Detector and Physics Status

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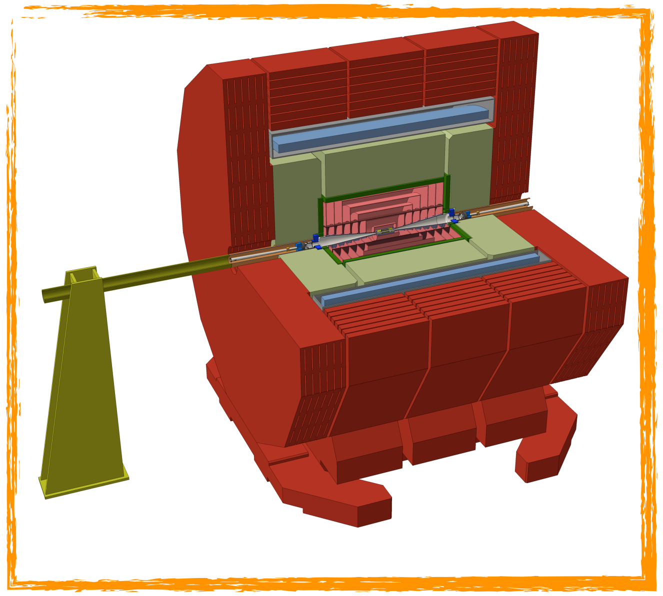
N. van der Kolk
on behalf of the CLICdp Collaboration

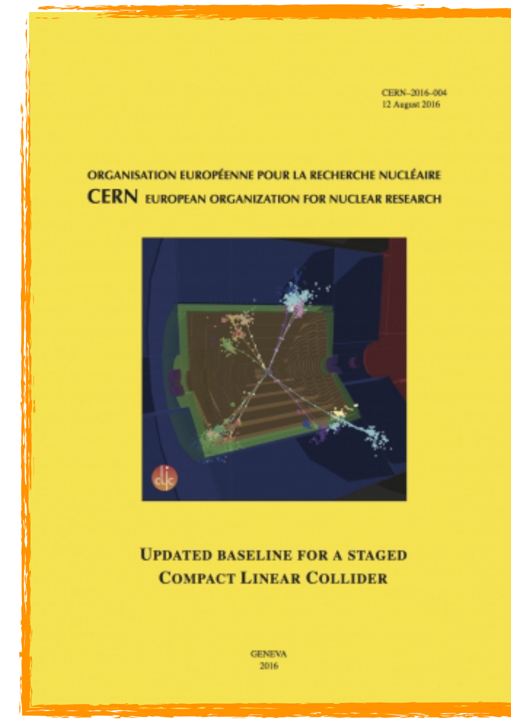
International Workshop on Future Linear Colliders
LCWS2016
5-9 DECEMBER, 2016
Aiina Center & MALIOS,
MORIOKA CITY, IWATE, JAPAN
TOHOKU UNIVERSITY

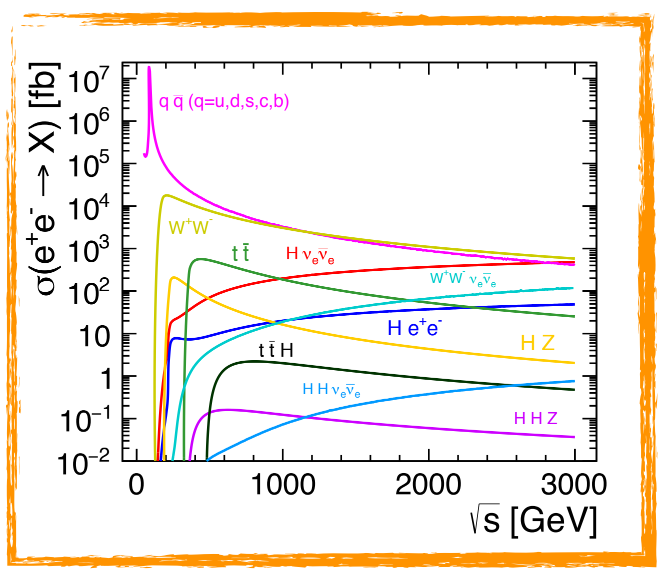
Outline



- CLICdp introduction

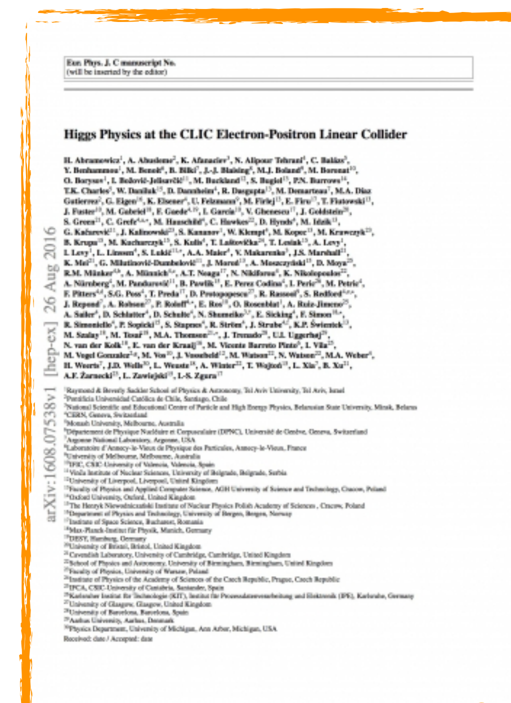
- Updated baseline staging scenario
arXiv:1608.07537


CERN-2016-004
12 August 2016
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER
GENEVA
2016



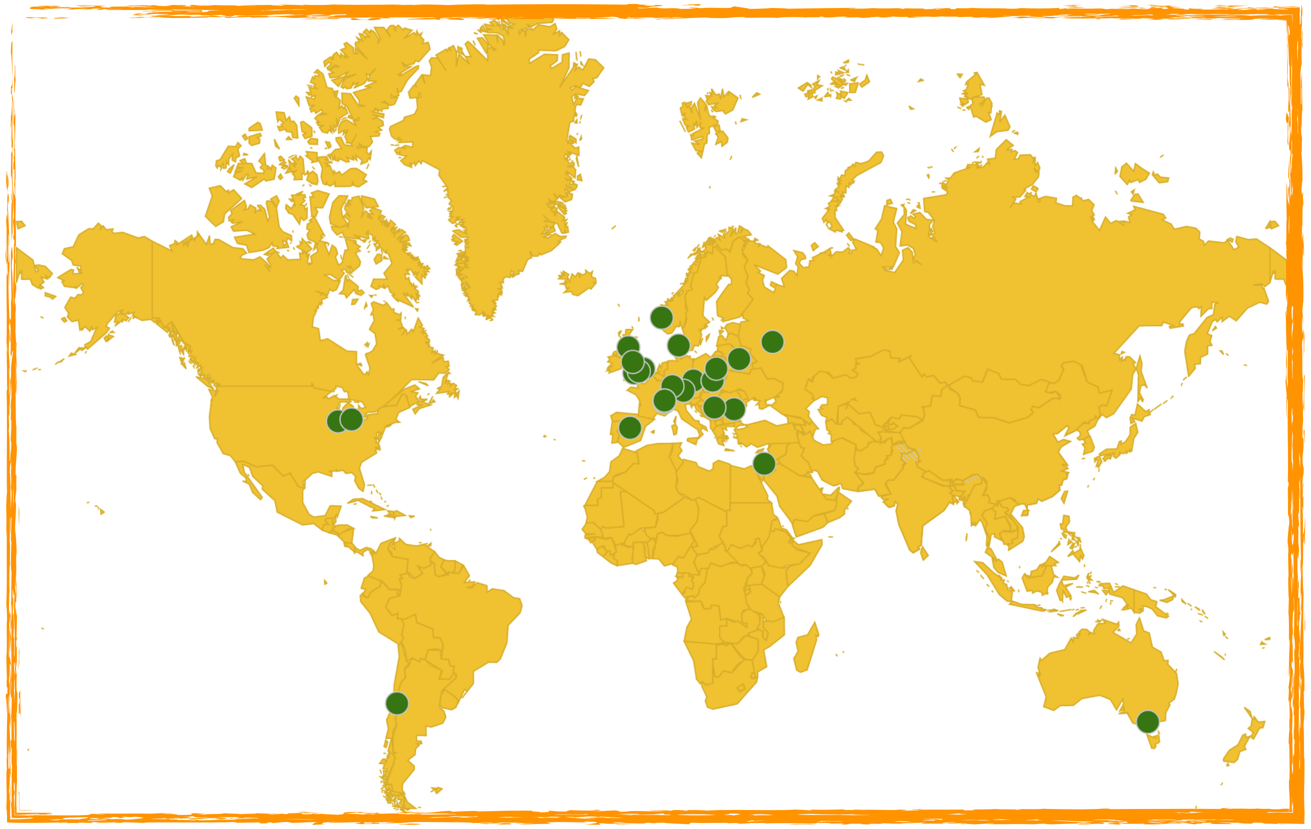
- New CLIC detector CLICdet

- Higgs physics overview
arXiv:1608.07538


Higgs Physics at the CLIC Electron-Positron Linear Collider

CLICdp Collaboration

- CLICdp: CLIC Physics and Detector Study
  - 28 institutes from 17 countries
  - Physics prospects and simulation studies
  - Detector optimisation and R&D for CLIC detector

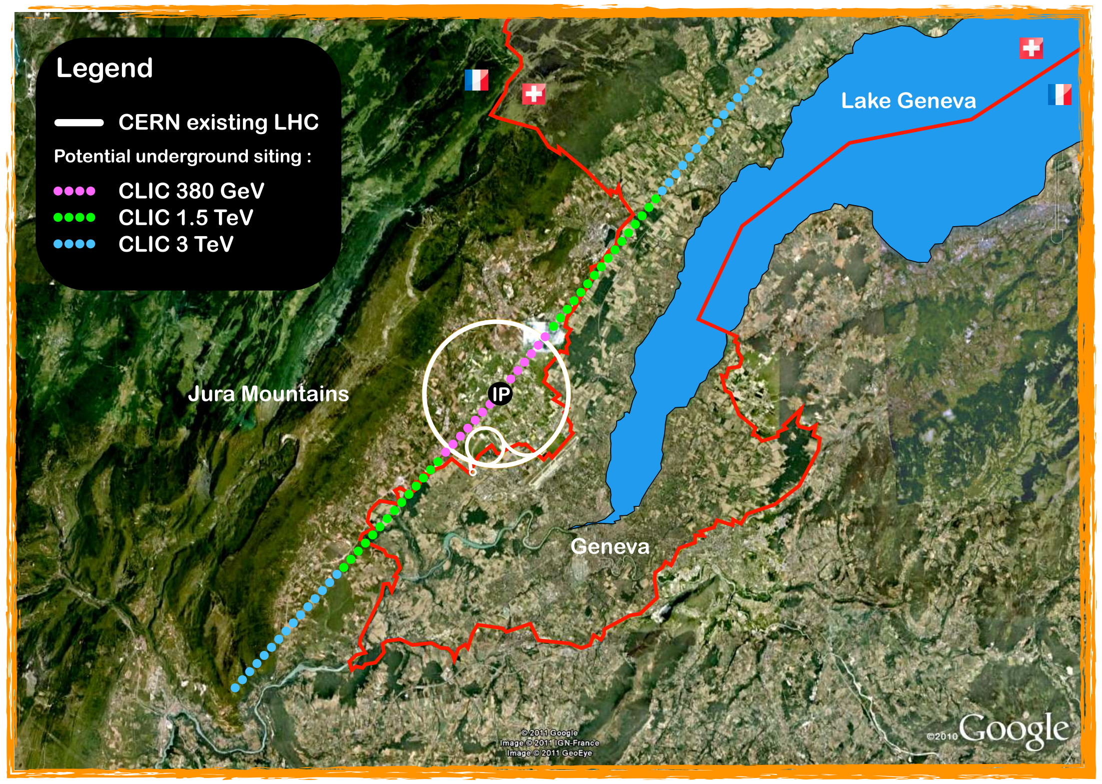


http://clicdp.web.cern.ch

Updated baseline staging scenario

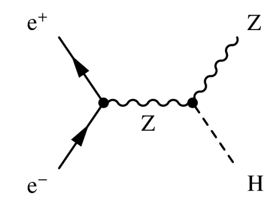
- CLIC CDR published in 2012
  - Higgs mass not fully taken into account in choice of staging scenario
  - Accelerator optimised for 3 TeV, with two low energy stages at 500 GeV and 1.4/1.5 TeV (not fully optimised)
- **Rebaselining:**
  Comprehensive studies of performance, cost and power optimisation and further Higgs and top-quark physics studies lead to updated staging scenario

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

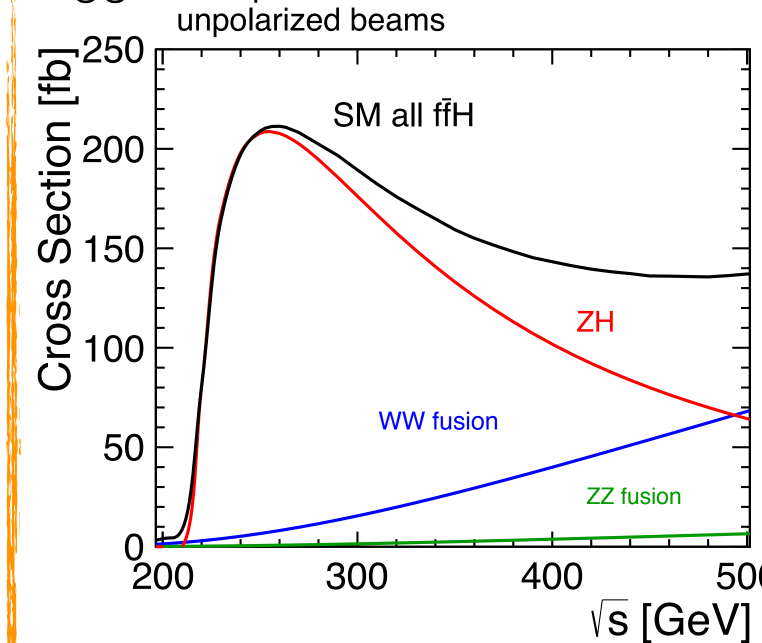


380 GeV

- **Higgs Physics**
  - Dominant Higgsstrahlung process provides model independent measurement of the coupling gHZZ to a precision of 0.8%
  - Together with WW fusion process gives access to total decay width and the coupling gHWW
  - Higgs mass to a precision of ~100 MeV
  - Best precision on cross-section around 350 GeV, precision of all Higgs couplings is limited by this uncertainty

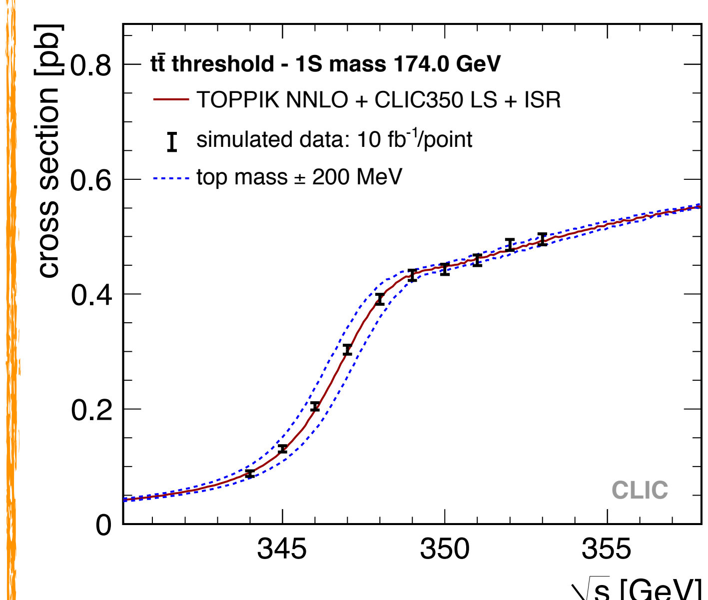


Higgs SM production cross-sections

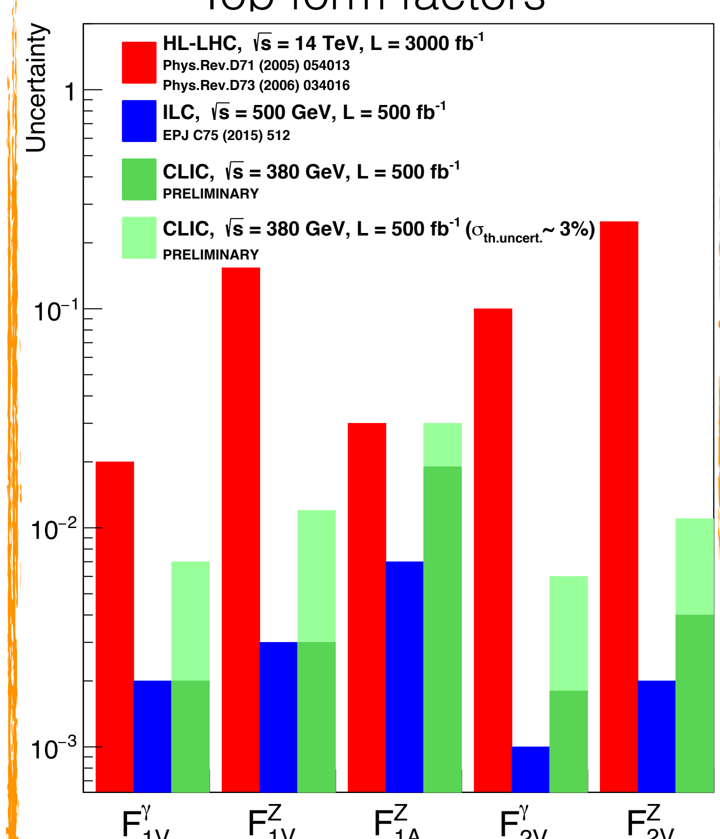


- **Top Physics**
  - Top mass to a precision of ~50 MeV from threshold scan around 350 GeV
  - Precision at the percent level on top form factors, above production threshold the boost helps accurate reconstruction
  - BSM in top sector best near the maximum cross-section at 420 GeV
- **380 GeV favourable for both Higgs and Top physics studies, supplemented with a top threshold scan around 350 GeV**
- **Accelerator**
  - Length: 11.4 km
  - Accelerating gradient: 72 MV/m
  - 1 drive beam complex

Top pair production cross section (threshold scan)

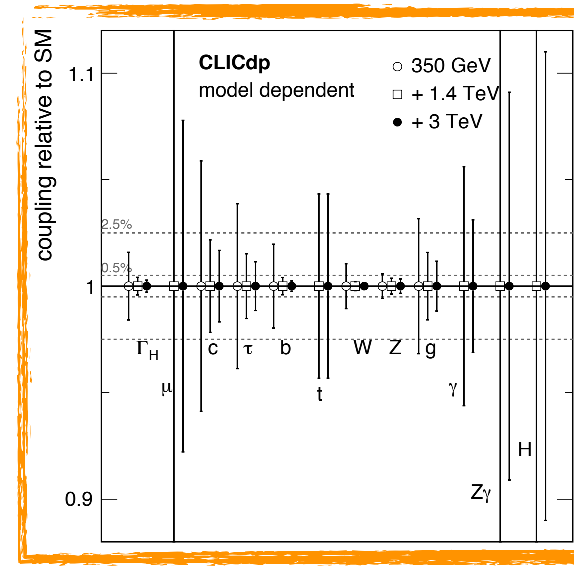


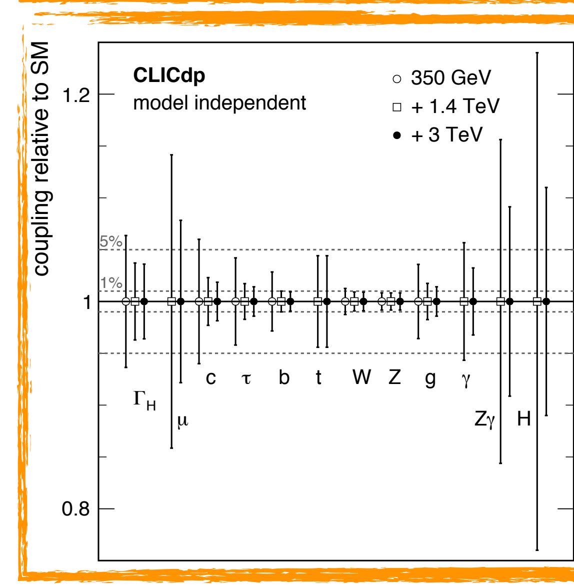
Top form factors



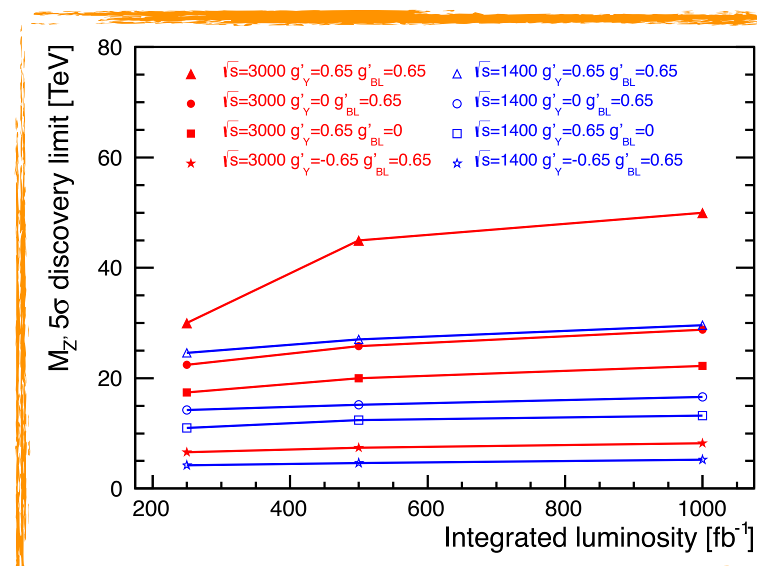
1.5 and 3 TeV

- **Higgs Physics**
  - WW-fusion and ZZ-fusion processes dominant
  - ~1% precision on the Higgs couplings to fermions and bosons
  - Higgs mass to ~32 MeV through H —> bb, ~24 MeV with polarisation (1.5 + 3 TeV)
  - Top yukawa coupling through Higgs e^+e^- —>ttH 4-5% statistical accuracy (with 80% electron polarisation)
  - Higgs self coupling through e^+e^- —>HHνν gives access to the coupling λ to 10% precision (1.5 + 3 TeV)
- **BSM physics**
  - Direct searches: e.g. SUSY particle masses with 1% accuracy up to approximately half the centre of mass energy
  - Indirect searches: deviations from SM predictions in Higgs and Top properties, or search for Z’ via e^+e^- —>μμ
  - Top sector: less statistical accuracy but improved reconstruction through boost and increased relative BSM contributions
- **Accelerator**
  - 3 TeV maximum envisioned energy
  - 1.5 TeV maximum energy for 1 drive beam complex
  - Length: 29.0 / 50.1 km
  - Accelerating gradient: 72 and 100 MV/m





Higgs couplings to fermions and bosons



Baseline Staging Scenario

- Full programme will span 22 years
  - 5 to 7 years at each energy stage
  - 2 year upgrade periods between stages
  - Luminosity ramp up for each energy stage
- Assume CLIC will operate for the equivalent of 125 days ($1.08\ 10^{7}$ s) per year at 100% efficiency

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
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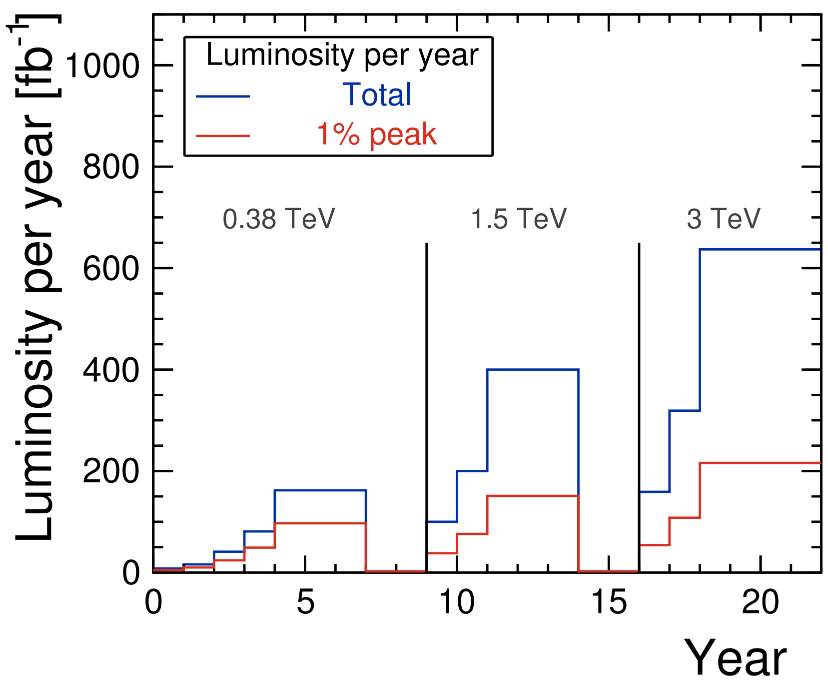
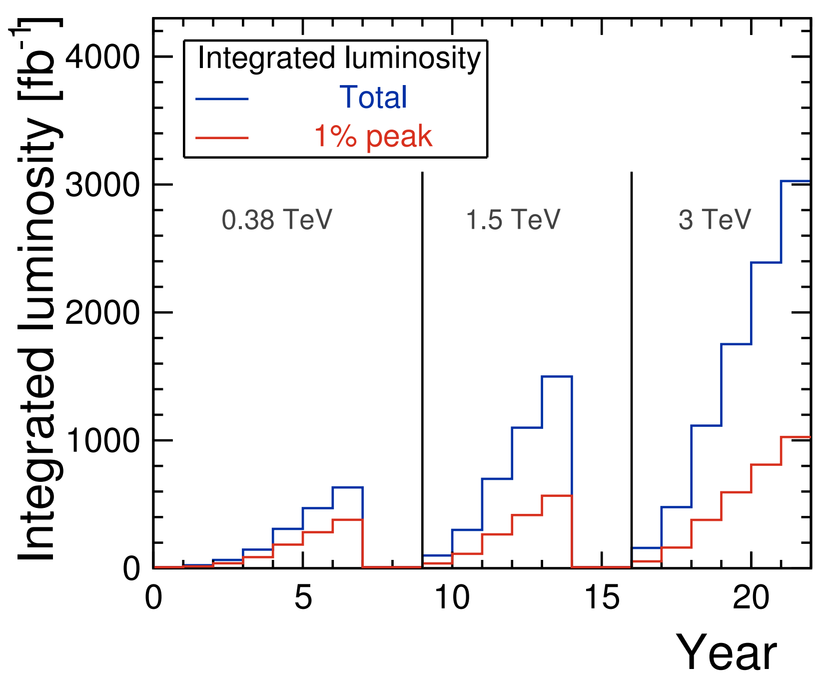
3	3000	3000





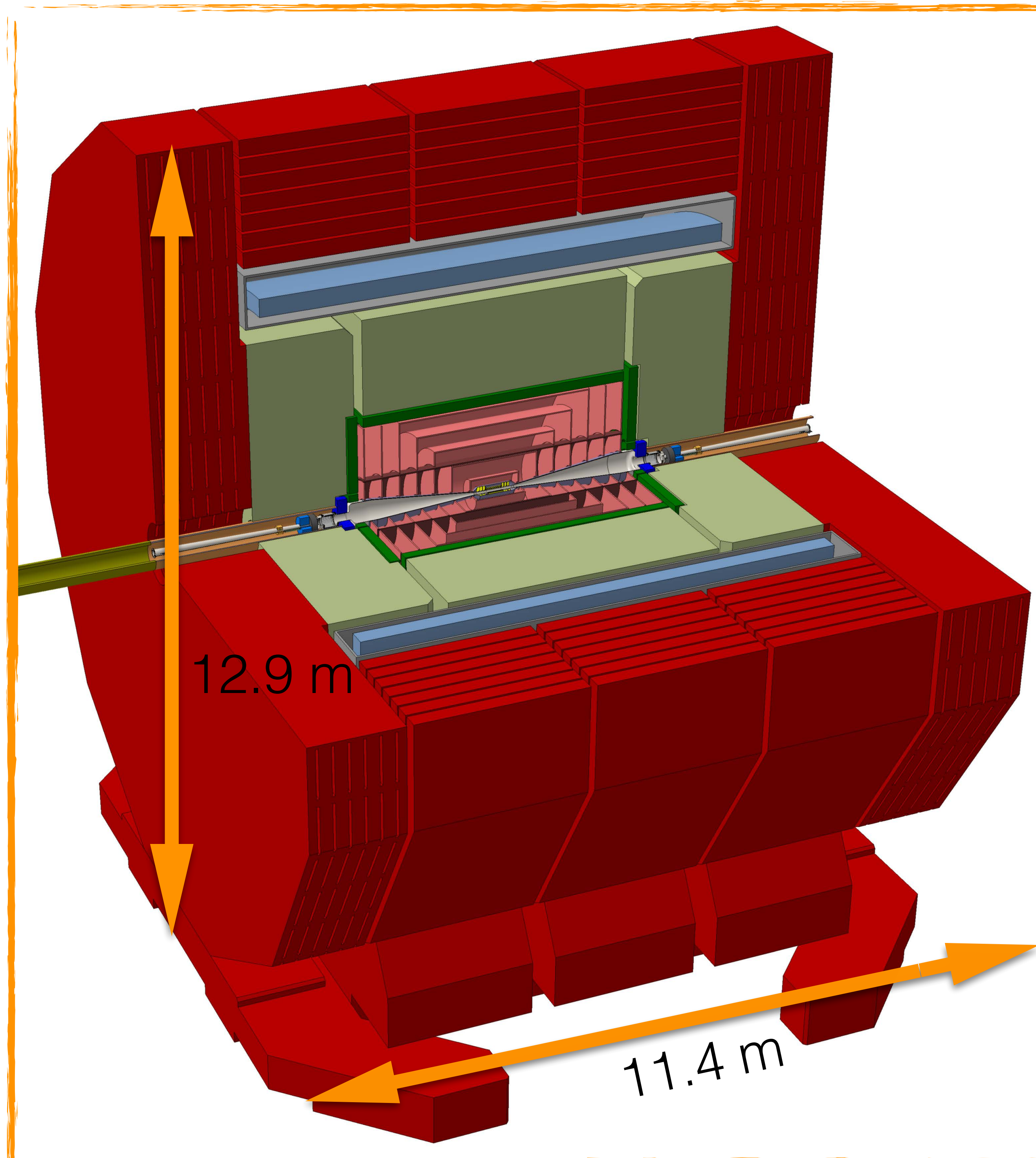
Post-CDR CLIC detector model

- Two detector models, CLIC_ILD and CLIC_SiD, were used in the CDR and for physics studies

- A new optimised model, **CLICdet**, has been developed for the next round of benchmark studies

- Implemented in simulation/ reconstruction software in DD4Hep (Detector Description for HEP)

- Public note under collaboration review at the moment



A single detector at CLIC

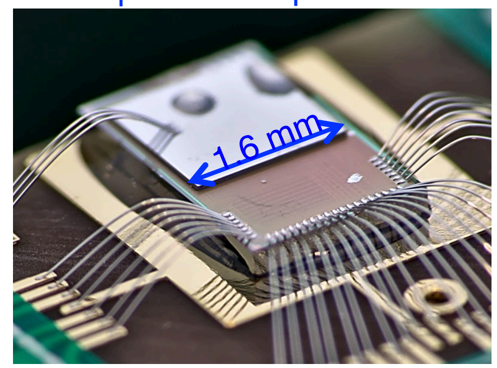
- Single detector
- All silicon tracker
- 4 Tesla magnet
- Return yoke:
  - Smaller outer radius due to less stringent requirements on stray fields
- Last quadrupole magnet (QD0) now outside of the detector at L* = 6 m allowed by the thinner yoke endcaps
  - Provides significantly better forward HCAL coverage

Concept	**CLICdet**	**CLIC_ILD**	**CLIC_SiD**
Vertex inner radius [mm]	31	31	27
Tracker technology	Silicon	TPC/Silicon	Silicon
Tracker half length [m]	2.2	2.3	1.5
Tracker outer radius [m]	1.5	1.8	1.3
ECAL barrel r_{min} [m]	1.5	1.8	1.3
ECAL barrel Δr [mm]	202	172	139
ECAL endcap z_{min} [m]	2.31	2.45	1.66
ECAL endcap Δz [mm]	202	172	139
HCAL absorber barrel / endcap	Fe / Fe	W / Fe	W / Fe
HCAL λ_I	7.5	7.5	7.5
HCAL barrel r_{min} [m]	1.74	2.06	1.45
HCAL barrel Δr [mm]	1590	1238	1177
HCAL endcap z_{min} [m]	2.45	2.65	1.80
HCAL endcap Δz [mm]	1590	1590	1595
Solenoid field [T]	4	4	5
Solenoid bore radius [m]	3.5	3.4	2.7
Solenoid length [m]	8.3	8.3	6.5
Overall height [m]	12.9	14.0	14.0
Overall length [m]	11.4	12.8	12.8
Overall weight [t]	8100	10800	12500

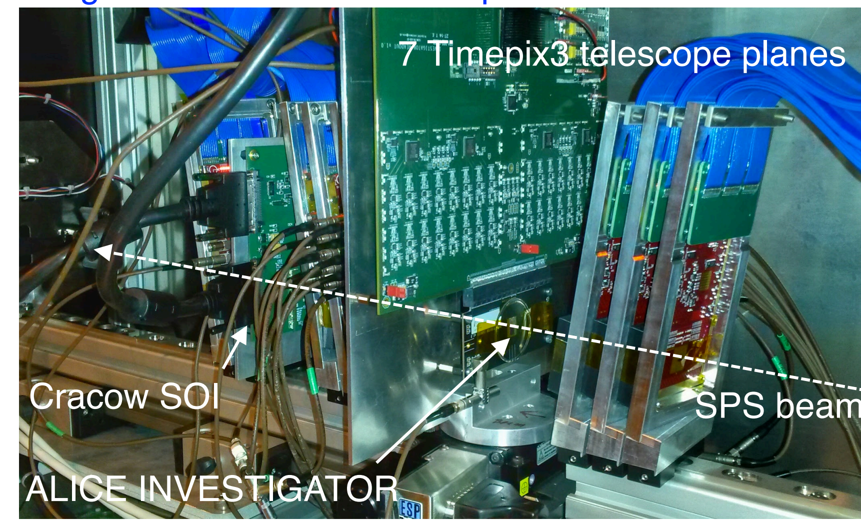
Vertex detector and R&D

- Vertex detector design not changed with respect to CLIC_ILD
- Very **active R&D program** combined for Vertex and Tracker
- 4 weeks of beam tests at SPS-H6 in 2016
- **Vertex detector:**
  - *CLICpix* + 50 µm thick active-edge sensor
  - *Timepix3* with thin (50-150 µm) active-edge sensors
- **Tracker:**
  - AGH Cracow SOI chip for tracker
  - ALICE INVESTIGATOR high-resistivity CMOS test chip
- New Chips (larger, improved performance)
  - *C3PD HV-CMOS* sensor —> standalone tests performed
  - *C3PDv2 HV-CMOS* sensor —> submitted for production
  - *CLICpix2* r/o ASIC —> submitted for production
- Systematic studies of capacitive coupling
  - Finite element simulations
  - Precision alignment of glue assemblies

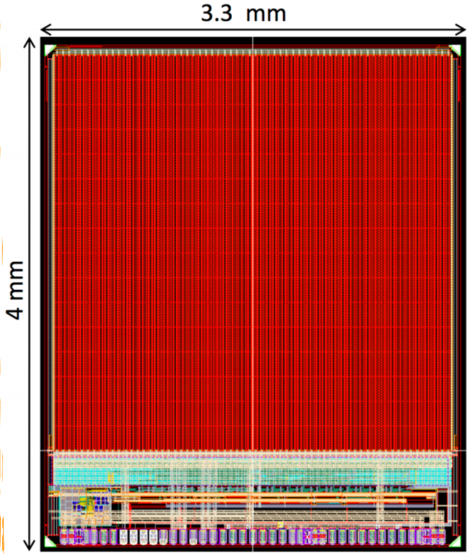
CLICpix with 50 µm sensor



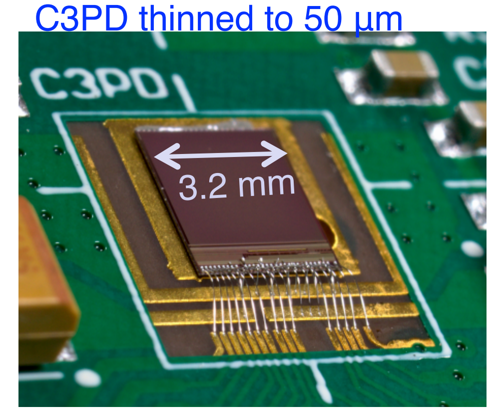
August 2016 test-beam setup in SPS-H6



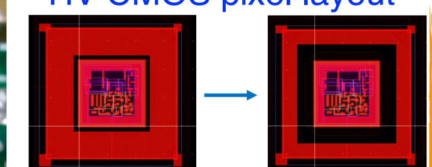
CLICpix2



C3PD thinned to 50 µm

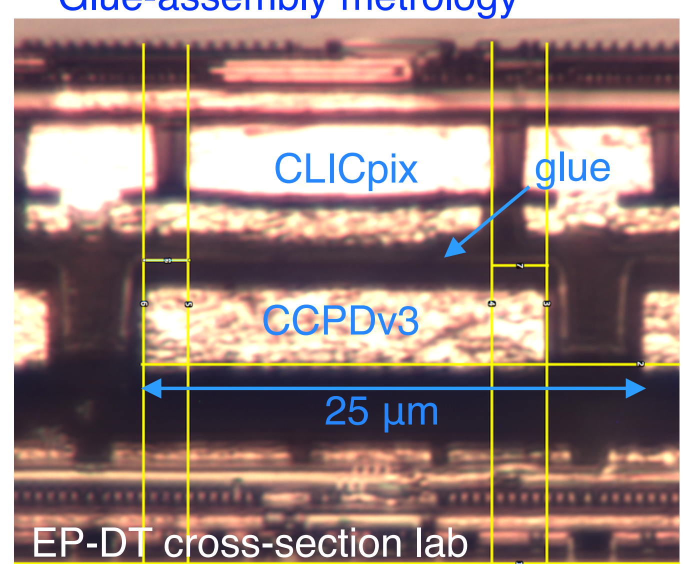


HV-CMOS pixel layout

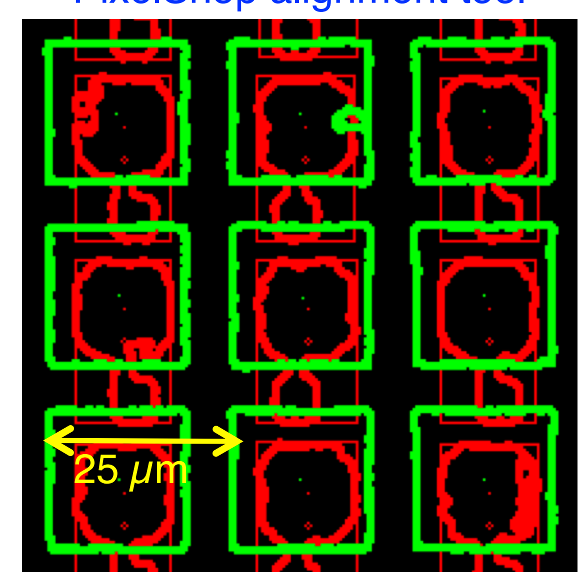


C3PD C3PDv2

Glue-assembly metrology

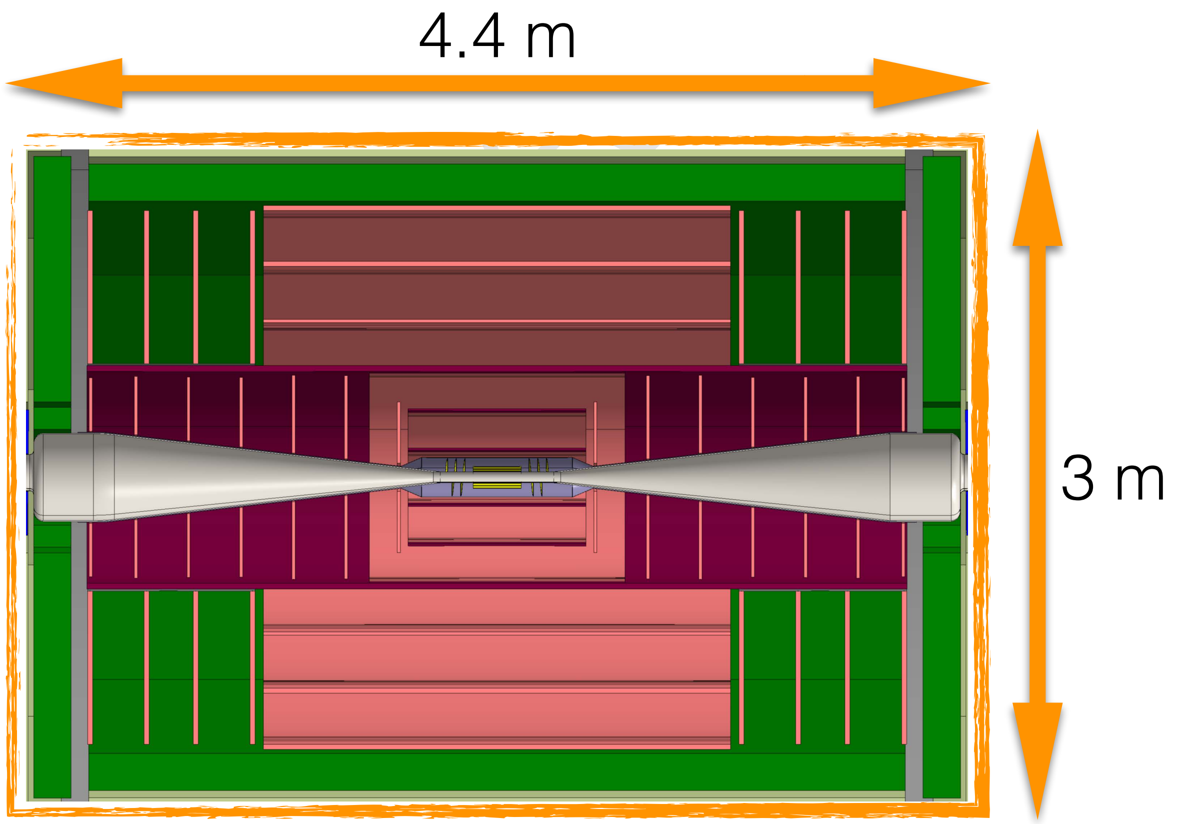


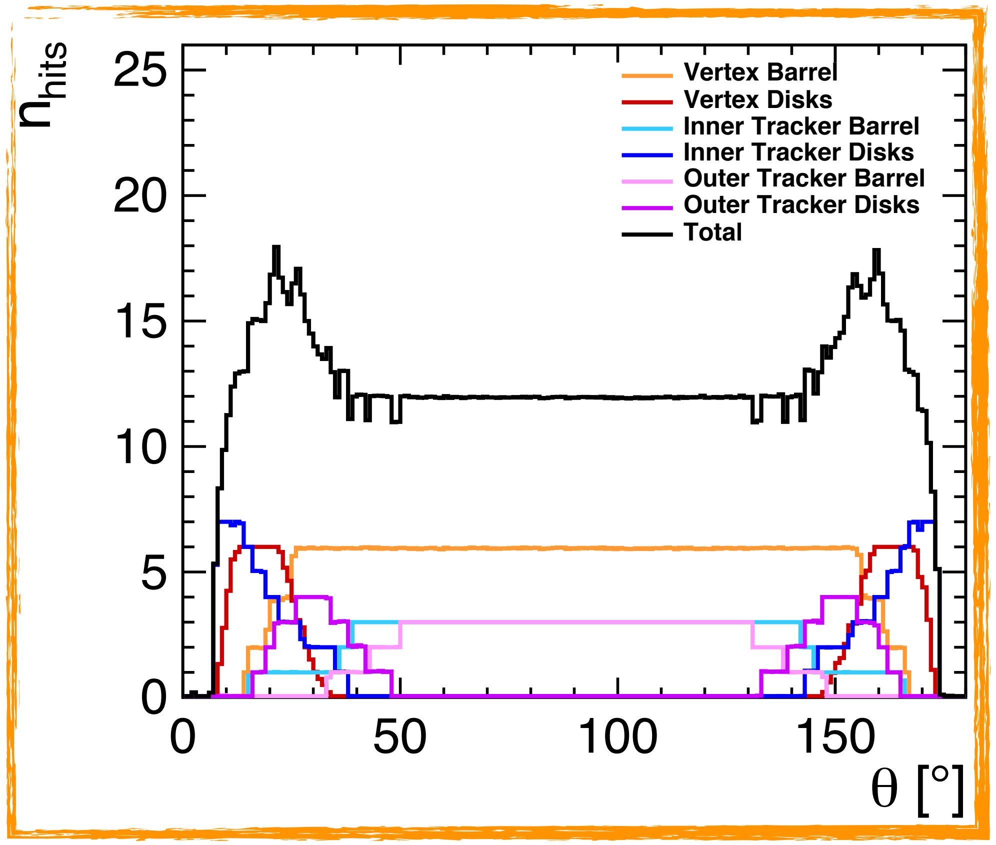
PixelShop alignment tool



Silicon tracker

- All silicon tracker
- Design driven by track momentum resolution
- Tracker and vertex R&D closely related
- Material budget:
  1.1% -1.4% X_0 per layer
- Position of support structure enables tracking close to the beam pipe
- Inner tracker region:
  3 barrel layers and 7 disks
- Outer tracker region:
  3 barrel layers and 4 disks
- Larger tracker, extended in particular in the forward coverage compared to CLIC_SiD





Silicon-Tungsten ECAL

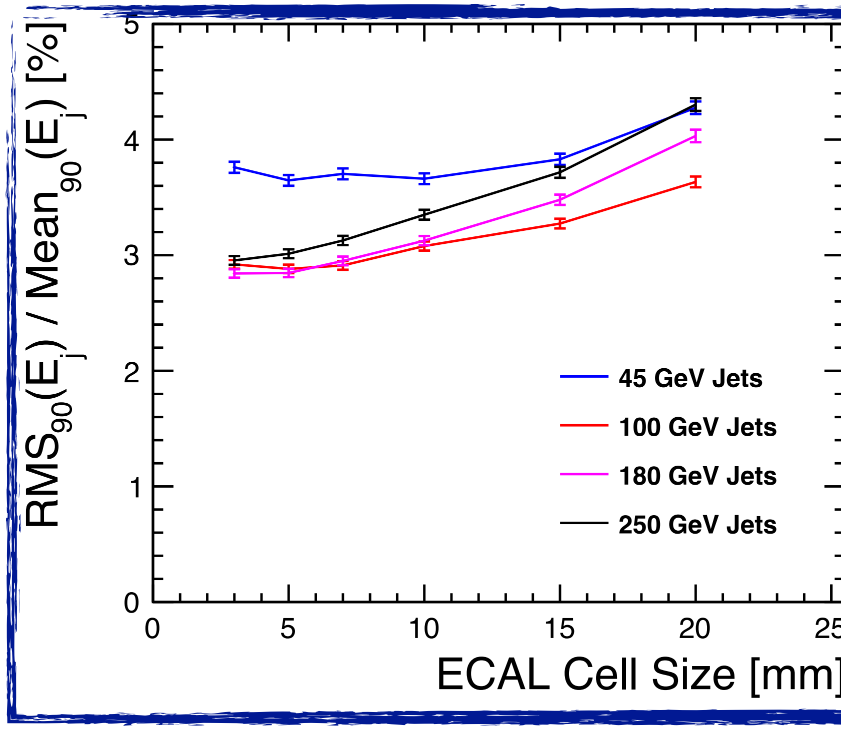
- ECAL optimisation now also taking into account energy resolution for high energy photons

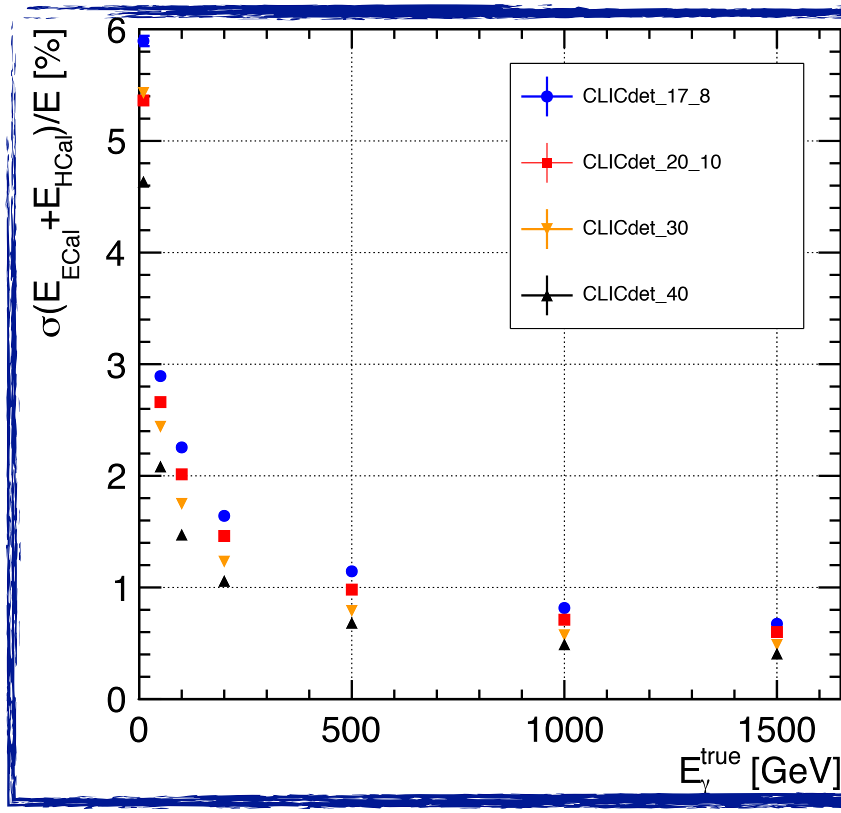
See talk by Matthias Weber on Wednesday at 13:50

  - Cell size 5x5X0.5 mm^3 optimal for jet energy resolution
  - No strong dependence of jet energy resolution on the number of layers
  - 40 layers of 1.9 mm tungsten optimal for high energy photons

- Material budget: 23 X_0
- Dimensions: R_{inner} 1.5 m, R_{outer} 1.7 m
- CMS HGCAL design based on CALICE R&D effort for linear colliders

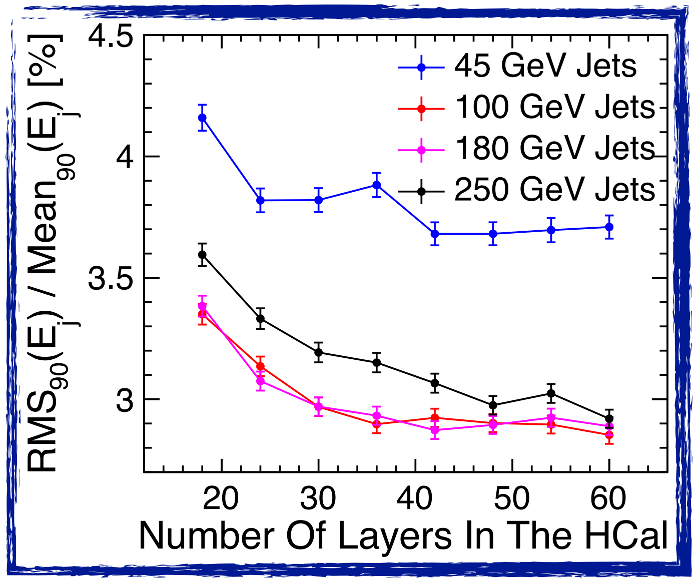
See talk by Matthias Weber on Thursday at 9:25

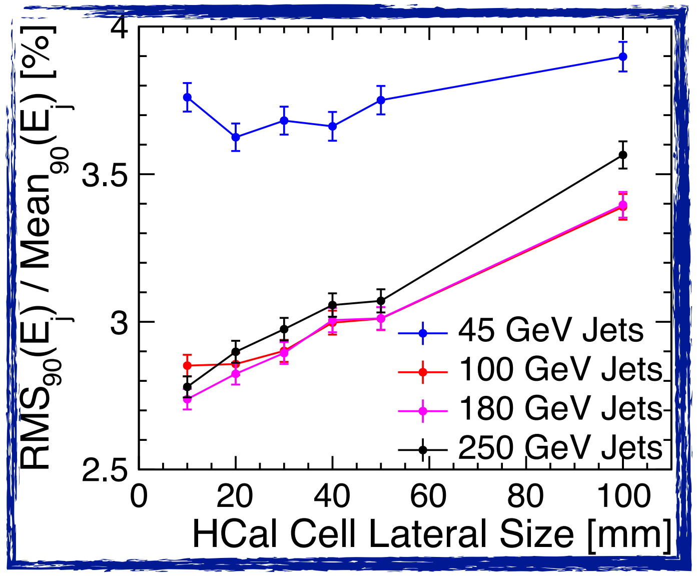


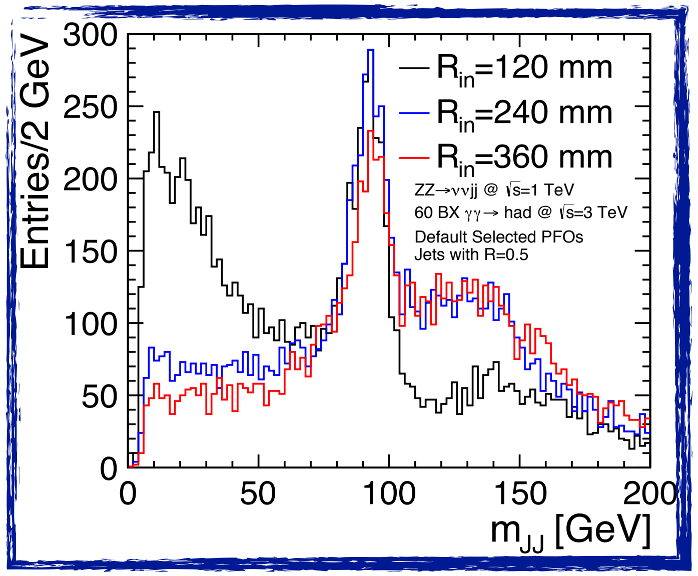


Scintillator-Steel HCAL

- Optimisation for jet energy resolution
- 60 layers of 19 mm thick steel and polystyrene scintillator tiles + SiPMs
- Tile size 30x30x3 mm^3
- Depth 7.5 λ_I
- Better forward coverage with respect to the CDR
  - Endcap R_{in} 250 mm
  - Improved di-jet invariant mass

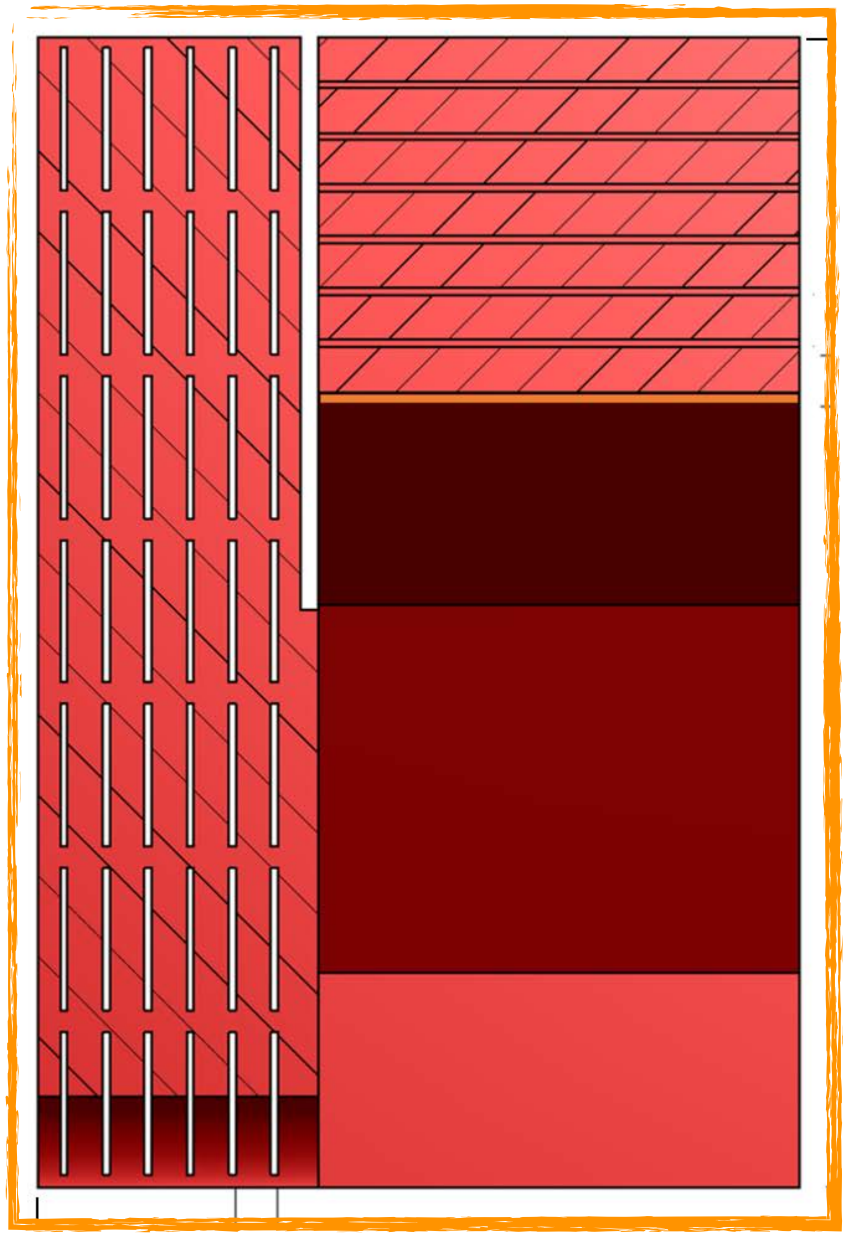






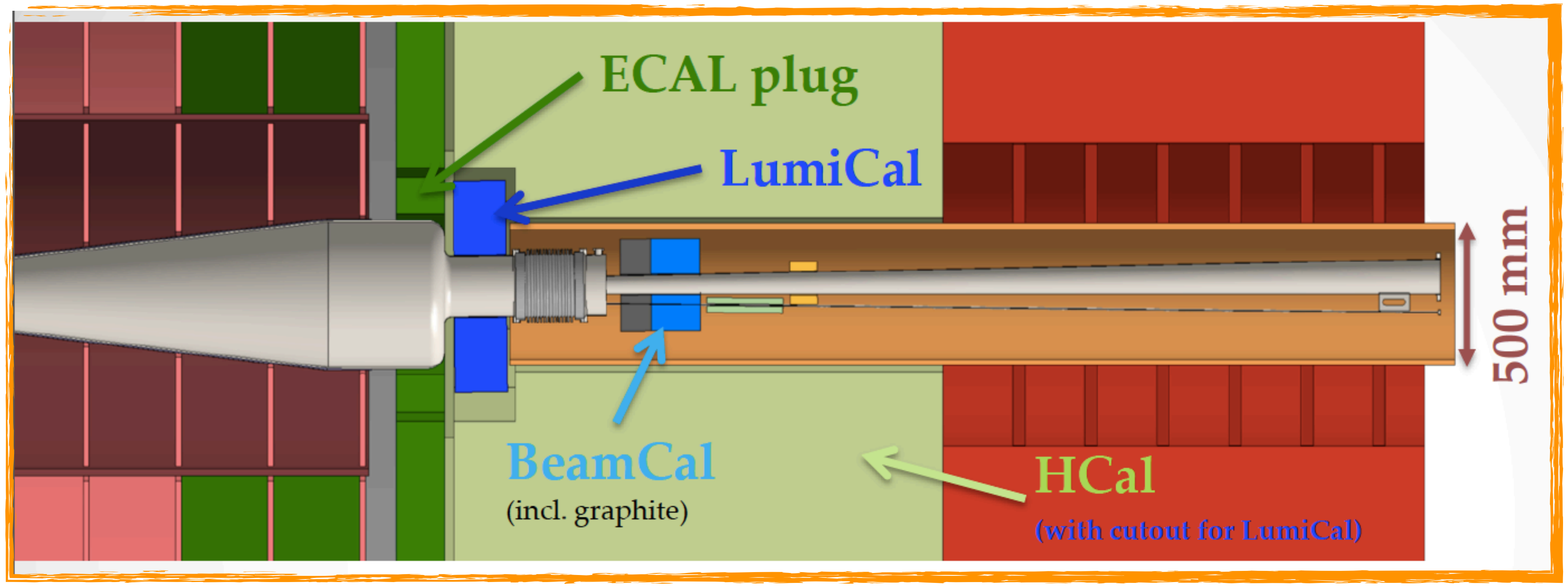
Muon system

- Smaller muon system due to thinner yoke
- Muon identification still sufficient
- 6 layers plus 1 layer in the barrel close to the coil
    - RPC with 30x30 mm^2 cell size
    - Alternative scintillator strips



Forward calorimeters

- Very forward region:
  - LumiCal for luminosity measurement (e+e- from Bhabha scattering): 30 layers of 3.5 mm tungsten with 0.32 mm silicon sensors
  - BeamCal for monitoring of collisions: 30 layers of 3.5 mm tungsten with diamond sensors (radiation hard)
- Provide coverage for electrons and photons down to very small angles (10 mrad)
- Position and radii slightly changed with respect to CLIC_ILD



Higgs physics overview paper

- Overview of CLIC Higgs physics submitted to EPJC
- Collaboration wide effort with more than 25 independent analyses
- Demonstrates the CLIC physics reach at its 3 energy stages

See talk by Philipp Roloff on Tuesday at 9:00

See talk by Mila Pandurovic on Wednesday at 14:20

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	0.84 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc} / \Gamma_H$	10.3 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		4.5 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	14.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.7 %

Channel	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	44 MeV
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	6.1 %	6.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	4.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	4.2 %	4.4 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	38 %	25 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	10 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	30 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	1.0 %	0.7 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	5.6 %	3.9 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	1.8 %	2.3 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb} / \Gamma_H$	8.4 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	32 %	16 %
$HH\nu_e\bar{\nu}_e$	with −80 % e$^-$ polarisation	λ	24 %	12 %

Preparation for next European Strategy

- CLIC summary report
  - Updated baseline for a staged Compact Linear Collider
    CERN yellow report CERN-2016-004, arXiv:1608.07537
  - Higgs Physics at the CLIC Electron-Positron Linear Collider
    Submitted to EPJC, arXiv:1608.07538
  - The New Optimised CLIC detector model CLICdet
    Under Collaboration review
  - An overview of CLIC Top Physics
    Publication planned 2017

    See talks by Rickard Ström on Thursday at 15:50 and Filip Zarnecki on Tuesday at 9:40
  - Extended BSM studies
    Publication planned 2017/2018

    See talk by Philipp Roloff on Thursday at 10:40
  - CLIC R&D report (main CLIC technology demonstrators)
    Summary publications 2017+2018
  - Plan for the period ~2019-2025 in case CLIC is supported by the next strategy

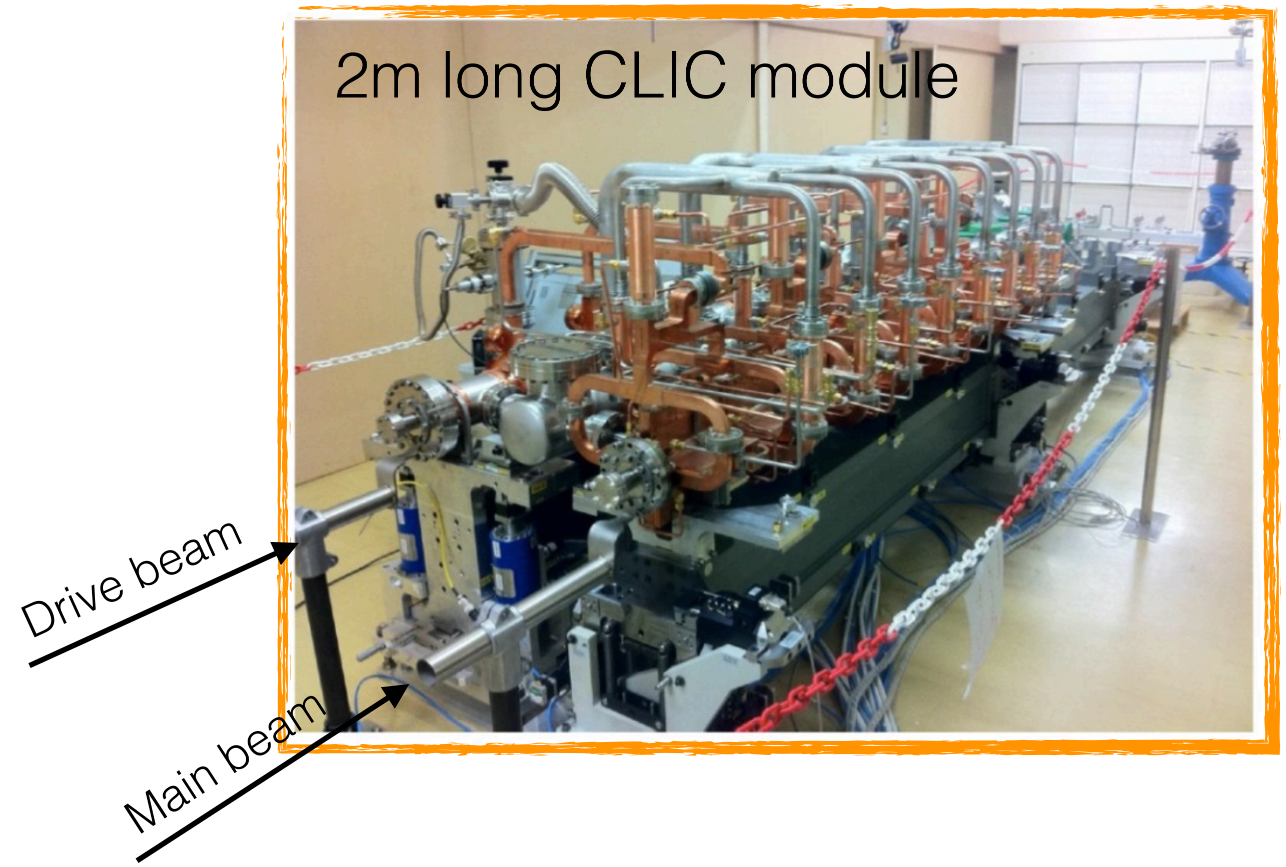
Summary

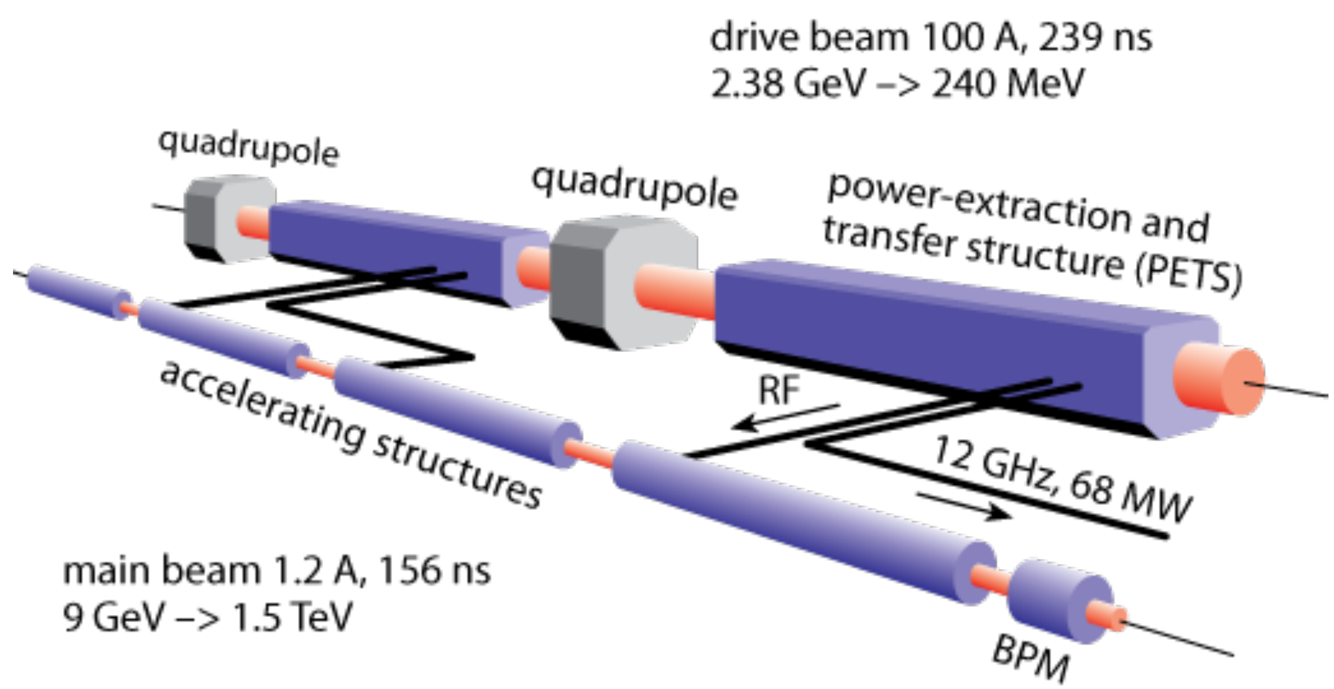
- Rebaselining of **CLIC staging scenario** optimising both Higgs and Top physics program in first energy stage
    - 380 GeV, 1.5 TeV, 3 TeV
- New single CLIC detector model **CLICdet** based on optimisation studies in full detector simulations
- Active R&D effort on Vertex and Tracker technologies, and on Calorimeters in collaboration with CALICE, FCAL and CMS
- **Higgs physics overview paper** finalised and submitted,
  Top physics overview and BSM physics overview being prepared
- Staged operation of CLIC offers an impressive energy frontier physics programme that reaches beyond the LHC.
  It is an excellent option for a post-LHC facility at CERN.

Backup slides

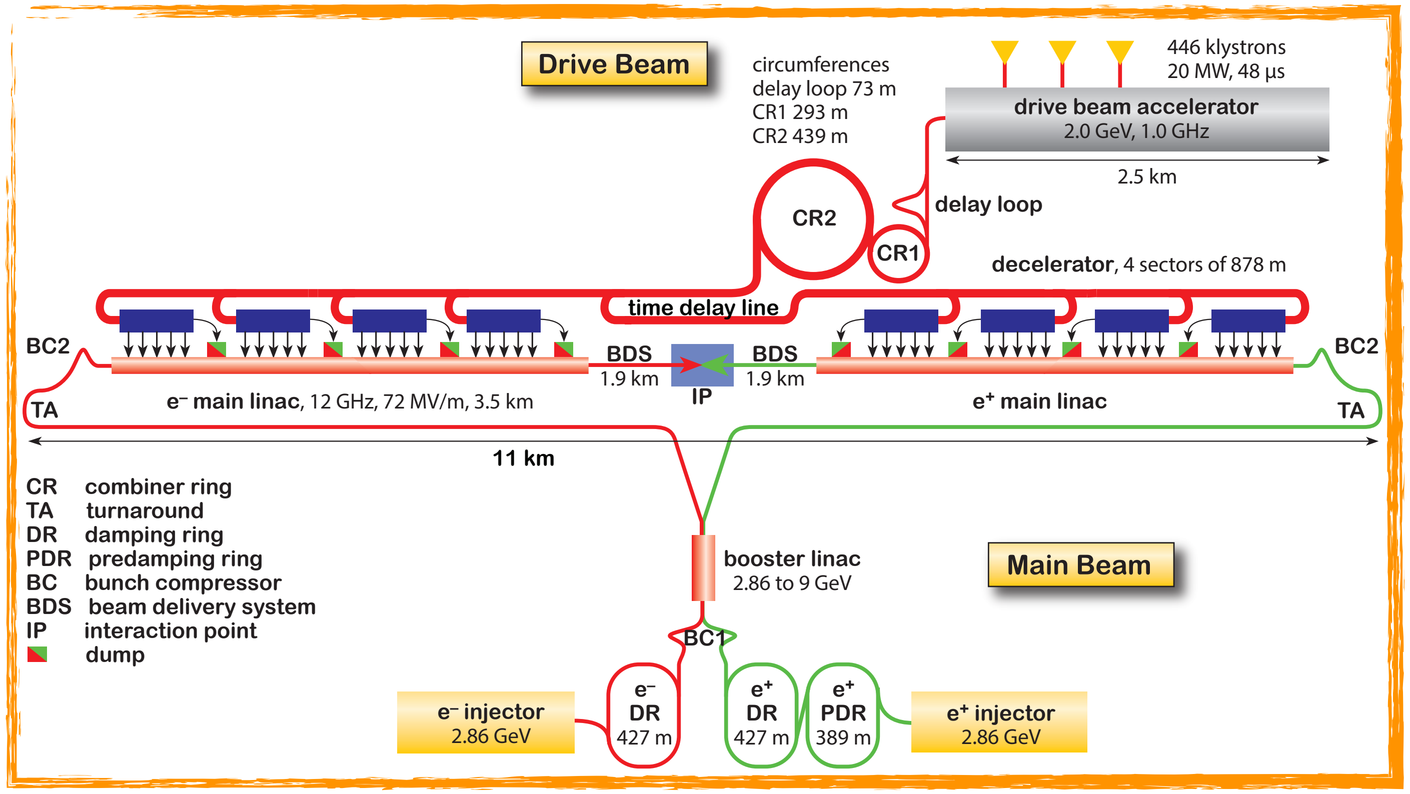
CLIC Accelerator

- High acceleration gradient at high frequency:
  100 MV/m at 12 GHz
- Room temperature
- Two-beam acceleration scheme
  - Drive beam supplies RF power:
    Low energy (2.4-240 GeV) and high current (100 A)
    12 GHz bunch structure
  - Main beam for physics:
    High energy (9 GeV - 1.5 TeV) and low current (1.2 A)
- 145 MV/m demonstrated in CTF3 test facility



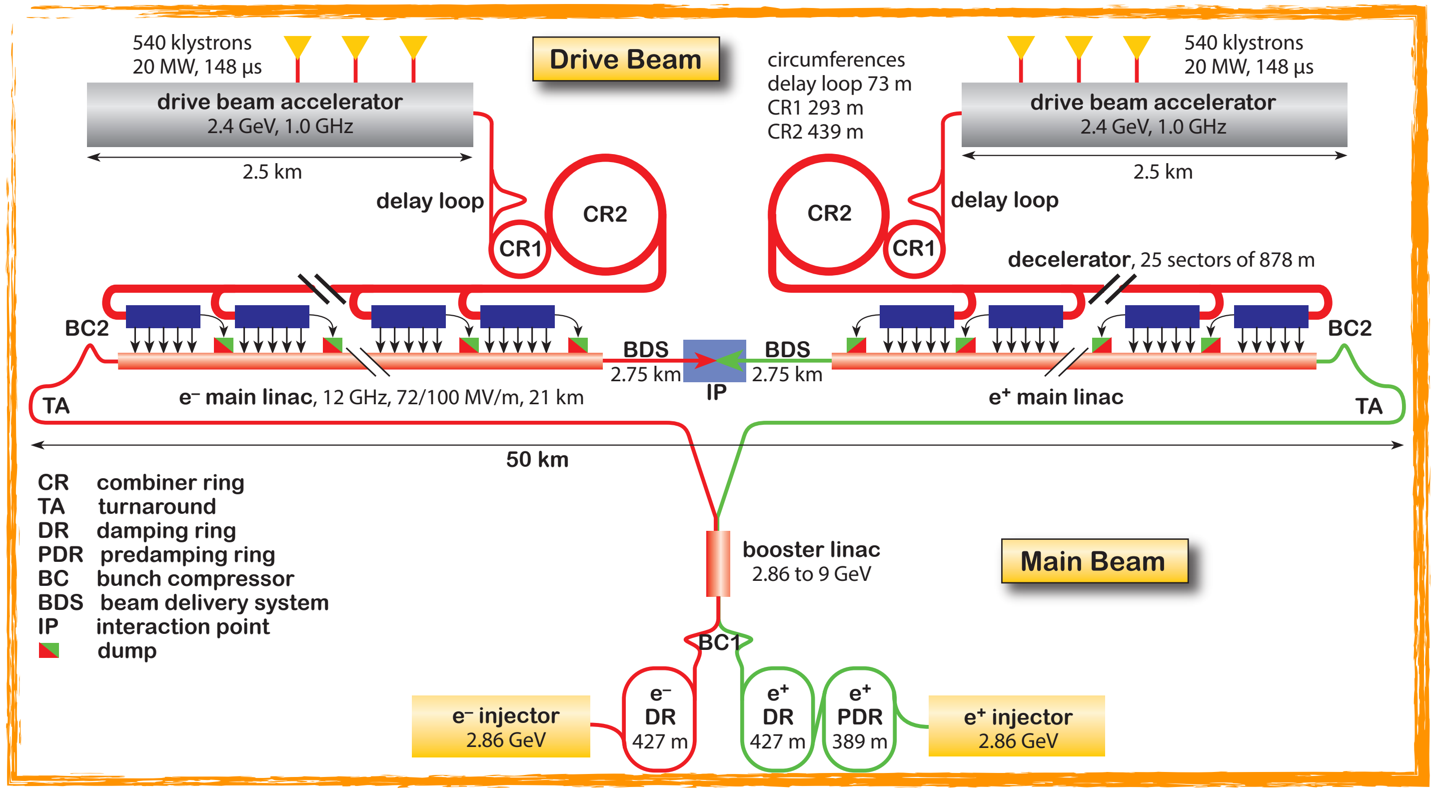


Accelerator complex



CLIC accelerator complex for 380 GeV

CLIC accelerator complex for 3 TeV

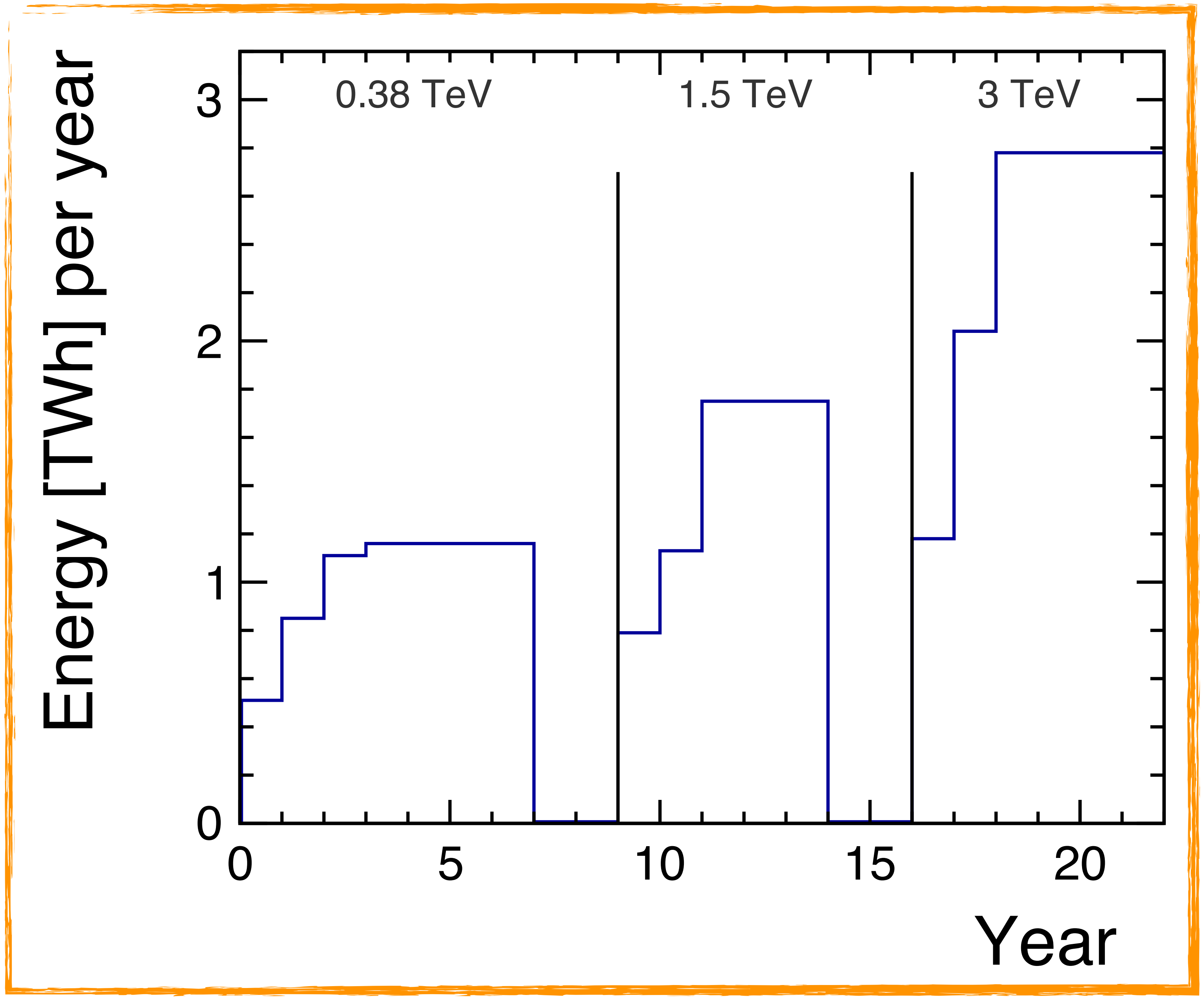


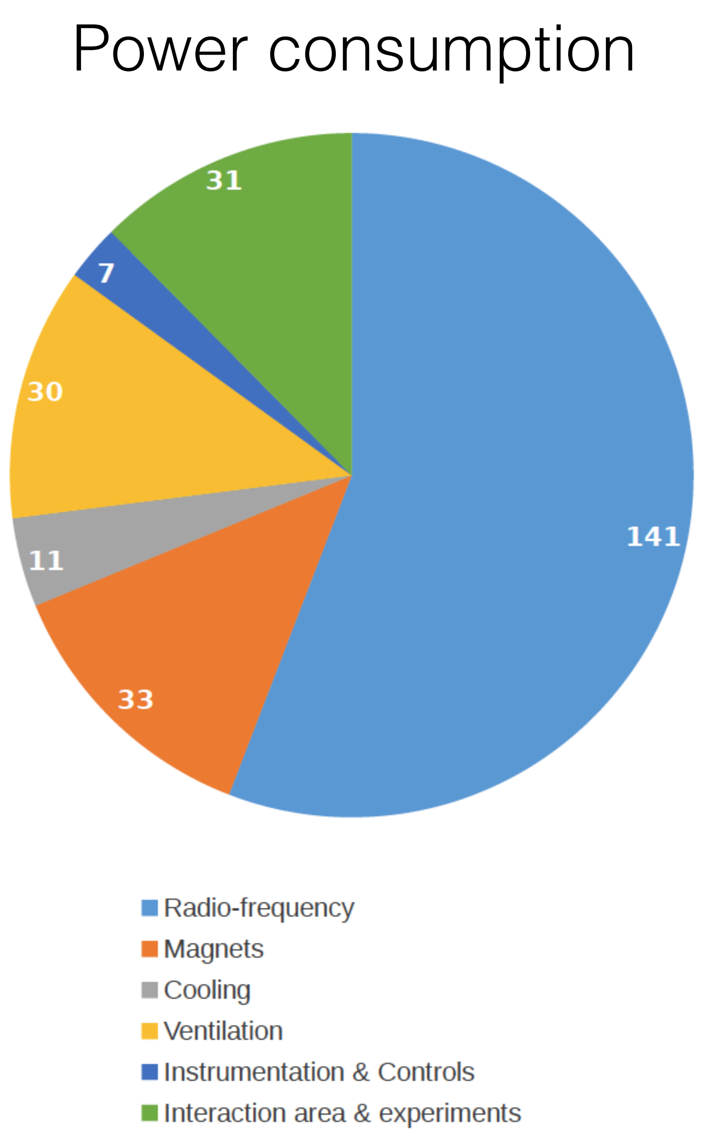
CLIC parameters

Table 9: Parameters for the CLIC energy stages. The power consumptions for the 1.5 and 3 TeV stages are from the CDR; depending on the details of the upgrade they can change at the percent level.

Parameter	**Symbol**	**Unit**	**Stage 1**	**Stage 2**	**Stage 3**
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	920/20	660/20	660/20
Normalised emittance (at IP)	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

CLIC energy consumption





Planning

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

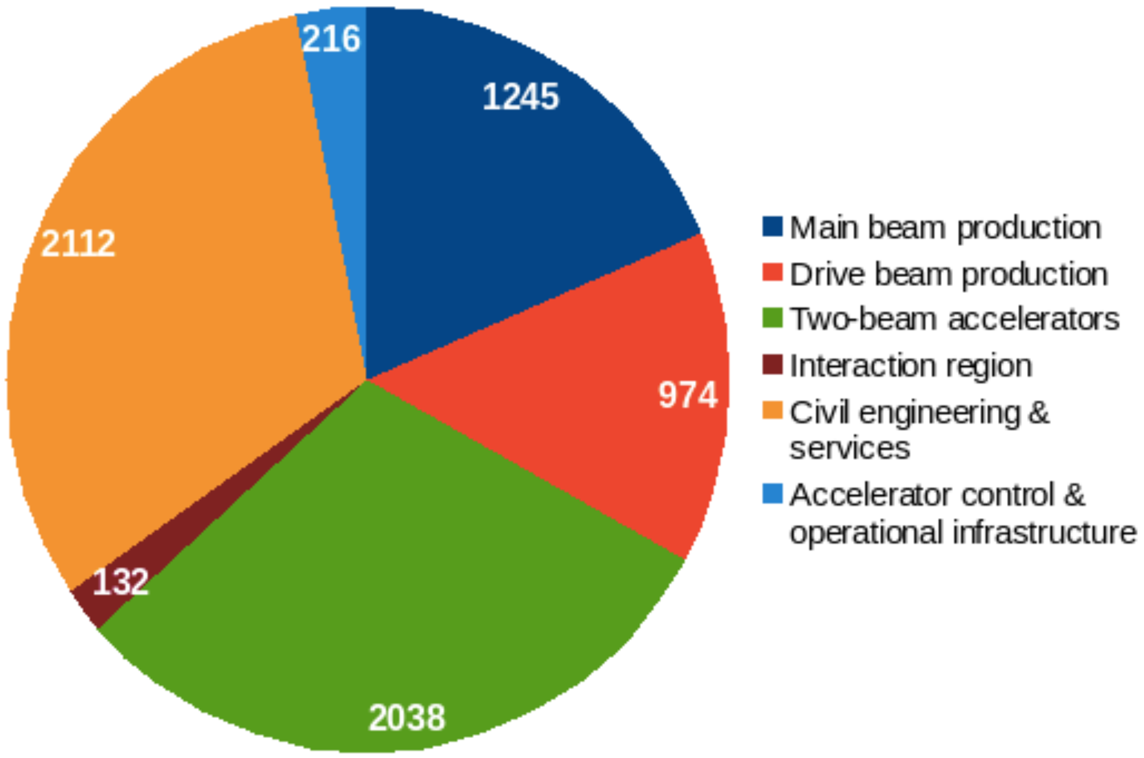
2035 First Beams

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

Cost estimation for 380 GeV CLIC

Table 11: Value estimate of CLIC at 380 GeV centre-of-mass energy.

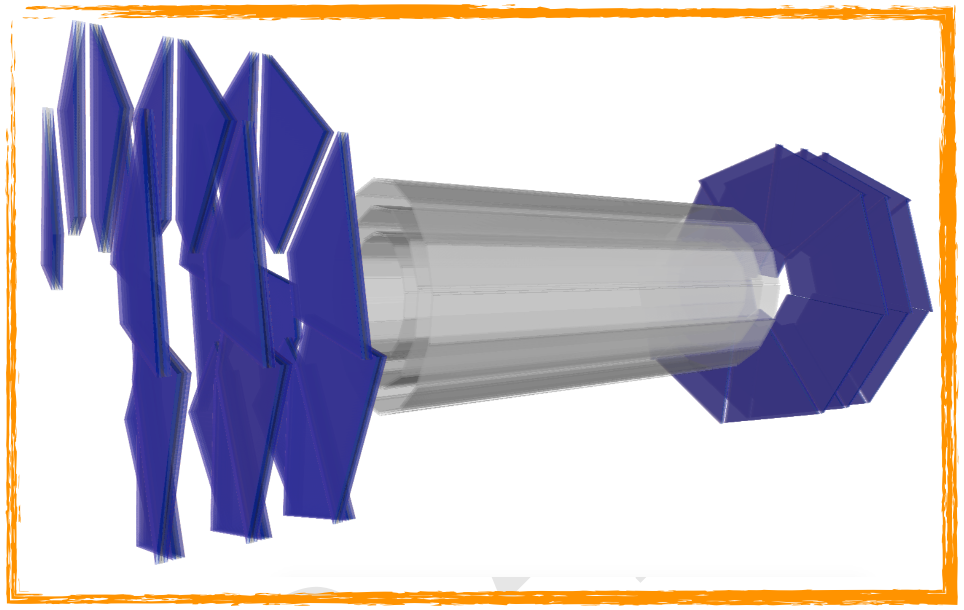
	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690

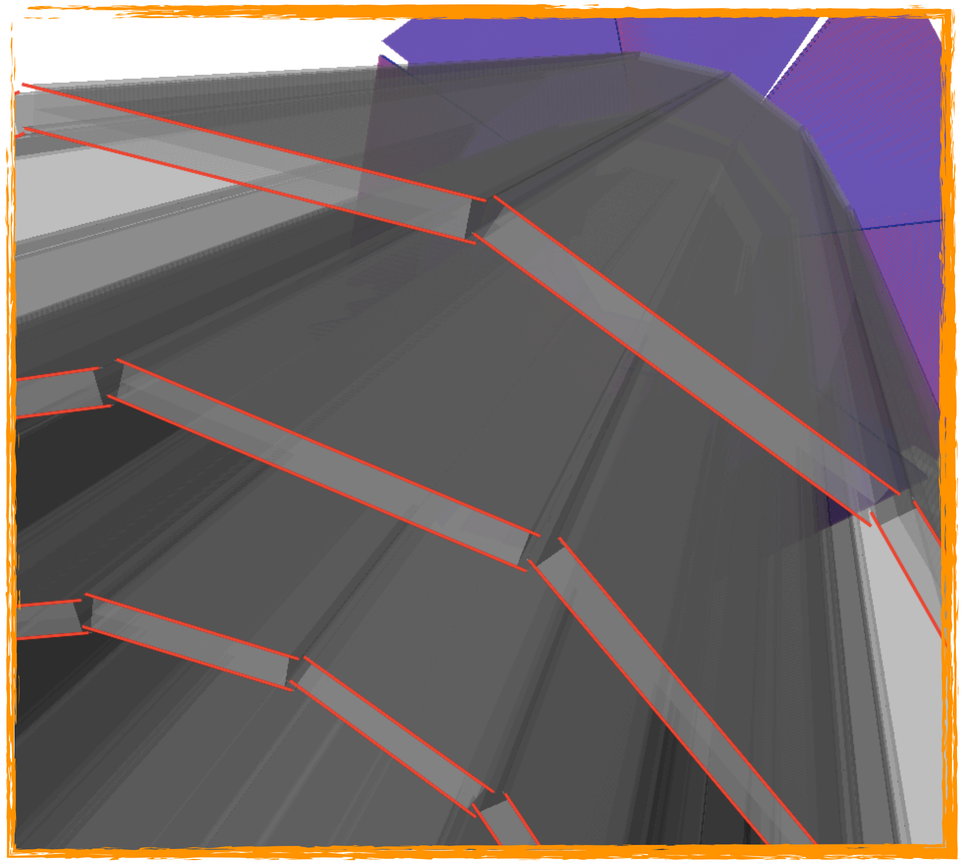


Estimated cost detector (CDR): 500 MCHF

Vertex detector

- Design driven by flavour tagging capabilities
- Cylindrical barrel, closed off by disks
    - Barrel: 3 double layers
    - Forward: 3 double segmented disks
    - Spiral layout enables efficient forced air flow cooling
- 0.2% X_0 per detection layer
- 25x25 μm^2 pixels (~ 2 G pixels)
- Single point resolution ~3 μm
- 10 ns time resolution





Tracker radius

- Transverse momentum resolution, angular track resolution and jet energy resolution using particle flow benefit from a larger tracker radius