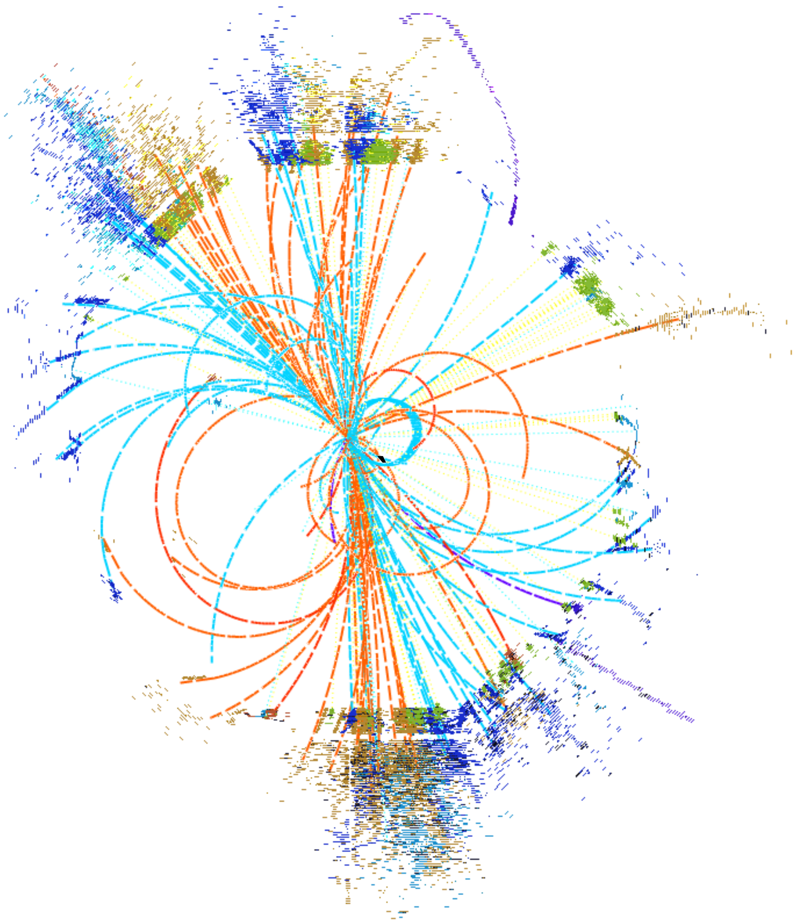
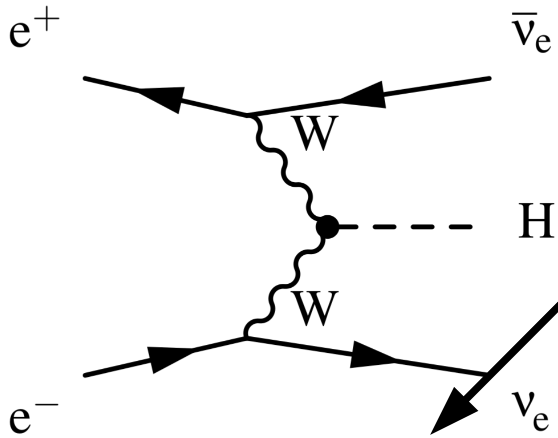
Higgs physics at CLIC

Philipp Roloff (CERN)
on behalf of the CLIC detector and physics study



International Workshop on Future Linear Colliders (LCWS13)
University of Tokyo, 12/11/2013

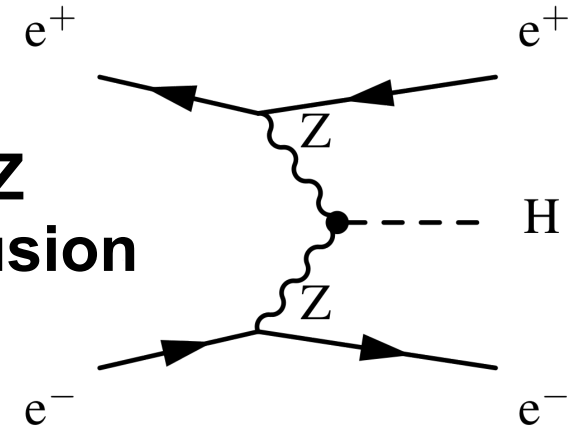
Reminder: Higgs production at CLIC

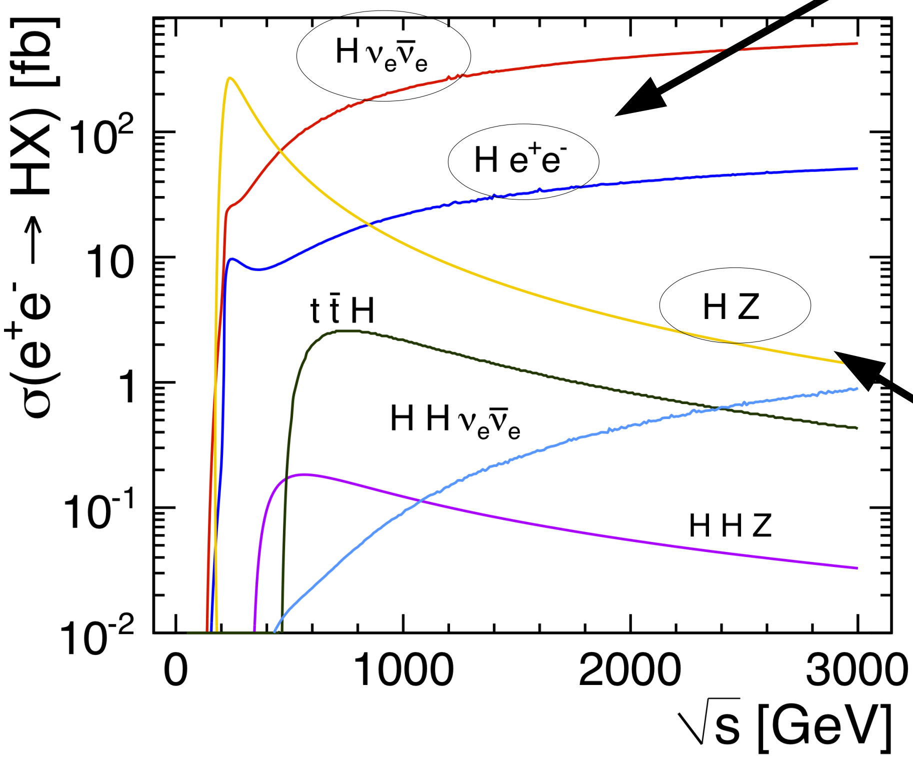


$\sigma \sim \log(s)$

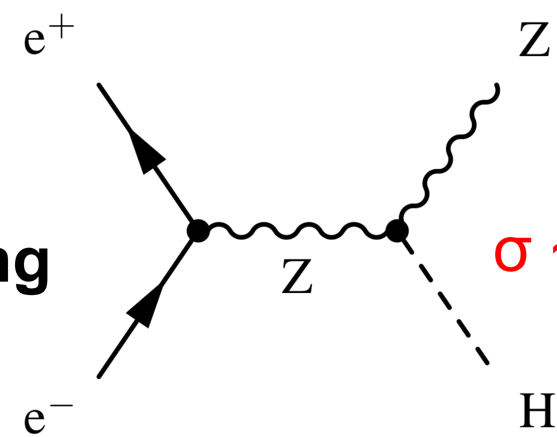
WW fusion

ZZ fusion



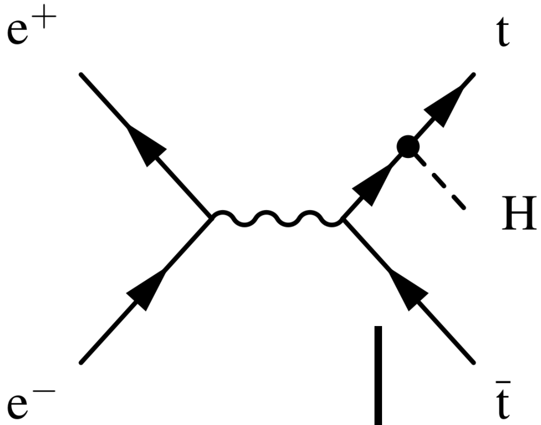


Higgs-strahlung

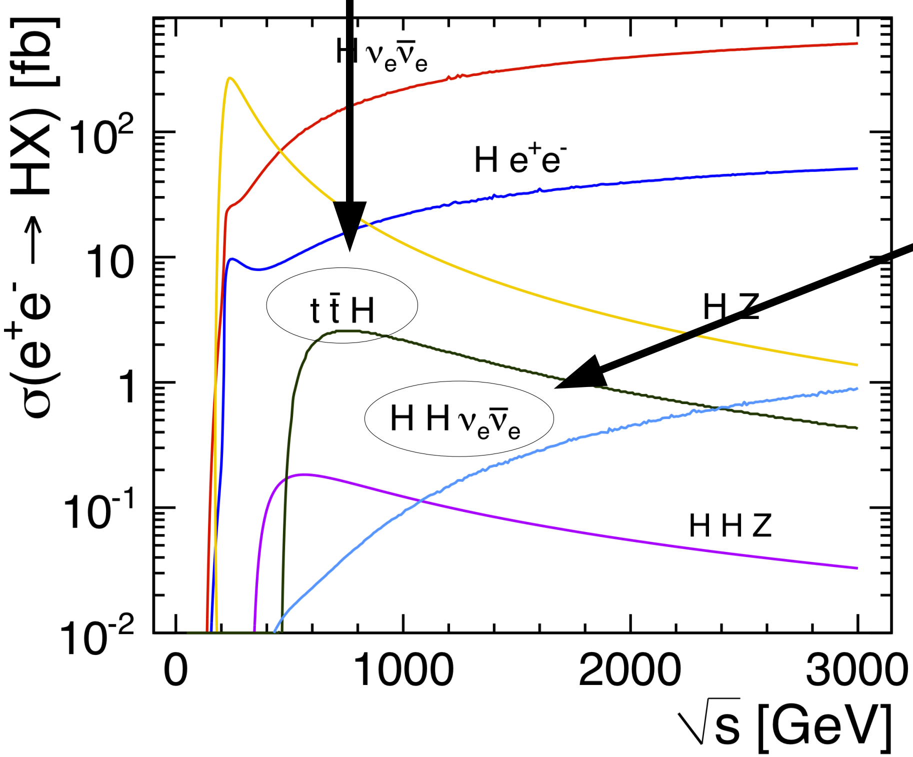


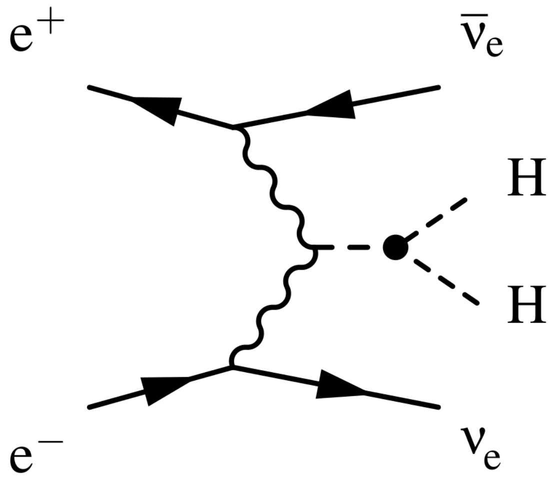
$\sigma \sim 1/s$

Reminder: Processes at higher energy

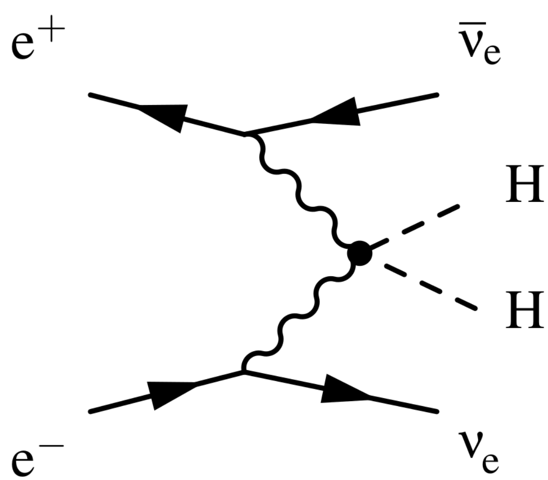


$t\bar{t}H$ production:
maximum at
around 800 GeV





Double Higgs production:
requires high energy



CLIC energy stages

- CLIC will be implemented in stages: optimised running conditions over a wide energy range
- The energy stages are defined by physics with additional technical considerations

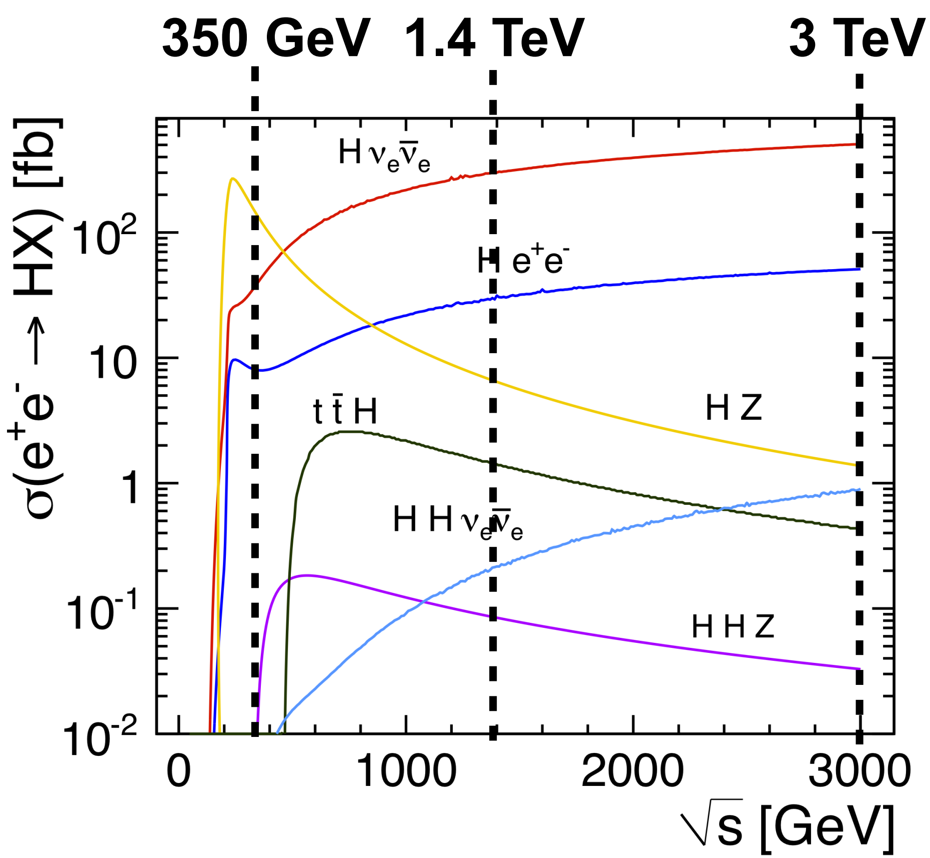
→ strategy can be adapted to discoveries at the LHC

Currently studied example scenario:

- **Stage 1:** 350/375 GeV, 500 fb^{-1}
HZ cross section, mass, $H\nu_e\bar{\nu}_e$ contribution sizeable, various branching rations, *top threshold scan*

- **Stage 2:** 1.4 TeV, 1.5 ab^{-1}
BSM physics, $t\bar{t}H$, Higgs self-coupling, rare Higgs decays

- **Stage 3:** 3 TeV, 2 ab^{-1}
BSM physics, Higgs self-coupling, rare Higgs decays



Assumptions and numbers

Unpolarised cross sections for m_H = 125 GeV including ISR:

	350 GeV	1.4 TeV	3 TeV
$\sigma(e^+e^- \rightarrow ZH)$	134 fb	9 fb	2 fb
$\sigma(e^+e^- \rightarrow H\nu_e\bar{\nu}_e)$	52 fb	279 fb	479 fb
$\sigma(e^+e^- \rightarrow He^+e^-)$	7 fb	28 fb	49 fb

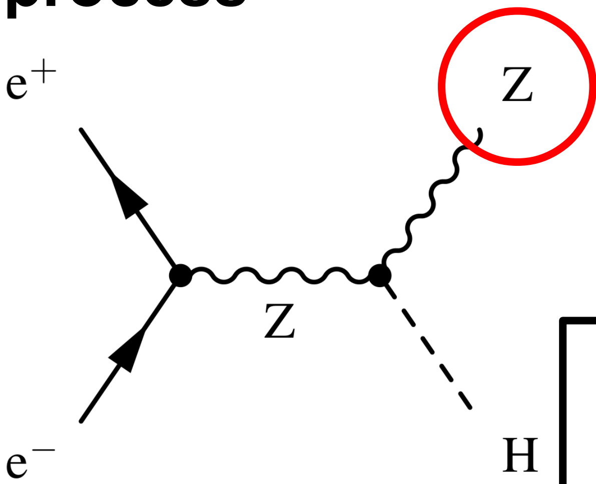
Numbers of events including ISR & Beam-strahlung:

	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	26 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

Number of $e^+e^- \rightarrow H\nu\bar{\nu}$ events significantly enhanced with polarisation

Polarization	Enhancement factor	
$P(e^-) : P(e^+)$	$e^+e^- \rightarrow ZH$	$e^+e^- \rightarrow H\nu_e\bar{\nu}_e$
unpolarized	1.00	1.00
-80% : 0%	1.18	1.80
-80% : $+30\%$	1.48	2.34

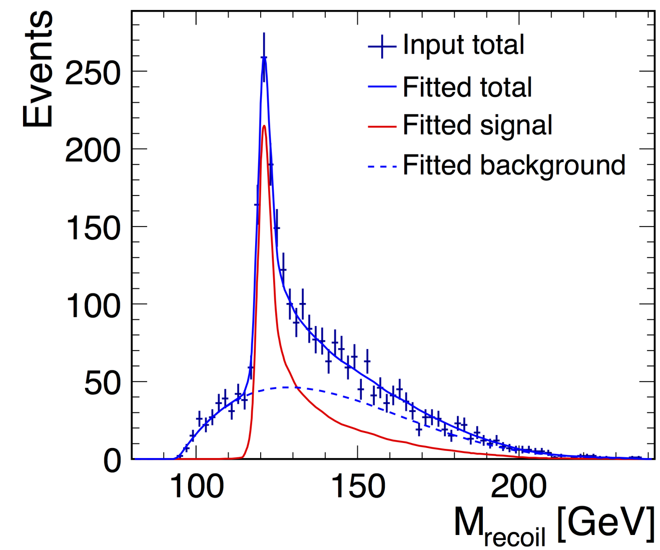
Higgsstrahlung process



- HZ events can be identified from Z recoil mass
→ model independent measurements of m_H and the g_{HZZ} coupling

$\Delta(m_H) \approx 120$ MeV
$\Delta(\sigma_{HZ}) / \sigma_{HZ} \approx 4\%$

$e^+e^+ \rightarrow ZH \rightarrow \mu^+\mu^-H$



$\sqrt{s}$	250 GeV	350 GeV	350 GeV
$\mathcal{L}_{int}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}
$\Delta(\sigma)/\sigma$	3%	3.7%	3.1%
$\Delta(g_{HZZ})/g_{HZZ}$	1.5%	1.9%	1.6%

ILC with $P(e^-) = -80\%$, $P(e^+) = +30\%$
→ lower cross section at 250 GeV compensated by higher luminosity at 350 GeV

Improvement from extension to hadronic Z decays expected
→ see preliminary study in talk by Mark Thomson

Measurements at 350 GeV (2)

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

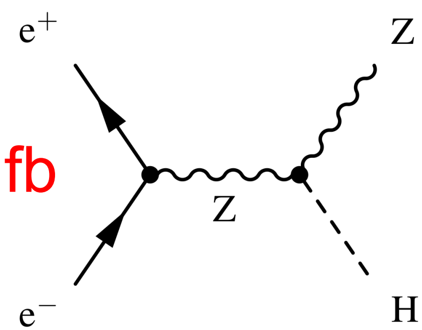
Assuming unpolarised beams

Sensitivity to the total Higgs decay width due to sizeable cross section for WW fusion:

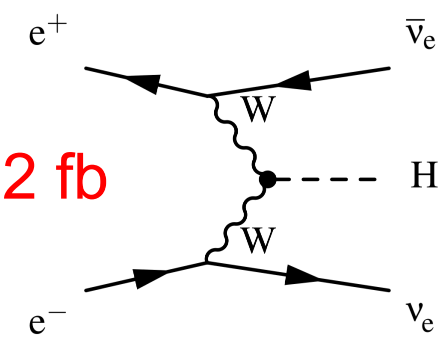
$$\frac{\sigma(e^+e^- \rightarrow ZH) \times BR(H \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow \nu_e\bar{\nu}_e H) \times BR(H \rightarrow b\bar{b})} \propto \left(\frac{g_{HZZ}}{g_{HWW}}\right)^2$$

$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

$\sigma \approx 134$ fb



$\sigma \approx 52$ fb



Measurements using $H\nu_e\bar{\nu}_e$ events at 1.4 TeV

Large Higgs samples produced in WW fusion at high energy:

→ Precision measurements of σ x BR

→ Access to rare decay modes

→ talks by Ivanka Bozovic-Jelisavcic ($H \rightarrow \mu^+\mu^-$ at 1.4 TeV) and Eva Sicking ($H \rightarrow Z\gamma$ and $H \rightarrow \gamma\gamma$ at 1.4 TeV)

Measurement	Observable	Stat. precision
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	< 3.7%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.3%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	2.9%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow gg)$		1.8%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	29%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \gamma\gamma)$		15% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	3% (estimated)
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*)$	g^4_{HWW} / Γ_H	1.1% (preliminary)

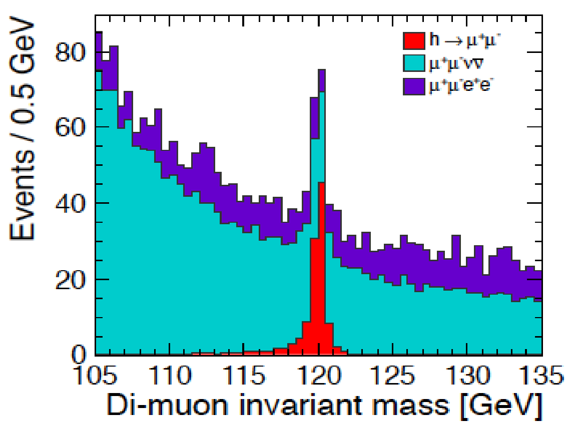
Assuming unpolarised beams

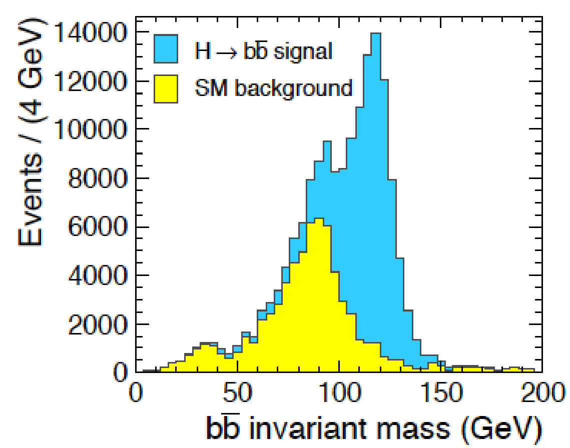
Higgs mass from $H \rightarrow b\bar{b}$ mass distribution: $\Delta(m_H) \approx 40$ MeV (estimated)

Measurements using $H\nu_e\bar{\nu}_e$ events at 3 TeV

Measurement	Observable	Stat. precision
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb} / \Gamma_H$	0.2%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc} / \Gamma_H$	2.7%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		1.8%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ} / \Gamma_H$	2% (estimated)
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	0.8% (preliminary)

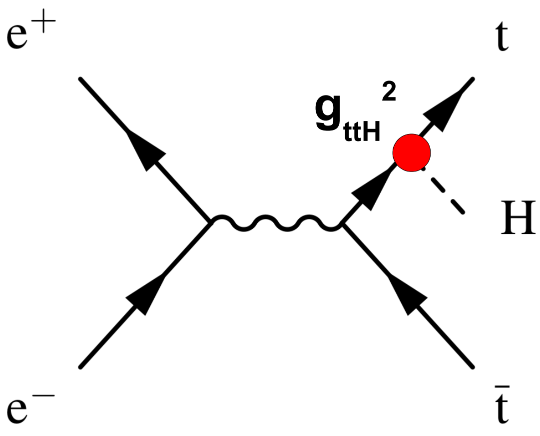
Assuming unpolarised beams



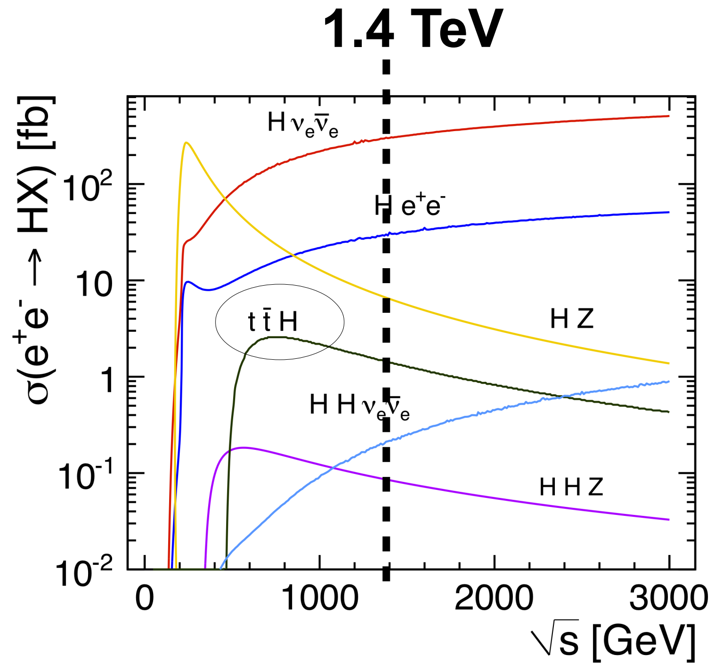


Higgs mass from $H \to b\bar{b}$ mass distribution: $\Delta(m_H) \approx 33$ MeV (estimated)

The $t\bar{t}H$ and Ze^+e^- final states at 1.4 TeV



→ The $t\bar{t}h$ cross section is directly sensitive to the top Yukawa coupling g_{ttH}



Investigated final states:

"*6 jets*": $t(\to qqb)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$

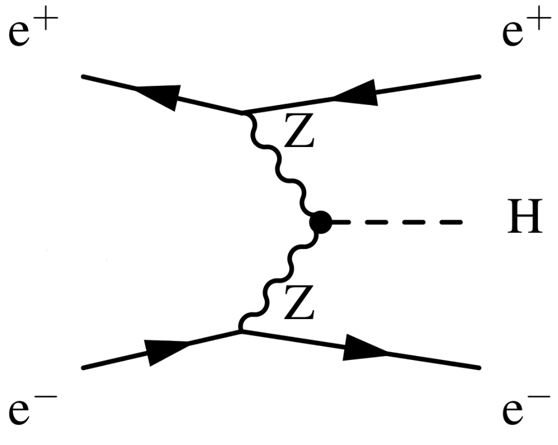
"*8 jets*": $t(\to qqb)\bar{t}(\to qq\bar{b})H(\to b\bar{b})$

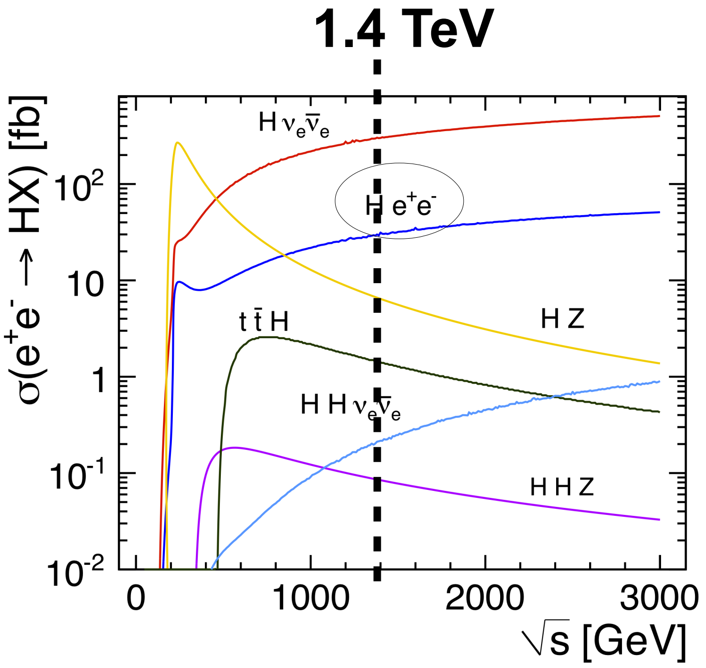
Combination of both final states:

$\Delta\sigma(t\bar{t}H) / \sigma(t\bar{t}H) = 8.1\% \to \Delta g_{ttH} / \sigma_{ttH} = 4.3\%$

→ see talk by Marcelo Vogel

Higgs production in ZZ fusion





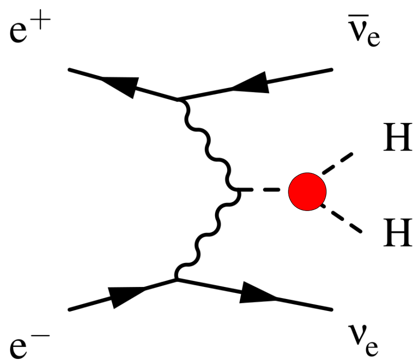
At high energy large samples of ZZ and WW fusion events available:

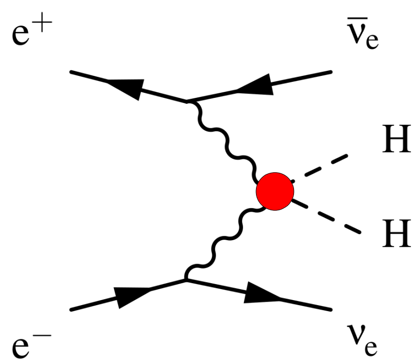
$$\frac{\sigma(He^+e^-) \times BR(H \to b\bar{b})}{\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}$$

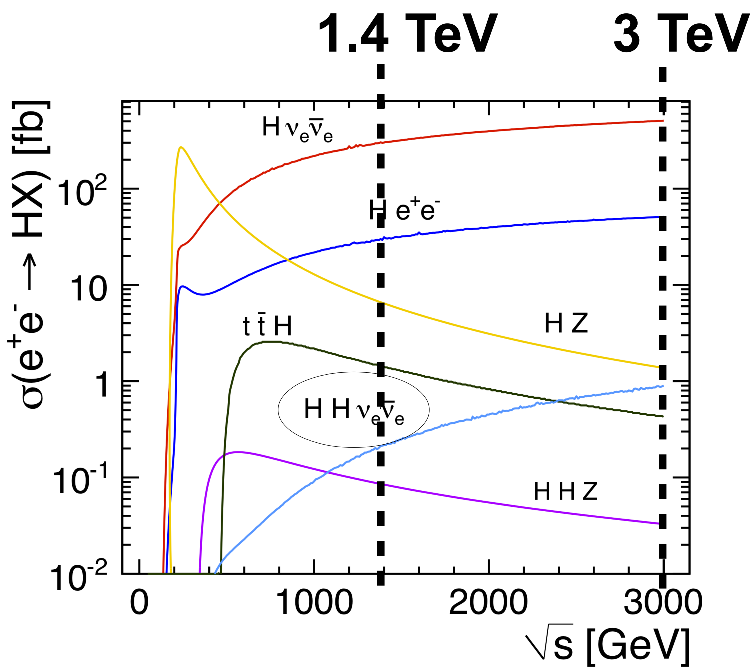
→ see talk by Aidan Robson

→ Precise determination of the ratio g_{HZZ} / g_{HWW}
(many systematic effects cancel in the ratio)

Double Higgs production at high energy







- The $HH\nu_e\bar{\nu}_e$ cross section is sensitive to the Higgs self coupling, λ, and the quartic g_{HHWW} coupling
- $\sigma(HH\nu_e\bar{\nu}_e)$ = 0.15 (0.59) fb at 1.4 (3) TeV

→ high energy and luminosity crucial

→ see talk by Tomas Lastovicka

Measurement	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
Δ(λ)	28%	16%
Δ(λ) for $P(e^-)$ = -80%	21%	12%

NB: The results on this slide were obtained for m_H = 120 GeV

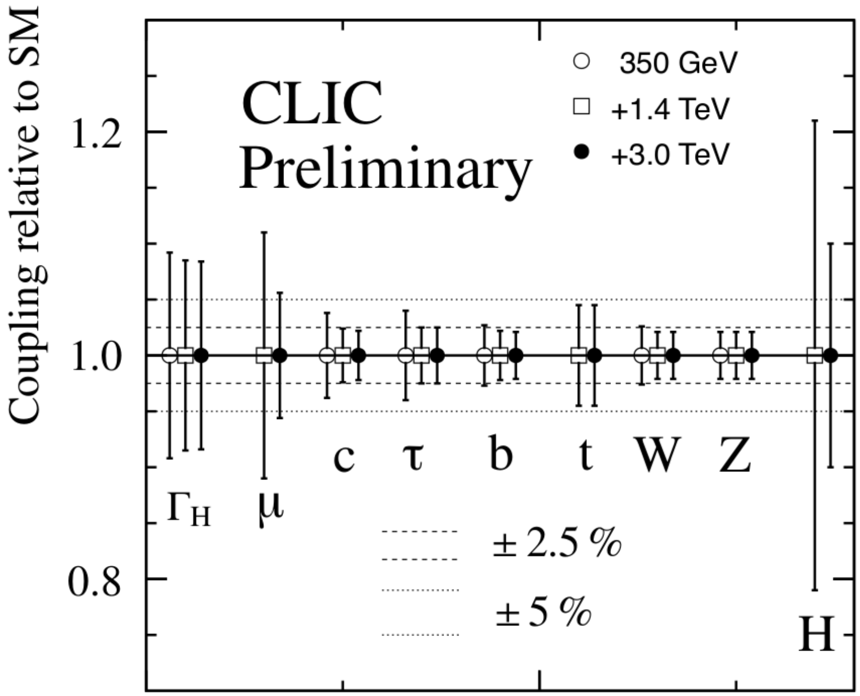
Current status: Snowmass white paper

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}	tbd	–	–
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	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	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
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	29%*	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	tbd	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%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	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	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarization	λ	–	21%	12%

arXiv:1307.5288
final update:
01/10/2013

†: estimate
*: preliminary

Combined analysis (1)



Parameter	Measurement precision		
	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
Γ_H	9.2%	8.5%	8.4%
λ	–	21%	10%
g_{HZZ}	2.1%	2.1%	2.1%
g_{HWW}	2.6%	2.1%	2.1%
g_{Hbb}	2.7%	2.2%	2.1%
g_{Hcc}	3.8%	2.4%	2.2%
$g_{H\tau\tau}$	4.0%	2.5%	tbd
$g_{H\mu\mu}$	–	11%	5.6%
g_{Htt}	–	4.5%	tbd

LCD-Note-2013-012

- Fit to currently available results and a few estimates (see slide 13)
- Event rates multiplies by 1.8 for WW fusion above 1 TeV

→ Simulates effect of $P(e^-)$ = -80% polarisation

- Fully model-independent
- Improvement expected when adding hadronic Z decays for σ(HZ)

Combined analysis (2)

Parameter	Measurement precision		
	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}	0.49%	0.33%	0.24%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.33%	0.21%
κ_{Hcc}	3.1%	1.1%	0.75%
$\kappa_{H\tau\tau}$	3.5%	1.4%	tbd
$\kappa_{H\mu\mu}$	–	11%	5.2%
κ_{Htt}	–	4.0%	tbd
κ_{Hgg}	3.6%	0.79%	0.56%
$\kappa_{H\gamma\gamma}$	–	5.5%	tbd

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

No invisible decays:

$$\Gamma_{H,model} = \sum_i \kappa_i^2 \cdot BR_i^{SM}$$

Sub-percent precisions at high energy

→ Results strongly dependent on fit assumptions

Summary and conclusions

- The first stage of a CLIC collider at 350 GeV provides precise determinations of the absolute values of many Higgs boson couplings

- Subsequent high-energy running, here assumed at 1.4 and 3 TeV, improves the precision of many observables significantly and gives access to rare Higgs decays

- High-energy CLIC operation provides the potential to measure the trilinear Higgs self-coupling at the 10% level

- Combined fits to all measurements at 350 GeV, 350 GeV + 1.4 TeV and 350 GeV + 1.4 TeV + 3 TeV were performed to extract the Higgs couplings and width simultaneously

- A comprehensive paper on Higgs physics at CLIC is in progress