Higgs Physics at CLIC

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On behalf of the CLICdp collaboration

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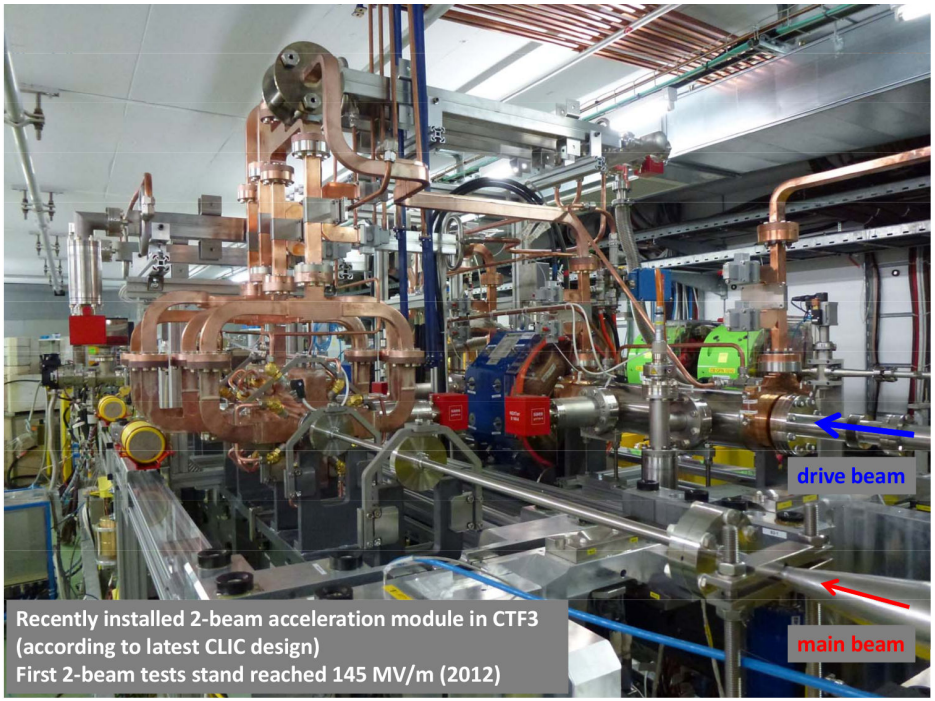
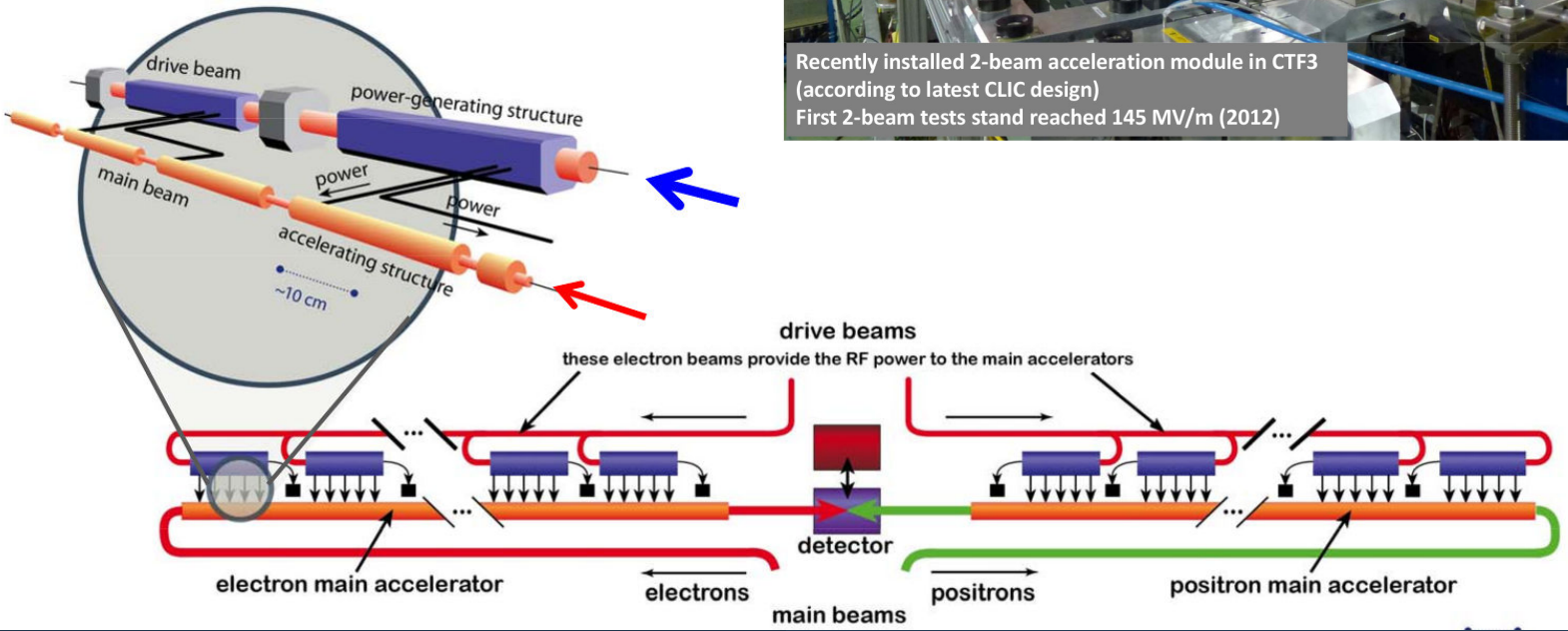
The Compact Linear Collider

Dual-beam acceleration scheme

- RF power generated by a 100 A drive beam at 12 GHz
- Room-temperature cavities
- High gradient
  $> 100\,\mathrm{MV/m}$ demonstrated
- Ultimate CM energy 3 TeV



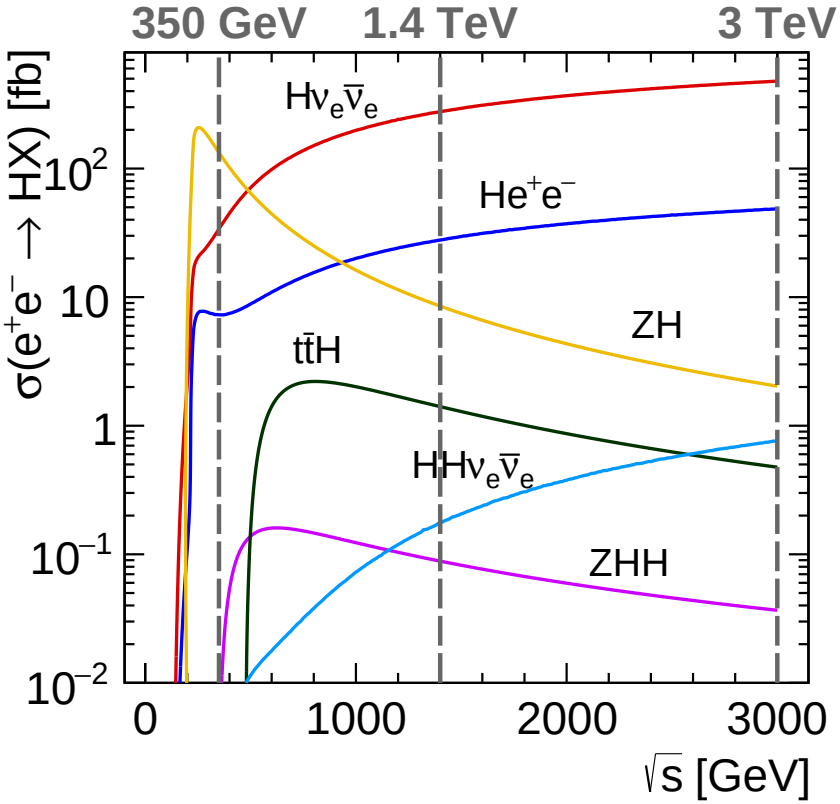
Recently installed 2-beam acceleration module in CTF3 (according to latest CLIC design)
First 2-beam tests stand reached 145 MV/m (2012)



CLIC energy stages

Staged construction and physics program

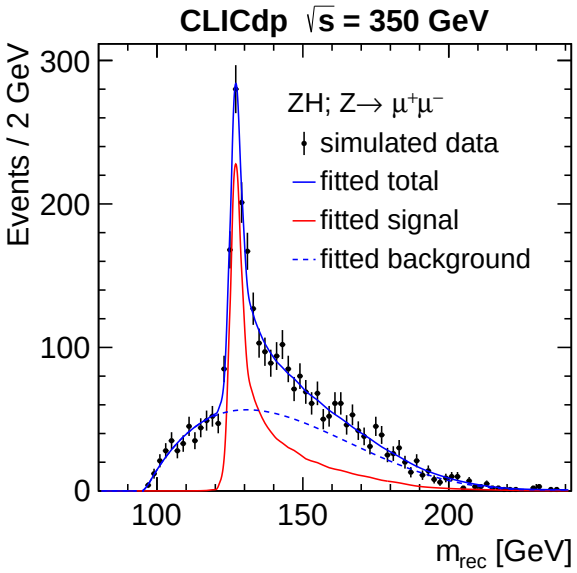
- Three stages: 350 GeV, 1.4 and 3 TeV
  (Now being updated with 380 GeV in the first stage)
- Optimized for the key physics goals in the shortest time.



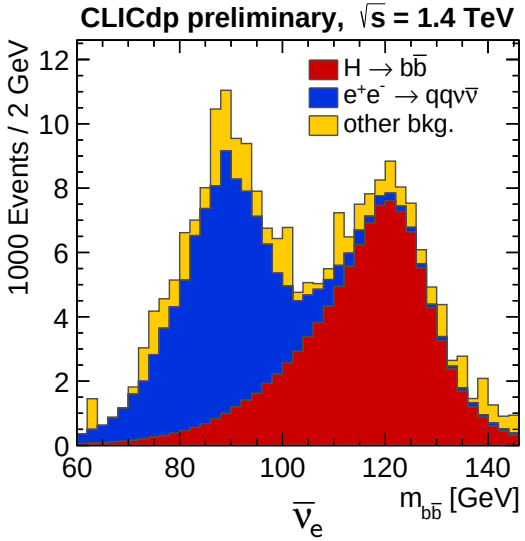
Higgs production statistics at each stage with unpolarized beams

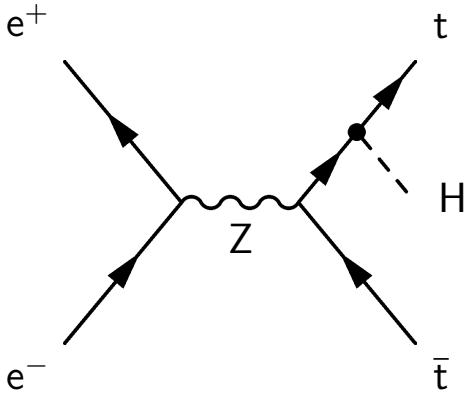
$\sqrt{s}$	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
N_{ZH}	68,000	20,000	11,000
$N_{H\nu_e\bar{\nu}_e}$	17,000	370,000	830,000
$N_{He^+e^-}$	3,700	37,000	84,000
$N_{t\bar{t}H}$		2,400	1,400
$N_{HH\nu_e\bar{\nu}_e}$		225	1,200

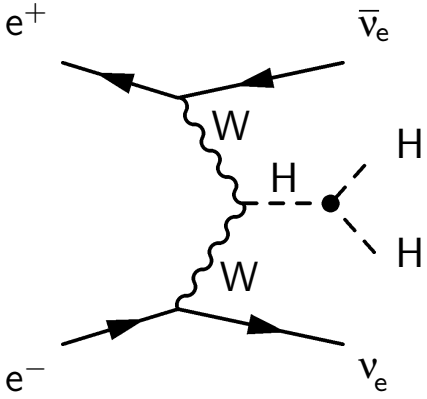
Higgs program at CLIC

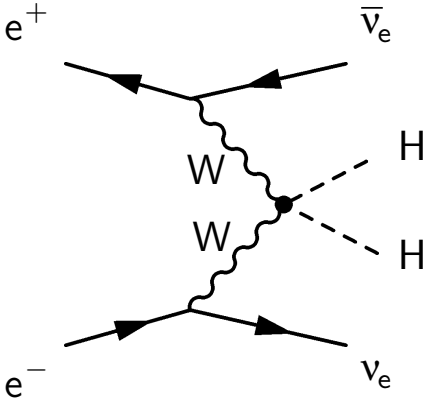


- Higgs recoil measurement allowing model-independent determination of Higgs couplings and width.
- Precise and model-independent couplings
- Precise mass
- Rare production processes, New Physics

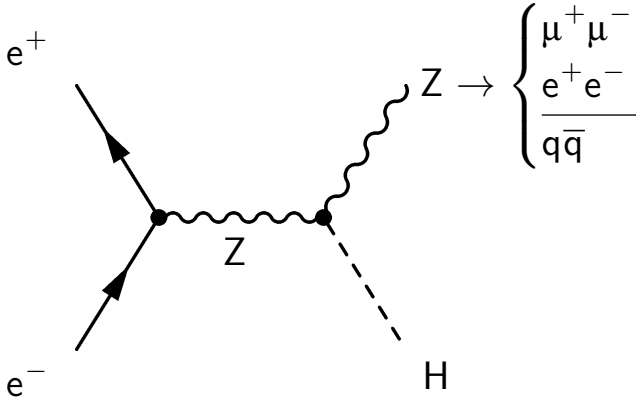


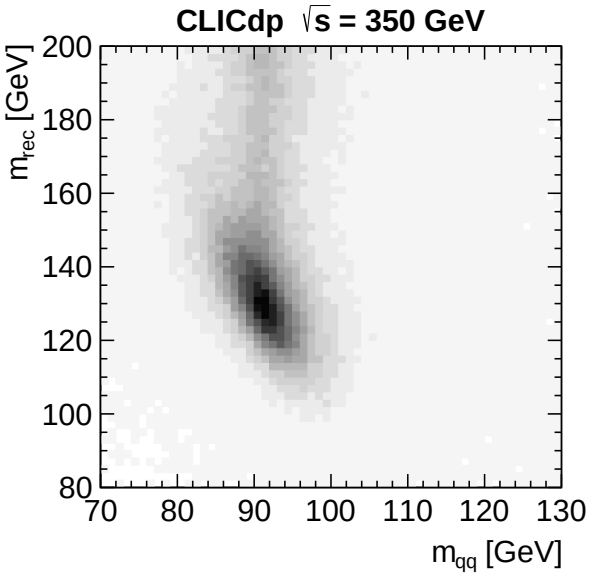




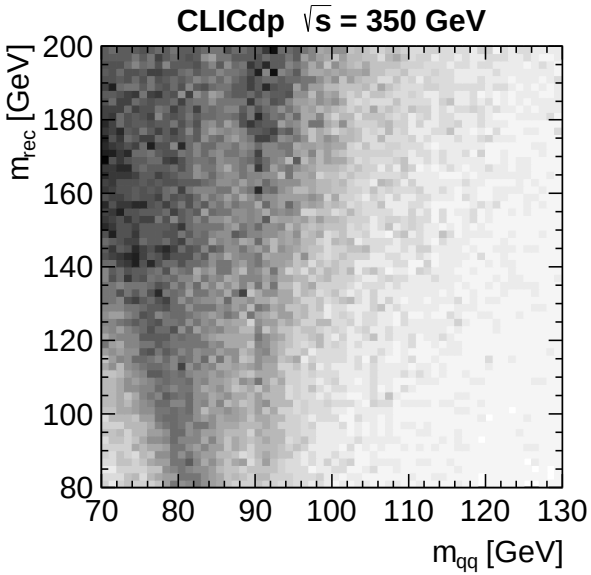


Higgsstrahlung recoil measurement

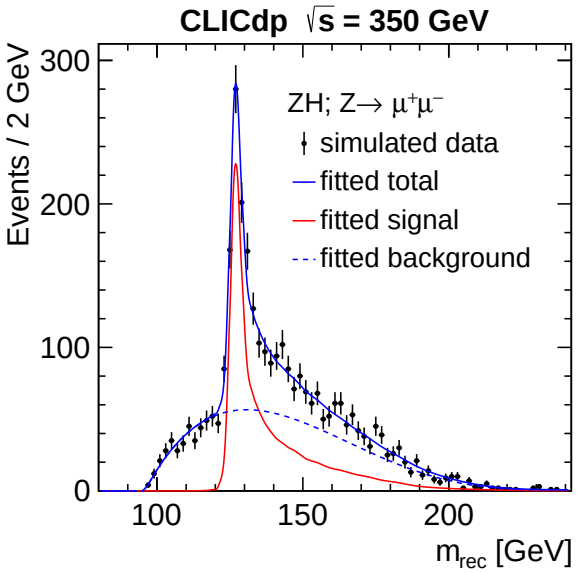




HZ; Z → qq̄ signal



HZ; Z → qq̄ background



- Reconstructing only the Z boson – Higgs recognized via the recoil mass
- $Z \to q\bar{q}$ analysis tailored for model independence
- m_H measured with stat. precision of 110 MeV

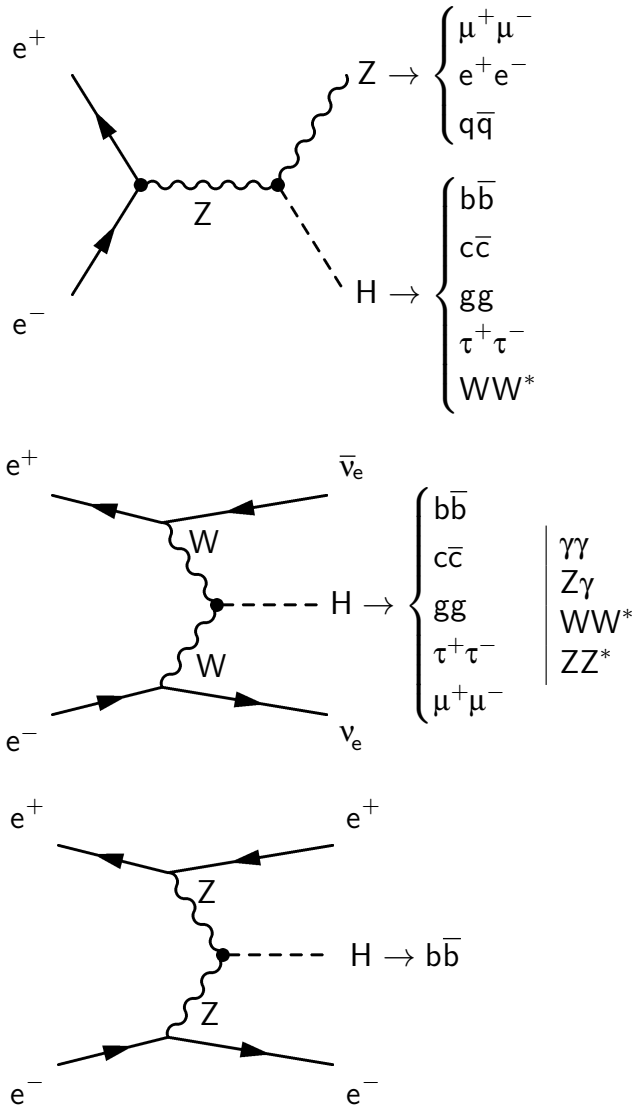
$BR_{Z\to\mu^+\mu^-} \approx 3.5\%$, $BR_{Z\to e^+e^-} \approx 3.5\%$	$\frac{\Delta\sigma_{HZ}}{\sigma_{HZ}} = 4.2\%$
$BR_{Z\to q\bar{q}} \approx 70\%$	$\frac{\Delta\sigma_{HZ}}{\sigma_{HZ}} = 1.8\%$

Combined:

$$\frac{\Delta\sigma_{HZ}}{\sigma_{HZ}} = 1.65\%$$

$$\frac{\Delta g_{HZZ}}{g_{HZZ}} = 0.8\%$$

$\sigma \times$ BR measurements



350 GeV

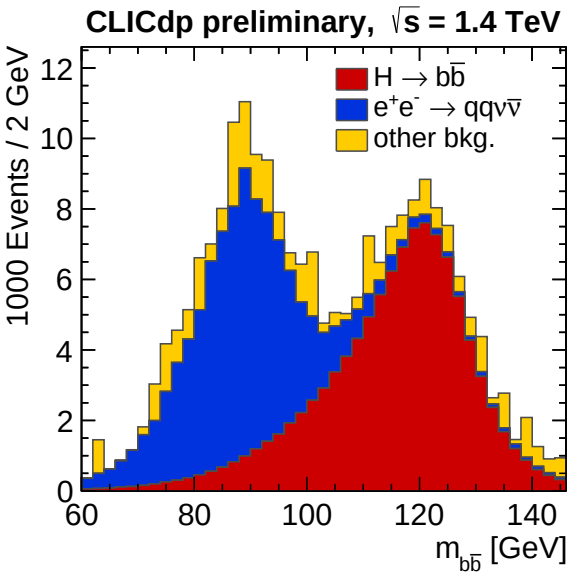
- HZ: H and Z decay candidates reconstructed
  - Z decay + missing energy allows constraining $BR_{H\to inv.}$ to <1%
- $H\nu_e\bar{\nu}_e$: H decay candidate and invis. energy
- First set of precise model-independent measurements, including Γ_H

>1 TeV

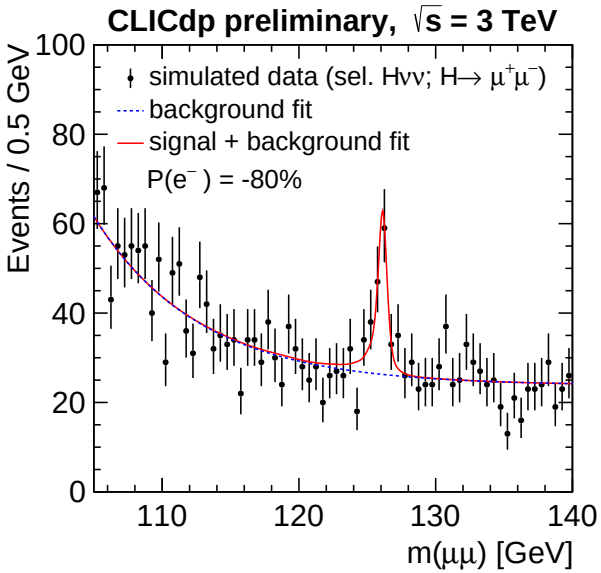
- Large samples of Higgs boson in W^+W^- fusion
- Excellent statistical precision
- Access to rare decays ($\mu^+\mu^-$, $\gamma\gamma$, $Z\gamma$)

Highlights above 1 TeV

- Precision measurements: $H \to b\bar{b}, c\bar{c}, gg$
  - Separation of hadronic flavours and gluons
    (Measurement of the $H \to c\bar{c}$ decay is a novelty w.r.t. the LHC)
  - Very precise measurement of $\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to b\bar{b}}$: 0.3%
  - Higgs mass measured to 33 MeV (1.4 and 3 TeV stages combined)
- Access to rare higgs decays ($H \to \mu^+\mu^-$, $H \to \gamma\gamma$, $H \to Z\gamma$)

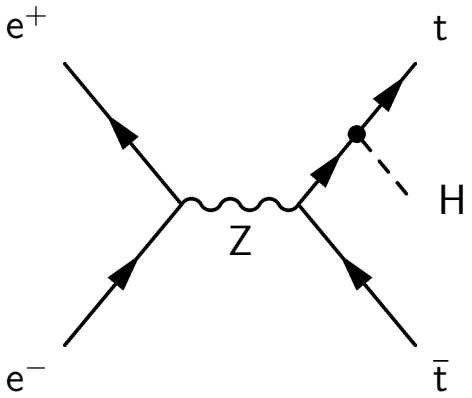


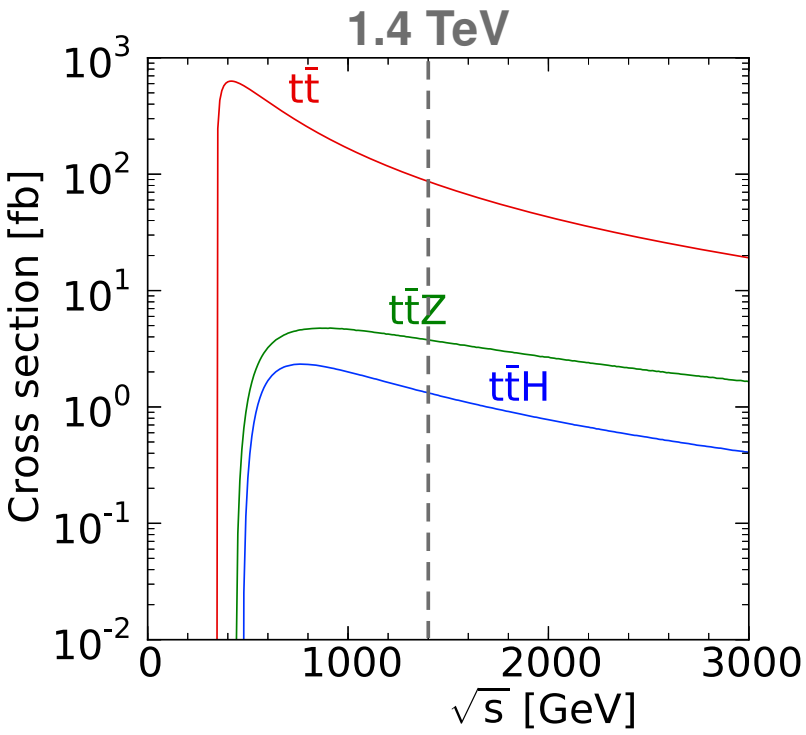
Distribution of $m_{b\bar{b}}$ for the selection of $H\nu_e\bar{\nu}_e; H \to b\bar{b}$ events at 1.4 TeV



$m_{\mu^+\mu^-}$ for the selection of $H\nu_e\bar{\nu}_e; H \to \mu^+\mu^-$ at 3 TeV and with $P(e^-) = -80\%$

Top Yukawa coupling



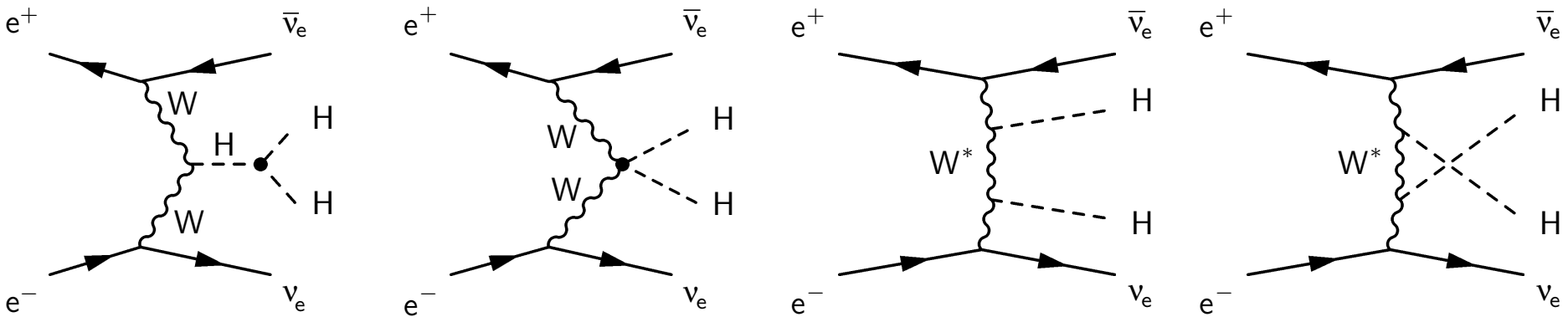


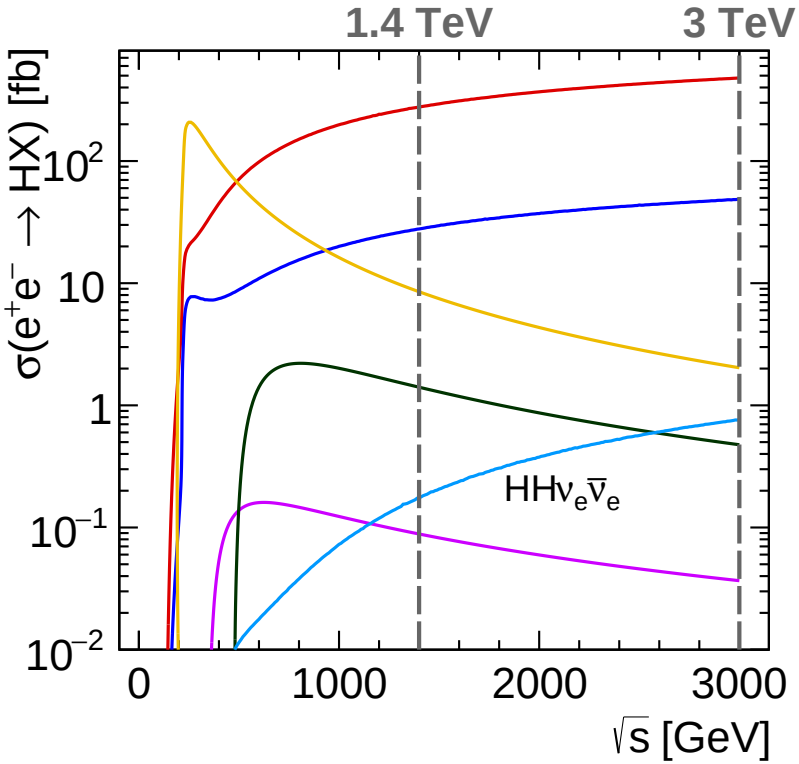
- Extracted directly from the measurement of the $t\bar{t}H$ cross section
- Complex final states with 6 or 8 jets, including 4 b quarks
- Jet clustering and flavor tagging capabilities of the detector are crucial here
- Measurement precision at a 1.4 TeV CLIC:

$$\frac{\Delta\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}} = 8.4\% \Rightarrow \frac{\Delta g_{Htt}}{g_{Htt}} = 4.4\%$$

See talk by F. Żarnecki in the "Top quark and EW Physics" session

Higgs self coupling





- The $HH\nu_e\bar{\nu}_e$ final state is sensitive to the Higgs self coupling λ and to the quartic g_{HHWW} coupling
- Extracted using generator
- High energy and luminosity crucial, polarization important

Statistical uncertainty of $\frac{\Delta\lambda}{\lambda}$ (preliminary):

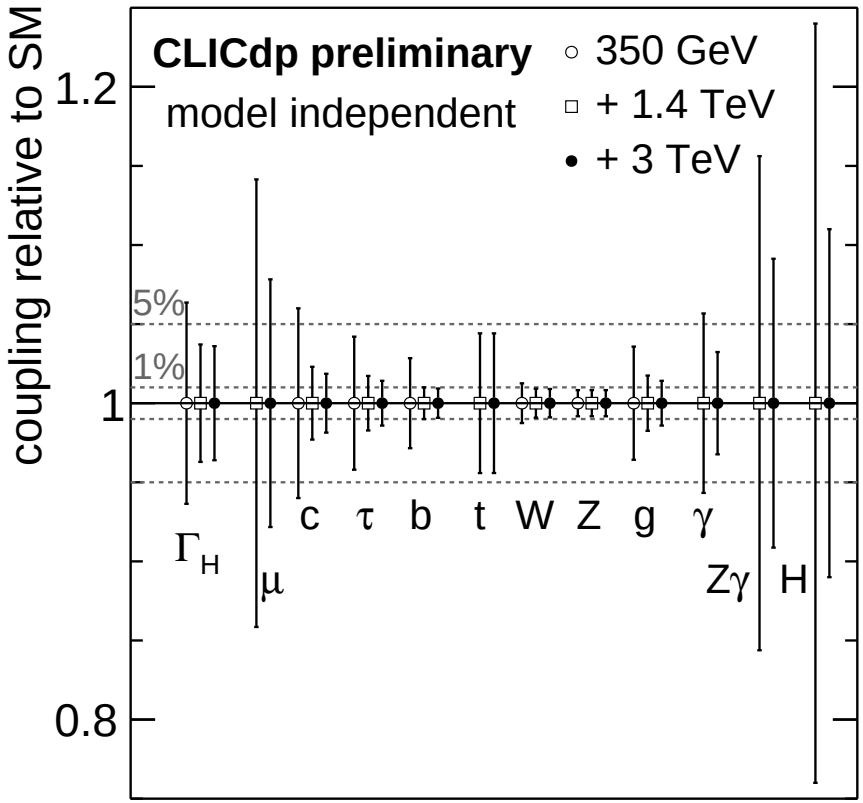
E_{CM}	$P(e^-) = 0$	$P(e^-) = -80\%$
1.4 TeV	32%	24%
3 TeV	16%	12%

Model-independent fit

Higgs couplings and width from the comprehensive set of measurements (σ_{HZ} and all $\sigma \times$ BR)

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

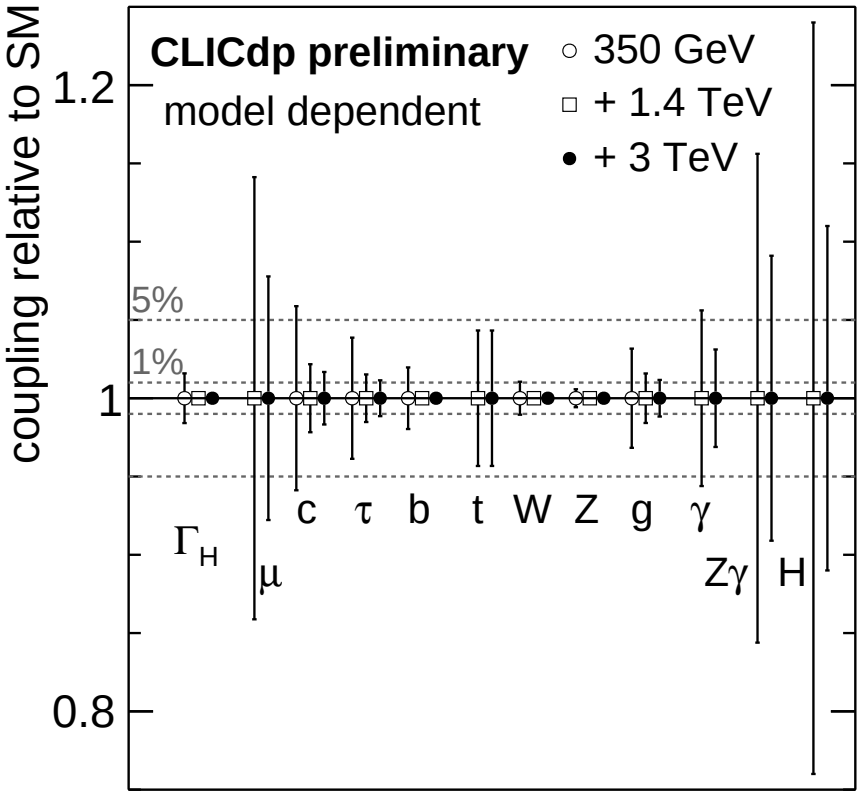
- E.g. $C_{ZH;H\to b\bar{b}} = g_{HZZ}^2 g_{Hbb}^2/\Gamma_H$
- ΔF_i – Measurement ucertainties
- Minimal model assumtions (e.g. narrow Γ_H)
- Higgsstrahlung recoil (g_{HZZ}) Limits the precision of all other parameters



Relative precision of determination of Higgs couplings in the model-independent fit at the successive operation stages of CLIC. At each stage data from all previous stages are included in the fit.

Model-dependent fit

- LHC-style analysis
- $C_i = \kappa_i^2 = \Gamma_i / \Gamma_i^{\text{measured}}$
- Main assumption: There are no invisible Higgs decays
- $\Gamma_{\text{H,md}} = \Gamma_{\text{H}}^{\text{SM}} \sum_i \kappa_i^2 \, \text{BR}_i$



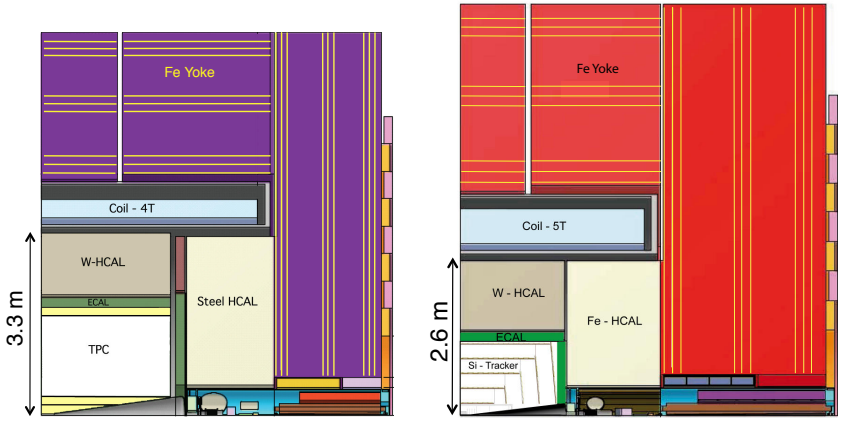
Relative precision of determination of Higgs width parameters in the model-dependent fit at the successive operation stages of CLIC. The total width $\Gamma_{\text{H},md}$ is derived from the fitted values κ_i. At each stage data from all previous stages are included in the fit.

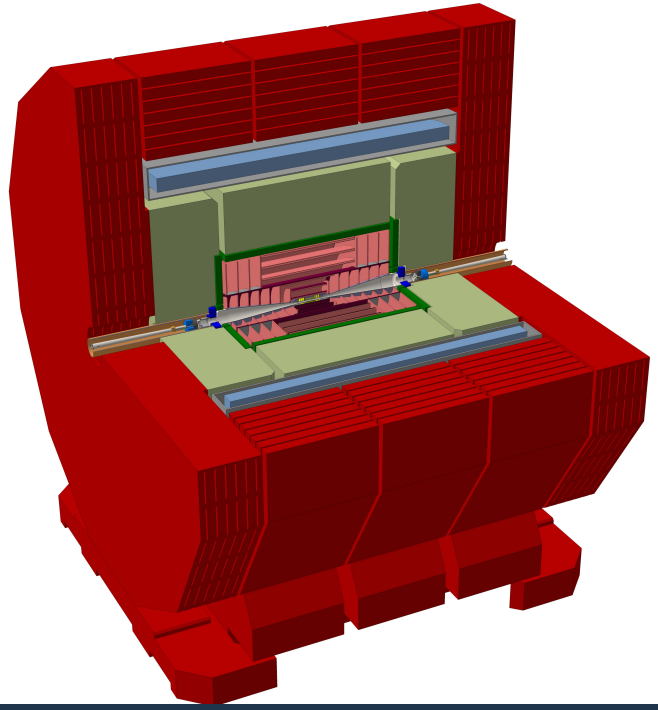
Summary

- A staged operation offering very competitive Higgs physics program already at the first stage:
  - Model-independent measurement of the Higgs couplings and total decay width.
  - Constraint on invisible Higgs decays $\Gamma_{\text{invis}}/\Gamma_{\text{H}} < 0.01$ at 90 % C.L.
- The full dataset brings in addition:
  - Measurement of most Higgs couplings with a percent precision
  - Access to rare Higgs decays
  - Higgs mass determined with precision down to 33 MeV
  - Direct measurement of the Top yukawa coupling
  - Measurement of the trilinear Higgs coupling
- CLIC Higgs physics paper to be public soon!

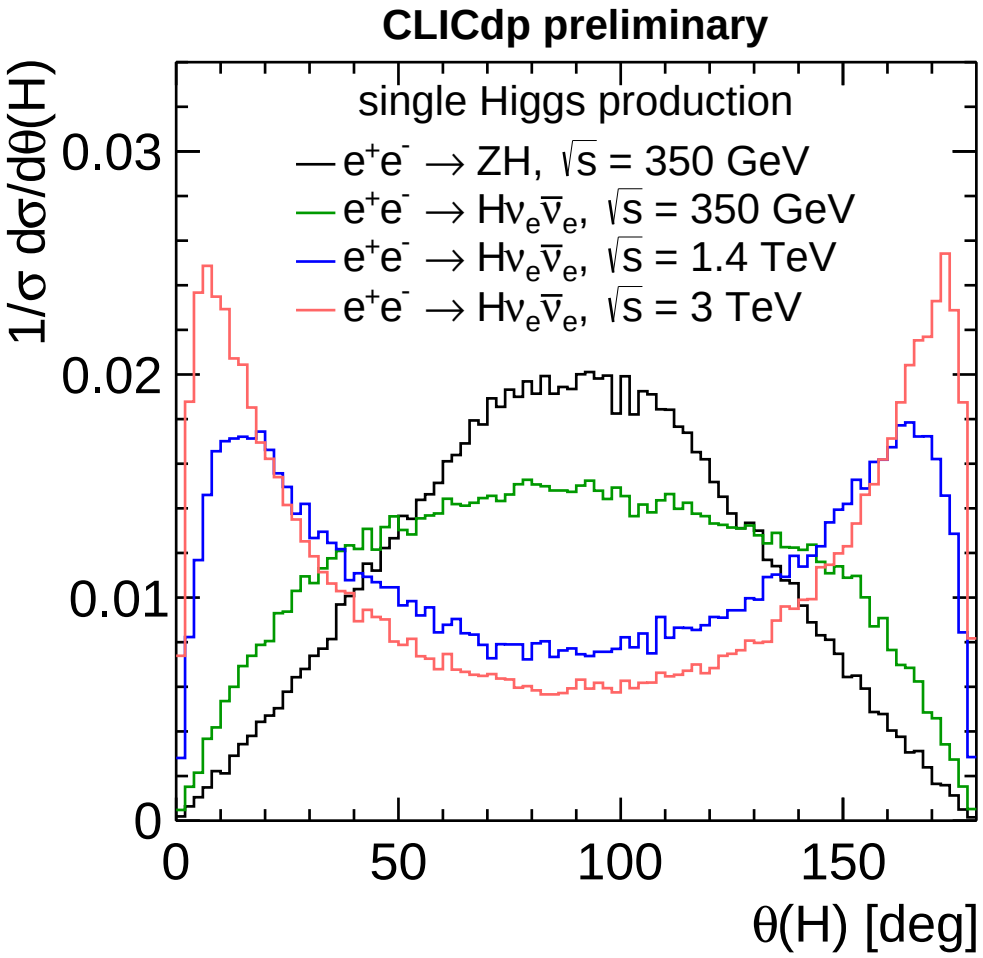
Backup slides

New CLICdp detector model





- Triggerless readout
- High granularity for background suppression and particle-flow analysis
- Power pulsing
- Optimization based on experience with CLIC_ILD and CLIC_SiD:
  - Single detector
  - Beam background reduction by time stamping requires an all Silicon tracker
  - More forward coverage
  - A more realistic design of the vertex detector: Spiral geometry for air cooling, realistic thickness and support structure
  - Lighter return yoke than in the 2-detector scheme



Polar angle distributions for single Higgs events at $\sqrt{s} = 350$ GeV, 1.4 TeV and 3 TeV, including the effects of the CLIC beamstrahlung spectrum and ISR. The distributions are normalised to unity.

$\sigma \times$ BR Measurement precision at 350 GeV

Measurement	Observable	Stat. precision
$\sigma(ZH) \times BR_{H\to invisible}$	Γ_{inv}	0.6 %
$\sigma(ZH) \times BR_{H\to b\bar{b}}$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	0.85 %
$\sigma(ZH) \times BR_{H\to c\bar{c}}$	$g^2_{HZZ} g^2_{Hcc}/\Gamma_H$	10.4 %
$\sigma(ZH) \times BR_{H\to gg}$		4.5 %
$\sigma(ZH) \times BR_{H\to \tau^+\tau^-}$	$g^2_{HZZ} g^2_{H\tau\tau}/\Gamma_H$	6.2 %
$\sigma(ZH) \times BR_{H\to WW^*}$	$g^2_{HZZ} g^2_{HWW}/\Gamma_H$	5.1 %
$\sigma(H\nu_e\bar{\nu}_e) \times BR_{H\to b\bar{b}}$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	1.9 %
$\sigma(H\nu_e\bar{\nu}_e) \times BR_{H\to c\bar{c}}$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	14.5 %
$\sigma(H\nu_e\bar{\nu}_e) \times BR_{H\to gg}$		5.8 %

CLIC BR measurement precision at 350 GeV with 500 fb^{-1} (Preliminary)

$\sigma \times$ BR Measurement precision above 1 TeV

Measurement	Observable	Stat. precision 1.4 TeV 1.5 ab^{-1}	Stat. precision 3 TeV 2 ab^{-1}
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to b\bar{b}}$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	0.4 %	0.3 %
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to c\bar{c}}$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	6.1 %	6.9 %
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to gg}$		5.0 %	4.3 %
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to \tau^+\tau^-}$	$g^2_{HWW} g^2_{H\tau\tau}/\Gamma_H$	4.2 %	4.4 %
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to \mu^+\mu^-}$	$g^2_{HWW} g^2_{H\mu\mu}/\Gamma_H$	38 %	25 %
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to \gamma\gamma}$		15 %	10 %*
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to Z\gamma}$		42 %	30 %*
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to WW^*}$	g^4_{HWW}/Γ_H	1.0 %	0.7 %*
$\sigma_{H\nu_e\bar{\nu}_e} \times BR_{H\to ZZ^*}$	$g^2_{HWW} g^2_{HZZ}/\Gamma_H$	5.6 %	3.9 %*
$\sigma_{He^+e^-} \times BR_{H\to b\bar{b}}$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	1.8 %	2.3 %*

* Extrapolated from 1.4 TeV

CLIC BR measurement precision above 1 TeV (Preliminary)