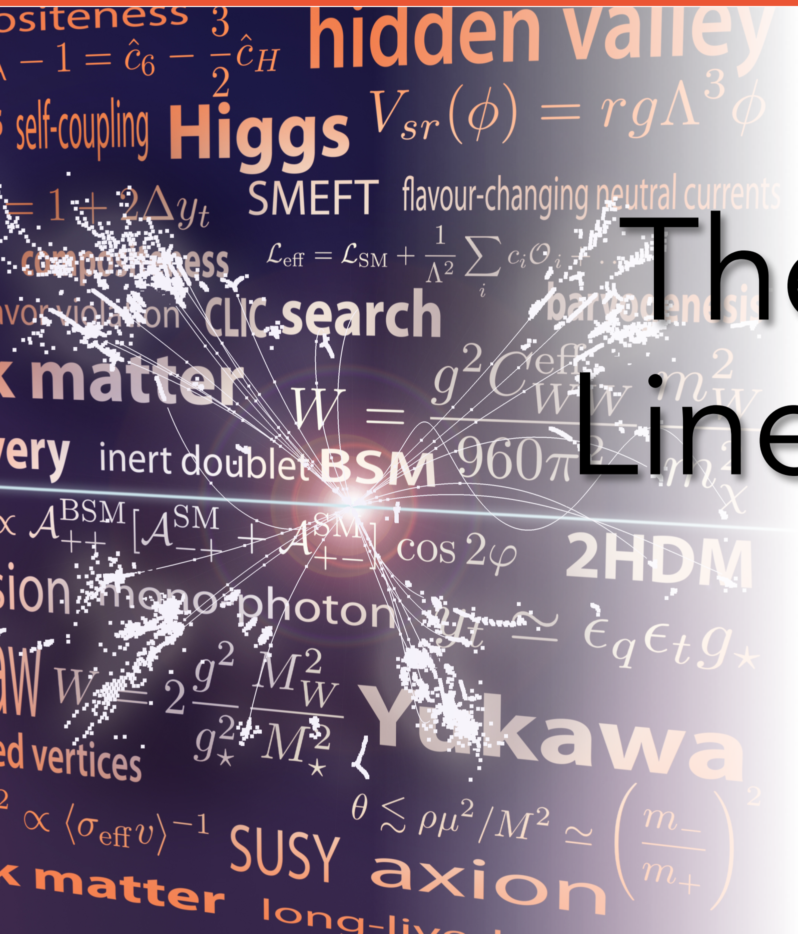
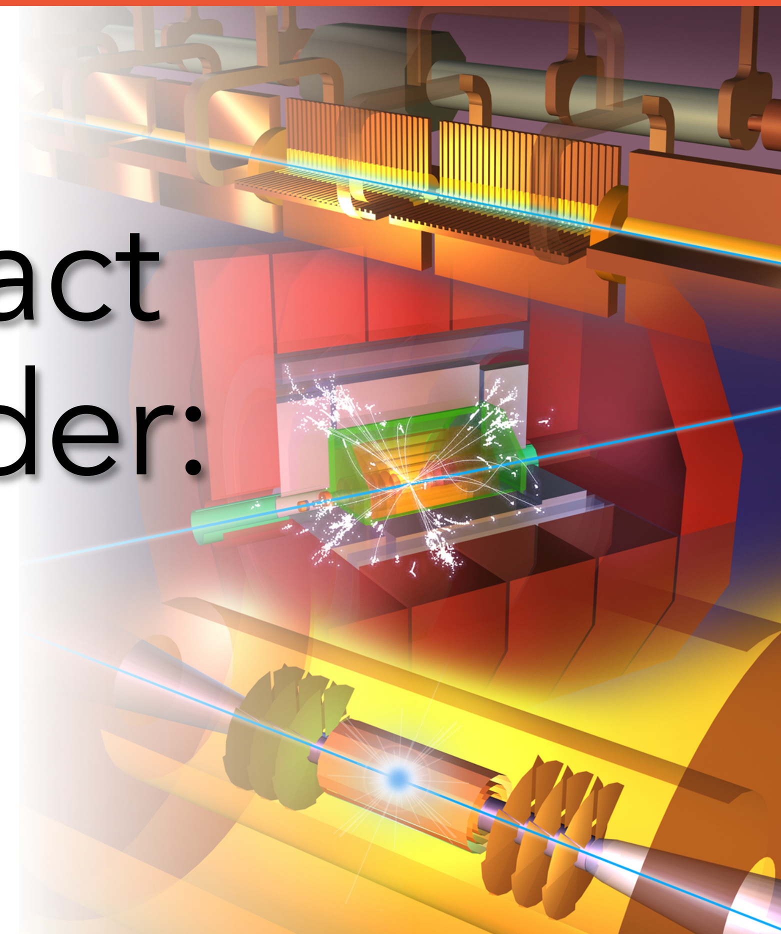


The Compact Linear Collider: CLIC



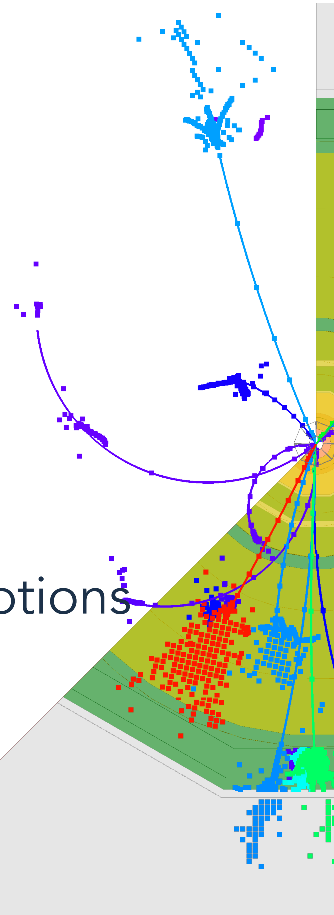
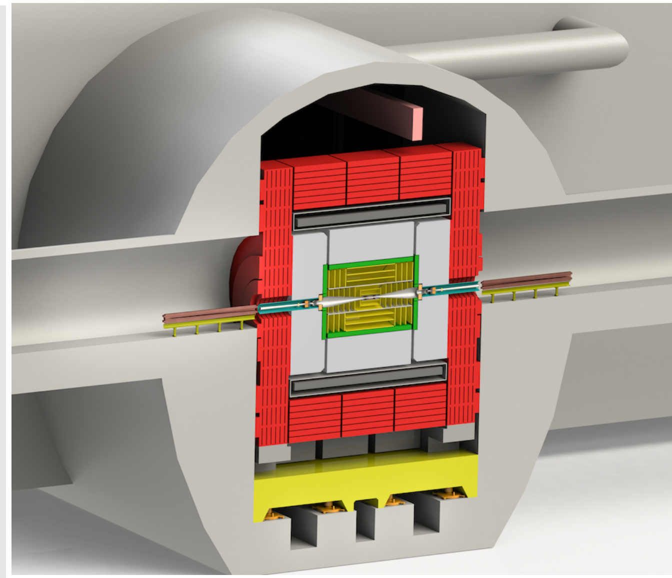
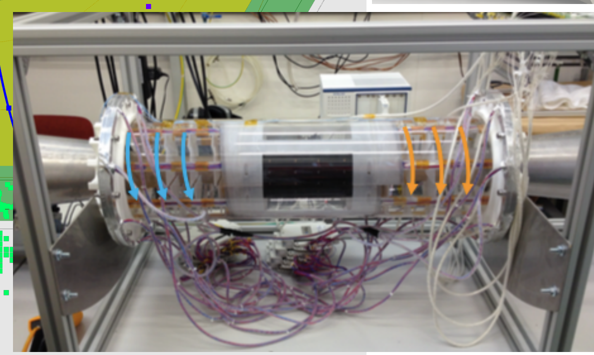
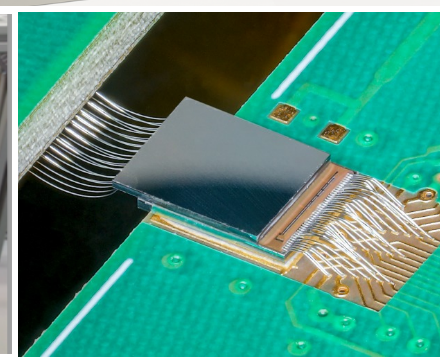
DESY Colloquium, 19 November 2019

Aidan Robson, University of Glasgow

CLIC

- Project overview
- Physics reach
- Detector concept & technologies
- Project realisation
- Comparison with other options
- Outlook

Compact Linear Collider:
e^+e^- collisions up to 3TeV
http://clic.cern/

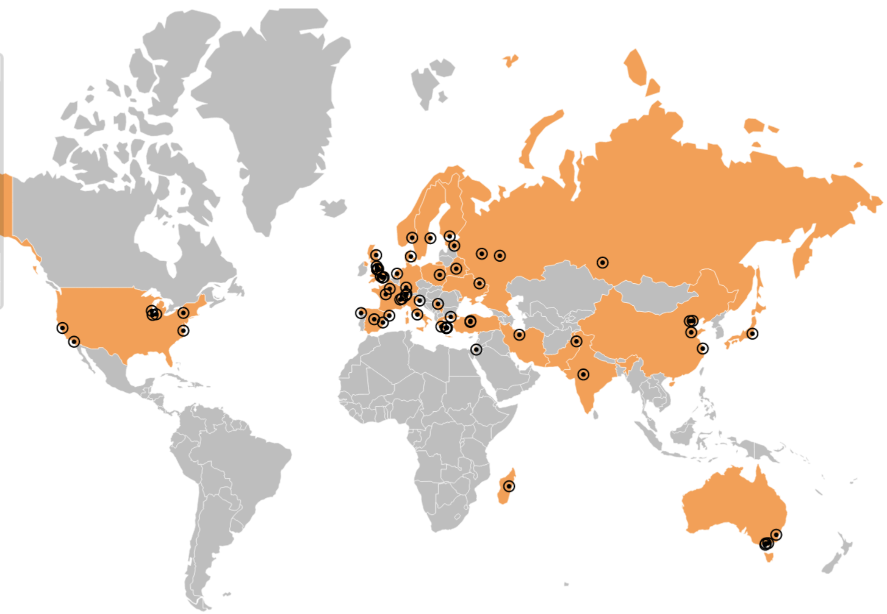





Collaborations

http://clic.cern/

CLIC accelerator collaboration
~60 institutes from 28 countries

CLIC accelerator studies:
- CLIC accelerator design and development
- (Construction and operation of CLIC Test Facility, CTF3)

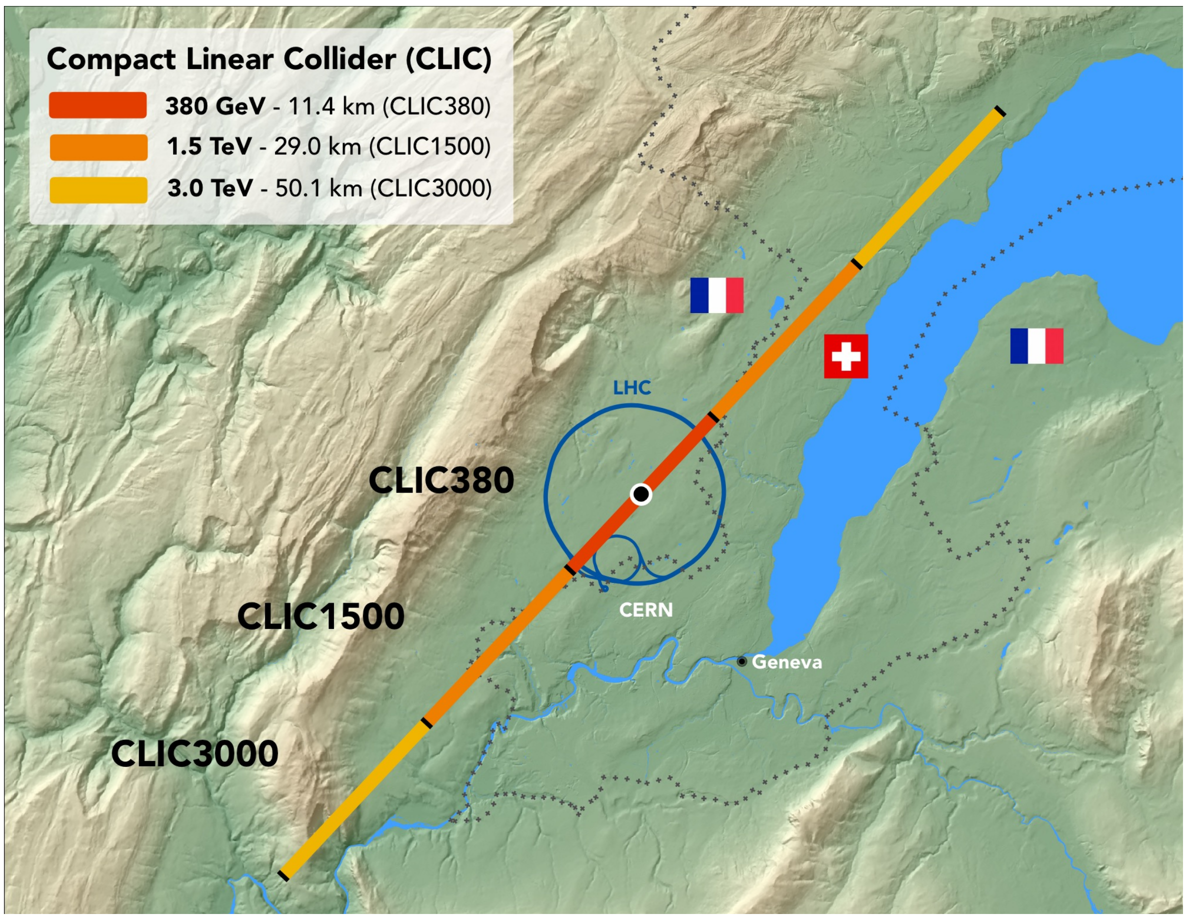


CLIC detector and physics (CLICdp)
30 institutes from 18 countries

Focus of CLIC-specific studies on:
- Physics prospects & simulation studies
- Detector optimization + R&D for CLIC

The Compact Linear Collider

- A high-luminosity, multi-TeV electron–positron collider
- Planned for construction at CERN in three energy stages:



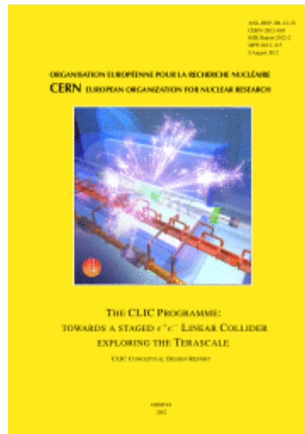
- 380GeV, focusing on precision Higgs boson and top-quark physics
- 1.5 and 3TeV, expanding Higgs and top studies including Higgs self-coupling, and opening higher direct and indirect sensitivity to Beyond Standard Model (BSM)
- Nominal physics programme lasts for 25–30 years; approvable in stages
- Benefit of linear machine: length/energy staging plan can be updated in response to developing physics landscape

CLIC History

- 3-volume CDR 2012

Accelerator

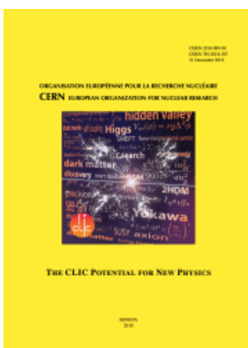
Physics & Detectors



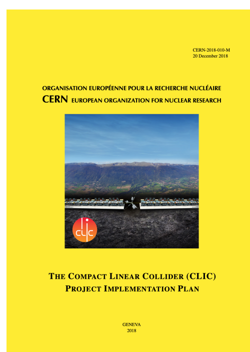
Strategy & Implementation

- 4 Yellow Reports 2018

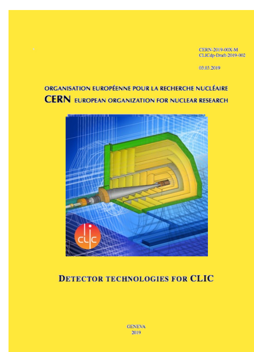
Summary Report



Physics Potential

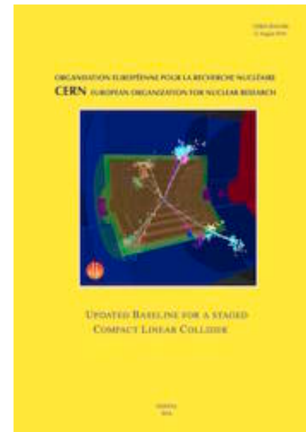


Project Implementation



Detector Technologies

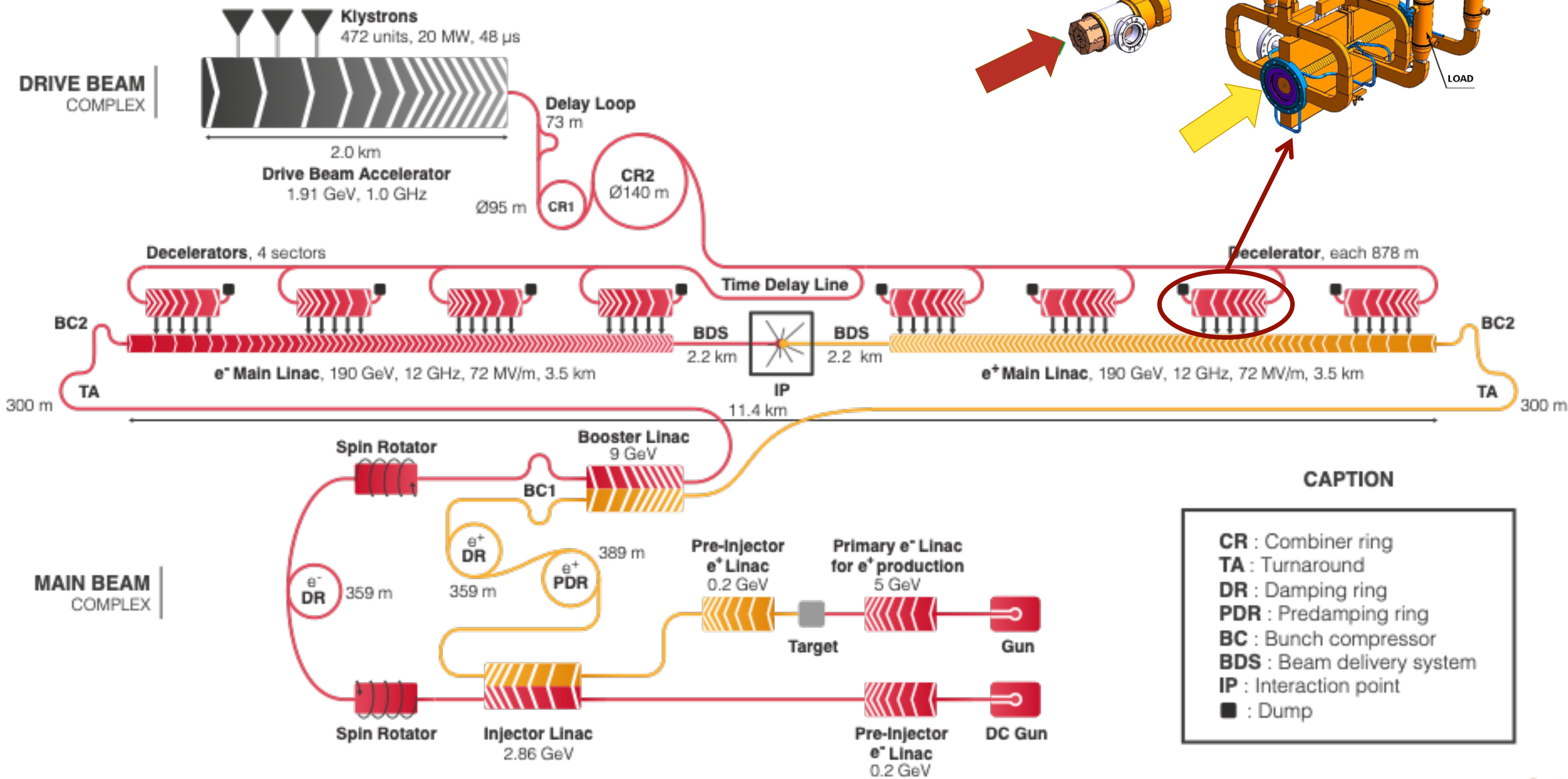
Updated Staging Baseline 2016



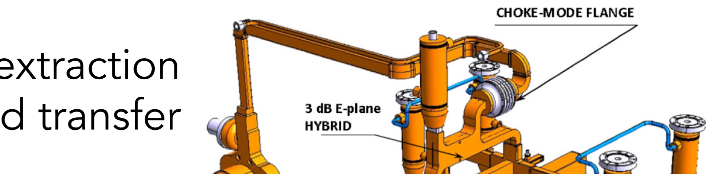
- Key accelerator technologies have been demonstrated
- CLIC is now a mature project – ready for construction starting ~2026, with first collisions ~2035

CLIC at 380GeV

- Two-beam acceleration scheme

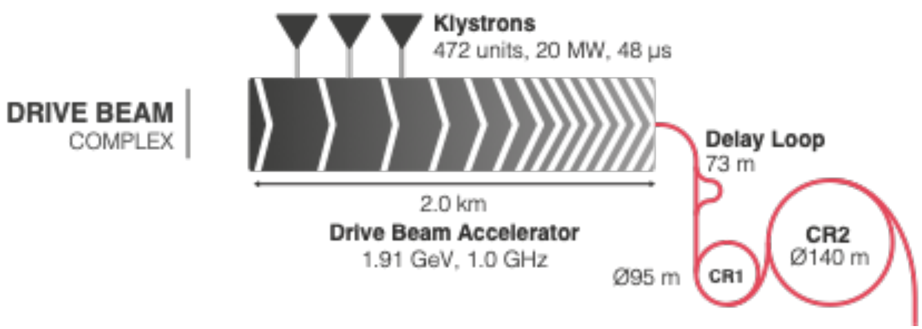


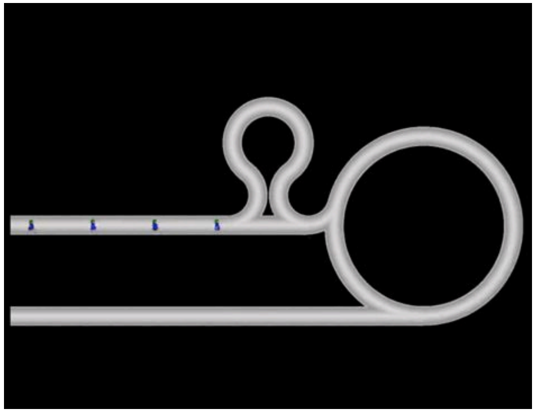
Power extraction and transfer

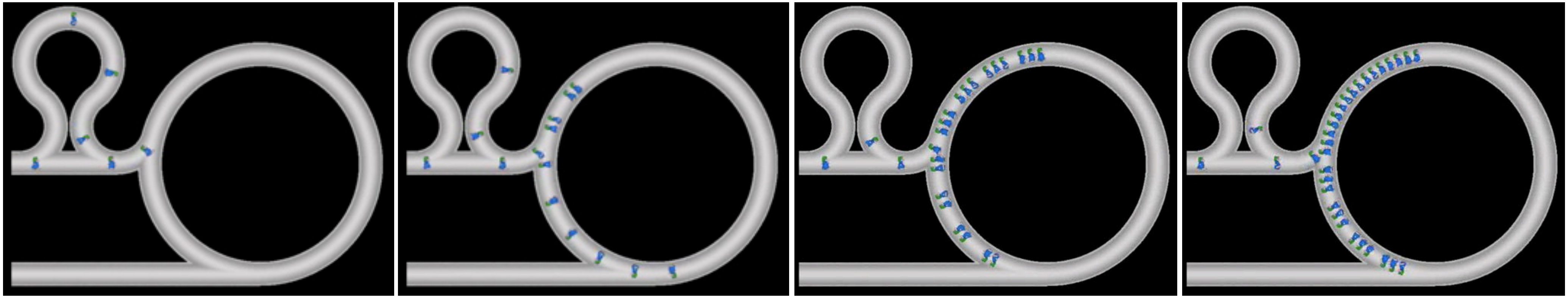


CLIC at 380GeV

- Delay loops create drive-beam structure



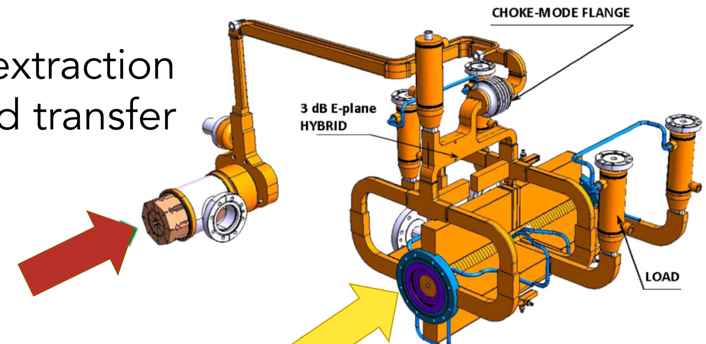


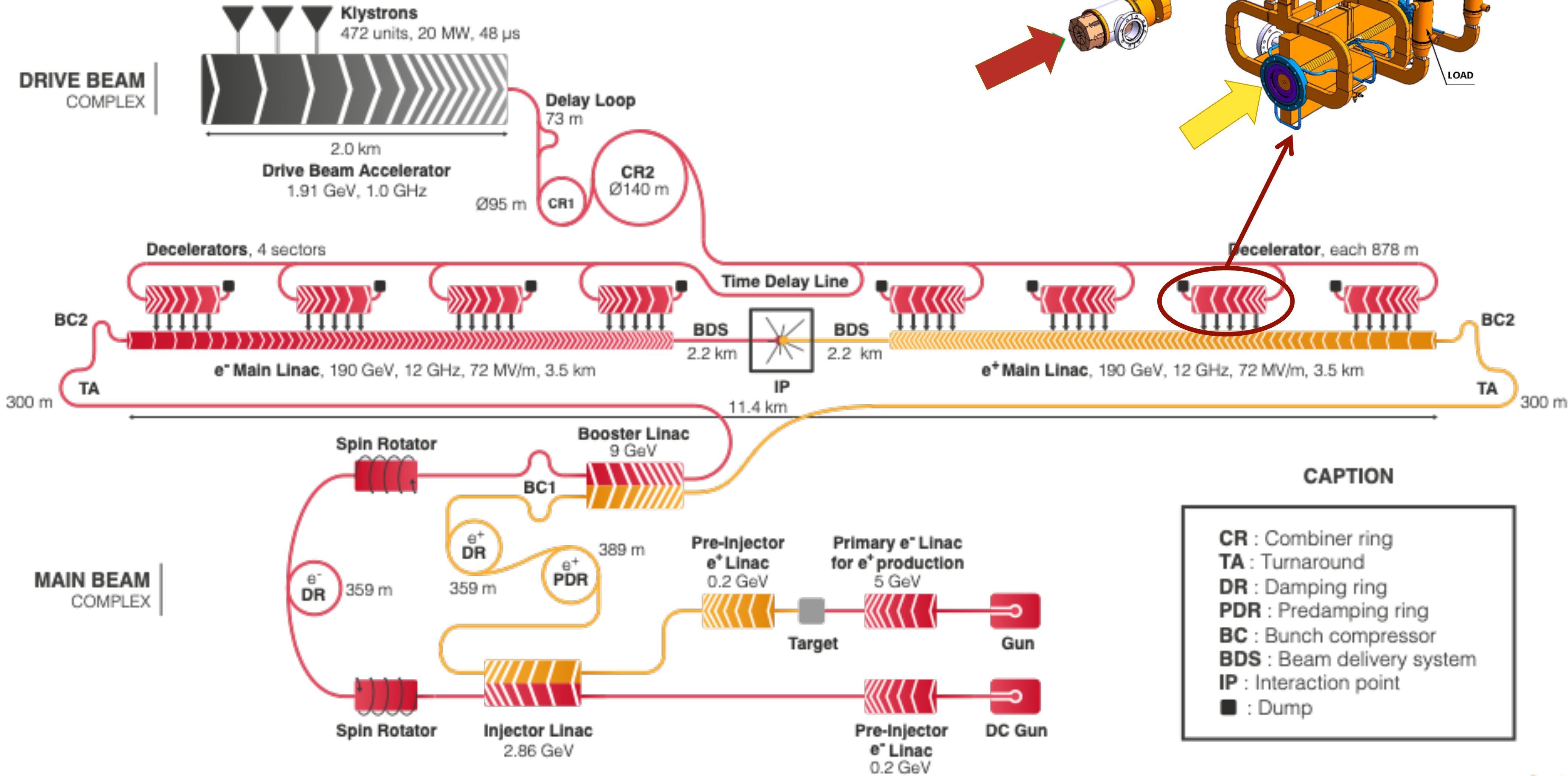


CLIC at 380GeV

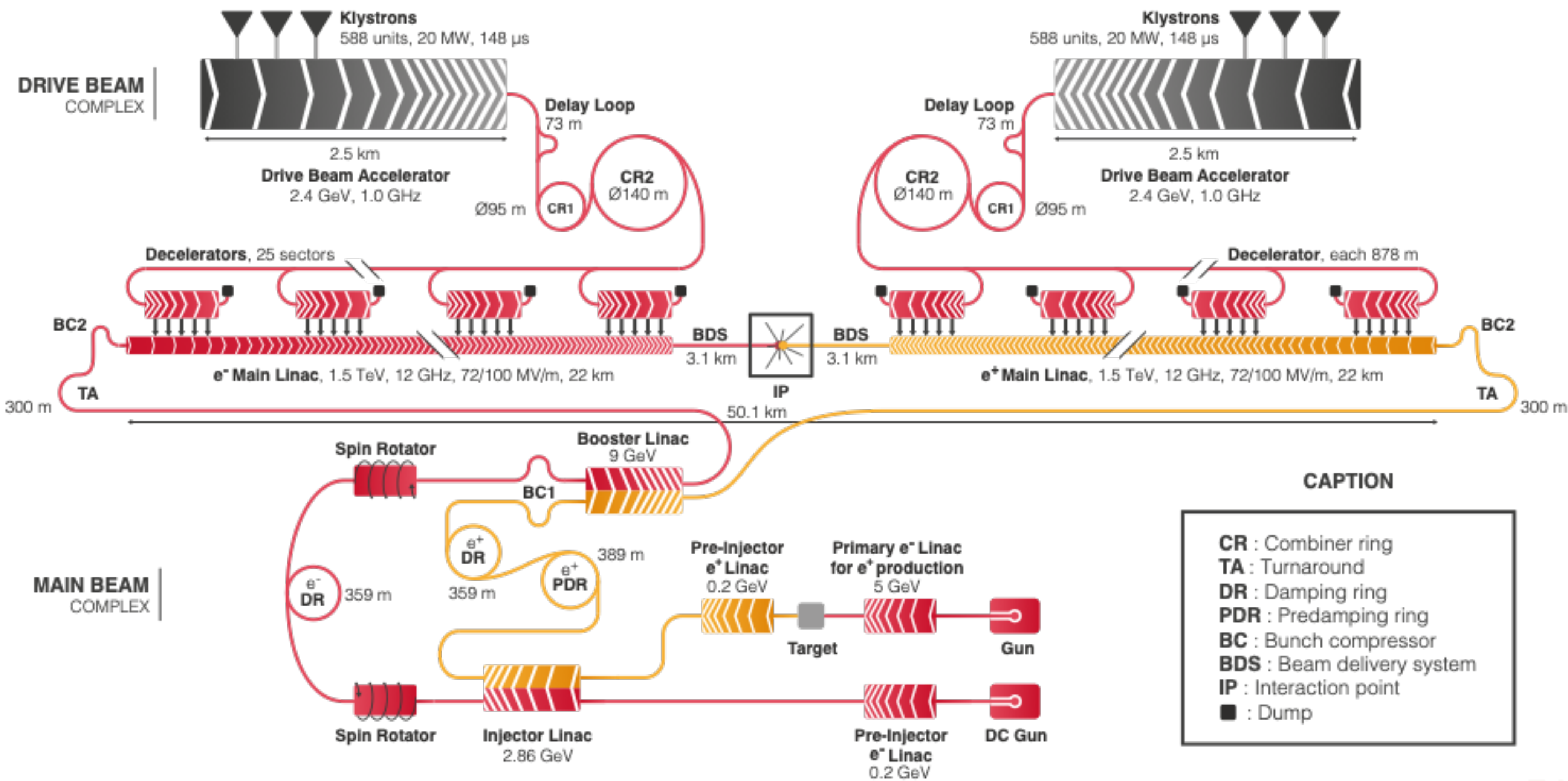
- Two-beam acceleration scheme

Power extraction and transfer





CLIC at 3TeV


DRIVE BEAM
COMPLEX
Klystrons
588 units, 20 MW, 148 µs
2.5 km
Drive Beam Accelerator
2.4 GeV, 1.0 GHz
Delay Loop
73 m
CR1
Ø95 m
CR2
Ø140 m
Decelerators, 25 sectors
Decelerator, each 878 m
BC2
TA
300 m
e⁻ Main Linac, 1.5 TeV, 12 GHz, 72/100 MV/m, 22 km
e⁺ Main Linac, 1.5 TeV, 12 GHz, 72/100 MV/m, 22 km
BDS
3.1 km
IP
50.1 km
MAIN BEAM
COMPLEX
Spin Rotator
Booster Linac
9 GeV
BC1
e⁺
DR
359 m
e⁺
PDR
389 m
e⁻
DR
359 m
Pre-injector
e⁺ Linac
0.2 GeV
Primary e⁻ Linac
for e⁺ production
5 GeV
Target
Gun
Injector Linac
2.86 GeV
Pre-injector
e⁻ Linac
0.2 GeV
DC Gun
CAPTION
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Accelerator challenges

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

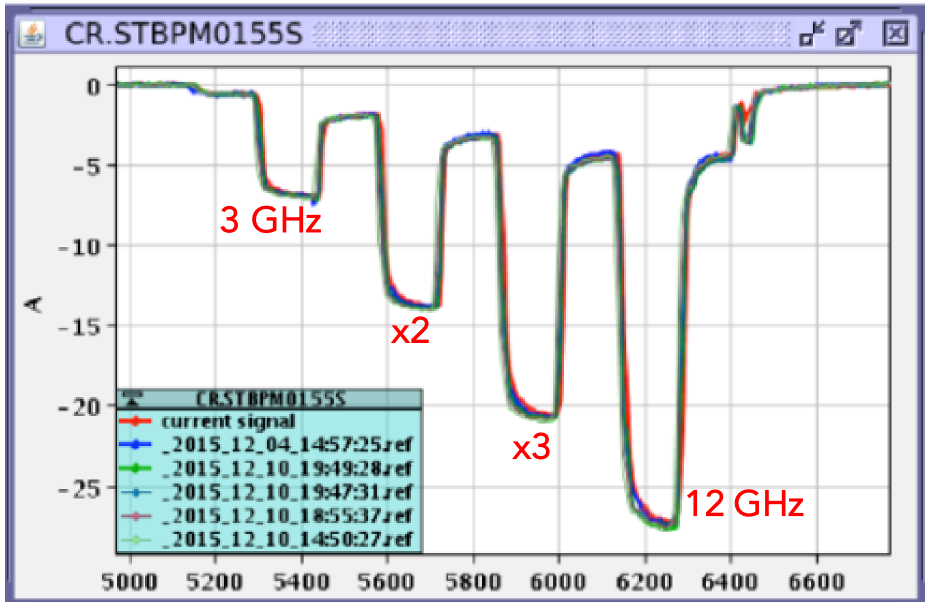
Four challenges:

High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

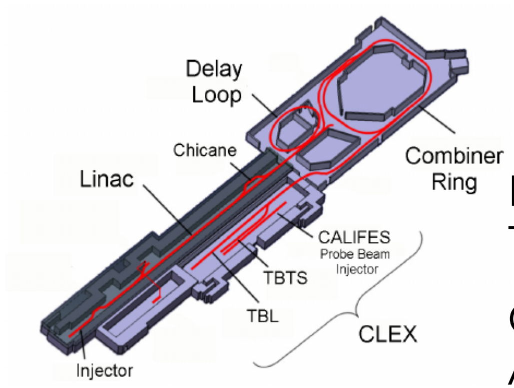
Alignment & stability



28A

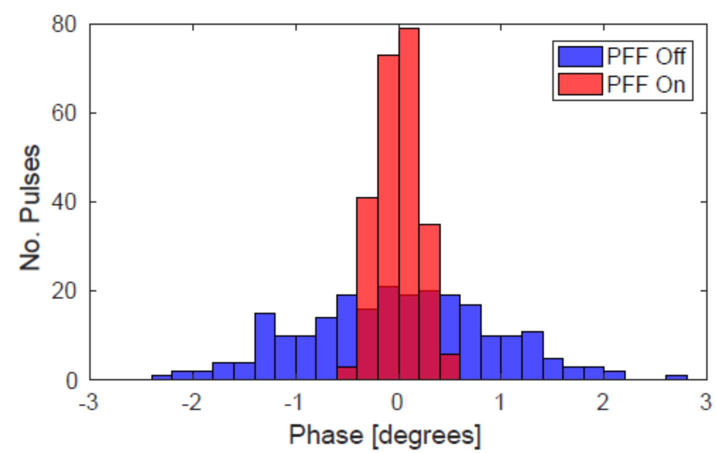
Current in combiner ring

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

Demonstrated 2-beam acceleration

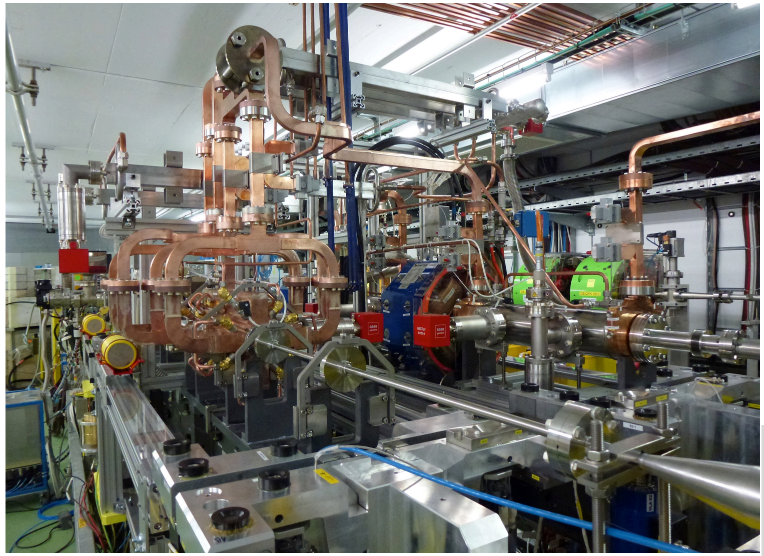
Four challenges:

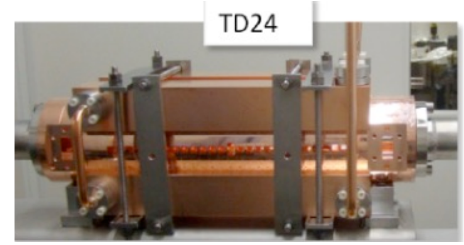
High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

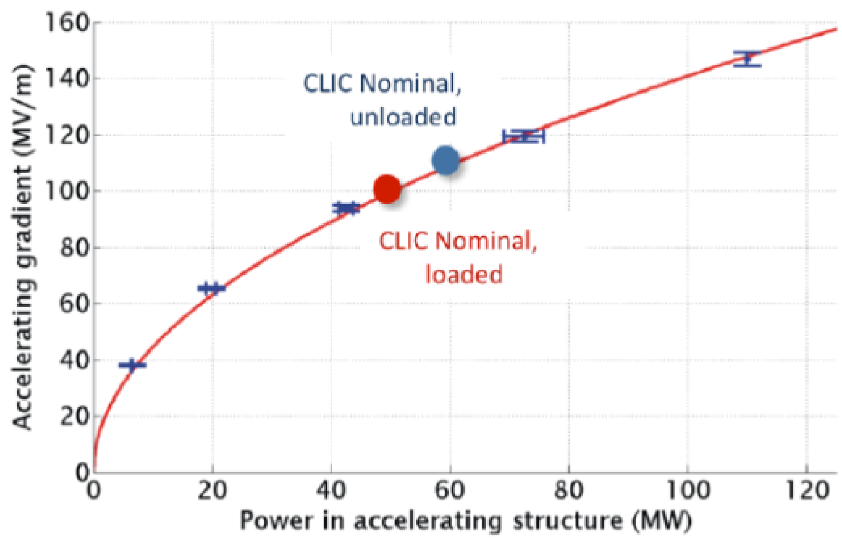
~100 MV/m gradient in main-beam cavities

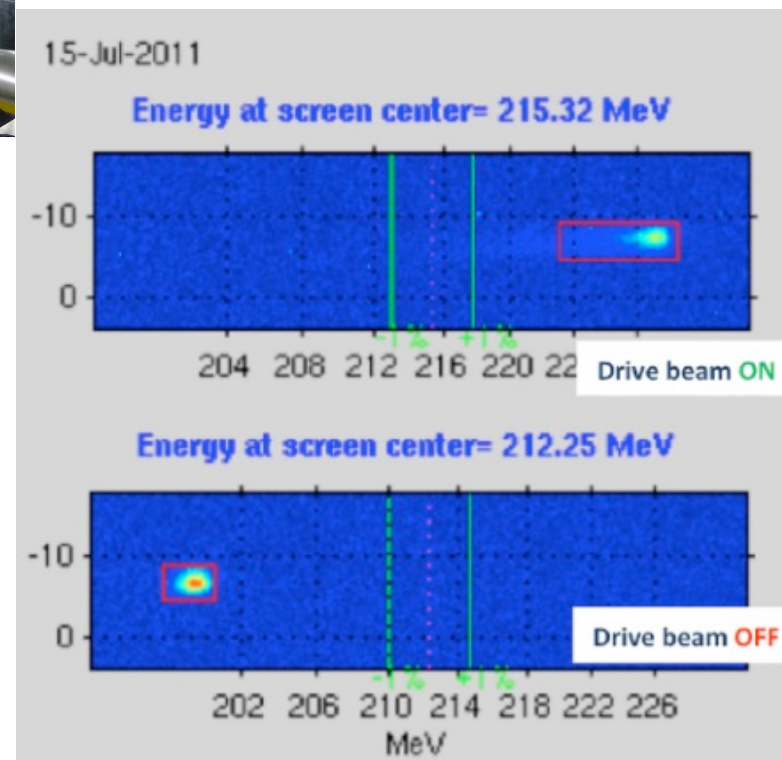
Alignment & stability





31MeV = 145MV/m





Accelerator challenges

X-band performance: achieved 100MV/m gradient in main-beam RF cavities

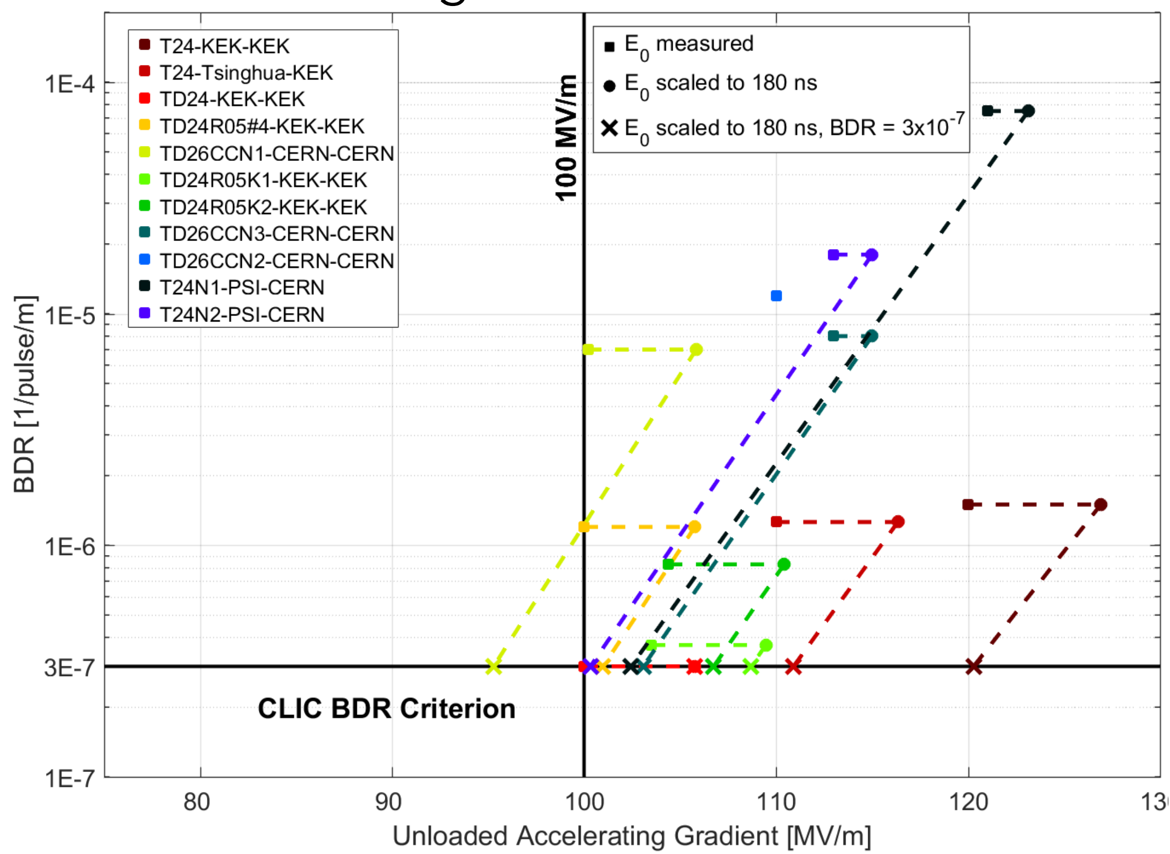
Four challenges:

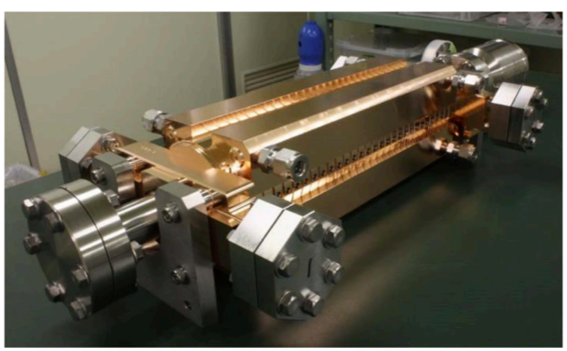
High-current drive beam bunched at 12 GHz

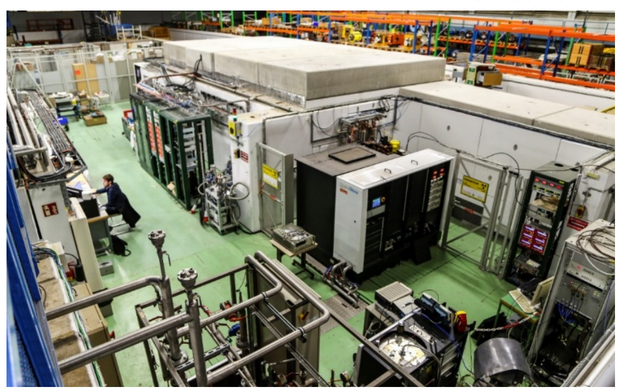
Power transfer + main-beam acceleration

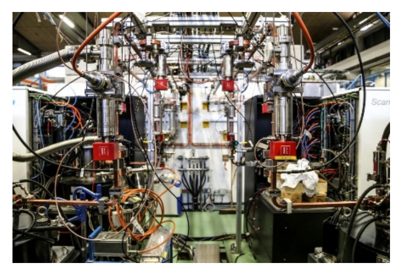
~100 MV/m gradient in main-beam cavities

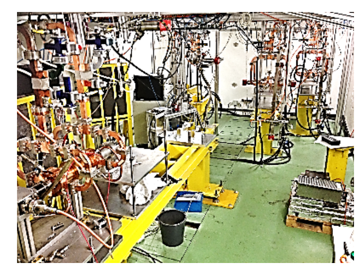
Alignment & stability











Accelerator challenges

Nano-beams

Four challenges:

High-current drive beam bunched at 12 GHz

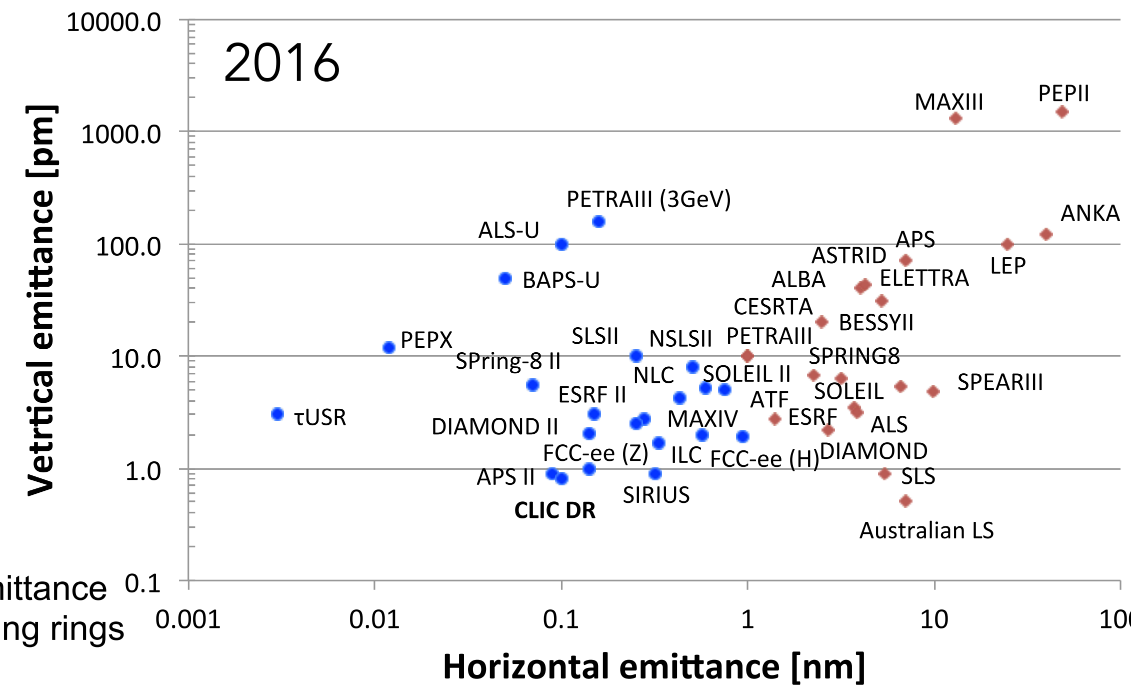
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

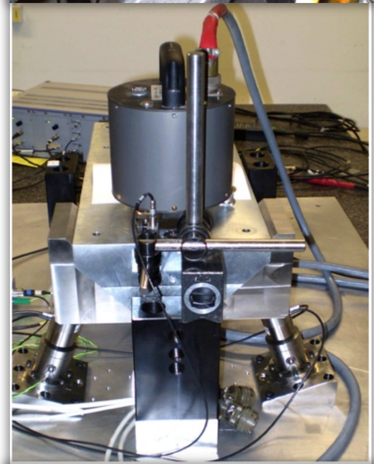
Alignment & stability

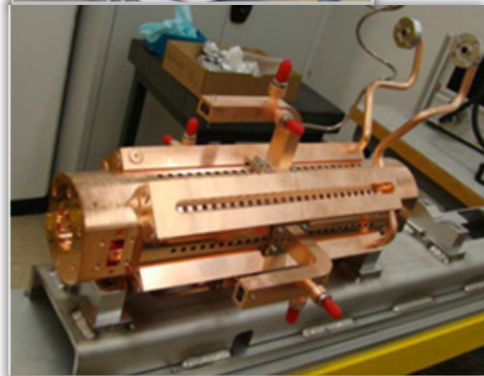
The CLIC strategy:

- Align components (10µm over 200m)
- Control/damp vibrations
  (from ground to accelerator)
- Measure beams well
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)



CLIC emittance at damping rings





Accelerator challenges

Nano-beams

Four challenges:

High-current drive beam bunched at 12 GHz

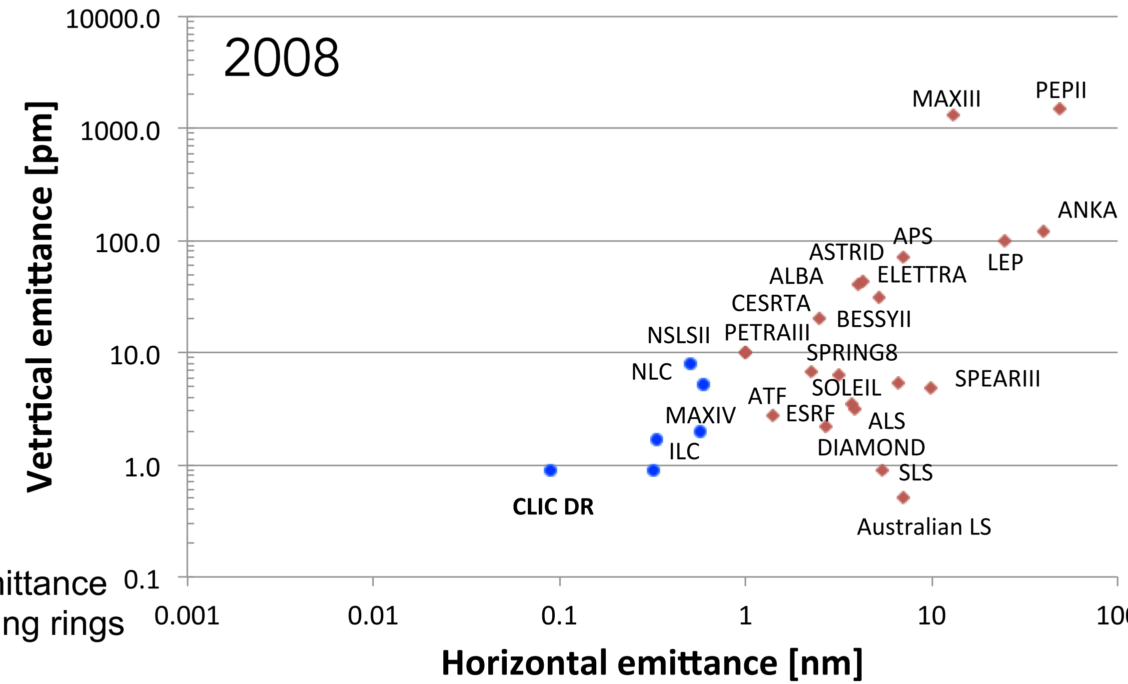
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

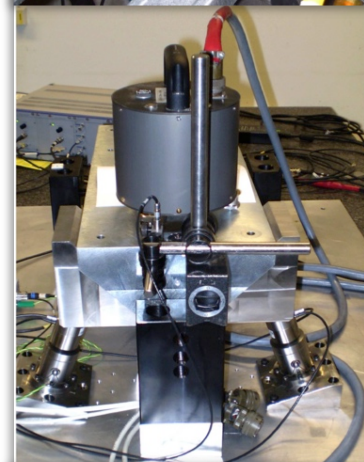
Alignment & stability

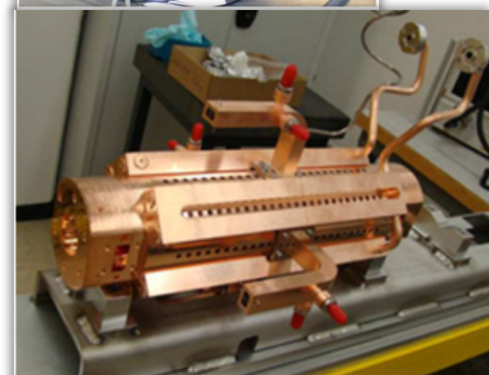
The CLIC strategy:

- Align components (10μm over 200m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)



CLIC emittance at damping rings





Physics landscape

- What is:

– dark matter?
– dark energy?
– origin of neutrino masses?
– origin of matter/antimatter asymmetry?

- Why are we not seeing new physics around the TeV scale?

– is the mass scale beyond the LHC reach?
– is the mass scale within the LHC's reach, but final states are elusive?

Address both possibilities:

- precision measurements
- sensitivity to elusive signatures
- extended energy/mass reach

- **Higgs is a new probe**

– what we've experimentally proven so far could hold in a wide range of BSM EWSB scenarios
– need to probe all aspects:

- Higgs couplings to lighter particles
- higher-order terms of the Higgs potential (self-couplings)
- possible existence of other particles coupled to the Higgs

Physics landscape

- For significant improvement on projected HL-LHC sensitivities, future facilities need Higgs couplings precisions at the sub-percent level

example scenarios in which *M* ~ 1TeV for new particles

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv: 1310.8361

- What we want from a next-generation collider:

–Guaranteed physics:
study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible precision and sensitivity

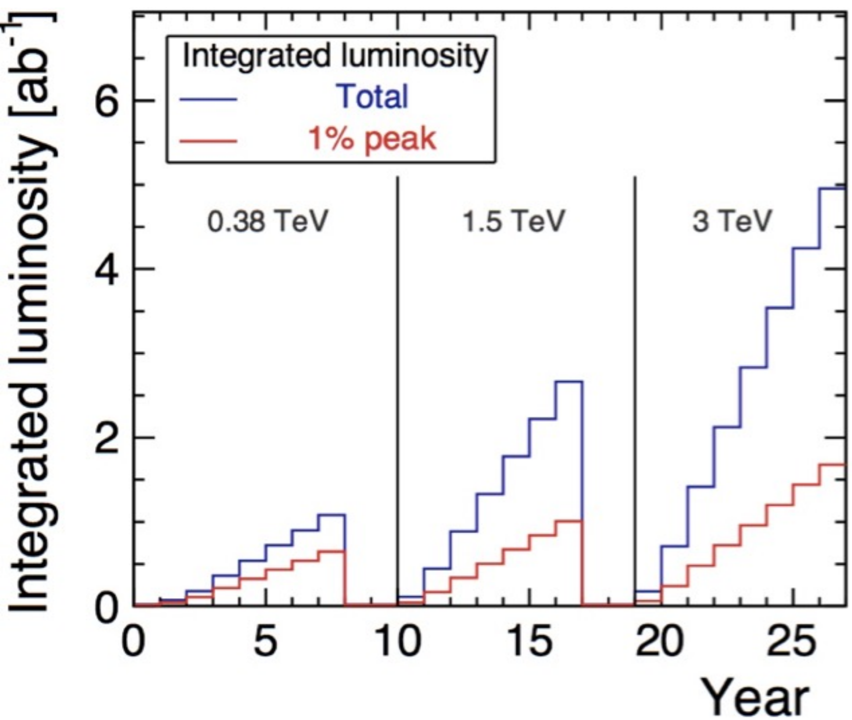
–Exploration potential:
exploit both direct (large Q^2) and indirect (precision) probes

CLIC Staging

3 pillars of the CLIC physics programme:

- Higgs physics
- Top-quark physics
- Beyond Standard Model physics

Staging scenario designed around this



Emphasis on getting to multi-TeV collisions quickly

- Physics programme extends over 25–30 years
- Ramp-up and up-time assumptions consistent with other future projects arXiv:1810.13022, Bordry et al.
- Electron polarisation:

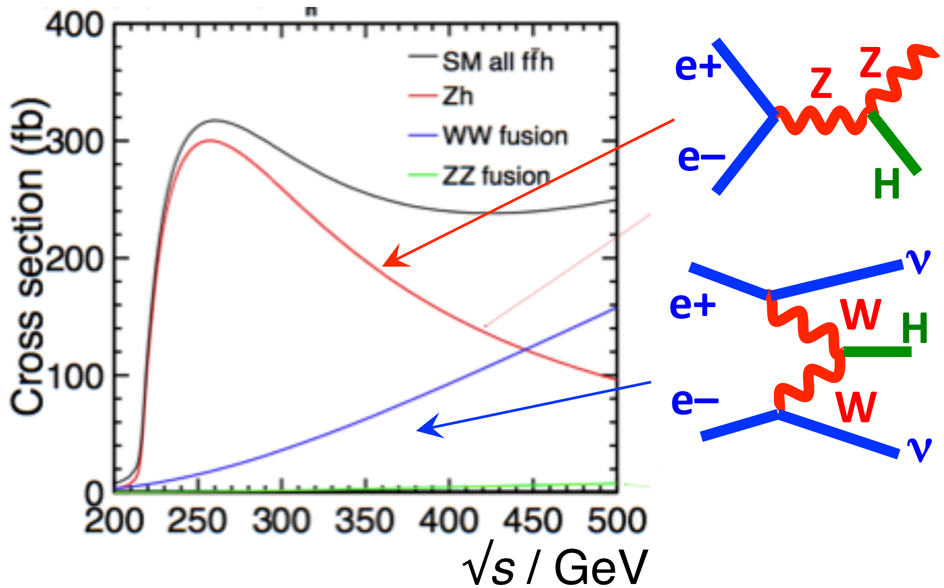
–enhances Higgs production at high-energy stages
–provides additional observables sensitive to NP
–helps to characterise new particles in case of discovery

Baseline polarisation scenario adopted:

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = -80\%$ $\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = +80\%$ $\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0

CLIC Physics at the initial stage

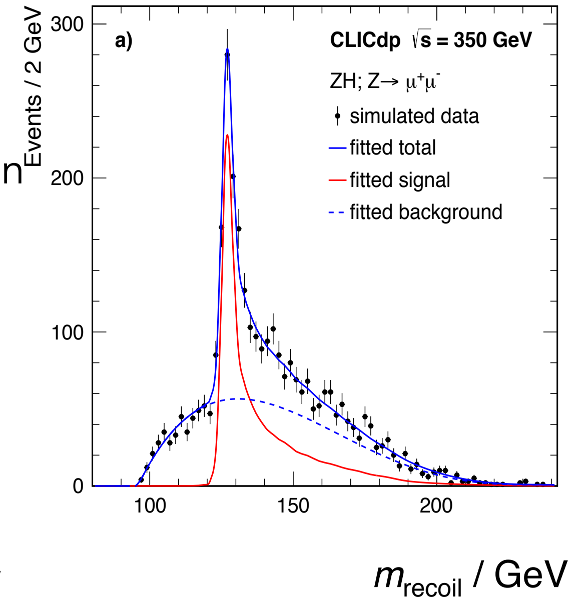
- Initial stage $\sqrt{s}$=380GeV
  - **Precision Higgs physics:**



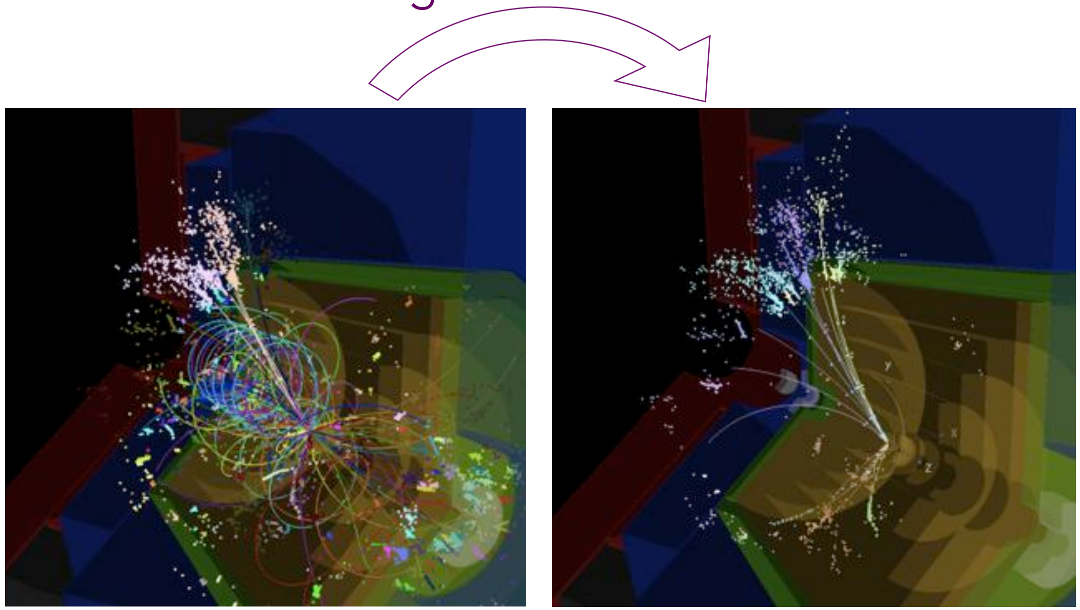
- ZH process allows H reconstruction Z recoil –> model-indep. extraction of g_{HZZ} coupling – need to start at energy where ZH is abundant

$$\sigma_{ZH} \propto g^2_{HZZ}$$

$$\frac{\sigma_{ZH}\,.\mathrm{Br(H\text{->}bb)}}{\sigma_{\nu\nu H}\,.\mathrm{Br(H\text{->}bb)}} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



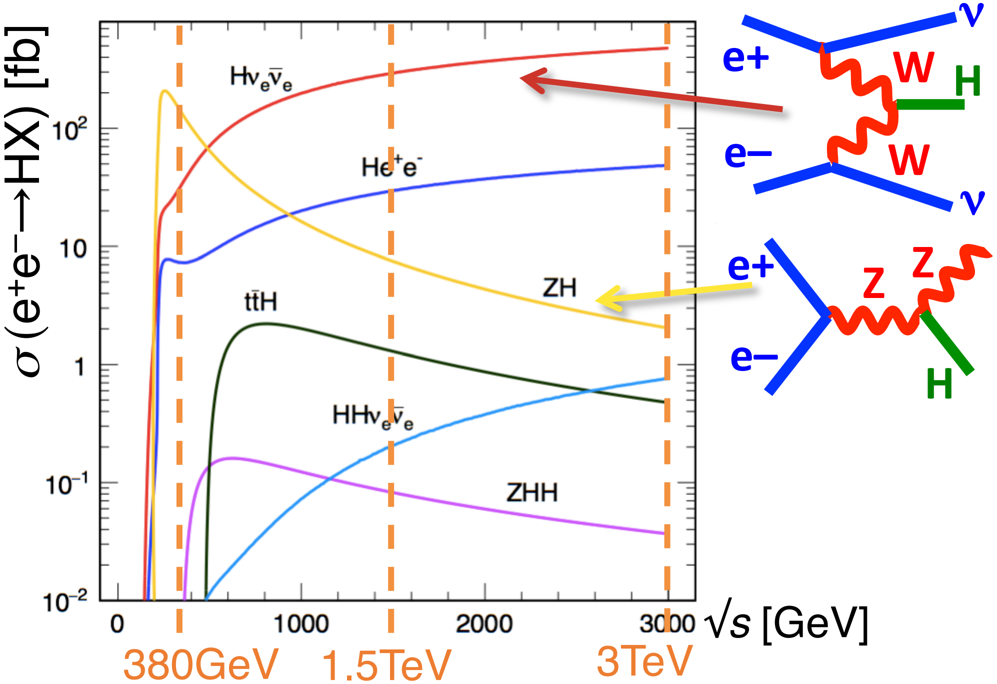
- At 380GeV we can use ZH(Z->qq) as well as ZH(Z->ll) – more separated from backgrounds – compensates for lower cross-section
- Higgs studies are all full GEANT-based simulation studies including beam backgrounds
- Imaging calorimetry allows e.g. H->bb/cc/gg separation

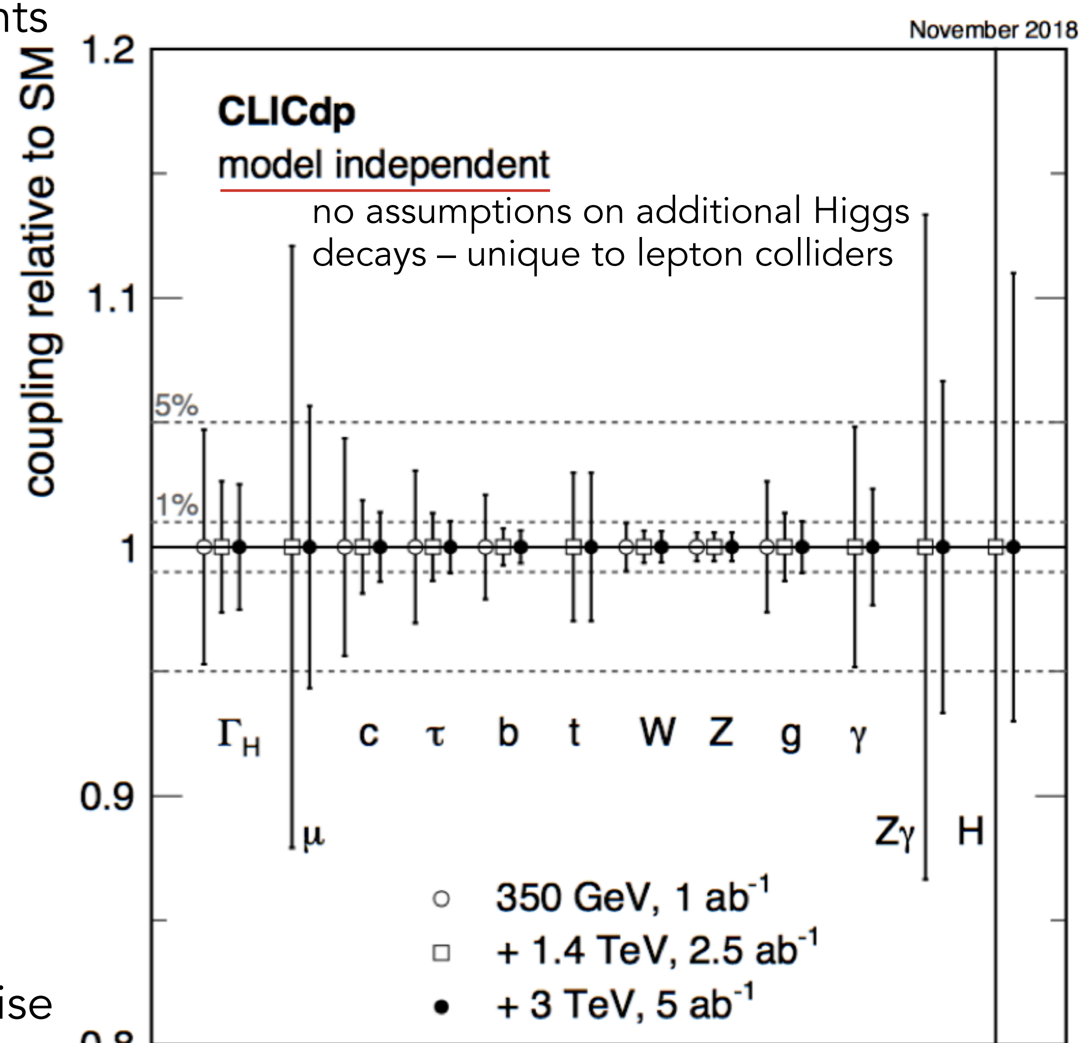


Higgs coupling sensitivity

- Combine all 3 stages for best measurements

  –> global fit including correlations





Based on Eur. Phys. J. C 77 475 (2017)
updated to new luminosity scenario arXiv:1812.01644

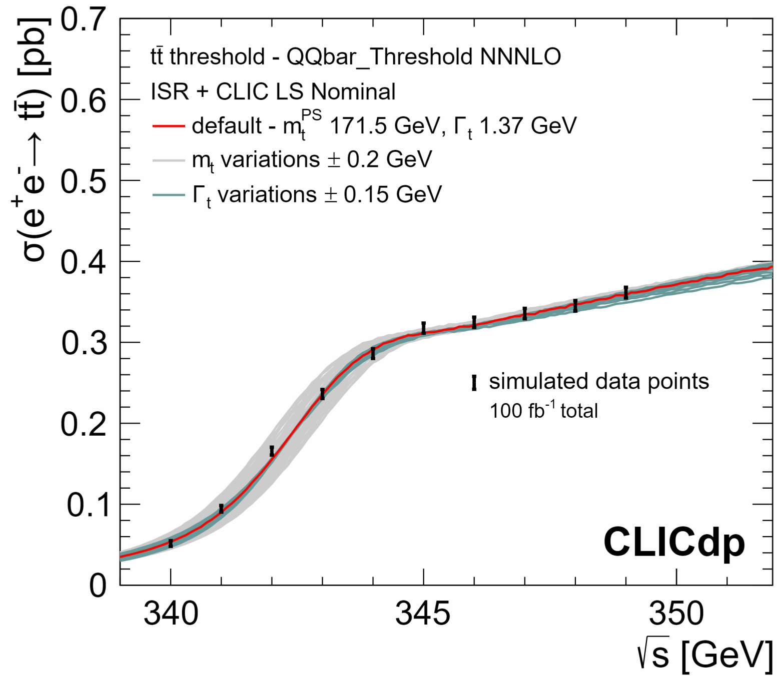
- Precision ≲1% for most couplings
- c/b/W/Z couplings significantly more precise than HL-LHC already after 380GeV stage
- BR(H→inv.) < 0.69% at 90% CL (for 350 GeV CLIC)
- Γ_H is extracted with 4.7 – 2.5% precision

–> Guaranteed physics case at initial stage

–> Each energy stage contributes significantly

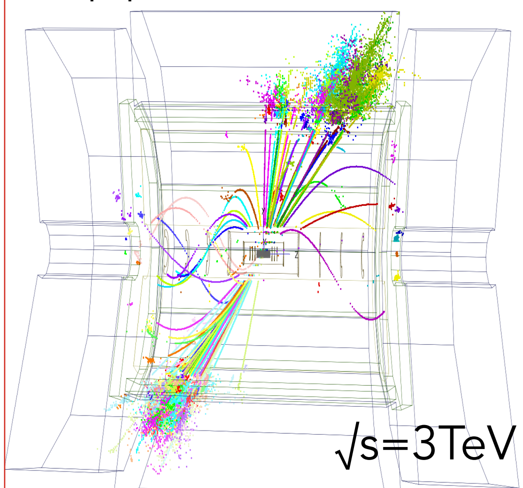
CLIC Physics at the initial stage

- Initial stage $\sqrt{s}$=380GeV
  - **Precision top-quark physics:**



- Intending threshold scan near $\sqrt{s}$=350 GeV (10 points, ~1 year) as well as main initial-stage baseline $\sqrt{s}$=380GeV
- sensitive to top mass, width and couplings
- observe 1S 'bound state', Δm_t ~ 50 MeV

First study of boosted top production in e^+e^-



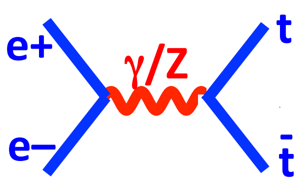
e^+e^- -> $t\bar{t}$ -> $q\bar{q}q\bar{q}b\bar{b}$

- Top pair-production cross-section, both polarisations ~1%
- Top forward-backward asymmetries ~3–4%
- Statistically optimal observables for top EWK couplings

  –> all input to global fits

–> initial and high-energy stages are very complementary

Polarisation provides new observables

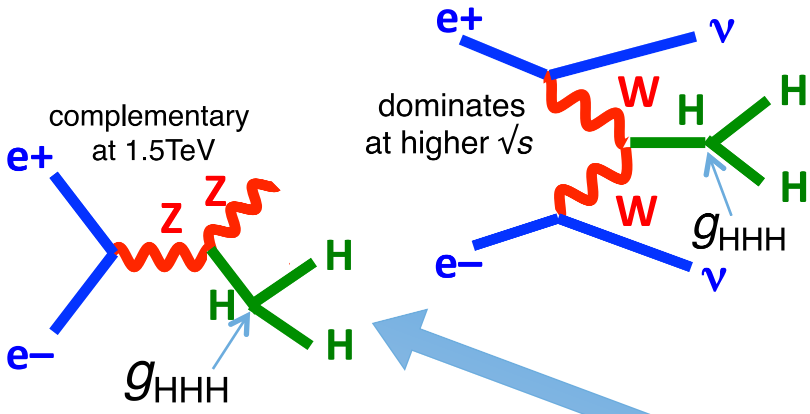


Top-quark physics at CLIC: JHEP11 (2019) 003

–> Guaranteed physics case at initial stage

Higgs self-coupling

- Higgs self-coupling requires high energy

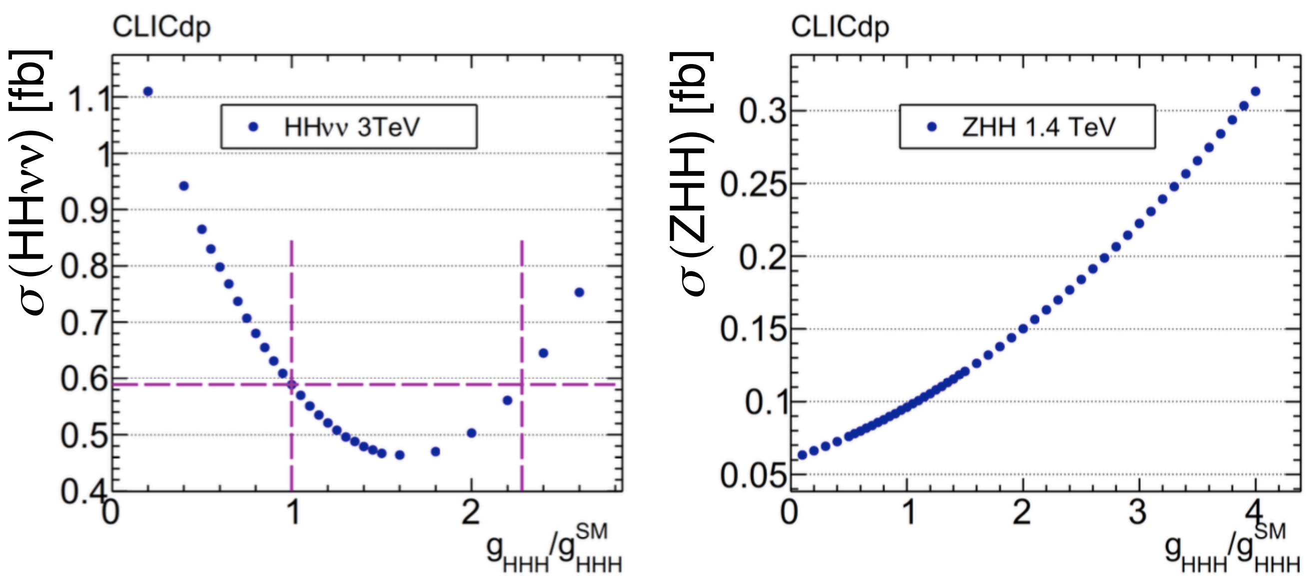


Double Higgs and self-coupling:

	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	>3σ EVIDENCE $\frac{\Delta\sigma}{\sigma} = 28\%$	>5σ OBSERVATION $\frac{\Delta\sigma}{\sigma} = 7.3\%$
σ(ZHH)	>5σ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4TeV: –34%, +36% rate-only analysis	1.4 + 3TeV: **–7%, +11%** differential analysis

arXiv:1901.05897

- Direct access to two processes that behave differently with non-SM values of self-coupling:



Template fit at 3TeV using two variables: *M*(HH) differential distribution and BDT score

Gives unrivalled sensitivity to Higgs self-coupling:

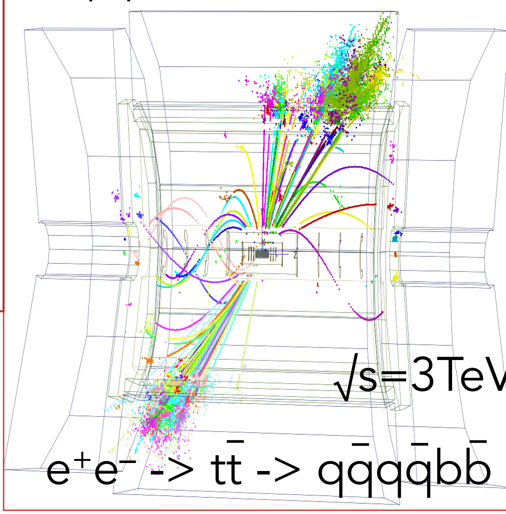
$$\Delta g_{HHH}/g_{HHH} = {}^{+11\%}_{-7\%}$$

High energy stages, 1.5 and 3 TeV

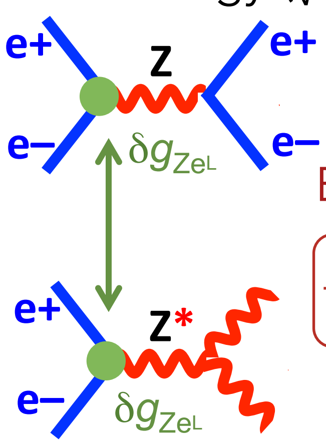
- Precision Higgs physics:
  - Increases VBF single-Higgs production
  - Adds ttH and HH production
  - Allows precise measurement of g_{HHH}
- Precision top-quark physics:
  - Cross-sections, asymmetries and optimal observables at all energies (necessary to disentangle effects), including boosted regime, study of ttH
- Precision two-fermion and multi-boson measurements
- BSM physics reach via precision measurements:

- Can probe CP-odd component of ttH coupling to $0.02<\Delta\sin^2\phi<0.08$ for full range of $\sin^2\phi$

First study of boosted top production in e^+e^-



At low energy ($\sqrt{s}=m_Z$)



Effect grows as s

$$\left(\frac{3000}{91.2}\right)^2 \sim 1000$$

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ => $\delta g_{ZeL} \sim 10^{-4}$

same precision!

...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3TeV} \sim 10\%$ => $\delta g_{ZeL} \sim 10^{-4}$

At high energy ($\sqrt{s}$=3TeV)

–> strongly benefit from high energies

Global sensitivity to BSM effects

Standard Model

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

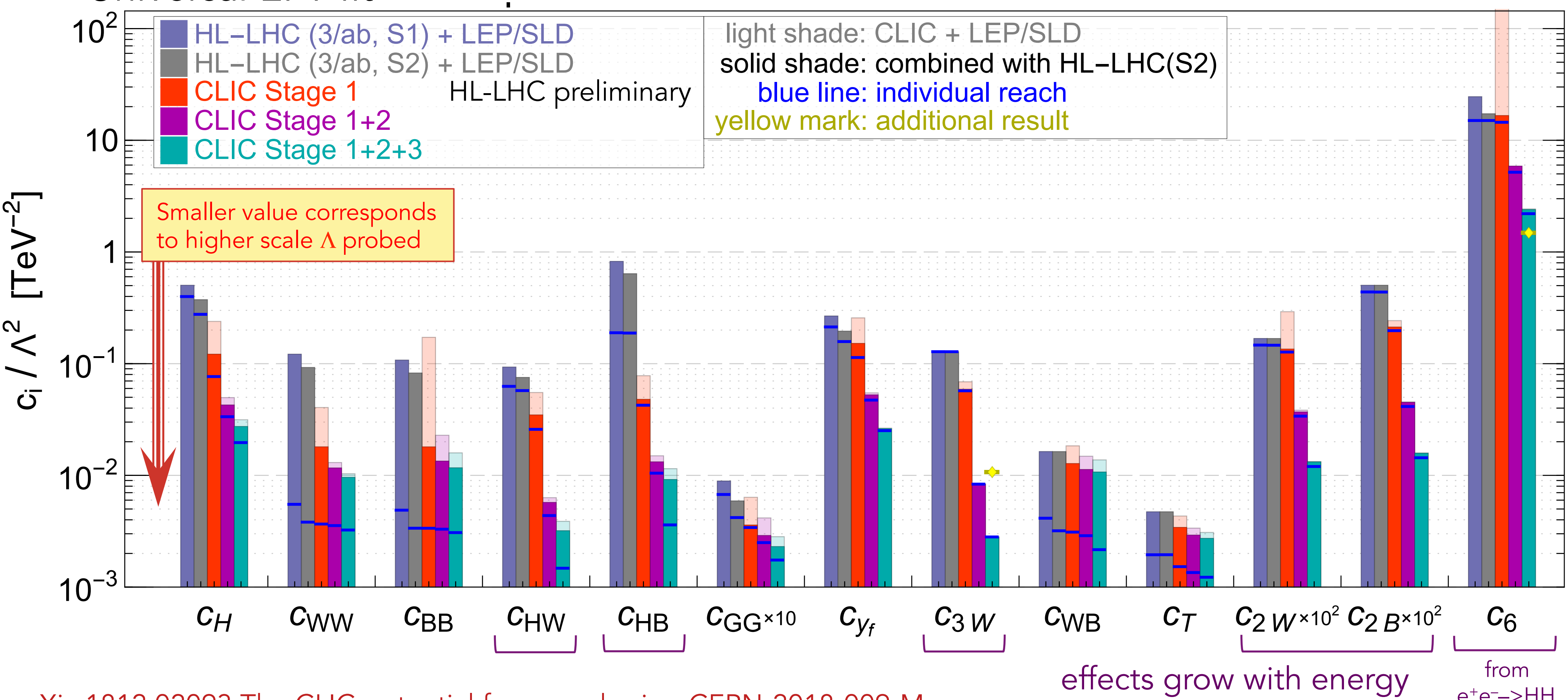
Scale of new decoupled physics

Dimension-6 operators

Includes CLIC measurements of:
- Higgs
- Top
- WW
- $e^+e^- \to f\bar{f}$

Strongly benefits from high-energy running

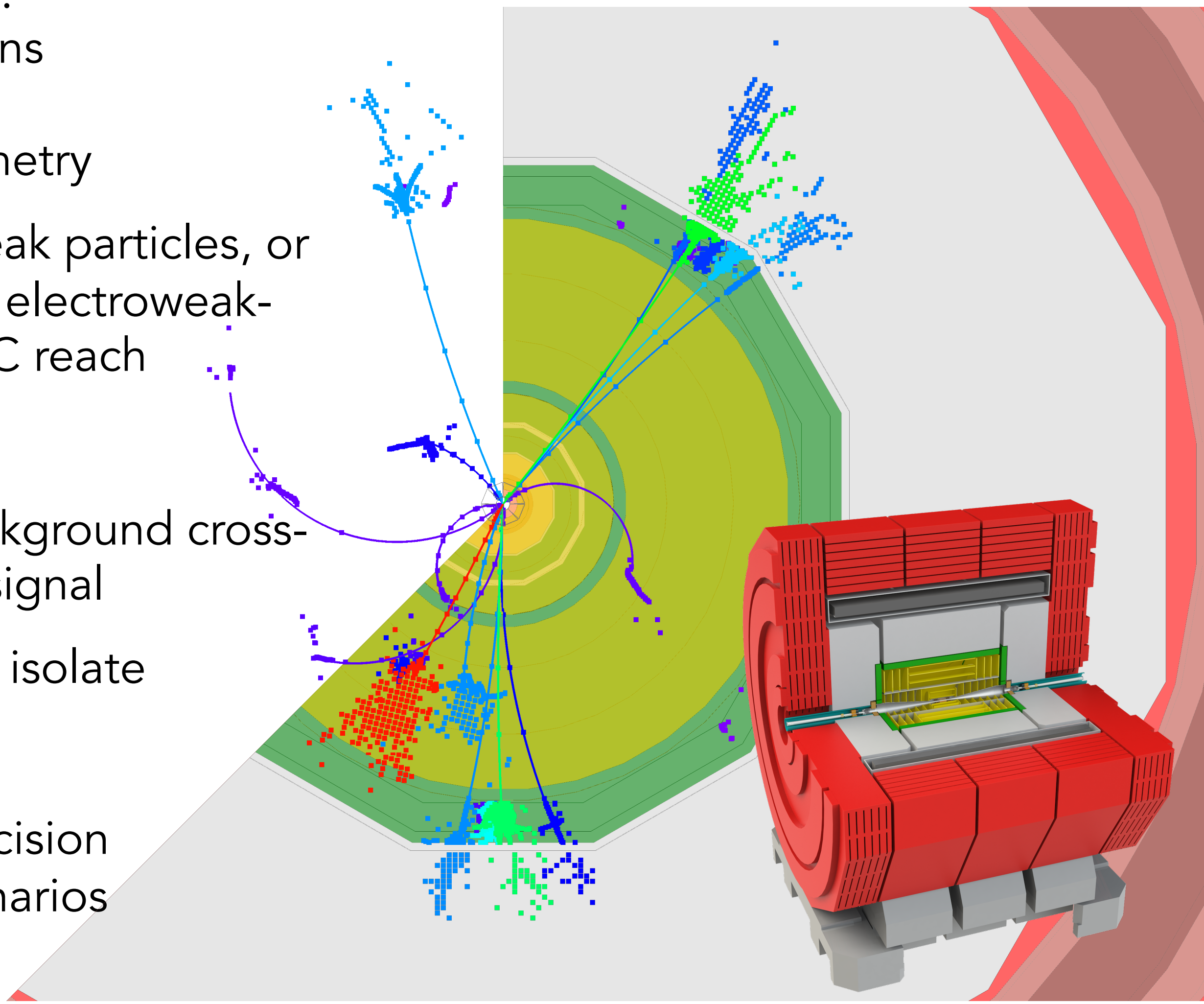
Universal EFT fit



arXiv:1812.02093 The CLIC potential for new physics, CERN-2018-009-M

New physics searches

- Issues not addressed by SM include:
  origin of the weak scale interactions
  dark matter
  origin of matter/antimatter asymmetry
- CLIC can probe TeV-scale electroweak particles, or particles that interact with the SM with electroweak-sized couplings, well above the HL-LHC reach
- Direct searches:
  - For standard final states, SM background cross-sections typically comparable with signal
  - Clean e^+e^- environment helps to isolate non-standard signatures
- Indirect searches: can interpret precision measurements in particular model scenarios

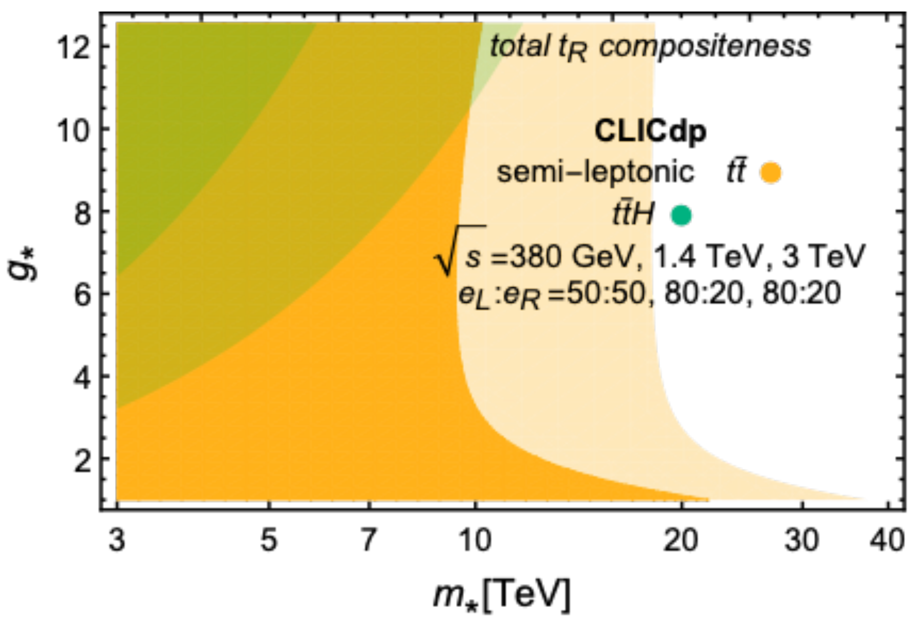


–> explore landscape for broad classes of theories

Higgs and top compositeness

- Composite Higgs or top would appear through SM-EFT operators – translate EFT limits into characteristic coupling strength g_* of composite sector and mass m_*

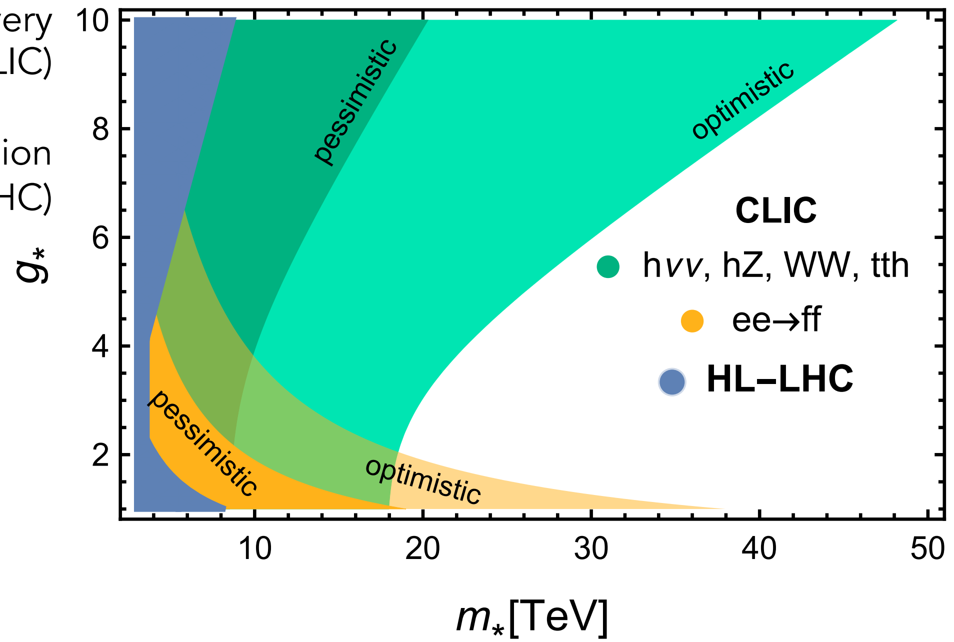
Top compositeness



Higgs compositeness

5-σ discovery regions (CLIC)

exclusion region (HL-LHC)

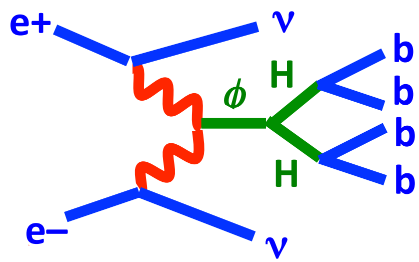


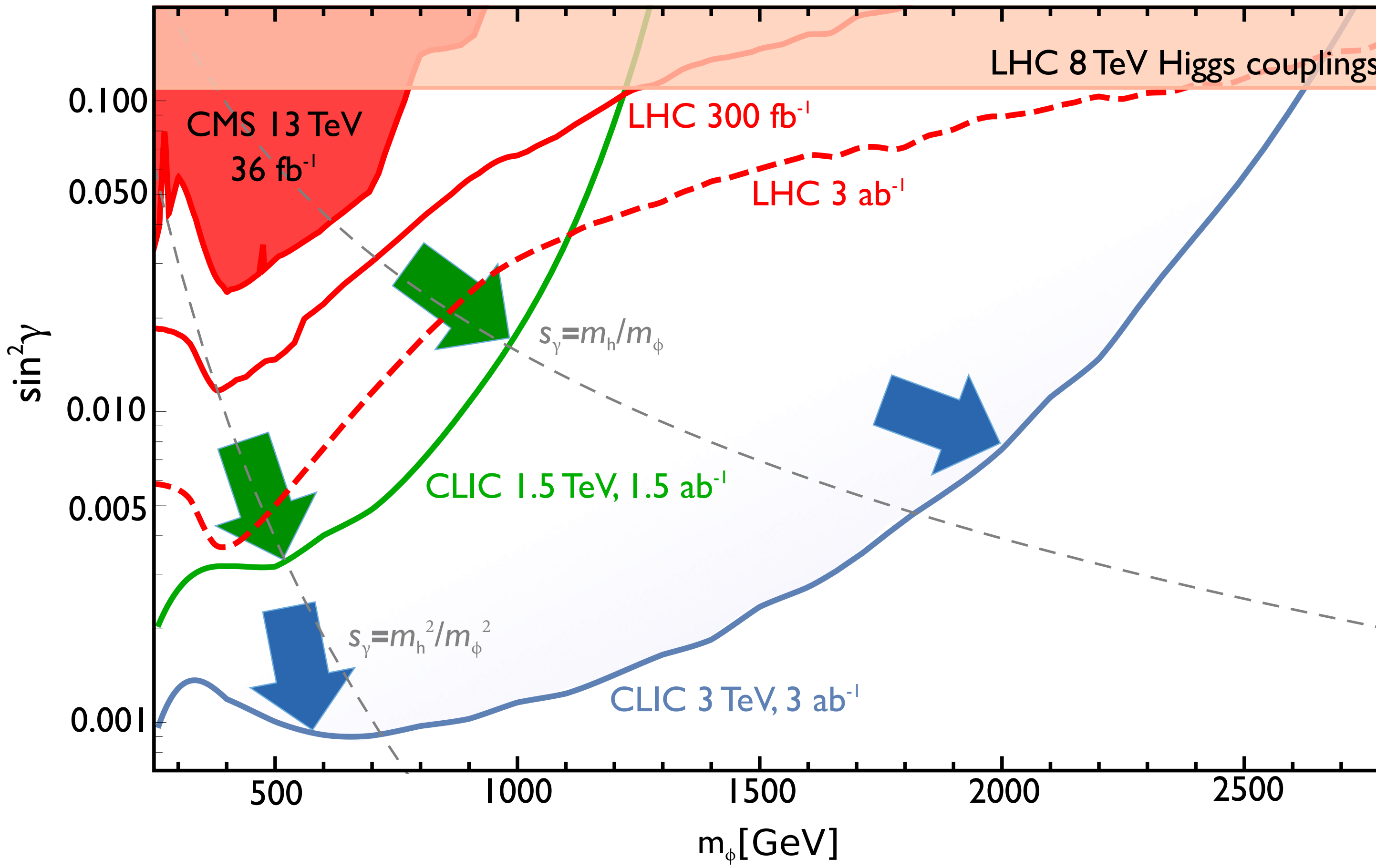
CLIC can ***discover*** compositeness up to ~10TeV compositeness scale (~30 – ~50TeV in favourable conditions) – above what HL-LHC can ***exclude***

arXiv:1812.02093 The CLIC Potential for New Physics

Higgs + heavy singlet

Direct search for real scalar singlet ϕ:





$$h = h_0 \cos\gamma + S \sin\gamma$$

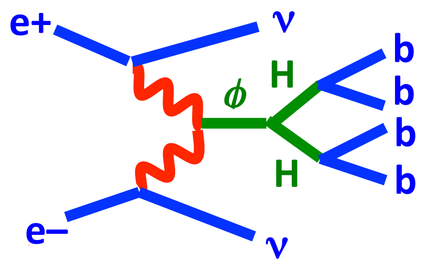
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

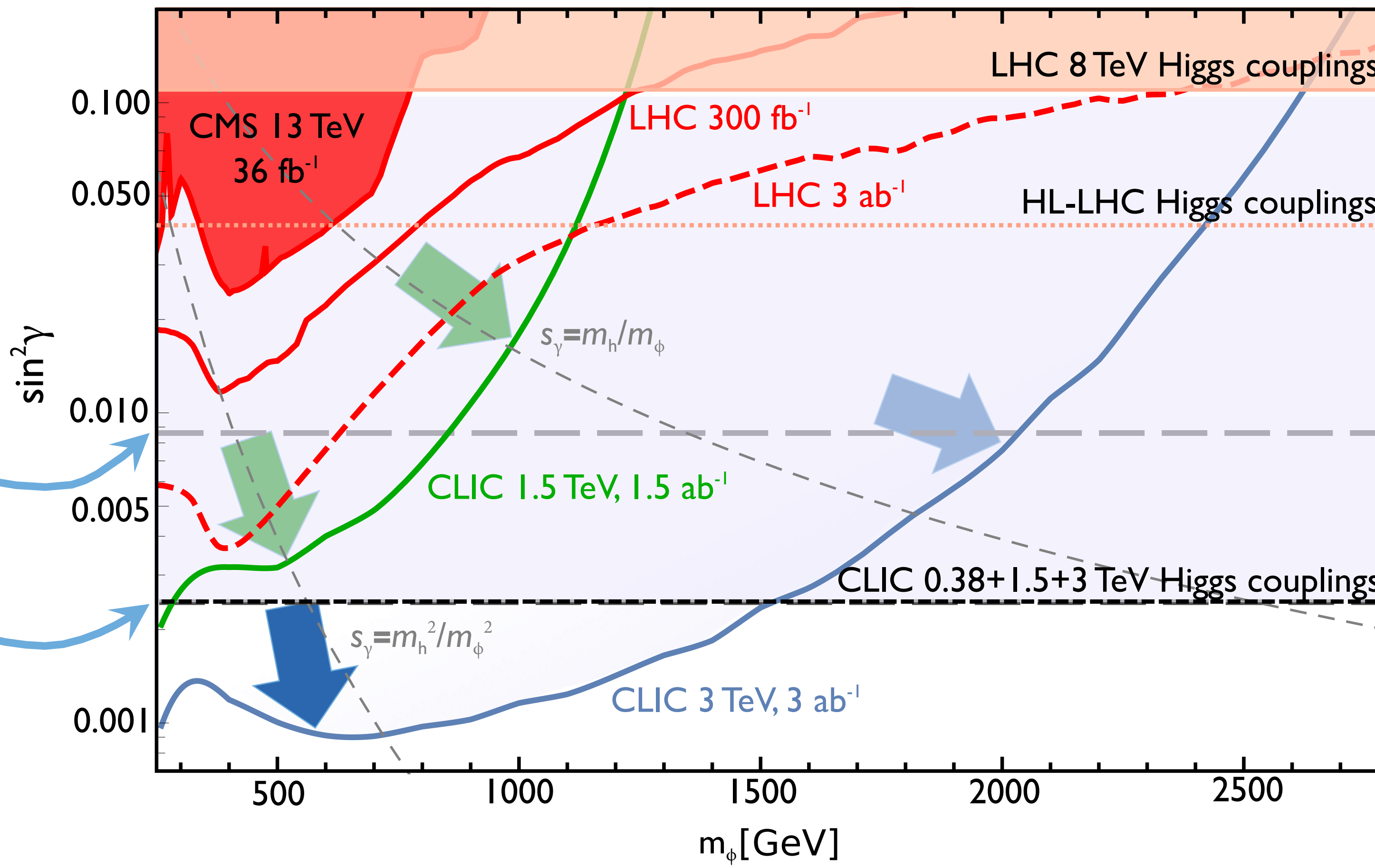
γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi
arXiv:1812.02093 The CLIC Potential for New Physics

Higgs + heavy singlet

Direct search for real scalar singlet ϕ :





Complementary:

Indirect search using Higgs couplings

arXiv: 1608.07538

$\sin^2\gamma$<0.9% 95% CL (380GeV)

$\sin^2\gamma$<0.24% 95% CL (380GeV+1.5TeV+3TeV)

$$h = h_0 \cos\gamma + S \sin\gamma$$

$$\phi = S \cos\gamma - h_0 \sin\gamma$$

γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi

arXiv:1812.02093 The CLIC Potential for New Physics

Dark matter

Higgsino:

WIMP dark matter candidate, connected to weak scale naturalness, and gauge coupling unification

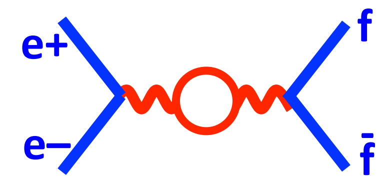
When other superpartners decoupled:
$\chi^{\pm}$ slightly heavier than χ^0
$\chi^{\pm} \to \pi^{\pm}\chi^0$ **leaving 'disappearing track' in detector**

Electroweak precision tests:

arXiv:1810.10993 - Di Luzio, Gröber, Panico

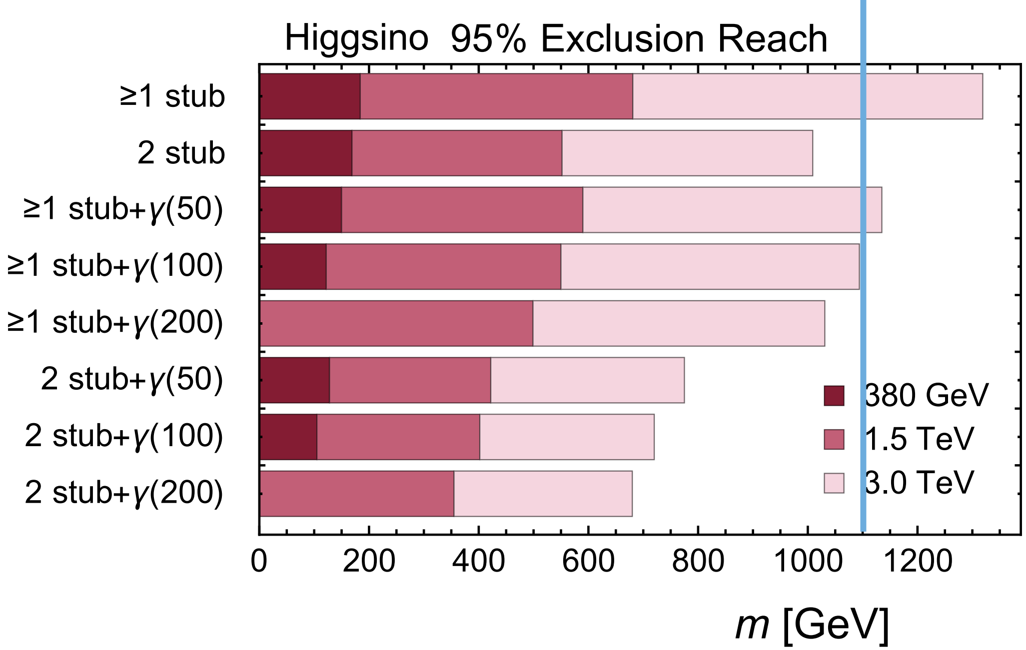
Precision measurements of $d\sigma/d(\cos\theta)$ in $e^+e^- \to f\bar{f}$

sensitive to new states
-> exclude mass ranges

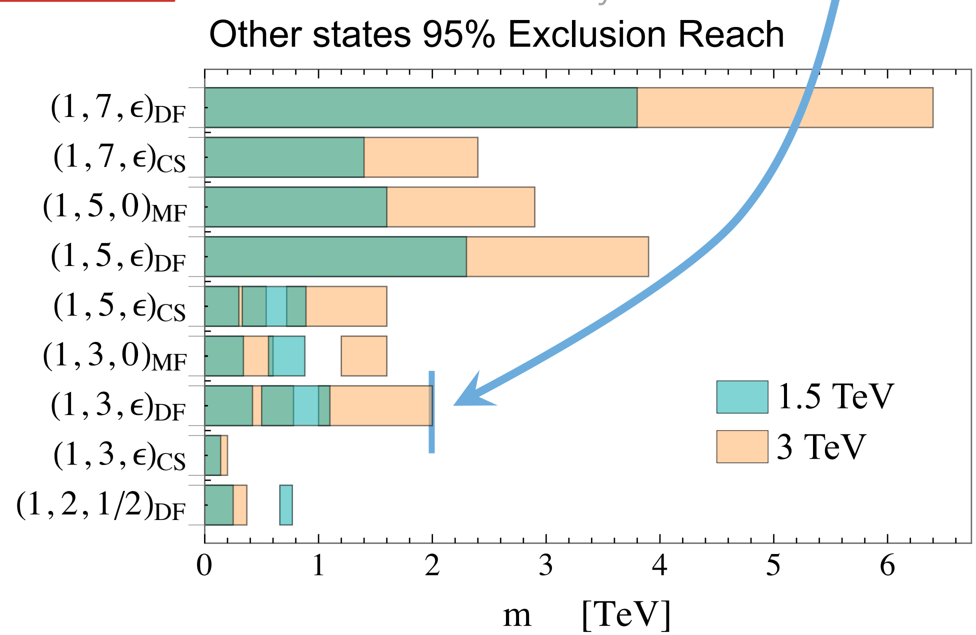


diverse experimentally

reach Higgsino mass of 1.1TeV, required for DM relic mass density – even with some level of background



e.g. for n=3 Dirac fermion, m=2TeV saturates DM relic mass density: can be excluded by CLIC



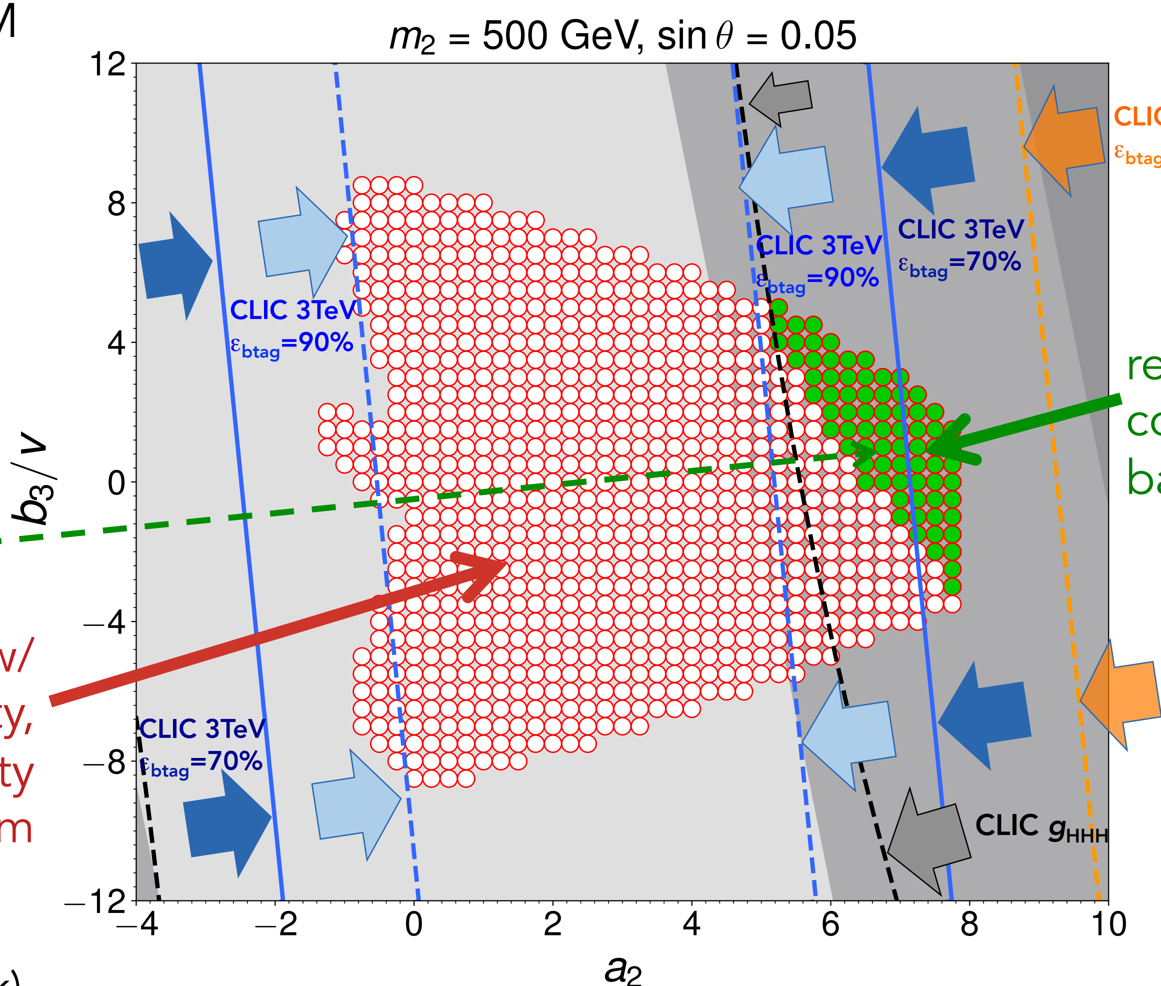
DF=Dirac Fermion, MF=Majorana Fermion, CS=Complex Scalar
SU(3)xSU(2)xU(1) representation; different n-tuplet multiplicities

arXiv:1812.02093 The CLIC Potential for New Physics

Baryogenesis

- We observe a matter-dominated universe
- For baryogenesis to account for this, need to add something to the SM
- EW phase transition required to be first order
- Explored for CLIC in the Higgs+singlet model: resonant di-Higgs searches Higgs self-coupling g_{HHH}
- Sensitive to the interesting region

arXiv:1807.04284 No, Spannowsky
arXiv:1812.02093 The CLIC Potential for New Physics



regions also compatible with baryogenesis

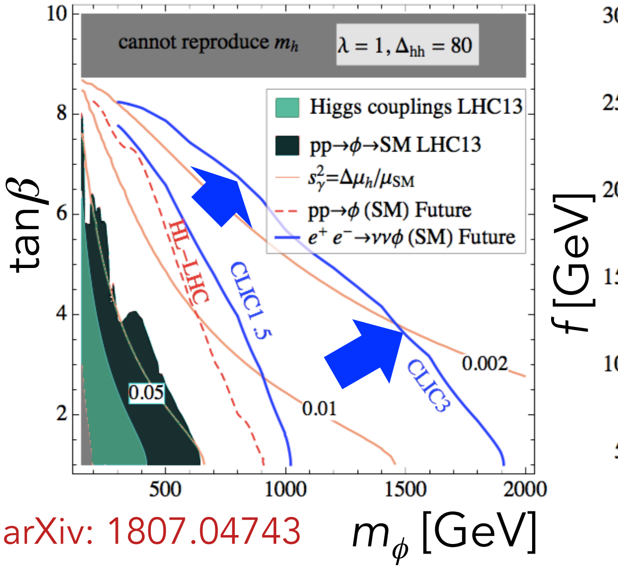
regions compatible w/ unitarity, perturbativity, and absolute stability of the EW vacuum

well-constrained by CLIC Higgs self-coupling (black) and CLIC resonant di-Higgs searches at 1.5TeV and 3 TeV

a_2 and b_3/v are parameters of the temperature-dependent effective potential; m_2 and θ are the singlet mass and mixing

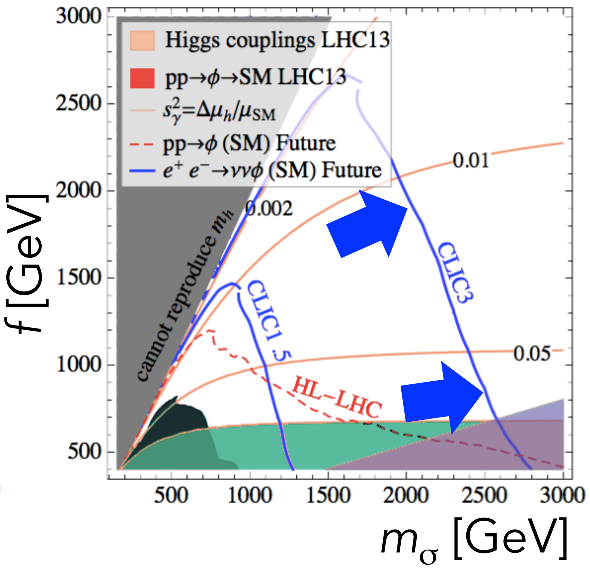
HL-LHC not sensitive at this low mixing sinθ=0.05

Interpretations and full programme



arXiv: 1807.04743

Higgs + singlet as **NMSSM**



Higgs + singlet as **Twin Higgs** model

- Precision Higgs couplings and self-coupling
- Precision electroweak and top-quark analysis
- Sensitivity to BSM effects in the SMEFT
- Higgs and top compositeness
- Baryogenesis
- Direct discoveries of new particles
- Extra Higgs boson searches
- Dark matter searches
- Lepton and flavour violation
- Neutrino properties
- Hidden sector searches
- Exotic Higgs boson decays

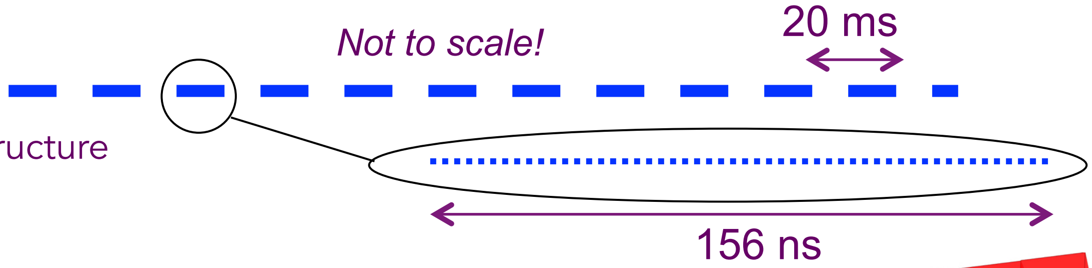
Many more studies in CERN Yellow Report:

The CLIC Potential for New Physics (250 pages)

arXiv:1812.02093 CERN-2018-009-M

Collider environment

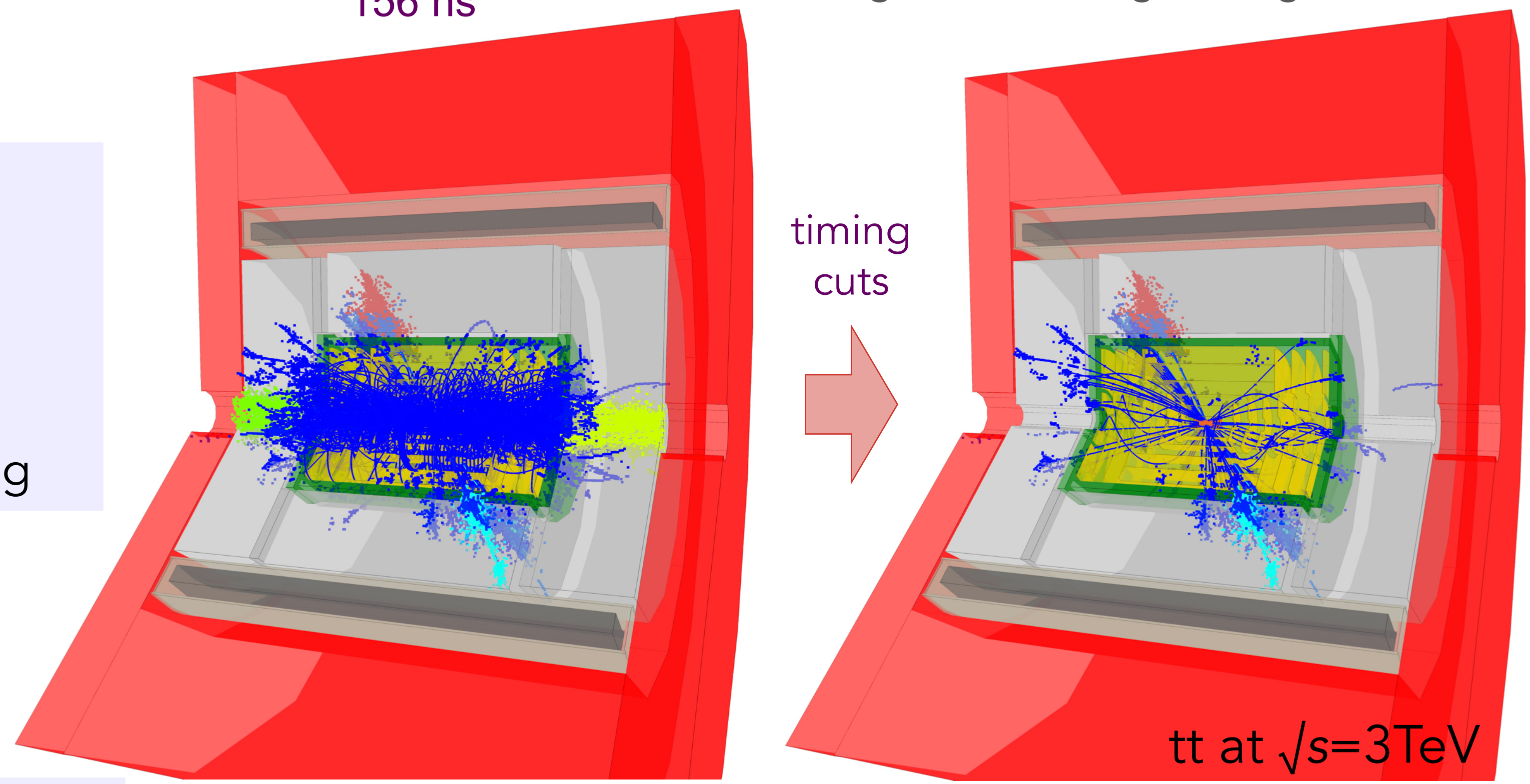
CLIC
Beam structure
at 3TeV



High bunch charge density
–> beam-related backgrounds
small effect at $\sqrt{s}$=380GeV
large effect at high energies

Precise timing required for beam background rejection

1ns in calorimetry,
5ns in vertexing/tracking



CALICE / FCAL

CLICdp vertexing/ tracking programme

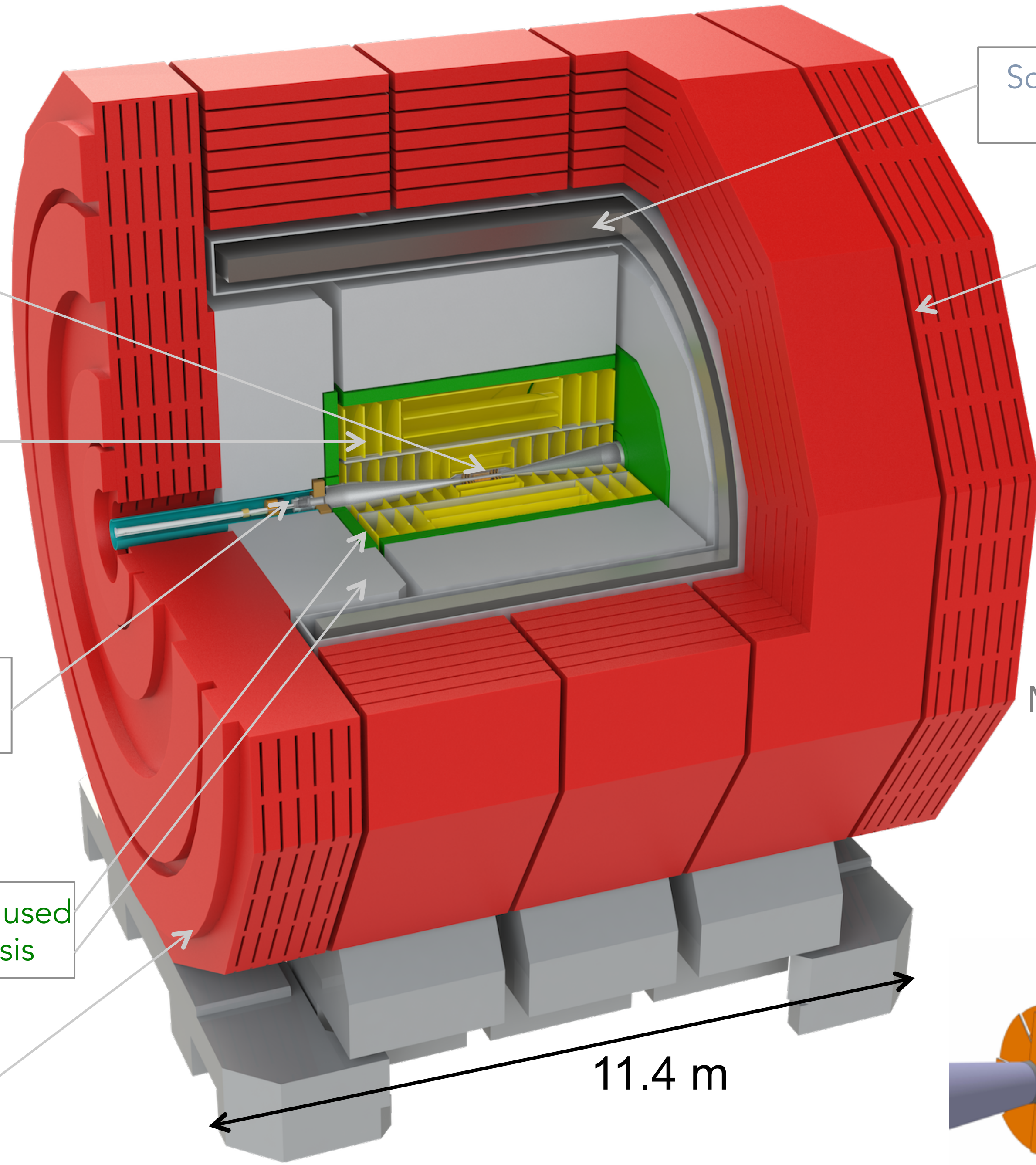
High precision:
- jet energy resolution
  - –> fine-grained calorimetry
- momentum resolution
- impact parameter resolution

$\sigma(E)/(E)$ ~ 3.5% for E>100GeV

$\sigma(p_T)/p_T^2$ ~ 2x10^{-5} GeV^{-1}

$\sigma_{d0} \sim 5 \oplus 15/(p[\text{GeV}]\sin^{3/2}\theta)$ µm

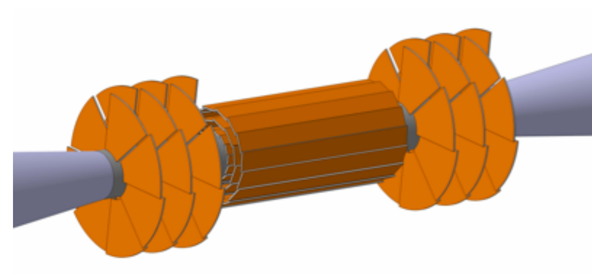
CLICdet



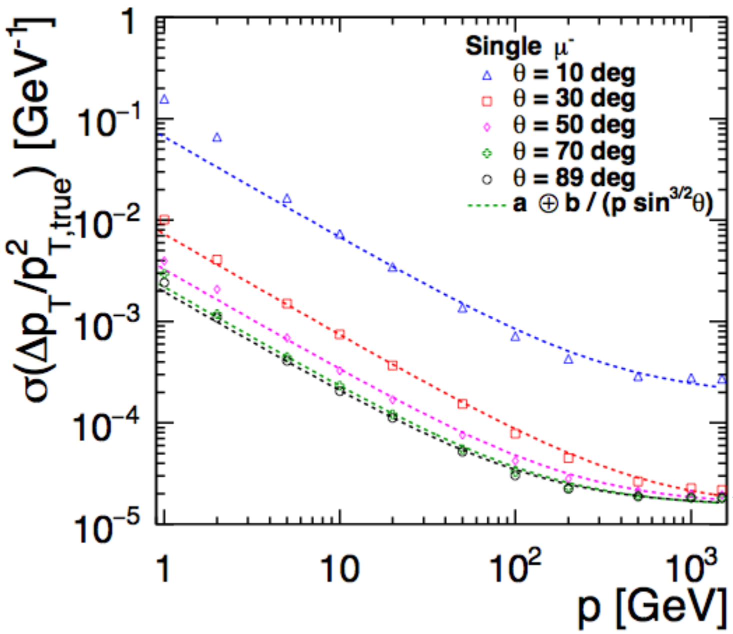
Triggerless readout

Tracker
spatial resolution: 7μm
Material: 1–2% X_0 / layer

Vertex detector
spatial resolution: 3μm
Material: 0.2% X_0 / layer
–> forced air cooling

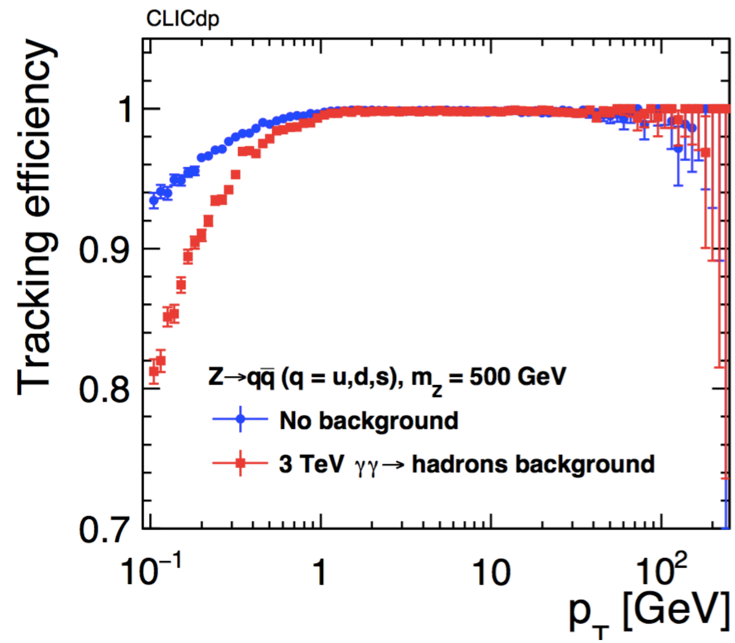


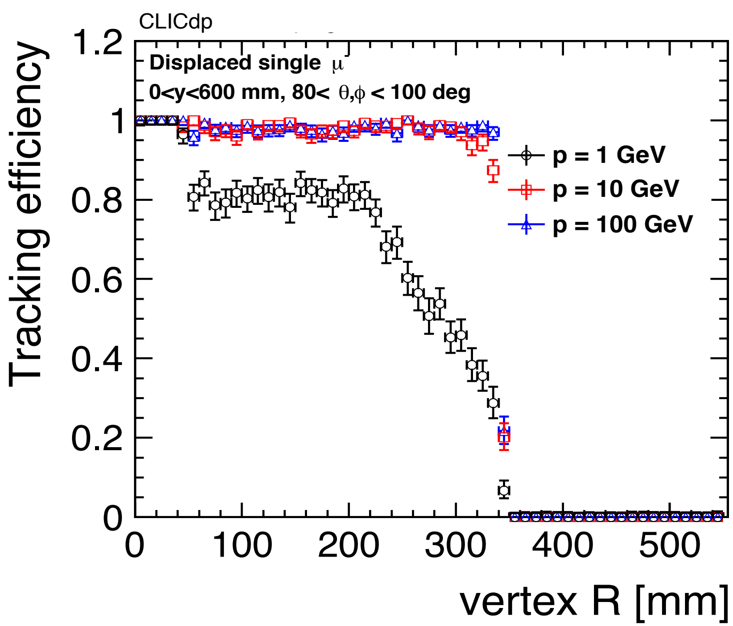
CLICdet Performance



performance goal: 2 x 10^{-5}

Full characterization of the detector model in arXiv:1812.07337

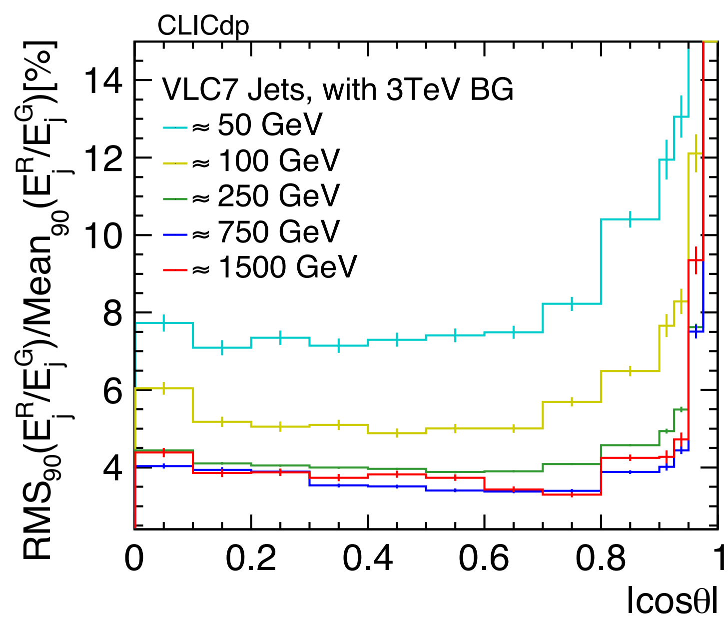




Displaced track reconstruction

Software tools developed/ maintained by the CERN group and widely used

Achieve jet energy resolution target in presence of beam backgrounds



Vertex and Tracking R&D

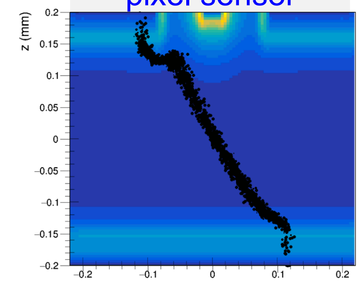
Stringent requirements for CLIC vertex & tracker detectors inspired broad and integrated technology R&D programme

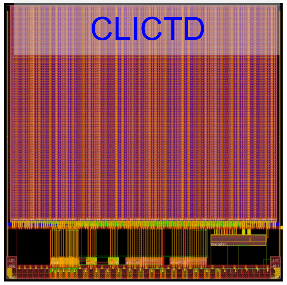
Benefit from rapid progress in Si industry and synergies with HL-LHC

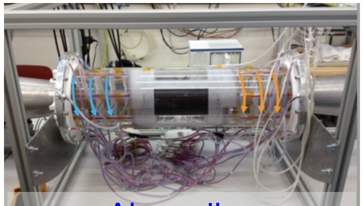
Highlights:

- Full efficiency obtained from hybrid assemblies of 50μm thin sensors that satisfy CLIC time-stamping requirements
- Sensor design with enhanced charge-sharing is underway to reach required spatial resolution with thin sensors
- Good progress towards reducing detector mass with active-edge sensors and through-Si interconnects
- Promising results from fully integrated technologies; CLIC-specific fully integrated designs underway (CLICTD, CLIPS)
- Developed advanced simulation/analysis tools for detector performance optimisation
- Feasibility of power-pulsing demonstrated; power consumption specification met
- Feasibility of air cooling demonstrated in simulation & full vertex detector mockup

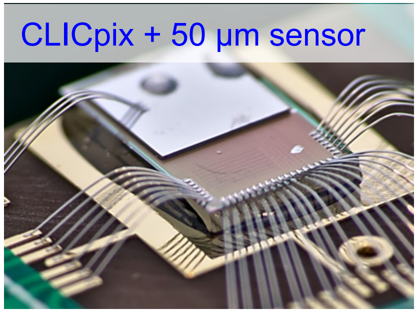
Allpix^2 simulation of HV-CMOS pixel sensor







Air cooling

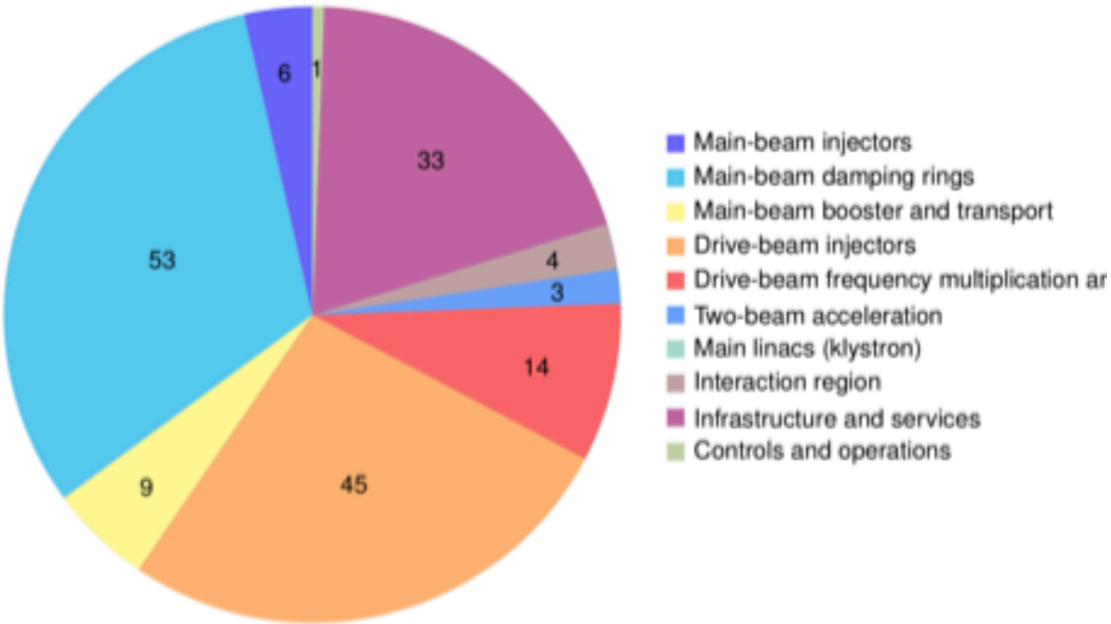


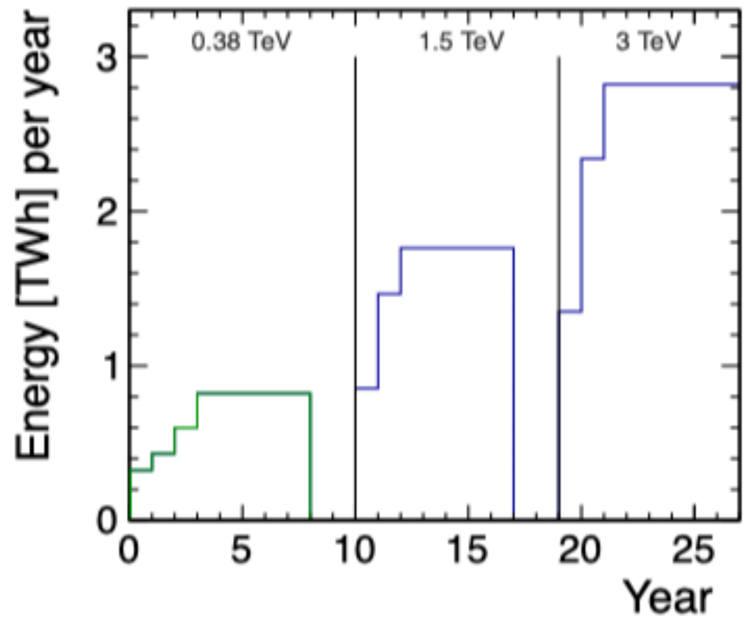
Realisation as a project

Power and energy

- Power estimate redone bottom-up for 380GeV CLIC

Much reduced compared with CDR, from optimised drive-beam complex, more efficient klystrons and injectors, and better estimates of nominal conditions





- Total power 168MW

(Klystron-based option: 164 MW)

- Fold with running model for energy consumption CERN currently consuming ~1.2TWh per year

Cost

- Machine recosted bottom-up in 2017–18
- 380GeV CLIC: 5.9 BCHF
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of main linac)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of main linac)

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

5890^{+1470}_{-1270} MCHF;

CLIC

2013 – 2019

Development Phase
Development of a project plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 – 2025

Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

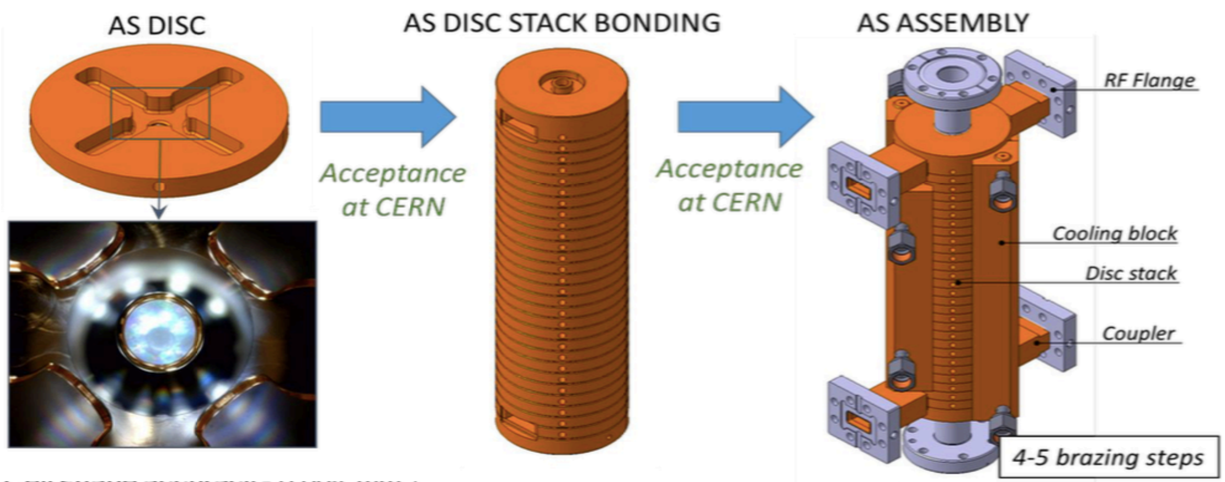
Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

2035
First collisions

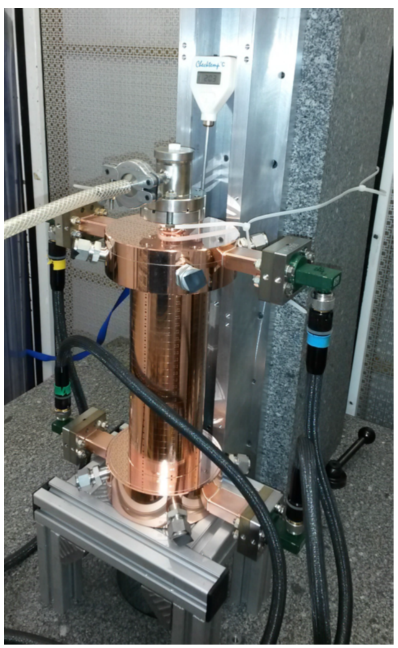
Towards industrialisation

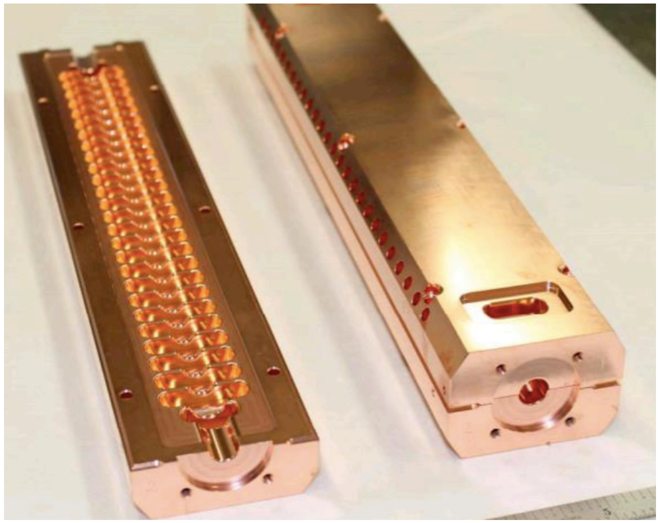


Investigating paths to industrialisation

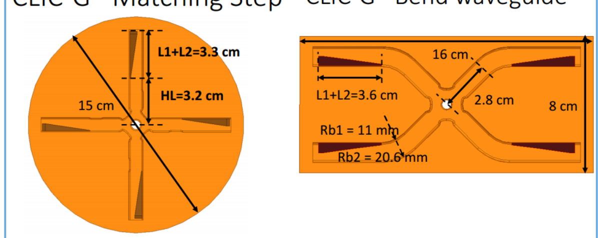
Baseline manufacturing technique:
bonding and brazing

Alternatives:
brazing as for SwissFEL
machining halves





Target is structures that are low-cost & easy-to-manufacture



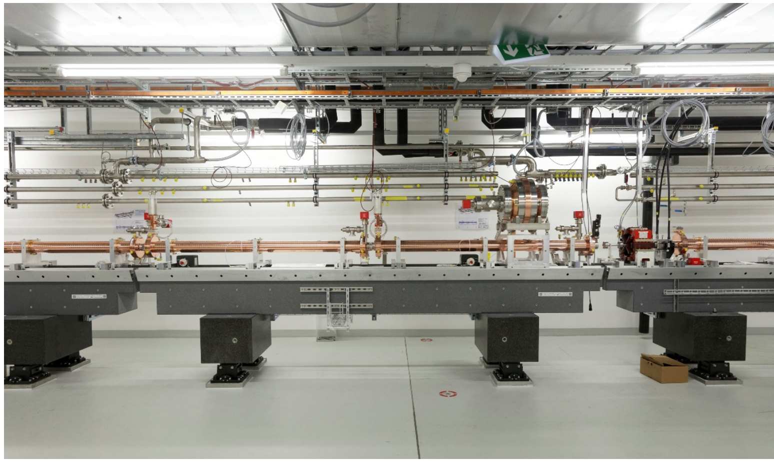
HL	32 mm	D2	5 mm
L1	31 mm	T2	5 mm
L2	2 mm	Mx	0.75 mm
D1	0.8 mm	Mz	1 mm
T1	0.6 mm	Tx	0 mm
		Tz	0.7 mm

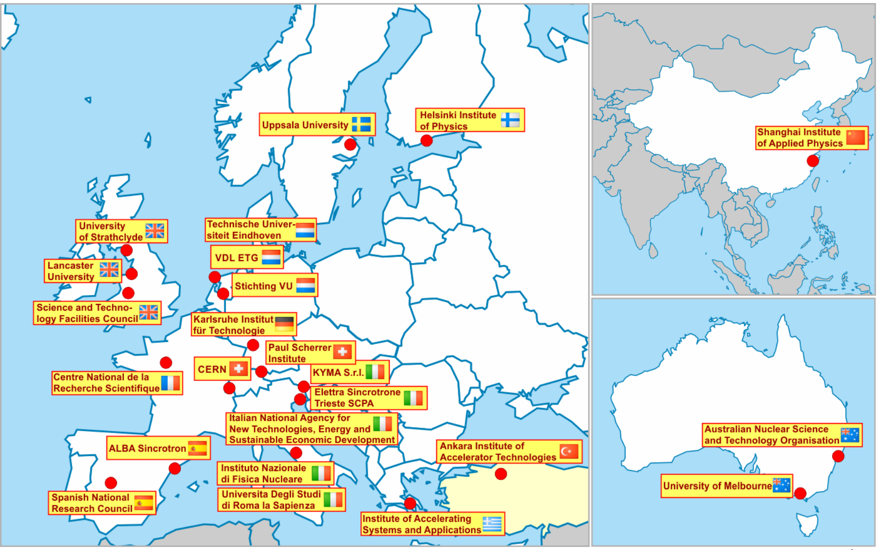
		D2	5.2 mm
L1	34 mm	T2	4.8 mm
L2	2 mm	Mx	0.2 mm
D1	1 mm	Mz	1 mm
T1	1 mm	Tx	0 mm
		Tz	0 mm

CLIC technology applications

SwissFEL: C-band linac

- 104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)
- Similar μm-level tolerances
- Length ~ 800 CLIC structures
- Being commissioned



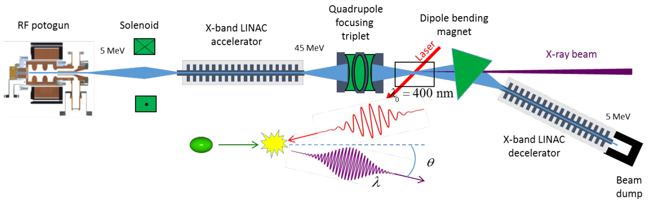


CompactLight

CLIC technology for different applications

- EU co-funded FEL design study
- SPARC at INFN-LNF
- …many other small systems…

INFN Frascati advanced acceleration facility EuPRAXIA@SPARC_LAB

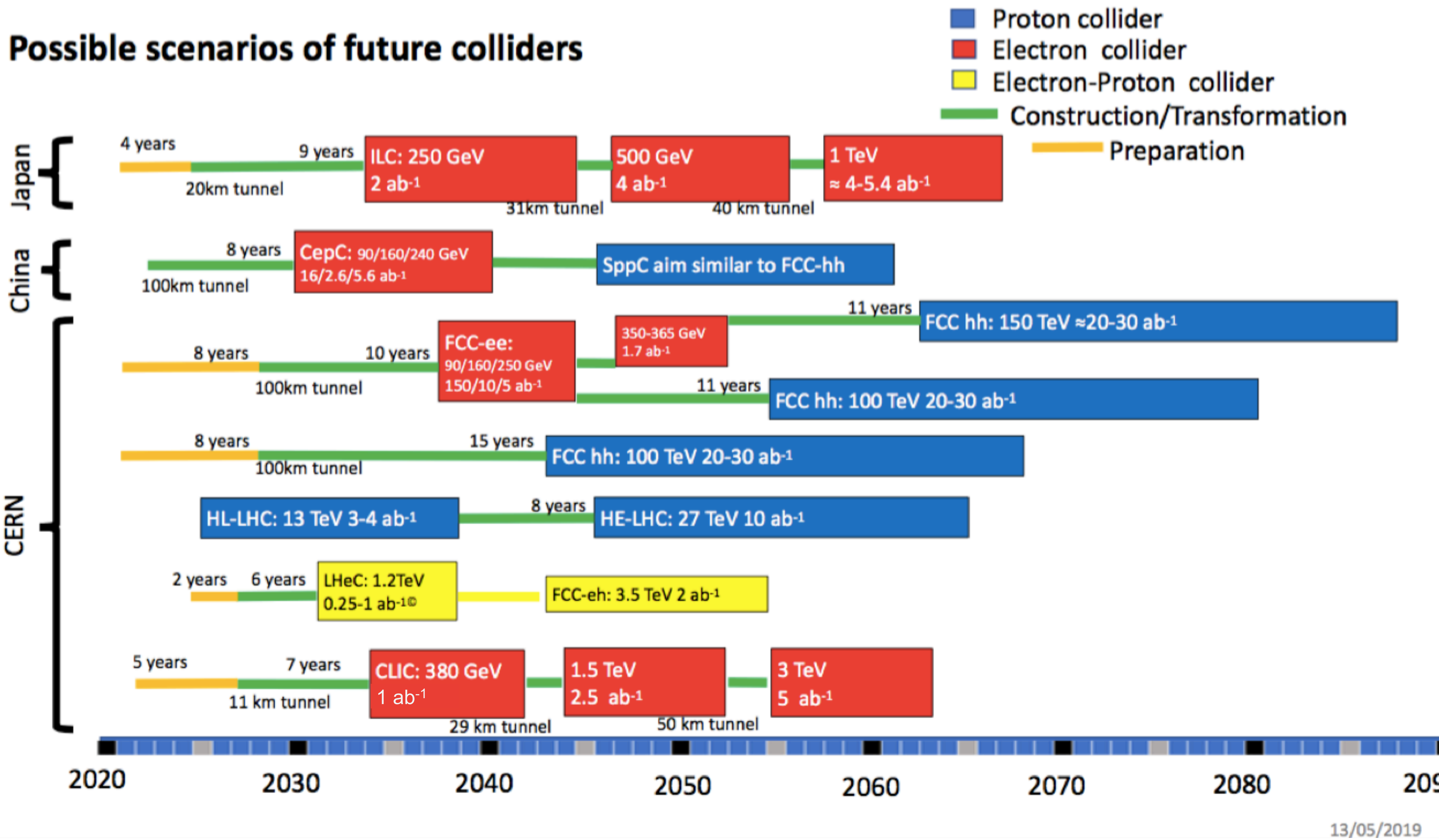


Eindhoven University led SMART*LIGHT Compton Source

Strategy considerations

Efforts to synthesize prospects from different proposed colliders summarized in European Strategy for Particle Physics Briefing Book

Possible scenarios



From U. Bassler via S. Bethke

EFT fit results projected onto Higgs couplings – improvement with respect to HL-LHC

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

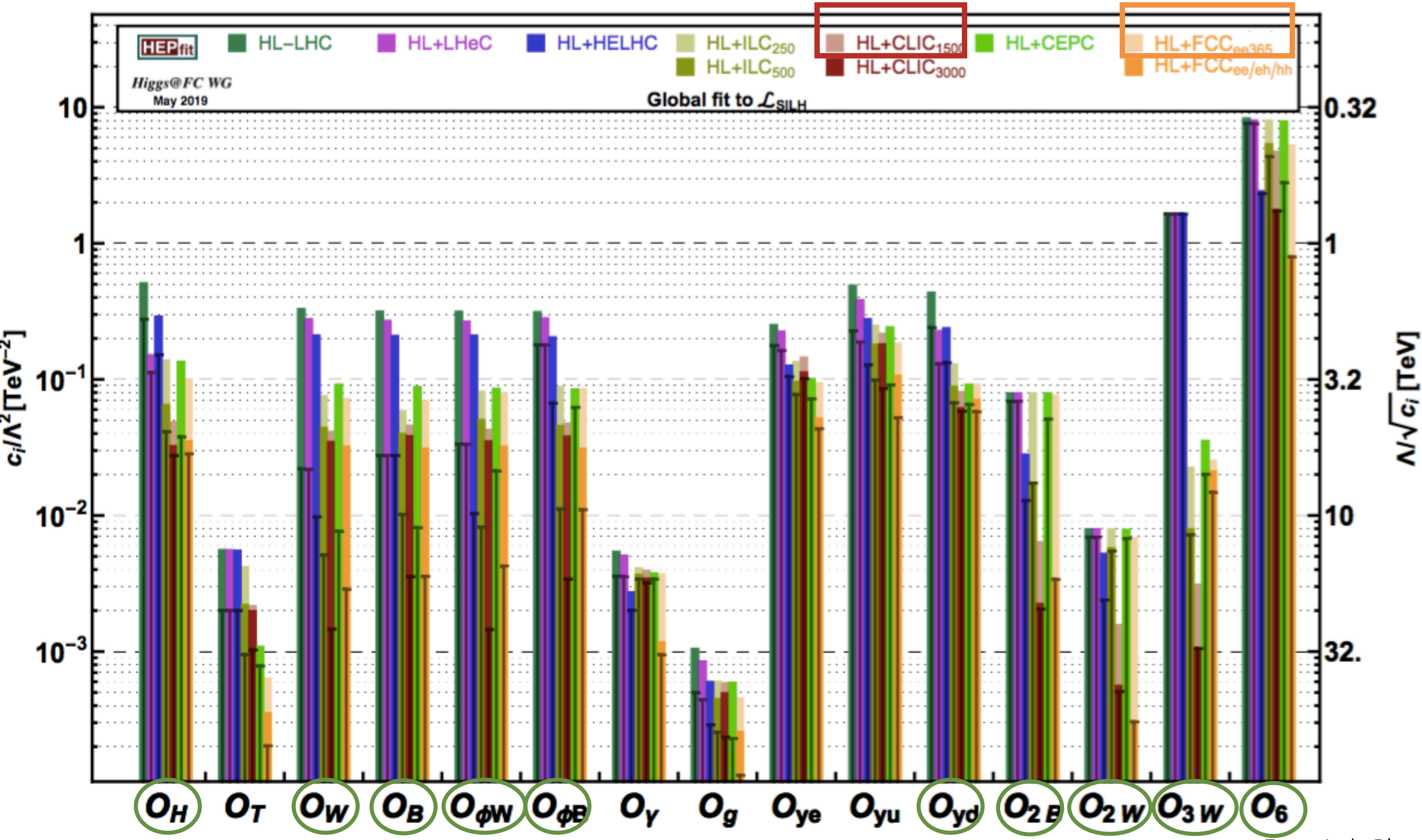
SMEFT ND (⋆) not measured at HL-LHC

From J. de Blas

ILC500, CLIC1500, FCCee365 perform broadly similarly for Higgs couplings

–> look beyond, to top and BSM programmes

EFT fit results

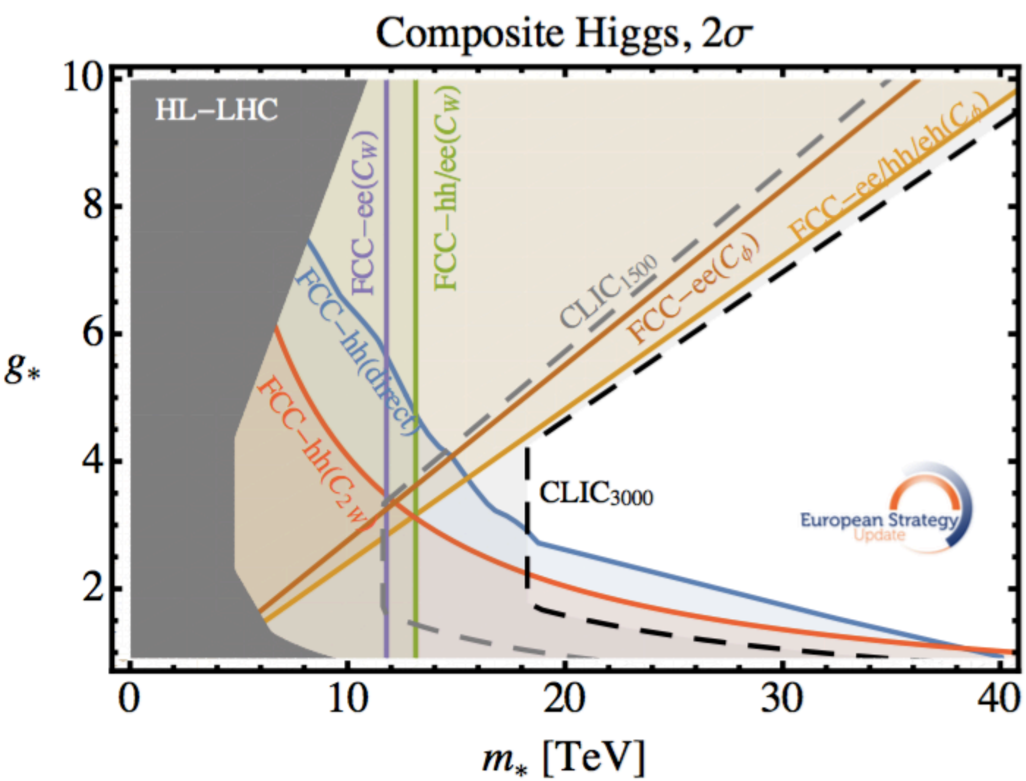


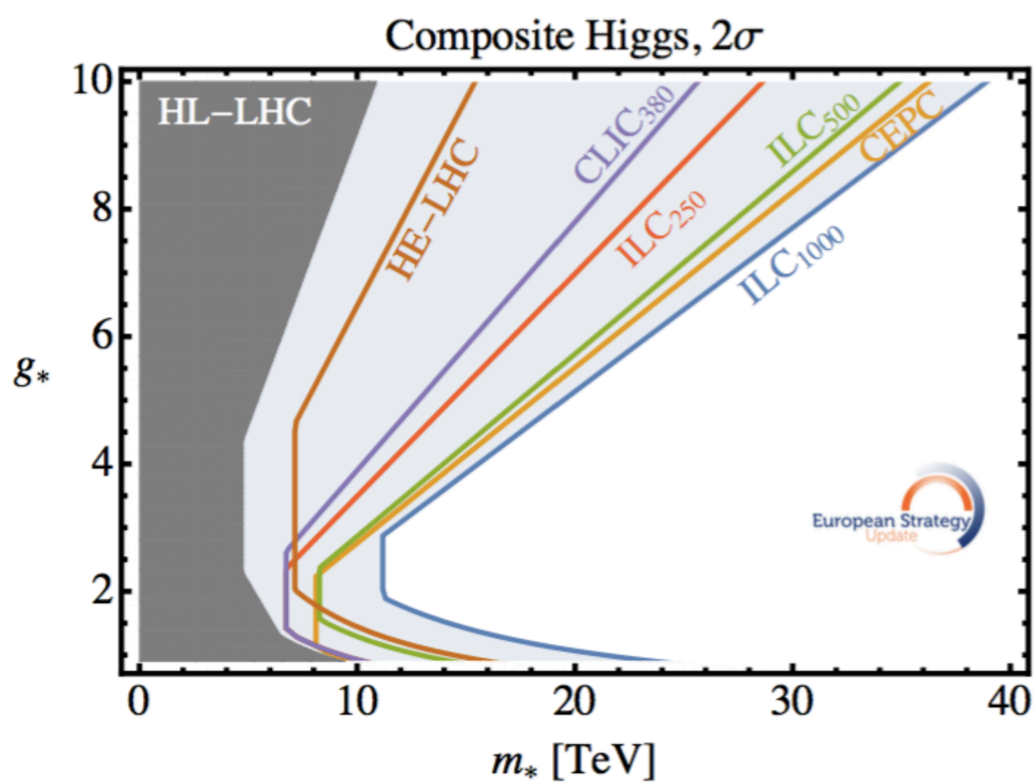
From J. de Blas

Highlighted where CLIC1500 more sensitive than FCCee – benefit of high energy

Interpretations and full programme

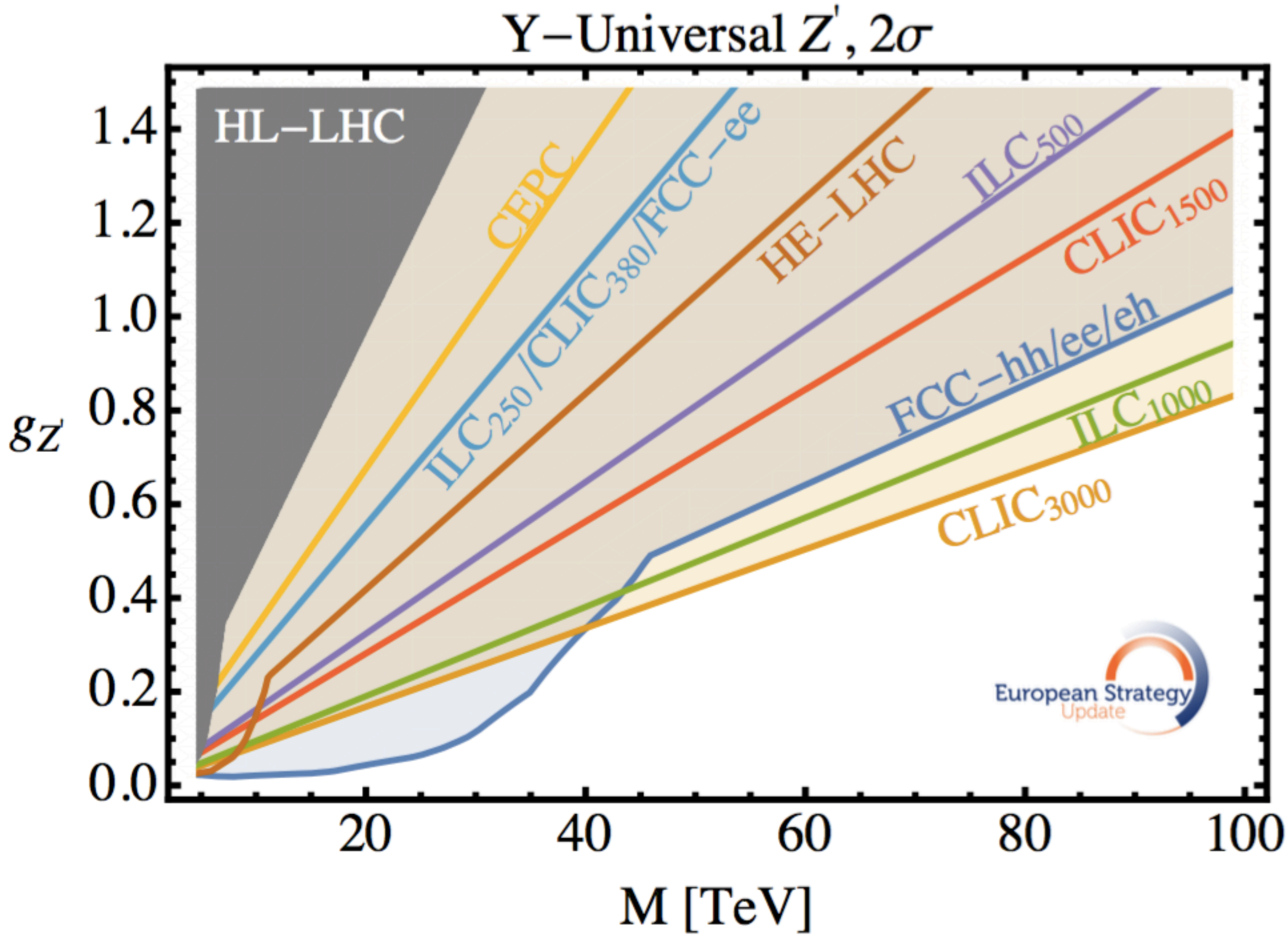
Wider programme; compare CLIC and FCChh:



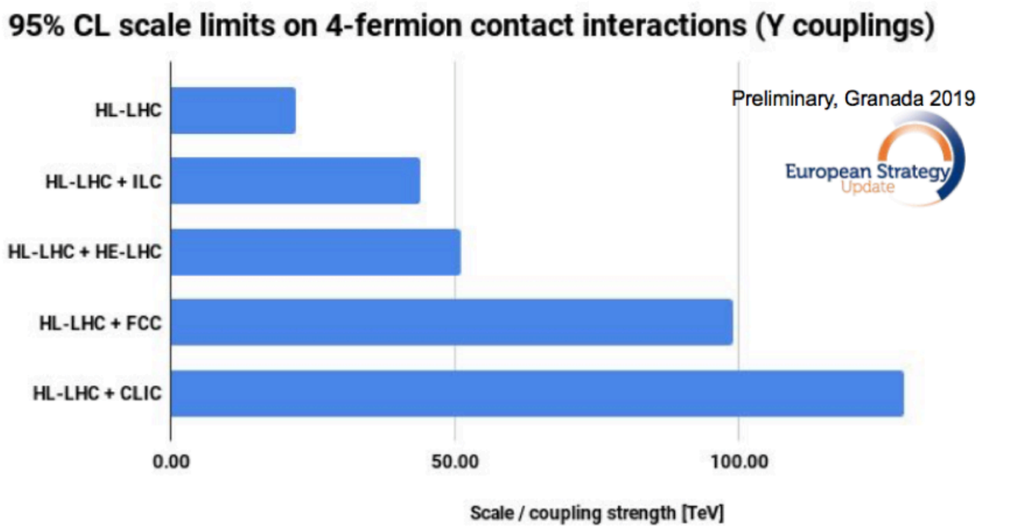


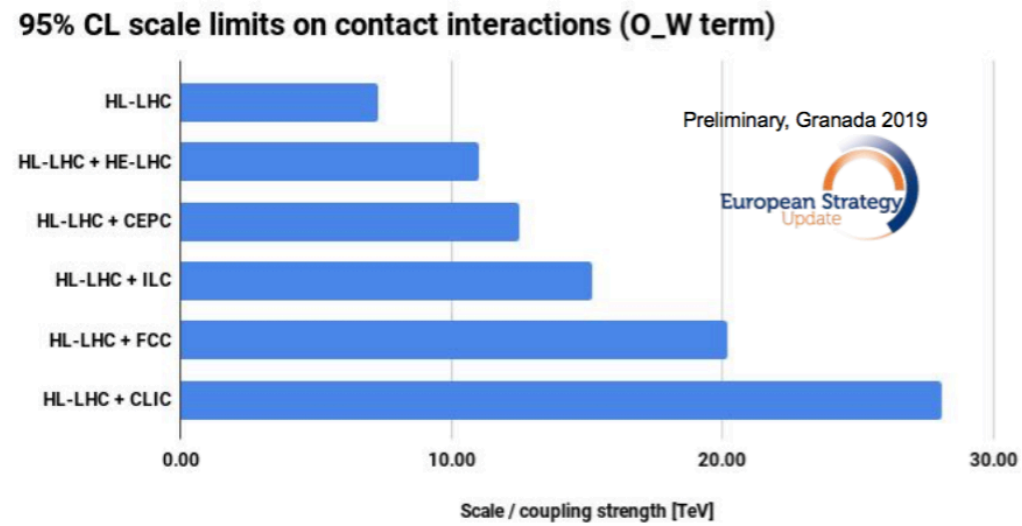
Interpretations and full programme

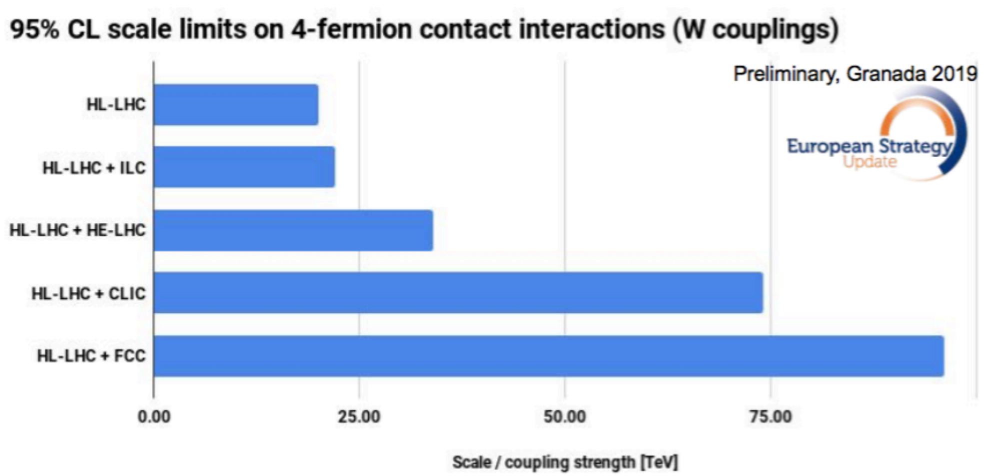
Wider programme; compare CLIC and FCChh:

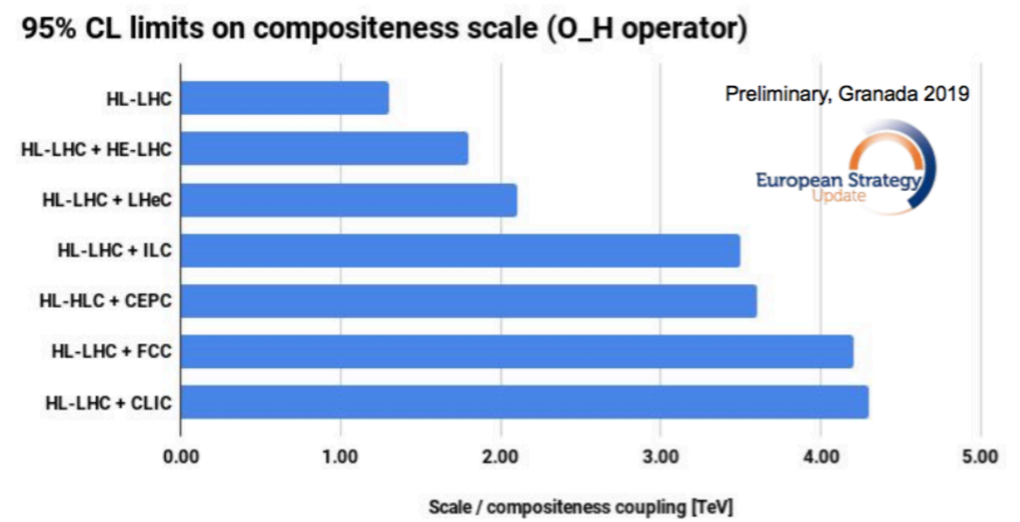


Interpretations and full programme









From J. Alcaraz, EWSB Dynamics and Resonances
https://indico.cern.ch/event/808335/contributions/3365188/attachments/1843613/3023844/Alcaraz_BSM1.pdf

Interpretations and full programme

FCC-hh has (unsurprisingly) the best mass reach for new resonances, in general:
– For new Z′ bosons via direct production with couplings ~weak coupling size
– For W′, gravitons, strongly-coupled resonances, vector-like quarks, ...

CLIC highly competitive for new physics via contact interactions:
– For new Z′ bosons with couplings > 1 (above the weak coupling size)
– For 2fermion - 2boson contact interactions (e+e-→ZH channel)
– New physics scales from deviations in Higgs couplings

From J. Alcaraz, EWSB Dynamics and Resonances
https://indico.cern.ch/event/808335/contributions/3365188/attachments/1843613/3023844/Alcaraz_BSM1.pdf

European Strategy for Particle Physics

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Strategy-making needs to inject cost, timelines, judgement on magnet readiness...

from D. Schulte, ESPP Open Symposium, Granada

Possible variations

Responding to issues arising during European Strategy discussions:

Z-pole running:
CLIC's staging scenario prioritizes high-energy running but it would be possible to have a dedicated run at the Z pole reaching luminosity of $0.36\mathrm{x}10^{-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (like "Giga-Z")

Interaction points:
CLIC's baseline is a single interaction point / single experiment. However, it would be possible to operate two detectors in push-pull mode, and at the initial energy stage it would be possible to have two beam-delivery systems and two interaction points

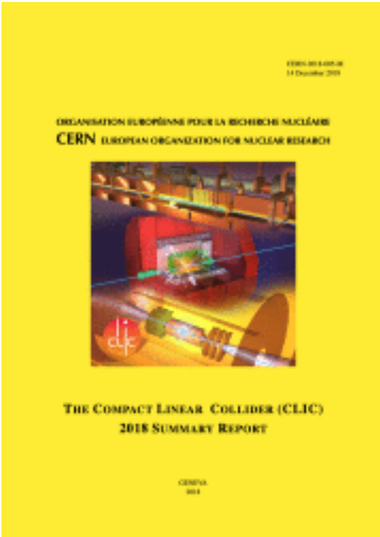
Luminosity:
It would be possible to run at 100Hz instead of 50Hz, and double the integrated luminosity collected

"My scenario"

- In my view the European Strategy should not assume an Asian collider (but of course adapt in case one is realised)
- We should invest in CLIC now so that it could be ready to go ahead in 2026
- Build CLIC380 starting in 2026
- See how wakefield acceleration techniques and high-field magnets develop (even muon colliders...?)
- After CLIC380, re-evaluate physics and R&D landscape and decide whether to continue to CLIC1500 (or CLIC1000 or whatever re-optimisation) or move to e.g. a hadron machine

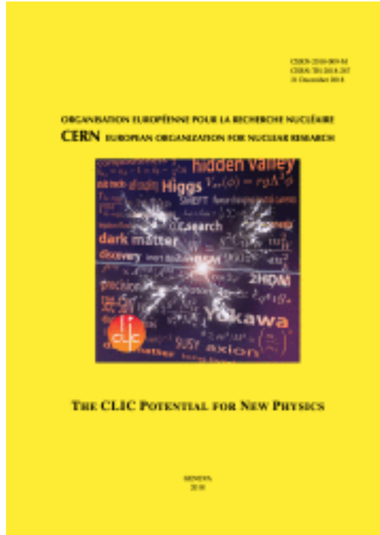
– CLIC provides the most flexible starting point

CLIC reports



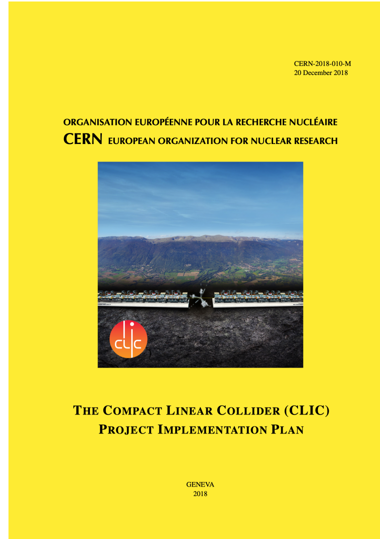
[CERN-2018-005-M](http://dx.doi.org/10.23731/CYRM-2018-002)

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



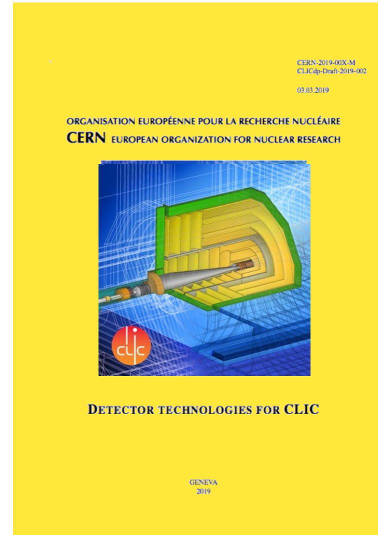
[CERN-2018-009-M](http://dx.doi.org/10.23731/CYRM-2018-003)

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



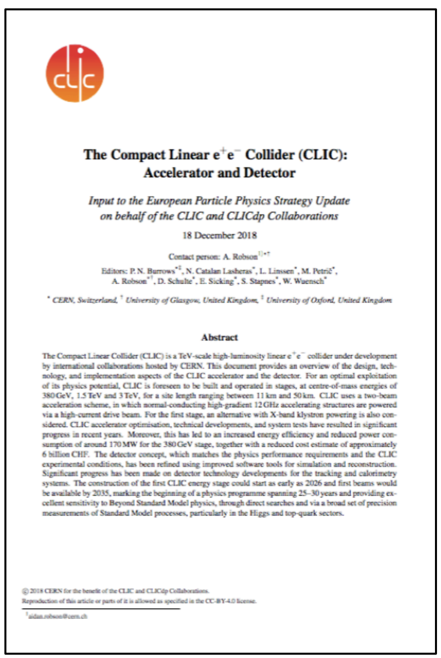
[CERN-2018-010-M](http://dx.doi.org/10.23731/CYRM-2018-004)

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



[CERN-2019-001](http://dx.doi.org/10.23731/CYRM-2019-001)

http://dx.doi.org/10.23731/CYRM-2019-001



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)*†]

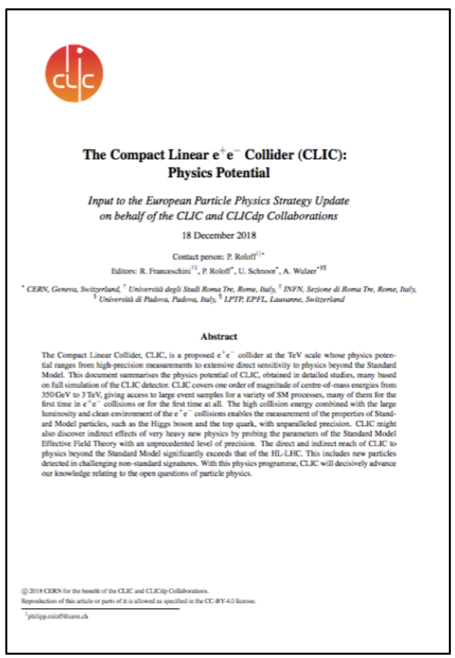
Editors: P. N. Burrows[*‡], N. Catalan Lasheras[*], L. Linssen[*], M. Petrič[*], A. Robson[*†], D. Schulte[*], E. Sicking[*], S. Stapnes[*], W. Wuensch[*]

[*] *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.



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.

Four CERN Yellow Reports:
- The CLIC 2018 Summary Report
- The CLIC Potential for New Physics
- The CLIC Project Implementation Plan
- Detector Technologies for CLIC

Two formal ESU submissions

Many supporting notes and papers

Available at:
http://clic.cern/european-strategy

CLIC perspective

- CLIC is now a mature project, ready to start construction in ~2026, with first collisions ~2035
- The main accelerator technologies have been demonstrated
- The coupling of lepton collider precision and multi-TeV energies gives a physics case that is broad and profound, from precision Higgs and top measurements, and their interpretation in new physics scenarios, to direct BSM searches
- The starting energy of 380GeV is optimised and provides a guaranteed physics programme
- The timescale is attractive
- The detector concept and detector technologies R&D are advanced
- A linear machine provides flexibility to adapt the staging scenario to a developing physics landscape, and polarisation gives extra physics sensitivity
- The cost is compatible with LHC-like resources, and the accelerator staging brings cost staging and accompanying implications on affordability
- A linear tunnel provides a natural infrastructure for the future beyond CLIC
- **CLIC is the best option for the next collider at CERN, and decisions are being taken now**

http://clic.cern/european-strategy