Physics at the Compact Linear Collider (CLIC)

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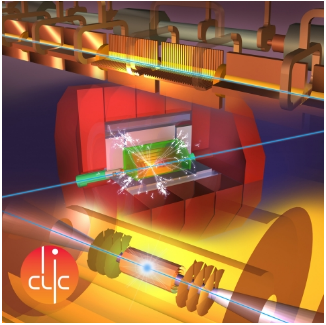
10.02.2021
Seminar Birmingham



Outline

Current state of particle physics

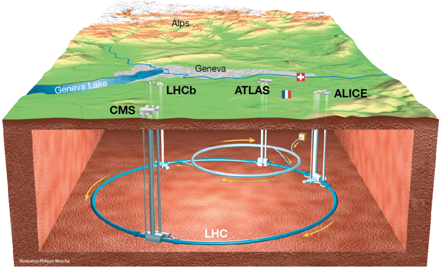
CLIC accelerator

CLIC detector model

CLIC physics potential

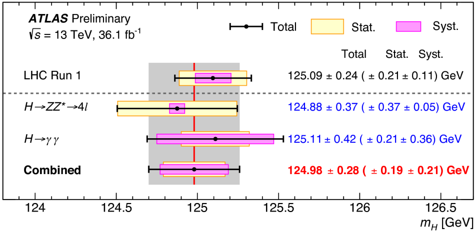
Summary and Outlook

The Large Hadron Collider and the Higgs boson



LHC: proton-proton collider

CME	7...8...13 TeV
Taking data	since 2010
4 experiments	ATLAS, ALICE, CMS, LHCb



- Discovery of a Higgs boson (2012) at CMS & ATLAS
- Sparked investigation of the nature of electroweak symmetry breaking ⇒ far from completed!

Phys. Rev. Lett. 114 (2015) 191803

Open questions and the physics landscape

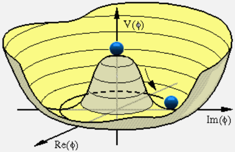
Open Questions

- Dark Matter
- Dark Energy
- Origin of baryon asymmetry
- Origin of neutrino masses

- Why are we not seeing new physics around the TeV scale?
  - mass scale beyond LHC reach?
  - mass scale within LHC reach, but final states are elusive?
- Need for
  - $\Rightarrow$ precision measurements
  - $\Rightarrow$ sensitivity to elusive signatures
  - $\Rightarrow$ extended energy/mass reach

New probe: the Higgs boson

- experimental results leave room for wide range of BSM EWSB scenarios
- still open aspects, including
  - Higgs couplings to lighter particles
  - Higgs self-coupling → shape of potential
  - possible other particles coupled to the Higgs

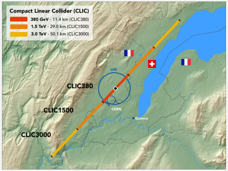


$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Proposed electron-positron colliders at the energy frontier

Linear e^+e^- colliders

- Compact Linear Collider CLIC

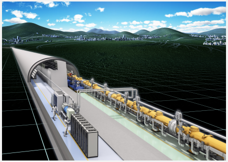


CERN

$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV

ℓ = 11 km, 29 km, 50 km

- International Linear Collider ILC



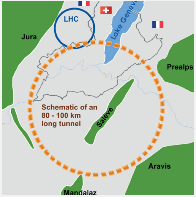
Japan

$\sqrt{s}$ = 250 GeV (500 GeV, 1 TeV)

ℓ = 17 km (31 km, 50 km)

Circular e^+e^- colliders

- Future Circular Collider FCC-ee



CERN

$\sqrt{s} = 90 - 350$ GeV

ℓ = 98 km

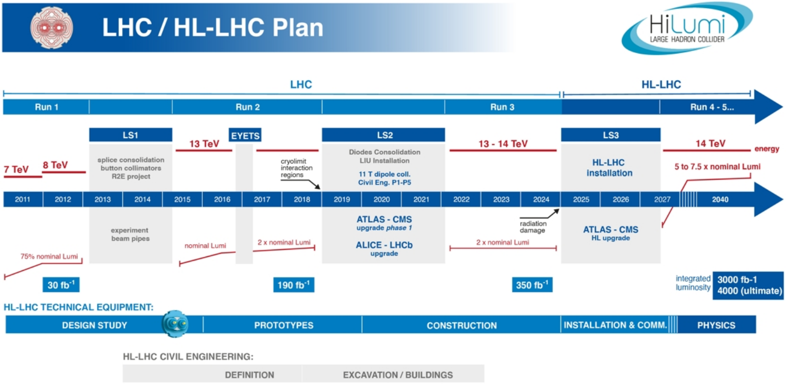
- Circular Electron Positron Collider

China

$\sqrt{s} = 90 - 240$ GeV

ℓ = 100 km

Planned timeline of LHC, HL-LHC

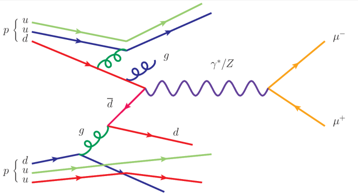


HL-LHC physics program

- Search for physics beyond the SM
- Continuation of top, Higgs, electroweak physics program of the LHC

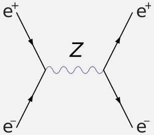
Electron-positron vs. hadron collider

Proton-proton collider



- Proton is compound object
  - Initial state unknown
  - Limited achievable precision
- High rates of QCD backgrounds
  - Complex triggers
  - High levels of radiation
- High-energy circular colliders possible

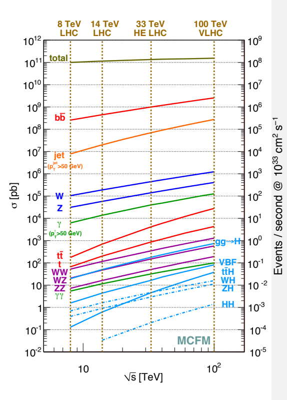
Electron-positron collider



- e^+, e^- are elementary
  - Initial state well-defined ($\sqrt{s}$, polarization)
  - High-precision measurements
- Clean experimental environment
  - Less/ no need for triggers
  - Lower radiation levels
- High energies ($\sqrt{s} > 350\,\text{GeV}$) require linear colliders

Interesting physics processes in pp and ee collisions

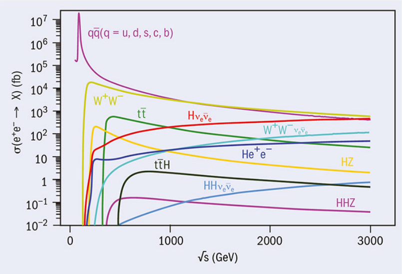
Proton-proton collider



`https://mcfm.fnal.gov/mcfm-Edep.pdf`

Interesting events suppressed by $\gtrsim 8$ orders of magnitude

Electron-positron collider

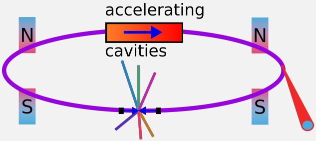


`http://clicdp.web.cern.ch/sites/clicdp.web.cern.ch/files/CCcli3_09_16.jpg`

More "clean", all events usable

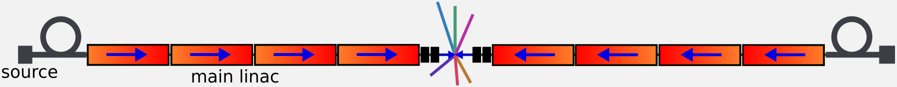
Circular and linear colliders

Circular colliders



- Beam circulates for a long time
- Few accelerating cavities, many magnets
- High energy → need strong magnets
- Synchrotron radiation $\sim \frac{E^4}{m^4 r}$

Linear colliders



- Beam passes only once
- Few magnets, many accelerating cavities
- High energy → need high accelerating gradient
- High luminosity → high beam power (high bunch repetition)

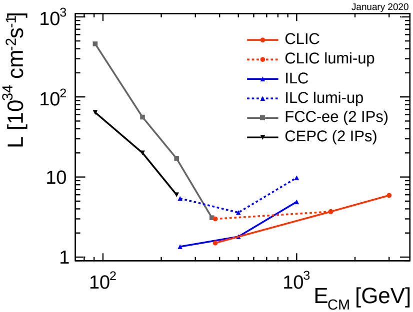
Electron-positron colliders

Circular e^+e^- colliders

- Energy limited by synchrotron radiation
- Large luminosity at lower energies
- Luminosity decreases with energy

Linear e^+e^- colliders

- Can reach highest energies
- Luminosity rises with energy
- Beam polarization possible at all energies



Past colliders:
LEP2 (209 GeV) peak luminosity
$\mathcal{L} = 10^{32}\text{cm}^{-2}\text{s}^{-1}$

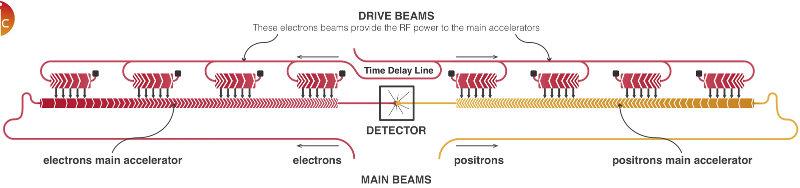
CLIC accelerator

The Compact Linear Collider CLIC

Goal	High gradient, efficient energy transfer (wall-plug to beam)
Means	High-frequency RF maximizes field in cavities for given energy
Challenge	Standard RF sources inefficient at high frequencies
CLIC solution	Use standard low-frequency RF sources to accelerate a drive beam; bring it to high frequency; transfer energy to main beam

Two-beam acceleration scheme

Dense, low energy drive beam RF power extracted to accelerate less particles per bunch to higher energy per particle



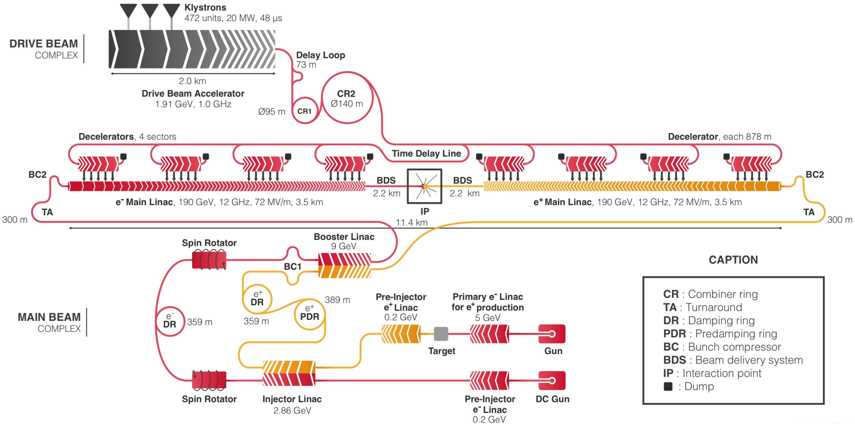
380 GeV

Layout of the CLIC accelerator complex

Drive beam high current (100 A); lower energy (2.4 GeV); 12 GHz after CRs & loops

Power Extraction and Transfer Structures decelerate the beam → extract its energy → guide it via waveguides to the main beam accelerating structures

Main beam High energy up to 1.5 TeV; lower current 1.2 A



CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

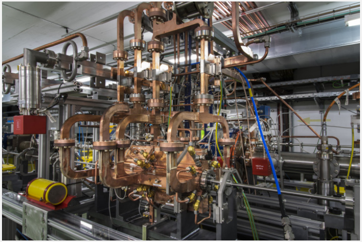
380 GeV

Real-life test facilities

CTF3, the CLIC Test Facility

Successful demonstration of

- Drive beam generation
- RF power extraction
- Gradient up to 145 MV/m



C-band facilities

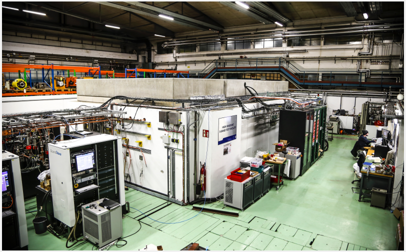
using CLIC technology (SwissFEL)

The two-beam module

Test module without beam for tests of

- thermo-mechanical effects
- engineering
- alignment and support
- vacuum, etc.

X-band test facility

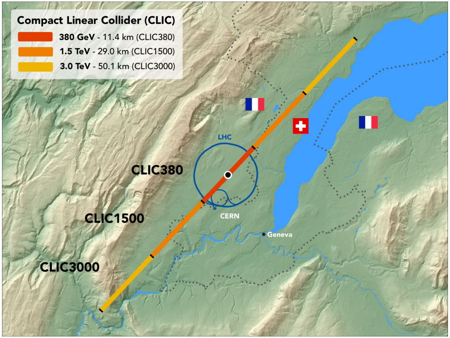


test and development of high-gradient accelerating structures

CLIC staged implementation and map

Baseline: several energy stages

Stage	$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]
1	380	1000
top scan	350	100
2	1500	2500
3	3000	5000

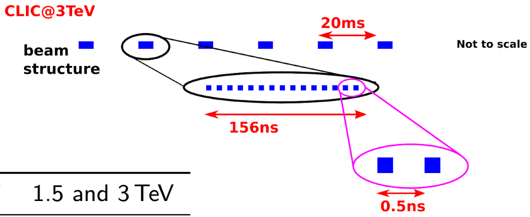


⇒ stages can be adapted to possible discoveries at the LHC

Even further in the future: Upgrade with Plasma Wakefield technology possible

Beam properties and experimental conditions

CLIC bunch structure and experimental conditions



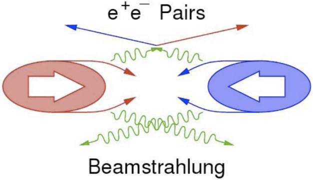
Energy stage(s)	380 GeV	1.5 and 3 TeV
Train repetition rate	50 Hz	50 Hz
Bunches / train	356	312
Train duration	178 ns	156 ns
Bunch separation	0.5 ns	0.5 ns
Duty cycle	0.00089 %	0.00078 %

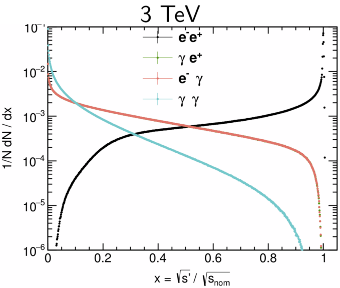
- Linear colliders operate in bunch trains
- Bunch separation drives timing requirements of the detector
  - 10 ns hit time-stamping in tracking
  - 1 ns accuracy for calorimeter hits
- Low duty cycle → power pulsing of detectors possible

Beam-beam interaction

High luminosities achieved by using extremely small beam sizes

- At 3 TeV: bunch size $\sigma_x = 40\,\text{nm}$, $\sigma_y = 1\,\text{nm}$, $\sigma_z = 44\,\mu\text{m}$
- Flat beams: high luminosity while minimizing electromagnetic fields
- Electromagnetic interaction of e^+ and e^- beams
  $\rightsquigarrow$ synchrotron radiation: *beamstrahlung*
- Collective (beam) effect; real photons





Beamstrahlung:

… modifies energy spectrum of the colliding e^+e^- pairs

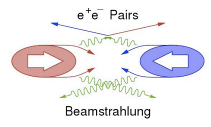
… **produces $e^\pm\gamma$ and $\gamma\gamma$ collisions**

… drives detector requirements to a large extend

Beam-induced backgrounds

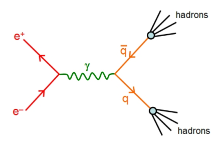
Coherent and incoherent e^+e^- pairs

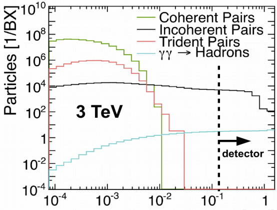
19k particles per bunch train (3 TeV)
High occupancies → impact on detector granularity and design



$\gamma\gamma \rightarrow$ hadrons

17k particles per bunch train (3 TeV)
Main background in calorimeters and trackers → impact on detector granularity, design and physics measurements





BX = bunch crossing

- Bunch trains with 312 bunches every 0.5 ns
- $\gamma\gamma \rightarrow$ hadrons suppressed with **timing cuts**

CLIC detector

Detector requirements

+ Momentum resolution:

Higgs recoil mass, $H \rightarrow \mu\mu$,
leptons from BSM processes

$$\frac{\sigma(p_T)}{p_T^2} \approx 2 \times 10^{-5} \mathrm{GeV}^{-1}$$

+ Energy resolution for light quarks:

W/Z/H separation

$$\frac{\sigma(E)}{E} \approx 3.5 - 5\,\% \text{ for } E = 50...1000\,\mathrm{GeV}$$

+ Impact parameter resolution:

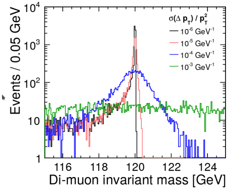
b/c tagging, e.g. Higgs couplings

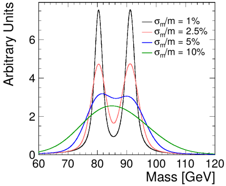
$$\sigma(d_0) = \sqrt{a^2 + b^2 \mathrm{GeV}^2/(p^2 \sin^3\theta)},$$

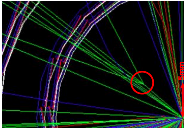
$$a \approx 5\mathrm{\mu m}, b \approx 15\mathrm{\mu m}$$

+ Lepton identification, very forward e/γ tagging

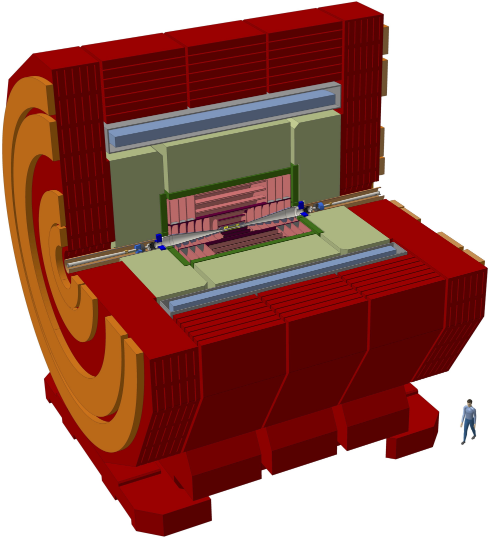
+ Requirements from beam-induced backgrounds







Overview of the detector



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

Particle Flow Calorimetry

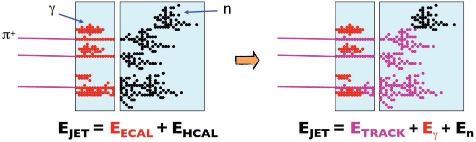
Particle Flow principle

Average jet composition

- 60 % charged particles
- 30 % photons
- 10 % neutral hadrons

Always use the best information

- charged particles → tracker
- photons → ECAL
- neutral hadrons → HCAL



http://www.hep.phy.cam.ac.uk/linearcollider/calorimetry/

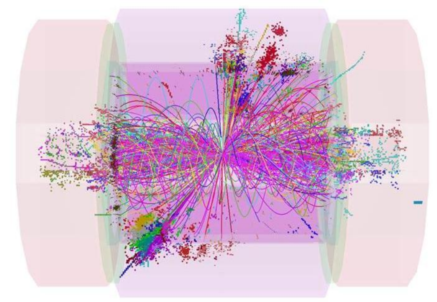
- Traditional approach: jet energy measured in ECAL and HCAL
- Particle Flow: Need very good spacial resolution to avoid confusion ⇒ highly granular calorimeters

⇒ Hardware + Software

Timing resolution to suppress backgrounds

$\gamma\gamma \to$ hadrons background: uniformly distributed in bunch train (unlike signal)
$\rightsquigarrow$ can be efficiently suppressed with pT-dependent timing cuts on reconstructed particles (= particle flow objects)

$t\bar{t}$ event at 3 TeV with background from $\gamma\gamma \to$ hadrons from bunch train



1.2 TeV background
in the reconstruction window $\geq 10\,\text{ns}$
around physics event

Timing resolution to suppress backgrounds

$\gamma\gamma \rightarrow$ hadrons background: uniformly distributed in bunch train (unlike signal)
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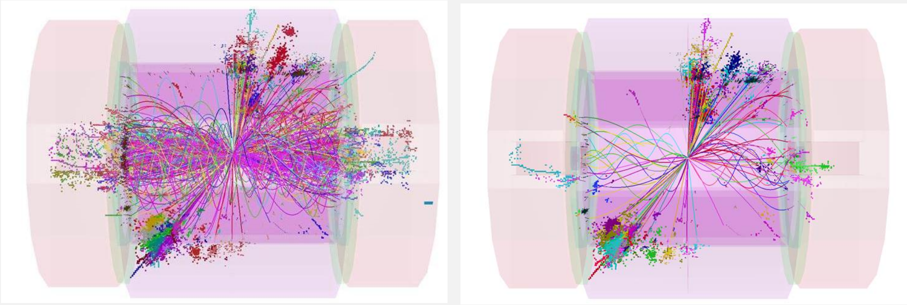
$t\bar{t}$ event at 3 TeV with background from $\gamma\gamma \rightarrow$ hadrons from bunch train



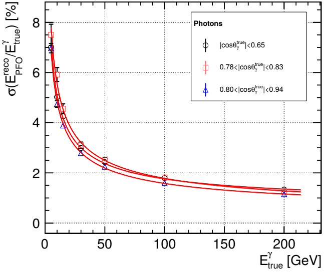
1.2 TeV background
in the reconstruction window ≥ 10 ns around physics event

100 GeV background
after timing cuts

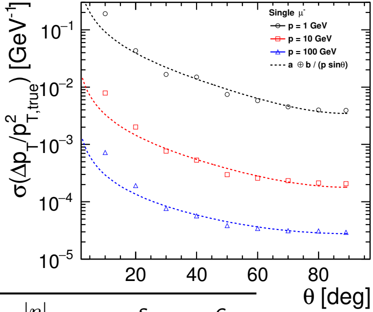
Detector performance in full simulation

Full detector simulation

- Simulation based on Geant4
- Reconstruction chain including tracking, particle flow, identification, flavor tagging



Tracking performance:
Momentum resolution



$\lvert\eta\rvert$	s	c
< 0.78	0.156	0.01
0.78...0.83	0.176	0.01
0.83...3	0.151	0.01

$$\Delta E = \sqrt{s^2 E + c^2 E^2}$$

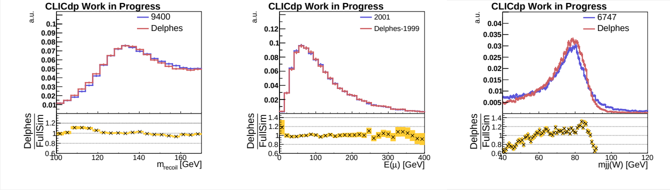
(stochastic term s, constant term c)

DELPHES fast simulation for CLICdet

- Performance parameters based on full simulation of CLICdet documented in `arXiv:1812.07337`
- Workflow: tracking and identification efficiencies, momentum and calorimeter resolutions, jet clustering, flavor tagging, isolation, particle flow
- Linear collider jet algorithm VLC implemented in DELPHES
- Separate cards for the 3 energy stages to mimic effect of beam-induced background on jet energy resolution

`1909.12728`

Validation compared to full simulation, for the three stages



HZ ($Z \rightarrow q\bar{q}$) at 350 GeV

$H\nu\nu$($H \rightarrow \mu\mu$) at 1.4 TeV

$WW \rightarrow \ell\nu q\bar{q}$ at 3 TeV

- Good agreement found for invariant masses, energy and angular observables of jets and leptons

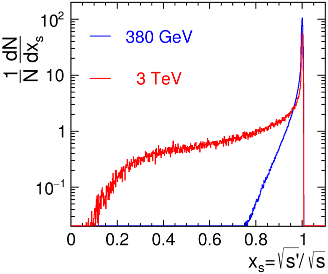
CLIC physics

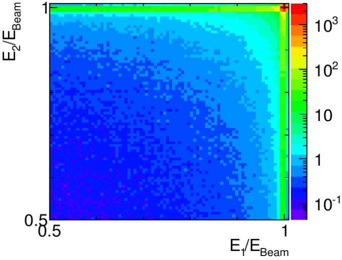
Simulation

Ingredients specific to linear collider Monte Carlo generation

- Beam polarization
- Hard processes for e^+e^-, $e^\pm\gamma$, $\gamma\gamma$
- Simulation of ISR
- Capabilities to include beamstrahlung from parametrization (e.g. CIRCE2) or beam-beam event files

Main generator: Whizard+Pythia





- Correlations between beams are important
- Impact on cross section measurements and lab-frame observables
- Simulation with beam-beam interactions tool GuineaPig

[1309.0372]

Jet reconstruction at CLIC

	hadron collider	lepton collider
Avoid contamination from:	pile-up	beam-induced backgrounds
Boost w.r.t. detector frame:	yes	no/less

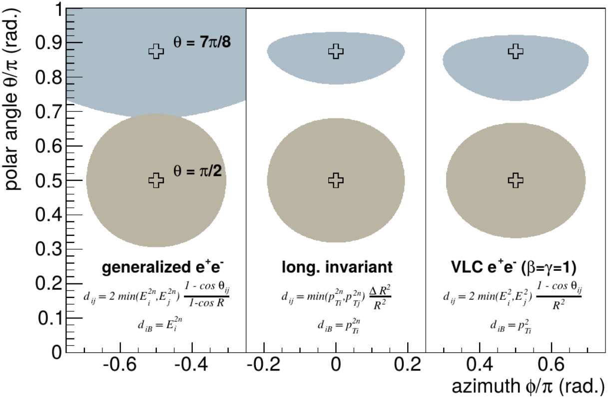
- Lepton colliders: $[E, \theta]$; hadron colliders: $[p_T, y]$
- $\gamma\gamma \rightarrow$ hadrons is forward peaked, reduce forward size for background robustness

VLC algorithm

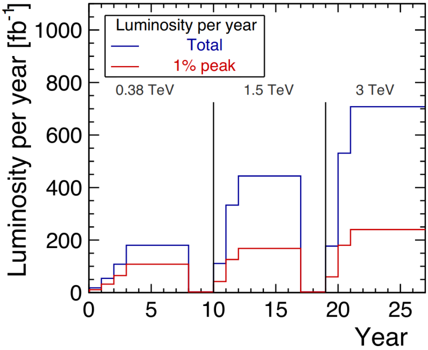
Valencia Linear Collider algorithm:

- Sequential recombination algorithm
- Modified distance measures

Long. invariant $\widehat{=}$ generalized k_T [1404.4294]



CLIC physics in three stages



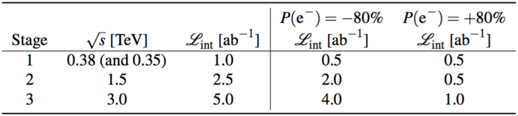
Stage 1
- Higgs physics: single Higgs production in HZ and VBF
- Top physics: $t\bar{t}$ production and threshold scan

$\Rightarrow$ precision far beyond that of the HL-LHC

Stage 2
- ttH production

Stage 2,3
- Searches for new particles
- Precision EW measurements providing indirect sensitivity to new physics at higher scales
- Higgs self-coupling

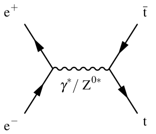
- 25-30 years physics programme
- Electron polarisation scenario:



			$P(e^-) = -80\%$	$P(e^-) = +80\%$
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	$\mathscr{L}_{\text{int}}$ [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

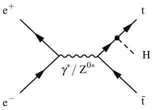
Top physics

$t\bar{t}$ production



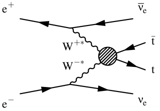
Stage 1: 380 GeV close to production maximum
→ large event samples

$t\bar{t}H$ production

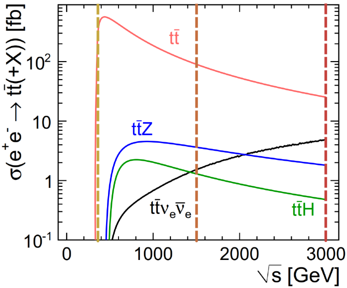


Maximum σ near 800 GeV
LC lumi higher at higher energy
→ CLIC Stage 2 close to maximum ttH rate

VBF $t\bar{t}H$



Benefits from highest energies

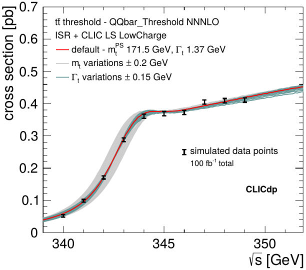


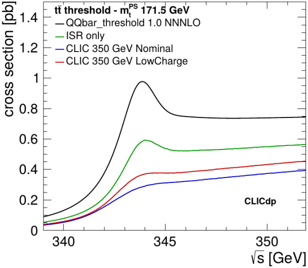
- Top mass
- Top electroweak couplings
- Rare top decays
- Top Yukawa coupling
- CP properties of $t \to H$ coupling
- BSM in H/t sectors

Top threshold scan

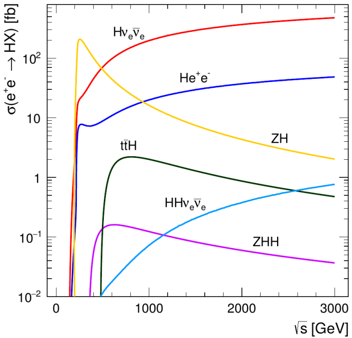
- Goal: Highest precision top mass measurement
- Dedicated runs of CLIC in several steps around 350 GeV (tt threshold), total 100 fb^{-1}
- Expected measurement precision on 1S mass : $\approx$ 50 MeV
  - Theoretical uncertainties: parametric uncertainties from α_s, perturbative QCD uncertainty (dominant)
  - Experimental uncertainties: beam energy and luminosity spectrum, remaining background predictions
  - Statistical uncertainty: 20 MeV
- CLIC beam parameters optimised for lower beamstrahlung

CLICdp work in progress



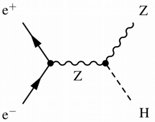


Higgs physics at CLIC



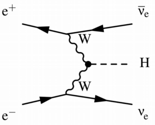
Stage 1: two production mechanisms → reduces uncertainties and guarantees model-independence

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



dominant up to ≈ 450 GeV

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



dominant above ≈ 450 GeV

Double Higgs production

ZHH: second stage
VBF: benefits from highest energies

Higgsstrahlung

$Z \rightarrow ee, \mu\mu$

- Identify HZ events from the Z recoil mass

$$M^2 = s - 2E_{q\bar{q}}\sqrt{s} + M^2_{q\bar{q}}$$

⇒ model-independent measurement of the g_{HZZ} coupling

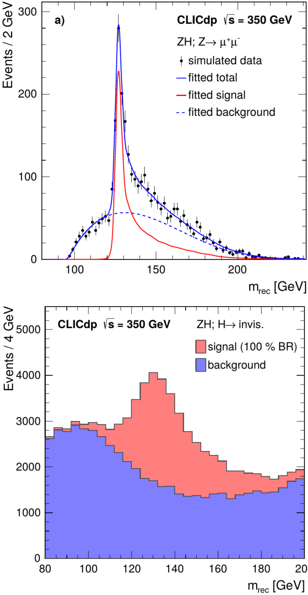
$Z \rightarrow q\bar{q}$

Measurement of $g_{HZZ} \rightsquigarrow$ substantial improvement in precision possible

$H \rightarrow$ invisible

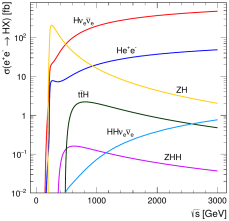
Find invisible Higgs decays in a model-independent way

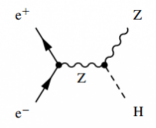
BR(H→inv.)<0.97 % at 90 % C.L. for CLIC at 350 GeV



All-hadronic HZ production at 3 TeV CLIC

Full simulation study with `Whizard+Pythia` and CLICdet detector model [arXiv:1911.02523]





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

Higgsstrahlung at CLIC

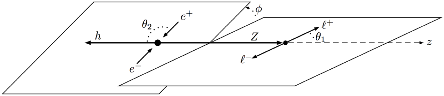
plays a large role in the determination of g_{HZZ} at the 380 GeV energy stage using the recoil method

- Cross section much lower at 3 TeV
- Promising impact of this channel on BSM through Effective Field Theories (EFT)

→ possible to make use of fully hadronic channel to gain statistics?

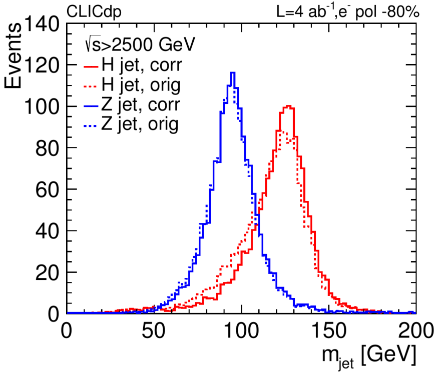
→ possible to utilize boosted jets and jet substructure?

- investigate HZ with $Z \to q\bar{q}$
- Goal: decay angles for EFT



Analysis of full-hadronic HZ

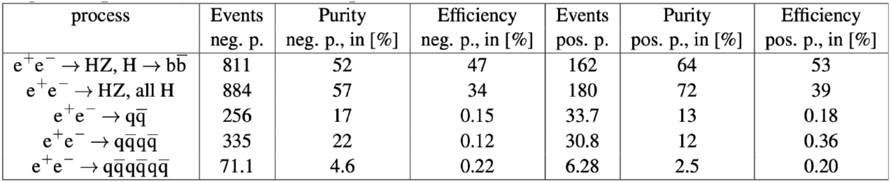
- HZ → $b\overline{b}$ $q\overline{q}$ at $\sqrt{s}_{\mathrm{eff}} > 2500\,\mathrm{GeV}$ characterised by 2 high-energy boosted fat jets, back-to-back in azimuth, each containing 2 sub-jets
- Excellent jet mass resolution → discriminate signal from background
- Jets: VLC $\beta = \gamma = 1.0$, $R = 0.7$, exclusive clustering $n = 2$ plus tight timing and p_{T} cuts on particle flow objects
- Correct for impact of neutrinos in b decays by projecting the MET on the boosted jets
- Use BDT based on jet observables and substructure observables



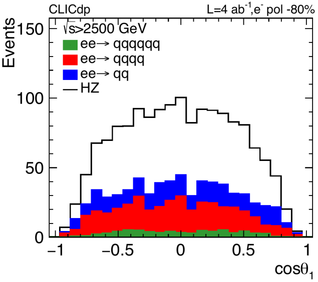
jets ordered by mass: H jet higher mass than Z jet

Results for HZ at 3 TeV

CLICdp-Note-2020-003



process	Events neg. p.	Purity neg. p., in [%]	Efficiency neg. p., in [%]	Events pos. p.	Purity pos. p., in [%]	Efficiency pos. p., in [%]
$e^+e^- \to HZ, H \to b\bar{b}$	811	52	47	162	64	53
$e^+e^- \to$ HZ, all H	884	57	34	180	72	39
$e^+e^- \to q\bar{q}$	256	17	0.15	33.7	13	0.18
$e^+e^- \to q\bar{q}q\bar{q}$	335	22	0.12	30.8	12	0.36
$e^+e^- \to q\bar{q}q\bar{q}q\bar{q}$	71.1	4.6	0.22	6.28	2.5	0.20



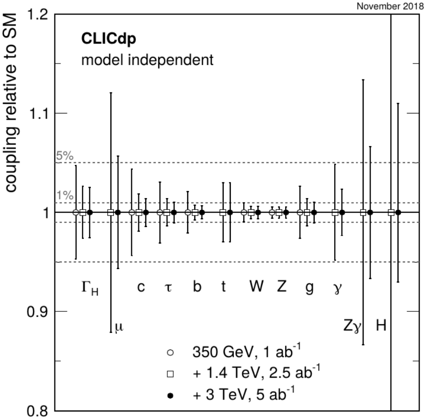
→ make use of fully hadronic channel to gain statistics ✓

→ utilize boosted jets and jet substructure ✓

- Statistical uncertainty on the cross setion is 4.4 % for negative beam polarisation run (4000 fb^{-1}) and 8.8 % for positive beam polarisation run (1000 fb^{-1}) → combined 4.0 %
- Statistics sufficient for extracting angular observables for EFT study (θ_1: angle between positively charged quark and original Z direction in the Z rest frame)

Higgs properties: combined fits

- Global fits to $\sigma \times$ BR measurements in HZ and VBF production in various channels → model-independent and model-dependent



Model-independent fit

Only possible at lepton colliders

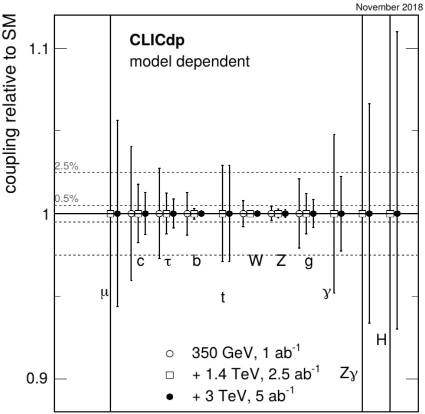
- 11 free parameters including the total width
- no assumptions on additional Higgs decays

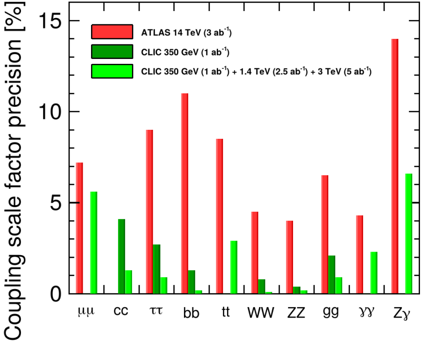
Eur. Phys. J. C 77, 475 (2017), updated 1812.01644

Model-dependent global fit

Model-dependent:

- 10 free parameters
- Total width is sum of partial widths ⇒ No decays to non-SM particles
- Comparison to LHC results



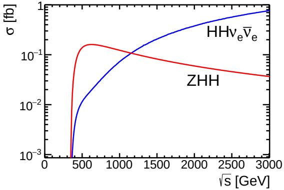


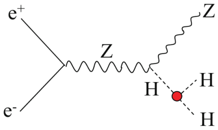
Higgs self-coupling at CLIC

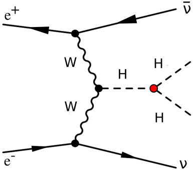
- Self-coupling determines shape of the Higgs potential
- Implications for vacuum metastability, hierarchy problem, electroweak phase transition, baryogenesis

Higgs self-coupling at linear colliders

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







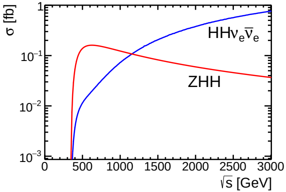
modification of the vertex ●
defined as $\kappa_{\mathrm{HHH}} := \frac{g_{\mathrm{HHH}}}{g_{\mathrm{HHH}}^{\mathrm{SM}}}$

Analysis strategy

Full simulation study with WHIZARD+PYTHIA and CLIC_ILD detector model Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling at CLIC

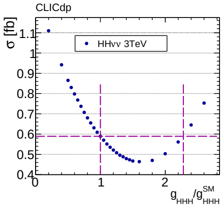
- Measure W-boson fusion di-Higgs production HH$\nu_e\bar{\nu}_e$ at 3 TeV in $b\bar{b}b\bar{b}$ and $b\bar{b}WW^*$
- Extract g_{HHH} from cross section and kinematics
- Take into account the smaller contributions from ZHH and HH$\nu_e\bar{\nu}_e$ at 1.4 TeV

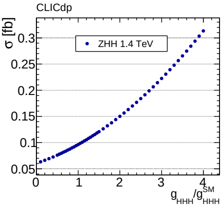


Cross-section dependence on g_{HHH}: →

⇒ 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 using 2 production modes and differential information

Sensitive differential distributions

Differential distributions help to distinguish different values of κ_{HHH} [1309.7038]
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 (→ resolve ambiguity)

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

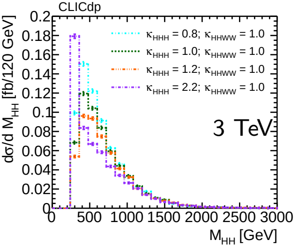
Signal selection: 4 b-tagged jets, missing E_T, Boosted Decision Tree

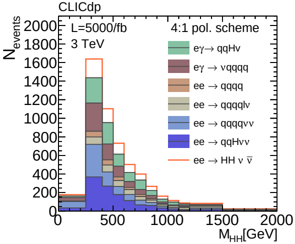
Signal region:

Signal = 766 events

Background = 4527 events

Invariant mass of Higgs boson pair:



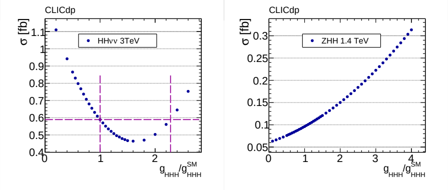


Measure g_{HHH} in di-Higgs events

From total rate of observed HH events

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

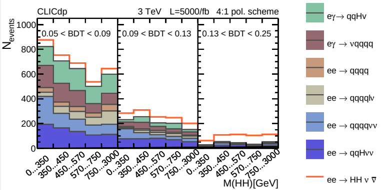
$\Rightarrow$ -10 %, + 11 %



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

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

$\Rightarrow$ -8 %, + 11 % precision on g_{HHH}



Global fit including Higgs self-coupling

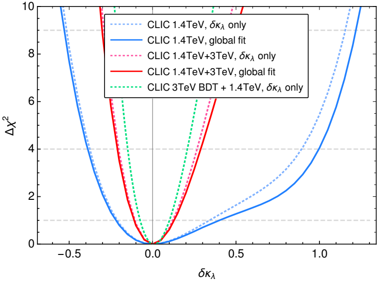
- Model broad range of possible new physics effects in Effective Field Theory (EFT)
- HH production measurements can be influenced by more BSM effects other than modified Higgs self-coupling
- Other BSM effects can be constrained in other measurements

⇒ 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]



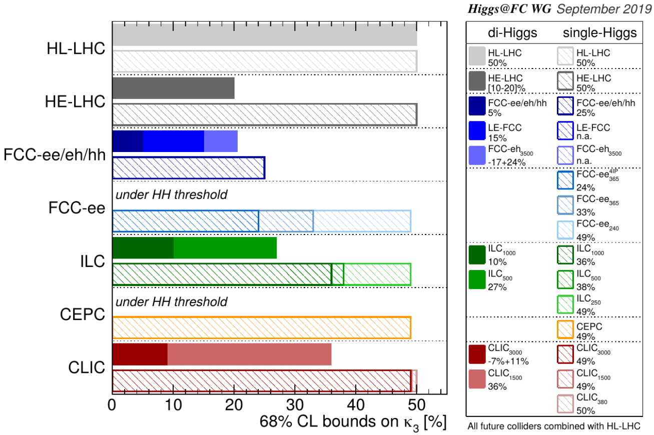
- - - - - CLICdp full-simulation analysis with differential information

$\Delta\chi^2 = 1$ 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)

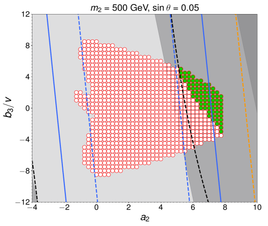
from [1910.11775]
$(\kappa_3 = \kappa_{\mathrm{HHH}})$



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 $\Delta\kappa_{\mathrm{HHH}} = 20\,\%$ 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)

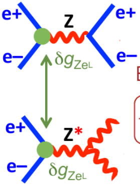
based on di-Higgs production at CLIC [No, Spannowski: 1807.04284] (using CLICdet Delphes card)

Indirect BSM reach via precision measurements

CLIC high-energy stages at 1.5 and 3 TeV:

- increases VBF Higgs production
- adds ttH and HH production
- precision top-quark physics
- precision measurements of two-fermion and multi-boson processes

At low energy ($\sqrt{s}=m_Z$)



Effect grows as s

$\left(\frac{3000}{91.2}\right)^2 \sim 1000$

At high energy ($\sqrt{s}$=3TeV)

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ => $\delta g_{Ze_L} \sim 10^{-4}$

$\updownarrow$ same precision!

...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3\mathrm{TeV}} \sim 10\%$ => $\delta g_{Ze_L} \sim 10^{-4}$

–> strongly benefit from high energies

Global sensitivity to BSM effects in EFT

Standard Model

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

Scale of new decoupled physics

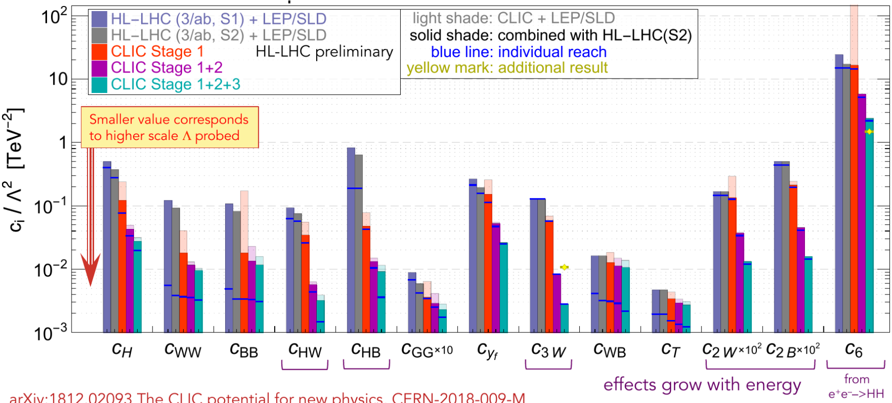
Dimension-6 operators

Includes CLIC measurements of

- Higgs
- Top
- WW
- $e^+e^- \to f\bar{f}$

Strongly benefits from high-energy running

Universal EFT fit

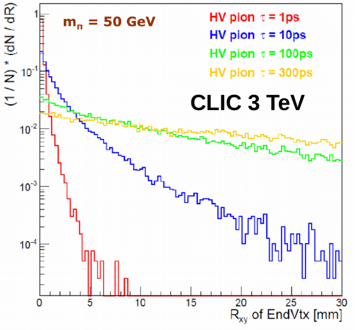


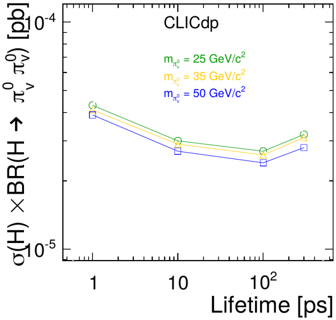
arXiv:1812.02093 The CLIC potential for new physics, CERN-2018-009-M

Long-lived particles at CLIC

- Long-lived particles signatures: displaced or disappearing tracks
- Challenging at the LHC due to pile-up, triggers
- 2 studies at CLIC:
  - Hidden valley Higgs decay: displaced vertices
  - Degenerate Higgsino Dark Matter: disappearing tracks

Hidden valley particles in
$H \to \pi_v \pi_v \to b\bar{b}b\bar{b}$



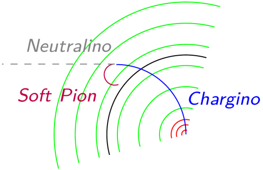


95 % C.L. limits on $\sigma\times$ BR
CLICdp-Note-2018-001

⇒ Require 5 hits for the tracking algorithm

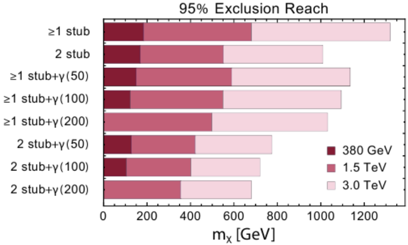
Degenerate Higgsino Dark Matter

- Small mass difference between chargino and neutralino; mixing: pure Higgsino
- Process: chargino pair production where the $\chi_1^\pm$ decay to a neutralino and a pion: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$
- Stub tracks from charged Higgsino with mass 1.05 TeV and lifetime 6.9 mm
- Whizard+Pythia, CLICdet at 3 TeV, with ISR and Beamspectrum included



stub track search:

- $\geq$ 4 hits in the tracking system
- disappearing within the tracking system
- no associated calorimeter entry
- prompt, isolated, minimum p_T
- dE/dx requirement

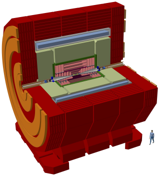


[1812.02093]

Result: reach 1.05 TeV = mass compatible with thermal DM density

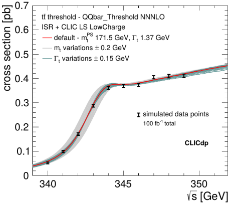
Summary and Outlook

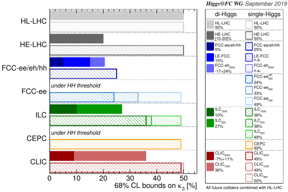
Summary



- CLIC: Compact Linear Collider = future electron-positron collider at the Terascale
- Accelerator scheme demonstrated in various test facilities
- CLICdet detector model adapted to CLIC high-energy beam environment
- Baseline energy stages optimised for physics cases
- CLIC physics: High-precision top, Higgs, and electroweak physics

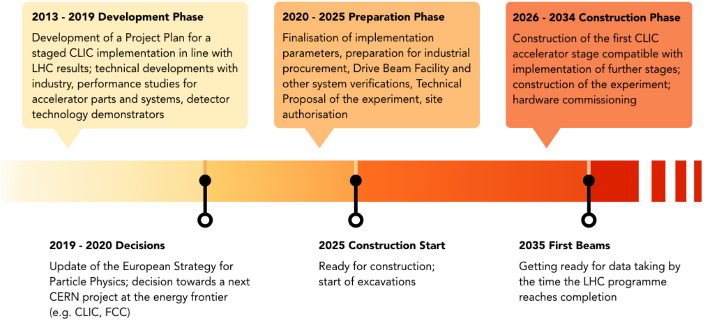
→ e.g. Top threshold scan, Higgs self-coupling in HH production





Outlook

- December 2018 - May 2020: European Strategy Update process
- 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, Drive Beam Facility and other system verifications, 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

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Thanks and further reading

Yellow reports:

- The CLIC potential for new physics (CERN-2018-009-M, arXiv:1812.02093)
- CLIC 2018 Summary Report (CERN-2018-005-M, arXiv:1812.06018)
- CLIC Project Implementation Plan (CERN-2018-010-M, arXiv:1903.08655)
- Detector technologies for CLIC (CERN-2019-001, arXiv:1905.02520)

Additional material

Additional Material

Luminosity and beam-beam interaction

Luminosity

$$\mathcal{L} \sim \frac{N^2}{\sigma_x \sigma_y}$$

Electromagnetic fields

$$B \sim \frac{\gamma N}{\sigma_z (\sigma_x + \sigma_y)}$$

$\Rightarrow$ prefer flat beams $\sigma_y \ll \sigma_x$

Bunch particles are strongly influenced by the fields: they are deflected and radiate Beamstrahlung

HH cross-section measurements at 1.4 and 3 TeV

- $HH\nu_e\overline{\nu}_e$ 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 ($\mathcal{L} = 5\,\mathrm{ab}^{-1}$)
$\sigma(HH\nu_e\overline{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \gtrsim 700\,\mathrm{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$2.1\,\sigma$	$2.4\,\sigma$

  - direct acces
  - two production modes

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

Full di-Higgs programme

- Unique capability of CLIC: measuring the Higgs self-coupling to -8 %, + 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:

Measurement	1.4 TeV	3 TeV
$\sigma(HH\nu_e\overline{\nu}_e)$	$3.5\,\sigma$ EVIDENCE $\frac{\Delta\sigma}{\sigma} = 28\,\%$	$> 5\,\sigma$ OBSERVATION $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$
$\sigma(ZHH)$	$2.1\,\sigma$	$2.4\,\sigma$
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -29 %, +67 % rate-only analysis	1.4 TeV + 3 TeV: -8 %, +11 % differential analysis at 3 TeV

\+ Global EFT fit

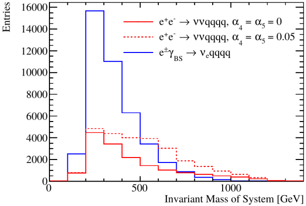
\+ BSM interpretation (e.g. Baryogenesis)

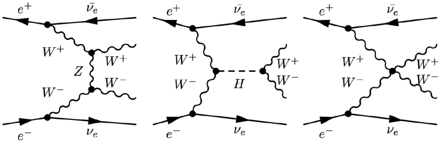
3 TeV result for $\sigma(ZHH)$ from CLICdp-Note-2020-003; all other results from Eur. Phys. J. C 80, 1010 (2020)

⇒ 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

Electroweak gauge boson scattering

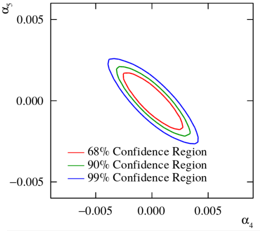
- Make use of fully hadronic final states (JER allows to separate W,Z)
- Example studies done in $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$ and $e^+e^- \rightarrow ZZ\nu\bar{\nu}$





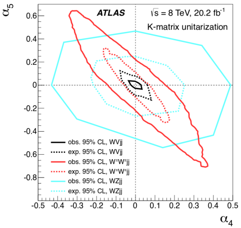
Limits on anomalous quartic gauge couplings via χ^2 fit to sensitive observables: M_{VV}, $\cos\theta^*{}_{VV}$, $\cos\theta^*{}_{Jets}$

Limits on anomalous quartic gauge couplings



CLIC 3 TeV ←

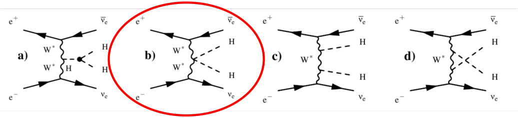
ATLAS Run 1 →



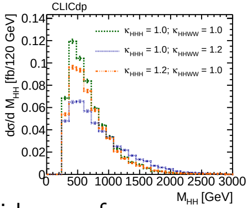
HL-LHC: Similar sensitivity as CLIC 3 TeV

Higgs self-coupling and Higgs-gauge coupling HHWW

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



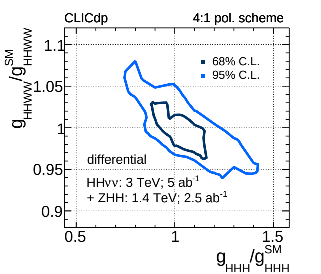
Modifications of invariant di-Higgs mass:



→ 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 $\sigma(\mathrm{ZHH})$ measurement at 1.4 TeV:



References

- **Electron-positron vs. hadron collider** `http://www.quantumdiaries.org/wp-content/uploads/2015/05/feynmanDiagram_DrellYan_wRad.png` `https://upload.wikimedia.org/wikipedia/en/thumb/e/ea/Electron-positron-z_boson.svg/1024px-Electron-positron-z_boson.svg.png`
- **Beam-induced backgrounds:** $\gamma\gamma \rightarrow$ hadrons diagram `http://cronodon.com/images/QCD_19.jpg`