Combined Fits of Higgs Couplings at CLIC

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on behalf of the
CLIC Detector and Physics Study

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

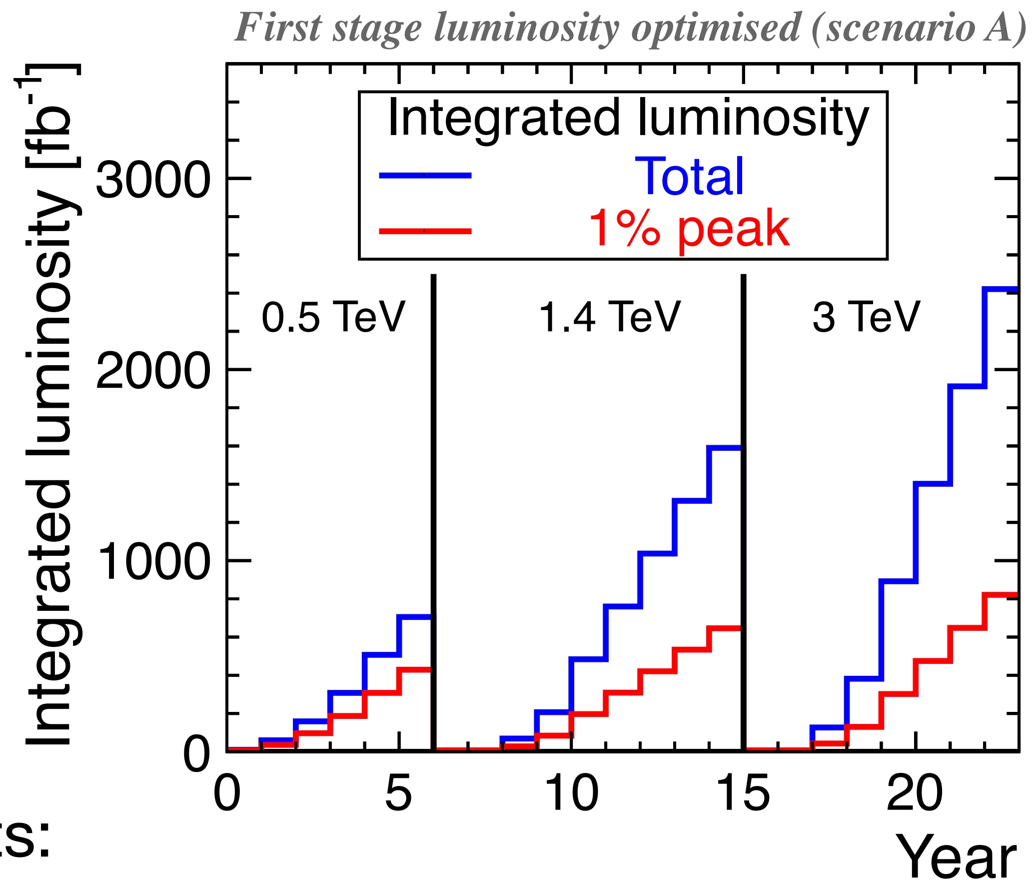
- Introduction: A staged Higgs physics program at CLIC
- Global fits of couplings
  - Model-independent and model-dependent fits
  - Handling correlations
  - Fit results
- Summary

A Staged Program to maximize Physics Potential

- For optimal luminosity, the energy of a collider based on CLIC technology can only be varied within a factor of ~ 3: Staged construction of the machine

Provides:

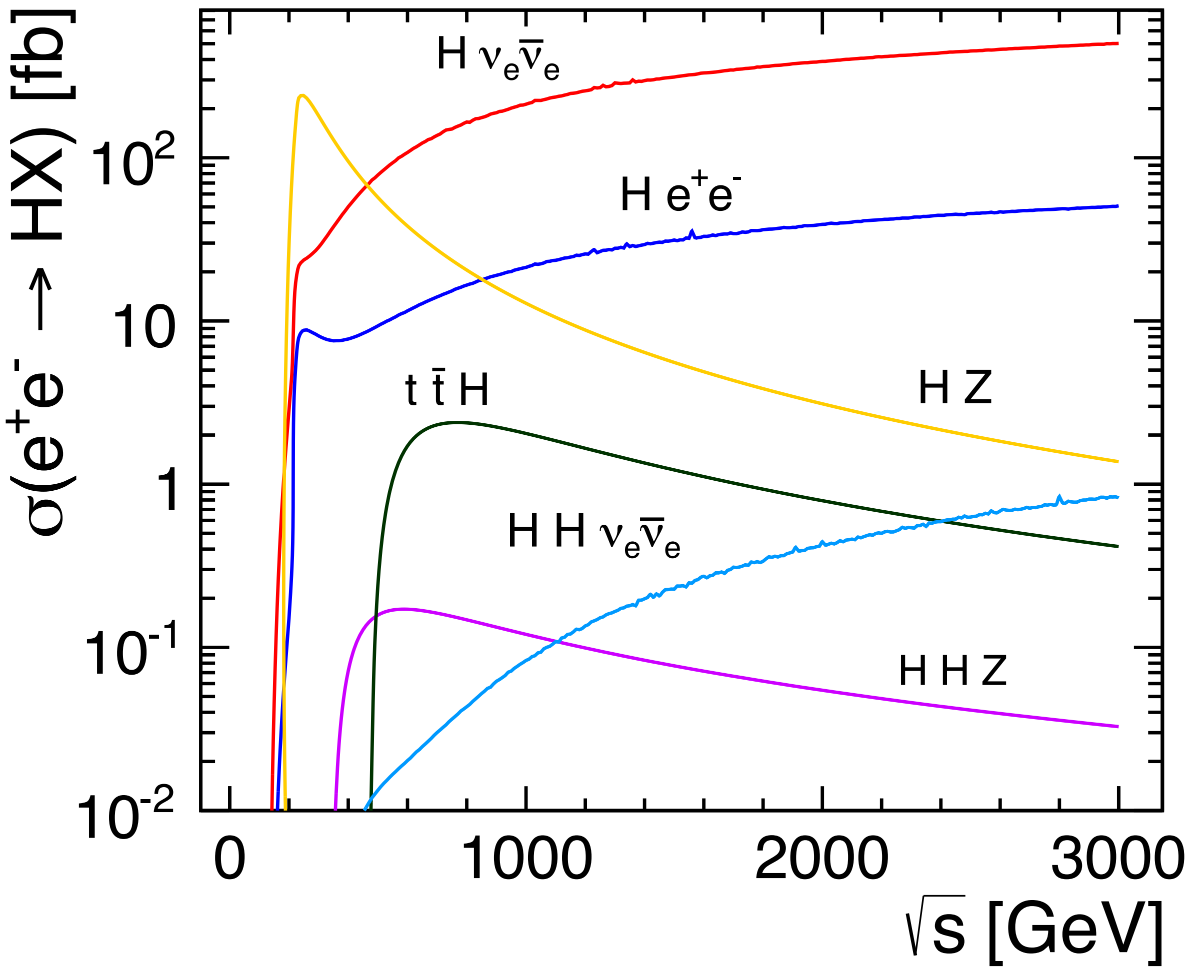
- earlier start of physics
- optimal use of physics potential

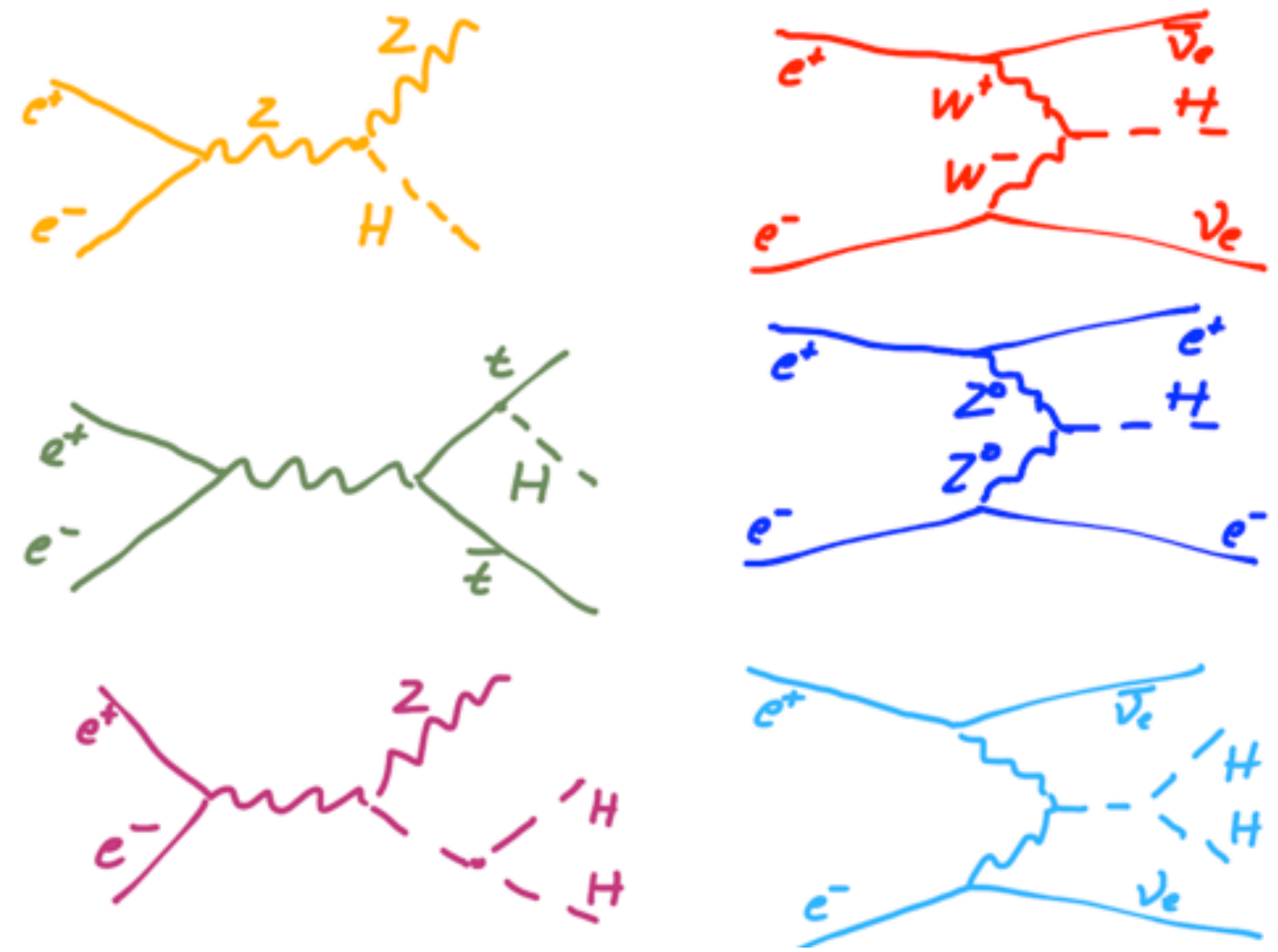


- Precise energy of the stages depends on physics - with considerations for technical constraints:
  - Studied scenario:
    - **350 / 375 GeV (500 fb^{-1})**
      - Higgs (including total width), Top threshold scan
    - **1.4 TeV (1.5 ab^{-1})**
      - BSM physics, ttH, Higgs self-coupling, rare Higgs decays
    - **3 TeV (2 ab^{-1})**
      - BSM physics, Higgs self-coupling, rare Higgs decays

Higgs Physics at CLIC

- Measurement of different processes at different energies





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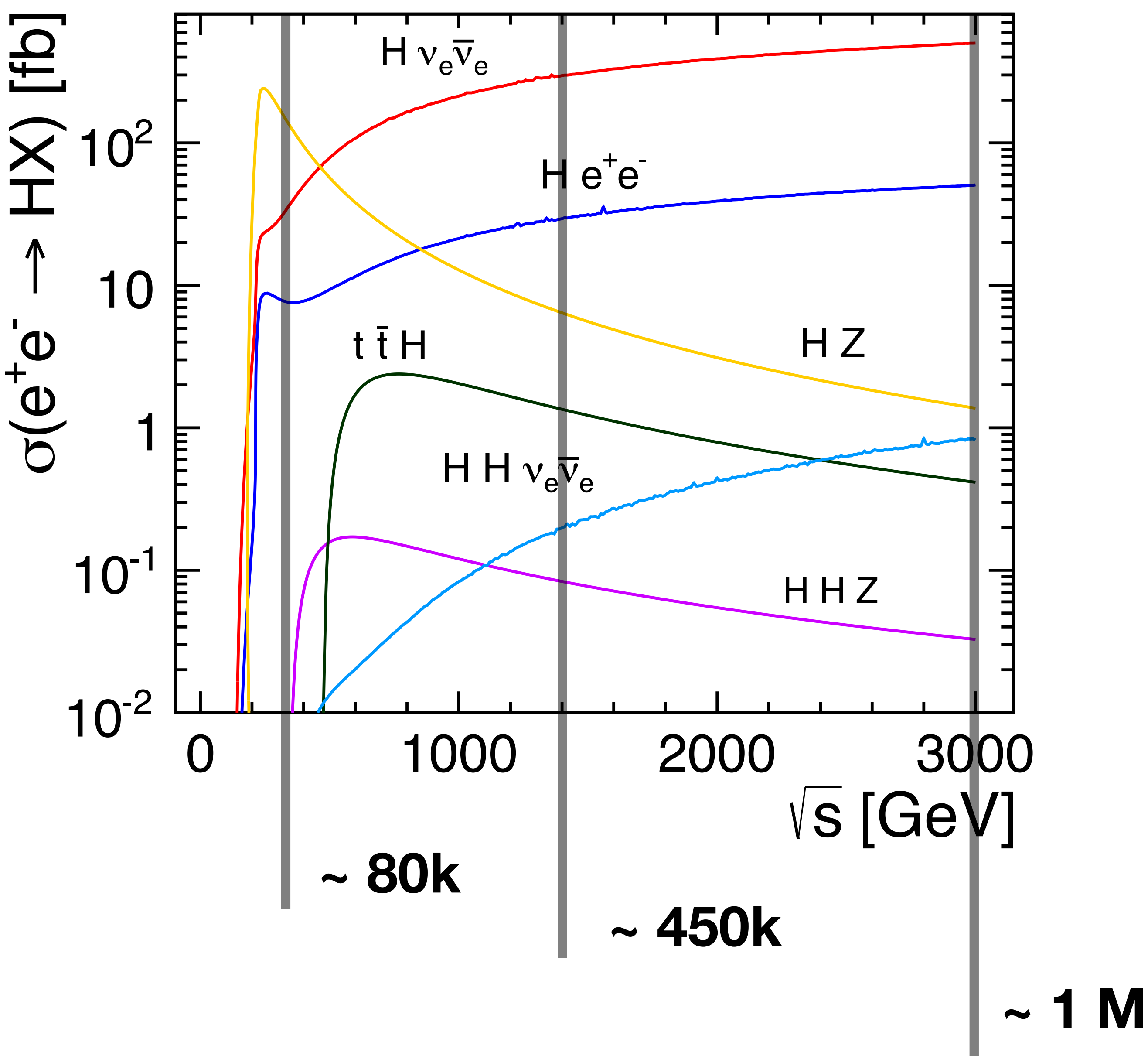

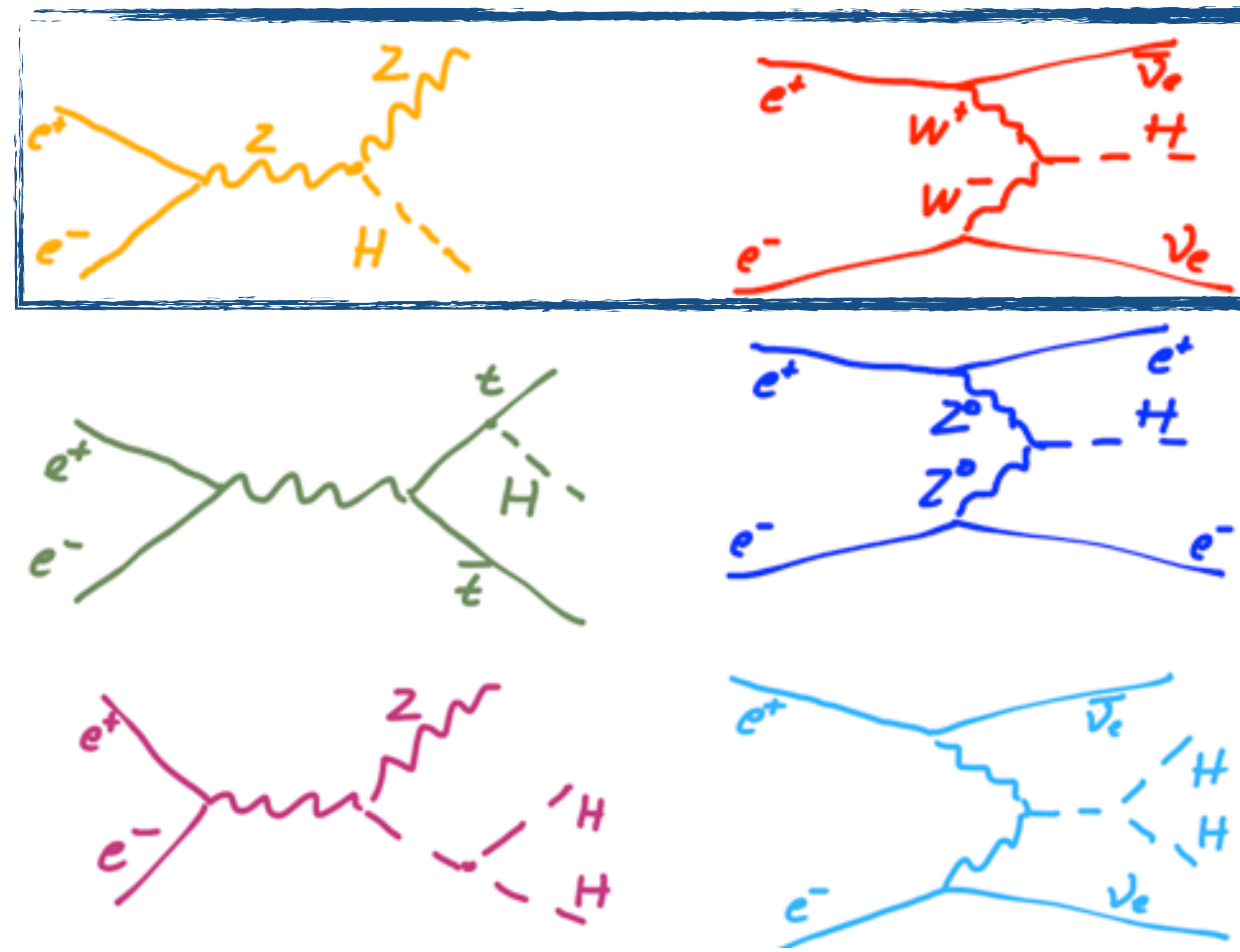

Higgs bosons per stage (w/o polarization)

(Polarization (80%, 0%) provides a boost of 1.8 for WW fusion)

Main production modes - give access to couplings and total width

Higgs Physics at CLIC

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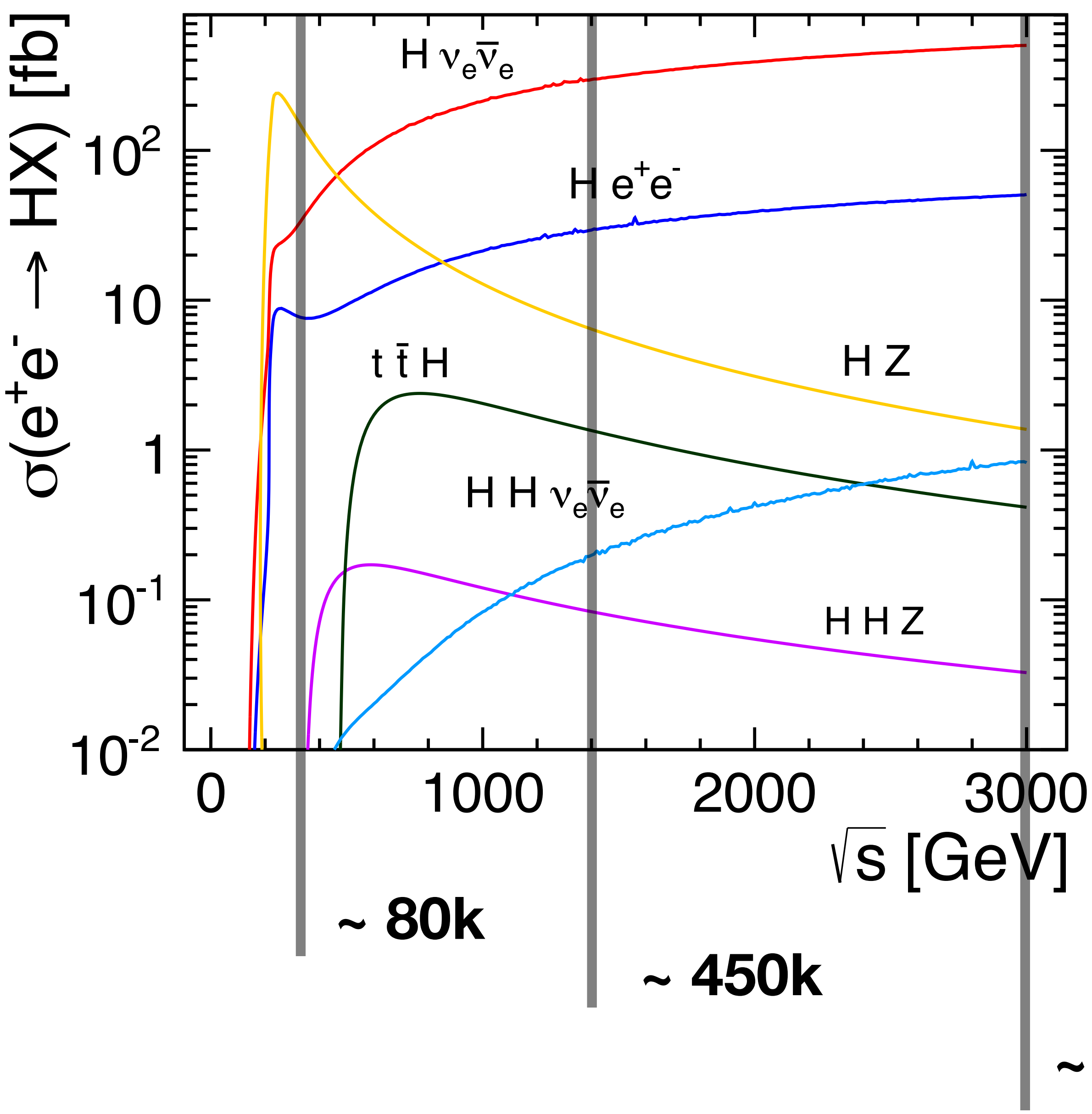
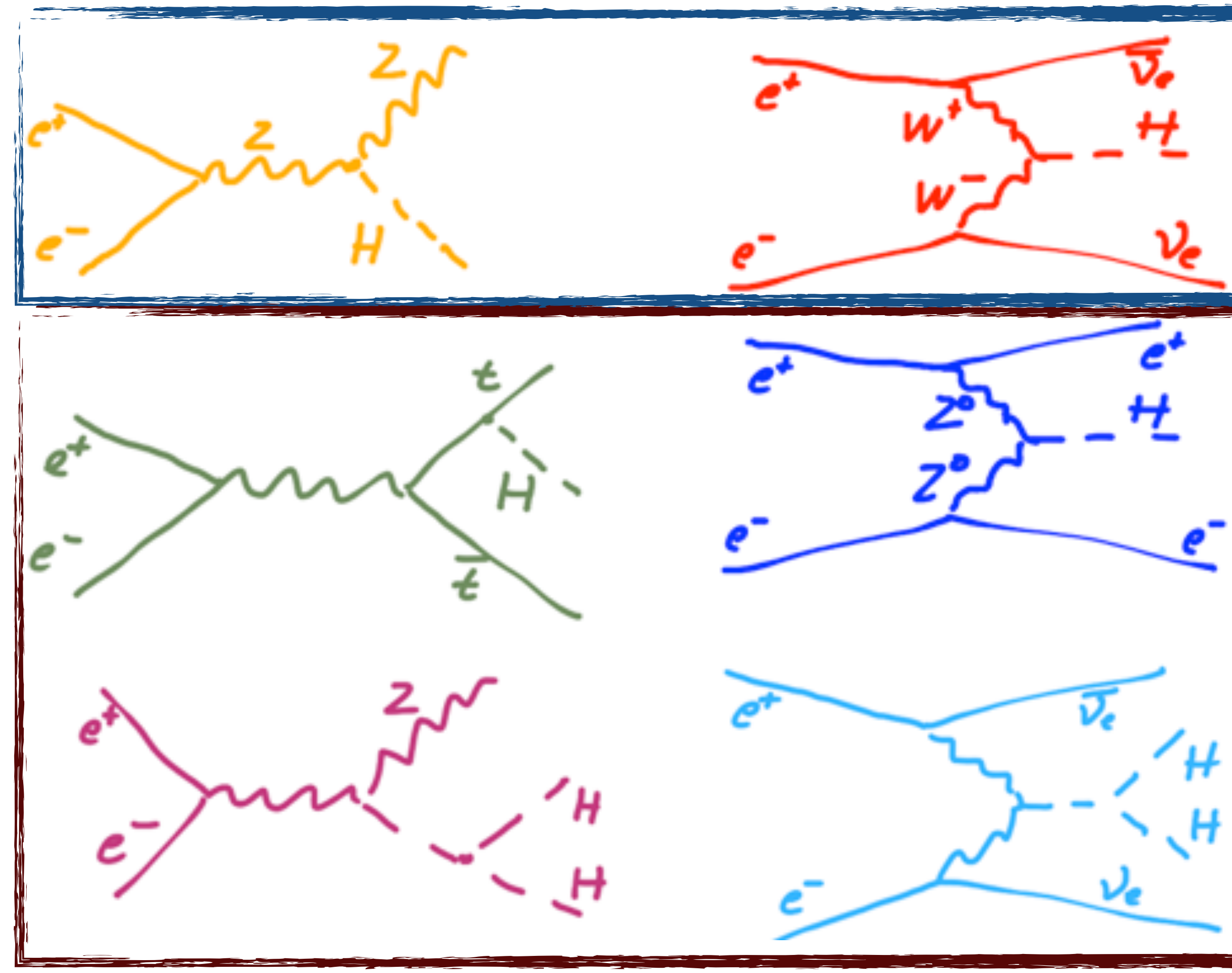




~ 1 M Higgs bosons per stage (w/o polarization)

(Polarization (80%, 0%) provides a boost of 1.8 for WW fusion)

Main production modes - give access to couplings and total width

Rarer Processes - ZZ fusion, direct access to top Yukawa, self-coupling

Exploring the Higgs Sector: Couplings

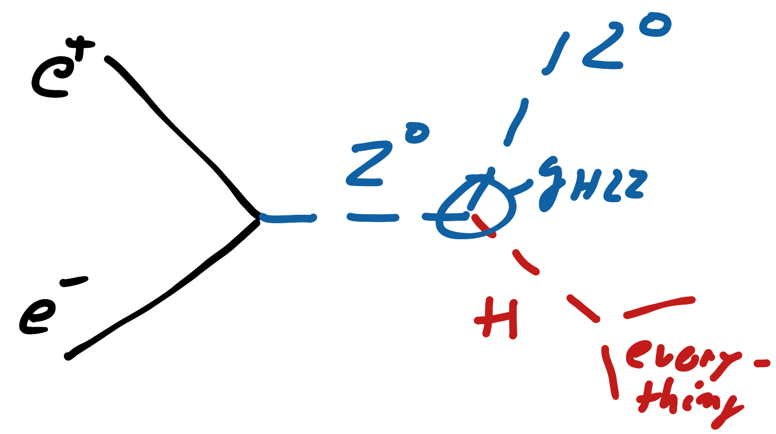
- The measurements at CLIC (and other lepton colliders) are:

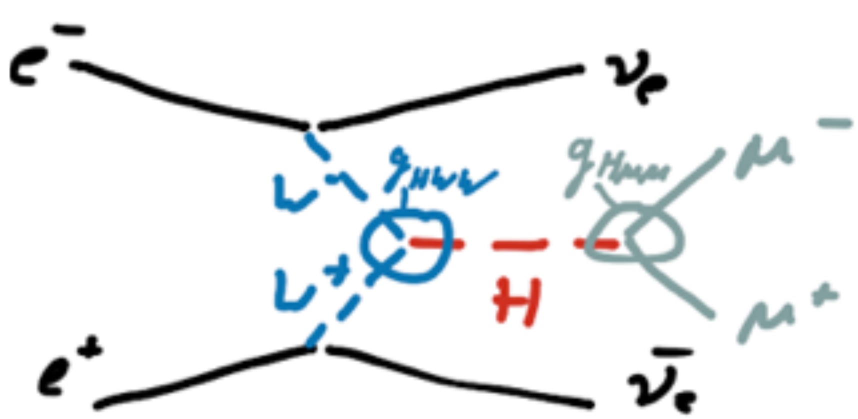
σ x BR (for specific Higgs decays)
σ (for model-independent recoil mass analysis)

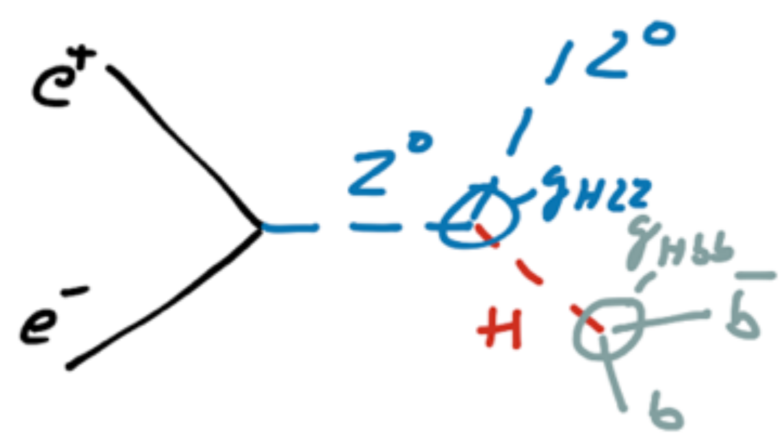
Both are sensitive to couplings:

$$\sigma_{\mathrm{recoil}} \propto g^2_{\mathrm{HZZ}}$$

$$\sigma \times \mathrm{BR}(\mathrm{H} \rightarrow \mathrm{ff}) \propto \frac{g^2_{\mathrm{Hii}} g^2_{\mathrm{Hff}}}{\Gamma_{\mathrm{tot}}}$$







The total width: A Case for 350 GeV

- A crucial ingredient to obtain the couplings: The total width
  - best results when combining ZH and VBF - 350 GeV ideal

$$\sigma(\mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to \mathrm{WW}^*) \propto \frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{tot}}}$$

$$\frac{\sigma(e^+e^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})}{\sigma(e^+e^- \to \mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

At 350 GeV w/o polarisation
134 fb for ZH
52 fb for Hvv

model-independent determination of g_{HWW} :
connection to model-independent g_{HZZ} from recoil via
high-BR H->bb decays in both production modes

The Full Picture: Global Fits

- From the measurements of σ and σ x BR the couplings and the total width are determined by a global fit:

$$\chi^2 = \sum_i \frac{(C_i - 1)^2}{\Delta F_i^2}$$

ΔF_i: uncertainty of measurement (σ or σxBR)

$$C_{\mathrm{ZH}} = g^2_{\mathrm{HZZ}}$$

$$C_{\mathrm{ZH,H}\to b\bar{b}} = \frac{g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

$$C_{\mathrm{H}\nu_e\bar{\nu}_e,\mathrm{H}\to b\bar{b}} = \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

...

Two fits:

Model-independent fit - total width as a free parameter

Model-dependent fit - LHC-like constraints

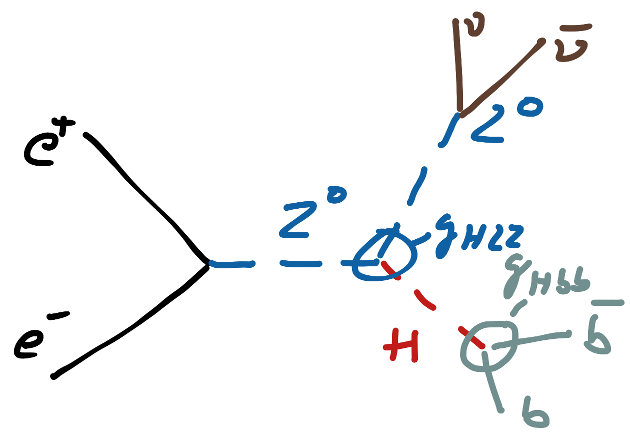
Assumptions: No BSM decays, the total width can be described by a few parameters which parametrize deviations of partial widths from the SM expectation

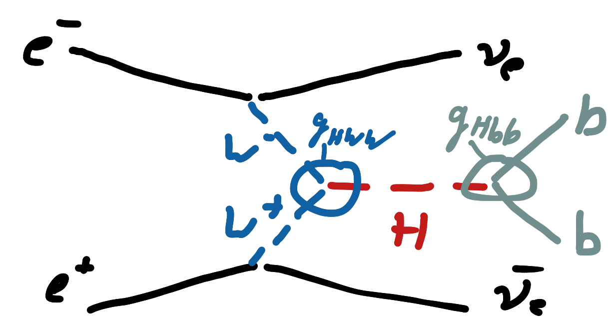
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{\mathrm{SM}}} \qquad \Gamma_{\mathrm{H,md}} = \sum_i \kappa_i^2 \, BR_i$$

In the fit: replace g_{Hii} with κ_{Hii}, Γ_{H} with $\Gamma_{\mathrm{H,md}}$

A Special Case: H->Jets at 350 GeV

- The 350 GeV analysis of H->Jets (bb, cc, gg) uses all production modes
  - Hνν final states receive a ~ 1:1 contribution of ZH and VBF, which are indistinguishable on an event-by-event basis





- Combined extraction of ZH and VBF contributions (for high-statistics bb final state only)
- Common event selection for bb, cc, gg final states, separation primarily based on flavor tagging

➩ Correlations between measurements

➩ see talk by Marco Szalay this afternoon

Handling Correlations / Combinations at 350 GeV

- Six correlation terms (since the cc and gg final states are treated inclusively in the analysis)
  - bb(ZH)/bb(VBF), bb(ZH)/cc(inclusive), bb(ZH)/gg(inclusive), bb(VBF)/cc(inclusive), bb(VBF)/gg(inclusive), cc(inclusive)/gg(inclusive)
    (correlation terms vary between a few % and -45% (H->bb in ZH and VBF))

one example:

$$\Delta\chi^2 = 2 \times corr(ZH, H \to bb; VBF, H \to bb) \times (\frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H} - 1) \times (\frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H} - 1)$$

$$/((\sigma \times BR(ZH, H \to bb)) \times (\sigma \times BR(VBF, H \to bb))$$

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$$/((\sigma \times BR(ZH, H \to bb)) \times (\sigma \times BR(VBF, H \to bb))$$

- Combined measurements of ZH and VBF in H->cc, gg:
  - Use ratio of VBF to ZH determined for H->bb final states
  - In the fit, the σ x BR of those two channels is expressed as a ZH / VBF combination:

$$\sigma \times \mathrm{BR(H \to cc)} \propto (1 - \mathrm{VBF}) \frac{g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hcc}}}{\Gamma_{\mathrm{tot}}} + \mathrm{VBF} \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hcc}}}{\Gamma_{\mathrm{tot}}}$$

The Impact of Correlations on the Fit

- Model-independent fit:
  - Including the ZH / VBF combination improves g_{Hcc} and g_{Hgg} by about 3%
  - Including correlations in addition:
    - g_{Hcc} and g_{Hgg} are slightly deteriorated again, coming out close to the values w/o correlations (within ~ 1%)
    - g_{Hbb} is deteriorated by ~ 5%
    - g_{HWW} is improved by ~3%
    - total width is improved by ~1.5%

- Model-dependent fit:
  - in general no improvement with inclusion of correlations - ~8% penalty on κ_{HZZ}, 3% on κ_{HWW}, ~2% on κ_{Hcc}, κ_{Hgg}

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➾ in general the effects of correlations are small - “nice to have”, but not absolutely necessary for the analysis.

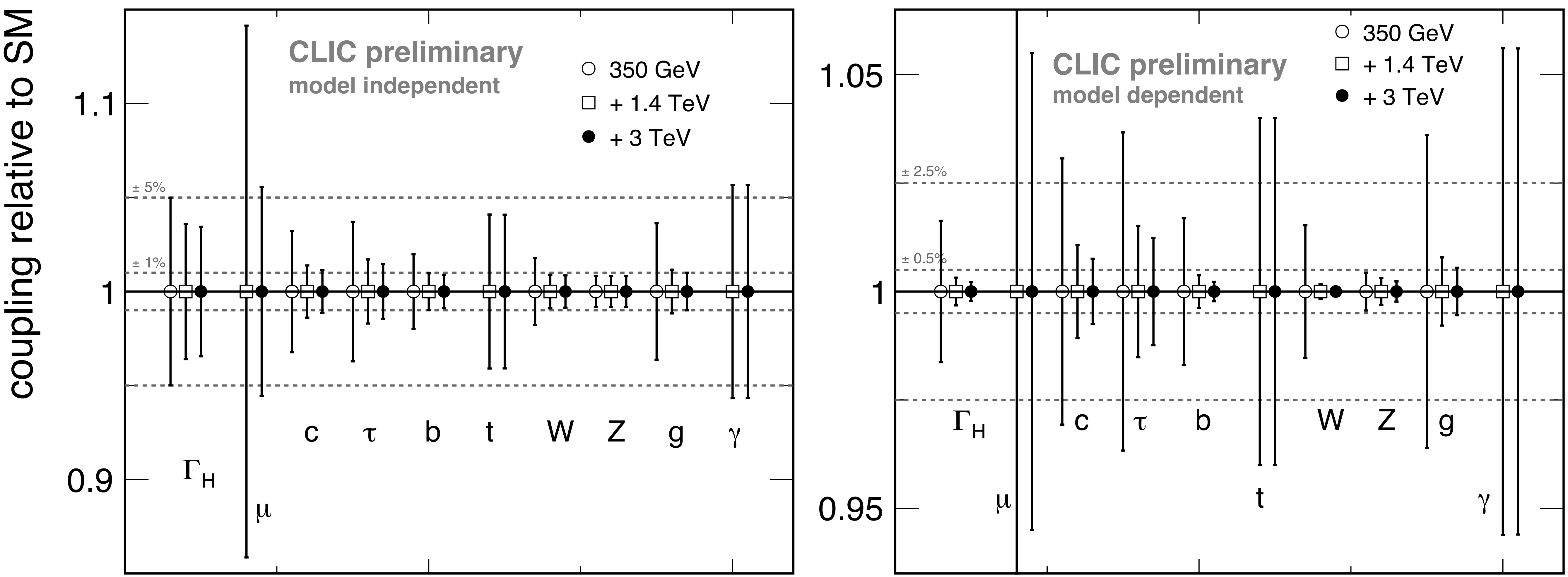
Measurement Summary

work in progress - current status

Channel	Measurement	Observable	Statistical precision		
			350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	4.2%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	42%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.4%	0.9%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarization	λ	–	24%	12%

Fit Results - Current Status

work in progress - current status



correlations for 350 GeV H->bb, cc, gg not included, input measurements include preliminary estimates

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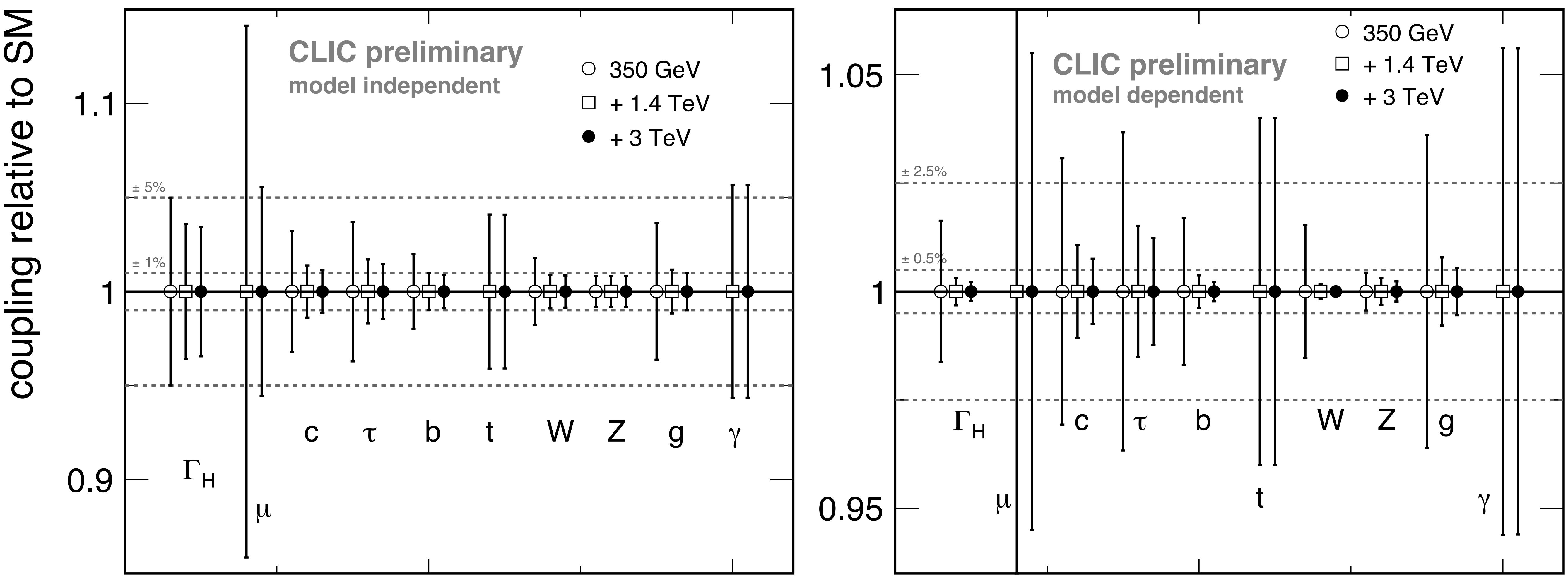


correlations for 350 GeV H->bb, cc, gg not included, input measurements include preliminary estimates

- ➩ model-independent 1% - level determination of most couplings in full program
- ➩ 1% to few ‰ with LHC-like model-dependence

Fit Results

- Model-independent:

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.8 %	0.9 %	0.9 %
g_{Hbb}	2.0 %	1.0 %	0.9 %
g_{Hcc}	3.2 %	1.4 %	1.1 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	–	14.1 %	5.6 %
g_{Htt}	–	4.1 %	$\leq$ 4.1 %
$g^{\dagger}_{Hgg}$	3.6 %	1.2 %	1.0 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	< 5.7 %
Γ_H	5.0 %	3.6 %	3.4 %

- Model-dependent:

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.44 %	0.31 %	0.23 %
κ_{HWW}	1.5 %	0.17 %	0.11 %
κ_{Hbb}	1.7 %	0.37 %	0.22 %
κ_{Hcc}	3.1 %	1.1 %	0.75 %
$\kappa_{H\tau\tau}$	3.7 %	1.5 %	1.2 %
$\kappa_{H\mu\mu}$	–	14.1 %	5.5 %
κ_{Htt}	–	4.0 %	$\leq$ 4.0 %
κ_{Hgg}	3.6 %	0.79 %	0.55 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	< 5.6 %
$\Gamma_{H,md,derived}$	1.6 %	0.32 %	0.22 %

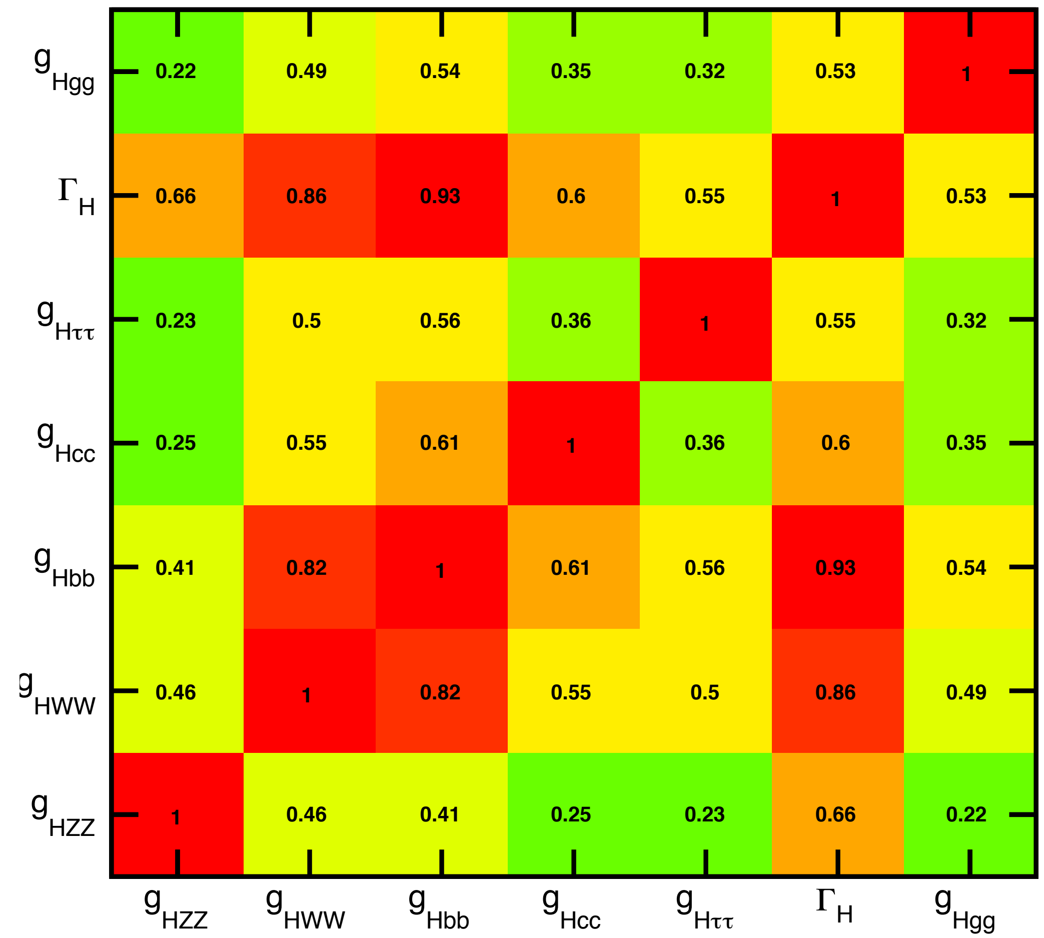
Fit Results - Fit Drivers

- Understanding the fit drivers: Parameter correlations

very strong correlation between Γ_H, g_{HWW}, g_{Hbb}, g_{HZZ} :
Width determination relies on H->bb in ZH and WBF

- Picture remains essentially unchanged for higher energies
- For model-dependent fit the correlations are substantially reduced - significant between g_{HWW} and g_{Hbb} at 350 GeV, moderate at higher energies

Model-independent fit, 350 GeV only



very strong correlation between g_{HWW} and g_{Hbb} : model-independent W coupling determined through H->bb final states

Summary

- CLIC offers the opportunity of a comprehensive Higgs program - three stages at 350 GeV, 1.4 TeV and 3 TeV provide precise measurements of all relevant processes

- The impact of the program is assessed by global fits to all measurements
  Two fit scenarios are studied
  - A model-independent fit with minimal assumptions
  - A model-dependent fit with “LHC-like” assumptions
- Correlations between measurements are implemented for the 350 GeV H->jets measurements - effects are on the few % level

- With the full program, most couplings can be determined
  - on the 1% level in a model-independent way
  - on the 1% to few ‰ level with “LHC-like” assumptions