

Tracker-technology R&D for CLIC

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on behalf of the CLICdp collaboration

International Workshop on Future Linear Colliders 2015
Whistler, Canada
05. 11. 2015



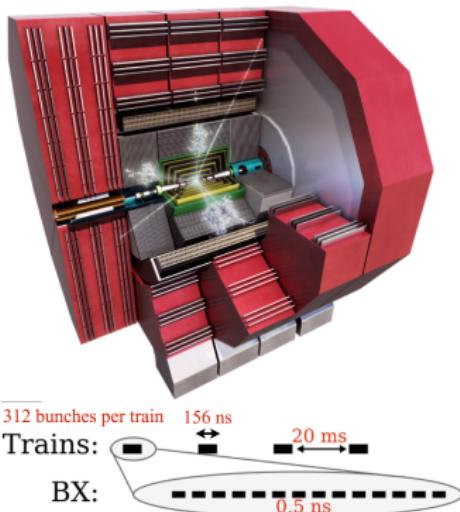
Outline

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



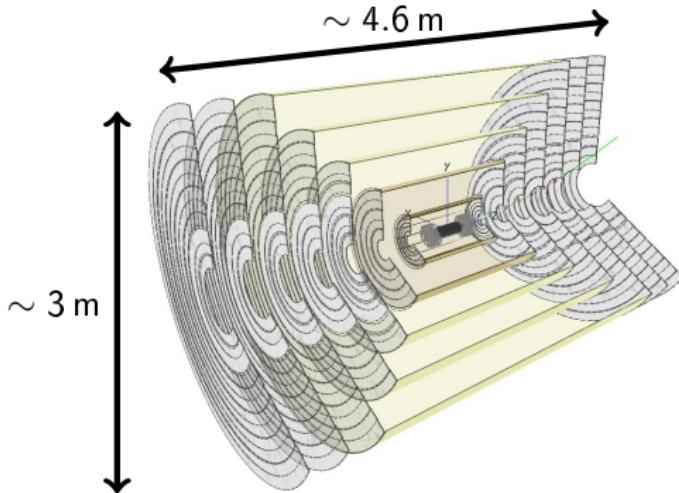
CLIC detector in a nutshell

- ▶ High precision:
 - ▶ jet energy resolution - $\sigma_E/E \sim 3.5\% - 5\%$
 - ▶ fine grained calorimetry - 13 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 - $3 \gamma\gamma \rightarrow \text{hadron}$ events per bunch crossing
 - ▶ requires precise timing $\leq 10 \text{ ns}$
 - ▶ pixel size $25 \times 25 \mu\text{m}^2$
- ▶ No issues from radiation damage:
 - ▶ 10^{-4} LHC levels
 - ▶ except for small forward calorimeters
- ▶ No trigger, full readout of 156 ns bunch train



Silicon tracker

- ▶ All silicon tracker
 - ▶ Evolving layout:
 - ▶ 5 barrel layers, 7 endcap discs
 - ▶ Radius ~ 1.5 m, half-length ~ 2.3 m
 - ▶ Operated in a 4 T magnetic field
 - ▶ 7 μm single point resolution
 - ▶ 10 ns timestamping
- ▶ High occupancy in certain regions calls for short strips and/or large pixels
- ▶ Very light, $\sim 2 \% X_0$ per layer
 - ▶ Requires very thin materials/sensors
 - ▶ Can take advantage from power-pulsing
 - ▶ Air cooling not possible (unlike CLIC vertex detector)



Sensor response simulation



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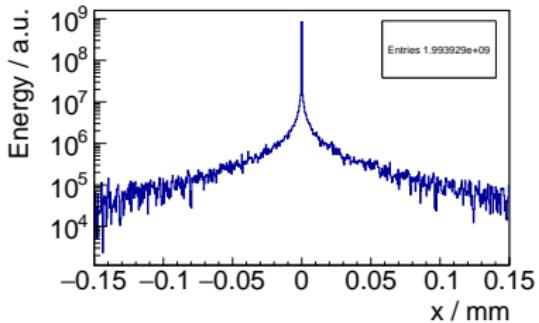
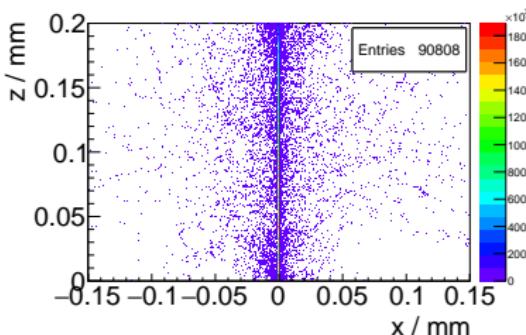
Motivation

- ▶ For overall detector performance, $7\text{ }\mu\text{m}$ single point resolution in 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 in thin sensors?
- ▶ Do we benefit from analog energy information?
- ▶ This study:
 - ▶ Energy deposition simulated by Geant4
 - ▶ T-CAD finite-element simulation of sensor response
 - ▶ Parametric model of front-end electronics



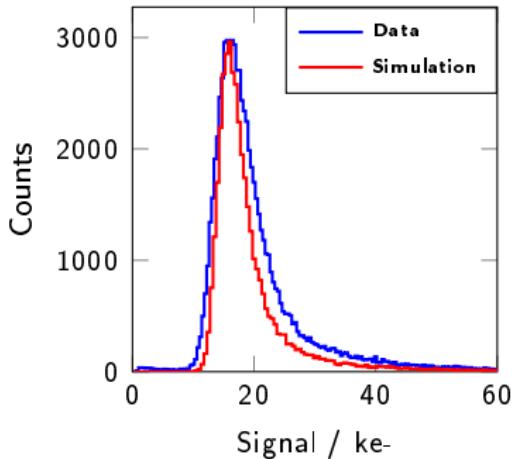
Energy deposition simulated by Geant4

- ▶ 200 μm thick piece of silicon
- ▶ 5 GeV electrons (DESY testbeam)
- ▶ Small range cut for production of secondary particles
- ▶ High spacial granularity for energy deposition
- ▶ Use average over many particle hits as input for T-CAD simulation



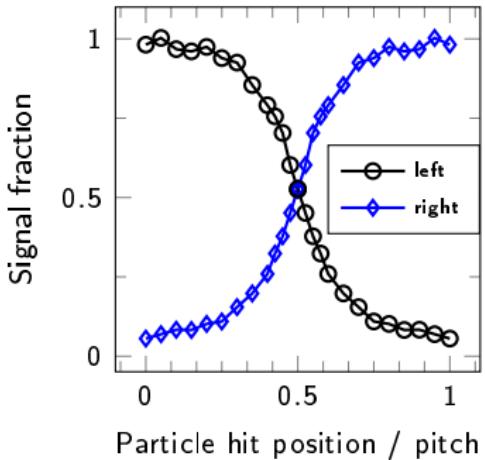
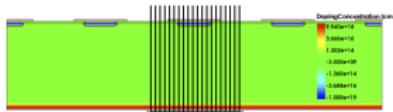
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- ▶ Use average over many particle hits as input for T-CAD simulation
- ▶ Signal distribution in good agreement to data, no electronics effects included in simulation



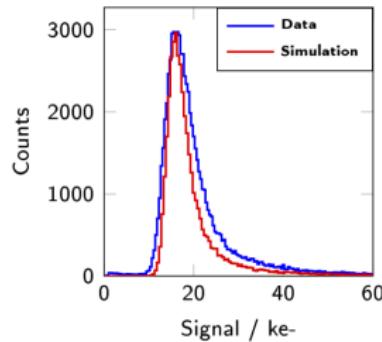
Sensor simulation using T-CAD

- ▶ T-CAD finite element simulation of silicon sensor using Geant4 results as input
- ▶ As starting point: p-in-n planar silicon sensor, 2 dimensional cut, possibility to include magnetic field
- ▶ Simulate particle hit at several positions in the unit cell, fixed incidence angle
- ▶ Readout of transient current → integration → charge signal per strip
- ▶ Realistic description of charge sharing

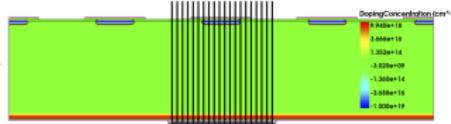


Event generation using parametric model of front-end electronics

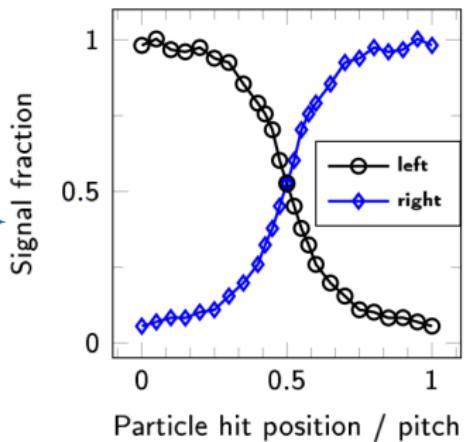
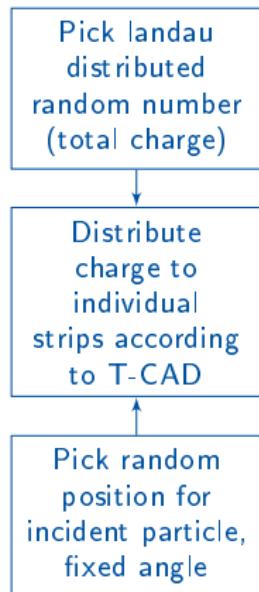
Pick landau distributed random number (total charge)



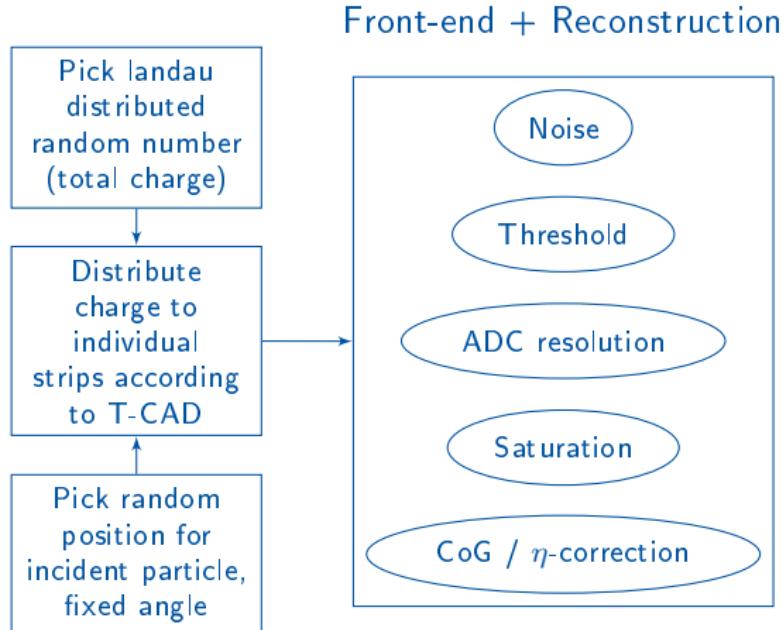
Pick random position for incident particle, fixed angle



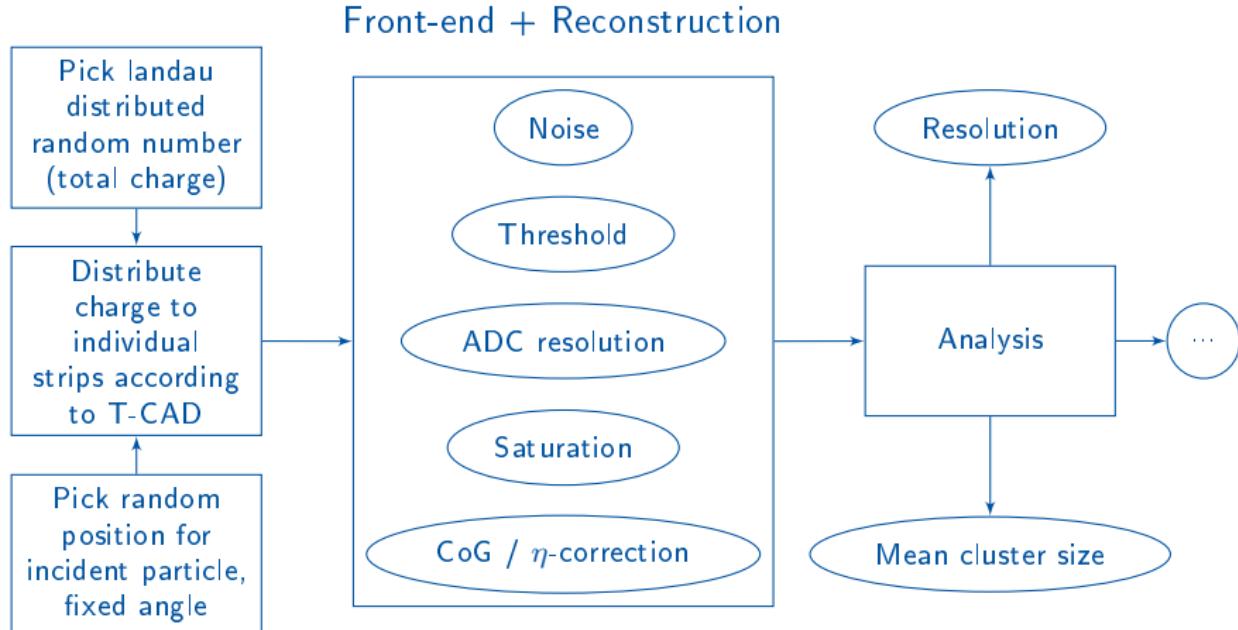
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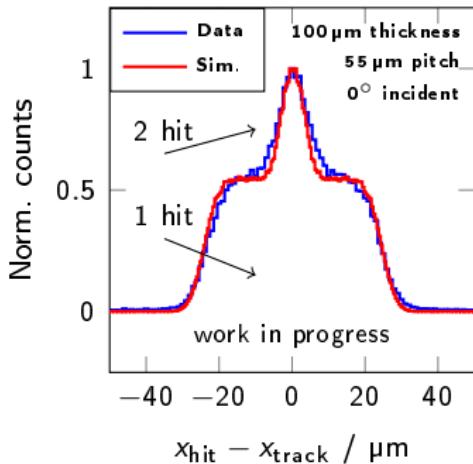
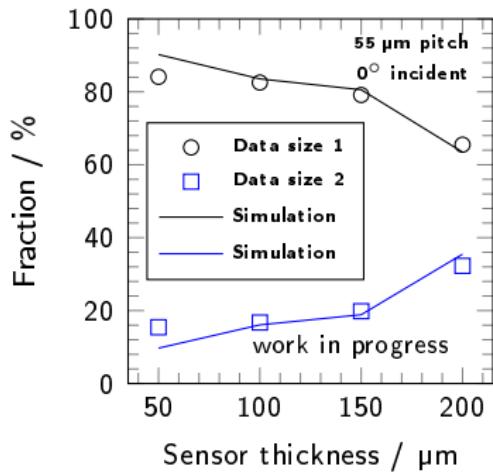


Event generation using parametric model of front-end electronics



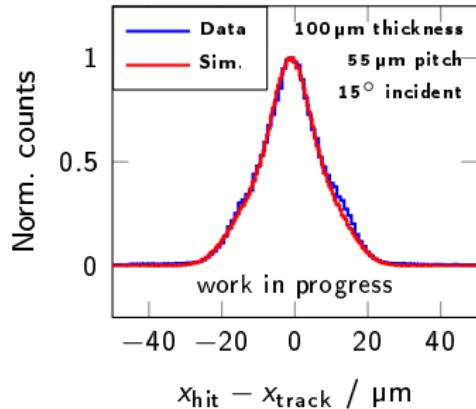
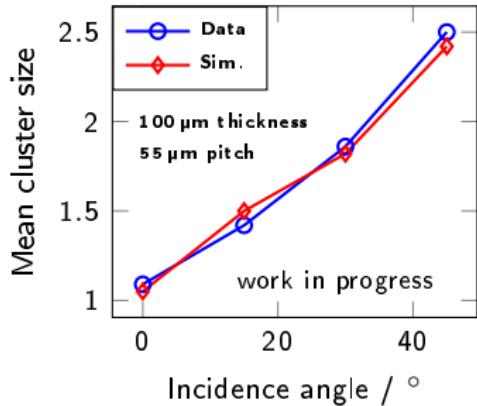
Validation - perpendicular incidence

- ▶ Validation of simulation model using test-beam data taken with planar sensors on Timepix readout chips at DESY (see talk by S. Redford on Wednesday)



- ▶ Good agreement with test-beam data

Validation - angular dependence



- ▶ Cluster size as function of incidence angle
- ▶ Geometric effect: clusters are larger with inclination
- ▶ Good agreement with test-beam data
- ▶ Residual distribution at 15°
- ▶ Good agreement to testbeam data, if longer pathlength in material is taken into account



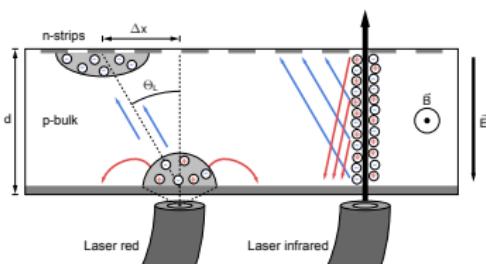
Magnetic field - Lorentz angle

- ▶ Drifting charge is deflected by Lorentz force

$$\tan(\Theta_L) = \mu_H B = r_H \mu B = \frac{\Delta x}{d}$$

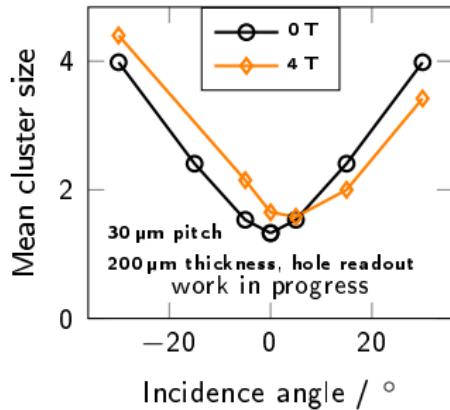
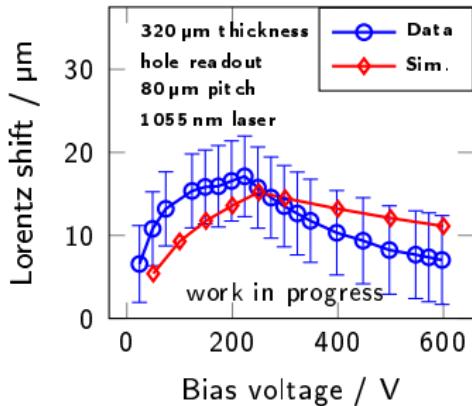
- ▶ μ_H mainly dependent on electric field and temperature
- ▶ Deflection angle results in a systematic shift of the reconstructed position
- ▶ In addition, influence on cluster size and resolution

- ▶ Measurement¹: create e-h pairs with laser pulse on sensor backside
- ▶ Determination of Lorentz shift from reconstructed position of charge as function of
 - ▶ Magnetic field
 - ▶ Bias voltage
 - ▶ Temperature



¹Studies on irradiated silicon sensors for the CMS Tracker at the HL-LHC, PhD thesis, A. Nürnberg, KIT, 2014, IEKP-KA/2014-04

Validation - Magnetic field

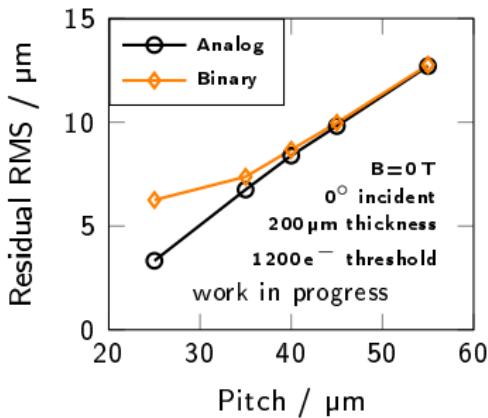
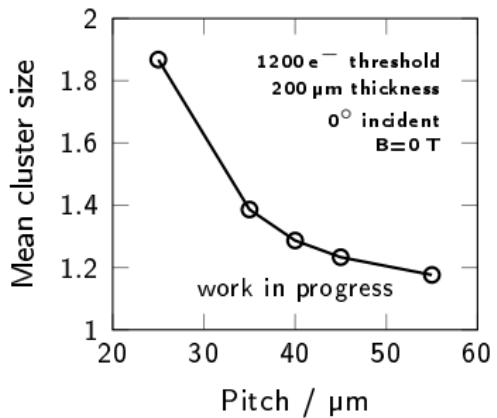


- ▶ Reproduce measurements with laser illumination
- ▶ Lorentz shift as function of applied bias voltage
- ▶ In agreement with measurement results
- ▶ Simulate particle incident with and without magnetic field
- ▶ At 4 T, minimal cluster size at incidence under the Lorentz angle, not at perpendicular incidence



Extrapolation: simulation results

- ▶ Simulation in good agreement to measurement results
- ▶ Possibility to extrapolate to different sensor geometries



- ▶ Increased charge sharing with lower pitch
- ▶ With charge sharing, benefit from analog readout
- ▶ Lower pitch and charge sharing results in better resolution

Beam induced background



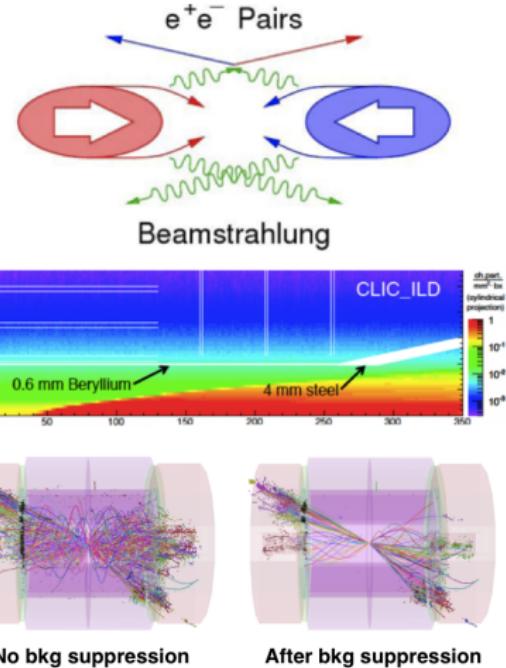
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Beam induced backgrounds

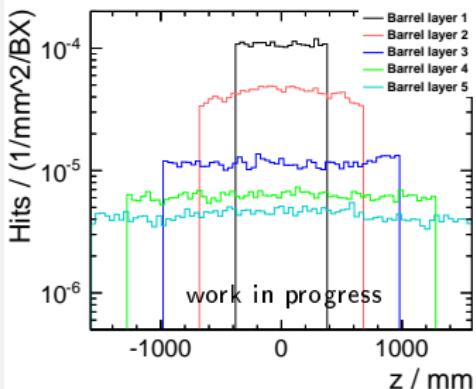
- ▶ Dense bunches, high energy, small transverse size leads to very high E-field, resulting in beamstrahlung
- ▶ Consequences:
 - ▶ beam-induced backgrounds: incoherent pairs, $\gamma\gamma \rightarrow$ hadron events
 - ▶ high occupancies drive small pixel/strip size for tracking
 - ▶ also geometric requirements on vertex detector inner radius
 - ▶ background energy deposits drive small cell size for calorimetry
 - ▶ high precision timing



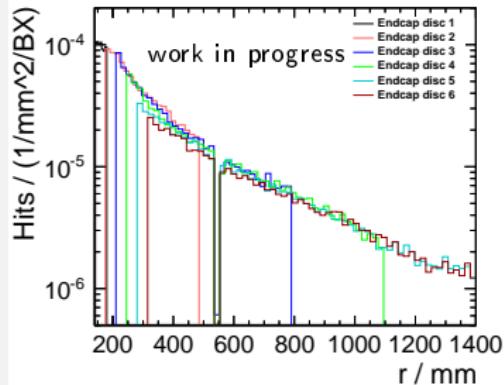
Hit-rate in main tracker

- ▶ Full Geant4 based detector simulation (Mokka)
- ▶ Evaluate hit-rate from beam induced background in the main tracker
- ▶ No digitization, no clustering, no safety factors

Barrel



Endcap discs

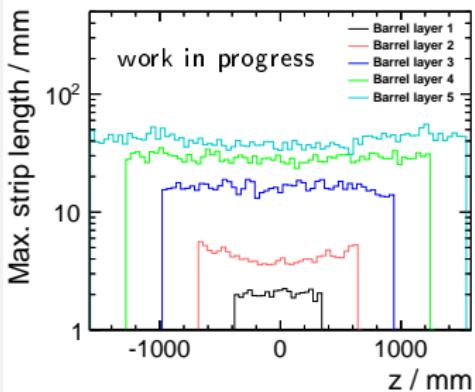


- ▶ Hit-rate depends strongly on radius, mostly independent of z-position

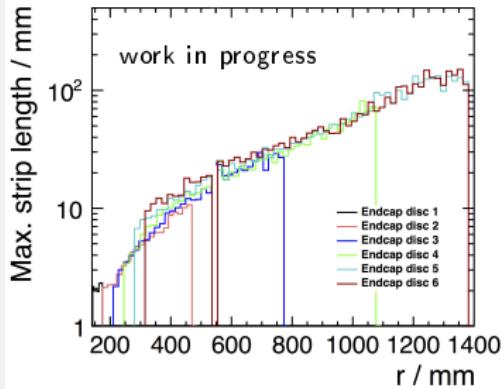
Max. strip length in the main tracker

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

Barrel



Endcap discs



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

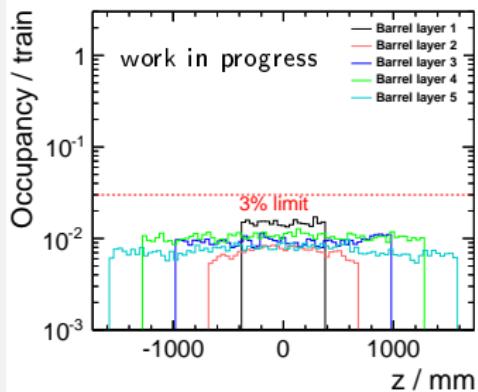


Working hypothesis on strip sizes

- ▶ 50 µm pitch in barrel and endcaps

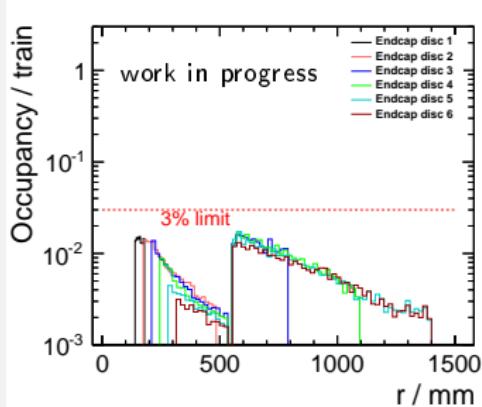
Barrel

Barrel layer	Strip length / mm
1 & 2	1
3	5
4 & 5	10



Endcap discs

- ▶ inner discs: 1 mm strips
- ▶ outer discs: 10 mm strips



Summary

- ▶ Simulation study of silicon sensor response
 - ▶ Simulation of energy deposit in silicon sensor using Geant4
 - ▶ T-CAD simulation of sensor response to particle hit, including Lorentz angle in the magnetic field
 - ▶ Monte-Carlo model allows estimation of performance parameters like resolution as function of operation conditions
 - ▶ Validation with test beam results taken on planar pixel sensors
 - ▶ However, planar sensors may not be the final answer for the main tracker
 - ▶ ⇒ Possibility to look at other technologies (e.g. HV-CMOS) by replacing T-CAD simulation part
- ▶ Occupancy due to beam induced background restricts the maximal strip length in the main tracker
 - ▶ Working hypothesis: 1 mm to 10 mm long strips in the main tracker

