Lorentz Angle Measurement in Irradiated CMS Pixel Sensors

Setup, Simulation and Results

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DESY CMS Pixel Group
5th Annual MT Meeting, Jena
06.03.2019

Motivation

- CMS Experiment
- Lorentz Angle

Measurement Setup

- Principle
- CMS Pixel Telescope
- Analysis

Simulation

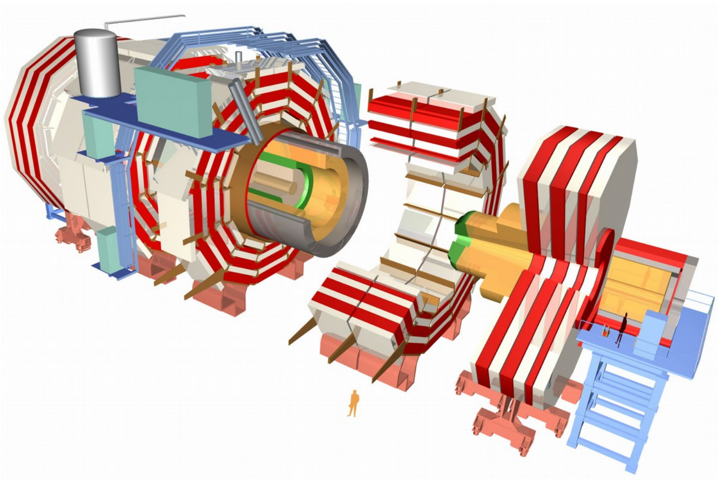
Results

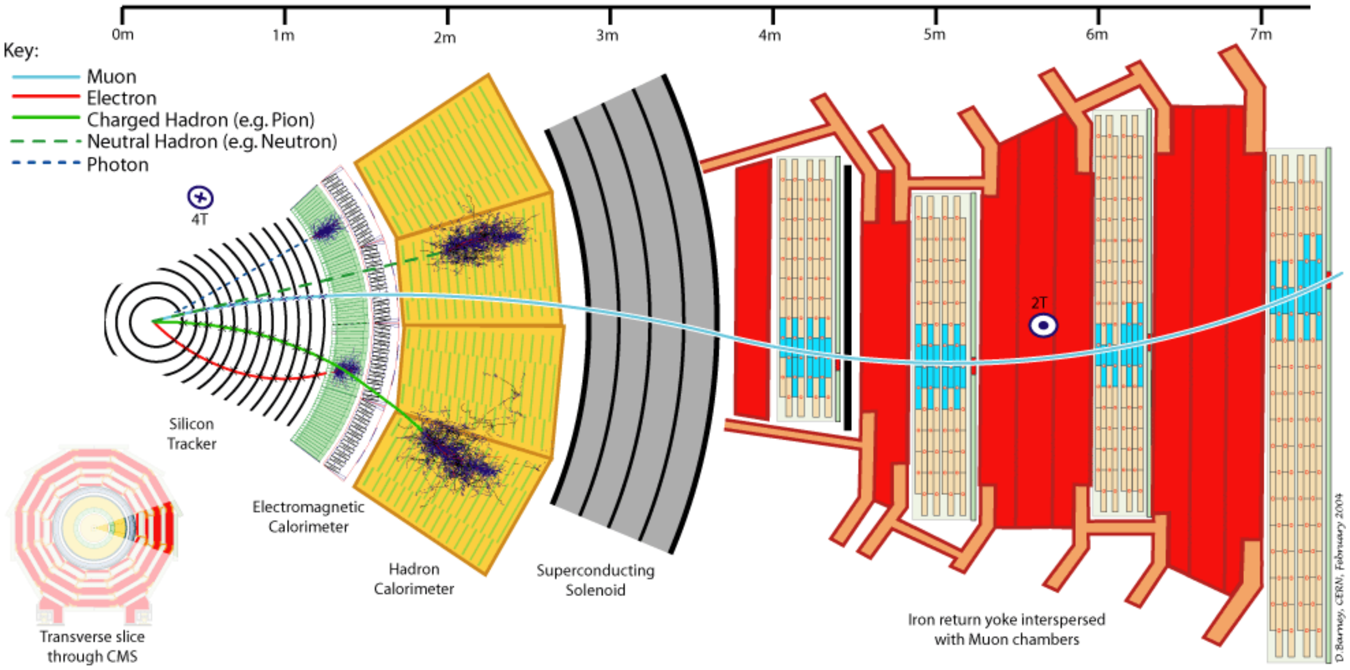
- Lorentz angle dependencies
- Extrapolation to CMS Operating Conditions

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CMS Detector

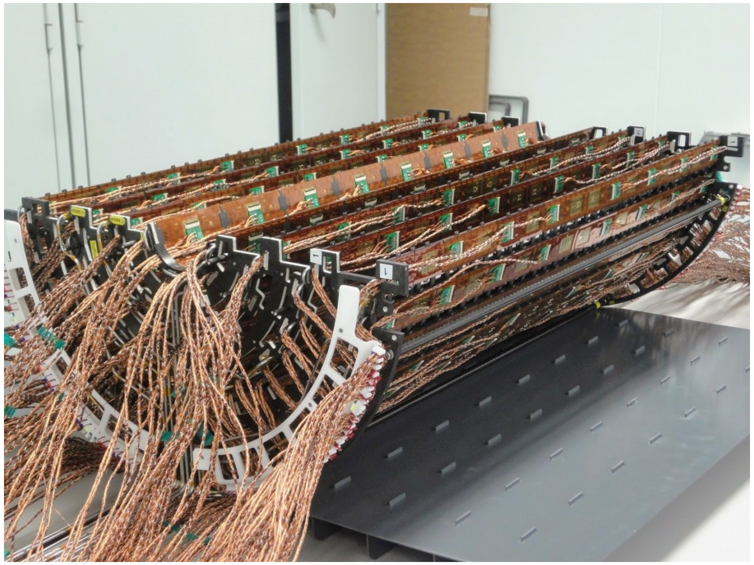
- General purpose detector at the LHC to measure the processes of high energetic particle collisions
- 3.8 T magnetic field
- Precision particle tracking with silicon sensors





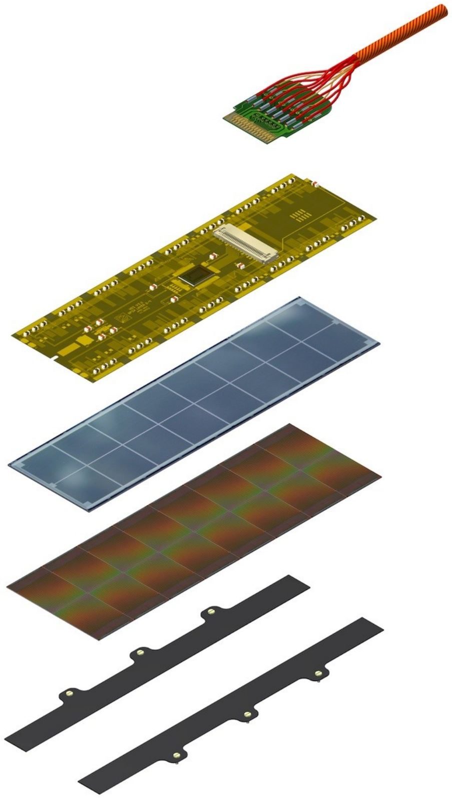
CMS Pixel Detector

- The innermost part of the CMS Detector is the Pixel Detector
- The Pixel Detector measures the particles track for information on …
  - the particle momentum
  - vertex positions (even more important for high pileup)
  - secondary vertices → B tagging
- Exchange of the Pixel Detector during the eYETS 2016/17
  - **4 Barrel Layers** + 3 Endcaps
  - Expected irradiation of $\Phi_{eq} = 1.5 \times 10^{15}$ n/cm^2 for the innermost layer



CMS Pixel Detector

- The CMS Barrel Pixel Detector module



Twisted pair cable

HDI (High Density Interconnect, signal and power handling)

n^+-in-n silicon sensor

16 readout chips, bump bonded to sensor

Base strips for mounting

- Sensor:
  - n^+-in-n sensor technology
  - 285 um thickness
  - 150 x 100 µm pitch
  - 52 x 80 = 4160 pixels/ROC
  - 16 ROCs → 4160 x 16 = 66560 pixels/module

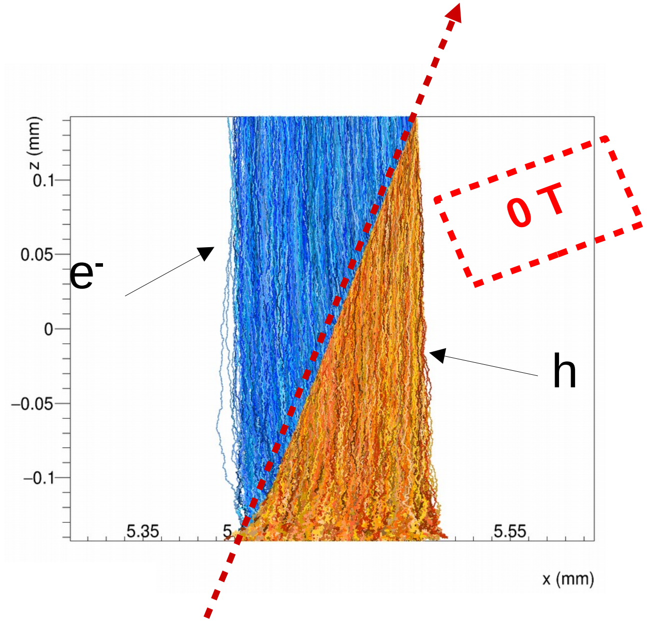
Pixel Detector Resolution

- Intrinsic resolution for binary readout tracking detectors: $\sigma = \frac{d}{\sqrt{12}}$

- Position resolution can be improved by charge sharing between multiple pixels

Solution 1:

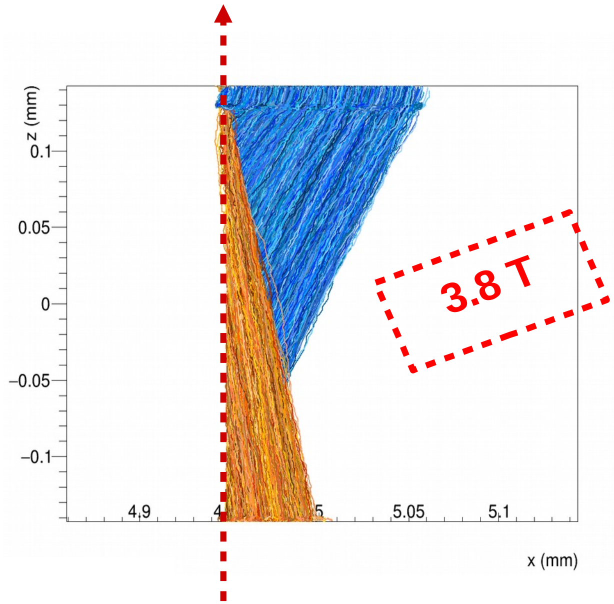
Inclined particle Incidence
(e.g. CMS Pixel Endcap)



Simulation:
AllPix^2

Solution 2:

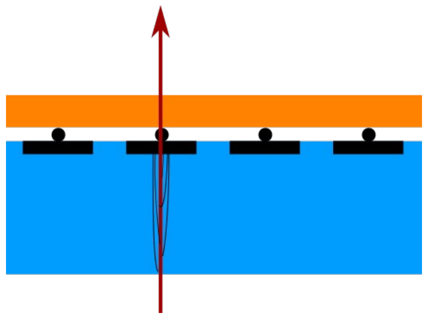
Lorentz Drift
(e.g. CMS Pixel Barrel)



Lorentz Angle

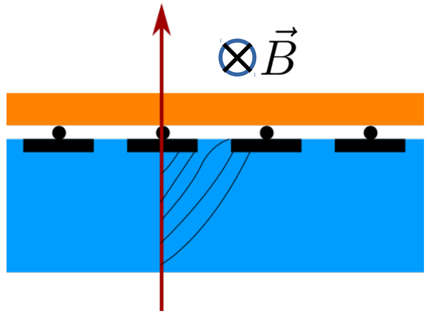
- Charge carrier drift inside the sensor without magnetic field:

$$\frac{d\vec{r}}{dt} = -\mu\vec{E}$$



- Charge carrier drift inside the sensor with magnetic field:

$$\frac{d\vec{r}}{dt} = \frac{\mu\left(-\vec{E} + \mu r_H \vec{E}\times\vec{B} - \mu^2 r_H^2\left(\vec{E}\cdot\vec{B}\right)\vec{B}\right)}{1+\mu^2 r_H^2 |\vec{B}|^2}$$



- In case of perpendicular electric & magnetic fields, there is an effective deflection with an angle of

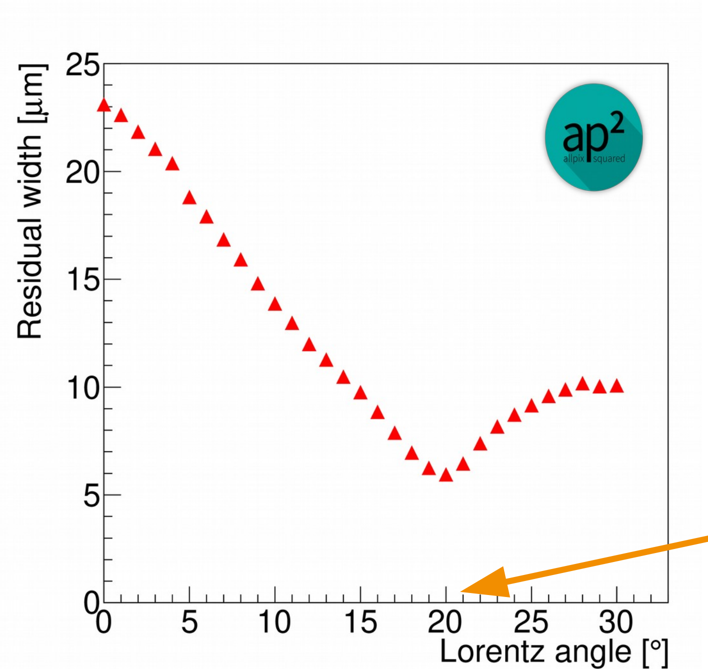
$$\tan(\theta_L) = r_H \mu B$$

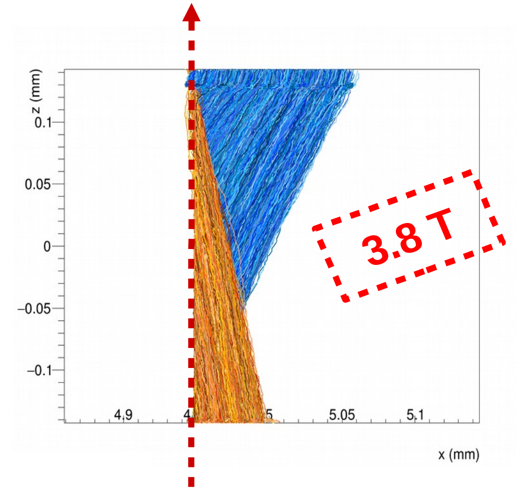
$\mu(\vec{E})$: Electron mobility
r_H: Electron Hall factor

Lorentz Angle

$\mu(\vec{E})$: Electron mobility
r_H: Electron Hall factor
w: Pixel pitch
d: Sensor thickness

- Effective Lorentz (deflection) angle: $\tan(\theta_L) = r_H \mu B$
- For the optimal resolution:
  - Charge sharing between two rows and/or columns:
  - Charge carriers are deflected by one pixel pitch: $\tan(\theta_L) = w/d$





Charge sharing
between two pixels
Lorentz angle: 19.3°

Measurement Setup

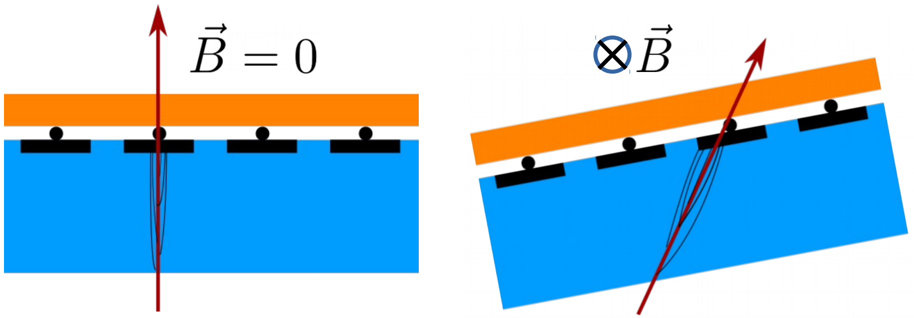
DESY II Test Beam Facility

CMS Pixel Telescope

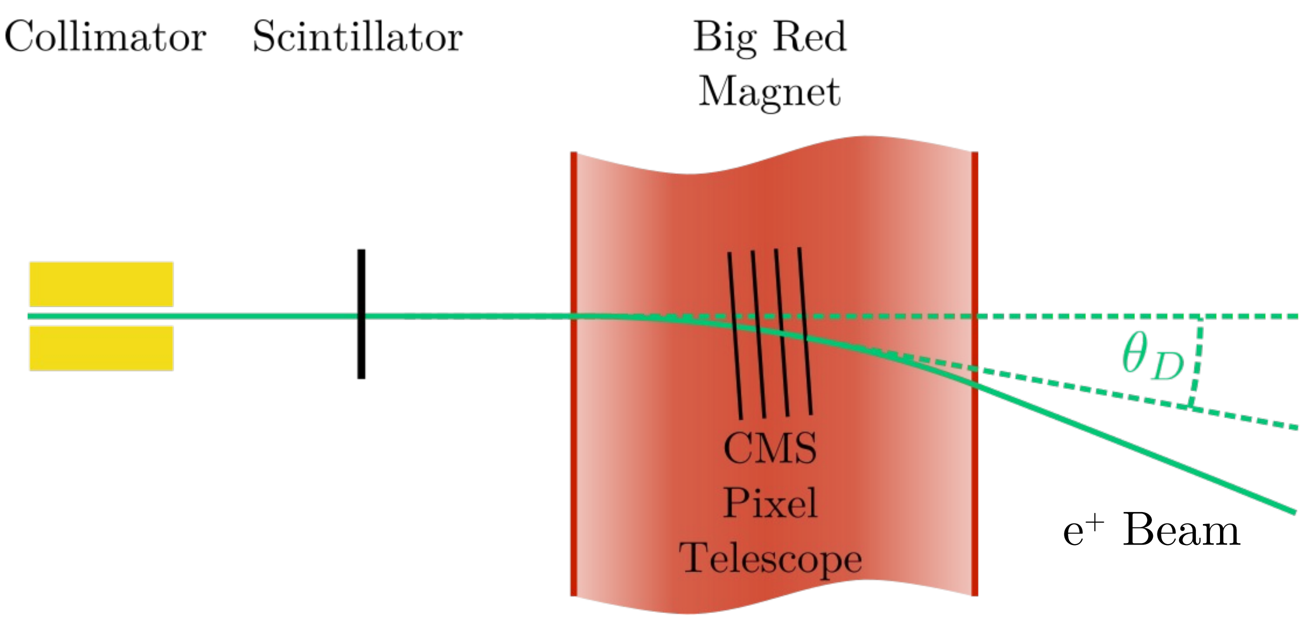
Analysis

Measurement Principle

- 2D scan:
  - Incidence angle (turn modules)
  - Magnetic field



- Find the track incidence angle resulting in the minimum horizontal cluster size for different magnetic fields



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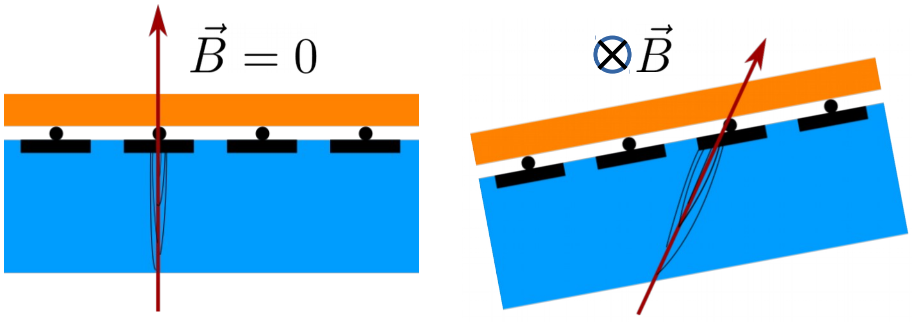

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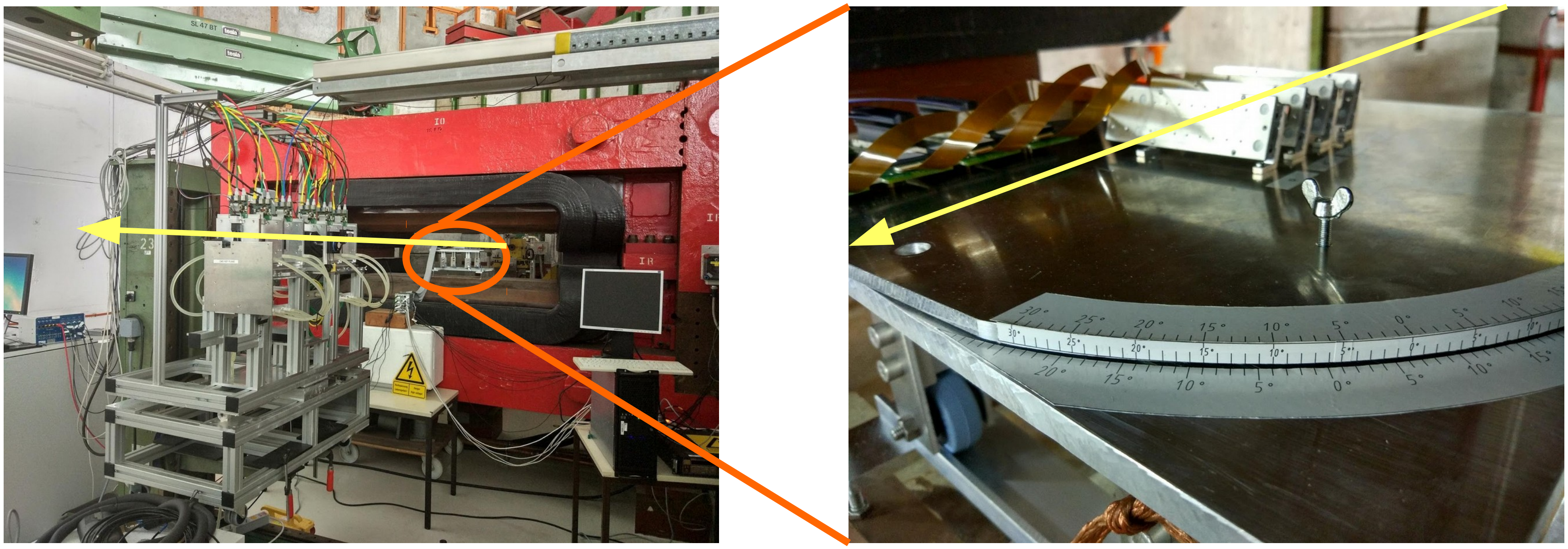
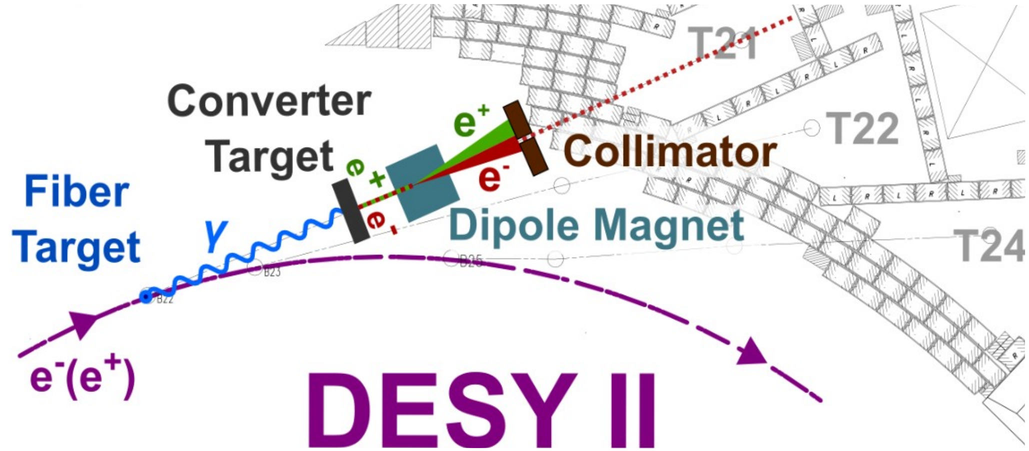
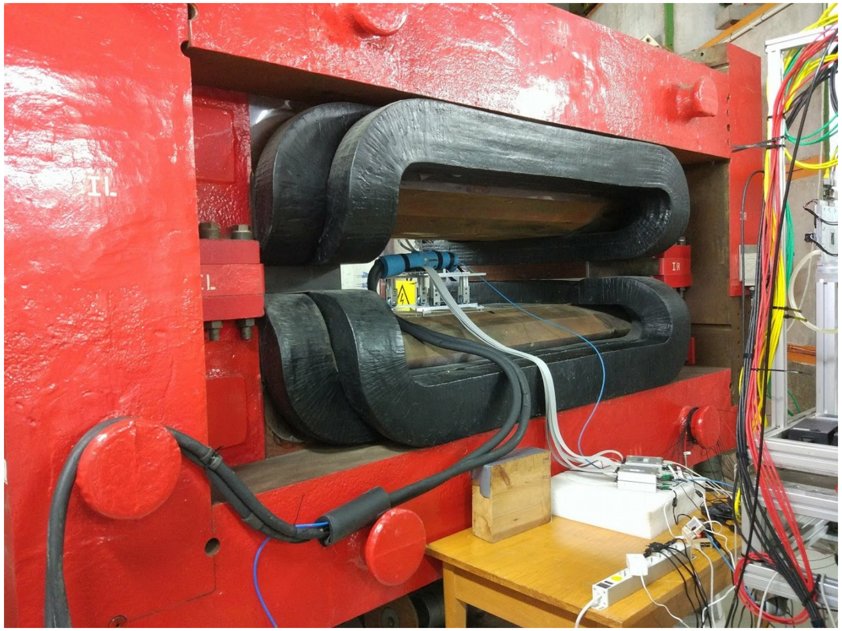


DESY II Test Beam Facility [1]

- Free positron or electron beams created from bremsstrahlung
- Energy: 1 – 6 GeV
- Particle rate: < 50 kHz (energy dependent)
- Three beam lines available
- This measurement:
  - TB 21
  - 5.6 GeV positrons
  - ~ 1 mrad angular spread
  - 1.35 T dipole magnet

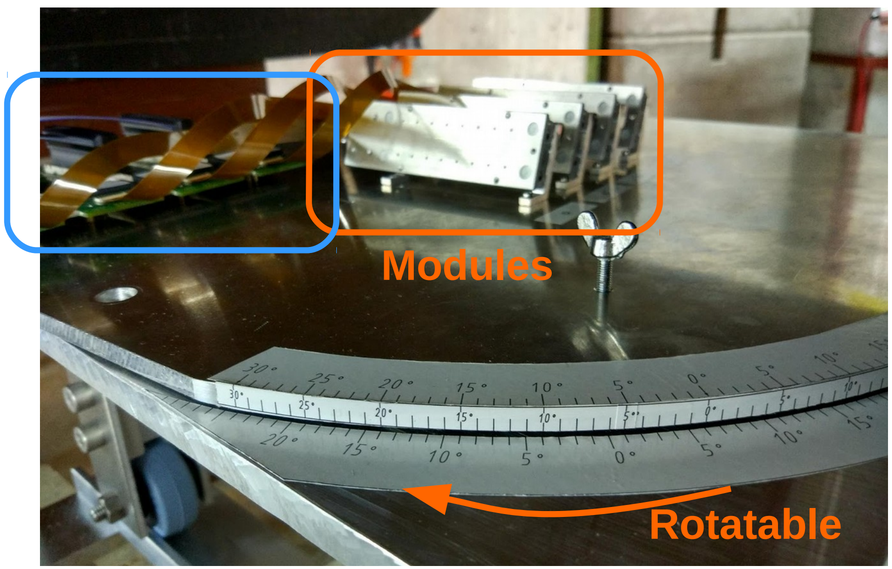


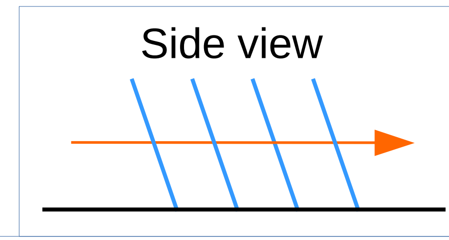


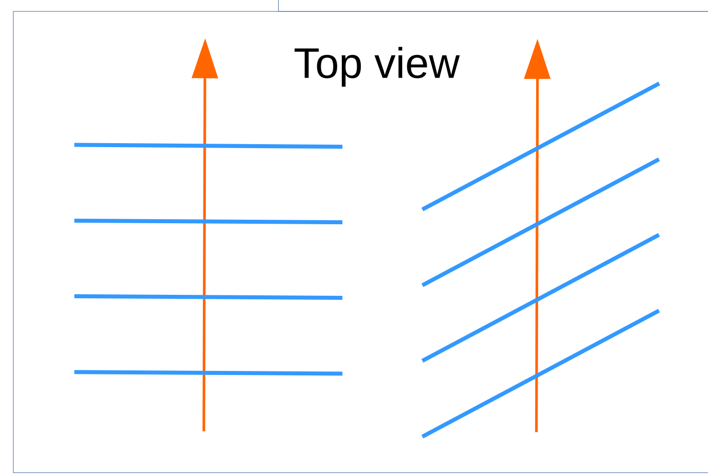
[1]: http://testbeam.desy.de

CMS Pixel Telescope

- CMS Pixel Telescope for use in the Test Beam:
  - 4 modules, 32 mm spacing
  - 19° tilt (optimal charge sharing, y), 0° or 27° turn (optimal charge sharing, x)
  - Cut out module handles for the reduction of material budget
  - Rotatable around y-axis (turn) and movable along x-axis
  - Use of non-magnetic materials







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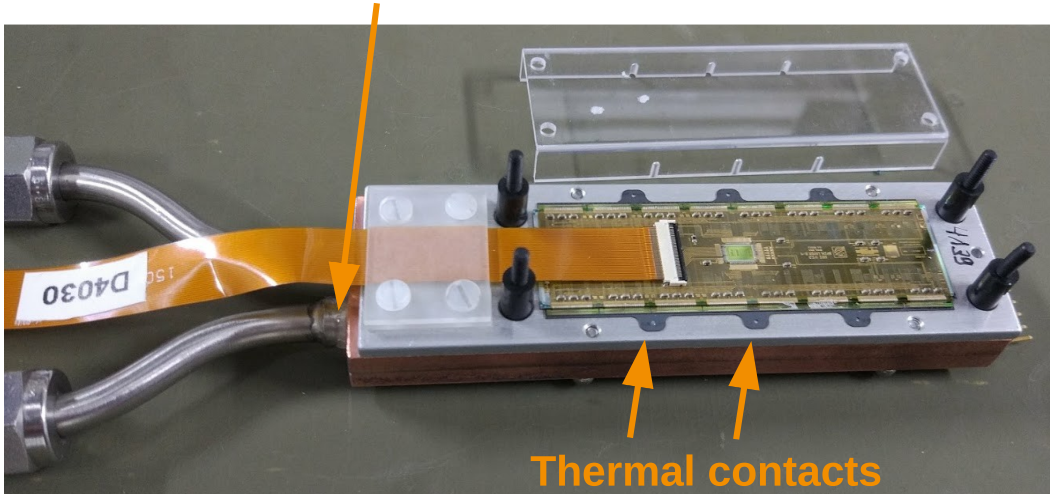
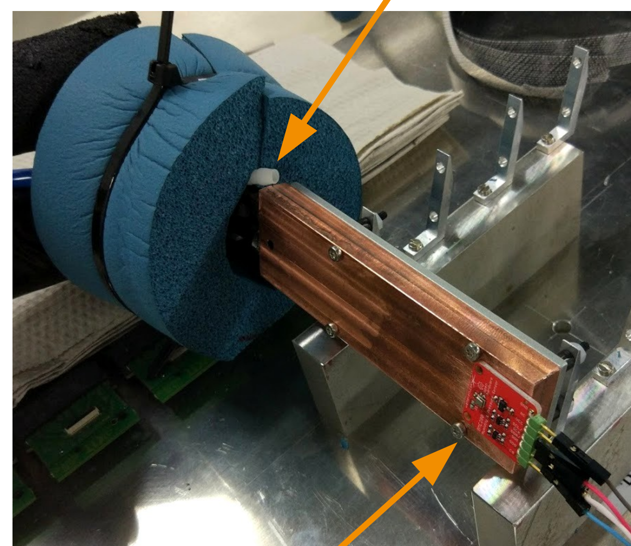
  - **Isolation and ethanol cooling for last module**





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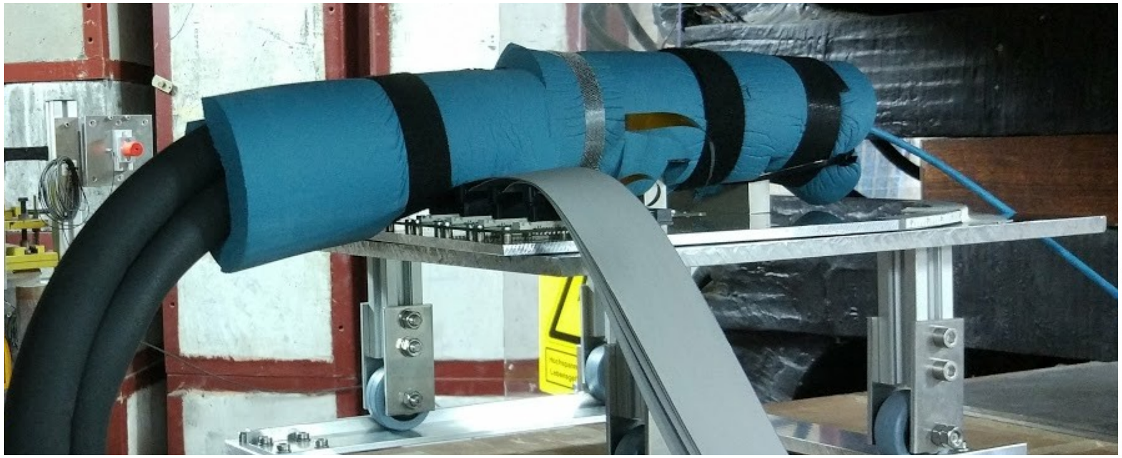

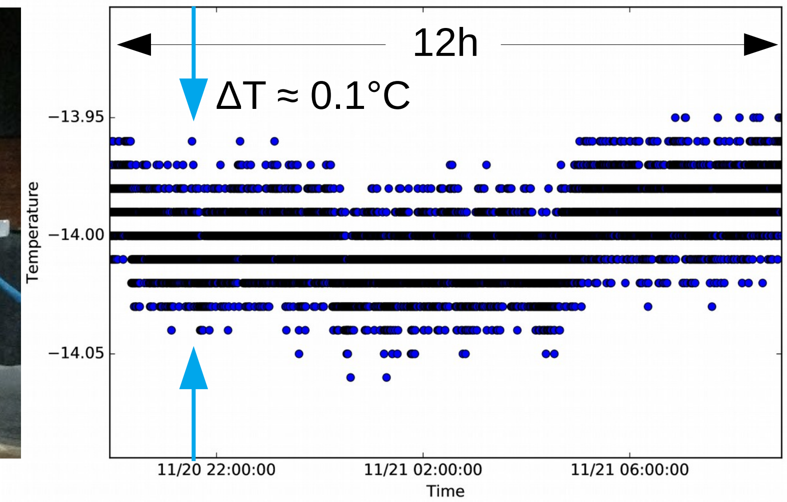

Tested Modules

- Eff. Lorentz angle measured at the following conditions:
  - Unirradiated:
    - +20°C, 150 V
    - -14°C, 150 V
    - -14°C, 250 V
    - -14°C, 350 V
  - Irradiated:
    - -14°C, 200 V
    - -14°C, 400 V
    - -14°C, 600 V

Tested Modules

Thanks to T. Weiler et al. @KIT for providing the irradiated module!

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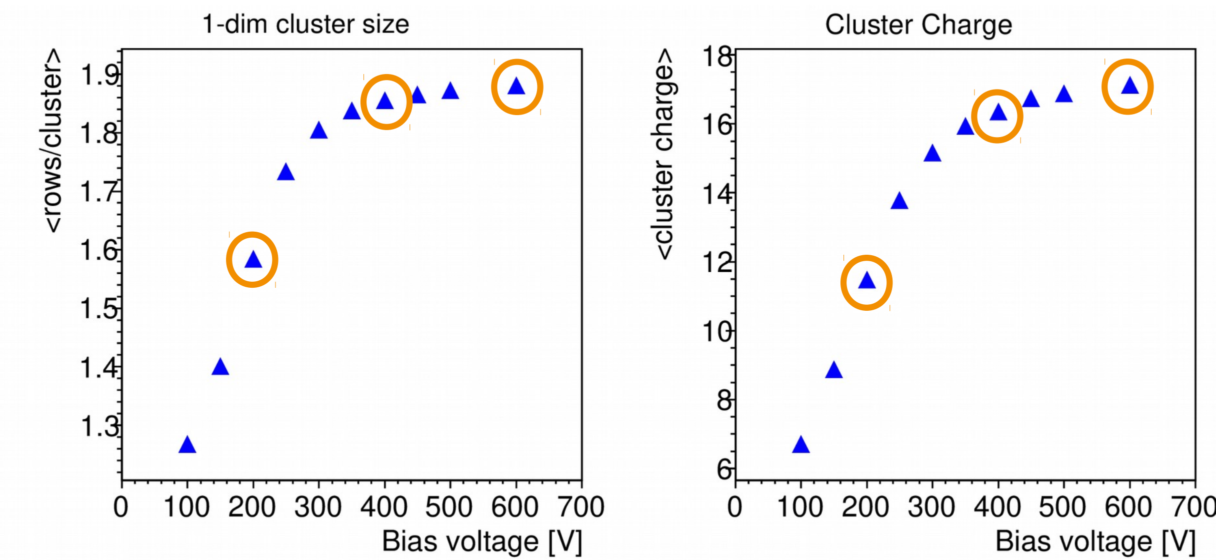
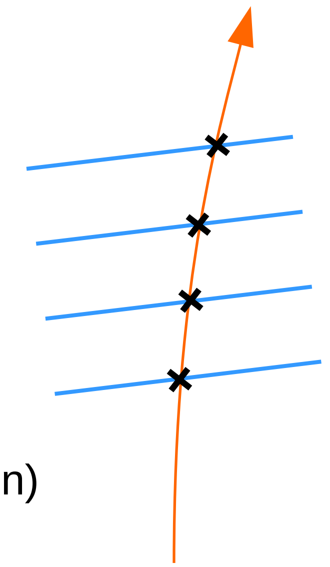


- Irradiated Module:
  - Fluence: Φ_{eq} = 4 x 10^{14} n/cm^2 (25 MeV protons @ KIT)
  - Tested and calibrated → One ROC faulty
  - Performed bias scan

Measurement / Analysis

- Per measurement of the Lorentz Angle:
  - Perform runs at various rotation angles to find the angle with the minimal cluster size ...
  - … for different magnetic fields



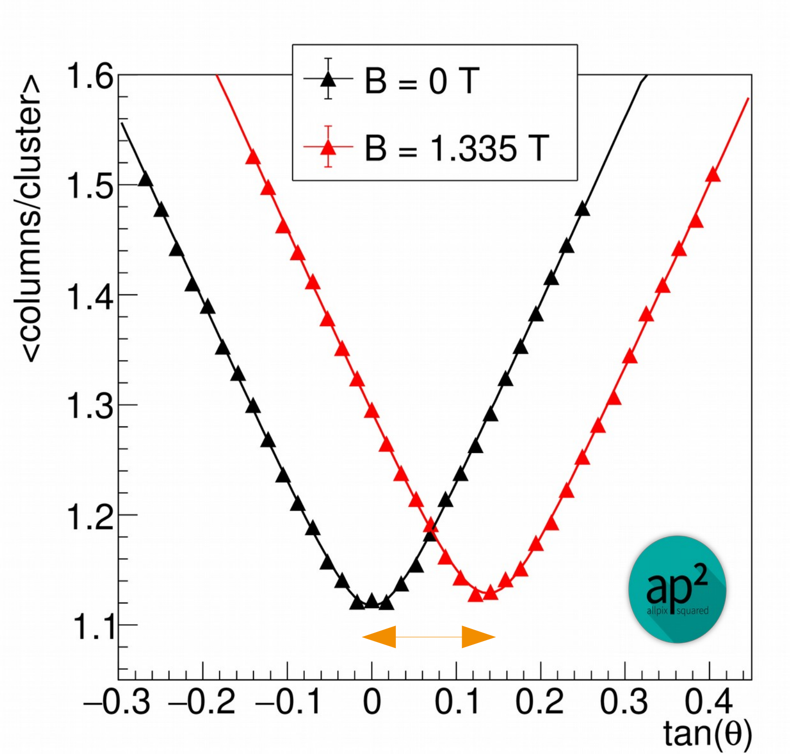
- Extraction of the Lorentz angle from data:
  - Particle incidence angle
    - Rotation of the telescope (determine from alignment)
    - Particle deflection in the magnetic field (measurement + simulation)
  - Projected cluster size
    - Select hits belonging to a reconstructed trajectory
    - Track finding via linear fit and fitting viaGeneral Broken Lines (GBL)
  - Plot cluster size vs. incidence angle for each magnetic field value

Measurement / Analysis

- Plot cluster size vs. incidence angle for each magnetic field value
- Perform fit to the data sets for each magnetic field

$$f(x) = p_0 + \sqrt{p_1^2 + p_2^2(x - x_{min})^2},\ x = \tan(\theta)$$

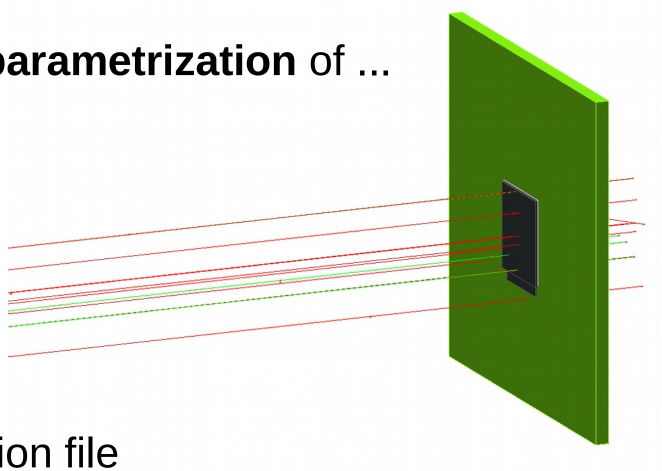
- The distance between the minima describes the effective Lorentz angle



Simulation

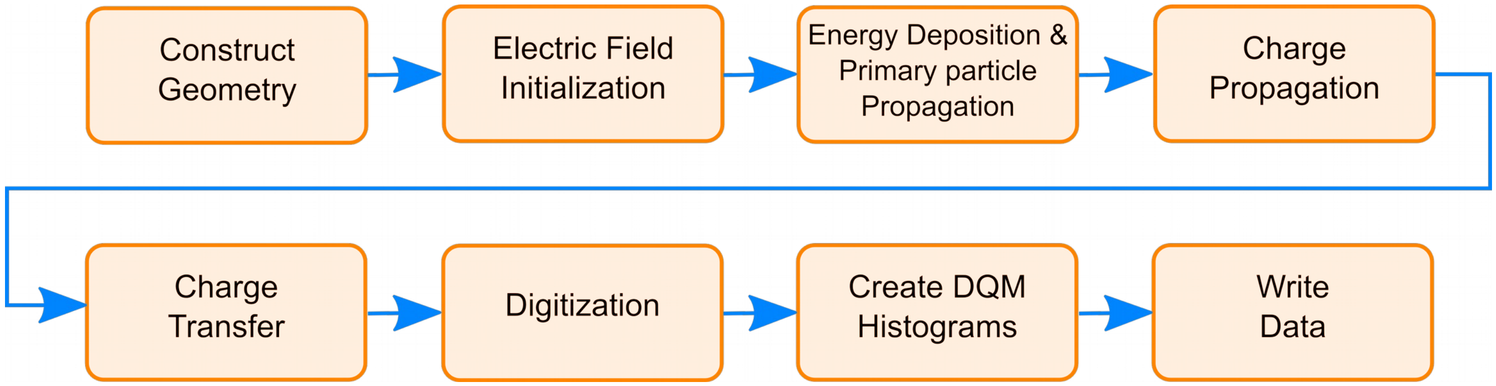
Allpix^2

Simulation – Allpix²



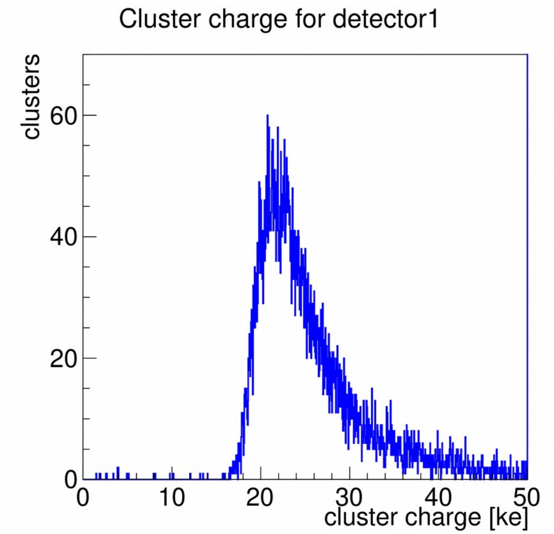
- Simulation of pixel detector responses for **testing** and the **parametrization** of ...
  - simulation models
  - detector/sensor models
  - experimental setups

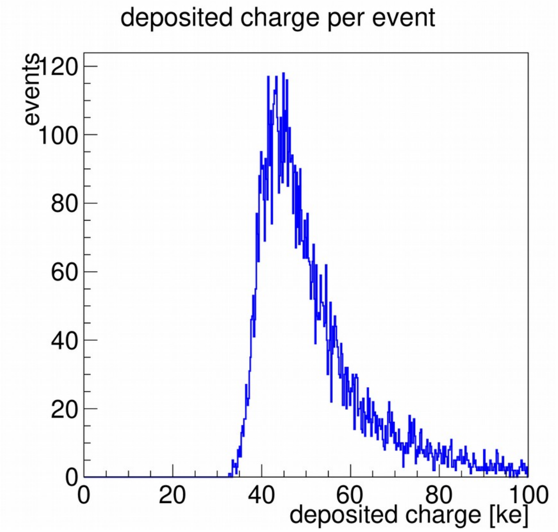
- The **workflow** is configurable by the user via the configuration file
- **Modules** are executed sequentially, each performing one specific task
  - Triggered by messages received from other modules

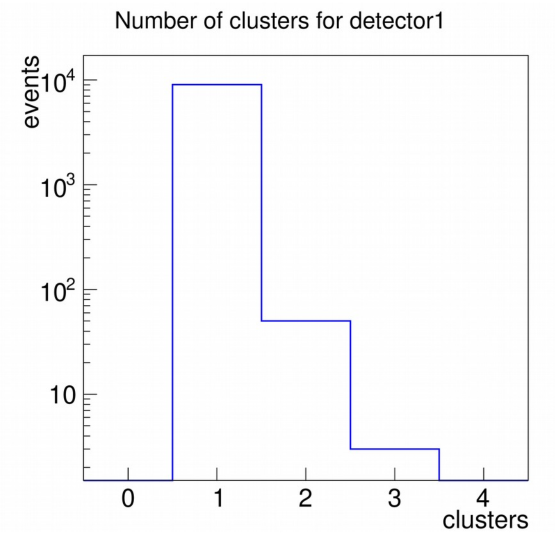


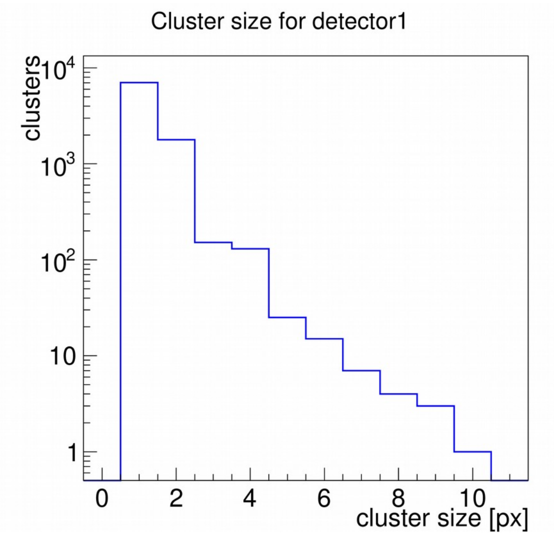
Simulation – Allpix²

- Detector output distributions





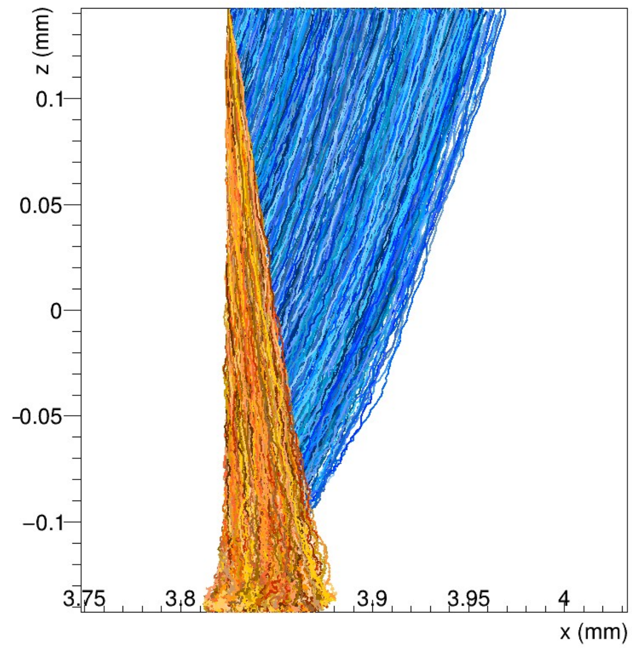


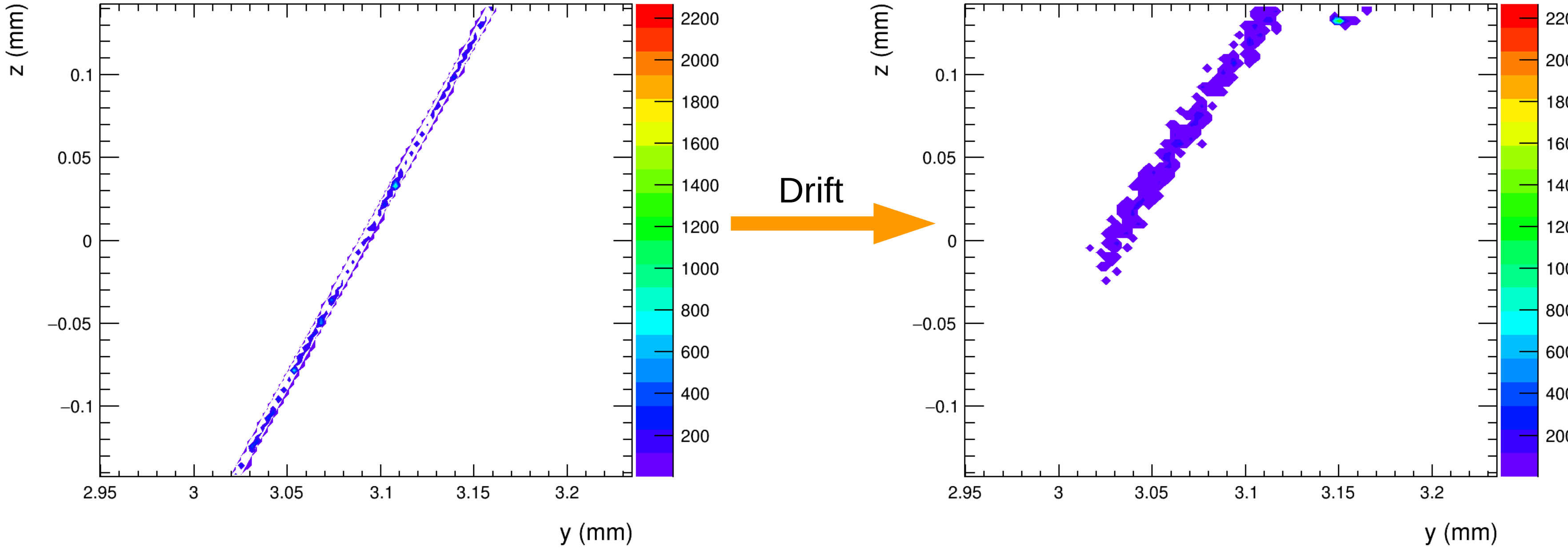


and many more...

Simulation – Allpix²

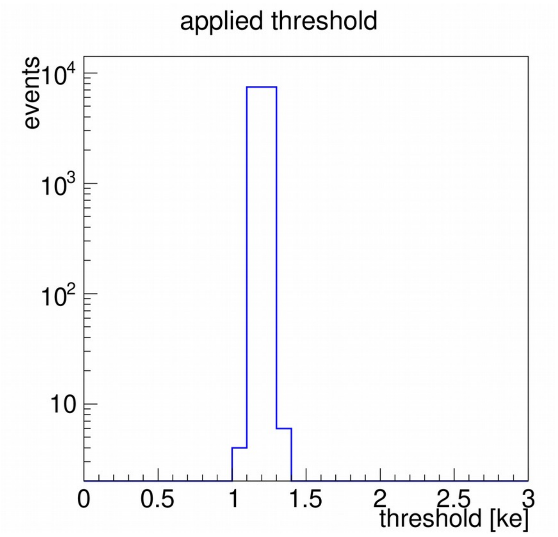
- Detector output distributions
- Information on charge carrier drift

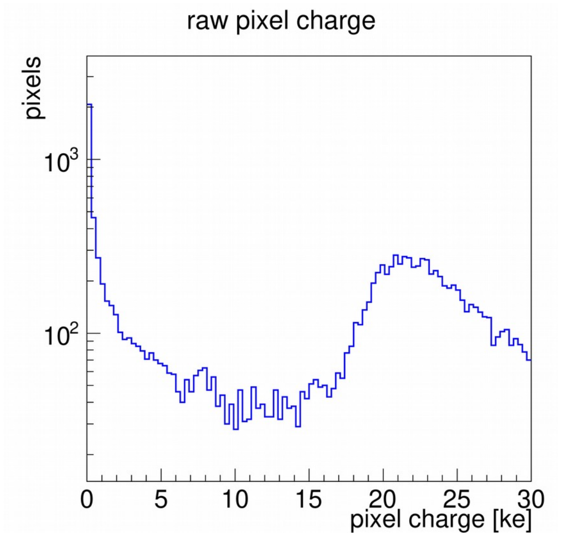


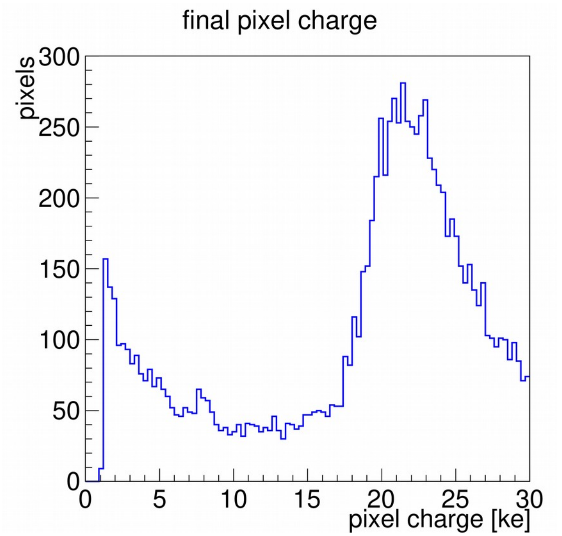


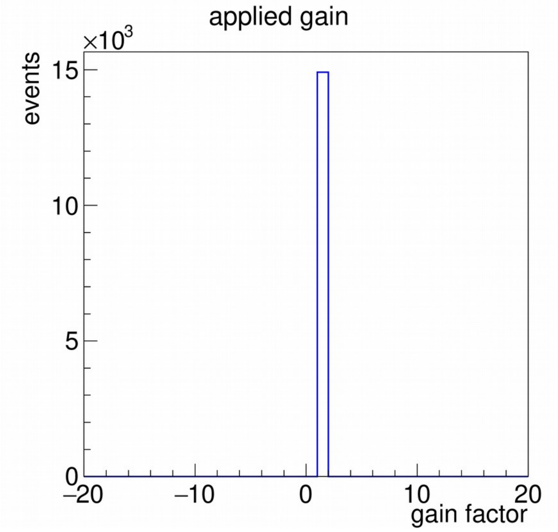
Simulation – Allpix²

- Detector output distributions
- Information on charge carrier drift
- Information on digitization process







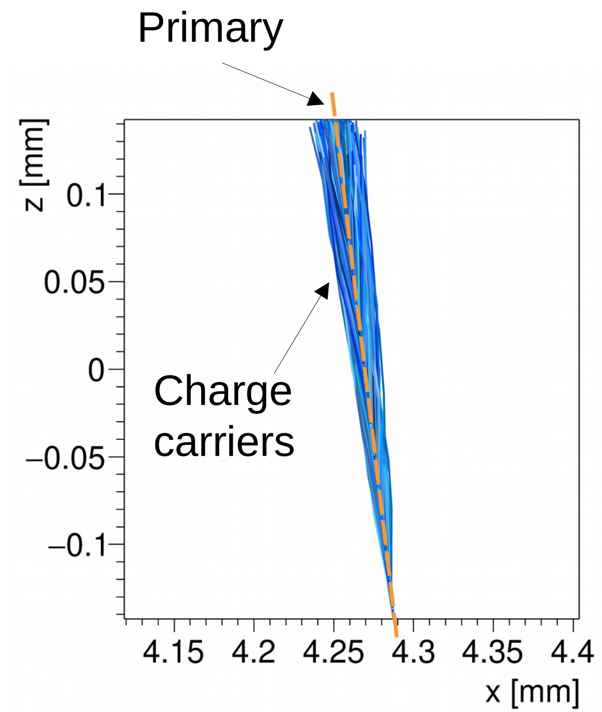


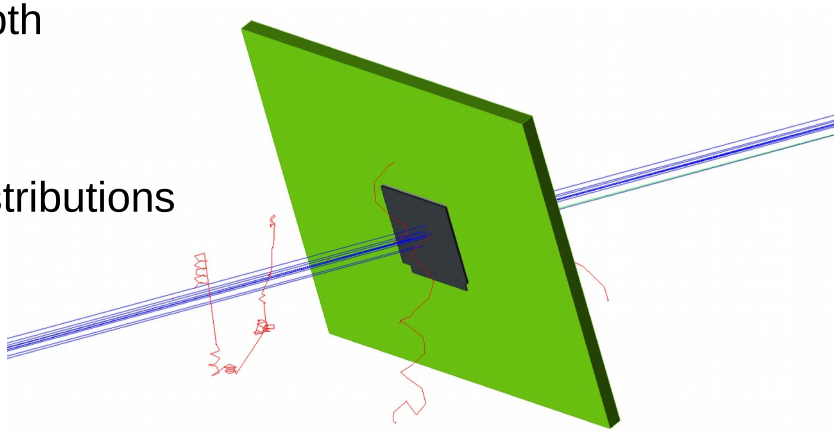
Simulation – Allpix^2

- Detector output distributions
- Information on charge carrier drift
- Information on digitization process
- Information on performance (resolution / efficiency) can be derived from higher level output, including the MC Truth information, including ROOT Trees, ASCII, LCIO, ...
  - Use Test Beam Analysis software for reconstructing Allpix^2 data!

Simulation – Lorentz angle

- Lorentz drift implemented in the charge carrier propagation
- Perform same scans as for the measurement for the unirradiated sample
  - No radiation damage model implemented yet
- Simplified setup:
  - One detector on a PCB
- Positron Beam: 1 TeV
- Electric field: linearly dependent on the sensor depth
- Rotation scans at 0 T and 1.335 T
- Extract the vertical cluster size from the control distributions





Results

Measurements and Simulations

Extrapolation to CMS Operating Conditions

Results

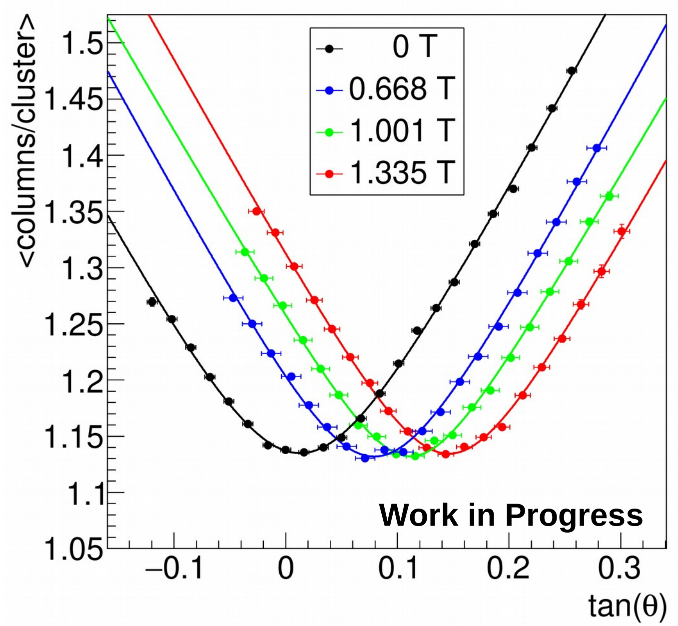
- Example:
  Unirradiated, -14°C, 150 V Bias

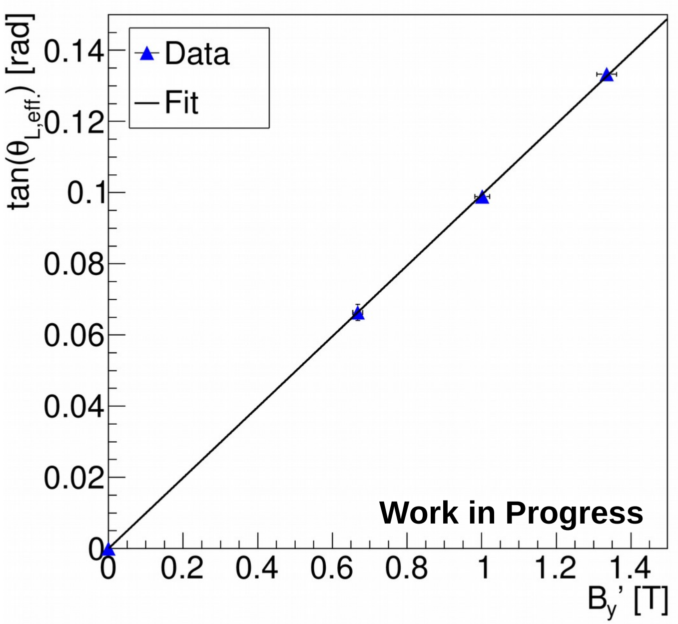
- Measured eff. Lorentz Angle @ 1.335 T:

$$\theta_L(1.335\,\mathrm{T}) = (7.59 \pm 0.10)\,^\circ$$

- Linear dependency of tan(θ) on magnetic field
  - Expected from $\tan(\theta_L) = r_H \mu B$
  - ➔ Only extract values @ 1.335 T

- No extrapolation to magnetic field @CMS possible due to the sensor tilt in the telescope
  (→ E and B not perpendicular,
  extrapolation via simulation)

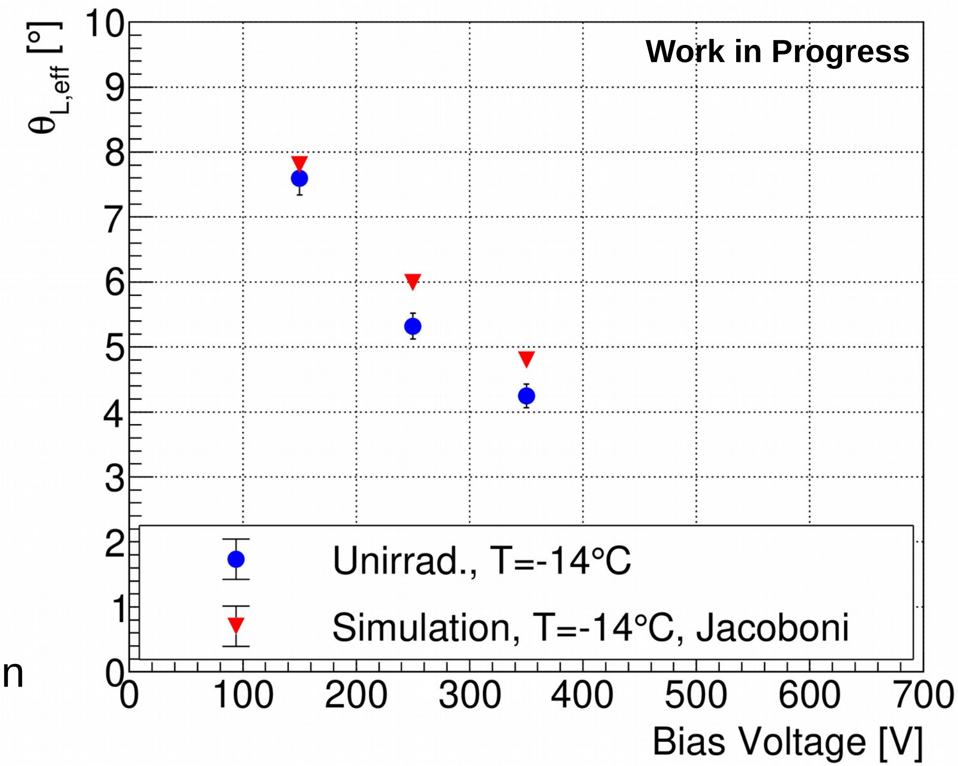




Results – Bias voltage

- Increase in bias voltage
  - ➔ Decrease in eff. Lorentz angle
    $$\tan(\theta_L) = r_H \mu B$$
  - Mobility is a function of the electric field
    $$\mu(E) = \frac{\mu_0}{\left(1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right)^{1/\beta}}$$

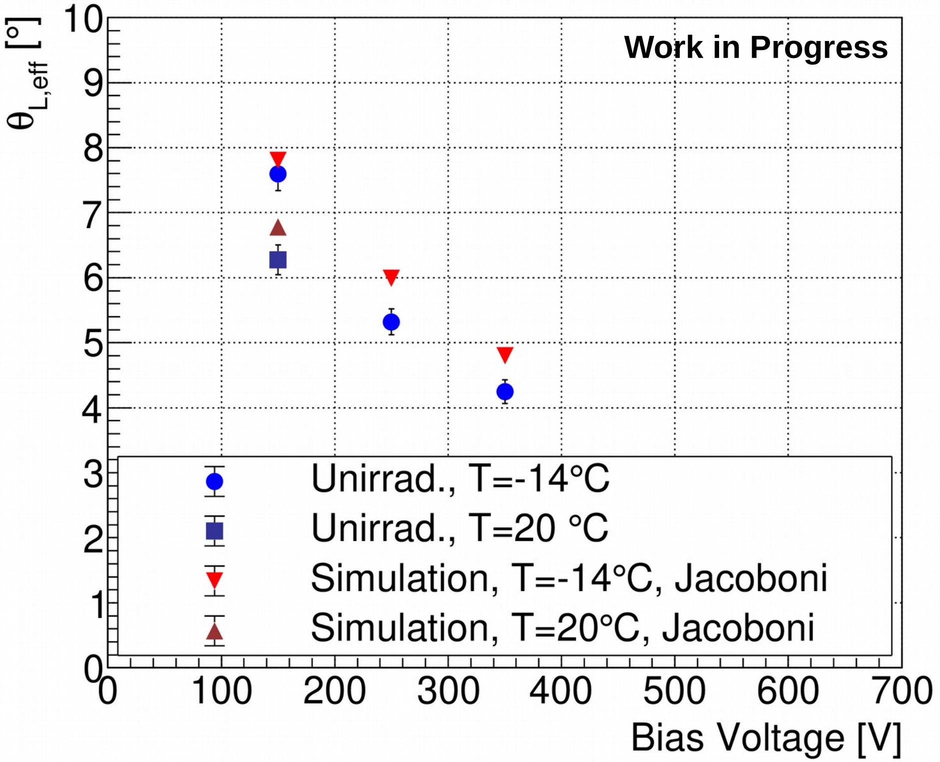
- Systematic ~ 10% deviation from simulation



$\mu(\vec{E})$: Electron mobility
r_H: Electron Hall factor
v_{sat}: Saturation drift velocity
β: Free parameter (≈ 1)

Results – Temperature

- Increase in temperature
  - ➔ Decrease in eff. Lorentz angle
    $$\tan(\theta_L) = r_H \mu B$$
  - Mobility is a function of temperature
    $$\mu(T) \approx A \cdot T^{-2.42}$$



$\mu(\vec{E})$: Electron mobility
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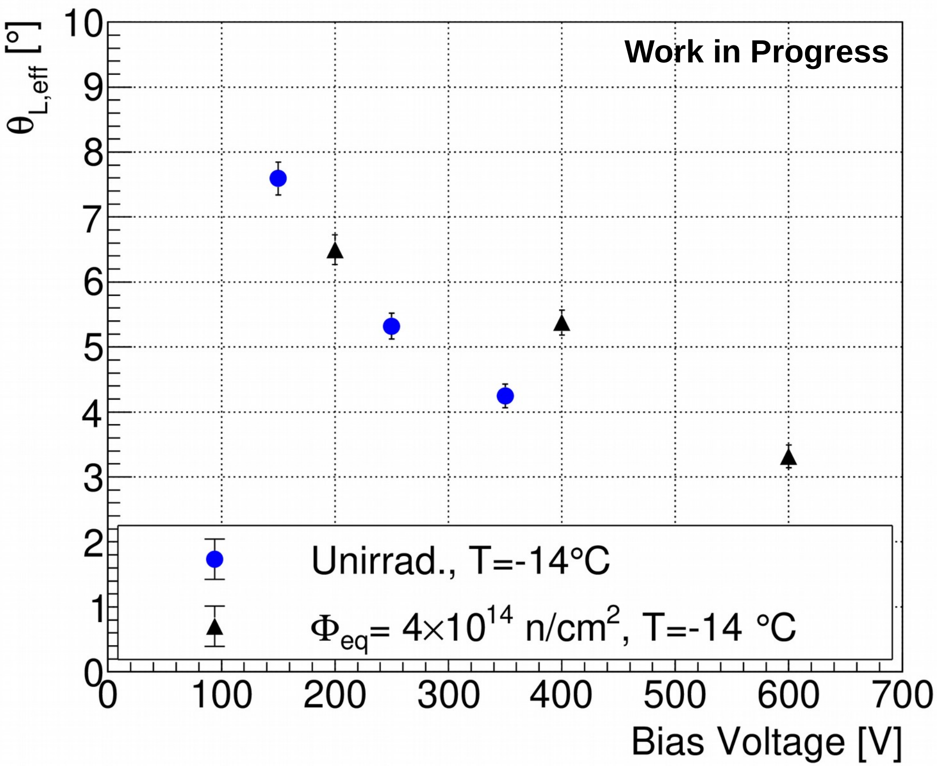
Results – Radiation damage

- Increase in irradiation fluence
  - ➔ Increase in eff. Lorentz angle
  - Radiation damage leads to a non-linear electric field in the bulk
  - For similar voltages the eff. Lorentz angle is increased after irradiation



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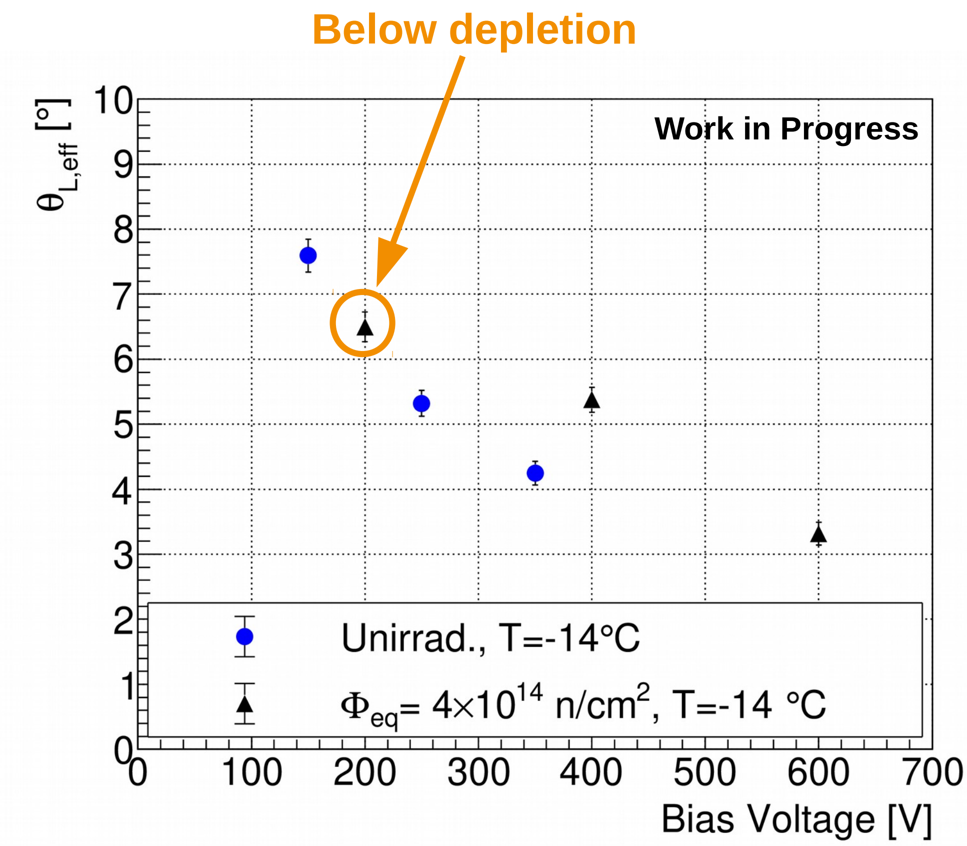

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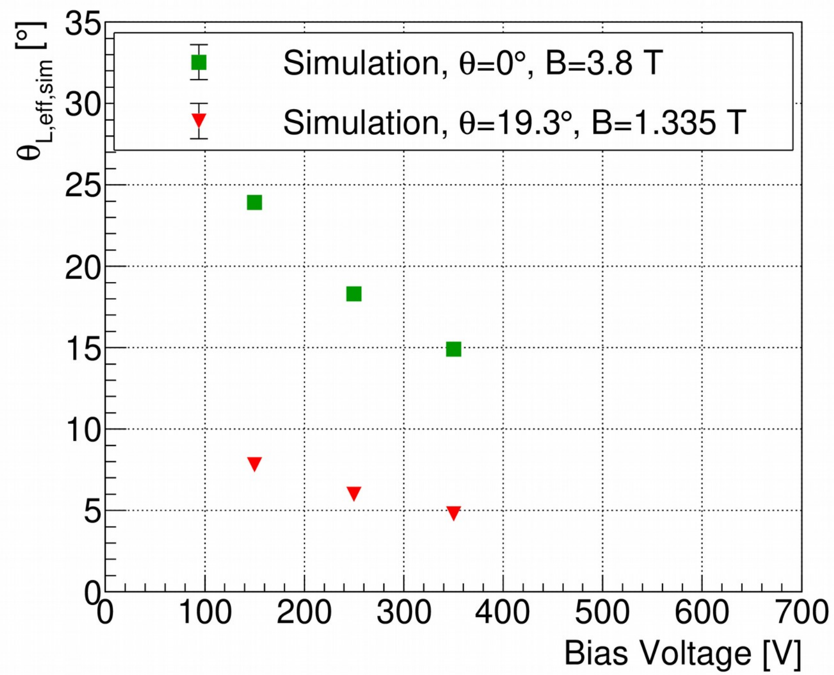
Extrapolation to CMS operating conditions

- Measured the Lorentz angle for a rotated sensor @ 1.335 T
- CMS Detector: Unrotated @ 3.8 T
- Linear extrapolation is not possible due to the the sensor rotation in the CMS Pixel Telescope

➔ Find conversion factor from simulations of both scenarios



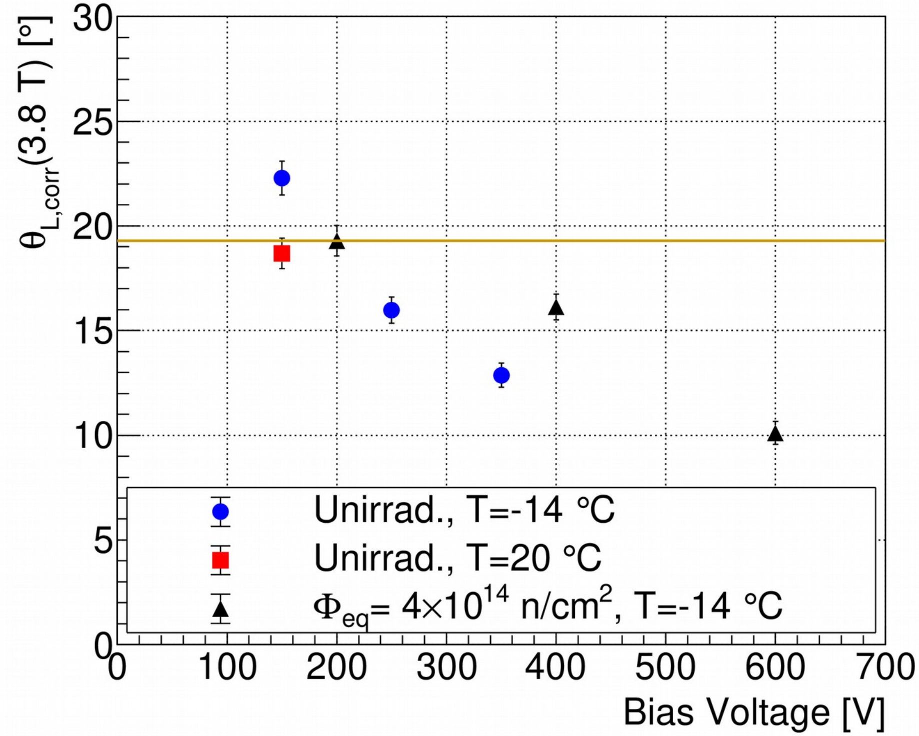
Scaling factor: 3.07 ± 0.03

- **Caveat:** Scaling factor calculated for unirrad. sensors and used also for irradiated samples

Extrapolation to CMS operating conditions

- Extrapolated measured eff. Lorentz angles to unrotated sensors @ 3.8 T
- Reminder: Optimal resolution around 19.3° (yellow line)

- Optimal resolution reached
  for unirradiated sensors around 200 V
- A high voltage is required to fully deplete irradiated sensors
  - Resolution is deteriorated



Conclusion

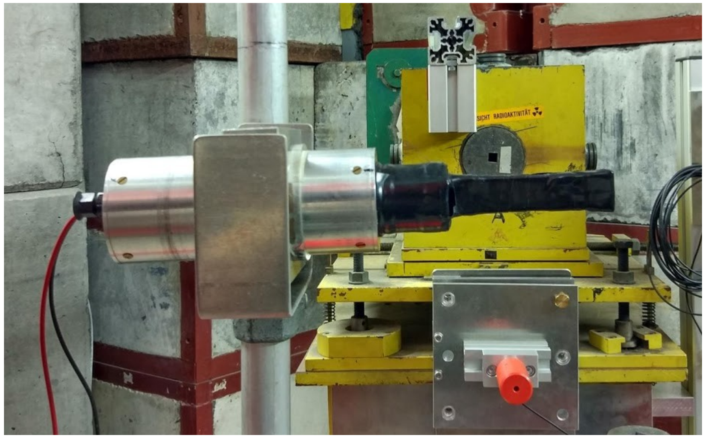
- CMS Pixel Module Telescope commissioned, with cooled detector operation
  - Realistic operational conditions and stable in temperature
  - Enables measurements with irradiated sensors

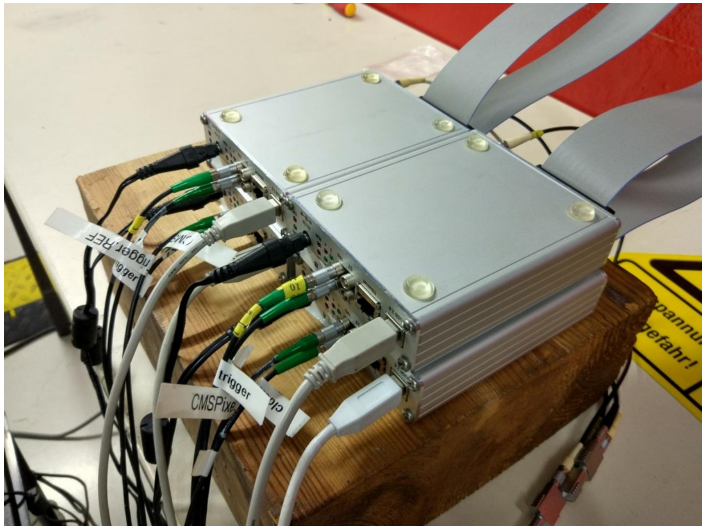
- Measurement of the effective Lorentz angle under various conditions
  - Measured the effects of temperature, bias voltage and irradiation
  - Lorentz angle in unirradiated sensor matches the requirement for optimal resolution
  - Optimal resolution cannot be maintained after reaching a certain irradiation fluence

Backup

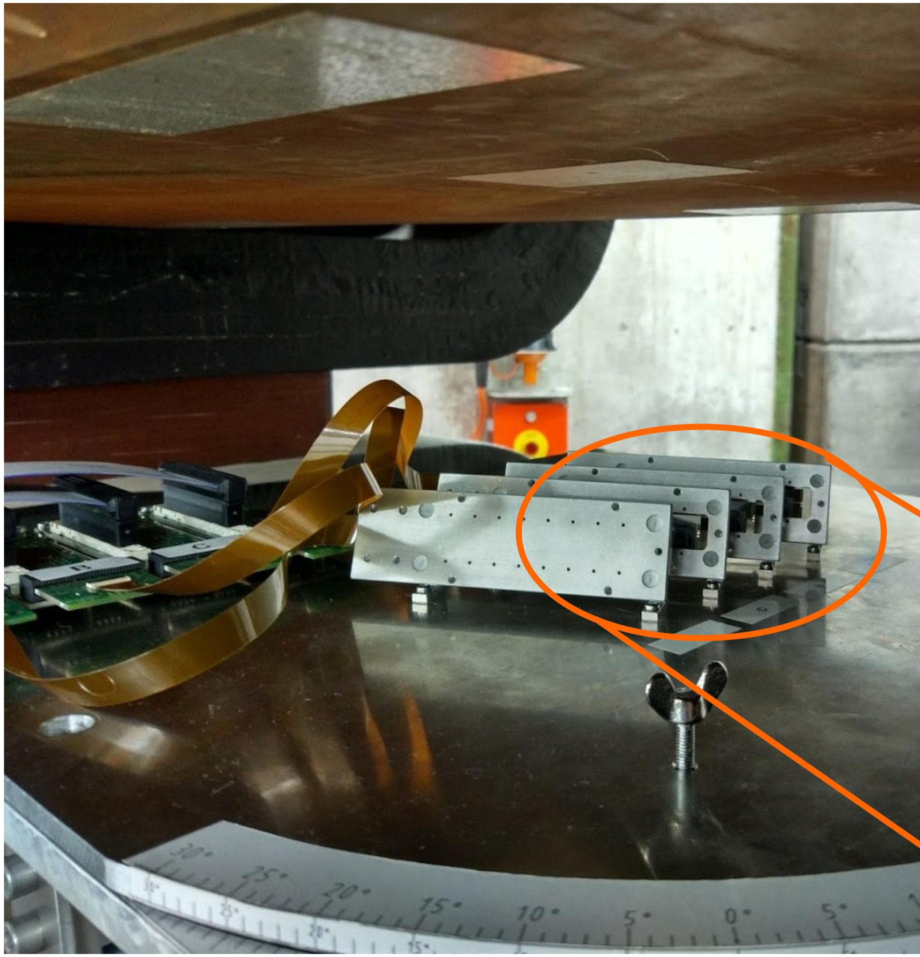
CMS Module Telescope – Triggering and DAQ

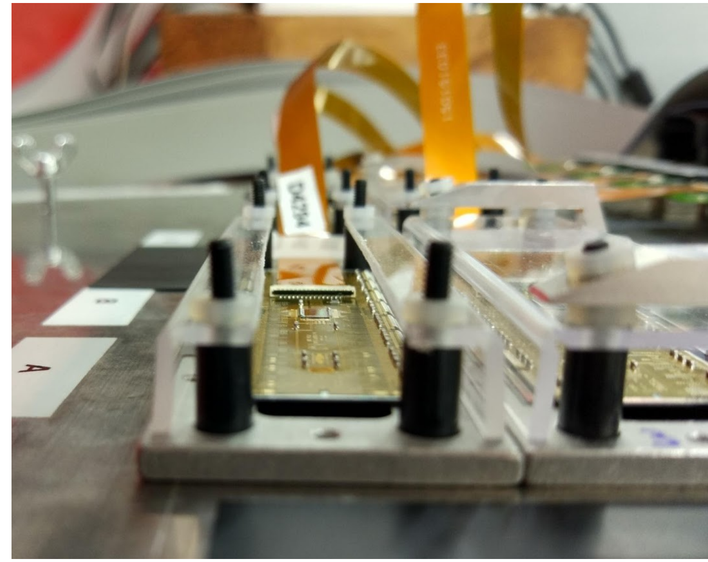
- CMS Pixel Detector Telescope TDAQ:
  - External scintillator as particle trigger
    - Particles are only allowed during an 11 ns time window inside the 25 ns clock
  - 4 DTBs as DAQ boards
  - EUDAQ as DAQ software
    - Each plane runs as a producer
    - Raspberry Pi controller and NIM coincidence unit instead of TLU:
      - GPIO pins are connected to a NIM coincidence unit (GPIO → LEMO)
      - RPi Controller switches on (off) the triggers when all producers are ready (are still running)





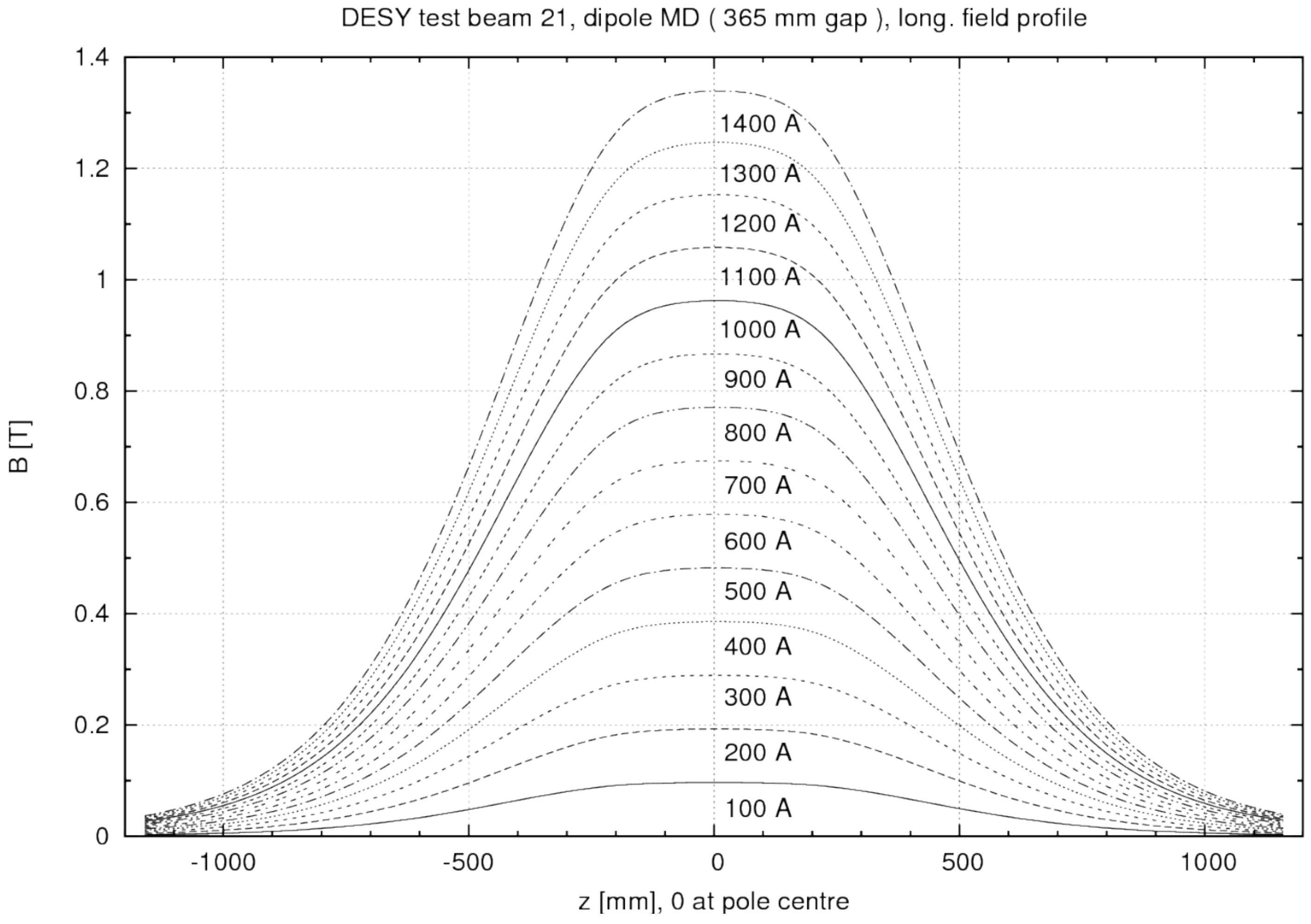
CMS Module Telescope – Images





- 27° tilted module mounting
- Module handle cut-outs

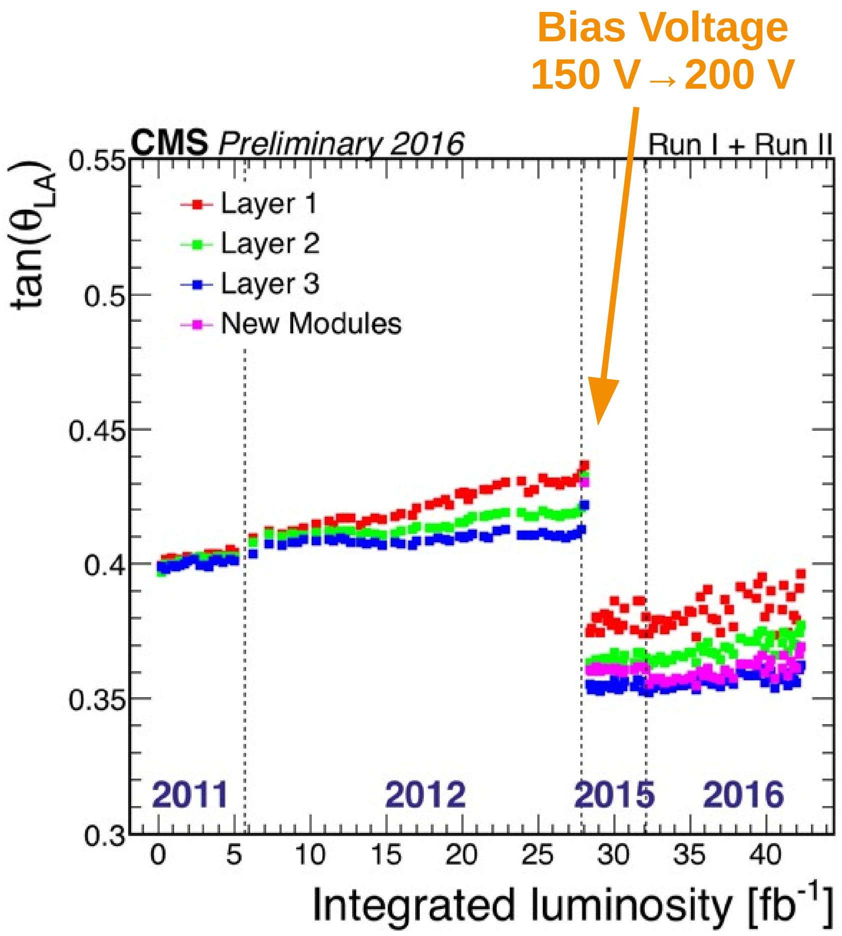
Magnetic field map – Big Red Magnet



Comparison to CMS Pixel Detector

- Overview over all scans performed at the original CMS Pixel Detector [3]
- Trend in eff. Lorentz Angle vs. integrated luminosity

- Similar to the test beam studies:
- Increase in irradiation fluence
  - ➔ Increase in eff. Lorentz angle



[3]: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2016