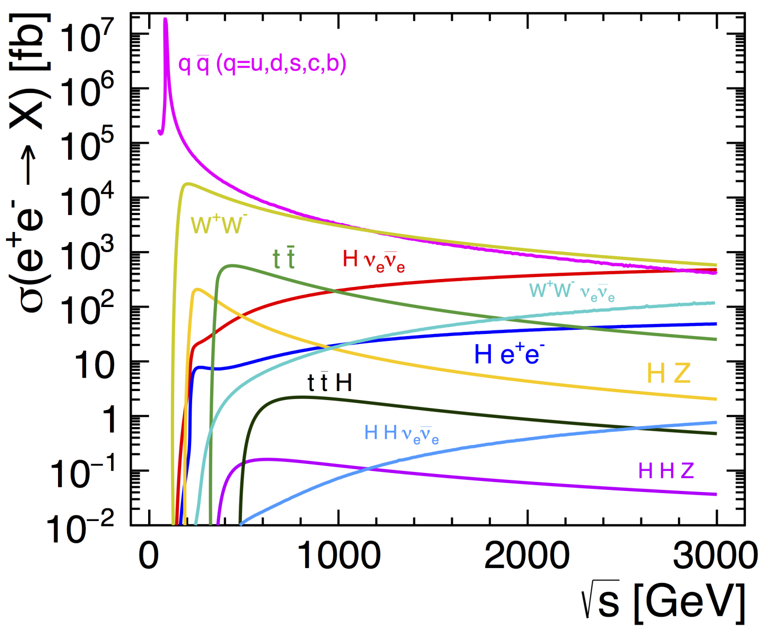
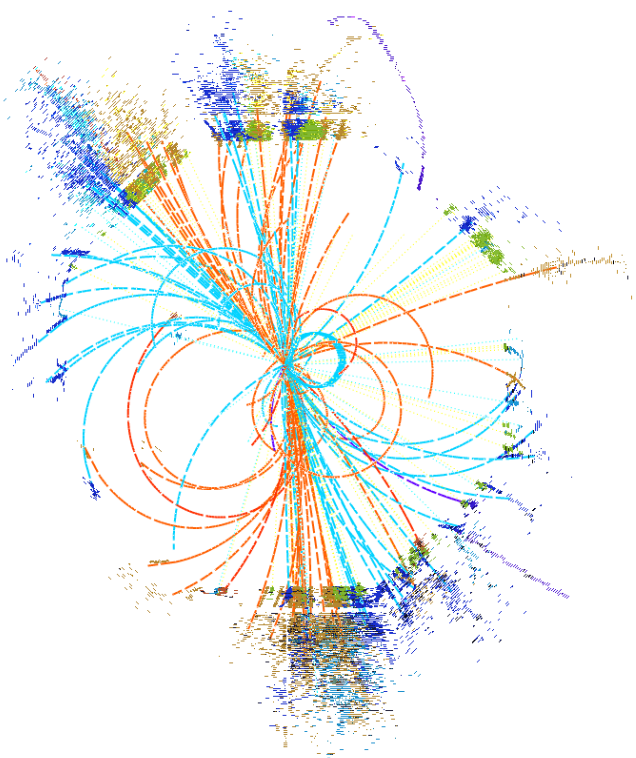
e$^+$e$^-$ collisions at the Compact Linear Collider

Philipp Roloff (CERN)

02/04/2019
Università degli Studi Roma Tre





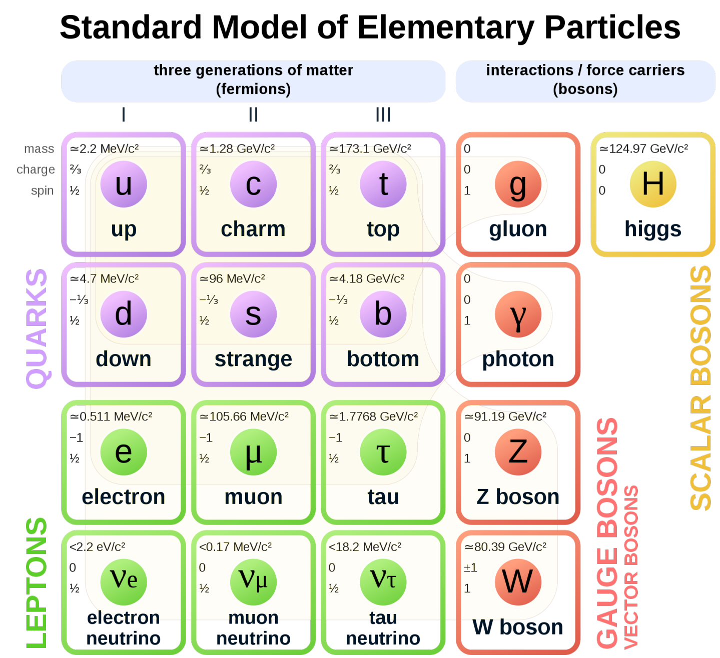
Introduction

• The Standard Model of particle physics has been extremely successful (including prediction of the Higgs boson discovered at the Large Hadron Collider)

• However, it does not explain observations of:

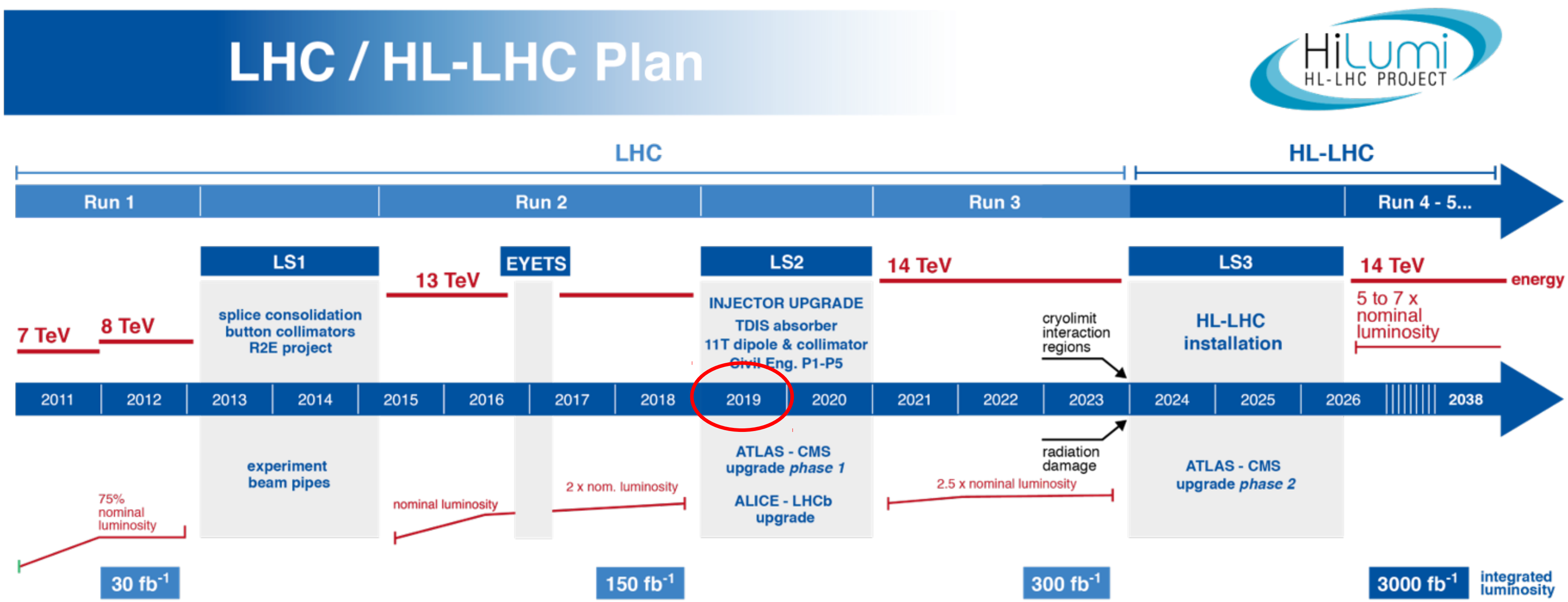
- Dark Matter
- The baryon-antibaryon asymmetry
- Light neutrino masses and mixing

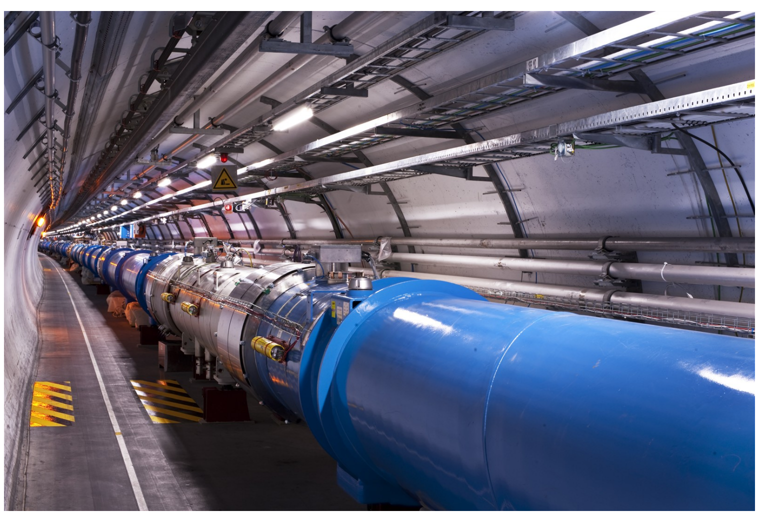
• No guaranteed regime where new physics will emerge



→ Exploration of new territory motivates ambitious future colliders

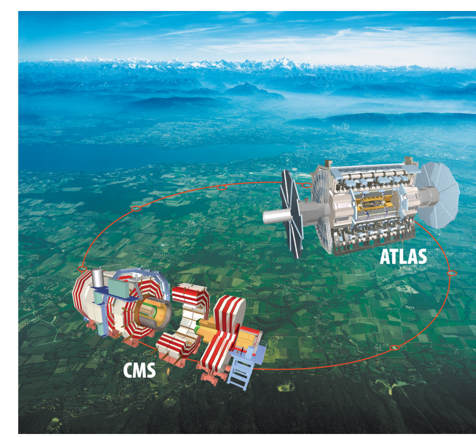
Future of the Large Hadron Collider (LHC)





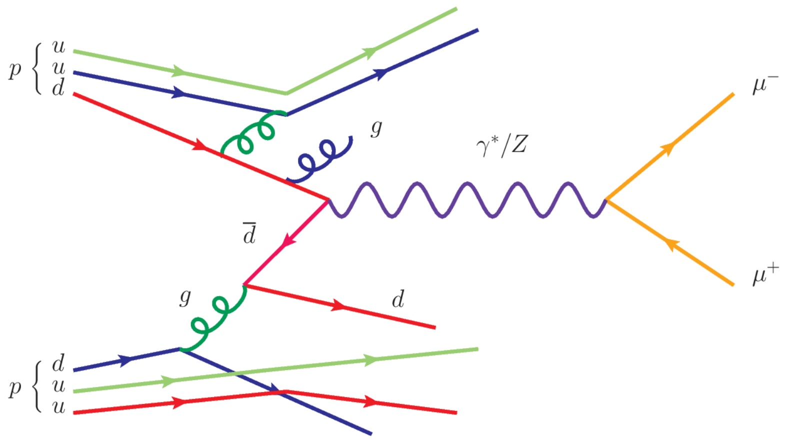
- Collect 20x more data within the next 20 years

This talk: what could be the next step?



Hadron and e$^+$e$^-$ colliders

Hadron colliders (e.g. LHC):

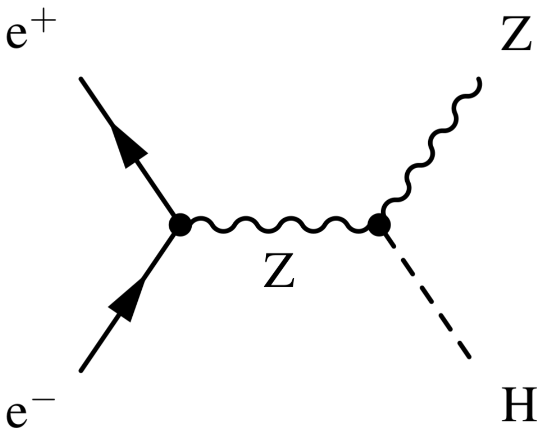


- **Proton is compound object**
  → Initial state unknown
  → Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
  → Complex triggers
  → High levels of radiation

e$^+$e$^-$ colliders:

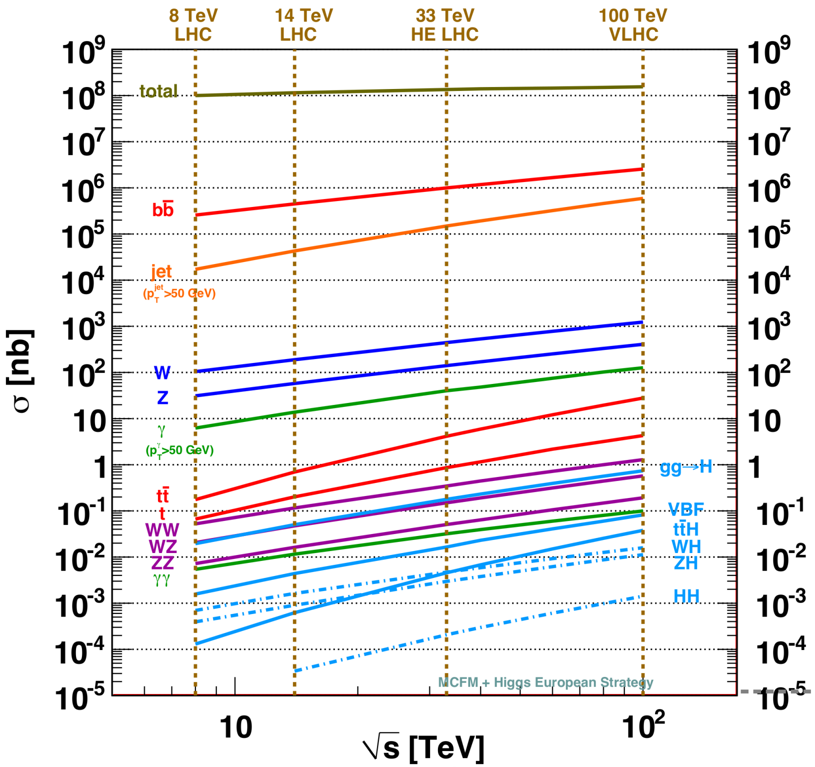


- **e$^+$e$^-$ are pointlike**
  → Initial state well-defined ($\sqrt{s}$, polarisation)
  → High-precision measurements

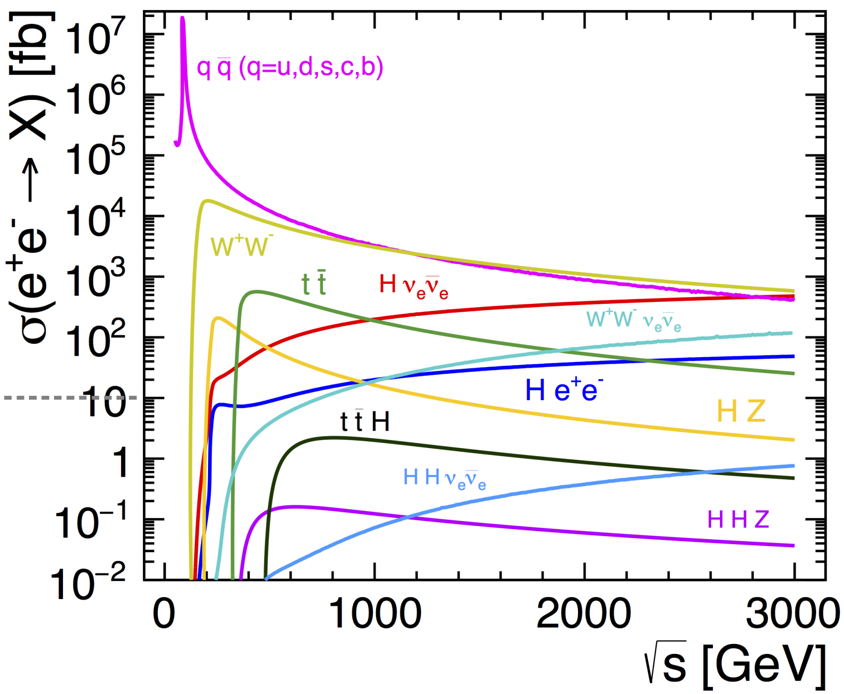
- **High energies ($\sqrt{s}$ ≥ 380 GeV) require linear colliders**

- **Clean experimental environment**
  → Less / no need for triggers
  → Lower radiation levels

pp and e$^+$e$^-$ collisions



8 orders of magnitude!



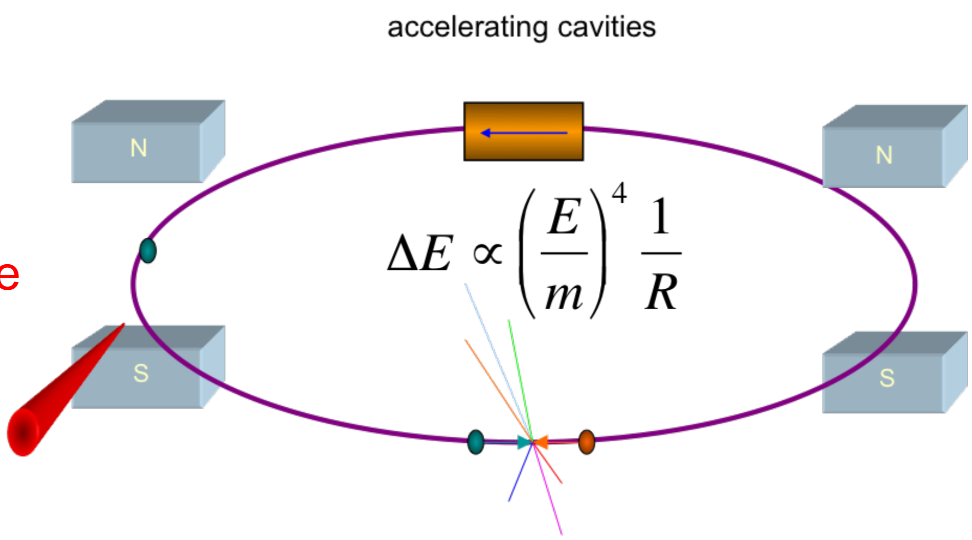
pp collisions:
Interesting events need to be found in huge number of collisions

e$^+$e$^-$ collisions:
More “clean”, all events usable

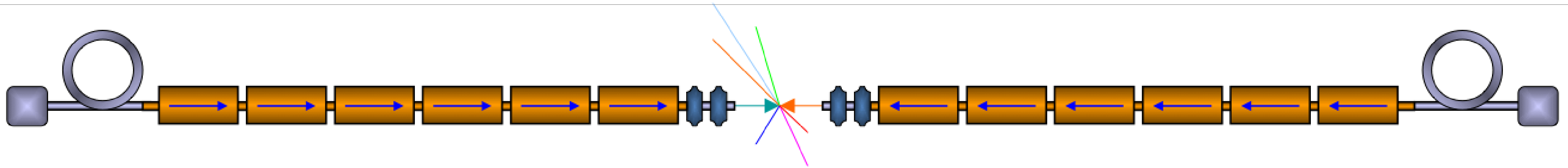
Circular vs. linear e^+e^- colliders

Circular colliders:
- Can accelerate the beam in many turns
- Can use the beam many times
- For electrons synchrotron radiation can be large

(e.g. 2.75 GeV/turn lost at LEP for E = 105 GeV)
→ maximal energy limited



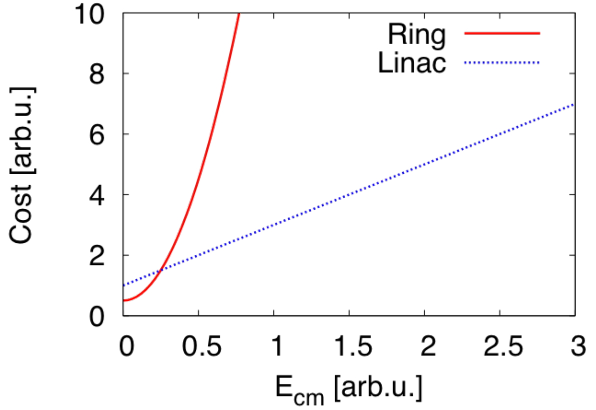
$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



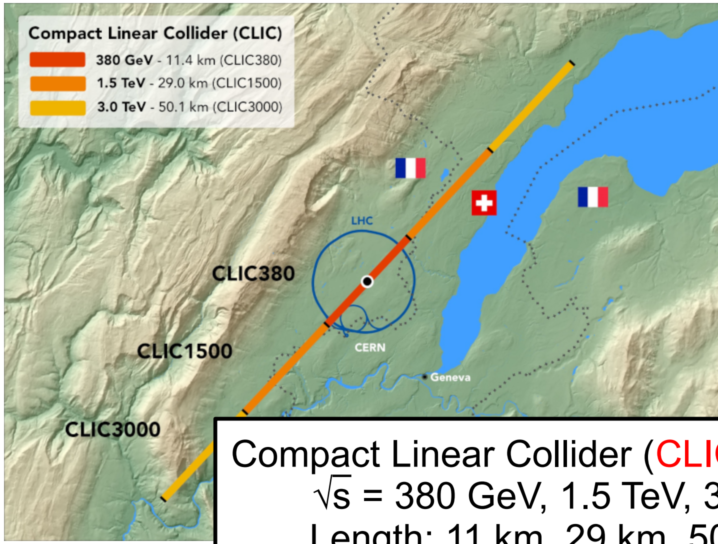
Linear colliders:
- Almost no radiation in a linac
- Have to achieve energy in a single pass

→ high acceleration gradients needed
- Have to achieve luminosity in single pass

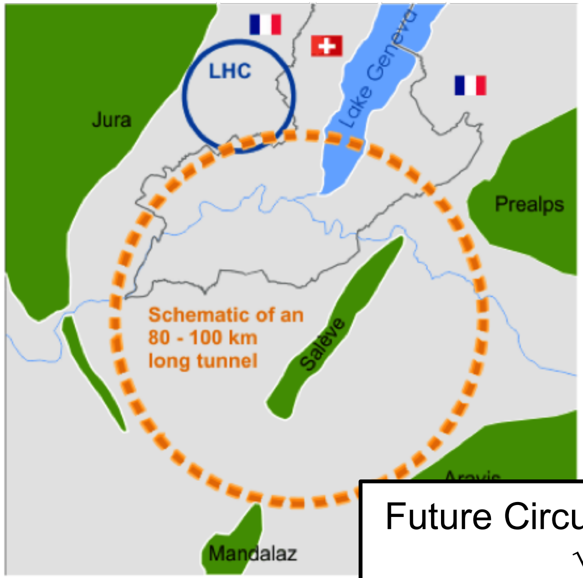
→ small beam size and high beam power needed



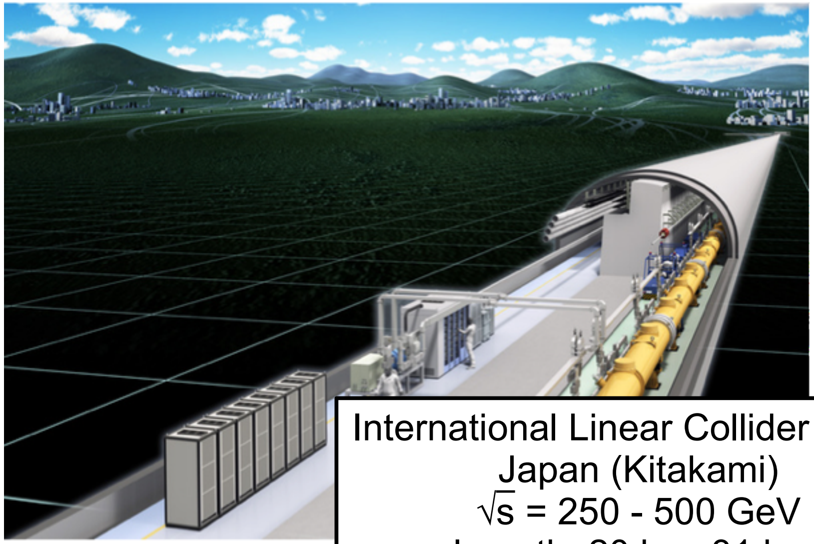
Studies of high-energy e^+e^- colliders



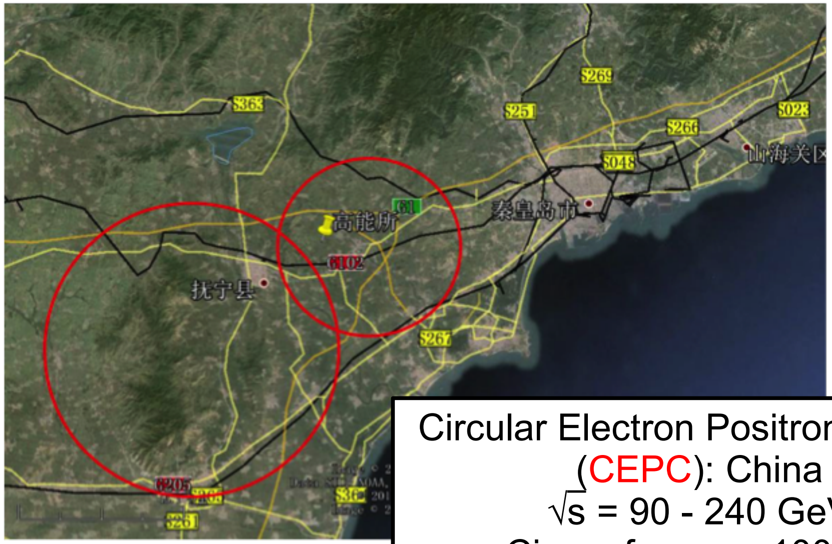
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 365 GeV
Circumference: 97.75 km

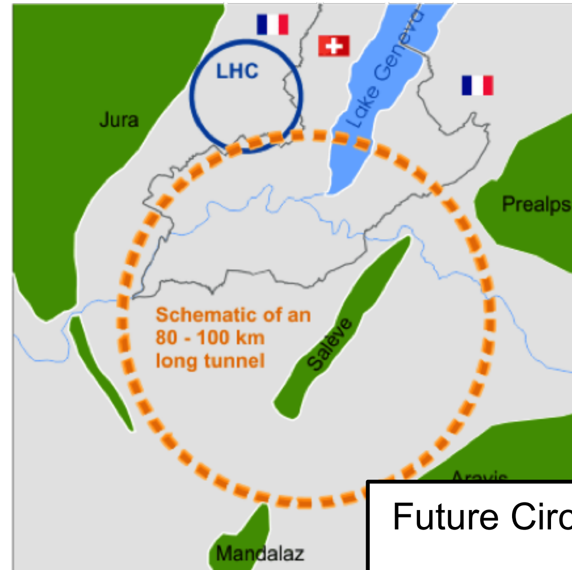


International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV
Length: 20 km, 31 km

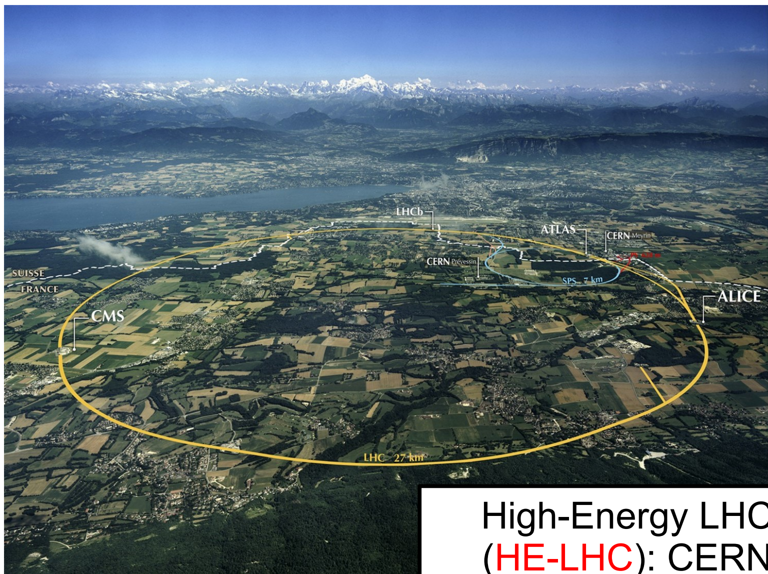


Circular Electron Positron Collider (CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

Studies of high-energy pp colliders



Future Circular Collider (FCC-hh): CERN
$\sqrt{s} \approx 100$ TeV
Circumference: 97.75 km

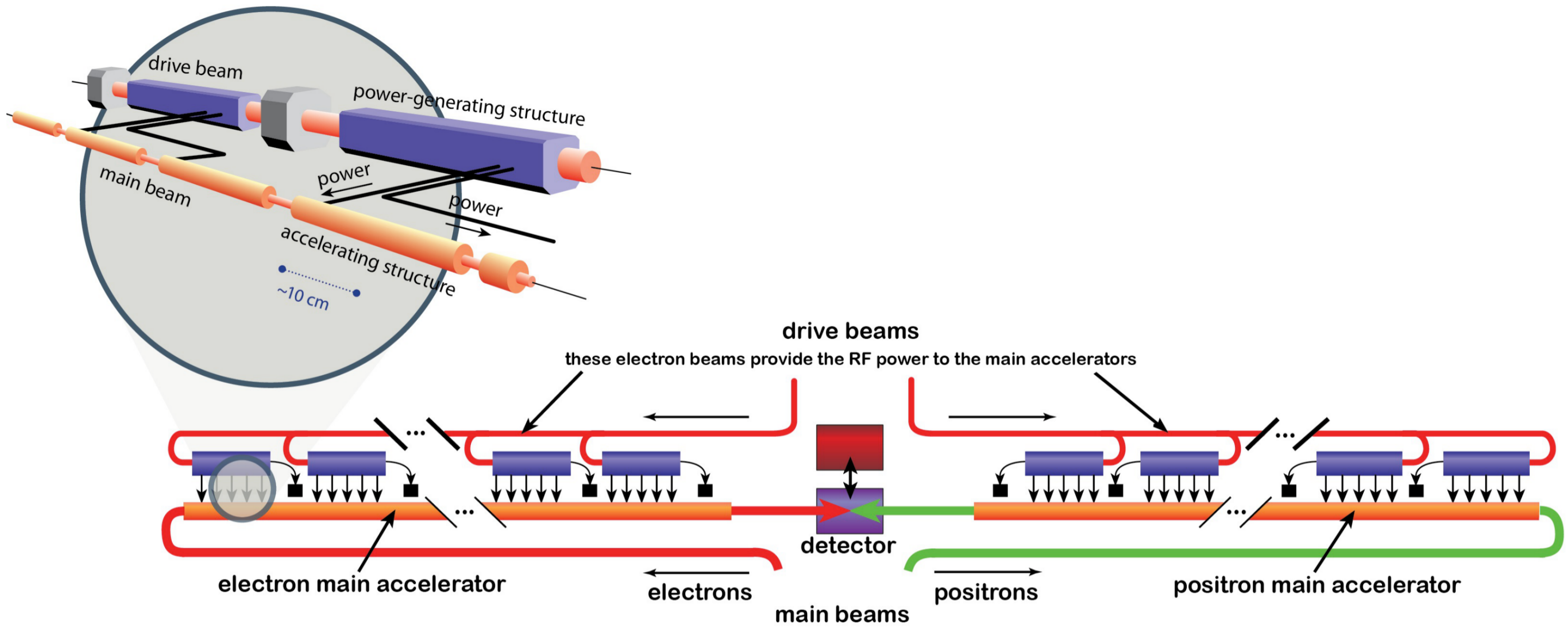


High-Energy LHC
(HE-LHC): CERN
$\sqrt{s} \approx 27$ TeV
Circumference: 27 km

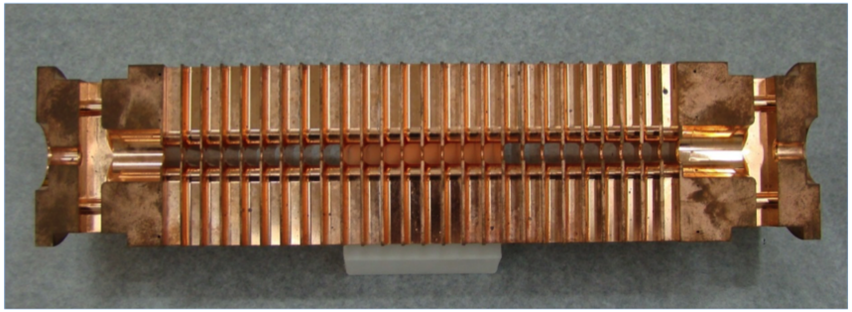
Super proton proton Collider
(SppC): China
$\sqrt{s} > 70$ GeV
Circumference: 100 km

Tunnels initially used for
e^+e^- collisions

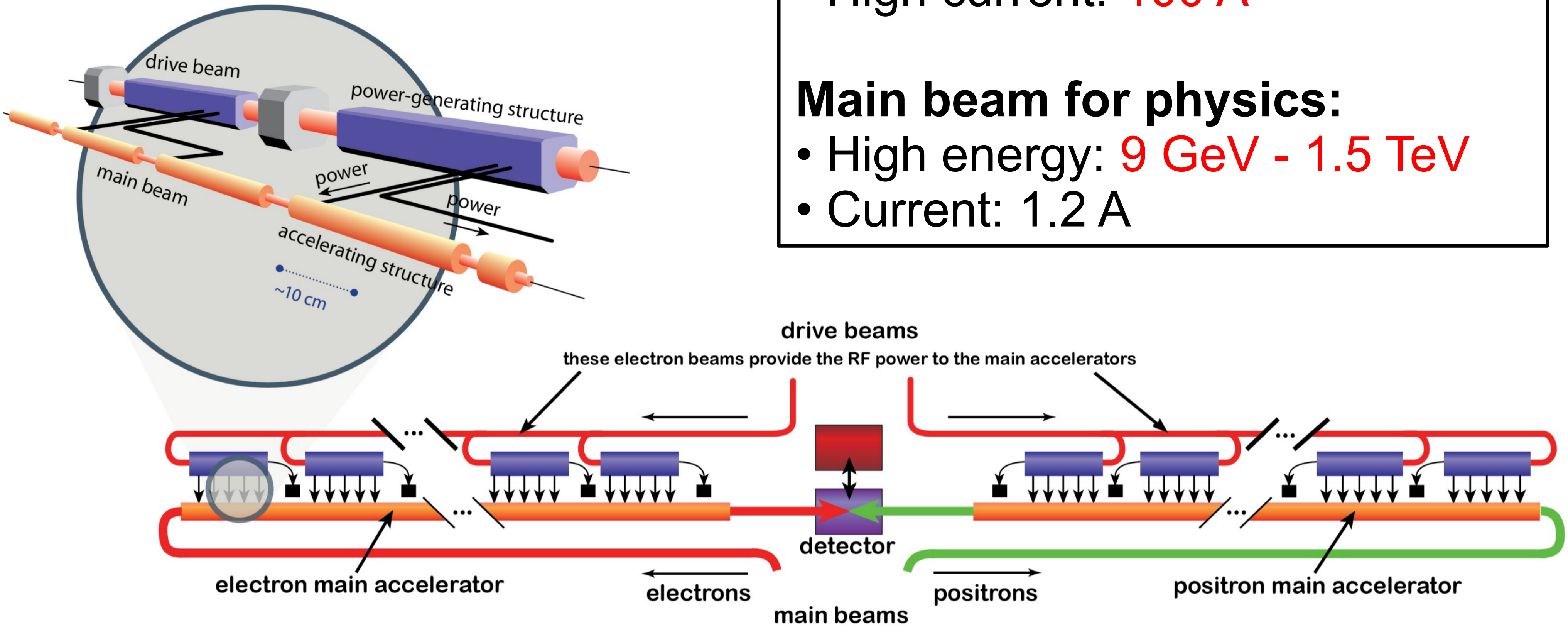
The Compact Linear Collider (CLIC)



Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
- Length: 50 km (for 3 TeV)
- $P(e^-) = \pm 80\%$



CLIC acceleration scheme

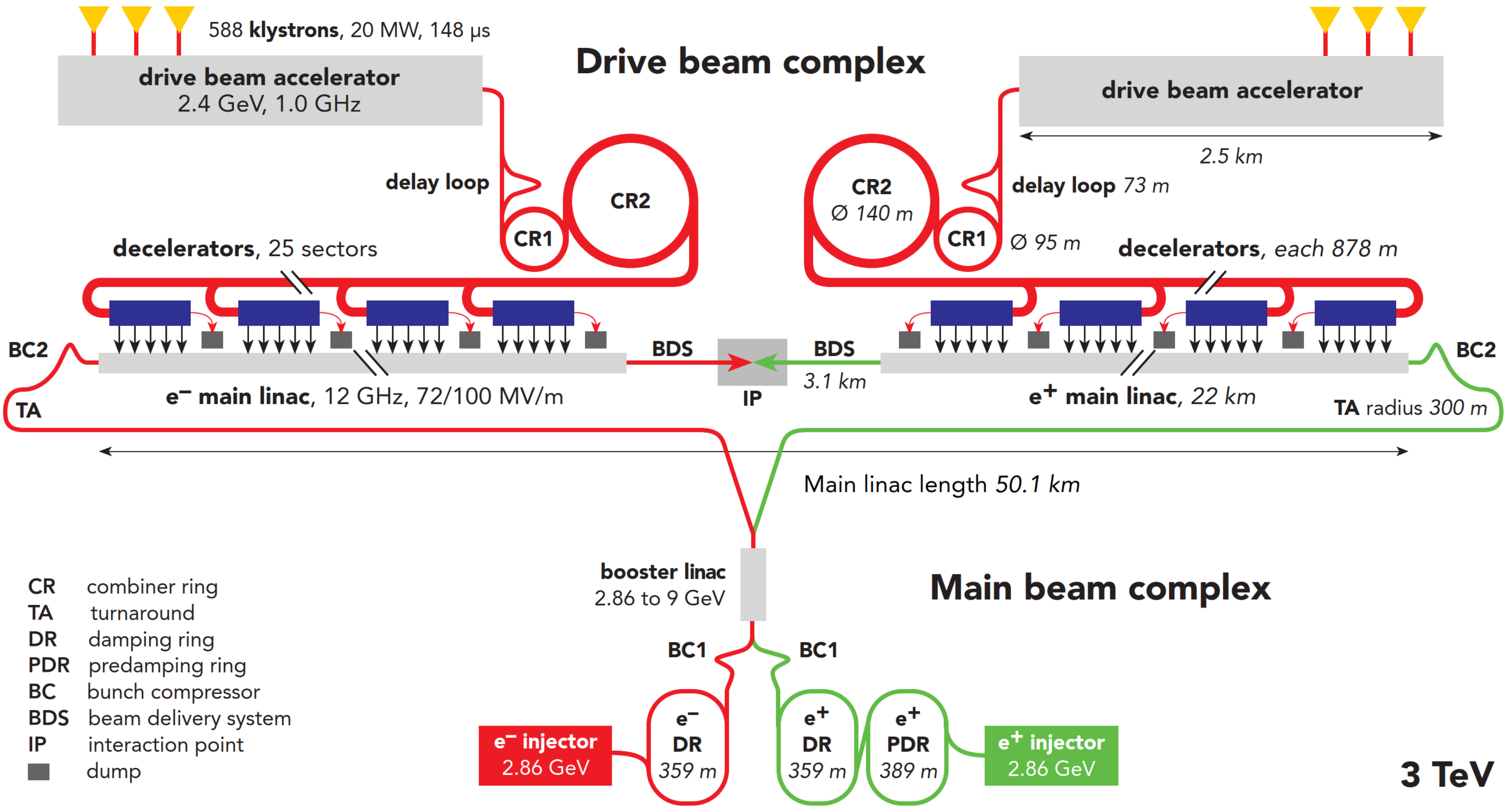


Drive beam supplies RF power:
- 12 GHz bunch structure
- Low energy:

2.4 GeV - 240 MeV
- High current: 100 A

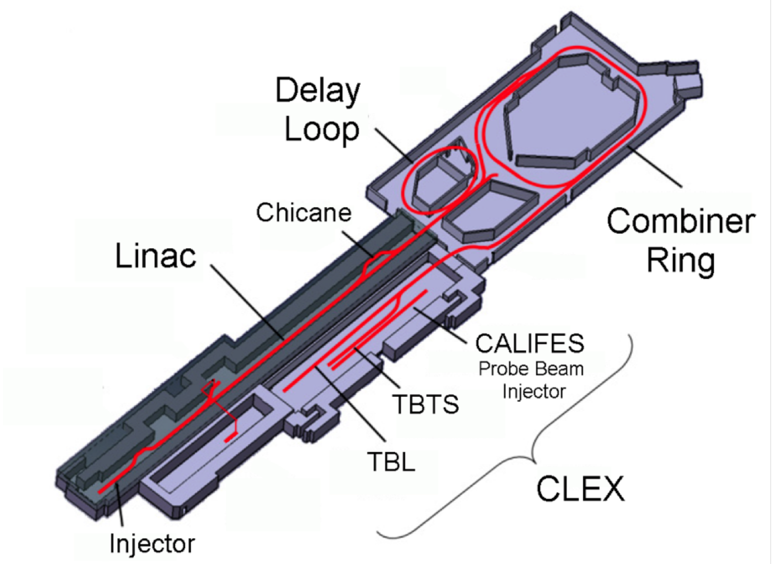
Main beam for physics:
- High energy: 9 GeV - 1.5 TeV
- Current: 1.2 A

CLIC layout at 3 TeV



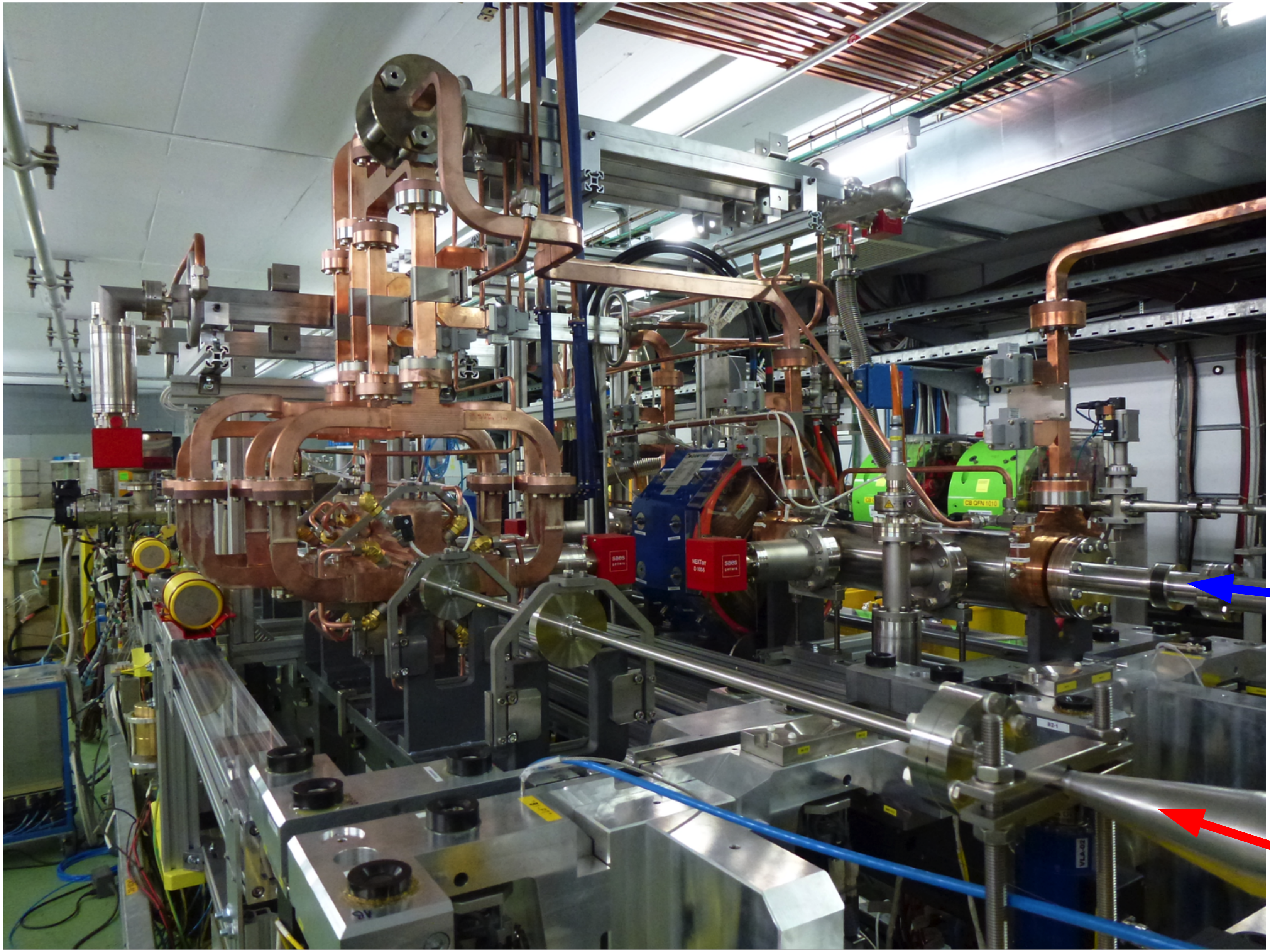
The CLIC Test Facility (CTF3)

CTF3 successfully demonstrated:
• Drive beam generation
• RF power extraction
• Two-beam acceleration up to a gradient of 145 MeV/m



• CTF3 completed its mission in 2016
• A new facility since 2017 (based on the CTF3 probe beam): CERN Linear Electron Accelerator for Research (CLEAR)

2-beam acceleration module in CTF3

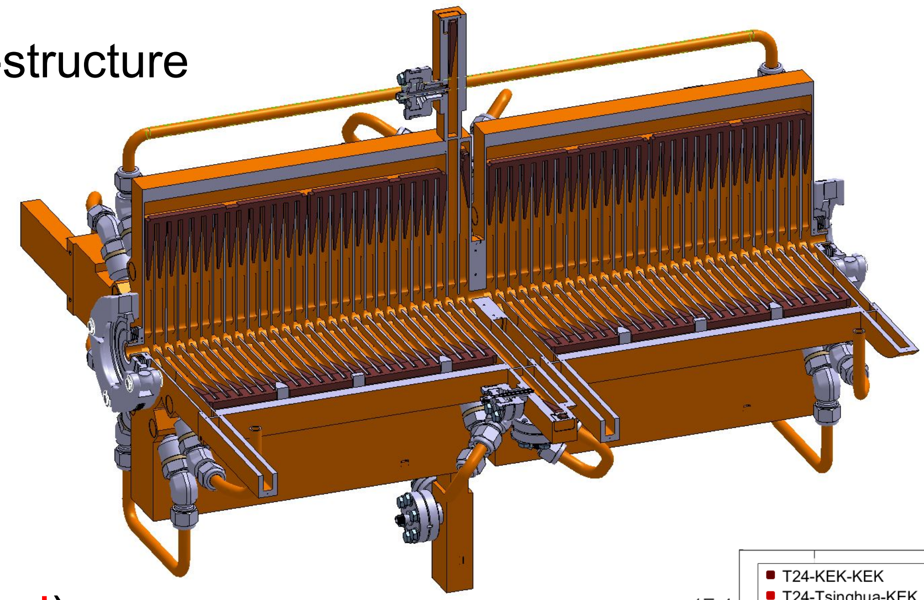


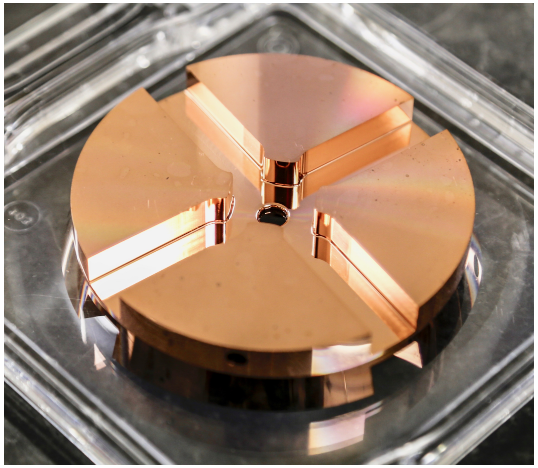
drive
beam

main
beam

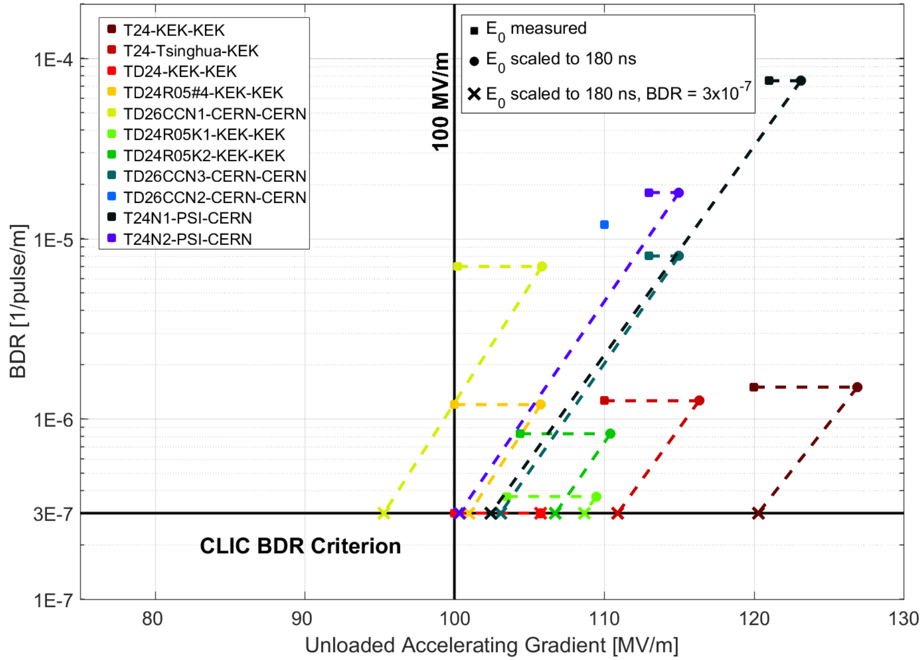
CLIC accelerating structures

Double-structure unit





- 12 GHz (X-band)
- Break down rate (BDR): $p \leq 3 \cdot 10^{-7}\ \mathrm{m}^{-1}\mathrm{pulse}^{-1}$
- R&D programme established gradient O(100MV/m)
- Shorter pulses have less breakdowns



CLIC technology applications

Collaboration with many facilities: photon sources, medical applications
→ lots of experience being built up

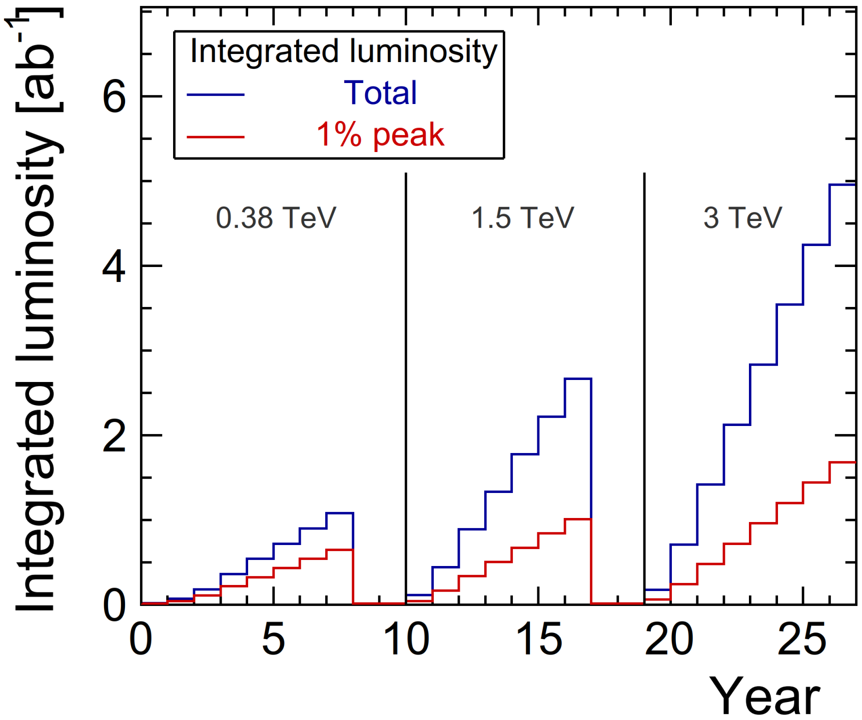
Example: SwissFEL
- 104 C-band structures (5.7 GHz, 2 m long)
- Beam up to 6 GeV at 100 Hz
- Similar μm-level tolerances
- Length similar to 800 CLIC structures

CLIC staged implementation

CLIC would be implemented in several energy stages

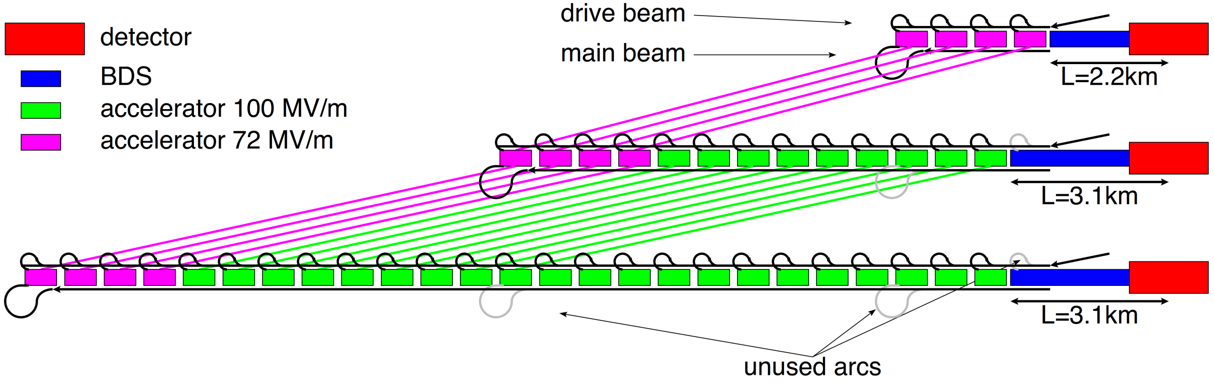
Current baseline scenario:

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\mathrm{int}}$ [ab^{-1}]	$P(\mathrm{e}^-) = -80\%$ $\mathscr{L}_{\mathrm{int}}$ [ab^{-1}]	$P(\mathrm{e}^-) = +80\%$ $\mathscr{L}_{\mathrm{int}}$ [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



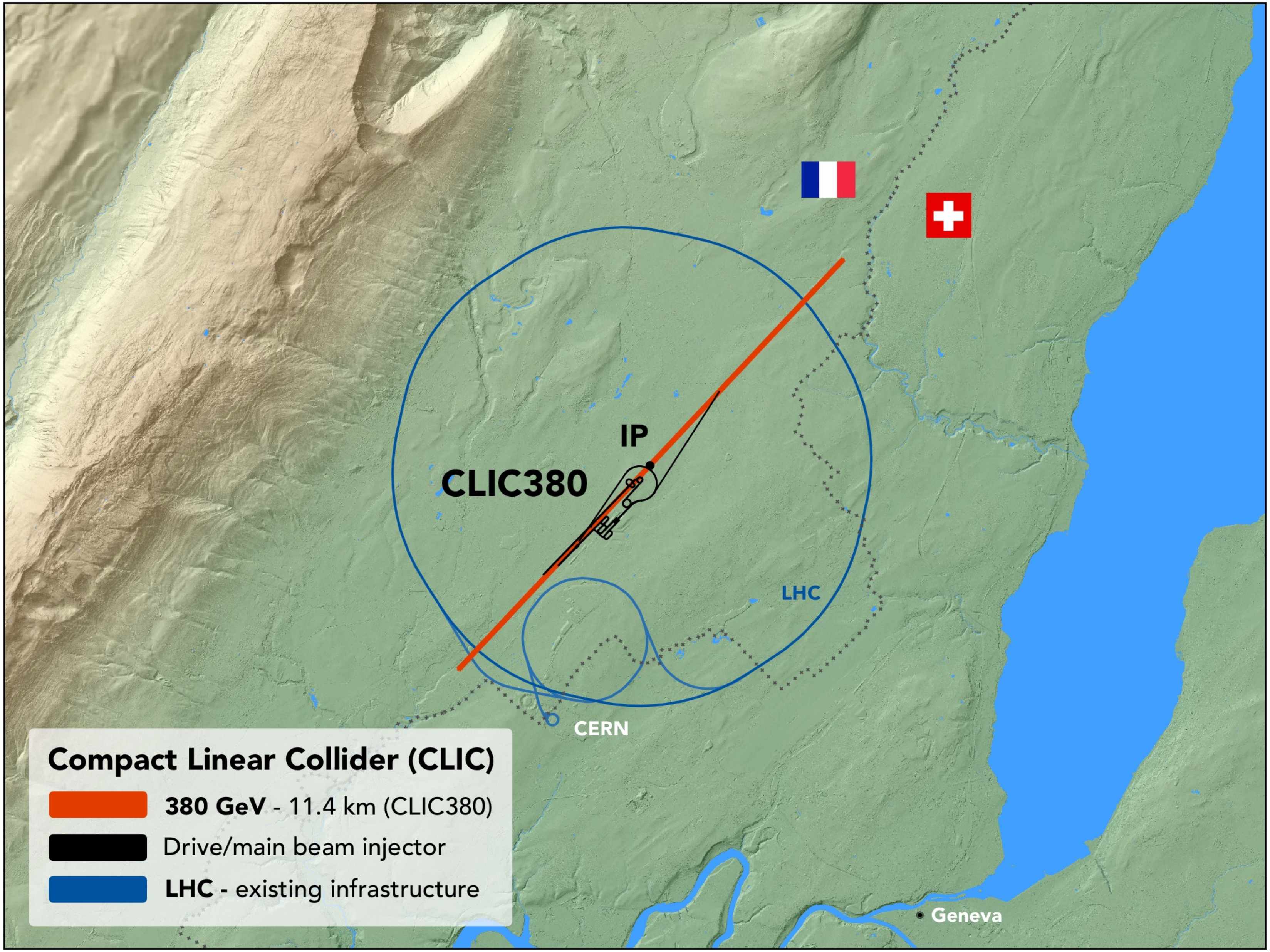
- The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)

- 1 year = 1.2×10^7 seconds (based on CERN experience)

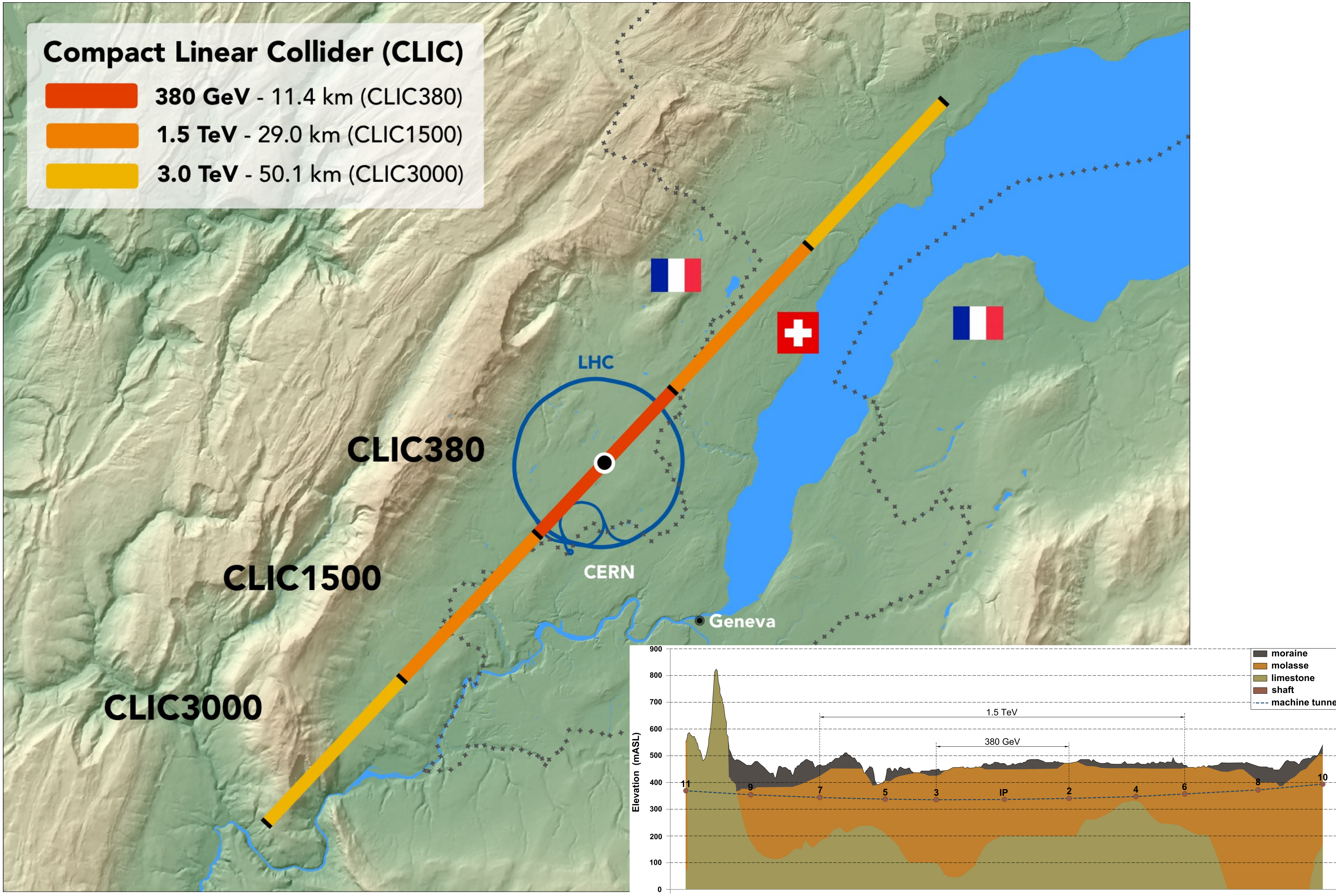


CERN-2018-005-M
arXiv:1812.01644

CLIC at 380 GeV

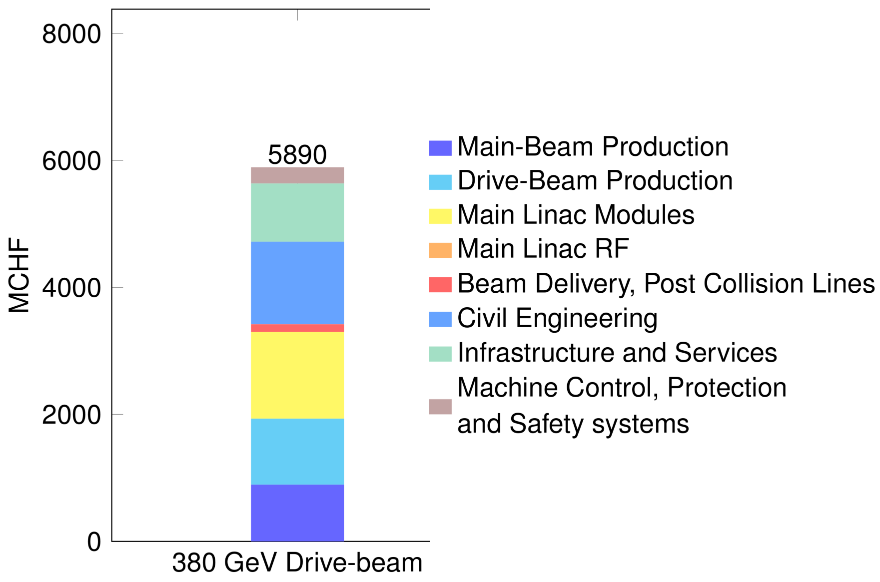


CLIC at 3 TeV



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
moraine
molasse
limestone
shaft
machine tunnel
1.5 TeV
380 GeV
Elevation (mASL)
900
800
700
600
500
400
300
200
100
0
11
9
7
5
3
IP
2
4
6
8
10

Cost and power



380 GeV: 5890^{+1470}_{-1270} MCHF

Upgrade to 1.5 TeV: add ≈5100 MCHF
Upgrade to 3 TeV: add another ≈7300 MCHF

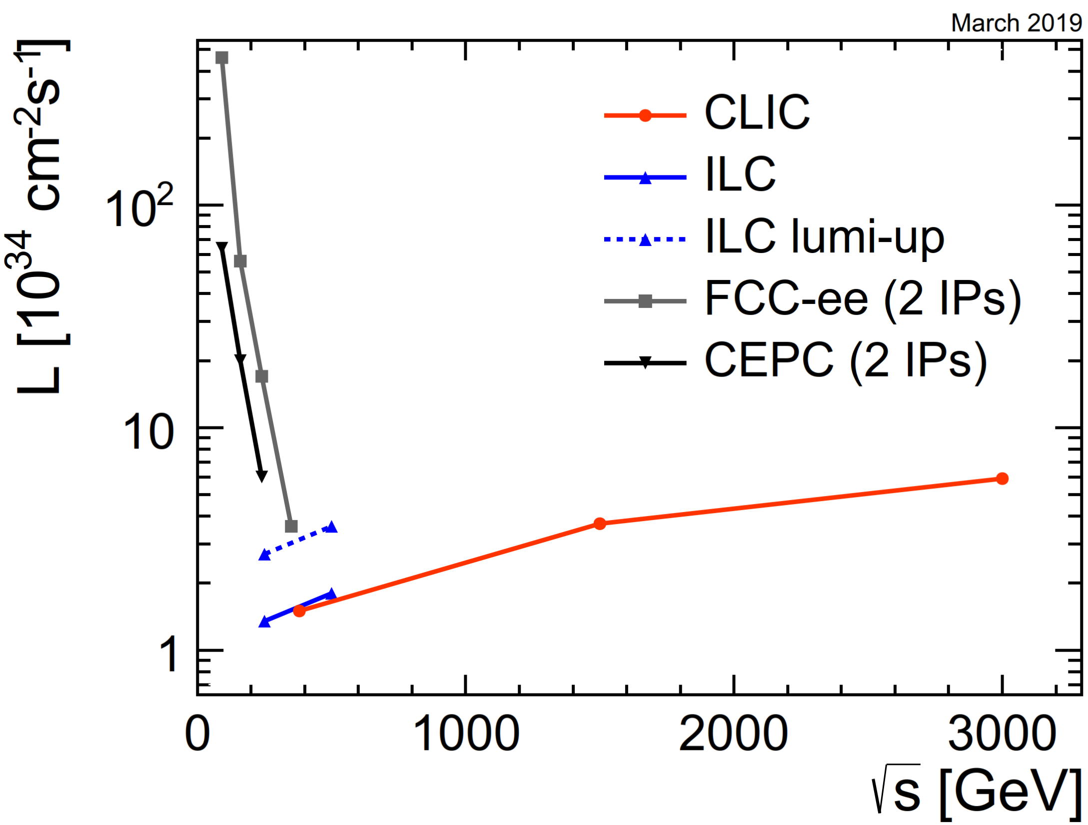
380 GeV: large improvement compared to CDR (2012)

1.5 and 3 TeV: power not yet optimised
→ will be done next

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

CERN-2018-005-M

Comparison to other e^+e^- collider options



Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies
- Potential to benefit from novel accelerator techniques

Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

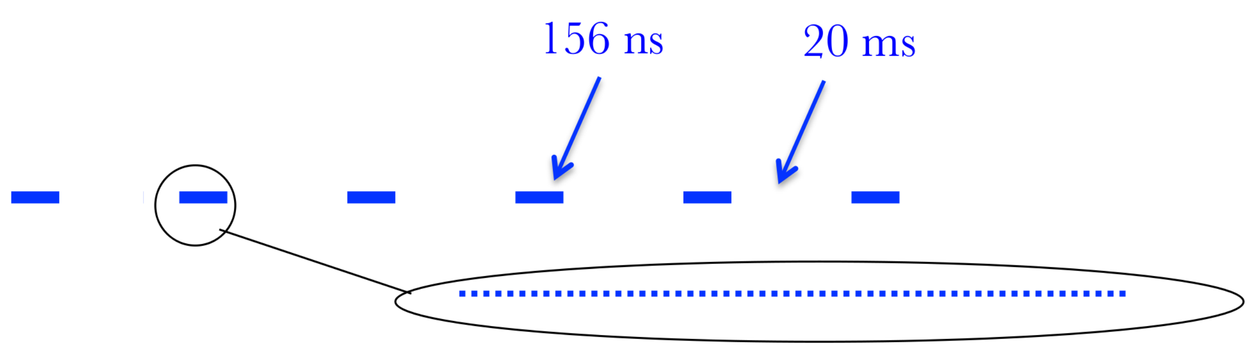
NB: Peak luminosity at LEP2 (209 GeV) was ≈ $10^{32}\ cm^{-2}s^{-1}$

CLIC experimental conditions

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
L above 99% of $\sqrt{s}$ ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Repetition frequency (Hz)	**50**	**50**	**50**
Bunch separation (ns)	**0.5**	**0.5**	**0.5**
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	**149/2.9**	**~60/1.5**	**~40/1**
Beam size at IP σ_z (μm)	**70**	**44**	**44**

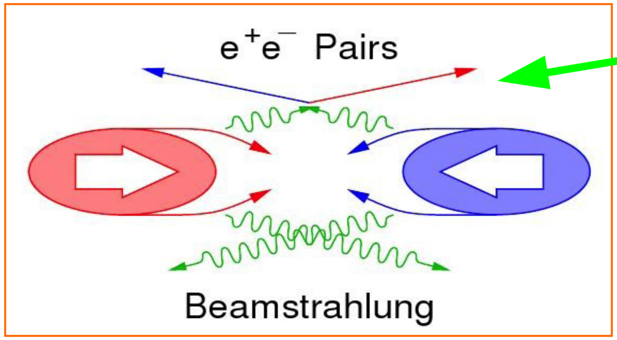
Drives timing requirements for CLIC detector

Very small beam

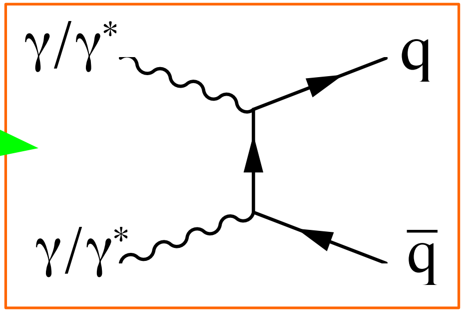


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam-induced backgrounds

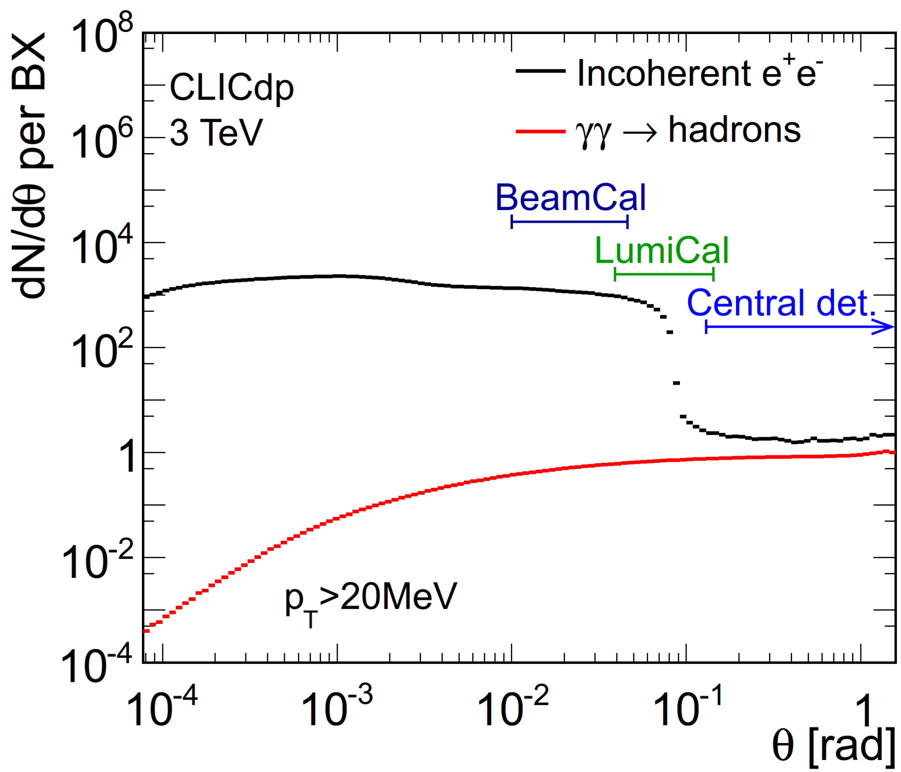


- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons



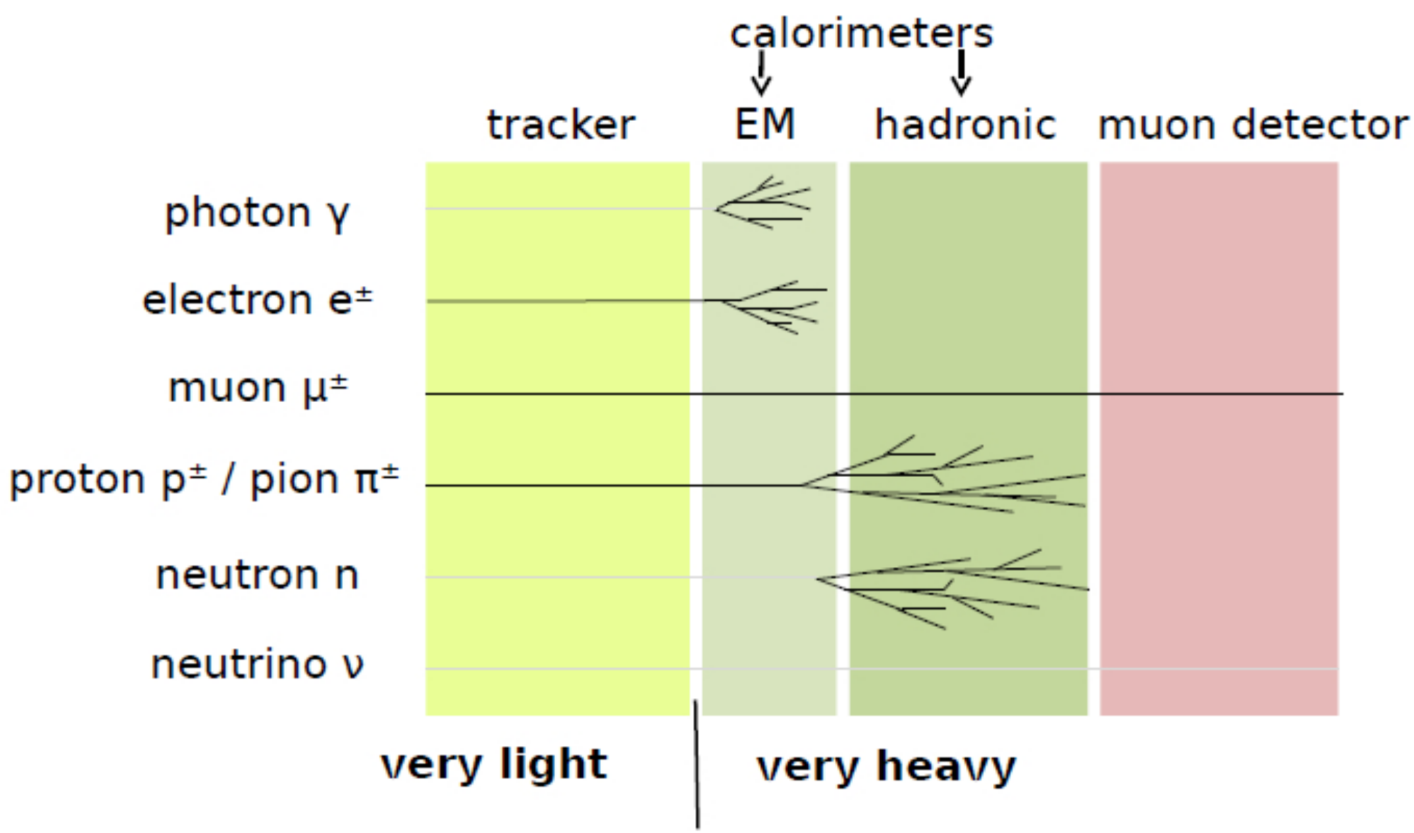
e^+e^- pairs:
High occupancies
→ Detector design issue
(small cell sizes)

$\gamma\gamma \rightarrow$ hadrons
Main background
in calorimeters and trackers
→ Impact on physics
(needs suppression in the data)

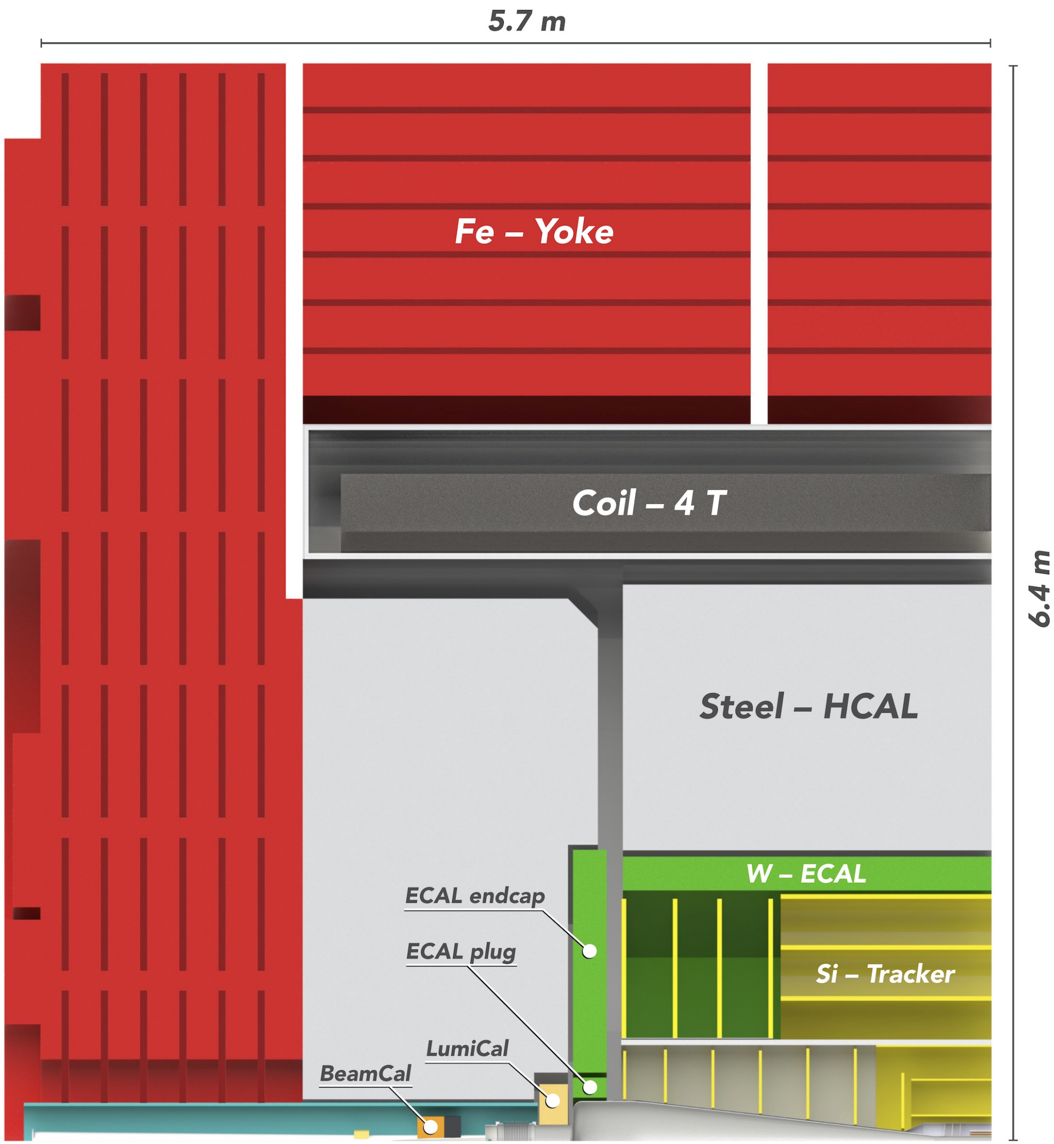


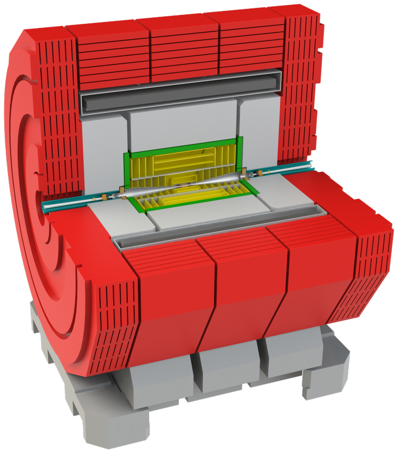
Principle of a particle physics detector

- Particles interact with detector material
  - Charged: Ionisation, exitation of detector atoms ...
  - Neutral: Photo effect, compton effect, pair production ....
- Particles differ in the way they interact with material
  - Identify particle types



CLIC detector concept





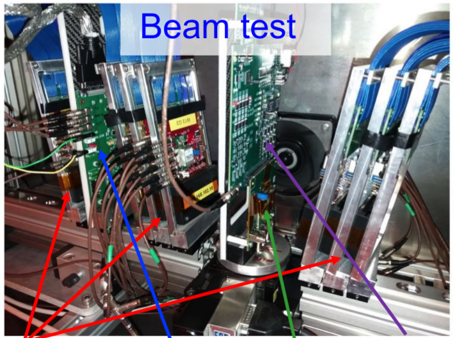
- Ultra low-mass vertex detector with ≈ 25 x 25 μm^2 pixels
- Main trackers: silicon-based (large pixels / short strips)
- Fine grained (PFA) calorimetry, 1+7.5 λ
- Strong solenoid magnet (4 T)
- Complex forward region with compact calorimeters
- Instrumented return yoke for muon ID

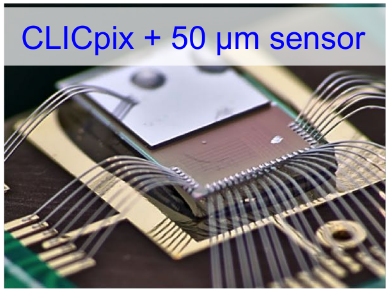
CLICdp-Note-2017-001

CLIC silicon vertex/tracker R&D

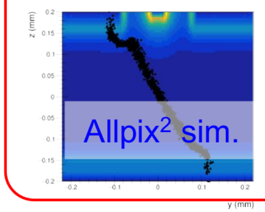
Sensor + readout technologies

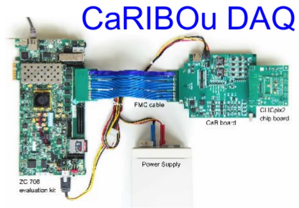
Sensor + readout technology	Currently considered for
Bump-bonded Hybrid planar sensors	Vertex
Capacitively coupled HV-CMOS sensors	Vertex
Monolithic HV-CMOS sensors	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensors	Vertex, Tracker



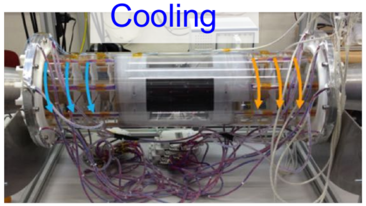


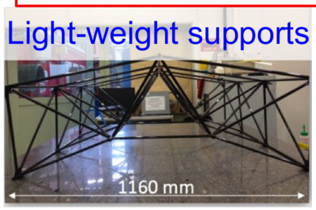
Simulation/Characterisation

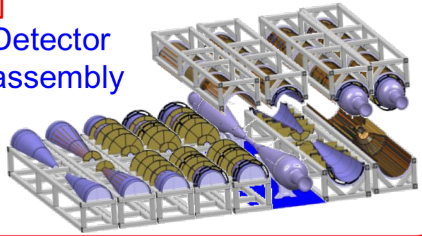




Detector integration







- Challenging requirements lead to extensive detector R&D program
- ~10 institutes active in vertex/tracker R&D
- Collaboration with ATLAS, ALICE, LHCb, Mu3e, AIDA-2020

D. Dannheim, VCI2019

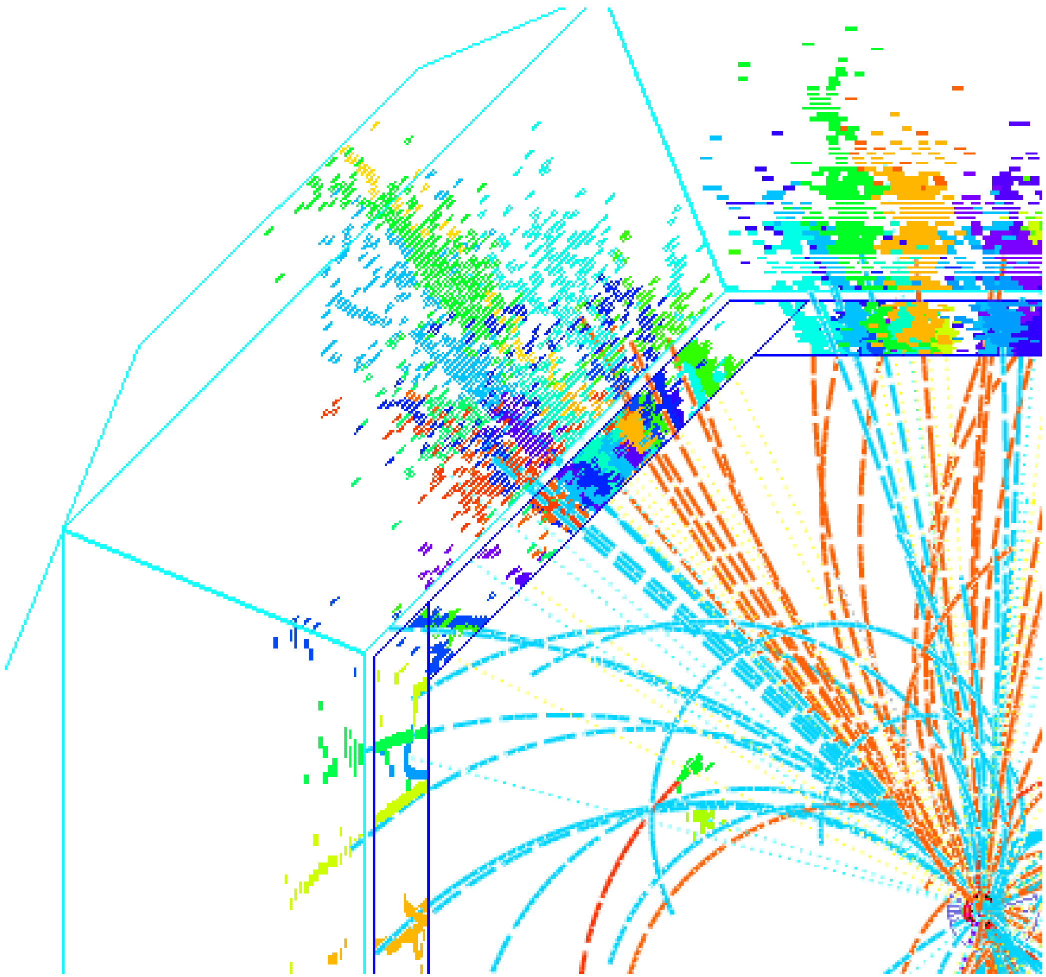
Calorimetry and PFA

Detector design driven by jet energy resolution and background rejection
→ Fine-grained calorimetry + particle flow analysis (PFA)

What is PFA?
Typical jet composition:
• 60% charged particles
• 30% photons
• 10% neutral hadrons

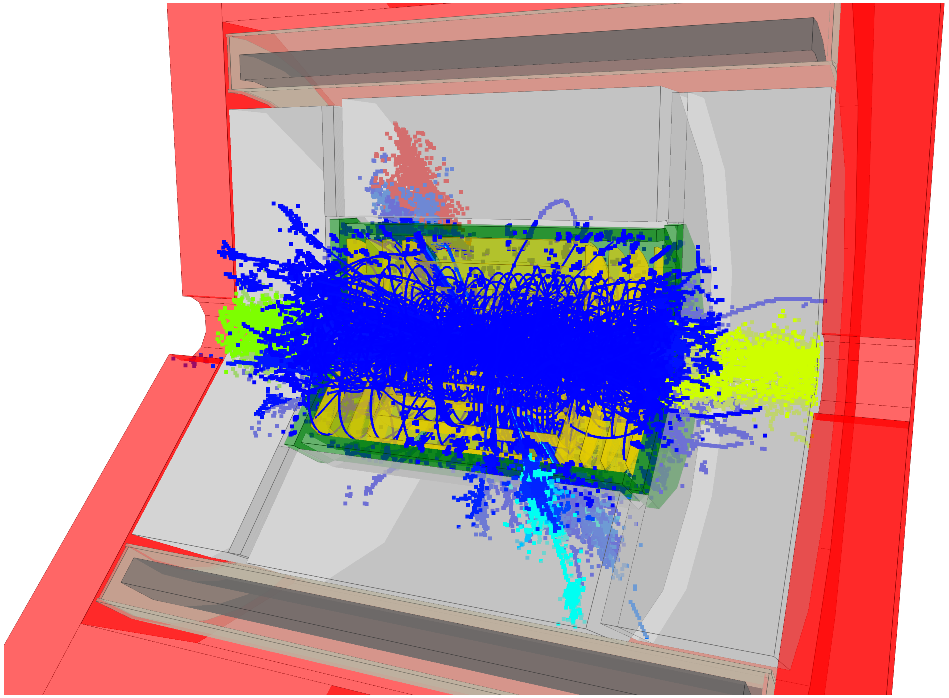
Always use the best available measurement:
• charged particles
→ tracking detectors:
• photons → ECAL:
• neutrals → HCAL:

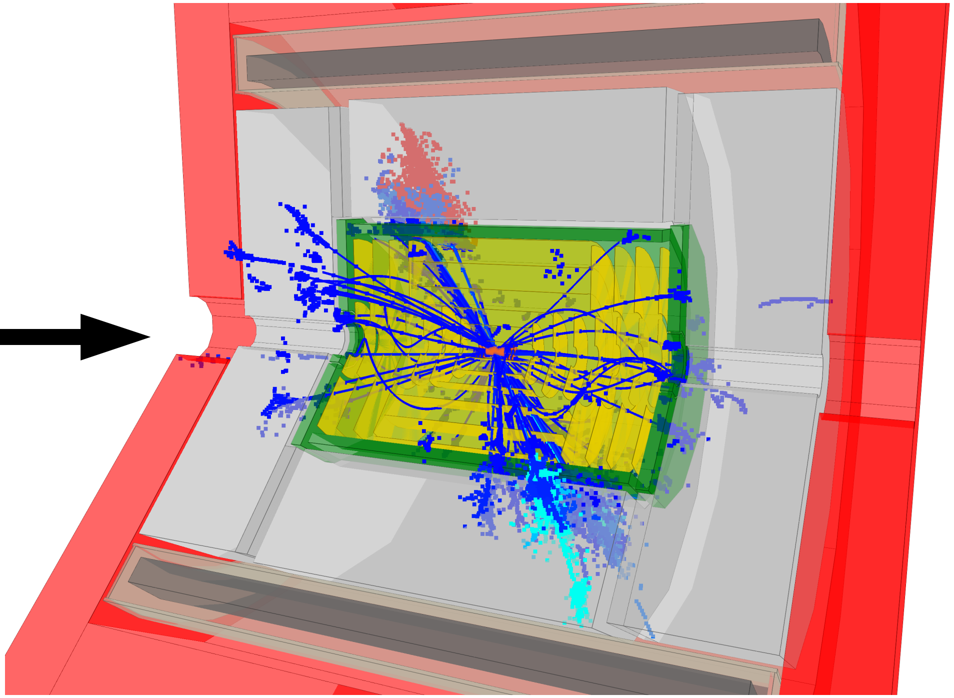
Hardware and software!



Background suppression

Beam-induced background from $\gamma\gamma \rightarrow$ hadrons can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles (= particle flow objects)

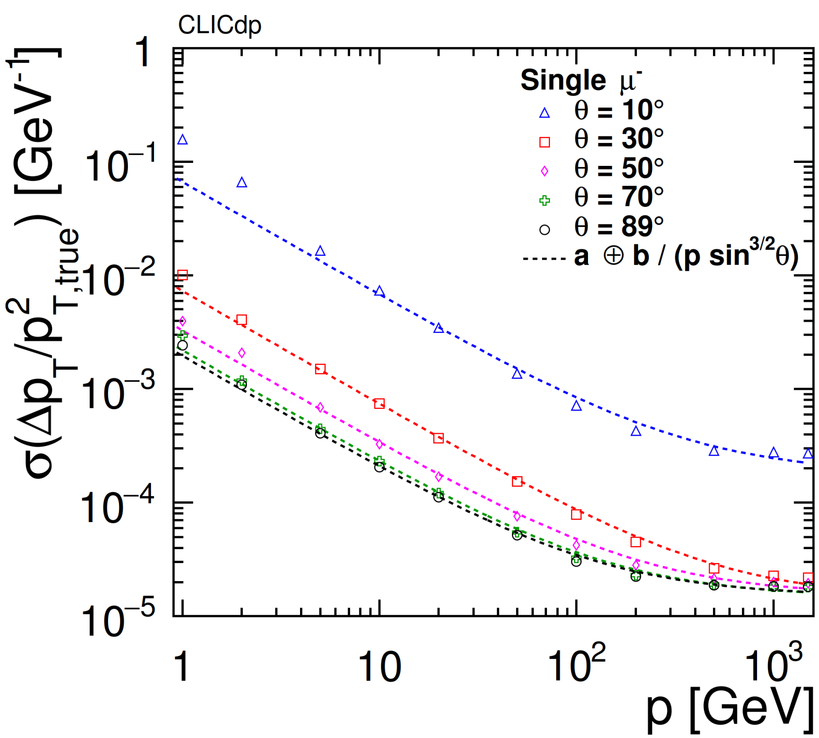




$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from $\gamma\gamma \rightarrow$ hadrons overlaid

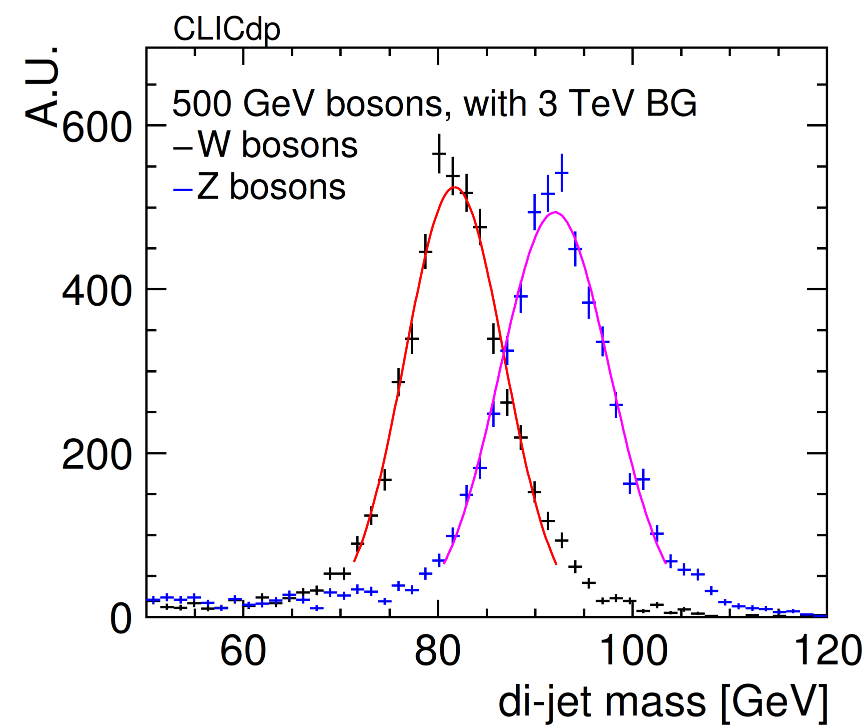
CLICdet performance in full simulation

Tracking



Transverse momentum resolution of 2 x 10^{-5} GeV^{-1} achieved for high-energy tracks in the central part of the detector

Hadronic W and Z decays

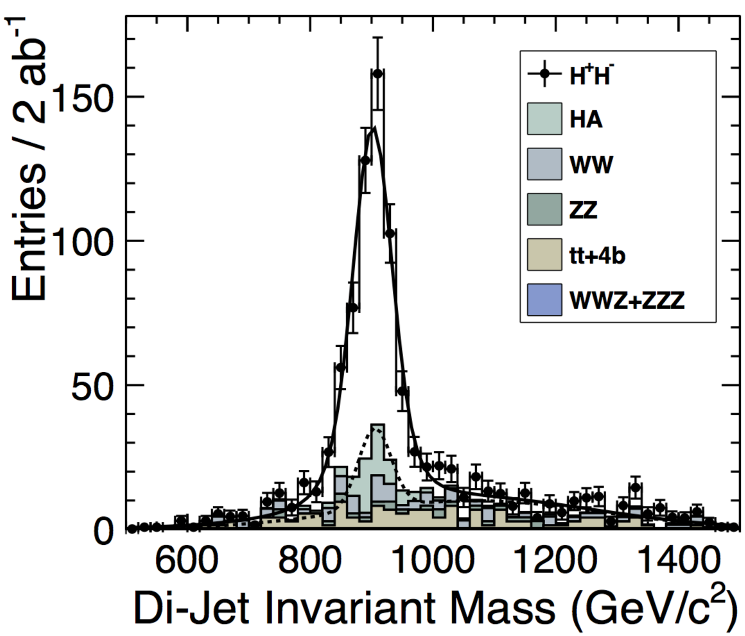


→ Physics projections are based on realistic full detector simulations and include the impact of beam-beam effects

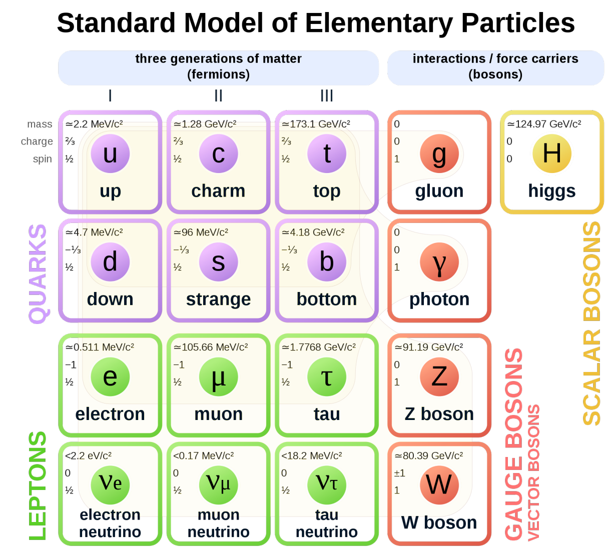
arXiv:1812.07337

How to look for new physics?

1.) Direct searches:
Looking for new particles and unknown effects



2.) Learning from SM processes:
- Precision study of production and decay properties of known SM particles
- Focus on the Higgs boson and top quark which have not been studied in e^+e^- collisions so far

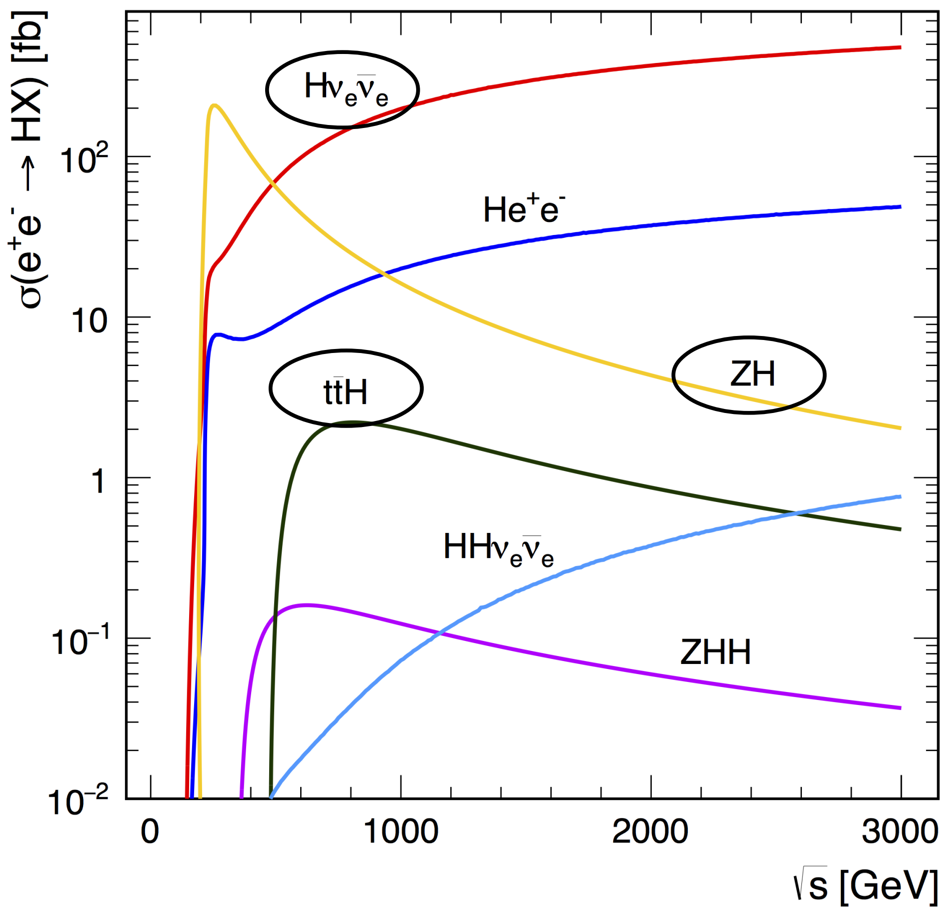


→ Both approaches benefit from the highest possible energies!

Higgs and top-quark physics:

- Single Higgs production
- Double Higgs production
- Top-quark mass
- EFT analysis

Single Higgs production



Higgsstrahlung: $e^+e^- \to ZH$

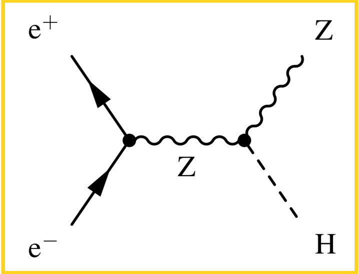
- $\sigma \sim 1/s$, dominant up to ≈ 450 GeV

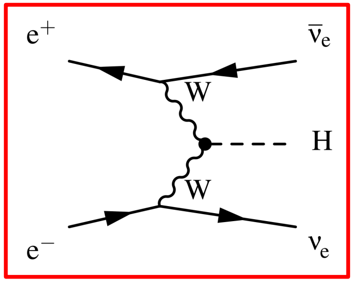
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

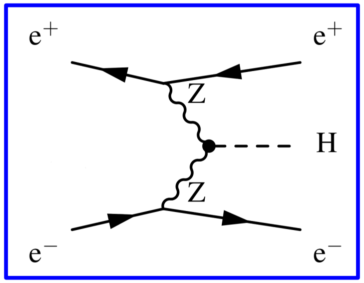
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy

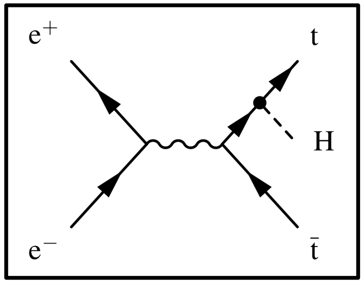
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling





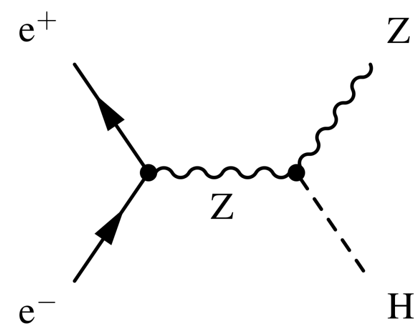




Higgsstrahlung: $e^+e^- \to ZH$

Using $Z \to e^+e^-, \mu^+\mu^-$:

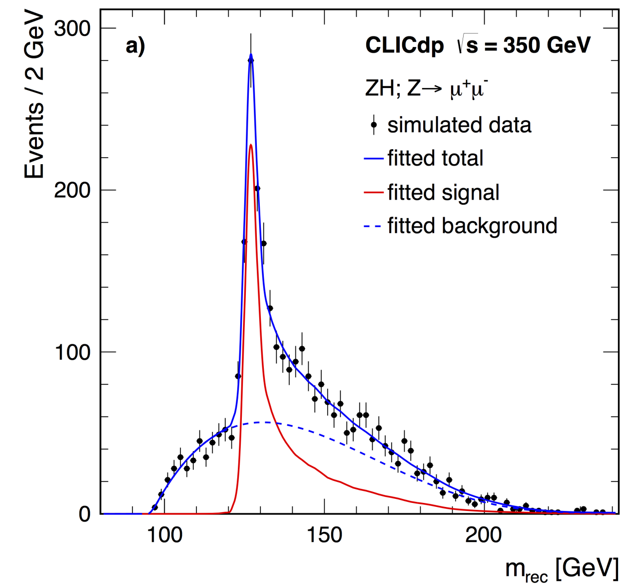
- HZ events can be identified from the Z recoil mass alone
  → Higgs width and couplings without assumptions (requires lepton collider)



- Best precision at 240/250 GeV (tracking resolution, beam energy spectra)

$$m^2_{recoil} = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

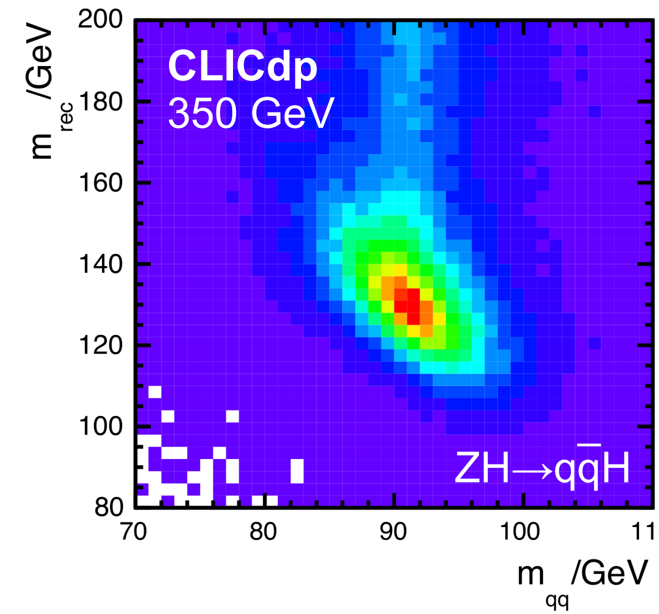
Known at lepton collider



Using $Z \to q\bar{q}$:

- Almost model-independent measurement of g_{HZZ} possible using hadronic Z decays
  → Substantial improvement in precision possible

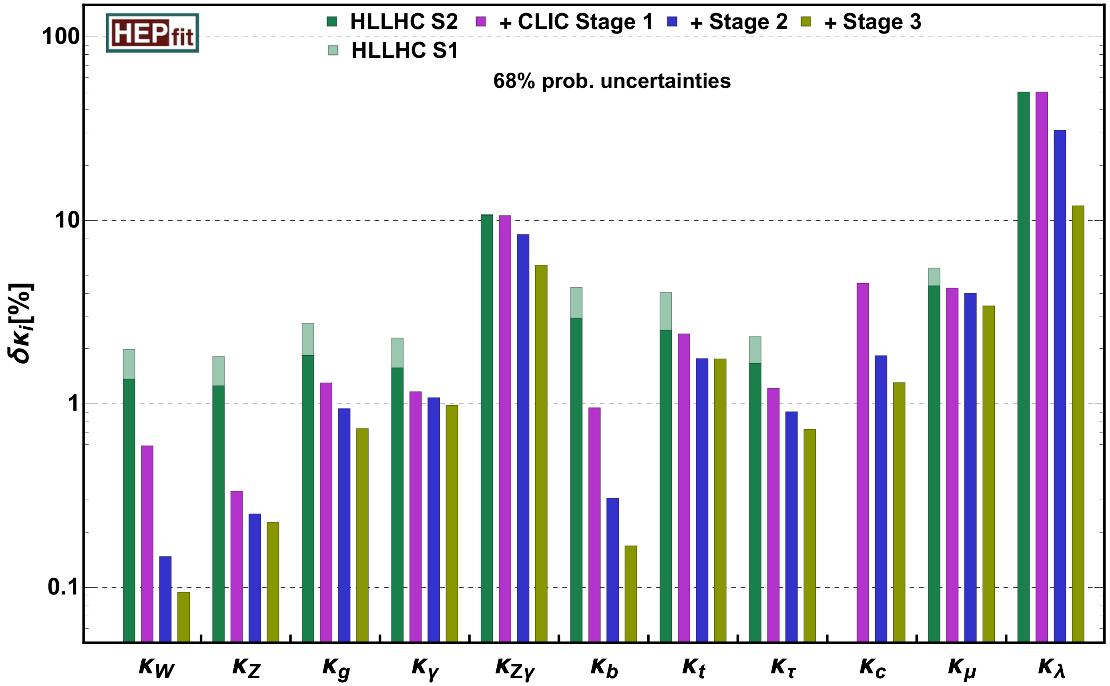
- Better precision at 350 GeV found than at 250 GeV or 420 GeV



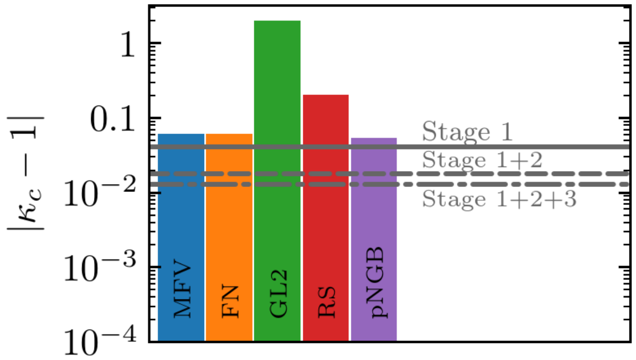
Eur. Phys. J. C 76, 72 (2016)

CLIC coupling sensitivity

Precision on Higgs coupling strength to other SM particles

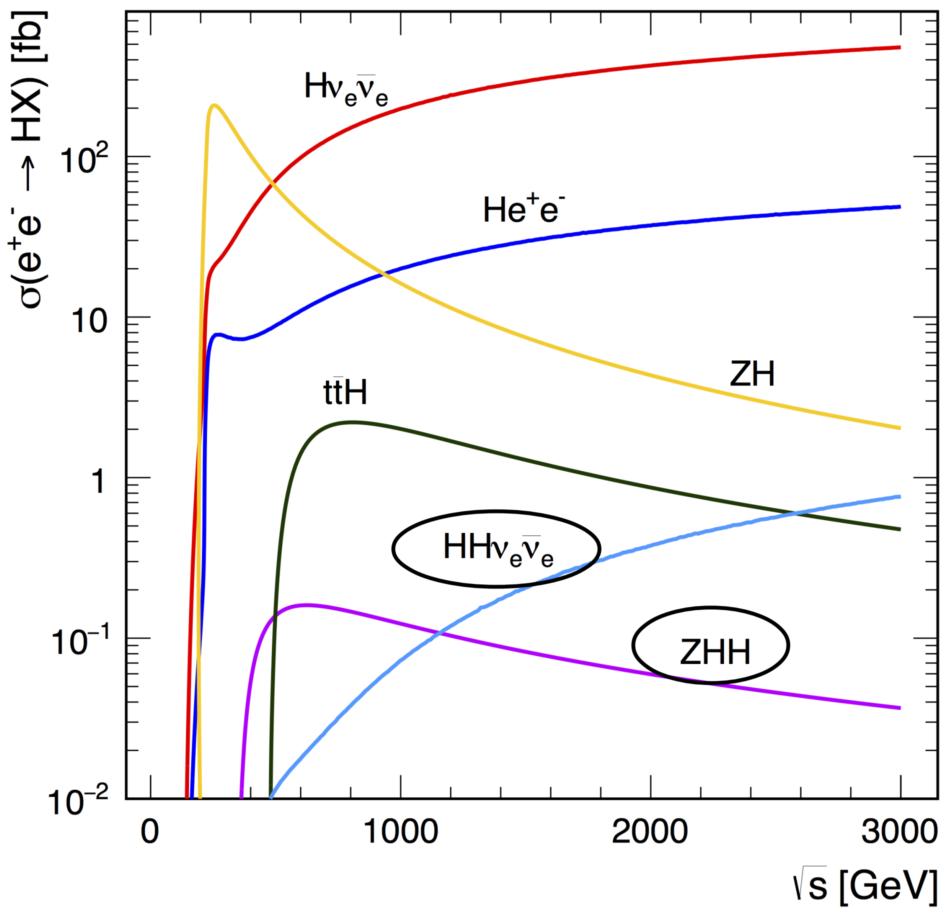


- Already the first CLIC stage significantly better than HL-LHC for several couplings: κ_W, κ_Z, κ_b and κ_c
- The full CLIC program enhances the precision further



Based on Eur. Phys. J. C 77, 475 (2017)
CERN-2018-009-M

Double Higgs production



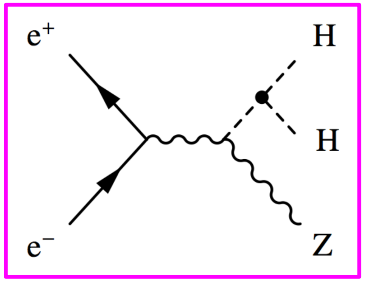
$e^+e^- \to$ ZHH:
- Cross section maximum ≈ 600 GeV

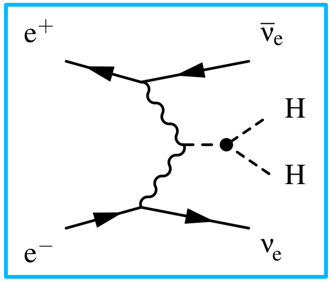
$e^+e^- \to HH\nu_e\bar{\nu}_e$:
- Benefits from high-energy operation

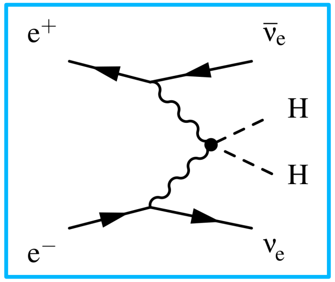
Projected precision:
- $\Delta(\lambda)$ = ±50% at HL-LHC
- $\Delta(\lambda)$ = -7% +11% at CLIC

for 1.4 and 3 TeV combined

arXiv:1901.05897



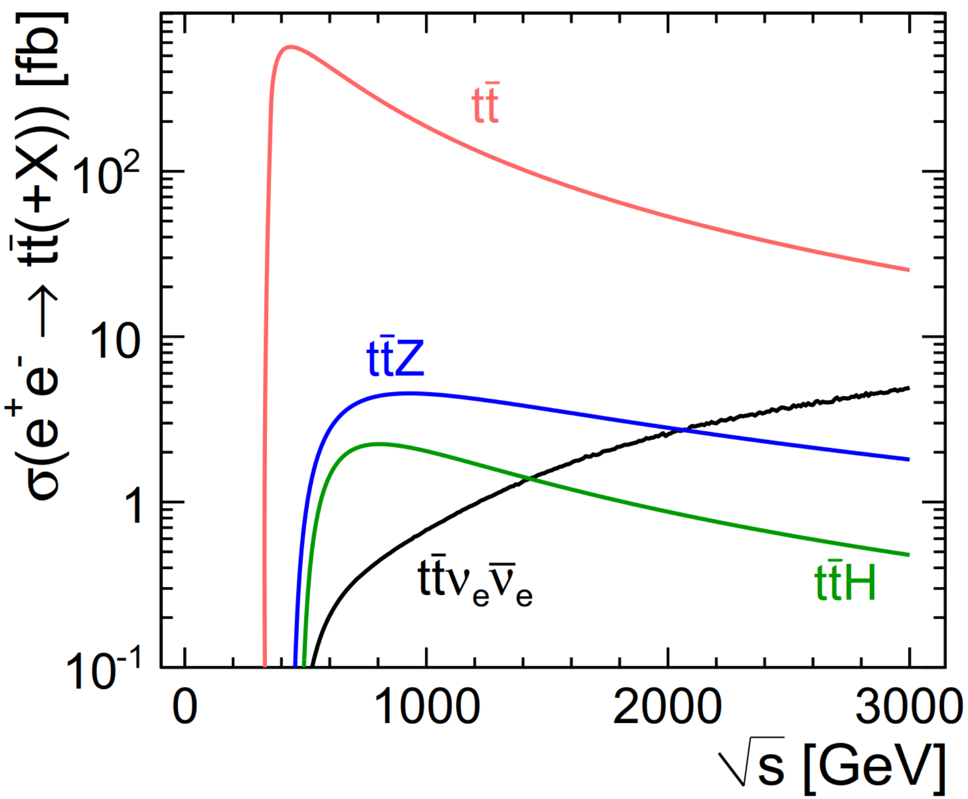




Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\;-15\,\%^b$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

Top-quark pair production



$e^+e^- \to t\bar{t}$:

- Production threshold at $\sqrt{s} \approx 2m_{top}$
- 380 GeV is near the maximum

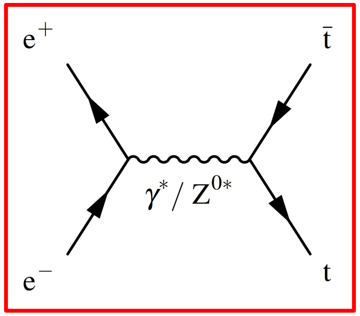
$\rightarrow$ large event samples (for rare decays etc.)

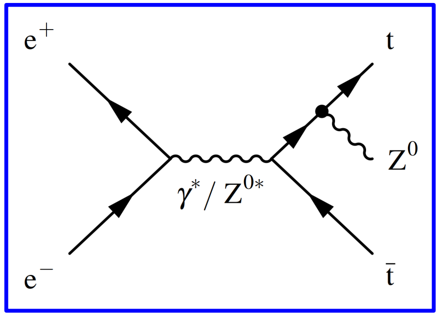
$e^+e^- \to t\bar{t}H$:

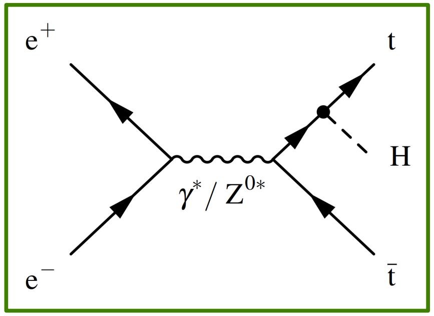
- Maximum near 800 GeV

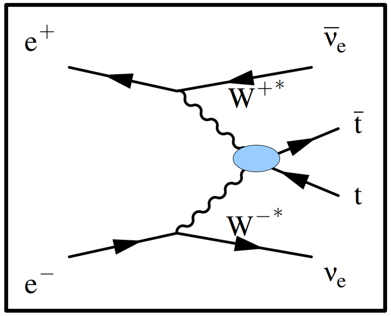
$e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$ (Vector Boson Fusion):

- Benefits from highest energies
- Potential high-energy probe of the top Yukawa coupling





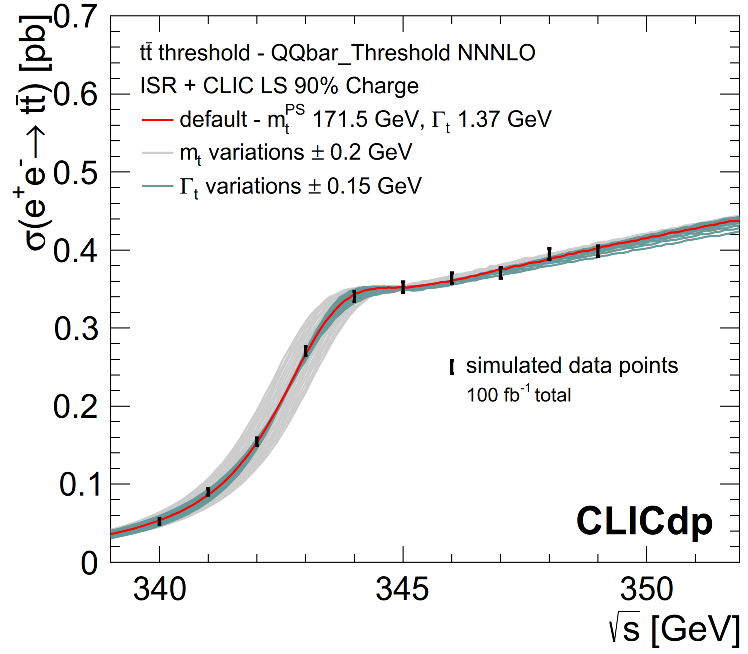




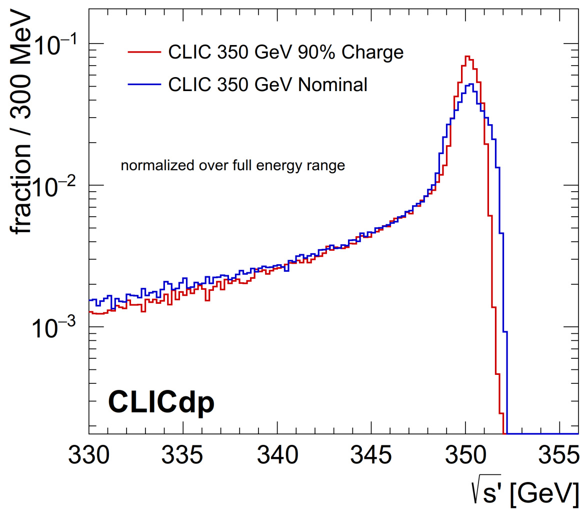
Threshold scan

- Measurement at different centre-of-mass energies in the $t\bar{t}$ production threshold region (data also useful for Higgs physics)
- Expected precision on 1S mass: ≈ 50 MeV (currently dominated by theory NNNLO scale uncertainty)
- Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the $\overline{\text{MS}}$ mass scheme

Phys. Rev. Lett. 114, 142002 (2015)



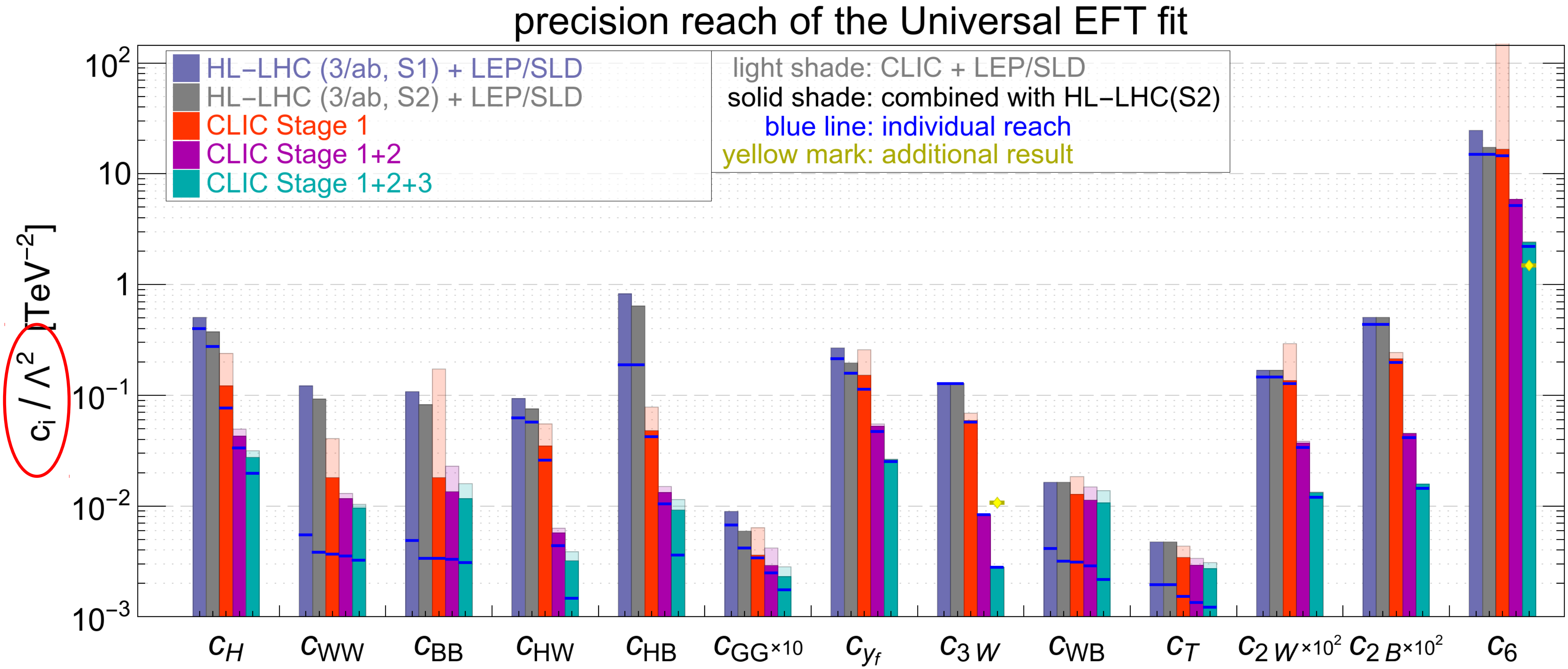
- Other methods: ISR photons, direct reconstruction (less precise)
- Precision at the HL-LHC limited to several hundred MeV



Optimised CLIC luminosity spectrum (90% bunch charge)

arXiv:1807.02441

Global Effective Field Theory fit



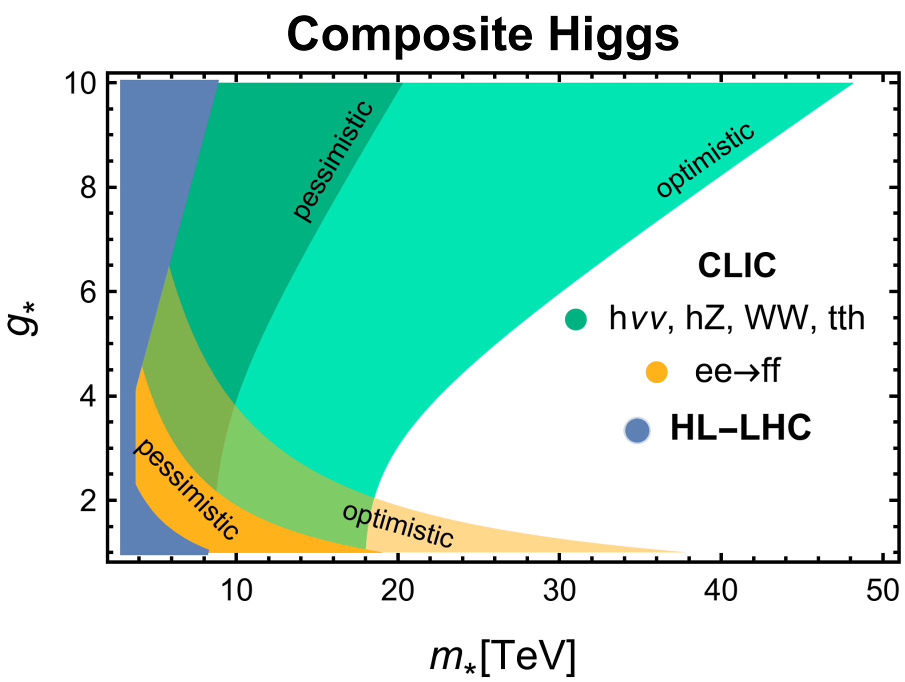
CERN-2018-009-M

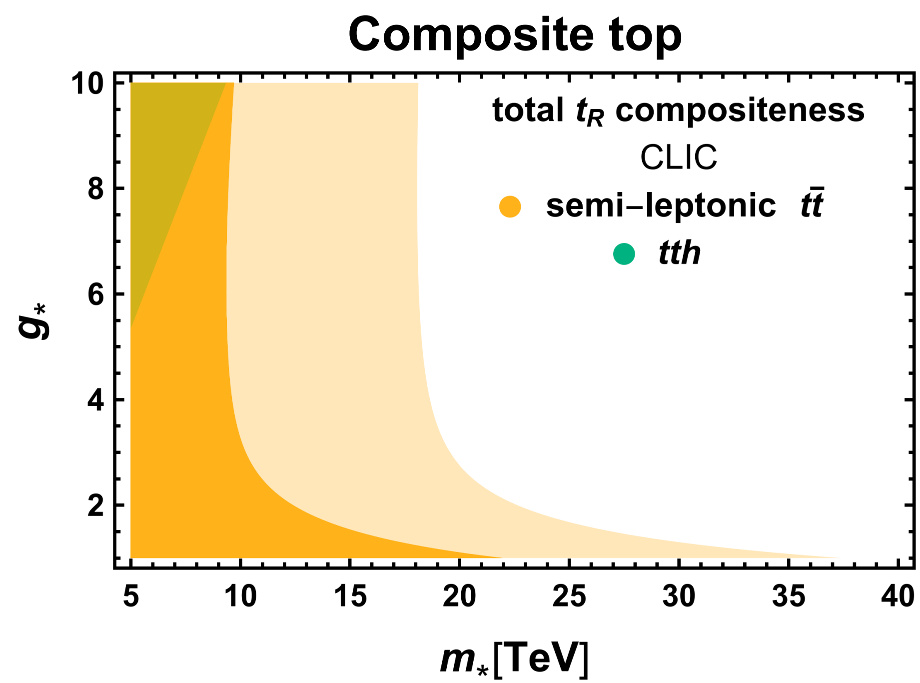
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

CLIC input to fit:
Higgs couplings, top quark observables,
WW production, two-fermion production

New physics potential

Compositeness at CLIC





m_*: compositeness scale

g_*: coupling strength of the composite sector

Discovery of Higgs compositeness scale up to 10 TeV (40 TeV for $g_* \approx 8$)

Discovery of top compositeness scale up to 8 TeV (20 TeV for small g_*)

CERN-2018-009-M

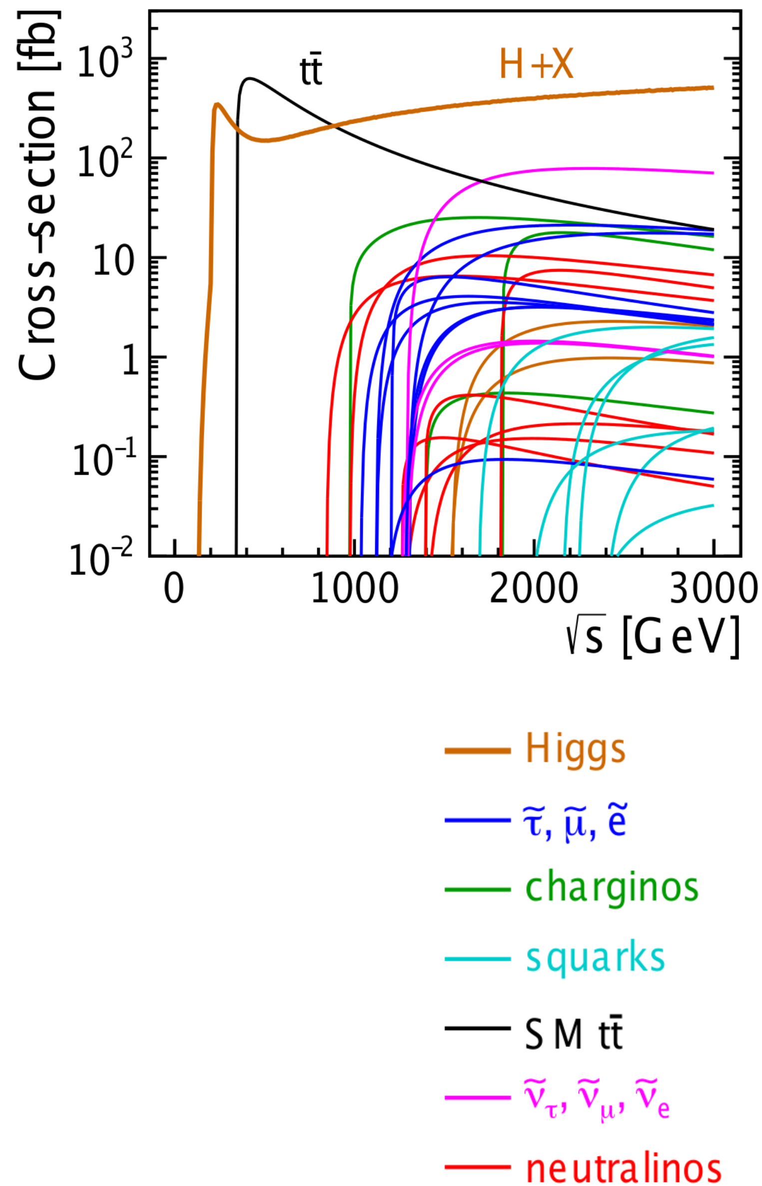
Direct new physics searches

• Direct observation of new particles coupling to $\gamma^*/Z/W$ → precision measurement of new particle masses and couplings

• The sensitivity often extends up to the kinematic limit (e.g. $M \leq \sqrt{s}\,/\,2$ for pair production)

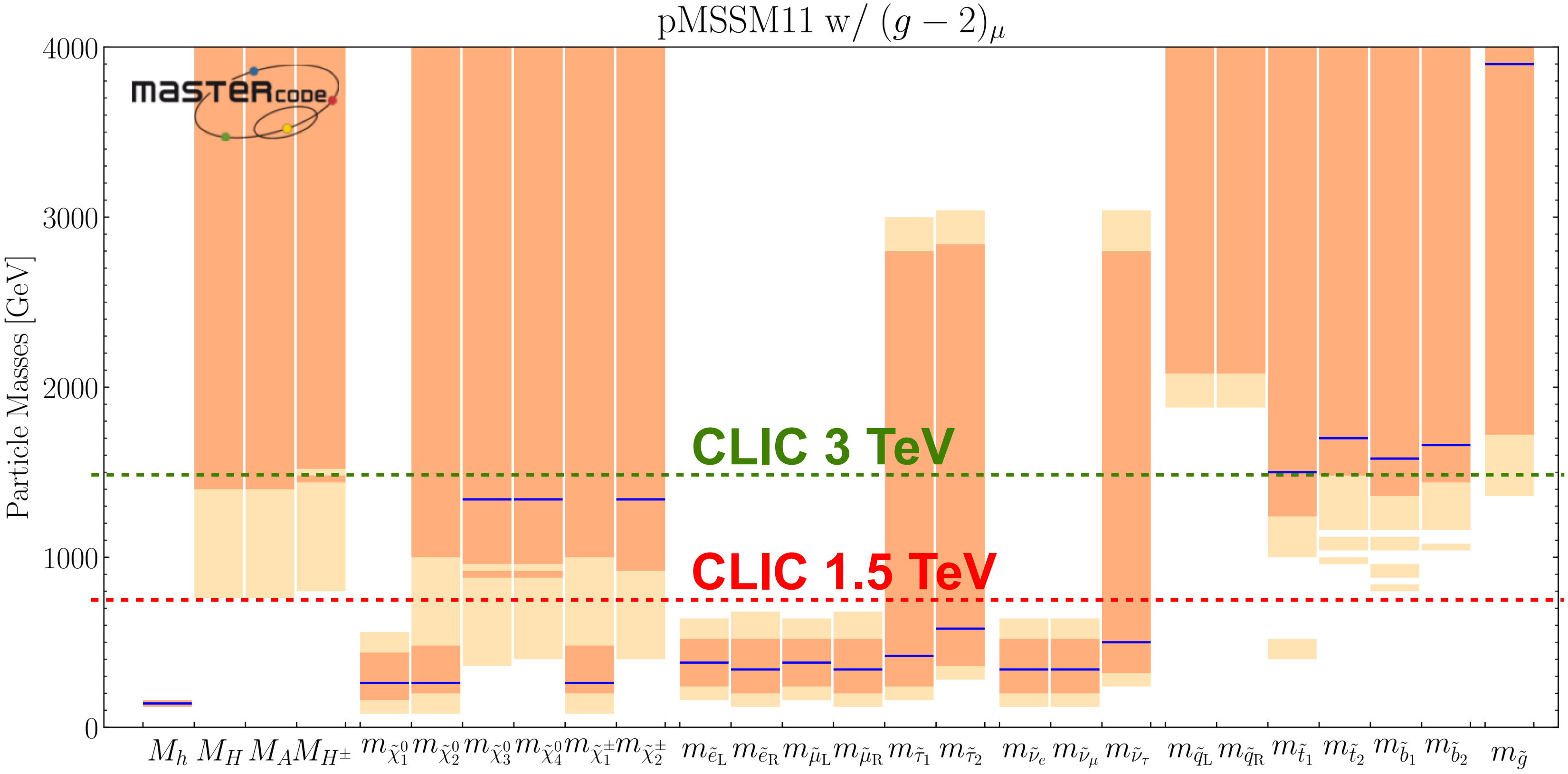
• Very rare processes accessible due to low backgrounds (no QCD) → CLIC especially suitable for electroweak states

• Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Direct observation of sparticles

Example: Phenomenological MSSM with 11 parameters



Blue lines: best fit values

Orange bands: 68% & 95% CL ranges

arXiv:1710.11091

- Global fit to current experimental data (LHC results, low-energy and flavour experiments, CDM measurements)
- In this model, many gaugions and sleptons are accessible at CLIC, stop and sbottom are possible

→ Direct discoveries are (still) a main motivation for high-energy CLIC operation

Higgs plus heavy singlet

Heavy singlet mixing with Higgs boson:

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

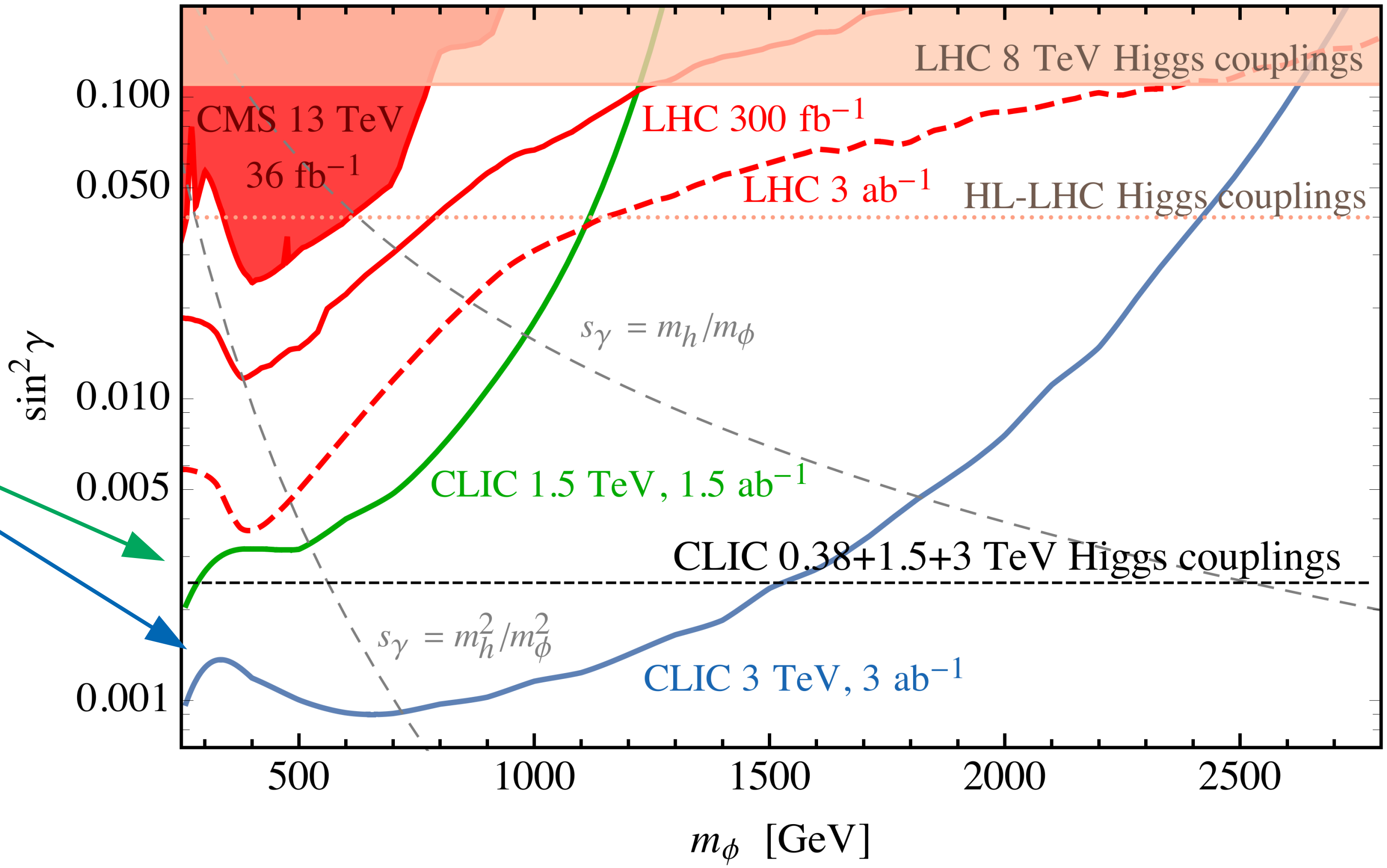
$\phi = S \cos\gamma - h_0 \sin\gamma$

Direct production:

$e^+e^- \rightarrow \nu\bar{\nu}\phi,\ \phi \rightarrow hh$

Indirect sensitivity from Higgs couplings

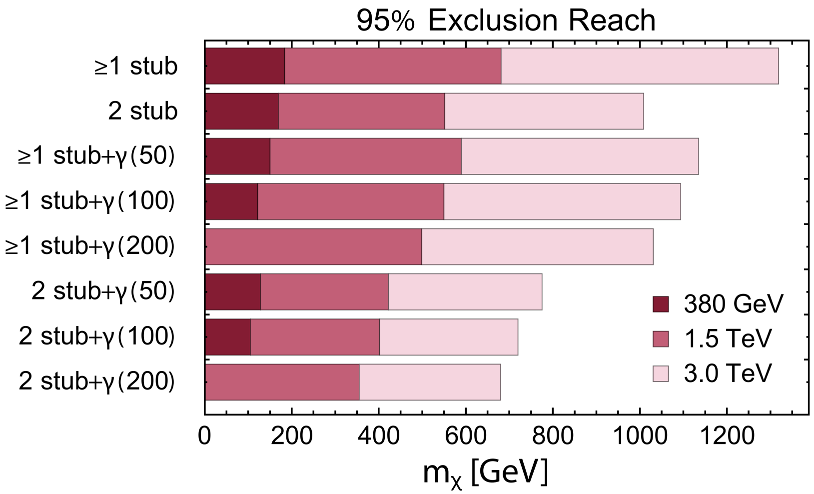
→ Both approaches are complementary



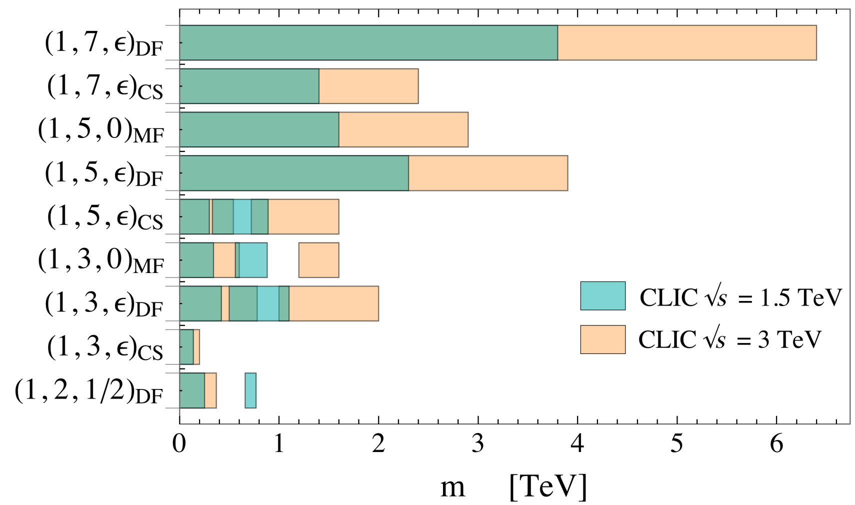
CERN-2018-009-M

Dark Matter searches...

… using stub tracks:



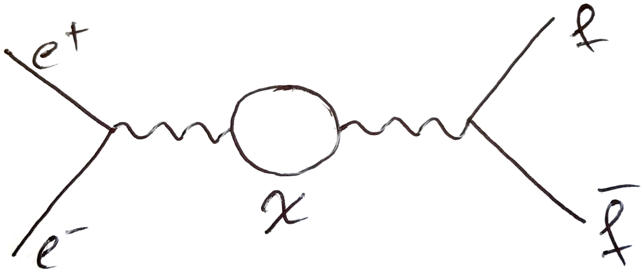
… in loops:



$e^+e^- \to \chi^+\chi^-(+\gamma)$
Small mass difference: $\chi^\pm \to \chi^0\pi^\pm$
Long-lifetime: $\chi^\pm$ leaves a short, disappearing ("stub") track in the detector

- CLIC might discover the thermal Higgsino at 1.1 TeV

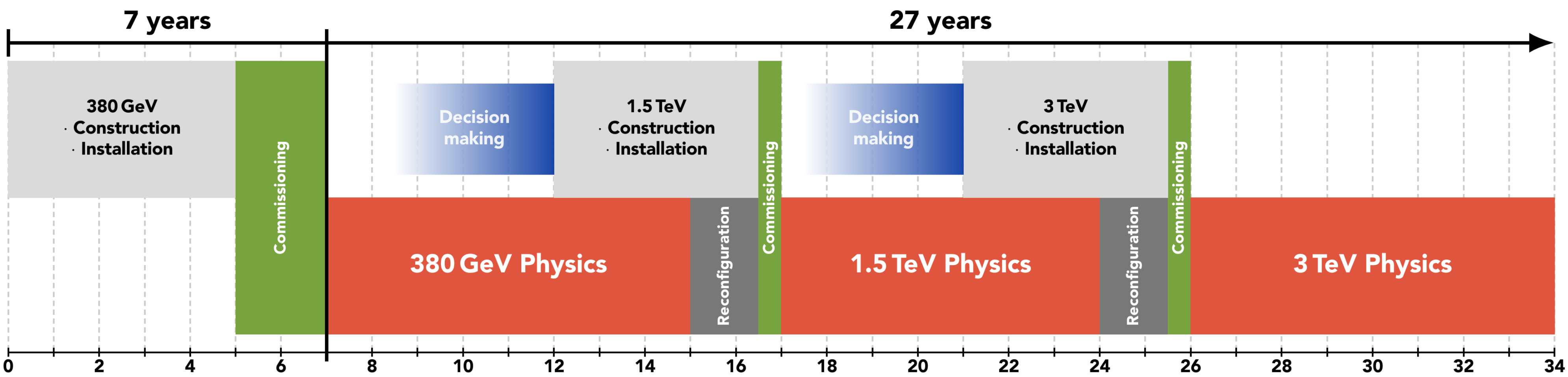
Electroweak n-plet states with hypercharge Y: (1,n,Y)



CERN-2018-009-M

Summary and conclusions

CLIC timeline



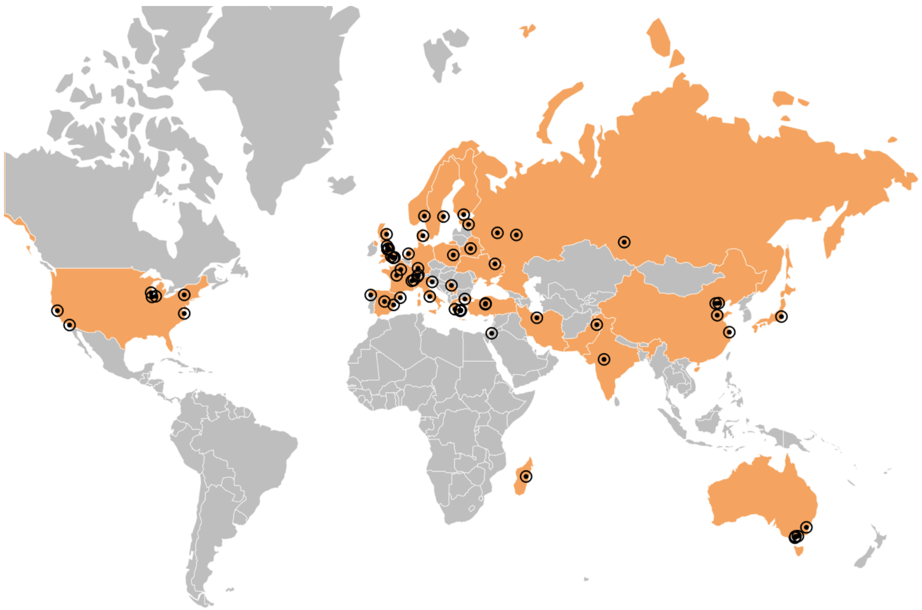
- Technology-driven schedule from start of construction

- After go-ahead, at least 5 years are needed before construction can start
→ first beams could be available by 2035

CERN-2018-005-M

CLIC collaborations

CLIC accelerator collaboration
≈60 institutes from 28 countries



http://clic-study.web.cern.ch

• CLIC accelerator design and development (construction and operation of CTF3)

CLIC detector & physics (CLICdp)
Collaboration: 30 institutes from 18 countries

http://clicdp.web.cern.ch

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

Summary and conclusions

- An e^+e^- collider is widely considered to be the next large international project high-energy particle physics

- CLIC is the only mature option for a multi-TeV e^+e^- collider

- Very active R&D projects for accelerator and physics/detector

- Energy-staging → optimal for physics:

380 GeV:	Optimised for precision SM Higgs and top physics
1.5 TeV, 3 TeV:	Best sensitivity for new physics searches, rare Higgs processes and decays

- 380 GeV CLIC could be ready for physics in 2035 – at “affordable” cost