CLIC detector optimization

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2nd ATLAS HV-MAPS Mini-Workshop
Univ. Geneva, 02. 07. 2015

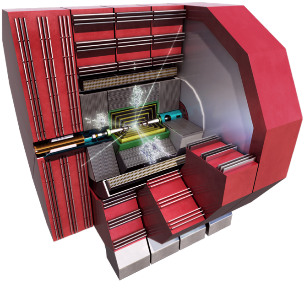
Outline

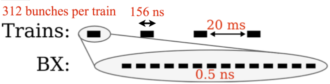
- CLIC detector, requirements on tracking detectors
- Tracker layout, performance
- Occupancy due to beam induced background
- Sensor response simulation, TCad based model

Introduction

CLIC detector in a nutshell

- High precision:
  - jet energy resolution - $\sigma_E/E \sim 3.5\,\% - 5\,\%$
    - fine grained calorimetry - $13\,\text{mm}^2$ ECAL cell size
  - Momentum resolution - $\sigma_{p_T}/{p_T}^2 \sim 2 \times 10^{-5}\,\text{GeV}^{-1}$
  - Impact parameter resolution - $\sigma_{r\phi} \sim 5 \oplus 15/(p \sin^{3/2} \Theta)\mu\text{m}$
- Overlapping beam induced background:
  - high rate - 3 $\gamma\gamma \rightarrow$hadrons per bunch crossing
  - requires precise timing $\leq 10\,\text{ns}$
  - Pixel size $25 \times 25\,\mu\text{m}^2$
- No issues from radiation damage:
  - 1×10^{-4} LHC levels
  - except for small forward calorimeters
- No trigger, full readout of 156 ns bunch train



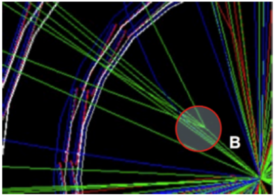


Vertex detector requirements

Goal: efficient tagging of heavy quarks through a precise determination of displaced vertices

Multi-layer barrel and endcap pixel detectors

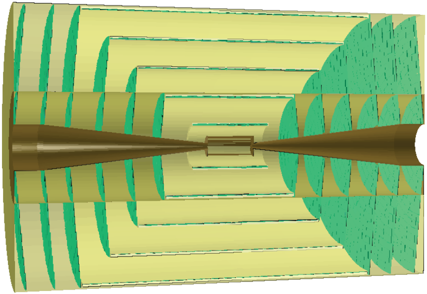
- 560 mm in length
- Barrel radius from 30 mm ∼ 70 mm



- Single point resolution of 3 µm
- Material budget $< 0.2\,\%X_0$ per layer
- No active cooling elements - use forced air flow cooling
- Limit the power dissipation to $50\,\mathrm{mW\,cm^{-2}}$
- Hit time slicing of 10 ns

Main silicon tracker

- Tracker requirements
  - 7 µm single point resolution
  - 10 ns timestamping
  - 5 barrel layers, 6 endcap discs
  - Radius ~ 1.5 m, half-length ~ 2.3 m

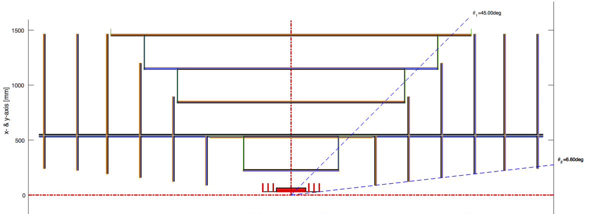


- High occupancy in certain regions calls for large pixels and/or short strips
- Very light, $\sim 1\,\%X_0$ per layer
  - Requires very thin materials/sensors
  - Can take advantage from power-pulsing
  - Air cooling probably not possible

Tracker layout study

Fast simulation model

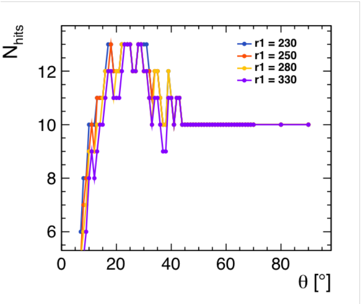
- LiC detector toy
- Full track reconstruction algorithm
- Multiple scattering included
- Automatised fast-simulation procedure allows for easy change of parameters
  - Position and number of tracking layers
  - Material budget
- Assume 7 µm single point resolution
- Realistic scaling of material budget for support, cables and cooling has been included

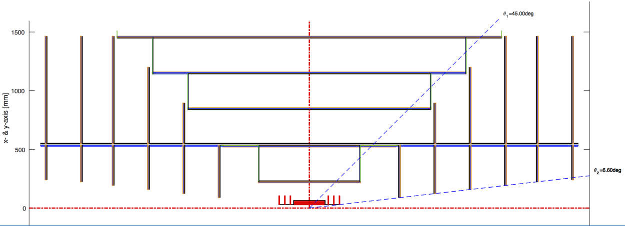


Tracker sensor layers, supports, cables, cooling, vertex sensor layers

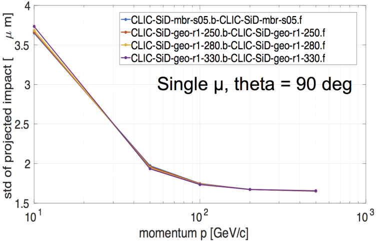
First barrel layer position

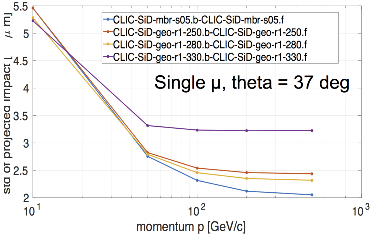
- Move out radius first barrel layer in steps of 50 mm:
  - 230 mm (starting point)
  - 250 mm
  - 280 mm
  - 330 mm
- Other barrel layers move out accordingly

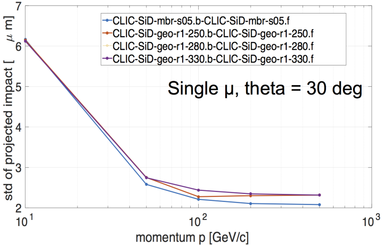




Results vs. momentum - d_0 resolution



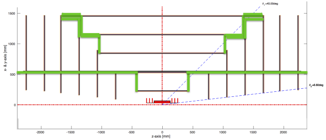


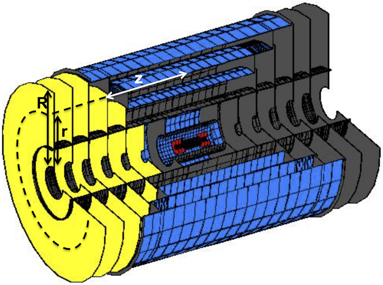


- Important to have a layer closer to the VXD
- At 90° no variation, same number of hits (and material budget) for all tracks

Model for cabels

- Material budget for cables and cooling should scale according to the layers size and position
- Assumed constant cable/cooling density





$$x_{cyl} : A_{cyl} = x_{ring} : A_{ring}$$

$$A_{cyl} = 2\pi r z$$
$$A_{ring} = \pi(R^2 - r^2)$$

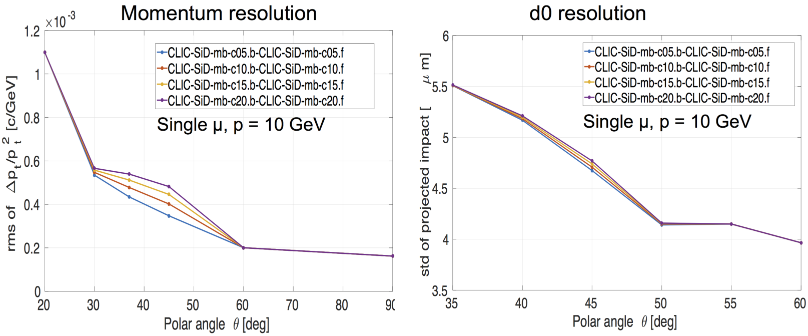
$$x_{ring} = \frac{x_{cyl}(R^2 - r^2)}{2rz}$$

$$x^{i,tot}_{ring} = x^i_{ring} + \sum_{j<i} x^j_{ring}$$

$1.0\%X_0$

Results changing material budget for cables

- Mat. budget for support fixed: 0.48 $\%X_0$ (barrel), 0.5 $\%X_0$ (forward)
- Mat. budget for sensor fixed: 0.5 $\%X_0$ (barrel), 0.88 $\%X_0$ (forward)
- Mat. budget for cables varied: 0.5 $\%X_0$, 1.0 $\%X_0$, 1.5 $\%X_0$, 2.0 $\%X_0$

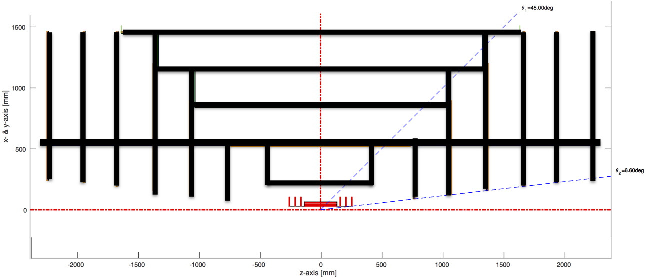


→ As expected in the cable region (30° to 50°) worsening of the p_T resolution, small effect on the d_0 resolution (dominated by vertex detector)

Model for supports

- For outer radii larger material is needed in order to match stability requirements
- Rough implementation: material for outermost layer 3 times larger than for innermost, linearly rescaled for layers in between

m.b. after scaling:
barrel 1: 0.48% X_0
barrel 2: /
barrel 3: 0.96% X_0
barrel 4: 1.20% X_0
barrel 5: 1.44% X_0



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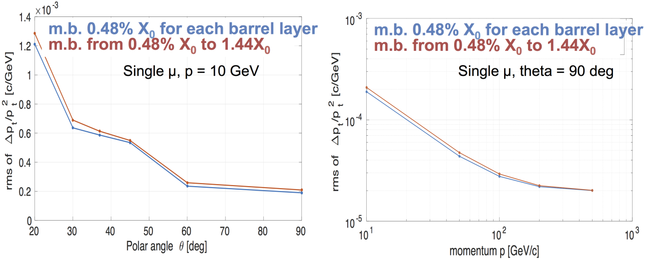
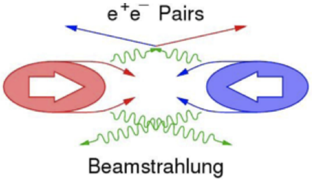


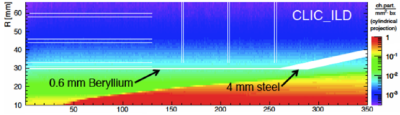
- Extra support material in the outer layers has no big impact on resolution

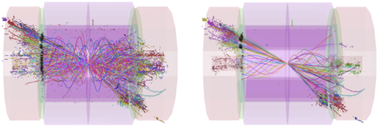
Beam induced background

Beam induced backgrounds

- Dense bunches, high energy, small transverse size leads to very high E-field, resulting in beamstrahlung
- Consequences:
  - reduction in $\sqrt{s}$
  - high occupancies drive small pixel/strip size for tracking
  - also geometric requirements on vertex detector inner radius
  - background energy deposits drive small cell size for calorimetry
  - high precision timing







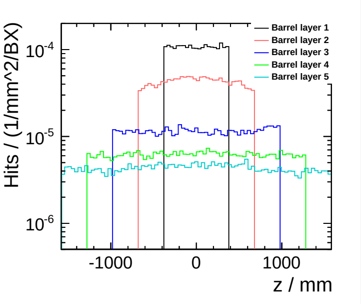
No bkg suppression

After bkg suppression

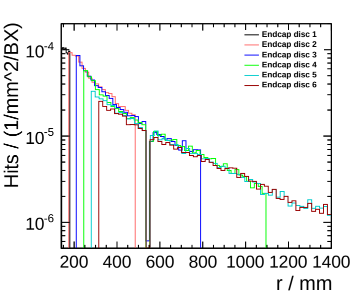
Hitrate in main tracker

- Full geant4 based detector simulation (Mokka)
- Evaluate hitrate from beam induced background in the main tracker
- No digitization, no clustering

Barrel



Endcap discs

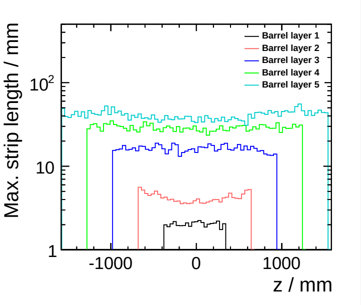


- Hitrate depends strongly on radius, mostly independent of z-position

Max. strip length in the main tracker

- Want to keep occupancy per bunch train below 3 %
- Beam induced background sets limit on maximal size of readout cells
- Assume 50 µm pitch, avg. clustersize 2.6, include process dependent safety factors (5 for incoherent pair production, 2 for $\gamma\gamma \rightarrow$ hadrons)

Barrel



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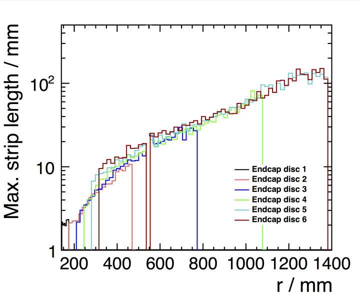


- Inner layers: few mm strip length, outer layers: few cm strip length

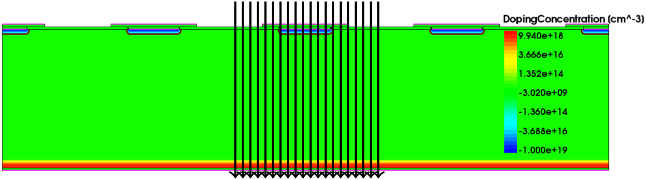
Sensor response simulation

Motivation

- For overall detector performance, 7 µm single point resolution in main tracker required
- How to achieve? What kind of sensor technology? What readout cell size is needed?
- Spatial resolution can be improved over the binary limit of $\frac{p}{\sqrt{12}}$, if charge is shared among two cells. Can we benefit from that?
- This study:
  - T-CAD simulation of sensor response
  - Implement a model to compare different sensor designs and readout schemes
  - Critera for comparison: efficiency, resolution and noise induced occupancy

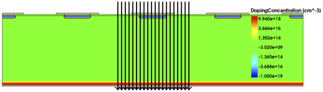
Sensor

- T-CAD finite element simulation of silicon sensor
- As starting point: p-in-n silicon strip sensor, best guess of process details, 2 dimensional cut, no B-field (yet)
- Simulate particle hit at several positions in the strip unit cell, fixed incidence angle
- Readout of current signal → integration over time → charge signal per strip

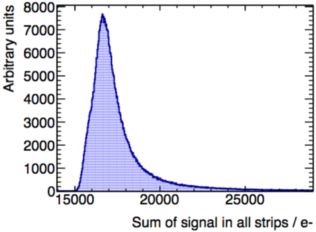


Toy monte carlo

Random position for incident particle, fixed angle



Landau distribution of charge

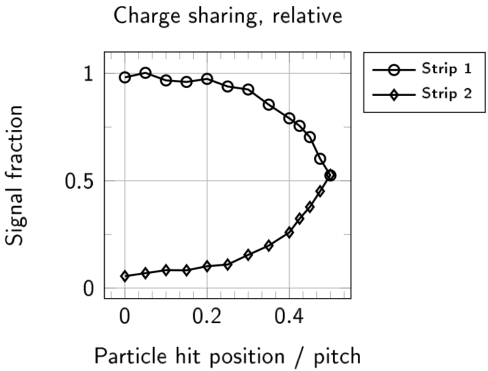


Toy monte carlo

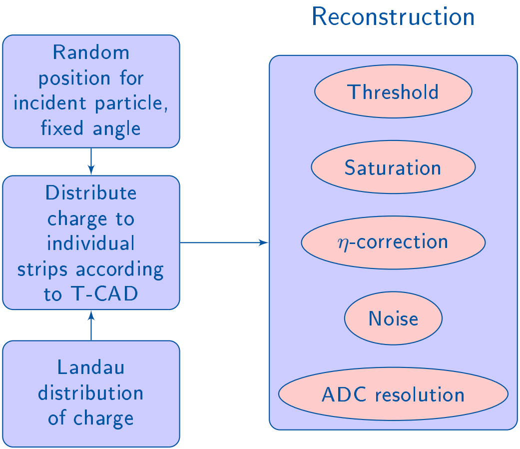
Random position for incident particle, fixed angle

Distribute charge to individual strips according to T-CAD

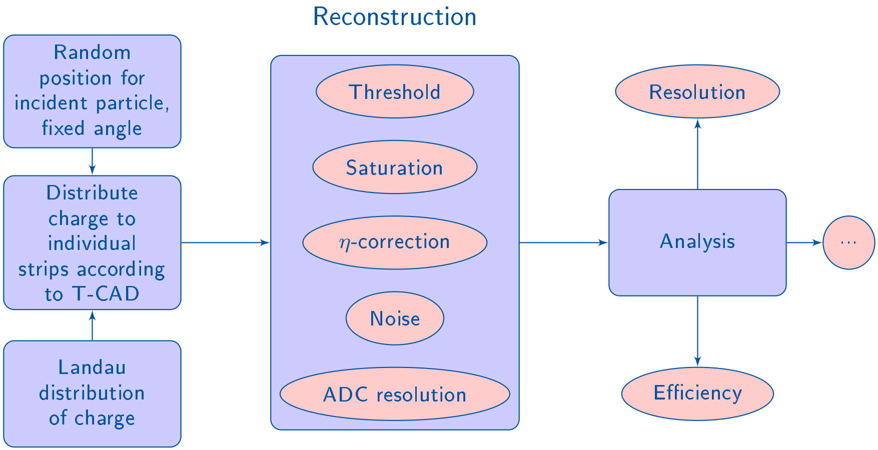
Landau distribution of charge



Toy monte carlo

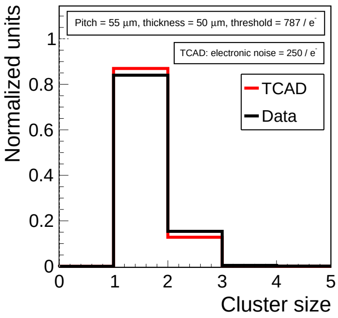


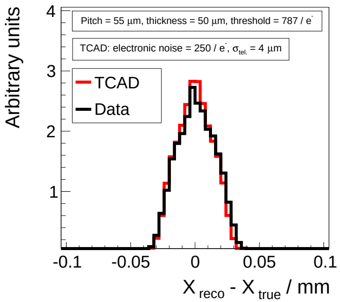
Toy monte carlo



Validation - perpendicular incident

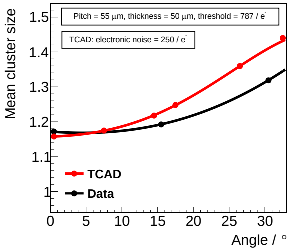
- Validation of simulation model using testbeam data taken with planar sensors on timepix readout chips at DESY



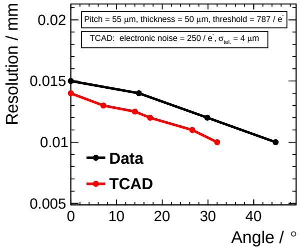


- Reconstruct particle hit position, center of gravity or η-method
- Calculate residual distribution by comparison to MC-truth particle hit
- Emulate telescope track resolution
- Good agreement to testbeam data

Validation - angular dependence

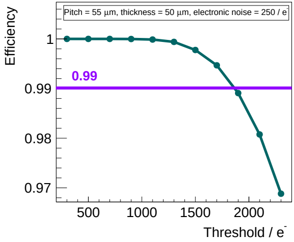


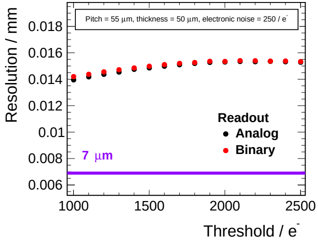
- Clustersize as function of incidence angle
- Geometric effect: clusters are larger with inclination
- Good agreement to testbeam data

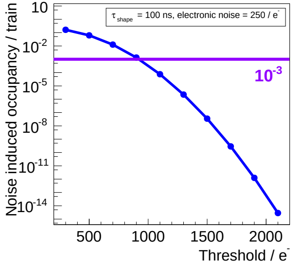


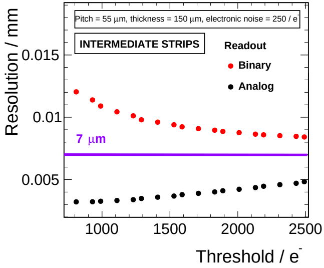
- Resolution as function of incidence angle
- Increased charge sharing in thin sensors results in better resolution
- Good agreement to testbeam data

Exemplary simulation results









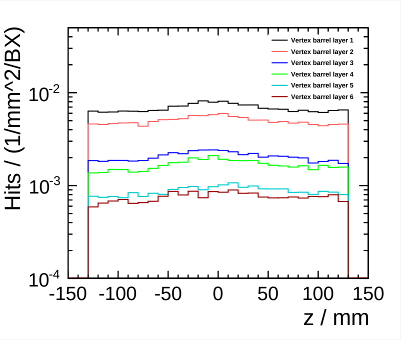
Summary

- Layout optimization using LiC toy fast simulation
  - Variation of tracker layout
  - Estimation of momemtum and impact parameter resolution
  - Realistic scaling for material budget of supports, cables and cooling
- Occupancy due to beam induced background restricts the maximal strip length in the main tracker
  - Few millimeters in the inner layers
  - Few centimeters in the outer layers
- Simulation study of silicon sensor response
  - Detailed T-CAD simulation of sensor response to particle hit
  - Toy model allows estimation of efficieny and resolution as function of operation parameters
  - However, planar sensors may not be the final answer for the main tracker
  - $\Rightarrow$ Possibility to look at other technologies (e.g. HV-CMOS) by replacing T-CAD simulation part

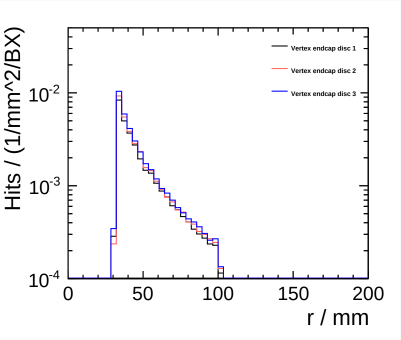
Backup

Hitrate in VXD

Barrel



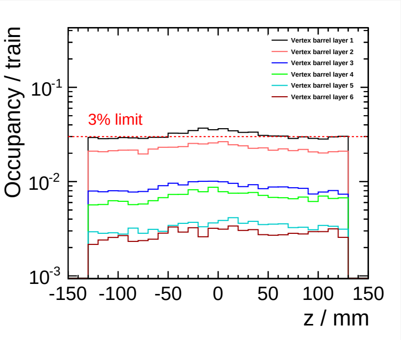
Endcap discs



- No z-dependence, steep fall-off in r

Occupancy in VXD

Barrel



Endcap discs