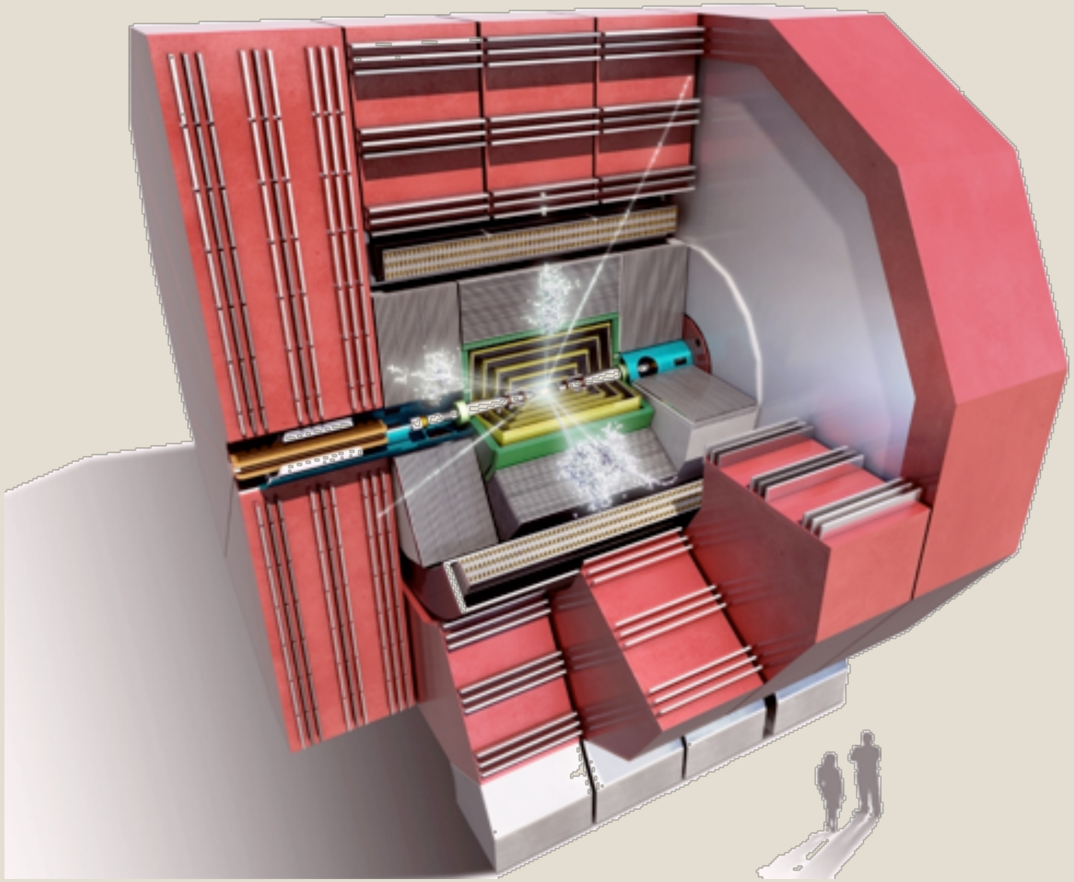
The CLIC Detector Concept
CLICdet_2015



Wolfgang Klempt CERN/EP
on behalf of the
CLICdp collaboration

10th FCC-ee physics workshop
5 February 2016

Outline

- Detector requirements
- Detector layout
- Vertex & tracker
- Calorimetry
- Simulation & reconstruction
- Remark on requirements for FCC-ee detector

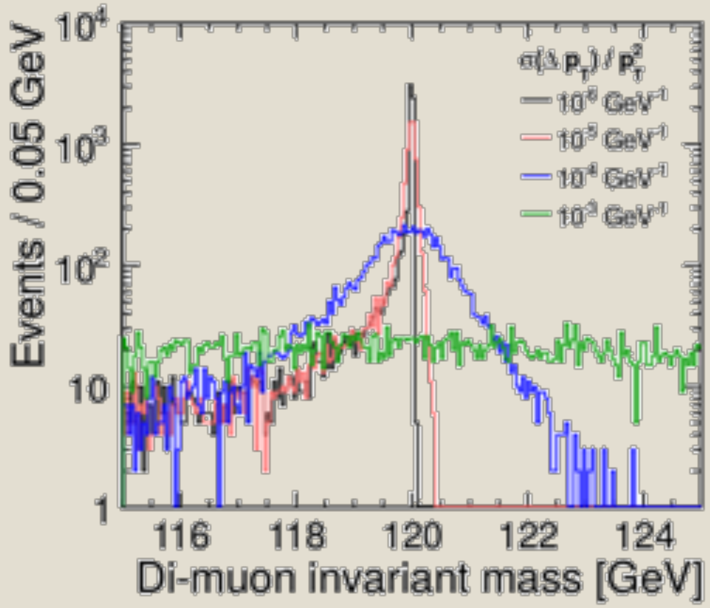
Detector Requirements

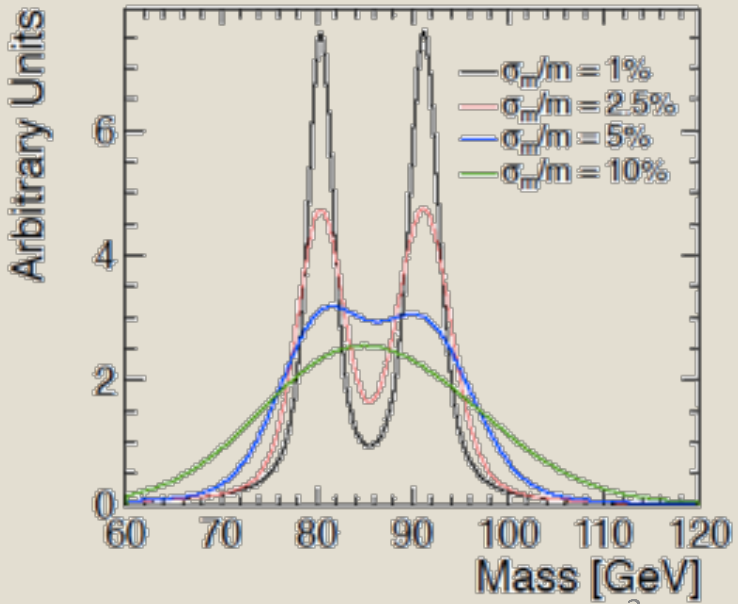
- Momentum resolution
  - Higgs recoil mass, smuon endpoint, **Higgs coupling to muons**

    $\rightarrow \sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\,\mathrm{GeV}^{-1}$
- Jet energy resolution
  - **Separation of W/Z/H di-jets**

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

    $\rightarrow \sigma_{r\phi} \sim 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$
- Also:
  - Beam induced backgrounds
  - CLIC beam structure





CLIC Beam Structure

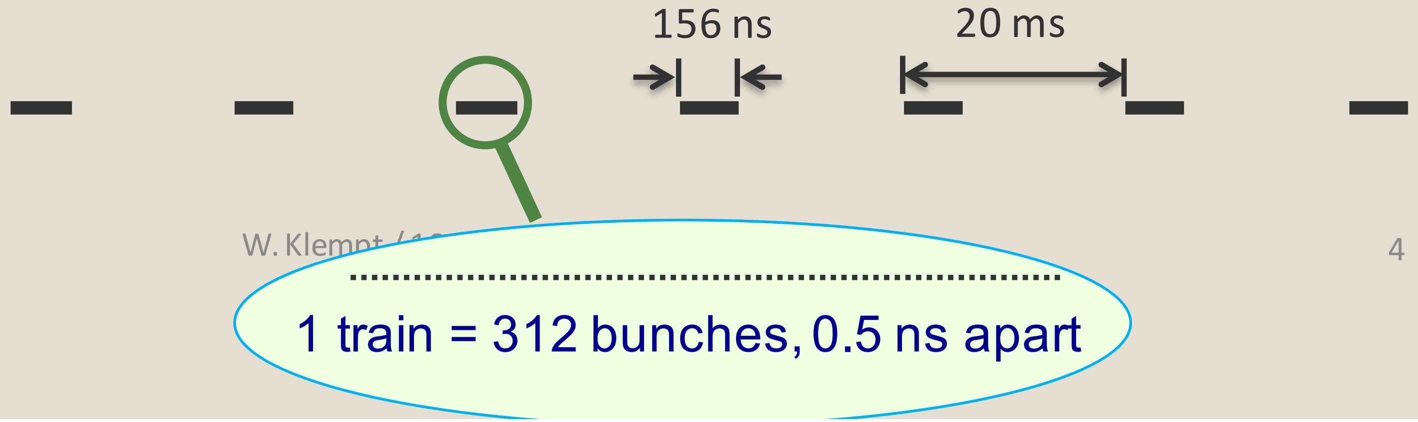
	CLIC at 3 TeV
Luminosity	5.9×10^{34} cm^{-2}s^{-1}
Bunch separation	**0.5 ns**
#Bunches per train	312
Train duration	**156 ns**
Train repetition rate	**50 Hz**
Particles per bunch	3.72×10^{9}
Crossing angle	20 mrad
σ_x / σ_y [nm]	≈ 45 / 1
σ_z [µm]	44

Requirements for time resolution and stamping

Low Duty cycle =>
Read out all (Triggerless)
Powerpulsing

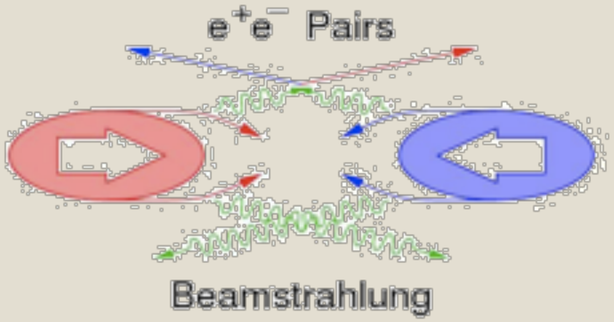
Beam spots very small
Beams strongly focused
⇒ Very high E-Fields
⇒ Beam-beam backgrounds

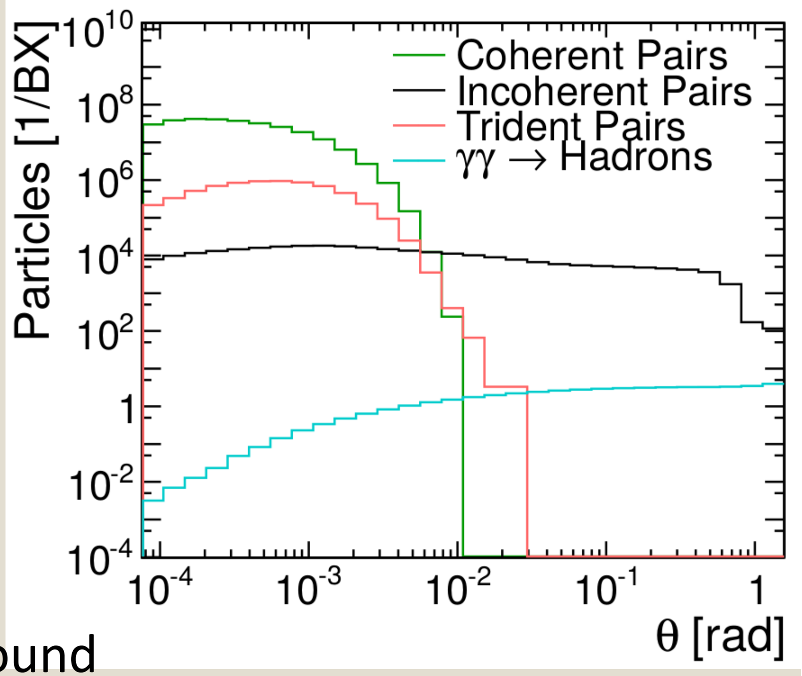
CLIC bunch structure



1 train = 312 bunches, 0.5 ns apart

Beam Induced Backgrounds





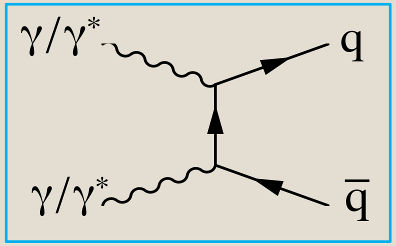
Pair-background

- Coherent e⁺e⁻ pairs: $7\times10^{8}/\mathrm{BX}$
  - – Very forward

=> - **Incoherent e⁺e⁻ pairs:** $3\times10^{5}/BX$
  Rather forward but of concern for background

=> **γγ to hadrons (3.2 events/BX @ 3 TeV)**

- Energy deposits (19 TeV/train @ 3 TeV)
- Also background in calorimeters and trackers



Both backgrounds lead to:

⇒High occupancies : influence detector design

⇒10 nsec time stamping for tracker hits

⇒1 nsec accuracy for calorimeter hits

Evolution of Detector Designs

ILD and SID: two general purpose detectors for ILC (LOI 2009-2010)

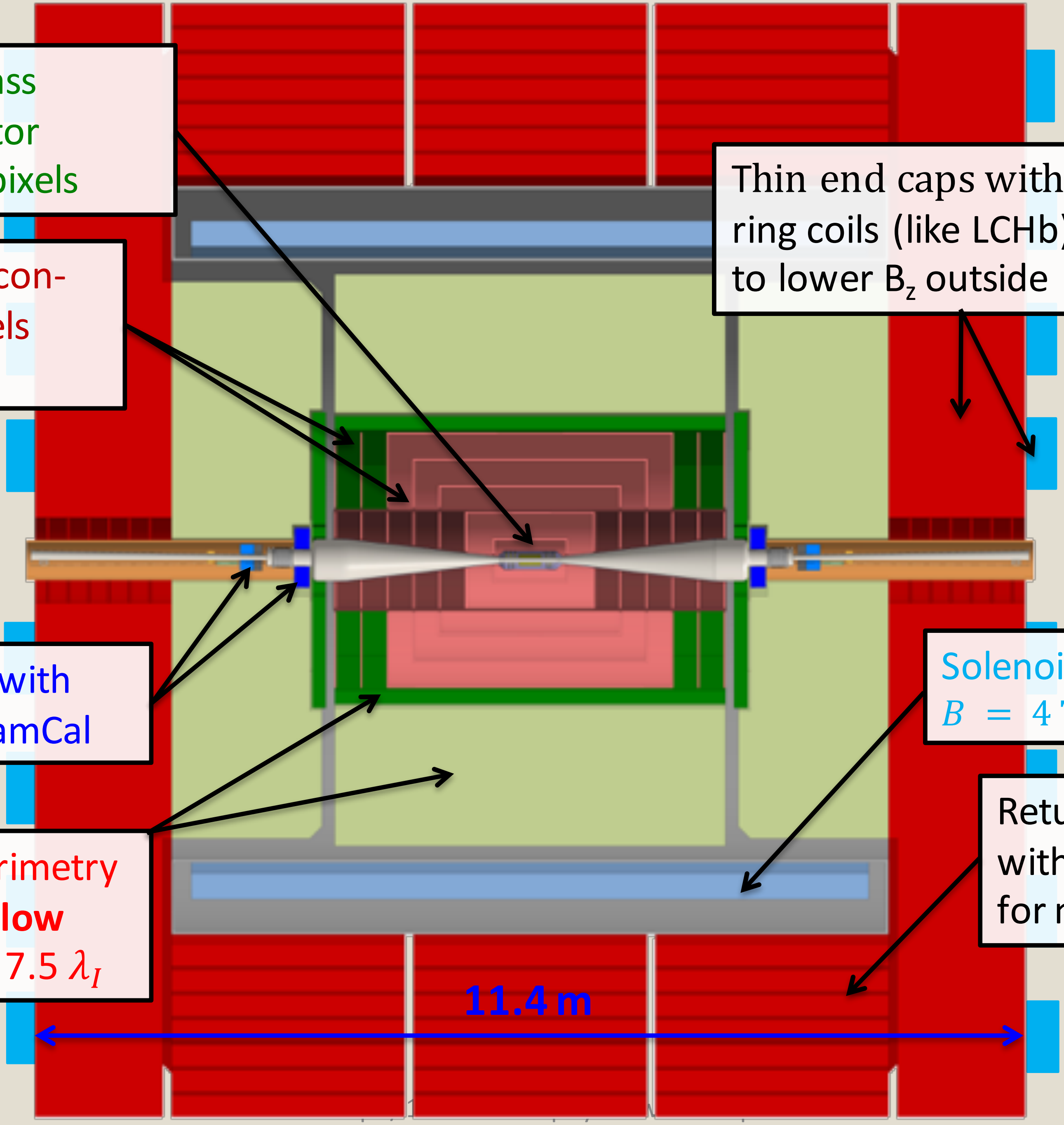
For the CLIC CDR (2012): Two general-purpose CLIC detector concepts

Based on initial ILC concepts but adapted to CLIC conditions

Since 2009 10 - 20 people were working on the project

Concept	ILD (ILC)	**CLIC_ILD**	SiD (ILC)	**CLIC_SiD**	**CLCdet_2015**	**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

Layout of CLICdet_2015



Ultra low-mass vertex detector with 25 µm pixels

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

Thin end caps with compensation ring coils (like LCHb) to lower B_z outside magnet

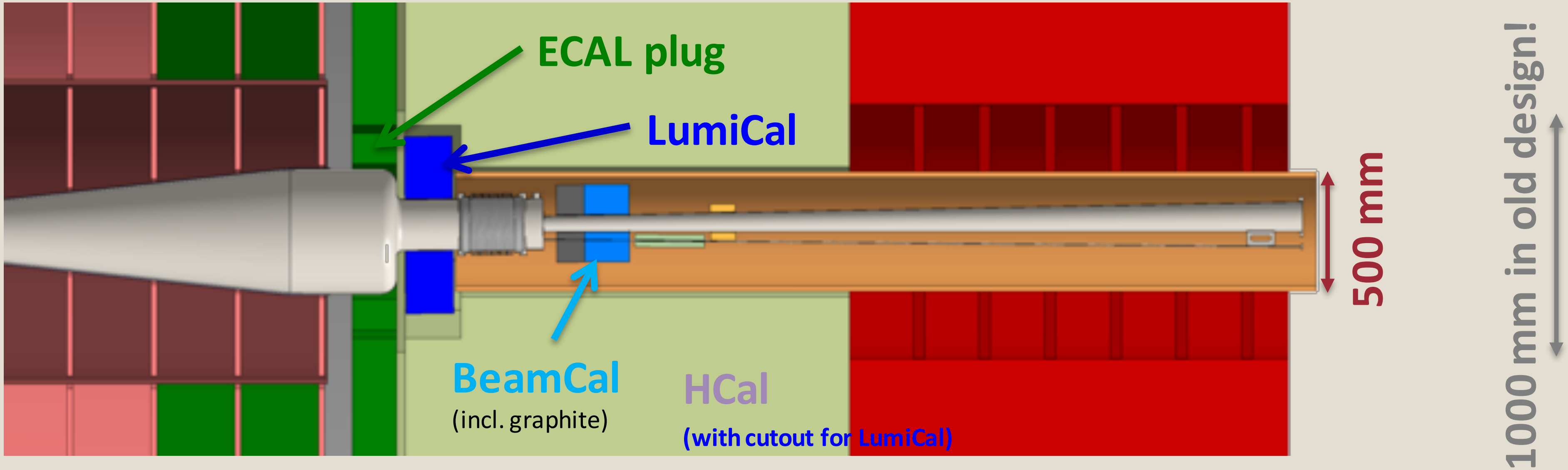
Forward region with LumiCal and BeamCal

Solenoid Magnet, $B = 4\,\mathrm{T}$, $R_{in} = 3.4\,\mathrm{m}$

Return yoke (Fe) with detectors for muon ID

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

Forward Region Layout in CLICdet_2015



Tracker acceptance down to ≈ 140 mrad (due to background from incoherent pairs)

Electron tagging:

- LumiCal: 44-80mrad with 95%-99% efficiency
- BeamCal: ≥15 mrad with 70%-80% efficiency

Extend **HCal Endcap coverage** closer to beampipe

Optimized for a working hypothesis of an $L^* = 6\ \mathrm{m}$

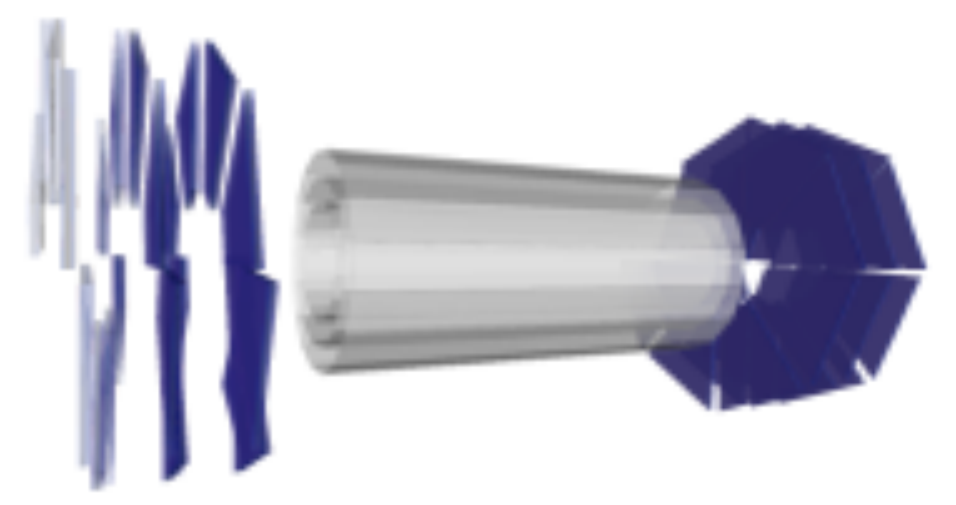
→ **QD0 outside detector region**

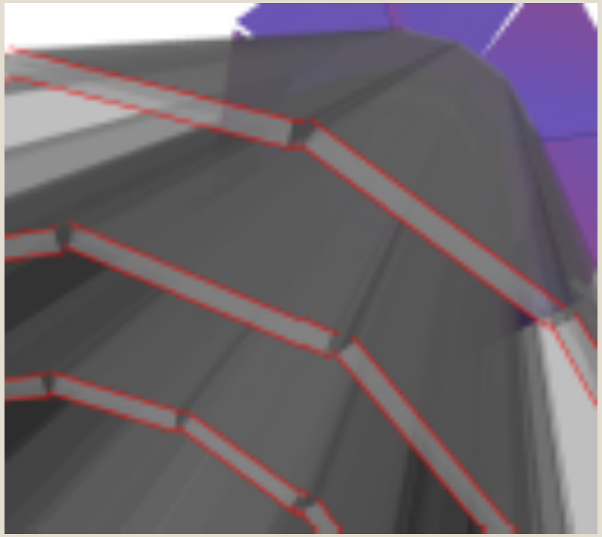
  - Simplified services, no need for an anti-solenoid
  - No need for rigid support
  - Smaller support outer radius: **250 mm**

Vertex Detector

Layout optimized for
flavor tagging, resolution and occupancy

- **Effect of material very critical**
  => cooling with airflow
- **Inner Radius**
  Beam background ↔ B-field
- **Spiral geometry of forward disks**
  (needed for air cooling)
- **Single layer vs. double layers**

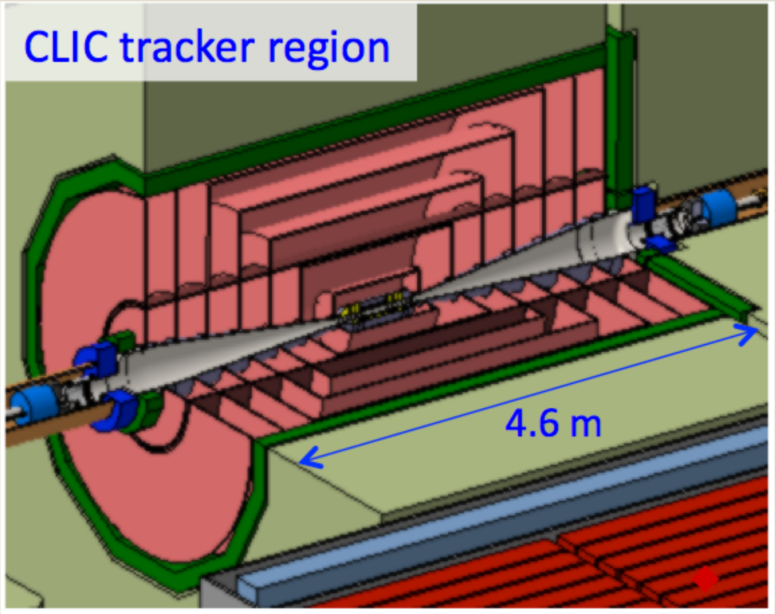




In CLICdet_2015:

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

Tracker Technology

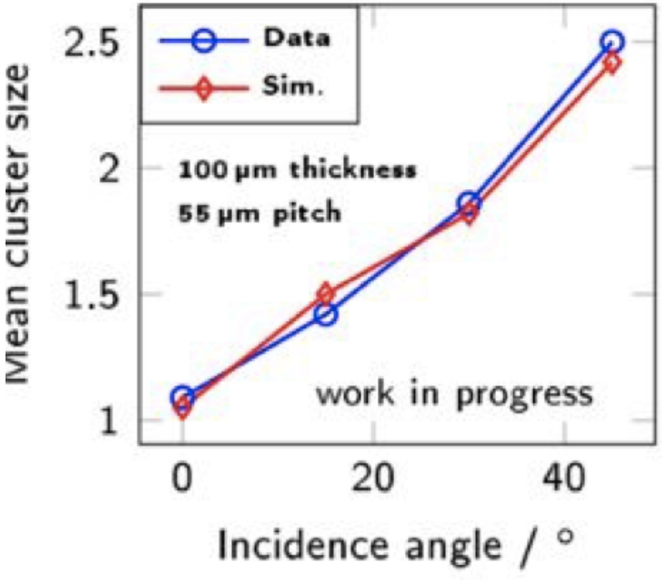


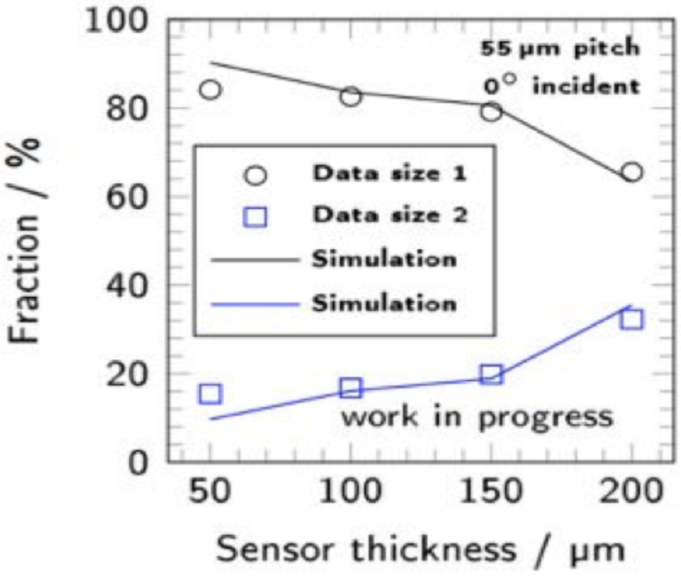
Inner and outer part separated by support tube
5-6 barrel, 7 forward layers, R~1.5m, L~4.6m

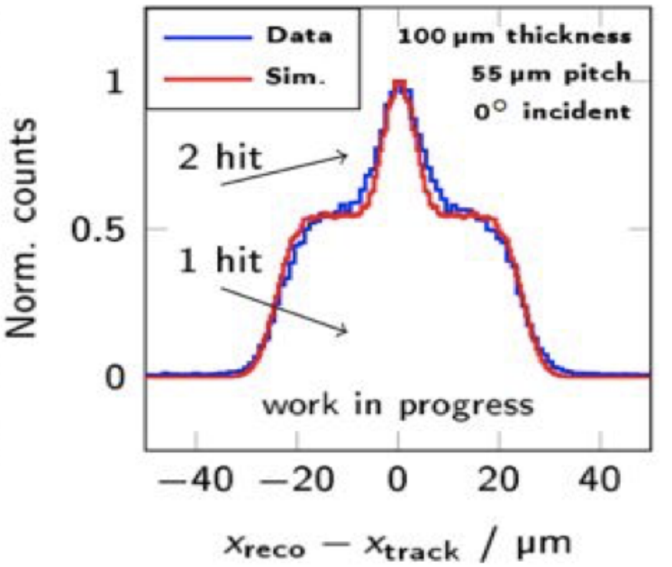
Aim for 7 μm single-point resolution:
Sensor technology? Readout cell size?
Charge sharing? dE/dx information?

Occupancy from backgrounds defines strip length
Time stamping of hits with 10 nsec required

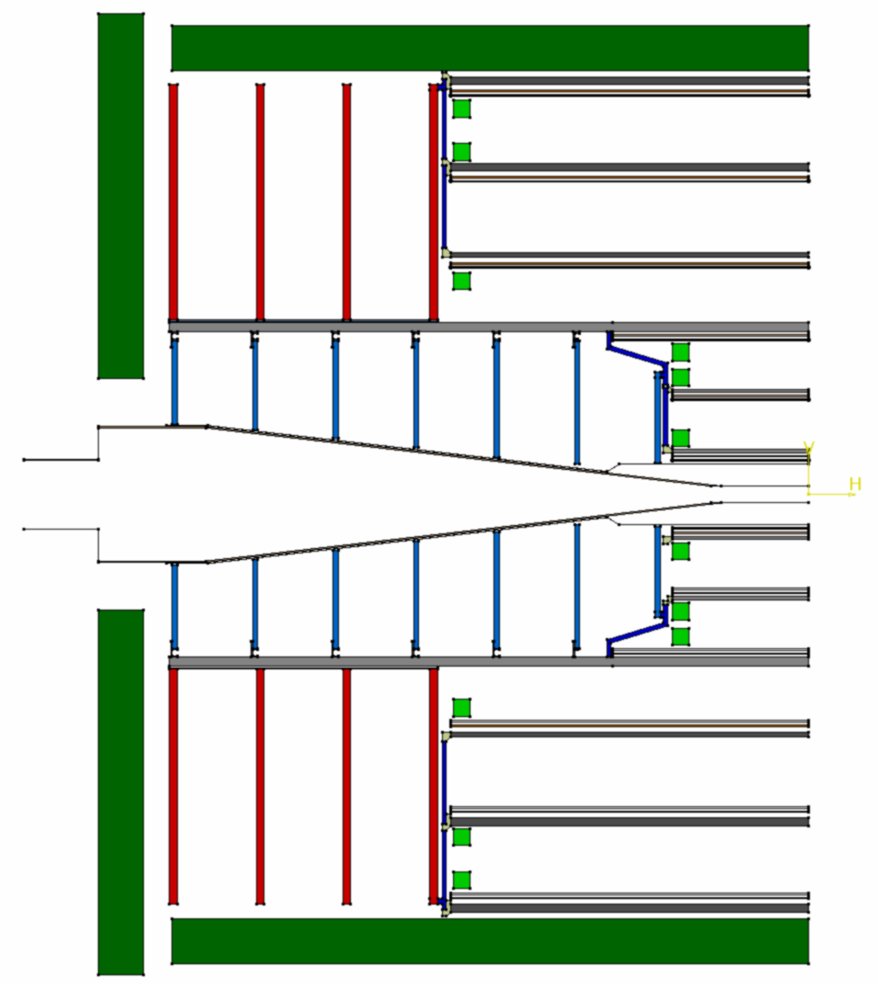
Developed simulation (Geant + TCAD + FE)
Good agreement with test beam data

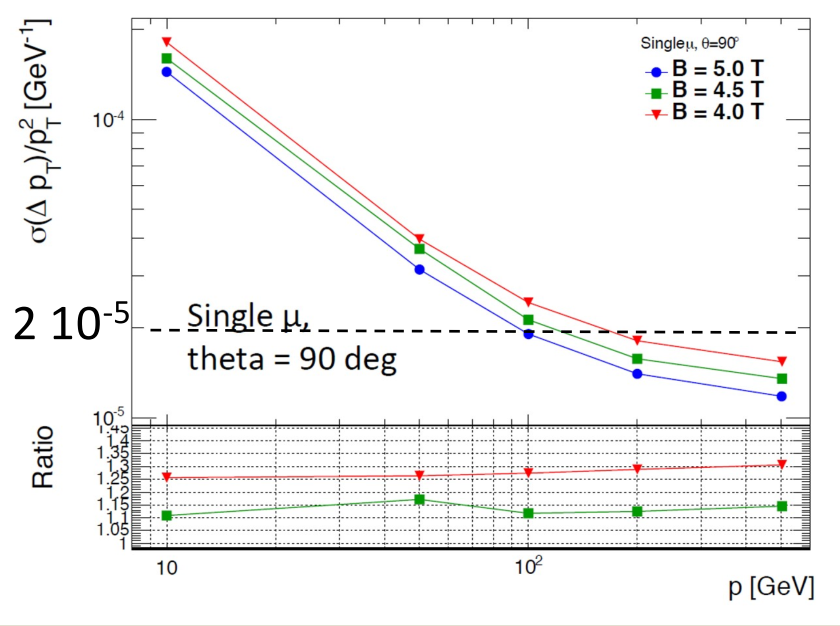


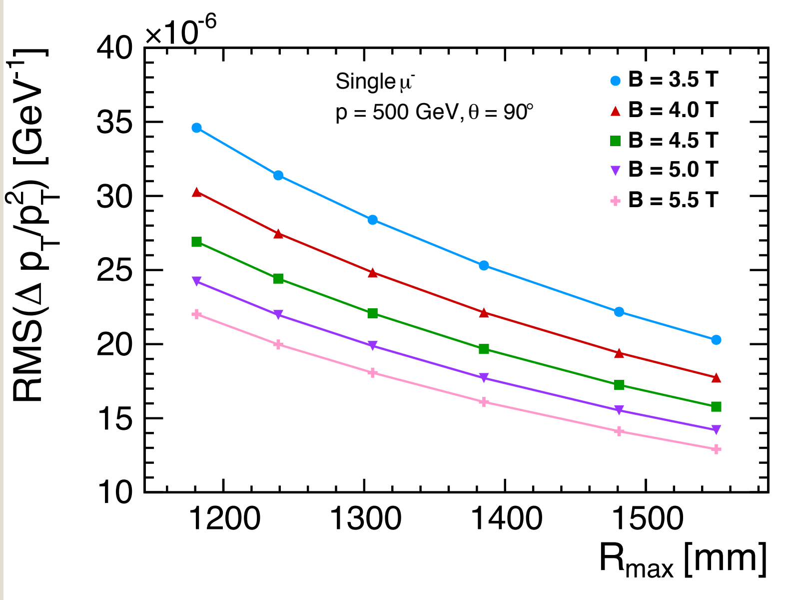




Tracker Layout (6 Barrel, 7 End Cap Layers)







PFA in Calorimetry

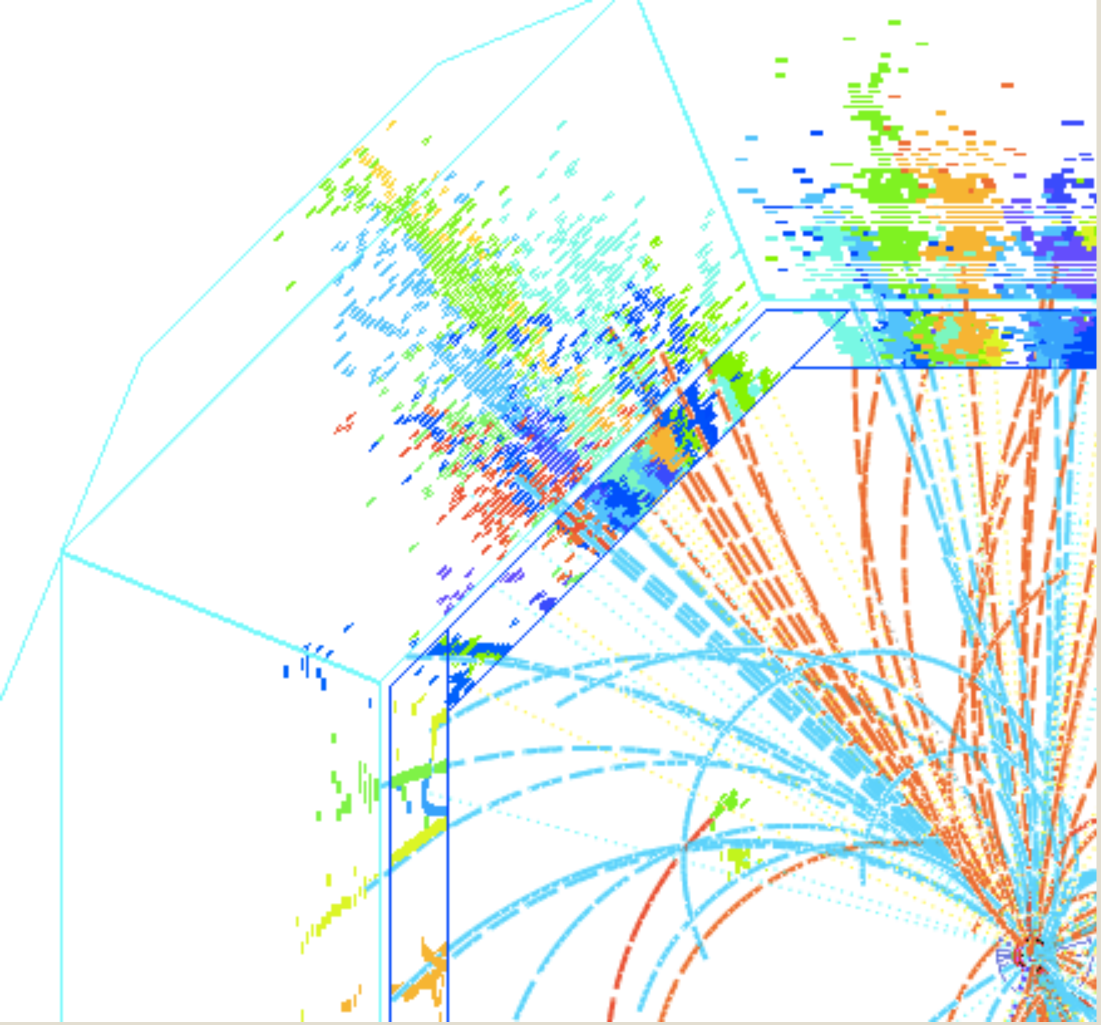
Jet energy resolution (JER) drives the overall detector design
($\sigma_E/E \sim 3.5\%$ for $E > 100$ GeV)
=> fine-grained calorimetry + Particle Flow Analysis (PFA)

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 !



E-Cal Optimization

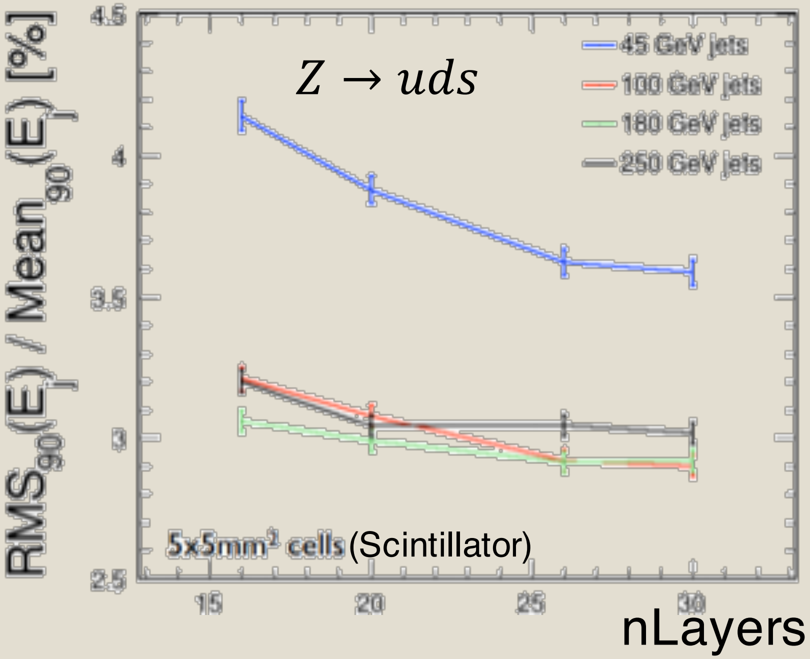
 # Layers: Not very important for higher energy jets (PFA confusion dominates):

Not much more improvement from 25 to 30 layers

In simulation kept constant depth of 23 X_0

Si vs Scint: No significant effect on JER

Cell size: JER **degradation** from 3% to ~3.5% when increasing cell size from 5x5 mm^2 to 15x15 mm^2



In CLICdet_2015:

- **Tungsten** absorber, **Silicon** active material
- **25** Layers, 23 X_0/ 1 λ_I
    - 17× 2.4 mm + 8 × 4.8 mm
- Use **5.1x5.1 mm^2** cells throughout

HCAL Optimization

Example: HCal Barrel Absorber

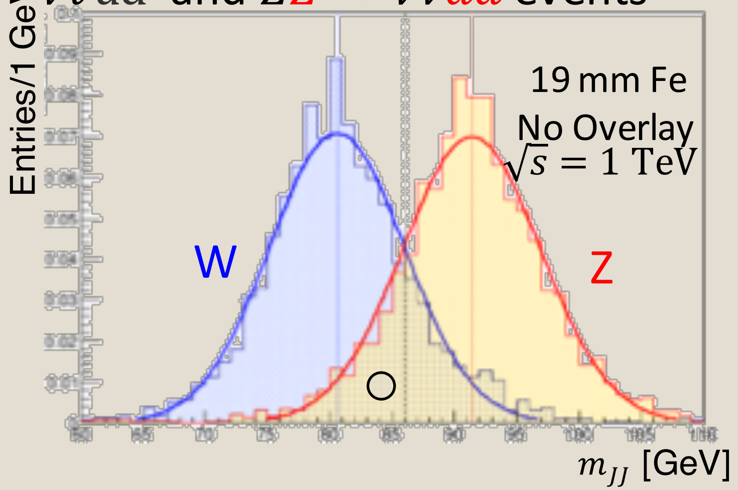
- 10 mm Tungsten (W) 70 Layers
- 19 mm Steel (Fe) 60 Layers
- Total thickness 7.5 λ_I

Full **Geant4** detector simulation + **PandoraPFA** + **FastJet**

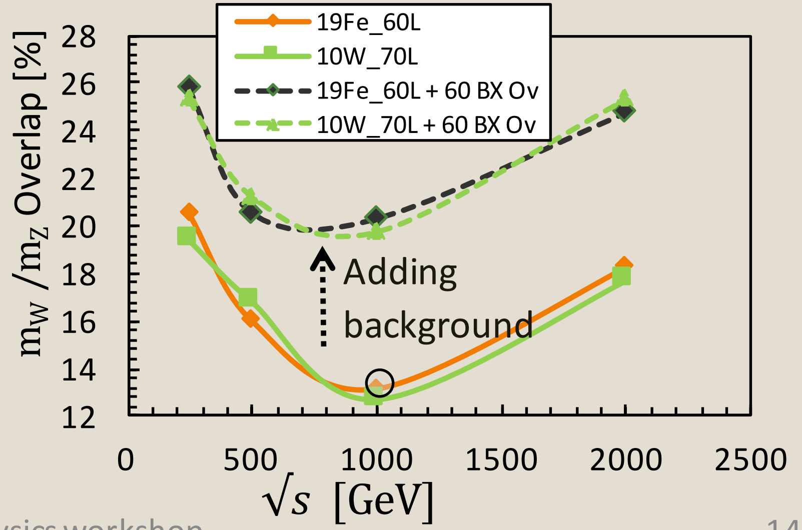
JER Performance shown to be **similar** for **tungsten** and **steel**

Steel is cheaper and more easy to use for construction

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



○ The shaded area gives one of the points on the plot below. Repeat for both models, all energies. Do also with background.

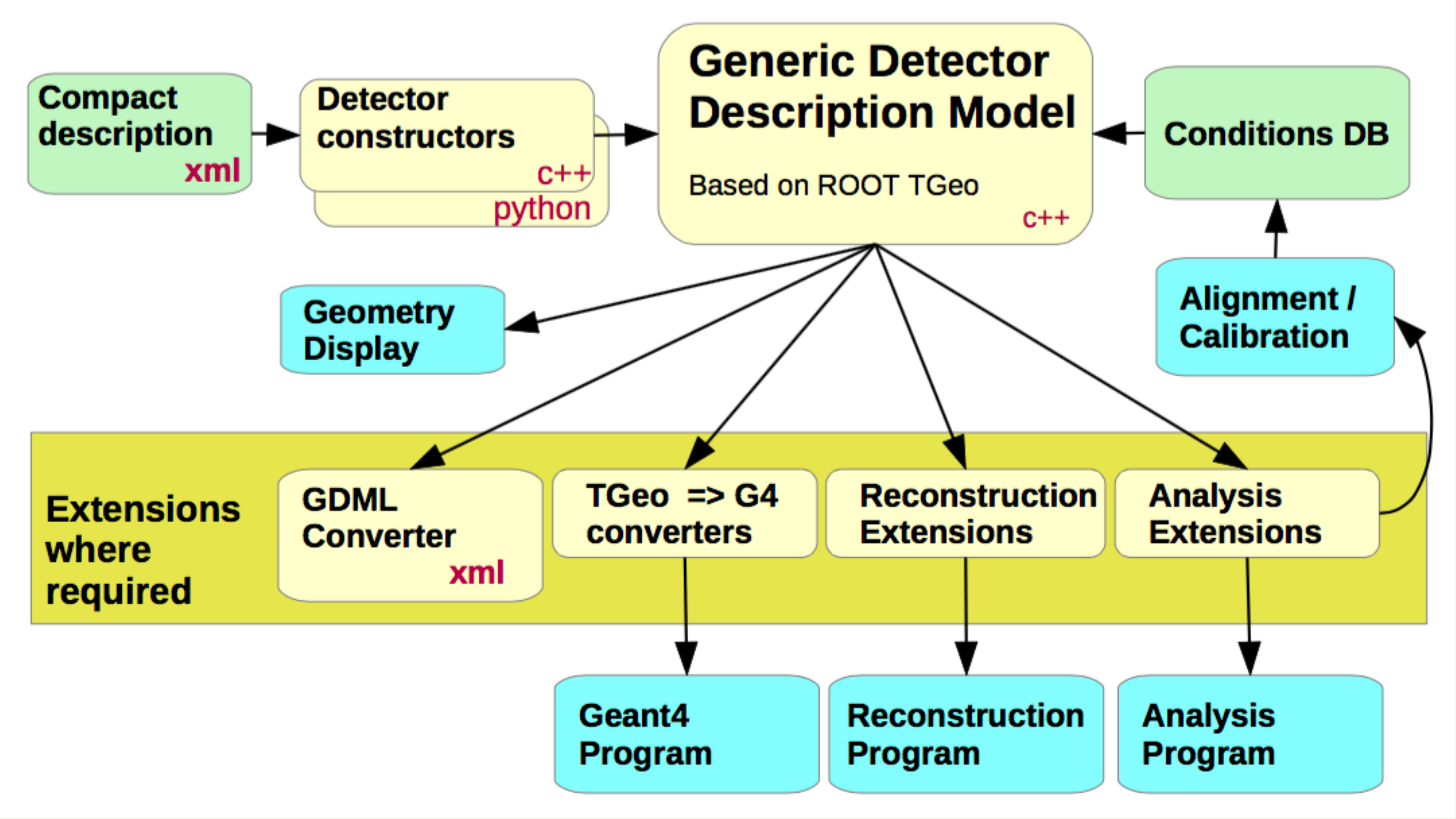


DD4hep Overview

DD4hep includes a standardized geometry description giving common input for: simulation, reconstruction and analysis

All pieces are interfaced with python

Ready to use



Requirements for FCC-ee Detector (from Machine)

30 mrad beam crossing angle:

- Rather big, do you really need it?
- May create problems with geometry: Beam pipe and forward acceptance

Down to ~3-4 nsec bunch spacing:

- How much interaction or background events per bunch crossing?
- Do you need to identify bunch crossing? Why not look at it as a DC machine?
- Do you need trigger or can you take all data to tape?
- In principle 3 nsec is ok for fast standard detectors, but power consumption?

L* = 2m (final focus quadrupoles inside detector):

- How big are (superconducting?) quadrupoles?
- How precise has positioning to be?

⇒ Geometry problem => compromise on forward acceptance

Compensating solenoid 1m away from vertex:

- What is the size of it?
- Influence on forward acceptance even bigger than for quadrupoles!
- How to measure luminosity?

Detectors for FCC-ee (2)

Start design effort with a linear collider detector

B-field: Possibly weaker (~2 T)
- Accelerator constraint
  - Beam crossing angle
- Lower max momentum

Calorimetry
- Jet energy (1/3 x LEP)

$$\boxed{\frac{\sigma_E}{E} \approx 3-4\,\%}$$

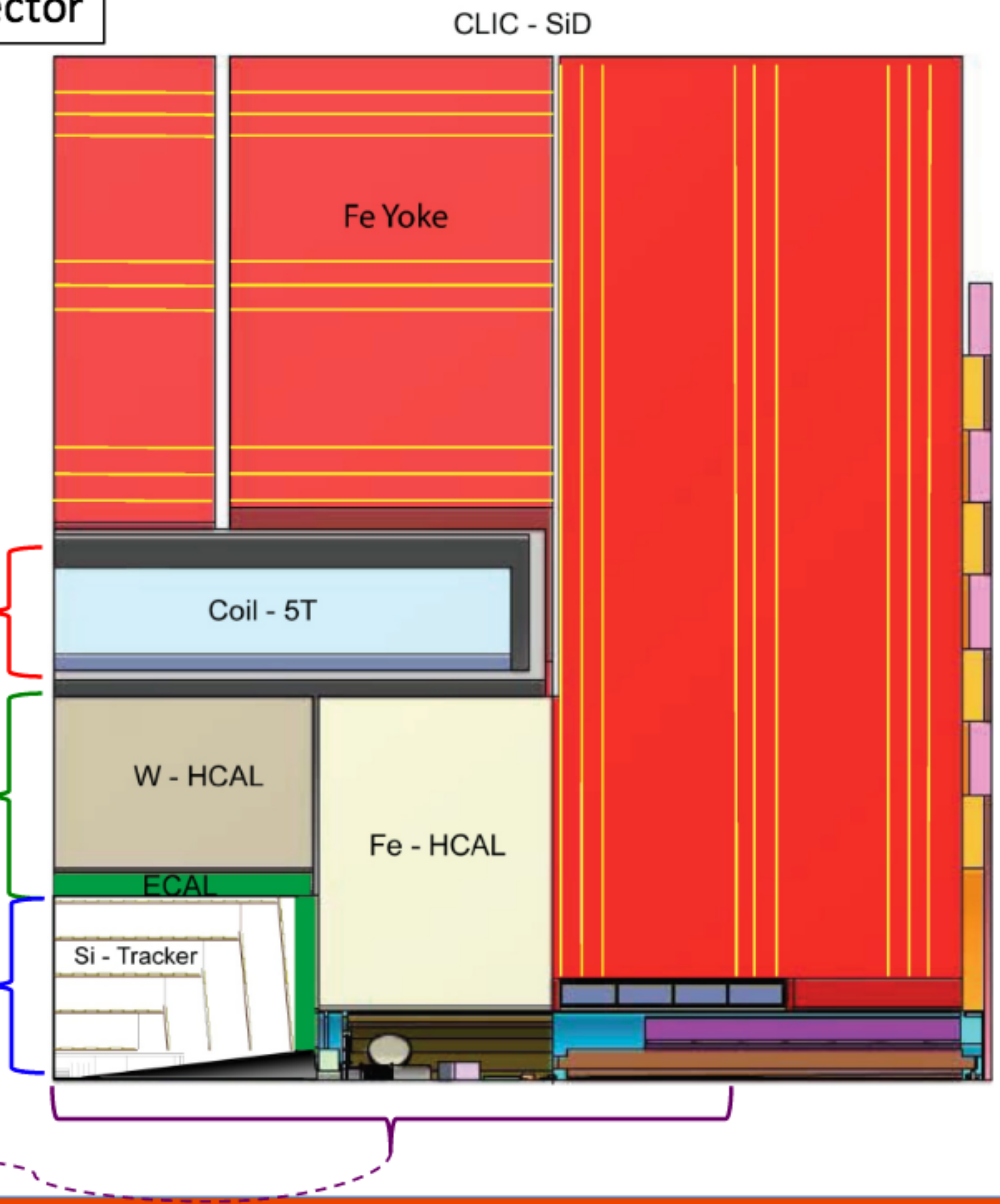
Momentum: (1/10 x LEP)

$$\boxed{\sigma_{1/p} < 5\times10^{-5}\,\mathrm{GeV}^{-1}}$$

Impact parameter: (1/3 x SLD)
- e.g. b/c-tagging

$$\boxed{\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

Hermetic: down to θ = 5 mrad



How can you optimize?

Momentum resolution is given by:

$$\frac{dP_T}{P_T} \sim \left(\frac{f(N) * P_T * \sigma(r\varphi)}{e * B * R^2}\right) \oplus \left(\frac{13.3\ MeV/c}{e * B * R * \sqrt{sin\theta}} * \sqrt{\frac{g(N) * t}{X_0}}\right)$$

$$for\ N = 6\ uniformly\ distributed\ layers:\ f(N) = 0.982\ \ and\ \ g(N) = 1.28$$

R_{max} is determined by cryostat: $R_{max} \approx 1.5$ m (if calorimeter inside cryostat with R ≈3.5m)

Impact parameter resolution:

$$\sigma(d_0) \sim \left(A * \frac{\sigma(r\varphi)}{r_2 - r_1} * (r_1 \oplus r_2)\right) \oplus \left(B * \frac{r_1}{P_T * \sqrt{sin\theta}} * \sqrt{\frac{t}{X_0}}\right)$$

Calorimetry:

- Same resolution as CLICdet-2015 but at lower jet energies
  => Particle Flow Analysis, maybe with higher segmentation?
- Energies are smaller. Can you make H-Cal thinner ? From 7.5 λ_I to 6.5 λ_I
- Maybe you can improve E-Cal resolution by using crystals divided in r?
  would improve energy resolution of single photons

Conclusions

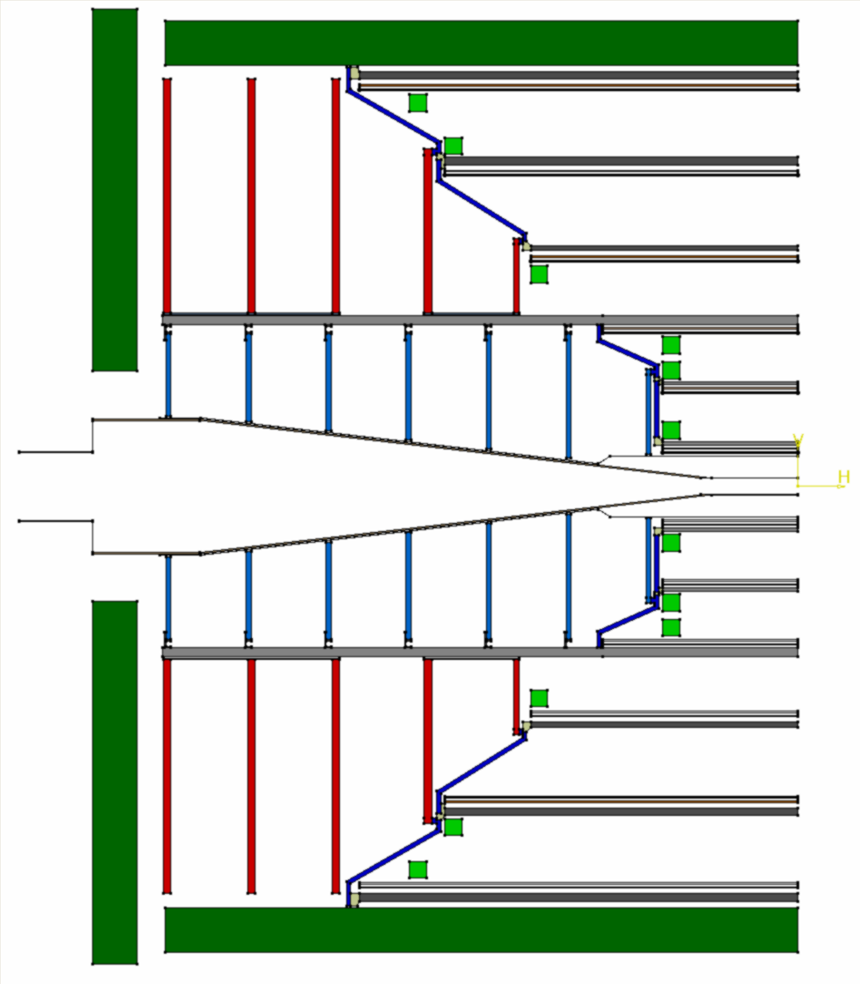
New detector concept CLICdet_2015 has been developed from previous CDR detector concepts using:

- B = 4 T
- 4.6 long, 3m diameter all Si Tracker
- 25 layer W+Si Ecal depth 23 X_0 / 1 λ_I
- 60 layer Fe + Scint Hcal depth 7.5 λ_I
- Thin end cap yoke with compensating coils

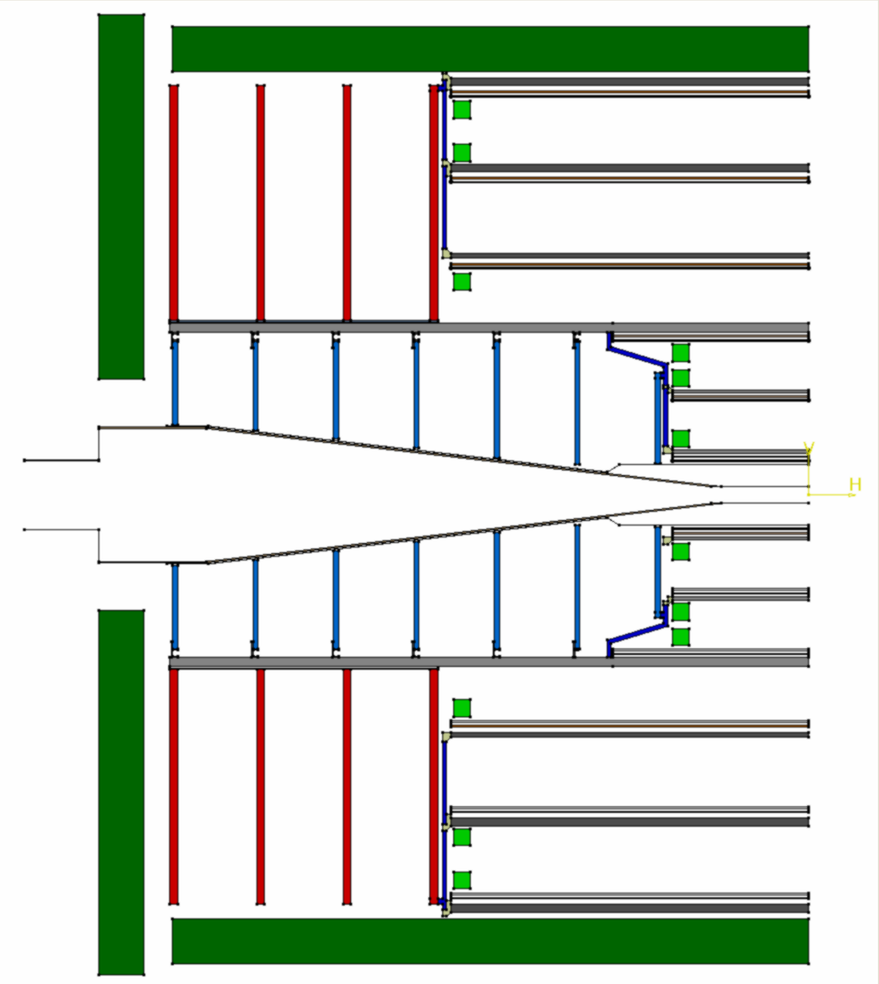
Detector for FCC-ee has very stringent requirements and presents a challenge to design and build

Backup

Tracker Layout (6 Barrel, 7 End Cap Layers)

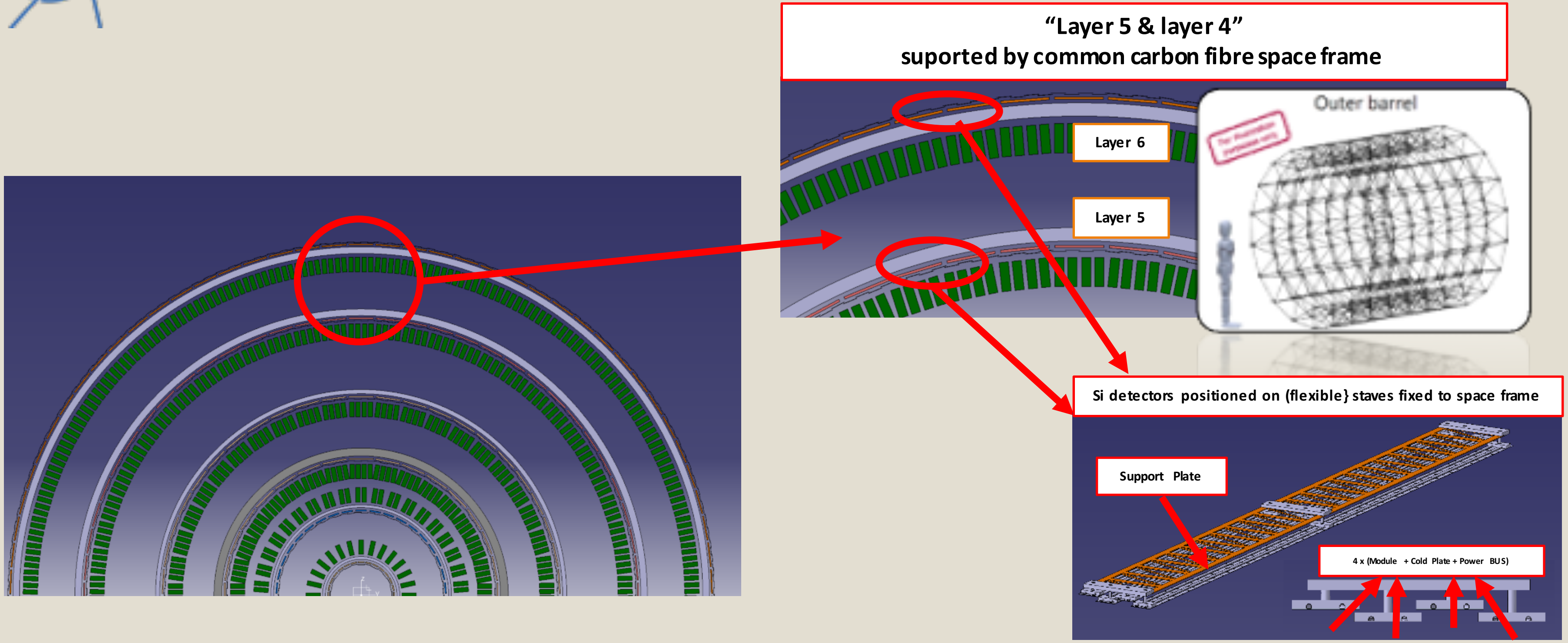


Pointing geometry
Increasing barrel length



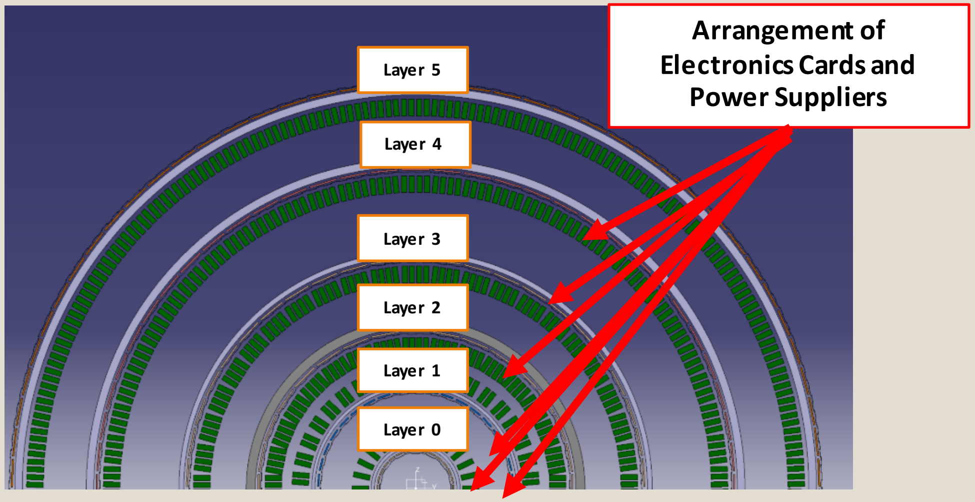
Geometry using
equal barrel length

Tracker Layout cont.



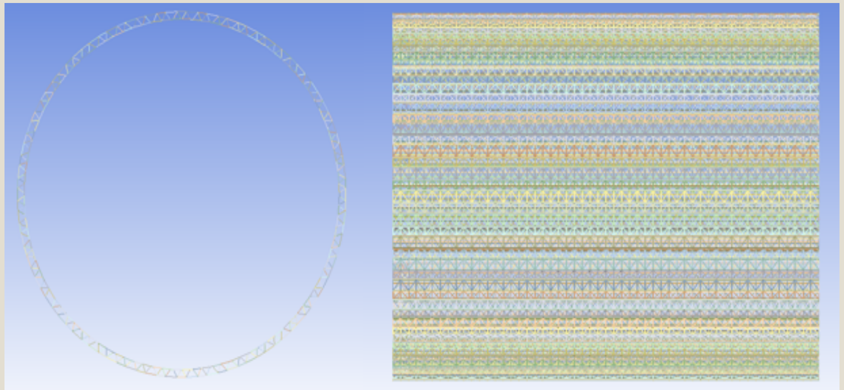
“Layer 5 & layer 4”
suported by common carbon fibre space frame

Si detectors positioned on (flexible} staves fixed to space frame

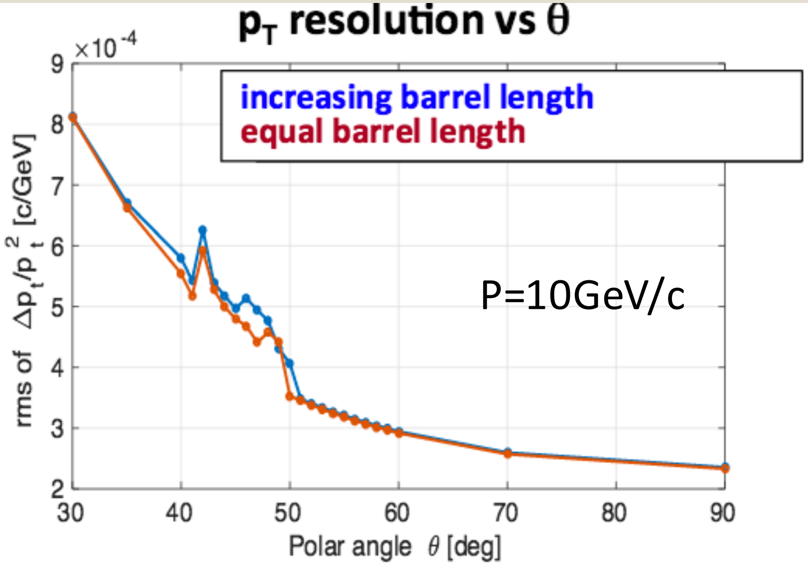


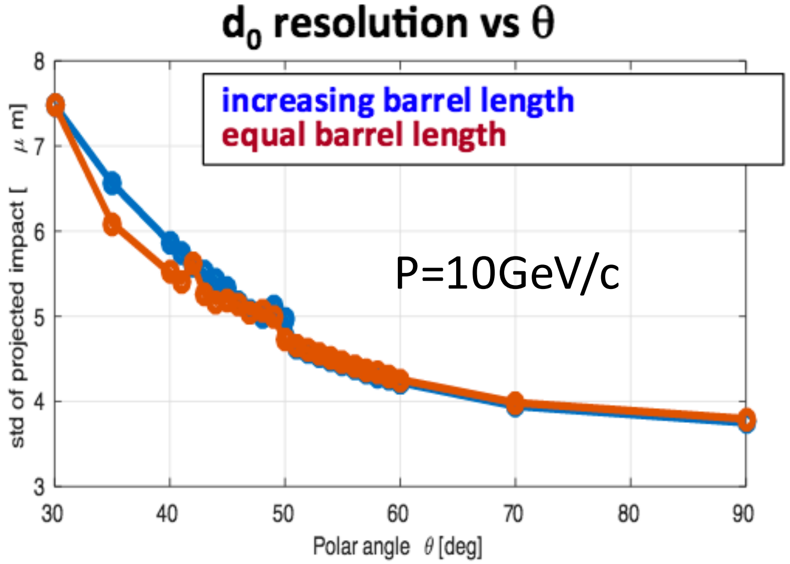
Arrangement of Electronics Cards and Power Suppliers

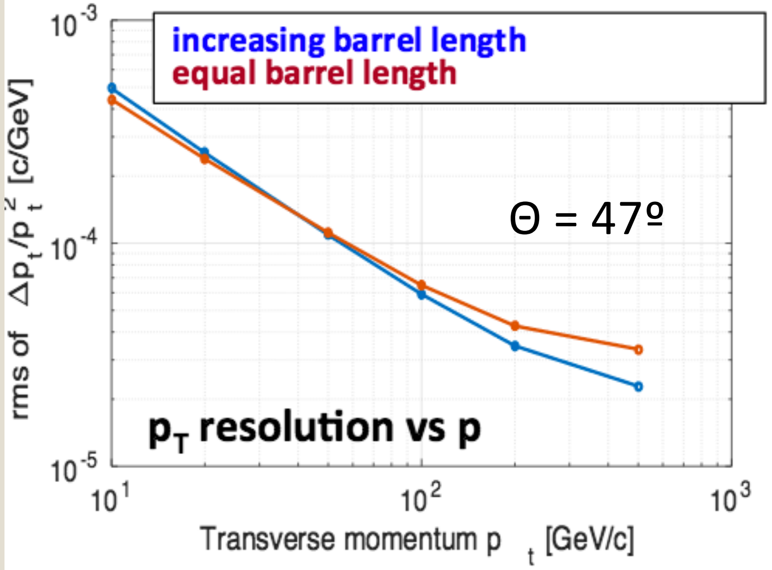
Barrels made from individual carbon fibre space frame

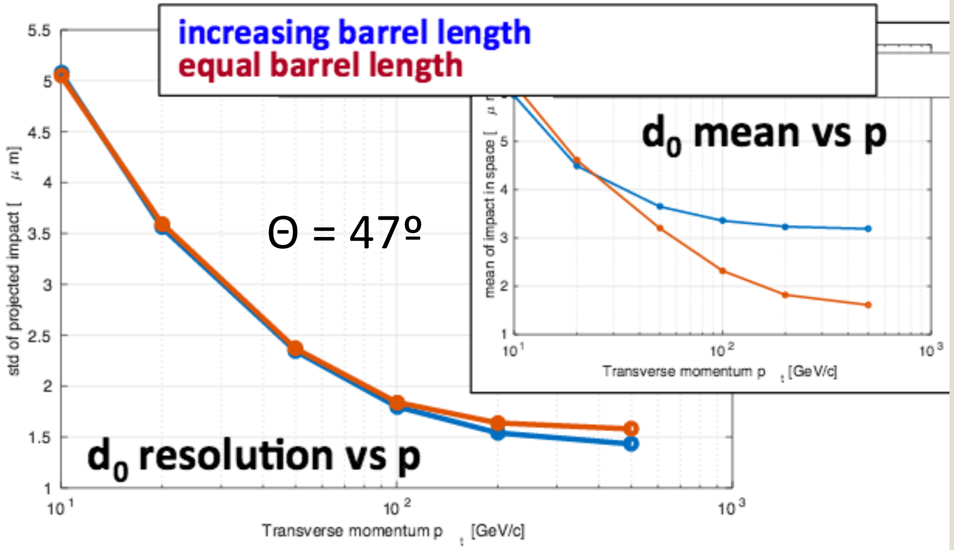


Tracker Resolution Performance (with fast simulation)

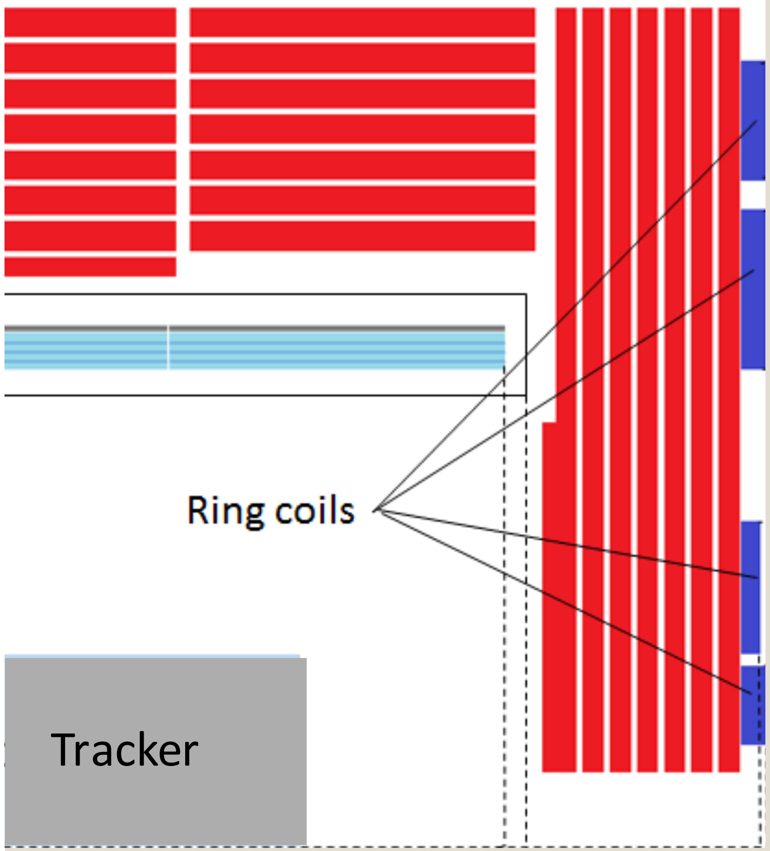

p_T resolution vs θ

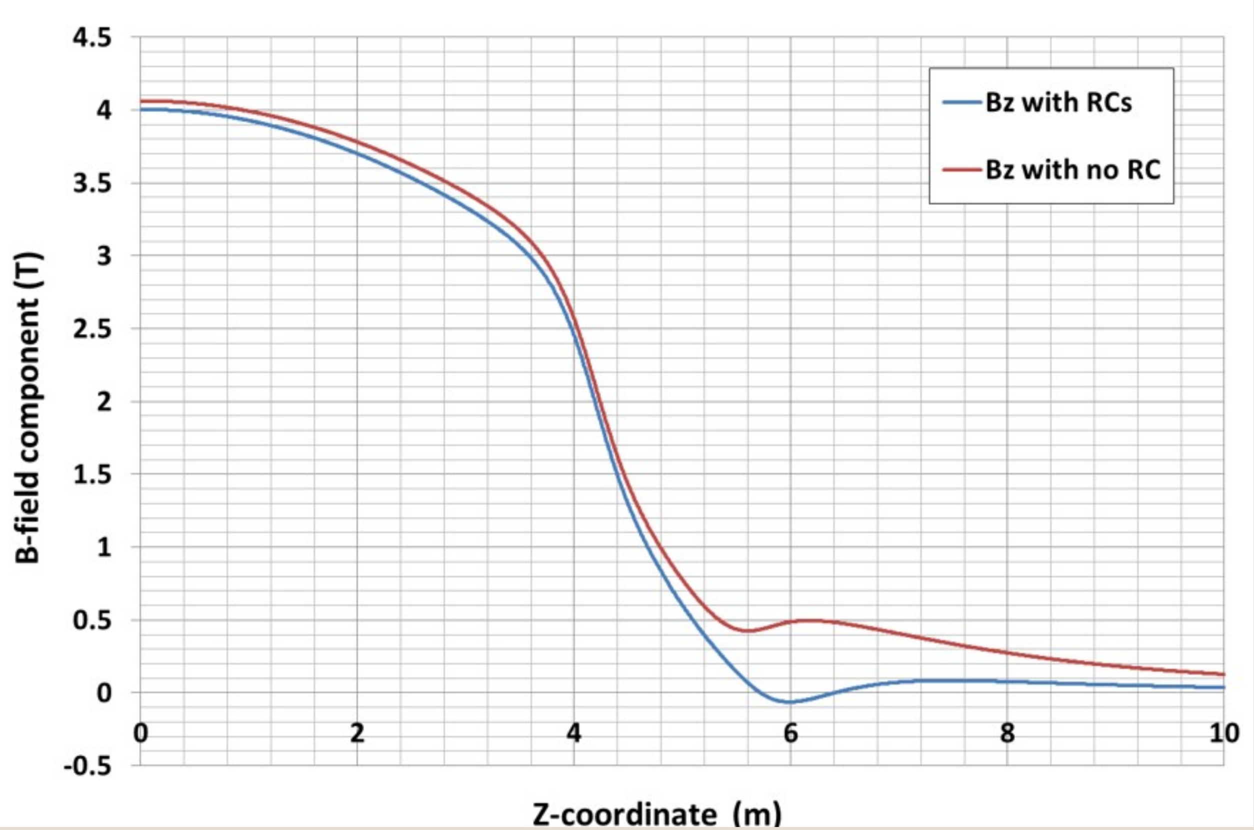

d_0 resolution vs θ


p_T resolution vs p


d_0 resolution vs p
d_0 mean vs p

Magnetic System Layout





View of the magnet system with "thin" Endcaps

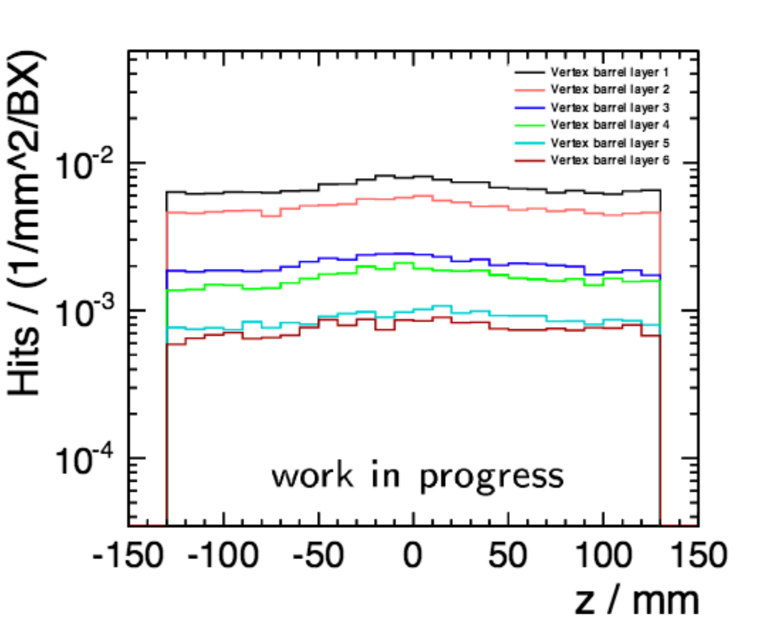
Compensating ring coils (like in LHCb) allow for lower Bz component outside magnet

B-field axial component **with** and **without** end coils as function of z

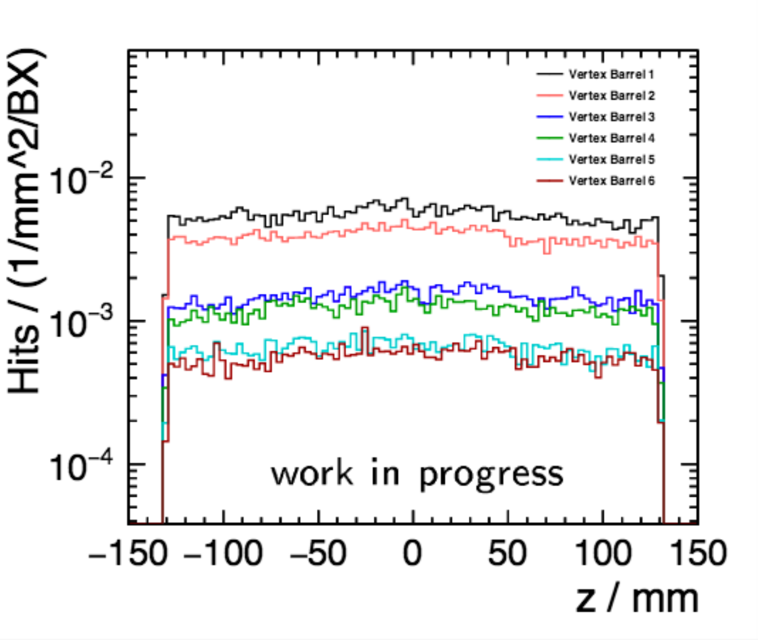
Hit-rate in Vertex detector - Barrel

- Hit-rate from incoherent pairs and $\gamma\gamma \to$ hadrons in the vertex detector

Mokka



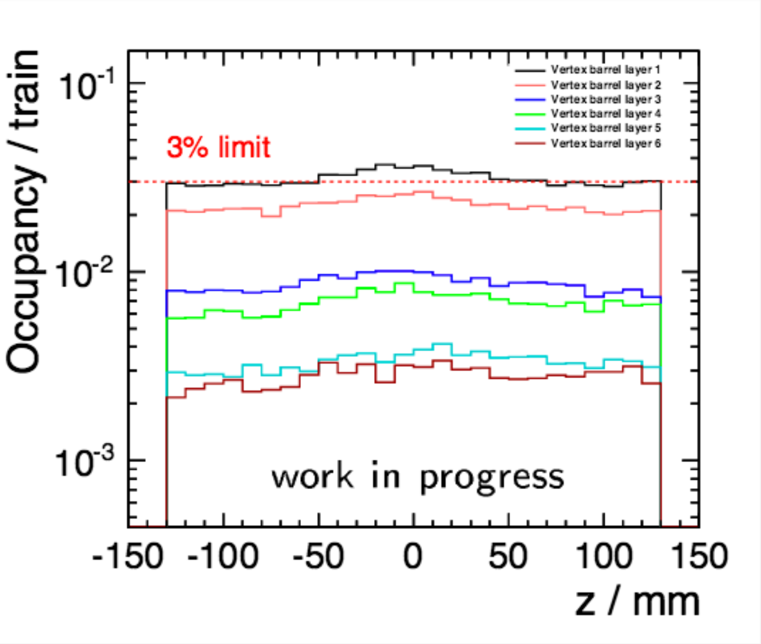
DD4hep



Occupancy in Vertex detector - Barrel

- Occupancy from incoherent pairs and $\gamma\gamma \to$ hadrons in the vertex detector
- Cluster size 5, safety factors of 5 for incoherent pair production, 2 for $\gamma\gamma \to$ hadrons

Mokka



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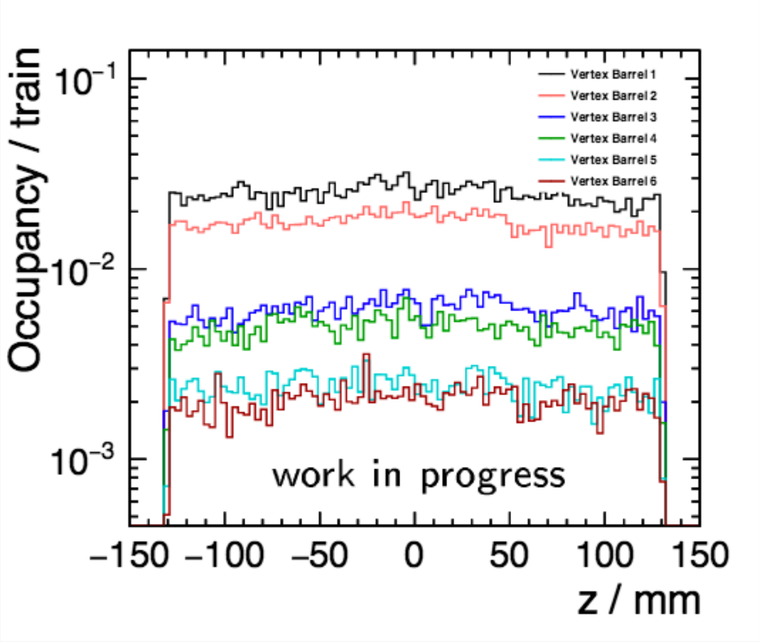
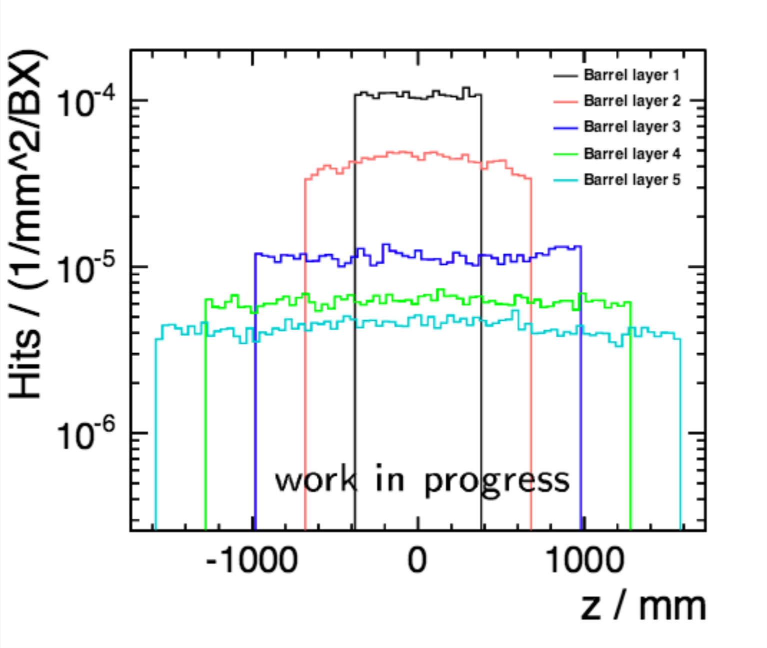


Hit-rate in main tracker - Barrel

- Hit-rate from incoherent pairs and $\gamma\gamma \rightarrow$ hadrons in the main tracker barrel

Mokka



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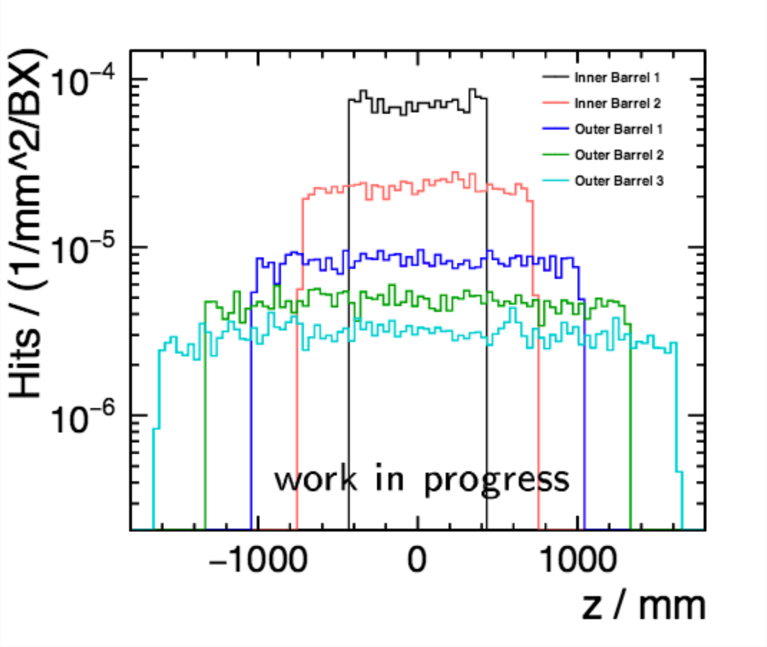
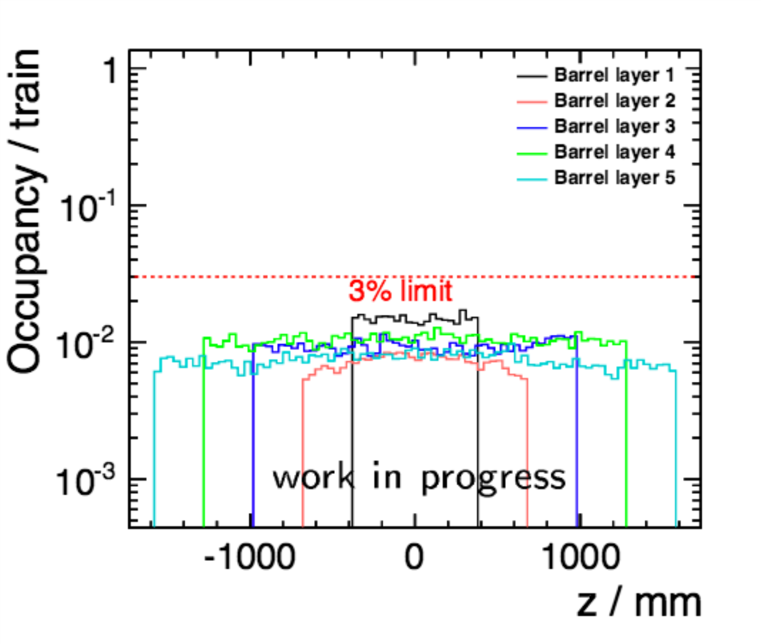


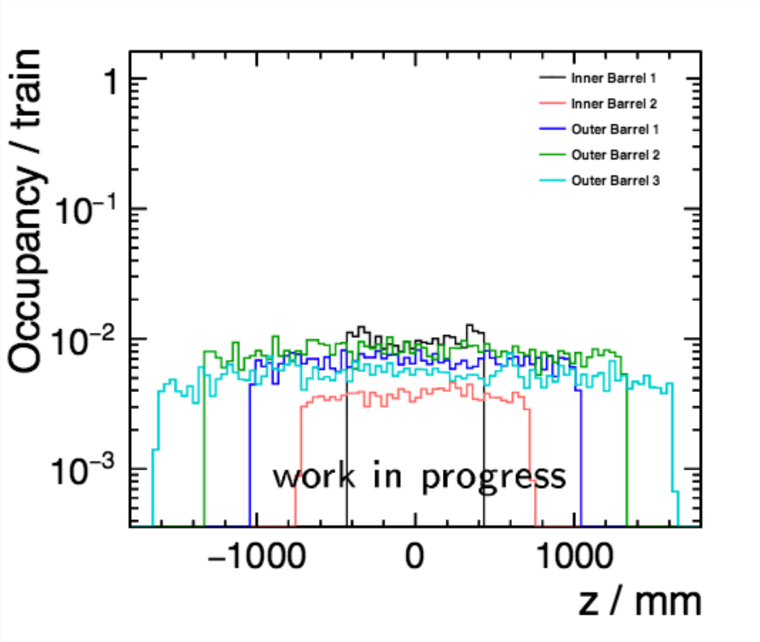
Occupancy in main tracker - Barrel

- Occupancy from incoherent pairs and $\gamma\gamma \to$ hadrons in the main tracker barrel
- Cluster size 2.6, safety factors of 5 for incoherent pair production, 2 for $\gamma\gamma \to$ hadrons

Mokka



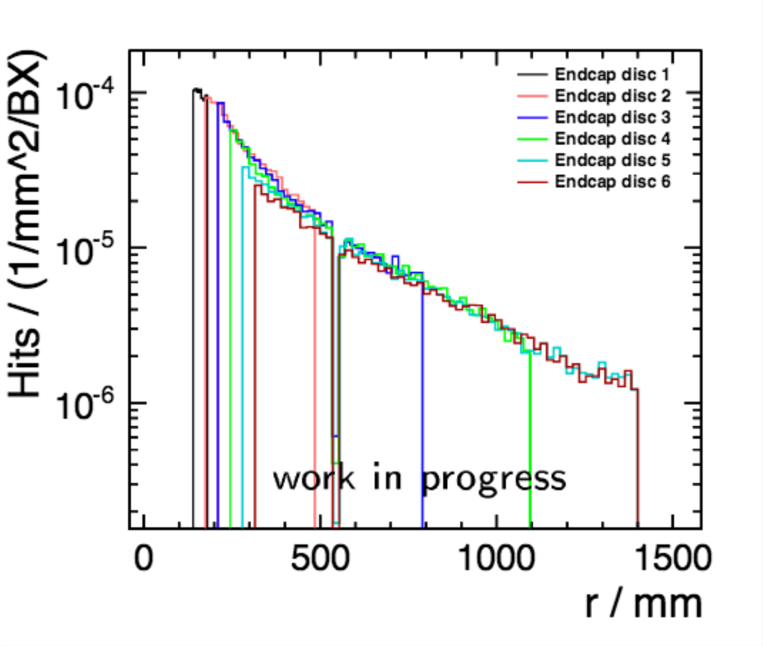
DD4hep



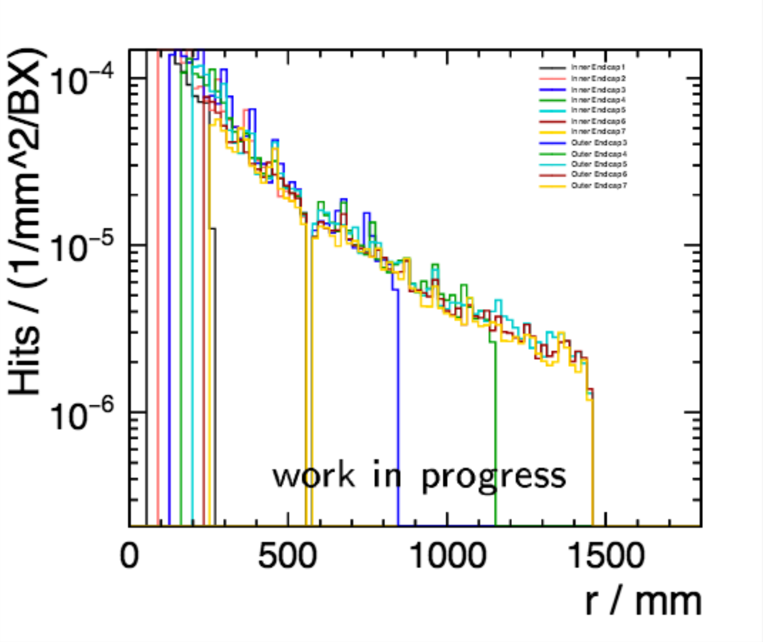
Hit-rate in main tracker - Endcaps

- Hit-rate from incoherent pairs and $\gamma\gamma \rightarrow$ hadrons in the main tracker endcaps

Mokka



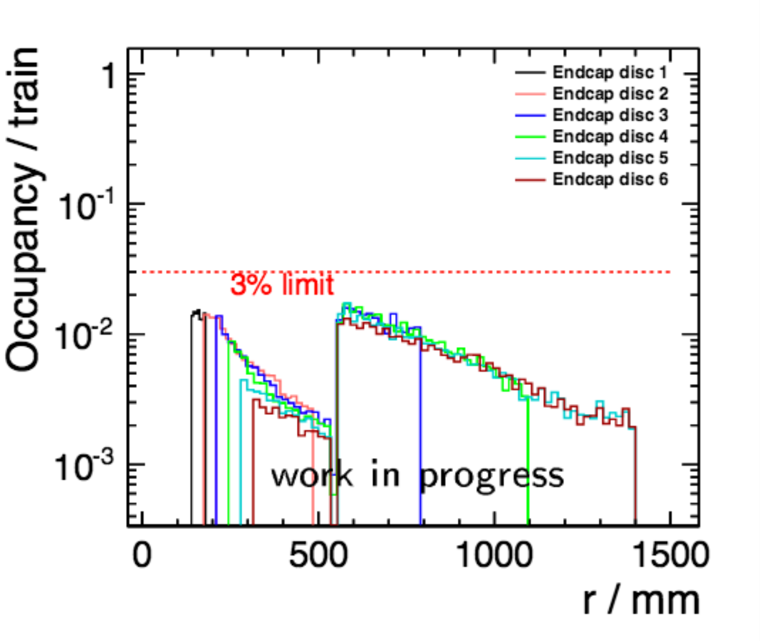
DD4hep



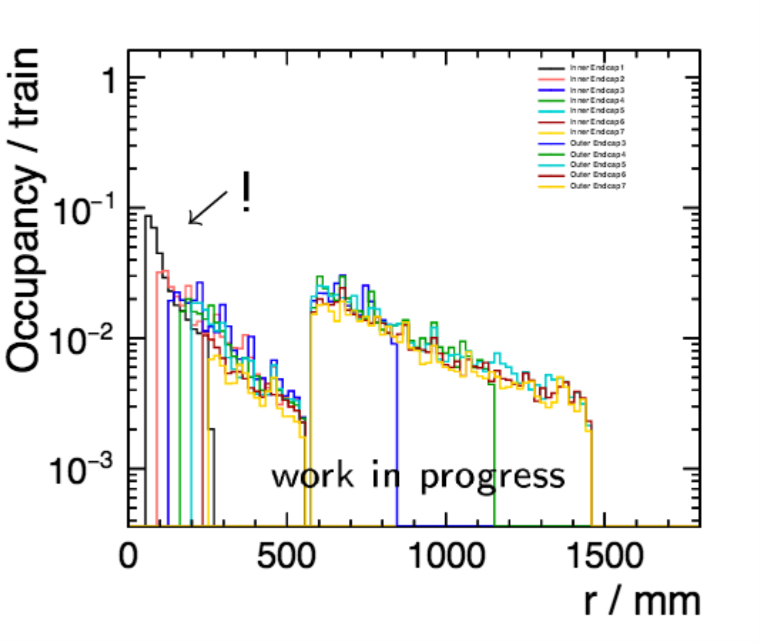
Occupancy in main tracker - Endcap

- Occupancy from incoherent pairs and $\gamma\gamma \rightarrow$ hadrons in the main tracker endcaps
- Cluster size 2.6, safety factors of 5 for incoherent pair production, 2 for $\gamma\gamma \rightarrow$ hadrons

Mokka



DD4hep



- High occupancy at low radius of the innermost forward disc