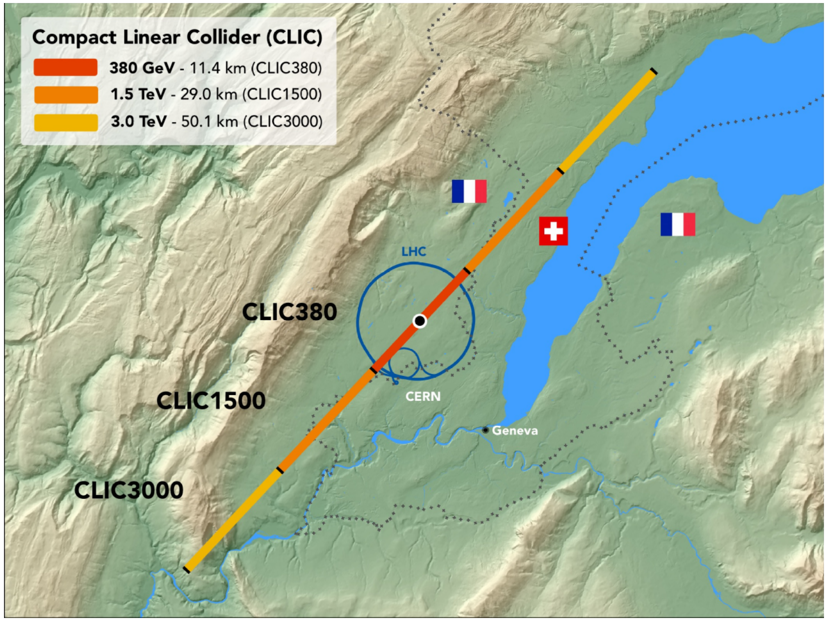
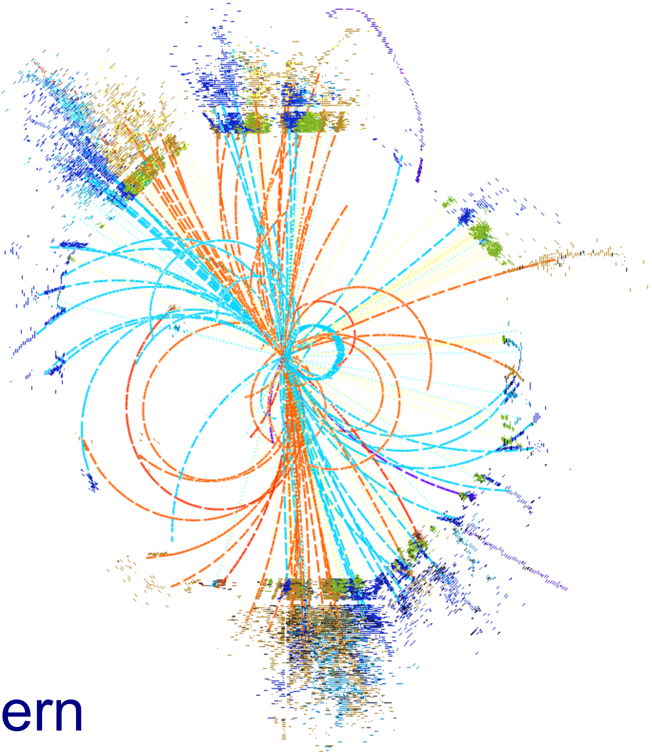
Precision measurements at CLIC

Philipp Roloff (CERN)

02/07/2020

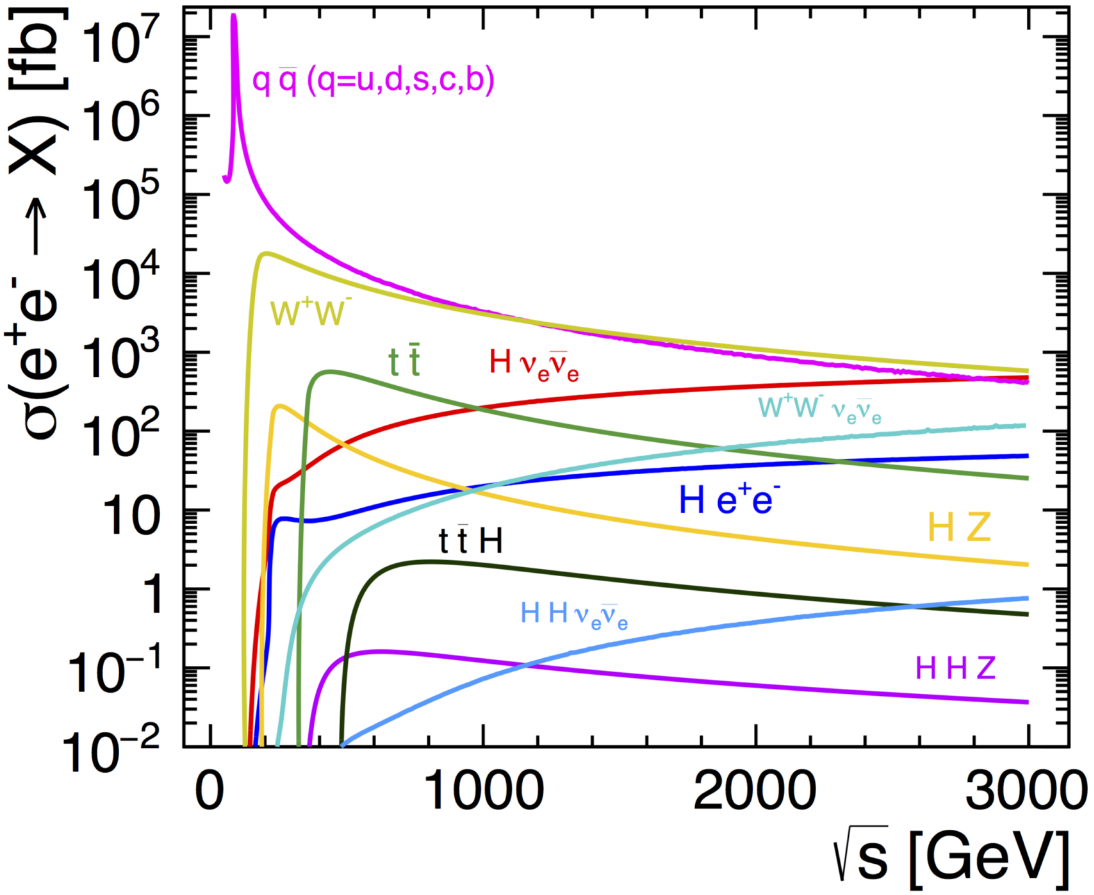
Snowmass EF04 topical group





CLIC Portal: clic.cern

Important processes in e^+e^- collisions

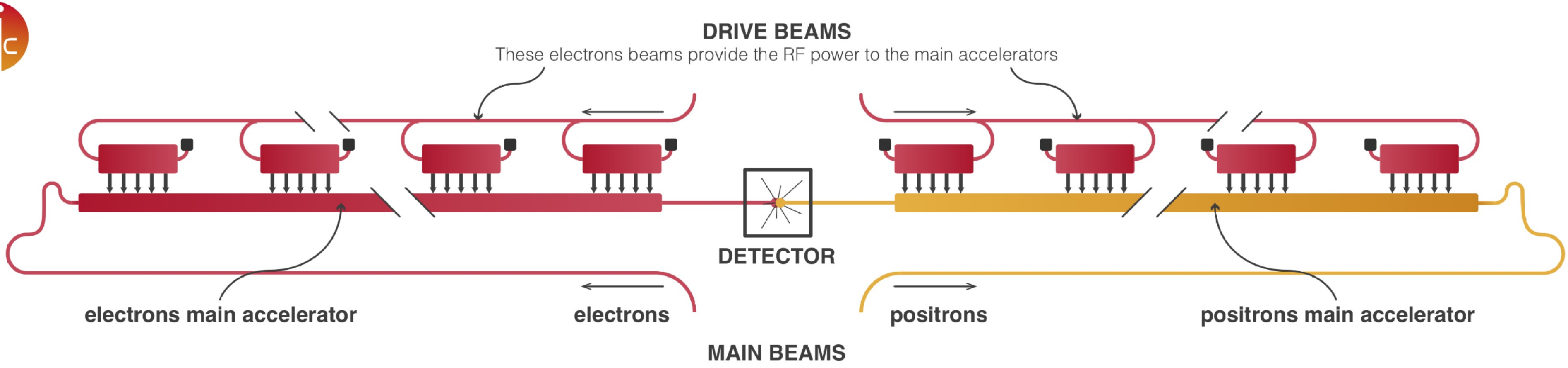


- **2-fermion production,** e.g. $q\bar{q}$
- **W-boson pair production (WW)**
- **Higgsstrahlung (HZ):** best at 240 - 380 GeV → "Higgs factory"
- **$t\bar{t}$ threshold:** 350 GeV
- **$t\bar{t}$ continuum:** ≥ 365 GeV
- **Double Higgsstrahlung (HHZ):** cross section maximum ≈ 600 GeV
- **Single and double Higgs in WW fusion ($H\nu_e\bar{\nu}_e$ and $HH\nu_e\bar{\nu}_e$):** cross section rises with energy

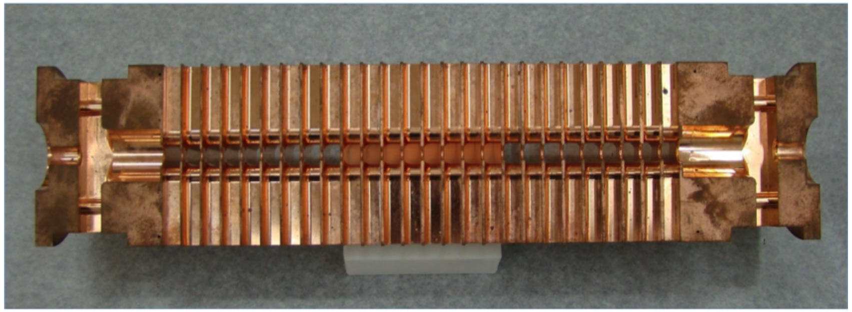
→ Wide range of physics opportunities, best explored in several energy stages

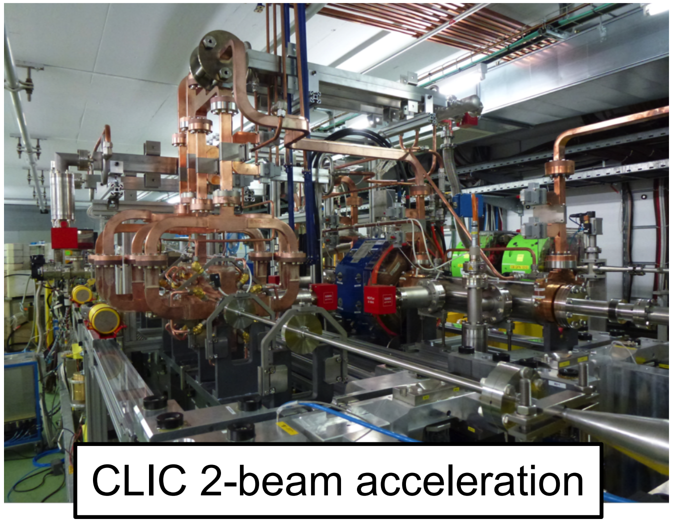
+ Direct searches for new particles:
highest possible energy

The Compact Linear Collider



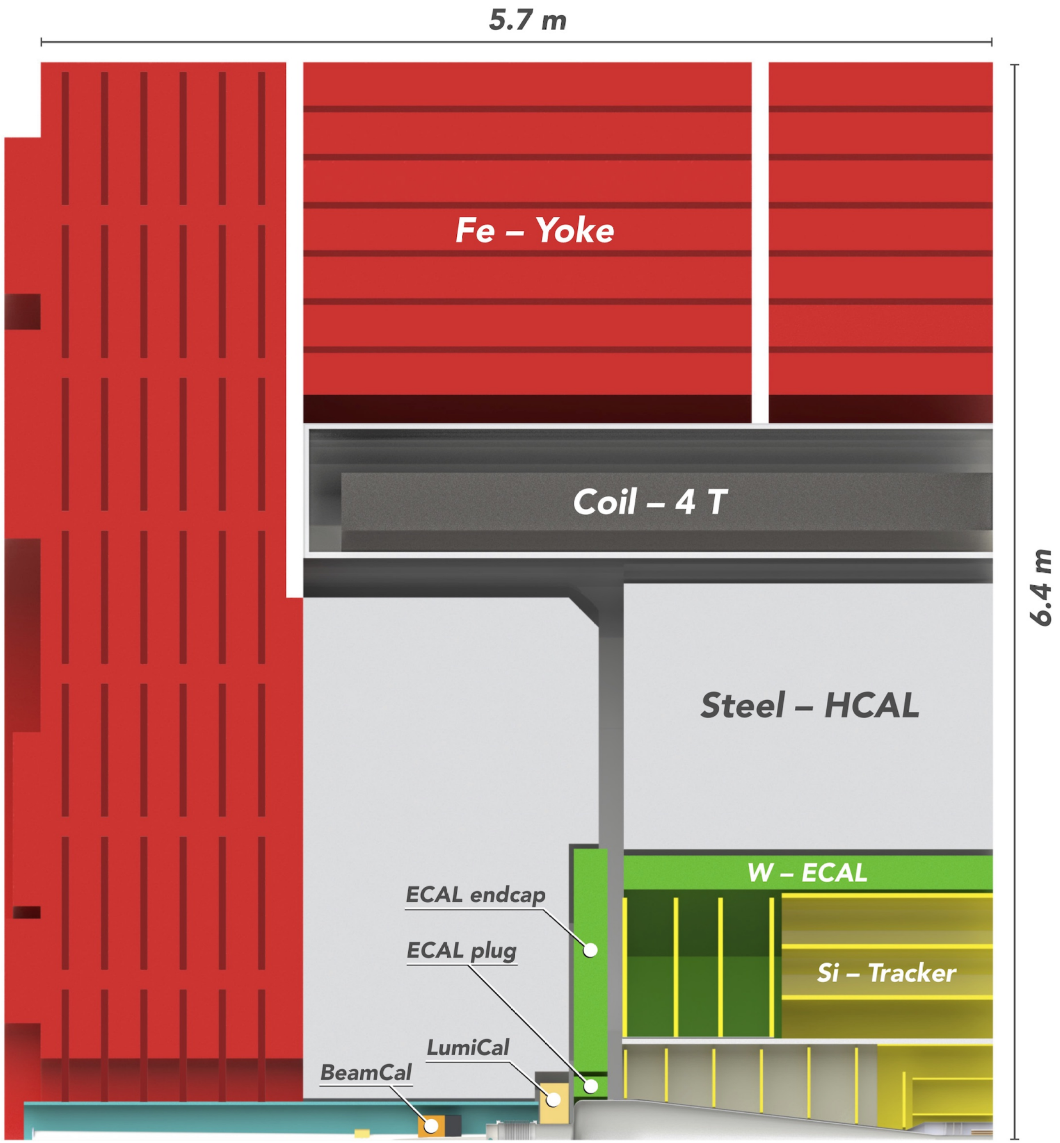
Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV (in several stages)
- $P(e^-) = \pm 80\%$

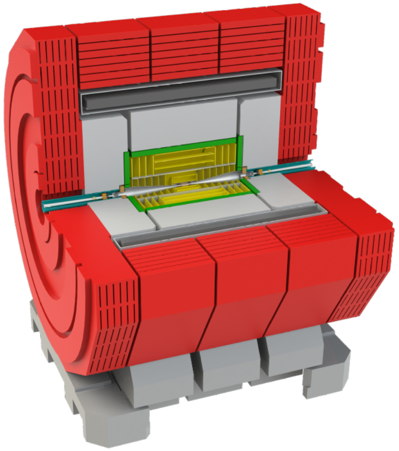




CLIC 2-beam acceleration

CLIC detector concept





Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)

Precise timing for background suppression
(bunch crossings 0.5 ns apart)**:**
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits

CLICdp-Note-2017-001
arXiv:1812.07337

CLIC staged implementation

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(\text{e}^-) = -80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(\text{e}^-) = +80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0

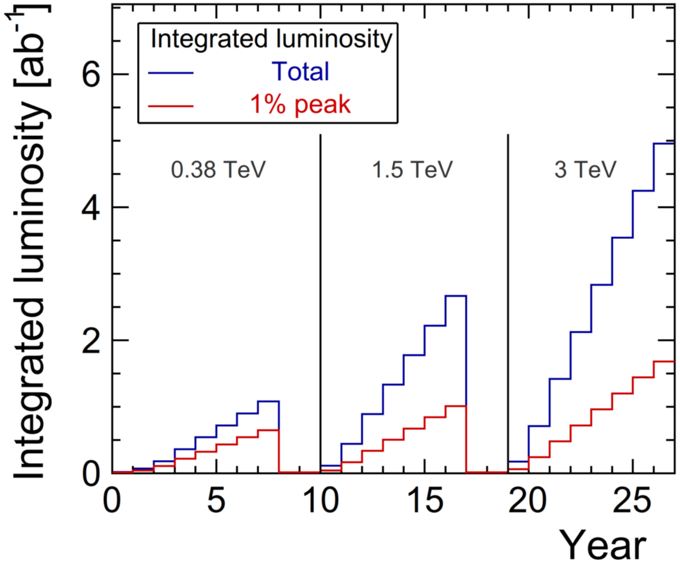
arXiv:1810.13022
arXiv:1812.01644

- CLIC would be implemented in several energy stages

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

- 1 year = 1.2×10^7 seconds (based on CERN experience)

NB: Many physics benchmark studies assumed slightly different energies for the first two stages: 380 → 350 GeV, 1.5 → 1.4 TeV



For reference: CLIC Higgs projections

$\sqrt{s}$ = 350 GeV:

Channel	Measurement	Observable	Statistical precision 350 GeV 1 ab^{-1}
ZH	Recoil mass distribution	m_{H}	78 MeV
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \text{invisible})$	Γ_{inv}	0.4 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{Z} \to \mathrm{l}^+\mathrm{l}^-)$	g^2_{HZZ}	2.7 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{Z} \to \mathrm{q\bar{q}})$	g^2_{HZZ}	1.3 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	0.61 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hcc}}/\Gamma_{\mathrm{H}}$	10 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{gg})$		4.3 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{H\tau\tau}}/\Gamma_{\mathrm{H}}$	4.4 %
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{HWW}}/\Gamma_{\mathrm{H}}$	3.6 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	1.3 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hcc}}/\Gamma_{\mathrm{H}}$	18 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{gg})$		7.2 %

$\sqrt{s}$ = 1.4 & 3 TeV:

Channel	Measurement	Observable	Statistical precision 1.4 TeV 2.5 ab^{-1}	 3 TeV 5.0 ab^{-1}
$\mathrm{H}\nu_e\bar{\nu}_e$	$\mathrm{H} \to \mathrm{b\bar{b}}$ mass distribution	m_{H}	36 MeV	28 MeV
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	2.6 %†	4.3 %†
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	0.3 %	0.2 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hcc}}/\Gamma_{\mathrm{H}}$	4.7 %	4.4 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{gg})$		3.9 %	2.7 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{H\tau\tau}}/\Gamma_{\mathrm{H}}$	3.3 %	2.8 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mu^+\mu^-)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{H\mu\mu}}/\Gamma_{\mathrm{H}}$	29 %	16 %
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \gamma\gamma)$		12 %	6 %*
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{Z}\gamma)$		33 %	19 %*
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^4_{\mathrm{HWW}}/\Gamma_{\mathrm{H}}$	0.8 %	0.4 %*
$\mathrm{H}\nu_e\bar{\nu}_e$	$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{ZZ}^*)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{HZZ}}/\Gamma_{\mathrm{H}}$	4.3 %	2.5 %*
$\mathrm{He}^+\mathrm{e}^-$	$\sigma(\mathrm{He}^+\mathrm{e}^-) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	1.4 %	1.5 %*
$\mathrm{t\bar{t}H}$	$\sigma(\mathrm{t\bar{t}H}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{Htt}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	5.7 %	–

- These numbers are for unpolarised electron beams
- The baseline scenario assumes 4:1 sharing of the −80% / +80% polarisation configurations (used on the following)

†: fast simulation
*: extrapolated from 1.4 to 3 TeV

arXiv:1812.01644
based on Eur. Phys. J. C 77, 475 (2017)

Comments on systematics

- A comprehensive study of systematic uncertainties requires more knowledge on the technical implementation of the detector
- The Higgs projections (and other studies) illustrate the level of precision desirable for the control of systematic effects → input for detector R&D
- At the first stage a few fb^{-1} could be collected at the Z-pole at the beginning of each year → unique possibilities for calibration of momentum scale, jet energy scale, flavour tagging

Examples: $H \to b\bar{b}$ in WW fusion at 3 TeV, L = 2 ab^{-1}, $\Delta(\sigma \times BR) = 0.3\%$ (stat.)

- Luminosity spectrum:

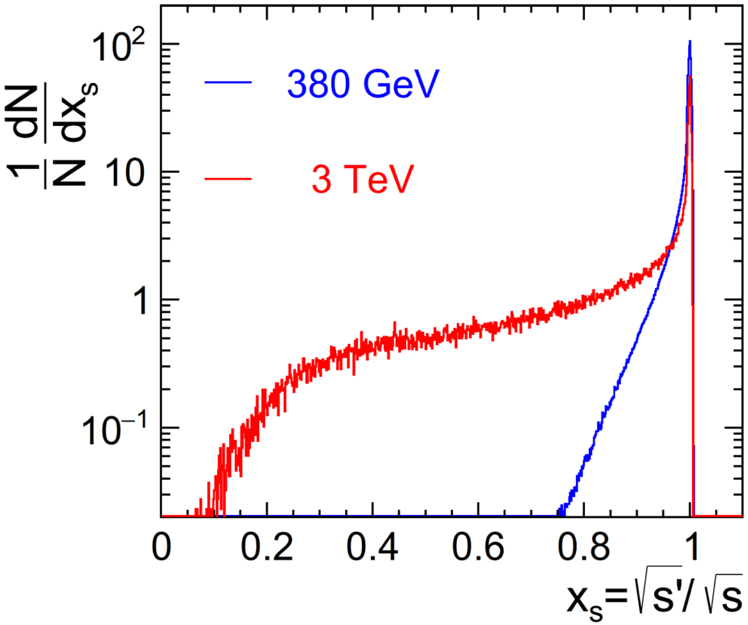
Model with 19 free parameters fitted to Bhabha events, parameter uncertainties and correlations propagated to measurement:
$\Delta(\sigma \times BR) = 0.15\%$

- Beam polarisation:

Can be measured using single W, Z and γ events with missing energy: $\Delta(\sigma \times BR) = 0.1\%$

- Total luminosity:

Accuracy of a few per mille can be achieved using the luminometer currently envisaged for CLIC (significantly better at lower energies)



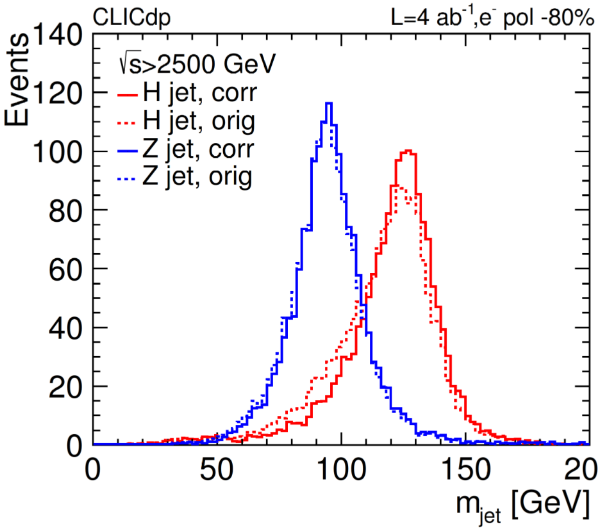
Eur. Phys. J. C 77, 475 (2017)

New: $e^+e^- \rightarrow ZH$ in full simulation

- $e^+e^- \rightarrow ZH$ at 3 TeV using $Z \rightarrow q\bar{q}$ and $H \rightarrow b\bar{b}$
→ <u>2 “fat” jets:</u> ZH event selection using substructure information
→ First study of b-tagging in boosted Higgs decays at CLIC

- Fast simulation results on σ(ZH) listed on slide 5 confirmed in full simulation

- Also projections for differential distributions (using subjet charge identification)



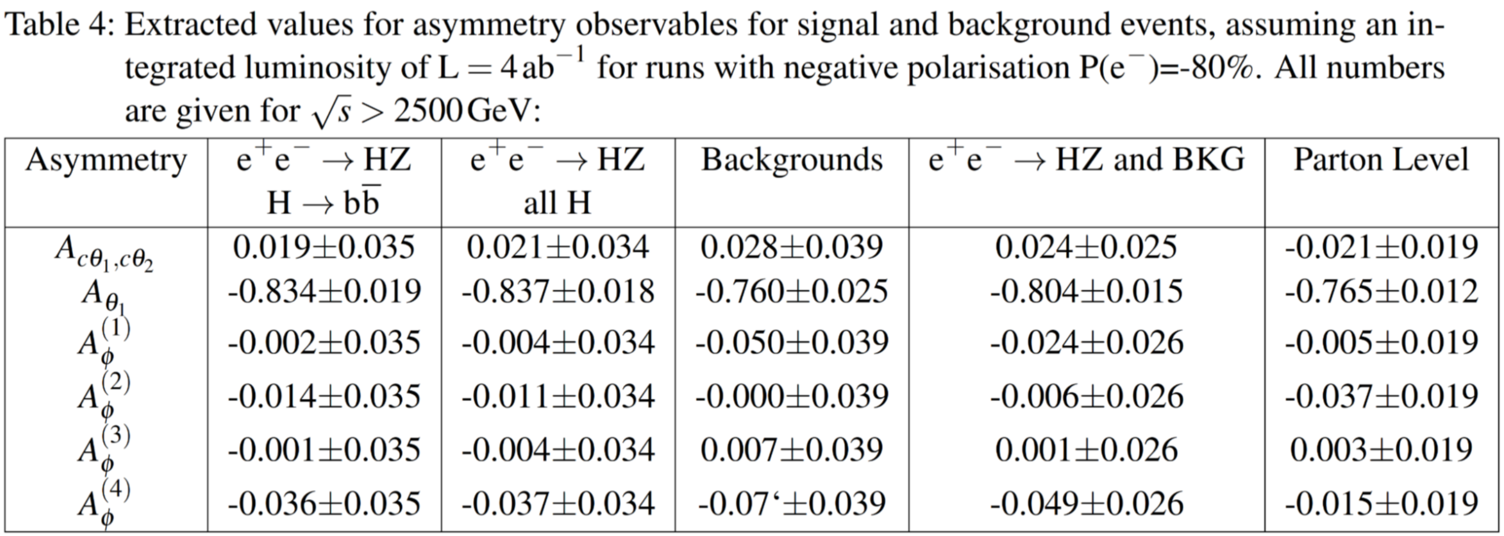


Table 4: Extracted values for asymmetry observables for signal and background events, assuming an integrated luminosity of $L = 4\,ab^{-1}$ for runs with negative polarisation P(e$^-$)=-80%. All numbers are given for $\sqrt{s} > 2500\,GeV$:

Asymmetry	$e^+e^- \rightarrow HZ$ $H \rightarrow b\bar{b}$	$e^+e^- \rightarrow HZ$ all H	Backgrounds	$e^+e^- \rightarrow$ HZ and BKG	Parton Level
$A_{c\theta_1,c\theta_2}$	0.019±0.035	0.021±0.034	0.028±0.039	0.024±0.025	-0.021±0.019
A_{θ_1}	-0.834±0.019	-0.837±0.018	-0.760±0.025	-0.804±0.015	-0.765±0.012
$A_\phi^{(1)}$	-0.002±0.035	-0.004±0.034	-0.050±0.039	-0.024±0.026	-0.005±0.019
$A_\phi^{(2)}$	-0.014±0.035	-0.011±0.034	-0.000±0.039	-0.006±0.026	-0.037±0.019
$A_\phi^{(3)}$	-0.001±0.035	-0.004±0.034	0.007±0.039	0.001±0.026	0.003±0.019
$A_\phi^{(4)}$	-0.036±0.035	-0.037±0.034	-0.07‘±0.039	-0.049±0.026	-0.015±0.019

arXiv:1911.02523

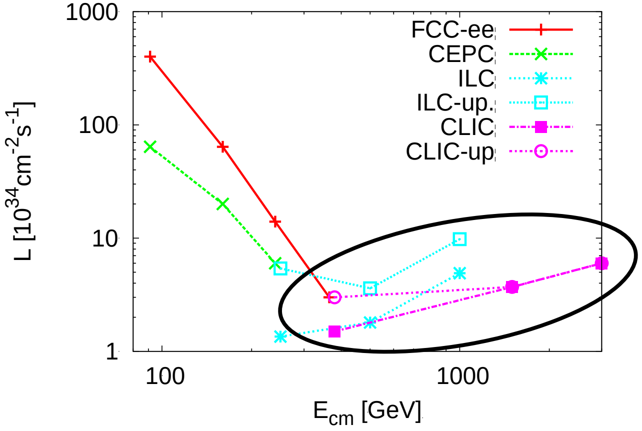
New: impact of longer first stage

Two modifications with respect to Baseline scenario (see slide 4):

- 100 Hz (bunch train) repetition rate instead 50 Hz at the first stage
→ modest increase of cost (5% level) and power (220 MW instead of 170 MW)

- Initial stage increased from 8 to 13 years

→ Integrated luminosity at 380 GeV increased by factor 4 to 4 ab^{-1}



Daniel Schulte, Granada Symposium

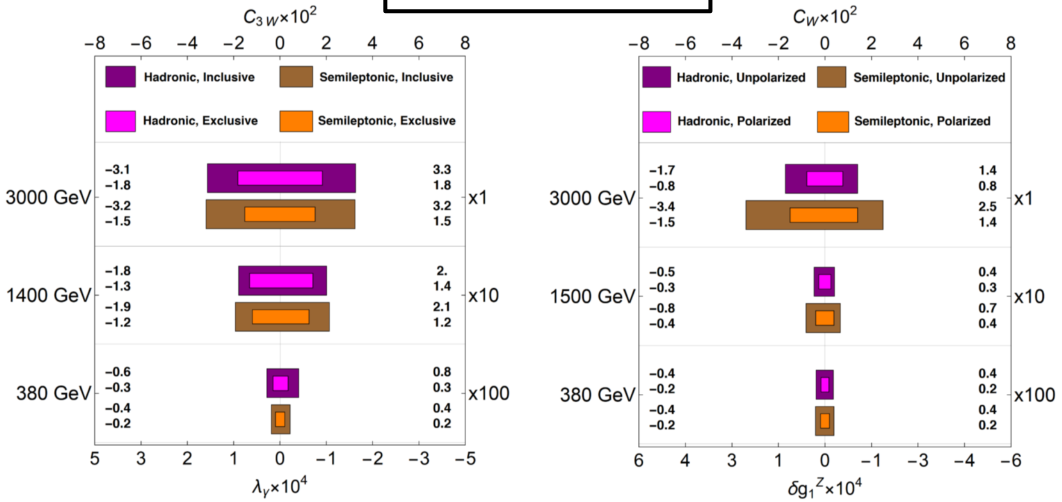
	Benchmark	HL-LHC	HL-LHC + CLIC		
			380 GeV 4 ab^{-1}	1.5 TeV 2.5 ab^{-1}	3 TeV 5 ab^{-1}
$g^{\rm eff}_{\rm HZZ}[\%]$	$\rm SMEFT_{ND}$	3.6	0.3	0.2	0.16
$g^{\rm eff}_{\rm HWW}[\%]$	$\rm SMEFT_{ND}$	3.2	0.3	0.17	0.14
$g^{\rm eff}_{\rm H\gamma\gamma}[\%]$	$\rm SMEFT_{ND}$	3.6	1.3	1.3	1.1
$g^{\rm eff}_{\rm HZ\gamma}[\%]$	$\rm SMEFT_{ND}$	11.	9.3	3.2	2.5
$g^{\rm eff}_{\rm Hgg}[\%]$	$\rm SMEFT_{ND}$	2.3	0.9	0.7	0.60
$g^{\rm eff}_{\rm Htt}[\%]$	$\rm SMEFT_{ND}$	3.5	3.1	2.1	2.1
$g^{\rm eff}_{\rm Hcc}[\%]$	$\rm SMEFT_{ND}$	–	2.1	1.5	1.2
$g^{\rm eff}_{\rm Hbb}[\%]$	$\rm SMEFT_{ND}$	5.3	0.64	0.42	0.36
$g^{\rm eff}_{\rm H\tau\tau}[\%]$	$\rm SMEFT_{ND}$	3.4	1.0	0.78	0.65
$g^{\rm eff}_{\rm H\mu\mu}[\%]$	$\rm SMEFT_{ND}$	5.5	4.3	4.1	3.5
$\delta g_{1Z}[\times 10^2]$	$\rm SMEFT_{ND}$	0.66	0.027	0.009	0.007
$\delta \kappa_\gamma[\times 10^2]$	$\rm SMEFT_{ND}$	3.2	0.044	0.023	0.017
$\lambda_Z[\times 10^2]$	$\rm SMEFT_{ND}$	3.2	0.022	0.0051	0.0018

NB: all projections in %

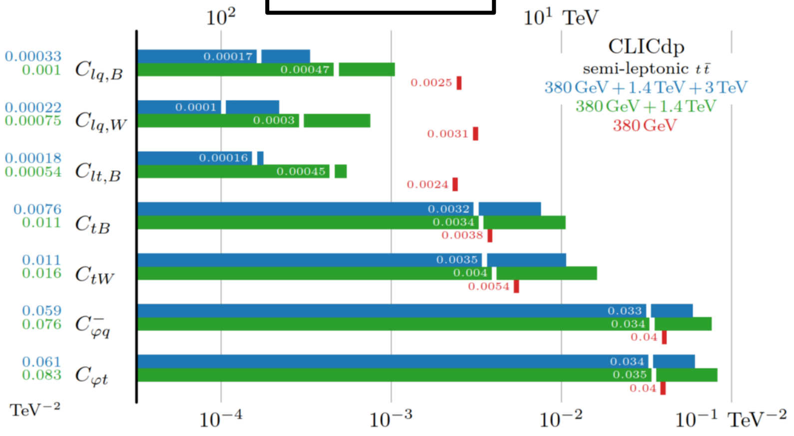
CERN-ACC-2019-0051
arXiv:2001.05278

Other crucial measurements

$e^+e^- \rightarrow W^+W^-$



$e^+e^- \rightarrow t\bar{t}$



$e^+e^- \rightarrow f\bar{f}$

Scenario (P_{e^-}, P_{e^+})	Current	CLIC Baseline $(\mp80\%, 0\%)$	CLIC Unpolarized $(0\%, 0\%)$
S	0.13	0.09 (0.05)	0.16 (0.10)
T	0.08	0.10 (0.05)	0.12 (0.07)
$W\,[\times10^6]$	600	1.7 (1.5)	3.0 (2.2)
$Y\,[\times10^6]$	900	2.0 (1.8)	2.3 (1.7)

arXiv:1812.02093
JHEP 11, 003 (2019)

EWPOs: return-to-Z events

- The energy loss due to ISR and Beamstrahlung provides large samples of return-to-Z events at the 380 GeV stage
→ In particular, significant improvement compared to LEP / SLD possible on A_e

- Generator-level study (Whizard 2) with cuts to simulate the geometric acceptance of the CLIC detector, suppress backgrounds from γγ and eγ interactions and include reconstruction efficiencies

- For example, more than 3.5 million hadronic Z decays pass the event selection assuming 1 ab^{-1} of integrated luminosity and 50:50 splitting of the -80%/+80% electron-beam polarisation configurations
(for comparison about 400000 hadronic Z decays at SLC, 16 million at LEP)

- 0.1% uncertainty on the electron beam polarisation from polarimeters or $e^+e^- \to W^+W^-$ events
→ also potential validation of the polarisation measurement at the Z-pole (see later)

$$A_{LR} = \frac{1}{|P|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e \qquad A^f_{FB,LR} = \frac{1}{P}\frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4}A_f$$

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.0006	0.00015
A_μ	0.142	0.0039	0.00014
A_τ	0.143	0.0055	0.00014
A_c	0.670	0.0019	0.00067
A_b	0.923	0.0036	0.00092

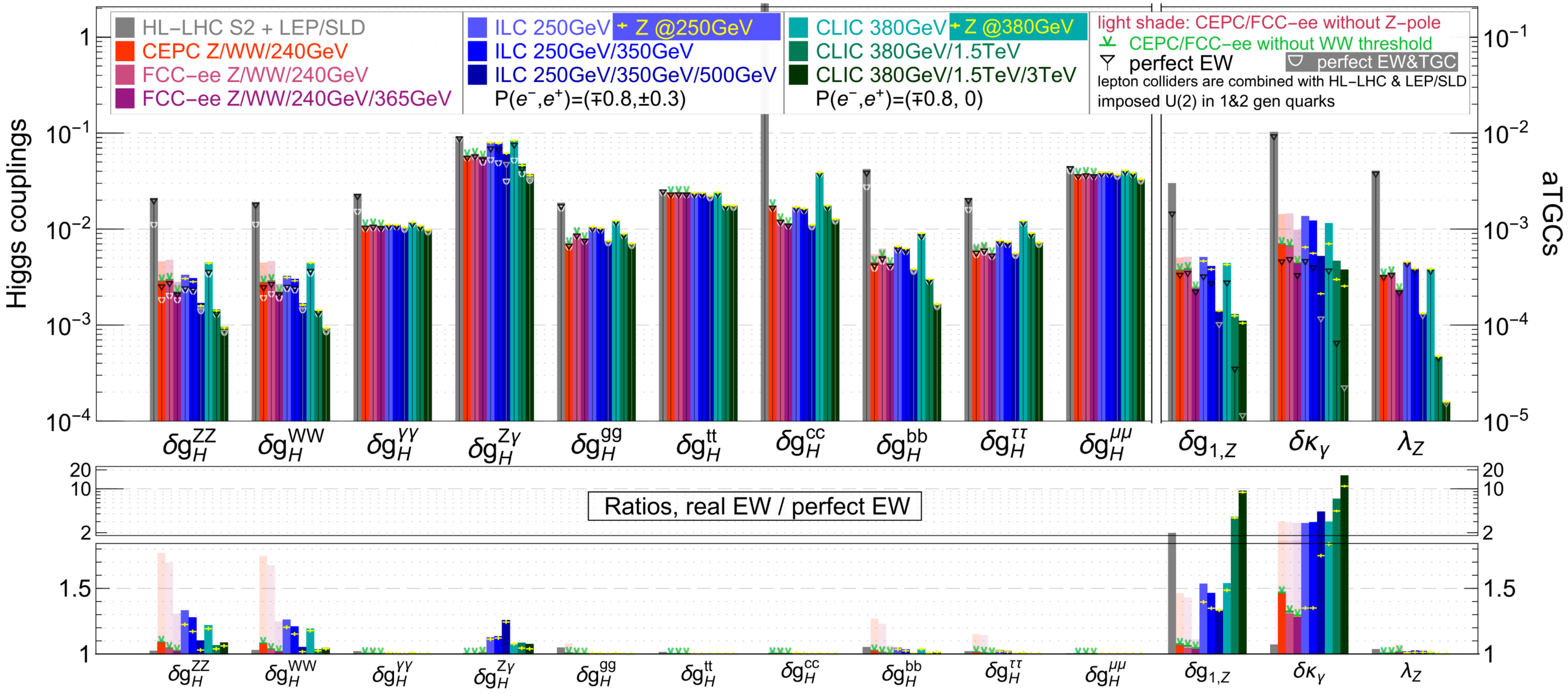
Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_\mathrm{e}$	0.0481	0.00012	0.00005
$1/R_\mu$	0.0481	0.00012	0.00005
$1/R_\tau$	0.0482	0.00016	0.00024
R_c	0.172	0.00042	0.00086
R_b	0.216	0.00031	0.00022
R_ν	0.286	0.0027	0.00029

from events with hard photons

J.-J. Blaising, Ph. R., CLICdp collaboration meeting 2019

Impact of EWPOs on Higgs couplings and TGCs

precision reach on effective couplings from full EFT global fit



- Impact of EWPOs on Higgs couplings generally small at CLIC (due to different energy stages, beam polarisation, $e^+e^- \rightarrow W^+W^-$ production)
- Some improvement from return-to-Z events at 380 GeV on TGCs

JHEP 12, 117 (2019)

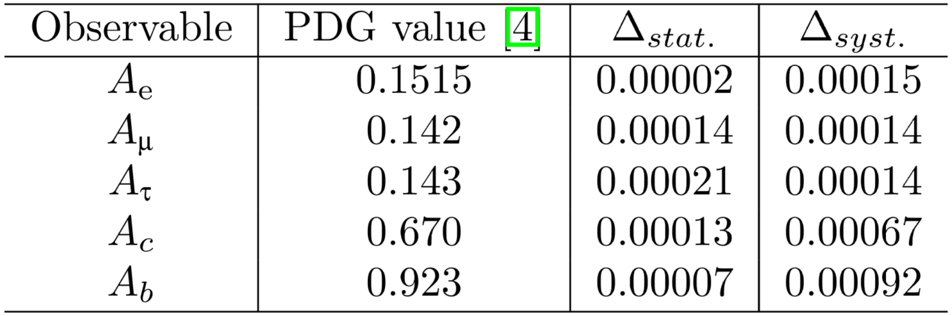
EWPOs: Z-pole operation

Fully-installed 380 GeV collider operated at Z-pole:
L = 2.3 x 10^{32} $cm^{-2}s^{-1}$ → very useful for calibration

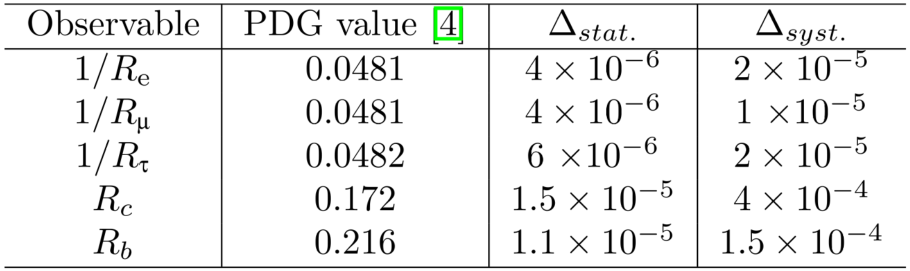
Initial installation of linac for Z-pole energy + adapted beam delivery system:
L = 0.36 x 10^{34} $cm^{-2}s^{-1}$ for 50 Hz operation → 100 fb^{-1} in a few years

100 fb^{-1} with 50:50 splitting of the -80% and +80% electron beam polarisations:
- about 4.5 billion Z bosons
- about 3 billion Z decays in hadronic final states

Uncertainty on beam polarisation:
- 0.1% from polarimeter upstream and downstream of the interaction point
- Blondel scheme (as foreseen at ILC) would require positron polarisation



Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.00002	0.00015
A_μ	0.142	0.00014	0.00014
A_τ	0.143	0.00021	0.00014
A_c	0.670	0.00013	0.00067
A_b	0.923	0.00007	0.00092



Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_e$	0.0481	4×10^{-6}	2×10^{-5}
$1/R_\mu$	0.0481	4×10^{-6}	1×10^{-5}
$1/R_\tau$	0.0482	6×10^{-6}	2×10^{-5}
R_c	0.172	1.5×10^{-5}	4×10^{-4}
R_b	0.216	1.1×10^{-5}	1.5×10^{-4}

NB: Systematic uncertainties on R_b, R_c and R_τ scaled from LEP (SLD)

CERN-ACC-2019-0051
J.-J. Blaising, Ph. R., CLICdp collaboration meeting 2019

References on CLIC physics potential

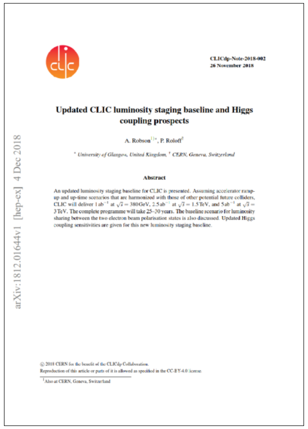
- Higgs physics analyses in full simulation: Eur. Phys. J. C 77, 475 (2017)
- The latest projections and “kappa-fits”: arXiv:1812.01644 (and arXiv:2001.05278)
- Higgs self-coupling: arXiv:1901.05897
- Top-quark physics analyses in full simulation (incl. $t\bar{t}$, $t\bar{t}H$): JHEP 11, 003 (2019)
- Other EW processes and EFT fits: CERN-2018-009-M

Eur. Phys. J. C (2017) 77:475
DOI 10.1140/epjc/s10052-017-4968-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Higgs physics at the CLIC electron–positron linear collider

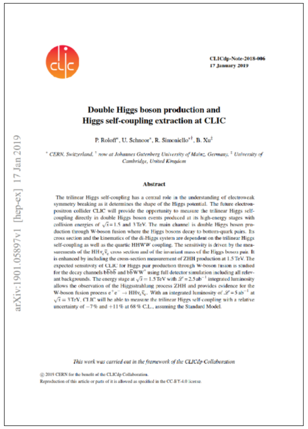


CLICdp-Note-2018-002
26 November 2018

Updated CLIC luminosity staging baseline and Higgs coupling prospects

A. Robson, P. Roloff

Abstract

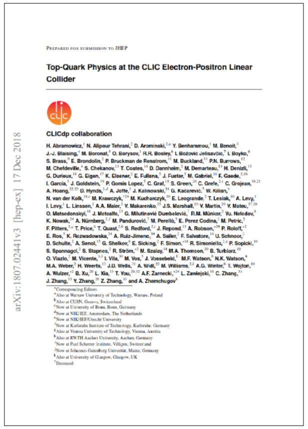


CLICdp-Note-2018-006
17 January 2019

Double Higgs boson production and Higgs self-coupling extraction at CLIC

P. Roloff, U. Schnoor, R. Simoniello, B. Xu

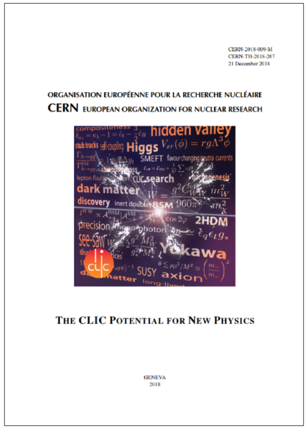
Abstract



PREPARED FOR SUBMISSION TO JHEP

Top-Quark Physics at the CLIC Electron-Positron Linear Collider

CLICdp collaboration



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21 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC POTENTIAL FOR NEW PHYSICS

GENEVA
2018

+ references given on the slides presented

Summary and conclusions

- The baseline CLIC program allows to study a wide range of EW processes: Higgs couplings, two-fermion production, WW production, top-quark couplings, …

- The impact of EWPOs on the Higgs coupling extraction is small due to the availability of several energy stages and beam polarisation

- Return-to-Z events at 380 GeV provide some improvement to the knowledge of the Z-boson couplings

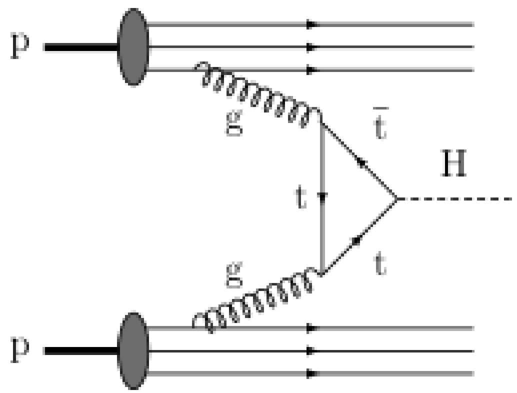
- A dedicated energy stage at 91 GeV (with an expected luminosity similar to the Giga-Z option for the ILC) would enhance the precision on Z-boson couplings significantly

Thank you!

Backup slides

Hadron and e^+e^- colliders

Hadron colliders:

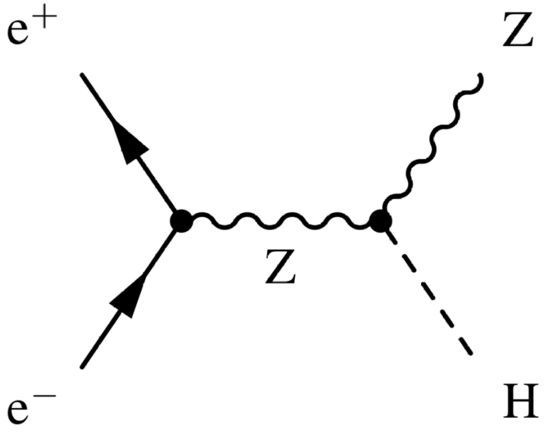


- **Proton is compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:

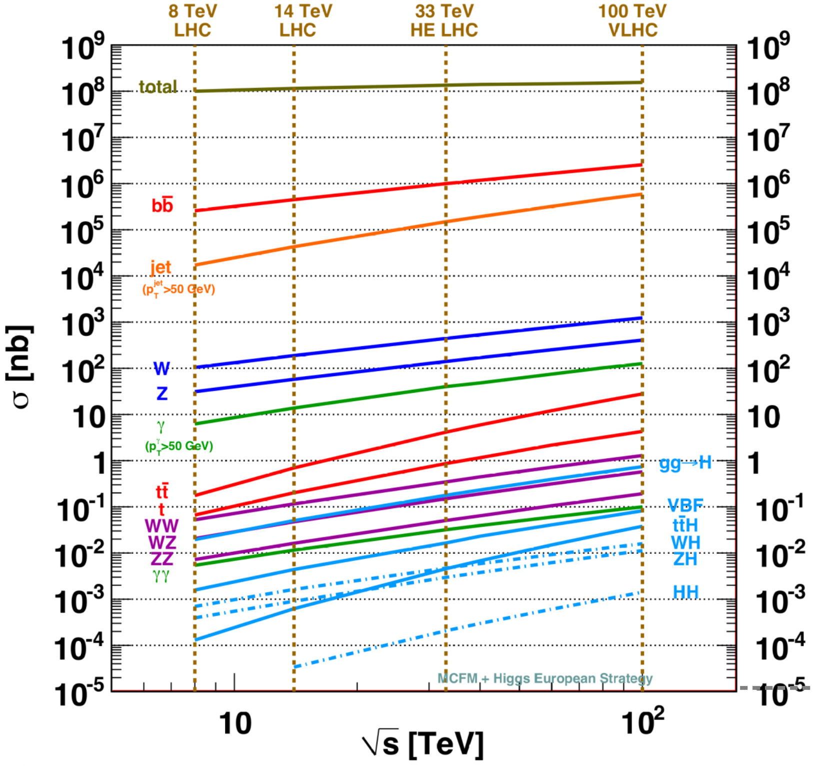


- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

- **High energies ($\sqrt{s}$ > 350 GeV) require linear colliders**

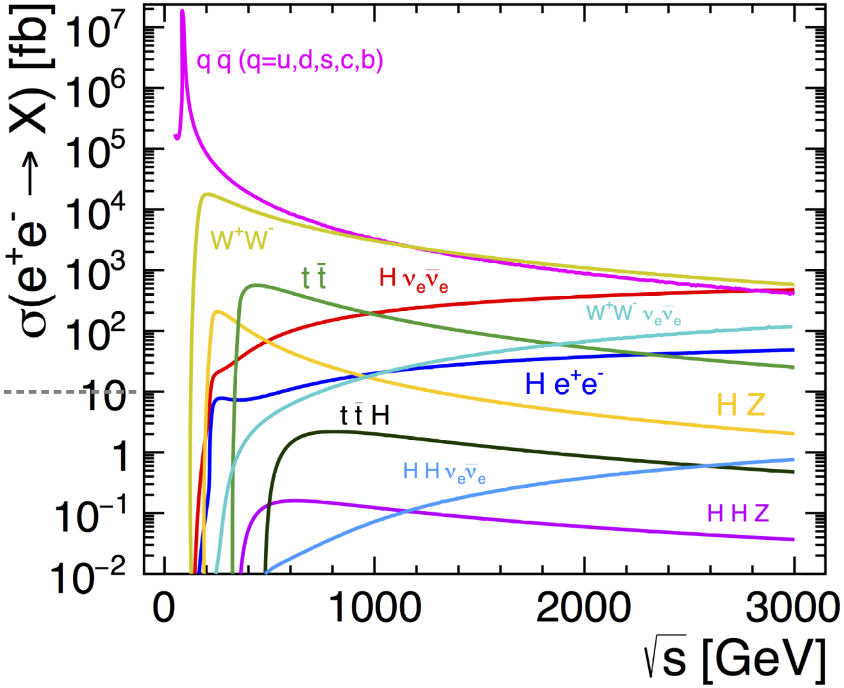
- **Clean experimental environment**
→ Less / no need for triggers
→ Lower radiation levels

pp and e^+e^- collisions



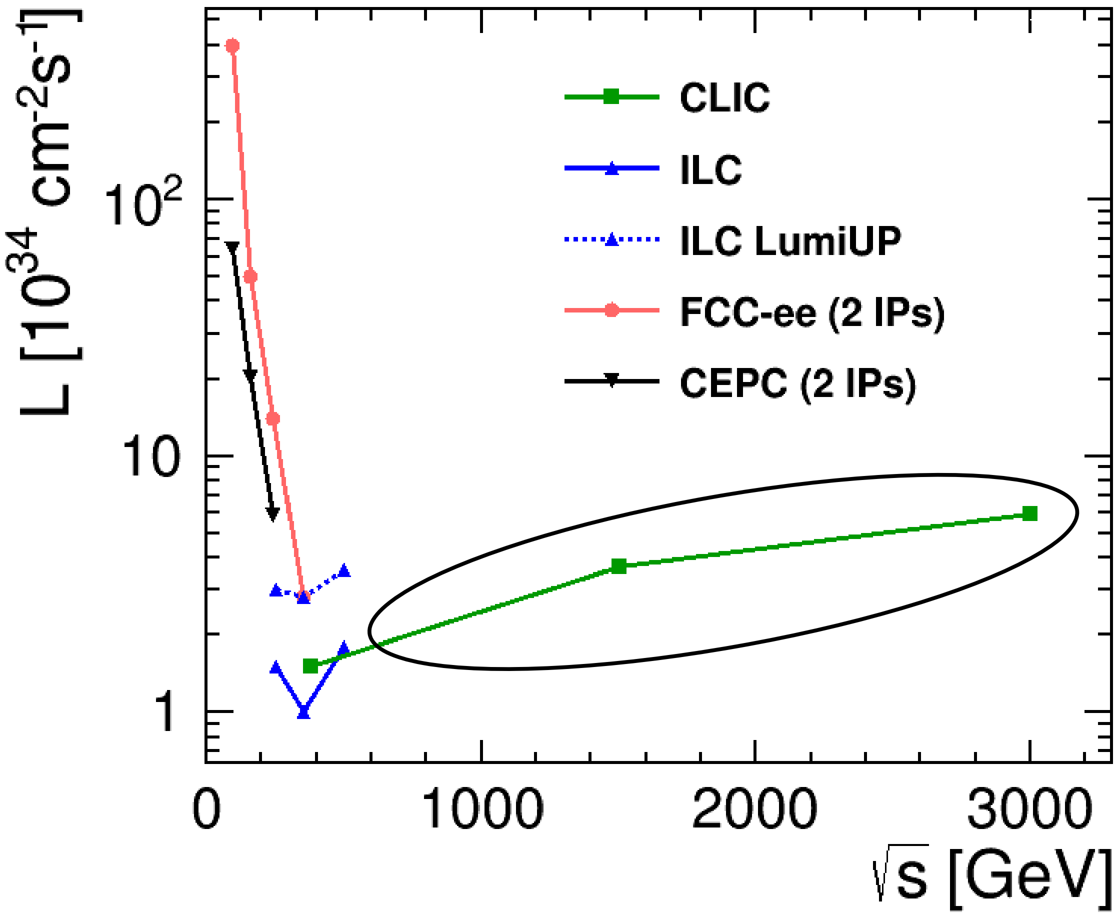
8 orders of Magnitude!

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



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

Comparison to other 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 ≈ $10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

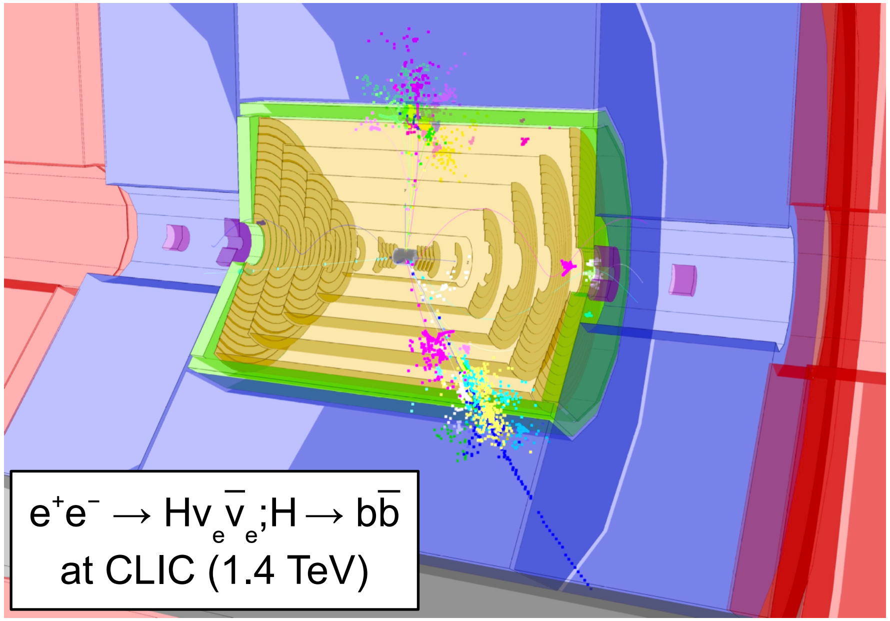
Higgs boson studies at CLIC

Collider stage:	No. H produced:
CLIC 380 GeV, 1 ab^{-1}	160000
CLIC 1.5 TeV, 2.5 ab^{-1}	1000000
CLIC 3 TeV, 5 ab^{-1}	3300000

- No triggers
→ all Higgs events usable
- Typical overall selection efficiencies: 20 - 60%

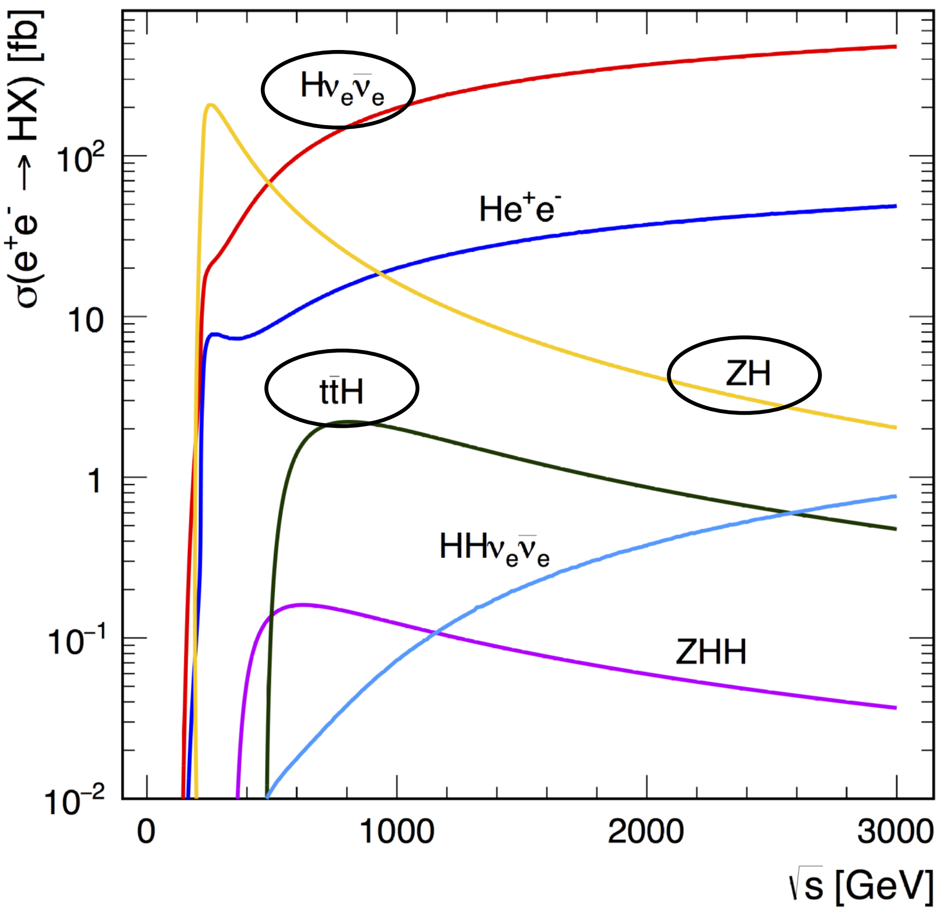
The projections shown in the following are based on realistic full detector simulations and include the impact of beam-beam effects

NB: Future improvements of the reconstruction algorithms are expected (not included here)



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

Single Higgs production



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

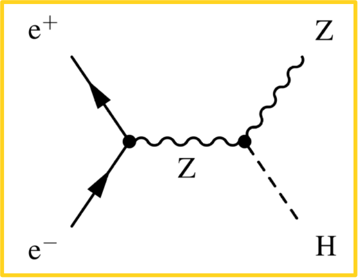
- $\sigma \sim 1/s$, dominant up to ≈ 500 GeV

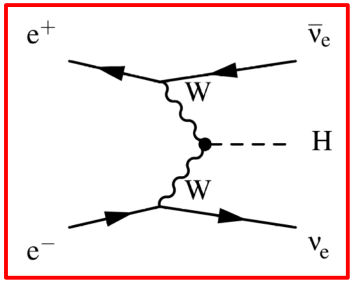
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

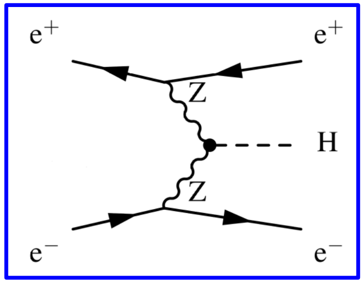
- $\sigma \sim \log(s)$, dominant above 500 GeV
- Large statistics at high energy

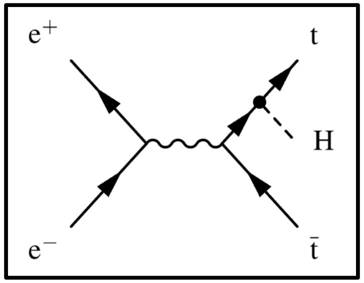
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

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

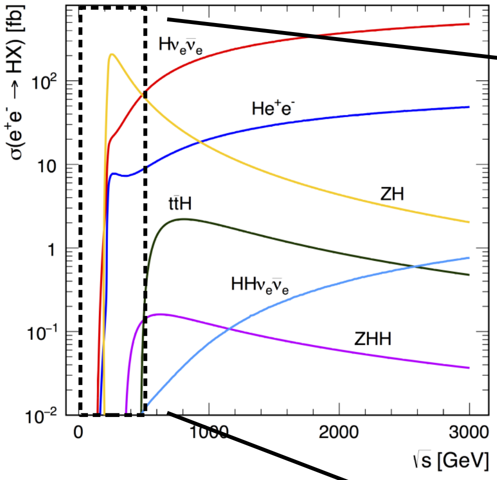


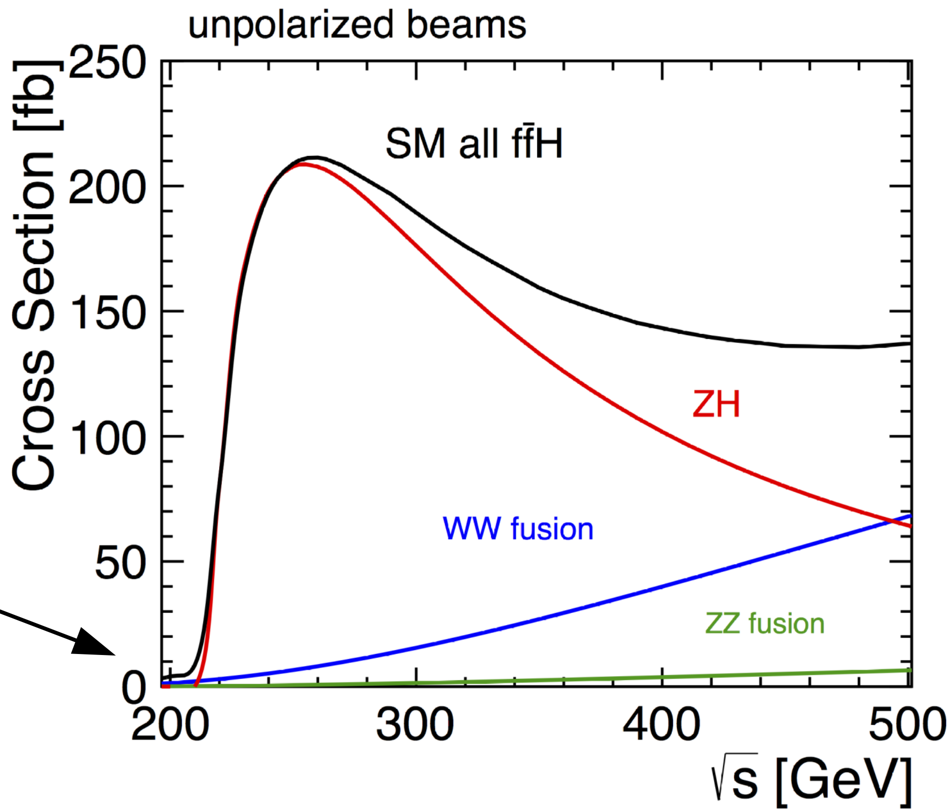






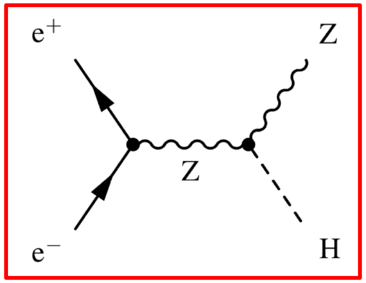
A closer look at $\sqrt{s}$ < 500 GeV

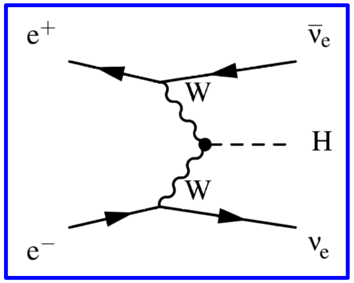




$\sqrt{s}$ = 250 GeV (ILC):
Maximum of the Higgsstrahlung cross section

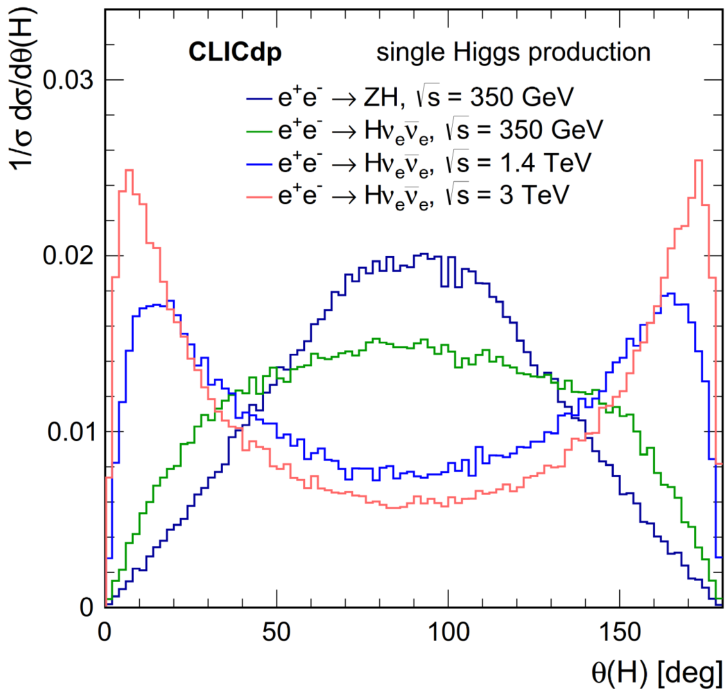
$\sqrt{s}$ = 350/380 GeV (ILC & CLIC):
Also allows to access the WW fusion process
→ Additional information for combined analysis





For reference: 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:

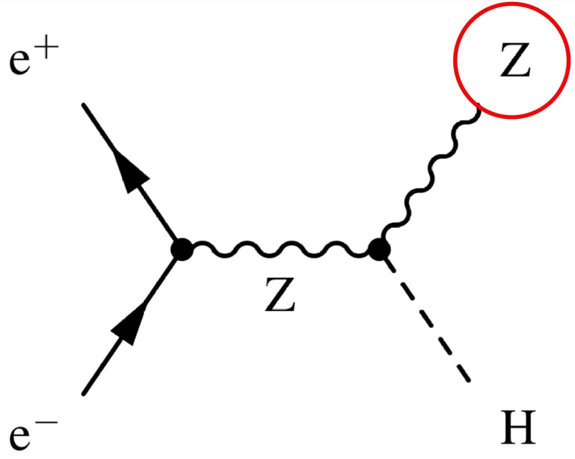
Polarisation	Scaling factor		
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84

Higgsstrahlung:
Polarisation dependence relatively small

WW fusion:
Large enhancement in the -80% configuration

Recoil method: Z → e⁺e⁻ and μ⁺μ⁻

ZH events can be identified from the Z recoil mass
→ Model-independent measurement of σ(ZH)

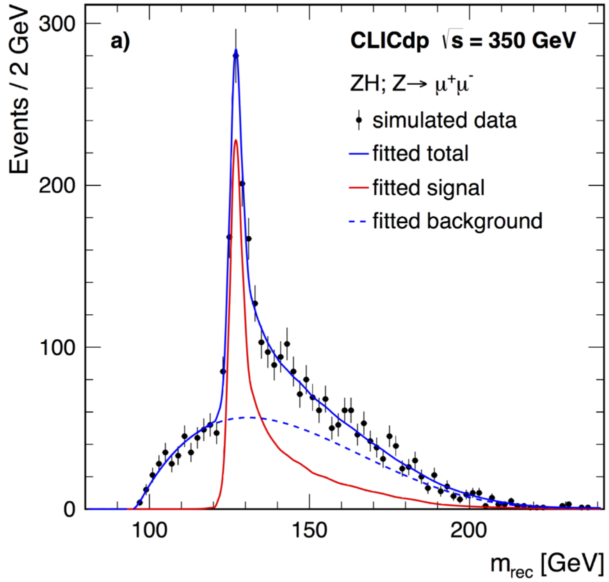


$$m^2_{recoil} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

Known at lepton collider

Best precision using Z → e⁺e⁻, μ⁺μ⁻ slightly above ZH threshold:
- Cross section at maximum
- Tracking resolution
- Impact of beam energy spectrum & ISR smaller

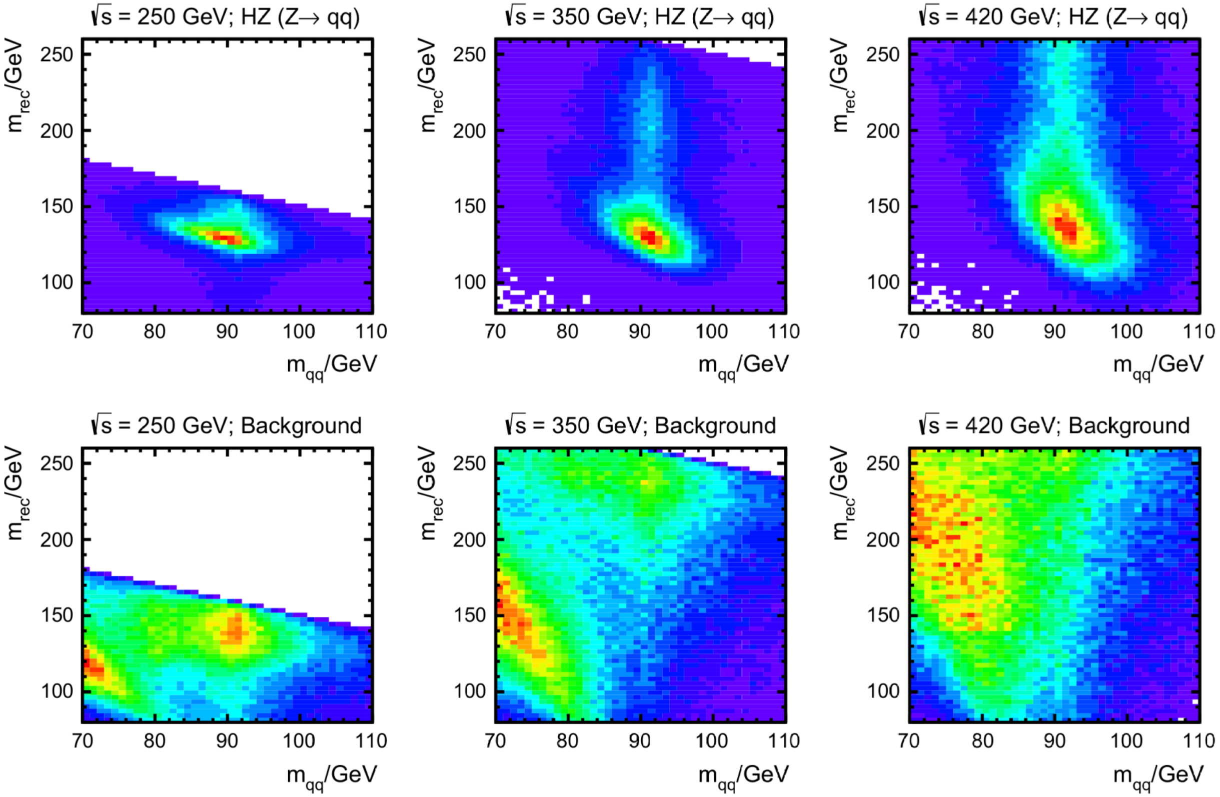
CLIC, √s = 350 GeV, L = 1 ab⁻¹
Δσ(HZ) / σ(HZ) = 2.7%
no polarisation



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

Recoil method: $Z\to q\bar{q}$

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

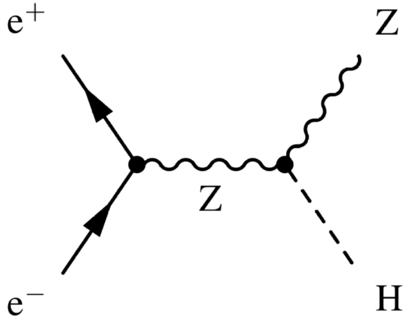


Hadronic Z decays provide the best sensitivity at 350 GeV

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

$\sqrt{s}$ [GeV]:	L_{int} [fb^{-1}]:	σ(ZH) [fb]	Δσ(ZH)
250	1000	136	±2.58%
350	1000	93	±1.27%
420	1000	68	±1.86%



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

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

Simultaneous extraction of:

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

→ precise flavour tagging

- Two production modes:

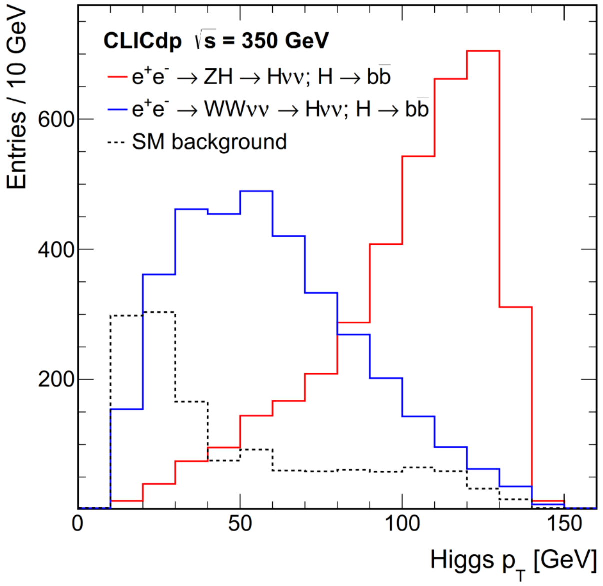
ZH and WW fusion

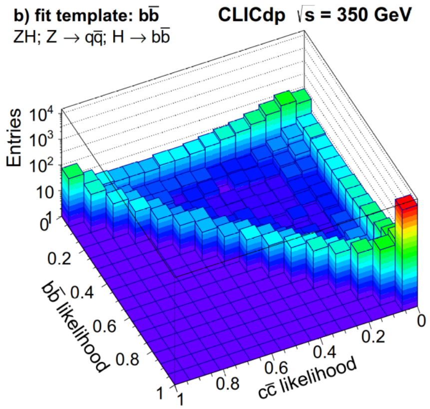
→ Higgs p_T spectrum

Uncertainties on σ x BR

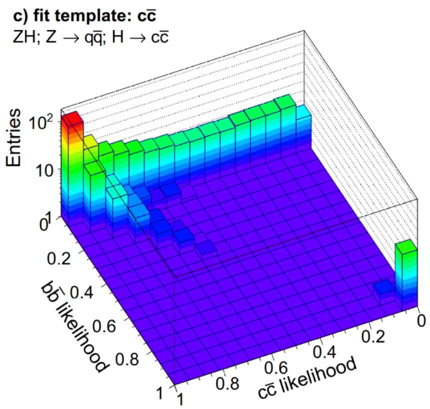
Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \rightarrow b\bar{b}$	0.61 %	1.3 %
$H \rightarrow c\bar{c}$	10 %	18 %
$H \rightarrow gg$	4.3 %	7.2 %

CLIC, $\sqrt{s}$ = 350 GeV, L = 1 ab^{-1}, no polarisation

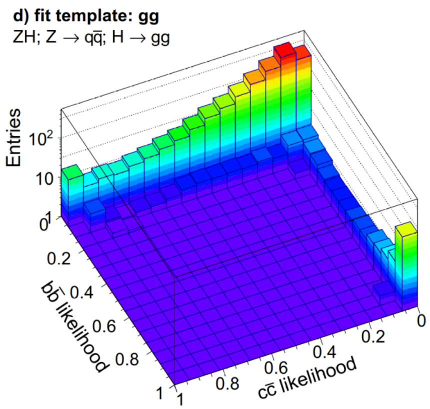




$H \rightarrow b\bar{b}$



$H \rightarrow c\bar{c}$



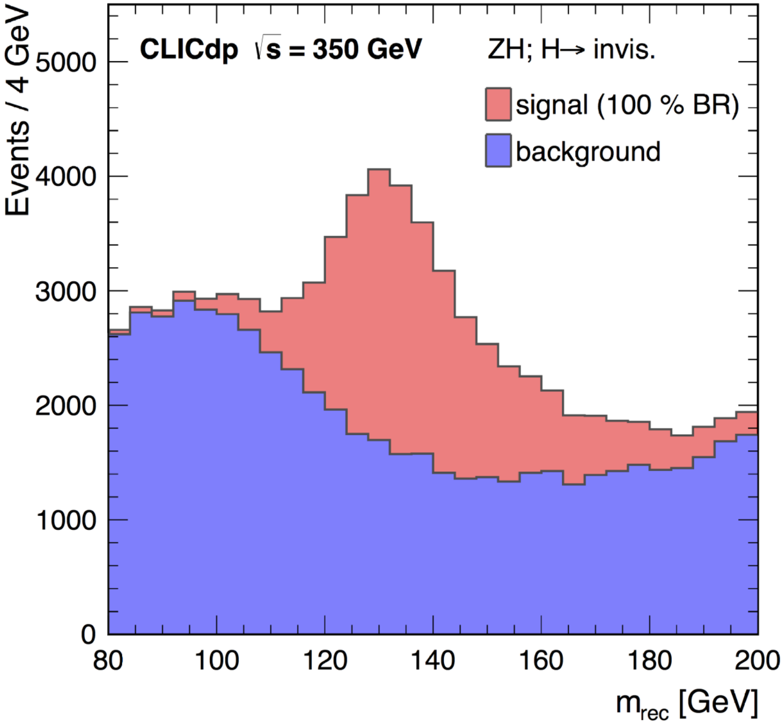
$H \rightarrow gg$

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

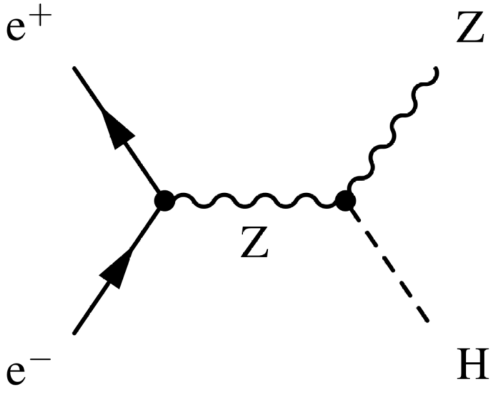
Invisible Higgs decays

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

CLIC, $\sqrt{s}$ = 350 GeV, L = 1 ab^{-1}
BR(H→inv.) < 0.69% at 90% CL

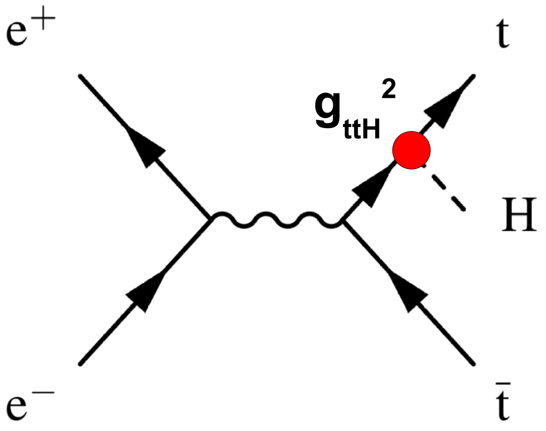


Example: Recoil mass from $Z \to q\bar{q}$ assuming all Higgs bosons decay invisibly (L = 0.5 ab^{-1})

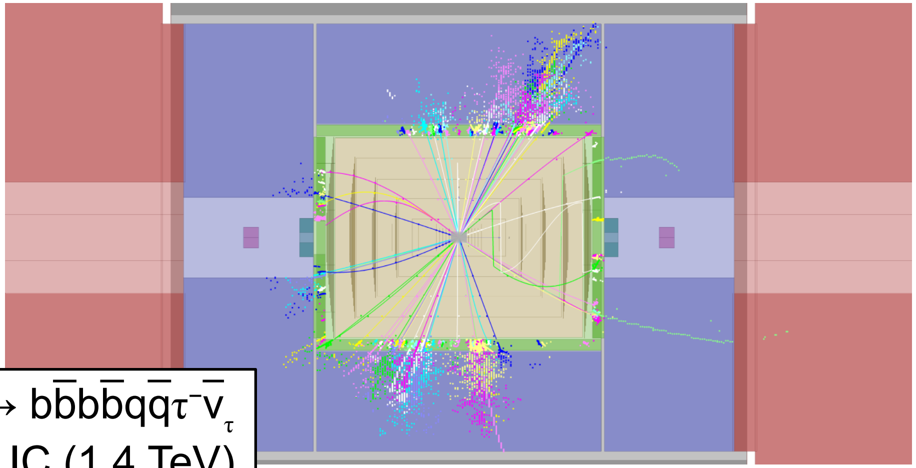


Eur. Phys. J. C 76, 72 (2016)

Top Yukawa coupling



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

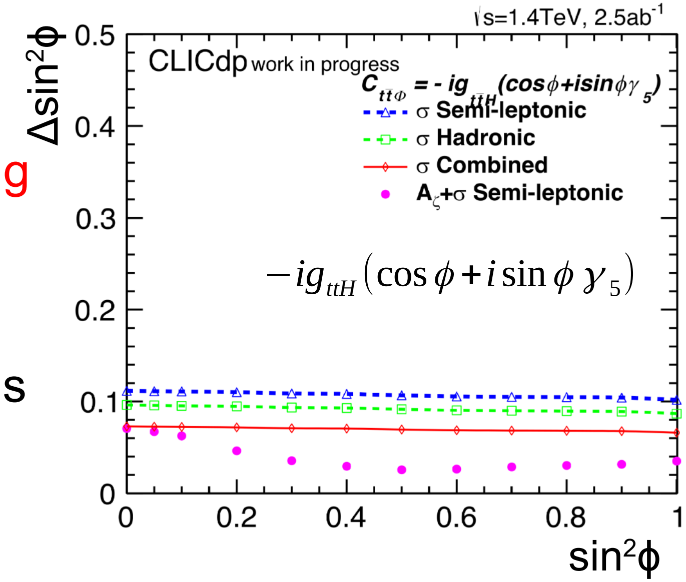


$t\bar{t}H \rightarrow b\bar{b}b\bar{b}q\bar{q}\tau^-\bar{\nu}_\tau$
at CLIC (1.4 TeV)

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

CLIC, $\sqrt{s}$ = 1.4 TeV, L = 2.5 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$ = 2.9%

- Sensitivity to CP mixing in the ttH coupling from σ($t\bar{t}H$)
- Differential distributions provide further improvement



arXiv:1807.02441

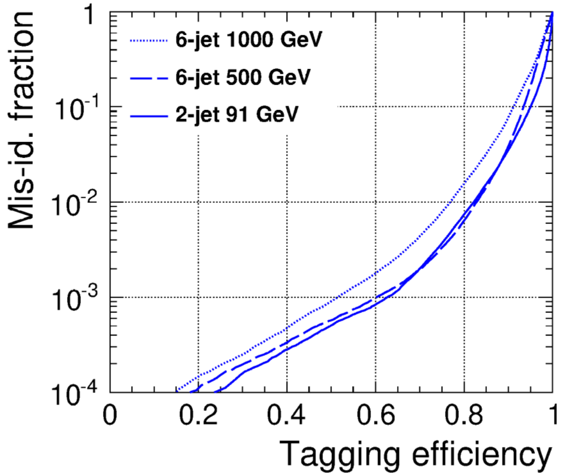
Experimental challenges

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

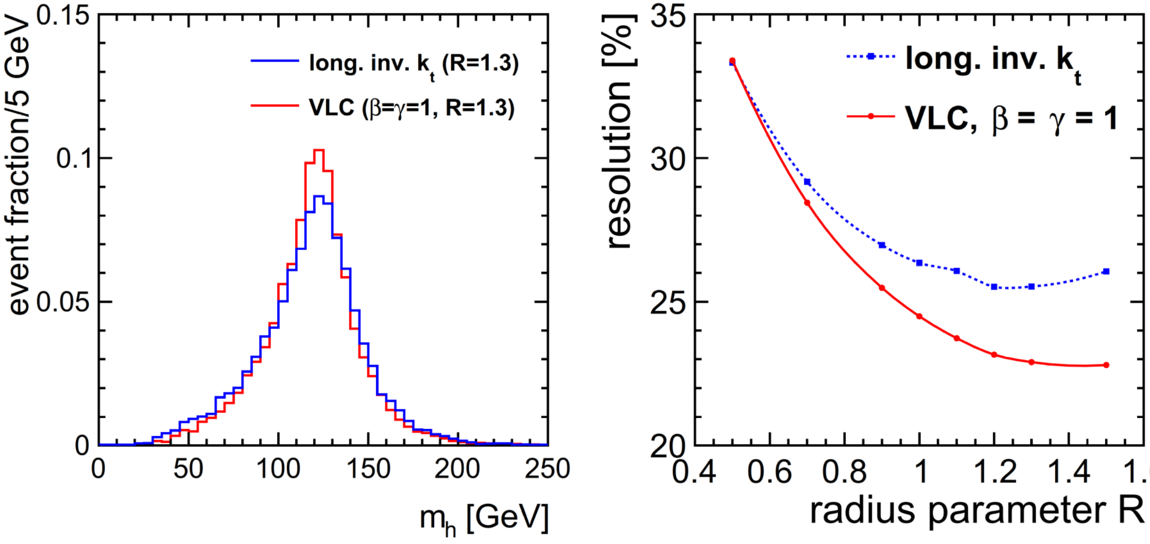
Main experimental challenges:

- b-tagging
- Forward detector coverage in case of $e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$
- Jet reconstruction

b-tagging



CLIC 3 TeV, HH→$b\bar{b}b\bar{b}$

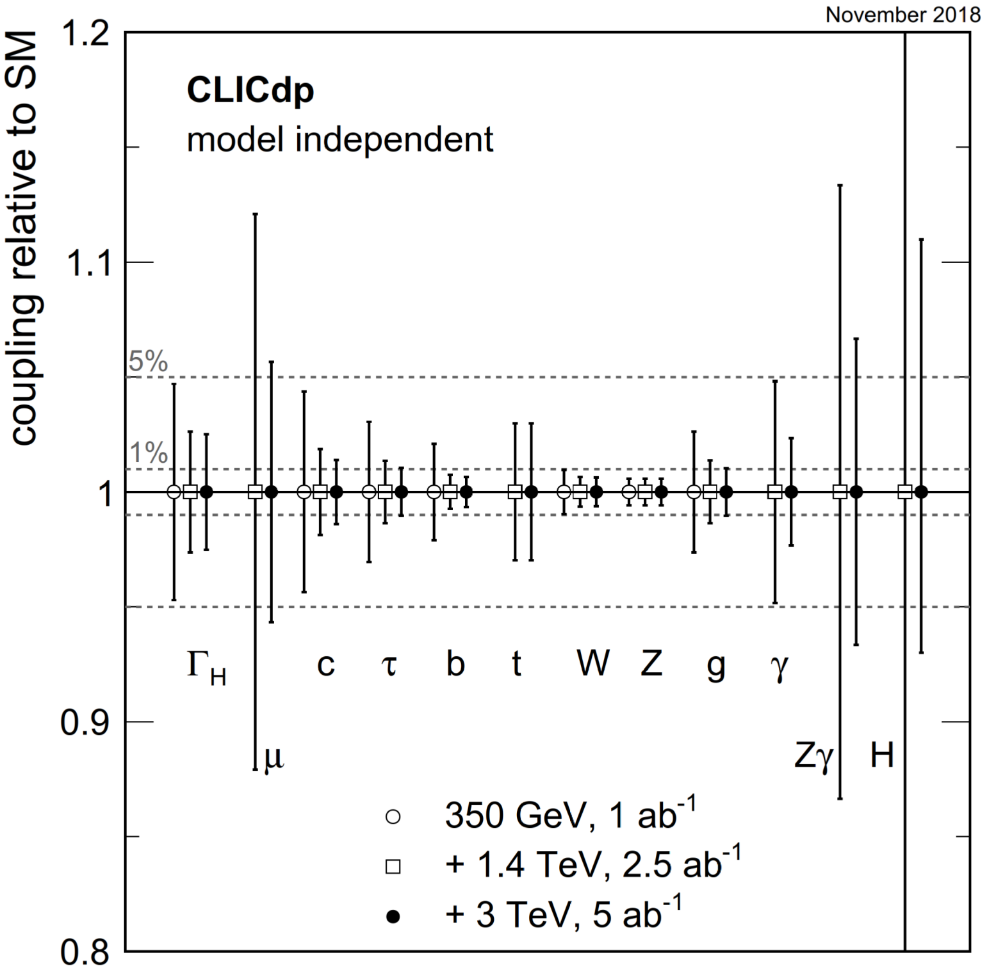


Nucl. Inst. Meth. A808, 109 (2016)

Eur. Phys. J C78, 144 (2018)

CLIC coupling sensitivity (1)

"Model-independent fit":



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

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

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

- No assumptions on additional Higgs decays (requires lepton collider)

- Correlations included where relevant:
  - $H\to b\bar{b}/c\bar{c}/gg$ (see also slide 10)
  - $H\to WW^*\to q\bar{q}q\bar{q}$ (contamination from other Higgs decays)

→ small (but not negligible) impact

- All results limited by 0.6% precision of g_{HZZ} from σ(HZ) measurement

- The Higgs width is extracted with 4.7% - 2.5% precision

arXiv:1812.01644
based on Eur. Phys. J. C 77, 475 (2017)

CLIC coupling sensitivity (2)

“Model-dependent fit”:

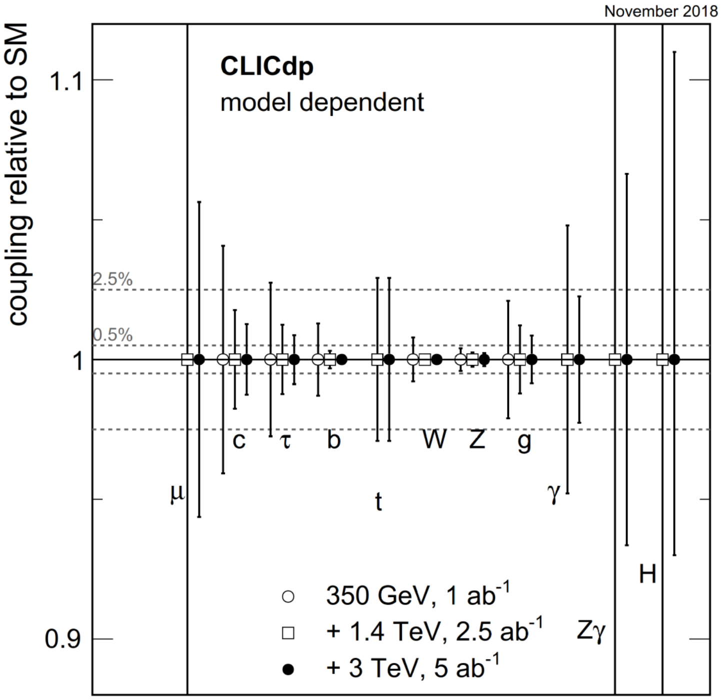
$$\kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

BR$_i$: SM branching fractions (prediction)

Only SM Higgs decays:

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

Parameter	Relative precision		
	350 GeV 1 ab^{-1}	+ 1.4 TeV + 2.5 ab^{-1}	+ 3 TeV + 5 ab^{-1}
κ_{HZZ}	0.4 %	0.3 %	0.2 %
κ_{HWW}	0.8 %	0.2 %	0.1 %
κ_{Hbb}	1.3 %	0.3 %	0.2 %
κ_{Hcc}	4.1 %	1.8 %	1.3 %
$\kappa_{\mathrm{H\tau\tau}}$	2.7 %	1.2 %	0.9 %
$\kappa_{\mathrm{H\mu\mu}}$	–	12.1 %	5.6 %
κ_{Htt}	–	2.9 %	2.9 %
κ_{Hgg}	2.1 %	1.2 %	0.9 %
$\kappa_{\mathrm{H\gamma\gamma}}$	–	4.8 %	2.3 %
$\kappa_{\mathrm{HZ\gamma}}$	–	13.3 %	6.6 %



arXiv:1812.01644
based on Eur. Phys. J. C 77, 475 (2017)

Theoretical uncertainties

“Model-dependent fit”:

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

BR_i: SM branching fractions (prediction)

Parameter	Relative precision		
	350 GeV 1 ab^{-1}	+ 1.4 TeV + 2.5 ab^{-1}	+ 3 TeV + 5 ab^{-1}
κ_{HZZ}	0.4 %	0.3 %	0.2 %
κ_{HWW}	0.8 %	0.2 %	0.1 %
κ_{Hbb}	1.3 %	0.3 %	0.2 %
κ_{Hcc}	4.1 %	1.8 %	1.3 %
$\kappa_{\mathrm{H}\tau\tau}$	2.7 %	1.2 %	0.9 %
$\kappa_{\mathrm{H}\mu\mu}$	–	12.1 %	5.6 %
κ_{Htt}	–	2.9 %	2.9 %
κ_{Hgg}	2.1 %	1.2 %	0.9 %
$\kappa_{\mathrm{H}\gamma\gamma}$	–	4.8 %	2.3 %
$\kappa_{\mathrm{HZ}\gamma}$	–	13.3 %	6.6 %

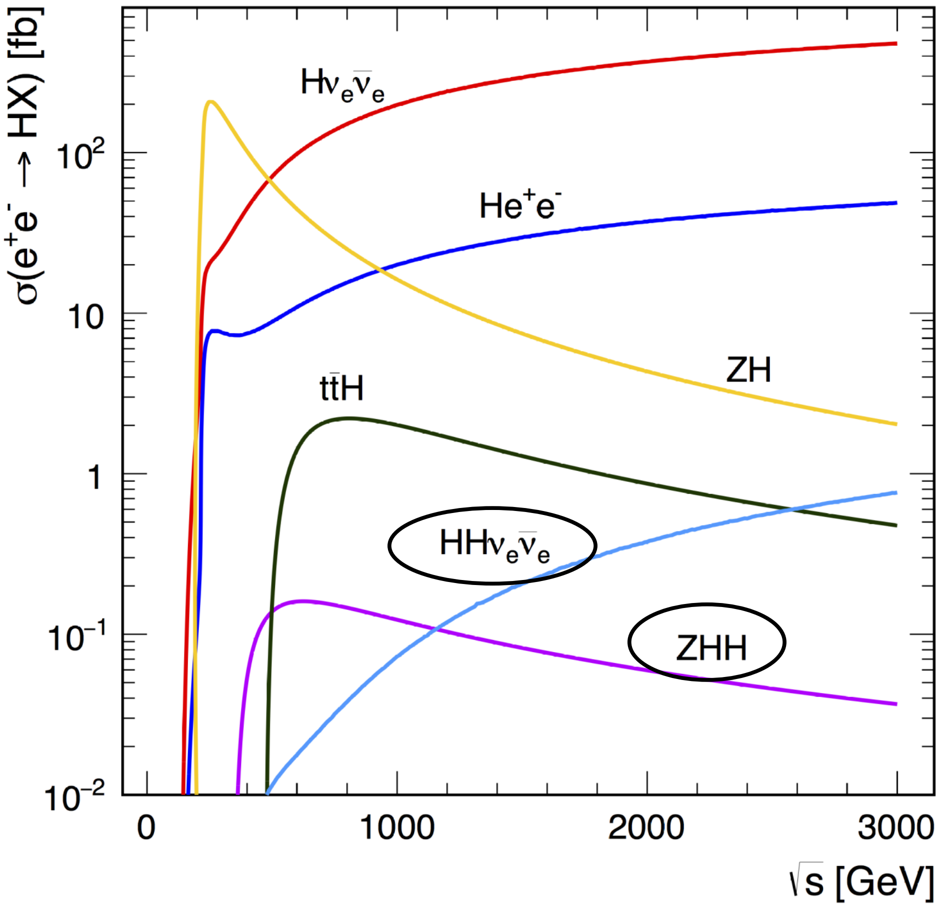
Only SM Higgs decays:

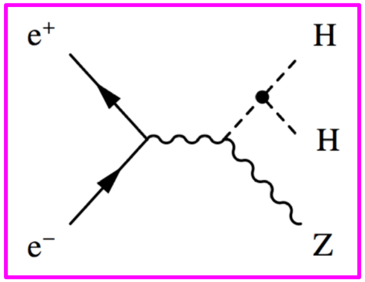
$$\boxed{\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \sum_i \kappa_i^2 \, BR_i}$$

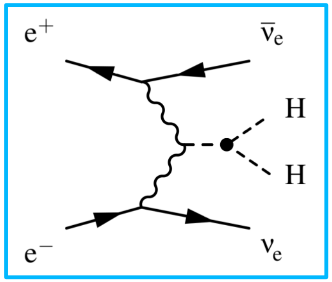
Parameter	Relative precision		
	350 GeV 1 ab^{-1}	+ 1.4 TeV + 2.5 ab^{-1}	+ 3 TeV + 5 ab^{-1}
κ_{HZZ}	0.5 %	0.4 %	0.4 %
κ_{HWW}	0.8 %	0.4 %	0.4 %
κ_{Hbb}	2.2 %	1.4 %	1.3 %
κ_{Hcc}	4.8 %	3.0 %	2.7 %
$\kappa_{\mathrm{H}\tau\tau}$	3.2 %	1.9 %	1.7 %
$\kappa_{\mathrm{H}\mu\mu}$	–	12.2 %	5.8 %
κ_{Htt}	–	2.9 %	2.8 %
κ_{Hgg}	4.5 %	3.9 %	3.8 %
$\kappa_{\mathrm{H}\gamma\gamma}$	–	5.1 %	2.8 %
$\kappa_{\mathrm{HZ}\gamma}$	–	13.8 %	7.5 %

Fit including theoretical uncertainties from CERN-2012-002
(LHC Higgs Cross Section Working Group)

Double Higgs production







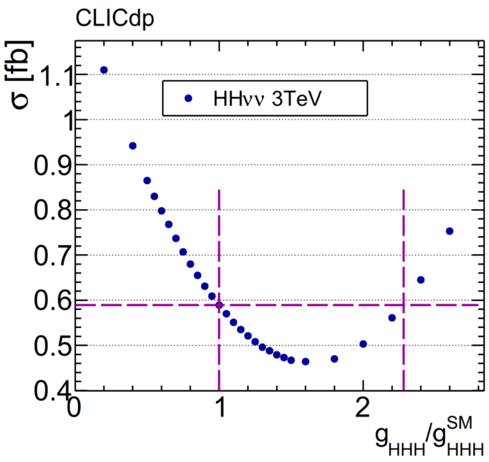
$e^+e^- \to$ ZHH:

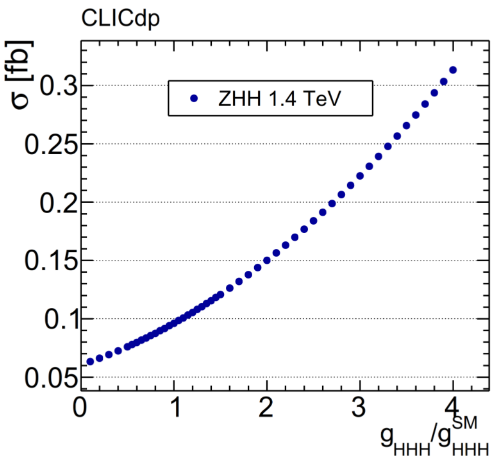
- Cross section maximum around 600 GeV

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

- Benefits from high-energy operation

Both processes provide complementary information:

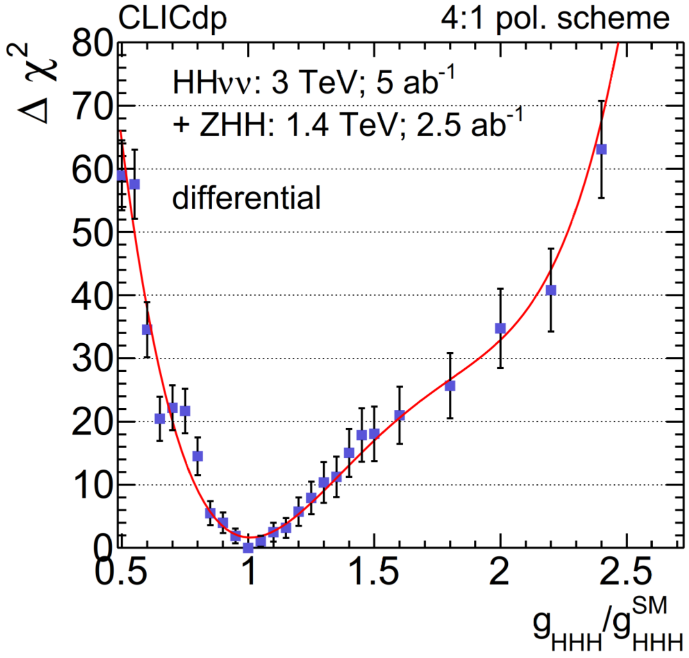


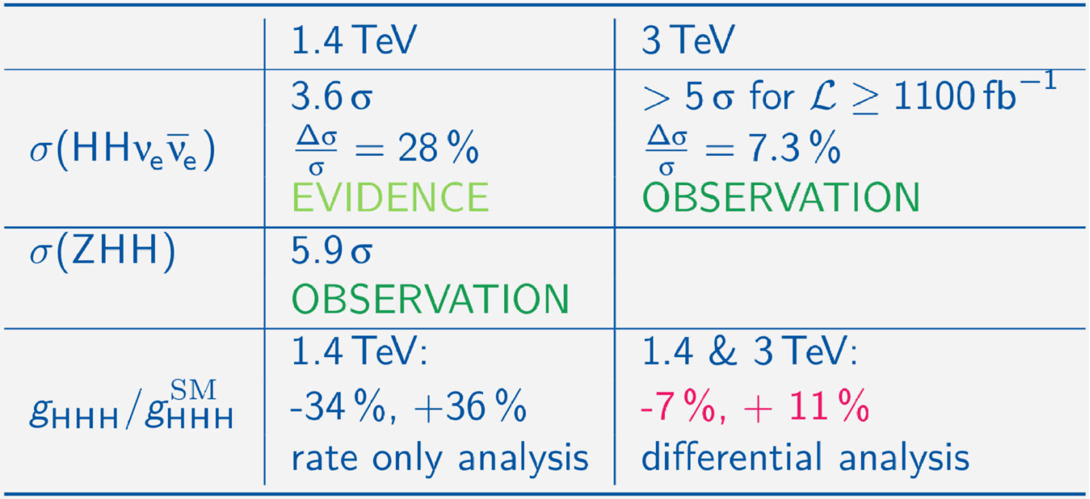


→ The ambiguity in the extraction of g_{HHH} from $\sigma(HH\nu_e\bar{\nu}_e)$ can be broken using differential distributions and / or σ(ZHH) at 1.4 TeV

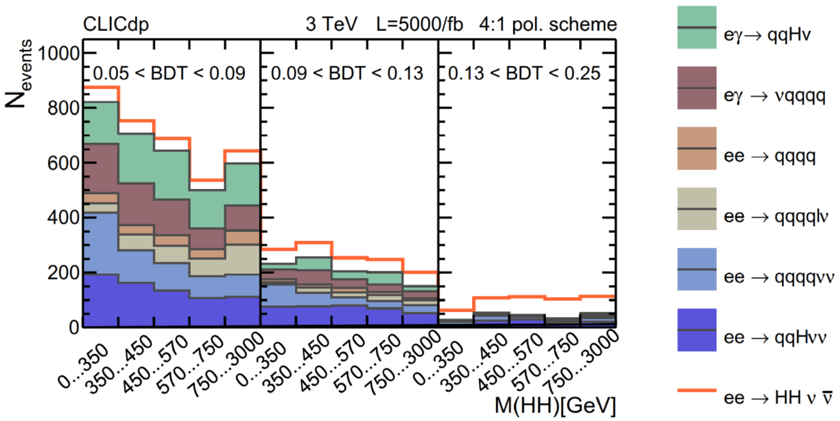
Higgs self-coupling measurements (1)

- $HH\rightarrow b\bar{b}b\bar{b}$ is the “golden channel” at CLIC, combination with $HH\rightarrow b\bar{b}WW^*$ leads to marginal improvement





	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \geq 1100\,\text{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$5.9\,\sigma$ OBSERVATION	
g_{HHH}/g^{SM}_{HHH}	1.4 TeV: -34 %, +36 % rate only analysis	1.4 & 3 TeV: -7 %, + 11 % differential analysis

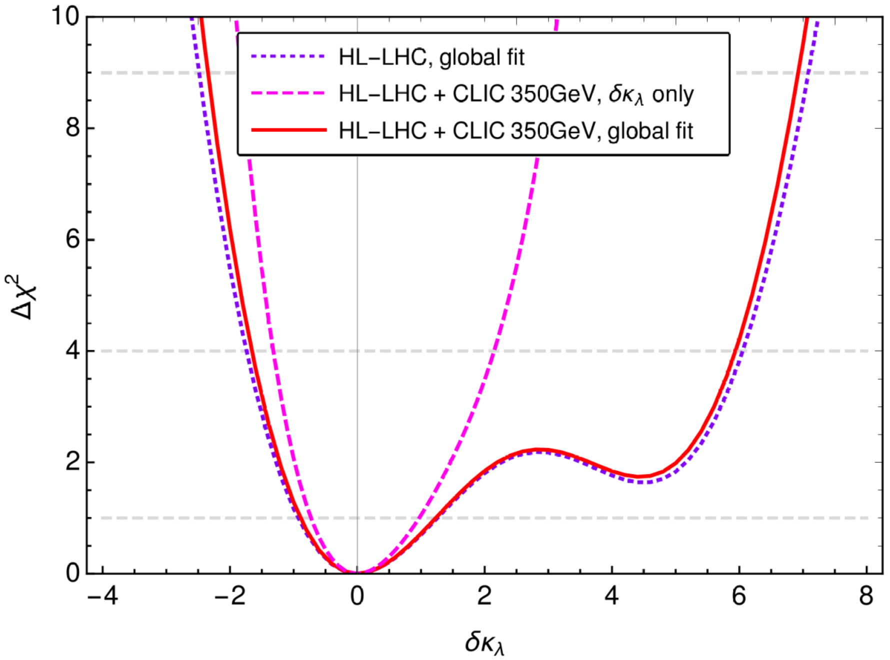


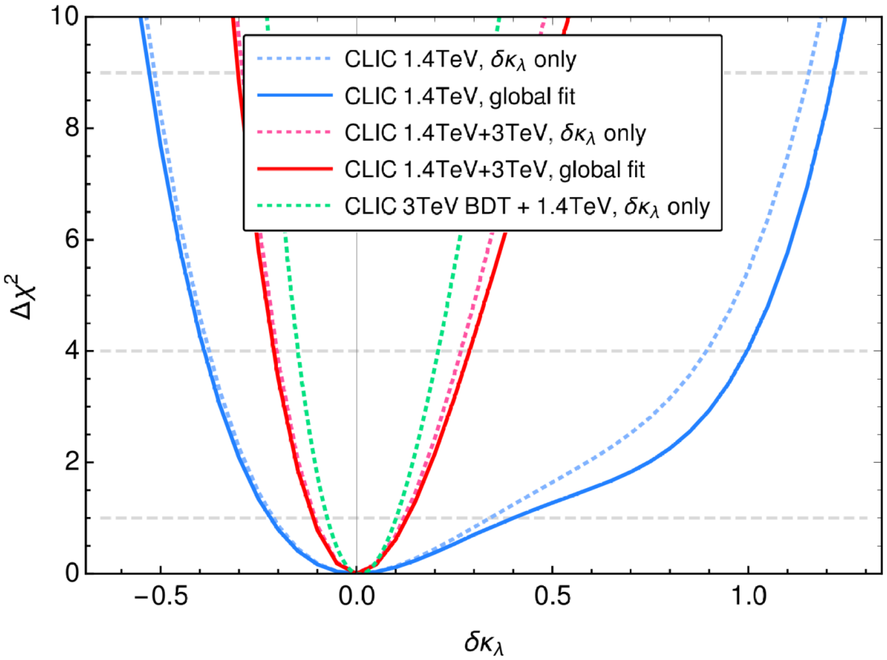
Template fit at 3 TeV
uses two variables: M(HH) and BDT score

NB: ZHH not full simulation yet

arXiv:1901.05897

Global perspective on the Higgs self-coupling





⋯⋯ Result from previous slide

→ Global fit of single and double Higgs production with 13 EFT operators
very similar to extraction of Higgs self-coupling alone at high energy

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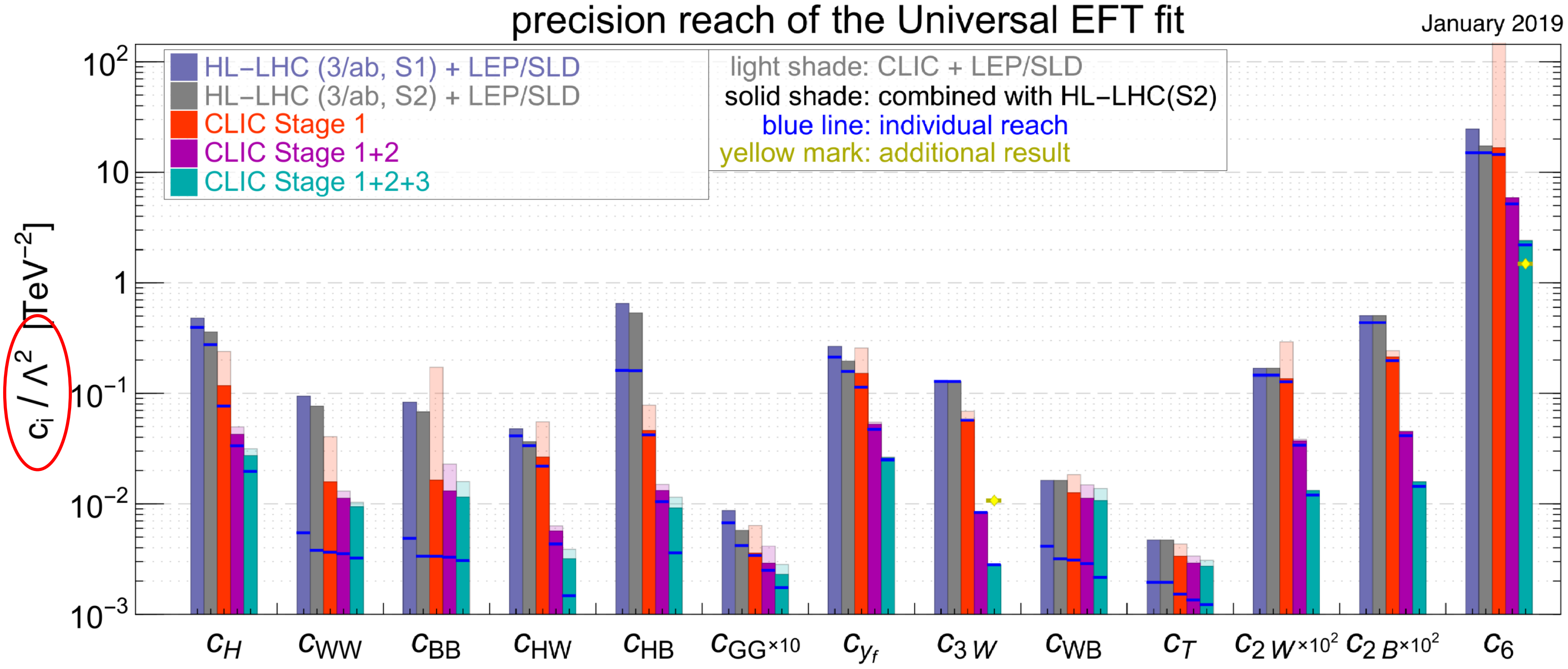
Other EW processes: global EFT fit



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

CLIC input to fit:
Higgs couplings, top quark observables,
WW production (no full simulation yet),
two-fermion production (no full simulation yet)

Z-pole: asymmetry parameters

Left-right asymmetry:

$$A_{LR} = \frac{1}{|P|} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e$$

→ using hadronic Z decays limited by systematic uncertainties

Uncertainty on beam polarisation:

$$\frac{\Delta A_{LR}}{A_{LR}} = \frac{\Delta P}{P}$$

Impact of collision energy:

$$dA_{LR}/d\sqrt{s} \approx 2 \times 10^{-5} / \,\mathrm{MeV}$$

→ collision energy needs to be controlled to a few MeV (1 MeV possible using $e^+e^- \rightarrow \mu^+\mu^-\gamma$)

Reconstruction of beam energy spread (several per mille) to be demonstrated

Other fermions → combined forward-backward left-right asymmetry:

$$A^f_{FB,LR} = \frac{1}{P} \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

Same impact of polarisation uncertainty as for A_{LR}