clic.cern

The Compact Linear Collider (**CLIC**): High Precision Physics beyond the HL-LHC

SPS Annual Meeting 2018, EPFL Lausanne

Konrad Elsener, CERN

Outline

- **The CLIC accelerator: status and plans**
- **A detector for CLIC**
- **Precision physics beyond HL-LHC**
- **Summary**

The CLIC project

Multi-TeV **electron-positron collisions** with high luminosity

To be built and operated **in stages** (total time: 25-30 years)

N.B. recently updated -> Europ. Strat. Update (previous scenario: CERN-2016-004)

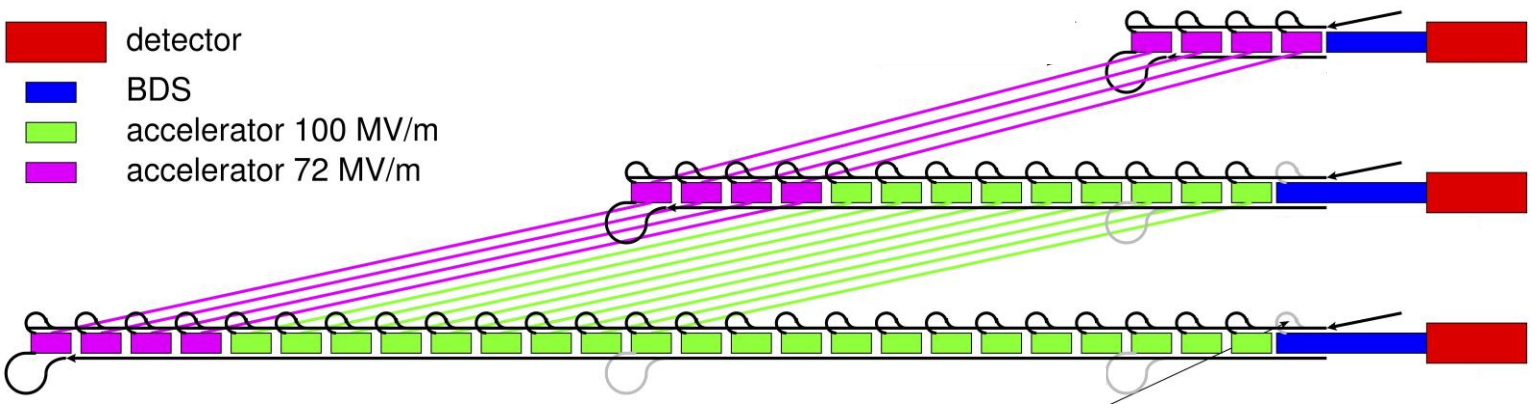
Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (ab^{-1})
1	380 350	1
2	1500	2.5
3	3000	5

Top physics above threshold; Higgs via ZH and WW-fusion

study top at threshold

New Physics, Higgs self coupling, ttH, …

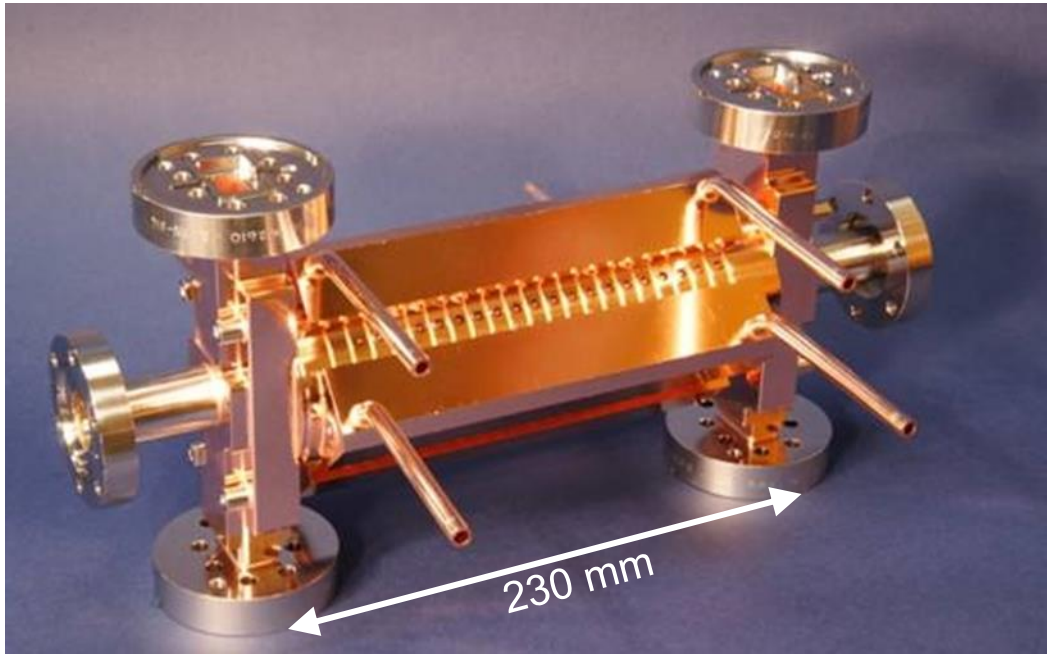
E / lumi to be updated with input from LHC and/or stage 1 of CLIC

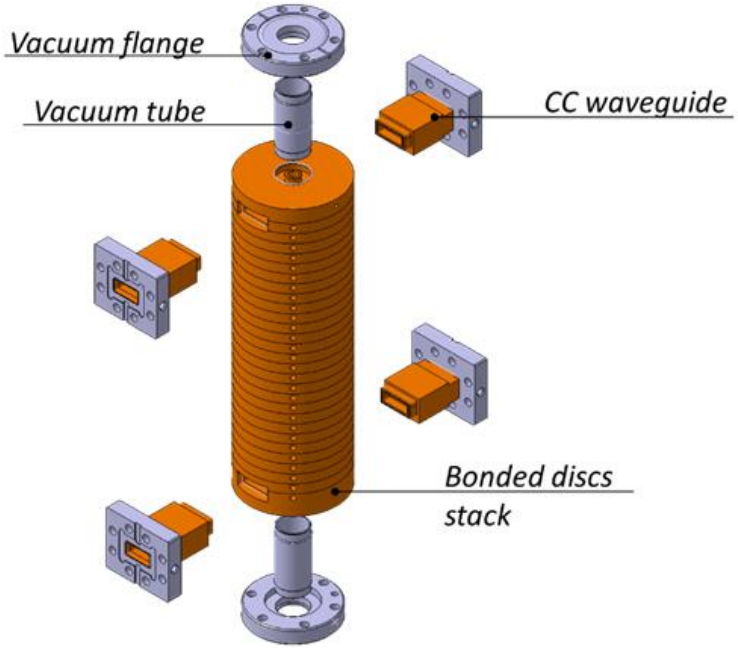


CLIC accelerating structure – normal cond. technology

RF frequency 12 GHz;
244 ns pulses @ 50 Hz

	380 GeV	3TeV
Length [cm]	27	24
Gradient [MV/m]	72	100
Number of structures	20600	143000



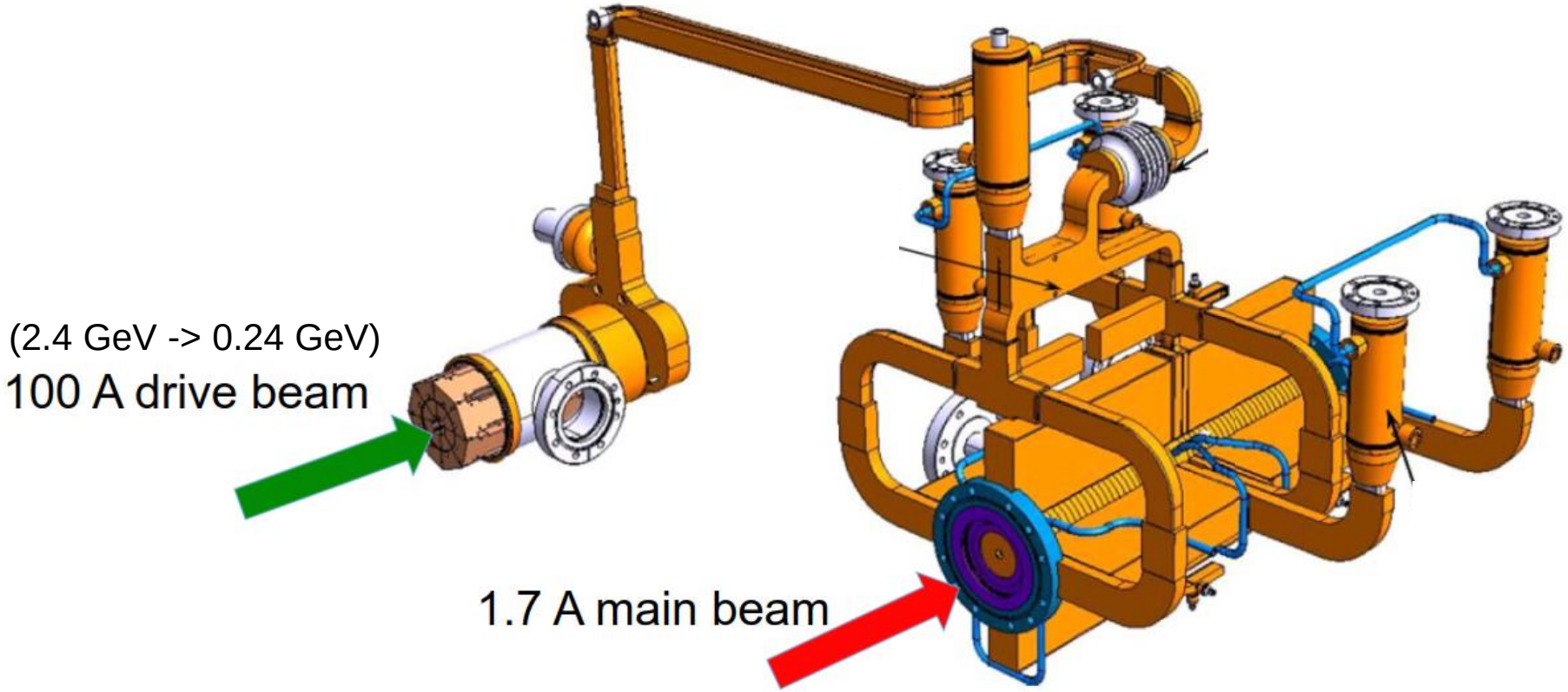


CLIC key parameters

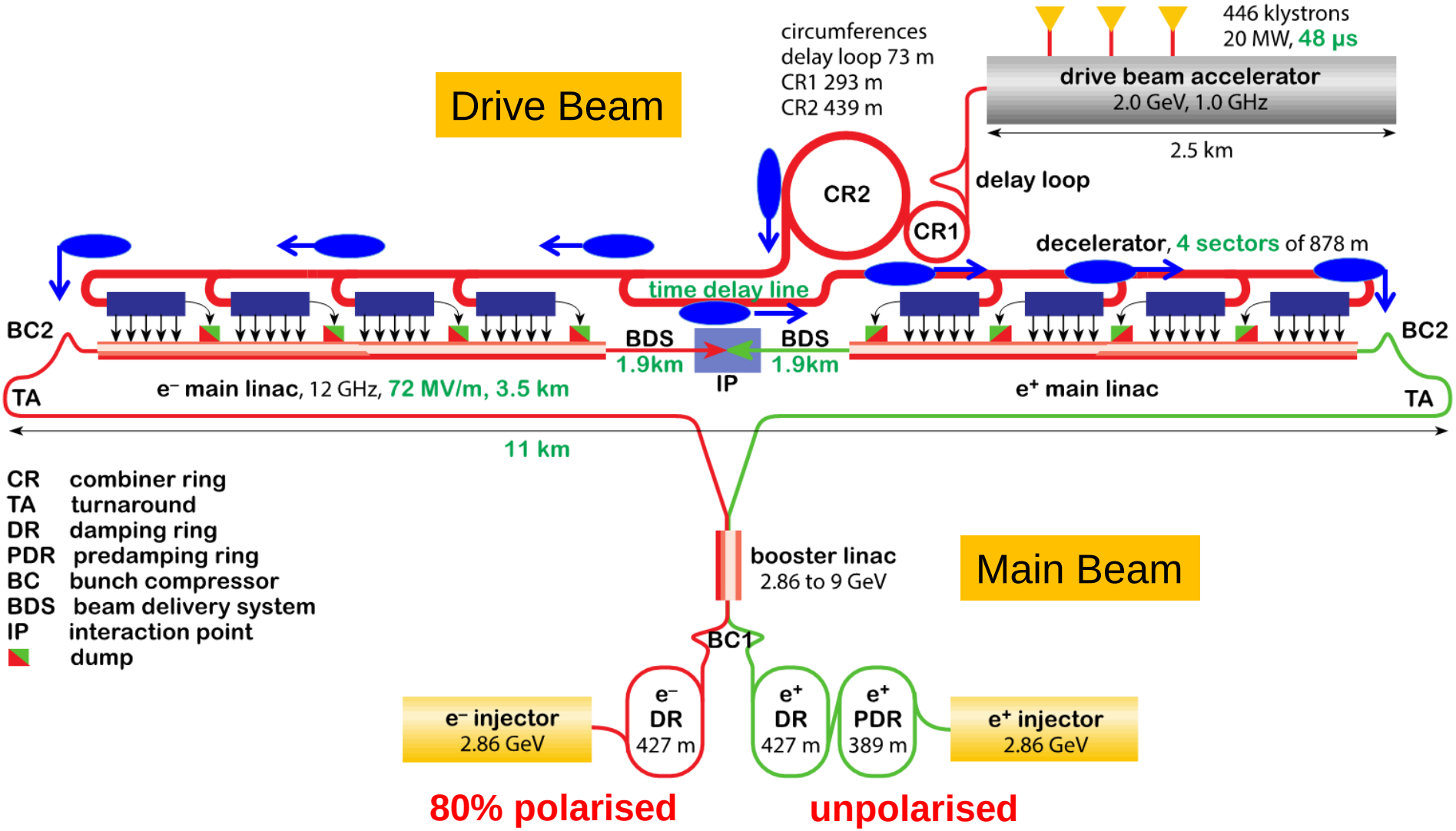
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total 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

Two-beam acceleration

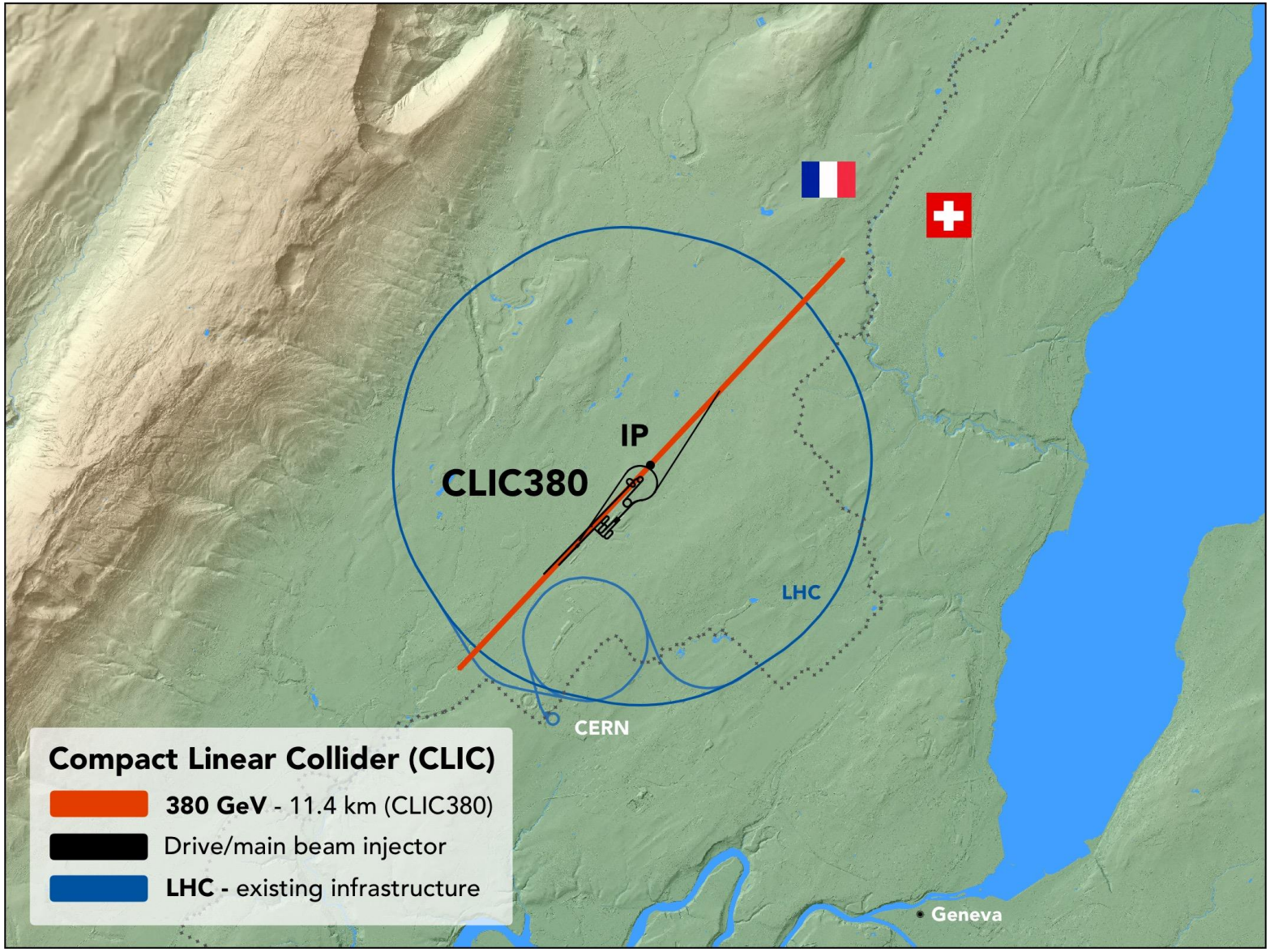
drive beam (12 GHz) –> main beam



CLIC at 380 GeV



CLIC at 380 GeV



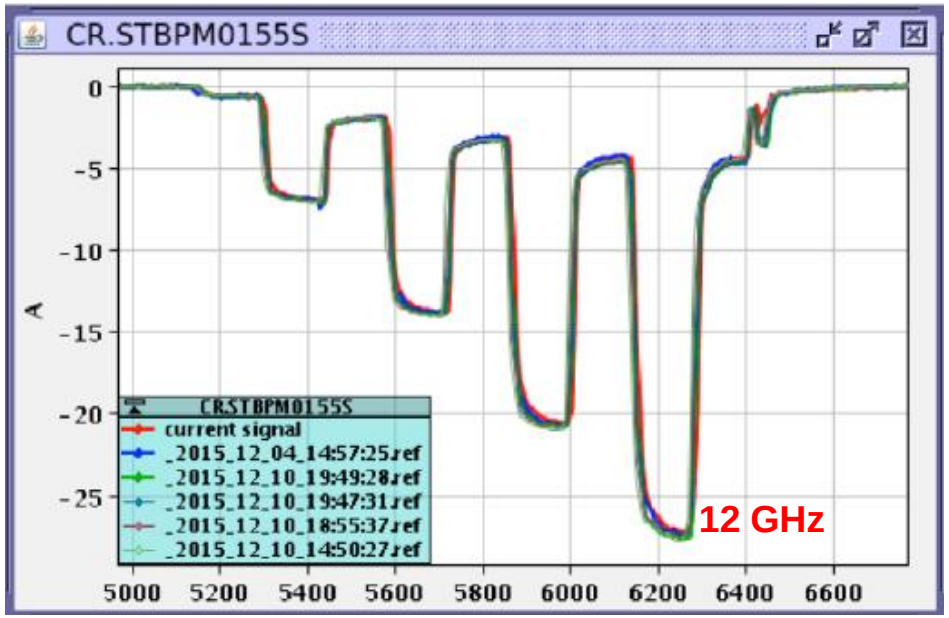
Key technical challenges for CLIC

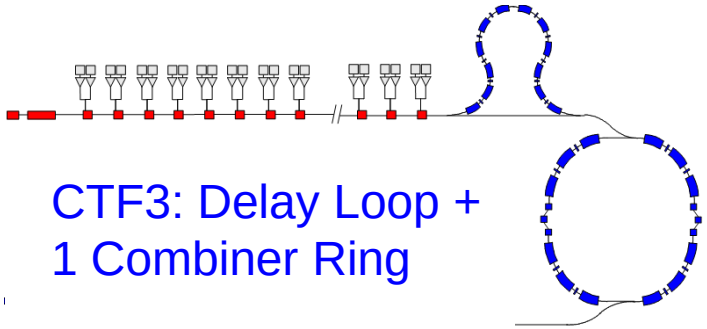
- **High-current drive beam bunched at 12 GHz**
- **Power transfer + main-beam acceleration**
- **100 MV/m gradient in main-beam accel. cavities**

- **Produce, transport + collide low-emittance beams**
- **System integration, engineering, cost, power …**

Status (CLIC Test Facility / CTF3 result)

- **Produced high-current drive beam bunched at 12 GHz**



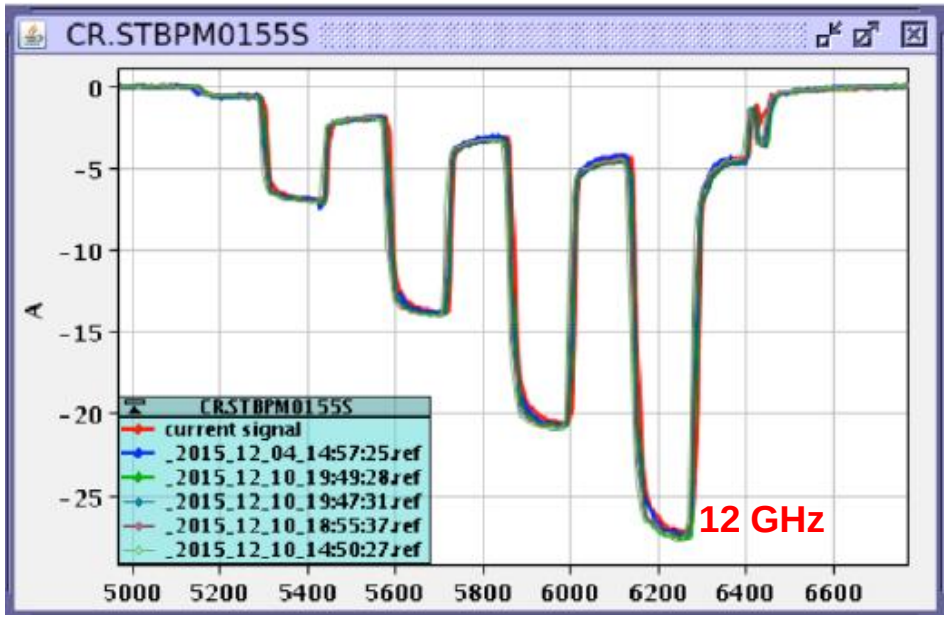


CTF3: Delay Loop +
1 Combiner Ring

28A

Status (CLIC Test Facility / CTF3 result)

- **Produced high-current drive beam bunched at 12 GHz**



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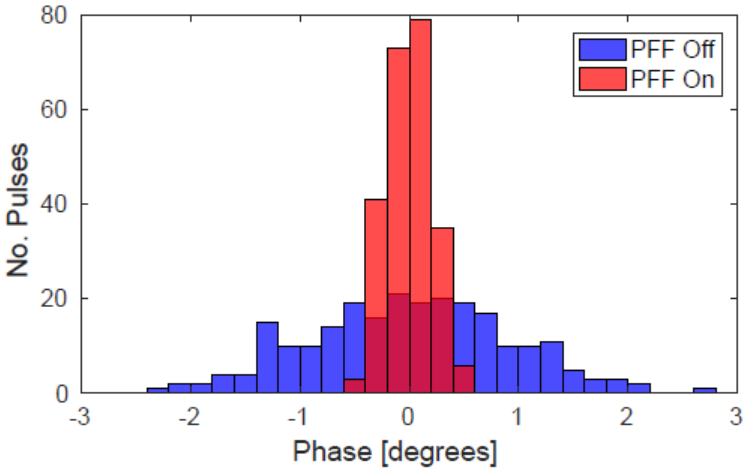
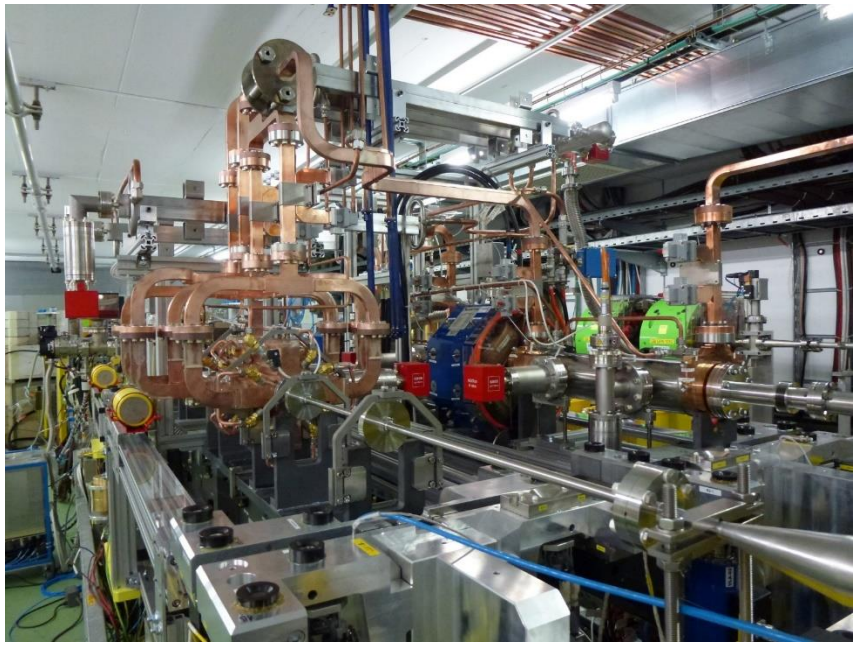
Arrival time stabilised to 50 fs

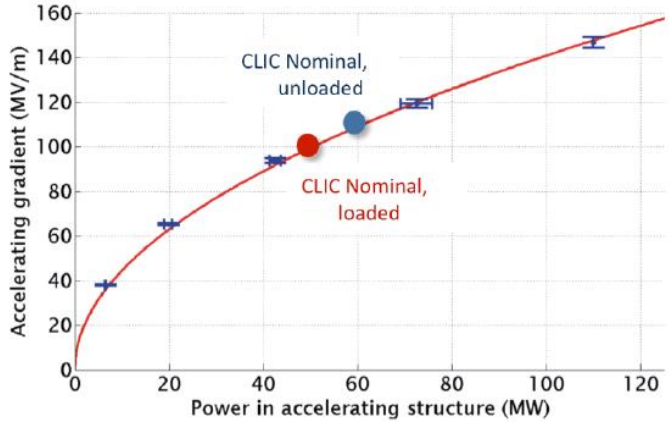


PFF – “phase feed forward”
(0.2 deg. <-> 50 fs)

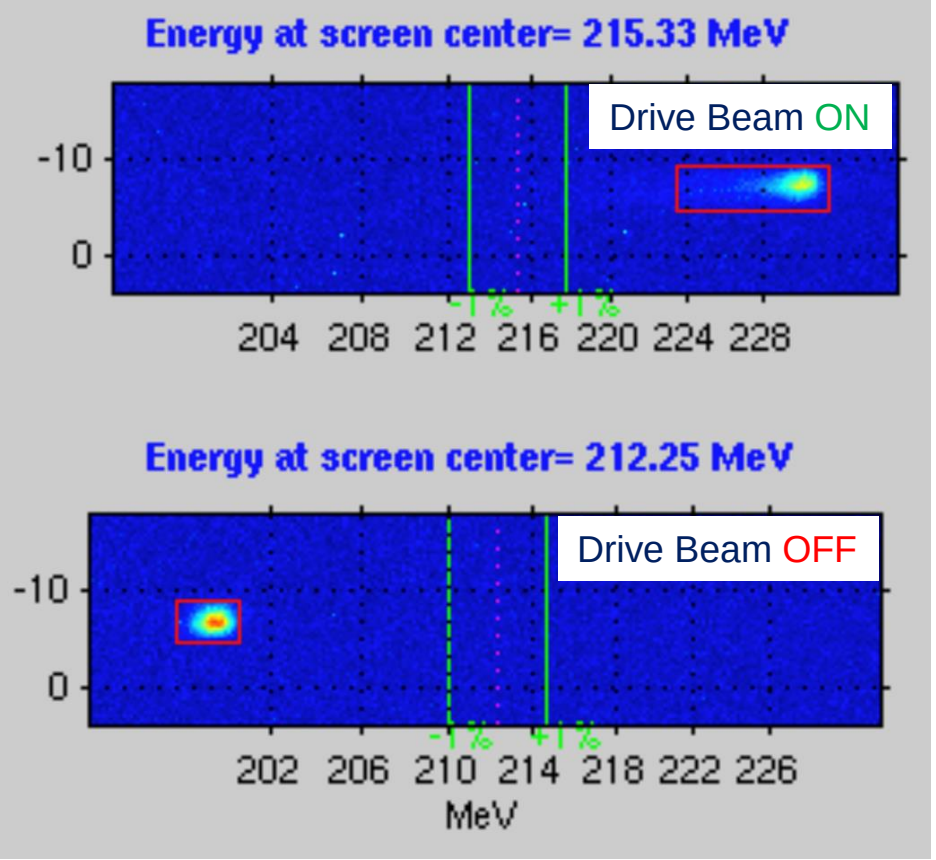
Status (CTF3 result)

- **Demonstrated two-beam acceleration**



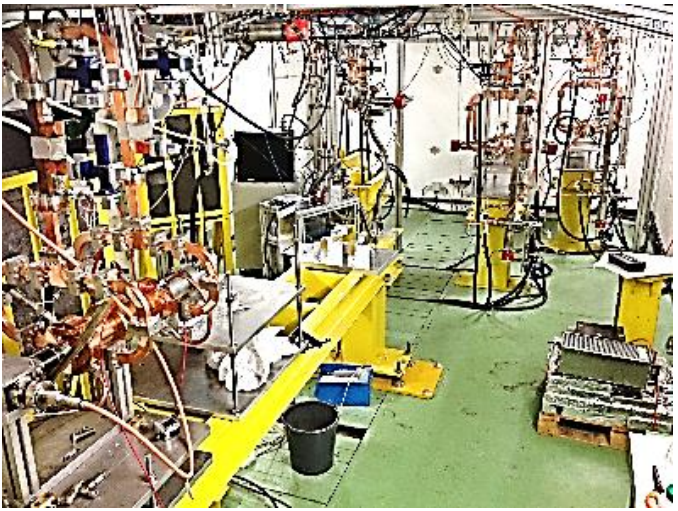


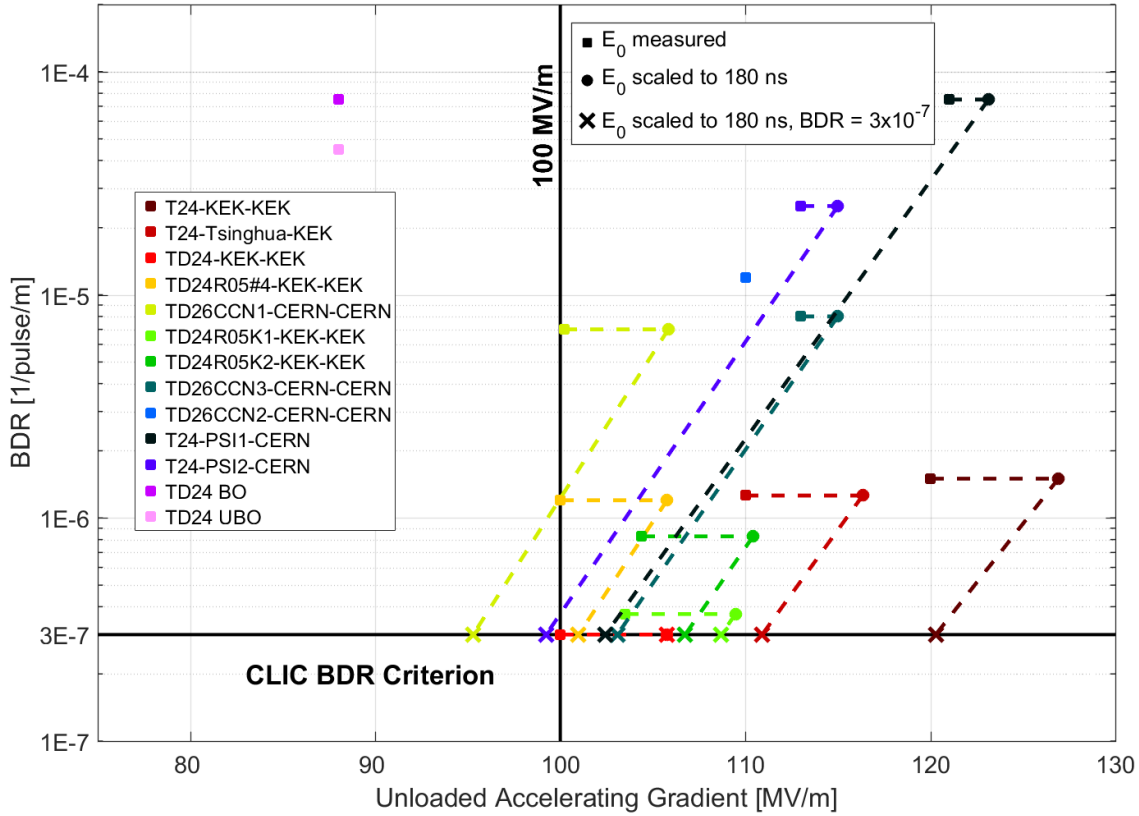
31 MeV = 145 MV/m

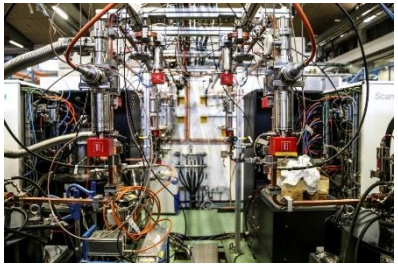


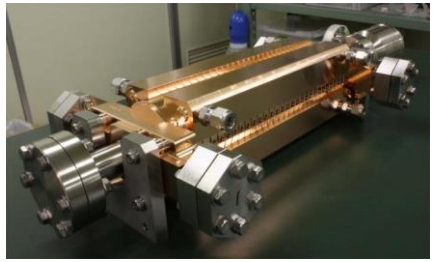
Status (high power tests around the world)

- **Achieved 100 MV/m gradient in main-beam RF cavities**









Key technical challenges for CLIC

- **High-current drive beam bunched at 12 GHz** ✓
- **Power transfer + main-beam acceleration** ✓
- **100 MV/m gradient in main-beam cavities** ✓

→ **Industrialisation of 12 GHz RF/structure technologies**

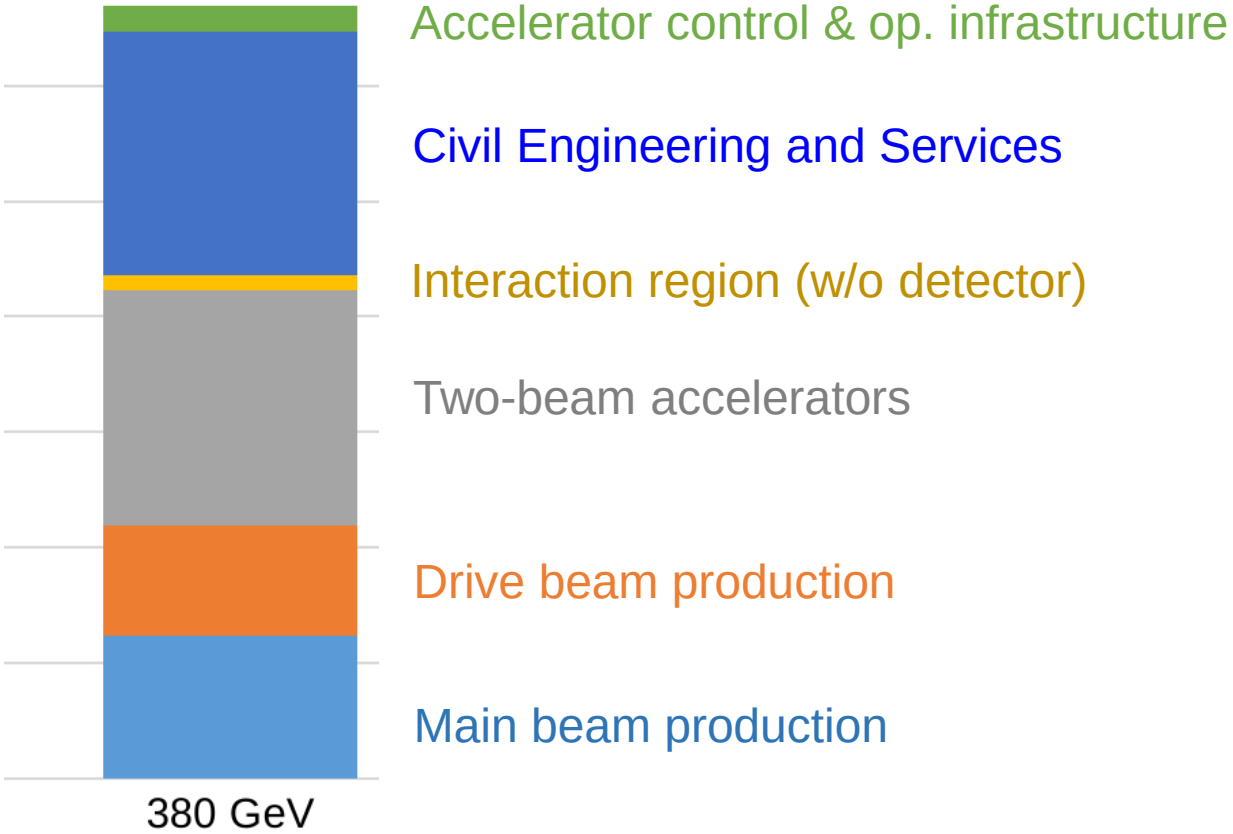
→ **Application to medium- and large-scale systems**

CLIC cost and power (380 GeV)

on-going: detailed bottom-up estimate of **cost** and **power**

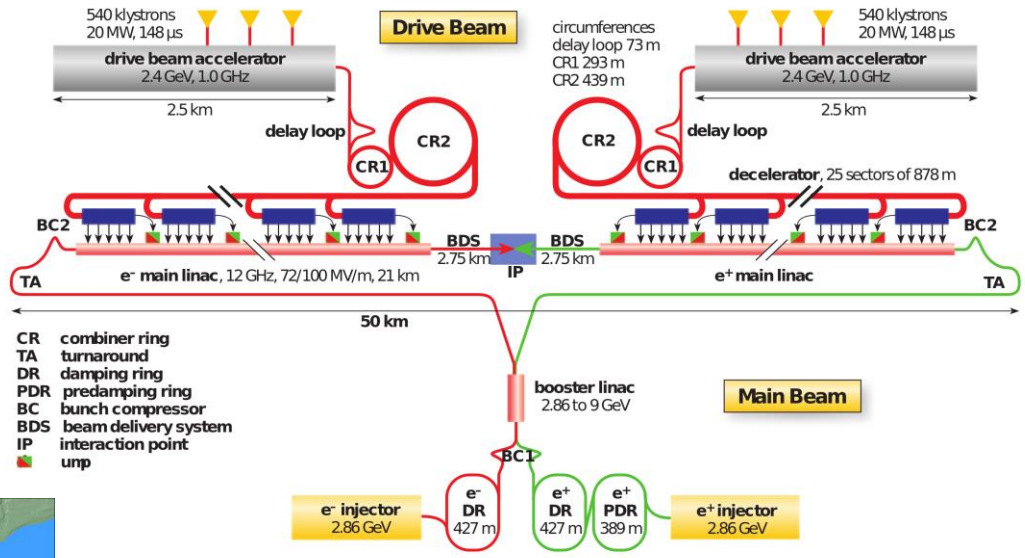
Present estimate: **O(6 GCHF)** for 380 GeV stage stage, power O(200 MW)

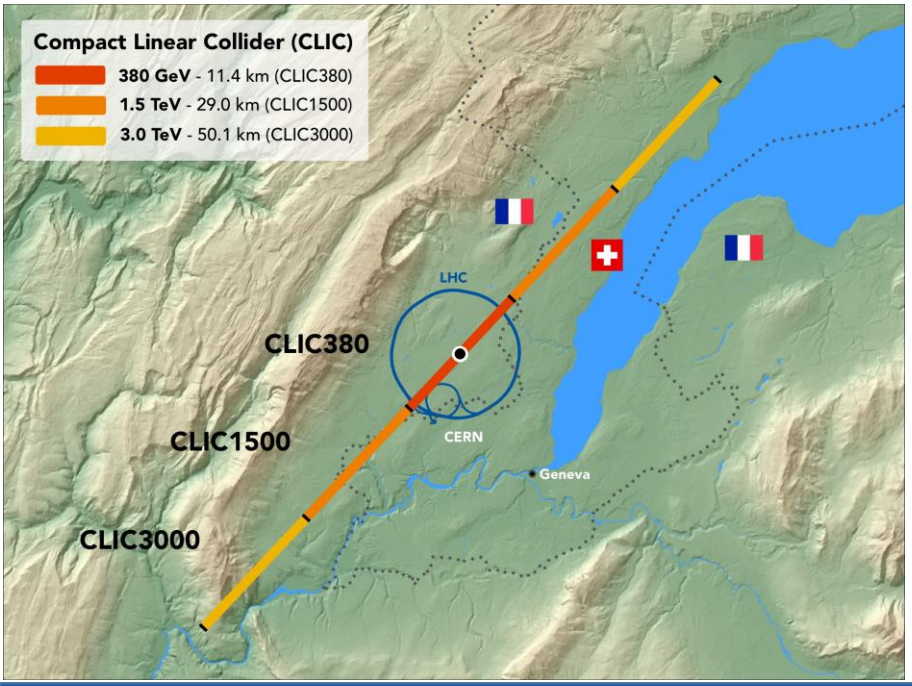
Considerable savings w.r.t. CERN-2016-004 estimate identified
(2016 estimates were extrapolated from 500 GeV CLIC (CDR 2012) – **6.7 GCHF**)

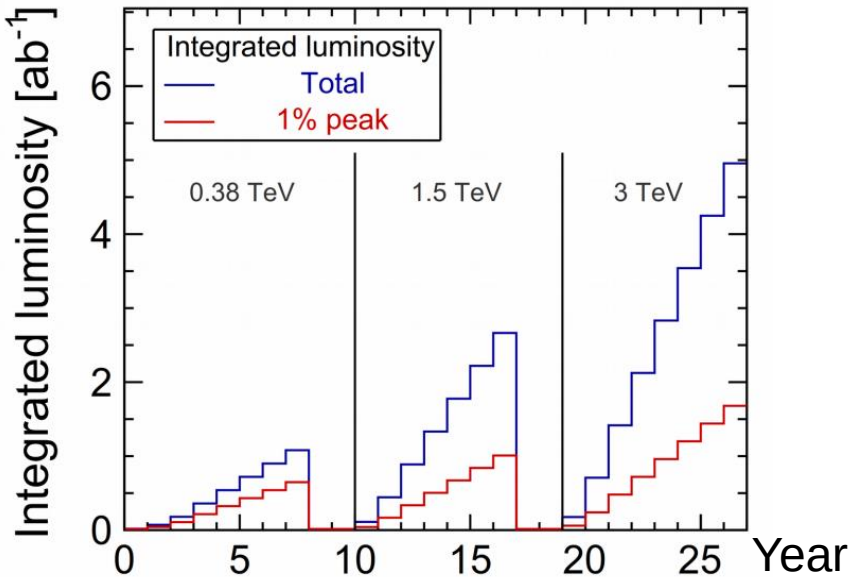


CLIC site and upgrade to 3 TeV

- re-use systems / components
- add more tunnel,
  linac and drive pulse length
- at 3 TeV, add 2nd drive beam







CLIC collaborations

CLIC/CTF3 accelerator collaboration
~70 institutes from **~30 countries**
(incl. **PSI, ETHZ)**
http://clic-study.web.cern.ch/

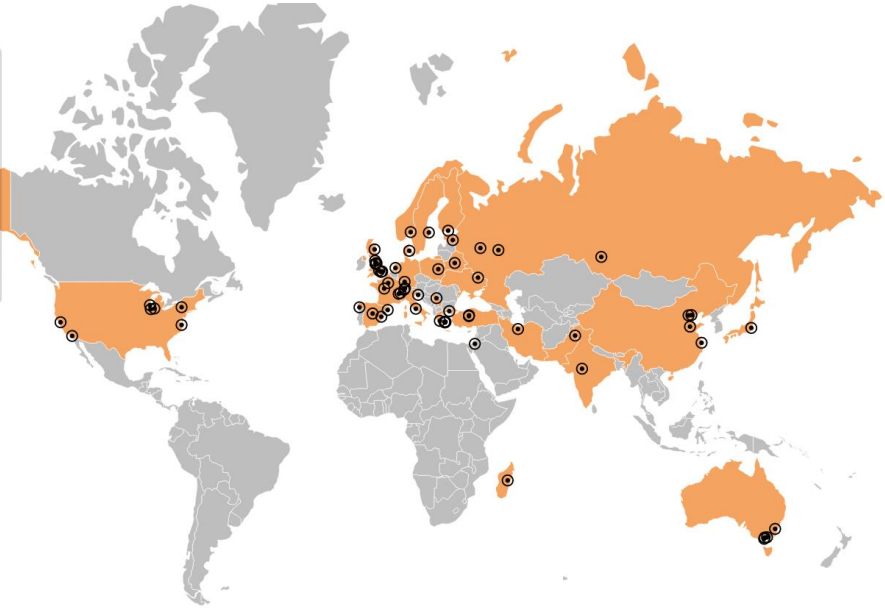
CLIC detector and physics (CLICdp)
30 institutes from **18 countries**
(incl. **Uni GE)**
http://clicdp.web.cern.ch/

CLIC accelerator studies:

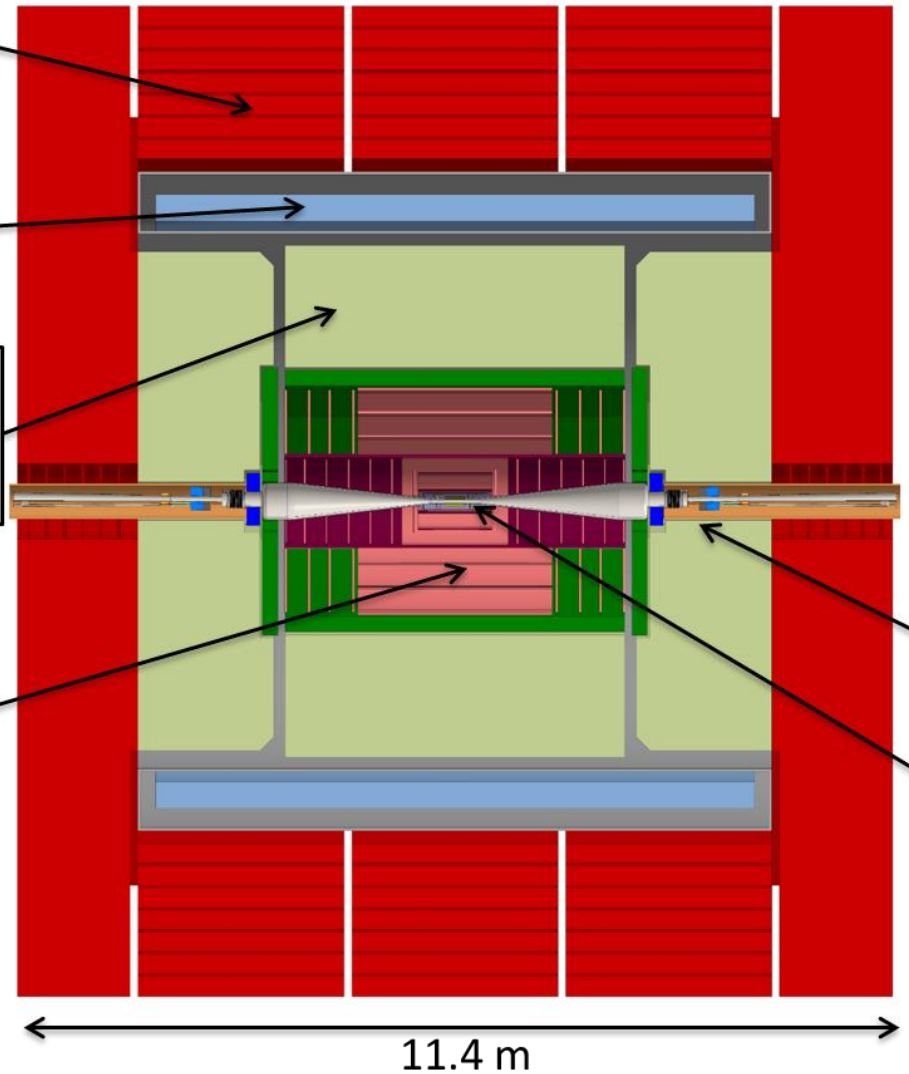
- CLIC accelerator design and development
- Construction and operation of CTF3

Focus of CLIC-specific studies on:

- Physics prospects and simulation studies
- Detector optimisation + R&D for CLIC



Detector for CLIC



return yoke (Fe) with muon-ID detectors

Superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

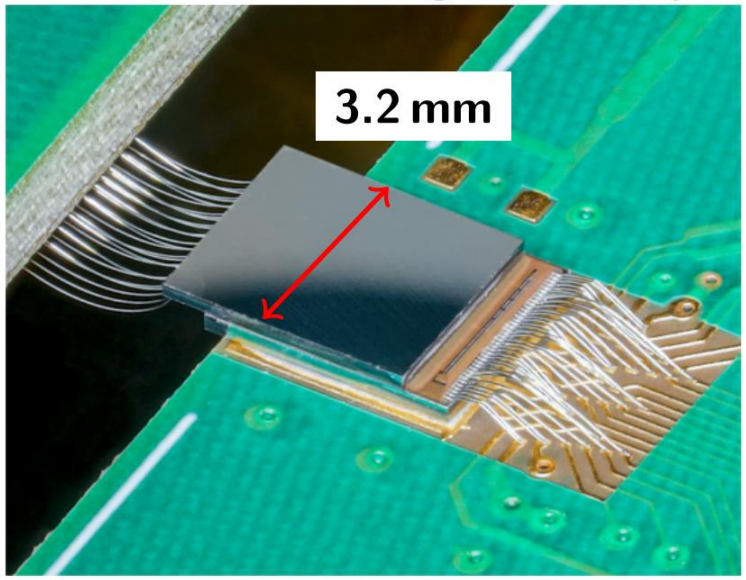
silicon tracker, (large pixels / short strips)

forward region with compact forward calorimeters

ultra low-mass vertex detector, ~25 µm pixels

CLIC detector R&D (examples)

CLICpix2 + C3PD glue assembly

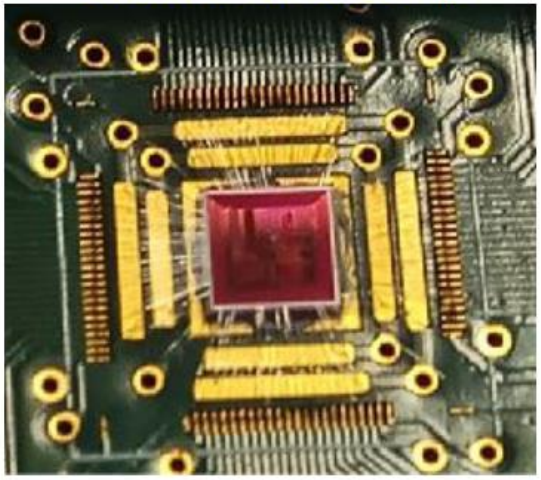


Vertex & Tracker

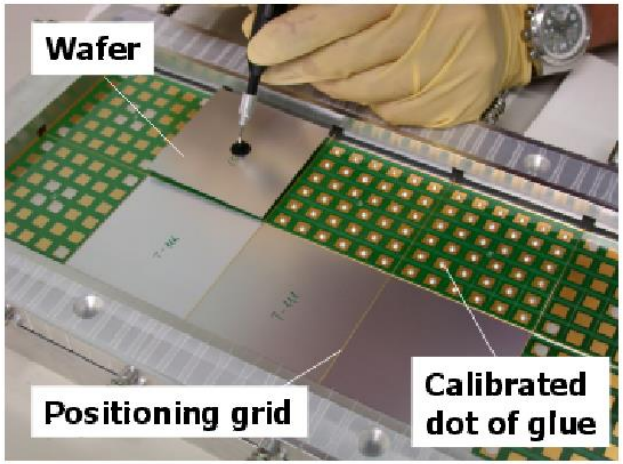
hybrid
(with UniGE)

monolithic

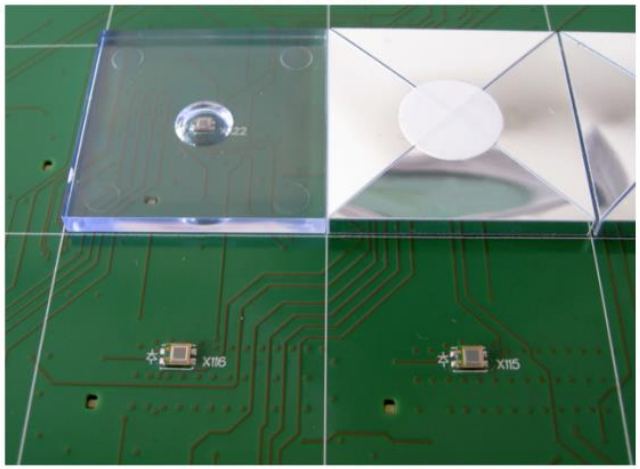
Cracow SOI test chip



CALICE silicon PIN diodes
$1 \times 1\,\mathrm{cm}^2$ in 6×6 matrices



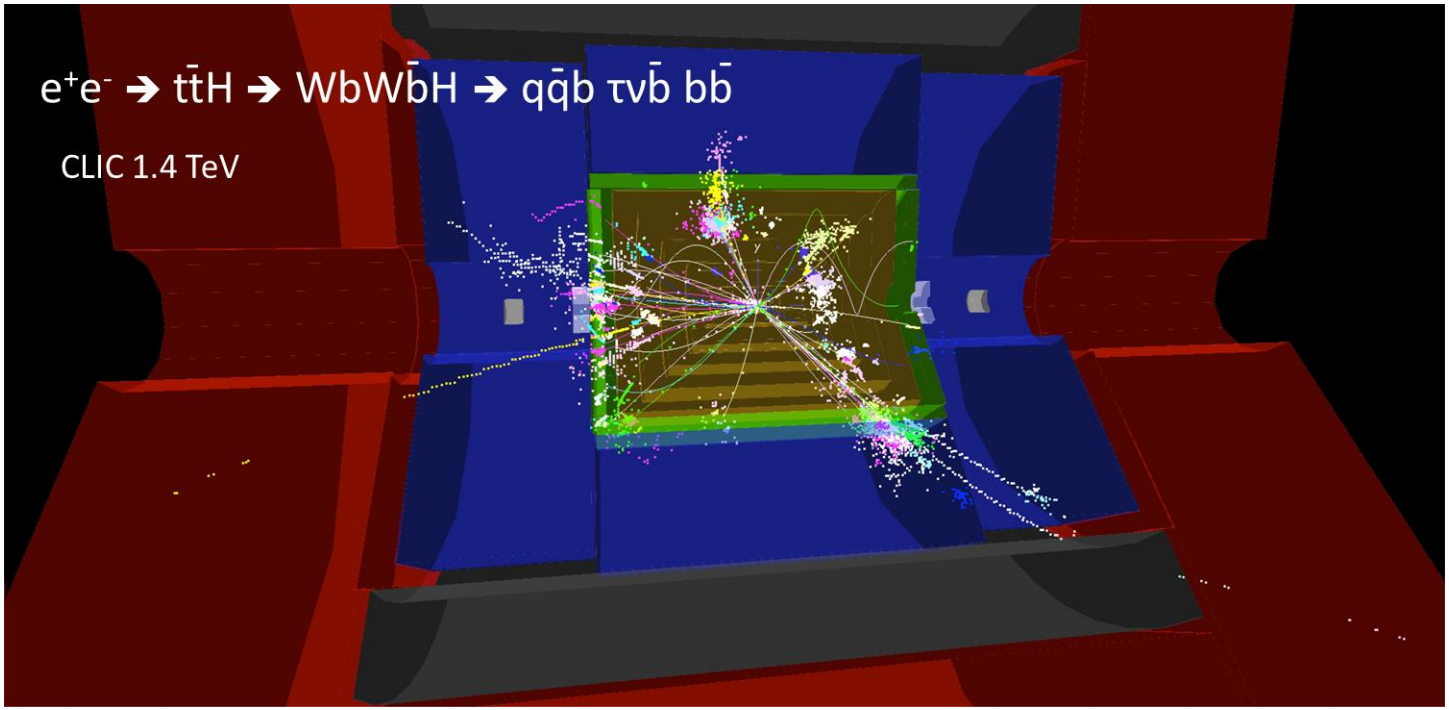
CALICE scint. tiles + SiPMs
$3 \times 3\,\mathrm{cm}^2$



Calorimetry

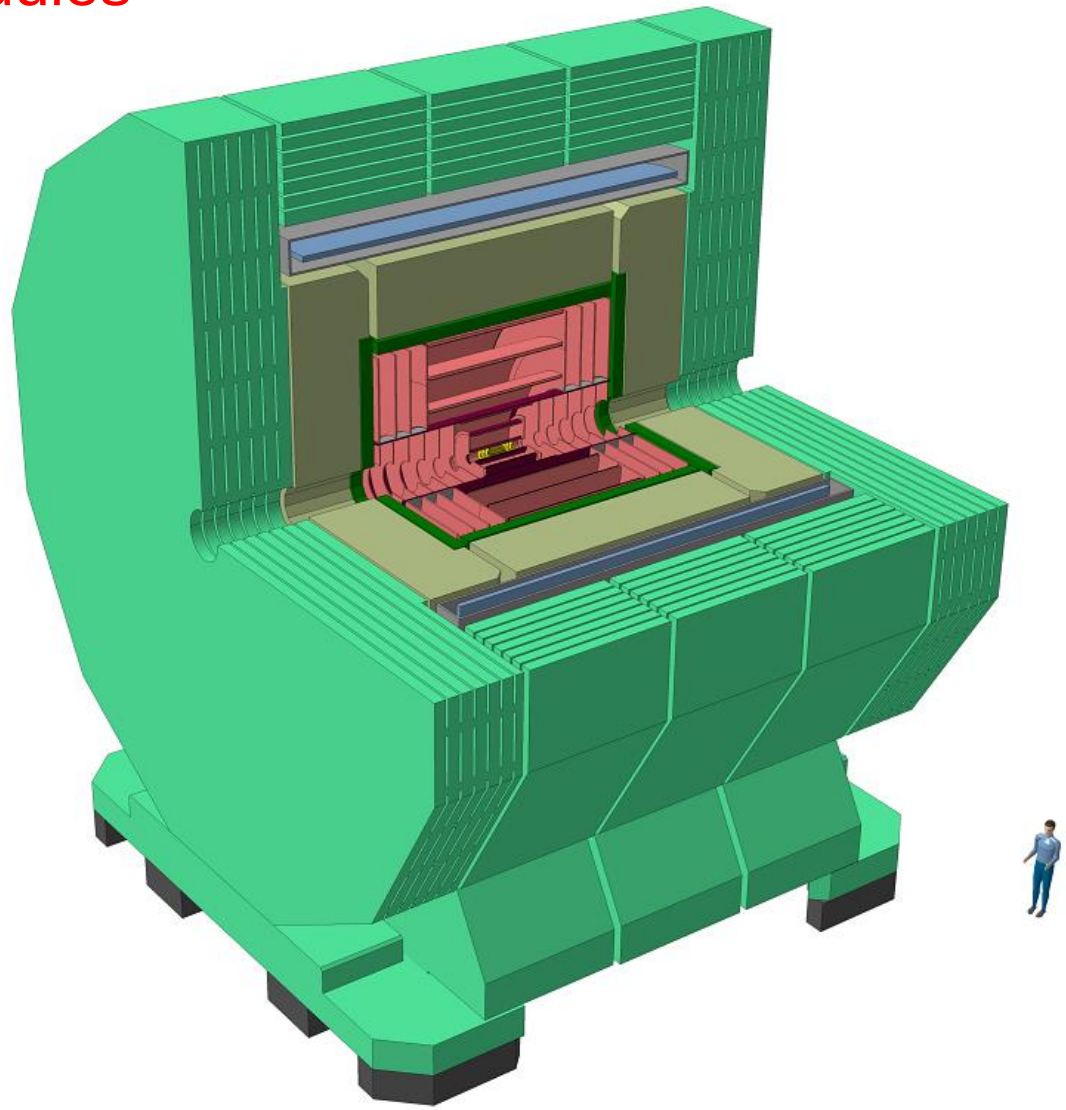
Full detector simulations

- Geant4 detector simulations including overlay of beam induced backgrounds
- reconstruction chain including reconstruction of tracks and clusters → particle flow objects → jets → flavour tagging



N.B.

CLIC Detector model (and software) adapted and used for FCC-ee studies

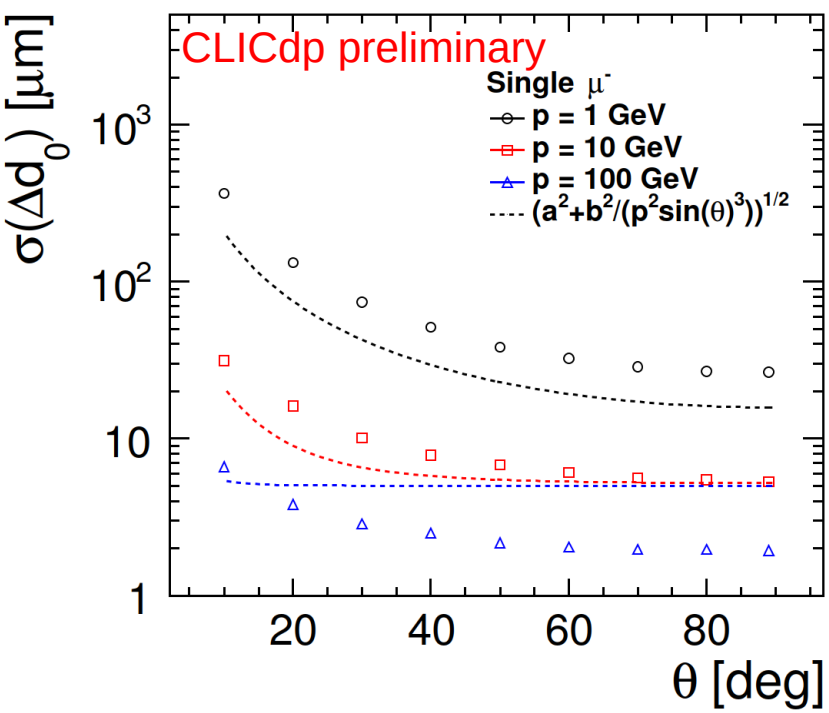


CLIC detector performance: Example (1)

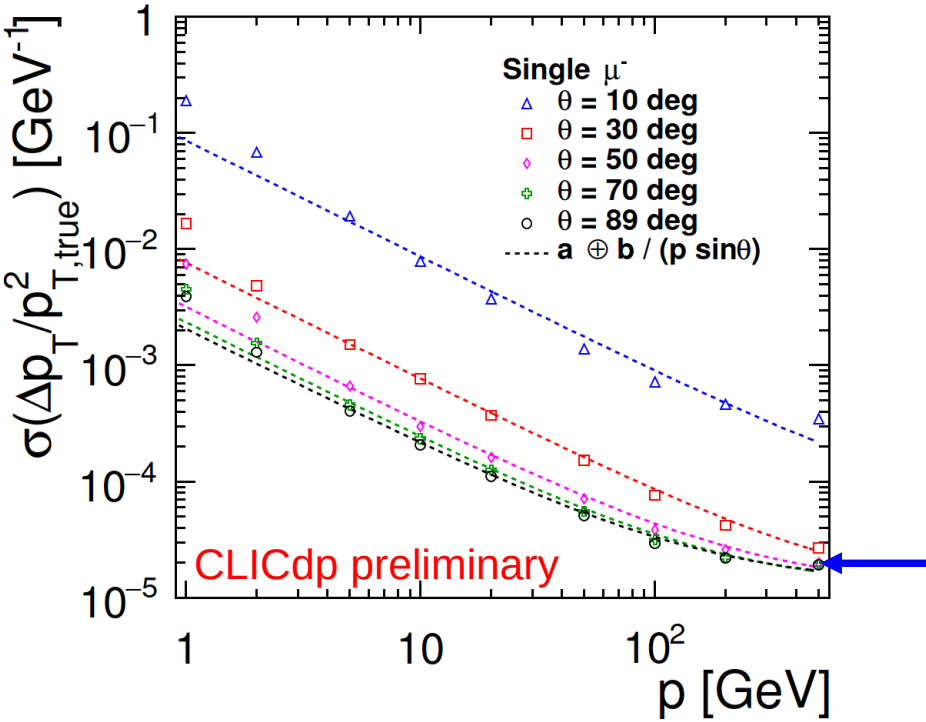
(full detector simulations)

Vertexing and Tracking

impact parameter



momentum resolution



dotted lines: performance goal, a = 5 µm, b = 15 µm

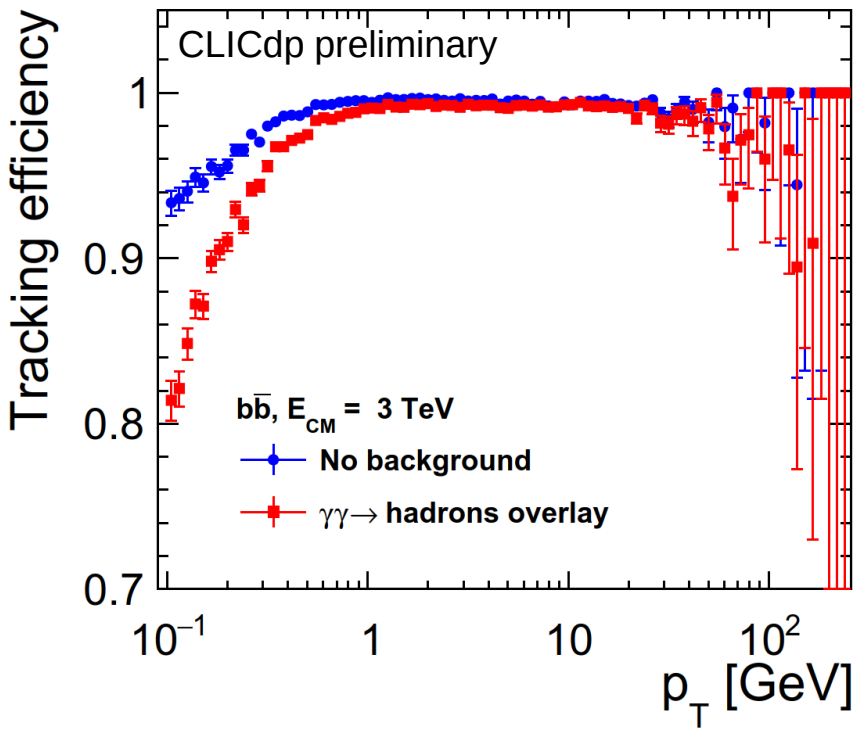
performance goal: 2×10^{-5}

CLIC detector performance: Example (2)

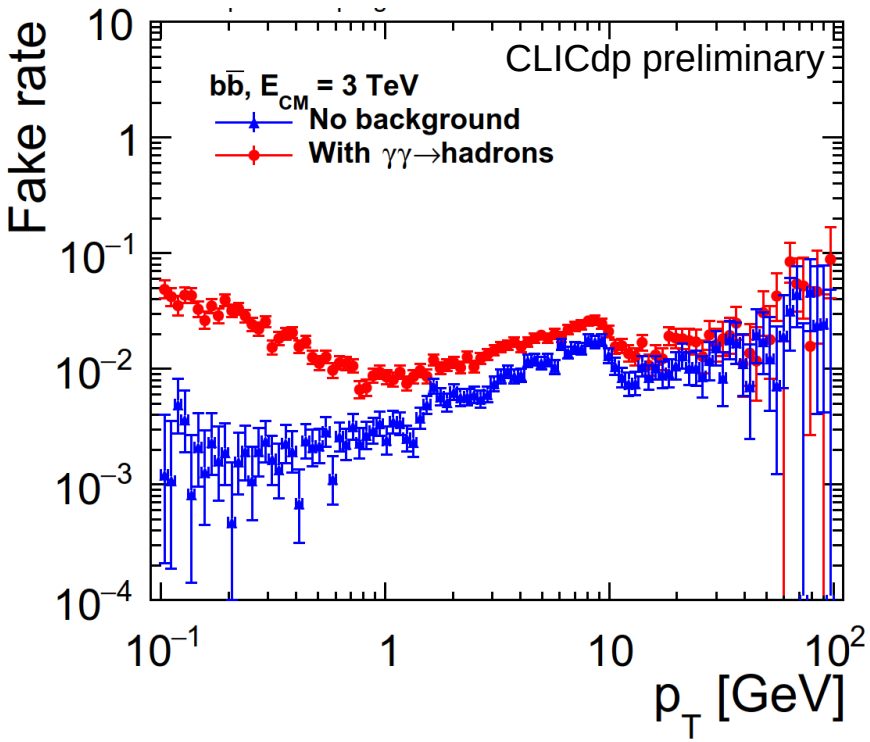
(full detector simulations)

Tracking efficiency and fake rate in complex events: $b\bar{b}$ at 3 TeV

(impact of beam-induced background)



100% efficiency > 1 GeV



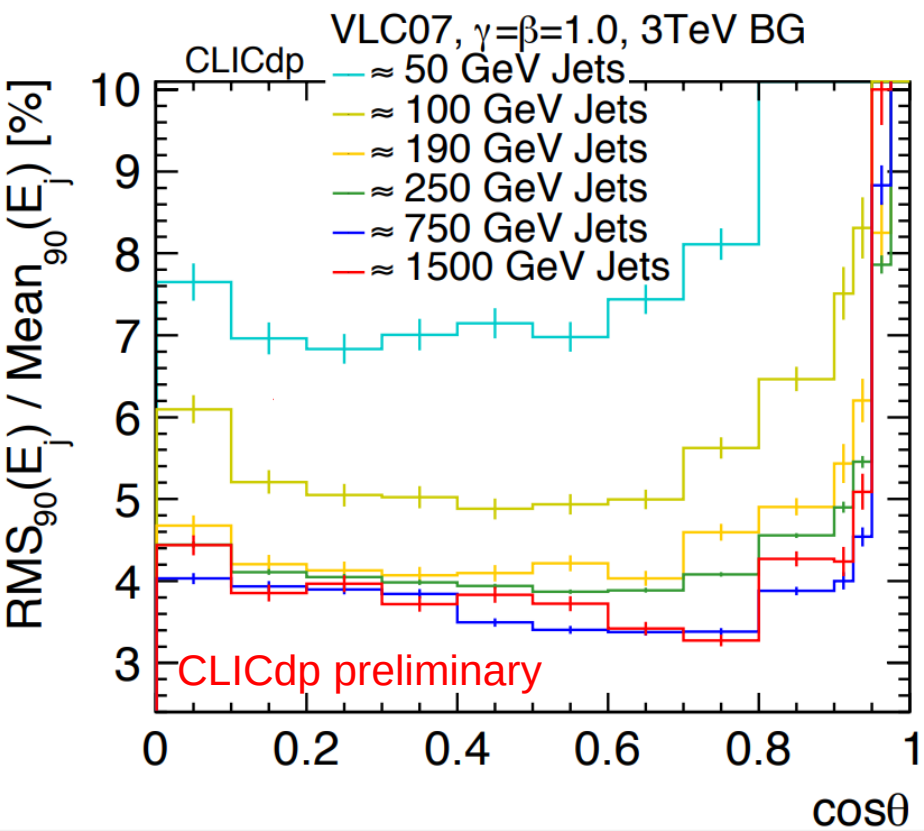
N.B. fake tracks ⇔ purity < 75%;
purity = N_{hits}_MC particle / N_{hits}_total

CLIC detector performance: Example (3)

(full detector simulations)

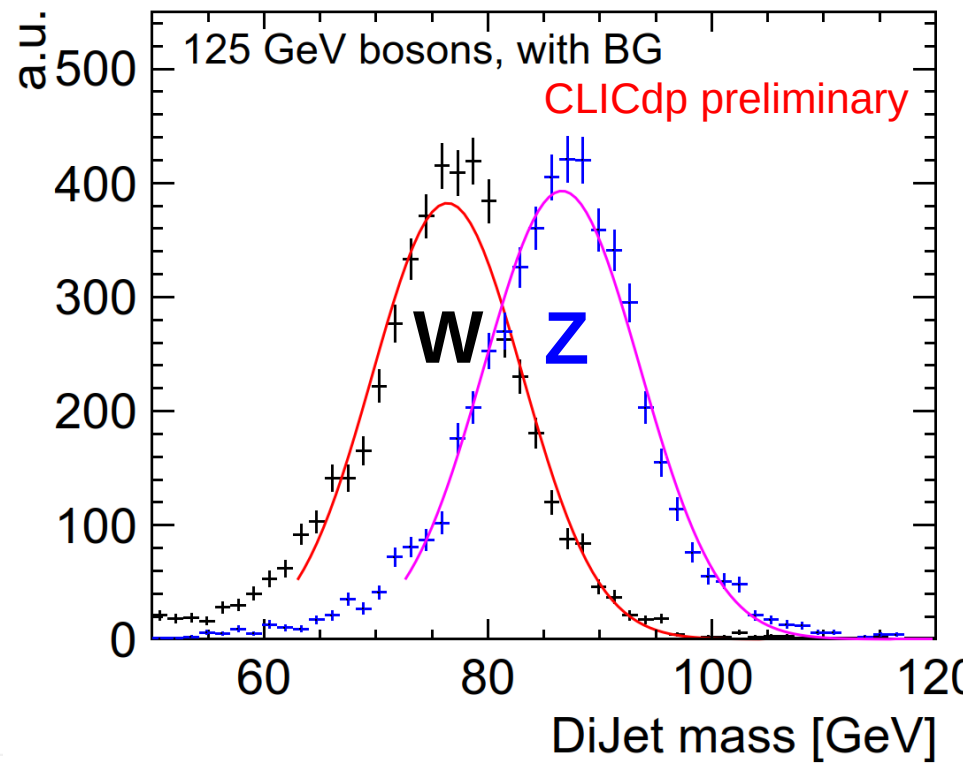
Calorimetry, using PANDORA Particle Flow Algorithms
(beam-induced background included)

Jet energy resolution

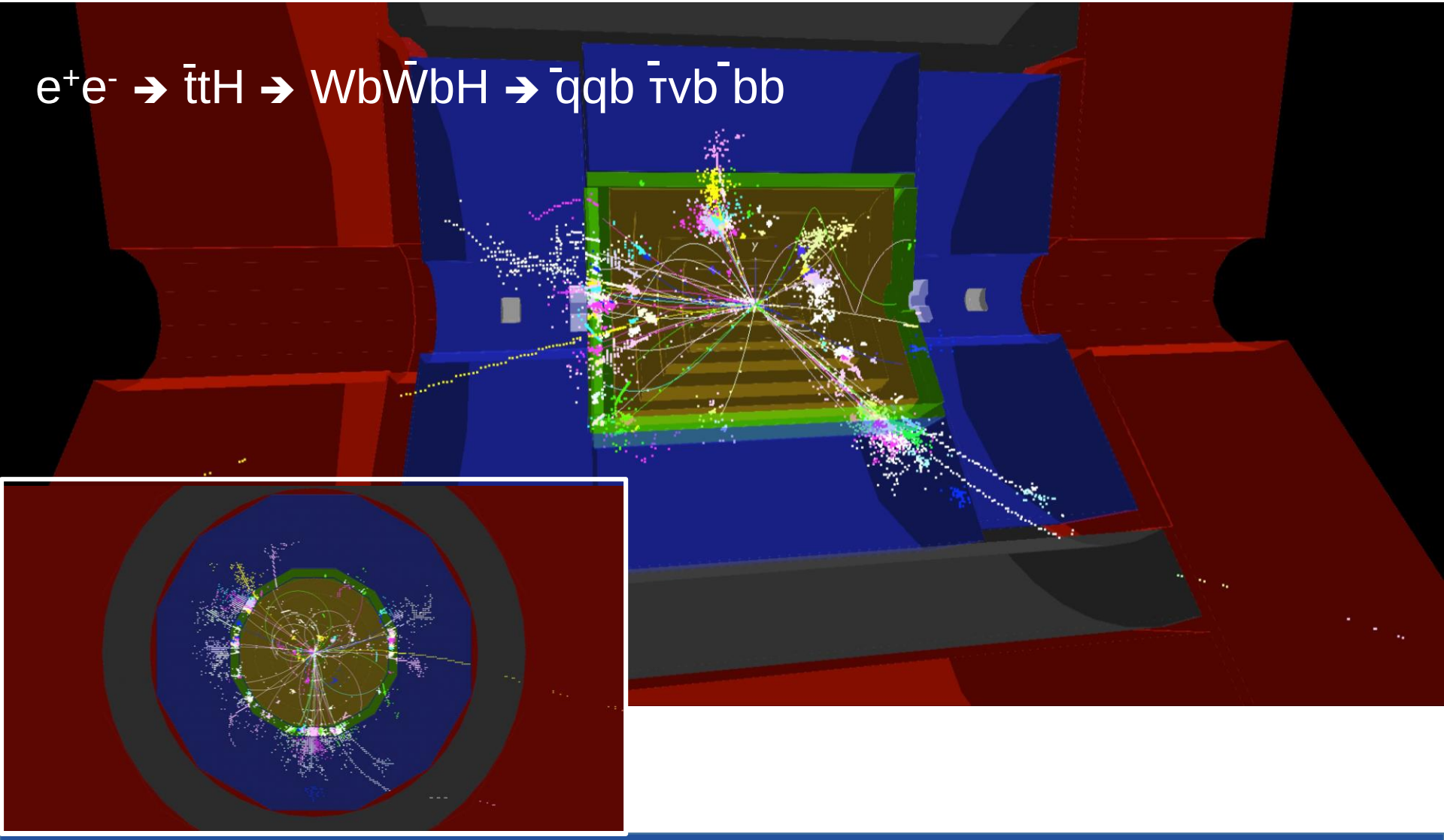


W/Z separation

(Example: di-jet mass distribution of 250 GeV c.m. WW and ZZ events)

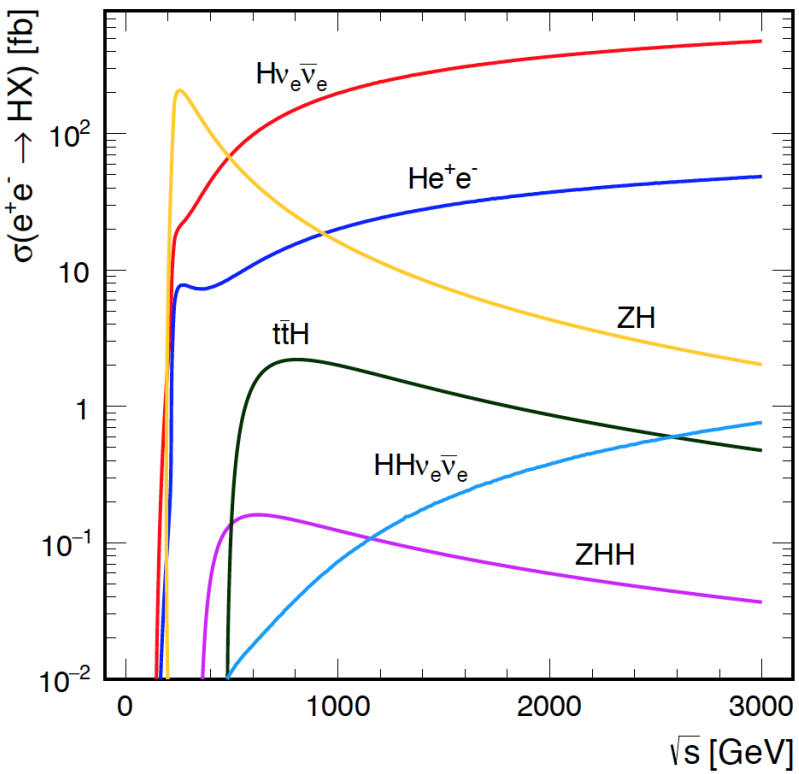


Physics at CLIC

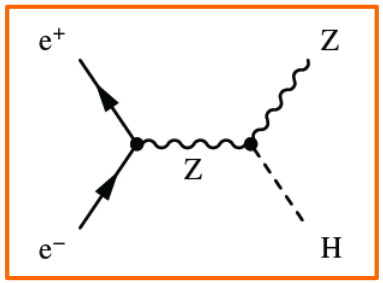


Higgs Physics at CLIC

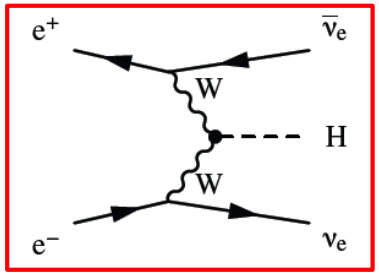
Eur. Phys. J. C 77, 475 (2017)



Dominant processes:



Higgsstrahlung
σ ~ 1/s
Higgs id. from Z recoil



WW(ZZ) - fusion
σ ~ log(s)
Large stat. at high E

	380 GeV	1.5 TeV	3 TeV
L_{int}	1 ab^{-1}	2.5 ab^{-1}	5 ab^{-1}
# ZH events	**120k**	30k	30k
# $H\nu_e\bar{\nu}_e$ events	40k	**650k**	**1.6M**
# He^+e^- events	7k	**70k**	**160k**

N.B.
high selection efficiencies

Higgs couplings (model-dependent)

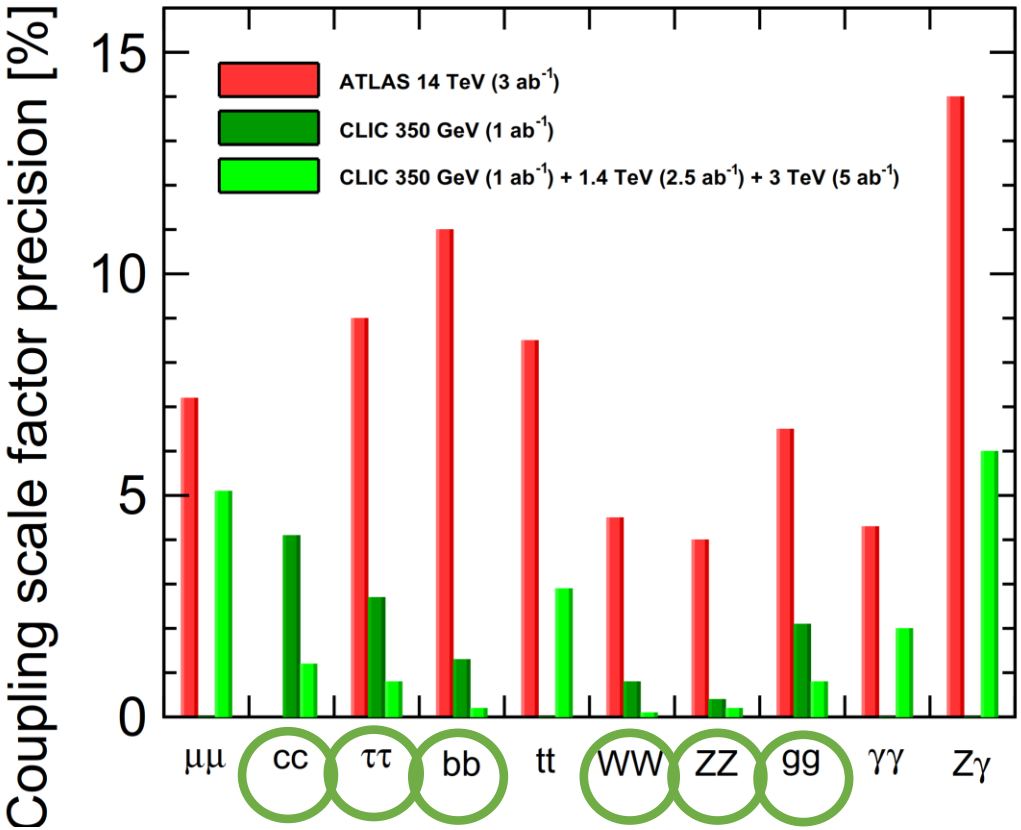
Model dependent fit:

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{SM}$$

BR$_i$: SM branching fractions (prediction)

Only SM Higgs decays:

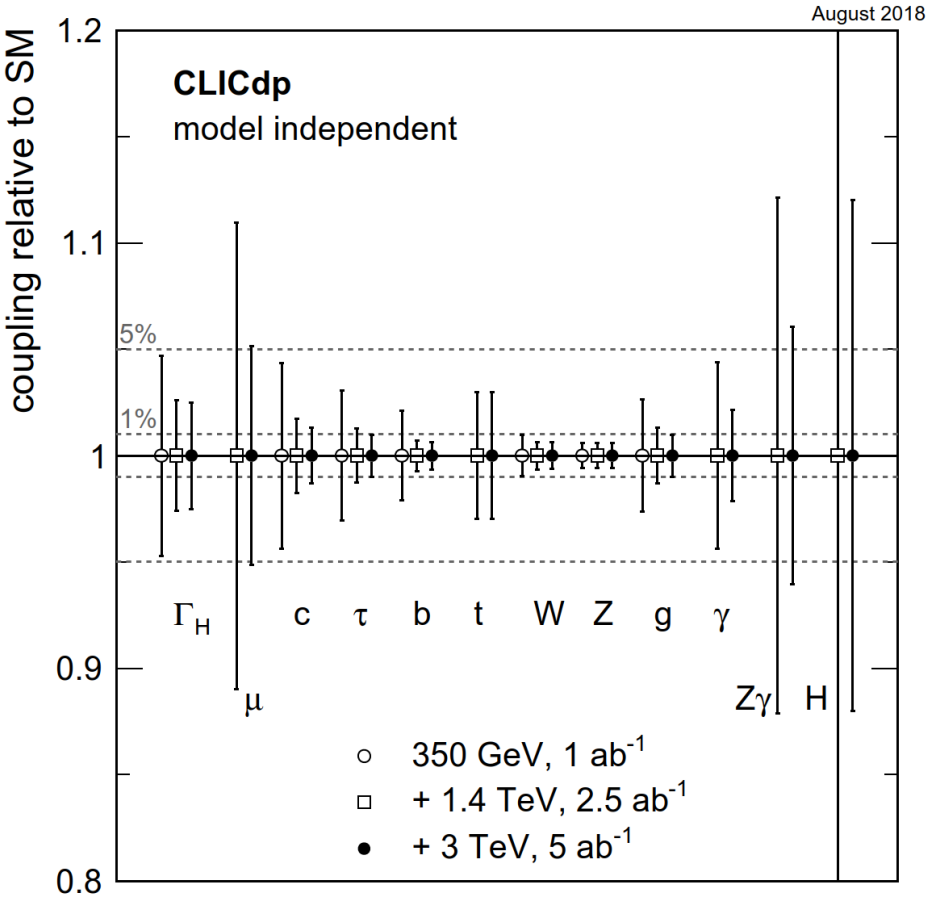
$$\frac{\Gamma_{H,md}}{\Gamma_H^{SM}} = \sum_i \kappa_i^2 \, BR_i$$



- first CLIC stage significantly more precise than HL-LHC for several of the couplings
- full CLIC program → still higher precision + access to rare events

ATLAS-PHYS-PUB-2014-016

Higgs couplings – model independent
unique at lepton colliders



Model-independent

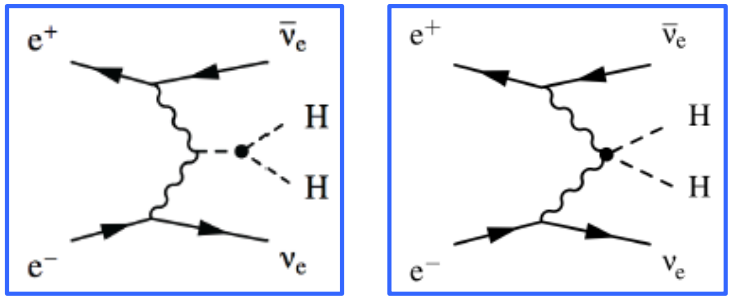
Higgs width is a free parameter, allows for additional non-SM decays

Full CLIC program, ~7-8 yrs of running at each stage

Model-independent: down to and below ±1% for most couplings

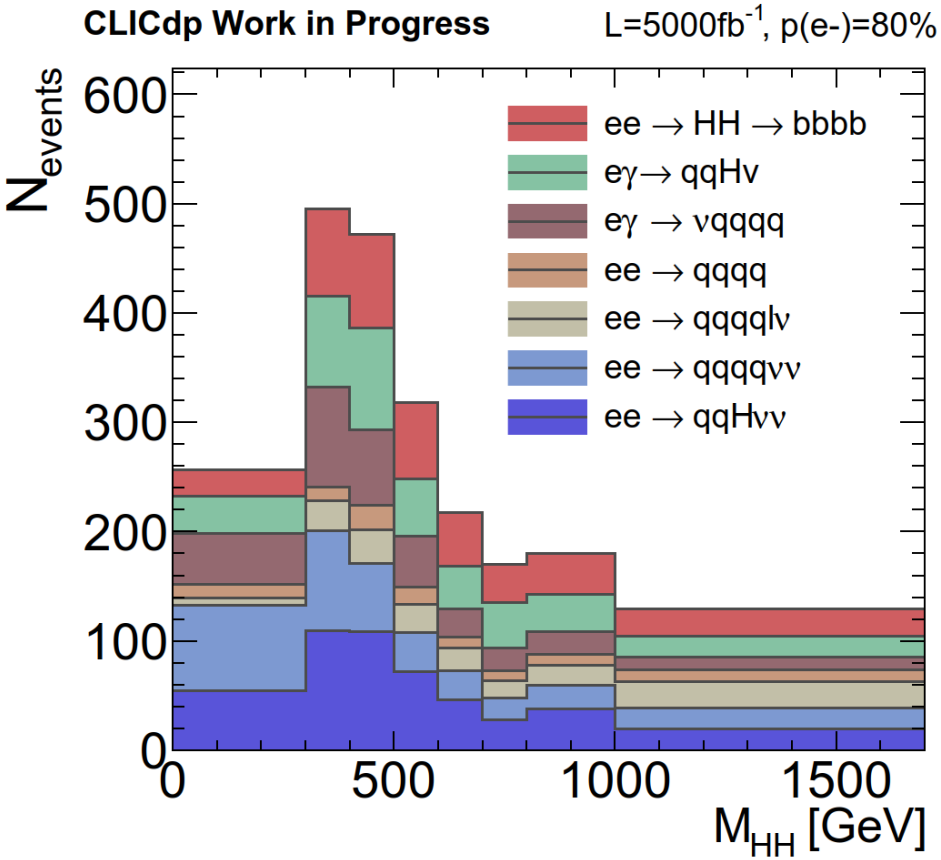
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±2.5% (model-independent)

Double Higgs production



- Cross section sensitive to g_{HHH} and g_{WWHH}
- Small cross section
  (about 700/6000 evts @ 1.5/3 TeV)
- Large backgrounds

⇒ **Requires high energy and high luminosity**



⇒ **$\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$**
for operation at 3 TeV

Double Higgs production **and New Physics**

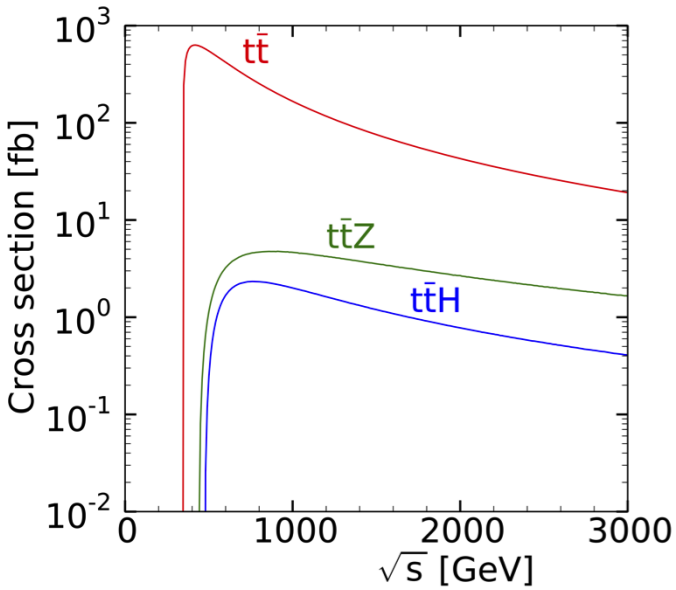
$\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$
for operation at 3 TeV

strong sensitivity to BSM

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $-15\,\%^{b}$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

Top Quark Physics at CLIC (arXiv:1807.02441)



Motivation:

So far top quark only measured at hadron colliders

Precision top physics in e^+e^-:

- sensitive to many BSM scenarios
- understanding EWSB
- testing ground of QCD

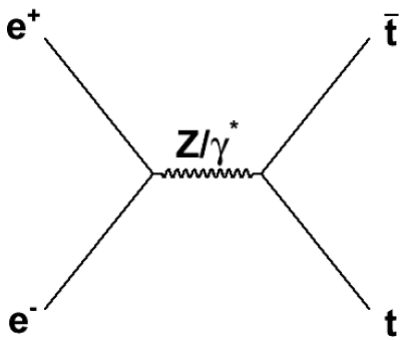
Top physics programme:

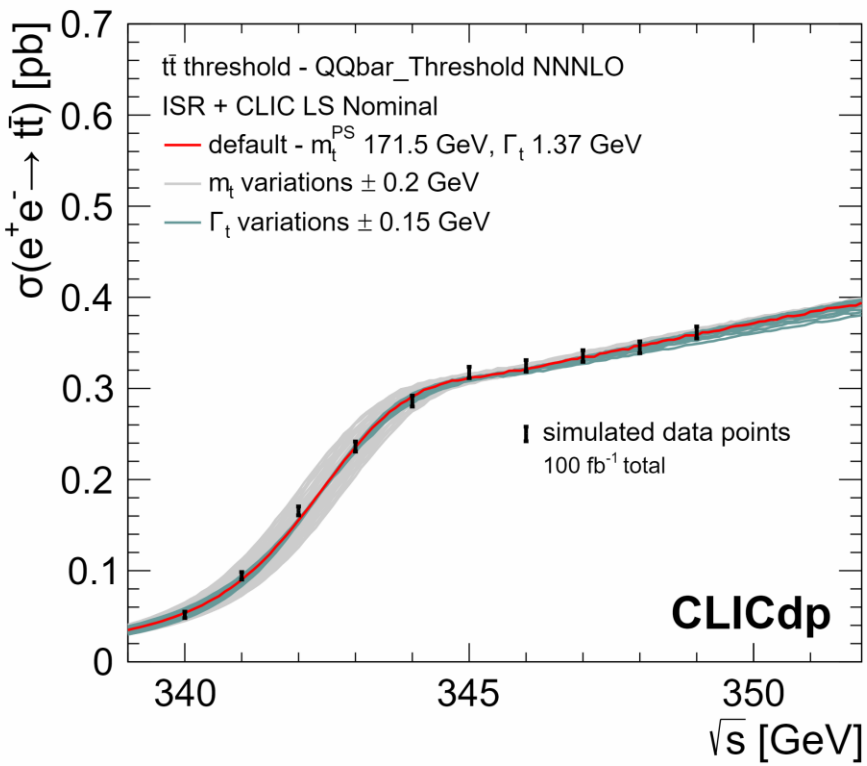
- Top quark **mass**
  - $t\bar{t}$ threshold scan at 350 GeV;
  - reconstructed mass above threshold
- **Electroweak couplings** to the top quark
  - At 380 GeV, and above 1 TeV (boosted top)
- **Yukawa coupling** through $t\bar{t}H$ production
- **Rare decays** (strongly suppressed in SM)

… …

CLIC 1st stage: threshold scan of top pair production

- **Top pair production cross section around the $t\bar{t}$ threshold**
- Resonant-like structure, very sensitive to m_{top}, and α_s

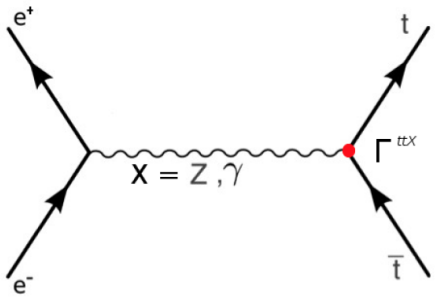


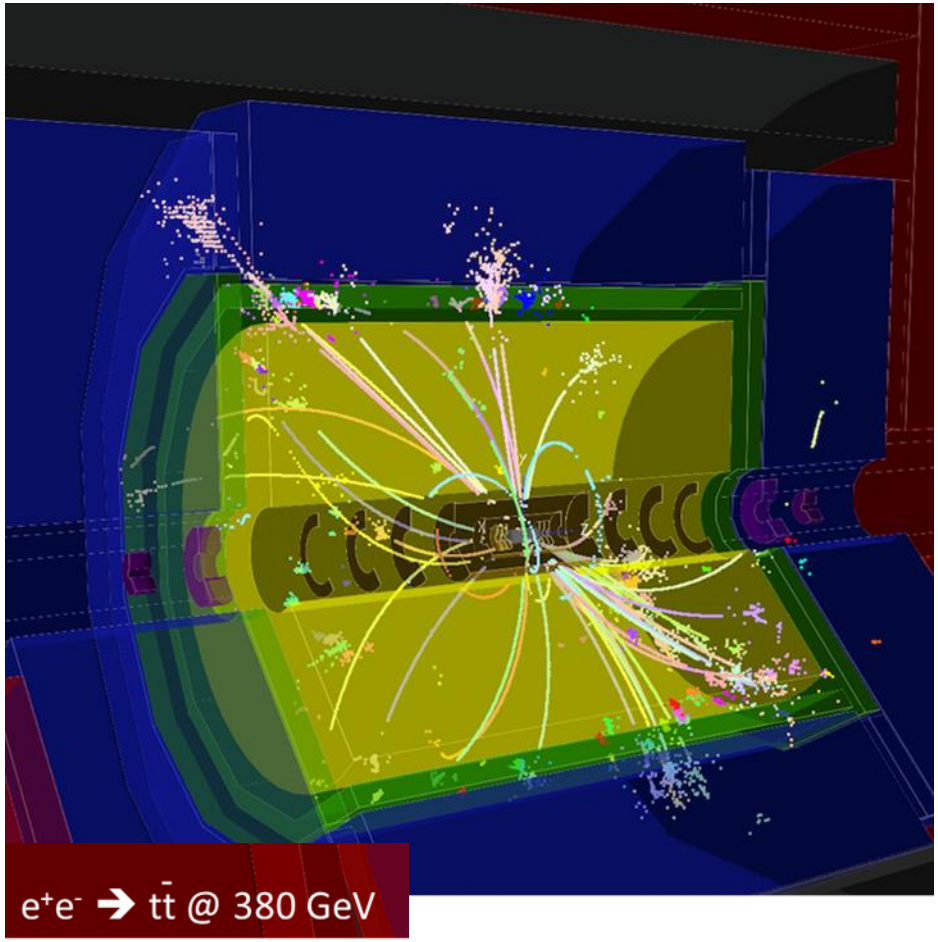


- Measurement at 10 different √s, 10 fb^{-1} each
- **Expected precision on mass: ≈50 MeV**
- error currently dominated by theory uncertainties

top quark couplings to Z and γ

Top quark pairs are produced via Z/γ
New physics would modify the ttV vertex



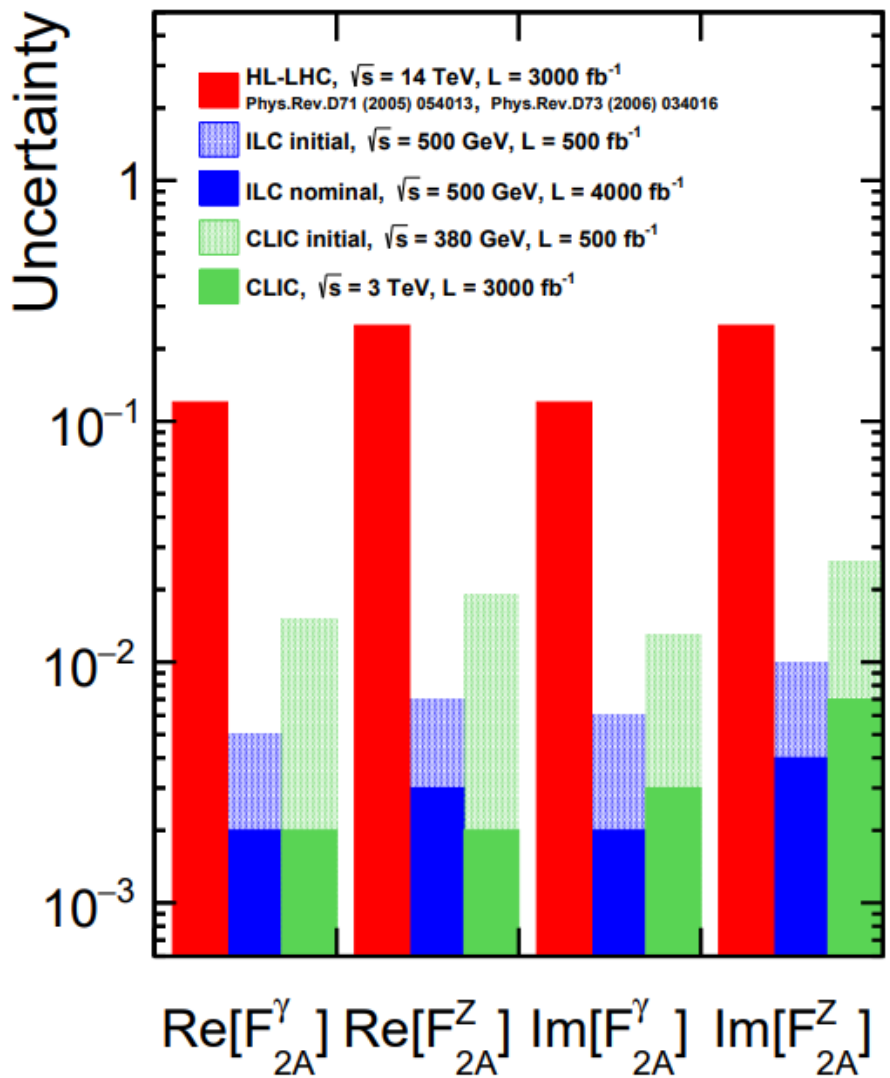


At a linear collider the **γ and Z form factors** can be disentangled *using beam polarization* by measuring:

- production cross section
- forward-backward asymmetry
- helicity angle distribution (in leptonic decays)

top quark couplings to Z and γ

expected precision at **LHC**, **ILC** (500 GeV) and **CLIC** (380 GeV / 3 TeV)



example: **CP-violating form factors**
68% C.L. limits
a sensitive probe of BSM physics

ILC: e^- and e^+ polarized (80% / 30%)

CLIC: e^- polarized (80%)

NB. old staging scenario, CERN-2016-004

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Summary

clic.cern

- **CLIC** – an excellent option for a future e^+e^- collider:
  380 GeV, upgrade stages of 1.5 TeV and 3 TeV
- key technological challenges:
  demonstrated feasibility at test benches / facilities
- great potential for precision physics (Higgs, top) beyond HL-LHC (studied in detail, using full simulation incl. backgrounds):
  < 1% accuracies on Higgs couplings already at the 1st stage
- New Physics - direct discovery in the TeV range, or indirect observation: 1% precision on top quark couplings to Z and γ ;
  Higgs self-coupling measured to 10% precision
- could be ready for physics by 2035 – at "affordable" cost (≅ 6 GCHF)

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

Thank you !

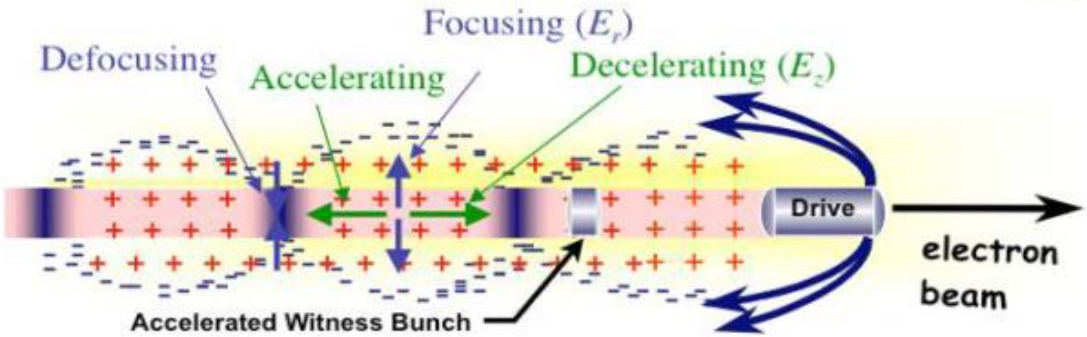
many thanks to Ph. Burrows, L. Linssen, E. Leogrande, Ph. Roloff, U. Schnoor, D. Schulte, S. Stapnes, M. Weber, W. Wuensch, A.F. Zarnecki…

additional material

Exploration of Future Upgrades

Started exploration of novel acceleration methods for high-energy upgrades

- Make sure CLIC is consistent with this



Plasma-based acceleration demonstrated gradients of 50 GV/m
Dielectric structures could lead to reduced cost

Main challenges

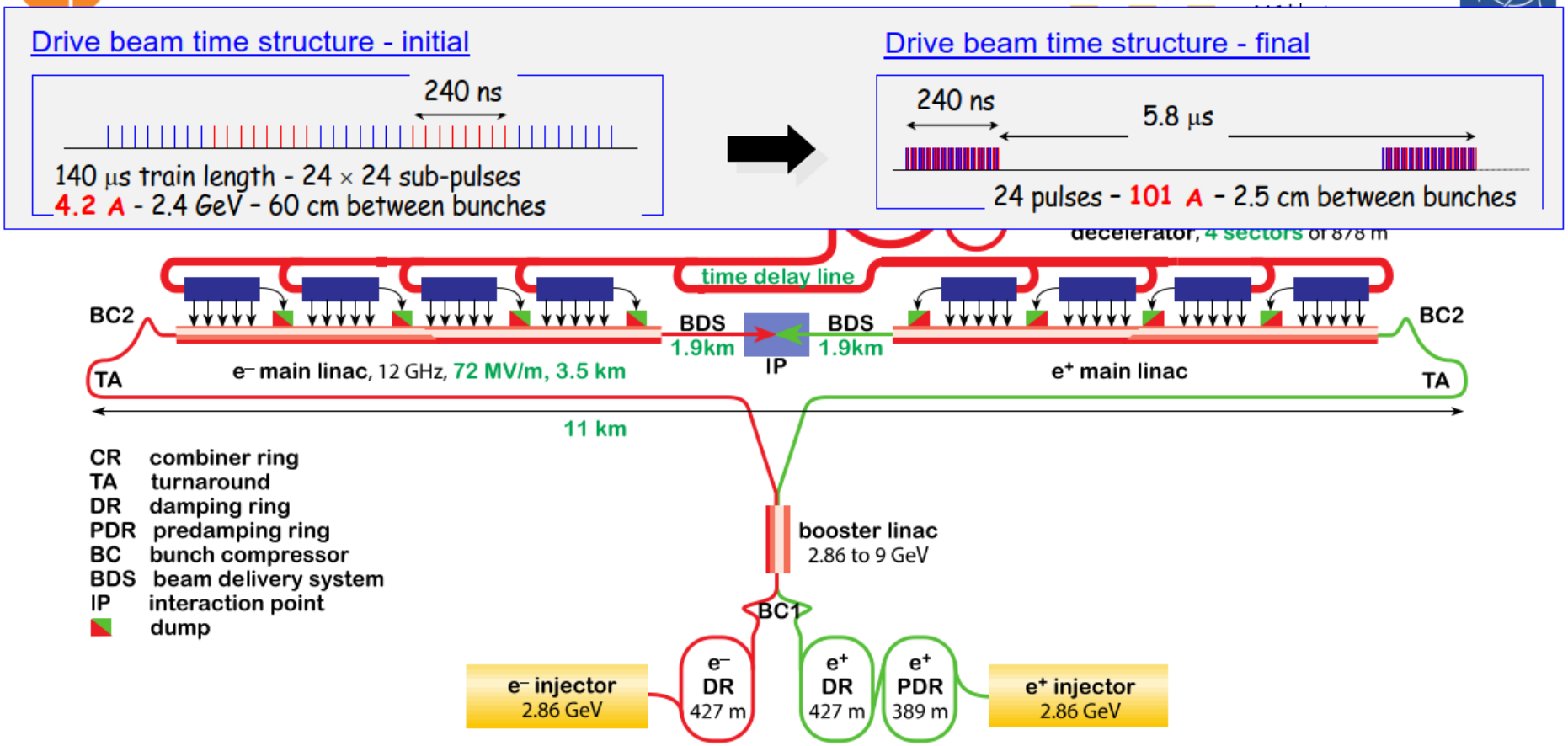
- Preservation of beam quality has to be explored theoretically and experimentally
- Efficiency and beam stability
- Many technical challenges

Might be possible to reuse drive beam

CERN Academic Training lectures on CLIC

- **Physics potential of a high-energy electron-positron collider**
- **Detector technology R&D for CLIC**
- **The CLIC accelerator design and performance**
- **Key technology developments for the CLIC accelerator**
- **Overview of applications using high-gradient acceleration, from photon sources to medical physics**

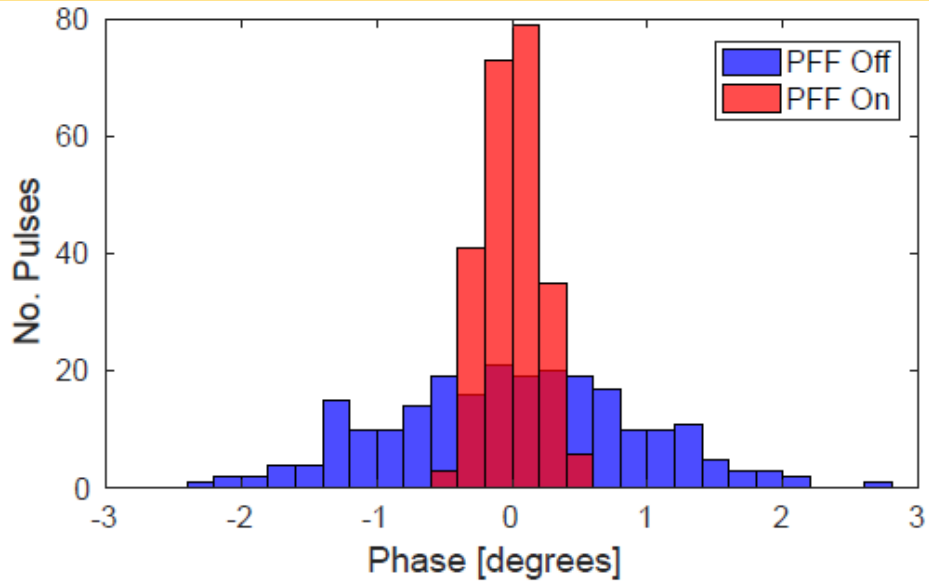
CLIC at 380 GeV



CLIC drive beam performance

Synchronisation of arrival time of drive / main beam

Arrival time with “phase feed forward” (PFF) system



one PFF system per turn-around loop;
prototype tested at CTF3

Time jitter <-> phase jitter at 12 GHz:
50 fs <-> 0.2 degree

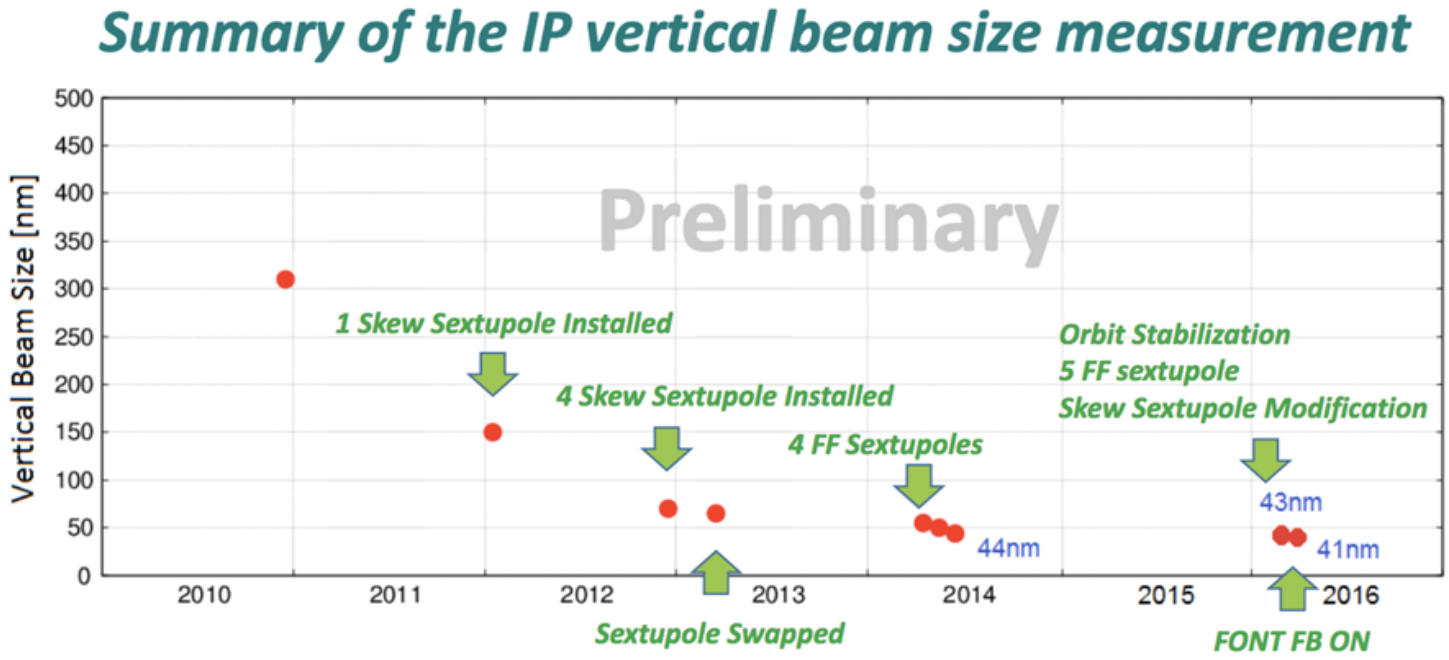
(phase monitors,
low latency digitizer/feedforward,
fast kickers)

Parameter (jitter)	CLIC goal	CTF3 measured
Arrival time	50 fs	50 fs
Current after linac	0.75×10^{-3}	$0.2\text{-}0.4 \times 10^{-3}$
Current at end	0.75×10^{-3}	$2\text{-}18 \times 10^{-3}$
Energy	1.0×10^{-3}	0.7×10^{-3}

Current stability understood: affected by very low CTF3 energy, 3 x larger beam and a delay loop design different from CLIC

Beam quality for luminosity

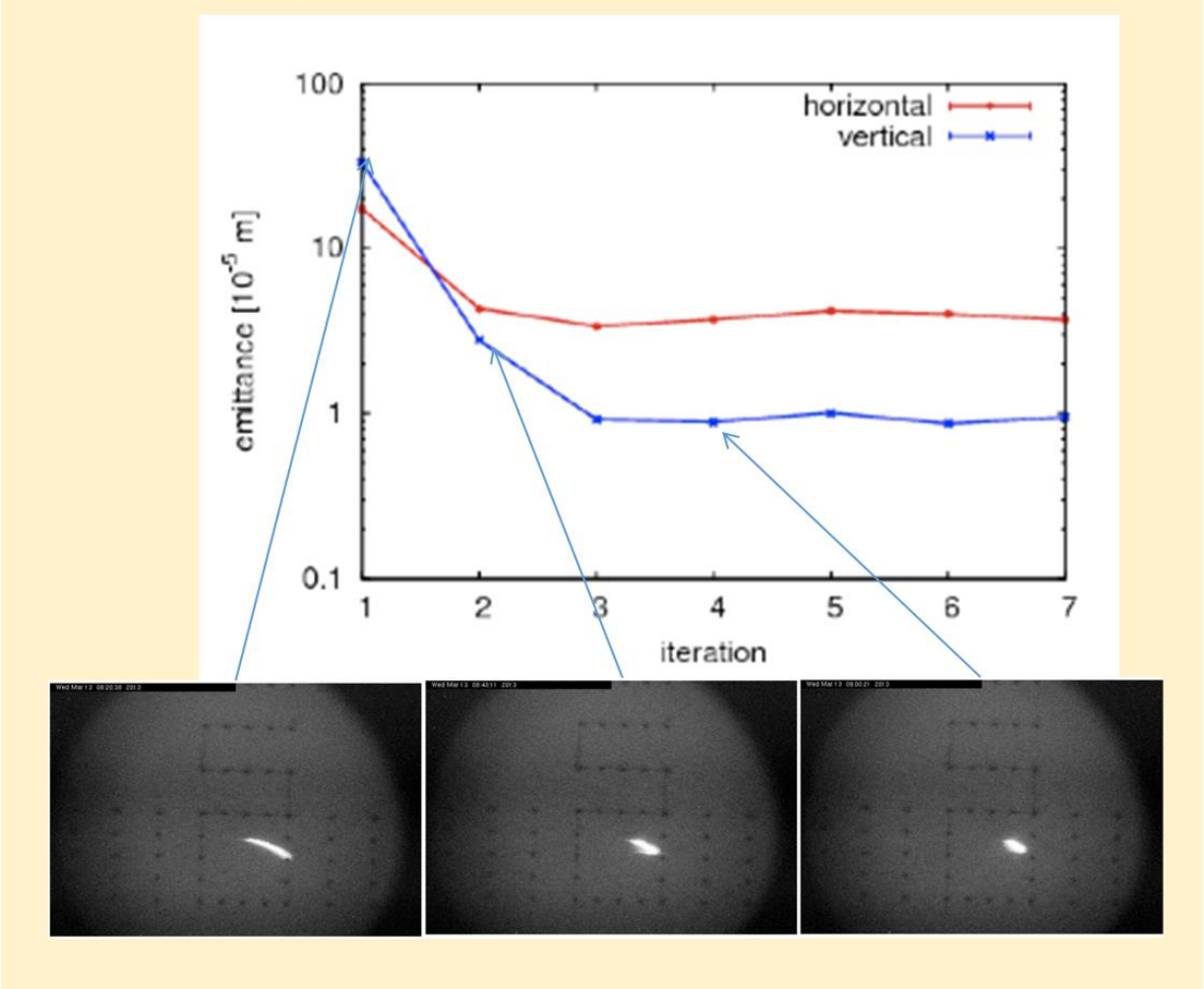
Small beam spot – tests at ATF2 (KEK)



NB. achieved 41 nm - close to target (37 nm)

Beam quality for luminosity

Innovative beam-based alignment – “dispersion-free steering”: tests over 500 m at FACET (SLAC)



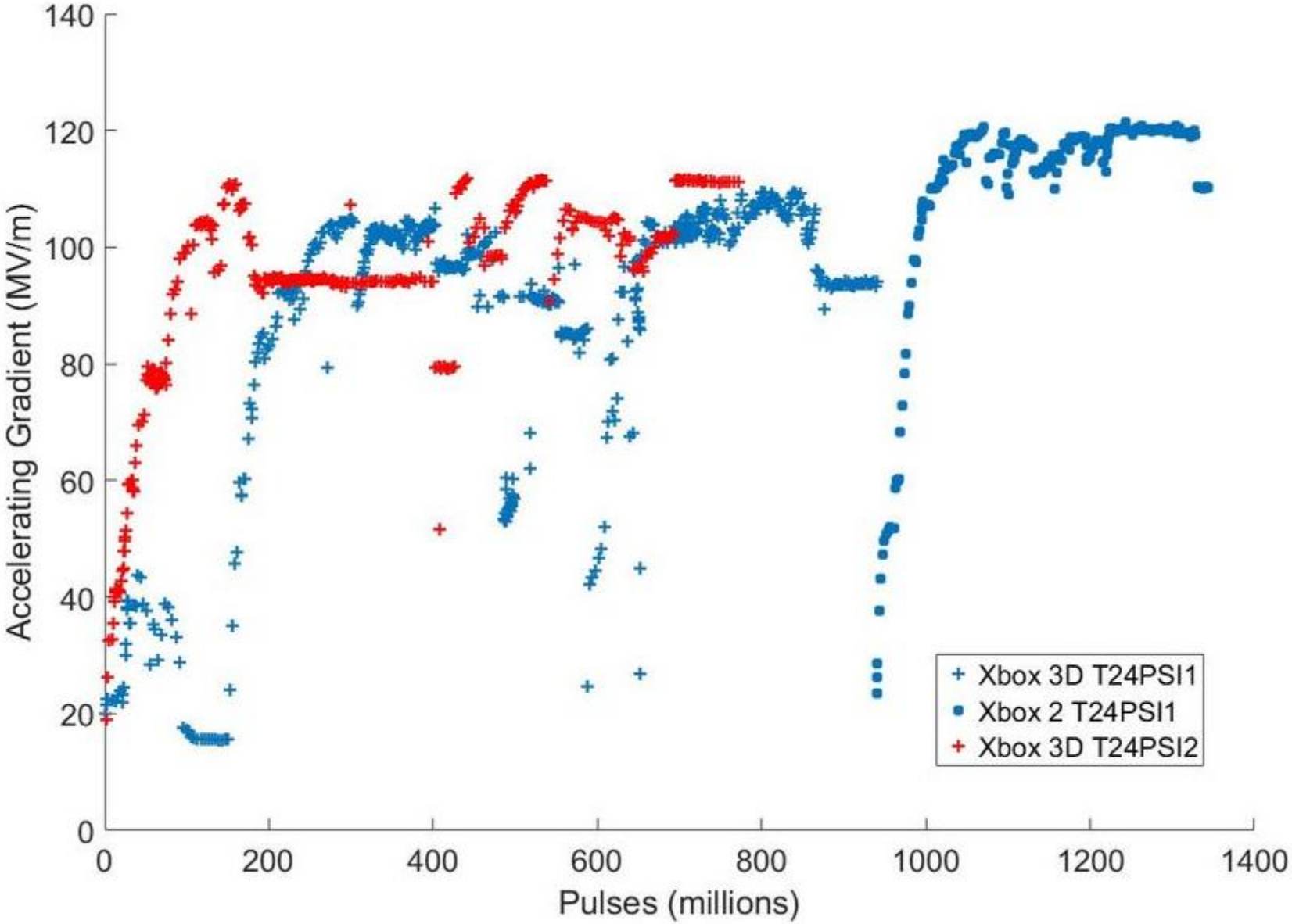
CERN Courier, April 2018

The rich exchange between different projects in the high-gradient community is typified by PSI and in particular the SwissFEL. Many essential features of the SwissFEL have a linear-collider heritage, such as the micron-precision diamond machining of the accelerating structures, and SwissFEL is now returning the favour. For example, a pair of CLIC X-band test accelerating structures are being tested at CERN to examine the high-gradient potential of PSI's fabrication technology, showing excellent results: both structures can operate at more than 115 MV/m and demonstrate potential cost savings for CLIC. In addition, the SwissFEL structures have been successfully manufactured to micron precision in a large production series – a level of tolerance that has always been an important concern for CLIC. Now that the PSI fabrication technology is established, the laboratory is building high-gradient structures for other projects such as Elettra, which wishes to increase its X-ray energy and flux but has performance limitations with its 3 GHz linac.

PSI News

X-band (12 GHz) radio-frequency (RF) accelerating structures are under consideration for future free electron lasers, medical linacs and linear colliders. Two such structures, built by PSI in the framework of a CERN/PSI collaboration, are currently being tested at high power at CERN. They are reported to have reached an accelerating gradient in excess of 115 MV/m, making them among the best X-band structures to have been tested by the CERN Linear Collider project group. The structures have benefitted from the fabrication protocols used for the SwissFEL C-band structures. The gradient continues to improve with further “conditioning” at CERN.

PSI News


Accelerating Gradient (MV/m)
Pulses (millions)
0
20
40
60
80
100
120
140
0
200
400
600
800
1000
1200
1400
Xbox 3D T24PSI1
Xbox 2 T24PSI1
Xbox 3D T24PSI2

New Physics: rare FCNC* top-quark decays

* Flavour-changing Neutral Current

FCNC top-quark decays are strongly suppressed in SM (CKM+GIM):

$$BR(t \to c\,\gamma) \sim 5 \cdot 10^{-14}$$
$$BR(t \to c\,H) \sim 3 \cdot 10^{-15}$$
$$BR(t \to c\,Z) \sim 1 \cdot 10^{-14}$$
$$BR(t \to c\,g) \sim 5 \cdot 10^{-12}$$

Significant enhancement possible in many BSM scenarios

Maximum branching fractions possible:

Model	2HDM	MSSM	$\not{R}$ SUSY	LH	Q singlet	RS
BR($t \to c\,\gamma$)	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8 \cdot 10^{-9}$	10^{-9}
BR($t \to c\,H$)	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4 \cdot 10^{-5}$	10^{-4}

New Physics: rare FCNC* top-quark decays

* Flavour-changing Neutral Current

Expected limits for 500 fb^{-1} collected luminosity at 380 GeV:

(significant improvement for 1 ab^{-1})

$$\mathrm{BR}(t \to c\gamma) < \cancel{4.7 \cdot 10^{-5}} \rightarrow \mathbf{2.6 \cdot 10^{-5}}$$

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) < \cancel{1.2 \cdot 10^{-4}} \rightarrow \mathbf{7.1 \cdot 10^{-5}}$$

$$\mathrm{BR}(t \to c\not{E}) < 1.2 - 4.1 \cdot 10^{-4}$$

(work in progress)