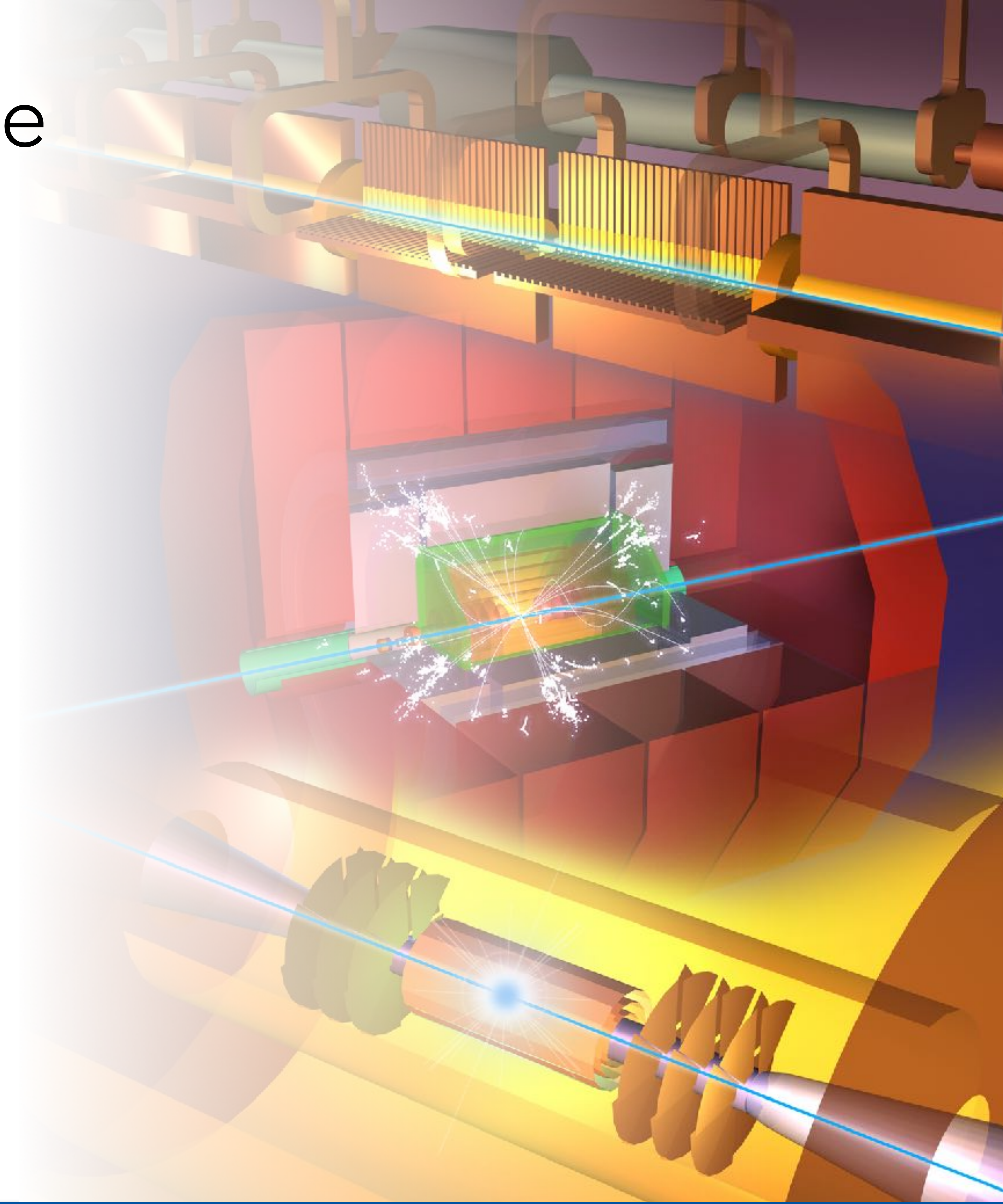
Rickard Ström
on behalf of the CLIC accelerator and CLICdp collaborations

The Compact Linear Collider (CLIC)
Accelerator, detector, physics potential

26th Nordic Particle Physics Meeting – Spåtind 2020
January 6, 2020

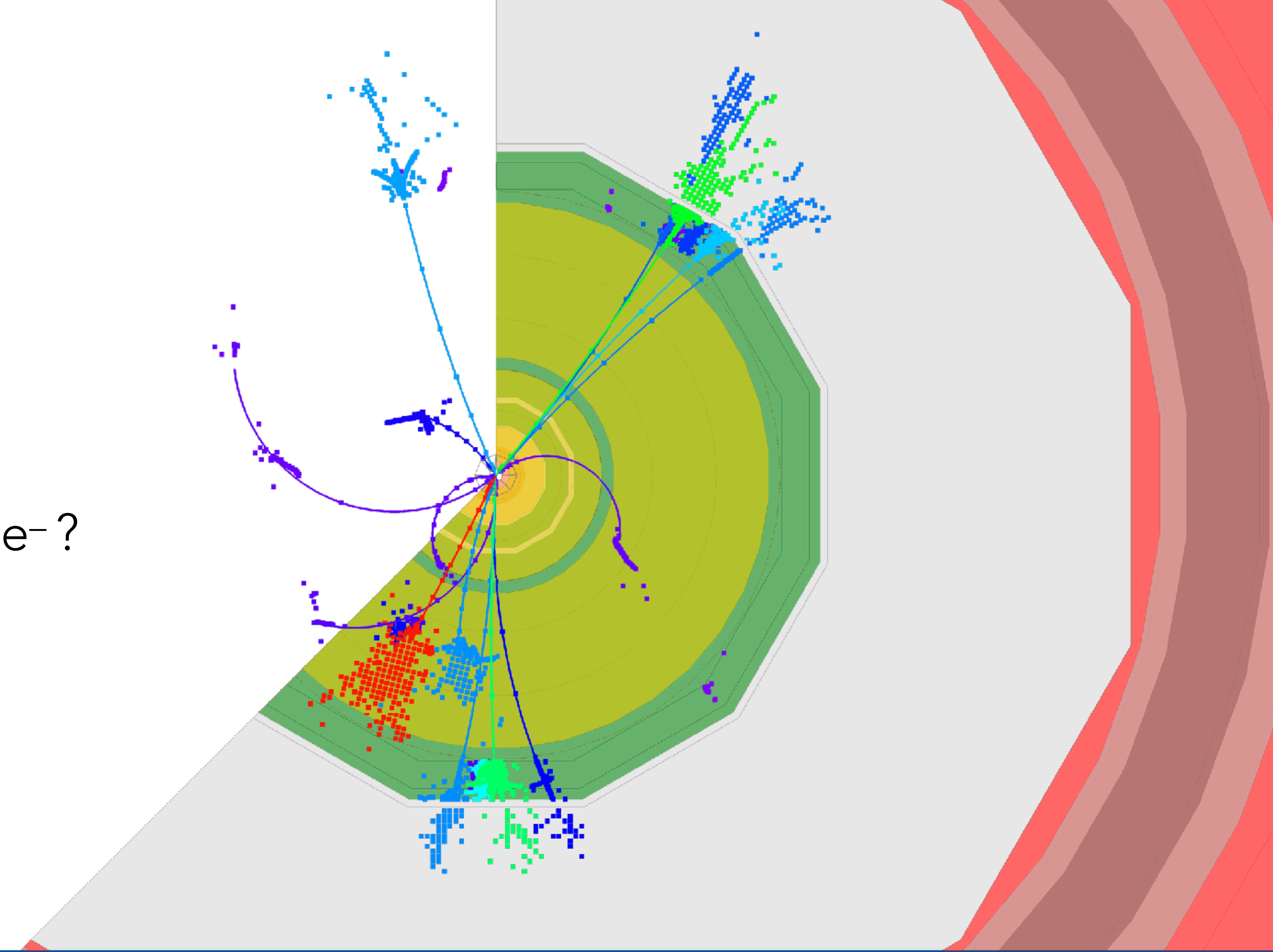
Outline

- Introduction
- Project overview
- Physics reach
- Accelerator complex
- A detector for CLIC
- Project realisation



Introduction

Why linear, why e^+e^-?

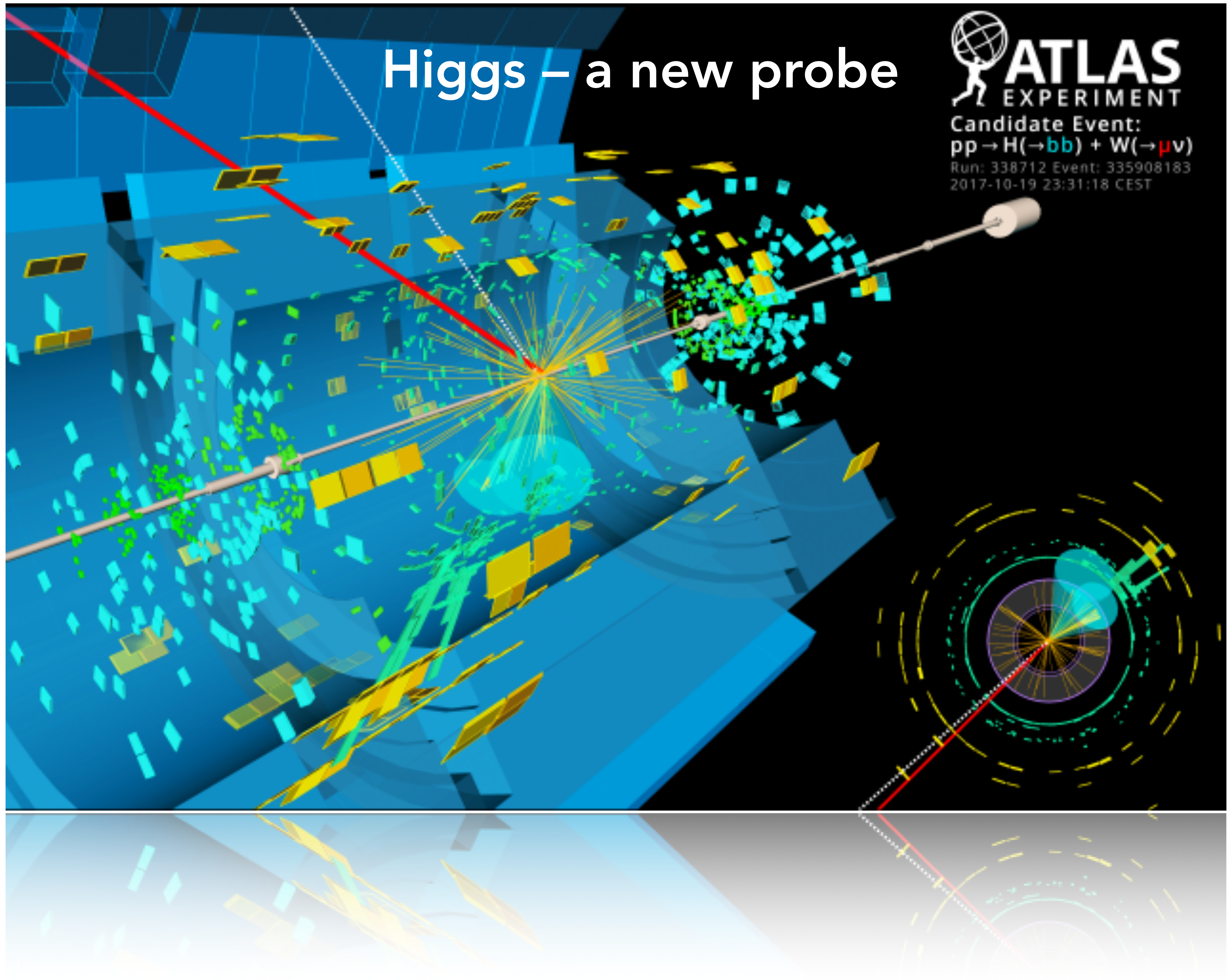


Physics landscape

- What is dark matter, what is the 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 LHC's reach, but signals elusive?

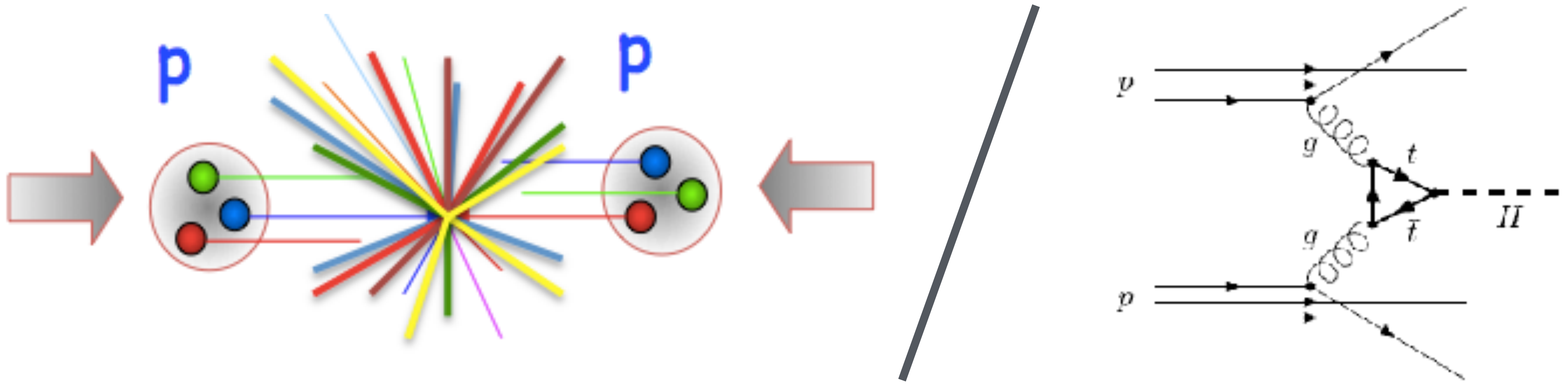
- What we've experimentally seen so far could hold in a wide range of BSM scenarios

- **Wish list for the next-generation collider:**
  - High-precision study of Higgs and top quark properties ('*guaranteed physics*') + exploration of EWSB phenomena
  - Sensitivity to elusive signatures
  - Extended energy/mass reach (direct and indirect)



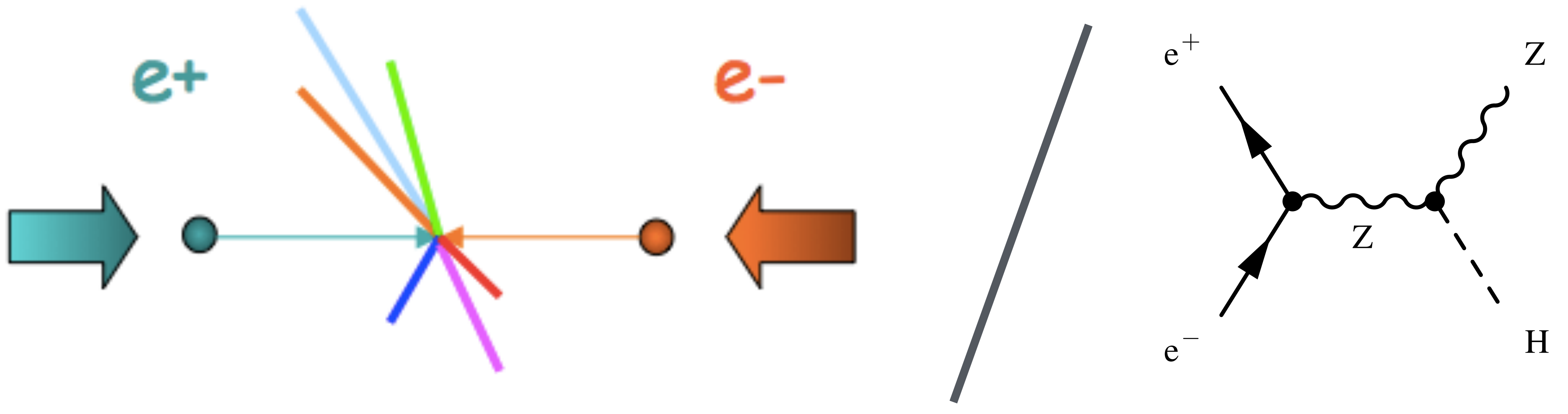
Hadron vs. lepton colliders

- **Protons are compound objects**
  - Initial state not known event-by-event
  - Limits achievable precision



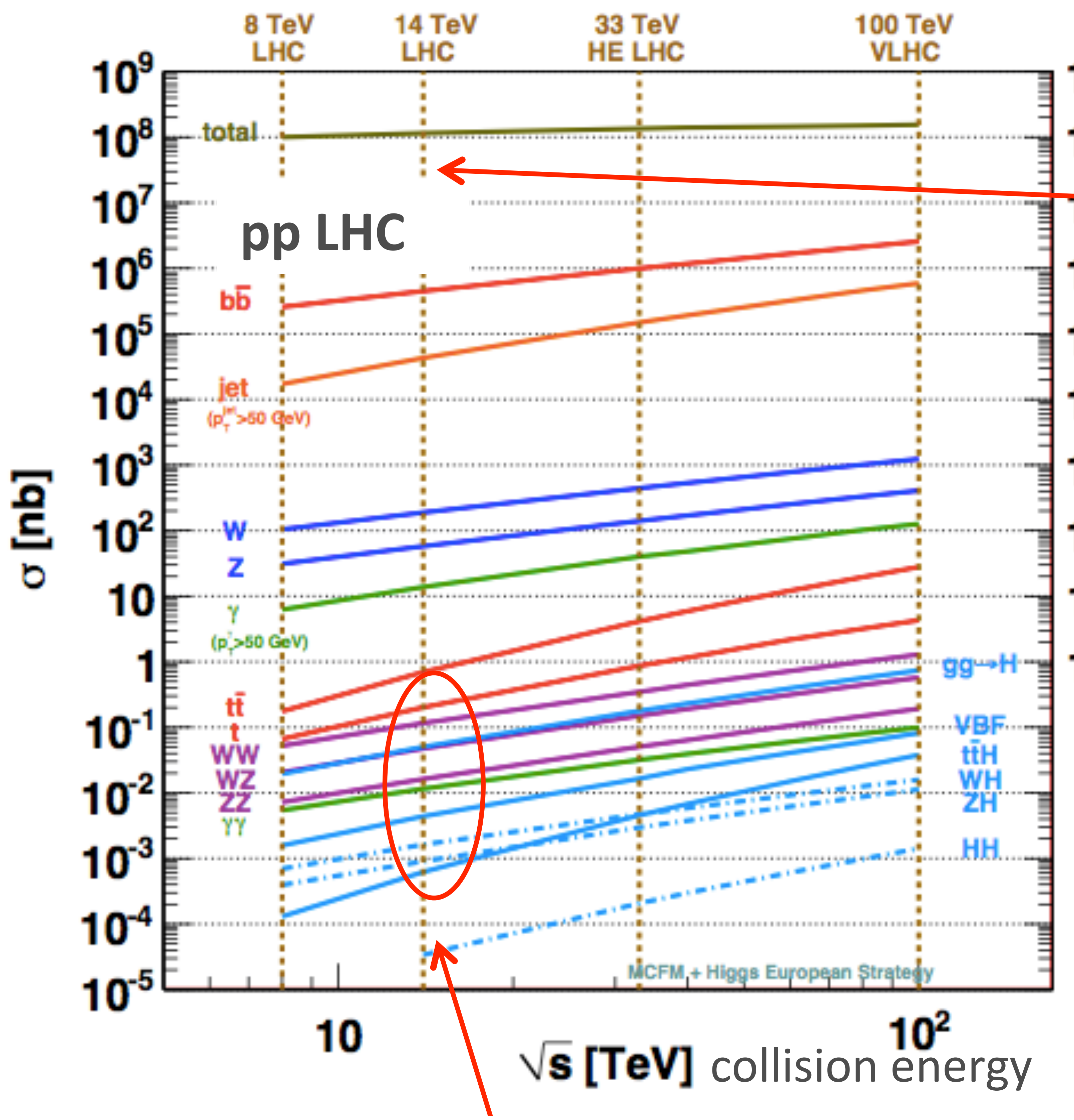
- High-energy circular colliders feasible
- High rates of QCD backgrounds
  - Complex triggering schemes
  - High levels of radiation
- **High cross-sections for coloured states**

- **Electrons/positrons are point like**
  - Initial state well defined (energy, polarisation)
  - High-precision measurements



- High-energy requires **linear collider**
- Cleaner experimental environment
  - Trigger-less readout
  - Low radiation levels
- **High sensitivity for electroweak states**

Hadron vs. lepton colliders

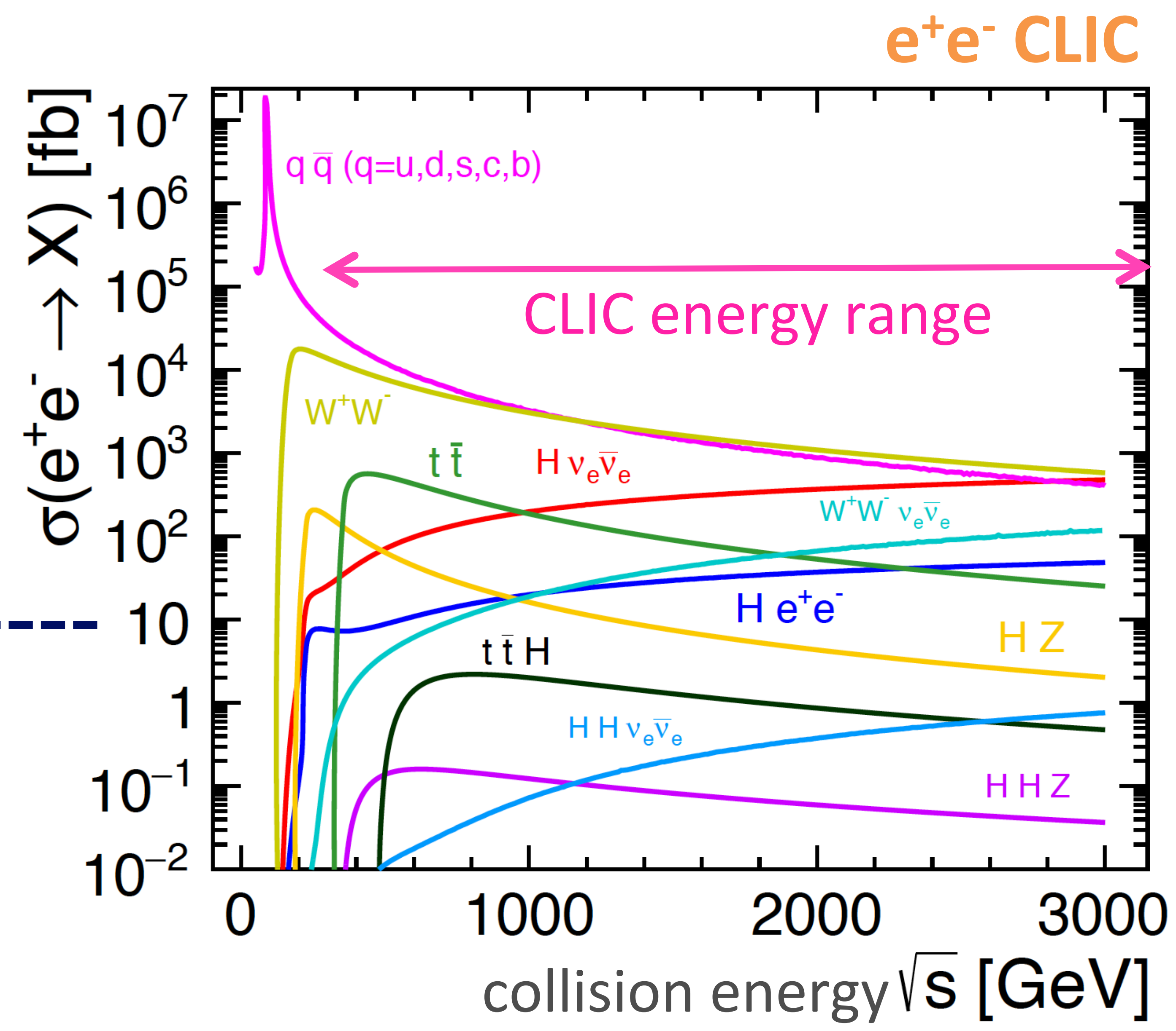


LHC total cross section

factor > 100 million !!

at LHC much of the interesting physics needs to be found among a huge number of collisions

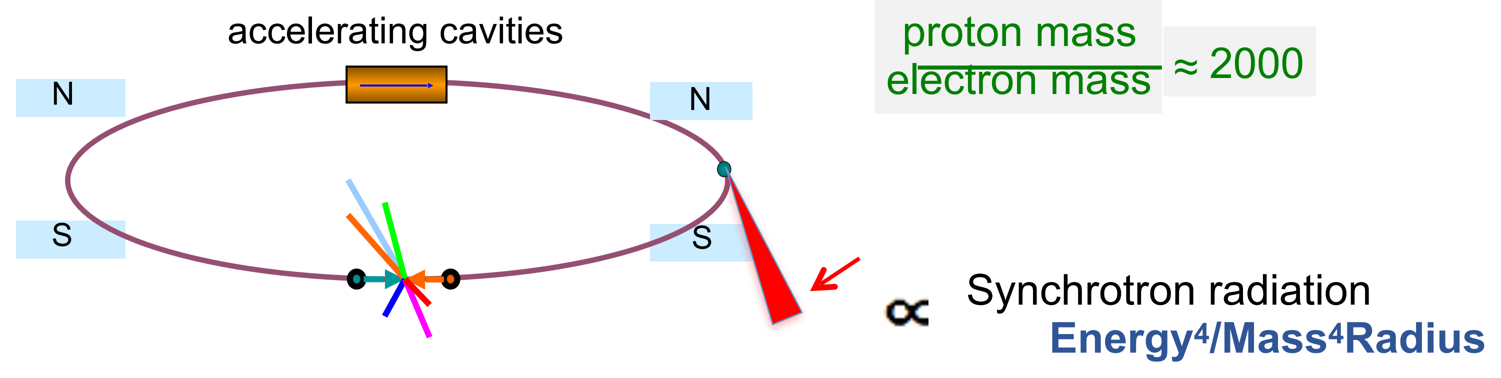
pp and e^+e^- collisions provide complementary physics information!

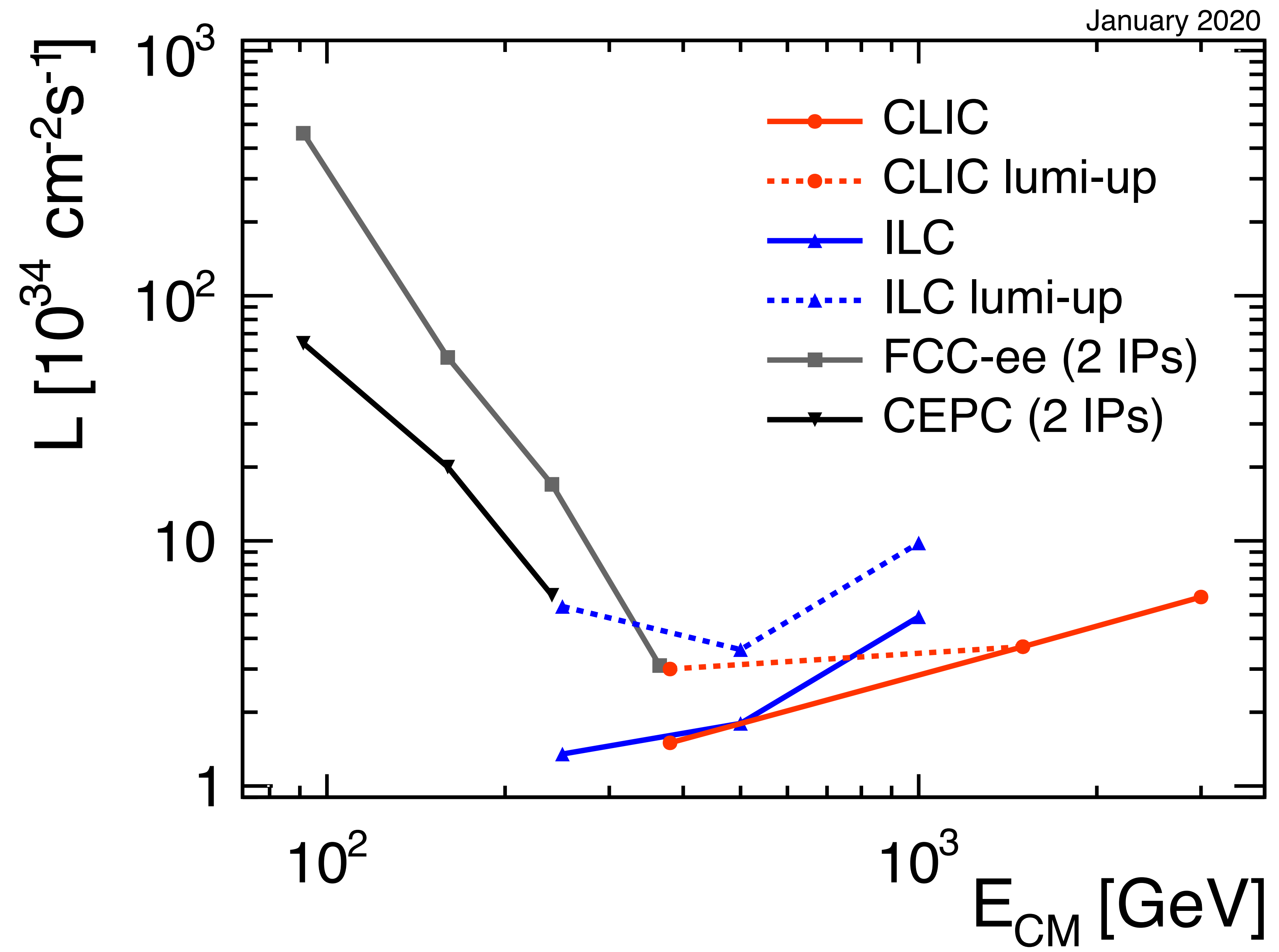


e^+e^- events are more "clean"

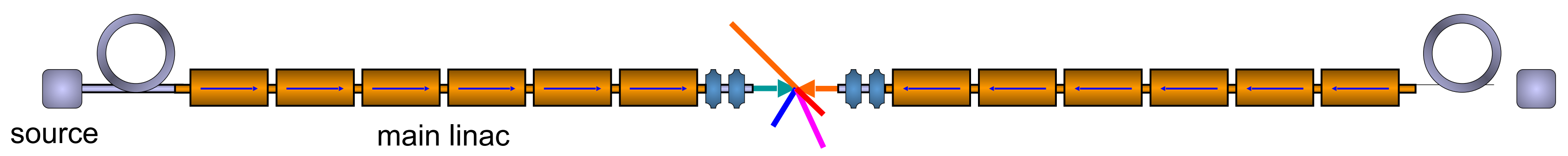
Circular vs. linear e^+e^- colliders

- **Circular colliders – bending / focusing / accelerating**
  - Acceleration gradual over many revolutions
    - FCC-ee: ~700 super-conducting RF cavities at 10 MV/m, per beam
  - Beams can be reused
  - Synchrotron radiation can be large (limits energy reach)
    - FCC-ee: 7.55 GeV/turn lost for a beam energy of 175 GeV

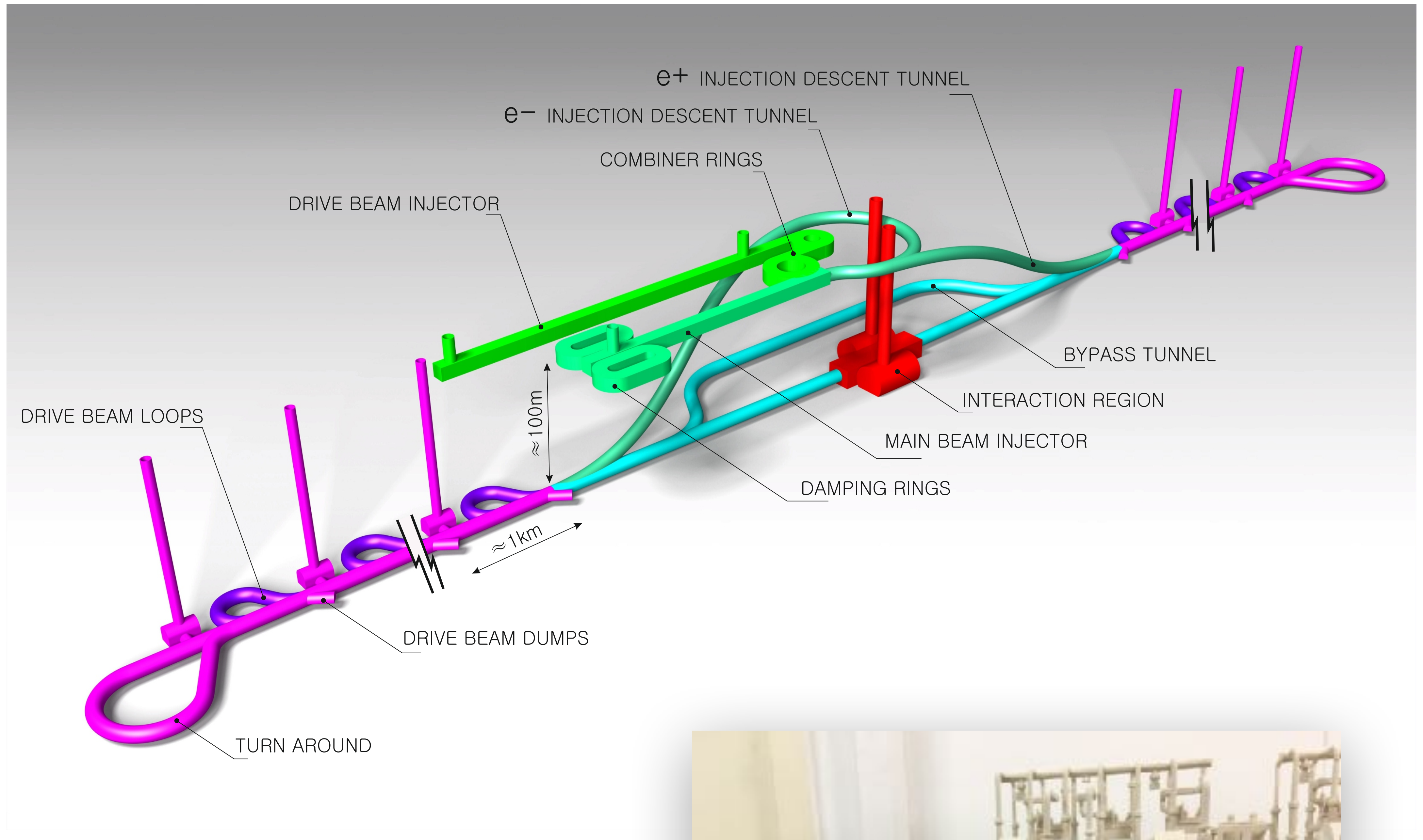




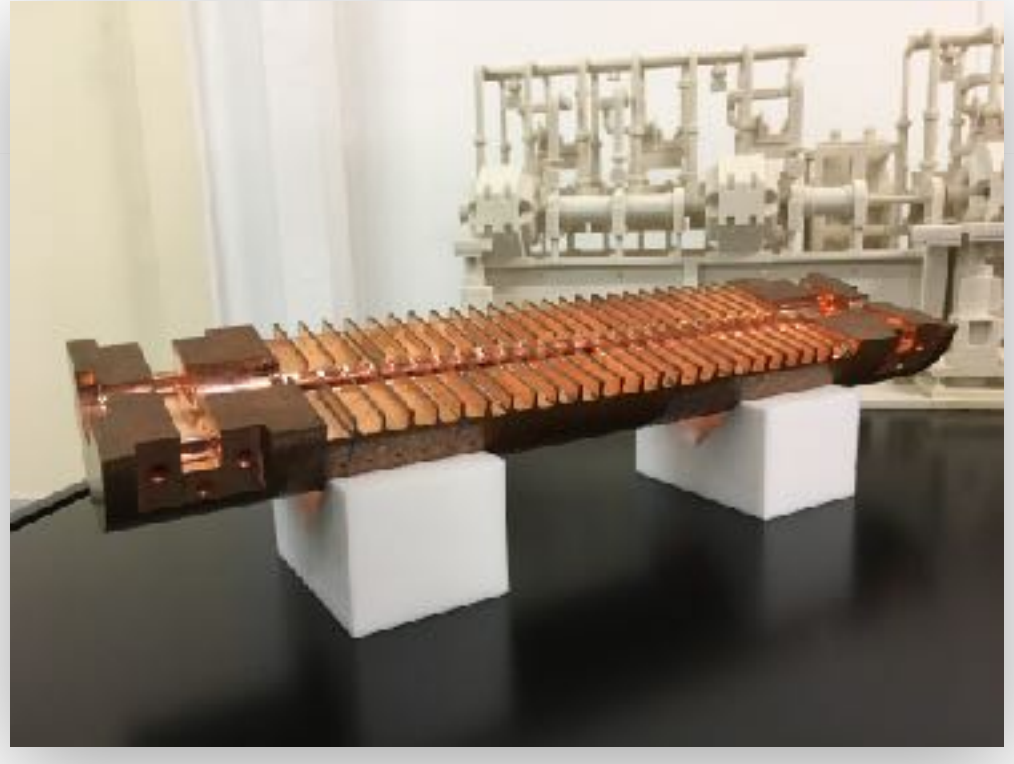
- **Linear colliders –** Bending / **focusing** / **accelerating**
  - Full collision energy must be delivered in one passage
    - CLIC at 380 GeV: ~20'500 normal-conducting RF cavities installed on 2900 modules (optimised for 72 MV/m)
  - Small beam size and high beam power needed to reach luminosity goal



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 overview documents in 2018
- Cost 5.9 BCHF for 380 GeV
- Power 168 MW at 380 GeV
- Key step: European Strategy for Particle Physics in May 2020 (deliberations on-going)

Resources

3-volume CDR 2012

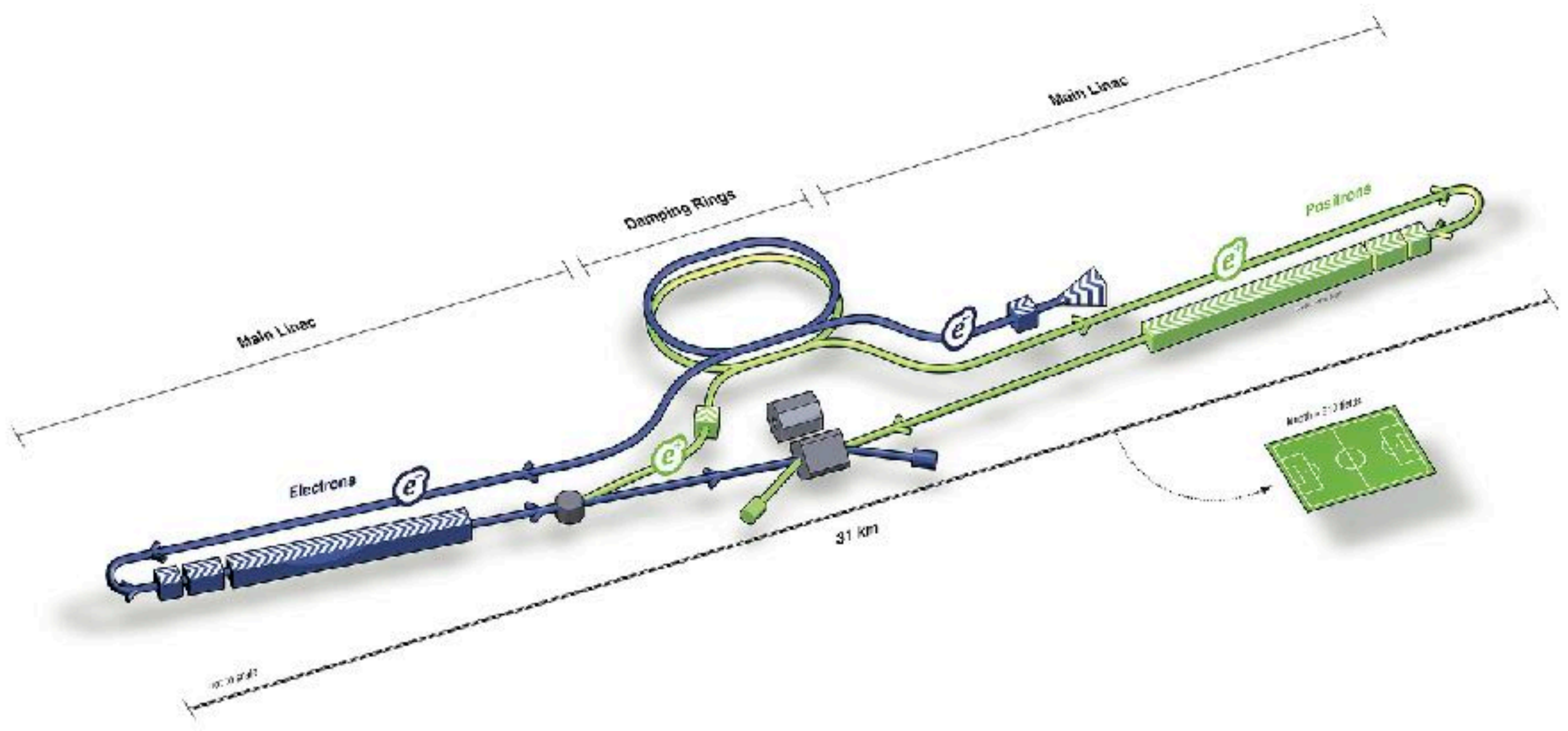
Updated Staging Baseline 2016

Available at:
clic.cern/european-strategy

4 CERN Yellow Reports 2018

2 formal submissions to the ESPPU 2018

Proposed e⁺e⁻ linear colliders – ILC



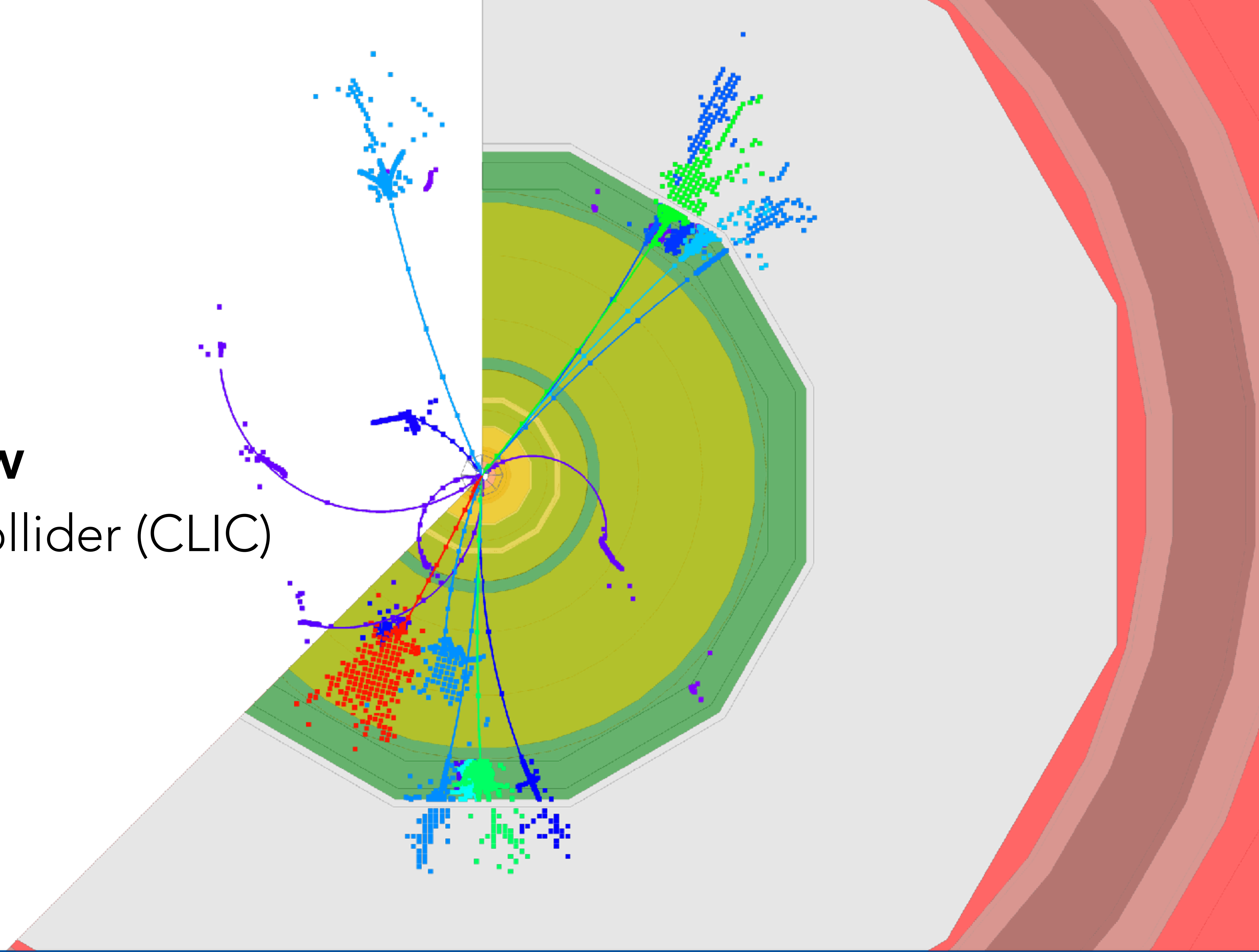
One of the niobium-based 1.3 GHz superconducting RF cavities proposed to be used at the ILC

The International Linear Collider (ILC)

- Electron-positron linear collider in Japan
- Conventional acceleration with superconducting RF cavities
- Originally 250–350–500 GeV and upgradable to 1 TeV
- TDR in 2013 (site selected)
- Initial stage now changed to 250 GeV
- Cost ~5 GILCU (1 ILCU ~ 1 USD)
- Power 129 MW at 250 GeV
- Evaluation still ongoing by Science Council of Japan and ministries

Project overview

Compact Linear Collider (CLIC)



Collaborations

CLIC accelerator

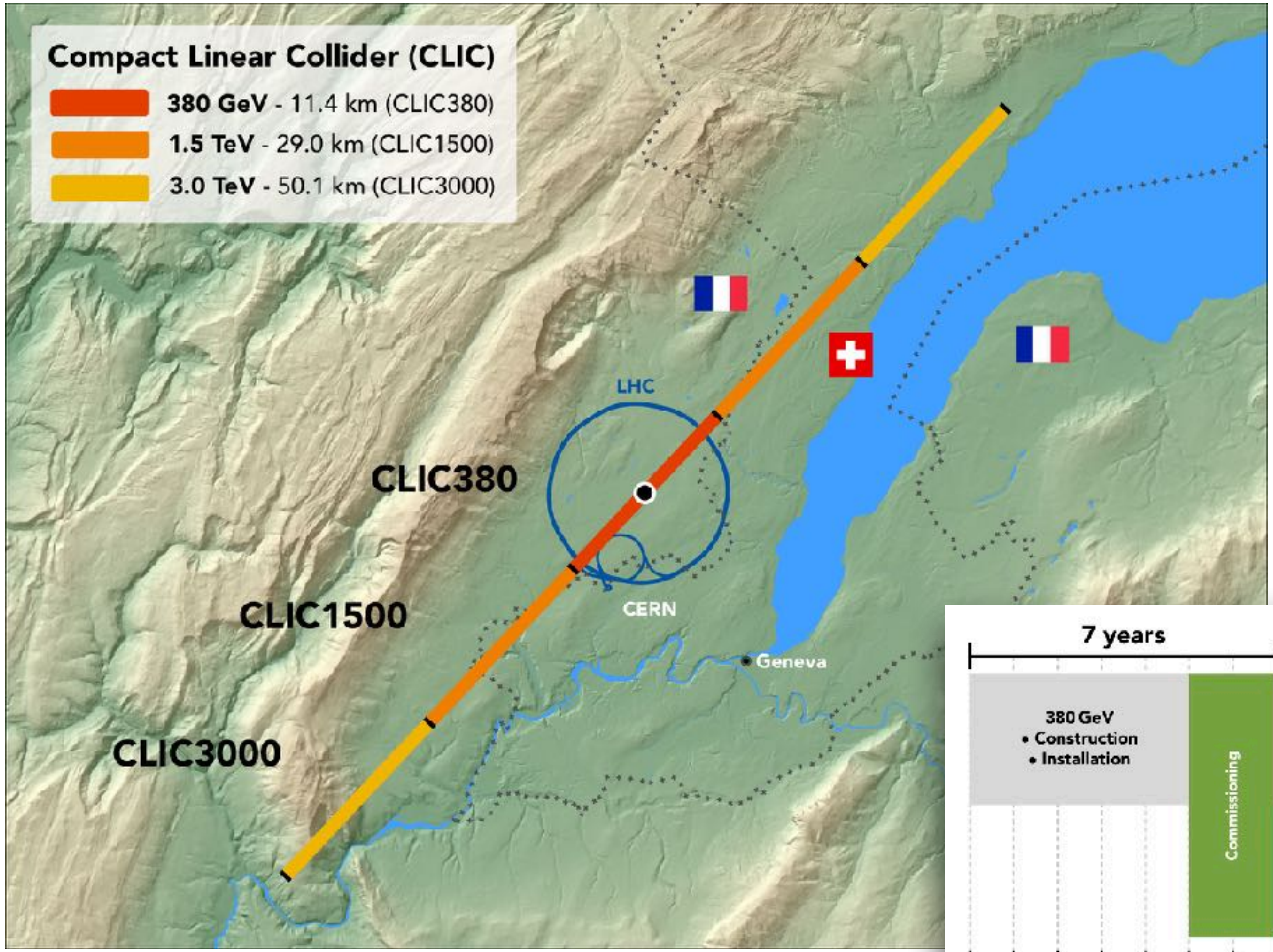
- ~50 institutes from 28 countries
- CLIC accelerator studies
- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility, CTF3

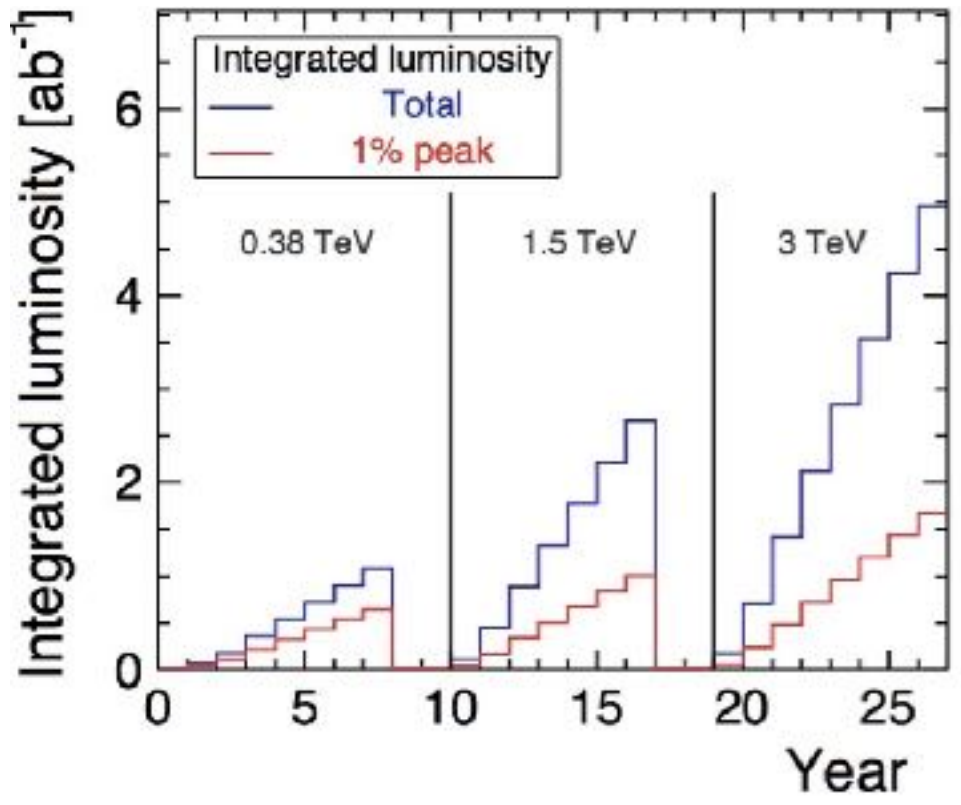
CLIC detector and physics (CLICdp)

- 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

CLIC accelerator footprint

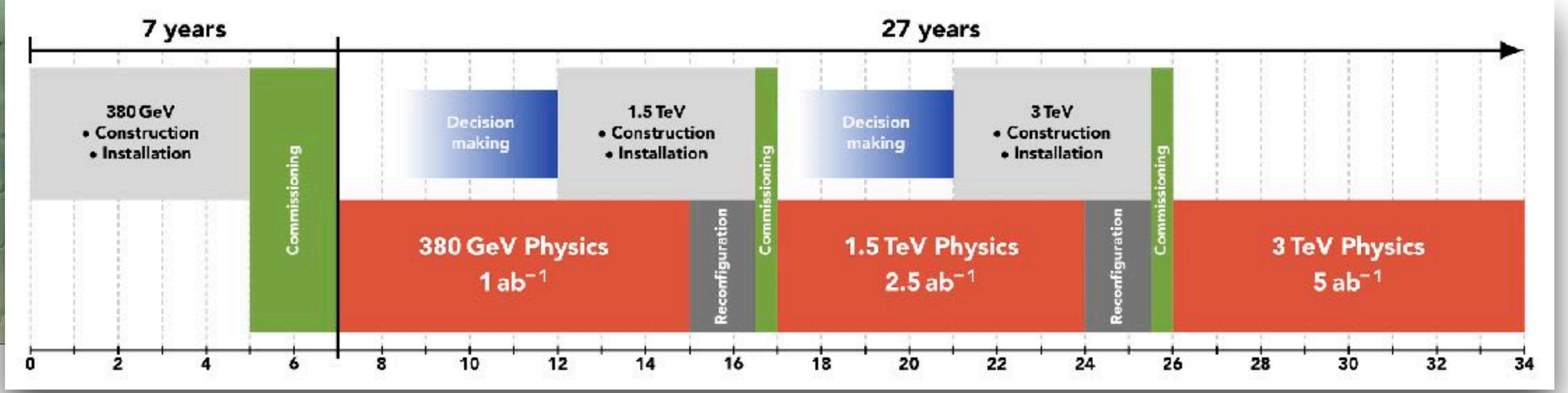




Ramp-up and up-time assumptions consistent with other future projects arXiv: 1810.13022, Bordry et al.

Technology-driven schedule from start of construction

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



Collision energy staging

- To fully exploit physics potential, CLIC would be implemented in several energy stages going up to multi-TeV energies
- **380 GeV** / **1.5 TeV** / **3.0 TeV**
- Electron beam polarisation at all stages
- The starting energy of 380 GeV is optimised and provides a **guaranteed physics programme**
- Emphasis on getting to multi-TeV collisions quickly
- Benefit of linear machine: length/energy staging plan can be updated in response to developing physics landscape
  - E.g. operation at the Z pole "Giga-Z" possible

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

- **Higgs/top** precision physics
- Top mass threshold scan

$\sqrt{s}$ = 1.5 (2.5 ab^{-1}) and 3 TeV (5.0 ab^{-1})

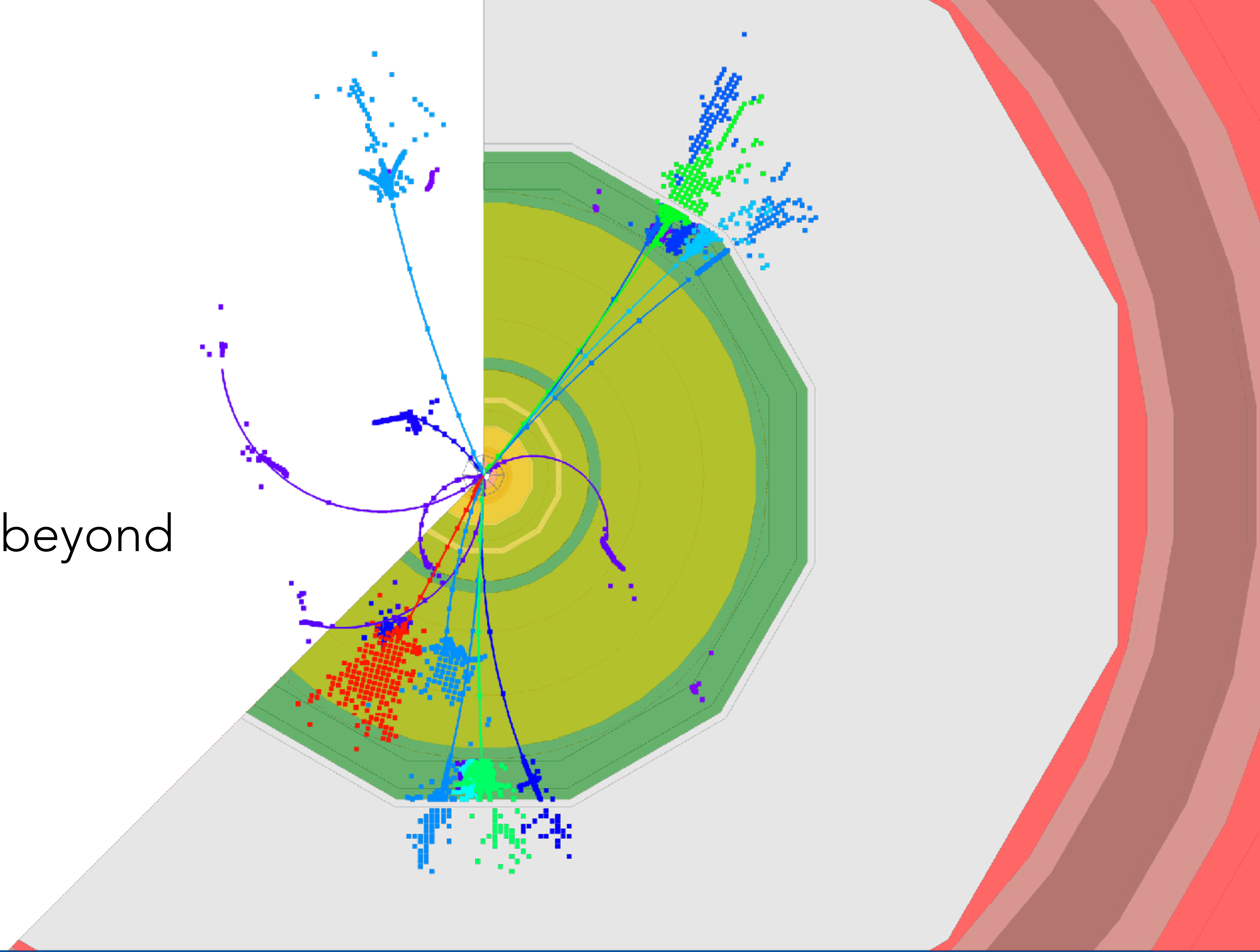
- Expanding Higgs/top studies including Higgs self-coupling
- Higher direct and indirect sensitivity to Beyond Standard Model (**BSM**)

CLIC pushes on both precision and energy frontiers, e.g. $\sigma(e^+e^- \to t\bar{t})$ to $\mathcal{O}(1\%)$ up to 3 TeV

$$\left|\frac{C}{\Lambda^2}\right| \lesssim \frac{\mathcal{O}(10\%)}{(\mathrm{TeV})^2} \quad \Longleftrightarrow \quad \left|\frac{C}{\Lambda^2}\right| \lesssim \frac{\mathcal{O}(0.1\%)}{(100\,\mathrm{GeV})^2}$$

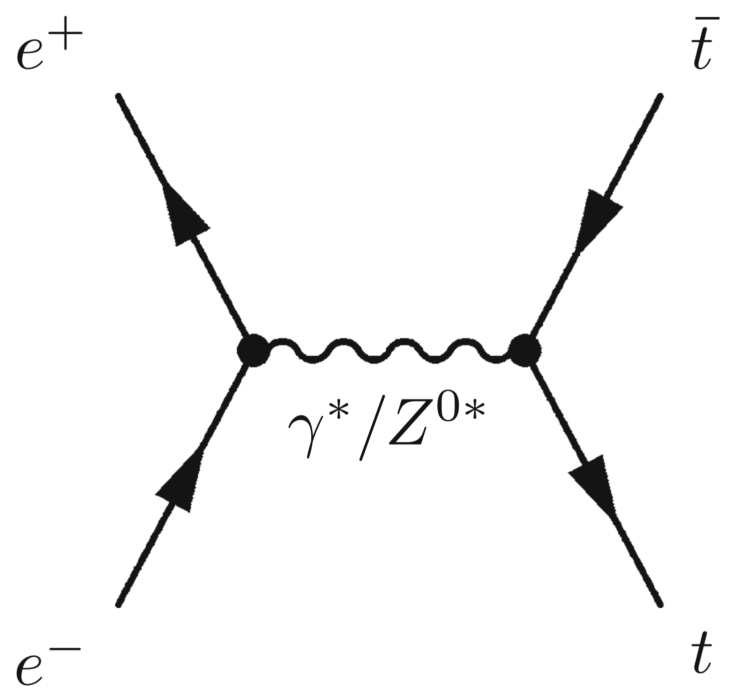
Physics reach

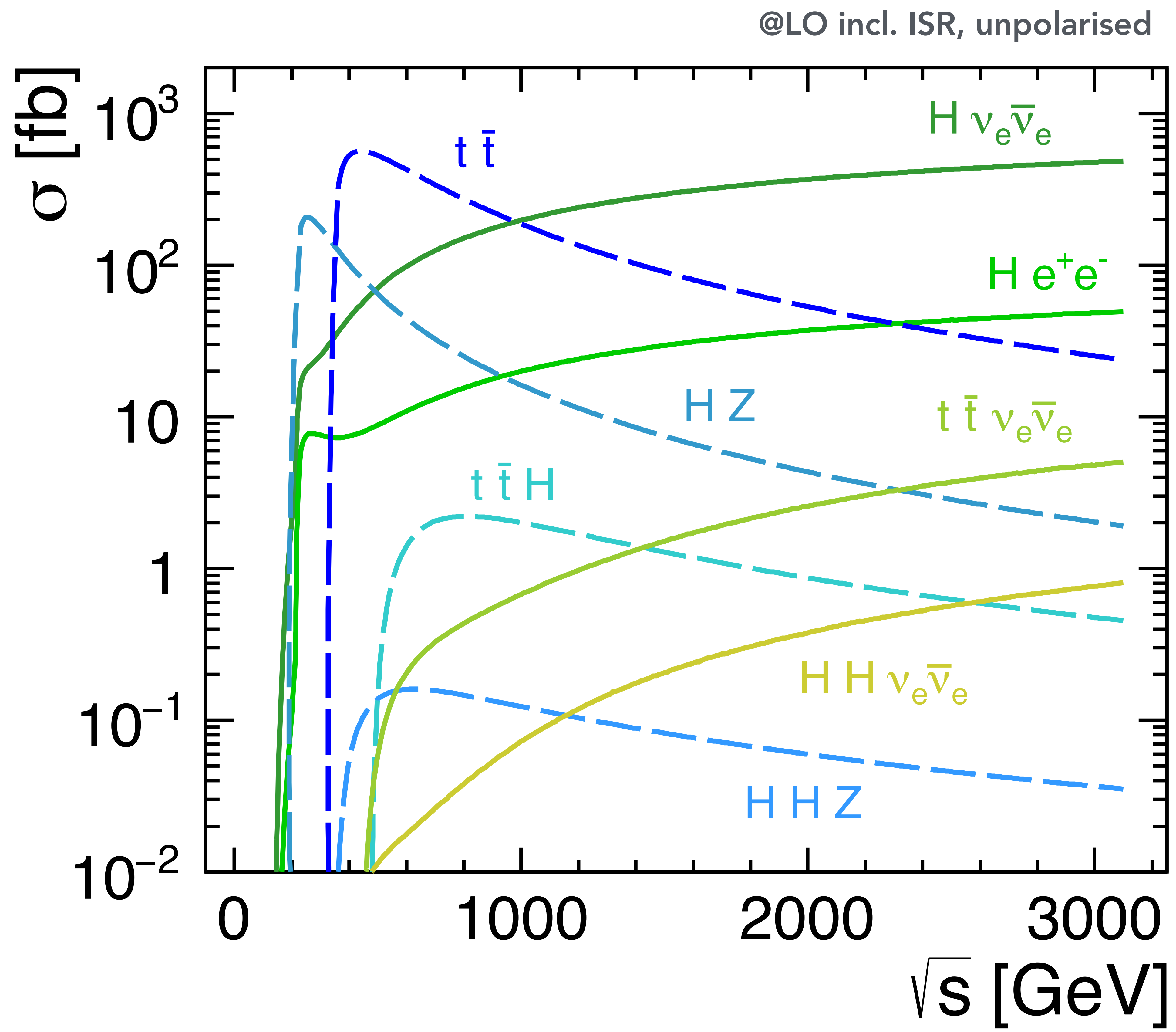
Standard Model & beyond



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})



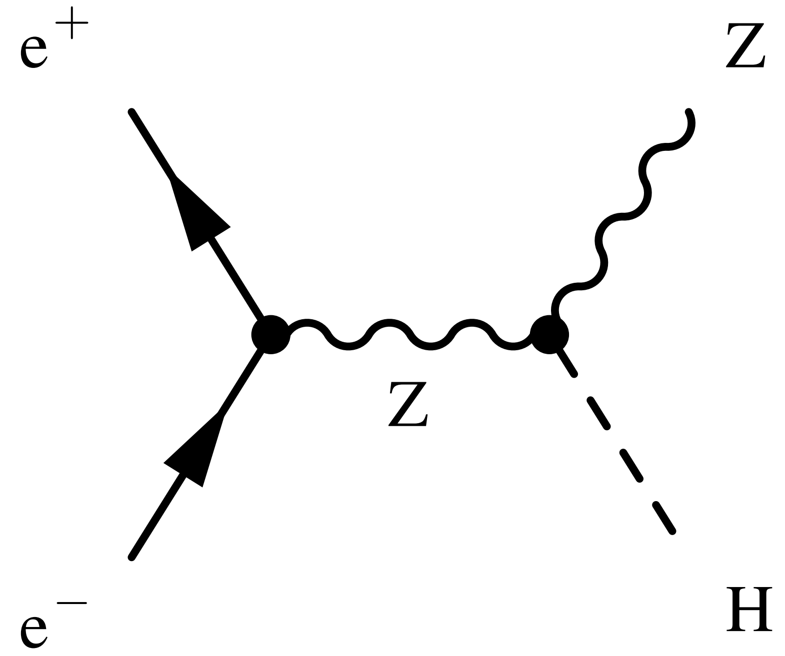


380 GeV
1 ab^{-1}

1.5 TeV
2.5 ab^{-1}

3 TeV
5.0 ab^{-1}

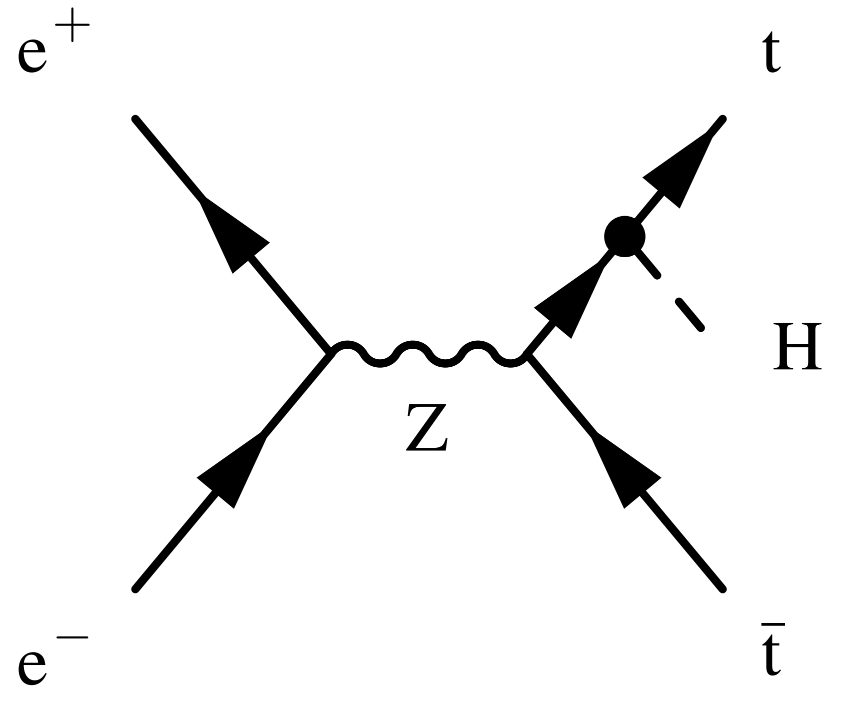
- **Higgsstrahlung** $e^+e^- \to HZ$ allows for absolute determination of **Higgs couplings to SM particles** – Z-recoil mass analysis

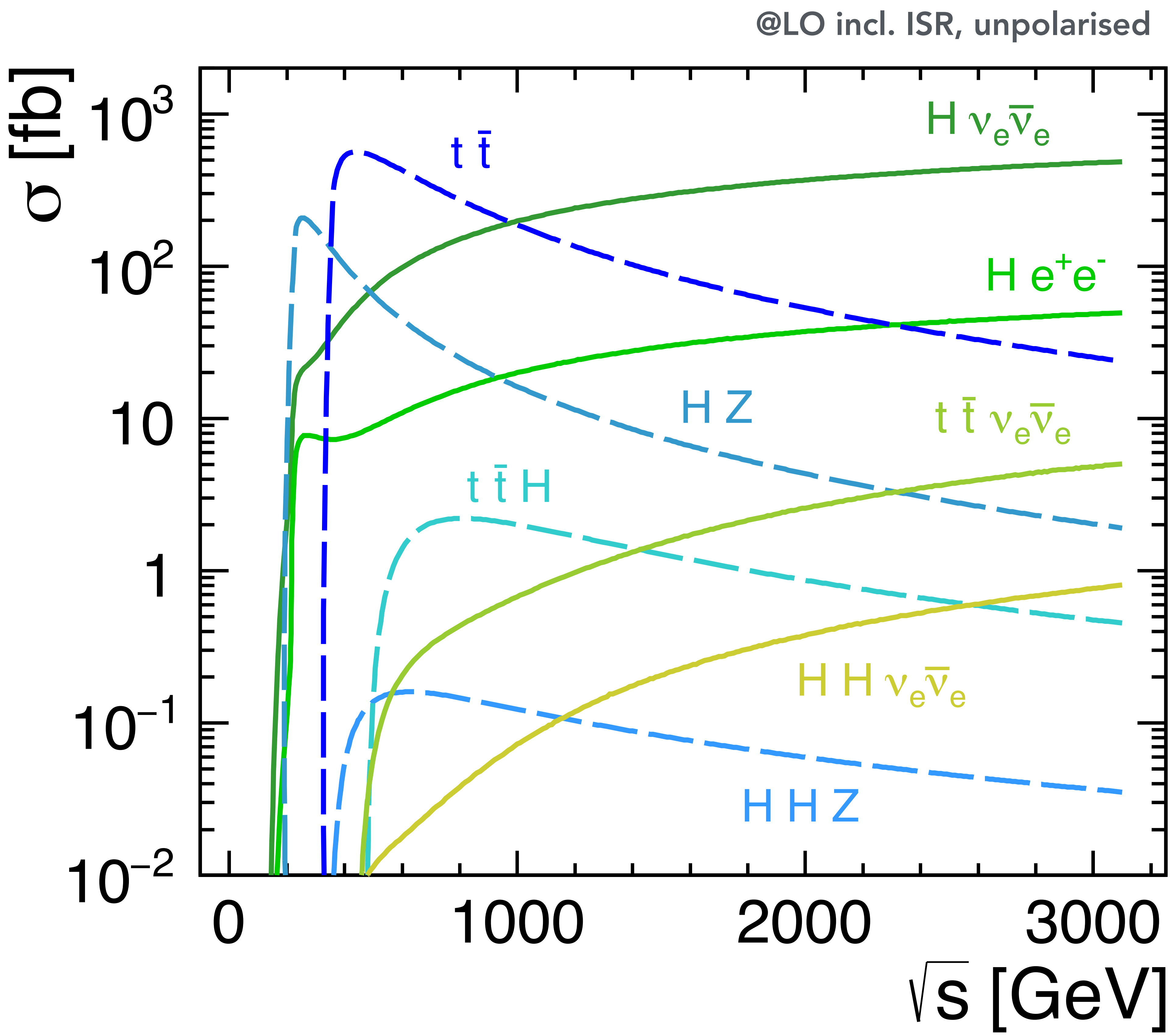


Higgs overview: Eur. Phys. J. C (2017)
Top overview: JHEP 11 (2019) 003

Dominant Higgs and top production at CLIC

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

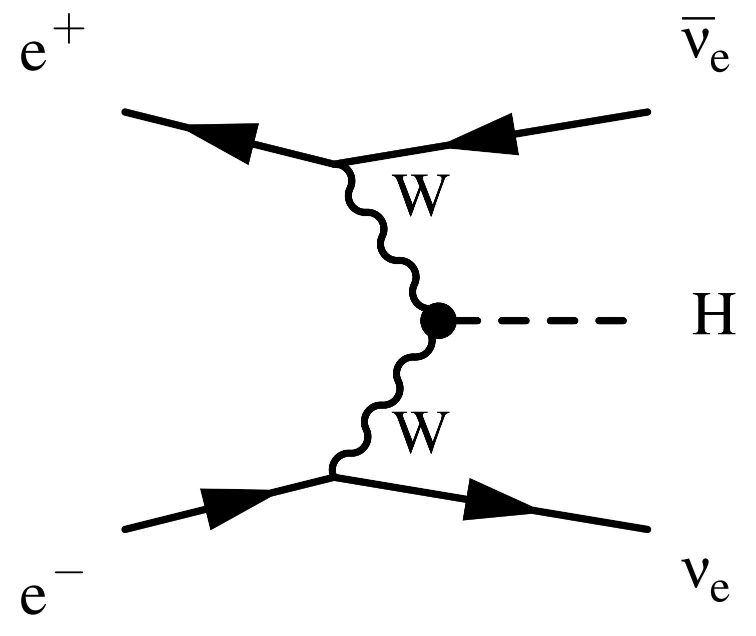




380 GeV
1 ab-1

1.5 TeV
2.5 ab-1

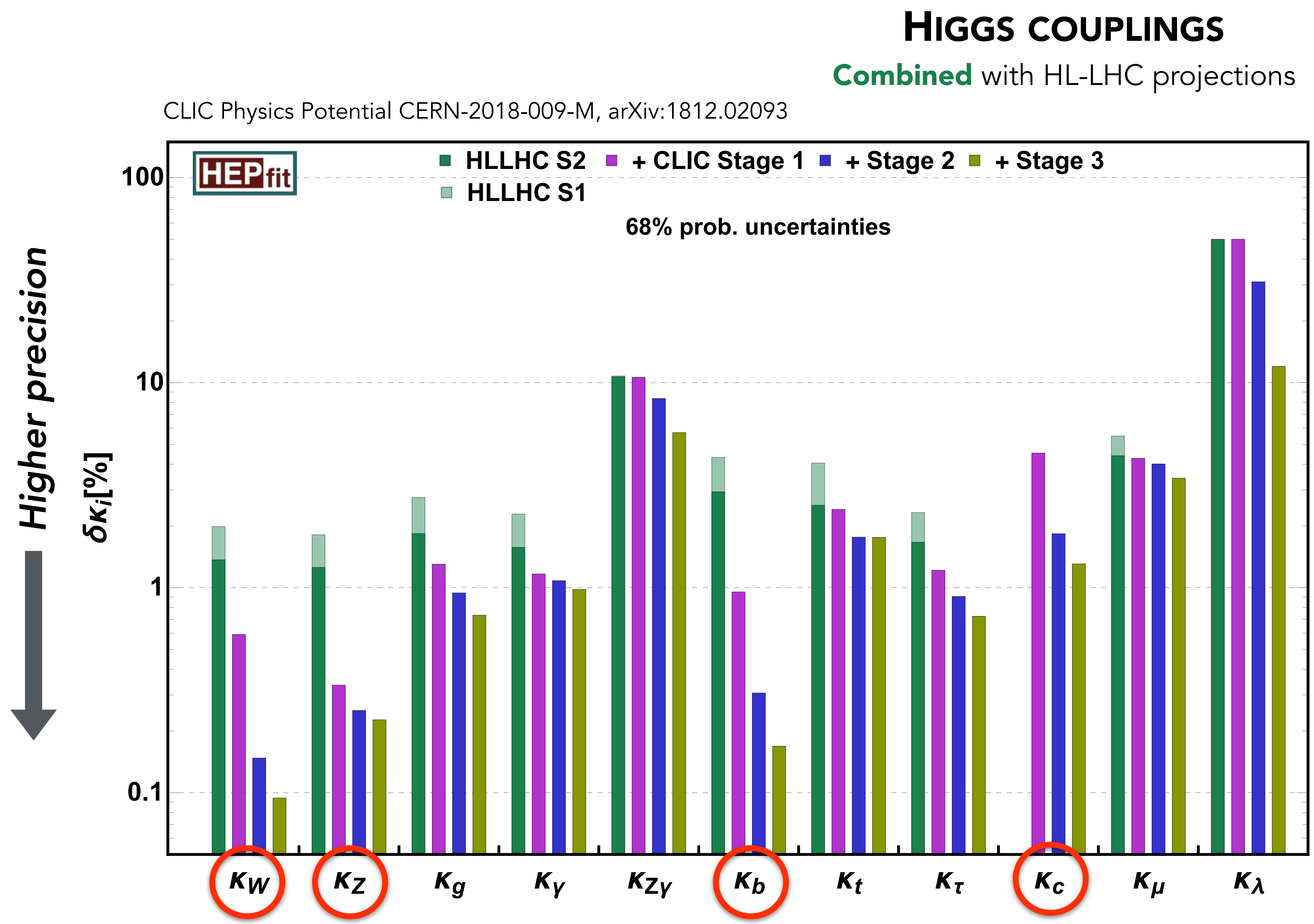
3 TeV
5.0 ab-1



- **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

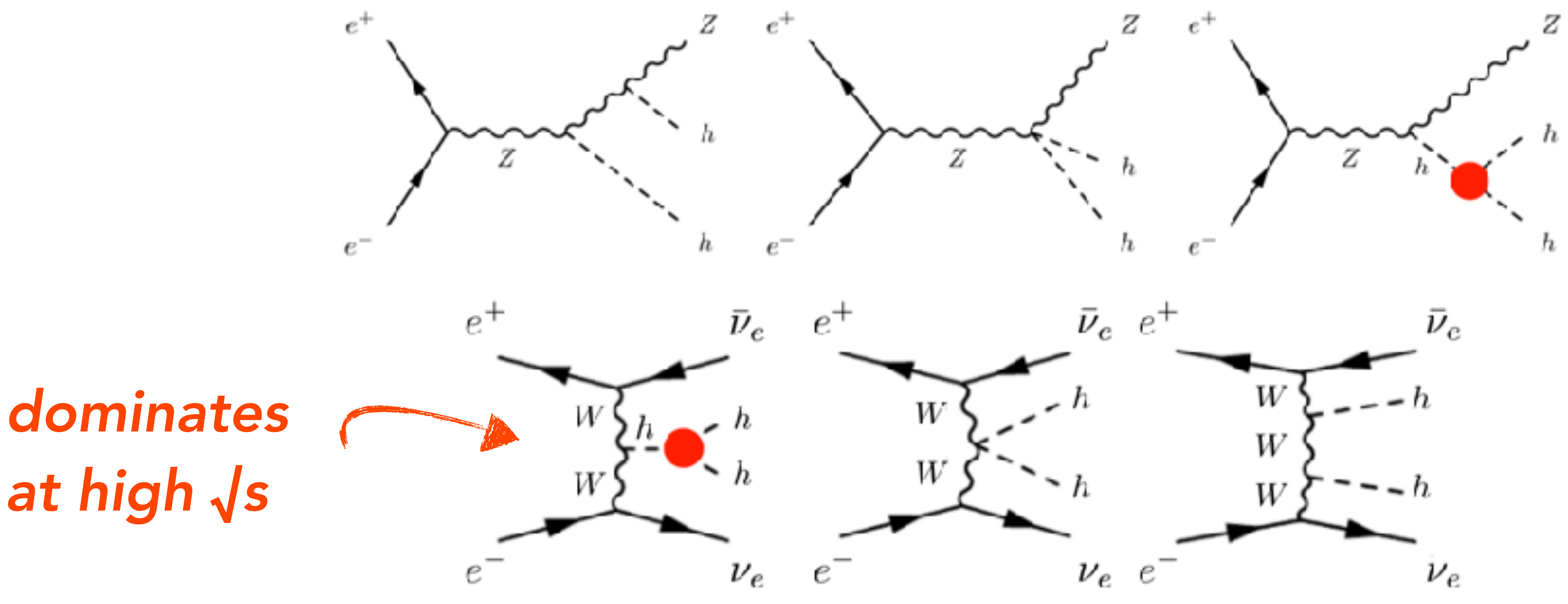
Precision Higgs couplings

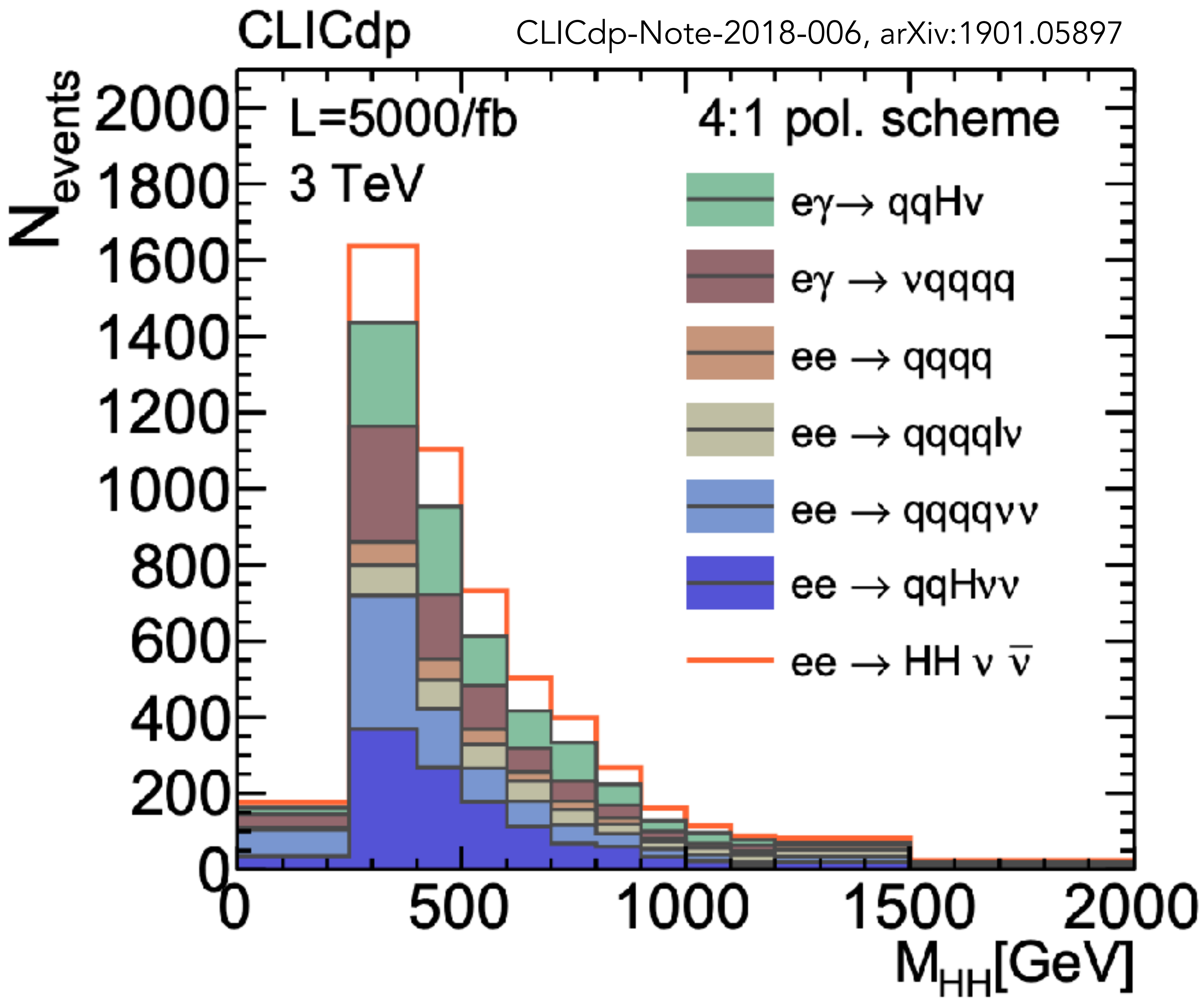


- CLIC enables **high-precision** measurements beyond HL-LHC (≲1% for most couplings)
- **Very large improvements for**
  - **W, Z, b, c**
- BR(H→inv.) < 0.69% at 90% CL (for 350 GeV CLIC)
- Γ_H is extracted with **4.7% (350 GeV) – 2.5% (3 TeV) precision**

Precision Higgs couplings

Higgs self-coupling

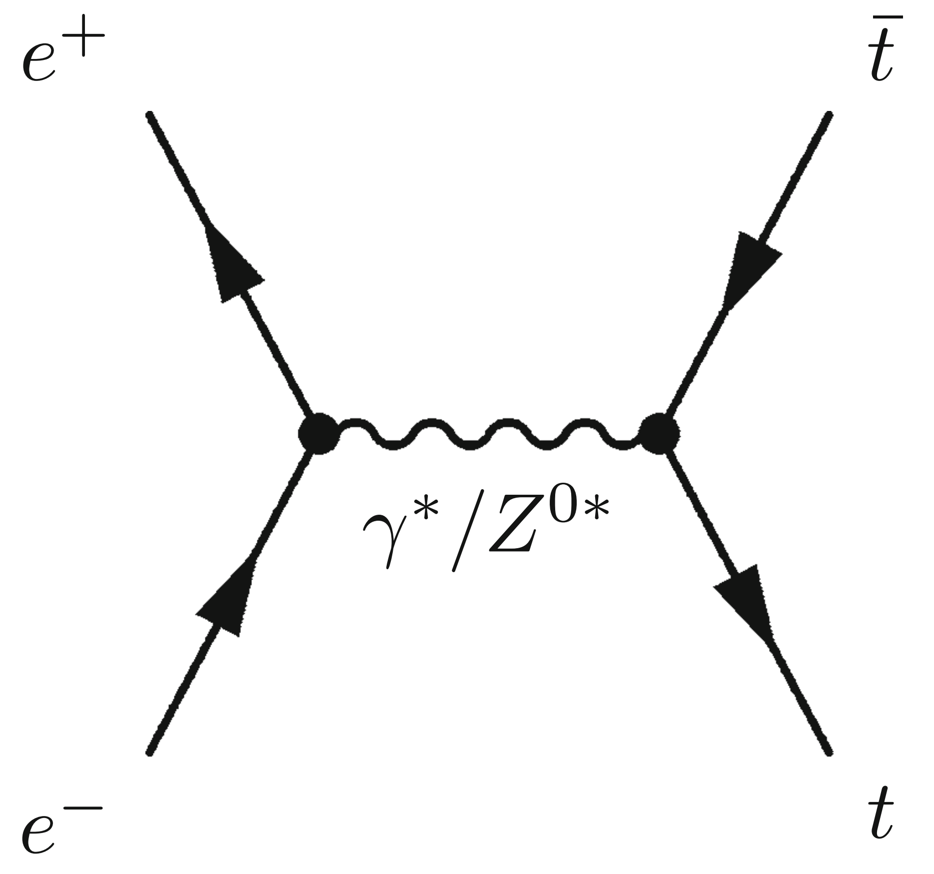


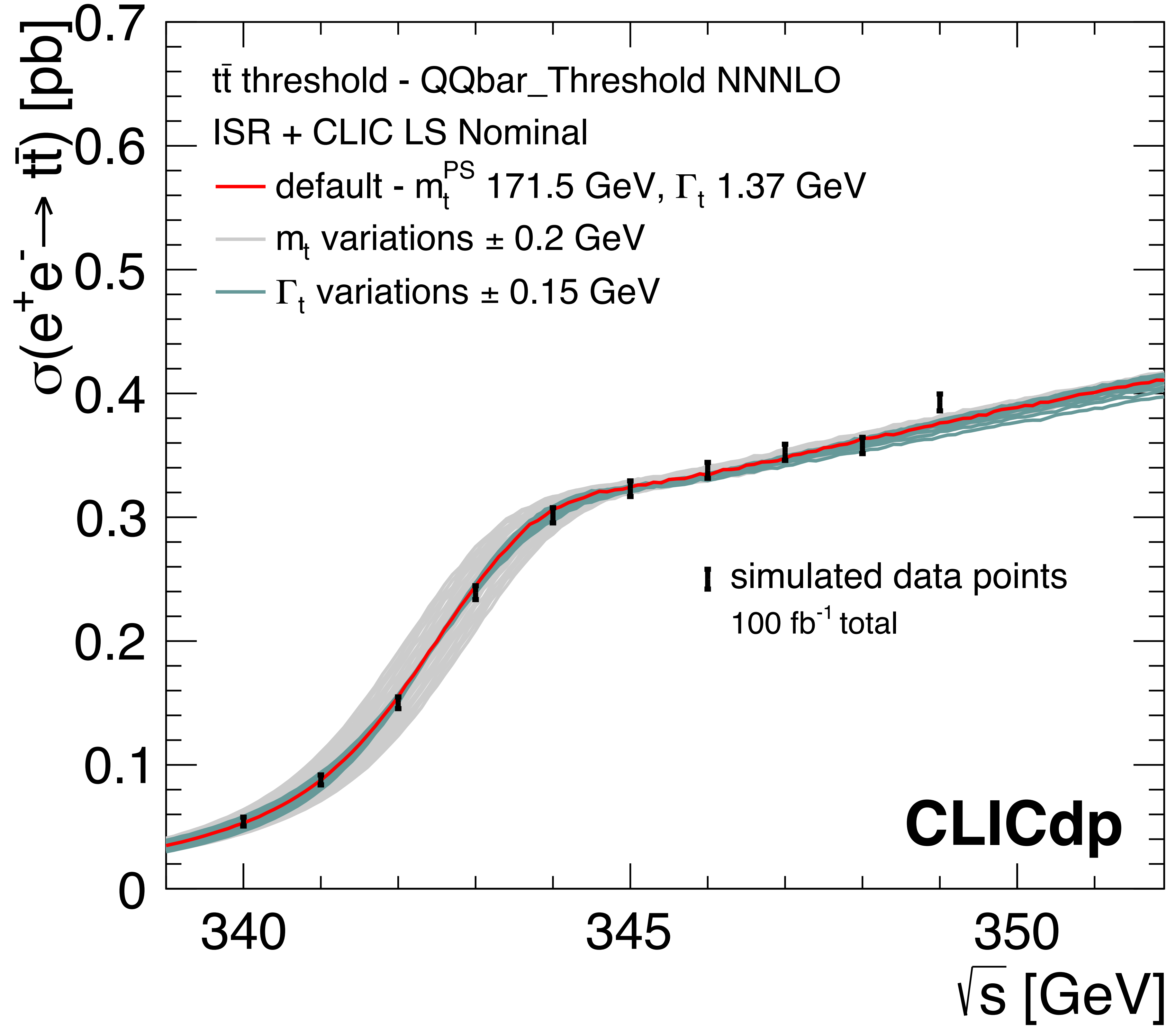


- **Direct access** to HH production at 1.5 and 3 TeV
- Challenging measurements – benefits from excellent heavy flavour tagging, jet energy resolution
- Template fit using two variables: M(HH) differential distribution and BDT score
- **Unique capability of CLIC**: measuring the Higgs self-coupling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

Top-quark mass from threshold scan

- Intending threshold scan near $\sqrt{s}$=350 GeV (10 points, ~1 year) as well as main initial-stage baseline $\sqrt{s}$=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

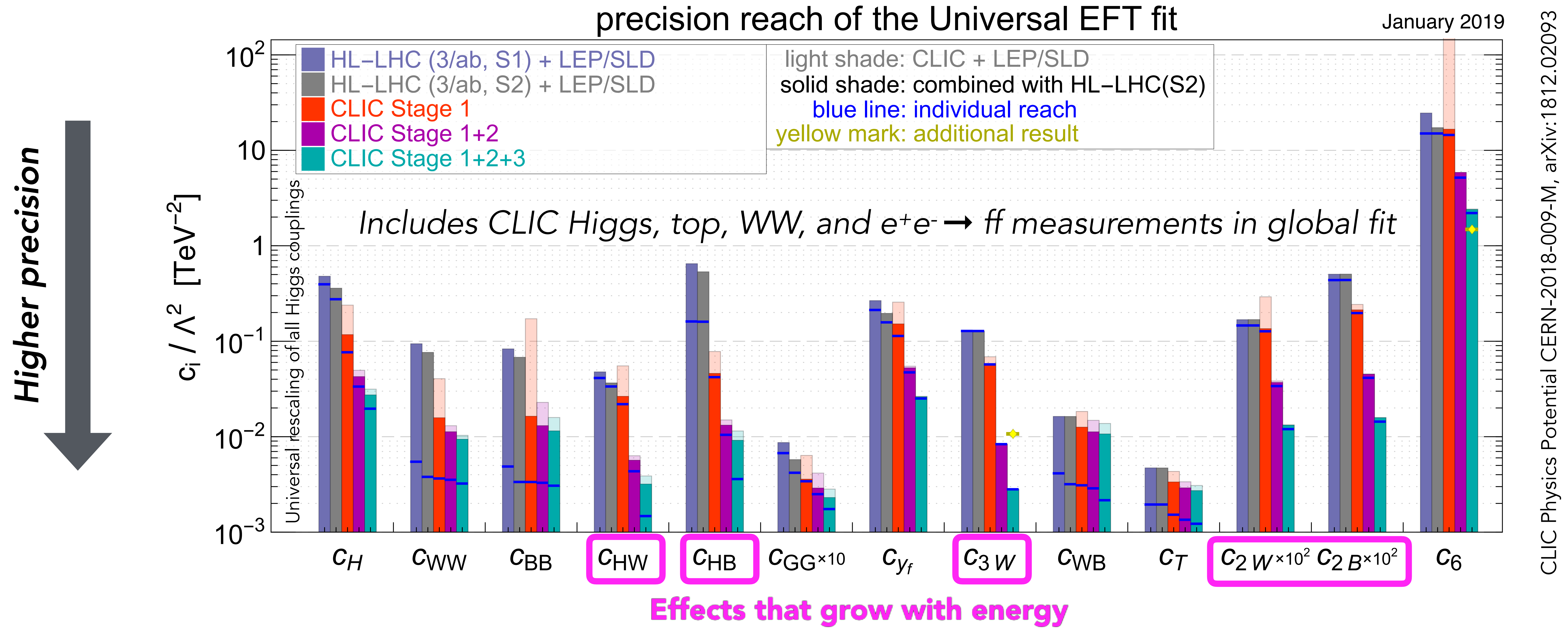
Global sensitivity to SMEFT BSM effects

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** — **New physics scale**

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



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

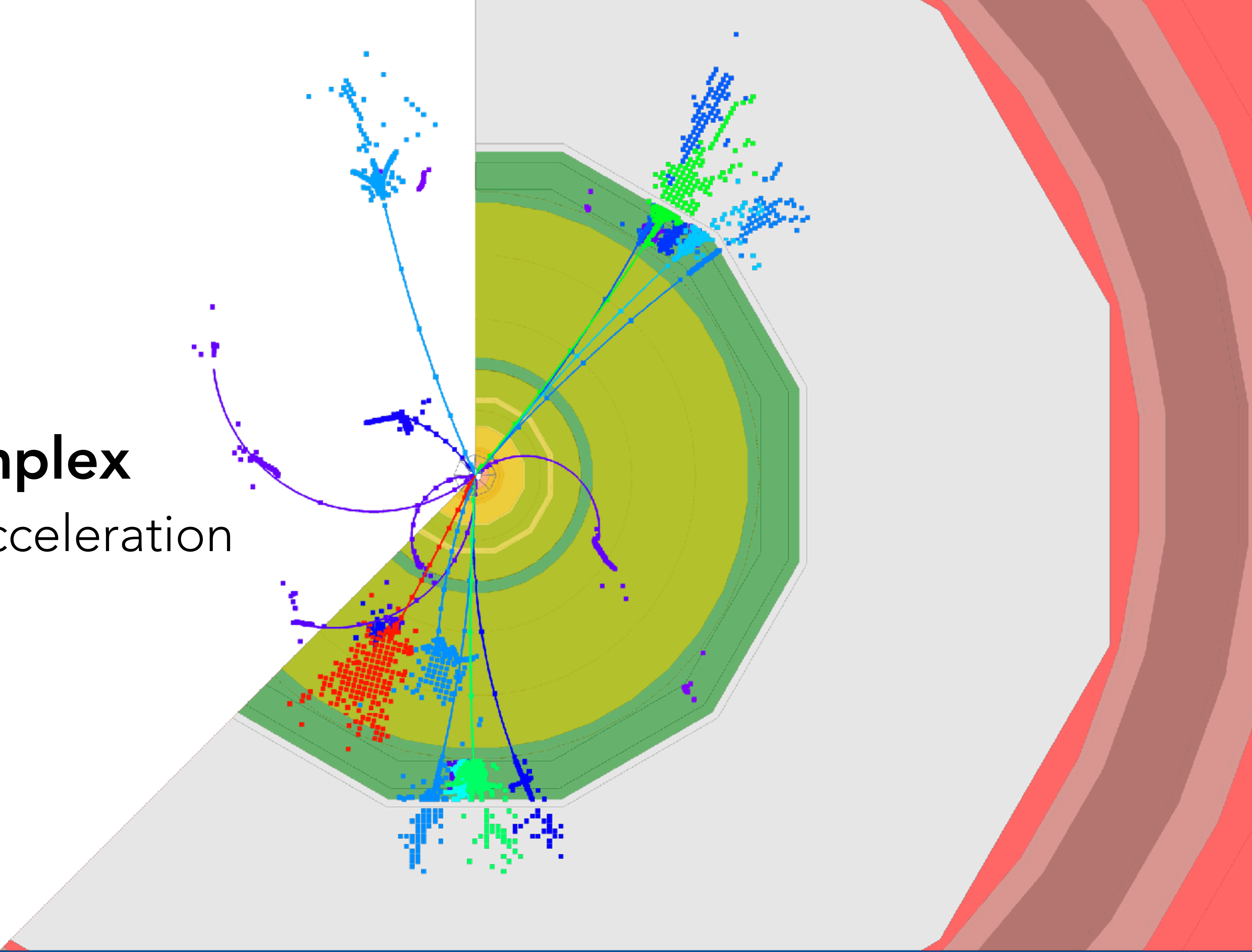
Process	HL-LHC	CLIC
Heavy Higgs scalar mixing angle $\sin^2\gamma$	$< 4\%$	$< 0.24\%$
Higgs self-coupling $\Delta\lambda$	$\sim 50\%$ at 68% C.L.	$[-7\%, +11\%]$ at 68% C.L.
BR(H $\rightarrow$ invisible)		$< 0.69\%$ at 90% C.L.
Higgs compositeness scale m_*	$m_* > 3$ TeV (> 7 TeV for $g_* \simeq 8$)	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 ($0.03\,\mathrm{m} < c\tau < 30\,\mathrm{m}$)
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

Accelerator complex

Novel two-beam acceleration



The two-beam acceleration concept

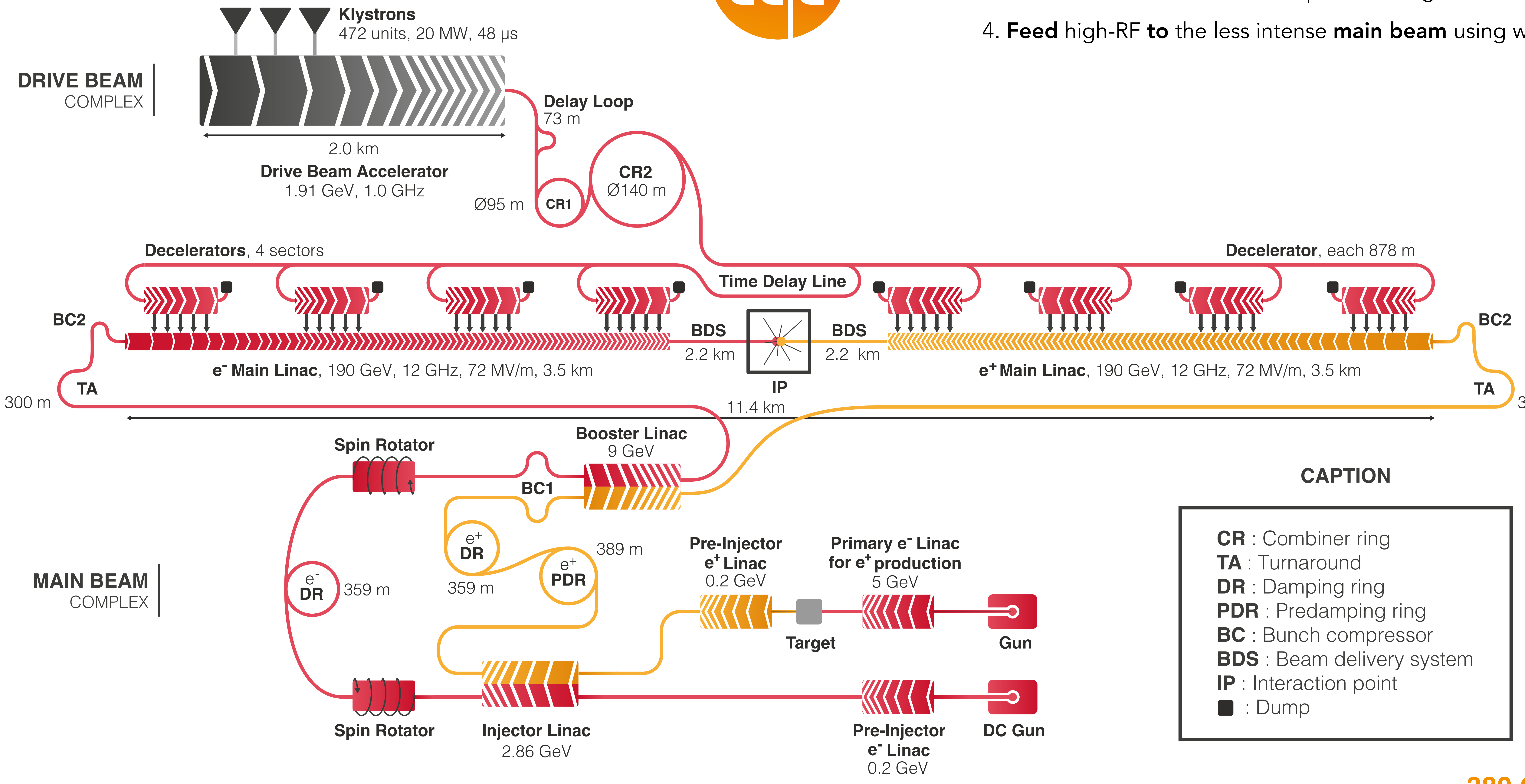
Why?

- **Compact** accelerator (~tens of km) ➜ **High acceleration fields** ➜ **High frequency RF** is a challenge
- **Klystrons** (amplifiers for high radio frequencies) used for particle acceleration, but scale unfavourably beyond a few GHz (maximum delivered power and efficiency)
- In the CLIC acceleration scheme, the klystrons are replaced with an intense particle beam, called the **drive beam**
  - Low-frequency klystrons efficiently generate long RF-pulses and their energy is stored in a long, high-current drive-beam pulse
  - The kinetic energy in the drive beam is converted into short high-peak RF pulses, which in turn is used to accelerate the main beams for collision

How?

1. **Drive beam** accelerated to a few GeV using conventional klystrons
2. **Frequency increased** using a series of delay loops and combiner rings
3. **Drive beam decelerated** through Power Extraction and Transfer Structures (PETS) producing high-RF
4. **Feed** high-RF **to** the less intense **main beam** using waveguides

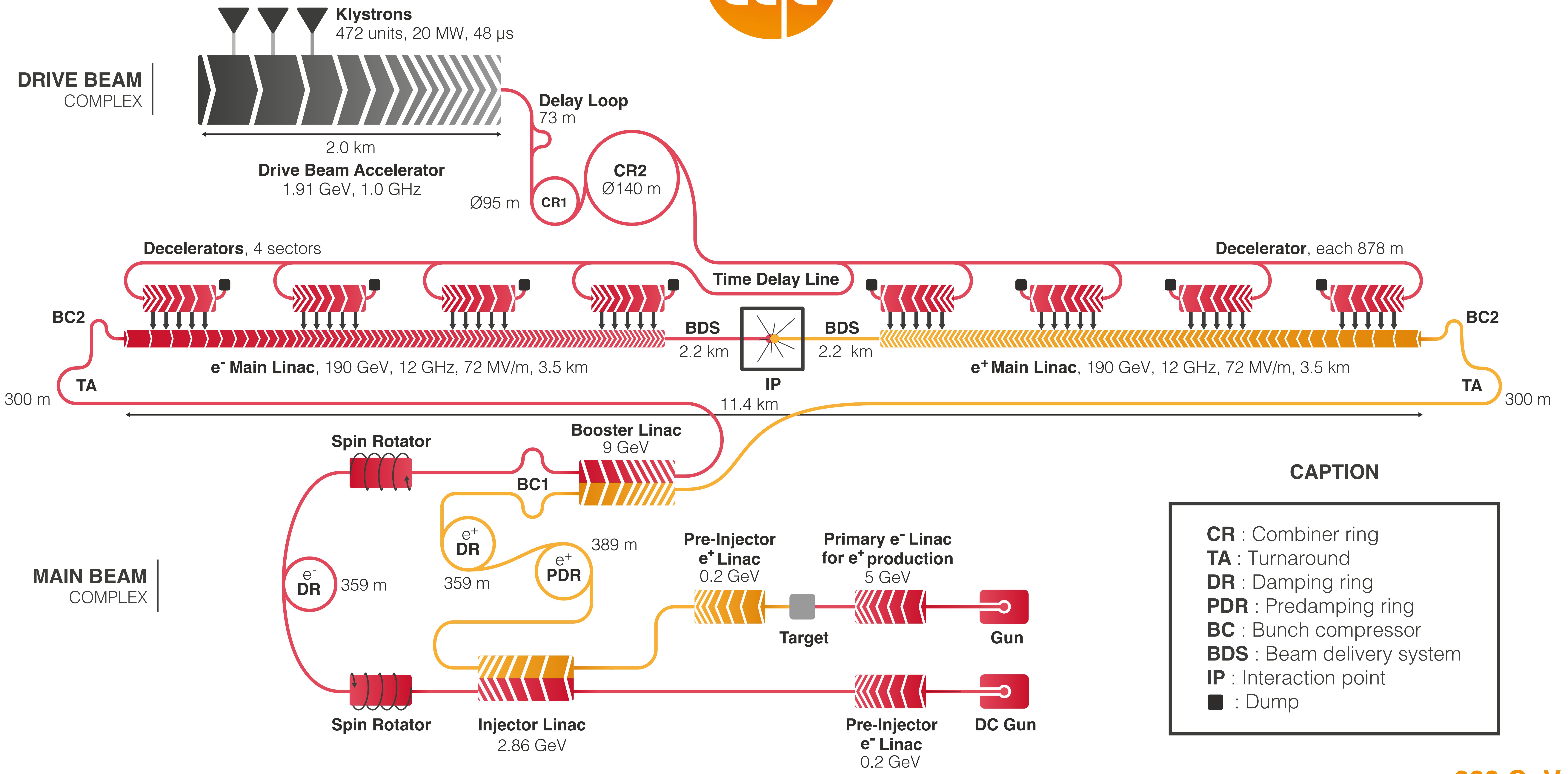
1. **Drive beam** accelerated to a few GeV using conventional klystrons
2. **Frequency increased** using a series of delay loops and combiner rings
3. **Drive beam decelerated** and produces high-RF
4. **Feed** high-RF **to** the less intense **main beam** using waveguides



CAPTION

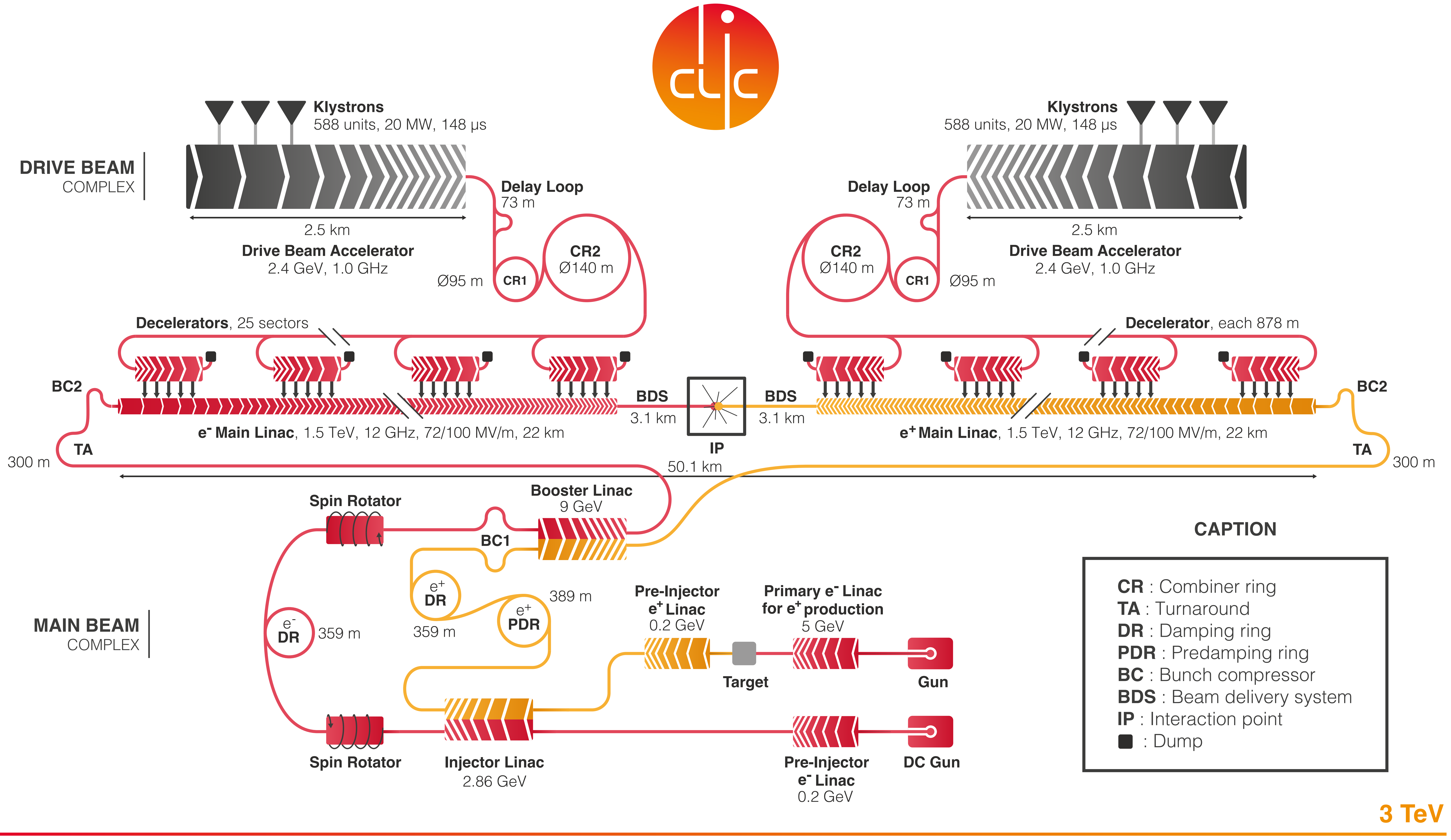
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

380 GeV



380 GeV

CLIC - Scheme of the Compact Linear Collider (CLIC)



CLIC - Scheme of the Compact Linear Collider (CLIC)


DRIVE BEAM COMPLEX
Klystron
588 units / 20 MW / 148 μs
Klystron
588 units / 20 MW / 148 μs
Delay loop
73 m
Delay loop
73 m
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
CR1
95 m
CR2
140 m
CR2
140 m
CR1
95 m
Decelerators / 25 sectors
Decelerators / each 878 m
Detector
BC2
BC2
BDS
3.1 Km
BDS
3.1 Km
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
TA
300 m
TA
300 m
Spin Rotator
Booster Linac
9 GeV
BC1
Pre-Injector
e^+ Linac
0.2 Gev
Primary e^- Linac
e^+ production
5 Gev
MAIN BEAM COMPLEX
e^- DR
359 m
e+ DR
359 m
e+ PDR
389 m
Target
Gun
Spin Rotator
Injector Linac
2.86 GeV
Pre-Injector
e^- Linac
0.2 GeV
DC Gun

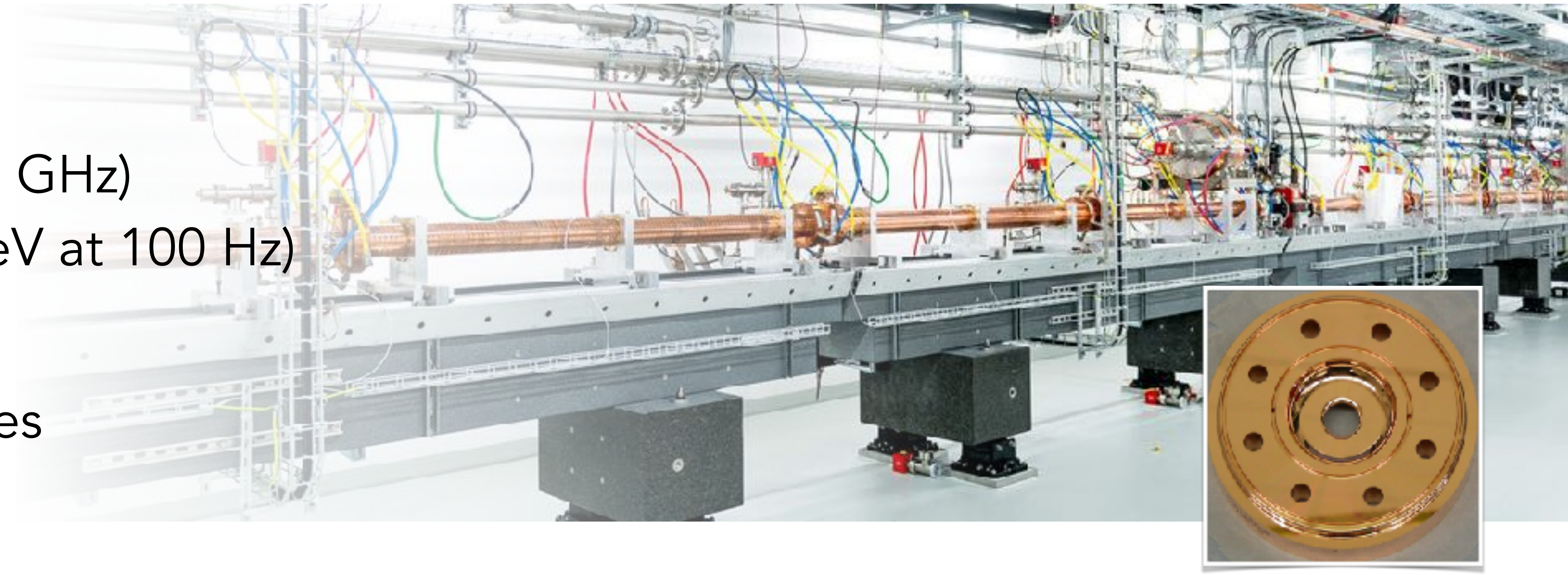
Accelerator challenges

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. ~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
- Two C-band XFELS (SACLA and SwissFEL) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

Technology applications

Photo: SwissFEL/PSI



SwissFEL: C-band linac

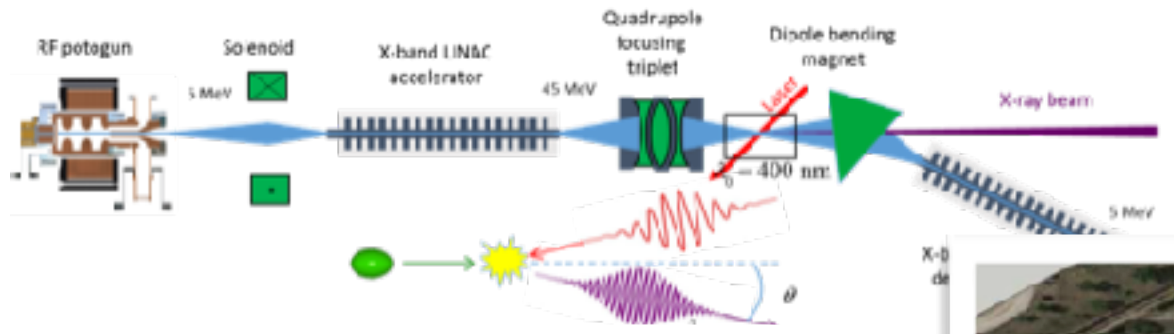
- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar μm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned

See academic training by W. Wuensch for more details: https://indico.cern.ch/event/668151/

CompactLight

CLIC technology for different applications

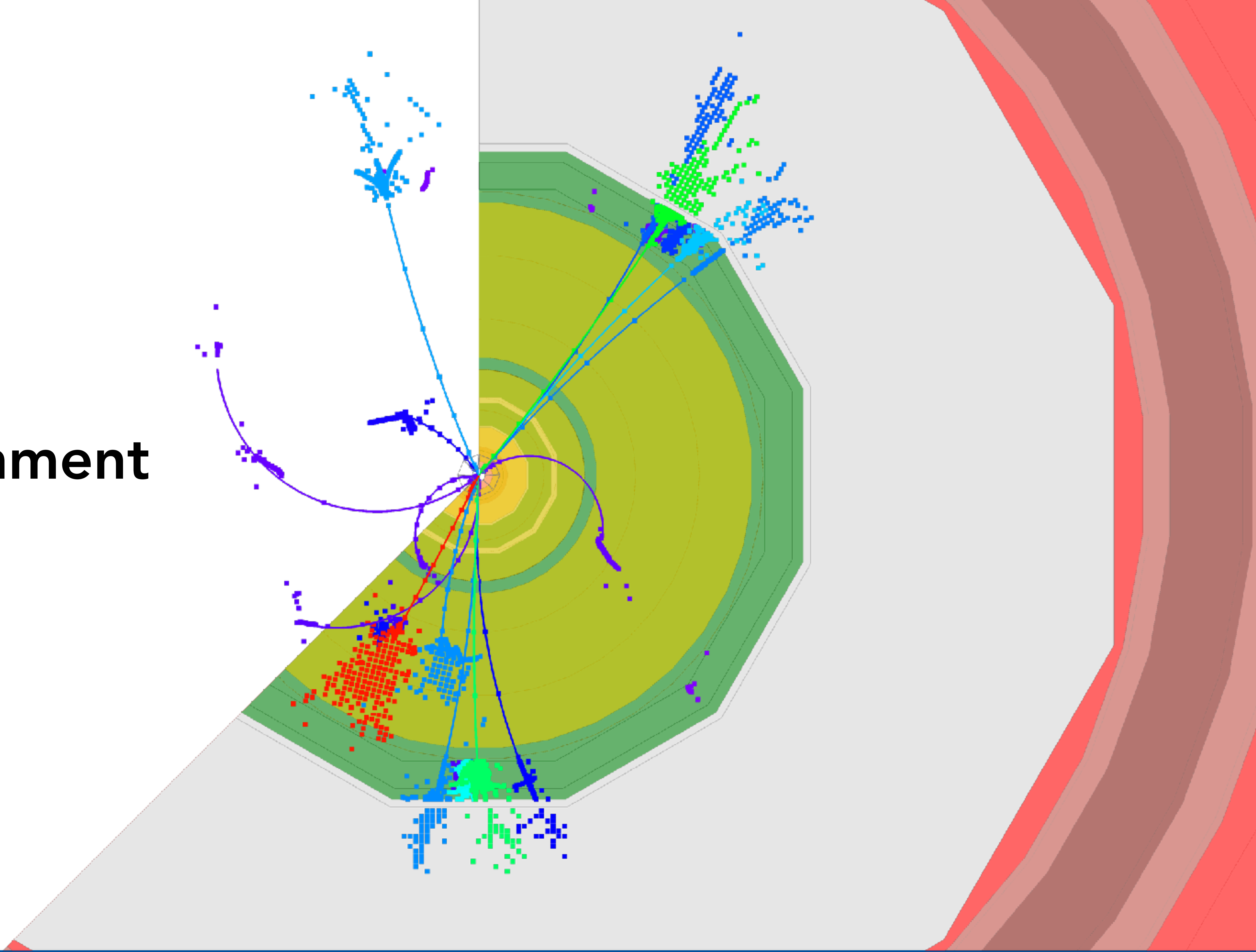
- EU co-funded FEL design study
- SPARC at INFN-LNF
- …many other small systems…



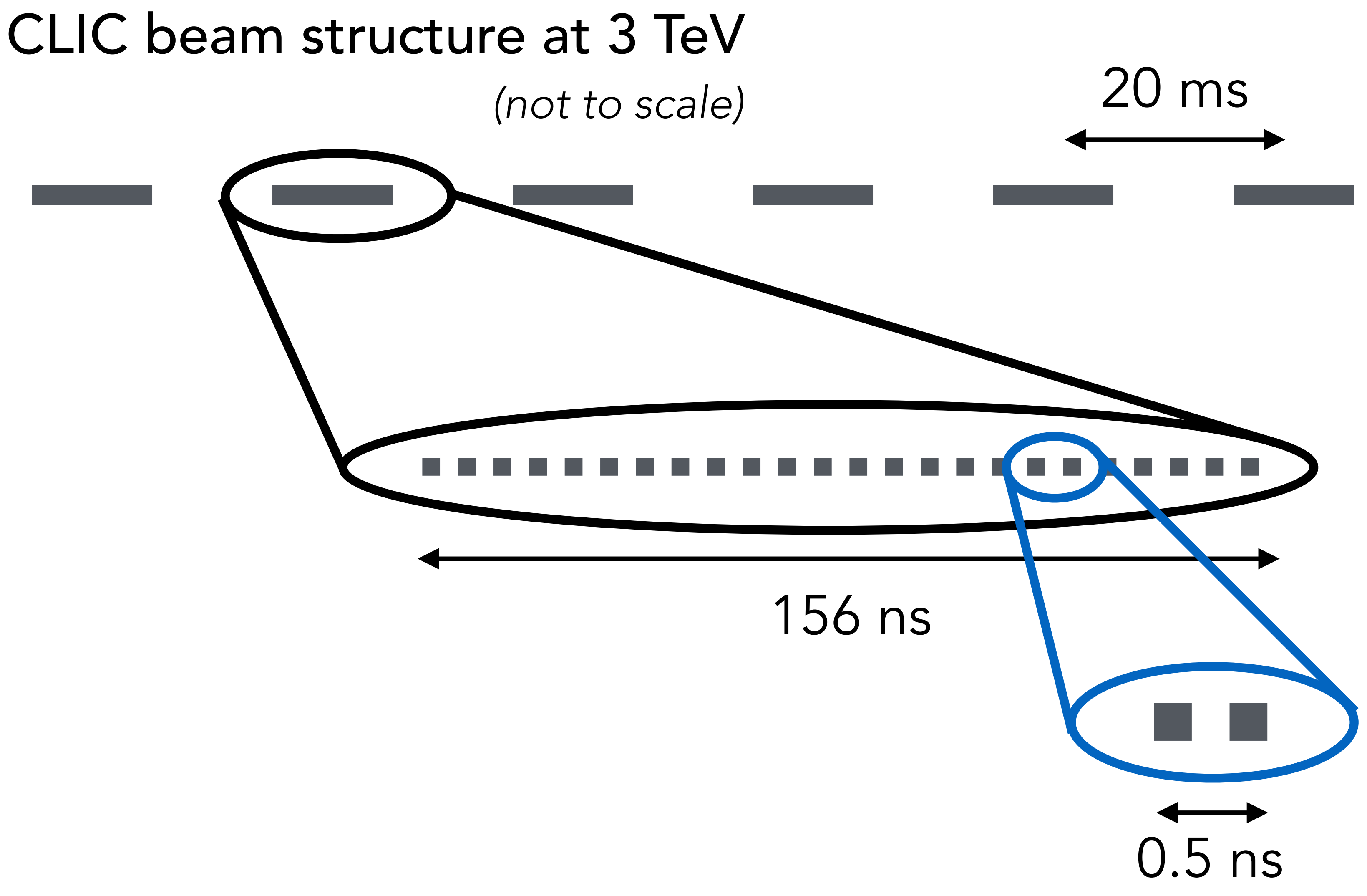
Eindhoven University led **SMART*LIGHT** Compton Source

INFN Frascati advanced acceleration facility **EuPRAXIA@SPARC_LAB**

Collider environment



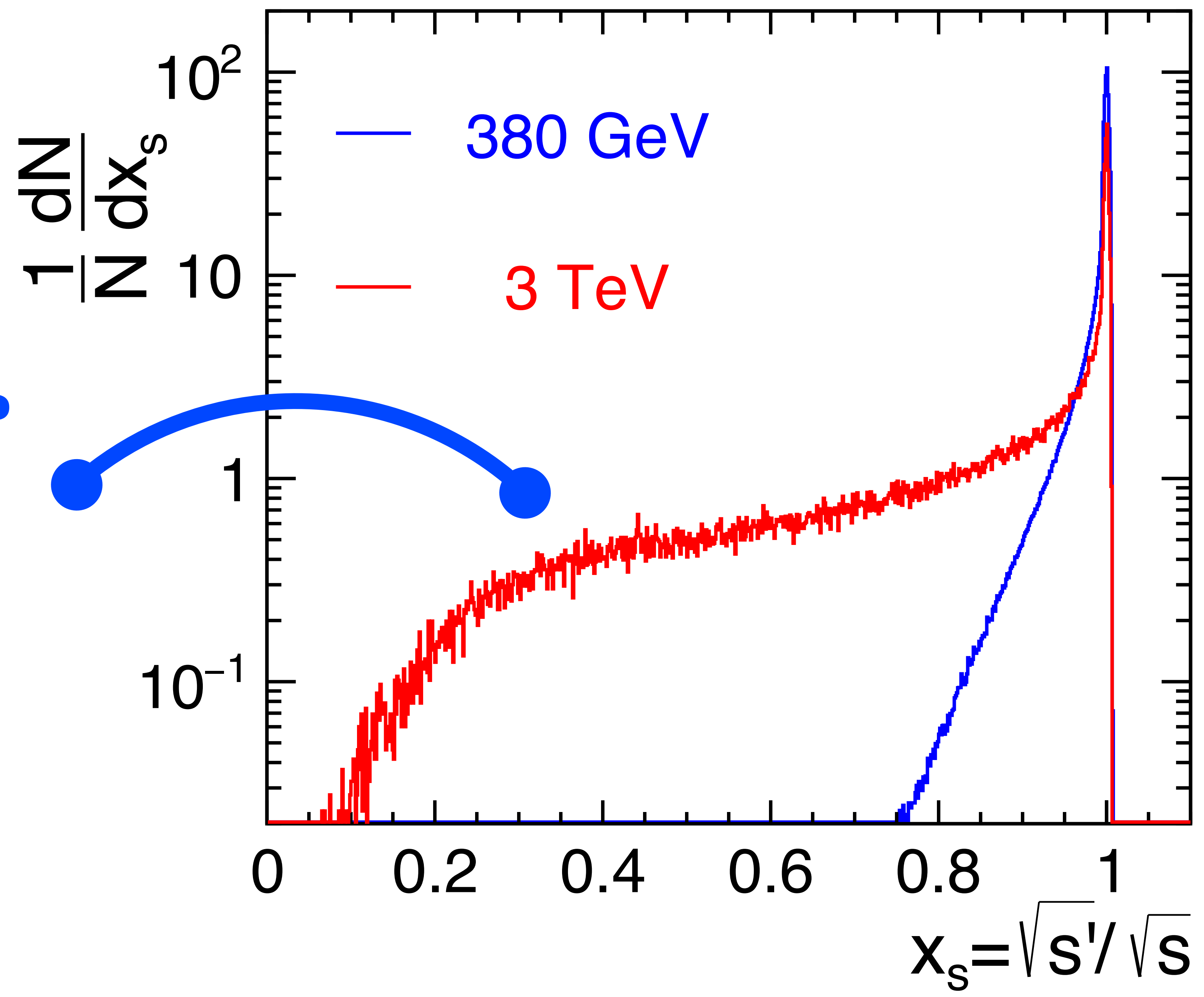
Collider environment



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

Energy loss at IP leads to energy spectrum

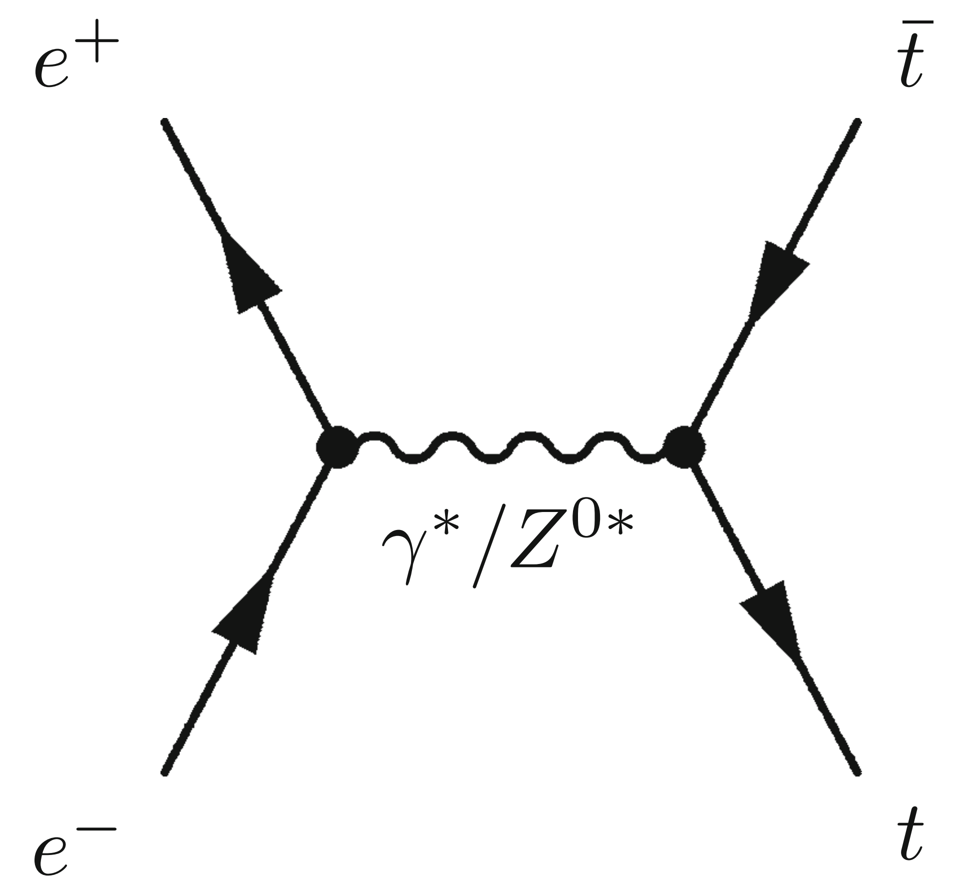
CLIC luminosity spectrum



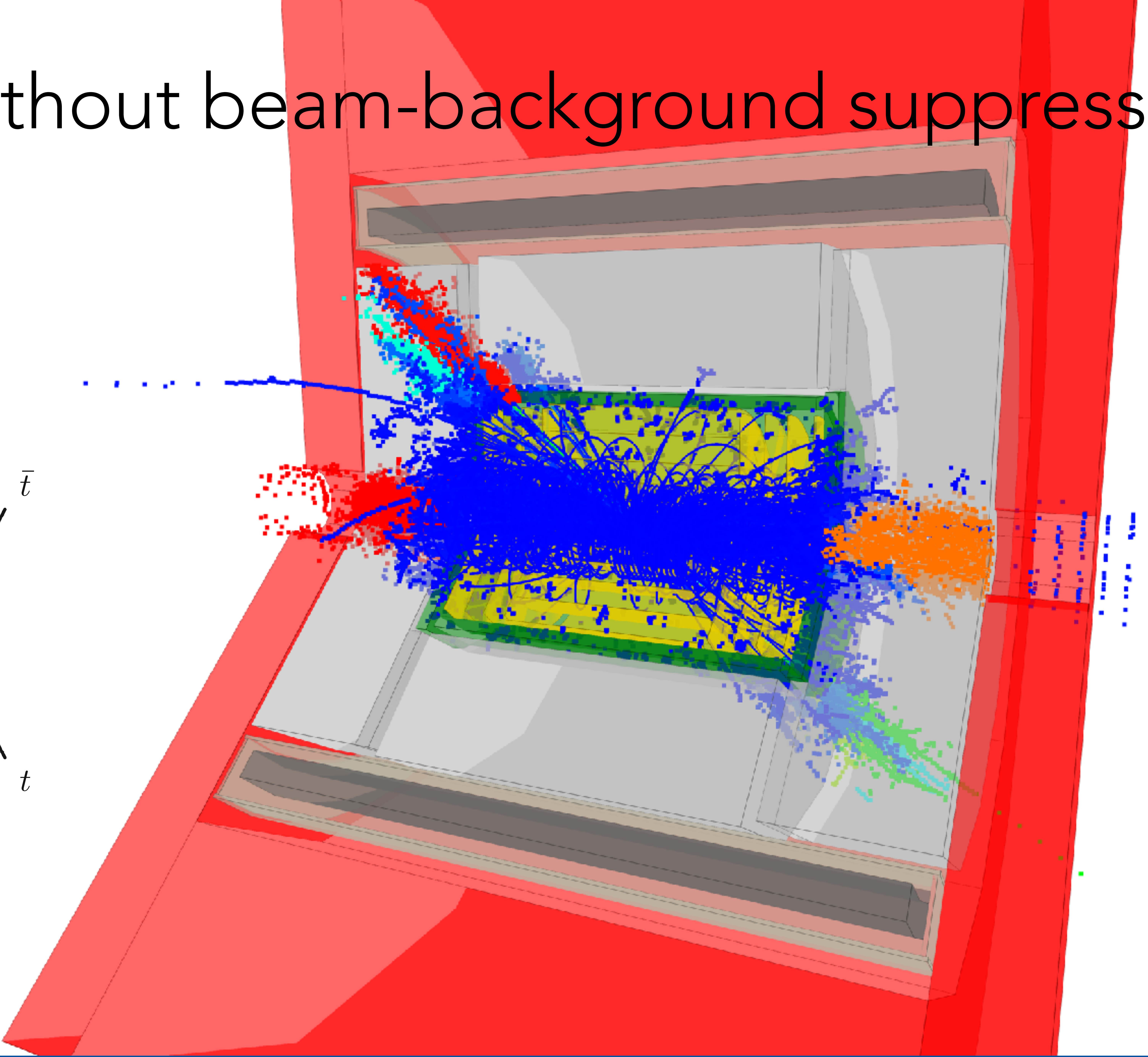
- High luminosities are achieved by using **extremely small beam sizes**
- 3 TeV: bunch size $\sigma_{x;y;z}$ = {40 nm; 1nm; 44 μm}
- Very high bunch charge density → beam-related backgrounds with **impact** on detector design and physics measurements
- Small effect at 380 GeV, large effect at high energies
- 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

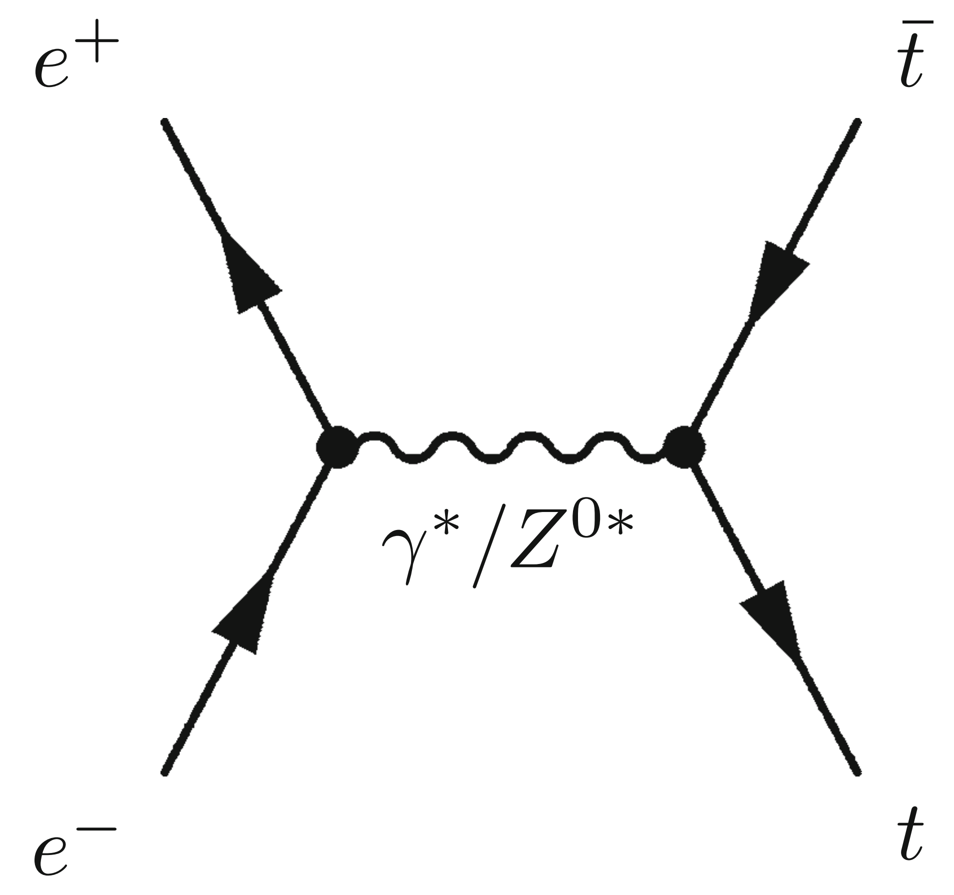
Without beam-background suppression



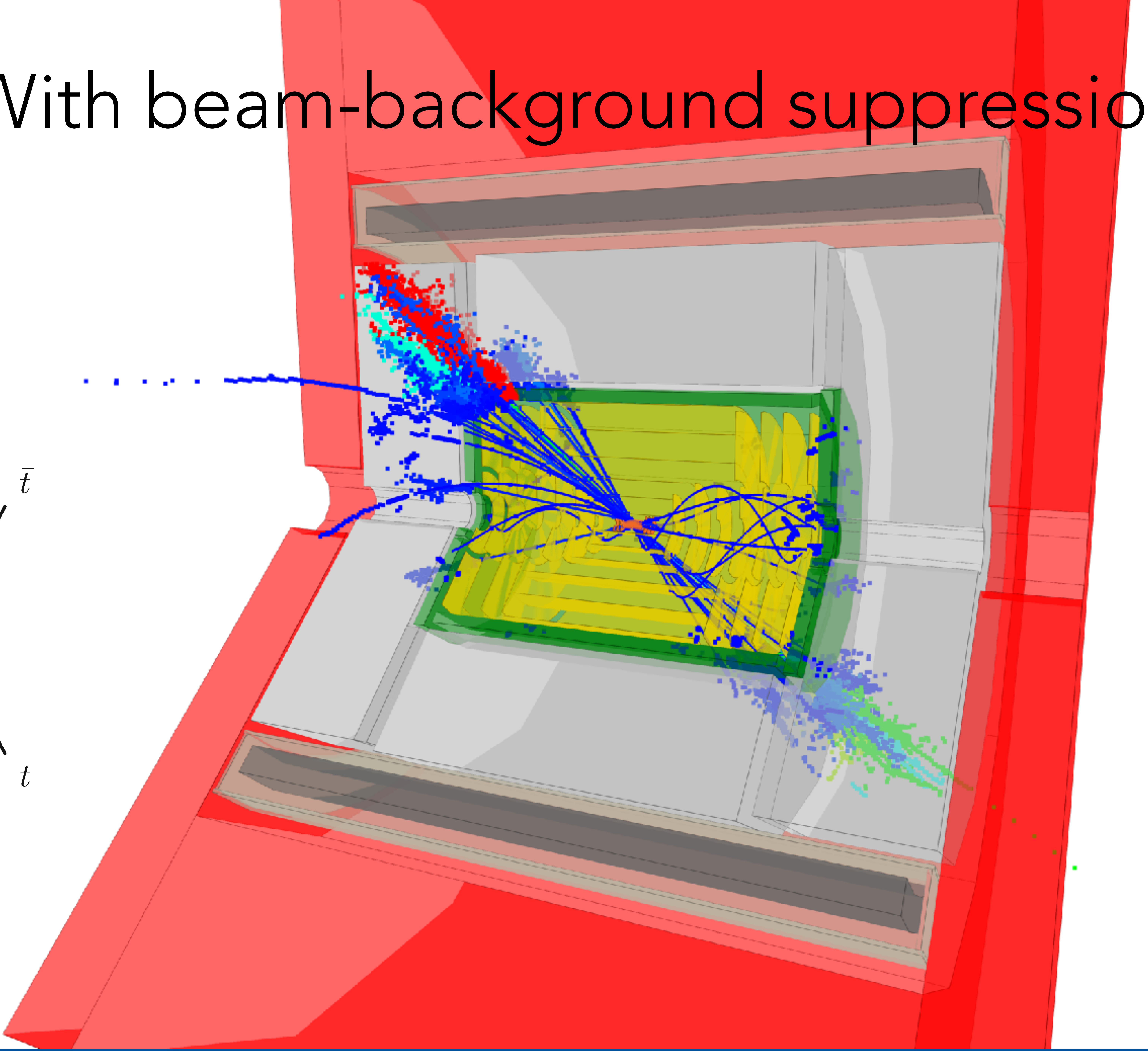
√s = 3 TeV
fully-hadronic



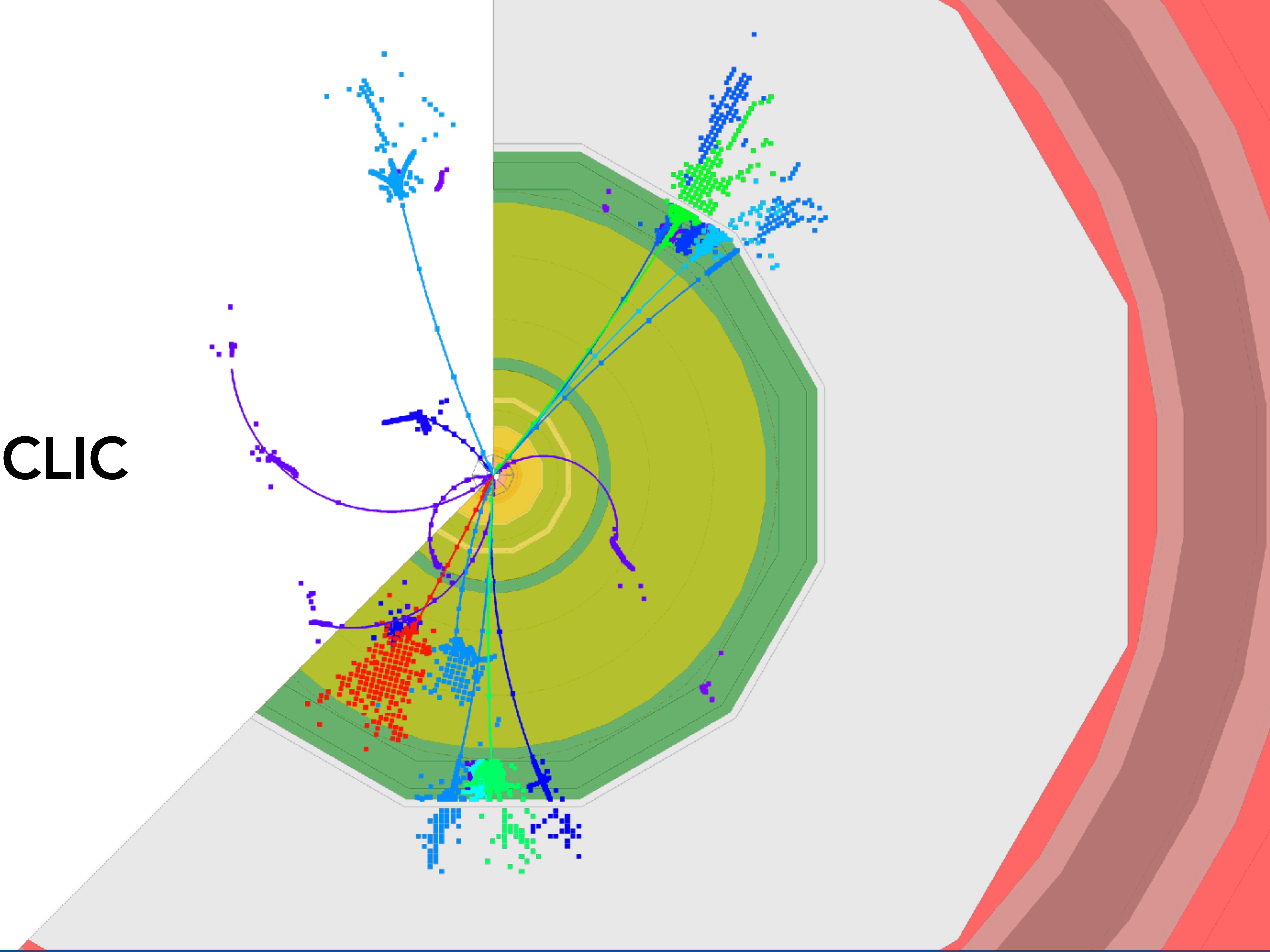
With beam-background suppression



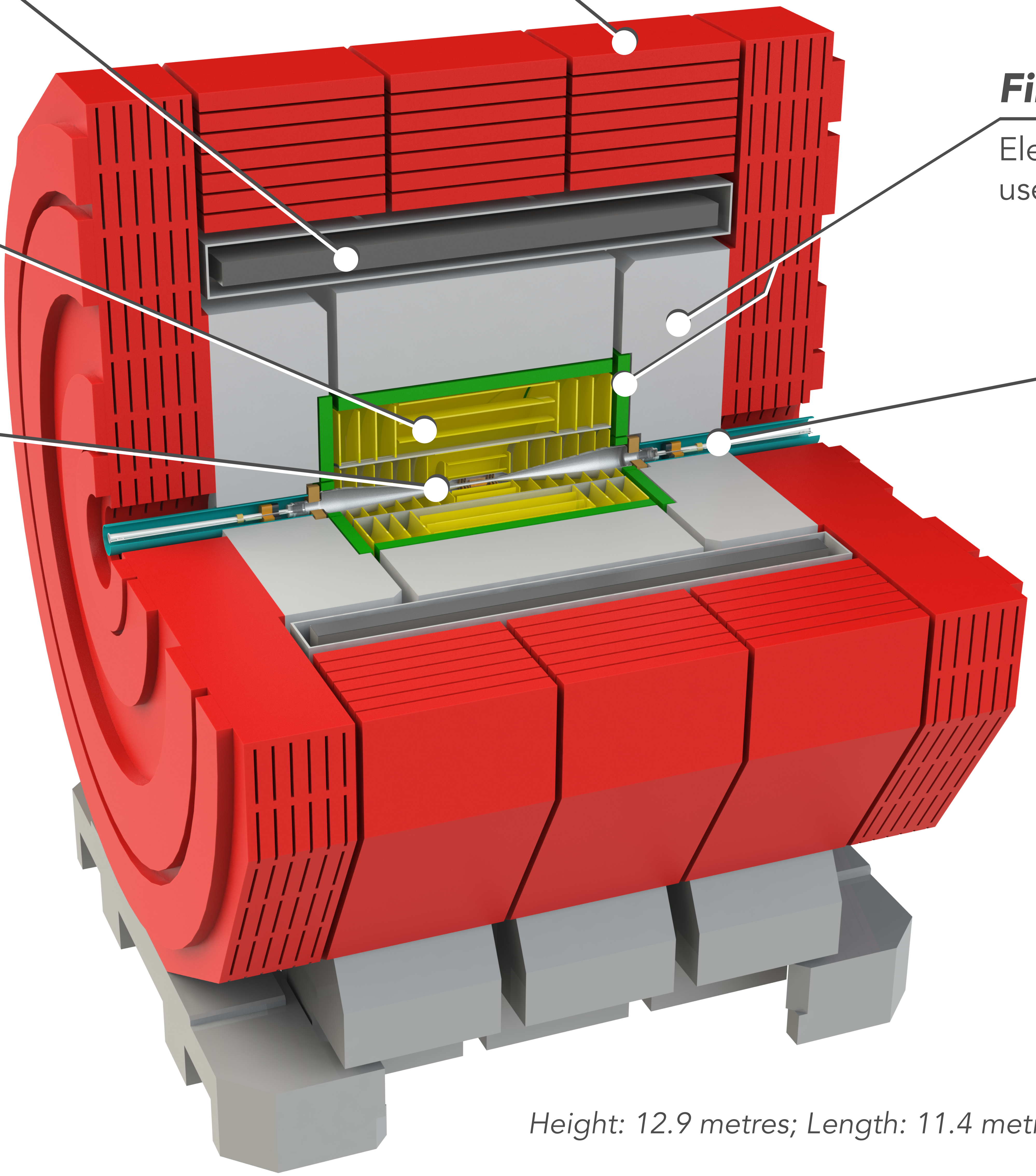
√s = 3 TeV
fully-hadronic



A detector for CLIC



The CLIC detector model



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

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

- 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

CLICdp June 2019

The CLIC detector model

Solenoidal Magnet
Superconducting magnet, magnetic field of 4 tesla

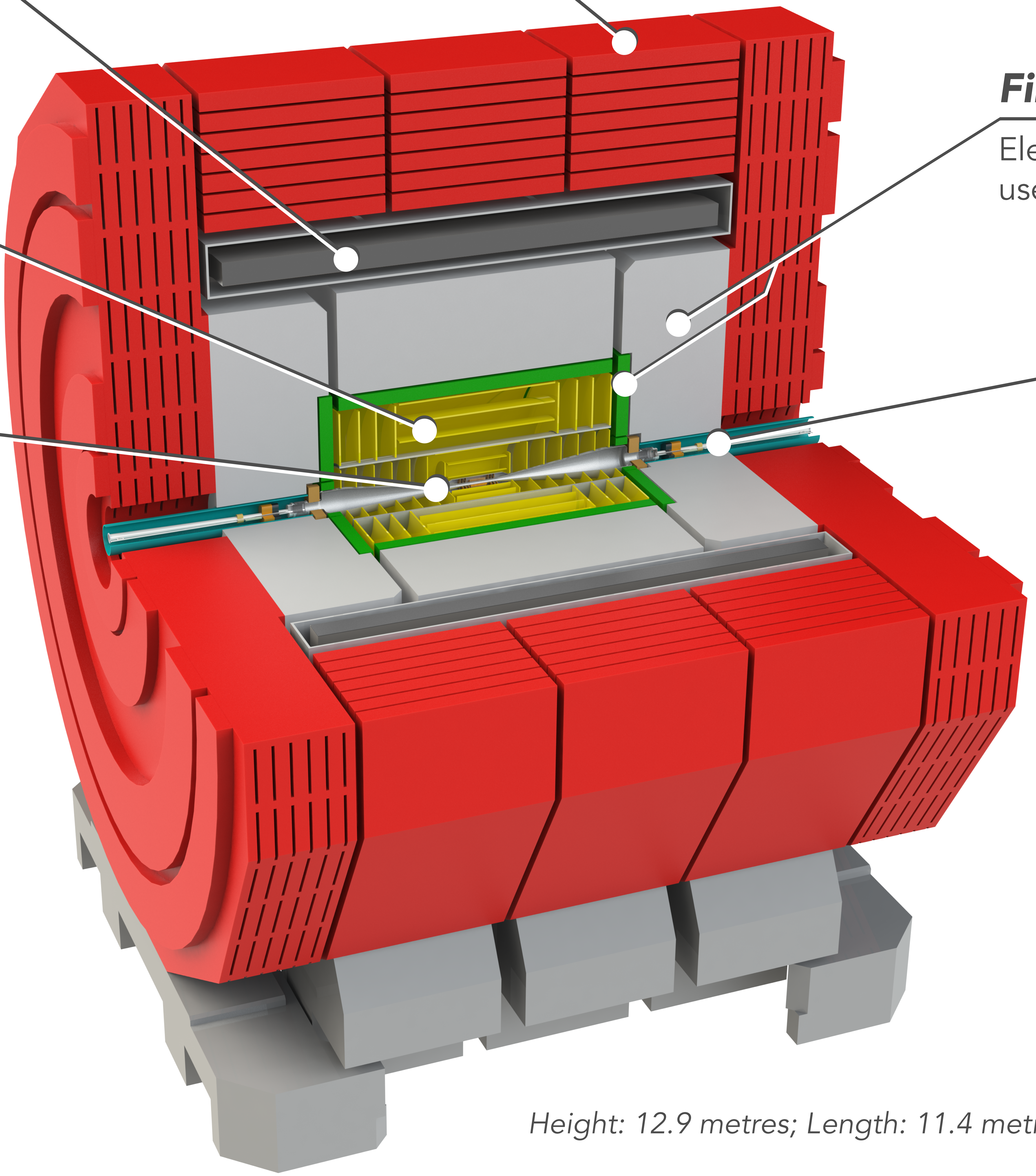
Return Yoke
Iron return yoke with detectors for muon ID

Tracking Detector
Silicon pixel detector, outer radius 1.5 metres

Fine-grained Calorimeters
Electromagnetic and hadronic calorimeters used for particle flow analysis

Vertex Detector
Ultra-low mass silicon pixel detector, inner radius 31 millimetres

Forward Region
Electromagnetic calorimeters for luminosity measurement and extended angular coverage



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Material: 7.5 λ_I

Learn more about the CLIC detector at clic.cern

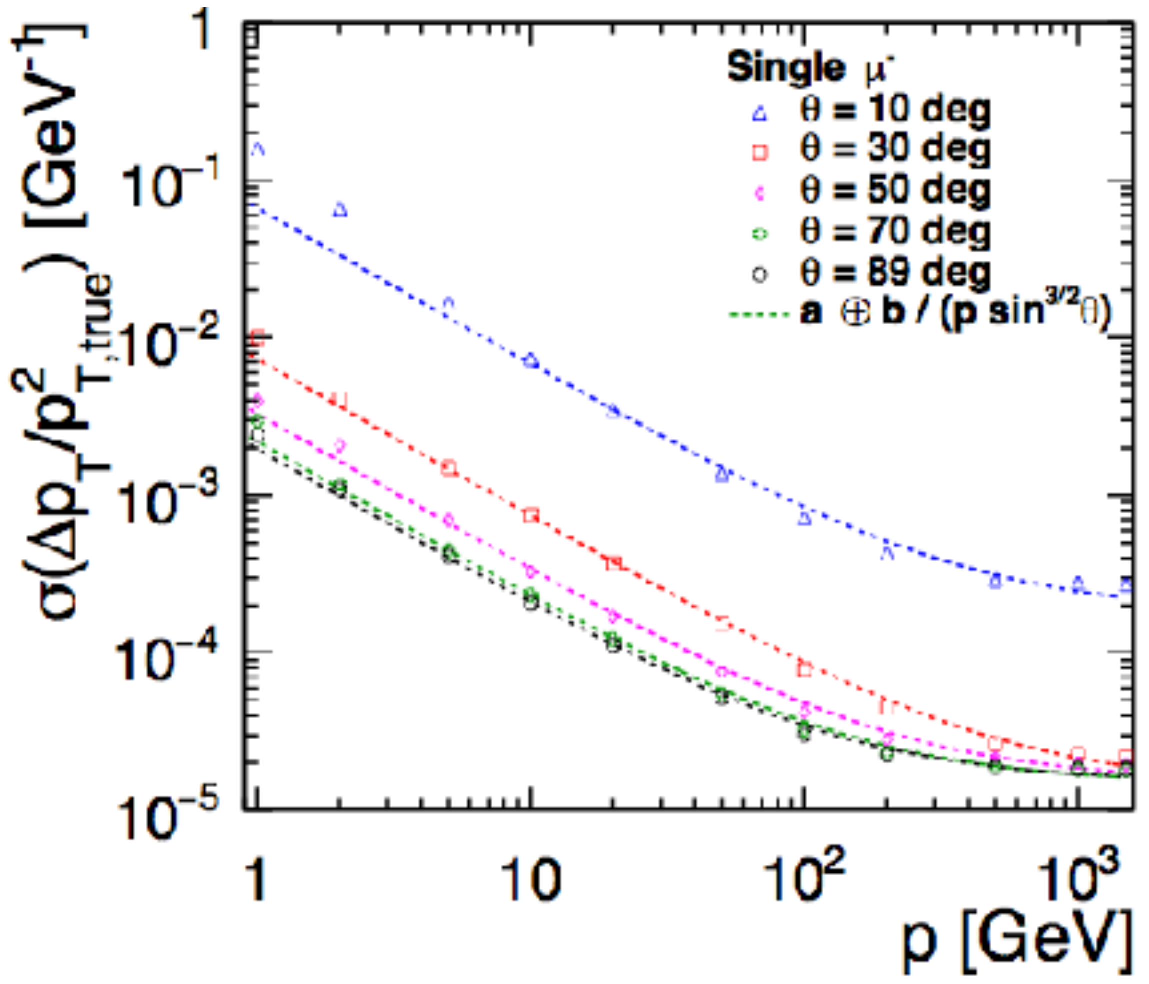
- Detector development is performed in collaboration with other projects studying future collider detector concepts + dedicated detector R&D collaborations: CALICE and FCAL

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

CLICdp June 2019

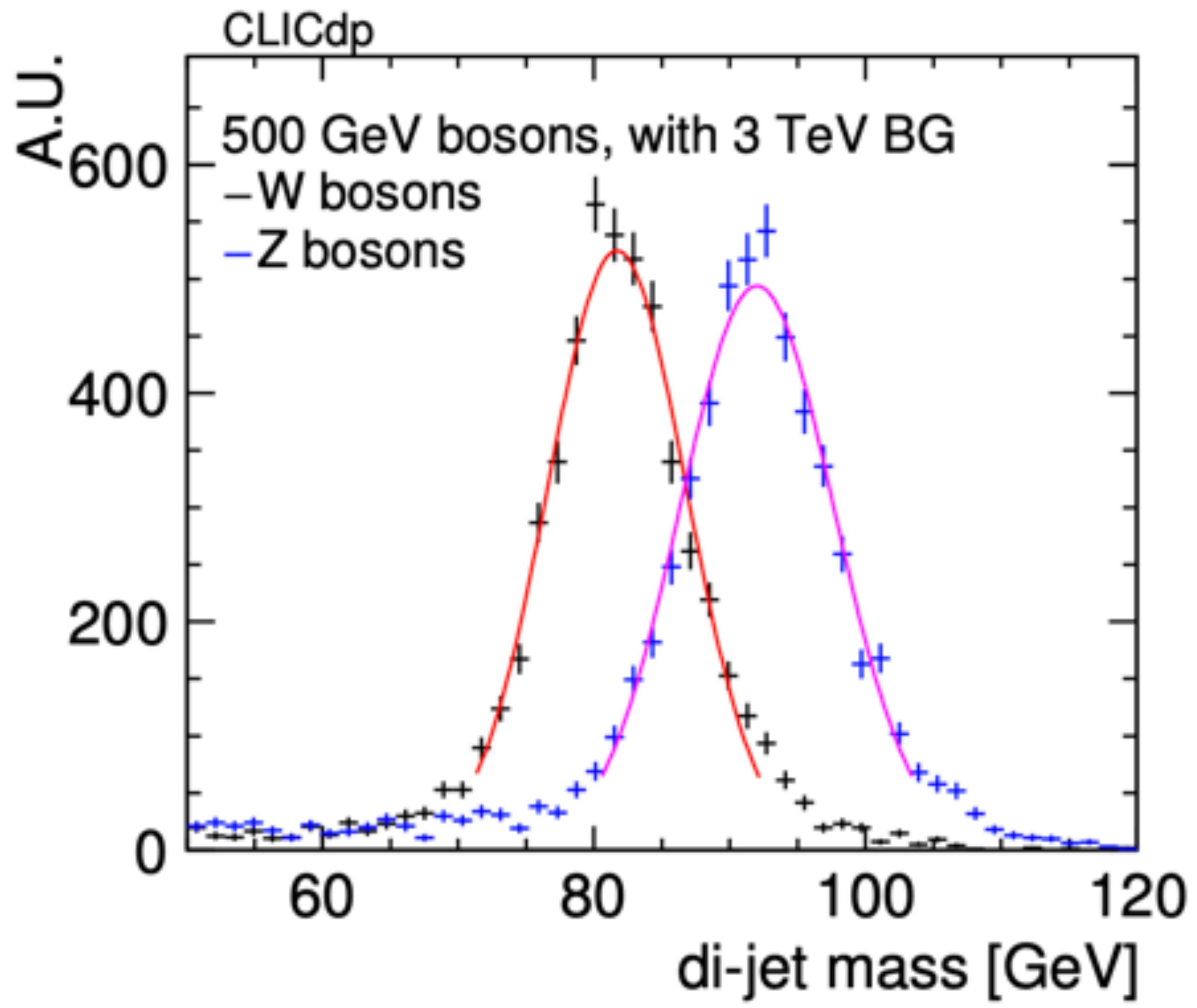
CLICdet Performance

Full characterisation of the detector model in arXiv:1812.07337

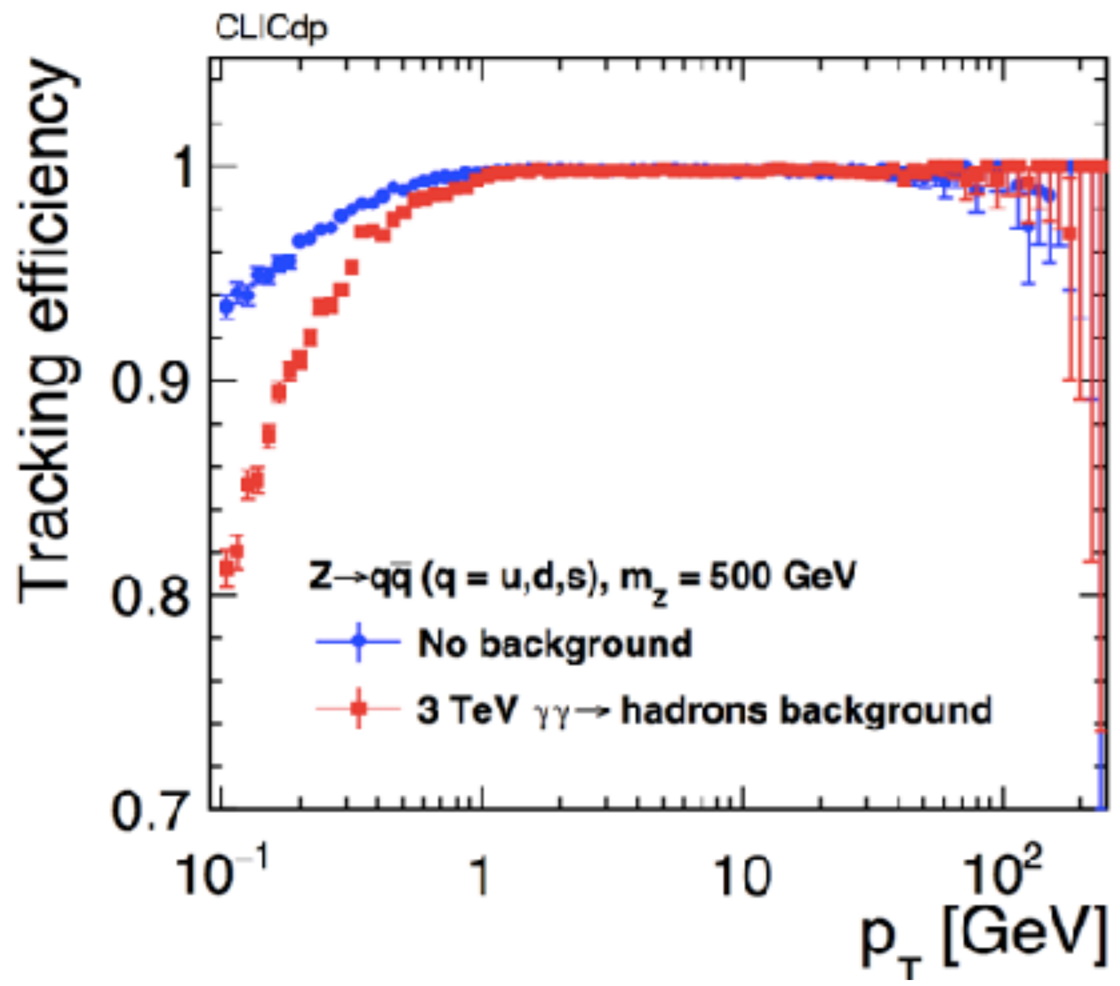


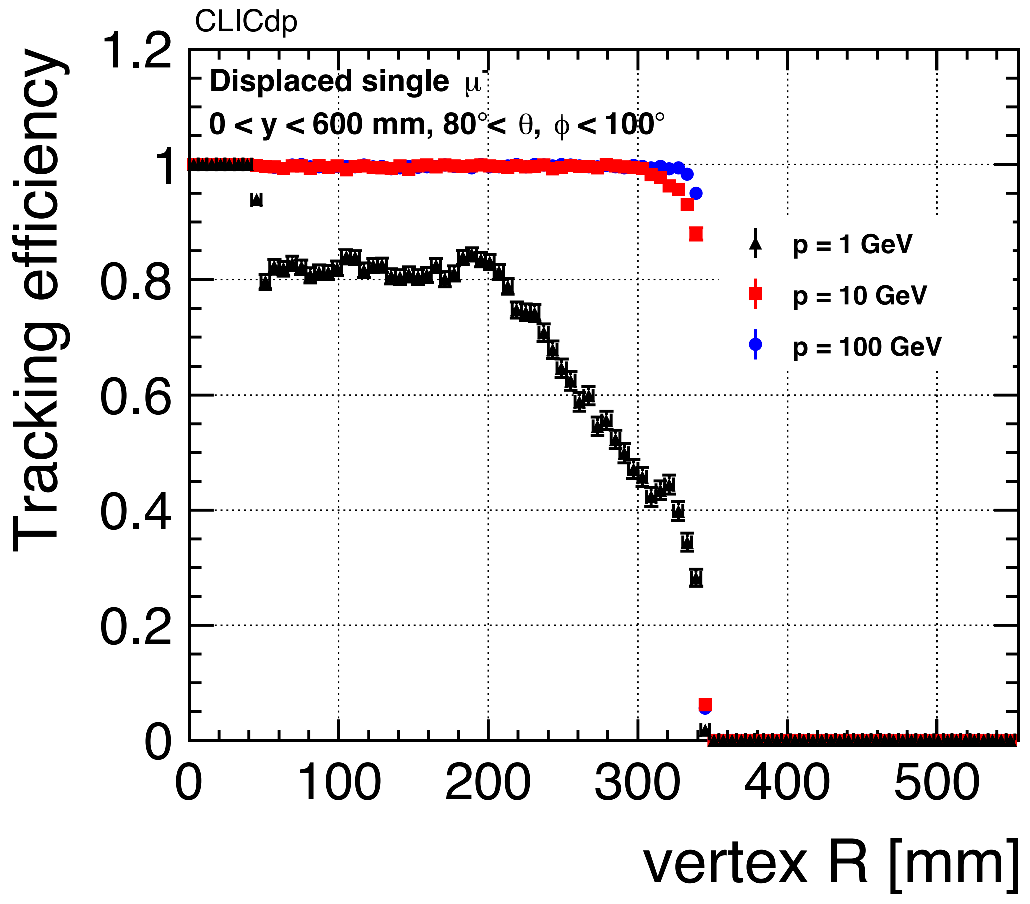
performance goal: 2x10-5

Achieve jet energy resolution target in presence of beam backgrounds

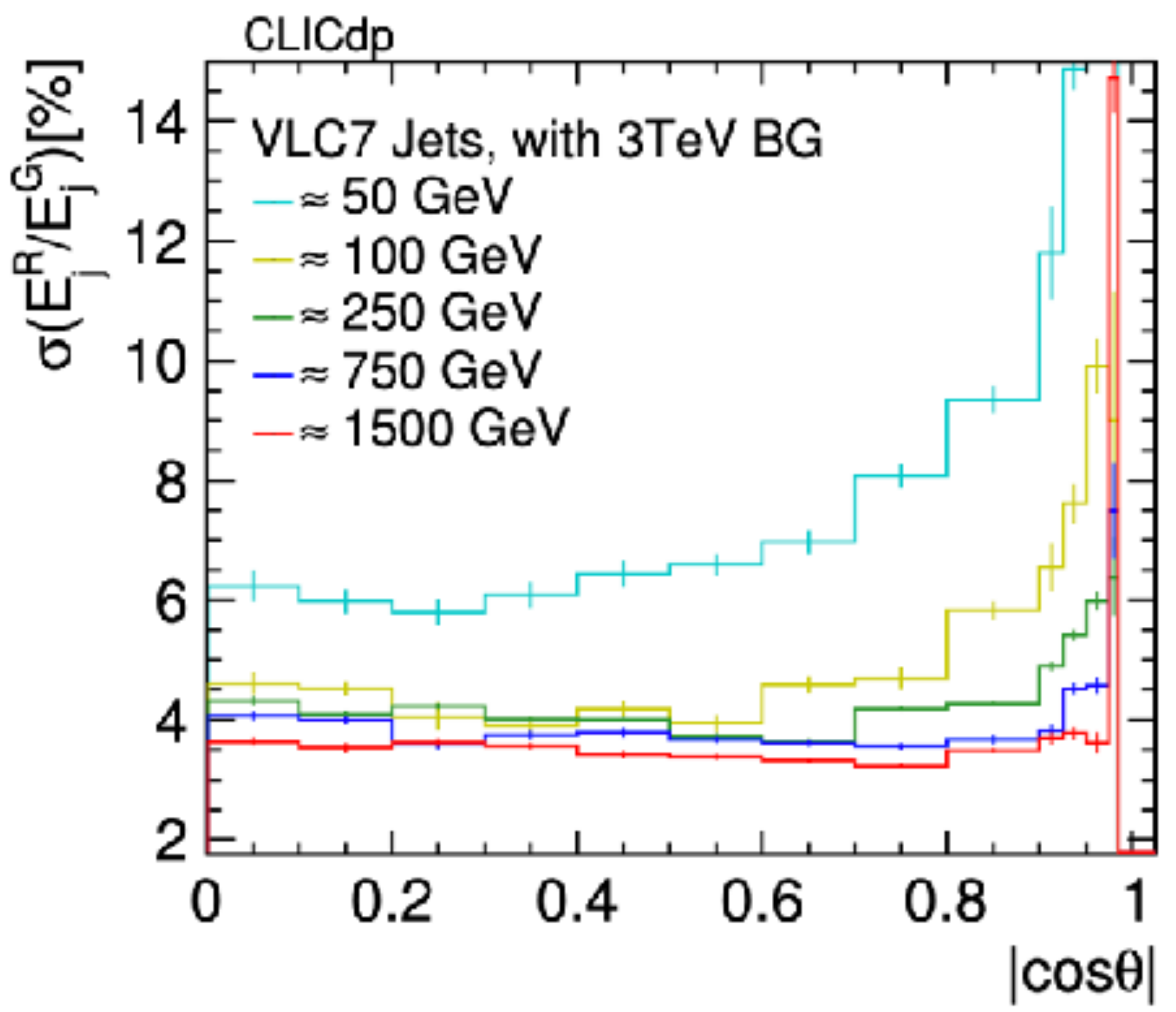


Displaced track reconstruction





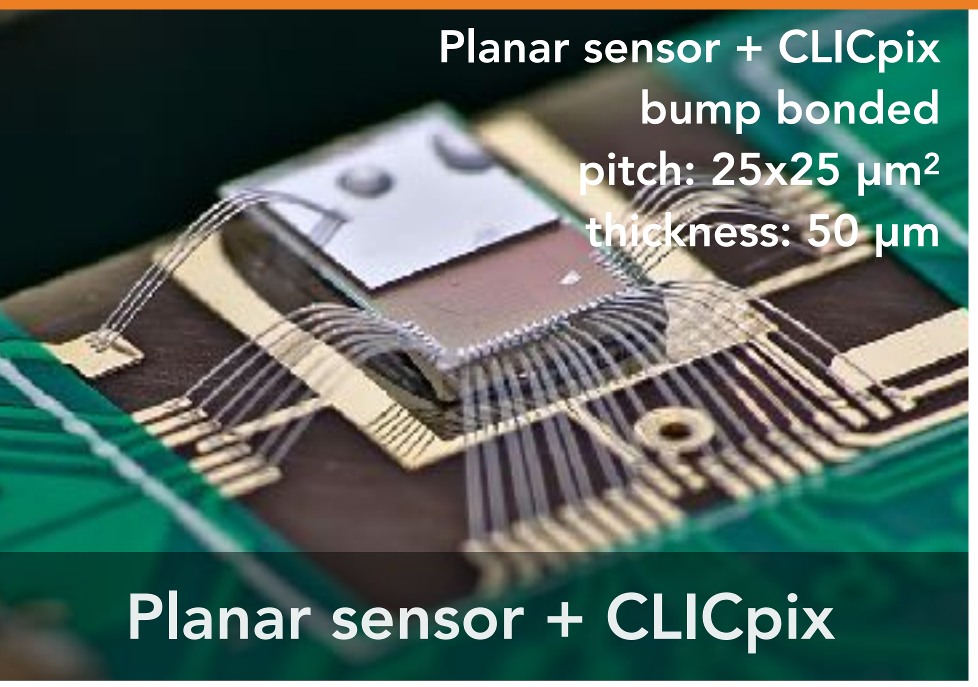
Software tools developed/ maintained by the CERN group and widely used

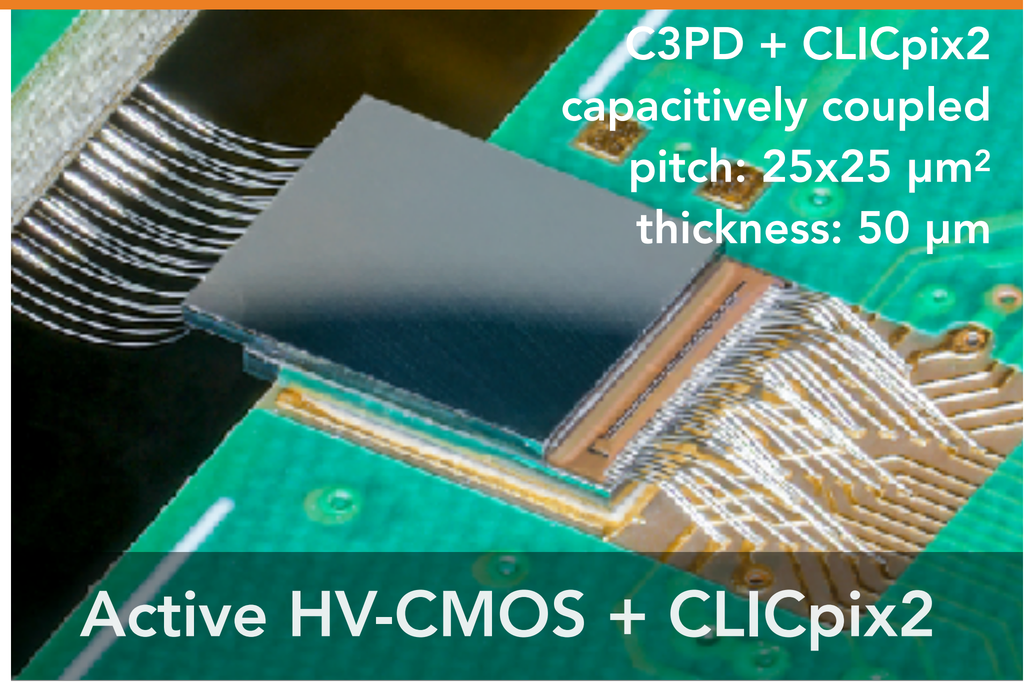


Vertex and tracking R&D

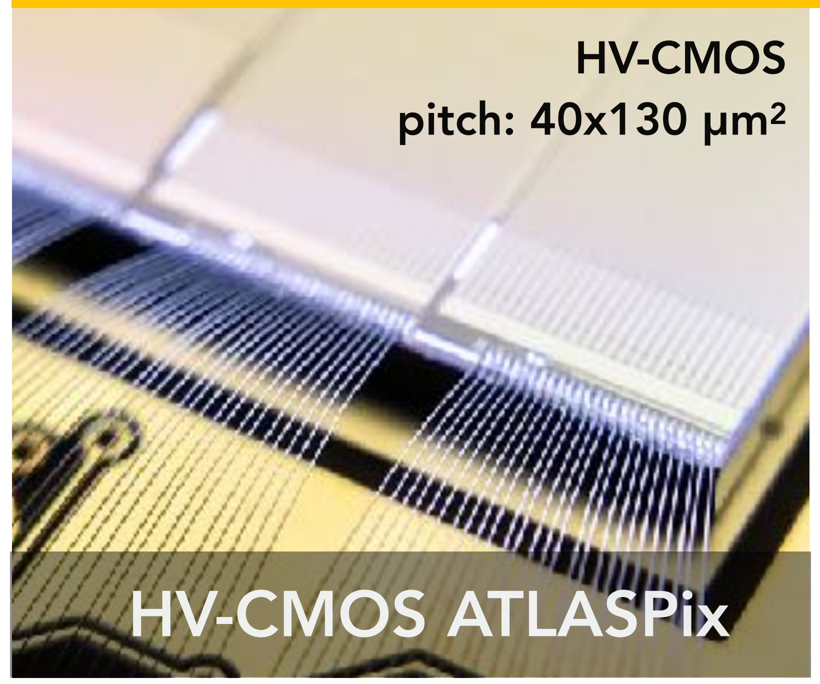
Highlights

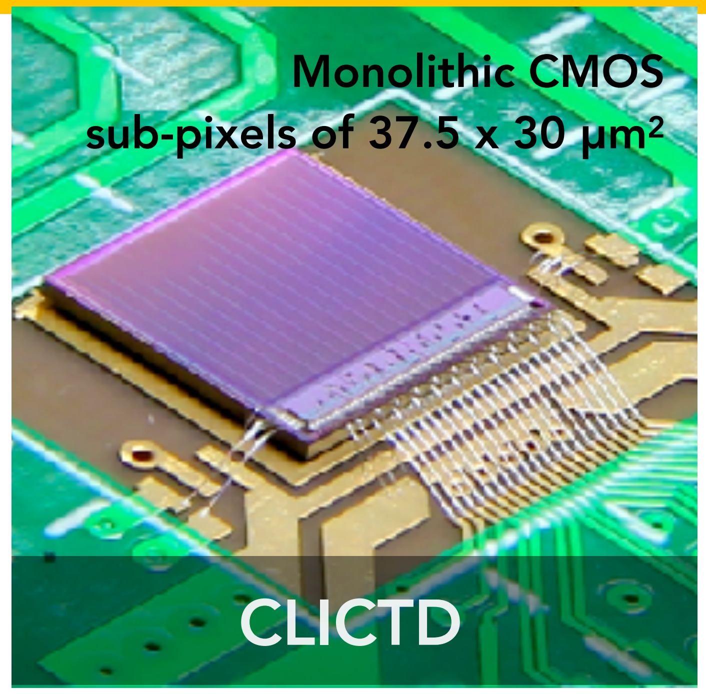
Hybrid assemblies

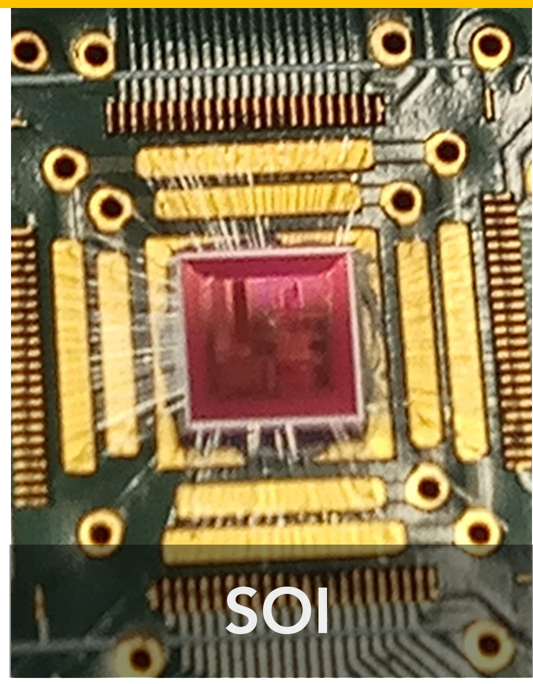




Monolithic assemblies





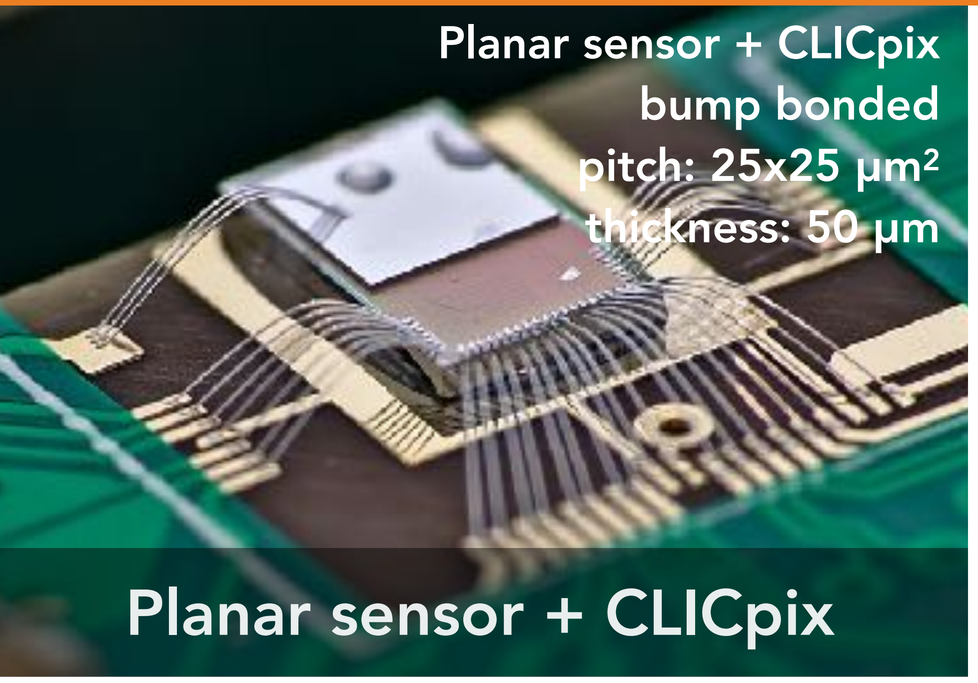


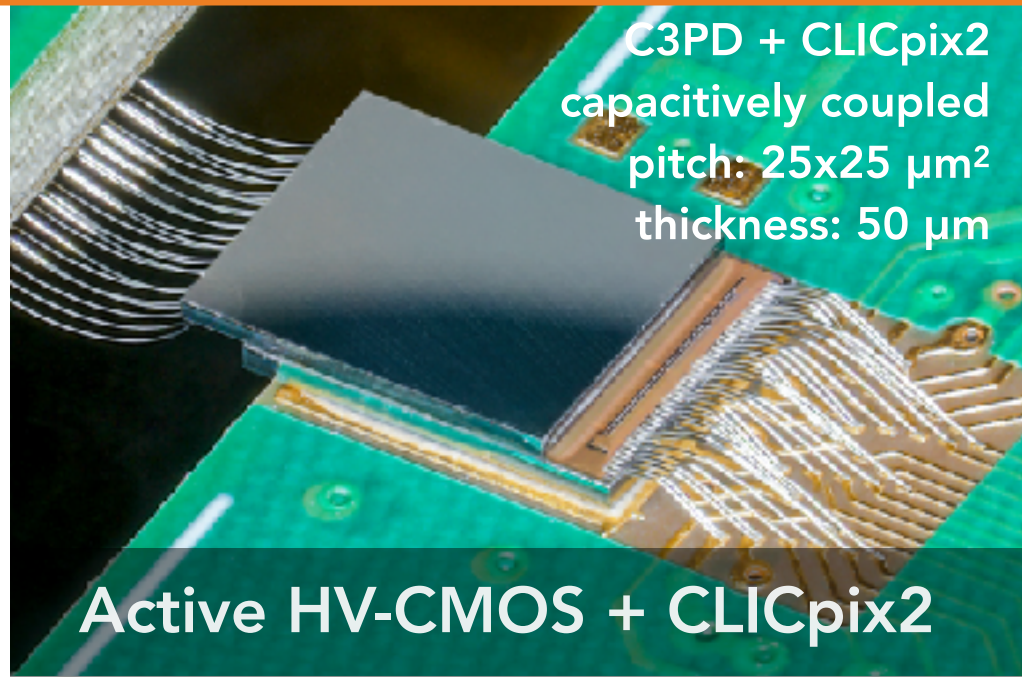
- Stringent requirements for CLIC inspired broad and integrated technology R&D programme
  - **Sensors, readout, powering, interconnects, mechanical integration, cooling, …**
- Benefit from rapid progress in Silicon industry and synergies with R&D for HL-LHC
- Feasibility of power-pulsing demonstrated
- Feasibility of air cooling demonstrated in simulation & full vertex detector mockup

Vertex and tracking R&D

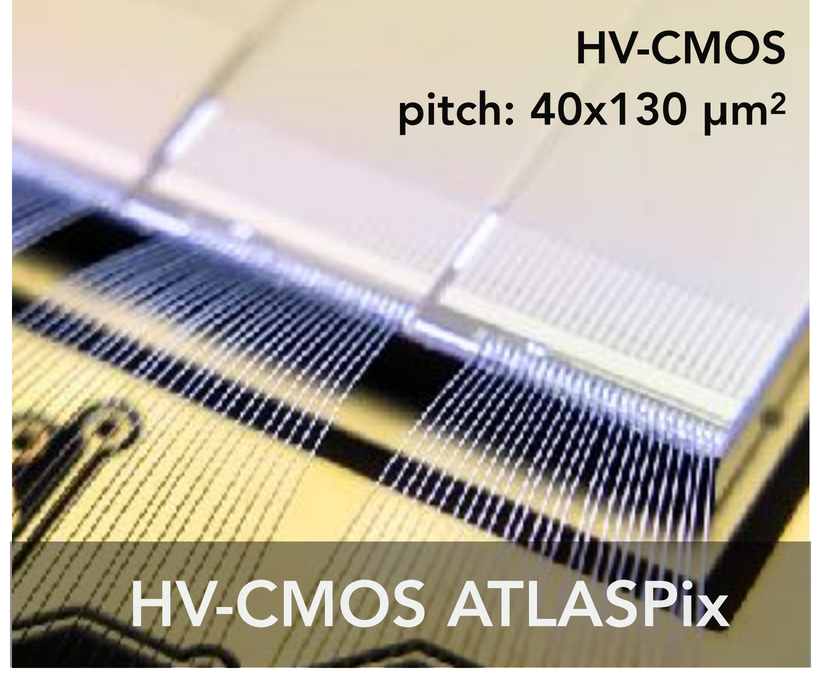
Highlights

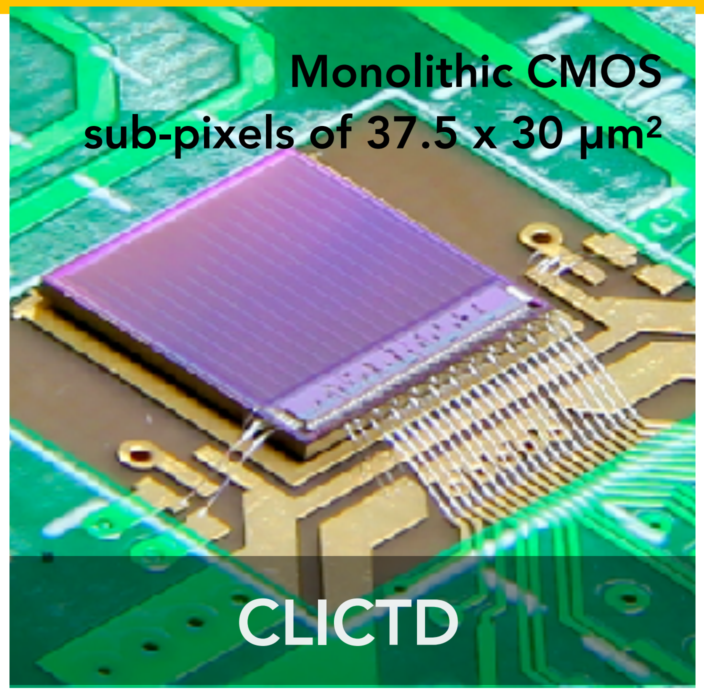
Hybrid assemblies

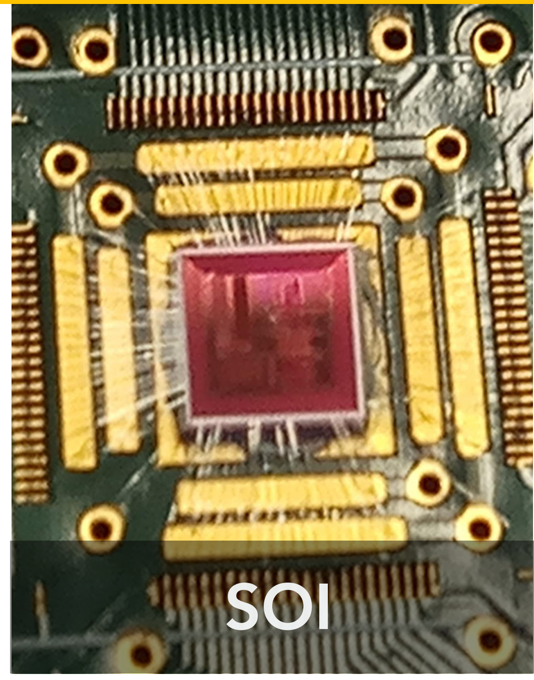




Monolithic assemblies



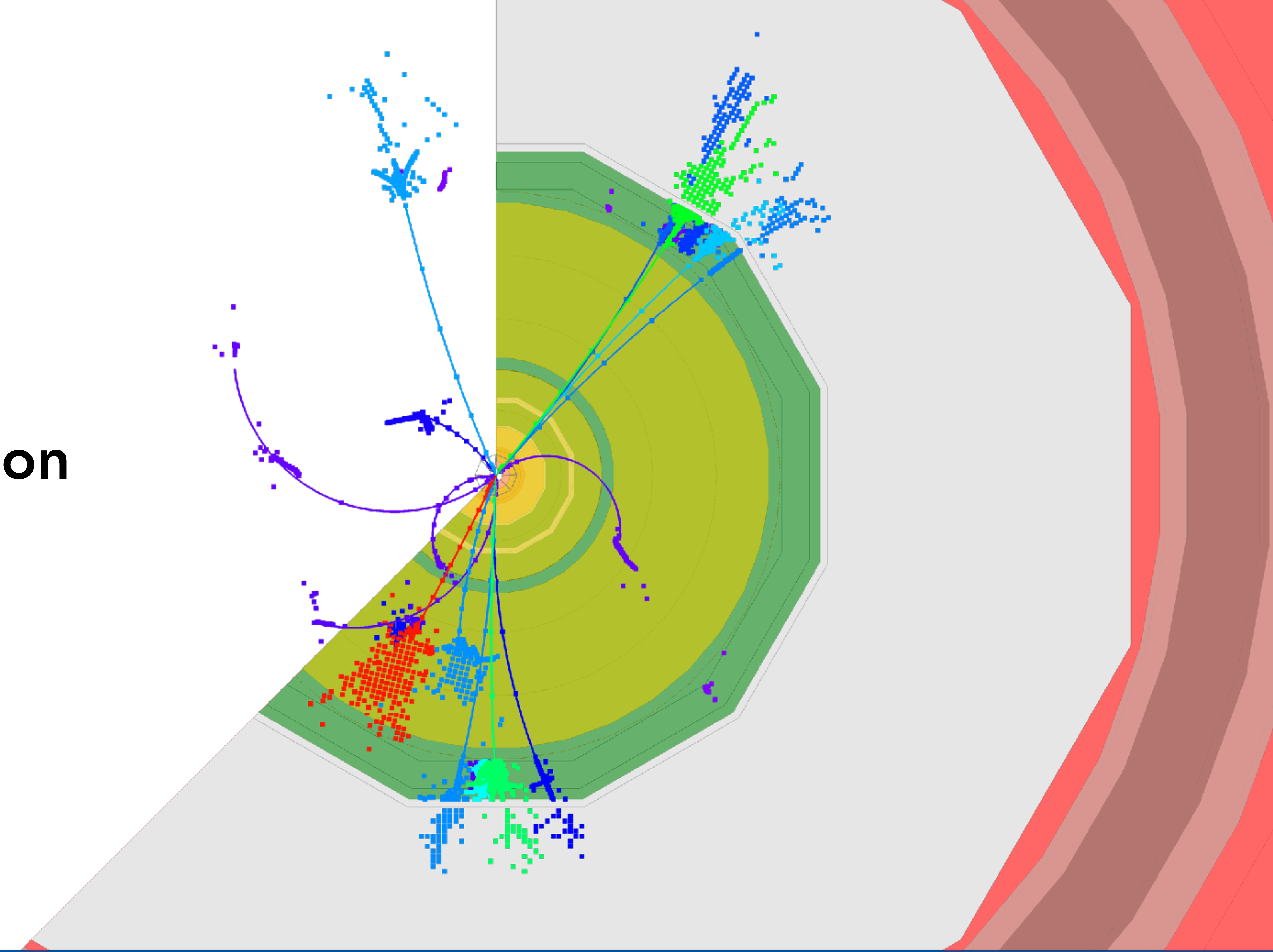




- Full efficiency from hybrid assemblies of 50 µm thin sensors that satisfy CLIC time-stamping
- Sensor design with enhanced charge-sharing is underway to reach required spatial resolution with thin sensors
- Good progress towards reducing detector mass with active-edge sensors and through-Si interconnects
- Promising results from fully integrated technologies
  - CLIC-specific designs underway
- Developed advanced simulation/analysis tools for detector performance optimisation (Allpix²)

Project realisation

What's next?



Possible scenarios

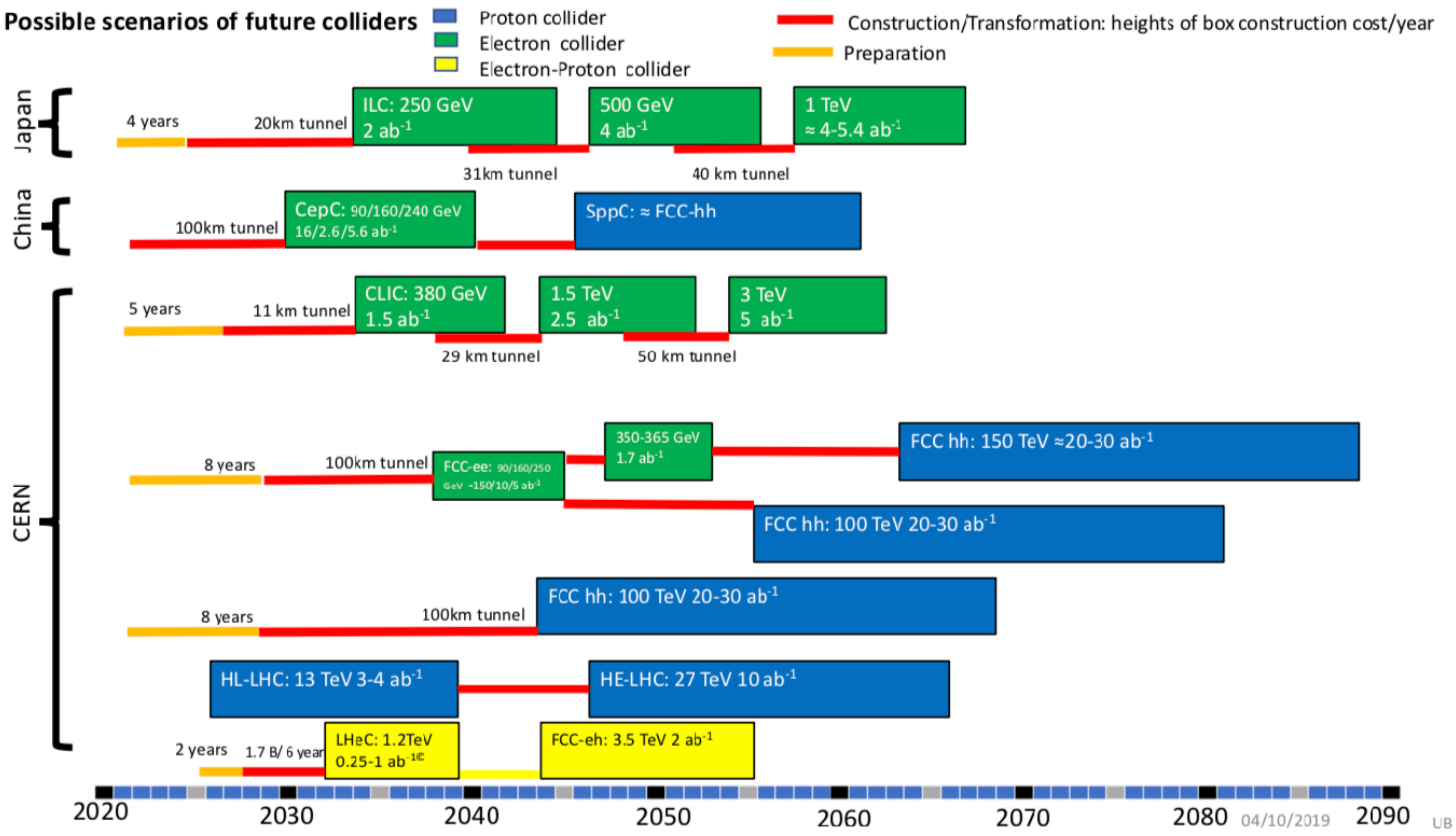
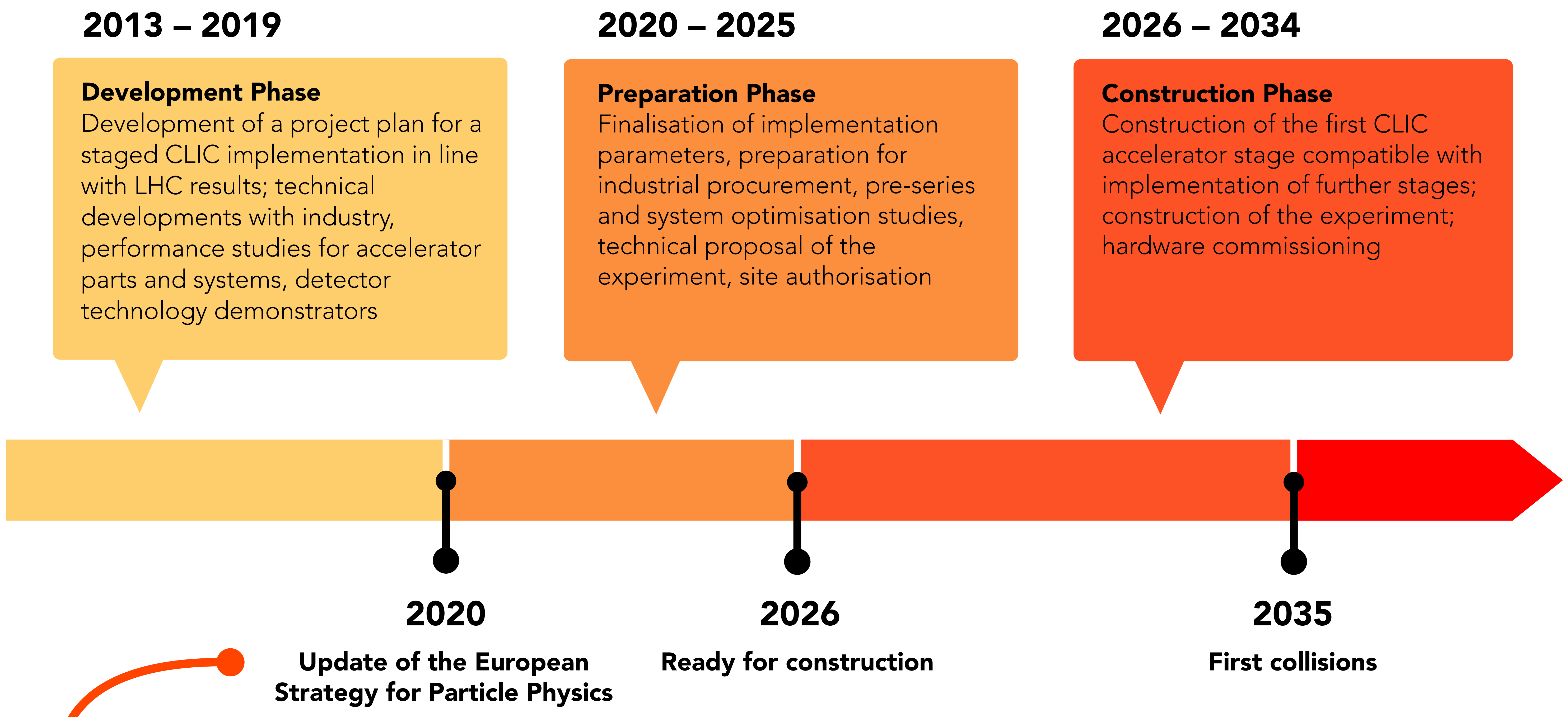


Image from the supporting note for the Briefing Book 2020

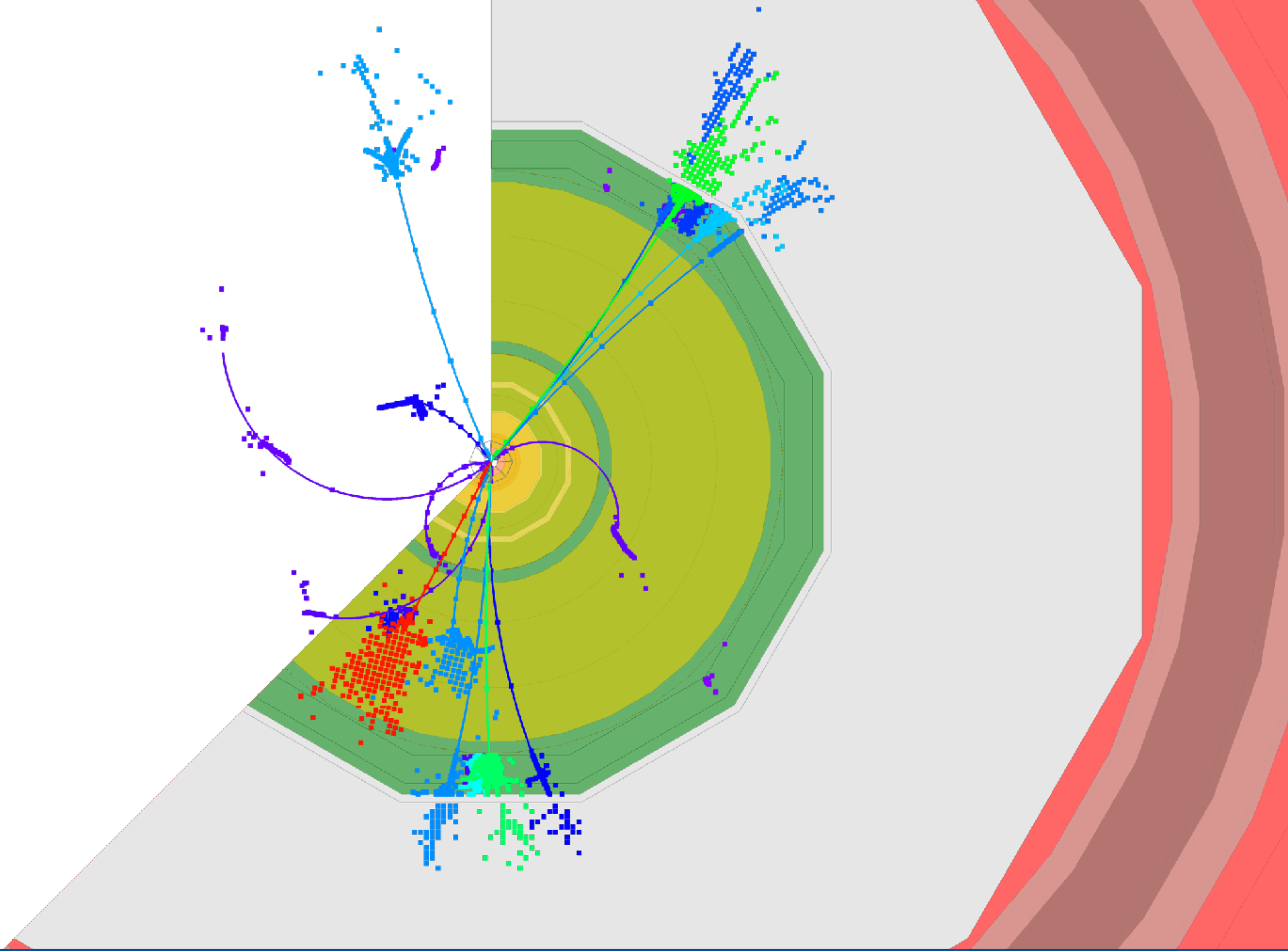
Strategy and timeline



Strategy-making needs to consider cost, timelines, technological readiness...

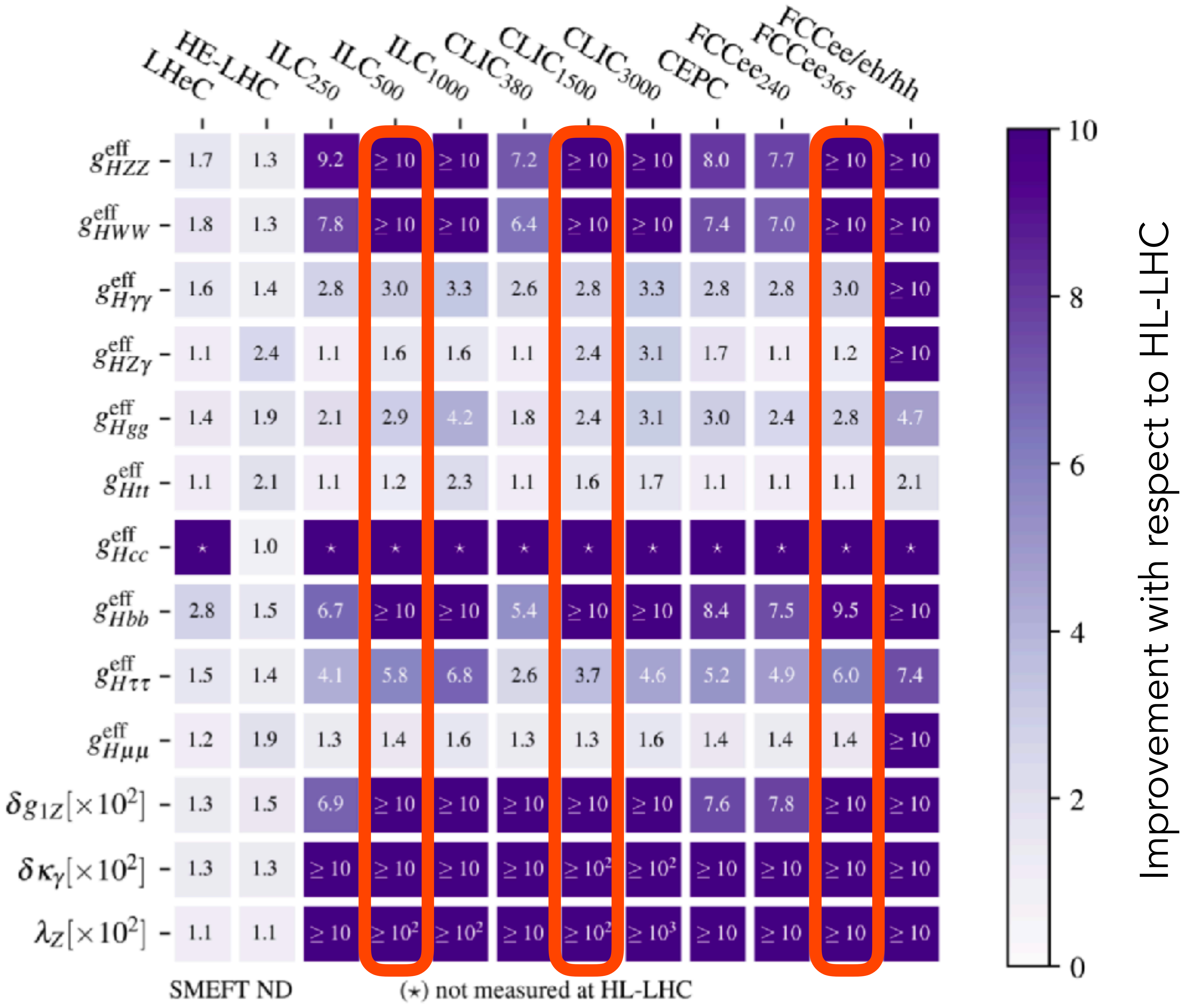
- CLIC is now a mature project, ready to start construction in ~2026, with first collisions ~2035
- **CLIC perspective:**
  - Invest in CLIC380 now
  - Keep a close eye on the development in wakefield acceleration techniques and high-field magnets
  - Re-evaluate the physics and R&D landscape after the initial CLIC stage and decide whether to continue towards CLIC3000 or move to e.g. a hadron machine

Summary
and outlook



EFT fit results

- ILC_{500}, $CLIC_{1500}$, $FCCee_{365}$ perform broadly similarly for Higgs couplings

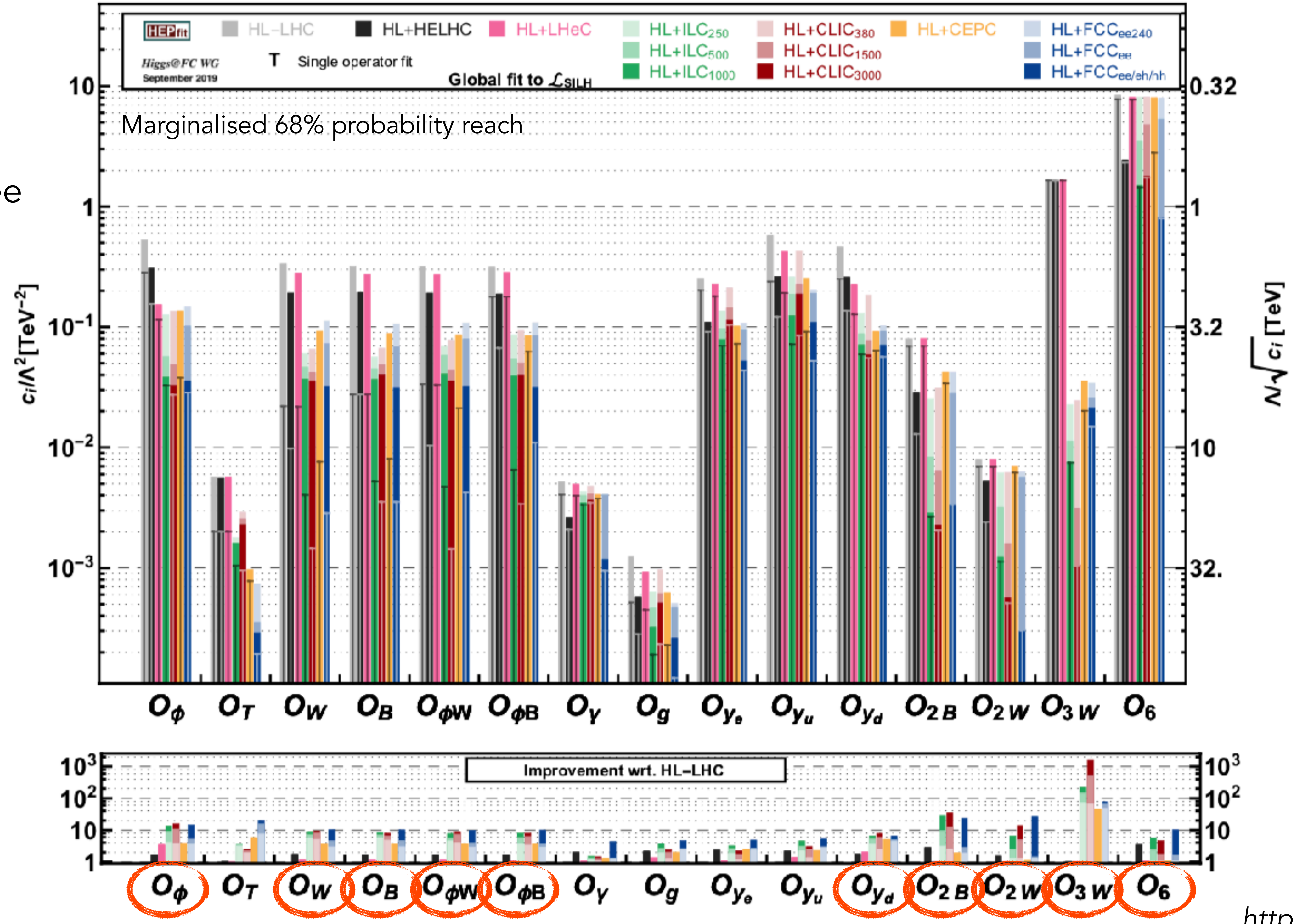


	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{eff}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{eff}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta \kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

ESPPU Briefing Book 2020
http://cds.cern.ch/record/2691414

EFT fit results

- Highlighted where CLIC1500 more sensitive than FCC-ee – benefit of high energy

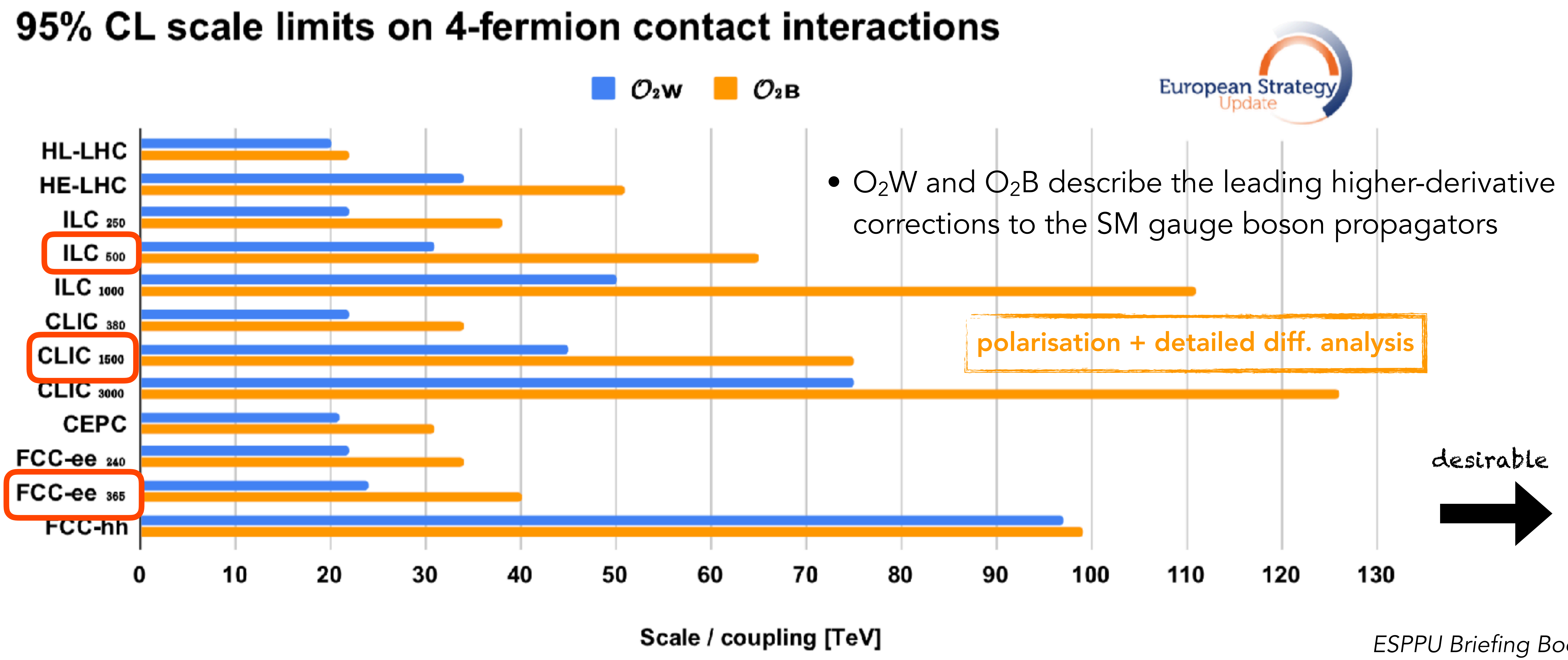


Higher precision

ESPPU Briefing Book 2020
http://cds.cern.ch/record/2691414

EFT fit results

Projections from di-fermion final states

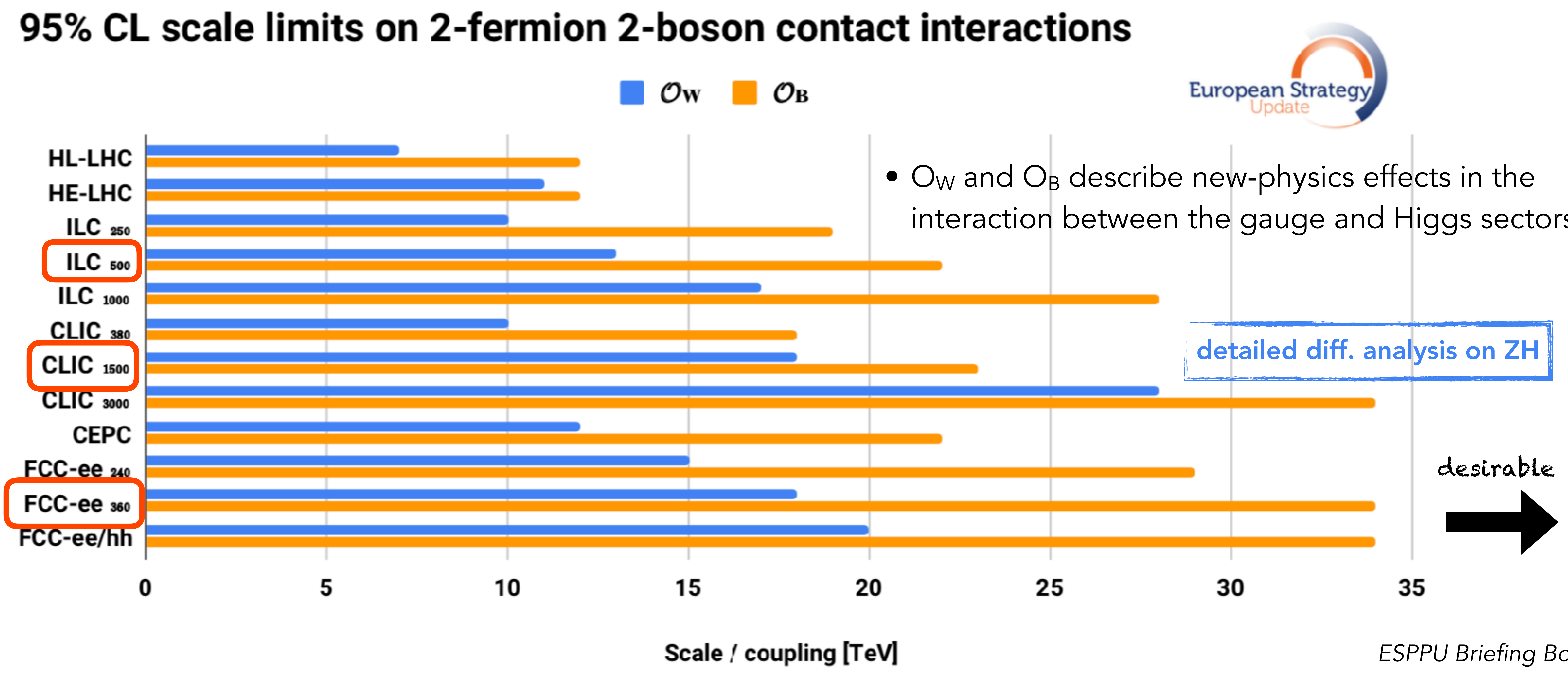


- O_2W and O_2B describe the leading higher-derivative corrections to the SM gauge boson propagators

ESPPU Briefing Book 2020
http://cds.cern.ch/record/2691414

EFT fit results

Projections from di-boson production



- O_W and O_B describe new-physics effects in the interaction between the gauge and Higgs sectors

ESPPU Briefing Book 2020
http://cds.cern.ch/record/2691414

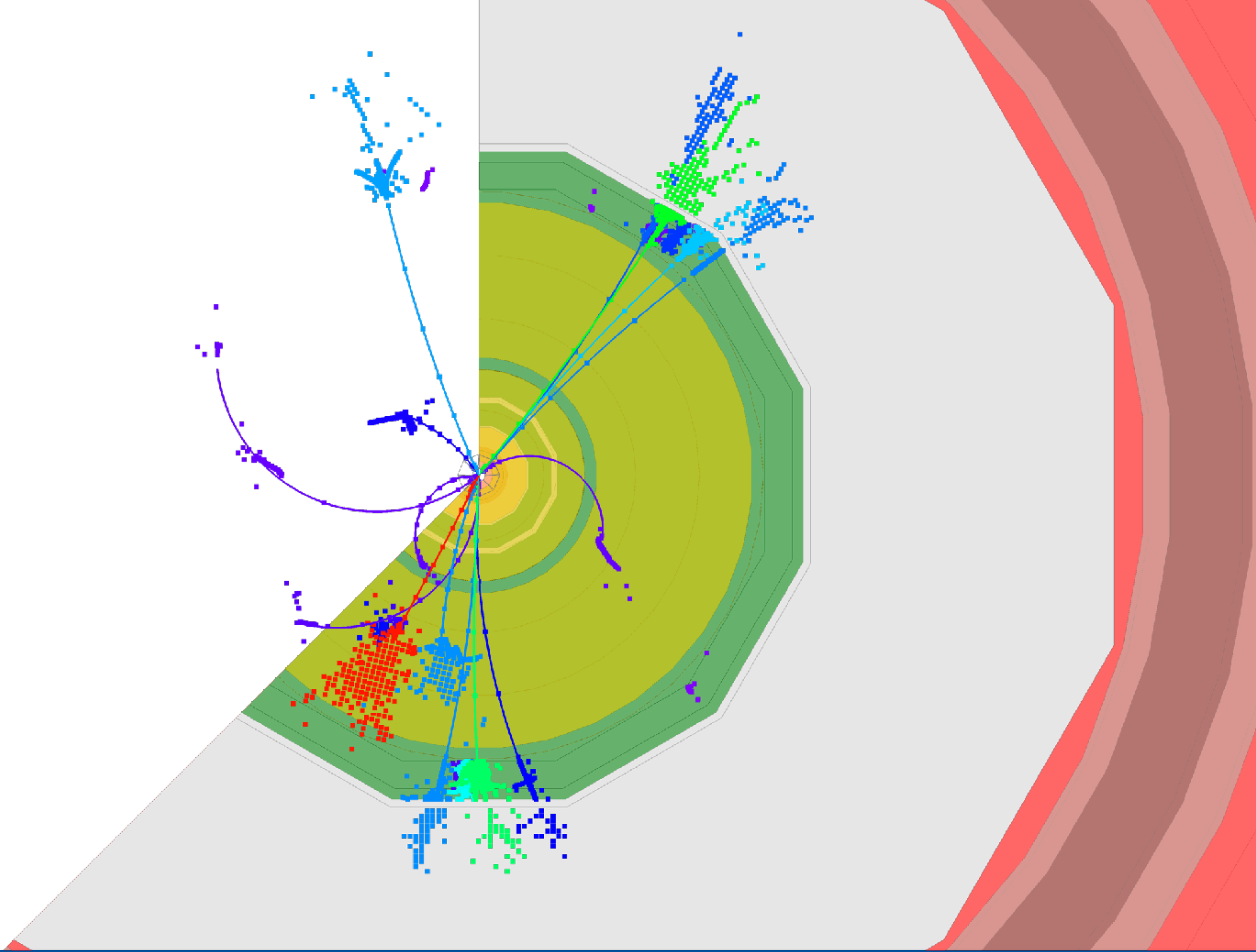
Summary 1/2

- CLIC is an attractive post-LHC facility for CERN
- Ready to start construction in ~2026
- First collisions by ~2035
- Physics programme ~30 years
- The advantages 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**
- FCC-hh has (unsurprisingly) the best mass reach for new resonances, but **CLIC is highly competitive** for new physics via contact interactions

Summary 2/2

- Accelerator staging brings cost staging, and accompanying affordability
- The main accelerator technologies have been demonstrated – performance goals can be met
- A linear machine provides flexibility to adapt the staging scenario to a developing physics landscape
- The linear tunnel also provides a natural infrastructure for the future beyond CLIC
- Project status summarised in a series of reports for the European Strategy for Particle Physics Update (ESPPU)

Resources



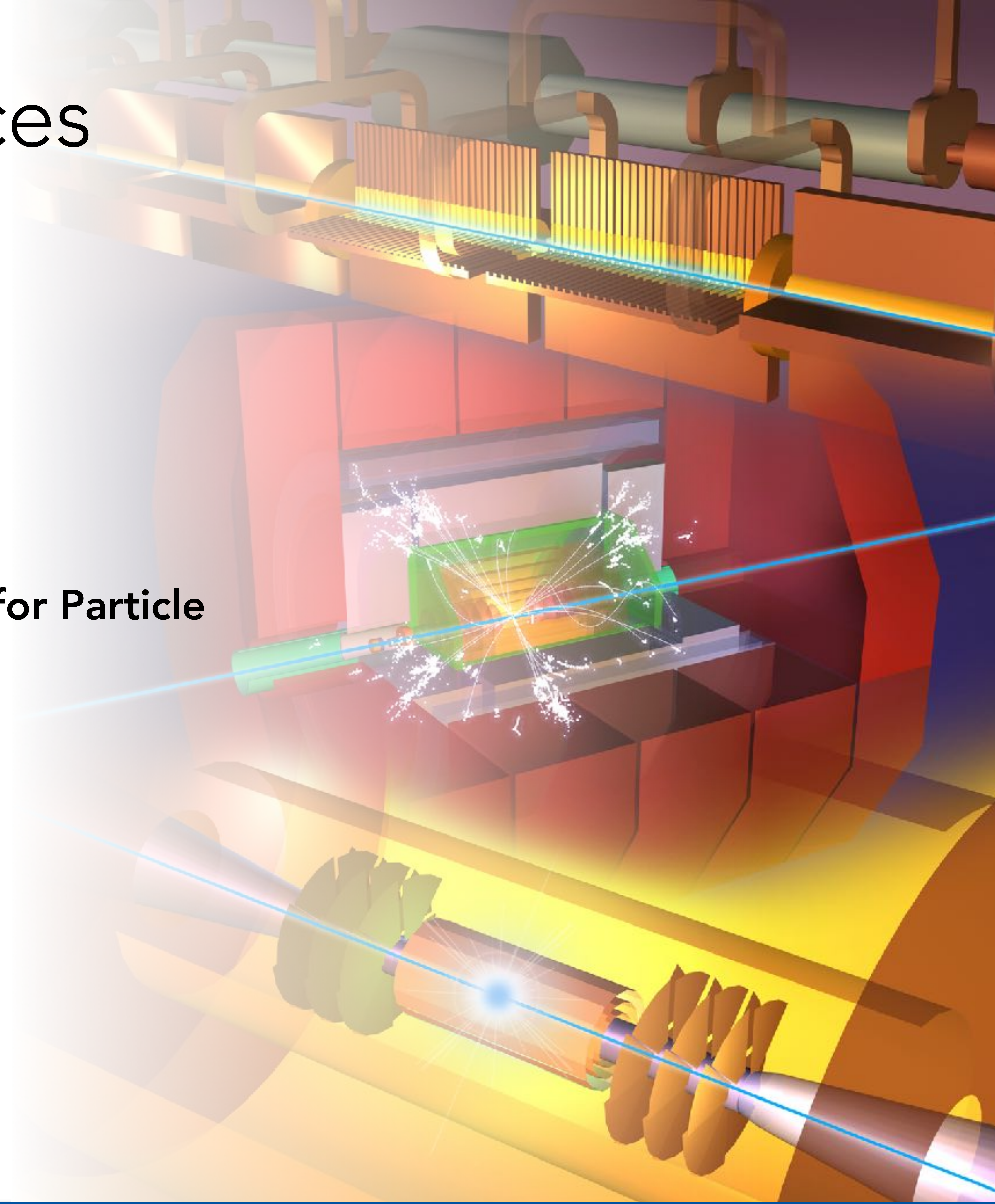
Resources

Compact Linear Collider Portal

https://clic.cern/

CLIC input to the European Strategy for Particle Physics Update 2018-2020

https://clic.cern/european-strategy



Resources

3-volume CDR 2012

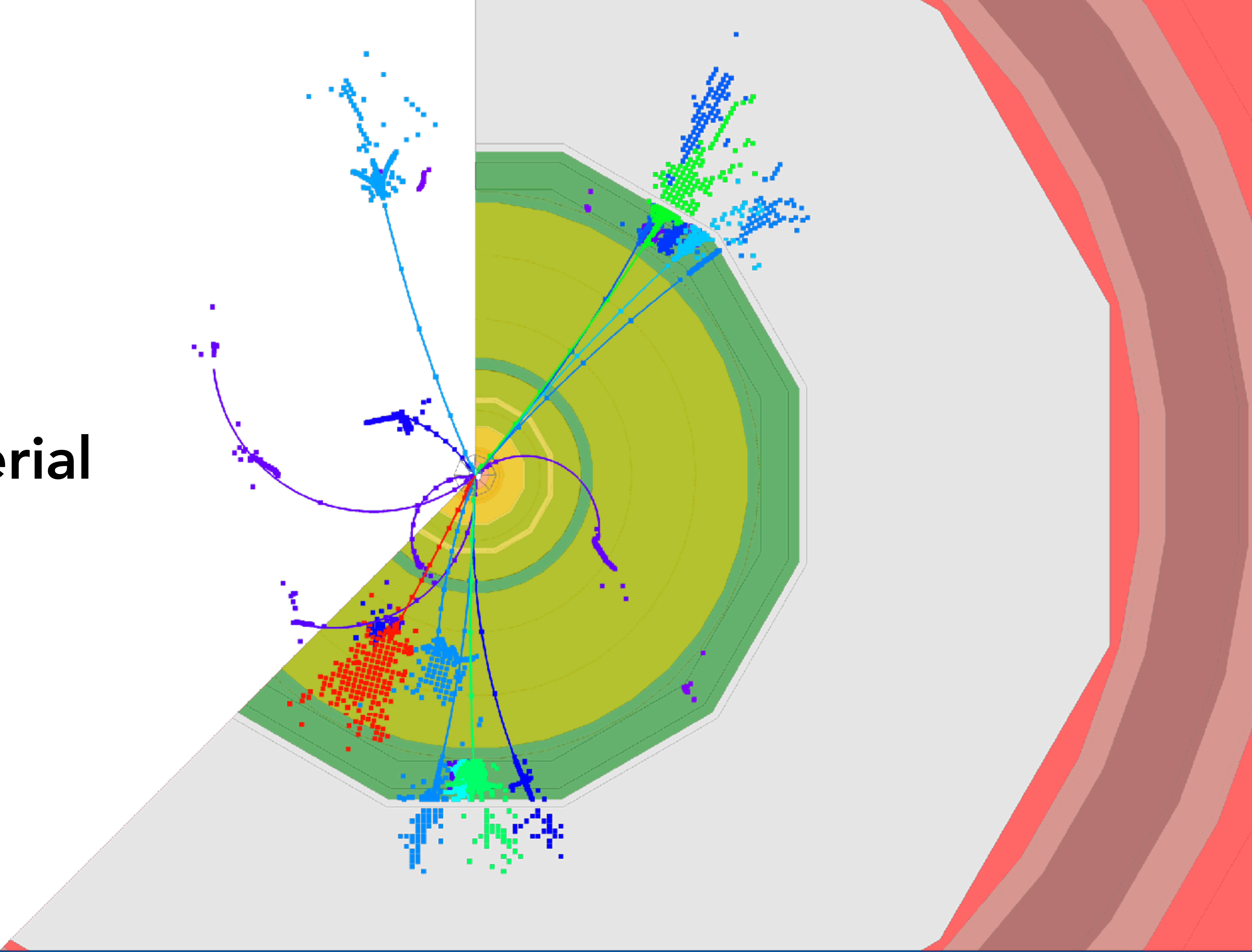
Updated Staging Baseline 2016

Available at:
clic.cern/european-strategy

4 CERN Yellow Reports 2018

2 formal submissions to the ESPPU 2018

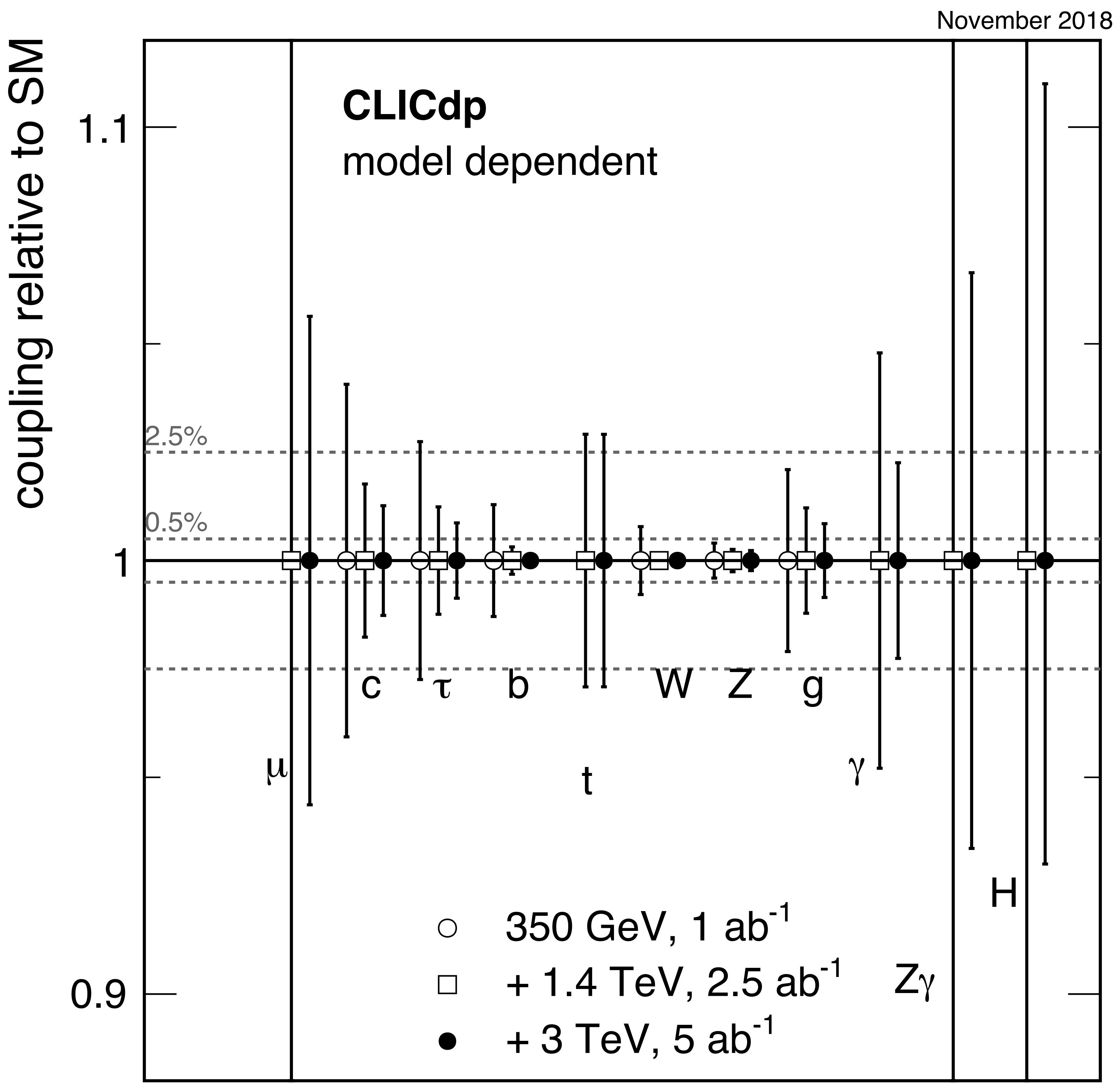
Additional material



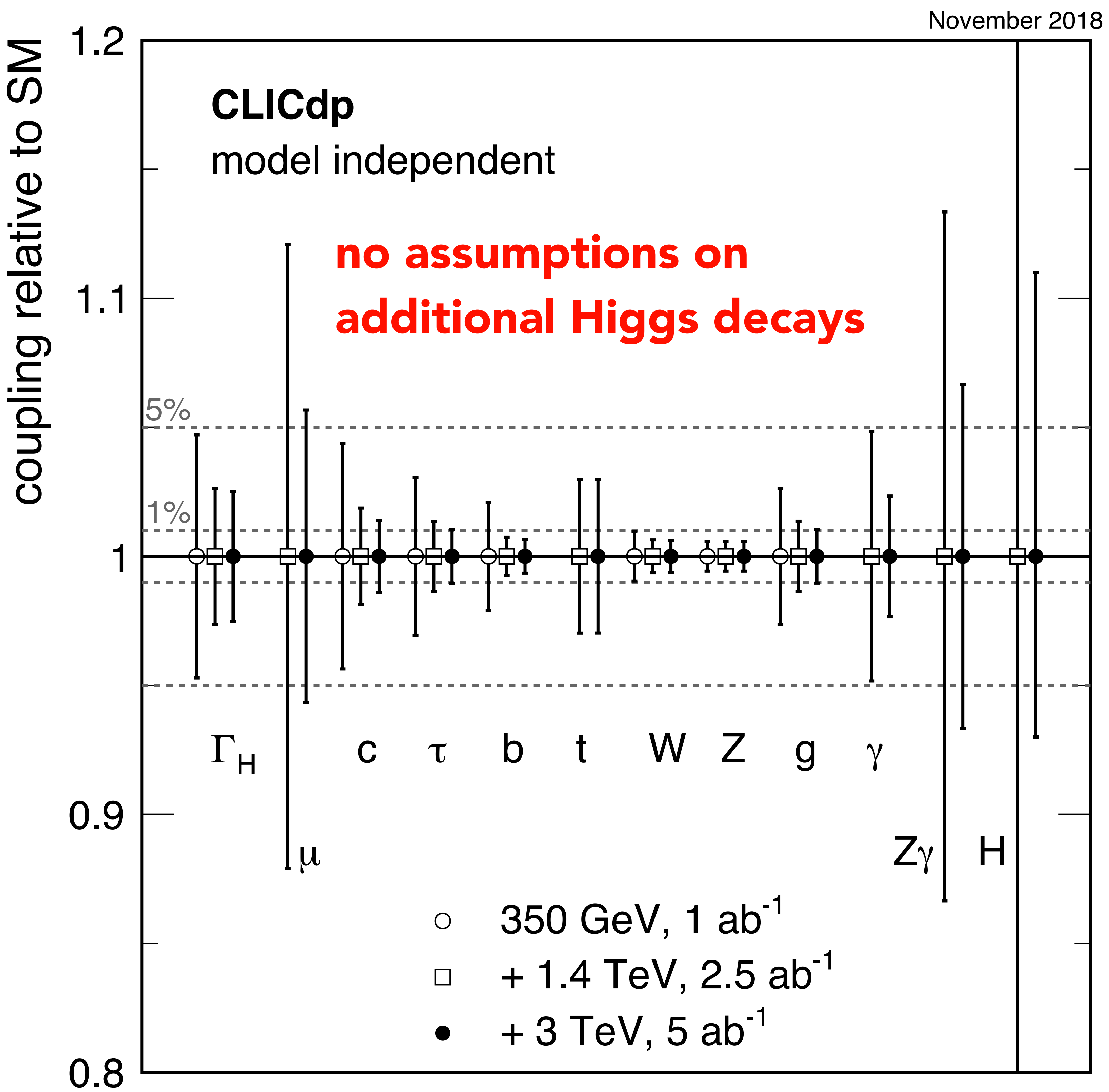
Precision Higgs couplings

Full CLIC program:

- Model-independent: down to ±1% for most couplings
- Model-dependent: ±1% down to ± few ‰ for most couplings

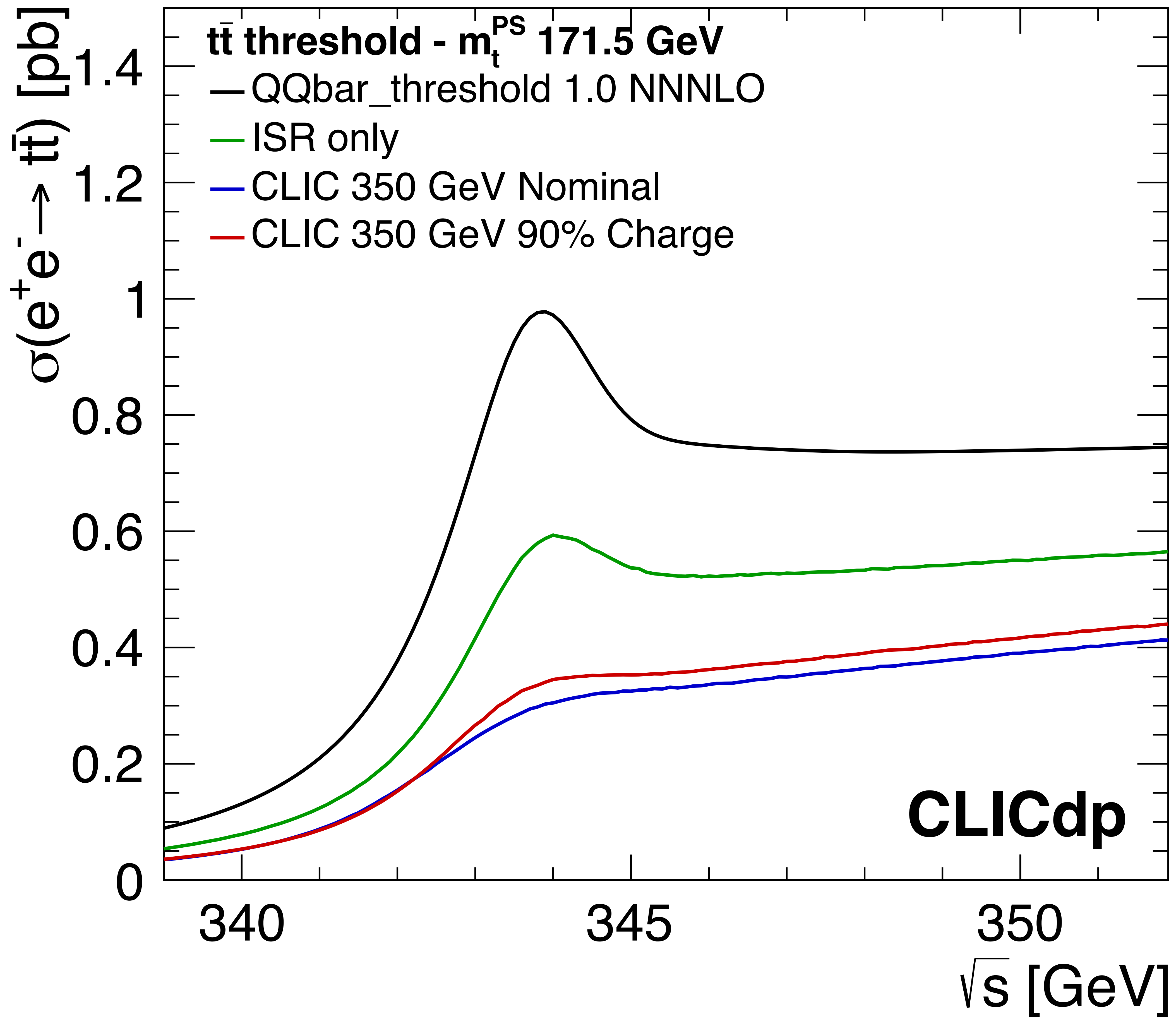


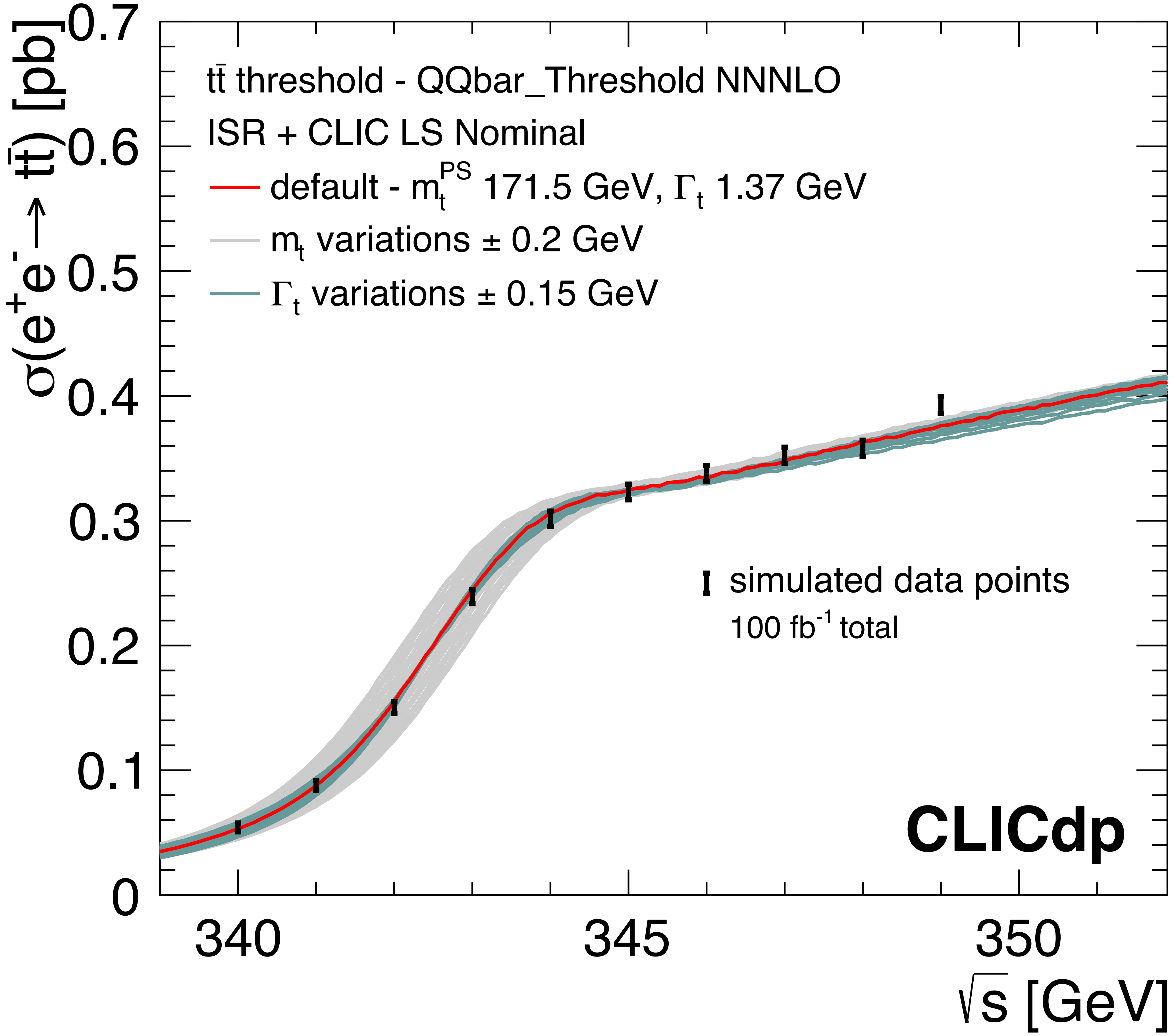
LHC-like fit, assuming SM decays only. Fit to deviations from SM BR's



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

Top-quark mass from threshold scan

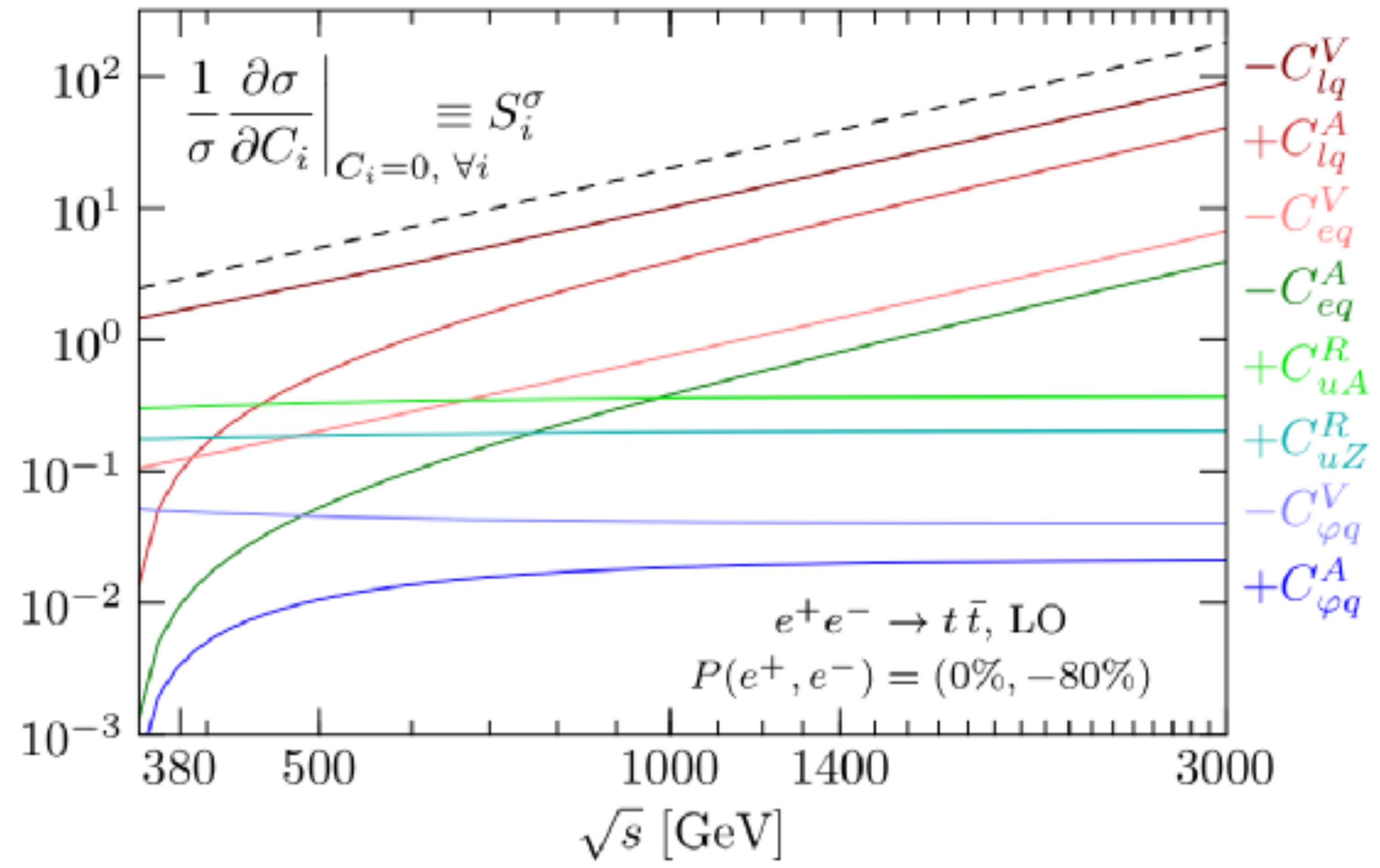




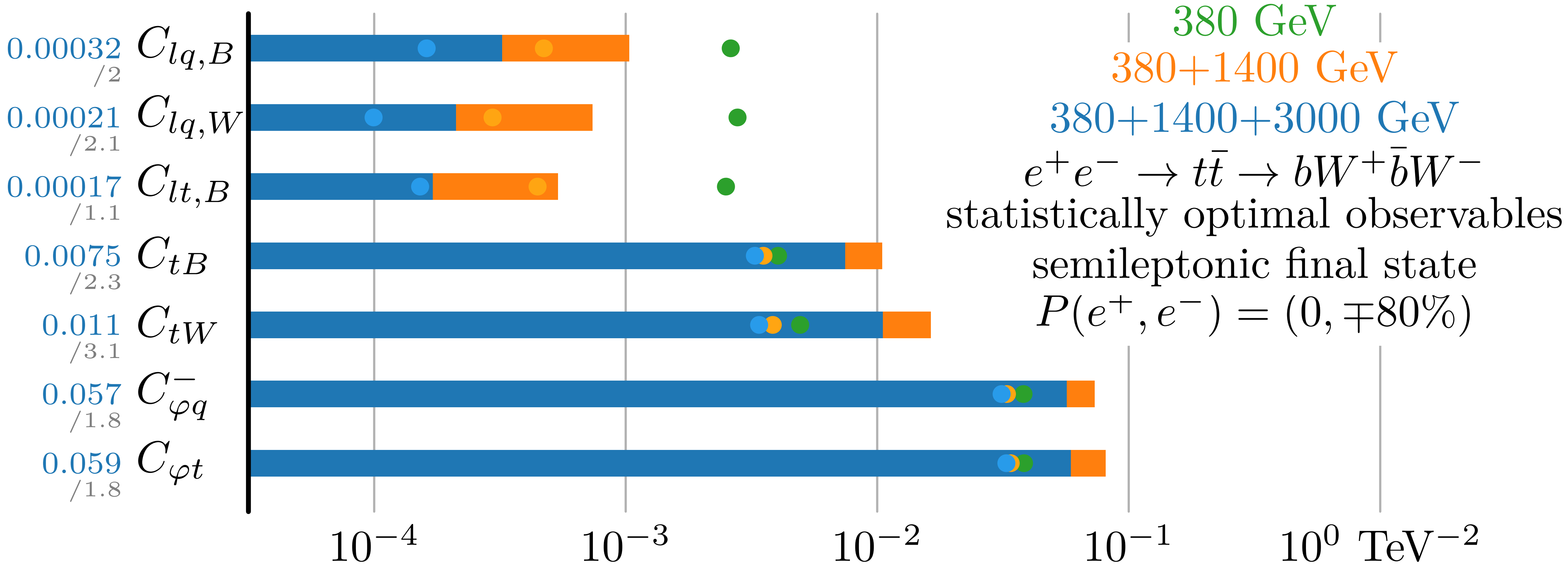
Global sensitivity to SMEFT BSM effects

Top-quark pair production measurements

- **Top-philic scenario – Universal + BSM/3rd family**
- Can be more **efficient indirect probes** of new physics than universal effects
- **2-fermion "vertex operators"** – sensitivity flat in energy → high precision already at 380 GeV
- **4-fermion "contact operators"** – represent a massive, new mediator beyond direct reach – sensitivity rises steeply with energy



Example: sensitivity of total ttbar cross-section to various dim-6 operators
JHEP 10 (2018) 168

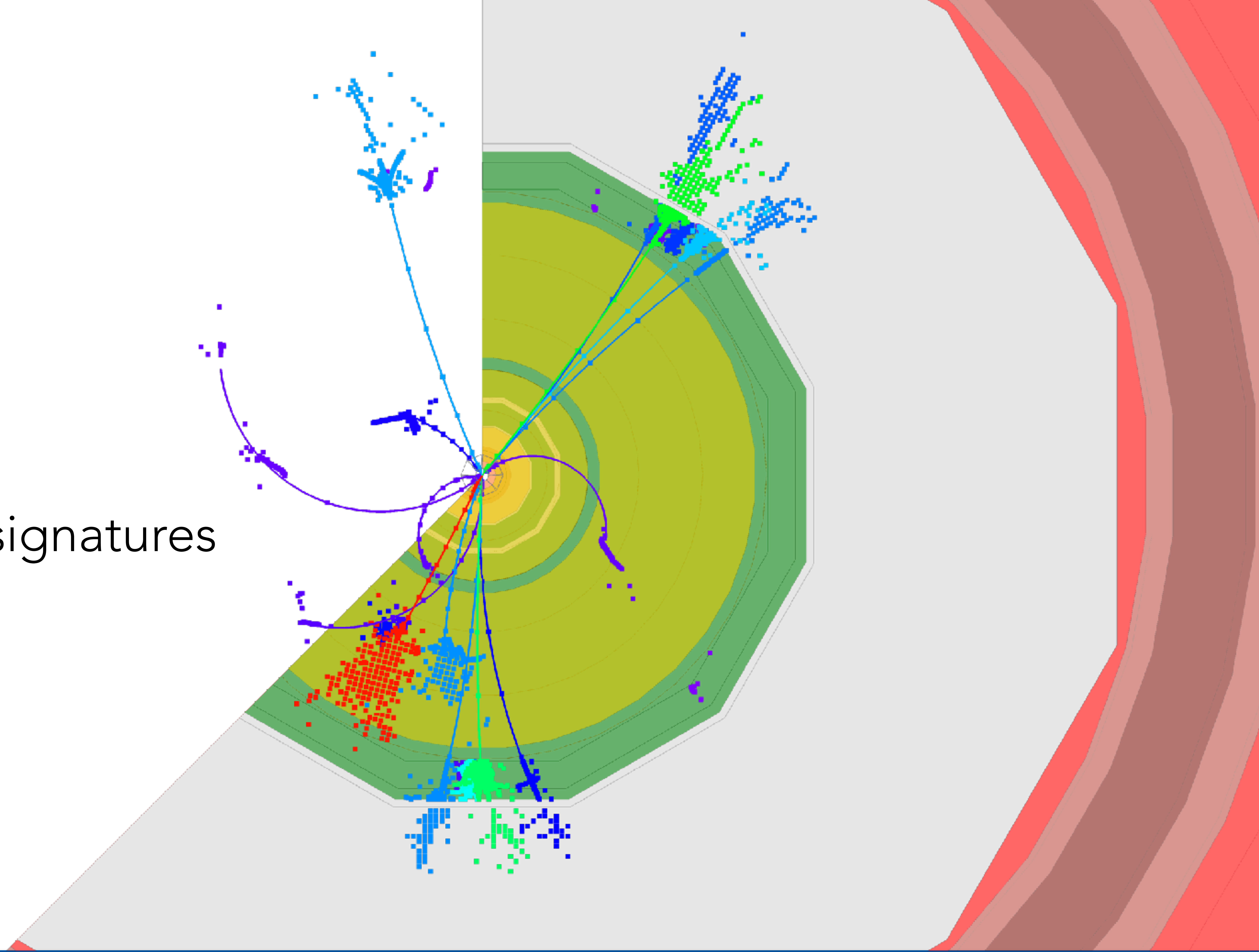


Higher precision

Top-philic global fit
bars: global, dots: individual

Physics reach

Examples of BSM signatures



Higgs and top compositeness

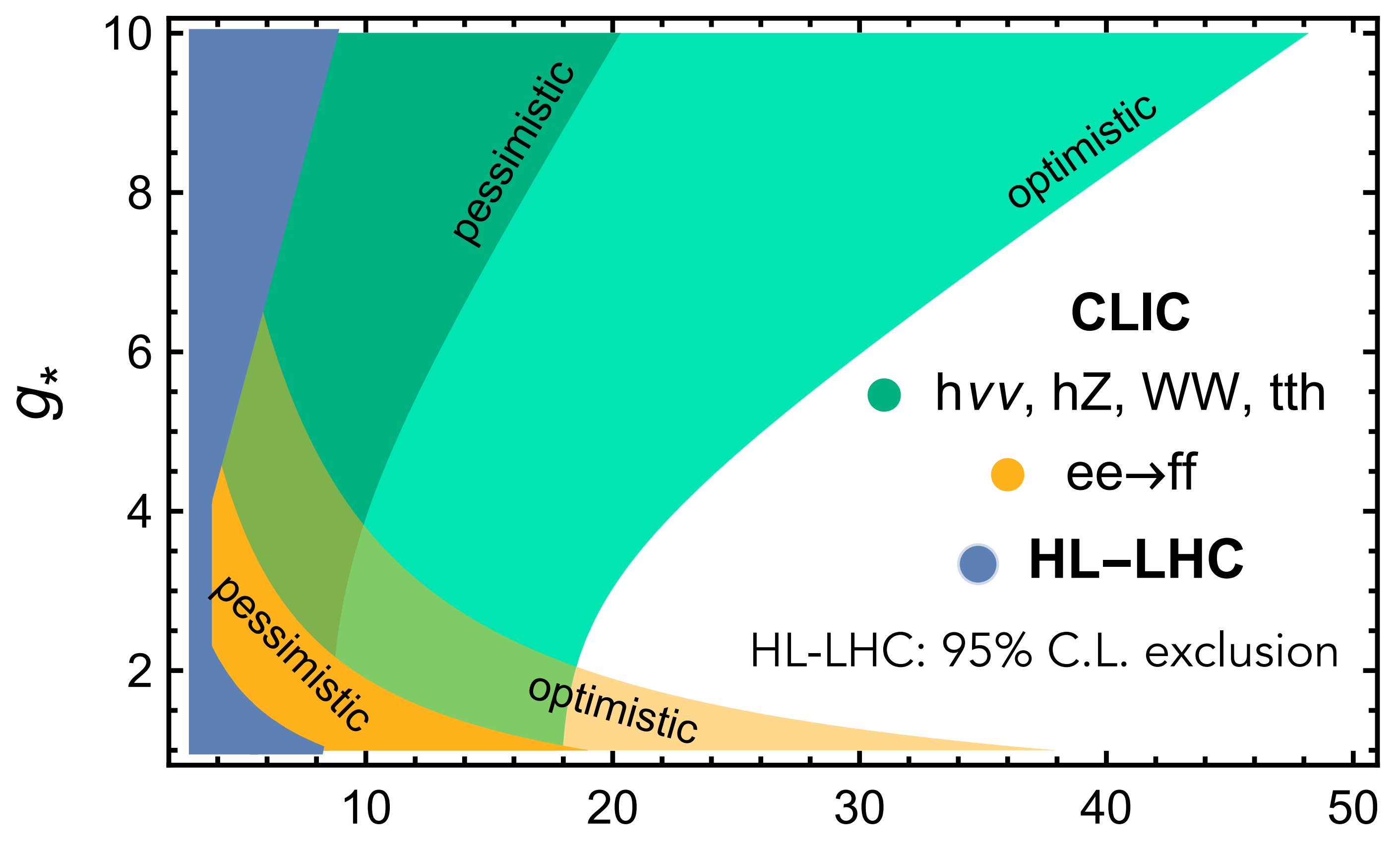
- Composite Higgs or top would appear through SM-EFT operators – translate EFT limits into composite sector
- Canonical scenario: Higgs as bound state
  - Pseudo-Nambu-Goldstone boson of underlying **strongly-interacting composite sector** (responsible for EWSB)
  - Characterised by **mass scale m_*** and **coupling strength g_***
  - SM fermions masses by **mixing** with the composite states
- Total t_R top compositeness scenario: the right-handed component is a fully composite state and the left-handed one is mostly elementary

> - CLIC will **discover** Higgs and top compositeness if the compositeness mass scale is **below 8 TeV**
> - Scales **up to 40 TeV**, in favourable conditions, above what HL-LHC can exclude

Discovery (5σ) reach on composite Higgs

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

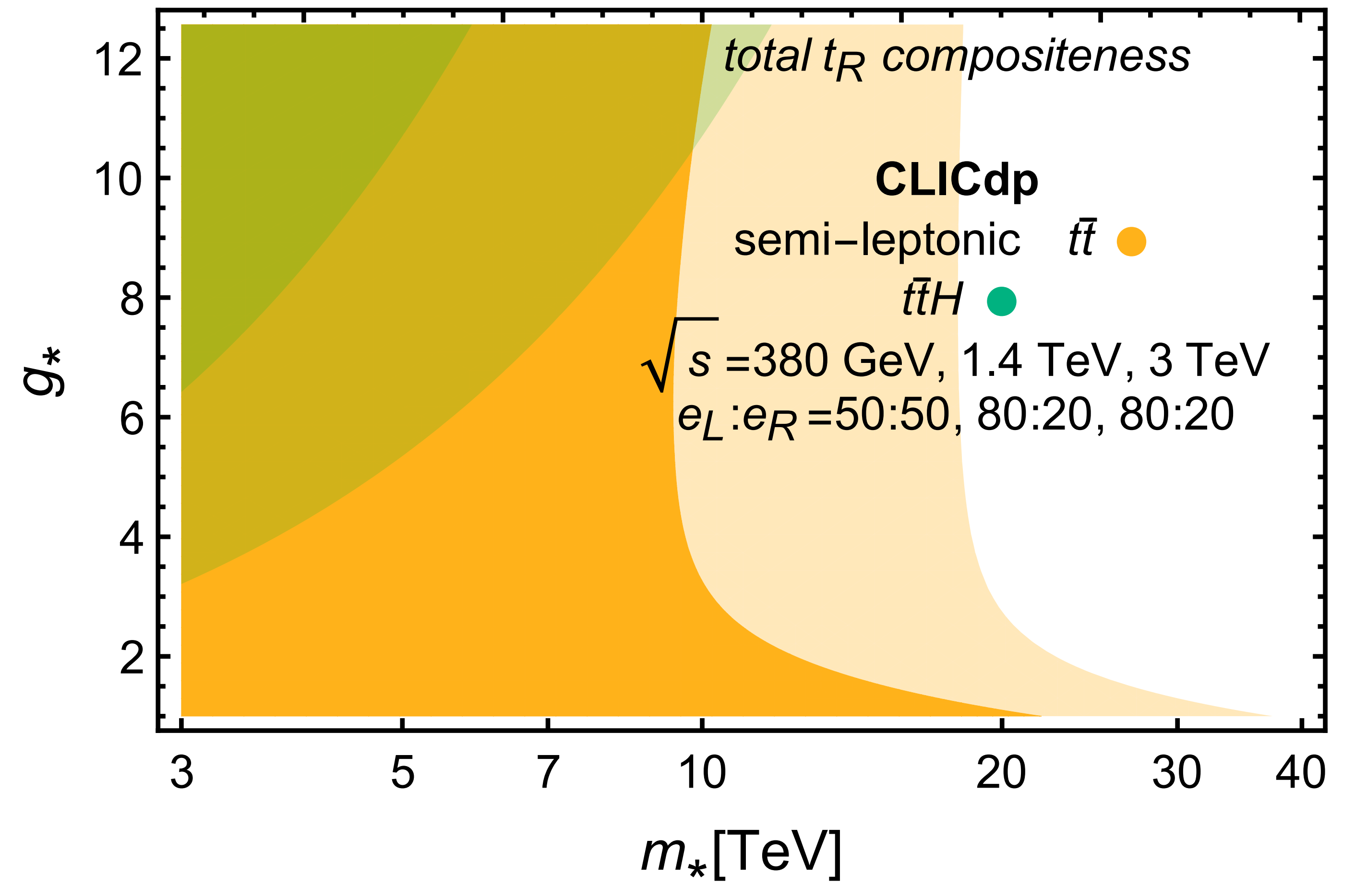
UNIVERSAL EFFECTS



Discovery (5σ) reach on composite top-quark

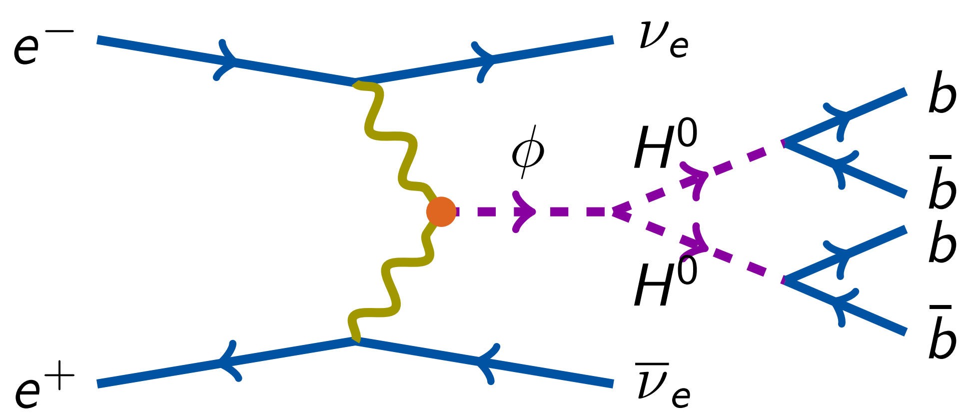
CLIC Physics Potential CERN-2018-009-M, arXiv:1812.02093

TOP-PHILIC EFFECTS



Extended Higgs sector – Heavy Scalar Singlets

- Extended scalar sector with new states that are not charged under the Standard Model gauge group (singlet)
- Appear in many BSM scenarios
- Interactions for example through **mixing with Higgs**
- **Example: heavy** $m_\phi > 2m_H$



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

Reduced Higgs couplings (universally rescaled)

⇕ **mixing**

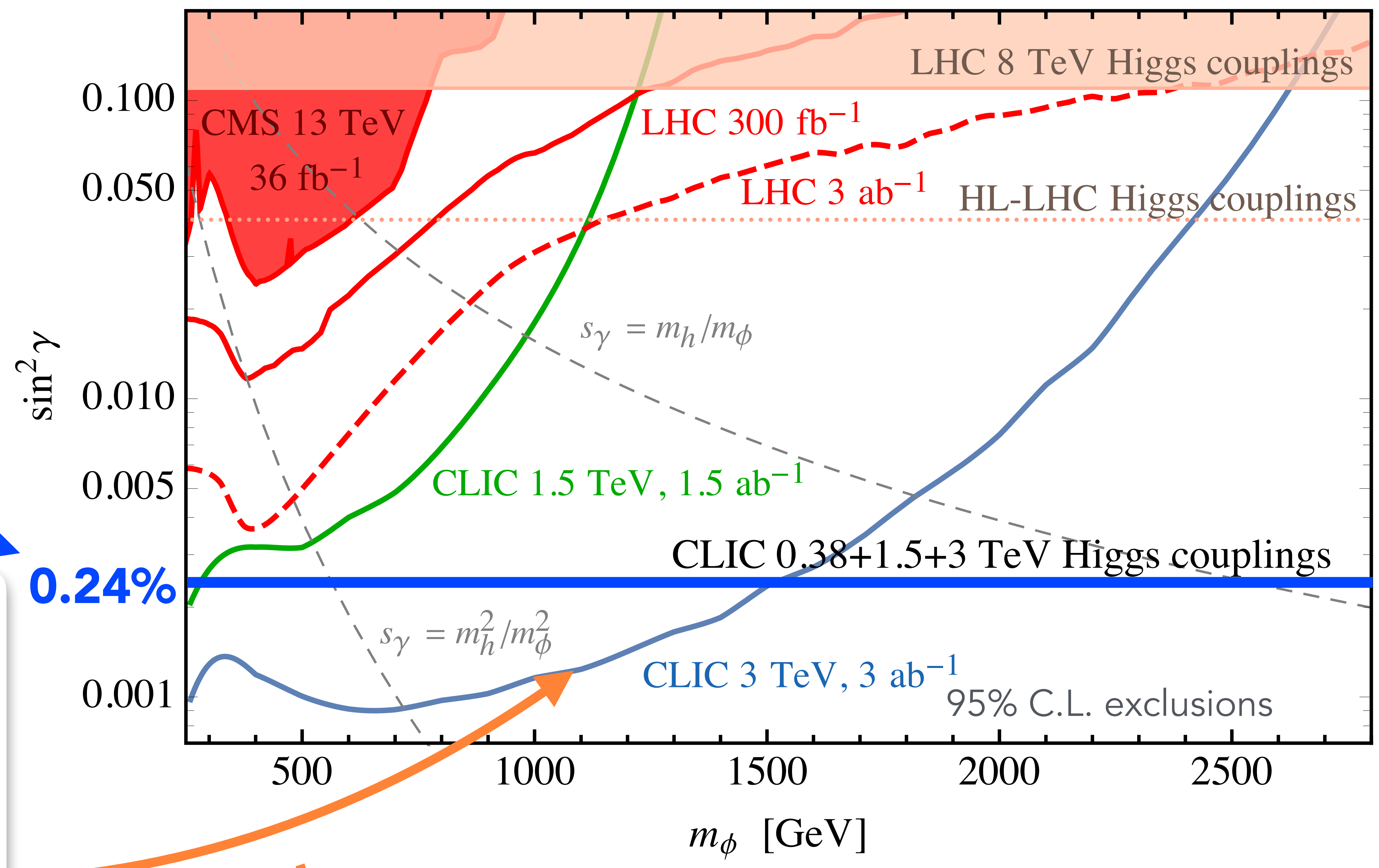
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

Couplings through mixing (production of heavy particle)

Indirect

Direct

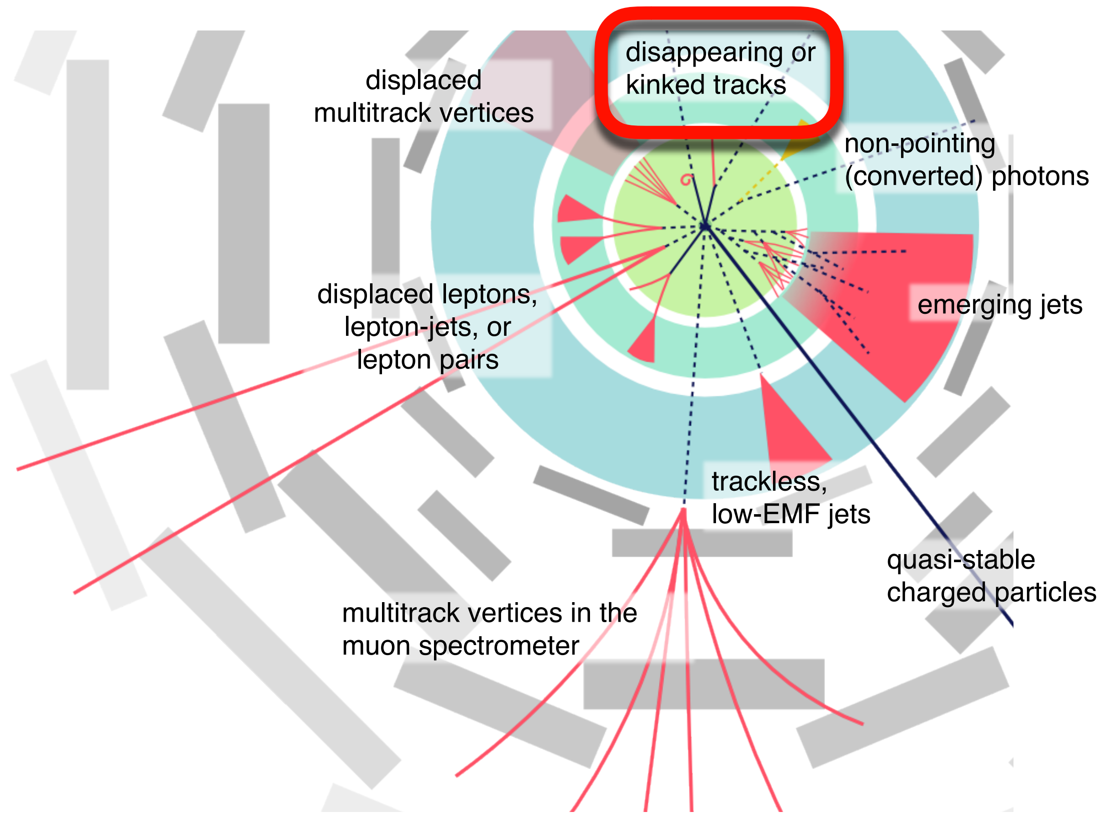
Heavy scalar singlets – 95% C.L. exclusion



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

Higgsino reach from stub tracks

- Higgsino: WIMP dark matter candidate, connected to weak scale naturalness, and gauge coupling unification
- Long-lived charged particles – Disappearing/stub tracks
- Such signature may be realised in models with a small mass splitting between dark sector particles, e.g. Chargino–Neutralino in SUSY models (other superpartners decoupled)
- Travels a macroscopic distance (of order 1 cm)
- At least 4 hits (from tracking performance studies)

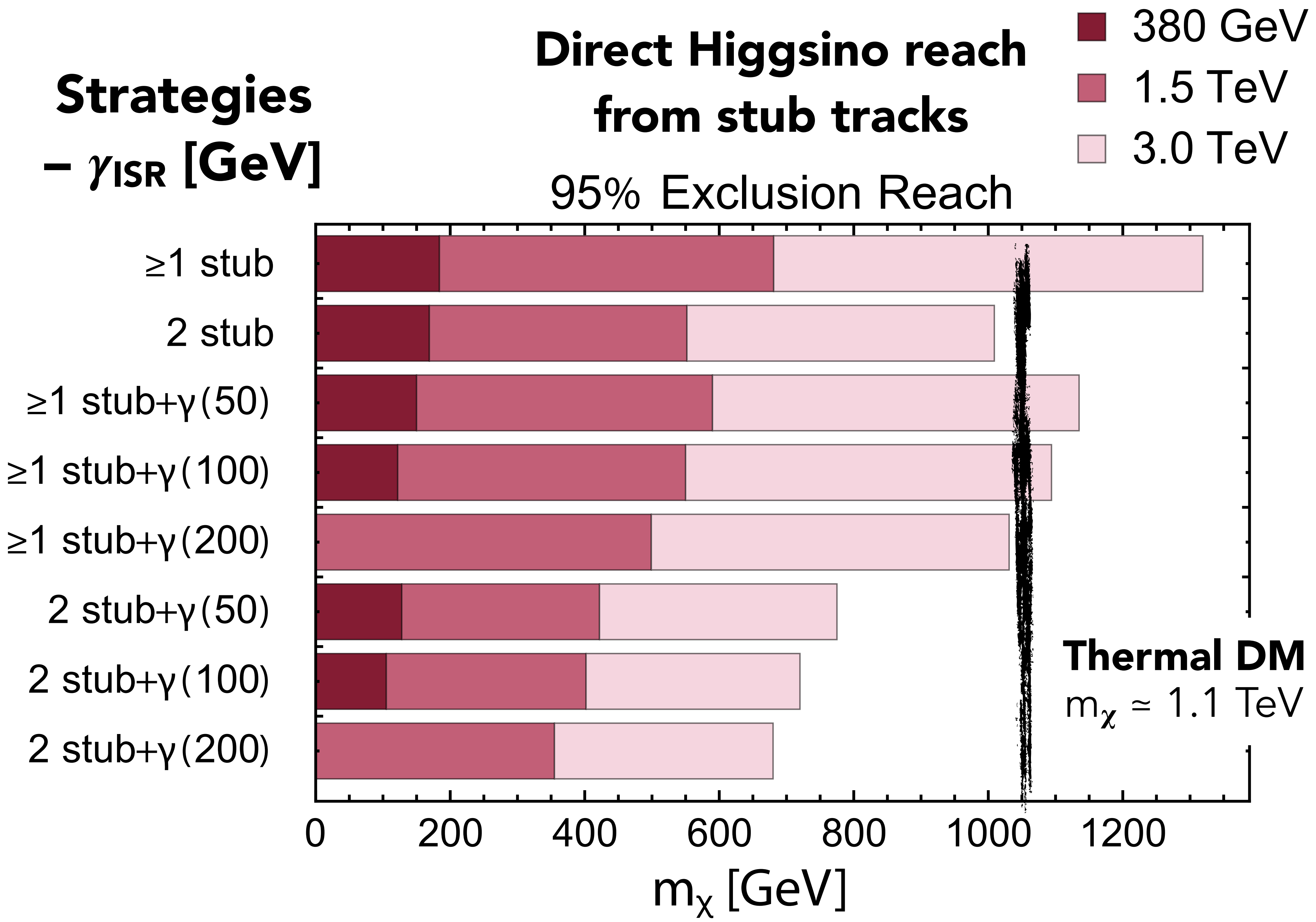


From presentation by Heather Russell, McGill Uni.

$$e^+e^- \rightarrow \chi^+\chi^-$$

$$\chi^\pm \rightarrow \chi^0\pi^\pm$$

soft SM Particle



- Benefit from the **clean environment** of e^+e^- collisions and **excellent tracking** detectors
- **Reach Higgsino mass of 1.1TeV**, required for DM relic mass density – even with some level of background

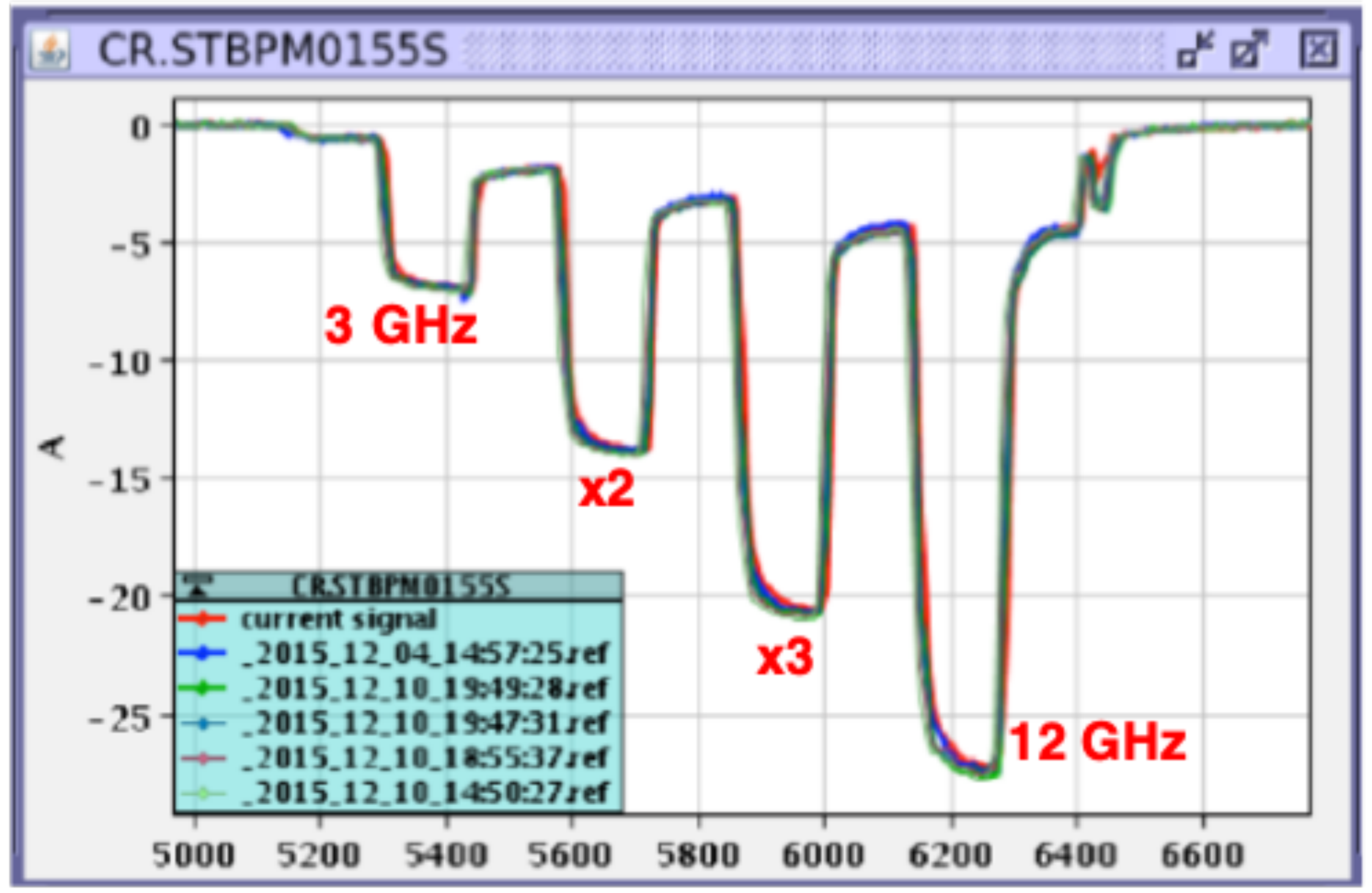
CLIC Physics Potential CERN-2018-009-M, arXiv:1812.02093

Accelerator challenges

Four main challenges:

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

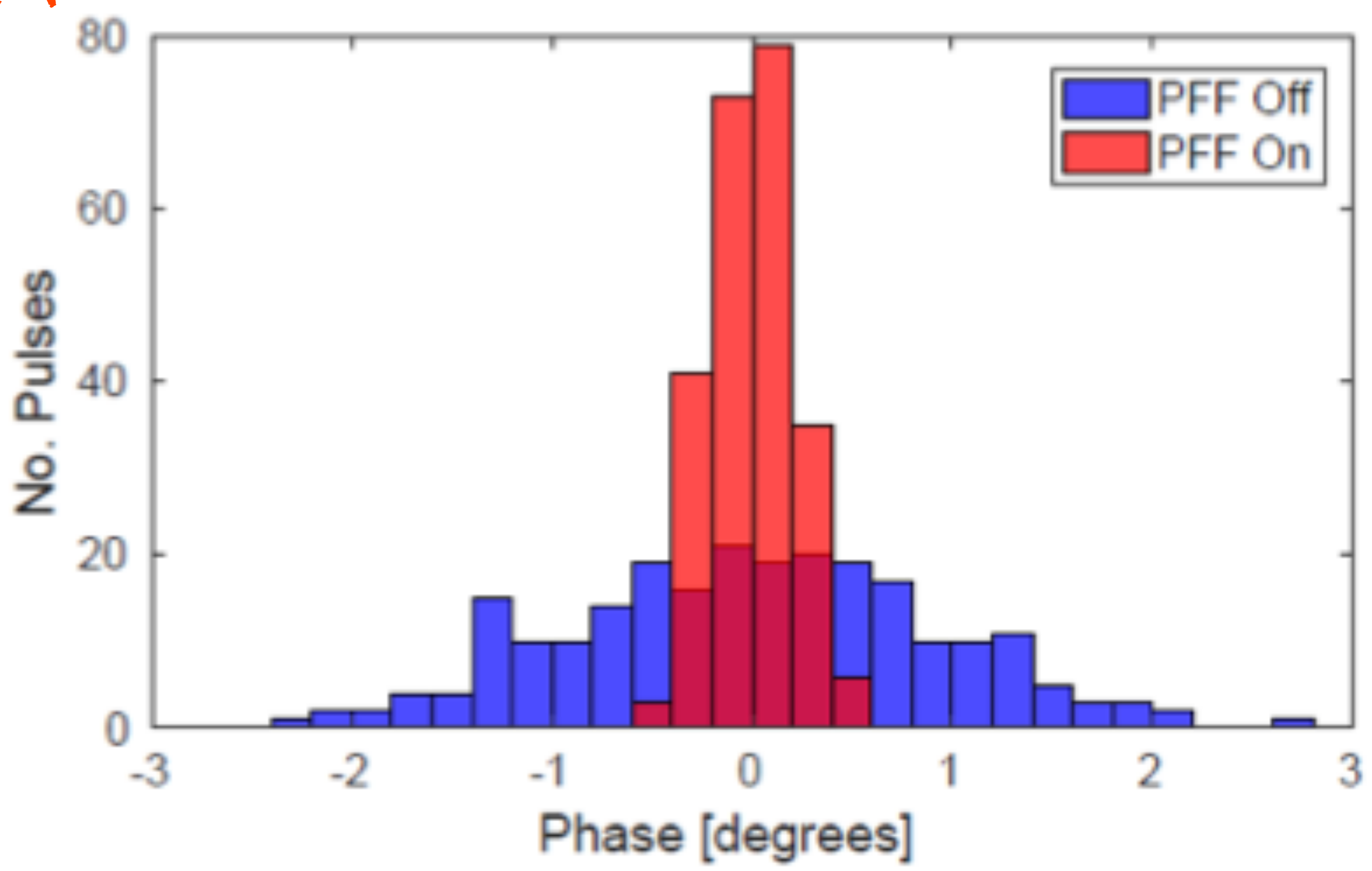
Drive beam quality:
Produced high-current drive beam bunched at 12 GHz



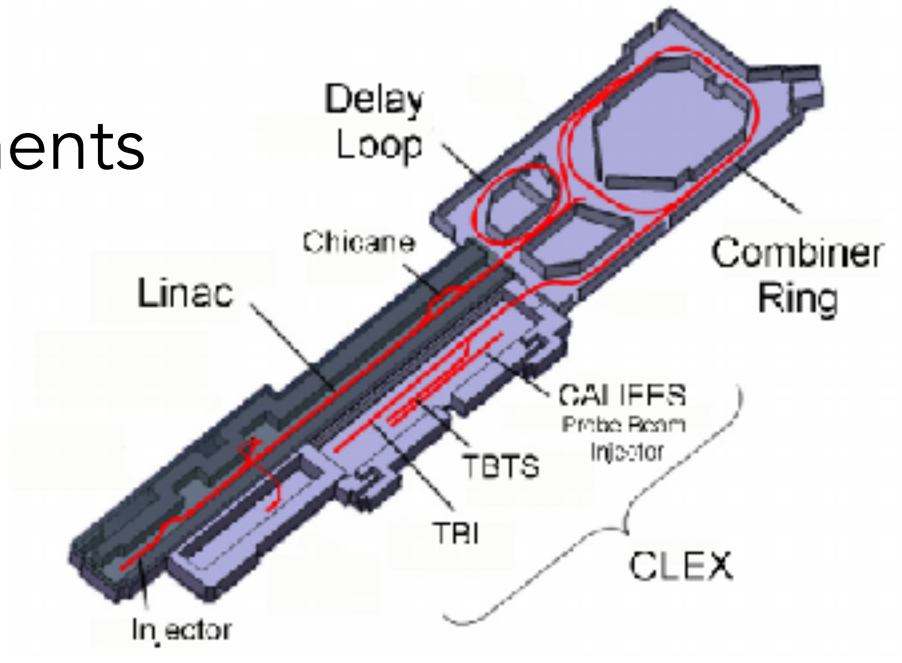
← 28A

Current in combiner ring

Drive beam arrival time stabilised to CLIC specification of 50 fs



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



Accelerator challenges

FOUR MAIN CHALLENGES:

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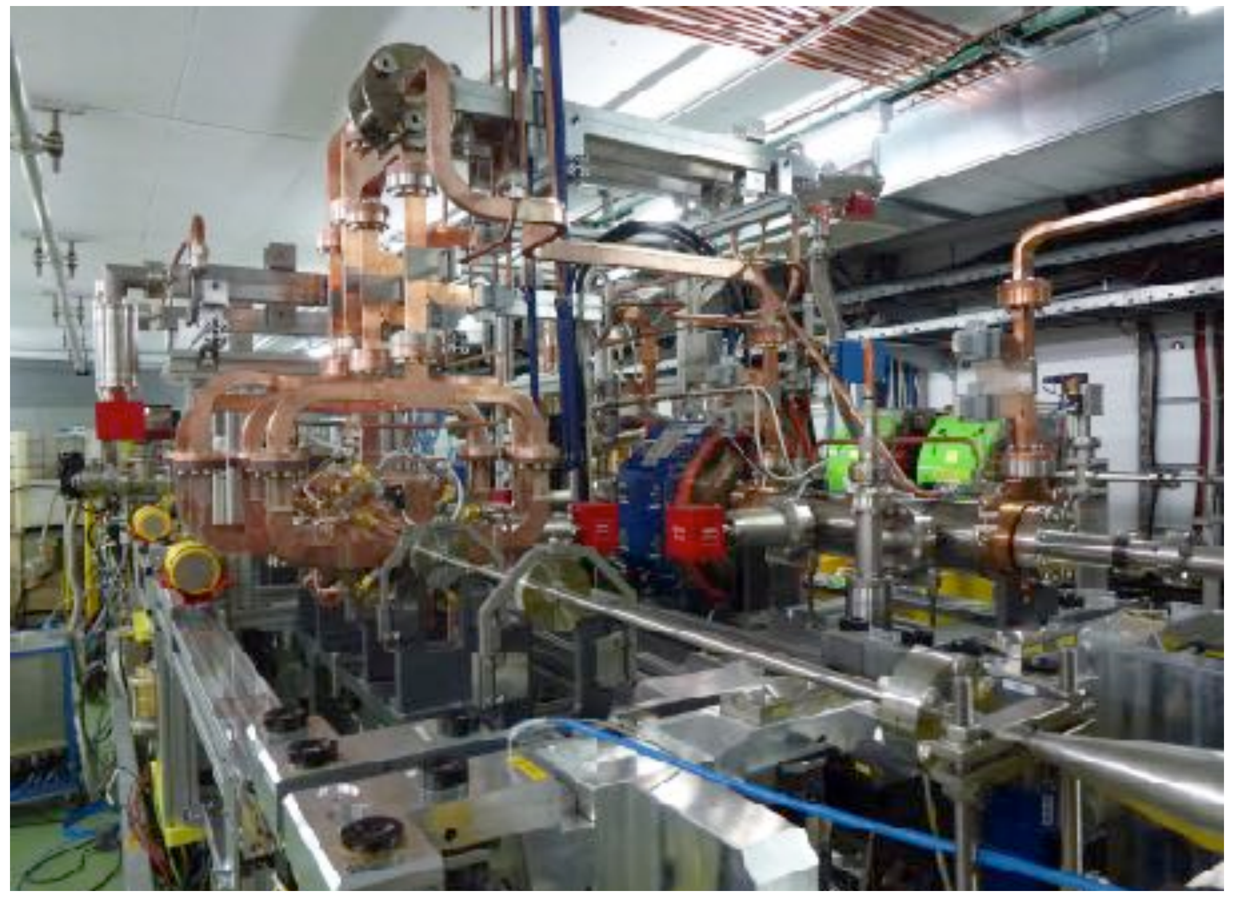
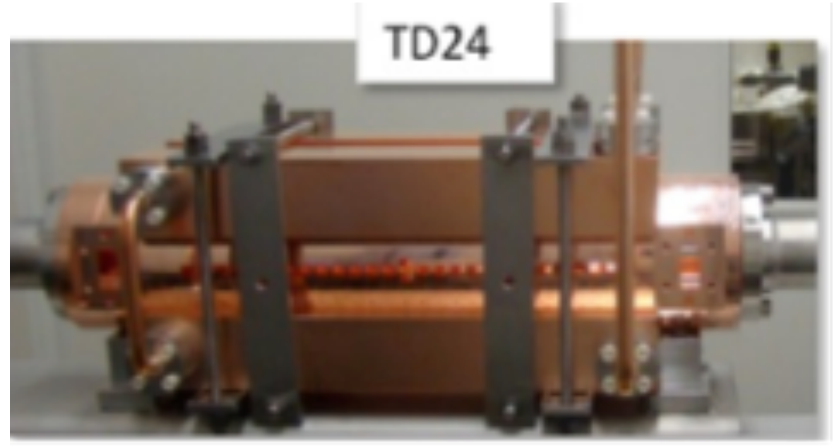
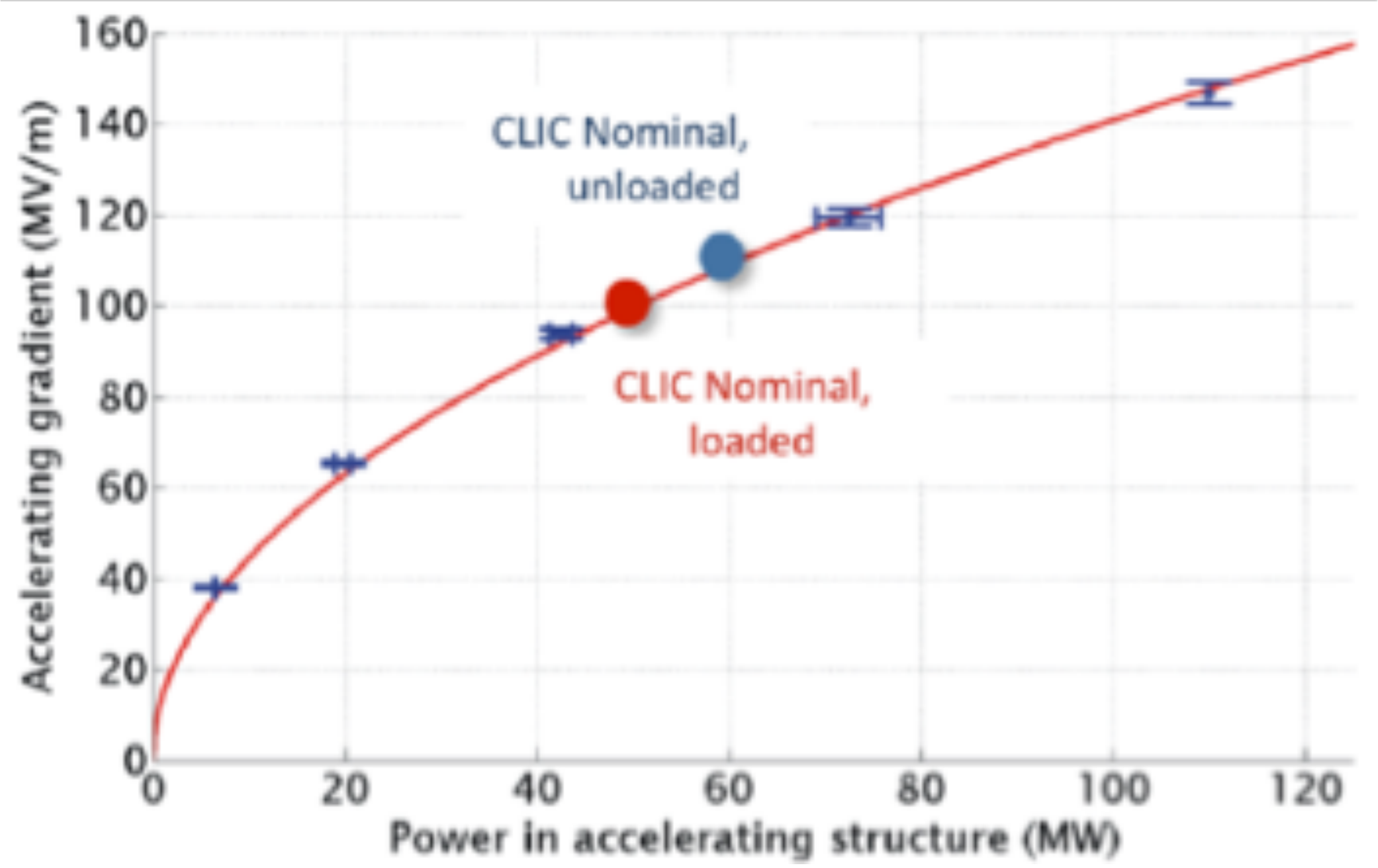
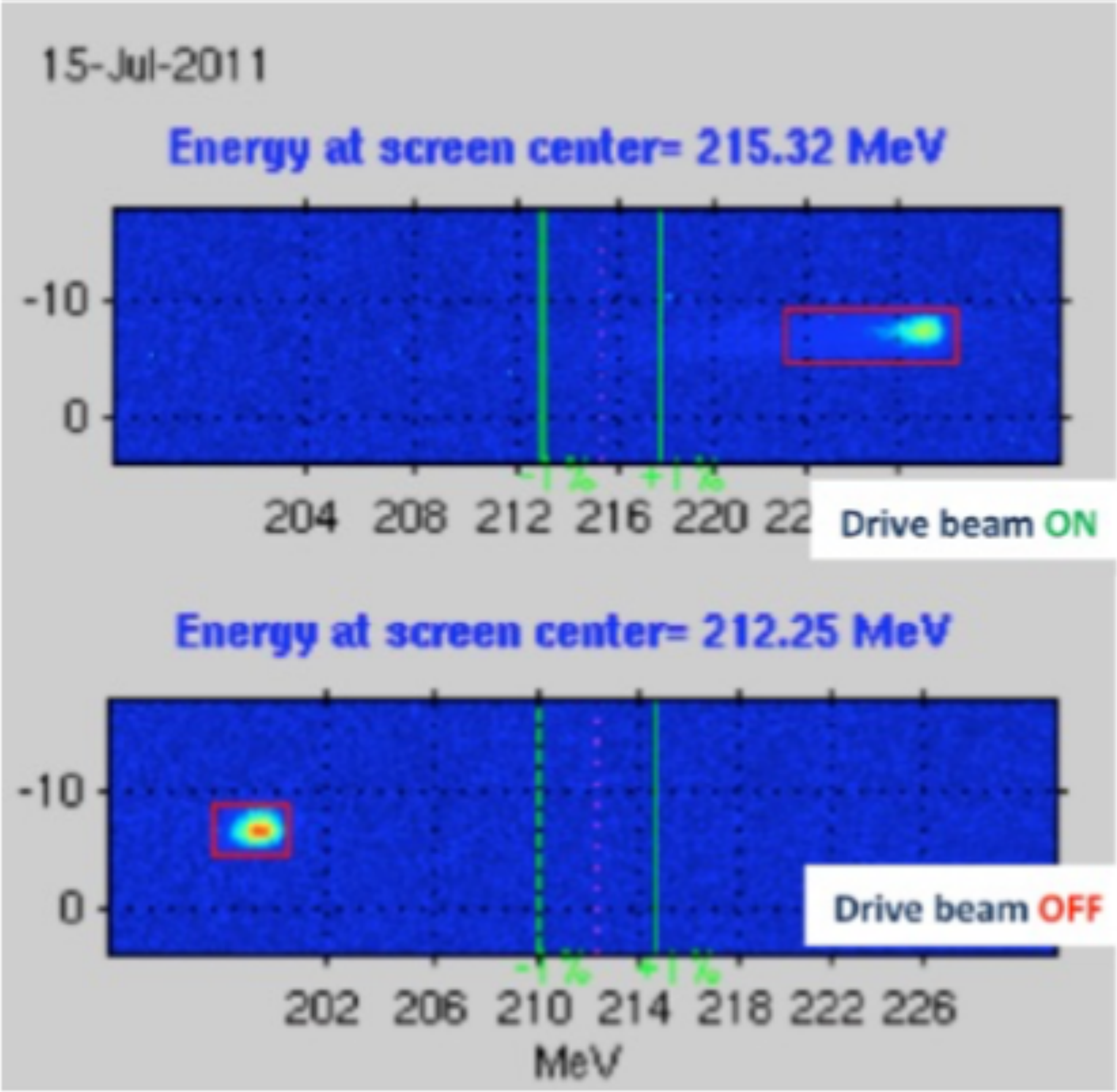
Demonstrated 2-beam acceleration





31 MeV = 145 MV/m





Accelerator challenges

FOUR MAIN CHALLENGES:

- High-current drive beam bunched at 12 GHz
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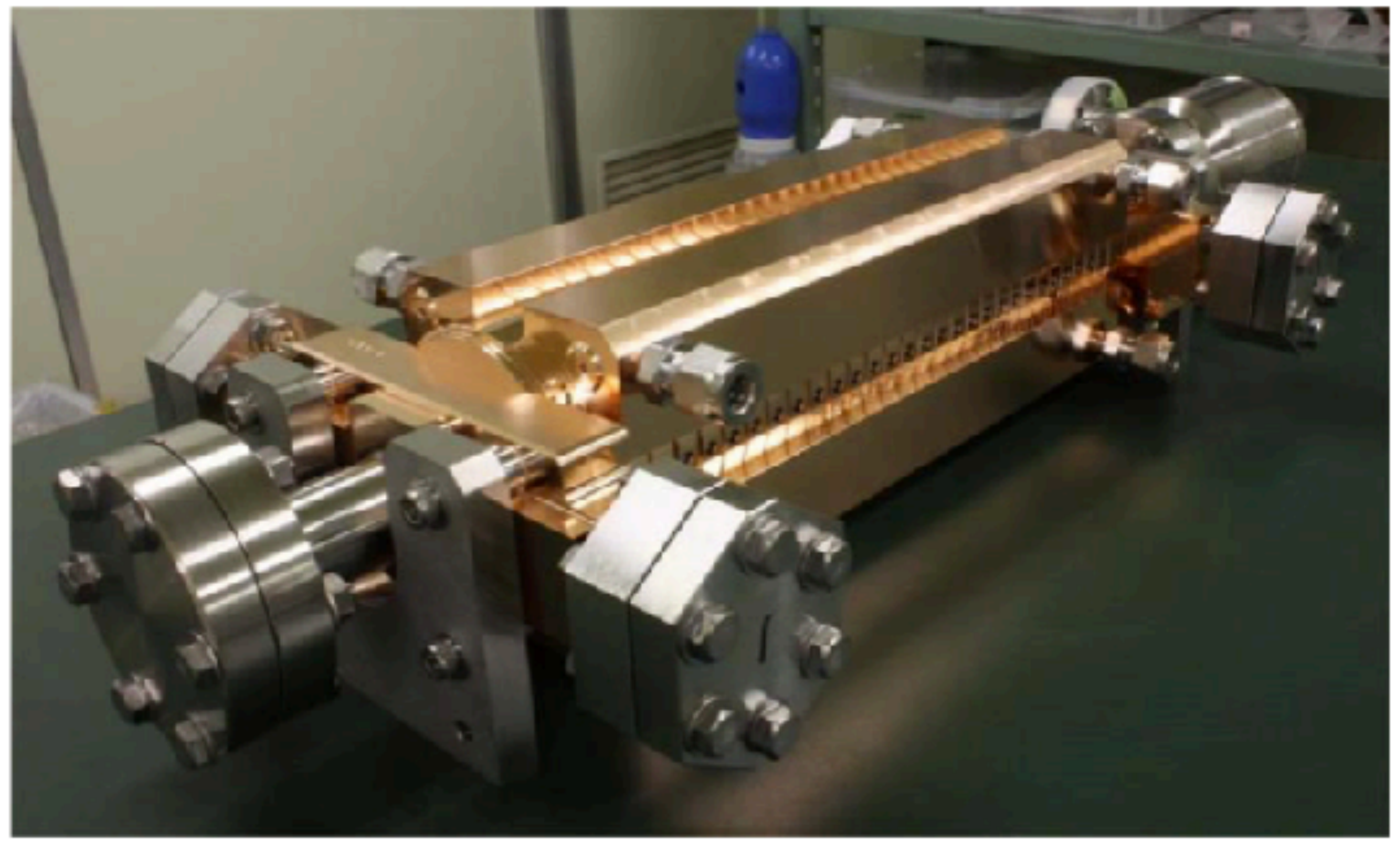
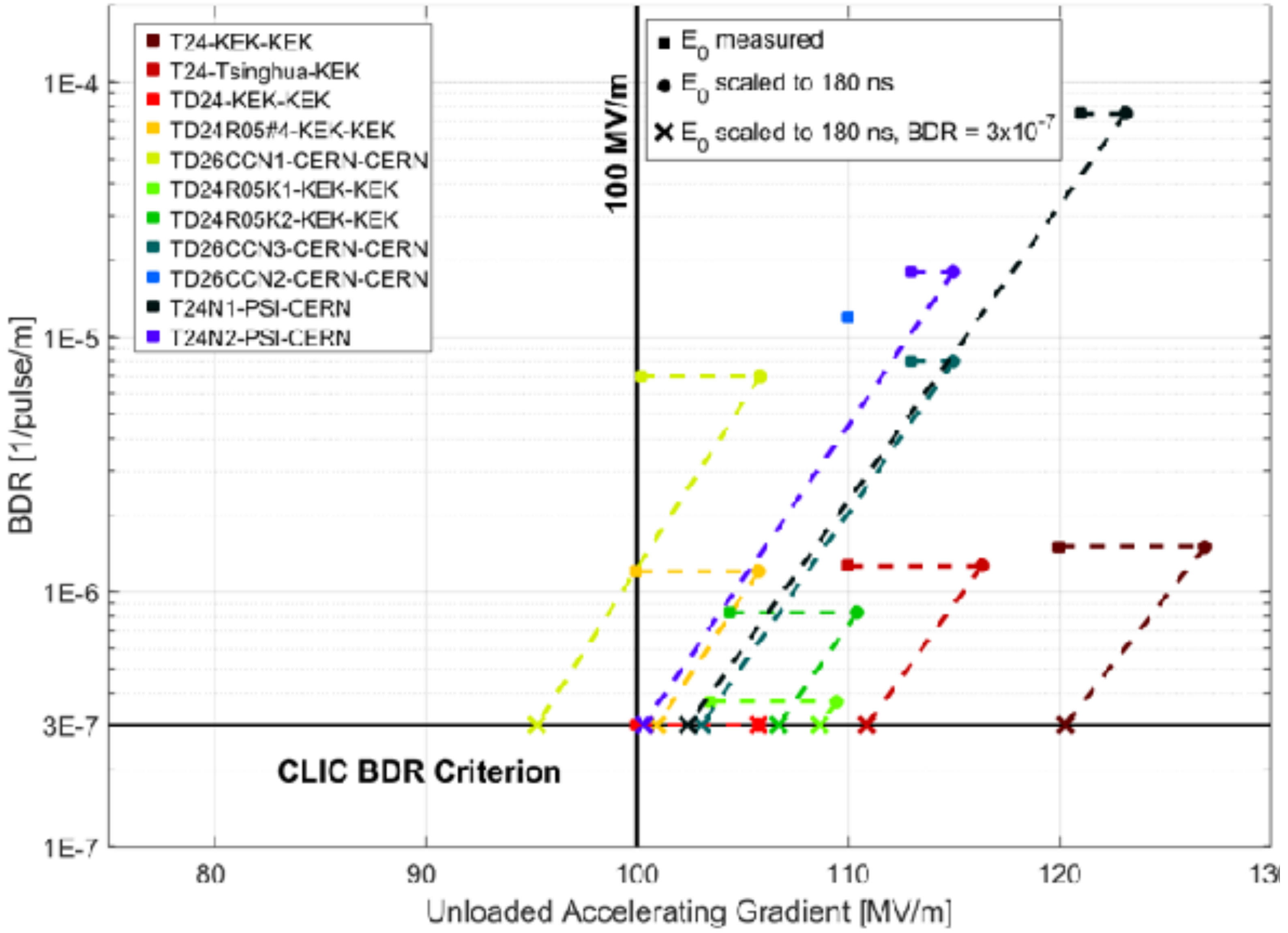
- **~100 MV/m gradient in main-beam cavities**
- Alignment & stability

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

Disk

Structure





XBox test facility, at CERN

Accelerator challenges

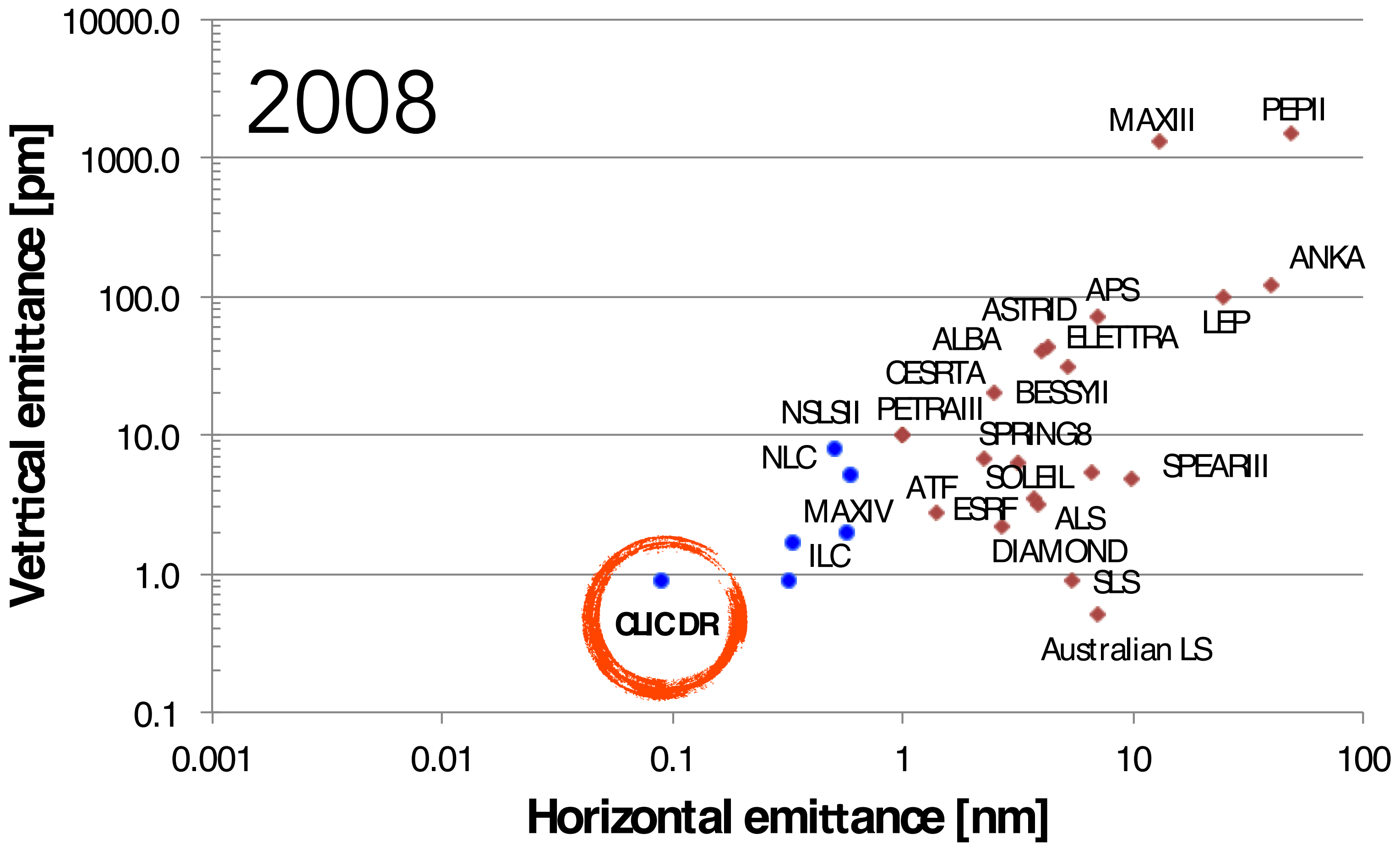
FOUR MAIN CHALLENGES:

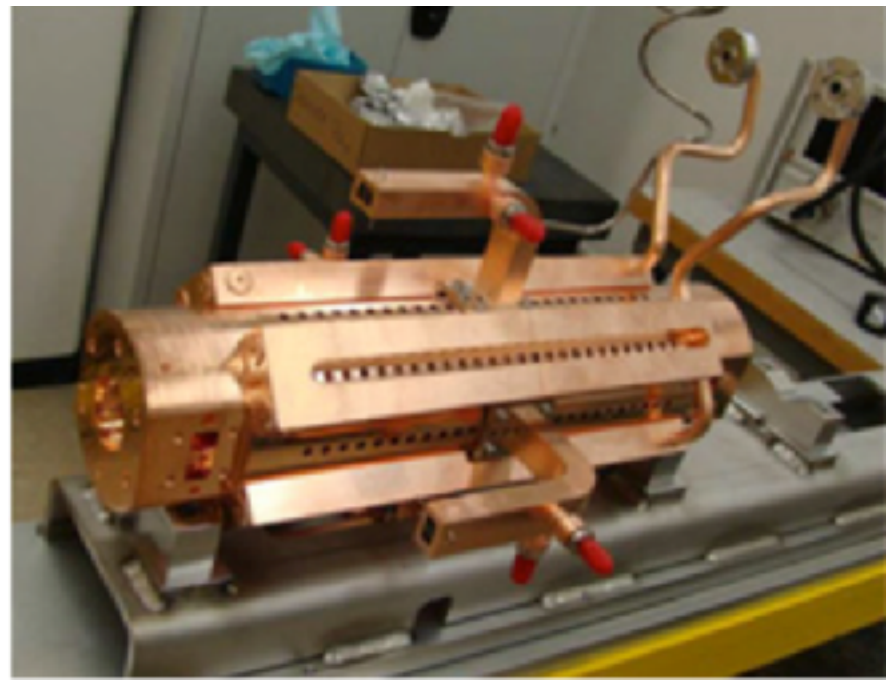
- High-current drive beam bunched at 12 GHz
- Power transfer + main-beam acceleration
- ~100 MV/m gradient in main-beam cavities
- **Alignment & stability**

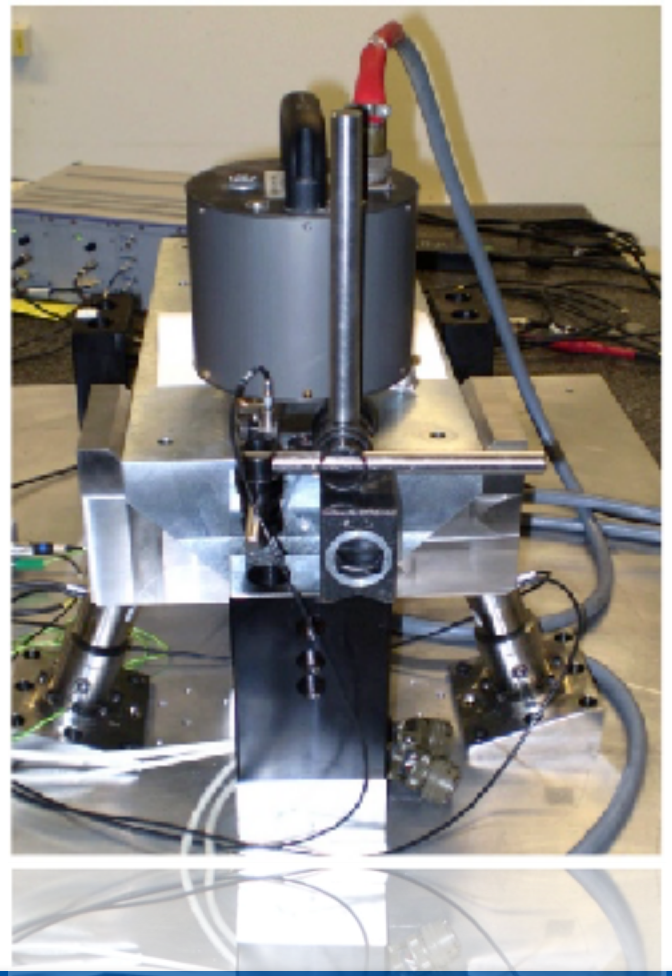
Nano-beams

- **The CLIC strategy**
- Align components (10 µm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well (allow to steer beam and optimise positions)
- Algorithms for measurements, beam and component optimisation, feedbacks
- Test in small accelerators of equipment and algorithm (FACET at Stanford, ATF2 at KEK, CTF3 at CERN, light-sources)

CLIC emittance at damping rings







Accelerator challenges

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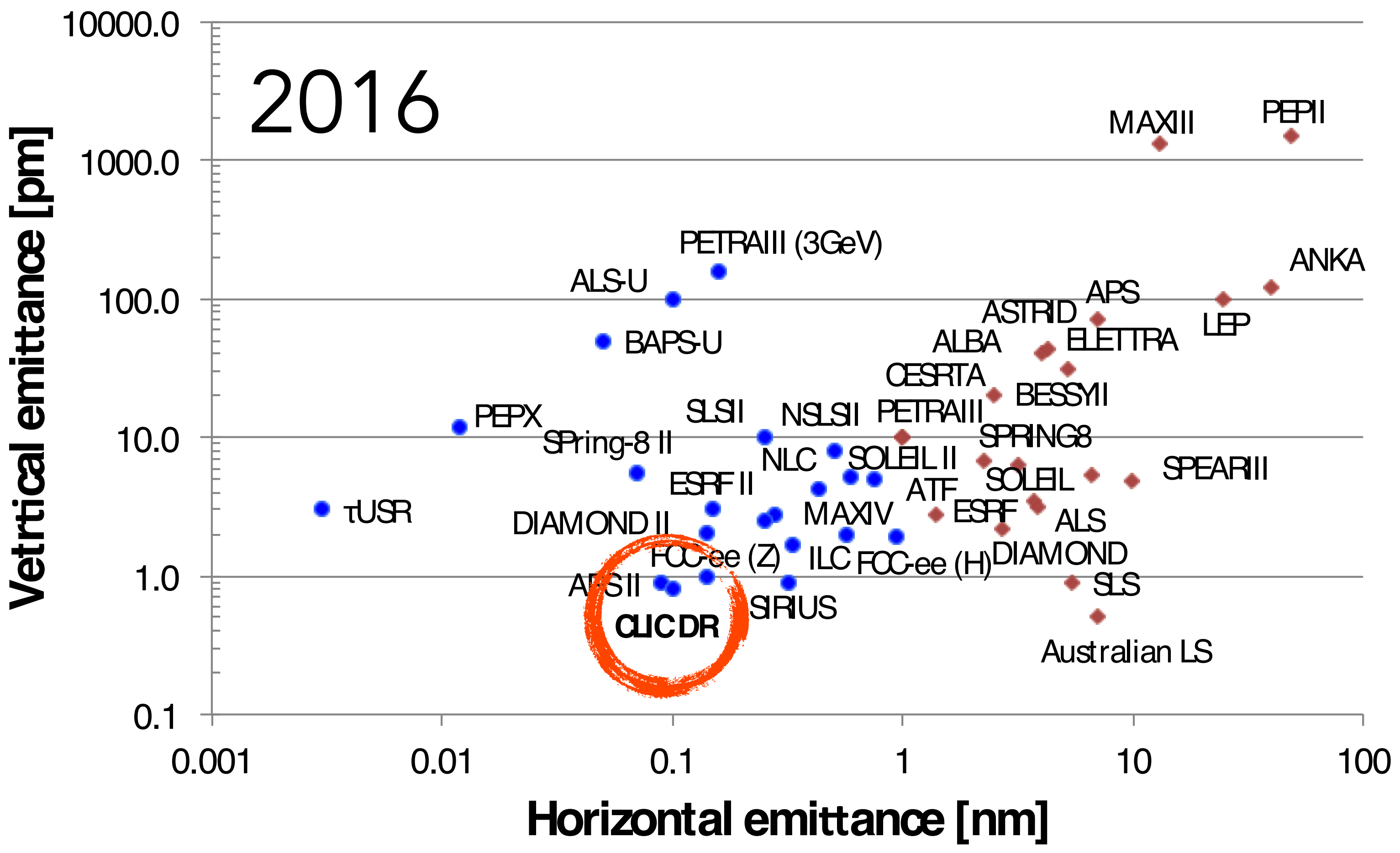
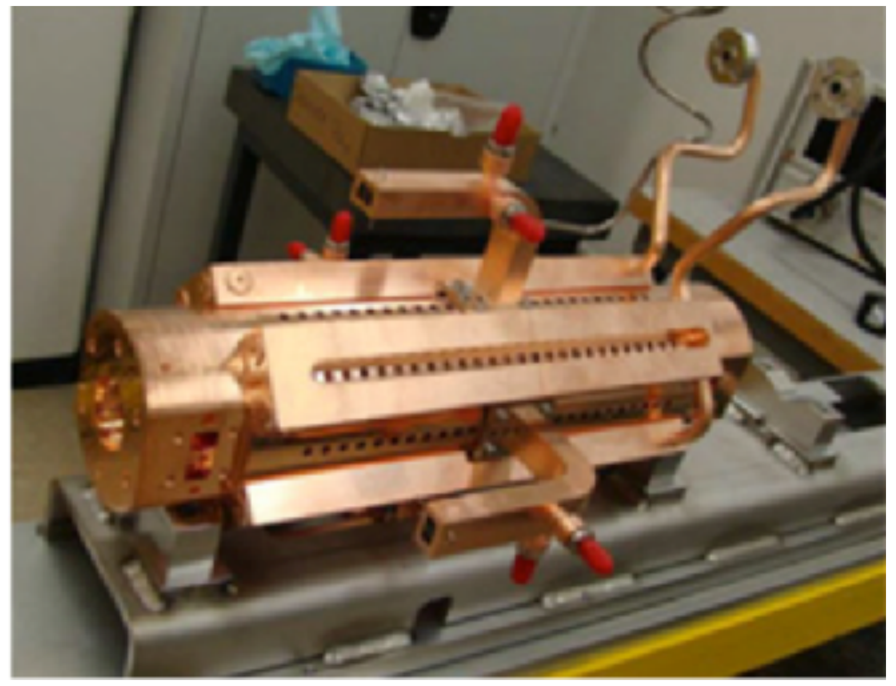
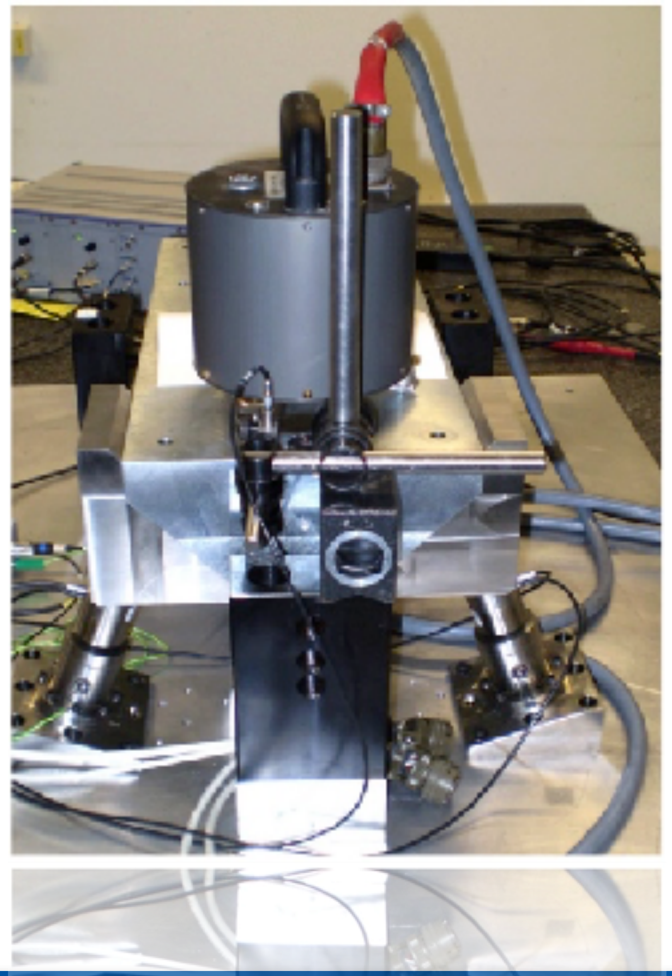
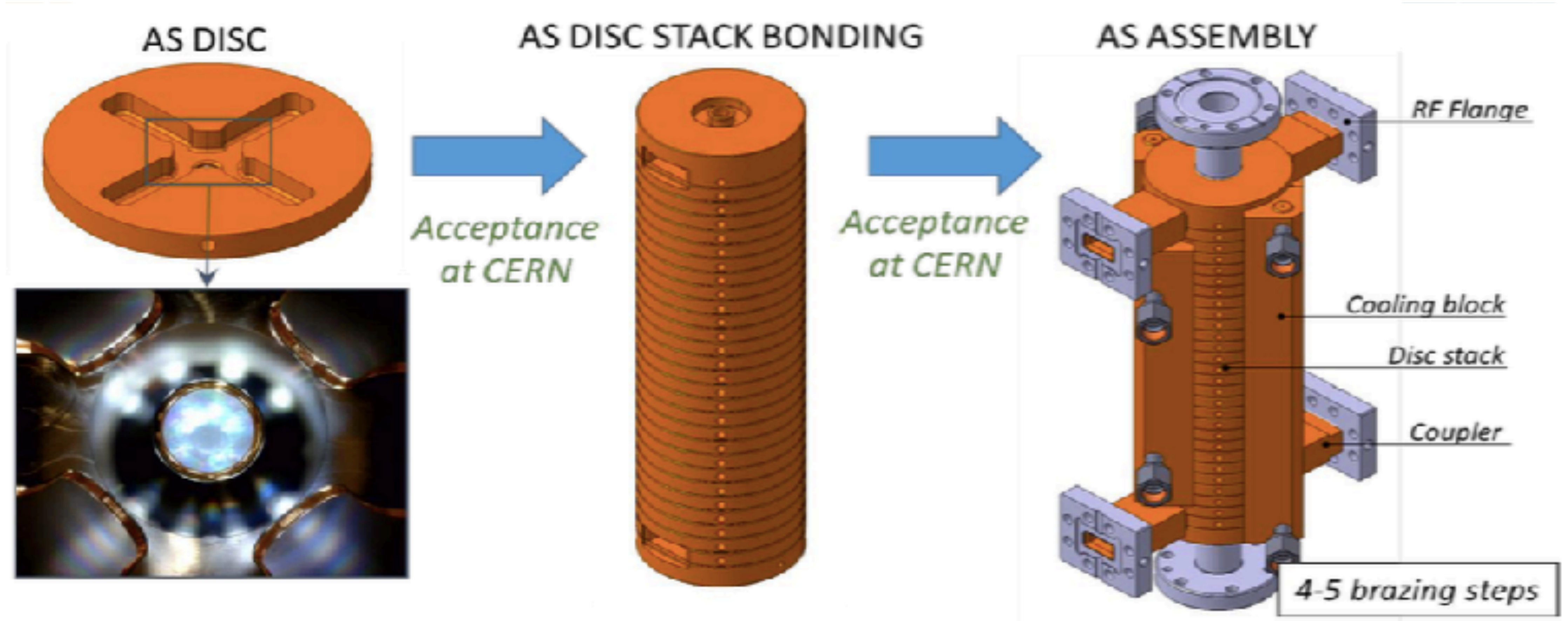
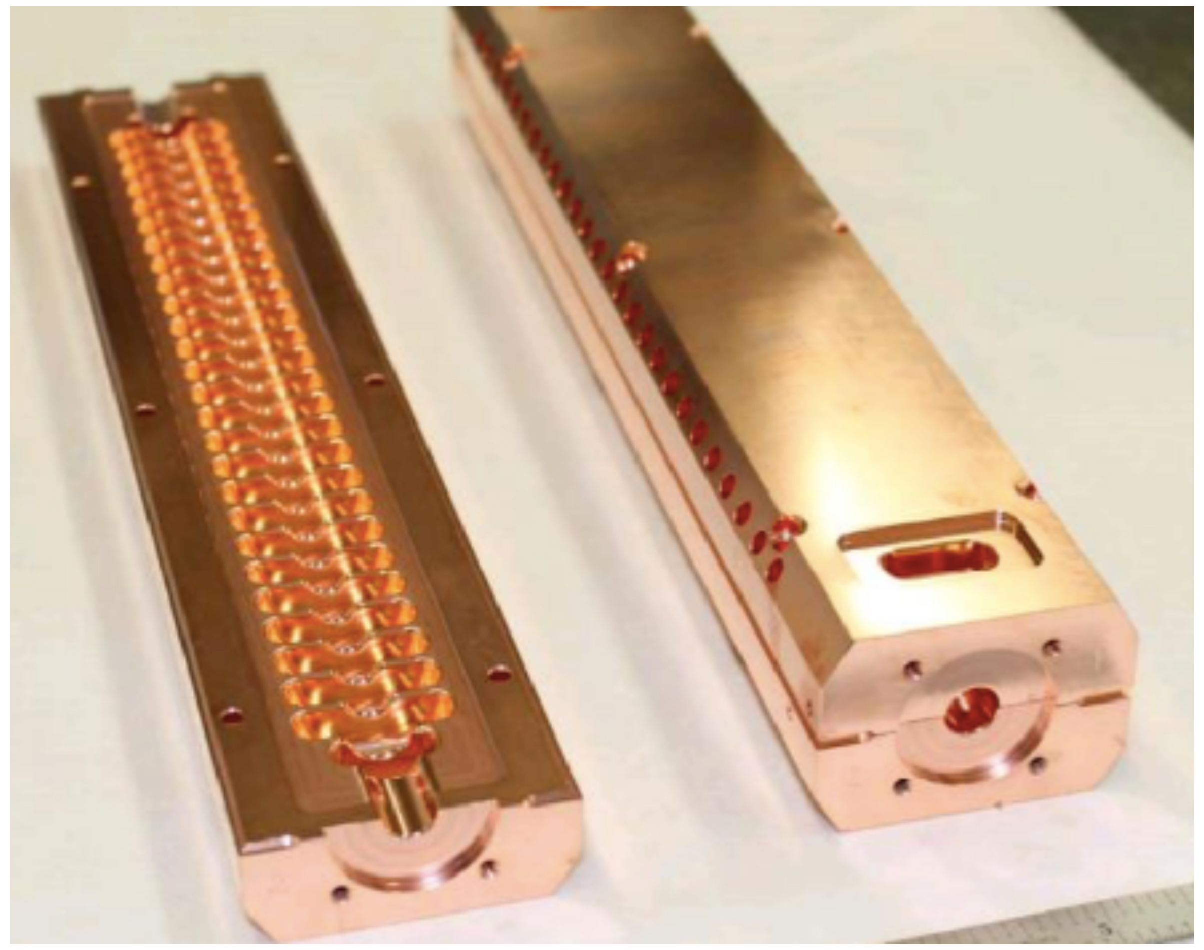


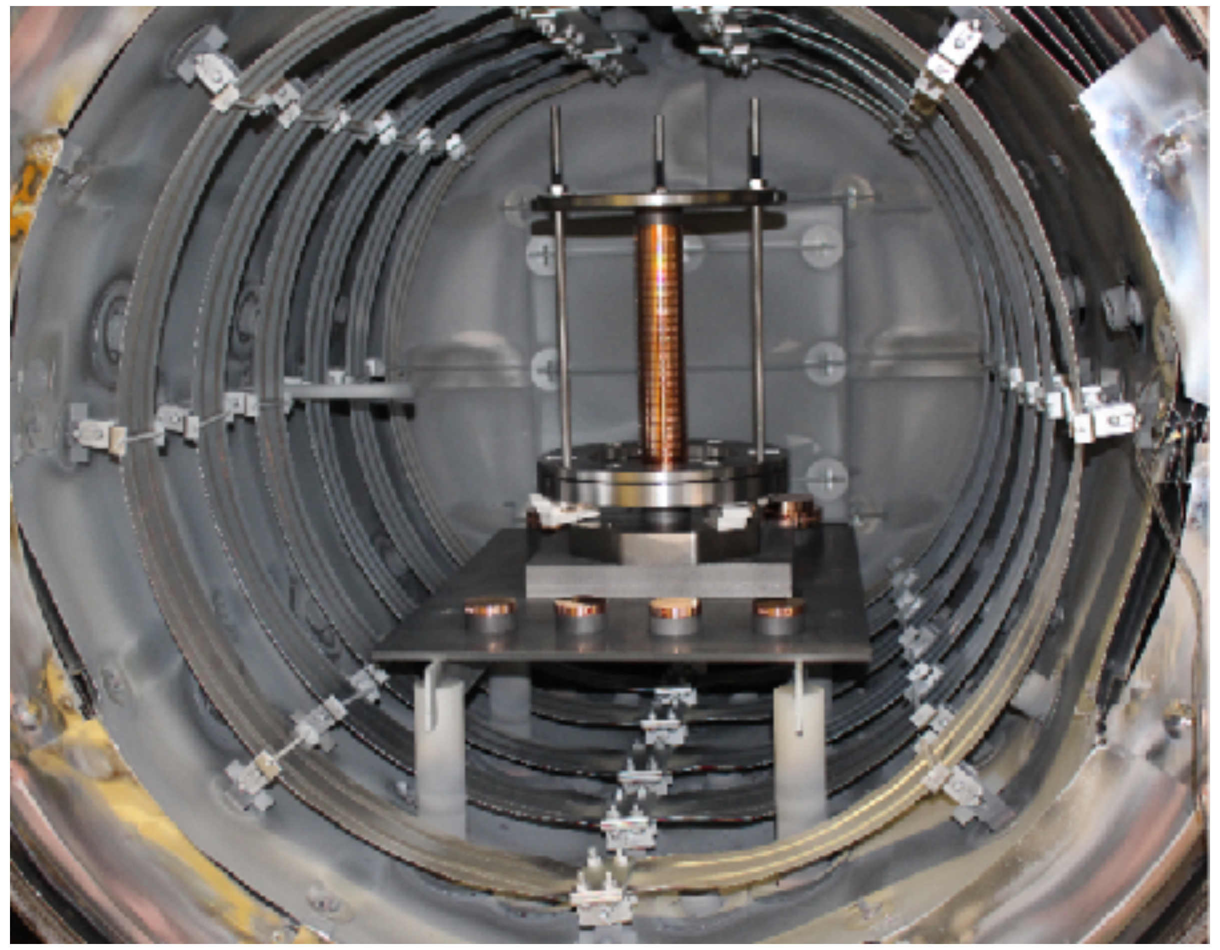




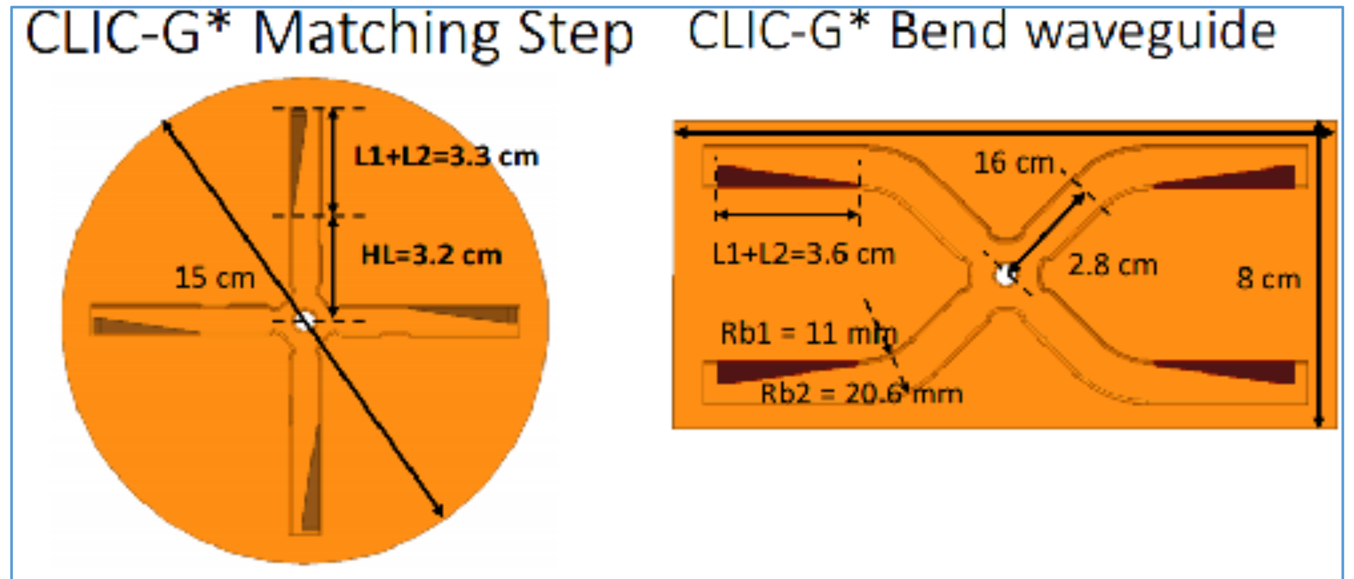
Towards industrialisation







- Investigating paths to industrialisation
- Target: low-cost and easy-to-manufacture structures
- Baseline manufacturing technique: bonding and brazing
- Alternatives:
  - Brazing as for SwissFEL
  - Machining halves



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

Cost and power

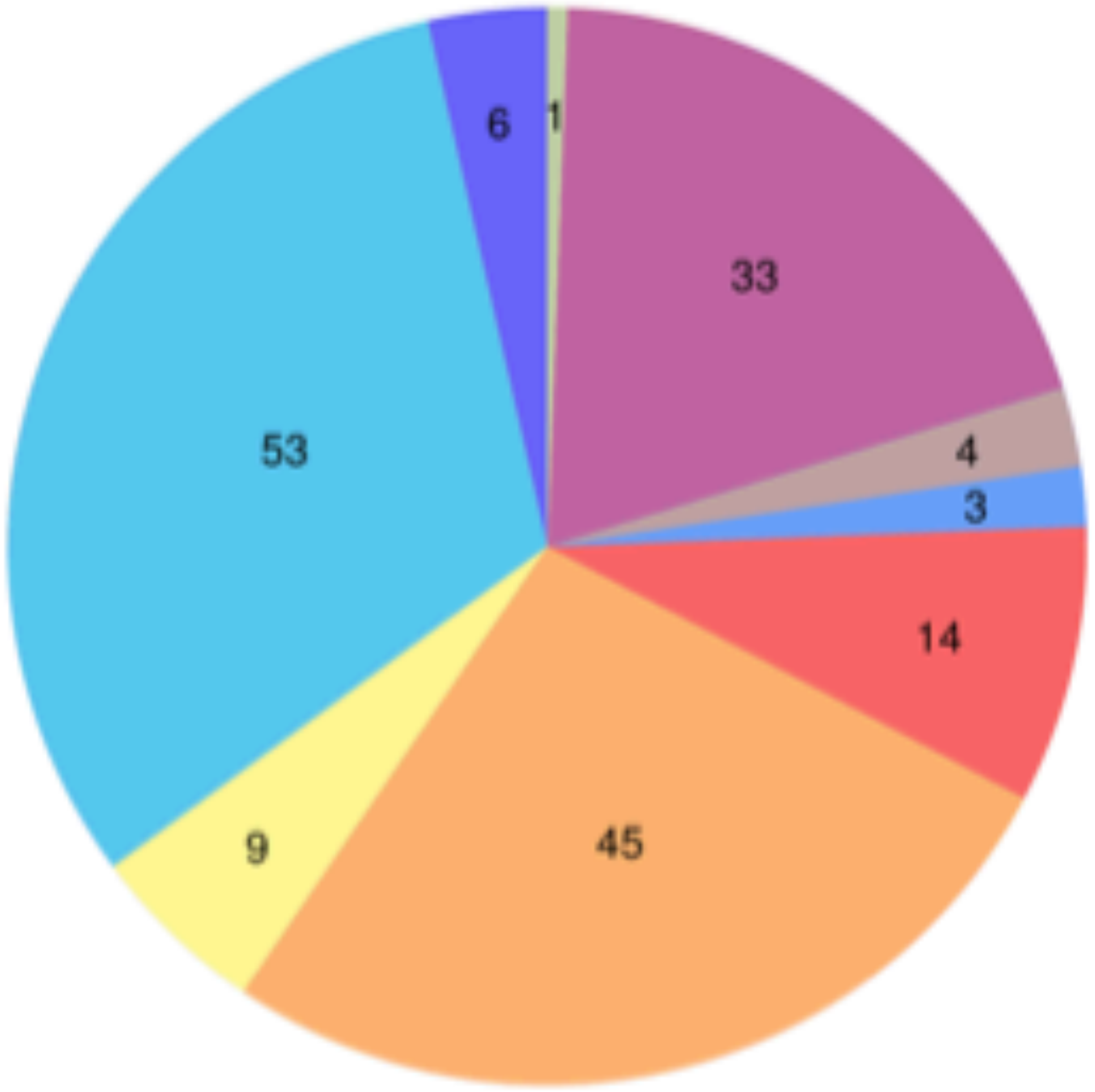
Cost

- CLIC380: 5.9 BCHF
- CLIC1500, add 5.1 BCHF
- CLIC3000, add 7.3 BCHF

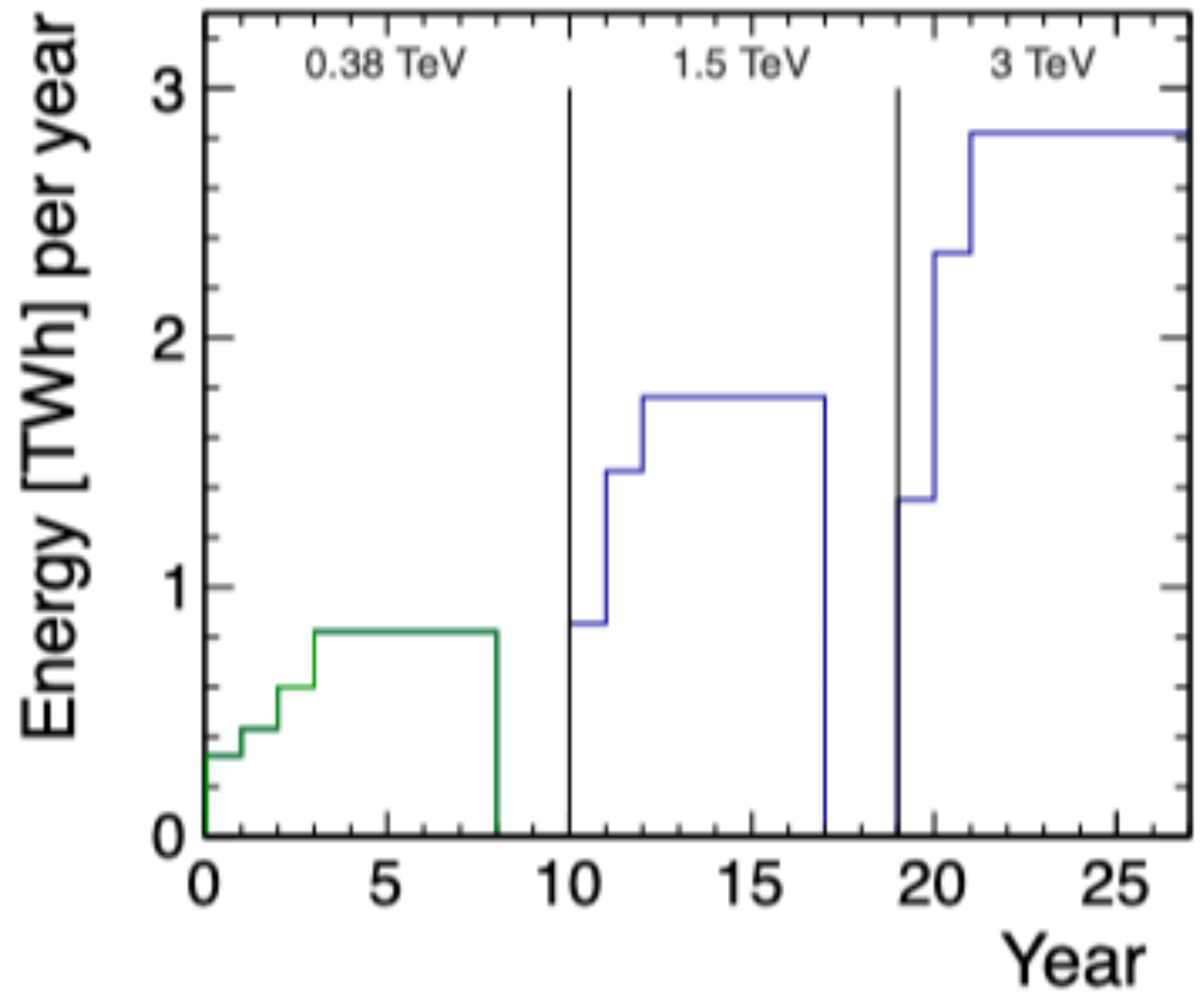
Main Beam Production	Injectors	175
	Damping Rings	309
	Beam Transport	409
Drive Beam Production	Injectors	584
	Frequency Multiplication	379
	Beam Transport	76
Main Linac Modules	Main Linac Modules	1329
	Post decelerators	37
Main Linac RF	Main Linac Xband RF	—
Beam Delivery and Post Collision Lines	Beam 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**

Power

- Total power 168 MW at 380 GeV
  - (Klystron-based option: 164 MW)



(CERN currently consuming ~1.2 TWh per year)



Overview of 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	$\mathscr{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	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

THE COMPACT LINEAR COLLIDER (CLIC) 2018 SUMMARY REPORT
CERN-2018-005-M

CLIC detector requirements

Vertex detector requirements

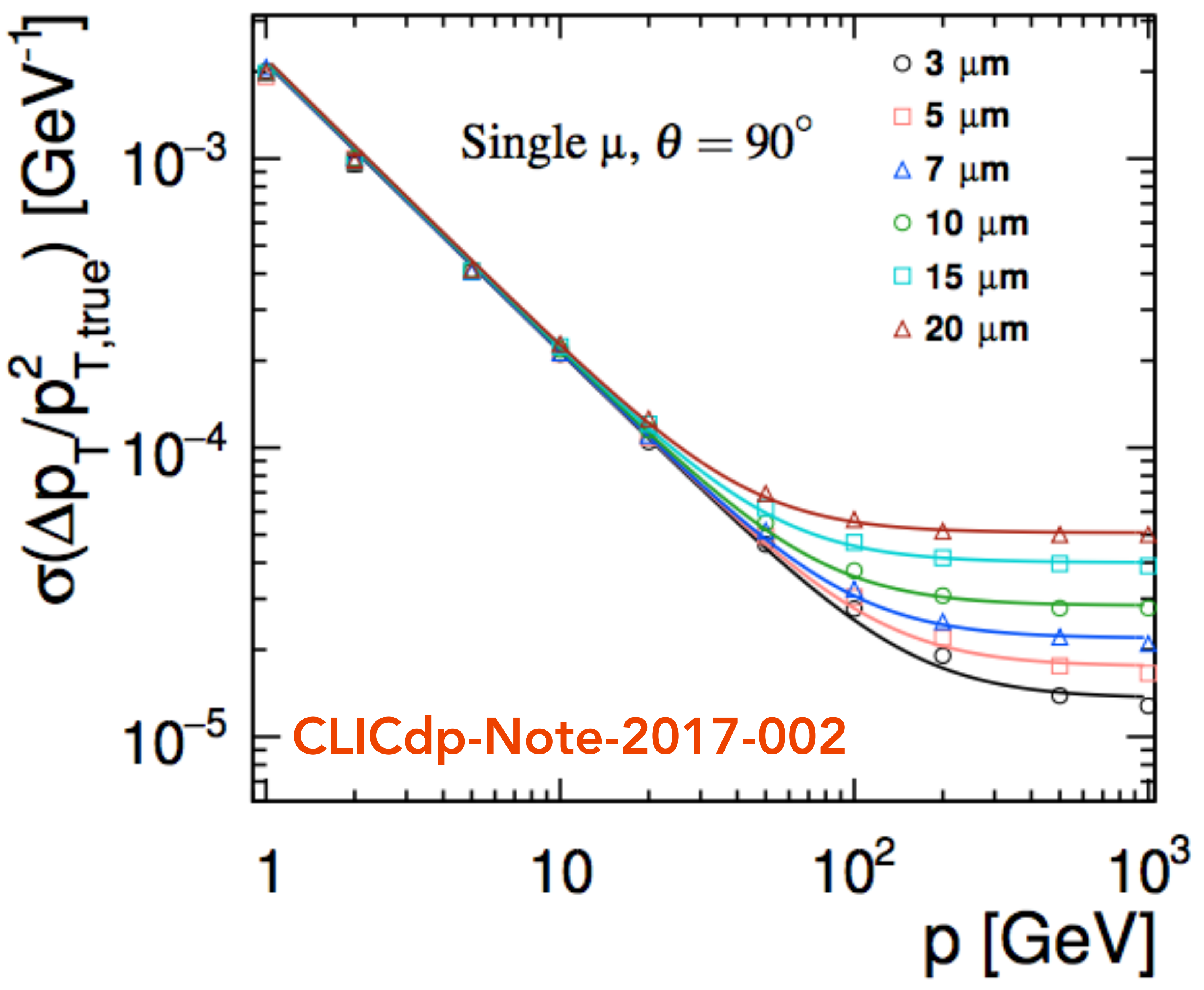
- Driven by displayed vertices resolution + increased precision for low-p_T tracks
  - High single-point resolution: **~3 µm**
  - Ultra-thin: ≲ **0.2% X_0 / layer** (50 µm active silicon)
  - Air cooling, low-power ASICs

Tracker detector requirements

- Driven by momentum resolution: **σ_{p_T} / p_T^2 ~ 2 x 10^{-5} GeV^{-1}**
  - Single-point resolution: **~7 µm** (large pixels / small strips)
  - Material budget **1-2% X_0 / layer**
  - Many layers, large outer radius ➞ has to cover ~100 m^2 surface area ➞ integrated sensors w. large pixels (≲ 30 µm × 1 mm) + low-mass supports, cabling and cooling

Calorimeter detector requirements

- Need very good jet-energy resolution (Particle Flow Algorithm (PFA))
  - **σ_E / E ~ 3.5%** in the range 100 GeV - 1 TeV



Transverse-momentum resolution in the CLIC tracking detector for various single-point resolution

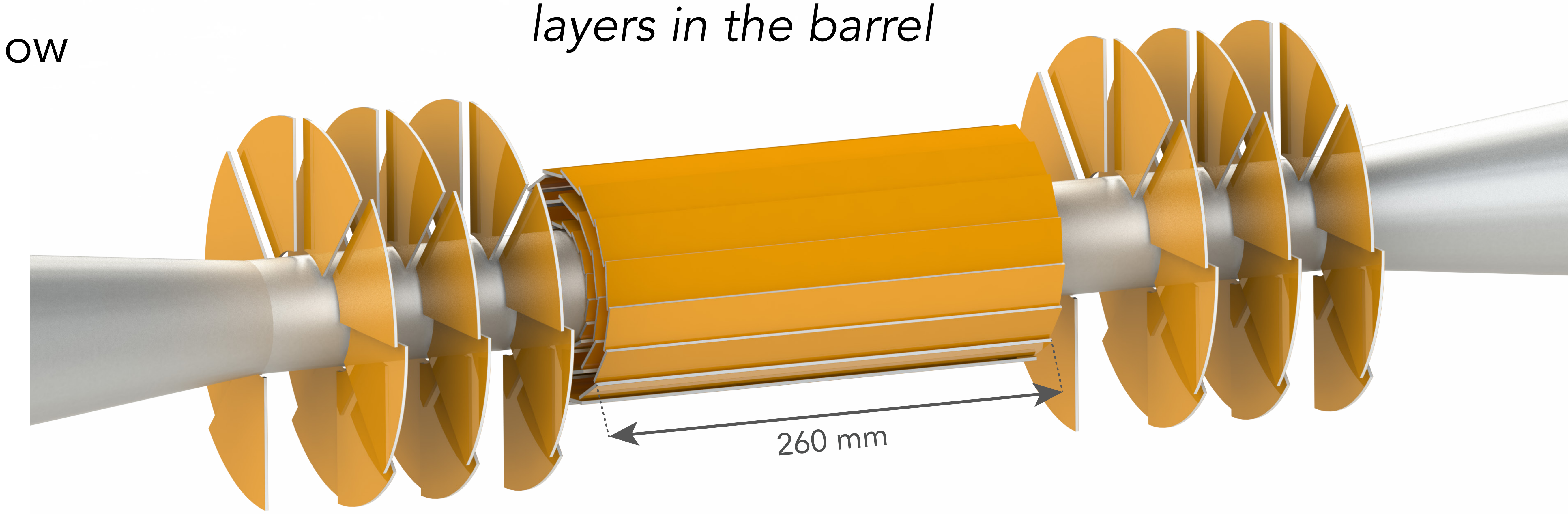
Vertex detector

- Design driven by flavour tagging performance (minimal scattering, high-resolution)
- To reach impact parameter resolution: very thin materials/sensors: 0.2% X_0 material per layer (equivalent to 200 μm of Si)
- **~1.3 billion pixels**, each 25 μm square with a single point resolution of ~3 μm
- **~0.84 m²**

- No material budget for liquid cooling. Cooling is achieved via:
  - **Active air cooling strategy** that induces a spiral airflow
  - **Power-pulsing** of the front-end electronics
- **~5 ns precise time stamping**

- Current technology choice assumes 25 μm square pixels, using hybrid pixel technology
  - ASIC thickness 50 μm connected to 50 μm sensor
  - Slim edge planar sensors and HV-CMOS both considered

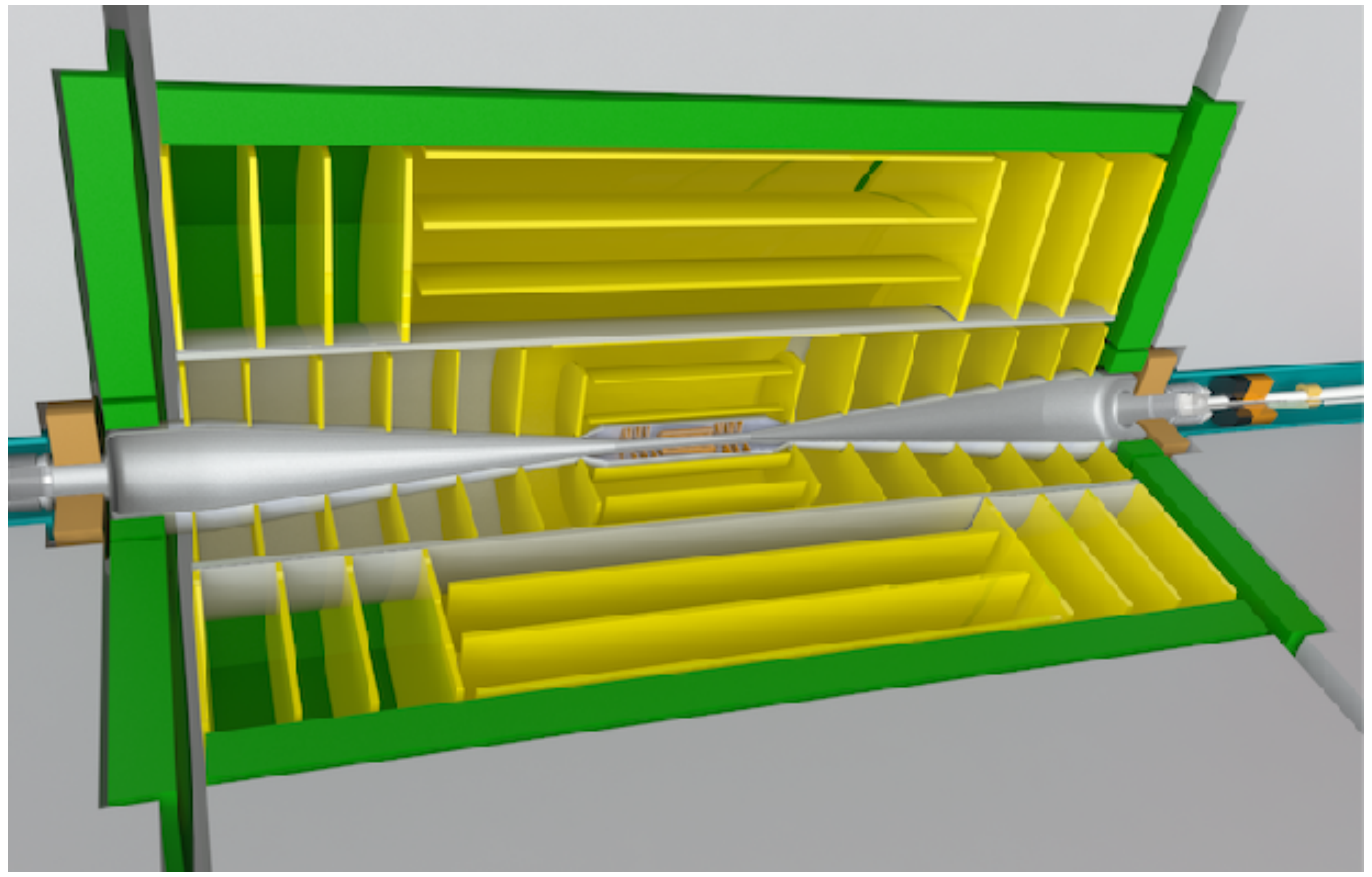
3 cylindrical double layers in the barrel



3 spiral double layers in the forward regions

Tracking detector

- Design optimised for good efficiency and momentum resolution (many layers, large lever arm)
- To provide the required track momentum resolution of $\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}$ GeV^{-1} build a **large** Silicon tracking volume in a 4 T magnetic field
- ~140 m^2 surface, **~600 million channels**
- Single point resolution of ~7 μm
- Large occupancy from beam-induced background - short strips/long pixels
- Low material budget 1-2% X_0 per layer
- Larger radius than CMS tracker, same material budget as ALICE (mechanically a great challenge)



- Inner tracker with 3 barrel layers and 7 forward disks
- Outer tracker with 3 barrel layers and 4 forward disks
- Support shell separating inner and outer trackers
- Monolithic detector with (elongated) pixels, 200 μm sensor, including electronics

Calorimeters

- Jet energy resolution of σ_E /E ~ 5 – 3.5%
  - Highly granular calorimeters required
- **Electromagnetic Calorimeter: Si-W**
  - 2 mm tungsten plates, 500 µm silicon sensors
  - 40 layers 22 X0 or 1 λl , 5 × 5 mm2 cell size
  - ~2500 m2 silicon, 100 million channels
- **Hadronic Calorimeter: Scint-Fe**
  - 19 mm thick steel plates, interleaved with 3 mm thick plastic scintillator + SiPMs
  - 60 layers: 7.5 λl , 30 × 30 mm2 scintillator cell size
  - ~ 9000 m2 scintillator, 10 million channels / SiPMs