Characterization of thin irradiated epitaxial silicon sensors for the CMS phase II pixel upgrade

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Wait, what? Why? …bear with me...

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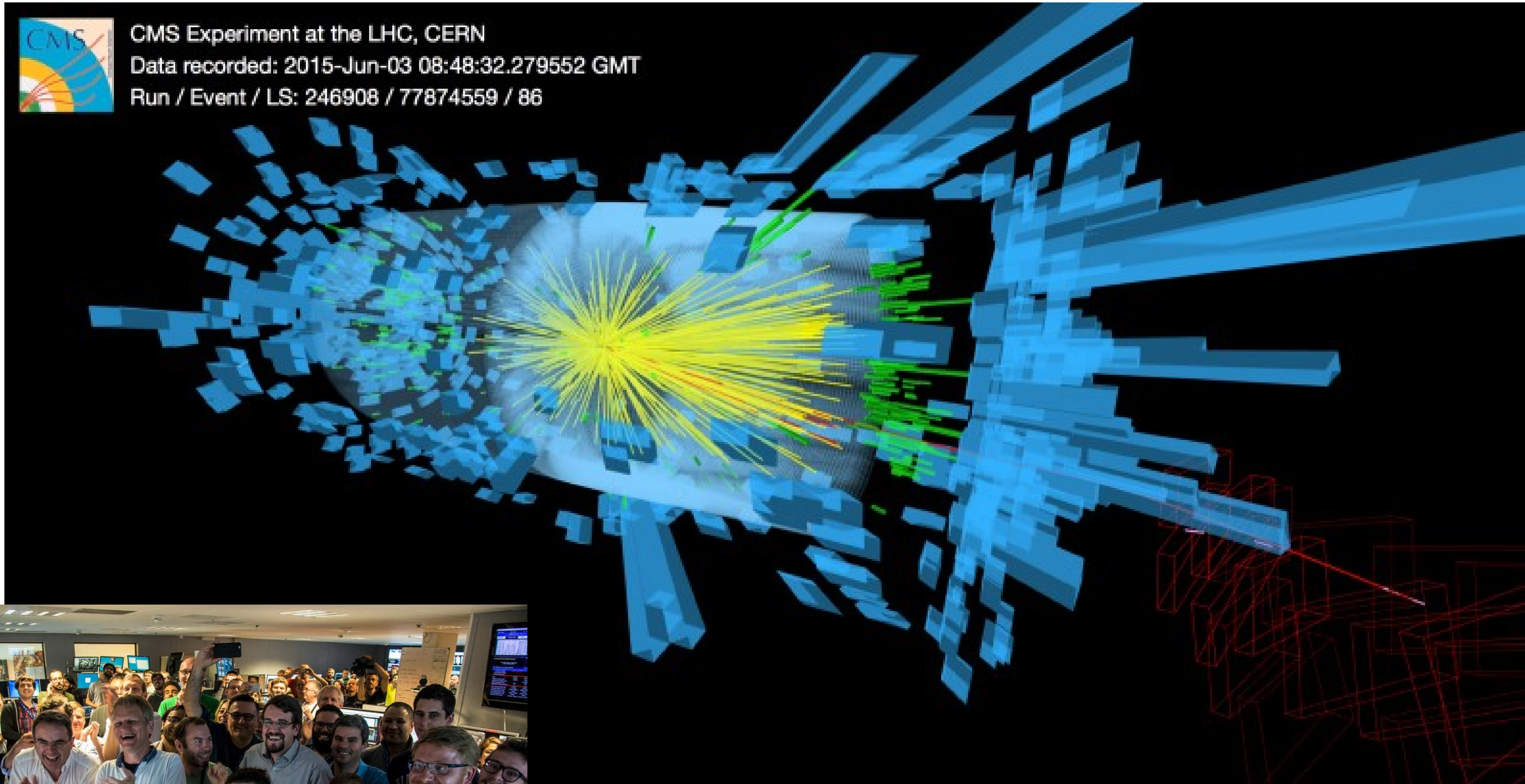
LHC is back!

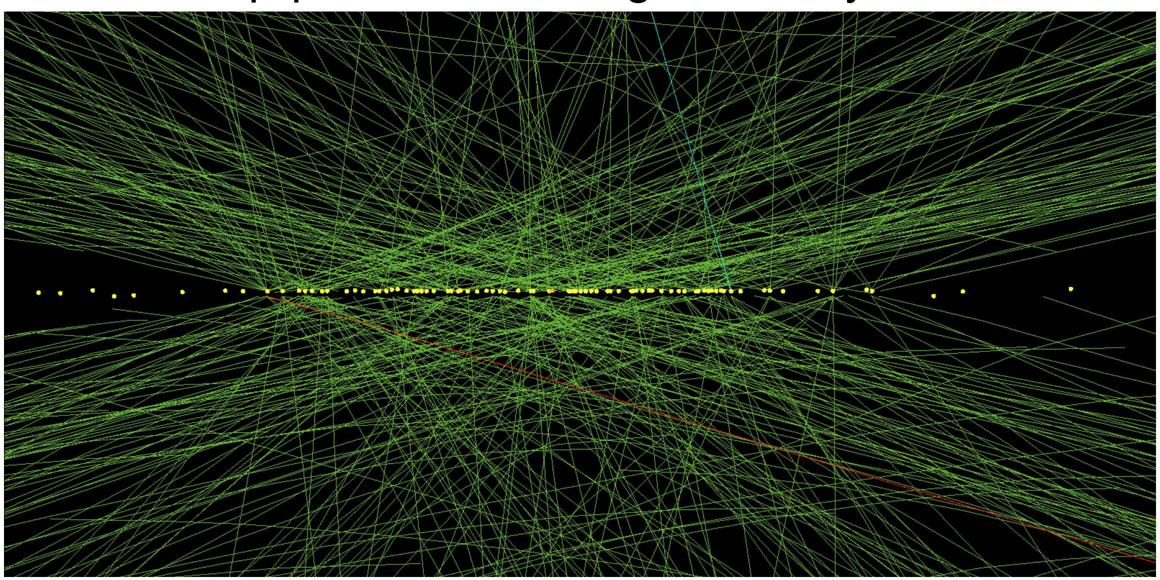


- First 13 TeV collisions in June after a long shutdown
- Luminosity being ramped up
- New period of exploration at the energy frontier

HL-LHC

High statistics is important for many analyses:
- SUSY
- Dark matter search
- Extra dimensions
- Higgs properties
- ….

78 p-p collisions in high intensity run



High Luminosity LHC (2025)

- Tenfold increase in statistics: 3000 fb^{-1}
- Luminosity increase to 5×10^{34} $cm^{-2}s^{-1}$
- Mean number of interactions per bunch crossing $\langle\mu\rangle \sim 140$ (every 25 ns)

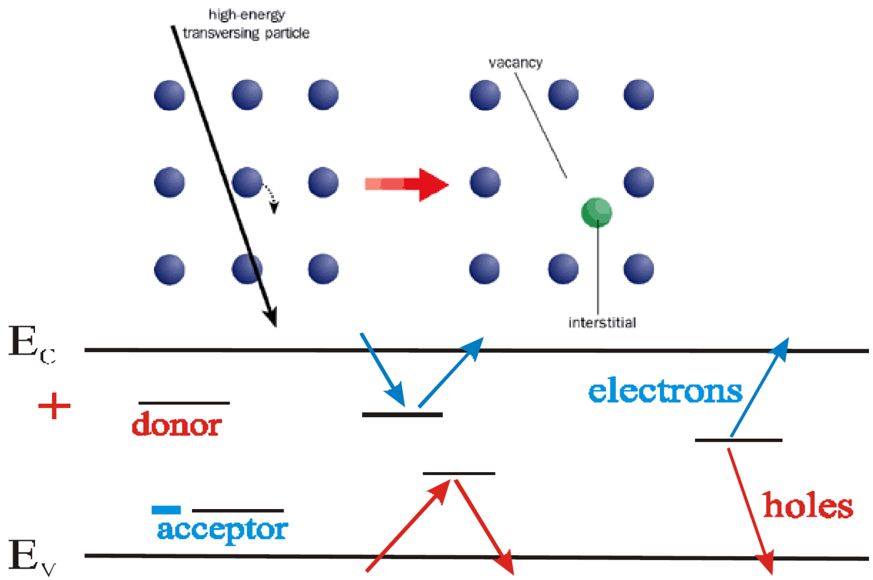
A challenge for the detector!
- Hit rate
- Radiation damage
- ...

→ Phase II tracker upgrade

Radiation damage in Si

Bulk damage

- Defect generation
- Change of U_{dep}
- Increase in leakage current (noise)
- Decrease in signal



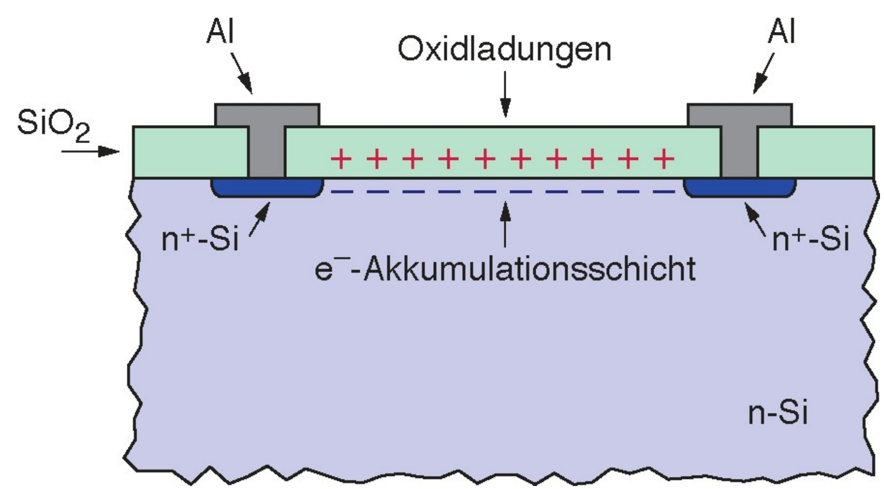
charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

Surface damage

- Positive charge at the Si-SiO_2 interface
- Modification of the electric field close to the surface
  → charge losses
  → noise increase
  → break down
- Creation of conductive layers
- Affects sensors and microelectronics

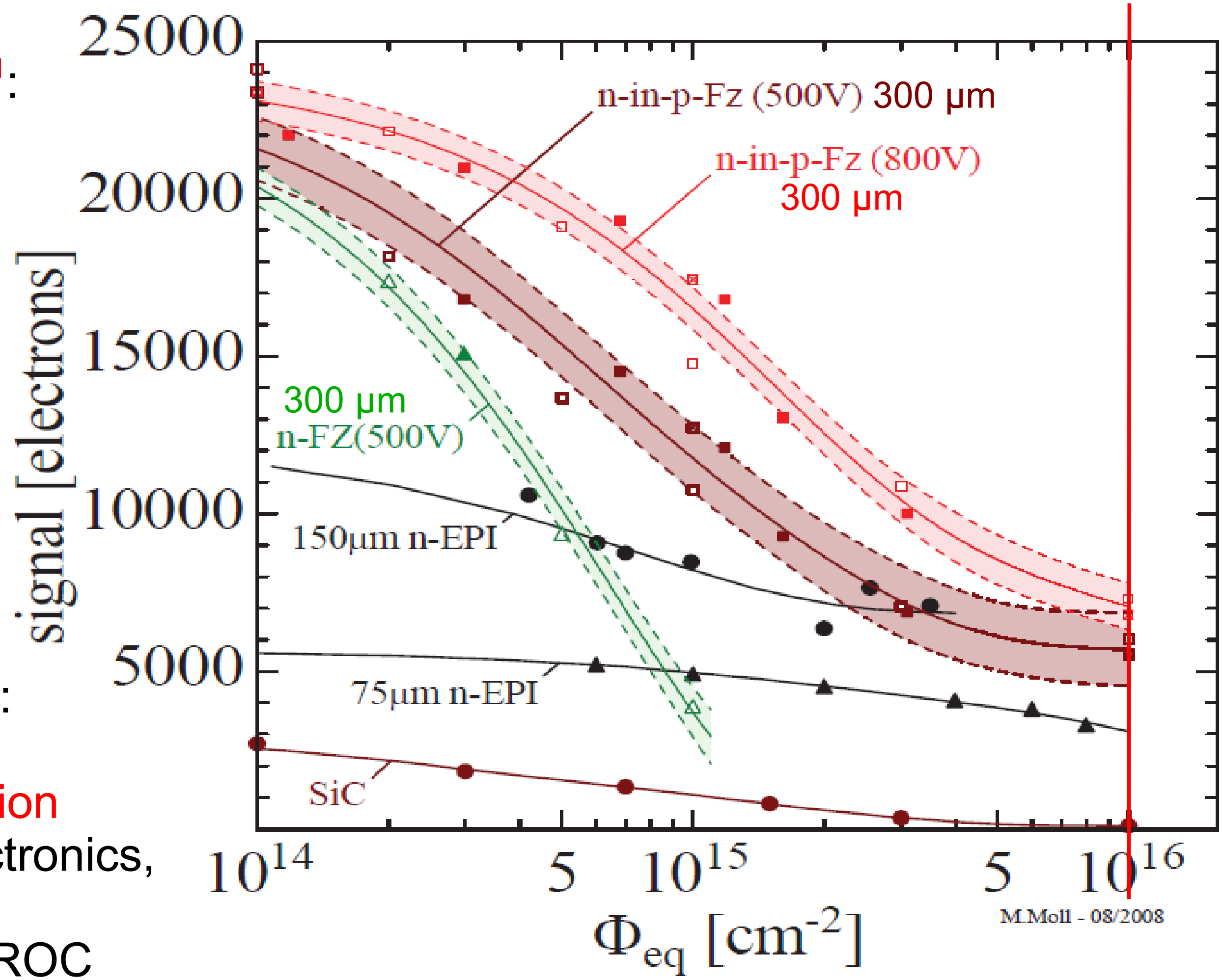


Relevant quantity: dose in the SiO_2

To compare damage of various particle types:
damage expressed as equivalent of 1 MeV neutrons [cm^{-2}]

Motivation

2025: High Luminosity-LHC
- Innermost pixel layers after 3000 fb^{-1}:
  - $\Phi_{eq} \sim 10^{16}$ cm^{-2} → bulk damage
  - 5 MGy → surface damage
- New material / design is required,
  is planar silicon a viable option?



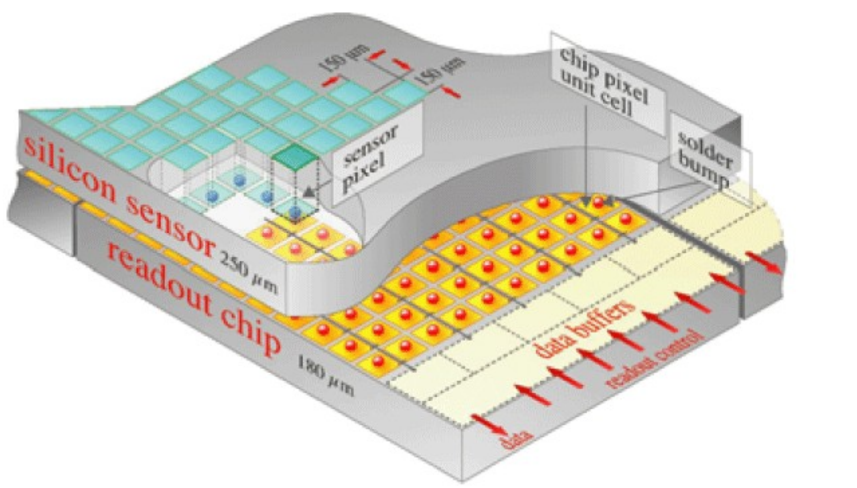
Thin sensors compared to thick ones:
- Less signal degradation
- Smaller signals even before irradiation
  → challenge for the readout electronics,
  low thresholds are required
  → RD 53 collaboration for pixel ROC
  for the HL-LHC

→ **characterization with MIP-like signals required**

Beam test of thin (100-200 µm) strip sensors to determine material characteristics

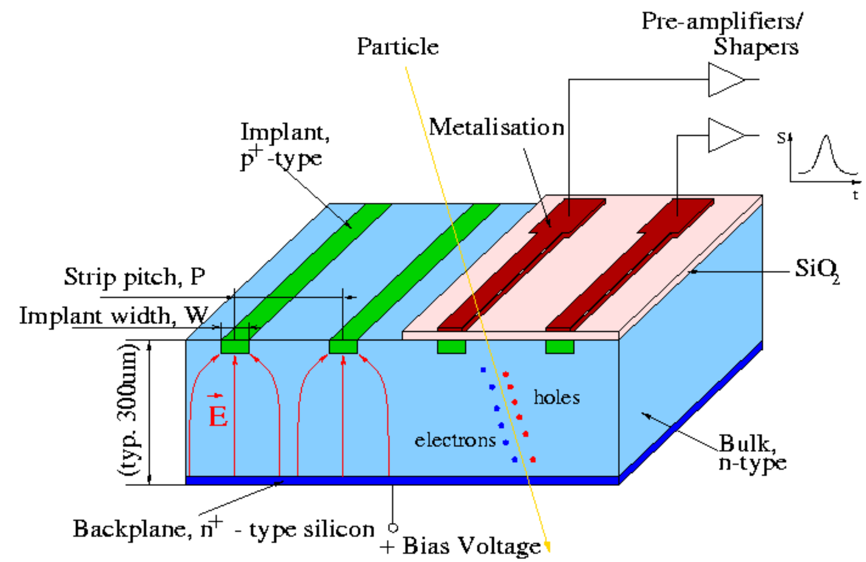
Strip detectors to study pixels?

Pixel detectors



- Noise level ~100 e⁻ before irradiation
- **Bump bonding**
- Heat treatment to achieve connection between sensor and readout
  → modification of sensor properties
- Irradiation of sensor and electronics
  → modification of electronics

Strip detectors



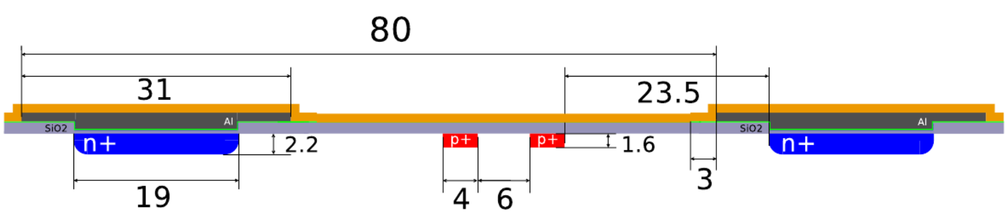
- Noise level ~800 e⁻ before irradiation
- **Wire bonding**
- No heat treatment for connection with readout electronics
- Separate irradiation
- No modification of electronics

Beam telescope to reconstruct hit position
→ **separation of noise from signal**

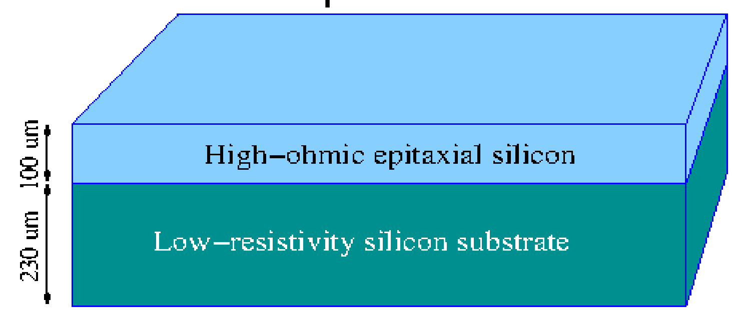
Sensors

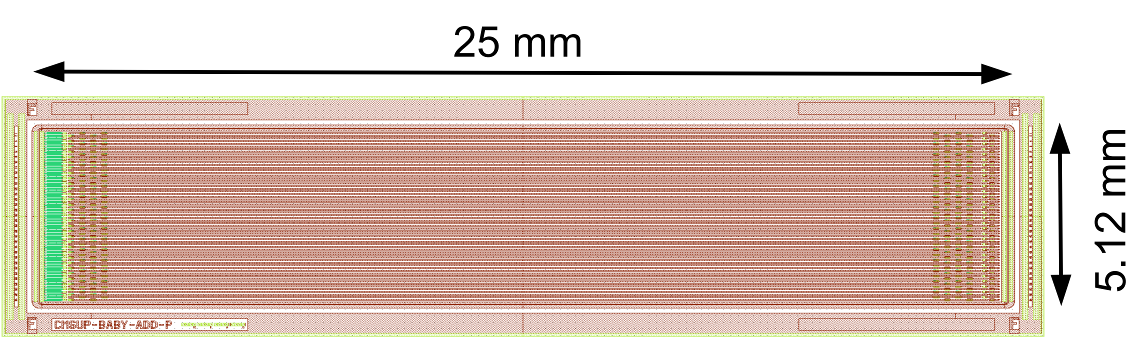
- Epitaxial silicon strips of n and p type (p-spray and p-stop isolation)
- **100 µm** active thickness
- 80 µm pitch
- Irradiation with 800 MeV and 23 GeV protons
- Fluences up to 1.3 x 10^{16} cm^{-2}
- MCZ and FTH with **200 µm** physical thickness
  - Only 1.3 x 10^{16} cm^{-2}

Epitaxial silicon → easy production of detectors with thin active thickness (100 µm)



Epi sensors

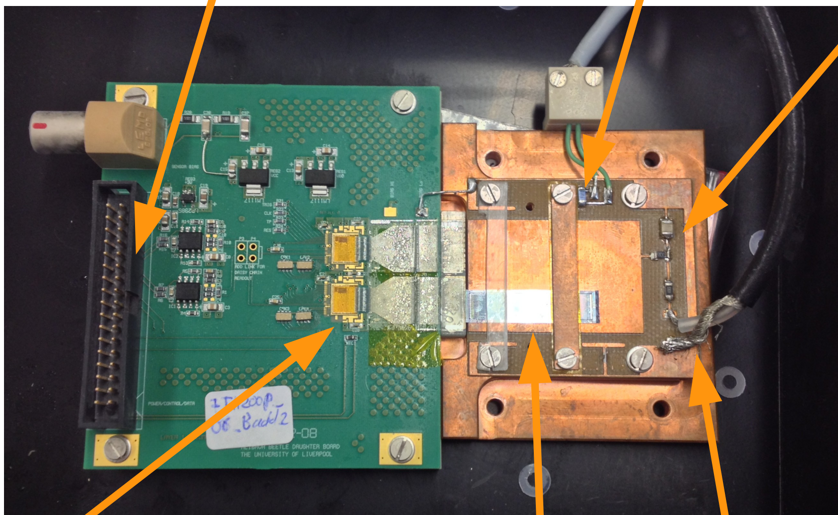


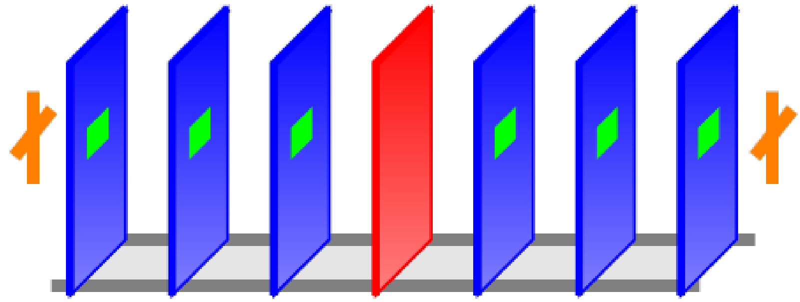


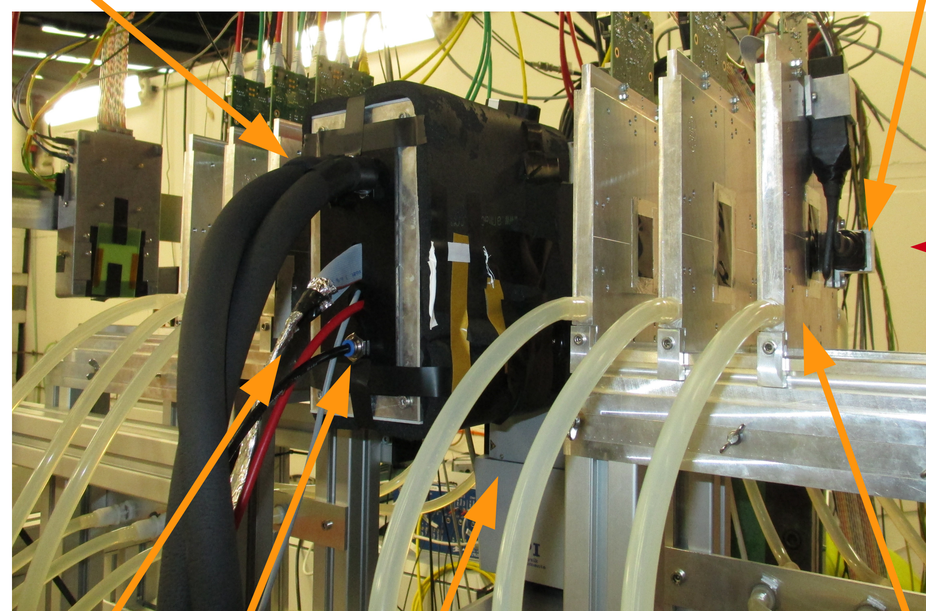
64 AC coupled strips

- **Results for p-type sensors**
- n-type sensors show micro discharges after irradiation (design issue)

Setup





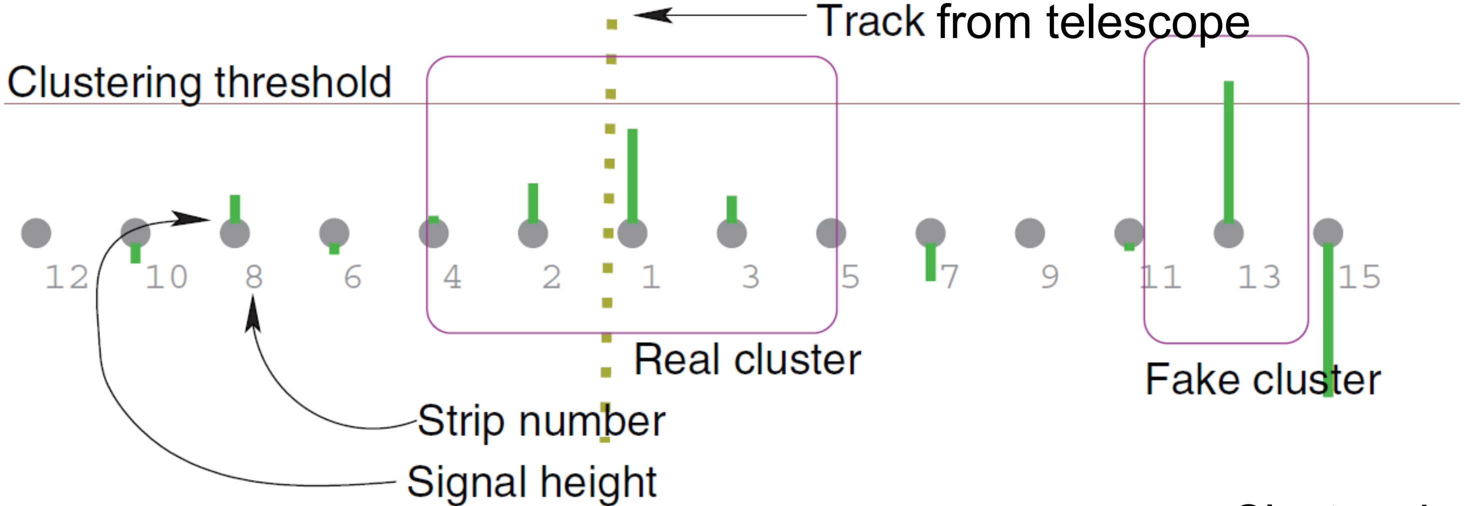


- Beam telescope to reconstruct tracks
  - DATURA and ACONITE
  - EUDET pixel telescopes
- Trigger scintillators to define events
- Cooling for irradiated samples
- ALiBaVa (A Liverpool Barcelona Valencia) readout system
- Readout of positive and negative signals
- Based on LHCb strip readout chip
- Analog pulse height for 2 x 128 channels

Cluster definition

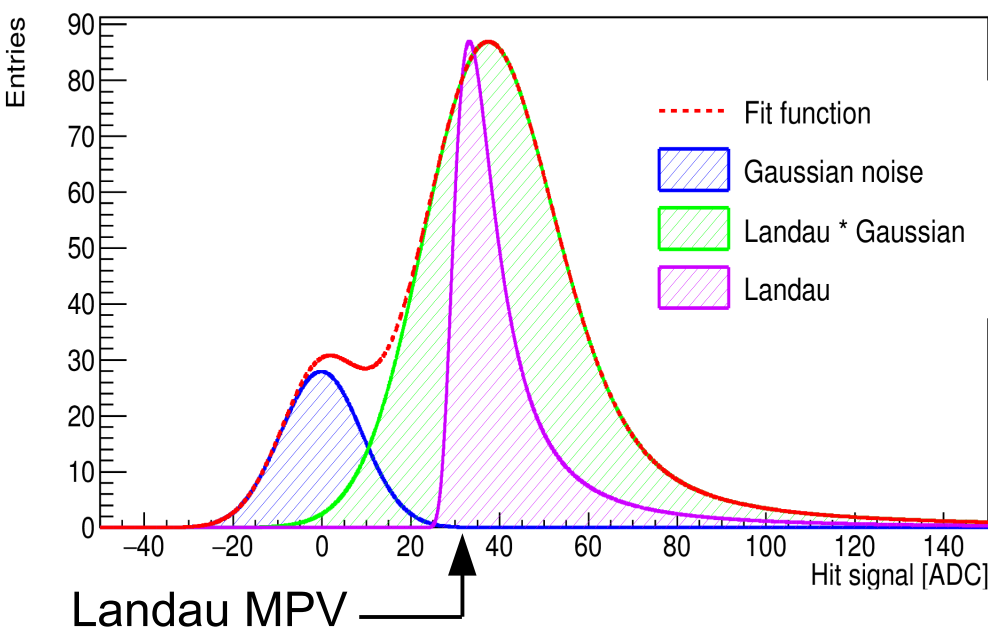
Charge definition:

Sum of the signal over 5 strips, centered on the hit one

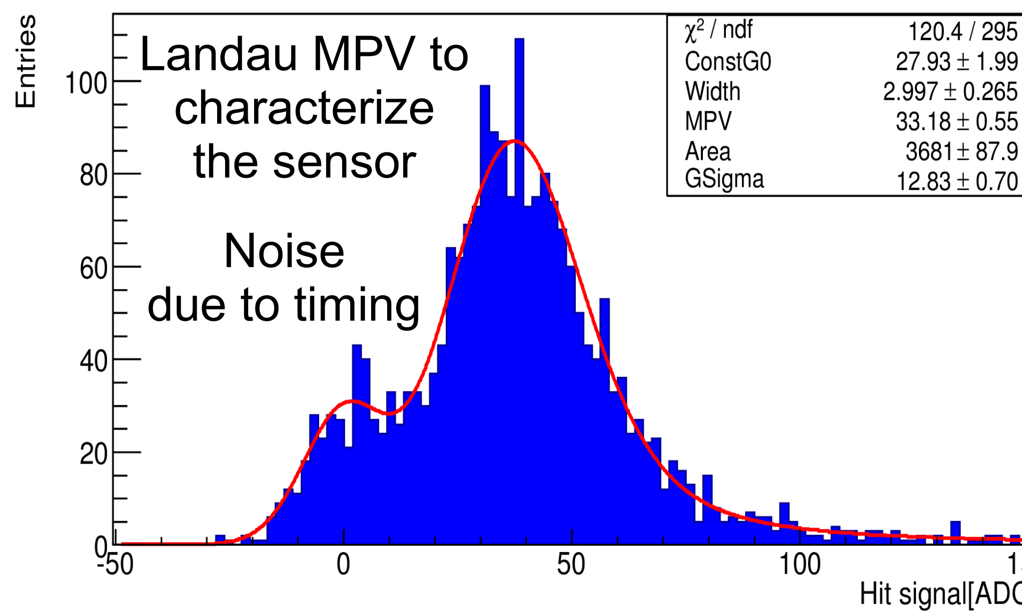


No threshold used in the analysis

T. Mäenpää et al, IEEE 2009

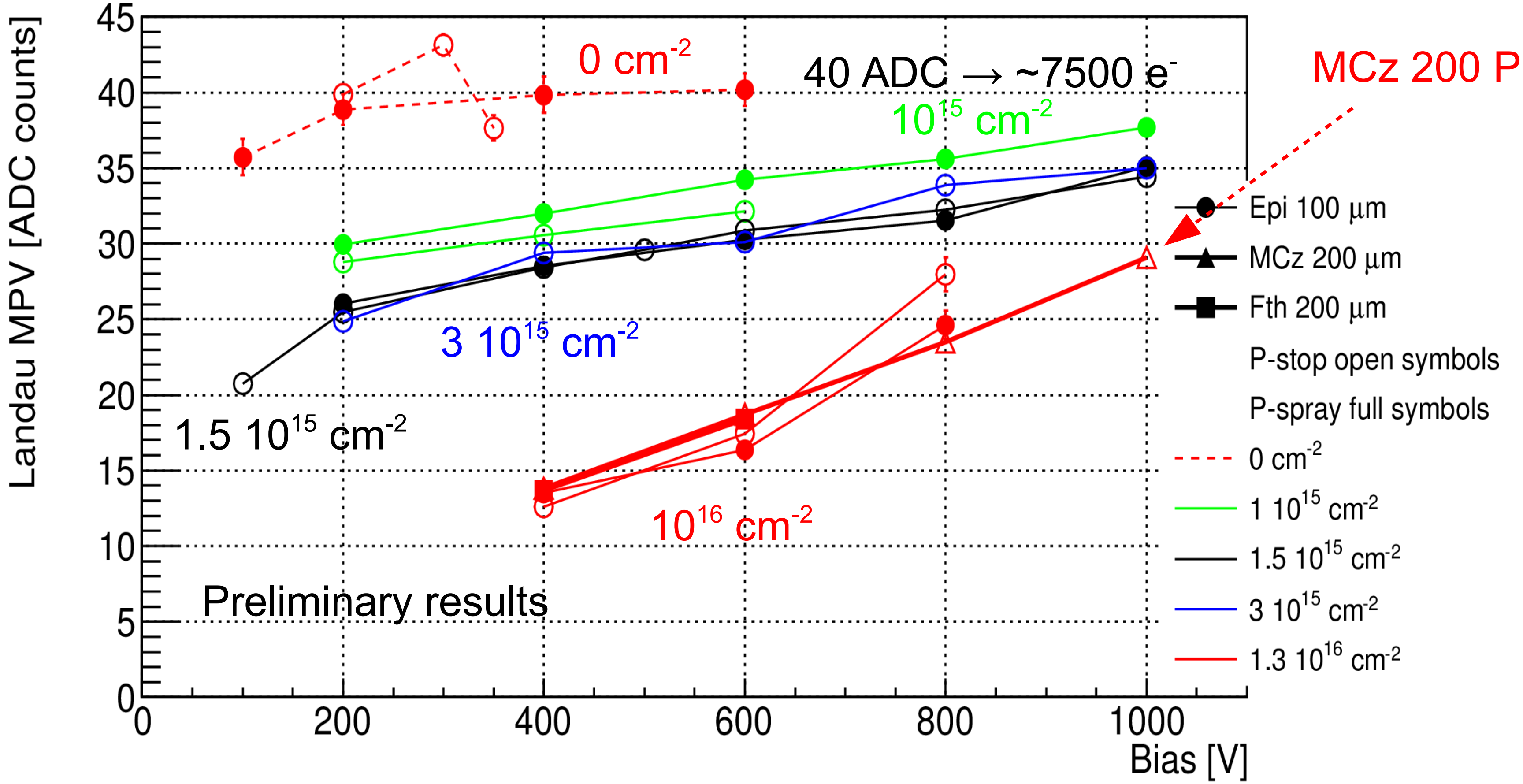


Cluster charge distribution



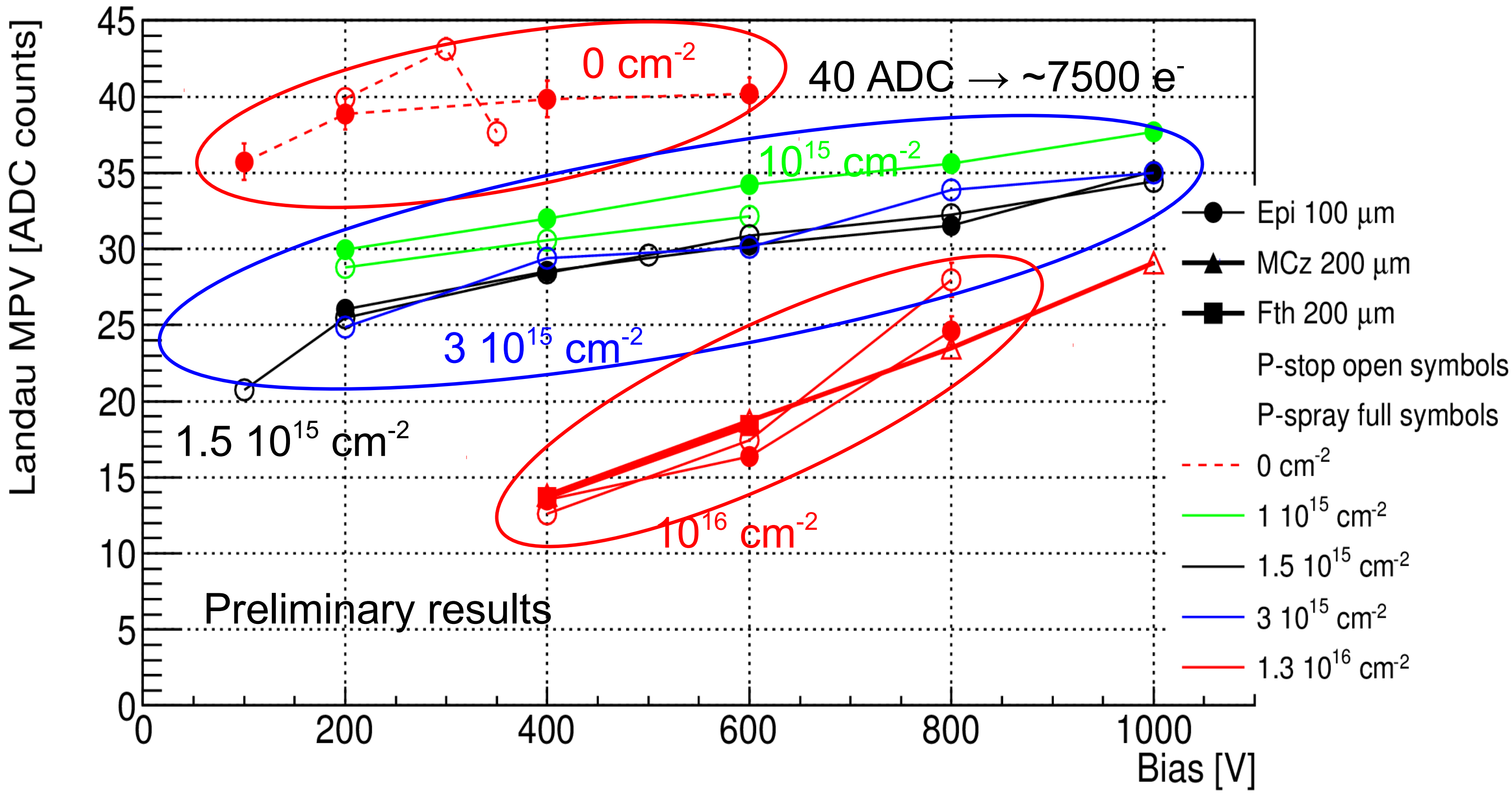
Epi100P, 23 GeV p, 3 x 10^{15} cm^{-2}, -800V, -20 °C

Charge collection p-bulk



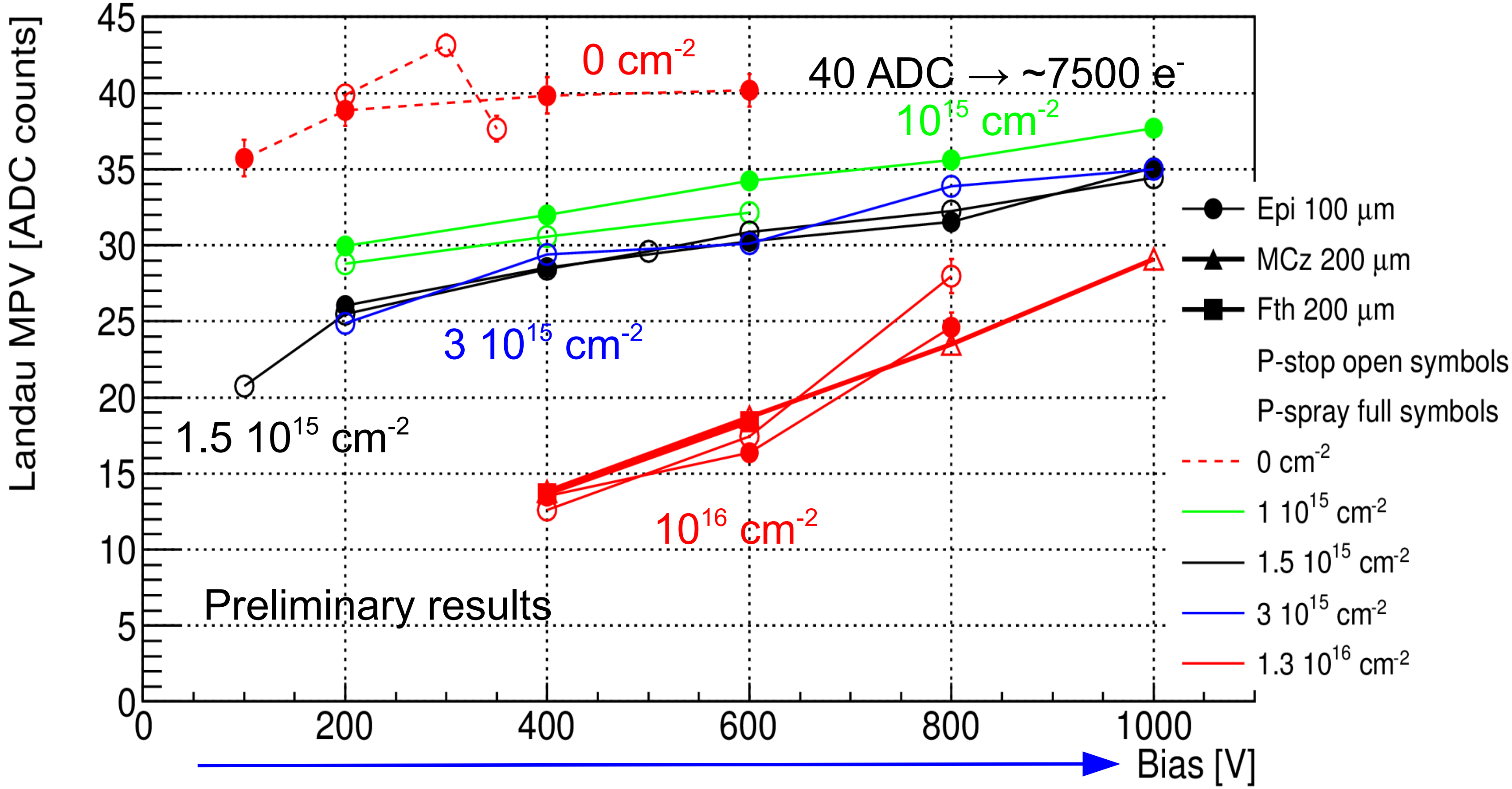
Charge collection p-bulk I

3 groups: unirradiated, ~10^{15} cm^{-2}, ~10^{16} cm^{-2}



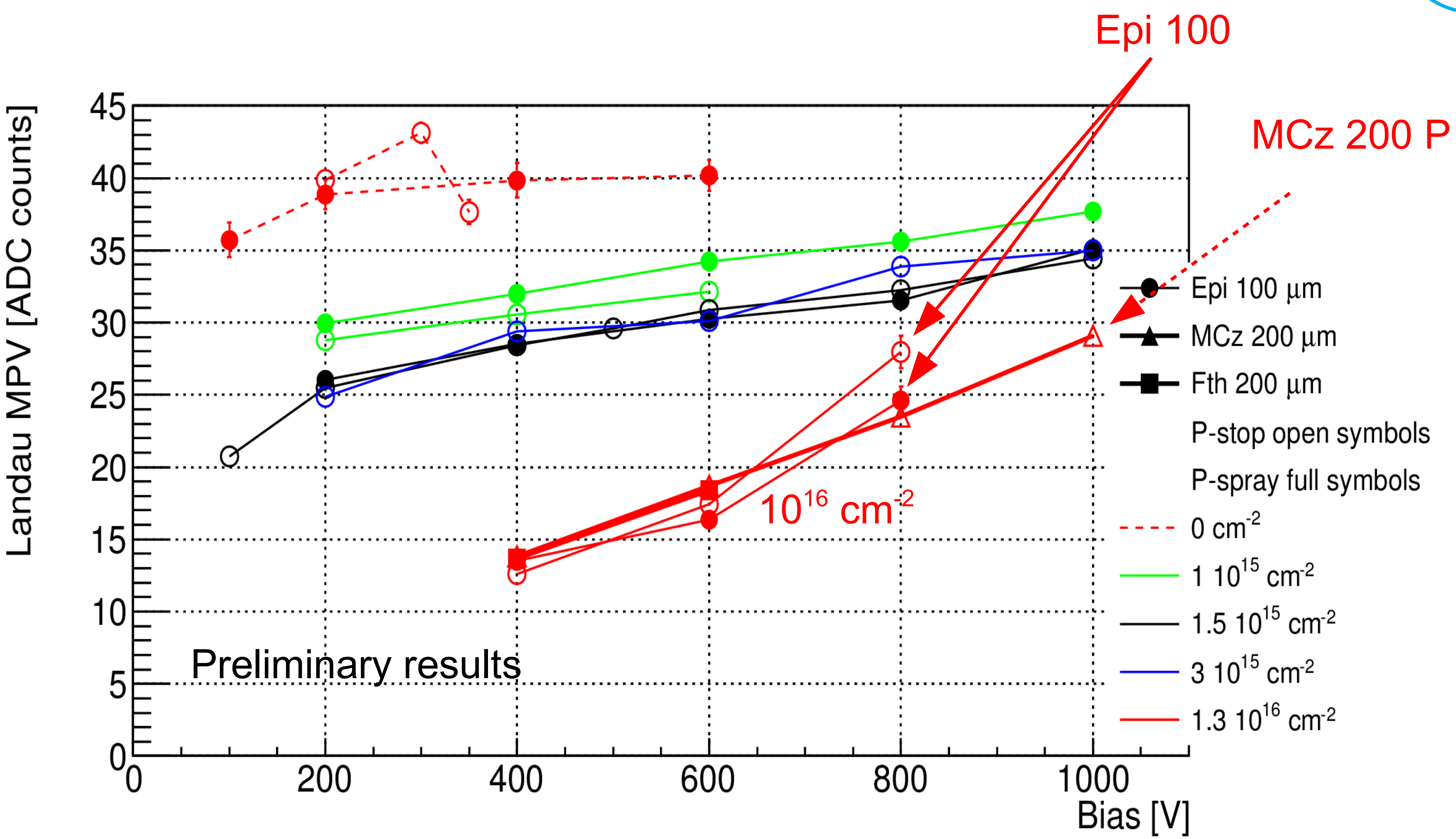
Charge collection degrades with irradiation

Charge collection p-bulk II



Charge collection increase with bias after irradiation

Charge collection p-bulk



At 10^{16} cm^{-2}:

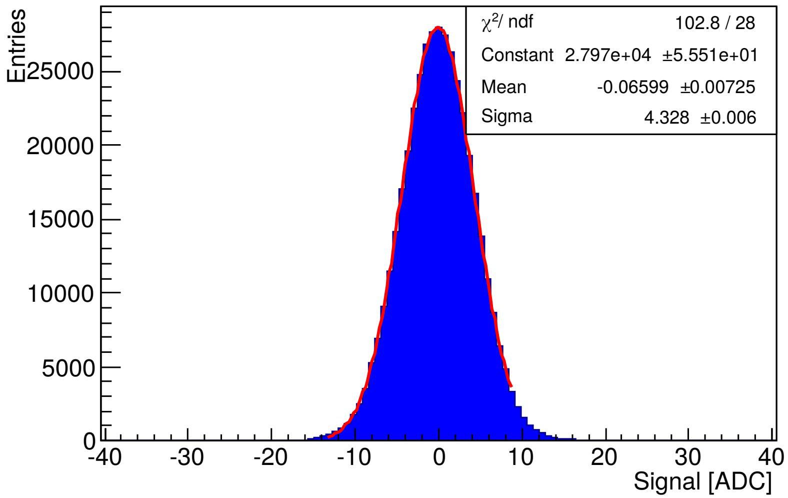
100 µm sensors → **faster signal recovery** with bias

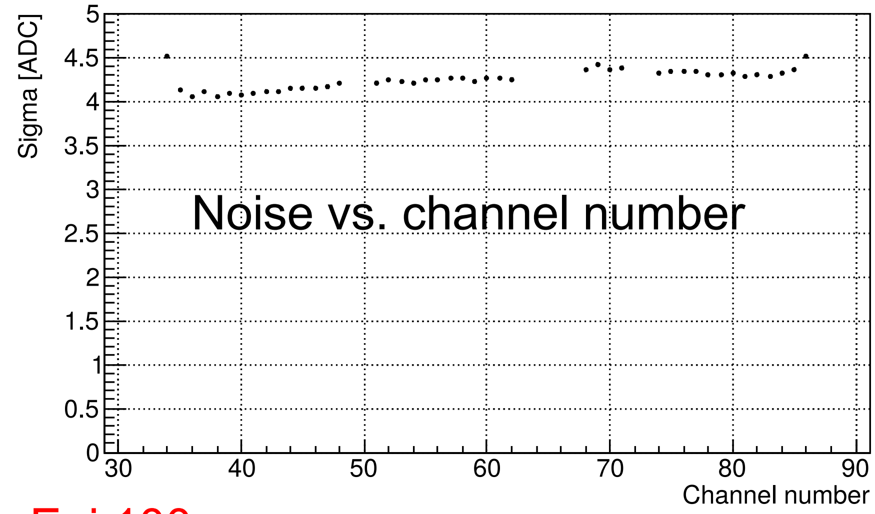
200 µm sensors → operation at **higher bias**

Similar pulse height achieved for both thicknesses

Noise p-bulk

Noise distr for one channel



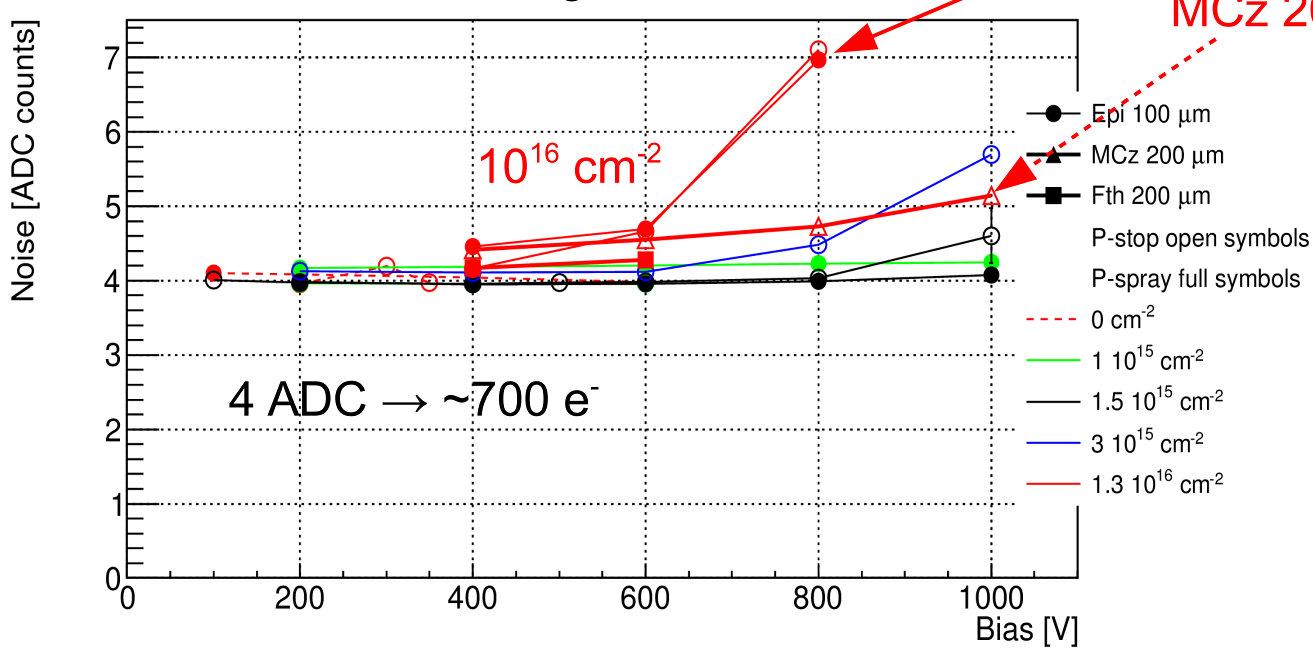


Epi100P, 23 GeV p, 3 x 10^{15} cm^{-2}, -800V, -20 °C

Mean value single channel noise

Epi 100

MCz 200 P



Up to 3 x 10^{15} cm^{-2}:
- Noise levels similar to pre-irradiation
- Noise increase at high bias

At 10^{16} cm^{-2}:
- **100 µm → higher noise**
  → charge multiplication?
- **200 µm → better noise figure**

Conclusions

The thin sensors show promising results:

- **100 µm**, p-bulk
  - Charge collection efficiency of ~65% after a fluence of 10^{16} cm^{-2}
  - Signal increase with bias ☺
  - Noise increase at high bias ☹
  - Good candidates for outer pixel layers (fluence ~10^{15} cm^{-2})
  - Further studies needed for operation after a fluence of 10^{16} cm^{-2}

- **200 µm**, p-bulk
  - Charge collection efficiency of ~35% after a fluence of 10^{16} cm^{-2}
    Compared to 100 µm sensors:
  - Slower signal increase with bias ☹
  - Smaller noise ☺

Can 150 µm sensors be a good compromise?
→ next common CMS sensor submission will give the answer!

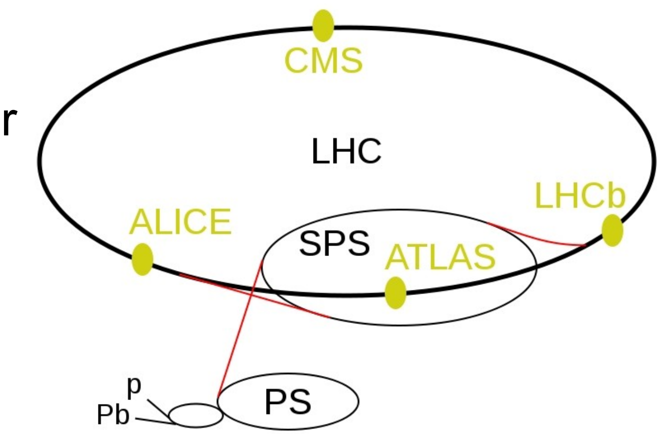
Special thanks to the test beam shifters!

Thank you for your attention!

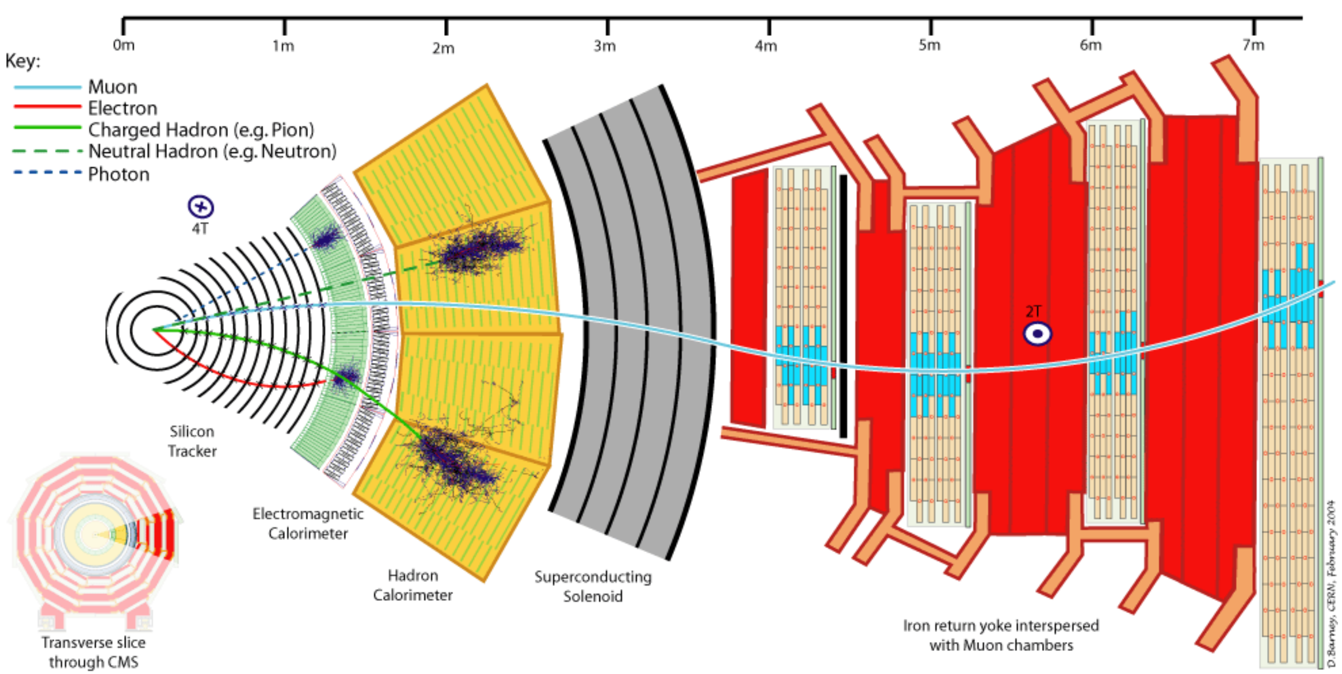
Backup

LHC and CMS

LHC:
- Large Hadron Collider
- Proton-proton and heavy ions collider
- 27 km circumference
- Operating at 13 TeV
- 4 interaction points



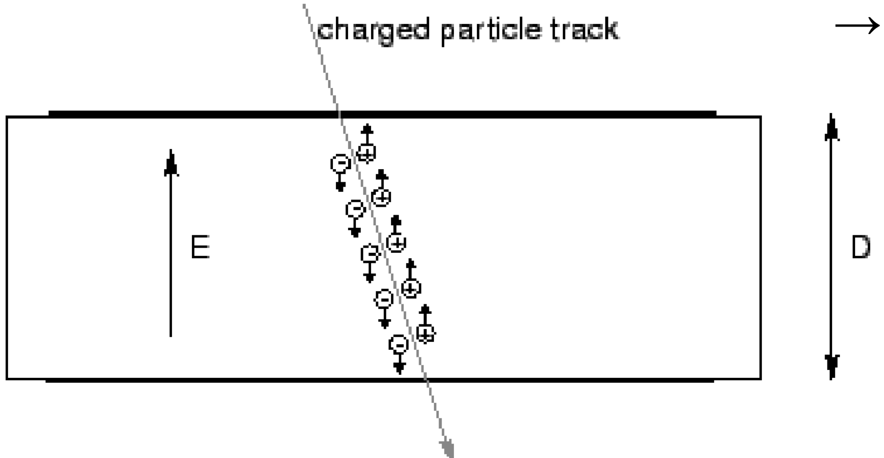
CMS:
- Compact Muon Solenoid
- General purpose experiment
- High luminosity interaction point



Achievements:
- Tests of the standard model
- Discovery of the Higgs boson by ATLAS and CMS

Silicon detectors for HEP

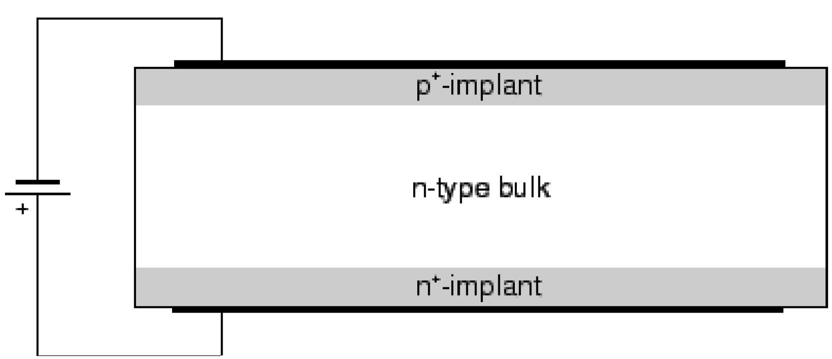
Solid state ionization detector



- Small mean ionization energy (3.6 eV / eh)
  → high signal, small thickness
- Small thickness → fast signal

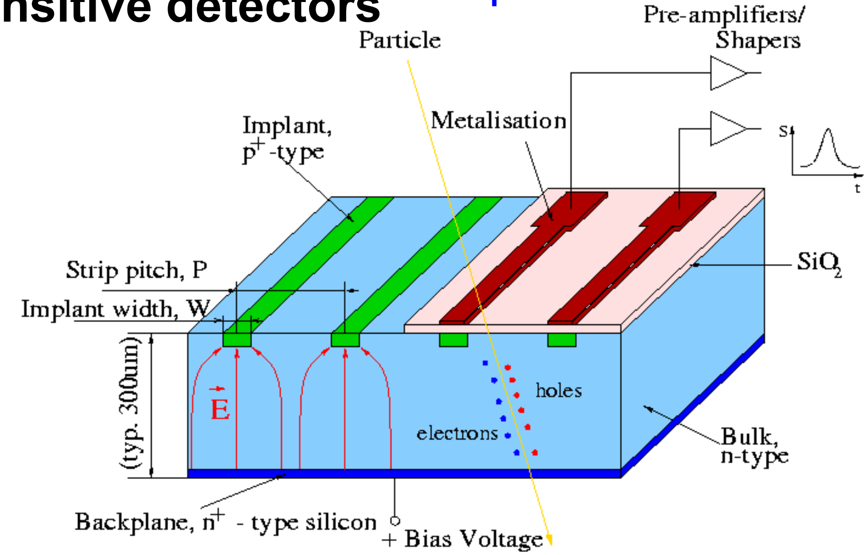
Thermally generated current

Rectifying junction (diode)

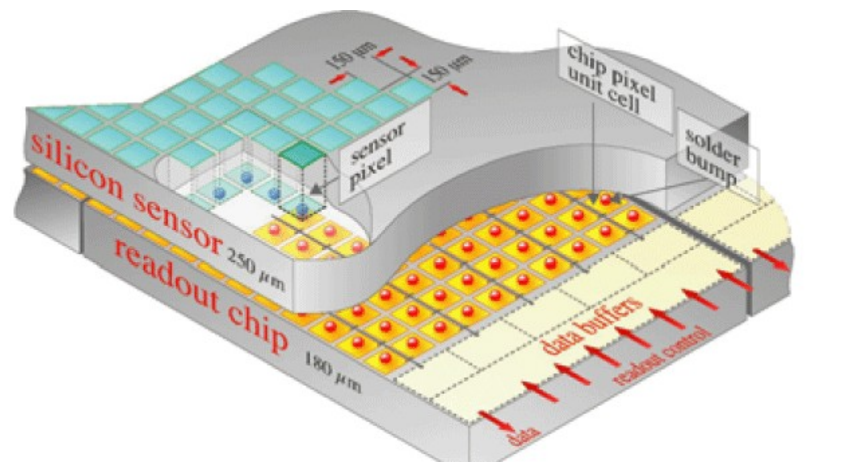


Structuring the electrodes
→ **position sensitive detectors**

Strip detectors

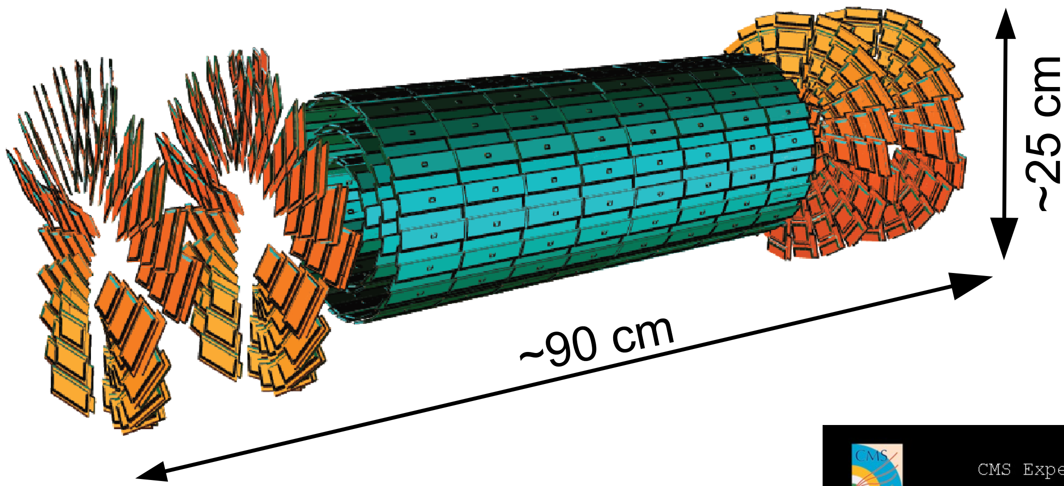


Pixel detectors



Mainly used in tracking and vertexing
Resolution in ~10 µm range

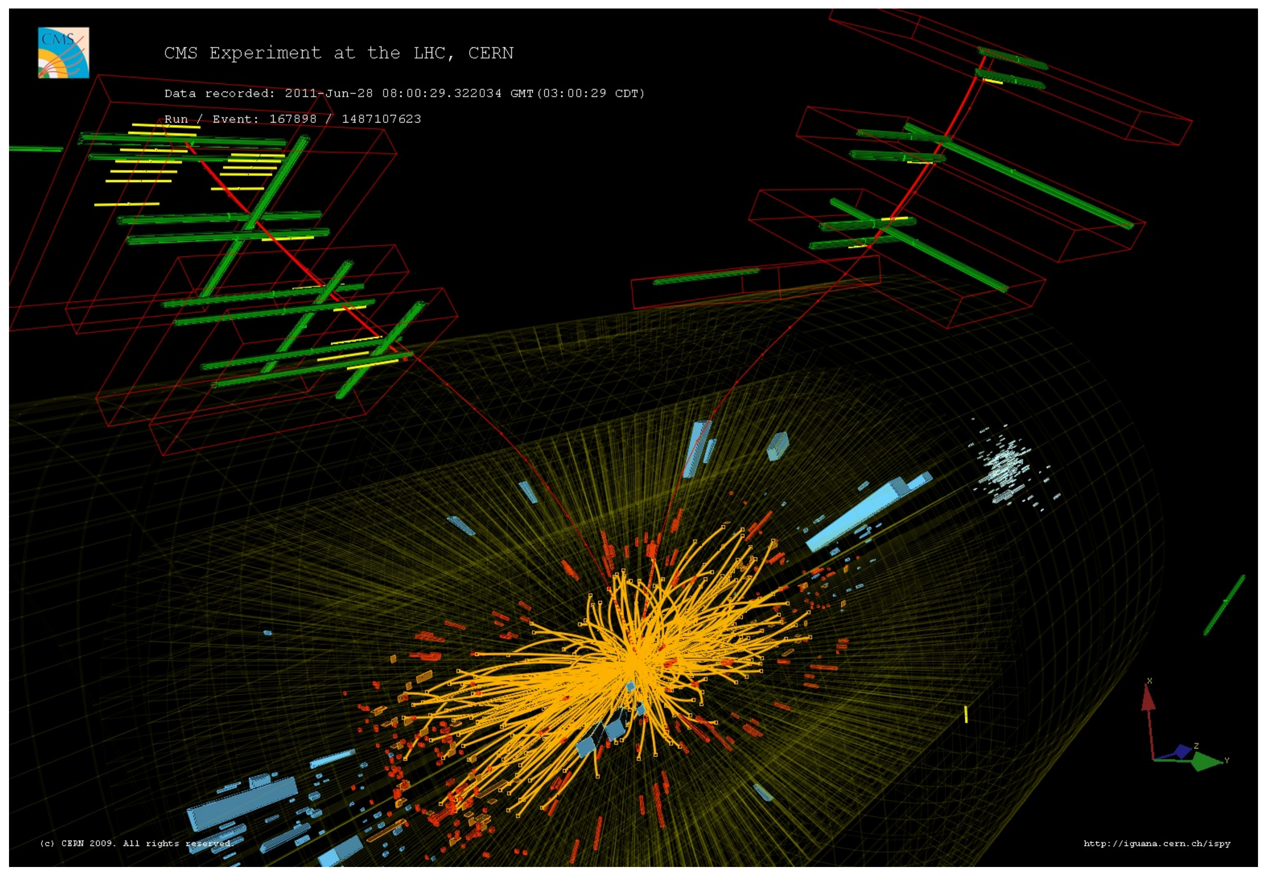
CMS pixel detector



Total area: 0.78 + 0.28 m^2
3 barrel layers
2 endcap discs
66 million 150 x 100 μm^2 pixels
285 μm n$^+$-in-n sensors
Charge sharing driven geometry

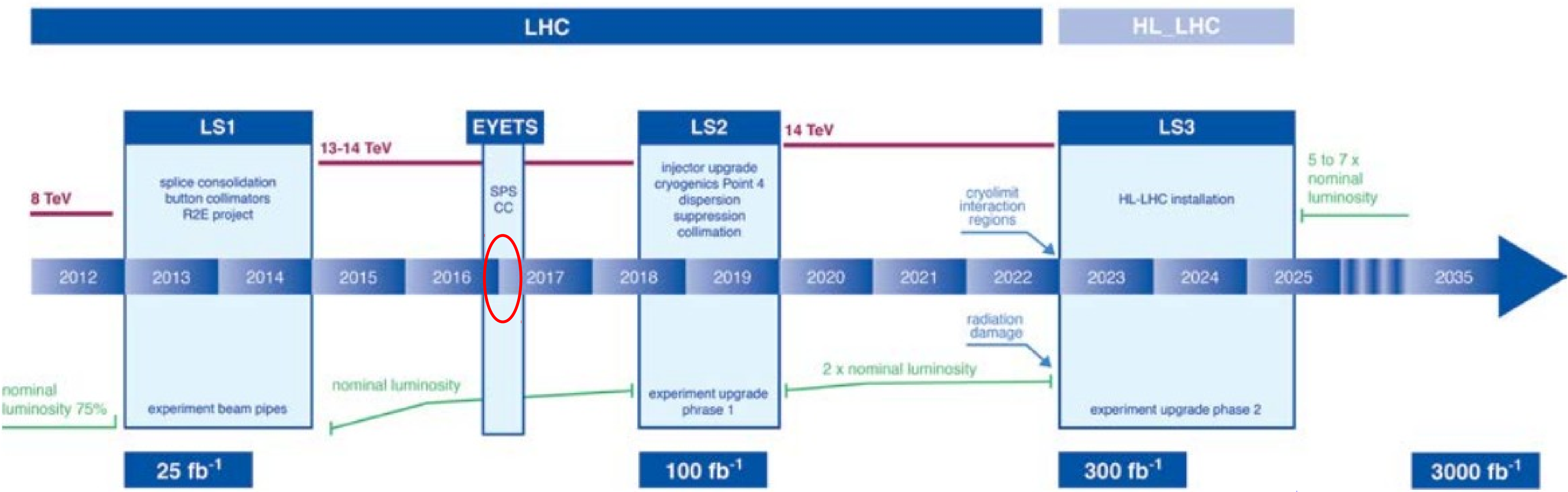
- Several sensor layers
- Cylindrical geometry
- **Measure primary and secondary vertexes**
- High track multiplicity environment
- Fundamental for b-physics
- Resolution 12 μm

$B_s \rightarrow \mu\mu$ event



LHC timetable

- Luminosity increase to 5 x 10^{34} $cm^{-2}s^{-1}$
- Mean number of interaction per bunch crossing <μ> ~140 (every 25 ns)



Pixel upgrade
"Phase I"

- Data losses
  - Buffering
  - Read out speed

↓

New pixel detector installed

Tracker upgrade
"Phase II"

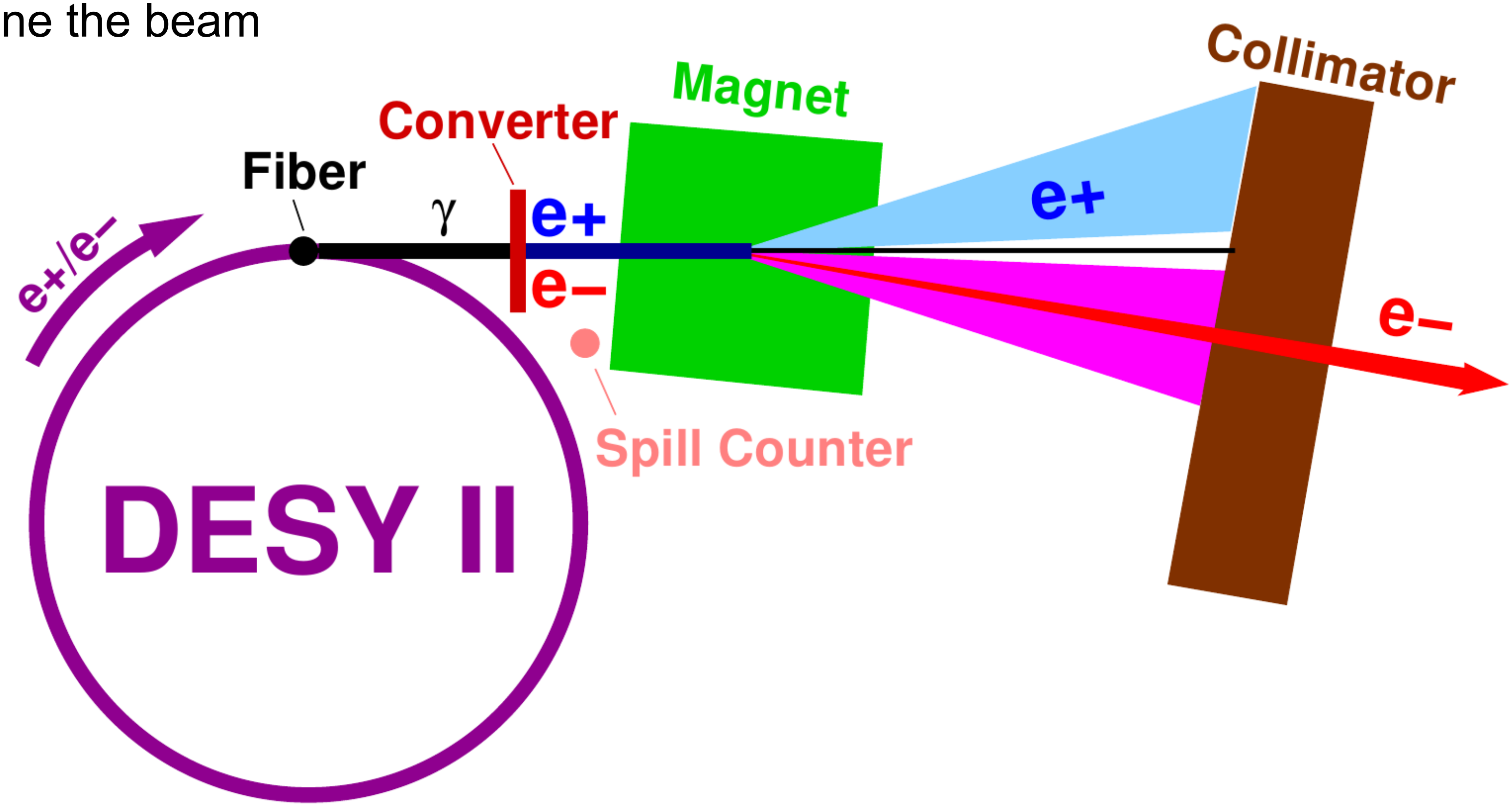
- Radiation damage
- Data losses

↓

New tracker and new pixel

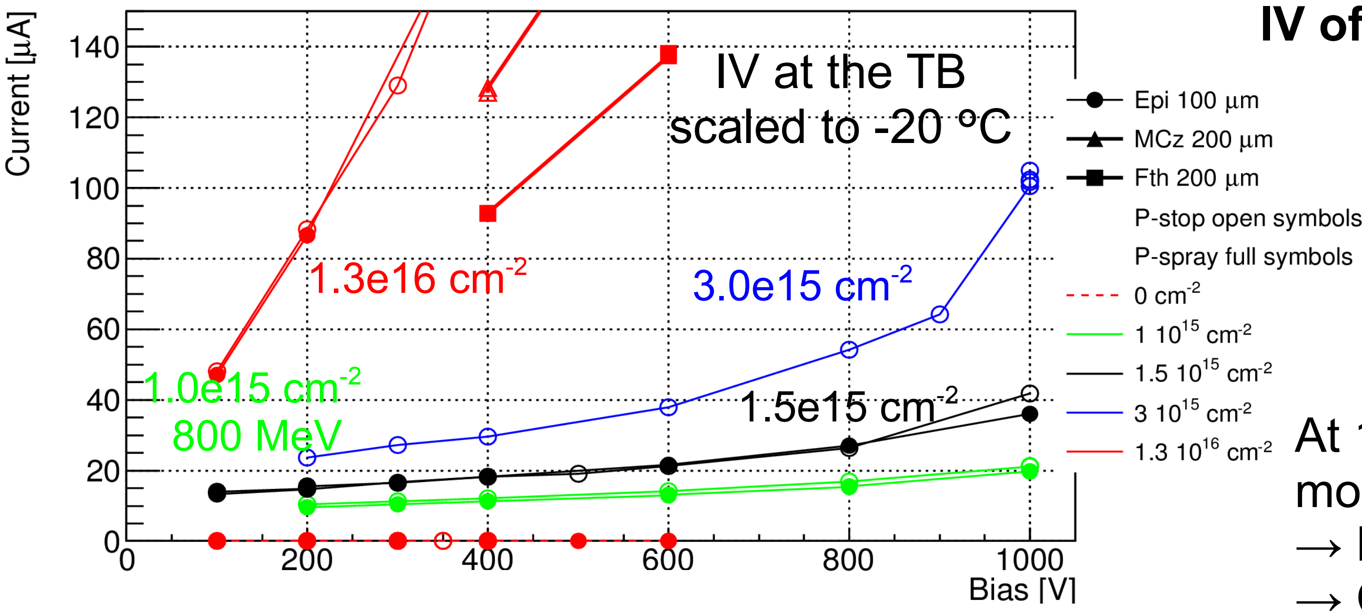
Beam generation at DESY II

Beam generation at DESY test beam:
- Bremsstrahlung on C fiber
- Conversion in e^+e^- on a metal target
- Momentum selection using a magnet
- Collimator to define the beam



IV characteristic p-bulk sensors

Strip sensors



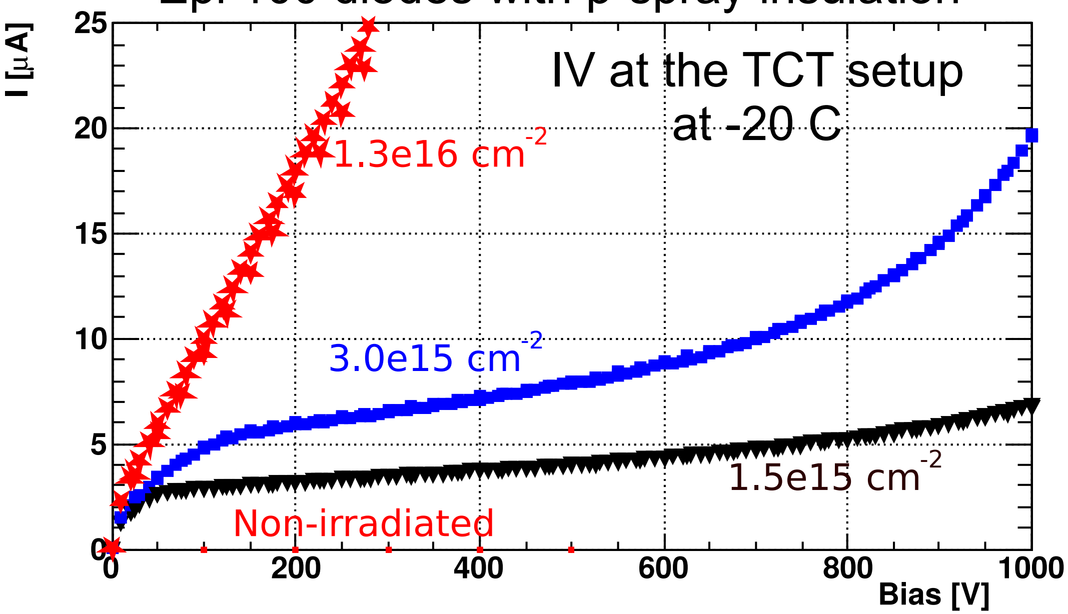
IV of both diodes and strip sensors show a "soft breakdown"

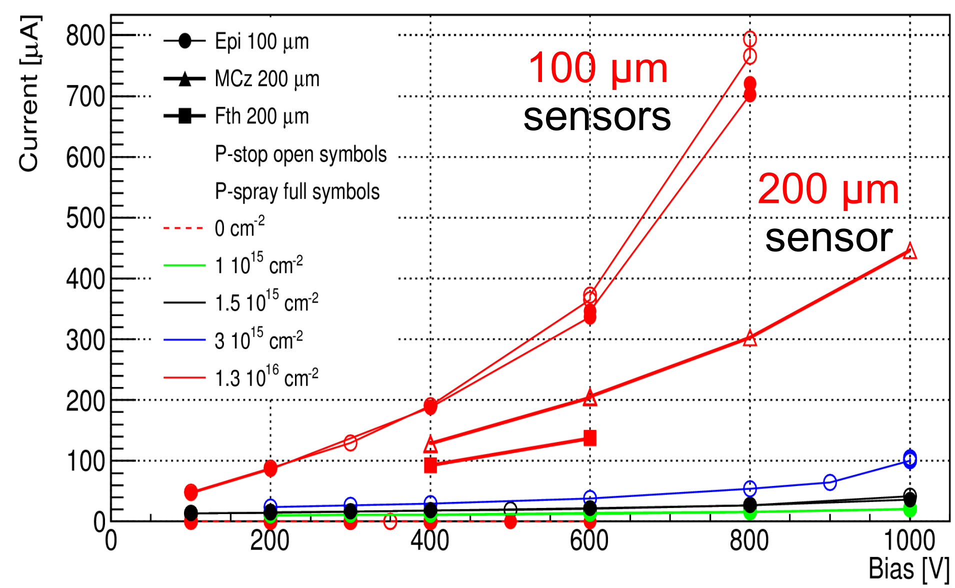
At 1.3e16 cm^{-2} 100 µm sensors draw more current than the 200 µm ones

→ No full depletion

→ Charge multiplication

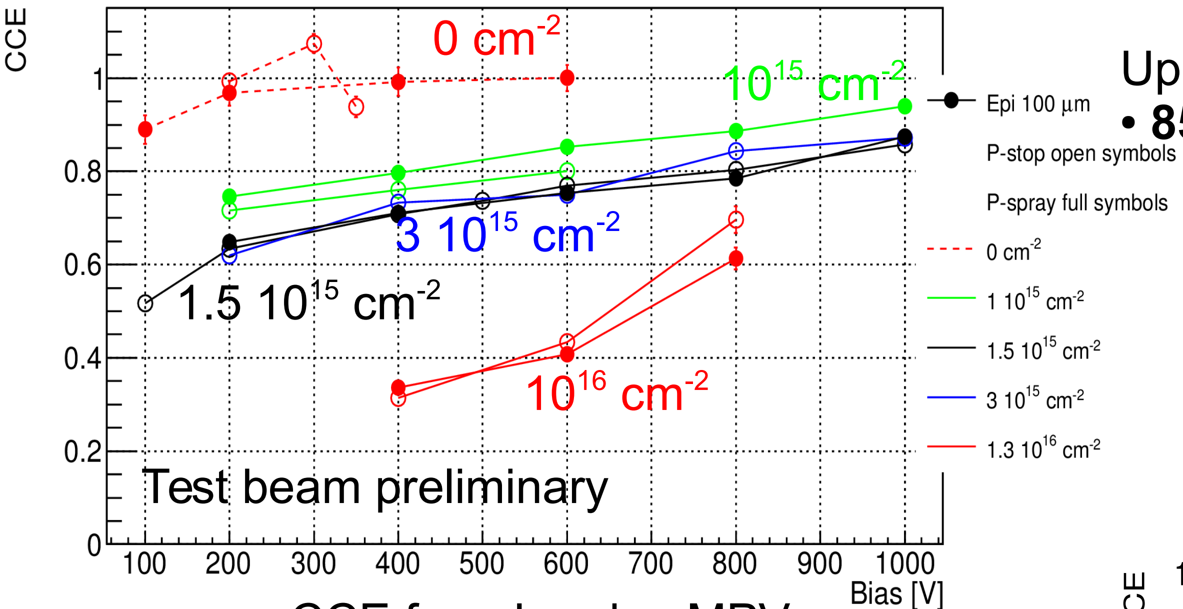
Epi 100 diodes with p-spray insulation





CCE Epi 100 p-bulk

Strip sensors at the TB



CCE from Landau MPV

Normalization between 200 and 400 V bias

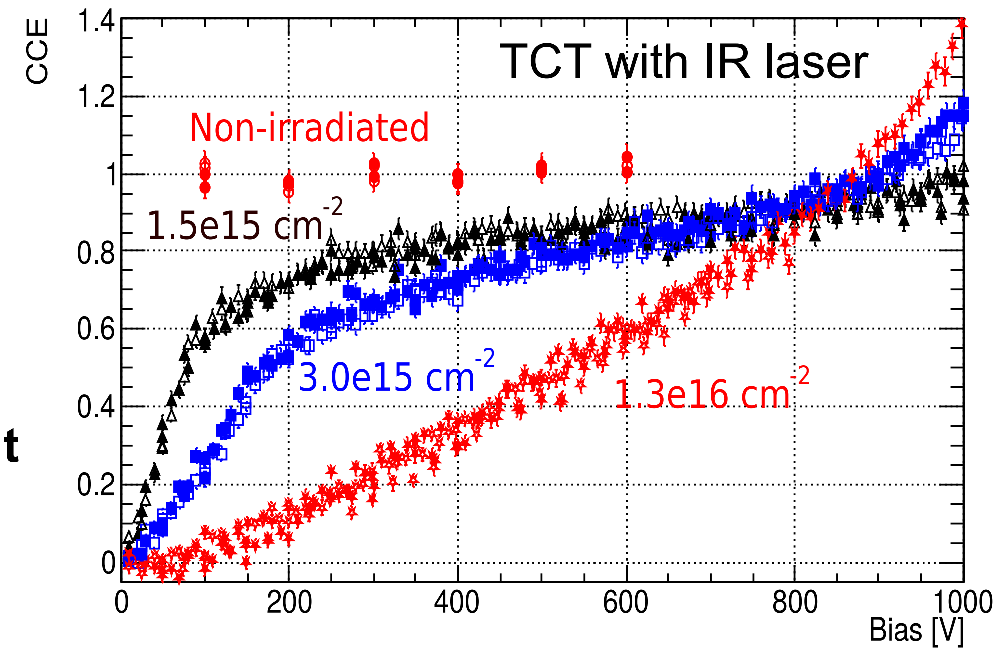
Up to 3 x 10^{15} cm^{-2}:

- **85% collected charge at high bias**

Difference between TB and TCT data to be studied

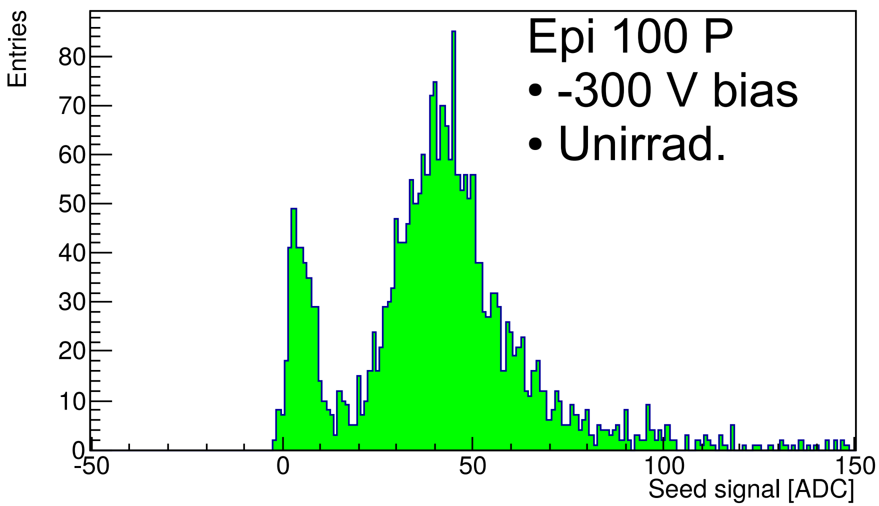
Charge multiplication in the diode measurement

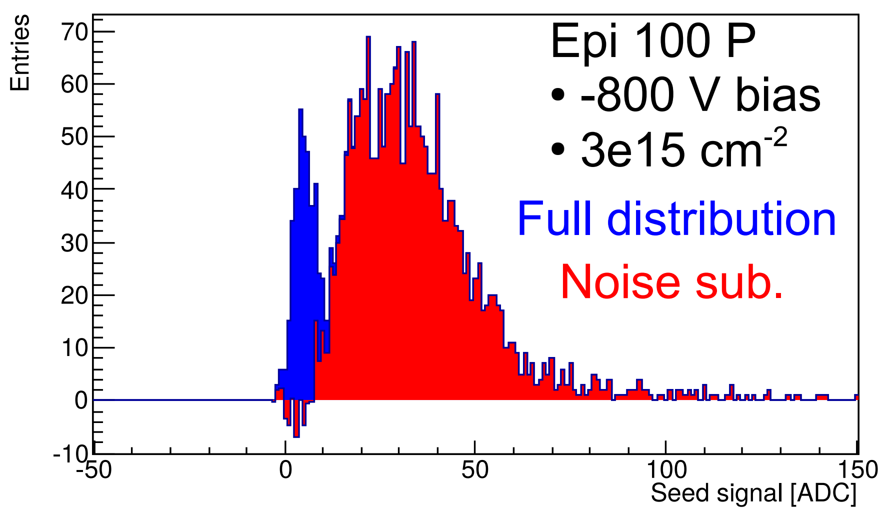
Diodes with p-spray insulation



Efficiency Epi 100 p-bulk

Seed strip charge distribution





The distribution gets broader with irradiation
→ influence on detection efficiency

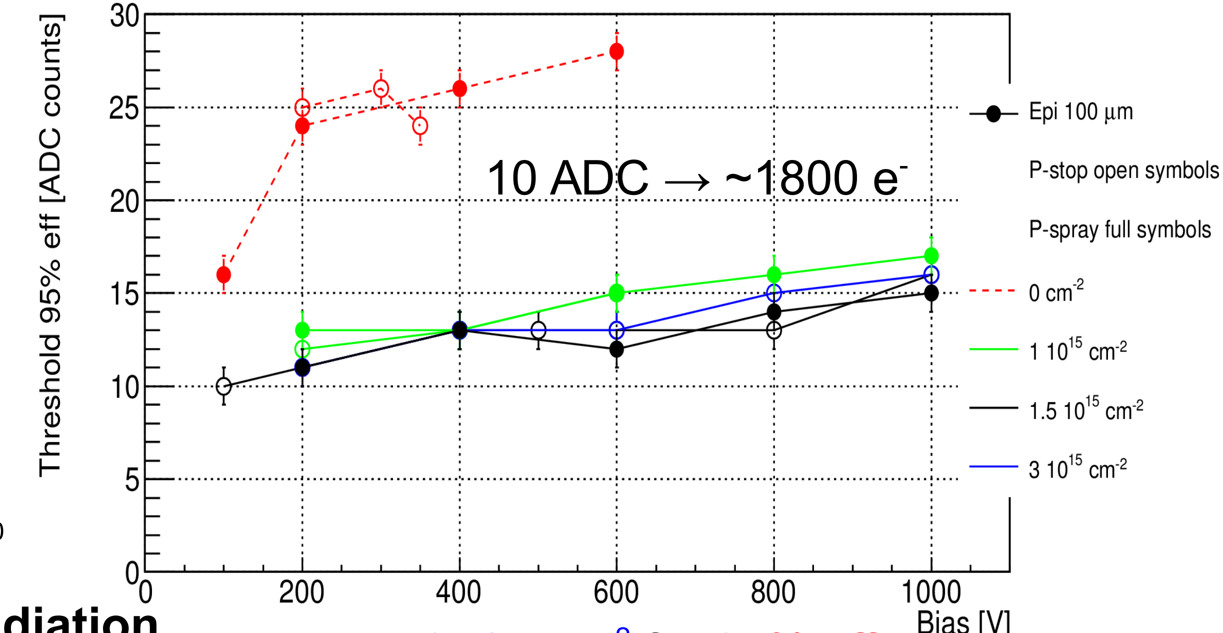
Most pixel systems use a threshold for zero suppression
→ how high can this threshold be?

CMS pixel threshold ~2300 e^-
- Noise < 150 e^-
- Cross talk is a limiting factor

→ efficiency of 99.3-99.8% (layer dependent)

This method can not access efficiency ~99%

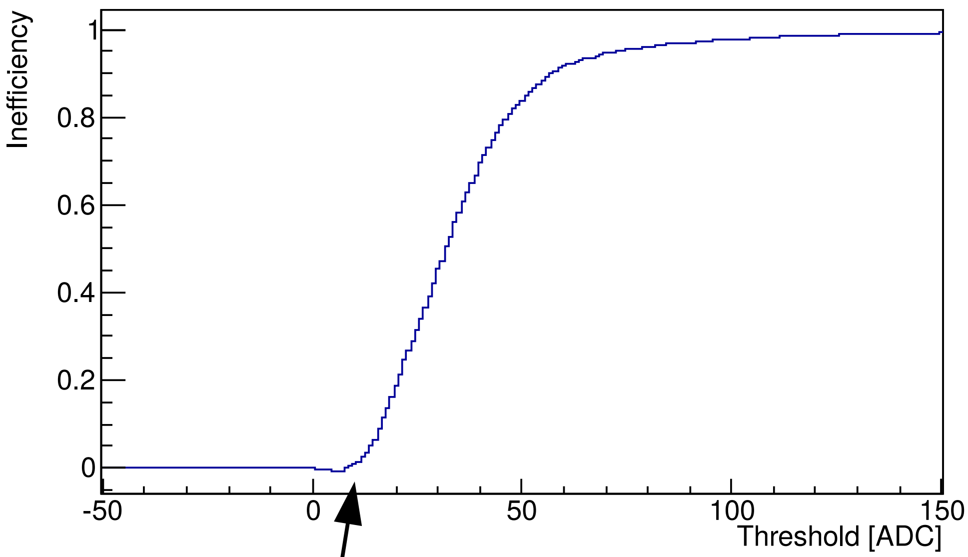
Max threshold to have 95% efficiency



Up to 3e15 cm^{-2} for 95% efficiency:
→ **Threshold ~2000 e^-**

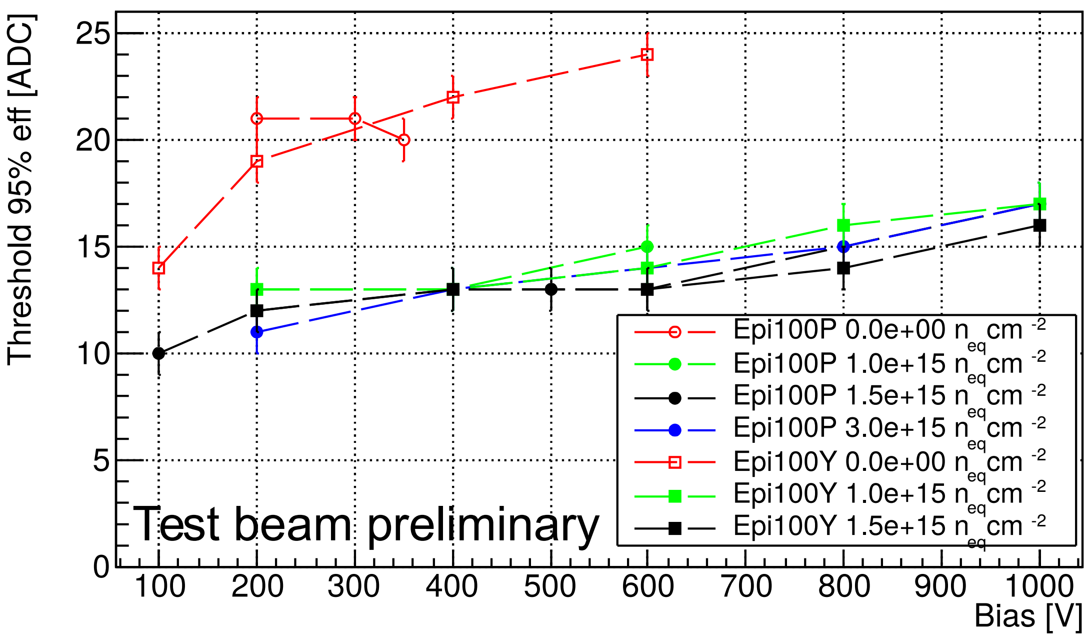
Efficiency estimation

Normalized integral of BG sub histo



Bumps due to BG subtraction

Threshold to get 95% efficiency



Same plot for 99% too much influenced by bumps

Oxygen content