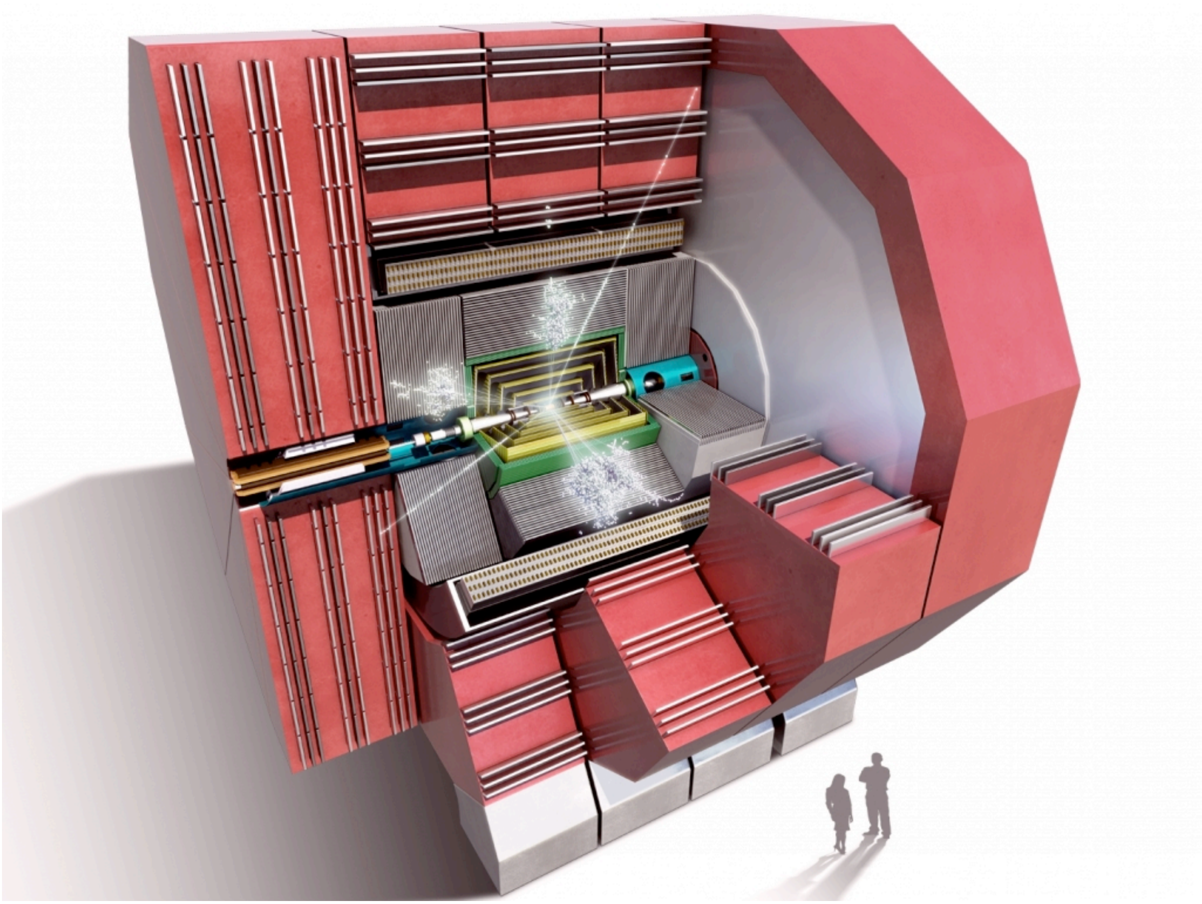
CLIC: physics and detectors at a future TeV-scale e^+e^- collider



Lucie Linssen, CERN

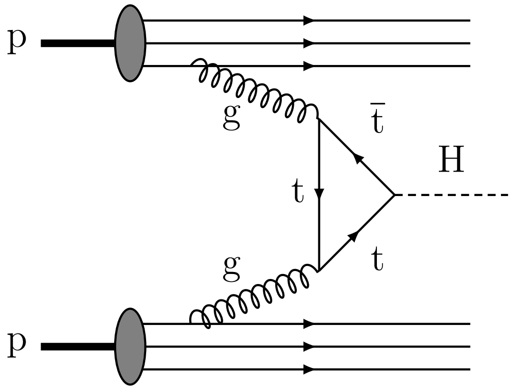
on behalf of the CLIC detector and physics study (CLICdp)

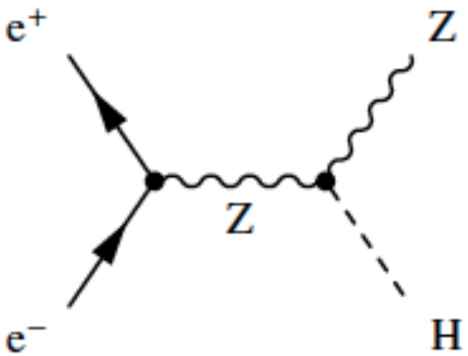
outline

- introduction to CLIC
- overall Physics scope and √s energy staging
- detector requirements and experimental conditions
- CLIC experiment, sub-detectors and R&D
- CLIC physics capabilities
  - Higgs
  - Top
  - New Physics
- summary

- introduction to CLIC

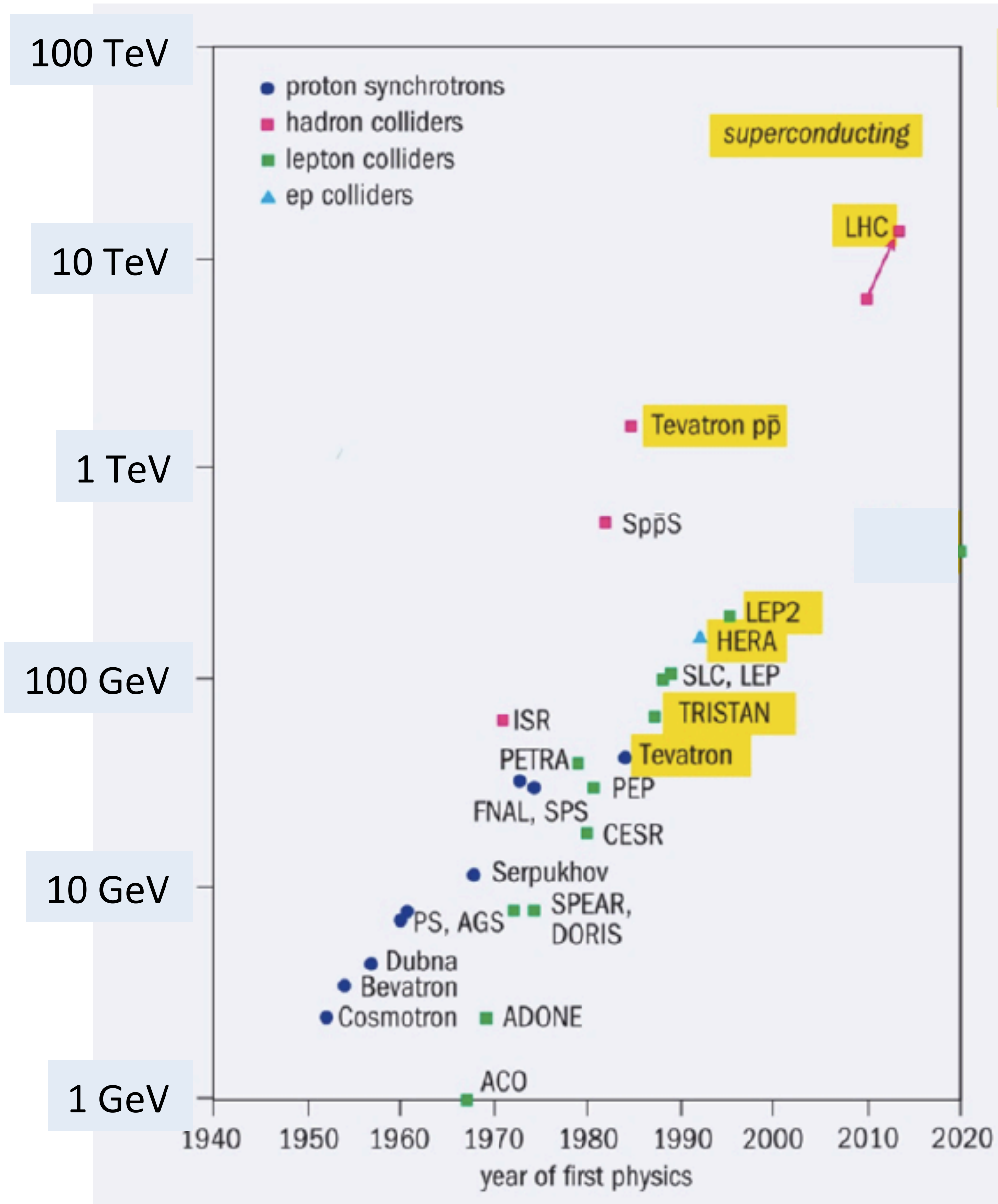
hadron vs. lepton colliders





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 (√s / polarization) → High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron rad.)
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 hadron and lepton colliders



pp and e^+e^- provide complementary information

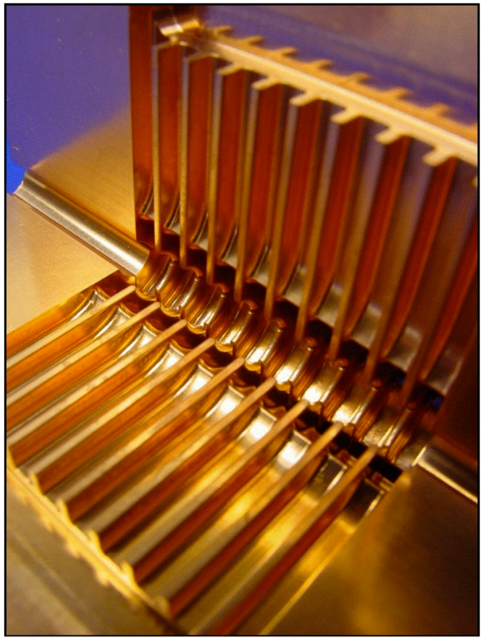
↓

particle physics needs both !

ILC and CLIC in just a few words

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

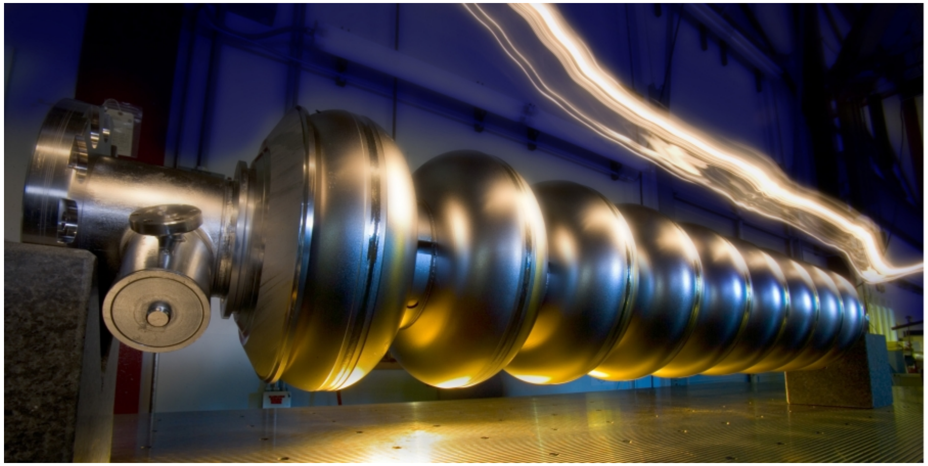
CLIC



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

CLIC focus is on energy frontier reach !

ILC



- Superconducting RF cavities
- Gradient 32 MV/m
- √s ≤ 500 GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

ILC talk by Frank Simon on 12/9

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

2006 statement "4":

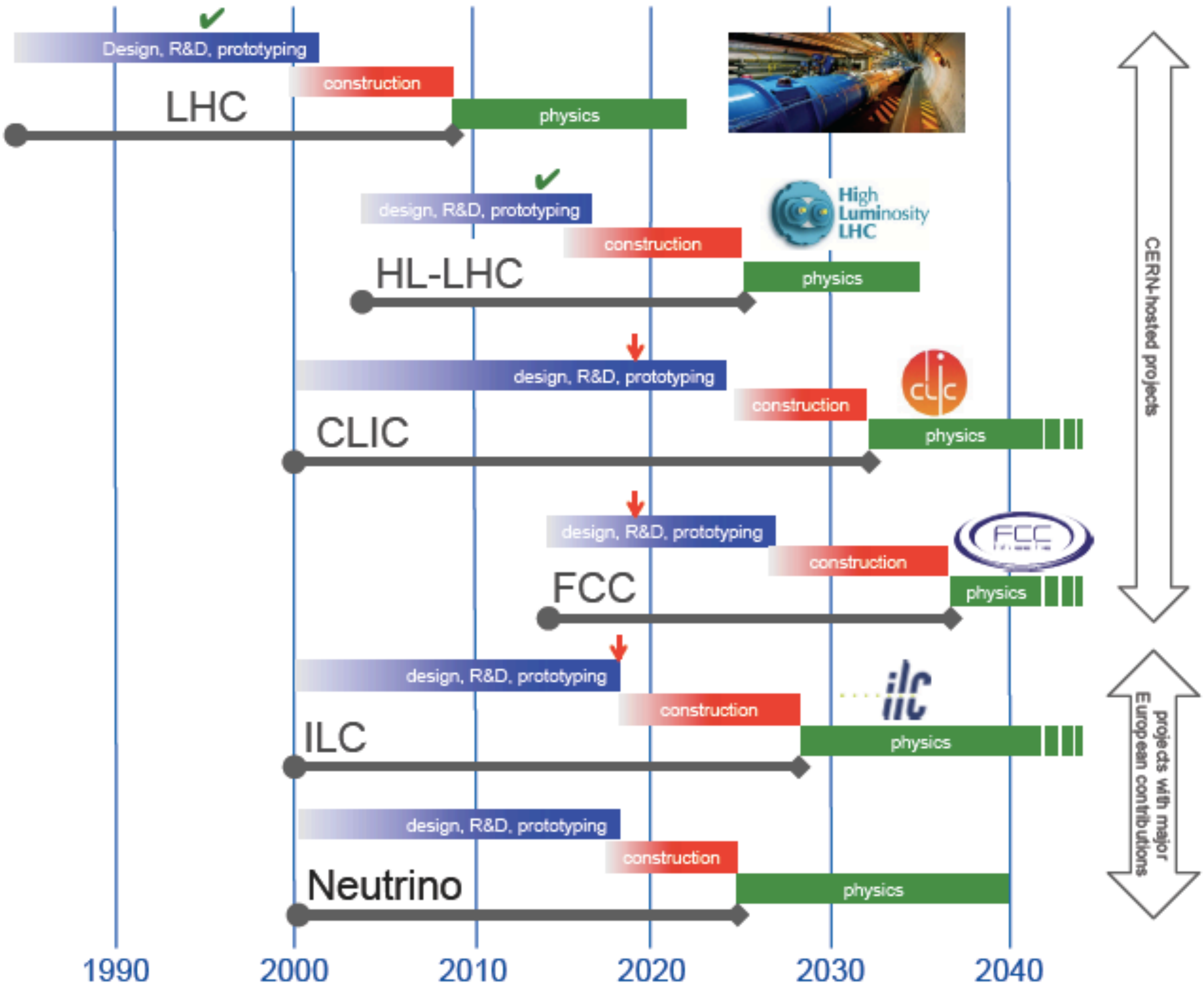
4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play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

2013 statement "d":

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

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.*

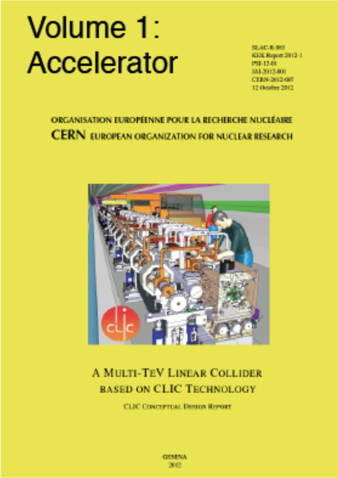
timeline: (HL-)LHC and future collider options

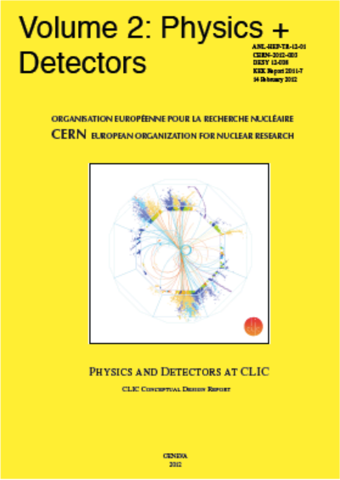


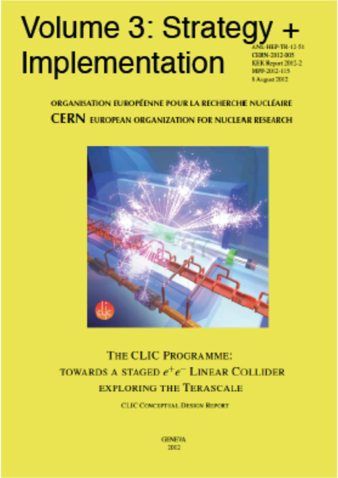
some documentation

CLIC Conceptual Design report (2012)

- **CLIC CDR (#1)**, A Multi-TeV Linear Collider based on CLIC Technology, CERN-2012-007, https://edms.cern.ch/document/1234244/
- **CLIC CDR (#2)**, Physics and Detectors at CLIC, CERN-2012-003, arXiv:1202.5940
- **CLIC CDR (#3)**, The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, CERN-2012-005, http://arxiv.org/abs/1209.2543







More recent update on CLIC physics potential (in particular Higgs)

- Physics at the CLIC e+e- Linear Collider, Input to the USA Snowmass process 2013, http://arxiv.org/abs/1307.5288

CLIC two-beam acceleration scheme

Accelerating gradient: 100 MV/m

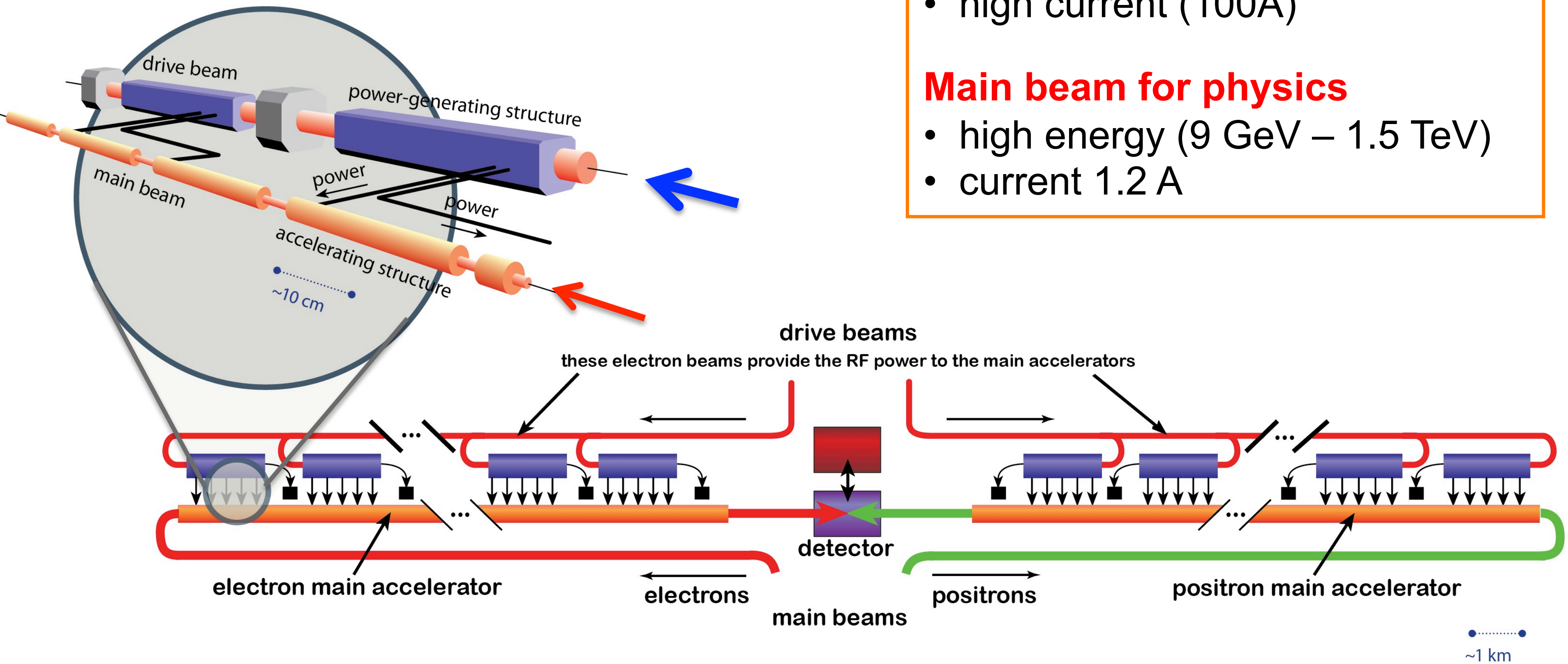
Two Beam Scheme:

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

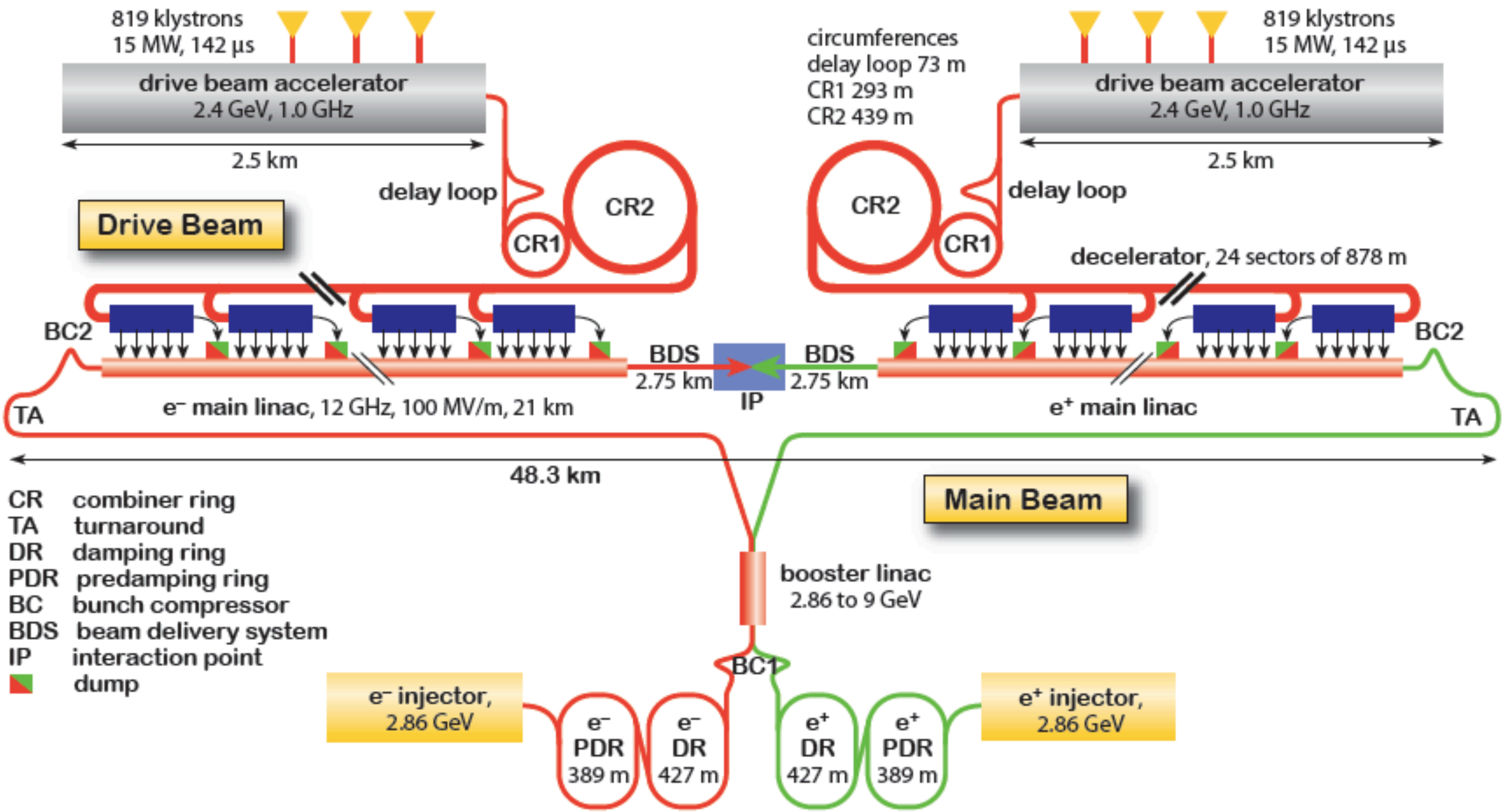


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

CLIC detector and physics (CLICdp)

Australia	Australian Collaboration for Accelerator Science (ACAS), University of Melbourne
Belarus	National Scientific and Educational Centre of Particle and High Energy Physics (NC-PHEP), Belarusian State University, Minsk
Chile	Pontificia Universidad Católica de Chile, Santiago
Czech Republic	Institute of Physics of the Academy of Sciences of the Czech Republic, Prague
Denmark	Department of Physics and Astronomy, Aarhus University
France	Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Annecy
Germany	Max-Plack-Institut für Physik, Munich
Israel	Department of Physics, Faculty of Exact Sciences, Tel Aviv University
Norway	Department of Physics and Technology, University of Bergen
Poland	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow
Poland	Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Cracow
Romania	Institute of Space Science, Bucharest-Magurele
Serbia	Vinca Institute for Nuclear Sciences, Belgrade
Spain	Spanish Network for Future Linear Colliders
Switzerland	CERN
United Kingdom	The School of Physics and Astronomy, University of Birmingham
United Kingdom	University of Bristol
United Kingdom	University of Cambridge
United Kingdom	University of Glasgow
United Kingdom	The Department of Physics of the University of Liverpool
United Kingdom	Oxford University
USA	Argonne National Laboratory, High Energy Physics Division
USA	University of Michigan, Physics Department

Light-weight cooperation structure
No engagements, on best-effort basis
With strong collaborative links to ILC

http://clicdp.web.cern.ch/

CLICdp: 23 institutes

Focus of CLIC-specific studies on:

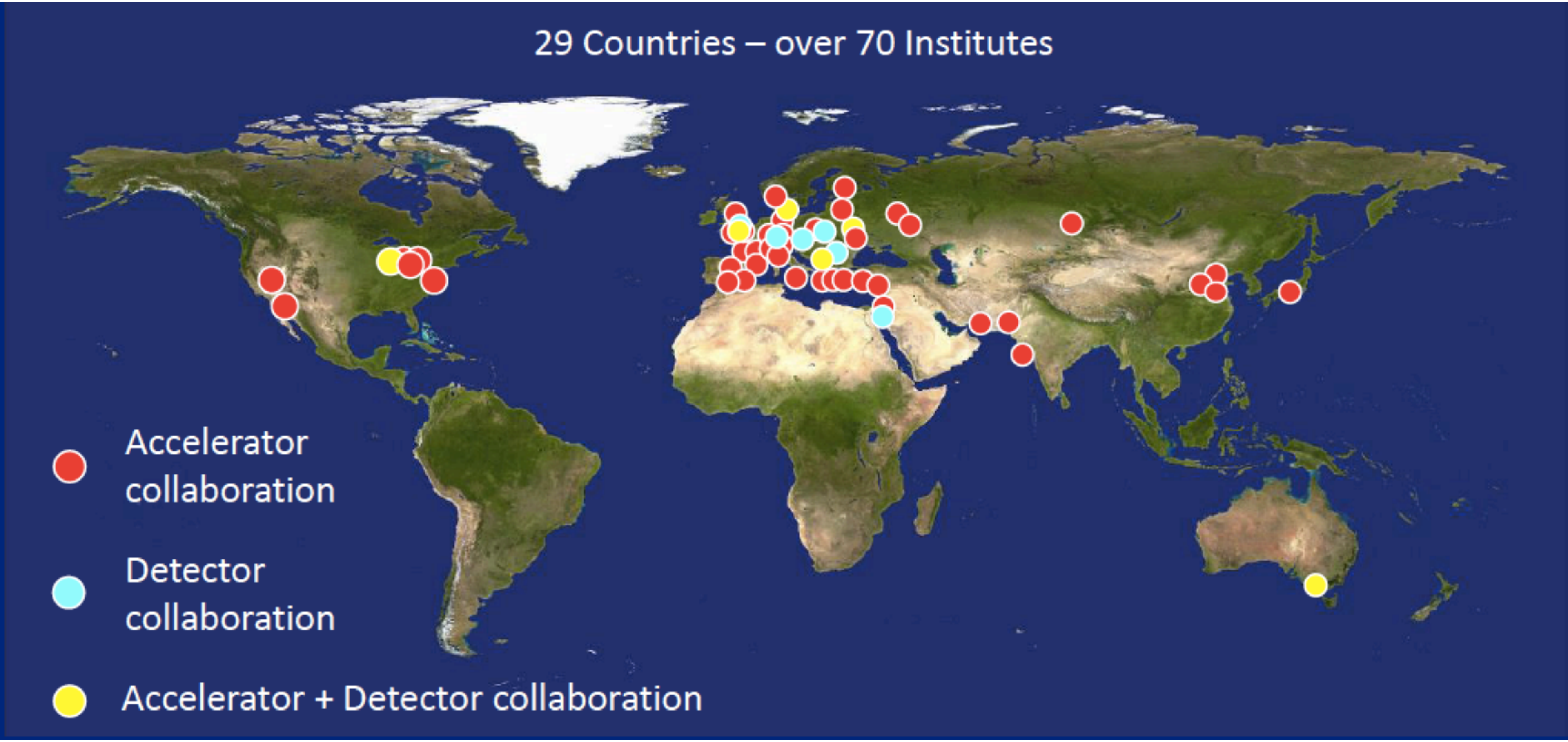
- Physics prospects and simulation studies
- Detector optimisation + R&D for CLIC

CLIC accelerator collaboration

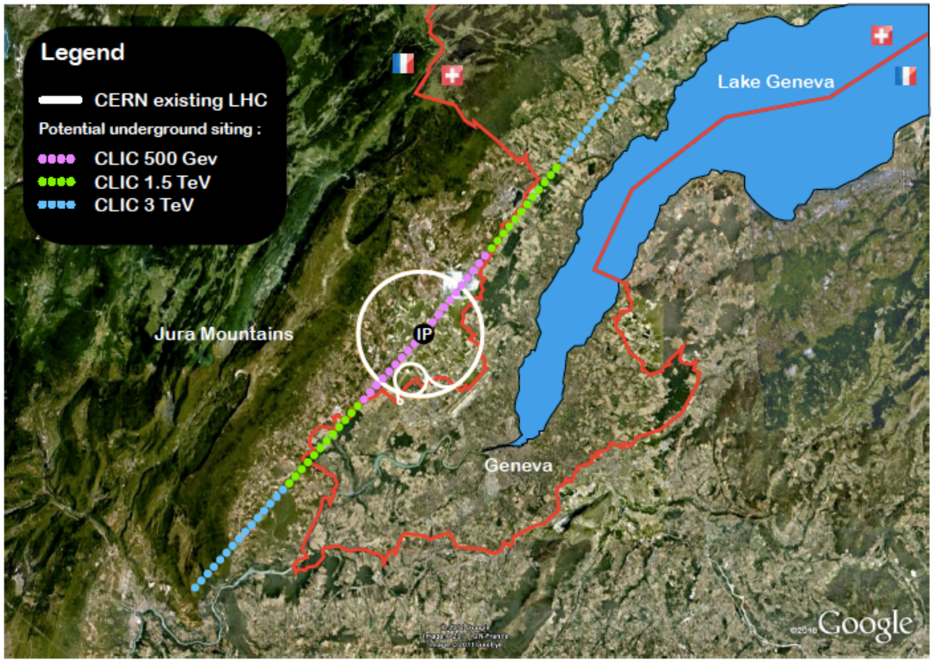
Collaboration to develop CLIC and to build and operate the CLIC test facility CTF3

http://clic-study.org/

CLIC/CTF3: ~50 institutes



- overall Physics scope and √s energy staging

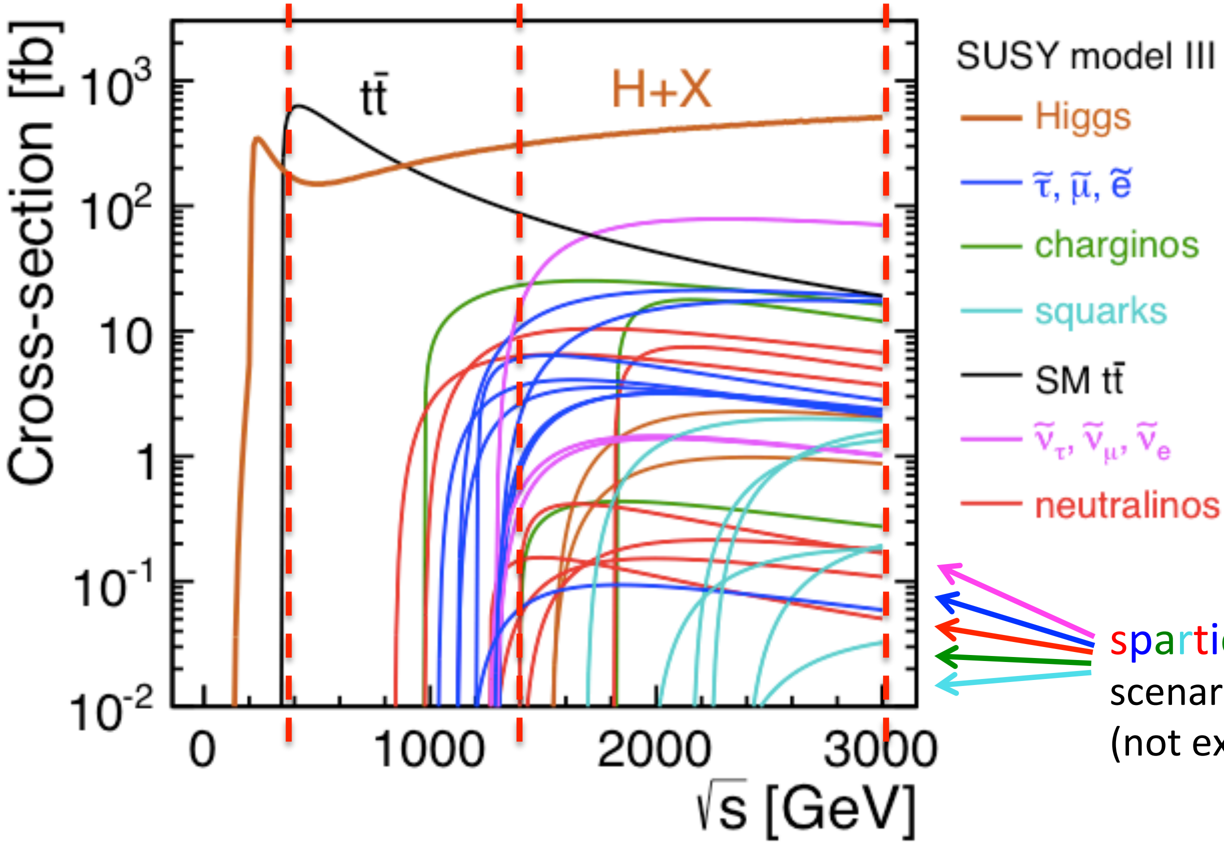


energy stages at CLIC

CLIC: e^+e^- collider, staged approach

- **350 – 375 GeV**, 500 fb^{-1} : precision Higgs and top physics
- **~1.4 TeV**, 1.5 ab^{-1} : **targeted at BSM physics,** precision Higgs
- **~ 3 TeV,** 2 ab^{-1} : **targeted at BSM physics,** precision Higgs

Exact energies of TeV stages would depend on LHC results

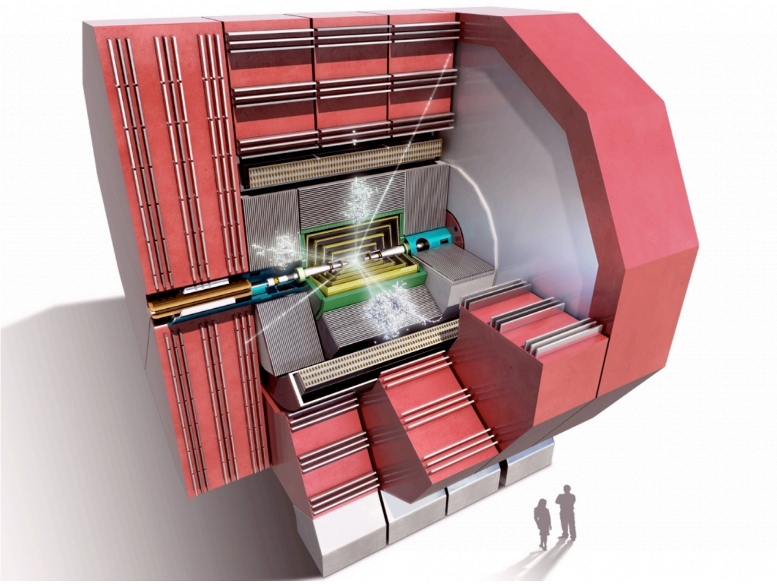


Example of energy staging

(with an example SUSY model)

sparticles in **SUSY** example scenario
(not excluded by LHC results)

- detector requirements and experimental conditions



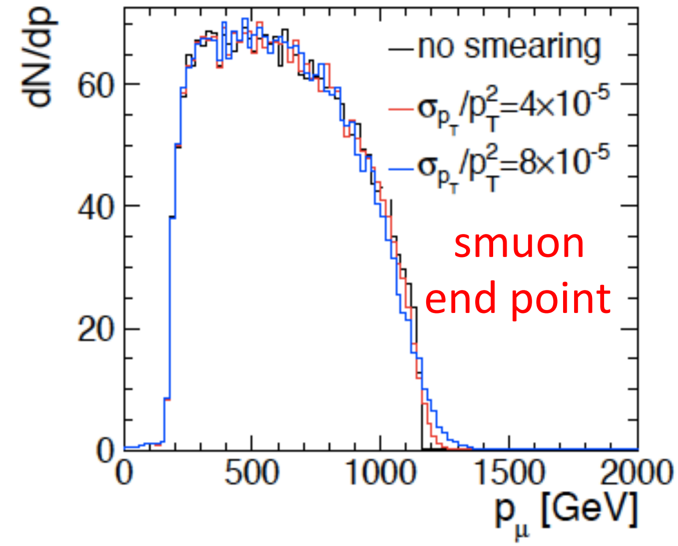
CLIC physics aims => detector needs

★ **momentum resolution:**

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

$$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}$$

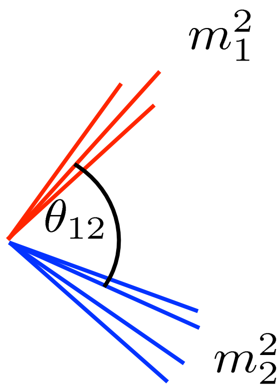


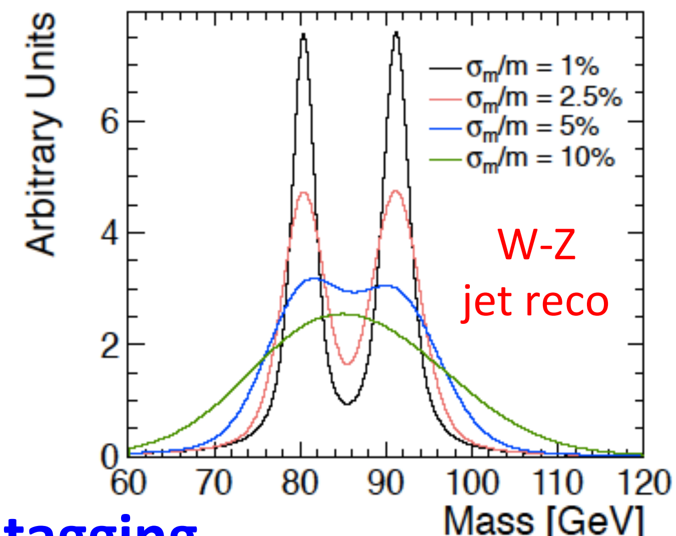
★ **jet energy resolution:**

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

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

(for high-E jets)





★ **impact parameter resolution:**

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

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

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

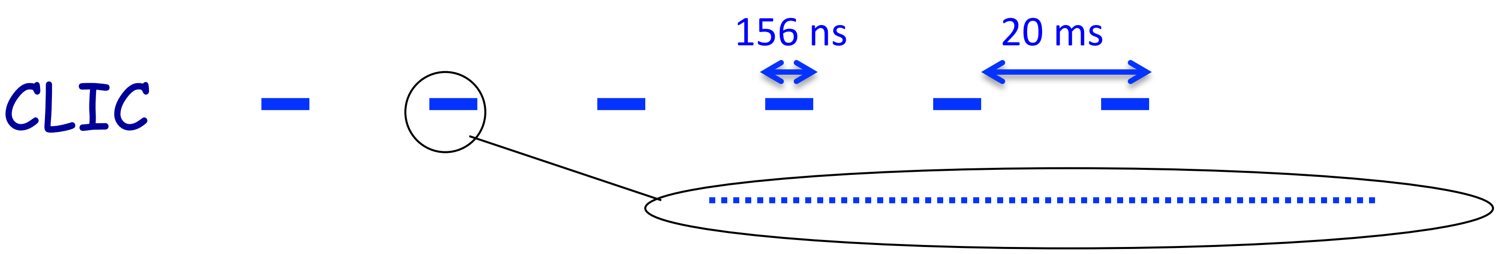
+ requirements from CLIC beam structure and beam-induced background

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

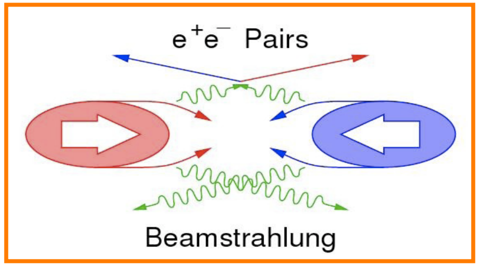
very small beam size



1 train = 312 bunches, 0.5 ns apart

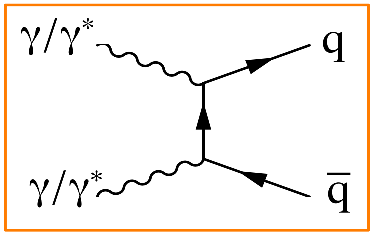
- not to scale -

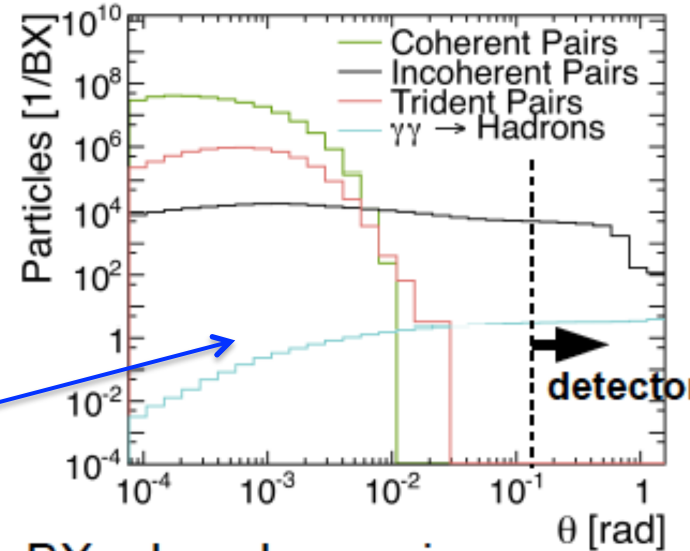
CLIC machine environment



Beam-beam background at IP:

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



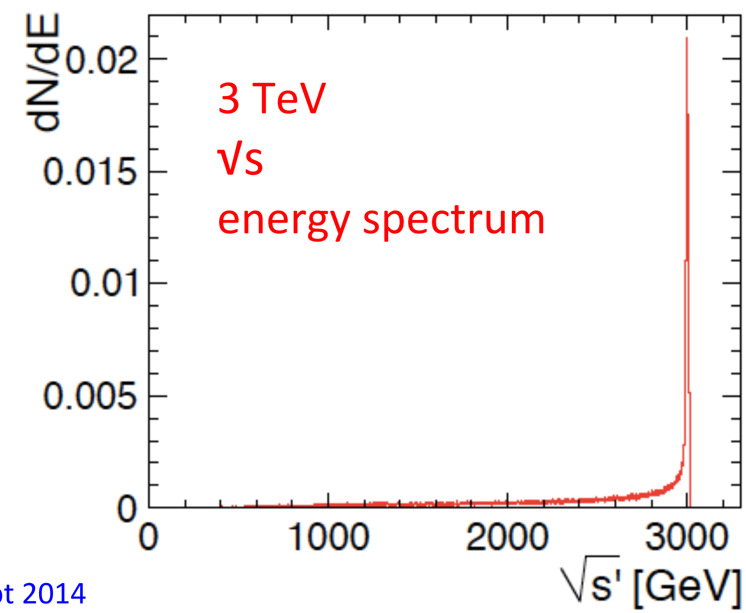


BX = bunch crossing

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 conditions => impact on detector

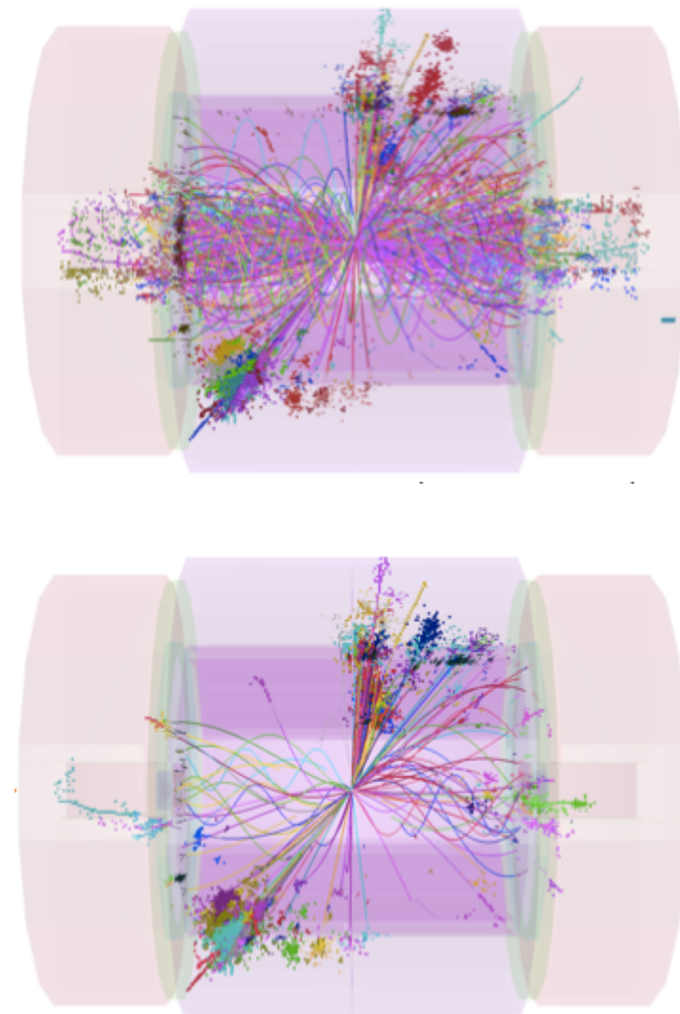
CLIC conditions => impact on detector technologies:

- **High tracker occupancies => need small cell sizes**
  (beyond what is needed for resolution)
  - Small vertex pixels
  - Large pixels / short strips in the tracker

- **Bkg energy => need high-granularity calorimetry**

- **Bkg suppression => overall need for precise hit timing**
  - ~10 ns hit time-stamping in tracking
  - 1 ns accuracy for calorimeter hits

- **Low duty cycle** 🙂
  - Triggerless readout
  - Allows for power pulsing
    - => less mass and high precision in tracking
    - => high density for calorimetry

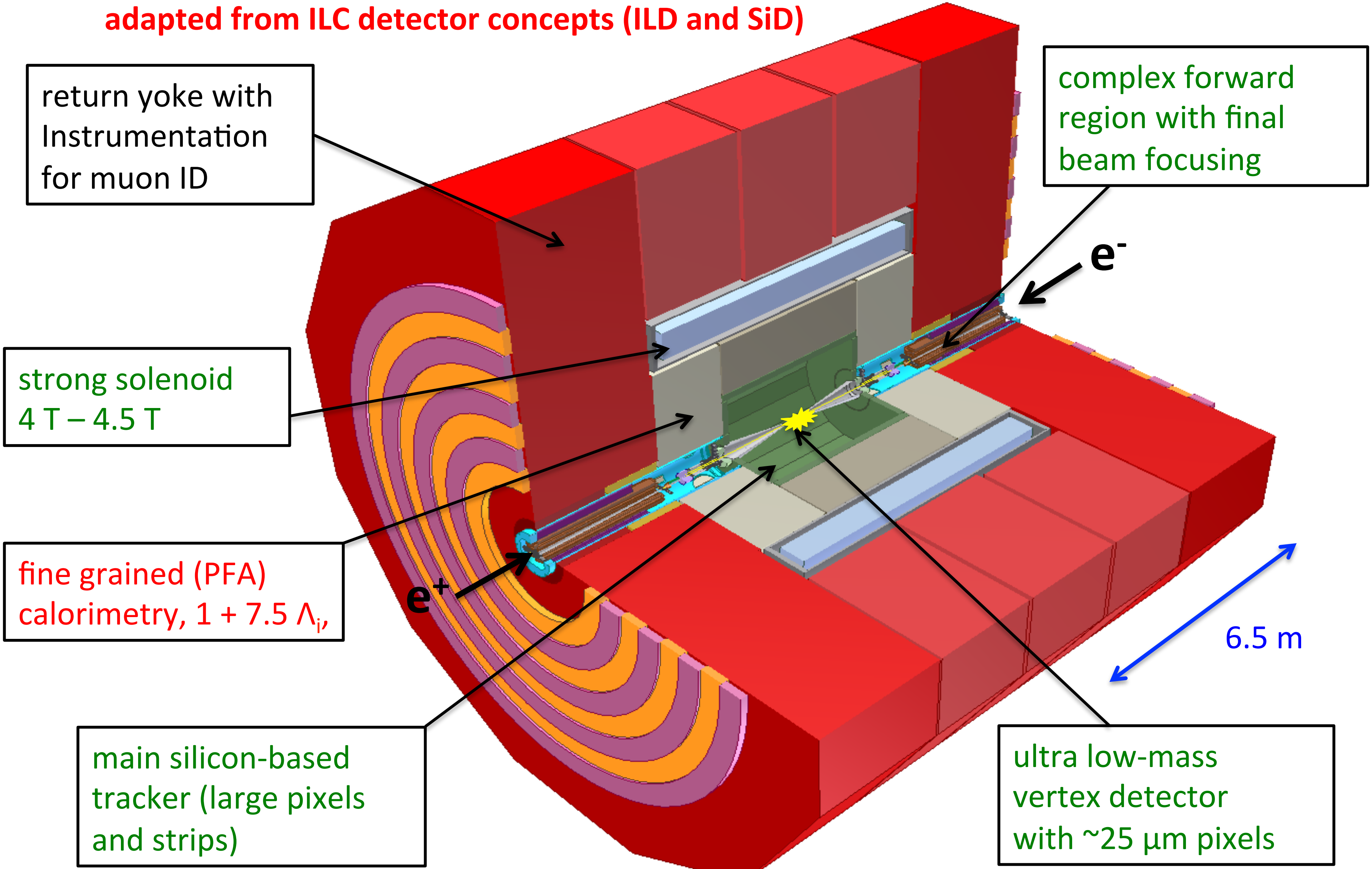


$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8$ jets

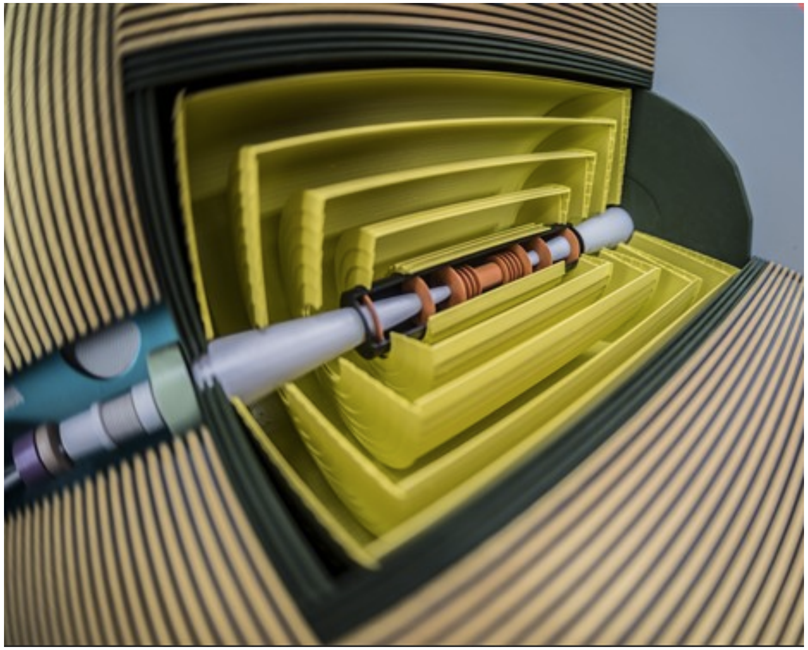
- a detector for CLIC

CLIC detector concept

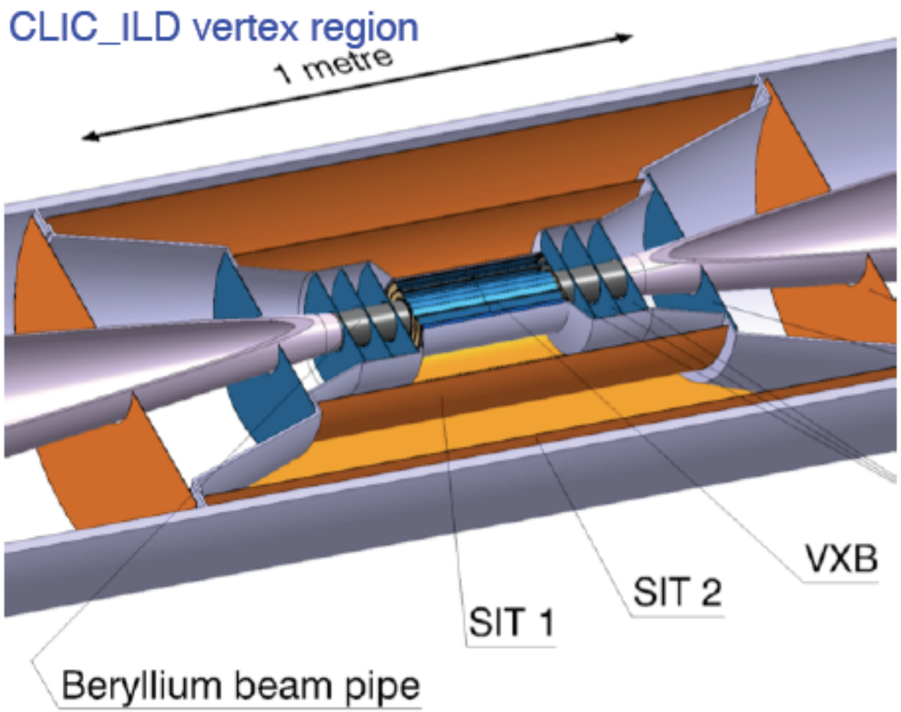
adapted from ILC detector concepts (ILD and SiD)

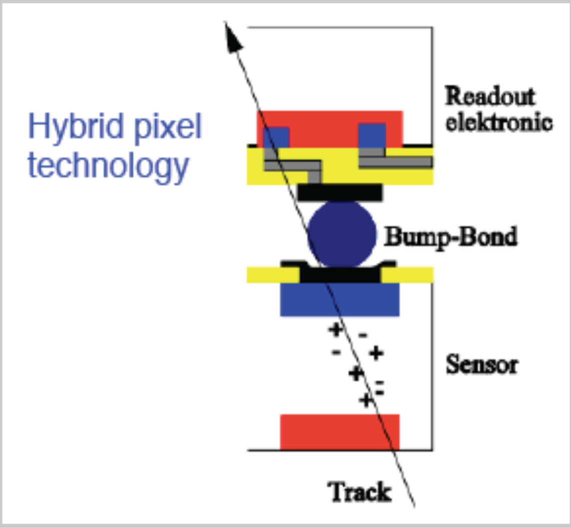


- vertex and tracking detectors



CLIC vertex detector

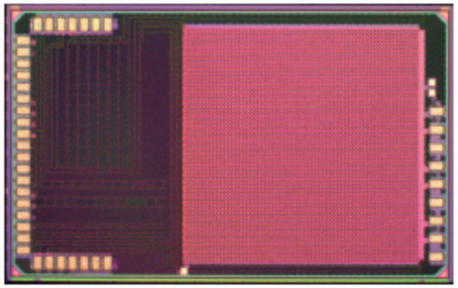




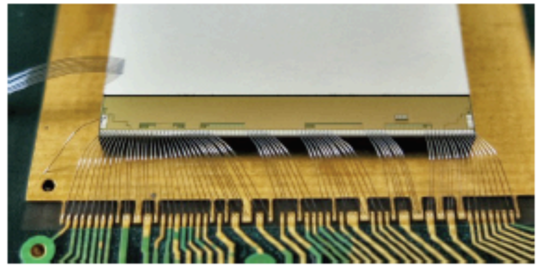
- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material per layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 50 mW/cm^2
- Time stamping 10 ns
- Radiation level $<10^{11}$ $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

CLIC vertex detector technology R&D

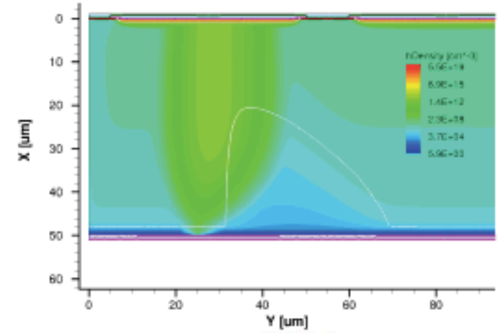
Readout ASICs



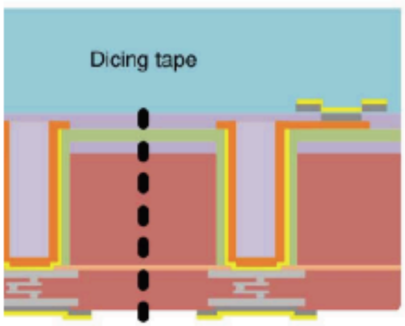
Sensors



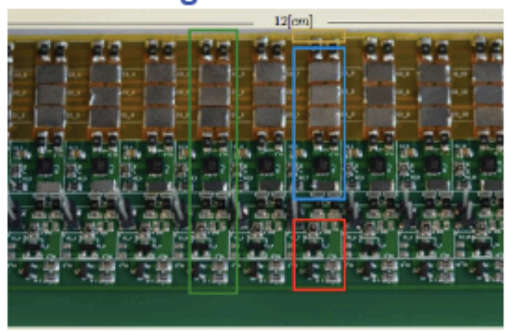
Simulations



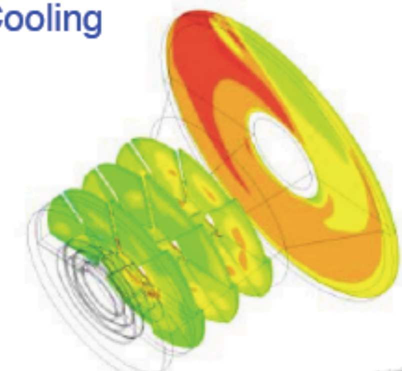
Interconnects



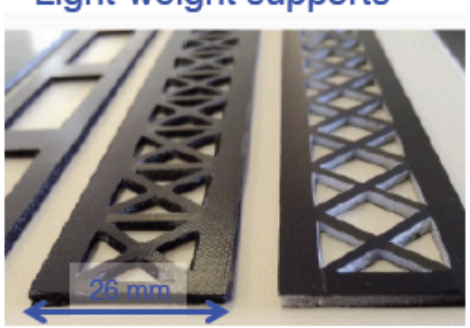
Powering



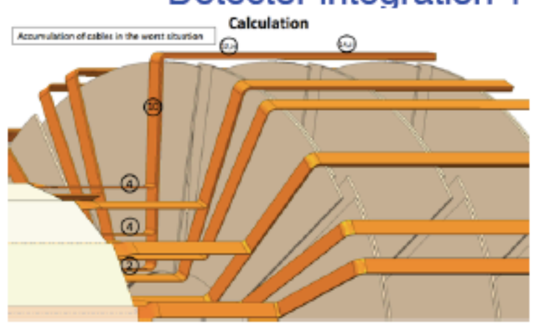
Cooling

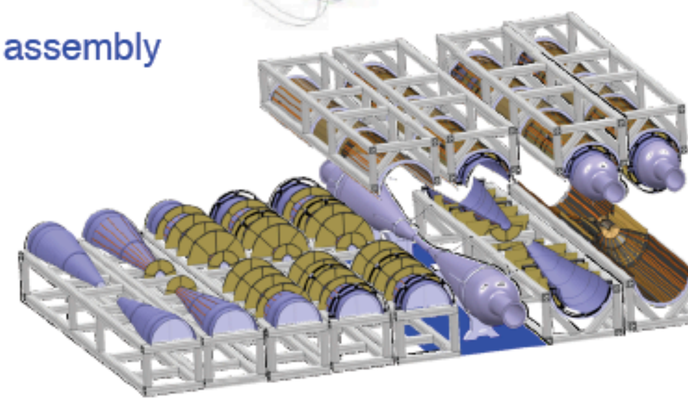


Light-weight supports



Detector integration + assembly

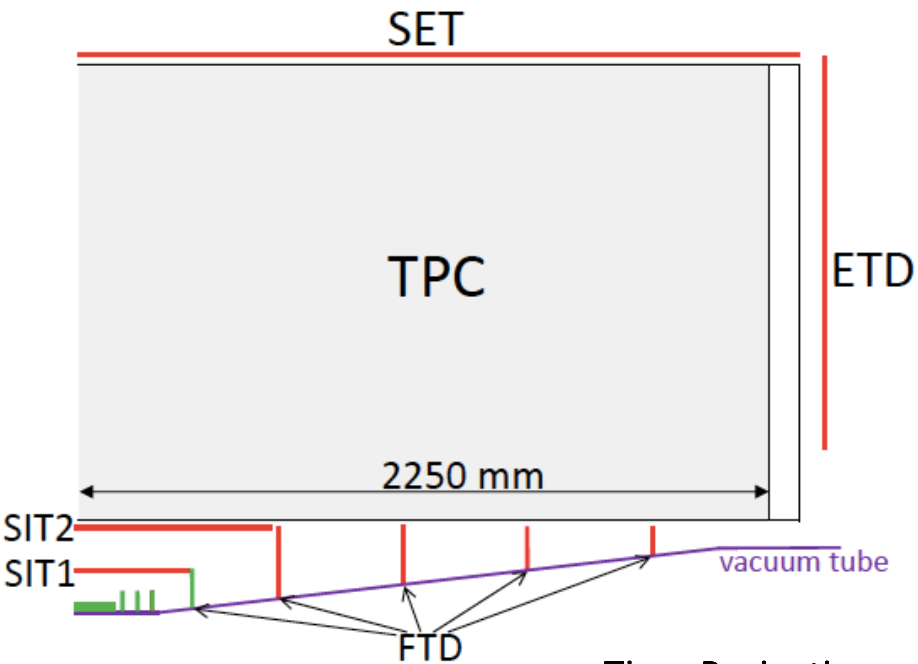


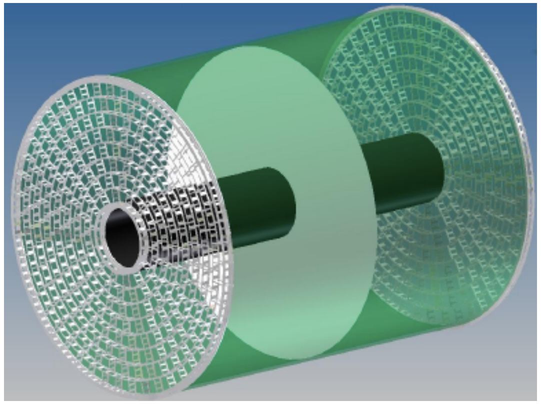


Integrated R&D effort, simultaneously addressing CLIC vertex-detector challenges

CLIC_ILD ↙ and CLIC_SiD ↘ tracker

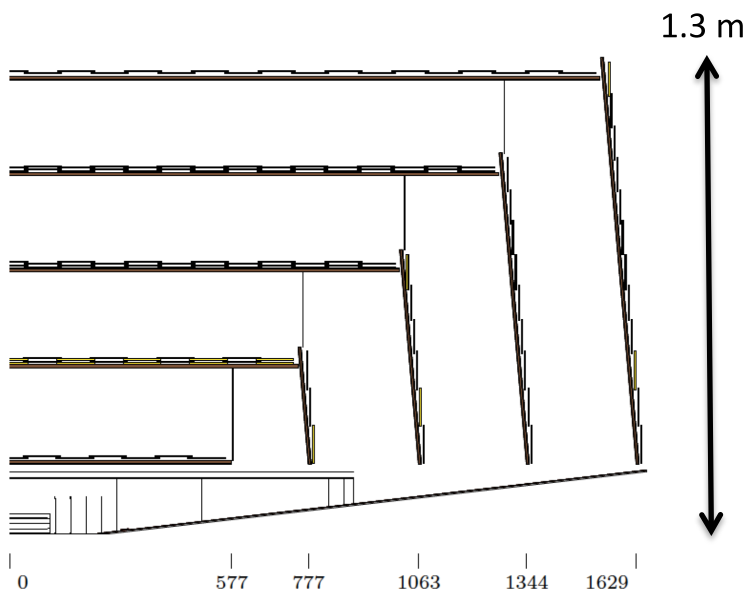
TPC + silicon tracker in 4 Tesla field

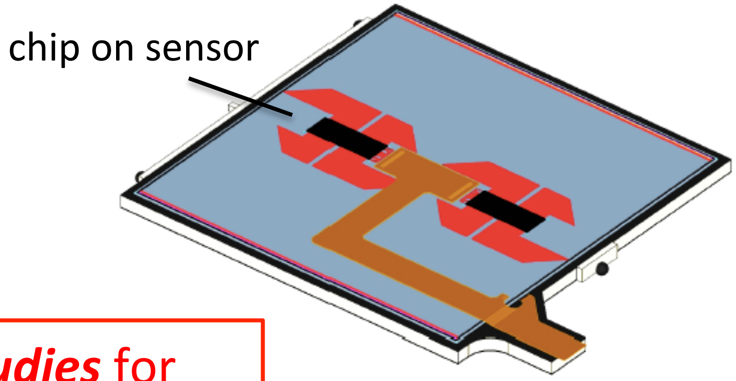




Time Projection Chamber (TPC) with MPGD readout

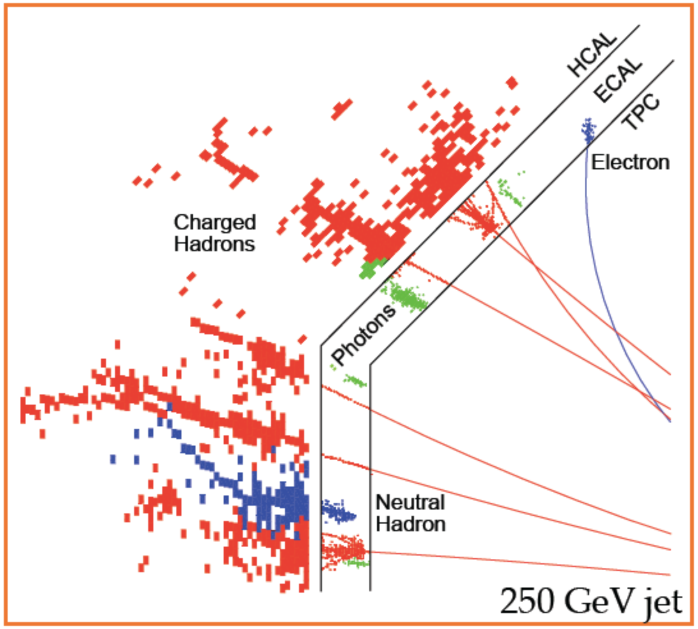
All-silicon tracker in 5 Tesla field





Silicon-based tracking studies for new CLIC detector model ongoing

- calorimetry



calorimetry and PFA

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

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

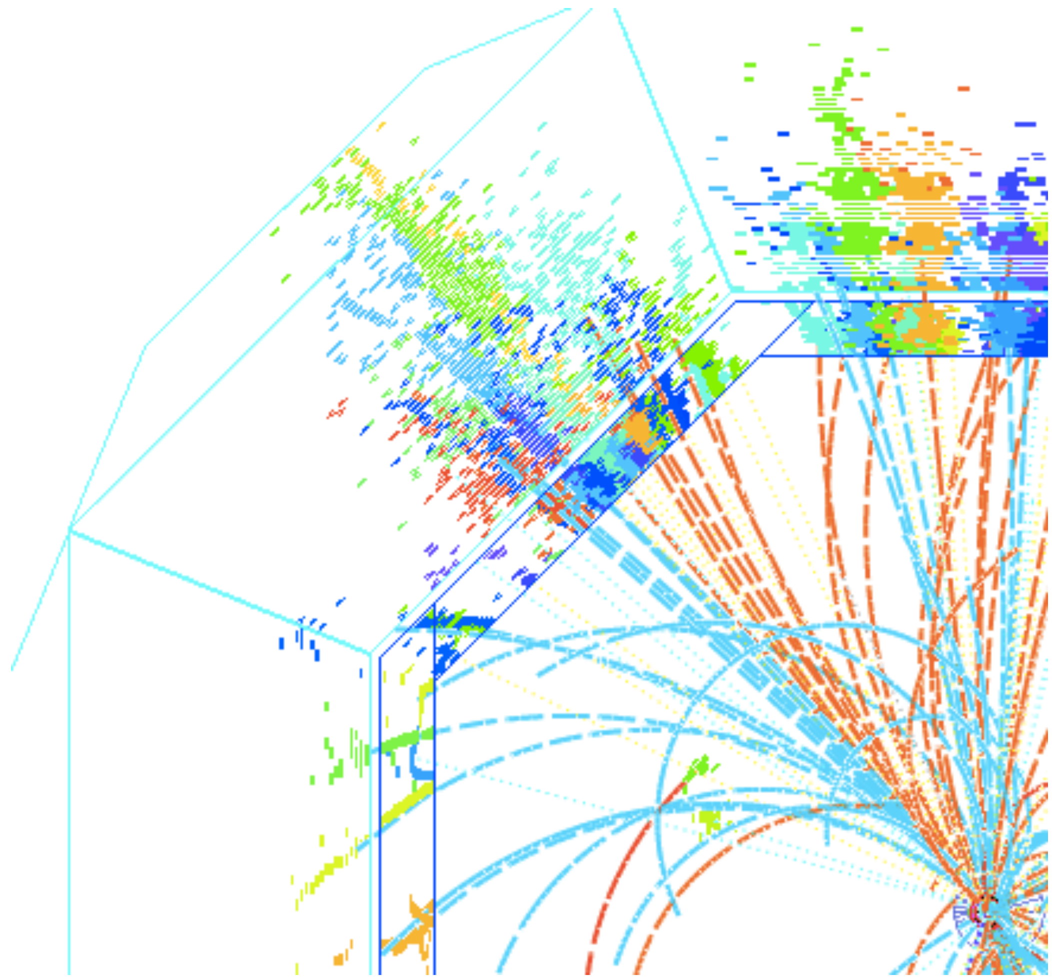
What is PFA?

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 !



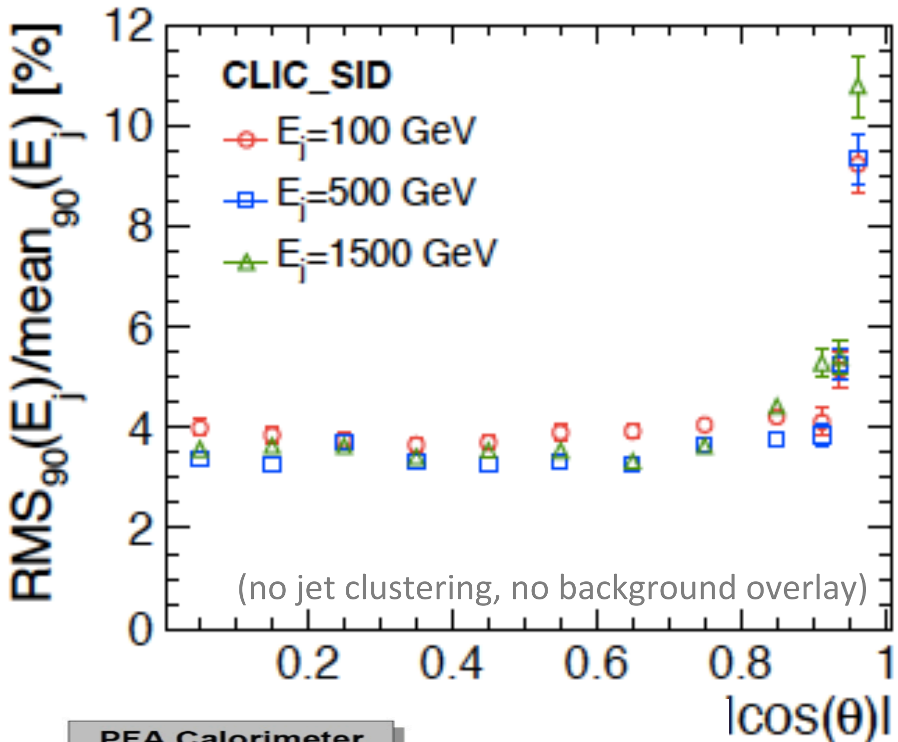
PFA calorimetry at CLIC

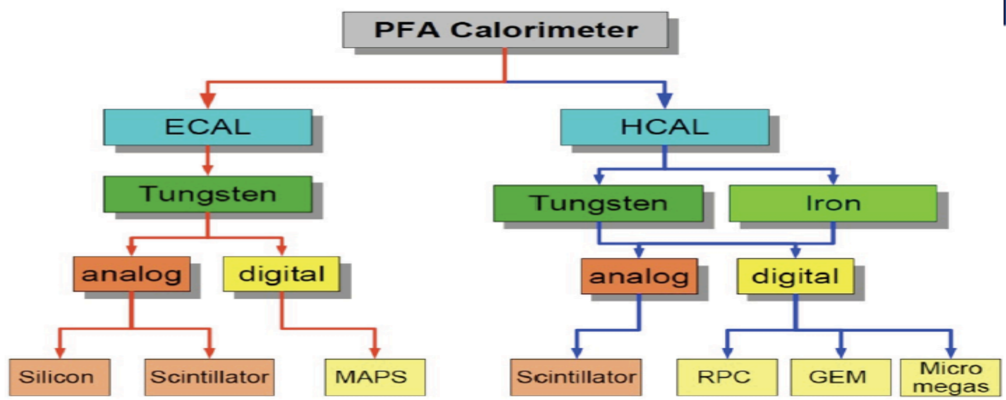
technology

simulated jet energy resolution

ECAL
Si or Scint. (active) + Tungsten (absorber)
cell sizes 13 mm^2 or 25 mm^2
30 layers in depth

HCAL
Several technology options: scint. + gas
Tungsten (barrel), steel (endcap)
cell sizes 9 cm^2 (analog) or 1 cm^2 (digital)
60-75 layers in depth
Total depth 7.5 Λ_i



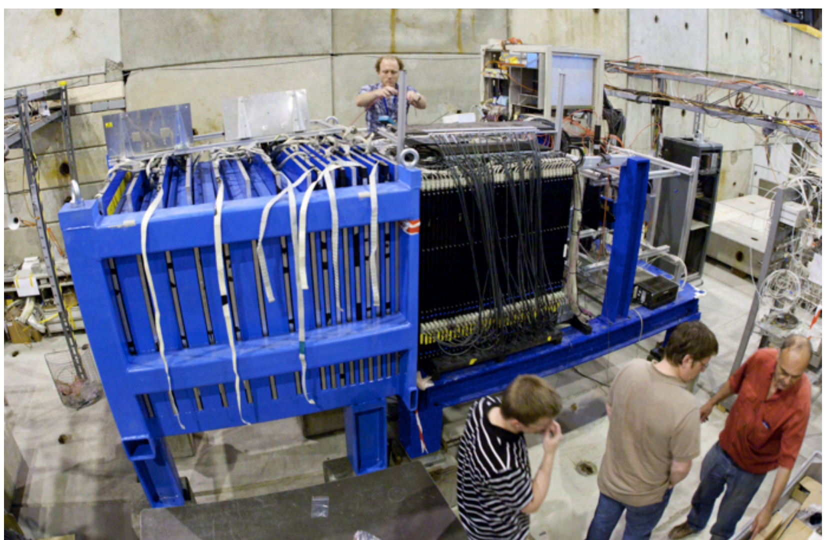


many technologies pursued

analog HCAL: scintillator-tungsten

HCAL tests with 10 mm thick **Tungsten absorber** plates,
Tests in 2010+2011 with scintillator active layers, 3×3 cm^2 cells => analog readout

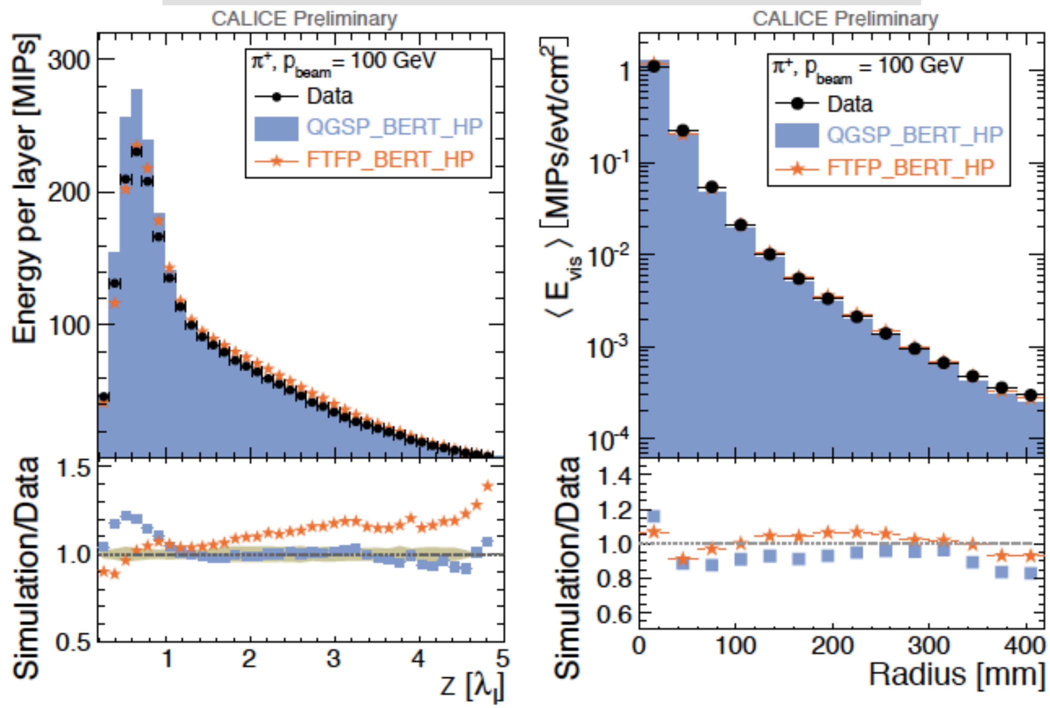
High precision on jets
↓
ECAL +HCAL have to fit inside coil
↓
CLIC needs Tungsten absorber in HCAL
↓
Requires beam tests to validate Geant4



CERN SPS 2011

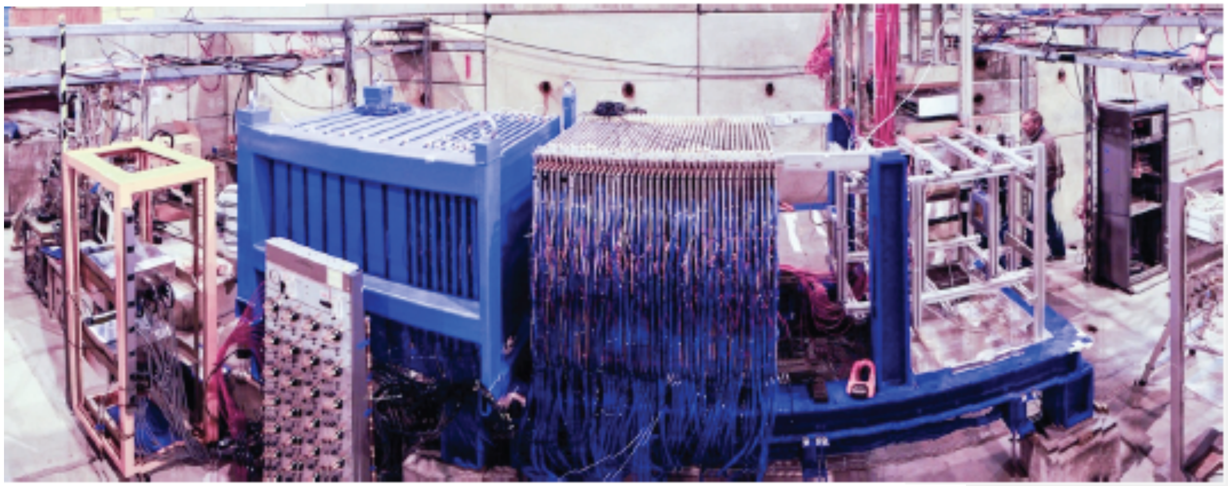
CALICE preliminary

Shower shapes for pions of 100 GeV

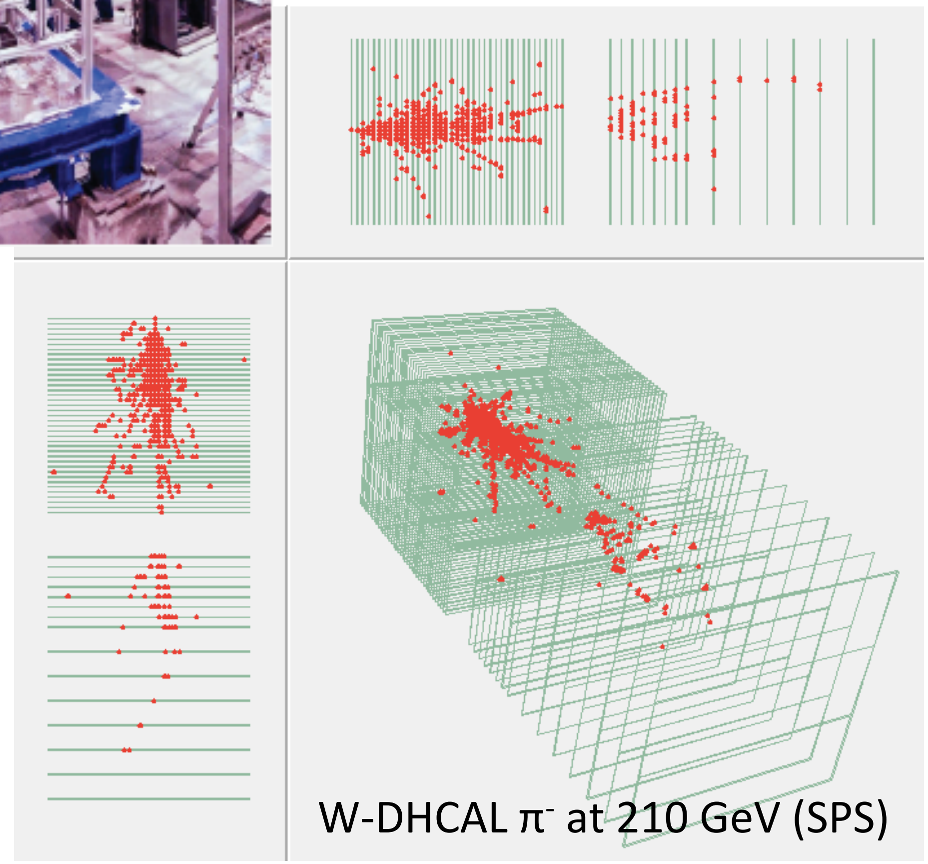


good agreement with Geant4

digital DHCAL: glass RPC's + tungsten



Steel DHCAL
Tungsten DHCAL
500'000 readout channels



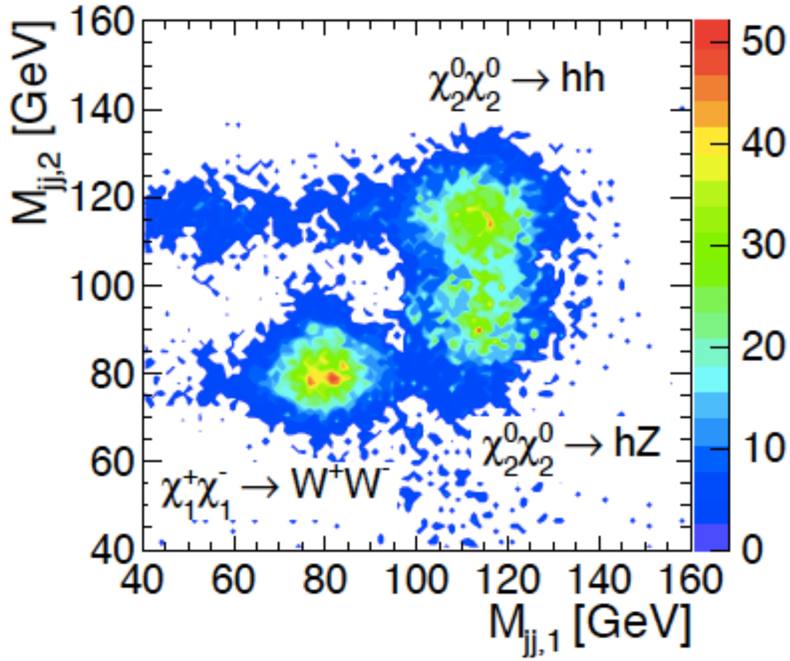
W-DHCAL π^- at 210 GeV (SPS)

54 glass RPC chambers, ~1m^2 each
PAD size 1×1 cm^2
Digital readout (1 threshold)
Fully integrated electronics
Total 500'000 readout channels

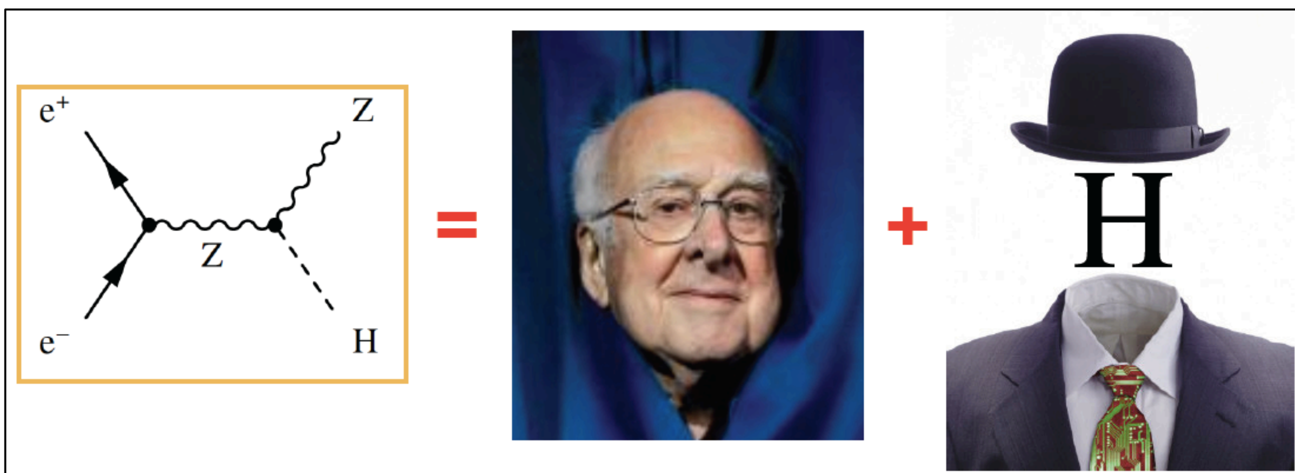
Other large-scale prototypes:
- 1m^3 semi-digital HCAL with glass RPC's
- 4 large (~1m^2) micromegas readout planes

- CLIC physics capabilities

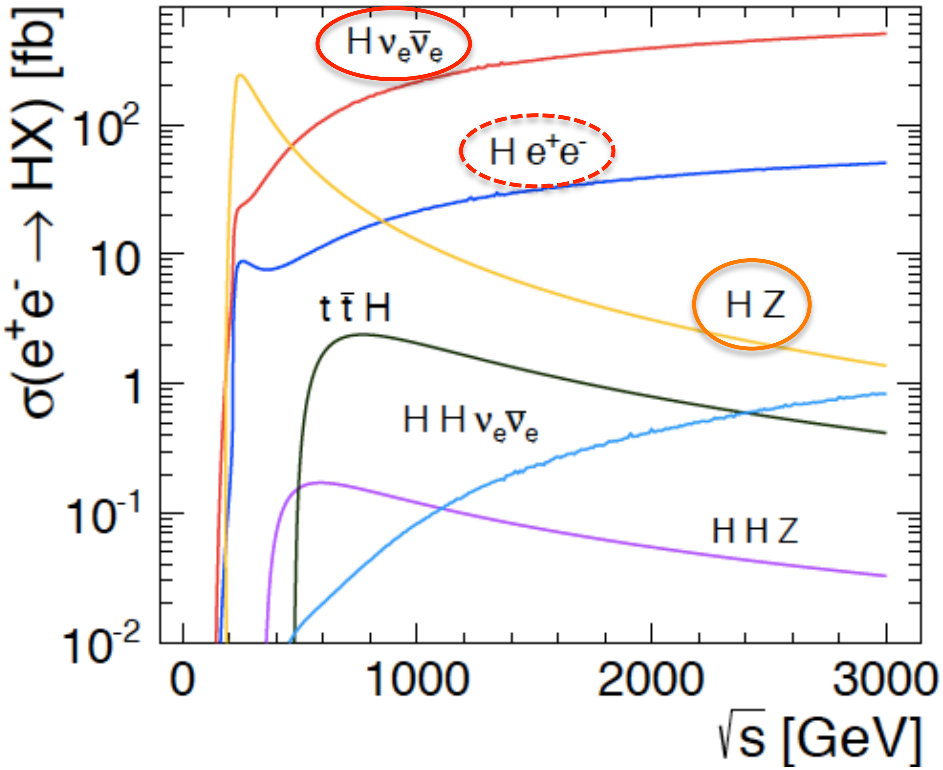
Examples of benchmark studies, Geant4-based full detector simulations
- with overlay of γγ background
- analyses include SM physics backgrounds.



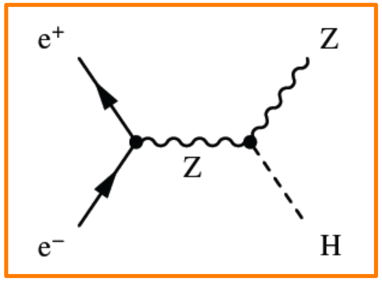
- Higgs physics



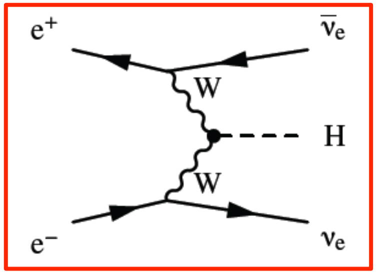
Higgs physics at CLIC



Dominant processes:



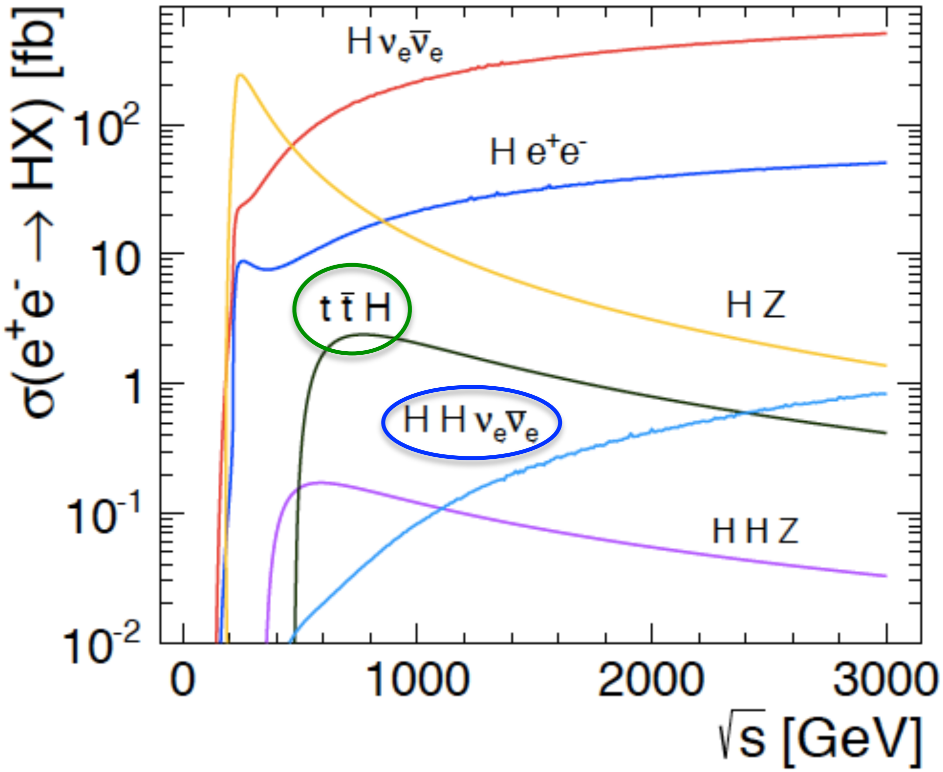
Higgsstrahlung decreases with √s



W(Z) - fusion increases with √s

	350 GeV	1.4 TeV	3 TeV
L_{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

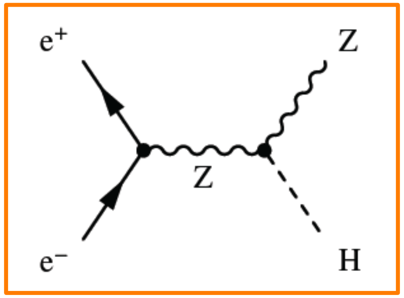


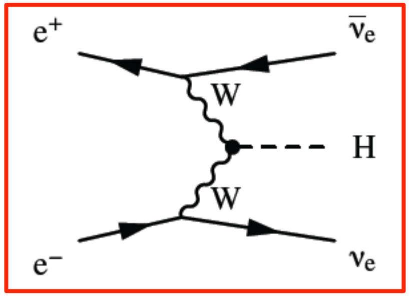
Higgs-Strahlung: $e^+e^- \to ZH$
- Measure H from Z-recoil mass
- Model-independent meas.: m_H, σ
- Yields absolute value of g_{HZZ}

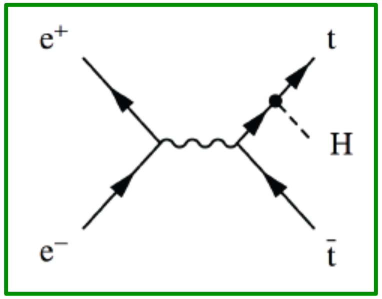
WW fusion: $e^+e^- \to H\nu_e\nu_e$
- Precise cross-section measurements in ττ, μμ, qq, … decay modes
- Profits from higher √s (≳350 GeV)

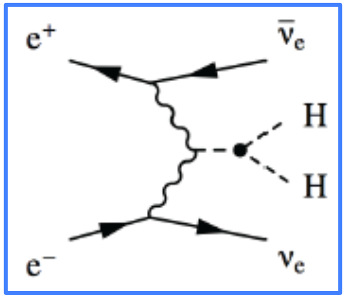
Radiation off top-quarks: $e^+e^- \to ttH$
- Measure top Yukawa coupling
- Needs √s≳700 GeV

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

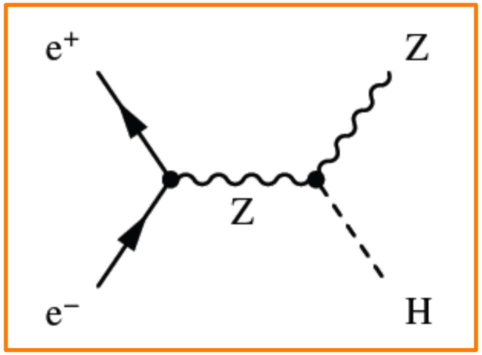




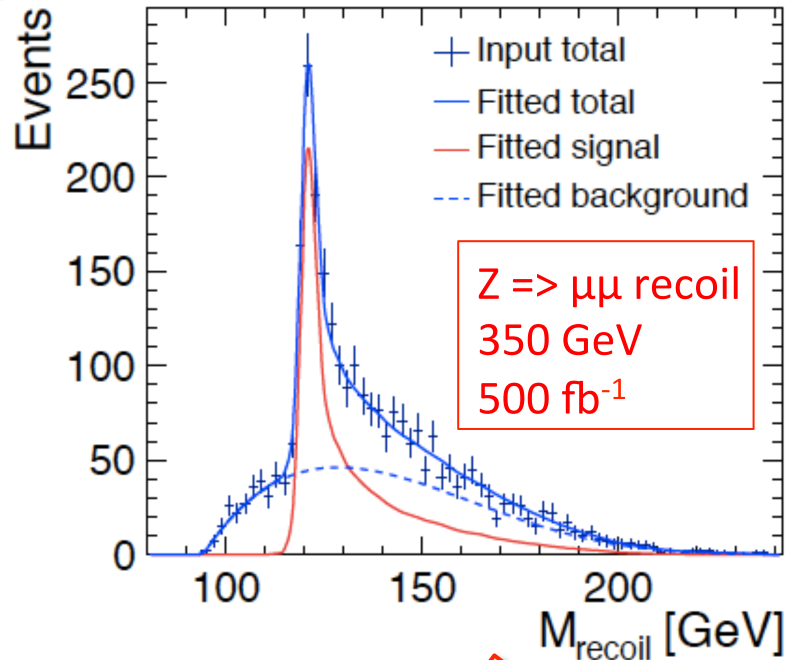




Higgsstrahlung



model-independent Higgs measurement
(coupling and mass)
yields absolute coupling value g_{HZZ}



Work in progress !

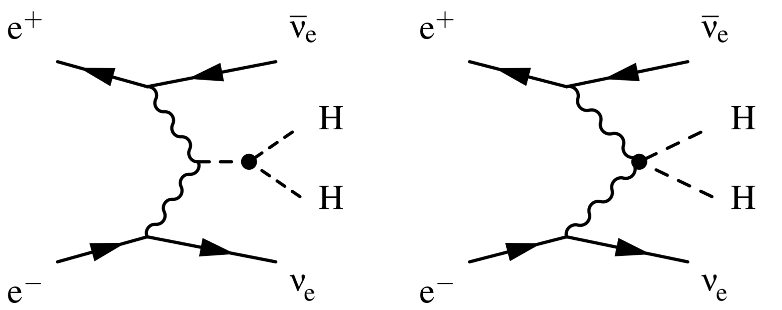
Identify Higgs through Z recoil

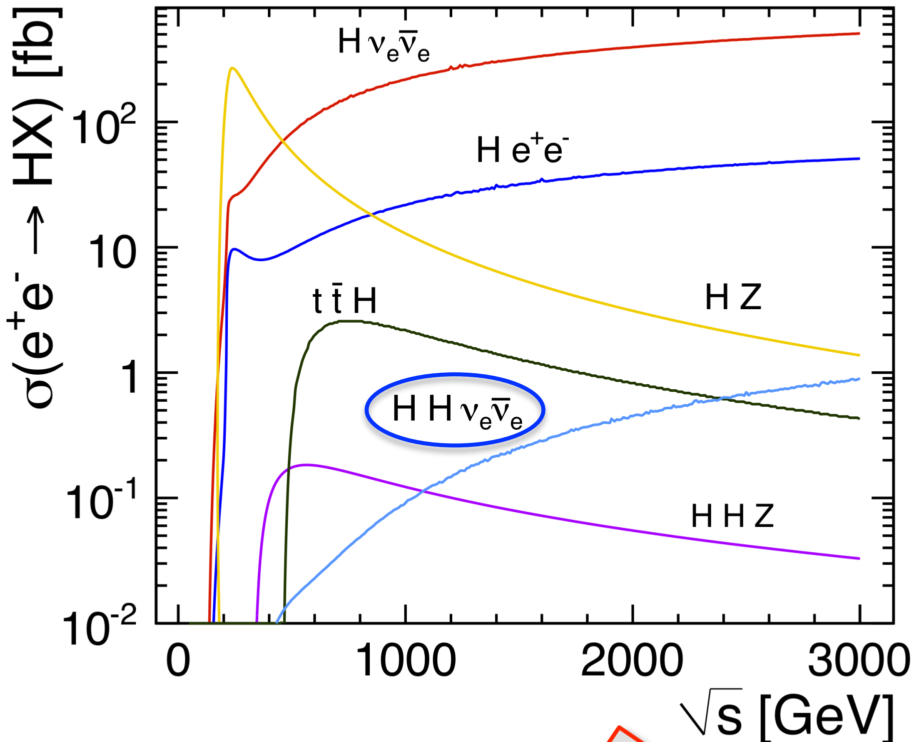
Z => μμ	~3.5%	very clean	$\Delta\sigma_{(HZ)} = \pm 4.2\%$
Z => ee	~3.5%	very clean	
Z => qq	~70%	model independent ?	$\Delta\sigma_{(HZ)} = \pm 1.8\%$

$$\Delta\left(\sigma_{HZ}\frac{\Gamma_{vis}}{\Gamma}\right) = \pm\ 1.7\% \quad + \quad \Delta\left(\sigma_{HZ}\frac{\Gamma_{invis}}{\Gamma}\right) = \pm 0.6\ \%$$

$\Delta g_{(HZZ)} = \pm 0.8\%$

double Higgs production





- The $HH\nu_e\nu_e$ cross section is sensitive to the Higgs self-coupling, λ, and the quartic g_{HHWW} coupling
- $\sigma(HH\nu_e\nu_e)$ = 0.15 (0.59) fb at 1.4 (3) TeV
  → high energy and luminosity crucial

	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
Δ(λ)	32%	16%
Δ(λ) for $p(e^-)$ = 80%	24%	12%

Work in progress !

summary of Higgs measurements

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	42%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarization	λ	–	24%	12%

Summary of CLIC Higgs benchmark simulations

http://arxiv.org/abs/1307.5288

Work in progress !

* Preliminary
+ Estimate

CLIC Higgs global fits

Work in progress !

★ Model-independent global fits

80% electron polarisation assumed above 1 TeV

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
m_H	120 MeV	30 MeV	20 MeV
λ	–	24%	11%
Γ_H [%]	5.0	3.6	3.4
g_{HZZ} [%]	0.8	0.8	0.8
g_{HWW} [%]	1.8	0.9	0.9
g_{Hbb} [%]	2.0	1.0	0.9
g_{Hcc} [%]	3.2	1.4	1.1
g_{Htt} [%]	–	4.1	4.1
$g_{H\tau\tau}$ [%]	3.5	1.6	< 1.5
$g_{H\mu\mu}$ [%]	–	14	5.6
g_{Hgg} [%]	3.6	1.1	1.0
$g_{H\gamma\gamma}$ [%]	–	5.7	< 5.7

★ ~1 % precision on many couplings

- limited by g_{HZZ} precision

★ Constrained "LHC-style" fits

- Assuming no invisible Higgs decays (model-dependent):

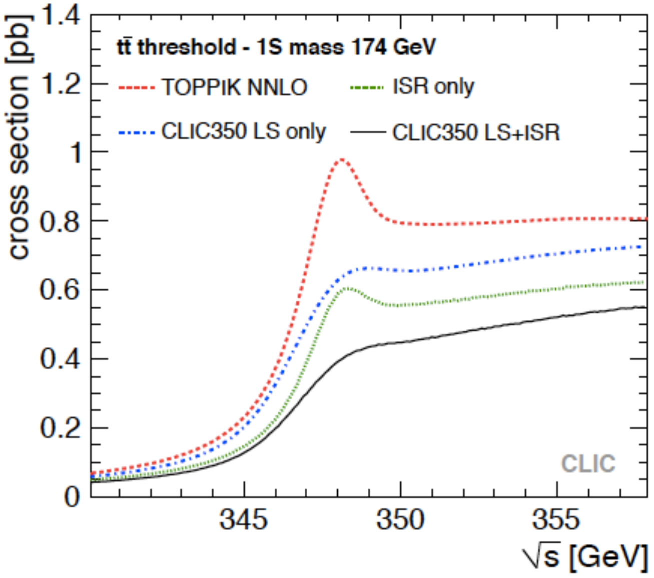
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}}$$

$$\Gamma_{H,md} = \sum_i \kappa_i^2 \, BR_i$$

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
$\Gamma_{H,model}$ [%]	1.6	0.29	0.22
κ_{HZZ} [%]	0.43	0.31	0.23
κ_{HWW} [%]	1.5	0.15	0.11
κ_{Hbb} [%]	1.7	0.33	0.21
κ_{Htt} [%]	3.1	1.0	0.74
$\kappa_{H\tau\tau}$ [%]	3.4	1.3	< 1.3
κ_{Hgg} [%]	3.6	0.76	0.56
$\kappa_{H\gamma\gamma}$ [%]	–	5.6	< 5.6

★ sub-% precision for most couplings

- Top physics

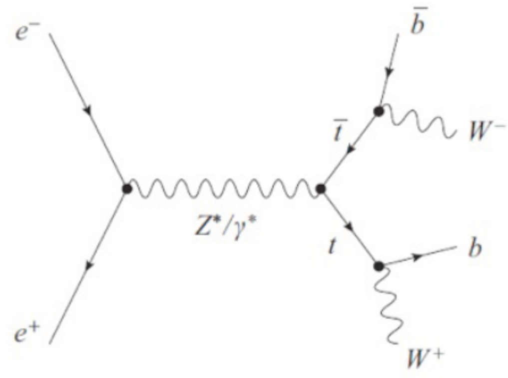


tt̄ threshold - 1S mass 174 GeV
TOPPIK NNLO
ISR only
CLIC350 LS only
CLIC350 LS+ISR
CLIC
cross section [pb]
√s [GeV]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
345
350
355

Top physics at CLIC

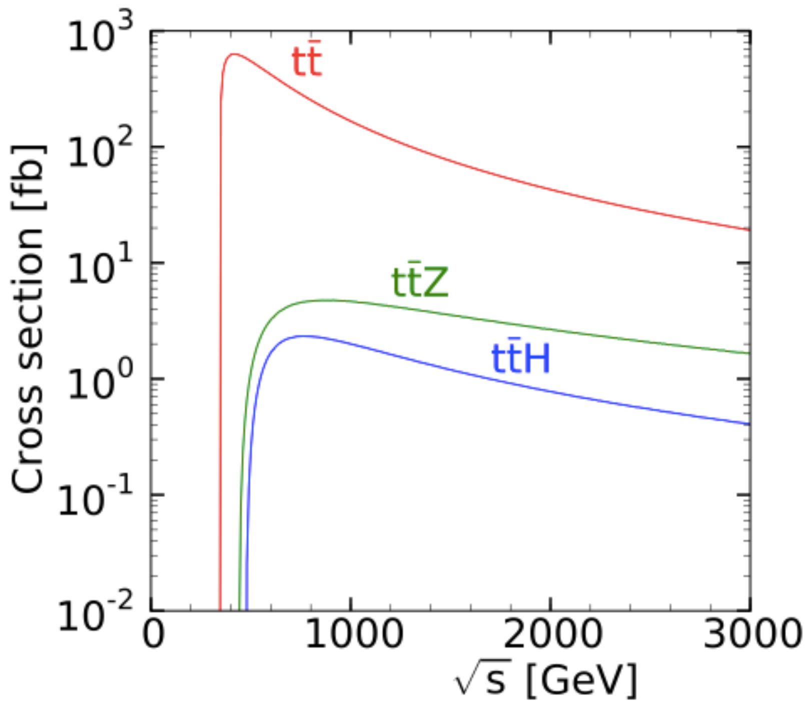
Exploration of scope for top physics at CLIC is in an early stage:

- Existing studies concentrate on top mass measurements
- Coupling to the Higgs (as part of Higgs studies)

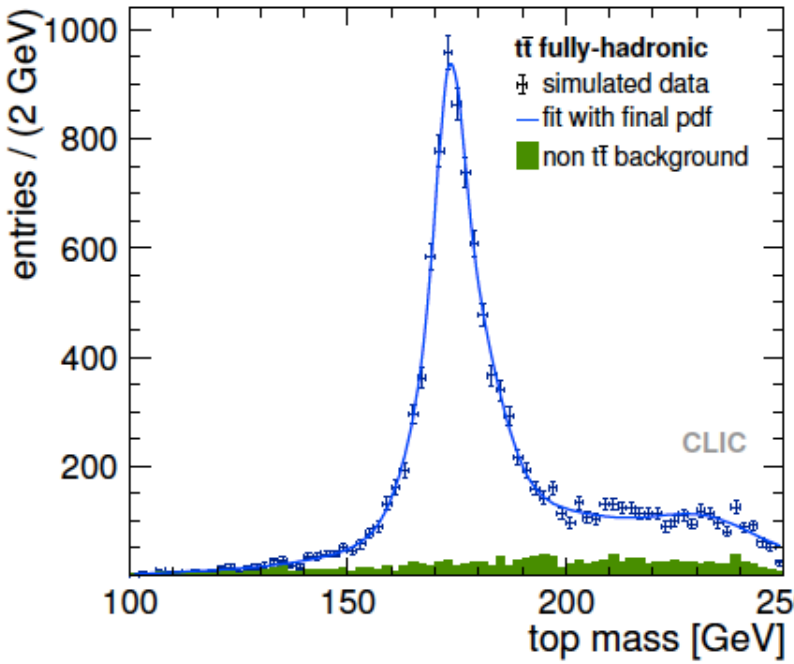


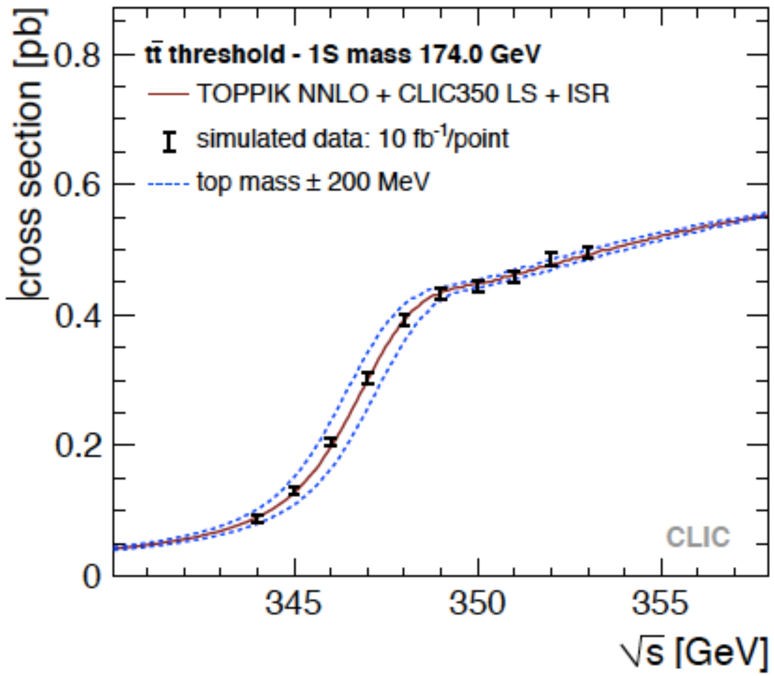
Further simulation studies of top physics at CLIC ------ coming soon

- Asymmetries to study couplings to γ, Z
- Measurement of couplings to W
- CP violation in top decays
- Flavour-changing top decays
- ....
- V_{tb} from single top events
  - 200'000 eγ=>tbν events expected at 3TeV



results of top benchmark studies





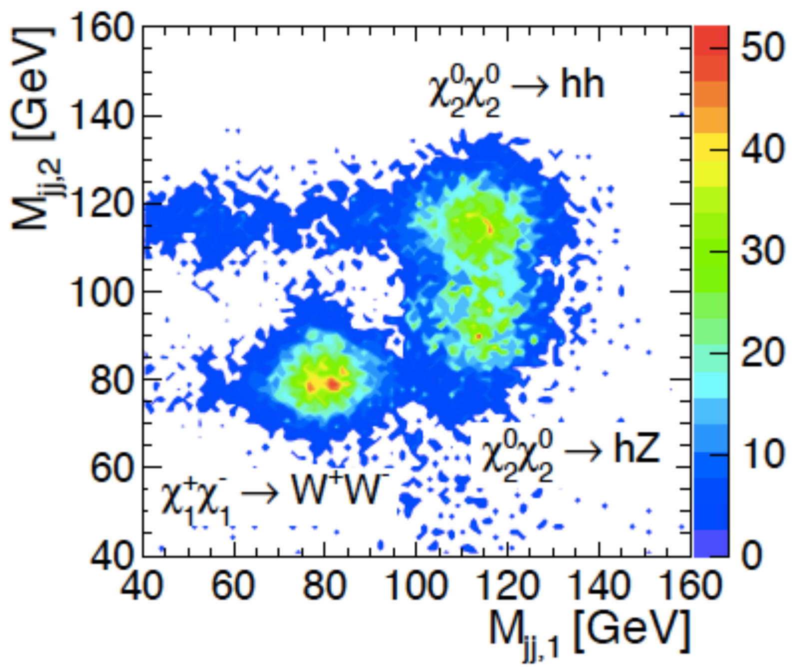
$\sqrt{s}$ (GeV)	Technique	Measured quantity	Integrated luminosity (fb^{-1})	Unit	Generator value	Stat. error
350	Threshold scan	Mass α_s	10×10	GeV	174 0.118	0.033 0.0009
500	Invariant mass	Mass	100	GeV	174	0.080

right

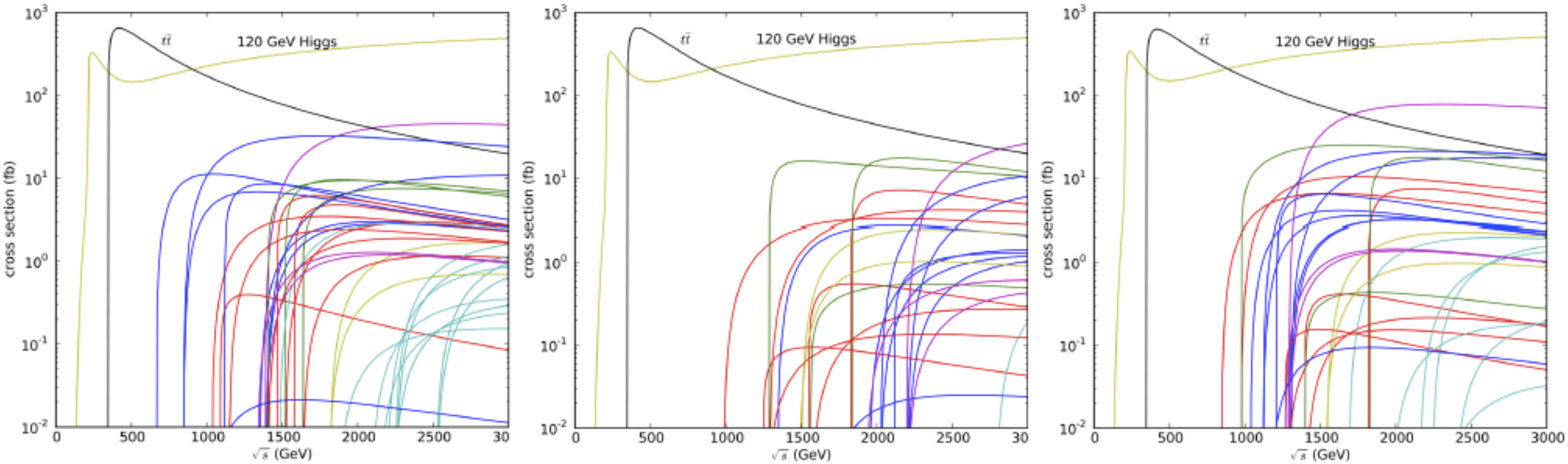
left plot

Final result is dominated by systematic errors (theor. normalisation, beam-energy systematics, translation of 1S mass to $\overline{\text{MS}}$ scheme) => 100 MeV error on top mass

- CLIC potential for New Physics



investigated SUSY models



CDR model I, 3 TeV:
- Squarks
- Heavy Higgs

CDR model II, 3 TeV:
- Smuons, selectrons
- Gauginos

CDR model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos

— Higgs
— $\tilde{\tau}, \tilde{\mu}, \tilde{e}$
— charginos
— squarks
— SM $t\bar{t}$
— $\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e$
— neutralinos

Wider capability than only SUSY: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"

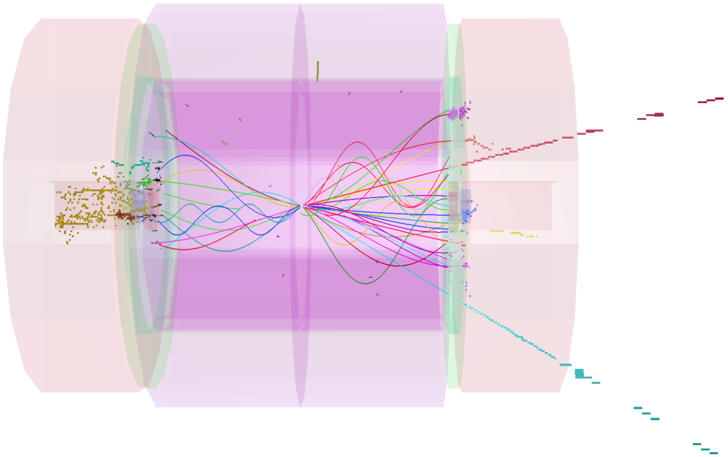
the simplest case: slepton at 3 TeV

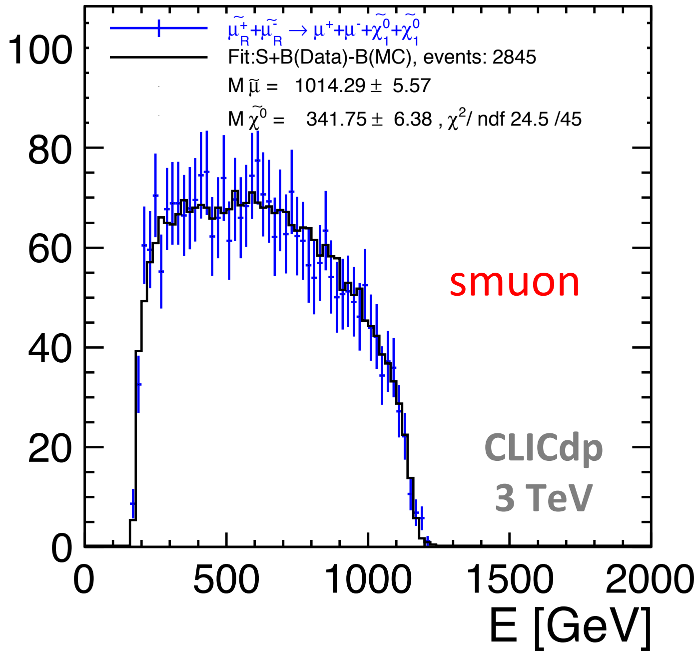
Slepton production at CLIC very clean

slepton masses ~ 1 TeV

Investigated channels include

- $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^- W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$





- Leptons and missing energy
- Masses from analysis of endpoints of energy spectra

stat. error, all channels combined →

$m(\tilde{\mu}_R)$: ± 5.6 GeV
$m(\tilde{e}_R)$: ± 2.8 GeV
$m(\tilde{\nu}_e)$: ± 3.9 GeV
$m(\tilde{\chi}_1^0)$: ± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$: ± 3.7 GeV

result: $\Delta m/m \leq 1\%$

di-jet masses: gauginos at 3 TeV

$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$

$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$

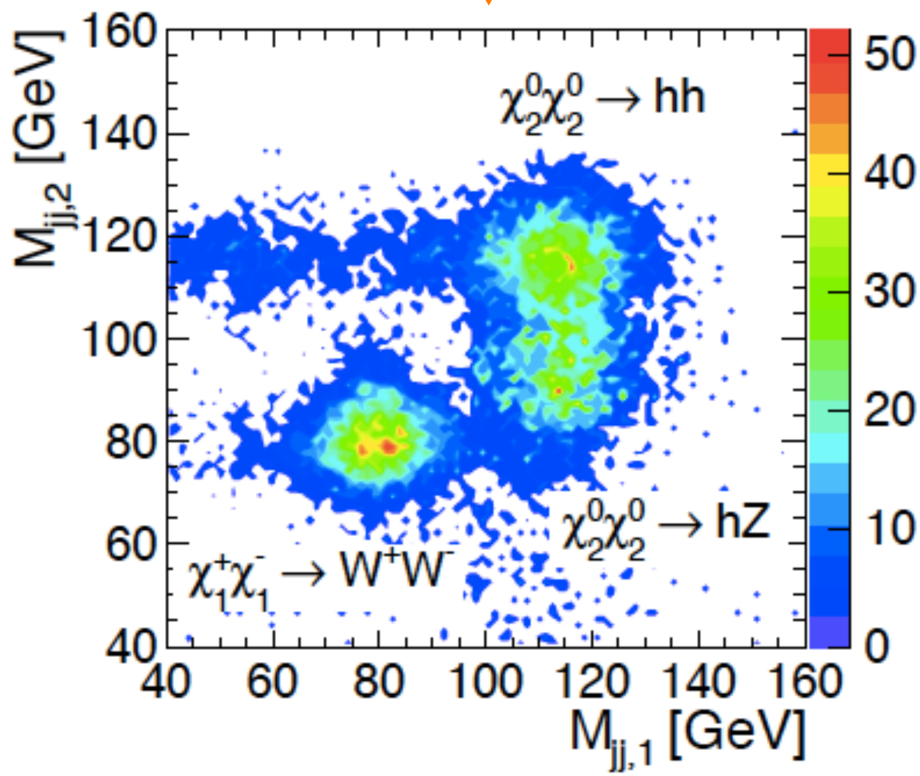
Chargino and neutralino pair production

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\,\%$$

$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\,\%$$

- separation using di-jet invariant masses (test of PFA)



$m(\tilde{\chi}_1^\pm)$: $\pm 7\,\mathrm{GeV}$

$m(\tilde{\chi}_2^0)$: $\pm 10\,\mathrm{GeV}$

use slepton study result

$m(\tilde{\chi}_1^0)$: $\pm 3\,\mathrm{GeV}$

result: $\Delta m/m \leq 1\%$

sensitivity to Higgs partners

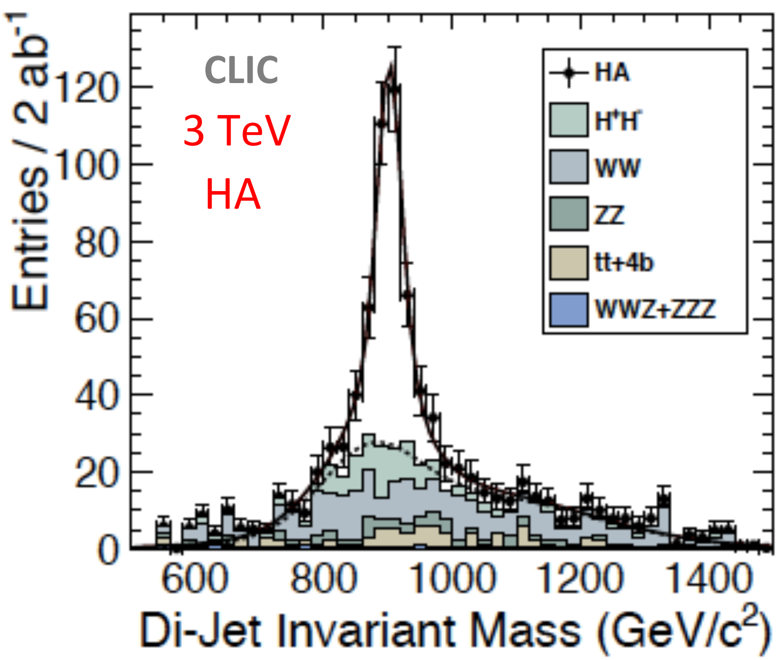
Higgs partners BSM ➔ **accessible up to √s/2**

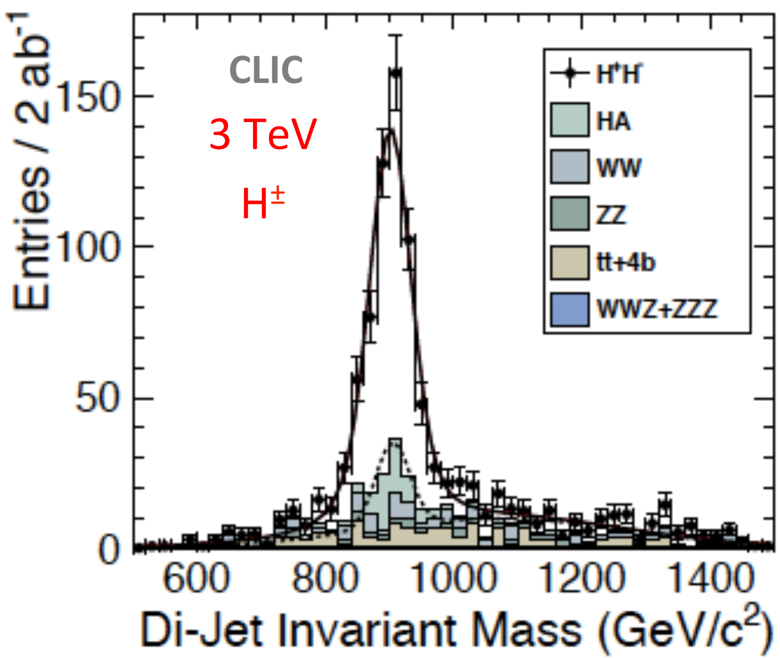
Example MSSM benchmark study at 3 TeV, 2 ab^{-1}
- e^+e^- ➔HA ➔$b\bar{b}b\bar{b}$
- e^+e^- ➔H^+H^- ➔$t\bar{b}b\bar{t}$

(H, A and H^+ almost degenerate in mass)

- Complex final states

$M_1 = 780$ GeV, $M_2 = 940$ GeV, $M_3 = 540$ GeV
$A_0 = -750$ GeV, $m_0 = 303$ GeV, $\tan\beta = 24$, $\mu > 0$
$m_t = 173.3$ GeV, $M_b(M_b) = 4.25$ GeV, $\alpha_S(M_Z) = 0.118$





result: $\Delta m/m$ = 0.3%

results of SUSY benchmarks

Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

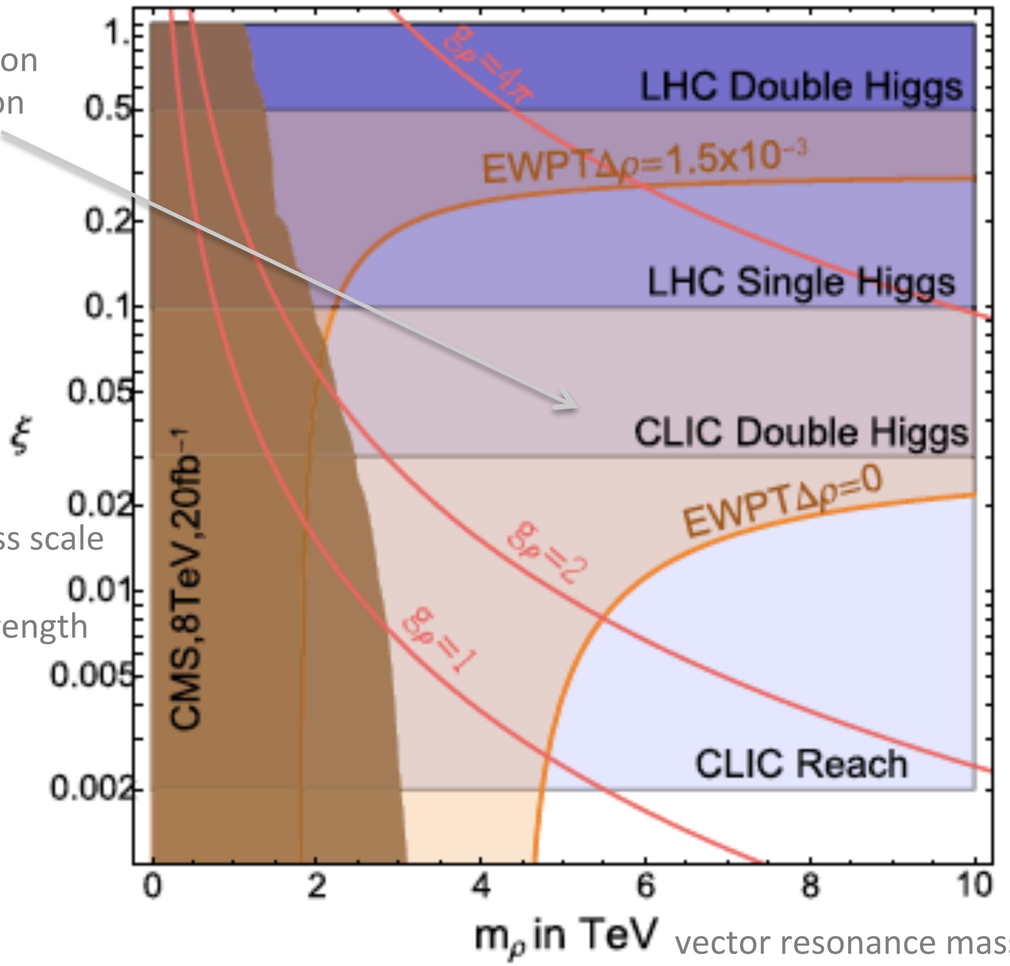
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}^+_R\tilde{\mu}^-_R \to \mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}^0_1$ mass	340.3	1.9%
		$\tilde{e}^+_R\tilde{e}^-_R \to e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}^0_1$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}^0_1\tilde{\chi}^0_1 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}^\pm_1$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}^+_1\tilde{\chi}^-_1 \to \tilde{\chi}^0_1\tilde{\chi}^0_1 W^+W^-$	II	$\tilde{\chi}^\pm_1$ mass	643.2	1.1%
		$\tilde{\chi}^0_2\tilde{\chi}^0_2 \to h/Z^0\, h/Z^0\, \tilde{\chi}^0_1\tilde{\chi}^0_1$		$\tilde{\chi}^0_2$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}^0_1\tilde{\chi}^0_1$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}^+_R\tilde{\mu}^-_R \to \mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}^0_1$ mass	357.8	0.1%
		$\tilde{e}^+_R\tilde{e}^-_R \to e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}^0_1$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}^0_1\tilde{\chi}^0_1 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}^\pm_1$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}^+_1\tilde{\tau}^-_1 \to \tau^+\tau^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}^+_1\tilde{\chi}^-_1 \to \tilde{\chi}^0_1\tilde{\chi}^0_1 W^+W^-$	III	$\tilde{\chi}^\pm_1$ mass	487	0.2%
		$\tilde{\chi}^0_2\tilde{\chi}^0_2 \to h/Z^0\, h/Z^0\, \tilde{\chi}^0_1\tilde{\chi}^0_1$		$\tilde{\chi}^0_2$ mass	487	0.1%

Large part of the SUSY spectrum measured at <1% level

composite Higgs bosons

allowed region EW precision tests

dimensionless scale parameter, measures strength of Higgs interactions

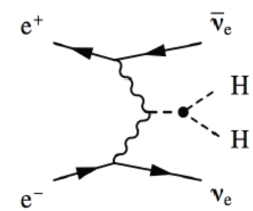


vector resonance mass of the composite theory

LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search WZ =>3 leptons

Allows to probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV

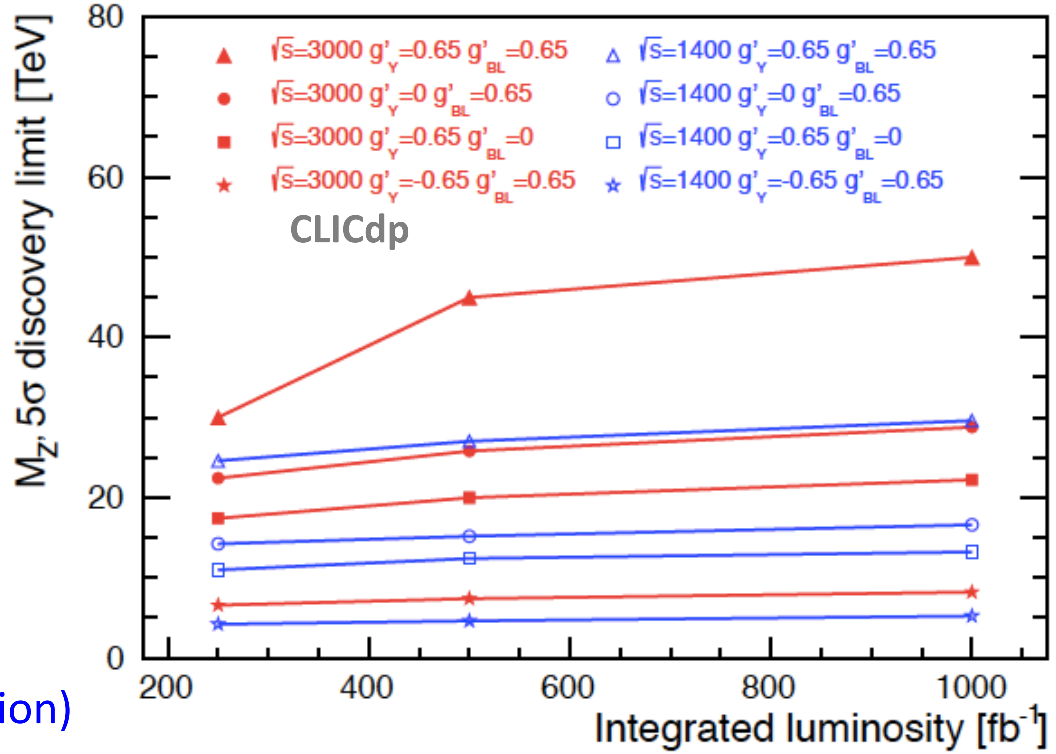
(70 TeV scale if combined with single Higgs production)

precision studies of $e^+e^- \rightarrow \mu^+\mu^-$

Minimal anomaly-free Z' model

$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$

(charge of SM fermions under U(1)' symmetry)



Observables:

- Total $e^+e^- \Rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry (±80% e^- polarisation)

If LHC discovers Z'

(e.g. for $M_{Z'}$=5 TeV)

Precision measurement of effective couplings

Otherwise:

Discovery reach up to tens of TeV (depending on the couplings)

summary

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

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

Energy staging ➔ optimal physics exploration

- **350 – 375 GeV**, 500 fb^{-1} : precision Higgs and top physics
- **~1.4 TeV**, 1.5 ab^{-1} : **targeted at BSM physics,** precision Higgs
- **~ 3 TeV,** 2 ab^{-1} : **targeted at BSM physics,** precision Higgs

Exact energies of TeV stages will depend on LHC results

Thank you !

http://clicdp.web.cern.ch/

SPARE SLIDES

why a **linear** e^+e^- collider?

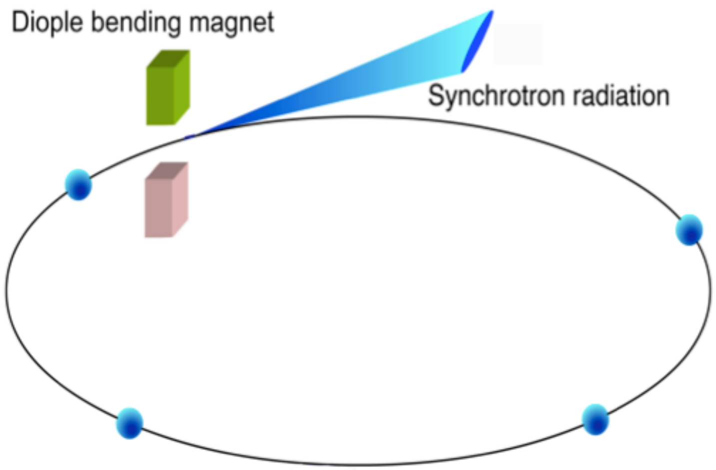
Answer: synchrotron radiation

Photons are emitted when bending the beam
Emitted power *P*:

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

ρ particle bending radius



energy^4
(particle mass)$^{-4}$
(bending radius)$^{-2}$

electrons are very light !

At LEP (~105 GeV electron beams) 2.75 GeV were lost per particle and per turn

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

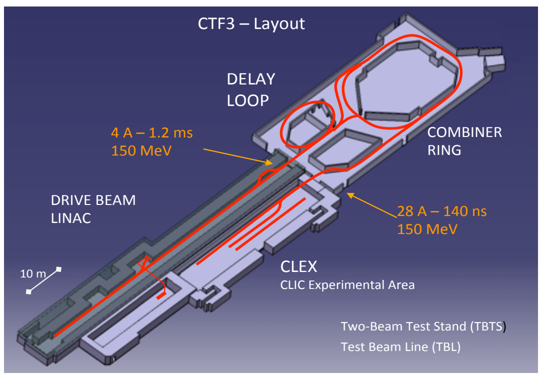
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

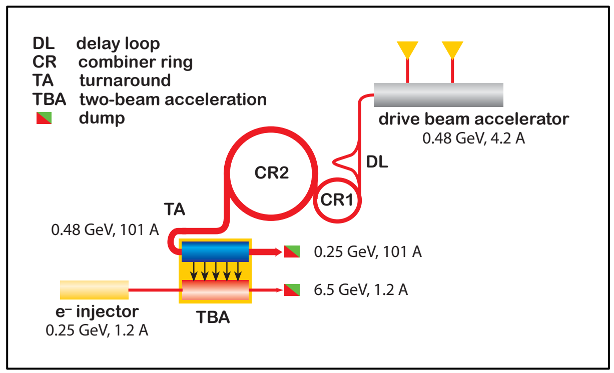
Prepare detailed Technical Proposals for the detector-systems.

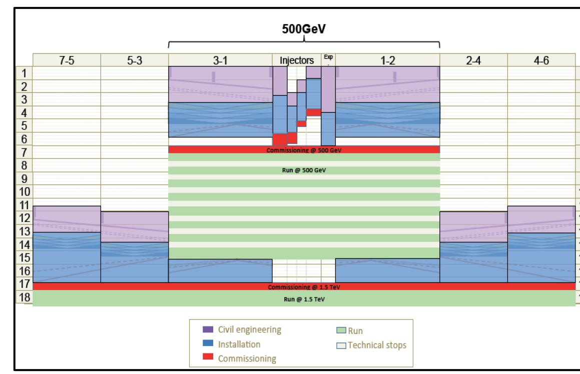
Construction Phase

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.

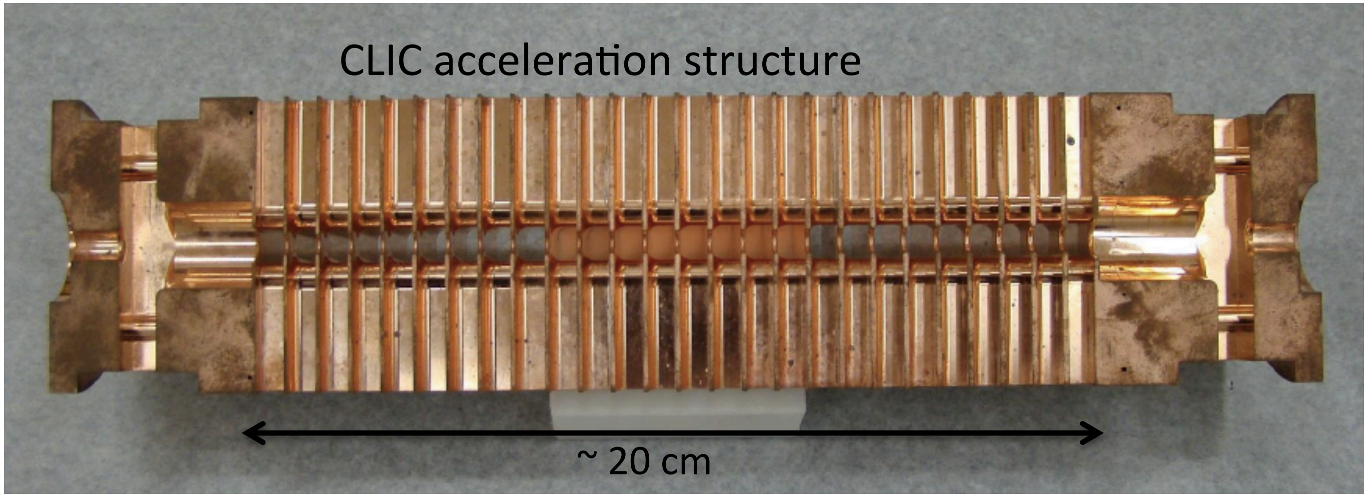
2024-25 Construction Start

Ready for full construction and main tunnel excavation.

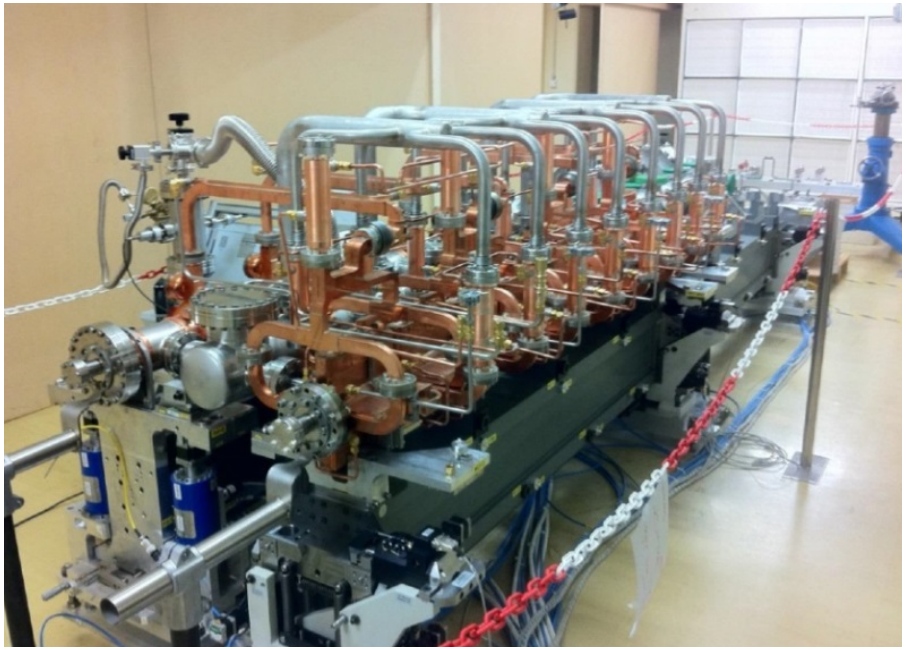
Commissioning

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

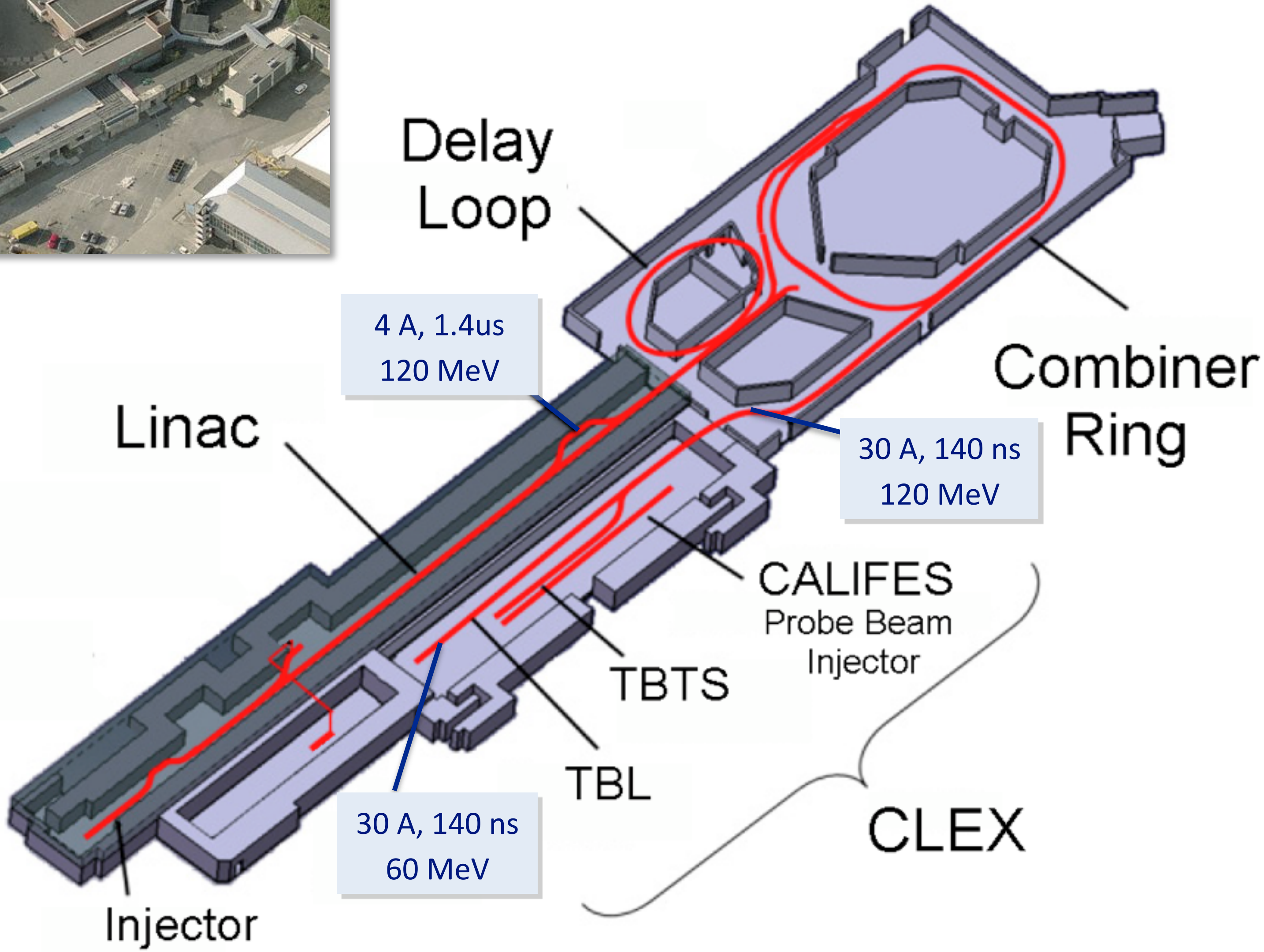
two-beam acceleration



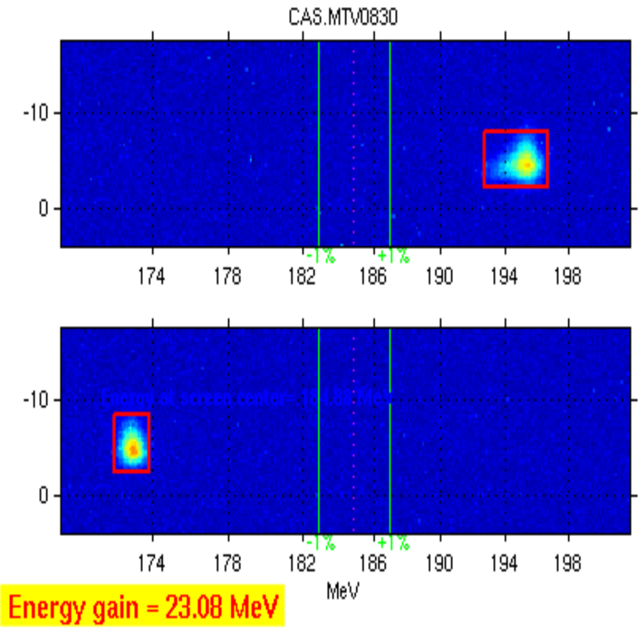
CLIC 2-beam module

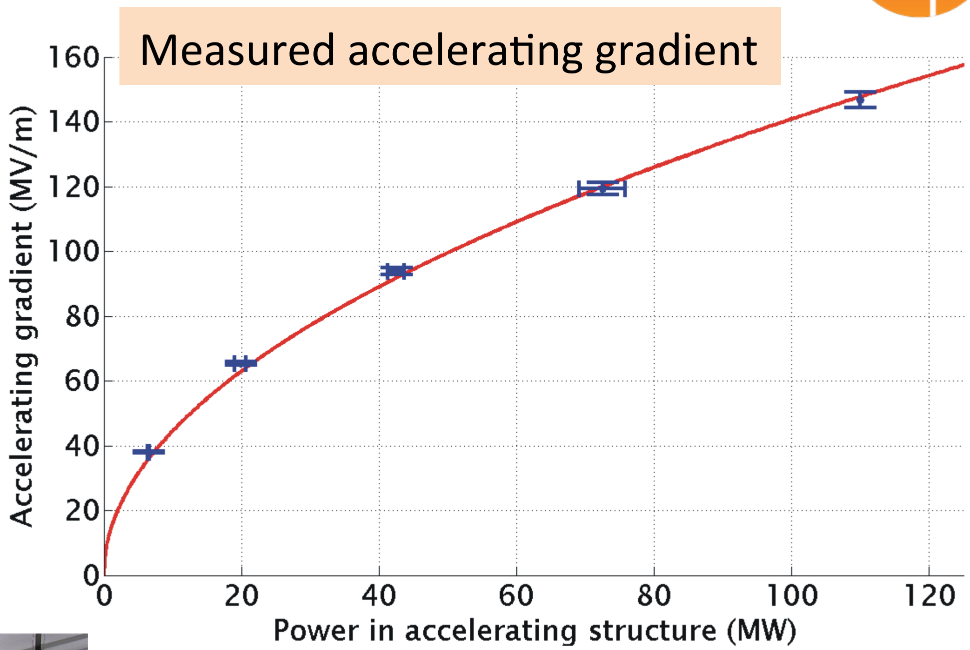


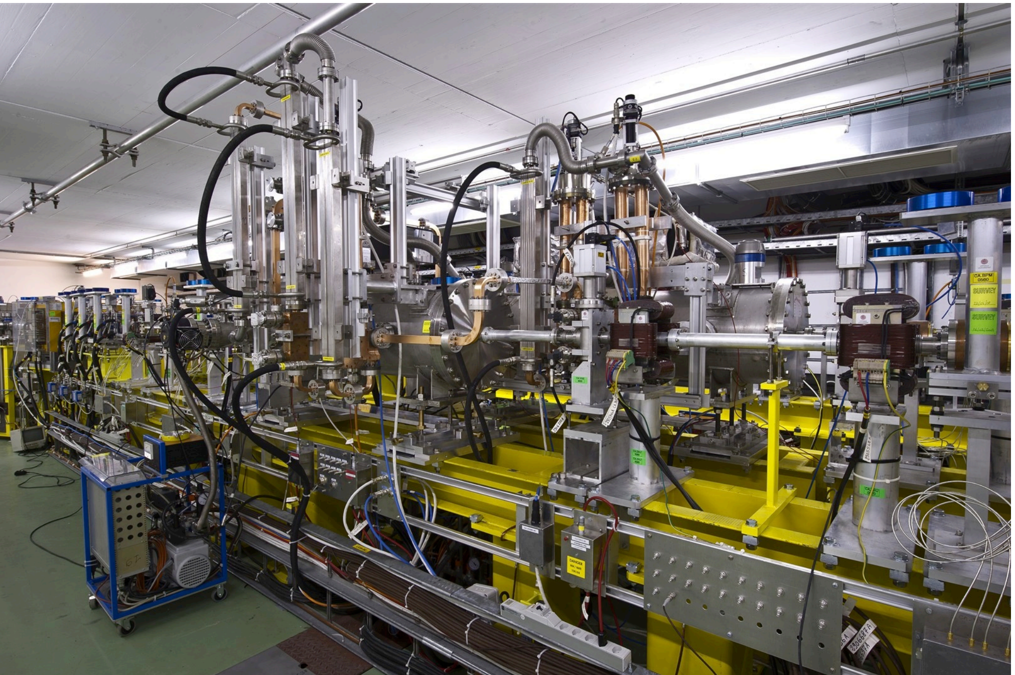
CLIC Test Facility (CTF3)



TBTS: Two Beam Acceleration



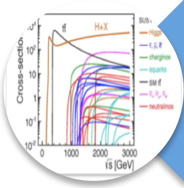




Maximum gradient 145 MV/m

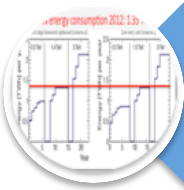
Consistency between
- produced power
- drive beam current
- test beam acceleration

Main activities and goals for 2018

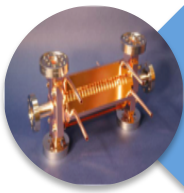


Physics studies related to energy frontier capabilities and potential new physics as it emerges from LHC

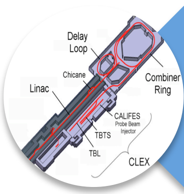
Detector R&D compatible with CLIC specifications



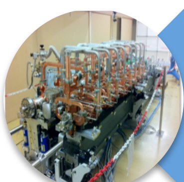
A re-baselined staged project plan, cost and power optimisation, increased industrialisation effort for cost-drivers



High Gradient structure development and significantly increased test-capacity for X-band RF-structures



System-test programmes in CTF3, at ATF and FACET, as well as system-tests in collaborative programmes with light-source laboratories



Technical systems developments, related among others to complete modules, alignment/stability, instrumentation and power sources

staged approach, scenario A+B

A

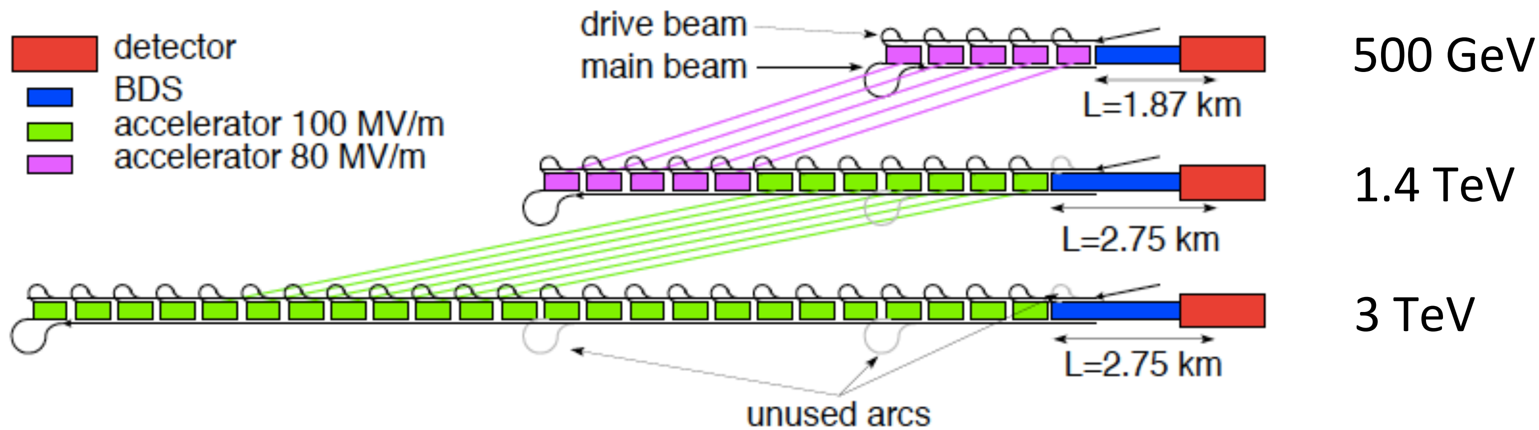


Fig. 3.5: Simplified upgrade scheme for CLIC staging scenario A. The coloured lines indicate the required movement of the modules from one stage to the next.

B

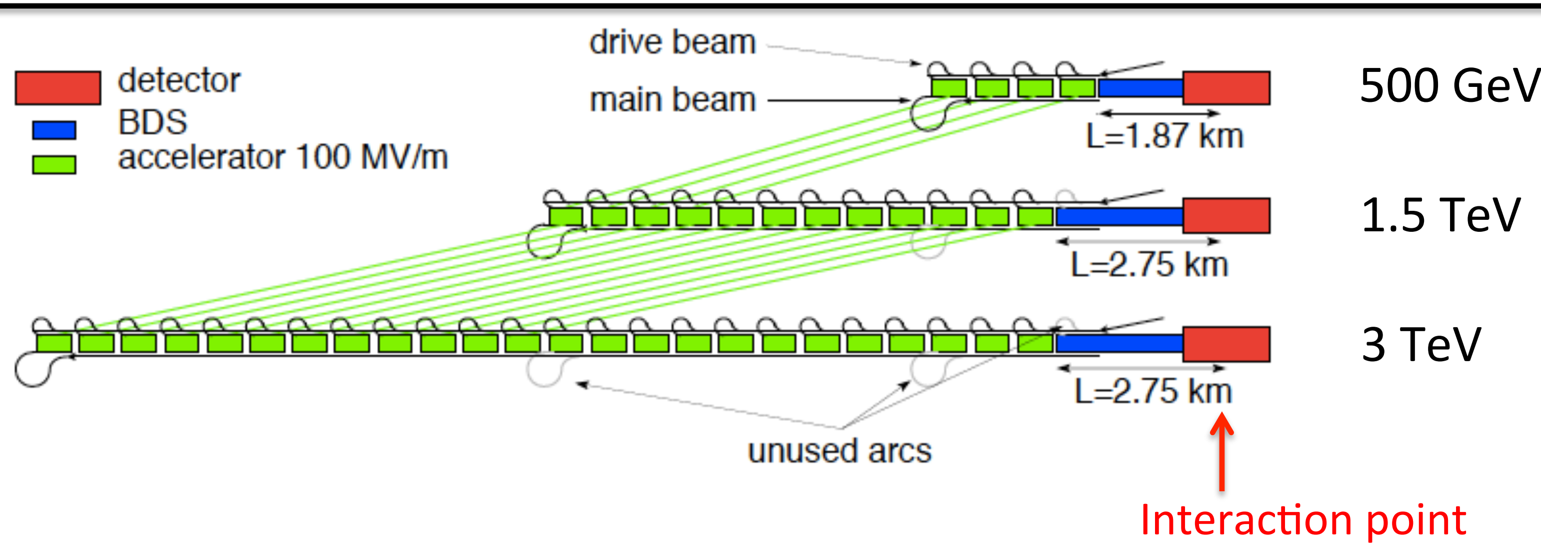


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

CLIC layout at 500 GeV

A

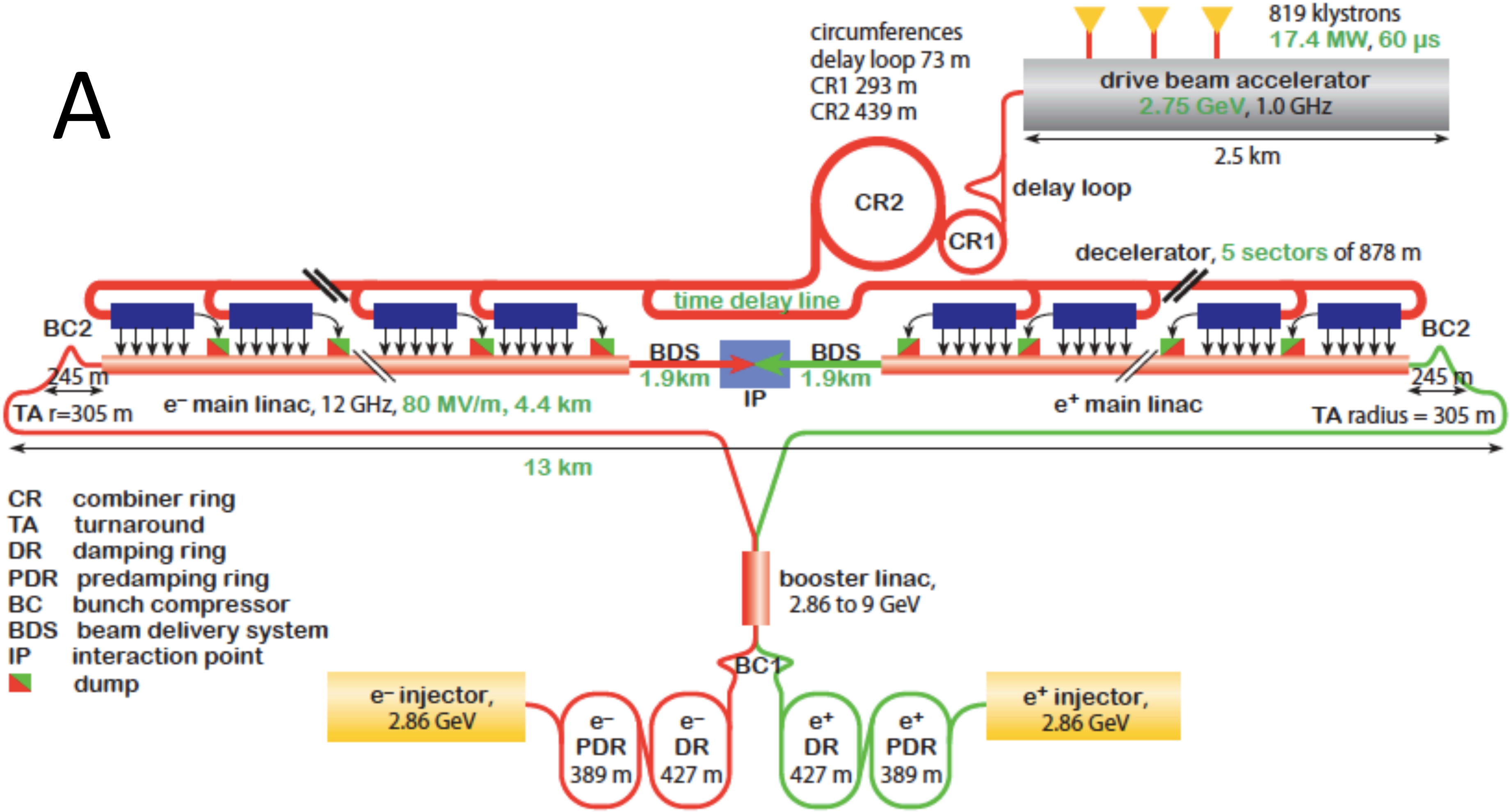


Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV. (scenario A)

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	$\mathscr{L}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	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"**

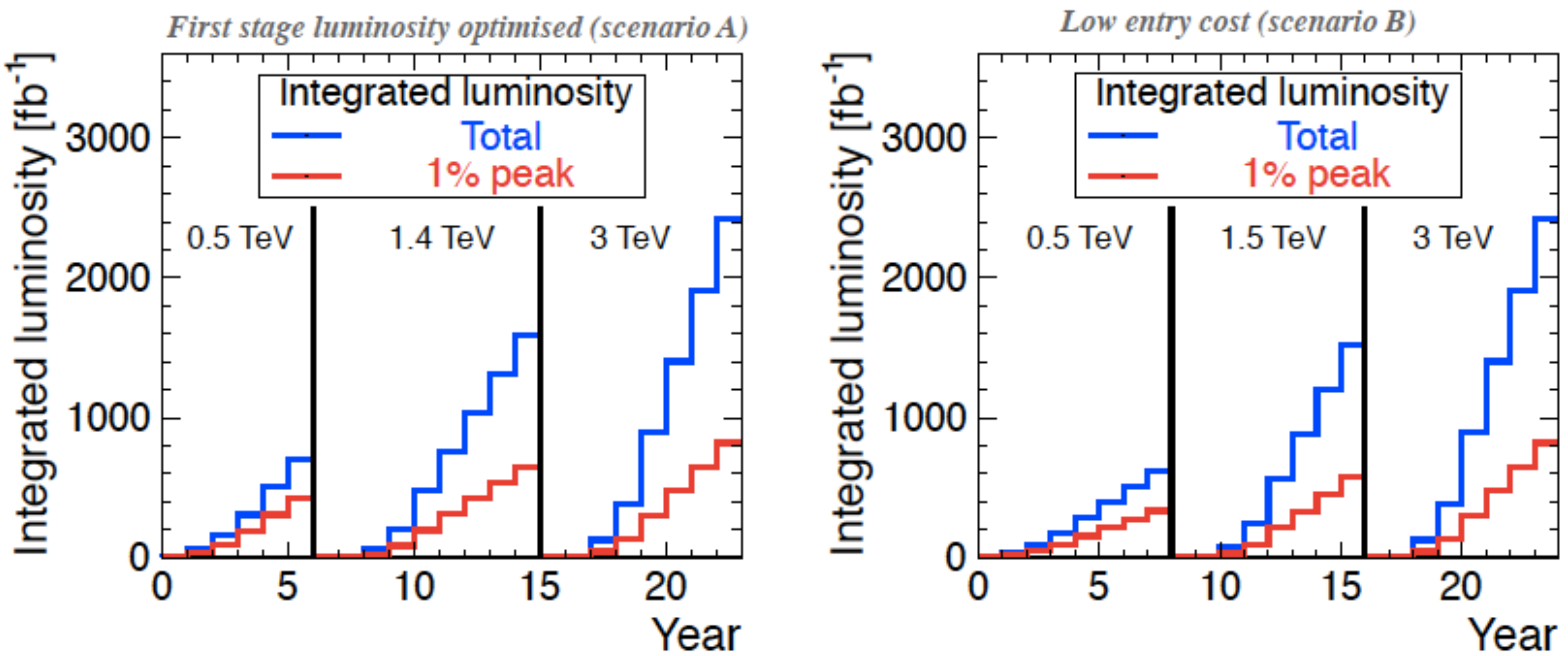


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two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

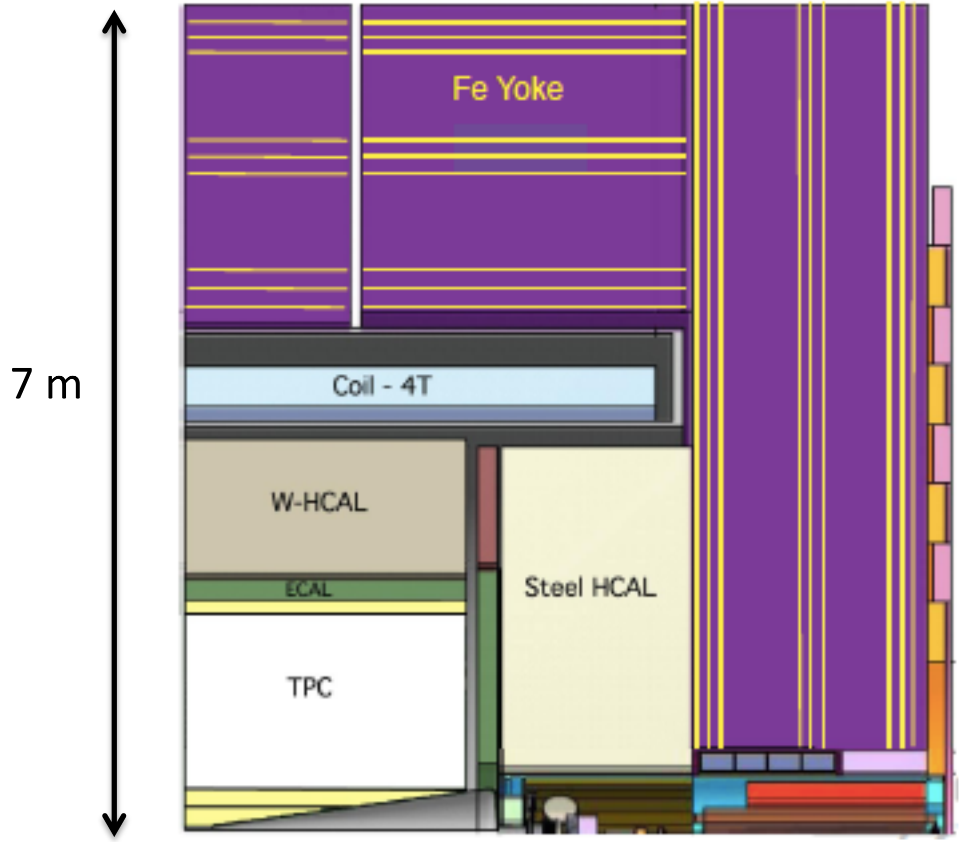
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

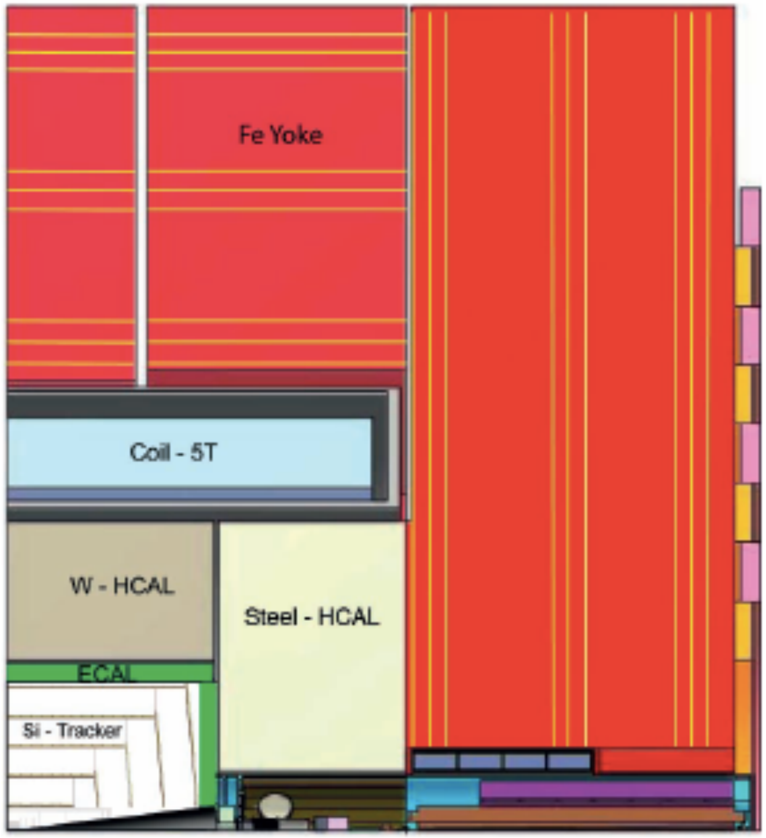
Based on initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

CLIC_ILD



CLIC_SiD



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**

CLIC vertex detector R&D roadmap

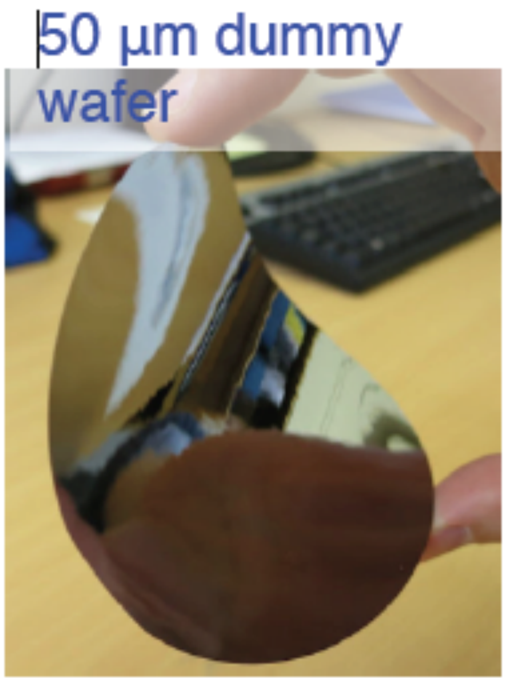
Hybrid approach pursued: (<= other options possible)

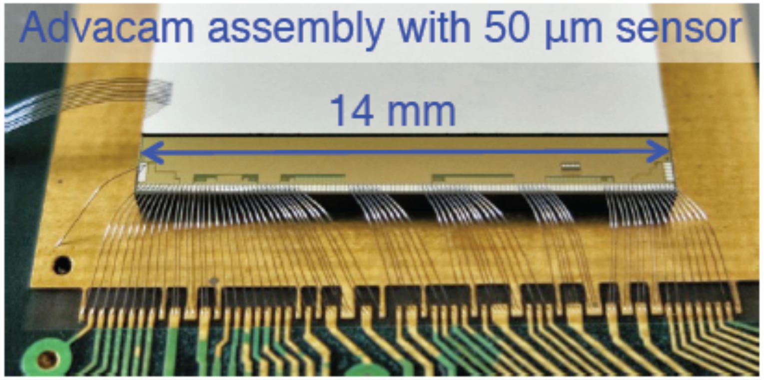
- Thin (~50 µm) silicon sensors
- Thinned high-density readout ASIC
  - R&D within Medipix/Timepix effort
- Low-mass interconnect
- Power pulsing
- Air cooling

CLICpix demonstrator ASIC

64×64 pixels, fully functional

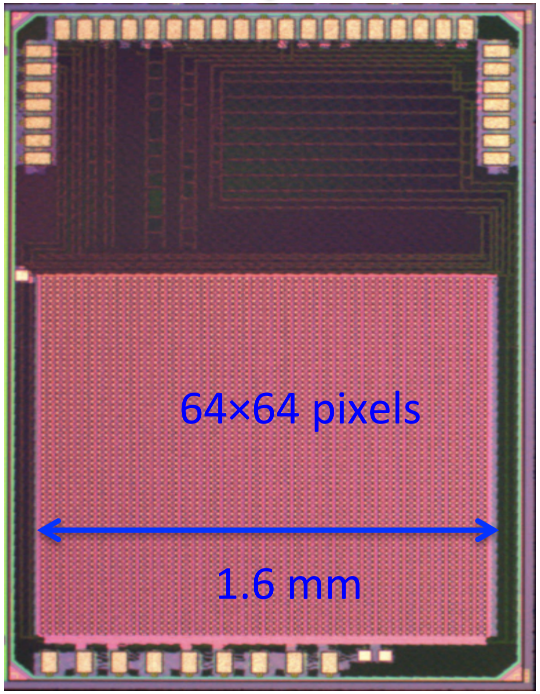
- 65 nm technology
- 25×25 µm^2 pixels
- 4-bit ToA and ToT info
- Data compression
- Pulsed power: 50 mW/cm^2





Very thin sensors !

Successfully tested at DESY test beam (with existing Timepix ASIC)



Hybrid vertex detector with HV-CMOS

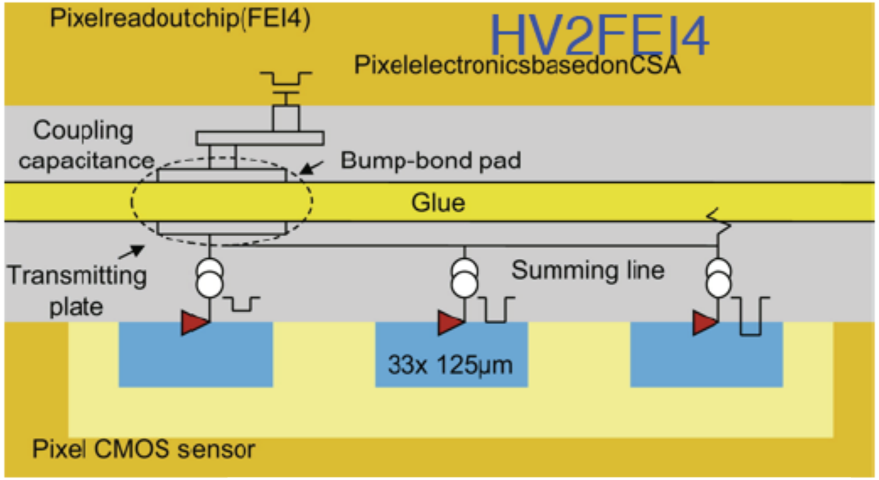
Pursuing an alternative readout option

Hybrid option with HV-CMOS:
Capacitive Coupled Pixel Detector (CCPD)

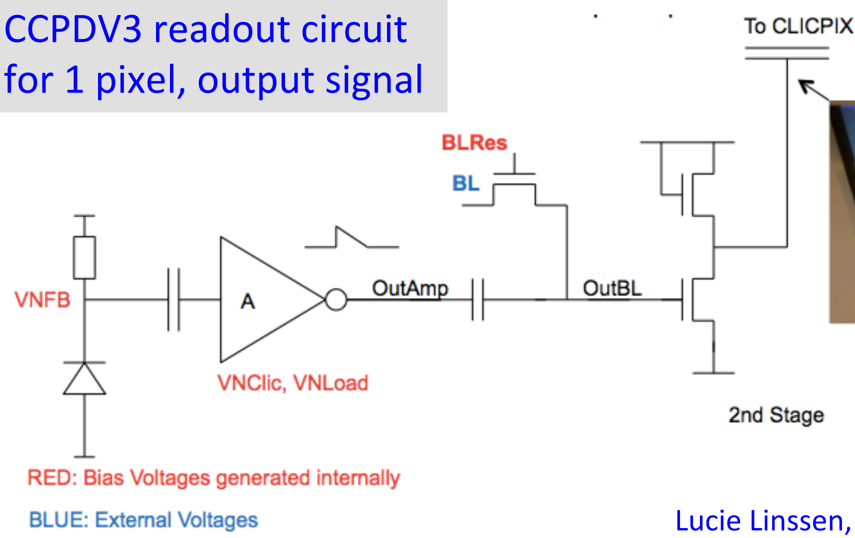
- HV CMOS chip as integrated sensor+ amplifier
- Capacitive coupling to readout chip through layer of glue => no bump bonding

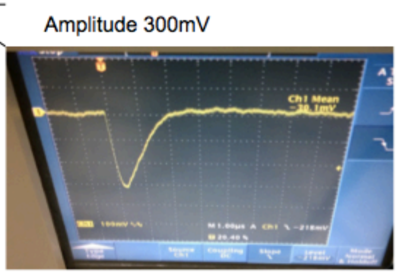
(ongoing R&D with FEI4, Timepix, CLICpix)

Status: first beam tests in August 2014

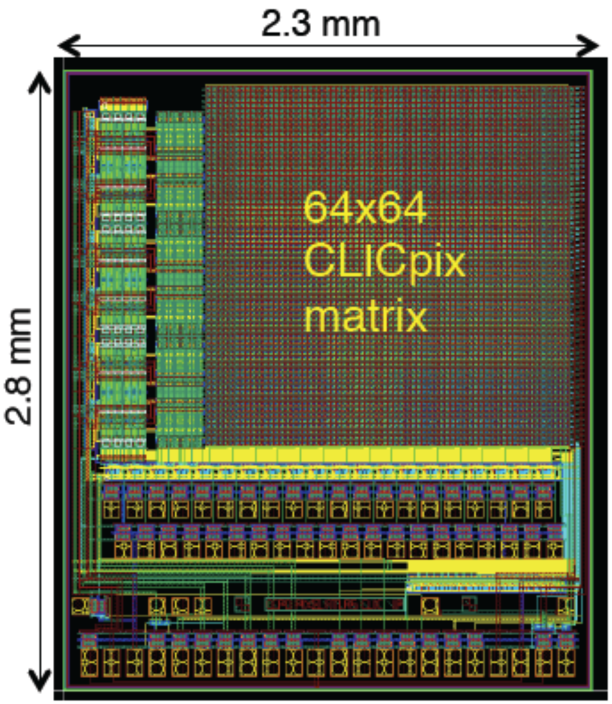


CCPDV3 readout circuit for 1 pixel, output signal





signal from HV-CMOS part alone

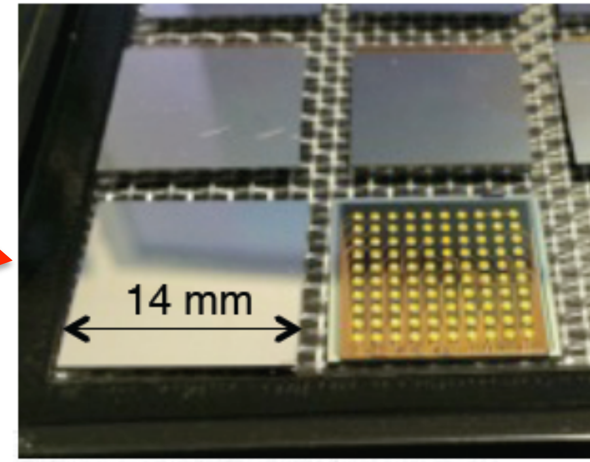


CCPDV3

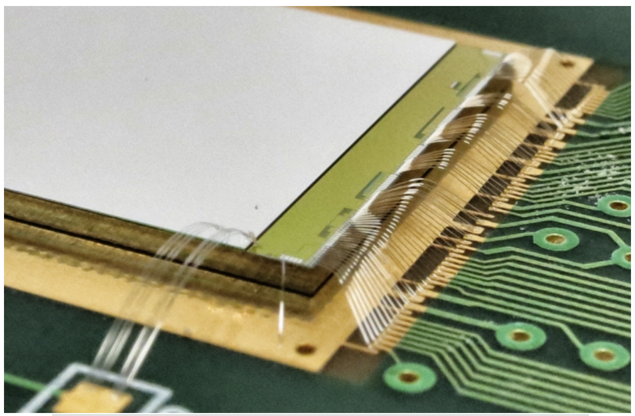
CLIC vertex detector: thin assemblies

Ultimate aim:

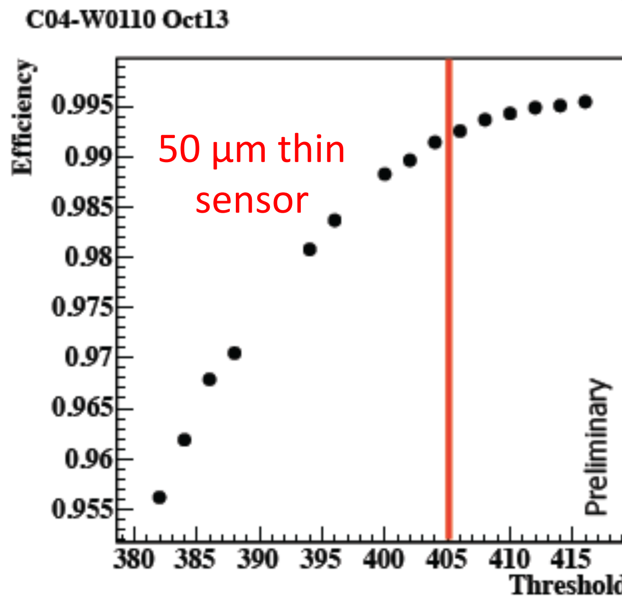
- 50 µm sensor on 50 µm ASIC
- Slim-edge sensors
- Through-Silicon Vias (TSV)
  - eliminates need for wire bonds
  - 4-side buttable chip/sensor assemblies
  - large active surfaces => less material



Medipix3RX with TSV by (CEA-LETI)



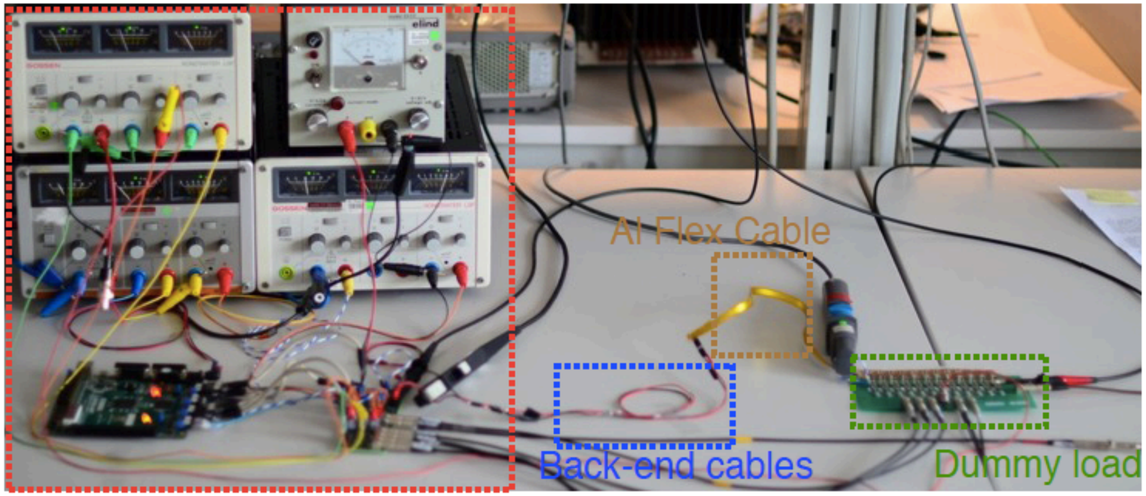
50 µm thin sensor on Timpix tested at test beam !



99.2% eff. at operating threshold

First successful picture using Medipix3RX with TSV

CLIC vertex R&D: power pulsing



Controlled current source

Design for low mass !

- Power pulsing with local energy storage in Si capacitors and voltage regulation with Low-Dropout Regulators (LDO)
- FPGA-controlled current source provides small continuous current

Local material: now 0.1%X_0/layer, can be reduced to 0.04%X_0/layer (Si-capacitor technology)

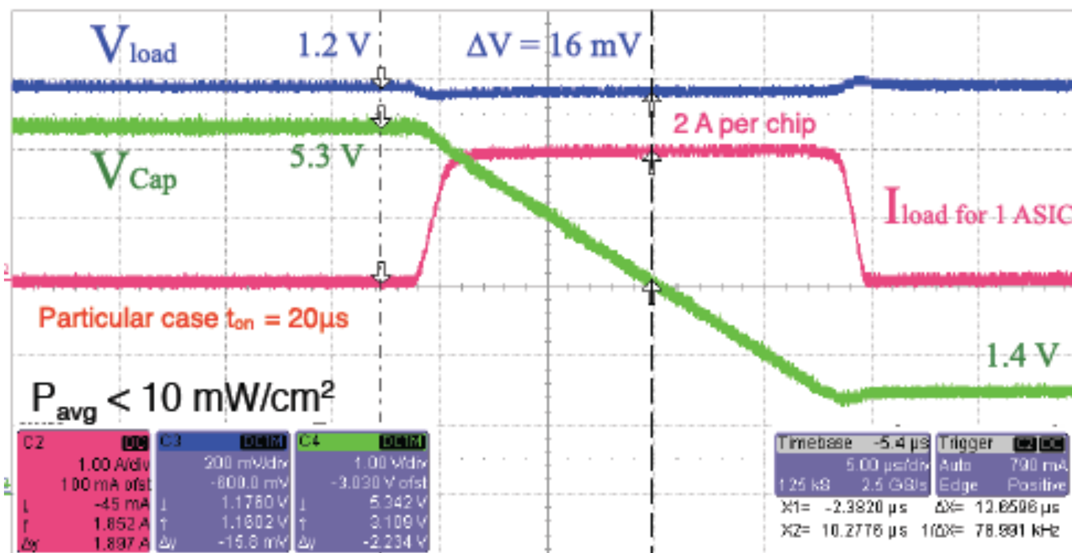
Analog:

- Voltage drop ~16 mV
- Measured average power dissipation <10 mW/cm^2

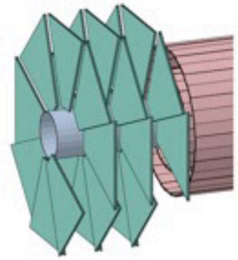
Digital

- Voltage drop ~70 mV
- Measured average power dissipation <35 mW/cm^2

Total dissipation <50 mW/cm^2

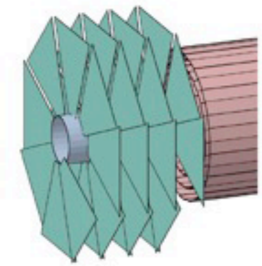


Vertex det. geometry optimisation



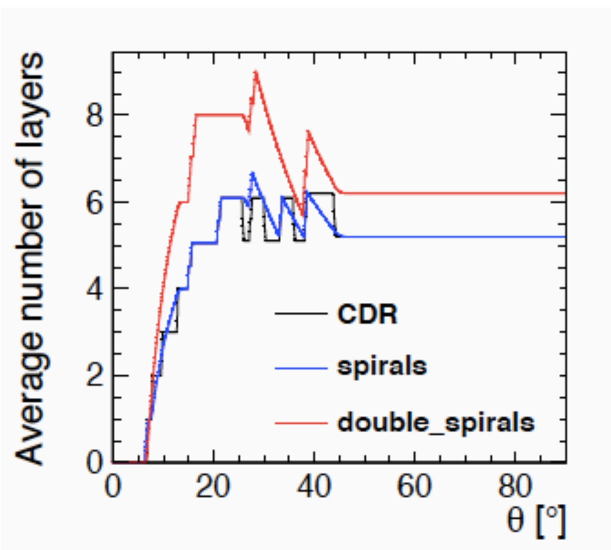
Double-sided layers

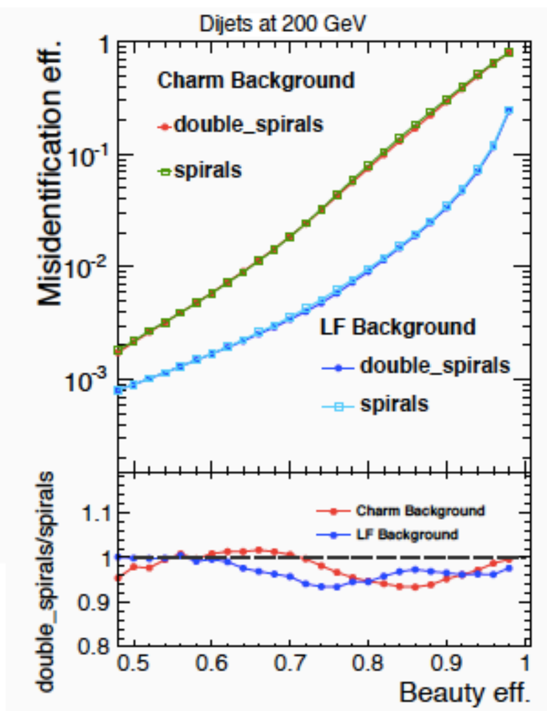
Comparison of 5 single-sided layers and 3 double-sided layers

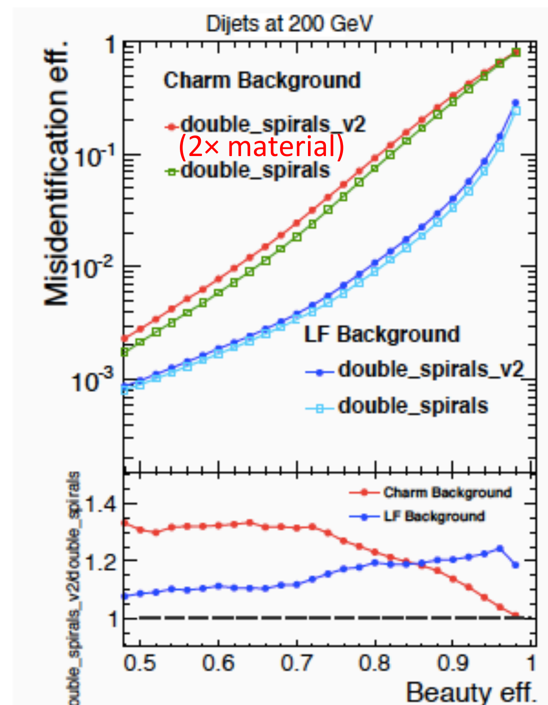


Single-sided layers

- Similar flavour tag performance for two considered layouts
- Increasing the material has a larger impact than the layout

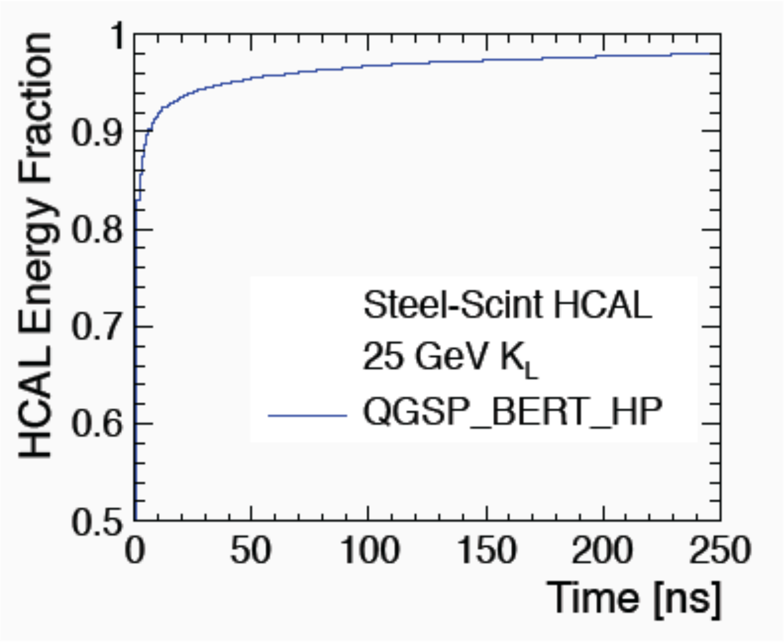


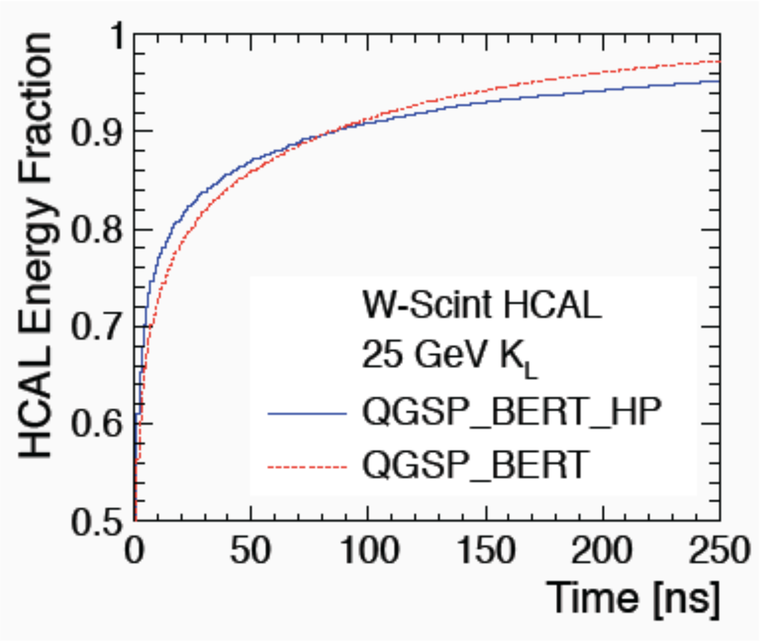




7

time development in hadronic showers



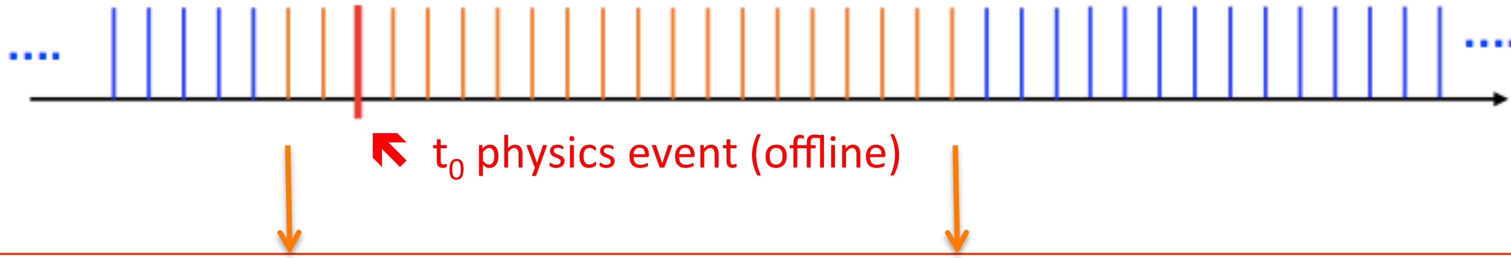


- In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight).
- In tungsten this takes almost ~100 ns. (depends on active material)
  - Response is slower due to the much larger component of the energy in slow neutrons.

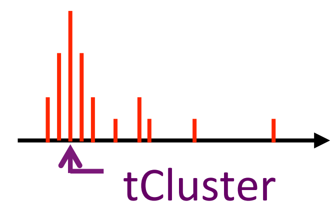
➢ Need to integrate over ~100 ns in reconstruction, keeping out pile-up hits…

background suppression at CLIC

Triggerless readout of full train



- **Full event reconstruction + PFA analysis with background overlaid**
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF
- **Then apply cluster-based timing cuts**
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects



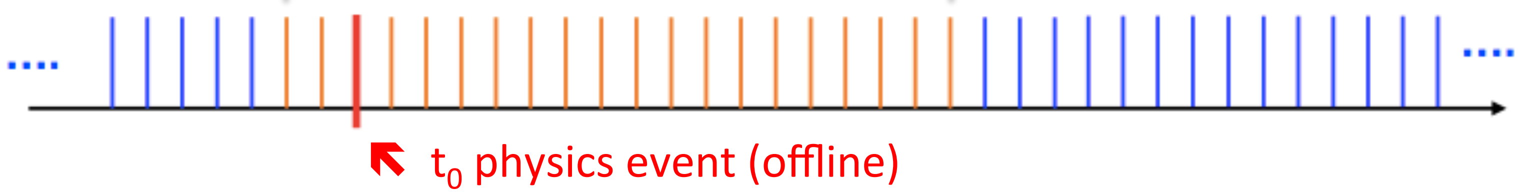
+

- **Use well-adapted jet clustering algorithms**
  - Making use of LHC experience (FastJet)

time window / time resolution

The event reconstruction software uses:

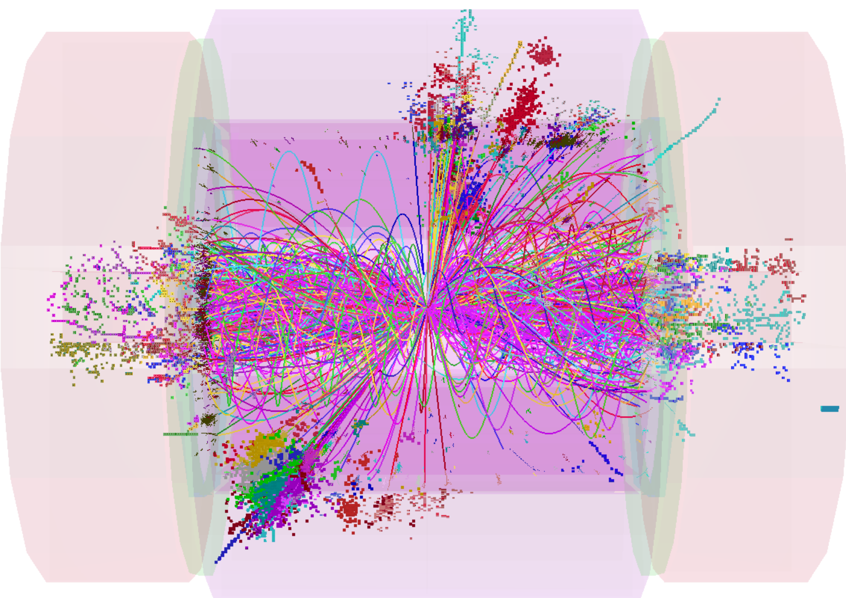
Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a



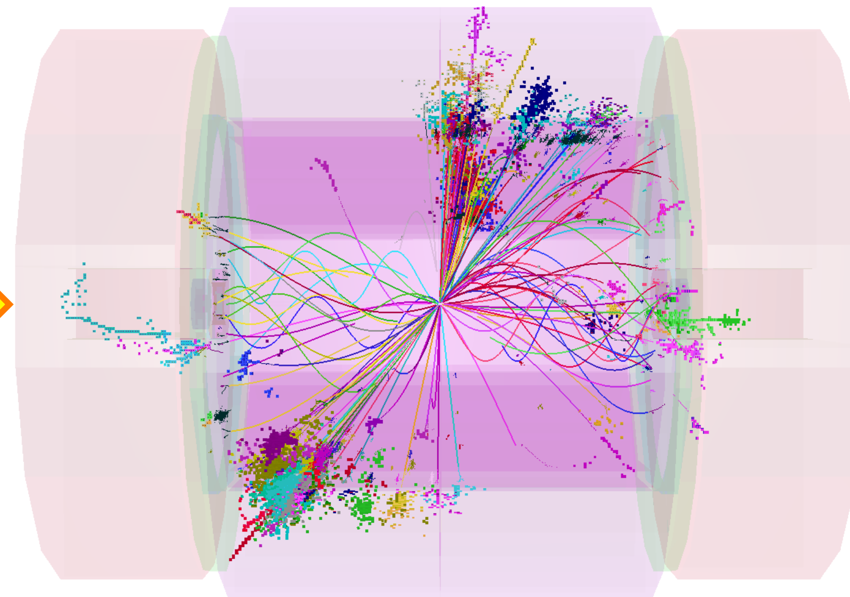
Translates in precise **timing requirements** of the sub-detectors

combined p_T and timing cuts

1.2 TeV



100 GeV



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

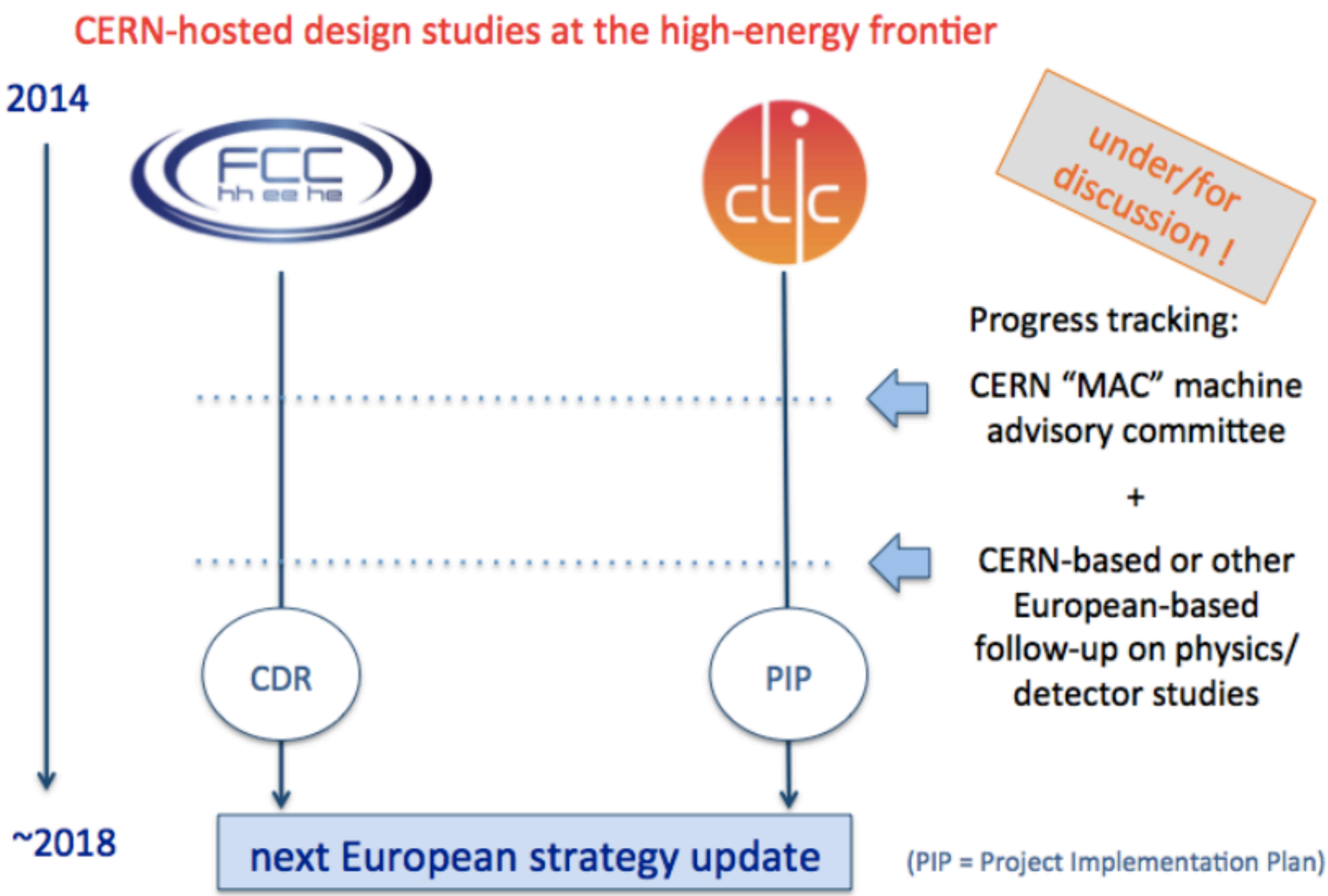
1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

PFO-based timing cuts

Region	p_t *range*	Time cut
Photons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
Neutral hadrons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.5$ nsec $t < 1.5$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
Charged PFOs		
all	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 3.0$ nsec $t < 1.5$ nsec

CLIC and FCC


CERN-hosted design studies at the high-energy frontier
2014
FCC
hh ee he
CLIC
under/for discussion !
Progress tracking:
CERN "MAC" machine advisory committee
+
CERN-based or other European-based follow-up on physics/ detector studies
CDR
PIP
~2018
next European strategy update
(PIP = Project Implementation Plan)