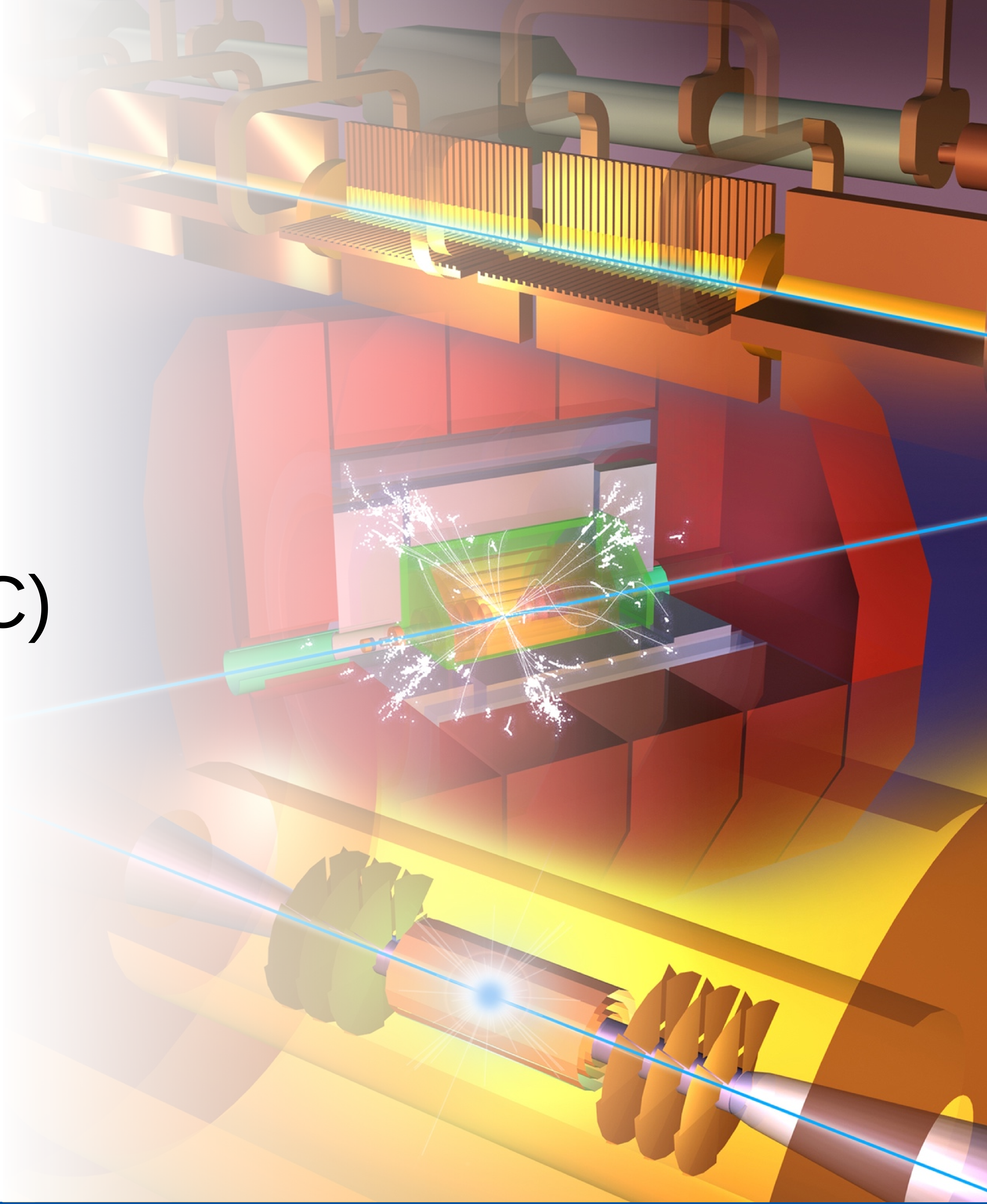
Steinar Stapnes
on behalf of CLIC

The Compact Linear Collider (CLIC)

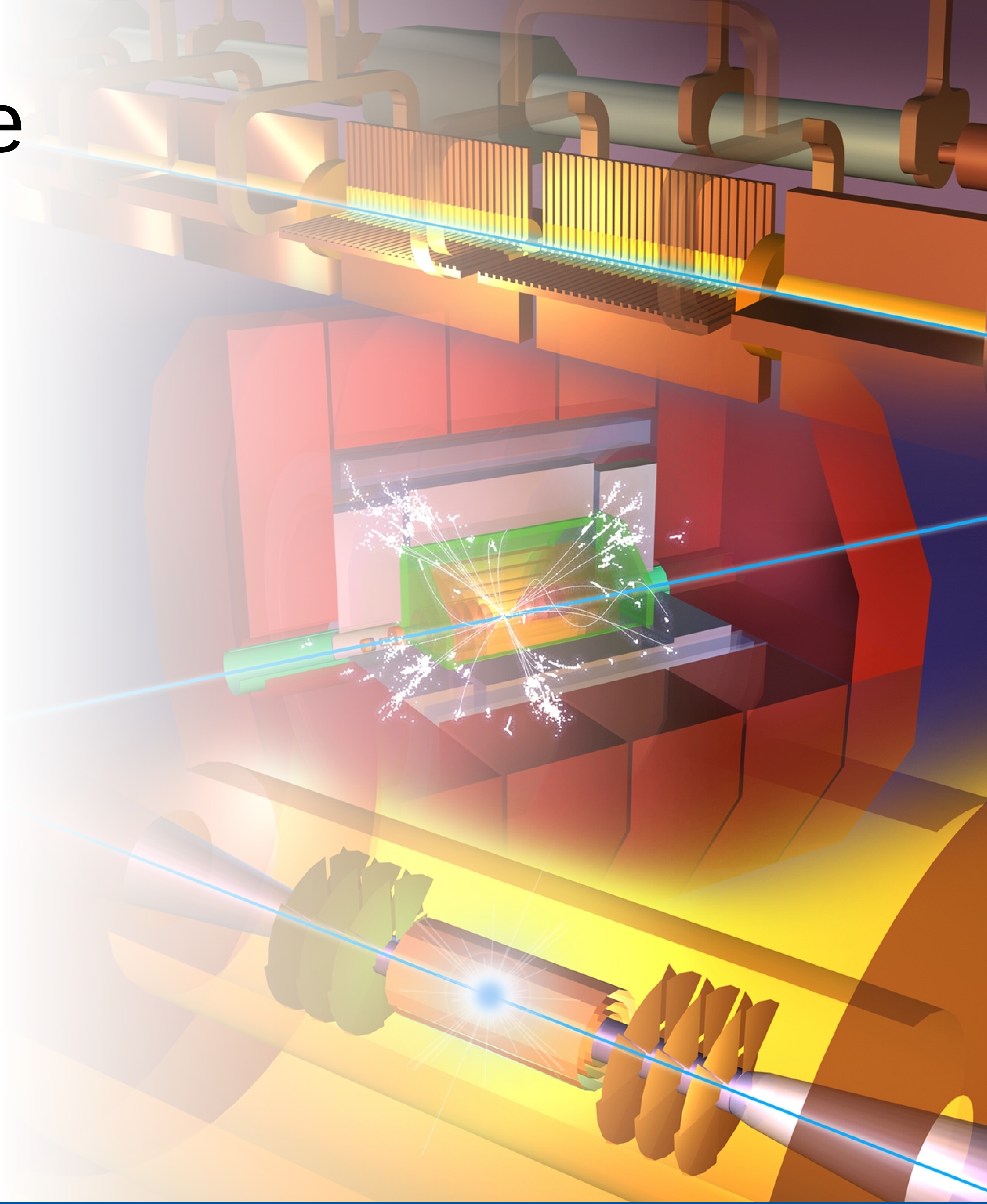


IAS 2020 – High Energy Physics Conference
January 20th, 2020

Outline

Project overview, followed by:

- Accelerator description
- Accelerator key technology, examples and recent activities
- Detector and physics (brief – as reference)
- Project realization



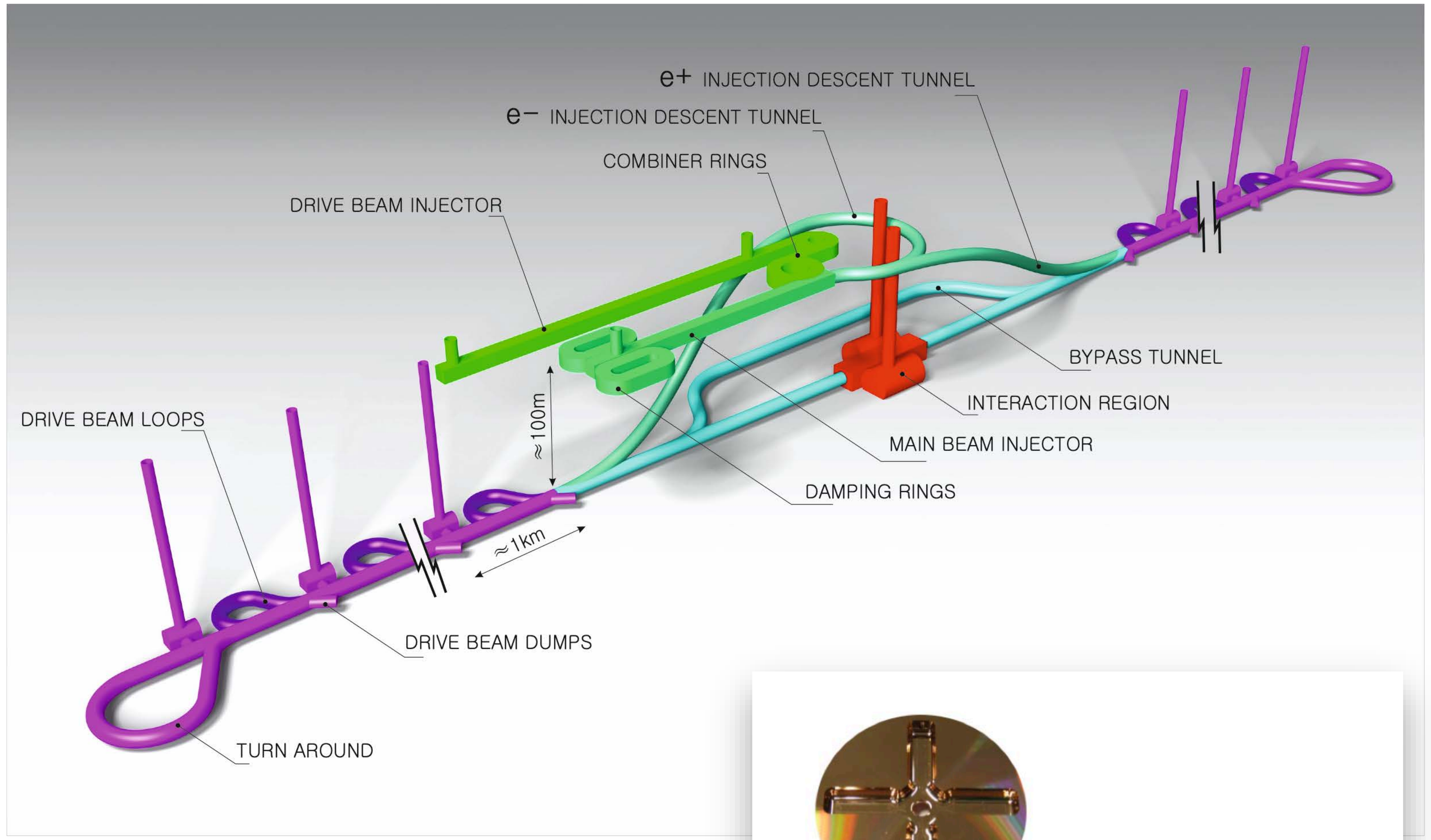
Collaborations

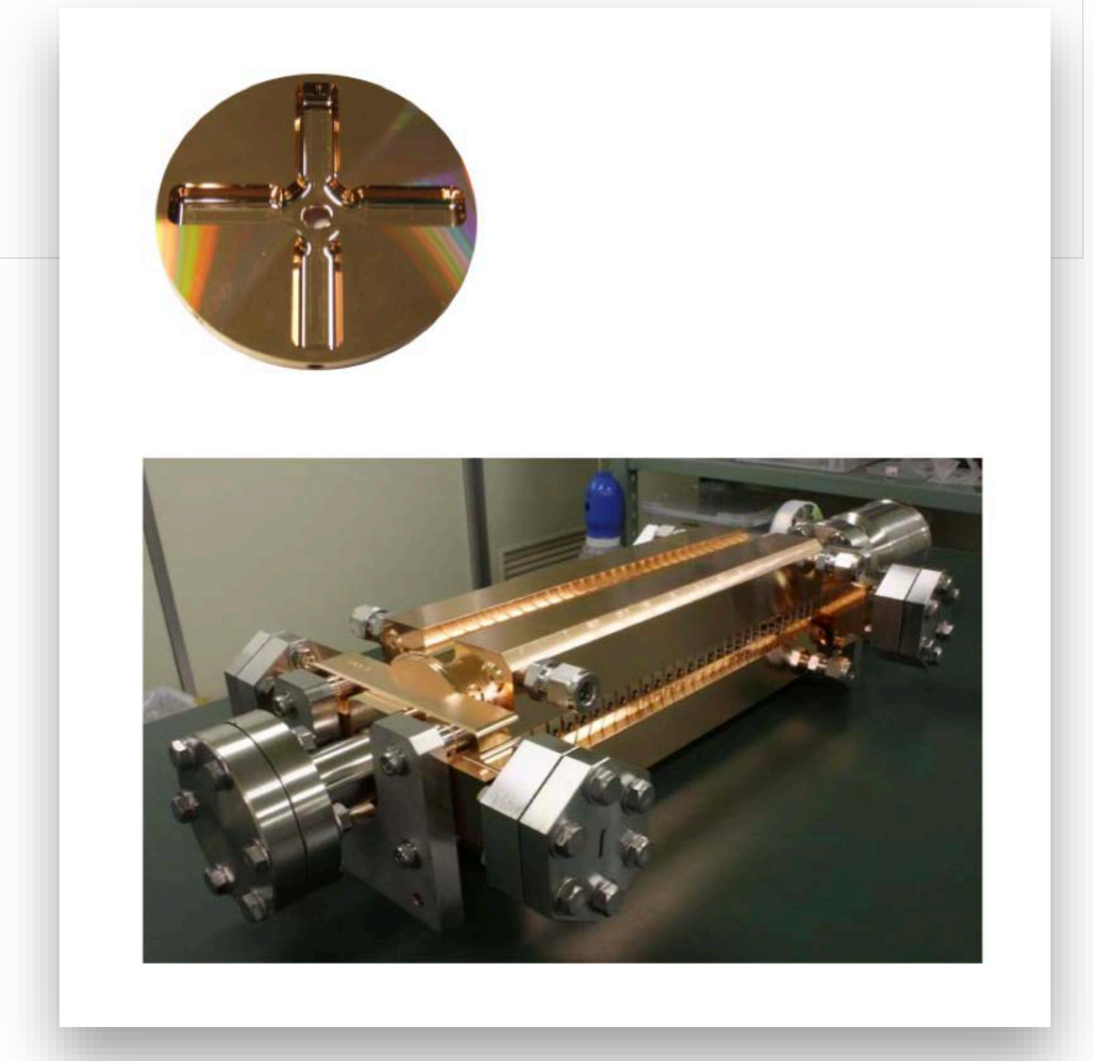
CLIC accelerator
- ~50 institutes from 28 countries
- CLIC accelerator studies
- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility, CTF3

CLIC detector and physics (CLICdp)
- 30 institutes from 18 countries
- Physics prospects & simulations studies
- Detector optimisation + R&D for CLIC

+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020

Proposed e^+e^- linear colliders – CLIC





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

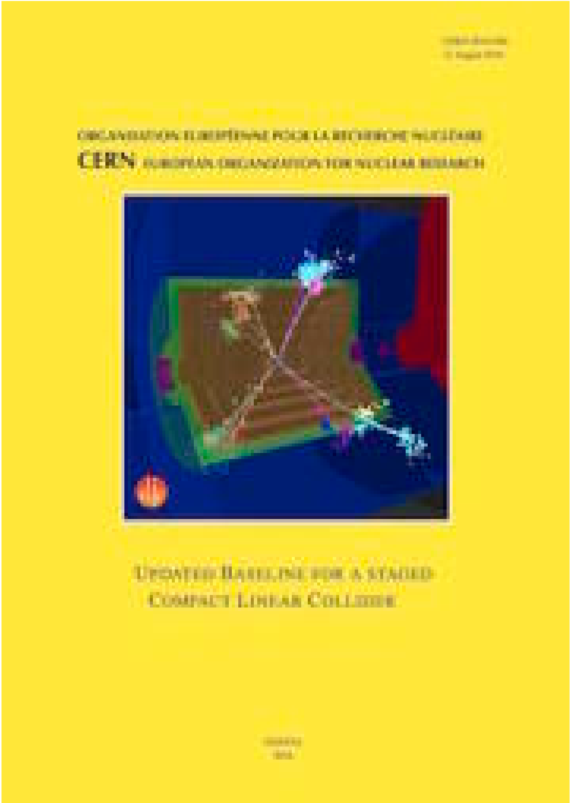
The Compact Linear Collider (CLIC)

- Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035)
- Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 cavities at 380 GeV)
- Staged programme with collision energies from 380 GeV up to 3 TeV
- CDR in 2012
- Updated project overview documents in 2018
- Cost 5.9 BCHF for 380 GeV
- Power 168 MW at 380 GeV
- Length ~11km in its initial phase
- Key step: European Strategy for Particle Physics in May 2020 (deliberations on-going)

Resources

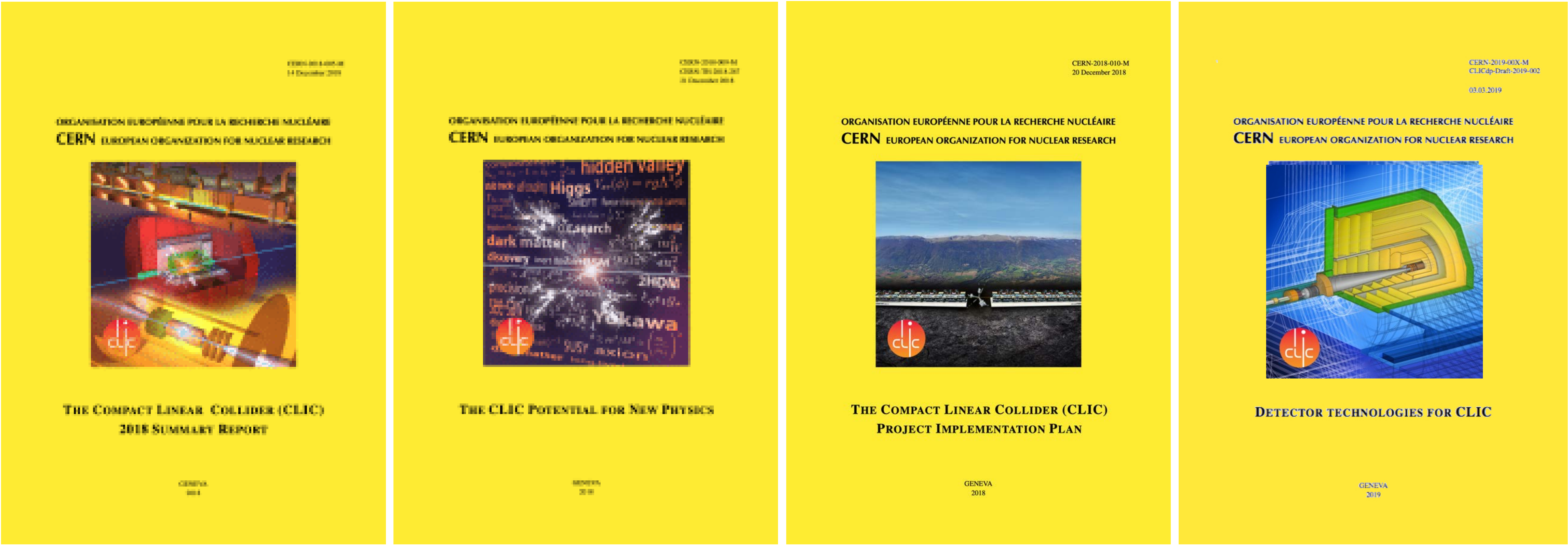
3-volume CDR 2012

Updated Staging Baseline 2016



Available at:
clic.cern/european-strategy

4 CERN Yellow Reports 2018



Two formal submissions to the ESPPU 2018

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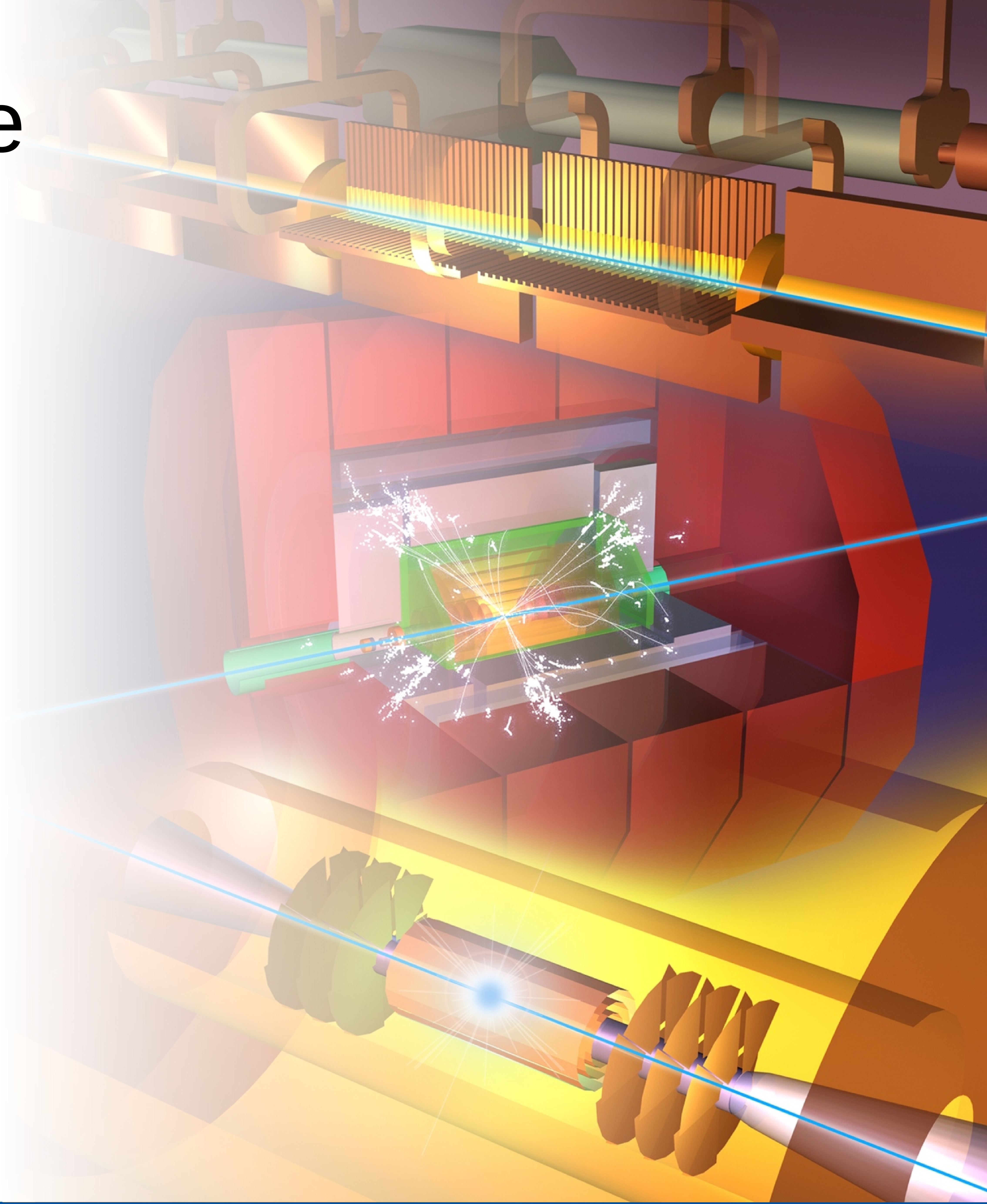
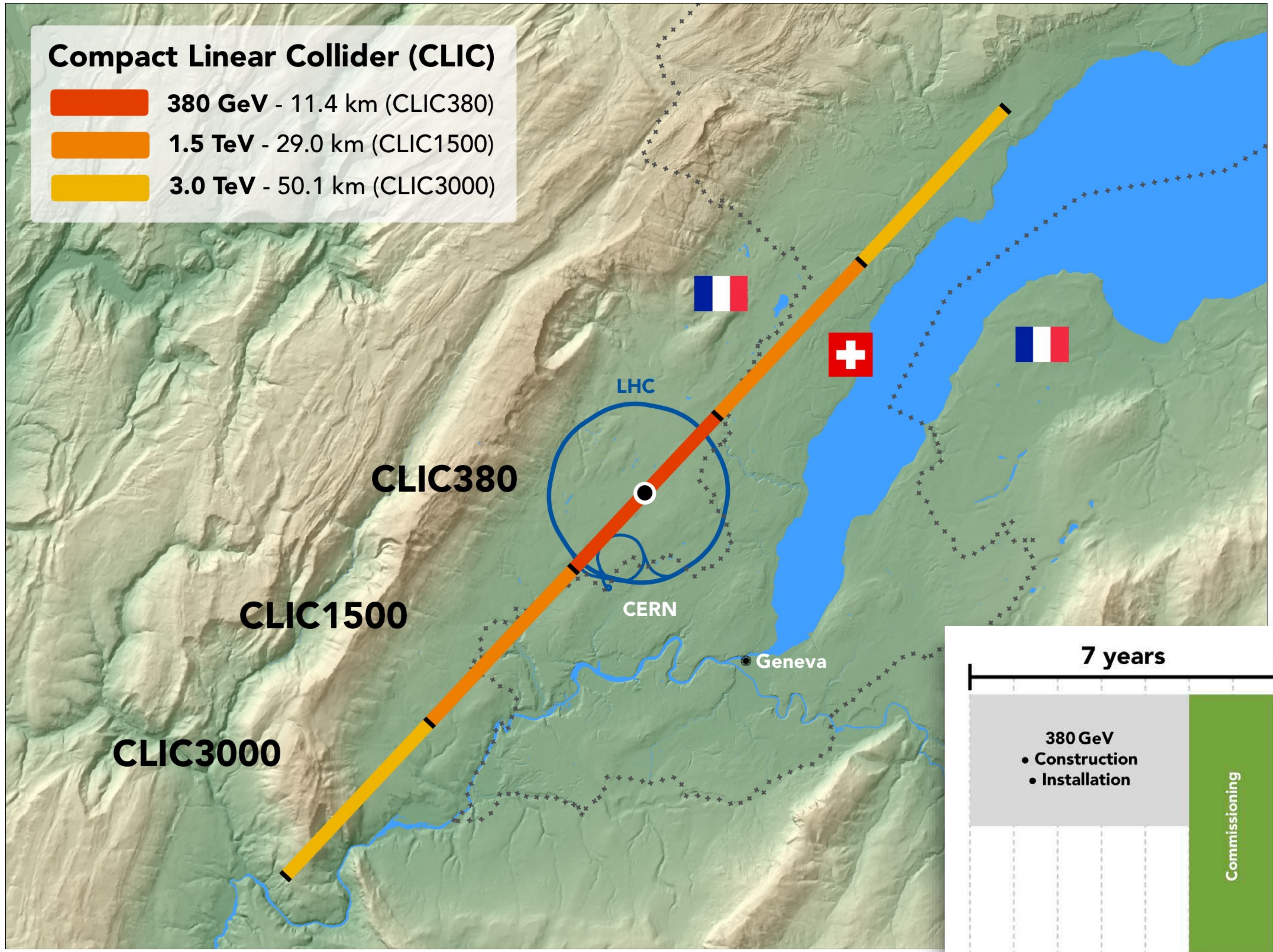
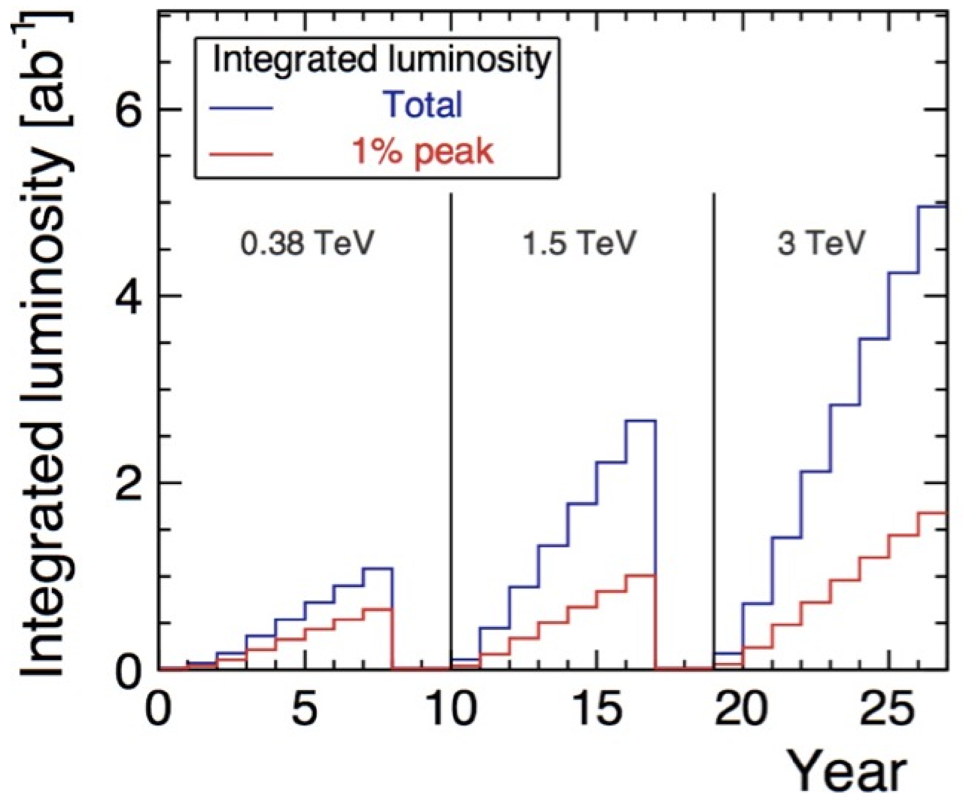


CLIC accelerator footprint

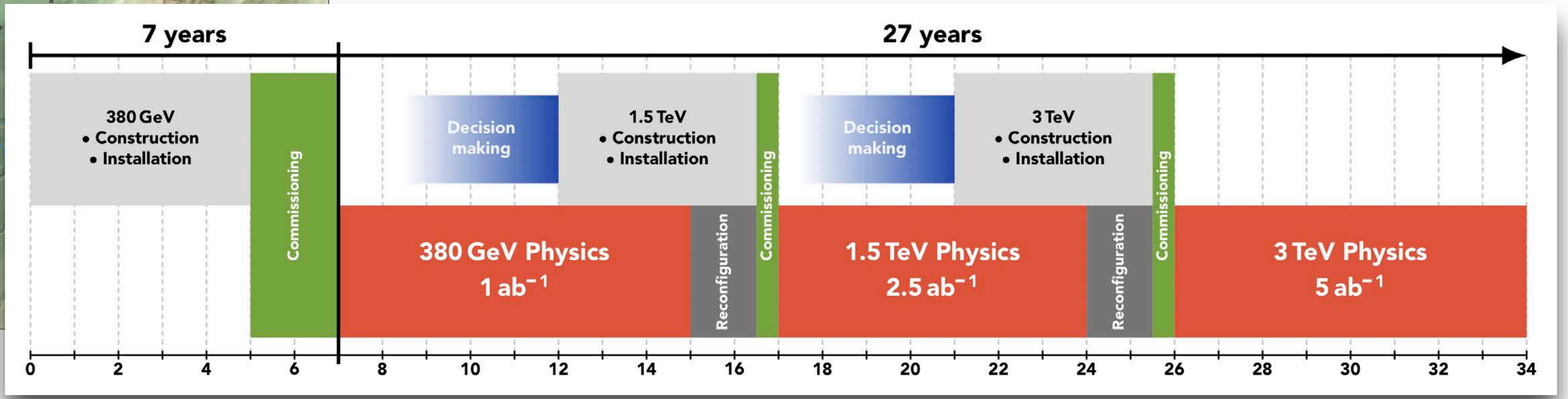




Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.

TECHNOLOGY-DRIVEN SCHEDULE from start of construction:

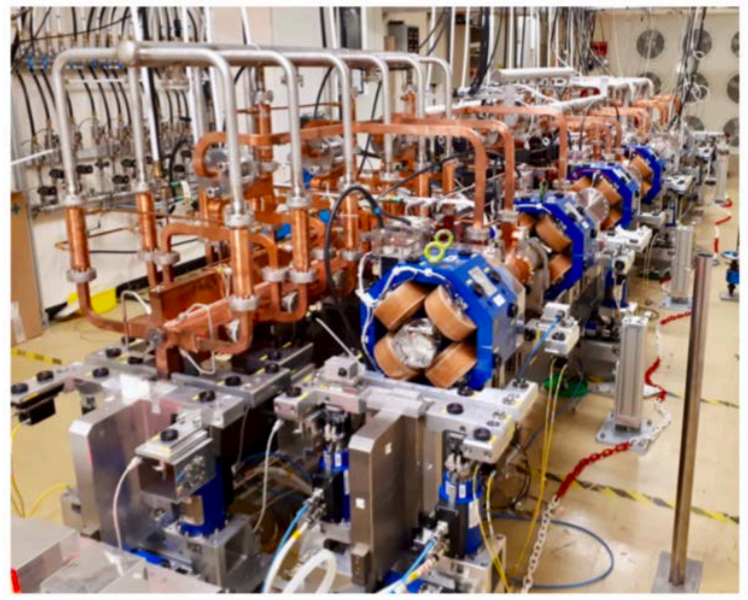
- First collisions by ~2035
- Baseline scenario of operation ~30 years

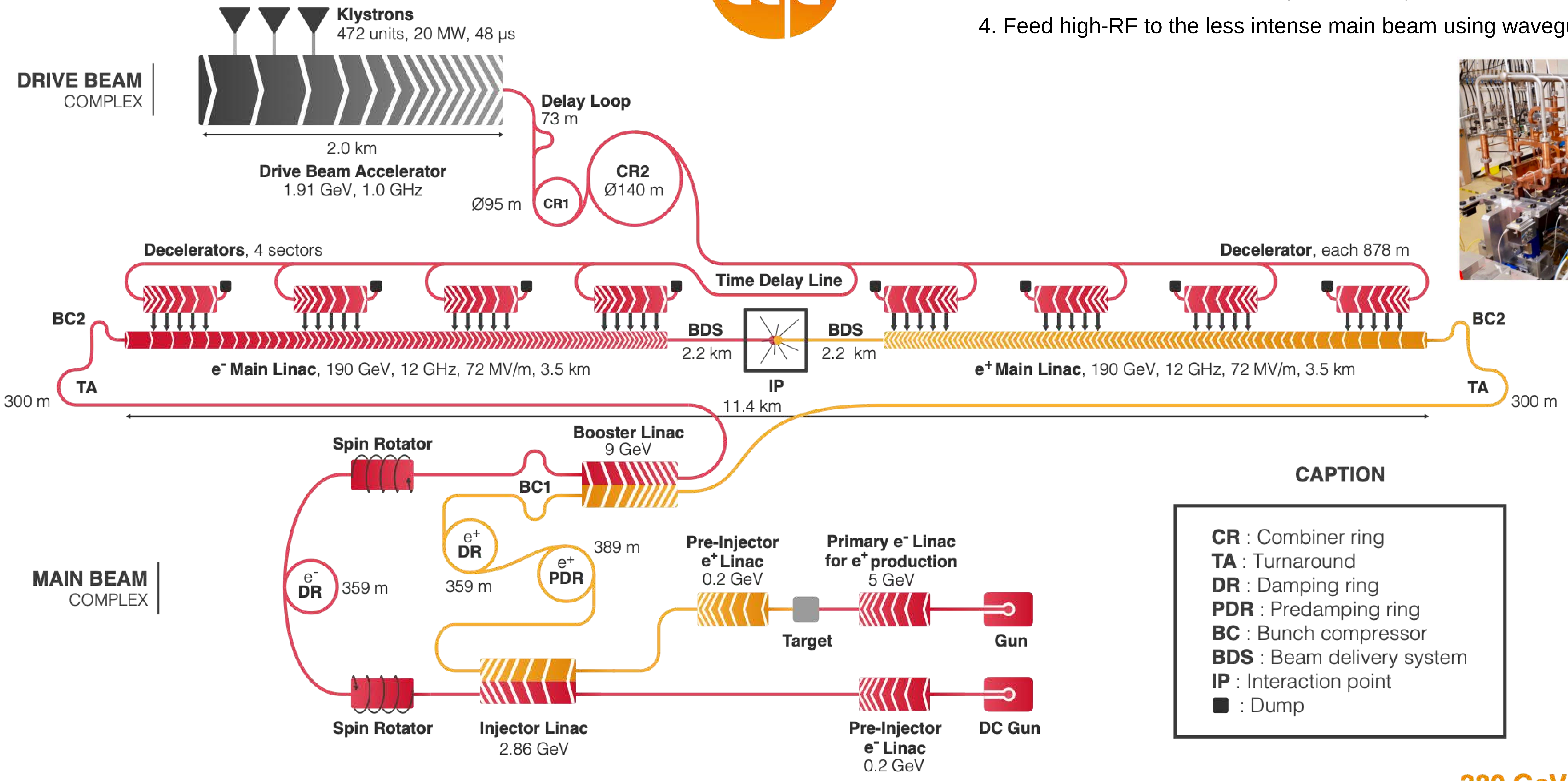


CLIC parameters

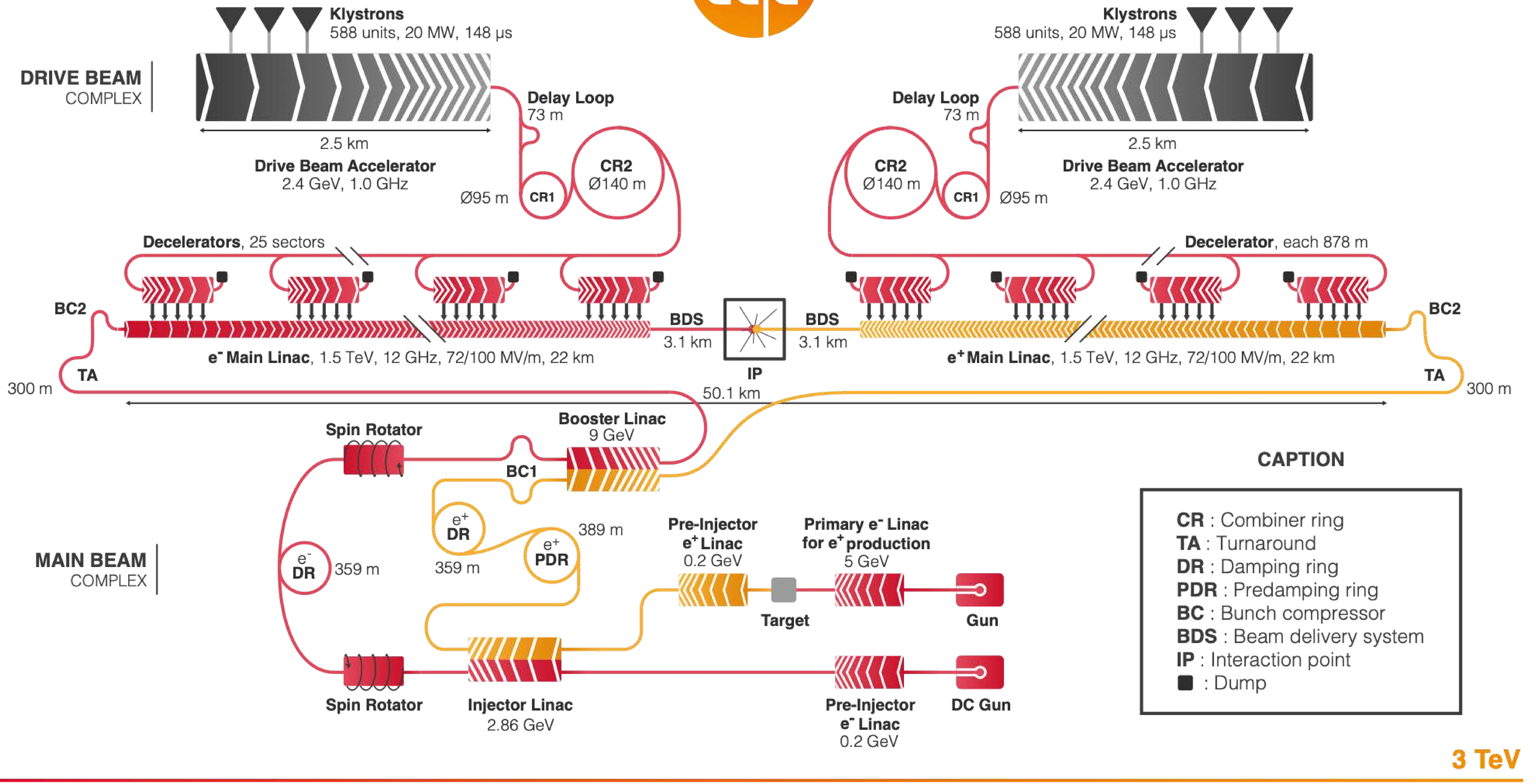
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total 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
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac 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)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides



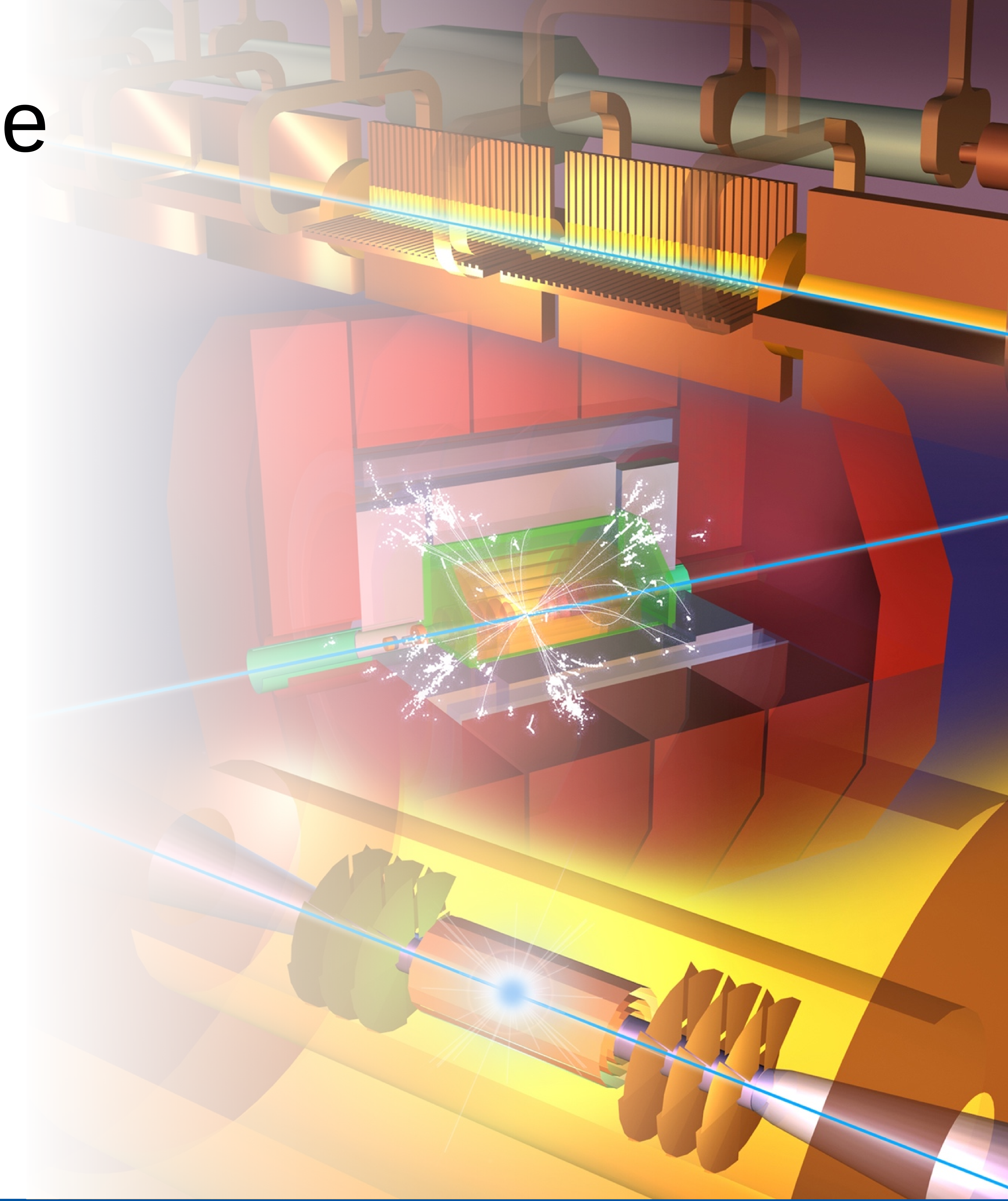


380 GeV



CLIC - Scheme of the Compact Linear Collider (CLIC)

Outline



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HV deck
Gun
Current transformer
Dump
HVPS
Capacitor
(b)
CBPM 830
CBPM 820
CBPM 810
Optical encoder
Reference interferometer
Multi-pass interferometer
(a)

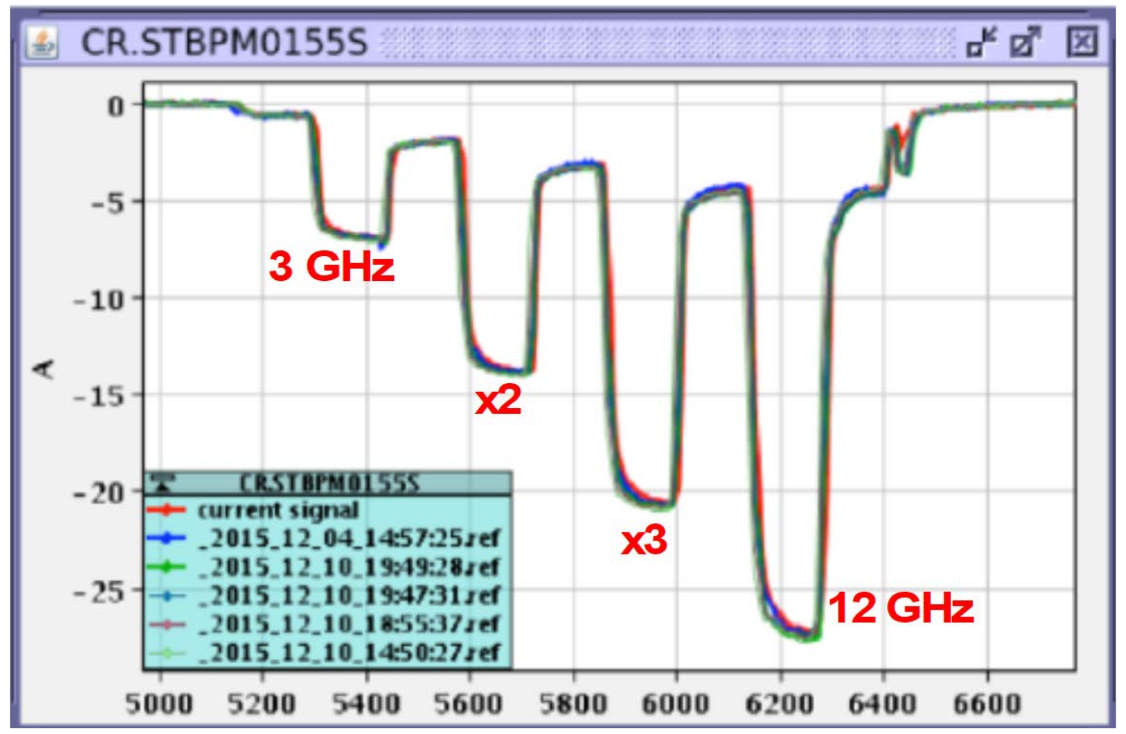
Accelerator challenges

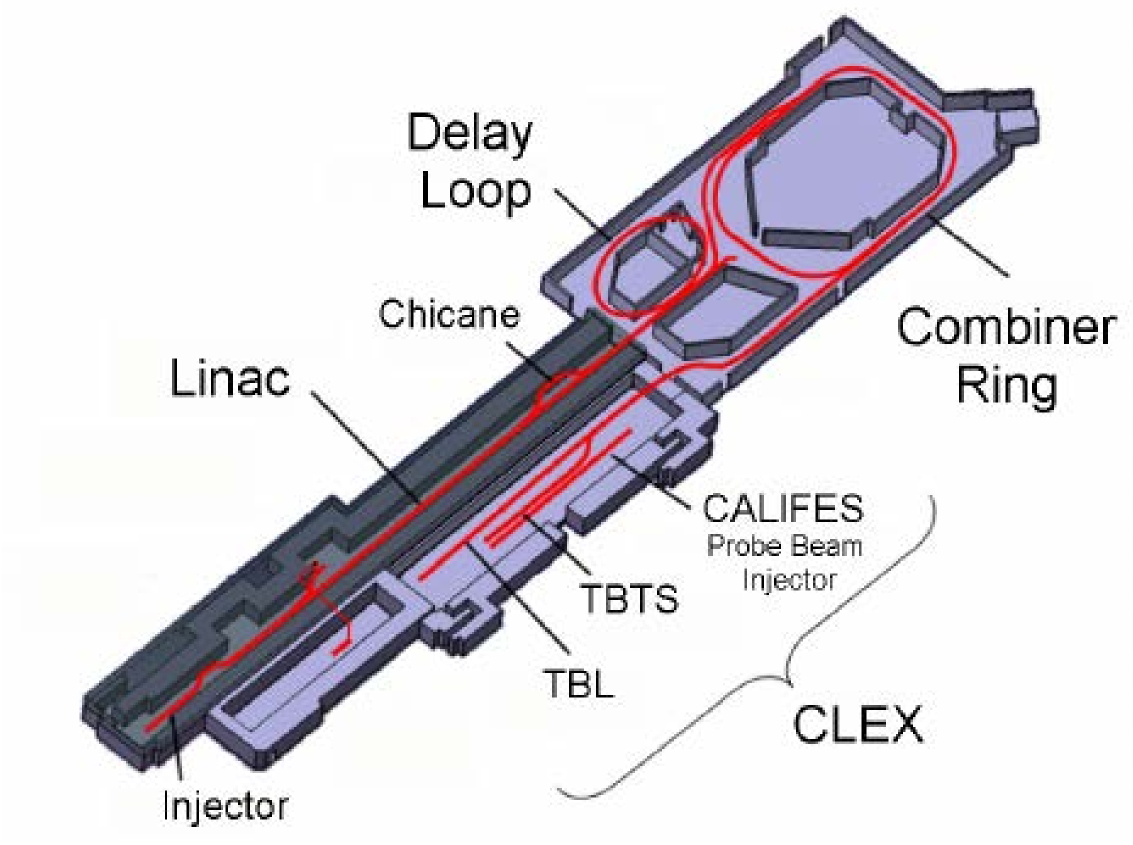
Details in PIP, DOI: http://dx.doi.org/10.23731/CYRM-2018-004

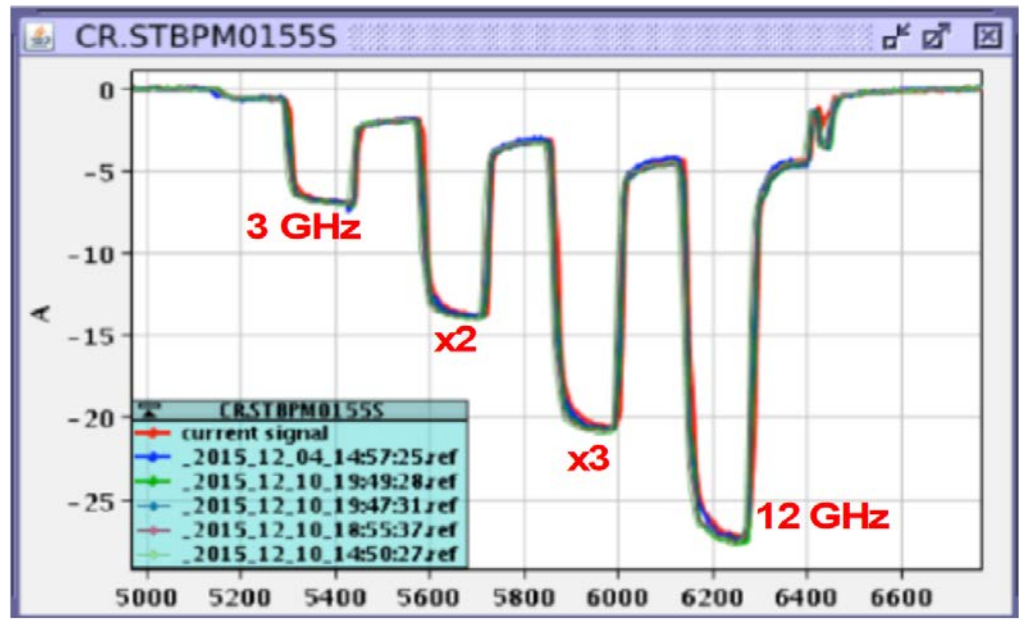
- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- Four main challenges
  1. High-current drive beam bunched at 12 GHz
  2. Power transfer and main-beam acceleration
  3. Towards 100 MV/m gradient in main-beam cavities
  4. Alignment and stability (“nano-beams”)
- The CTF3 (CLIC Test Facility at CERN) programme addressed all drive-beam production issues
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations
- X-band technology developed and verified with prototyping, test-stands, and use in smaller systems
- Two C-band XFELS (SACLA and SwissFEL) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

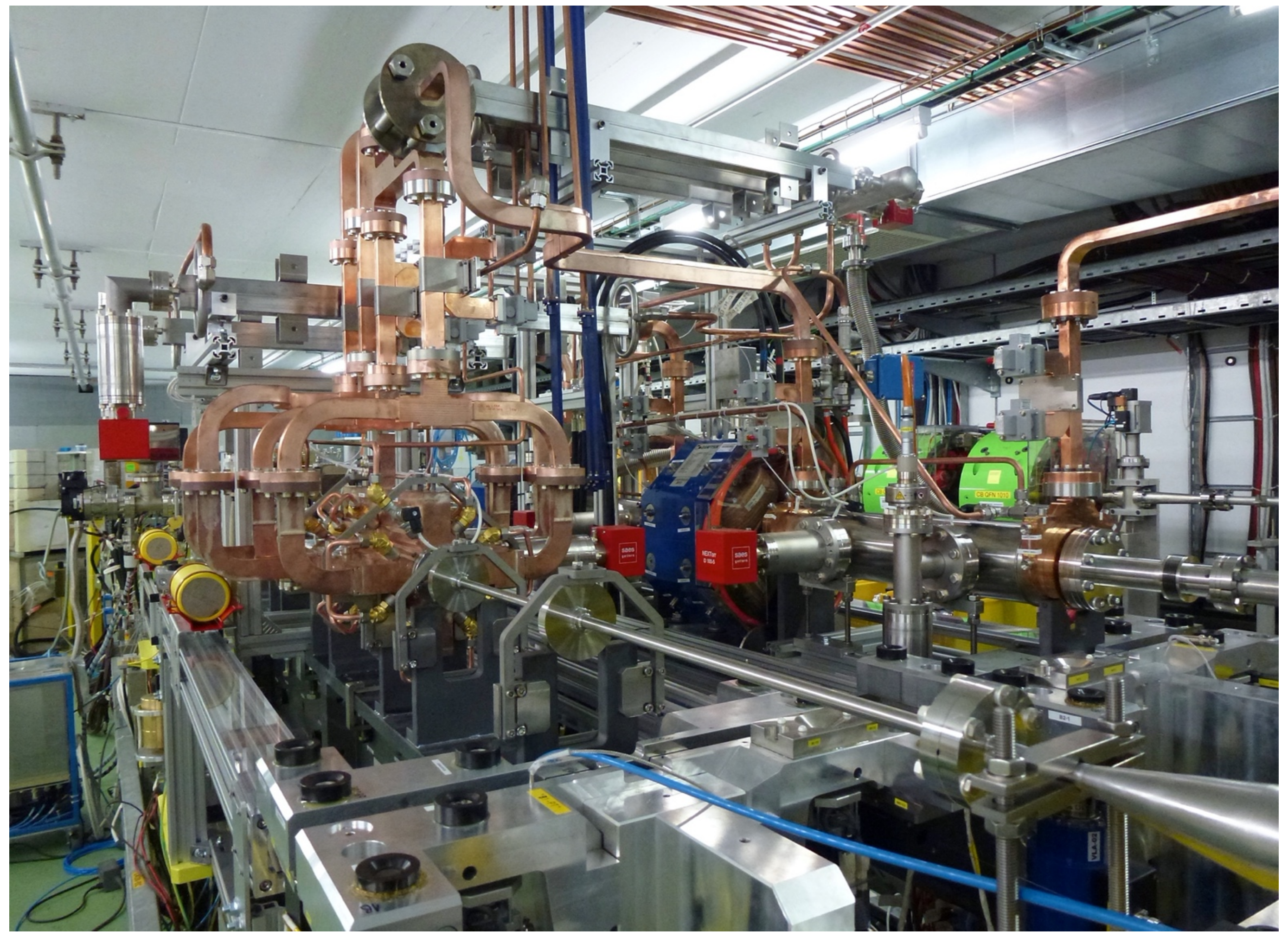
Two beam acceleration

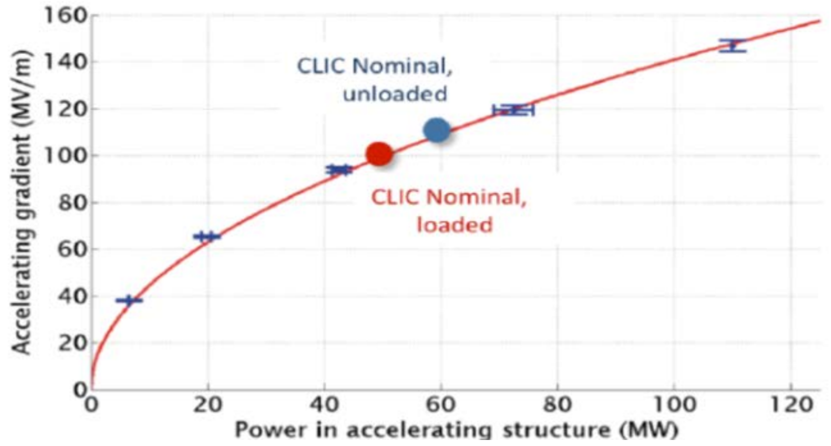
Demonstrated 2-beam acceleration



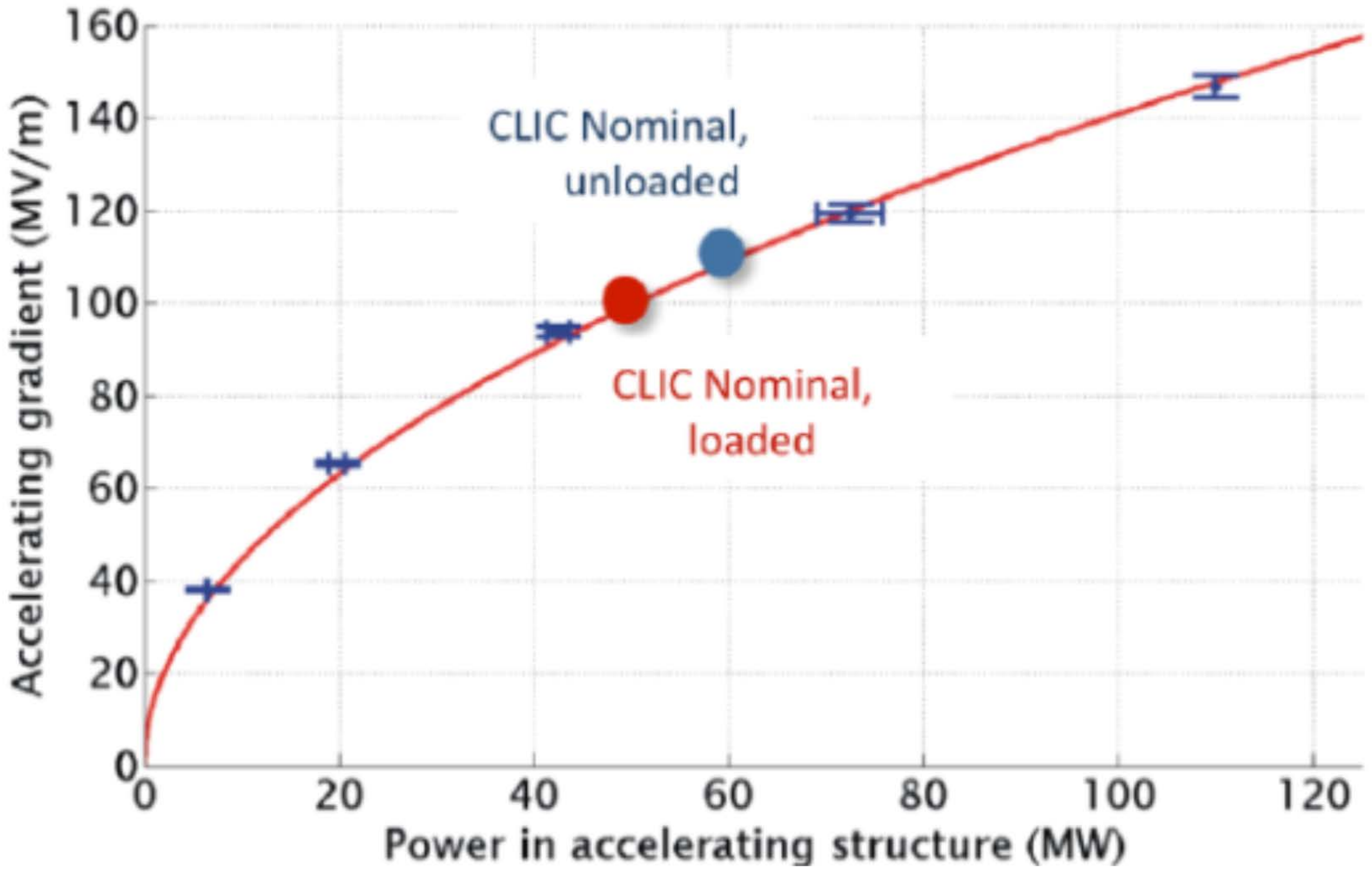


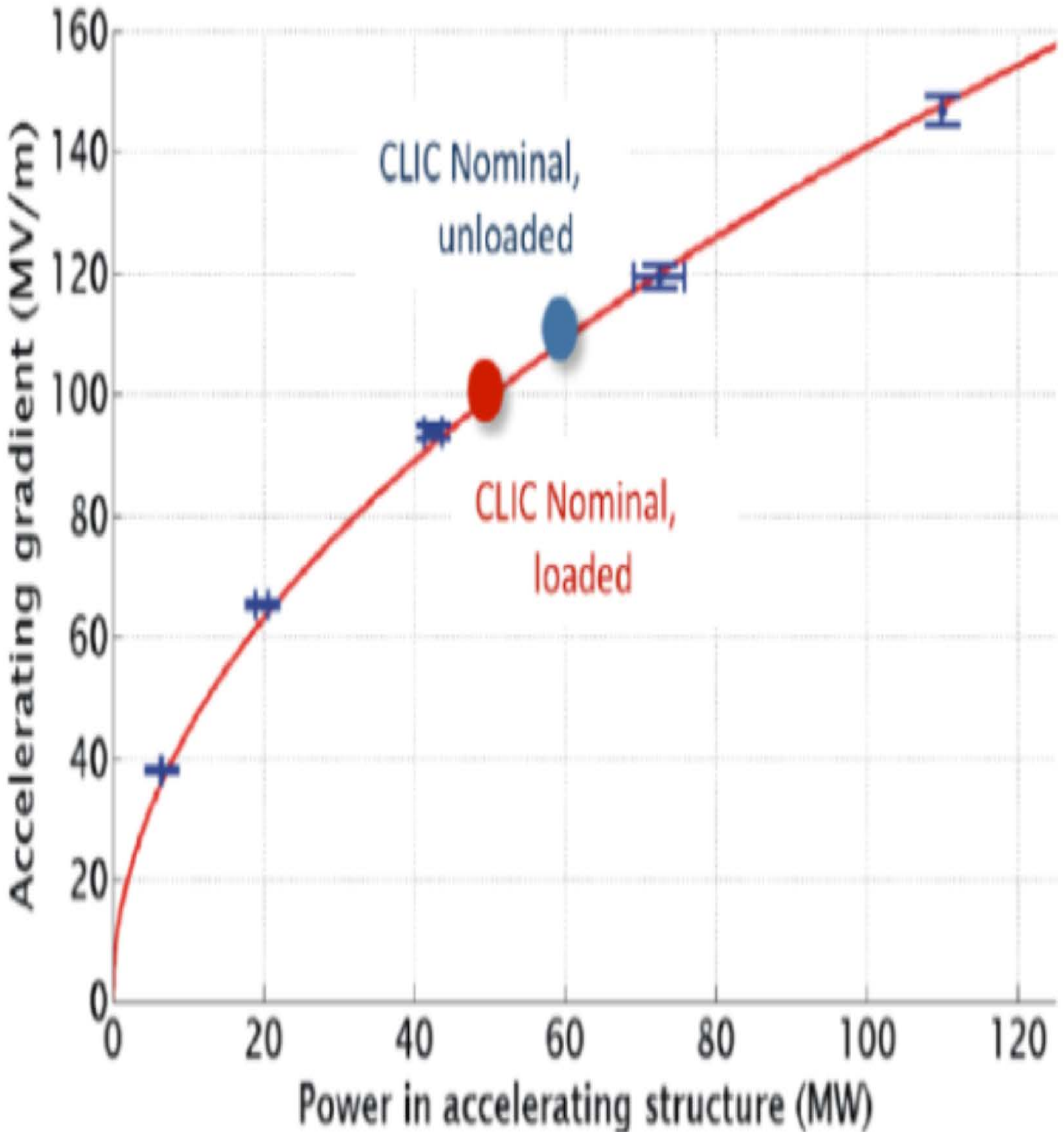






31MeV = 145MV/m





Technology spread

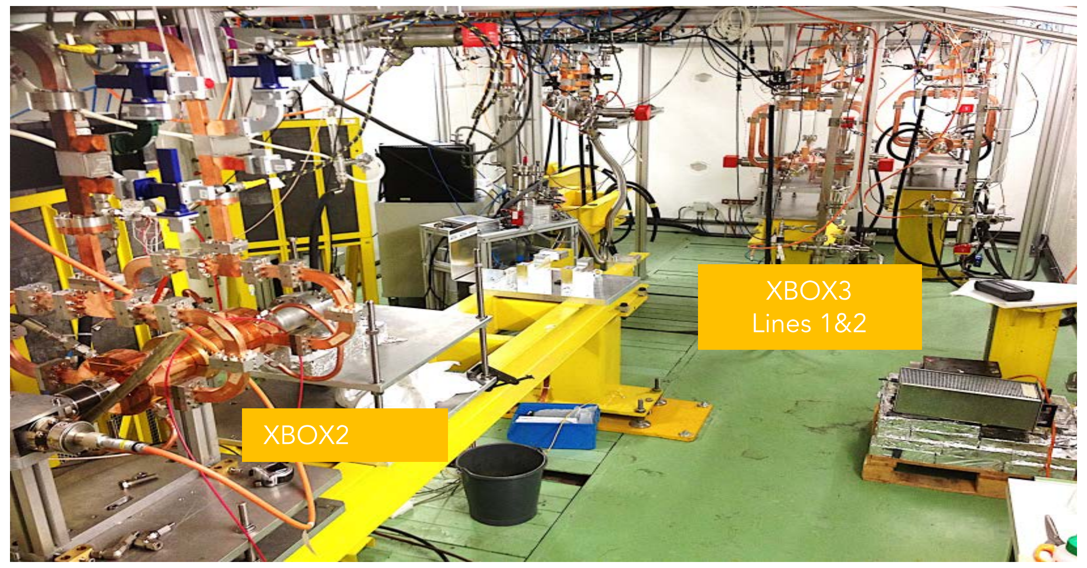
Prototype components

Laboratory with commercial
- Accelerating structures
- pulse compressors
- alignment
- stabilization
- etc.

Full commercial supply
- X-band klystrons
- solid state modulators
- etc.

Systems and 100 MeV-range facilities

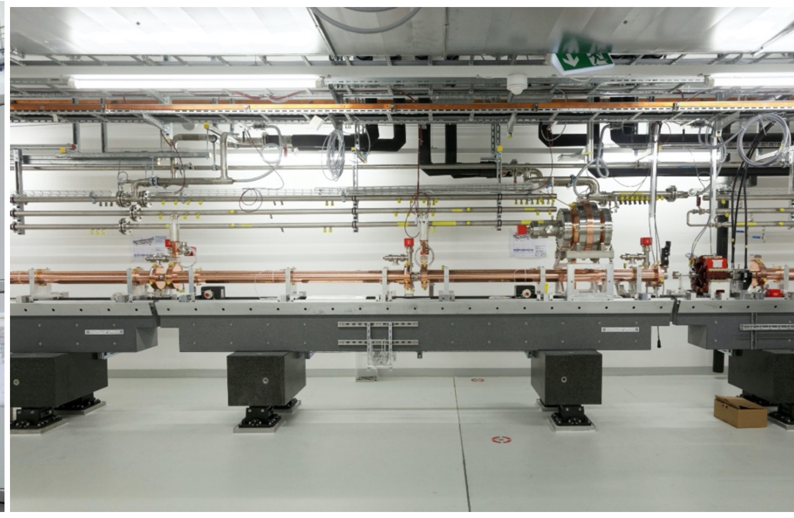
- XBoxes at CERN
- (NEXTEF KEK)
- Test stand at Tsinghua
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Deflectors at SLAC, Shanghai, PSI, DESY and Trieste
- NLCTA
- Smart*Light
- FLASH

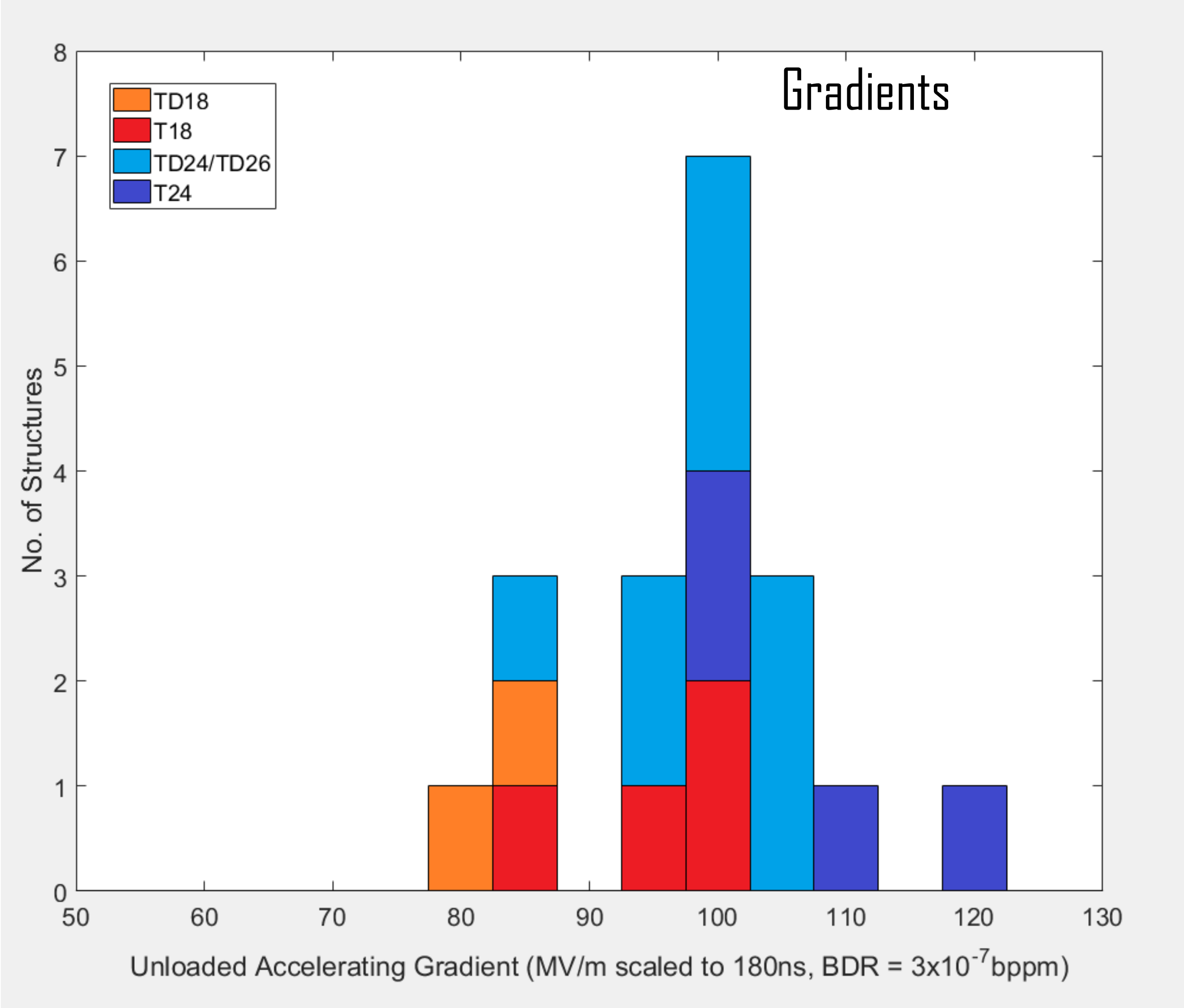


Normal-conducting, low- emittance GeV-range facilities

Operational
- SACLA
- SwissFEL

Swissfel: Specs similar, and reached





X-band GeV-range facilities

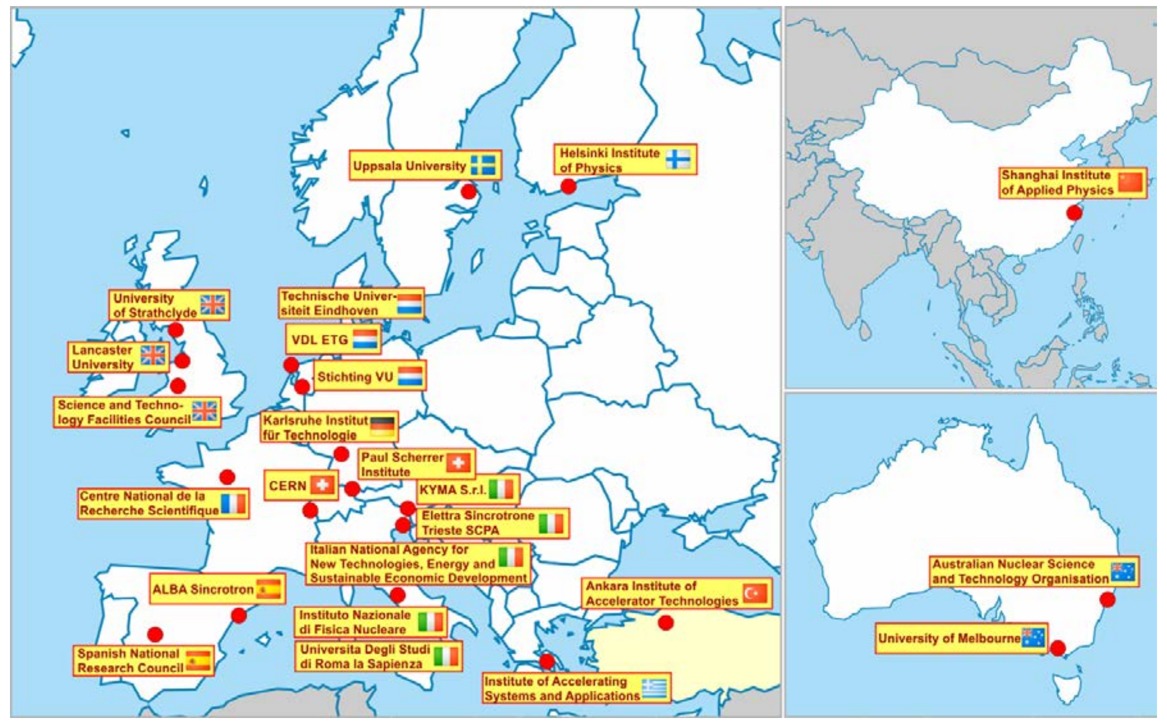
Planning:
- EU-Praxia
- eSPS
- CompactLight
- XARA

Technology spread

Photo: SwissFEL/PSI

SwissFEL: C-band linac

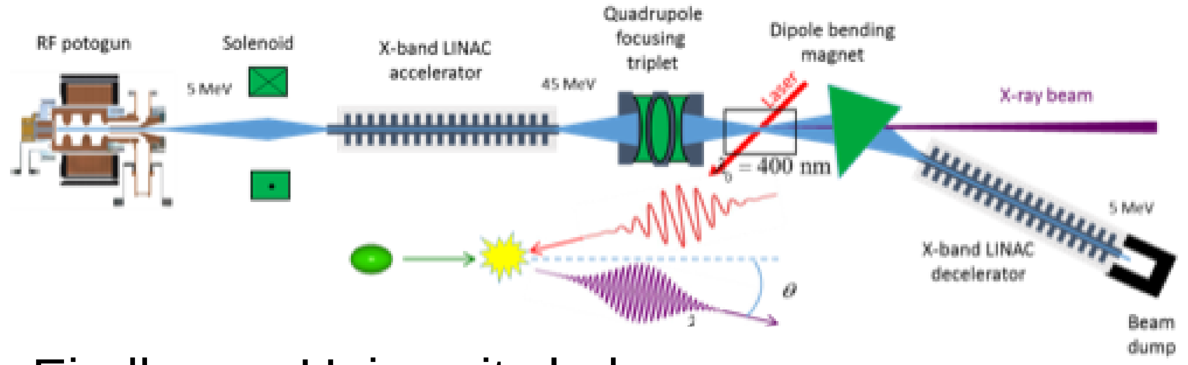
- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar µm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned



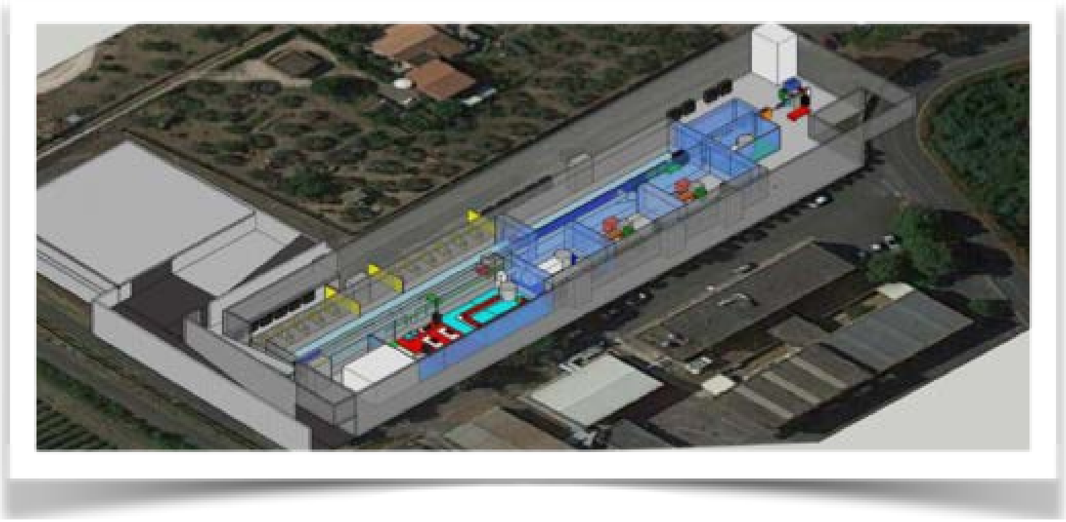
CompactLight

CLIC technology for different applications

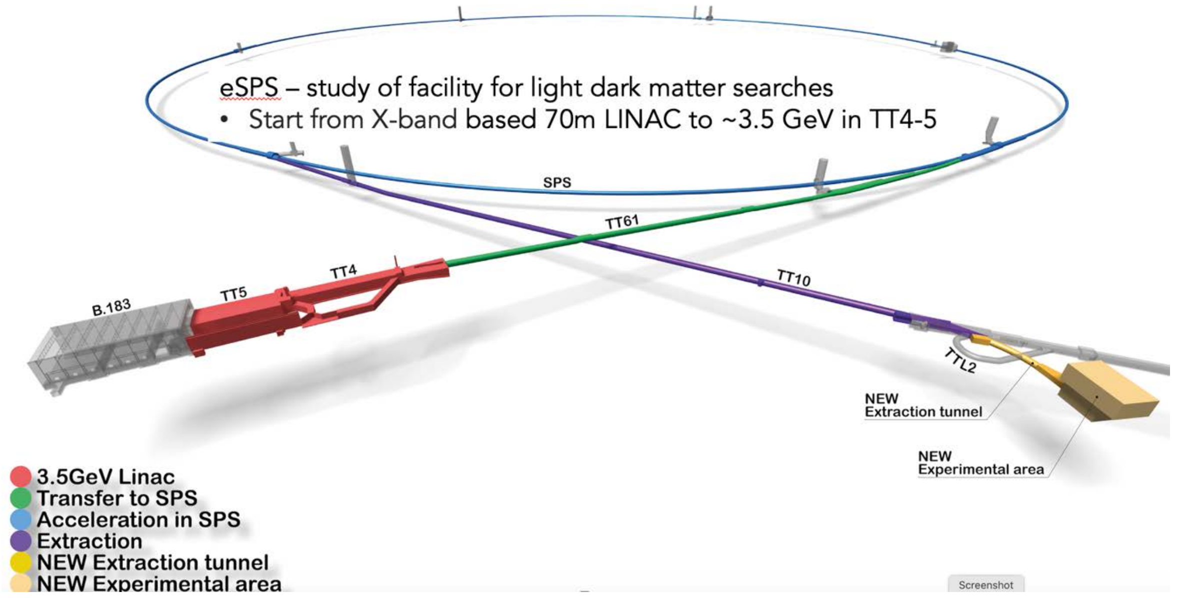
- EU co-funded FEL design study
- 1 GeV linac at INFN-LNF
- …many other small systems...



Eindhoven University led SMART*LIGHT Compton Source

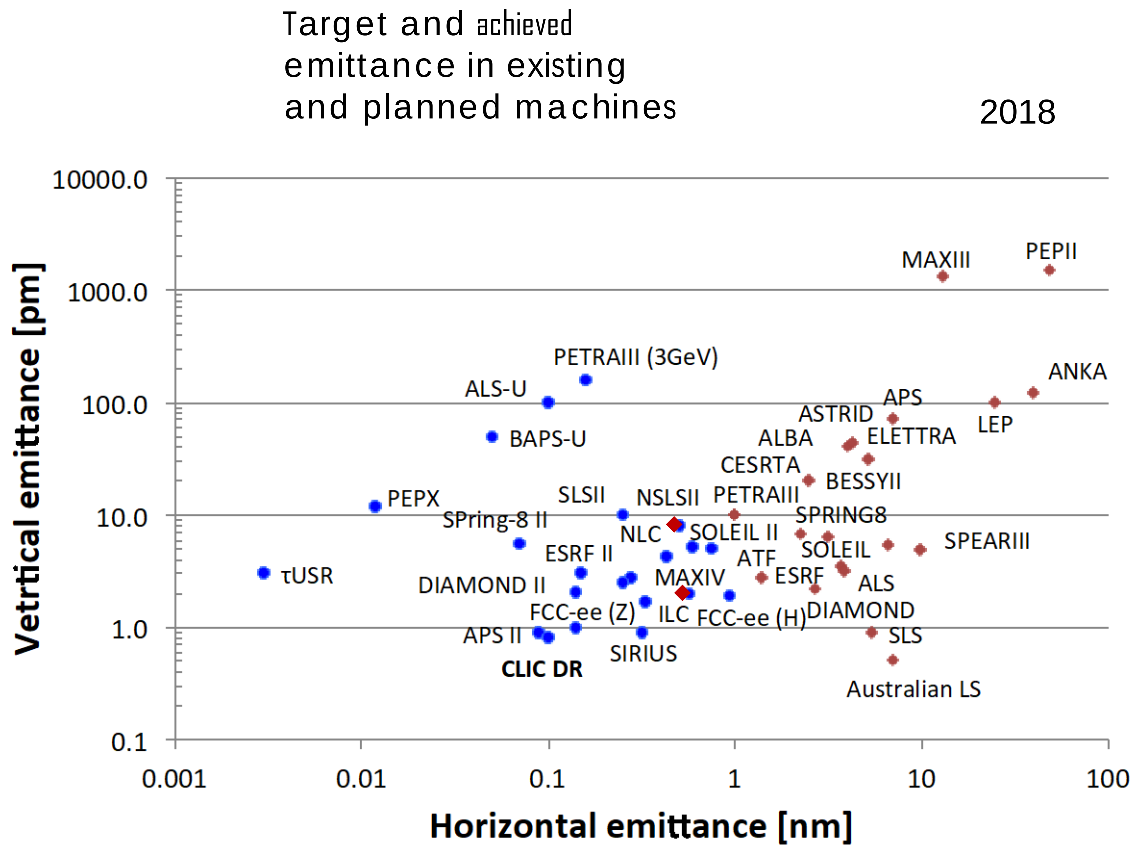


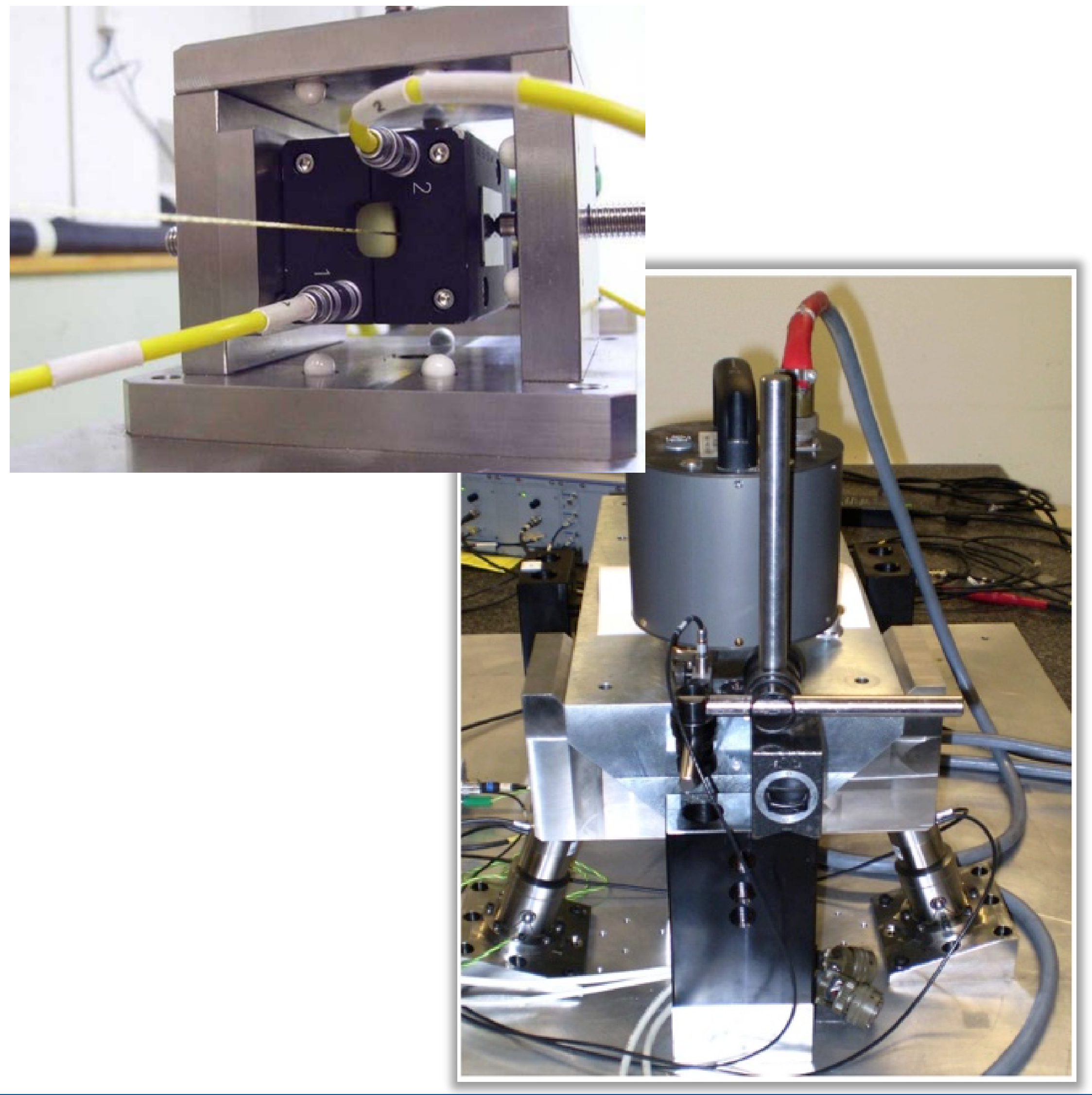
INFN Frascati advanced acceleration facility EuPRAXIA@SPARC_LAB



CERN: eSPS study (3.5 GeV X-band linac)

Low emittance generation and preservation





Low emittance damping rings

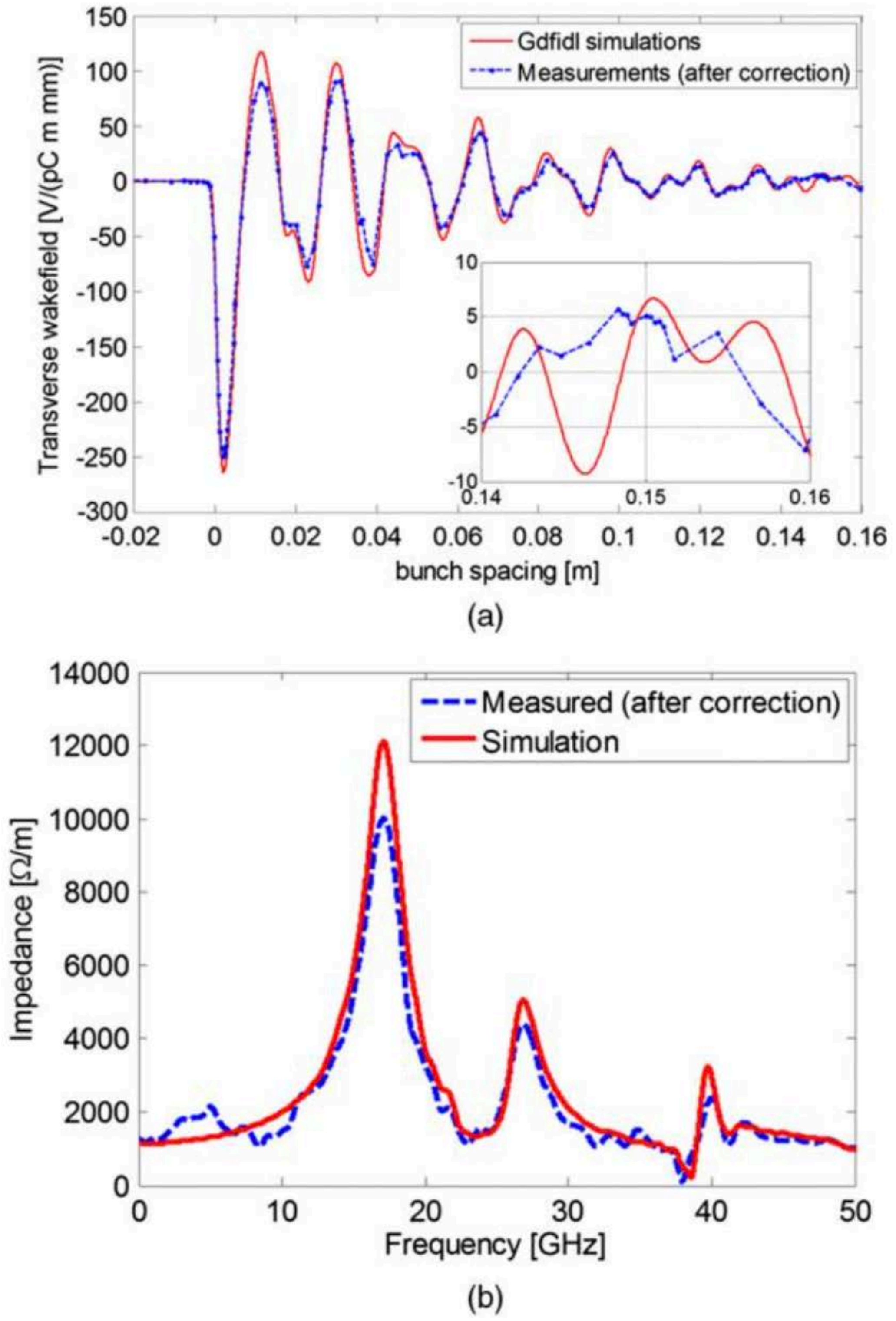
Preserve by

- Align components (10 μm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

iteration 0 iteration 1 iteration 3

Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.



Wake-field measurements in FACET

(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

CLIC studies 2019

CERN-2018-005-M CERN-2018-009-M CERN-2018-010-M CERN-2019-001

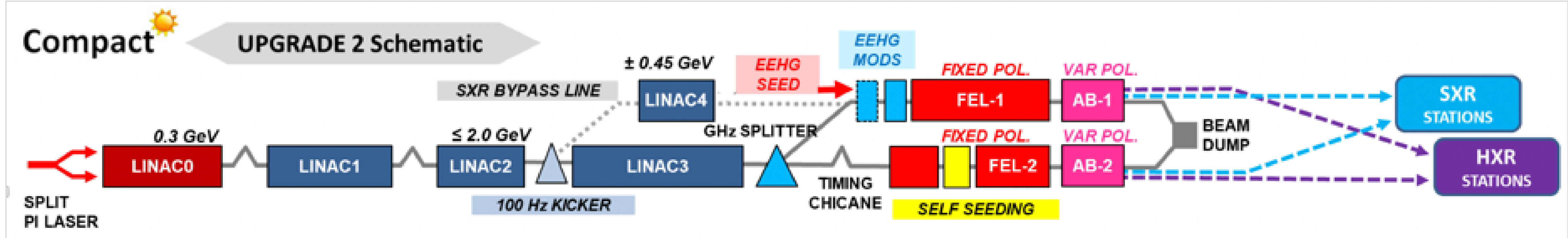
CLIC EPSS input – including background papers – completed end 2018/early 2019, widely presented in 2019

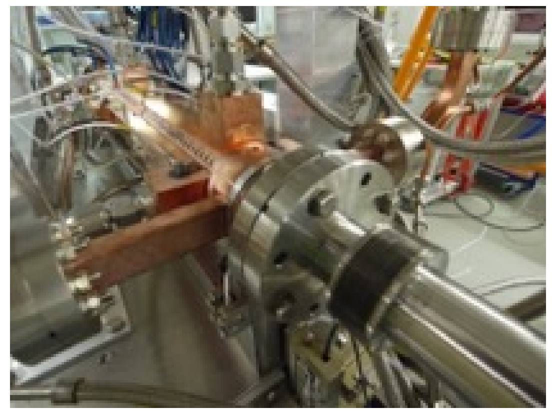
- Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma (CLIC-note)
- Further studies of positron production and beam delivery system for improved performance

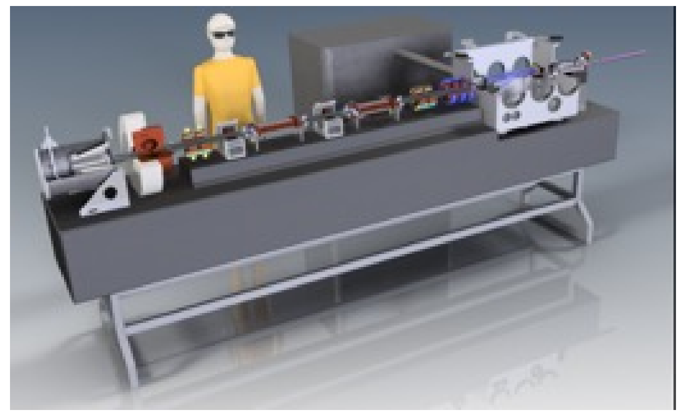
Technical and experimental studies:

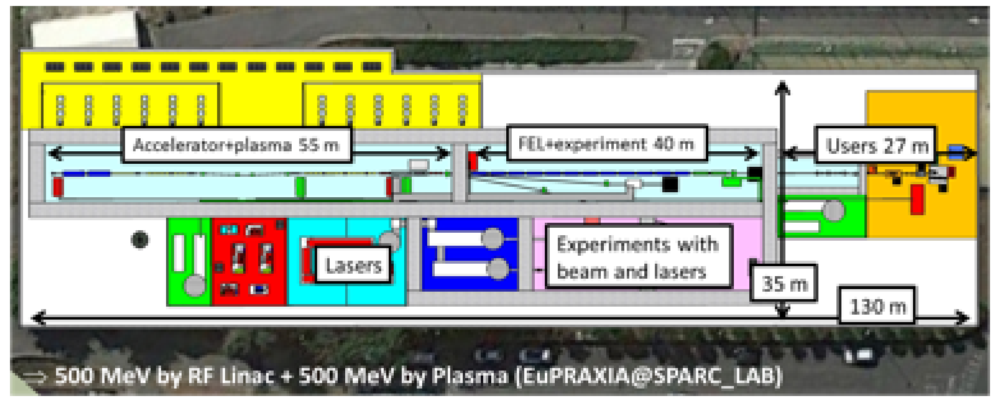
- Xbox (test-stand) meas./optim. of X-band components
- CLEAR activities (instrumentation, irradiation, plasma focusing, THz, wakefields, medical acc., training)
- High efficiency klystrons, module studies

More on: Xboxes, CLEAR, High Eff RF









⇒ 1 GeV by high gradient RF Linac only (EuSPARC)

Application of X-band technology (examples):

- A compact FEL (CompactLight: EU Design Study 2018-20)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF
- eSPS for light dark matter searches (within the PBC-project)

More information: Overview talk, CompactLight

After Granada

Three questions:

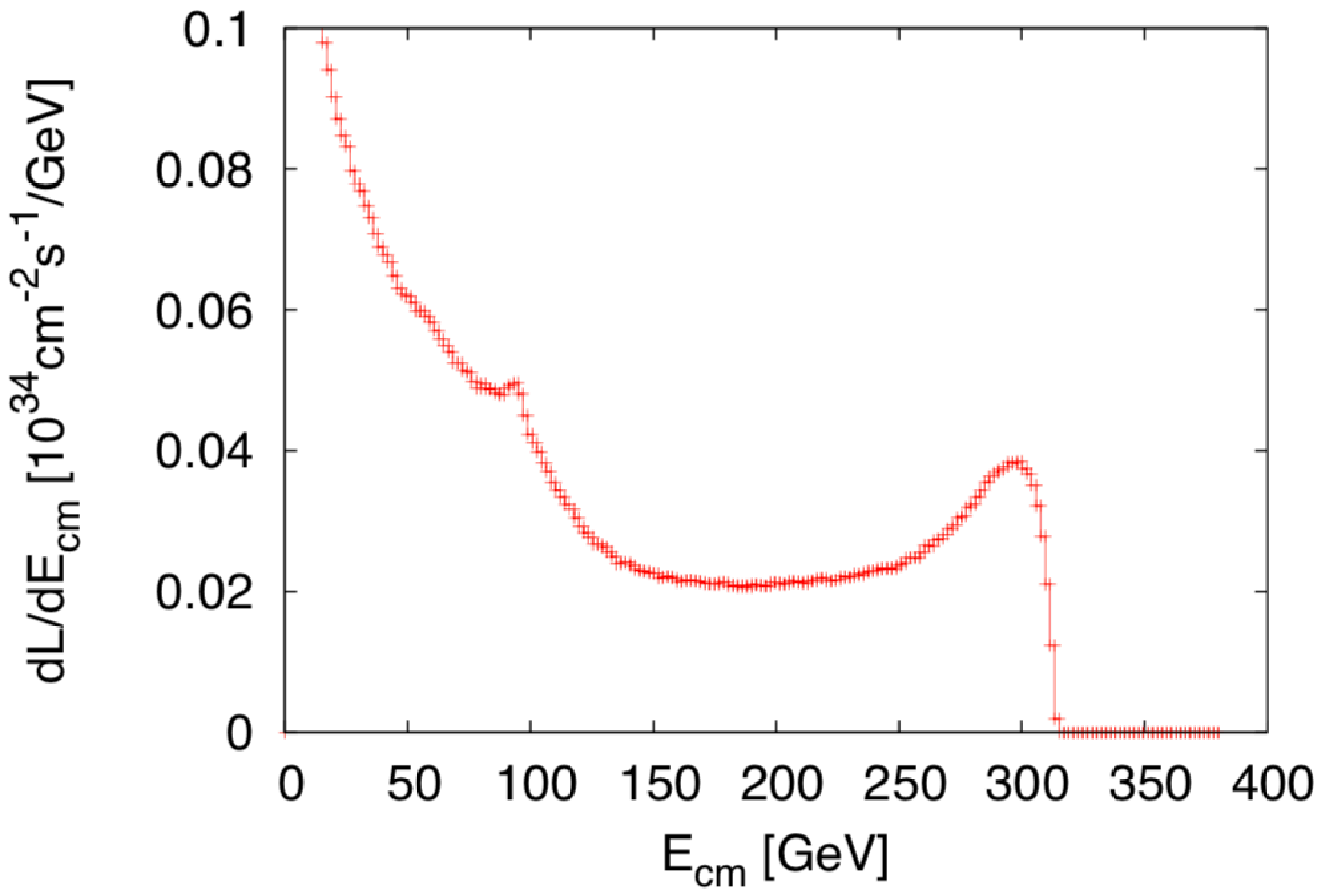
- Z pole performance, $2.3 \times 10^{32} - 0.4 \times 10^{34}\ cm^{-2}\ s^{-1}$
  - The latter number when accelerator configured for Z running (either early or end of first stage)

- Gamma – Gamma spectrum (example)

- Luminosity margins and increases
  - Baseline includes estimates static and dynamic degradations from damping ring to IP: $1.5 \times 10^{34}\ cm^{-2}\ s^{-1}$, a "perfect" machine will give : $4.3 \times 10^{34}\ cm^{-2}\ s^{-1}$, so significant possibilities for doing better

  - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of +50 MW and ~5% cost increase

- Note at: http://cds.cern.ch/record/2687090



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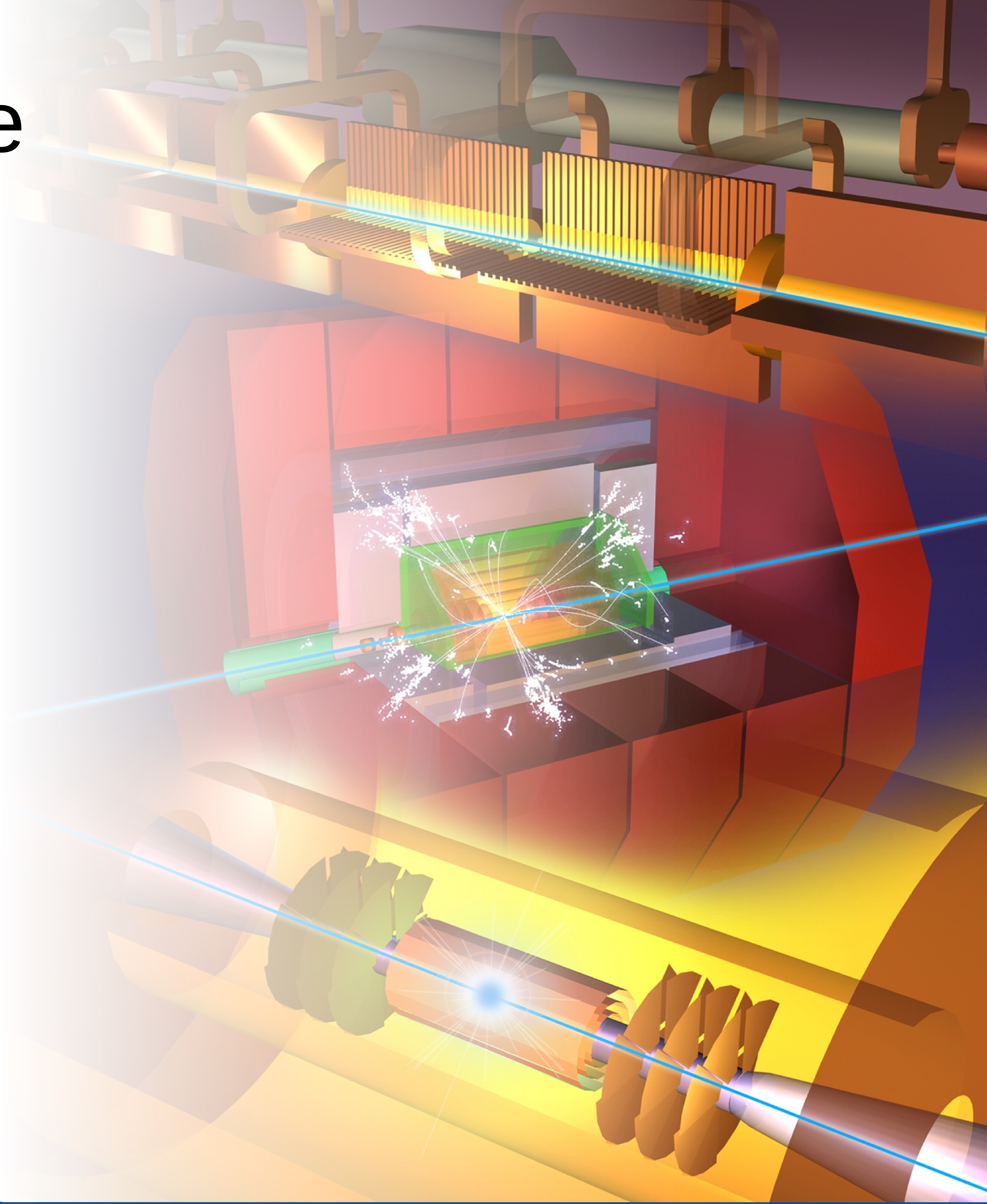
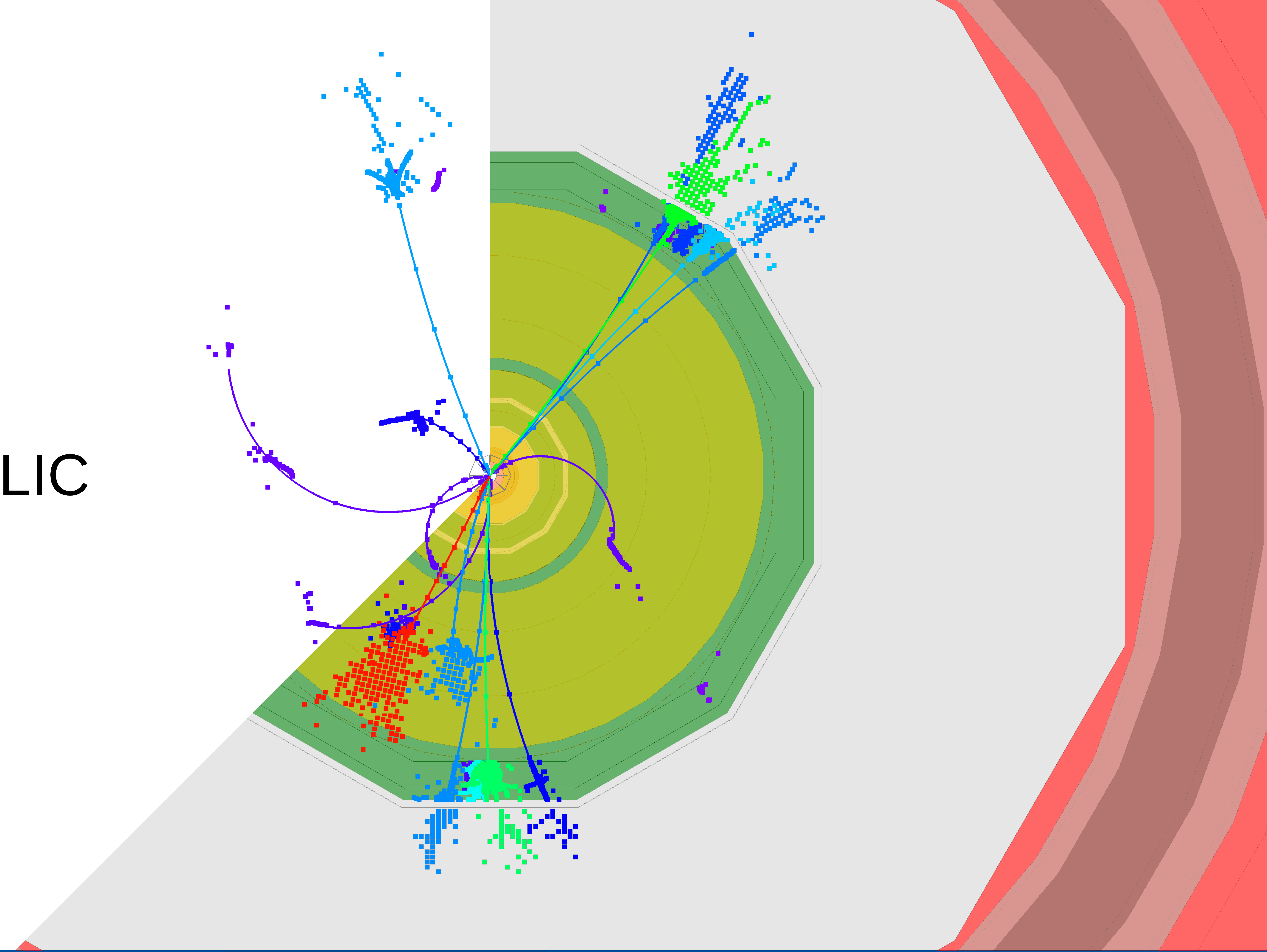
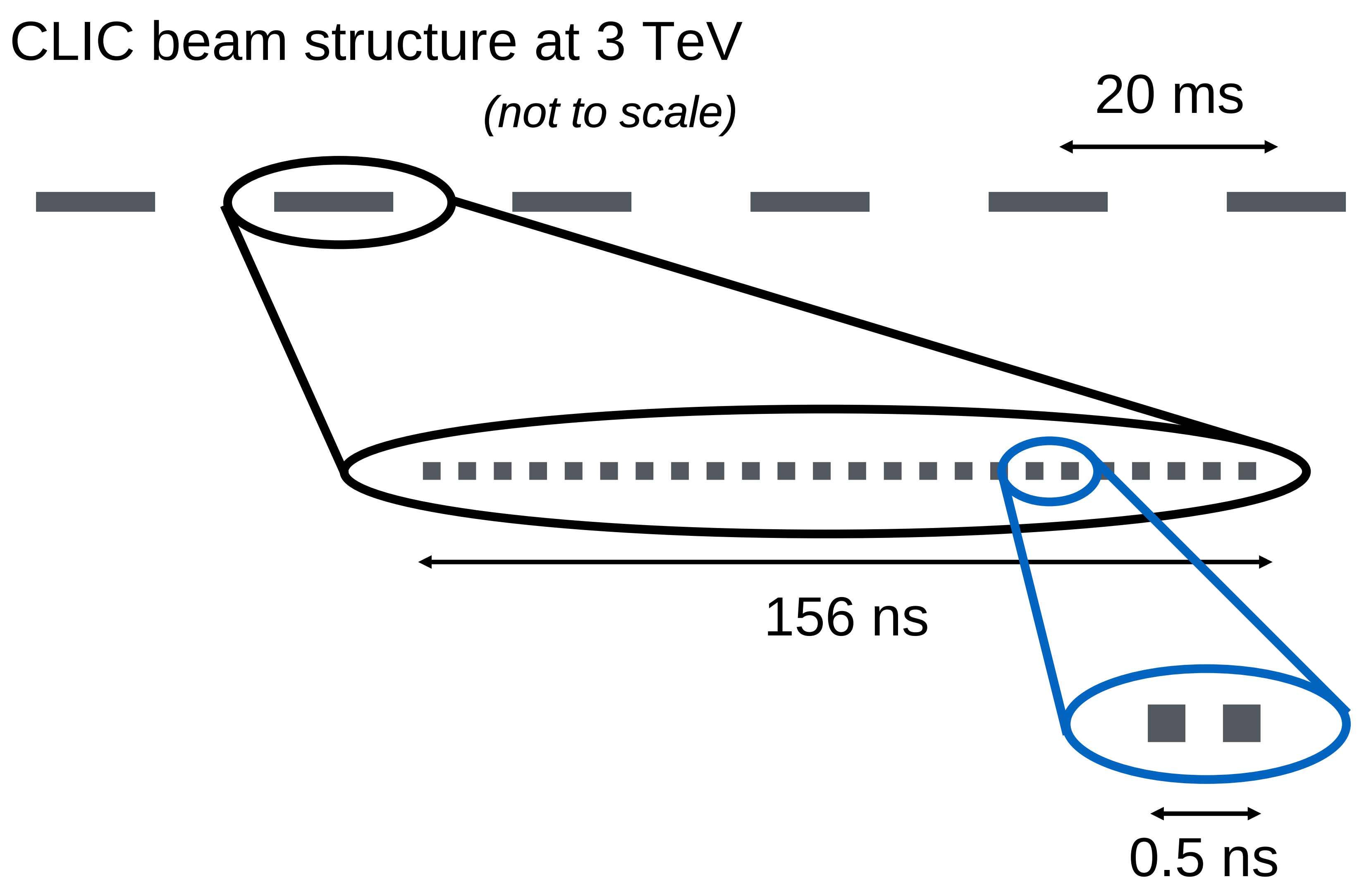


A detector for CLIC

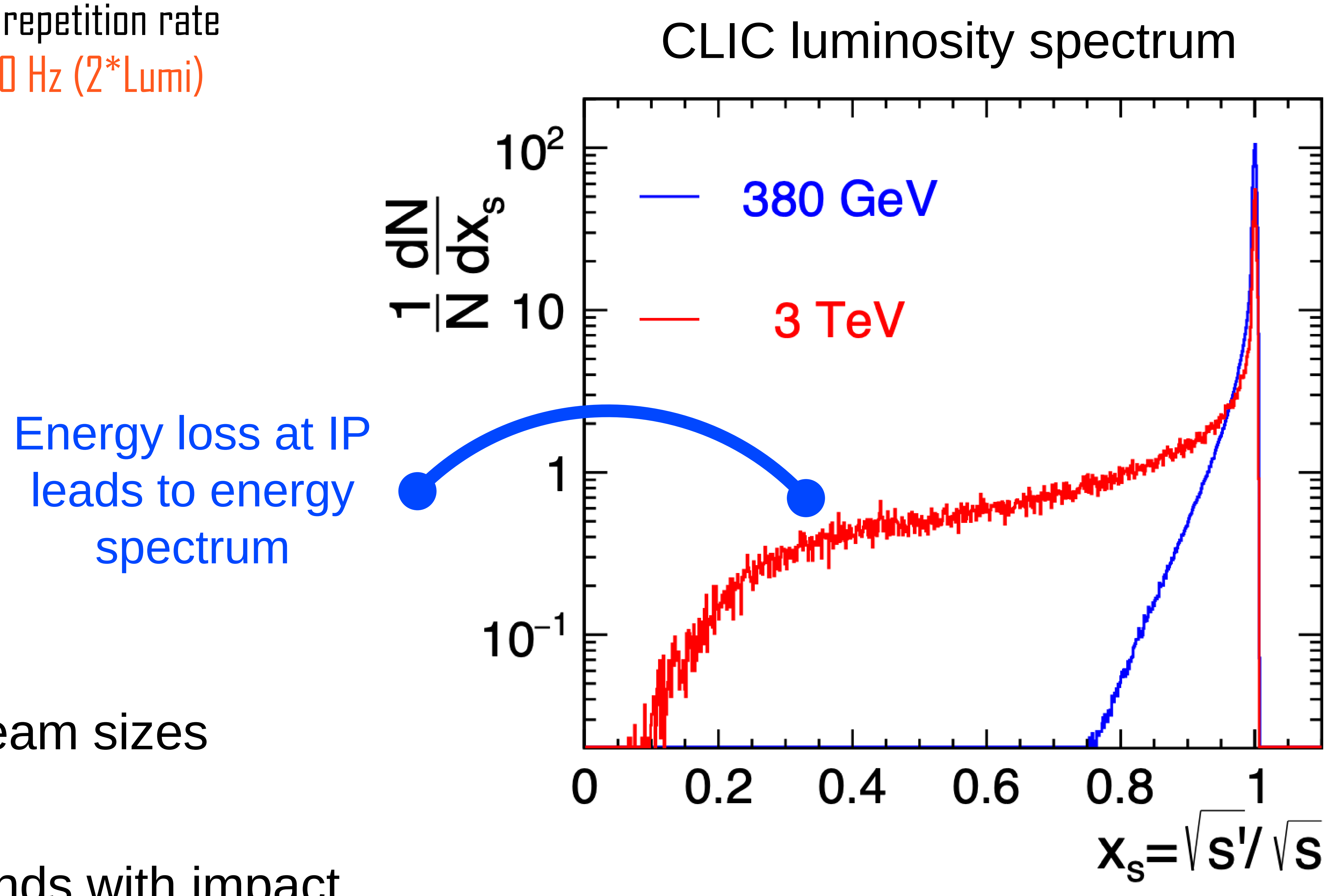
(slides from recent talk of R.Ström)



Collider environment



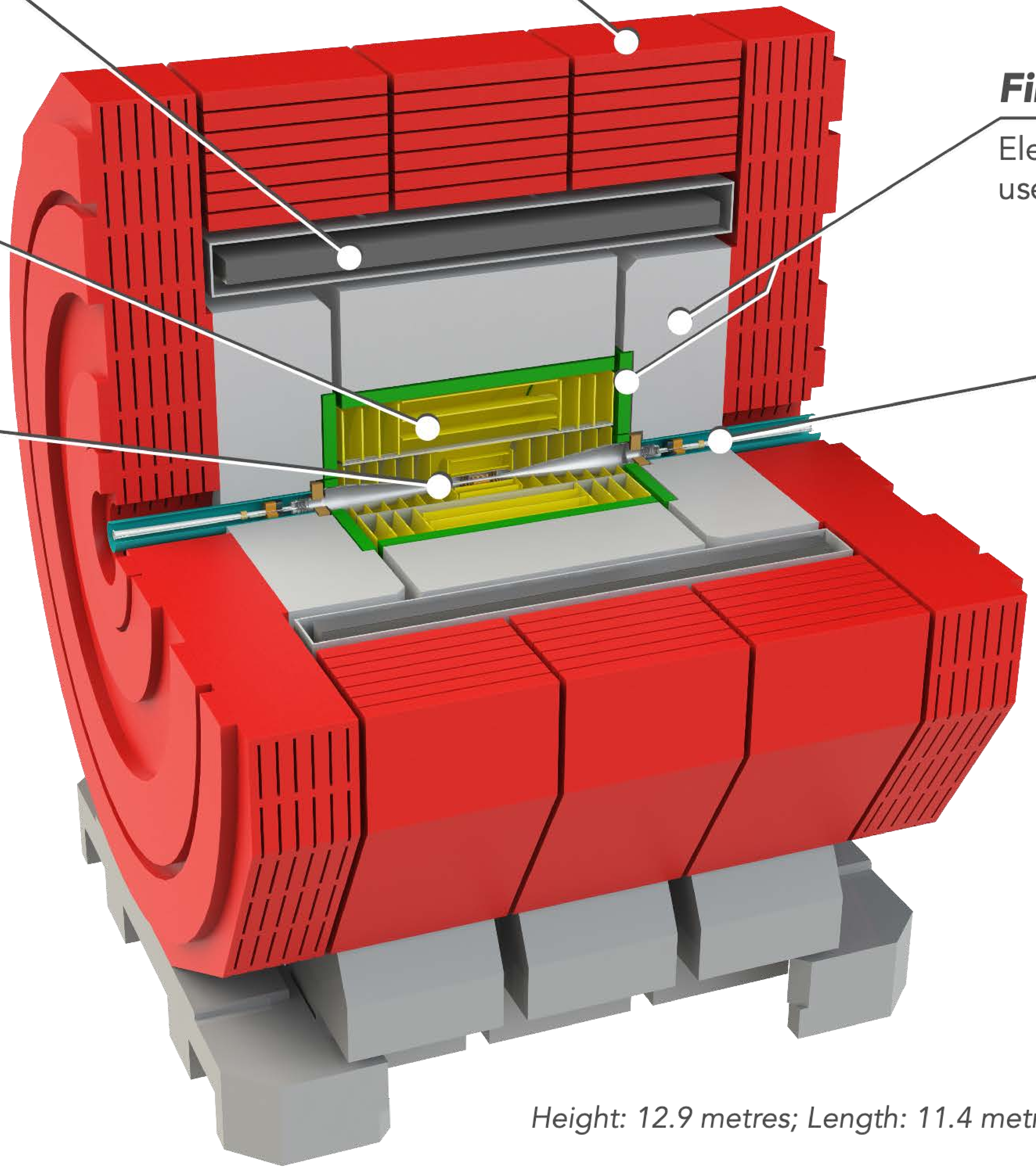
50 Hz bunch train repetition rate
Update studied: 100 Hz (2*Lumi)
(note)



- High luminosities are achieved by using extremely small beam sizes
- 3 TeV: bunch size $\sigma_{x;y;z}$ = {40 nm; 1nm; 44 μm}
- Very high bunch charge density → beam-related backgrounds with impact on detector design and physics measurements
- Small effect at 380 GeV, large effect at high energies
- Combined p_T and timing cuts used to reduce out-of-time background (~ns timing required for beam background rejection)

- Most physics process studied well above production threshold; profit from full luminosity
- The impact of ISR is similar to that of beamstrahlung

The CLIC detector model



Tracking detector
Material: 1–2% X_0 / layer
Single-point resolution: 7 micrometres

Vertex detector
25 micrometre pixels
Material: 0.2% X_0 / layer
Single-point resolution: 3 micrometres
Forced air-flow cooling

Electromagnetic calorimeter
40 layers (silicon sensors, tungsten plates)
Material: 22 X_0 + 1 λ_I

Hadronic calorimeter
60 layers (plastic scintillators, steel plates)
Material: 7.5 λ_I

Learn more about the CLIC detector at clic.cern

Height: 12.9 metres; Length: 11.4 metres; Weight: 8100 tonnes

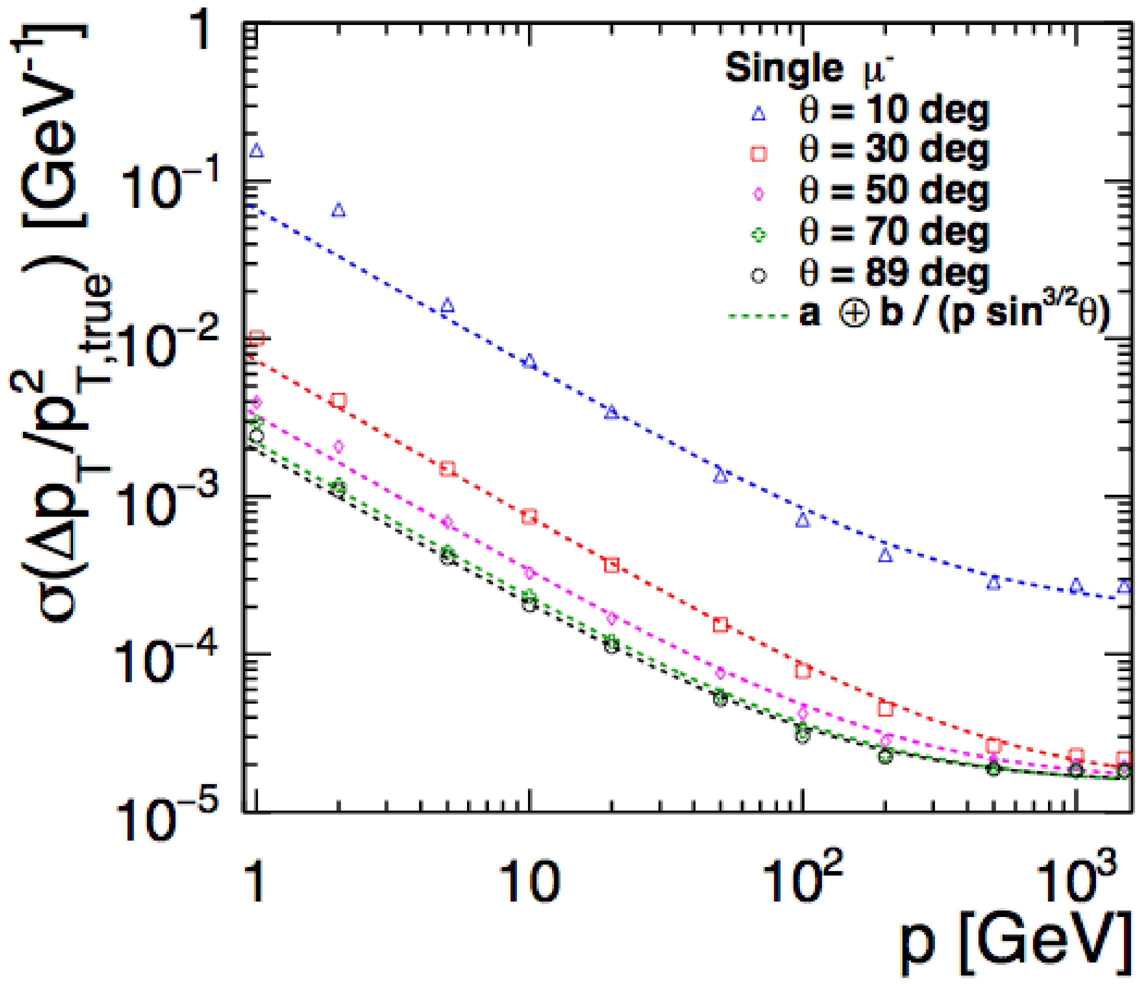
- CLIC’s baseline is a single interaction point/single experiment
- Two detectors in push-pull mode possible
- Two beam-delivery systems and two interaction points possible at 380 GeV

clic

CLICdp June 2019

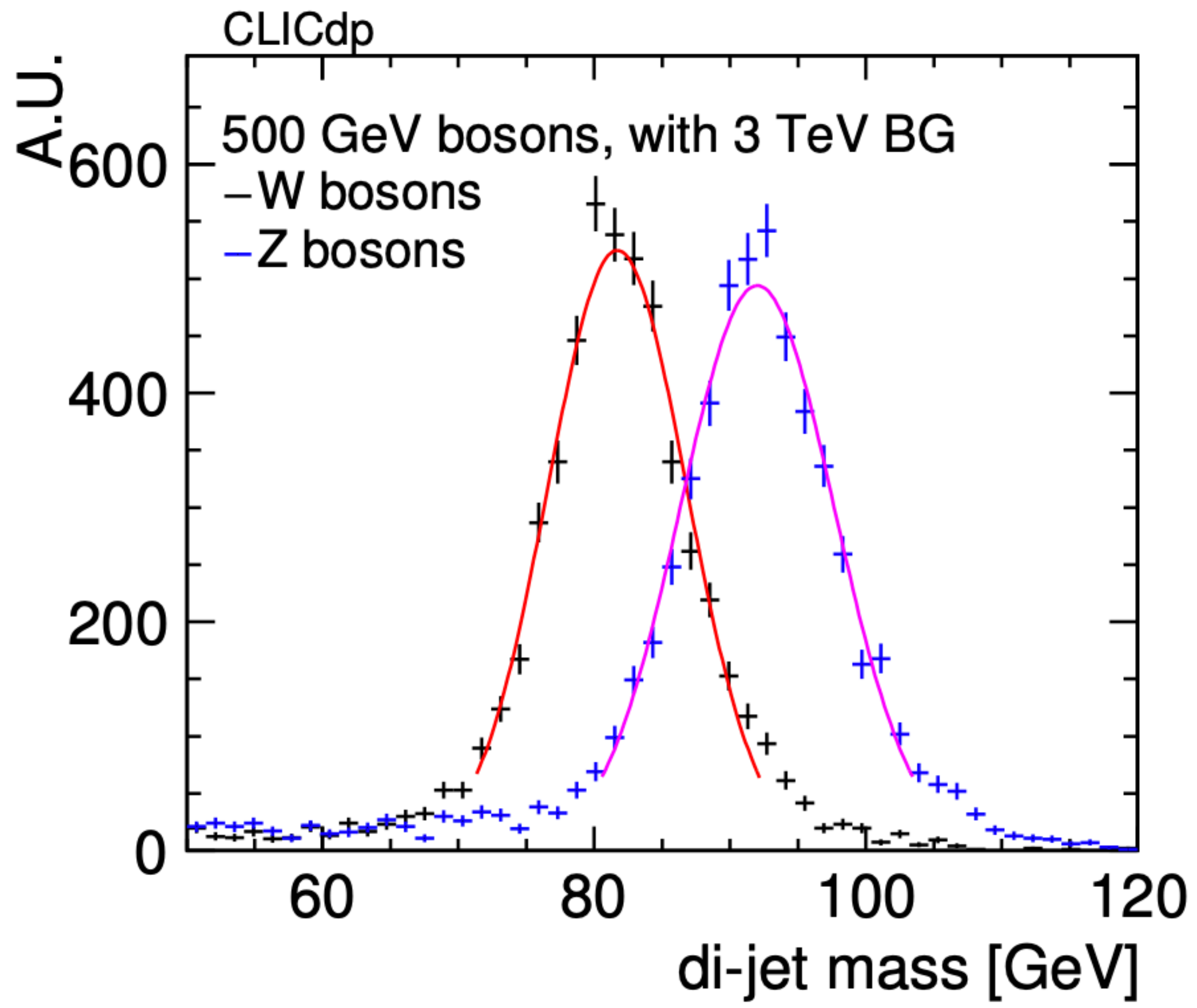
CLICdet Performance

Full characterisation of the detector model in arXiv:1812.07337

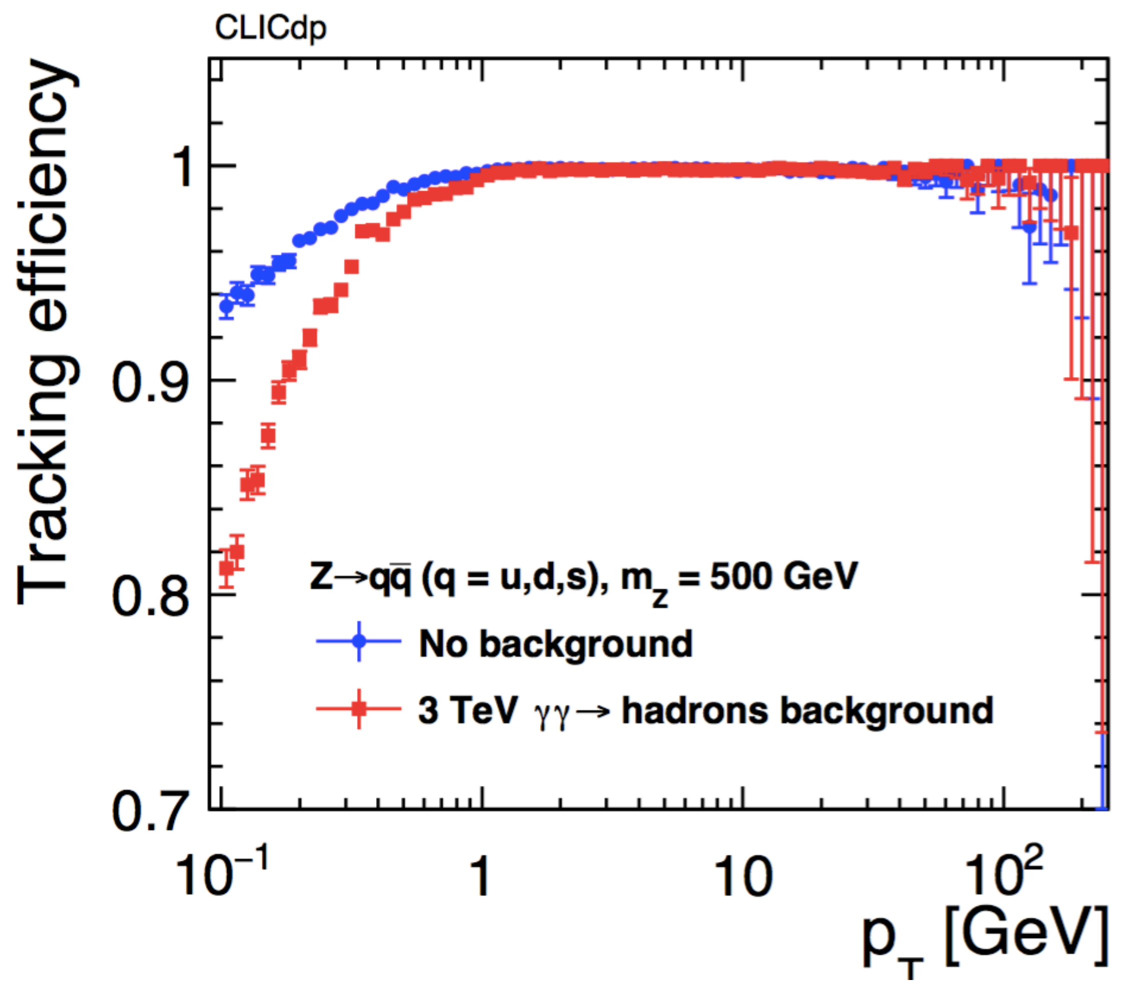


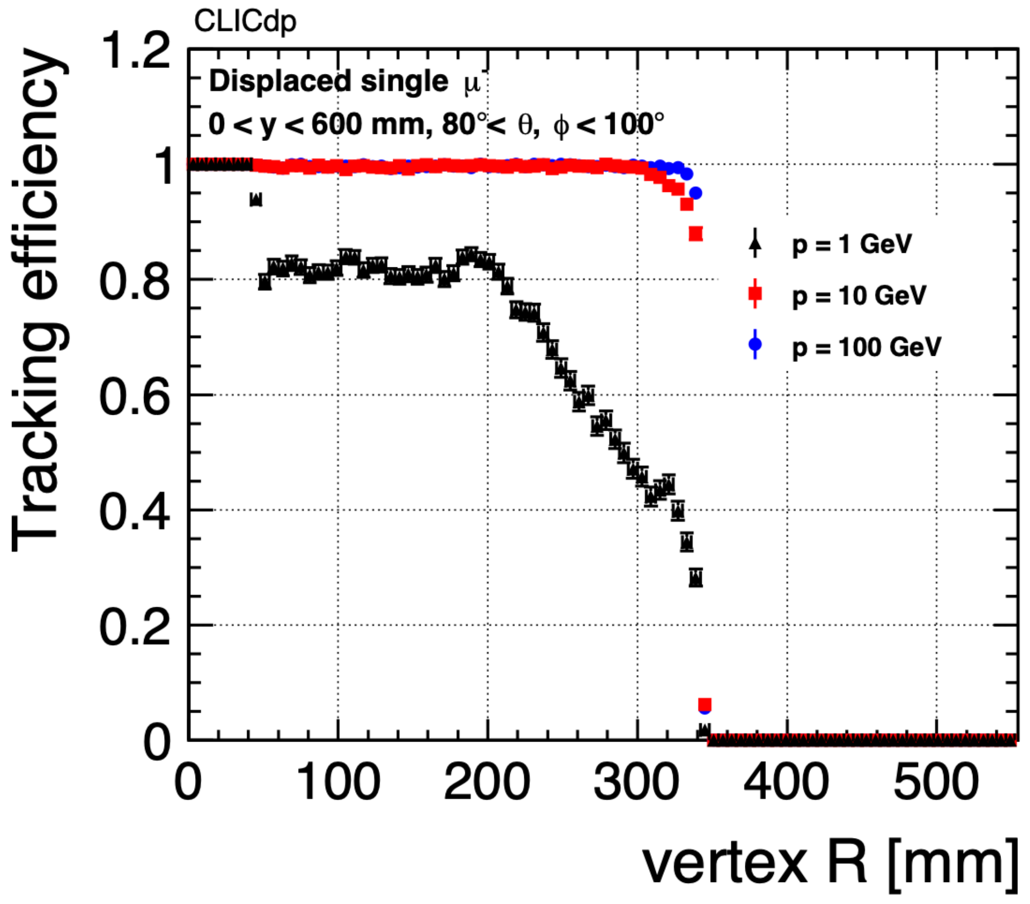
performance goal: 2×10^{-5}

Achieve jet energy resolution target in presence of beam backgrounds

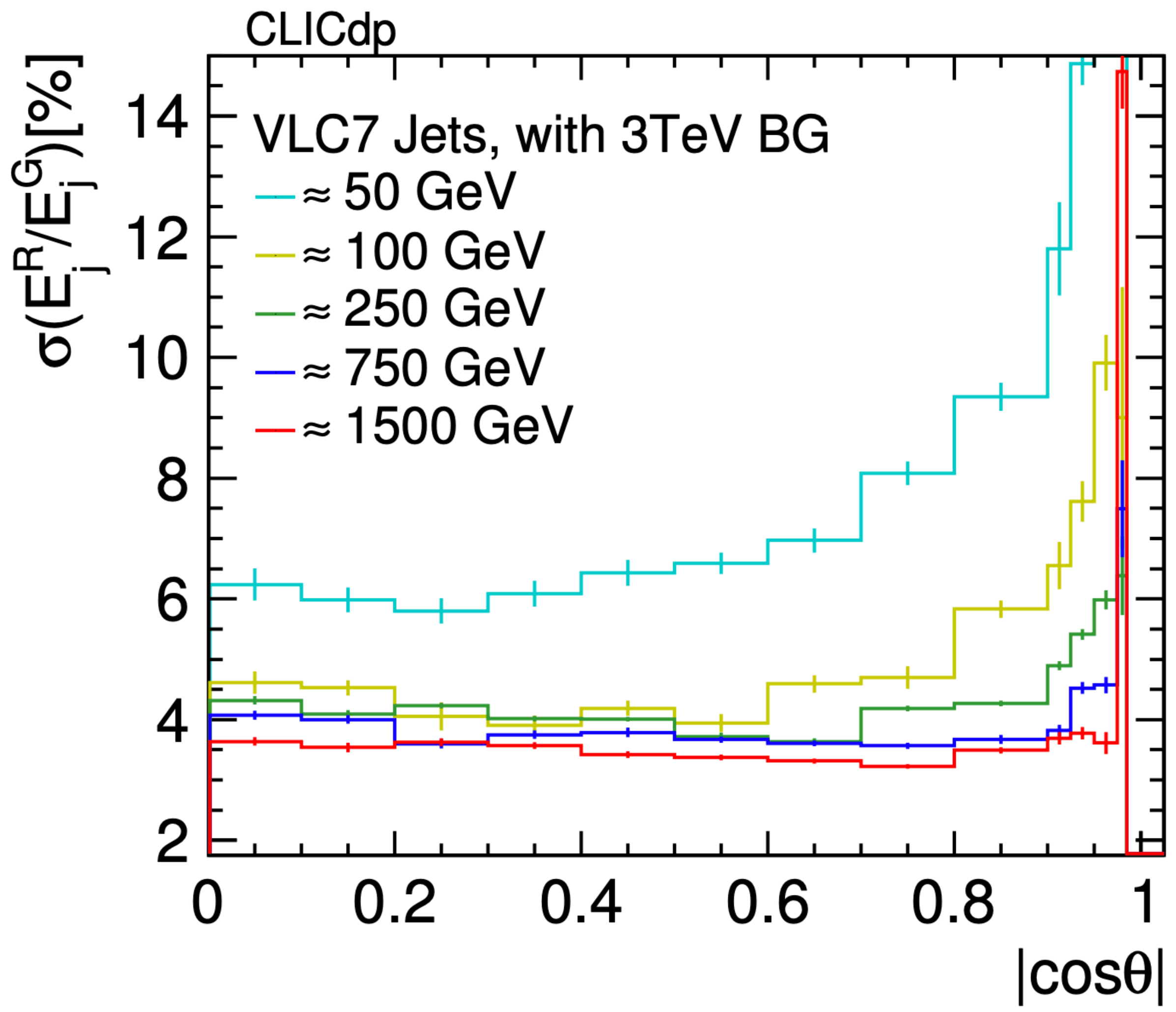


Displaced track reconstruction





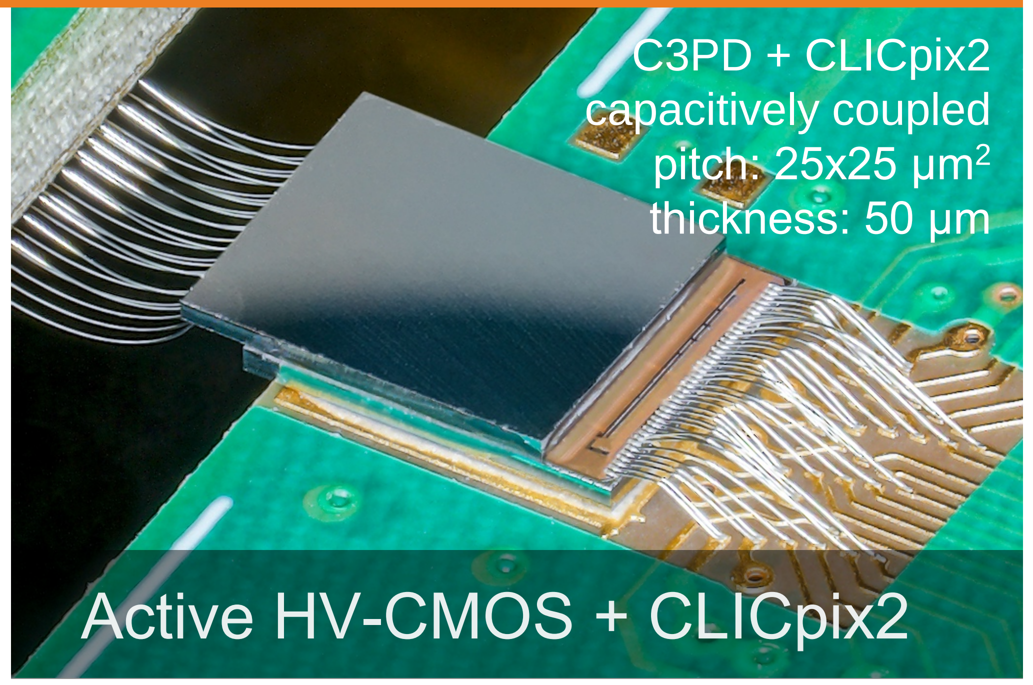
Software tools developed/ maintained by the CERN group and widely used



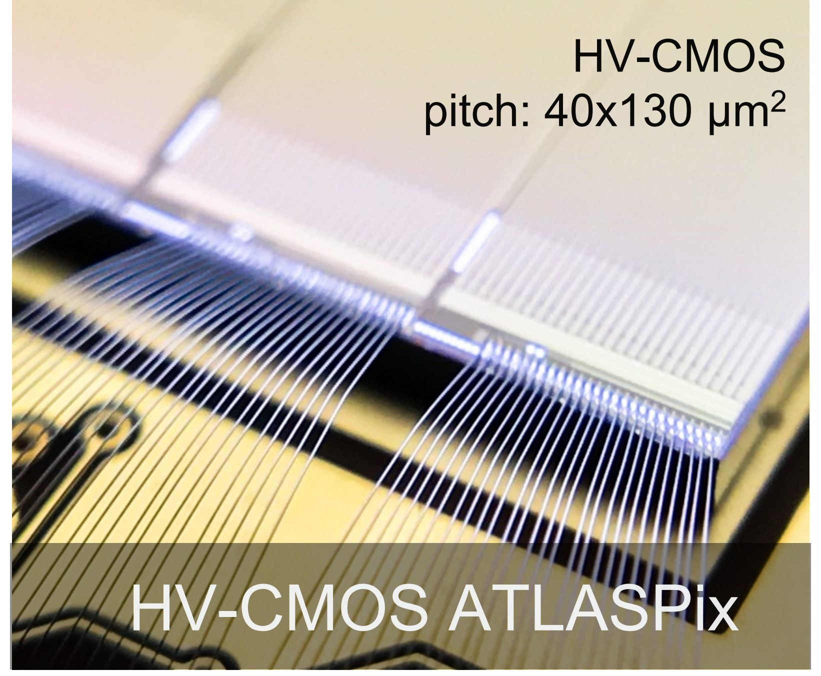
Vertex and tracking R&D

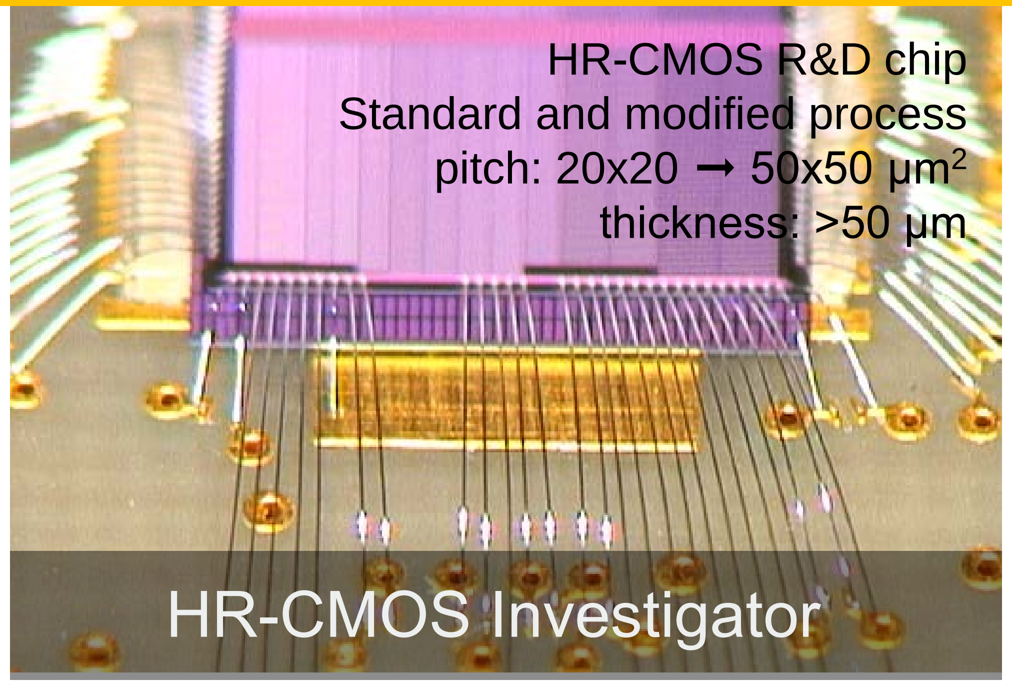
Highlights

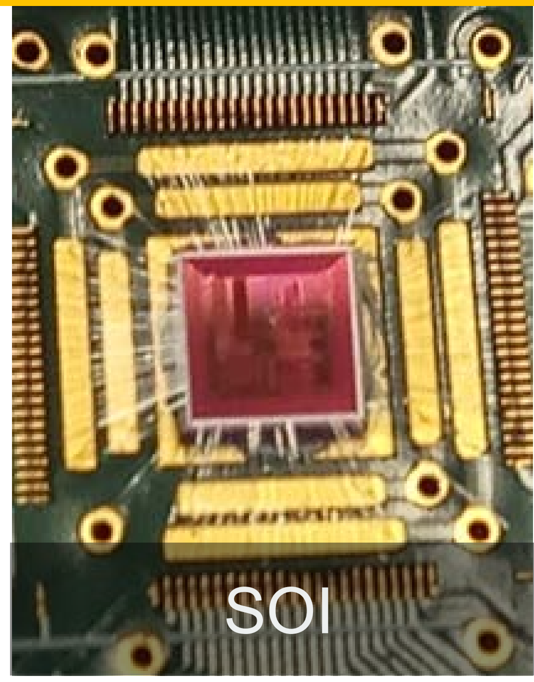
Hybrid assemblies



Monolithic assemblies





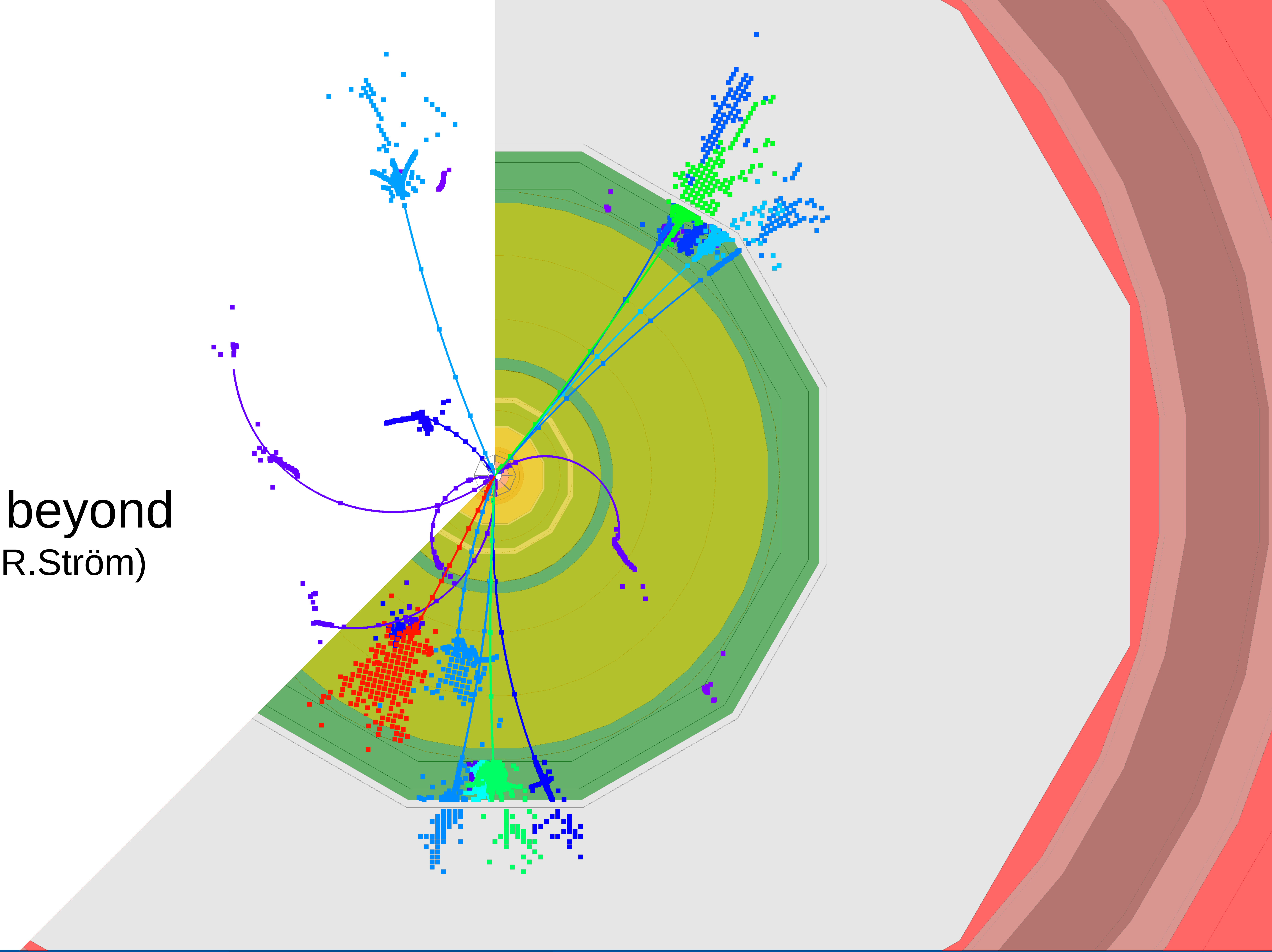


- Full efficiency from hybrid assemblies of 50 μm thin sensors that satisfy CLIC time-stamping
- Sensor design with enhanced charge-sharing is underway to reach required spatial resolution with thin sensors
- Good progress towards reducing detector mass with active-edge sensors and through-Si interconnects
- Promising results from fully integrated technologies
  - CLIC-specific designs underway
- Developed advanced simulation/analysis tools for detector performance optimisation (Allpix^2)

Physics reach

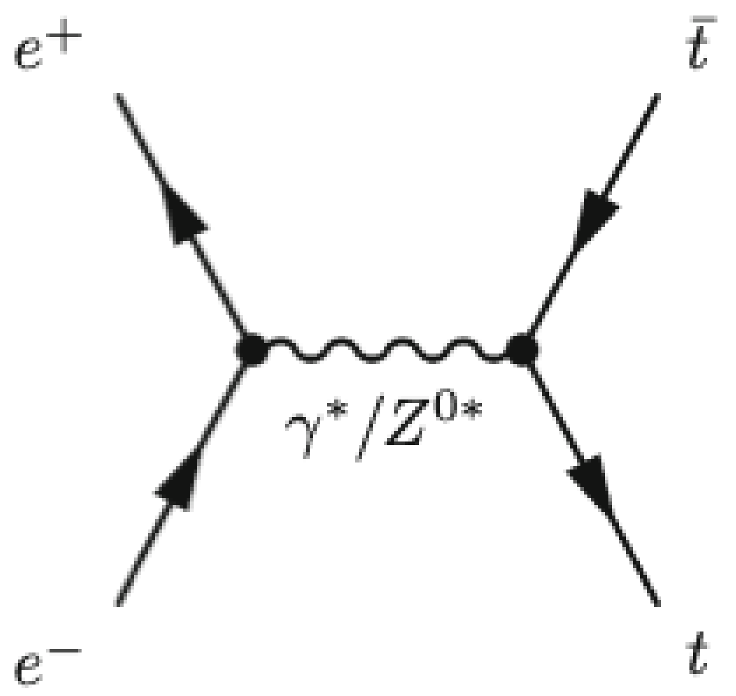
Standard Model & beyond

(slides from recent talk of R.Ström)

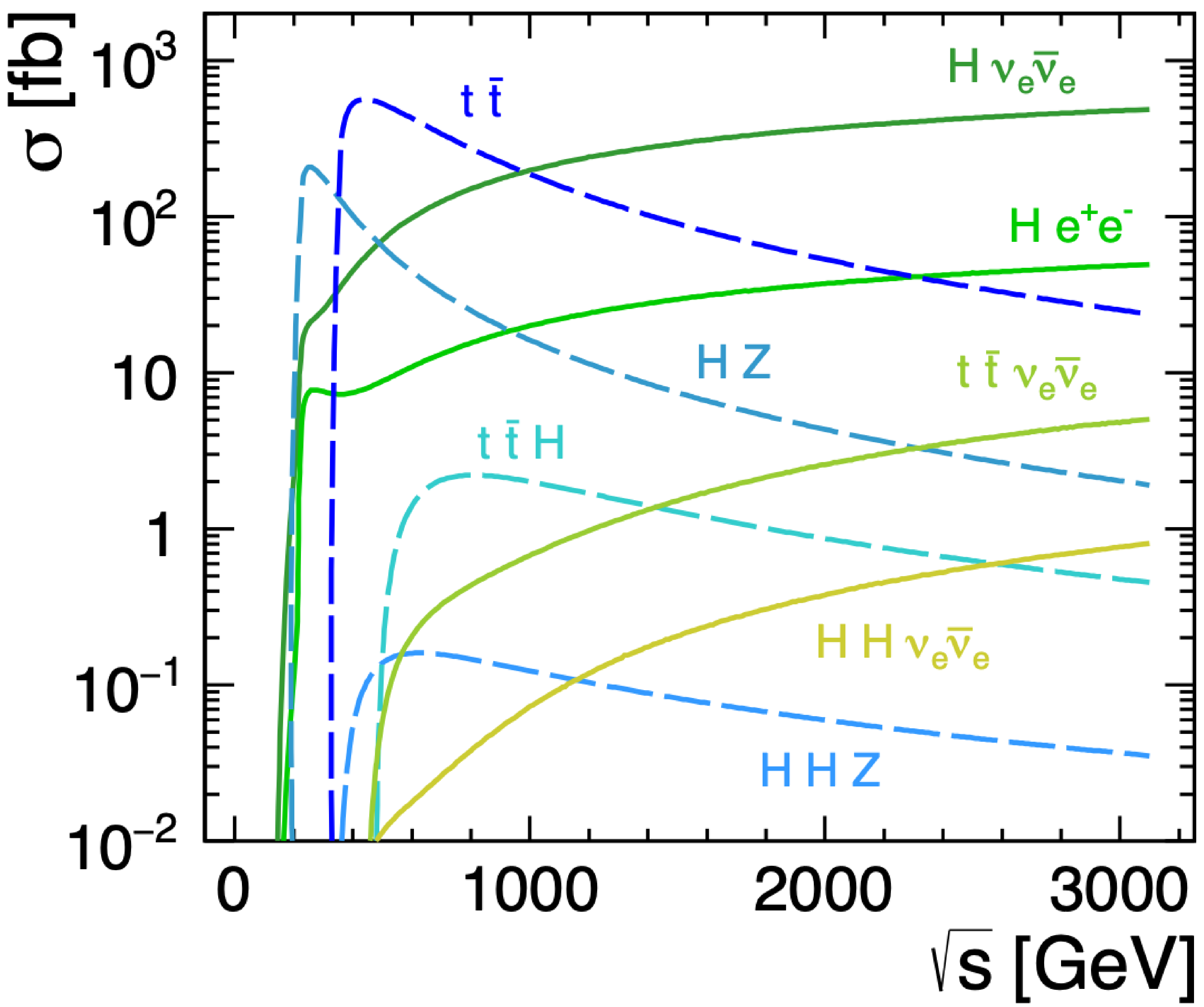


Dominant Higgs and top production at CLIC

- Top-quark pair production > 2.5 million top-decays, detailed study of couplings and competitive limits on rare decays (FCNC)
- Dedicated top-pair production threshold scan at 350 GeV – top-quark mass with a precision of around 50 MeV (100 fb^{-1})



@LO incl. ISR, unpolarised

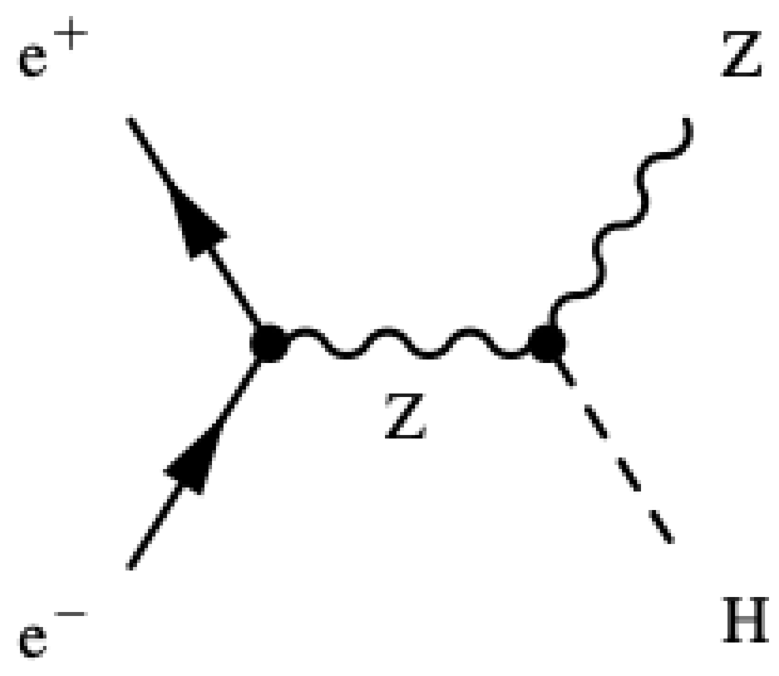


380 GeV
1 ab^{-1}

1.5 TeV
2.5 ab^{-1}

3 TeV
5.0 ab^{-1}

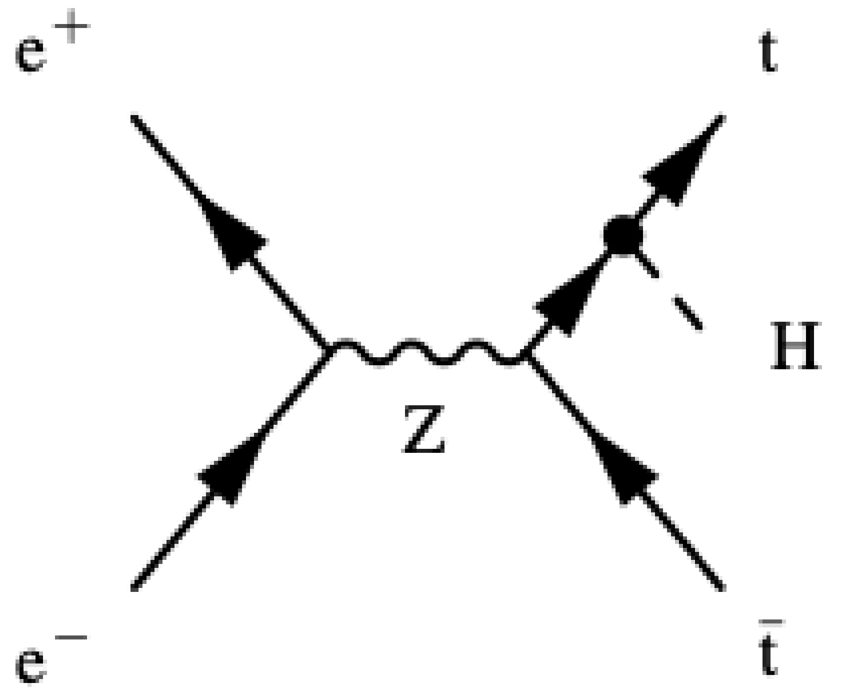
- Higgsstrahlung $e^+e^- \to HZ$ allows for absolute determination of Higgs couplings to SM particles – Z-recoil mass analysis

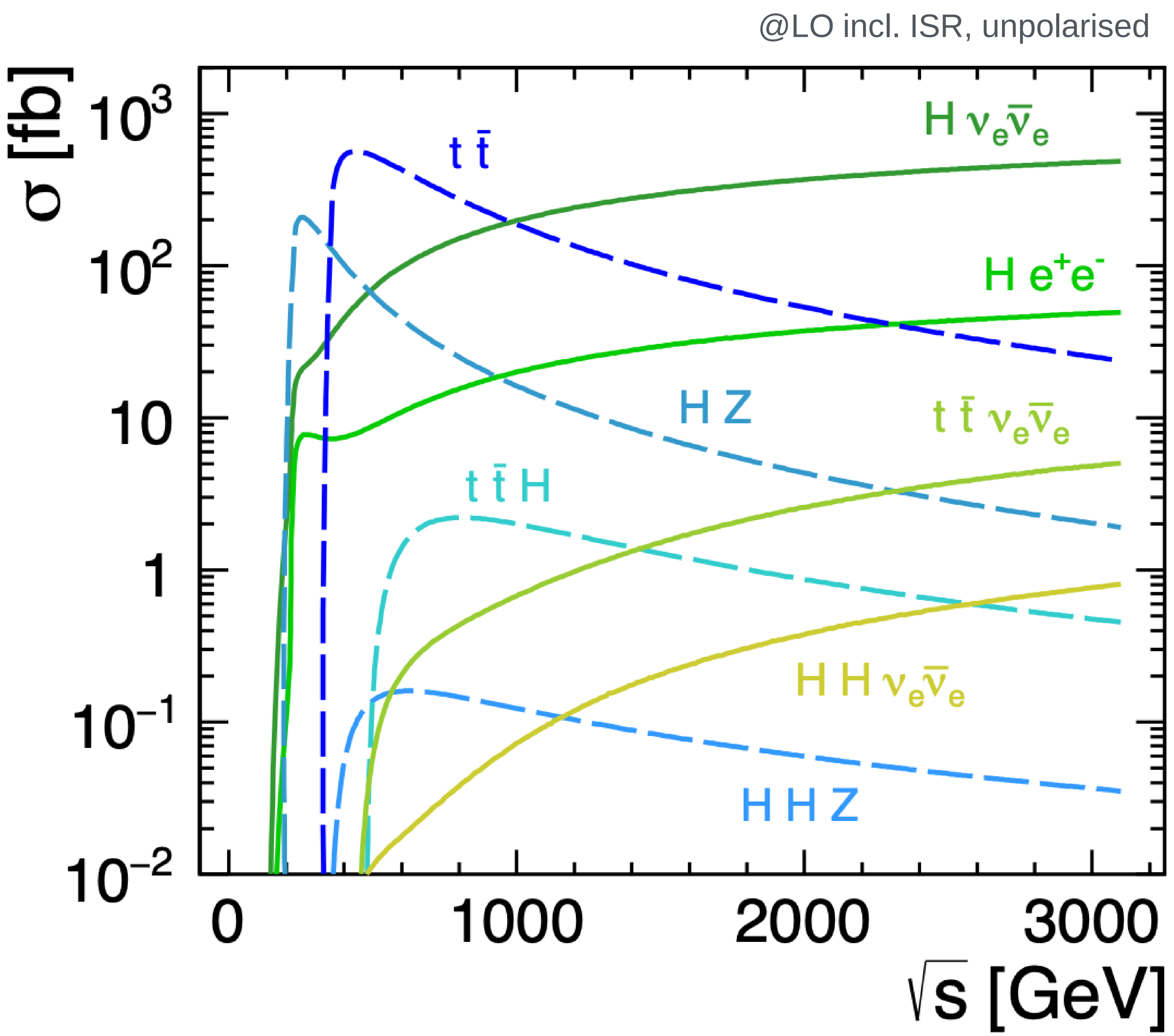


Higgs overview: Eur. Phys. J. C (2017)
Top overview: JHEP 11 (2019) 003

Dominant Higgs and top production at CLIC

- Associated production extraction of top Yukawa coupling with a precision of ~2.7% (ttH)





380 GeV
1 ab^{-1}

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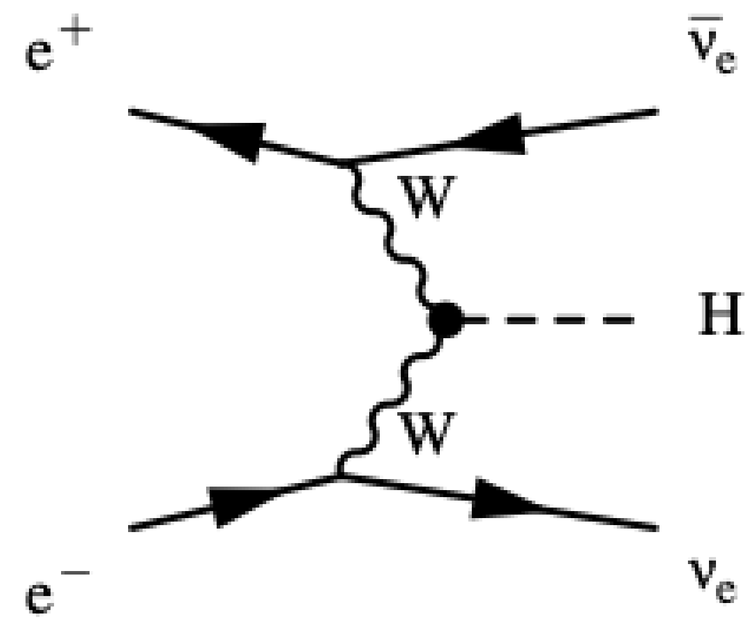
5.0 ab^{-1}



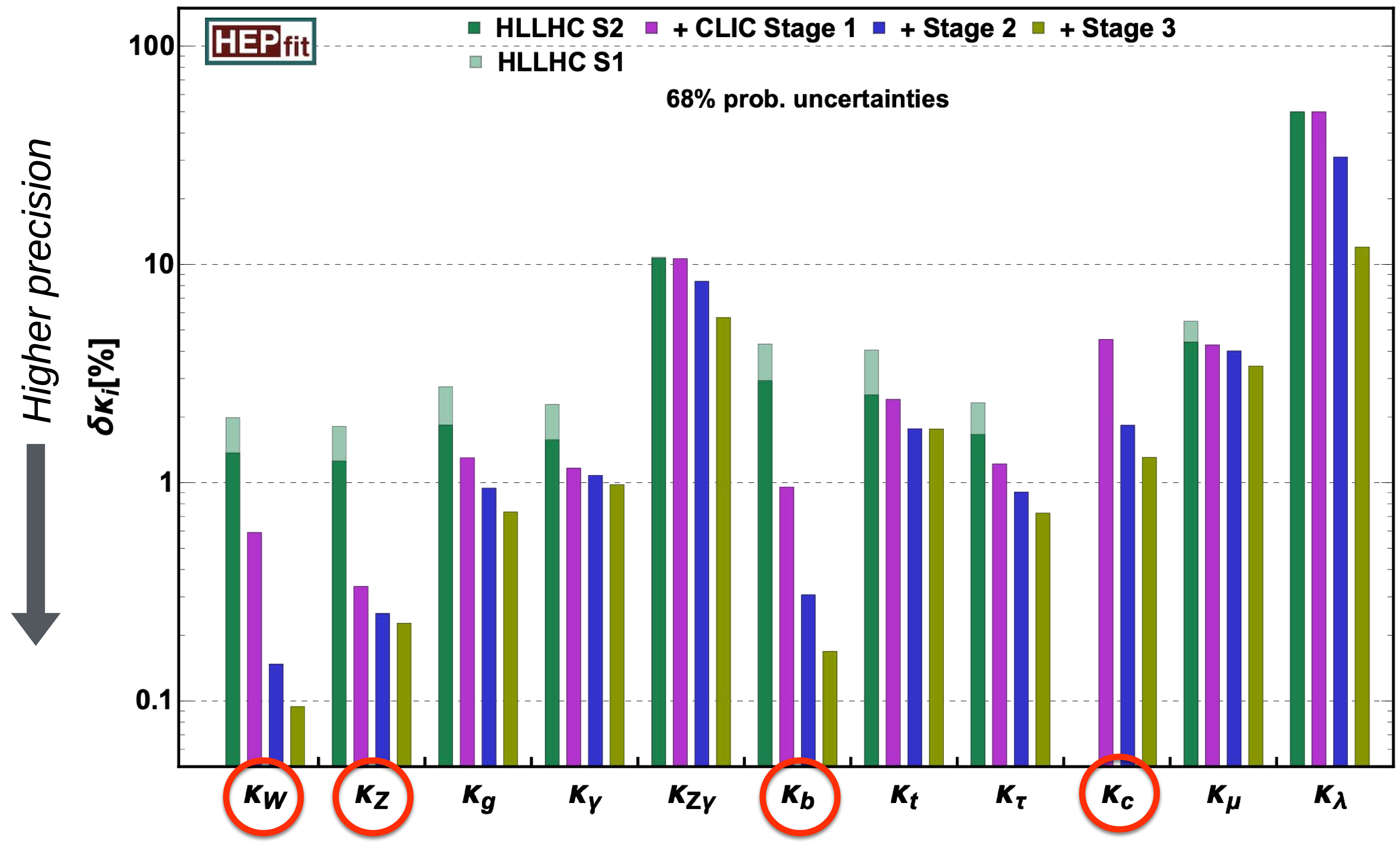
- Vector-boson fusion (VBF) benefits from high √s
  - Unprecedented precision on Higgs couplings to SM particles and the trilinear Higgs coupling (double Higgs production)
  - On-shell W^+W^-tt production

Higgs overview: Eur. Phys. J. C (2017)
Top overview: JHEP 11 (2019) 003

Precision Higgs couplings

HIGGS COUPLINGS
Combined with HL-LHC projections

CLIC Physics Potential CERN-2018-009-M, arXiv:1812.02093

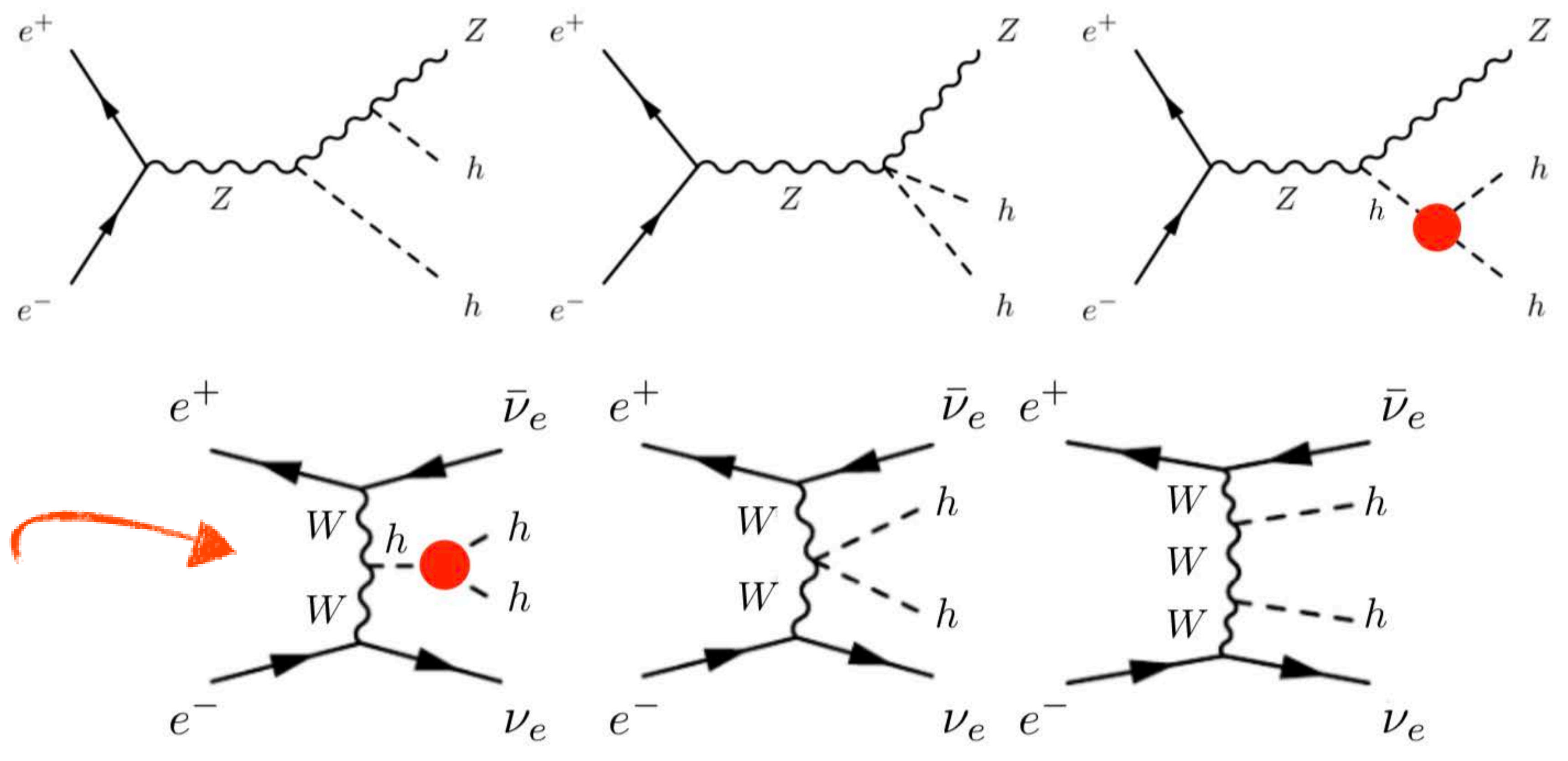


- CLIC enables high-precision measurements beyond HL-LHC (≲1% for most couplings)
- Very large improvements for
  - W, Z, b, c
- BR(H→inv.) < 0.69% at 90% CL (for 350 GeV CLIC)
- Γ_H is extracted with 4.7% (350 GeV) – 2.5% (3 TeV) precision

Precision Higgs couplings

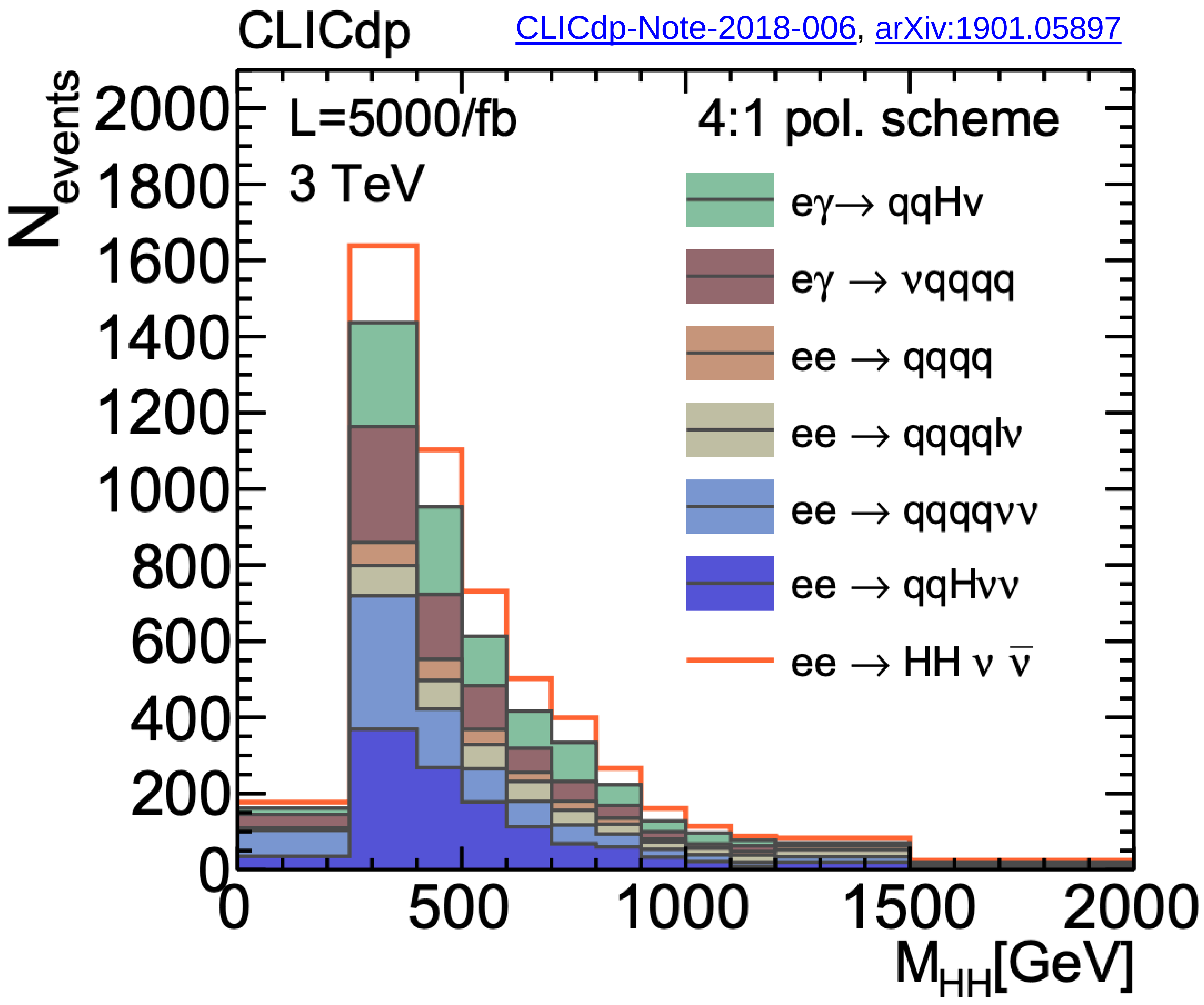
HIGGS SELF-COUPLING

dominates at high √s



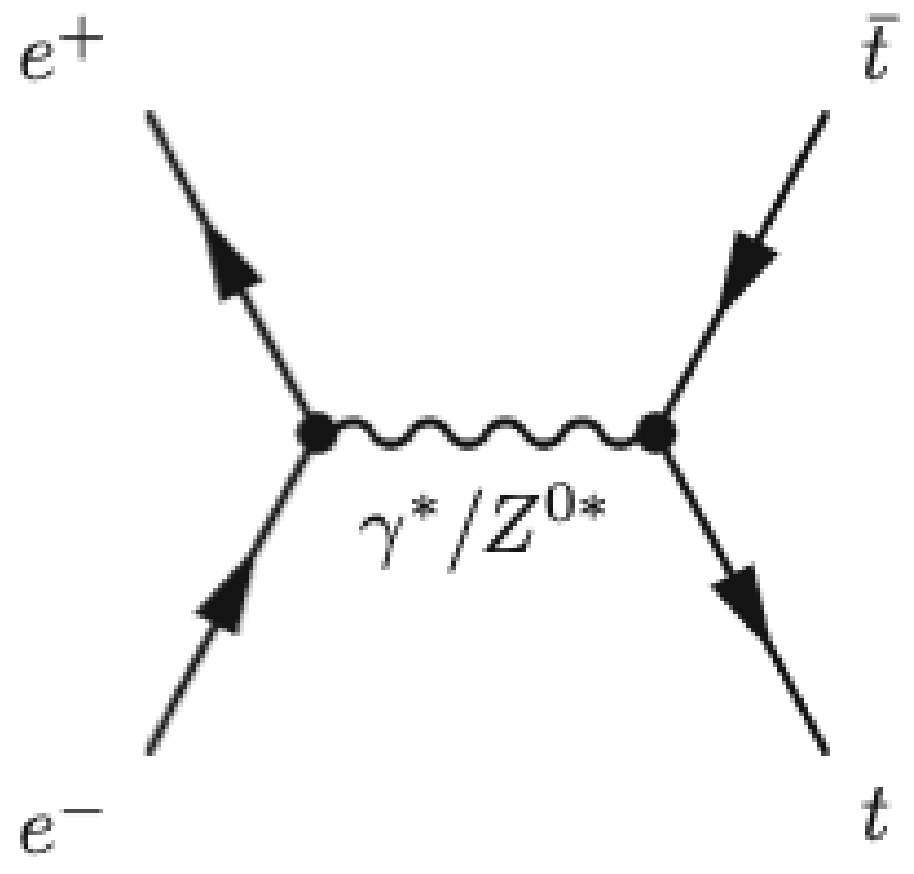
- Direct access to HH production at 1.5 and 3 TeV
- Challenging measurements – benefits from excellent heavy flavour tagging, jet energy resolution
- Template fit using two variables: M(HH) differential distribution and BDT score
- Unique capability of CLIC: measuring the Higgs self-coupling to -7%, +11% accuracy (full programme)

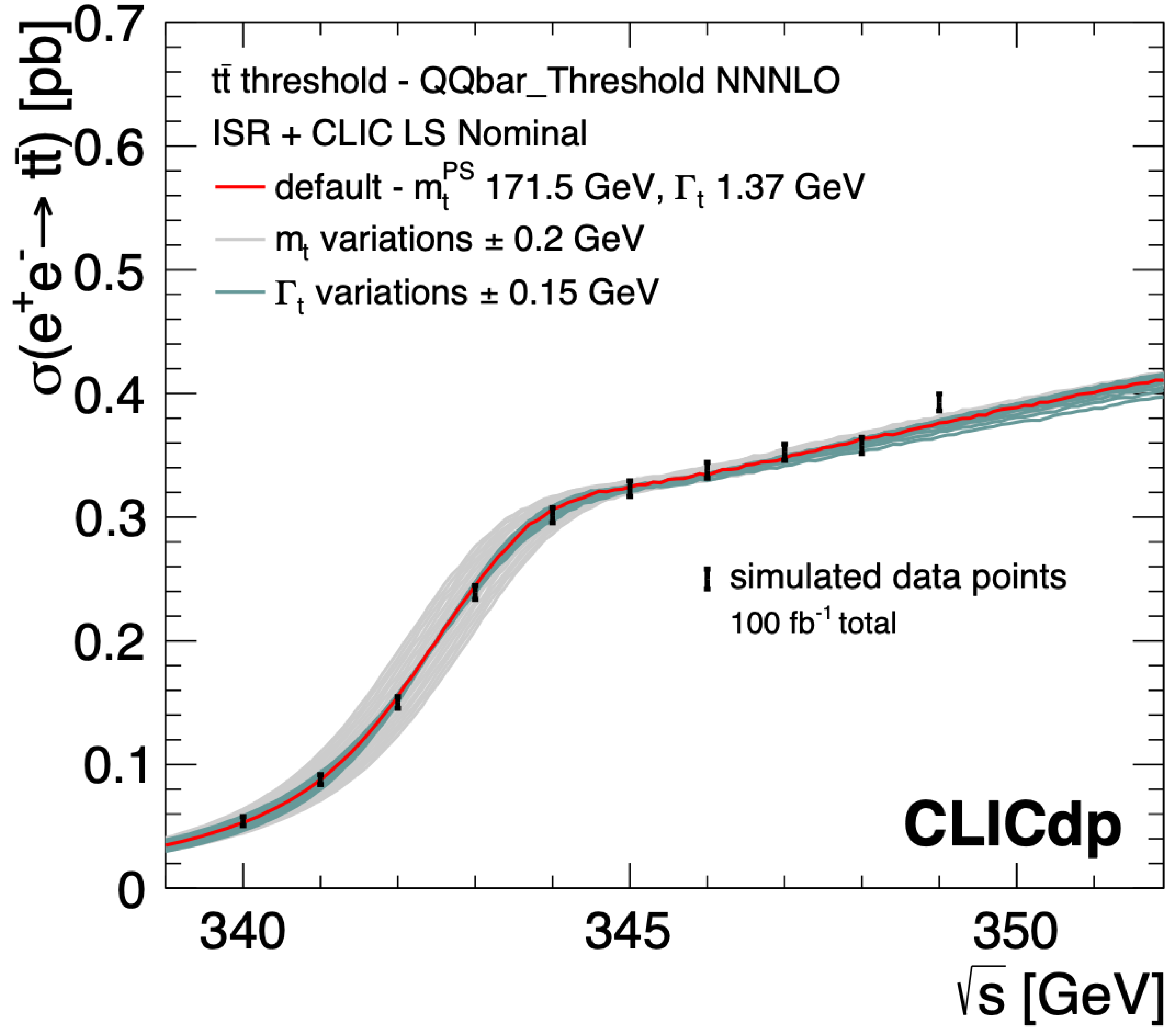
CLICdp-Note-2018-006, arXiv:1901.05897



Top-quark mass from threshold scan

- Intending threshold scan near √s=350 GeV (10 points, ~1 year) as well as main initial-stage baseline √s=380 GeV





- The cross section and the position and shape of the turn-on curve are strongly dependent on the precise value of the top-quark mass and width, Yukawa coupling, and strong coupling α_s
- Observe 1S 'bound state', Δm_t ~ 50 MeV (stat+sys)
  - Dominated by theory N^3LO scale uncertainty
  - Theoretical uncertainty ≈10 MeV when transforming 1S mass to MS scheme

Global sensitivity to SMEFT BSM effects

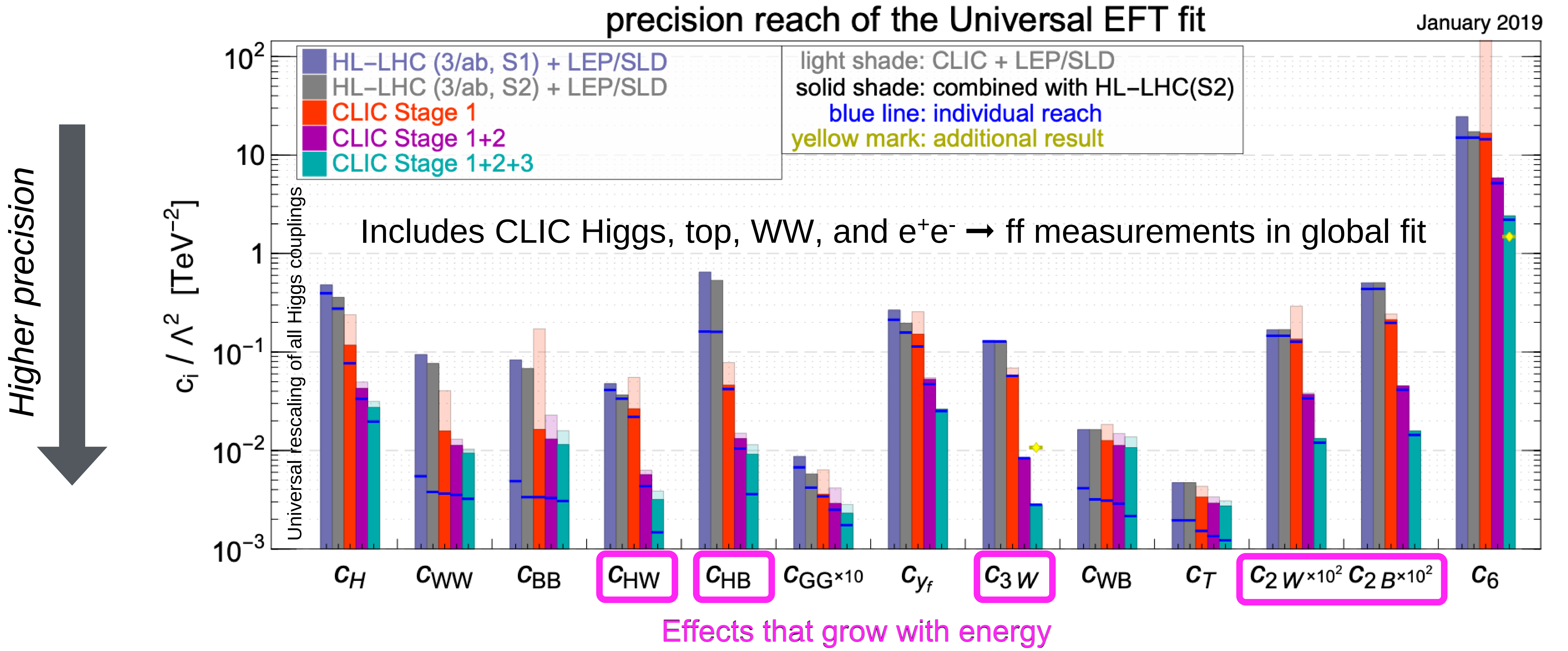
Higgs, top, WW, ff projections

- Already the initial stage of CLIC is very complementary to the HL-LHC
- The high-energy stages, unique to CLIC among all proposed e^+e^- colliders, are found to be crucial for the precision programme

Standard Model — Wilson coefficients

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{O}_i + \mathcal{O}(\Lambda^{-4})$$

New physics scale



CLIC Physics Potential CERN-2018-009-M, arXiv:1812.02093

New physics searches

- Many BSM examples worked out in detail for CLIC
- CLIC can probe TeV-scale electroweak particles, or particles that interact with the SM with electroweak-sized couplings, well above the HL-LHC reach

Process	HL-LHC	CLIC
Heavy Higgs scalar mixing angle $\sin^2\gamma$	$< 4\%$	$< 0.24\%$
Higgs self-coupling $\Delta\lambda$	$\sim 50\%$ at 68% C.L.	$[-7\%, +11\%]$ at 68% C.L.
BR(H $\to$ invisible)		$< 0.69\%$ at 90% C.L.
Higgs compositeness scale m_*	$m_* > 3$ TeV (> 7 TeV for $g_* \simeq 8$)	Discovery up to $m_* = 10$ TeV (40 TeV for $g_* \simeq 8$)
Top compositeness scale m_*		Discovery up to $m_* = 8$ TeV (20 TeV for small coupling g_*)
Higgsino mass (disappearing track search)	> 250 GeV	> 1.2 TeV
Slepton mass		Discovery up to ~ 1.5 TeV
RPV wino mass		> 1.5 TeV ($0.03\,\text{m} < c\tau < 30\,\text{m}$)
Z′ (SM couplings) mass	Discovery up to 7 TeV	Discovery up to 20 TeV
NMSSM scalar singlet mass	> 650 GeV ($\tan\beta = 4$)	> 1.5 TeV ($\tan\beta = 4$)
Twin Higgs scalar singlet mass	$m_\sigma = f > 1$ TeV	$m_\sigma = f > 4.5$ TeV
Relaxion mass	< 24 GeV	< 12 GeV (all for vanishing $\sin\theta$)
Relaxion mixing angle $\sin^2\theta$		$\leq 2.3\%$
Neutrino Type-2 see-saw triplet		> 1.5 TeV (for any triplet VEV) > 10 TeV (for triplet Yukawa coupling $\simeq 0.1$)
Inverse see-saw RH neutrino		> 10 TeV (for Yukawa coupling $\simeq 1$)
Scale $V_{LL}^{-1/2}$ for LFV $(\bar{e}e)(\bar{e}\tau)$		> 42 TeV

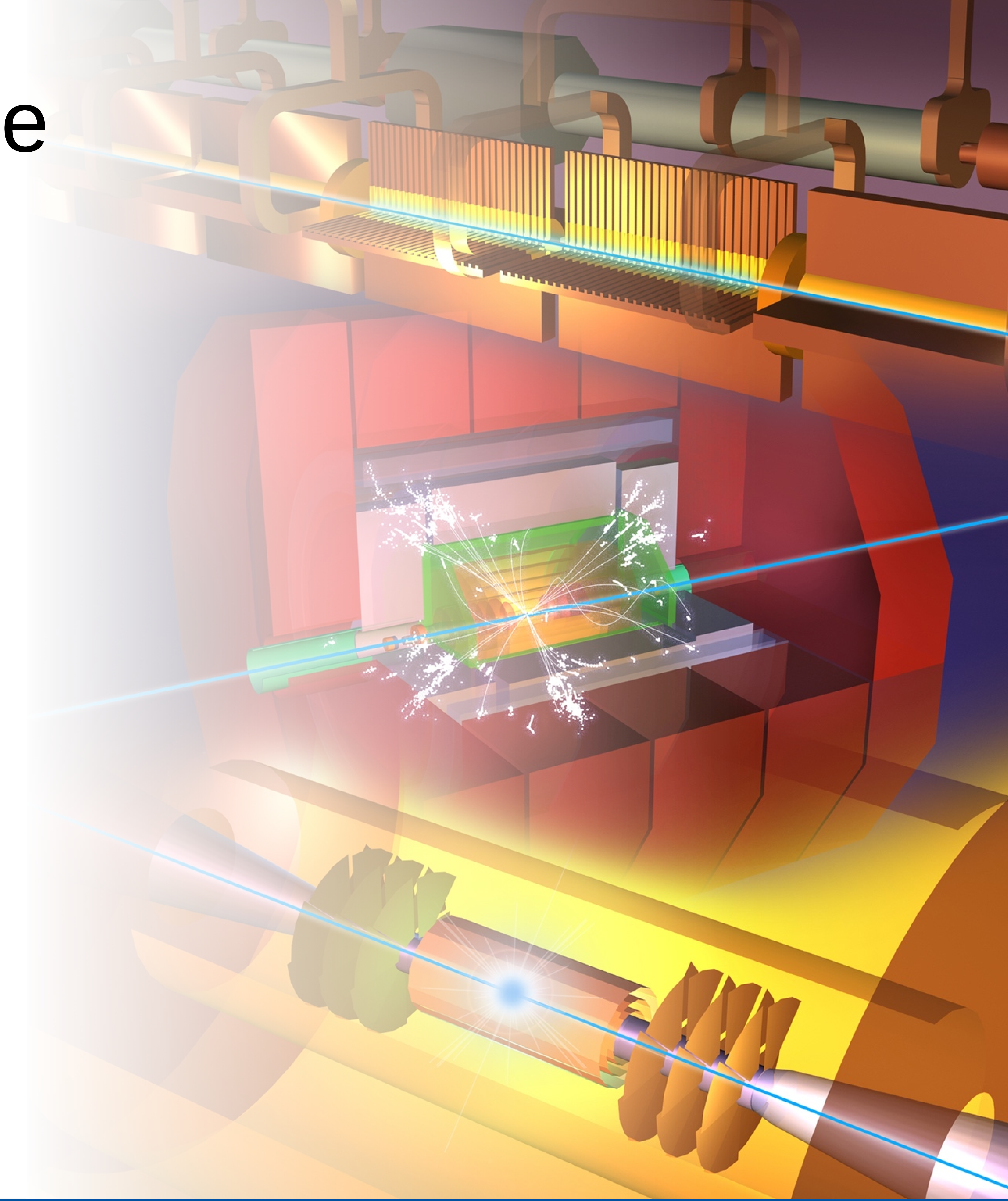
- Precision Higgs couplings and self-coupling
- Precision electroweak and top-quark analysis
- Sensitivity to BSM effects in the SMEFT
- Higgs and top compositeness
- Baryogenesis
- Direct discoveries of new particles
- Extra Higgs boson searches
- Dark matter searches
- Lepton and flavour violation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

+ Many more studies in CERN Yellow Report: "The CLIC Potential for New Physics" arXiv:1812.02093 / CERN-2018-009-M

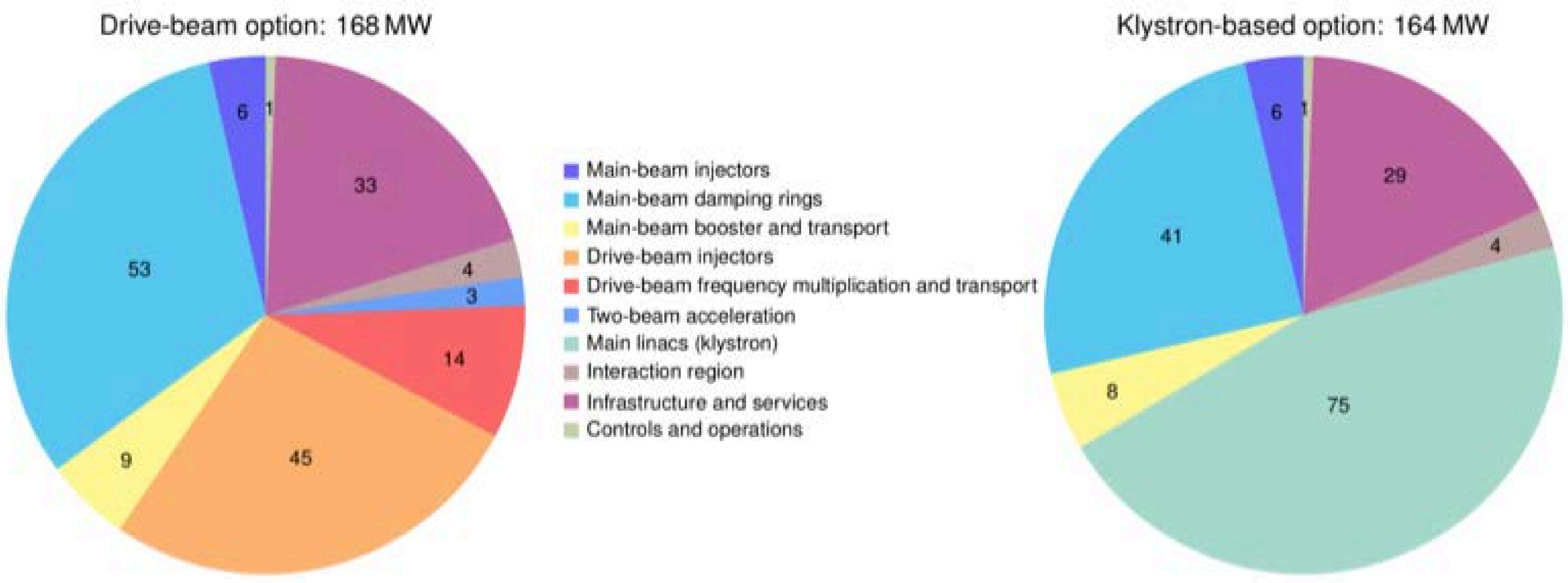
Outline

Project overview, followed by:

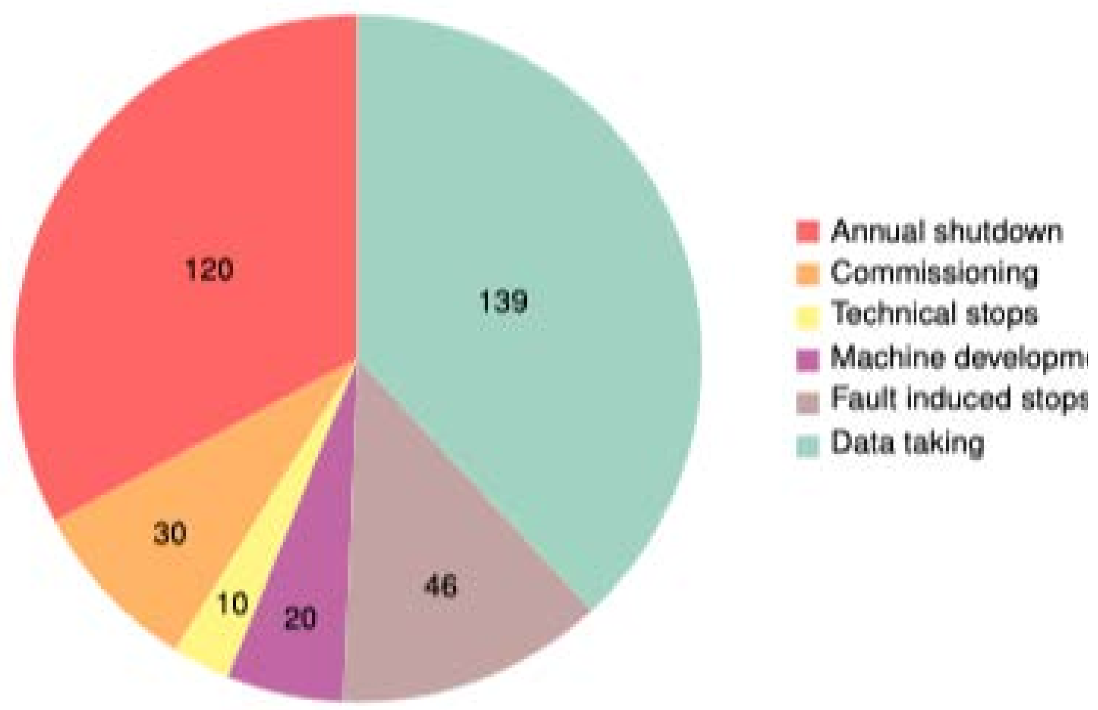
- Accelerator description
- Accelerator key technology, examples and recent activities
- Detector and physics (brief – as reference)
- **Project realization**

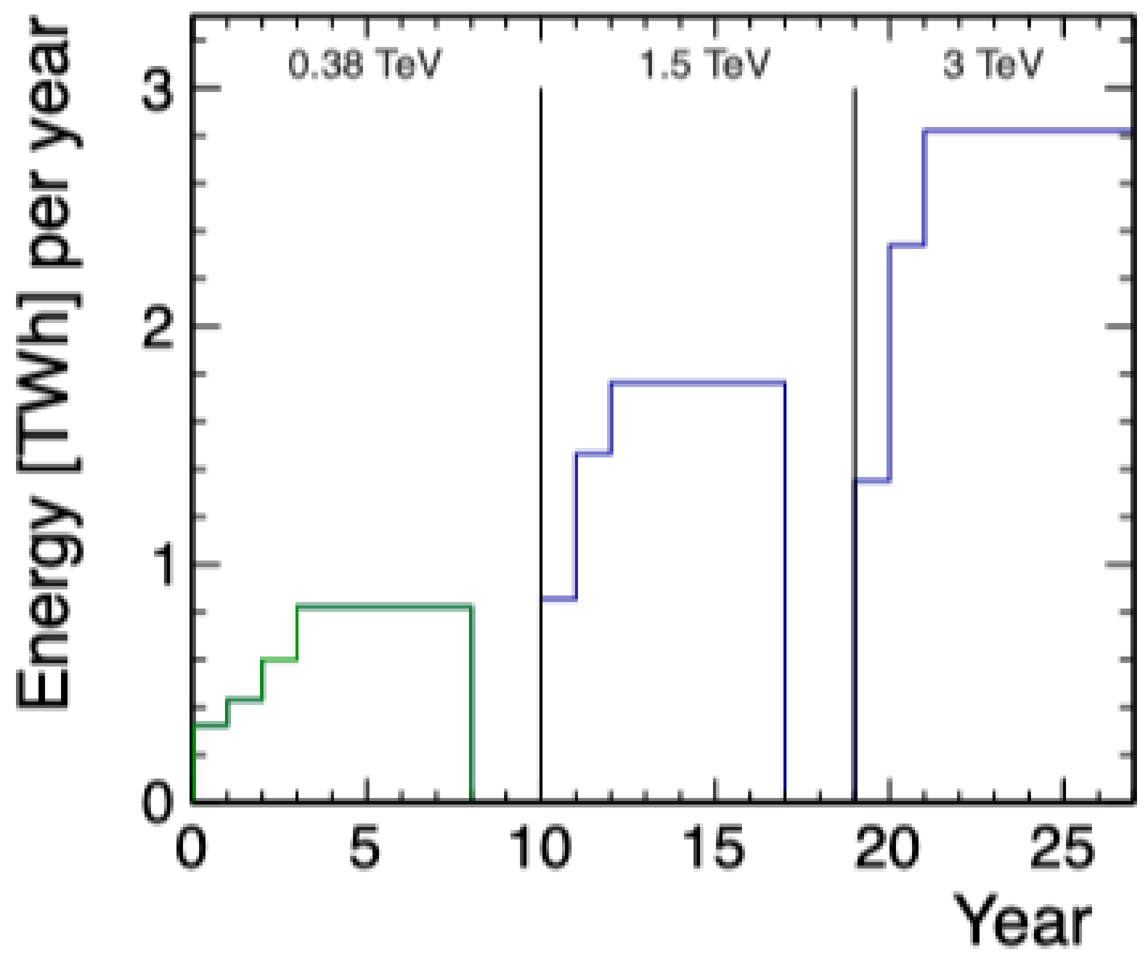


Power and energy



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





Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

Further savings possible, main target damping ring RF
Will look also more closely at 1.5 and 3 TeV numbers next

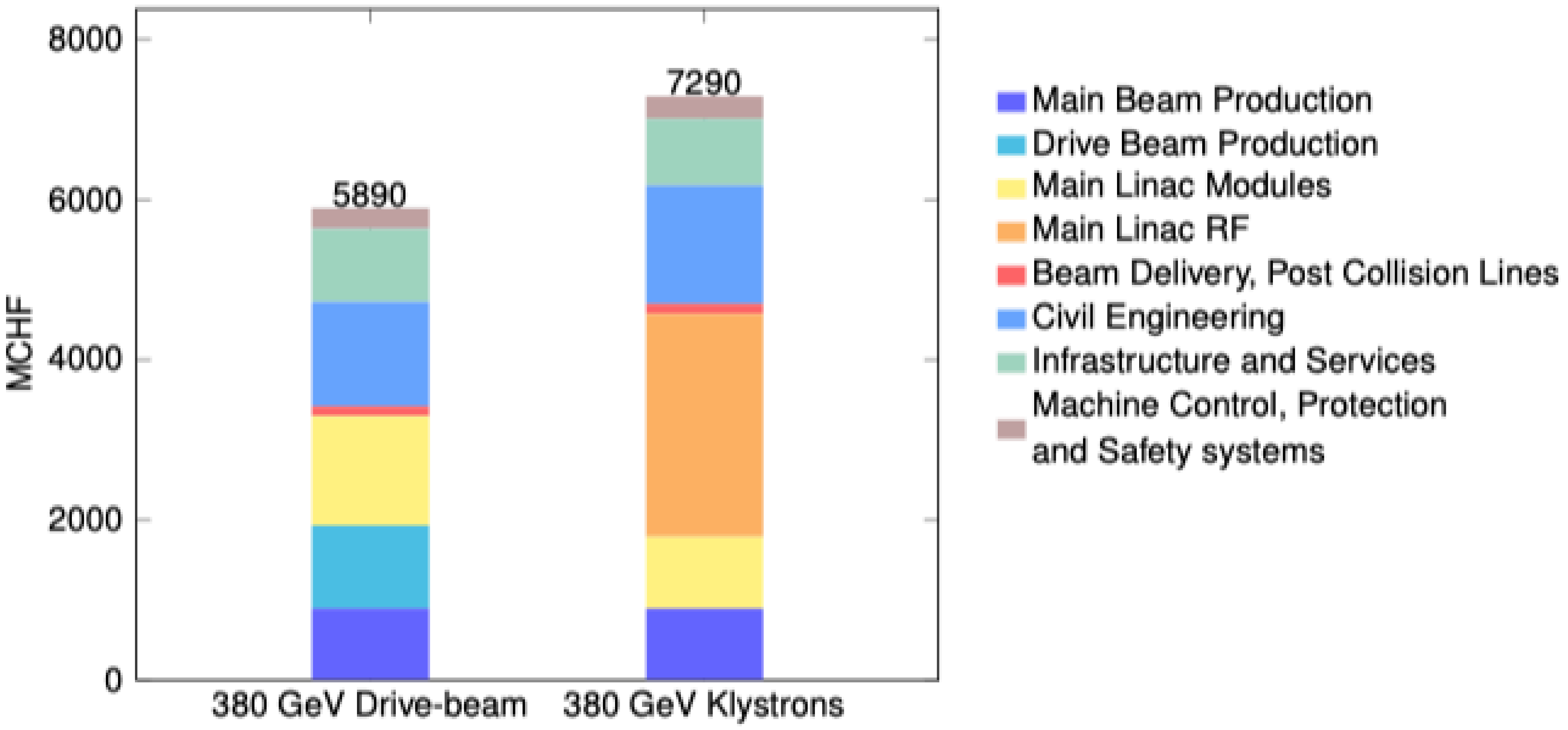
From running model and power estimates at various states – the energy consumption can be estimated

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

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.

Schedule

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

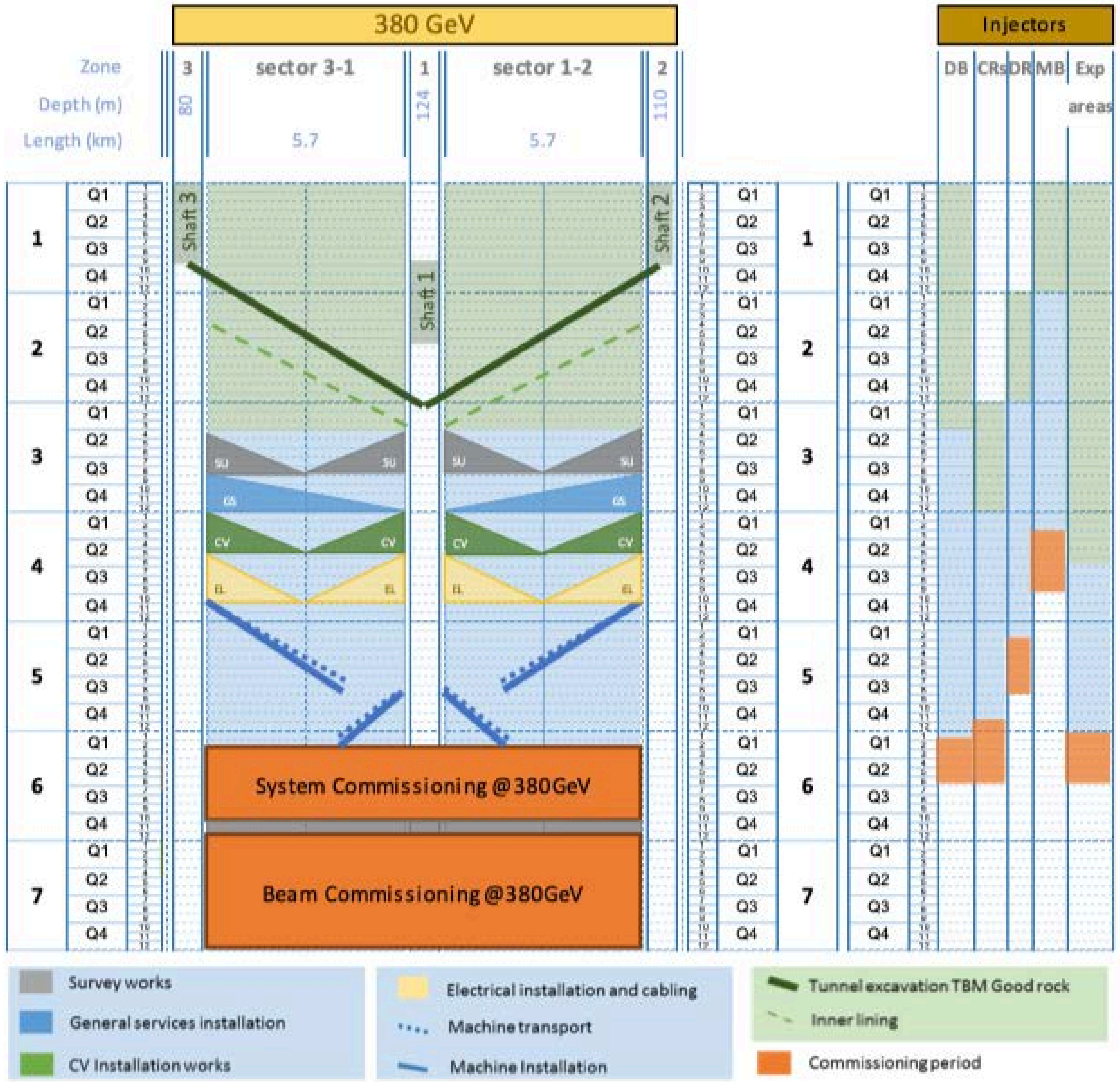
Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2020
Update of the European Strategy for Particle Physics

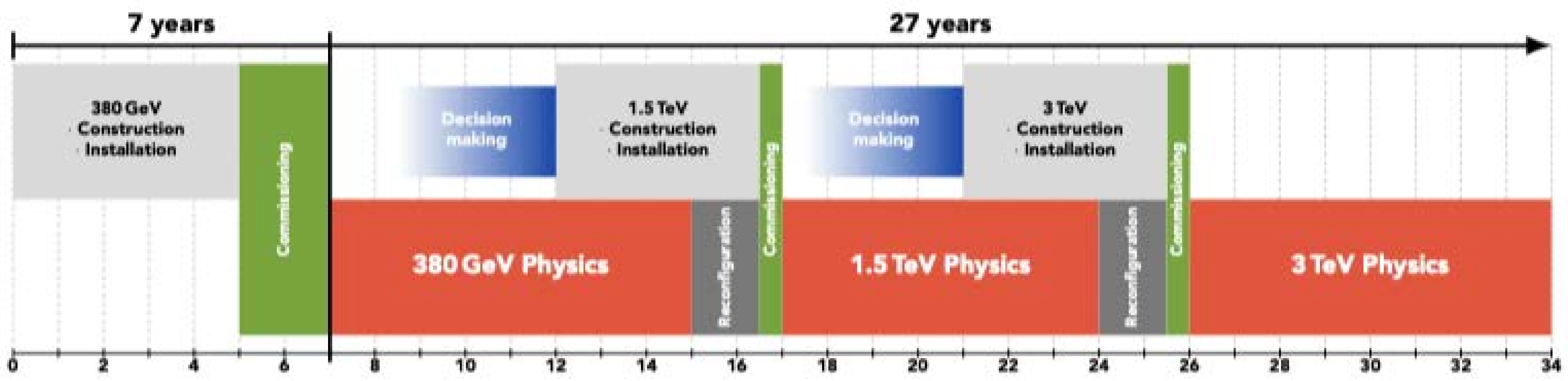
2026
Ready for construction

2035
First collisions

Updated schedule:
Construction + commissioning for 380 GeV: 7 yr
Full physics programme 27 yr



Looong term future for a LC – NAT



CLIC programme - what about new technology ?

- Working group for use of Novel Acceleration Technologies (NAT) – plasma with various drivers, dielectrics, etc (short chapter in Project Implementation Plan document)
  - Physics and accelerator parameters (luminosity in particular)
  - Consider status of various studies
  - Key challenges beam-quality, positrons, energy efficiency for suitable luminosities

- Possible re-use of tunnel/infrastructure/drive-beams/injectors etc interesting for a LC infrastructure

- The fact the actual effective ML might remain short (and hence possibly “cheap” and inter-changeable in a limited time) makes this long term perspective worth considering

- Have not found any “constrains/guidance” from these very long term “hopes” that would impact the design of CLIC stages 1-3
  - CLIC is laser-straight and with a “reasonable” crossing angle likely to compatible with higher beam energies and the bunch separations needed for these technologies

Summary

- CLIC is now a mature project, ready to move towards next phase preparing for a 380 GeV stage
- There is an consistent way forward with initial LC at “SM energies”, keeping the options open for future upgrades and/or circular accelerators further on
- The cost and implementation time for CLIC 380 are similar to LHC
- The physics case is broad and profound, and being further developed
- The detector concept and detector technologies R&D are advanced
- The full project status has been presented in a series of Yellow Reports and other publications: **http://clic.cern/european-strategy**

Picture from the CLIC week 2019,
Next will take place March 9-13 2020

Thanks to all my CLIC colleagues

- a special thanks to R.Ström, I have used many of his slides -