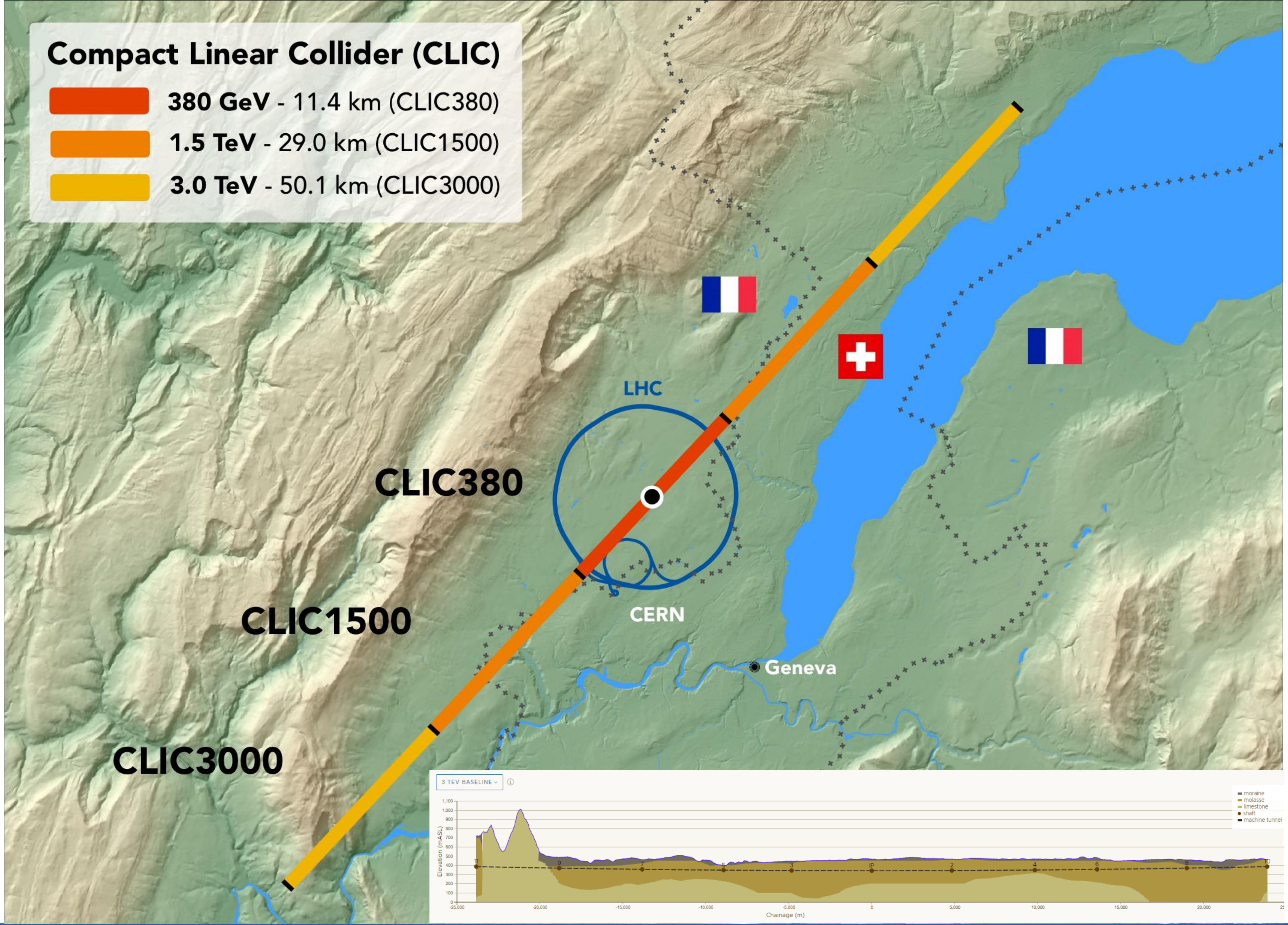
Status of the CLIC project

Aleksander Filip Żarnecki

High Energy Physics Seminar
15 March 2019

This is not the only option for CERN...

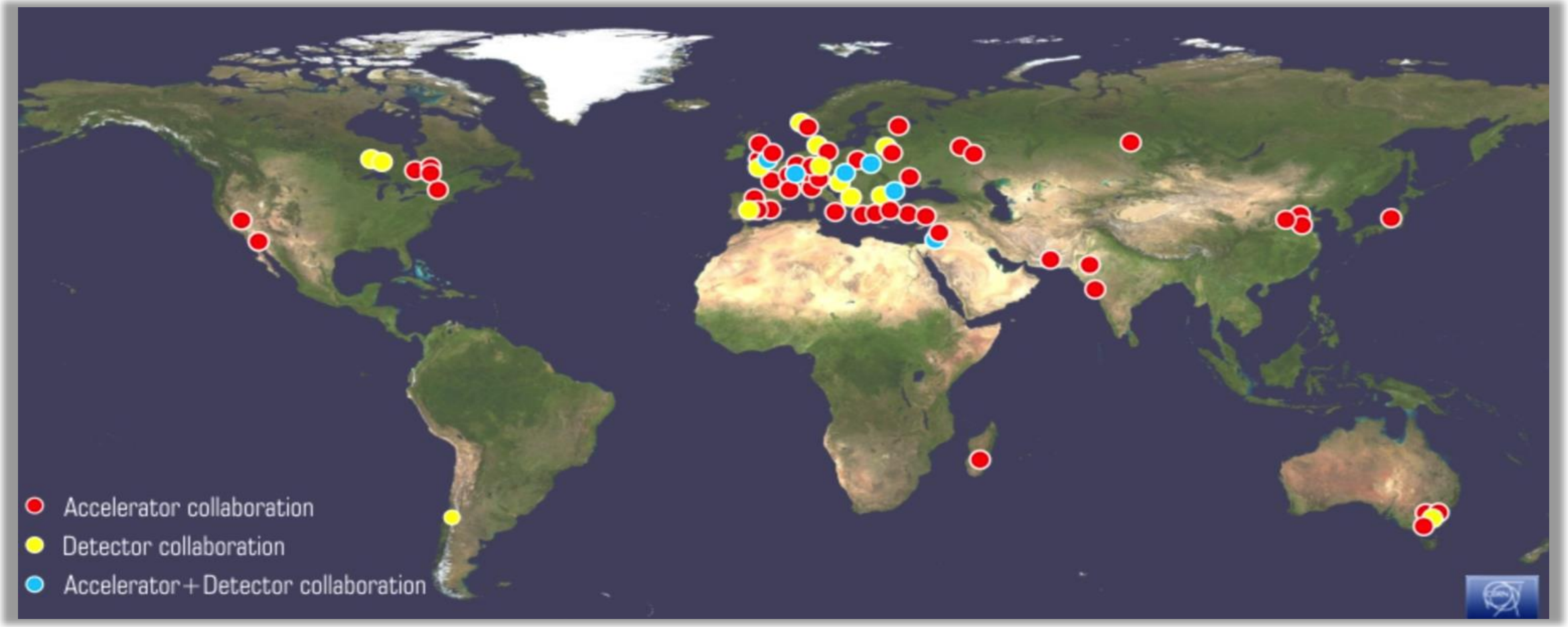

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

Collaborations

http://clic.cern/

CLIC accelerator collaboration
53 institutes from 31 countries

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



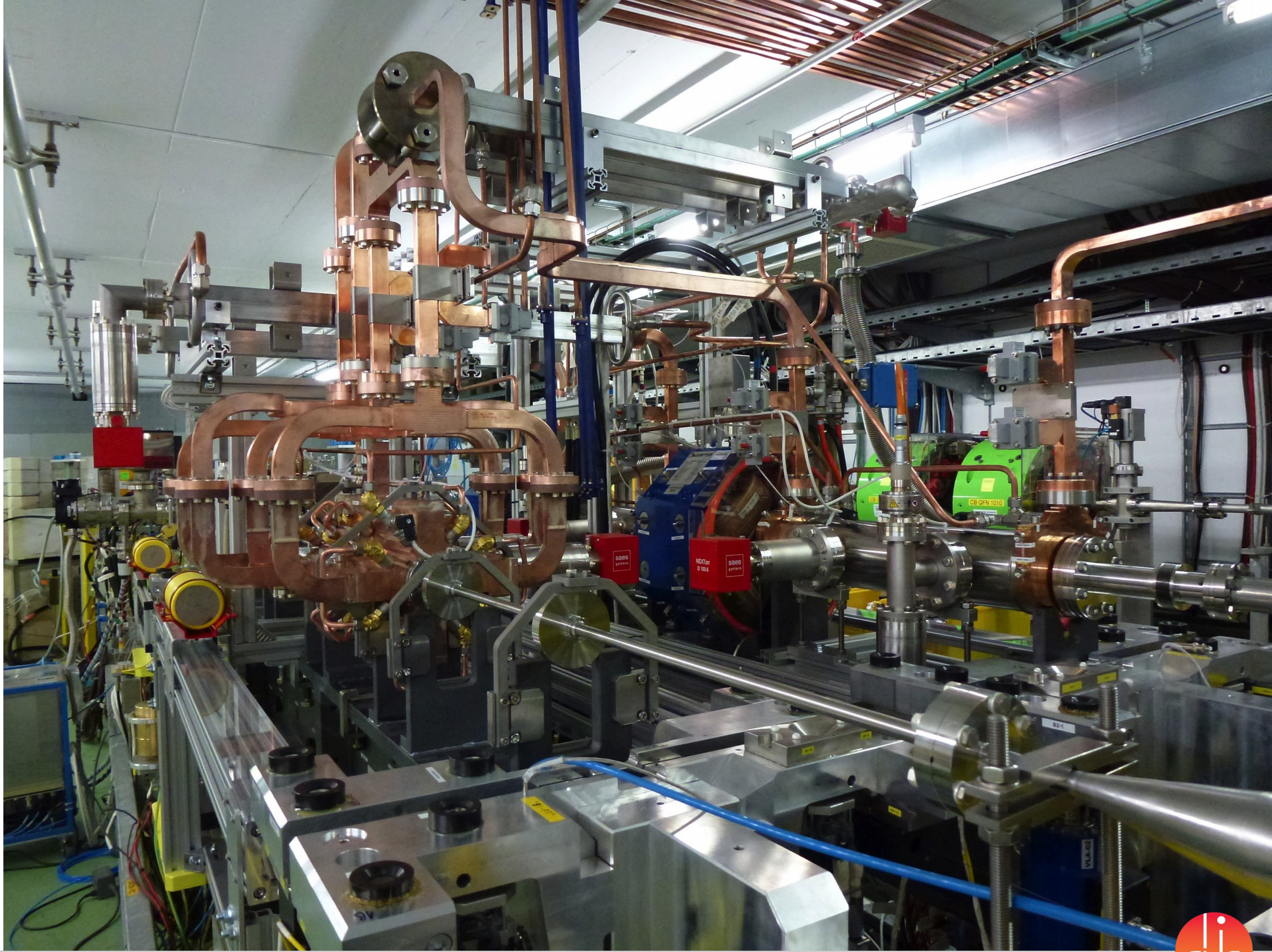
Status of the CLIC project

Based on the reports presented at **CLIC Week 2019**,
recent CLIC and CLICdp publications
and **CLICdp presentations at ICHEP'2018**

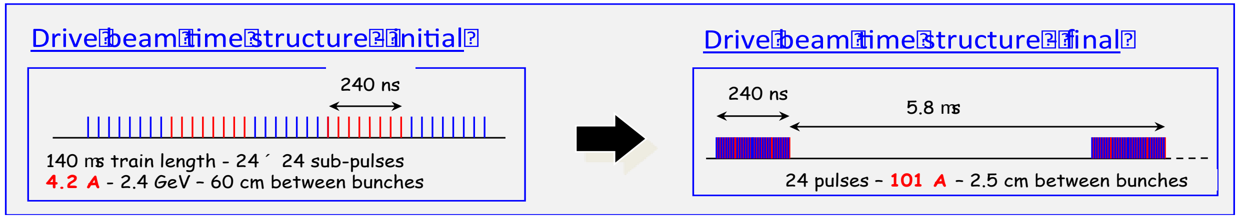
Outline

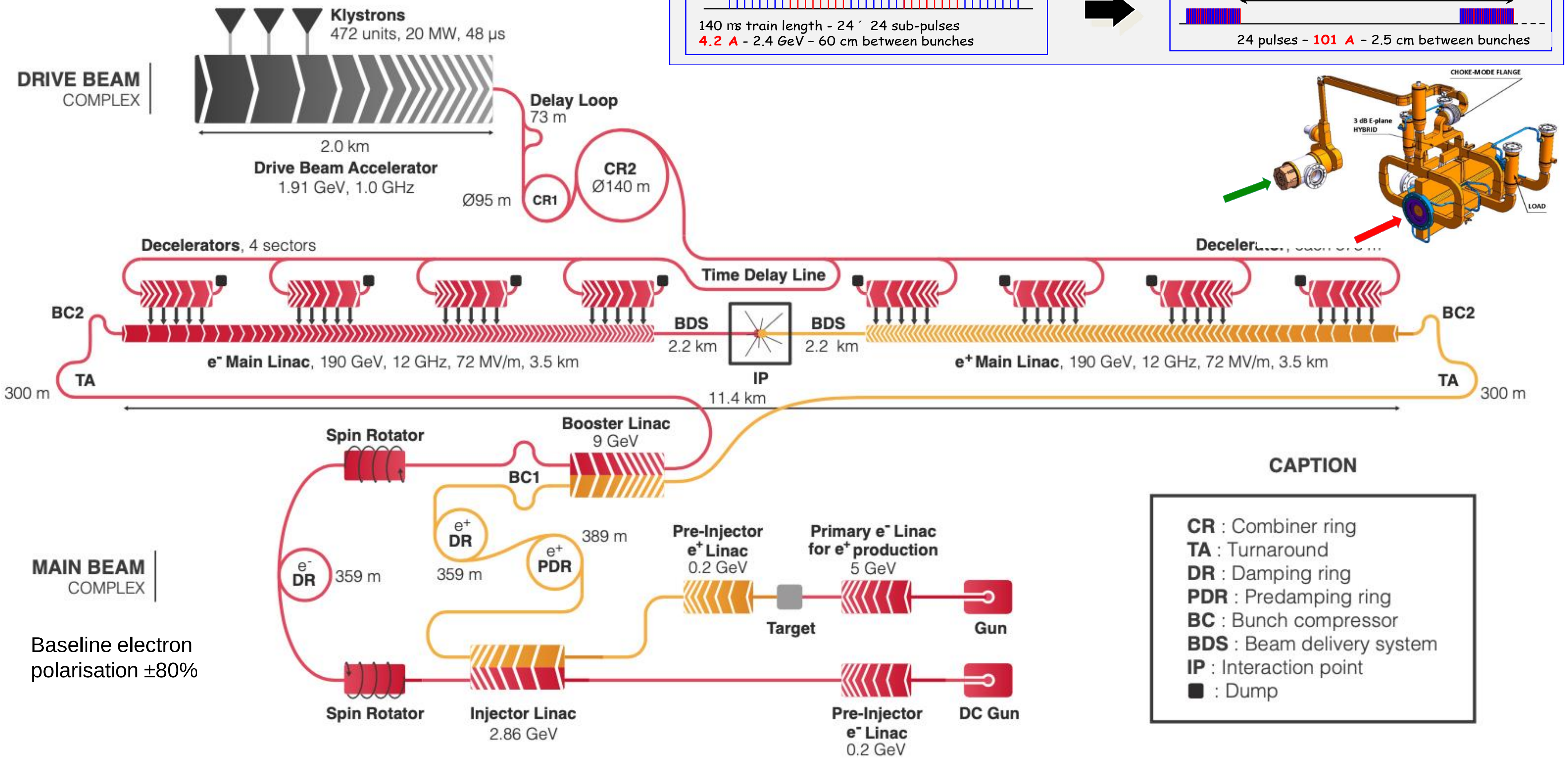
- Accelerator design
- Detector concept
- Physics Program
- Status of the project

Accelerator design



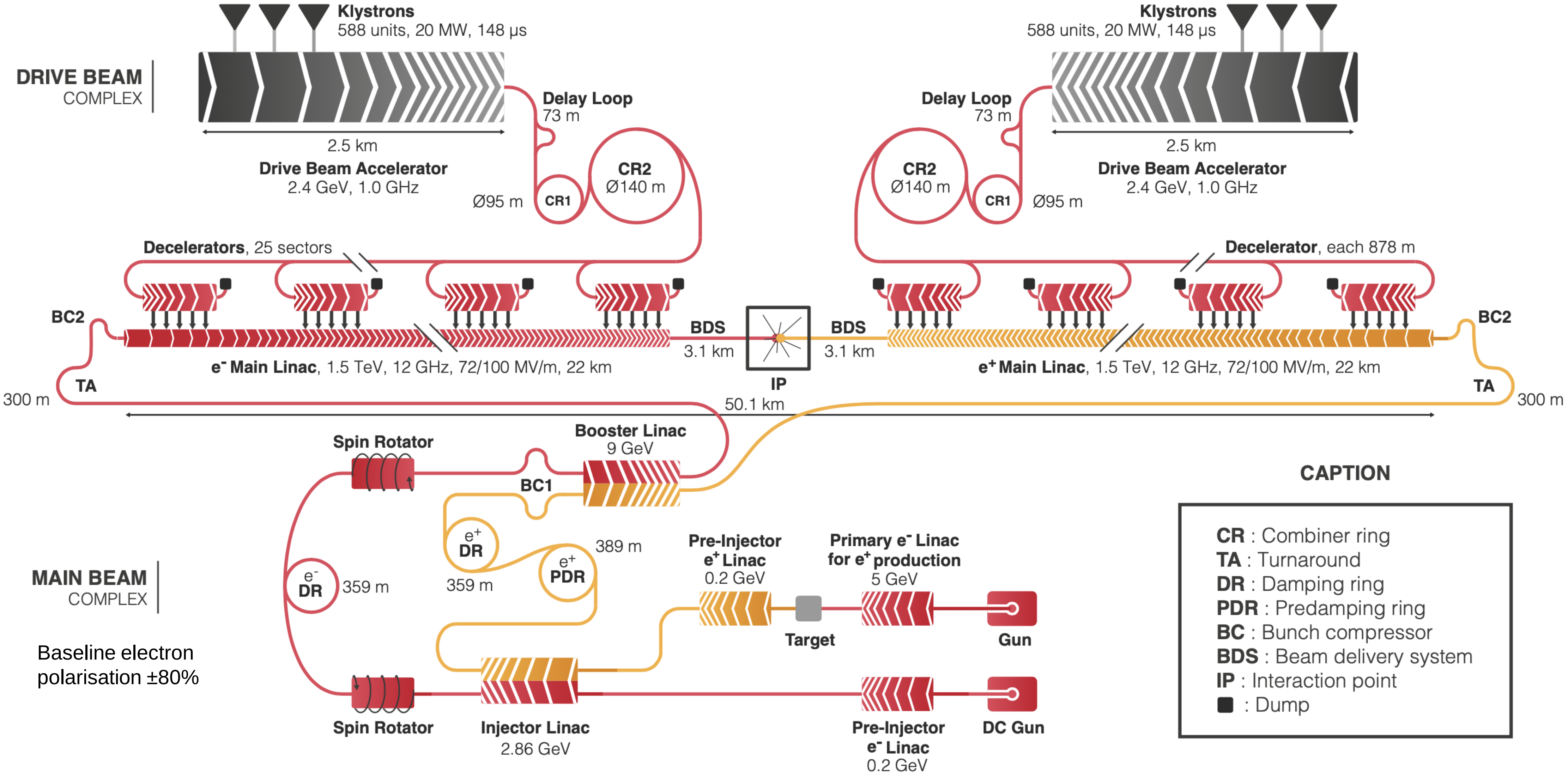
CLIC 380 GeV layout and power generation





Baseline electron polarisation ±80%

CLIC layout – 3TeV

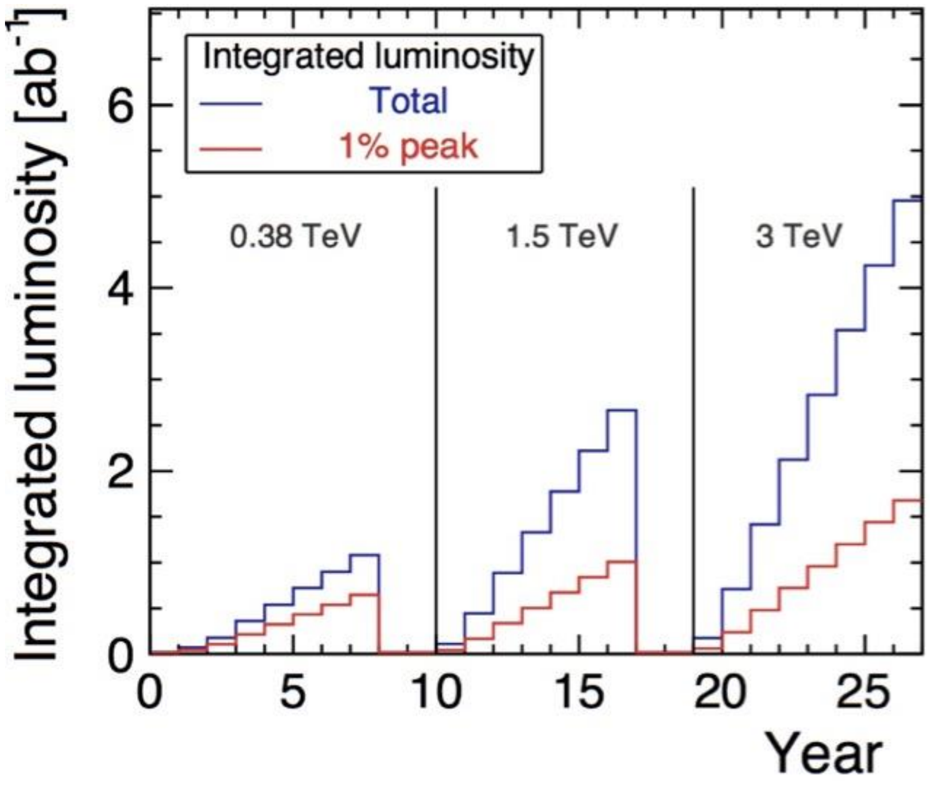


Baseline electron polarisation ±80%

CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Updated CLIC Staging



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at √s=380GeV ; (80:20) at √s=1.5 and 3TeV

Staging and live-time assumptions following guidelines consistent with other future projects: Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN arXiv:1810.13022, Bordry et al.

Accelerator challenges

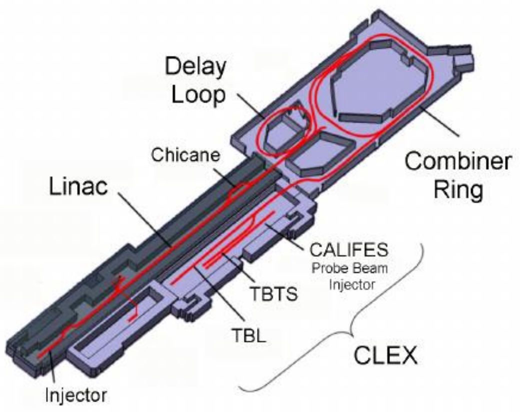
Four challenges:

High-current drive beam bunched at 12 GHz

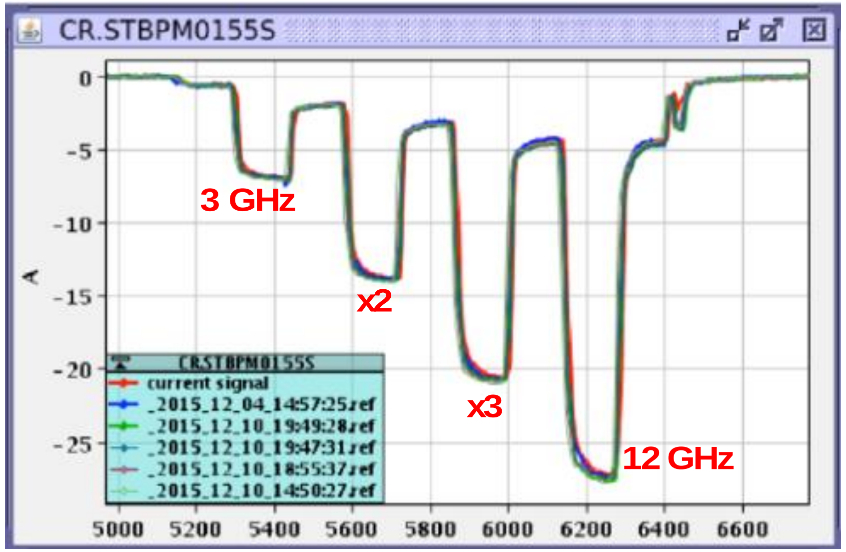
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability



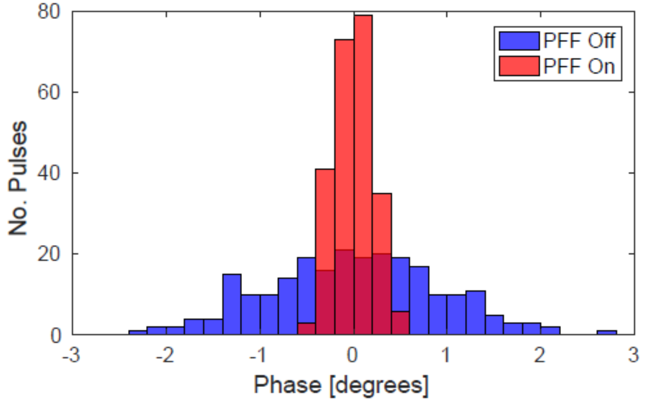
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



Current in combiner ring

28A

Drive beam arrival time stabilised to CLIC specification of 50fs



Examples of measurements from CLIC Test Facility, CTF3, at CERN.

CTF3 now the ‘CERN Linear Electron Accelerator for Research’ facility, CLEAR

Accelerator challenges

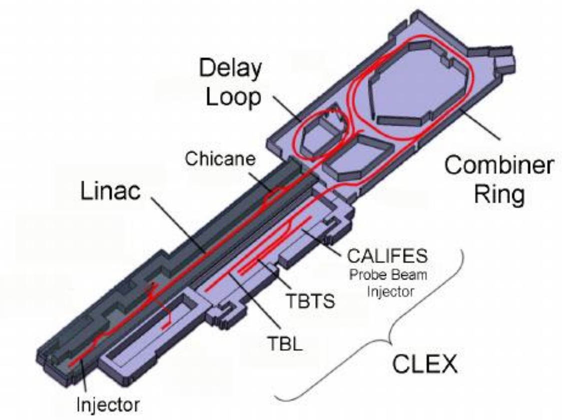
Four challenges:

High-current drive beam bunched at 12 GHz

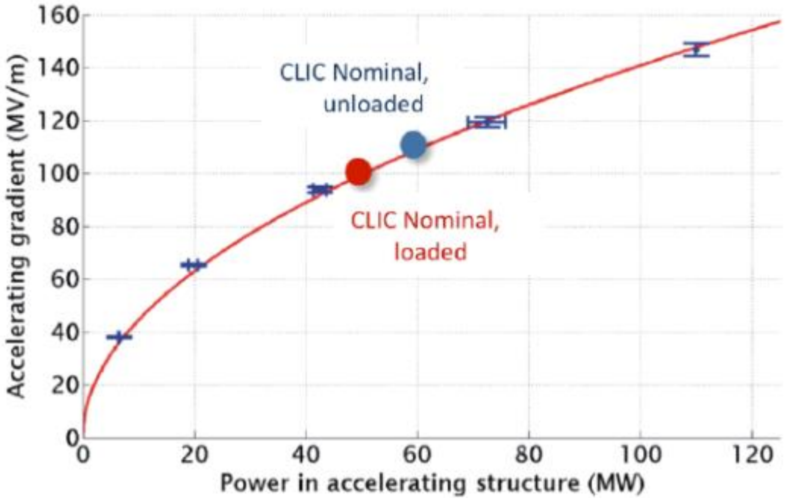
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

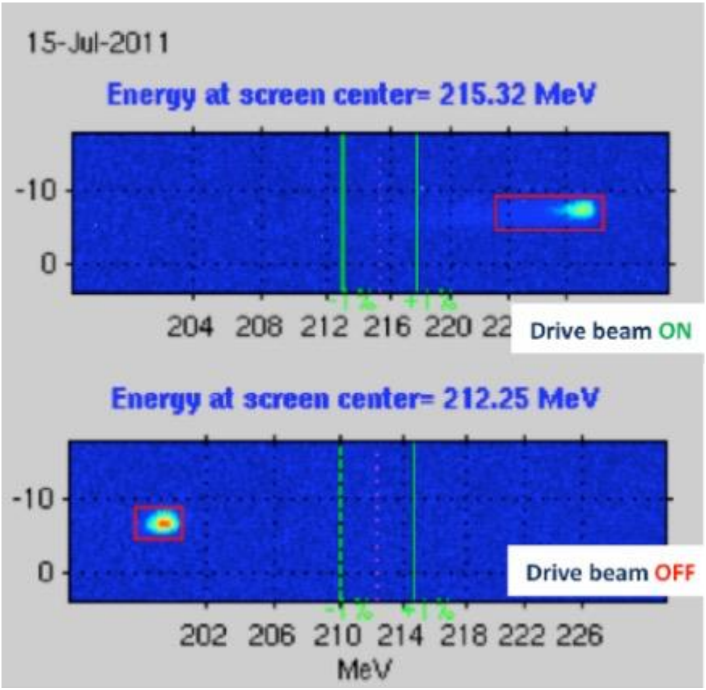
Alignment & stability



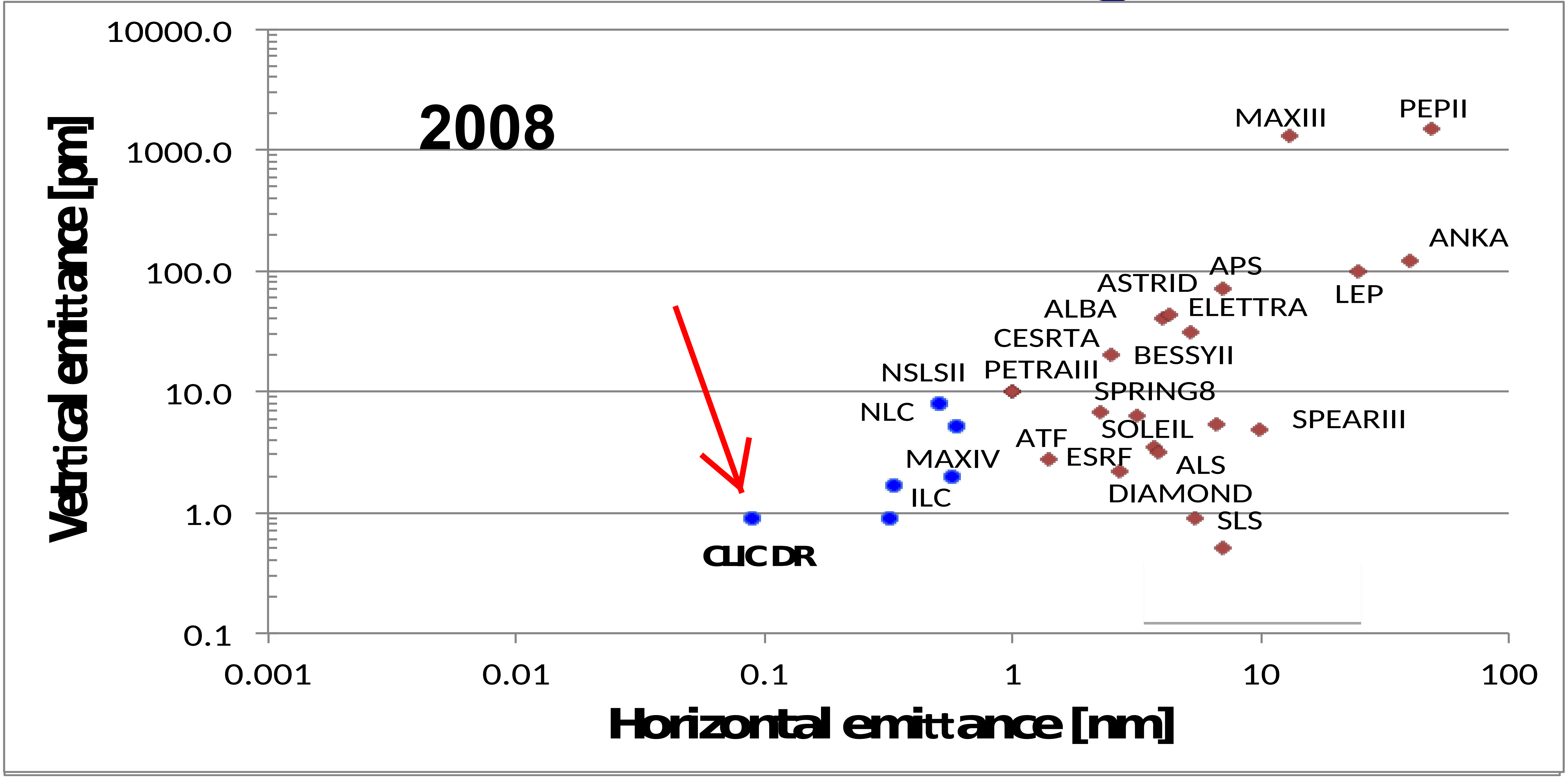
Demonstrated 2-beam acceleration



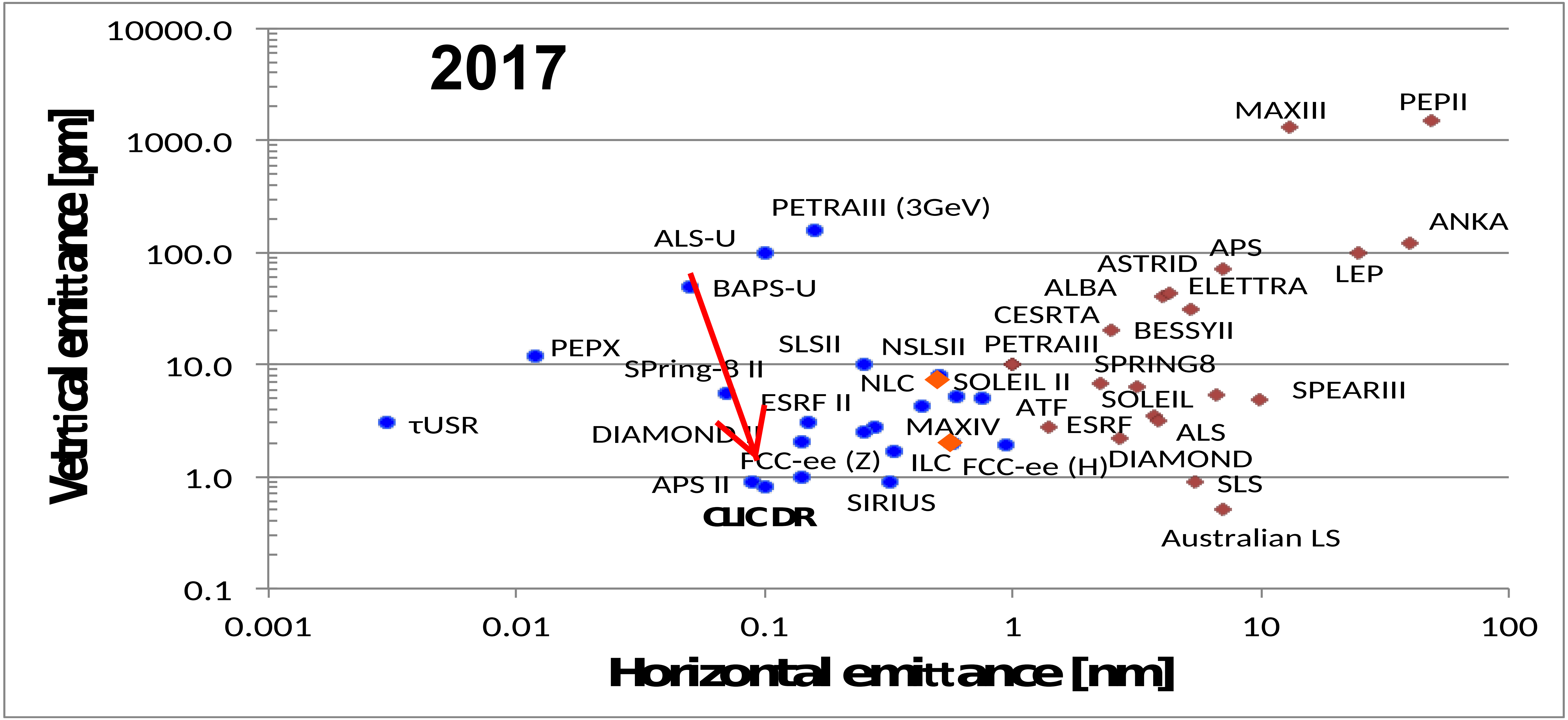
31MeV = 145MV/m



Emittance targets

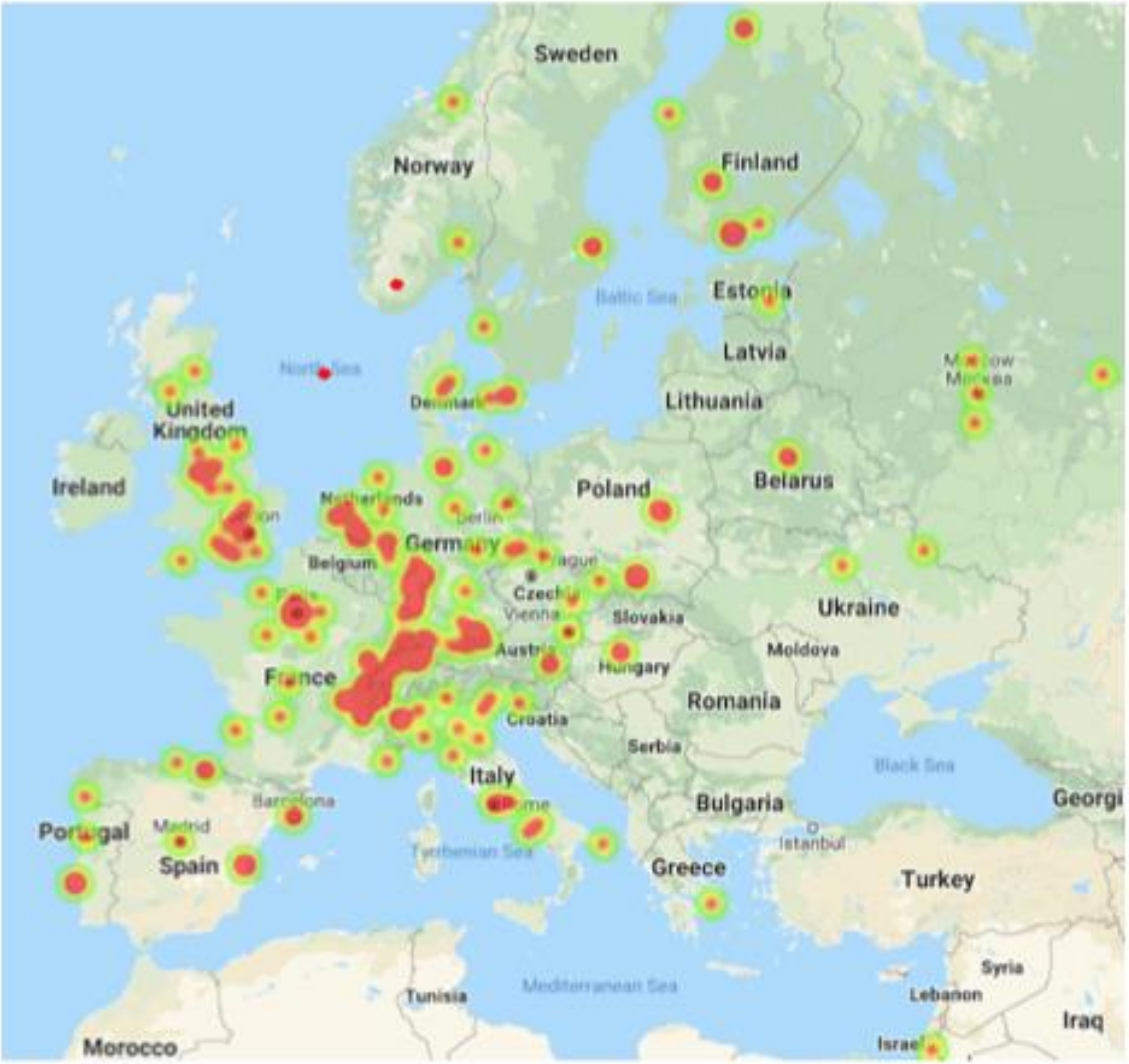


Emittance targets



X-band technology base now very wide

- X-band activities and studies in institutes and industry (intensity linked to resources, publications …)
- Similar maps possible to draw for Asian and US activities (and for other technologies than X-band)
- X-band used as part of machines (linearizers, deflectors) or as main RF



Compact

EU funded design study for a compact and low-cost XFEL.

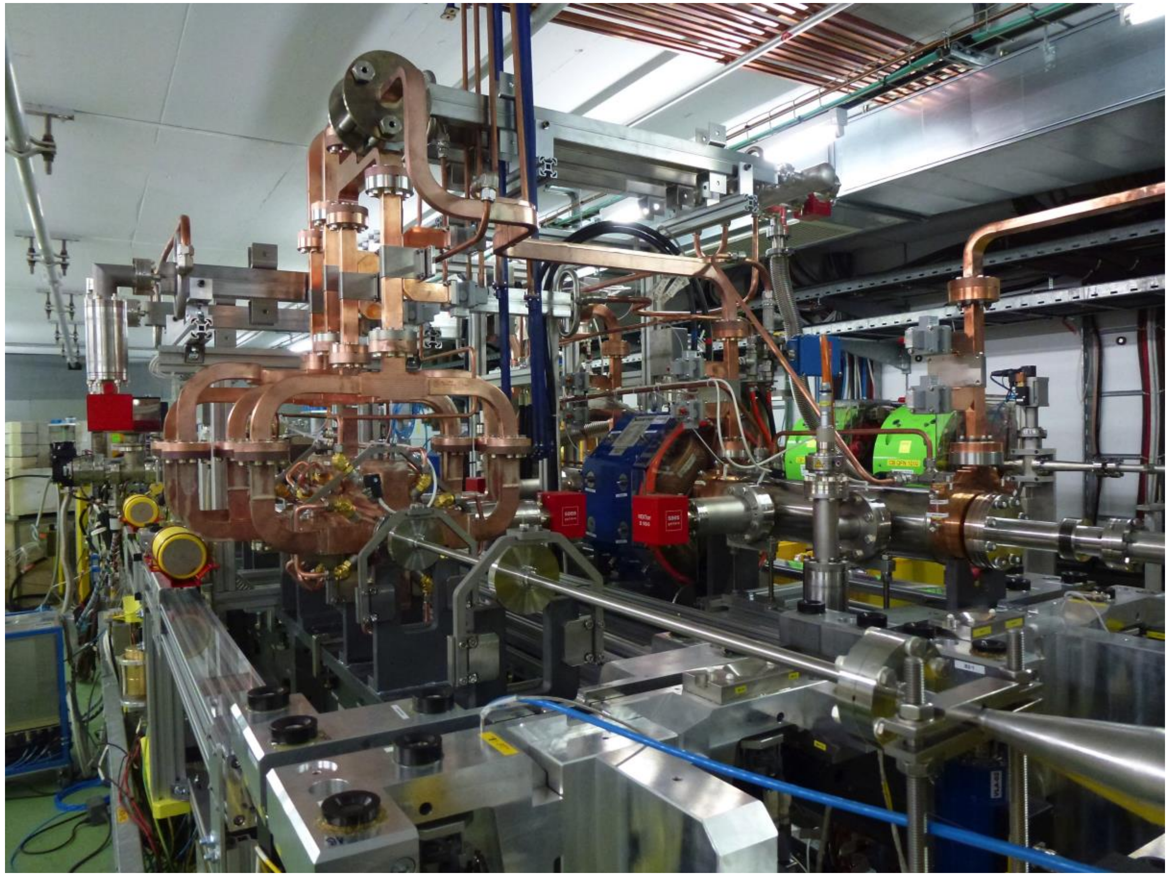
Target - SwissFEL performance at half the cost, to bring XFELs to national and regional facilities.

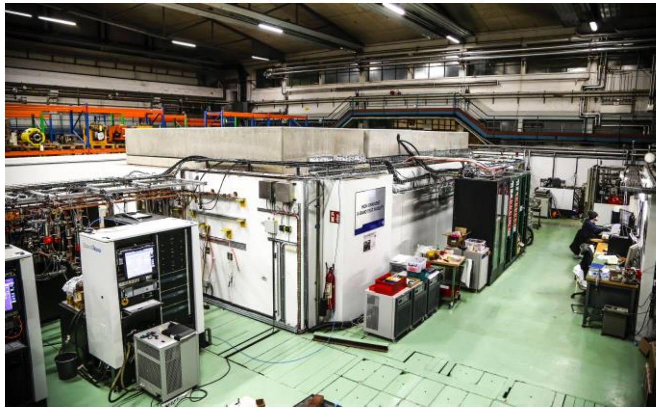
Based on advances in:

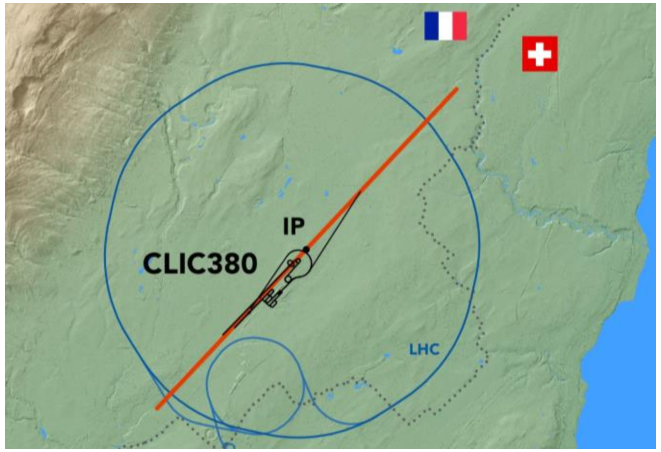
- Injectors
- X-band linac technology
- Undulators

CLIC main achievements

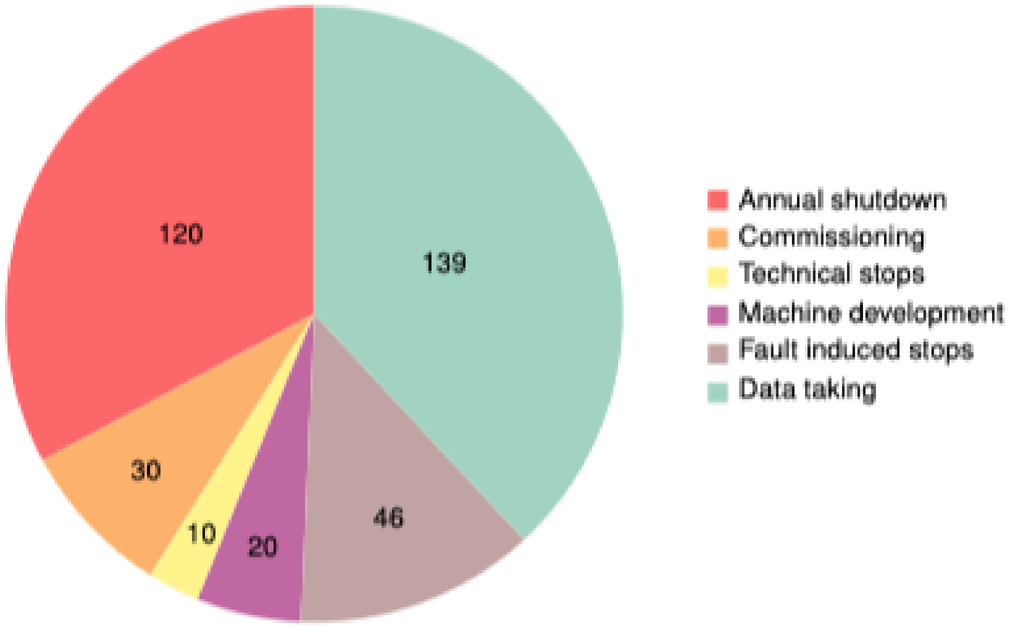
Key technologies have been demonstrated
CLIC is now a mature project ready for implementation



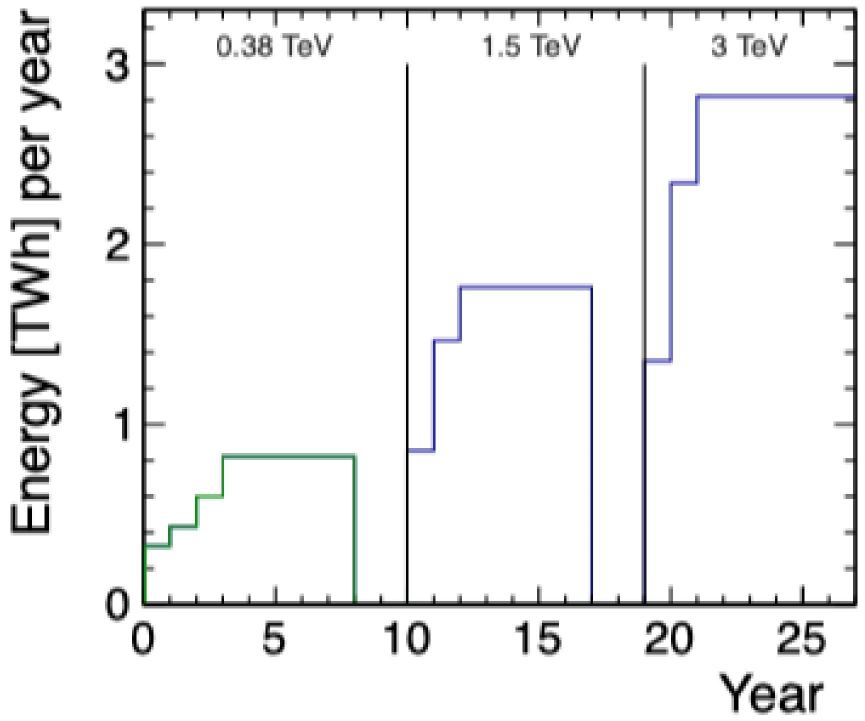




Energy



Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17



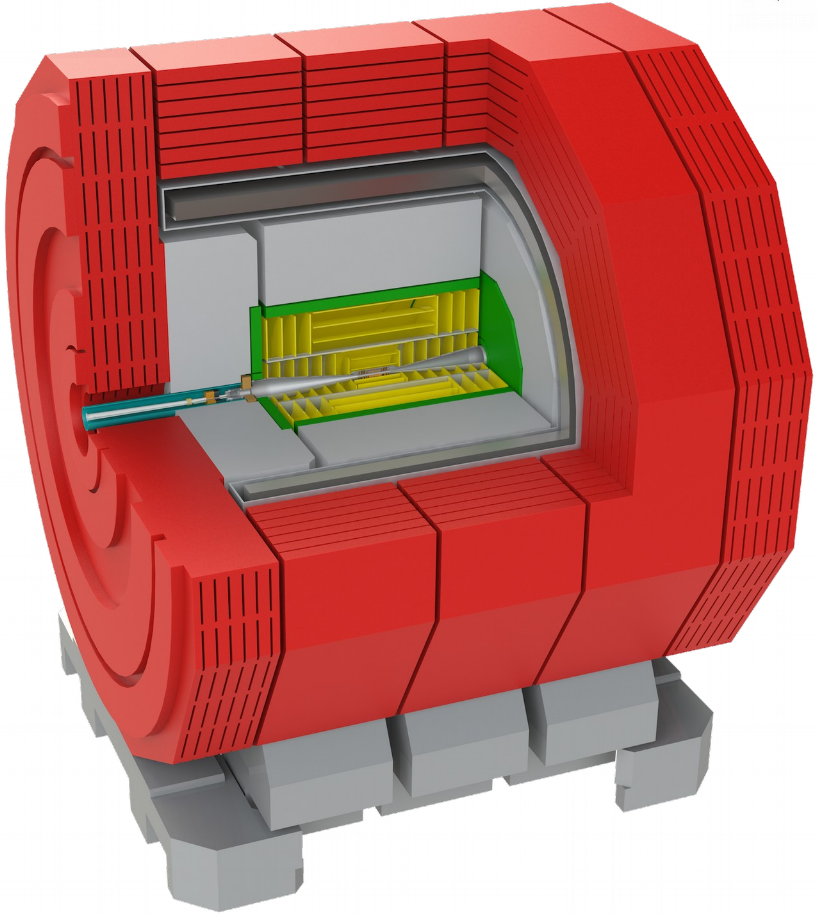
From running model and power estimates at various states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

~

CLICdet

Detector Concept for CLIC

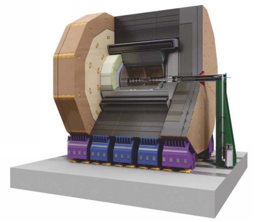


Detector Requirements

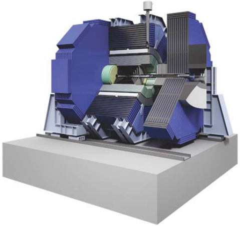
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m\ \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed LC detector concepts:

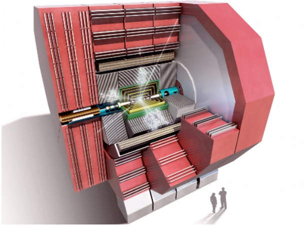
ILD



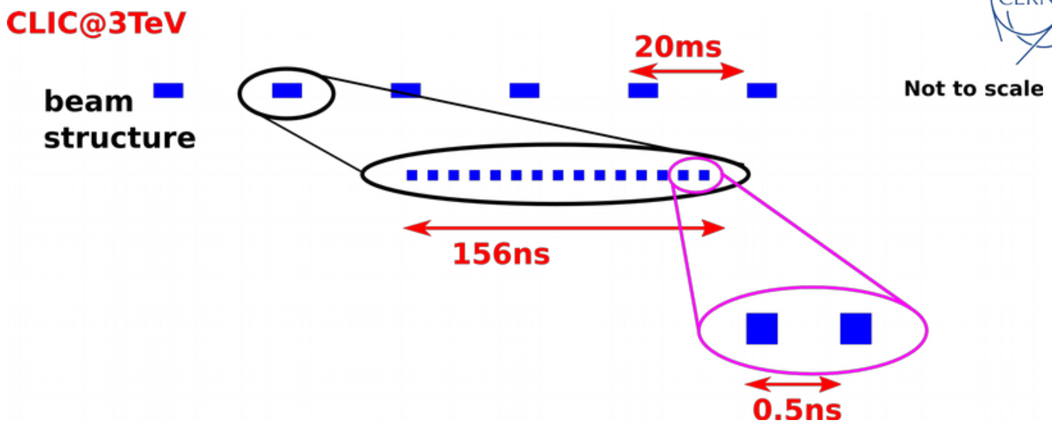
SiD



CLIC



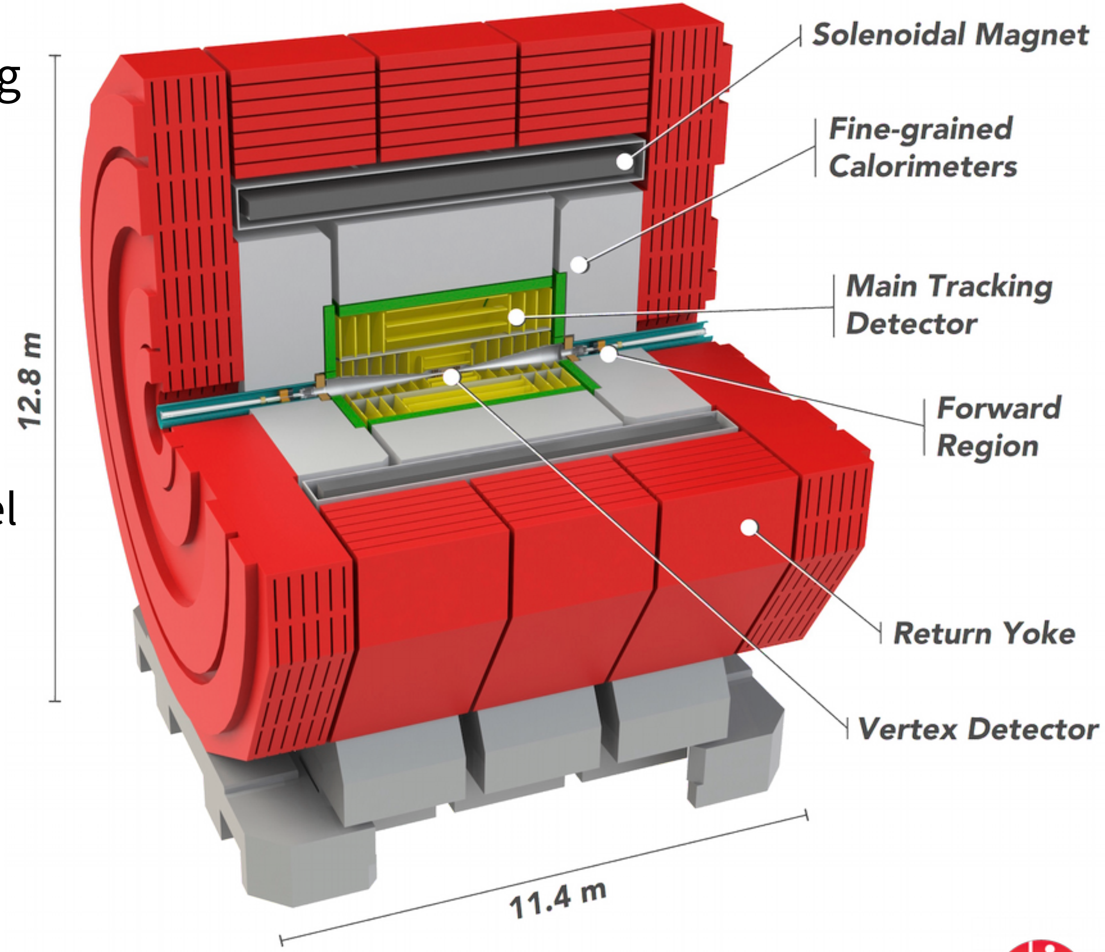
Experimental Conditions



- CLIC operates in bunch trains, repetition rate of 50 Hz
  - Low duty cycle
  - Possibility for power pulsing: switch detector components off between trains to reduce heat dissipation
- 312 bunches within train (at 3 TeV), separated by 0.5 ns
- Bunch separation & cross-section of background events drive timing requirements for detector
  - 1 ns time resolution for calorimeters
  - 5 ns single-hit resolution for vertex/tracking detectors

CLICdet – the CLIC detector Concept

- Low-mass all-silicon vertex and tracking detectors, R = 1.5 m
- High-granularity calorimeters:
  - ECAL: 22 X_0 + 1 λ_I
    40 layers Si sensors, W plates
  - HCAL: 7.5 λ_I
    60 layers plastic scintillator/SiPM, steel
- 4T superconducting solenoid
- Return yoke,
  Muon detectors interleaved
- **Optimized for Particle Flow Analysis**



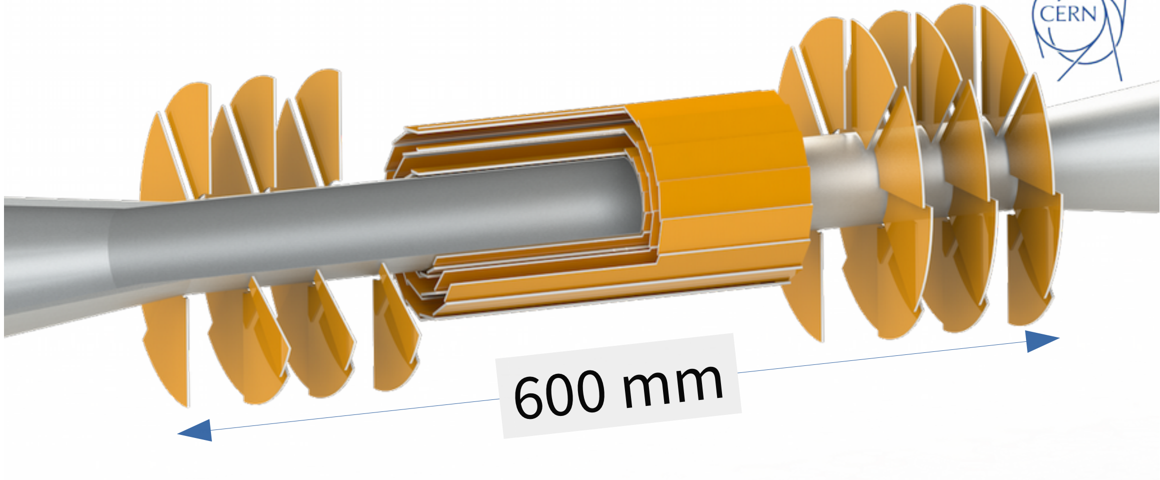
Vertex Detector

Design driven by flavor tagging

- Minimal scattering
- High-resolution

Requirements

- **Low mass**
  0.2% X_0 per layer
- **Low power consumption**
  50 mW/cm^{-2} for air-flow cooling
- **High single-point resolution**
  σ_{SP} ~ 3 µm
- **Precise time stamping** ~ 5 ns



Current design:

- Hybrid pixel detectors in double layers
- 50+50 µm sensor+ASIC, 25 µm pitch
- Surface area of ~ 0.84 m^2
- Three barrel layers, 2x three spiral disks

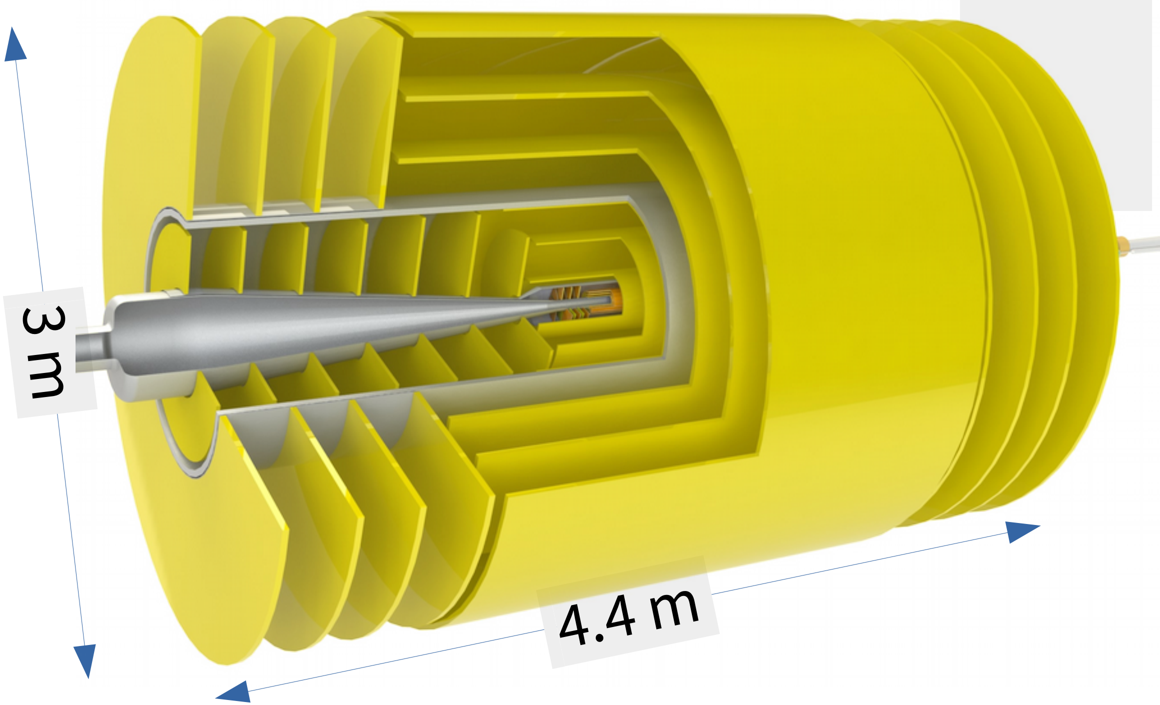
Tracking Detector

Design optimized for good efficiency & momentum resolution

- Many layers
- Large lever arm

Requirements

- **Low mass, high rigidity**
  1 – 2% X_0 per layer
- **Good single-point resolution**
  $\sigma_{SP} \sim 7\ \mu m$
- **High granularity**
  few % occupancy from backgrounds

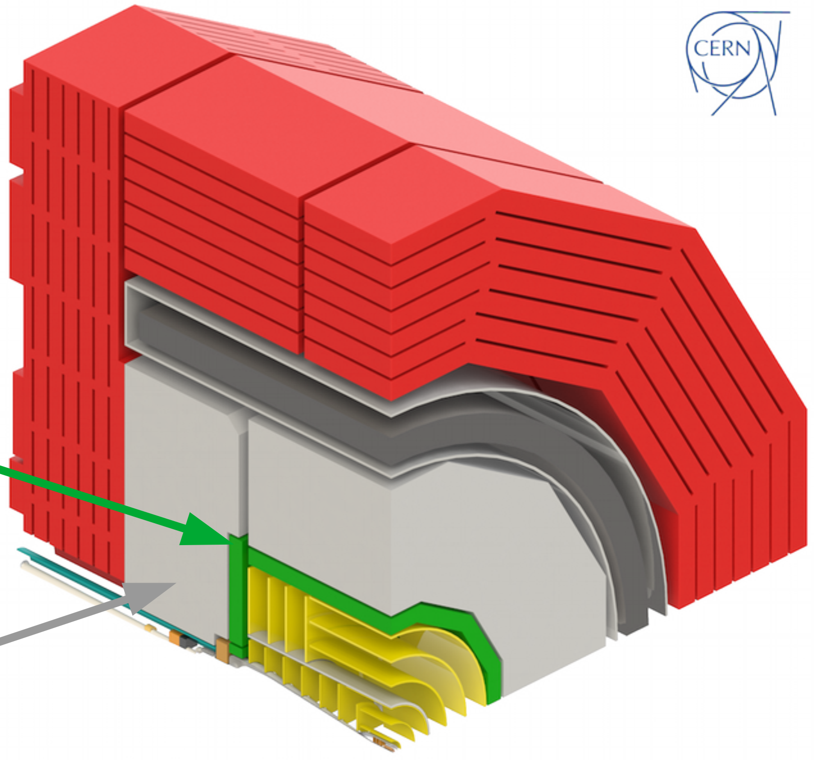


Current design:

- Monolithic detector with (elongated) pixels
- 200 µm sensor, including electronics
- Surface area of approx. 140 m^2
- Leakless water cooling

Calorimeters

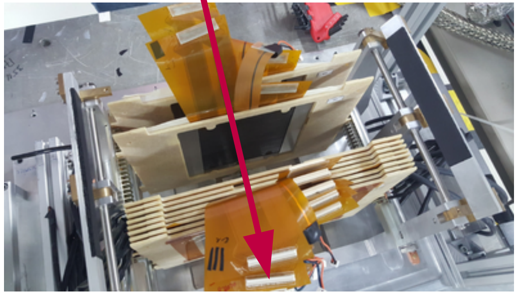
- Jet energy resolution of $\sigma_E/E \sim 5 - 3.5\%$
  - Highly granular calorimeters required
- **Electromagnetic Calorimeter: Si-W**
  - 2 mm tungsten plates, 500 µm silicon sensors
  - 40 layers 22 X_0 or 1 λ_I, 5 × 5 mm² cell size
  - ~2500 m² silicon, 100 million channels
- **Hadronic Calorimeter: Scint-Fe**
  - 19 mm thick steel plates, interleaved with 3 mm thick plastic scintillator + SiPMs
  - 60 layers: 7.5 λ_I, 30 × 30 mm² scintillator cell size
  - ~ 9000 m² scintillator, 10 million channels / SiPMs

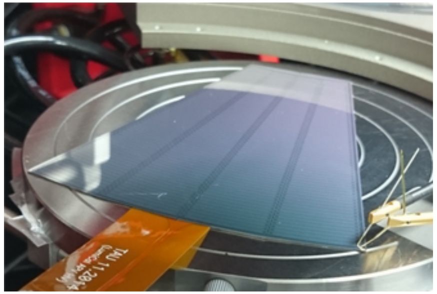


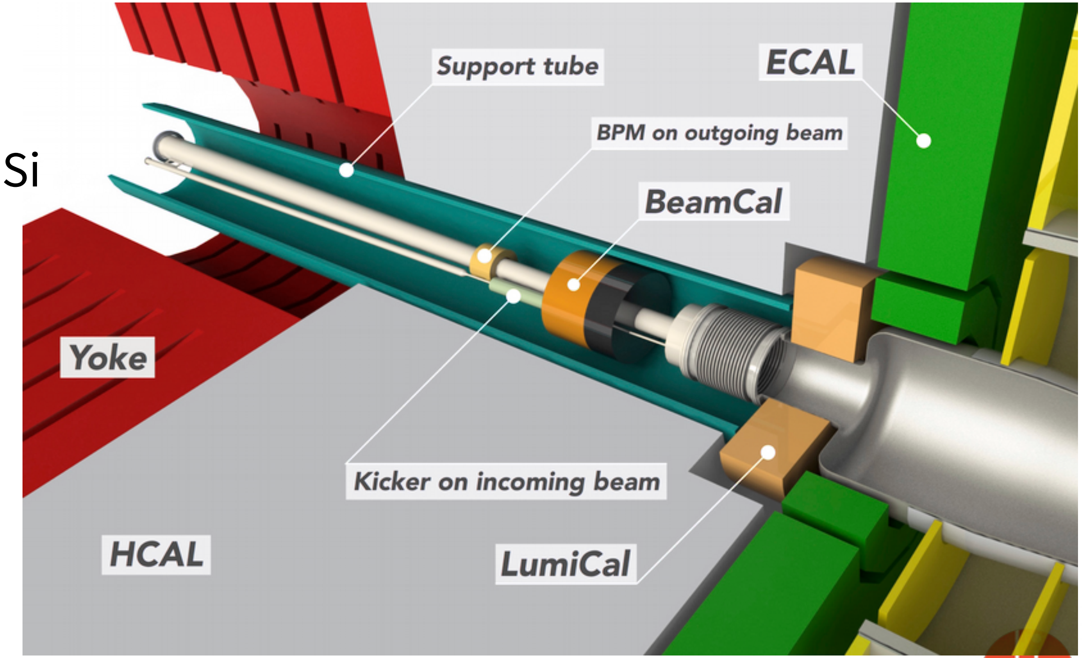
Forward Instrumentation: BeamCal & LumiCal

- Very forward electromagnetic sampling calorimeters
  - **LumiCal** for luminosity measurement via Bhabha scattering (few per mille accuracy)
  - **BeamCal** for very forward electron tagging (for beam tuning)
- e and γ acceptance down to small angles
  - Compact design, small Molière radius
- Current design: BeamCal: GaAs, LumiCal: Si
- Talk by M. Idzik on LumiCal tests & ASIC

e^- DESY Testbeam

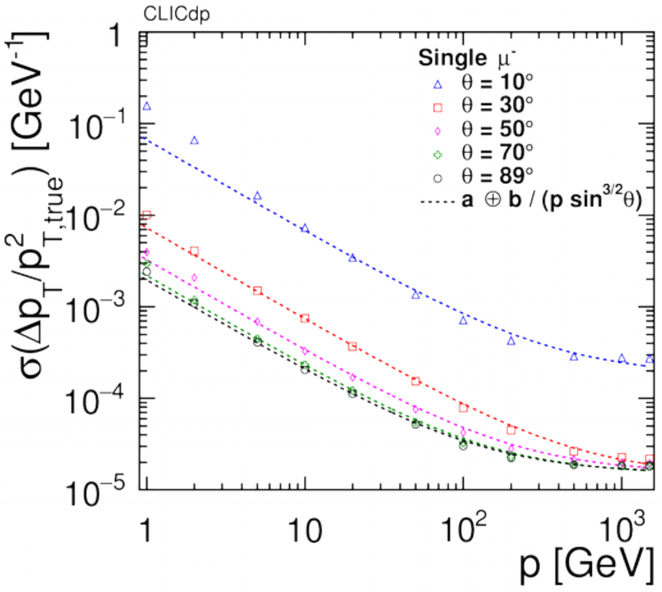


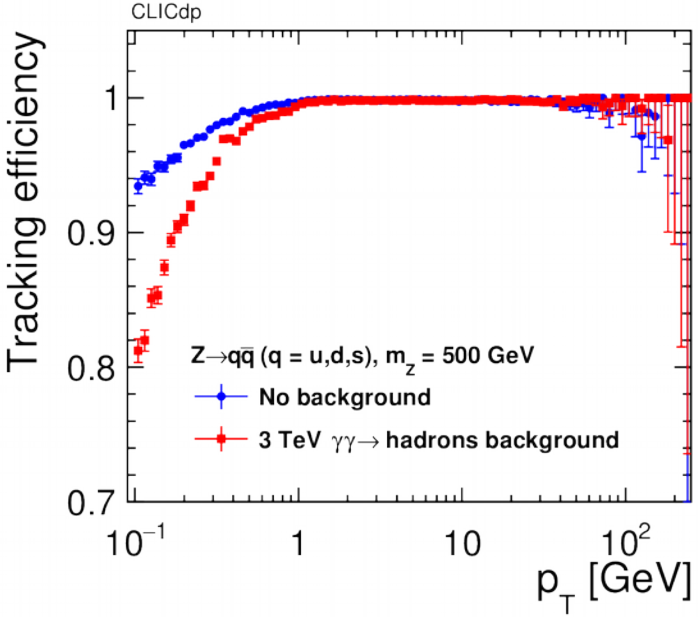


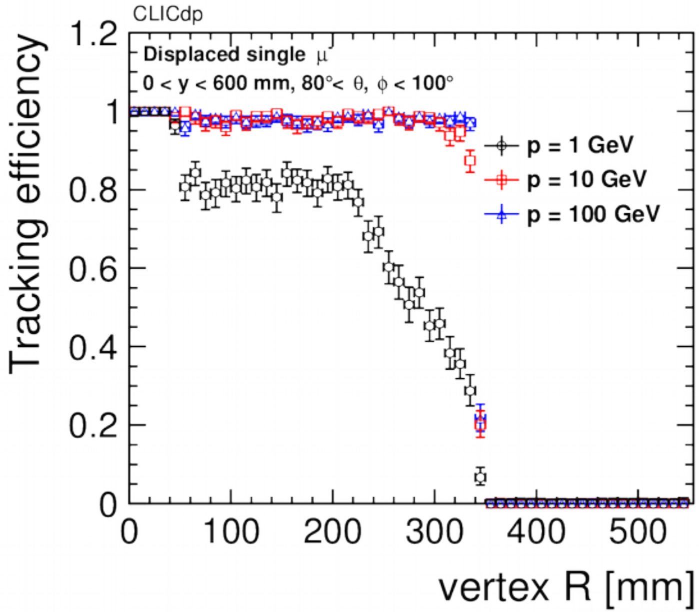


CLICdet Tracking Performance

- Achieved momentum resolution 2 x 10^{-5} GeV^{-1} for high energy muons in the barrel
- Tracking efficiency very high, negligible impact of background particles > 1 GeV
- High efficiency for displaced tracks within acceptance (min. 5 tracker hits required)



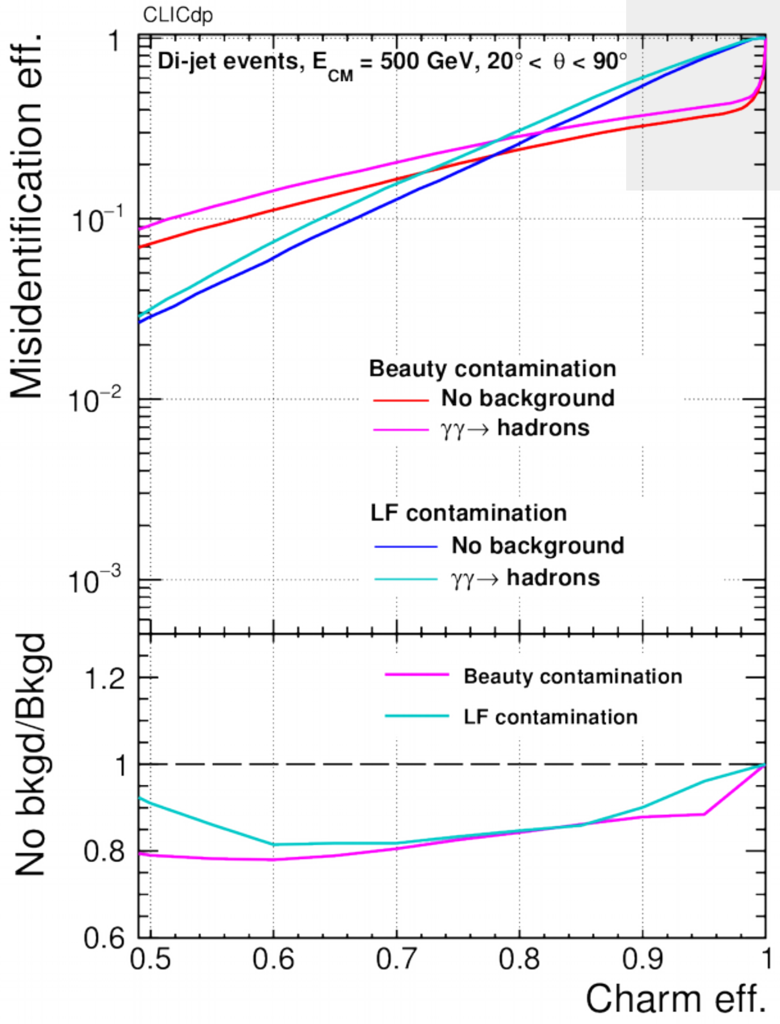




Flavor Tagging Performance

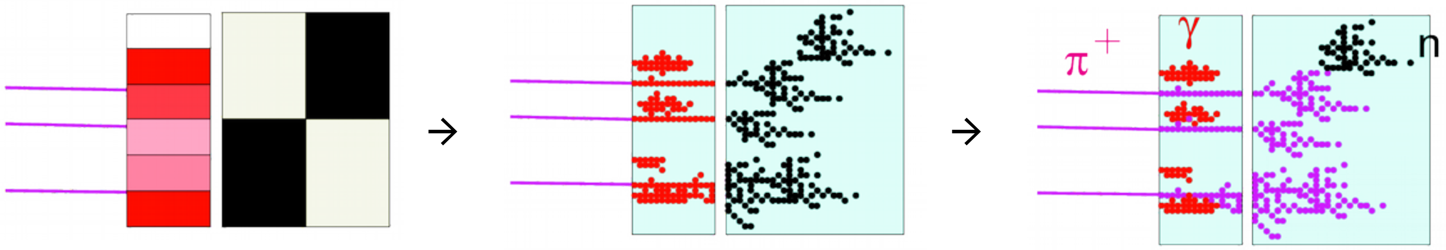
- Several studies on flavor tagging efficiencies performed, to be found in performance note
  - LCFIPlus package is used for flavor tagging

- Charm tagging performance
  - Using di-jet samples, E_{CM} = 500 GeV
  - With and without background (3 TeV, 30 BX)
  - At 80% charm identification efficiency, beauty/light-flavor misidentification is
    - 25% without backgrounds
    - 30% with 3 TeV background overlay

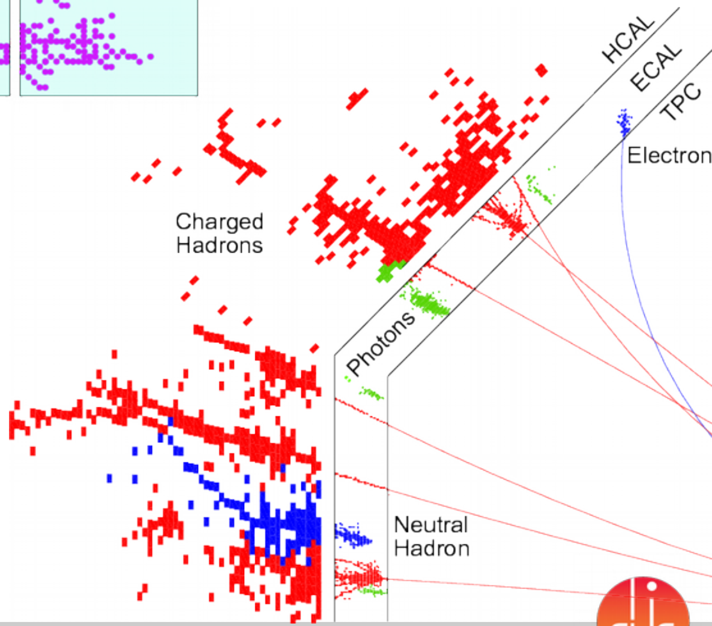


Jet Reconstruction & Particle Flow Algorithm

- Calorimeter clusters reconstructed via particle flow by **PandoraPFA**
  - Uses reconstructed tracks and muon hits to match calorimeter hits

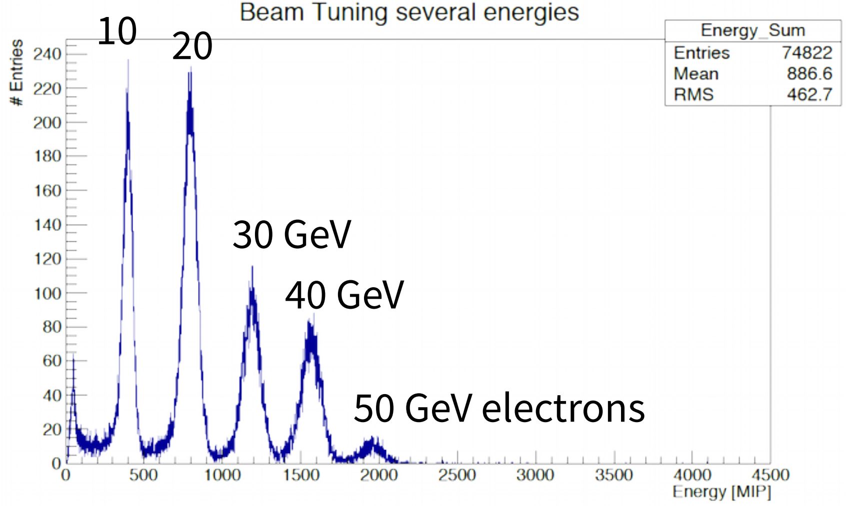


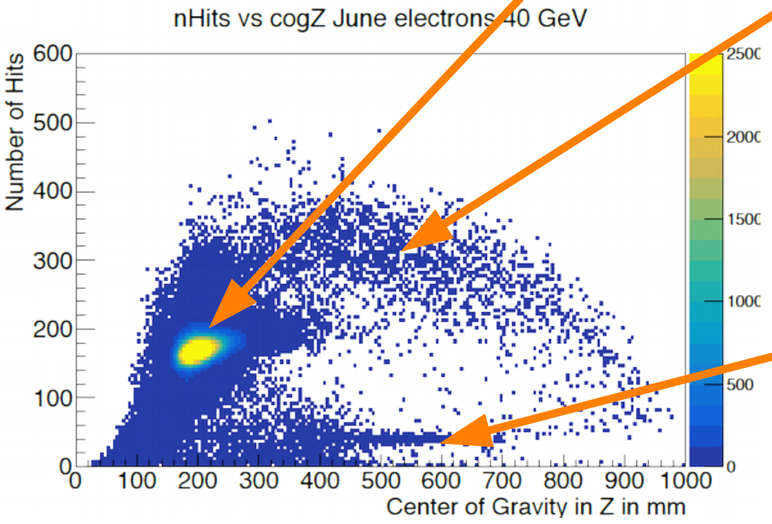
  - Requires highly granular calorimeter detectors
  - Talk on Software compensation by F. Simon
- Jets formed using VLC algorithm with R = 0.7
- Dedicated note:
  "Jet performance at CLIC" (CLICdp-Note-2018-004)

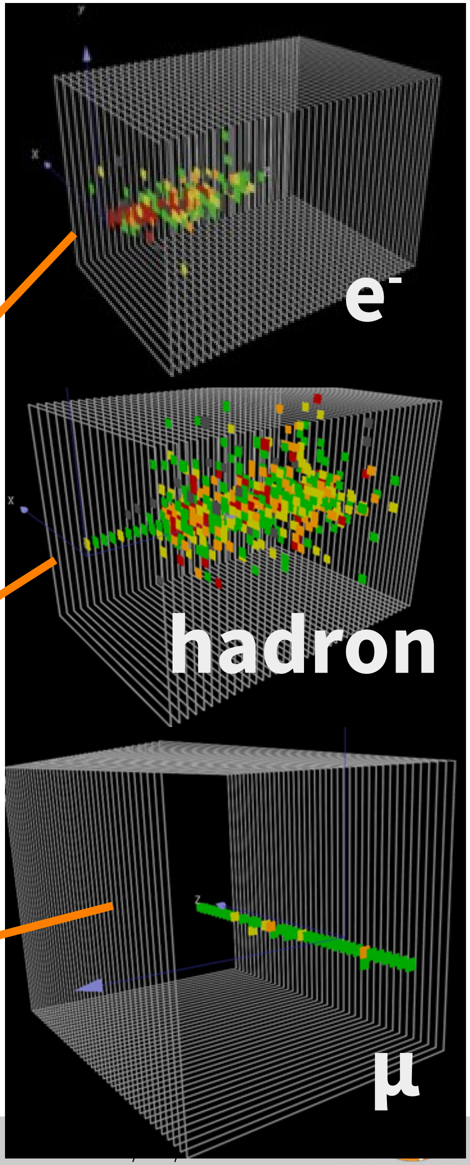


AHCAL Prototype Test Beam Results

- Many test beam campaigns in 2018 at SPS H2 beam line
  - Calibration with muons, energy scans for e-, π
- Prototype can resolve spatial and temporal development of hadronic showers in detail

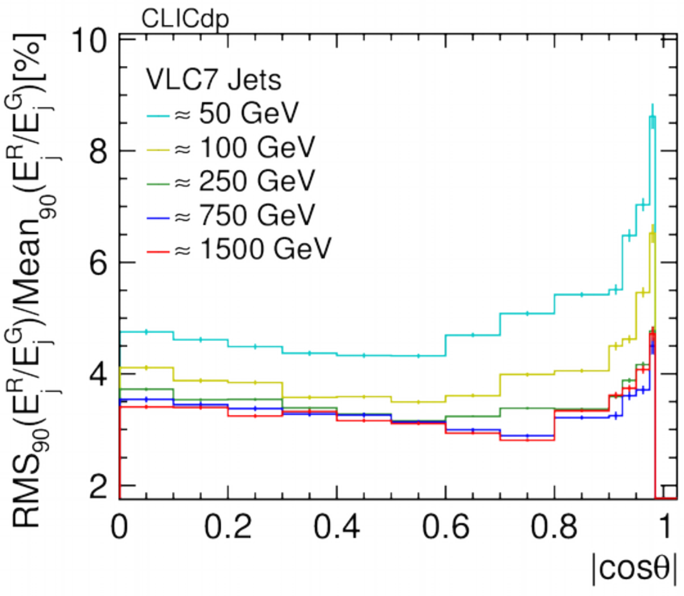


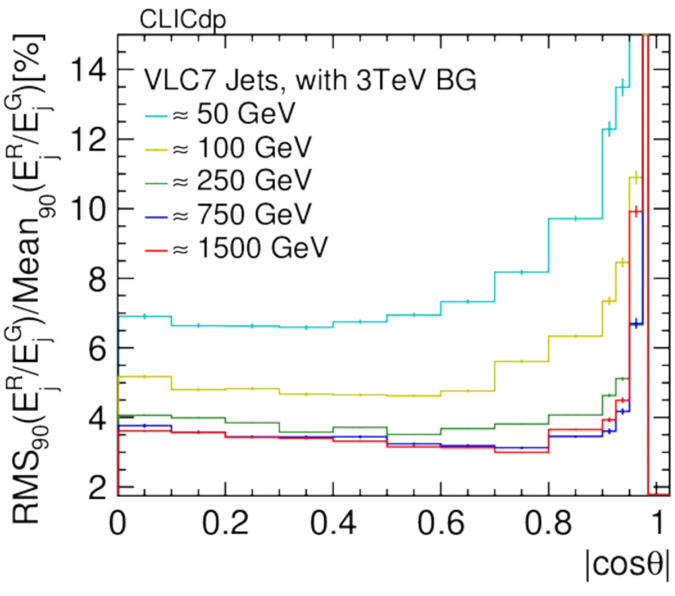


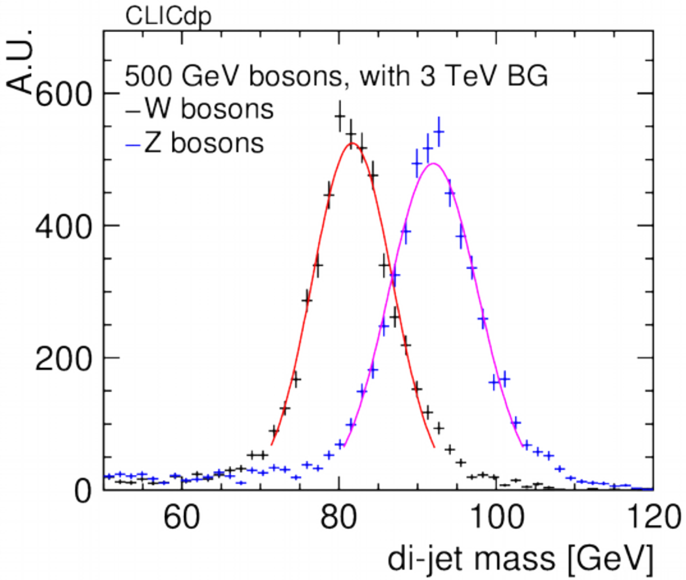


Jet Energy & Missing E_T Resolution

- Jet energy resolution from $Z/\gamma^* \rightarrow qq$, compare reconstructed and MC truth jets
  - Impact from 3 TeV backgrounds especially for low-energy jets, resolution 6-8%
- W/Z mass: 2σ separation with VLC7 jets, including 3 TeV backgrounds

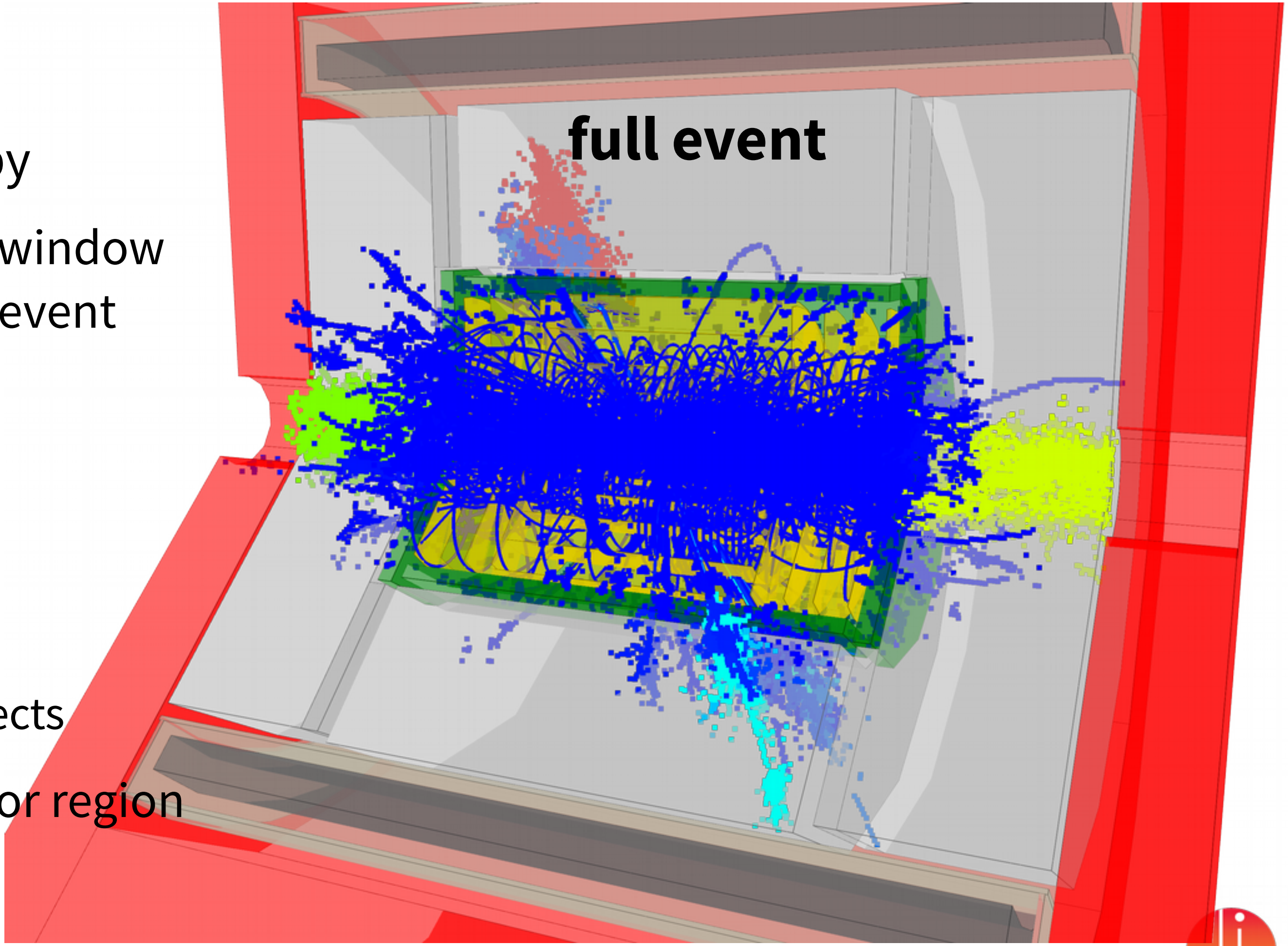






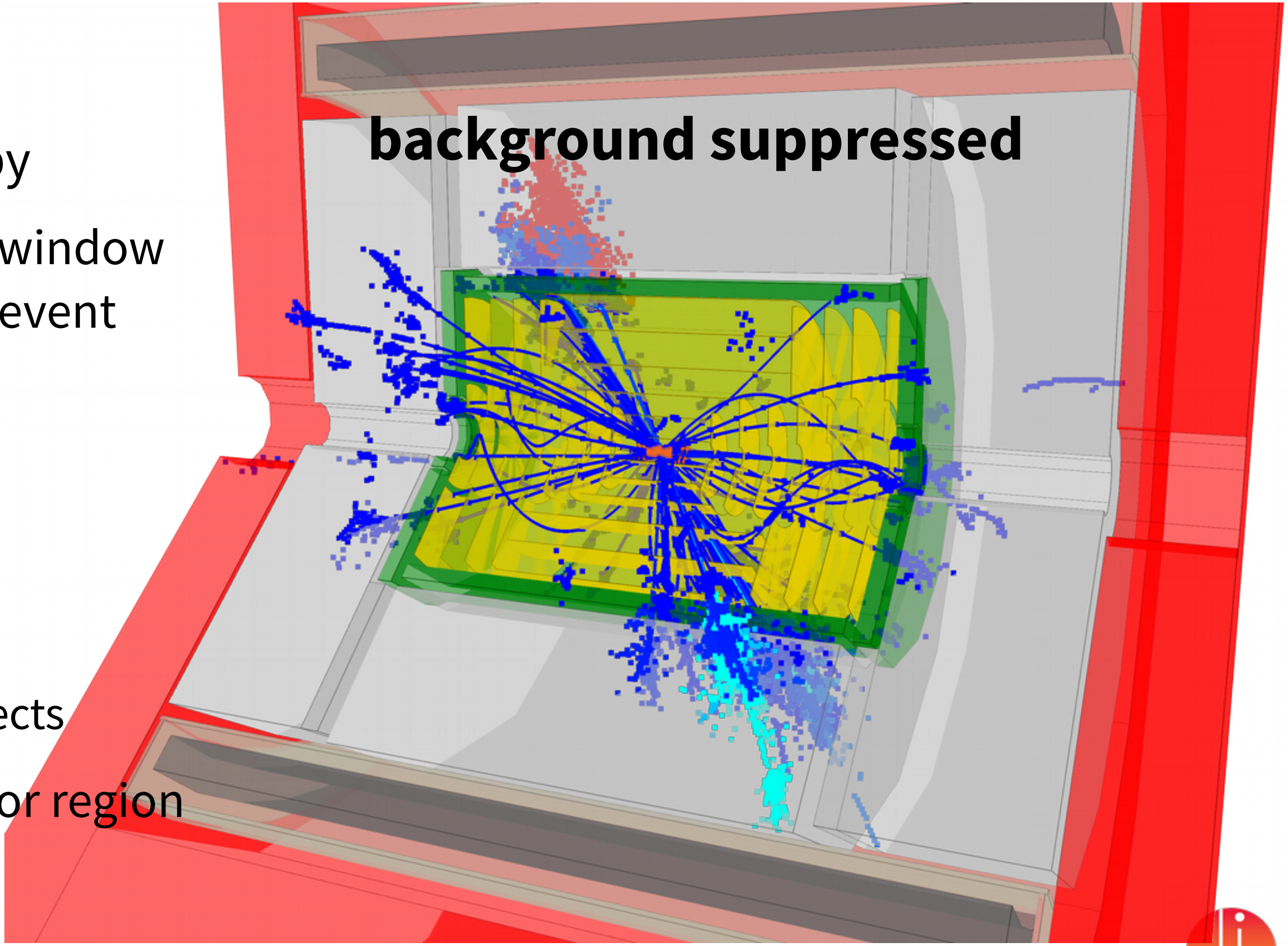
Background suppression @ **3 TeV**

- Fully-hadronic $t\bar{t}$ event
- Background suppression by
  - Defining reconstruction window 10 ns before, 30 ns after event
  - Building physics objects
  - Suppression via
    - Timing requirements
    - Particle type and p_T
    - Retaining high-p_T objects
  - Cuts adapted per detector region



Background suppression @ **3 TeV**

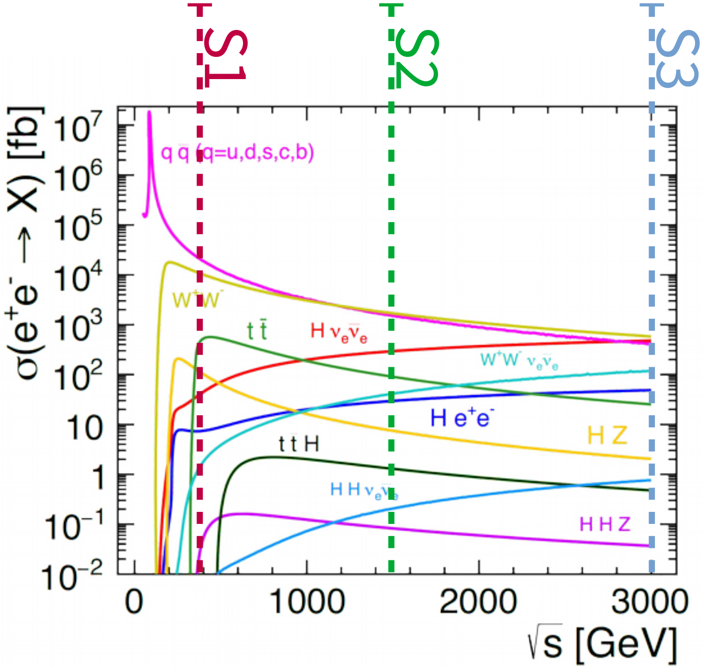
- Fully-hadronic $t\bar{t}$ event
- Background suppression by
  - Defining reconstruction window 10 ns before, 30 ns after event
  - Building physics objects
  - Suppression via
    - Timing requirements
    - Particle type and p_T
    - Retaining high-p_T objects
  - Cuts adapted per detector region



Physics Program

CLIC Physics Program – in 3 Stages

- Dedicated CLICdp Physics session in this workshop (Wed. & Thur.)
- Talk by F. Riva in this session: "Precision Physics and motivations for a high energy LC"



Stage 1: $\sqrt{s}$ = 380 GeV (1.0 ab^{-1})

- Higgs/top precision physics
- Top mass threshold scan

Stage 2: $\sqrt{s}$ = 1.5 TeV (2.5 ab^{-1})

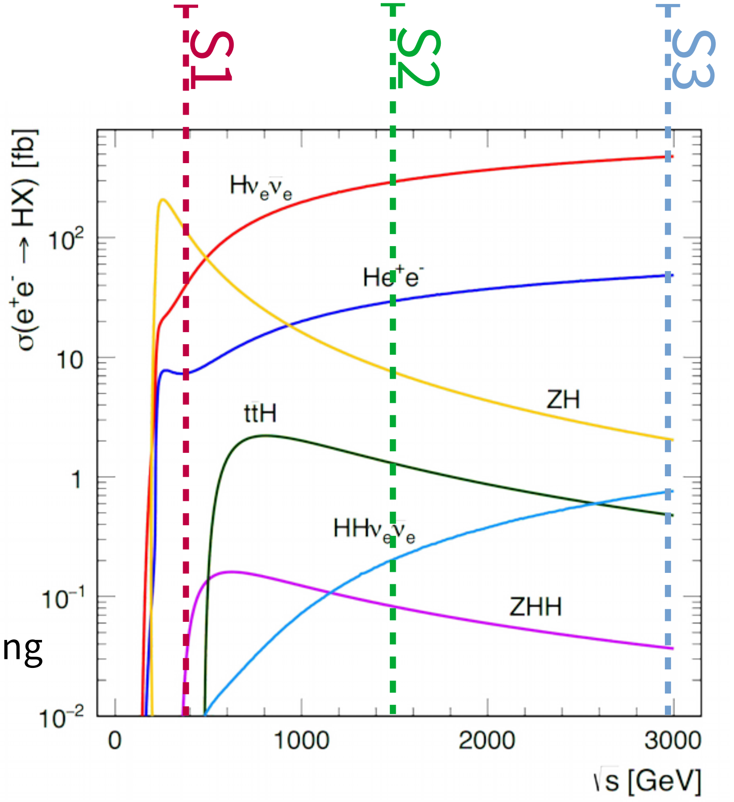
- Focus: BSM searches
- Higgs/top precision physics

Stage 3: $\sqrt{s}$ = 3 TeV (5.0 ab^{-1})

- Focus: BSM searches
- Higgs/top precision physics

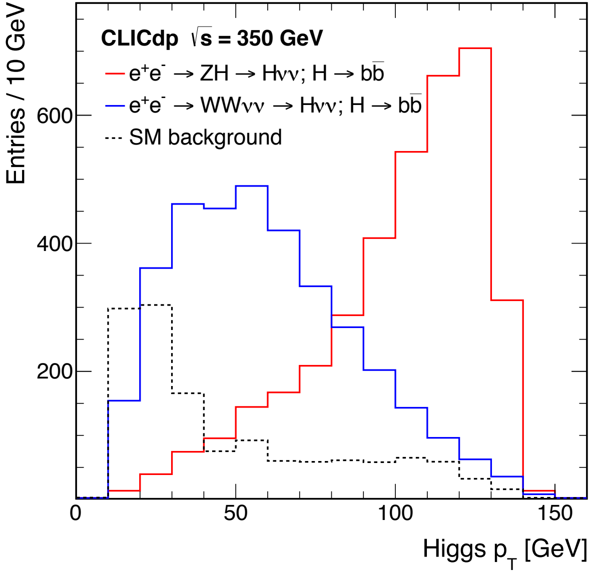
Higgs Physics

- Initial stage: study of Higgs boson production in
  - Higgsstrahlung ($e^+e^- \rightarrow ZH$)
  - WW-fusion ($e^+e^- \rightarrow H\,\nu_e\nu_e$)
  - Precise measurements of cross sections, decay width Γ_H, couplings (model-independent)
- High-energy stages:
  - High-statistics WW-fusion samples constrain Higgs couplings
  - Studies of rarer processes ($e^+e^- \rightarrow ttH$, $e^+e^- \rightarrow HH\,\nu_e\nu_e$) to measure top Yukawa coupling,
  - CLIC only proposed lepton collider for direct meas. of Higgs self-coupling
    - Talk on Higgs boson self-coupling by U. Schnoor
- **Detailed paper published:**
  "Higgs physics at the CLIC electron-positron linear collider"

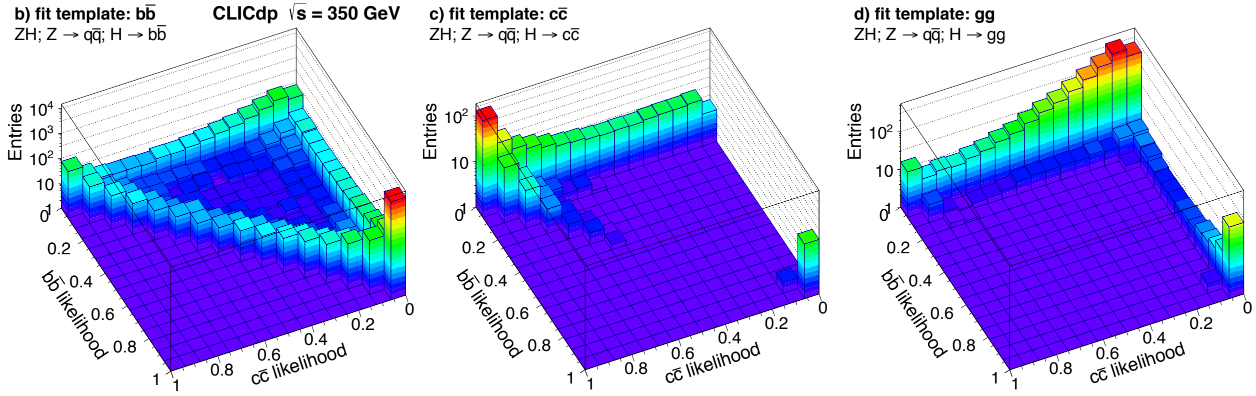


- Three decay modes bb/cc/gg
  → precise flavour tagging

- Production Mode: ZH or WW fusion
  →Higgs p_T spectrum



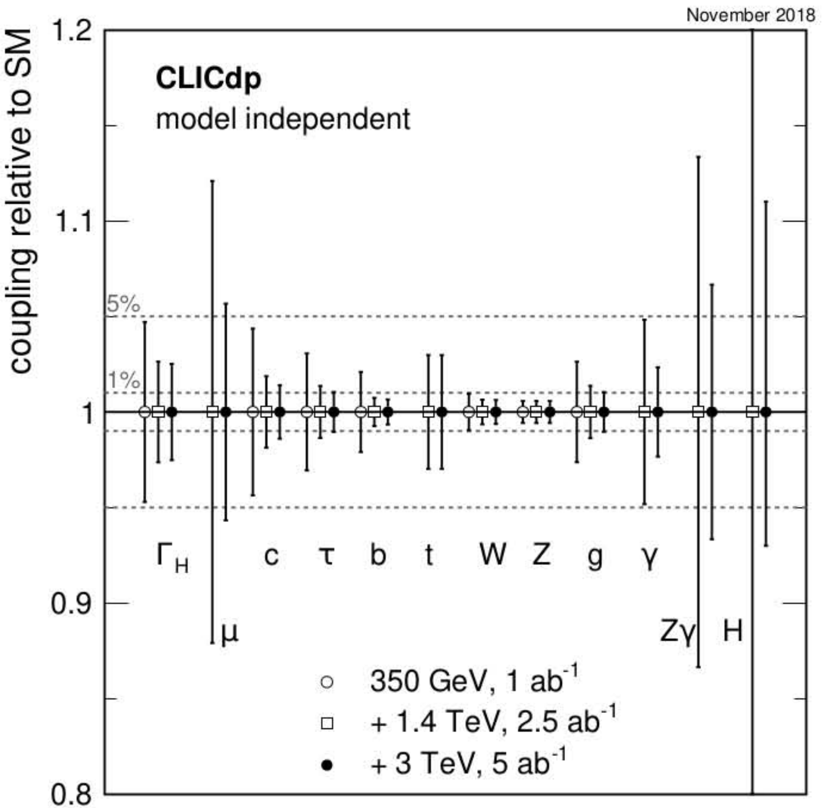
H→bb H→cc H→gg

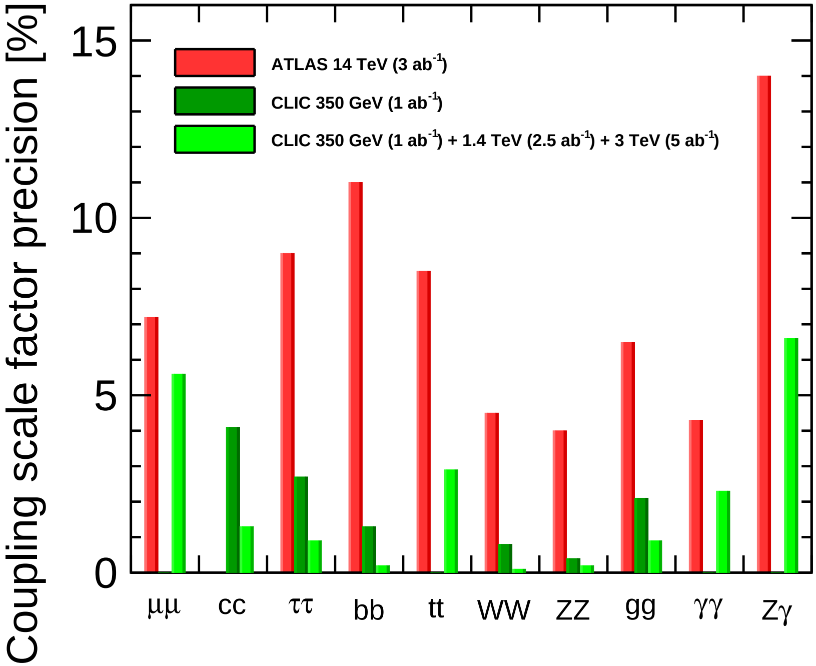


EPJC 76, 72 (2016)
arXiv:1708.08912

Fit templates using 2D distributions of bb vs cc likelihoods

Parameter	Relative precision		
	350 GeV 1 ab^{-1}	+ 1.4 TeV + 2.5 ab^{-1}	+ 3 TeV + 5 ab^{-1}
g_{HZZ}	0.6 %	0.6 %	0.6 %
g_{HWW}	1.0 %	0.6 %	0.6 %
g_{Hbb}	2.1 %	0.7 %	0.7 %
g_{Hcc}	4.4 %	1.9 %	1.4 %
$g_{H\tau\tau}$	3.1 %	1.4 %	1.0 %
$g_{H\mu\mu}$	—	12.1 %	5.7 %
g_{Htt}	—	3.0 %	3.0 %
$g^{\dagger}_{Hgg}$	2.6 %	1.4 %	1.0 %
$g^{\dagger}_{H\gamma\gamma}$	—	4.8 %	2.3 %
$g^{\dagger}_{HZ\gamma}$	—	13.3 %	6.7 %
Γ_H	4.7 %	2.6 %	2.5 %




Coupling scale factor precision [%]
0
5
10
15
ATLAS 14 TeV (3 ab^{-1})
CLIC 350 GeV (1 ab^{-1})
CLIC 350 GeV (1 ab^{-1}) + 1.4 TeV (2.5 ab^{-1}) + 3 TeV (5 ab^{-1})
μμ
cc
ττ
bb
tt
WW
ZZ
gg
γγ
Zγ

Higgs self-coupling in the Standard Model

In the SM

- Higgs potential in SM: $V = -m_H^2|\phi|^2 + \lambda|\phi|^4$

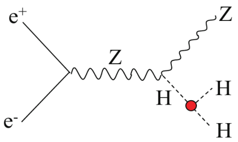
$\Rightarrow$ Self-coupling λ determines shape of the potential

- Relation of mass m_H and self-coupling λ:
  $m_H^2 = 2\lambda v^2$

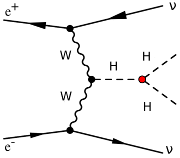
$\Rightarrow$ Relation of mass and self-coupling indicates if the H(125) boson originates from the Higgs field responsible for electroweak symmetry breaking

- Interaction Lagrangian: trilinear self-coupling
  $g_{HHH} = 6\lambda v$

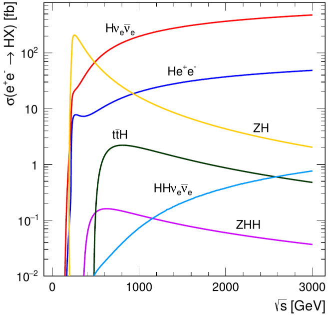
Double Higgsstrahlung ZHH



W-boson fusion $HH\nu_e$



Higgs pair event numbers



Eur. Phys. J. C77, 475 (2017)

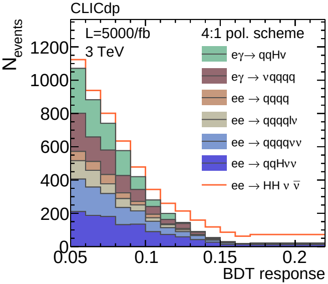
Three energy stages of CLIC –
Expected numbers of events with two Higgs bosons:

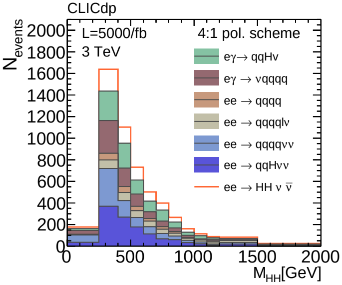
	380 GeV $1\,\mathrm{ab}^{-1}$	**1.4 TeV** $2.5\,\mathrm{ab}^{-1}$	**3 TeV** $5\,\mathrm{ab}^{-1}$	
ZHH	≈20	170	140	
$HH\nu_e\bar{\nu}_e$	≈2	550	4400	with beam polarisation
$HH\nu_e\bar{\nu}_e$	≈1	370	3000	without beam polarisation

- No HH production channel accessible below 500 GeV in e^+e^-
- ZHH production starts to be accessible at $\sqrt{s} \gtrsim 500$ GeV
- $HH\nu_e\bar{\nu}_e$ production grows with energy
- Beam polarisation $P(e^-) = -80\,\%$ ($+80\,\%$): multiply $HH\nu_e\bar{\nu}_e$ rate by factor 1.8 (0.2)

Event selection for 3 TeV $HH\nu_e\bar{\nu}_e$

- Signal and background samples produced with CLIC_ILD detector simulation and reconstruction
- Event selection based on multivariate analysis (BDT), b-tagging of jets





$b\bar{b}b\bar{b}$ analysis:

Signal region:

Signal = 766 events

Background = 4527 events

Conclusions

- Unique capability of CLIC: measuring the Higgs self-coupling to -7 %, + 11 % accuracy
- Direct accessibility of HH production at 1.4 and 3 TeV
- Challenging measurements: small cross section, forward b-quarks
- Benefits from excellent heavy flavor tagging, jet energy resolution of CLIC detector

CLIC double Higgs and Higgs self-coupling programme:

	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \geq 1100\,\text{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$5.9\,\sigma$ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -34 %, +36 % rate only analysis	1.4 & 3 TeV: -7 %, + 11 % differential analysis

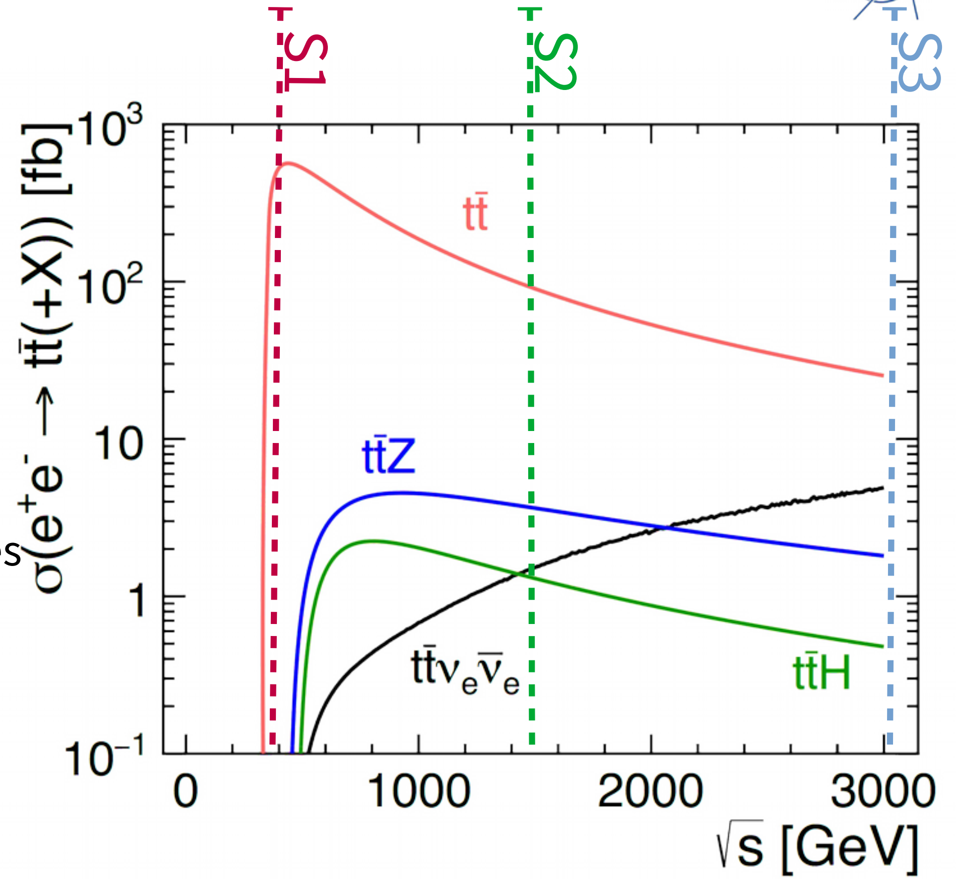
\+ Global EFT fit ($\rightarrow$ Francesco's talk)

\+ BSM interpretation (e.g. Baryogenesis)

$\Rightarrow$ Together with the high-precision Higgs and top physics programme at CLIC, this measurement will clarify the nature of the electroweak symmetry breaking mechanism

Top-Quark Physics

- Initial stage: focus on
  - top-quark pair production
  - tt pair production threshold scan at 350 GeV
    - Precise measurement of top-quark mass in well-defined theoretical framework
- Higher-energy stages:
  - top-quark pairs in association with other particles
  - ttH production, top Yukawa coupling
  - Vector boson fusion (VBF) production
  - Combine measurements in global fits
- **Detailed paper in journal review:** “Top-Quark Physics at the CLIC Electron-Positron Linear Collider”

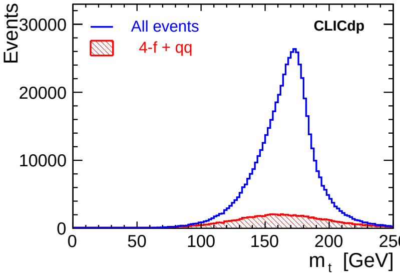


Top quark mass

Top quark pair production events

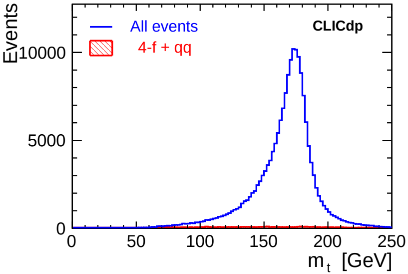
Reconstructed invariant mass for the hadronic top-quark decays for 1000 fb^{-1} at 380 GeV

Hadronic $t\bar{t}$ selection



$\sigma^{stat} = 30$ MeV

Semi-leptonic $t\bar{t}$ selection

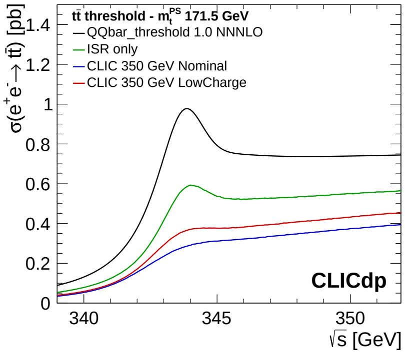


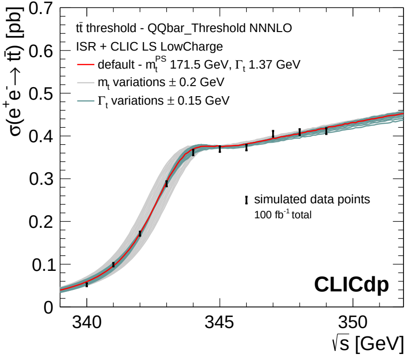
$\sigma^{stat} = 39$ MeV

But the systematic uncertainties (JES and **theory**) are much larger!

Threshold scan

Top pair production cross section around threshold
is very sensitive to top-quark mass, width and other model parameters
The dependence is smeared by ISR and CLIC luminosity spectra.

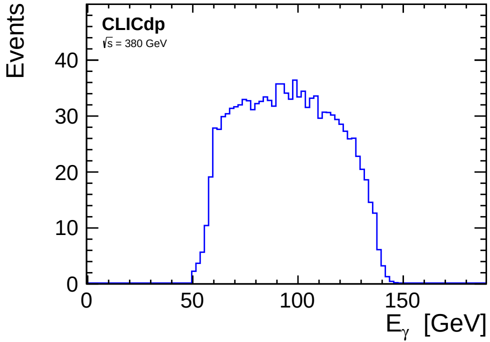




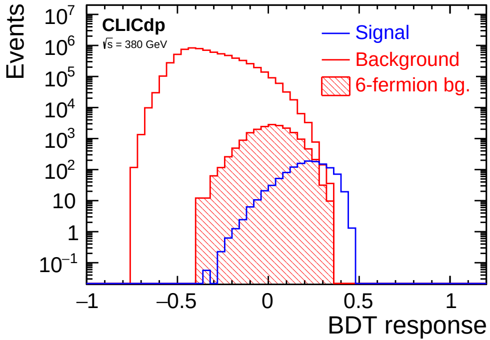
Expected statistical uncertainty for 100 fb^{-1} is 19 MeV (dedicated spectra)

Signal-background discrimination

Pre-selection based on the reconstructed photon energy.
Require $E_\gamma > 50$ GeV



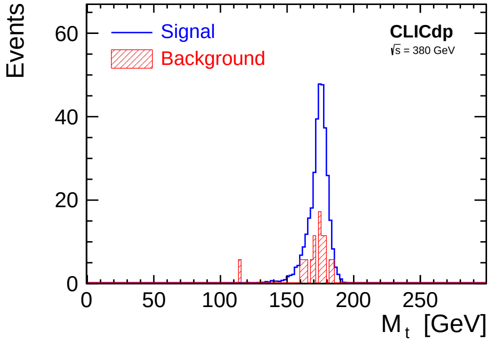
Limit from BDT response distribution for SM background events and FCNC signal
distributions shown for $BR(t \to c\gamma) = 10^{-3}$



Search for $t \to c\gamma$

Final results

Reconstructed $c\gamma$ invariant mass
For BDT selection cut, BDT > 0.29



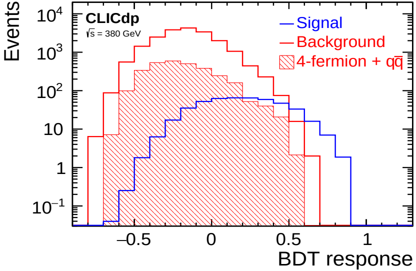
Expected limits for 1000 fb^{-1} collected at 380 GeV CLIC
calculated using the CL_s approach

$$BR(t \to c\gamma) \quad < \quad 2.6 \cdot 10^{-5}$$

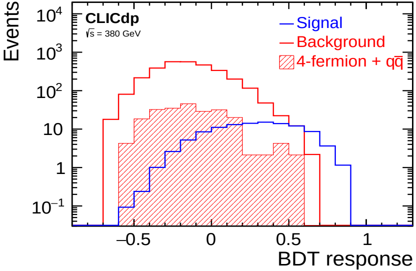
Multivariate analysis

Used for final signal vs background discrimination

Hadronic sample



Semi-leptonic sample



Expected limit

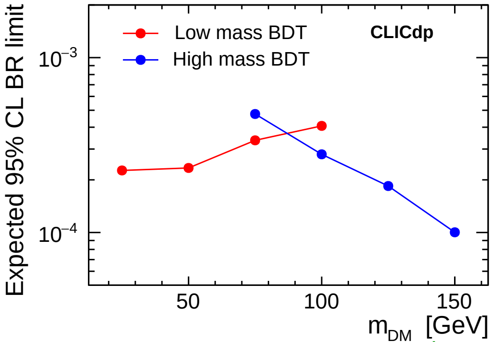
95% CL, $1000\,\mathrm{fb}^{-1}$ collected at 380 GeV

$\mathrm{CL_s}$ method applied to BDT response distributions

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) \quad < \quad 8.8 \cdot 10^{-5}$$

Results

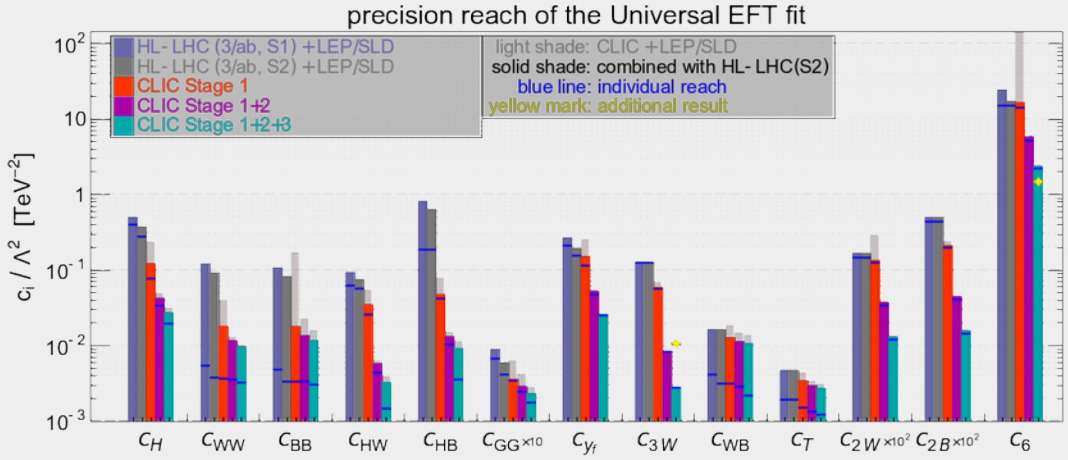
Expected limits for $1000\,\mathrm{fb}^{-1}$ collected at 380 GeV CLIC
calculated using the CL_s approach



$$BR(t \to c\not{E}) < 1.0 - 3.4 \cdot 10^{-4}$$

Beyond-Standard-Model Physics

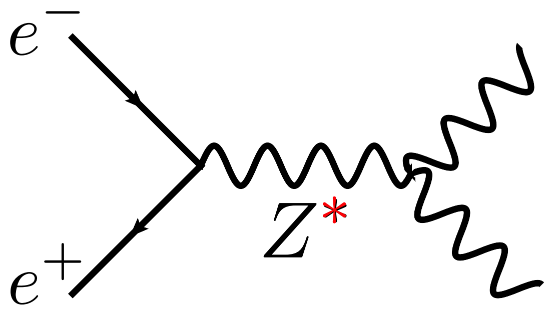
- **Indirect searches** through precision observables
  - Allow discovery of new physics beyond the center-of-mass energy of the collider
- **Direct production** of new particles
  - Possible up to the kinematic limit
  - Precision measurements
  - Complements the HL-LHC program
- EFT fits combining measurements, talk by F. Riva

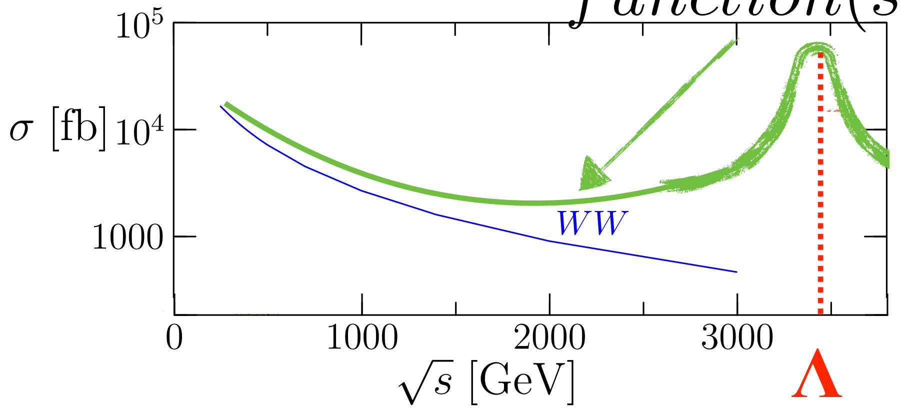


- **Comprehensive report published:** "The CLIC Potential for New Physics"

Precision (B)SM Tests

At High Energy: Infinite Observables → ~~Infinite~~ finite Information





Taylor expansion

$$function(s) = f(0) + f'(0)s + f''(0)s^2 + \cdots$$

Effective Field Theory (EFT)

= systematic Taylor expansion for all observables

It captures **all** heavy new physics ▸ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$

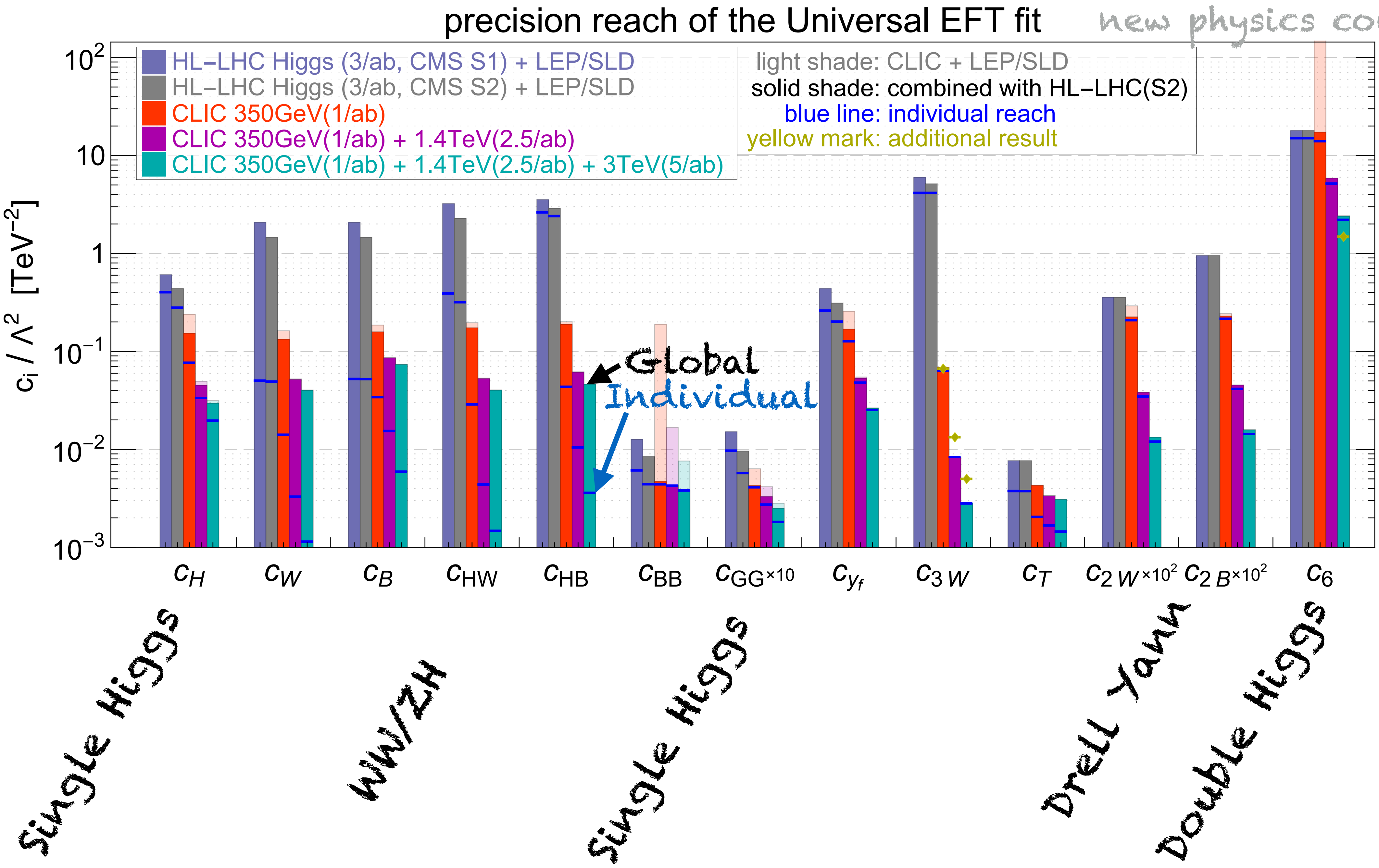
$f(0)$ and $f'(0)$ at same order

(dimension-6 EFT)

Global Fit

to all universal effects

new physics couples only to bosons



BSM Reach

≈ 1 TeV

≈ 3 TeV

≈ 10 TeV

Correlation, CLIC 350GeV+1.4TeV+3TeV

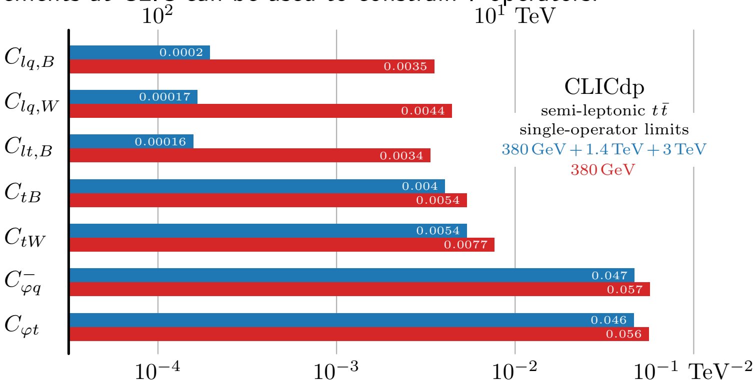
	c_H	c_W	c_B	c_{HW}	c_{HB}	c_{BB}	c_{GG}	c_{y_f}	c_{3W}	c_T	c_{2W}	c_{2B}
c_H	100	9	−17	−4	13	2	−62	−12	0	9	4	−2
c_W	9	100	−68	−95	94	8	−3	16	0	−8	2	−1
c_B	−17	−68	100	42	−88	−6	0	−9	−1	62	−6	6
c_{HW}	−4	−95	42	100	−79	−7	4	−16	0	−15	0	−1
c_{HB}	13	94	−88	−79	100	8	−2	14	1	−34	4	−4
c_{BB}	2	8	−6	−7	8	100	2	7	0	0	0	0
c_{GG}	−62	−3	0	4	−2	2	100	4	0	0	0	0
c_{y_f}	−12	16	−9	−16	14	7	4	100	0	6	1	0
c_{3W}	0	0	−1	0	1	0	0	0	100	−1	0	0
c_T	9	−8	62	−15	−34	0	0	6	−1	100	0	4
c_{2W}	4	2	−6	0	4	0	0	1	0	0	100	−42
c_{2B}	−2	−1	6	−1	−4	0	0	0	0	4	−42	100

Gu'18

EFT interpretation

Possible BSM effects induced by heavy new physics (above the direct reach of CLIC) are universally described by Effective Field Theory (EFT)

Top-quark measurements at CLIC can be used to constrain 7 operators:



First CLIC stage crucial for constraining 4 operators

Heavy Scalar Singlets

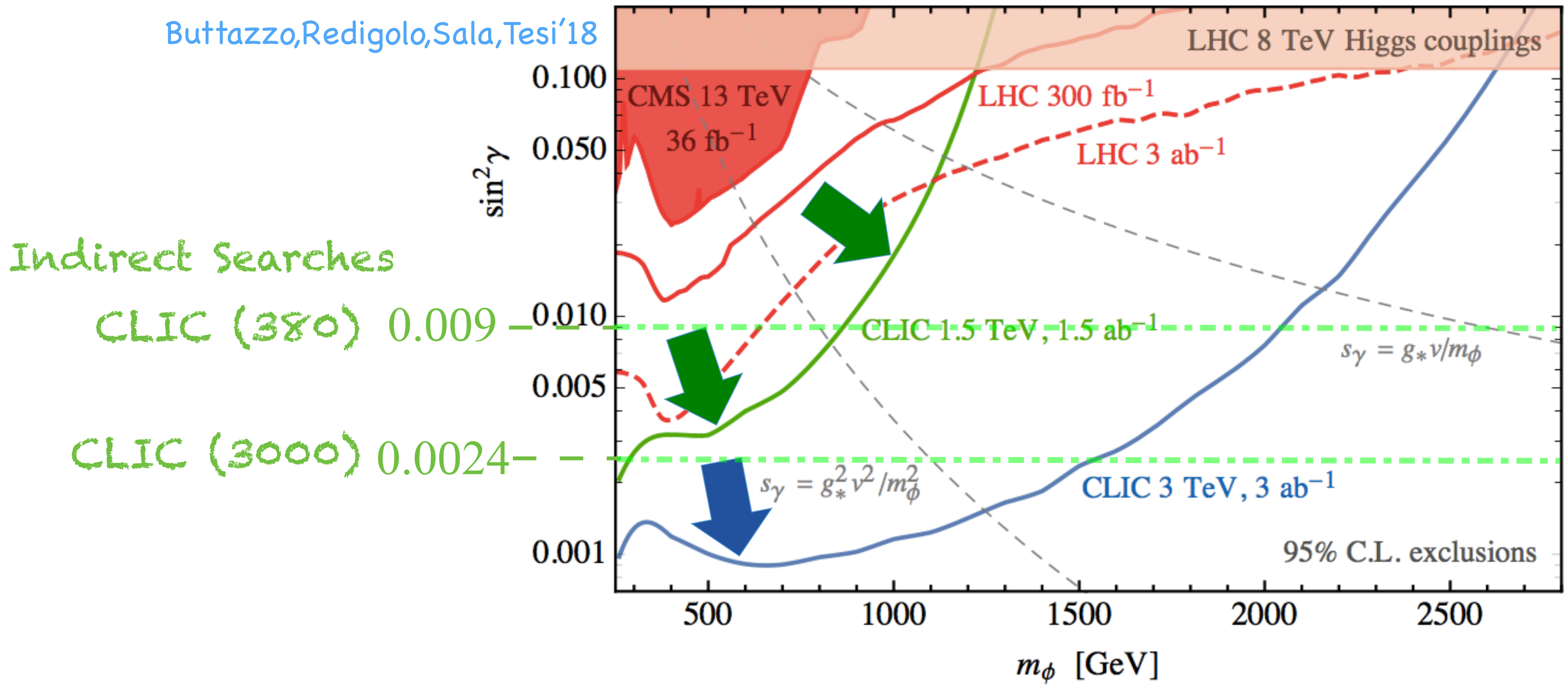
Heavy neutral spin-0 appear in many BSM scenario

ϕ-h mix:

$\phi = S\cos\gamma - h_0 \sin\gamma,$ → inherit Higgs couplings → Direct Searches

$h = h_0 \cos\gamma + S\sin\gamma,$ → reduce Higgs couplings → Indirect Searches

Buttazzo,Redigolo,Sala,Tesi'18



Inert Doublet Model

One of the simplest extensions of the Standard Model (SM).
The scalar sector consists of two doublets:

- Φ_S is the SM–like Higgs doublet,
- Φ_D (inert doublet) has four additional scalars H, A, $H^{\pm}$.

$$\Phi_S = \begin{pmatrix} G^{\pm} \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} H^{\pm} \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

We assume a discrete Z_2 symmetry under which

- SM Higgs doublet Φ_S is *even*: $\Phi_S \to \Phi_S$ (also other SM→SM)
- inert doublet Φ_D is *odd*: $\Phi_D \to -\Phi_D$.

⇒ Yukawa-type interactions only for Higgs doublet (Φ_S).
The inert doublet (Φ_D) does not interact with the SM fermions!

⇒ The lightest inert particle is stable: a natural candidate for dark matter!
We assume the neutral scalar H is the dark matter particle.

$$m_H < m_A,\ m_{H^{\pm}}$$

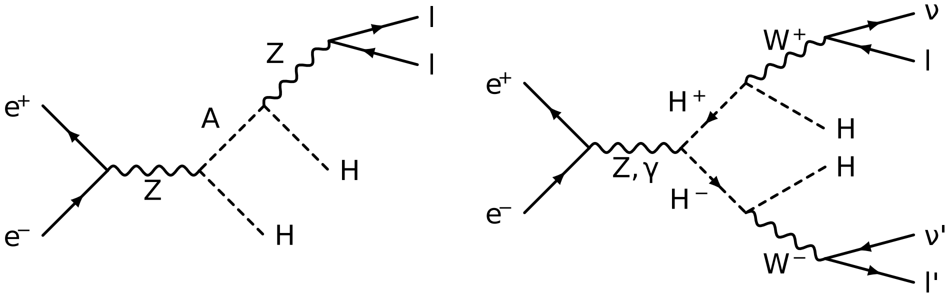
Search strategy

Same flavour lepton pair production can be considered a signature of the AH production process followed by the A decay:

$$e^+e^- \;\rightarrow\; HA \rightarrow HHZ^{(\star)} \rightarrow HH\mu^+\mu^-$$

while the production of the different flavour lepton pair is the expected signature for H^+H^- production:

$$e^+e^- \;\rightarrow\; H^+H^- \rightarrow HHW^{+(*)}W^{-(*)} \rightarrow HH\ell^+\ell'^-\nu\bar{\nu}'$$

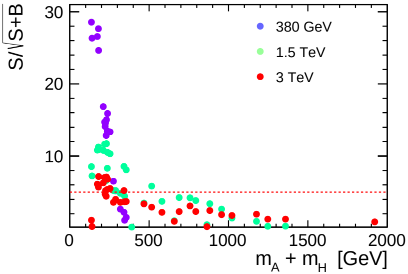


CLIC prospects for IDM discovery

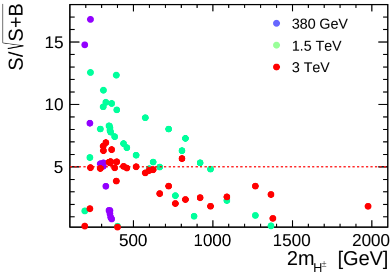
BDT selection and signal significance analysis performed for 41 benchmark scenarios

Results for: $1000\,\mathrm{fb}^{-1}$ at 380 GeV, $2500\,\mathrm{fb}^{-1}$ at 1.5 TeV and $5000\,\mathrm{fb}^{-1}$ at 3 TeV

AH signature ($\mu^+\mu^-$)



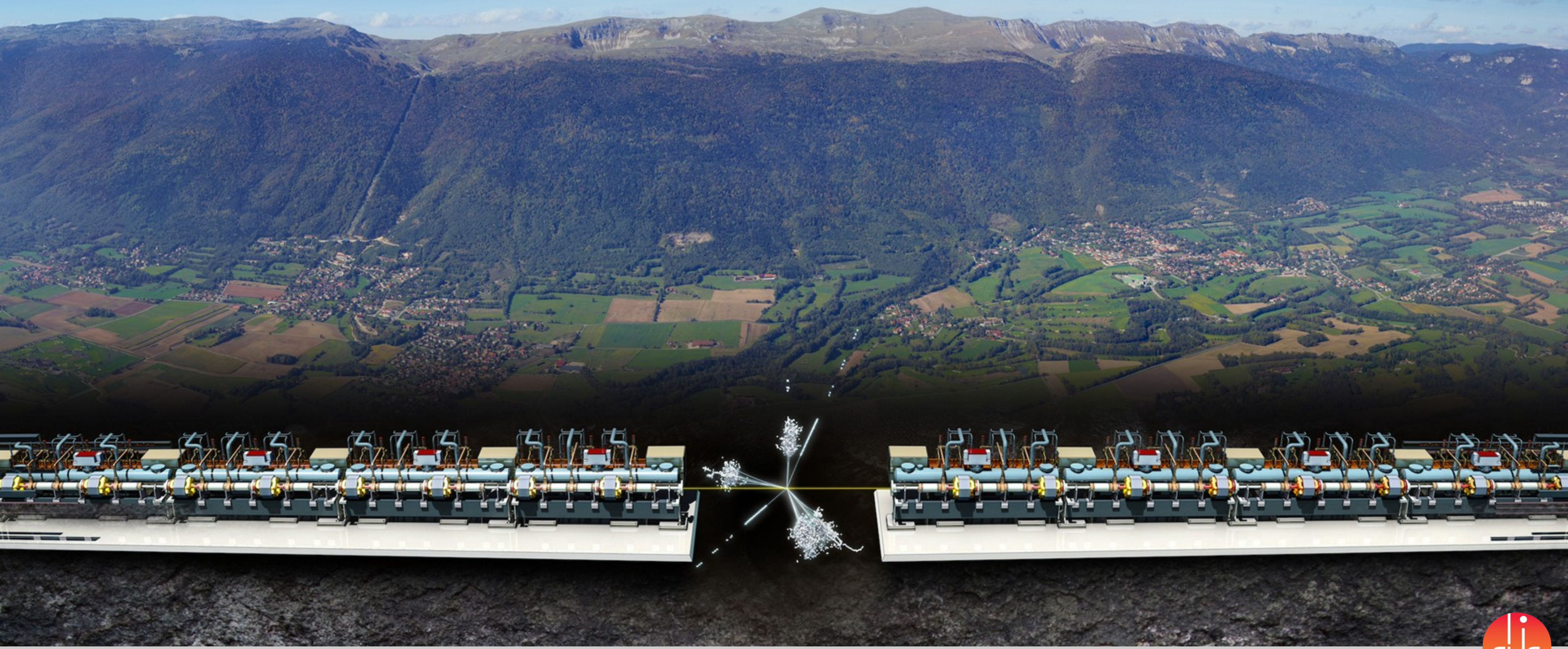
H^+H^- signature ($\mu^\pm e^\mp$)



Visible increase in discovery reach for 1.5 TeV:

- neutral scalar production: $m_A + m_H < 550$ GeV (290 GeV @ 380 GeV)
- charged scalar production: $m_{H^\pm} < 500$ GeV (150 GeV @ 380 GeV)

Status of the project



CLIC next phase

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, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

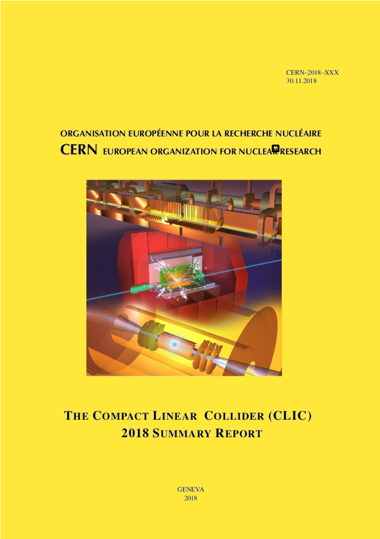
Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

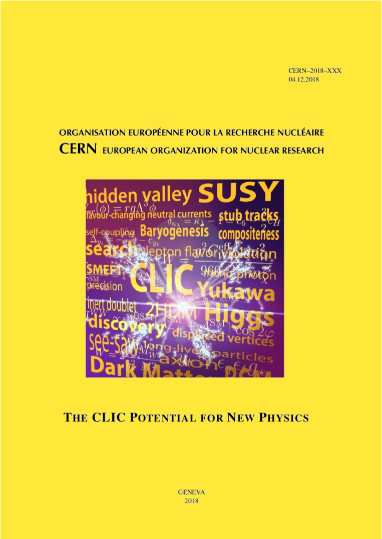
2035
First collisions

CLIC reports



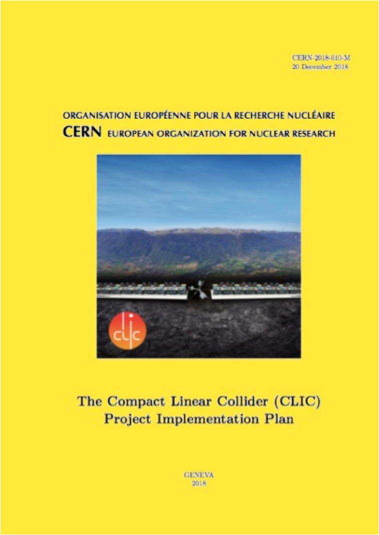
CERN-2018-005-M

http://dx.doi.org/10.23731/CYRM-2018-002



CERN-2018-009-M

http://dx.doi.org/10.23731/CYRM-2018-003



CERN-2018-010-M

http://dx.doi.org/10.23731/CYRM-2018-004

The CLIC 2018 Summary Report
The CLIC Potential for New Physics
The CLIC Project Implementation Plan

–> all published
as 2018 CERN Yellow Reports

CLIC reports

The Compact Linear e^+e^- Collider (CLIC): Accelerator and Detector

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Contact person: A. Robson[1)*†]

Editors: P. N. Burrows[*‡], N. Catalan Lasheras[*], L. Linssen[*], M. Petrič[*], A. Robson[*†], D. Schulte[*], E. Sicking[*], S. Stapnes[*], W. Wuensch[*]

[*] *CERN, Switzerland,* [†] *University of Glasgow, United Kingdom,* [‡] *University of Oxford, United Kingdom*

Abstract

The Compact Linear Collider (CLIC) is a TeV-scale high-luminosity linear e^+e^- collider under development by international collaborations hosted by CERN. This document provides an overview of the design, technology, and implementation aspects of the CLIC accelerator and the detector. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in stages, at centre-of-mass energies of 380 GeV, 1.5 TeV and 3 TeV, for a site length ranging between 11 km and 50 km. CLIC uses a two-beam acceleration scheme, in which normal-conducting high-gradient 12 GHz accelerating structures are powered via a high-current drive beam. For the first stage, an alternative with X-band klystron powering is also considered. CLIC accelerator optimisation, technical developments, and system tests have resulted in significant progress in recent years. Moreover, this has led to an increased energy efficiency and reduced power consumption of around 170 MW for the 380 GeV stage, together with a reduced cost estimate of approximately 6 billion CHF. The detector concept, which matches the physics performance requirements and the CLIC experimental conditions, has been refined using improved software tools for simulation and reconstruction. Significant progress has been made on detector technology developments for the tracking and calorimetry systems. The construction of the first CLIC energy stage could start as early as 2026 and first beams would be available by 2035, marking the beginning of a physics programme spanning 25–30 years and providing excellent sensitivity to Beyond Standard Model physics, through direct searches and via a broad set of precision measurements of Standard Model processes, particularly in the Higgs and top-quark sectors.

© 2018 CERN for the benefit of the CLIC and CLICdp Collaborations.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

[1] aidan.robson@cern.ch

The Compact Linear e^+e^- Collider (CLIC): Physics Potential

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Contact person: P. Roloff[1)*]

Editors: R. Franceschini[†‡], P. Roloff[*], U. Schnoor[*], A. Wulzer[*§¶]

[*] *CERN, Geneva, Switzerland,* [†] *Università degli Studi Roma Tre, Rome, Italy,* [‡] *INFN, Sezione di Roma Tre, Rome, Italy,* [§] *Università di Padova, Padova, Italy,* [¶] *LPTP, EPFL, Lausanne, Switzerland*

Abstract

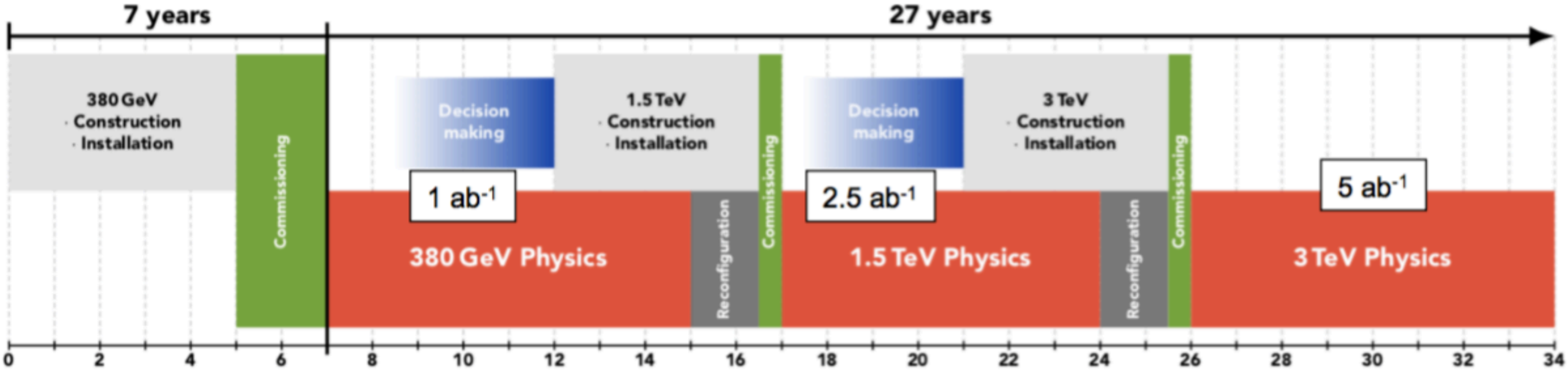
The Compact Linear Collider, CLIC, is a proposed e^+e^- collider at the TeV scale whose physics potential ranges from high-precision measurements to extensive direct sensitivity to physics beyond the Standard Model. This document summarises the physics potential of CLIC, obtained in detailed studies, many based on full simulation of the CLIC detector. CLIC covers one order of magnitude of centre-of-mass energies from 350 GeV to 3 TeV, giving access to large event samples for a variety of SM processes, many of them for the first time in e^+e^- collisions or for the first time at all. The high collision energy combined with the large luminosity and clean environment of the e^+e^- collisions enables the measurement of the properties of Standard Model particles, such as the Higgs boson and the top quark, with unparalleled precision. CLIC might also discover indirect effects of very heavy new physics by probing the parameters of the Standard Model Effective Field Theory with an unprecedented level of precision. The direct and indirect reach of CLIC to physics beyond the Standard Model significantly exceeds that of the HL-LHC. This includes new particles detected in challenging non-standard signatures. With this physics programme, CLIC will decisively advance our knowledge relating to the open questions of particle physics.

© 2018 CERN for the benefit of the CLIC and CLICdp Collaborations.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

[1] philipp.roloff@cern.ch

Two formal European Strategy Update submissions made on 18th December

CLIC schedule:
TDR 2025, start construction 2026



Cost of stage 1: CHF 5.9B
stage 2: + CHF 5.1B
stage 3: + CHF 7.3B

FCC cost and schedule (from DG's new year message)

Purely technical schedule, assuming green light to preparation work in 2020.
A 70 years programme

8 years preparation	10 years tunnel and FCC-ee construction	**15 years FCC-ee operation**	11 years FCC-hh preparation and installation	**25 years FCC-hh operation pp/PbPb/eh**
2020-2028		**2038-2053**		**2064-2090**

FCC-ee

Estimated cost: ~ **11.6** BCHF: 5.4 B (tunnel), 5.1 B (injectors + collider up to √s=240 GeV), 1.1 B (additional RF for operation at √s ~365 GeV)

FCC-hh

Estimated cost: ~ **17** BCHF (13.6 B collider [magnets!] + injectors) if built after FCC-ee (tunnel and part of infrastructure exists); 24 BCHF if standalone.

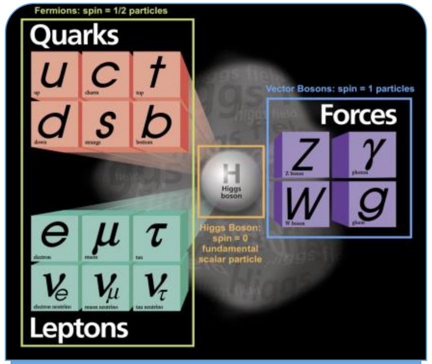
❑ Same fit applied to all Higgs factories inputs (for unbiased comparison)

Collider	HL-LHC	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\text{FCC-ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

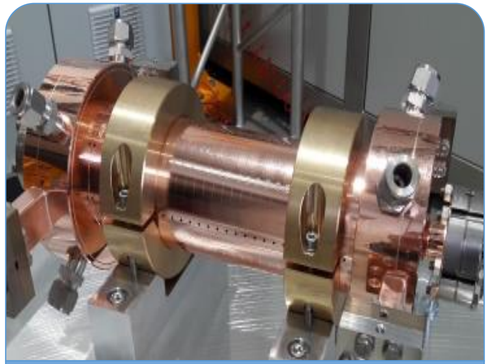
$ x2
+12y

- ◆ The FCC-ee precision better than HL-LHC by large factors (for the copious modes)
  - ● The FCC-ee is best on the e^+e^- Higgs factory market
- ◆ It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - ● Combination better by a factor up to 2 (4) than 240/250 (365/380) GeV alone

The CLIC project

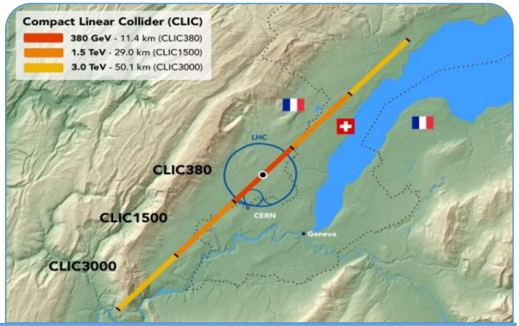


Physics case



Technical implementation and solutions

Organization and community



Industrial basis and future flexibility

For any next machine the largest challenges are the cost and timescales/size involved ….

Key activities for a CLIC TDR in the Preparation Phase will be:

1. Prepare technically for industrial production (examples for cost and power drivers on next slide)
2. Pursue large systems tests (not necessarily at CERN)
3. Final design/parameters, cost/power, schedules, CE/site/infrastructure

Thank you!

Resources

Compact Linear Collider Portal
http://clic.cern/

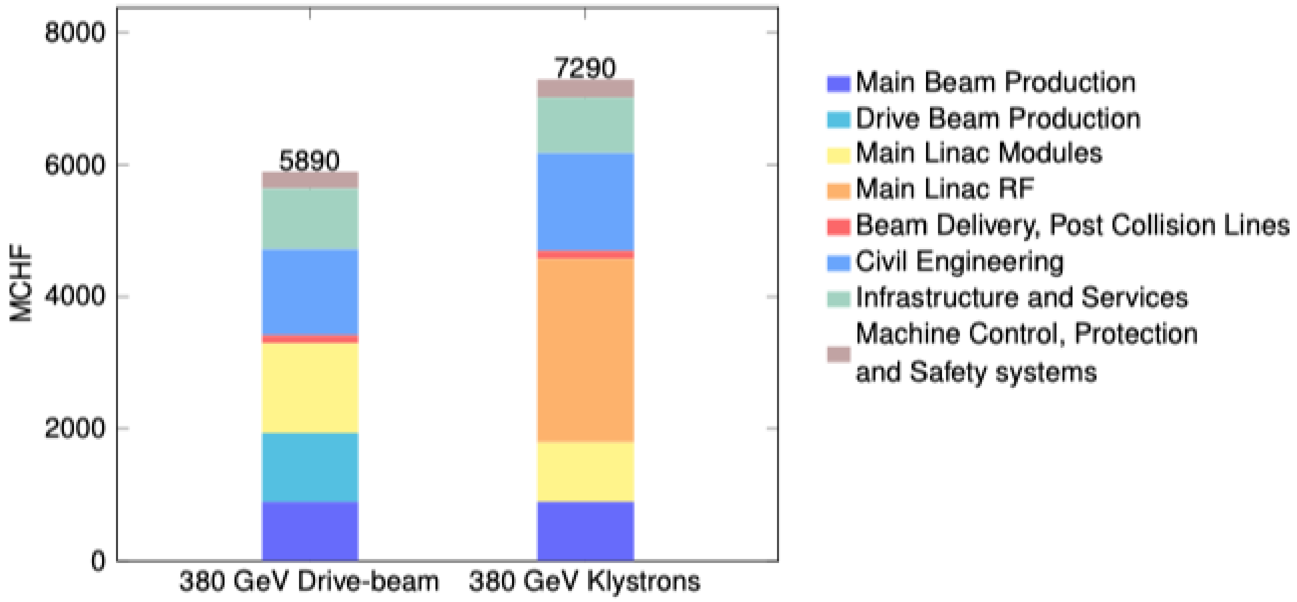
CLIC input to the European Strategy for Particle Physics Update 2018-2020
http://clic.cern/european-strategy

CLICdp Publications on CERN Document Server
https://cds.cern.ch/collection/CLIC Detector and Physics Study

Cost - I

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 November – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Cost - II

Other cost estimates:

Construction:

- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

Operation:

- 116 MCHF (see assumptions in box below)
- Energy costs

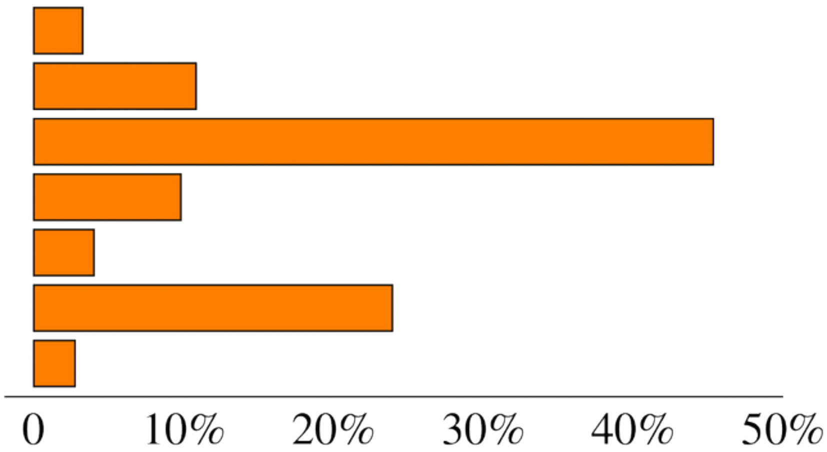
– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

Cost Estimate for the CLIC Detector

- Based on detector work breakdown structure, aimed at 30% uncertainty
- Main cost driver: silicon sensors for electromagnetic calorimeter
  - Example: 25% cost reduction of silicon per unit of surface → overall detector cost reduction by > 10%

System	Cost fraction	Cost[MCHF]
Vertex		13
Silicon Tracker		43
Electromagnetic Calorimeter		180
Hadronic Calorimeter		39
Muon System		16
Coil and Yoke		95
Other		11
Total		397



Key Parameters

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
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
Charge 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)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589