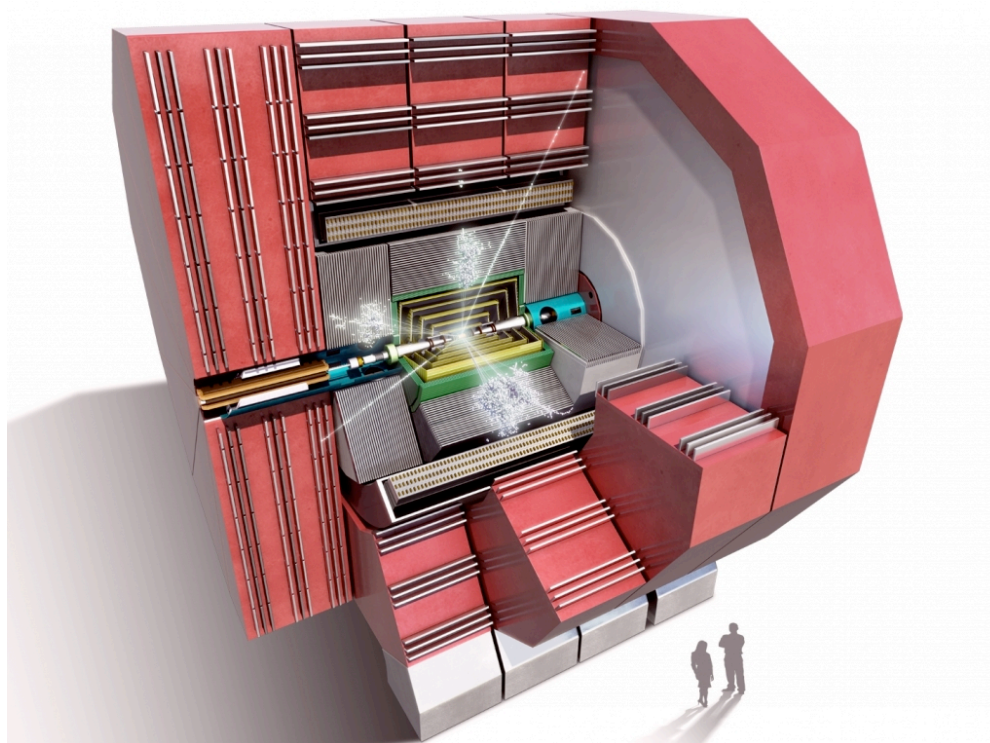


The Compact Linear e^+e^- Collider (CLIC) project



Lucie Linssen, CERN
on behalf of the CLICdp collaboration

outline

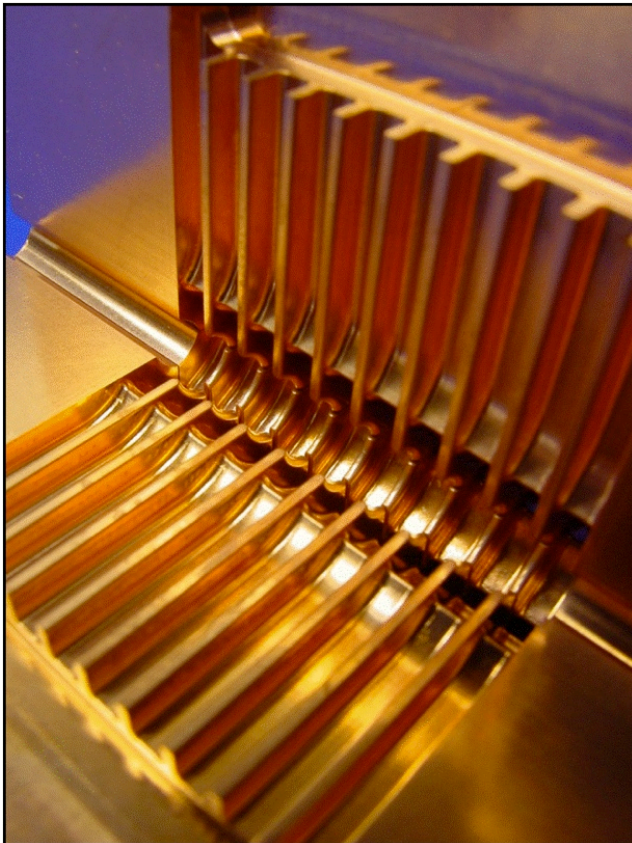


- Introduction
- The CLIC accelerator
- CLIC detector concept and experimental conditions
- CLIC energy staging choice and physics potential
- Summary

CLIC in just a few words



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



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

- **1980-ies**: => start of (a modest) CLIC accelerator R&D
- **2004**: Strengthening of CLIC accelerator R&D and start of CLIC/CTF3 collab.
- **2008**: New start of Detector and Physics studies for CLIC
 - In close collaboration with ILC, with ILC detectors as a starting point
- **2012**: **CLIC Conceptual Design Report** published
- **2012**: CLIC detector and physics collaboration (**CLICdp**) was set up
- **2012/2013**: CLIC input to the European strategy and to USA Snowmass

Volume 1: Accelerator

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TeV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

Volume 2: Physics + Detectors

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

Volume 3: Strategy + Implementation

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC PROGRAMME:
TOWARDS A STAGE-6 * LINEAR COLLIDER
EXPLORING THE TERASCALE

CLIC CONCEPTUAL DESIGN REPORT

arXiv:1307.5288

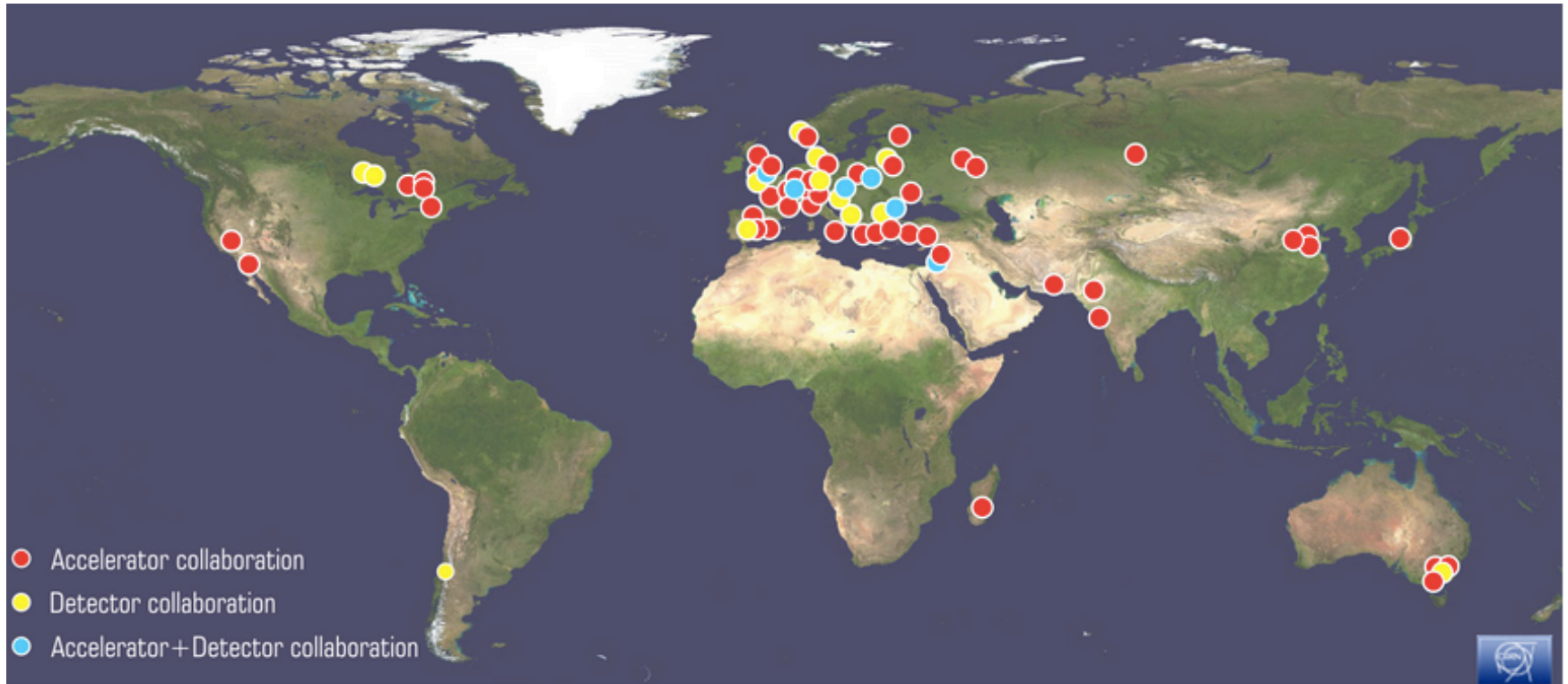
CLIC accelerator collaboration



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

<http://cllc-study.web.cern.ch/>

CLIC/CTF3: ~50 institutes



CLIC detector and physics (CLICdp)



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

<http://clikdp.web.cern.ch/>

CLICdp: 25 institutes

Focus of CLIC-specific studies on:

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

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	Karlsruher Institut für Technologie (KIT), Institut für Prozessdatenverarbeitung und Elektronik (IPE), Karlsruhe
Germany	Max-Planck-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
Switzerland	Département de Physics Nucléaire et Corpusculaire (DPNC), Geneva
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



- the CLIC accelerator



[illegible]

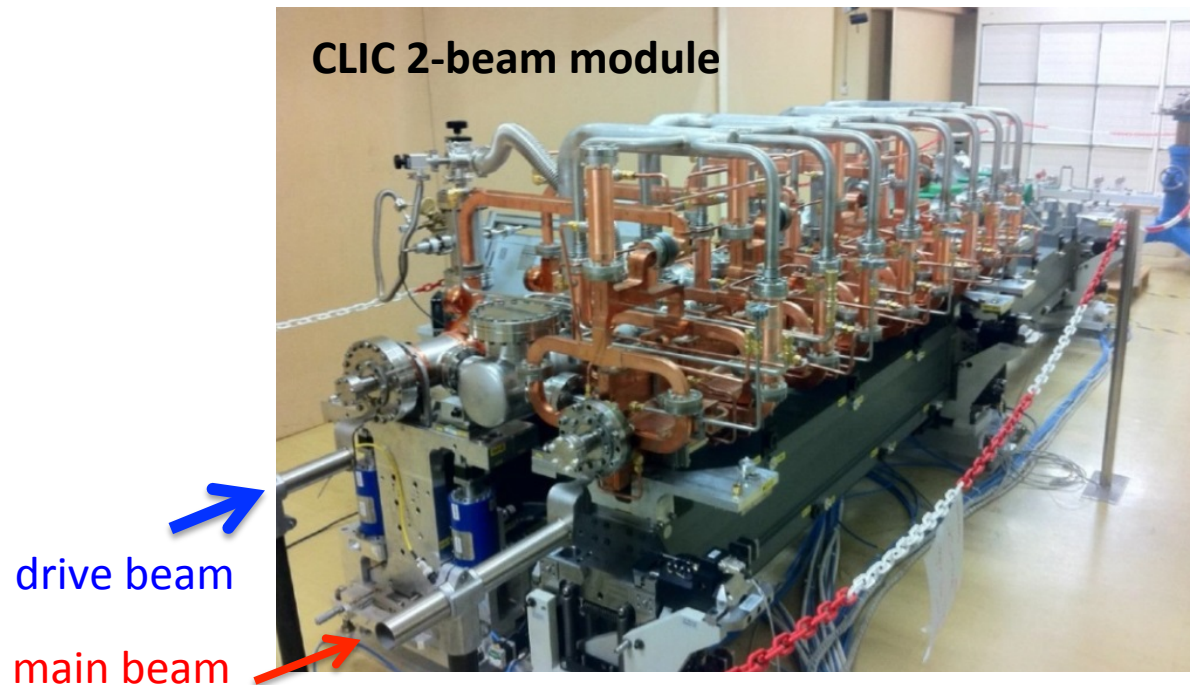
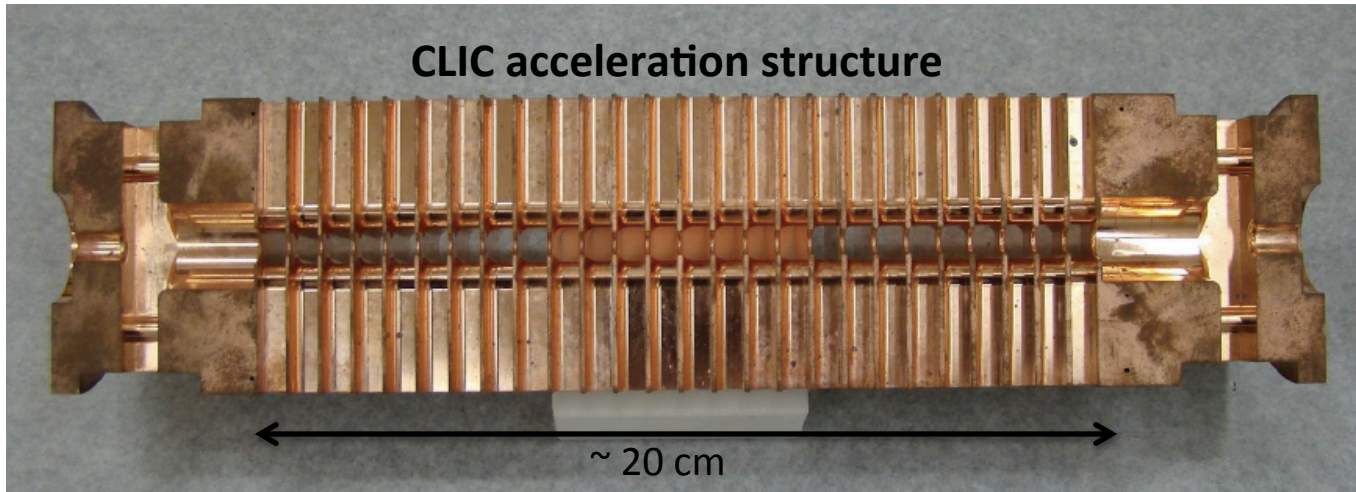
Drive Beam supplies RF power

- ## Main beam for physics

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



CLIC acceleration modules



CLIC layout at 3 TeV

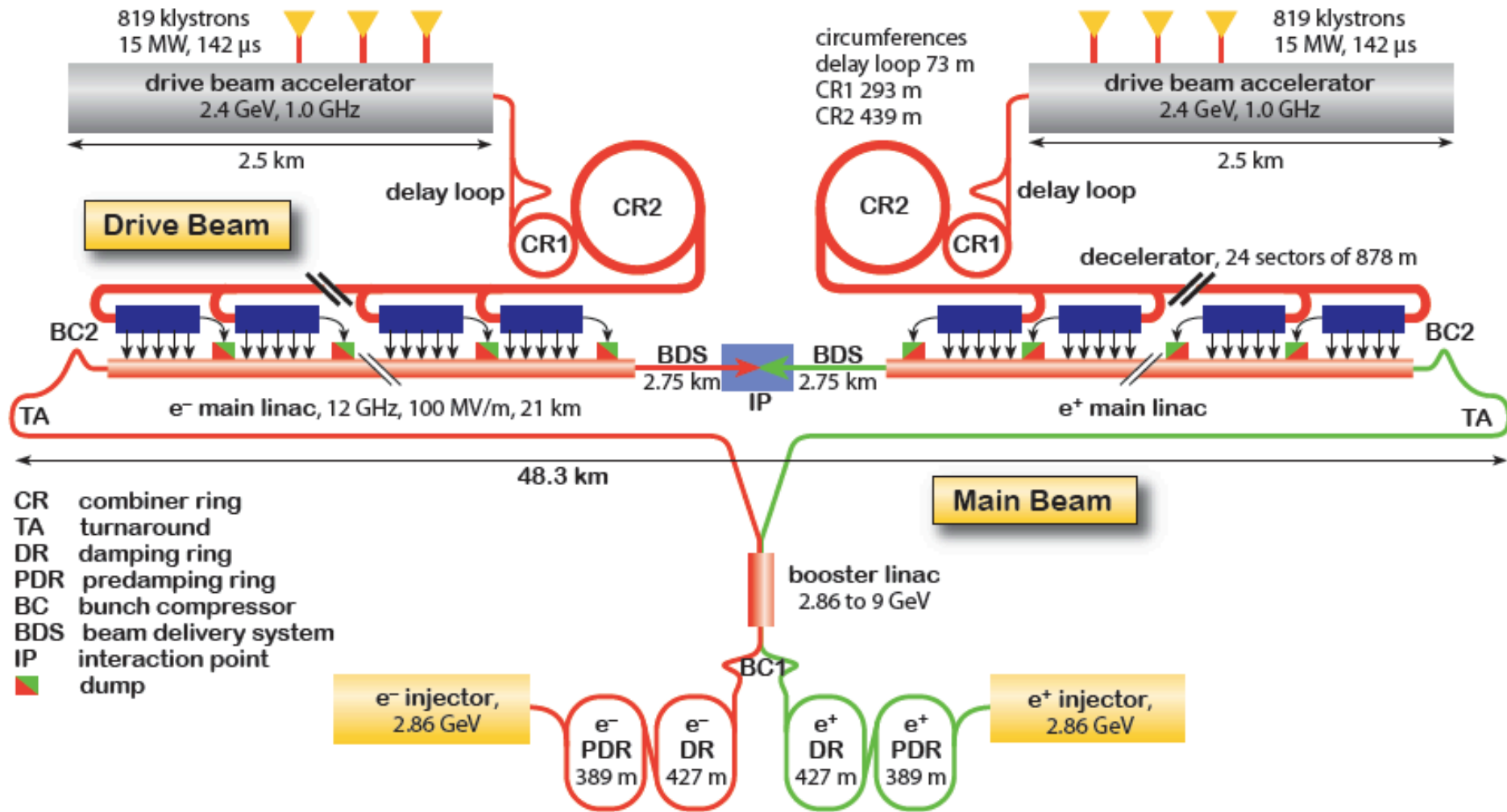
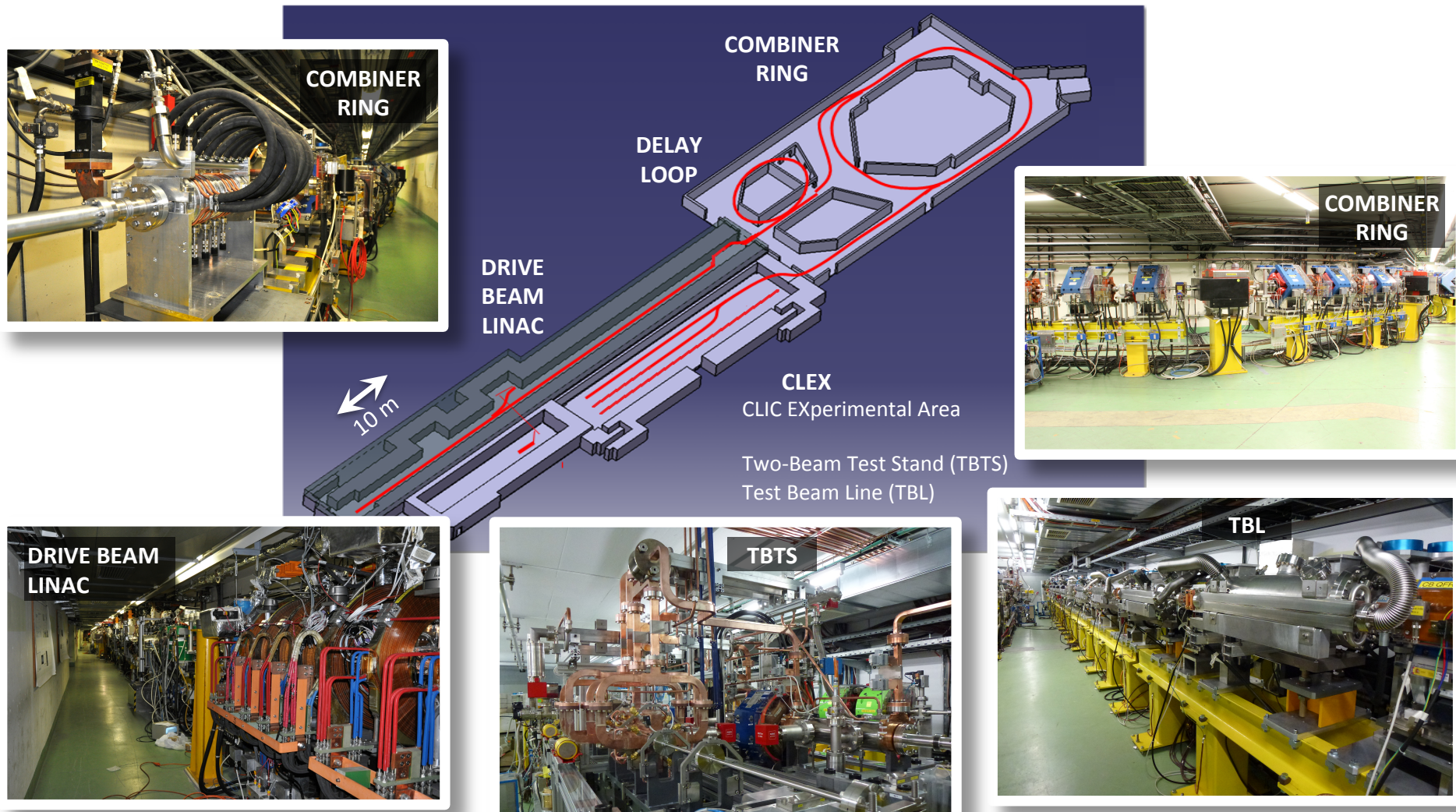


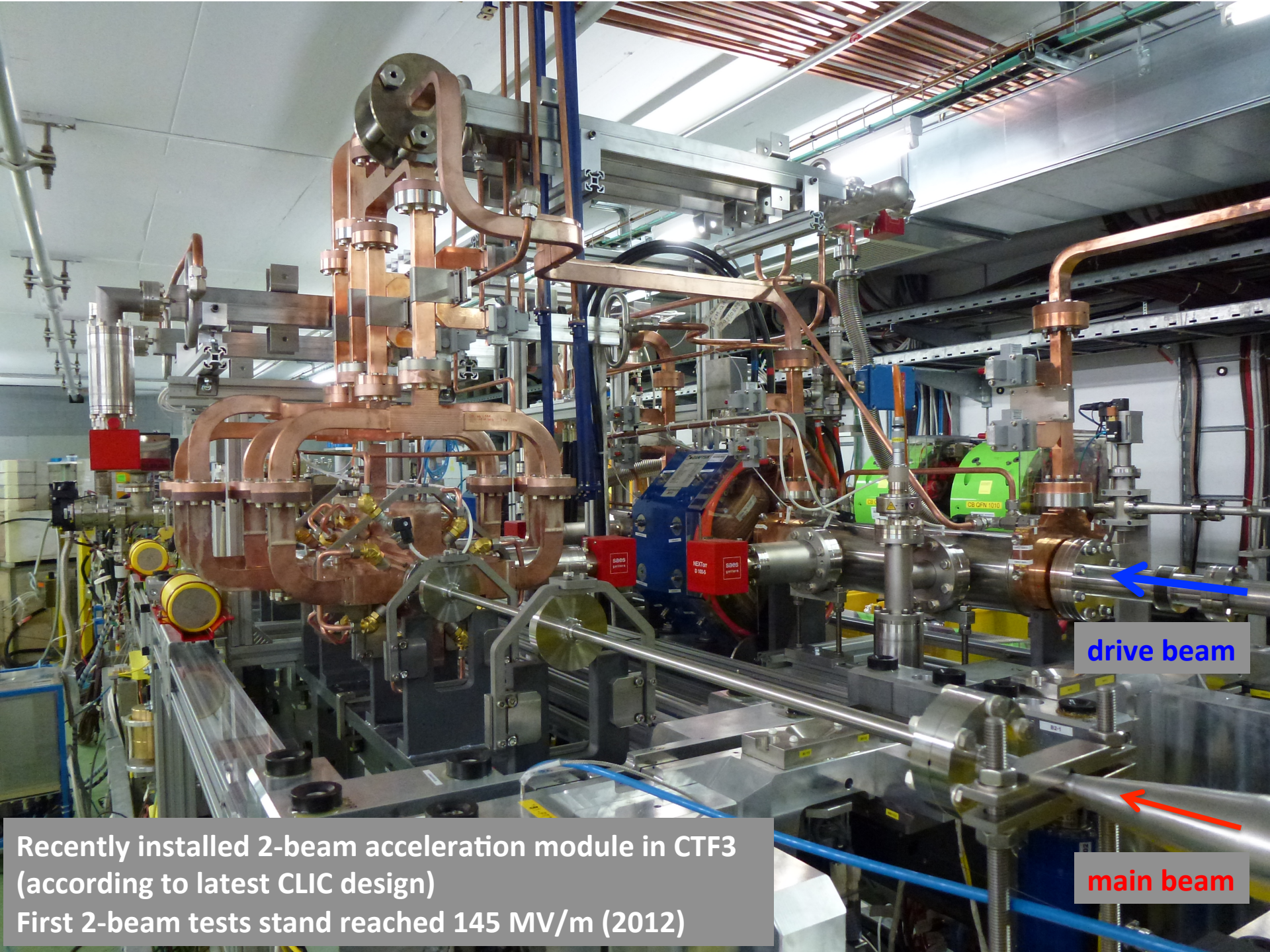
Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

CLIC test facility (CTF3)



a small CLIC to test basic principles and key performance parameters





drive beam

main beam

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

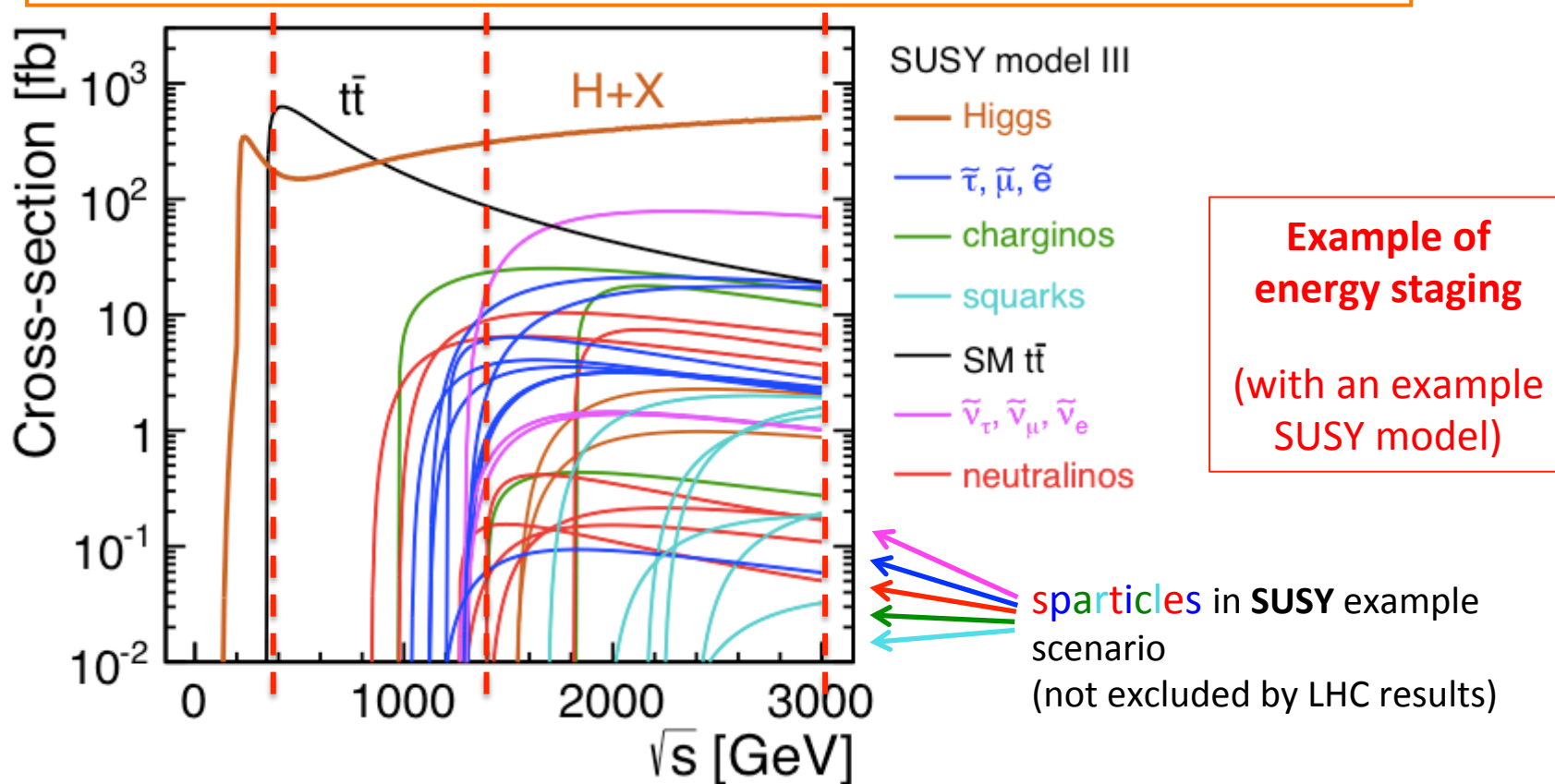
CLIC physics programme...



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

- ~ 380 GeV, 500 fb^{-1} : precision Higgs and top physics
- ~ 1.4 TeV, 1.5 ab^{-1} : targeted at BSM physics, precision Higgs, top
- ~ 3 TeV, 2 ab^{-1} : targeted at BSM physics, precision Higgs

Exact energies of TeV stages will depend on LHC results



CLIC staged implementation

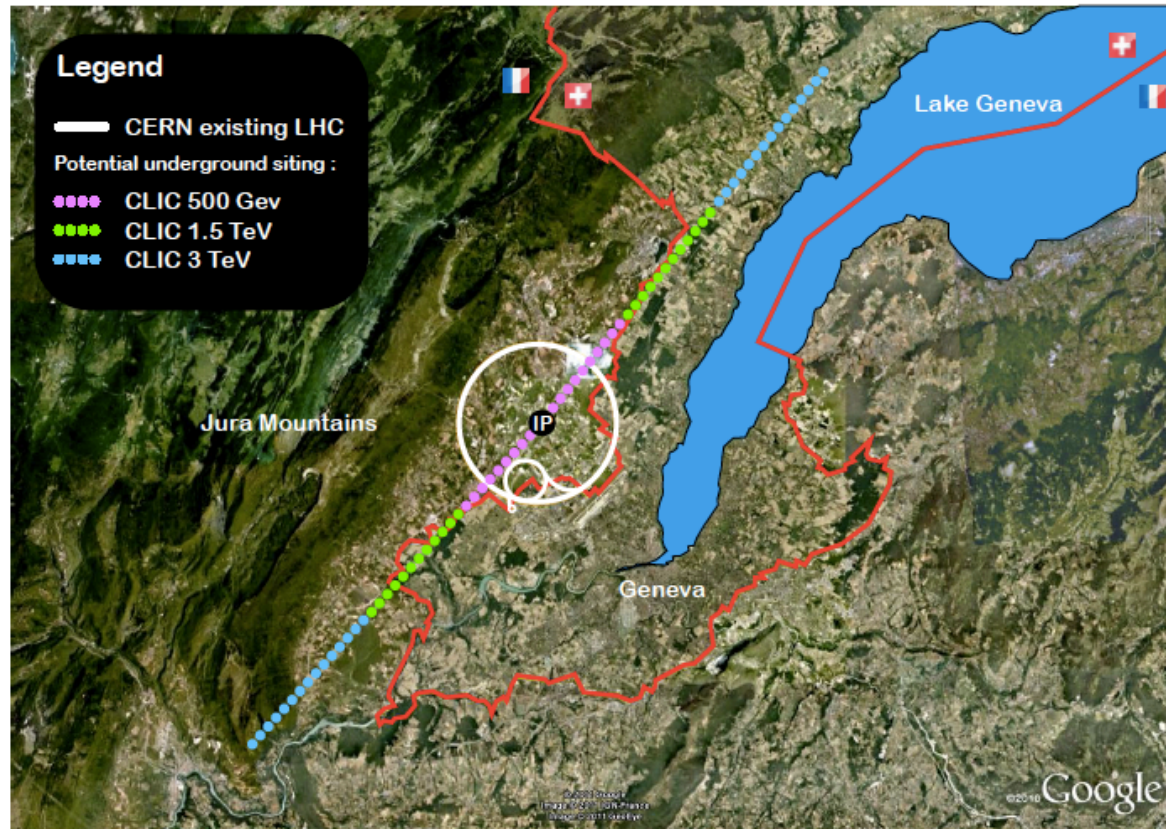


staged operation



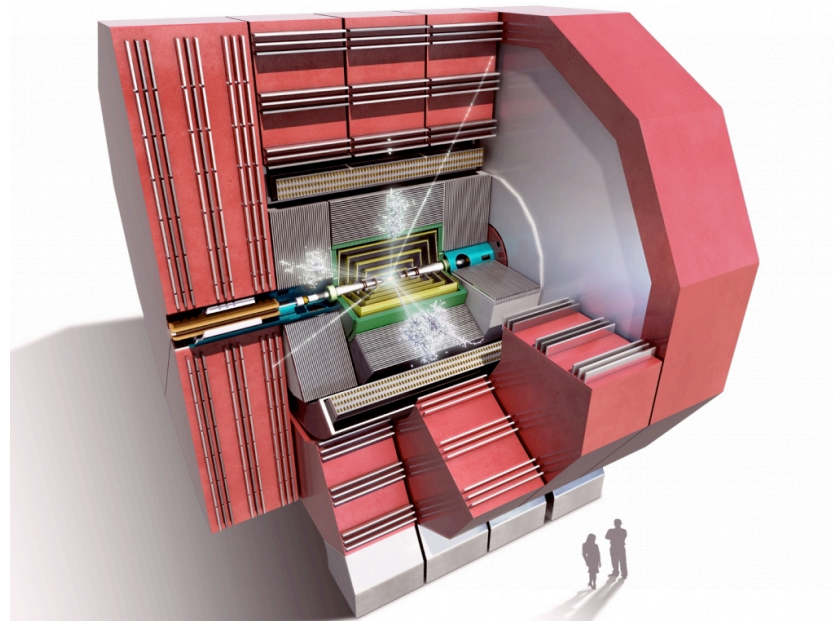
optimal for physics

Collision energy (GeV)	Site length (km)	Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	# 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



Note: #Higgs is without enhancement from polarisation

- detector requirements and experimental conditions



CLIC physics aims => detector needs



★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

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

★ jet energy resolution:

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

$$\frac{\sigma_E}{E} \sim 3.5 - 5 \% \quad (\text{for high-E jets})$$

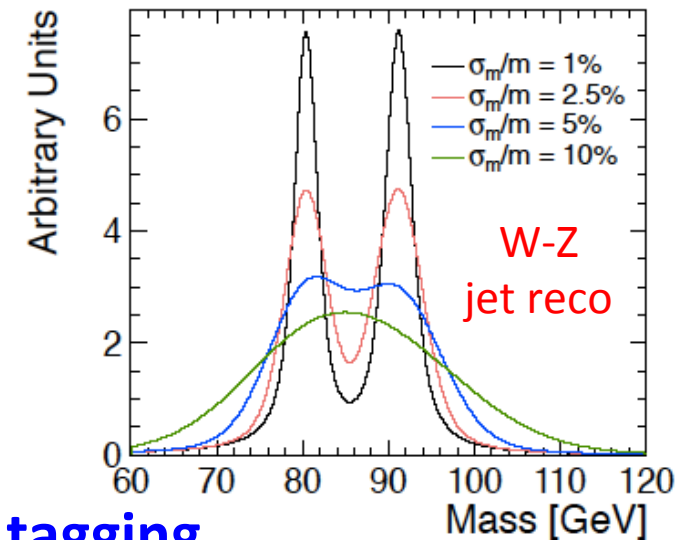
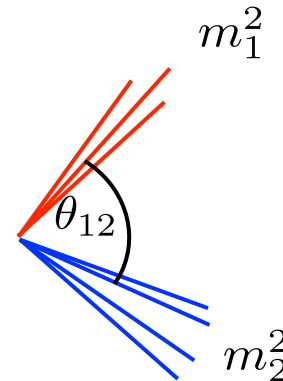
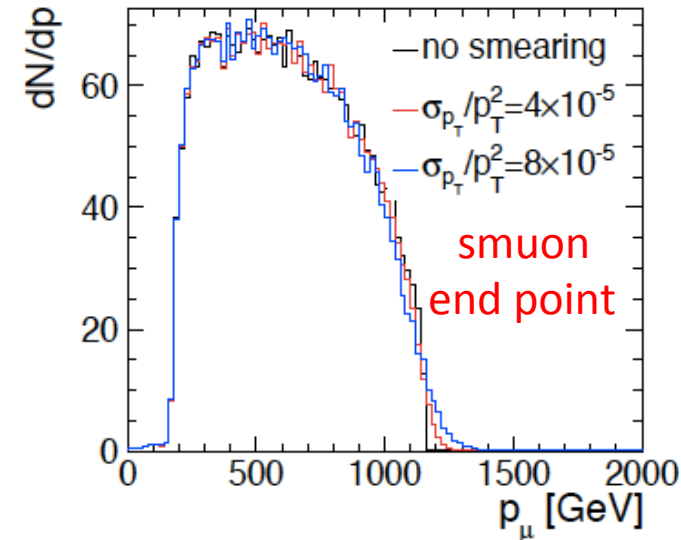
★ impact parameter resolution:

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

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

★ angular coverage, very forward electron tagging

+ requirements from CLIC beam structure and beam-induced background



CLIC experimental conditions



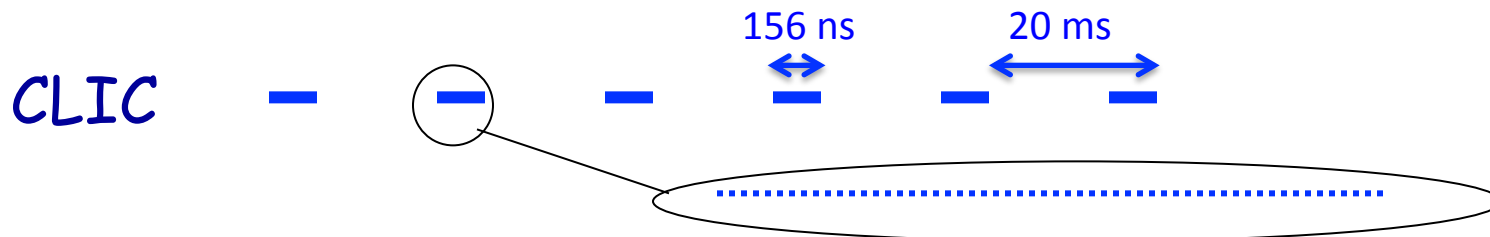
	CLIC at 3 TeV
$L \text{ (cm}^{-2}\text{s}^{-1}\text{)}$	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
Duty cycle	0.00078%
$\sigma_x / \sigma_y \text{ (nm)}$	$\approx 45 / 1$
$\sigma_z \text{ (}\mu\text{m)}$	44

Drives **timing requirements** for CLIC detector

Low duty cycle

- Triggerless readout
- Power pulsing (turning power off when not needed)

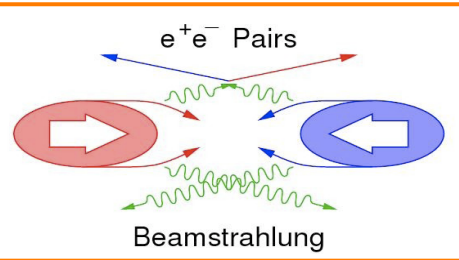
Very small beam profile at interaction point
 $\Rightarrow$ Very high E-fields $\Rightarrow$
beam-beam background



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

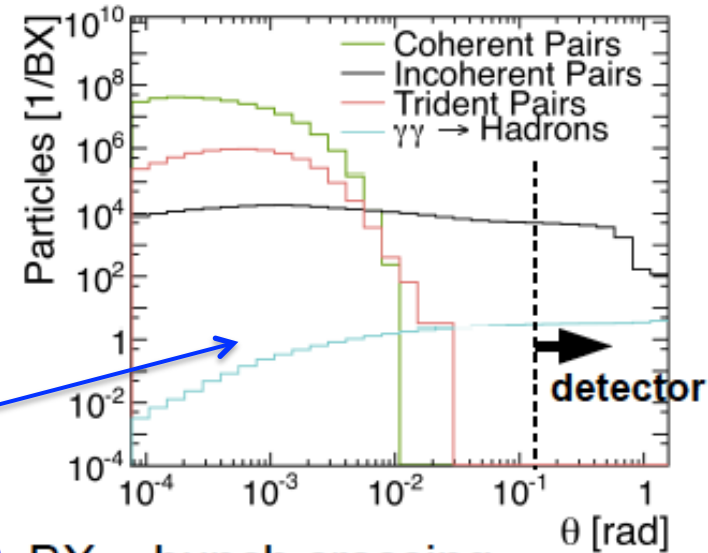
- Pair-background

- High occupancies

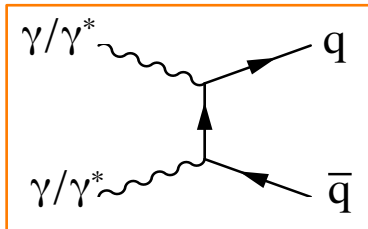
$\gamma\gamma$ to hadrons

- Energy deposits

(19TeV/train @ $\sqrt{s}$ 3TeV)



BX = bunch crossing



Beamstrahlung → important energy losses right at the interaction point

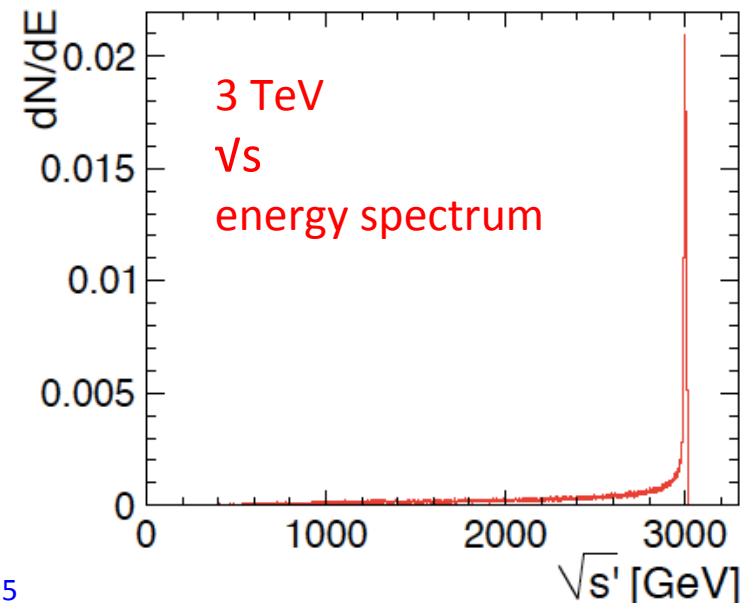
E.g. full luminosity at 3 TeV:

$$5.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

Of which in the 1% most energetic part:

$$2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

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



- a detector for CLIC

Combining requirements from:
Precision physics + beam conditions at CLIC



Particle Flow Analysis (PFA) + calorimetry



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



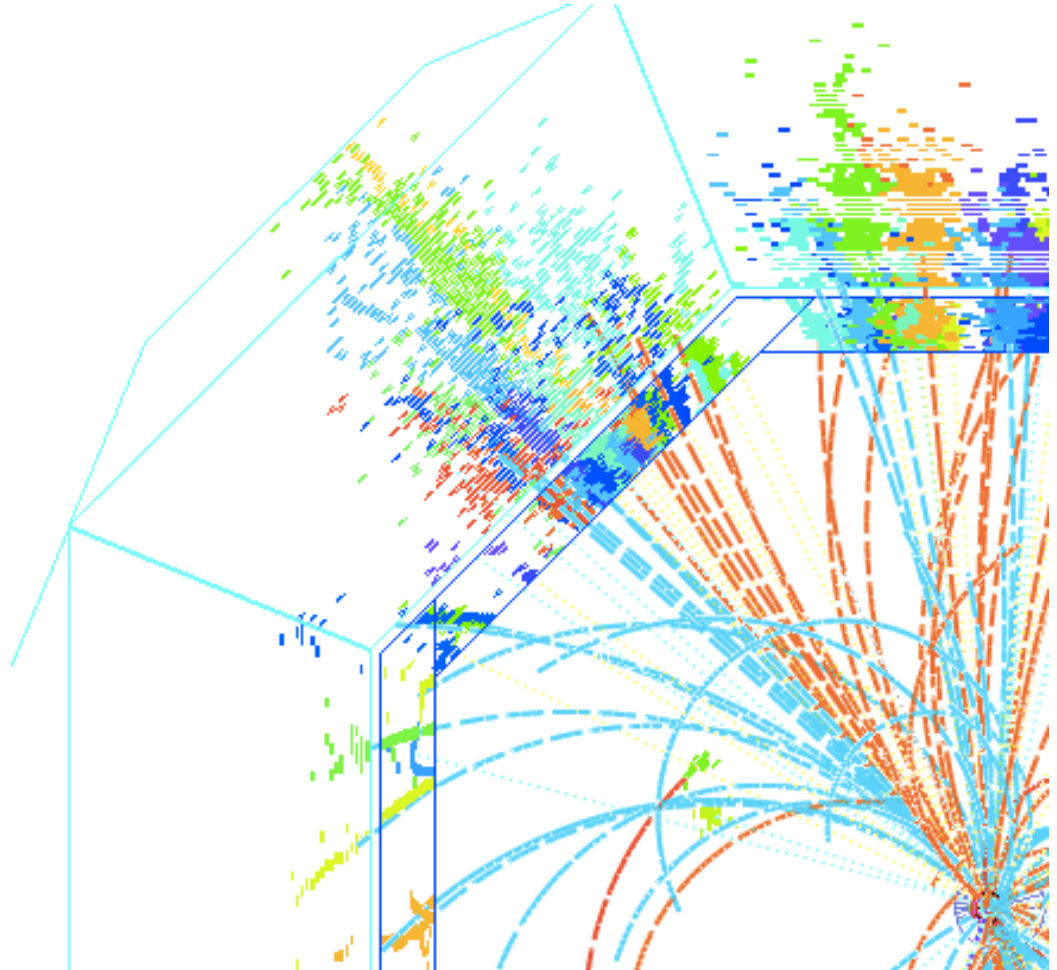
Always use the best info you have:

60% => tracker 😊 😊

30% => ECAL 😊

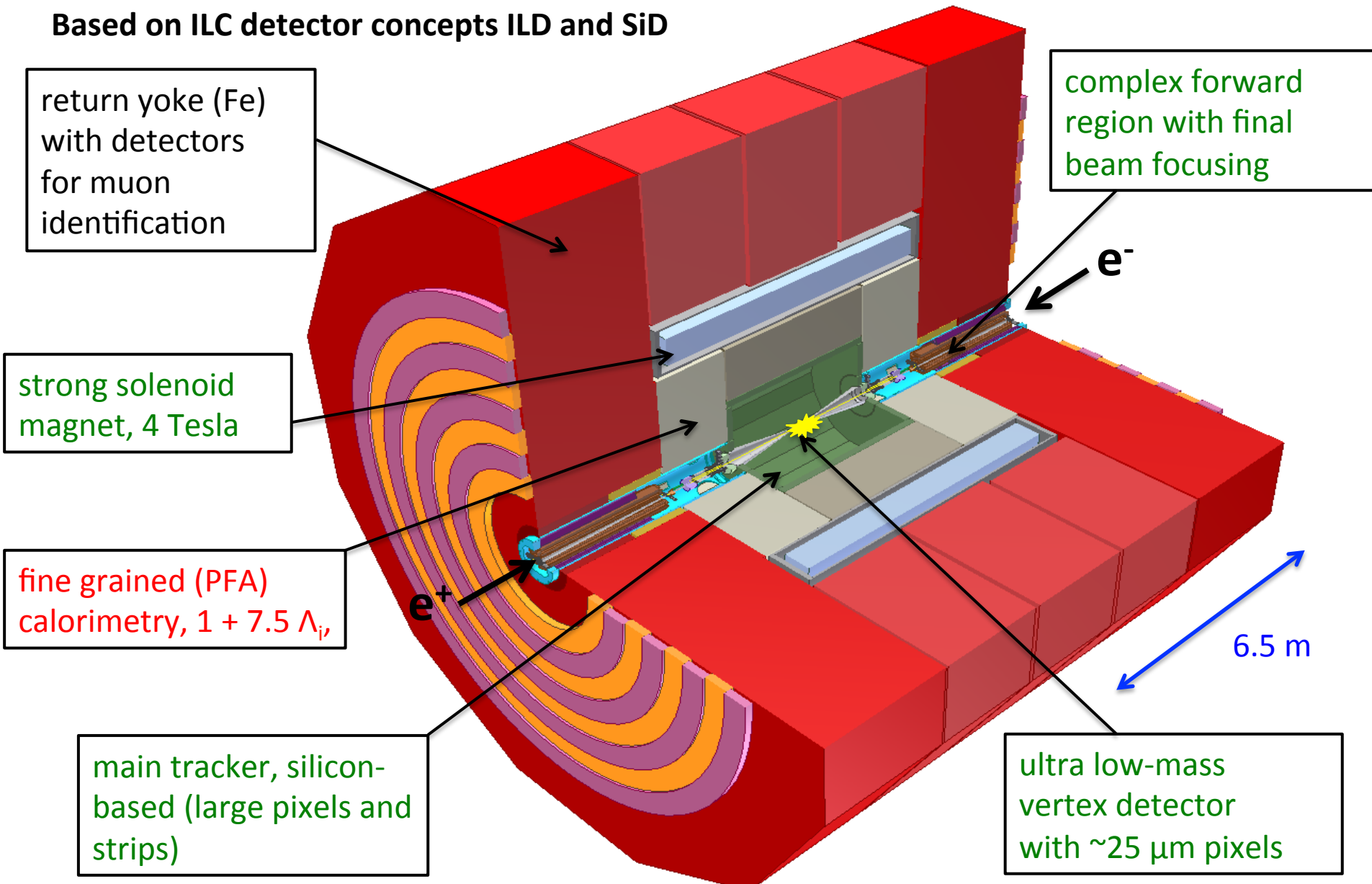
10% => HCAL 😞

Hardware + software !



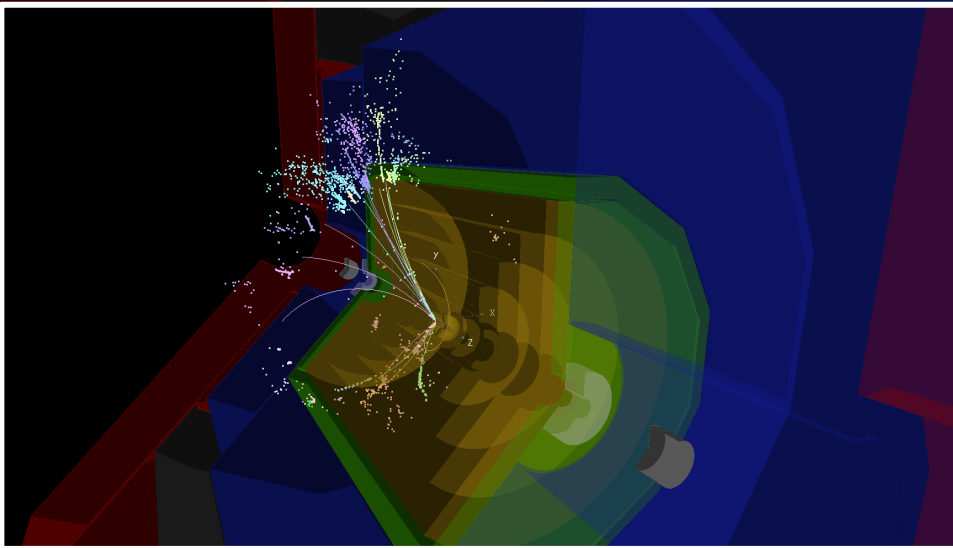
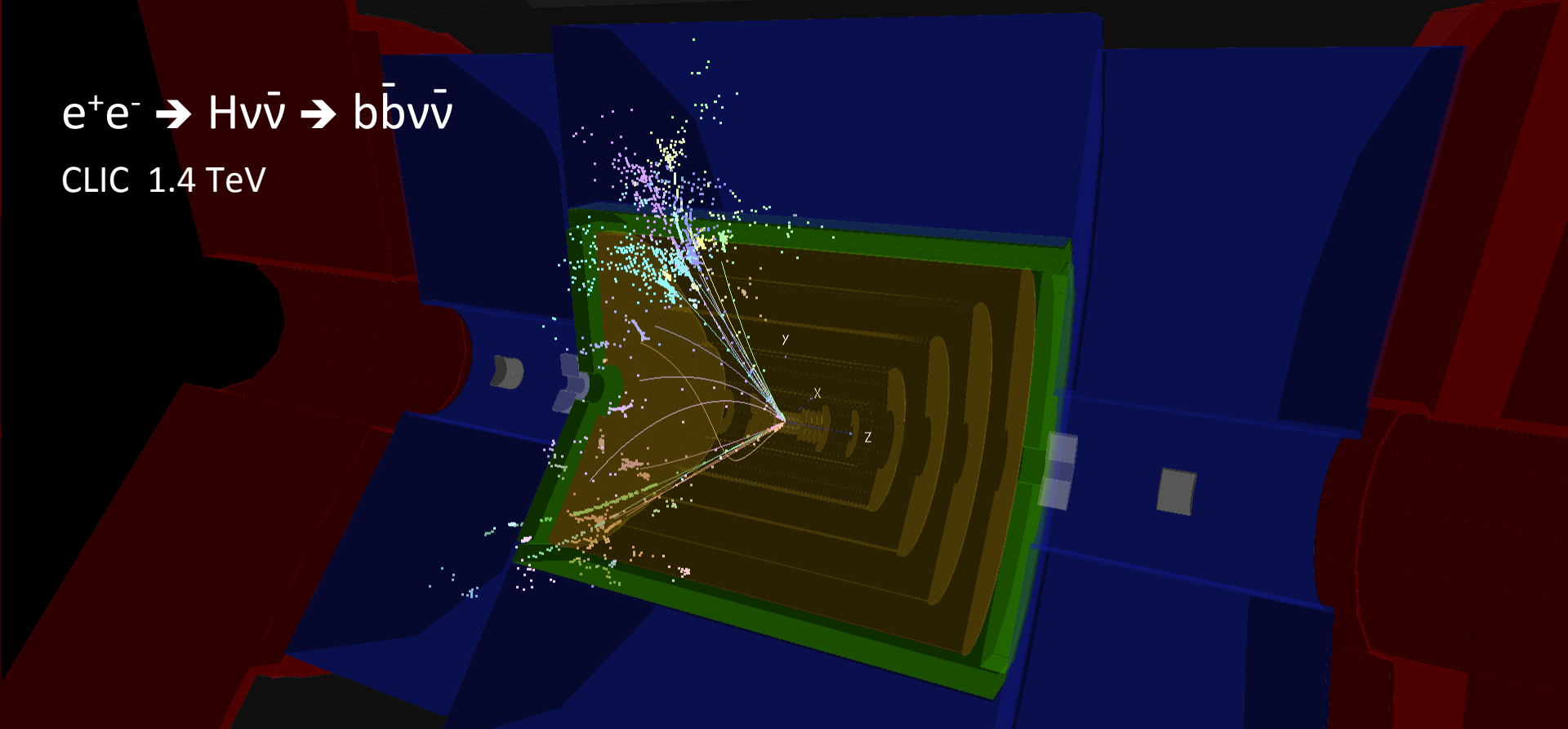
CLIC detector concept

Based on ILC detector concepts ILD and SiD

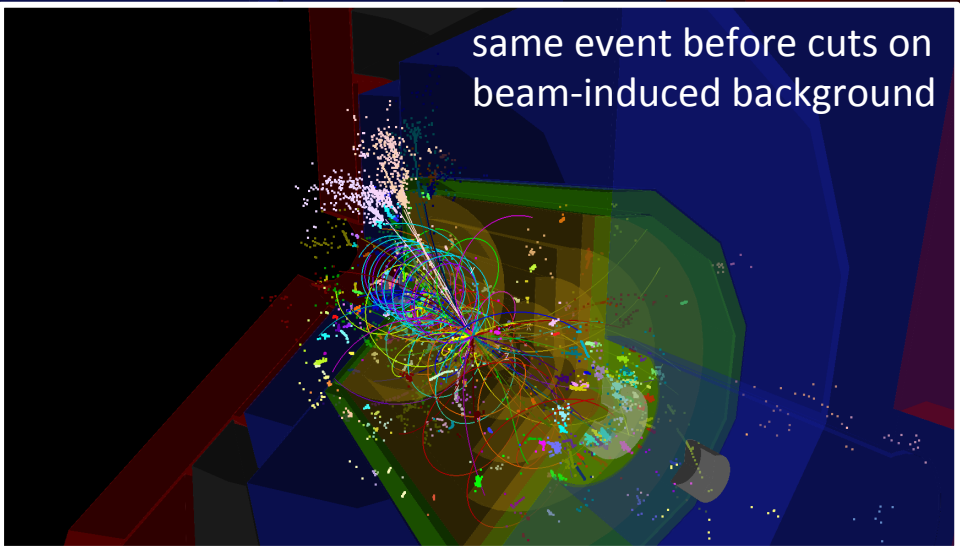


$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

CLIC 1.4 TeV

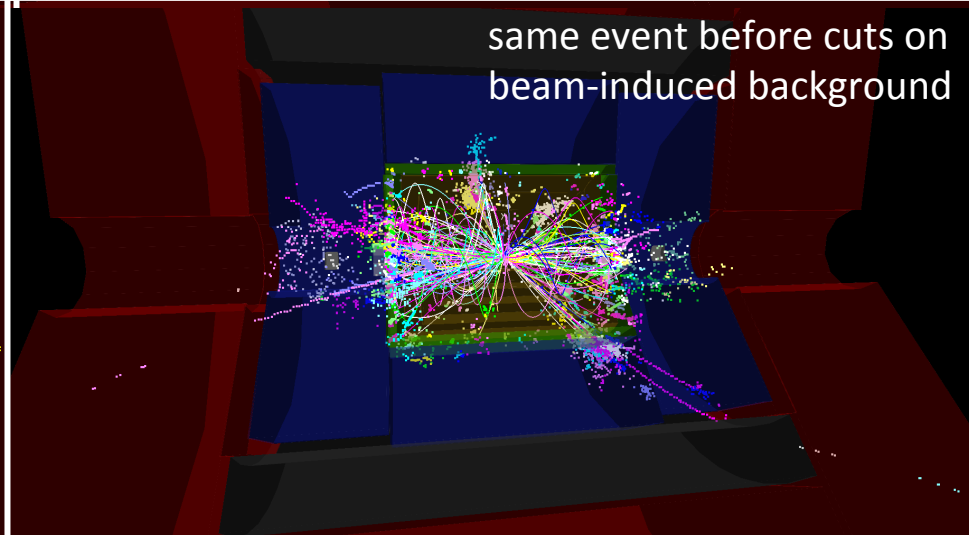
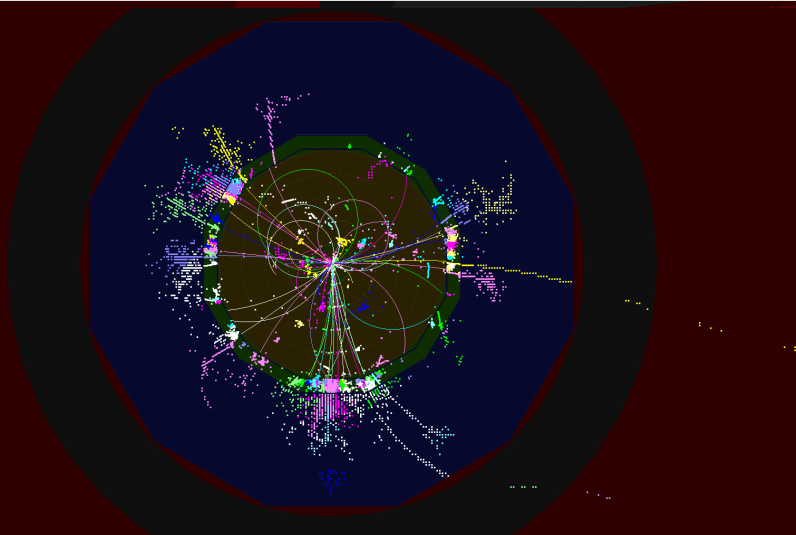
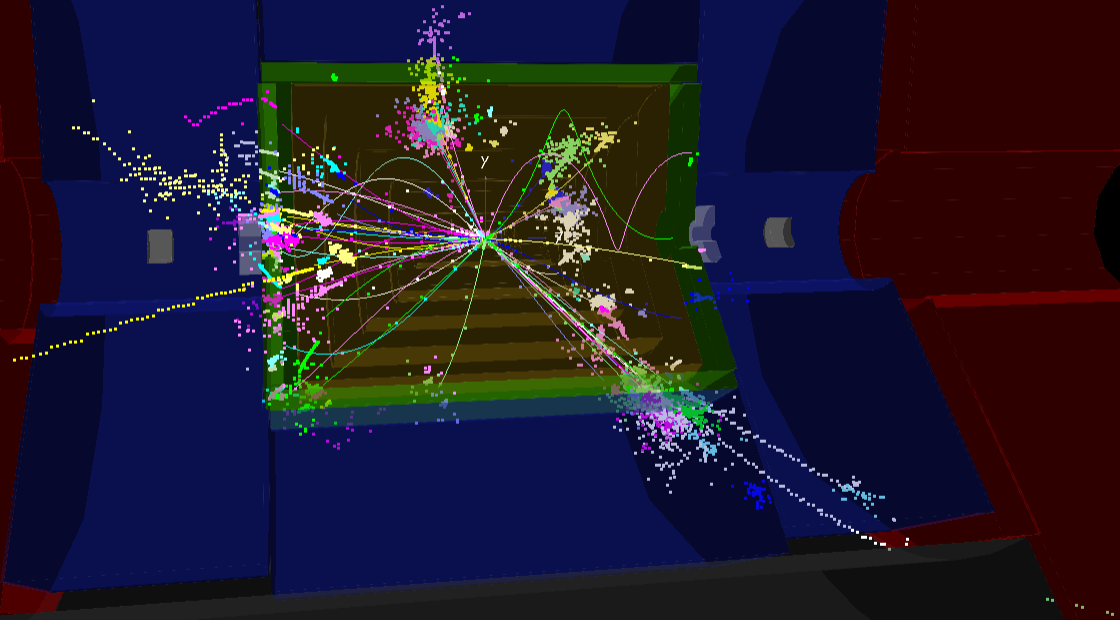


same event before cuts on
beam-induced background

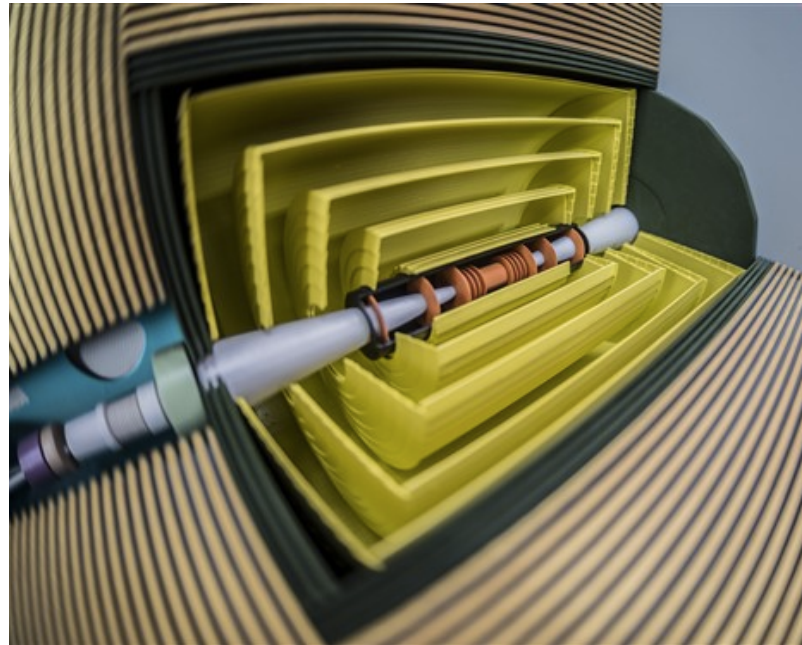


$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\tau\nu\bar{b}b\bar{b}$

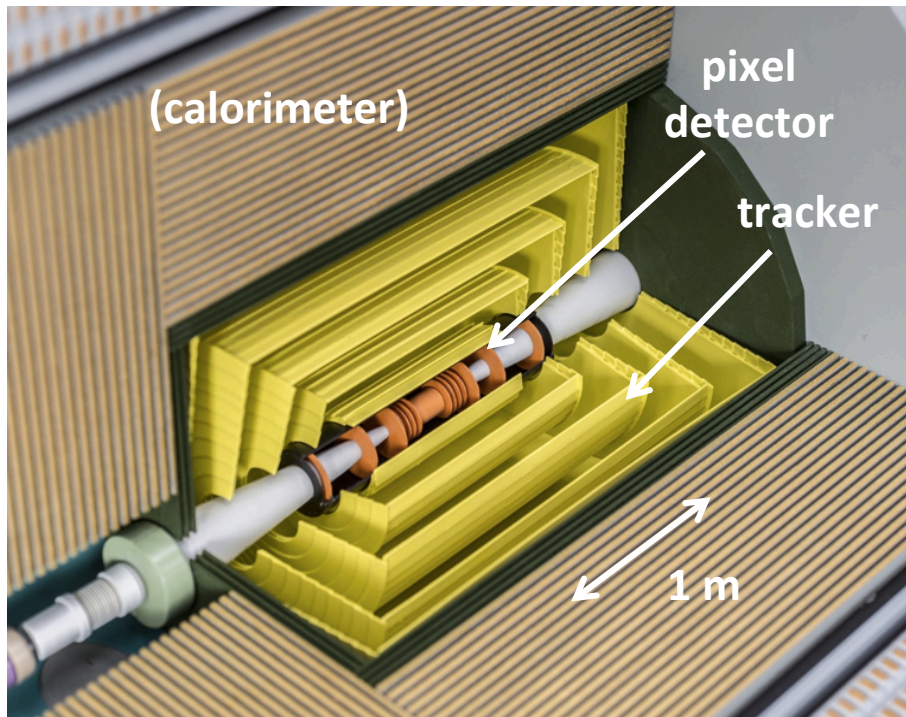
CLIC 1.4 TeV



- vertex and tracking detectors



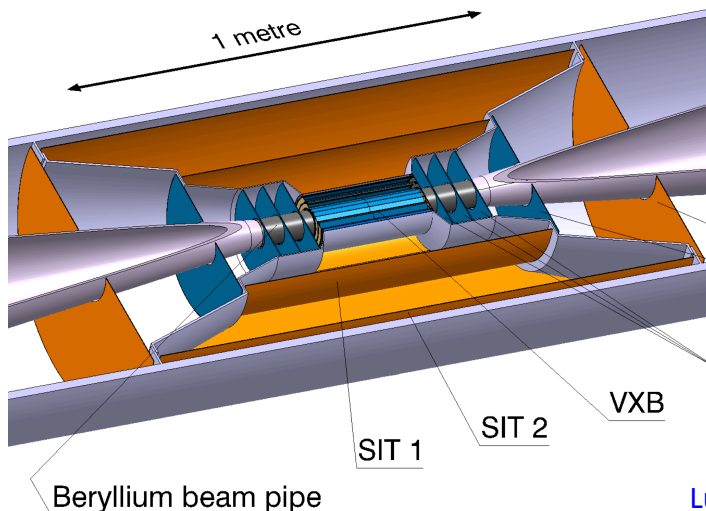
Pixel detector



Flavour tagging capabilities drive the design of the pixel detector

has to be extremely accurate and light !

- 2 billion pixels
- 3 μm single point accuracy
- 25*25 μm^2 pixels (25 times smaller pixel area at LHC)
 - Pulse height measurement
 - Time measurement to 10 ns
- Ultra-light => 0.2% X_0 per layer
 - Very thin materials/sensors
 - Low-power design, power pulsing, air cooling
 - Aim: 50 mW/cm²
- Radiation level 10⁴ lower than LHC



high-tech R&D
covering several disciplines

CLIC vertex detector R&D roadmap



Hybrid approach pursued: ($\leq$ other options possible)

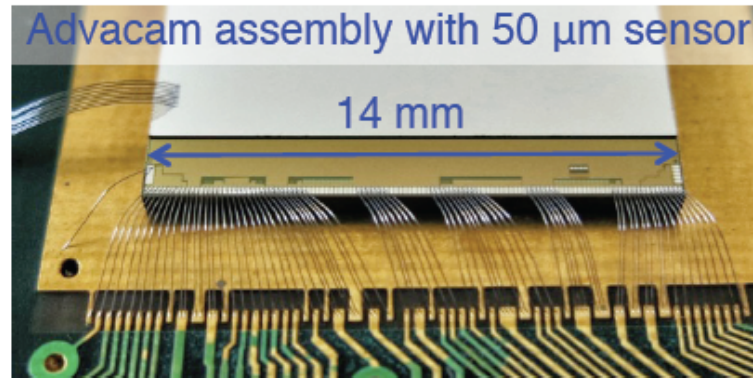
- Thin ($\sim 50\text{ }\mu\text{m}$) **silicon sensors**
- Thinned high-density **readout ASIC** ($50\text{ }\mu\text{m}$)
 - R&D within Medipix/Timepix effort
- **Low-mass interconnect**
- **Power pulsing**
- **Air cooling**

CLICpix demonstrator ASIC 64×64 pixels, fully functional

- 65 nm technology
- $25\times 25\text{ }\mu\text{m}^2$ pixels
- 4-bit ToA and ToT info
- Data compression
- Pulsed power: 50 mW/cm^2

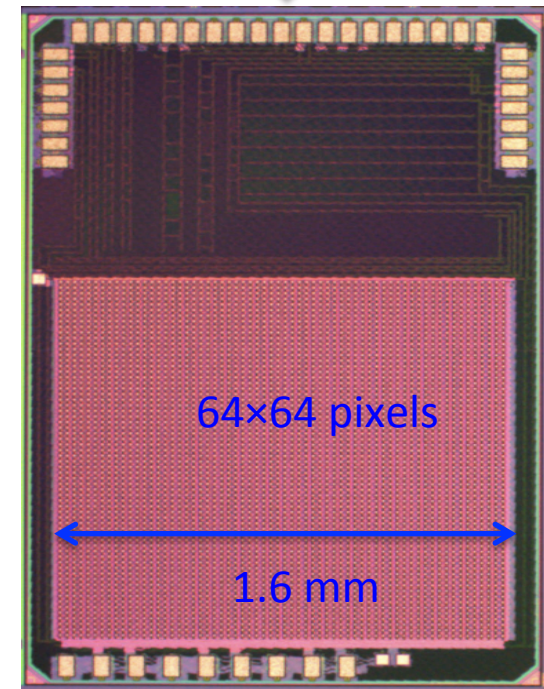


$50\text{ }\mu\text{m}$ dummy
wafer



Very thin sensors !

Successful tests at DESY/CERN test beams
(with existing Timepix ASIC)



Hybrid vertex detector with HV-CMOS



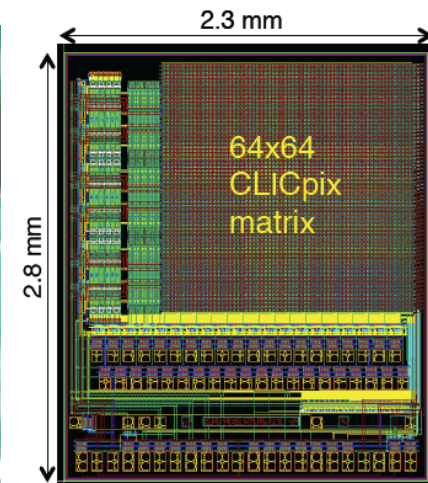
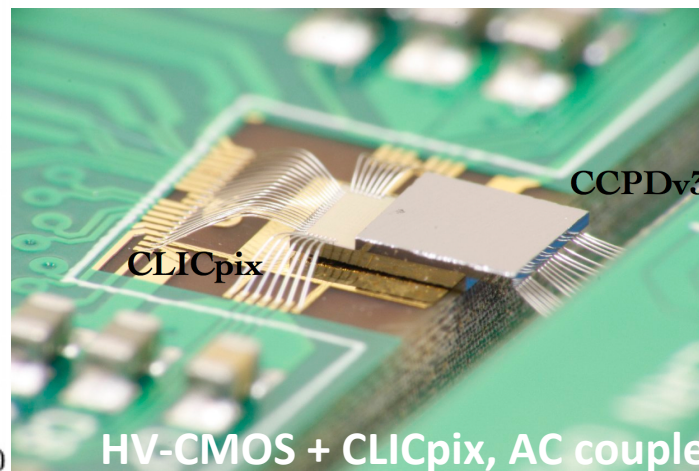
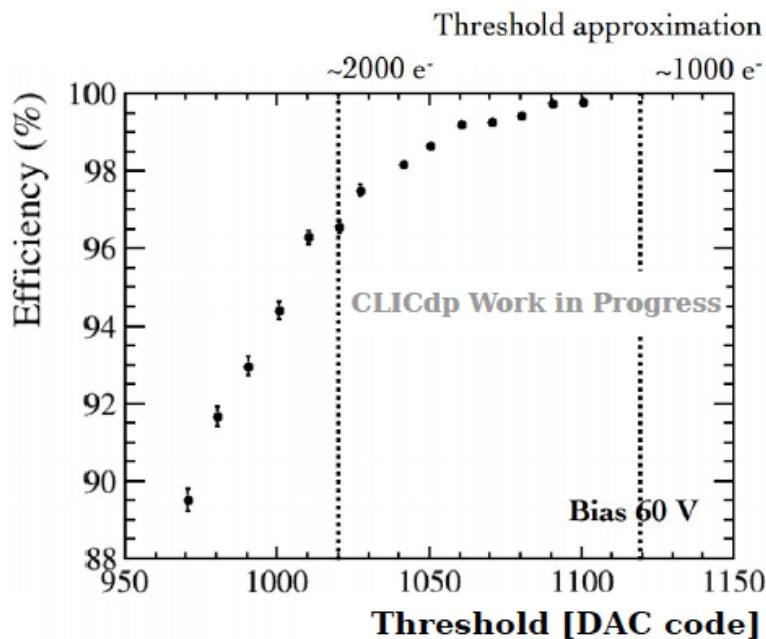
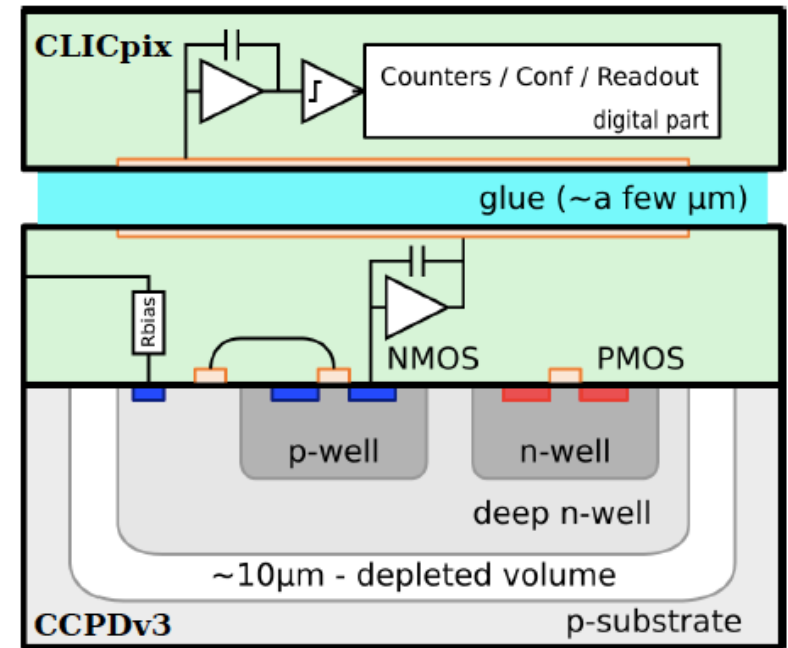
Pursuing an alternative readout option

Hybrid option with HV-CMOS:

Capacitive Coupled Pixel Detector (CCPD)

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

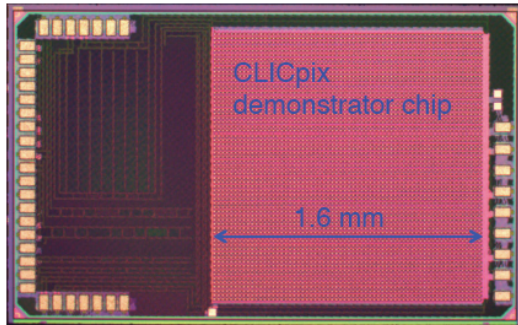
Status: beam tests in 2014/2015



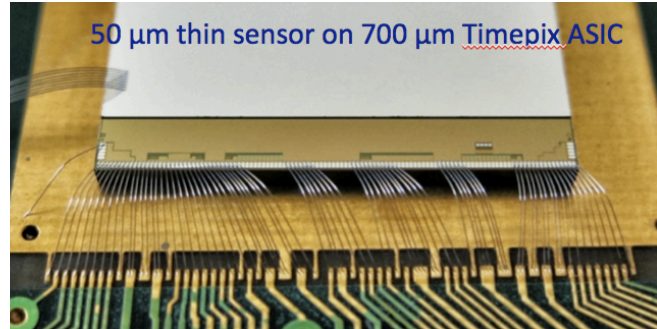
pixel detector R&D



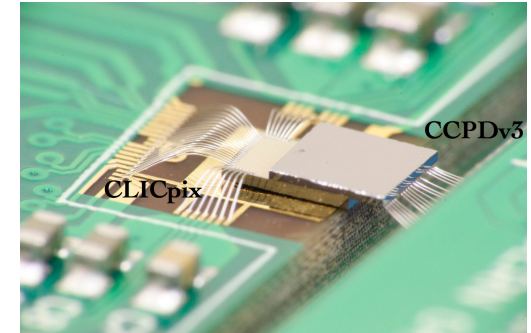
electronics chip (65 nm)



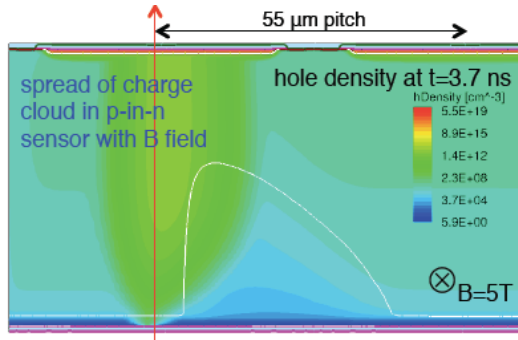
thin electronics + sensor assembly



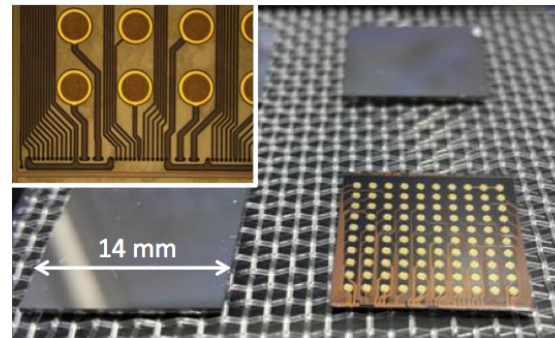
HV-CMOS sensor + CLICpix



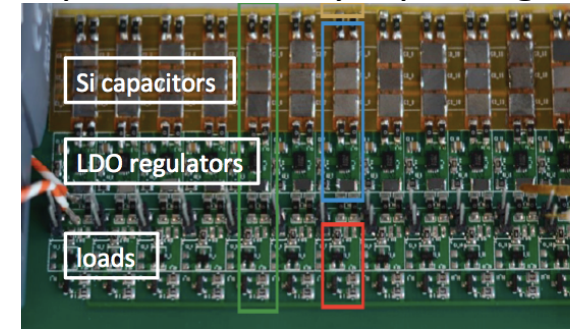
signal simulations



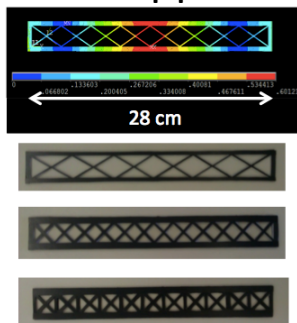
interconnect technology



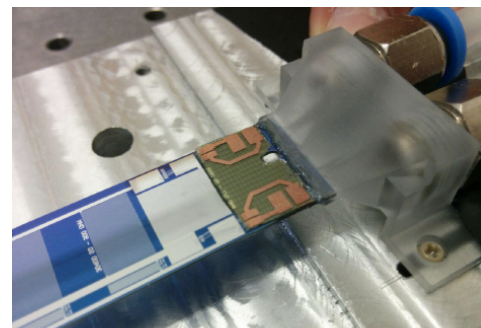
power delivery + pulsing



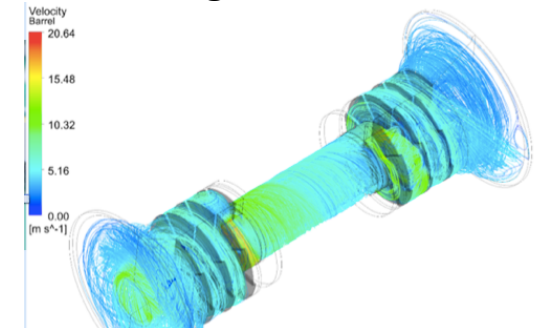
thin supports



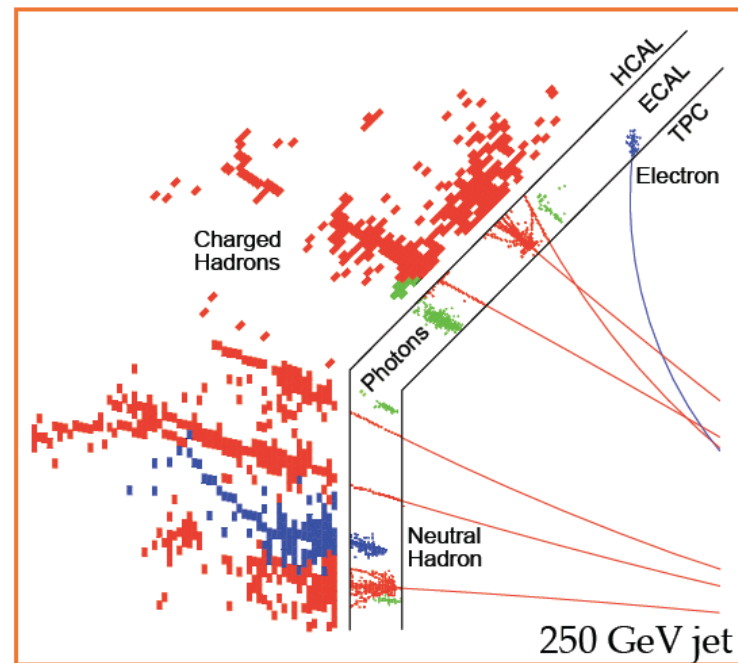
micro-channel cooling

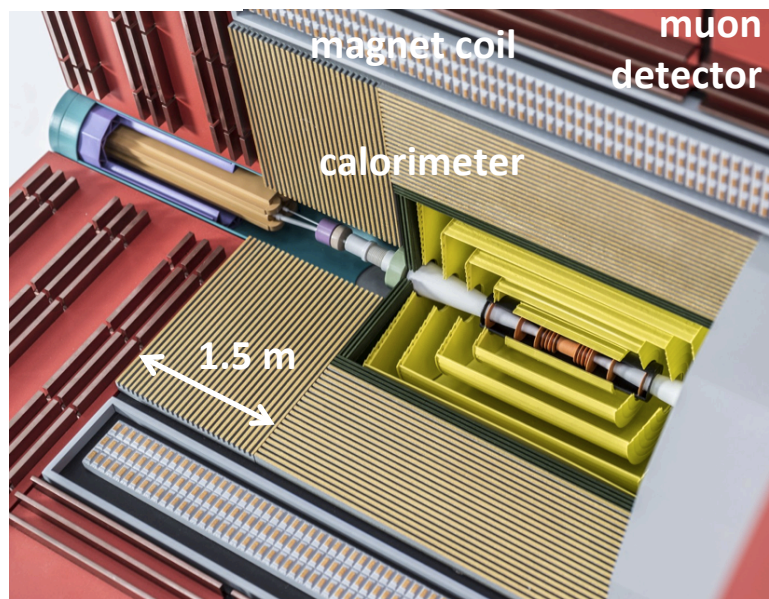


air cooling simulations/tests



- Calorimetry





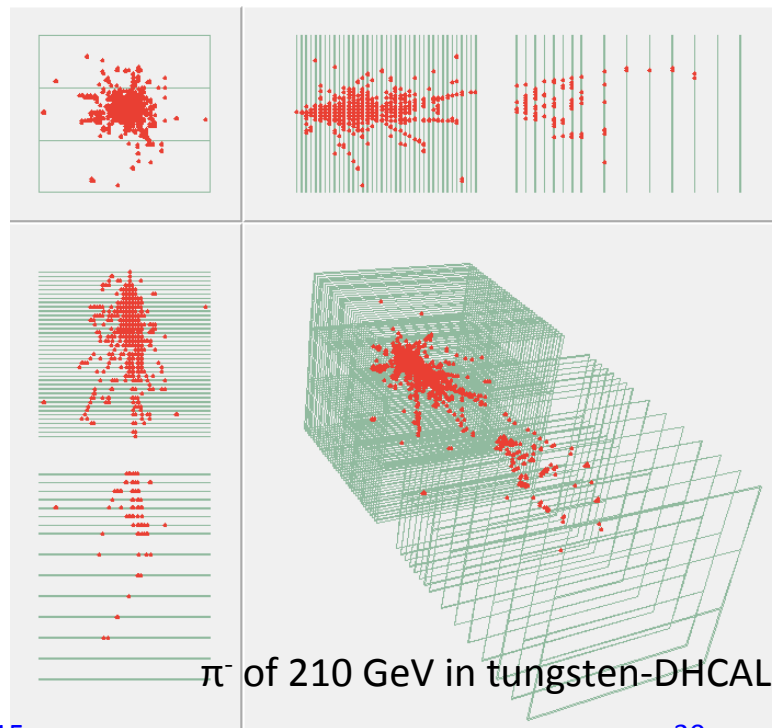
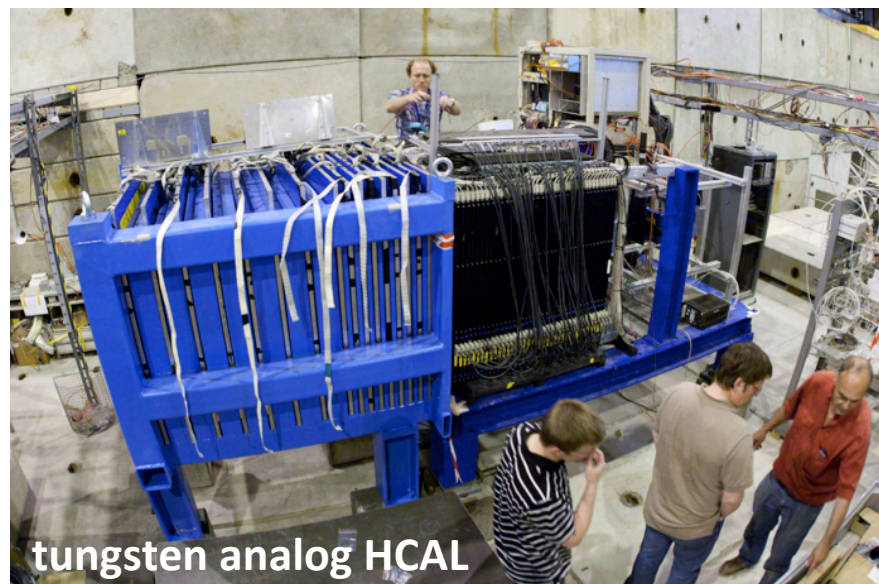
fine-grained calorimeters

“electromagnetic (ECAL) + hadronic (HCAL)”

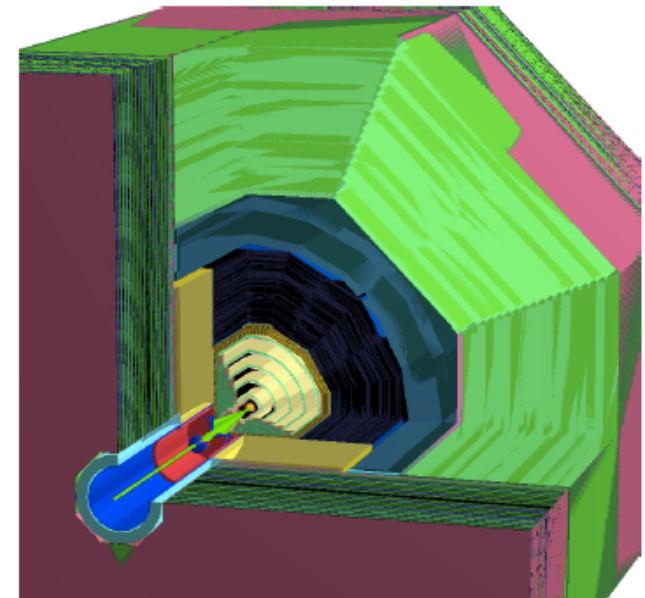
	# layers	cell sizes	technology option
ECAL	~25	5×5 mm ²	silicon
HCAL	~60	3×3 cm ²	scintillator+SiPM

~60 million readout channels (300* larger than LHC)

R&D in the framework of **CALICE** collaboration



- Detector optimisation and software development



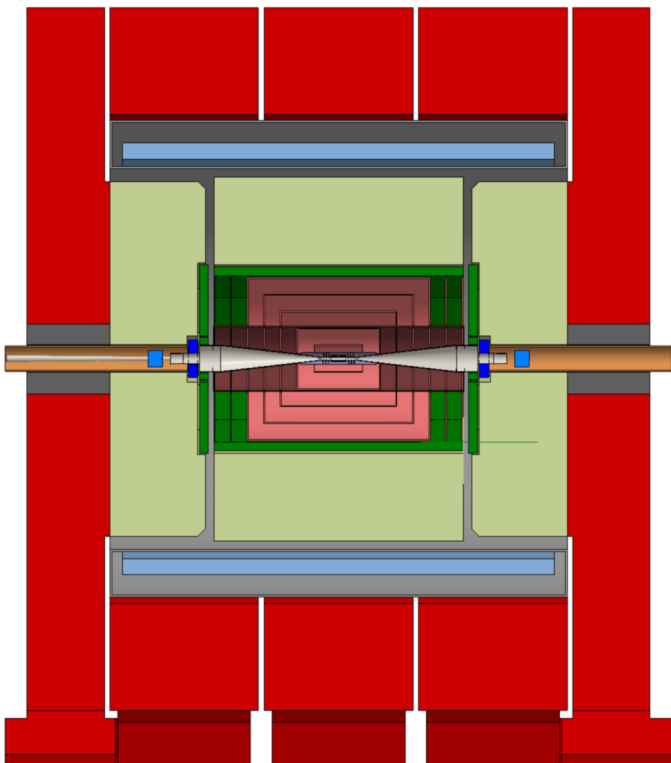
New CLIC detector model

towards one CLIC detector model

include lessons learnt so far

include experience from hardware R&D

*Aim: new CLIC detector concept in 2015
for future physics benchmark studies*



Improvements of simulation / reconstruction software

Most important new elements:

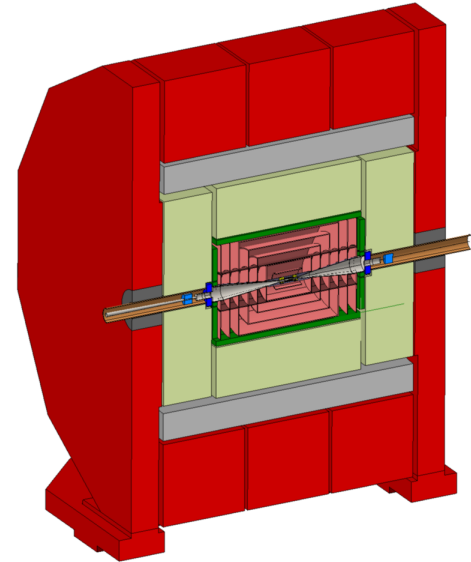
- New **geometry description (DD4hep)**
 - For simulation, reconstruction, event display, alignment....
 - Generic, developed under AIDA (EU), also for other users (FCC)
- **New/optimised track reconstruction** for all-silicon tracker

Optimisation studies for new model



Already agreed working hypotheses in 2014:

- Vertex: $0.2\%X_0/\text{layer}$
- Vertex: variable layer geometry
- Vertex: disks
- Tracker: length 2.3 m
- Tracker: radius
- ECAL: 25 layers, $5\times$
- HCAL: steel absorbers
- Solenoid field: 4 Tesla



Ongoing assessments:

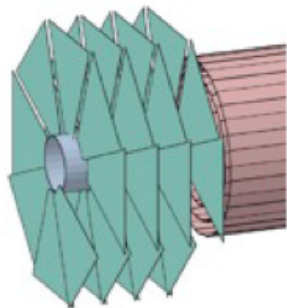
- Tracker layout optimisation
- Lateral cell sizes
- Detector or in tunnel?
- Yoke and coils, stray field
- Need for a
- Luminosity per $L^* = 6\text{m}$
- Overall layout details (barrel/endcap transition, etc. in parametric drawing)
-

Further progress made in 2015:

- If Q_0 outside detector $\Rightarrow$ then $L^* = 6\text{m}$
- 6 muon layers in yoke considered enough
- Enlarge HCAL forward coverage $\Rightarrow R_{\text{in}}$ at $\sim 24\text{ cm}$
- Timing cuts in Pandora are better understood
-

Vertex detector optimisation

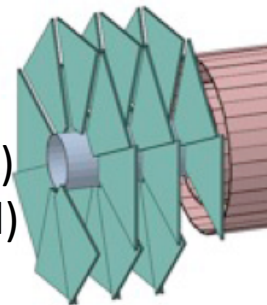
Work in progress !



Spiral disks
Single layers

Using flavour tagging as a gauge

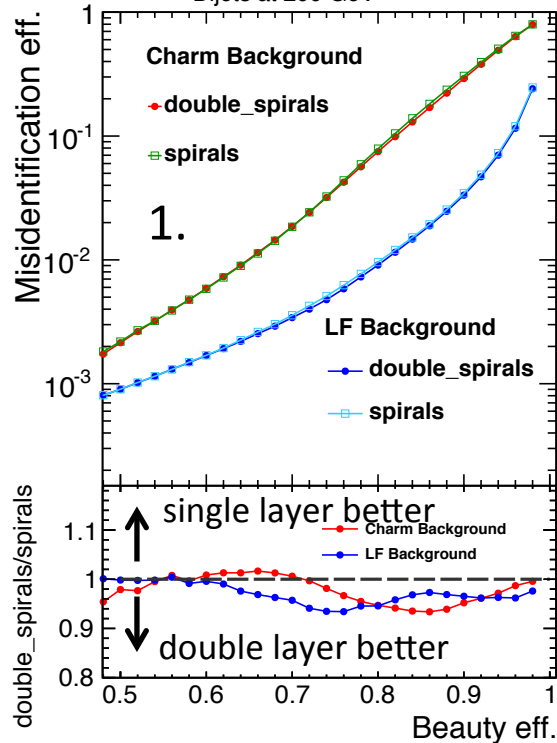
1. Test single vs. double layers
2. More realistic material (0.2% X_0 /layer)
3. Vary inner radius (for 4 T or 5 T B-field)



Spiral disks
double layers

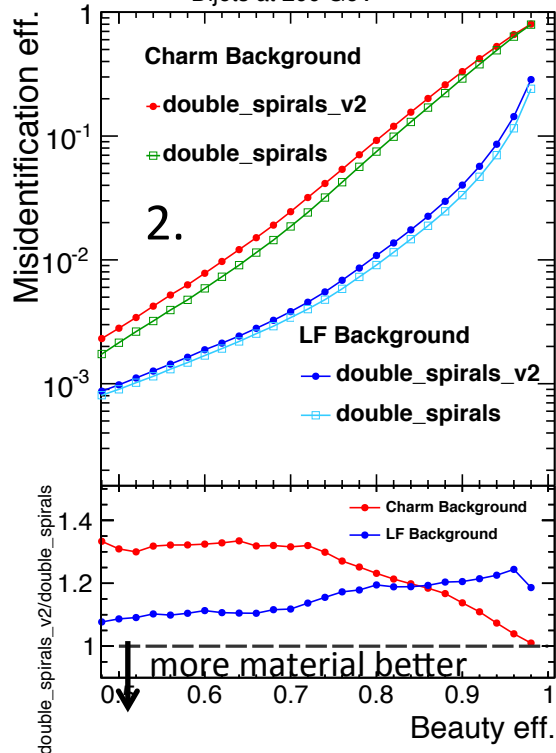
Single layers / double layers

Dijets at 200 GeV



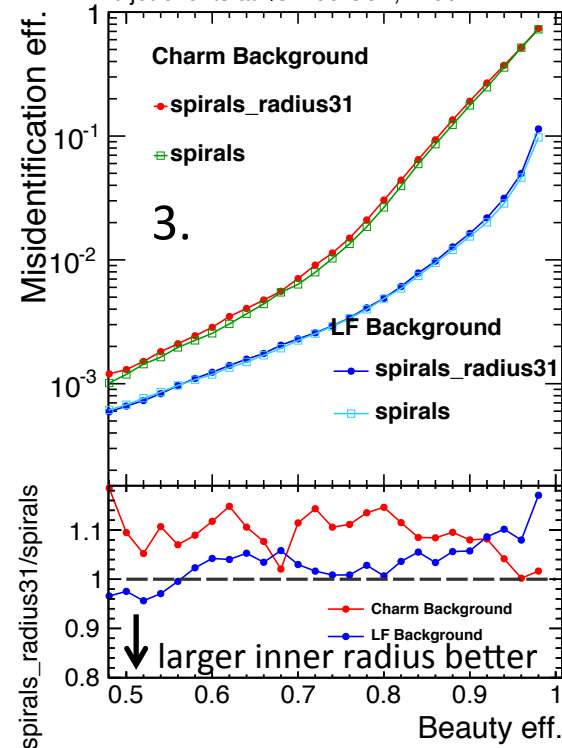
0.1% X_0 /layer / 0.2% X_0 /layer

Dijets at 200 GeV



Inner radius 27 mm / 31 mm

dijet events at $\sqrt{s}=200$ GeV, $\theta=90^\circ$



main silicon tracker

7 μm single point accuracy
time-stamping 10 ns

~5-6 tracking layers

Radius ~1.5 m, half-length ~2.3 m

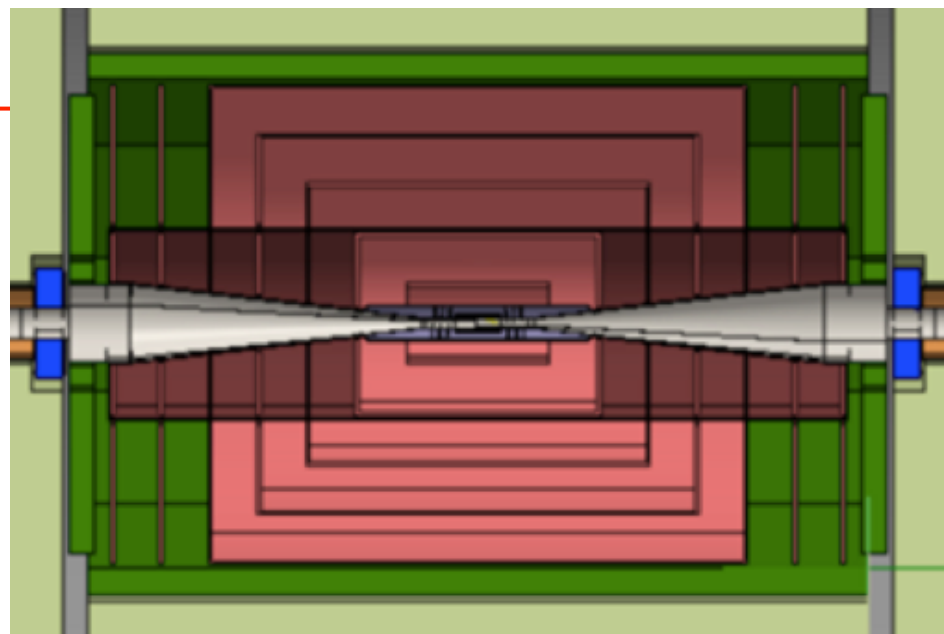
High occupancies in certain regions:

- Requires **large pixels and/or short-strips**

Very light $\Rightarrow \sim 1\%X_0$ per layer

- Requires very thin materials/sensors
 $\Rightarrow$ compatible with charge sharing and 7 μm accuracy?
- Is power pulsing feasible ?
- Air cooling is probably not feasible in a large tracker volume

Radiation level 10^4 lower than LHC



all-silicon tracker optimisation ongoing

+

now starting a tracker hardware R&D

ECAL optimisation

Work in progress !



Study to understand:

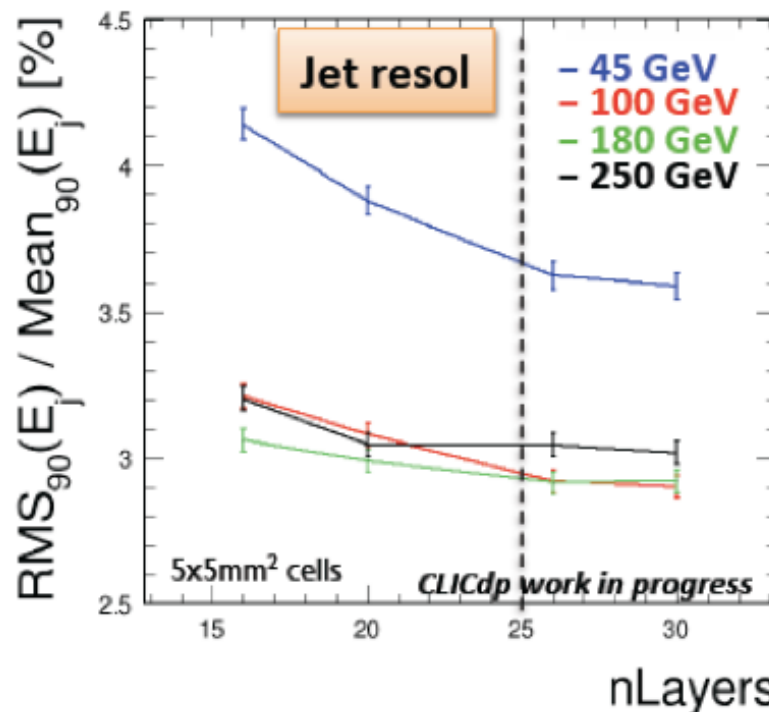
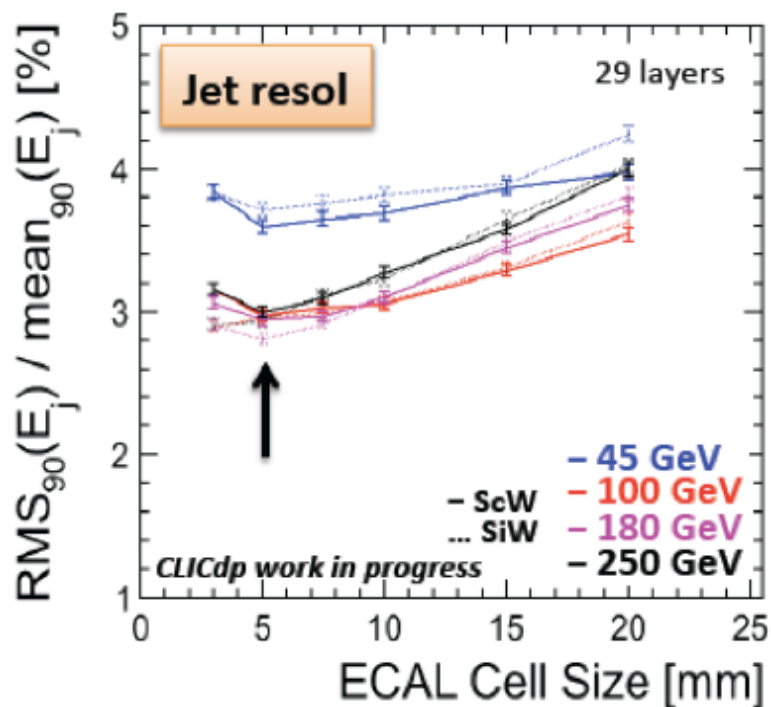
- Different active materials (Si and Scint)
- Requirements for granularity (cell sizes, # layers)

High p_t jet resolution is dominated by confusion

Small cells sizes also needed for τ ID

=> best with $5 \times 5 \text{ mm}^2$ cells

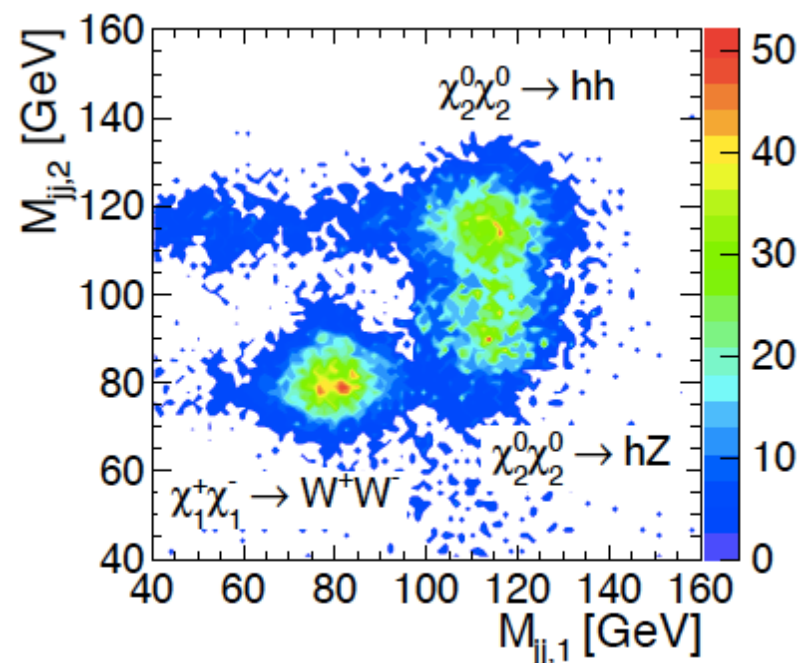
Conclusion: 25 layers of Si-tungsten with $5 \times 5 \text{ mm}^2$ cell size



- CLIC physics capabilities

Physics benchmark studies, Geant4-based full detector simulations

- with overlay of $\gamma\gamma$ background
- analyses include SM physics backgrounds.



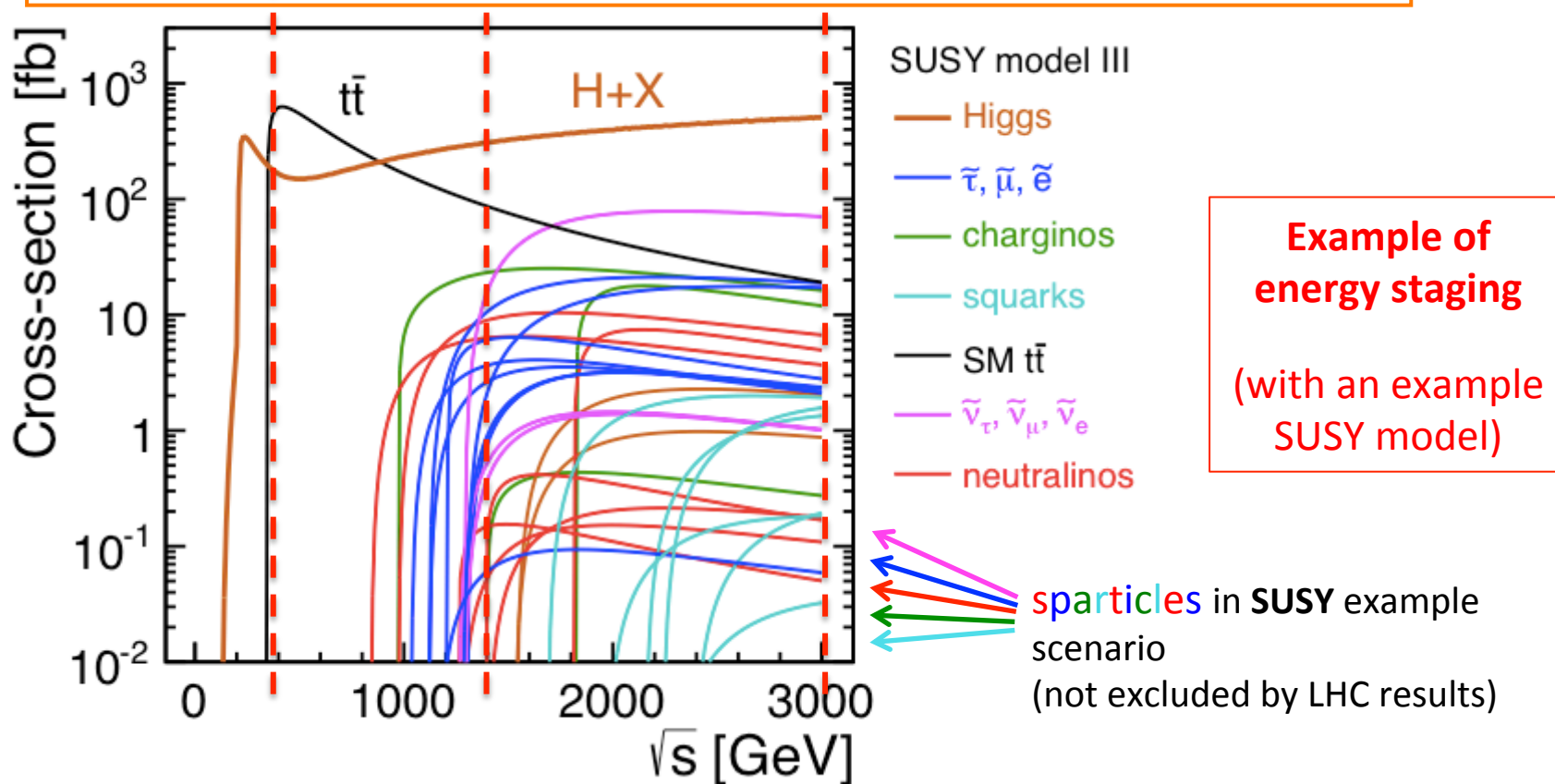
CLIC physics programme...



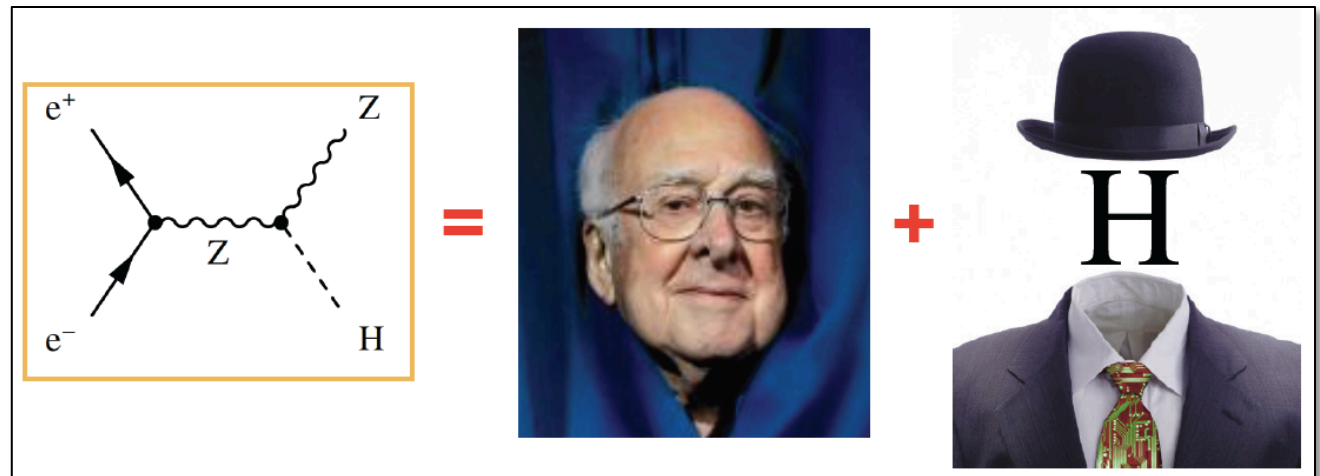
CLIC: e^+e^- collider, staged approach

- ~ 380 GeV, 500 fb^{-1} : precision Higgs and top physics
- ~ 1.4 TeV, 1.5 ab^{-1} : targeted at BSM physics, precision Higgs, top
- ~ 3 TeV, 2 ab^{-1} : targeted at BSM physics, precision Higgs

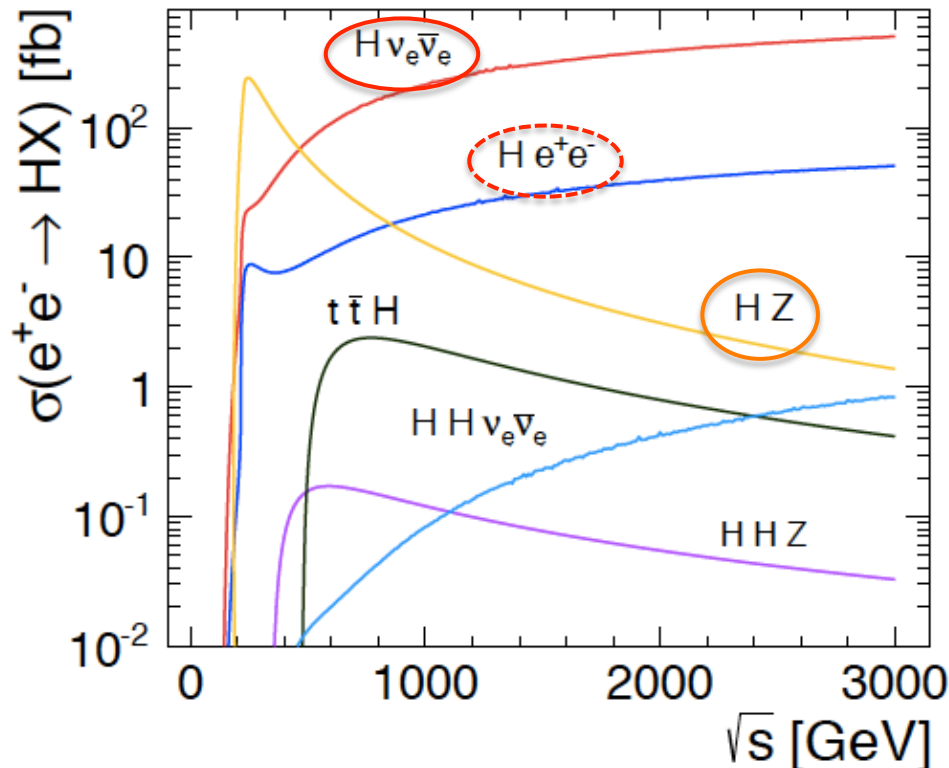
Exact energies of TeV stages will depend on LHC results



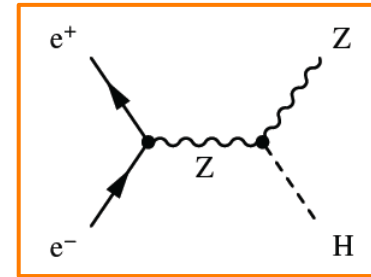
- Higgs physics



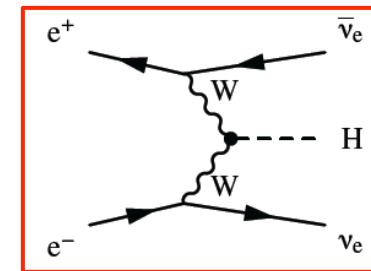
Higgs physics at CLIC



Dominant processes:



Higgsstrahlung
decreases with $\sqrt{s}$

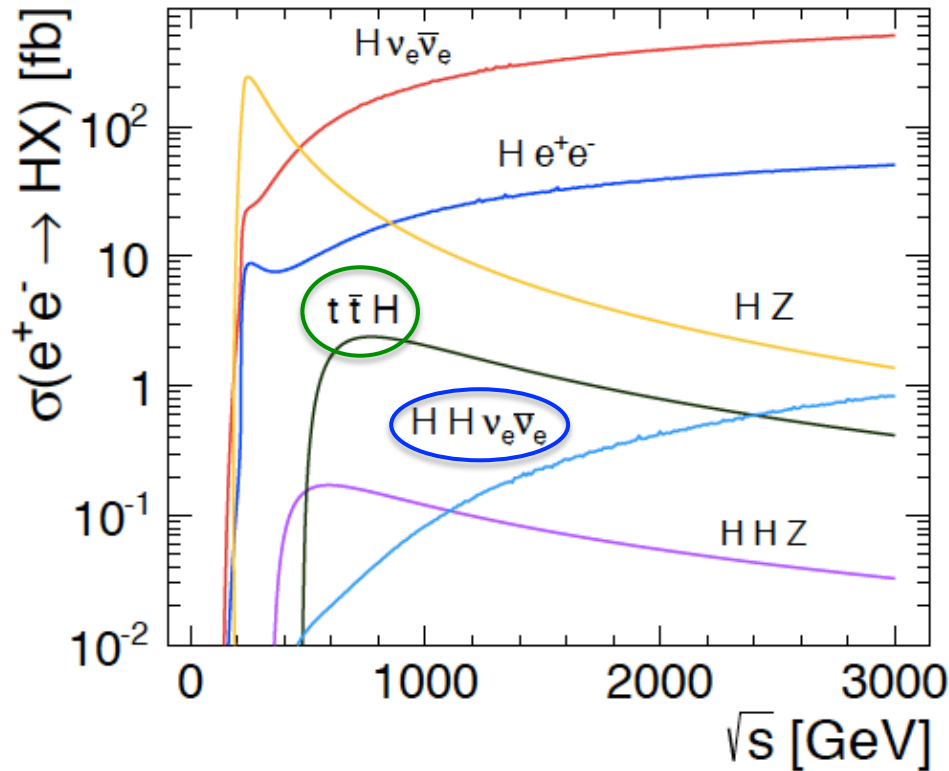


W(Z) - fusion
increases with $\sqrt{s}$

	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

For unpolarised beams.
Hvv increases $\times 1.8$ for
-80% e^- polarisation
(CLIC baseline)

Higgs physics at CLIC



Higgs-Strahlung: $e^+e^- \rightarrow ZH$

- Measure H from Z-recoil mass
- Model-independent meas.: m_H , σ
- Yields absolute value of g_{HZZ}

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

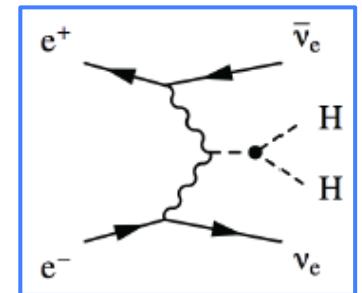
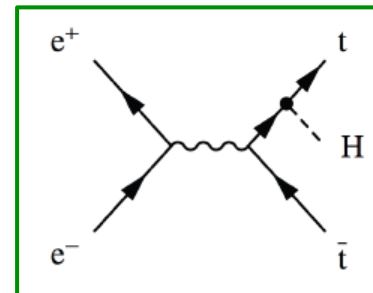
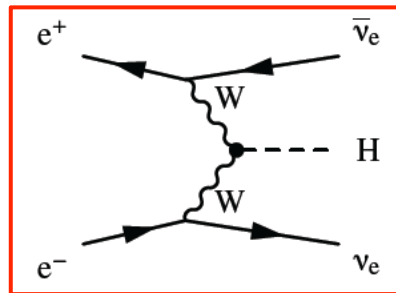
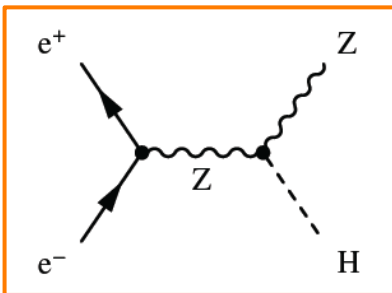
- Precise cross-section measurements in $\tau\tau$, $\mu\mu$, qq , ... decay modes
- Profits from higher $\sqrt{s}$ ($\gtrsim 350$ GeV)

Radiation off top-quarks: $e^+e^- \rightarrow t\bar{t}H$

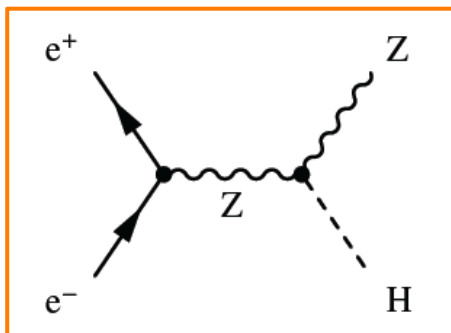
- Measure top Yukawa coupling
- Best at $\sqrt{s} \gtrsim 700$ GeV

Double-Higgs prod.: $e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$

- Measure tri-linear self coupling
- Needs high $\sqrt{s}$ ($\gtrsim 1.4$ TeV)

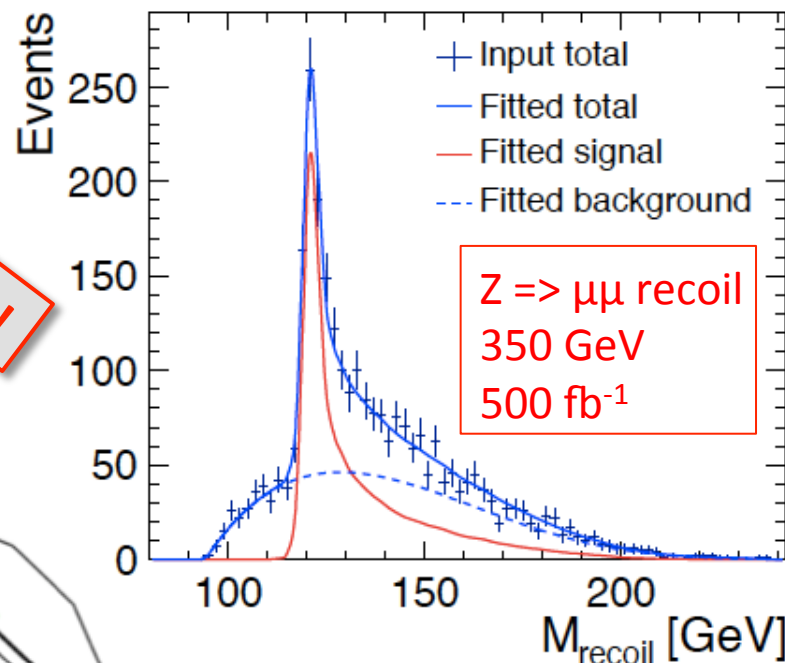
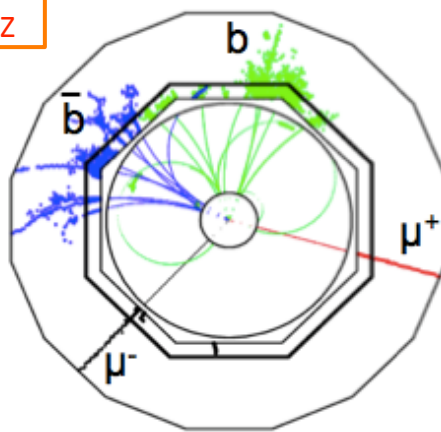
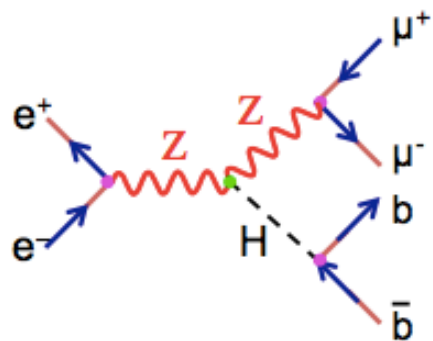


Higgsstrahlung $e^+e^- \Rightarrow HZ$



Work in progress !

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



Identify Higgs through Z recoil

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

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

+ gives access to invisible
Higgs decay

$BR(H \Rightarrow \text{inv}) < 0.97\% @ 90\% \text{ CL}$

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	$\sigma(\text{HZ}) \times BR(H \rightarrow \text{invisible})$	Γ_{inv}	0.6%	—	—
ZH	$H \rightarrow b\bar{b}$ mass distribution	m_H	tbd	—	—
Hv _e $\bar{\nu}_e$	$H \rightarrow b\bar{b}$ mass distribution	m_H	—	40 MeV*	33 MeV*
ZH	$\sigma(\text{HZ}) \times BR(Z \rightarrow \ell^+ \ell^-)$	g_{HZZ}^2	4.2%	—	—
ZH	$\sigma(\text{HZ}) \times BR(Z \rightarrow q\bar{q})$	g_{HZZ}^2	1.8%	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow b\bar{b})$	$g_{\text{HZZ}}^2 g_{\text{Hbb}}^2 / \Gamma_H$	1% [†]	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow c\bar{c})$	$g_{\text{HZZ}}^2 g_{\text{Hcc}}^2 / \Gamma_H$	5% [†]	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow g\bar{g})$	—	6% [†]	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow \tau^+ \tau^-)$	$g_{\text{HZZ}}^2 g_{\text{H}\tau\tau}^2 / \Gamma_H$	6.2%	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow WW^*)$	$g_{\text{HZZ}}^2 g_{\text{HWW}}^2 / \Gamma_H$	2% [†]	—	—
ZH	$\sigma(\text{HZ}) \times BR(H \rightarrow ZZ^*)$	$g_{\text{HZZ}}^2 g_{\text{HZZ}}^2 / \Gamma_H$	tbd	—	—
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	$g_{\text{HWW}}^2 g_{\text{Hbb}}^2 / \Gamma_H$	3% [†]	0.3%	0.2%
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	$g_{\text{HWW}}^2 g_{\text{Hcc}}^2 / \Gamma_H$	—	2.9%	2.7%
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow g\bar{g})$	—	—	1.8%	1.8%
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow \tau^+ \tau^-)$	$g_{\text{HWW}}^2 g_{\text{H}\tau\tau}^2 / \Gamma_H$	—	4.2%	tbd
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow \mu^+ \mu^-)$	$g_{\text{HWW}}^2 g_{\text{H}\mu\mu}^2 / \Gamma_H$	—	38%	16%
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow \gamma\gamma)$	—	—	15%	tbd
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow Z\gamma)$	—	—	42%	tbd
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow WW^*)$	$g_{\text{HWW}}^4 / \Gamma_H$	tbd	1.4%	0.9% [†]
Hv _e $\bar{\nu}_e$	$\sigma(\text{Hv}_e \bar{\nu}_e) \times BR(H \rightarrow ZZ^*)$	$g_{\text{HWW}}^2 g_{\text{HZZ}}^2 / \Gamma_H$	—	3% [†]	2% [†]
He ⁺ e ⁻	$\sigma(\text{He}^+ e^-) \times BR(H \rightarrow b\bar{b})$	$g_{\text{HZZ}}^2 g_{\text{Hbb}}^2 / \Gamma_H$	—	1% [†]	0.7% [†]
t $\bar{t}$ H	$\sigma(t\bar{t}H) \times BR(H \rightarrow b\bar{b})$	$g_{\text{Htt}}^2 g_{\text{Hbb}}^2 / \Gamma_H$	—	8%	tbd
HHv _e $\bar{\nu}_e$	$\sigma(\text{HHv}_e \bar{\nu}_e)$	g_{HHWW}	—	7%*	3%*
HHv _e $\bar{\nu}_e$	$\sigma(\text{HHv}_e \bar{\nu}_e)$	λ	—	32%	16%
HHv _e $\bar{\nu}_e$	with -80% e ⁻ polarization	λ	—	24%	12%

Summary of CLIC Higgs
benchmark simulations

for more info:

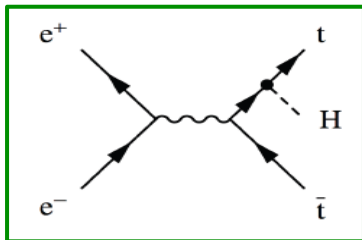
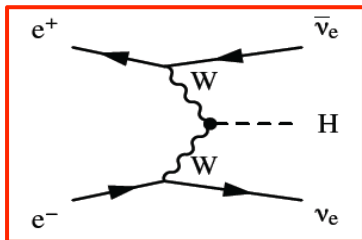
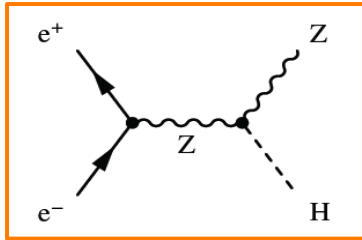
<http://arxiv.org/abs/1307.5288>

Work in progress !

* Preliminary

+ Estimate

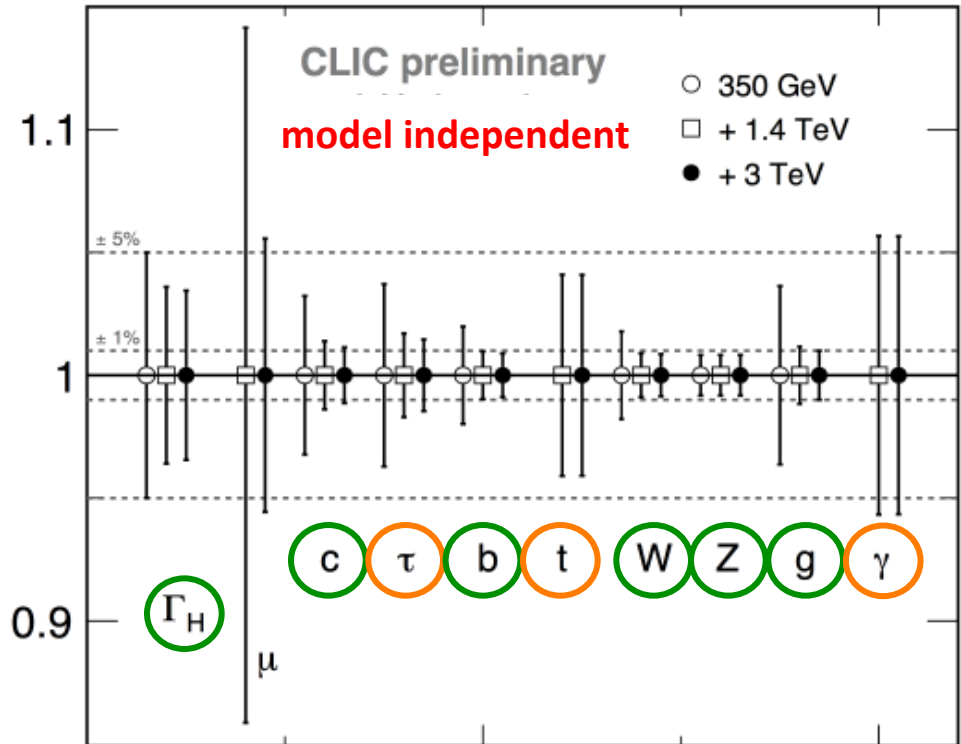
Higgs coupling to mass



combining all
Higgs
information

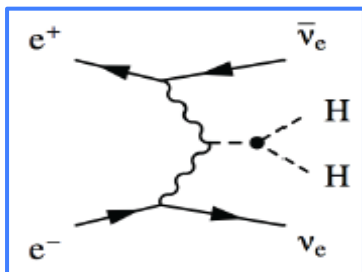
production
+
decay

coupling relative to SM



○ much more accurate than HL-LHC
○ similar accuracy as HL-LHC

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



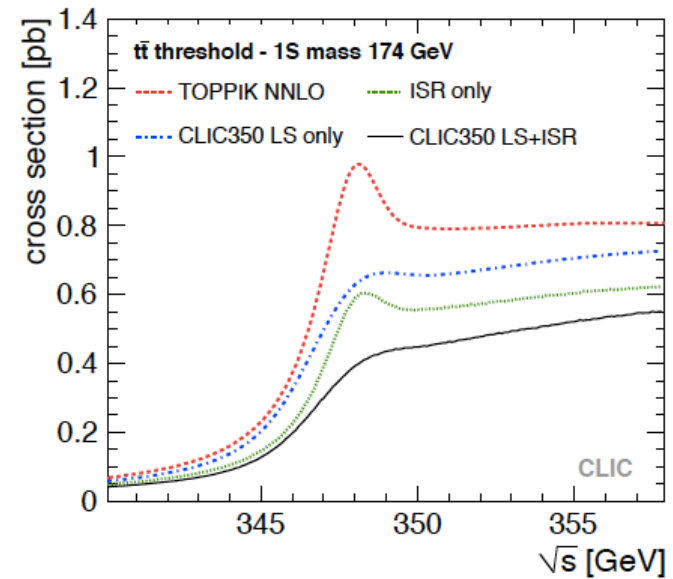
Higgs self-coupling $H \Rightarrow HH$

Gives access to understanding the Higgs field

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

Work in progress !

- Top physics



Accurate top mass measurement

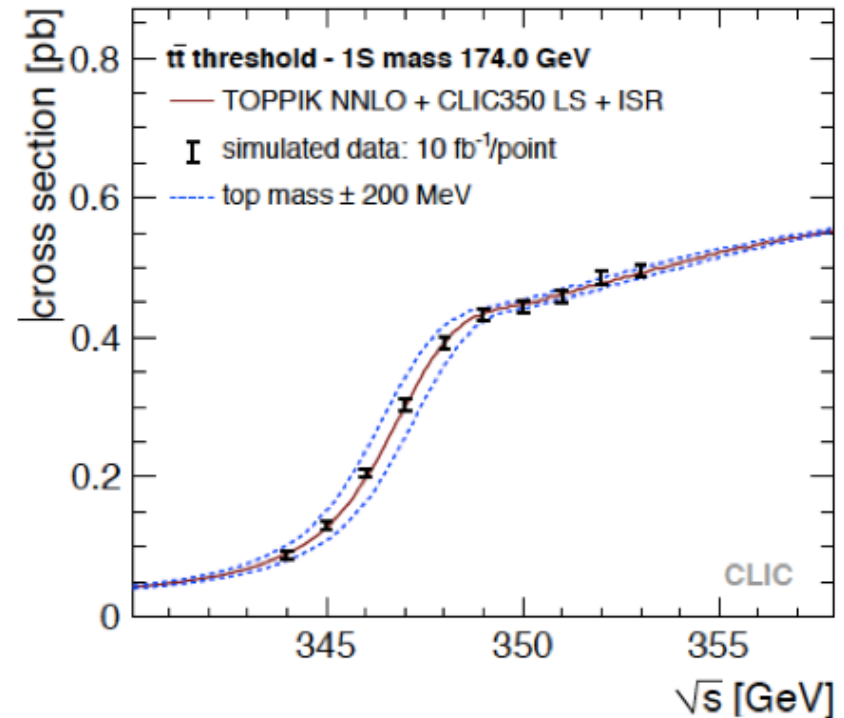
$t\bar{t}$ threshold scan

10 centre-of-mass points, 10 fb^{-1} each

$$\Delta_{\text{stat}}(m_t) = 34 \text{ MeV}$$

$$\Delta_{\text{stat}}(\alpha_s) = 0.0009$$

Theoretical uncertainty $O(50\text{-}100 \text{ MeV})$
when transforming measured 1S mass
to $\overline{\text{MS}}$ scheme



Other top (b) physics subjects:

Explore potential of $t\bar{t}$ or single top events as a probe for new physics, at the first stage and possibly at higher energies:

A_{FB}^t (and A_{FB}^b)

top quark couplings to γ , Z and W

Search for FCNC top decays

V_{tb} from $e\gamma \Rightarrow tb\nu_e$ (at high energies)

choice of lower CLIC energy stage (1)

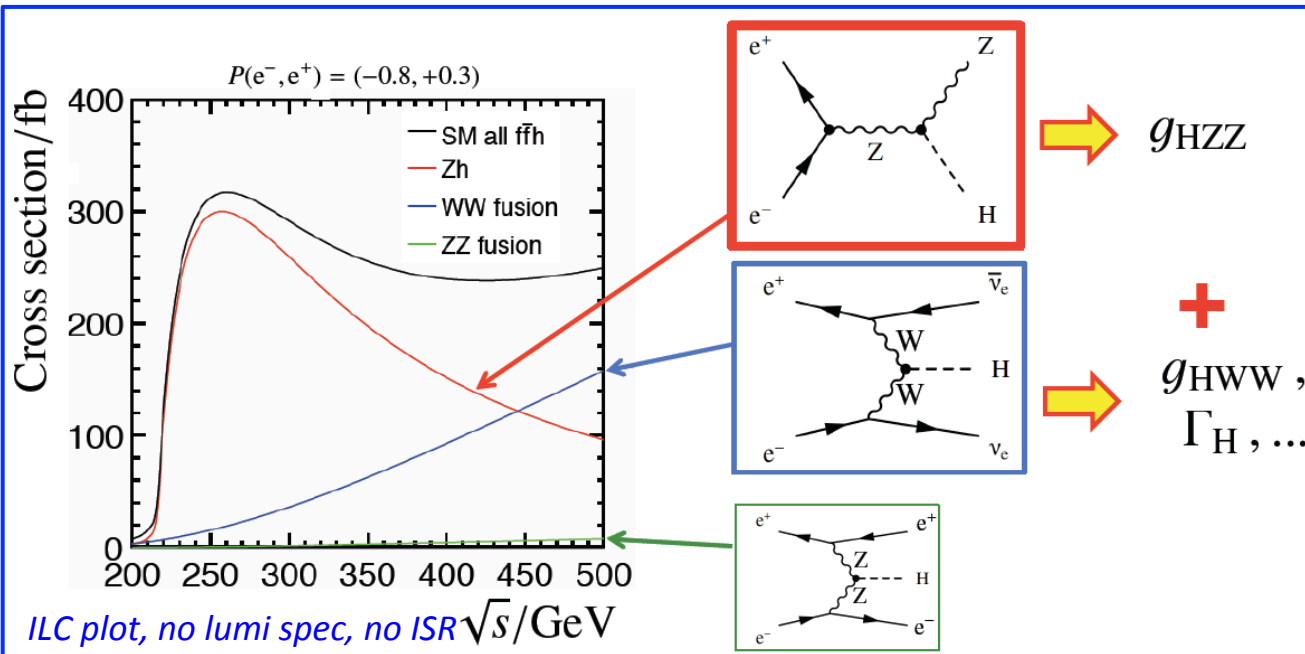
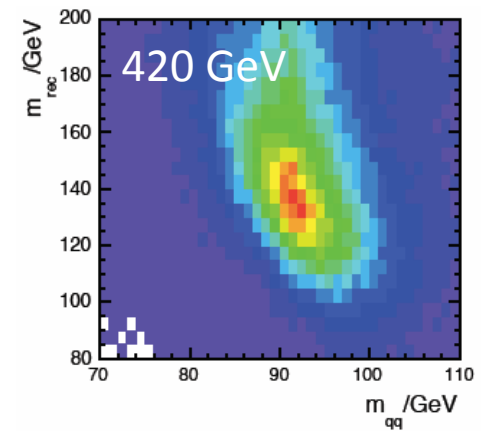
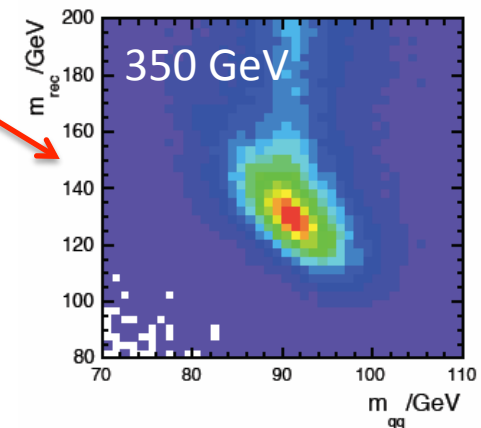
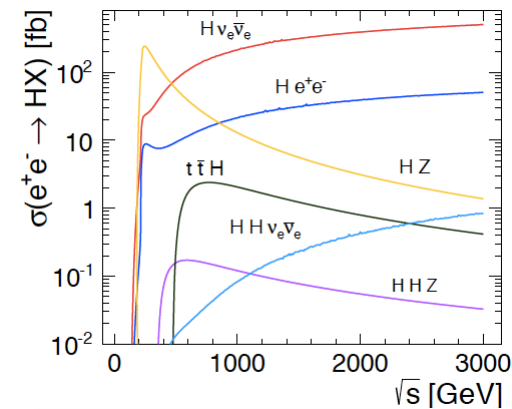


Guaranteed physics case #1: Higgs physics

HZ production $\Rightarrow \sqrt{s} \sim 250 - 450 \text{ GeV}$

Recoil mass measurement $\Rightarrow \sqrt{s} < 400 \text{ GeV}$

H from WW fusion $\Rightarrow \sqrt{s} > 350 \text{ GeV}$



choice of lower CLIC energy stage (2)

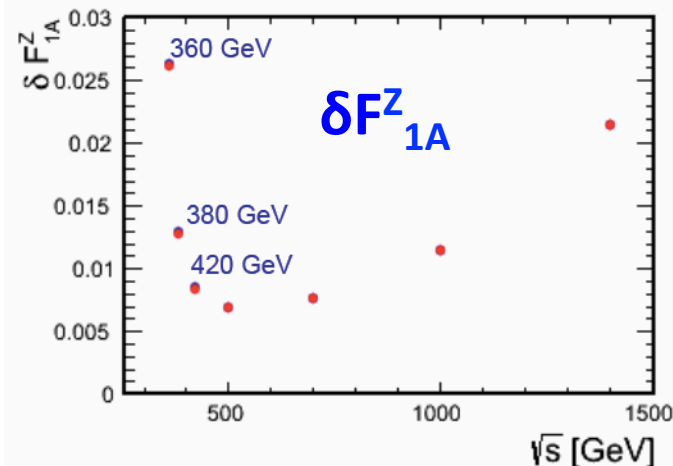
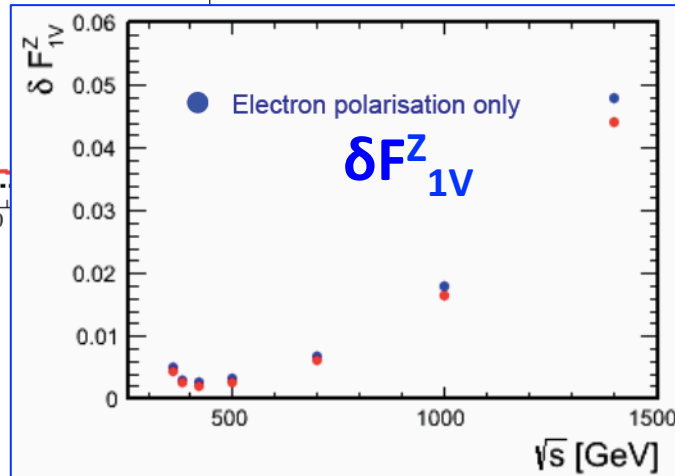
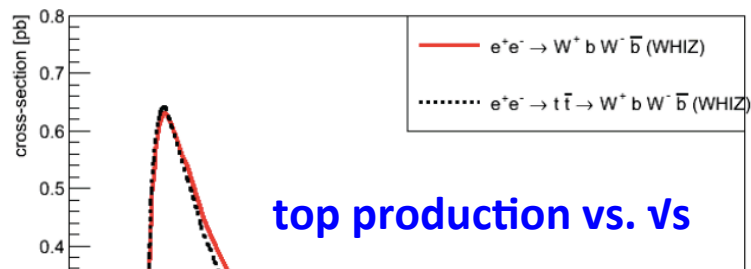
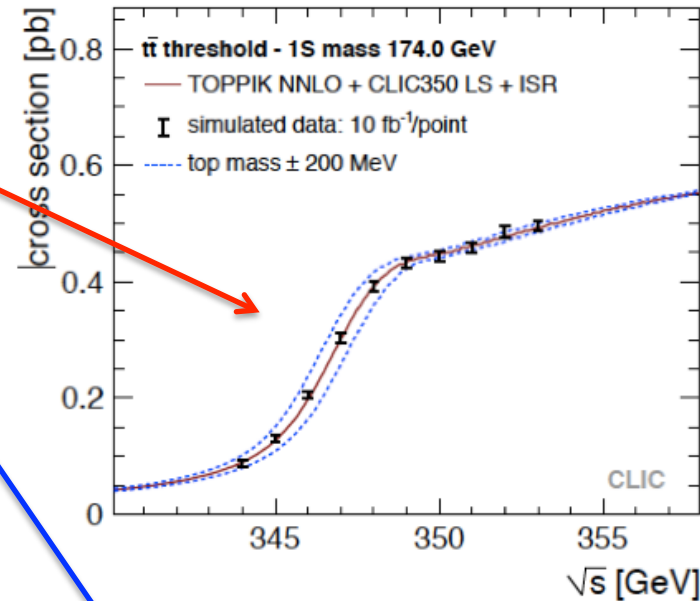


Guaranteed physics case #2: top physics

top at threshold $\Rightarrow \sqrt{s} \sim 345 - 355 \text{ GeV}$

top couplings (γ, Z) $\Rightarrow \sqrt{s} > 360 \text{ GeV}$

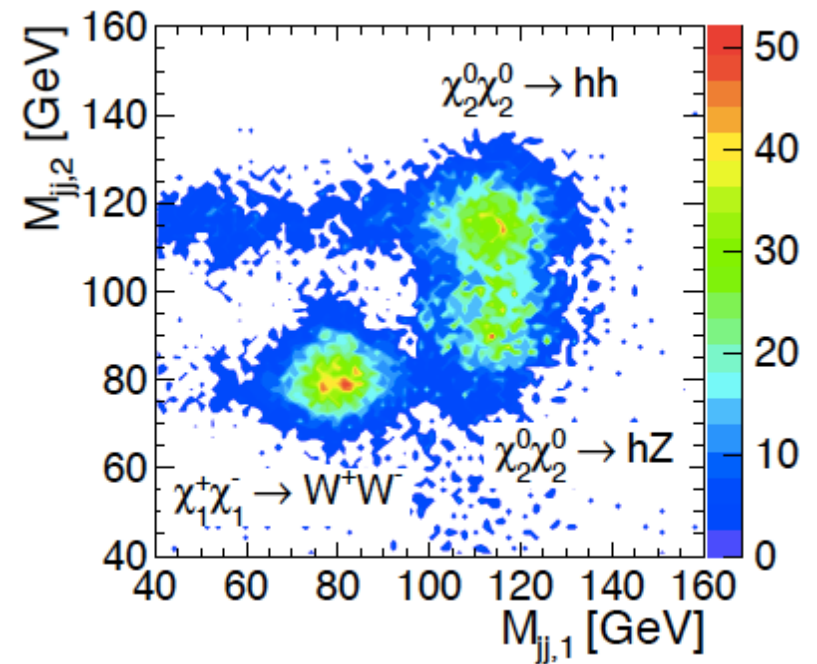
BSM from top pairs $\Rightarrow \sqrt{s} > 380 - ? \text{ GeV}$



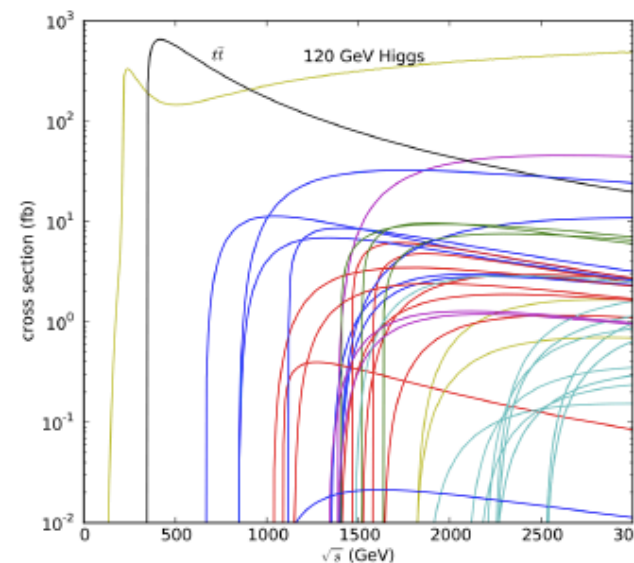
Current compromise
for first energy stage:

380 GeV

- CLIC potential for New Physics

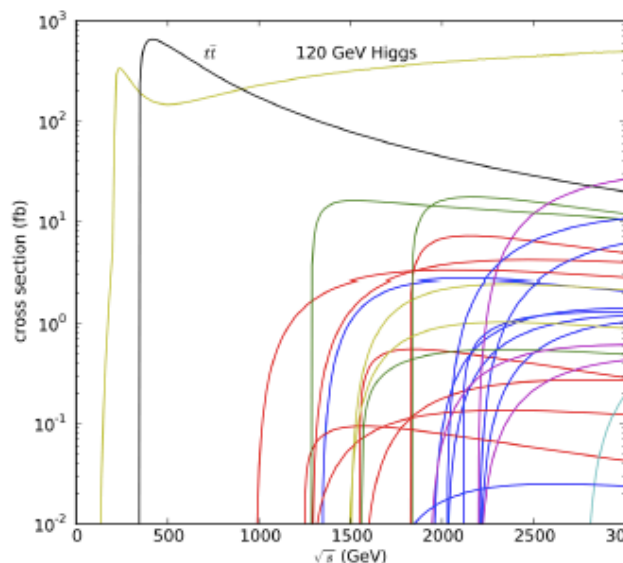


investigated SUSY models



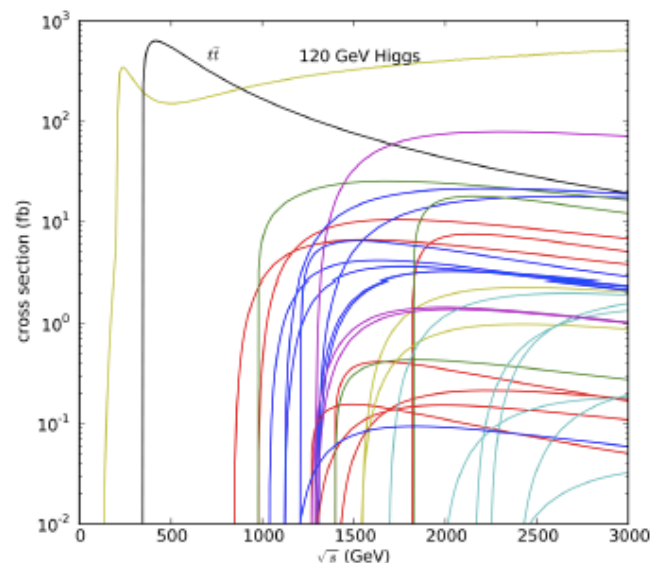
CDR model I, 3 TeV:

- 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”

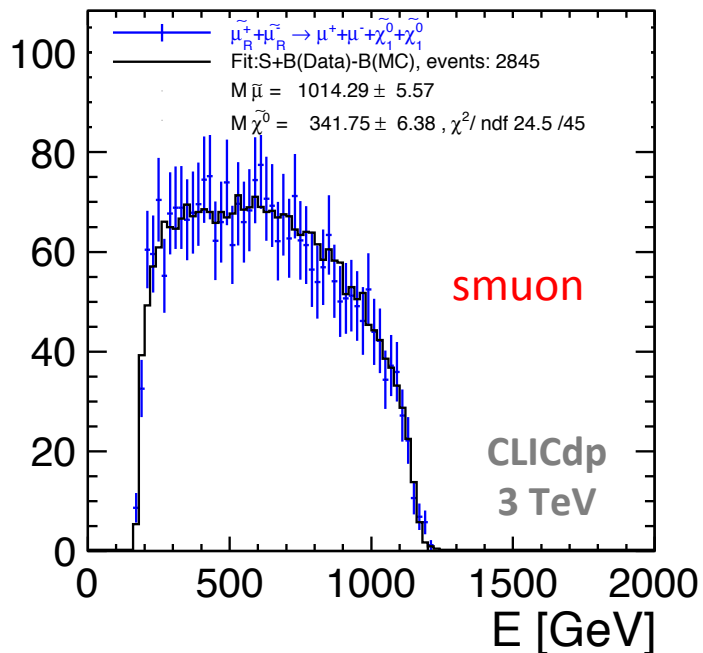
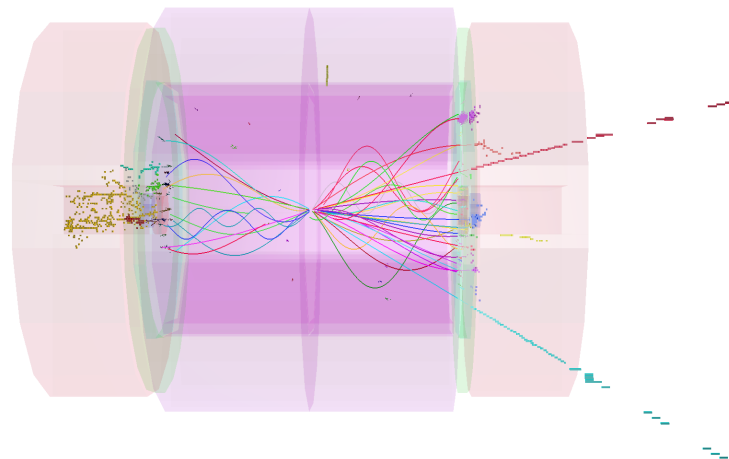
the simplest case: slepton at 3 TeV

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



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

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

di-jet masses: gauginos at 3 TeV

Chargino and neutralino pair production

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

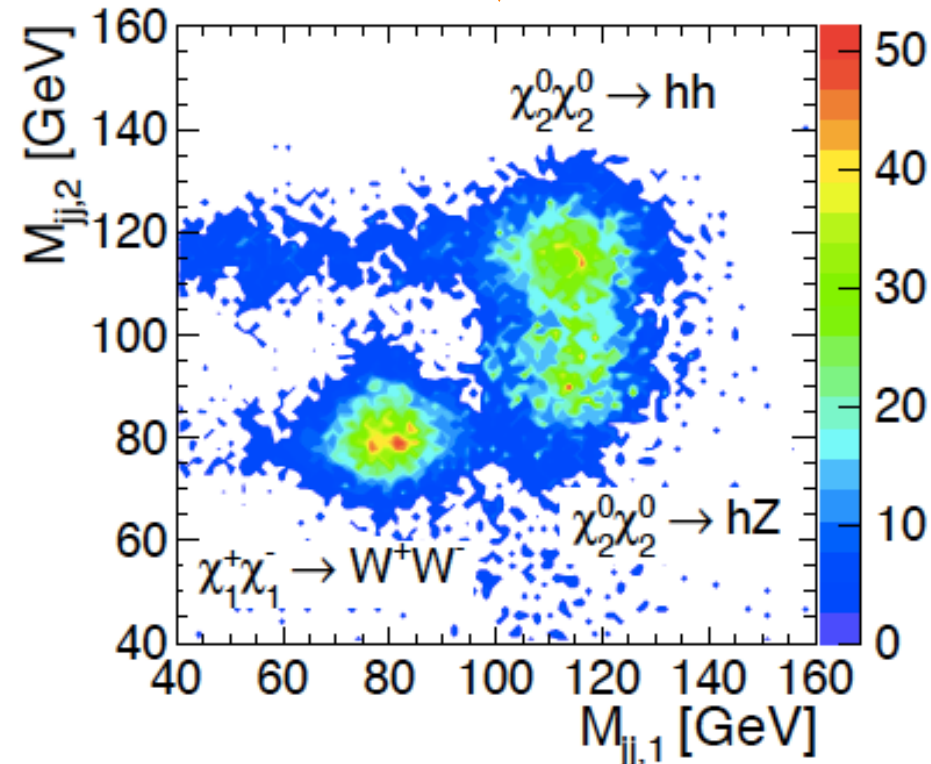
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82 \%$$

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

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

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

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




$$m(\tilde{\chi}_1^\pm) : \pm 7 \text{ GeV}$$
$$m(\tilde{\chi}_2^0) : \pm 10 \text{ GeV}$$



use slepton study result

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

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

sensitivity to Higgs partners

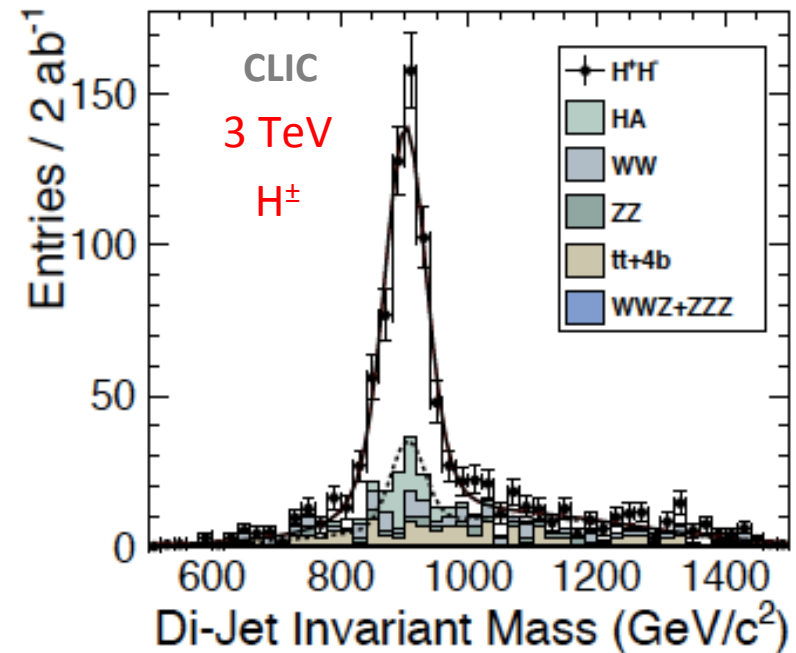
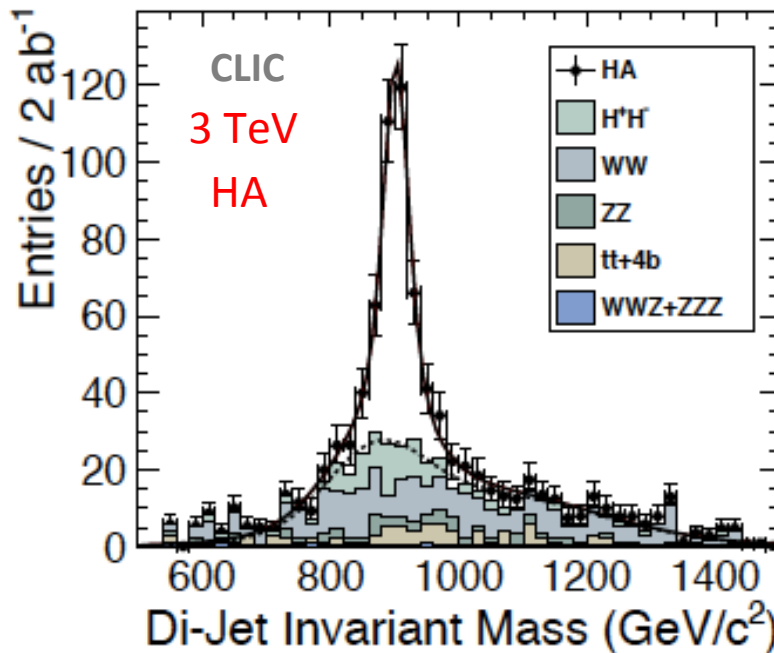
Higgs partners BSM $\rightarrow$ accessible up to $\sqrt{s}/2$

Example MSSM benchmark study at 3 TeV, 2 ab^{-1}

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

(H, A and $H^\pm$ almost degenerate in mass)

- Complex final states



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

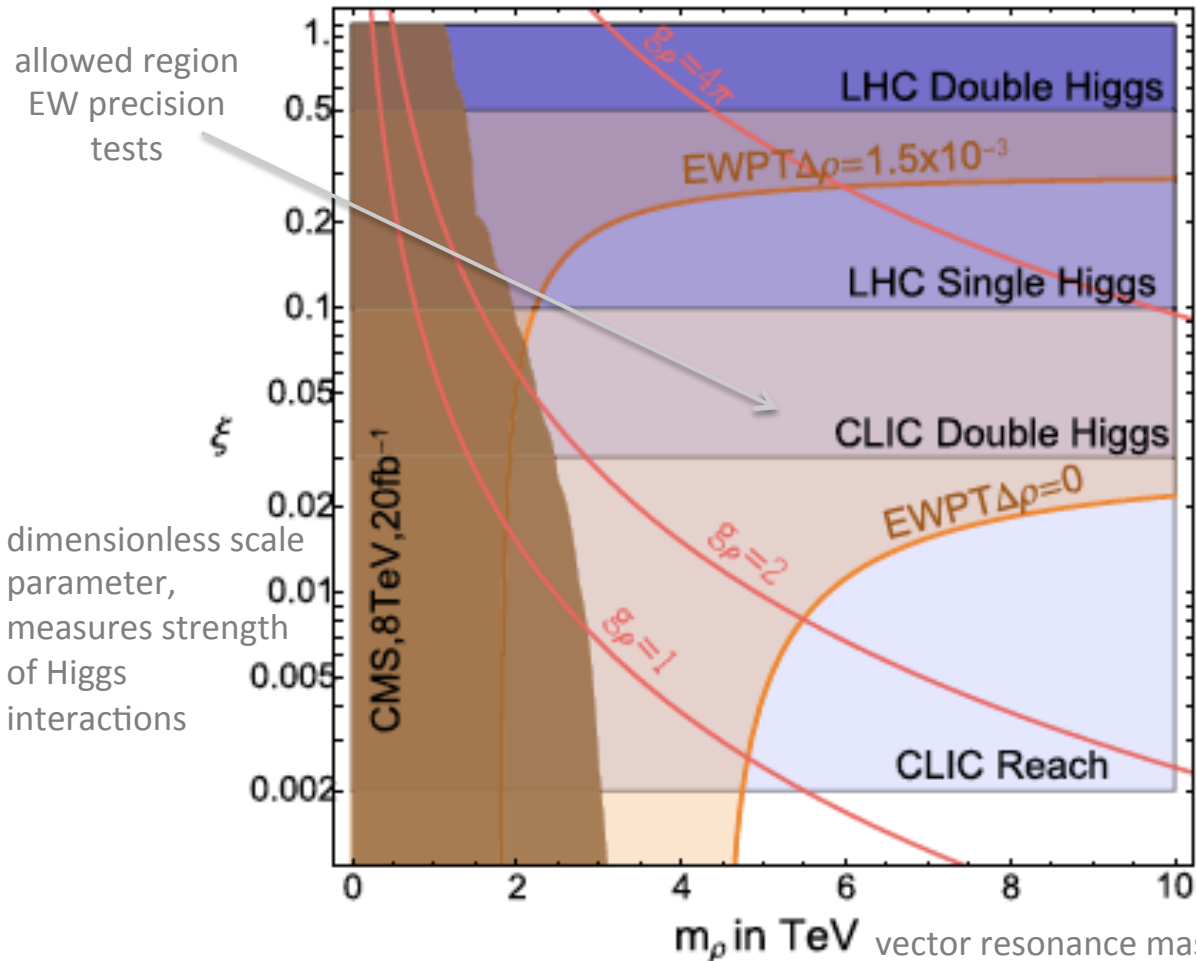
results of SUSY benchmarks

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	$\tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$	II	$\tilde{\ell}$ mass	1097.2	0.4%
		$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h/Z^0 h/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Squarks	$\tilde{q}_R \tilde{q}_R \rightarrow q \bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0 A^0 \rightarrow b \bar{b} b \bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^\pm H^\mp \rightarrow t \bar{b} b \bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
1.4	Stau	$\tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$	III	$\tilde{\tau}_1$ mass	517	2.0%
		$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h/Z^0 h/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\chi}_1^\pm$ mass	487	0.2%
				$\tilde{\chi}_2^0$ mass	487	0.1%

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

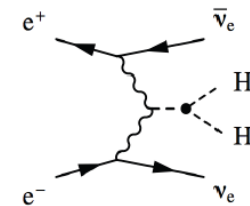
composite Higgs bosons



LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search $WZ \Rightarrow 3$ 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

$Q_f = g_Y'(Y_f) + g_{BL}'(B-L)_f$
(charge of SM fermions under $U(1)'$ symmetry)

Observables:

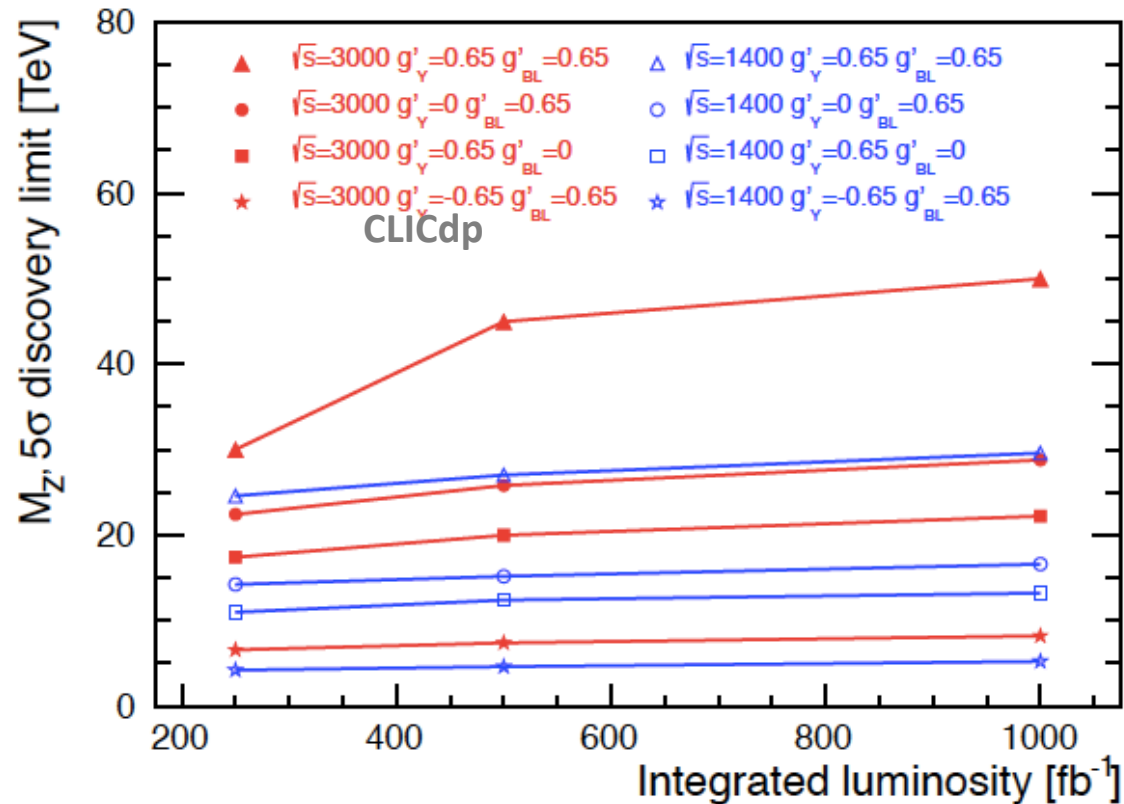
- Total $e^+e^- \Rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry
(with $\pm 80\%$ e^- polarisation)

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)

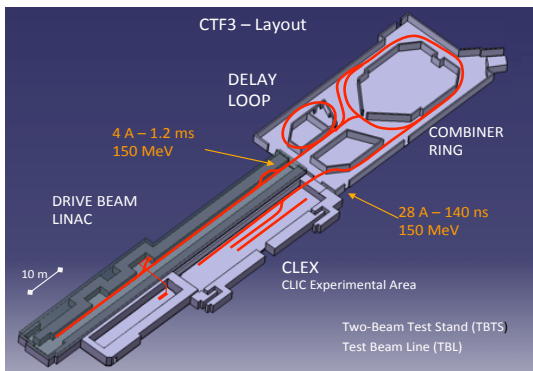


CLIC strategy and objectives



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.



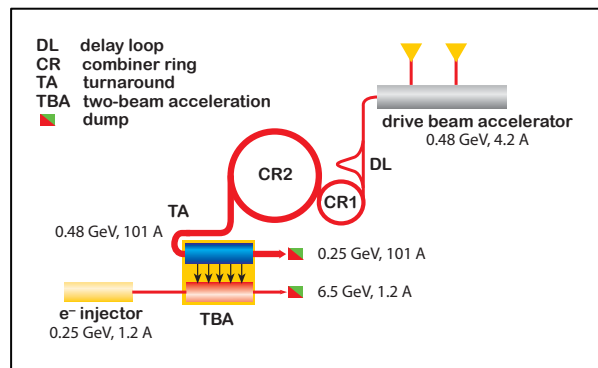
2018-19 Decisions

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.

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.



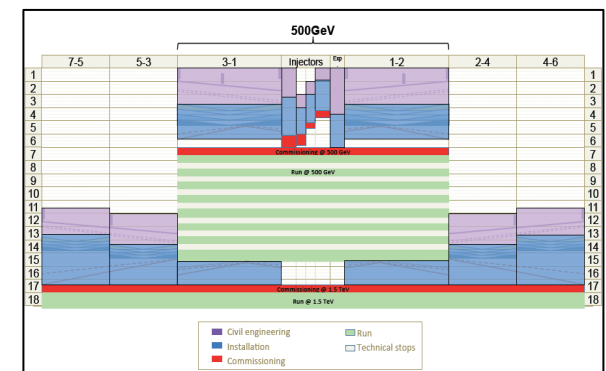
2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Construction Phase

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

Preparation for implementation of further stages.



Commissioning

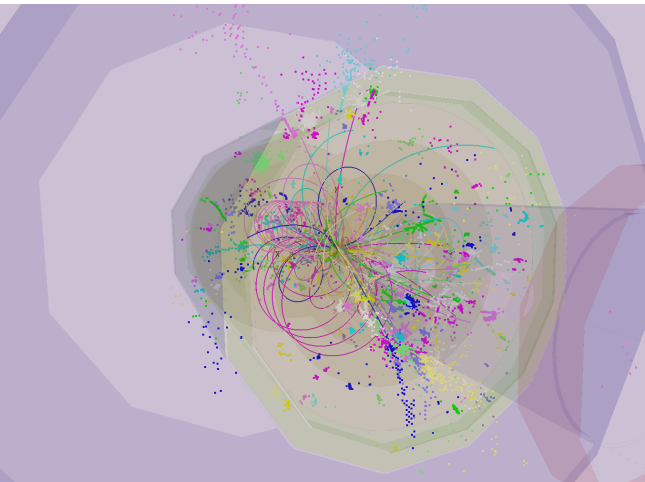
Becoming ready for data-taking as the LHC programme reaches completion.

Many years of R&D have been invested in CLIC
 Large-scale tests have confirmed the technology
 No show stoppers identified

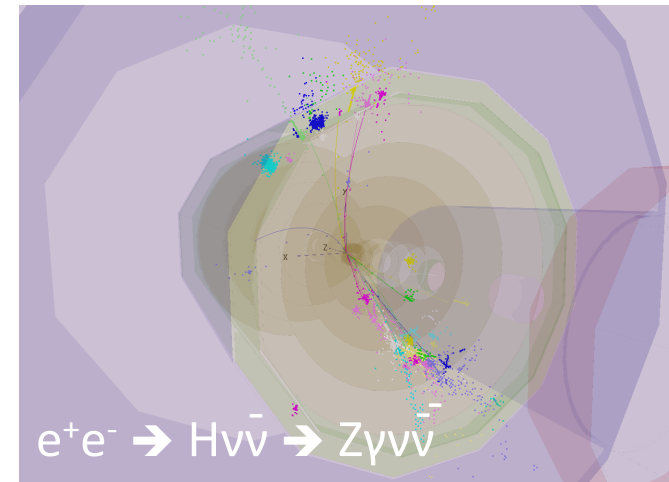
CLIC is currently the only option to reach multi-TeV e^+e^- collisions
 an available option for CERN after LHC

CLIC offers a wealth of accurate physics measurements
A powerful tool to address the open questions in particle physics

challenging R&D
very active R&D collaborations
 for accelerator and physics/detector



<http://clcdp.web.cern.ch/>
<http://cllc-study.web.cern.ch/>



SPARE SLIDES

CLIC Higgs global fits



Work in progress !

★ Model-independent global fits

Parameter	Measurement precision		
	350 GeV 500 fb ⁻¹	+ 1.4 TeV +1.5 ab ⁻¹	+3.0 TeV +2.0 ab ⁻¹
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 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	—	14.1 %	5.6 %
g_{Htt}	—	4.1 %	≤ 4.1 %
$g_{Hgg}^{\dagger}$	3.6 %	1.2 %	1.0 %
$g_{H\gamma\gamma}^{\dagger}$	—	5.7 %	< 5.7 %
Γ_H	5.0 %	3.6 %	3.4 %

★ ~1 % precision on many couplings

- limited by g_{HZZ} precision

★ Constrained “LHC-style” fits

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

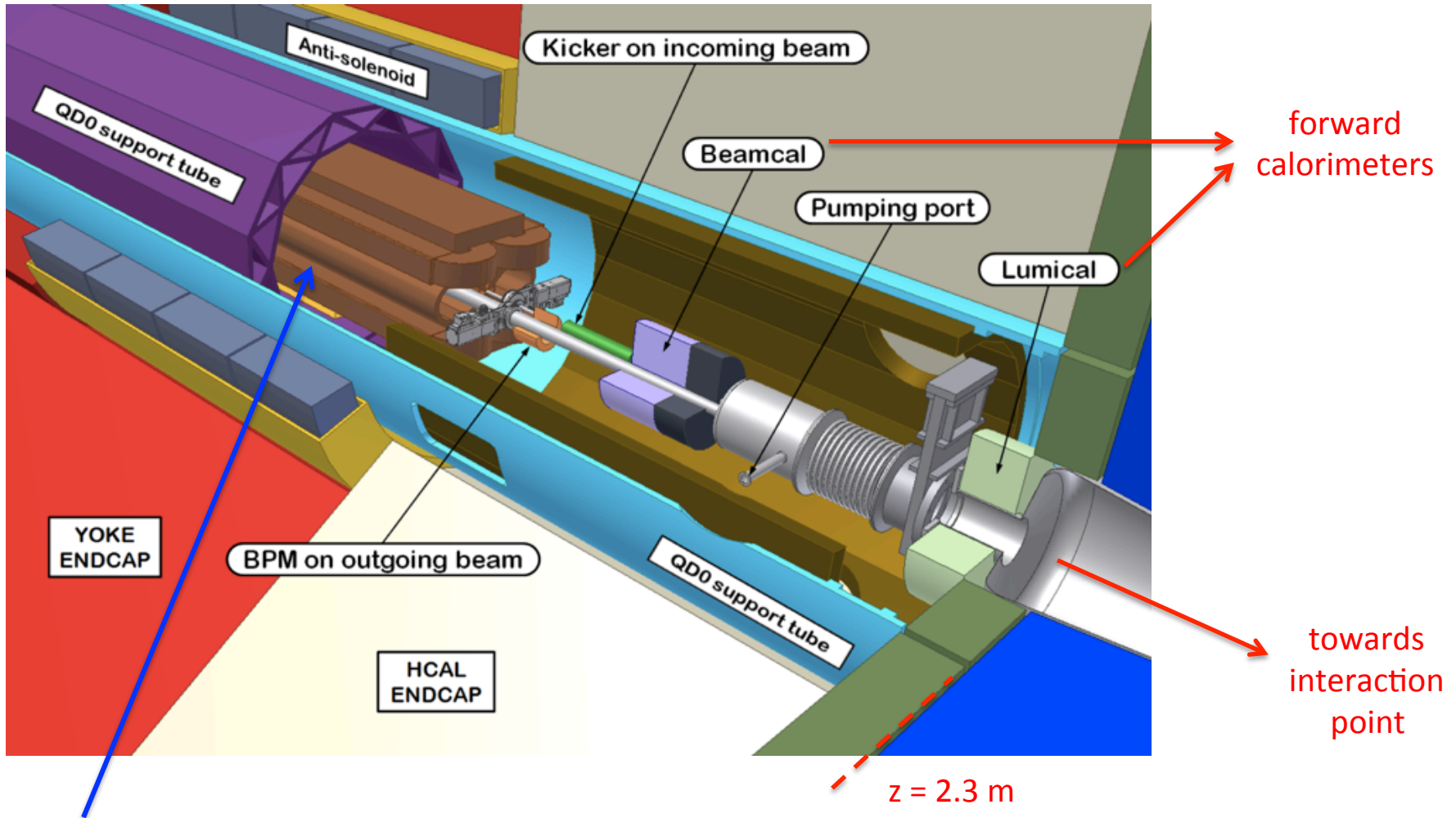
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}}$$

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

Parameter	Measurement precision		
	350 GeV 500 fb ⁻¹	+ 1.4 TeV +1.5 ab ⁻¹	+3.0 TeV +2.0 ab ⁻¹
κ_{HZZ}	0.44 %	0.31 %	0.23 %
κ_{HWW}	1.5 %	0.17 %	0.11 %
κ_{Hbb}	1.7 %	0.37 %	0.22 %
κ_{Hcc}	3.1 %	1.1 %	0.75 %
$\kappa_{H\tau\tau}$	3.7 %	1.5 %	1.2 %
$\kappa_{H\mu\mu}$	—	14.1 %	5.5 %
κ_{Htt}	—	4.0 %	≤ 4.0 %
κ_{Hgg}	3.6 %	0.79 %	0.55 %
$\kappa_{H\gamma\gamma}$	—	5.6 %	< 5.6 %
$\Gamma_{H,md,derived}$	1.6 %	0.32 %	0.22 %

★ sub-% precision for most couplings

Forward region layout

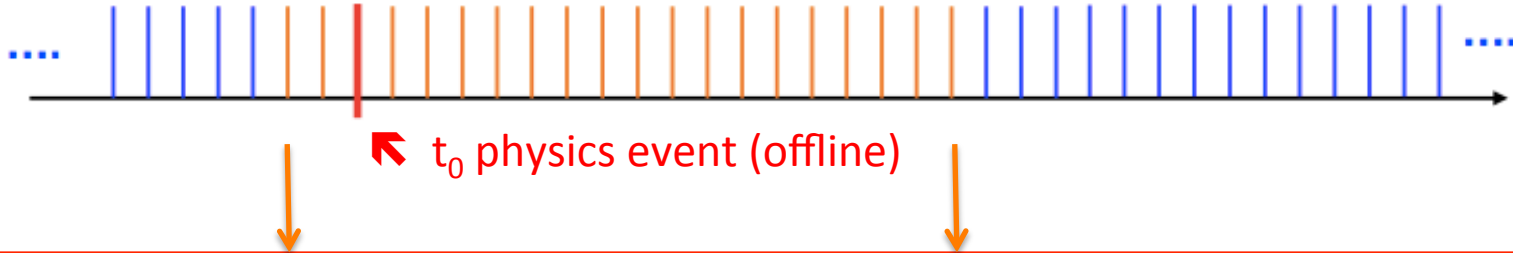


**Final beam focusing elements
=> important acceptance loss in forward region**

background suppression at CLIC



Triggerless readout of full train

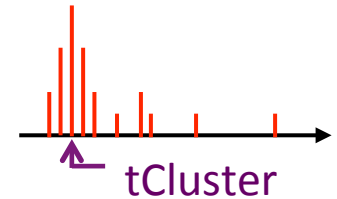


- **Full event reconstruction + PFA analysis with background overlaid**

- => 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



19 TeV → 1.2 TeV → 100 GeV

+

- **Use well-adapted jet clustering algorithms**

- Making use of LHC experience (FastJet k_t algorithm)

CLIC conditions => impact on detector



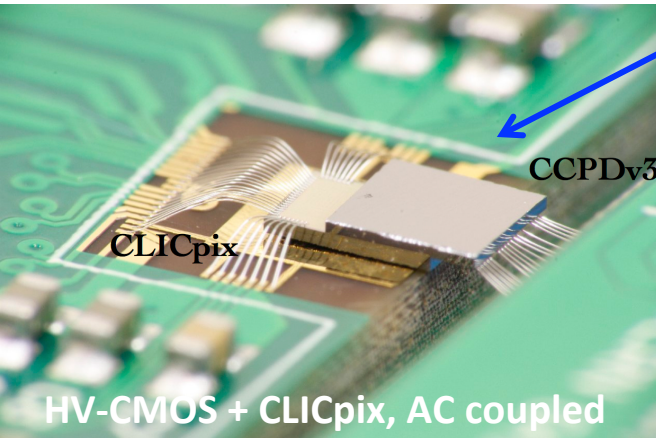
CLIC conditions => impact on detector technologies:

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

2014 => WG vertex detector technology



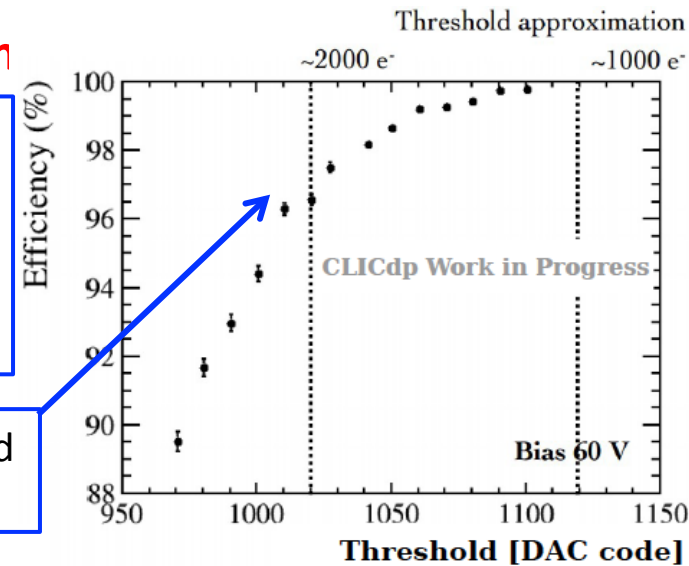
Successful 2014 beam tests with novel HV-CMOS techn



Active HV-CMOS sensor
AC-coupled (glue) to complex
CLICpix readout chip

- Fast signal !
- Small pixels

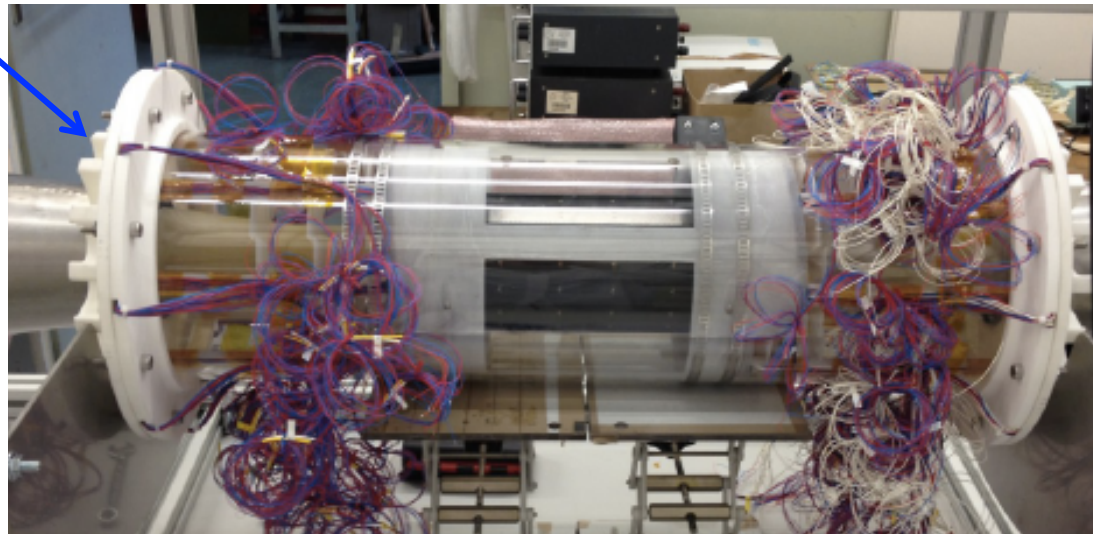
High efficiency achieved
at test beam



Engineering studies on support structures and air cooling

Full-scale thermo-mechanical
mock-up of the vertex detector

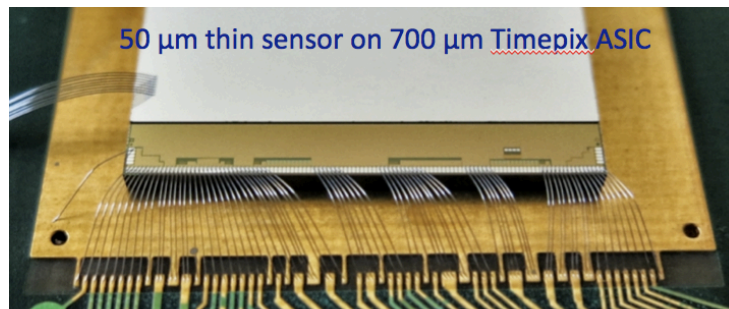
Ultra-light supports tested for
vibration stability in air flow



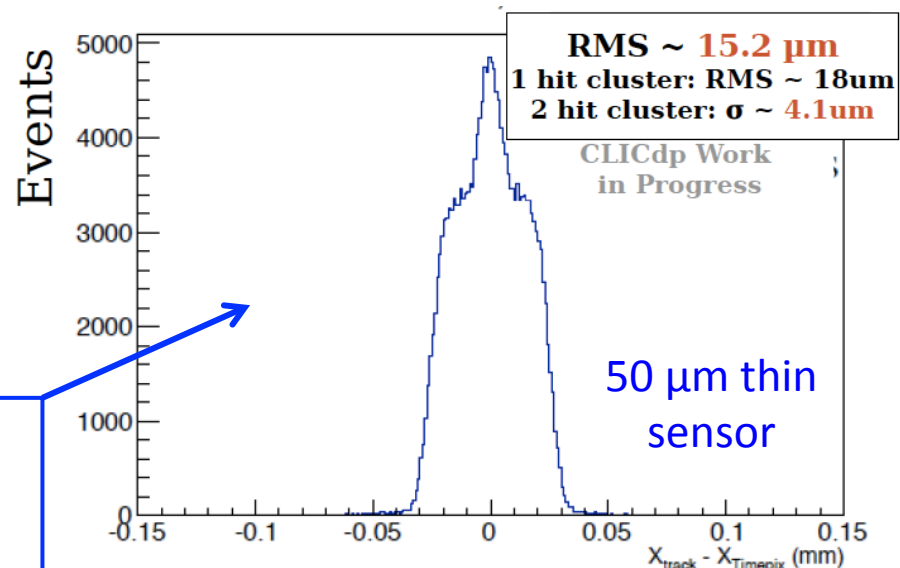
2014 => WG vertex detector technology



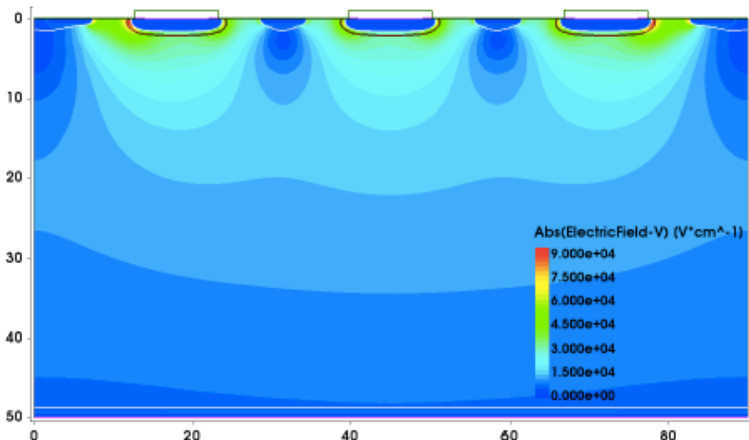
Analysis of 2013 test beam data



Required position resolution ($\sim 3 \mu\text{m}$) can be achieved with charge sharing between neighbouring pixels. But, how to get charge sharing for all hits ?

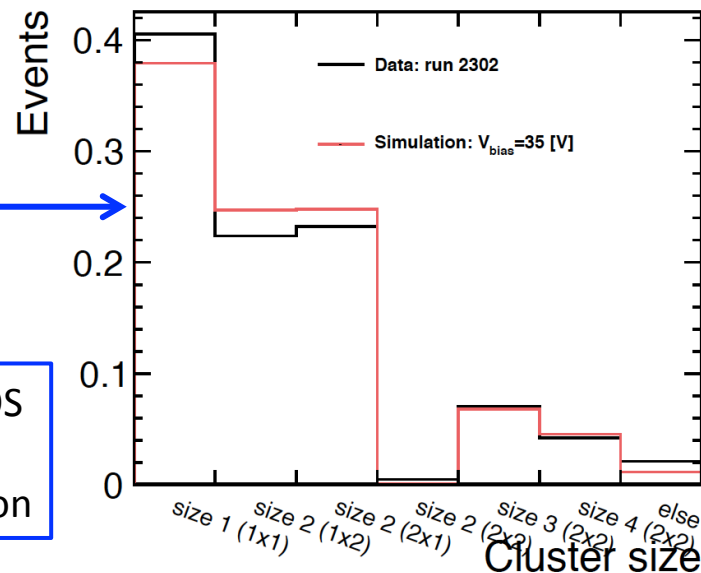


Better understanding through detailed simulations



Prediction of hit cluster sizes in a pixel detector

E-field in a HV-CMOS sensor for a given integrated irradiation



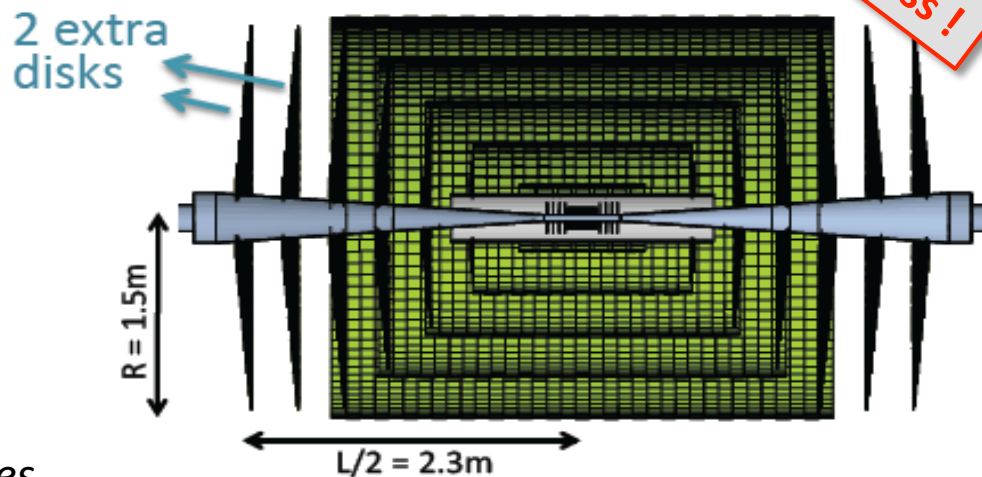
Main tracker and B-field choice



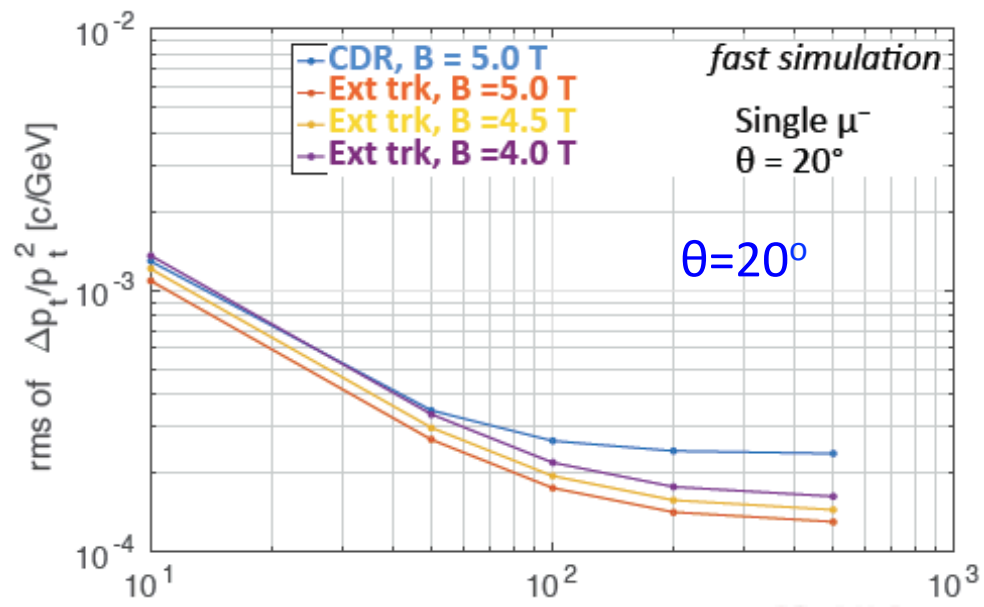
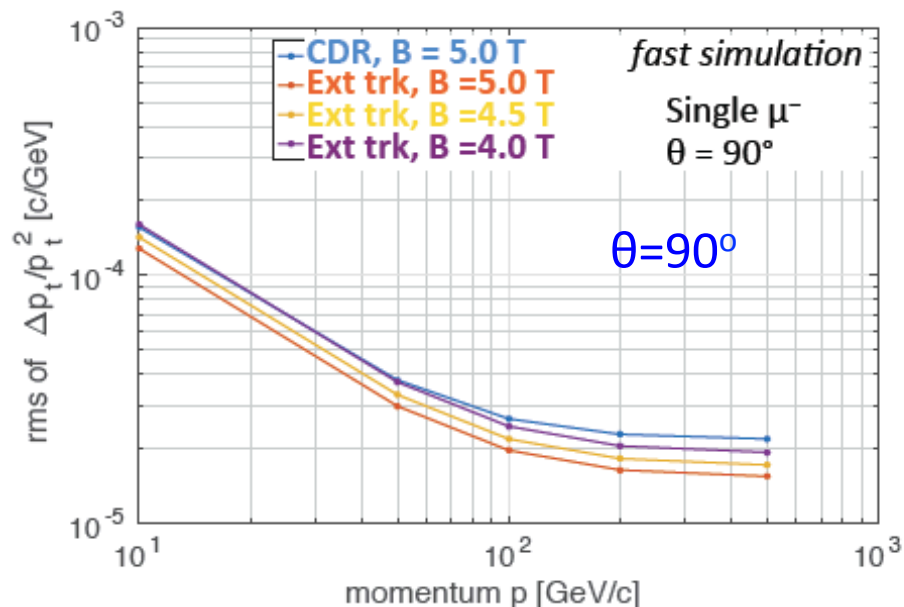
$$\frac{\sigma(p_T)}{p_T^2} \propto \frac{1}{BR^2}$$

Large tracker size has advantage

- **R=1.5 m**
 - **Half-length = 2.3 m** (stretched wrt CDR)
- B-field gives +10% improvement for +0.5 T
Compromise: **4 T** (inner bore radius ~3.2 m)



Jet performance was checked for those values



PFA calorimetry at CLIC



Technology (CDR)

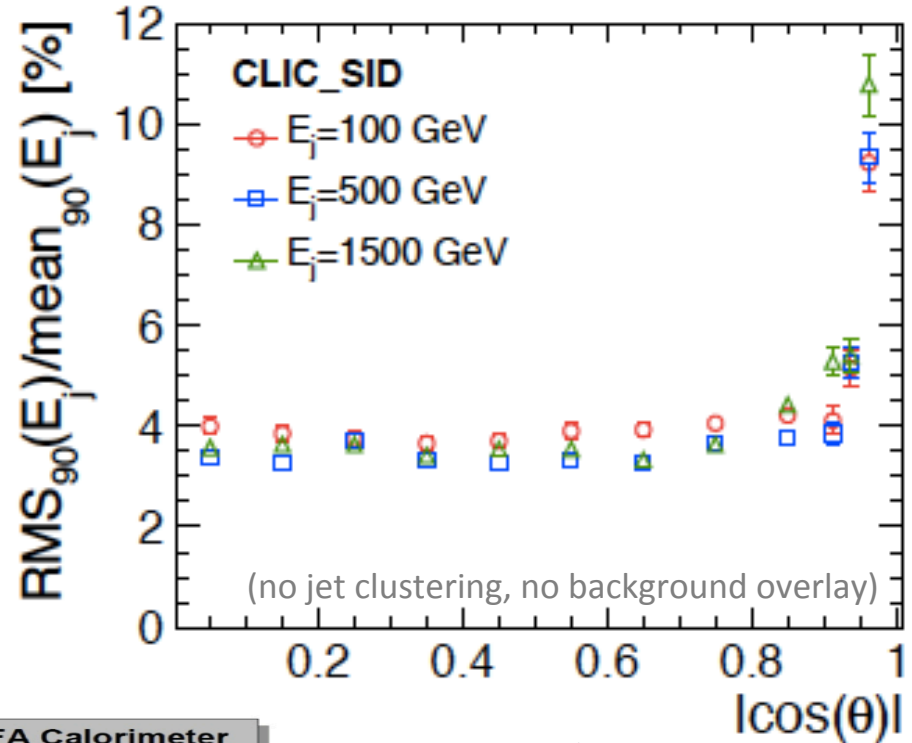
ECAL

Silicon (active) + Tungsten (absorber)
cell sizes $\sim 25 \text{ mm}^2$
30 layers in depth ($\sim 23 X_0$)

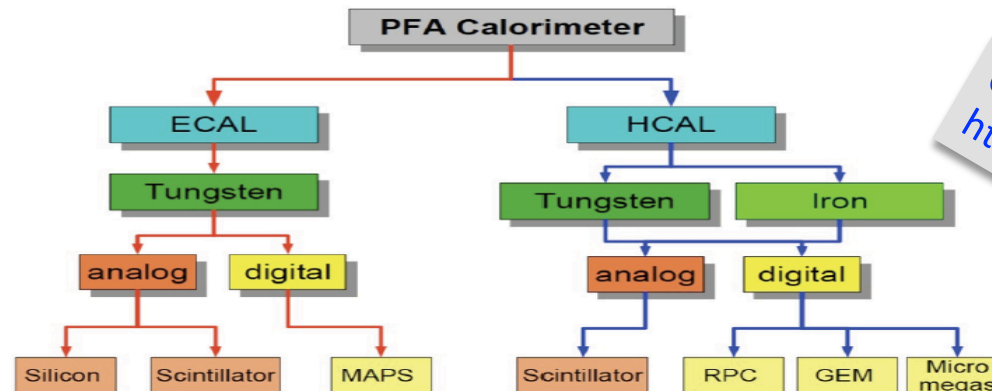
HCAL

Scintillator+SiPM (active)
Tungsten (barrel), steel (endcap)
cell sizes 9 cm^2 (analog)
75/60 layers in depth
Total depth $7.5 \Lambda_i$

simulated jet energy resolution



many technologies
pursued



CALICE collaboration
<http://fcal.desy.de/>

Forward calorimetry

2 forward calorimeters: Lumical + Beamcal

- Electron / photon acceptance to small angles
- Luminosity measurement
- Beam feedback

Absorbers: tungsten, 40 layers of $1 X_0$

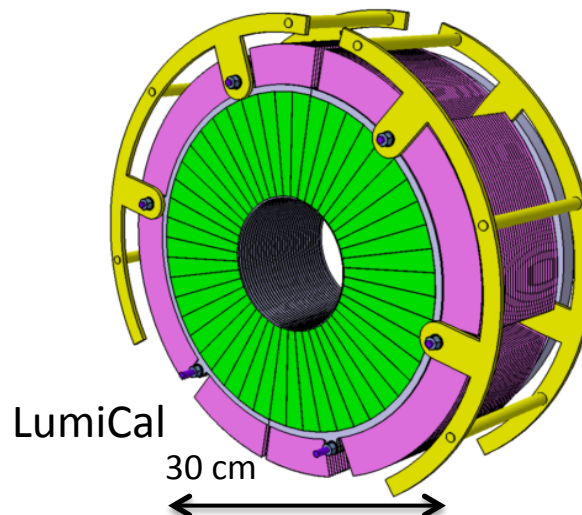
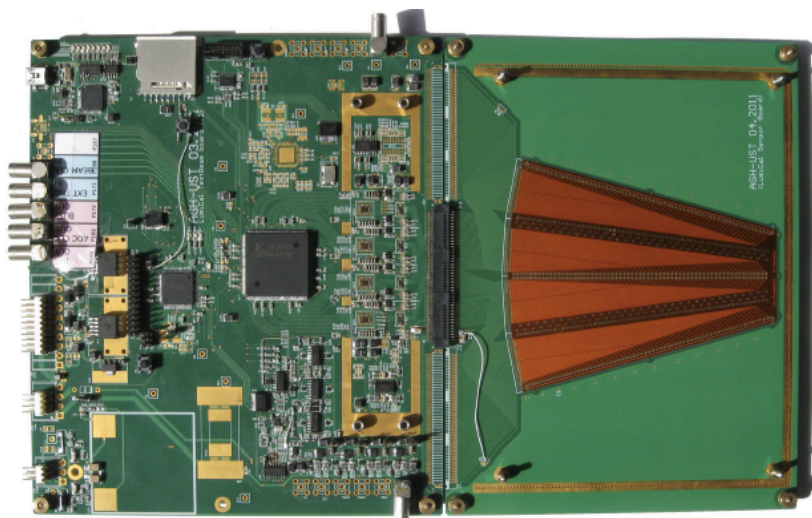
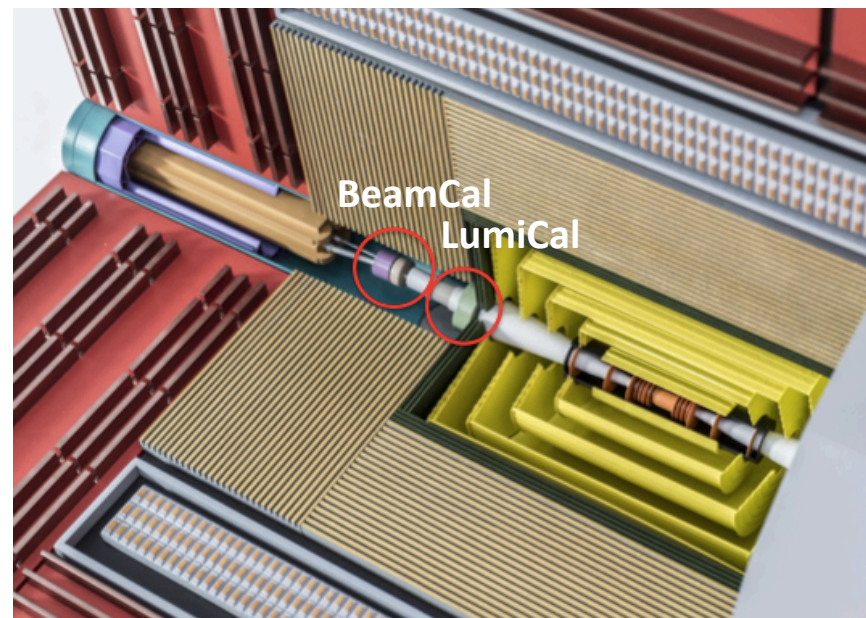
Sensors: BeamCal **GaAs**, LumiCal **silicon**

Angular coverage:

BeamCal 10 - 40 mrad, LumiCal 38 – 110 mrad

Doses up to 1 Mgy

Neutron fluxes of up to 10^{14} per year



Very compact !

FCAL collaboration
<http://fcal.desy.de/>

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	$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	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	$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	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”**

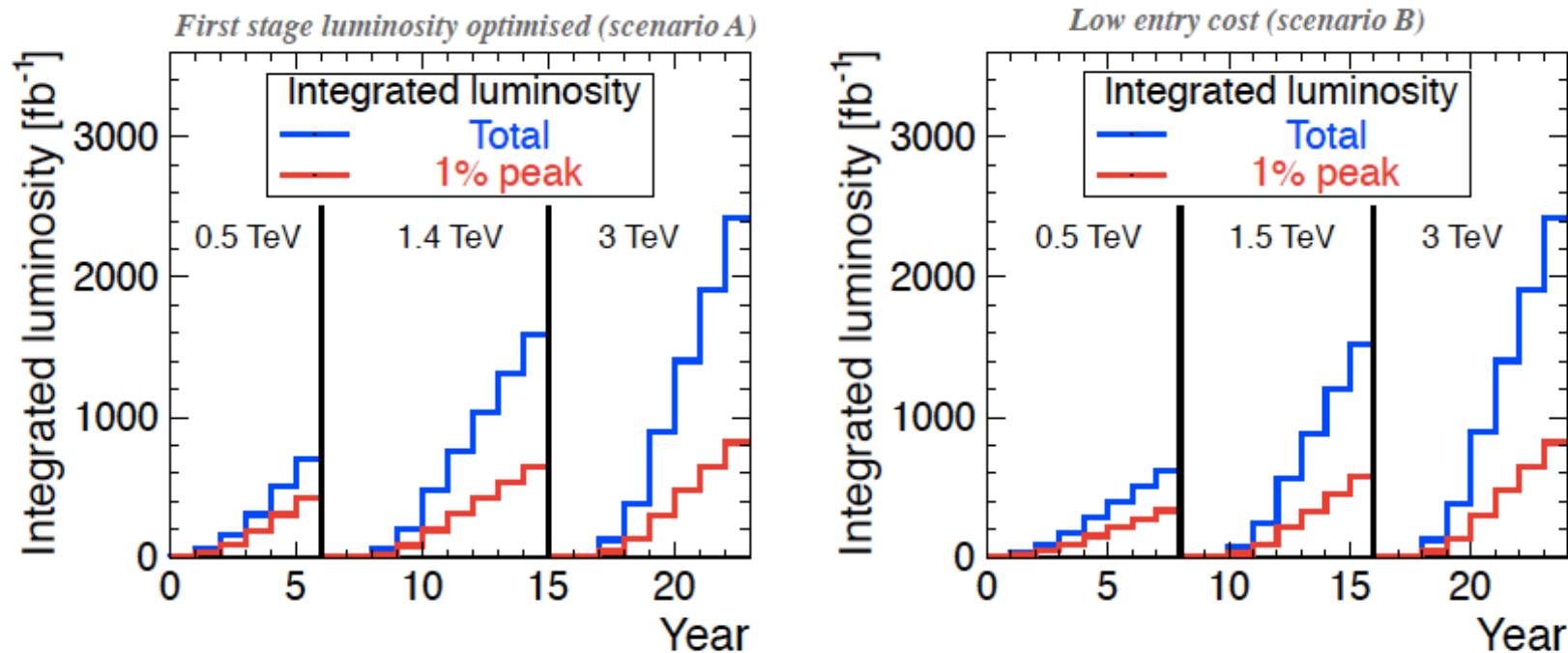


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two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

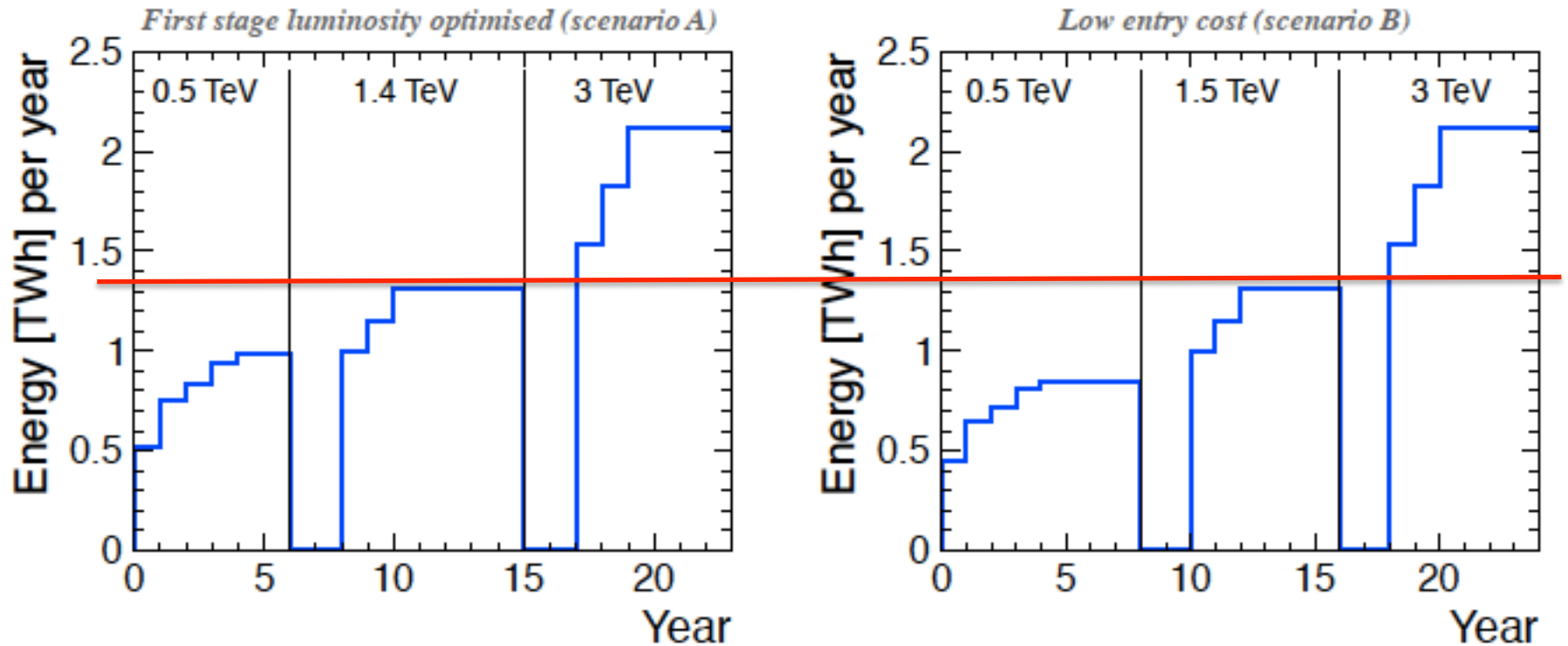
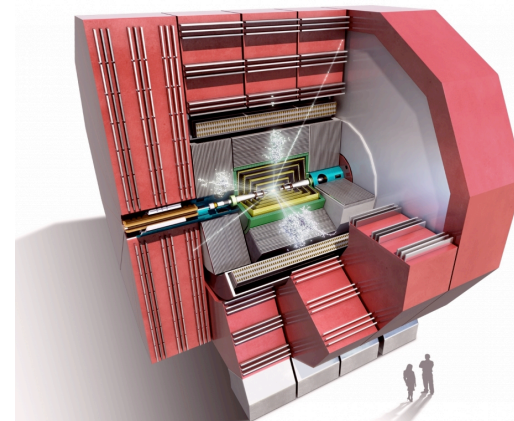


Fig. 5.7: Development of yearly energy consumption for staging scenarios A (left) and B (right).

CLIC 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..)

European Strategy statements

=> 2006/2013 CLIC-related statements

2006 statement “4”:

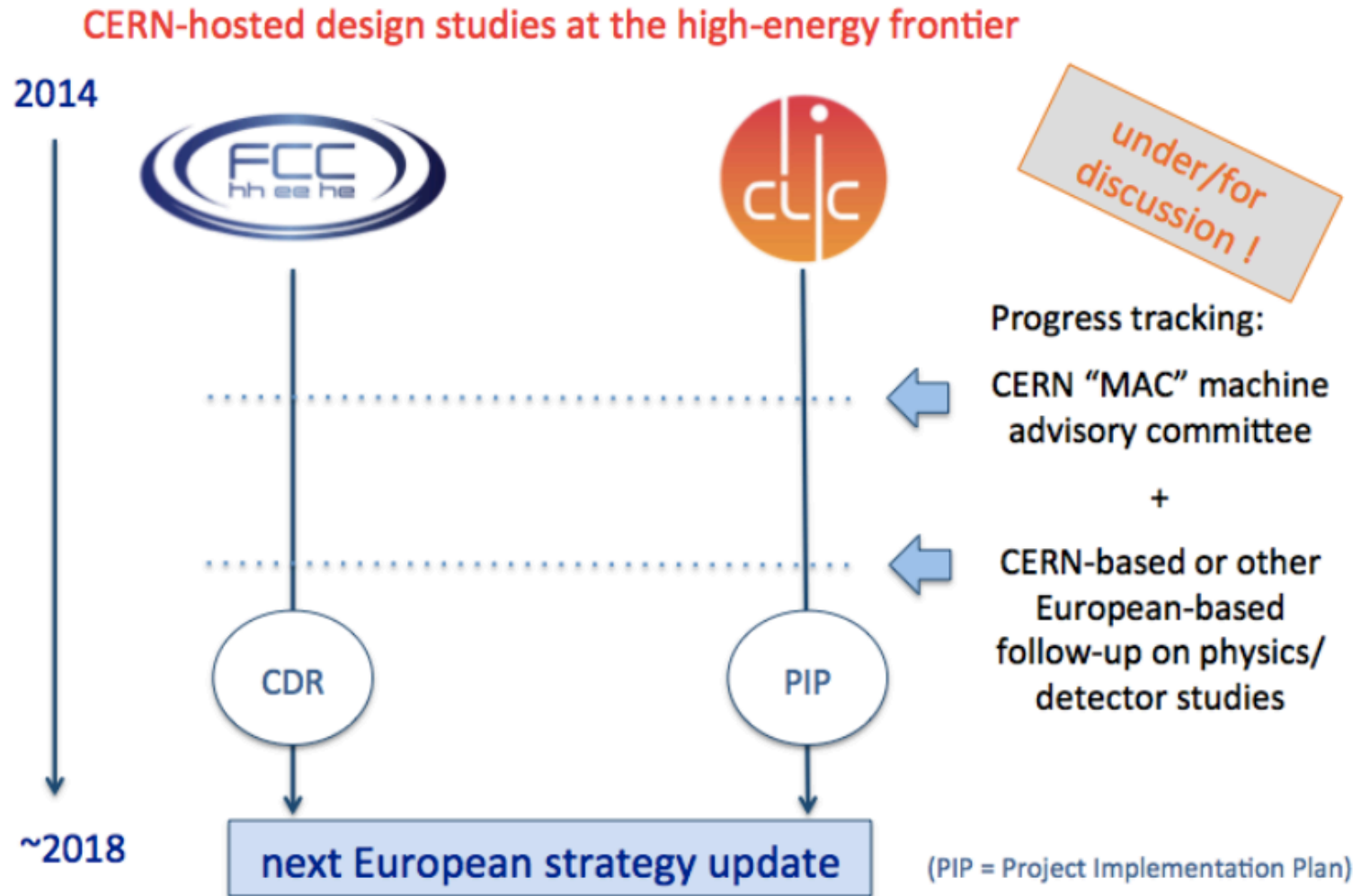
4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play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

CLIC and FCC



timeline: (HL-)LHC and future collider options

