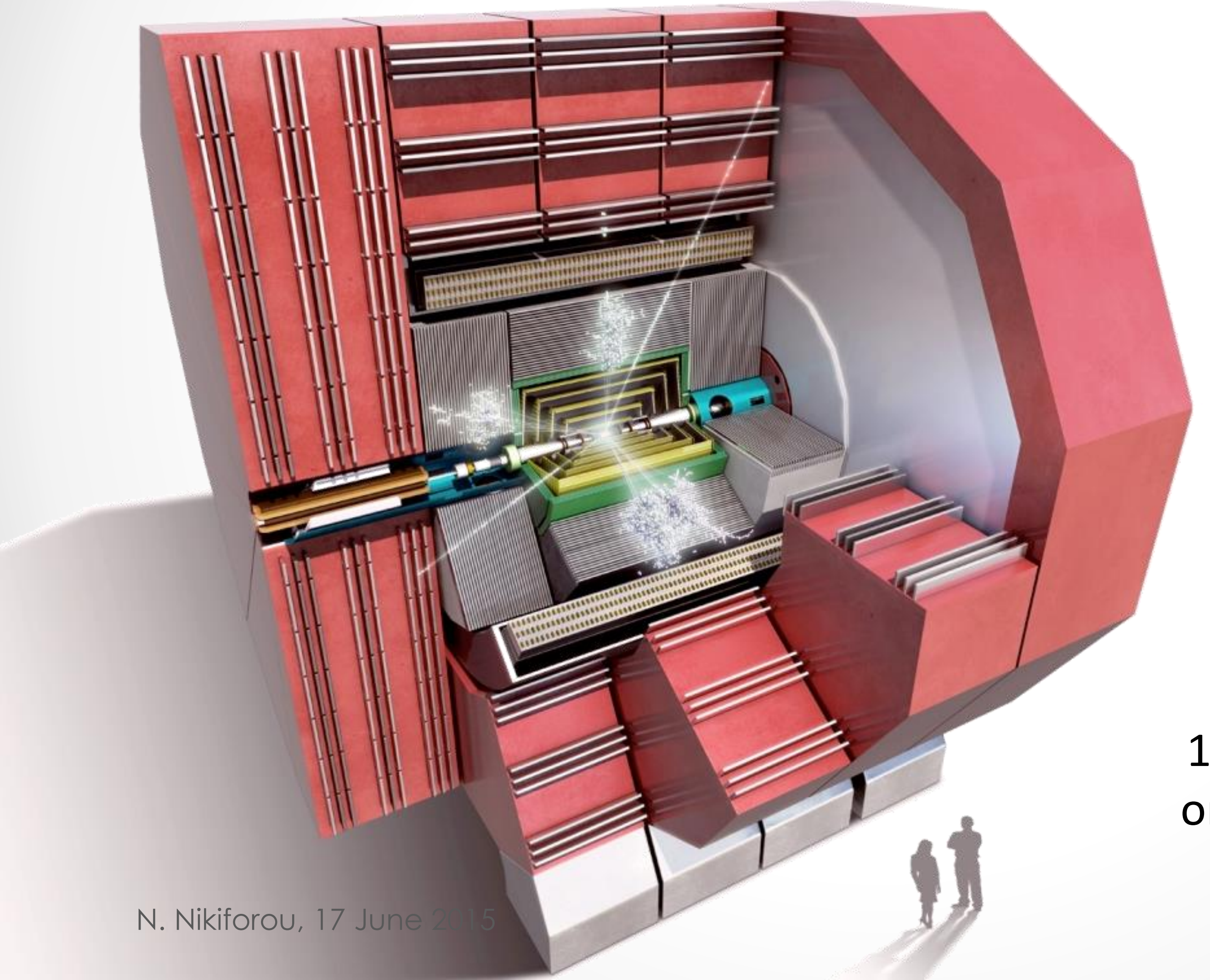
The new CLIC Detector Simulation Model with Full Silicon Tracking



Nikiforos Nikiforou

CERN/PH-LCD

on behalf of the

CLICdp collaboration

1st FCC-ee mini-Workshop
on Detector Requirements
CERN, June 17th 2015

Outline

- Detector requirements and experimental conditions
- Evolution of detector models since the CDR
- CLIC detector concept and ongoing optimization efforts
- Implementation in Software
- Conclusions

CLIC Physics Goals → Detector Requirements

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, **Higgs coupling to muons**

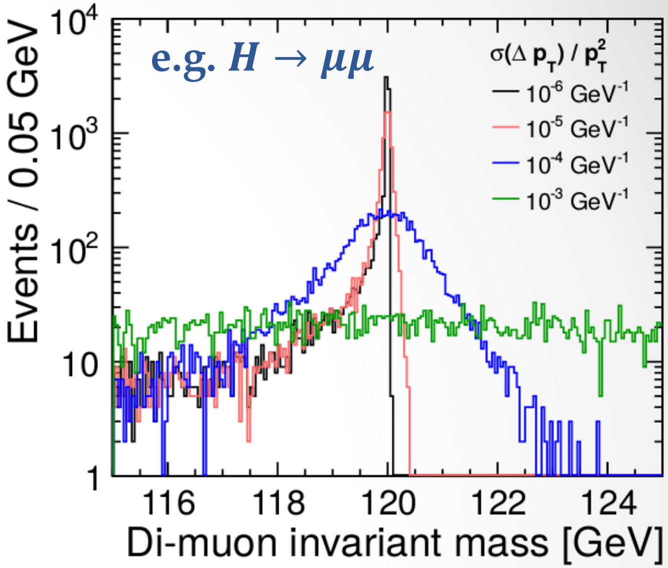
    $\rightarrow \sigma_{P_T}/p_T^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Jet energy resolution
  - **Separation of W/Z/H di-jets**

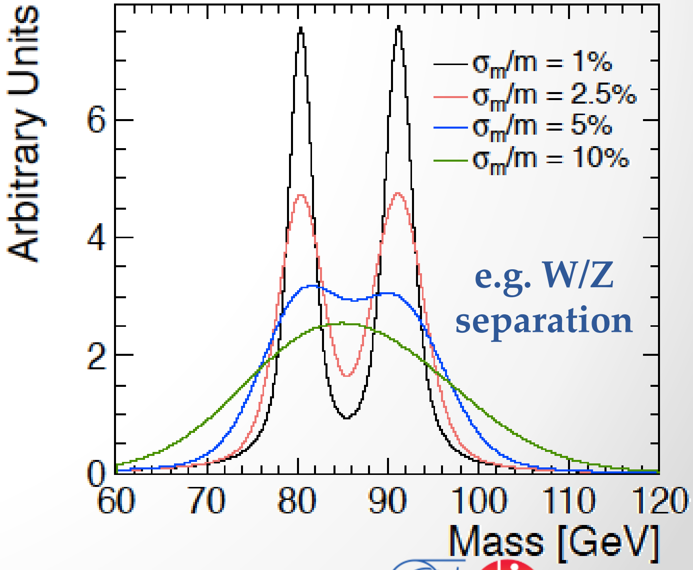
    $\rightarrow \sigma_E/E \sim 3.5\%$ for $\mathrm{E} > 100$ GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios

    $\rightarrow \sigma_{r\phi} \sim 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$
- Angular coverage
  - Very forward electron tagging

    $\rightarrow$Down to $\theta = 10$ mrad

+ Requirements due to CLIC beam structure and beam-induced backgrounds





The CLIC Experimental Environment

	CLIC at 3 TeV
Luminosity	5.9×10^{34} cm^{-2}s^{-1}
Bunch separation	**0.5 ns**
#Bunches per train	312
Train duration	**156 ns**
Train repetition rate	**50 Hz**
Particles per bunch	3.72×10^{9}
Crossing angle	20 mrad
σ_x / σ_y [nm]	≈ 45 / 1
σ_z [μm]	44

Drive **timing requirements** for the CLIC detector

Low duty cycle

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

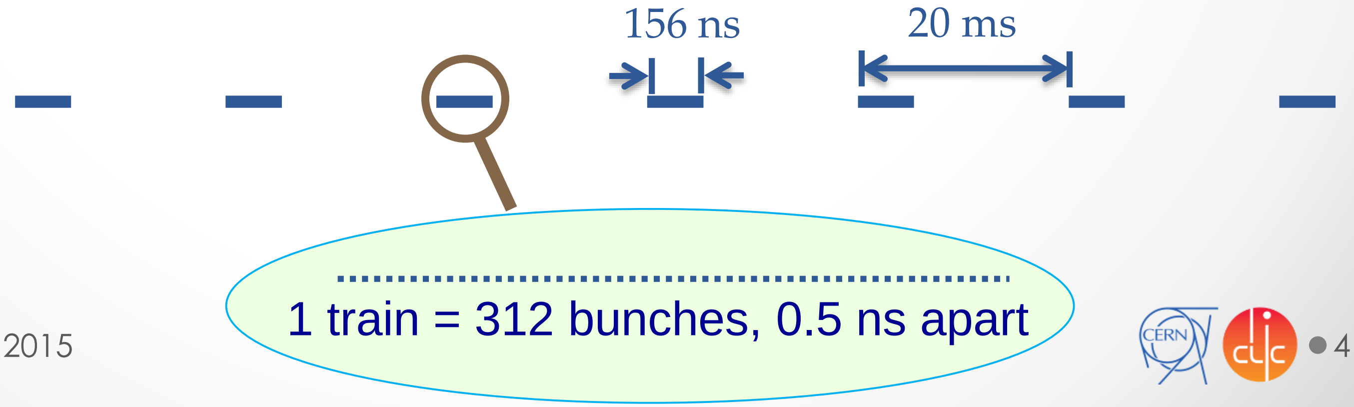
Very small beam profile at the interaction point

⇒ Very high E-fields ⇒

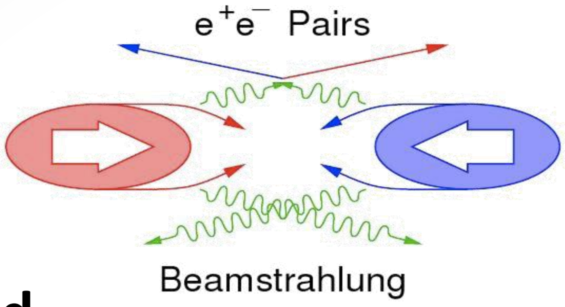
Beam-beam background

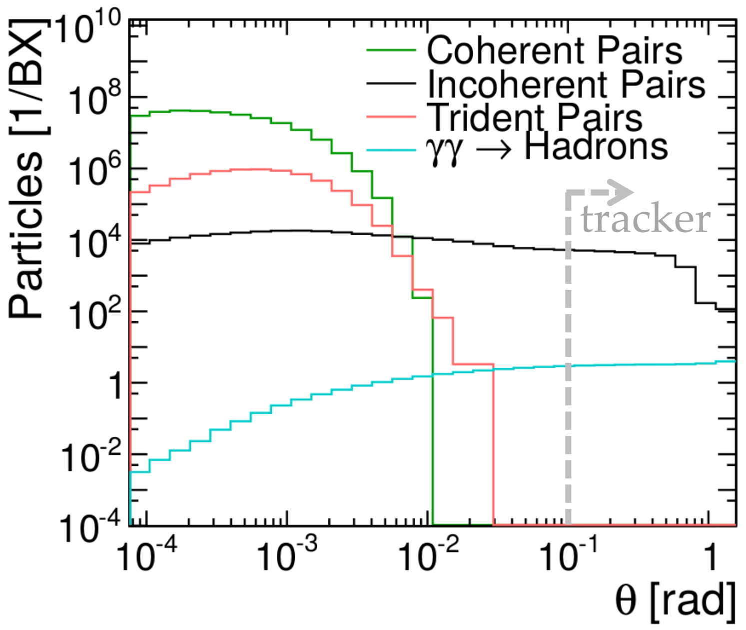
CLIC bunch structure

- not to scale -

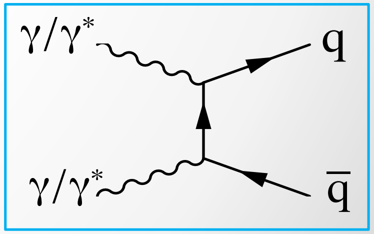


Beam-Induced Backgrounds





- Beamstrahlung:
  - ○ **Pair-background**
    - Coherent e^+e^- pairs: 7×10^8/BX
      - ○ Very forward
    - **Incoherent e^+e^- pairs**: 3×10^5/BX
      - ○ Rather forward
      - ○ High occupancies influence detector design
  - ○ **γγ to hadrons (3.2 events/BX @ 3 TeV)**
    - Energy deposits (19 TeV/train @ 3 TeV)
    - Main background in calorimeters and trackers



Evolution of Detector Designs

For the CLIC CDR (2012): Two general-purpose CLIC detector concepts

- Based on initial ILC concepts (ILD and SiD) but Optimized and adapted to CLIC conditions

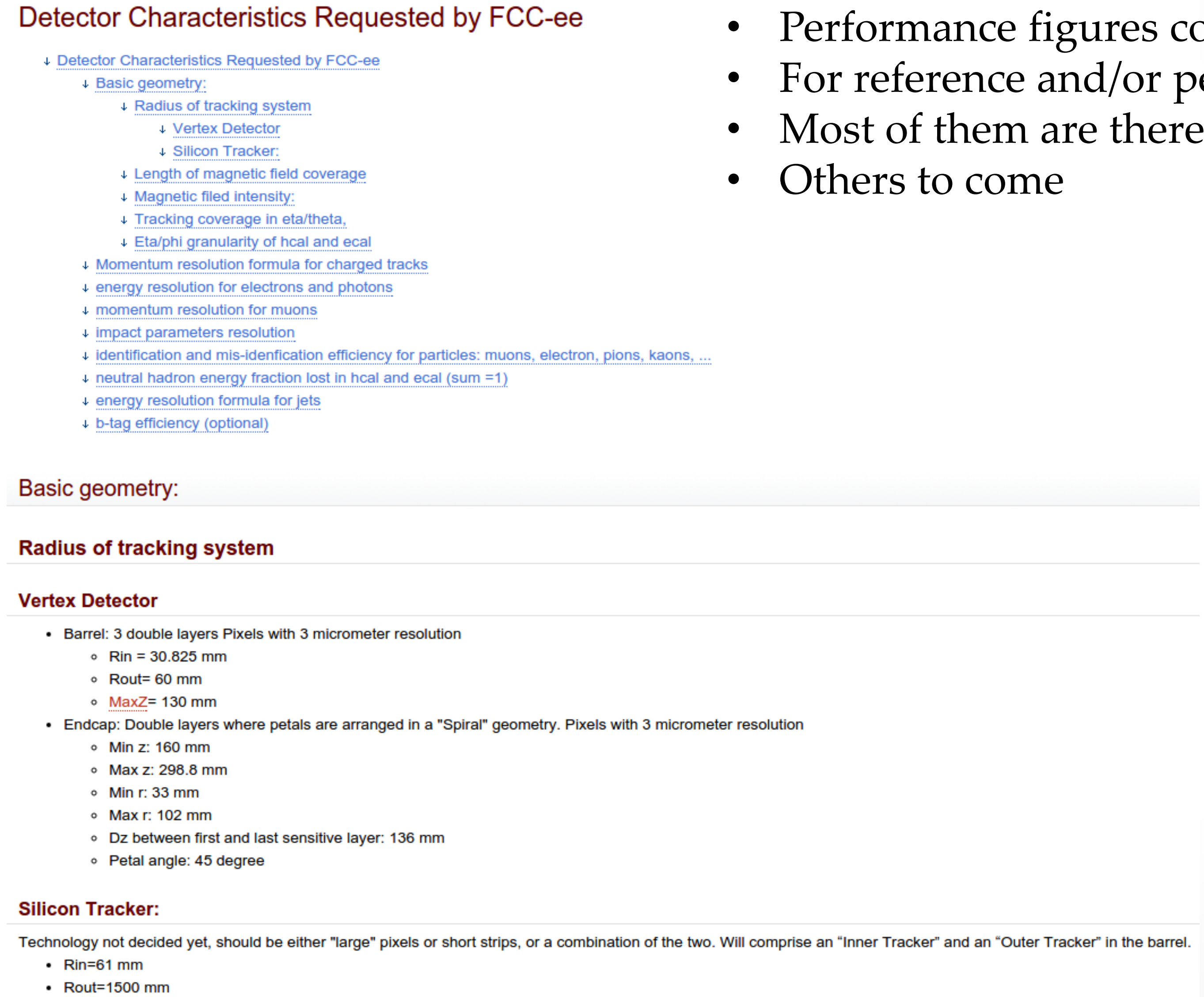
Concept	ILD (ILC)	**CLIC_ILD**	SiD (ILC)	**CLIC_SiD**	**New Model**	**CMS†**
Tracker	TPC/Silicon	**TPC/Silicon**	Silicon	**Silicon**	**Silicon**	Silicon
Solenoid Field [T]	3.5	**4**	5	**5**	**4**	3.8
Solenoid Free Bore [m]	3.3	**3.4**	2.6	**2.7**	**3.4**	3.0
Solenoid Length [m]	8	**8.3**	6	**6.5**	**8.3**	13
VTX Inner Radius [mm]	16	**31***	14	**27***	**31***	40
ECAL Inner Radius [m]	1.8	**1.8**	1.3	**1.3**	**1.5**	1.3
ECAL ΔR [mm]	172	**172**	135	**135**	**159**	500
HCAL Absorber B / E	Fe	**W / Fe**	Fe	**W / Fe**	**Fe**	Brass
HCAL λ_I	5.5	**7.5**	4.8	**7.5**	**7.55**	5.8 Barrel/10 EC
Overall Height [m]	14	**14**	12	**14**	**14**	14.6
Overall Length [m]	13.2	**12.8**	11.2	**12.8**	**10.4**	21.6

* For $\sqrt{s} \lesssim 500$ GeV a variant with a VTX inner radius smaller by 6 mm is used

† See [16] for a nice comparison of CLIC and LHC detectors

CLIC Detector Performance Figures Twiki

https://twiki.cern.ch/twiki/bin/view/CLIC/ClicNDM_PerformanceNumbers



Detector Characteristics Requested by FCC-ee

Basic geometry:

Radius of tracking system

Vertex Detector

- Barrel: 3 double layers Pixels with 3 micrometer resolution
  - Rin = 30.825 mm
  - Rout= 60 mm
  - MaxZ= 130 mm
- Endcap: Double layers where petals are arranged in a "Spiral" geometry. Pixels with 3 micrometer resolution
  - Min z: 160 mm
  - Max z: 298.8 mm
  - Min r: 33 mm
  - Max r: 102 mm
  - Dz between first and last sensitive layer: 136 mm
  - Petal angle: 45 degree

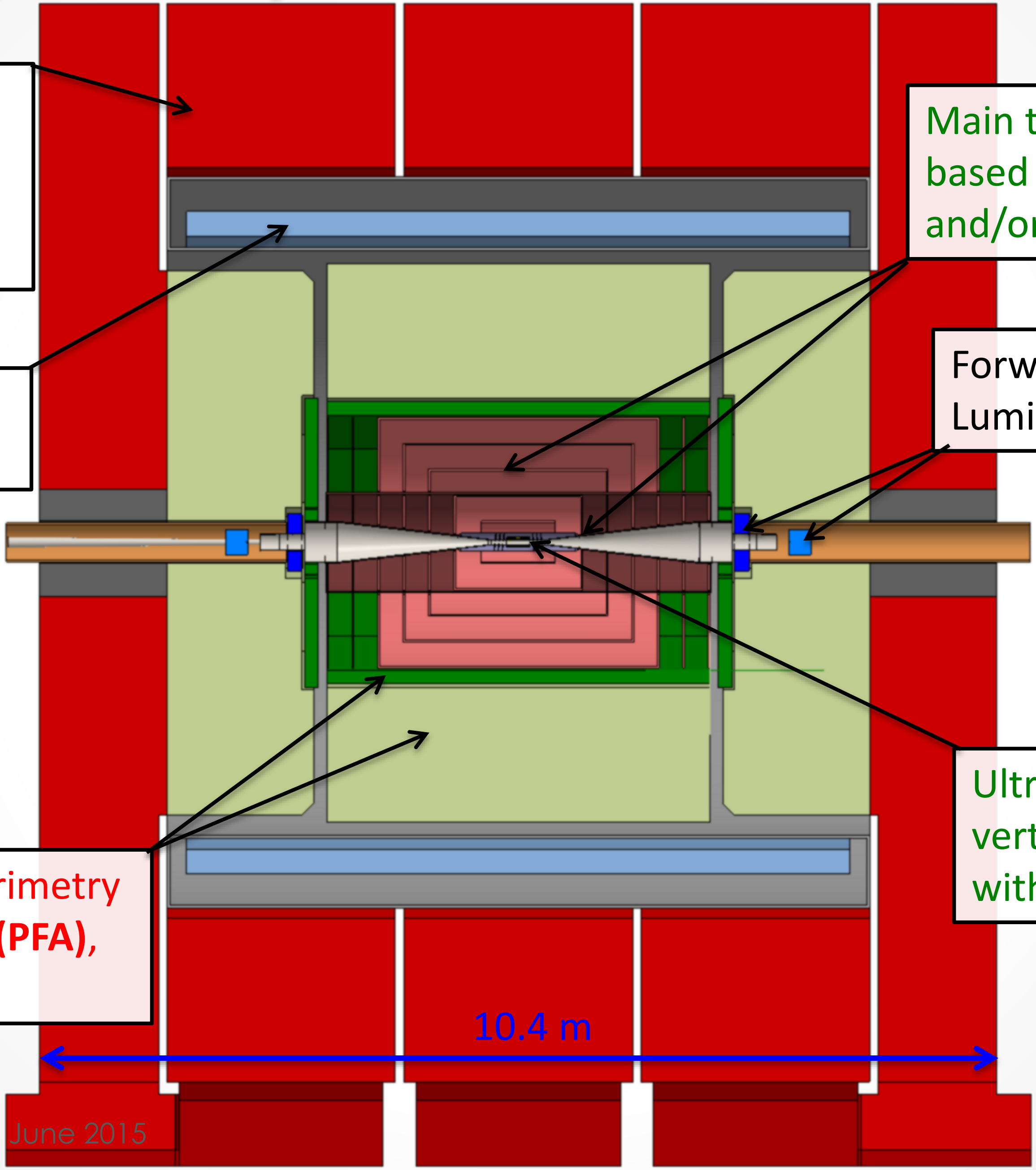
Silicon Tracker:

Technology not decided yet, should be either "large" pixels or short strips, or a combination of the two. Will comprise an “Inner Tracker” and an “Outer Tracker” in the barrel.

- Rin=61 mm
- Rout=1500 mm

- Performance figures collected in twiki
- For reference and/or perhaps sue in fast sim
- Most of them are there, with some references
- Others to come

Proposed Layout in New Detector Model



Return yoke (Fe) with detectors for muon identification

Solenoid Magnet, 4 Tesla

Fine grained calorimetry for **Particle Flow (PFA)**, Depth: 1 + 7.5 λ_I

Main tracker, silicon-based (large pixels and/or strips)

Forward region with LumiCal and BeamCal

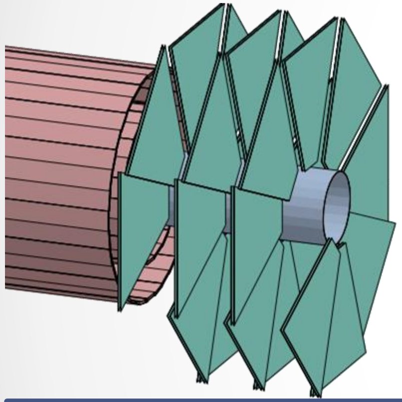
Ultra low-mass vertex detector with ~25 µm pixels

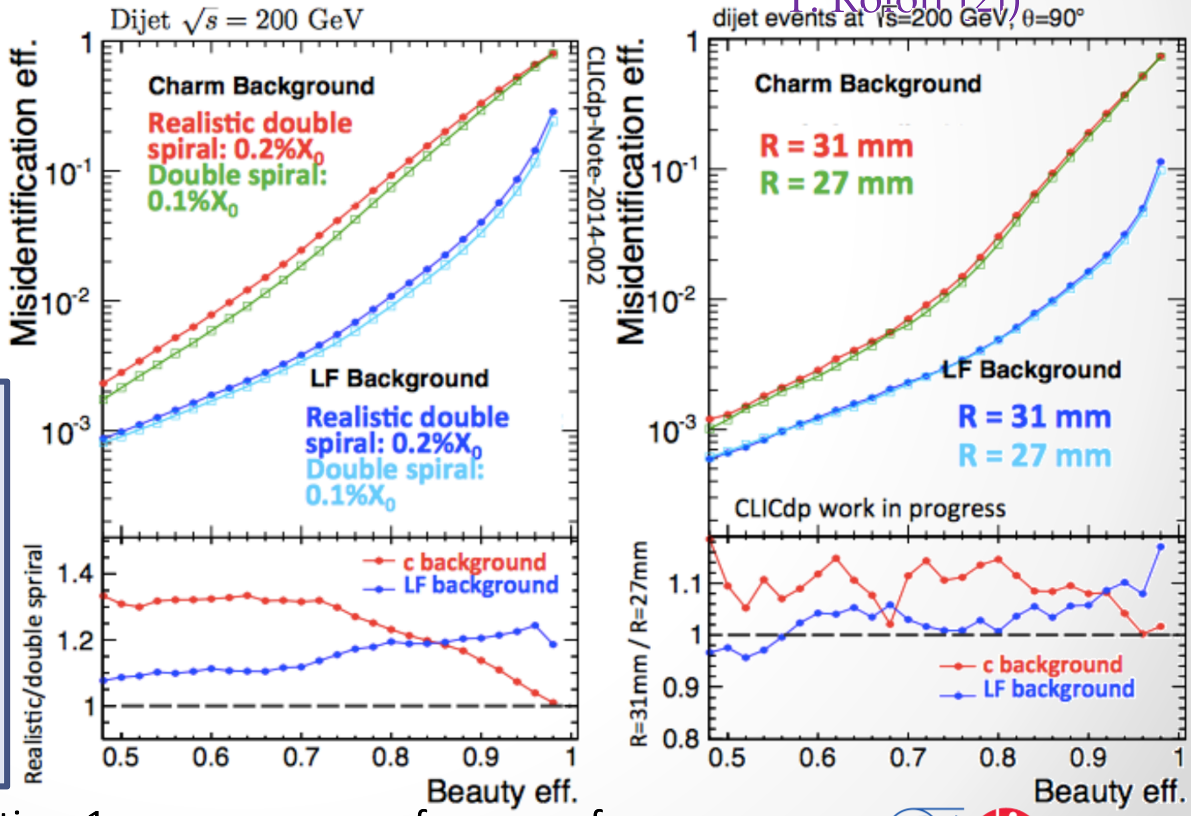
Vertex Detector Optimization

Use flavor tagging as a gauge in various tests :

1. Effect of material (most significant effect on performance)
2. **Vary inner radius (dictated by background rates ↔ B-field)**
3. Effect of spiral geometry (only small impact, better airflow)
4. Single vs. double layers (minor impact, benefits for support)

(N.Alipour Tehrani, P. Roloff [2])





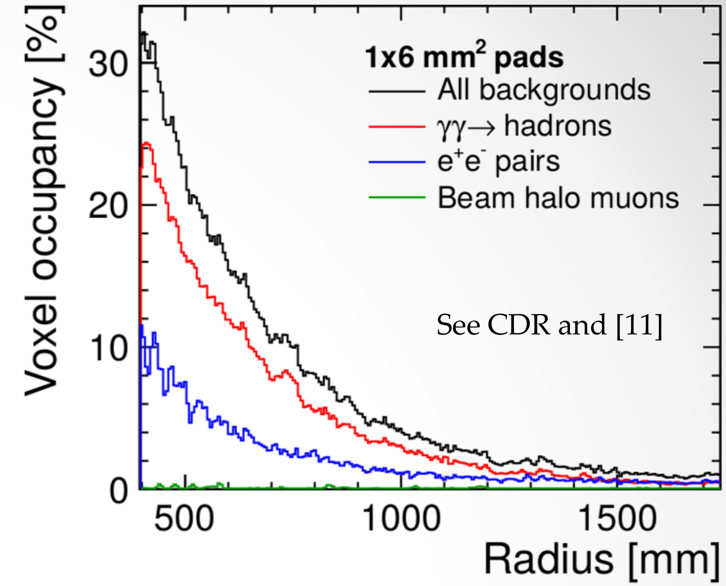
Ratio > 1 means worse performance for more material (left) or larger radius (right)

In the new detector model:

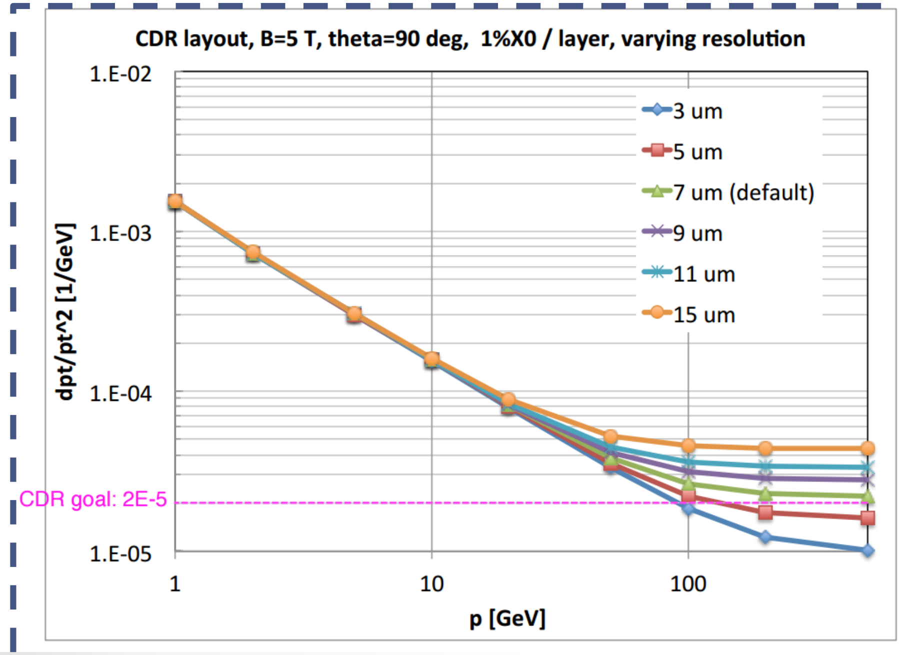
- **Double layers with spirals**
- $0.2\%X_0$ **per (single) layer**
- $R_{in} = 31$ mm
- **Pixel size: 25 µm**
- **3 µm single point resolution**

Silicon Tracker

- A TPC tracker would have very high occupancies (30%) for CLIC @ 3 TeV with 1x6 mm^2 pads (without safety factors)
  - We use an All-Silicon Tracker for our new model



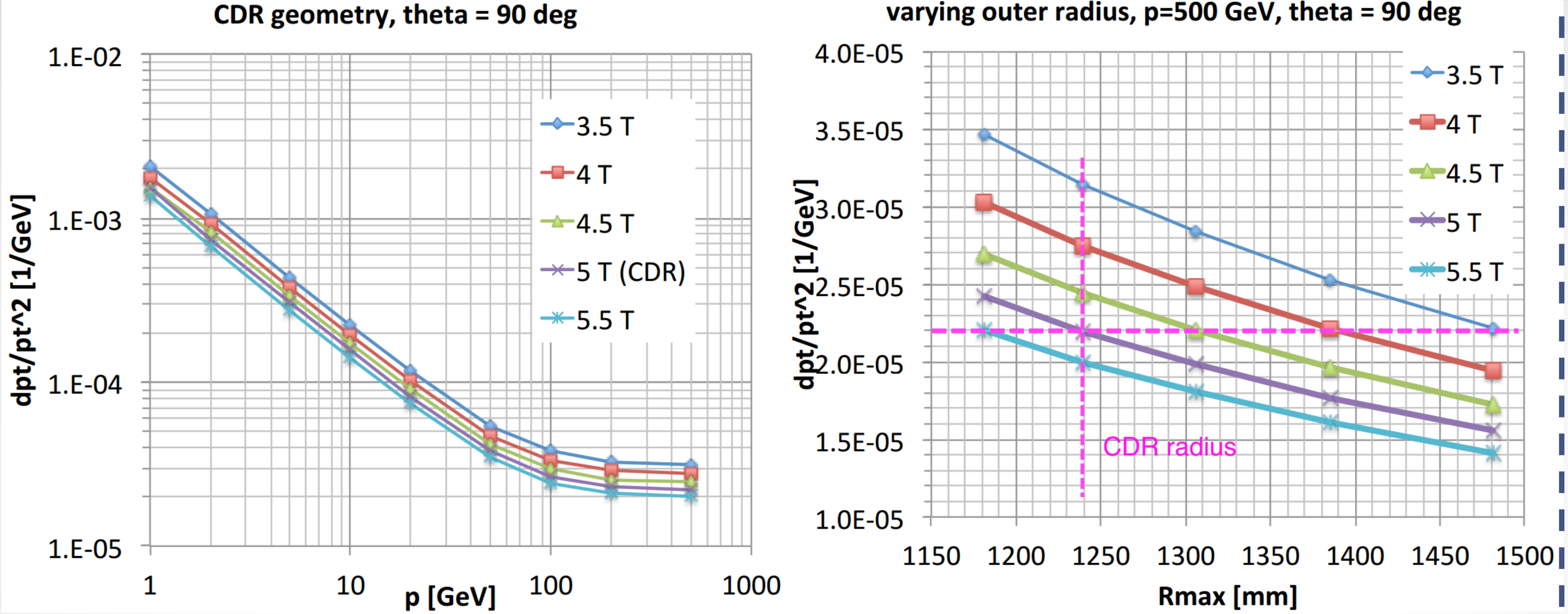
See CDR and [11]



Fast simulation studies (LicToy) with CLIC_SID_CDR geometry (D. Dannheim et al. [3])

- Fast Simulation studies (LicToy) to determine optimal parameters
- Material Budget→ $\sim 1\% X_0$ per layer
  - Requires very thin materials/sensors
  - Less critical than in Vertex Detector
- Single point resolution: ~7 µm
  - Critical for high-momentum tracks

Silicon Tracker Radius/ B-field



Fast simulation studies (LicToy) with CLIC_SID_CDR geometry (D. Dannheim et al. [3])

- Tracking performance depends on tracker **radius** and **magnetic** field

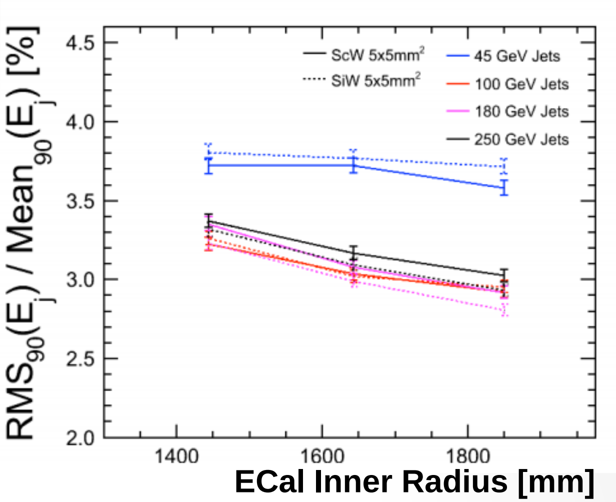
$$\frac{\sigma(p_T)}{p_T^2} \propto \frac{\sigma^{meas}}{\sqrt{N}\boldsymbol{B}\cdot\boldsymbol{R}^2}$$

Stronger dependence on *R*

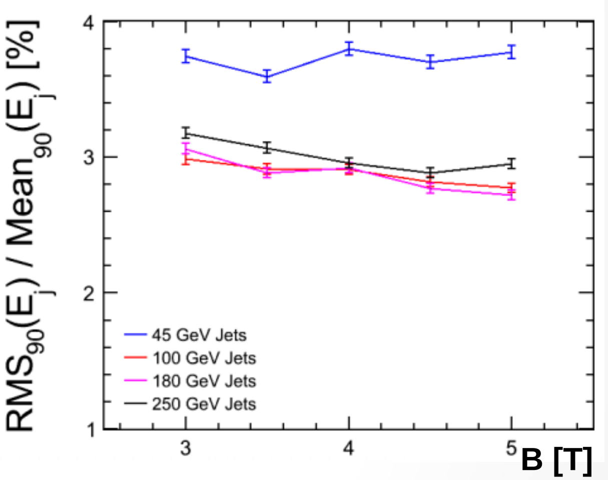
- **Can compensate reduction of *B* in new detector by rescaling *R* by** $\sqrt{\boldsymbol{B}_{nom}/\boldsymbol{B}}$
- Increase from 1.3 m (CLIC_SID) but not much gain by going to 1.8 m (CLIC_ILD) -> **Converged to 1.5 m for new model**

More on Magnetic Field

- **B-Field and R affect Particle Flow Performance**
  - Previous ILD studies by M. Thomson and J. S. Marshall [4,5]
- **Aiming for an outer tracking radius of 1.5 m**
- A magnetic field strength of up to 4.5 T should be technically feasible
  - **Use 4 T for next simulation model**



- **Effects of non-uniform magnetic field currently under investigation**
  - Implementation of more realistic field map underway
  - Changes in tracking software



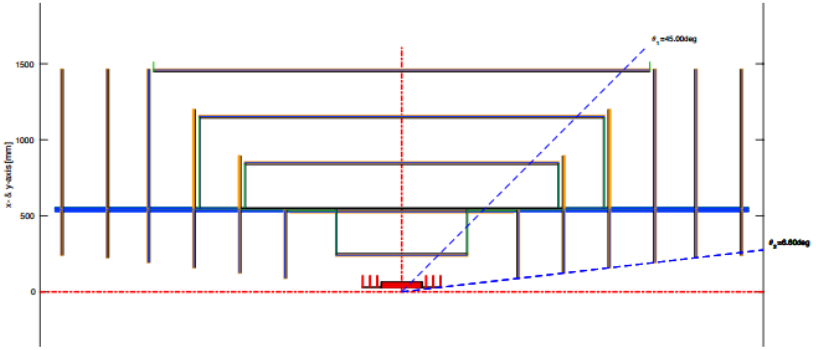
- **Tracker length: at least ~CLIC_ILD (4.6 m)**
  - **Motivated by physics in the forward region (e.g. Higgs self-coupling)**
  - Reduce Endcap Yoke thickness by ~1.2 m and use End coils

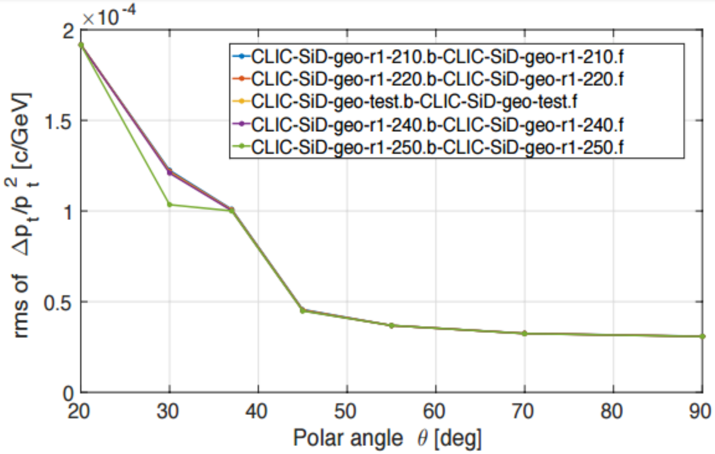
More Tracker Optimization (R. Simoniello[9])

- **Fast Simulation** (LicToy) Study varying **geometry and layout** (**R**, length, number of layers, etc) as well as **material** (supports, cabling, cooling)
  - Use p_T and d_0 resolution to gauge performance
- **Full simulation studies** also ongoing with new Reconstruction Software

Move r position of the first barrel layer

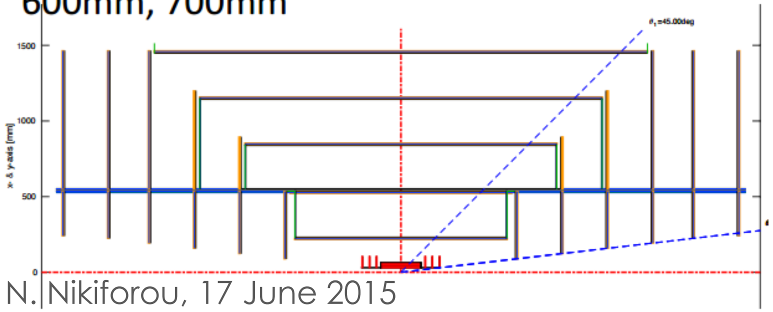
Scan of r1 from 230mm to 210, 220, 240, 250mm





Change length of the first barrel layer

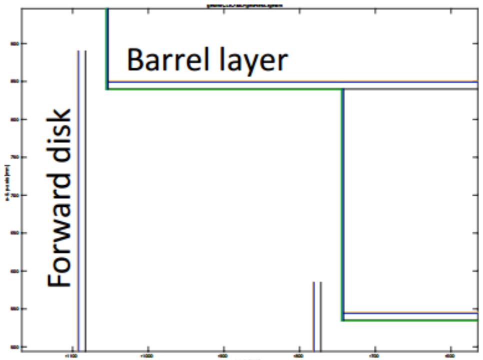
z1 varied from 430mm to 450mm, 500mm, 600mm, 700mm



Optimise gap between barrel/forward and the outer radius of the forward disk

- Δr = 40 mm
- Gap = 30 mm

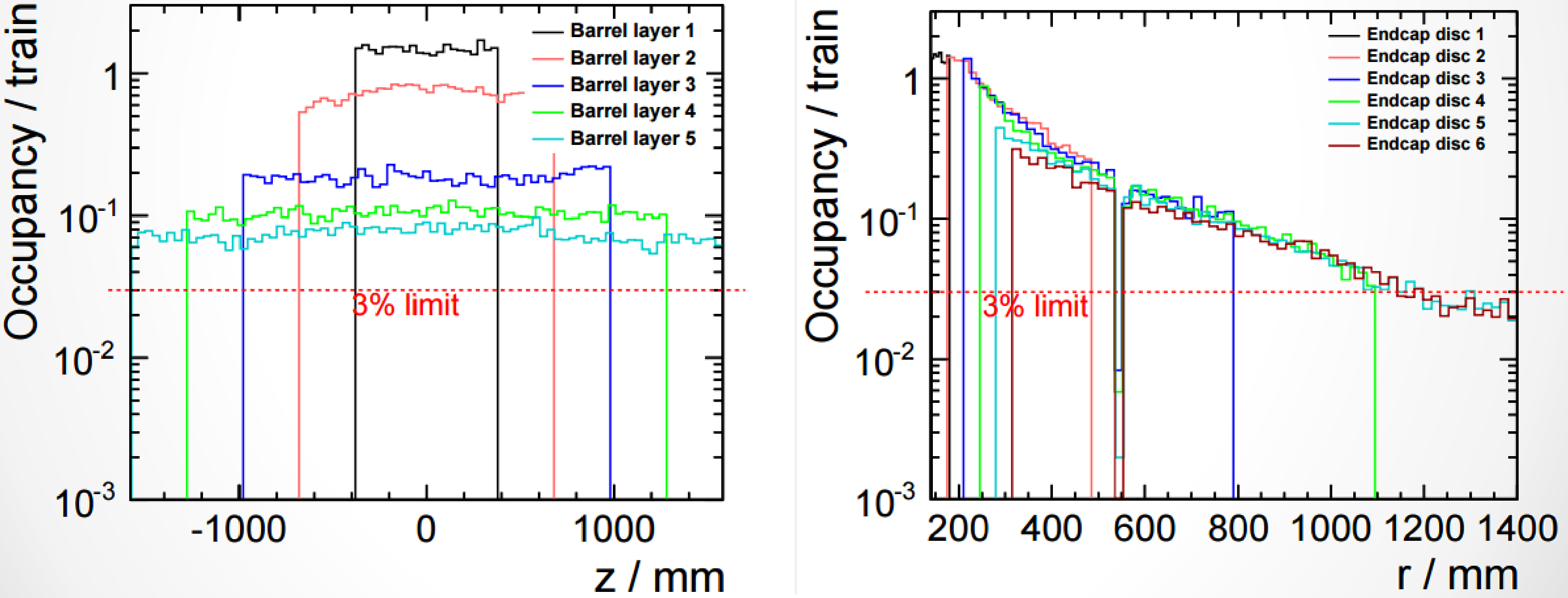
- Not full scan performed yet
- Gaps are not pointing to IP



Occupancy in the main tracker

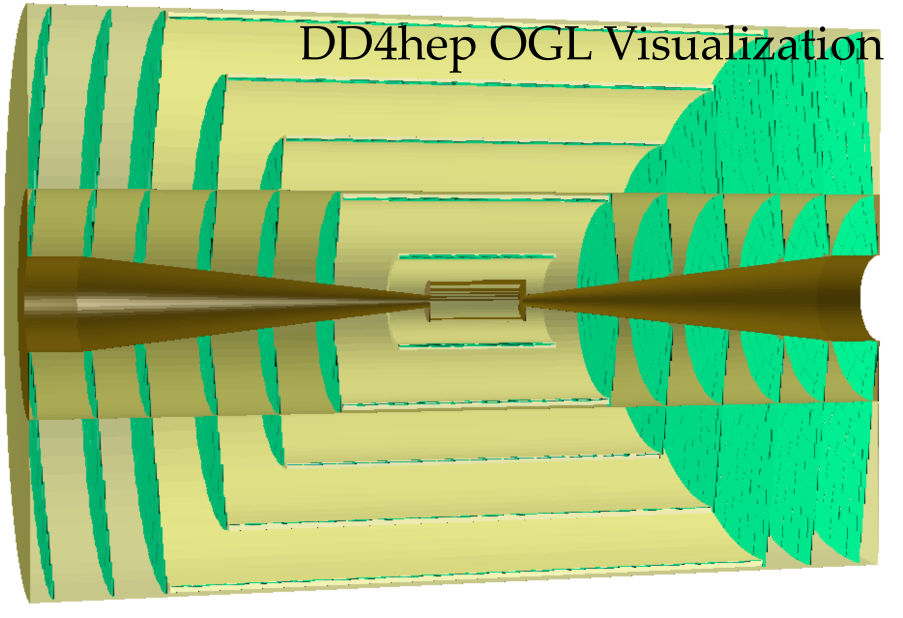
- High occupancies in certain regions
- Full Mokka-based (Geant4) simulation using a modified CLIC_ILD detector driver (TPC replaced with Si Layers)
- Assume 100 mm × 50 μm strips, avg. cluster size 2.6 , **safety factors** 5 (pairs) and 2 $(\gamma\gamma \rightarrow had)$

(Recent study by A. Nurnberg[10]. See also LCD-Note-2011-021[15])



- **Need for large pixels and/or short-strips**
- Maximal strip length to be below 3% limit depends on layer (2 – 50 mm in barrel)

Silicon Tracker: Recap



- ***Optimization for an all-silicon tracker ongoing***
- 5 – 6 tracking layers with **an *Inner* and *Outer Tracker***
    - Support tube for extraction with beampipe assembly

- Power pulsing?
- Air cooling is probably not feasible in a large tracker volume
- Radiation level 10^4 times lower than LHC

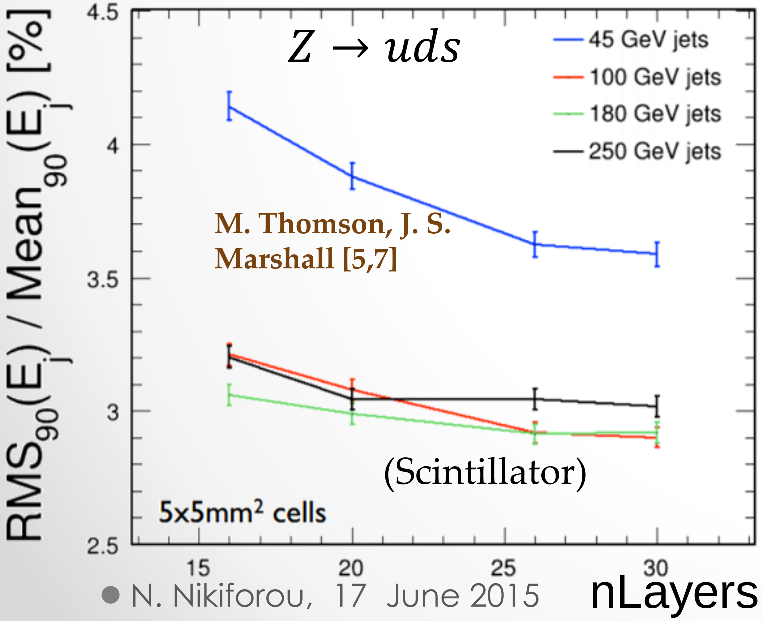
- ***Now starting a tracker hardware R&D***

Calorimeter Optimization

- High granularity imaging calorimeters to use with **Pandora Particle Flow Algorithms**
- Variations on **Number and Layout of Layers**, **Cell size**, **absorber material and thickness**, **active material and thickness**, **total depth, …**
- Optimization performed also in collaboration with ILD
  - Used mainly ILD-based Mokka drivers and ILD software chain
- **Need to recalibrate detector response with each variation**
  - Developed a quasi-automatic calibration procedure
- Gauge model performance using:
  - Single particle response
  - **Jet Energy Resolution** ($Z \rightarrow uds, WW \rightarrow \nu\ell ud, ZZ \rightarrow \nu\nu dd$)

ECal Optimization

- **Si vs Sc:** No significant effect on JER
- **# Layers:** Not very important for higher energy jets (PFA confusion dominates): **Not much more improvement from 25 to 30 layers**
- **Cell size:** Becomes important for higher energy jets (where PFA confusion dominates)
  - JER **degradation** from 3% to ~3.5% when increasing cell size from 5x5 mm^2 to 15x15 mm^2
  - Combinations of different granularities in layers considered
    - No significant gain for the extra complexity



M. Thomson, J. S. Marshall [5,7]

Working hypotheses for the simulation model:

- **Silicon active material, Tungsten absorber**
- **25 Layers, 23 X_0/ 1 λ_I**
- **Use 5x5 mm^2 cells throughout**

HCal Optimization

E.g. study overlap of m_W and m_Z measurement in $WW \to \nu\ell ud$ and $ZZ \to \nu\nu dd$ events

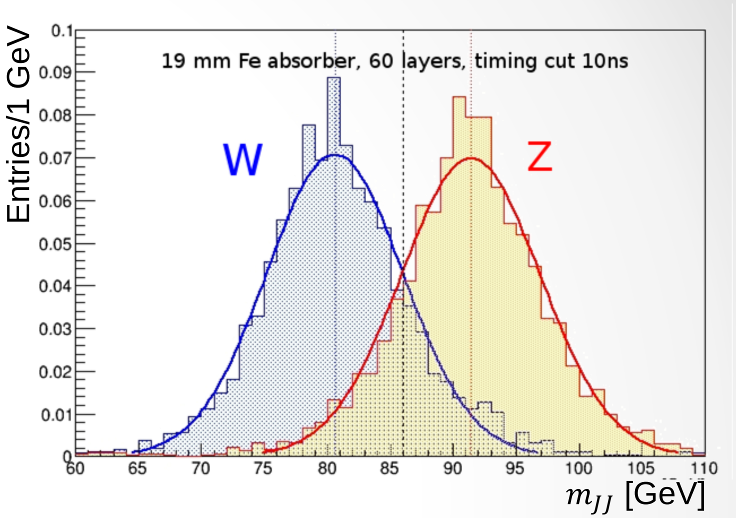
- Example: HCal Barrel Absorber
  - 10 mm Tungsten (W)
  - 19 mm Steel (Fe)

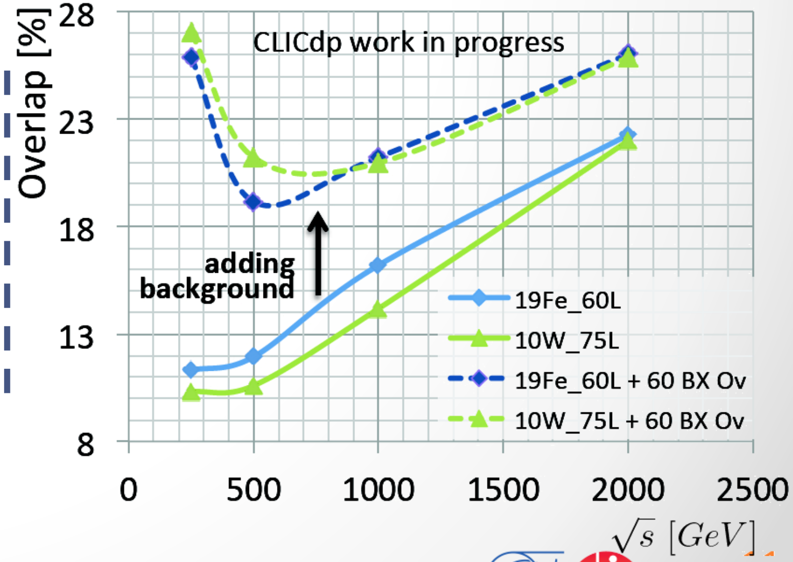
Keep same Depth at ~7.5 λ_I

- Full Geant4 detector simulation + PandoraPFA + FastJet
- Performance shown to be **similar** for **tungsten** and **steel**
- **Steel is cheaper and easier to process**

⇒ Use Steel as an absorber for the HCal

- 60 layers
- 20 mm Steel/3 mm Scintillator
- 30x30 mm^2 Cell size

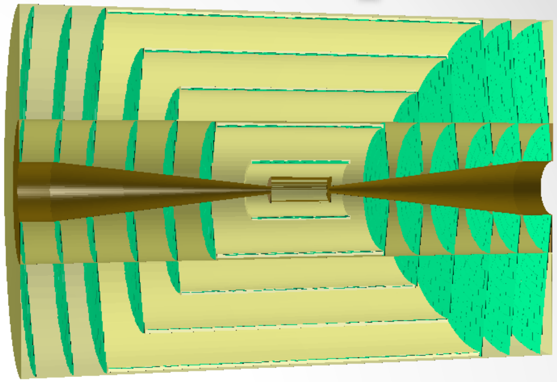




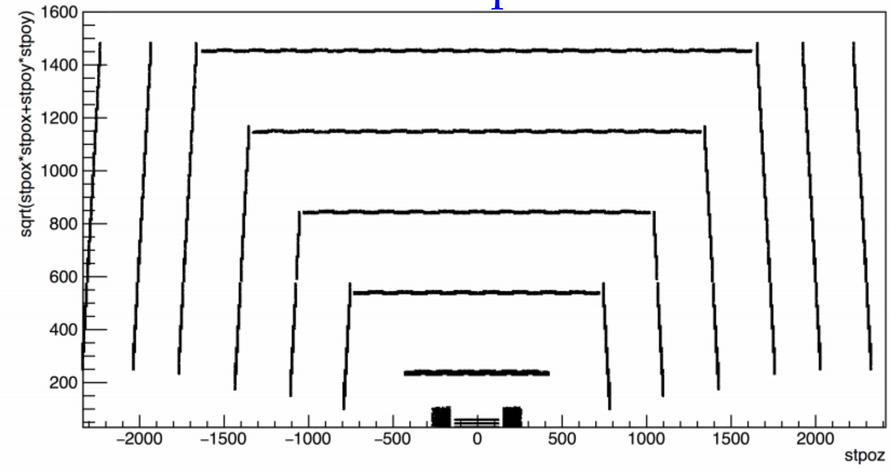
Implementation in SW

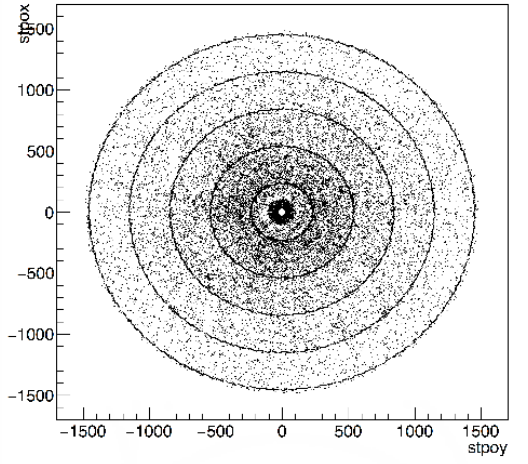
- Detector Implemented in DD4hep and in very good state
  - In package “lcgeo” with sharing/reuse of subdetector drivers with other experiments where possible
- Evolving, more detail being added continuously
  - Geometry driver development paradigm evolved from an SiD model (resized, adapted to CLIC_SiD) <- **DD4hep is Flexible!**
- **A Simulation and Reconstruction framework based on DD4hep and DDG4/DDRec is the way forward for us**
- **Working in collaboration with ILD to develop/validate reconstruction software based on DD4hep**
  - **Tracking software**
  - **PandoraPFA**

Vertex and Tracker in DD4hep



- Fairly resizable and scalable drivers implemented in DD4hep
    - Simpler drivers (e.g. no spirals) available as well
- Most important parameters (radii, layers, module layout,…) controlled by the “compact” xml
    - In principle not even need to recompile C++ driver!
- It works well too! Hit map from 100 *Hνν* events simulated with DDG4 below

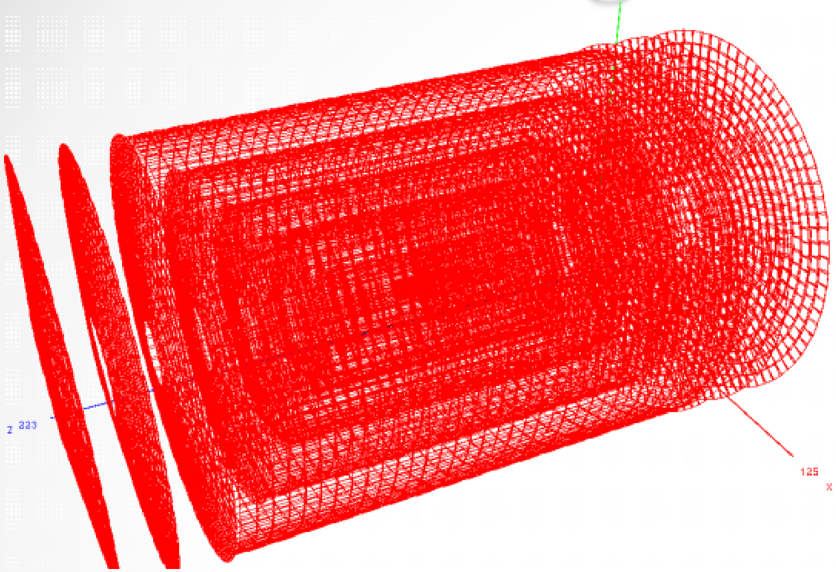


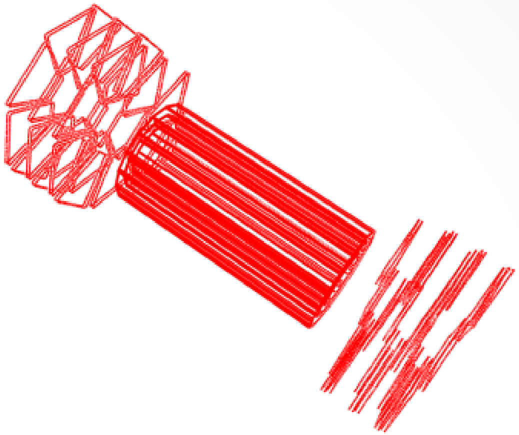


M. Petric [14]

Tracking in an All Si-Tracker

F. Gaede [13]
R. Simoniello [9]



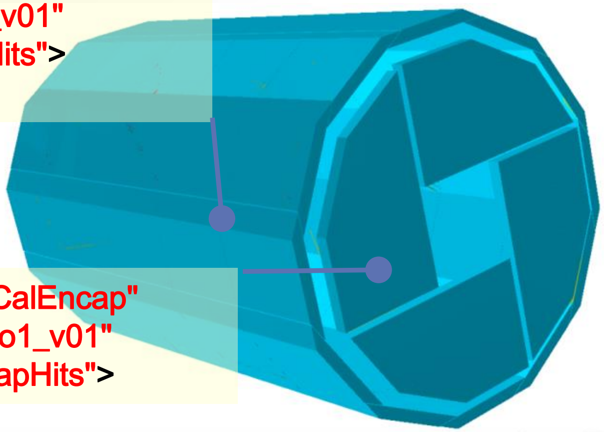


The (>19000) tracking surfaces in the CLIC model

- **Based on DD4hep/DDRec**
- **Track Fitting Strategy:**
  - Fit inside-out starting with vertex pixel hits
    - 1D hits in main tracker (strips) provide no constraint in z so cannot be used to initialize tracks
  - Finally smooth back to third hit and fit inside from there
- Current pattern recognition being developed from ILD Celloular Automaton-based Vertex patt. Rec.

Calorimeters

```
<detector name="ECalBarrel"
type="ECalBarrel_o1_v01"
readout="ECalBarrelHits">
```



```
<detector name="ECalEncap"
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```
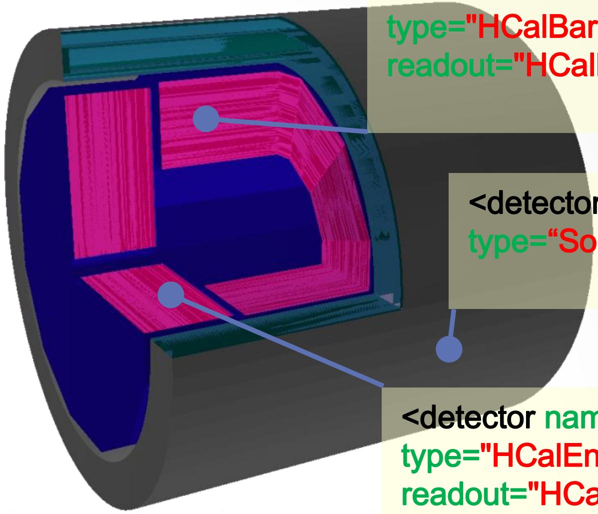



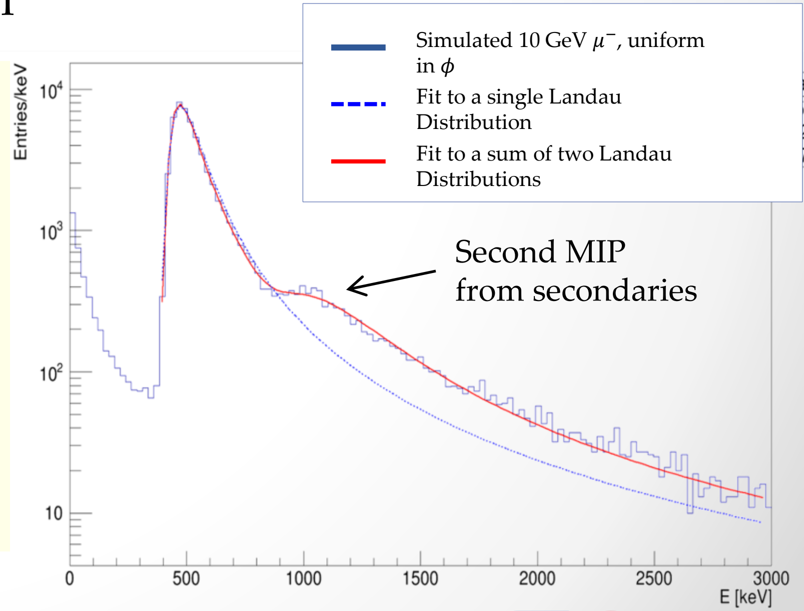
```
<detector name="HCalBarrel"
type="HCalBarrel_o1_v01"
readout="HCalBarrelHits">
```

```
<detector name=“Solenoid"
type=“Solenoid_o1_v01"
```

```
<detector name="HCalEncap"
type="HCalEndcap_o1_v01"
readout="HCalEndcapHits">
```

- Fairly scalable drivers
- Radii, Layer/module composition in compact xml

```
<detector ...>
...
 <dimensions numsides=“HCal_symmetry" rmin="HCal_inner_R" z="HCal_half_L*2“ />
 <layer repeat="(int) HCal_layers" >
  <slice material="Steel235" thickness="0.5*mm“/>
  <slice material="Steel235" thickness=“19*mm“/>
  <slice material=“Polystere" thickness=“3*mm“ sensitive=“yes“/>
  <slice material="PCB" thickness="0.7*mm“/>
  <slice material=“Steel235" thickness=“0.5*mm“/>
  <slice material=“Air" thickness=“2.7*mm“/>
  </layer>
</detector>
```



- Simulation and reconstruction under validation

Conclusions

- New simulation model for a detector at CLIC evolving from previous CDR models based on modified ILD designs
- Optimization result of a big effort from many people and still ongoing
- **Important R&D efforts also ongoing (not covered today)**
- New detector model implemented and being refined in DD4hep with relative **flexibility/scalability**
- Users of ILCSOFT and the ILD software chain
- Developing **simulation** and **reconstruction** software based on **DD4hep** in collaboration with ILD
- Some references available on next slide

References

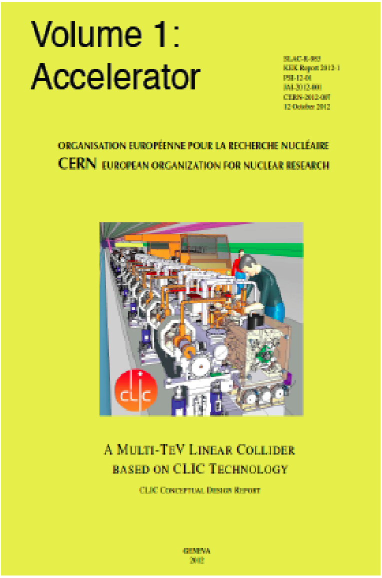
1. *L. Linssen et al.*, ***Physics and Detectors at CLIC : CLIC Conceptual Design Report***, CERN-2012-003
2. *N.Alipour Tehrani and P. Roloff*, ***Optimisation Studies for the CLIC Vertex-Detector Geometry***, CLICdp-Note-2014-002
3. *D. Dannheim et al.*, Slides at https://indico.cern.ch/event/309925/contribution/2/material/slides/0.pdf
4. *M. Thomson, Nucl.Instrum.Meth. A611 (2009)*
5. *J. Marshall*, Slides at http://indico.cern.ch/event/309926/contribution/1/material/slides/0.pdf
6. *B. Cure*, Slides at https://indico.cern.ch/event/314325/contribution/1/material/slides/1.pdf
7. *M. Thomson*, Slides at http://indico.cern.ch/event/309926/contribution/1/material/slides/0.pdf
8. M. Valentan et al, LiC Detector Toy Fast Simulation
9. R. Simoniello, Slides at https://indico.cern.ch/event/376800/session/3/contribution/5/material/slides/0.pdf
10. A. Nurnberg, Slides at https://indico.cern.ch/event/376800/session/2/contribution/28/material/slides/0.pdf
11. M. Killenberg, LCD-Note-2011-029
12. J. S. Marshall, Slides at https://indico.cern.ch/event/336335/session/6/contribution/5/material/slides/0.pdf
13. F. Gaede, Slides at https://indico.cern.ch/event/376800/session/0/contribution/12/material/slides/0.pdf
14. M. Petric, Slides at https://indico.cern.ch/event/376800/session/0/contribution/11/material/slides/0.pdf
15. D. Dannheim, A. Sailer, Beam-Induced Backgrounds in the CLIC detectors, LCD-Note-2011-021
16. E. van Der Kraaij, Detector challenges at CLIC, contrasted with the LHC case, slides at http://indico.cern.ch/event/210720/

Backup Material

…

CLIC and Detector Documentation

- 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 the Snowmass Process in the US



Volume 1:
Accelerator

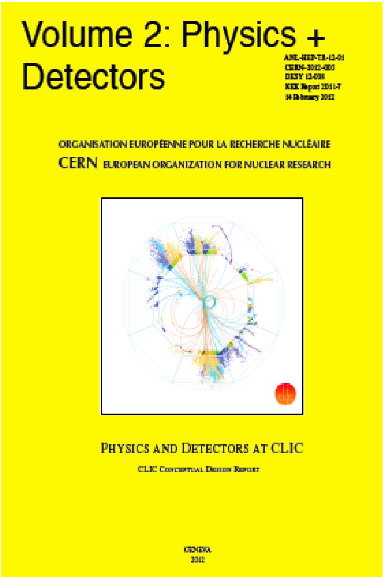
SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

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

GENEVA
2012

CERN-2012-007



Volume 2: Physics +
Detectors

ANL-HEP-TR-12-01
CERN-2012-003
DESY 12-008
KEK Report 2011-7
14 February 2012

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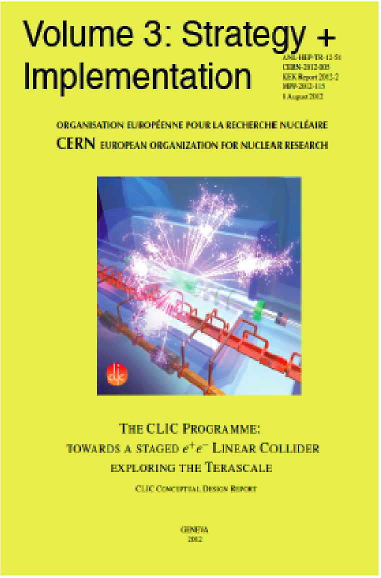
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

CERN-2012-003



Volume 3: Strategy +
Implementation

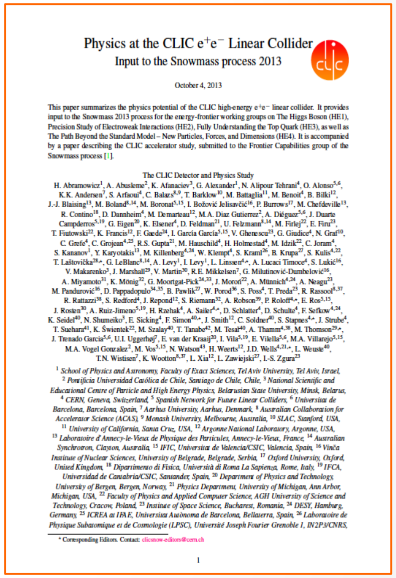
ANL-HEP-TR-12-51
CERN-2012-005
KEK Report 2012-2
MPP-2012-115
1 August 2012

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

THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

CERN-2012-005



Physics at the CLIC e^+e^- Linear Collider
Input to the Snowmass process 2013

October 4, 2013

This paper summarizes the physics potential of the CLIC high-energy e^+e^- linear collider. It provides input to the Snowmass 2013 process for the energy-frontier working groups on The Higgs Boson (HE1), Precision Study of Electroweak Interactions (HE2), Fully Understanding the Top Quark (HE3), as well as The Path Beyond the Standard Model – New Particles, Forces, and Dimensions (HE4). It is accompanied by a paper describing the CLIC accelerator study, submitted to the Frontier Capabilities group of the Snowmass process [1].

The CLIC Detector and Physics Study
H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], G. Alexander[1], N. Alipour Tehrani[4], O. Alonso[5,6], K.K. Andersen[7], S. Arfaoui[4], C. Balazs[8,9], T. Barklow[10], M. Battaglia[11], M. Benoit[4], B. Bilki[12], J.-J. Blaising[13], M. Boland[8,14], M. Boronat[5,15], I. Božović Jelisavčić[16], P. Burrows[17], M. Chefdeville[13], R. Contino[18], D. Dannheim[4], M. Demarteau[12], M.A. Diaz Gutierrez[2], A. Diéguez[5,6], J. Duarte Campderros[5,19], G. Eigen[20], K. Elsener[4], D. Feldman[21], U. Felzmann[8,14], M. Firlej[22], E. Firu[23], T. Fiutowski[22], K. Francis[12], F. Gaede[24], I. García García[5,15], V. Ghenescu[23], G. Giudice[4], N. Graf[10], C. Grefe[4], C. Grojean[4,25], R.S. Gupta[21], M. Hauschild[4], H. Holmestad[4], M. Idzik[22], C. Joram[4], S. Kananov[1], Y. Karyotakis[13], M. Killenberg[4,24], W. Klempt[4], S. Kraml[26], B. Krupa[27], S. Kulis[4,22], T. Laštovička[28,*], G. LeBlanc[8,14], A. Levy[1], I. Levy[1], L. Linssen[4,*], A. Lucaci Timoce[4], S. Lukić[16], V. Makarenko[3], J. Marshall[29], V. Martin[30], R.E. Mikkelsen[7], G. Milutinović-Dumbelović[16], A. Miyamoto[31], K. Mönig[32], G. Moortgat-Pick[24,33], J. Moroń[22], A. Münnich[4,24], A. Neagu[23], M. Pandurović[16], D. Pappadopulo[34,35], B. Pawlik[27], W. Porod[36], S. Poss[4], T. Preda[23], R. Rassool[8,37], R. Rattazzi[38], S. Redford[4], J. Repond[12], S. Riemann[32], A. Robson[39], P. Roloff[4,*], E. Ros[5,15], J. Rosten[30], A. Ruiz-Jimeno[5,19], H. Rzehak[4], A. Sailer[4,*], D. Schlatter[4], D. Schulte[4], F. Sefkow[4,24], K. Seidel[40], N. Shumeiko[3], E. Sicking[4], F. Simon[40,*], J. Smith[12], C. Soldner[40], S. Stapnes[4,*], J. Strube[4], T. Suehara[41], K. Świentek[22], M. Szalay[40], T. Tanabe[42], M. Tesař[40], A. Thamm[4,38], M. Thomson[29,*], J. Trenado Garcia[5,6], U.I. Uggerhøj[7], E. van der Kraaij[20], I. Vila[5,19], E. Vilella[5,6], M.A. Villarejo[5,15], M.A. Vogel Gonzalez[2], M. Vos[5,15], N. Watson[43], H. Weerts[12], J.D. Wells[4,21,*], L. Weuste[40], T.N. Wistisen[7], K. Wootton[8,37], L. Xia[12], L. Zawiejski[27], I.-S. Zgura[23]

[1] School of Physics and Astronomy, Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel, [2] Pontificia Universidad Católica de Chile, Santiago de Chile, Chile, [3] National Scientific and Educational Centre of Particle and High Energy Physics, Belarusian State University, Minsk, Belarus, [4] CERN, Geneva, Switzerland, [5] Spanish Network for Future Linear Colliders, [6] Universitat de Barcelona, Barcelona, Spain, [7] Aarhus University, Aarhus, Denmark, [8] Australian Collaboration for Accelerator Science (ACAS), [9] Monash University, Melbourne, Australia, [10] SLAC, Stanford, USA, [11] University of California, Santa Cruz, USA, [12] Argonne National Laboratory, Argonne, USA, [13] Laboratoire d'Annecy-le-Vieux de Physique des Particules, Annecy-le-Vieux, France, [14] Australian Synchrotron, Clayton, Australia, [15] IFIC, Universitat de Valencia/CSIC, Valencia, Spain, [16] Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia, [17] Oxford University, Oxford, United Kingdom, [18] Dipartimento di Fisica, Università di Roma La Sapienza, Rome, Italy, [19] IFCA, Universidad de Cantabria/CSIC, Santander, Spain, [20] Department of Physics and Technology, University of Bergen, Bergen, Norway, [21] Physics Department, University of Michigan, Ann Arbor, Michigan, USA, [22] Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Cracow, Poland, [23] Institute of Space Science, Bucharest, Romania, [24] DESY, Hamburg, Germany, [25] ICREA at IFAE, Universitat Autònoma de Barcelona, Bellaterra, Spain, [26] Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier Grenoble 1, IN2P3/CNRS,

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[*] Corresponding Editors. Contact: clicsnow-editors@cern.ch

1

arXiv:1307.5288

More on Beam-Beam Effects

Beamstrahlung can cause important energy losses right at the interaction point

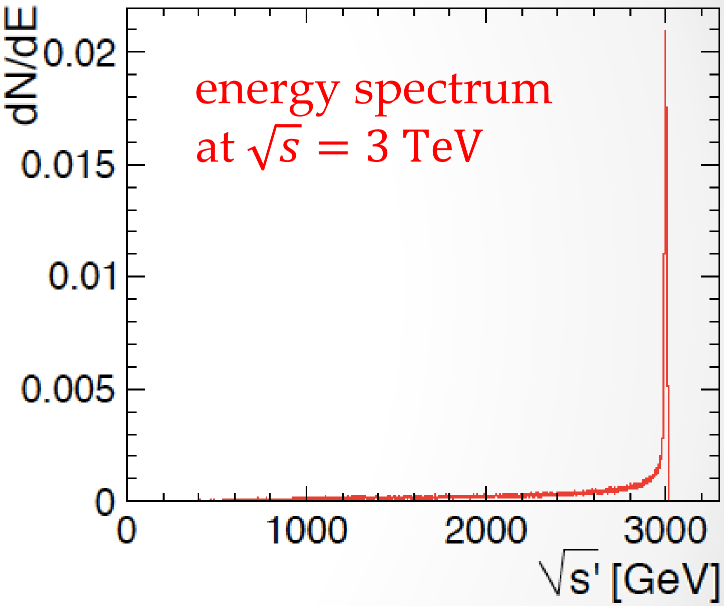
E.g. full luminosity at 3 TeV:

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

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



energy spectrum
at $\sqrt{s} = 3$ TeV

CLIC power and energy consumption

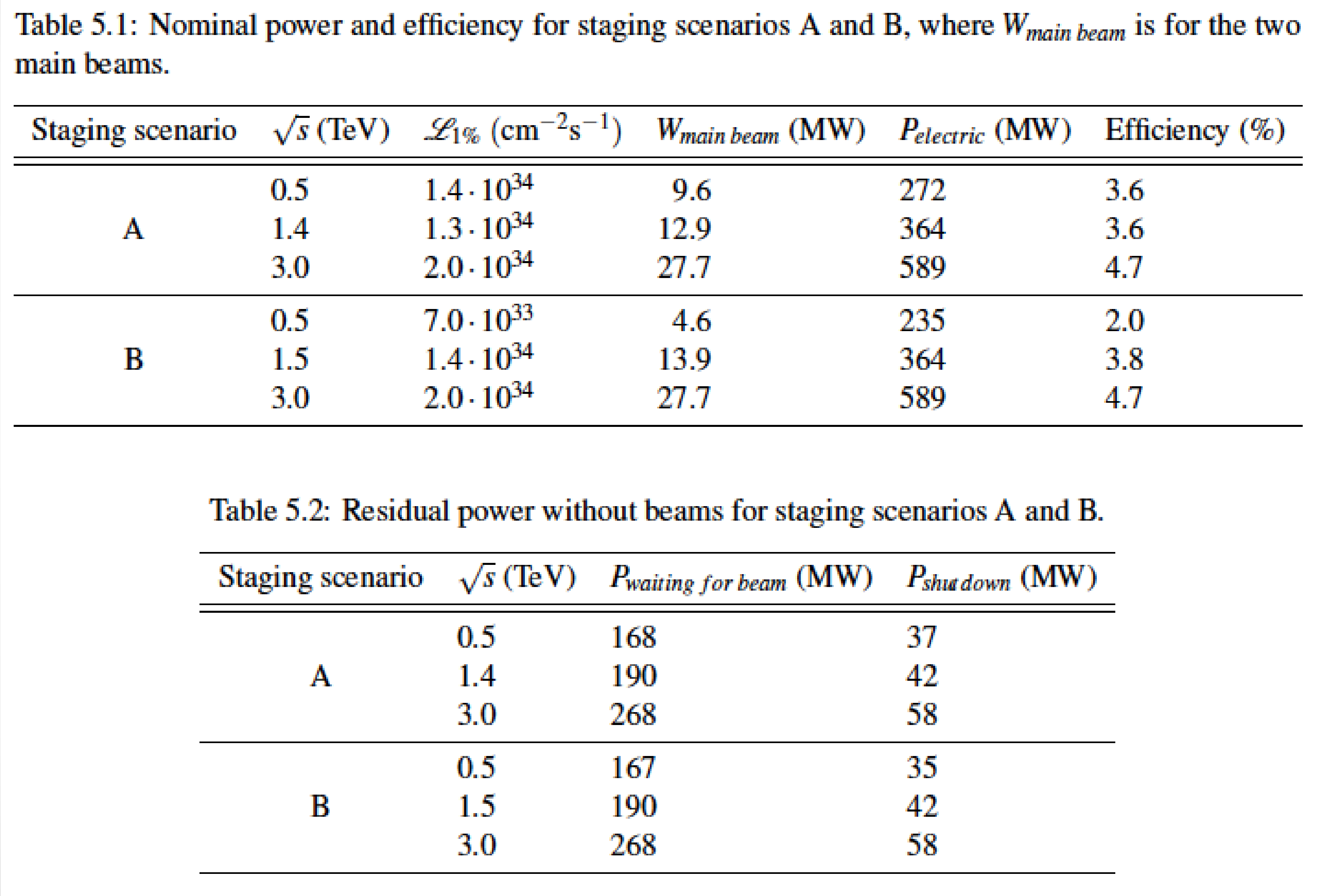


Table 5.1: Nominal power and efficiency for staging scenarios A and B, where $W_{main\ beam}$ is for the two main beams.

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

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

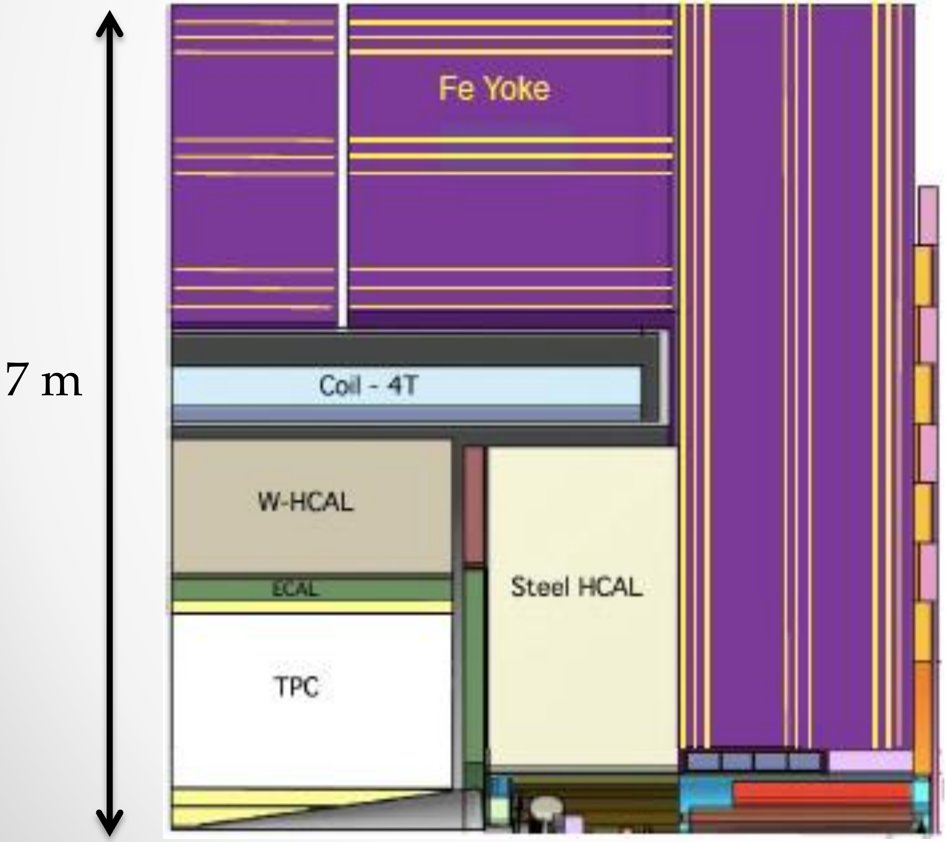
Staging scenario	$\sqrt{s}$ (TeV)	$P_{waiting\ for\ beam}$ (MW)	$P_{shut\ down}$ (MW)
A	0.5	168	37
	1.4	190	42
	3.0	268	58
B	0.5	167	35
	1.5	190	42
	3.0	268	58

CLIC_ILD and CLIC_SiD

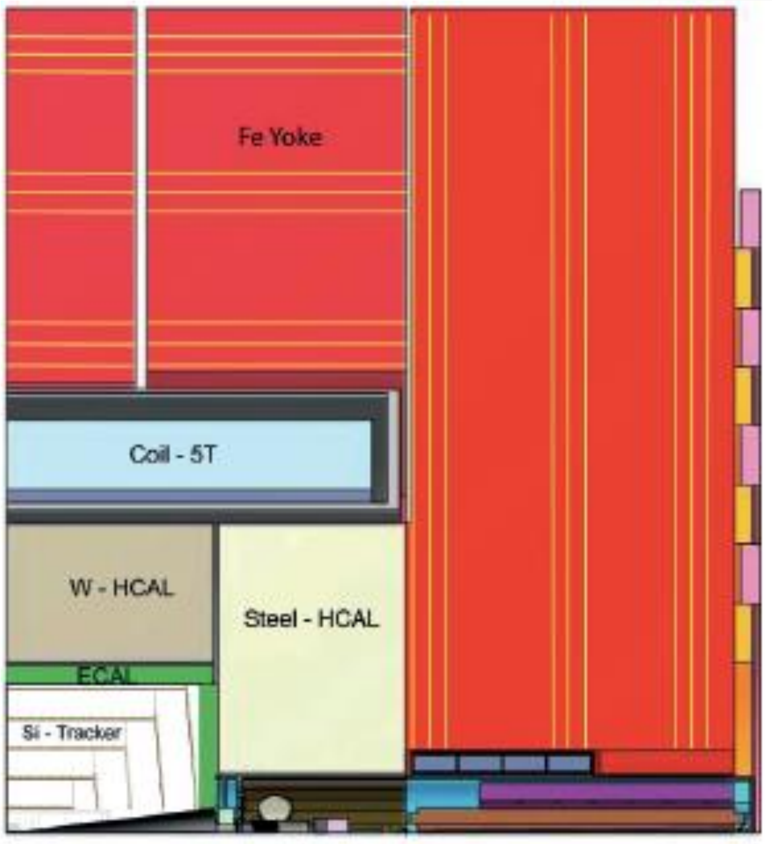
For the CLIC CDR (2012):

- Two general-purpose CLIC detector concepts
- Based on initial ILC concepts (ILD and SiD)
- Optimised and adapted to CLIC conditions

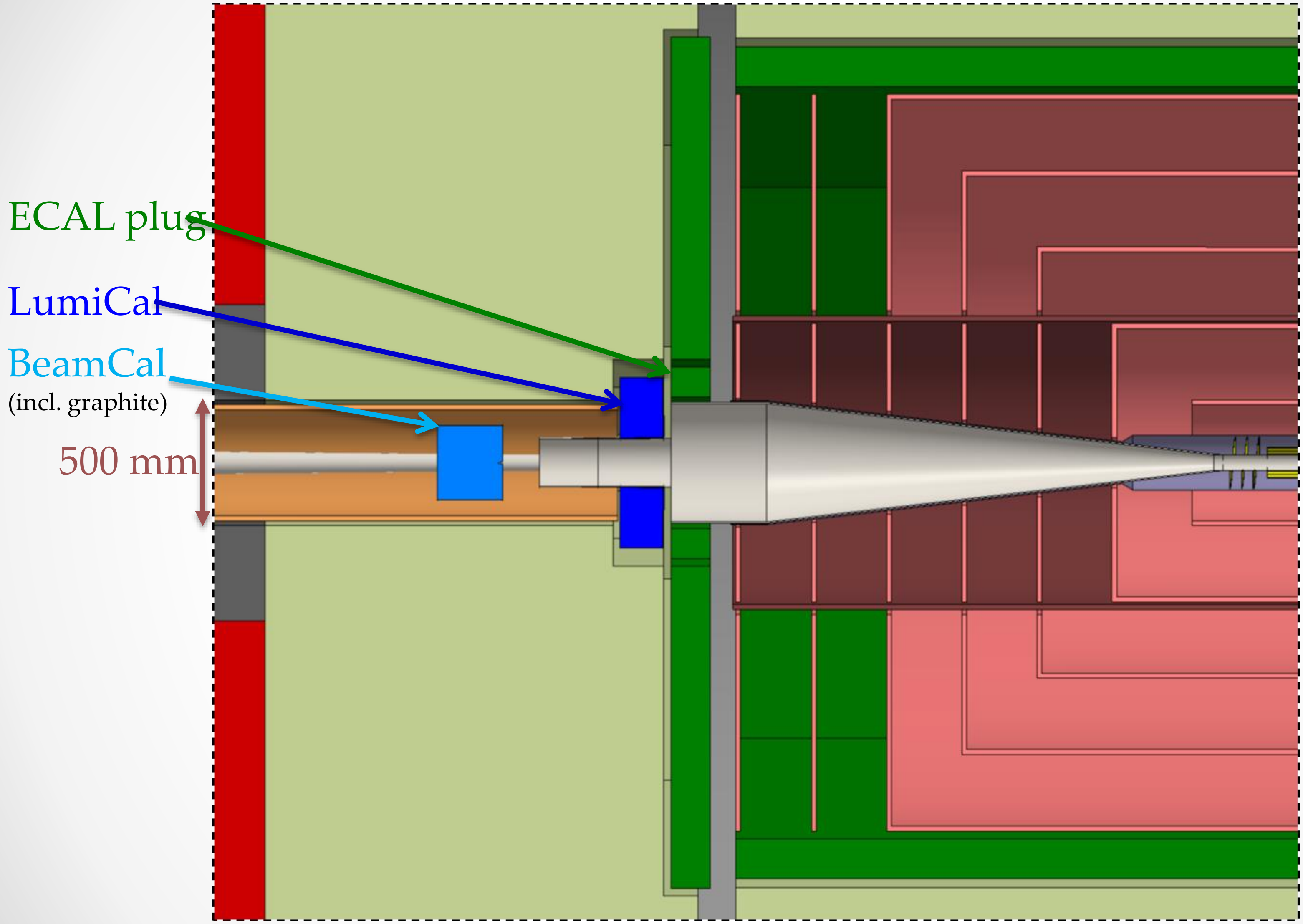
CLIC_ILD



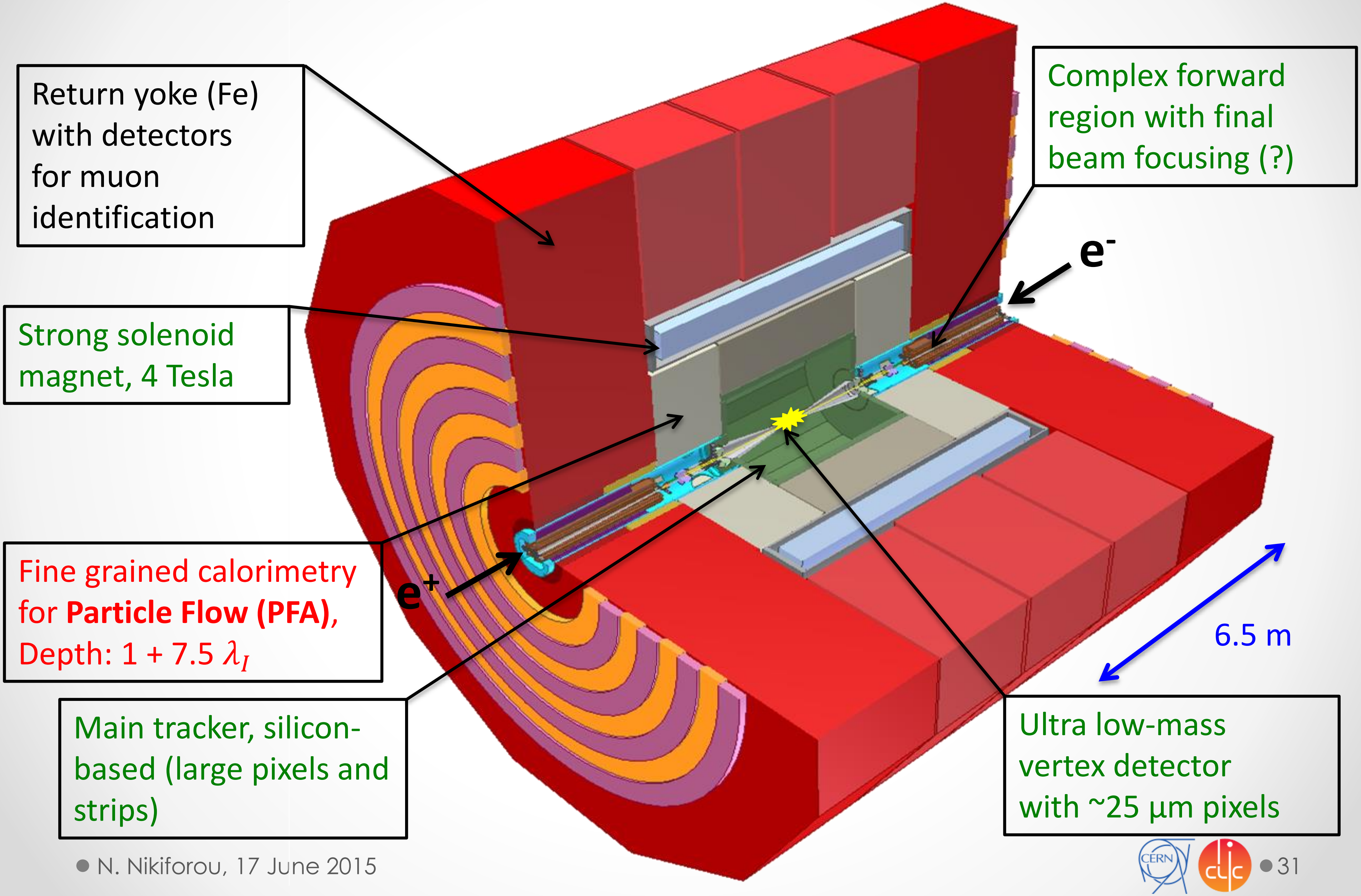
CLIC_SiD



Forward Region Layout in the New Model



Basic Outline of a Detector at CLIC



Return yoke (Fe) with detectors for muon identification

Complex forward region with final beam focusing (?)

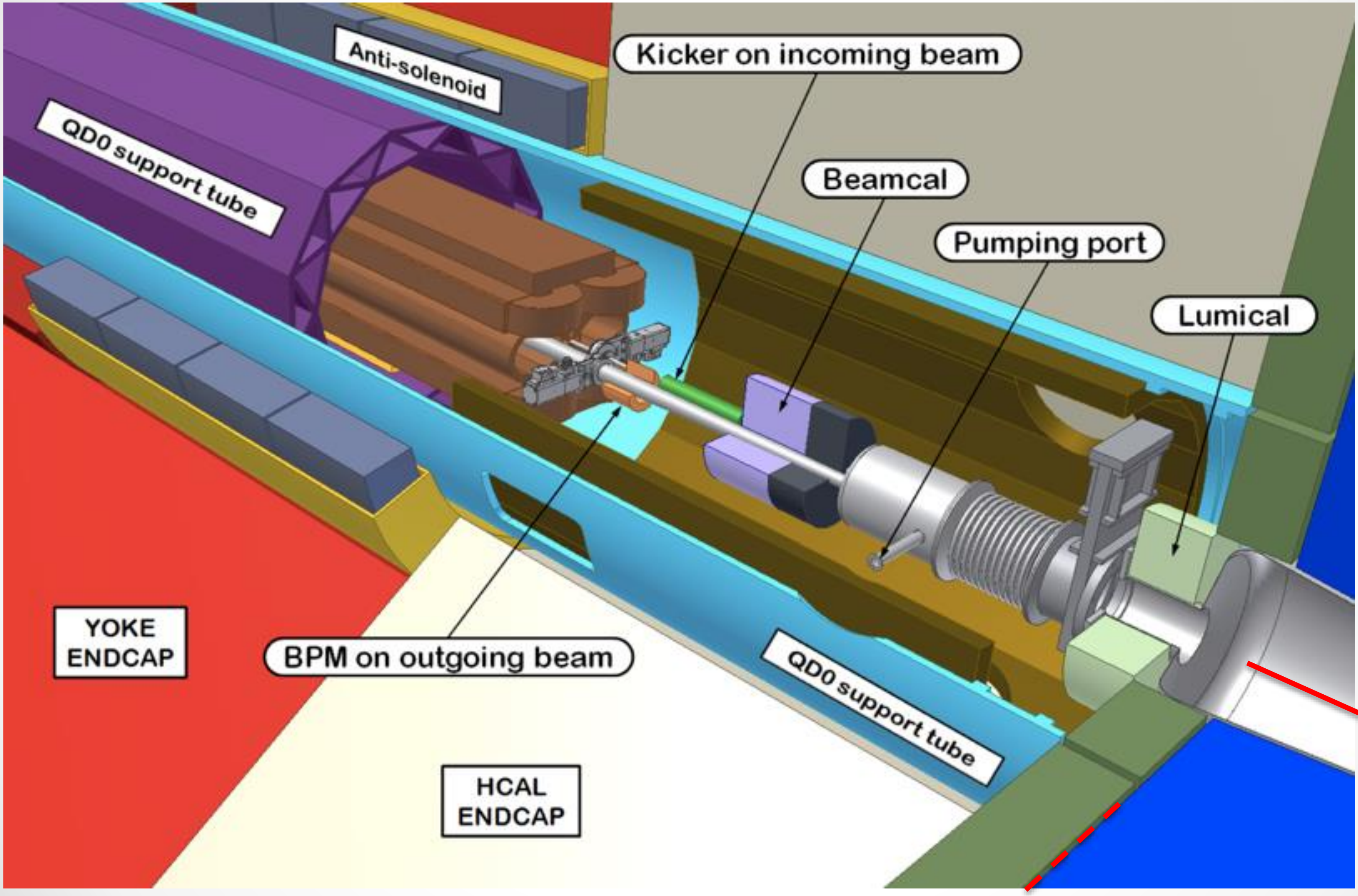
Strong solenoid magnet, 4 Tesla

Fine grained calorimetry for **Particle Flow (PFA)**, Depth: 1 + 7.5 λ_I

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

Ultra low-mass vertex detector with ~25 µm pixels

(Older) Forward region layout



towards interaction point

z = 2.3 m

Comparison CLIC/LHC Detector

In a nutshell:

CLIC detector:

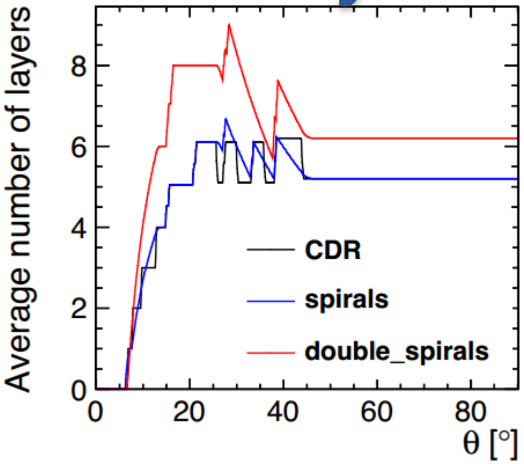
- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (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**

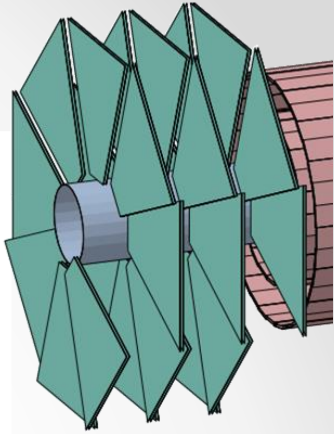
LHC detector:

- **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**

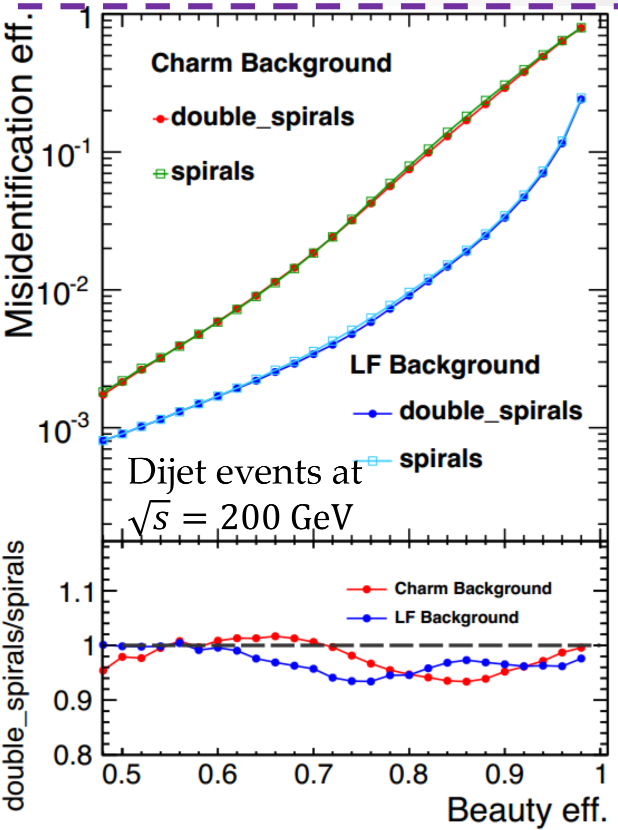
Vertex Detector: double layers

- 0.18% X_0 per double-layer in simulation
- Spiral Geometry (better airflow)
- Barrel: 5 single-layers ⇒ 3 double-layers
- Endcap: 4 single-layers ⇒ 3 double-layers

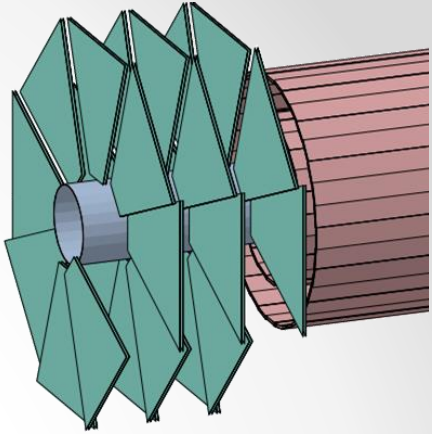




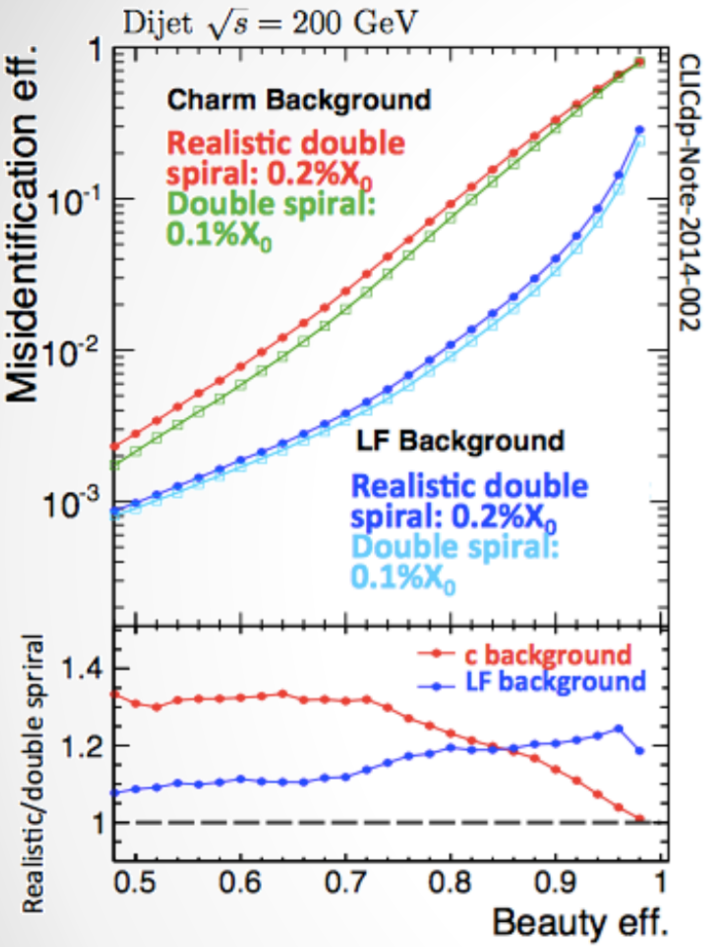
- Estimate changes in performance due to layout by studying the **flavor-tagging performance** (N. Alipour Tehrani, P. Roloff [2])
- *b*-quark misidentification as a function of *b*-quark Identification efficiency with a background rich in *c*-quarks (Top lines) or **L**ight-**F**lavored quarks (bottom lines). Similar study performed for *c*-tagging
- Lower panel shows ratio of double-layer over the single-layer geometries
  - **Almost the same as single-layer layout**



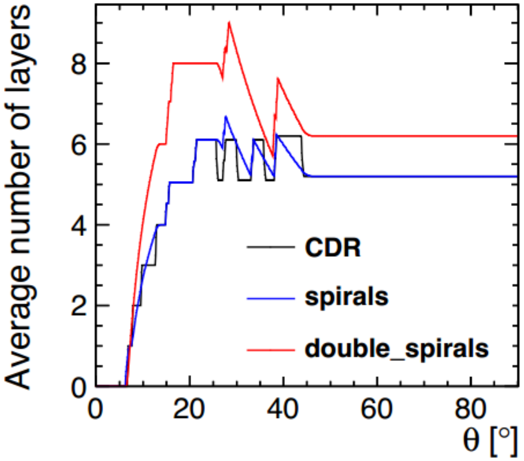
Vertex Detector Optimization



Spiral Geometry
(better airflow)



Effect of extra material:
Ratio > 1 means worse performance for more material



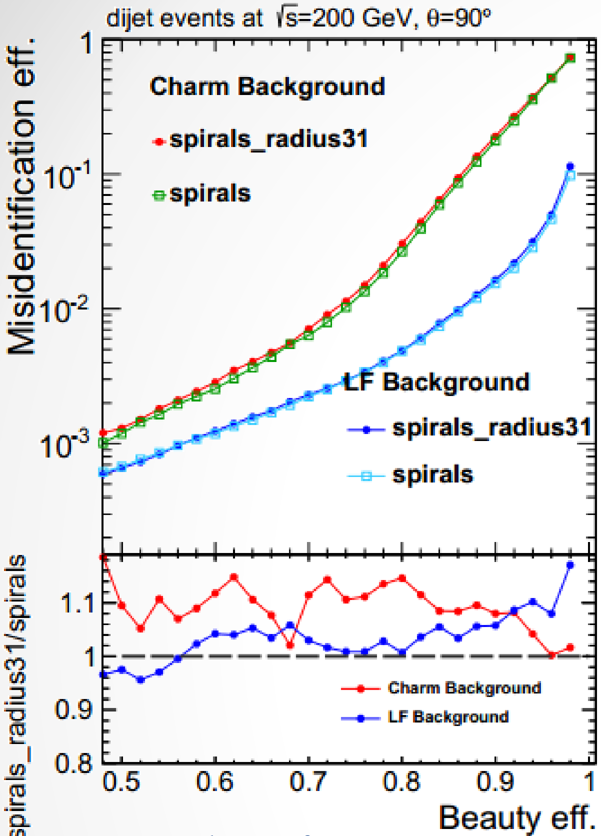
Use flavor tagging as a gauge in various tests:

1. **Effect of material (most significant effect on performance)**
2. Test single vs. double layers
3. Vary inner radius (for 4 T or 5 T B-field)

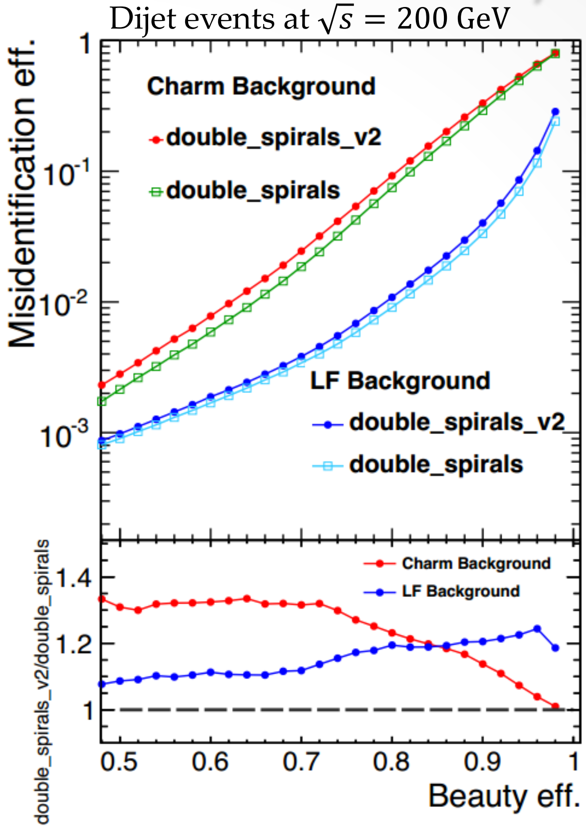
In the new detector model: Use double layers with spirals and modules with $0.2\% X_0$ per (single) layer, $R_{in} = 31$ mm

(N.Alipour Tehrani, P. Roloff [2])

Vertex Detector : Effect of Inner Radius /Material



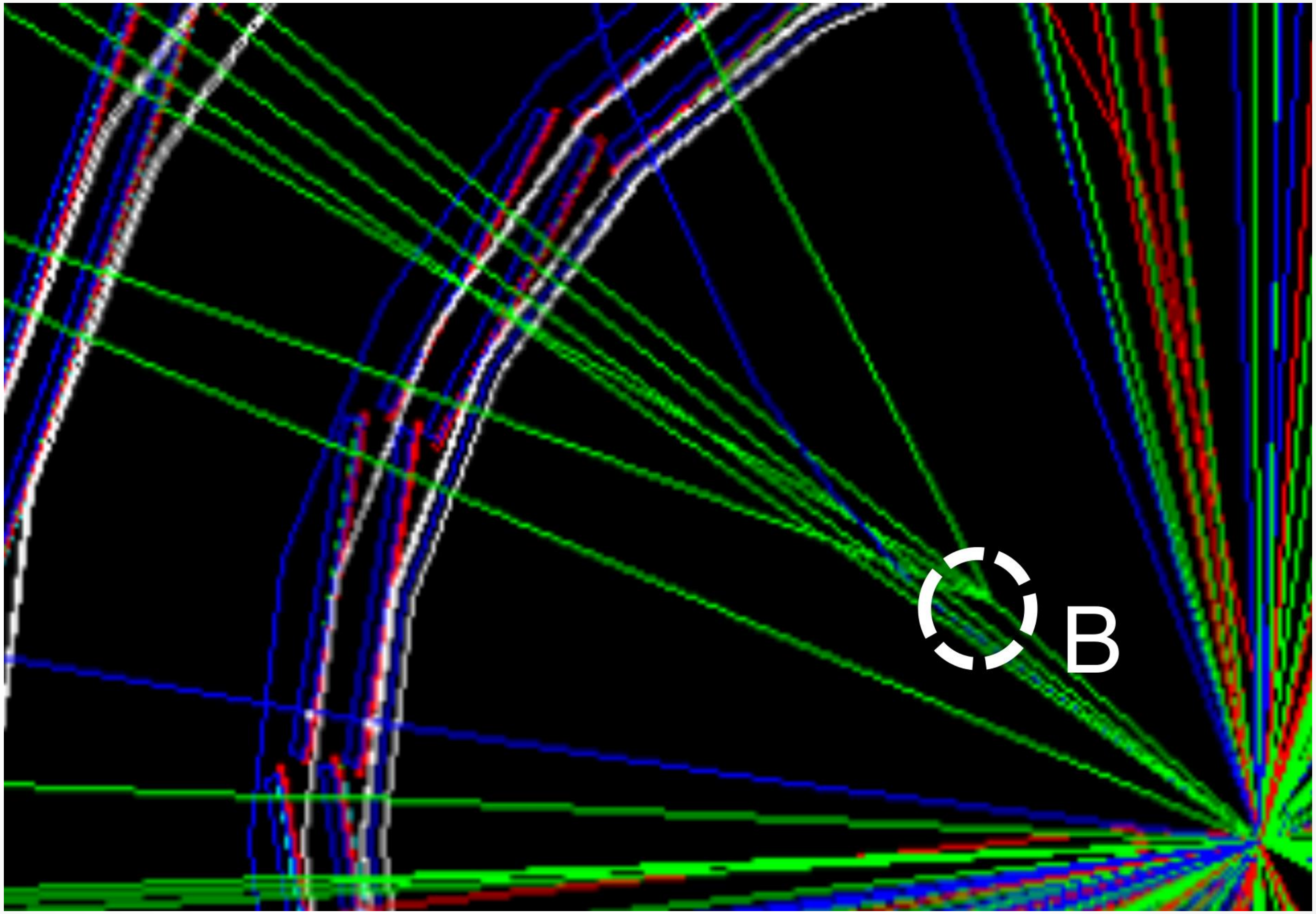
(N.Alipour Tehrani, P. Roloff [2])



- Inner Radius from 27 mm to **31 mm**
- Compensates for increase in the rate of Incoherent e-pair background if B-field is reduced
- **Small effect in flavor-tagging performance**

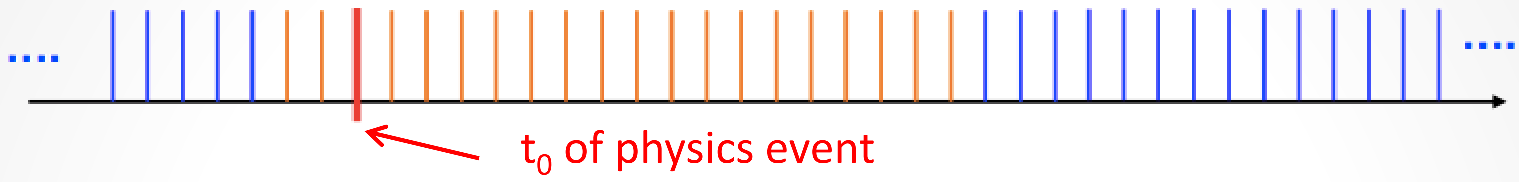
- Double-layer modules were simulated with twice as much material
- Extra material leads to undesirable increase of fake rate

In the new detector model: Use double layers with spirals and modules with $0.2\%X_0$ per (single) layer


B

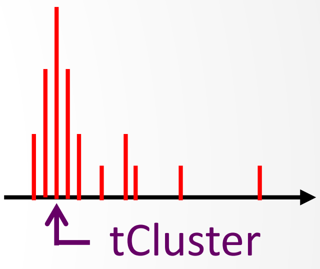
Background Suppression

Triggerless readout of entire train:



- Identify t_0 of physics event offline
  - Correct for shower development and TOF, define reconstruction window around t_0
  - Pass all calorimeter hits and tracks within window to reconstruction

→ Obtain physics objects with precise p_T and cluster time information



- Then apply cluster-based timing cuts
  - Cuts depend on particle type, p_T and detector region

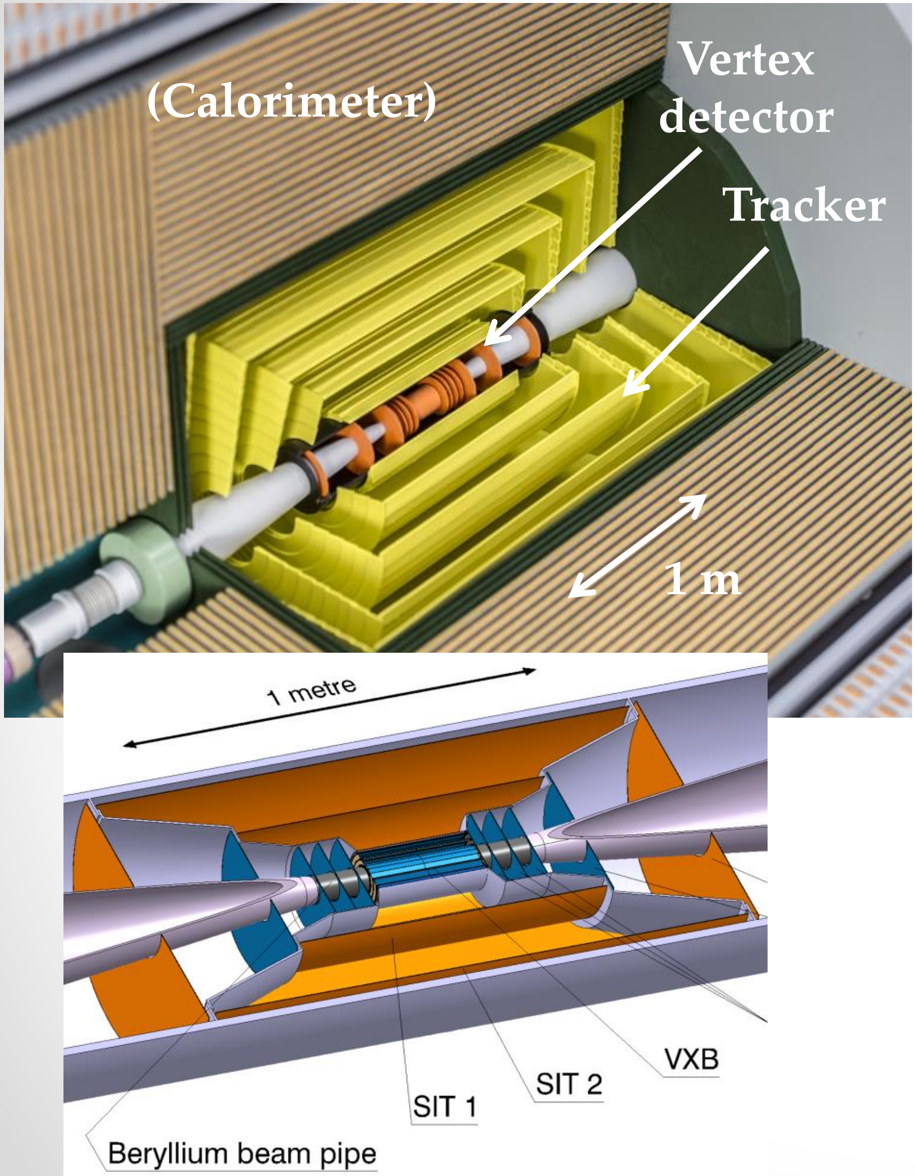
→Protects high-p_T physics objects

- **Also**: use hadron collider-type jet algorithms (*FastJet*)

General Requirements on Detector Technologies

- **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
  - Background suppression
    - Need **high-granularity calorimetry**
    - $\mathbf{1\ ns}$ accuracy for calorimeter hits
    - $\sim\mathbf{10\ ns}$ hit time-stamping in tracking
  - Low duty cycle
    - Triggerless readout
    - Allows for **power pulsing**
      - less mass and high precision in tracking
      - high density for calorimetry

Vertex Detector (pixels)



Flavor tagging capabilities drive the design of the vertex detector

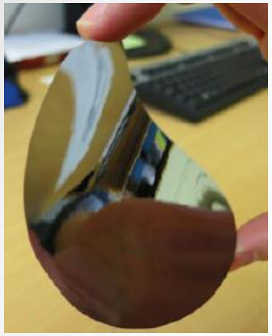
has to be extremely accurate and light !

- 2 billion pixels
- 3 μm single point resolution
- 25x25 μm^2 pixels (25 times smaller pixel area than 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/cm^2
  - Radiation level 10^4 lower than LHC

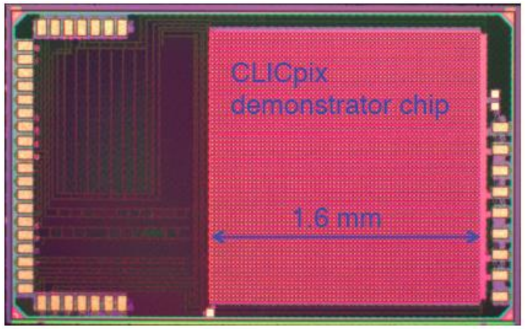
high-tech R&D covering several disciplines

Vertex Detector R&D

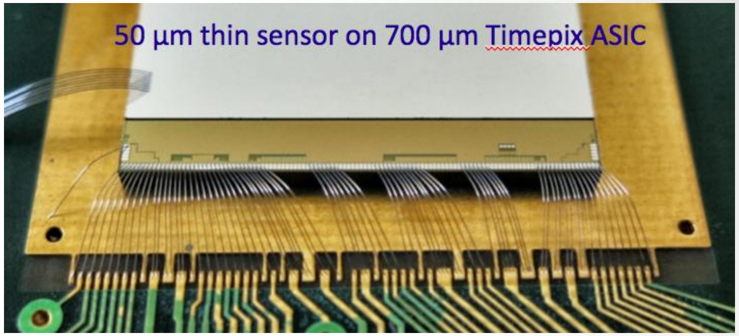
thin silicon sensor



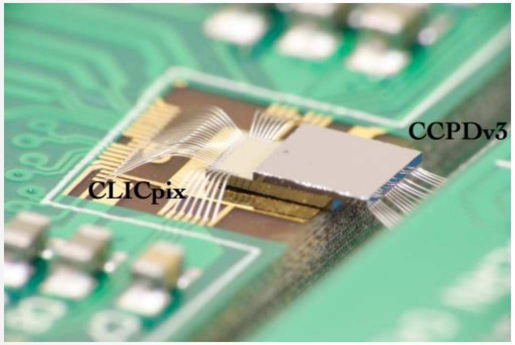
electronics chip (65 nm)



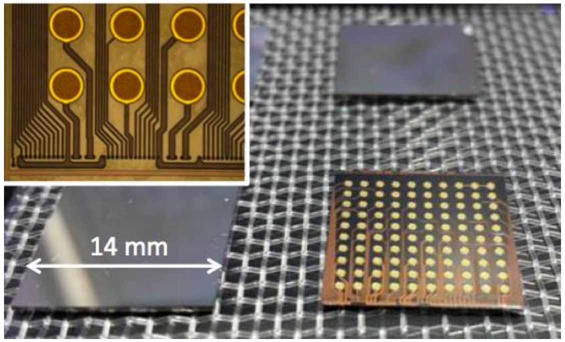
thin electronics + sensor assembly



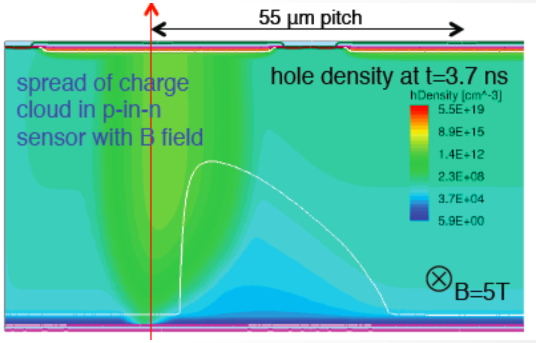
HV-CMOS sensor + CLICpix



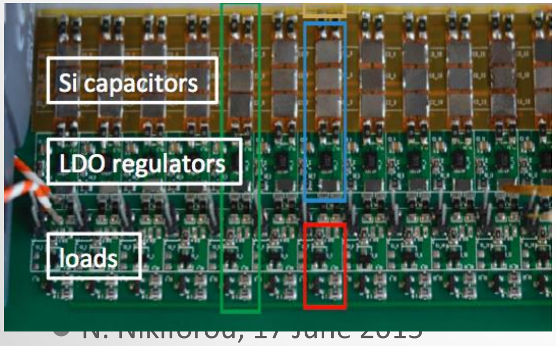
interconnect technology



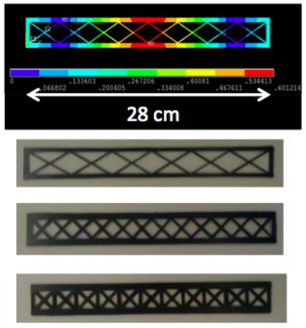
signal simulations



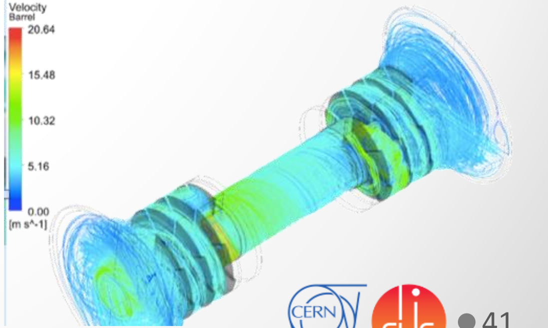
power delivery + pulsing



thin supports



air cooling simulations/tests



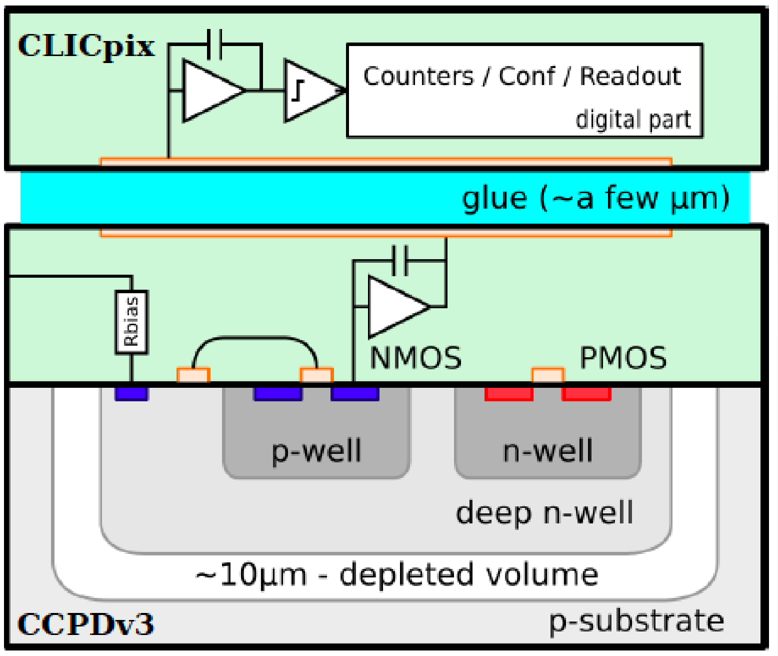
Hybrid Vertex Detector with HV-CMOS

Pursuing an alternative readout option

Hybrid option with High Voltage-CMOS:

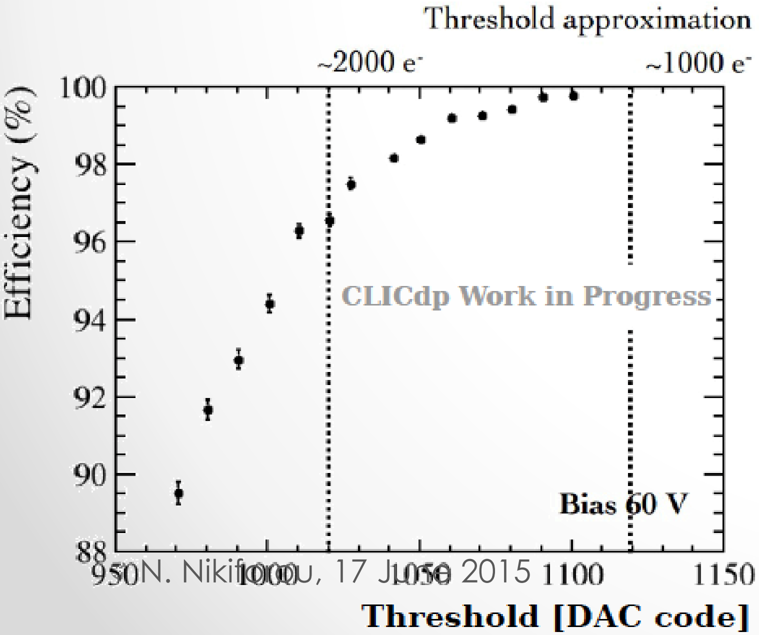
Capacitive Coupled Pixel Detector (CCPD)

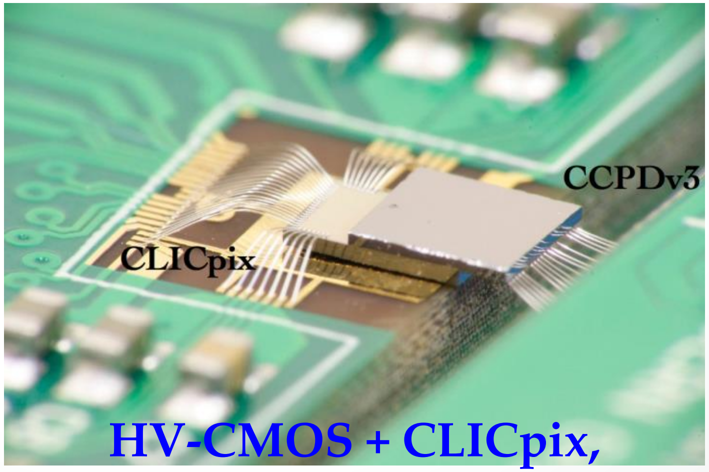
- HV-CMOS chip as integrated sensor + amplifier
- Capacitive coupling to CLICpix readout chip through layer of glue ⇒no bump bonding



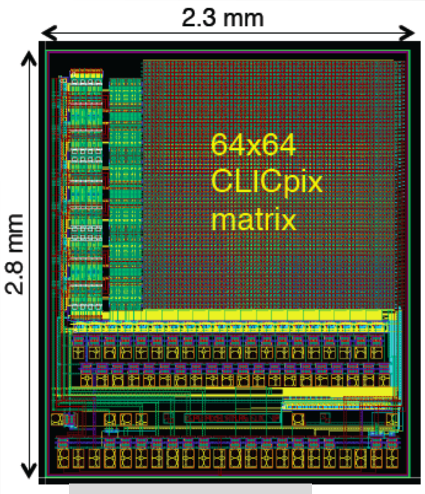
Status: successful initial beam tests in 2014

Further beam tests in 2015





HV-CMOS + CLICpix, AC coupled



CCPDV3

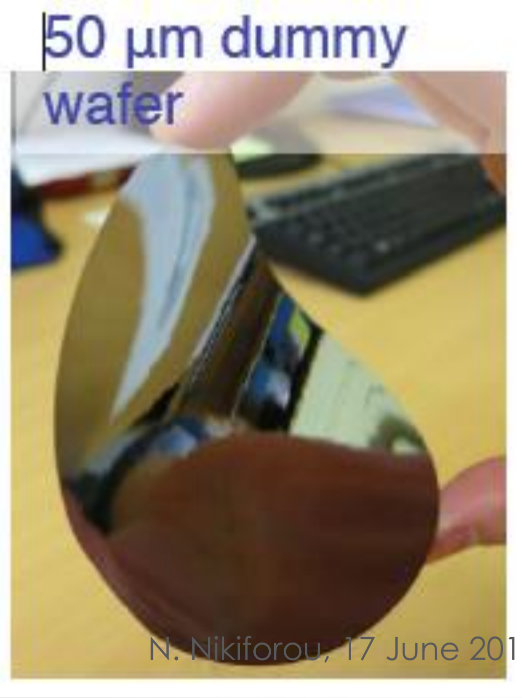
CLIC Vertex Detector R&D Roadmap

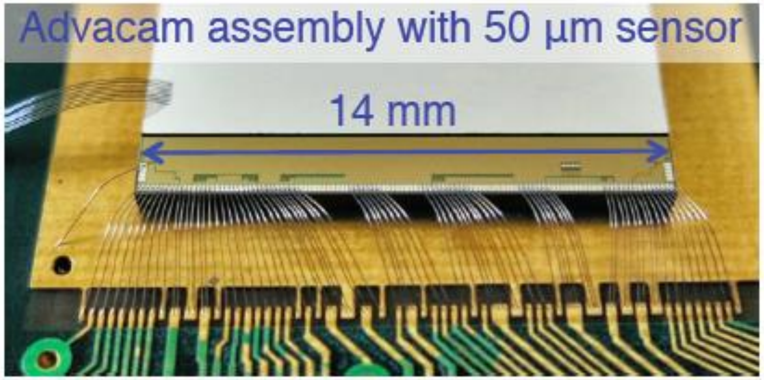
Hybrid approach pursued: (<= other options possible)
- Thin (~50 μm) silicon sensors
- Thinned high-density readout ASIC (50 μm)
  - R&D within Medipix/Timepix effort
- Low-mass interconnect
- Power pulsing
- Air cooling

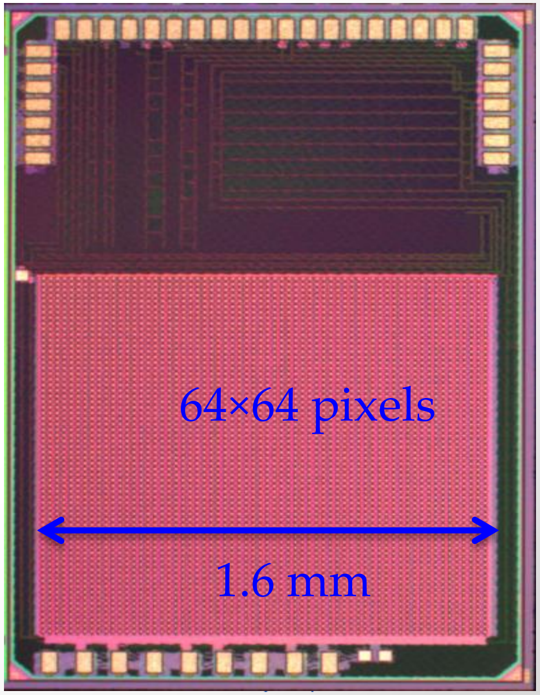
CLICpix demonstrator ASIC

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

⇩







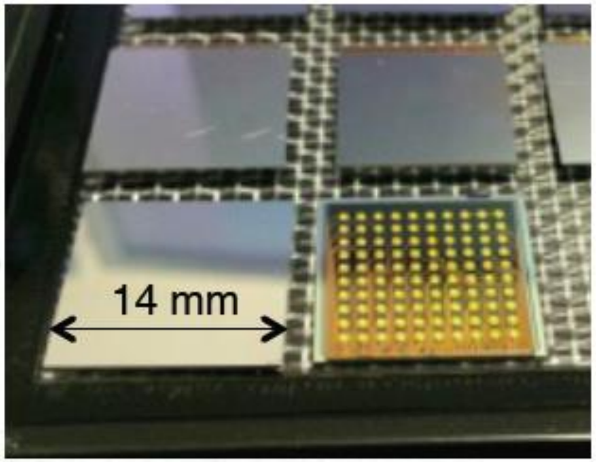
Very thin sensors !

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

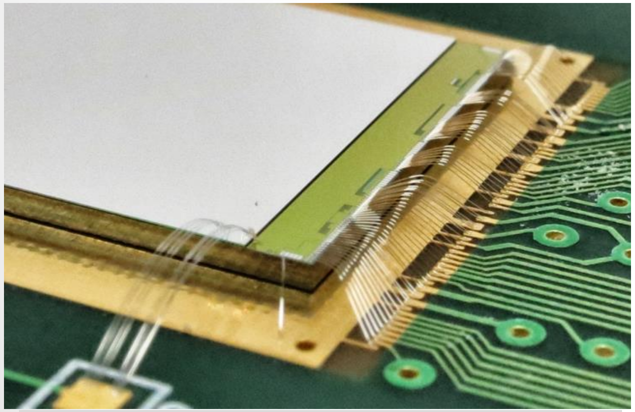
CLIC vertex detector: thin assemblies

Ultimate aim:

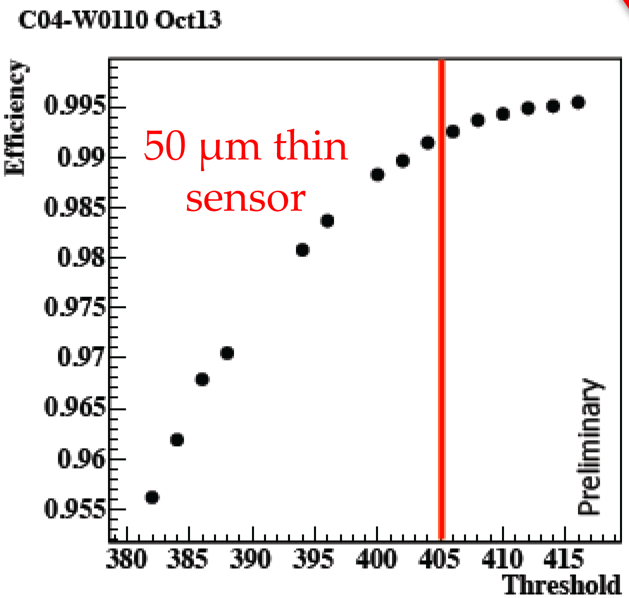
- 50 µm sensor on 50 µm ASIC
- Slim-edge sensors
- Through-Silicon Vias (TSV)
  - eliminates need for wire bonds
  - 4-side buttable chip/sensor assemblies
  - large active surfaces => less material



Medipix3RX with TSV by (CEA-LETI)



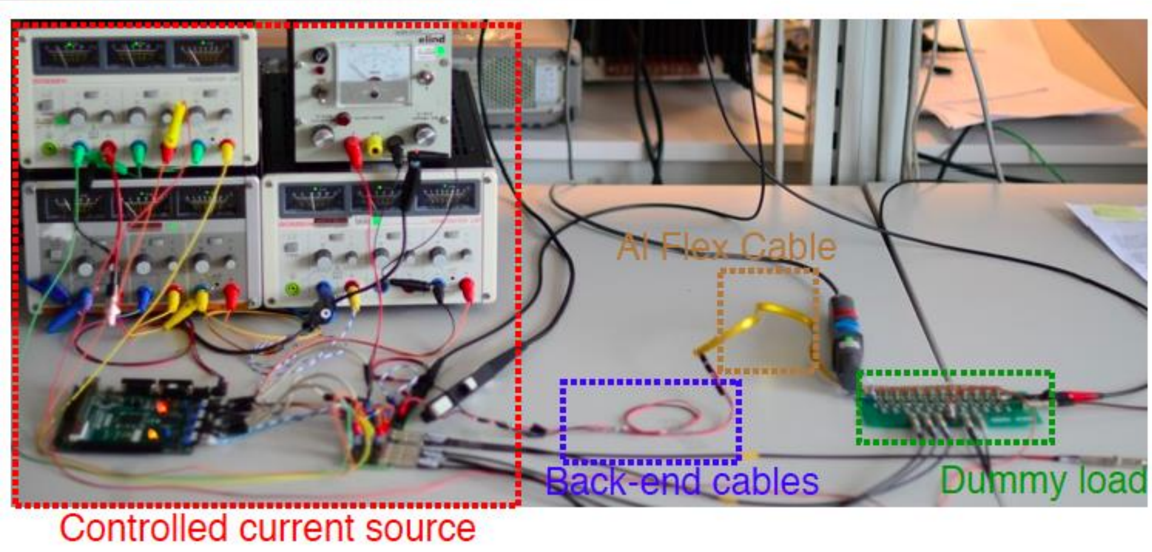
50 µm thin sensor on Timepix tested at test beam !



99.2% eff. at operating threshold

First successful picture using Medipix3RX with TSV

CLIC Vertex R&D: Power Pulsing



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)

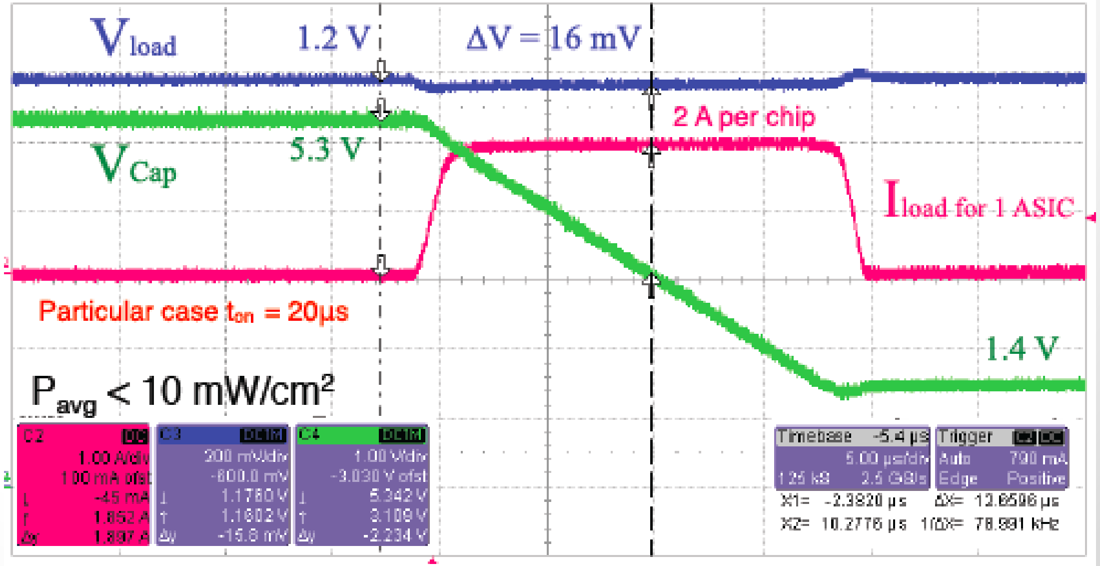
Analog:

- Voltage drop ~16 mV
- Measured average power dissipation <10 mW/cm²

Digital

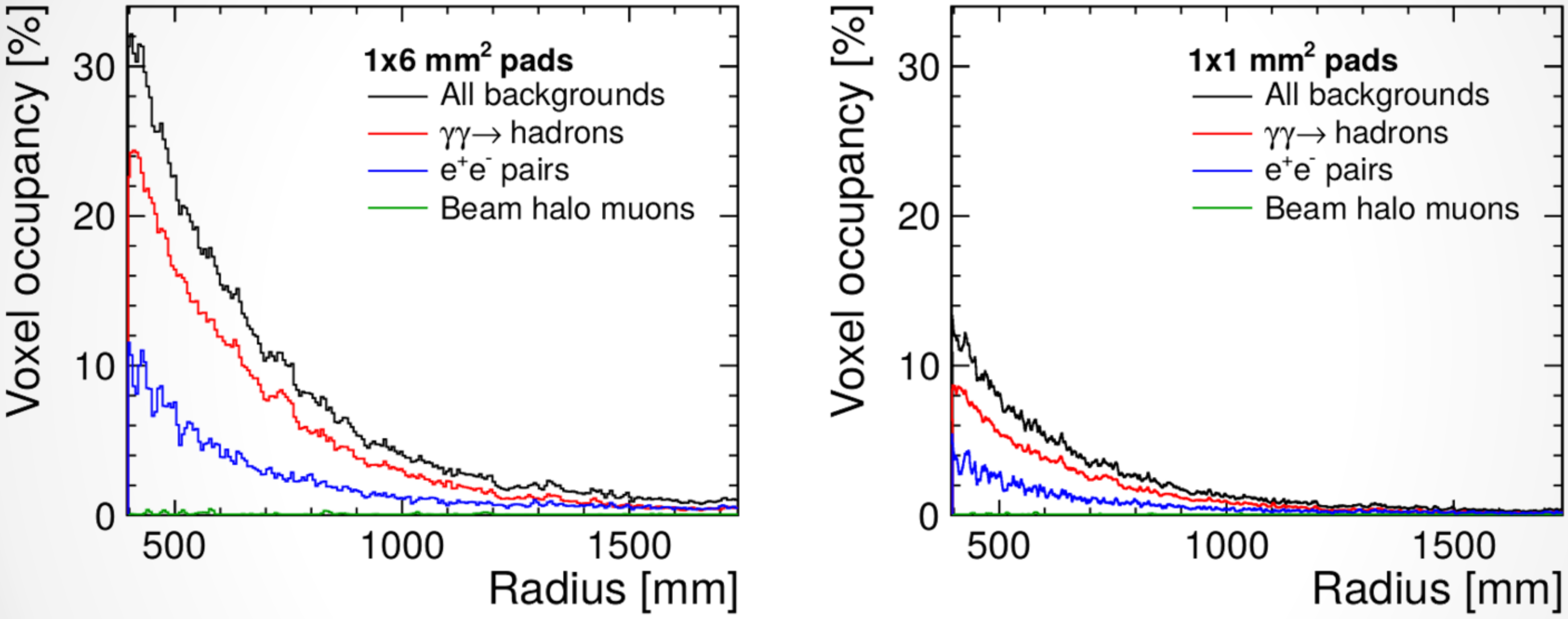
- Voltage drop ~70 mV
- Measured average power dissipation <35 mW/cm²

Total dissipation <50 mW/cm²



TPC Occupancy in CLIC_ILD

From CDR. See also LCD-Note-2011-029 [11]



(a) Voxel occupancies for 1 × 6 mm^2 pads (b) Voxel occupancies for 1 × 1 mm^2 pads

Fig. 5.11: Voxel occupancies for different pad sizes, averaged per pad row in the TPC for particles originating from $\gamma\gamma \rightarrow$ hadrons, incoherent pairs and beam-halo muons. The data correspond to one complete bunch train and do not include safety factors.

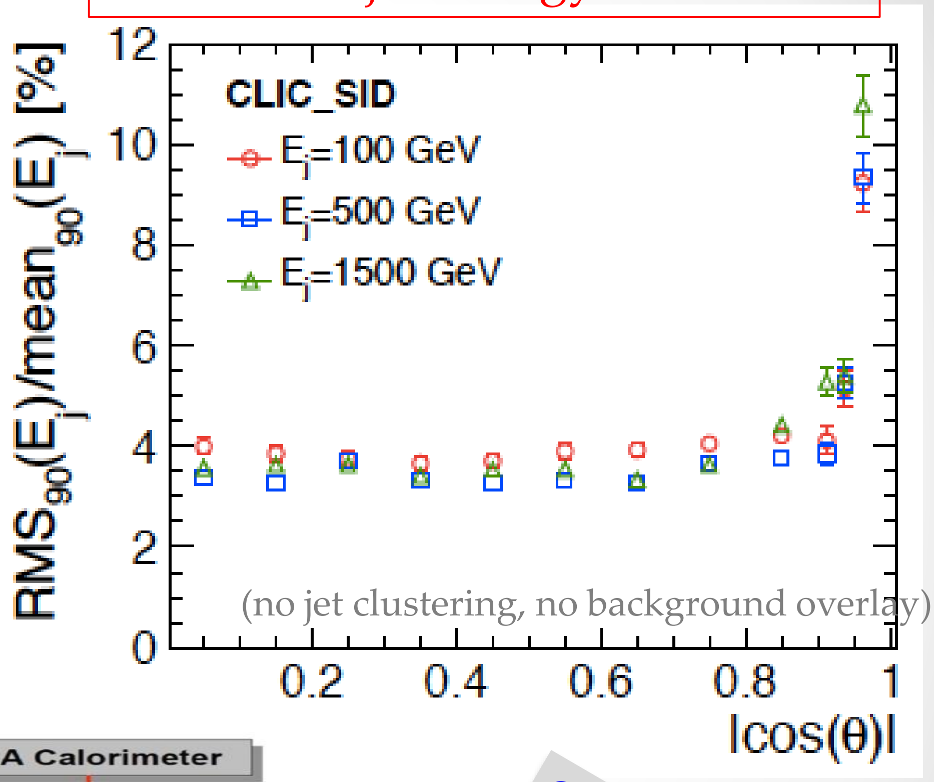
PFA Calorimetry at CLIC

Technology (CDR)

ECAL
Silicon (active) + Tungsten (absorber)
cell sizes ~25 mm^2
30 layers in depth (~23 X_0)

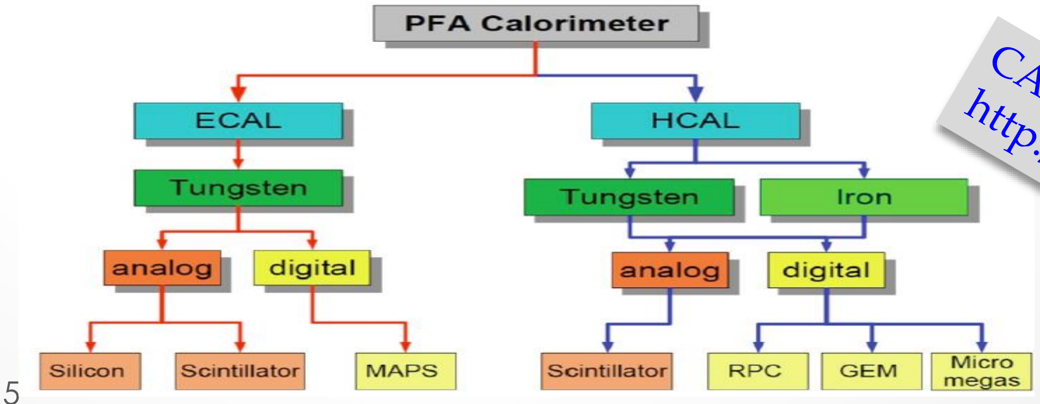
HCAL
Scintillator+SiPM (active)
Tungsten (barrel), steel (endcap)
cell sizes 9 cm^2 (analog)
75/60 layers in depth
Total depth 7.5 Λ_i

simulated jet energy resolution



(no jet clustering, no background overlay)

many technologies pursued

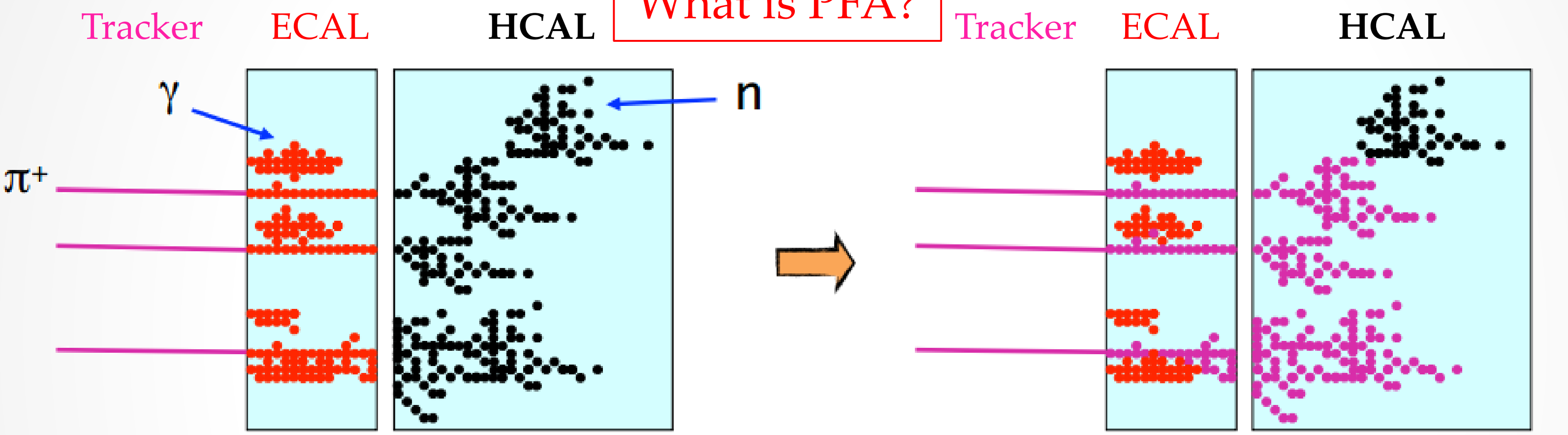


CALICE collaboration
http://fcal.desy.de/

Calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design
⇒ fine-grained calorimetry + Particle Flow Algorithm (PFA)

What is PFA?



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

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

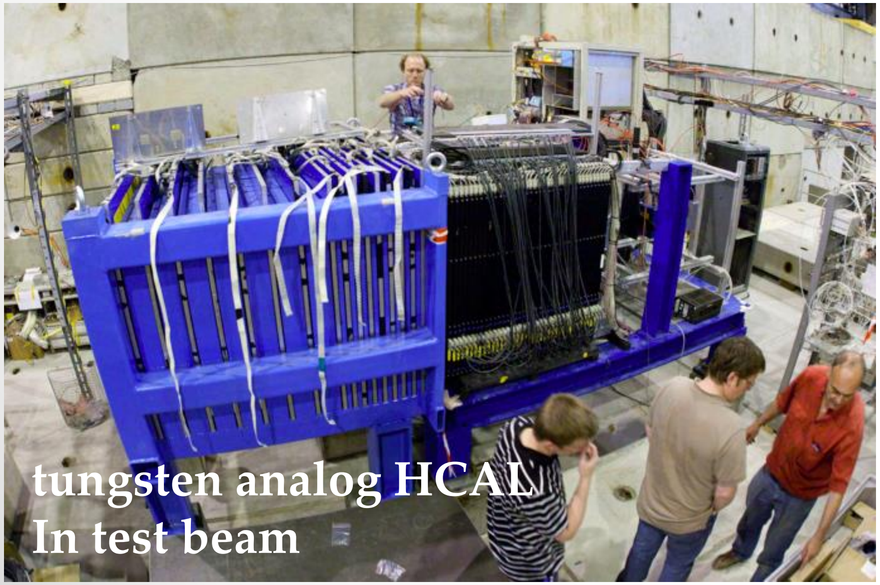
Always use the best info you have:
60% ⇒ tracker 🙂 🙂
30% ⇒ ECAL 🙂
10% ⇒ HCAL ☹

Hardware + software !

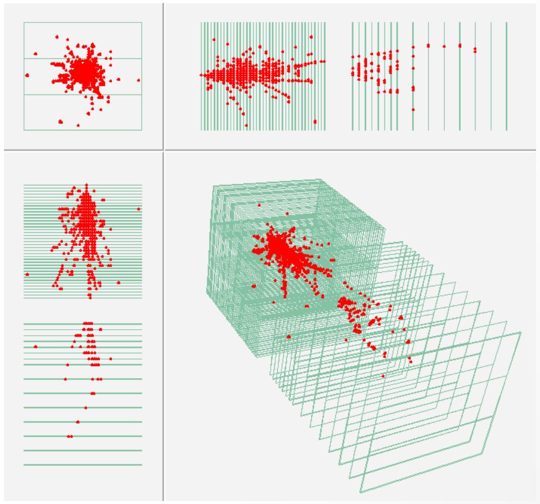
Calorimeter R&D

- **Developing high-granularity calorimeters**
  - ~80 million readout channels
  - (400x larger than LHC)
- To be used with Particle Flow Algorithm
- R&D in the framework of **CALICE** collaboration
  - Investigating different absorber materials, readout technologies and techniques

	# layers	**cell sizes**	**technology option**
ECAL	~25	5×5 mm^2	Silicon
HCAL	~60	3×3 cm^2	Scintillator + SiPM

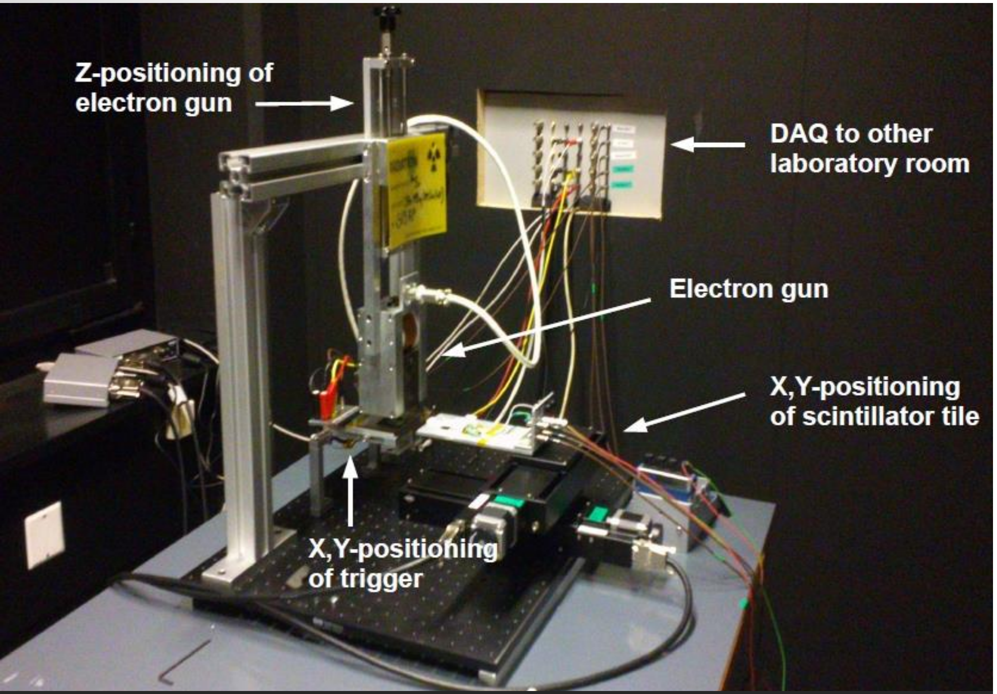


tungsten analog HCAL
In test beam

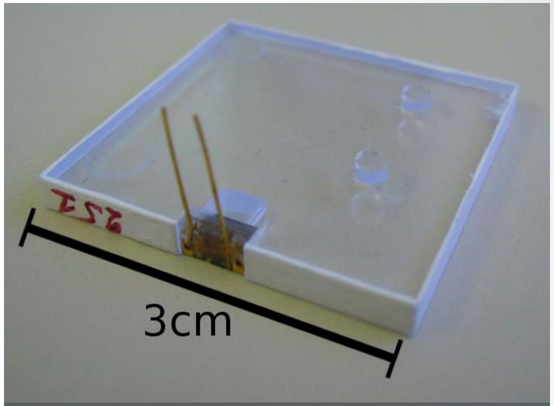


210 GeV π^- in tungsten-DHCAL

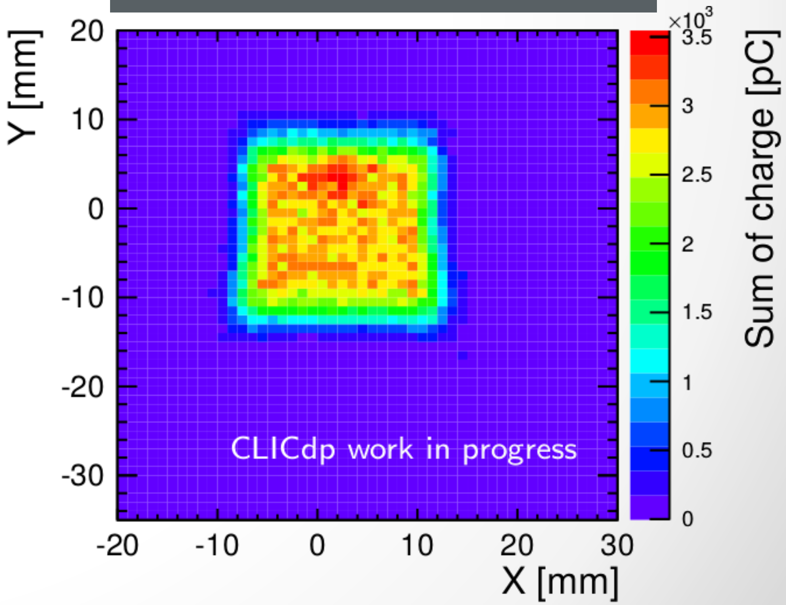
R&D on Scintillator+SiPM



Electron gun in AC-regulated dark room



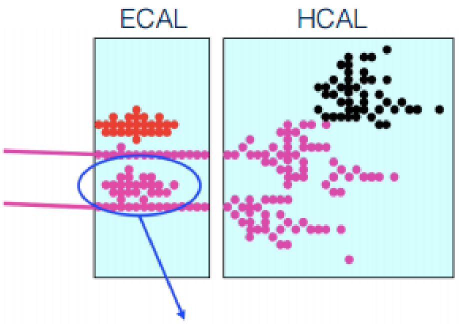
Scintillator Tile with mounted SiPM



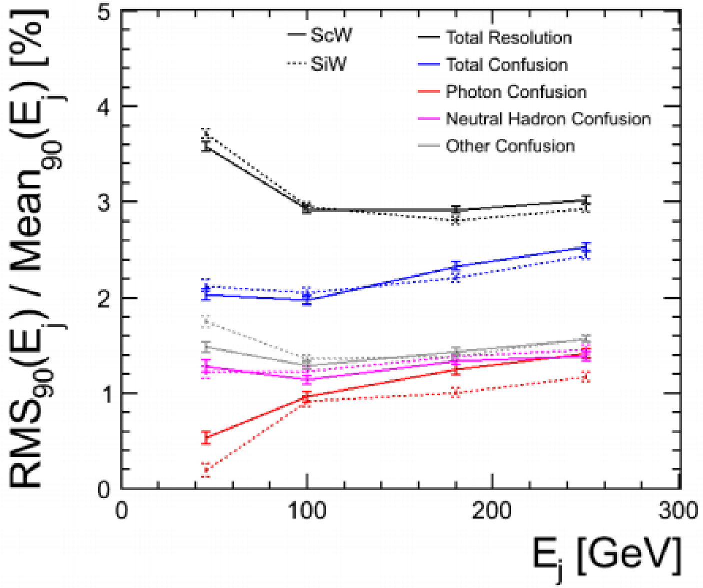
- Also have a dedicated lab at CERN for Scintillator + **Si**licon **P**hoto**M**ultiplier testing
- Test bench: **electron gun**, **D**evice **U**nder **T**est on movable table, trigger scintillators, read-out electronics
- Study response, uniformity, noise, cross-talk, ...

ECal Optimization (J.S. Marshall [12])

- **Starting point: 29 layers W absorber ($23X_0, 1\lambda_I$), 30 layers Si active medium (1 pre-sampler), divided into $5\text{x}5\text{mm}^2$ pixels.**
- Particle flow means performance depends critically on pattern-recognition, not just intrinsic ECAL energy resolution.
- Granularity requirements and use of Si make ECAL expensive: consider scintillator (Sc) with SiPM readout as active medium.
- Examined wide range of ECAL models, developing detailed understanding of resulting **jet energy resolutions.**



Failure to separate photons from nearby charged hadrons: **"photon confusion"**



Jet energy resolution:

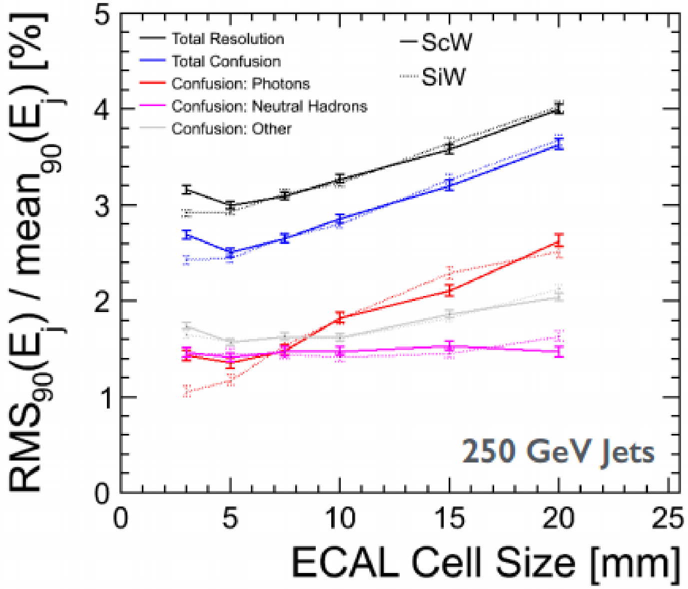
Total resolution

Total confusion

Photon

Neutral hadron

Other

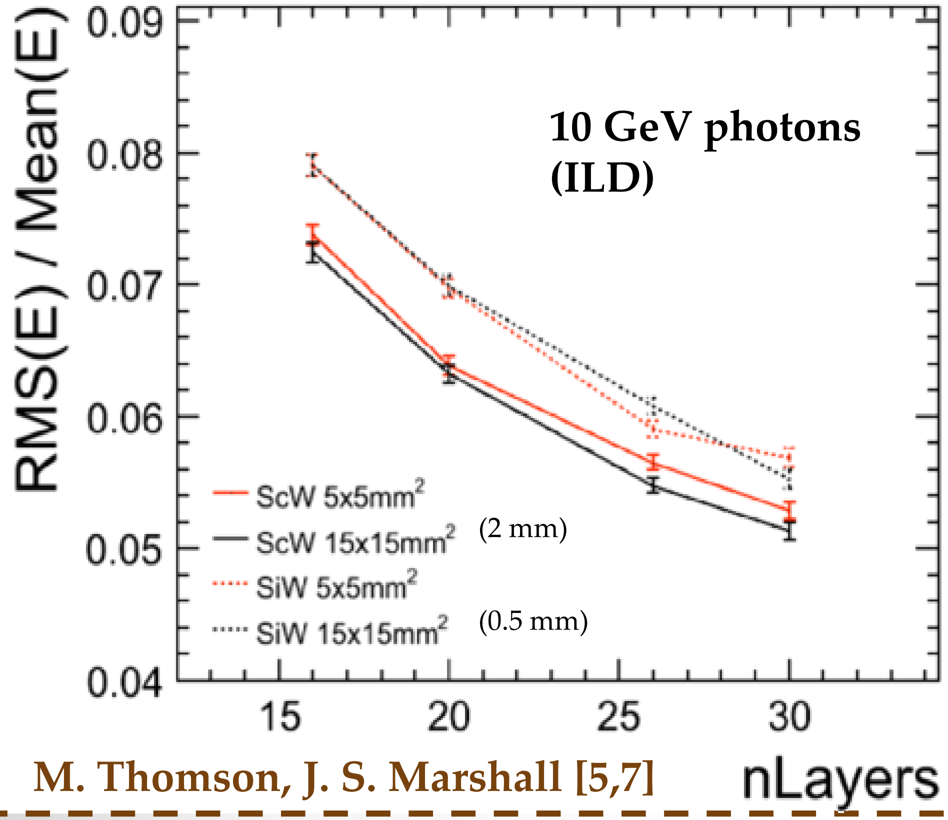


[51]

ECal Optimization: Active Material, Number of Layers, Granularity

ILD-based baseline model: **SiW ECal with 29 layers** (23 X_0 / 1 λ_I):

- Tungsten absorber: **20x2.1 mm + 9x 4.2 mm**
- Silicon Active material, **500 μm** thickness, **5x5 mm^2** cells



M. Thomson, J. S. Marshall [5,7]

- Scintillator instead of silicon may give a slightly better resolution
  - Depends on active element thickness
  - Also considered Si/Sc combinations
- **Stronger dependence on number of layers ($\sim 1/\sqrt{N}$)**

Forward Calorimetry

R&D performed within the FCAL collaboration

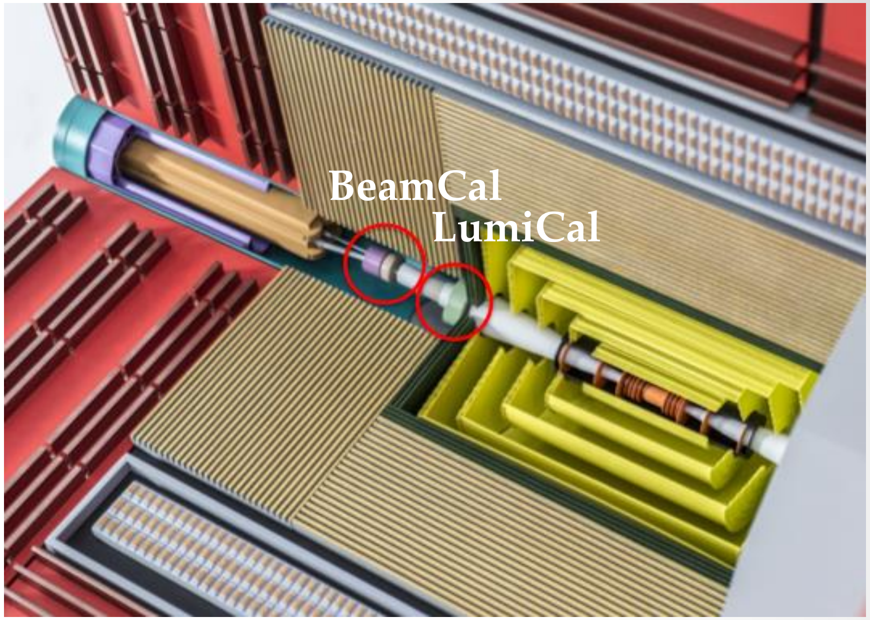
2 forward calorimeters:

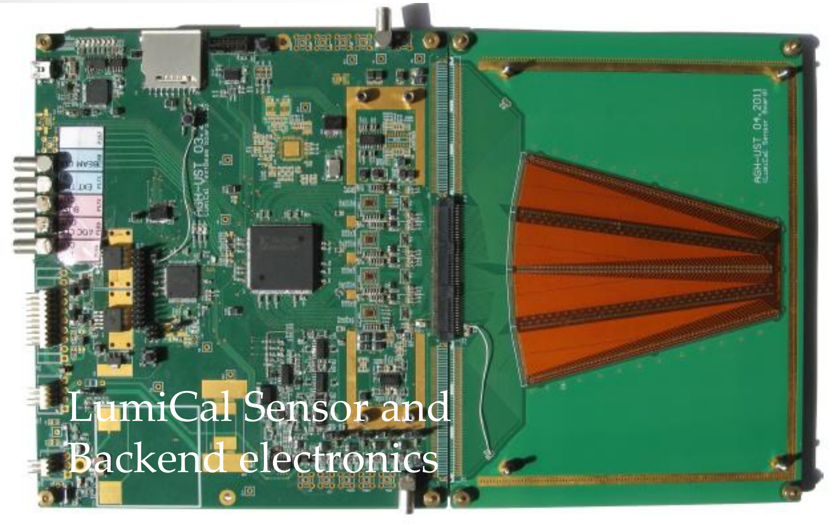
- **LumiCal + BeamCal**
- **Electron / photo**n acceptance to small angles
- Luminosity measurement
- Beam feedback

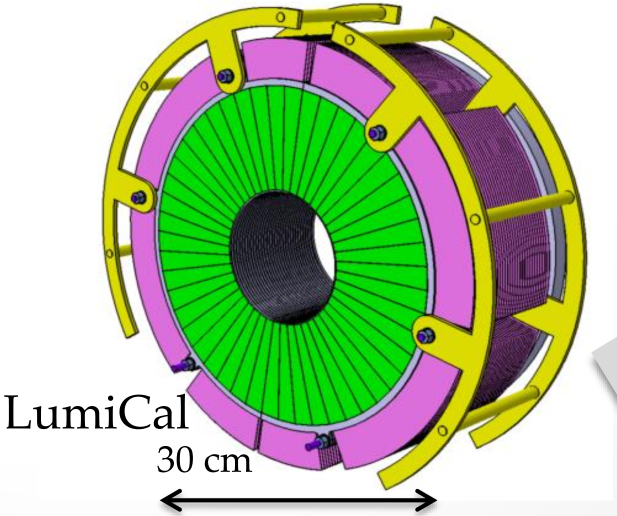
Absorbers: tungsten, 40 layers of 1 X_0
Sensors: BeamCal GaAs, LumiCal silicon

Angular coverage:
BeamCal 10 - 40 mrad, LumiCal 38 – 110 mrad

Doses up to 1 MGy
Neutron fluxes of up to 10^{14} per year





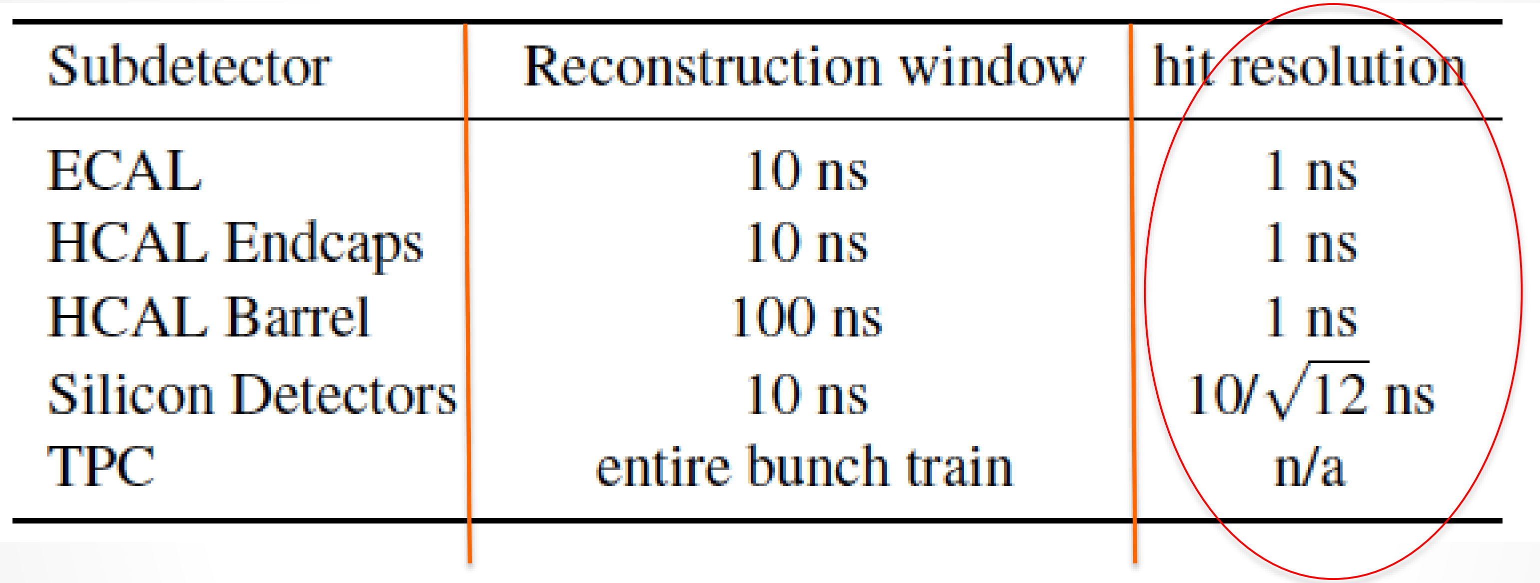


Very compact !

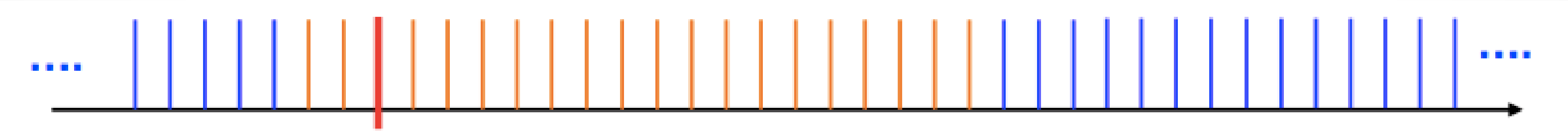
FCAL collaboration
http://fcal.desy.de/

Time window / time resolution

The event reconstruction software uses:



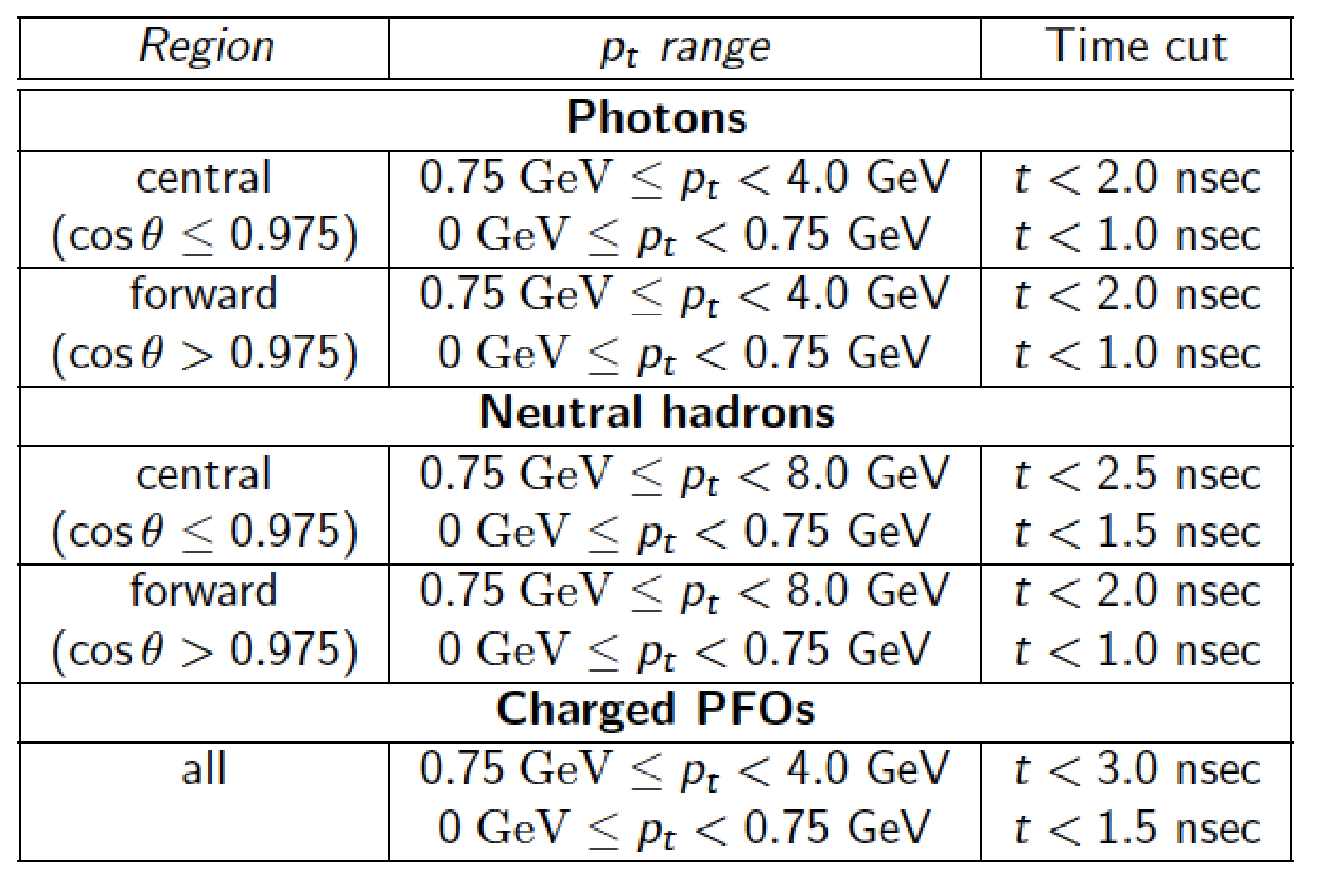
Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a



t_0 physics event (offline)

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

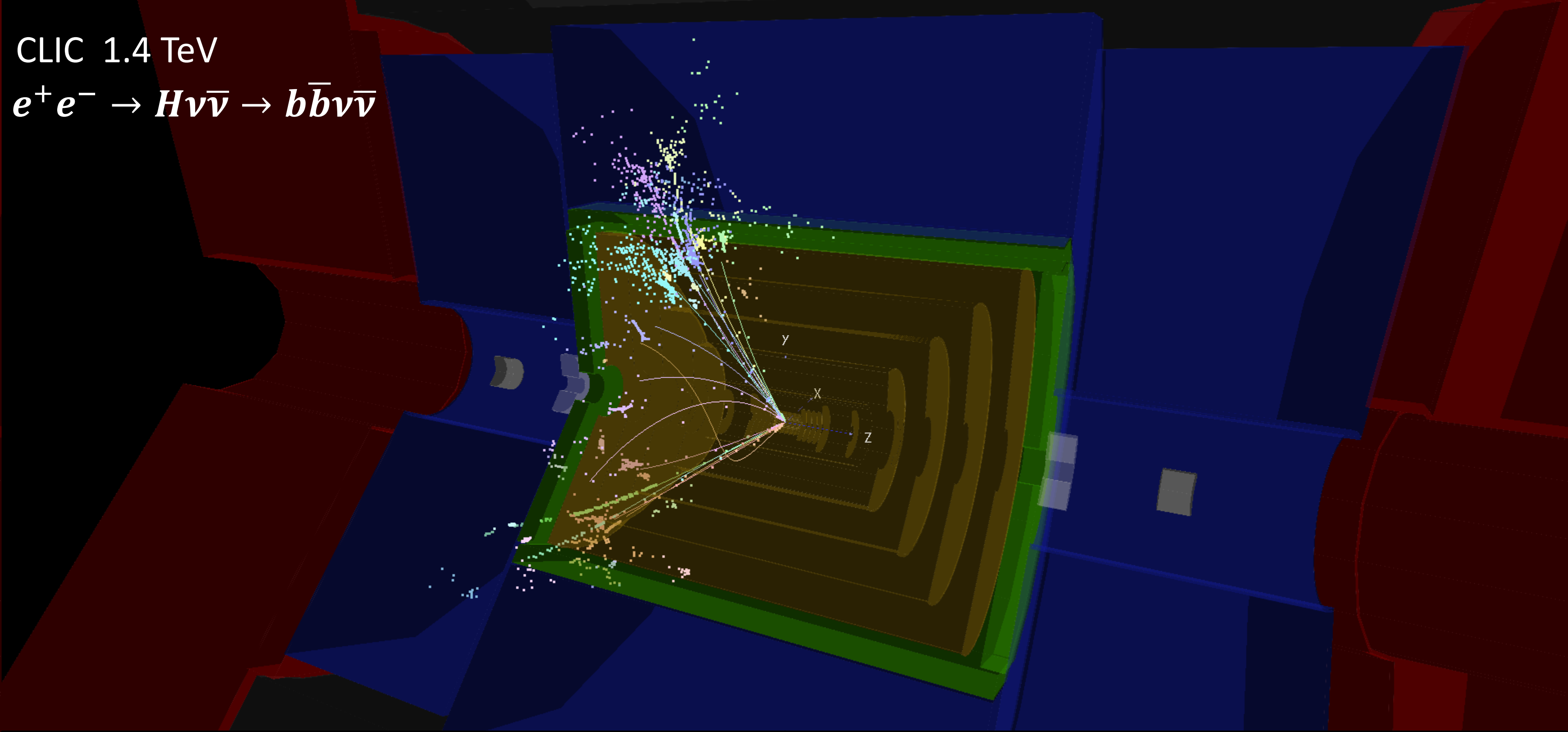
PFO-based Timing Cuts

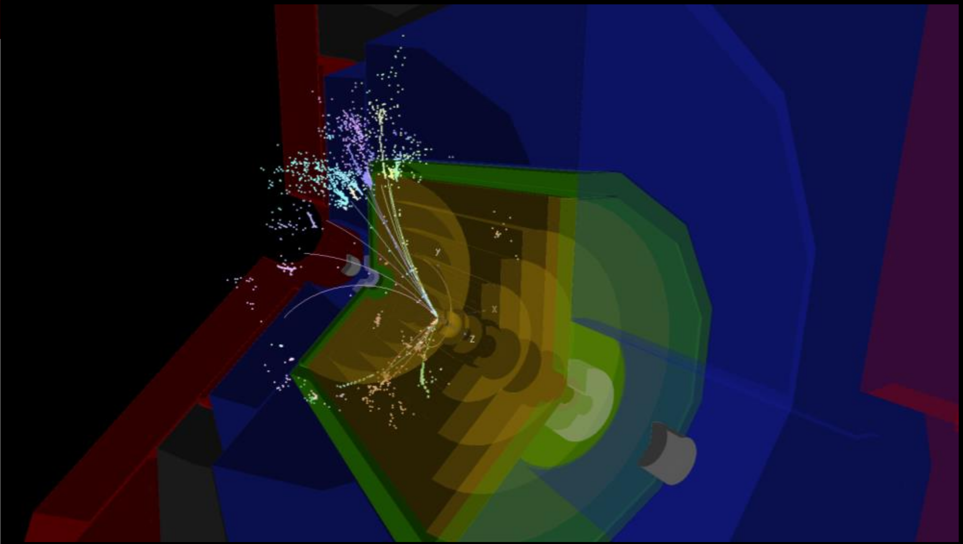


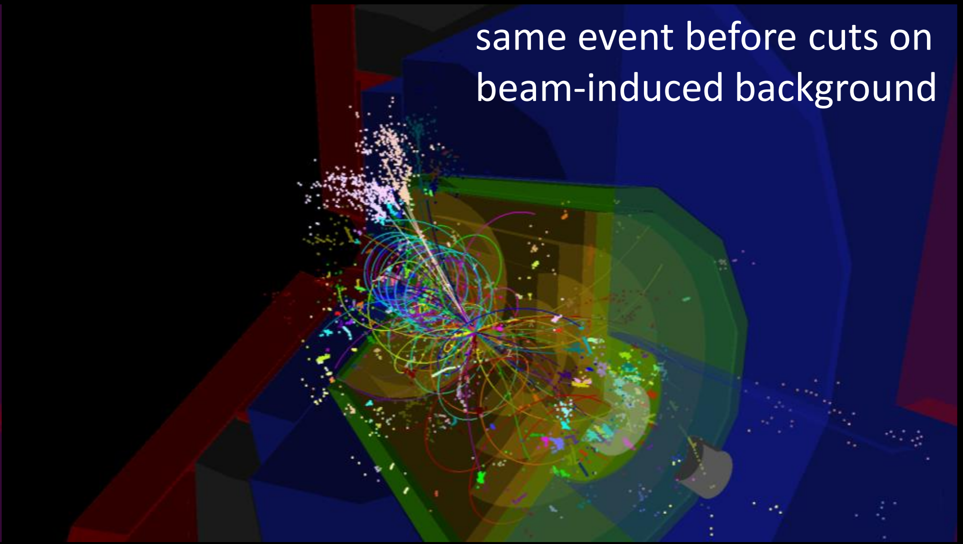
Region	p_t *range*	Time cut
	Photons	
central $(\cos\theta \leq 0.975)$	$0.75 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$ $0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
forward $(\cos\theta > 0.975)$	$0.75 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$ $0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 2.0$ 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 1.4 TeV

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



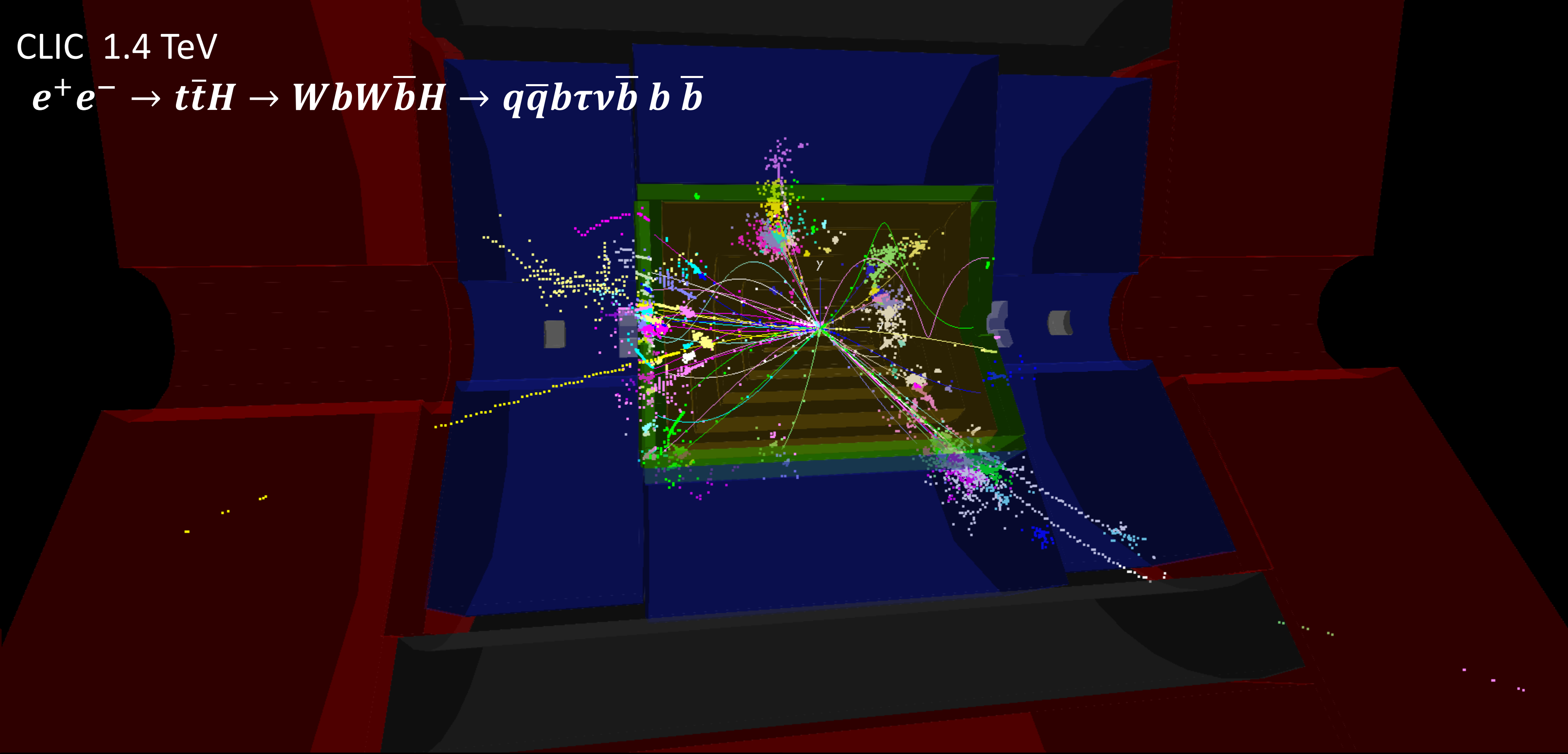


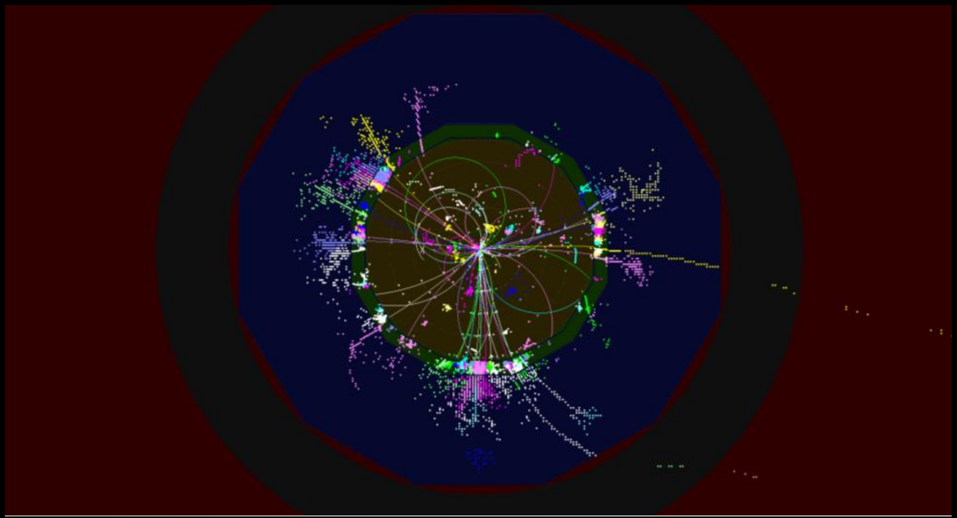


same event before cuts on beam-induced background

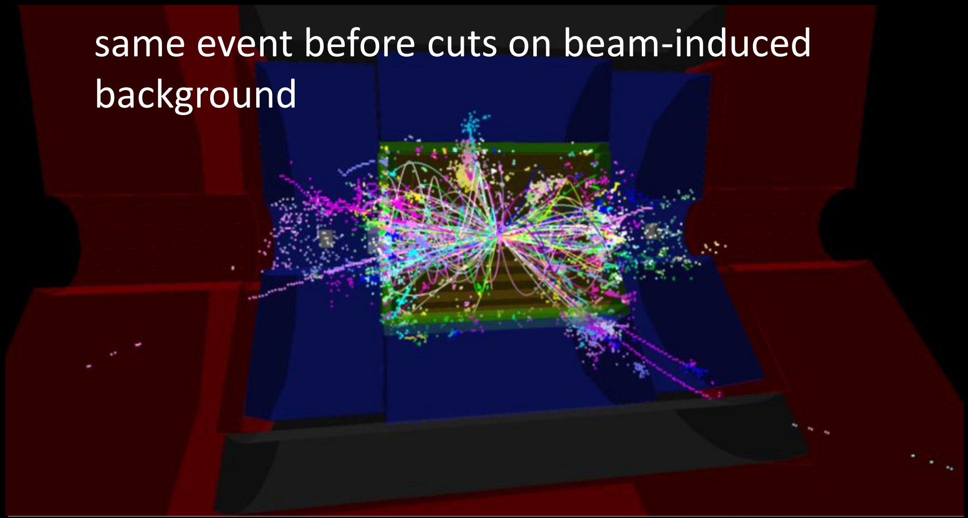
CLIC 1.4 TeV

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



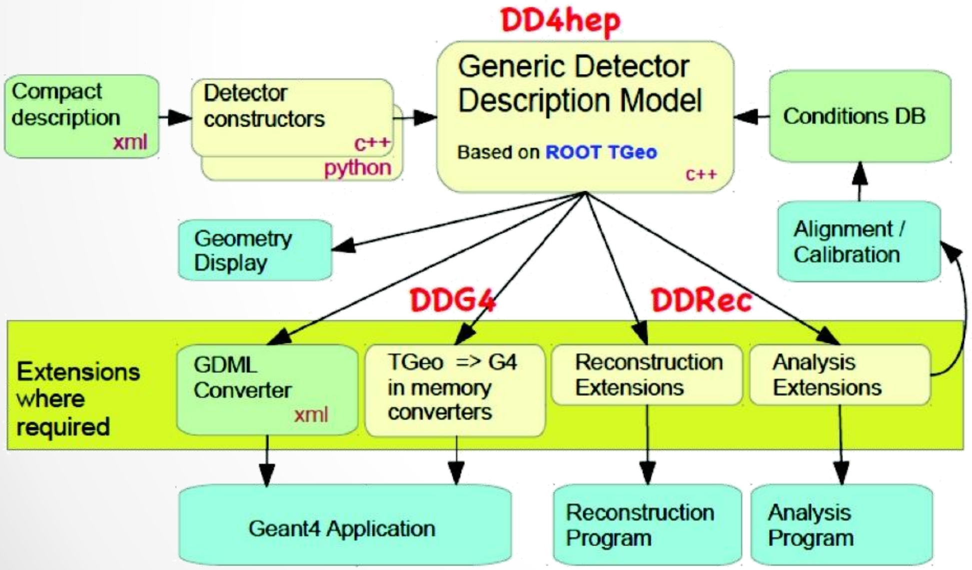


same event before cuts on beam-induced background



HEP Software Development

- Strong involvement with **simulation and reconstruction software** development in collaboration with ILC
- Developing and maintaining the **ILCDirac grid computing framework**
- Developing a **new Detector Geometry Description and Simulation Framework: Detector Description 4 HEP (DD4hep)**
    - **Will be used by others too: ILC, FCC, LHCb, …**



DD4hep

Generic Detector Description Model

Based on **ROOT TGeo**

c++

Compact description

xml

Detector constructors

c++

python

Conditions DB

Alignment / Calibration

Geometry Display

DDG4

DDRec

Extensions where required

GDML Converter

xml

TGeo => G4 in memory converters

Reconstruction Extensions

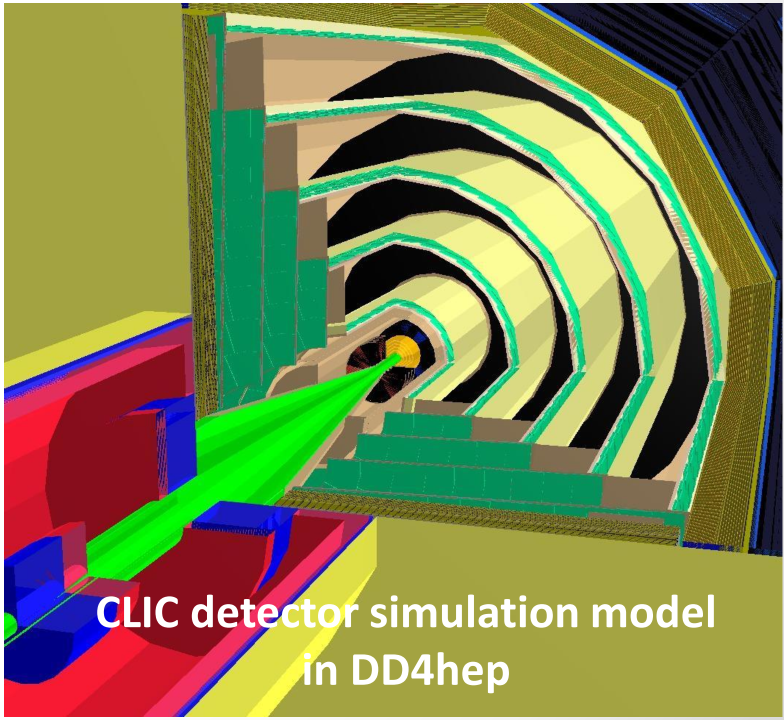
Analysis Extensions

Geant4 Application

Reconstruction Program

Analysis Program

Schematic overview of the DD4hep framework



CLIC detector simulation model in DD4hep