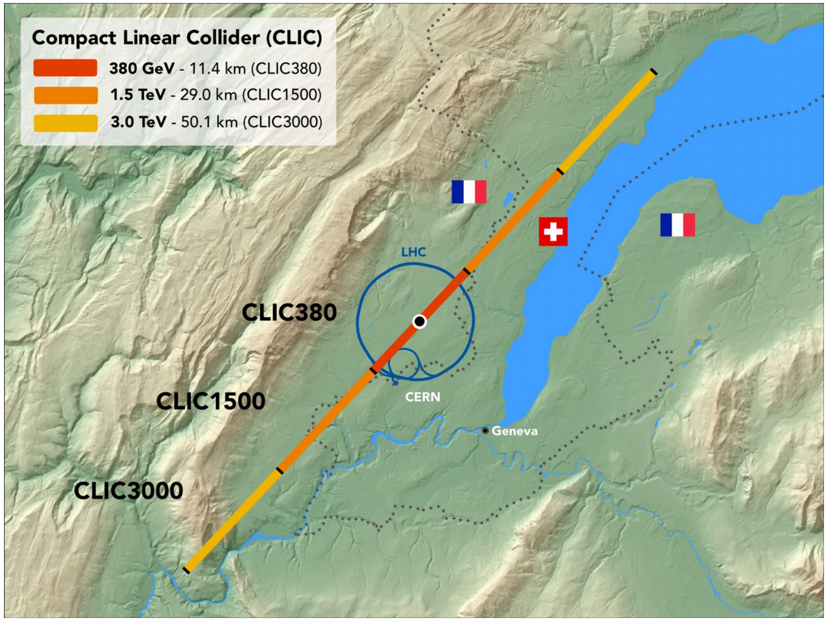
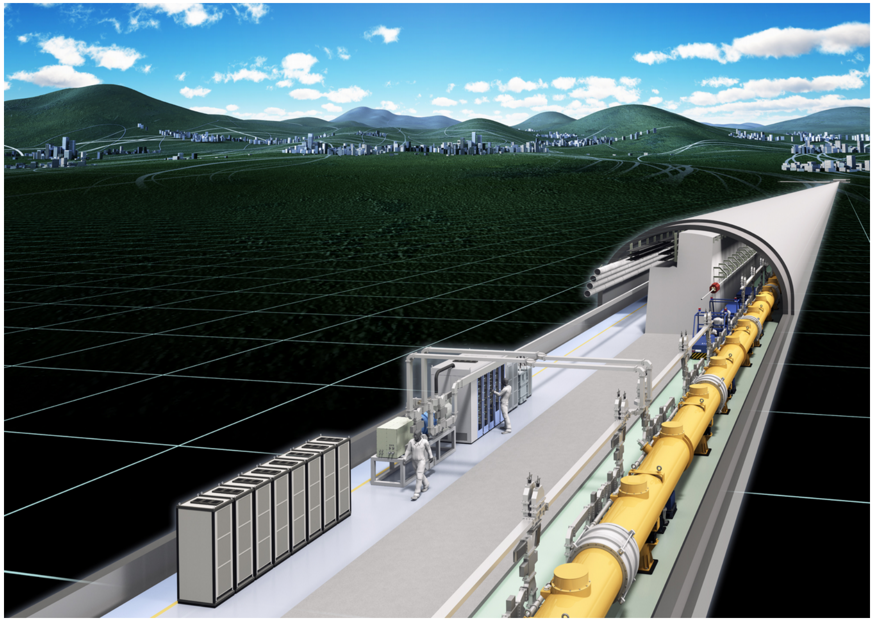
Higgs at linear colliders (ILC & CLIC)

Philipp Roloff
(CERN/EP-LCD)

01/06/2018
EP/TH faculty meeting:
Measurement of Higgs properties at present and future colliders

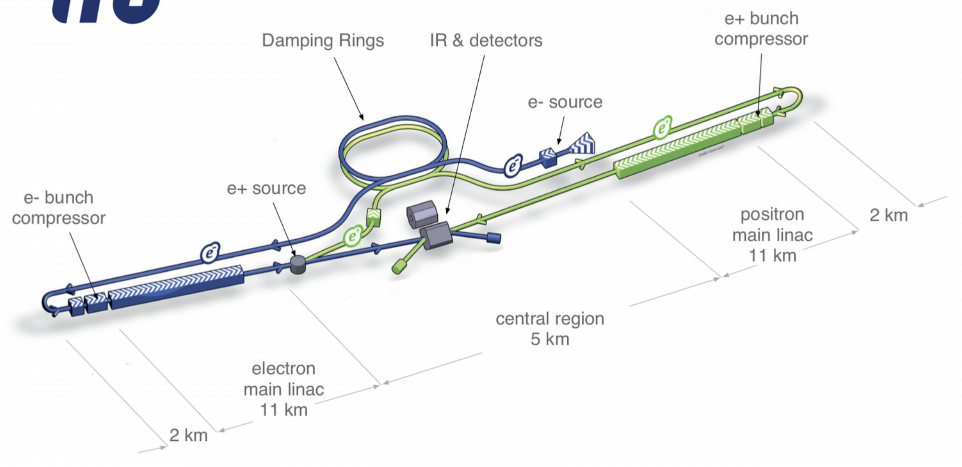


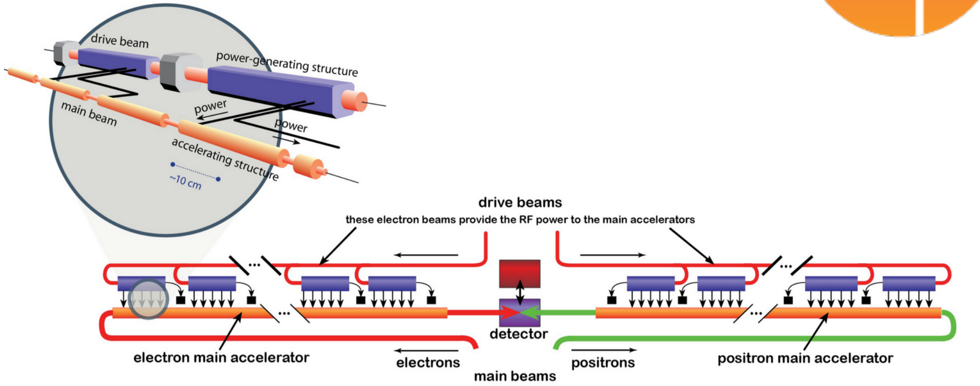


Contents of this talk

- Introduction
- Single Higgs production and analysis highlights
- Higgs couplings at ILC and CLIC
- Double Higgs production

Introduction: ILC and CLIC



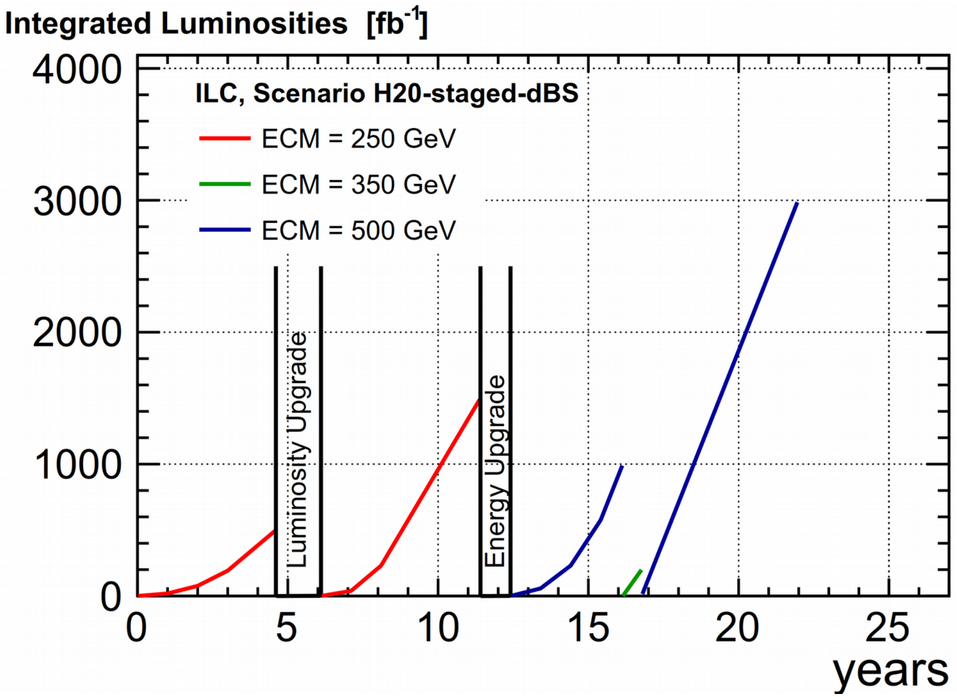


International Linear Collider (ILC):
- Based on superconducting RF cavities
- Gradient: 32 MV/m
- Energy: 250 - 500 GeV
- $P(e^-) = \pm 80\%$, $P(e^+) = \pm 30\%$
- Length: 20 km (250 GeV), 31 km (500 GeV)

Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
- $P(e^-) = \pm 80\%$
- Length: 11 km (380 GeV), 50 km (3 TeV)

Linear colliders have the potential to profit from novel accelerator techniques

ILC staged implementation



$\sqrt{s}$ [GeV]:	L_{int} [fb^{-1}]:
250	500 + 1500
350	200
500	4000

- 1 year = 1.6×10^7 seconds

- The ILC is now proposed with a staged design, with the first stage at 250 GeV with a luminosity goal of 2 ab^{-1}

- Luminosity upgrade requires machine upgrades (double number of bunches per pulse)

arXiv:1710.07621
arXiv:1711.00568

CLIC staged implementation

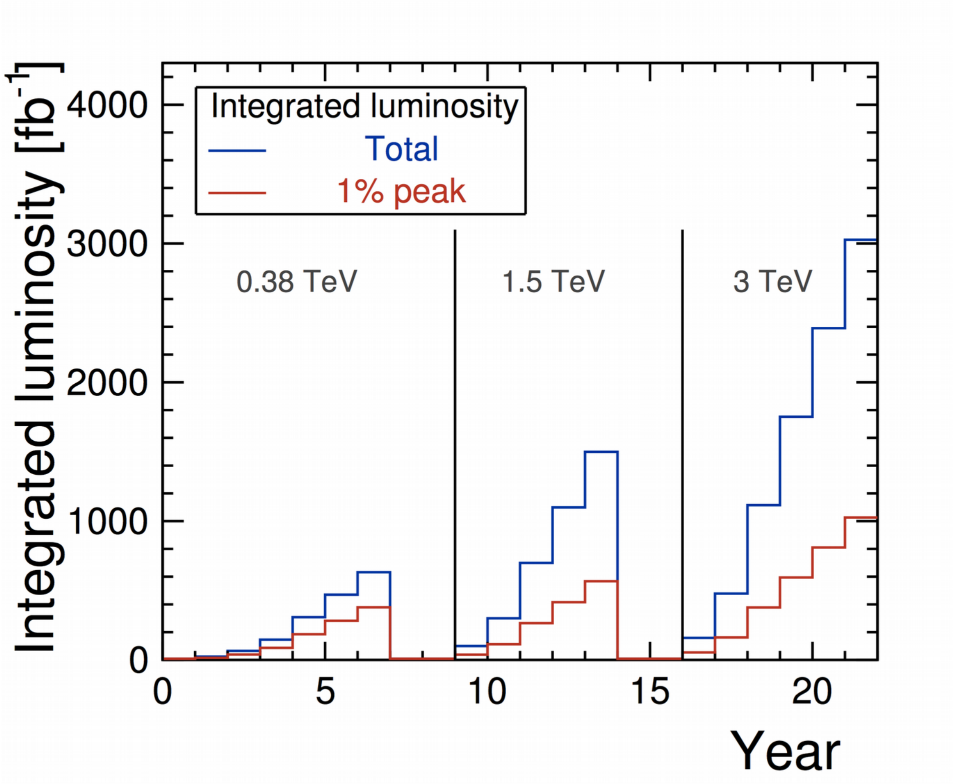
CLIC would be implemented
in several energy stages

Baseline scenario:

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

- Initial stage at 380 GeV optimised to cover Higgs and top measurements (including $t\bar{t}$ threshold scan)

- This strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)



- 1 year = 1.08×10^7 seconds (based on CERN experience)

- The physics performance studies assumed slightly different energies for the first two stages: 380 → 350 GeV, 1.5 → 1.4 TeV

CERN-2016-004

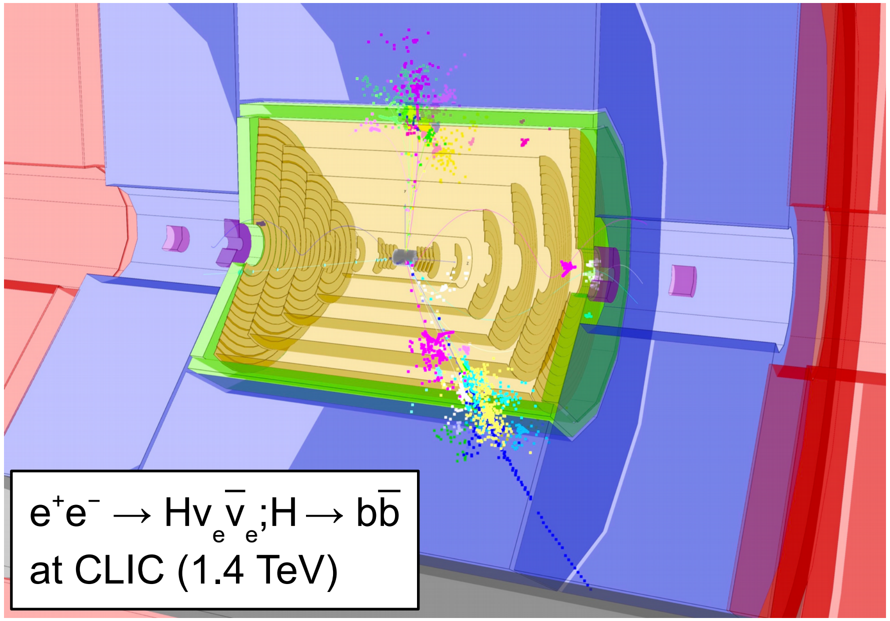
Higgs bosons in e^+e^- collisions

Collider stage:	No. H produced:
ILC 250 GeV, 2 ab^{-1}	500000
CLIC 350 GeV, 500 fb^{-1}	100000
ILC 500 GeV, 4 ab^{-1}	500000
CLIC 1.4 TeV, 1.5 ab^{-1}	430000
CLIC 3 TeV, 3 ab^{-1}	1400000

- No triggers
→ all Higgs events usable

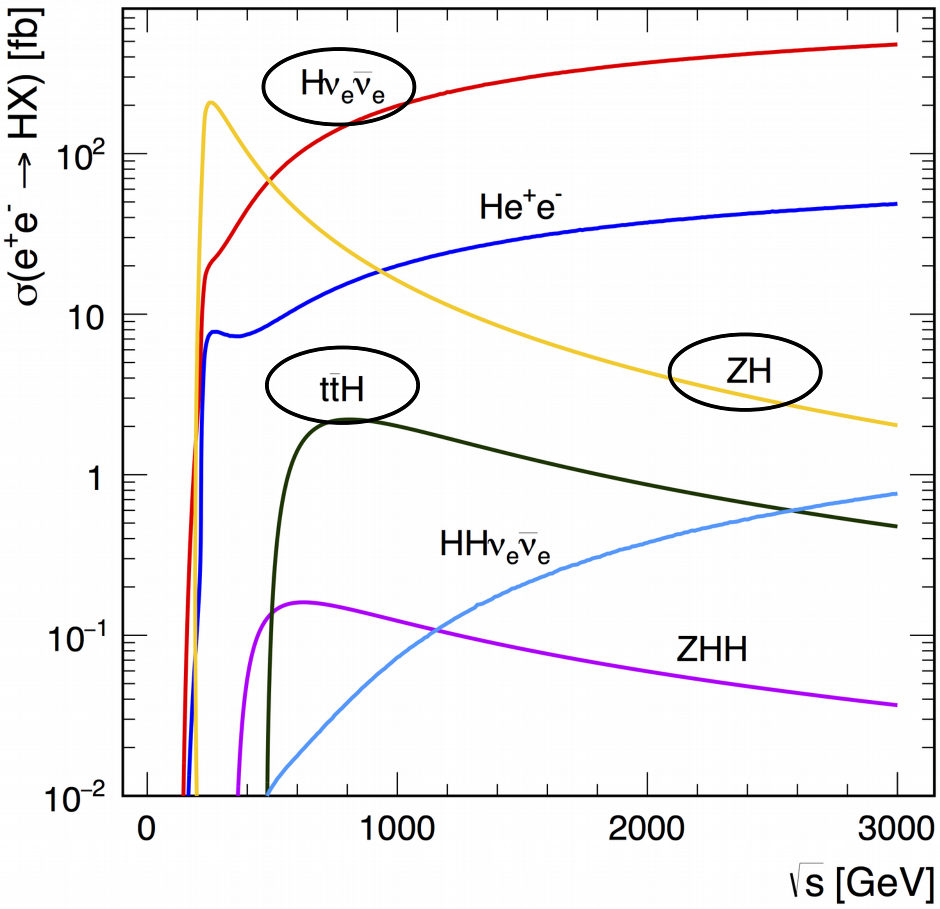
- Typical overall selection efficiencies: 20 - 60%

The projections shown in the following are based on realistic full detector simulations and include the impact of beam-beam effects



$e^+e^- \rightarrow H\nu_e\bar{\nu}_e; H \rightarrow b\bar{b}$
at CLIC (1.4 TeV)

Single Higgs production



Higgsstrahlung: $e^+e^- \to ZH$

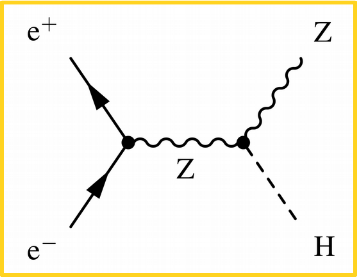
- $\sigma \sim 1/s$, dominant up to ≈ 500 GeV

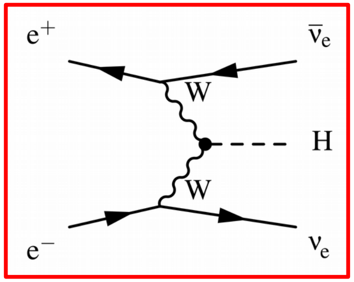
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

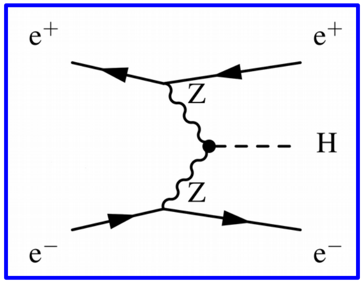
- $\sigma \sim \log(s)$, dominant above 500 GeV
- Large statistics at high energy

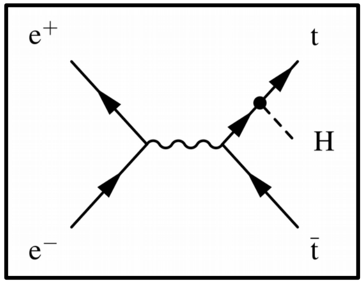
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling

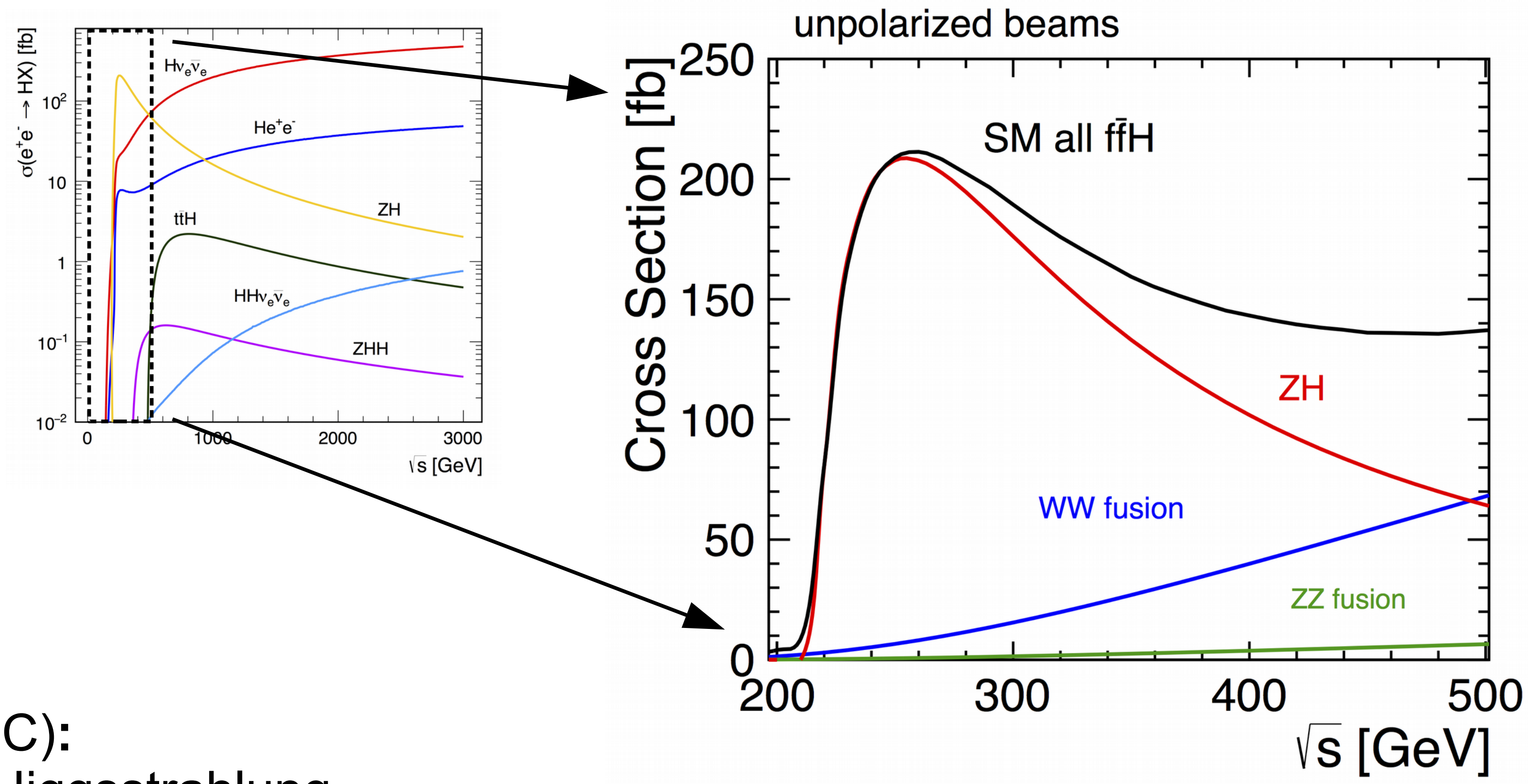






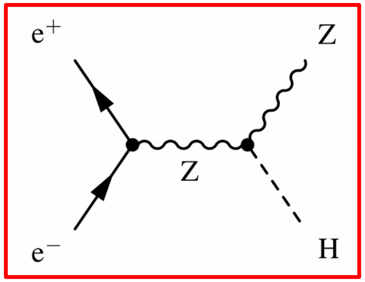


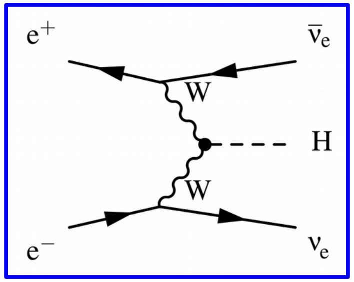
A closer look at $\sqrt{s}$ < 500 GeV



$\sqrt{s}$ = 250 GeV (ILC):
Maximum of the Higgsstrahlung cross section

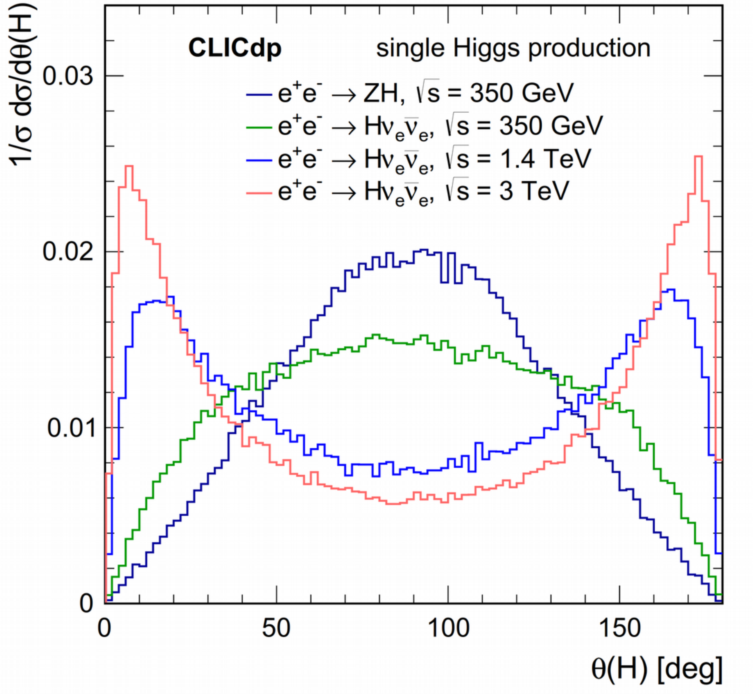
$\sqrt{s}$ = 350/380 GeV (ILC & CLIC):
Also allows to access the WW fusion process
→ Additional information for combined analysis





Kinematics and polarisation

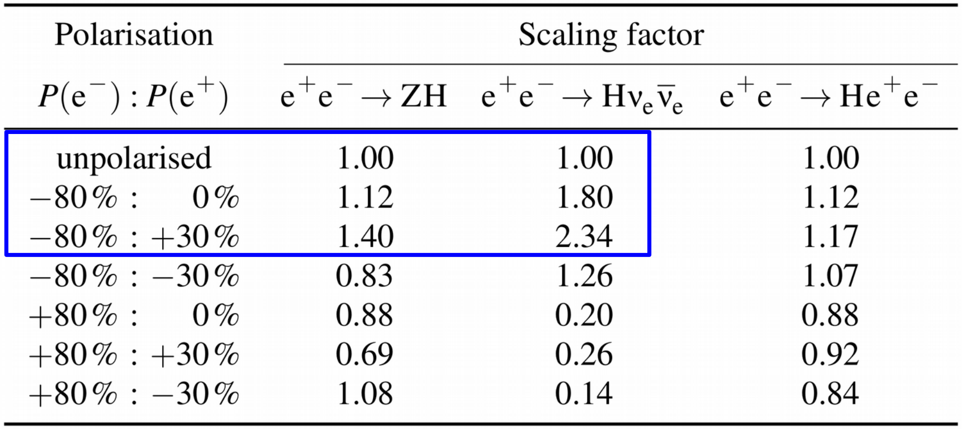
Higgs polar angle:



At a few hundred GeV:
Higgs bosons produced mostly in the central detector

At high energy:
Good forward detector coverage required

Impact of polarisation:



Polarisation	Scaling factor		
$P(e^-):P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84

Higgsstrahlung:
Polarisation dependence relatively small

WW fusion:
Large enhancement in the -80% and -80%/+30% configurations

Analysis highlights

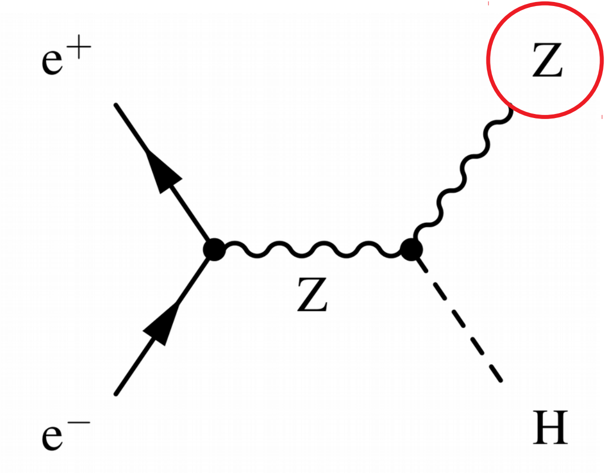
- Recoil method for Higgsstrahlung events
- Invisible Higgs decays
- CP properties in $H \to \tau^+\tau^-$
- Hadronic Higgs decays: $H \to b\bar{b}/c\bar{c}/gg$
- $e^+e^- \to t\bar{t}H$

Recoil method: Z → e^+e^- and $\mu^+\mu^-$

Using Z → e^+e^-, $\mu^+\mu^-$:
ZH events can be identified from the Z recoil mass
→ Model-independent measurement of σ(ZH) and m_H

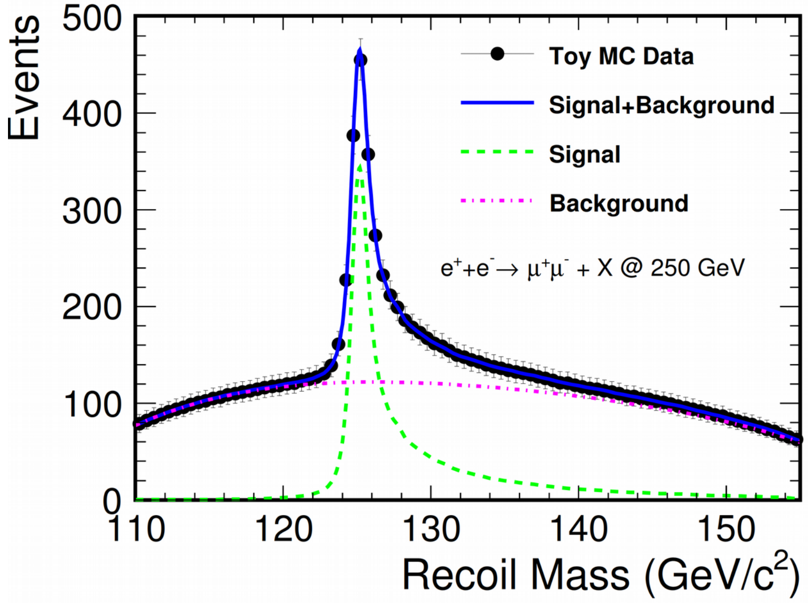
$$m^2_{recoil} = \left(\boxed{\sqrt{s}} - \boxed{E_Z}\right)^2 - \boxed{\left|\vec{p}_Z\right|}^2$$

Known at lepton collider



Best precision at 250 GeV:
- Cross section at maximum
- Tracking resolution
- Impact of beam energy spectrum & ISR smaller

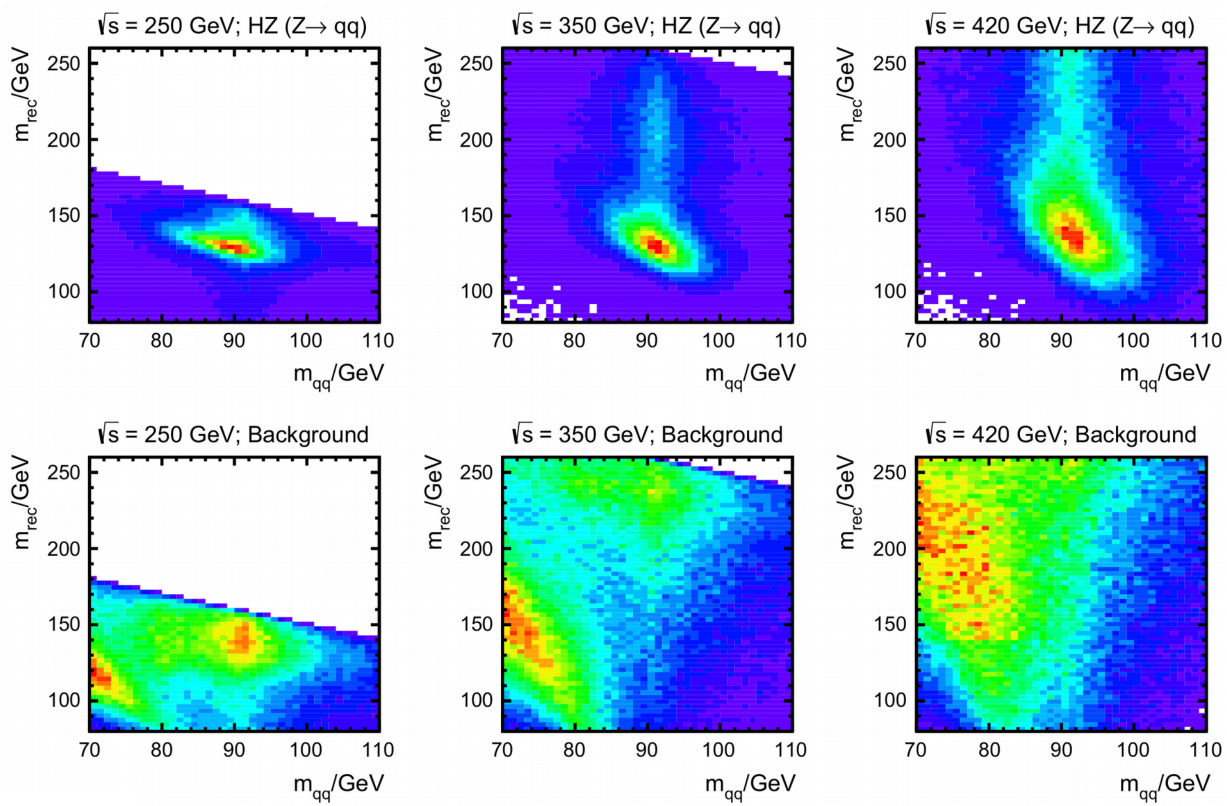
ILC, $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
Δσ(HZ) / σ(HZ) = 1.0%
Δm_H = 14 MeV



Phys. Rev. D 94, 113002 (2016)

Recoil method: Z→$q\bar{q}$

$\sqrt{s}$ = 250 GeV: $\sqrt{s}$ = 350 GeV: $\sqrt{s}$ = 420 GeV:

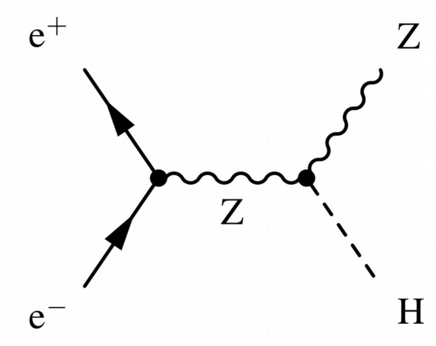


Hadronic Z decays provide the best sensitivity at 350 GeV

Optimisation study for the first CLIC stage (together with top physics):

- At 250 GeV the background is more signal-like
- At 420 GeV the cross section is lower and the jet energy resolution is worse

$\sqrt{s}$	$\mathcal{L}$	σ(HZ)	$\Delta\sigma_{\text{vis.}}$	$\Delta\sigma_{\text{invis.}}$	Δσ(HZ)
250 GeV	500 fb^{-1}	136 fb	±3.63 %	±0.45 %	±3.65 %
350 GeV	500 fb^{-1}	93 fb	±1.71 %	±0.56 %	±1.80 %
420 GeV	500 fb^{-1}	68 fb	±2.42 %	±1.02 %	±2.63 %



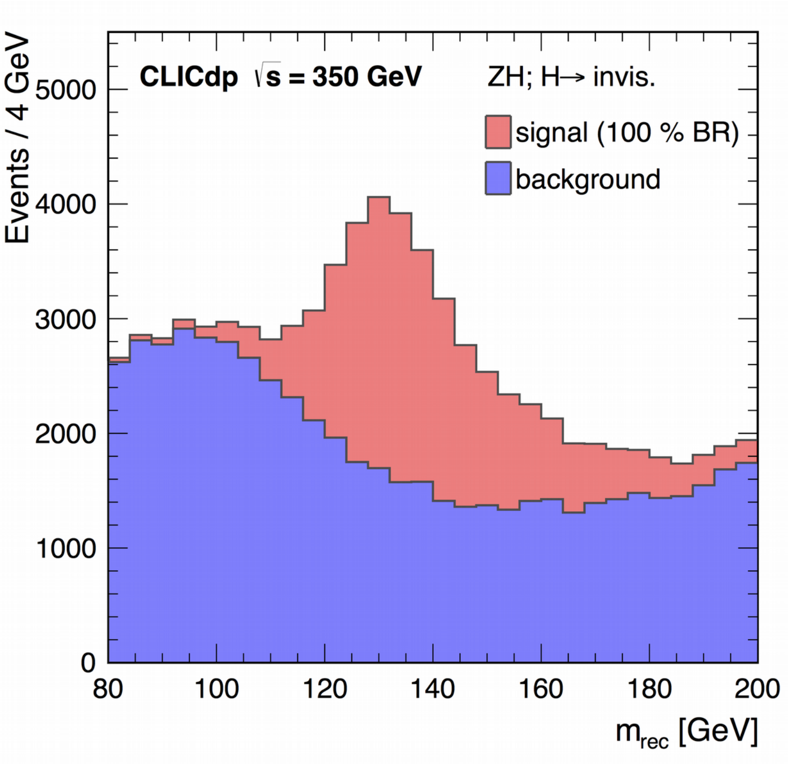
Eur. Phys. J. C 76, 72 (2016)

Invisible Higgs decays

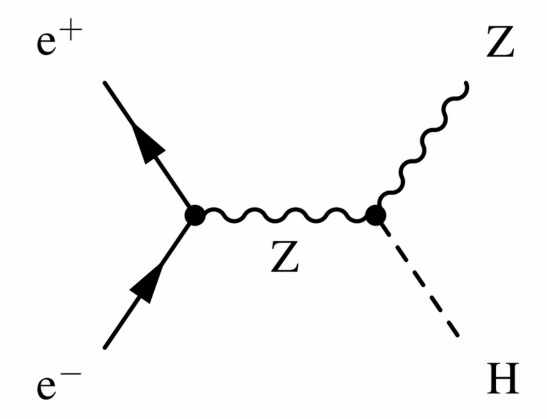
The recoil mass technique also allows to identify invisible Higgs decays in a model-independent manner

CLIC, $\sqrt{s}$ = 350 GeV, L = 500 fb^{-1}
BR(H→inv.) < 0.97% at 90% CL

ILC, $\sqrt{s}$ = 250 GeV, L = 250 fb^{-1}
BR(H→inv.) < 0.86% (0.61%) at 95% CL
for -80%/+30% (+80%/-30%) polarisation



Example: Recoil mass from $Z \rightarrow q\bar{q}$ assuming all Higgs bosons decay invisibly



Eur. Phys. J. C 76, 72 (2016)
arXiv:1708.08912

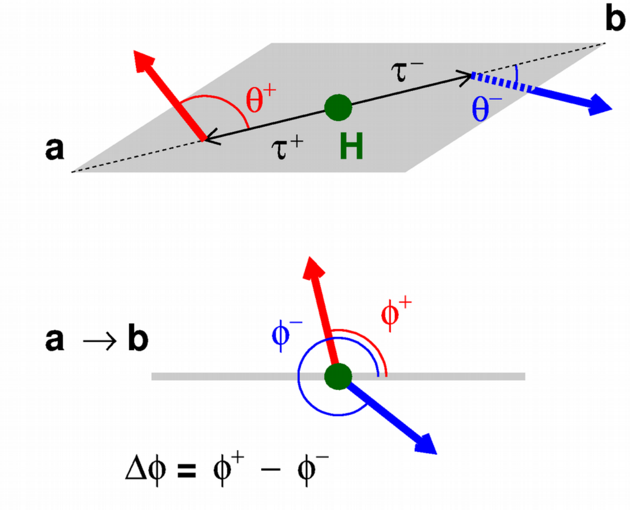
CP state of tau lepton pairs from H → $\tau^+\tau^-$

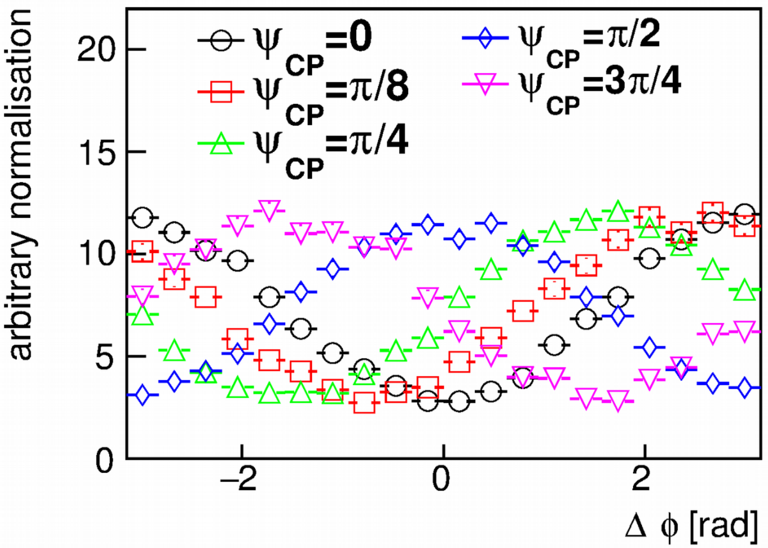
$$\boxed{-ig_{\tau\tau H}\left(\cos\psi_{CP}+i\sin\psi_{CP}\gamma_5\right)}$$

ψ_{CP} = 0: Standard Model
ψ_{CP} = π/2: Purely CP-odd coupling

Using $e^+e^- \rightarrow ZH$; $H \rightarrow \tau^+\tau^-$;
$\tau^\pm \rightarrow \pi^\pm\nu$ and $\tau^\pm \rightarrow \pi^\pm\pi^0\nu$

ILC, $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
$\Delta\psi_{CP} / \psi_{CP}$ = 75 mrad (or 4.3°)





arXiv:1804.01241

$H \rightarrow b\bar{b}/c\bar{c}/gg$ at $\sqrt{s}$ = 350 GeV

Simultaneous extraction of:

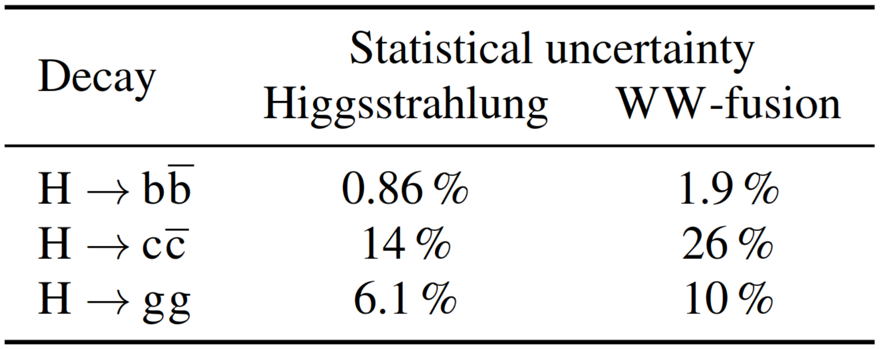
- Three decay modes: $b\bar{b}/c\bar{c}/gg$

→ precise flavour tagging

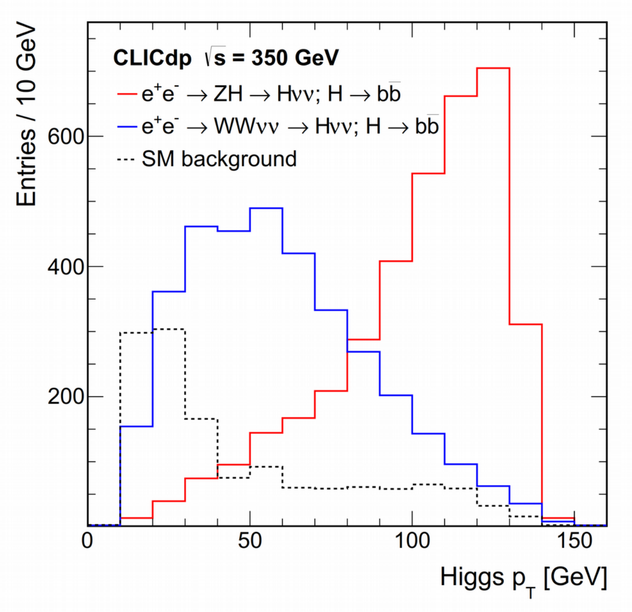
- Two production modes: ZH and WW fusion

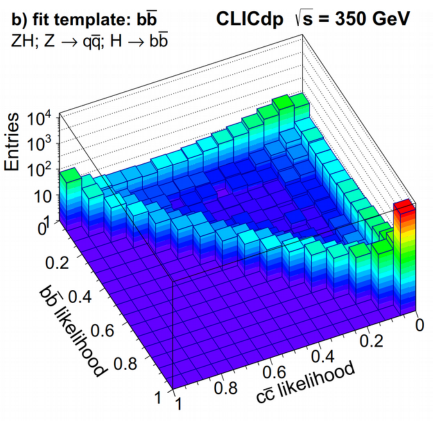
→ Higgs p_T spectrum

CLIC, $\sqrt{s}$ = 350 GeV, L = 500 fb^{-1}

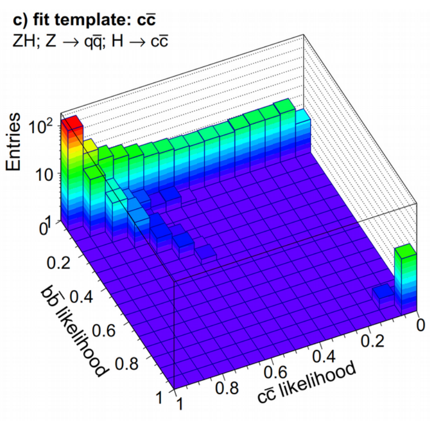


Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \rightarrow b\bar{b}$	0.86 %	1.9 %
$H \rightarrow c\bar{c}$	14 %	26 %
$H \rightarrow gg$	6.1 %	10 %

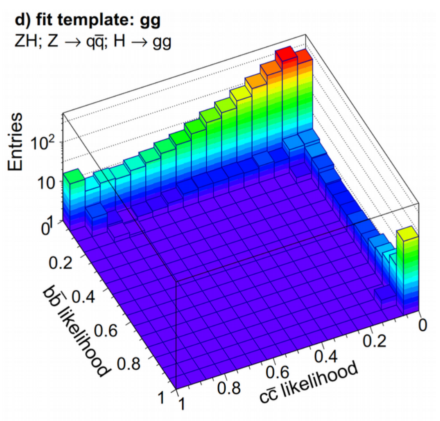




$H \rightarrow b\bar{b}$



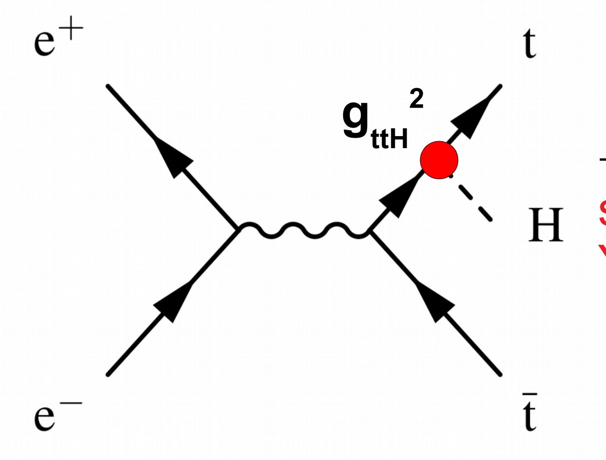
$H \rightarrow c\bar{c}$



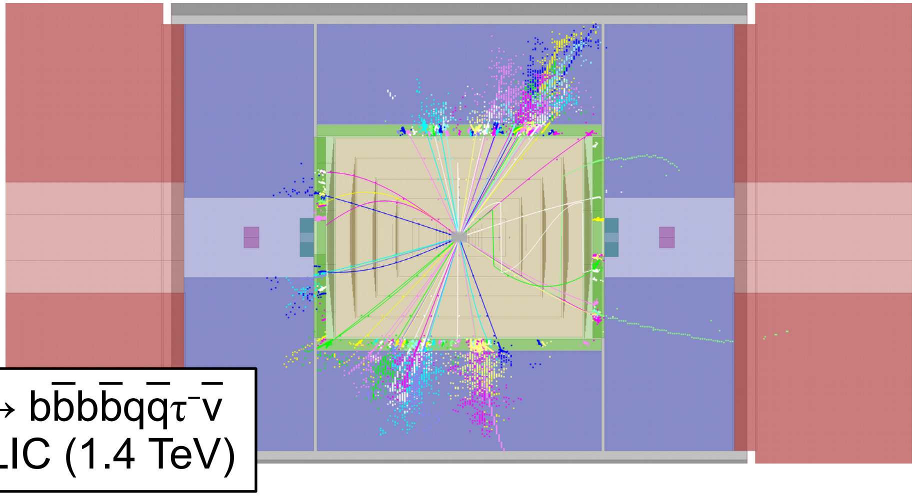
$H \rightarrow gg$

Eur. Phys. J. C 77, 475 (2017)

Top Yukawa coupling



→ $\sigma(t\bar{t}H)$ is directly sensitive to the top Yukawa coupling g_{ttH}



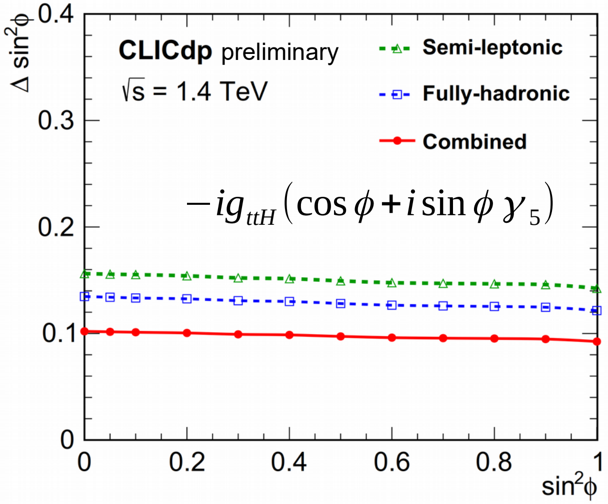
$t\bar{t}H \to b\bar{b}b\bar{b}q\bar{q}\tau^-\bar{\nu}$
at CLIC (1.4 TeV)

Most important final states:
$e^+e^- \to t\bar{t}H \to q\bar{q}bl\nu\bar{b}b\bar{b}$
$e^+e^- \to t\bar{t}H \to q\bar{q}bq\bar{q}\bar{b}b\bar{b}$
→ Roughly similar sensitivity

ILC, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}**:**
$\Delta g_{ttH}/g_{ttH}$ = 6.3%
(would be ≈3% for $\sqrt{s}$ = 550 GeV)

CLIC, $\sqrt{s}$ = 1.4 TeV, L = 1.5 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$ = 3.8%

- Sensitivity to CP mixing in the ttH coupling from $\sigma(t\bar{t}H)$
- Differential distributions under investigation

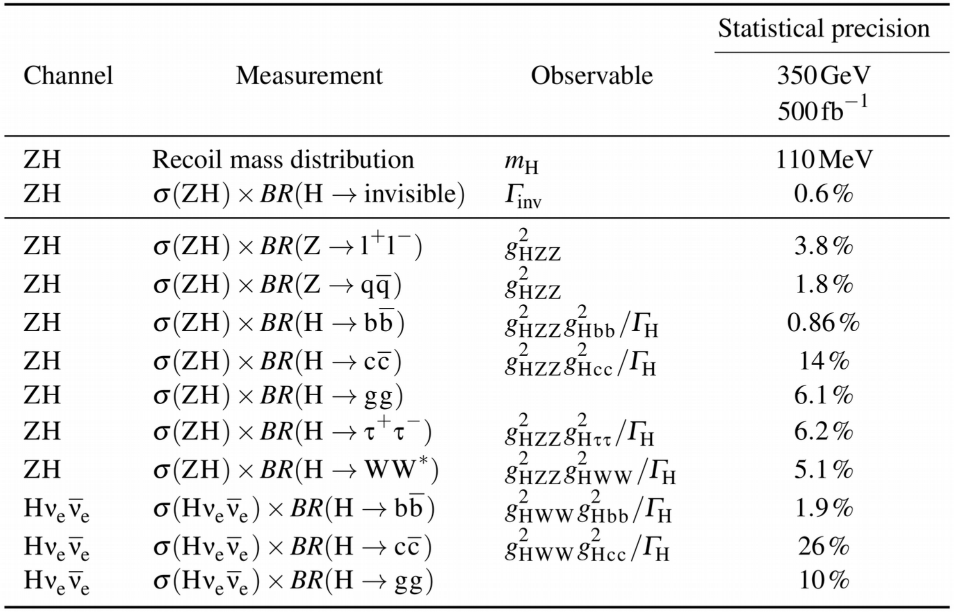


arXiv:1506.05992
Eur. Phys. J. C 77, 475 (2017)

Higgs couplings at ILC and CLIC

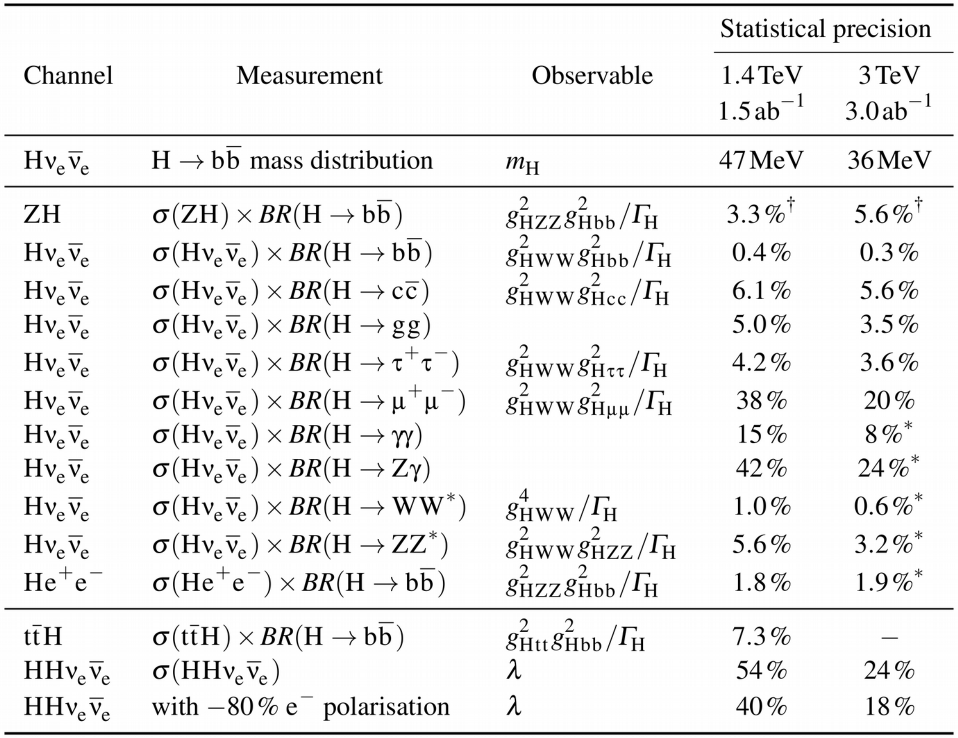
Overview: CLIC projections

√s = 350 GeV:



Channel	Measurement	Observable	Statistical precision
			350 GeV $500\,\mathrm{fb}^{-1}$
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	0.86 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc}/\Gamma_H$	14 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		6.1 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau}/\Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW}/\Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	26 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		10 %

√s = 1.4 & 3 TeV:



Channel	Measurement	Observable	Statistical precision	
			1.4 TeV $1.5\,\mathrm{ab}^{-1}$	3 TeV $3.0\,\mathrm{ab}^{-1}$
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	36 MeV
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	3.3 %†	5.6 %†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	6.1 %	5.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	3.5 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau}/\Gamma_H$	4.2 %	3.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu}/\Gamma_H$	38 %	20 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	8 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	24 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	1.0 %	0.6 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ}/\Gamma_H$	5.6 %	3.2 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	1.8 %	1.9 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb}/\Gamma_H$	7.3 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54 %	24 %
$HH\nu_e\bar{\nu}_e$	with −80 % e^- polarisation	λ	40 %	18 %

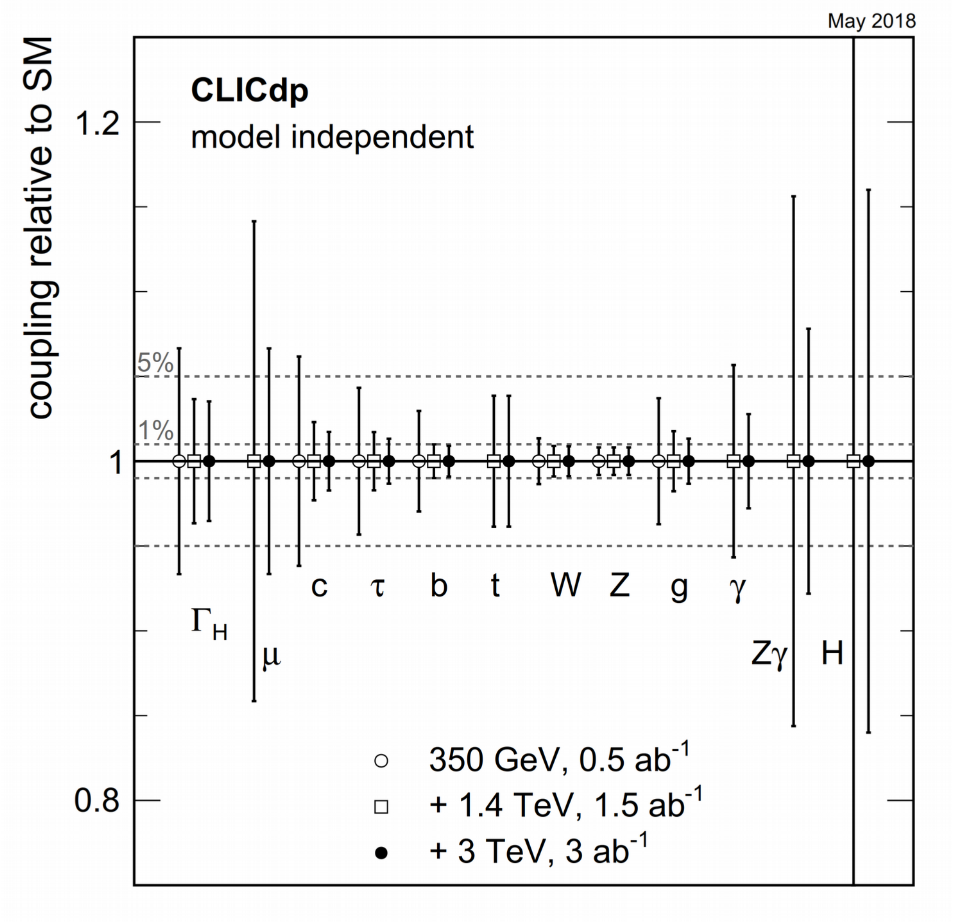
- Unpolarised electron beam (equivalent to 50% in both configurations)
- With present knowledge, more data would be collected with $P(e^-) = -80\%$ at high energy

†: fast simulation

*: extrapolated from 1.4 to 3 TeV

Based on Eur. Phys. J. C 77, 475 (2017)

CLIC coupling sensitivity (1)



$\sigma(ZH) \sim g^2_{HZZ}$

$\sigma(ZH) \times BR(H\rightarrow VV/ff) \sim g^2_{HZZ} g^2_{HVV/Hff} / \Gamma_H$

$\sigma(H\nu_e\bar{\nu}_e) \times BR(H\rightarrow VV/ff) \sim g^2_{HWW} g^2_{HVV/Hff} / \Gamma_H$

- No assumptions on additional Higgs decays (requires lepton collider)
- Correlations included where relevant
- All results limited by 0.8% from σ(HZ) measurement
- The Higgs width is extracted with 6.7 - 3.5% precision

Based on Eur. Phys. J. C 77, 475 (2017)

CLIC coupling sensitivity (2)

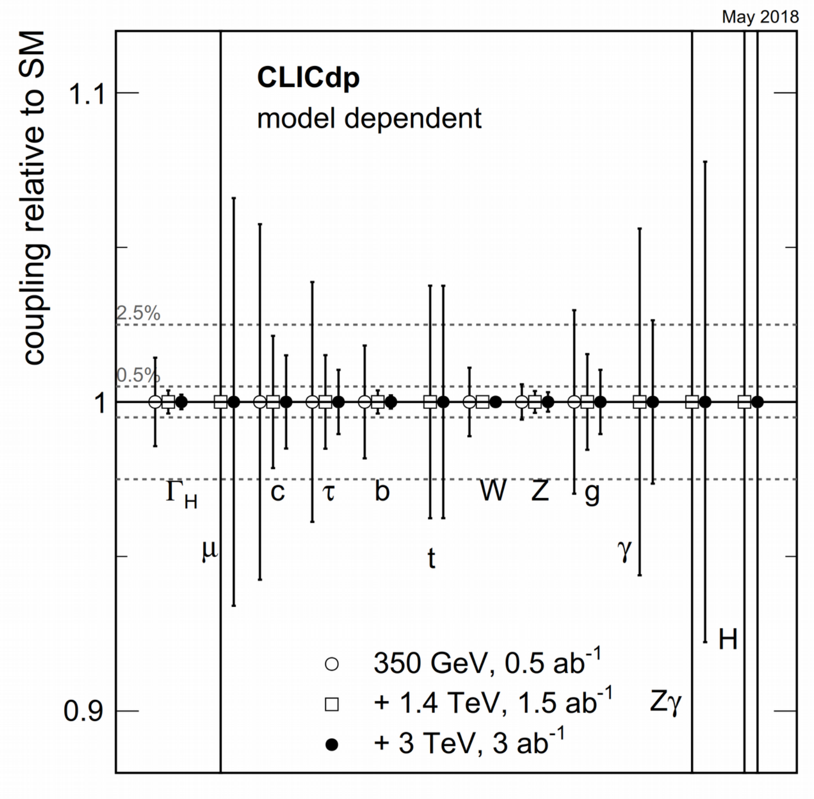
Model dependent fit:

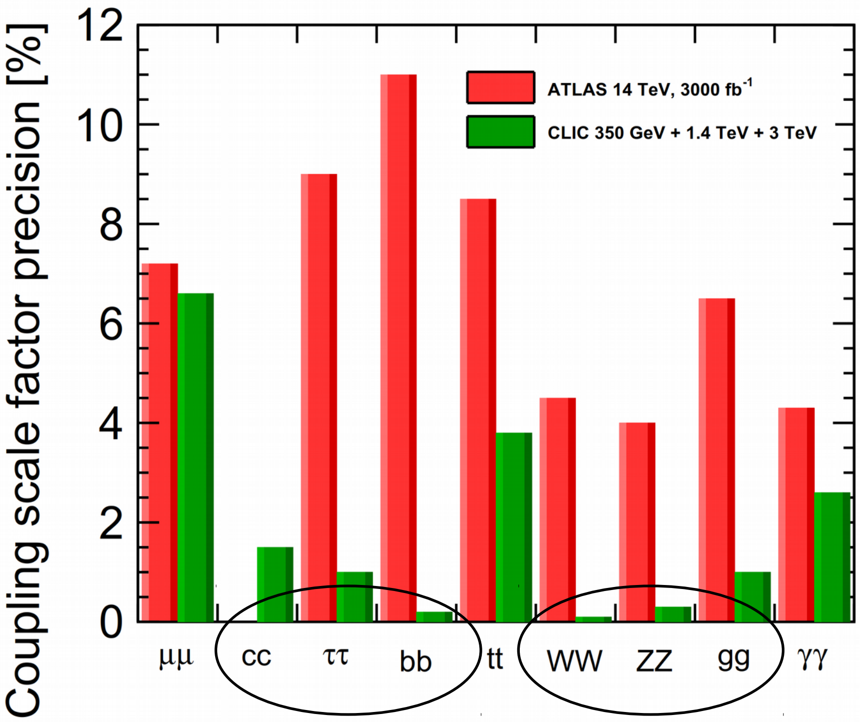
$$\kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

BR$_i$: SM branching fractions (prediction)

Only SM Higgs decays:

$$\boxed{\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \sum_i \kappa_i^2 \, BR_i}$$





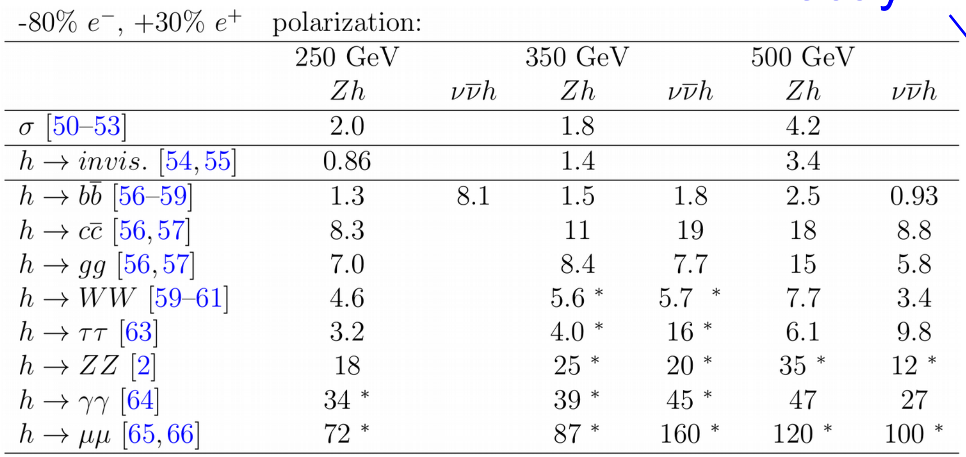
Based on Eur. Phys. J. C 77, 475 (2017)
ATLAS-PHYS-PUB-2014-016

Overview: ILC projections

Projections for σ(ZH) and σ x BR measurements at the ILC

Production channel and energy

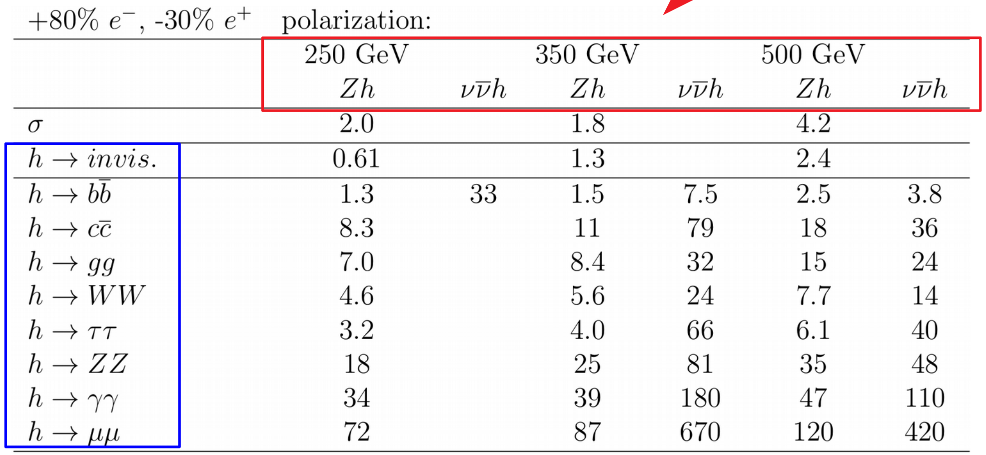
Decay mode



-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54, 55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56, 57]	8.3		11	19	18	8.8
$h \to gg$ [56, 57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65, 66]	72 *		87 *	160 *	120 *	100 *

P(e⁻) = -80%, P(e⁺) = +30%, L = 250 fb^{-1}



+80% e^-, -30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	2.0		1.8		4.2	
$h \to invis.$	0.61		1.3		2.4	
$h \to b\bar{b}$	1.3	33	1.5	7.5	2.5	3.8
$h \to c\bar{c}$	8.3		11	79	18	36
$h \to gg$	7.0		8.4	32	15	24
$h \to WW$	4.6		5.6	24	7.7	14
$h \to \tau\tau$	3.2		4.0	66	6.1	40
$h \to ZZ$	18		25	81	35	48
$h \to \gamma\gamma$	34		39	180	47	110
$h \to \mu\mu$	72		87	670	120	420

P(e⁻) = +80%, P(e⁺) = -30%, L = 250 fb^{-1}

Assumed luminosities and polarisation sharing:
2 ab^{-1} with (−+,+−,−−,++) = (45%,45%,5%,5%) at 250 GeV
4 ab^{-1} with (−+,+−,−−,++) = (40%,40%,10%,10%) at 500 GeV

*: extrapolated

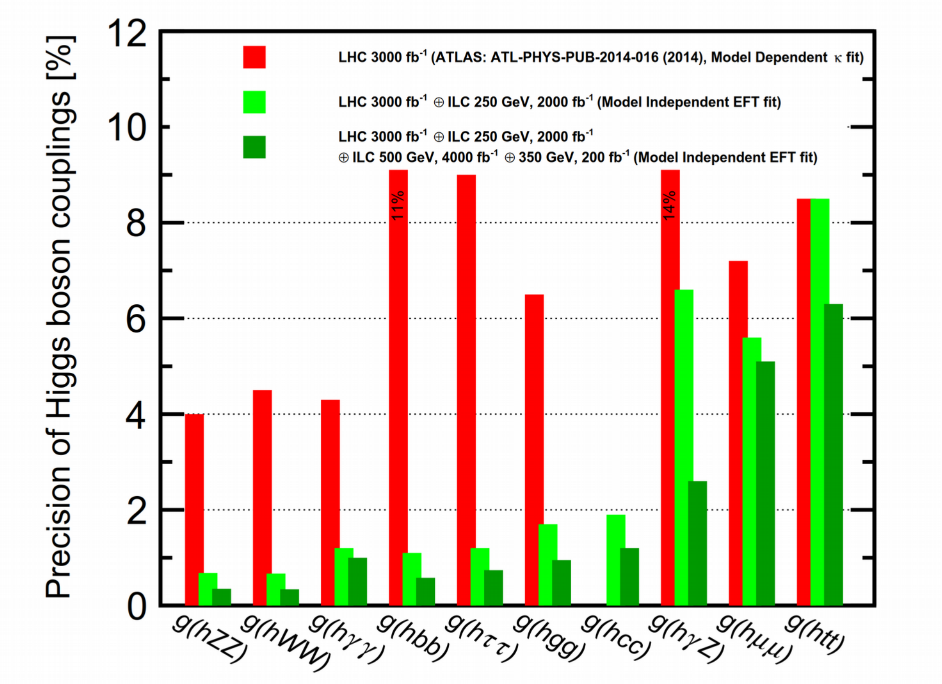
Phys. Rev. D 97, 053003 (2018)

ILC coupling sensitivity

- Fits based on the "kappa" and EFT frameworks

- Similar to CLIC, several couplings measured much better than HL-LHC

- H → $c\bar{c}$ difficult at hadron colliders



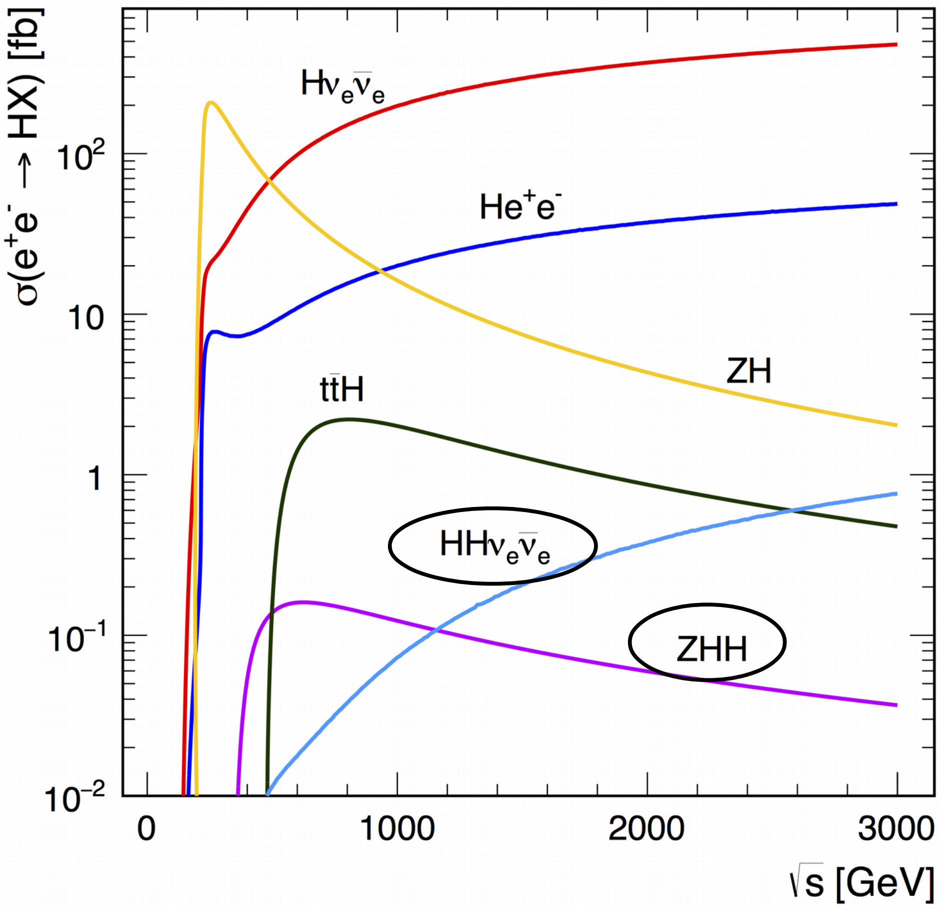
	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
Γ_h	3.9	2.5	1.7	1.6
$BR(h \to inv)$	0.32	0.32	0.29	0.29
$BR(h \to other)$	1.6	1.6	1.3	1.2

- All fits include $BR_{\gamma\gamma}/BR_{ZZ}$, $Br_{\gamma Z}/Br_{\gamma\gamma}$ and $BR_{\mu\mu}/BR_{\gamma\gamma}$ from HL-LHC

- The EFT fit also includes ZH angular distributions, EW precision data and $e^+e^- \to W^+W^-$

arXiv:1710.07621

Double Higgs production



$e^+e^- \rightarrow ZHH$:

- Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \leq 0.2$ fb)

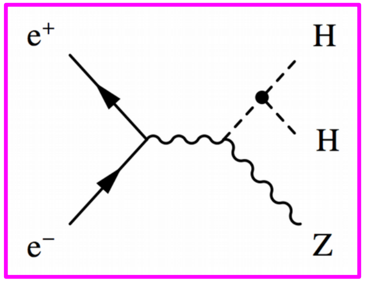
$e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$:

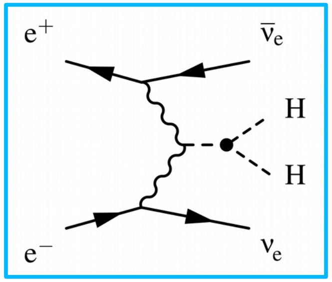
- Benefits from high-energy operation
- Also allows to extract the quartic WWHH coupling

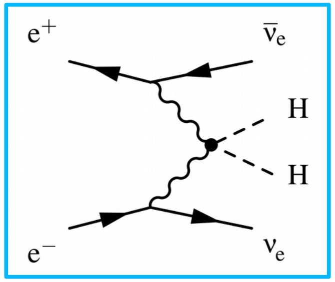
The deviations of the Higgs self-coupling from its SM expectation might be sizeable:

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\;-15\,\%^b$
NMSSM	$-25\,\%$

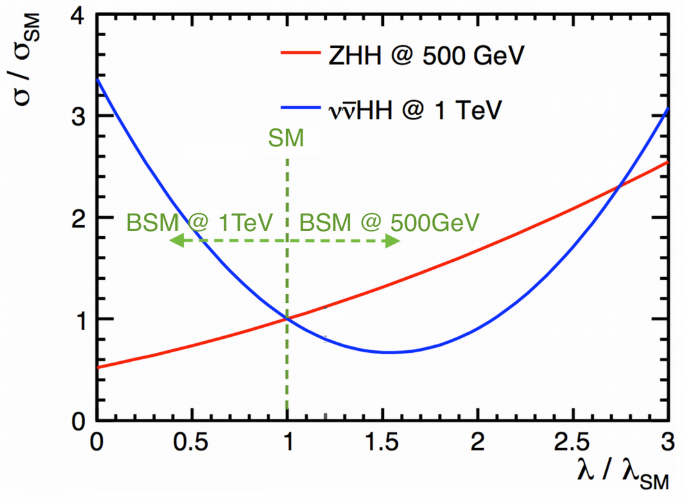
Phys. Rev. D 88, 055024 (2013)

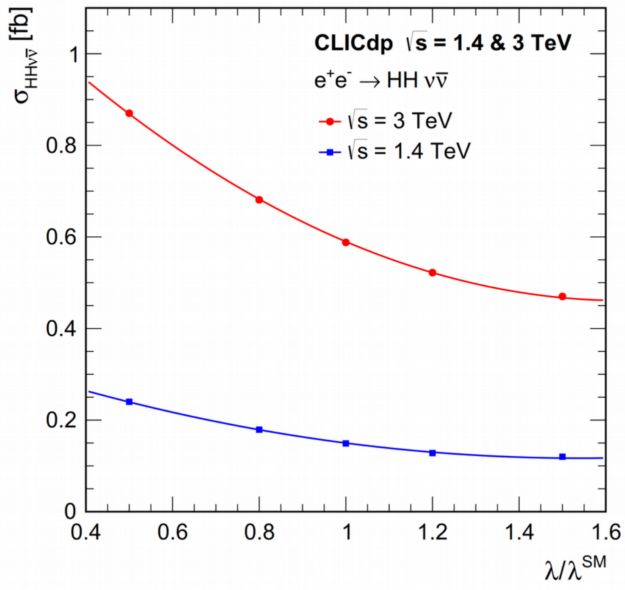






Higgs self-coupling measurements





$HH\to b\bar{b}b\bar{b}$ is the "golden channel" in e^+e^- collisions, combination with $HH\to b\bar{b}WW^*$ leads to small improvement

ILC, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}**:**
$\Delta\lambda/\lambda$ = 27%

CLIC, $\sqrt{s}$ = 1.4 TeV, L = 1.5 ab^{-1} + $\sqrt{s}$ = 3 TeV, L = 3 ab^{-1}**:**
$\Delta\lambda/\lambda$ = 16% for $P(e^-)$ = -80% from the total cross section
$\Delta\lambda/\lambda \approx$ 10% for $P(e^-)$ = -80% from diff. distributions

$\lambda > \lambda_{SM}$: $\sigma(ZHH)$ at 500 GeV enhanced
$\lambda < \lambda_{SM}$: $\sigma(HH\nu_e\bar{\nu}_e)$ at high energy enhanced

arXiv:1506.05992
Eur. Phys. J. C 77, 475 (2017)

Summary and conclusions

- A lepton collider would enhance our understanding of the Higgs boson significantly beyond the capabilities of the HL-LHC

- The ILC at 250 GeV provides precise measurements of many Higgs couplings and the Higgs mass using the Higgsstrahlung process

- CLIC at 380 GeV also gives access to the WW fusion process (and top pair production)

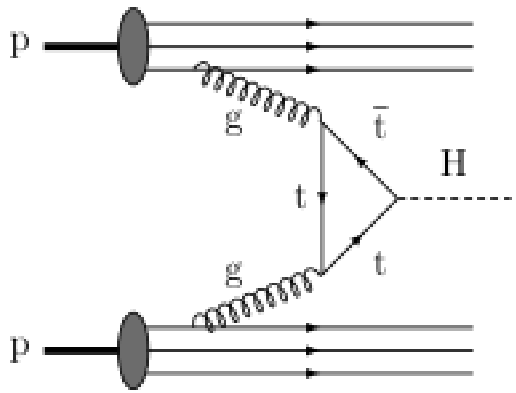
- Both colliders allow to measure the Higgsstrahlung cross section and extract the total Higgs width in a model-independent manner

- An energy of at least 500 GeV gives access to $t\bar{t}H$ (best between 800 GeV and 1.5 TeV) and double Higgs production (profits from the highest possible energies)

Backup slides

Hadron and e^+e^- colliders

Hadron colliders:

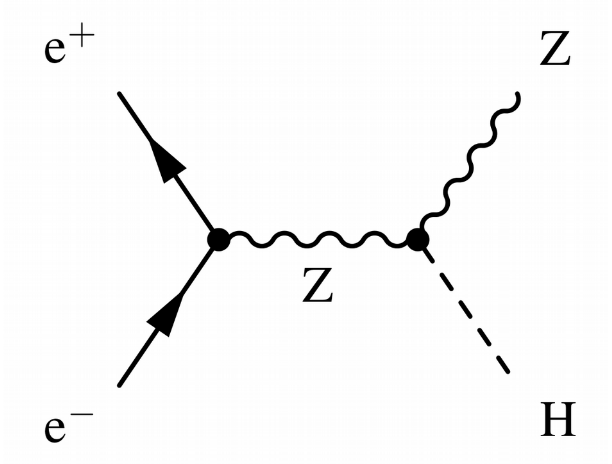


• Proton is compound object
→ Initial state unknown
→ Limits achievable precision

• High-energy circular colliders possible

• High rates of QCD backgrounds
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:

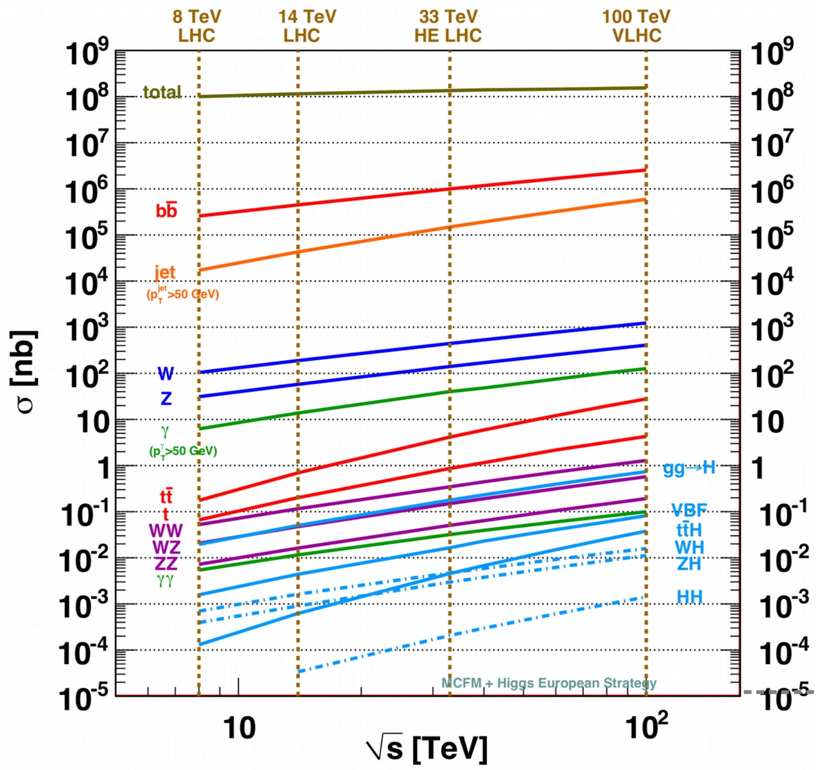


• e^+e^- are pointlike
→ Initial state well-defined (√s, polarisation)
→ High-precision measurements

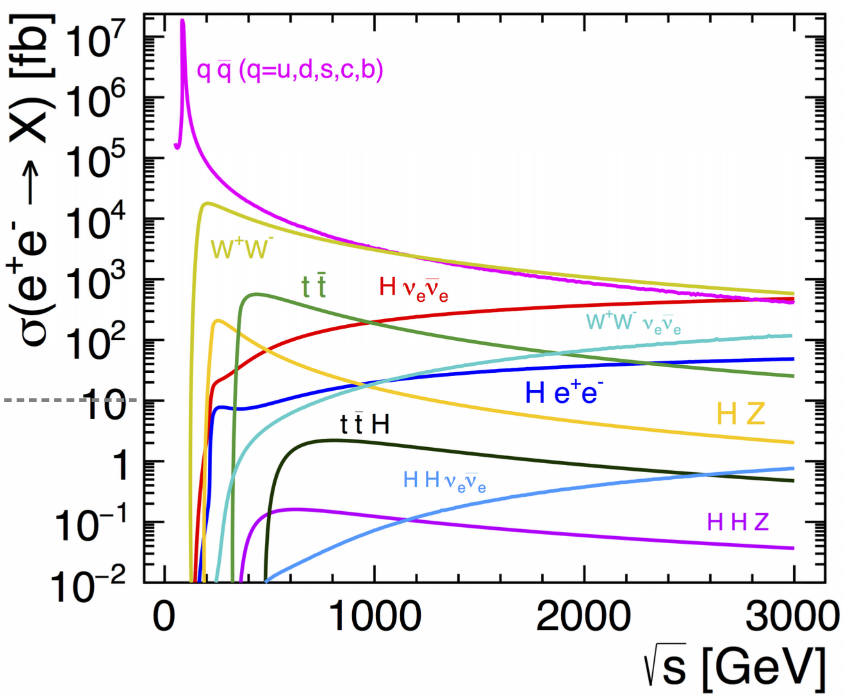
• High energies (√s > 350 GeV) require linear colliders

• Clean experimental environment
→ Less / no need for triggers
→ Lower radiation levels

pp and e^+e^- collisions



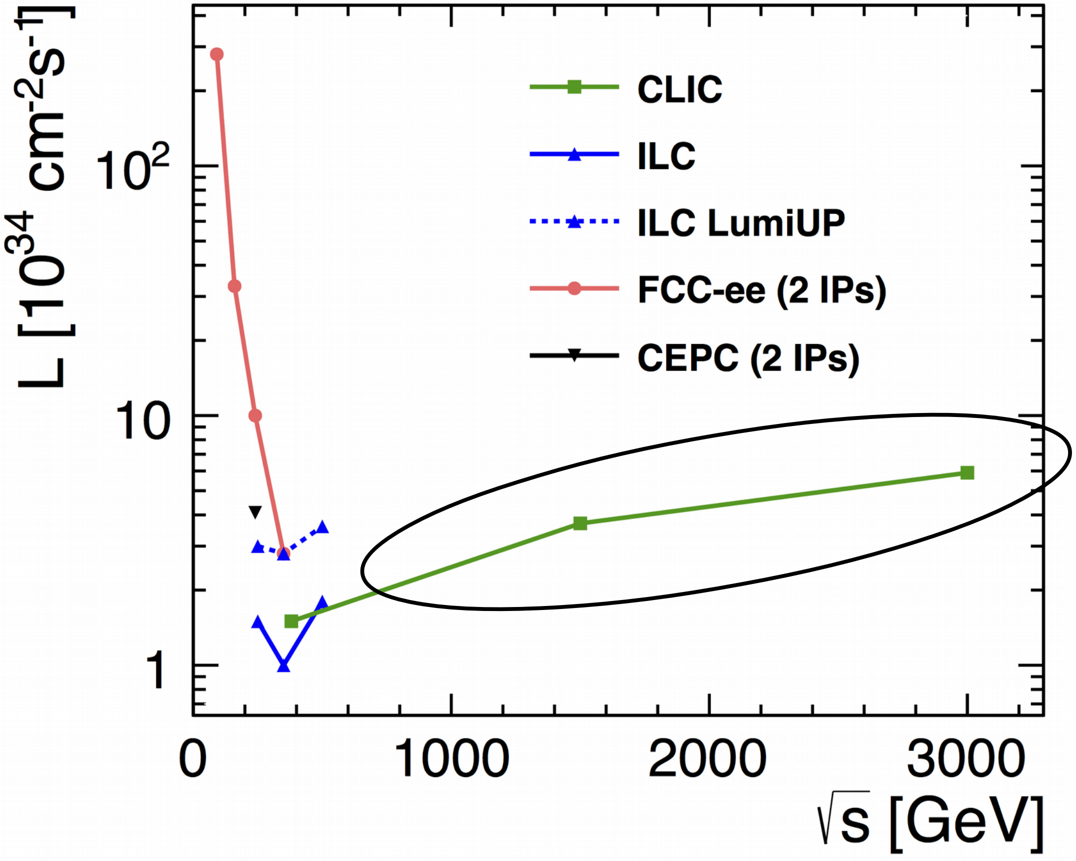
8 orders of Magnitude!



pp collisions:
Interesting events need to be found in huge number of collisions

e^+e^- collisions:
More “clean”, all events usable

Comparison of e^+e^- collider options



Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

NB: Peak luminosity at LEP2 (209 GeV) was ≈10^{32} cm^{-2}s^{-1}

BSM potential of Higgs production & $e^+e^- \rightarrow W^+W^-$

Effective Field Theory:

Standard Model

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

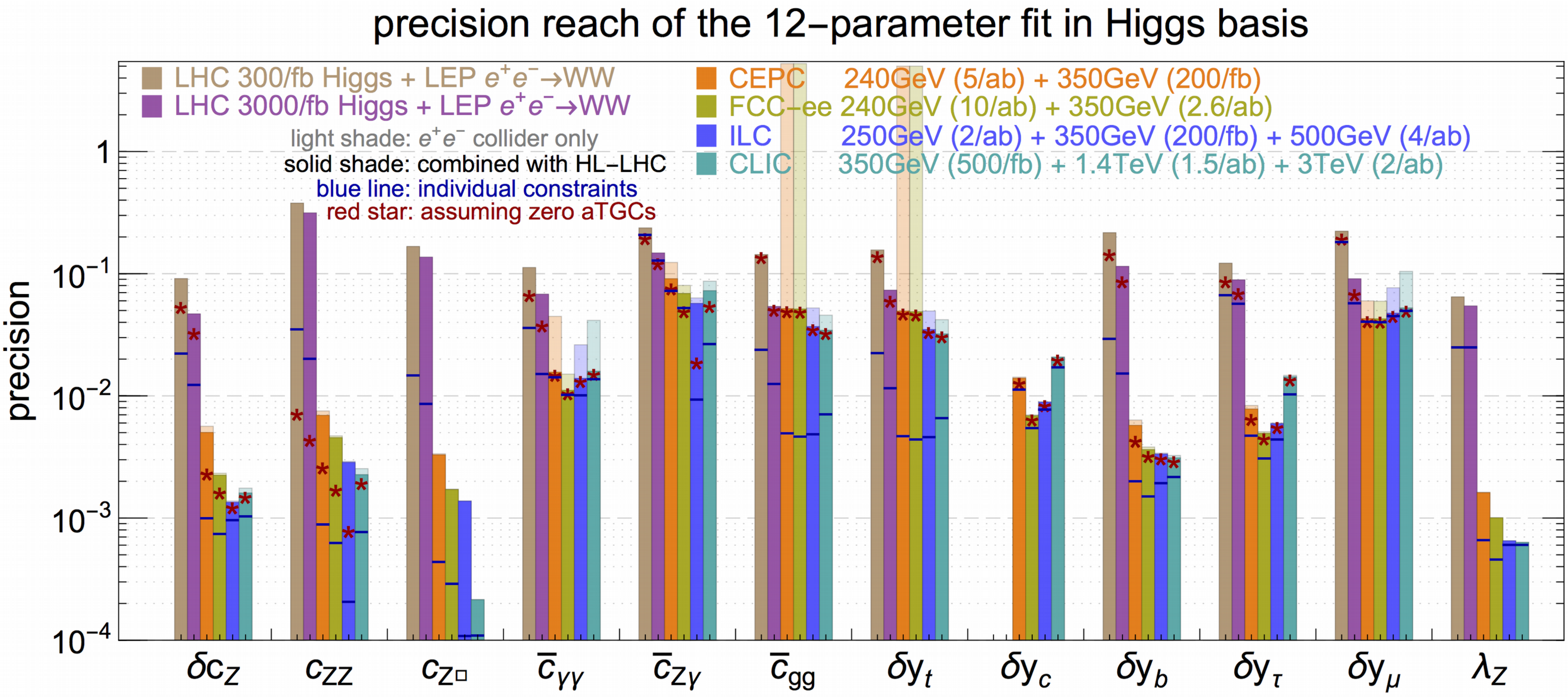
Dimension-6 operators

Scale of new decoupled physics

- Model-independent framework for probing indirect signs of new physics → very useful for comparison of future collider options / parameters

- **Input to fits:** Higgs production in Higgsstrahlung and WW fusion, $e^+e^- \rightarrow t\bar{t}H$, weak boson pair production: $e^+e^- \rightarrow W^+W^-$

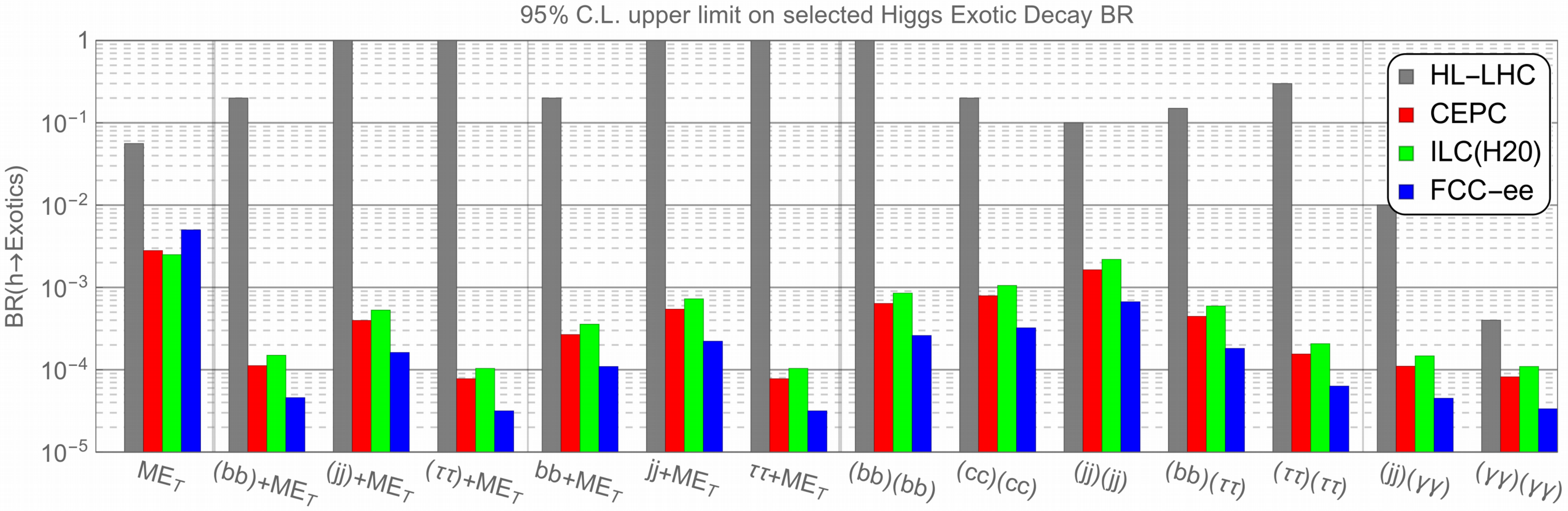
Comparison of different collider options



- Many EFT parameters can be measured significantly better at CLIC compared to the HL-LHC
- H→$c\bar{c}$ only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 1705, 096 (2017)

Exotic Higgs decays



- An e^+e^- Higgs factory would provide large improvements compared to the HL-LHC
- The ILC projections are for 2 ab^{-1} at 250 GeV
- Potential of WW fusion at higher energies to be explored

(more than 1 million Higgs decays at 3 TeV CLIC)

arXiv:1612.09284