IFAE 2017: XVI Incontri di fisica delle alte energie

The INFN R&D: new pixel detector for the High Luminosity Upgrade of the LHC

- INFN Pixel R&D: main design features
- CMS results: thin-planar before & after irradiation
- CMS results: 3D before irradiation
- ATLAS results: 3D before irradiation
- Summary and prospects

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20/04/2017

INFN Pixel R&D: main design features

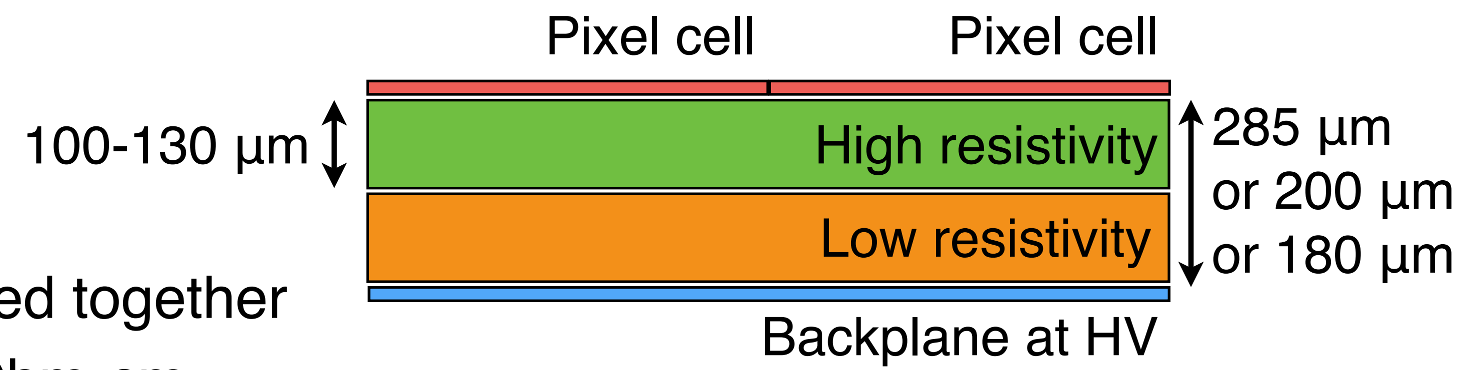
High Luminosity upgrade of the CERN-LHC: operation conditions	Sensor design contraints
Luminosity $5\text{x}10^{34}/(\text{cm}^2\cdot\text{s})$, up to 200 events/25 ns bunch crossing	Maintain occupancy at % level and increase the spatial resolution ➜ pixel cell size ~ 25x100 μm^2 or 50x50 μm^2 (currently 100x150 μm^2 CMS, 50x250 μm^2 ATLAS)
Radiation level for first pixel layer at 3000 fb^{-1} ~$2\text{x}10^{16}$ n_{eq}/cm^2 (~10 years) ➜ carriers lifetime ~0.3 ns, mean free path ~30 µm for electrons at saturation velocity	Reduce electrodes distance to increase electric field and thus the signal ➜ thin planar or 3D columnar technologies

Joint ATLAS-CMS INFN collaboration, partnership with Fondazione Bruno Kessler-FBK (Trento, Italy), for the development of **thin planar** and **3D columnar n-in-p** sensors on **6” FZ wafers** with **Direct Wafer Bond**([1]):

- **Planar**
  - process options: p-spray and/or p-stop
  - periphery design: standard and active-edge
- **3D columnar**
  - single sided process, optimised by FBK

([1]) IceMos Technology, Belfast

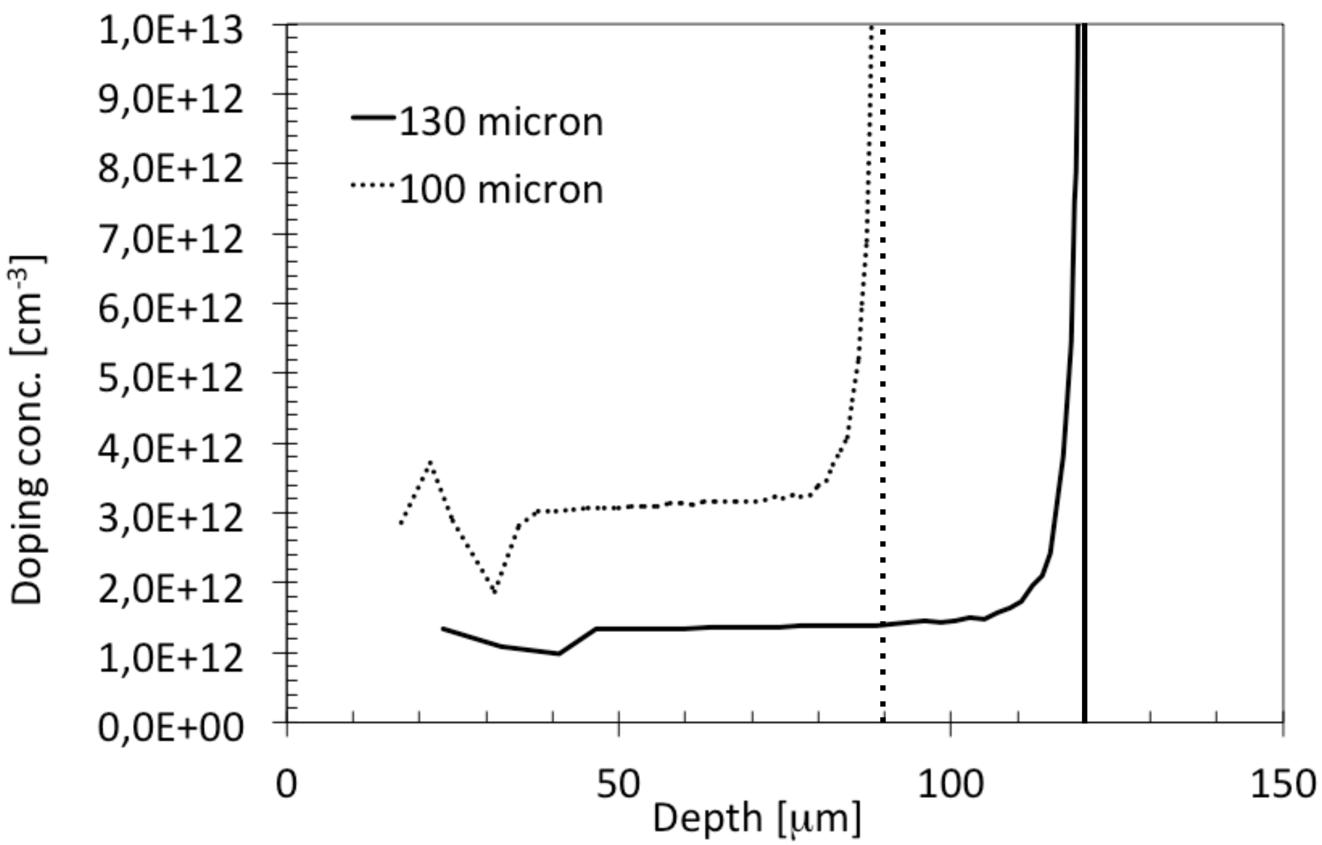
INFN Pixel R&D: main design features



Direct Wafer Bond([1])

- Two wafers, high and low resistivity, bonded together
- p-type high resistivity (active layer) > 3 kOhm•cm
- Active layer thickness: two choices, 100 μm and 130 μm
- Thinning process after fabrication: final total sensor thickness from 285 μm down to 180 μm

Doping concentration profile measurement



Effective thickness reduced by Boron diffusion from wafer carrier: ~10 μm

MIP Most Probable Value expected at:

- ~6000 e⁻ for 100 μm thick sensors
- ~8000 e⁻ for 130 μm thick sensors

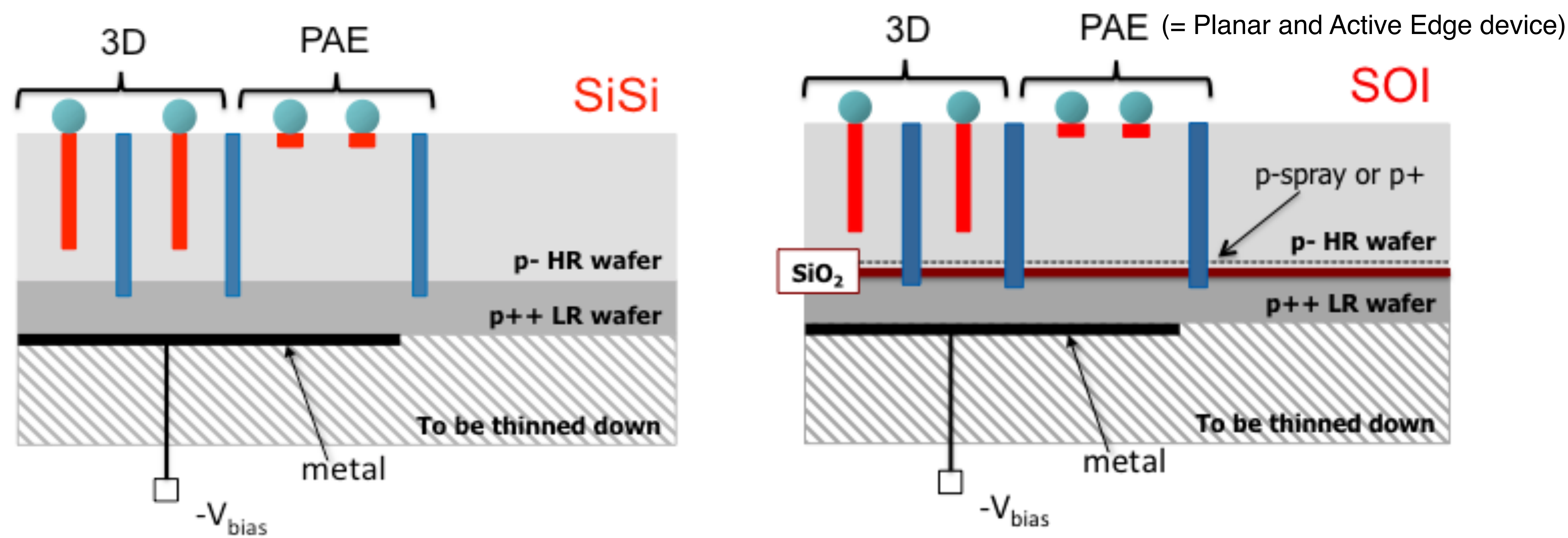
NIMA 824 (2016) 388

([1]) IceMos Technology, Belfast

INFN Pixel R&D: main design features

Prototypes assembly main features

- Hybridisation with chip via bump-bonding: SnAg([1]) and Indium([2])
- Spark protection (only for thin planar sensors): on sensor (periphery) and chip (periphery or whole area) by BCB (Benzo-Cyclo-Butene) layer ~2 µm thick([1])



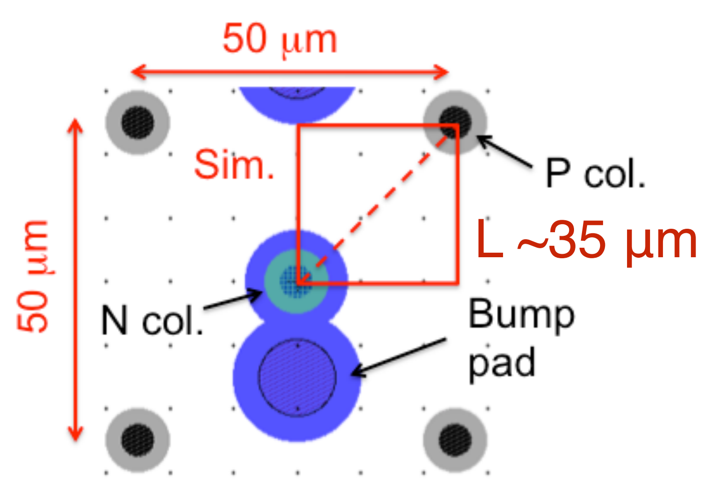
3D single sided process, optimised by FBK (more details in backup slides)

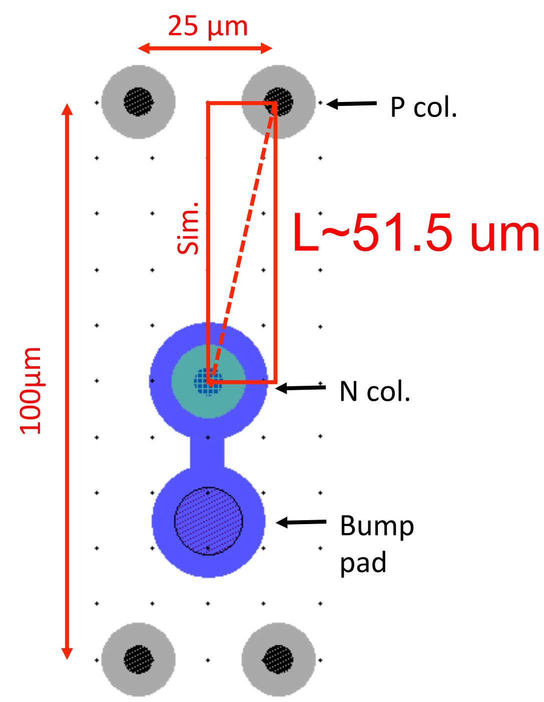
- Thin sensors on support wafer: SiSi or SOI
- Ohmic columns/trenches depth > active layer depth (for bias)
- Junction columns depth < active layer depth (for higher $V_{breakdown}$)
- Reduction of columns diameter to ~5 µm
- Holes (at least partially) filled with poly-Si

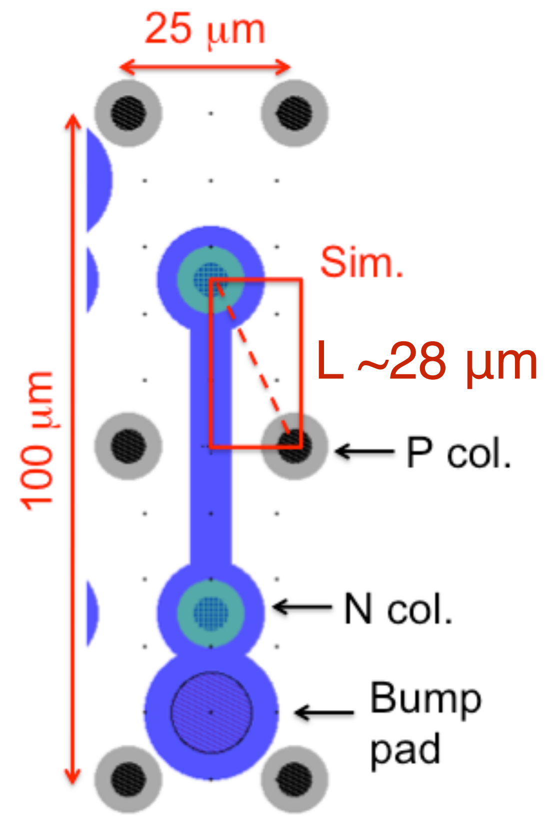
([1]) IZM Fraunhofer, Berlin

([2]) Leonardo Finmeccanica, Rome

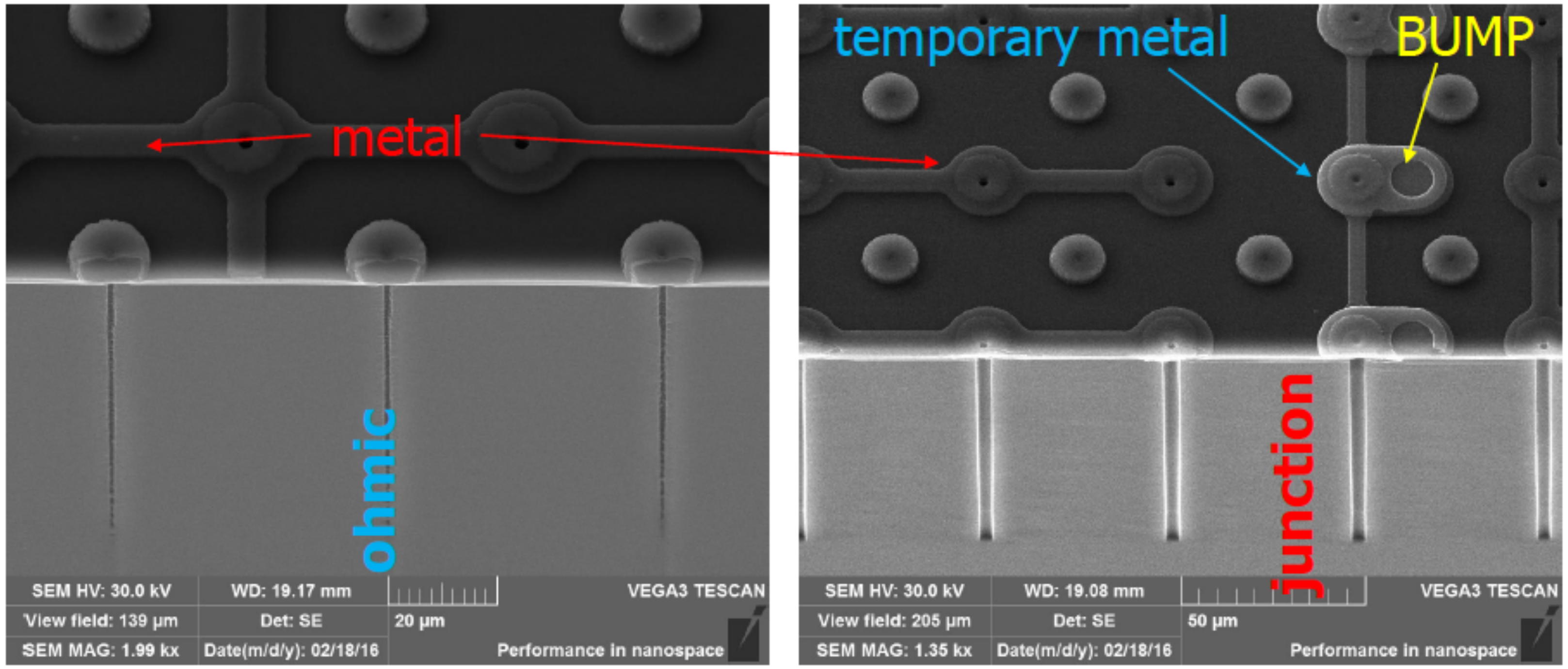
INFN Pixel R&D: main design features



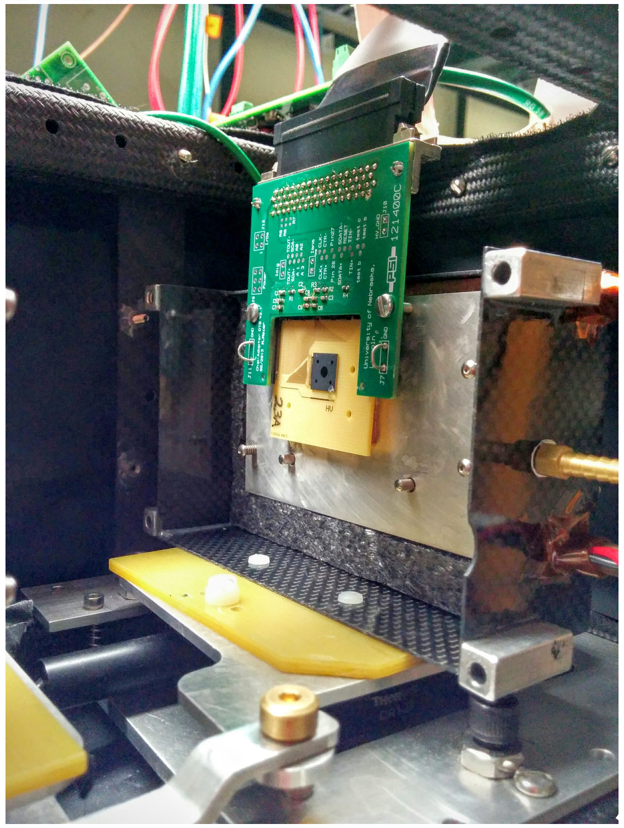


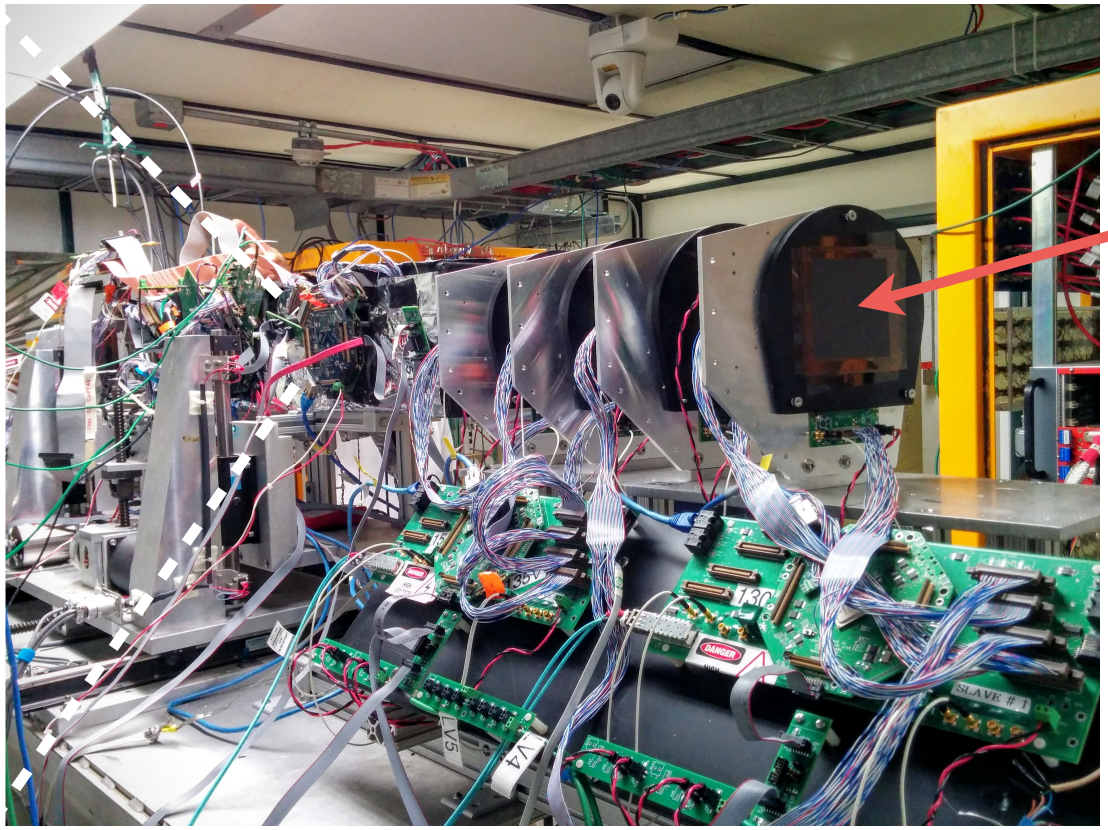


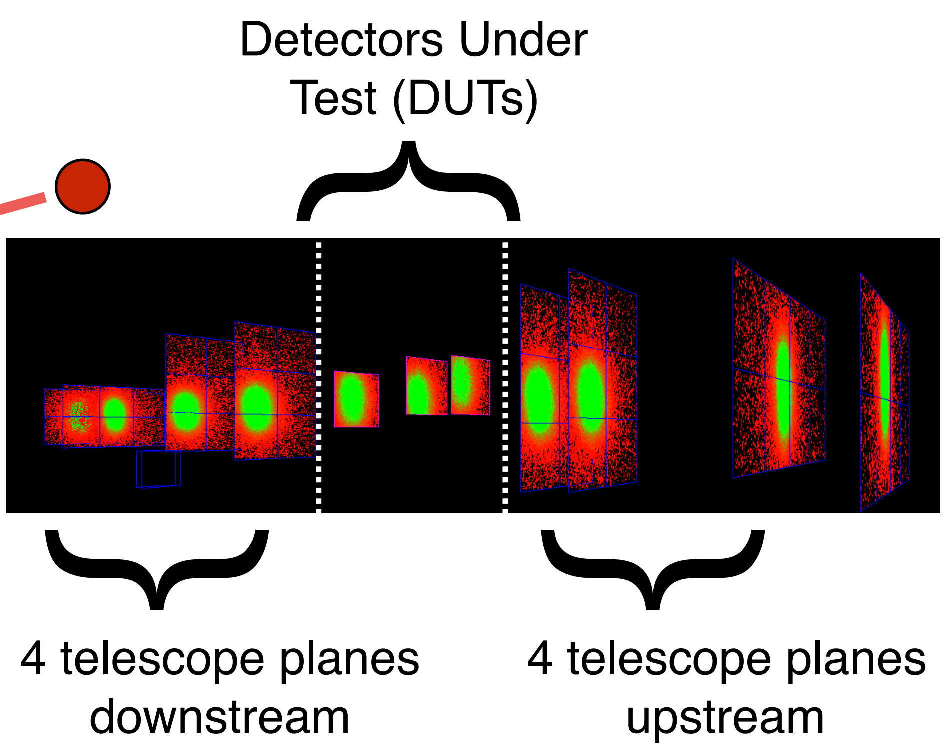
- 50x50 µm² with 1 junction electrode (1E) and 25x100 µm² with 1 junction electrode (1E) enough space for bump pad
- 25x100 µm² with 2 junction electrodes (2E) has bump pad too close to ohmic columns ➜ under test **bumps on columns**
- 100x150 and 50x250 µm² cell sizes made for compatibility with available readout chip



CMS results: testbeam setup







Testbeam carried out at Fermilab MTest area (*NIM-A 811 (2016) 162-169*)

- 120 GeV protons from Main Injector
- 8 pixel planes
- based on PSI46 analog chip (100x150 μm^2 pixel cell, 80 rows and 52 columns)
- ~8 µm resolution on each coordinate

Sensors bump-bonded to CMS pixel readout chip PSI46 digital chip (100x150 μm^2 cell size)

Base requirements for testbeam data analysis

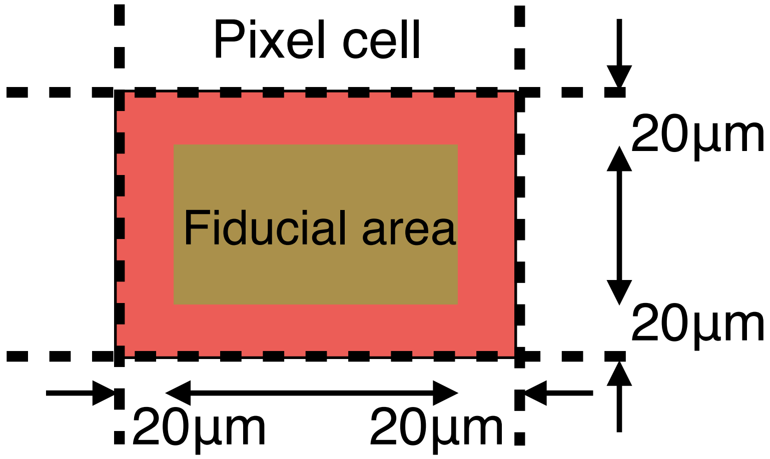
- tracks with 8 associated hits (one per plane)
- no more than 5 hits on each plane
- track X^2 / d.o.f. ≤ 5
- only one track per event

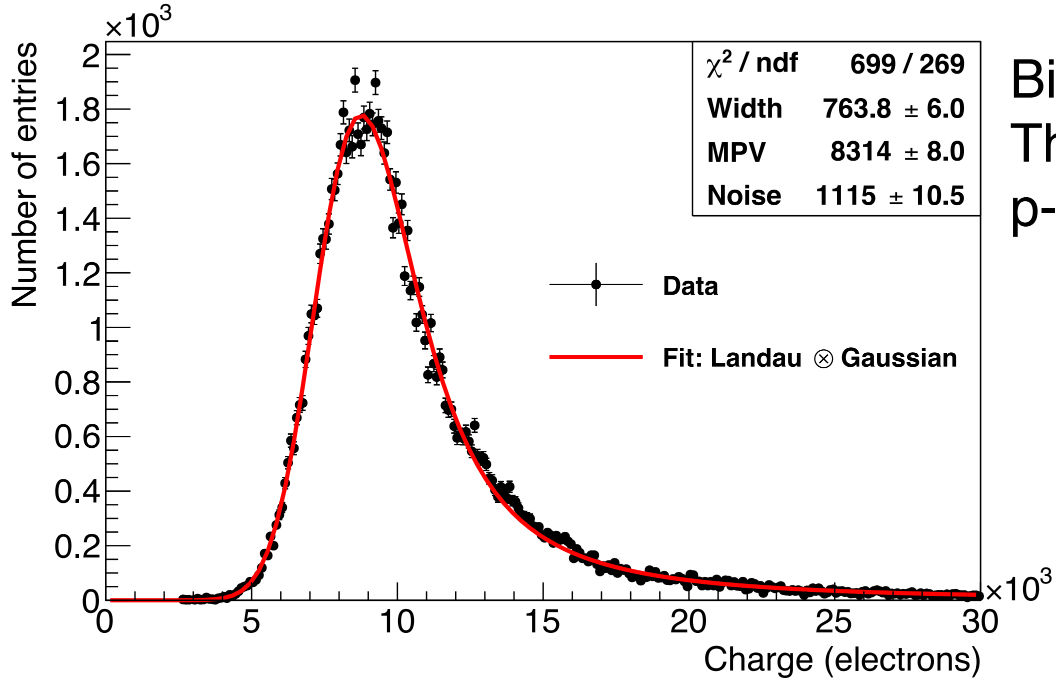
Other specific requirements might be requested depending on the analysis

CMS results: thin-planar before irradiation

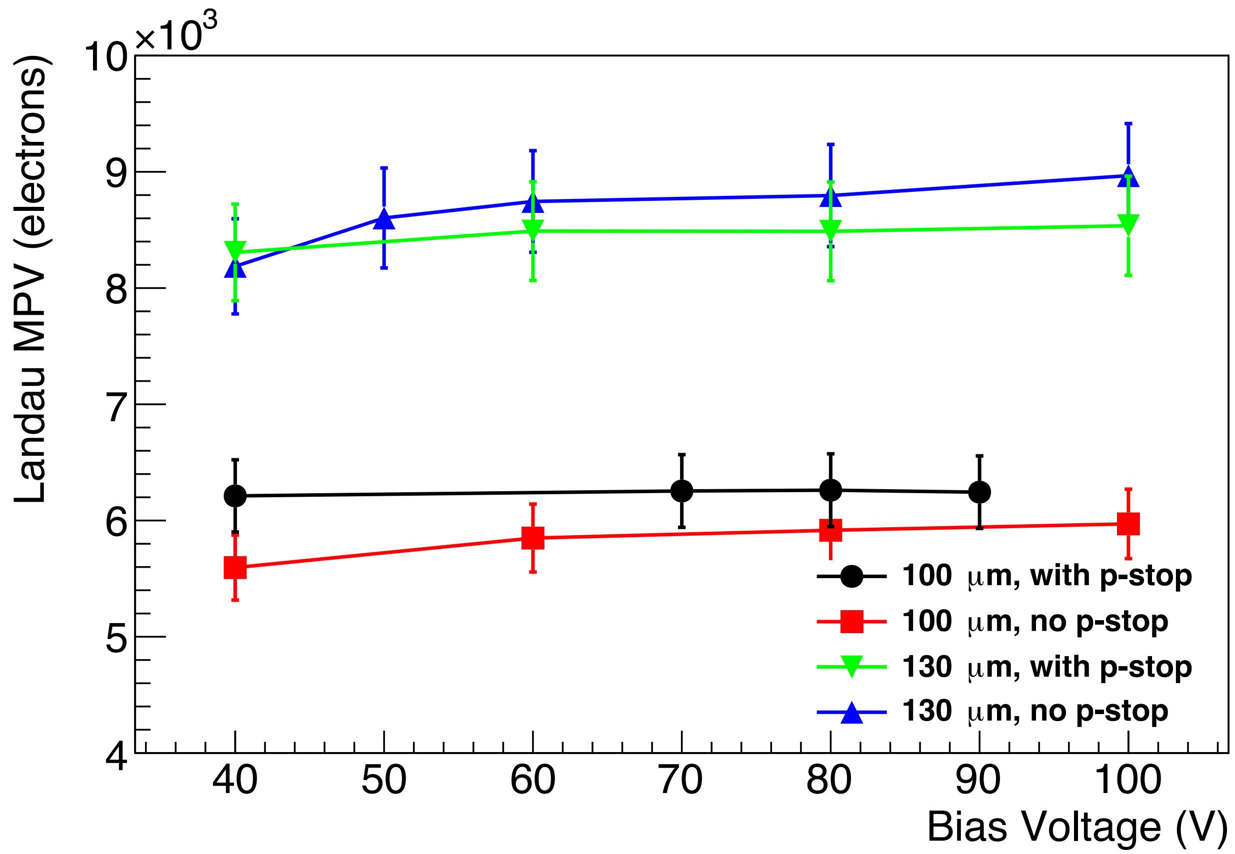
Requirements

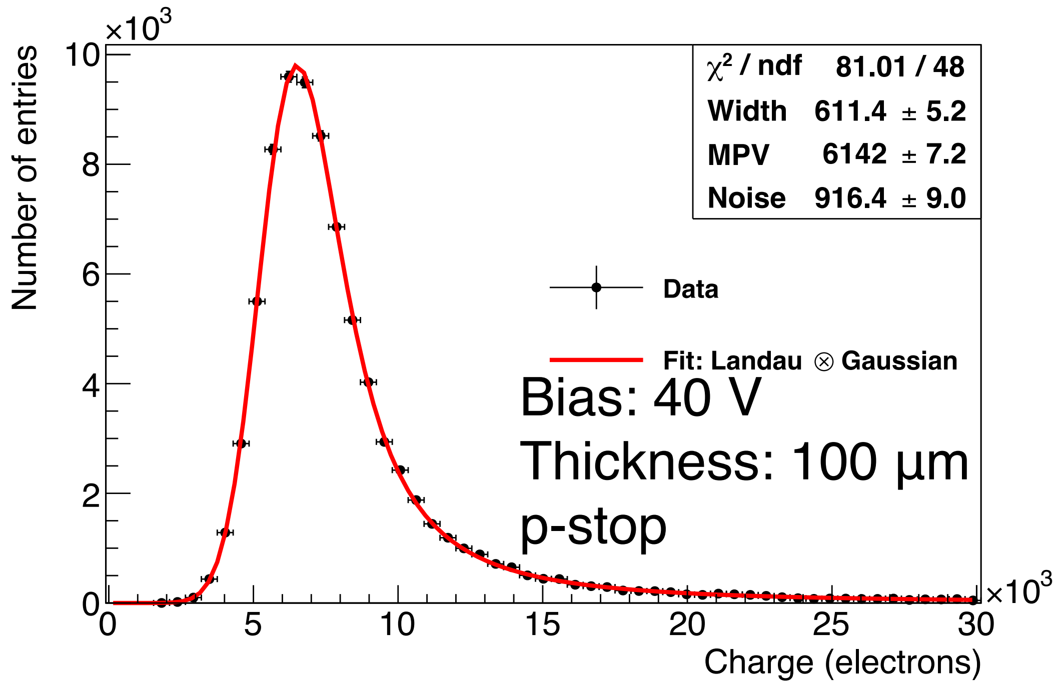
- single pixel clusters
- predicted track impact point located 20 µm far from cell edges





Bias: 50 V
Thickness: 130 µm
p-stop



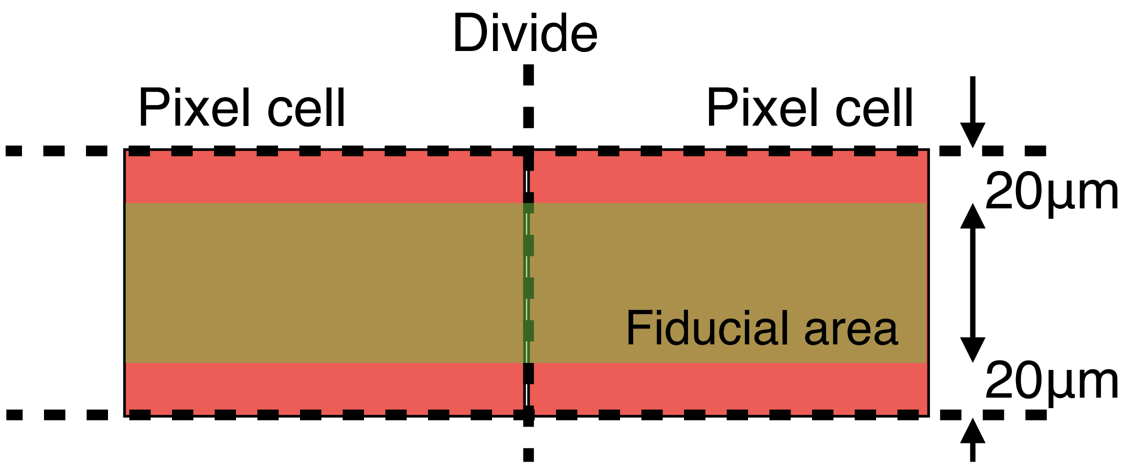


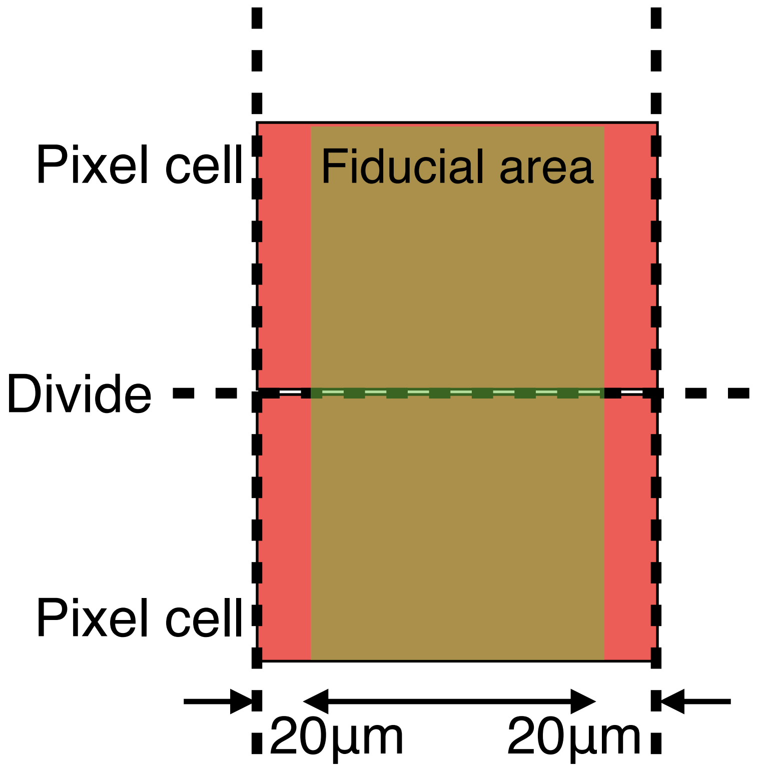
Bias: 40 V
Thickness: 100 µm
p-stop

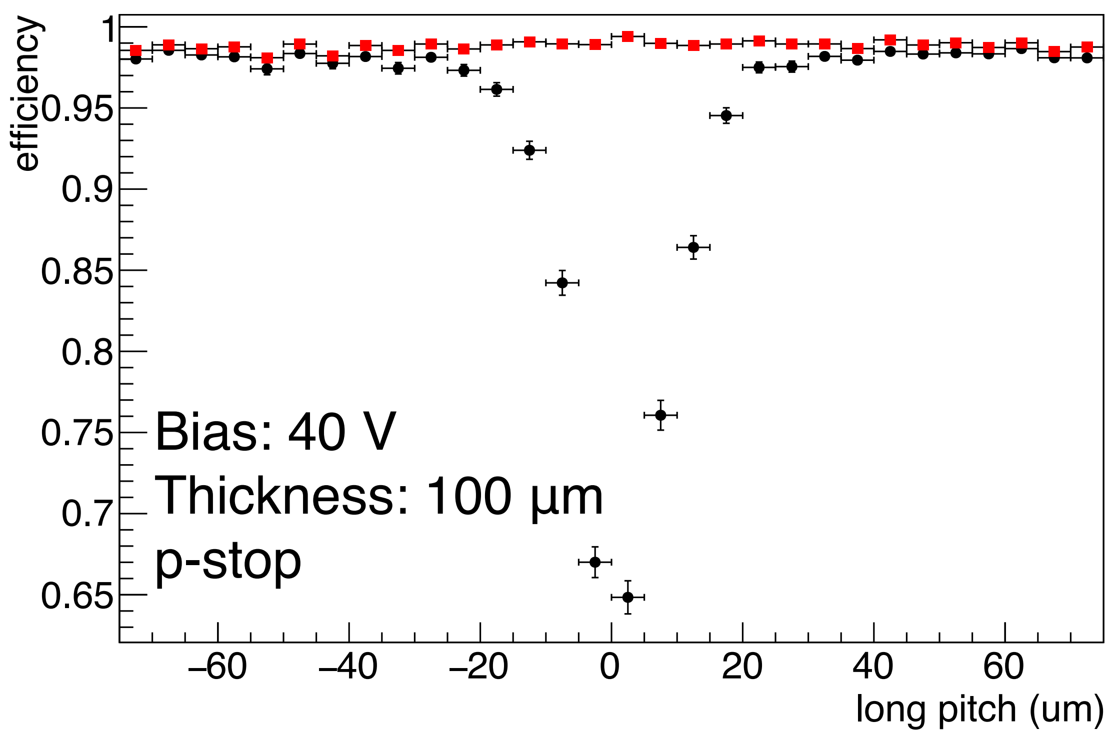
Averaging over full sample the ratio MPV@130 µm / MPV@100 µm is ~1.38 (expected 1.33)

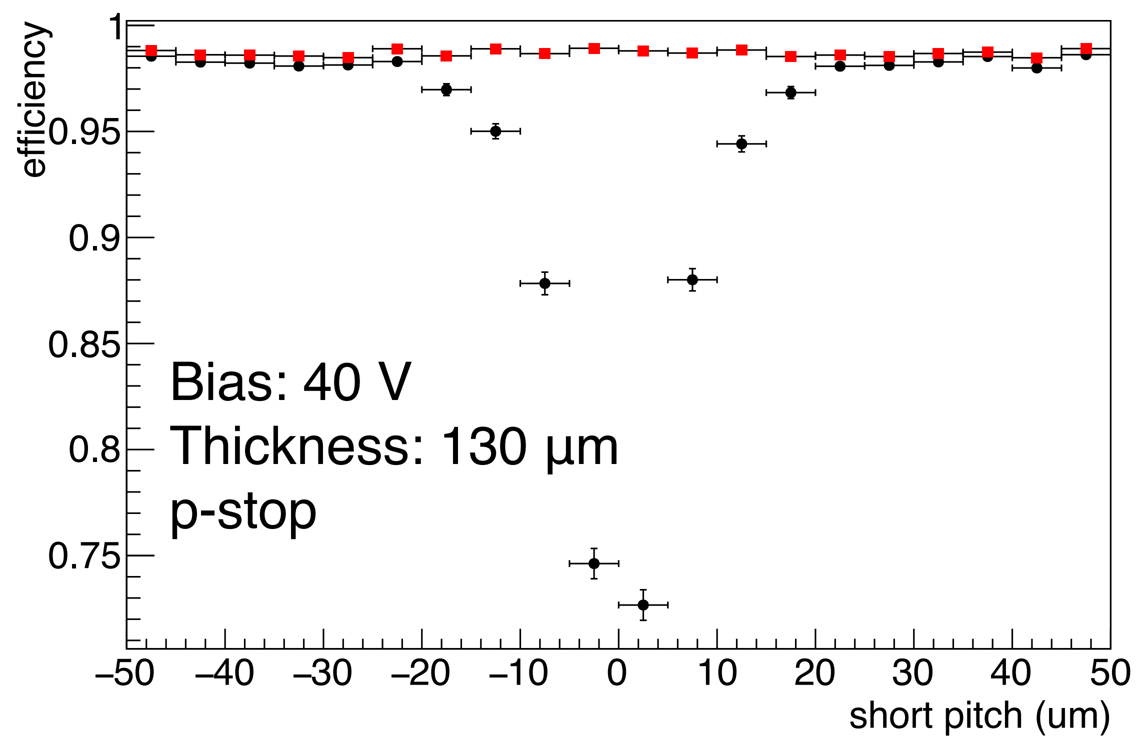
Efficiency scan across cell's divide (long pitch (row direction) and short pitch (column direction))

- Efficiency of pointed pixel
- Efficiency of pointed + closer pixel on same row (col)









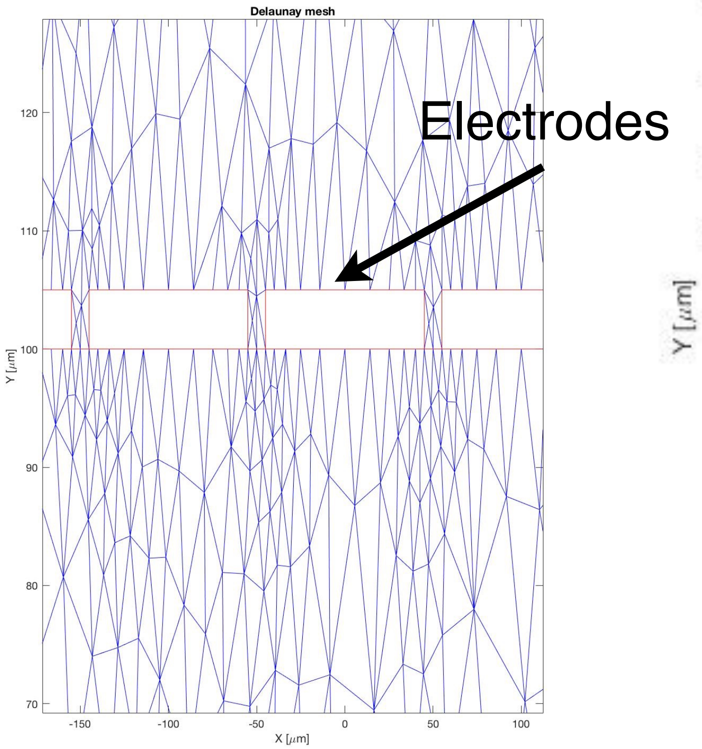
The sensors are fully efficient in both views

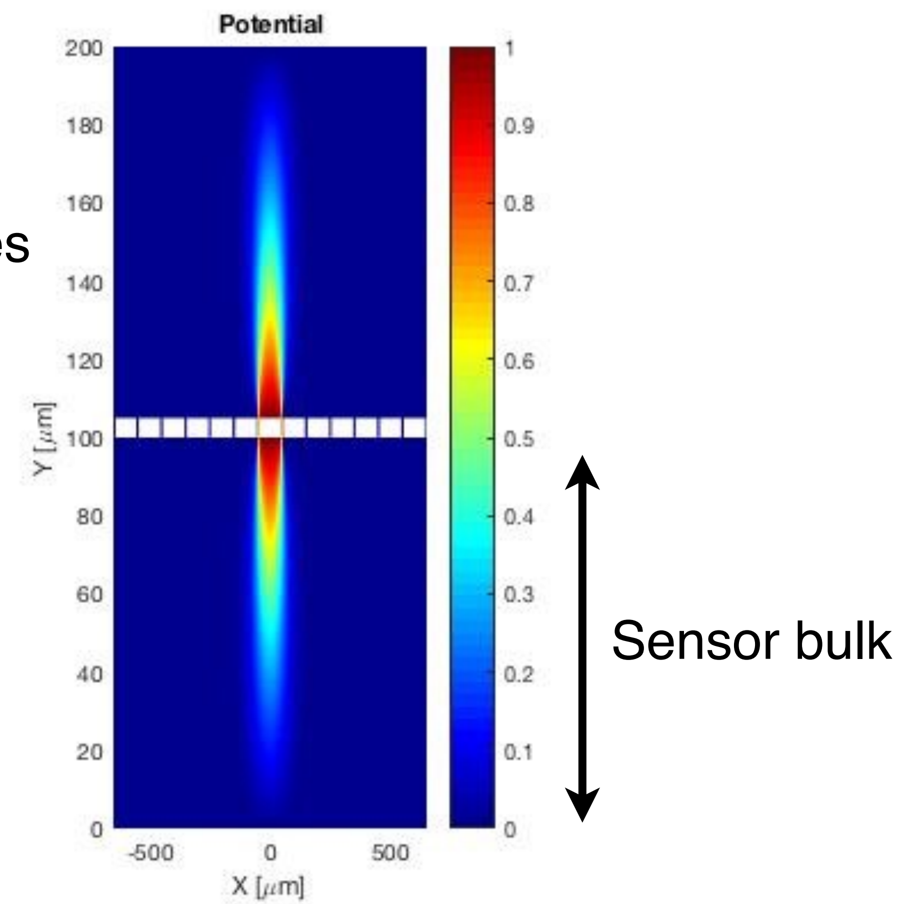
Irradiation performed at Los Alamos with 800 MeV protons

- Irradiation done after flip-chip assembly
- Constraints from radiation tolerance of PSI46 digital chip ~250 Mrad
- Non uniform irradiation
- **Fluence: 1.0 - 1.2x10^{15} n_{eq} / cm^2**

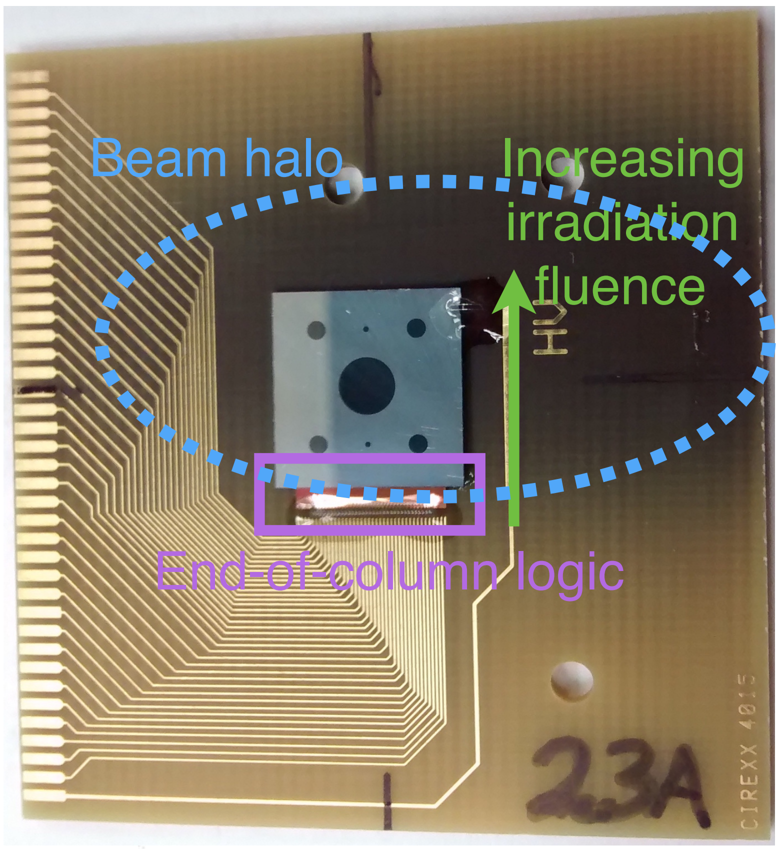
Radiation level measured by in situ dosimetry and cross checked with 2D MATLAB simulation predictions

Finite element analysis to solve Poisson equation

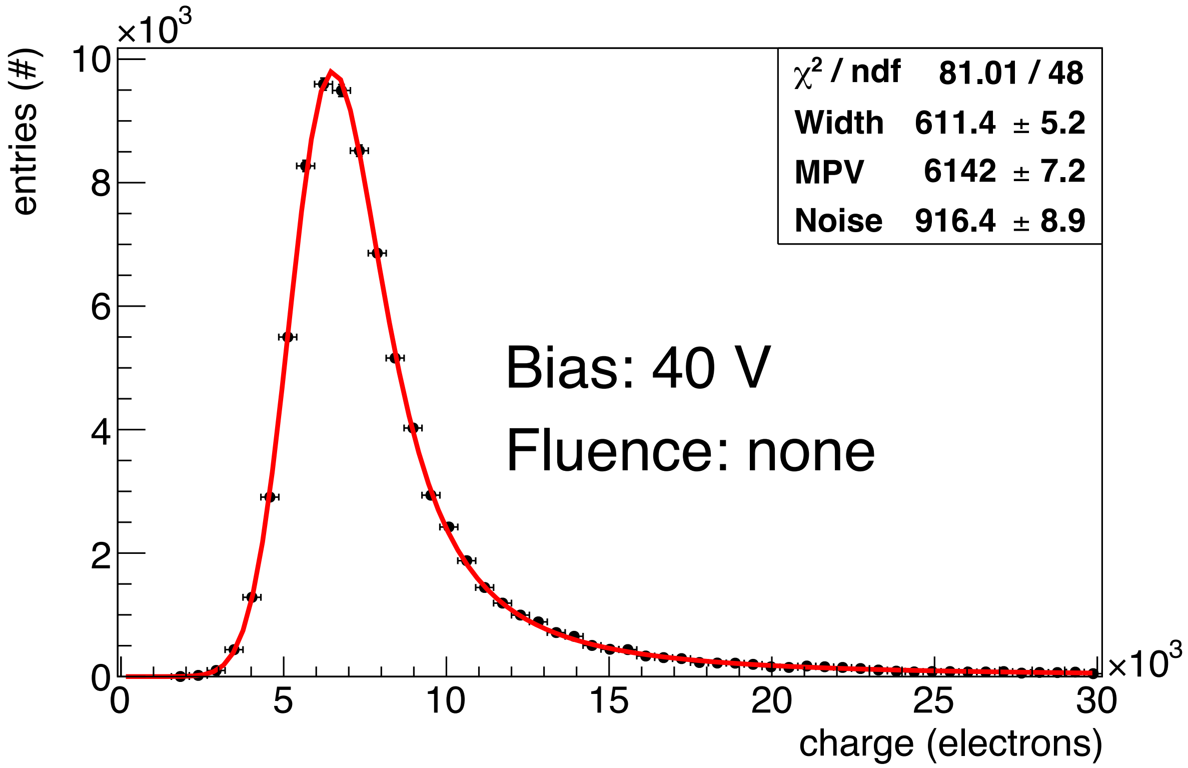




Weighting potential

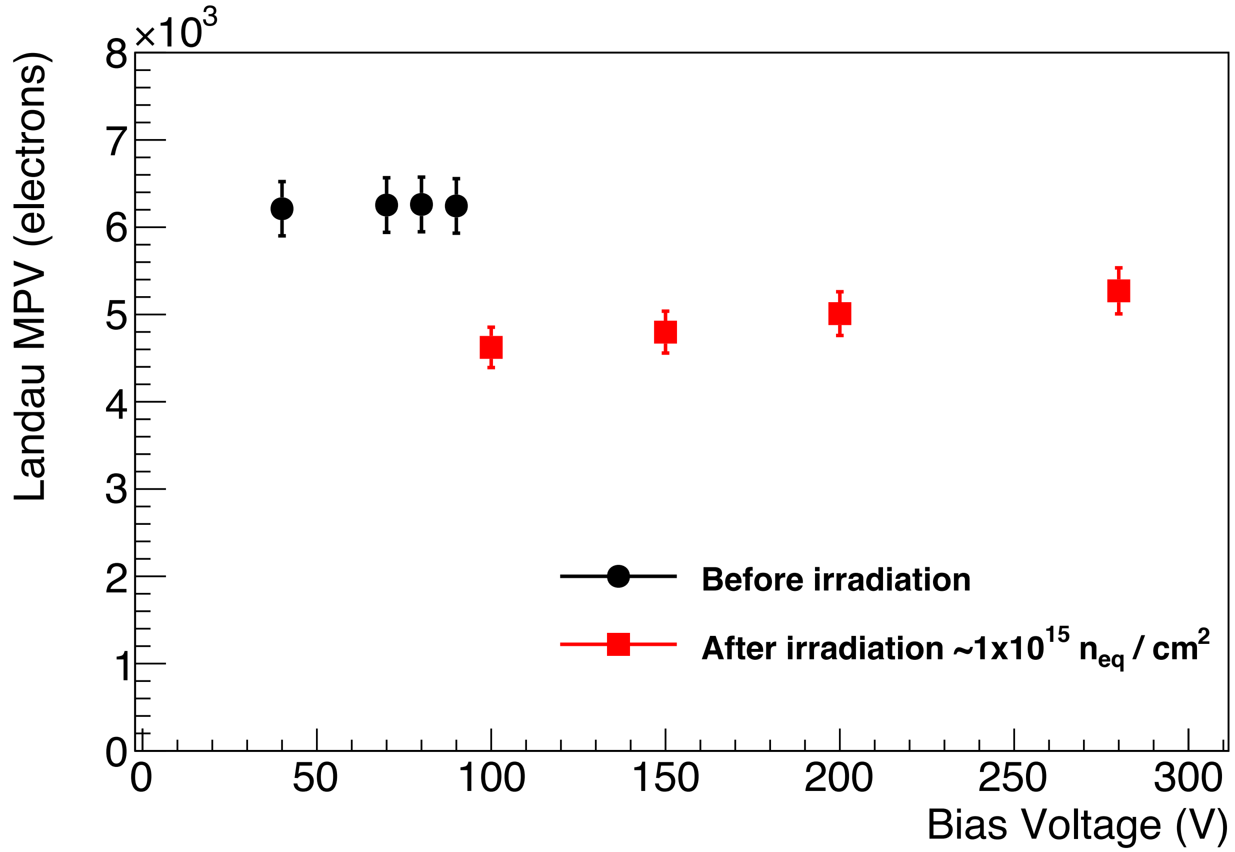


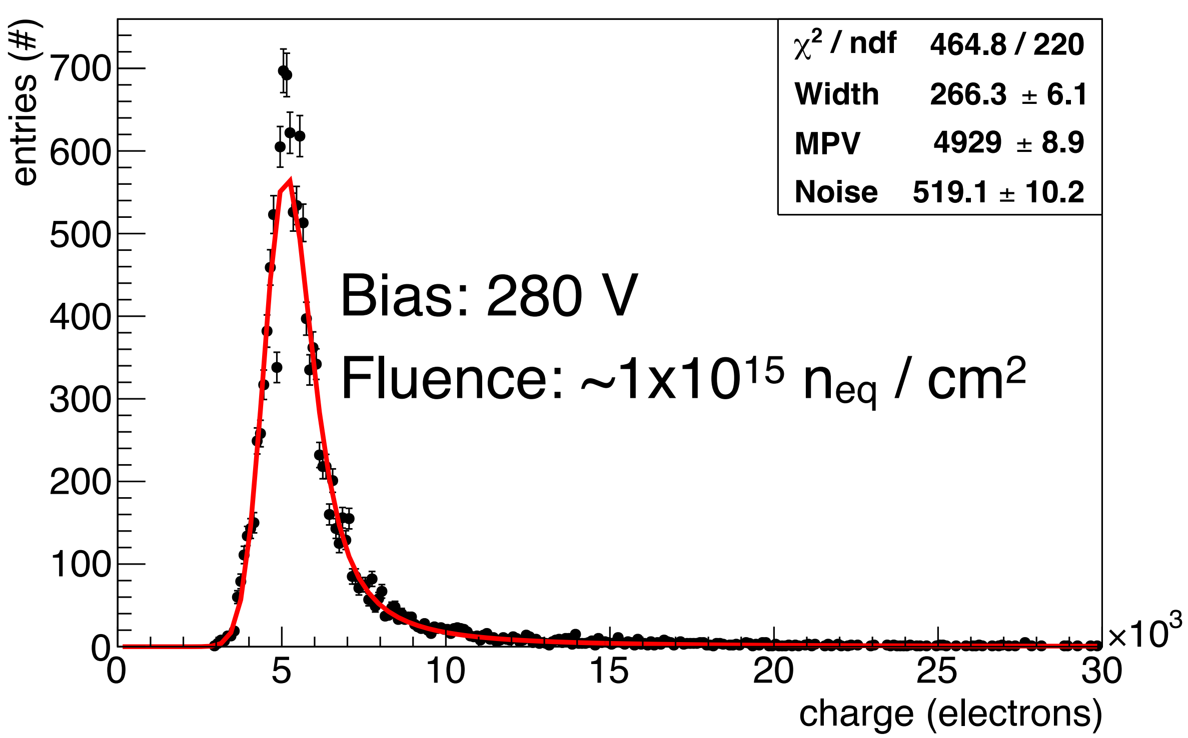
CMS results: thin-planar after irradiation



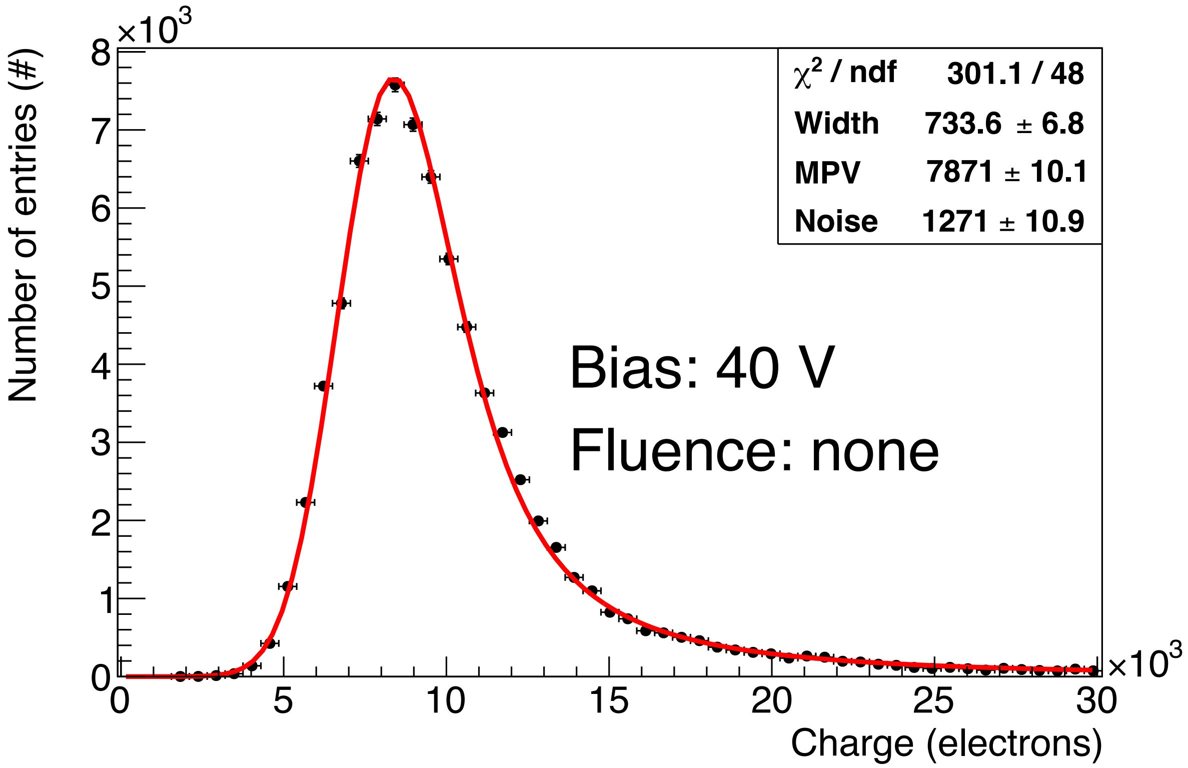
Landau distribution before and after irradiation

- Fluence: ~1x10[15] n_{eq} / cm[2]
- Sensor thickness: **100 μm**



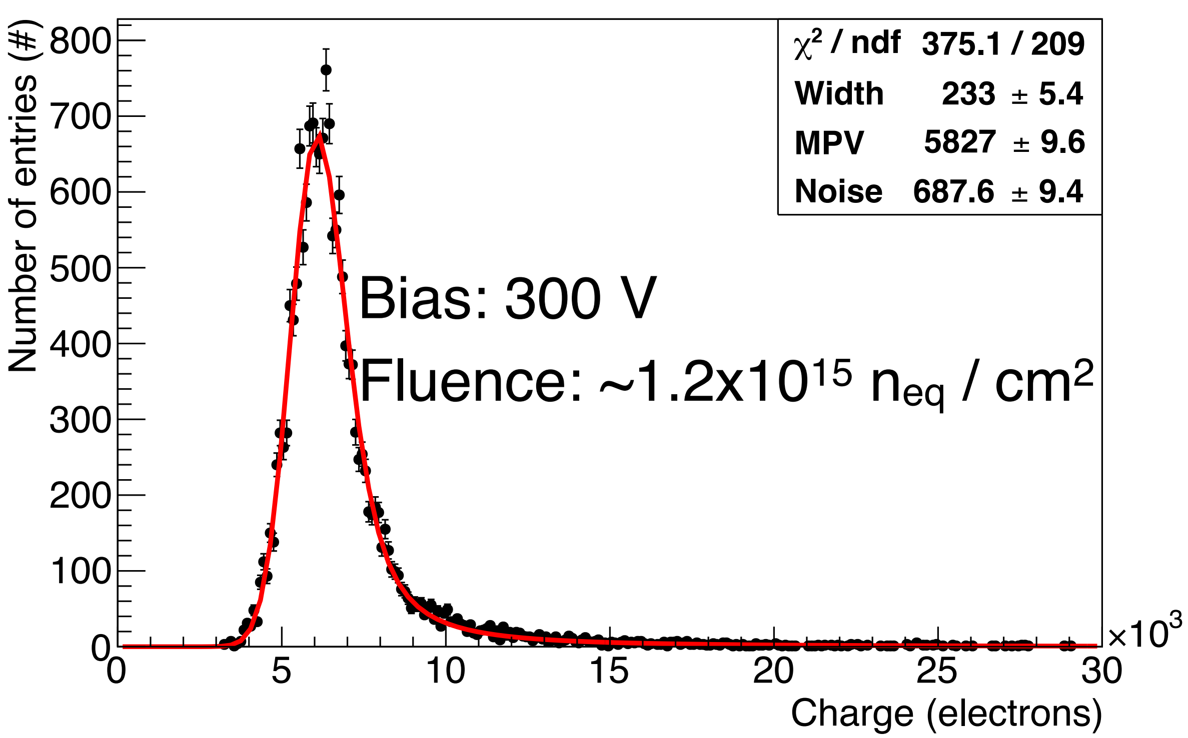


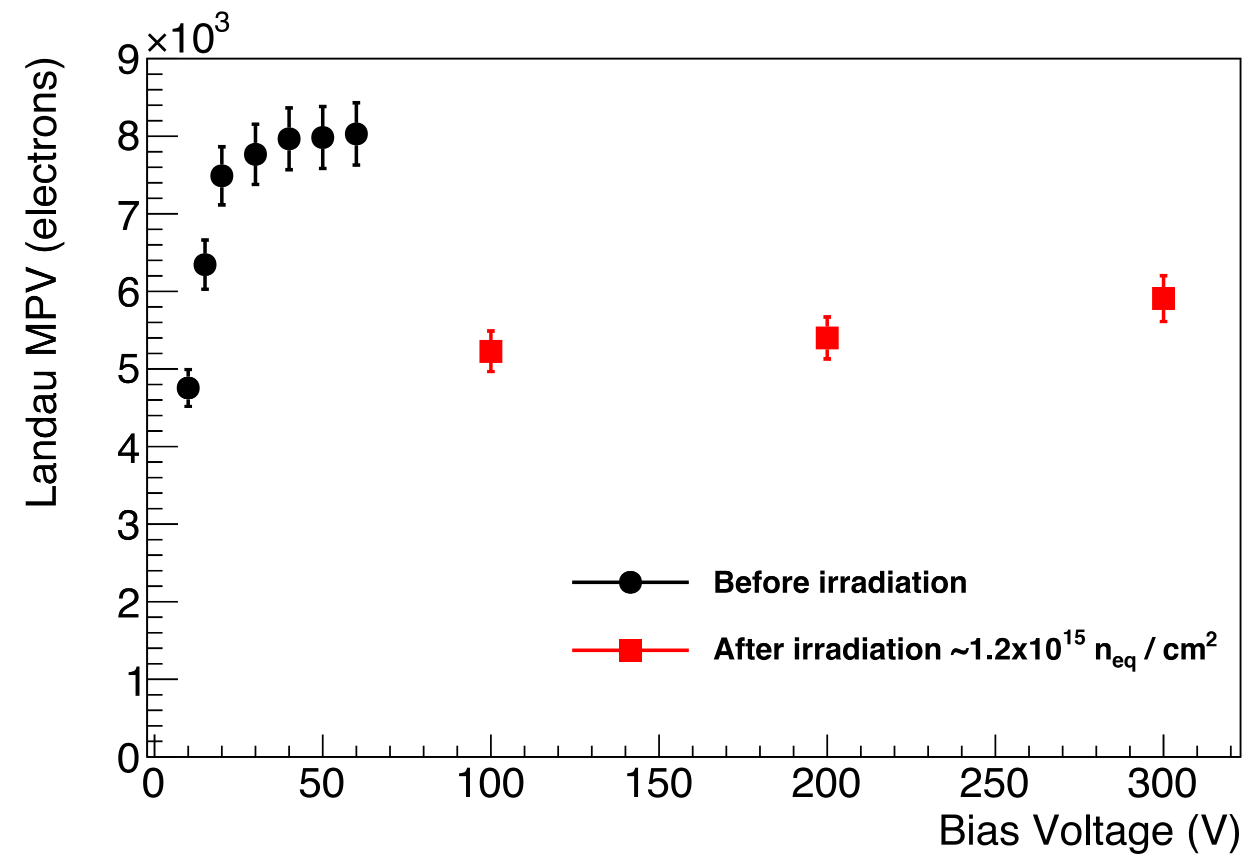
CMS results: thin-planar after irradiation



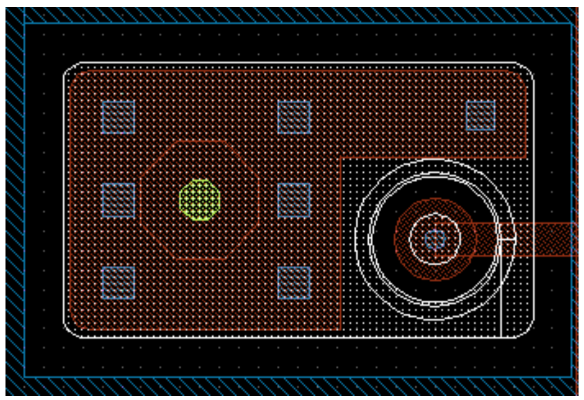
Landau distribution before and after irradiation

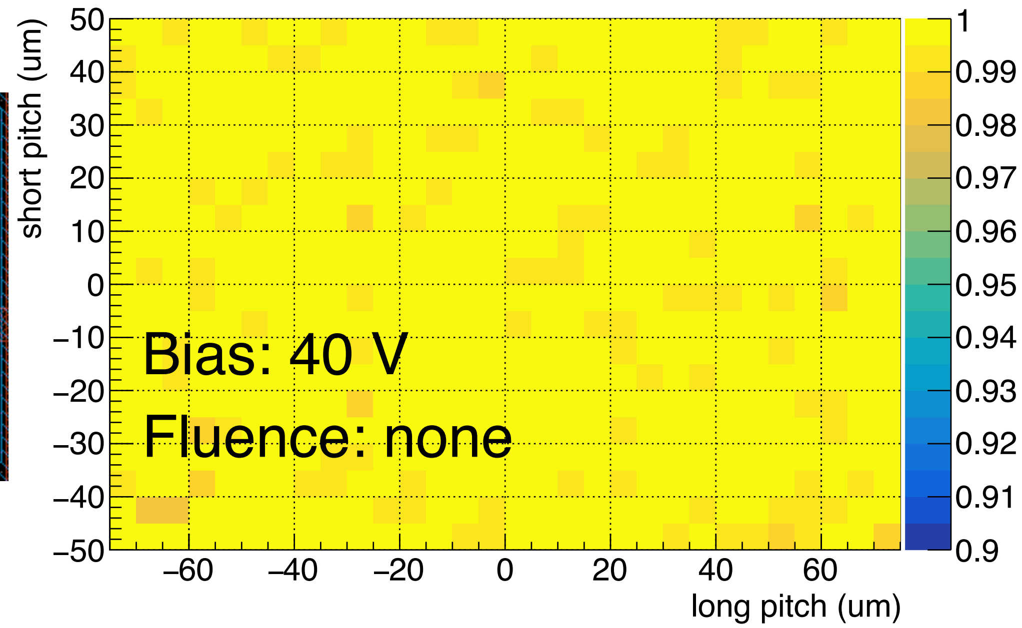
- Fluence: ~1.2×10^{15} n_{eq} / cm^2
- Sensor thickness: **130 µm**

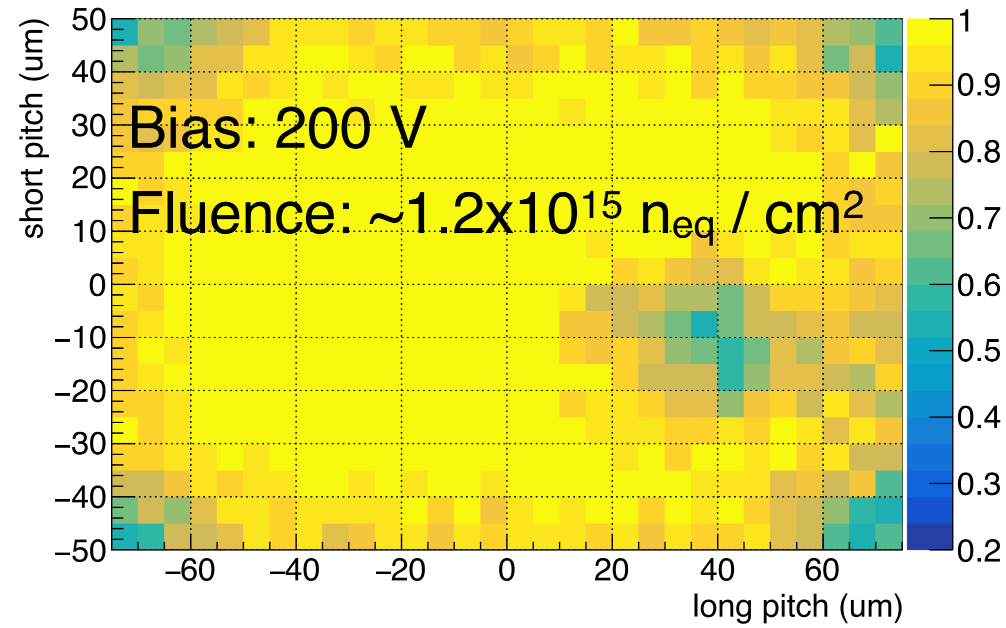




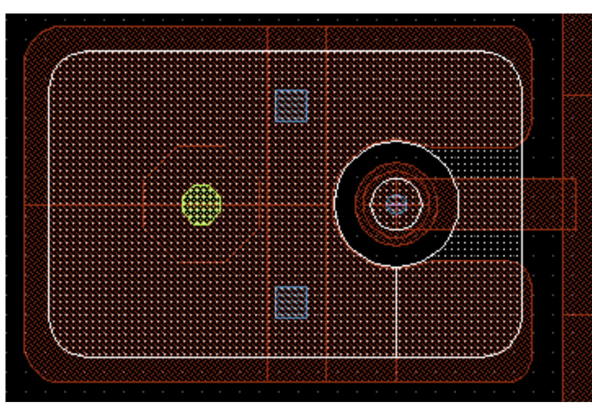
Efficiency affected by punch through structure (**some** modules **affected before** irradiation, **all** modules **affected after irradiation**)

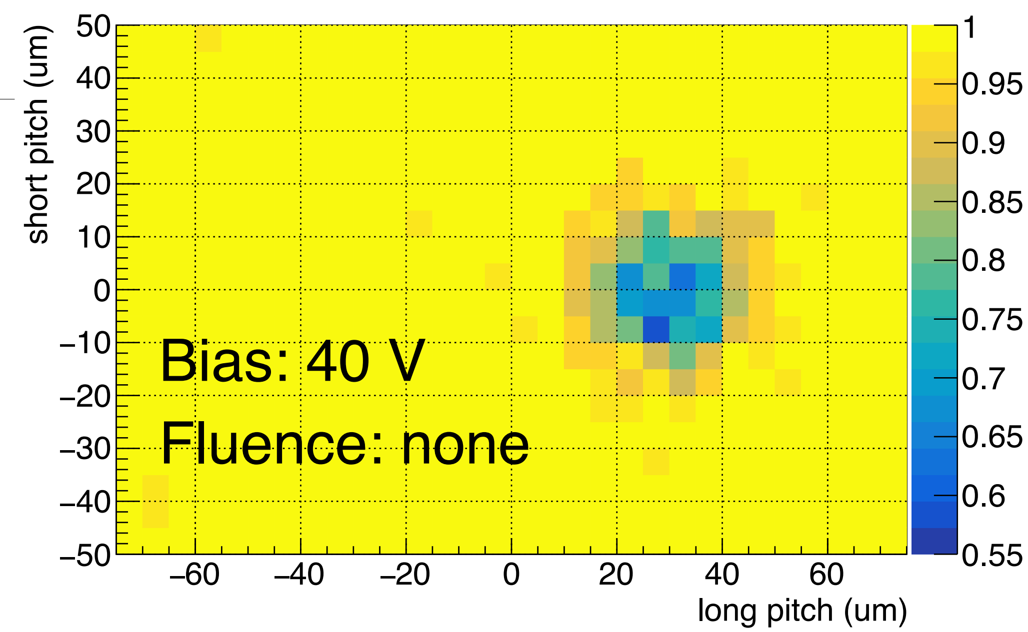






Thickness: 100 µm
Punch through
p-stop





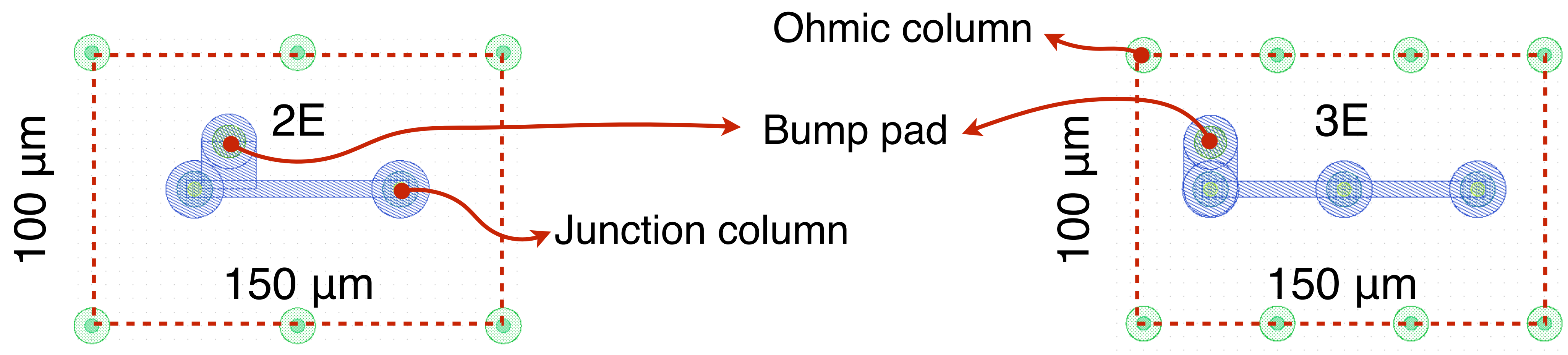
Thickness: 100 µm
Punch through
no p-stop

Simulation studies ongoing to optimise geometry/process of bias structure

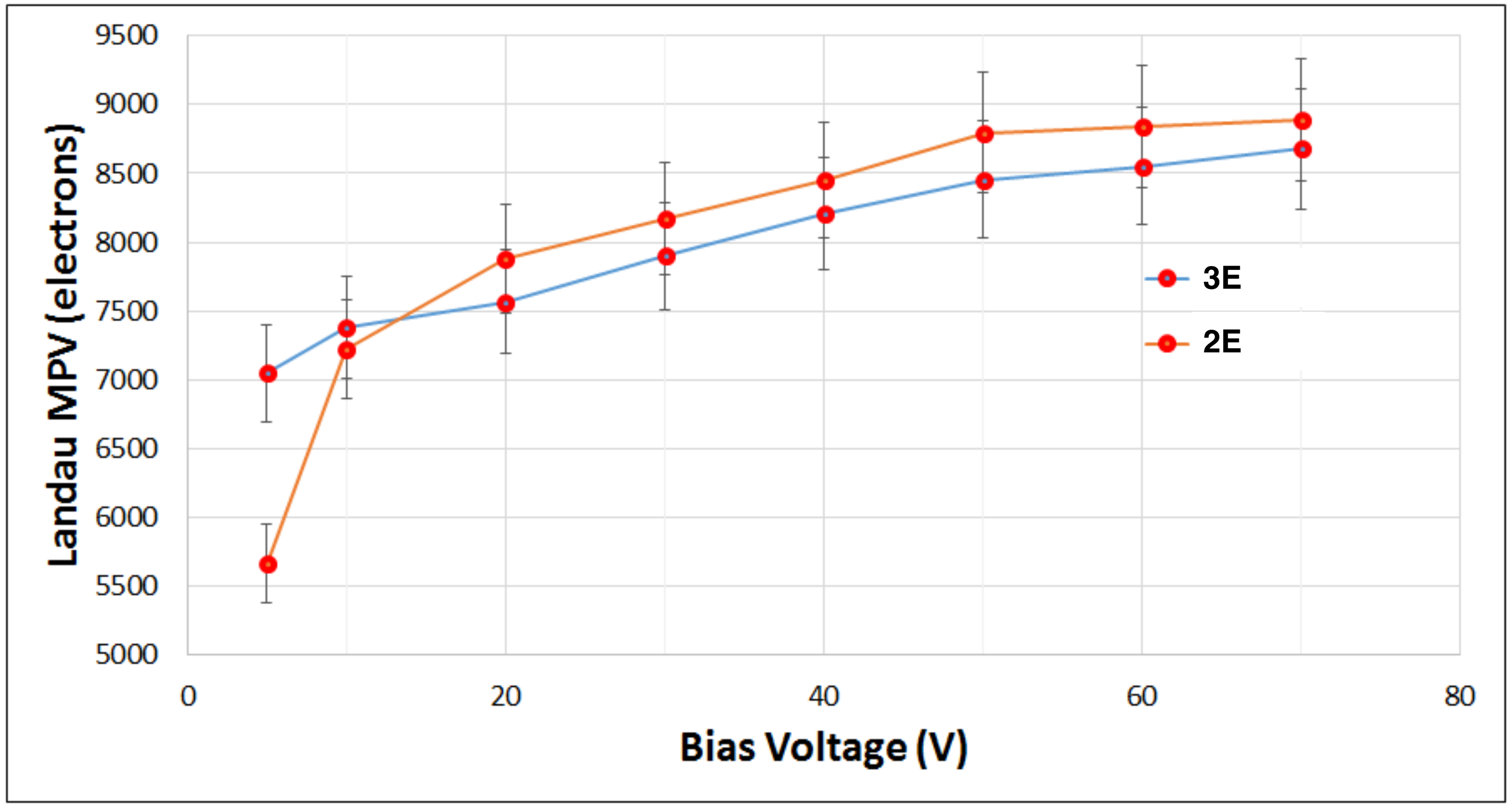
- For small pitch pixel design can be critical (i.e. common 4-fold bias dot)

CMS results: 3D before irradiation

3D columnar, **130 µm thick** sensors, **100x150 µm²** cell size with 2 (2E) and 3 (3E) junction electrodes



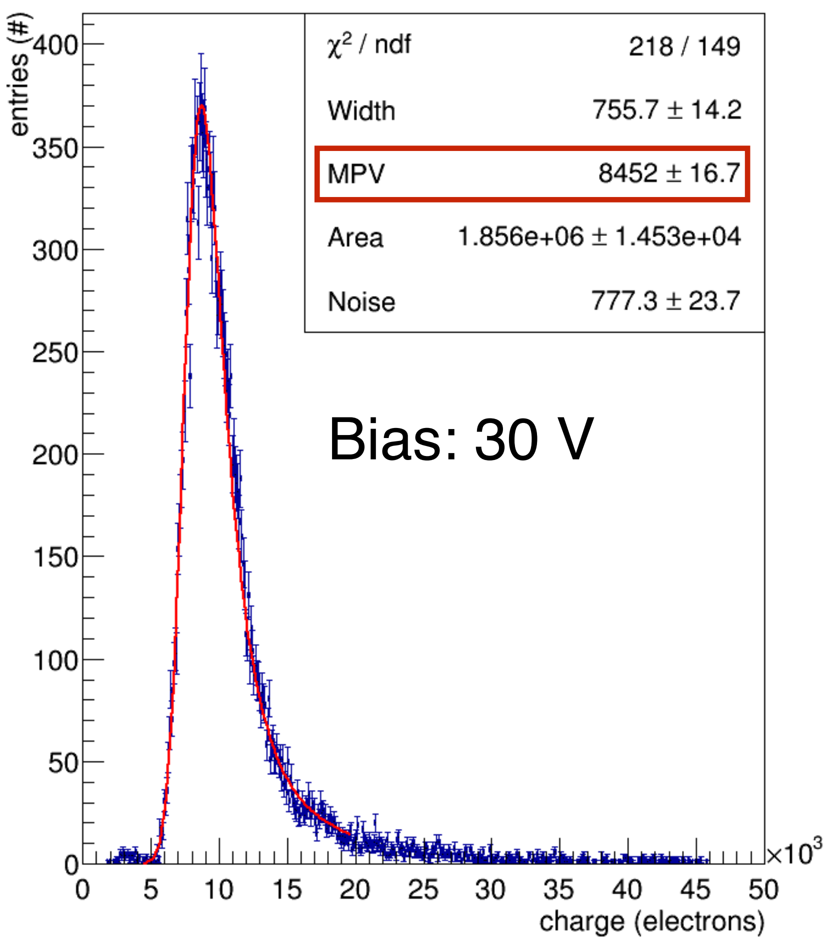
- For bias voltage > 20 V 2E and 3E are compatible within calibration uncertainty
- At saturation the collected charge is compatible with planar sensors
- At low bias voltage (< 15 V) 3E shows greater charge collection efficiency than 2E as expected

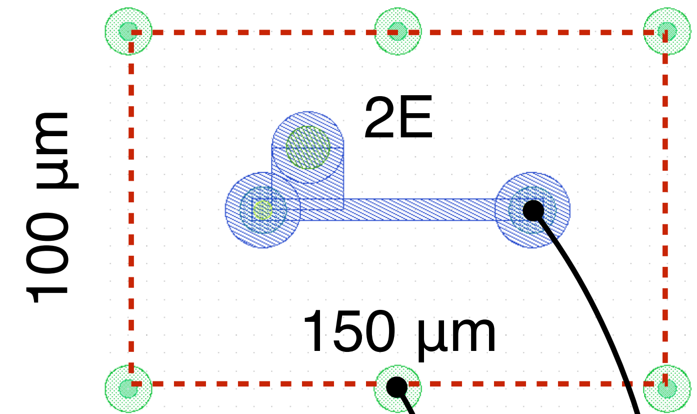


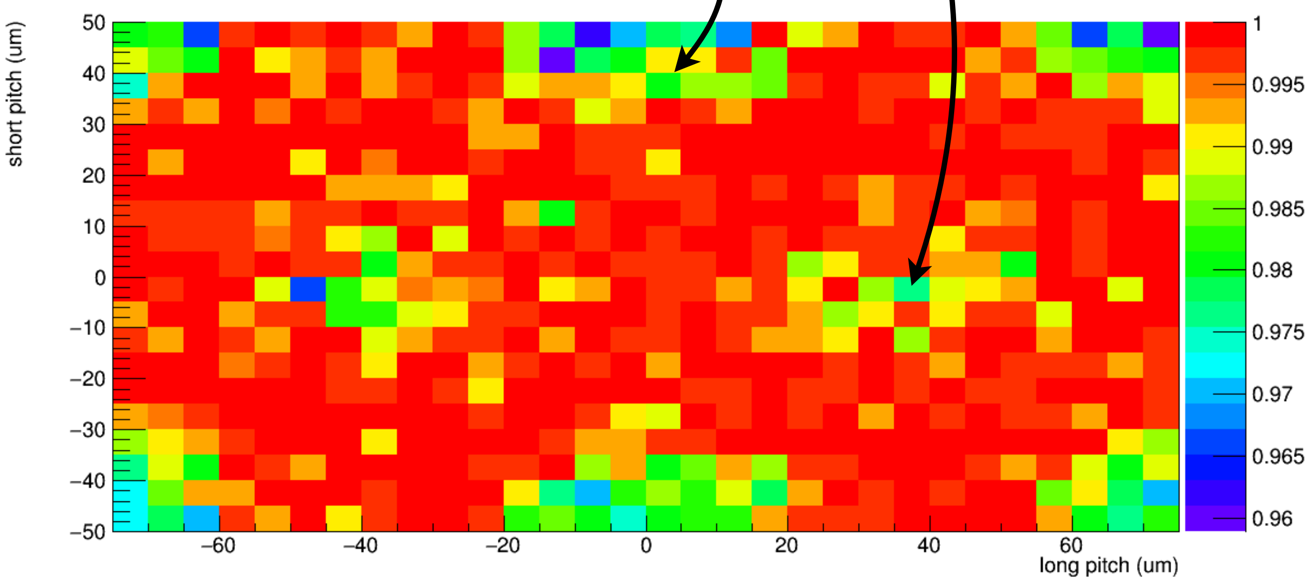
CMS results: 3D before irradiation

Efficiency map on cell for orthogonal tracks

- Bias voltage: 40 V







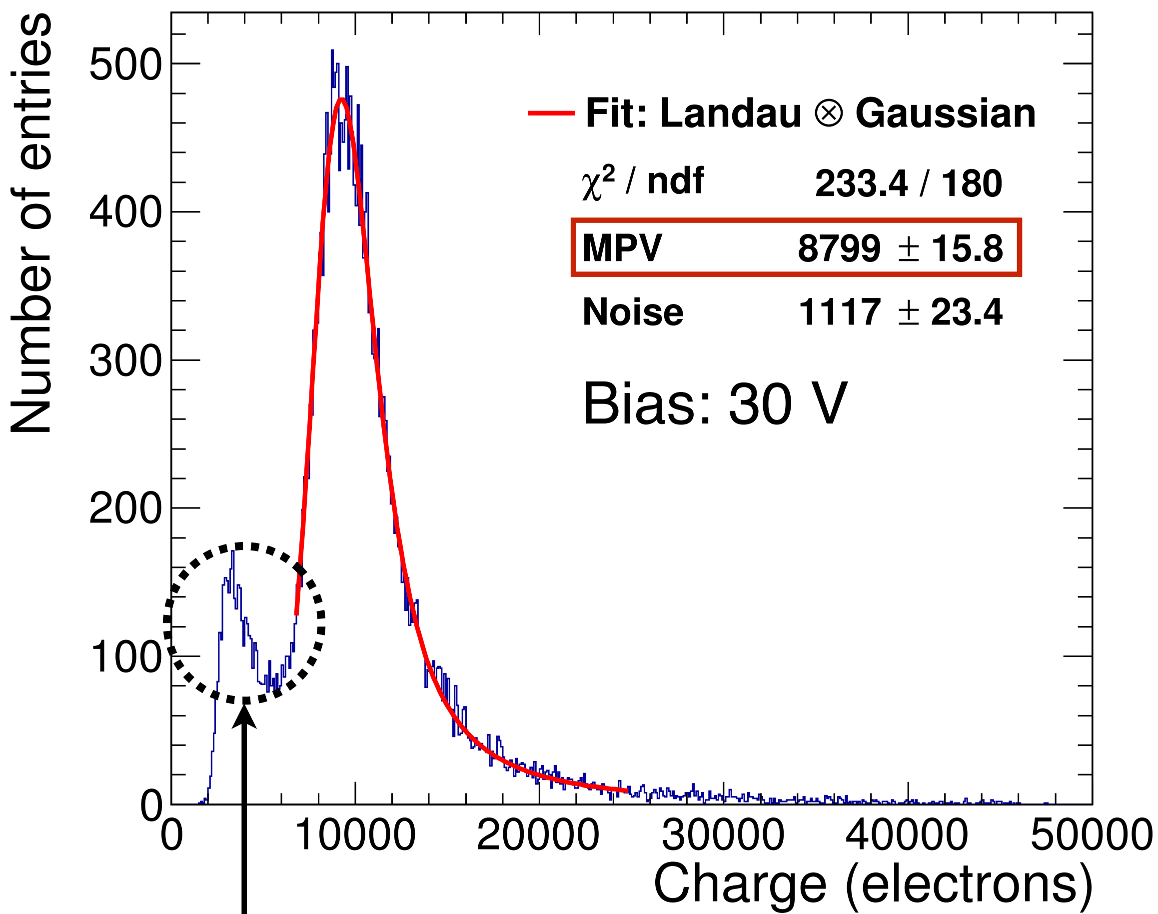
Overall efficiency: (99.40 ± 0.04)%

Visible efficiency deterioration on both junction and ohmic columns

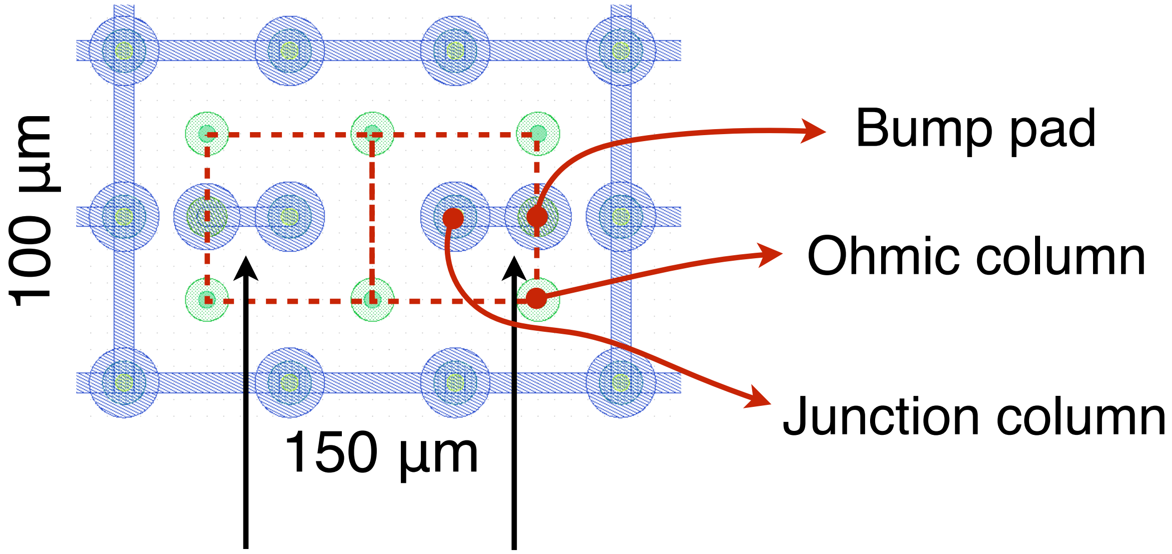
CMS results: 3D before irradiation

Charge collection

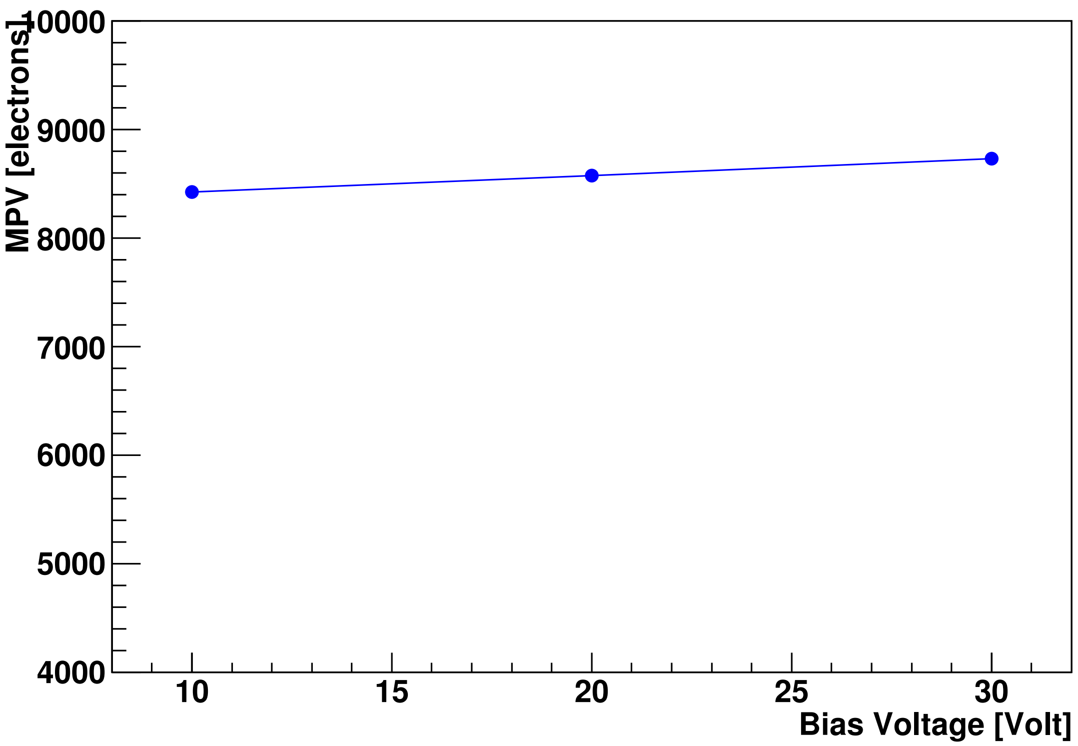
- Cell size: **50x50 μm² 1E**
- 130 μm thick sensors



Charge shared with adjacent pixels which are not being readout



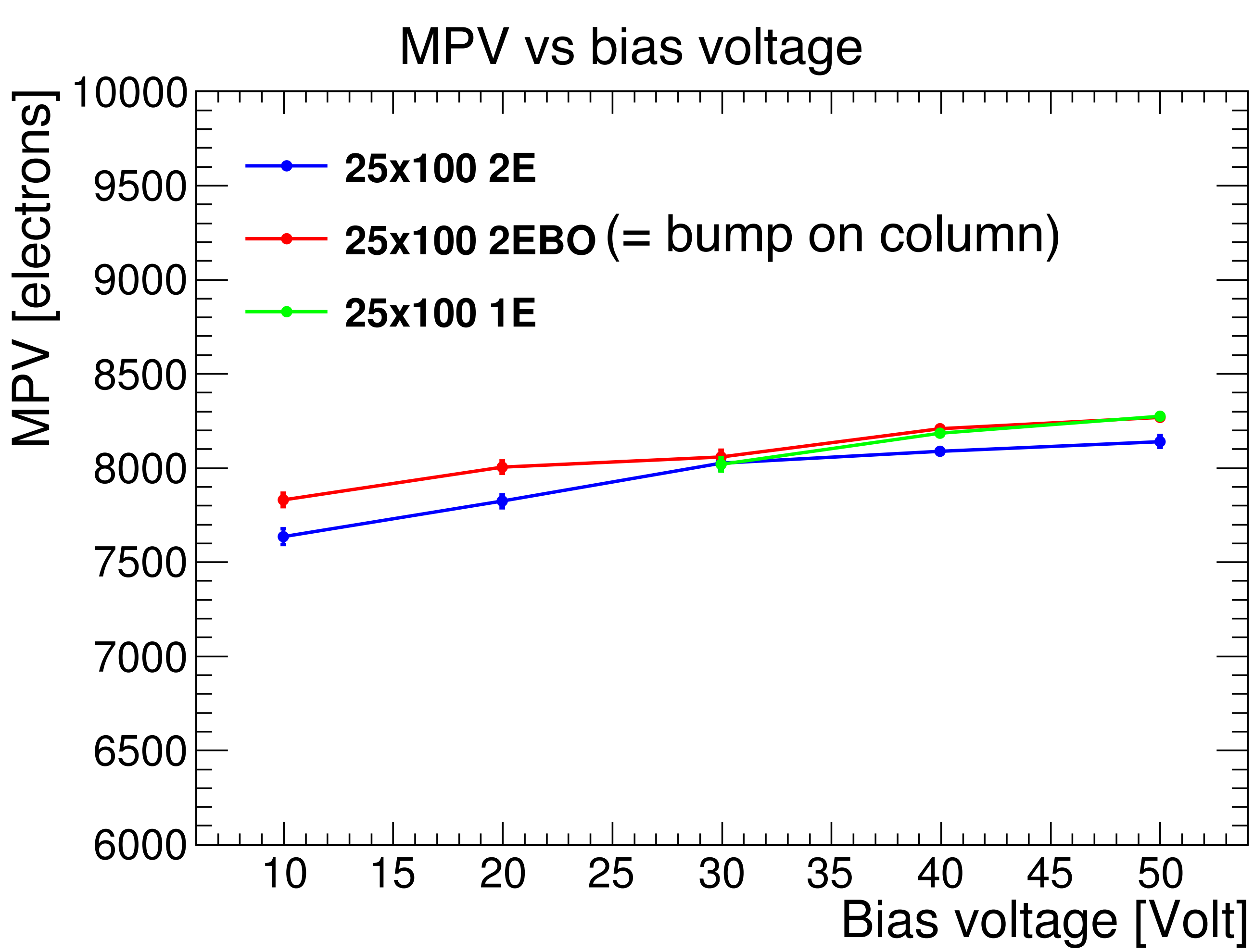
MPV vs bias voltage

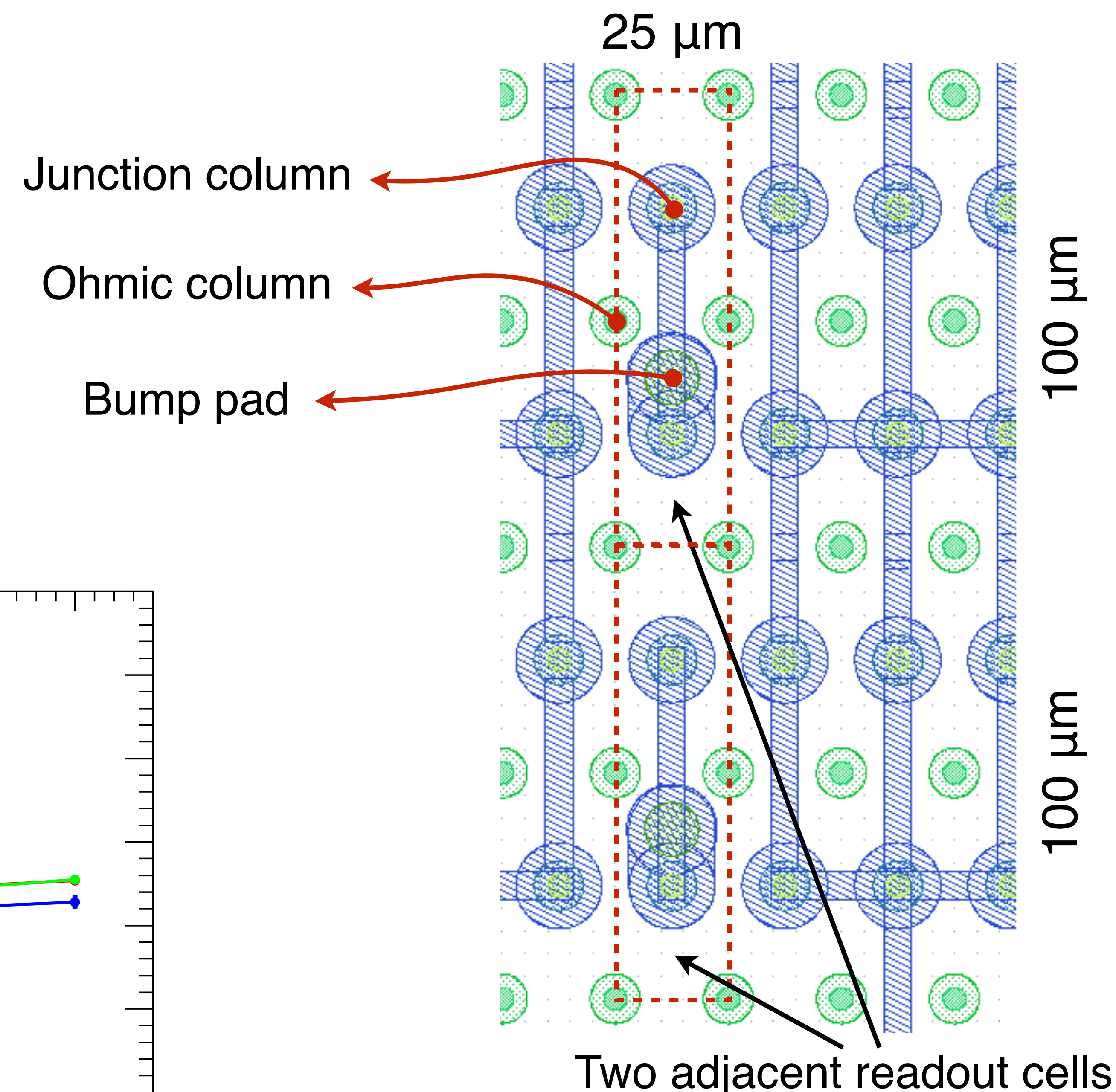


CMS results: 3D before irradiation

Charge collection

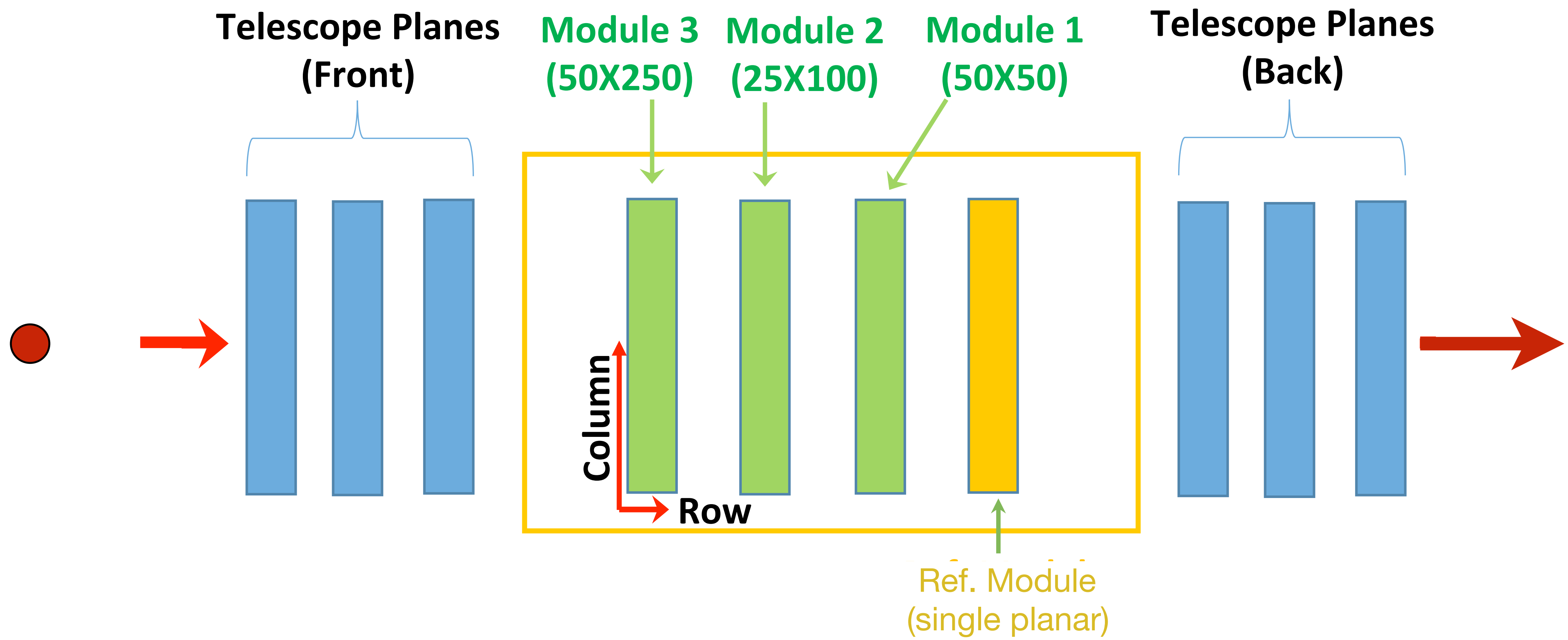
- Cell size: **25x100 μm² 1E and 2E and 2E with bump on column**
- 130 μm thick sensors





- bump on column collects ~200 e⁻ less ➜ further studies ongoing
- 25x100 μm² collects ~700 e⁻ less than 50x50 μm² @ same voltage ➜ probably sharing with nearby cells not readout

ATLAS results: 3D before irradiation

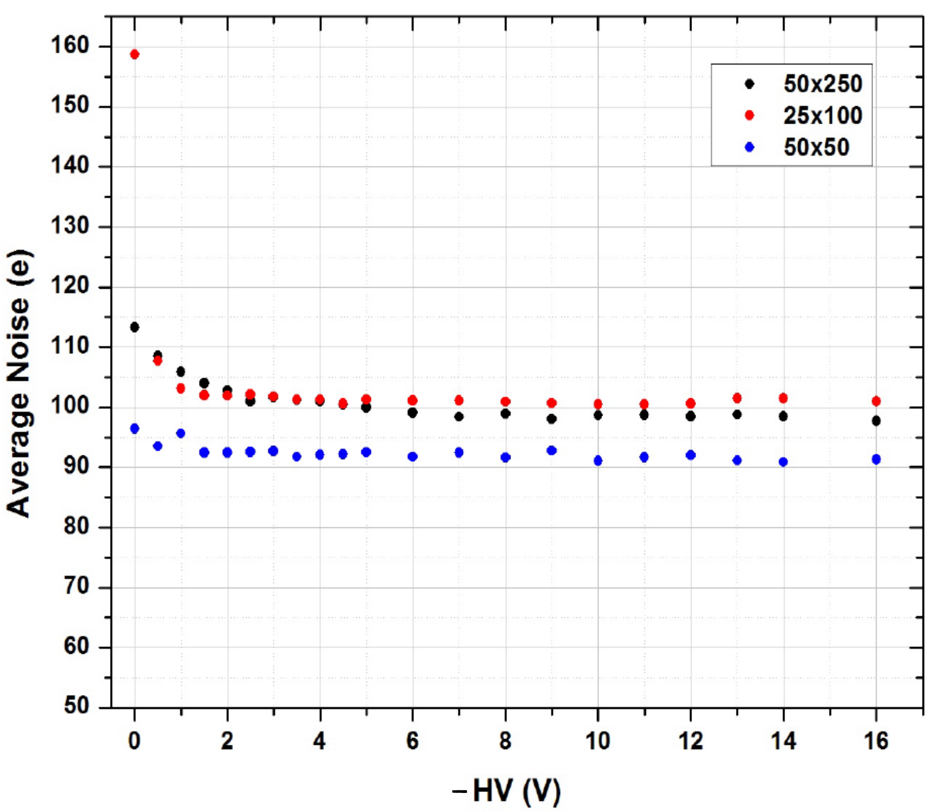


"Aconite" telescope on CERN SPS H6A beam line

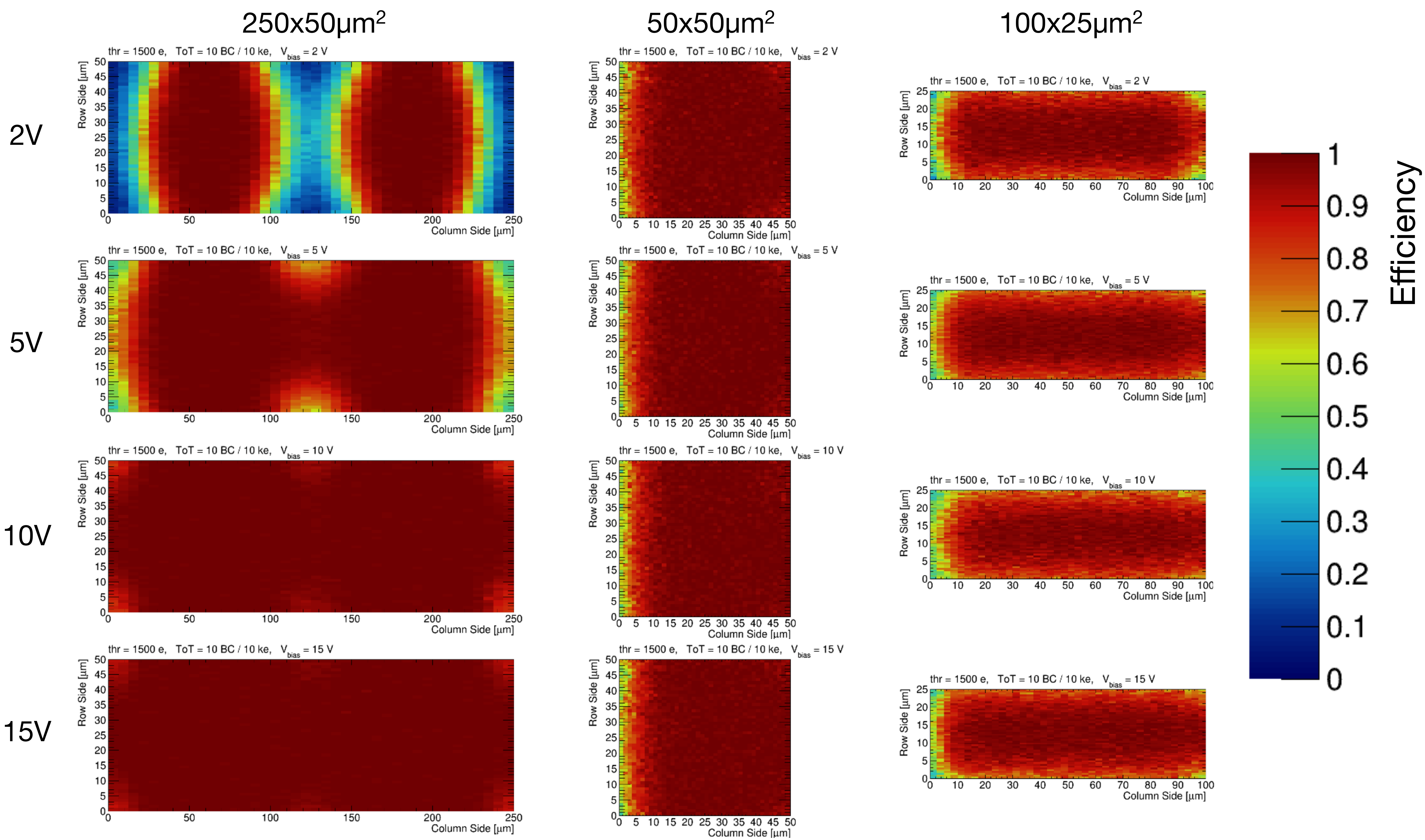
- 120 GeV pions
- 6 pixel planes
- based on Mimosa26 chip (18.4 µm pitch, square pixel cells, 576 rows and 1152 columns)
- ~2 µm resolution on each coordinate

Three DUTs **50x50 1E**, **25x100 1E**, and **50x250 2E µm²**, **130 µm thick** + planar module as reference (150 µm thick sensor) bump-bonded to ATLAS FE-I4 chip

Noise vs bias voltage for the three DUTs

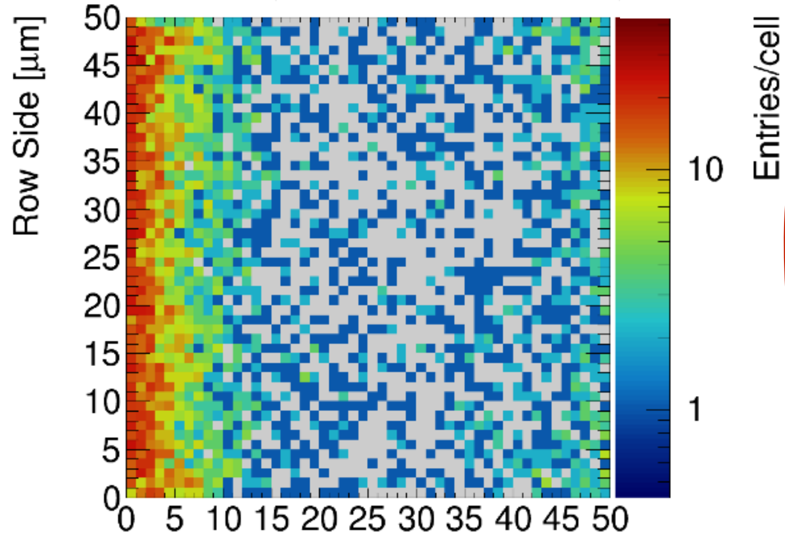


Efficiency maps vs bias voltage (thr = 1500 e⁻, ToT = 10 BC / 10 ke⁻)

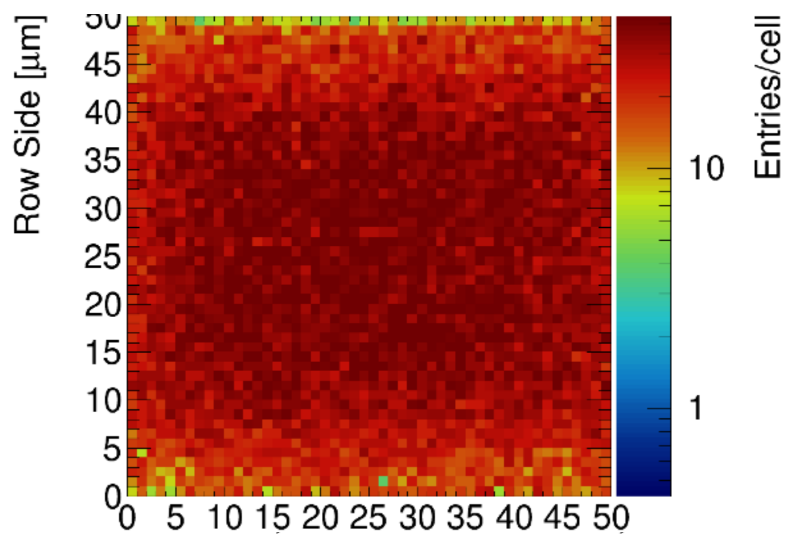


ATLAS results: 3D before irradiation

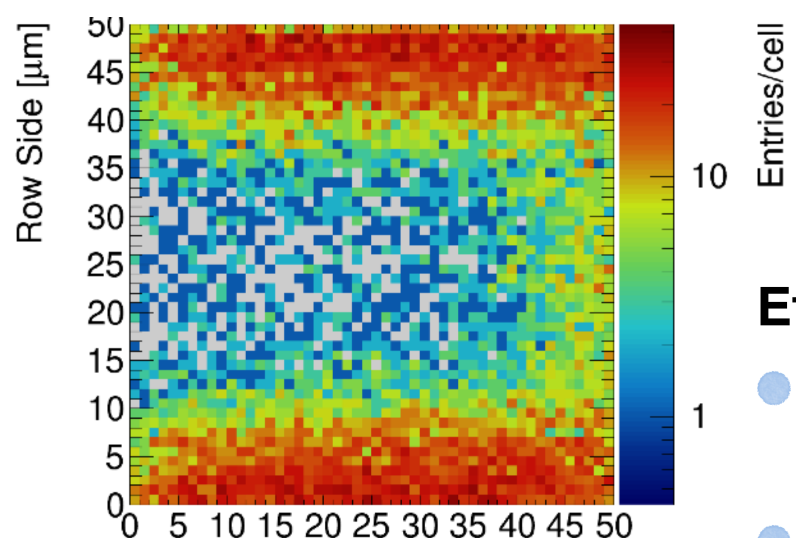
Inefficiency map



Efficiency for size 1 clusters



Efficiency for size 2 clusters

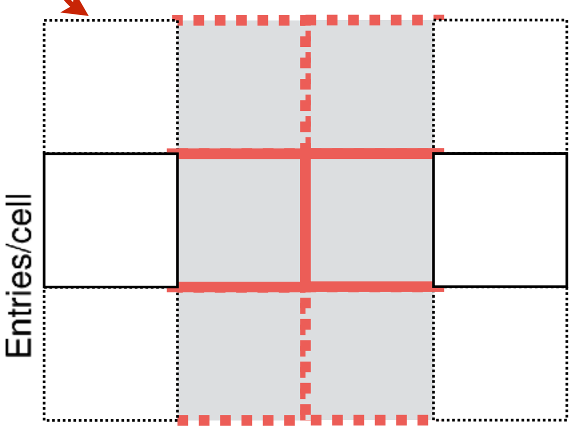


Bias: 10 V
Cell size: 50x50 μm²

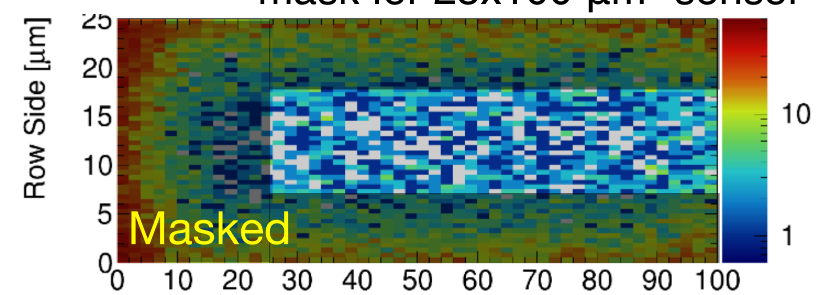
Due to chip-sensor pitch mismatch

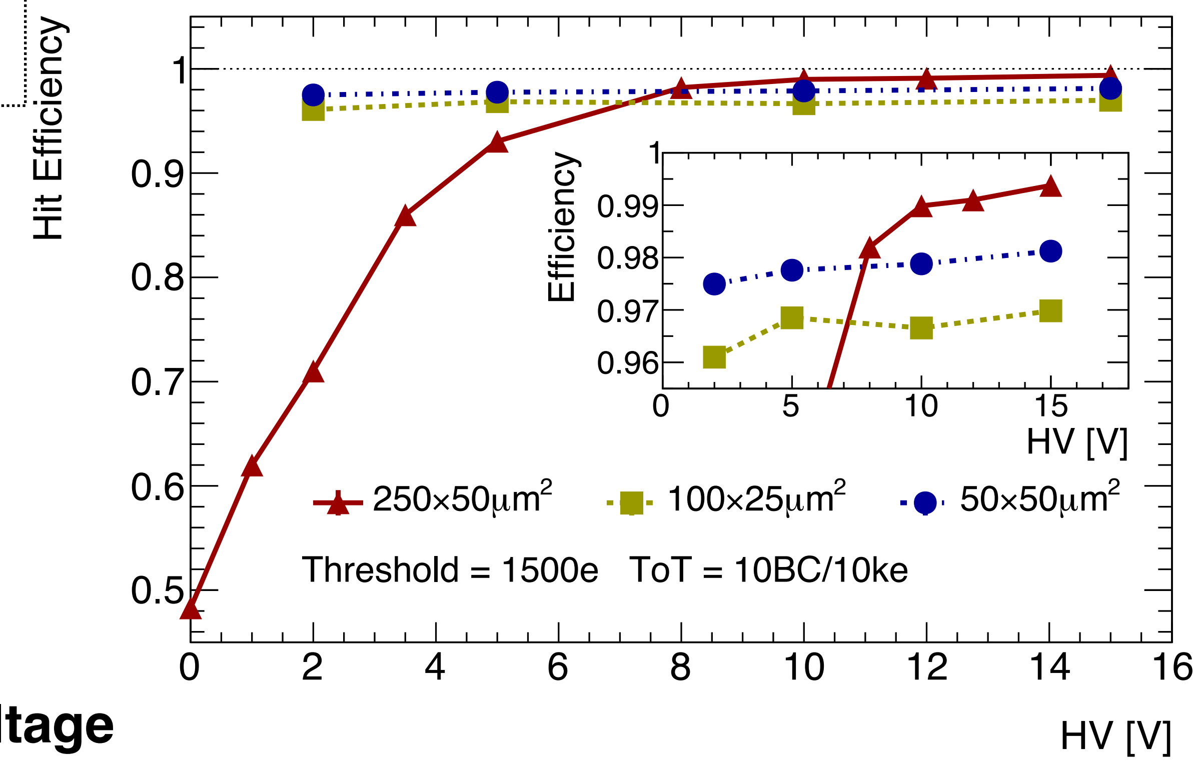
- **50x50 μm²** cells have neighbouring cells on **3** out of 4 sides
- **25x100 μm²** cells have neighbouring cells on **1** out of 4 sides
- **50x250 μm²** cells have neighbouring cells on **4** out of 4 sides

Masking is necessary to compute unbiased efficiency



mask for 25x100 μm² sensor





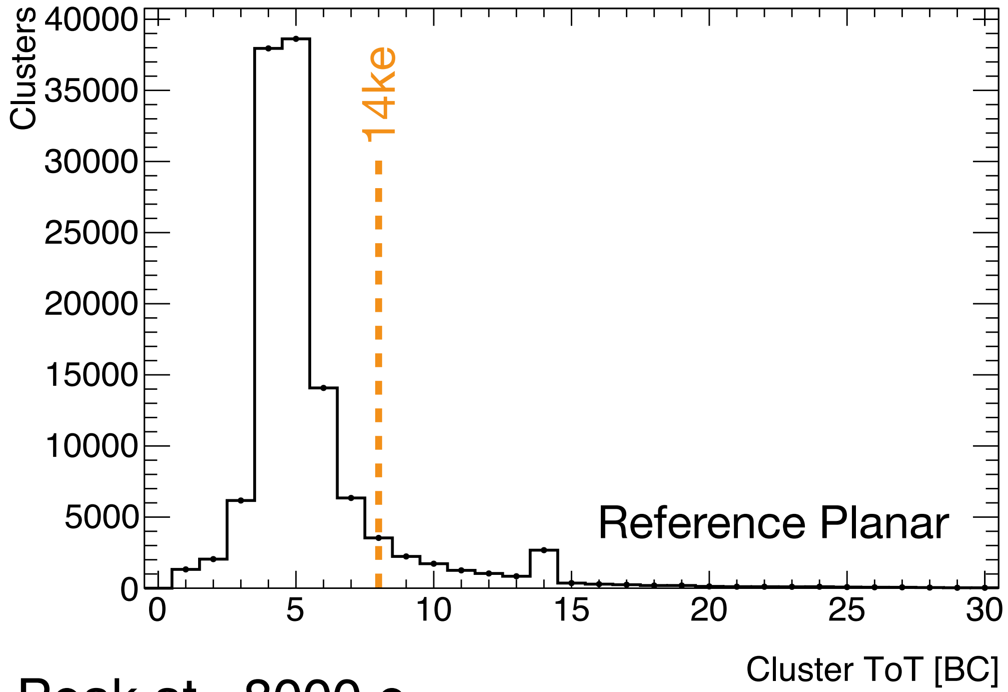
Efficiency vs bias voltage

- **50x50 μm²:** almost flat at **~98%** efficiency for 2 V < HV bias < 15 V (slight increase of ~1%)
- **25x100 μm²:** qualitatively similar trend to 50x50 μm²
- **50x250 μm²:** efficiency **> 99% above ~10 V** (ramping up to ~10 V)

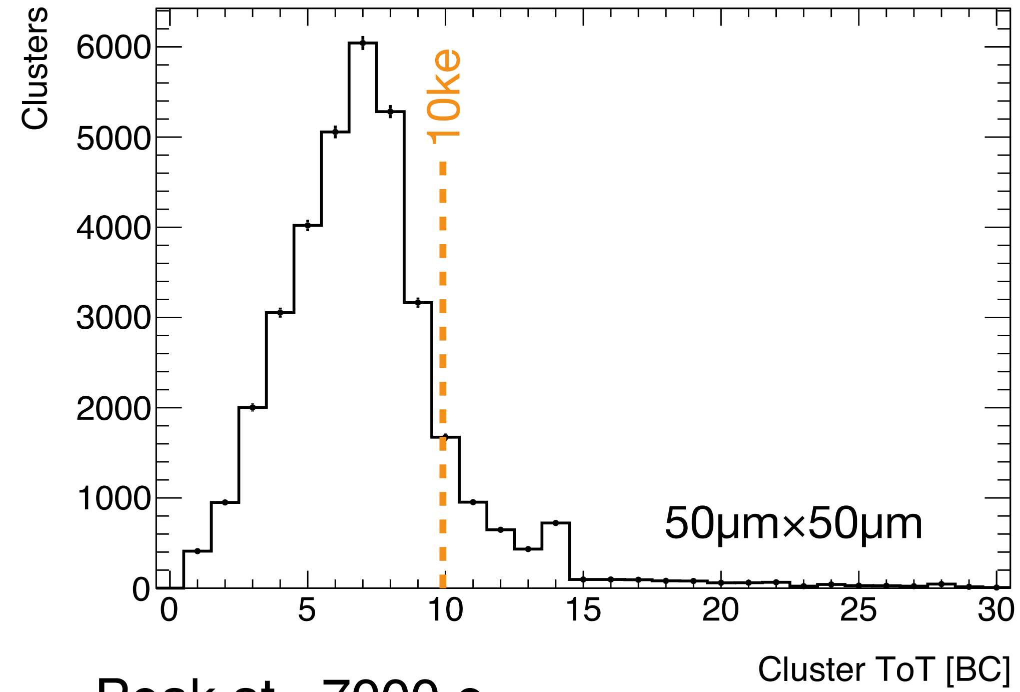
ATLAS results: 3D before irradiation

Charge collection at bias voltage = 10 V

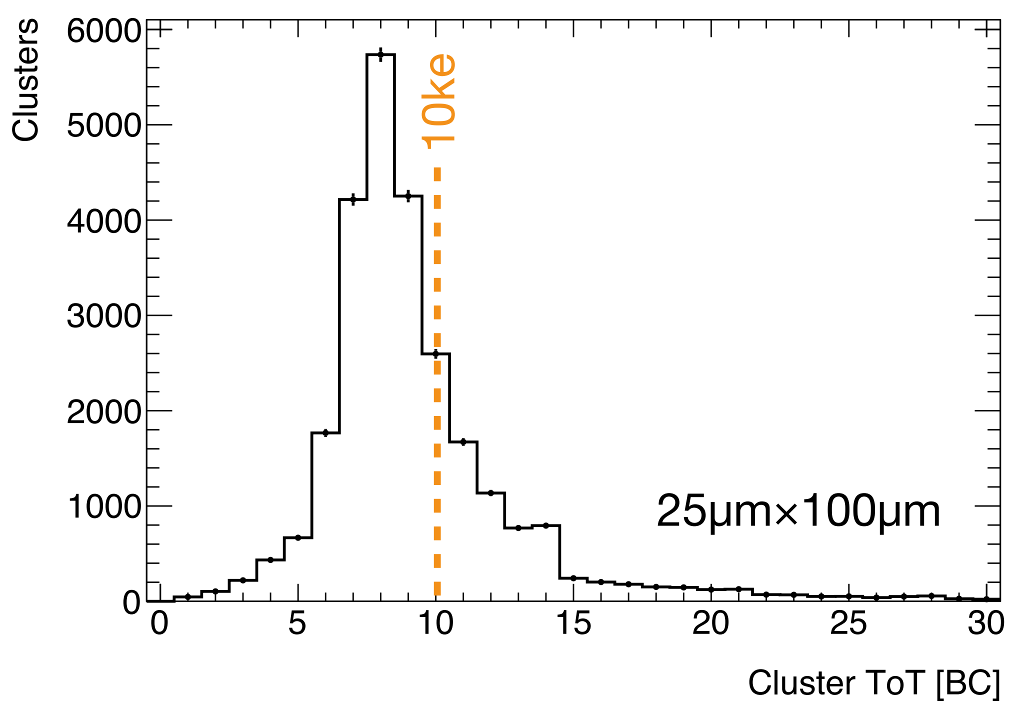
Peak at ~8750 e⁻ (150 um thick)



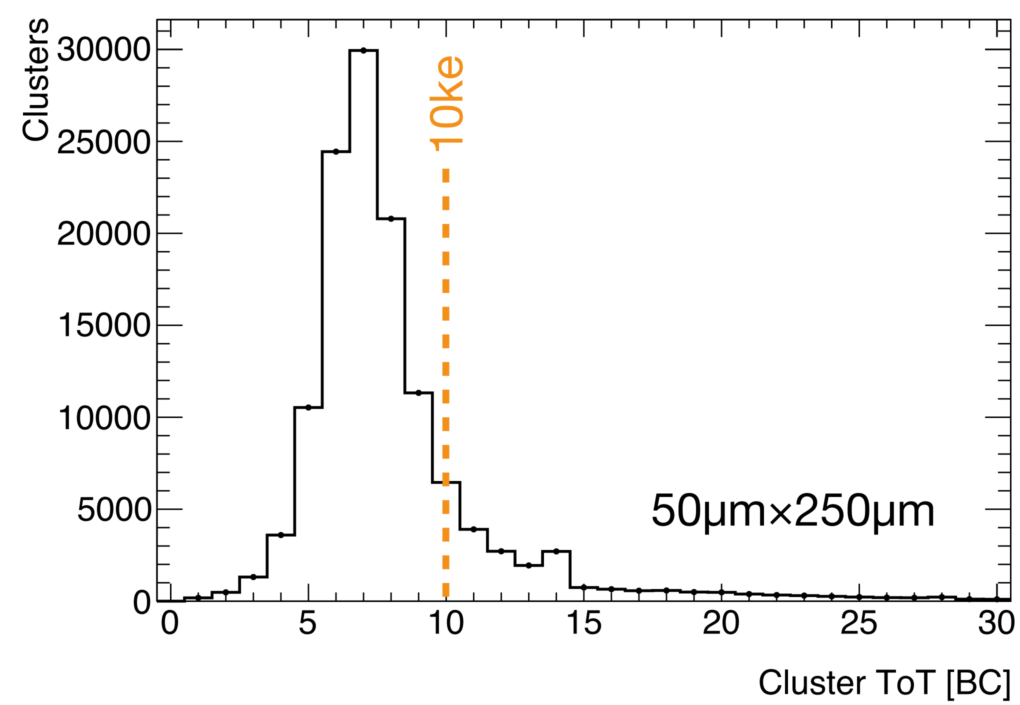
Peak at ~7000 e⁻



Peak at ~8000 e⁻



Peak at ~7000 e⁻



Collected charge MPV of 3D modules ~ as expected from sensor thickness

Summary and prospects

- First prototype sensors, both thin planar and 3D columnar, developed within INFN Pixel R&D collaboration with partnership FBK, show good data quality and behave as expected
- Further studies, especially at higher radiation dose, are ongoing

- CMS 3D and thin planar modules will be irradiated ~summer 2017:
  - with 24 GeV protons at CERN up to 5×10^{15} n_{eq} / cm^2
  - with neutrons at Lubiana up to 10^{16} n_{eq} / cm^2
- CMS testbeam campaign foreseen ~fall 2017

- ATLAS 3D modules are being irradiated up to ~10^{16} n_{eq} / cm^2:
  - 6 modules with 24 GeV protons at CERN
  - 3 modules with 23 MeV protons at KIT

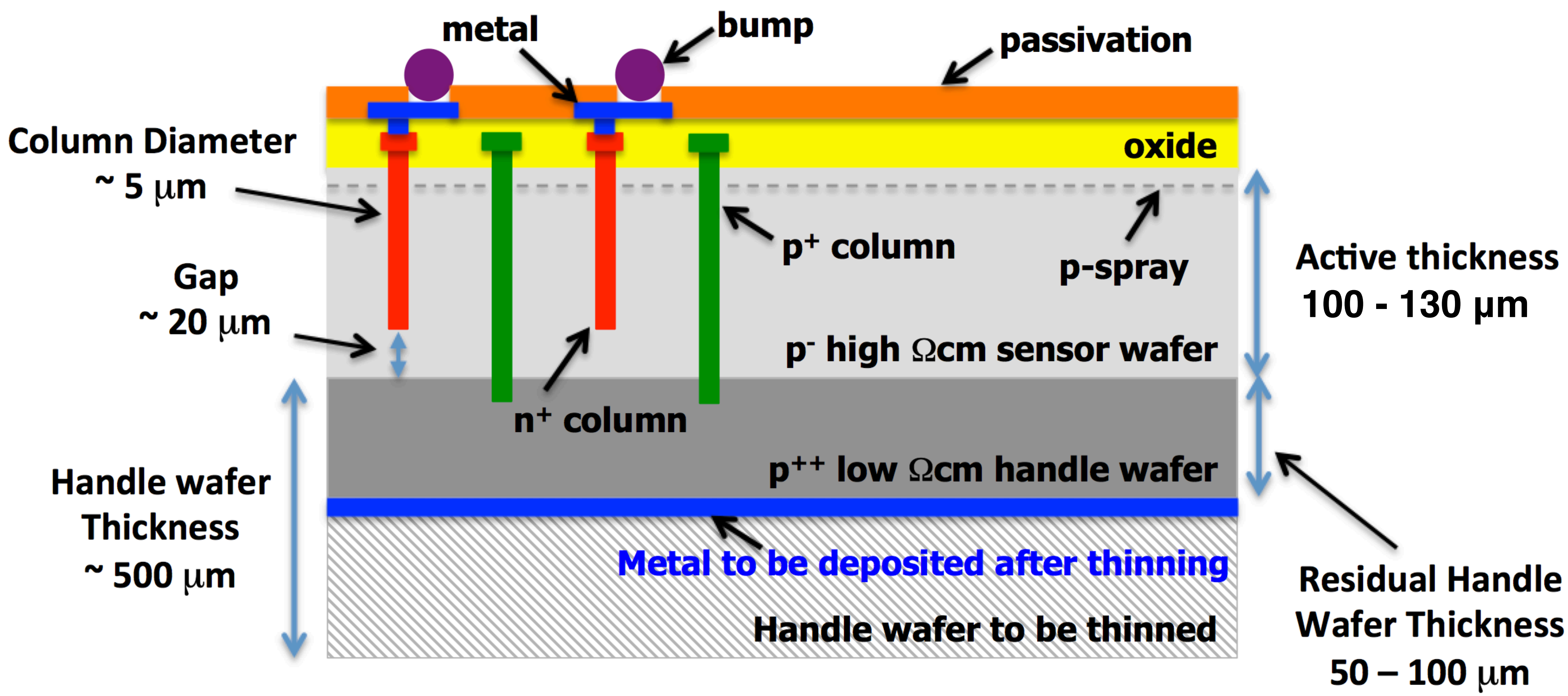
- New wafers made with Direct Wafer Bonding (DWB) with SOI are being processed and will be tested in comparison with SiSi DWB

- As soon as RD53 chip (joint ATLAS-CMS collaboration to develop high radiation tolerant readout chip in 65 nm CMOS technology) will be available the plan is to bump-bond new sensors with RD53 chip (higher radiation resistance, capability to readout both 50x50 μm^2 and 25x100 μm^2 cells)

Backup

INFN Pixel R&D: main design features

- Devices single sided processed: it can be thinned
- Pixel Unit Cell design with variety of collecting electrodes
- Location of pad for bump-bonding optimised



Standard pixel prototype

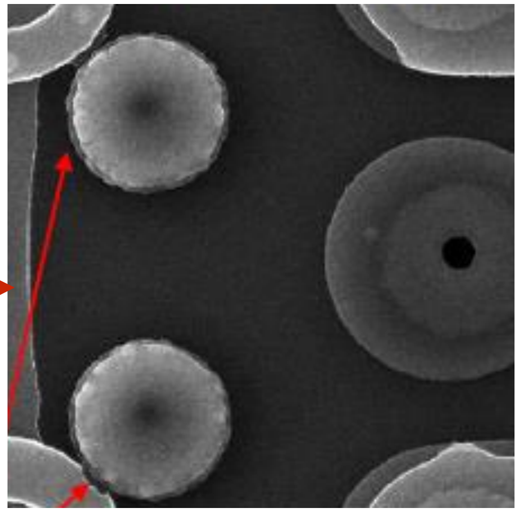
- 100x150 μm^2 pitch
- Readout by PSI46dig chip (phase-1)
- 130 μm active thickness

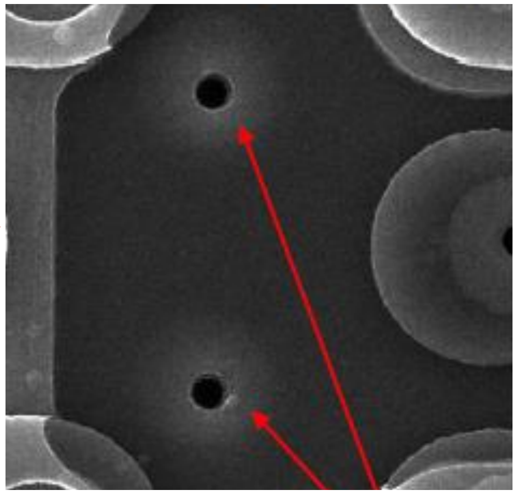
Small pitch pixel prototype

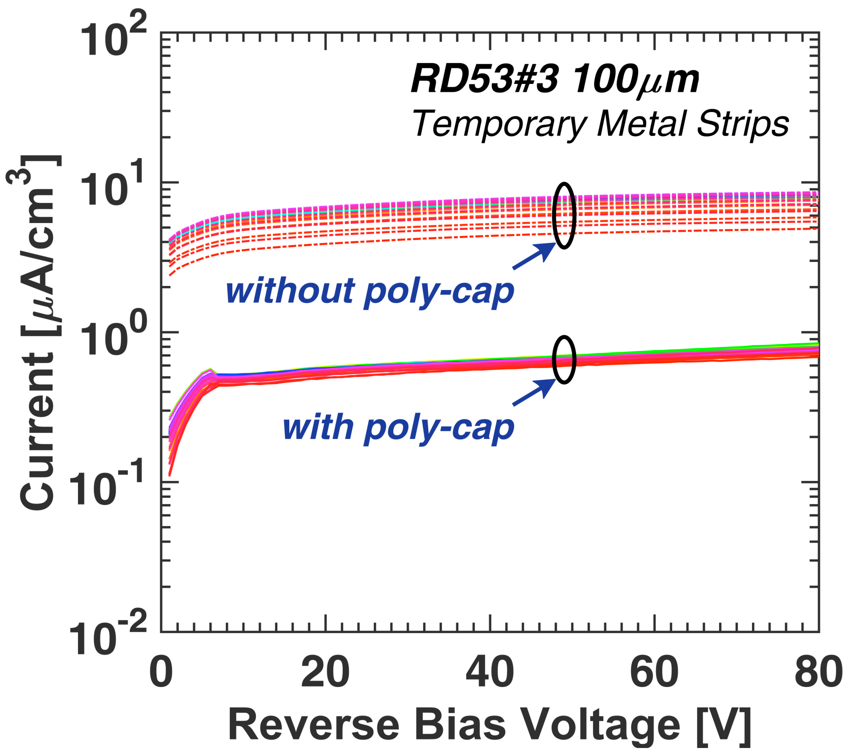
- 50x50 μm^2 and 25x100 μm^2 cell size
- Readout cell adapted for PSI46dig chip (phase-1)

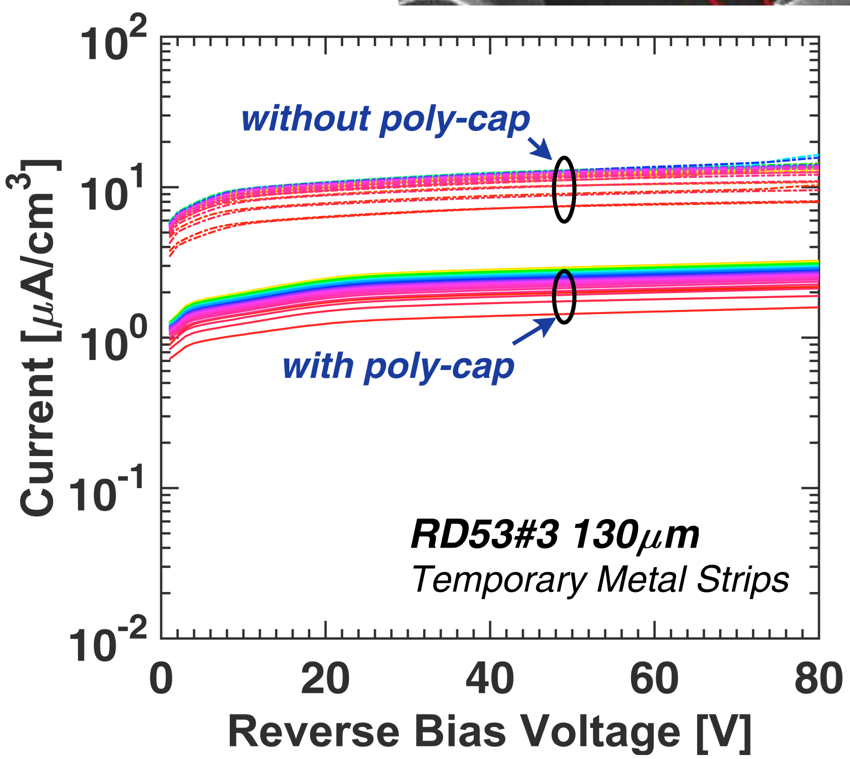
INFN Pixel R&D: main design features

- After column filling with poly-Silicon, residual remains outside the columns (on the surface)
- Two possibilities for removal
  - **with mask:** a poly-cap remains on the columns
  - **without mask:** entirely removal of the poly-cap ➜ some consequences in damaging the aperture of the columns (i.e. higher leakage current)



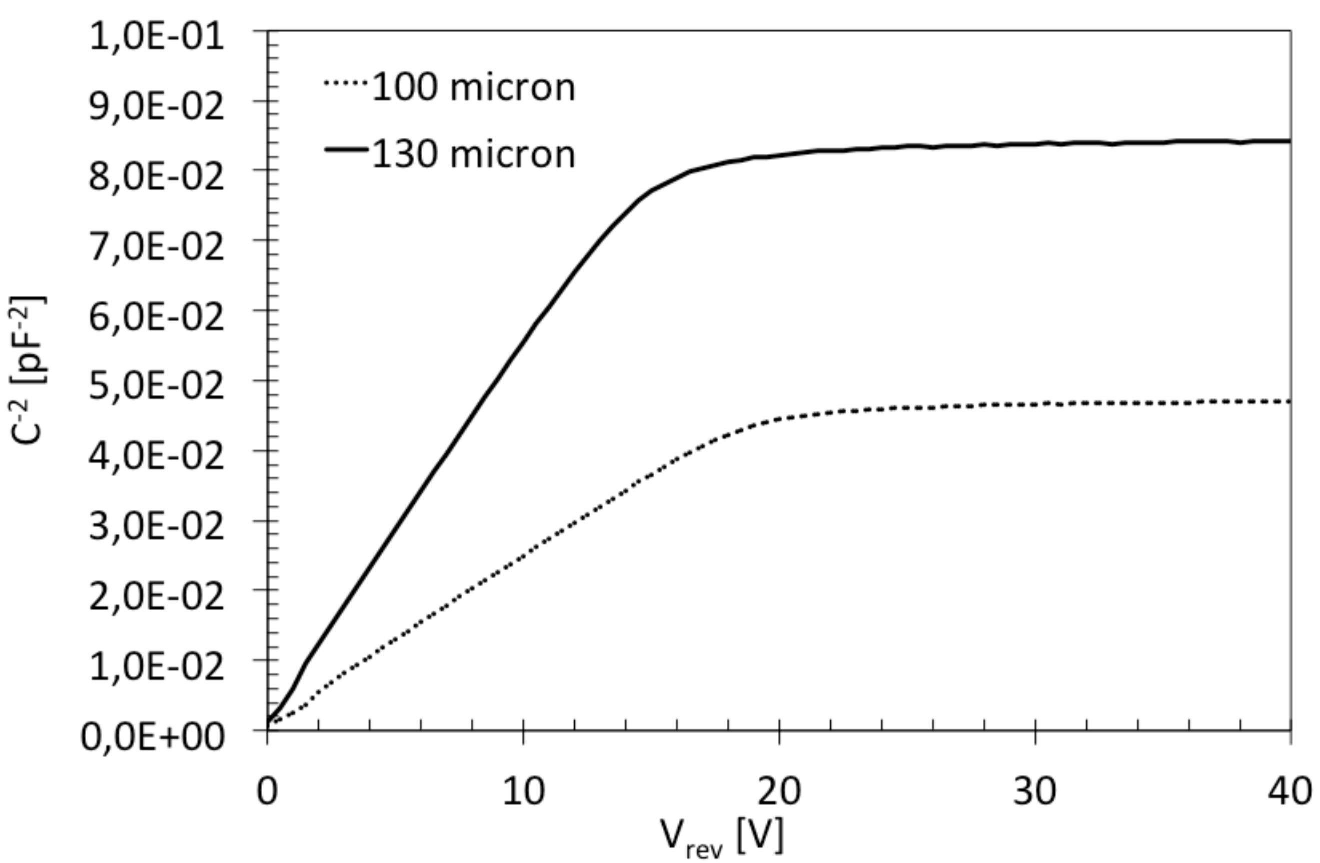






Full depletion voltages

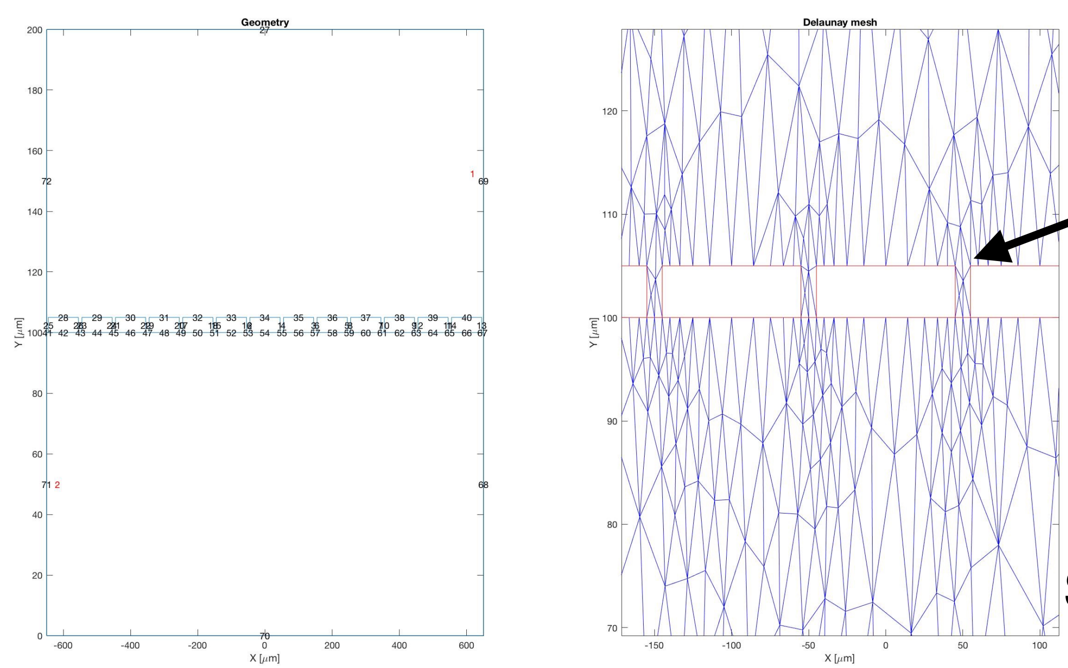
- $V_{full\ dep}$ ~16V for 100 µm thick
- $V_{full\ dep}$ ~20V for 130 µm thick



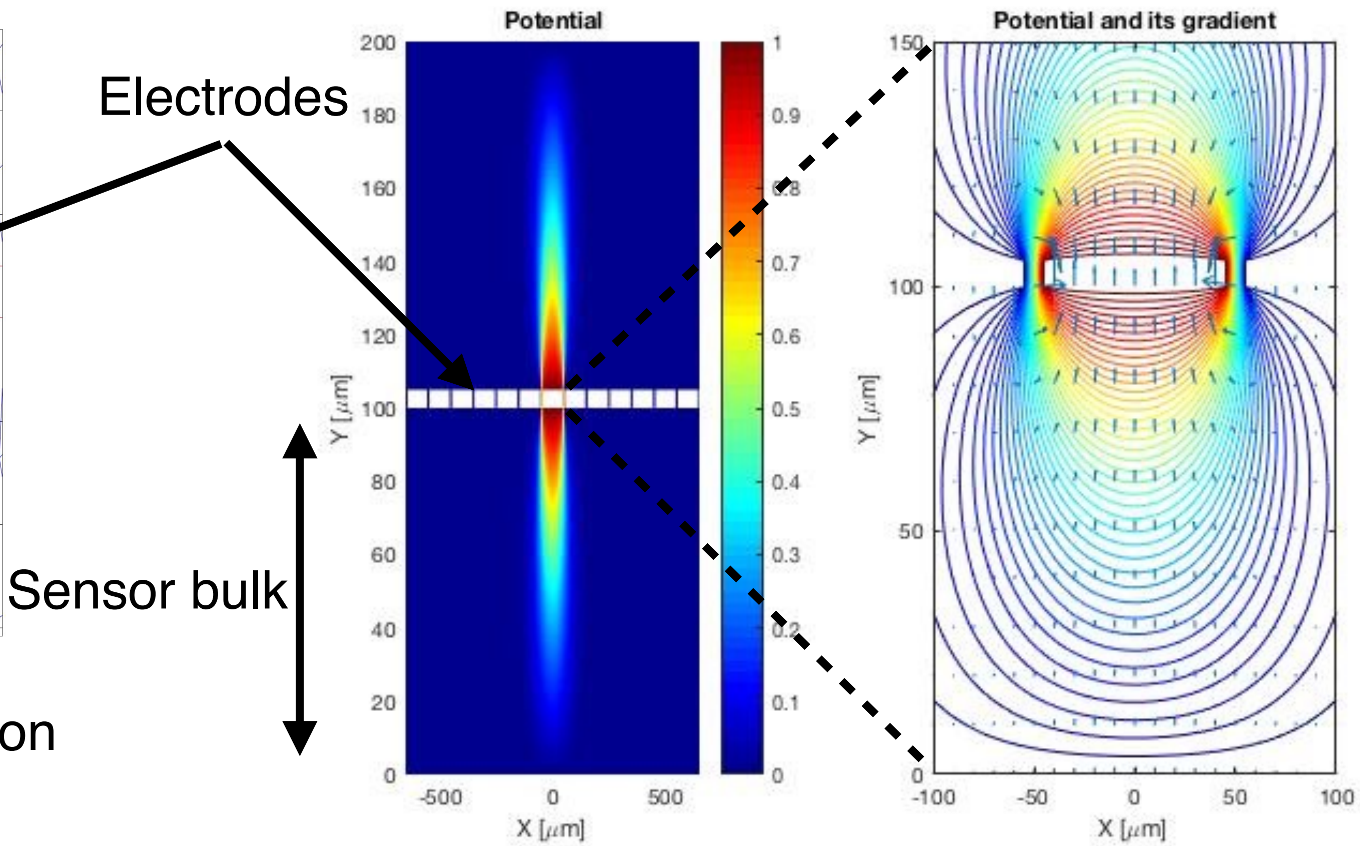
INFN Pixel R&D: main design features

We performed a simulation of the charge transport with MATLAB:

- 2D simulation
- velocity dependence from electric field taken into account
- space charge corresponding to nominal/un-irradiated resistivity
- e-h pairs per micron: 60
- radiation damage effects simulated with finite carrier lifetimes ➜ from carrier lifetimes we evaluate irradiation fluence: $1/\tau_{e/h} = \boldsymbol{\beta_{e/h}} \cdot \Phi$ (*2016 JINST 11 P04023*) (in the following the errors on fluence are derived only from propagation of error on $\boldsymbol{\beta_{e/h}}$)



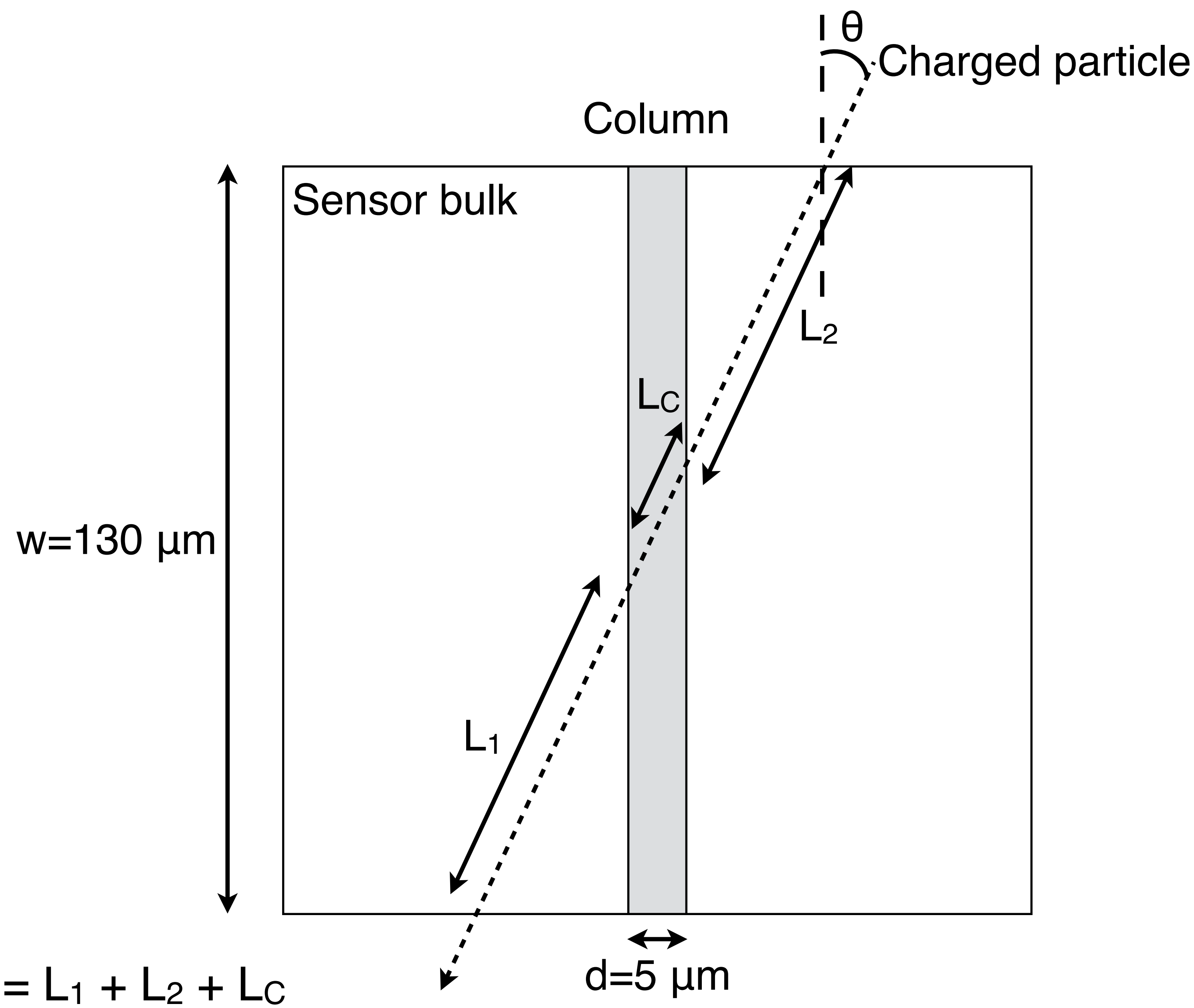
Finite element analysis to solve Poisson equation



Weighting potential

The irradiation was not uniform ➜ we concentrate our modelling on a small region in the highly irradiated zone

CMS results: 3D before irradiation



$$\begin{cases} L = L_1 + L_2 + L_C \\ L\cos(\theta) = w \\ L_C \sin(\theta) = d \\ L_C / L < \text{Threshold} / \text{MIP} \end{cases}$$

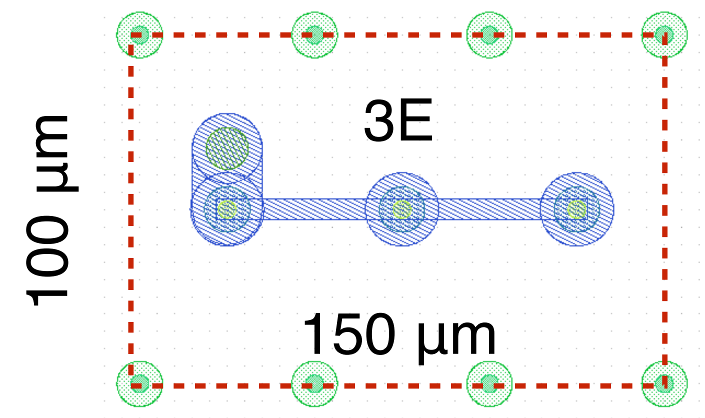
⇓

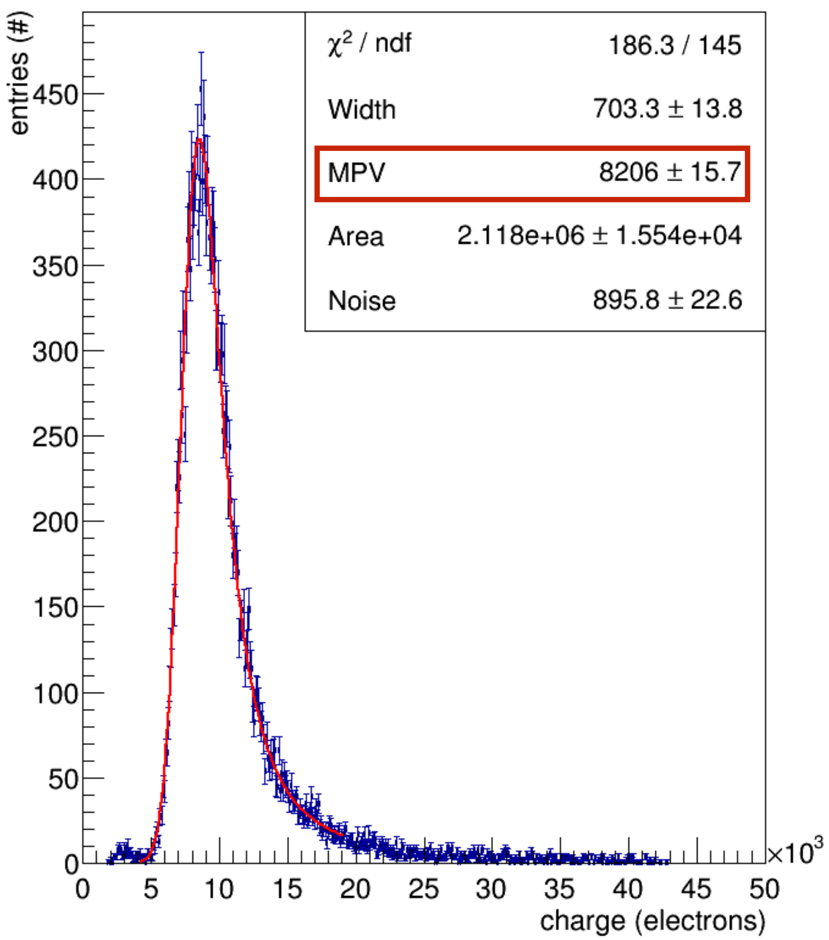
$$\tan(\theta) > (d \cdot \text{MIP}) / (w \cdot \text{Threshold})$$

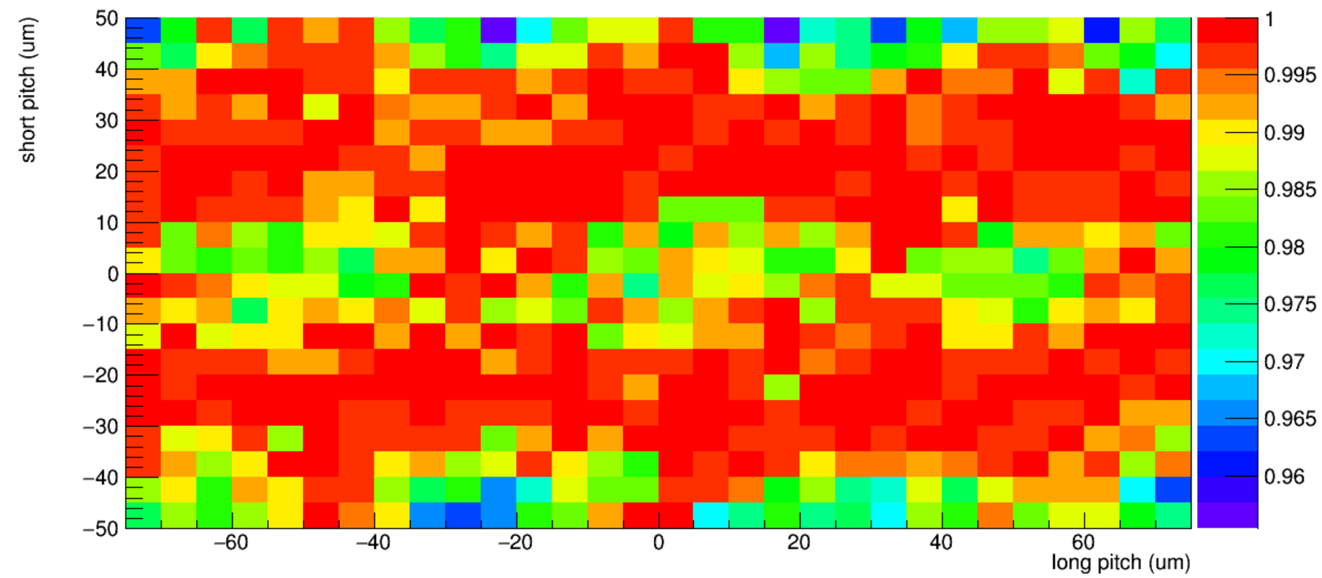
CMS results: 3D before irradiation

Efficiency map on cell for orthogonal tracks

- Bias voltage: 40 V







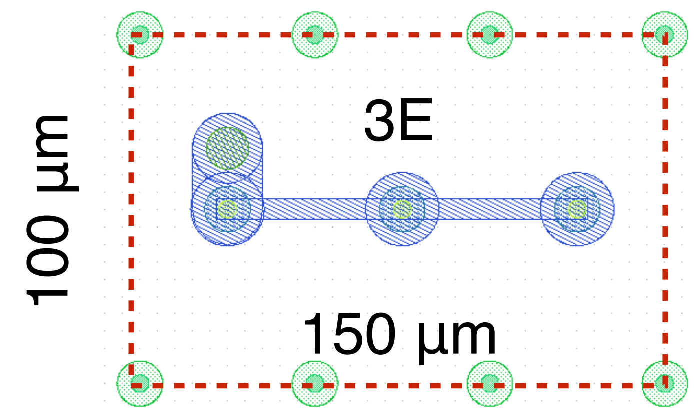
Overall efficiency: (99.19 ± 0.05)%

Visible efficiency deterioration on both junction and ohmic columns

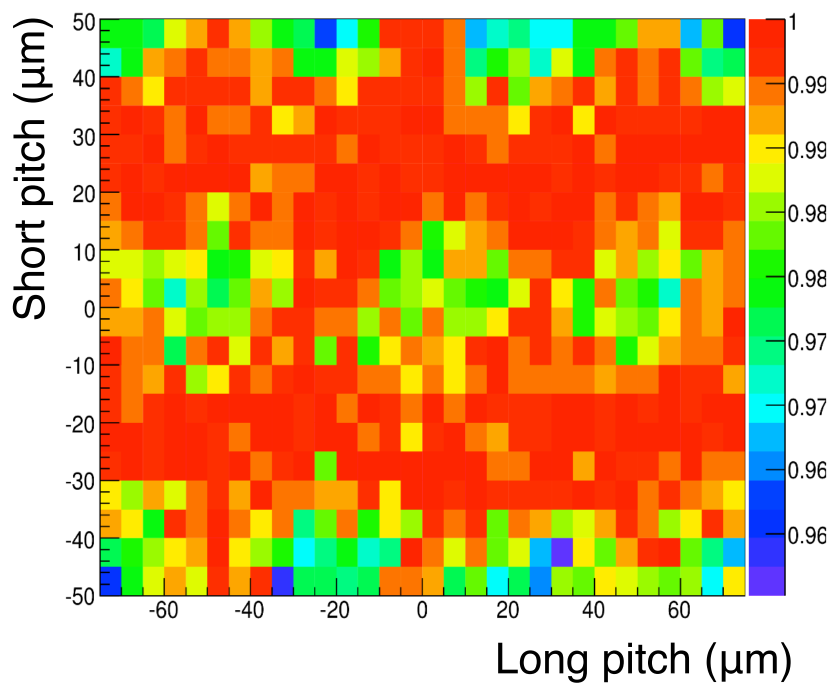
CMS results: 3D before irradiation

Efficiency map on cell

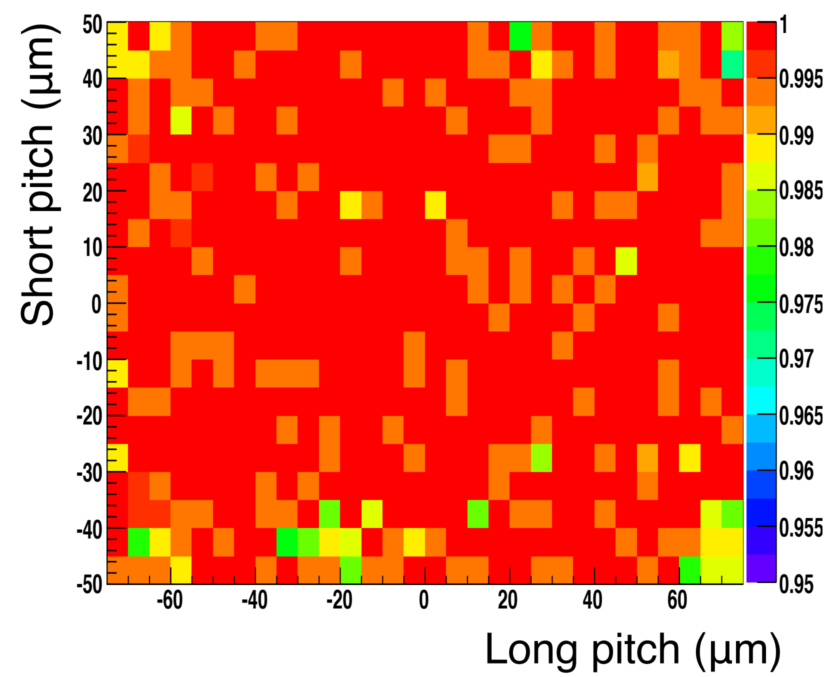
- Bias voltage: 30 V



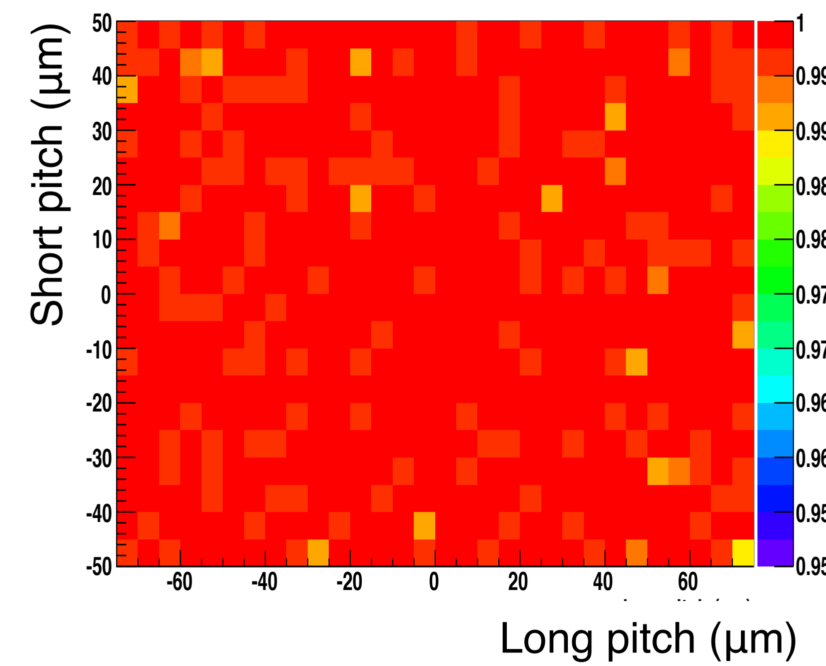
Orthogonal tracks



5 degrees tilt



10 degrees tilt



Angle (degree)	Efficiency 3E	Efficiency 2E
0	99.27	99.45
5	99.77	99.85
10	99.88	99.87

Column inefficiency shadowed by tilt, compatible with simple geometric considerations (tilt angle > 9º, see backup slides)

Simulated signal efficiency

- Simplified simulation domain (2D slice), no pixel edge effects
- Very high average signal efficiency
- Significant variations of signal efficiency with hit position
- Possible impact ionisation effects at high field