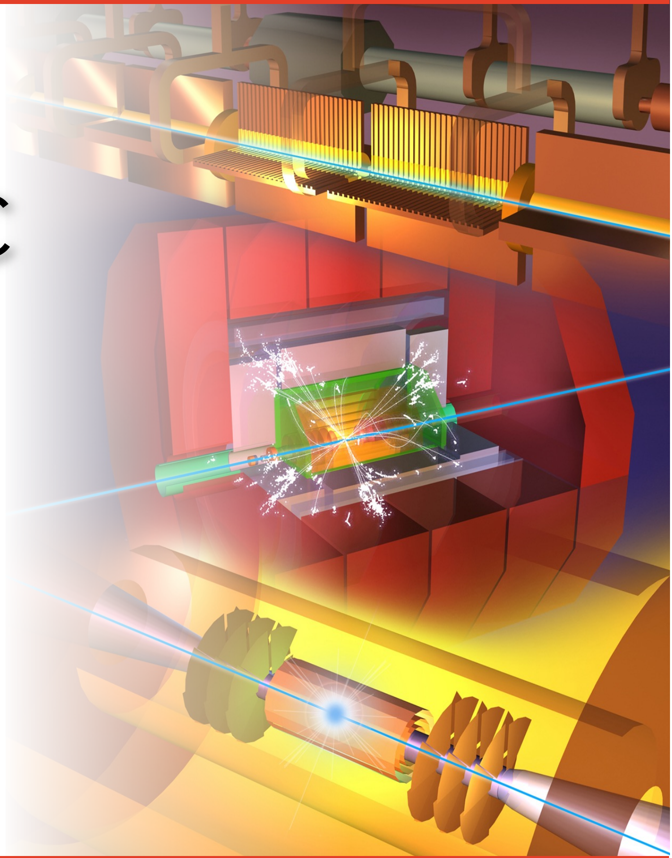
Experimentation at CLIC – CLICdet

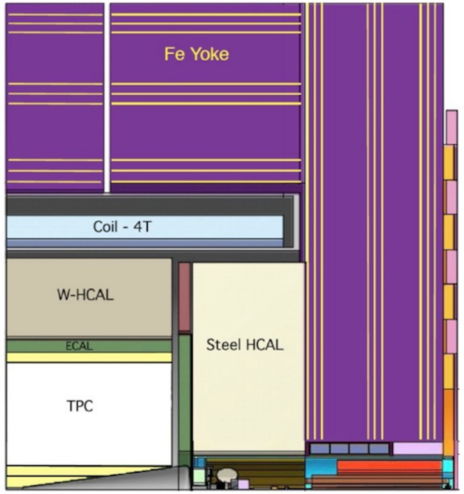


ILC IDT WG3/Detector Technologies
28 June 2024

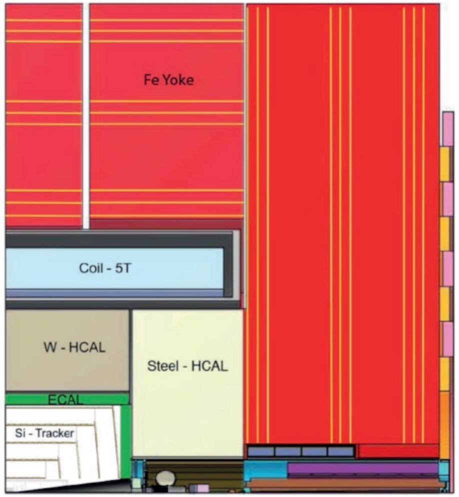
Aidan Robson
University of Glasgow

Context

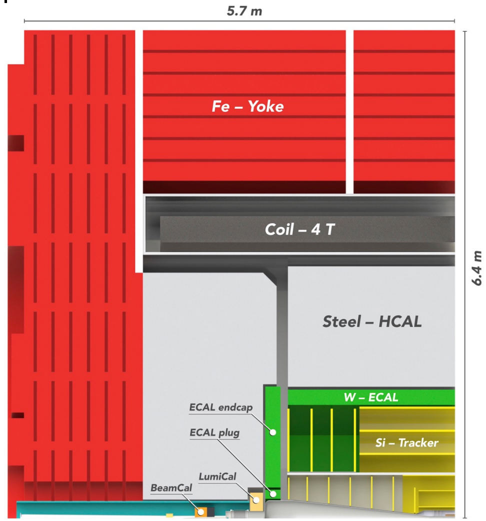
- For the CLIC CDR in 2012, CLIC_ILD and CLIC_SID models were used, minimally adjusted from the ILC concepts
  –> most of our sensitivity studies have been done using these two detector models
- More recently this was optimised into a single CLICdet detector concept, finalised in 2017
  –> some recent sensitivity studies are done using this detector model



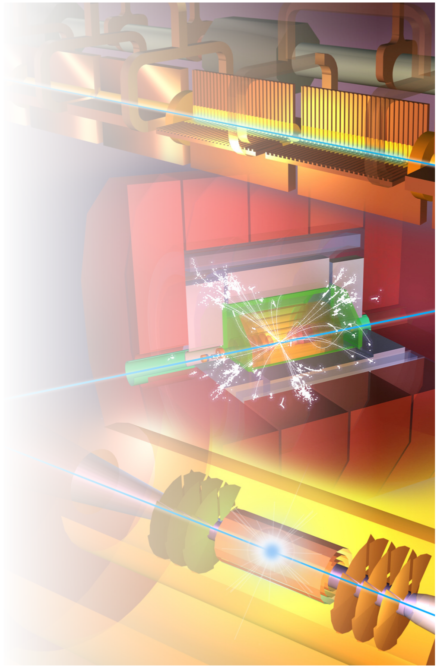
CLIC_ILD



CLIC_SID



CLICdet

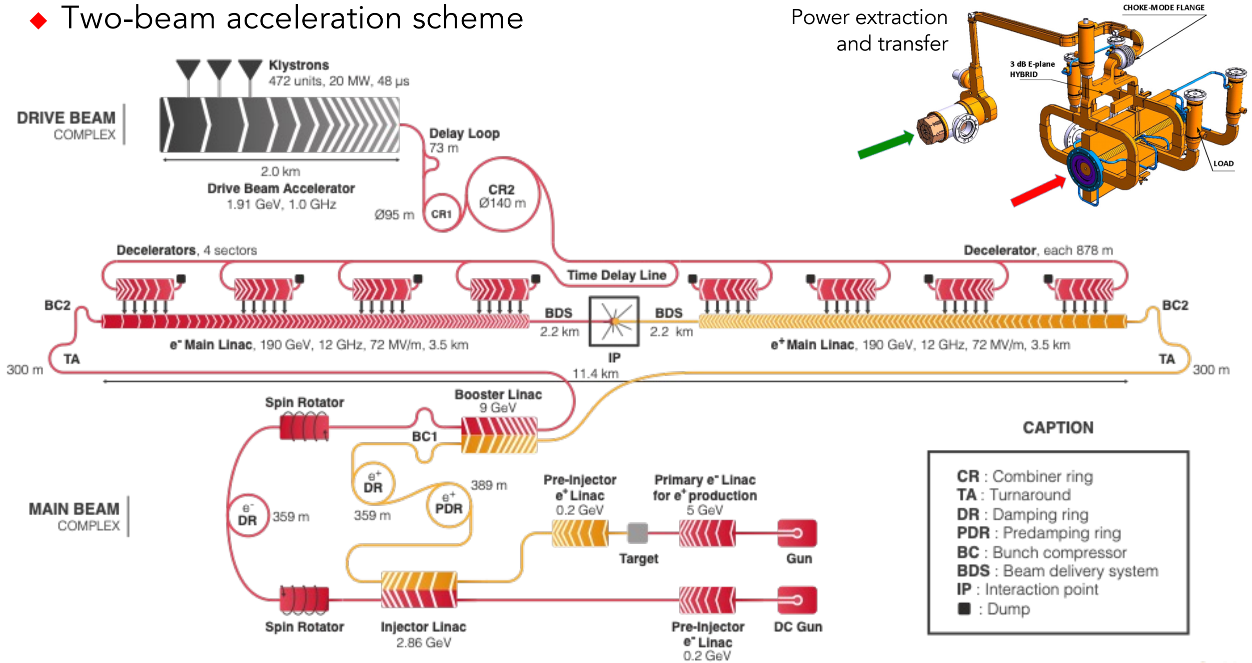


Concept	ILD	CLIC_ILD	SiD	CLIC_SiD
Tracker	TPC/Silicon	TPC/Silicon	Silicon	Silicon
Solenoid Field (T)	3.5	4	5	5
Solenoid Free Bore (m)	3.3	3.4	2.6	2.7
Solenoid Length (m)	8.0	8.3	6.0	6.5
VTX Inner Radius (mm)	16	31	14	27
ECAL r_{min} (m)	1.8	1.8	1.3	1.3
ECAL Δr (mm)	172	172	135	135
HCAL Absorber B / E	Fe	W / Fe	Fe	W / Fe
HCAL λ_{I}	5.5	7.5	4.8	7.5
Overall Height (m)	14.0	14.0	12.0	14.0
Overall Length (m)	13.2	12.8	11.2	12.8

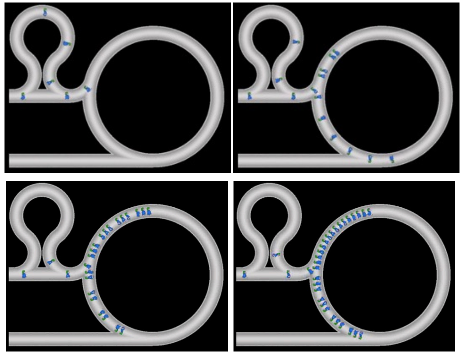
- I will highlight some of the differences arising from the CLIC experimental environment
  – detector concept has been developed to function up to $\sqrt{s}$=3TeV
- For very much more detail see:
  CLICdet: The post-CDR CLIC detector model https://cds.cern.ch/record/2254048
  A detector for CLIC: main parameters and performance http://cds.cern.ch/record/2649437
- Thanks to all colleagues whose plots/slides I have taken…

Accelerator

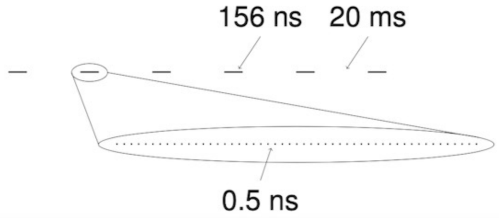
- Two-beam acceleration scheme



- Delay loops create drive-beam structure



- Colliding beam trains:

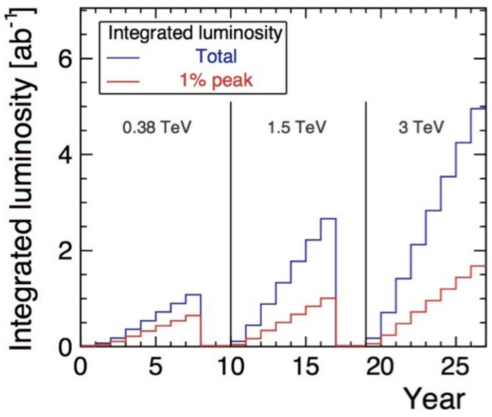


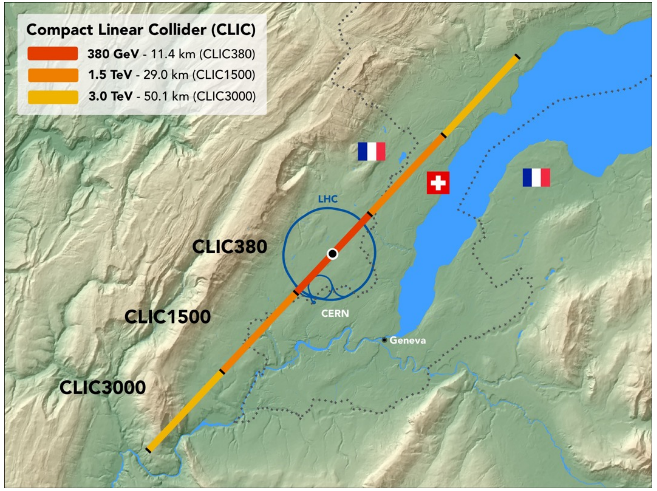
Par.	Unit	380 GeV	3 TeV
θ_c	mrad	16.5	20
n_b		352	312
N		$5.2 \cdot 10^9$	$3.72 \cdot 10^9$
σ_x	nm	≈ 149	≈ 45
σ_y	nm	≈ 2.9	≈ 1
σ_z	µm	70	44
$\mathcal{L}$	$1/\text{cm}^2\text{s}^1$	$1.5 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$\mathcal{L}_{0.01}$	$1/\text{cm}^2\text{s}^1$	$0.9 \cdot 10^{34}$	$2.0 \cdot 10^{34}$

- Very large gradient and room temperature copper cavities require short RF pulses of less than 200 ns
- Bunch spacing of Δt = 0.5 ns with ≈ 300 bunches per train at 50 Hz
- Short bunch spacing requires crossing angle θ_C to avoid parasitic collision
- Crab crossing scheme to avoid loss of geometrical overlap of colliding bunches

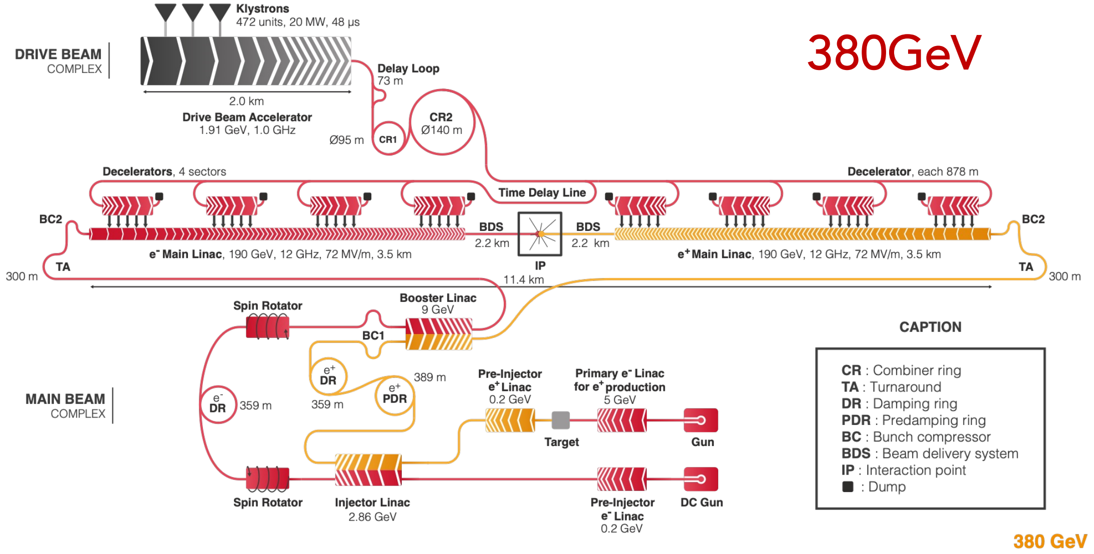
Accelerator

- ◆ Increase energy by extending main linacs, increasing drivebeam pulse-length and power, and adding second drivebeam to go above 1.5TeV.
- ◆ Baseline running scenario:
  - 1 ab^{-1} at $\sqrt{s}$=380 GeV ← Also an option to double rep rate to 100Hz at initial stage
  - 2.5 ab^{-1} at $\sqrt{s}$=1.5 TeV
  - 5 ab^{-1} at $\sqrt{s}$=3 TeV

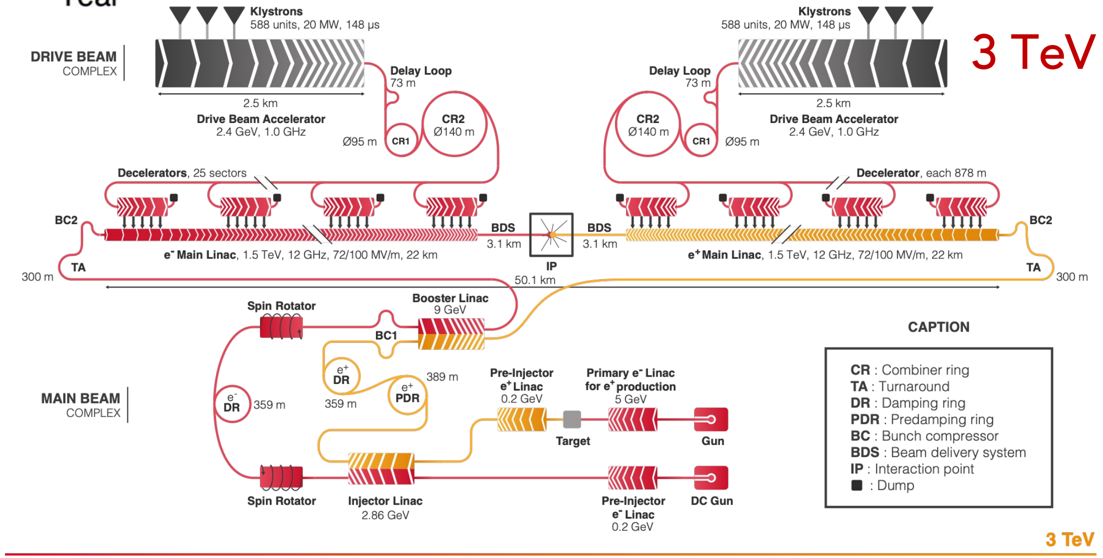




380GeV



3 TeV

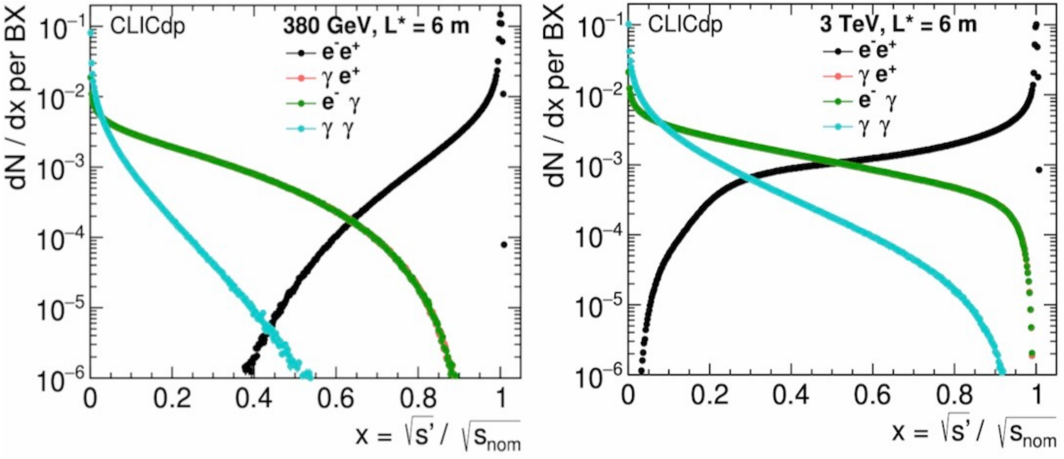


CLIC - Scheme of the Compact Linear Collider (CLIC)

Beamstrahlung

- Large luminosities require high bunch charge and small beams
- Leads to large electromagnetic fields during bunch crossing
- The bunch particles are strongly deflected by the fields and radiate Beamstrahlung

- Beamstrahlung radiation leads to collisions far below the nominal centre-of-mass energy $\sqrt{s}$
  –> Luminosity spectrum
  and collisions between $e^{\pm}\gamma$ and $\gamma\gamma$

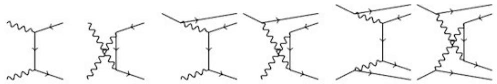


Luminosity in $10^{34}cm^{-2}s^{-1}$		
Collision	380 GeV	3 TeV
e^-e^+	1.51	6.35
$e^-\gamma$	0.80	5.05
γe^+	0.80	5.05
$\gamma\gamma$	0.50	4.49

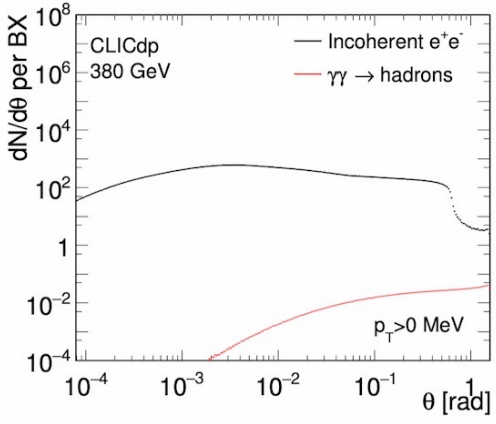
$\sqrt{s'}/\sqrt{s}$	380 GeV	3 TeV
> 0.99	58%	36%
> 0.90	87%	57%
> 0.80	96%	69%
> 0.70	98.7%	76.8%
> 0.50	99.96%	88.6%

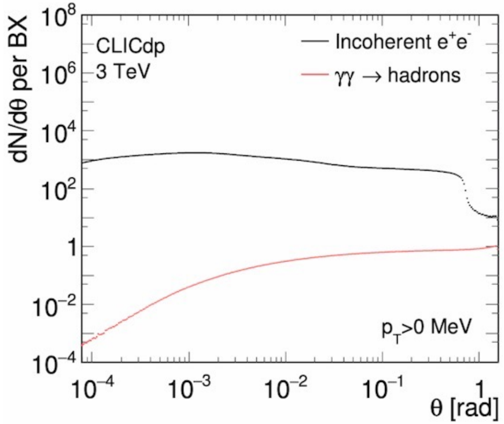
Beam-induced backgrounds

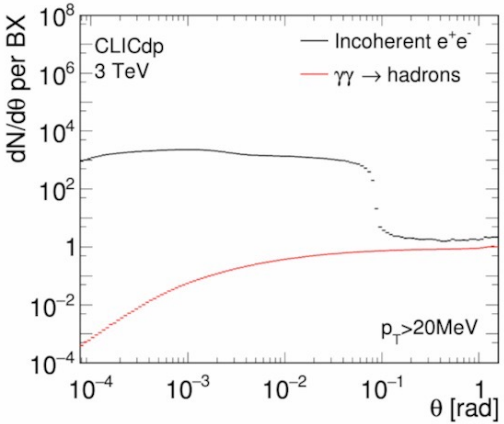
- Beamstrahlung photons collide with beam particles or other photons

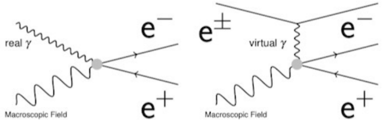


  - *Incoherent* e^+e^- pairs
  - $q\bar{q}$ pairs in $\gamma\gamma \to$ Hadron events
- Incoherent pairs have largest concentration at small angles
- backgrounds strongly depend on centre-of-mass energy

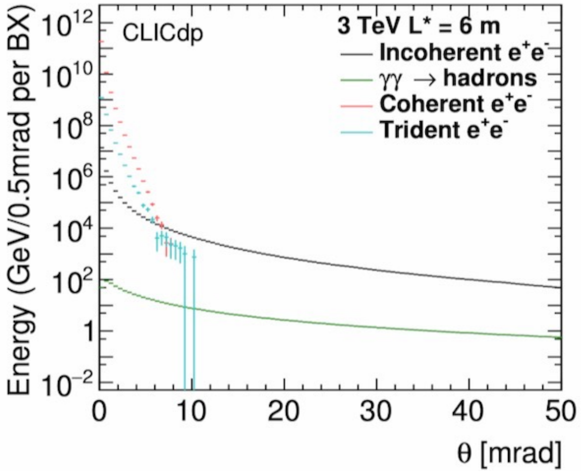






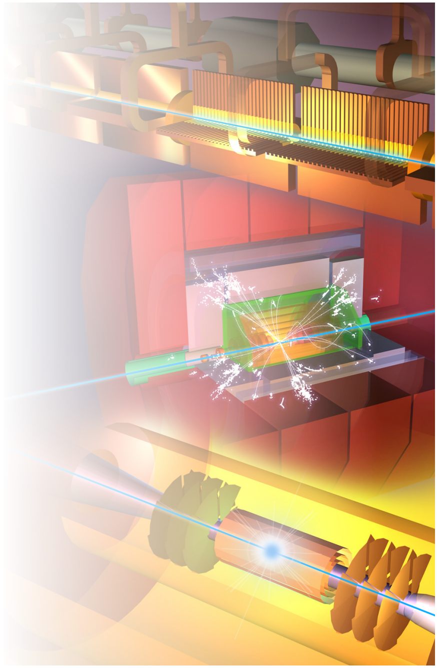


- Real or virtual photons interact with the very strong fields to create e^+e^- pairs
- Coherent processes only significant for $\sqrt{s} > 1$ TeV
- Coherent pairs limit the lower acceptance of the detector to 10 mrad around the outgoing beam-axis



Main changes with respect to ILC detectors

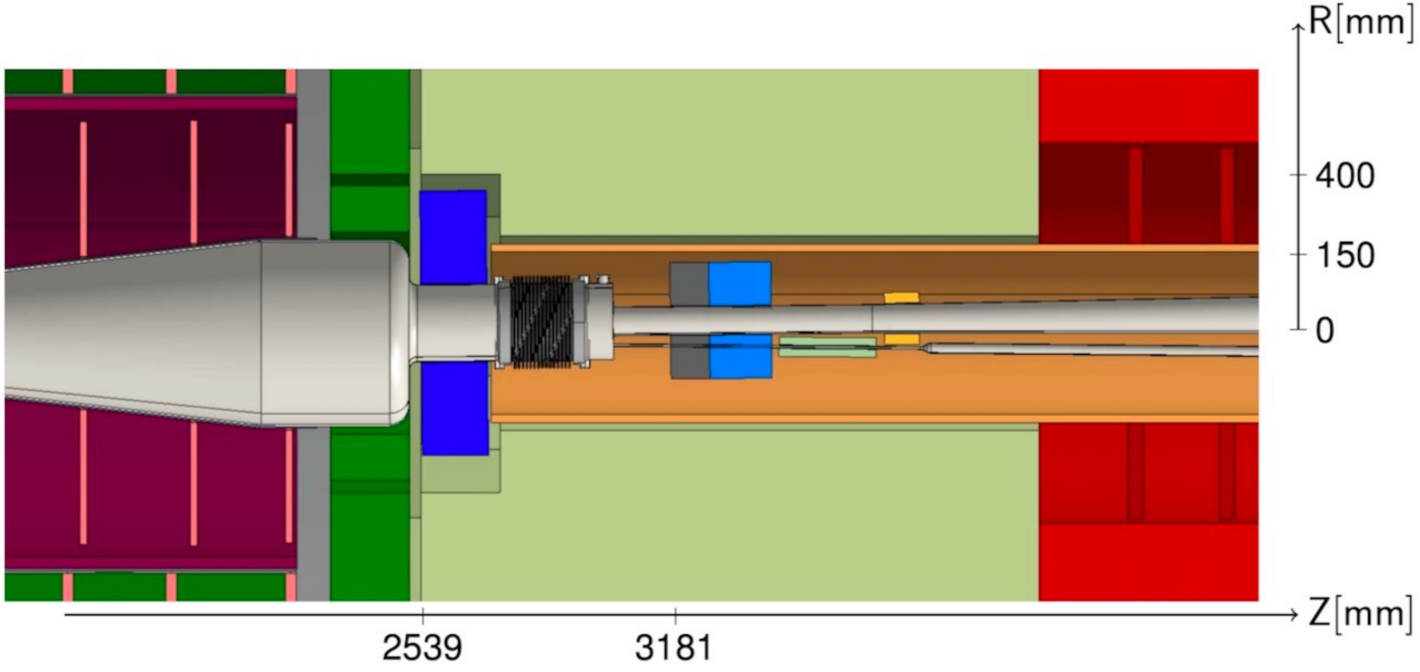
- Modifications from ILC detector concepts driven by CLIC beam conditions:
  – crossing angle 20 mrad
  – forward region adaptations (BeamCal, LumiCal)
  – larger vertex inner radius
  – ns-level timing requirements for all detectors
  – final focus stability (QD0) –> QD0 removed from detector

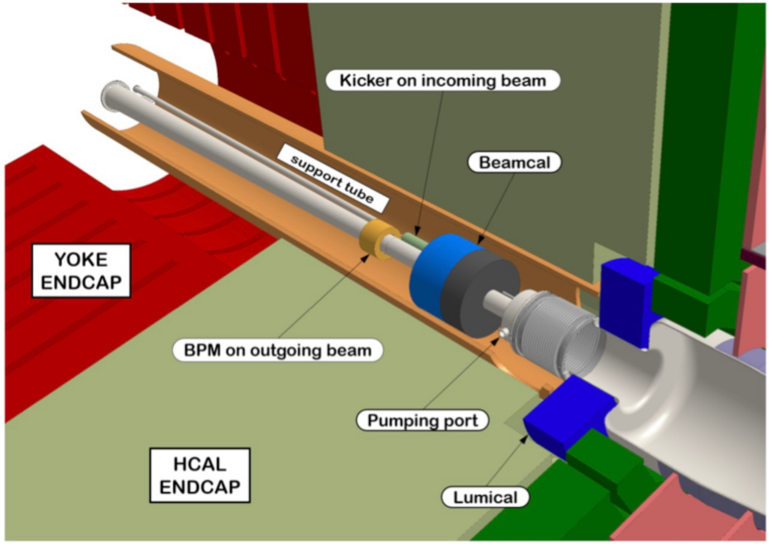


- Modifications driven by higher $\sqrt{s}$ at CLIC:
  – deeper HCAL (7.5λ)

Very forward region

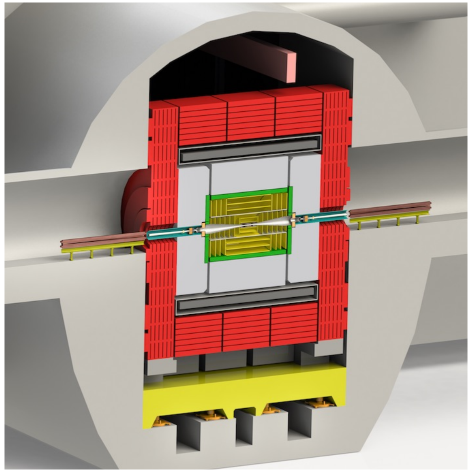
- Crossing angle of 20 mrad between beam axes
- Minimal acceptance of a cone of 10 mrad half-opening due to coherent pairs at 3 TeV
- Forward e.m. calorimeters: **LumiCal** and **BeamCal**, **ECal** and **HCal** endcaps
- The BeamCal is located in the centre of the HCal endcap

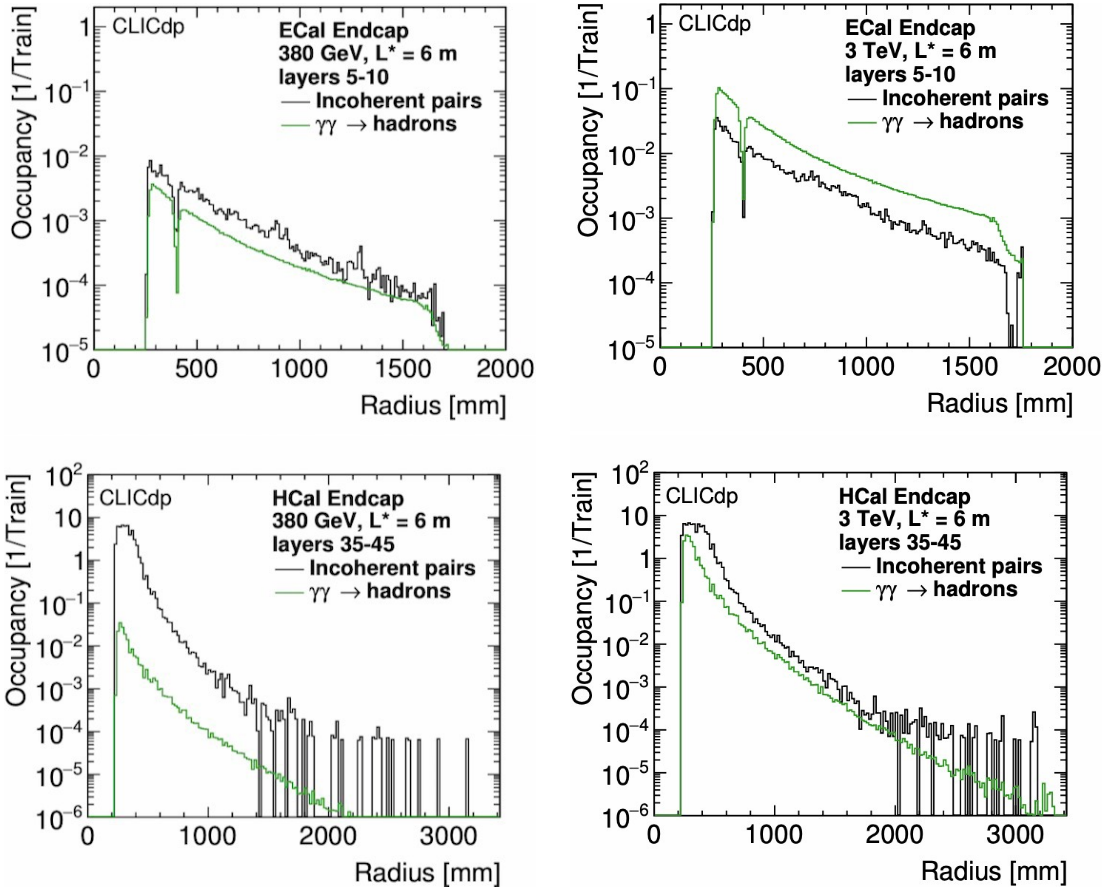




Very forward region

◆ To enlarge the angular coverage of the HCAL endcap the final focus quadrupole QD0 was moved from the detector to the accelerator tunnel. To keep it close to the interaction point the iron yoke endcap thickness was reduced; compensated by a set of end coils.





◆ The incoherent pairs showering in the BeamCal create a large neutron flux into the HCal endcap

◆ At the inner radius of the HCal endcap most cells see an energy deposit above 0.3 MIP per readout window

◆ Shielding inside the HCal endcap can absorb many of the particles and greatly reduce the occupancy, at the price of HCal endcap coverage
  –> needs further study

◆ Reducing the tile size also reduces the occupancy, at the price of higher number of channels

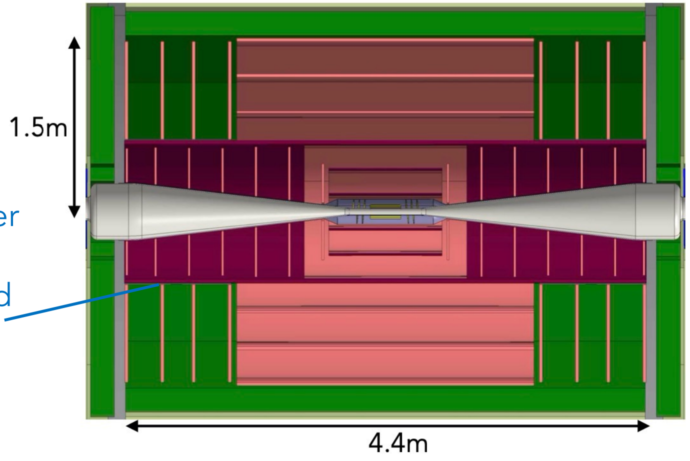
Tracker considerations

◆ Occupancy studies using the CLIC 3 TeV beam conditions found an occupancy of about 30% in the CLIC_ILD TPC pads (without safety factors), caused mainly by the long readout time and the fact that background hits are integrated over the full CLIC bunch train –> therefore an all-silicon tracker is chosen for CLICdet

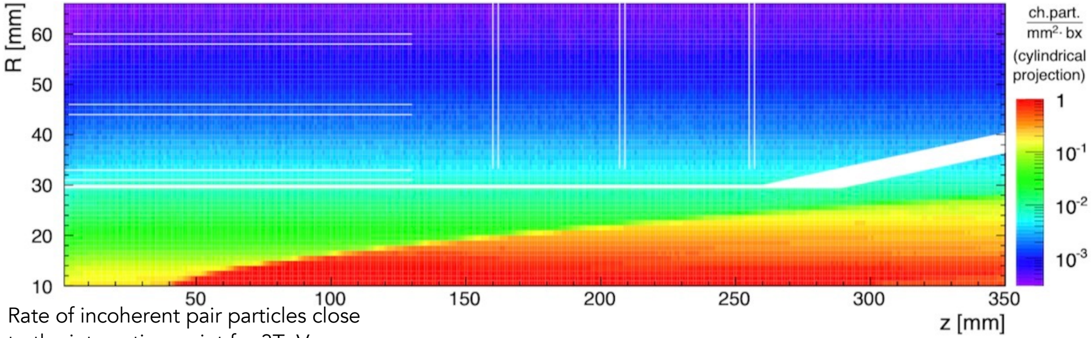
◆ Large flux of low momentum particles from incoherent pairs limits the inner radius of the vertex detector

◆ Beam pipe radius = 29mm => inner barrel radius = 31mm

◆ Smaller radius possible at lower centre-of-mass energy



Moving support tube to higher radius compared with CDR models helps improve forward tracker disk angular coverage



Rate of incoherent pair particles close to the interaction point for 3TeV

- Total sensitive area = 137m²
- cells sizes:

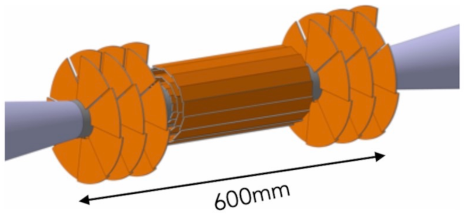
subdetector	layout sizes*
Inner Tracker Disk 1	25×25 μm ²
Inner Tracker Disks 2–7	50 μm ×1 mm
Outer Tracker Disks	50 μm ×10 mm
Inner Tracker Barrel 1–2	50 μm ×1 mm
Inner Tracker Barrel 3	50 μm ×5 mm
Outer Tracker Barrel 1–3	50 μm ×10 mm

* disks: RΦ x R barrel: RΦ x z

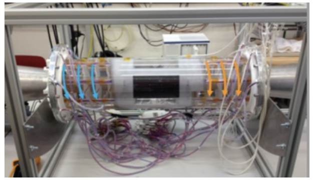
- 200 μm sensor thickness

motivated by track reconstruction needs (to avoid confusion)

motivated by occupancy studies (3% readout occupancy goal over bunch train)



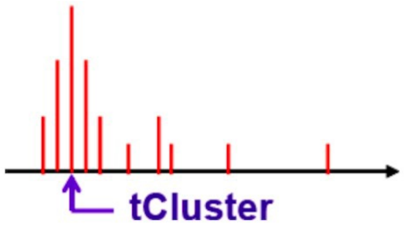
Beam structure with 20ms between bunch trains allows power-pulsing. Aim for air-cooled vertex detector; spiral endcap design for air flow (feasibility demonstrated in simulation & full detector thermal mockup)



Timing and clustering

- CDR studies showed that the impact of particles from beam-induced backgrounds on the physics can be minimised through:
  – Optimisation of detector design, in particular cell sizes
  – Full event reconstruction with particle-flow analysis in a time window around the physics event, followed by p_T and timing cuts on reconstructed particles
  – Optimised jet-clustering algorithms

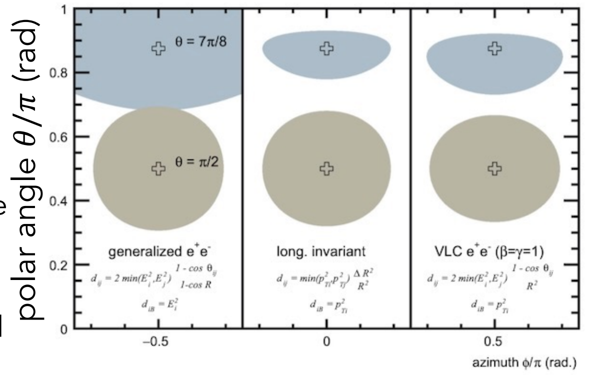
- Read out full bunch train and identify time of physics event
- Select hits around the event using the time resolution of the sub-detectors
- Reconstruct objects: clusters and tracks
  - Calculate cluster time based on truncated mean time of hits, correct for time of flight
- Accept reconstructed particles depending on particle type, cluster time, and transverse momentum



Default 3 TeV timing cuts

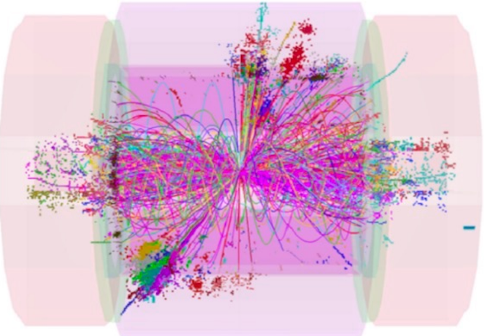
Region	p_T range	time cut
Photons		
central	$0.75\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\cos\theta \leq 0.975$	$0\,\text{GeV} \leq p_T < 0.75\,\text{GeV}$	$t < 1.0\,\text{ns}$
forward	$0.75\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\cos\theta > 0.975$	$0\,\text{GeV} \leq p_T < 0.75\,\text{GeV}$	$t < 1.0\,\text{ns}$
neutral hadrons		
central	$0.75\,\text{GeV} \leq p_T < 8.0\,\text{GeV}$	$t < 2.5\,\text{ns}$
$\cos\theta \leq 0.975$	$0\,\text{GeV} \leq p_T < 0.75\,\text{GeV}$	$t < 1.5\,\text{ns}$
forward	$0.75\,\text{GeV} \leq p_T < 8.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\cos\theta > 0.975$	$0\,\text{GeV} \leq p_T < 0.75\,\text{GeV}$	$t < 1.0\,\text{ns}$
charged particles		
all	$0.75\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 3.0\,\text{ns}$
	$0\,\text{GeV} \leq p_T < 0.75\,\text{GeV}$	$t < 1.5\,\text{ns}$

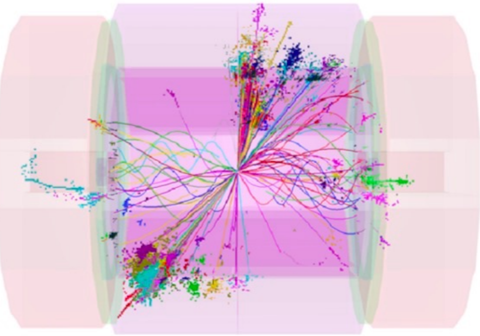
- $\gamma\gamma \to$ hadron background and longitudinal boost due to beamstrahlung make LEP jet algorithms unsuited for CLIC
- Use hadron collider jet algorithm features
  – cluster forward particles into beam jets
  – benefit from longitudinal invariance. Particle distance measure using $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$
- Specialised VLC jet algorithm
- Reconstruction parameters should be tuned to particular analyses



Jet areas obtained from different types of jet clustering algorithm

$e^-e^+ \to HH$ with $\gamma\gamma \to$ hadron background overlaid before and after *tight* timing selection cuts

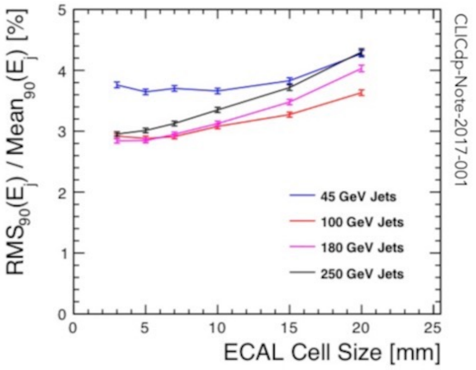




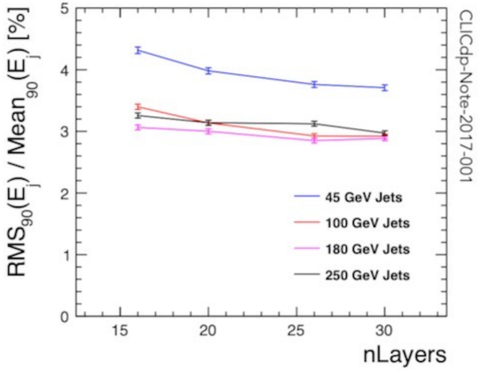
Calorimeter optimisation

- Jet energy resolutions studied for different calorimeter geometries and granularities

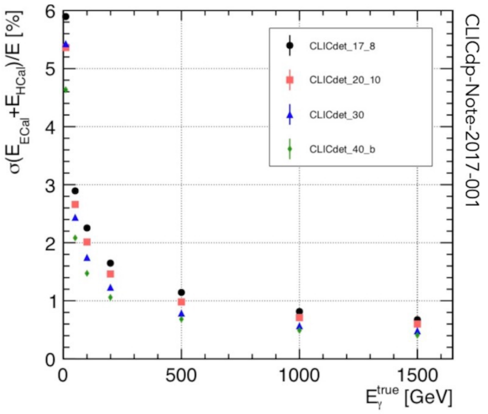
ECAL



5 x 5 mm2 cell size a good compromise, further improvement possible, but at the expense of significant increase in channel count



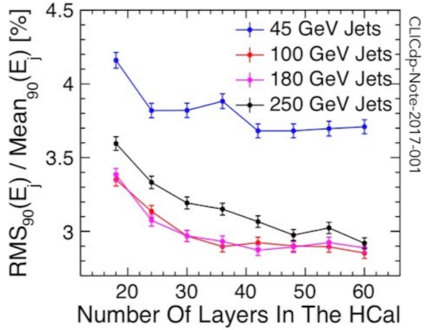
From a jet energy resolution perspective, 25 layers distributed over 23 X0 appear sufficient, with 17 layers with finer sampling and 8 layers with thicker absorber



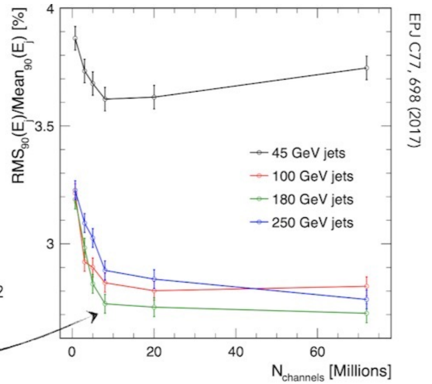
But for photons at high energy, best performance obtained for a 40 layer ECAL with 1.9 mm / layer, substantially better than 25 layer option with coarse layers in rear: improvement at all energies, with up to ~40% for TeV photons

HCAL

- Jet energy resolution as a function of the number of layers (keeping calorimeter thickness constant): high sampling beneficial! (performed in ILD context)



30 x 30 mm²



- Cell size optimisation with software compensation (separate training for each data point, binning range not optimal for low energies and small cells)

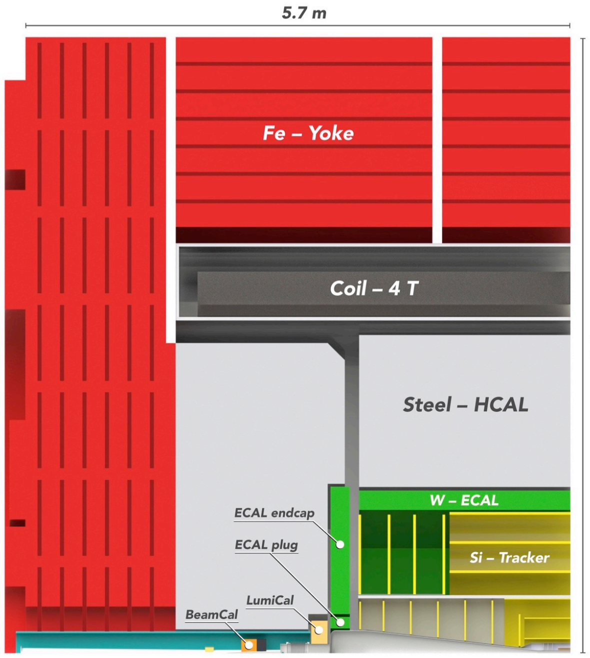
ECal

- Si-W sampling calorimeter
- cell size 5 x 5 mm²
- 40 layers (1.9 mm thick W plates)
- $22X_0$, $1\lambda_I$

HCal

- Scintillator-steel sampling calorimeter
- SiPMs read-out
- cell size 30 x 30 mm²
- 60 layers (20 mm thick steel plates)
- $7.5\lambda_I$

CLIC Detector



Essential characteristics:

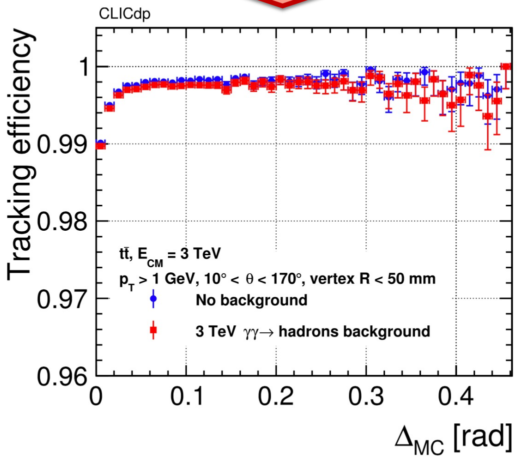
- B-field: 4T
- Vertex detector with 3 double layers
- Silicon tracking system: 1.5m radius
- ECAL with 40 layers ($22\,X_0$)
- HCAL with 60 layers ($7.5\,\lambda$)

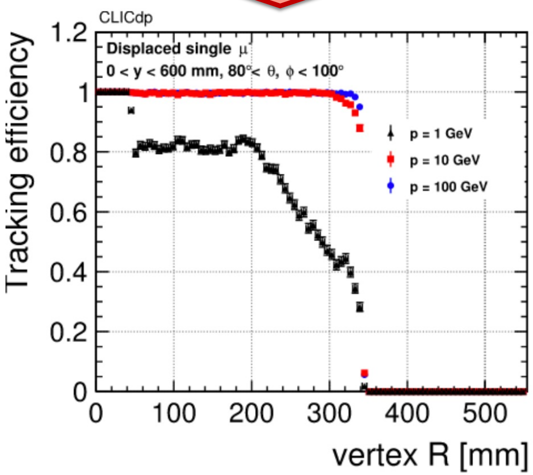
Precise timing for background suppression (bunch crossings 0.5ns apart)

- ~10ns hit time-stamping in tracking
- 1ns accuracy for calorimeter hits

CLICdp-Note-2017-001
arXiv:1812.07337

- High-performing detector optimized for CLIC beam environment
- Full GEANT-based simulation, including beam-induced backgrounds, available for optimization and physics studies
- Mature reconstruction chain allows detailed performance characterisation – e.g. for tracking: effect of busy environment; displaced track reconstruction





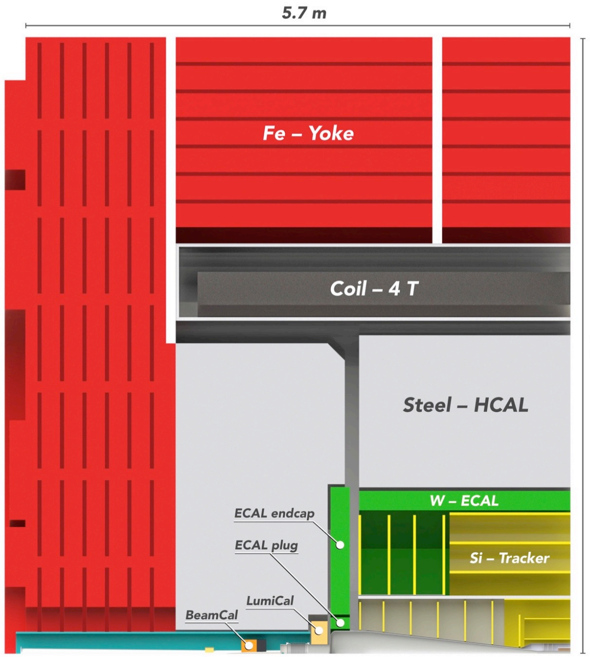
NIM A**956** (2020) 163304

Software framework:

- Originally in iLCSoft, the simulation/ reconstruction is now fully embedded in the **Key4HEP** ecosystem

–> a common target for all future collider options
– existing reconstruction algorithms "wrappered" for the new framework

CLIC Detector



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CLICdp-Note-2017-001
arXiv:1812.07337

Different energy stages 380 GeV, 1.5 TeV, 3 TeV:

- Beam conditions and parameters, and beam-induced backgrounds are rather different for different CLIC energy stages
- While detector designed for 3 TeV, different detector layouts could be considered for each stage – but in practice calorimeters, solenoid, yoke and muon systems would remain unchanged
- Different crossing angle implies a change of vacuum pipe and therefore BeamCal moving from 380GeV to higher energies
- Reduction in number and p_T of incoherent pairs at 380GeV means beampipe can be 6mm smaller
  –> first vertex barrel layer can be moved to a smaller radius
  –> positions of remaining vertex barrel layers can be reoptimised
  –> still to study adapting the rest of the inner tracker layout

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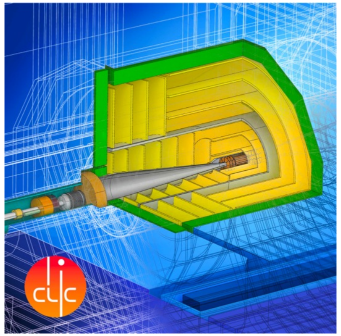
- Originally in iLCSoft, the simulation/ reconstruction is now fully embedded in the **Key4HEP** ecosystem

–> a common target for all future collider options
– existing reconstruction algorithms "wrappered" for the new framework

Detector R&D towards CLICdet



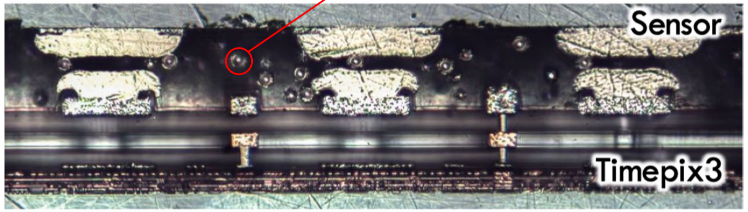
Calorimeter R&D –> within CALICE and FCAL
Silicon vertex/tracker R&D:
- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
  –> now integrated in the **CERN EP detector R&D** programme and **DRD3** activities

A few examples:
[these are CLIC-specific]

*Challenge is to realise **all** of :*
material budget, position resolution, power consumption, time resolution

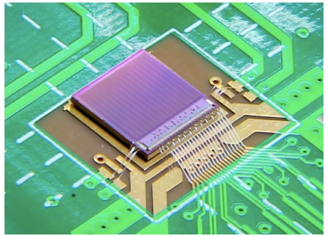
1. Hybrid assemblies:

- Development of bump bonding process for CLICpix2 hybrid assemblies with 25 μm pitch
https://cds.cern.ch/record/2766510

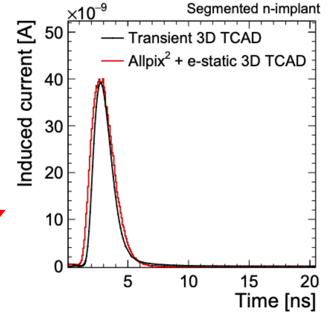


- Successful sensor+ASIC bonding using Anisotropic Conductive Film (ACF), e.g. with CLICpix2, Timepix3 ASICs.
ACF now also used for module integration with monolithic sensors.
https://agenda.linearcollider.org/event/9211/contributions/49469/
https://cds.cern.ch/record/2891650

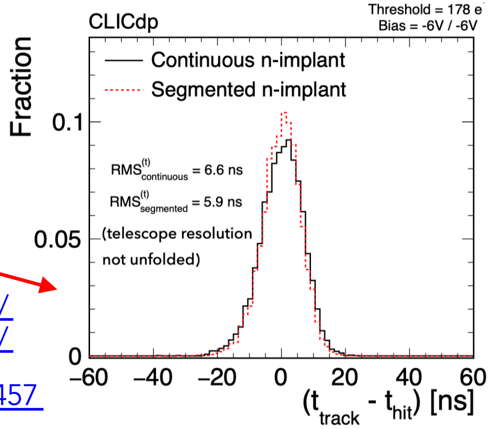
2. CLICTD monolithic tracking sensor:



Detailed simulations, Allpix^2 transient Monte Carlo combined with electrostatic 3D TCAD.



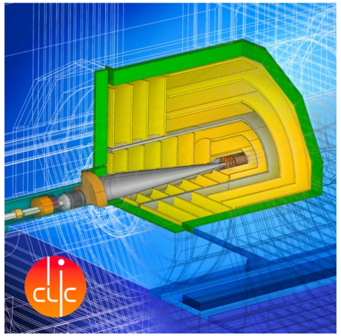
Beam tests at DESY, e.g. 5.8 ns CLICTD time resolution achieved



https://agenda.linearcollider.org/event/9211/contributions/49443/

https://cds.cern.ch/record/2813457

Detector R&D towards CLICdet



Calorimeter R&D –> within CALICE and FCAL
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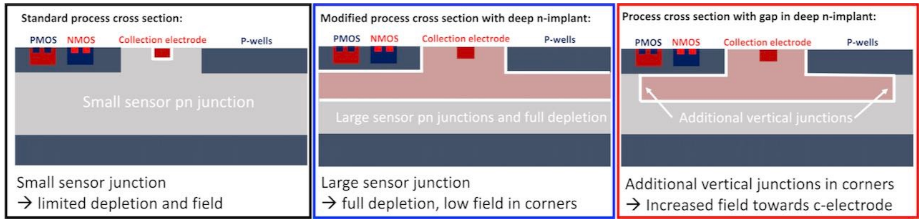
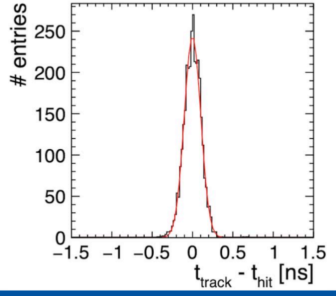
A few examples: **3. Monolithic pixel sensors:**

*[these are **not** CLIC-specific, but EP R&D / DRD3 leading on from previous work]*

◆ Exploring sub-nanosecond pixel timing with ATTRACT FASTPIX demonstrator in 180 nm monolithic CMOS
https://arxiv.org/abs/2306.05938

Pixel pitches from 8.66μm to 20μm ; 25μm thickness
Standard process plus two process modifications investigated



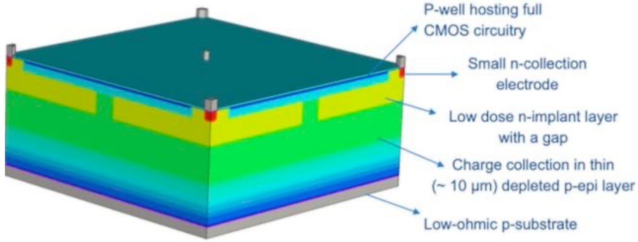


Reaches spatial resolution down to 1μm and O(100ps) timing precision for the modified process with higher-dose deep n-implant.

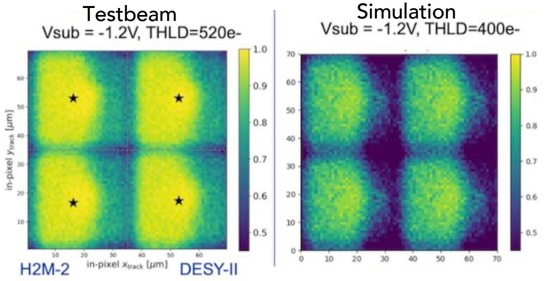
Details of process and electrode size improved time residual width by ~17% showing importance of optimisations.

◆ Characterisation of the H2M 'hybrid-to-monolithic' monolithic demonstrator in 65 nm CMOS imaging process
https://indico.cern.ch/event/1402825/contributions/6002310/

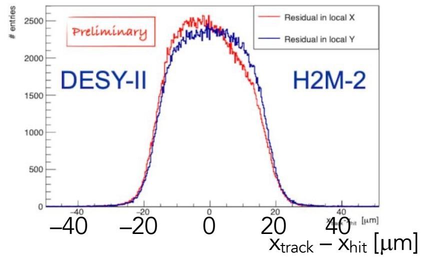
Hybrid pixel detector architecture in a monolithic chip, 'digital on top'
35μm pixel pitch, 50μm thickness
Fully efficient operation in test-beam
Investigating possibility to backside-thin



Impact of n-wells on charge-collection efficiency observed and qualitatively confirmed by simulations; ongoing work to match quantitatively



Spatial resolution dominated by pitch;
Timing thought dominated by sensor effects, > ~30ns

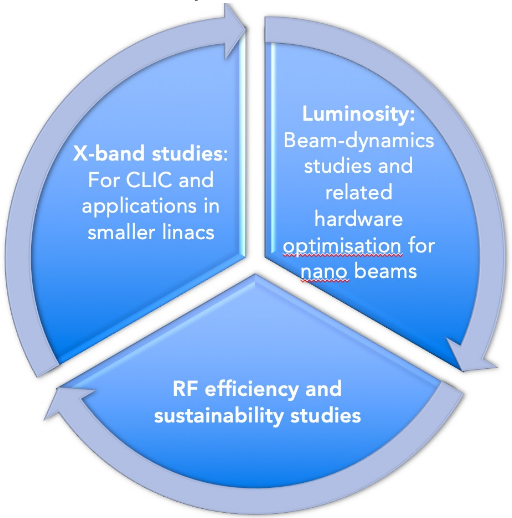


–> Lepton Collider focused monolithic sensor R&D project within DRD3 – 10 institutes
https://indico.cern.ch/event/1402825/contributions/6002321/

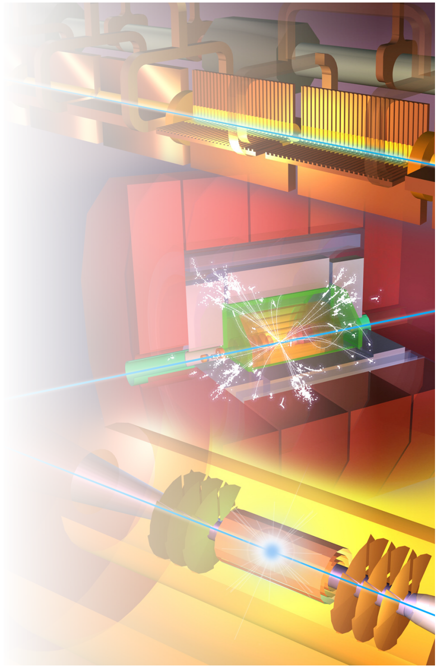
CLIC Project Readiness 2025

Project Readiness Report as a step toward a TDR – for next European Strategy Update
Fastest timescale: project approval ~2028,
Project (tunnel) construction could start in ~2030.

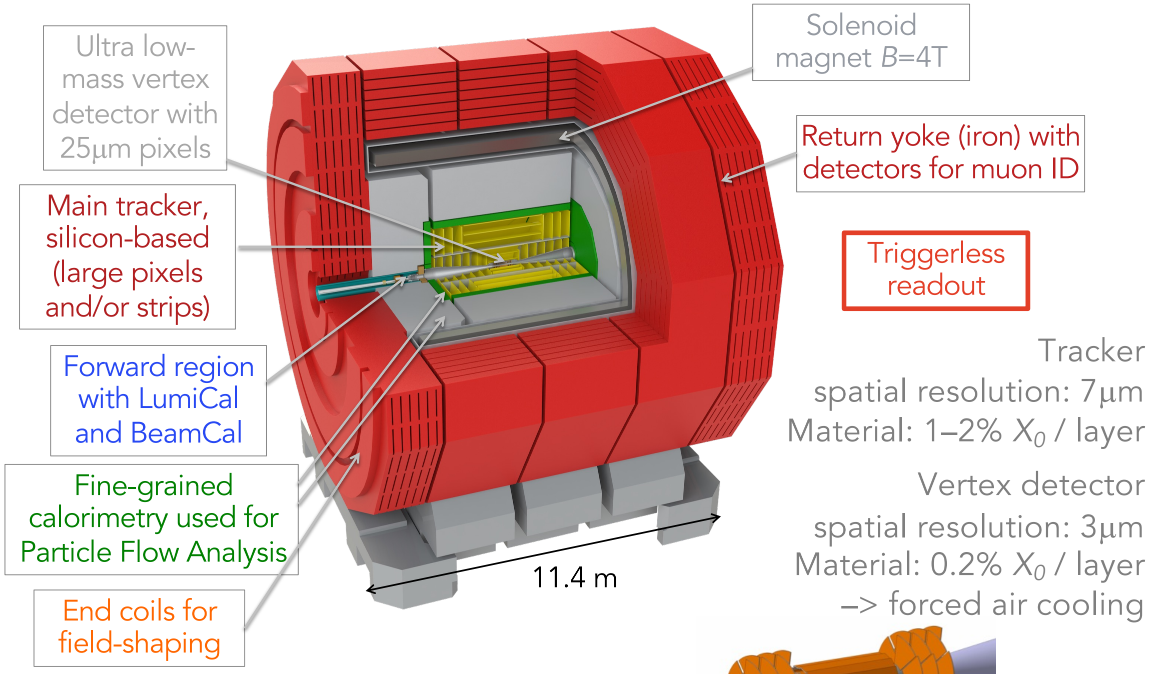
Focusing on:
- The X-band technology readiness for the 380 GeV CLIC initial phase
- Optimizing the luminosity at 380 GeV
- Improving the power efficiency for both the initial phase and at high energies

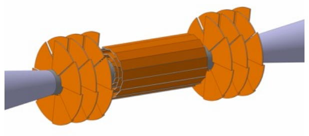


Goals for these studies by ~2025:
- Improved 380 GeV parameters/ performance/project plan
- Push multi-TeV options/parameters



Outlook





- Building on ILC collaboration experience, CLICdet is a detector concept dedicated for the CLIC beam environment
- The CLICdp collaboration remains active but resources very limited; targeted activities maintained in context of wider efforts
- A Higgs factory is the community priority, but there is continued interest in the physics reach of TeV-scale e^+e^- collisions
- Essential to keep different options for e^+e^- collider realisation available, as any particular project may encounter hurdles