Higgs Physics at CLIC

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on behalf of the CLICdp collaboration

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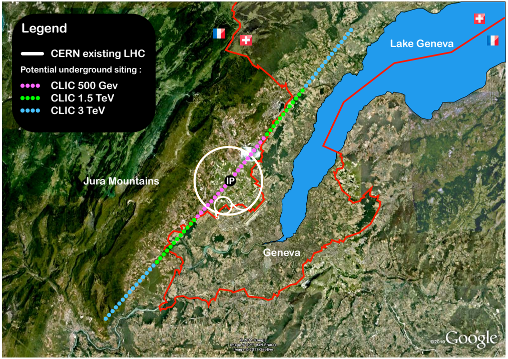
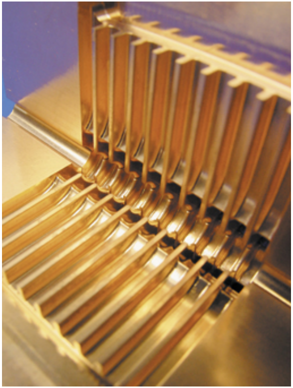
Compact Linear Collider

CLIC is the only mature option for a future multi-TeV e^+e^--collider

- Gradient of 100 MV/m
- Staged $\sqrt{s}$ from 350 GeV to 3 TeV
- High luminosity ($\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)



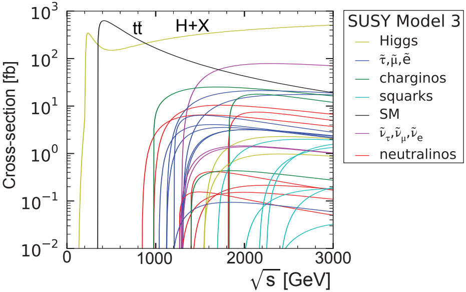


- Prototype of copper accelerating structures for CLIC

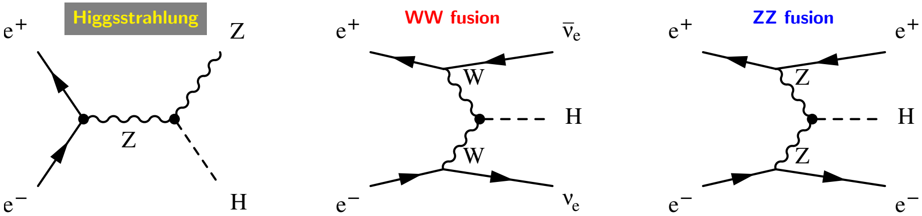
CLIC energy stages for maximal physics potential

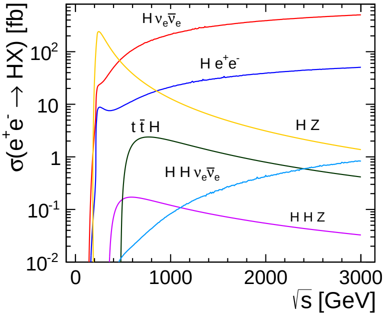
- High luminosity over wide range of $\sqrt{s}$ → staged construction
- CLIC energy stages defined by physics → adapt to discoveries at LHC

- Currently studied scenario
  - $\sqrt{s}$=350 GeV/375 GeV, 500 fb^{-1}
    - SM Higgs physics including total width measurement
    - Top threshold scan
  - $\sqrt{s}$=1.4 TeV, 1.5 ab^{-1}
    - BSM physics
    - $t\bar{t}H$, Higgs self coupling
    - Rare Higgs decays
  - $\sqrt{s}$=3 TeV, 2 ab^{-1}
    - BSM physics
    - Higgs self coupling
    - Rare Higgs decays



Higgs physics at CLIC (1)



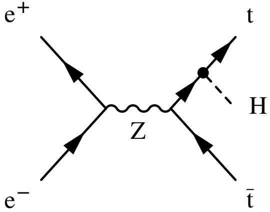


	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

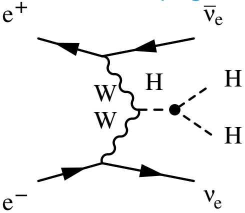
- Large samples of Higgs bosons achievable at CLIC without beam polarisation
- 80 % e^- polarisation foreseen at CLIC
  $\rightarrow$ 12 % more HZ and He^+e^- events
  $\rightarrow$ 80 % more $H\nu_e\bar{\nu}_e$ events

Higgs physics at CLIC (2)

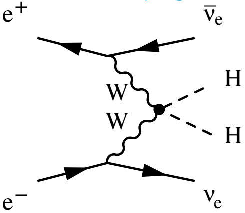
Top Yukawa coupling

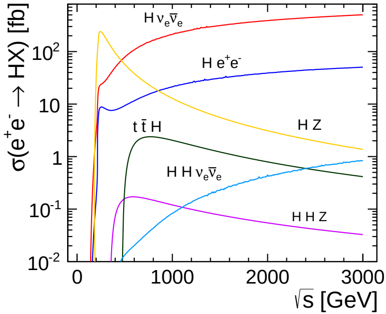


Trilinear self coupling



Quartic coupling





	1.4 TeV	3 TeV
L_{int}	1.5 ab^{-1}	2 ab^{-1}
# $t\bar{t}H$ events	2400	-
# $HH\nu_e\bar{\nu}_e$ events	225	1 000

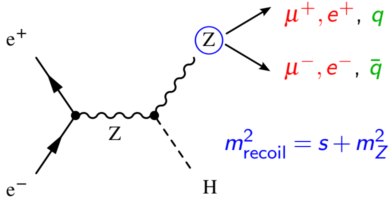
- High energies and luminosities needed to access rare Higgs production processes

Results from full Geant4 detector simulations

Including pileup from beam induced backgrounds;

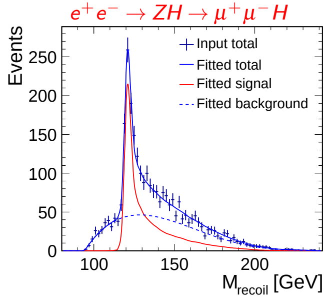
assuming unpolarised beams

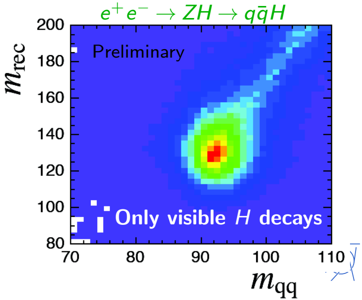
Higgsstrahlung at $\sqrt{s} = 350\,\mathrm{GeV}$



$$m^2_{\mathrm{recoil}} = s + m^2_Z - 2E_z\sqrt{s}$$

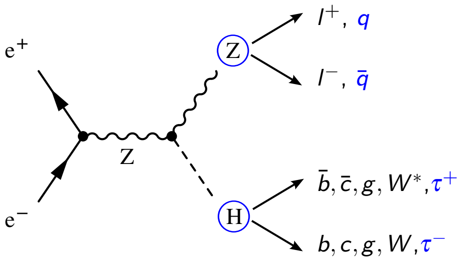
- Measure HZ events from Z recoil mass
- Includes invisible Higgs decays
- Measurement of g_{HZZ} coupling
- $Z \to e^+e^- / \mu^+\mu^-$ decay
  - $\mathrm{BR}(Z \to \mu^+\mu^- / e^+e^-) \approx 7\,\%$
  - Fully model independent
  - $\Delta\sigma_{HZ}/\sigma_{HZ} \approx 4.2\,\% \to \Delta(g_{HZZ})/g_{HZZ} \approx 2.1\,\%$
- $Z \to q\bar{q}$ decay
  - $\mathrm{BR}(Z \to q\bar{q}) \approx 70\,\%$
  - Challenge: $Z \to q\bar{q}$ reconstruction may depend on H decay mode
  - $\Delta\sigma_{HZ}/\sigma_{HZ} \approx 1.8\,\% \to \Delta(g_{HZZ})/g_{HZZ} \approx 0.9\,\%$



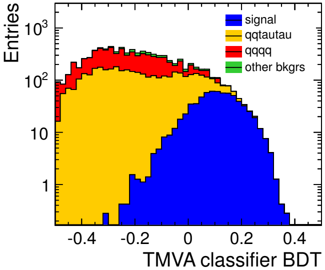


Higgsstrahlung at $\sqrt{s} = 350$ GeV

- Measurement of HZ cross section times Higgs branching ratio
- Example: $H \to \tau^+\tau^-$



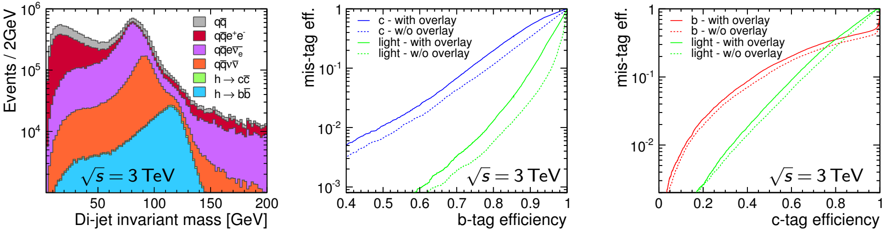
$e^+e^- \to ZH \to q\bar{q}\tau^+\tau^- @\sqrt{s} = 350$ GeV



Measurement	Observable	Statistical precision
$\sigma(HZ) \times \mathrm{BR}(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau}/\Gamma_H$	5.7%
$\sigma(HZ) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	1% (estimated)
$\sigma(HZ) \times \mathrm{BR}(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc}/\Gamma_H$	5% (estimated)
$\sigma(HZ) \times \mathrm{BR}(H \to gg)$		6% (estimated)
$\sigma(HZ) \times \mathrm{BR}(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW}/\Gamma_H$	2% (estimated)

Higgs production in *WW* fusion

- Large Higgs samples from *WW* fusion at high energies
  - Precision measurement of $\sigma \times$ BR for frequent Higgs decays
  - Access to rare Higgs decay modes

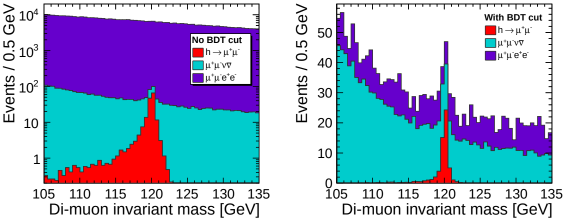


- Example: Precision measurement at $\sqrt{s} = 3$ TeV: 830 000 $H\nu_e\bar{\nu}_e$ events
  - $H \to \bar{b}b$ (BR $\approx 58\,\%$), $H \to gg$ (BR $\approx 8\,\%$) and $H \to \bar{c}c$ (BR $\approx 3\,\%$)
  - $H \to \bar{c}c$ and $H \to gg$ are impossible at hadron colliders
  - Separation of different hadronic final states using flavour tagging
  - $\Delta(\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to b\bar{b})) = 0.2\,\%$
  - $\Delta(\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to gg)) = 1.8\,\%$
  - $\Delta(\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to c\bar{c})) = 2.7\,\%$

Higgs production in WW fusion: Rare decays

- $\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \mu^+\mu^-)$
  - $\mathrm{BR}(H \to \mu^+\mu^-) = 0.022\,\%$
  - Requires precision tracking
  - $\Rightarrow$ 38 % at $\sqrt{s} = 1.4$ TeV
  - $\Rightarrow$ 16 % at $\sqrt{s} = 3$ TeV
- $\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \gamma\gamma)$
  - $\mathrm{BR}(H \to \gamma\gamma) = 0.23\,\%$
  - $\Rightarrow$ 15 % at $\sqrt{s} = 1.4$ TeV
- $\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to Z\gamma)$
  - $\mathrm{BR}(H \to Z\gamma) = 0.16\,\%$
  - Study Z decays to e^+e^-, $\mu^+\mu^-$, $q\bar{q}$
  - $\Rightarrow$ 42 % at $\sqrt{s} = 1.4$ TeV

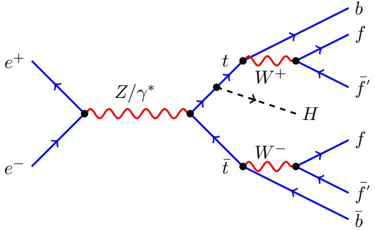
$H \to \mu^+\mu^-$ @ $\sqrt{s} = 3$ TeV

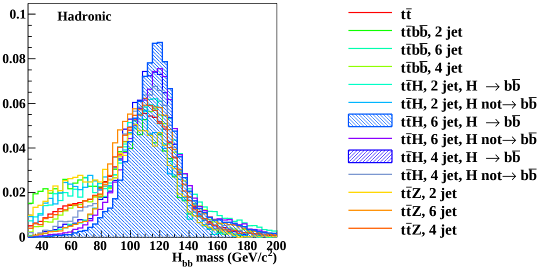


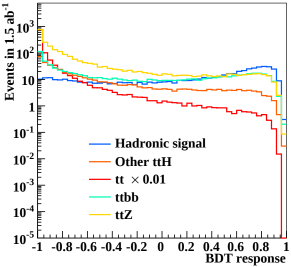
Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	0.3%	0.2%
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	2.9%	2.7%
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to gg)$		1.8%	1.8%
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau}/\Gamma_H$	3.7%(prel.)	tbd
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu}/\Gamma_H$	38%	16%
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \gamma\gamma)$		15%	tbd
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to Z\gamma)$		42%	tbd
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to WW^*)$	g^4_{HWW}/Γ_H	1.1%(prel.)	0.8%(prel.)
$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ}/\Gamma_H$	3%(est.)	2%(est.)

$t\bar{t}H$ production at $\sqrt{s} = 1.4$ TeV

- Study of $H \to b\bar{b}$ decay and two t-decays
  Semi-leptonic: $t(\to q\bar{q}b)\bar{t}(\to l\nu\bar{b})\,H(\to b\bar{b})$
  Fully hadronic: $t(\to q\bar{q}b)\bar{t}(\to q\bar{q}b)H(\to b\bar{b})$
- Challenging for detector
  - Jet clustering in complex final state (8 jets)
  - Flavour tagging
  - Lepton identification
  - Reconstruction of missing energy

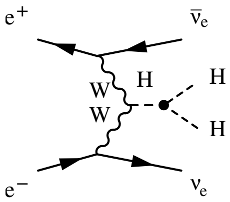


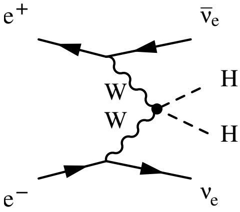


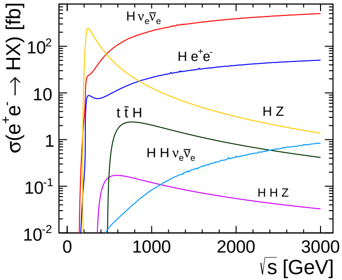


- $\Delta\sigma(t\bar{t}H)/\sigma(t\bar{t}H) = 8.1\,\%$, $\Delta g_{t\bar{t}H}/g_{t\bar{t}H} = 4.3\,\%$

Double Higgs production in WW fusion







- $HH\nu_e\bar{\nu}_e$ cross section is sensitive to Higgs self coupling λ and quartic coupling g_{HHWW}
- $HH \to b\bar{b}b\bar{b}$ events are selected in analysis
- Challenge: Forward jet reconstruction

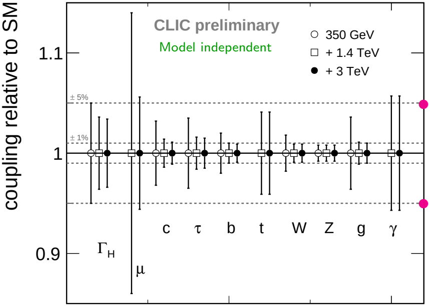
Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	7% (prel.)	3% (prel.)
$\sigma(HH\nu_e\bar{\nu}_e)$	λ	32%	16%
with 80 % e^- polarisation	λ	24%	12%

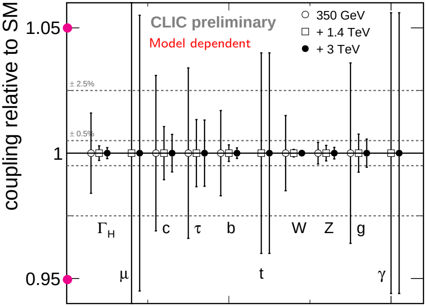
			Statistical precision		
Channel	Measurement	Observable	350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to l^+l^-)$	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	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
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%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%*	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	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	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%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Ht\bar{t}}g^2_{Hbb}/\Gamma_H$	–	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^- polarisation	λ	–	24%	12%

Results without beam polarisation †: estimated, *: prelimary

Global fits

- Fit of presented statistical precisions → extract couplings and Higgs width
- Fit results at higher energy include measurements from lower energies





- Fully model independent approach, unique for lepton colliders
- All results are limited by $\sigma(HZ)$ measurement
- Higgs width extraction with 5.0-3.4 % precision

- LHC-like constraints: no invisible decays, fixed total width
- Sub-percent precision, but strongly depend on fit assumptions
- Higgs width extraction with 1.6-0.22 % precision

Assuming 80 % electron beam polarisation at 1.4 TeV and 3 TeV

Global fits

- Fit of presented statistical precisions → extract couplings and Higgs width
- Fit results at higher energy include measurements from lower energies

Parameter	Measurement precision		
Model independent	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
m_H	120 MeV	30 MeV	20 MeV
λ	–	24%	11%
Γ_H [%]	5.0	3.6	3.4
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_{Htt} [%]	–	4.1	4.1
$g_{H\tau\tau}$ [%]	3.5	1.6	< 1.5
$g_{H\mu\mu}$ [%]	–	14	5.6
g_{Hgg} [%]	3.6	1.1	1.0
$g_{H\gamma\gamma}$ [%]	–	5.7	< 5.7

Parameter	Measurement precision		
Model dependent	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
$\Gamma_{H,model}$ [%]	1.6	0.29	0.22
κ_{HZZ} [%]	0.43	0.31	0.23
κ_{HWW} [%]	1.5	0.15	0.11
κ_{Hbb} [%]	1.7	0.33	0.21
κ_{Hcc} [%]	3.1	1.1	0.75
κ_{Htt} [%]	–	4.0	4.0
$\kappa_{H\tau\tau}$ [%]	3.4	1.3	< 1.3
$\kappa_{H\mu\mu}$ [%]	–	14	5.5
κ_{Hgg} [%]	3.6	0.76	0.54
$\kappa_{H\gamma\gamma}$ [%]	–	5.6	< 5.6

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- All results are limited by $\sigma(HZ)$ measurement
- Higgs width extraction with 5.0-3.4 % precision

- LHC-like constraints: no invisible decays, fixed total width
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- Higgs width extraction with 1.6-0.22 % precision

Assuming 80 % electron beam polarisation at 1.4 TeV and 3 TeV

Summary

- CLIC Higgs physics program at centre-of-mass energies from $\sqrt{s} = 350\,\text{GeV}$ to $\sqrt{s} = 3\,\text{TeV}$

- At $\sqrt{s} = 350\,\text{GeV}$
  - Precise determination of absolute values of many Higgs boson couplings
- At $\sqrt{s} = 1.4\,\text{TeV}$ and $\sqrt{s} = 3\,\text{TeV}$
  - Increases precision of observables
  - Gives access to rare Higgs processes and decay modes
  - Potential to measure Higgs self coupling

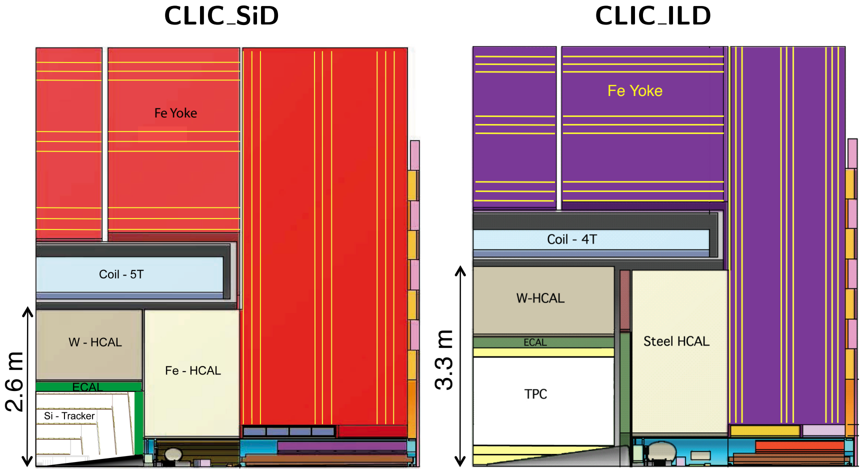
- Combined fits to all measurements
  - Extraction of couplings and Higgs width

- Comprehensive paper on Higgs physics at CLIC in preparation

Backup

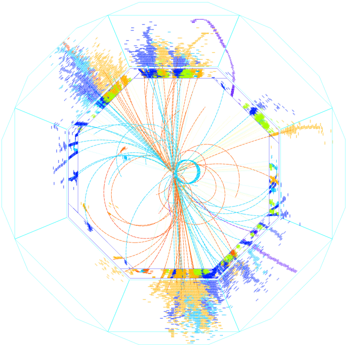
CLIC detector concepts

- Based on ILC detector concepts SiD and ILD, optimised for CLIC conditions



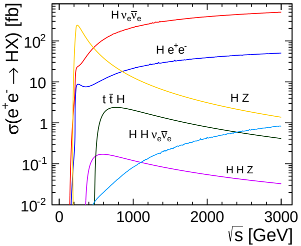
Detector simulation and reconstruction

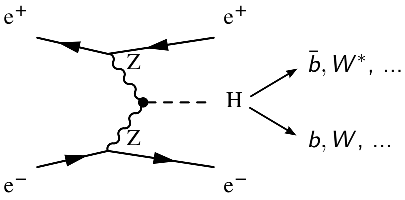
- Full detector simulation of signal and background events
  - Assuming $m_H = 126\,\text{GeV}$
  - Event generation with WHIZARD v.1.95, including initial state radiation and the CLIC beam spectrum
  - Fragmentation using Pythia
  - Full Geant4 detector simulation
  - Overlay of $\gamma\gamma \rightarrow$ hadrons background
  - Particle flow reconstruction and particle identification using PandoraPFA
  - Full event reconstruction



Higgs production in ZZ fusion

- *ZZ* fusion cross section ~ 10 times lower than for *WW* fusion
- Event identification including tagging of forward electrons





- $\Delta(\sigma(He^+e^-)) \approx 1\,\%$ (preliminary) including most frequent visible Higgs decays
- $\Delta(\sigma(He^+e^-) \times \mathrm{BR}(H \to b\bar{b})) \approx 1.5\,\%$ (preliminary)
- Comparison of one Higgs decay mode in WW fusion and ZZ fusion

$$\frac{\sigma(Hee) \times \mathrm{BR}(H \to b\bar{b})}{\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to b\bar{b})} = \frac{\sigma(Hee)}{\sigma(H\nu_e\bar{\nu}_e)} \quad \Rightarrow \quad g_{HZZ}/g_{HWW}$$

Global fits of combined analysis results

- Use statistical precision of all measurements to estimate couplings g and total width Γ_H in global fit
- Minimisation of

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

  using
  - $C_{ZH} = g^2_{HZZ}$,
    $C_{ZH,H\to b\bar{b}} = (g^2_{HZZ} \cdot g^2_{Hbb})/\Gamma_H$, ...
    (normalised to SM expectation)
  - $\Delta F_{ZH} = \delta(\sigma_{e^+e^-\to ZH})$,
    $\Delta F_{ZH,H\to b\bar{b}} = \delta(\sigma_{e^+e^-\to ZH} \times \mathrm{BR}_{H\to b\bar{b}})$, ...
- Two fit options
  - Model independent fit: total width as free parameter
  - Model dependent fit: LHC-like constraints
    - $\kappa_i = \Gamma_i/\Gamma_i^{\mathrm{SM}}$
    - No invisible Higgs decays: $\Gamma_{H,\mathrm{model}} = \sum_i \kappa_i^2 \cdot \mathrm{BR}_i^{\mathrm{SM}}$