PHYSICS POTENTIAL OF THE

Compact Linear Collider

LLWI 2017

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On behalf of the CLICdp collaboration

Lake Louise, 25 February 2017

CLIC Detector and Physics (CLICdp)

- Light-weight collaboration structure

CLICdp: 29 institutes

clicdp.cern.ch

Focus of CLIC-specific studies on:

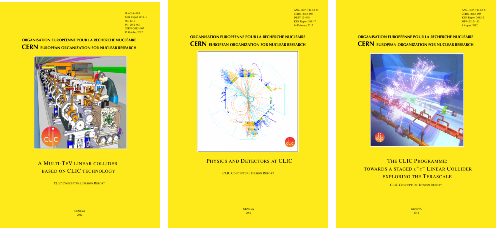
Physics prospects and simulation studies

Detector optimisation + R&D for CLIC

Timeline:

2012: CLICdp Collaboration was set up

2012: CLIC Conceptual Design Report published



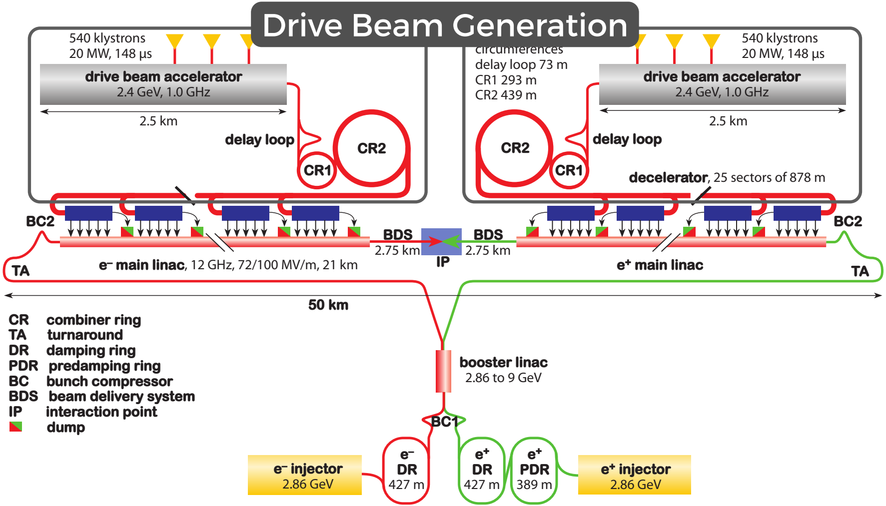
2012→: Input to European strategy process

2015: New detector concept based on CDR findings

2016: Updated staging baseline

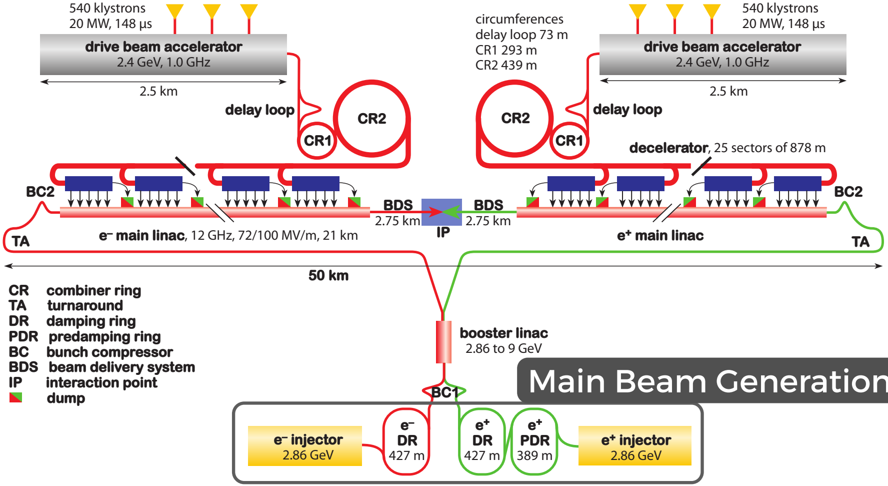
2016: Higgs physics at CLIC study completed

CLIC Accelerator @ 3 TeV



- Generation of high current (100 A) drive beam with delay loop and combiner rings

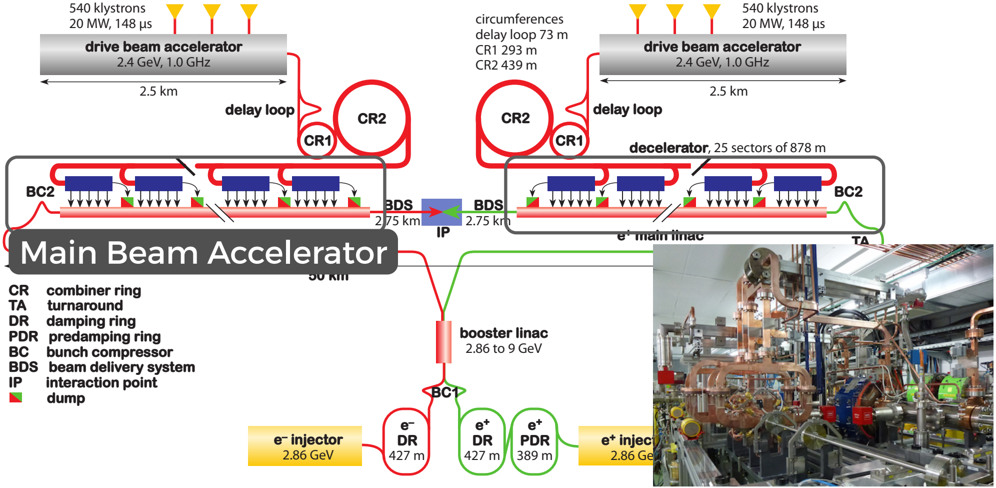
CLIC Accelerator @ 3 TeV



Main Beam Generation

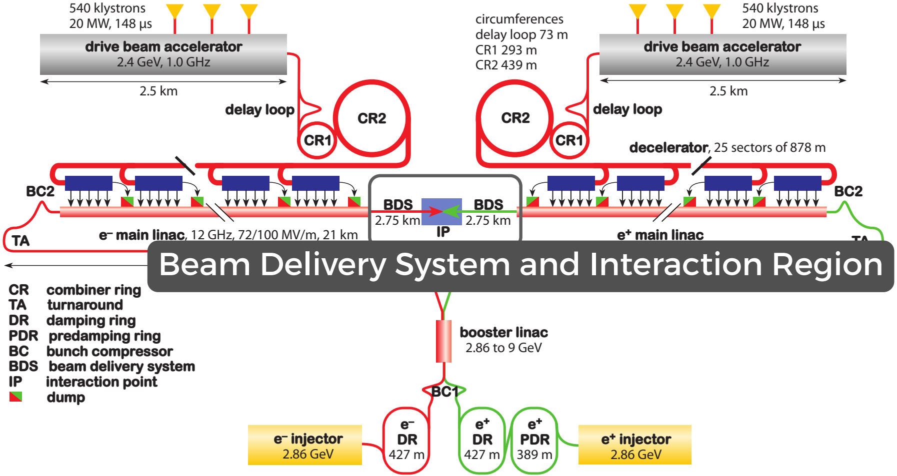
- Generate polarised electron beam

CLIC Accelerator @ 3 TeV



- Drive beam deceleration: Power Extraction and Transfer
- Two beam acceleration: Transfer RF from drive to main beam

CLIC Accelerator @ 3 TeV

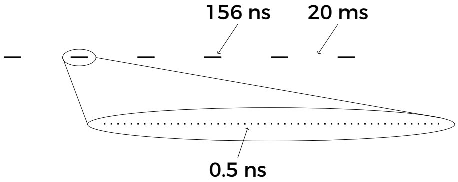


Beam Delivery System and Interaction Region

CLIC Accelerator

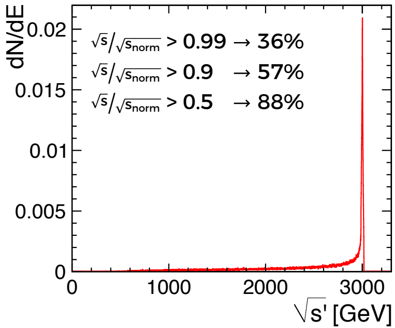
- Copper cavities operated at room temperature
- Gradient: 100 MV/m
- Deflection of particles by other bunch → beamstrahlung
- Energy loss determines the luminosity spectrum

$\sqrt{s}$	3 TeV
$\mathcal{L}$ [cm^{-2}s^{-1}]	5.9×10^{34}
Rep rate [Hz]	50
Duty cycle	0.00078%
$\sigma_{x,y}$ [nm]	40×1
σ_z [μm]	44



CLIC: trains at 50 Hz, 1 train = 312 bunches

Has large impact on detector requirements



CLIC Energy Stages

- New CLIC staging baseline: CERN yellow report (CERN-2016-004)
- With "affordable" first stage at 380 GeV, focused on Higgs physics and top quark physics

Current scenario:

Stage 1: 600 fb^{-1} @ 350/380 GeV

Precision SM Higgs and top physics

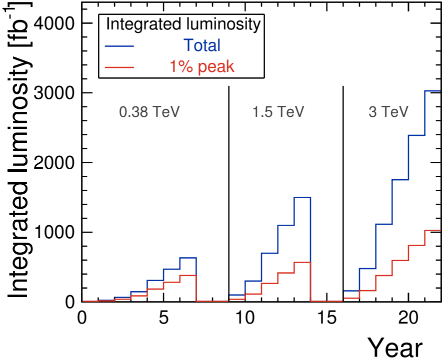
Stage 2: 1.5 ab^{-1} @1.5 TeV:

BSM physics, rare Higgs processes

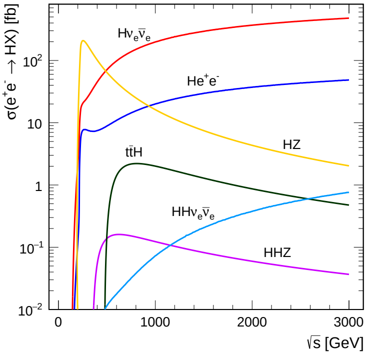
Stage 3: 3 ab^{-1} @ 3 TeV :

BSM physics, rare Higgs processes

Each stage corresponds to 5-7 years



Higgs Measurements

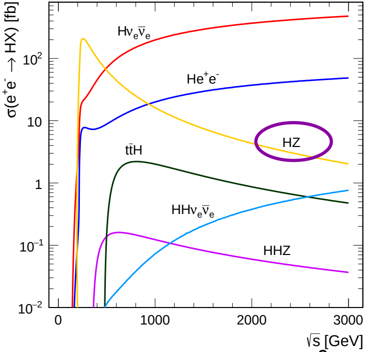


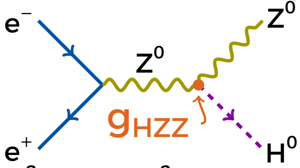
- Geant4 based detector simulation and event reconstruction with event overlay
- Studies carried out at three stages

$\sqrt{s}$	350 GeV	1.4 TeV	3 TeV
$\int \frac{d\mathcal{L}}{ds'} ds'$	$500\,\text{fb}^{-1}$	$1.5\,\text{ab}^{-1}$	$2\,\text{ab}^{-1}$
$\sigma(e^+e^- \to ZH)$	133 fb	8 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	34 fb	276 fb	477 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	48 fb
ZH events	68 000	20 000	11 000
$H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
He^+e^- events	3700	37 000	84 000

- $H\nu_e\bar{\nu}_e$ increases $\times 1.8$ for 80% e^- polarisation
- High selection efficiencies !

Higgs Measurements

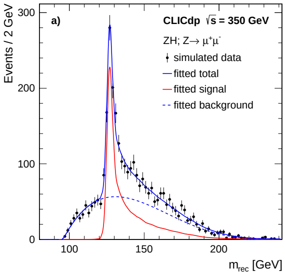


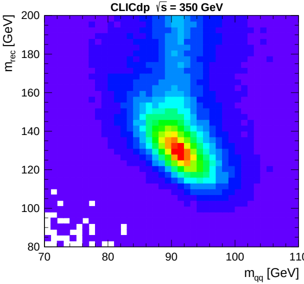


$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$

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

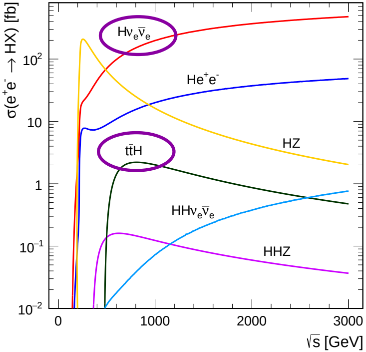
- $Z \to \ell^+\ell^-$, Higgs identified from recoil
- model-independent determination of Higgs mass and g_{HZZ} (uncertainty ~ 2%)
- $Z \to q\bar{q}$
- selection ensures model-independent determination of g_{HZZ} (uncertainty ~ 0.9%)





Combined uncertainty ~ 0.8%

Higgs Measurements

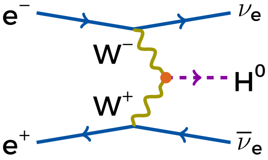


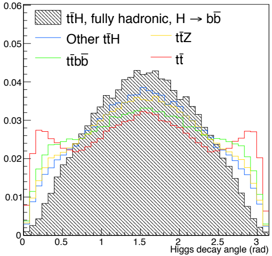
WW Fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

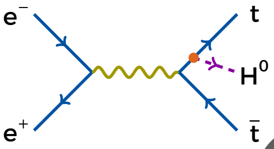
- $\sigma \propto \log s$, dominant > 450 GeV
- Access to $H \to c\bar{c}$ and rare Higgs decays like $H \to \mu^+\mu^-$

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

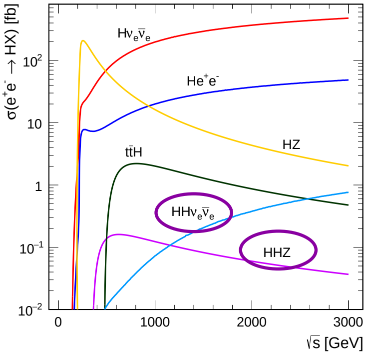
- Sensitive to top Yukawa coupling
- Cross section peaks @ 800 GeV, measured @ 1.4 TeV $\Delta(g_{Htt}) = 4.4\%$





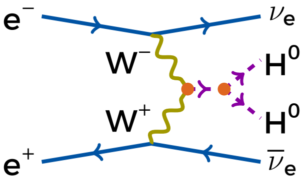


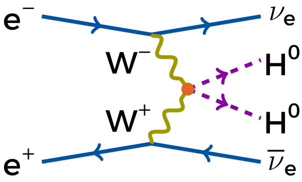
Higgs Measurements



Double Higgs Production

- $e^+e^- \to$ ZHH max. @ 600 GeV
- $e^+e^- \to HH\nu_e\overline{\nu}_e$
- Only 225(1200) $HH\nu_e\overline{\nu}_e$ events at 1.4(3) TeV
- High luminosity and high energy crucial
- Sensitive to Higgs self-coupling λ($\sim$ 12%) and the quartic coupling g_{HHWW} ($\sim$ 3%)

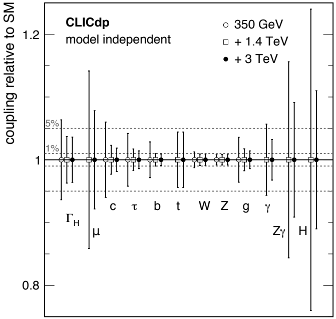


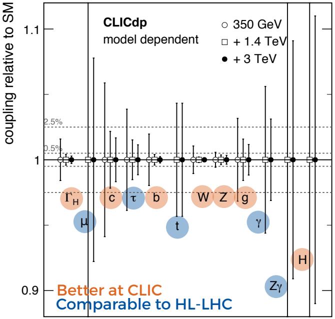


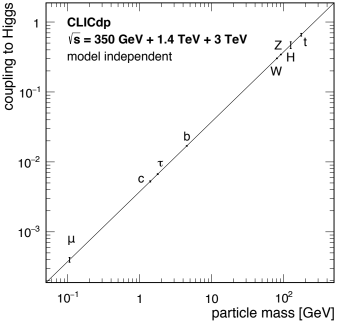
Higgs Measurements Summary

arXiv:1608.07538

Lepton collider allows one to measure Higgs properties with high precision

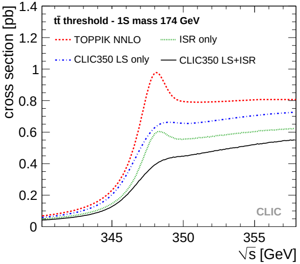


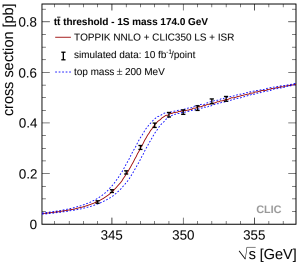




- Model independent extraction only at lepton colliders
- Due to model independent measurement of g_{HZZ}
- Many couplings measured with $\sim 1\%$ precision
- Higgs width extracted with 5-3.5% precision
- Model dependent fits can achieve precision below 1%

Top Pair Production Threshold

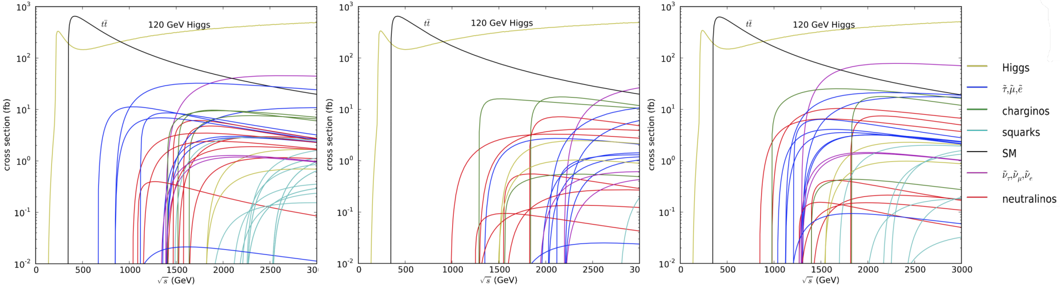




- Measure $t\bar{t}$ production at different E_{CMS} around threshold
- Cross section distorted by ISR and Luminosity Spectrum
- Combined with selection efficiency and background contamination
- Precision on 1S mass: ~ 50 MeV
- Theoretical uncertainty ~ 10 MeV when transforming the measured 1S mass to the $\overline{\text{MS}}$ mass scheme
- Precision at the LHC limited to about 500 MeV
- Interesting top physics also above top threshold
- Top physics overview paper in preparation

Prospects for BSM Physics at CLIC

- Direct searches via pair-production up to kinematic limit ~ $\sqrt{s}/2$
- Precision measurements of new particle masses and couplings



CDR Model I, 3 TeV:
- Squarks
- Heavy Higgs

CDR Model II, 3 TeV:
- Smuons, selectrons
- Gauginos

CDR Model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos

- In general $\mathcal{O}(1\%)$ precision on masses and cross-sections
- Wider applicability: classify spin and quantum numbers

Prospects for BSM Physics at CLIC

Sleptons and Gauginos

- Slepton signature very clean: leptons and missing energy

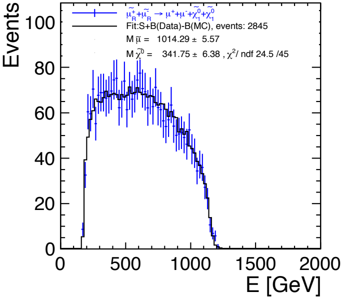
  $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
- Endpoint of spectra → mass
- Slepton mass precision < 1% for sleptons below 1 TeV

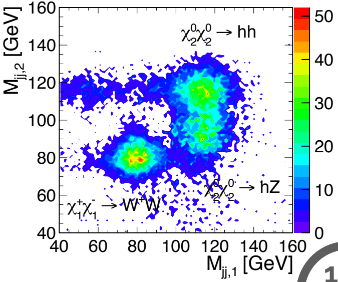
- Chargino and neutralino → 4 jets and E_{Miss}

  $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$

  $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 h^+h^-$

  $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 Zh$
- Gaugino mass precision 1 – 1.5%

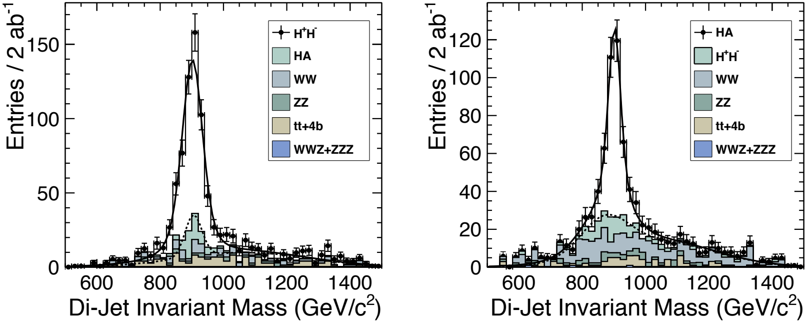




Prospects for BSM Physics at CLIC

Heavy Higgs Bosons

- Degenerate in mass → complex final state, heavy flavour jets
  $e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$
  $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$
- Separation requires heavy-flavour tagging (benchmark for detector optimisation)
- Precision of 0.3% on heavy Higgs masses



From Physics Aims to Detector Needs

- Momentum resolution

  Higgs recoil, H $\rightarrow \mu\mu$ or ℓ from BSM

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

- Jet energy resolution

  W/Z/h di-jet separation

  $\frac{\sigma(E)}{E} \sim 3.5 - 5\%$

  for E = 1000 – 50 GeV

- Impact parameter resolution

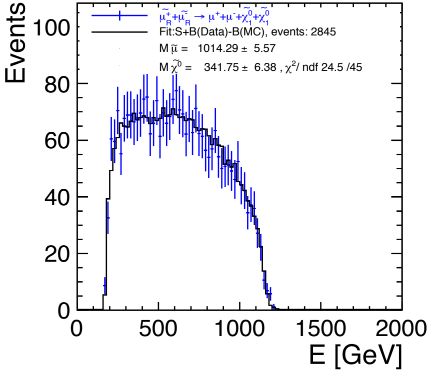
  b/c tagging, Higgs couplings

  $\sigma_{r\phi} = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2 / (p^2 \sin^3\theta)}$

  with a = 5 μm and b = 15 μm

- Large angular coverage down to 10 mrad

  lepton identification, very forward electron tagging



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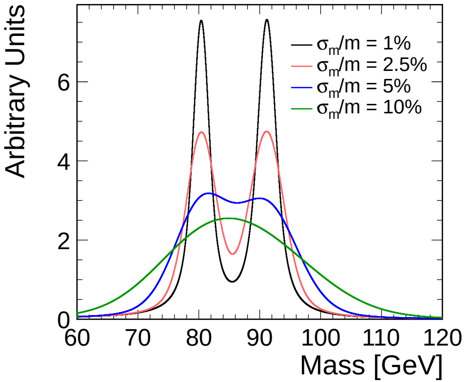

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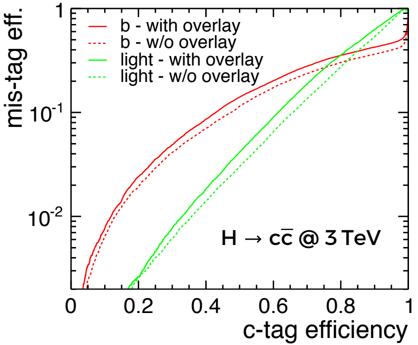
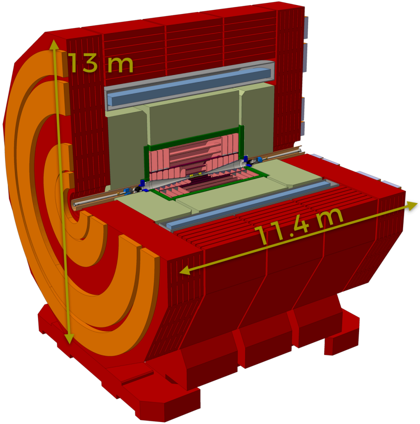


New CLIC Detector Concept

- R&D + simulation-based optimisation → new detector concept
- New concept and simulation software chain being developed



- B Field of 4 T
- Vertex: 3 double layers
  - Single-hit accuracy 3 μm
  - $0.2\% X_0$ per detection layer
  - Power pulsing → 50 mW cm^{-2}
- Silicon tracker: r = 1.5 m
- ECal (silicon + W) with 40 layers ($22X_0$)
- HCal (scintillator + Fe) with 60 layers (7.5λ)
- Precise timing for background
  - 10 ns stamping for tracks

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

Summary and Conclusions

- Proton-proton and electron-positron colliders yield complementary information
- CLIC offers a wealth of accurate e^+e^- physics measurements
- Offers an “affordable” stage @ 380 GeV with guaranteed physics
- Is upgradable up to 3 TeV
- Well-established physics programme
  - Precision Higgs physics, top physics, BSM physics...
- CLIC is one of the options for CERN after the HL-LHC, as are HE-LHC/FCC-hh/FCC-ee
- Very active R&D programme ongoing
- The CLIC technology has been demonstrated in large scale-tests
  - No show stoppers identified
  - CLIC can gear up towards construction within a few years

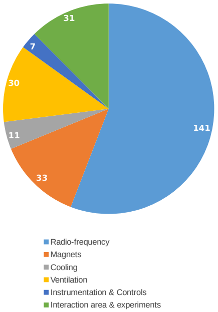
BACKUP

CLIC cost estimate

- Preliminary estimate (scaled CDR) with room for improvement.
- New estimate will be provided for European Strategy Update

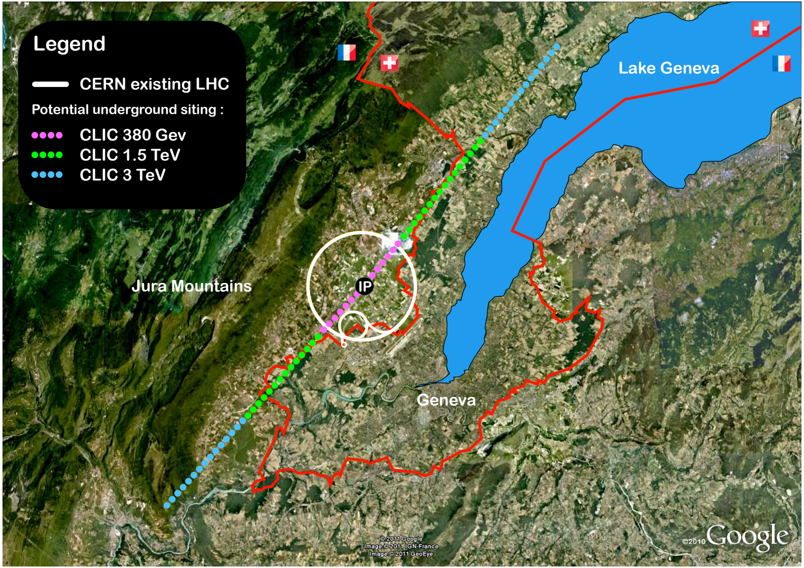
System	Value for 380 GeV [MCHF]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control	216
Total	6690

- Value for the CLIC accelerator at $\sqrt{s}$ = 380 GeV (11.4 km site length)



@ 380 GeV power consumption 252 MW

CLIC Layout



Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
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