CLIC Project and Physics Potential

André Sailer
on Behalf of the CLICdp Collaboration

CERN-EP-LCD

Corfu Summer Institute: Workshop on the Standard Model and Beyond
September 2, 2018

Table of Contents

CLICdp Collaboration

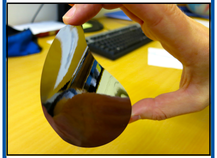
CLICdp focuses on CLIC-specific studies of

- Physics prospects and simulation studies
- Detector optimisation and hardware R&D for CLIC
  - Together with CALICE and FCal collaborations

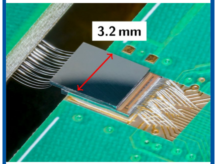
CLIC collaboration developing the accelerator technology

CLIC detector and physics (CLICdp): 30 institutes from 18 countries

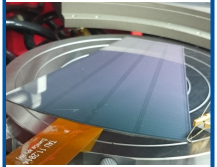
50 μm thick silicon wafer



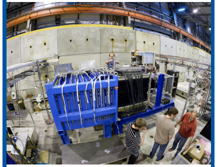
CLICpix2 + C3PD glue assembly



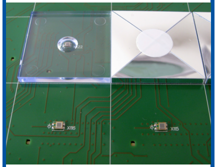
LumiCal Sensor



Calorimeter Test Beam



Scintillator Tile



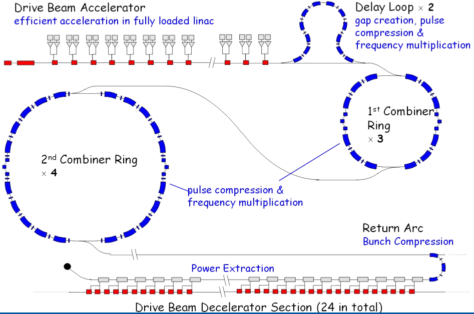
CLIC Accelerator

Acceleration Scheme
Running Scenario
Beam-Beam Effects
Beam-induced Backgrounds

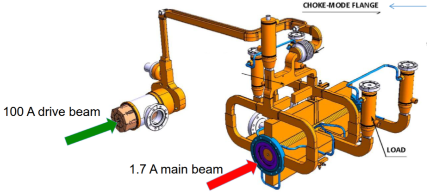
CLIC Accelerator

The Compact Linear Collider (CLIC) is a multi-TeV electron–positron collider

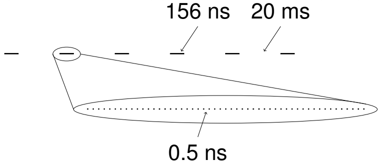
- Large gradients (100MV/m) given by room temperature copper cavities with two-beam acceleration
- Efficient continuous acceleration of a drive beam, “combined” into short pulses, shown in CTF3



- The drive beam is decelerated to transfer the energy into the main beam



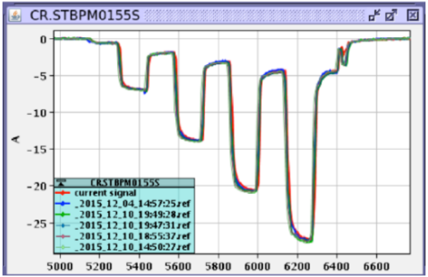
- Main beam comes in 150 ns trains with 50 Hz



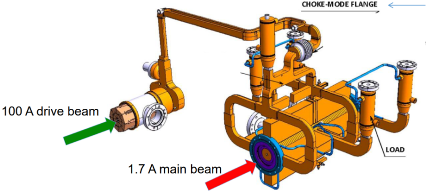
CLIC Accelerator

The Compact Linear Collider (CLIC) is a multi-TeV electron–positron collider

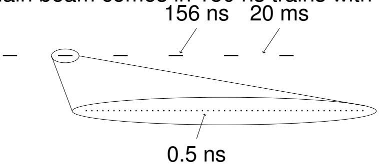
- Large gradients (100MV/m) given by room temperature copper cavities with two-beam acceleration
- Efficient continuous acceleration of a drive beam, “combined” into short pulses, **s**hown in CTF3



- The drive beam is decelerated to transfer the energy into the main beam

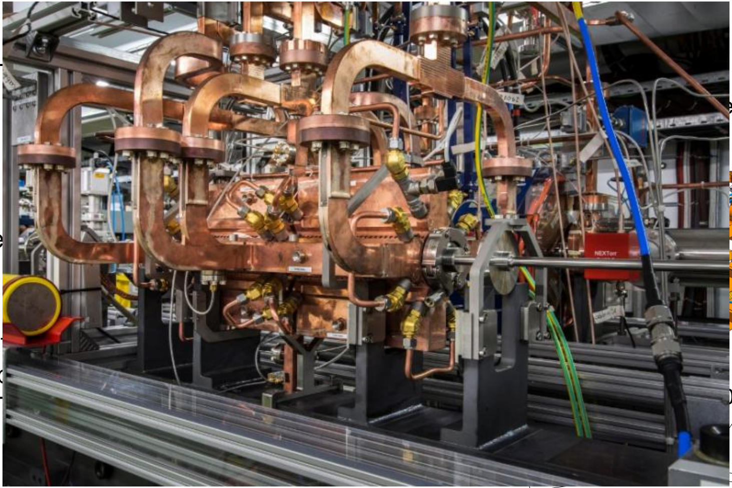


- Main beam comes in 150 ns trains with 50 Hz

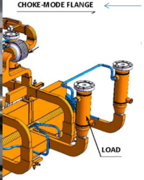


CLIC Accelerator

The Compact L

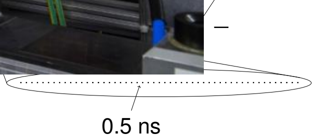


ed to transfer the



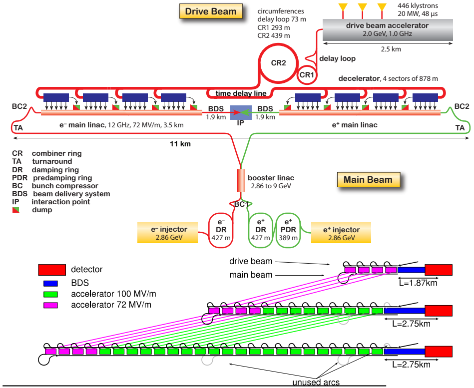
- Large gradie
  temperature
  acceleration
- Efficient con
  beam, “comb
  shown in CT

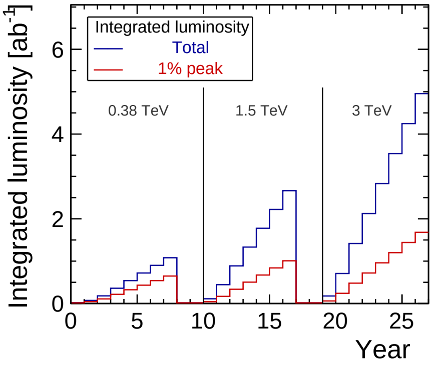
trains with 50 Hz
) ms



Construction and Running Scenario

- **First stage around 380 GeV for top-threshold scan, top-quark and Higgs physics**
- Second stage at 1.5 TeV possible with single CLIC drive beam
- 3 TeV stage with one drive beam complex for each beam
- updated staged construction and running of CLIC over 25–30 years*

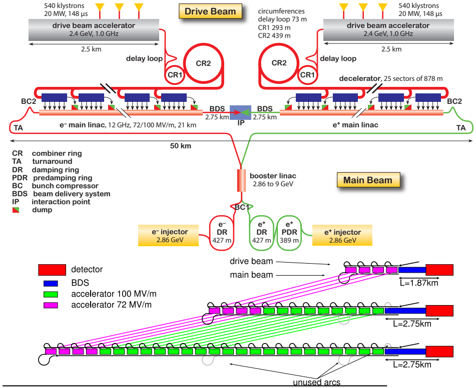


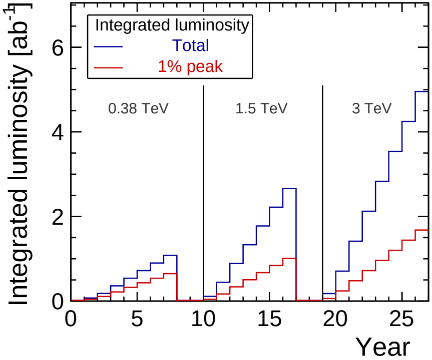


*Not all analyses updated for this scenario yet

Construction and Running Scenario

- First stage around 380 GeV for top-threshold scan, top-quark and Higgs physics
- Second stage at 1.5 TeV possible with single CLIC drive beam
- **3 TeV stage with one drive beam complex for each beam**
- updated staged construction and running of CLIC over 25–30 years*





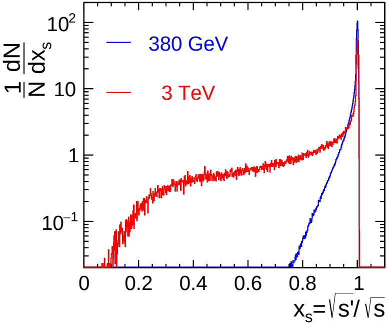
*Not all analyses updated for this scenario yet

Luminosity and Beam-Beam Effects

- Large luminosities require high bunch charge N and small beams $\sigma_{x/y/z}$ (given the other constraints from the accelerator) $L \propto \frac{N^2}{\sigma_x \sigma_y}$
- Leads to large electromagnetic fields during bunch crossing $B \propto \frac{\gamma N}{\sigma_z(\sigma_x+\sigma_y)}$
  - Use flat beams $\sigma_y \ll \sigma_x$

Par.	Unit	380 GeV	3 TeV
N		$5.2 \cdot 10^9$	$3.72 \cdot 10^9$
σ_x	nm	≈ 149	≈ 45
σ_y	nm	≈ 2.9	≈ 1
σ_z	µm	70	44
$\mathscr{L}$	$1/\text{cm}^2\text{s}^1$	$1.5 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$\mathscr{L}_{0.01}$	$1/\text{cm}^2\text{s}^1$	$0.9 \cdot 10^{34}$	$2.0 \cdot 10^{34}$

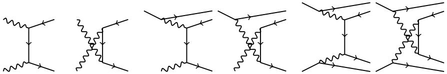
- The bunch particles are strongly deflected by the fields and radiate *Beamstrahlung*



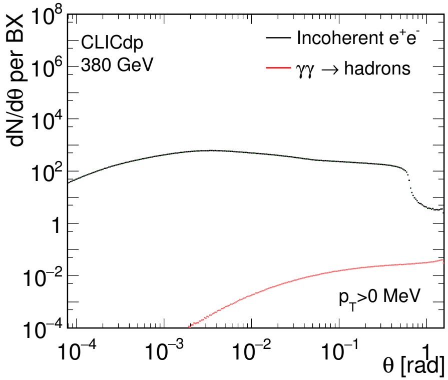
$\sqrt{s'}/\sqrt{s}$	380 GeV	3 TeV
> 0.99	58%	36%
> 0.90	87%	57%
> 0.50	99.96%	88.6%

Beam-induced Backgrounds

- Beamstrahlung photons
  collide with beam particles or other photons

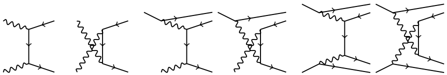


  - *Incoherent* e^+e^- pairs
  - $q\bar{q}$ pairs in $\gamma\gamma \to$ Hadron events
- Backgrounds strongly depend on centre-of-mass energy
- Incoherent pairs have largest concentration at small angles, and small transverse momentum
- Detector acceptance starts at 10 mrad

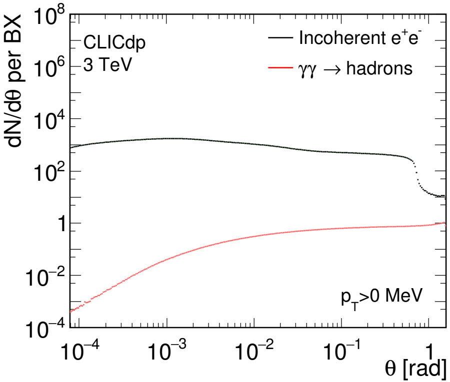


Beam-induced Backgrounds

- Beamstrahlung photons
  collide with beam particles or other photons

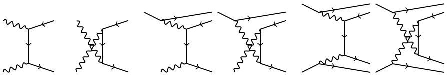


  - *Incoherent* e^+e^- pairs
  - $q\bar{q}$ pairs in $\gamma\gamma \to$ Hadron events
- Backgrounds strongly depend on centre-of-mass energy
- Incoherent pairs have largest concentration at small angles, and small transverse momentum
- Detector acceptance starts at 10 mrad

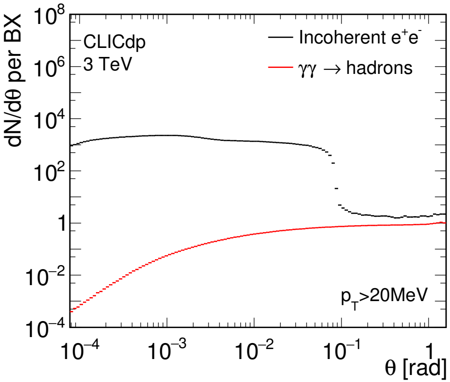


Beam-induced Backgrounds

- Beamstrahlung photons
  collide with beam particles or other photons



  - *Incoherent* e^+e^- pairs
  - $q\bar{q}$ pairs in $\gamma\gamma \to$ Hadron events
- Backgrounds strongly depend on centre-of-mass energy
- Incoherent pairs have largest concentration at small angles, **and small transverse momentum**
- Detector acceptance starts at 10 mrad



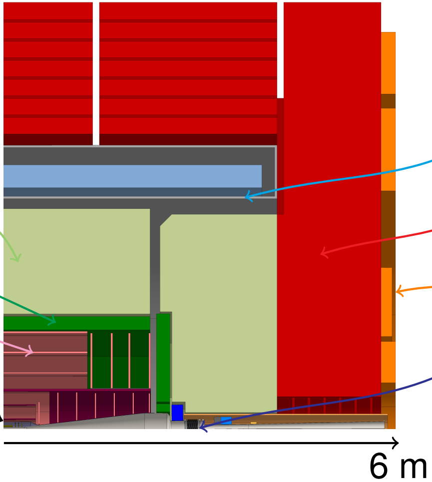
Detector for CLIC

Layout
Performance
Background Mitigation

Detector for CLIC

General purpose detector for Particle Particle Flow reconstruction

- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker
- Vertex Detector with 25 μm pixels

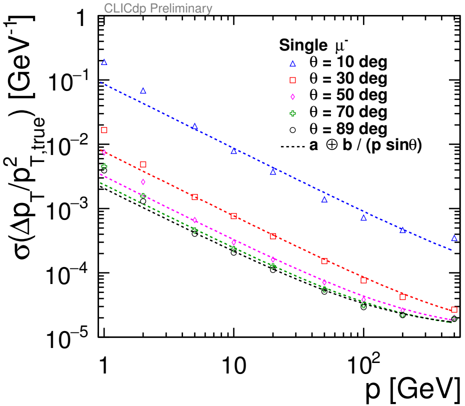


- Superconducting Solenoid of 4 T
- Iron Yoke with RPCs for Muon ID
- End-coils
- Forward calorimeters for EM coverage down to 10 mrad

Detector Performance

From full simulation and reconstruction studies with $\gamma\gamma \rightarrow$ hadron backgrounds

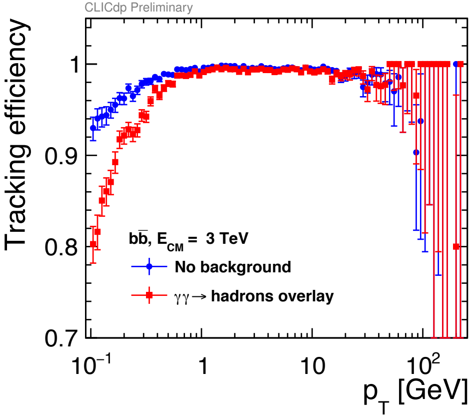
- **Momentum resolution of** $2 \times 10^{-5}/\mathrm{GeV}$ **for central high momentum tracks**
- High tracking efficiency
- Jet energy resolution better than 5% for jets above 200 GeV
- Separation of W and Z Jets
- Good c and b-tagging performance



Detector Performance

From full simulation and reconstruction studies with $\gamma\gamma \to$ hadron backgrounds

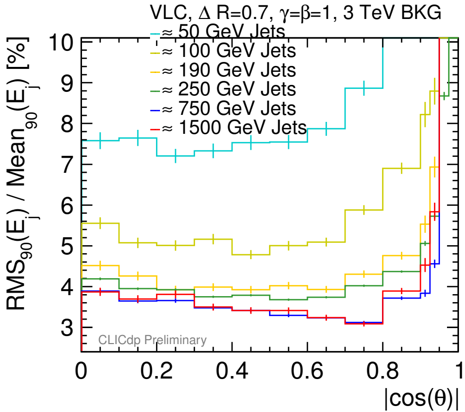
- Momentum resolution of 2×10^{-5}/GeV for central high momentum tracks
- **High tracking efficiency**
- Jet energy resolution better than 5% for jets above 200 GeV
- Separation of W and Z Jets
- Good c and b-tagging performance



Detector Performance

From full simulation and reconstruction studies with $\gamma\gamma \rightarrow$ hadron backgrounds

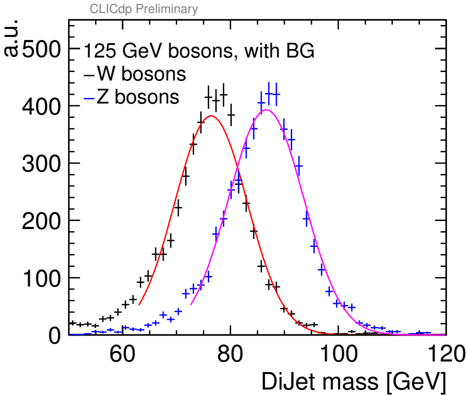
- Momentum resolution of 2×10^{-5}/GeV for central high momentum tracks
- High tracking efficiency
- **Jet energy resolution better than 5% for jets above 200 GeV**
- Separation of W and Z Jets
- Good c and b-tagging performance



Detector Performance

From full simulation and reconstruction studies with $\gamma\gamma \to$ hadron backgrounds

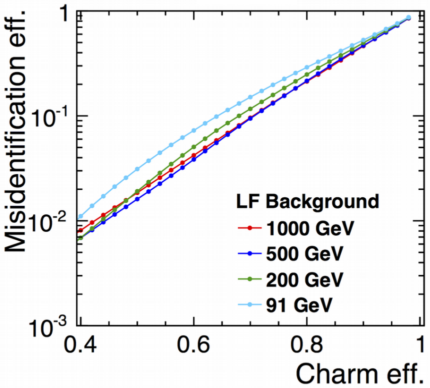
- Momentum resolution of $2 \times 10^{-5}/\mathrm{GeV}$ for central high momentum tracks
- High tracking efficiency
- Jet energy resolution better than 5% for jets above 200 GeV
- **Separation of W and Z Jets**
- Good c and b-tagging performance



Detector Performance

From full simulation and reconstruction studies with $\gamma\gamma \to$ hadron backgrounds

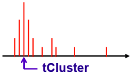
- Momentum resolution of 2×10^{-5}/GeV for central high momentum tracks
- High tracking efficiency
- Jet energy resolution better than 5% for jets above 200 GeV
- Separation of W and Z Jets
- **Good c and b-tagging performance**



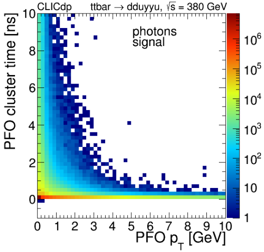
CLICdp-Note-2014-002

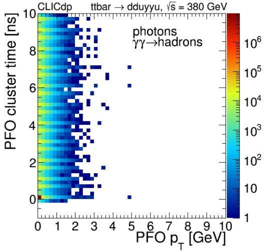
Background Mitigation

- Read out full bunch train and identify time of physics event
- Select hits around the event using the time resolution of the sub-detectors
- Calculate average cluster time and correct for time-of-flight



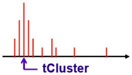
- Accept reconstructed particles depending on particle type, cluster time, and transverse momentum
- Selection cuts reduce background from 1.2 TeV to 100 GeV.
- Further background reduction through jet-clustering



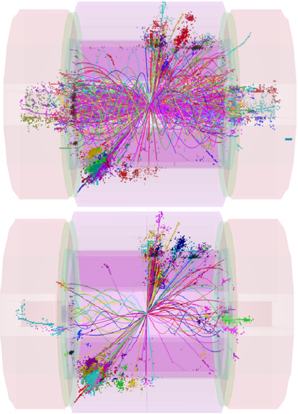


Background Mitigation

- Read out full bunch train and identify time of physics event
- Select hits around the event using the time resolution of the sub-detectors
- Calculate average cluster time and correct for time-of-flight



- Accept reconstructed particles depending on particle type, cluster time, and transverse momentum
- **Selection cuts reduce background from 1.2 TeV to 100 GeV.**
- Further background reduction through jet-clustering



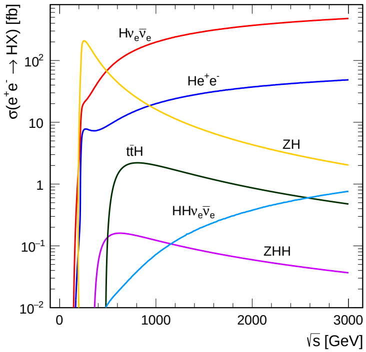
$e^-e^+ \to HH$ with $\gamma\gamma \to$ hadron background overlaid before and after timing selection cuts.

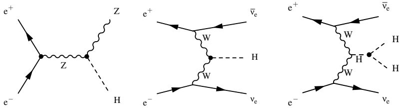
Physics at CLIC

Higgs
Top Quark
Beyond Standard Model

Higgs Processes

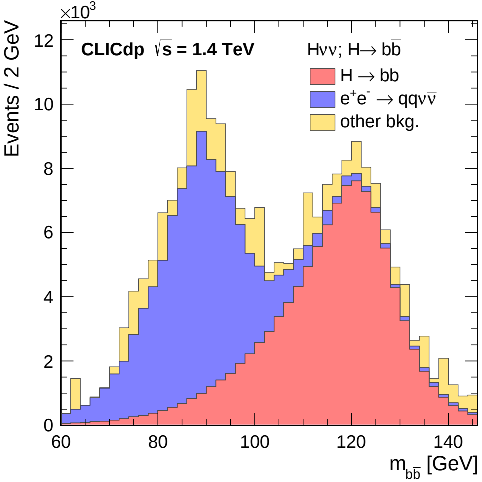
- Higgsstrahlung dominates at smaller centre-of-mass energy: $\propto 1/s$
- chose working point at $\sqrt{s} = 380$ GeV
  - Trade-off between cross-section, luminosity, and jet topology, more-boosted jets simplify separation
  - Can also do top physics at this energy
- WW-fusion dominates at larger energies: $\propto \log(s)$
- Rarer decays more available at higher energy
- Triple Higgs coupling in $\mathrm{HH}\nu_e\bar{\nu}_e$ benefits from highest energy
- All studies summarised in a comprehensive paper [1]





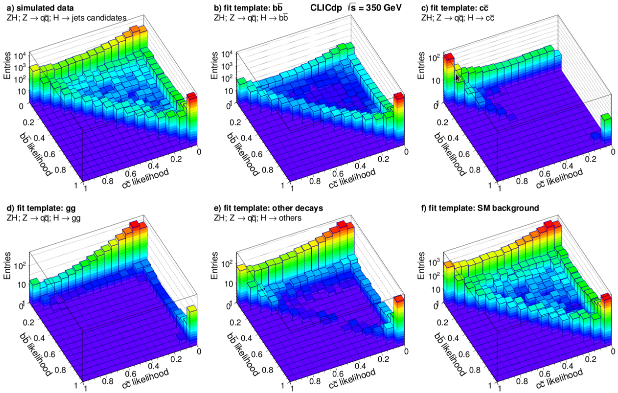
Selected Analysis

- $H \to b\bar{b}$ **requires good flavour tagging and jet energy resolution.**
- Higgs to charm, bottom and gluon coupling measurement $H \to b\bar{b}$, $H \to cc$, $H \to gg$
- $H \to \mu^+\mu^-$ visible thanks to excellent momentum resolution



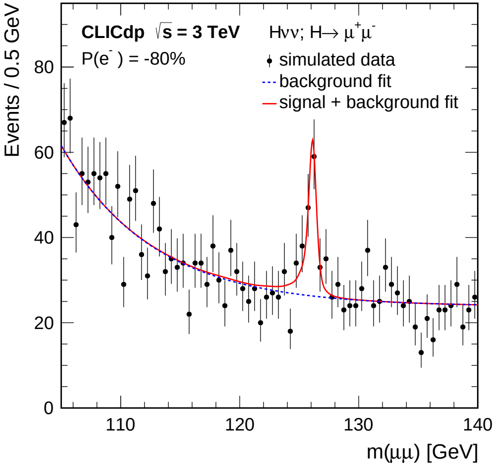
Selected Analysis

- $H \to b\bar{b}$ requires good flavour tagging and jet energy resolution.
- **Higgs to charm, bottom and gluon coupling measurement** $H \to b\bar{b}$, $H \to cc$, $H \to gg$
- $H \to \mu^+\mu^-$ visible thanks to excellent momentum resolution



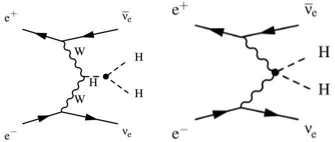
Selected Analysis

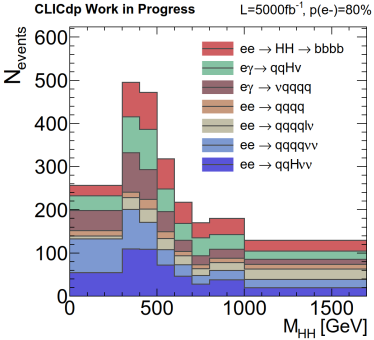
- $H \to b\bar{b}$ requires good flavour tagging and jet energy resolution.
- Higgs to charm, bottom and gluon coupling measurement $H \to b\bar{b}$, $H \to cc$, $H \to gg$
- $H \to \mu^+\mu^-$ **visible thanks to excellent momentum resolution**



Double Higgs Production

- Studies of double Higgs production require highest energy and large luminosities
- Small cross-section and high background rates, complex final states
- With updated running scenario, combining 1.5 TeV and 3 TeV
  $\Delta g_{\mathrm{HHH}} / g_{\mathrm{HHH}} \approx 10\%$ reachable





All Higgs Results

Chan.	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.86 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	14 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		6.1 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	26 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		10 %

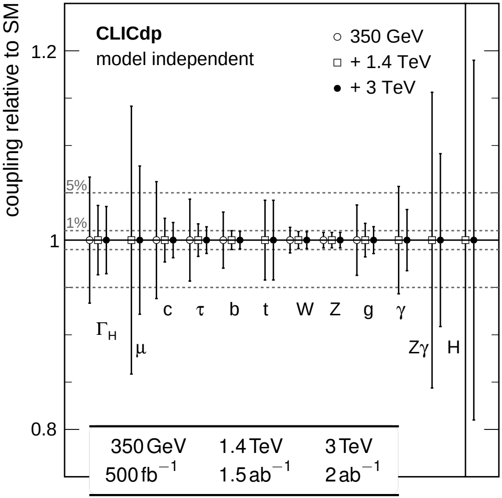
Chan.	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	44 MeV
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	6.1 %	6.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	4.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	4.2 %	4.4 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	38 %	25 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	10 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	30 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	1.0 %	0.7 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	5.6 %	3.9 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1.8 %	2.3 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	8 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54 %	29 %
$HH\nu_e\bar{\nu}_e$	with –80 % e^- polarisation	λ	40 %	22 %

Model Independent Extraction of Higgs Couplings

- Global χ^2 fit of the measured cross-section and cross-section times branching ratios with SM expectations to extract the Higgs couplings g_{Hxx} and total width Γ_H

$$\chi_i^2 = \frac{(C_i/C_i^{SM} - 1)^2}{\Delta F_i^2}$$

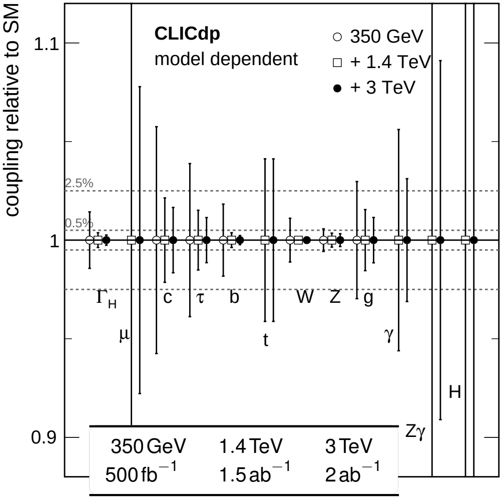
- No assumption on invisible Higgs decays



Model Dependent Extraction of Higgs Couplings

- Global χ^2 fit of the measured cross-section and cross-section times branching ratios (BR) with SM expectations to extract the Higgs couplings $g_{\mathrm{H}xx}$
- Assumption that the total width is sum partial widths

$$\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \sum_i \kappa_i^2 \mathrm{BR}_i \quad \text{with} \quad \kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

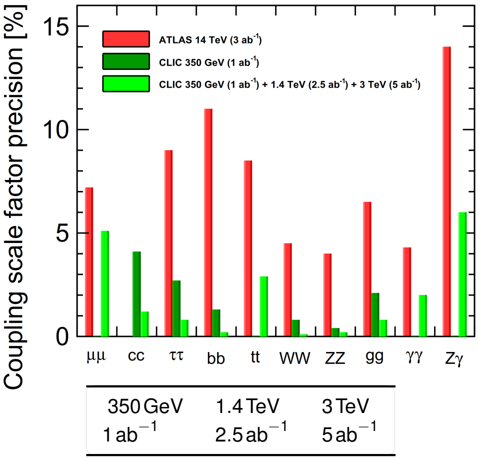


Model Dependent Extraction of Higgs Couplings

- Global χ^2 fit of the measured cross-section and cross-section times branching ratios (BR) with SM expectations to extract the Higgs couplings $g_{\mathrm{H}xx}$
- Assumption that the total width is sum partial widths

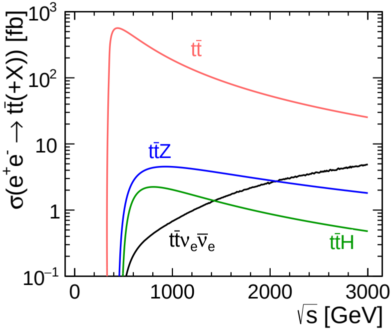
$$\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \sum_i \kappa_i^2 \mathrm{BR}_i \quad \text{with} \quad \kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

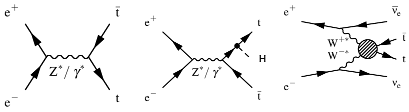
- Higher precision than HL-LHC expectations [2]



Top Quark Studies

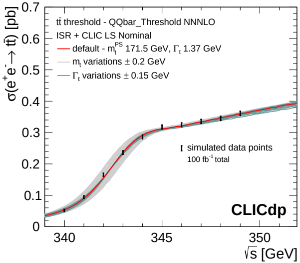
- 350 GeV and 380 GeV
  - Threshold scan around 350 GeV
  - Top-quark mass from radiative events
  - Flavour-changing neutral current top-quark decays
  - Direct reconstruction of the top quark
- 1.4 TeV and 3 TeV
  - Vector boson fusion production of top pairs
  - Top Yukawa coupling
- Kinematic studies of top-pair production at all stages
- Summarised in comprehensive paper [3]

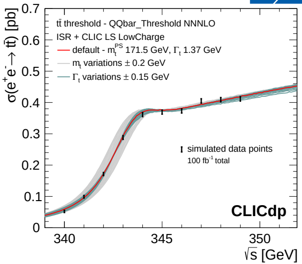


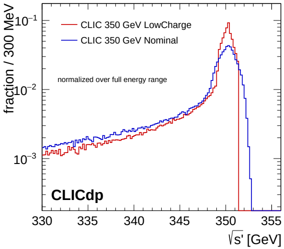


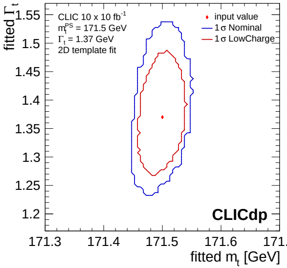
Top Threshold Scan

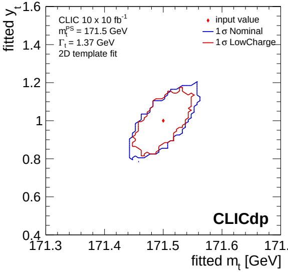
- 10 points with 10 fb^{-1} from 340 GeV to 349 GeV
- Expected uncertainty on the top-mass $\sigma_{m_t} \approx 50$ MeV
- Multi parameter extractions benefit from improved luminosity spectrum from low bunch charge







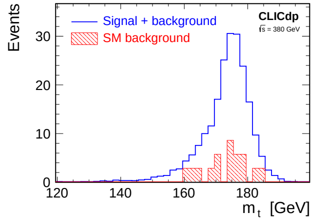




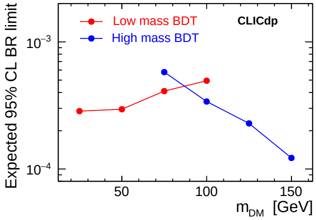
Flavour Changing Neutral Current

- Flavour Changing neutral current events could be observed in rare top-quark decays
- top decaying to charm, where the *charm tagging* capability at CLIC can be exploited
- Results: 95% C.L. limits (500 fb^{-1} @ 380 GeV)
  - $BR(t \to c\gamma) < 4.7 \cdot 10^{-5}$
    HL-LHC[4]: $BR(t \to c\gamma) < 7.4 \cdot 10^{-5}$
  - $BR(t \to cH) \times BR(H \to b\bar{b}) < 1.2 \cdot 10^{-4}$
    HL-LHC[5]: $BR(t \to cH) < 2 \cdot 10^{-4}$
  - $t \to c\not{E}$: depends on invisible mass, BDTs trained for different masses

$t \to c\gamma$

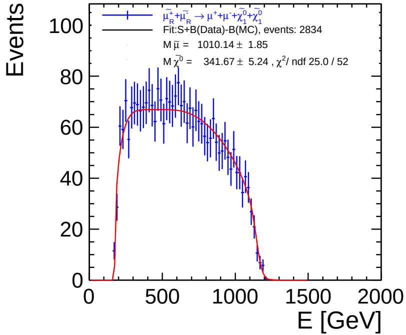


$t \to c\not{E}$



BSM Examples

- Direct searches can find particles up to 1.5 TeV
  - **Smuon and Neutralino masses from fit to di-muon + missing energy search**
- Indirect
  - Deviation from Standard Model observables (muon pair production and asymmetries) can point to BSM scales of several tens of TeV
- Comprehensive report on BSM – direct searches, precision measurements/EFT interpretations, flavour physics – under works



BSM Examples

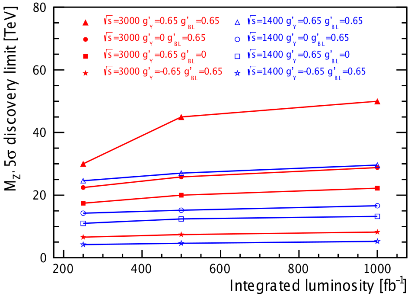
Direct searches can find particles up to 1.5 TeV

- Smuon and Neutralino masses from fit to di-muon + missing energy search

Indirect

- **Deviation from Standard Model observables (muon pair production and asymmetries) can point to BSM scales of several tens of TeV**

Comprehensive report on BSM – direct searches, precision measurements/EFT interpretations, flavour physics – under works



Summary

Summary

- CLIC is an excellent option for a future electron–positron collider
- Rich precision physics program for Higgs and top physics beyond HL-LHC precision
- Discovery potential for New Physics
- Ongoing hardware R&D, physics and detector optimisation studies

$\Longrightarrow$ clic.cern $\Longleftarrow$

References

[1] CLICdp Collaboration. "Higgs physics at the CLIC electron–positron linear collider". In: *European Physical Journal C* 77.7 (17, 2017). URL: https://arxiv.org/abs/1608.07538.

[2] ATLAS Collaboration. *Projections for measurements of Higgs boson signal strengths and coupling parameters with the ATLAS detector at a HL-LHC*. 2014. URL: https://cds.cern.ch/record/1956710.

[3] CLICdp Collaboration. *Top-Quark Physics at the CLIC Electron-Positron Linear Collider*. 2018. URL: https://arxiv.org/abs/1807.02441.

[4] CMS Collaboration. *The Phase-2 Upgrade of the CMS Endcap Calorimeter*. Technical Design Report of the endcap calorimeter for the Phase-2 upgrade of the CMS experiment, in view of the HL-LHC run. Geneva, Nov. 2017. URL: https://cds.cern.ch/record/2293646.

[5] ATLAS Collaboration. *Expected sensitivity of ATLAS to FCNC top quark decays $t \rightarrow Zu$ and $t \rightarrow Hq$ at the High Luminosity LHC*. 2016. URL: https://cds.cern.ch/record/2209126.

[6] Ignacio Garcia Garcia et al. "Jet reconstruction at high-energy electron–positron colliders". In: *Eur. Phys. J. C* 78.2 (June 2017), p. 144.

Further information on CLIC

- Academic training lectures: https://indico.cern.ch/event/668147/

Backup Slides

Time-line

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

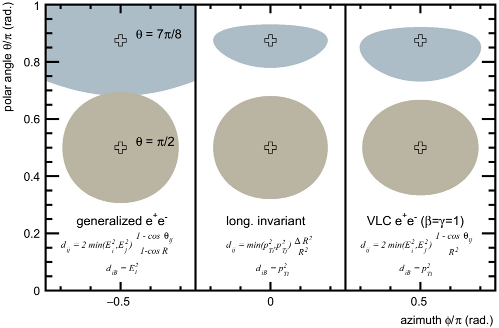
Ready for construction; start of excavations

2035 First Beams

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

Jet Clustering

- $\gamma\gamma \to$ hadron background and longitudinal boost due to Beamstrahlung make LEP jet algorithms unsuited for CLIC
- Use hadron collider jet algorithm features
  - Cluster forward particles into *beam* jets
  - Benefit from longitudinal invariance. Particle distance measure using $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$
- Specialised *VLC* jet algorithm [6]
- Reconstruction parameters can and have to be tuned to specific analyses, see the presentation on the physics studies



Jet areas obtained from different types of jet clustering algorithm