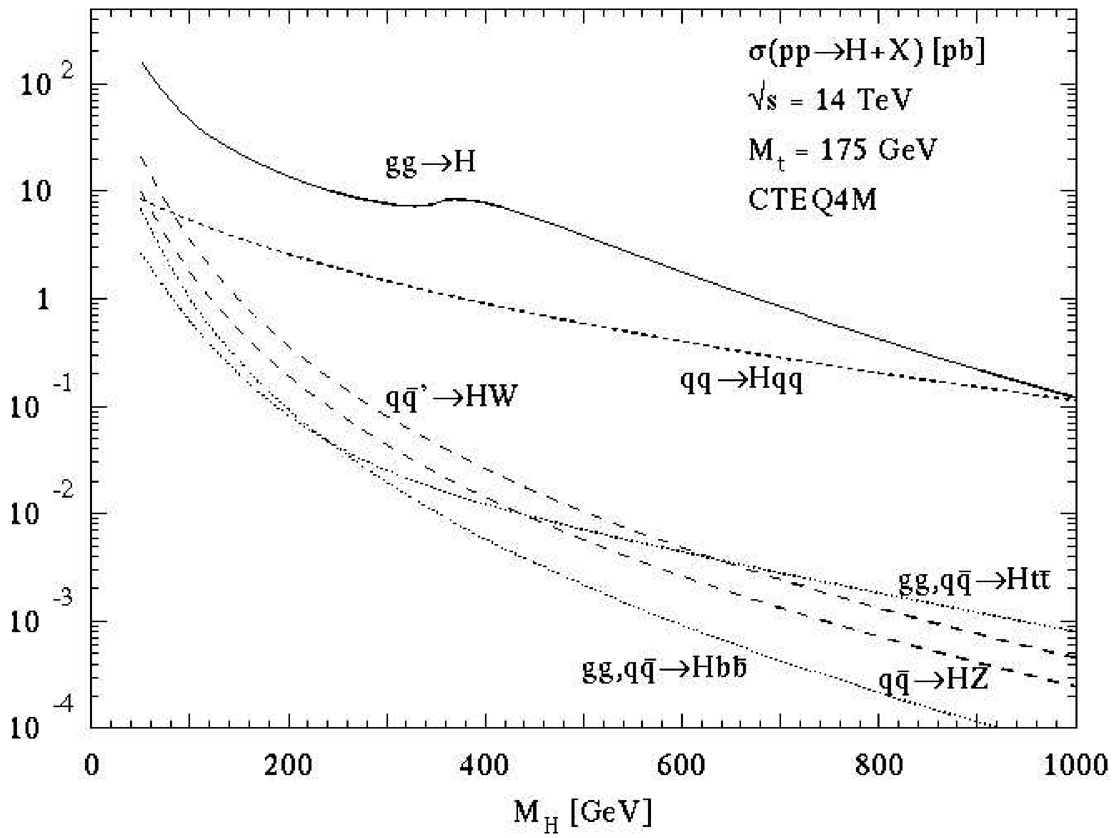
$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Higgs coupling measurements is one of the main tasks of future colliders

2. Higgs coupling determination at the LHC

[*M. Dührrsen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]

Higgs production at the LHC:



gluon fusion: $gg \to H$

weak boson fusion (WBF):
$q\bar{q} \to q'\bar{q}'H$

top quark associated
production: $gg, q\bar{q} \to t\bar{t}H$

weak boson associated
production: $q\bar{q}' \to WH, ZH$

Some LHC specifics:

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

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

QCD backgrounds $\Rightarrow$ not all decay modes accessible, e.g. $H \to b\bar{b}$

Measurement of $\sigma \times$ BR: narrow width approximation:

$$\Rightarrow \sigma(H) \times \text{BR}(H \to d_1 d_2) = \frac{\sigma(H)^{\text{SM}}}{\Gamma_{\text{prod}}^{\text{SM}}} \times \frac{\Gamma_{\text{prod}}\,\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

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

$\Rightarrow$ Determination of ratios of partial width via global fit
[*M. Dührssen '03*]

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

Strategy: mild theoretical assumptions

$\rightarrow$ consider general multi-Higgs-doublet model
(w/o additional Higgs singlets)
($\Rightarrow$ including e.g. MSSM)

$\Rightarrow$ HVV coupling bounded from above by SM value, $\Gamma_V \leq \Gamma_V^{\text{SM}}$, $V = W, Z$
$\Rightarrow$ upper bound on Γ_V

Observation of Higgs production
$\Rightarrow$ lower bound on production couplings
lower bound on total width Γ_{tot}

Observation of $H \rightarrow VV$ in WBF
$\Rightarrow$ determines $\Gamma_V^2/\Gamma_{\text{tot}}$
$\Rightarrow$ determines lower bound on Γ_{tot}

$\Rightarrow$ Absolute determination of Γ_{tot} and Higgs couplings via global fit

$\Rightarrow$ nearly model independent analysis

Estimate of errors:

Statistical errors:

Assume SM rates for production and decay in each luminosity scenario

Systematic errors:

– 5% luminosity error
– uncertainties on reconstruction: identification of leptons: 2%
identification of photons: 2%
identification of b quarks: 3%
– forward tagging/veto jets: 5%
– error propagation for background determination from side-band analyses: from 0.1% ($H \to \gamma\gamma$) to 5% ($H \to WW^*, H \to \tau^+\tau^-$)
– theoretical and parametric uncertainties for Higgs production: ggH: 20%, $t\bar{t}H$: 15%, WH, ZH: 7%, WBF: 4%
– theoretical and parametric uncertainties on Higgs decays: 1% (as a future expectation)

⇒ log likelihood function based on statistical and systematic errors

Decay channels considered:

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

Actual analysis assumptions (even less restrictive):

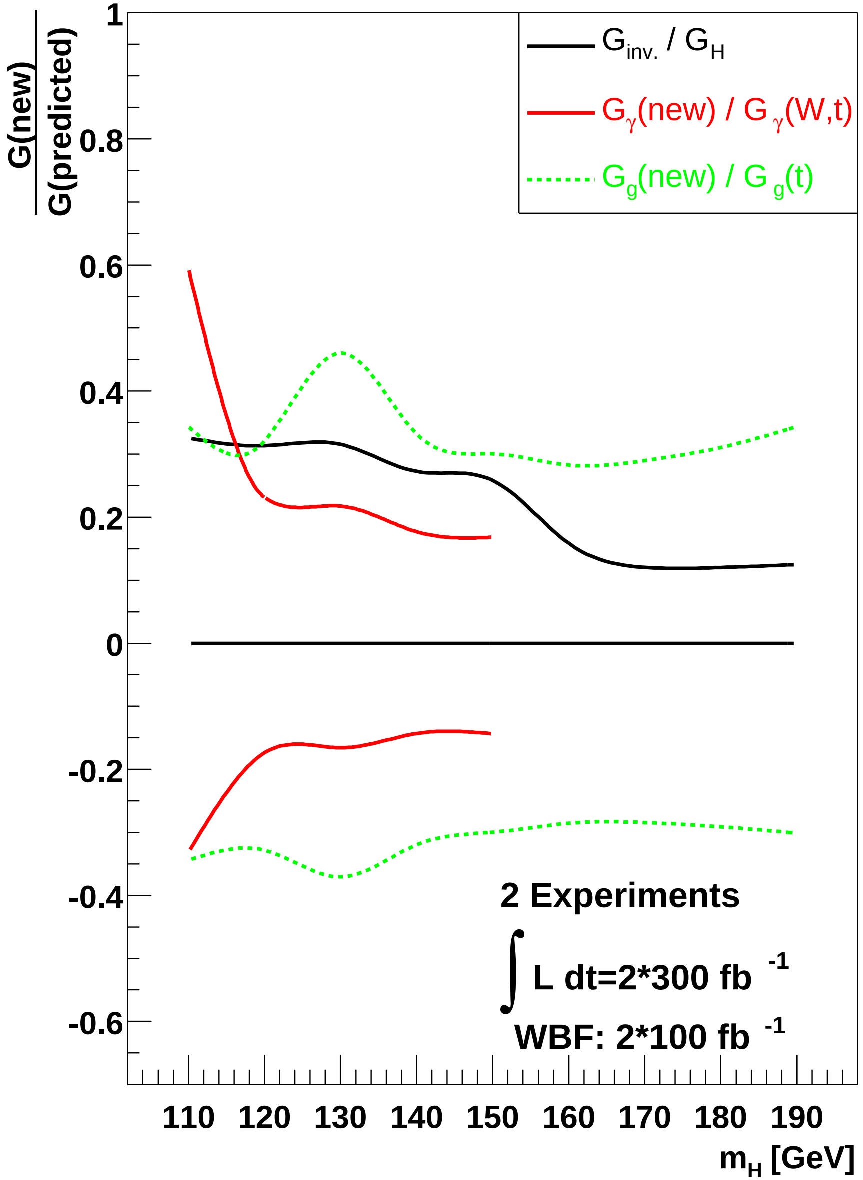
$$g^2_{HVV} \leq 1.05 \times g^2_{HVV,\mathrm{SM}}, \quad V = W, Z$$

5% margin to allow for
- theoretical uncertainties in translation of partial widths to g^2_{HVV}
- small admixtures of exotic states (triplets, . . .)

- Allow for additional particles contributing to $H \to \gamma\gamma$ and $gg \to H$
  (⇒ fitted by pos. /neg. additional partial width to $H \to \gamma\gamma$ and $gg \to H$)

- Allow for additional Higgs decay width
  (⇒ fitted by additional partial width)

Constraints on extra partial widths:



Detection of SM rates

$\Rightarrow$ constraints on widths:

$2 * 300 + 2 * 100$ fb^{-1} scenario:

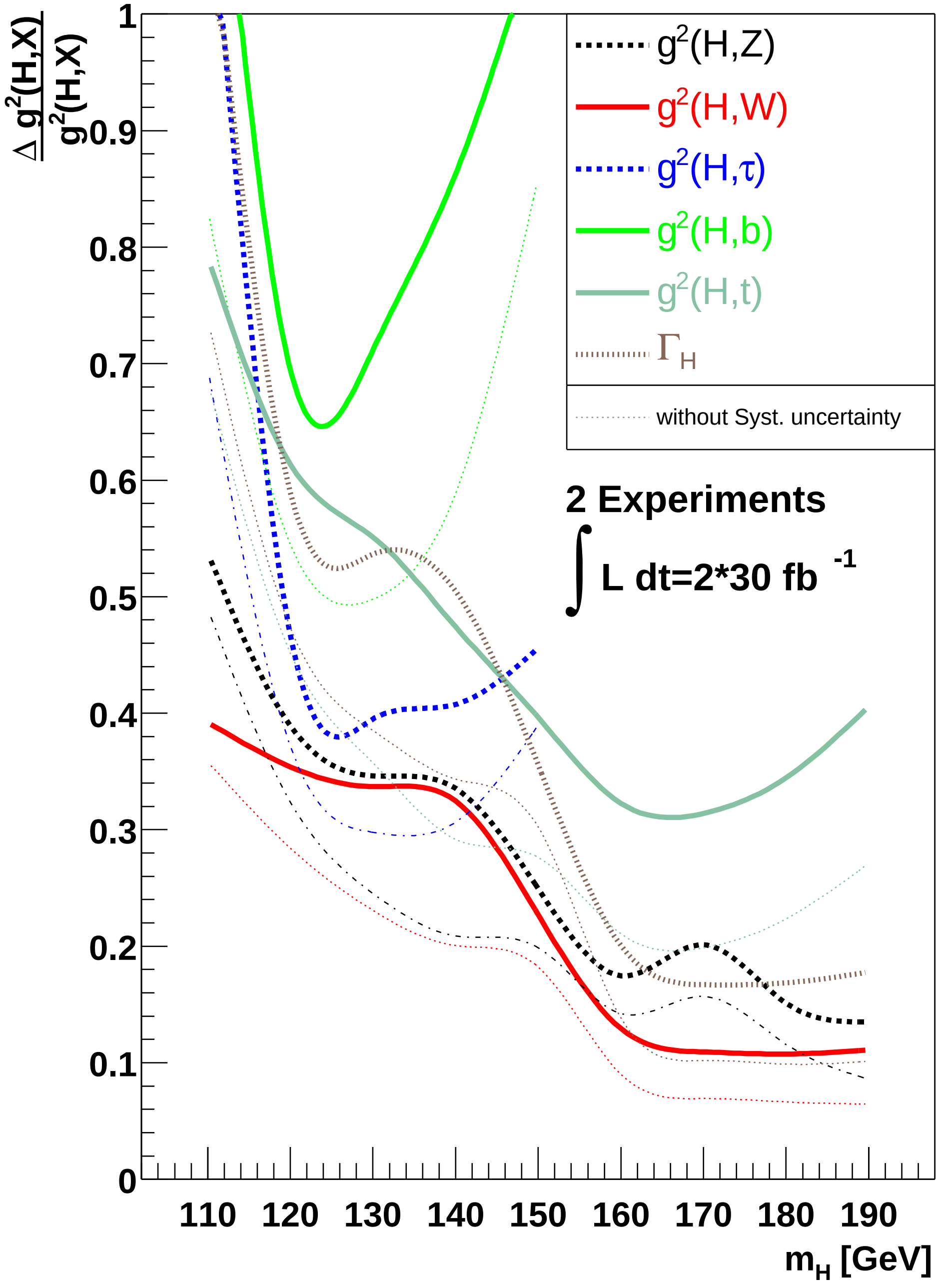
$\Delta\Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\rm SM}$

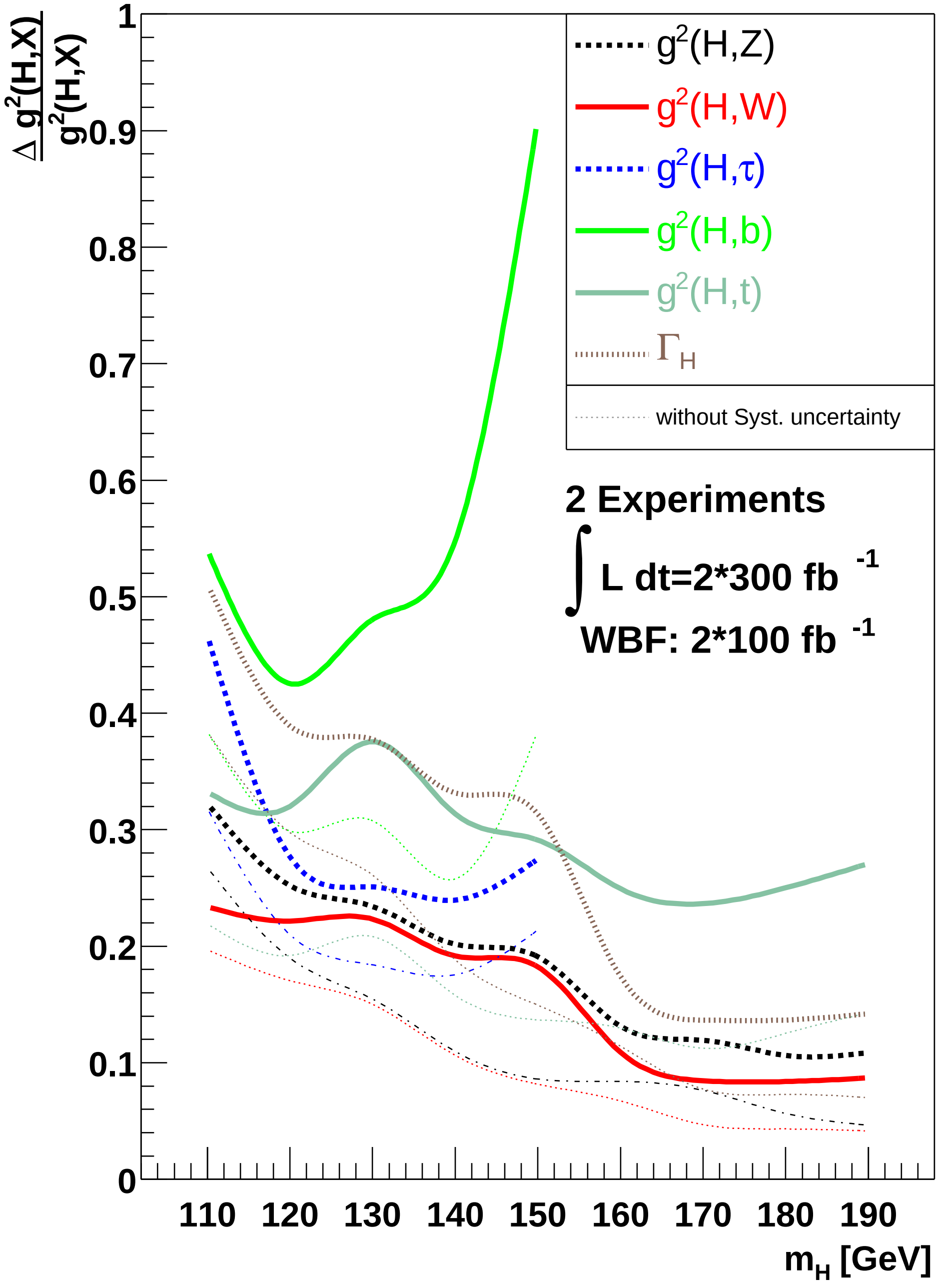
$\Delta\Gamma_g \leq 0.4 \times \Gamma_g^{\rm SM}$

$\Delta\Gamma_{\rm inv} \leq 0.2 \times \Gamma_{\rm tot}^{\rm SM}$

$\Rightarrow$ restrictions on new physics

Relative precisions for partial and total widths: two scenarios





Observations:

low luminosity scenario: $2 * 30\ \text{fb}^{-1}$:

for a light Higgs: results significantly worse as compared to higher luminosity scenario

high(er) luminosity scenario: $2 * 300 + 2 * 100\ \text{fb}^{-1}$:

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

– 10% accuracies for HVV couplings above WW threshold

high luminosity scenario: $2 * 300\ \text{fb}^{-1}$:

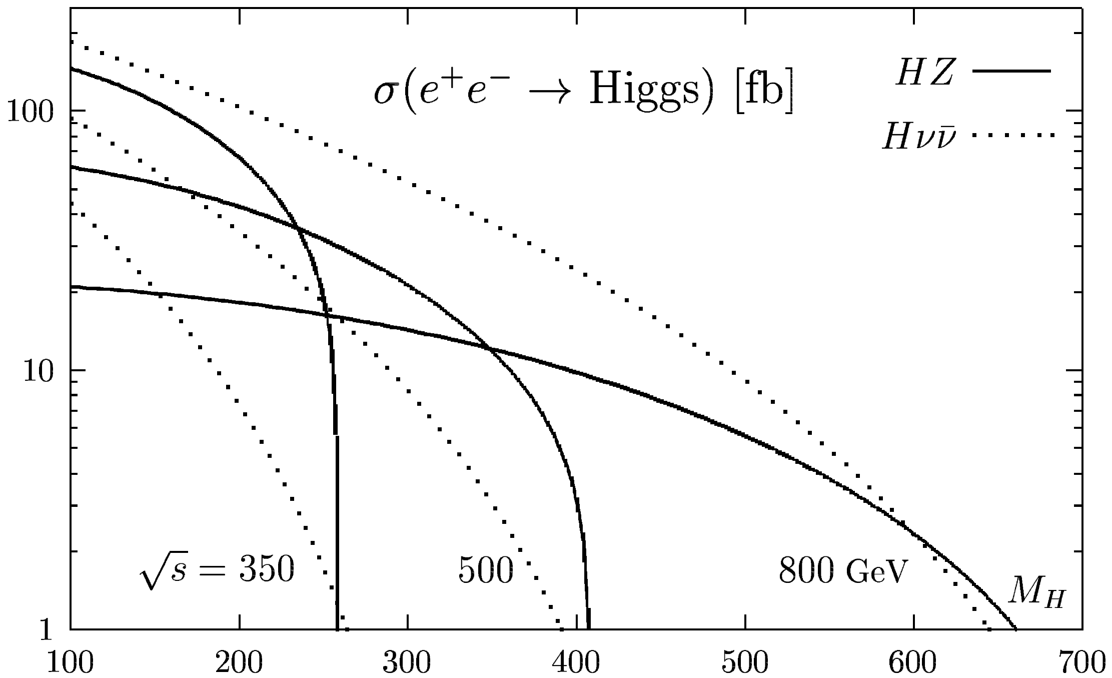
significant improvement over $2 * 300 + 2 * 100\ \text{fb}^{-1}$ only in $H\tau\tau$ coupling (WBF crucial for $H \to \tau^+\tau^-$)

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

3. Higgs coupling determination at the ILC

[TESLA TDR '01] [Abe et al. '01] [Abe et al. '01] [T. Barklow '03]

Higgs production at the ILC:



Higgs-strahlung:
$e^+e^- \to Z^* \to ZH$

weak boson fusion (WBF):
$e + e- \to \nu\bar{\nu}H$

Some ILC specifics:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

Some ILC results (500 fb^{-1}@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%$, $\delta g_{WWH} \approx 2 - 5\%$
$\delta g_{Hb\bar{b}} \approx 1 - 2\%$ (for $M_H \lesssim 150$ GeV)

However: No good determination of $g_{Ht\bar{t}}$ and $g_{H\gamma\gamma}$

$\delta g_{Ht\bar{t}} =?$, $\delta g_{H\gamma\gamma} = 23\%$ (for $M_H = 120$ GeV)

4. LHC $\oplus$ ILC

Idea: use data from the 350 GeV ILC
to replace theory assumptions in LHC analysis

$\Rightarrow$ better determination of $g_{Ht\bar{t}}$ and $g_{H\gamma\gamma}$

(in a model independent analysis)

Existing result:

[*K. Desch, M. Schumacher '04*]

LHC: $t\bar{t}H \to t\bar{t}\,WW^*$, $t\bar{t}\,b\bar{b}$ (300 fb^{-1})

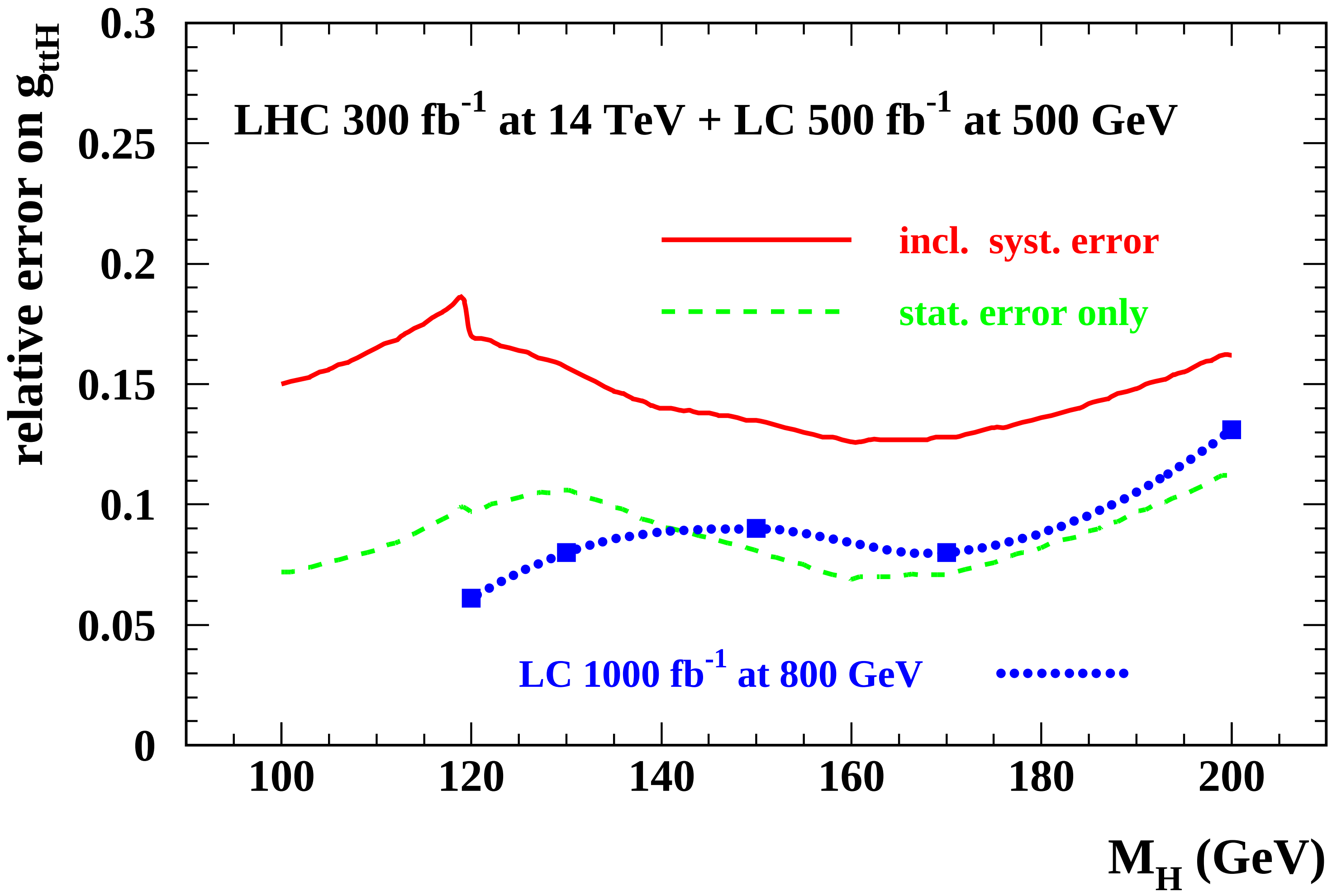
ILC: BR($H \to WW^*$), BR($H \to b\bar{b}$) (500 fb^{-1} @ $\sqrt{s} = 500$ GeV)

$\Rightarrow$ fit for $g_{Ht\bar{t}}$ $\to$ T

$\Rightarrow$ determination of $g_{Ht\bar{t}}$ to 15%

Fit for $g_{Ht\bar{t}}$:

[*K. Desch, M. Schumacher '04*]



New result:

→ Use more ILC input and all LHC channels in a combined fit

Inputs from the ILC to the fit:

– M_H

– $\sigma_{\rm tot}(e^+e^- \to HZ)$

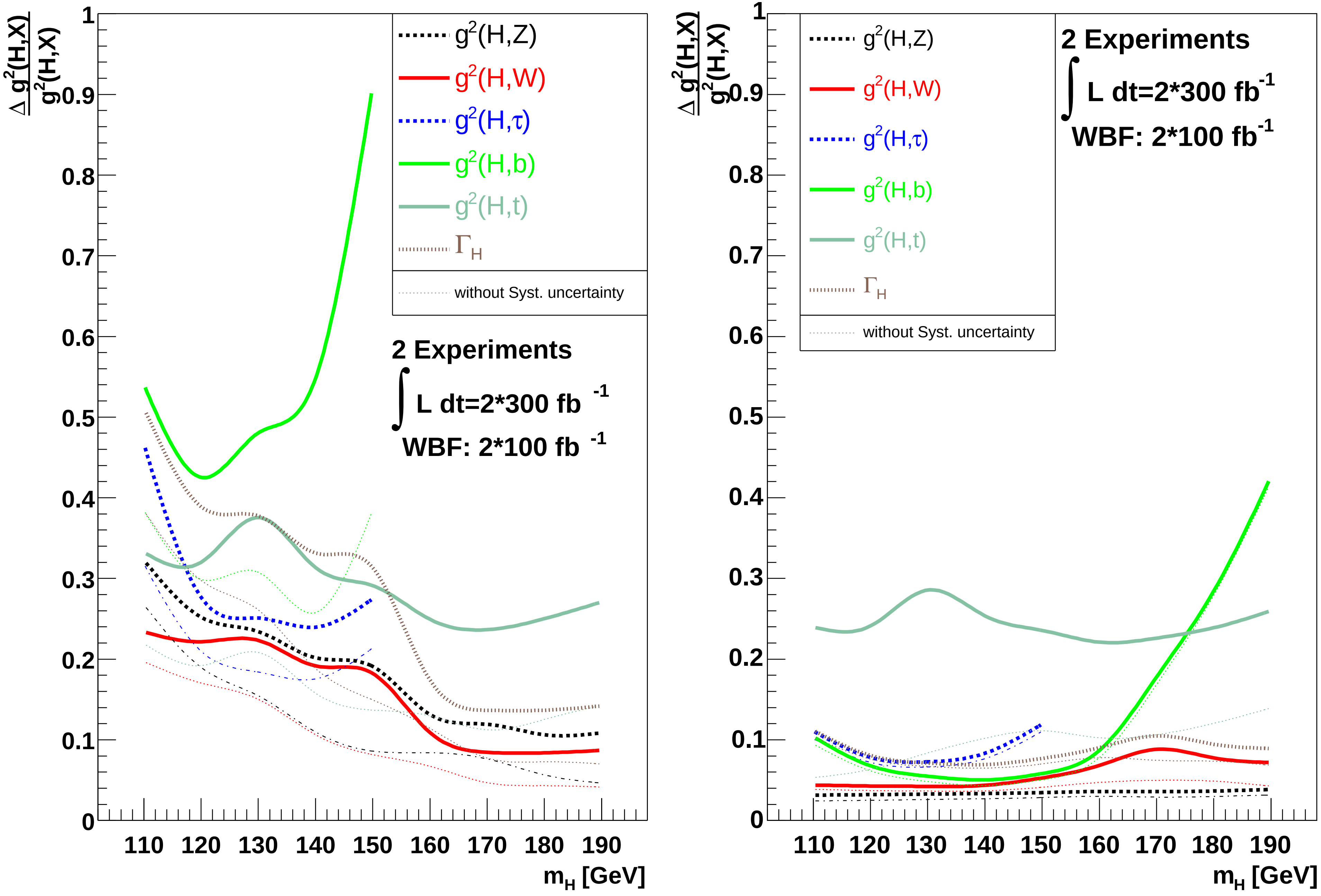
– $\sigma_{\rm tot}(e^+e^- \to HZ) \times {\rm BR}(H \to X) \quad (X = b\bar{b},\ \tau^+\tau^-,\ gg,\ WW^*)$

– $\sigma_{\rm tot}(e^+e^- \to \nu\bar{\nu}H) \times {\rm BR}(H \to b\bar{b})$

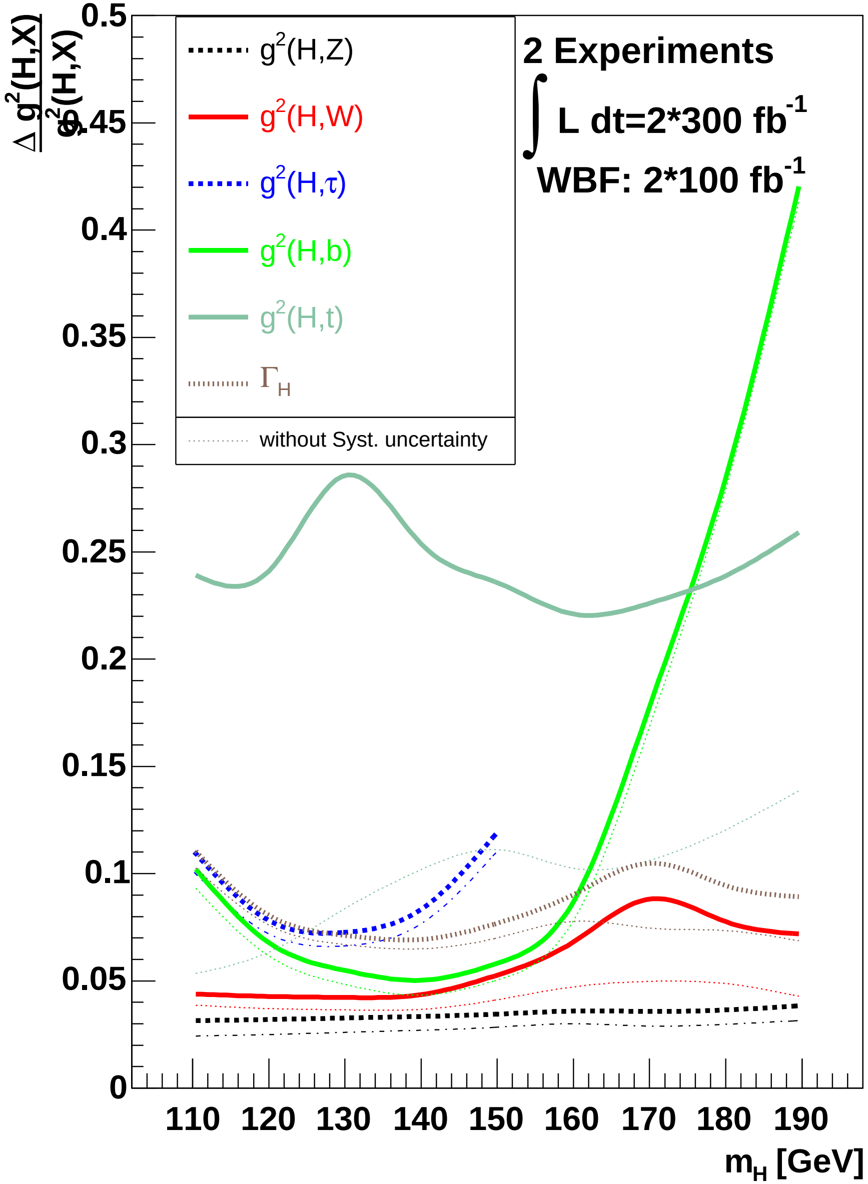
⇒ (hopefully) better determination of $g_{Ht\bar{t}}$, $g_{H\gamma\gamma}$
(in a model independent way!)

WARNING: results still preliminary

Compare old and new results for $g_{Ht\bar{t}}$:



New results for $g_{Ht\bar{t}}$:



Note: we show Δg^2

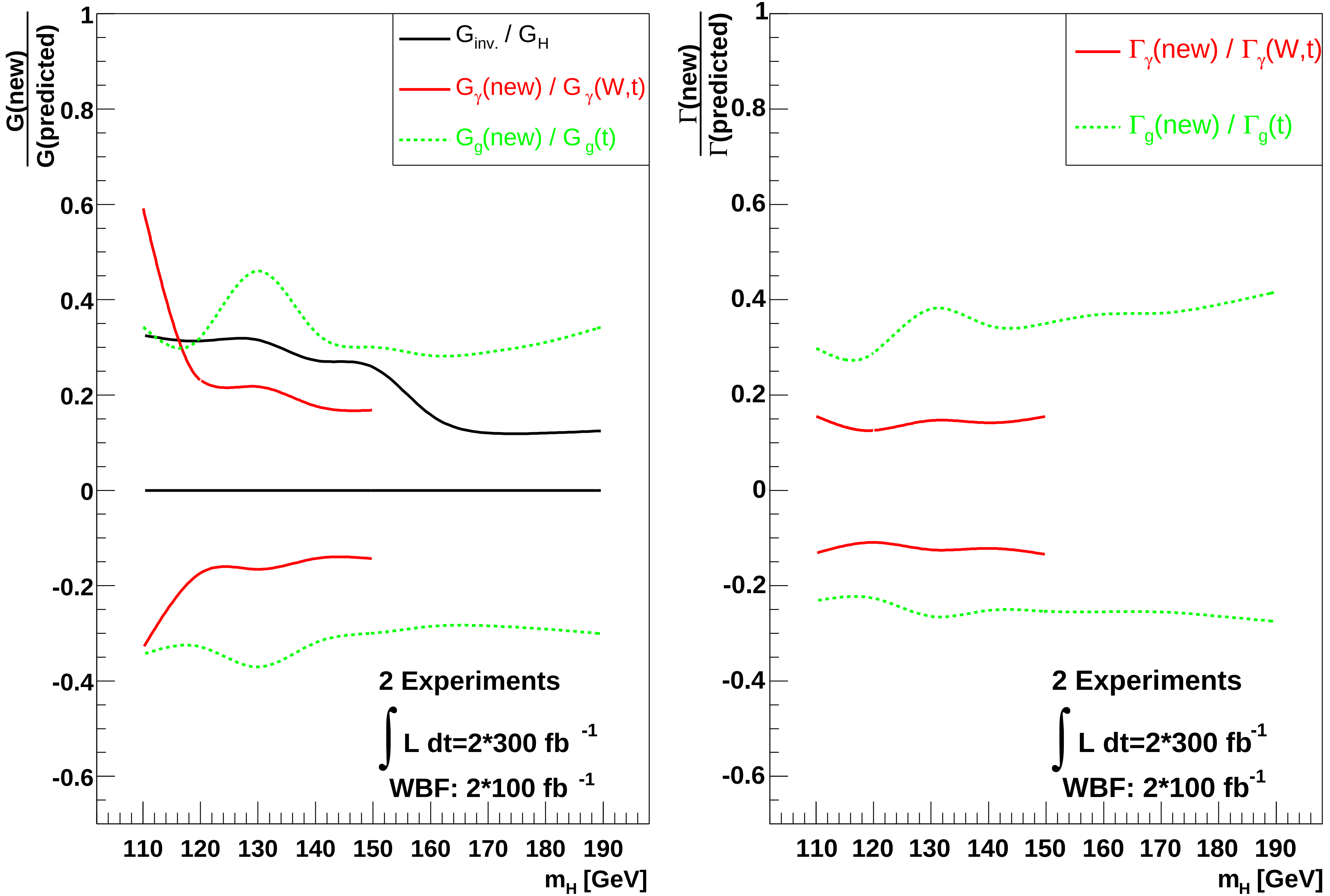
[K. Desch, M. Schumacher '04] show Δg

drastic improvement in all channels
due to ILC input
(often ILC precision)

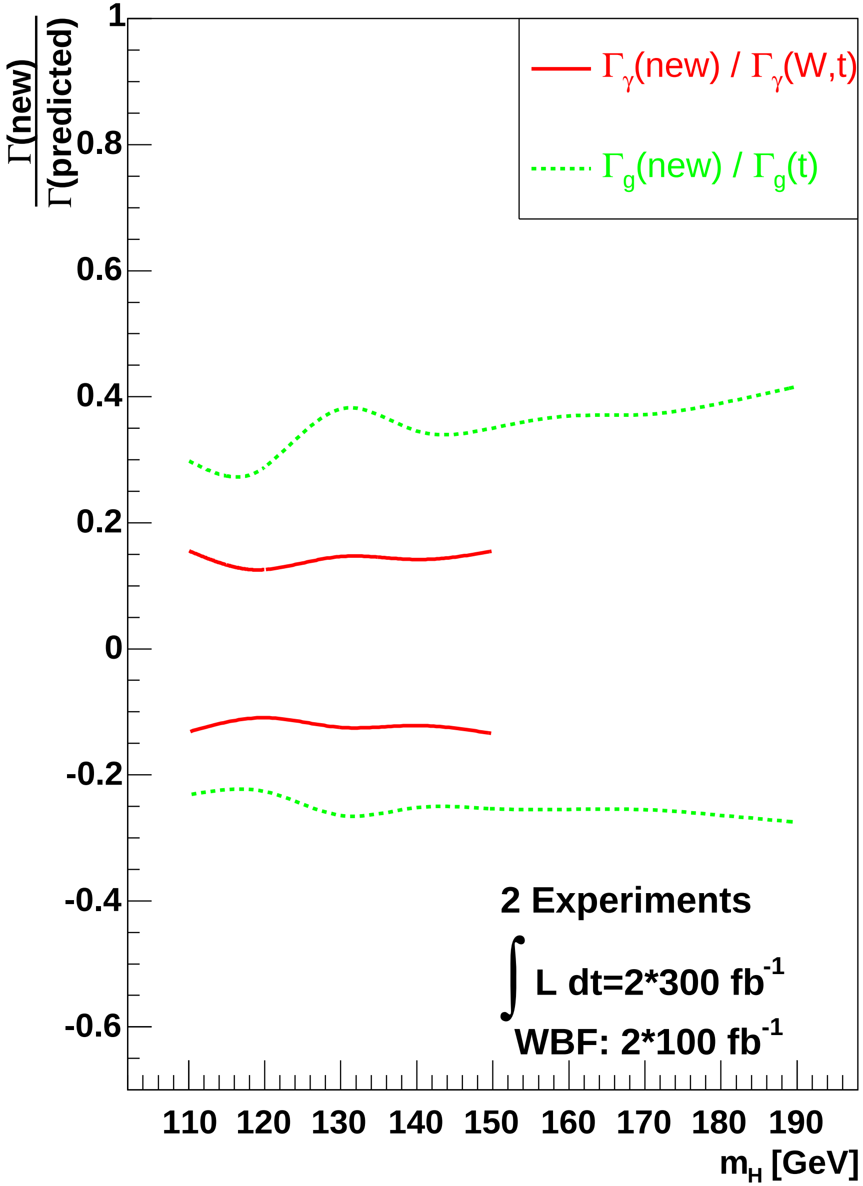
$\Rightarrow$ determination of $g_{Ht\bar{t}}$ to 11-14%

$\Rightarrow$ somewhat better than other analysis

Compare old and new results for $g_{H\gamma\gamma}$:



New results for $g_{H\gamma\gamma}$:



$\Rightarrow$ determination of $g_{H\gamma\gamma}$ to $\sim 7-8\%$

$\Rightarrow$ ILC input helps at lower M_H values

5. Conclusions

- Higgs coupling determination at the LHC:

  coupling determination necessary to establish the Higgs mechanism

  $\rightarrow$ nearly model independent analysis

  $\Rightarrow$ coupling determination down to 20-40%

- Idea: use ILC input to overcome theory assumptions

- ILC input from 500 fb^{-1} @ $\sqrt{s} = 350$ GeV

  ($\rightarrow$ ILC will determine nearly all couplings model independent
  with a high accuracy)

- However: no good ILC ($\sqrt{s} \lesssim 500$ GeV) precision for $g_{Ht\bar{t}}$ and $g_{H\gamma\gamma}$

- New (preliminary) result:

  $\Delta g_{Ht\bar{t}} = 11 - 14\%$ (old LHC/ILC analysis: 13-19%)

  $\Delta g_{H\gamma\gamma} = 7 - 8\%$ (old LHC analysis: 8-30%)