Higgs physics at CLIC

Natasa Vukasinovic

VINCA Institute of Nuclear Sciences, Belgrade, SERBIA

on behalf of the CLICdp Collaboration

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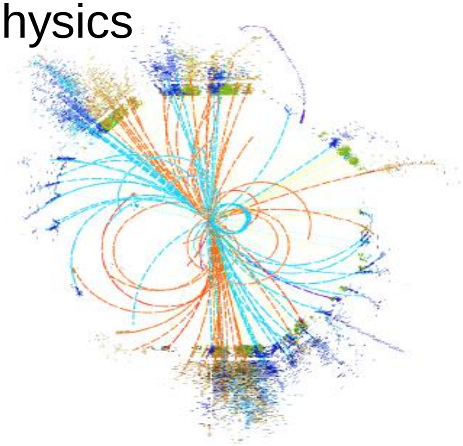
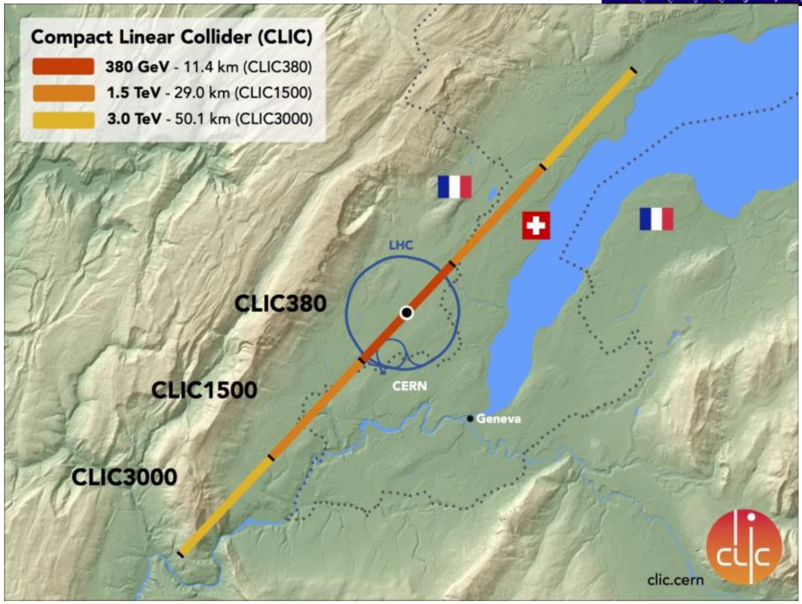


Overview

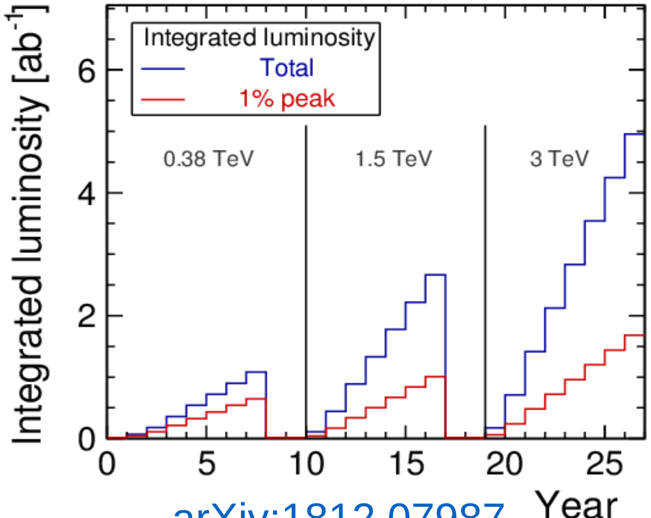
- CLIC project
- Detector for CLIC
- Higgs production at CLIC
- Higgs width and invisible BR
- Higgs-self coupling
- Higgs couplings – combined and EFT fits
- Higgs as a portal to BSM physics (compositeness, Higgs+heavy singlet, CPV in the Higgs sector)
- Summary

Compact LInear Collider

- Feasible and attractive option for an e^+e^- collider at CERN
- CLIC is now a mature project: ready for construction starting ~2026, with first collisions ~2035



- Two-beam acceleration scheme - key accelerator technologies have been demonstrated
- High acceleration gradient 100 MV/m
- Staged construction from 380 GeV up to 3 TeV
- Baseline ± 80 % electron polarization
  - enhances Higgs production at high-energy stages
  - additional observables sensitive to New Physics
  - characterization of new particles
- High-precision Standard Model (Higgs and top-quark) physics and BSM physics



arXiv:1812.07987

Collaborations

http://clic.cern/

CLIC accelerator collaboration

~60 institutes from 28 countries

CLIC accelerator studies:

- CLIC accelerator design and development
- (Construction and operation of CLIC Test Facility, CTF3)

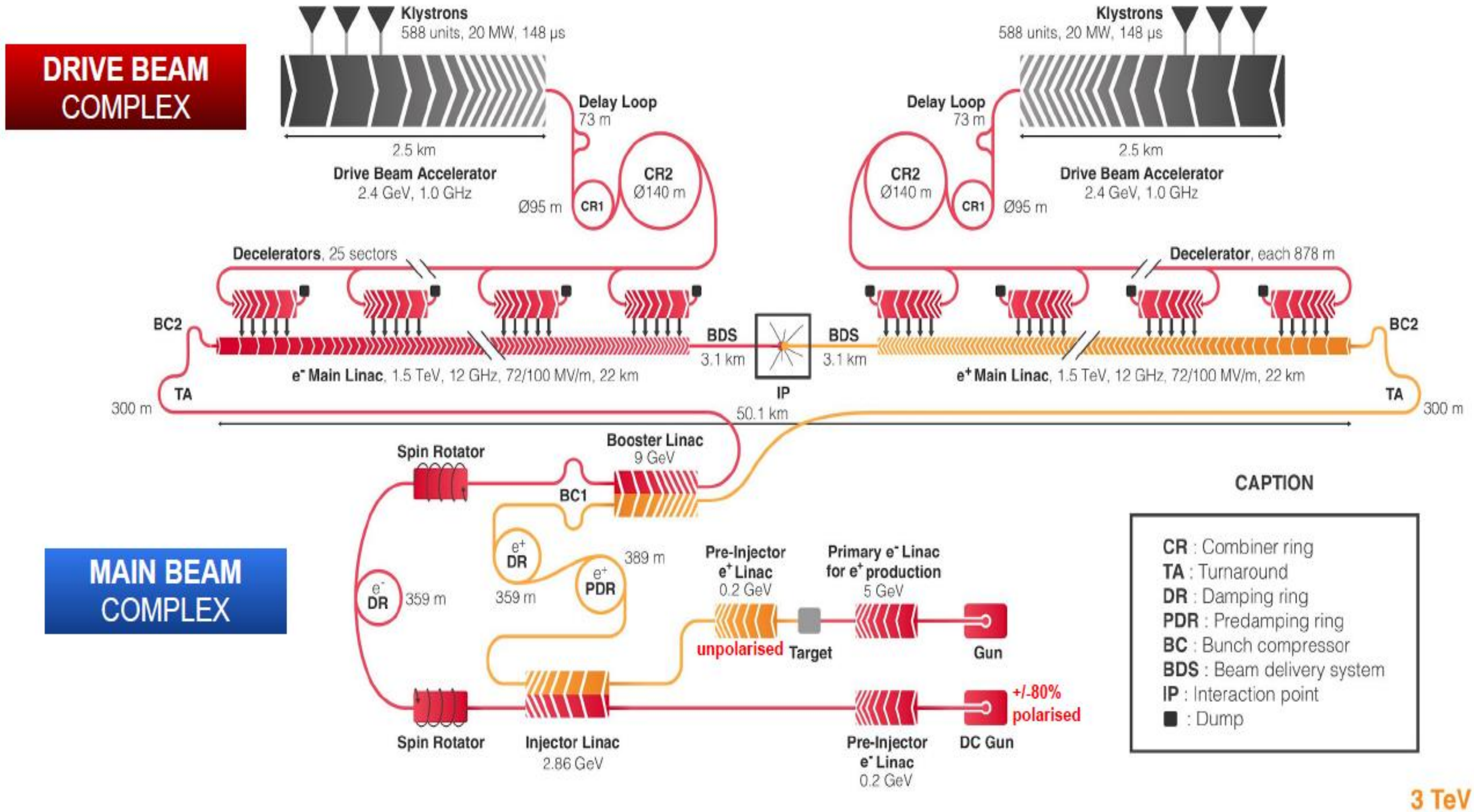
CLIC detector and physics (CLICdp)

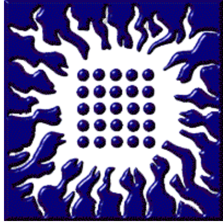
30 institutes from 18 countries

Focus of CLIC-specific studies on:

- Physics prospects & simulation studies
- Detector optimization + R&D for CLIC

CLIC accelerator layout @ 3 TeV

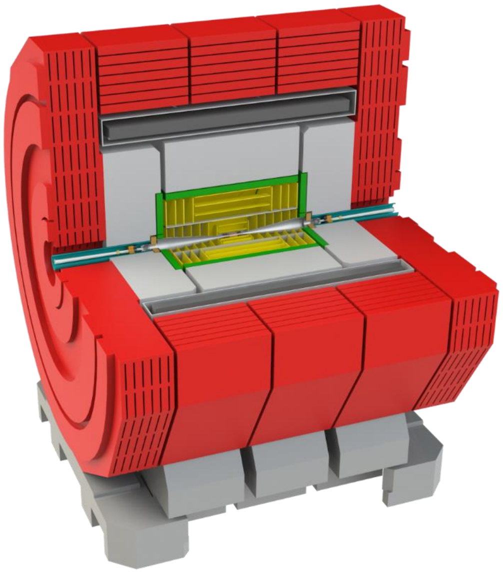


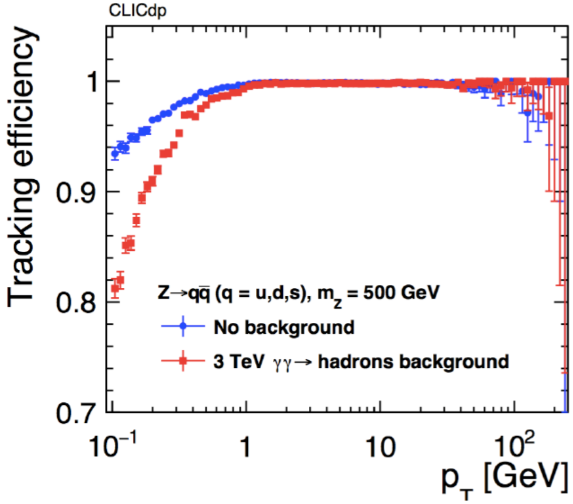


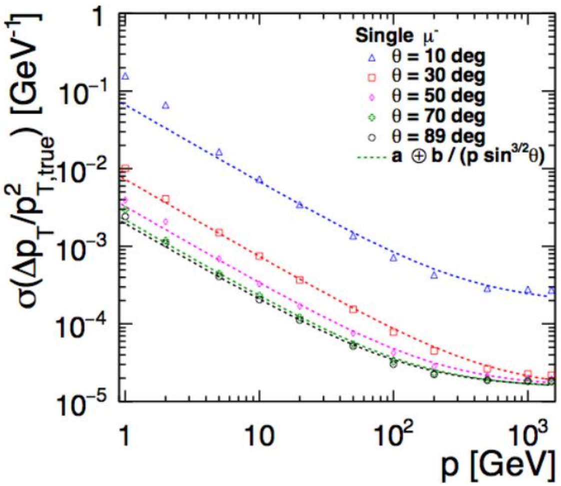
Detector for CLIC

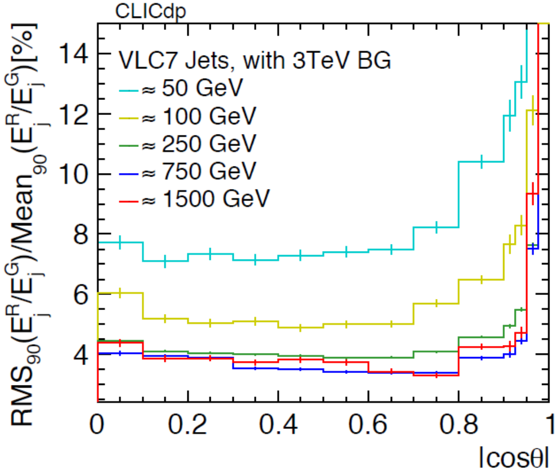
- CLICdet detector optimized for the precision physics program

- Particle reconstruction and identification with Particle Flow paradigm
- H, W, Z (jets) separation
- Efficient lepton identification and p_T determination



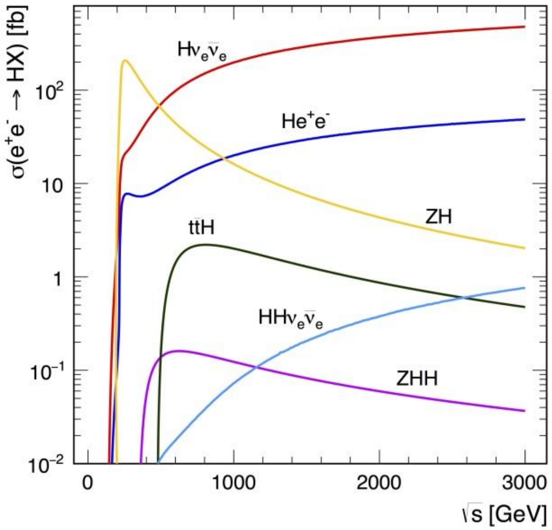




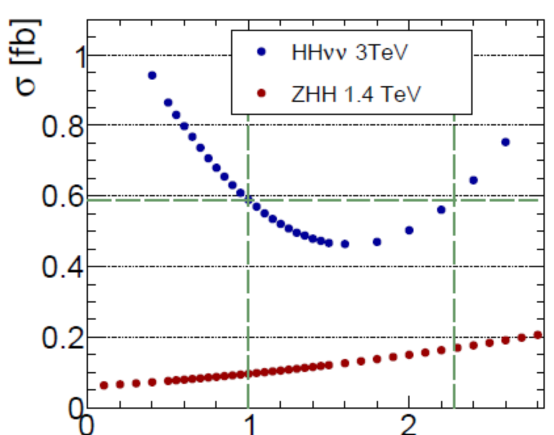


Full characterization of the detector model in arXiv:1812.07337

Higgs production at CLIC



HHνν and ZHH: different behavior of cross-section for non-SM trilinear Higgs coupling



arXiv:1901.05897v2

- CLIC exploits three highest cross-section Higgs production processes:
  1) *Higgsstrahlung ($e^+e^- \to ZH$)* - dominant below 500 GeV; Most of the Higgs couplings can be determined with a better precision than at HL-LHC already from HZ
  2) *WW-fusion ($e^+e^- \to H\nu_e\bar{\nu}_e$)* - dominant above 500 GeV
  3) *ZZ-fusion ($e^+e^- \to He^+e^-$)* - similar behavior with $\sqrt{s}$ as WW-fusion
- Staged concept enables full statistics of collected data to be exploited

Project	No. Higgs
CLIC 0.38+1.4+3 TeV [1]	$3\cdot10^6$ / $4.5\cdot10^{6(*)}$
ILC 250/500 GeV [2]	$8\cdot10^{4(*)}$ / $8\cdot10^{4(*)}$
CEPC 250 GeV [3]	$1\cdot10^6$
FCCee 240/365 GeV [4]	$1.02\cdot10^6$ / $0.22\cdot10^6$

* with polarization, [1] arXiv:1812.07986v1 [hep-ex], [2] ILC-REPORT-2013-040, [3] IHEP-CEPC-DR-2018-02, [4] EPJ Special Topics 228, 261-623 (2019)

Higgs properties: Γ_H and invisible decays

- Γ_H - various possibilities from individual (i.e. H→ZZ in HZ or H → WW decays in WW-fusion) to global measurements (κ-framework , EFT fit)

- Γ_H uncertainty obtained from the model dependent fit (κ-framework) ranges from 2.6% (1.6%) at 350 GeV (3 TeV)

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{SM} \qquad \frac{\Gamma_{H,md}}{\Gamma_H^{SM}} = \sum_i \kappa_i^2 BR_i$$

- **Invisible Higgs decays - connection between the Higgs boson and dark matter searches**

- In the SM, BR(H→inv) = 0.11%
- Curent LHC limit ~ 15-20% @ 95%CL

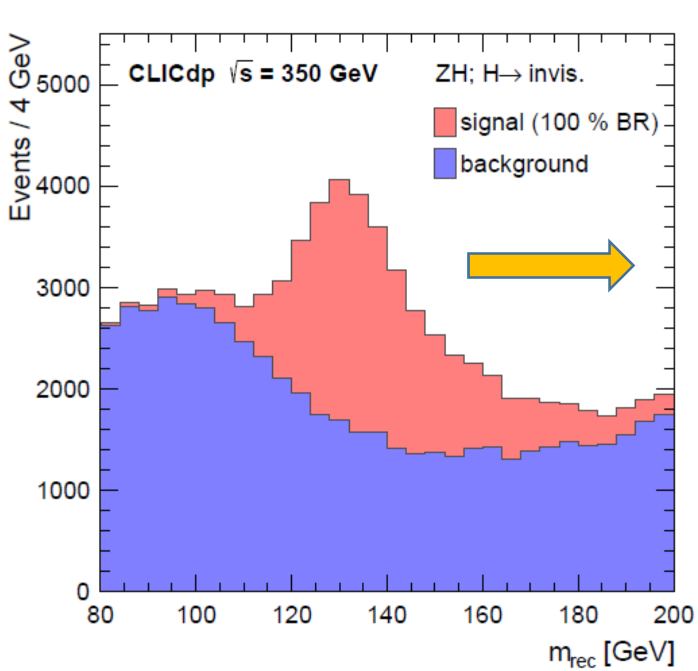
Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
	90% CL	95% CL upper bound on BR_{inv} [%]	
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30

3 TeV CLIC indirect measurement would improve HL-LHC limits on Higgs BRinv almost by an order of magnitude

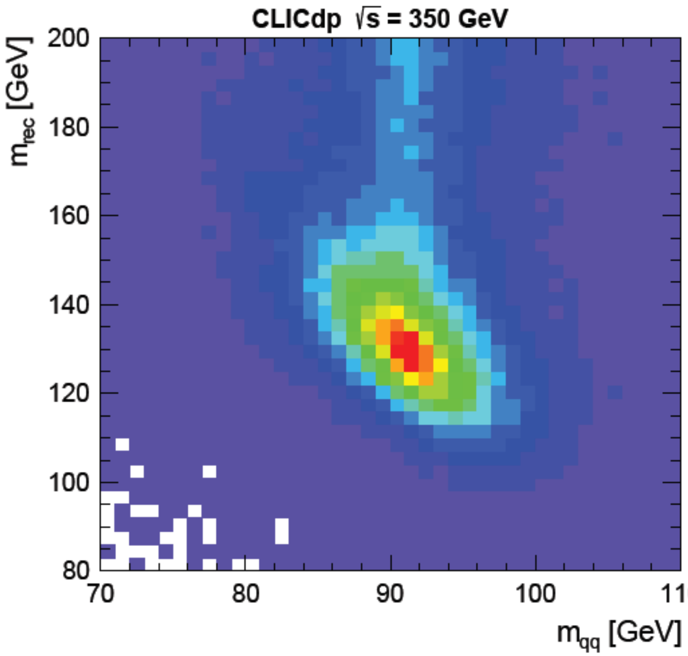
Direct measurement of BR_{inv}

Direct searches for Invisible width: fundamentally different in a hadron collider (MET uncertainties) and a lepton collider (Z recoil)

- Model-independent, by recoil mass technique at 350 GeV, 1 ab^{-1}
- Signature: $e^+e^- \rightarrow ZH, Z \rightarrow q\bar{q}$ + missing energy



Recoil mass from $Z \rightarrow q\bar{q}$, assuming 100 % invisible Higgs decays

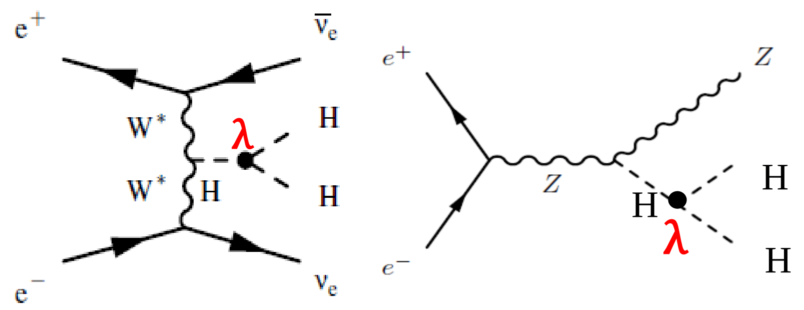


Excellent jet reconstruction to distinguish btw. Higgs and Z jets (example: di-jet invariant mass vs. recoil mass, $ZH \rightarrow qqX$ at $\sqrt{s} = 350$ GeV)

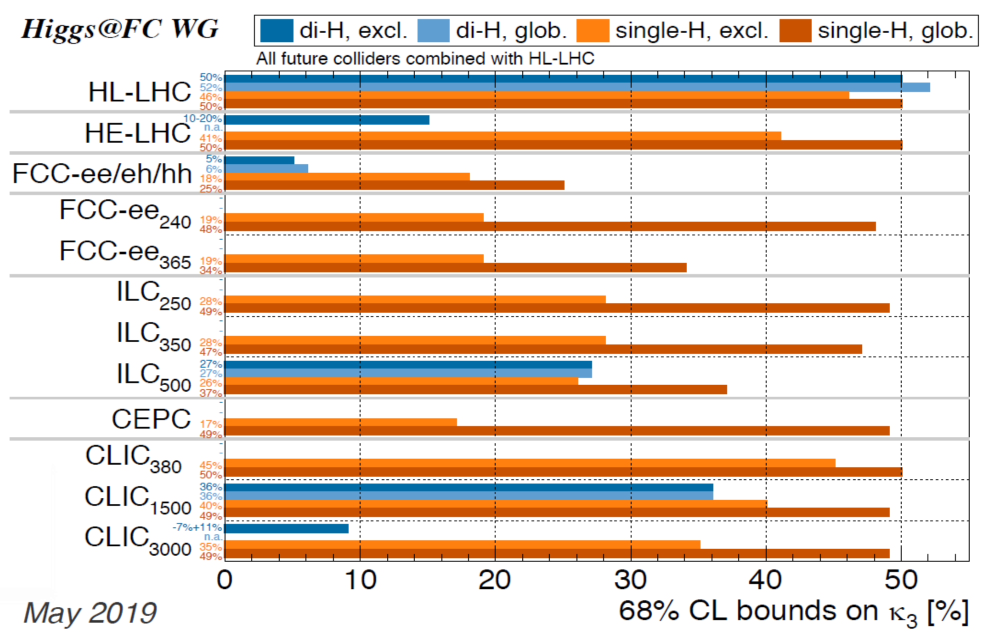
Eur. Phys. J. C 76, 72 (2016)

Higgs self-coupling

Process	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	3.5σ EVIDENCE $\frac{\Delta\sigma}{\sigma} = 29\%$	> 5σ OBSERVATION $\frac{\Delta\sigma}{\sigma} = 7.3\%$
$\sigma(ZHH)$	2.1σ EVIDENCE	2.4σ EVIDENCE
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -29%, +67% rate-only analysis	1.4 + 3 TeV: -8%, +11% differential analysis



- Template fit at 3TeV using two variables: m(HH) differential distribution and BDT score
- Dominated by statistical uncertainty, CLIC has unrivalled sensitivity to Higgs self-coupling
- Situation is different at hadron colliders where precision of λ measurement is limited by theoretical uncertainties



Clear benefits on precision of λ w.r.t. to low-energy e^+e^- colliders

Higgs couplings: combined fits

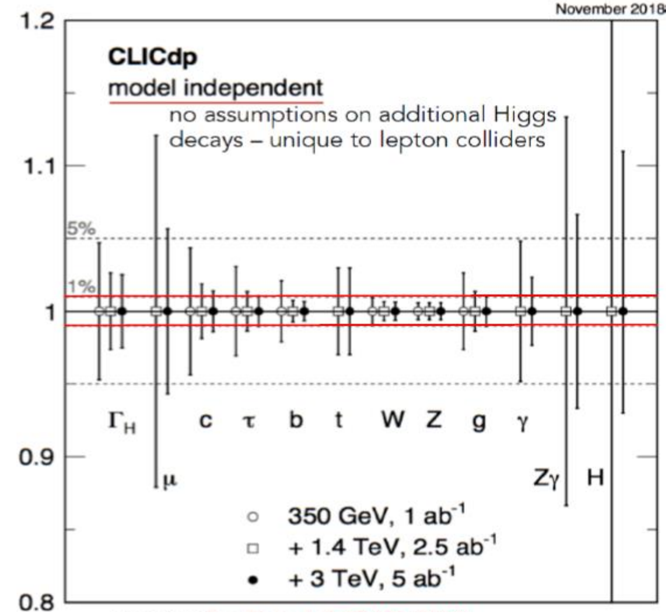
e^+e^- colliders:

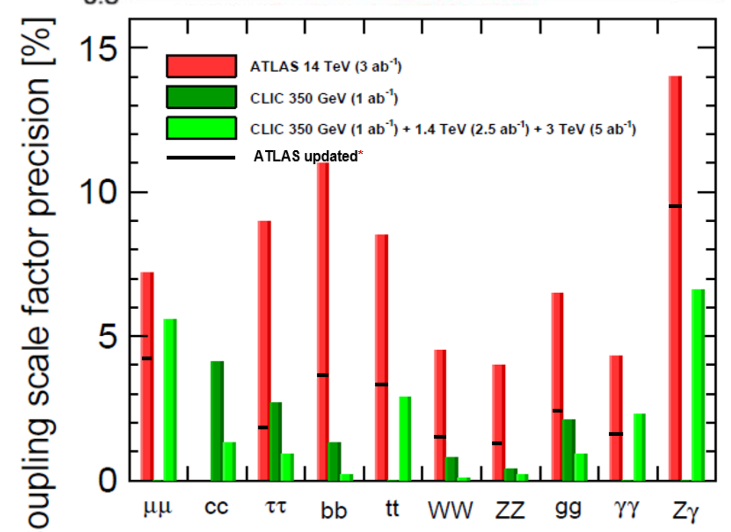
Absolute measurement of the ZH cross-section

Absolute measurement of the Higgs BRs

Nearly model-independent determination of the Higgs total width and couplings

- All stages combined- each contributes significantly
- Detailed studies: full detector simulation of physics and background processes including beam-beam interactions, global fit including correlations
- Most couplings can be measured below 1% stat. uncertainty in a model independent (dependent) way
- Already at the first stage better precision than at HL-LHC, in particular for c/b/W/Z couplings





* Update for the European Strategy for Particle Physics , arXiv:1905.03764v2

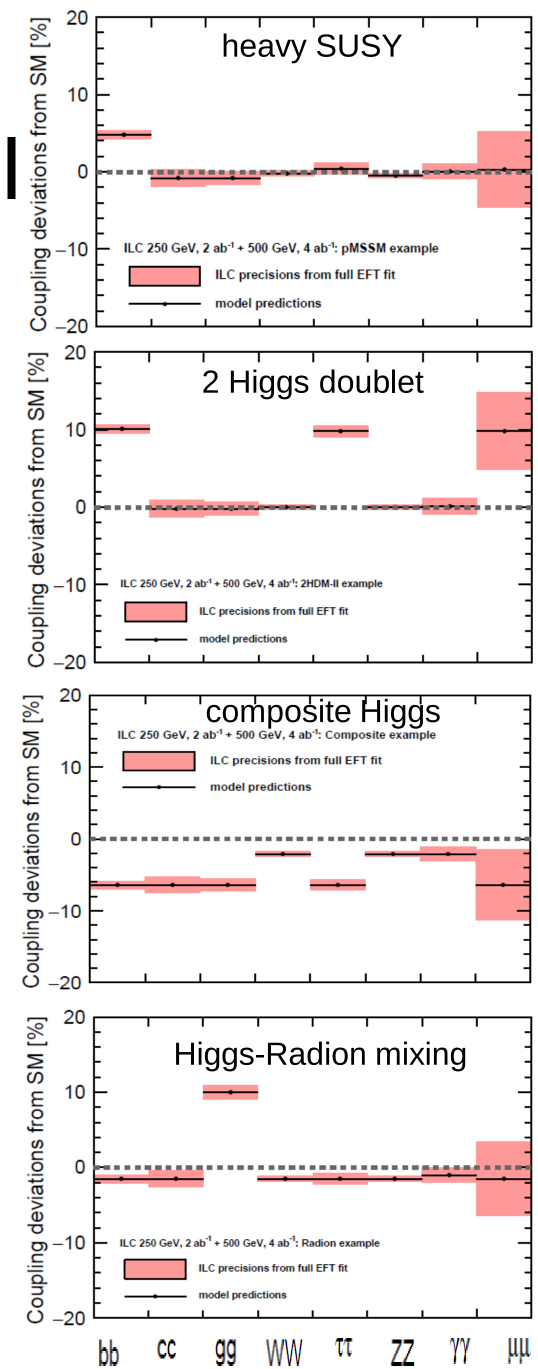
Higgs couplings: sensitivity to BSM model

Collider	Mode	W	Z	g	γ	$Z\gamma$	c	top	b	μ	τ
HL-LHC	S_2	1.7	1.5	2.5	1.8	9.8	-	3.4	3.7	4.3	1.9
HE-LHC	S_2	1.5	1.3	2.2	1.6	6.9	-	3.2	3.5	2.2	1.7
CLIC	Model Dep 350 GeV	0.8	0.4	2.1	-	-	4.1	-	1.3	-	2.7
	Model Dep 1.4 TeV	0.2	0.3	1.2	4.8	13.3	1.8	2.9	0.3	12.1	1.2
	Model Dep 3 TeV	0.1	0.2	0.9	2.3	6.6	1.3	2.9	0.2	5.6	0.9
	Model Indep 350 GeV	1.0	0.6	2.6	-	-	4.4	-	2.1	-	3.1
	Model Indep 1.4 TeV	0.6	0.6	1.4	4.8	13.3	1.9	3.0	0.7	12.1	1.4
	Model Indep 3 TeV	0.6	0.6	1.0	2.3	6.7	1.4	3.0	0.7	5.7	1.0
CEPC	7 param Fit	1.3	0.13	1.5	3.7	-	2.1	-	1.2	-	1.3
	10 param Fit	1.4	0.25	1.5	3.7	-	2.2	-	1.3	8.7	1.5
ILC	EFT Fit 250	0.55	0.56	1.6	1.1	-	1.8	-	1.0	4.0	1.2
	EFT Fit 500	0.37	0.38	0.96	1.0	-	1.2	6.3	0.6	3.8	0.77
FCC_{ee}	240 GeV	1.3	0.2	1.6	4.8	-	1.7	-	1.3	10.1	1.4
	365 GeV	0.43	0.17	1.01	3.9	-	1.21	-	0.61	9.0	0.74
FCC_{hh}		-	-	-	0.4	0.91	-	0.95	-	0.65	-
FCC_{eh}	no theo	0.22	0.35	1.1	2.1	-	1.2	-	0.60	-	0.93
LHeC		0.70	1.2	3.5	6.8	-	3.8	-	1.9	-	3.1

M.Cepeda for the Higgs@Future Colliders Group
for the Update of the European Strategy for Particle Physics

In many BSM models (for new particles in the TeV range) one expects only % level deviations from the Higgs SM-couplings

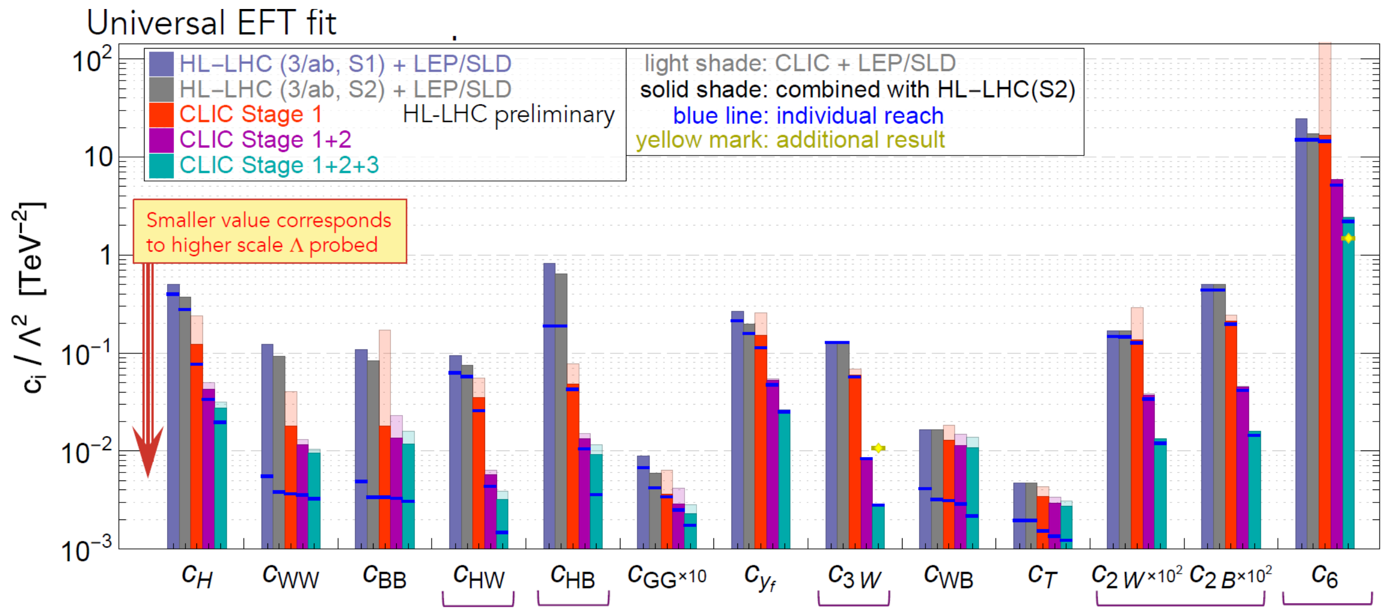
CLIC meets these requirements with its global fits



Examples of expected deviations of the Higgs couplings to several BSM models inaccessible at HL-LHC [*]

*Georg Weiglein, Higgs requirements from theory, DESY, Hamburg, May 2019

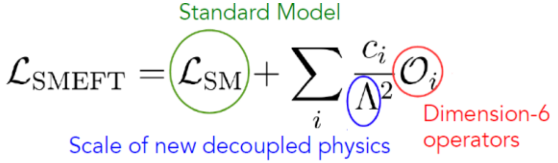
Higgs couplings EFT fit – global sensitivity to BSM physics



arXiv:1812.02093 The CLIC potential for new physics, CERN-2018-009-M

Staged approach maximizes EFT fit sensitivity to contributions from BSM physics and enables to exploit EFT operators energy dependence

Sometimes, an order of magnitude improvement w.r.t. HL-LHC (c_{HW}, c_{HB}, c_{3W})

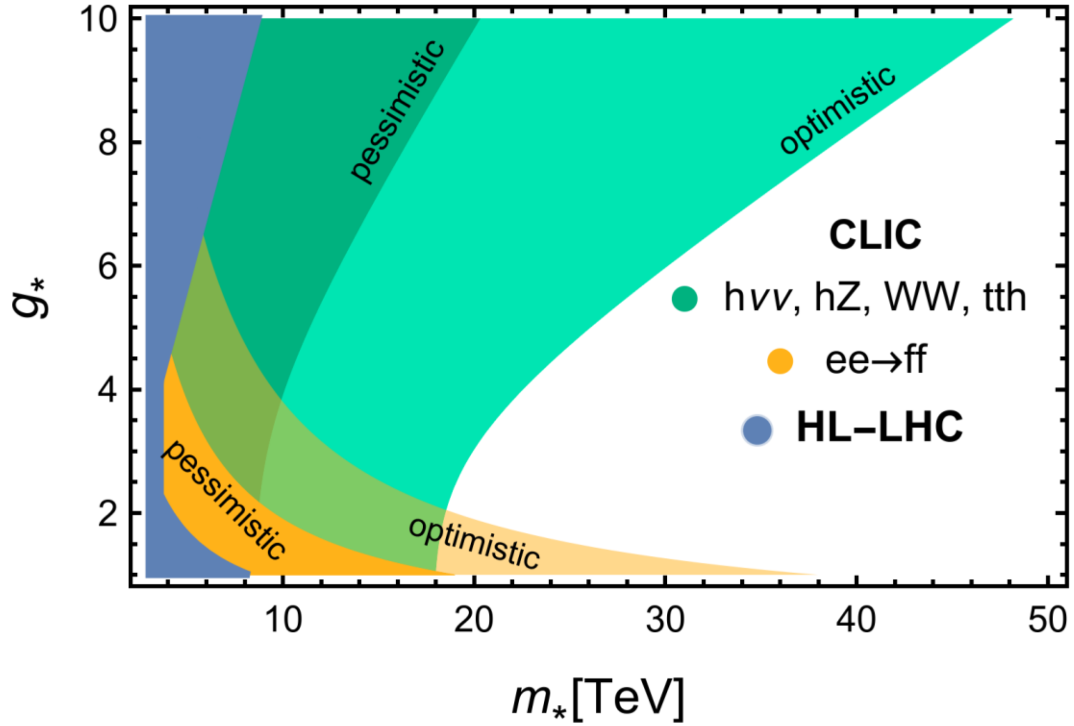


Couplings receive contribution from dim-6 operators from BSM physics at the scale Λ, independent of realization of a particular physics model

Higgs as a portal to New Physics: Compositeness

- Higgs boson is a pseudo-Nambu-Goldstone boson of an underlying strongly-interacting composite sector
- Composite Higgs would appear through EFT operators – translate EFT limits into characteristic coupling strength *g** of composite sector and mass *m**
- CLIC can *discover* compositeness up to ~10TeV compositeness scale (the most pessimistic case)
- Above HL-LHC exclusion range

5σ discovery regions (CLIC)
exclusion region (HL-LHC)

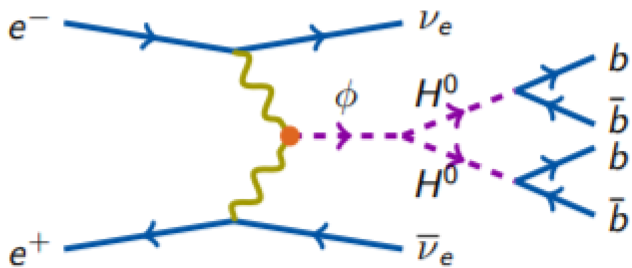


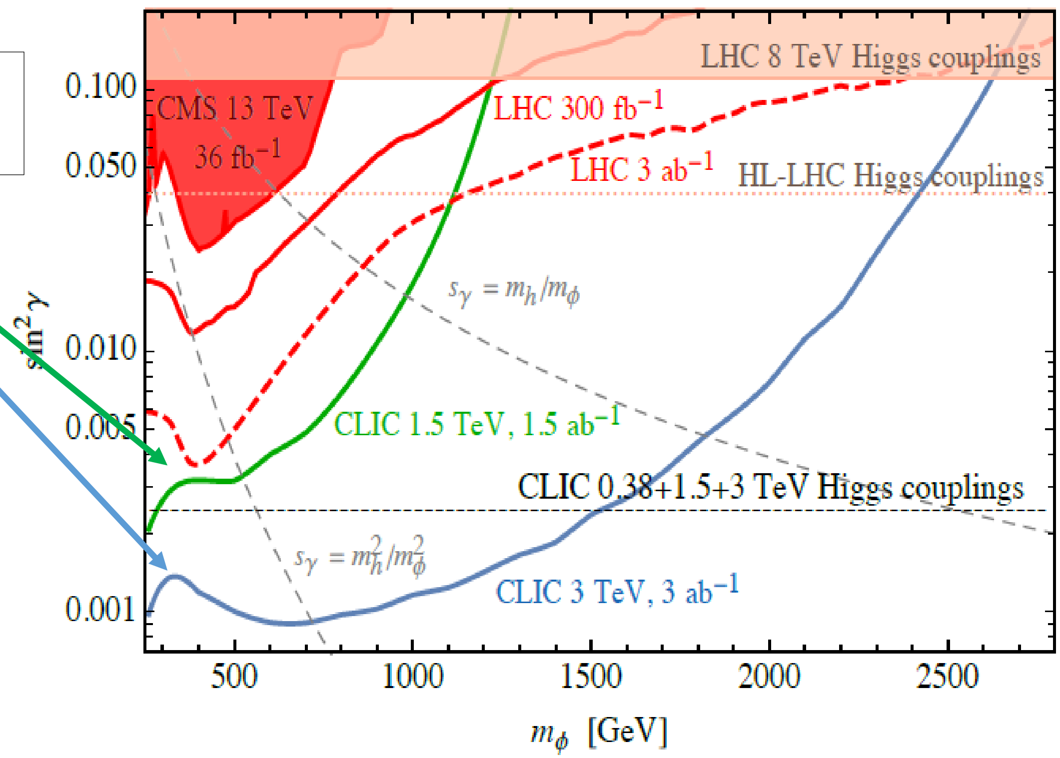
arXiv:1812.02093 The CLIC Potential for New Physics

Higgs as a portal to New Physics: Higgs + heavy singlet

[arXiv:1812.02093](https://arxiv.org/abs/1812.02093) The CLIC Potential for New Physics

Direct search for real scalar singlet ϕ





- The SM scalar sector is extended by a new state that is not charged
- Mixing with the SM-Higgs boson with the mixing angle γ

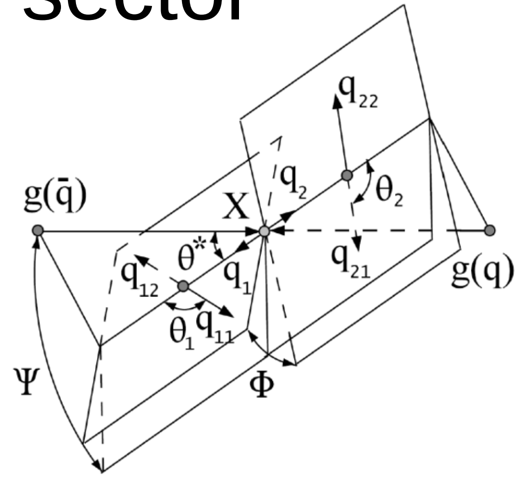
Indirect search using Higgs couplings
(SM-Higgs couplings are rescaled by cos γ)
$sin^2\gamma \leq 0.24\%$ at 95% CL

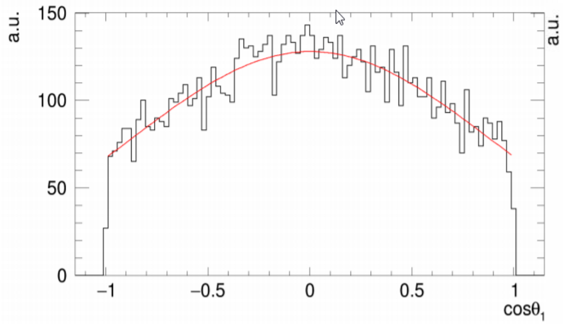
Higgs as a portal to New Physics: CPV in the Higgs sector

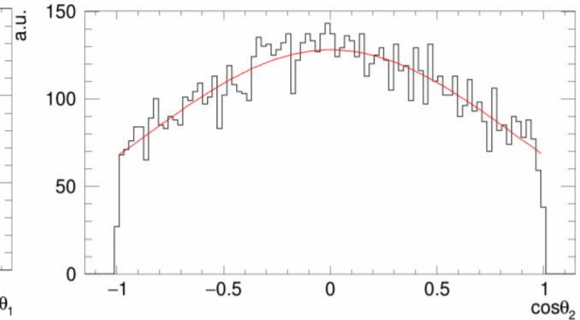
- Eventual observation of CPV in the Higgs sector will be a New Physics per se
- Observed SM-like Higgs (h) boson can be a (CPV) mixture of scalar and pseudoscalar states

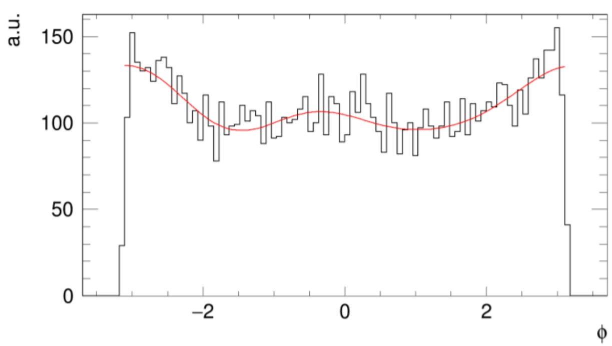
$$h = H \cdot \cos\alpha + A \cdot \sin\alpha$$

- So far, only ILC reported (statistical) sensitivity of 4.3deg. to CPV mixing angle in $h \rightarrow \tau\tau$ decay arXiv:1804.01241 [hep−ex] (FCCee gives estimate of 10 deg. for ESPPU, EPJC 79, 474 (2019))
- H→ZZ (in the leptonic and bbll channel) of particular interest due to sensitivity to α
- Ongoing analysis is based on utilization of full kinematic information (mass and angular distributions) of Higgs decay products sensitive on Higgs spin-parity
- 3 sensitive observables reconstructed for J=0 state



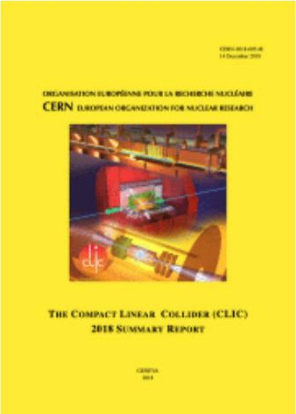






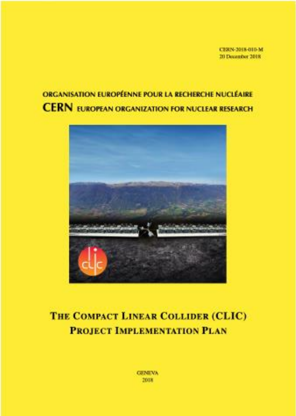
Summary

- CLIC is a mature project, ready to start construction in already in 2026
- multi-TeV energies and data exploitation from all-energy stages gives a physics case for precision Higgs measurements and their interpretation in new physics scenarios
- Already at the lowest center-of-mass energy better precision than at HL-LHC is achievable on the Higgs couplings
- Dominated by statistical uncertainty, CLIC has unrivalled sensitivity to Higgs self-coupling (differently from hh machines where theoretical uncertainties dominates systematics)
- High-energy stages enable enhanced sensitivity (w.r.t. to Higgs factories@250GeV) to realization of BSM, also in the Higgs sector

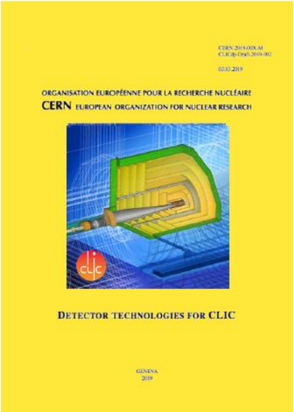


CERN-2018-005-M

CERN-2018-009-M



CERN-2018-010-M

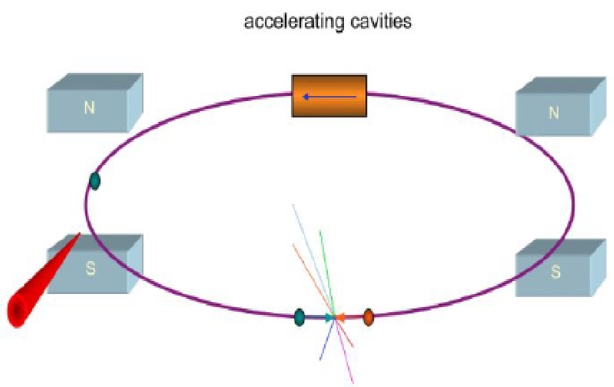


CERN-2019-001

Additional material

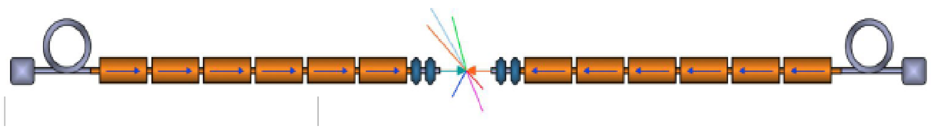
Circular vs. linear e^+e^- colliders

Circular colliders



- Can accelerate beam in many turns
- Can collide beam many times
- Possibility of several interaction regions
- Limited energy due to synchrotron radiation
  - $m_p/m_e \approx 2000$
  - Synchrotron radiation~ $E^4/(m^4 \cdot \text{Radius})$

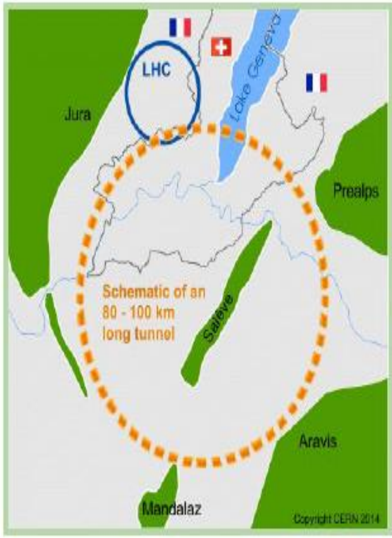
Linear colliders



- Very little synchrotron radiation
- One interaction region
- Can reach high energies

- Have to achieve **energy** in a single pass
  - High acceleration gradients needed
- Have to achieve **luminosity** in single pass
  - Small beam size and high beam power
  - Beamstrahlung, energy spread

Future high-energy e^+e^- colliders

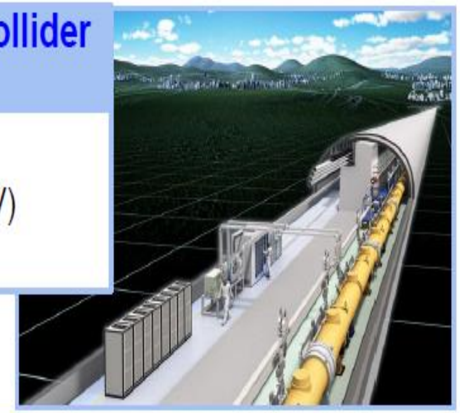


Future Circular Collider (FCC-ee)

CERN
e^-e^+, $\sqrt{s}$: 90 - 365 GeV
(followed by pp, $\sqrt{s}$: ~100 TeV)
Circumference: 97.75 km

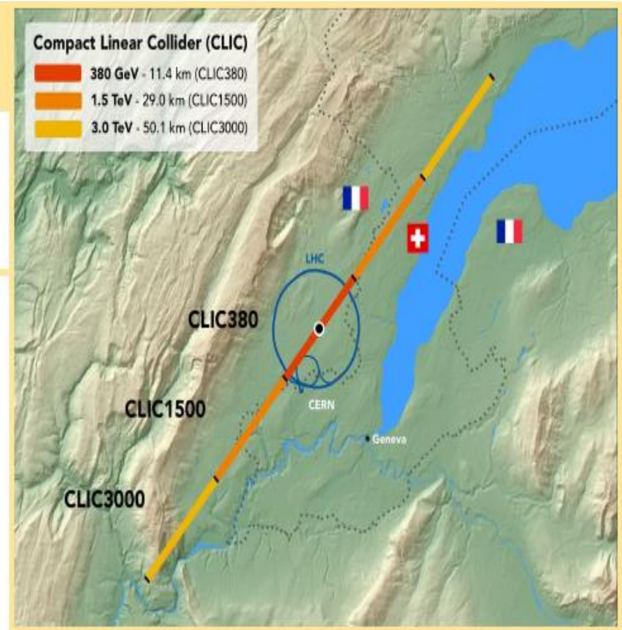
International Linear Collider (ILC)

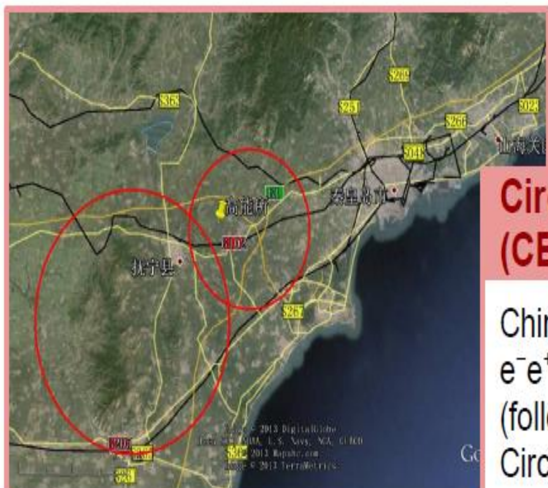
Japan (Kitakami)
e^-e^+, $\sqrt{s}$: 250 GeV (500 GeV)
Length: 17 km (31 km)



Compact Linear Collider (CLIC)

CERN
e^-e^+, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

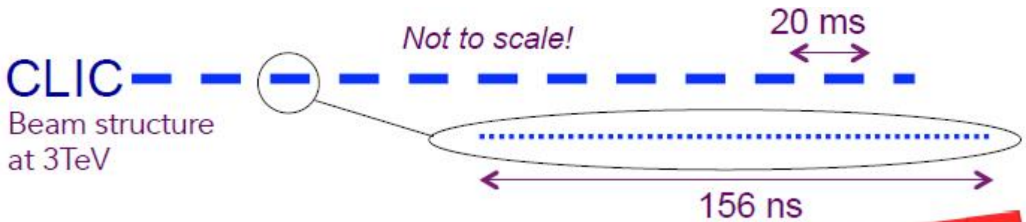




Circular Electron Positron Collider (CEPC)

China
e^-e^+, $\sqrt{s}$: 90 – 240 GeV
(followed by pp, $\sqrt{s}$: ~100 TeV)
Circumference: ~100 km

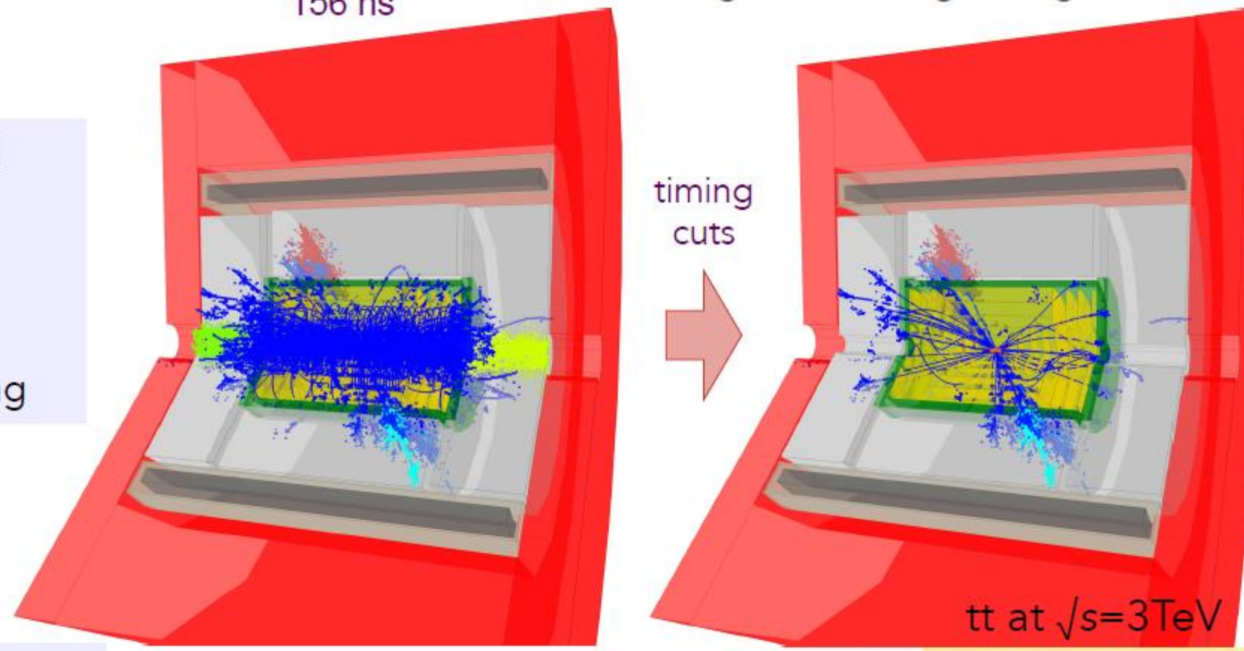
Collider environment



High bunch charge density
–> beam-related backgrounds
small effect at $\sqrt{s}$=380GeV
large effect at high energies

Precise timing required for beam background rejection

1ns in calorimetry,
5ns in vertexing/tracking



High precision:
- jet energy resolution
  –> fine-grained calorimetry
- momentum resolution
- impact parameter resolution

$\sigma(E)/(E) \sim 3.5\%$ for E>100GeV
$\sigma(p_T)/p_T^2 \sim 2\text{x}10^{-5}$ GeV^{-1}
$\sigma_{d0} \sim 5 \oplus 15/(p[\text{GeV}]\sin^{3/2}\theta)$ µm

DESY → CALICE / FCAL
DESY → CLICdp vertexing/ tracking programme

European Strategy for Particle Physics

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Schedule

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

European Strategy Update

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

2035
First collisions

Higgs properties: mass

- Current experimental precision ~0.1% (160 MeV)
- Impact of the m_H uncertainty on the HZZ decay width - m_H needs be improved to around 10 MeV to avoid any limitation on ZZ/WW couplings (@e+e- colliders)
- HL-LHC reach dependent on muon p_t momentum calibration with high statistics (10-20 MeV plausible)

- Example of a recoil mass measurement in ZH at CLIC (statistically limited w.r.t. $H\rightarrow bb$ invariant mass measurement in WW-fusion)

M.Cepeda for the Higgs@Future Colliders Group
for the Update of the European Strategy for Particle Physics

Collider Scenario	Strategy	δm_H (MeV)
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160
HL-LHC	$m(ZZ)$	10-20
$CLIC_{380}$	ZH recoil	78
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[15]
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23