Physics at the Compact Linear Collider

Ulrike Schnoor (CERN)

Institutsseminar IKTP TU Dresden
17 May 2018

Outline

Present and future of particle physics at high-energy colliders

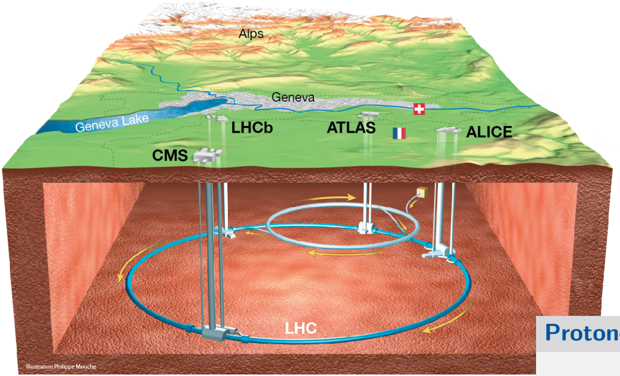
CLIC accelerator

CLIC detector model

CLIC physics potential

Summary and Outlook

The Large Hadron Collider

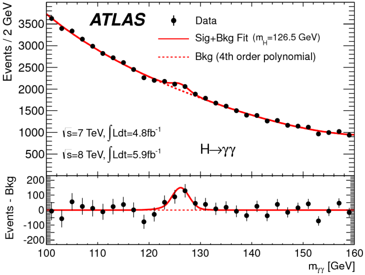


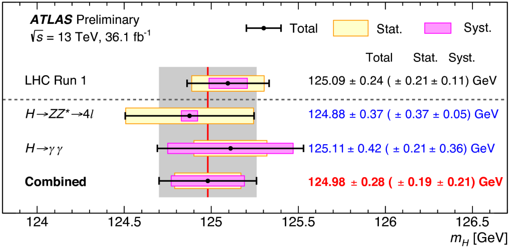
Proton-proton collider

CME	7...8...13 TeV
Taking data	since 2010
Luminosity	10^{34} cm^{-2} s^{-1}
4 experiments	ATLAS, ALICE, CMS, LHCb

The Higgs boson

- Discovery of a Higgs boson (2012) at CMS & ATLAS
- Observed decays: WW, ZZ, $\gamma\gamma$, $\tau\tau$

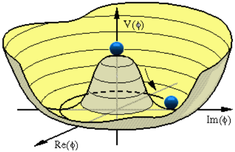




Sparked investigation of the nature of electroweak symmetry breaking ⇒ far from completed!

Phys. Rev. Lett. 114 (2015) 191803

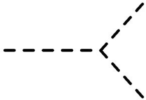
Open questions in Higgs physics

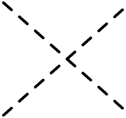


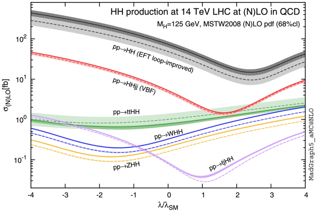
SM Higgs mechanism:

- $V = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$
- λ related to Higgs self-coupling

Self-couplings measurement $\rightsquigarrow$ shape of the potential







Other open questions

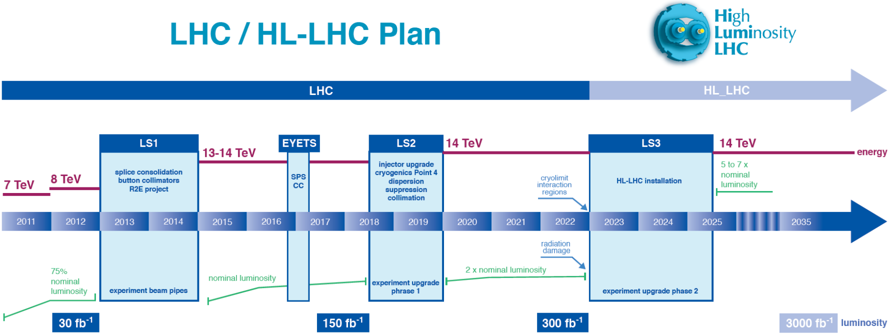
In the Higgs sector:

- Origin of Yukawa couplings
- Coupling to longitudinal EW gauge bosons
- CP property
- ...

Other areas:

- Dark matter
- Baryon-antibaryon asymmetry
- Hierarchy problem
- ...

Planned timeline of LHC, HL-LHC



https://cds.cern.ch/record/1975962

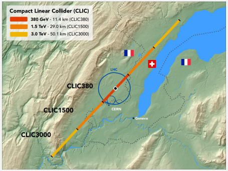
HL-LHC physics program

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

Proposed electron-positron colliders at the energy frontier

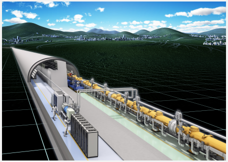
Linear e^+e^- colliders

- Compact Linear Collider CLIC



CERN
$\sqrt{s} = 380\,\text{GeV},\ 1.5\,\text{TeV},\ 3\,\text{TeV}$
$\ell = 11\,\text{km},\ 29\,\text{km},\ 50\,\text{km}$

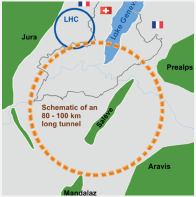
- International Linear Collider ILC



Japan
$\sqrt{s} = 250\,\text{GeV}\ (500\,\text{GeV},\ 1\,\text{TeV})$
$\ell = 17\,\text{km}\ (31\,\text{km},\ 50\,\text{km})$

Circular e^+e^- colliders

- Future Circular Collider FCC-ee



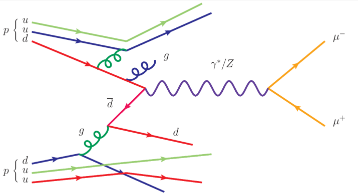
CERN
$\sqrt{s} = 90 - 350\,\text{GeV}$
$\ell = 98\,\text{km}$

- Circular Electron Positron Collider

China
$\sqrt{s} = 90 - 240\,\text{GeV}$
$\ell = 100\,\text{km}$

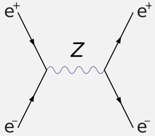
Electron-positron vs. hadron collider

Proton-proton collider



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

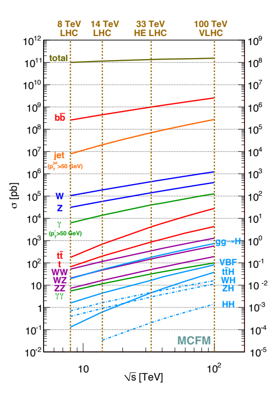
Electron-positron collider



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

Interesting physics processes in pp and ee collisions

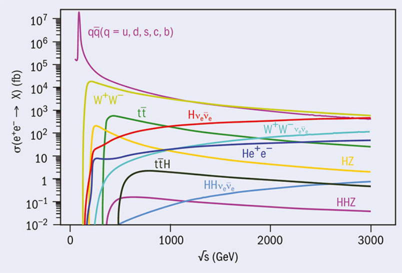
Proton-proton collider



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

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

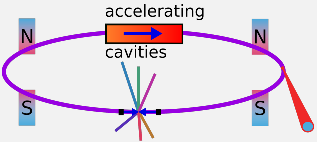
Electron-positron collider



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

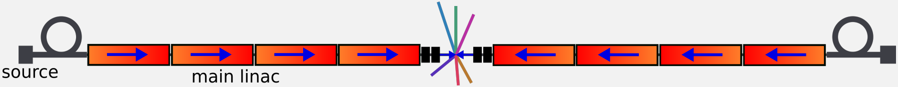
More "clean", all events usable

Circular colliders



- Beam circulates for a long time
- Few accelerating cavities, many magnets
- High energy $\rightarrow$ 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 $\rightarrow$ need high accelerating gradient
- High luminosity $\rightarrow$ high beam power (high bunch repetition)

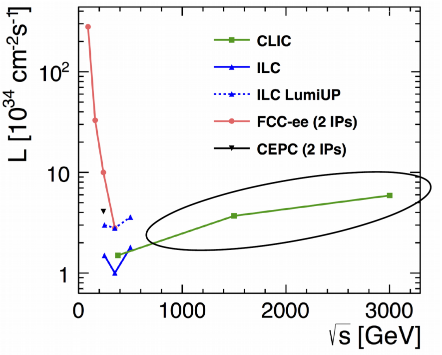
Electron-positron colliders

Linear e^+e^- colliders

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

Circular e^+e^- colliders

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



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

CLIC accelerator

The Compact Linear Collider CLIC

Novel technology: radio-frequency devices and two-beam acceleration scheme

Goal High gradient, efficient energy transfer (wall-plug to beam)

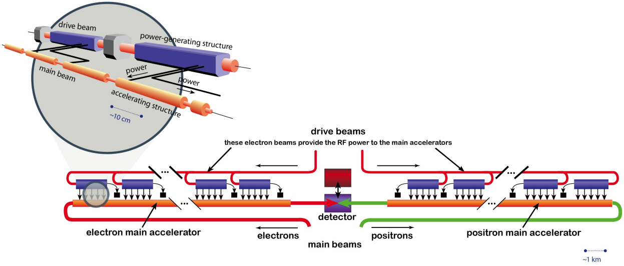
Means High-frequency RF maximizes field in cavities for given energy

Challenge Standard RF sources inefficient at high frequencies

→ **Idea** Use standard low-frequency RF sources to accelerate a drive beam, which is then brought to high frequency

Two-beam acceleration

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



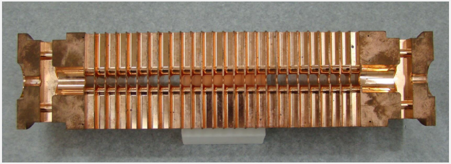
Two-beam acceleration scheme

Drive beam high current (100 A); lower energy (2.4 GeV)
12 GHz frequency after combiner rings/delay loops

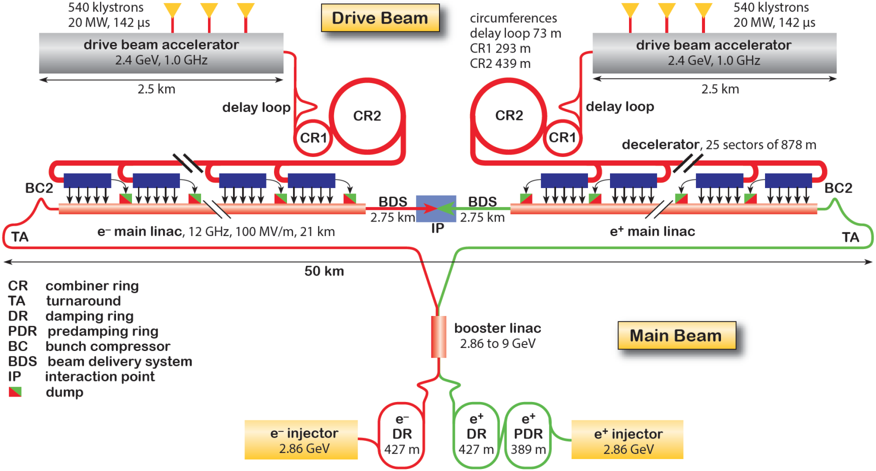
Power Extraction and Transfer Structures (PETS): decelerate the beam → extract its energy → guide it via waveguides to the main beam accelerating structures

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

CLIC technology

- RF cavities: 
- Operated at room temparature
- Gradient 100 MV/m

Layout of the CLIC accelerator complex

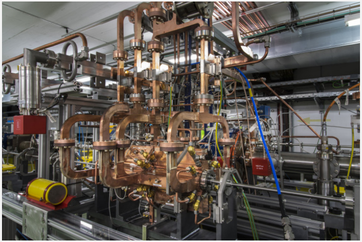


Real-life test facilities

CTF3, the CLIC Test Facility

Successful demonstration of

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



C-band facilities

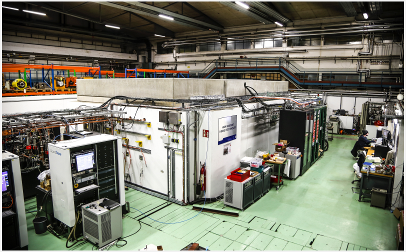
using CLIC technology (SwissFEL)

The two-beam module

Test module without beam for tests of

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

X-band test facility

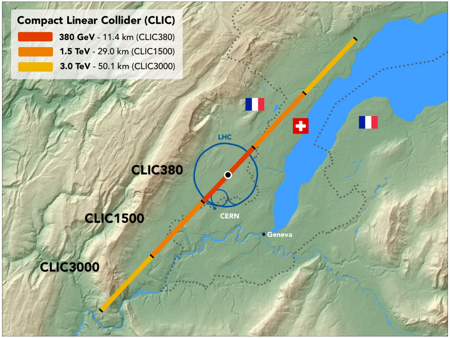


test and development of high-gradient accelerating structures

CLIC staged implementation and map

Baseline: several energy stages

Stage	$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]
1	380	500
top scan	350	100
2	1500	1500
3	3000	3000

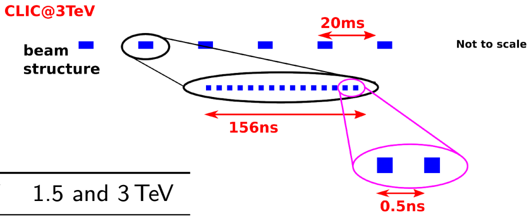


⇒ stages can be adapted to possible discoveries at the LHC

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

Beam properties and experimental conditions

CLIC bunch structure and experimental conditions



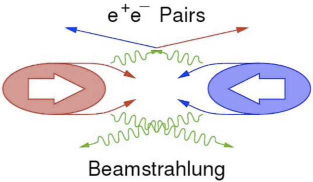
Energy stage(s)	380 GeV	1.5 and 3 TeV
Train repetition rate	50 Hz	50 Hz
Bunches / train	356	312
Train duration	178 ns	156 ns
Bunch separation	0.5 ns	0.5 ns
Duty cycle	0.00089 %	0.00078 %

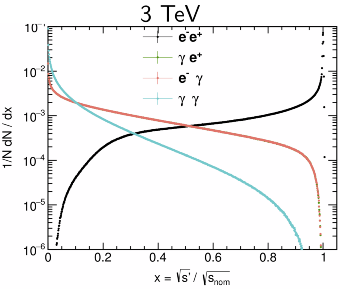
- Linear colliders operate in bunch trains
- Bunch separation drives timing requirements of the detector
  - 10 ns hit time-stamping in tracking
  - 1 ns accuracy for calorimeter hits
- Low duty cycle $\rightarrow$ power pulsing of detectors possible

Beam-beam interaction

High luminosities achieved by using extremely small beam sizes

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



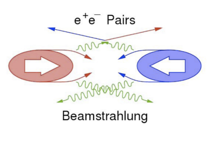


Beamstrahlung:

... modifies energy spectrum of the colliding e^+e^- pairs
... **produces $e^\pm\gamma$ and $\gamma\gamma$ collisions**
... drives detector requirements to a large extend

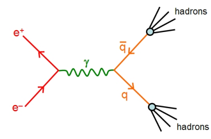
Coherent and incoherent e^+e^- pairs

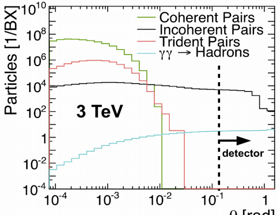
19k particles per bunch train (3 TeV)
High occupancies → impact on detector granularity and design



$\gamma\gamma \to$ 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
- $\gamma\gamma \to$ hadrons suppressed with timing cuts

CLIC detector

Detector requirements

+ Momentum resolution:
Higgs recoil mass, $H \to \mu\mu$,
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

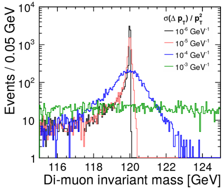
$$\frac{\sigma(E)}{E} \approx 3.5 - 5\,\% \text{ for } E = 50 \ldots 1000\,\mathrm{GeV}$$

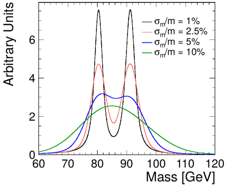
+ Impact parameter resolution:
b/c tagging, e.g. Higgs couplings

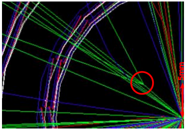
$$\sigma(d_0) = \sqrt{a^2 + b^2 \mathrm{GeV}^2 / (p^2 \sin^3\theta)},$$

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

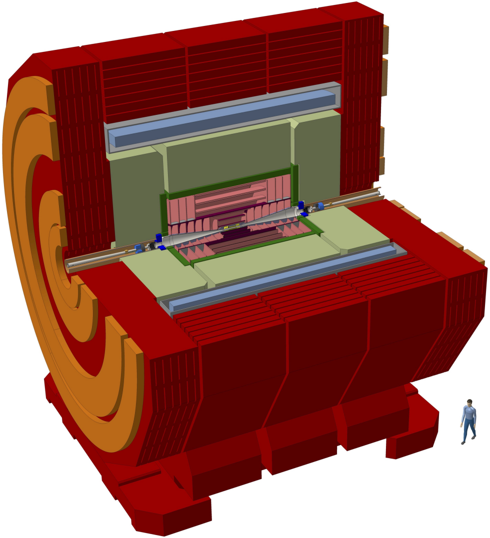
+ Lepton identification, very forward e/γ tagging
+ Requirements from beam-induced backgrounds







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

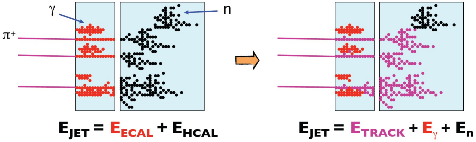
Particle Flow principle

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/

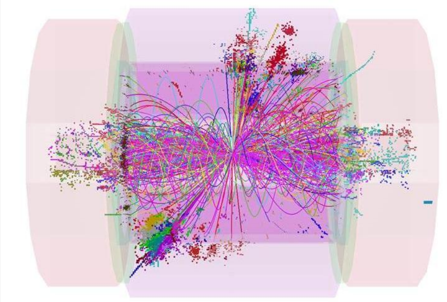
- Traditional approach: jet energy measured in ECAL and HCAL
- Particle Flow: Need very good spacial resolution to avoid confusion ⇒ highly granular calorimeters

⇒ Hardware + Software

Timing resolution to suppress backgrounds

$\gamma\gamma \rightarrow$ 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 $\gamma\gamma \rightarrow$ hadrons from bunch train

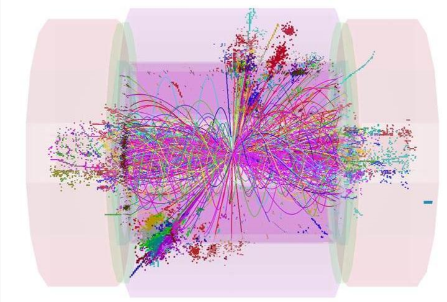


1.2 TeV background
in the reconstruction window $\geq$ 10 ns
around physics event

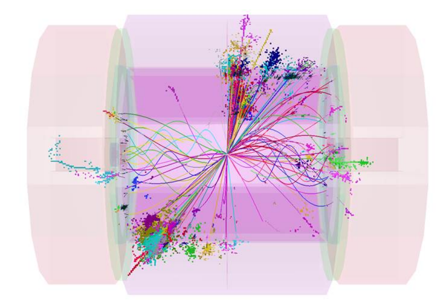
Timing resolution to suppress backgrounds

$\gamma\gamma \rightarrow$ 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 $\gamma\gamma \rightarrow$ hadrons from bunch train



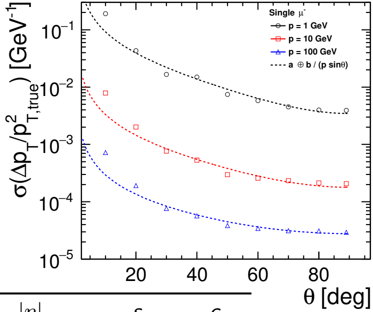
1.2 TeV background
in the reconstruction window $\geq$ 10 ns around physics event



100 GeV background
after timing cuts

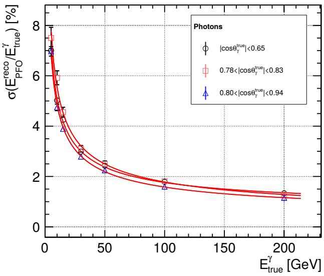
Detector performance in full simulation

Tracking performance:
Momentum resolution



Full detector simulation

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



$\lvert\eta\rvert$	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)

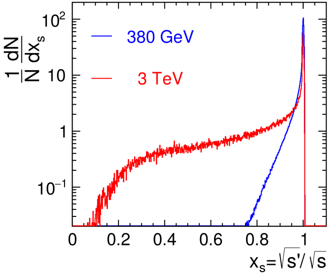
CLIC physics

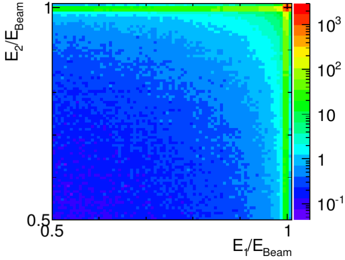
Simulation

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

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

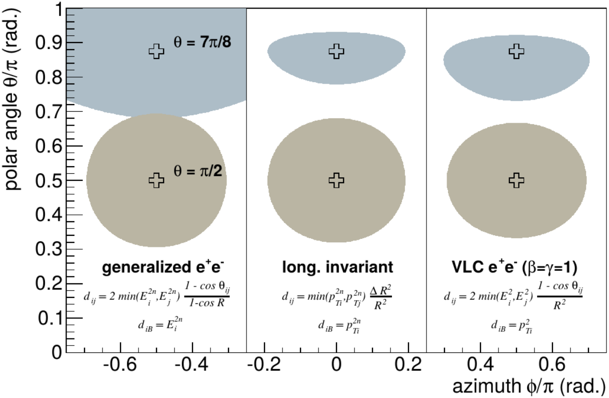
- Lepton colliders: $[E, \theta]$; hadron colliders: $[p_T, y]$
- $\gamma\gamma \rightarrow$ hadrons is forward peaked, reduce forward size for background robustness

VLC algorithm

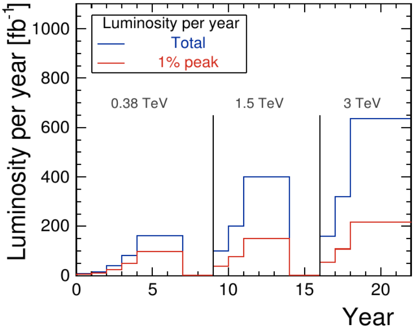
Valencia Linear Collider algorithm:

- 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

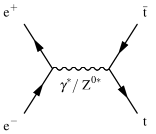
Stage 2

- ttH production

Stage 2,3

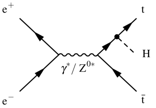
- Searches for new particles
- Precision EW measurements providing indirect sensitivity to new physics at higher scales
- Higgs self-coupling
- BSM Searches

$t\bar{t}$ production



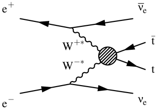
Stage 1: 380 GeV close to production maximum
→ large event samples

$t\bar{t}H$ production

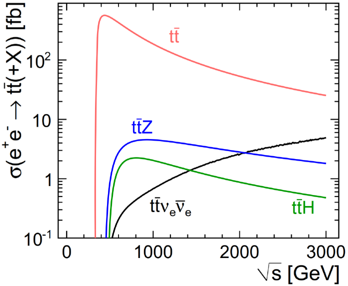


Maximum σ near 800 GeV
LC lumi higher at higher energy
→ CLIC Stage 2 close to maximum ttH rate

VBF $t\bar{t}H$



Benefits from highest energies

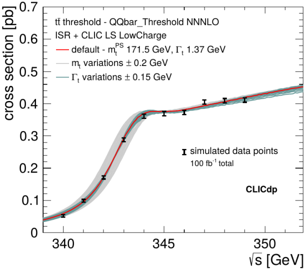


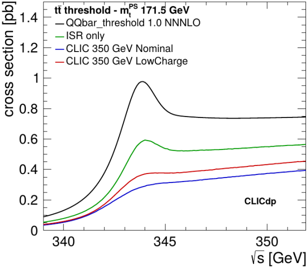
- Rare top decays
- Top mass
- Top electroweak couplings
- Top Yukawa coupling
- CP properties of $t \rightarrow H$ coupling
- BSM in H/t sectors

Top threshold scan

- Goal: Highest precision top mass measurement
- Dedicated runs of CLIC in several steps around 350 GeV (tt threshold), total $100\,\text{fb}^{-1}$
- Expected measurement precision on 1S mass : ≈ 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





Flavor-changing neutral current top decays

- Make use of the c-tagging capabilities of CLICdet to search for t → c FCNC
- FCNC strongly suppressed in the SM ⇒ measurement would reveal new physics
- Analysis performed for 380 GeV (production maximum)
- Search in 3 channels $t \to cH$, $t \to c\gamma$, and $t \to c$+MET decays
- Select events with $t\bar{t}$ signature with “spectator top” (SM) and “signal top” (FCNC)
- Combinatorics of final state: minimize χ^2 measure, e.g.

$$\chi^2 = \frac{(M_{t1}^{rec} - m_{top})^2}{\sigma_t} + \frac{(M_{t2}^{rec} - m_{top})^2}{\sigma_t} + \frac{(M_{W1}^{rec} - m_W)^2}{\sigma_W} + \frac{(M_{W2}^{rec} - m_W)^2}{\sigma_W}$$

$t \to c\gamma$

- Isolated photon with $E \geq$50 GeV required

Limit:

$\mathrm{BR}(t \to c\gamma) < 4.7{\times}10^{-5}$

$t \to cH$

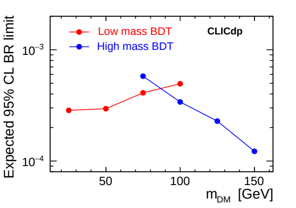
- Consider only $H \to bb$
- Make use of kinematics and flavor tagging

Limit:

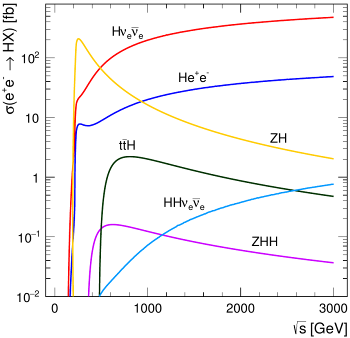
$\mathrm{BR}(t \to cH) < 1.2 \times 10^{-4}$

$t \to c$+MET

Heavy stable new scalar, escapes detector

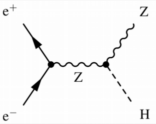


Higgs physics at CLIC



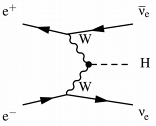
Stage 1: two production mechanisms → reduces uncertainties and guarantees model-independence

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

Benefits from highest energies

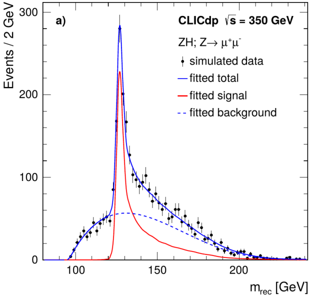
Higgsstrahlung

$Z \to ee, \mu\mu$

- Identify HZ events from the Z recoil mass

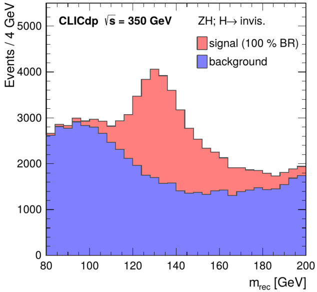
$$M^2 = s - 2E_{q\bar{q}}\sqrt{s} + M^2_{q\bar{q}}$$

$\Rightarrow$ model-independent measurement of the g_{HZZ} coupling



$Z \to q\bar{q}$

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



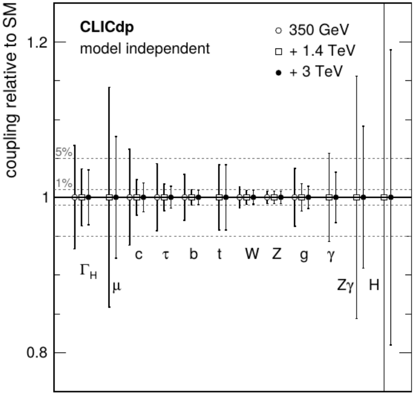
$H \to$ invisible

Find invisible Higgs decays in a model-independent way

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

Higgs properties: combined fits

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



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

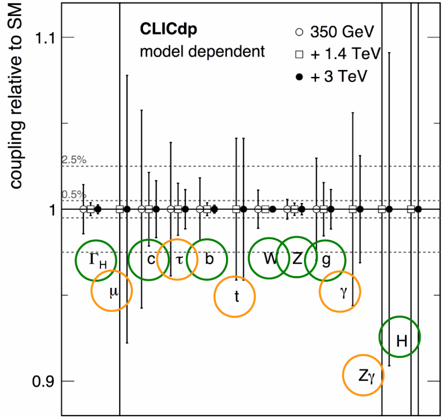
Model-independent fit

Only possible at lepton colliders

- 11 free parameters including the total width

Model-dependent:

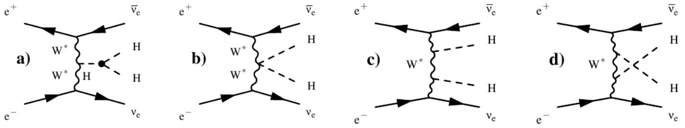
- 10 free parameters
- Total width is sum of partial widths ⇒ No decays to non-SM particles
- Comparison to LHC results



○ significantly better than HL-LHC or not possible at hadron colliders

○ similar to HL-LHC

Double Higgs production



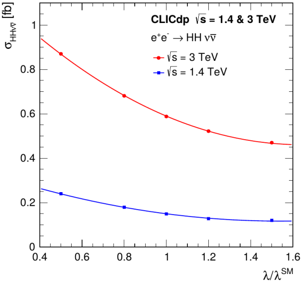
⇒ Measure Higgs trilinear self-coupling λ and quartic $HHWW$ coupling

- Cross section precision at 3 TeV:

$$\frac{\Delta[\sigma(HH\nu\bar{\nu})]}{\sigma(HH\nu\bar{\nu})} = 20\,\%$$

⇒ Extract limits on λ from cross-section variation

⇝ Expected limits from Stage 2 ($1.5\,\mathrm{ab}^{-1}$) & 3 ($3\,\mathrm{ab}^{-1}$) with e^- beam polarisation:



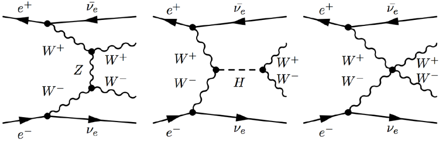
$$\frac{\Delta\lambda}{\lambda} = 16\,\%$$

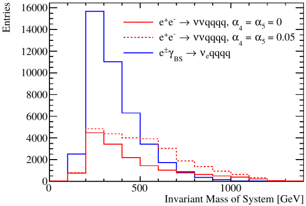
Differential distributions

Template fit to sensitive variables (e.g. $M(HH)$) improves sensitivity to $\Delta\lambda/\lambda \approx 10\,\%$

Electroweak gauge boson scattering

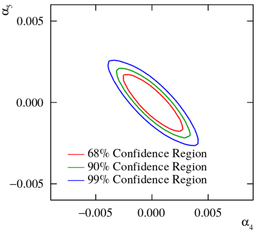
- Make use of fully hadronic final states (JER allows to separate W,Z)
- Example studies done in $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$ and $e^+e^- \rightarrow ZZ\nu\bar{\nu}$





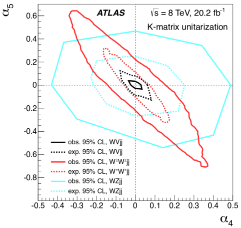
Limits on anomalous quartic gauge couplings via χ^2 fit to sensitive observables: M_{VV}, $\cos\theta^*_{VV}$, $\cos\theta^*_{Jets}$

Limits on anomalous quartic gauge couplings



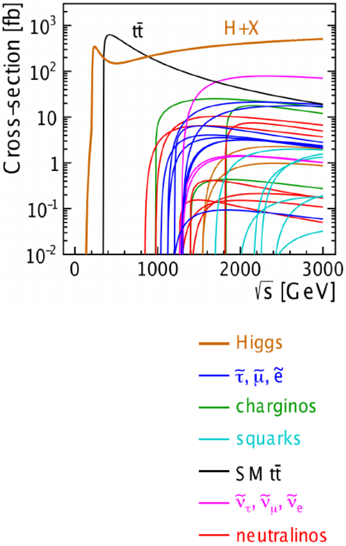
CLIC 3 TeV ←

ATLAS Run 1 →

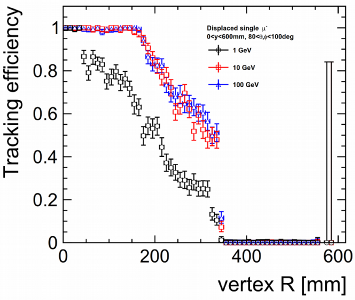


HL-LHC: Similar sensitivity as CLIC 3 TeV

- CLIC well suitable for direct searches/discoveries
- In case of a discovery at the LHC, CLIC could measure new particles properties (scrutinize the underlying theory using polarised e^- beam, threshold scans)
- Sensitivity of CLIC often extends up to the kinematic limit (pair production: $M \leq \sqrt{s}/2$)
- CLIC is particularly suitable for electroweak states in very rare processes

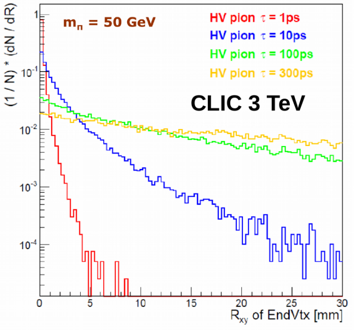


- Long-lived particles signatures: displaced or disappearing tracks
- Challenging at the LHC



Require 5 hits for the tracking algorithm

Example model: Hidden valley particles
Possible discovery channel
$H \to \pi_v \pi_v \to b\bar{b}b\bar{b}$

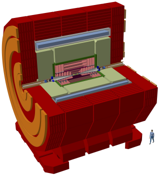


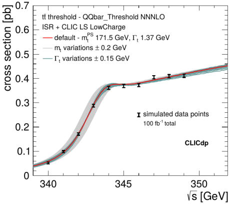
Summary and Outlook

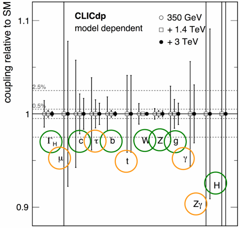
Summary

- 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

Additional Material

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