CLIC Physics and Detectors

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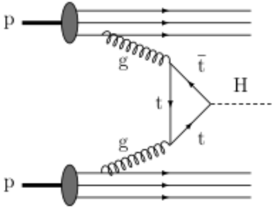
Summer School and Workshop on the Standard Model and Beyond 2016

Corfu, Greece – September 8, 2016

Linear lepton colliders

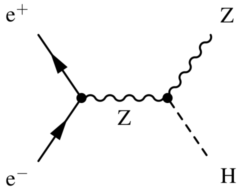
Hadron versus lepton colliders

Hadron colliders



1) Proton is compound object
   - Initial state unknown
   - Limits achievable precision
2) High rates of QCD backgrounds
   - Complex triggers
   - High levels of radiation
3) High-energy circular colliders possible

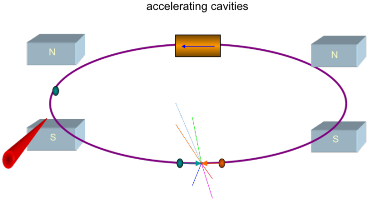
Lepton colliders

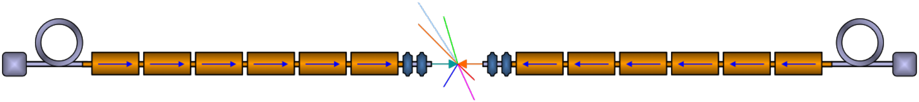


1) e^+e^- are point-like
   - Initial state well-defined (energy, polarisation)
   - High-precision measurements
2) Clean experimental environment
   - Trigger-less readout
   - Low radiation levels
3) High energies require linear colliders

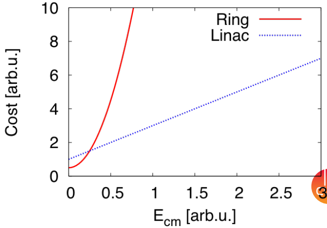
Circular vs. linear e^+e^- colliders

- **Circular colliders**
  - Can accelerate beam in many turns
  - Can use beam many times
  - For electrons synchrotron radiation can be large
    - Synchrotron radiation per turn
      $\sim$ Energy^4/(Mass^4 $\cdot$ Radius)
    - $\text{Mass}_{\text{proton}}/\text{Mass}_{\text{electron}} \approx 2000$
    - E.g. 2.75 GeV/turn lost at LEP for $E = 105$ GeV
      $\rightarrow$ Maximal energy limited





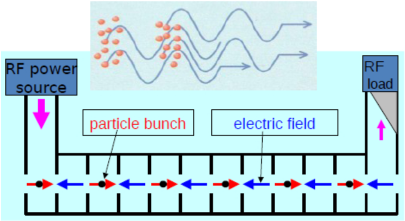
- **Linear colliders:**
  - Almost no radiation in a linac
  - Have to achieve energy in a single pass
    $\rightarrow$ High acceleration gradients needed
  - Have to achieve luminosity in single pass
    $\rightarrow$ Small beam size and high beam power needed



The Compact Linear Collider (CLIC)

Reminder: particle acceleration

- Radio frequency (RF) accelerator:
  synchronise particles with an RF electromagnetic wave

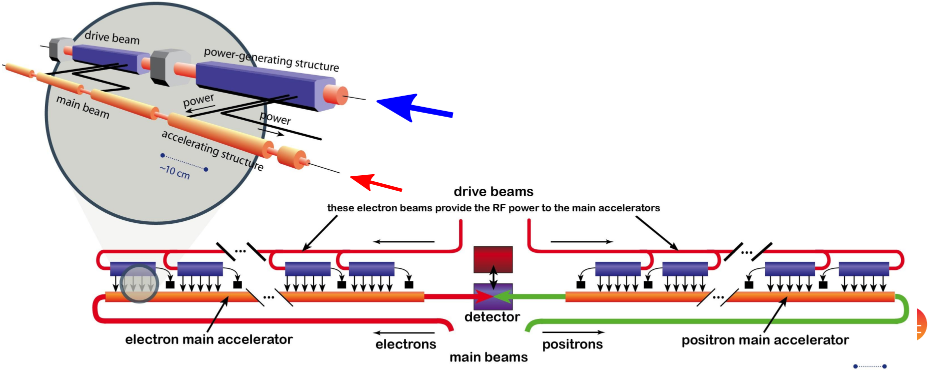


- CLIC aims for high collision energies (up to 3 TeV)
- Requires very strong acceleration to keep accelerator length reasonable
- Acceleration is more efficient at high frequency

→ **CLIC**: 100 MV/m (100 million Volts per metre) at 12 GHz
(LHC: 5 MV/m and 400 MHz)

Two-beam acceleration scheme

- **Drive beam supplies RF power**
  - 12 GHz bunch structure
  - High current 100 A
  - Low energy 2.4 GeV –240 GeV
- **Main beam for physics**
  - Lower current 1.2 A
  - High energy 9 GeV – 1.5 TeV



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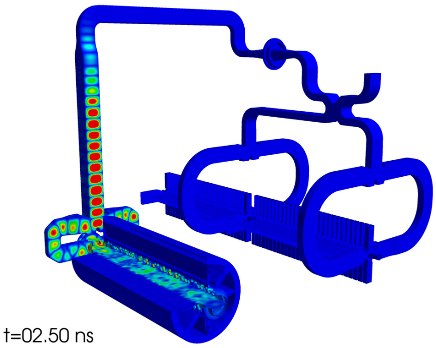
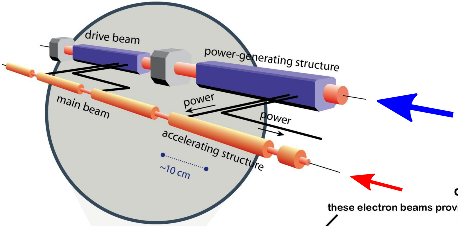
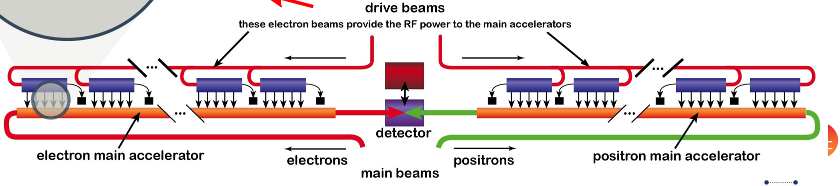
Electromagnetic field simulation



A. Candel et al., SLAC-PUB-14439





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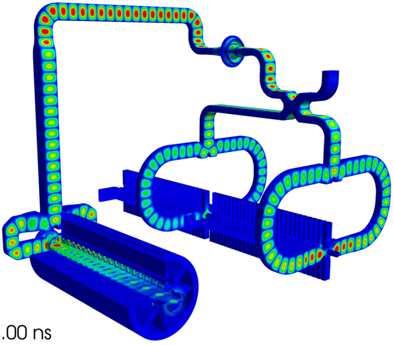

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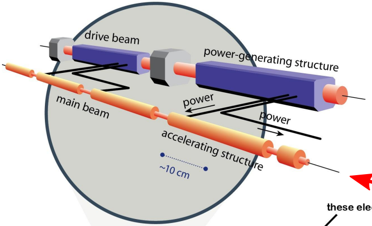

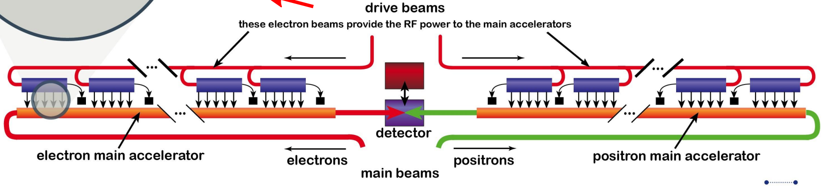

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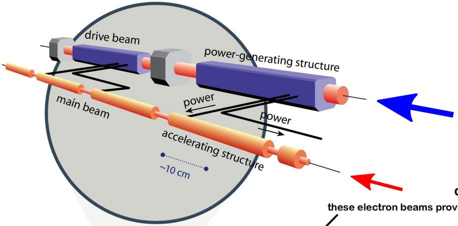

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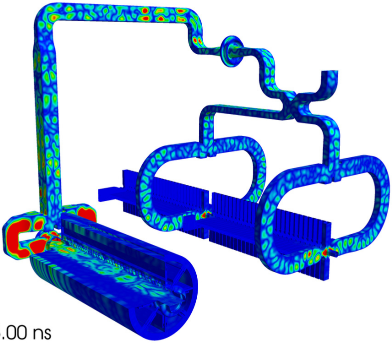

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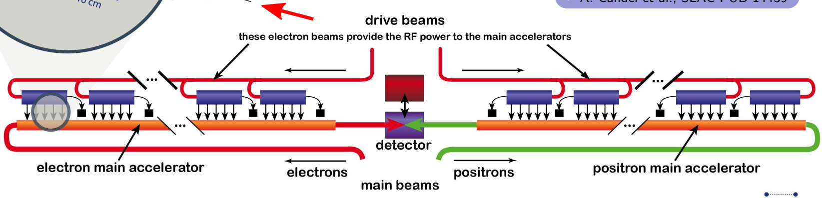
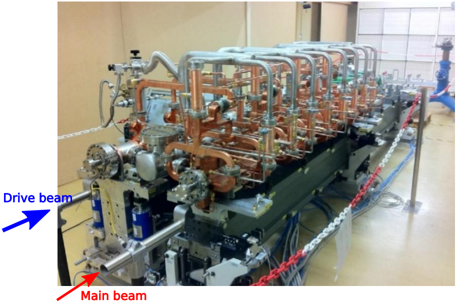
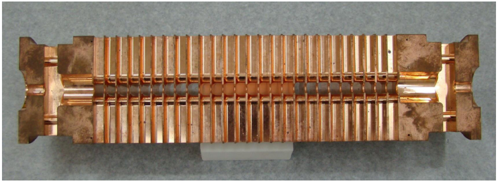


CLIC accelerator modules

CLIC two-beam module



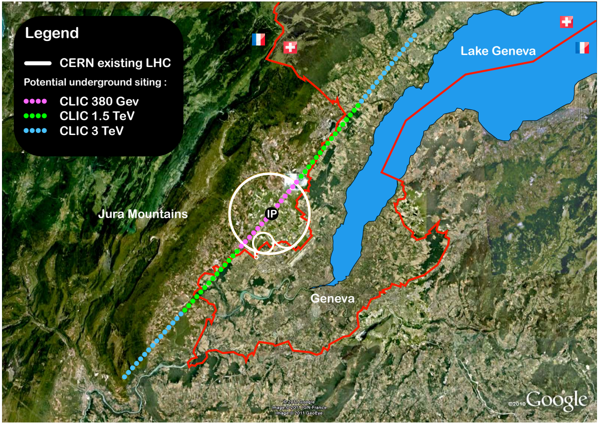
CLIC accelerating structure



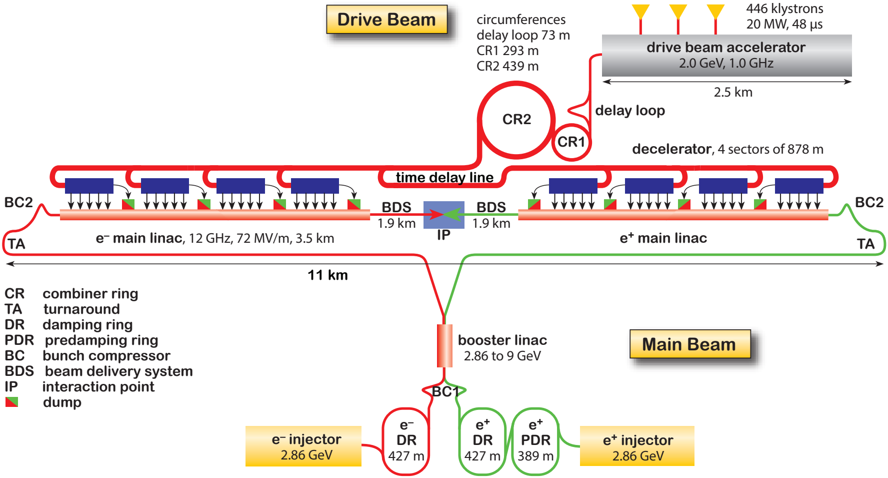
- Two-beam module of 2 m length
- Operating at room temperature
- 20,000 modules needed for 3 TeV accelerator of 50 km length

Staged implementation

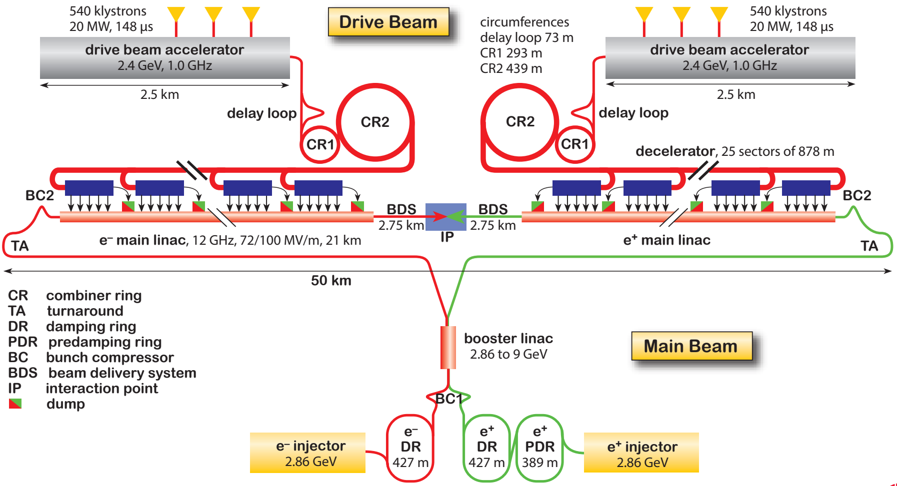
- Want to reach high luminosities ($\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)
- Achievable for $\sqrt{s}$ from 350/380 GeV to 3 TeV in staged construction
- Three stages with 11 km – 50 km length
- Constructing next stage while taking data with current stage



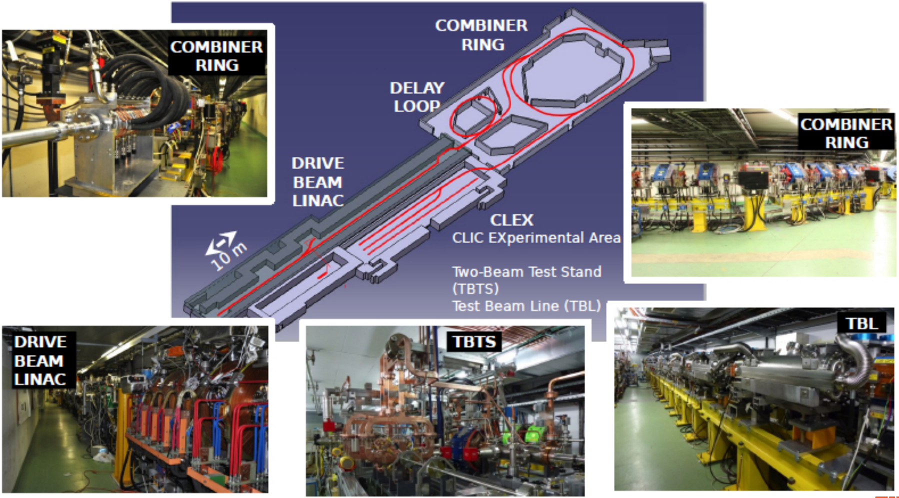
CLIC layout at 380 GeV



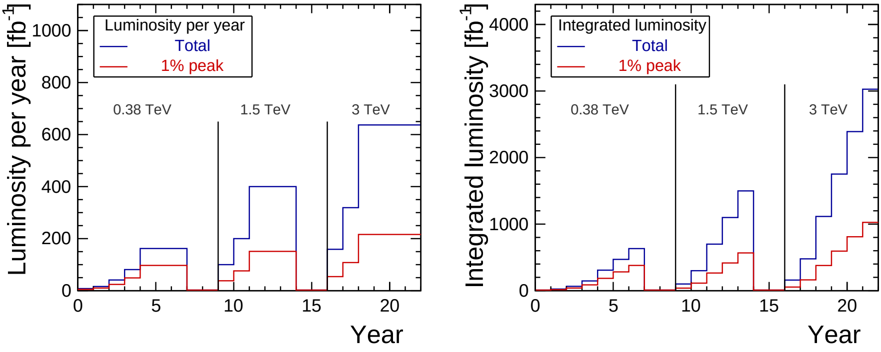
CLIC layout at 3 TeV



CLIC Test Facility at CERN



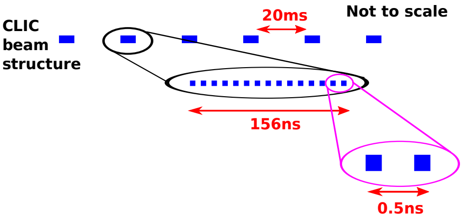
CLIC programme



- CLIC programme of 22 years:
  7 years (380 GeV), 5 years (1.5 TeV), 6 years (3 TeV)
  interleaved by 2-years upgrade periods

- Luminosity ramp up of 4 years / 2 years
  (5%, 10%,) 25%, 50%, 100%

Experimental conditions at 3 TeV CLIC



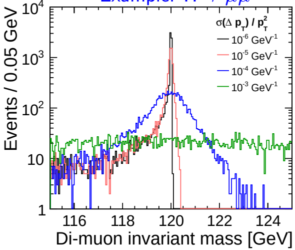
	CLIC at 3 TeV
Luminosity	$5.9 \cdot 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
Train repetition rate	50 Hz
Train duration	156 ns
Bunch crossings / train	312
Bunch separation	0.5 ns
Duty cycle	0.00078%
Beam size σ_x/σ_y	~40 nm / 1 nm
Beam size σ_z	44 μm

CLIC detector requirements

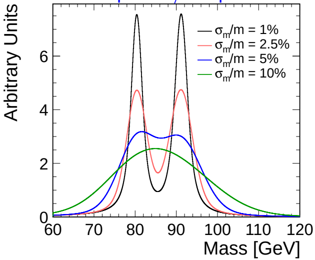
CLIC physics aims → detector needs

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - → $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - → $\sigma_{r\varphi} \sim 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\mu\mathrm{m}$
- Jet energy resolution
  - Separation of W/Z/H di-jets
  - → $\sigma_E/E \sim 3.5\%$ for jets above 100 GeV
- Angular coverage
  - Very forward electron tagging
  - → Down to $\theta = 10\,\mathrm{mrad}$
- Requirements from CLIC beam structure and beam-induced backgrounds
  - Tight timing cuts in the order of 1-10 ns (depending on detector region)

Example: H→ $\mu\mu$

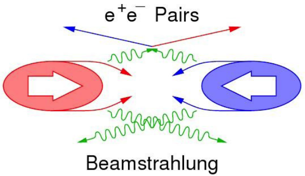


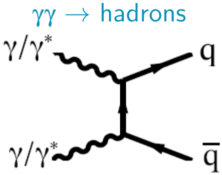
Example: W/Z separation



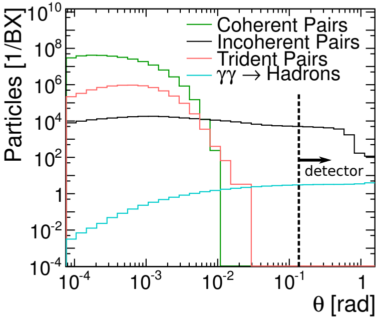
Detector needs: beam induced backgrounds

- Small bunch size: $\sigma_{x;y;z} = \{40\,\text{nm}; 1\,\text{nm}; 44\,\mu\text{m}\}$ → strong beam-beam interactions





- Coherent e^+e^- pairs
  - $7 \cdot 10^8$ per BX, very forward
- Incoherent e^+e^- pairs:
  - $3 \cdot 10^5$ per BX, rather forward
  - High occupancies → impact on detector design
- $\gamma\gamma \to$ hadrons
  - "Only" 3.2 events per BX at 3 TeV
  - Main background in calorimeters and trackers → Impact on physics

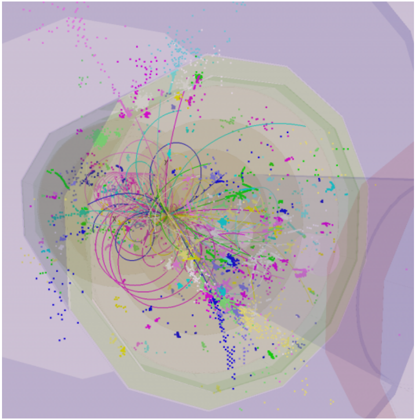


CLIC detector needs: beam-induced backgrounds

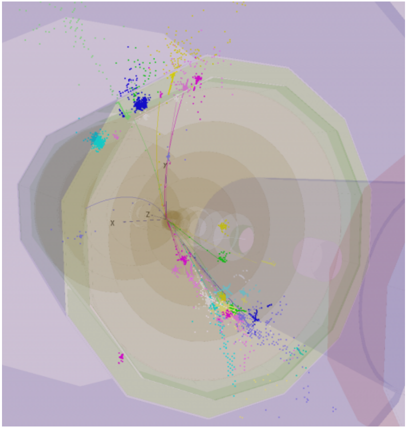
Example:

H $\rightarrow$ Zγ; Z $\rightarrow$ q$\overline{\text{q}}$ @ 1.4 TeV before and after rejecting out-of-time background

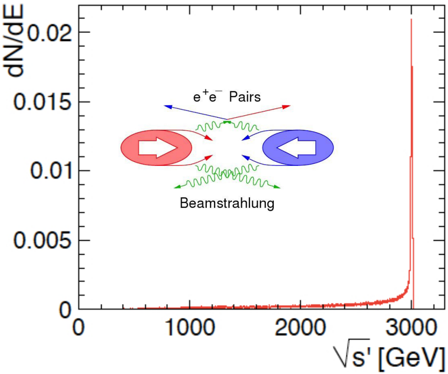
Before background rejection



After background rejection



Beam energy spectrum



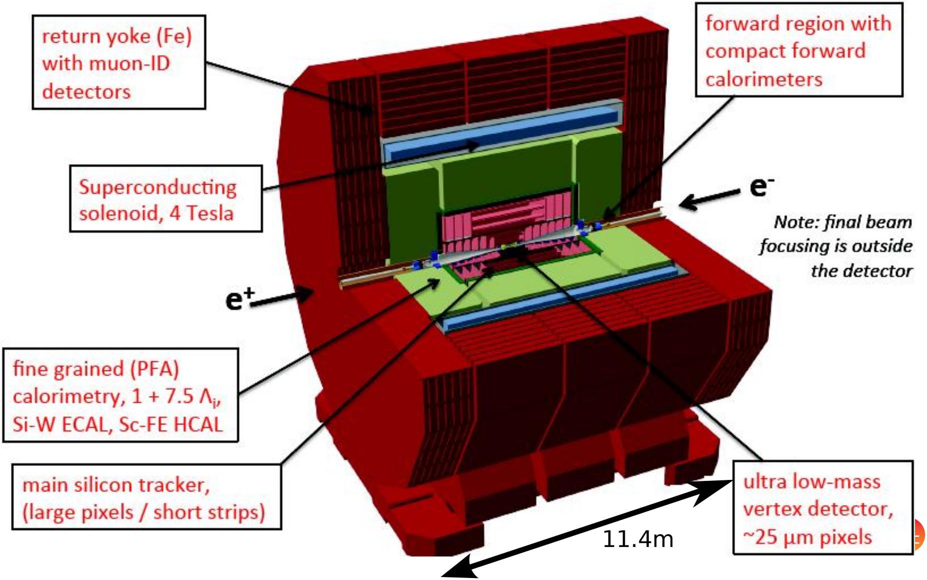
- Due to beamstrahlung energy is lost right at the interaction point
- Collision energy is reduced by the amount lost in beamstrahlung before collision
- Example:
  - Full luminosity at 3 TeV: $5.9 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 1% most energetic part: $2.0 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Most physics processes are studied well above production threshold
- Can profit from almost full luminosity

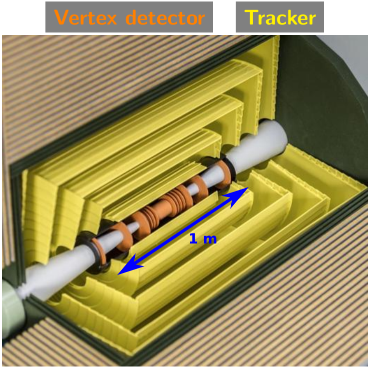
CLIC detector

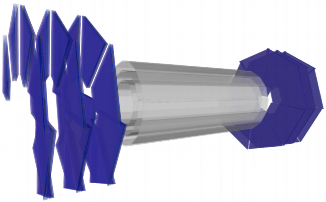
(selection)

CLIC detector



CLIC vertex detector



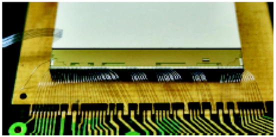


- Flavour tagging capabilities drive the design of the pixel detector
- Vertex detector needs to be extremely accurate and light
  - Single point resolution of $\sigma < 3\,\mu m$
    - → Pixel pitch $\approx 25\,\mu m$ (25 times smaller pixels than at LHC) and analogue readout
  - Material budget $< 0.2\,\%X_0$ per layer
    - → $50\,\mu m$ sensor + $50\,\mu m$ ASIC, low mass support, power pulsing, air cooling
    - → Low power dissipation of $50\,mW/cm^2$
  - Time stamping $\leq 10\,ns$ for background suppression
  - Radiation level 10^4 times lower than at LHC

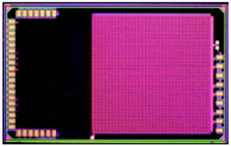
→ Comprehensive vertex detector R&D

Silicon Vertex and Tracker R&D

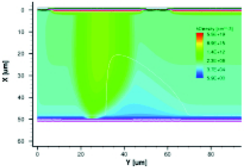
Sensors



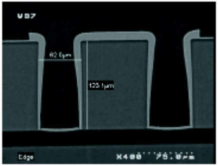
Readout ASICs



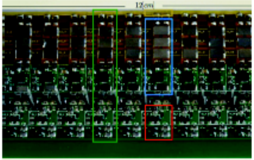
Simulations



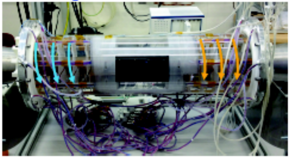
Interconnects



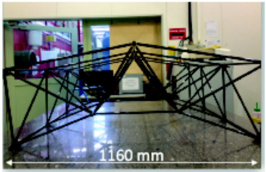
Powering



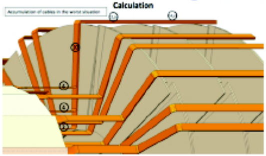
Cooling

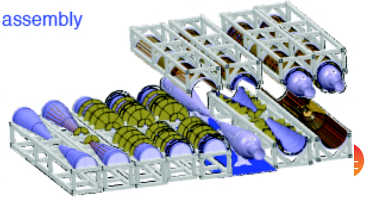


Light-weight supports

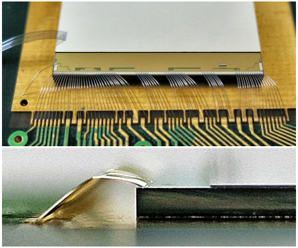


Detector integration + assembly

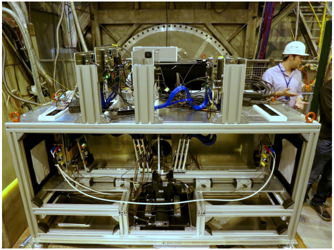




Example: Test beam experiments with pixel detectors



- Test-beam measurements with ultra thin sensors (50 µm)
    - High detection efficiency ($> 99\%$) under normal operating condition
    - Resolution limited by single-pixel clusters
    - Resolution degrades for thinner sensors

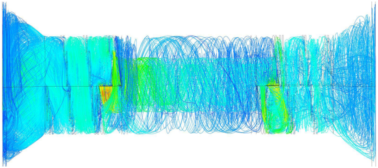


- CERN-LCD Timepix3 telescope
    - Permanent installation at CERN SPS H6B
    - Movement and rotation stages for automatic scans
    - High rate up to 10 M particles/s
    - Track timing $<$ 2 ns accuracy
    - Track pointing resolution 2 µm

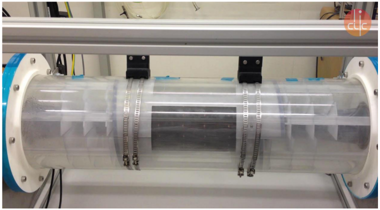
Example: Vertex detector cooling

- Vertex detector with low material budget
  → Power pulsing and air cooling
- Heat load of 50 mW/cm^2 extractable using spiral air flow
  → Test concept in simulations
- Verify simulation results using real size vertex-detector mockup
  - Visual test of air flow using smoke
  - Study spiral air-flow feasibility, temperature and vibrations

Simulation of air flow and heat transport



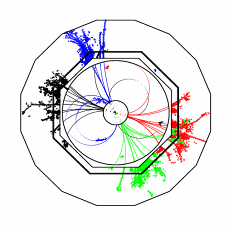
Visual test of spiral air flow

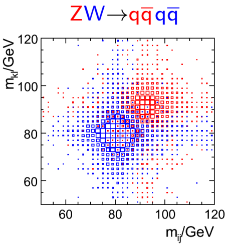


Measurement of velocity and temperature

Calorimetry: Jet energy resolution

- Jet energy resolution (JER) requirements depend on physics goals
- Starting point for detector design
  - → Ability to separate hadronic W and Z decays





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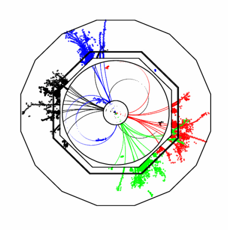
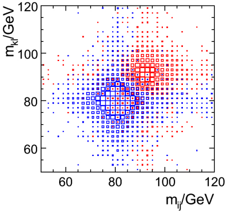
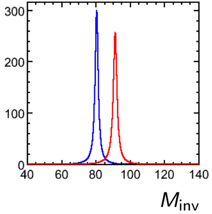


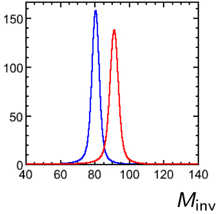
ZW→$q\bar{q}q\bar{q}$



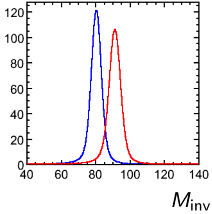
Perfect → 3.1σ W/Z sep.



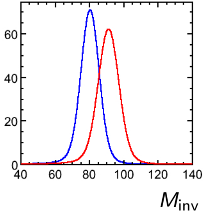
2% JER → 2.9σ sep.



3% JER → 2.6σ sep.



6% JER → 1.8σ sep.



- 3%–4% jet energy resolution gives ∼ 2.6 − 2.3σ W/Z separation

Particle Flow Calorimetry

3%–4% jet energy resolution reachable with Particle Flow Analysis (PFA)

Motivation:

- Average jet composition
  - 60% charged particles
    30% photons
    10% neutral hadrons

→ Always use the best information

- 60% → tracker ☺
  30% → ECAL ☺
  10% → HCAL ☹

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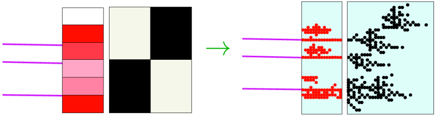
  30% → ECAL ☺
  10% → HCAL ☹

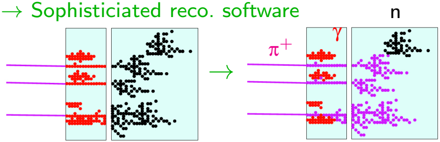
Particle Flow Analysis: Hardware + Software

- Hardware: Resolve energy deposits from different particles
  → High granularity calorimeters



$E_{jet} = E_{ECAL} + E_{HCAL}$

- Software: Identify energy deposits from each individual particle
  → Sophisticiated reco. software

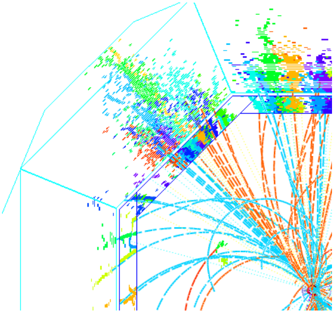


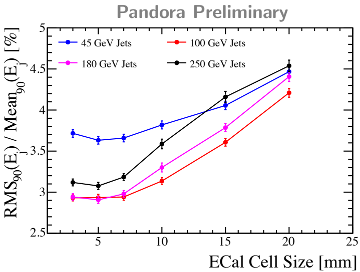
$E_{jet} = E_{track} + E_{\gamma} + E_{n}$

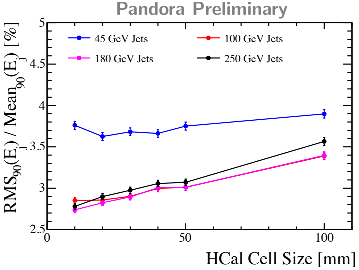
Graphics by M. Thomson, J. Marshall

Optimise calorimeter for particle flow

→ Reco. details in backup slides







- High granularity of calorimeters
  - → Separate overlapping showers to reduce confusion

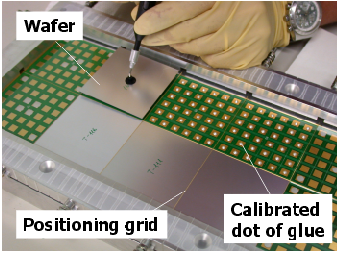
$$\sigma_{\text{jet}} = \sqrt{\sigma^2_{\text{track}} + \sigma^2_{\text{el.-m.}} + \sigma^2_{\text{had.}} + \sigma^2_{\text{confusion}}}$$

- JER of 3%–4% when using
  - → ECAL cell size: $\sim 1 \times 1\,\text{cm}^2$
  - → HCAL cell size: $\sim 3 \times 3\,\text{cm}^2$

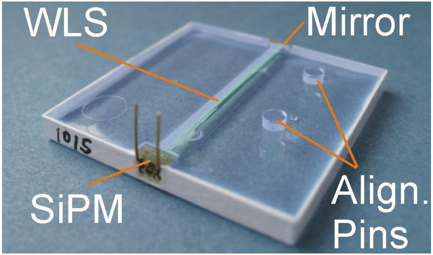
rms_{90} and mean_{90} $\hat{=}$ rms and mean in smallest range of E_{rec} dist. containing 90% of events

Active layer technology: Examples

Silicon PIN diodes ($1 \times 1\,\mathrm{cm}^2$ in 6×6 matrices)

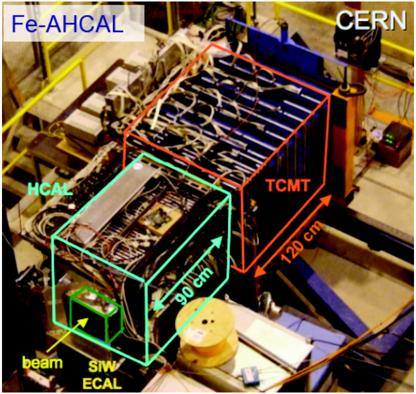


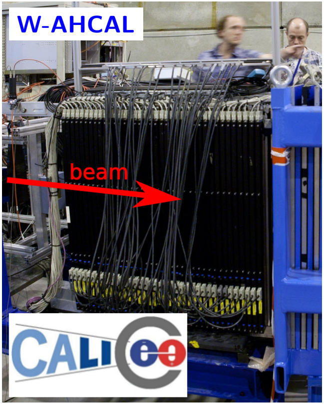
Scintillator tiles/strips (here $3 \times 3\,\mathrm{cm}^2$) + SiPMs



CALICE test beam experiment: Example

- Test beam experiments in 2006–2015 at DESY, CERN, FNAL
- Prototypes of up to ~1 m^3, ~2 m^3 including Tail Catcher Muon Tracker

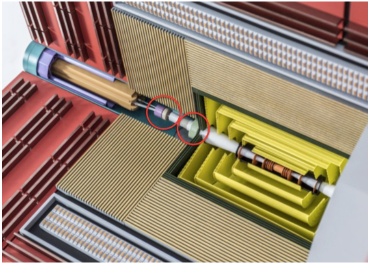




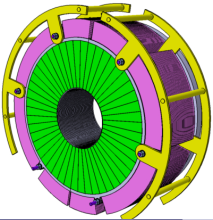
AHCAL/Si-ECAL: ~ 10 000 readout channels

Forward CALorimetry: FCAL

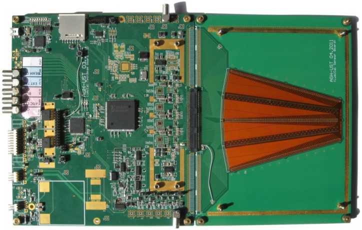
- Very forward e.m. calorimeters: LumiCal + BeamCal
- Very compact design (sensors, read-out + tungsten plates)



- e^- and γ acceptance to small angles
- Luminosity measurement
- Beam feedback
- BeamCal GaAs, LumiCal silicon
- Tungsten absorber



LumiCal module with Si sensor (one sector)

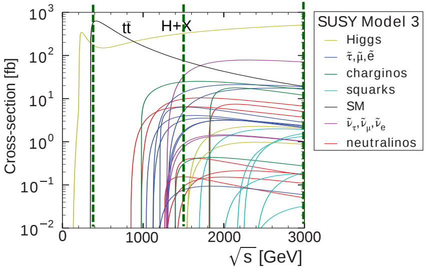


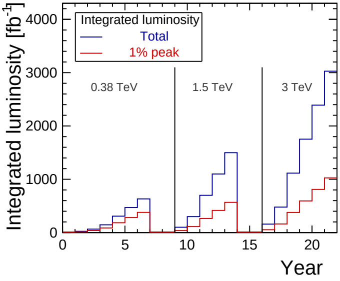
CLIC physics programme

(selection)

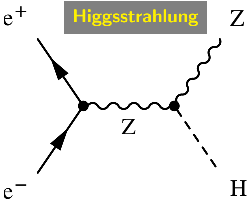
CLIC physics program

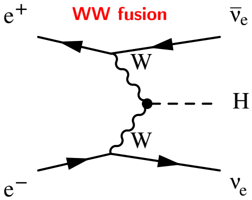
- High luminosity over wide range of $\sqrt{s}$
  $\rightarrow$ Staged construction
- CLIC energy stages defined by physics
  $\rightarrow$ Adapt to discoveries at LHC
- Proposed scenario
  1) $\sqrt{s} =$ 380 GeV, 500 fb^{-1} and
     $\sqrt{s} = \sim$350 GeV, 100 fb^{-1}
     - SM Higgs physics including total width measurement
     - Top precision measurements
  2) $\sqrt{s} =$ 1.5 TeV, 1.5 ab^{-1}
     - New physics
     - $t\bar{t}H$, Higgs self coupling
     - Rare Higgs decays
  3) $\sqrt{s} =$ 3 TeV, 3 ab^{-1}
     - New physics
     - Higgs self coupling
     - Rare Higgs decays

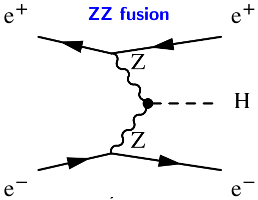


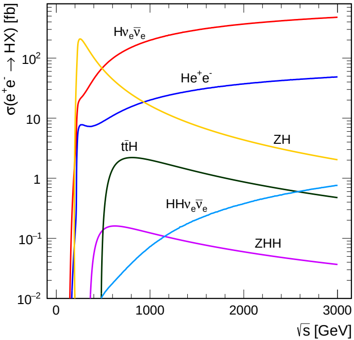


Higgs physics at CLIC (1)







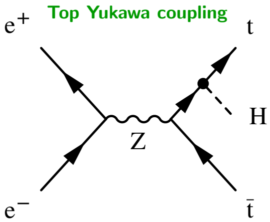


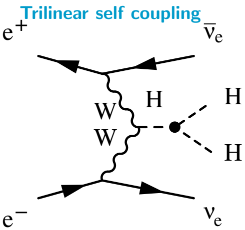
	350 GeV*	1.4 TeV*	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}*
# ZH events	68 000	20 000	11 000
# $H\nu\bar{\nu}$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

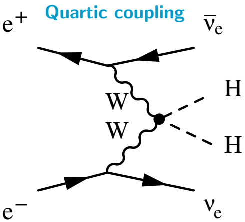
* previously studied staging scenario

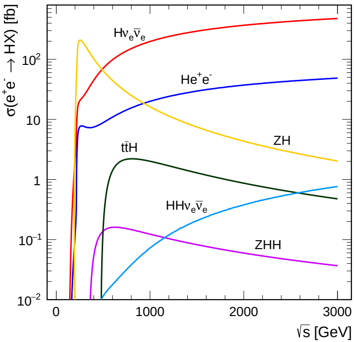
- Large samples of Higgs bosons achievable at CLIC without beam polarisation
- 80 % e^- polarisation foreseen at CLIC
  $\rightarrow$ 12 % more HZ and He^+e^- events
  $\rightarrow$ 80 % more $H\nu\bar{\nu}$ events

Higgs physics at CLIC (2)







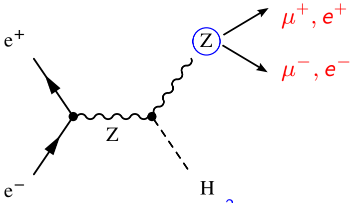


	1.4 TeV*	3 TeV
L_{int}	1.5 ab^{-1}	2 ab^{-1}*
# $t\bar{t}H$ events	2400	1400
# $HH\nu\bar{\nu}$ events	225	1 200

* previously studied staging scenario

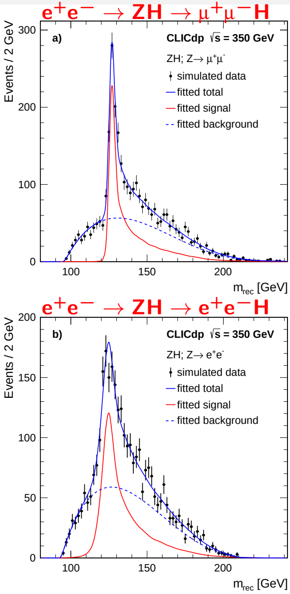
- High energies and luminosities needed to access rare Higgs production processes

Higgsstrahlung at $\sqrt{s} = 350\,\mathrm{GeV}$

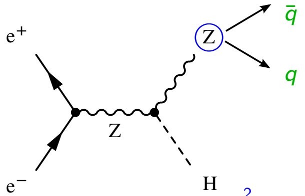


$$m^2_{\mathrm{recoil}} = s + m^2_{\mathrm{Z}} - 2E_{\mathrm{Z}}\sqrt{s}$$

- Measure HZ events from Z recoil mass
- Also sensitive to invisible Higgs decays
- Measurement of g_{HZZ} coupling
- $\mathrm{Z} \to \mathrm{e^+e^-}/\mu^+\mu^-$ decay
  - $\mathrm{BR}(\mathrm{Z} \to \mu^+\mu^-/\mathrm{e^+e^-}) \approx 7\,\%$
  - Fully model independent
  - $\Delta\sigma_{\mathrm{HZ}}/\sigma_{\mathrm{HZ}} \approx 3.8\,\% \to \Delta(g_{\mathrm{HZZ}})/g_{\mathrm{HZZ}} \approx 1.9\,\%$

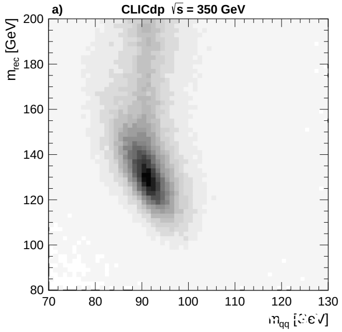


Higgsstrahlung at $\sqrt{s} = 350\,\text{GeV}$



$$m^2_{\text{recoil}} = s + m^2_Z - 2E_Z\sqrt{s}$$

$e^+e^- \rightarrow ZH \rightarrow q\bar{q}H$



- Measure HZ events from Z recoil mass also in hadronic Z decays
- $Z \rightarrow q\bar{q}$ decay
    - $\text{BR}(Z \rightarrow q\bar{q}) \approx 70\,\%$
    - Challenge: $Z \rightarrow q\bar{q}$ reconstruction may depend on H decay mode
    - $\Delta\sigma_{HZ}/\sigma_{HZ} \approx 1.8\,\% \rightarrow \Delta(g_{HZZ})/g_{HZZ} \approx 0.9\,\%$

Results from 25 independent full Geant4 detector simulations including backgrounds

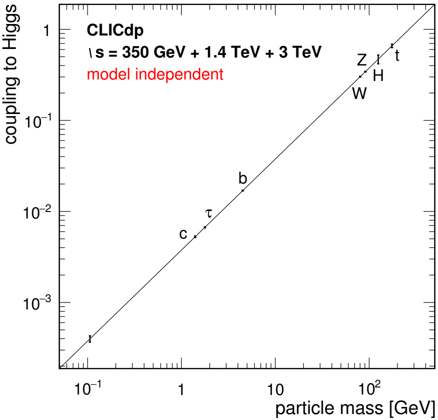
Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	110 MeV	–	–
ZH	$\sigma(HZ) \times$ BR($H \to$ invisible)	Γ_{inv}	0.6%	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	47 MeV	44 MeV
ZH	$\sigma(HZ) \times \mathrm{BR}(Z \to l^+l^-)$	g^2_{HZZ}	3.8%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.84%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	10.3%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(H \to gg)$		4.5%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times \mathrm{BR}(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	5.1	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.9	0.4%	0.3%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	14.3%	6.1%	6.9%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to gg)$		5.7%	5.0%	4.3%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	4.2%	4.4%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	25%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to \gamma\gamma)$		–	15%	10%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to Z\gamma)$		–	42%	30%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to WW^*)$	g^4_{HWW}/Γ_H	–	1.0%	0.7%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times \mathrm{BR}(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	5.6%	3.9%*
Hee	$\sigma(Hee) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1.8%	2.3%*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times \mathrm{BR}(H \to b\bar{b})$	$g^2_{Ht\bar{t}}g^2_{Hbb}/\Gamma_H$	–	8.4%	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarisation	λ	–	24%	12%

Results without beam polarisation

*: extrapolated

Higgs coupling to mass

- Combine results of studied Higgs production and decay channels in global fit
  → extract couplings and Higgs width
- Fully model independent approach, unique for lepton colliders



- Based on results from full Geant4 detector simulations including backgrounds
- Global fit assumes 80 % electron beam polarisation at 1.4 TeV and 3 TeV
- **Publication** "Higgs Physics at the CLIC Electron-Positron Linear Collider" arXiv:1608.07538

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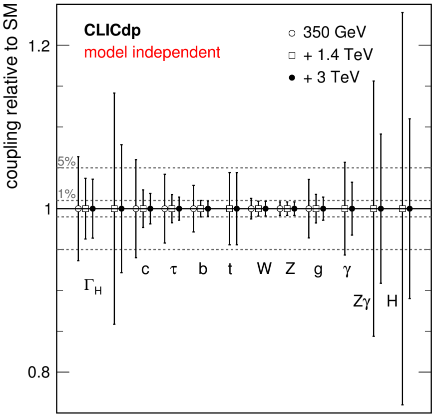

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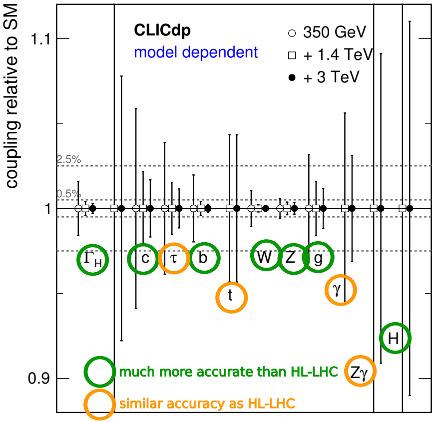

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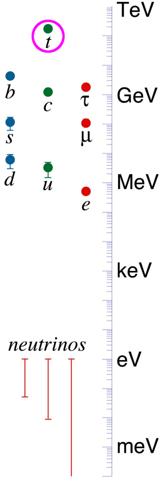
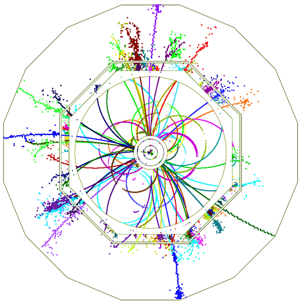
Top quark physics



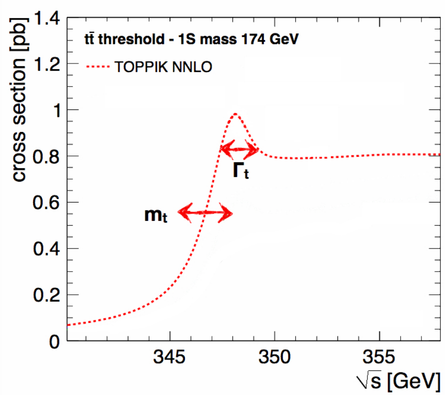
- Top quark is heaviest known elementary particle
- Largest coupling to Higgs → key to understanding of electroweak symmetry breaking
- The only quark that decays before hadronisation
- Contributes via loops to processes that can be studied with high precision
  → Sensitive to many BSM scenarios

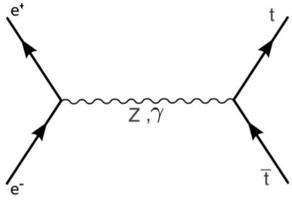
$e^+e^- \rightarrow t\bar{t} \rightarrow 6$ jets



Top threshold scan

- Top pair production cross section around threshold
  - Resonance-like structure corresponding to narrow $t\bar{t}$ bound state
  - Very sensitive to top properties and model parameters
  - Measurement not possible at hadron colliders





- Top quark mass m_t
- Top quark width Γ_t

Top threshold scan

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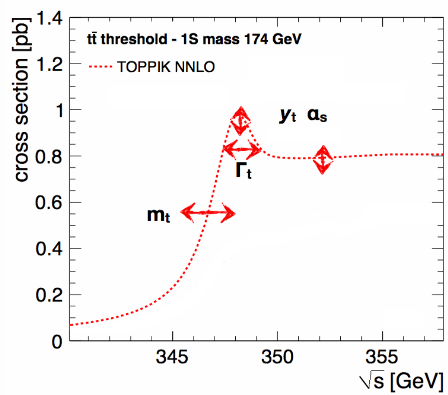
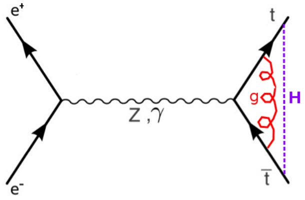
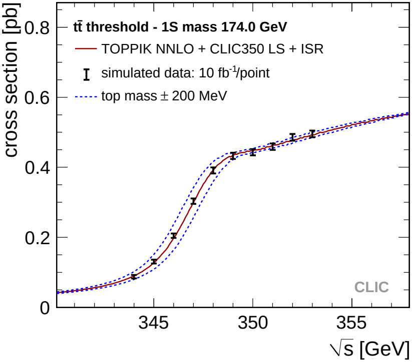


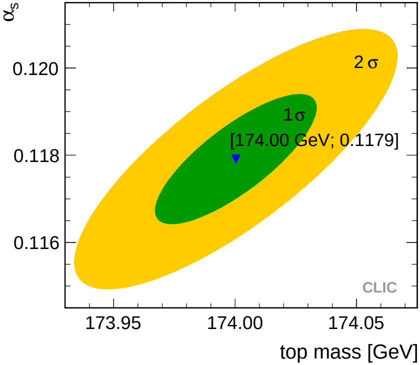


- Top quark mass m_t
- Top quark width Γ_t
- Strong coupling α_s
- Top Yukawa coupling Y_t

Top quark physics

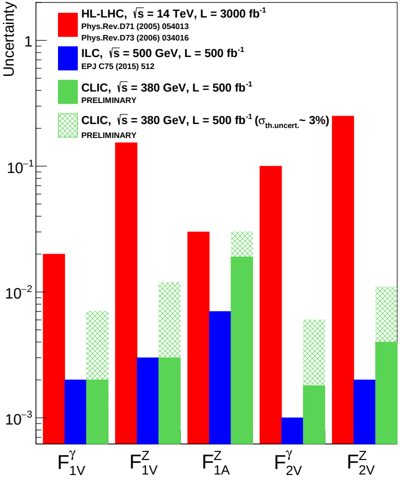
K. Seidel et al. Eur. Phys. J. C (2013) 73: 2530





- Precision top mass measurement possible already with 100 fb^{-1}
- Energy scan with 10 cross-section measurements of each 10 fb^{-1}
- Total uncertainty on the top mass of 50 MeV feasible
  → Significantly better than at HL-LHC

Top quark physics

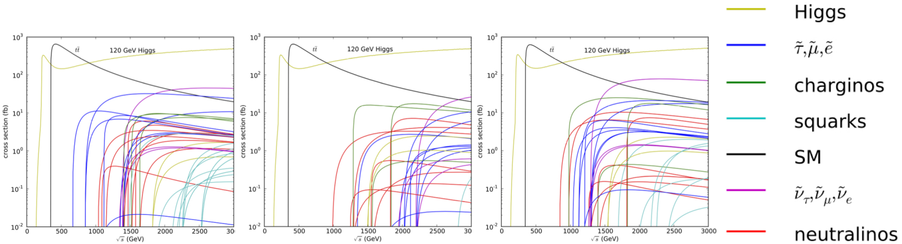


- Above threshold, top quark pairs are produced via Z boson or γ exchange
- Contributions of Z and γ depend on the beam and top-quark polarisation

- Use polarised e^- beams
- Measure forward-backward asymmetry of top quarks
- Extract top-quark coupling to γ and Z (form factors)

- Already inital stage of boh CLIC and ILC significantly better than HL-LHC reach

Searches for physics beyond the standard model (BSM)



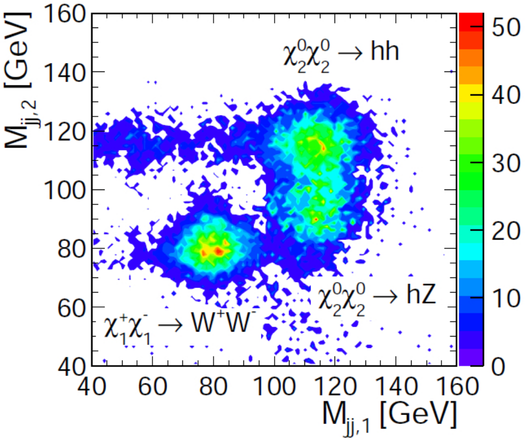
Model 1
- Squarks
- Heavy Higgs

Model 2
- Smuons, selectrons
- Gauginos

Model 3
- Smuons, selectrons
- Stau
- Gauginos

- Wide range of mass, spin and quantum numbers tested for CLIC
- Studied in full Geant4 detector simulations including beam induced backgrounds

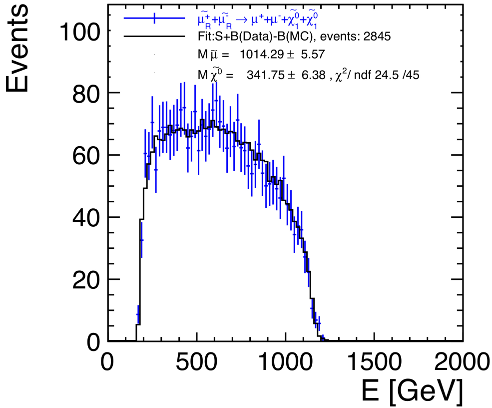
Example: Chargino and Neutralino pair production



- Reconstructed W, Z and h candidates in hadronic decays
- Four jets and missing energy
- Combine W, Z and h candidates from same events
- Peaks for individual chargino and neutralino decays are visible

- Statistical precision achievable at CLIC in the sub-percent and percent region in studied models

Example: Smuons



- Slepton production very clean at CLIC
- Slepton masses approximately 1 TeV
- Example: $e^+e^- \to \tilde{l}\bar{\tilde{l}} \to l^+l^-\tilde{\chi}^0\tilde{\chi}^0$
- Events with leptons and missing energy
- Extract slepton masses from endpoints of lepton energy spectra

- Statistical precision of few GeV achievable at CLIC

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

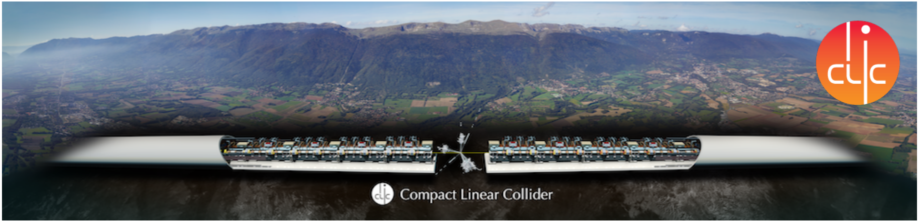
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

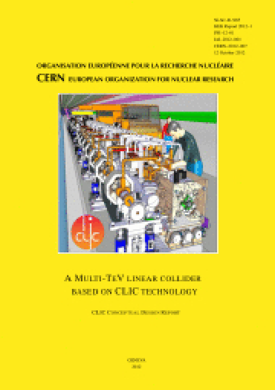
2035 First Beams

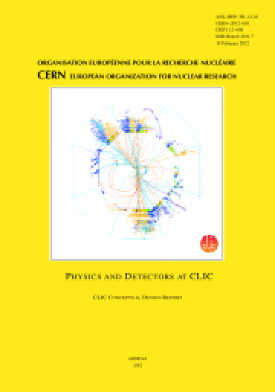
Getting ready for data taking by the time the LHC programme reaches completion

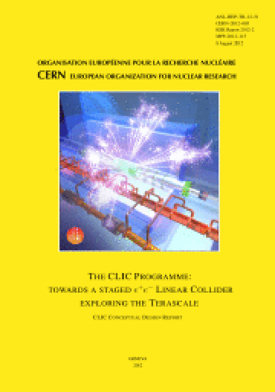


CLIC conceptual design report

- 3 volumes CLIC conceptual design report

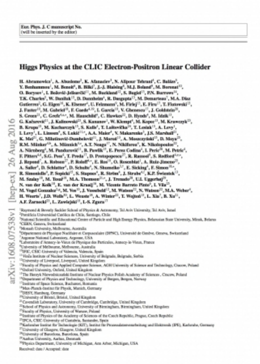






New CLIC publications

- Published mid-August 2016
  - Updated baseline for a staged Compact Linear Collider ▸ arXiv:1608.07537
  - CLIC Higgs paper ▸ arXiv:1608.07538



Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Higgs Physics at the CLIC Electron-Positron Linear Collider

arXiv:1608.07538v1 [hep-ex] 26 Aug 2016

Summary

- CLIC is a very interesting option for the post-HL-LHC phase
- Rich field of R&D on accelerator, detectors and physics
- Physics benchmark studies show excellent physics potential of CLIC including precision measurements and a large discovery potential

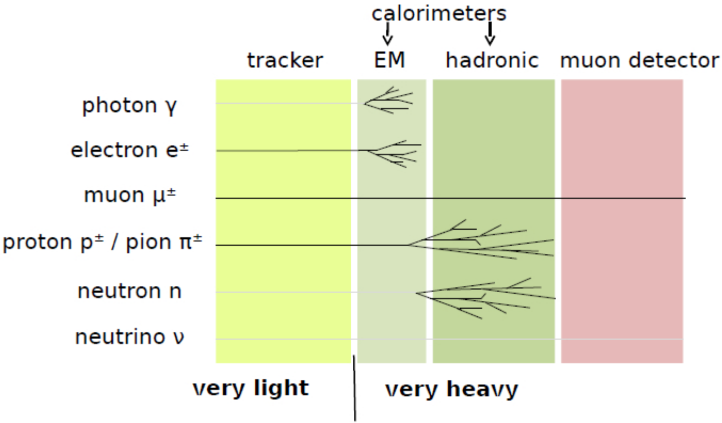
Participants of the CLIC workshop in January 2016

- Find more information on http://clicdp.web.cern.ch/ and http://clic-study.web.cern.ch/

Backup

Reminder: Particle detection (1)

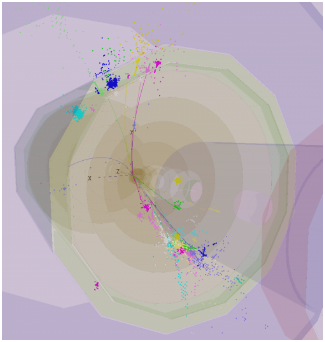
- Particles make small changes in the material they traverse
  - ionisation, atomic effects, nuclear effect ← all very small
- Particles differ in the way they interact with material
  - We can use it to identify particle types



Reminder: Particle detection (2)

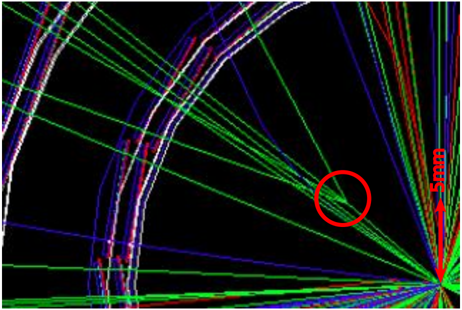
- Many of the elementary particles we know have very short life times
  - W, Z, Higgs and many more
- We only see the products of their decay

Quarks hadronise to jets



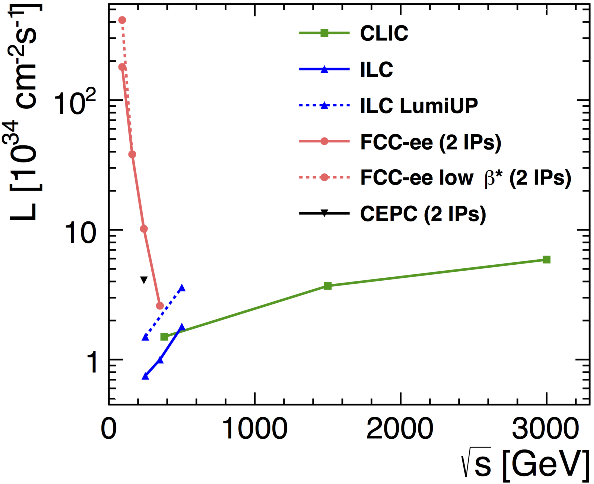
- Cannot observe quarks directly, as they hadronise into jets of particles

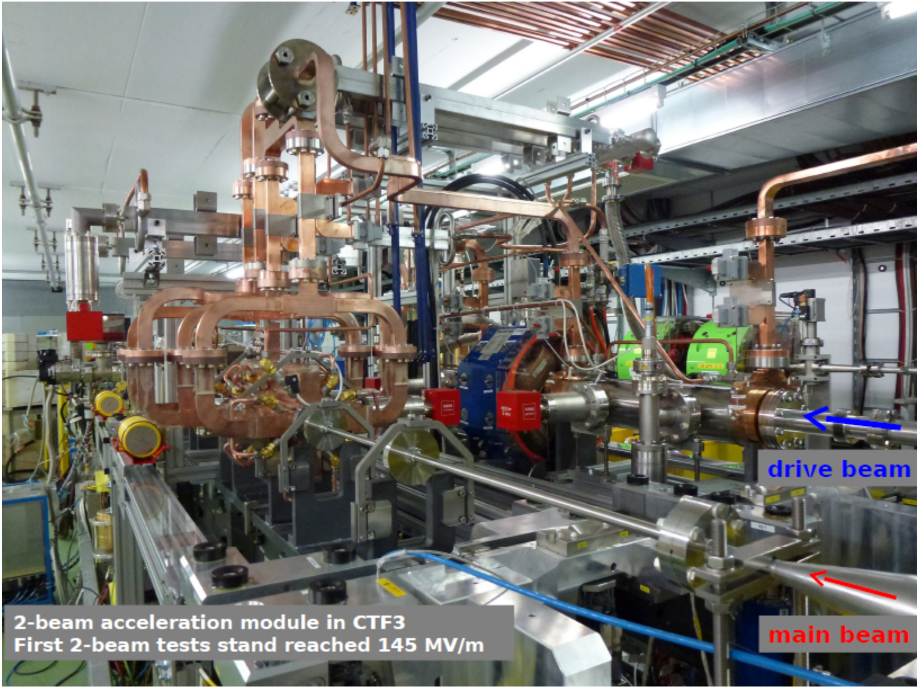
Secondary vertex at r=5 mm: b-quark



- Identify hadron containing b-quark via secondary vertex reconstruction

Future colliders

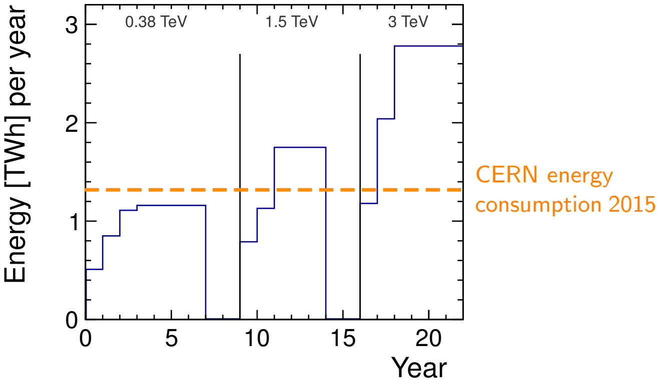



drive beam
main beam
2-beam acceleration module in CTF3
First 2-beam tests stand reached 145 MV/m

CLIC vs. ILC

Property	unit	ILC at 500 GeV	ILC at 1 TeV	CLIC at 380 GeV	CLIC at 3 TeV
L	$cm^{-2}s^{-1}$	$1.8 \cdot 10^{34}$	$3.5 \cdot 10^{34}$	$1.5 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$L_{0.01}$	$cm^{-2}s^{-1}$	$1.0 \cdot 10^{34}$	$1.2 \cdot 10^{34}$	$0.9 \cdot 10^{34}$	$2.0 \cdot 10^{34}$
$L_{0.01}/L$	%	58	59	60	34
Repetition rate	Hz	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	ns	727 µs	897 µs	178 ns	156 ns
BX / train		1312	2450	356	312
Bunch separation	ns	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	%	0.36	0.36	0.00089	0.00078
σ_x/σ_y	nm	474/5.9	481/2.8	∼150/3	∼40/1
σ_z	µm	300	250	70	44

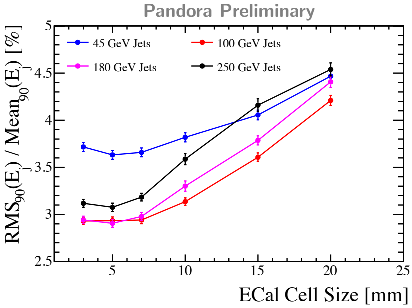
Yearly energy consumption

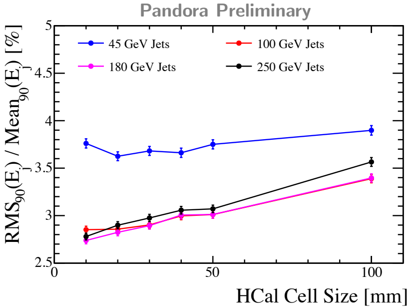


- Including reduced operation in the first years at each energy
- At 380 GeV, a single positron target is used for the first three years (-10 MW with respect to nominal)

(Note → 380 GeV numbers scaled from CDR design at 500 GeV
→ To be repeated with detailed tech. description of 380 GeV CLIC)

Reconstruction information for cell size optimisation





- HCal timing cuts: 100 ns
- ECal timing cuts: 100 ns
- HCal Hadronic Cell Truncation: Optimised for each detector model
- Software: ilcsoft_v01-17-07, including PandoraPFA v02-00-00
- Digitiser: ILDCaloDigi, realistic ECal and HCal digitisation options enabled
- Calibration: PandoraAnalysis toolkit v01-00-00

More details in LCWS2015 talk by S. Green