Double Higgs boson production and Higgs self-coupling at CLIC

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on behalf of the CLICdp collaboration

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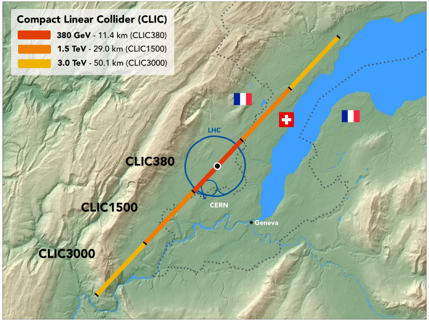
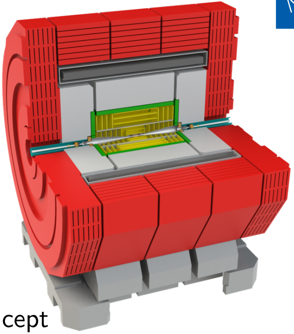
The Compact Linear Collider CLIC

- Future e^+e^- collider at the TeV scale
- Novel accelerator technique based on a two-beam acceleration scheme
- Demonstrated high gradient of 100 MV/m
- Staged operation at 380 GeV, 1.5 TeV, and 3 TeV



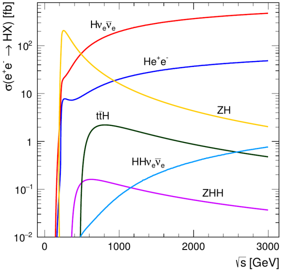


- CDR published in 2012
- Optimised detector concept
- Full simulation studies of performance and physics
- Input to the European Strategy Update 2019
  https://clic.cern/european-strategy
  - Accelerator and Detector: [arXiv:1812.07987]
  - Physics Potential: [arXiv:1812.07986]
- First beams in 2035

CLIC@EPS: A. Robson (New Physics Potential) 12.7.; F. Zarnecki (Top physics) 12.7.; E. Leogrande (Detector) Poster

Higgs pairs at CLIC

[arXiv:1901.05897]



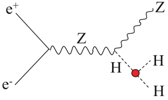
Eur. Phys. J. C77, 475 (2017)

Three energy stages of CLIC –
Expected numbers of Higgs pair events:

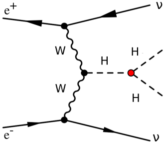
	380 GeV	1.4 TeV	3 TeV
int. luminosity	$1\,ab^{-1}$	$2.5\,ab^{-1}$	$5\,ab^{-1}$
$P(e^-)$=-0.8/+0.8 *	1:1	4:1	4:1
ZHH	≈20	170	140
$HH\nu_e\bar{\nu}_e$	≈2	550	4400

*Luminosity share between $P(e^-, e^+) = (-0.8,0)/(+0.8,0)$

Double Higgsstrahlung:



W-boson fusion:



- No HH production channel accessible below 500 GeV in e^+e^-
- Sizable ZHH production starts at $\sqrt{s} \gtrsim 500$ GeV
- $HH\nu_e\bar{\nu}_e$ production grows with energy
- Influence of **beam polarisation:**
  $P(e^-) = -80\,\%$ $(+80\,\%)$: $HH\nu_e\bar{\nu}_e$ rate modified by factor 1.8 (0.2)

Current CLIC baseline has the second energy stage at 1.5 TeV instead of 1.4 TeV which is still used for the full-simulation samples studied here

Higgs self-coupling in the Standard Model

In the SM

- Higgs potential in SM: $V = -m_{\mathrm{H}}^2|\phi|^2 + \lambda|\phi|^4$

$\Rightarrow$ Self-coupling λ determines shape of the potential

- Relation of mass m_{H} and self-coupling λ:

  $m_{\mathrm{H}}^2 = 2\lambda v^2$

$\Rightarrow$ Relation of mass and self-coupling indicates if the H(125) boson originates from the Higgs field responsible for electroweak symmetry breaking

- Interaction Lagrangian: trilinear self-coupling

  $g_{\mathrm{HHH}} = 6\lambda v$

Higgs self-coupling in the Standard Model

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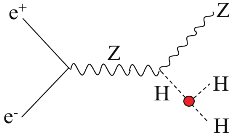
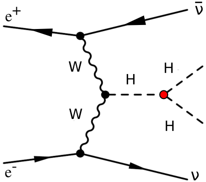
- Interaction Lagrangian: trilinear self-coupling
  $g_{HHH} = 6\lambda v$

$\Rightarrow$ measure g_{HHH} as effective coupling to check for deviations of λ from the SM:





modification of the vertex ●
defined as $\kappa_{HHH} := \frac{g_{HHH}}{g_{HHH}^{SM}}$

Higgs self-coupling beyond the Standard Model

Deviations from SM value expected e.g. in models ...

- ... with additional scalar particles (e.g. extended Higgs sectors, SUSY, additional singlets)
- ... where the Higgs is composite
- ... with first-order electroweak phase transition

Expected deviations in certain models

Deviations in g_{HHH}, in the model's parameter space where no signal appears at the LHC, but g_{HHH} is non-SM

Model	$\Delta g_{\mathrm{HHH}}/g_{\mathrm{HHH}}^{\mathrm{SM}}$
Mixed-in Singlet	-18 %
Composite Higgs	tens of %
Minimal Supersymmetry	-2 % to -15 %
NMSSM	-25 %

Gupta, Rzehak, Wells [1305.6397]

In case

- no signal of new EWSB states observed at the LHC

  and

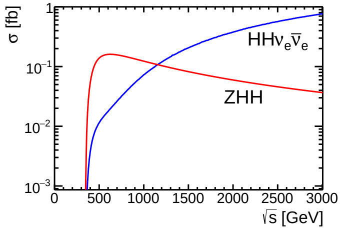
- no significant deviations of the Higgs to SM particles couplings measured at LHC

the Higgs self-coupling could be the first evidence that the Higgs sector is non-standard

Analysis strategy

Higgs self-coupling at CLIC

- Measure W-boson fusion di-Higgs production $HH\nu_e\bar{\nu}_e$ at 3 TeV
- Extract g_{HHH} from cross section and kinematics
- Take into account the smaller contributions from ZHH and $HH\nu_e\bar{\nu}_e$ at 1.4 TeV

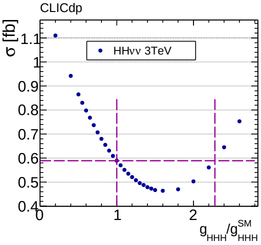


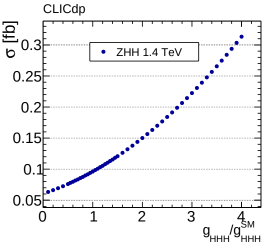
Cross-section dependence on g_{HHH}: $\longrightarrow$

$\Rightarrow$ Measurements of cross sections can be used to extract g_{HHH}/g_{HHH}^{SM}

- Ambiguity in $HH\nu_e\bar{\nu}_e$

@CLIC: resolved by 2 production modes





Sensitive differential distributions

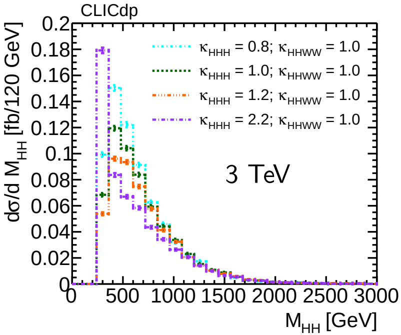
Differential distributions help to distinguish different values of κ_{HHH} [Contino et al: 1309.7038]

$$\kappa_{\mathrm{HHH}} := \frac{g_{\mathrm{HHH}}}{g_{\mathrm{HHH}}^{\mathrm{SM}}}$$

Shape differences in lower invariant mass M_{HH} region for

- different values of κ_{HHH}
- in particular, distinguish $\kappa_{\mathrm{HHH}} < 1$ from $\kappa_{\mathrm{HHH}} > 1$ even if similar cross section ($\rightarrow$ resolve ambiguity)

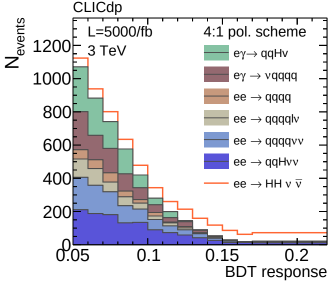
Invariant mass of Higgs boson pair:

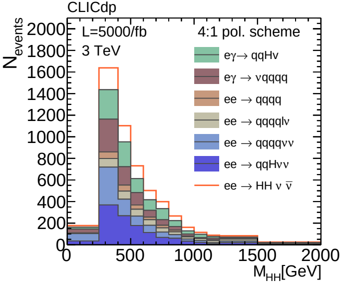


3TeV $\mathrm{HH}\nu_e\bar{\nu}_e$ analysis makes use of differential information

Event selection for 3 TeV $HH\nu_e\bar{\nu}_e$

- Signal and background samples produced with CLIC_ILD full detector simulation and reconstruction
- Most abundant: $HH \to b\bar{b}b\bar{b} \Rightarrow$ four b-tagged jets in the forward region and missing E_T
- Backgrounds from ZH and electroweak diboson production
- Event selection based on multivariate analysis (BDT), b-tagging of jets, invariant mass reconstruction





$b\bar{b}b\bar{b}$ analysis:

Signal region:

Signal = 766 events

Background = 4527 events

Beam polarisation at higher-energy stages: 80 % (20 %) of the run using $P(e^-) = -80\,\%(+80\,\%)$
→ denoted as "4:1 pol. scheme"

HH cross-section measurements at 1.4 and 3 TeV

- $\mathrm{HH}\nu_e\bar{\nu}_e$ production at 1.4 and 3 TeV studied in full simulation
- ZHH production at 1.4 TeV: assumptions based on full-simulation ZH study
- Minimal programme of CLIC for HH cross-section measurements:

	1.4 TeV ($\mathcal{L} = 2.5\,\mathrm{ab}^{-1}$)	3 TeV ($\mathcal{L} = 5\,\mathrm{ab}^{-1}$)
$\sigma(\mathrm{HH}\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \gtrsim 700\,\mathrm{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(\mathrm{ZHH})$	$5.9\,\sigma$ OBSERVATION	not studied yet (less sensitive to self-coupling)

  - direct acces
  - two production modes

- Next: extracting g_{HHH} from these measurements

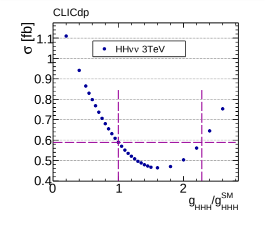
Current CLIC baseline has the second energy stage at 1.5 TeV instead of 1.4 TeV which is still used for the full-simulation samples studied here

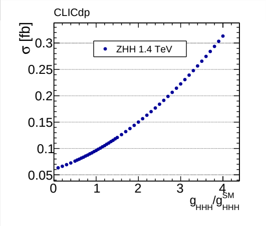
Measure g_{HHH} in di-Higgs events

From total rate of observed HH events

Measure the cross section,
extract the self-coupling:
$\Delta\sigma \rightsquigarrow \Delta g_{HHH}/g_{HHH}^{SM}$

$\Rightarrow$ -10 %, + 11 %

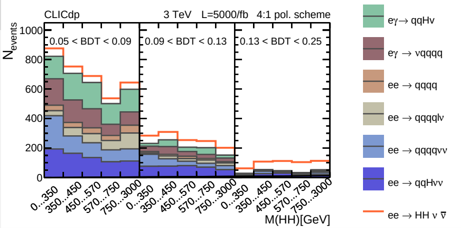




From differential information in $HH\nu_e\bar{\nu}_e$ events

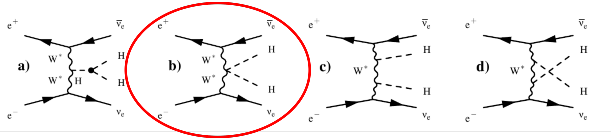
- Use two observables sensitive to g_{HHH}: BDT score and M_{HH}
- Perform template fit for different g_{HHH}

$\Rightarrow$ -7 %, + 11 % precision on g_{HHH}

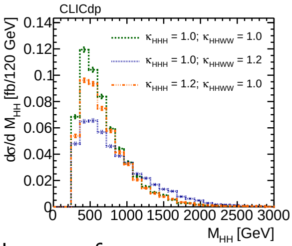


Higgs self-coupling and Higgs-gauge coupling HHWW

Several diagrams contribute to $HH\nu_e\bar{\nu}_e$, incl. HHWW vertex $\rightarrow$ modification parametrized as $\kappa_{HHWW} = g_{HHWW}/g^{SM}_{HHWW}$:



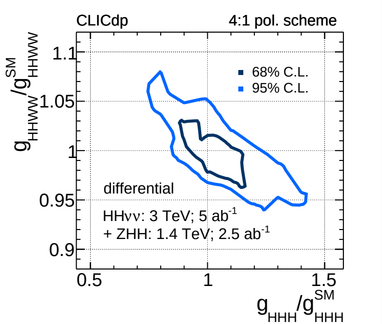
Modifications of invariant di-Higgs mass:



$\rightarrow$ distinguish g_{HHH} from g_{HHWW}

2D limits

Simultaneous fit of g_{HHH} and g_{HHWW} based on M_{HH} in bins of the BDT score plus the $\sigma(ZHH)$ measurement at 1.4 TeV:



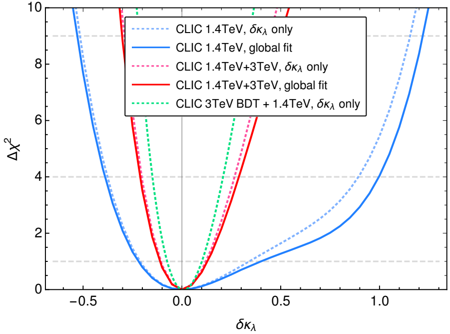
Global fit

- Model broad range of possible new physics effects in Effective Field Theory (EFT)
- HH production measurements can be influenced by more BSM effects other than modified Higgs self-coupling
- Other BSM effects can be constrained in other measurements

⇒ estimate total effect: global SM-EFT fit

⇒ at CLIC: global and individual constraints on Higgs self-coupling very similar due to the comprehensive, high-precision Higgs programme at all three energy stages

Results from: The CLIC Potential for New Physics [1812.02093, Sec. 2.2]

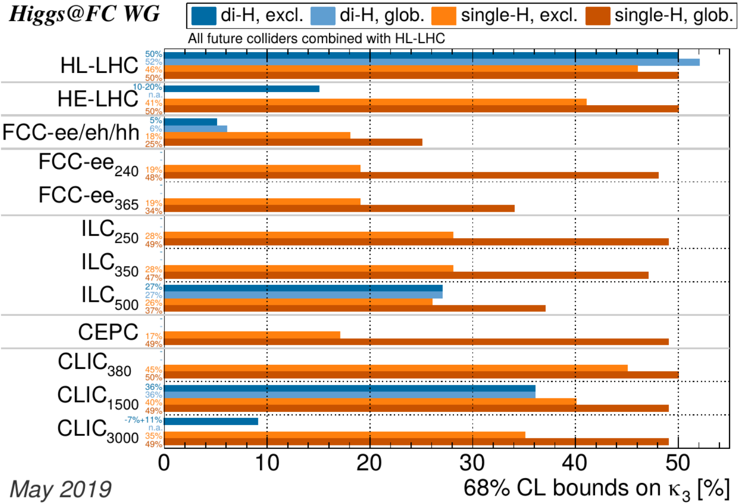


----- CLICdp full-simulation analysis with differential information

$\Delta\chi^2 = 1$ corresponds to 68 % C.L.

Comparison to other proposed projects

- CLIC is earliest project where $\Delta\kappa_{\mathrm{HHH}} < 10\,\%$ can be reached
- Direct access and two sizable production modes at CLIC
- **Global** and **exclusive** constraints very similar (see previous slide)



from [1905.03764]
$(\kappa_3 = \kappa_{\mathrm{HHH}})$

Conclusions

- Unique capability of CLIC: measuring the Higgs self-coupling to -7 %, + 11 % uncertainty
- Direct accessibility of HH production at 1.4 and 3 TeV
- Challenging measurements: small cross section, forward b-quarks
- Benefits from excellent heavy flavor tagging, jet energy resolution of CLIC detector

CLIC double Higgs and Higgs self-coupling programme:

	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \gtrsim 700\,\mathrm{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$5.9\,\sigma$ OBSERVATION	
$\Delta\kappa_{HHH}$	1.4 TeV: -34 %, +36 % rate only analysis	1.4 & 3 TeV: -7 %, + 11 % differential analysis

+ Global EFT fit

+ BSM interpretation (e.g. Baryogenesis)

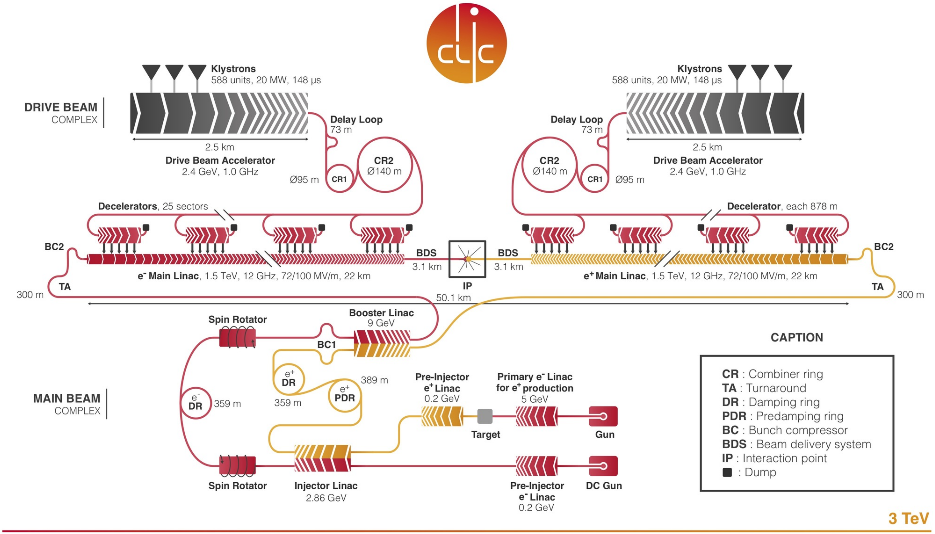
⇒ Together with the high-precision in the couplings of the Higgs to SM particles at CLIC, this measurement will test the nature of the electroweak symmetry breaking mechanism

Additional Material

Further reading

- **arXiv:1901.05897:** Double Higgs boson production and Higgs self-coupling extraction at CLIC
- **arXiv:1812.02093 /CERN-2018-009-M:** The CLIC Potential for New Physics (Sec. 2.2)

CLIC accelerator complex at 3 TeV



CLIC timeline

2013 – 2019

Development Phase
Development of a project plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 – 2025

Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

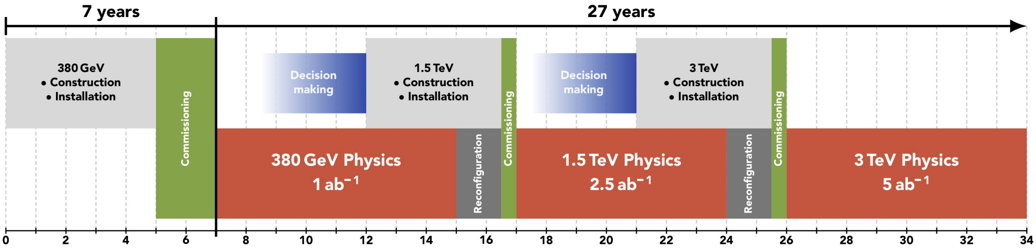
Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2020
Update of the European Strategy for Particle Physics

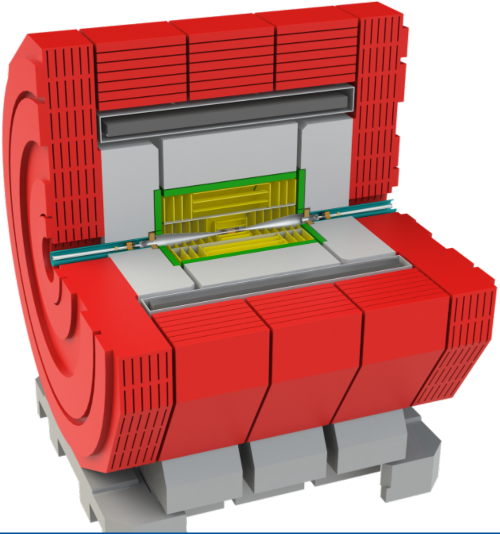
2026
Ready for construction

2035
First collisions

CLIC schedule



CLIC Detector: CLICdet



Designed for Particle Flow Analysis and optimized for CLIC environment

- 4 T B-field
- Vertex detector (3 double layers)
- Large Silicon tracker R=1.5m
- Highly granular calorimeters:
  - Si-W-ECAL
    40 layers (22 X_0)
  - Scint-Fe-HCAL
    60 layers (7.5 λ_I)

Precise timing for background suppression

Brief overview Higgs physics at CLIC

Stage 1

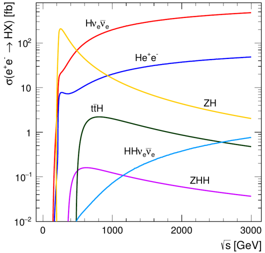
- Higgsstrahlung and W-boson fusion H production
- Model-independent measurement of HZZ coupling
- $H \to$ invisible

Stage 2

+ $e^+e^- \to ttH$:
  top Yukawa coupling

Stage 3

+ Double Higgs production



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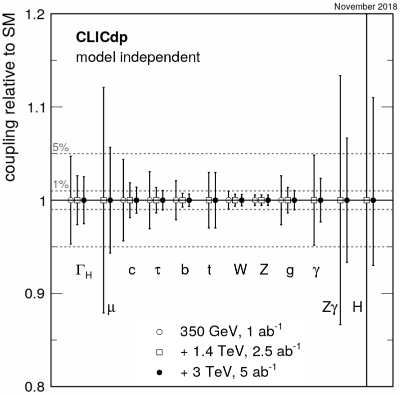
All Stages:
Model-independent global fit of couplings:



1812.01644

Double Higgs production at other colliders

Hadron collider

CHALLENGE:

- Small cross section
- Overwhelming background in high-BR channels

Current limits from LHC:

HH $\rightarrow$ $b\bar{b}b\bar{b}$, HH $\rightarrow$ $b\bar{b}\ \tau\tau$, HH$\rightarrow$$b\bar{b}\ \gamma\gamma$ combined (ATLAS):

-5.0 $< \kappa_{HHH} <$12.1 (95 % C.L.)

ATLAS-CONF-2018-043

Prospects for HL-LHC:

- with systematics: $0.52 \leq \kappa_{HHH} \leq 1.5$
- without systematics: $0.57 \leq \kappa_{HHH} \leq 1.5$

(68 % C.L.) https://cds.cern.ch/record/2650162/

Electron-positron collider

CHALLENGE:

- ZHH accessibility opens around ≈500 GeV
- Small cross section
- W-boson fusion channel grows with energy ⇒ high-energy e^+e^- collider advantageous

Prospects for ILC at 500 GeV: $\mathcal{L} = 4\,\mathrm{ab}^{-1}$

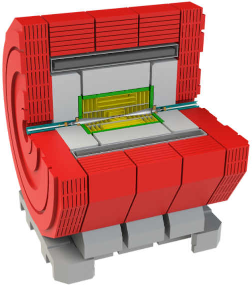
$\Delta\kappa_{HHH} = 27\,\%$ (68 % C.L.)

[1506.05992]

Indirect measurements of the Higgs self-coupling in single Higgs production possible at **ILC-250** and **FCC-ee**, but no direct di-Higgs production

Processes with two Higgs bosons at CLIC

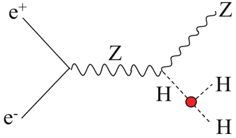
$e^- \longrightarrow$



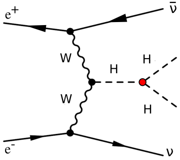
$\longleftarrow e^+$

Processes producing two Higgs bosons:

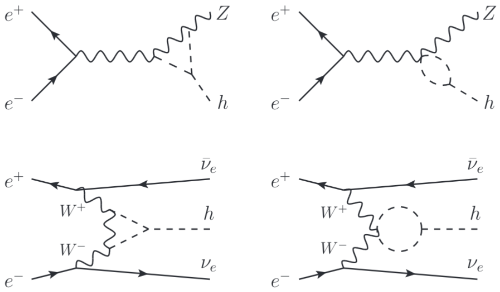
Double Higgsstrahlung ZHH



W-boson fusion $HH\nu_e\bar{\nu}_e$



Indirect measurements of the Higgs self-coupling



- Measure Higgs self-coupling contributing in loops
- Model-dependent
- Higgs self-coupling effect suppressed w.r.t. direct effects in these diagrams (e.g. gHZZ) $\rightarrow$ limiting sensitivity
- Global fit necessary
- Possible at CLIC-380, FCC-ee, ILC-250

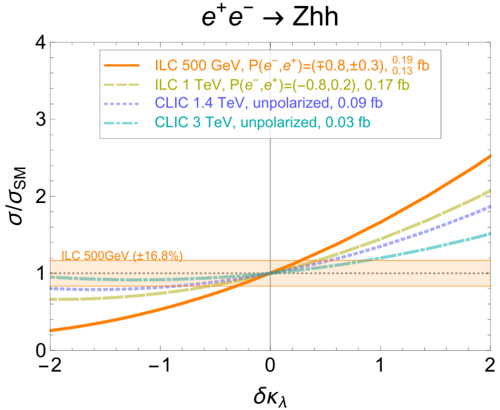
ILC-250

Strategy described in
1710.07621

FCC-ee

global fit, full programme with all stages
$\rightarrow \Delta\kappa_{\mathrm{HHH}} = 42\,\%$
CERN-ACC-2018-0057

ZHH



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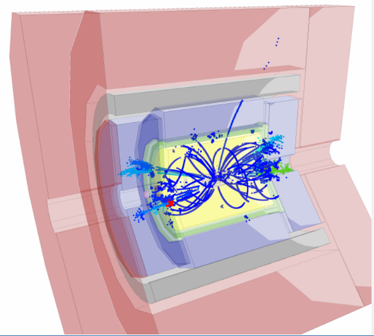
Double Higgs boson events from W-boson fusion

$HH\nu_e\bar{\nu}_e$ events identified by decay products of the two Higgs bosons

- Most abundant: $HH \rightarrow b\bar{b}b\bar{b}$
- Apply b-tagging to jets
- Reconstruct invariant masses

$HH\nu_e\bar{\nu}_e \rightarrow b\bar{b}b\bar{b}\ \nu_e\bar{\nu}_e$ events in the detector at CLIC

After removing beam-induced background:



- Four b-jets in the forward region
- Signals and backgrounds contain missing energy
- Background events in particular from
  - ZH
  - diboson

Cross-section measurement of $HH\nu_e\bar{\nu}_e$ at 3 TeV

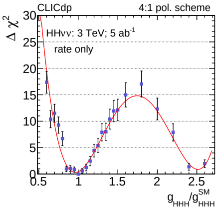
- First step for self-coupling extraction: cross-section measurement
- $HH\nu_e\bar{\nu}_e$ cross section scales with 1.8 (0.2) for $P(e^-) = -80\,\%(+80\,\%)$
- Cross-section accuracy depends on the luminosity and polarisation scheme:

	Data Percentage with		
$\mathcal{L}[\text{fb}^{-1}]$	$P(e^-) = -80\,\%$	$P(e^-) = +80\,\%$	$\Delta\sigma/\sigma$
3000	0 %	0 %	11.6 %
3000	100 %	0 %	8.7 %
5000	0 %	0 %	9.0 %
5000	**80 %**	**20 %**	**7.4 %**
5000	100 %	0 %	6.7 %

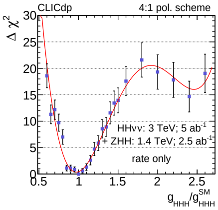
$\longrightarrow$ **4:1 polarisation scheme = current baseline**
[1812.01644]

Analysis overview and results

Constraints for κ_{HHH} for 68 % C.L.



$[0.90, 1.12] \cup [2.40, 2.61]$

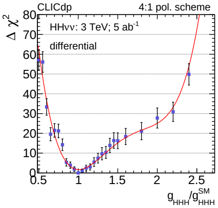


$[0.90, 1.11]$

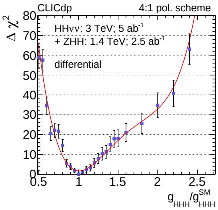
Final sensitivity of CLIC on $g_{\mathrm{HHH}}/g_{\mathrm{HHH}}^{\mathrm{SM}}$ based on

- differential information in $\mathrm{HH}\nu_e\bar{\nu}_e$ at 3 TeV
- cross-section measurement of ZHH at 1.4 TeV

$\Rightarrow$ **-7 %, +11 %**



$[0.93, 1.12]$



$[0.93, 1.11]$

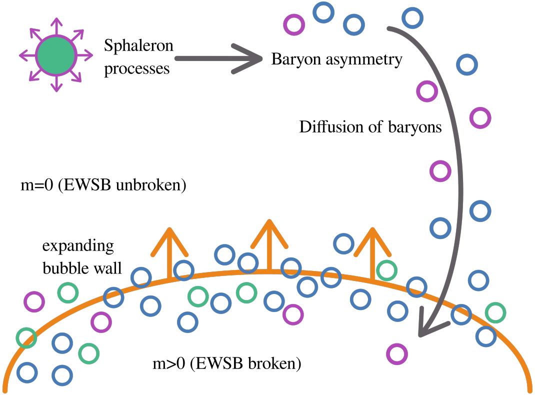
Higgs self-coupling and Baryogenesis

- Non-standard Higgs self-coupling plays a role in various BSM models
- Example: Electroweak Baryogenesis = one explanation for the matter-antimatter asymmetry in the universe

Ingredients to Electroweak Baryogenesis:

- C and CP-violating processes
- Baryon number violation
- Thermal inequilibrium

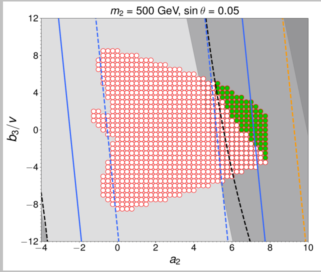
can be realised through first-order phase transition in EW symmetry breaking: potential barrier between vacuum “bubbles” where EW symmetry is broken and the unbroken vacuum



Interpretation: Baryogenesis

- Shape of the Higgs potential connected to the phase transition of the early universe from the unbroken to the broken electroweak symmetry
- Baryogenesis with a Higgs + singlet model: CLIC sensitive to the interesting regions

singlet mass m_2 and mixing angle θ



b_3/v, a_2: parameters of effective potential

--- CLIC 1.5 TeV $\epsilon_{b-tag} = 90\,\%$

--- constraint from $\Delta\kappa_{HHH} = 20\,\%$ at $95\,\%$ C.L.

--- CLIC 3 TeV di-Higgs searches $\epsilon_{b-tag} = 90\,\%$

— CLIC 3 TeV di-Higgs searches $\epsilon_{b-tag} = 70\,\%$

○ regions compatible with unitarity, perturbativity, and absolute stability of the EW vacuum

● regions also compatible with baryogenesis

■ Gray areas: indirect reach from other measurements at Stage 1 (dark), Stage 2 (middle), Stage 3 (light)

based on di-Higgs production at CLIC
[No, Spannowski: 1807.04284]
(using CLICdet Delphes card)