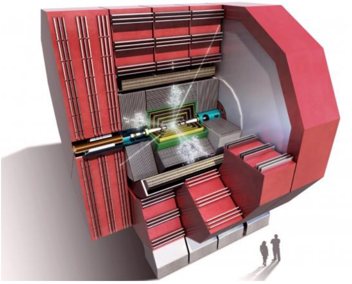
CLIC: a future linear collider at the foot of the Jura



Lucie Linssen, CERN

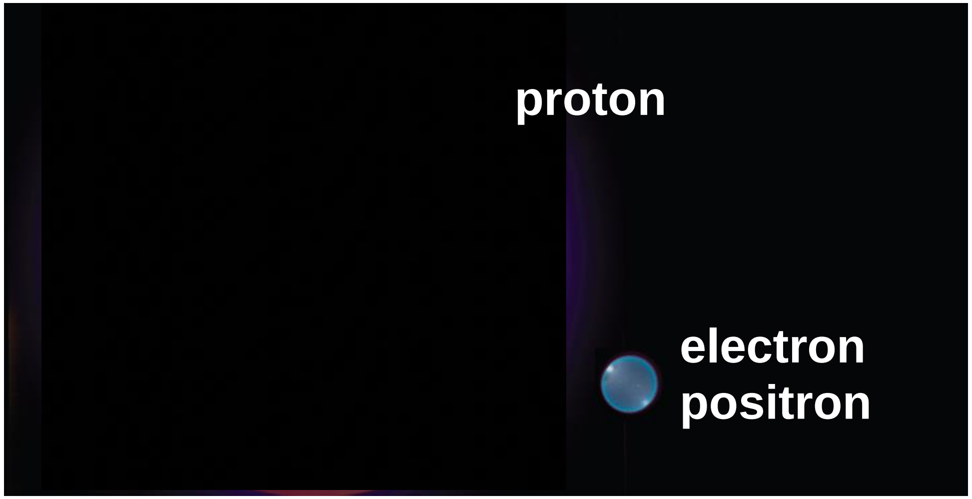
CERN60 public conference:
Past, present future: LHC and future possibilities

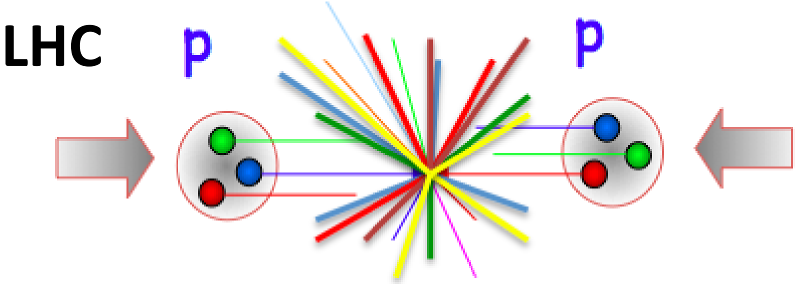
outline

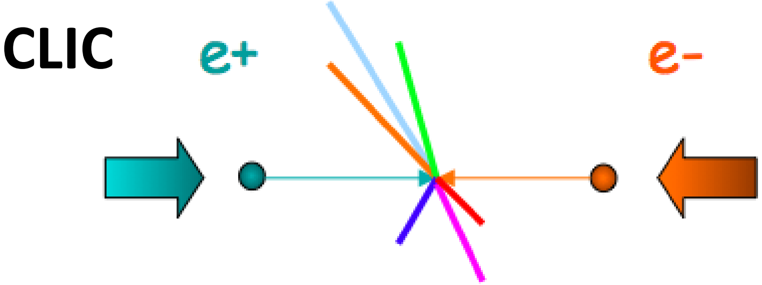
- proton versus electron colliders
- short introduction to particle acceleration
- the Compact Linear Collider (CLIC)
- short introduction to particle detectors
- a detector for CLIC
- snapshot of physics at CLIC
- collaboration
- what’s next ?

- proton versus electron colliders

from discovery to precision

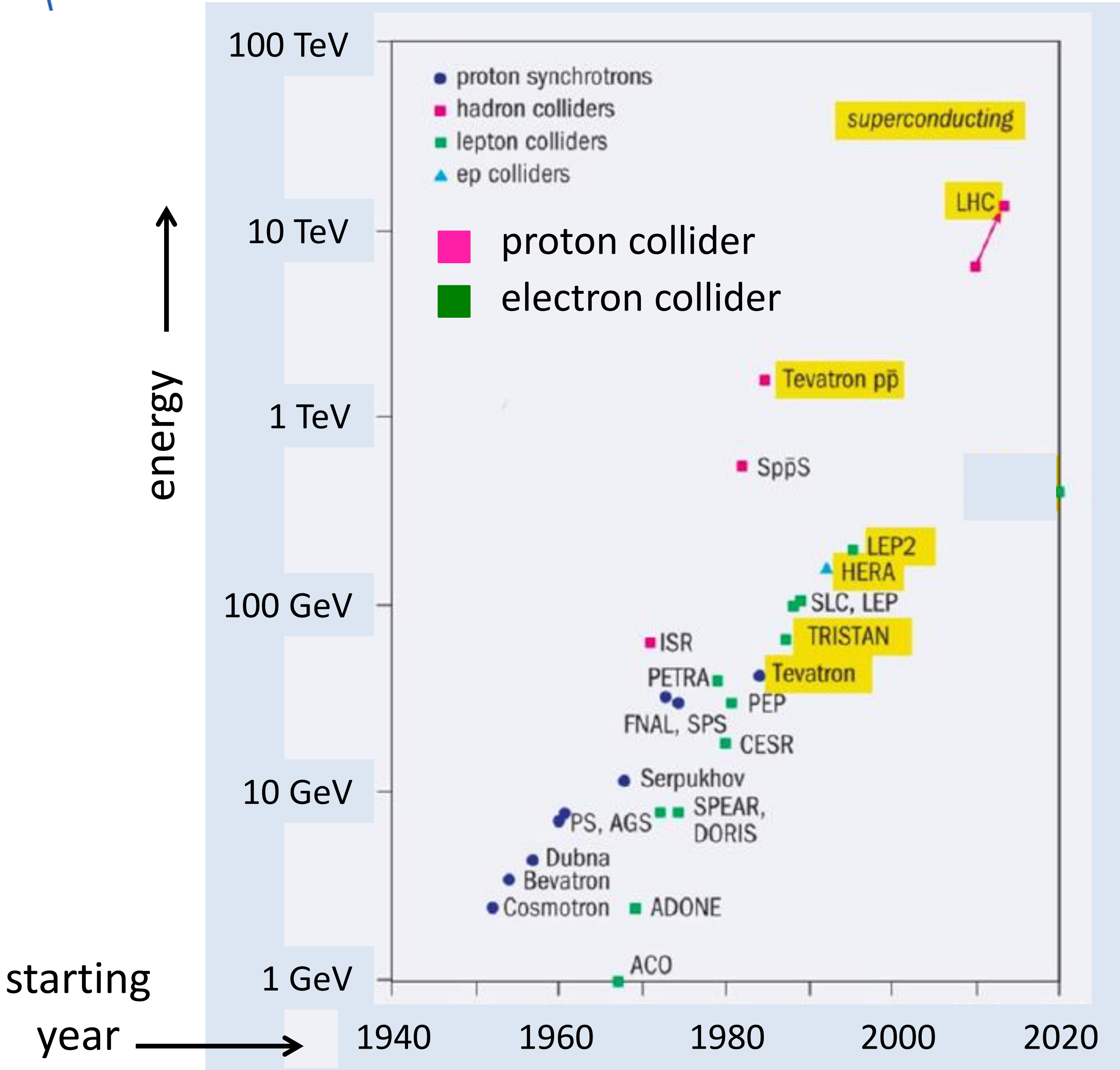






p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined ($\sqrt{s}$ / polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**

history of proton and electron colliders



pp and e^+e^- provide complementary information

↓

particle physics needs both !

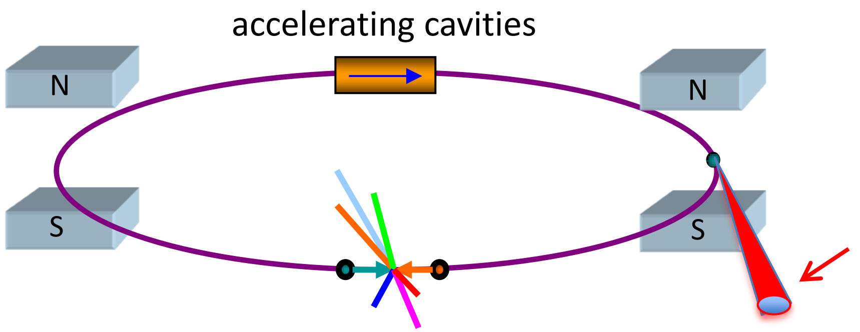
historically, electron colliders lag behind in energy

why ?

- short introduction to particle acceleration

circular or linear collider ?

Circular Collider



$\frac{\text{proton mass}}{\text{electron mass}} \approx 2000$

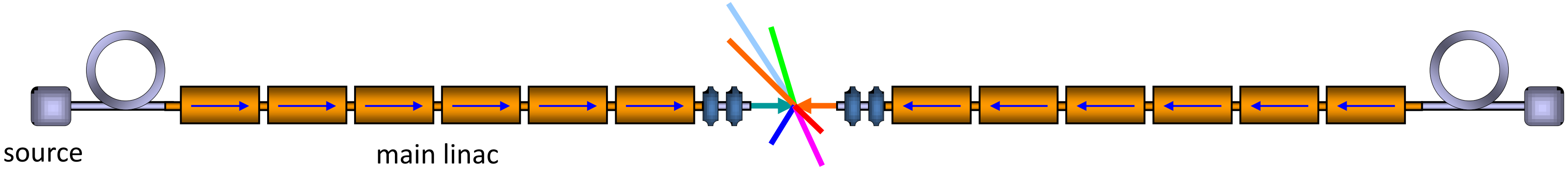
Synchrotron radiation
$\propto$ **Energy^4/Mass^{4}Radius**

many magnets, few accelerating cavities

beam circulates for a long time (at 11000 turns/sec in LHC)

high energy → strong magnets needed   more synchrotron radiation loss

Linear Collider



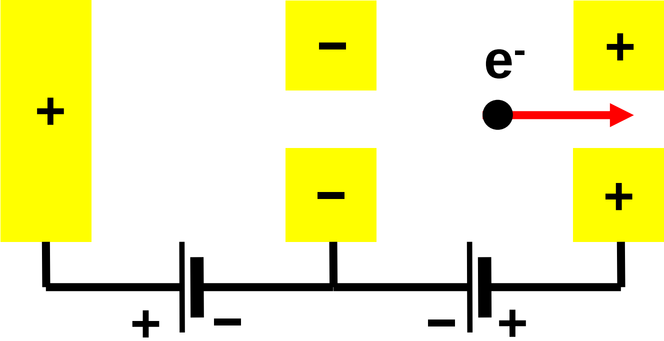
few magnets, many accelerating cavities

beam passes only once

high energy → high accelerating gradient needed

high luminosity → high beam power (high bunch repetition)

principle of particle acceleration

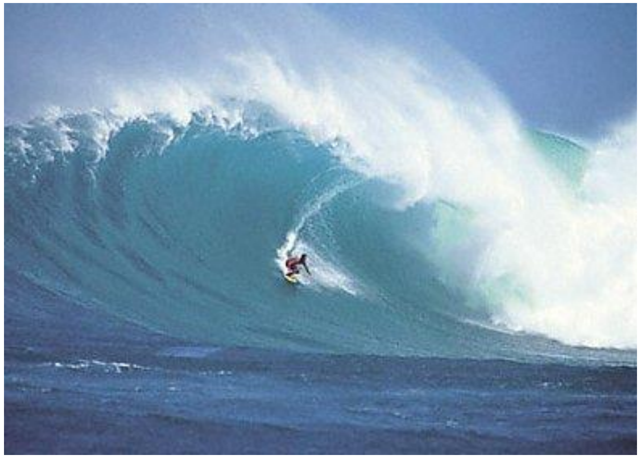


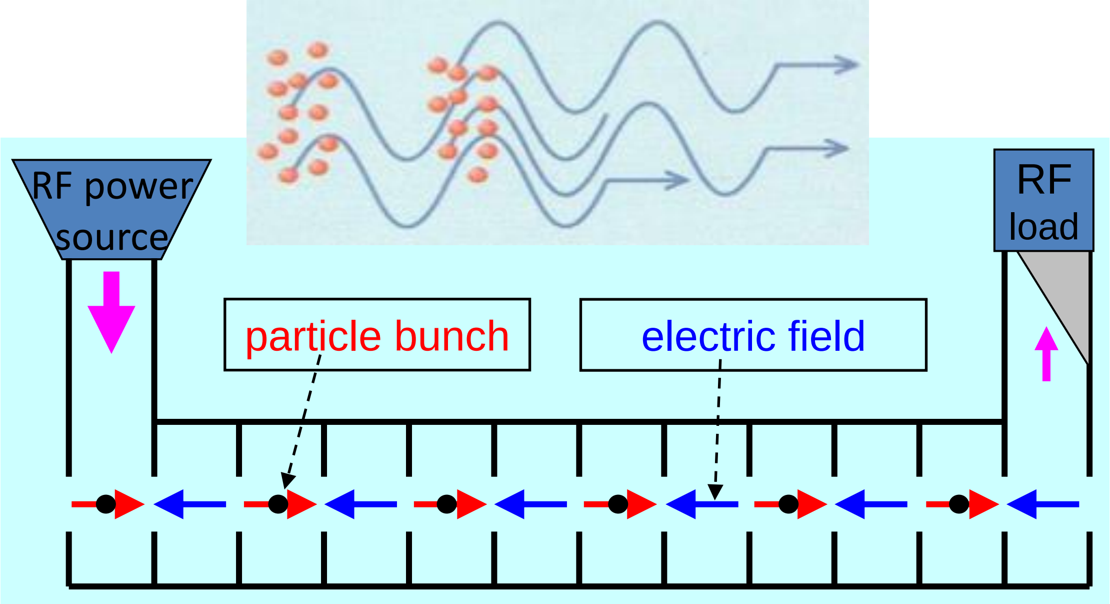
CLIC aims for **high collision energy (3 TeV)**

- need very strong acceleration
- more efficient at high frequency

CLIC:

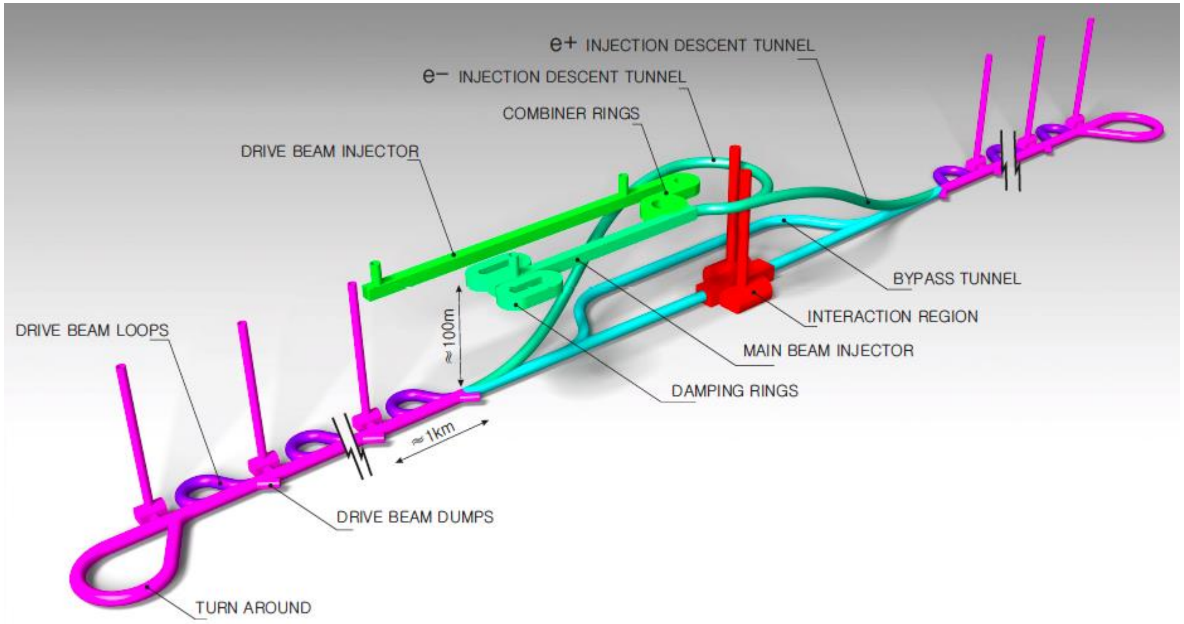
- 100 MV/m (100 million Volts per metre !)
- 12 GHz (at LHC it’s 5 MV/m and 400 MHz)





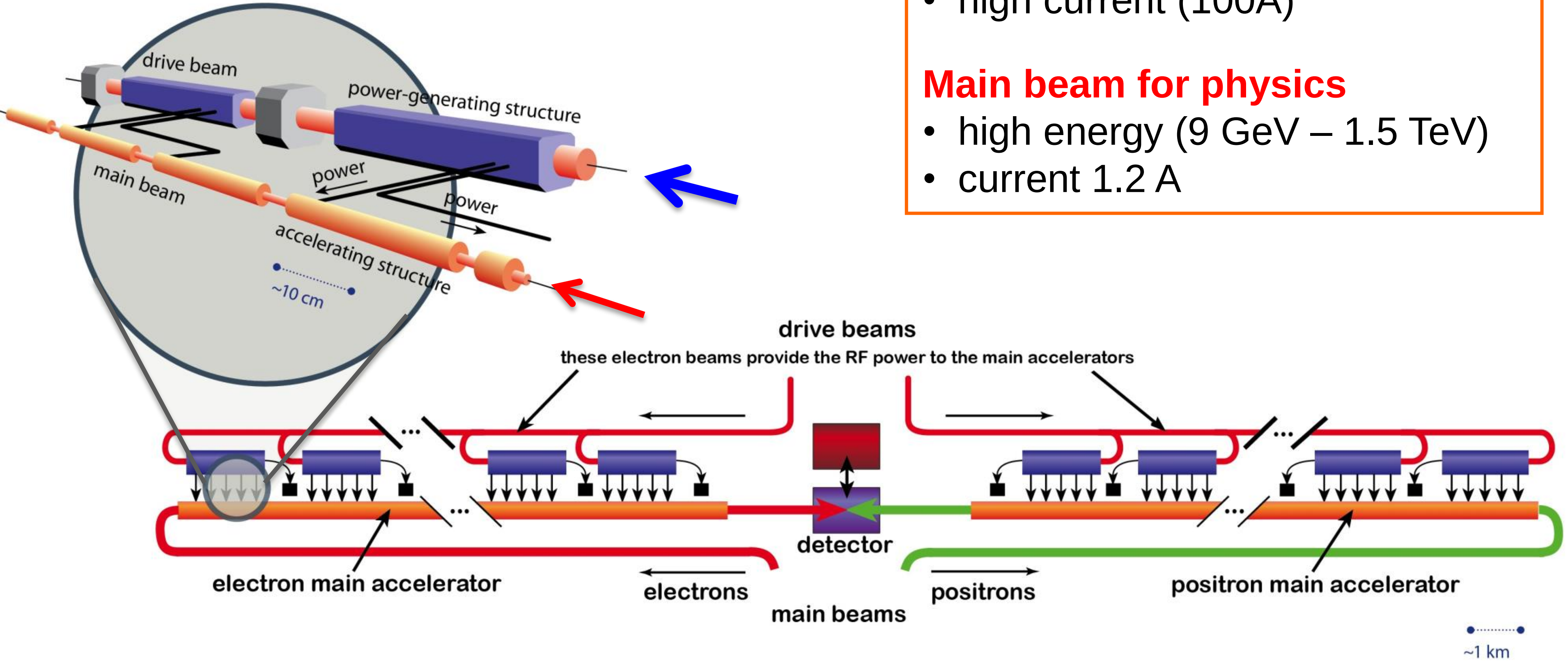
RF (radio frequency) accelerator: synchronise particle with an RF electromagnetic wave!

- the Compact Linear Collider (CLIC)



CLIC two-beam acceleration scheme

Accelerating gradient: 100 MV/m



Two Beam Scheme:

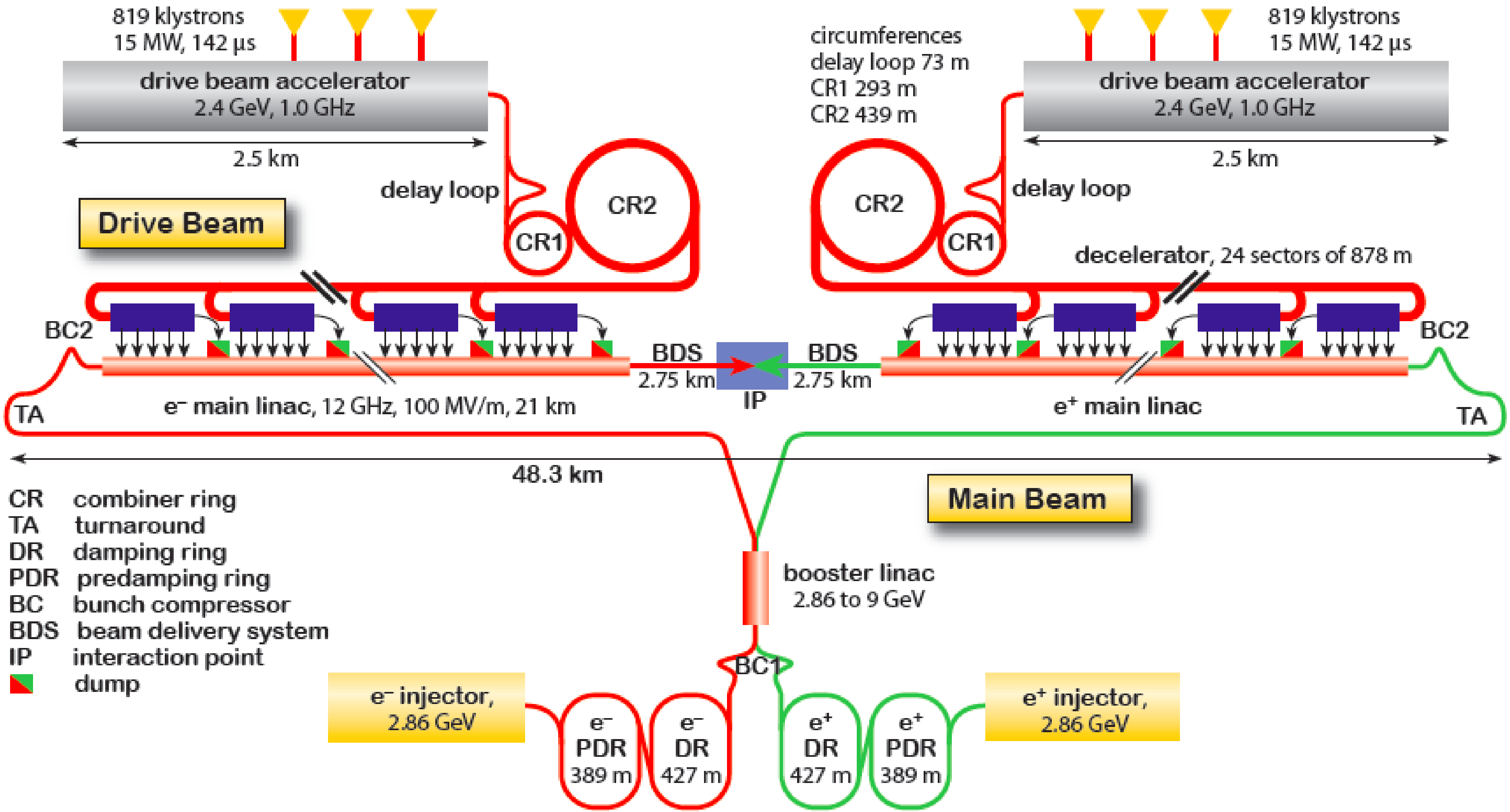
Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

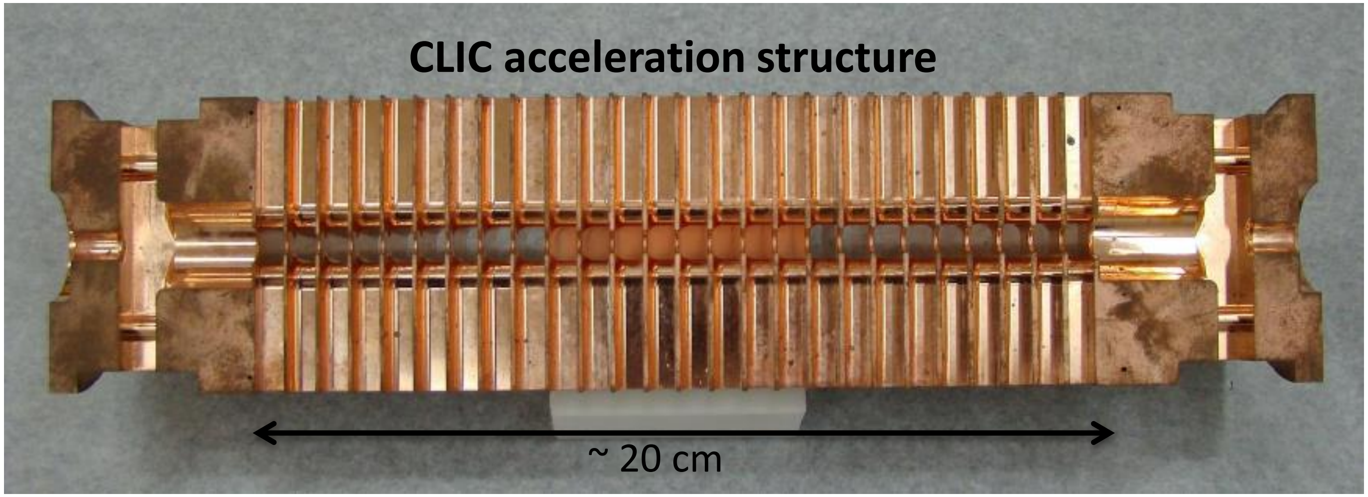
CLIC layout at 3 TeV

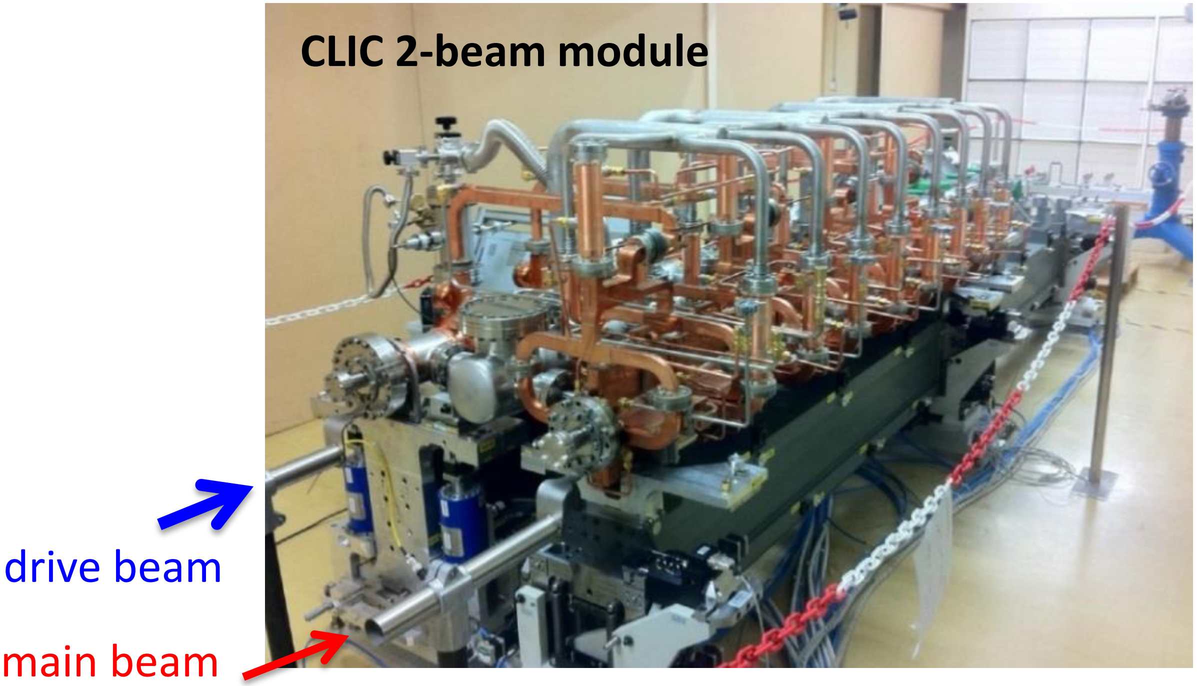


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

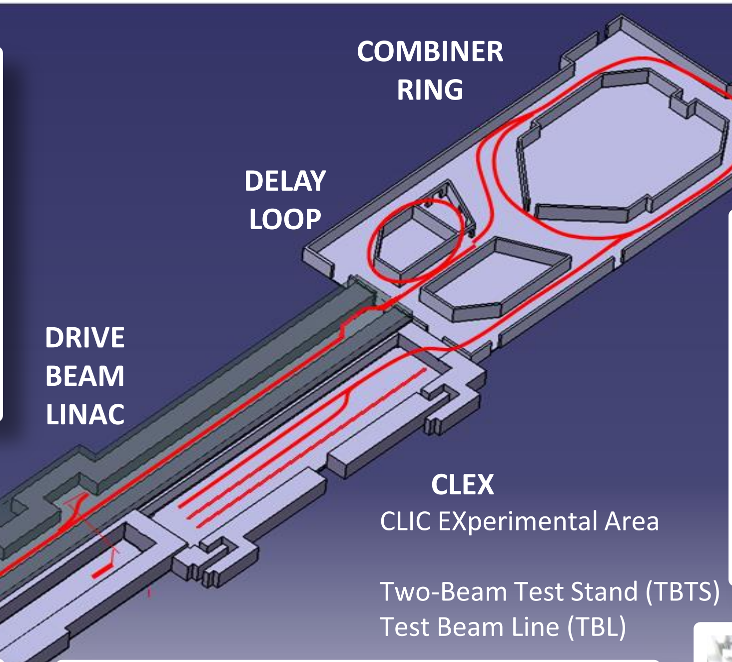
CLIC acceleration modules

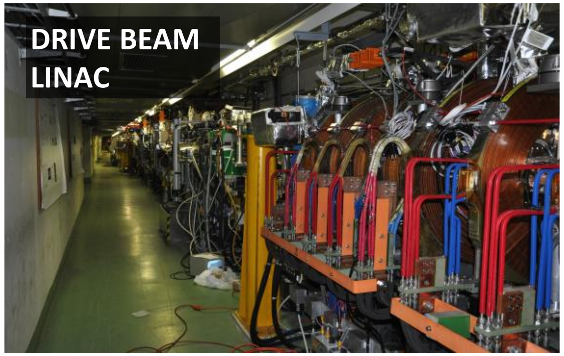


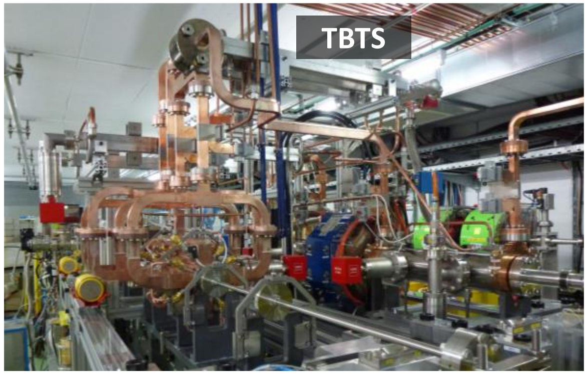


CLIC test facility (CTF3)

a small CLIC to test basic principles and key performance parameters







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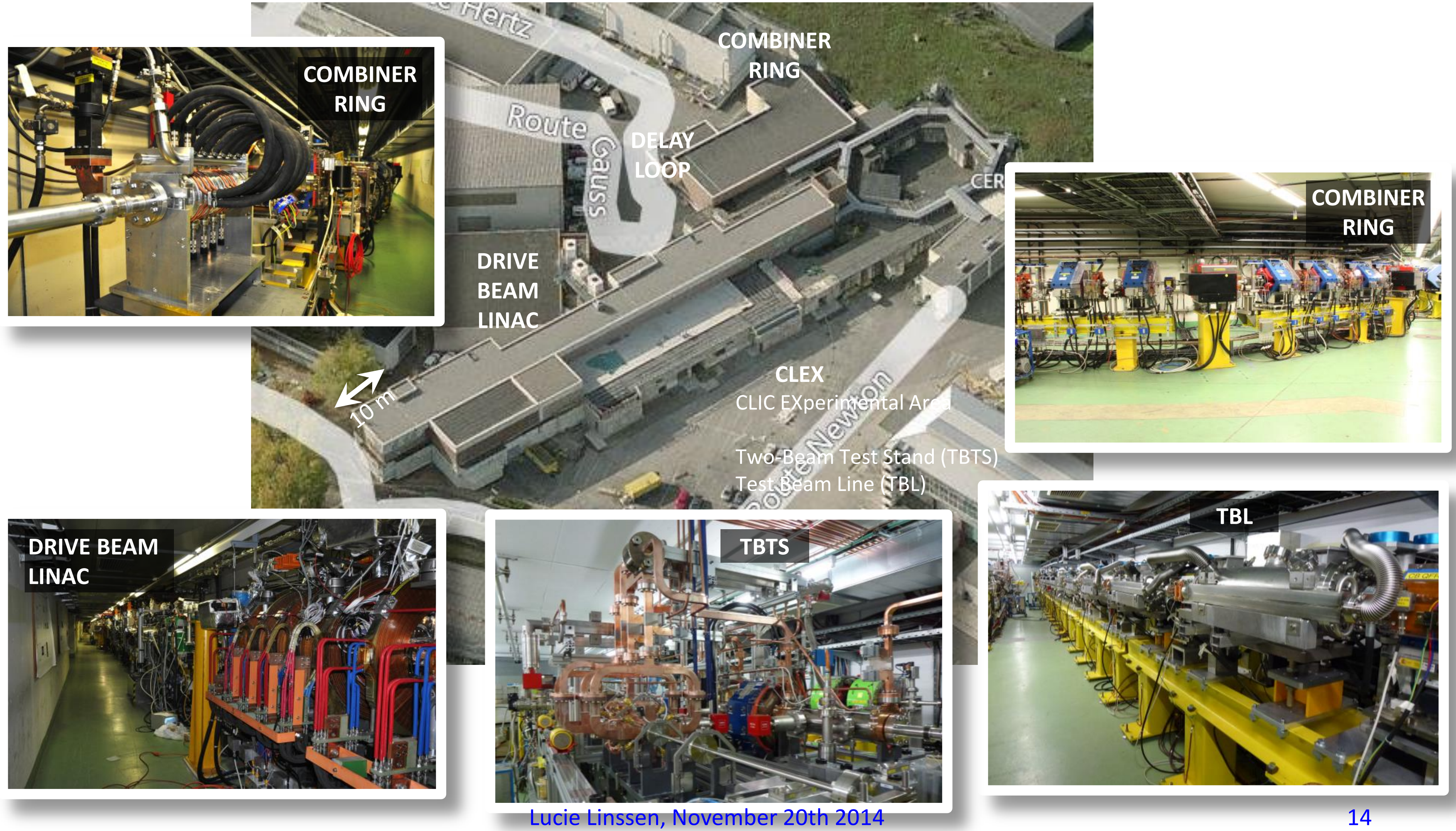
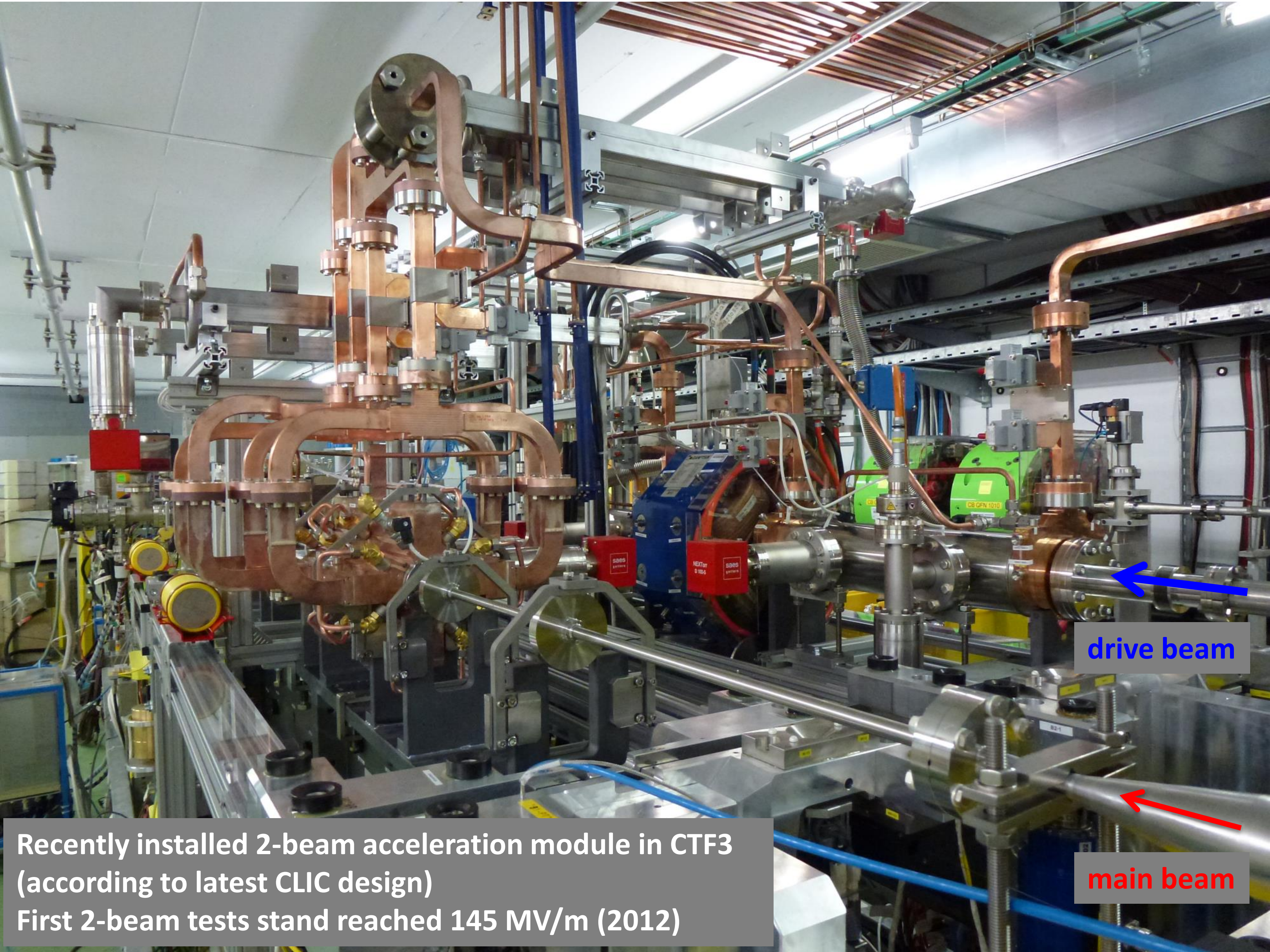




Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)
First 2-beam tests stand reached 145 MV/m (2012)

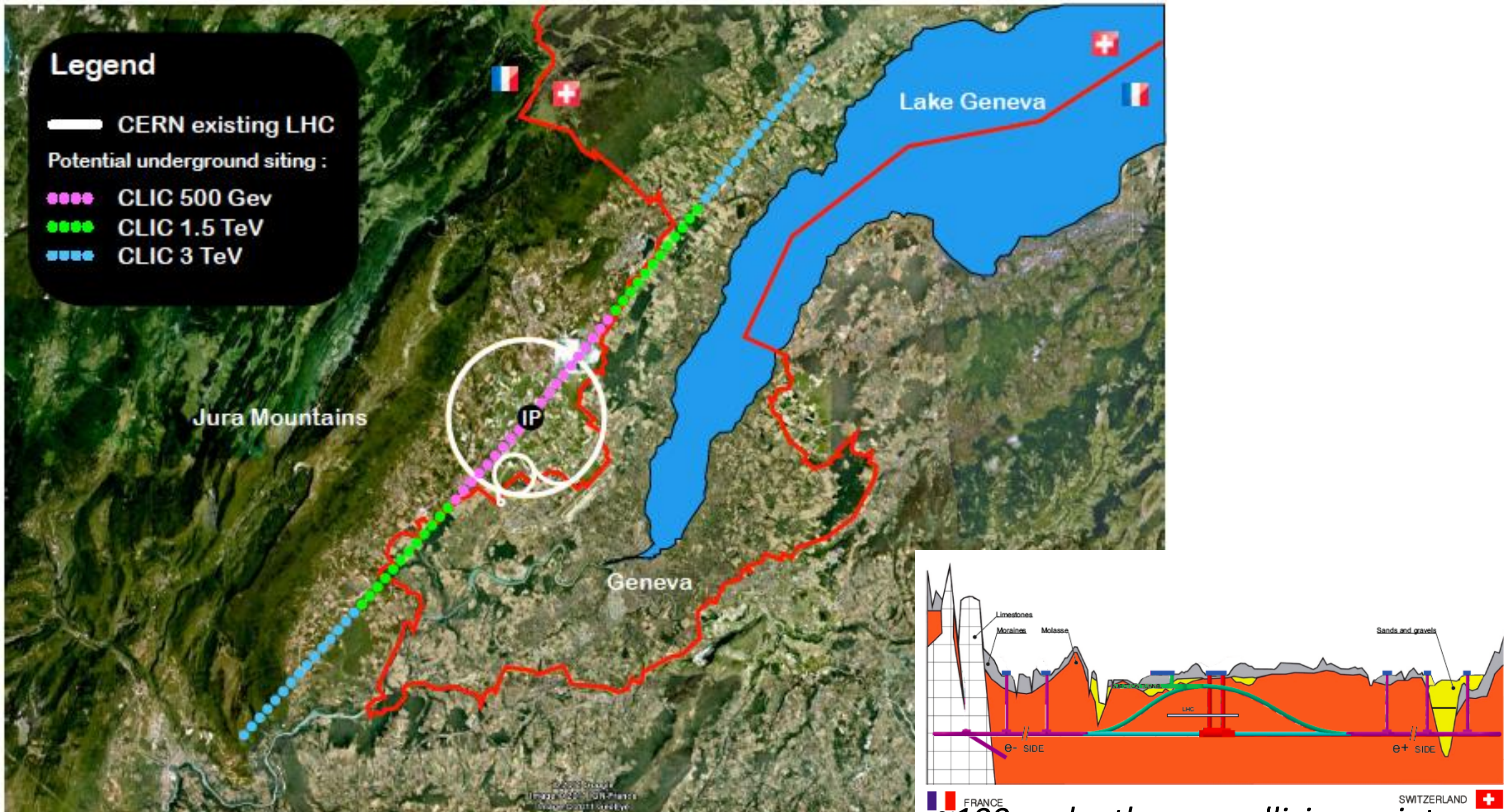
CLIC at the foot of the Jura

staged operation

↓

optimal for physics

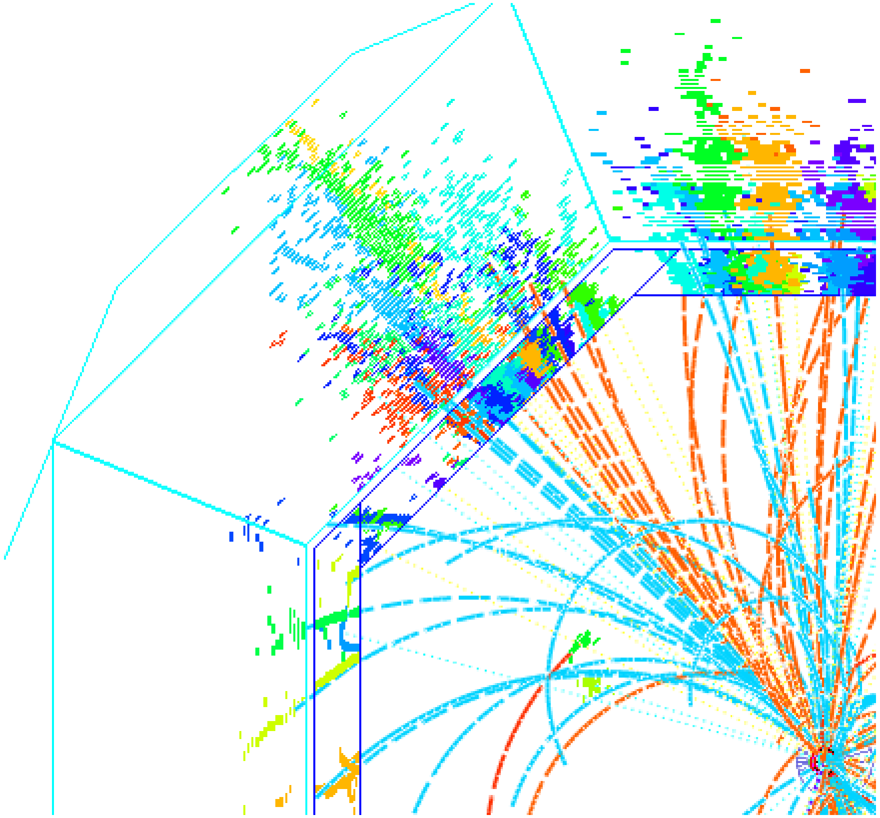
Collision energy (GeV)	Site length (km)	Luminosity ($cm^{-2}s^{-1}$)	# Higgs events in ~4 yrs
350	11	1.5×10^{34}	90000
1500	27	3.5×10^{34}	430000
3000	48	6×10^{34}	920000



~100 m depth near collision point

Note: #Higgs is without enhancement from polarisation

- short introduction to particle detectors



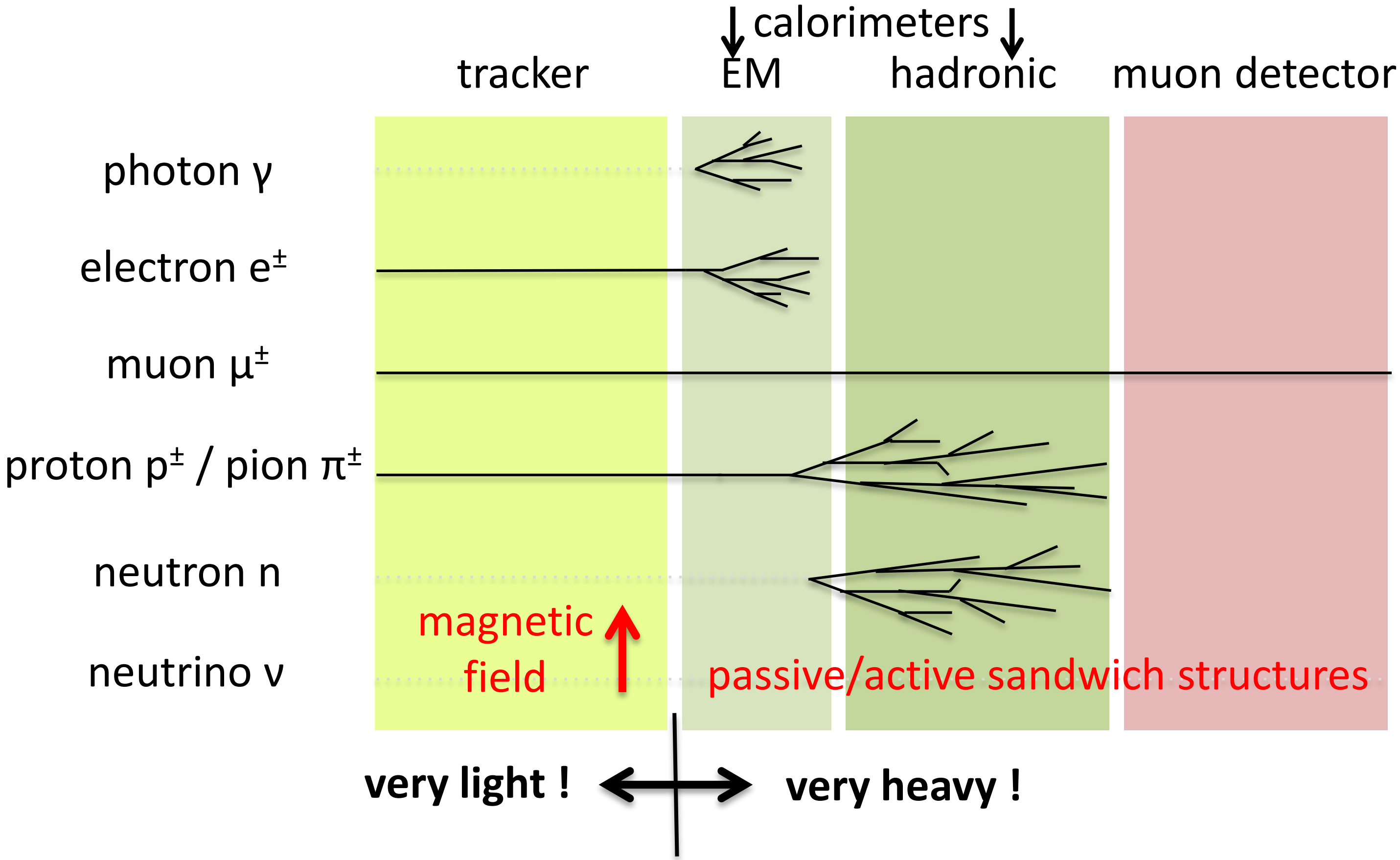
particle detection (1)

Particles make small changes in the material they traverse

- ionisation, atomic effects, nuclear effect <= all very small !

Particles differ in the way they interact with material

- We can use it to identify particle types !



calorimeters

tracker

EM

hadronic

muon detector

photon γ

electron $e^{\pm}$

muon $\mu^{\pm}$

proton $p^{\pm}$ / pion $\pi^{\pm}$

neutron n

neutrino ν

magnetic field

passive/active sandwich structures

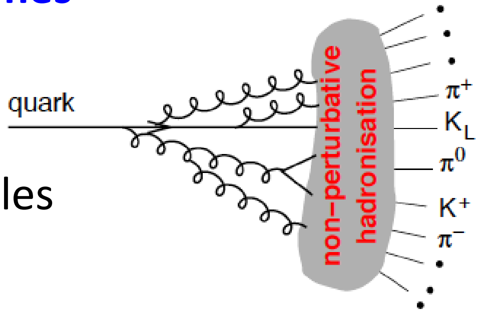
very light ! **very heavy !**

particle detection (2)

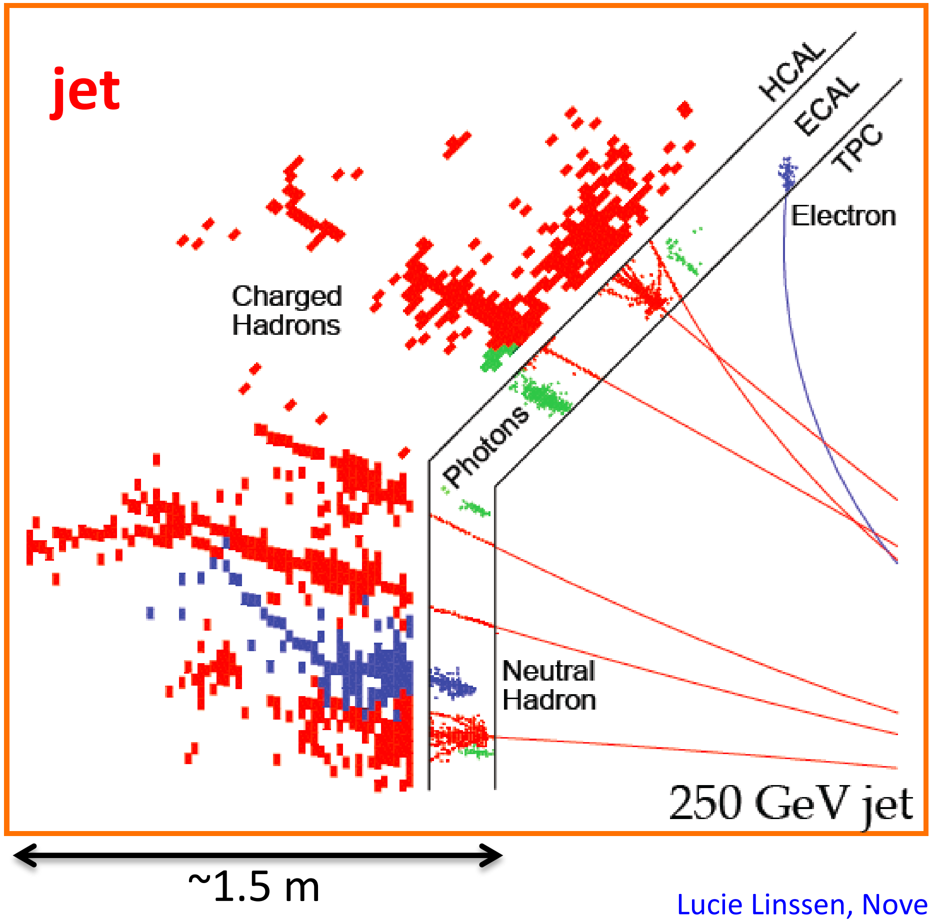
Many of the elementary particles we know have very short life times

- **W, Z, Higgs** (!) and many more

We only see the products of their decay



quarks cannot be observed, as they hadronise in to "jets" of particles

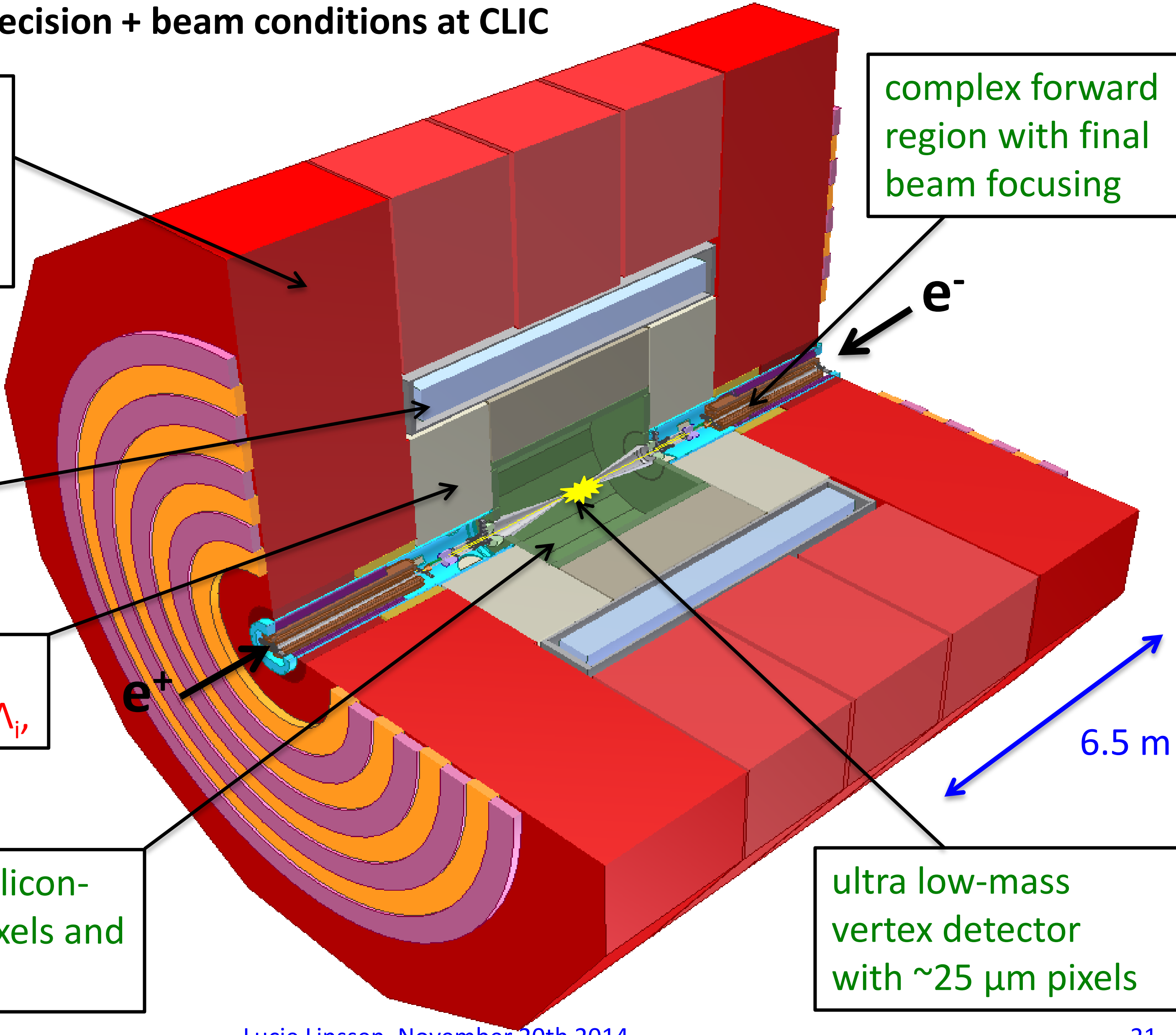


reconstructing the original particles from the visible decay products
=> key ingredient of particle detection

- a detector for CLIC

CLIC detector concept

Combining high precision + beam conditions at CLIC



return yoke (Fe) with detectors for muon identification

complex forward region with final beam focusing

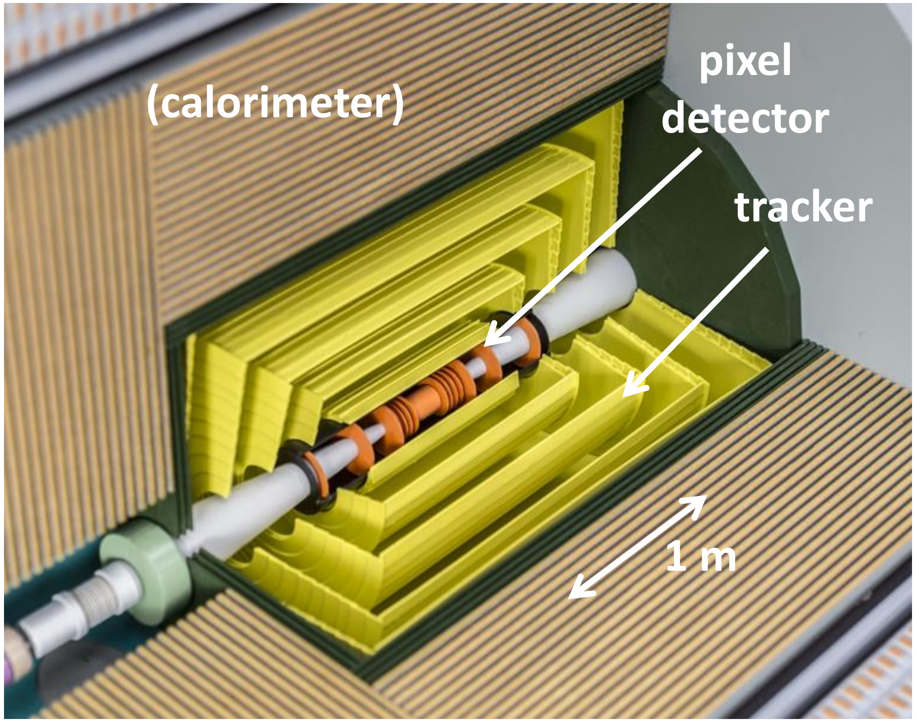
strong solenoid magnet, 4 Tesla

fine grained (PFA) calorimetry, $1 + 7.5\ \Lambda_i$,

main tracker, silicon-based (large pixels and strips)

ultra low-mass vertex detector with ~25 μm pixels

detector technology => “very light”



pixel detector and tracker

measure direction and momentum
of charged particles

have to be extremely accurate and light !

Pixel detector:
- 2 billion pixels
- 3 µm measurement accuracy (1/300 mm)
- 25*25 µm^2 pixels (25 times smaller pixel area at LHC)
  - Pulse height measurement
  - Time measurement to 10 ns
- Ultra-light
  - Power pulsing at 50 Hz (less heat dissipation)
  - Air cooling

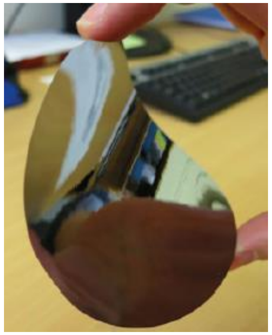
Technologies involved:
- Very thin (50 µm) silicon sensor
- Full electronics circuit per pixel (microelectronics)
- Ultra-light power delivery and cables
- Ultra-light supports, stable with air cooling
- etc….

High-tech R&D
covers many disciplines

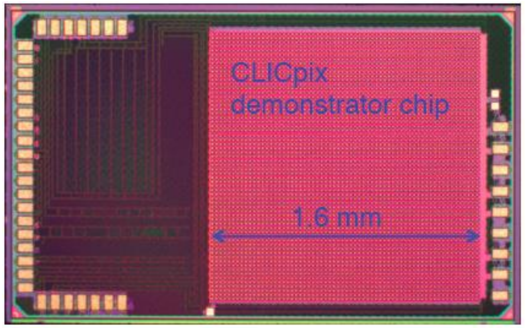
spin-off to other fields
(medical, material science)

pixel detector R&D

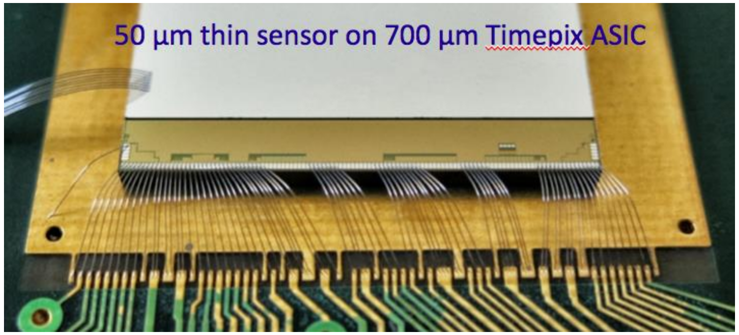
silicon sensor



electronics chip (65 nm)

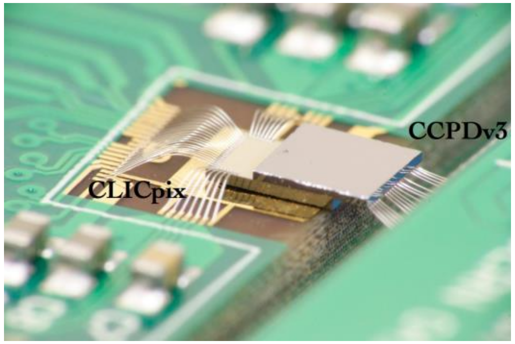


thin electronics + sensor assembly

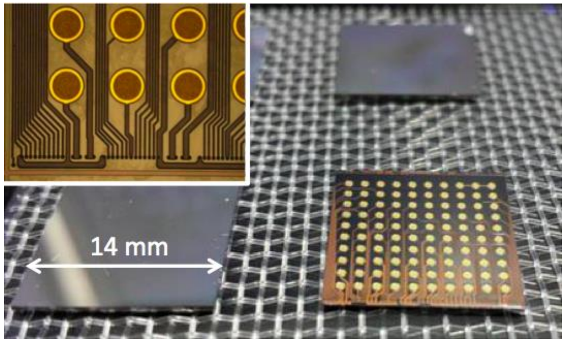


50 µm thin sensor on 700 µm Timepix ASIC

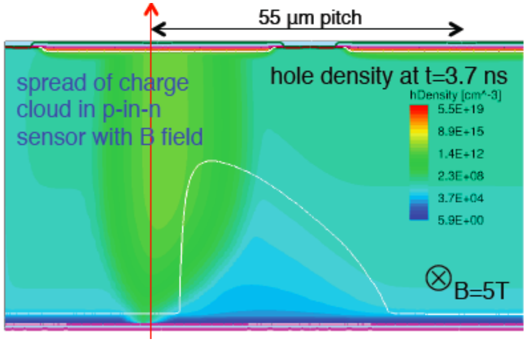
HV-CMOS sensor + CLICpix



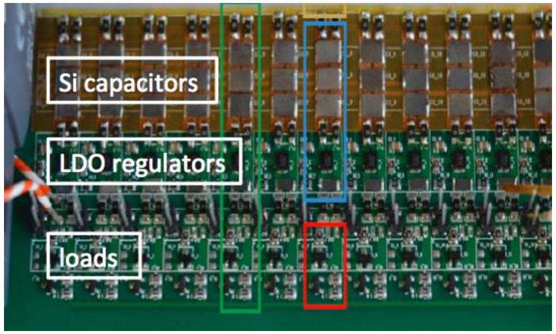
interconnect technology



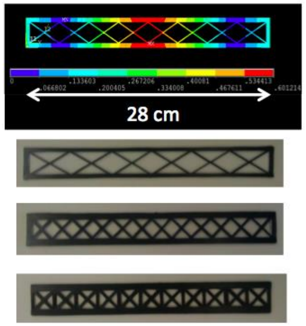
signal simulations



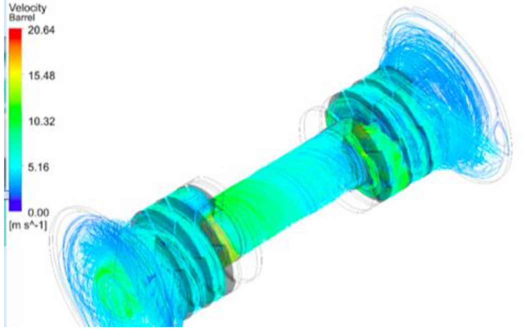
power delivery



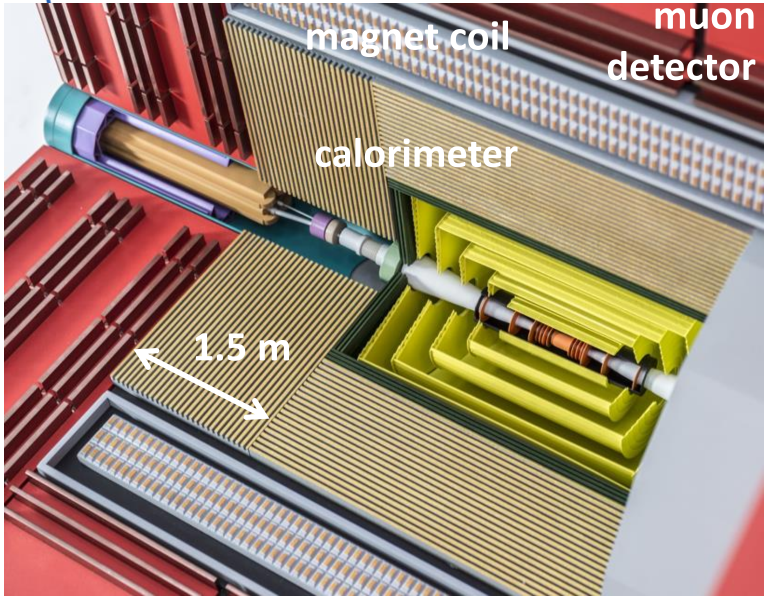
thin supports



air cooling simulations



detector technology => “very heavy”

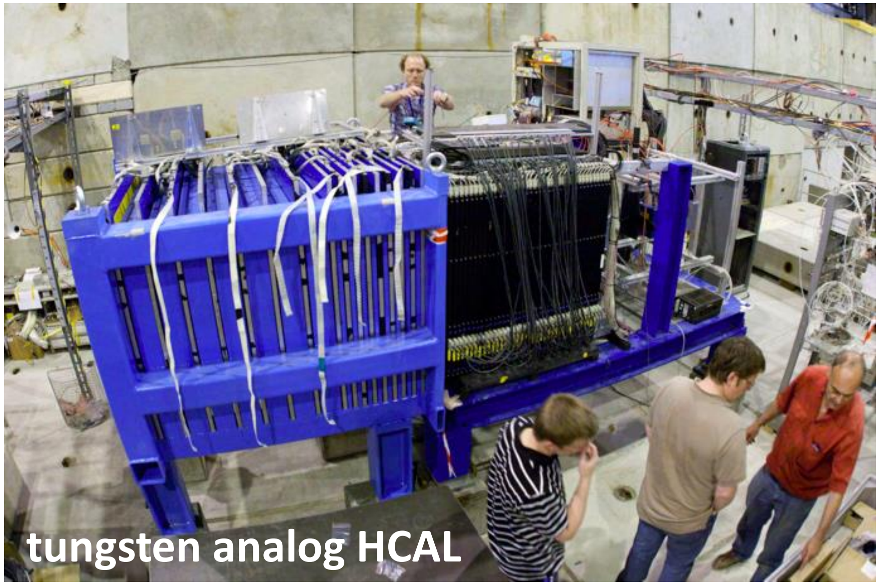


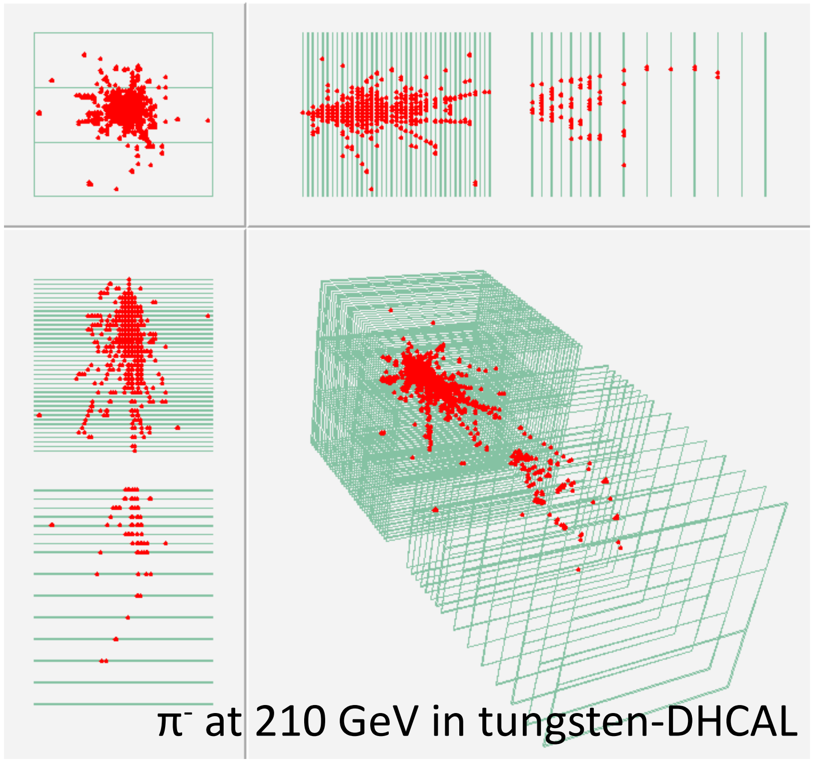
calorimeters

“electromagnetic + hadronic”

particles interact with heavy material => showers
make a sandwich ~60 layers
heavy absorbers + fine-grained detectors

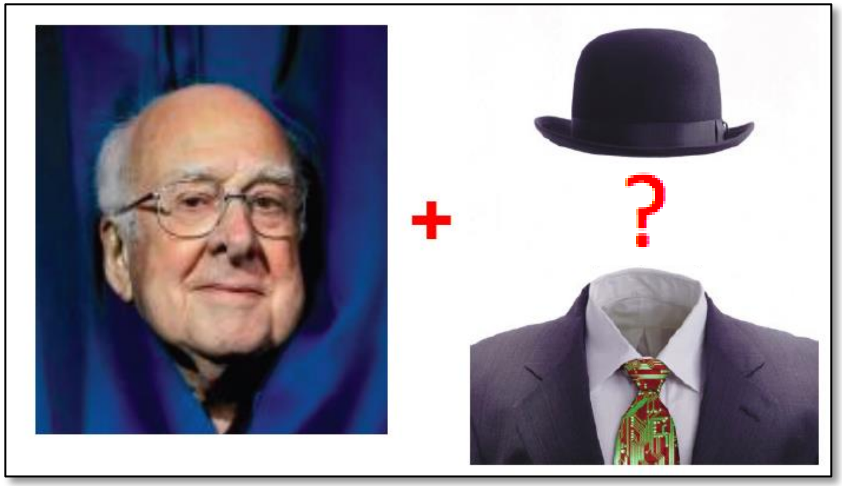
extremely heavy and compact
80 million readout channels (400* larger than LHC)





π^- at 210 GeV in tungsten-DHCAL

- Snapshot of physics at CLIC



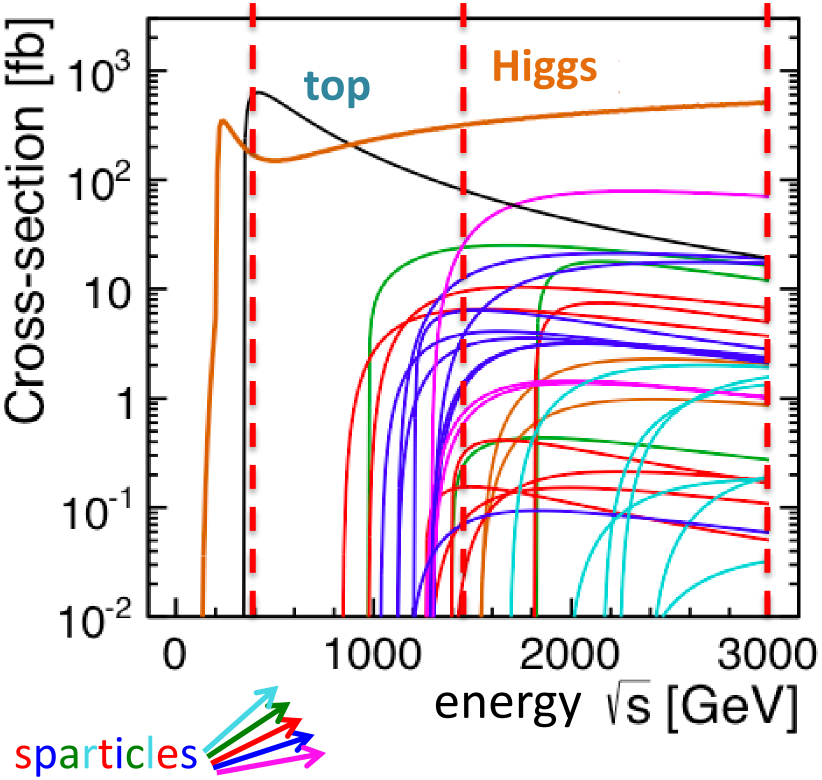
which physics at CLIC?

Accurate measurement of known physics:

- **Higgs** => a completely new type of particle => accuracy needed !
- **Top quark** => the heaviest known particle

Searching for New Physics:

- **Direct searches** => see particle masses up to Mass = energy/2
- **Indirect searches**, via high-precision measurements



sparticles

(in a SUSY physics model)

CLIC in stages => best physics potential

- **~350 GeV** (500 fb^{-1}) :

  precision **Higgs** and **top** physics
- **~1.5 TeV** (1.5 ab^{-1}):

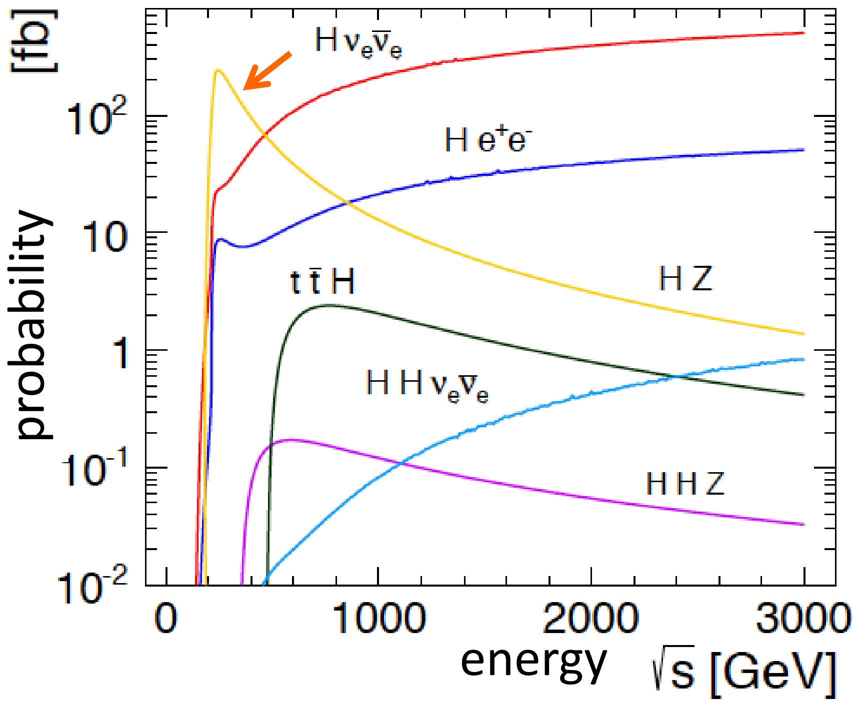
  New Physics, precision **Higgs**
- **~3 TeV (**2 ab^{-1}):

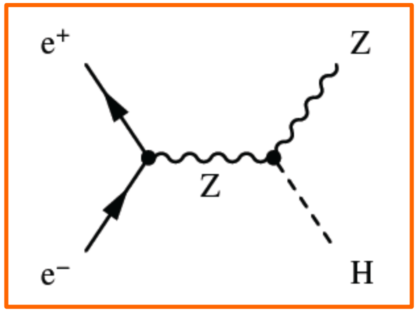
  New Physics, precision **Higgs**

LHC results will tell what's the best scenario

Higgs physics (1)

Higgs production at CLIC



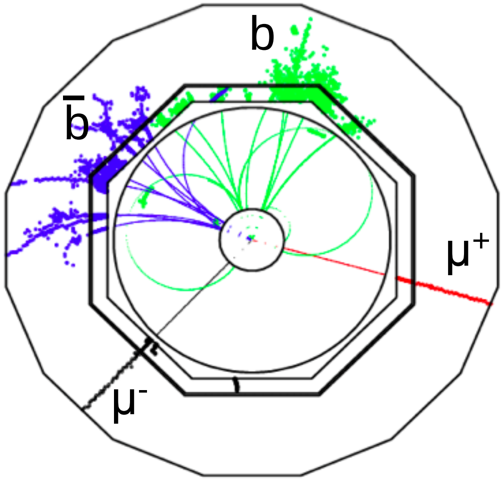


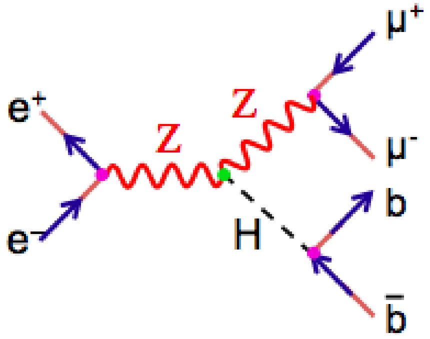
Very clean process

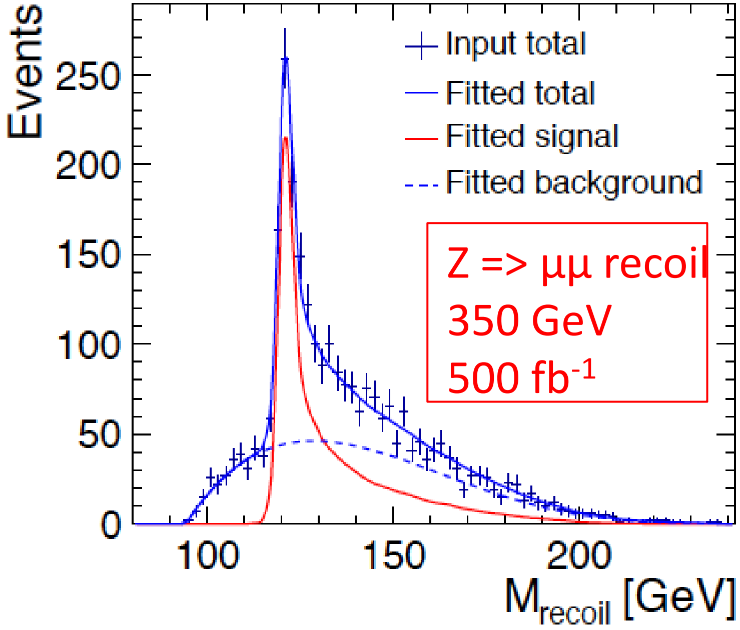
Can "see" Higgs by looking at Z only !

Model-independent Higgs measurement !

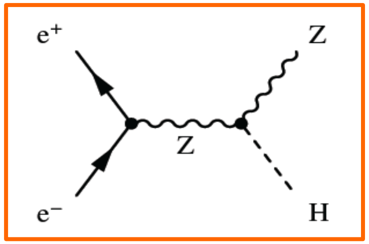
*can also "see" **invisible Higgs** decays: 1% accuracy*

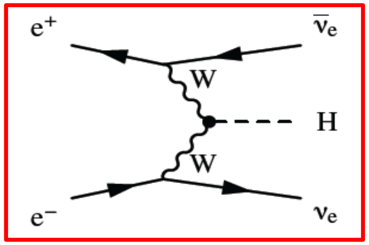


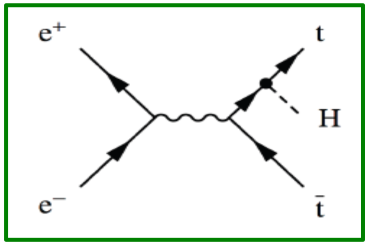




Higgs coupling to mass

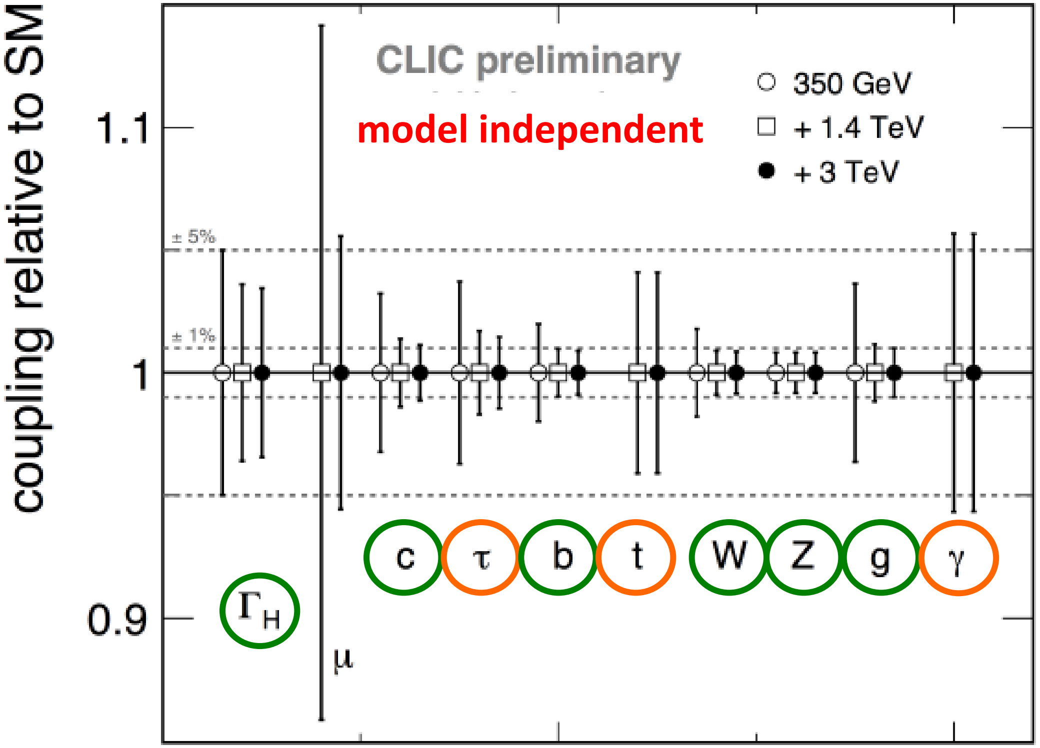






combining all Higgs information

production + decay



○ much more accurate than HL-LHC

○ similar accuracy as HL-LHC

Note: contrary to (HL-)LHC, CLIC results are model-independent

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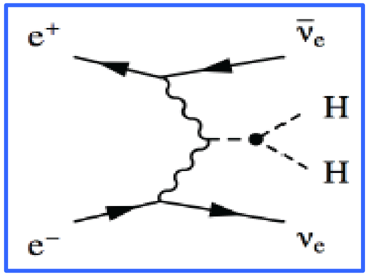


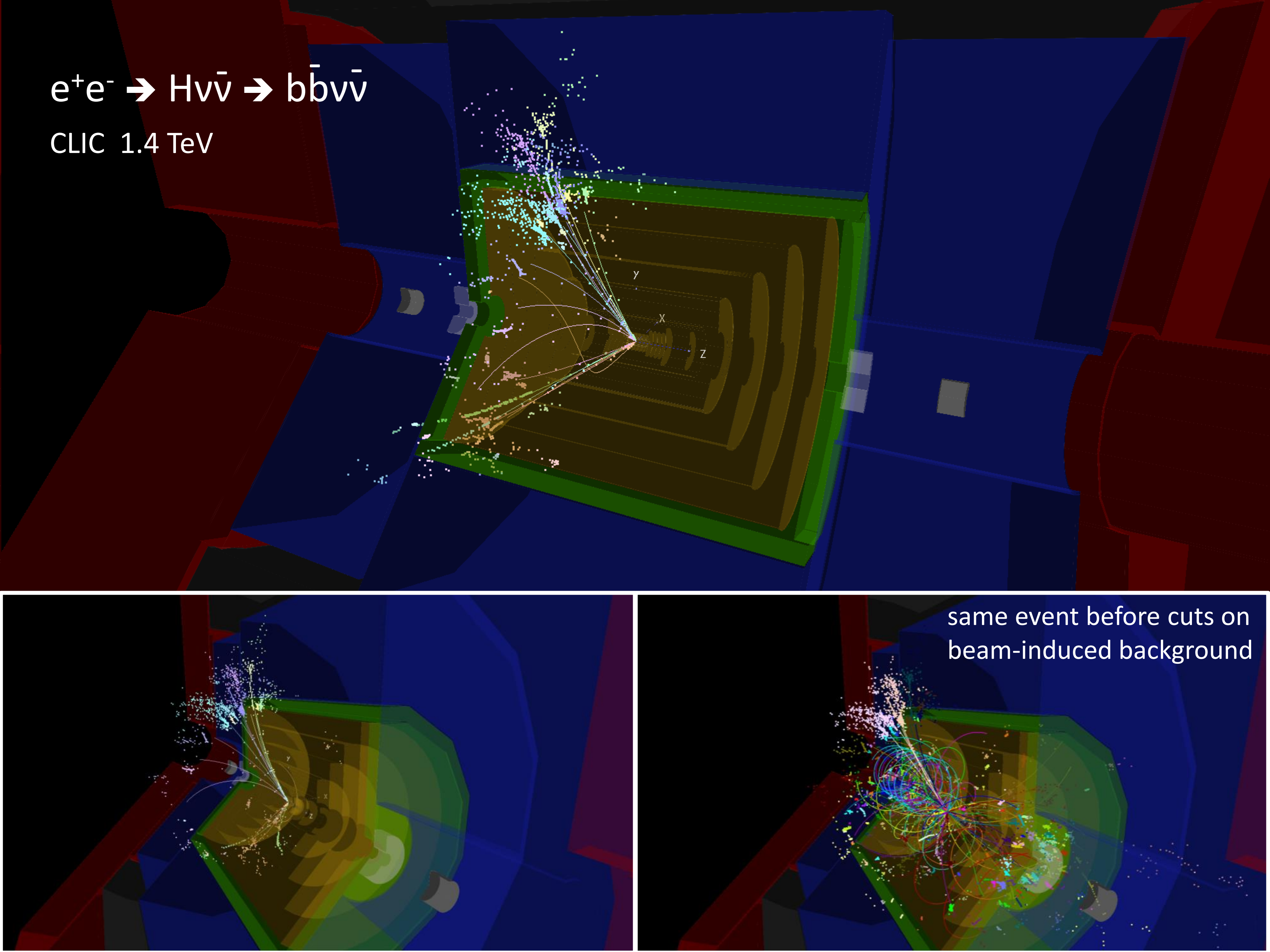
Higgs self-coupling H=> HH

Gives access to understanding the Higgs field

Requires high energies => coupling g_{HHH} to 24% at 1.4 TeV, 10% at +3 TeV

$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

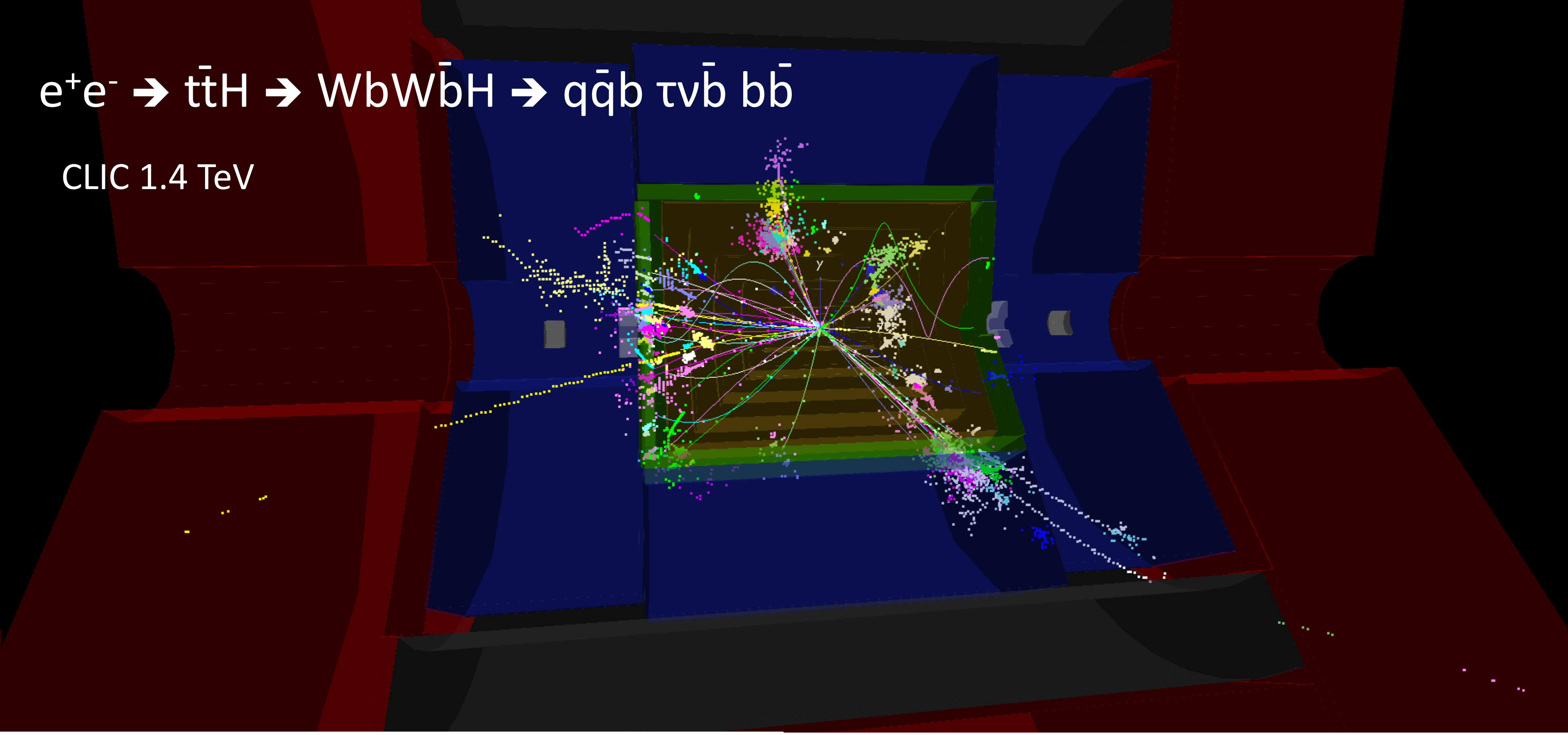
CLIC 1.4 TeV

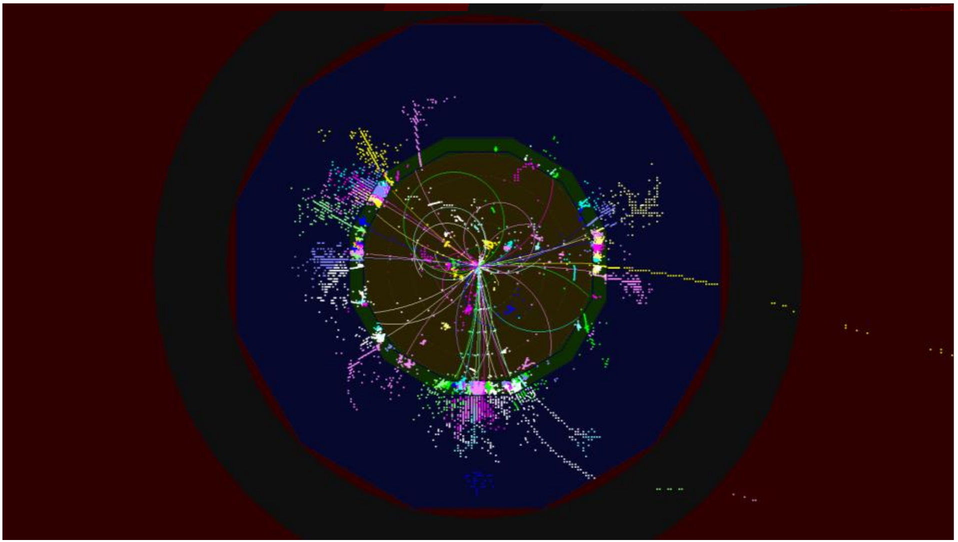


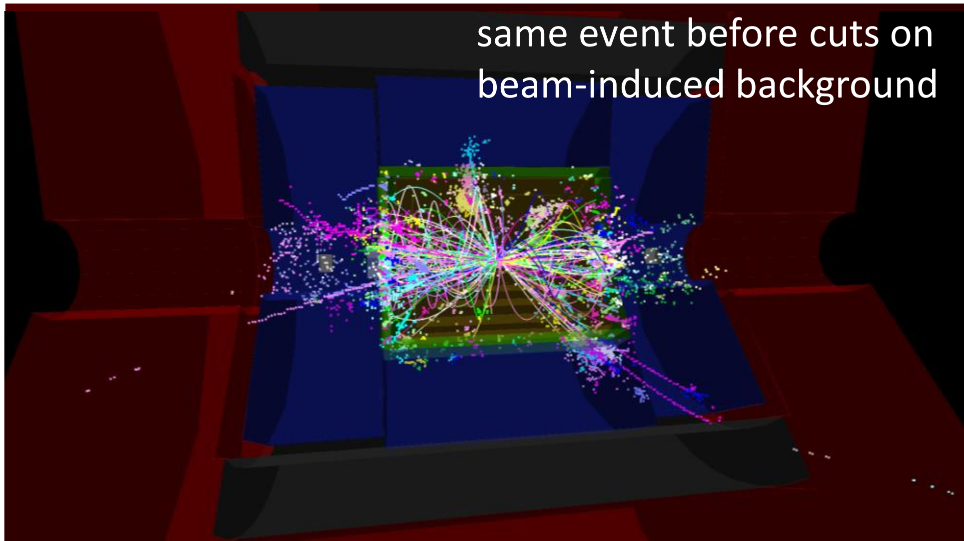
same event before cuts on beam-induced background

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV







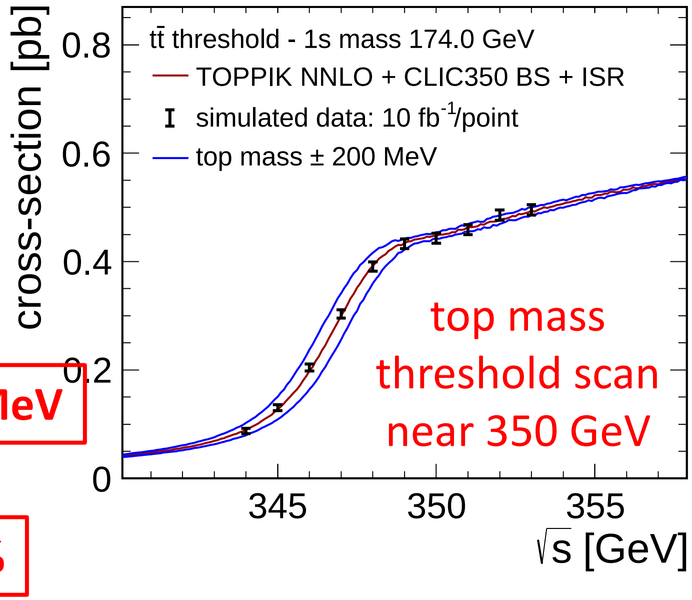
same event before cuts on beam-induced background

snapshot of other physics at CLIC

CLIC physics potential:

Accurate measurement of known physics:
- **Higgs**
- **Top quark**

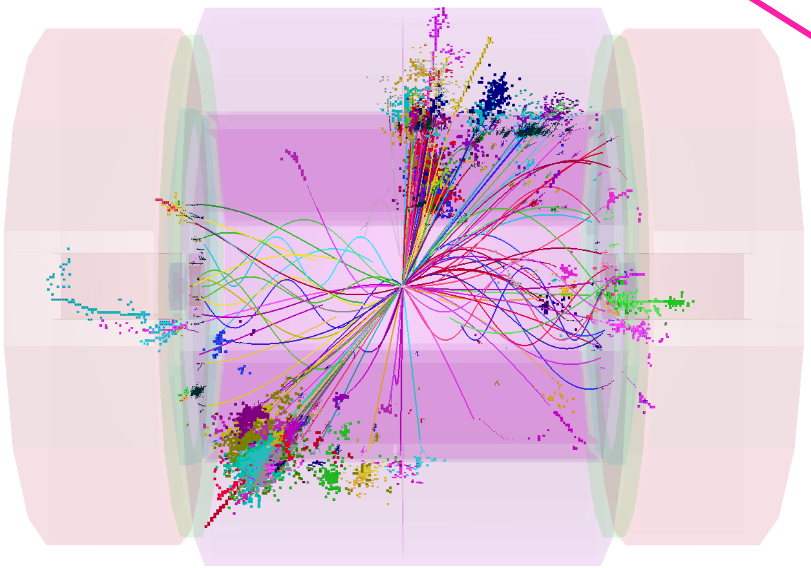
Searching for New Physics:
- **Direct searches**
- **Indirect searches**



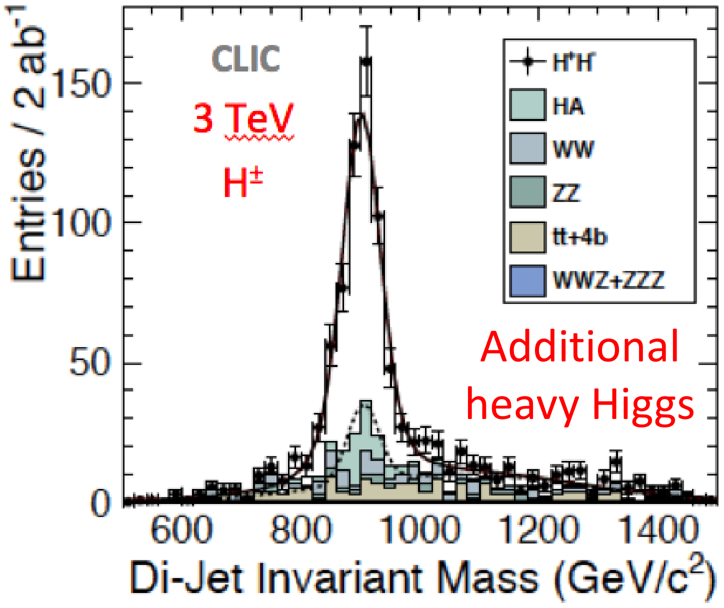
top mass threshold scan near 350 GeV

Δ*m* < 100 MeV

Δ*m*/*m* = 0.3%



$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8$ jets



3 TeV

H$^\pm$

Additional heavy Higgs

- collaboration

who is working on CLIC ?

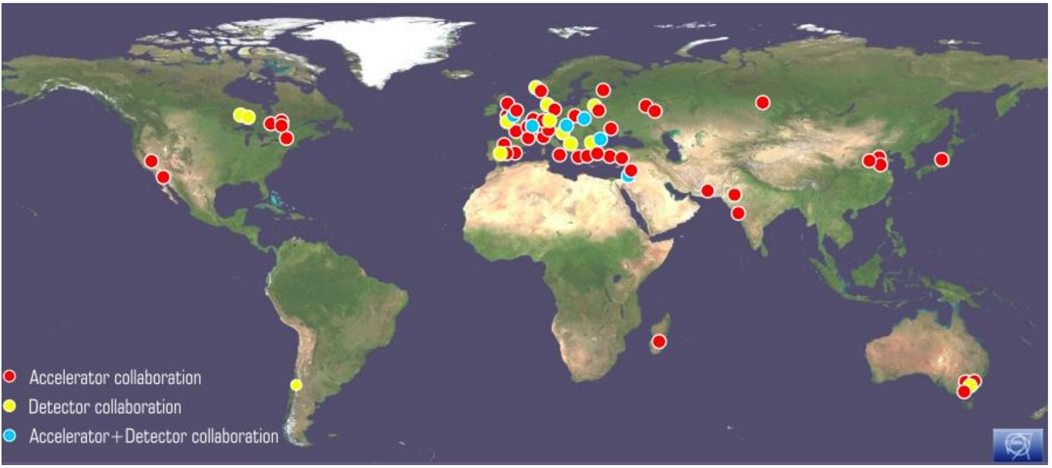
Global collaboration:

>60 institutes from >**25 countries** collaborate on the CLIC study

Collaboration set up in a semi-formal way
Each institute agrees to work on specific items:

- CLIC+CTF3 accelerator development http://clic-study.org/
- Detector development and physics studies http://clicdp.web.cern.ch/

CLIC provides many **opportunities for technology R&D**
Excellent **learning environment for young professionals**



- what’s next ?

options for the future

European countries determine together: **"European strategy for particle physics"**

Last update of the strategy in 2013**:**

- Highest priority is **LHC** running, and High-Luminosity LHC upgrade (**HL-LHC**)

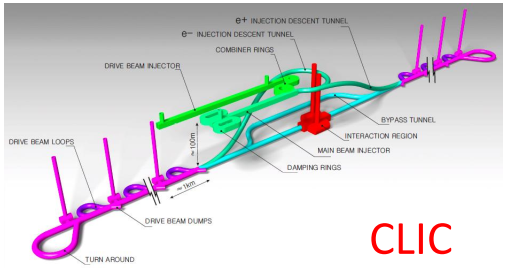
Other priorities listed:

- Design studies for a **future collider at CERN after the LHC**
  - **FCC** (see next talk) and **CLIC**
- **Participation in global projects**:
  - High-energy colliders (e.g. possible projects ILC-Japan and CEPC-China)
  - Neutrino physics (with a possible large facility in the USA)
- **Other projects involving CERN accelerators** (diversity)

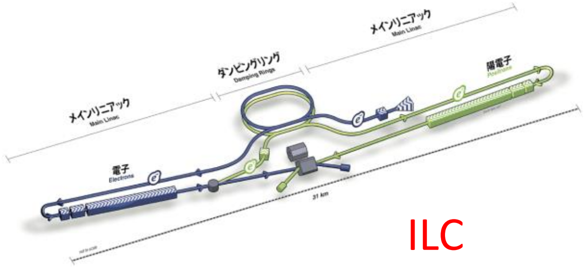
Next update of European strategy: 2018-2019

Physics indications from LHC => may help to decide what is the best facility to build

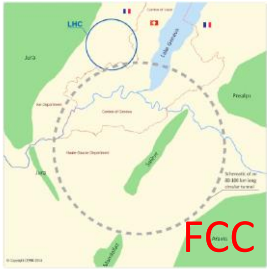
=> we need to be ready for the decision !



CLIC



ILC

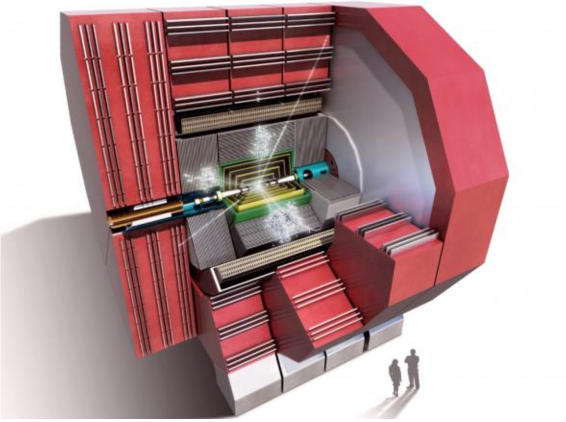


FCC

CEPC

CLIC plans

Activities foreseen in the coming ~5 years



- **New CLIC staged baseline design**

  optimised for cost and energy consumption
- **High-gradient structures**

  development + increase of test capacity
- **Industrialisation of components**

  cost drivers
- **System tests**

  at CTF3, ATF and FACET
- Further **component developments**
- **Collaboration**

  with light sources and other projects (ILC, FCC..)

- **New optimised detector design**
- **Detector R&D**

  demonstrators of main technical challenges
- **Physics studies**

  following LHC results
- **Collaboration**

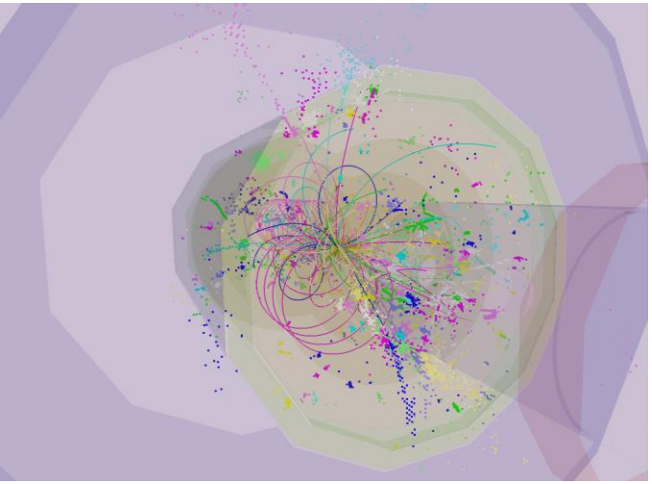
  with other projects (ILC, HL-LHC, FCC..)

Many years of R&D have been invested in CLIC
Large-scale tests have confirmed the technology
No show stoppers identified
CLIC is currently the only option to offer multi-TeV e^+e^- collisions

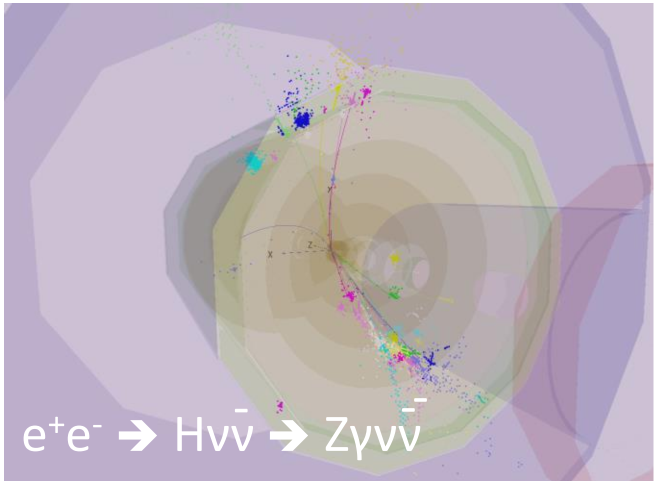
CLIC offers a wealth of possible physics measurements
Very high accuracies can be achieved
A powerful tool to address the open questions in particle physics

Very **active R&D collaborations** for accelerator and physics/detector

join us at



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

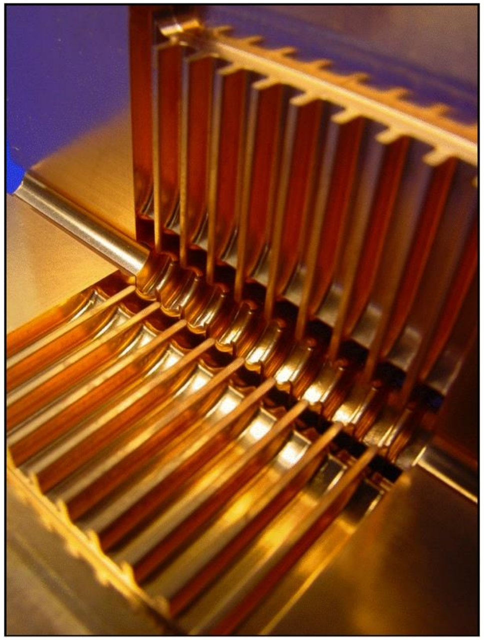


With many thanks to the members of the CLIC/CLICdp collaborations for providing material for this talk

SPARE SLIDES

ILC and CLIC in just a few words

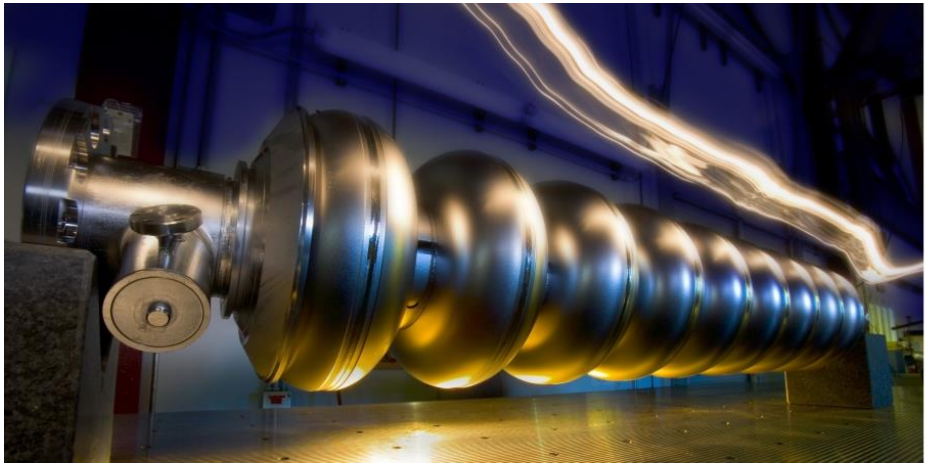
CLIC



- 2-beam acceleration scheme, at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders
Luminosities: few 10^{34} cm^{-2}s^{-1}

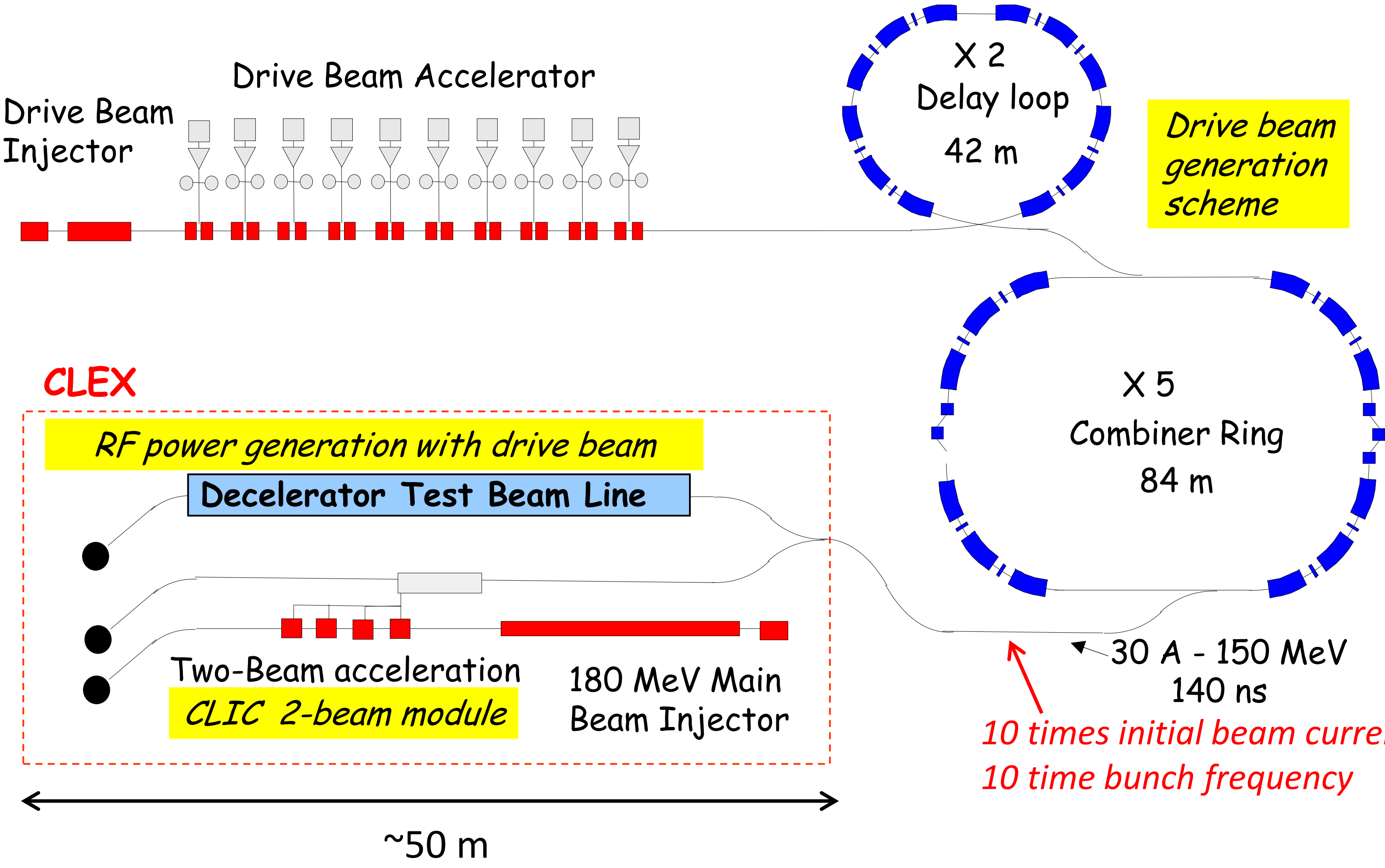
ILC



- Superconducting RF cavities
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

CLIC test facility (CTF3)

a small CLIC to test basic principles and key performance parameters



Drive beam generation scheme

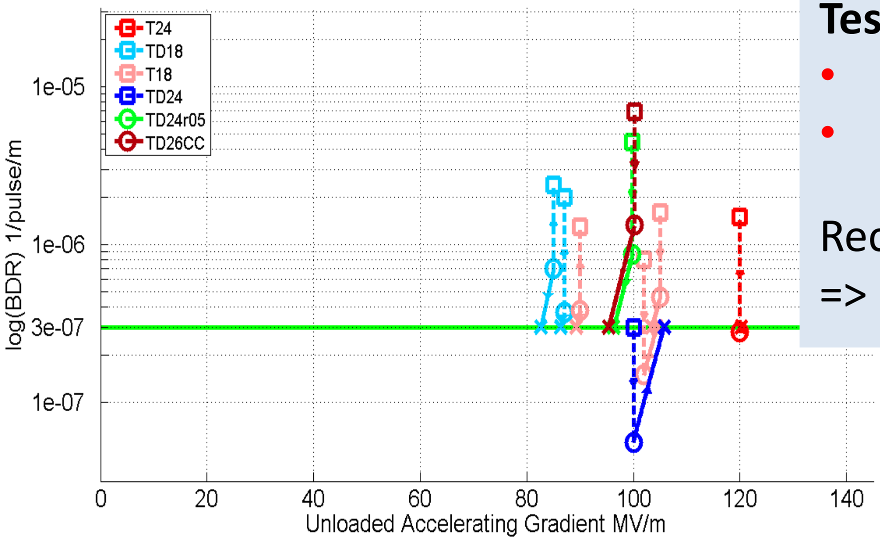
RF power generation with drive beam

CLIC 2-beam module

10 times initial beam current
10 time bunch frequency

[link to animation showing drive beam generation]

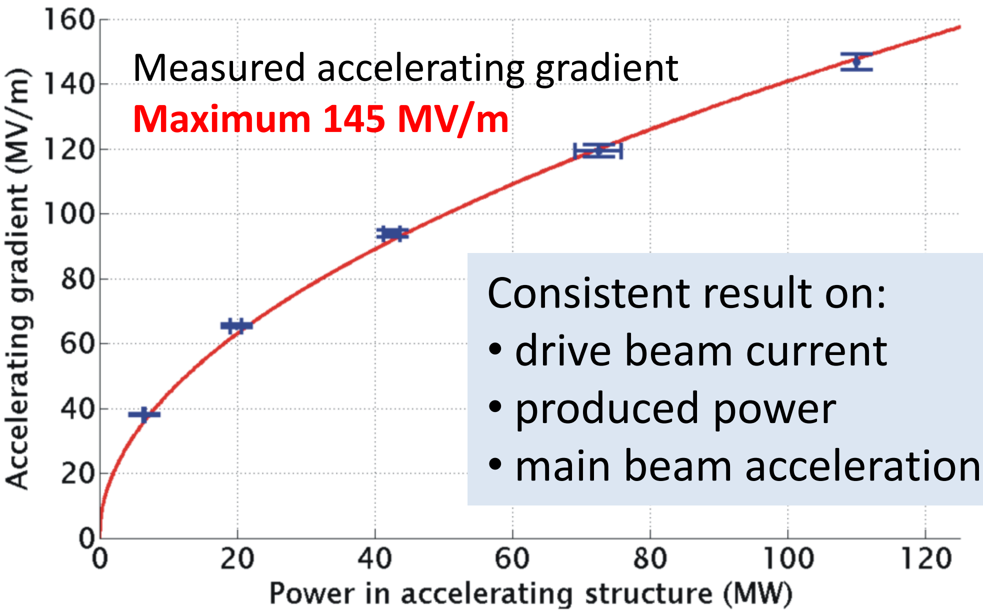
some CLIC achievements



Tests of various acceleration structures, requiring:

- ≥100 MV/m
- breakdown rate smaller than $3*10^{-7}$

Recent structure tests **with beam loading** in CTF3,
=> no adverse effect on breakdown rate (preliminary)

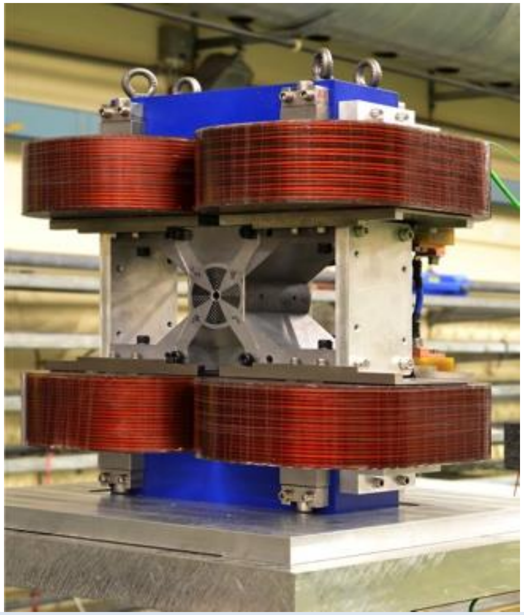


Measured accelerating gradient

Maximum 145 MV/m

Consistent result on:

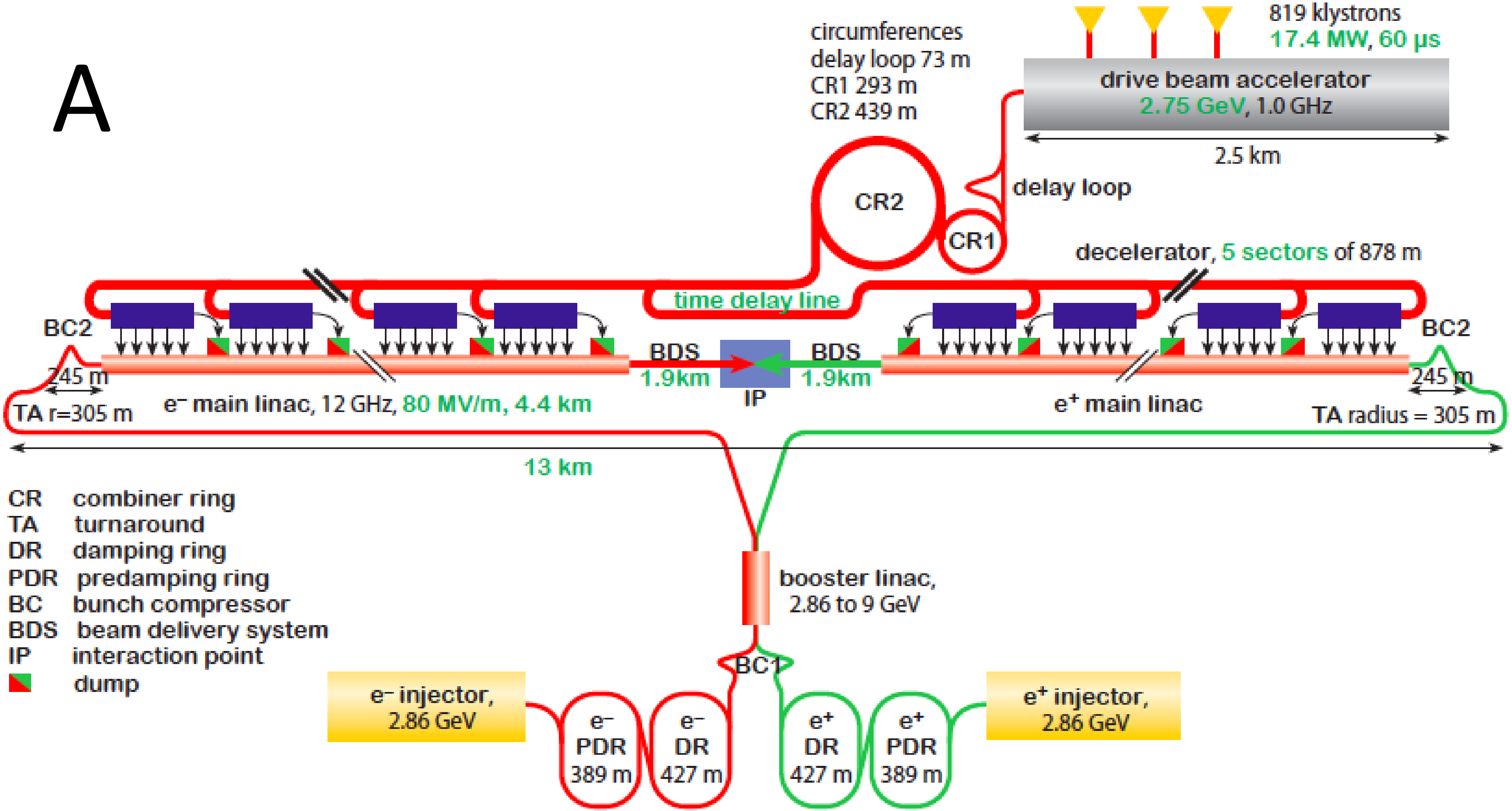
- drive beam current
- produced power
- main beam acceleration



Strong **final focus quadrupole** (short prototype). Compatible with ultra-high mechanical stability.

CLIC layout at 500 GeV

A



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV. (scenario A)

parameters, scenario A

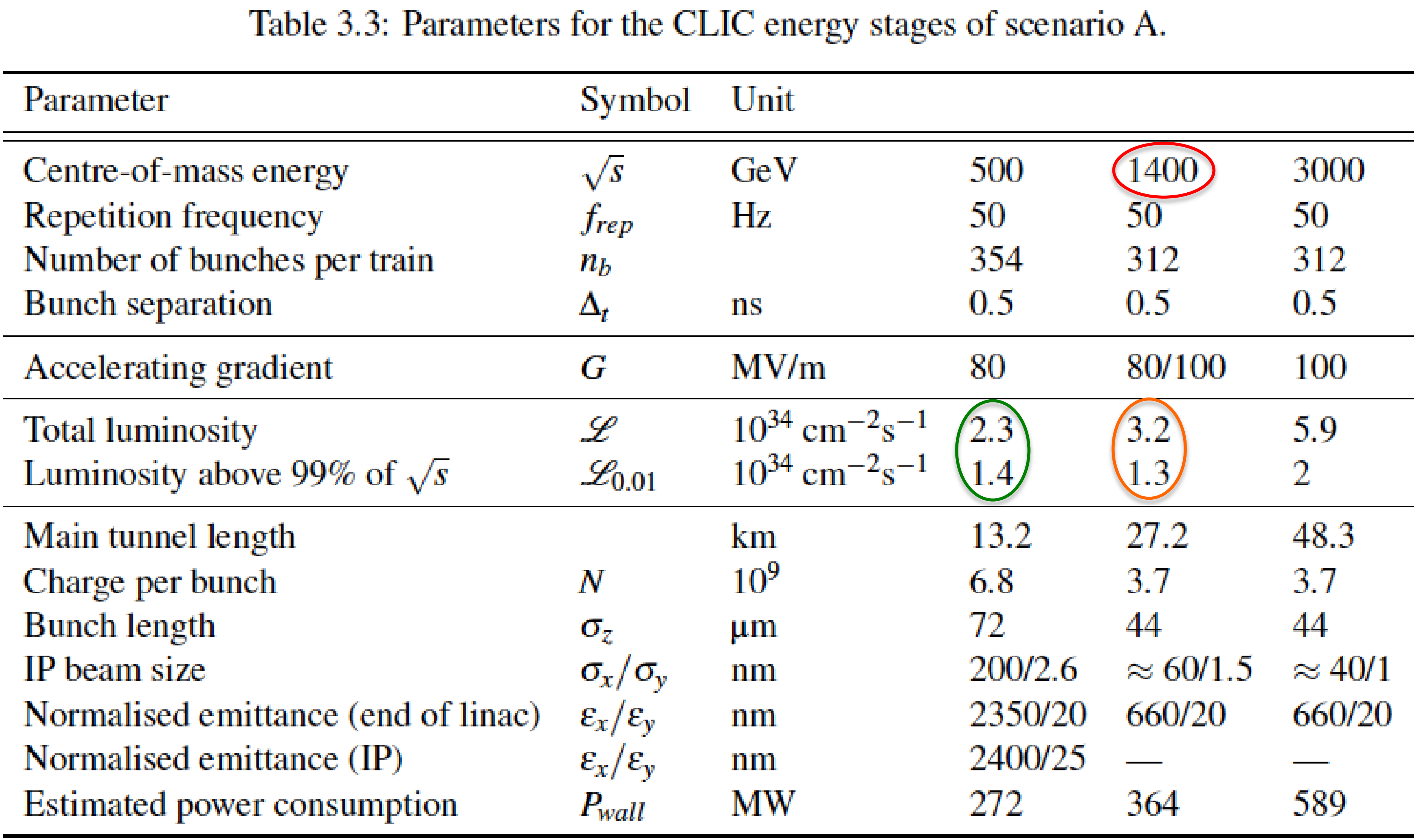


Table 3.3: Parameters for the CLIC energy stages of scenario A.

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\approx$ 60/1.5	$\approx$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

parameters, scenario B

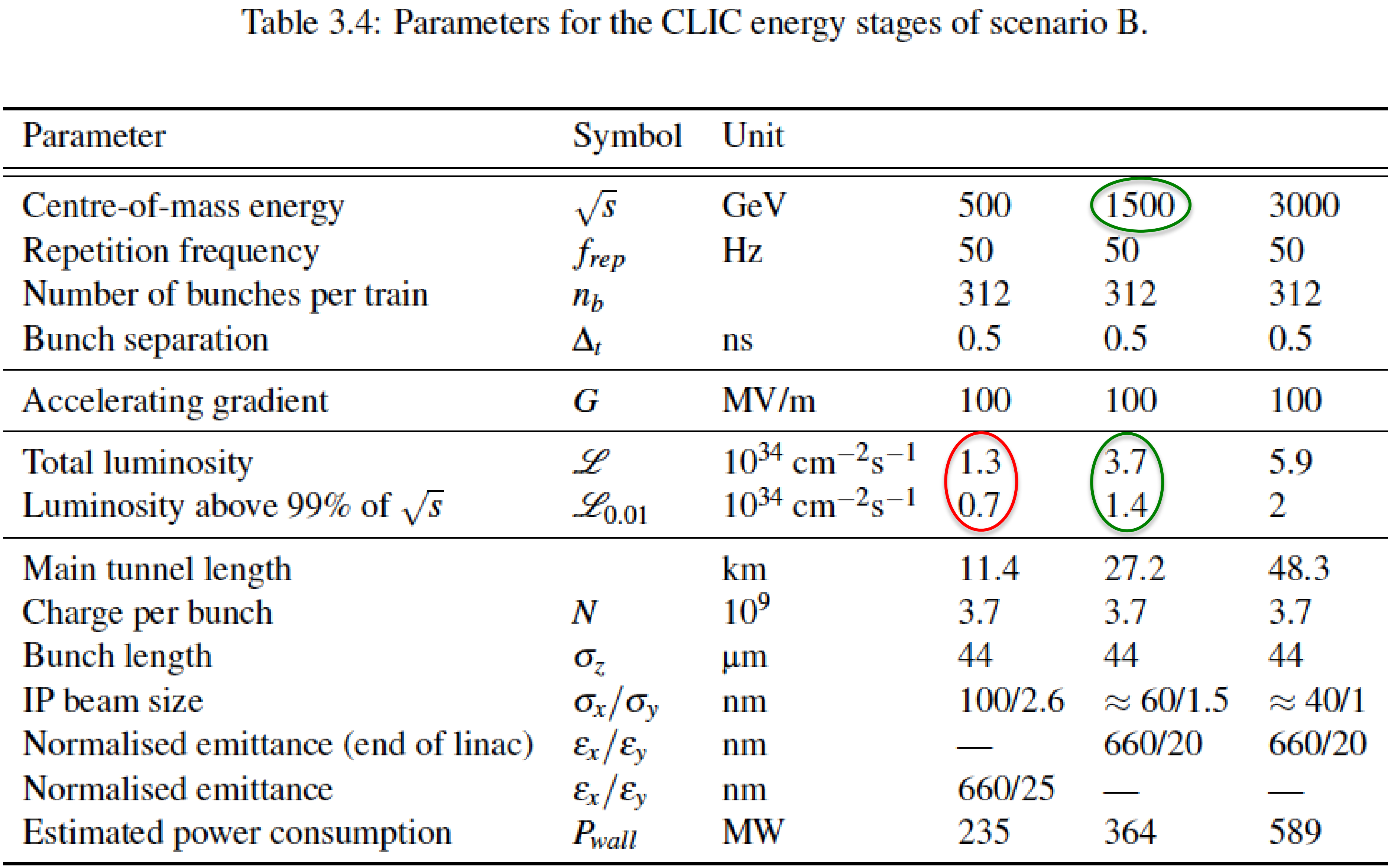


Table 3.4: Parameters for the CLIC energy stages of scenario B.

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\approx$ 60/1.5	$\approx$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

integrated luminosity

Possible scenarios “A” and “B”, these are **“just examples”**

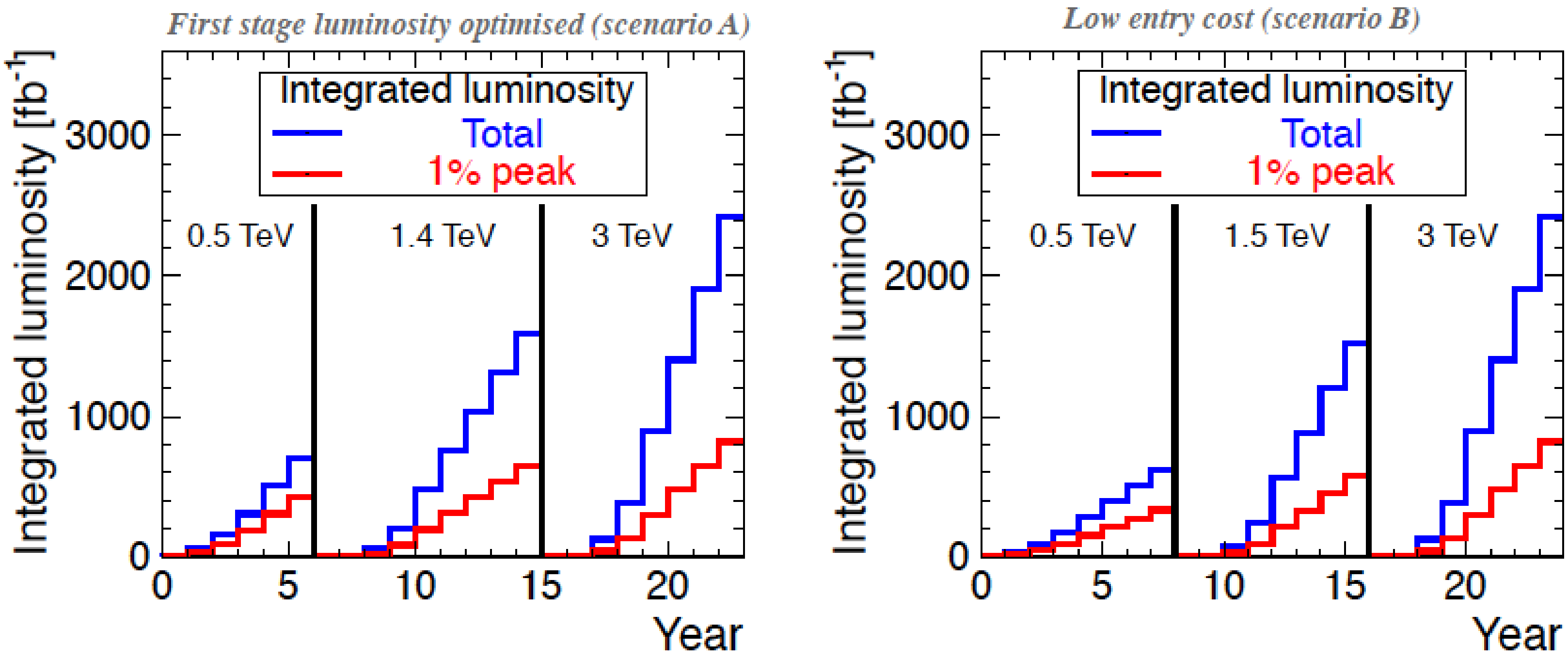


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

=> CLIC can provide an evolving and rich physics program over several decades

CLIC power and energy consumption

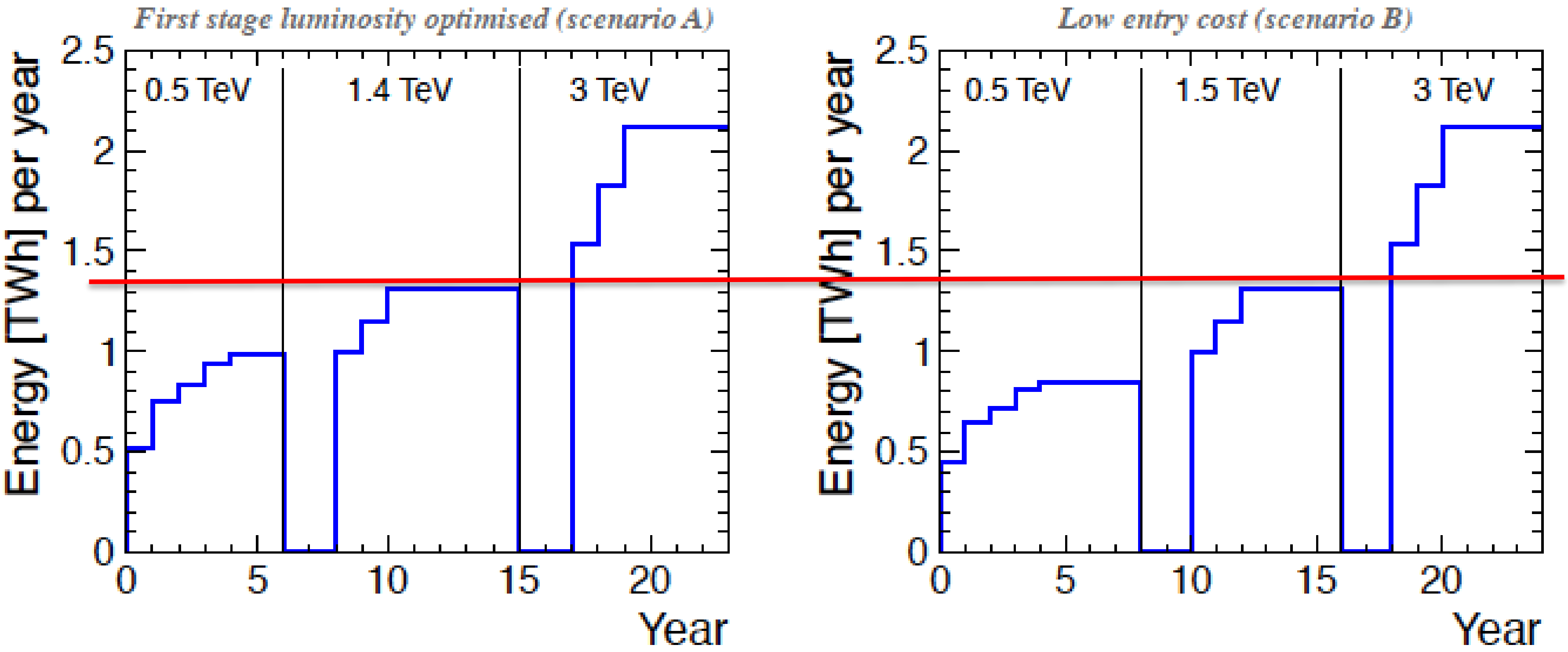


Fig. 5.7: Development of yearly energy consumption for staging scenarios A (left) and B (right).

CLIC power and energy consumption

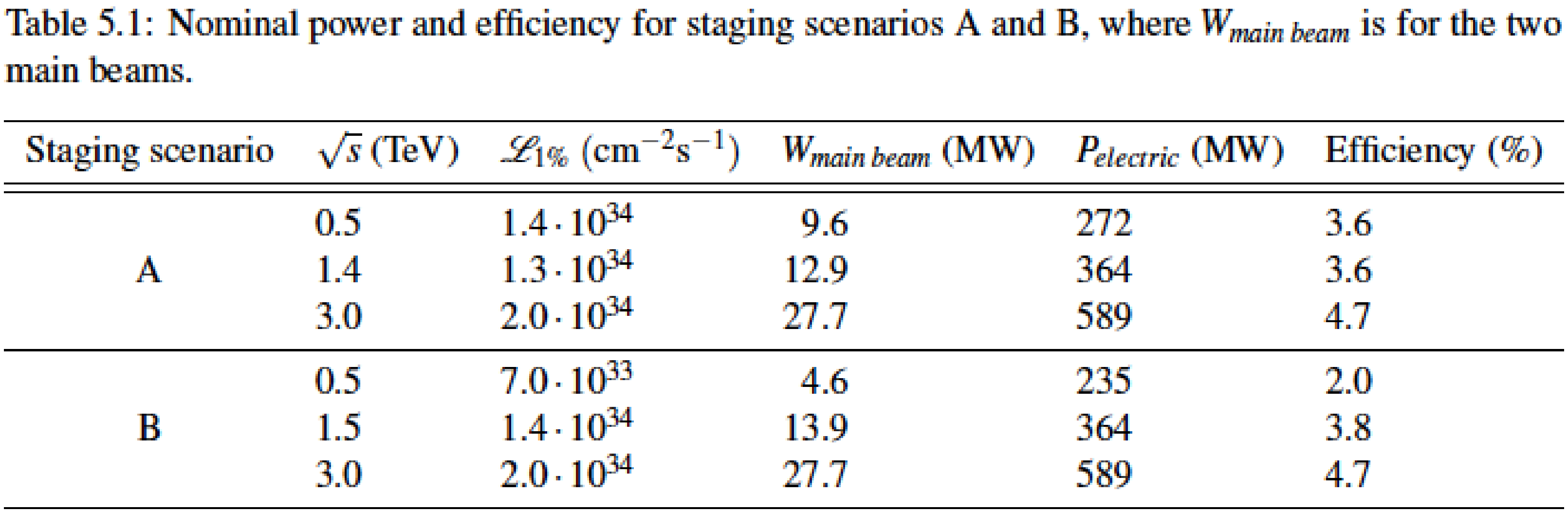


Table 5.1: Nominal power and efficiency for staging scenarios A and B, where $W_{main\ beam}$ is for the two main beams.

Staging scenario	$\sqrt{s}$ (TeV)	$\mathscr{L}_{1\%}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$W_{main\ beam}$ (MW)	$P_{electric}$ (MW)	Efficiency (%)
A	0.5	$1.4 \cdot 10^{34}$	9.6	272	3.6
	1.4	$1.3 \cdot 10^{34}$	12.9	364	3.6
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7
B	0.5	$7.0 \cdot 10^{33}$	4.6	235	2.0
	1.5	$1.4 \cdot 10^{34}$	13.9	364	3.8
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7

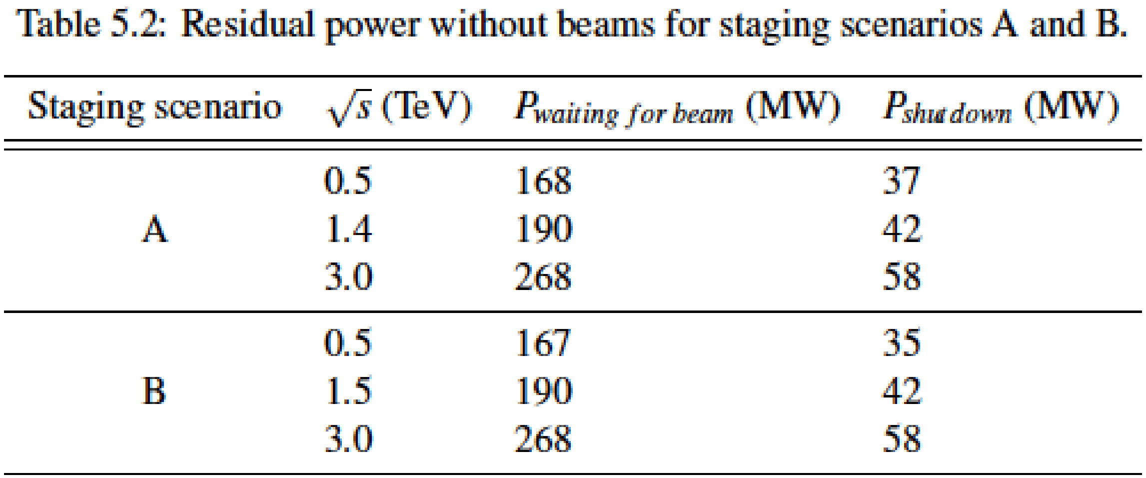


Table 5.2: Residual power without beams for staging scenarios A and B.

Staging scenario	$\sqrt{s}$ (TeV)	$P_{waiting\ for\ beam}$ (MW)	$P_{shut\ down}$ (MW)
A	0.5	168	37
	1.4	190	42
	3.0	268	58
B	0.5	167	35
	1.5	190	42
	3.0	268	58

CLIC physics aims => detector needs

- ★ **momentum resolution:**

  e.g. Smuon endpoint

  Higgs recoil mass, Higgs coupling to muons

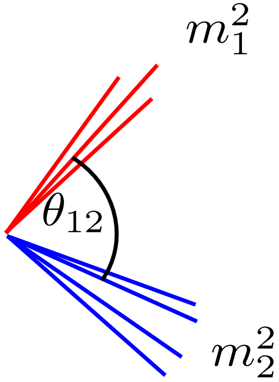
$$\boxed{\sigma_{p_T}/p_T^2 \sim 2\times 10^{-5}\ \mathrm{GeV}^{-1}}$$

- ★ **jet energy resolution:**

  e.g. W/Z/h di-jet mass separation

$$\boxed{\frac{\sigma_E}{E} \sim 3.5 - 5\ \%}$$

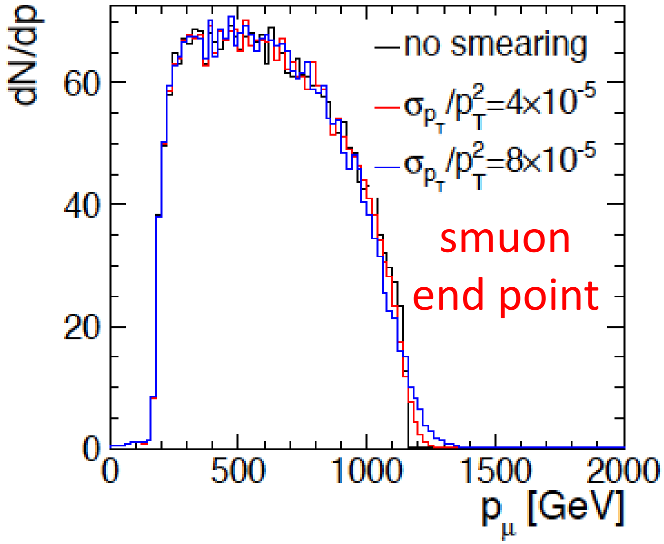
(for high-E jets)



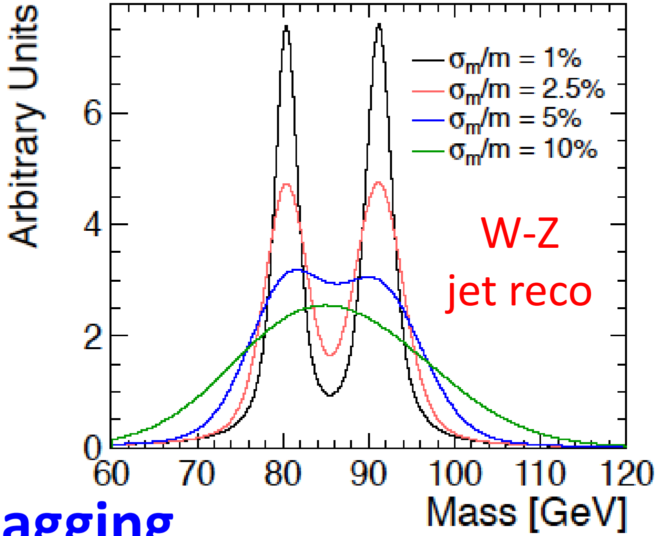
- ★ **impact parameter resolution:**

  e.g. c/b-tagging, Higgs BR

$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$



smuon end point

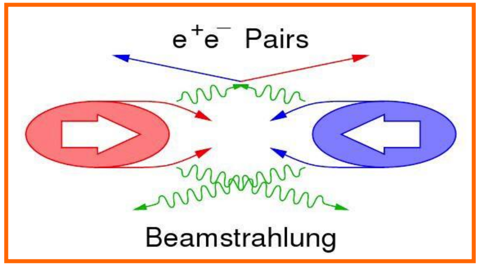


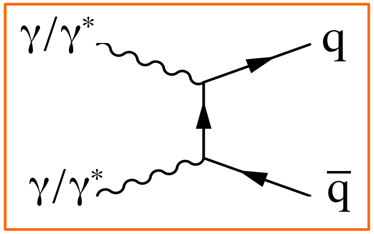
W-Z jet reco

- ★ **angular coverage, very forward electron tagging**

+ requirements from CLIC beam structure and beam-induced background

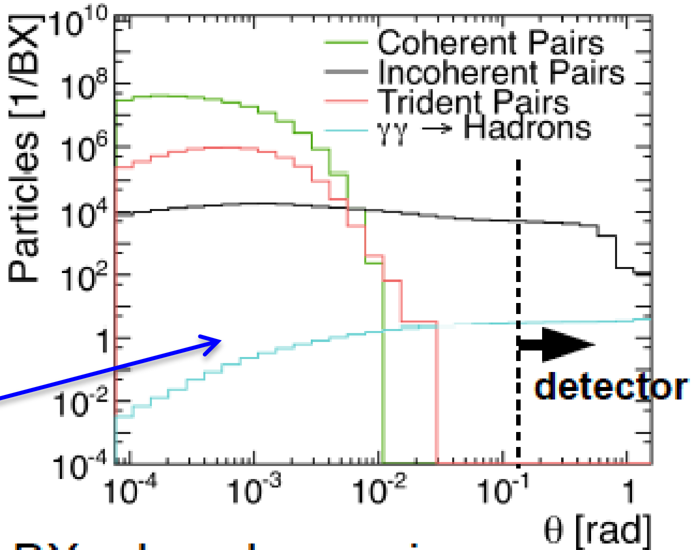
CLIC machine environment





Beam-beam background at IP:

- Small beams => very high E-fields
  - **Beamstrahlung**
    - Pair-background
      - High occupancies
    - γγ to hadrons
      - Energy deposits



BX = bunch crossing

Beamstrahlung ➔ important energy losses right at the interaction point

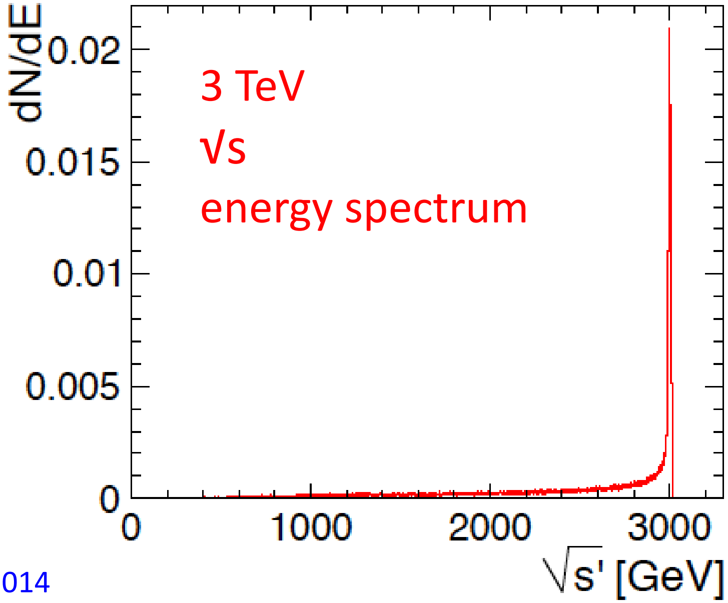
E.g. full luminosity at 3 TeV:

5.9×10^{34} cm^{-2}s^{-1}

Of which in the 1% most energetic part:

2.0×10^{34} cm^{-2}s^{-1}

Most physics processes are studied well above production threshold => profit from full luminosity

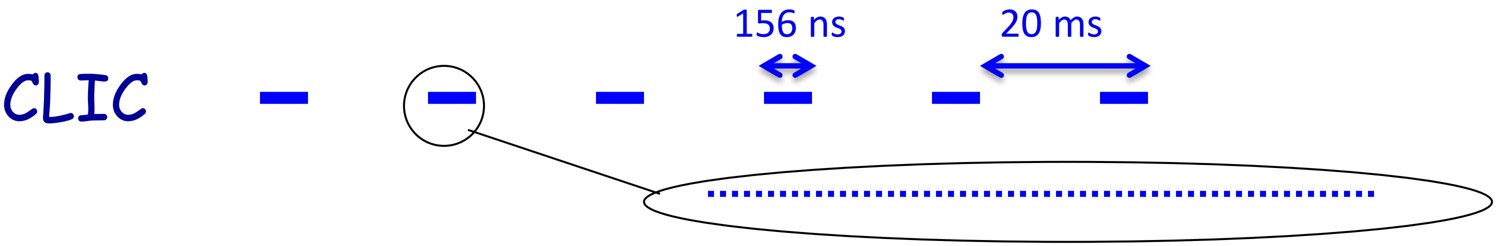


CLIC machine environment

	CLIC at 3 TeV
L (cm^{-2}s^{-1})	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
Duty cycle	0.00078%
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Drives timing requirements for CLIC detector

very small beam size



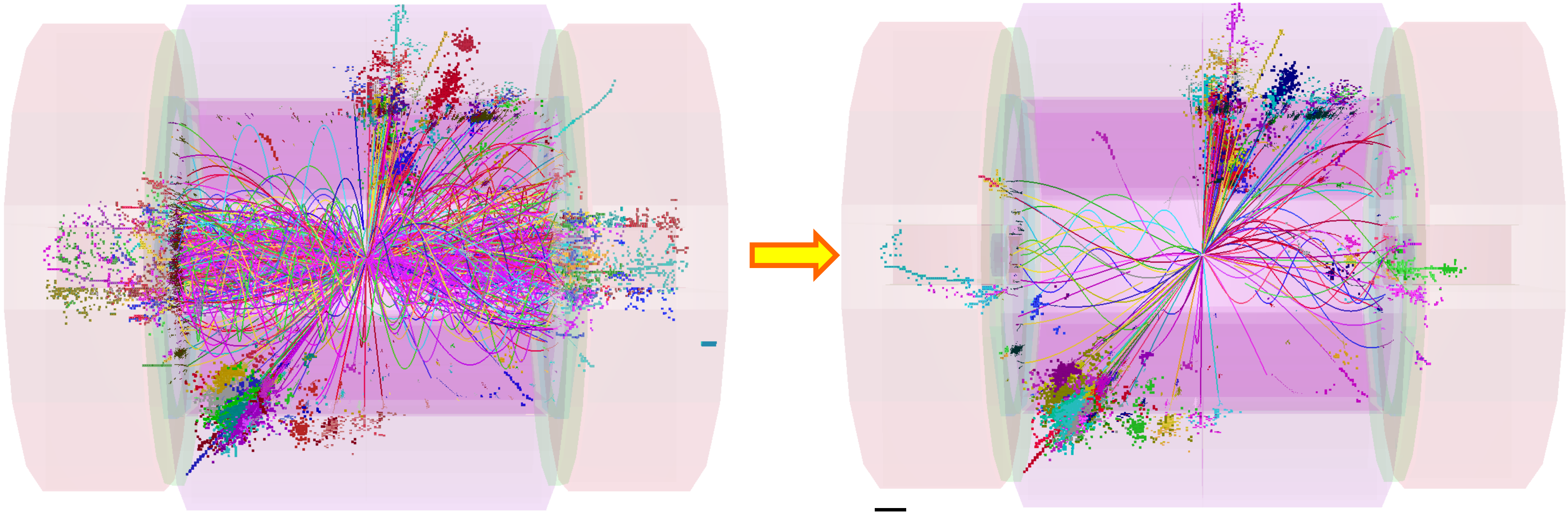
1 train = 312 bunches, 0.5 ns apart

- not to scale -

combined p_T and timing cuts

1.2 TeV

100 GeV



$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8 \text{ jets}$$

1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

comparison CLIC ⇔ LHC detector

In a nutshell:

CLIC detector:

- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (1ns, 10ns)
- **“No” issue of radiation damage (10^{-4} LHC)**
  - Except small forward calorimeters
- **Beam crossings “sporadic”**
- **No trigger, read-out of full 156 ns train**

LHC detector:

- **Medium-high precision:**
  - Very precise ECAL (CMS)
  - Very precise muon tracking (ATLAS)
- **Overlapping minimum-bias events:**
  - High background rates, high energies
  - High occupancies
  - Can use vertex separation in z
  - Need precise time-stamping (25 ns)
- **Severe challenge of radiation damage**
- **Continuous beam crossings**
- **Trigger has to achieve huge data reduction**

calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

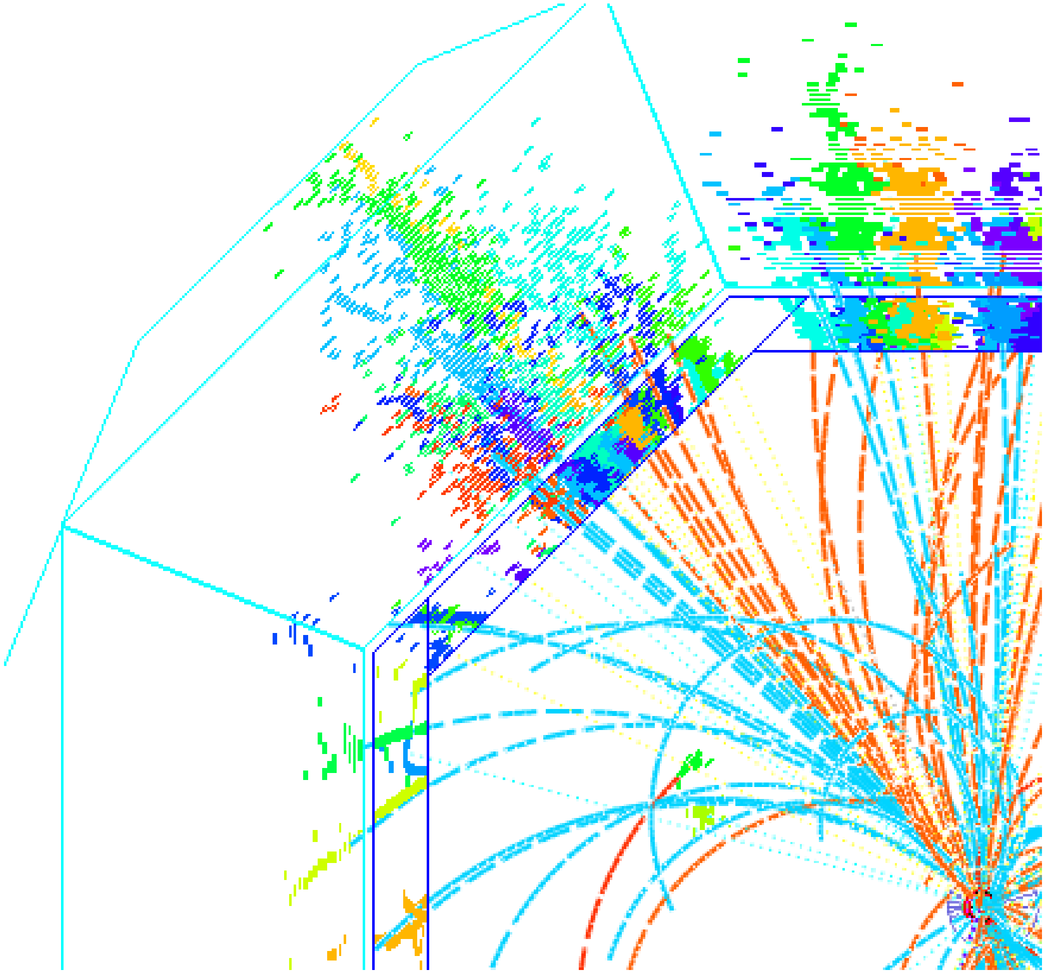
What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutral hadrons

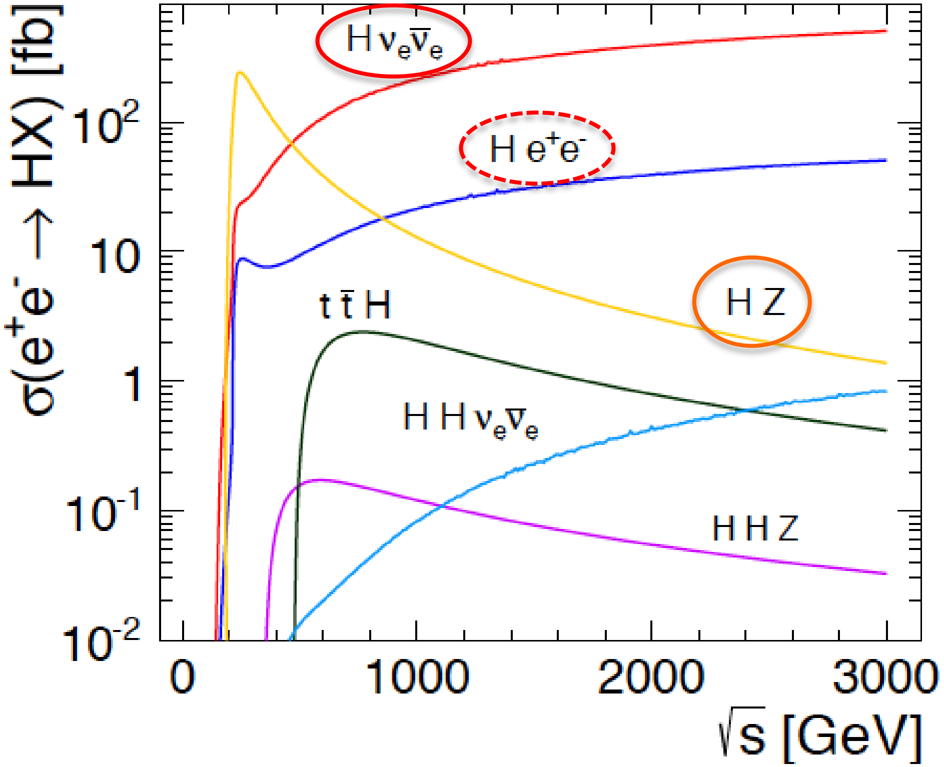
↓

Always use the best info you have:
60% => tracker ☺ ☺
30% => ECAL ☺
10% => HCAL ☹

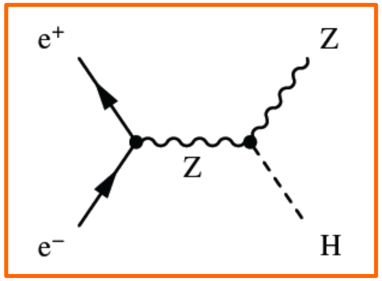
Hardware + software !



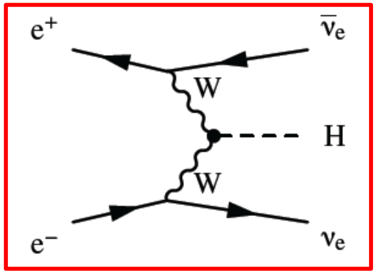
Higgs physics at CLIC



Dominant processes:



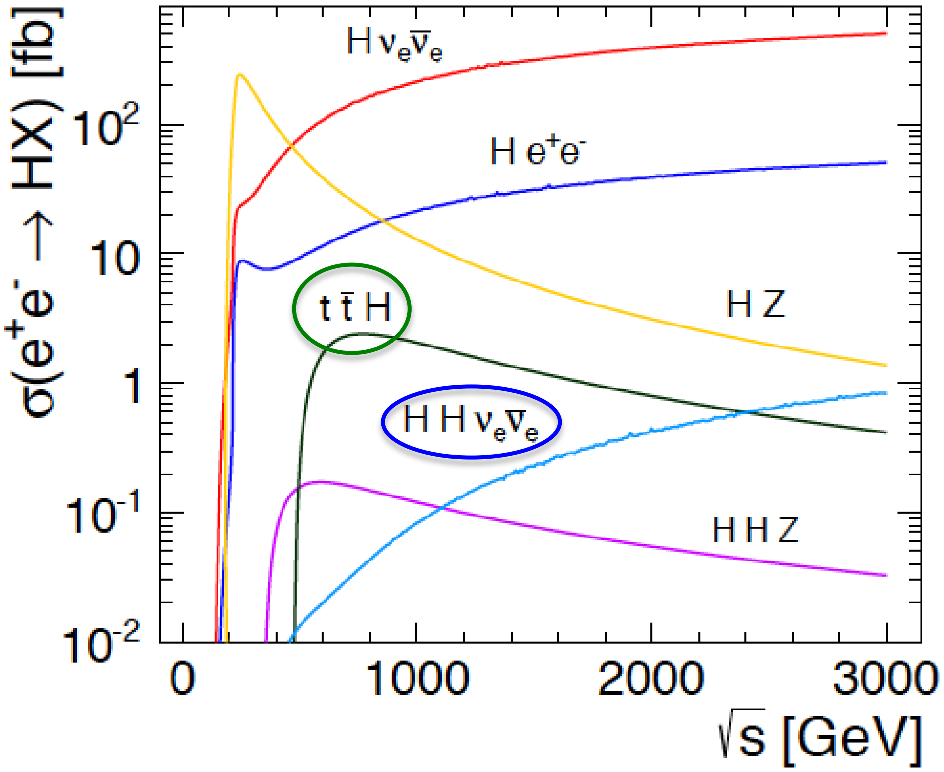
Higgsstrahlung decreases with √s



W(Z) - fusion increases with √s

	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{\text{int}}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

Higgs physics at CLIC

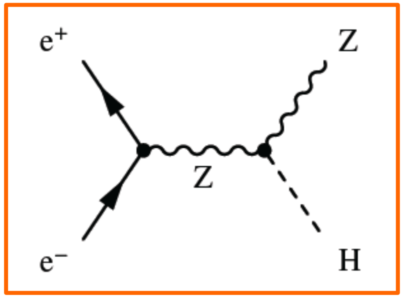


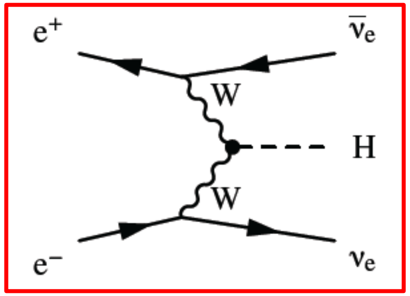
Higgs-Strahlung: $e^+e^- \to ZH$
- Measure H from Z-recoil mass
- Model-independent meas.: m_H, σ
- Yields absolute value of g_{HZZ}

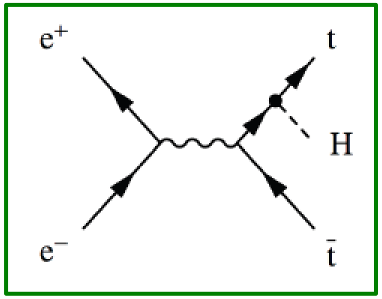
WW fusion: $e^+e^- \to H\nu_e\nu_e$
- Precise cross-section measurements in ττ, μμ, qq, … decay modes
- Profits from higher $\sqrt{s}$ ($\gtrsim$350 GeV)

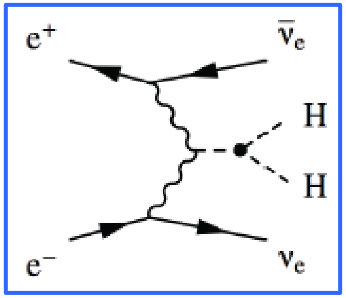
Radiation off top-quarks: $e^+e^- \to ttH$
- Measure top Yukawa coupling
- Needs $\sqrt{s} \gtrsim 700$ GeV

Double-Higgs prod.: $e^+e^- \to HH\nu_e\nu_e$
- Measure tri-linear self coupling
- Needs high $\sqrt{s}$ ($\gtrsim$1.4 TeV)









Higgs physics at CLIC

- ★ Expected precision for CLIC programme
  - Evaluated using full G4 simulations/full reconstruction ⇨ global fit

Coupling	350 GeV	+1.4 TeV	+3.0 TeV
HZZ	0.8 %	0.8 %	0.8 %
HWW	1.8 %	0.9 %	0.9 %
Hbb	2.0 %	1.0 %	0.9 %
Hcc	3.2 %	1.4 %	1.1 %
Hgg	3.6 %	1.1 %	1.0 %
Htt	3.5 %	1.5 %	1.4 %
Hμμ	-	19 %	10 %
Htt	-	4.5 %	4.5 %
HHH	-	24 %	12 %
G_H	5.0 %	3.6 %	3.4 %
G_{invis}/G_H	<1.0 %		

⇨ CLIC gives O(1%) model independent Coupling determinations

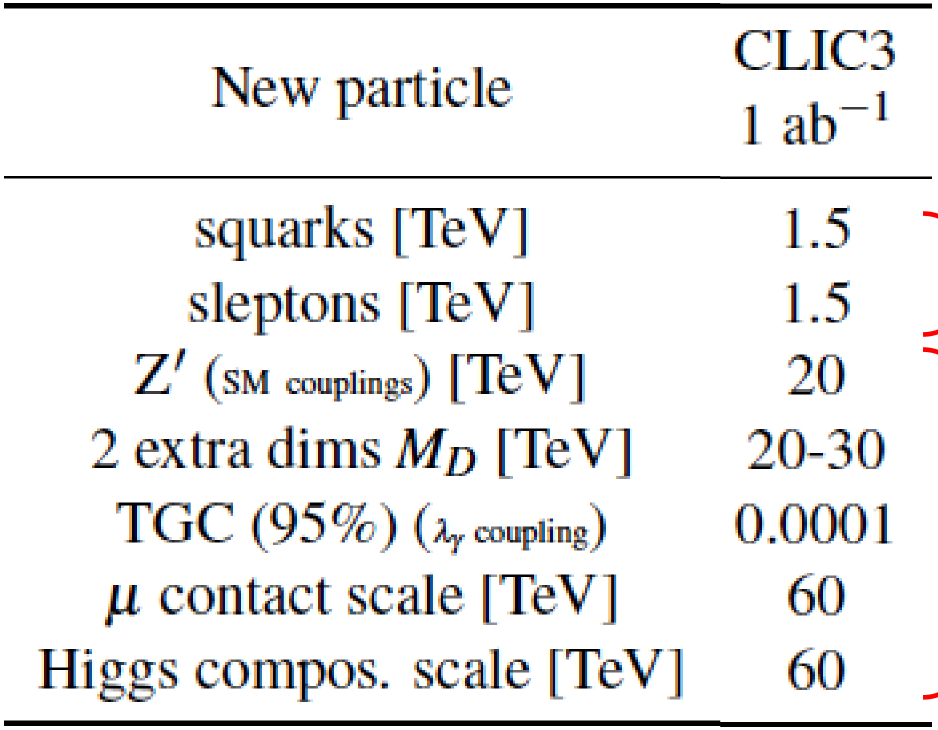
⇨ Self-coupling

⇨ Higgs total width

⇨ Invisible width

Physics reach

e.g. CLIC at 3 TeV



New particle	CLIC3 1 ab^{-1}
squarks [TeV]	1.5
sleptons [TeV]	1.5
Z' (SM couplings) [TeV]	20
2 extra dims M_D [TeV]	20-30
TGC (95%) (λ_γ coupling)	0.0001
μ contact scale [TeV]	60
Higgs compos. scale [TeV]	60

Direct

Loop /
Effective operator

CLIC strategy and objectives

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

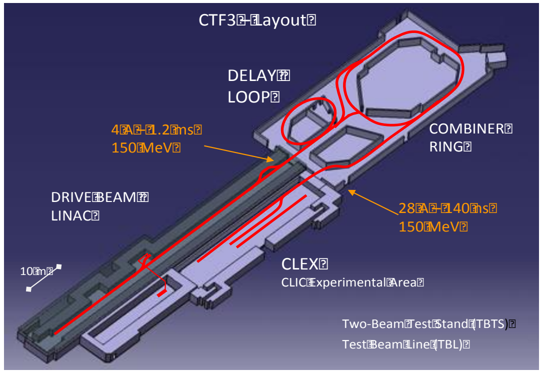
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

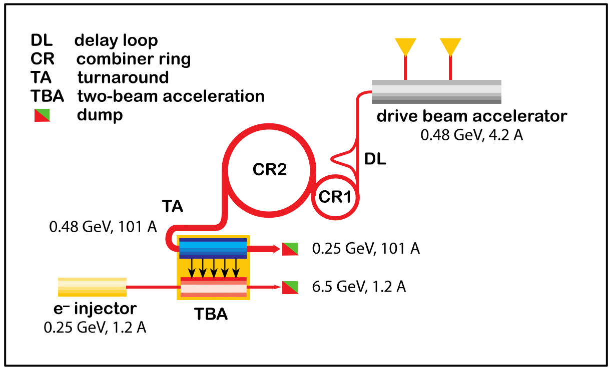
Prepare detailed Technical Proposals for the detector-systems.

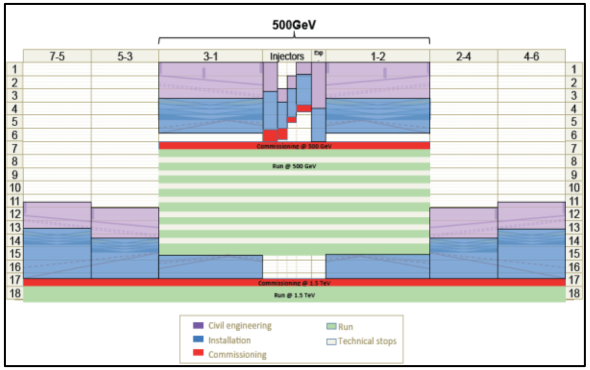
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

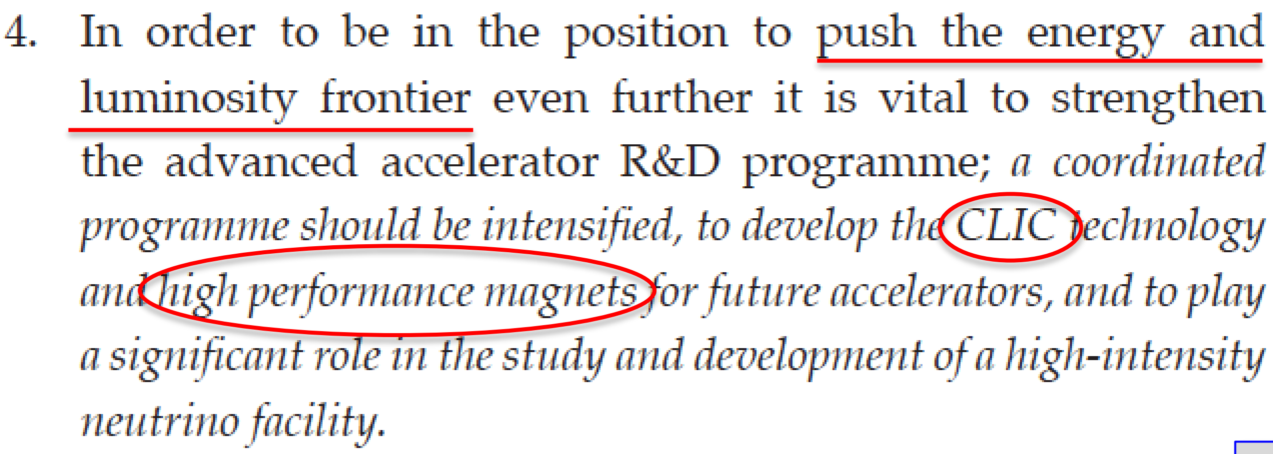
Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

European Strategy statements
=> 2006/2013 CLIC-related statements

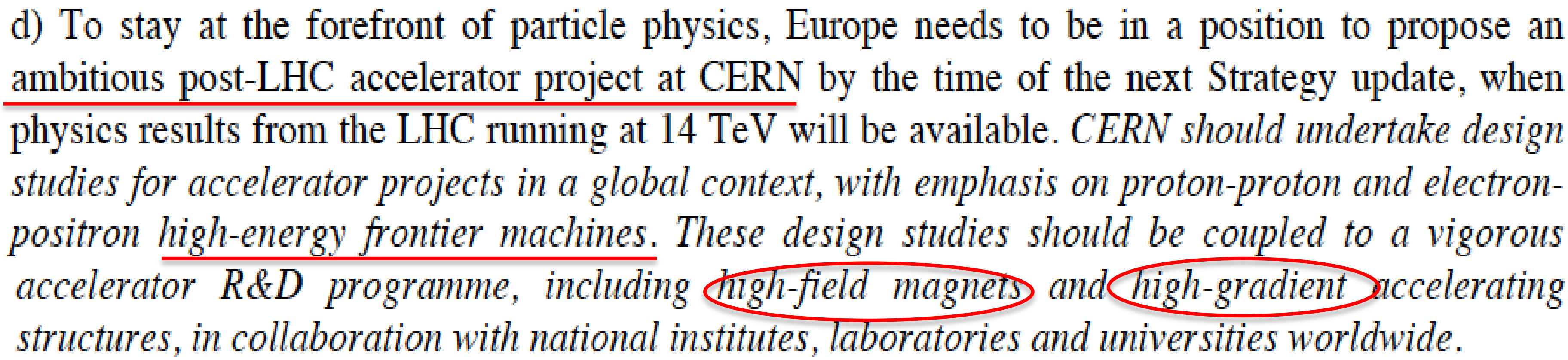
2006 statement “4”:



4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.*

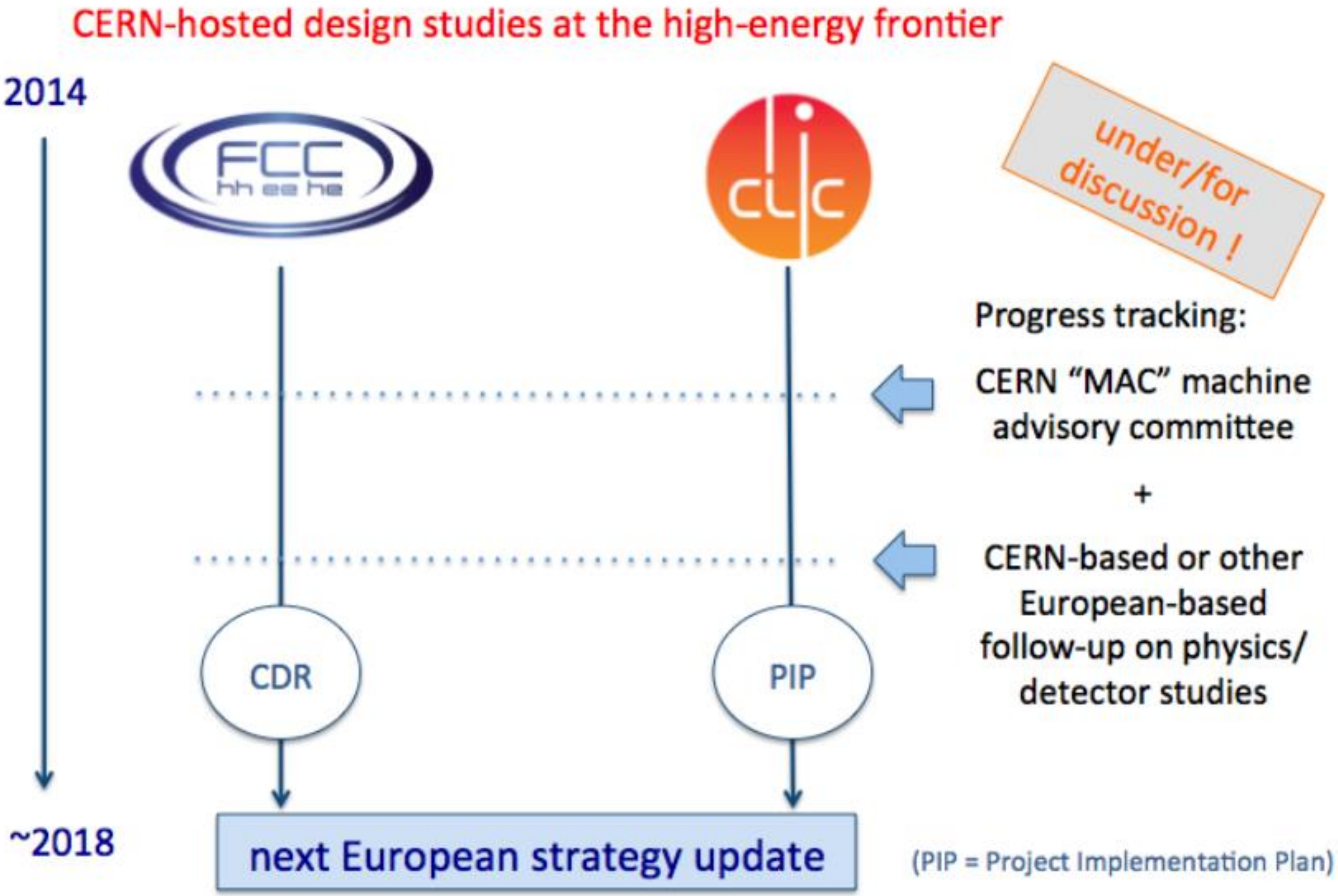
pp or e^+e^-
↙ at high-energy frontier

2013 statement “d”:



d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

CLIC and FCC



CERN-hosted design studies at the high-energy frontier

2014

~2018

under/for discussion !

Progress tracking:

CERN "MAC" machine advisory committee

+

CERN-based or other European-based follow-up on physics/ detector studies

next European strategy update

(PIP = Project Implementation Plan)

timeline: (HL-)LHC and future collider options