Introduction to CLIC

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Overview

Introduction:

1. Introduction

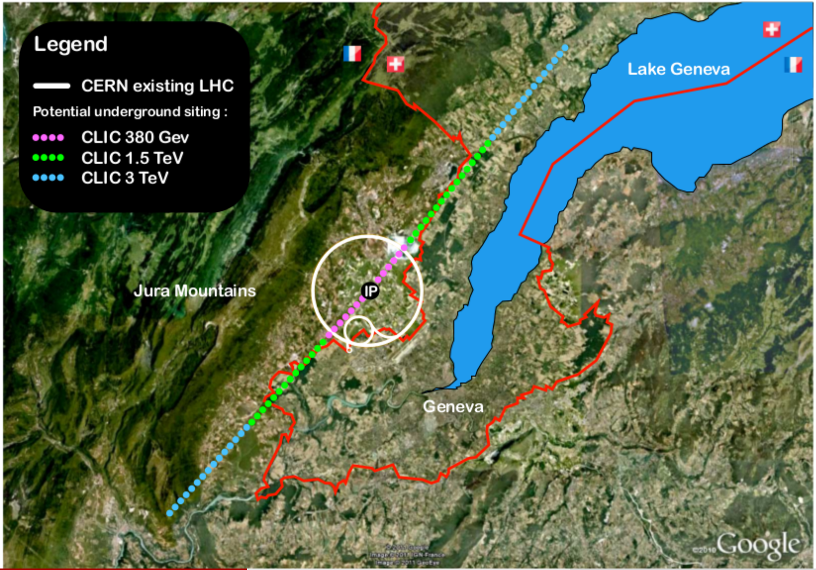
CLIC Project Motivation

- Physics motivation:
  - Precise measurements of Higgs boson and top quark properties
  - Beyond Standard Model searches: supersymmetry (SUSY), dark matter, extra dimensions, technicolor, etc.
- CLIC study researches the feasibility of parameters needed to achieve physics goals:
  - Implementing two-beam acceleration scheme in order to reach beyond state-of-art accelerating gradient
  - Obtaining nanometer-scale beam sizes at interaction point with low emittances
  - High resolution tracking detectors and high granularity calorimeters

Compact Linear Collider Project Overview

- CLIC study is an international collaboration with more than 70 institutes from more than 30 countries
- A linear collider at the multi-TeV scale, offers a compelling physics program of discoveries and precision measurements, complementing the LHC
- Energy staging at: 380 GeV, 1.5 TeV and 3 TeV allows for precise physics study of Higgs boson, top quark properties and insight into New Physics phenomena
- CLIC two-beam acceleration scheme allows one to achieve never seen before accelerating gradients in room temperature cavities and in an energy efficient way

CLIC layout


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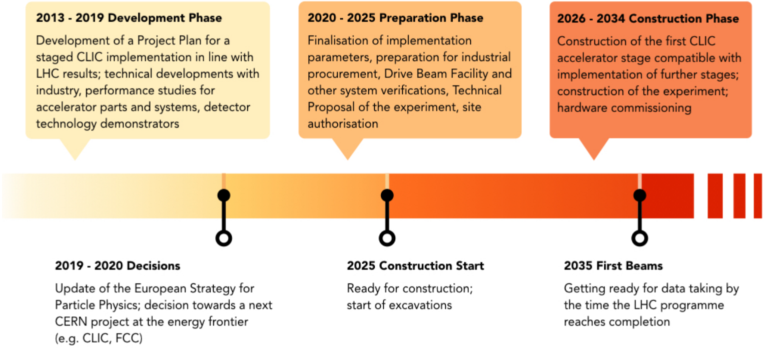
CLIC timeline



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

Linear Accelerator choice

Linear accelerator-design has been chosen due to its advantages over a circular solution:

- Linear machine doesn't face high energy losses due to synchrotron radiation, where $P \propto \frac{E^4}{m^4 r^2}$
- No upper limit for achievable collision energy
- Better luminosity performance at higher energies

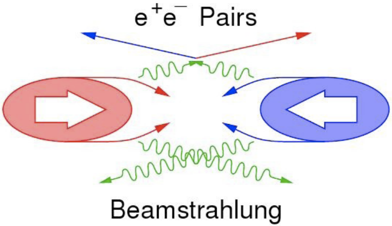
Linear concept disadvantages:

- Lower repetition rate than a circular machine, around 50 Hz instead of several kHz
- Need for higher accelerating gradients ($\sim$ 100 MV/m instead of $\sim$ 10 MV/m) and nanometer scale sizes at interaction point as a beam can be used only once

CLIC Parameter Overview

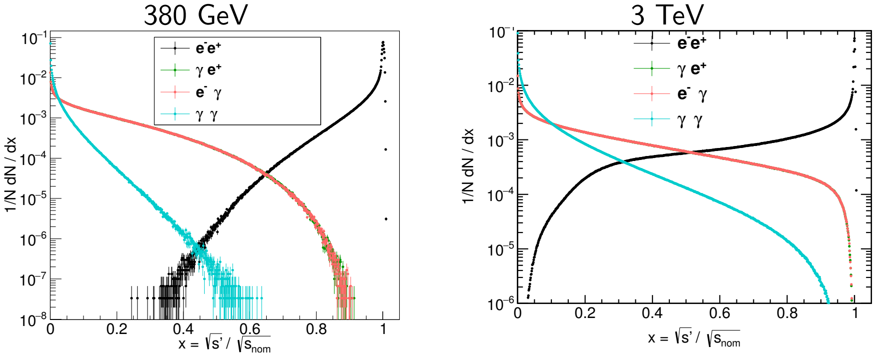
parameter (unit)	**Stage 1**	**Stage 2**	**Stage 3**
Collision energy $\sqrt{s}$ (GeV)	380	1500	3000
Repetition frequency (Hz)	50	50	50
Number of bunches per train	352	312	312
Bunch separation (ns)	0.5	0.5	0.5
Accelerating gradient (MV/m)	72	72/100	72/100
Total luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	1.5	3.7	5.9
Luminosity above 99% $\sqrt{s}$	0.9	1.4	2.0
Main tunnel length (km)	11.4	29.0	50.1
Number of particles per bunch (10^9)	5.2	3.7	3.7
Bunch length σ_z (μm)	70	44	44
IP beam size $\sigma_x/\sigma y$ (nm)	149/2.9	60/1.5	40/1
Estimated power consumption (MW)	252	364	589

Background creation



- Synchrotron radiation is created in strong focusing magnets of the Final Focus System
- Beamstrahlung is a type of synchrotron radiation caused by charged particles' interactions with the electromagnetic field of the incoming beam, it is strongly linked with the beam pinching effect
- It is the main cause of the lower energy tail in $e^- e^+$ luminosity spectrum
- Beamstrahlung interactions with e^-, e^+ or other photons lead to production of unwanted particles: coherent and incoherent pairs, trident cascades and hadrons

Luminosity spectra at 380 GeV & 3 TeV



- Beamstrahlung photon emission gives a rise to the low energy tails of e^-e^+ luminosity spectra
- Unwanted collisions have total luminosity of the same order as e^-e^+

Beam parameter choice

Geometrically luminosity can be aproximated by following expression:

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}, \tag{1}$$

where: $\mathcal{L}$ - luminosity, N - number of particles, σ_x, σ_y - horizontal/vertical beam size

While the number of produced beamstrahlung photons is proportional to:

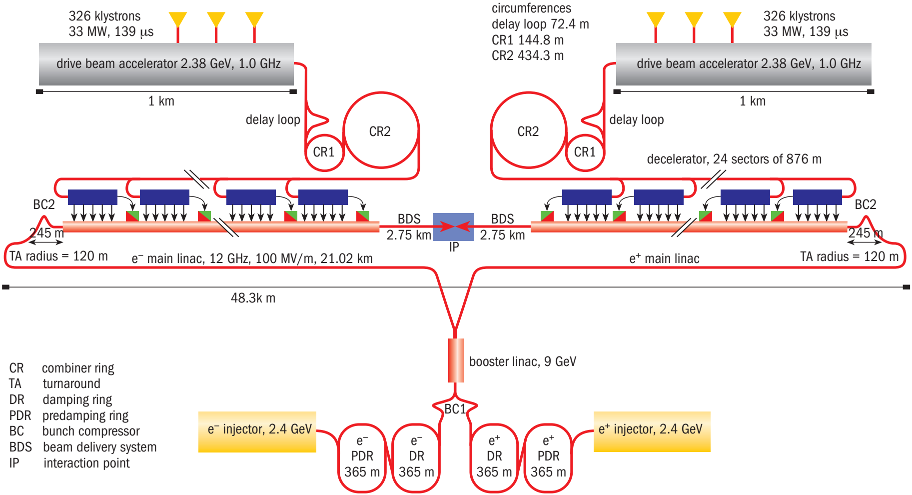
$$n_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \tag{2}$$

- Having σ_x or σ_y much bigger than the other allows us to minimize the beamstrahlung while leaving luminosity at the desired level
- Thus the choice for CLIC horizontal-to-vertical ratio of 50:1 at 380 GeV and 40:1 at 3 TeV

CLIC Accelerator:

2. CLIC Accelerator
    - Accelerator Overview
    - Accelerating Gradient Challenge
    - Generation and Preservation of Ultra-low Emittances
    - CLIC Test Facility 3

CLIC complex layout

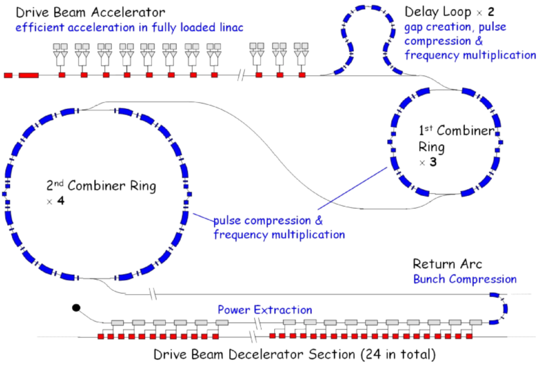


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point

High Accelerating Gradient Challenge

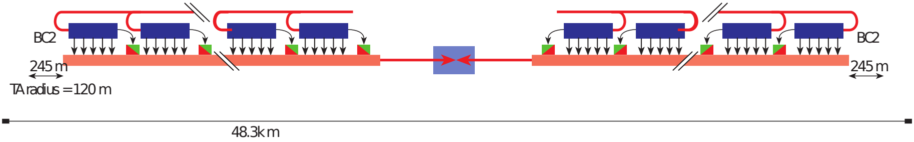
- State of the art superconducting cavities can provide 35 MV/m but require costly cryogenics installation
- Widely used accelerator power sources - klystrons - cannot efficiently provide pulses at required frequency (12 GHz), pulse duration (152 ns)
- Required 9.2 TW peak RF power, 244 ns pulse length repeated at 50 Hz would need 35 000 klystrons to provide enough power - unfeasible and cost ineffective
- Klystrons can be used to give power to classical low frequency cavities and accelerate a so-called drive beam
- This beam with low energy (2.4 GeV) and high current (100 A) is used as a power source for high frequency RF cavities
- Drive beam is thus decelerated in special Power Extraction and Transfer Structures (PETS) to only 10% of its initial energy

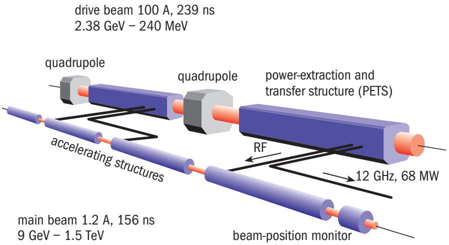
Drive Beam Recombination Complex



- Using a delay loop and phase coding, the beam intensity doubles
- Over three revolutions in Combiner Ring 1, the beam intensity increases 3 times
- Four trains from CR1 are combined in CR2 giving a total of 24-fold compression
- Feasibility proven at CTF3

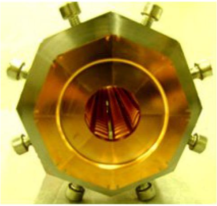
Two-beam Acceleration

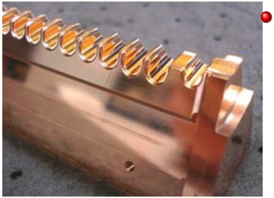




- The Drive beam is transported in parallel to the Main Beam and then reversed at its sector starting at low energy end
- Beam is decelerated in PETS with maximal extraction efficiency of 90% and energy is transported to the Main Beam accelerating cavities
- One drive beam train powers a sector around 900 m long

The Power Extraction and Transfer Structures (PETS)





- Is a passive microwave device. The Drive Beam interacts with the constant impedance of the periodically loaded waveguide and excites the synchronous mode

- The RF power is collected downstream using the RF power extractor, a waveguide network is connecting PETS to the accelerating structures
- Converts the TM_{01} mode in 23 mm diameter circular waveguide into a TE_{10} mode in a rectangular waveguide with a calculated efficiency of 99.4%
- Maximum power extraction efficiency from a beam is driven by adiabatic undamping: decelerated beam's envelope increases by a factor of $\sqrt{1/(1-\eta_{\mathrm{extr}})} \sim 3$

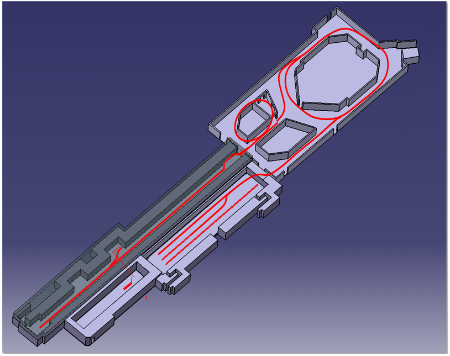
Generation of Ultra-low Emittances

- Cathode particle source provides beams with emittances several orders of magnitude greater than needed, especially in the case of positrons
- Synchrotron radiation damping when circulating in rings is the solution
- 52 2.5 T superconducting wigglers are used in Damping Rings to achieve ultra-low horizontal emittance

Preservation of Ultra-low Emittances

- Preservation of ultra-low emittances consists of designing beam transport systems and aims to mitigate static and dynamic imperfections
- The main source of dynamic imperfections comes from ground motion, which is mitigated by active stabilisation of the magnets, and fluctuations of the Drive Beam intensity and phase
- The most important static imperfections are the misalignments of the beam position monitors and the accelerating structures
- BPMs are mounted on girders equipped with movers with have 10 μ m step precision
- After a pre-alignment with RMS precision of 0.1 mm a beam-based procedure is foreseen for Main Linac and Beam Delivery System, where the magnet positions can be modified to achieve the target luminosity

CLIC Test Facility 3

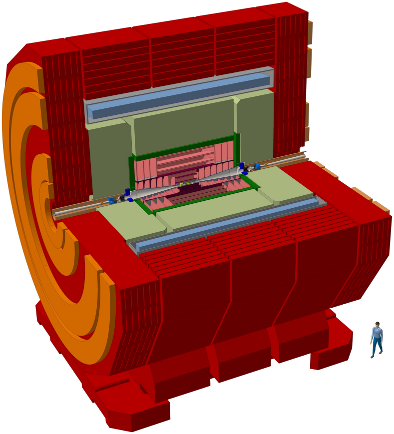


- Main goal was to prove feasibility issues of the two beam acceleration scheme:
  - Drive Beam Generation – high-current electron beam with the time structure needed to generate 12 GHz RF power
  - RF power production and two-beam issues – efficient production and transfer of power to 100 MV/m accelerating structures
  - Decelerated beam stability

Detector:

3. Detector
   - CLICdet Overview
   - Tracking & Calorimetry
   - Background Studies

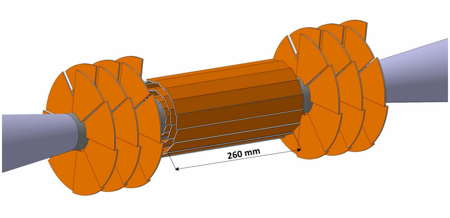
CLICdet Overview



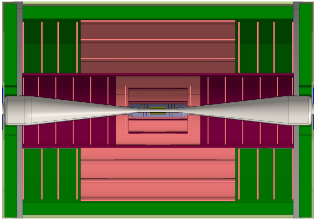
- Ultra light Tracker and Vertex
- Forward EM calorimeters (LumiCal & BeamCal)
- Fine grain calorimeters: HCAL and ECAL for particle flow reconstruction
- 4 T solenoid ($R_{\text{in}} = 3.4$ m)
- Return yoke and muon chambers
- Power pulsed operation with full readout of 156 ns bunch train

Tracking detectors overview

vertex detector



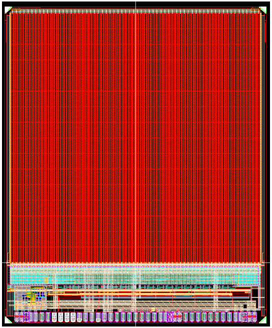
tracker



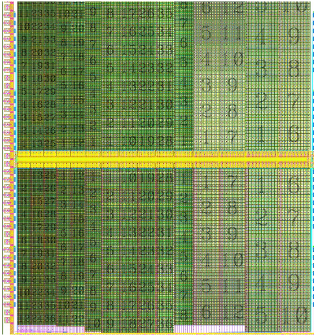
- Both tracking detectors have low material budget: 0.2% X_0 per vertex layer and 1.0% X_0 per tracker layer
- Elongated pixels/short strips (30 μm x 1 mm) in tracker are used to achieve single point resolution of 7 μm and prevent too high occupancies from beam-beam backgrounds
- Vertex detector with spatial resolution of 3 μm, needed for finding secondary vertices
- Fast timing detectors: $\sim$10 ns

Sensors Overview

CLICpix2

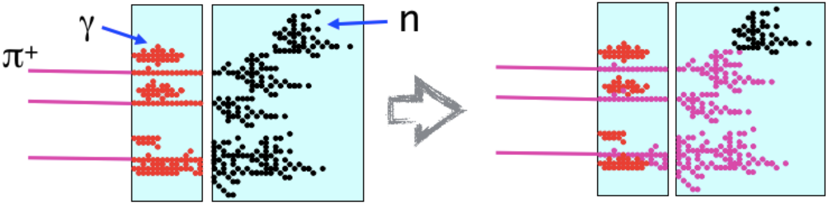


ALICE investigator



- CLICpix2 is a second generation sensor built in CMOS technology, with a matrix of 128x128 pixels; multiple columns readout possible
- Complete design ready and full simulations ongoing
- Integrated high-resistivity CMOS will be the most probable choice for CLIC Tracker Detector

Calorimeters Overview - Particle Flow approach

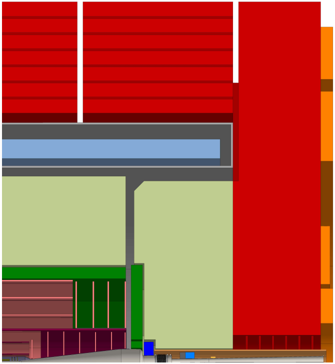


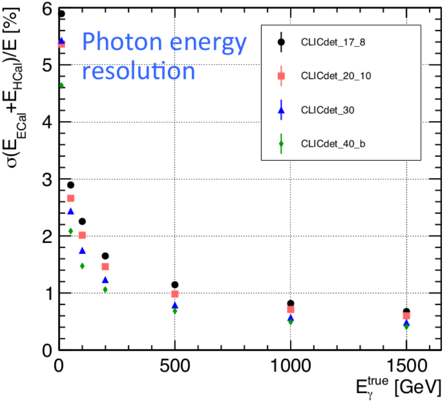
$$E_{JET} = E_{ECAL} + E_{HCAL}$$

$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

- Typical jet composition: 60% charged particles (tracker detector), 30% photons (ECAL) and 10% neutrons (HCAL)
- New approach to jet reconstruction: particle flow calorimetry
- Requires high granularity calorimeters to resolve deposits from different particles and sophisticated software to make correct associations

Calorimeters Overview - Electromagnetic ECAL

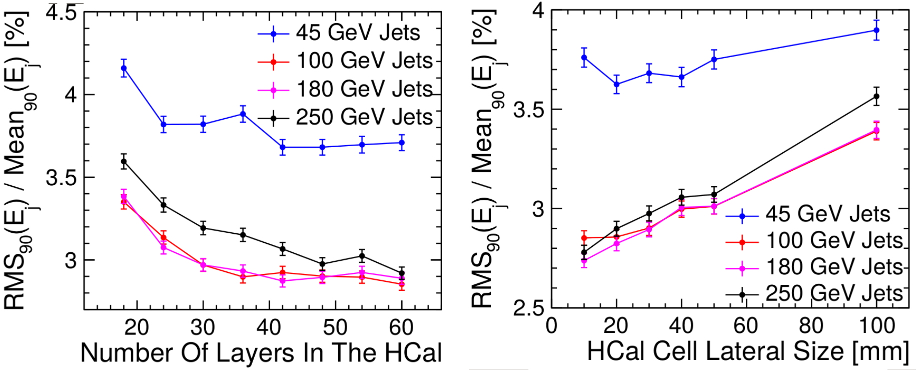




- 40 layers of SiW, a total of 20 X_0 (1 λ_1)
- Good photon energy resolution O(10-1000 GeV), similar to ATLAS:

$$\frac{\sigma_E}{E} \sim 4 - 0.4\% \tag{3}$$

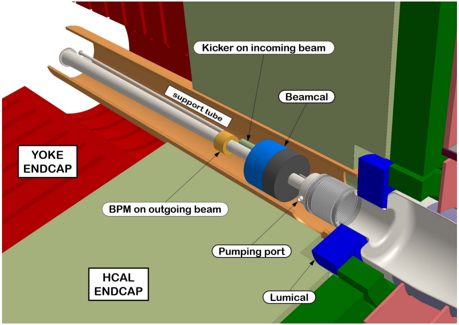
Calorimeters Overview - Hadronic HCAL



- 60 layers of steel scintillator, a total of 7.5 λ_1
- Acceptance down to $\theta \sim 5^{o}$, $\eta \sim 3.1$
- Excellent jet energy resolution:

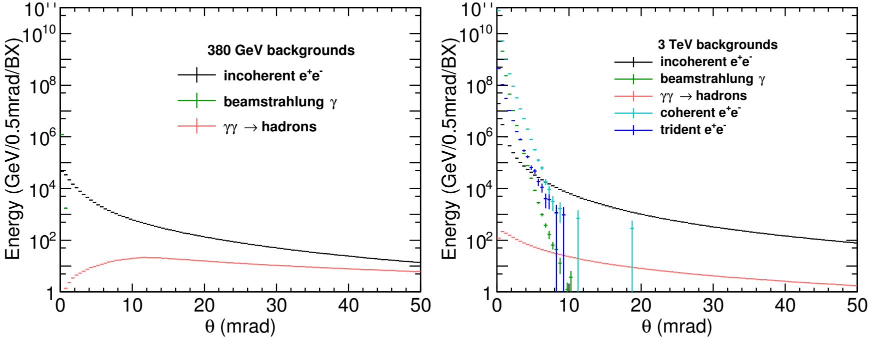
$$\frac{\sigma_E}{E} \sim 5 - 3.5\% \tag{4}$$

Calorimeters overview - forward detectors



- LumiCal for luminosity measurement (0.1% precision)
- BeamCal for very forward tagging of high energy electromagnetic particles, though
  - No track information
  - No e/γ idenfication
  - Centered at outgoing beamline (high occupancies from beam-beam backgrounds)

Backgrounds' angular energy distributions at 380 GeV & 3 TeV

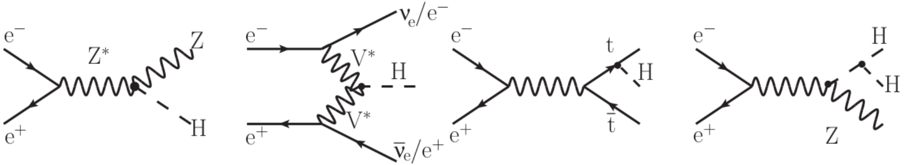


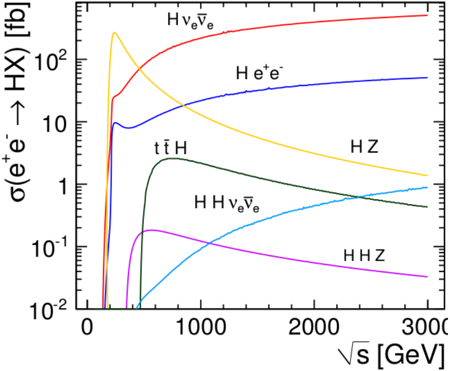
- Incoherent pairs and hadrons are the only significant source of direct background at both energy stages
- Coherent pairs may cause limited energy depositions in the forward detector region in the 3 TeV design

Physics Programme:

4. Physics Programme
   - Higgs Boson and $\mathrm{t\bar{t}}$ Measurements
   - Beyond the Standard Model

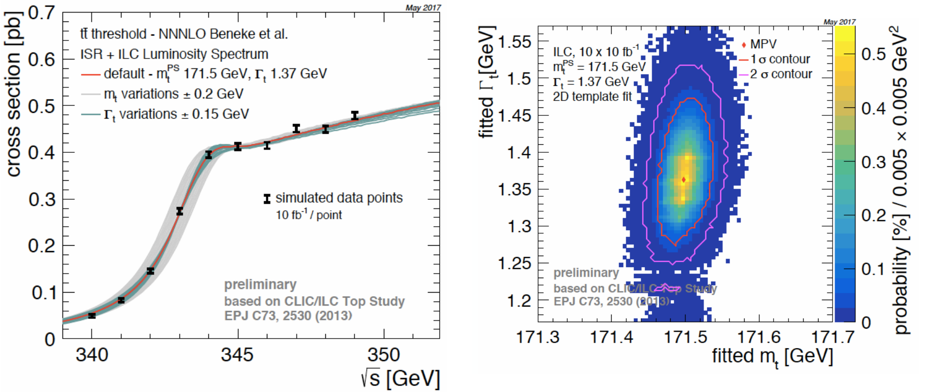
Higgs boson measurements





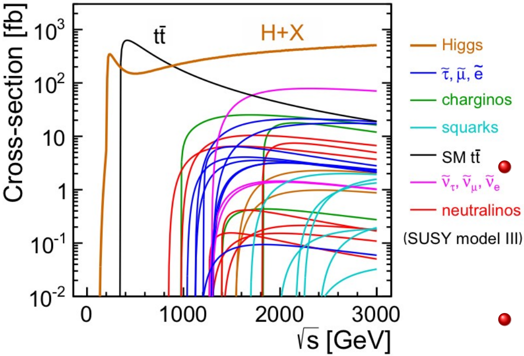
- High precision measurement of Higgs properties:
  - Couplings with sub-1% level (a 1% level for rare decays)
  - Higgs width: 3.4%
- Model independent couplings determination:
  - Mass recoil method in: $e^+e^- \to Z(ee/\mu\mu/qq)H$ events

$t\bar{t}$ Measurements



- Top mass can be measured in theoretically well defined mass schemes in a threshold scan (∼350 GeV), possible precision: ∼ 50 MeV
- Top quark as a tool for BSM physics, sensitive couplings
- Precision measurement of the top EW couplings ($E > 350$ GeV)

Beyond the Standard Model Searches



- At $\sqrt{s} = 3$ TeV energy stage direct searches are possible for supersymmetric partners, dark matter particles, etc. with masses $m \leq \sqrt{s}/2$
- Indirect discovery potential up to particle masses of 60 TeV (composite Higgs, μ contact scale)
- In case of any discovery made in (HL-)LHC precise measurements possible at CLIC

Summary and Outlook:

5 Summary and Outlook

Summary and Outlook

- CLIC is a mature international project with most of its feasibility issues addressed up to this date
- Allows for precise Higgs boson and $t\bar{t}$ measurements, beyond the reach of HL-LHC
- Thanks to its precision it will make possible the searches for New Physics phenomena at 3 TeV energy stage

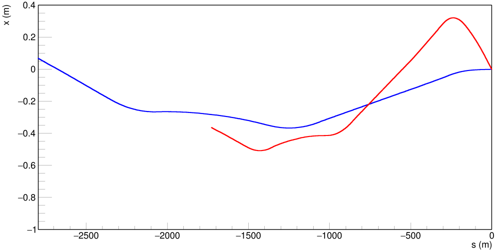
Future of the project:

- A decision whether CLIC study will continue and be build is expected to be made in 2019-2020 update to European Strategy for Particle Physics
- Intense preparation for an updated documentation until then

Thank you!

Backup

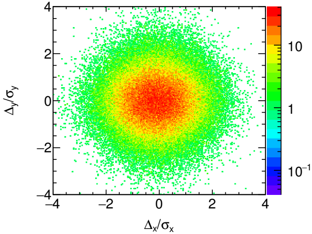
Beam delivery system design



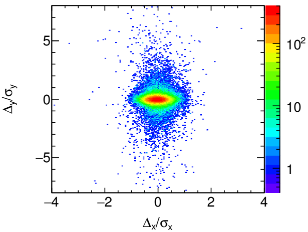
- How much of the beamline is needed for a reliable study of synchrotron radiation impact on the detector or the IP? Prelimary assumption: simulate the straight part from the last sbend on.
- 380 GeV, $L^* = 4.3$ m design: 15.65 m, containing: QD0, OCTD0, SD0, DEC0, QF1, OCT1 and SF1
- 3 TeV, $L^* = 3.5$ m design: 14.21 m, containing: QD0, DD0, SD0, QF1, OCTF1 and SF1

Beam distributions at IP

380 GeV

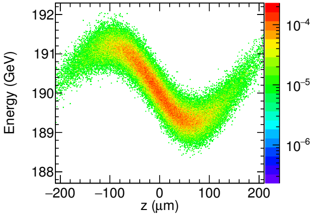


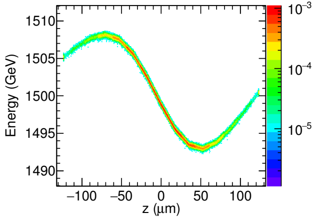
3 TeV



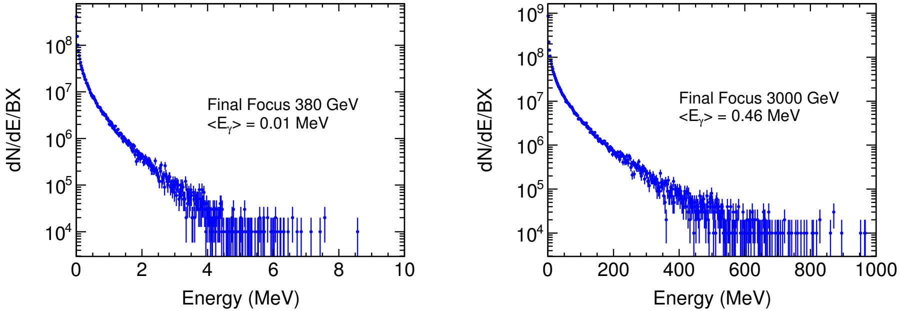
design	σ_x (nm)	σ_y (nm)
baseline 380 GeV	149	2.90
PLACET 380 GeV (core)	148.7	3.03

design	σ_x (nm)	σ_y (nm)
baseline 3 TeV	40	1
PLACET 3 TeV (core)	45.3	1.2



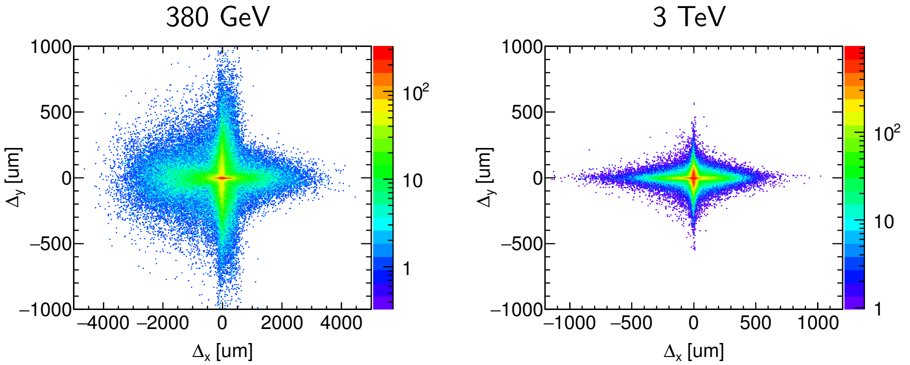


Synchrotron radiation energy spectra



- At 380 GeV there are 23.5 SR photons per particle produced along the entire Beam Delivery System, with 22.6 coming from sbends and 0.8 from quadrupoles
- At 3 TeV there are 59.1 photons per particle, with 57.1 from sbends and 2.0 from quadrupoles

Synchrotron radiation distributions in IP region



- Only photons coming from the Final Focus System have been included and extrapolated to the IP region
- The observed distributions resemble the beam sizes ratios between the two energy stages (380 GeV to 3 TeV ratio of $\tilde{4}$:1 horizontally and $\tilde{2}$:1 vertically)
- There are no energy depositions in the detector coming from SR