Characterization of new silicon pixel detectors for the ATLAS upgrade

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Young Scientists Workshop
Ringberg Castle
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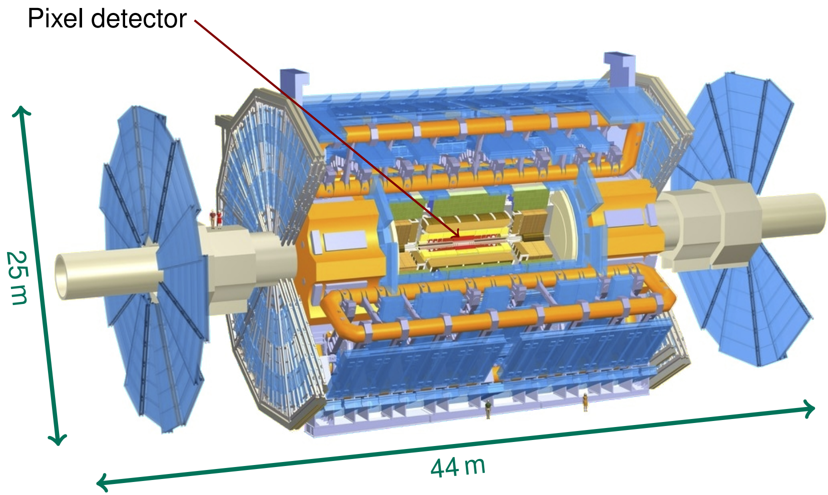
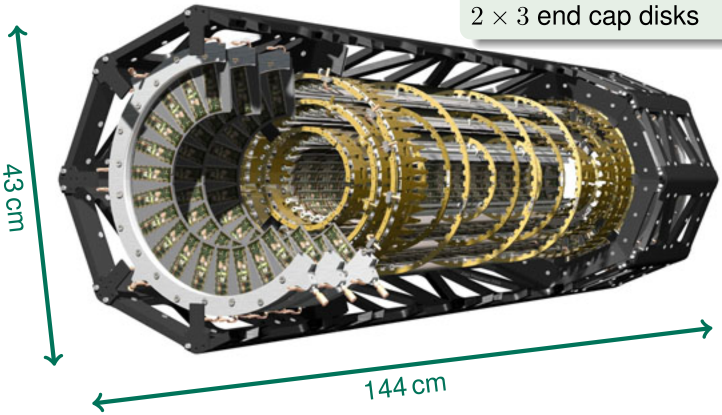
Overlook

The ATLAS Detector



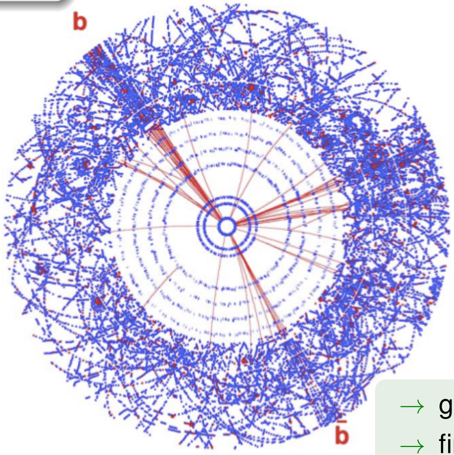
The silicon pixel tracker

3 barrel layers
2×3 end cap disks



The pixel tracker challenge

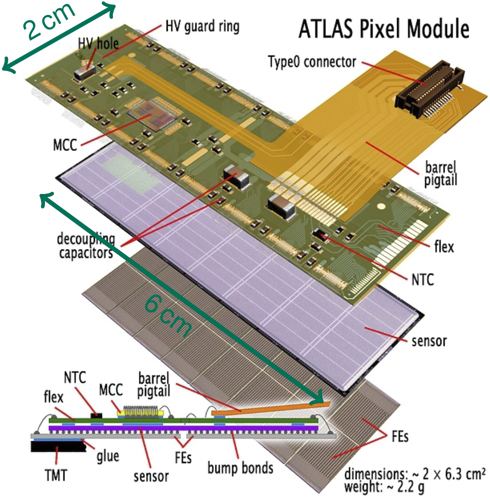
$H \to b\bar{b}$



- $\rightarrow$ good momentum resolution
- $\rightarrow$ find secondary vertexes (b-tagging)

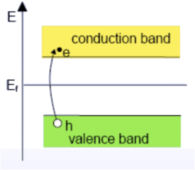
The present ATLAS pixels

- 46080 Pixel channels per module: $50\,\mu m \times 400\,\mu m$
- n-in-n silicon sensors: $\sim 300\,\mu m$ thick
- FE-I3 readout chip with $\sim 3000\,e^-$ lowest threshold.



What a silicon pixel detector is

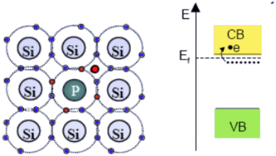
- A pure intrinsic semiconductor has equal electron and hole densities
  - Transferred energy:
    - $\rightarrow$ electron exited from the valence to the conduction band
    - $\rightarrow$ MIP: ~ 8000 e$^-$-h pairs $\times 100\,\mu\mathrm{m}$



- Doping $\rightarrow$ introduce impurities in the Si lattice:

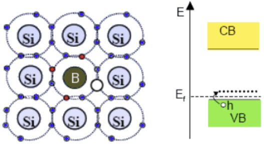
n-type:

- $\rightarrow$ free electrons
- $\rightarrow$ Fermi level near the Conduction Band



p-type:

- $\rightarrow$ free holes (electron vacancies)
- $\rightarrow$ Fermi level near the Valence Band



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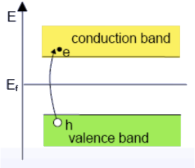

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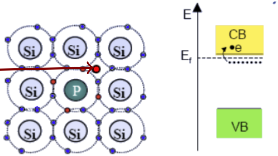

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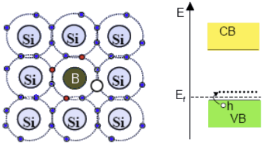

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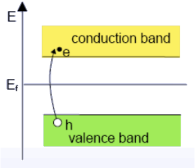

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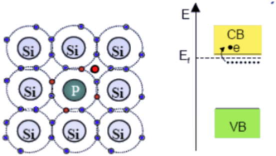

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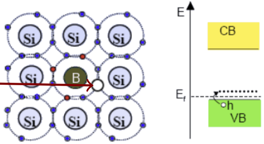
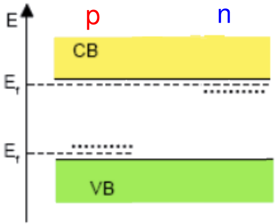


Reversed bias p-n junction

- p-n junction:
  - → there must be a single Fermi level
  - → band structure deformation
  - → potential difference in the junction
  - → charge flows until the equilibrium



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  - → $V_B > V_{\text{dep}}$ → maximum collected charge

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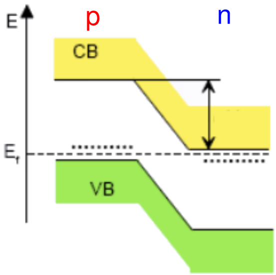

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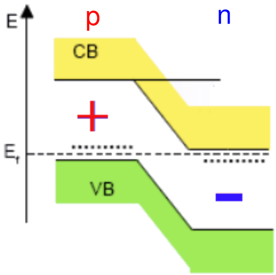

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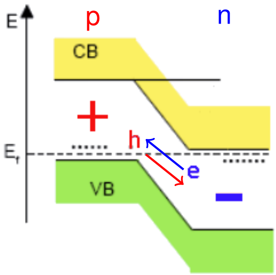

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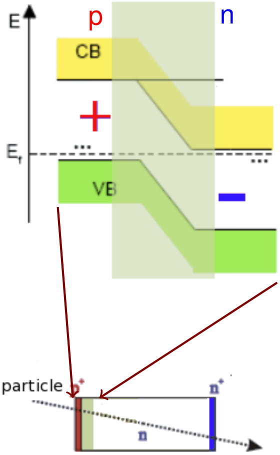

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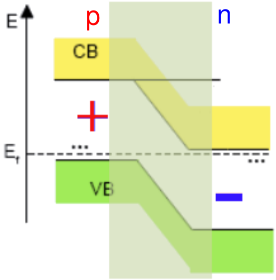

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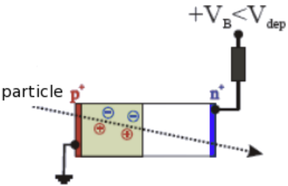

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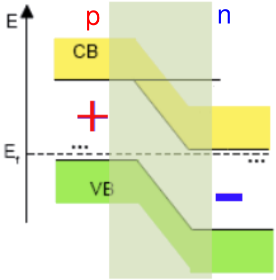

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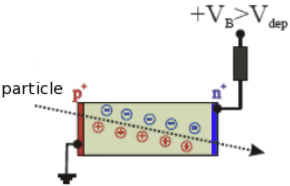
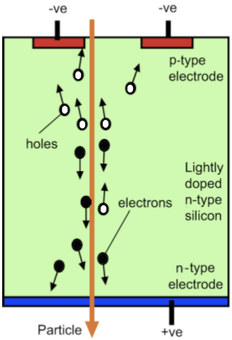
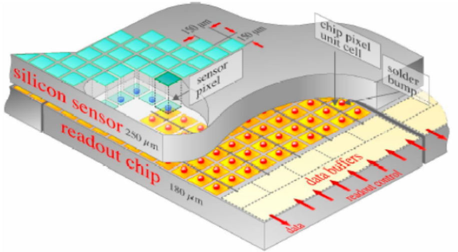
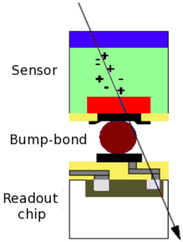


- Pixel surface segmentation
  - → True 3D spatial information
- Readout chip coupling (bump bonding)







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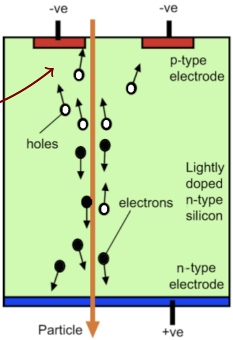

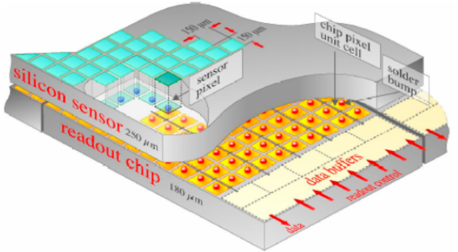

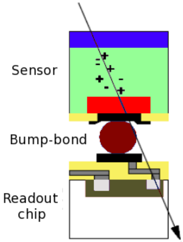

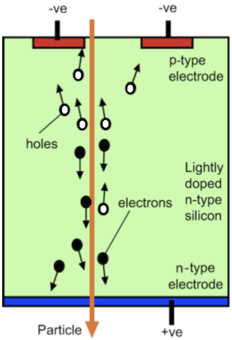

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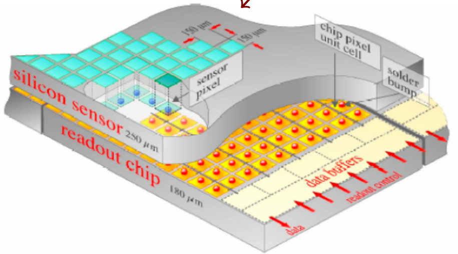

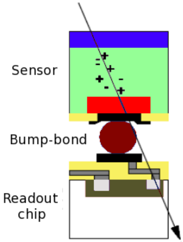

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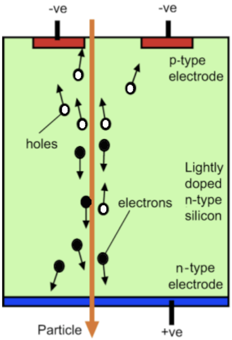
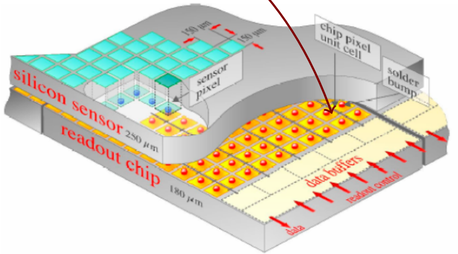
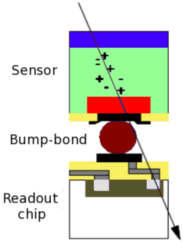
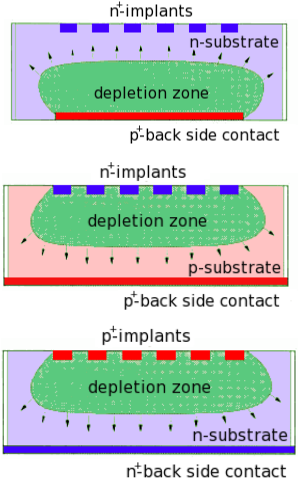






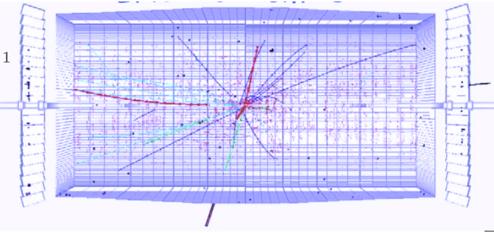
Different pixel technology

- **n-in-n:**
  - → electron collection
  - → depletion from the backside
  - → double-sided process
- **n-in-p:**
  - → electron collection
  - → depletion from the frontside
  - → single-sided process
- **p-in-n:**
  - → hole collection
  - → depletion from the frontside
  - → single-sided process

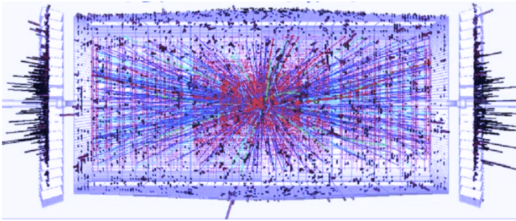


The LHC upgrade program

- **LHC now**
  - → E_{CM} = 8 TeV
  - → Luminosity = $6 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



- **LHC design**
  - → E_{CM} = 14 TeV
  - → Luminosity = $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **HL-LHC (∼2020)**
  - → Luminosity $\sim 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - → high event rate for rare decay search
  - → extremely high radiation dose for the innermost pixel layers



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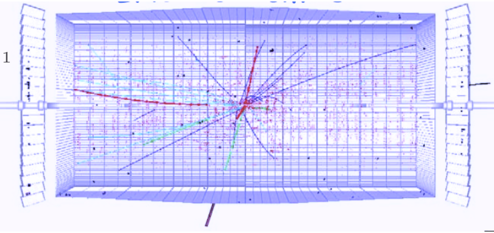

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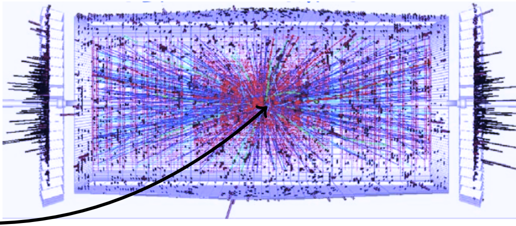
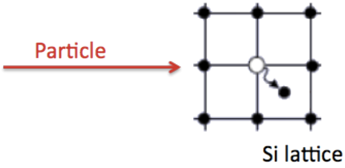


Radiation damage in silicon detectors

Displacement of lattice atoms (crystal damage)



- **recombination centers**
  - → affect doping concentration
  - → increase of depletion voltage
  - → consequent current increase

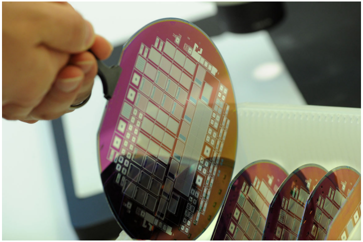
  } heat increase
- **generation centers**
  - → increase of leakage current

  } heat + noise increase
- **trapping centers**
  - → mean free path reduced
  - → decrease of charge collection efficiency

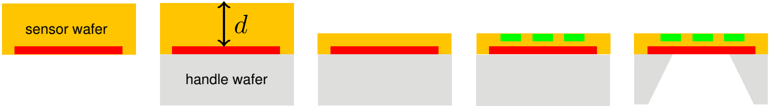
  } signal decrease

Our new thin silicon detectors

- $75\,\mu m$ and $150\,\mu m$ thinned sensors
  - $\rightarrow$ lower trapping probability
  - $\rightarrow$ lower depletion voltage ($V_{dep} \sim d^2$)
  - $\rightarrow$ less multiple scattering
- n-in-p
  - $\rightarrow$ depletion from the pixel side
  - $\rightarrow$ single side process



- lower signals $\rightarrow$ new FE-I4 readout chip that allows lower thresholds



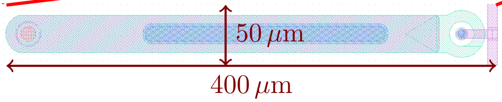
1. Implant backside on sensor
2. Bond sensor wafer to handle wafer
3. Thin sensor side to desired thickness
4. Process on top side
5. Structure resist, etch backside up to oxide/implant

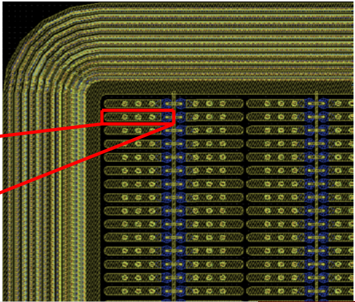
Characterization in a test-beam experiment

The characterization purpose:

probing the detector surface with a precision of a few microns to study its performances before and after irradiation

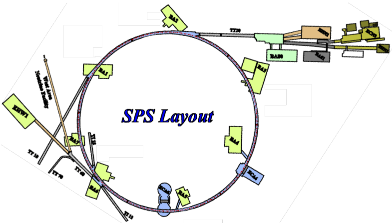
- Charge sharing properties
- Efficiency
- Spatial resolution
- Edge effects

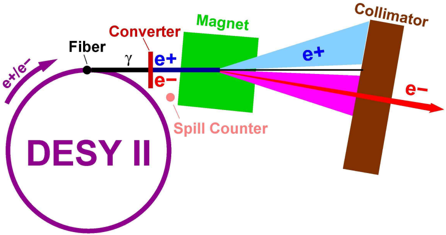




What we need:

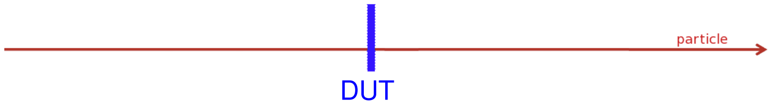
- **a pure and well defined source of particles:**
  - SpS at CERN: 120 GeV pions
  - DESY at Hamburg: 4 GeV electrons $\rightarrow$ Multiple Scattering (MS)





What we need:

- **an external fixed reference frame:**



→ tracking planes made of other pixel detectors

→ scintillators to determine when a particle is crossing the telescope

→ track reconstruction and projection on the Detector Under Test

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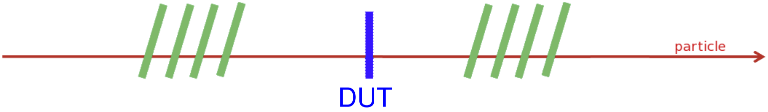

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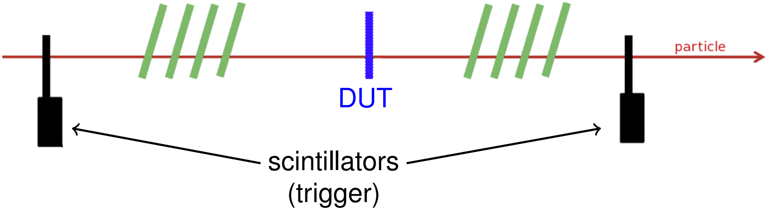

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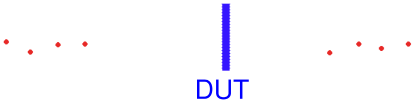

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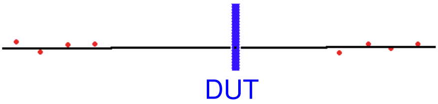

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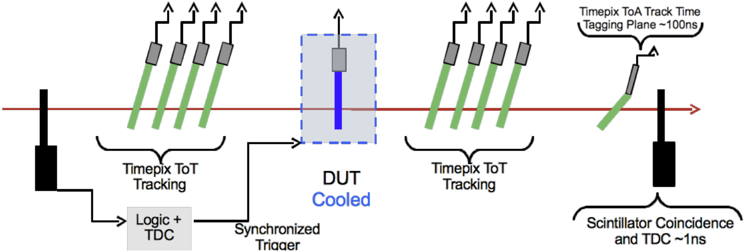
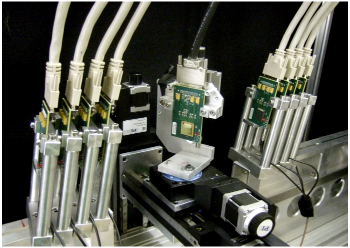
The Timepix telescope

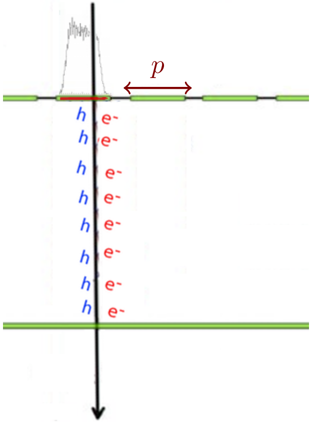


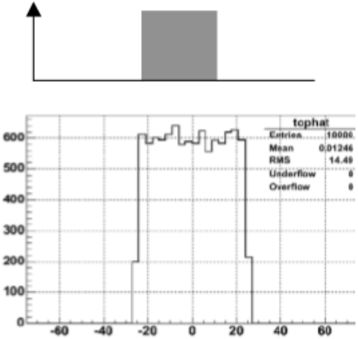
- MEDIPIX: $55\,\mu m \times 55\,\mu m$
- $300\,\mu m$ thick p-in-n
- Tilted planes $\rightarrow$ charge sharing
- ToA plane $\rightarrow$ improved trigger
- Pointing resolution $\sim 1.5\,\mu m$



Charge sharing

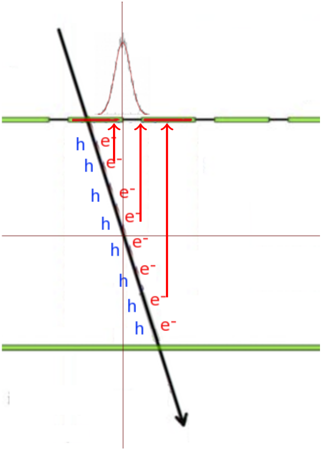
- Single pixel spatial resolution $= \dfrac{p}{\sqrt{12}}$
- Improved resolution by charge weighting in adjacent pixels

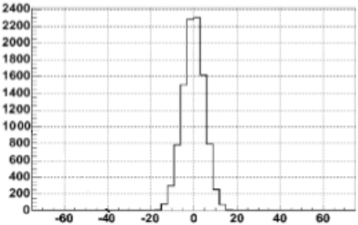




Charge sharing

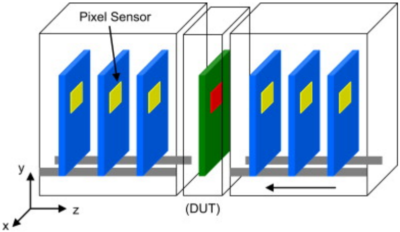
- Single pixel spatial resolution $= \frac{p}{\sqrt{12}}$
- Improved resolution by charge weighting in adjacent pixels

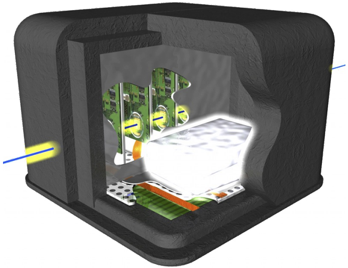




The EUDET telescope

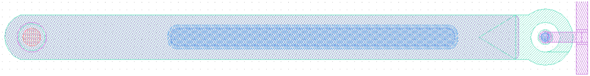
- MIMOSA: $18.4\,\mu m \times 18.4\,\mu m$
- $50\,\mu m$ thick CMOS (MAPS)
- Small pixel pitch but no charge reading
- Very thin $\rightarrow$ less MS
- Pointing resolution between $2\,\mu m$ and $5\,\mu m$



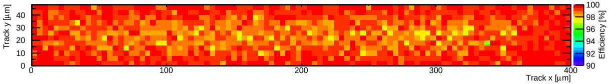


The single pixel cell efficiency

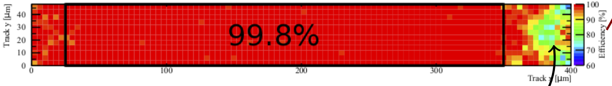
- The single pixel cell ($50\,\mu\text{m} \times 400\,\mu\text{m}$):



- Not irradiated sample $\rightarrow$ efficiency: $(99.3 \pm 0.2)\%$



- $5 \times 10^{15}\,\text{n}_{\text{eq}}\text{cm}^{-2}$ irradiated sample at 600 V
$\rightarrow$ efficiency: $(98.6 \pm 0.3)\%$



punch trough is not connected to the readout

Summary

- the harsh radiation environment at HL-LHC will require new radiation hard detectors
- n-in-p detectors have already shown good results after high irradiation

Now:

- new FE-I4 modules $150\,\mu\mathrm{m}$ thick irradiated up to $4 \times 10^{15}\,\mathrm{n_{eq}cm^{-2}}$ have already been tested:
  - at DESY with the Eudet telescope and
  - at SpS with both Eudet and Timepix
- ... and data analysis is ongoing!

Future plans:

- new FE-I4 chip production to test
- further irradiation up to $2 \times 10^{16}\,\mathrm{n_{eq}cm^{-2}}$