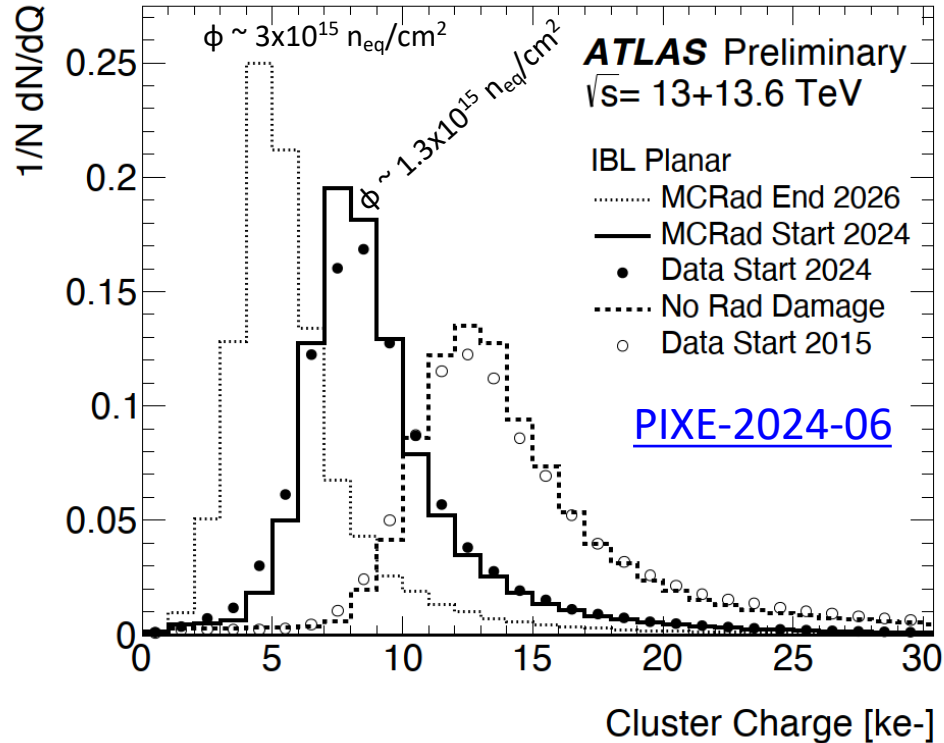

Including radiation damage effects to silicon sensors in LHC experiments MonteCarlo simulations: status and perspectives

Marco Bomben –
Laboratoire AstroParticule et Cosmologie (APC)
& Université Paris Cité, Paris



Why do we need to model radiation damage?



Acknowledgments

This seminar is the result of the work of many people over several years

- A work that will continue in the next years!

I would like to thank all the colleagues that shared with me their knowledge and time to achieve the results I am going to present today

In particular: Ben Nachman, Marco Battaglia, Marcello Bindi, Morris Swartz, all the past and present members of the ATLAS Silicon Radiation Damage group, the ATLAS Pixel group, the ATLAS Radiation Damage Simulation group, the colleagues of RD50, in particular Joern Schwandt and Michael Moll

Radiation effects at the LHC experiment

Several workshops, the last two took place in [2018](#) and [2019](#)

Radiation effects at the LHC experiments and impact on operation and performance

23–24 Apr 2018
CERN
Europe/Zurich timezone

Enter your search term

C

Radiation effects in the LHC experiments and impact on operation and performance

11–12 Feb 2019
CERN
Europe/Zurich timezone

Enter your search term

Q

Radiation effects at the LHC experiment

The wealth of results and discussions that emerged during the workshops have been summarized in a [CERN Yellow Report](#) published in 2021.

It covers radiation background simulation, radiation damage to sensor and electronics measurements and **simulation of detector response**

Radiation effects in the LHC experiments: Impact on detector performance and operation

Editor: I. Dawson

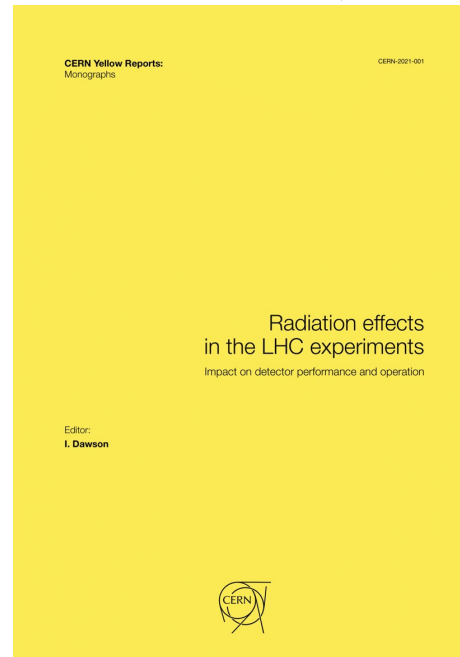
Section editors: M. Bindi, **M. Bomben**, E. Butz, P. Collins, A. de Cosa, I. Dawson, S. Mallows, M. Moll
B. Nachman, J. Sonneveld

Abstract

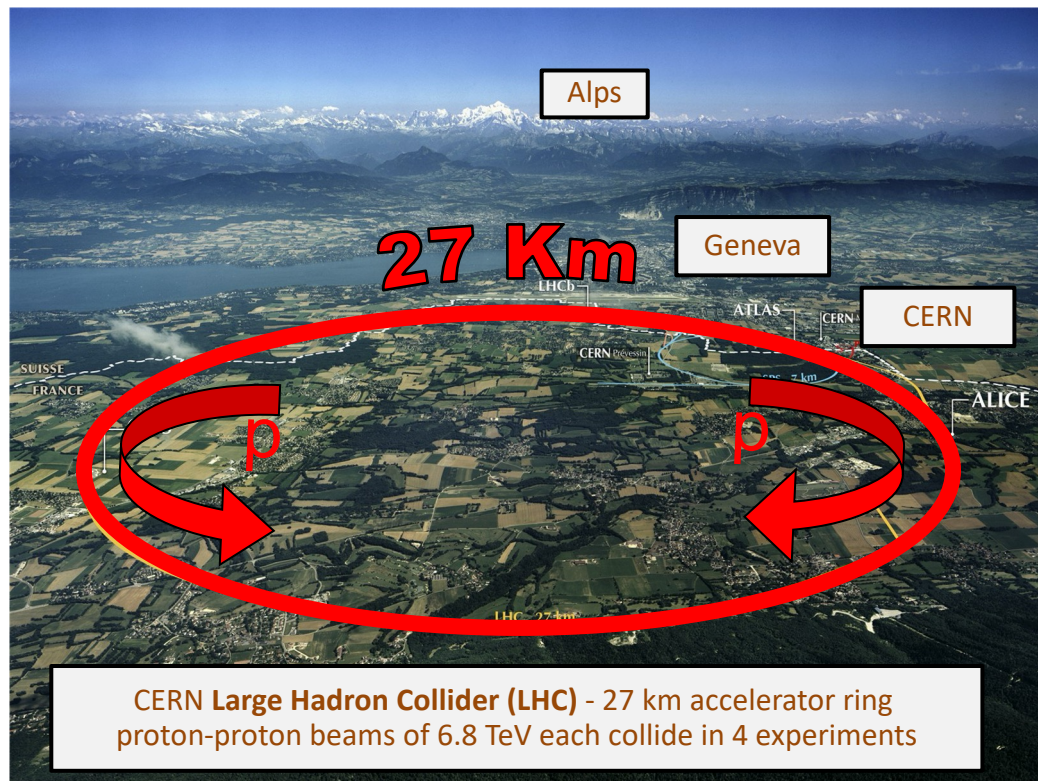
This report documents the knowledge and experiences gained by the LHC experiments in running detector systems in radiation environments during 2010–2018, with a focus on the inner detector systems. During this time, the LHC machine has delivered a large fraction of the design luminosity to the experiments and the deleterious effects of radiation on detector operation are being observed and measured. It is timely to review the findings from across the experiments. Questions we aim to answer include: Are the detector systems operating and performing as expected? How reliable are the radiation damage models and predictions? How accurate are the Monte Carlo simulation codes? Have there been unexpected effects? What mitigation strategies have been developed? A major goal of this report is to provide a reference for future upgrades and for future collider studies, summarizing the experiences and challenges in designing complex detector systems for operation in harsh radiation environments.

Keywords

Radiation effects; LHC experiments; radiation environments; simulation; modelling; detectors; electronics.



CERN & LHC - Large Hadron Collider

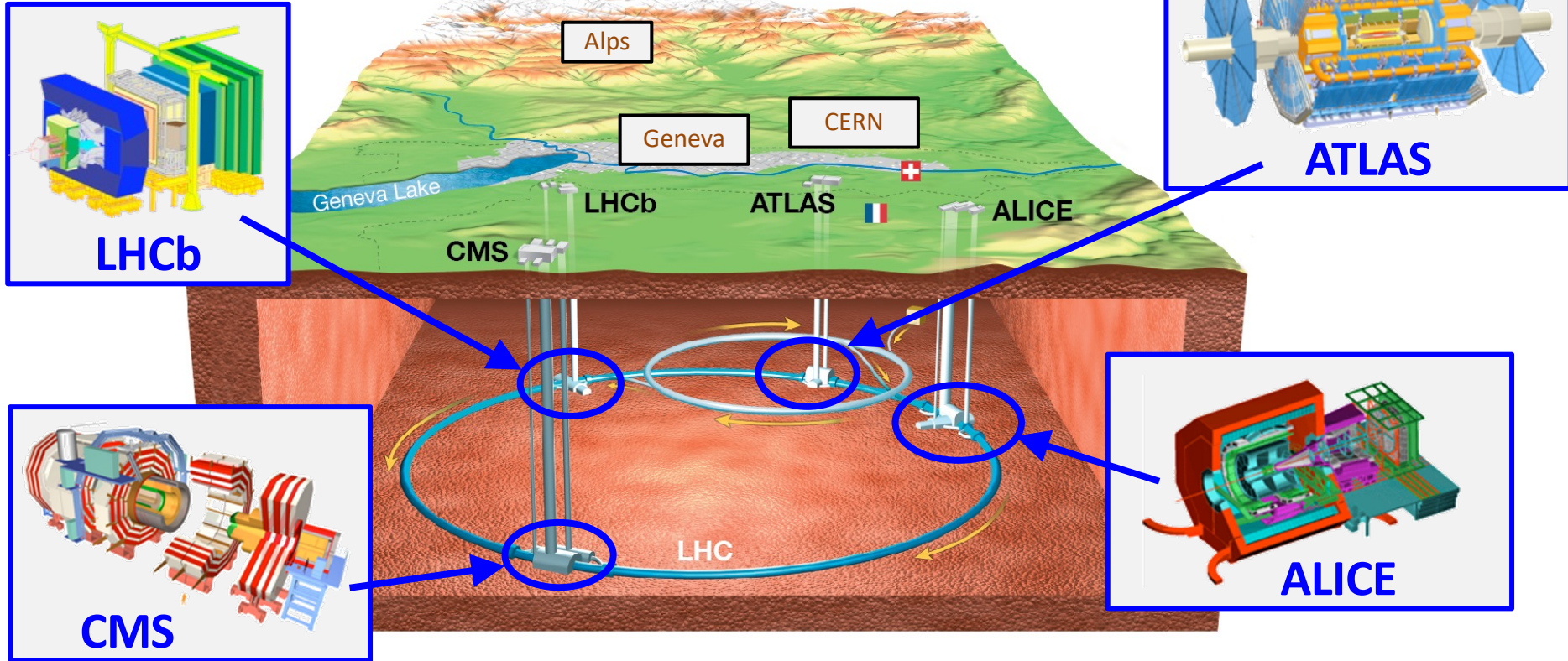


also a program with Pb beams at up to 5.36 TeV per nucleon

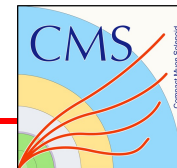
- **CERN (2023):** [M. Moll, Simdet 2023](#)
 - 23 member states
 - ~13400 scientists (users)
 - ~2660 personnel (staff) + 900 Fellows
 - Budget ~1230 MCHF (France: 13.2%)
- **LHC: 27 km tunnel**
 - ≈ 4600 MCHF + 1200 MCHF (accelerator + experiments)
 - 1232 dipoles $B=8.3\text{T}$ (959)
 - Design: pp $\sqrt{s} = 14\text{ TeV}$ ($L_{\text{design}} = 10^{34}\text{ cm}^{-2}\text{ s}^{-1}$)
heavy ions (e.g. Pb-Pb; 5TeV)
- **Circulating beams:**
 - 2008: first beam
 - 2009-13: **Run 1** at 2 x 4 TeV
 - 2012: Higgs Boson “discovered”
 - 2015-18: **Run 2** at 2 x 6.5 TeV ($10^{34}\text{ cm}^{-2}\text{ s}^{-1}$ reached)
 - 2018-22: Long Shutdown 2 (LS2)
 - 2022-26: **Run 3** at 2 x 6.8 TeV
 - 2026-30: Long Shutdown 3 (LS3)
 - **2030: HighLumi-LHC** (Run 4,)
 - collect 3000-4000 fb^{-1} until ~ 2042 (20 times more than today)



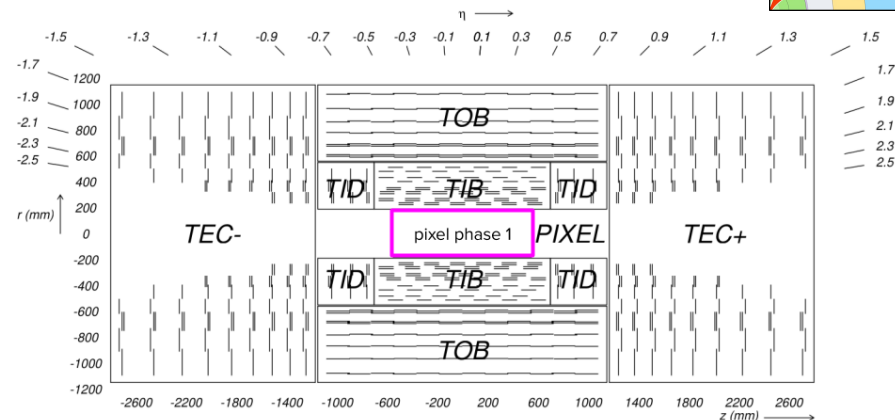
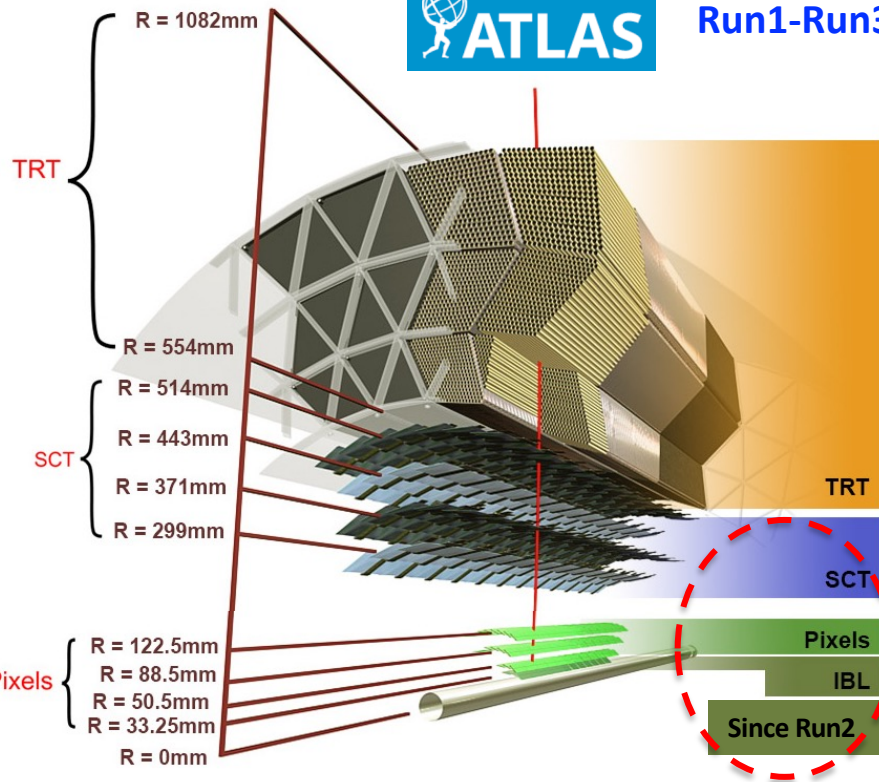
The LHC Experiments



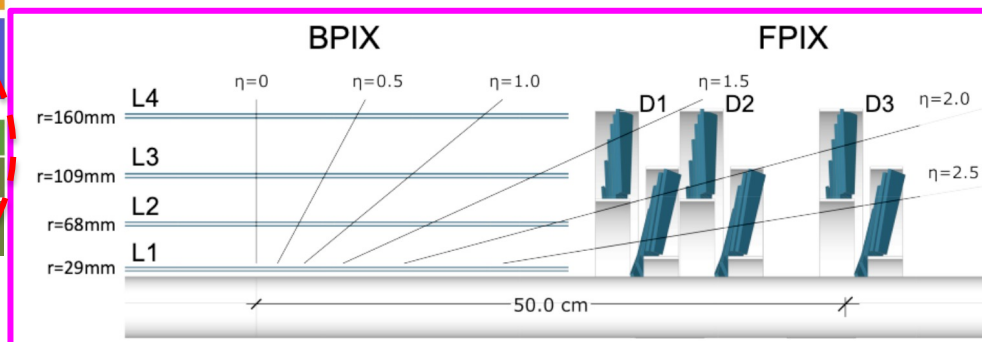
Silicon detectors in LHC experiments



Run1-Run3

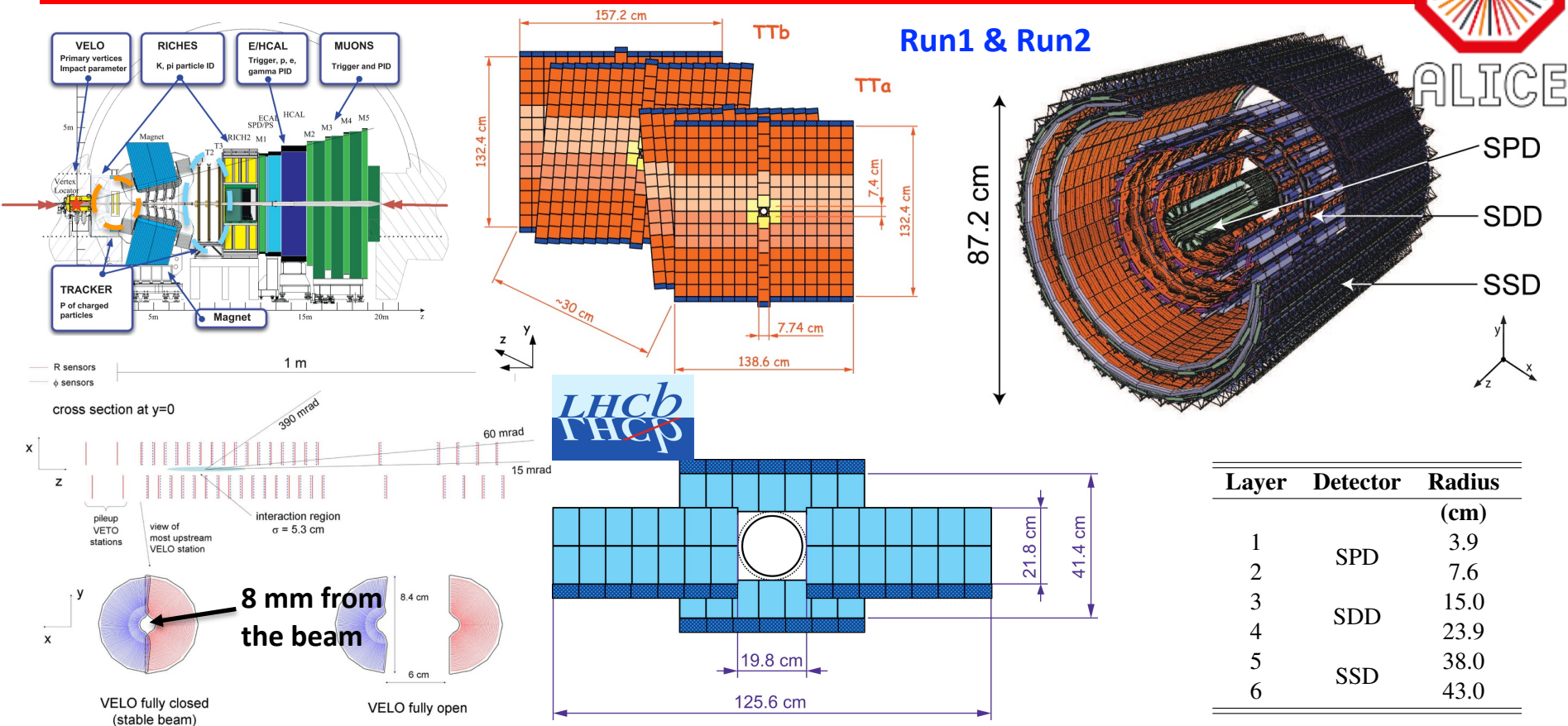


Since 2017; L1 exchanged in 2021



3D modules at $|\eta| > 2.5$ in IBL

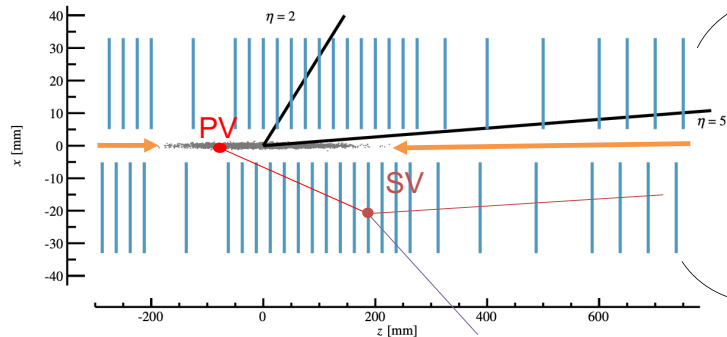
Silicon detectors in LHC experiments



Silicon detectors in LHC experiments

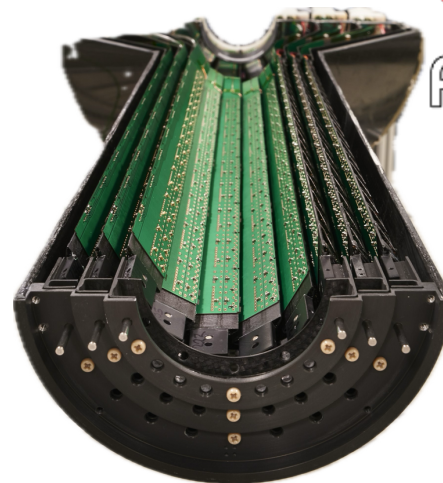


ALICE



Run3

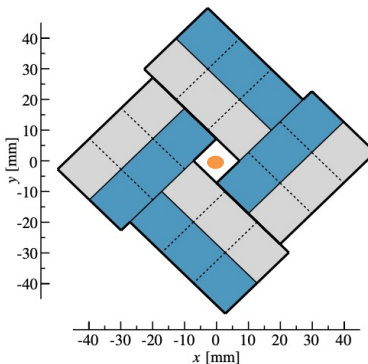
[G. Cordova, Vertex 2025](#)



Since Run3: Velopix

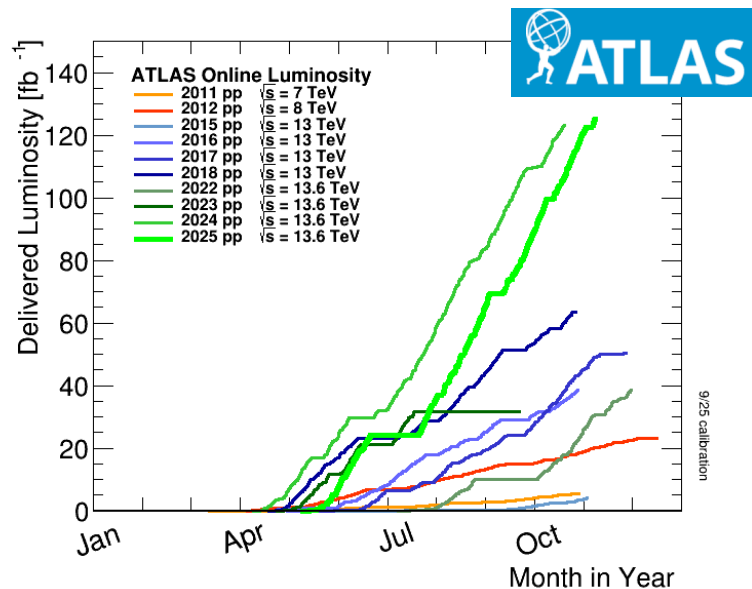


**~5.1 mm from
the beam**



7 barrel layers of “ALPIDE” maps
Closest at 22 mm
10 m² active area – largest MAPS-based
detector today
Rated for $\Phi \sim 3 \times 10^{12}$ (1 MeV) n_{eq}/cm^2
and dose ~ 270 kRad

Run1+2+3 luminosities



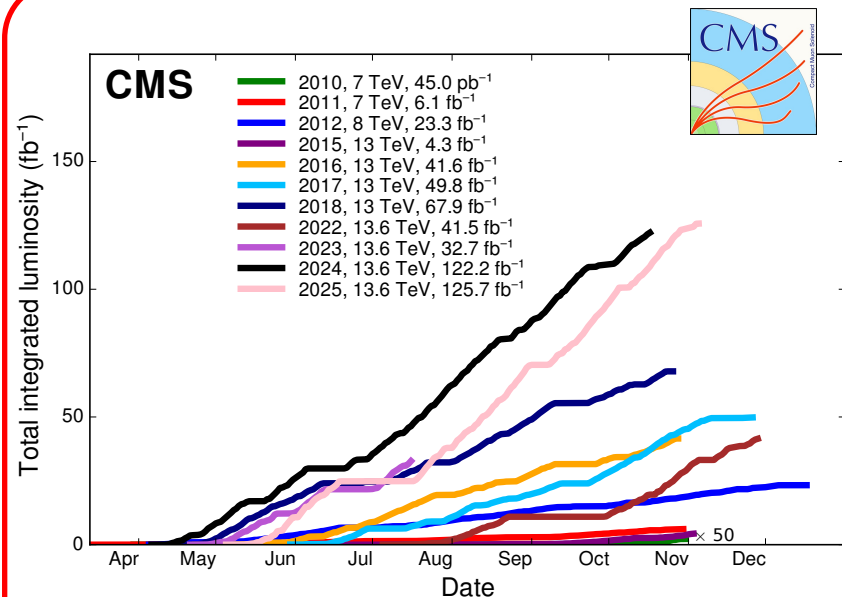
Run1, ~ 29 fb⁻¹

Run2, ~ 161 fb⁻¹

Run3, ~ 319 fb⁻¹

=====

Total (IBL/PIX) ~ 480/509 fb⁻¹



Run1, ~ 29 fb⁻¹

Run2, ~ 164 fb⁻¹

Run3, ~ 322 fb⁻¹

Total (L1/Rest) ~ 322/440 fb⁻¹



~ 10 fb⁻¹ in Run1+2; ~ 22 fb⁻¹ in Run3

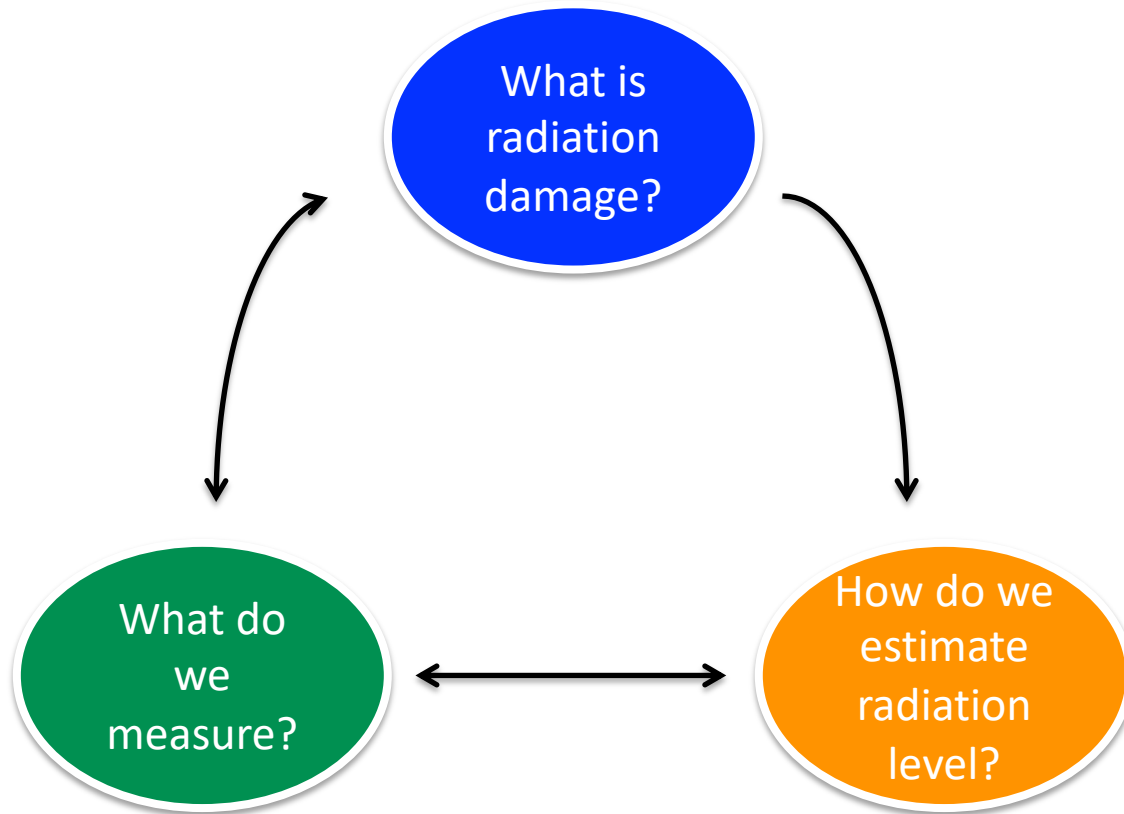


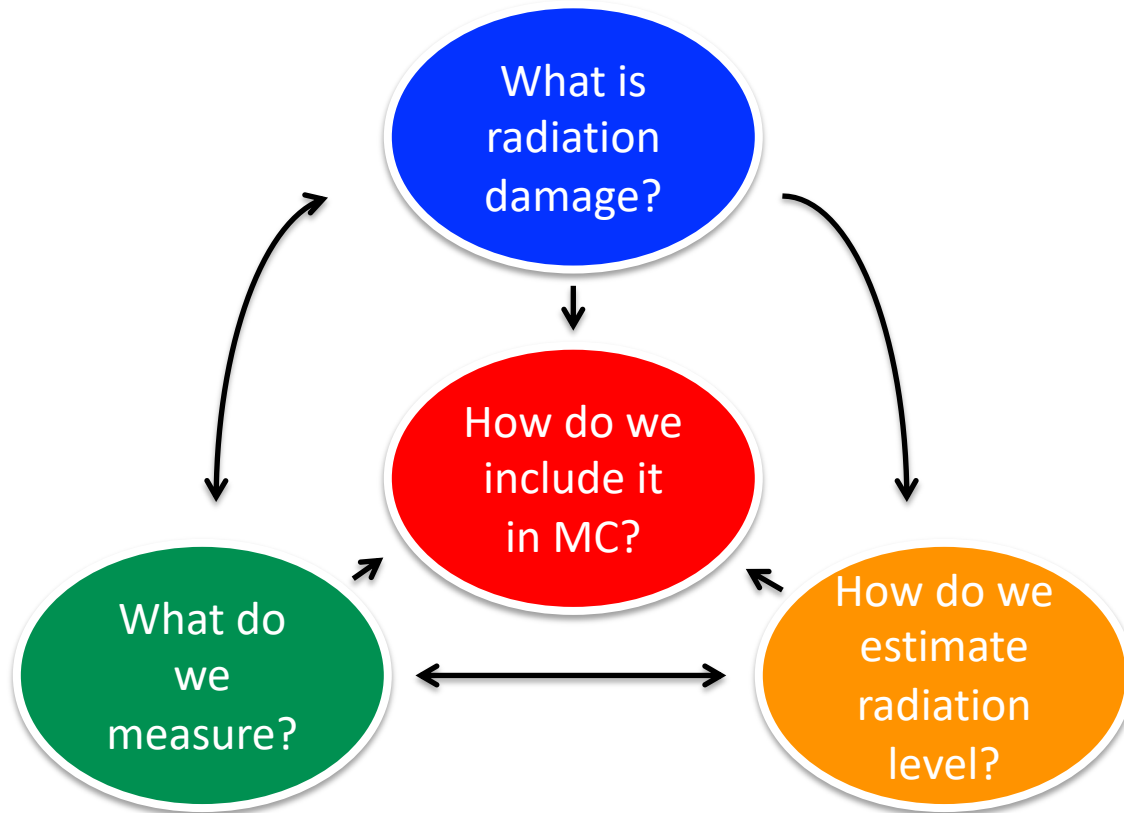
What is
radiation
damage?

```
graph TD; A([What is radiation damage?]) --> B([How do we estimate radiation level?]);
```

What is
radiation
damage?

How do we
estimate
radiation
level?



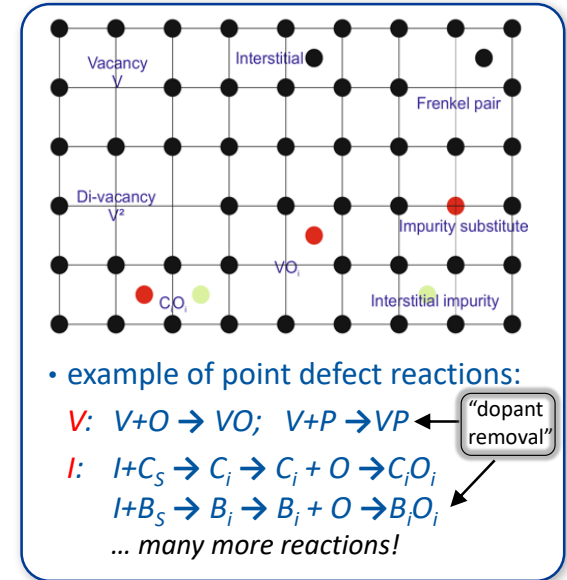
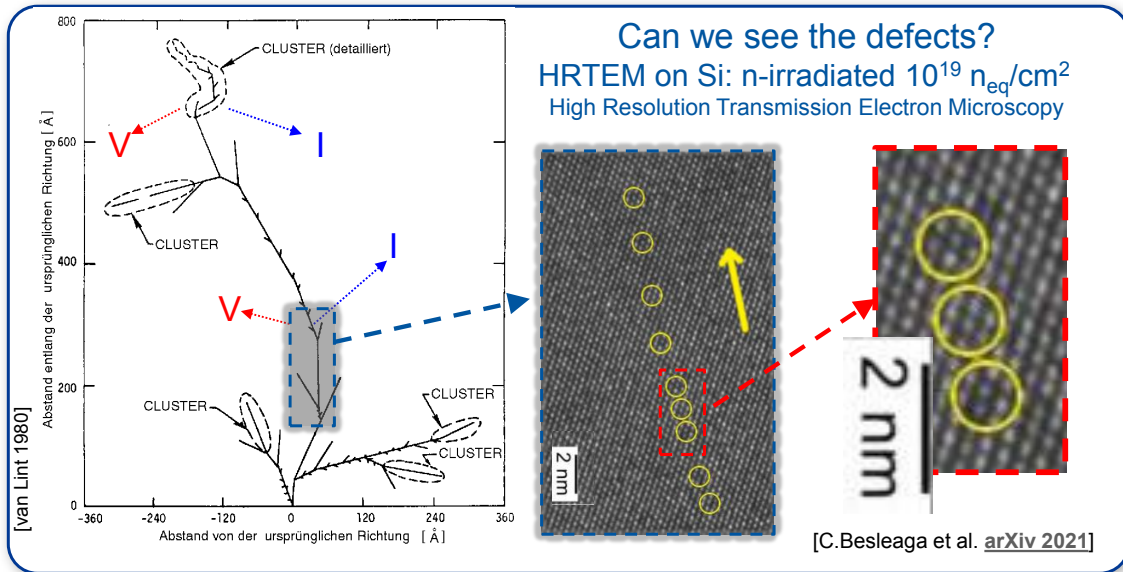
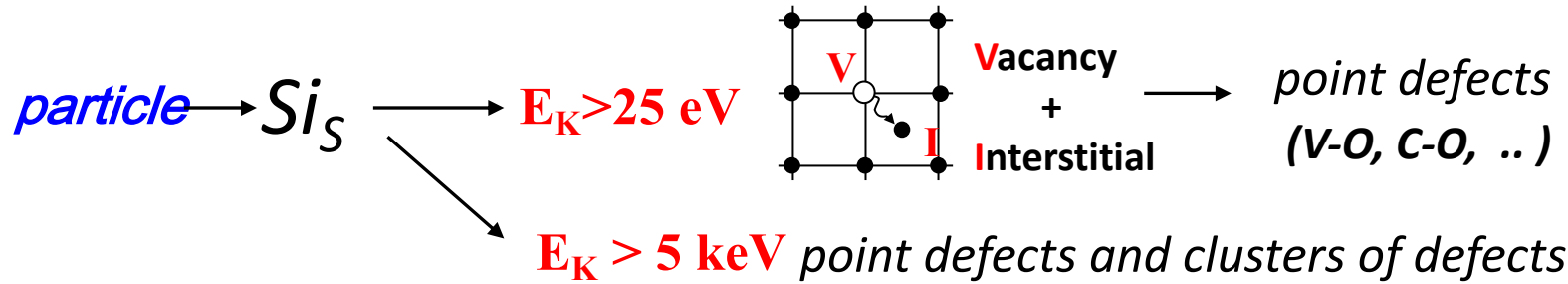


A blue oval with a white border containing the text "What is radiation damage?".

What is
radiation
damage?

Radiation damage to Silicon sensors

M. Moll, 2021



Non Ionising Energy Loss - NIEL

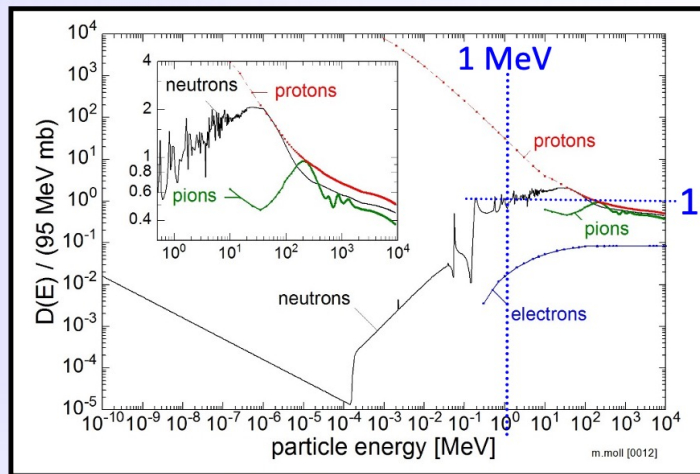
• Displacement Damage function

- Normalization of radiation fields to 1 MeV neutron equivalent damage (n_{eq})

$$\Phi_{eq} = \kappa_x \Phi_x$$

Damage factors

$$\left\{ \begin{array}{l} \kappa_p = 0.57 \text{ (23 GeV protons)} \\ \kappa_p = 1.85 \text{ (26 MeV protons)} \\ \kappa_\pi = 1.14 \text{ (192 MeV pions)} \\ \kappa_n = 0.92 \text{ (TRIGA reactor neutrons)} \end{array} \right.$$

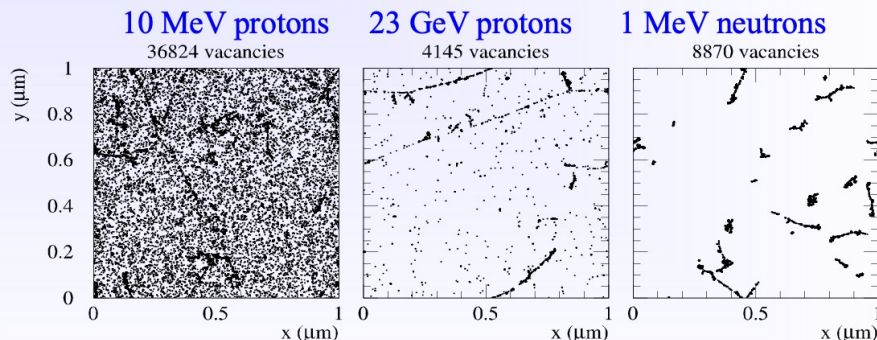


[Data: A. Vasilescu and G. Lindstroem]

NIEL hypothesis:
Damage $\propto$
of vacancies

• NIEL Hypothesis:

- Assumption: NIEL scaling of damage parameters
- Applied to predict damage of radiation fields in HEP
- “NIEL violation” observed:
 - Material dependence
 - Proton vs. neutron damage
 - ...

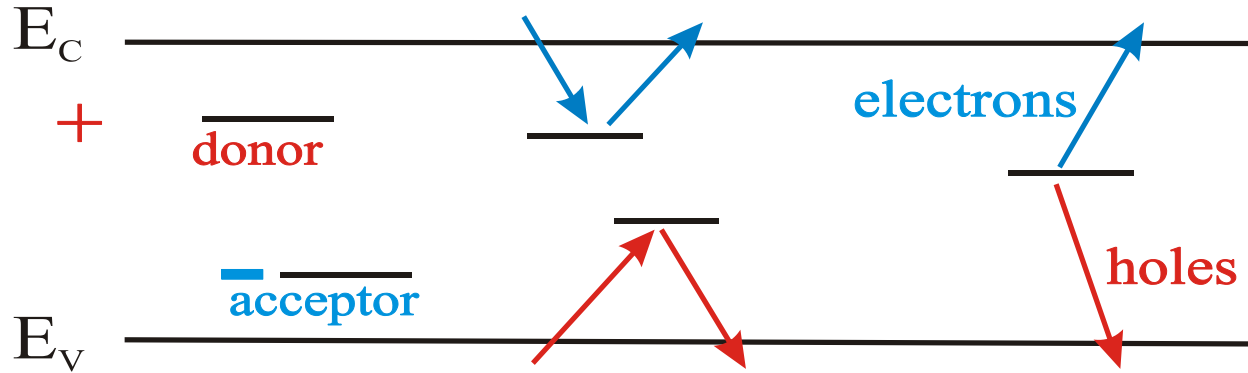


[M. Huhtinen, NIMA 491(2002), 194]

Simulation: Vacancies in $(1\mu\text{m})^3$ after 10^{14} particles/cm²

[M. Moll, 2018](#)

Microscopic effects



Radiation damage
creates states in the
forbidden gap

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

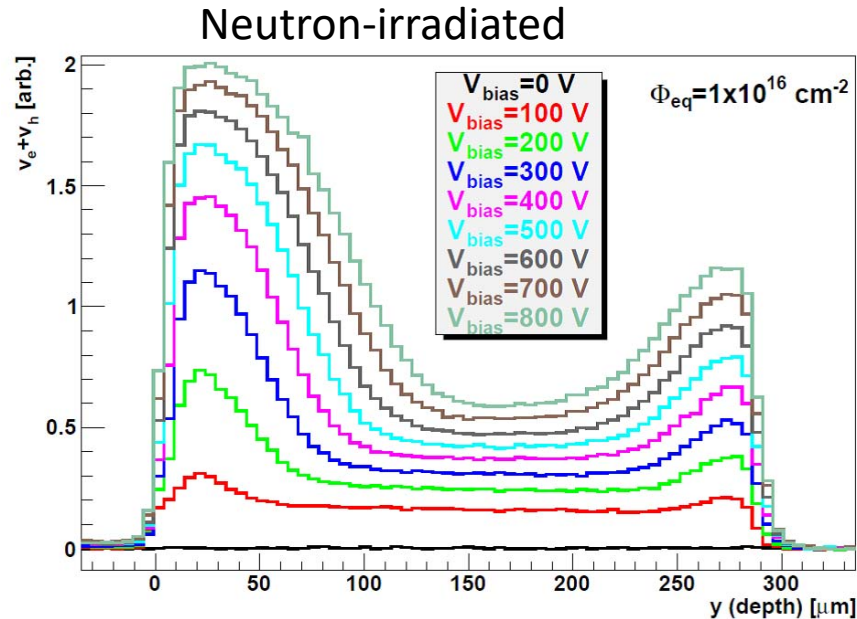
generation

⇒ leakage current

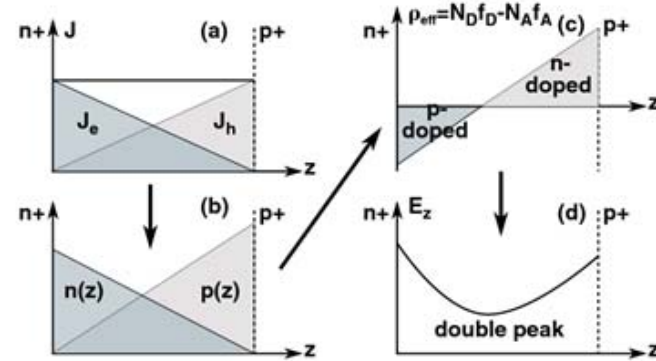
Levels close to
midgap
most effective

[M. Moll, 2018](#)

Deformation of electric field



[G. Kramberger et al., 2014](#)

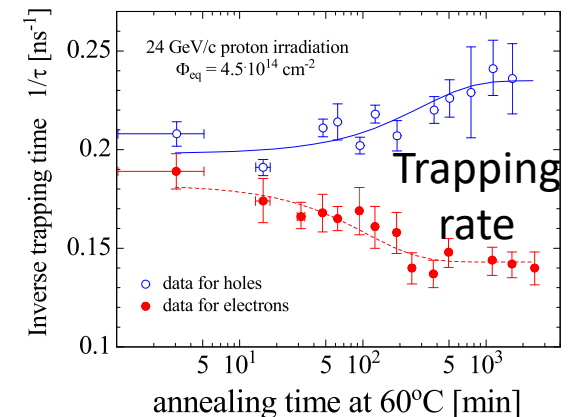
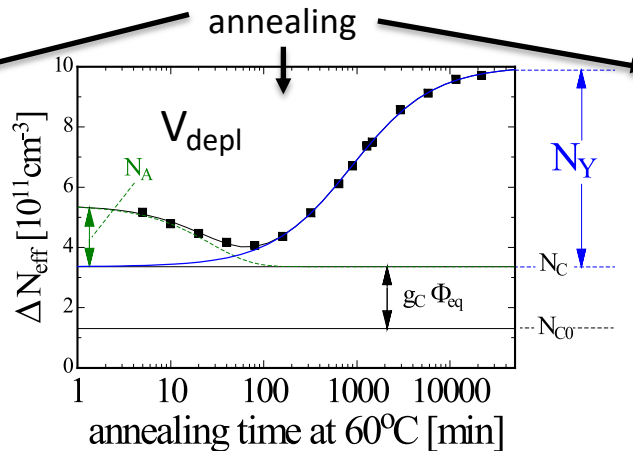
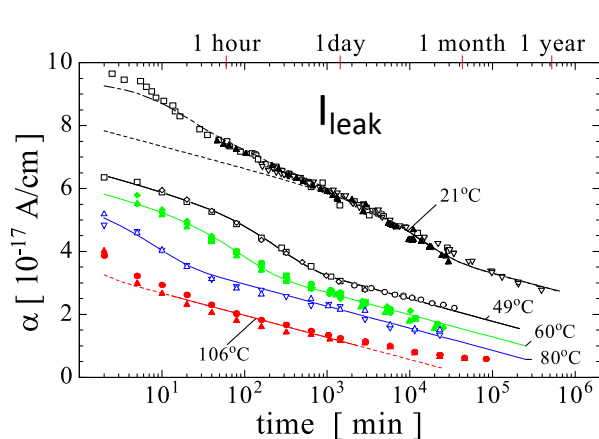
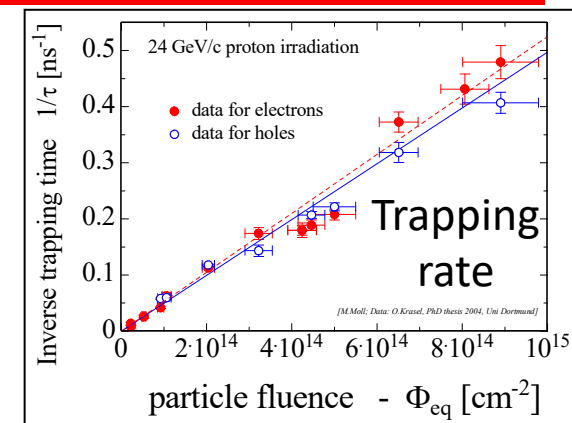
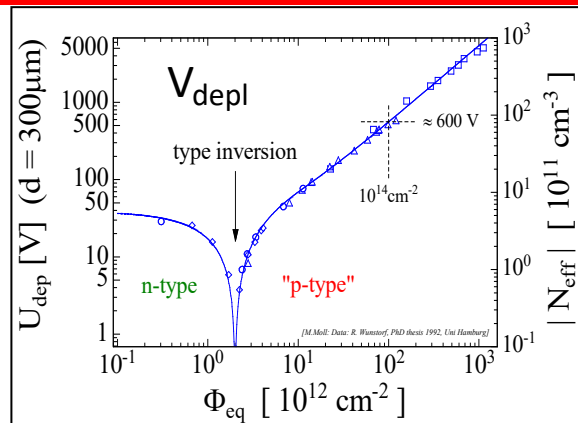
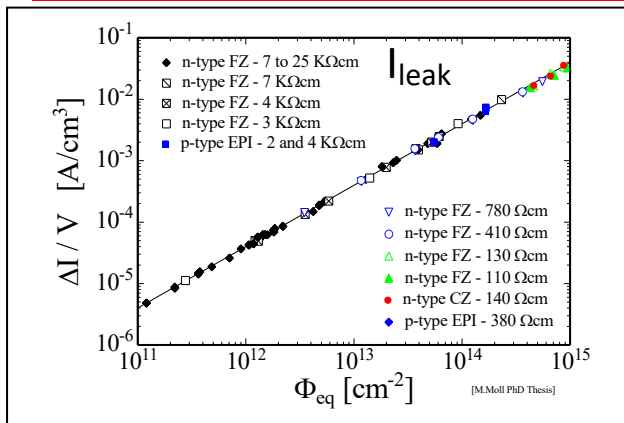


[EVL \(2002\)](#)

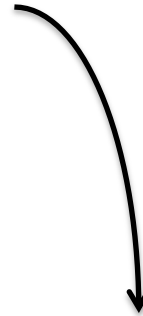
Free carriers drifting towards electrodes get trapped and thus modify the space charge distribution, hence the electric field

Macroscopic effects

M. Moll, 2018



What is
radiation
damage?

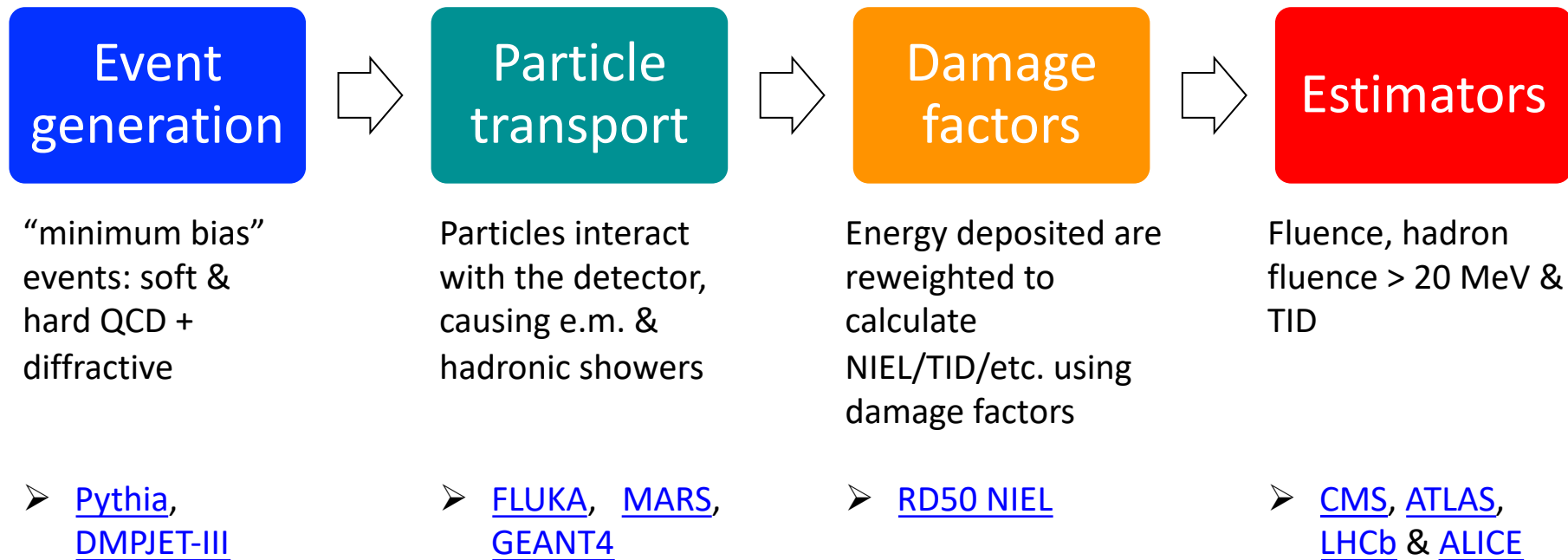


How do we
estimate
radiation
level?

Motivation & Strategy

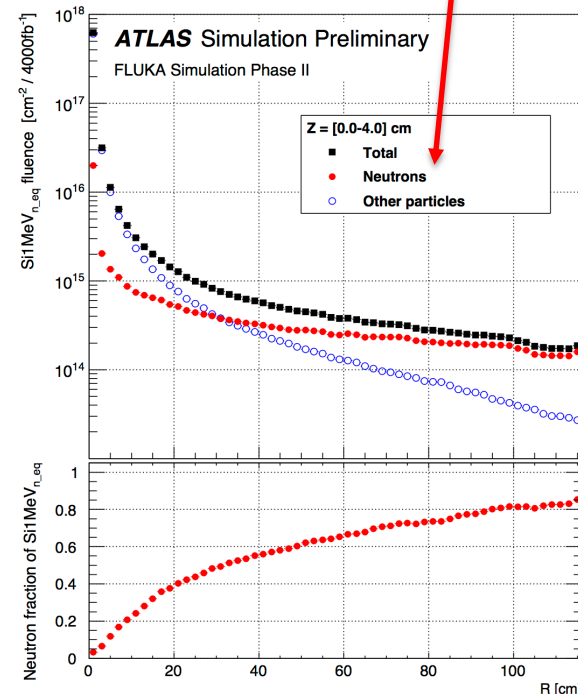
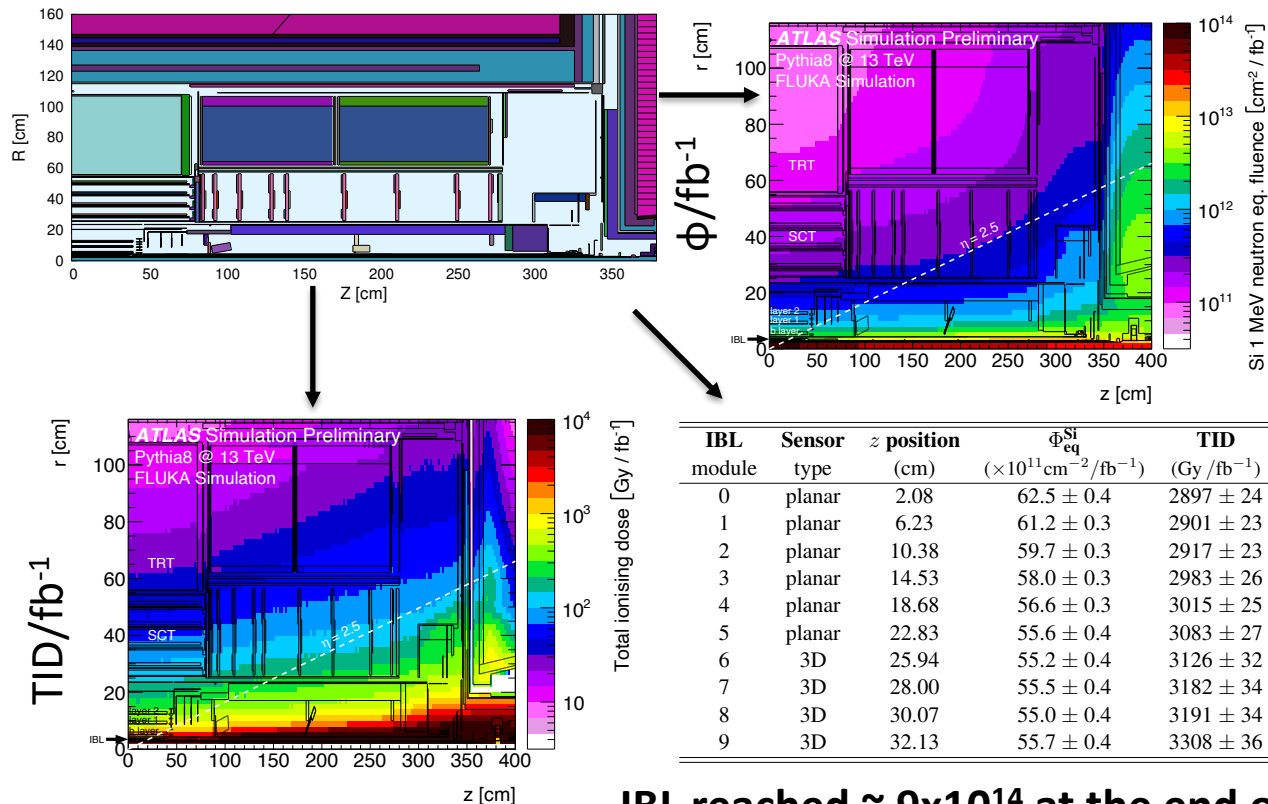
Simulating radiation environment is crucial in designing new experiments or upgrading them

- Especially when a completely new $\sqrt{s}$ domain is explored!



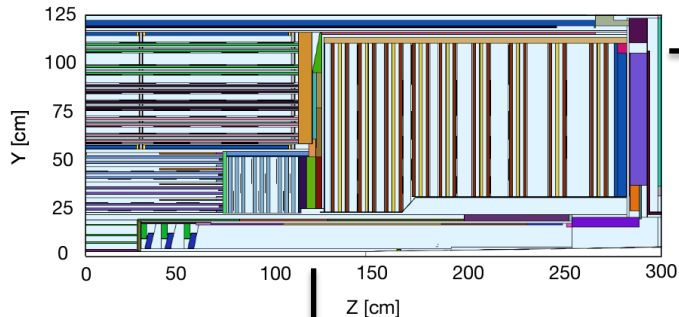
Inner detector region & part of the surrounding calorimeter (magenta)

Important for albedo neutrons!

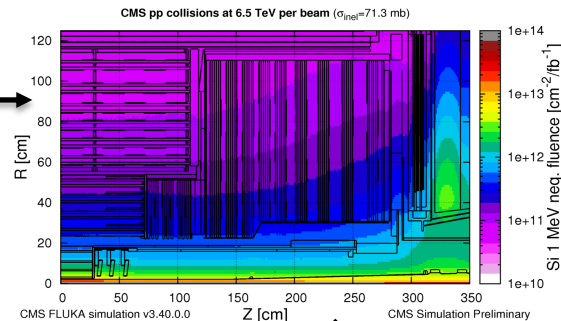
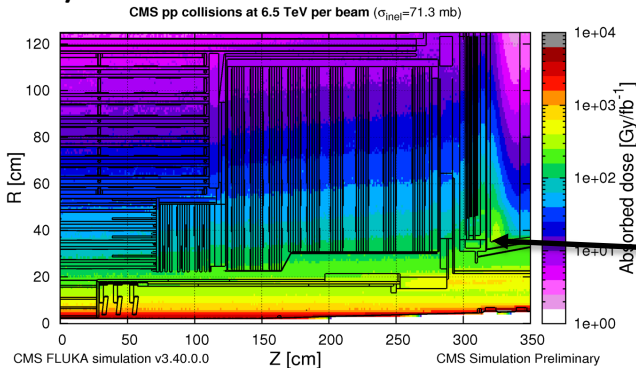


IBL reached $\sim 9 \times 10^{14}$ at the end of Run2, now is at $\sim 2.5 \times 10^{15}$

Inner detector region in FLUKA geometry (sim. includes all detector, services, cavern walls, infrastructure...)



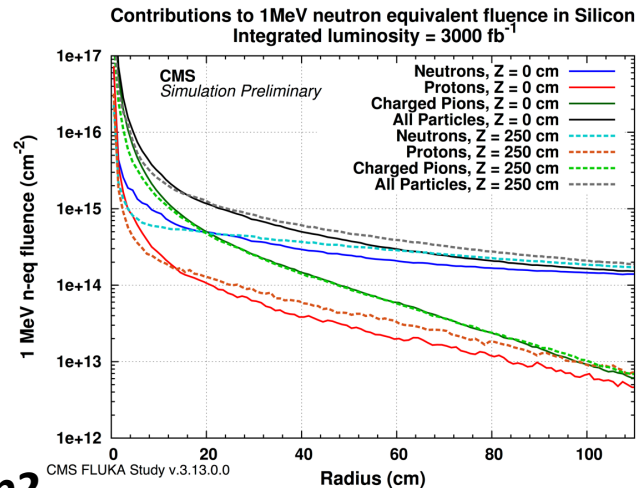
TID/fb⁻¹



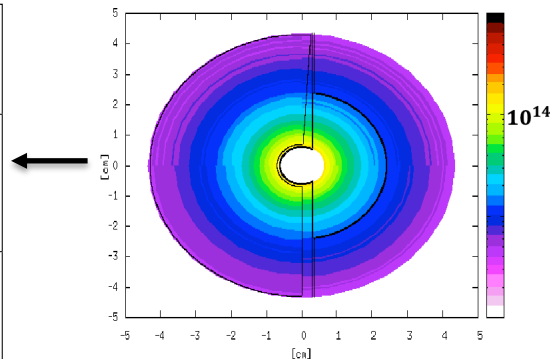
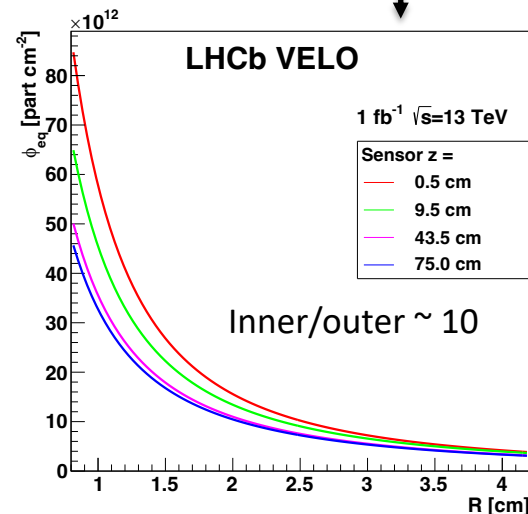
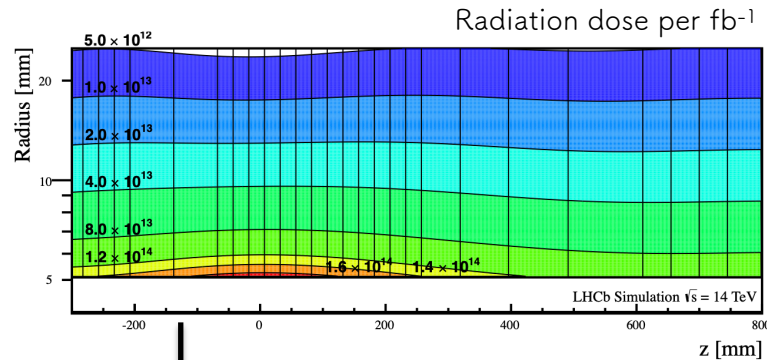
Radiation damage fields in tracker volume influenced by many factors like magnetic field, scattering on tracker material, vacuum chambers, backscattering from heavier detector elements

Close to IP: π 's dominate

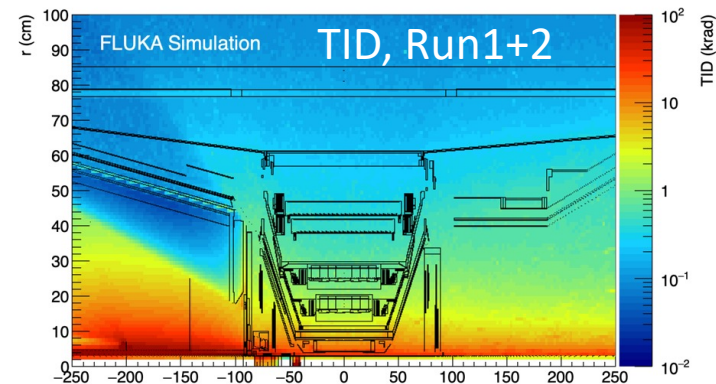
Larger radii: n's are dominant



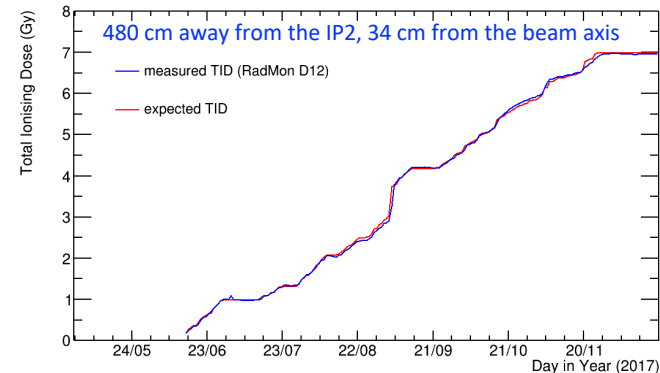
L1 reached $\sim 8 \times 10^{14}$ at the end of Run2

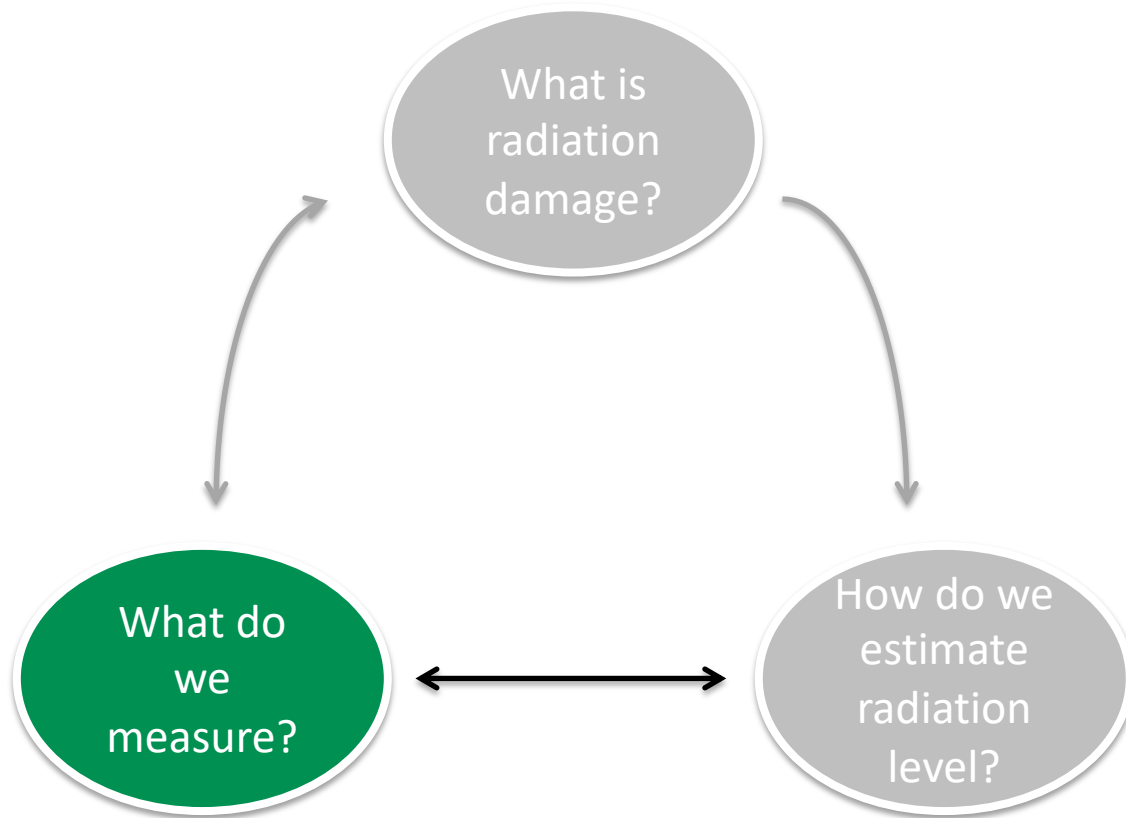


In Run3: most irradiated sensors already at 2.1×10^{15} cm⁻²



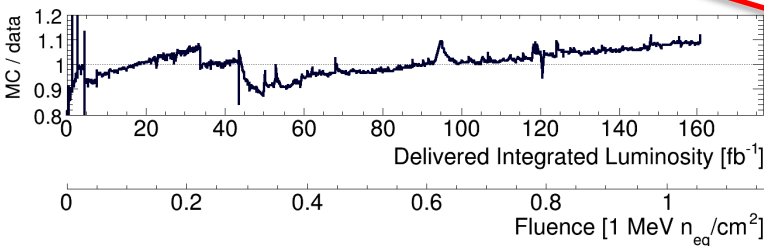
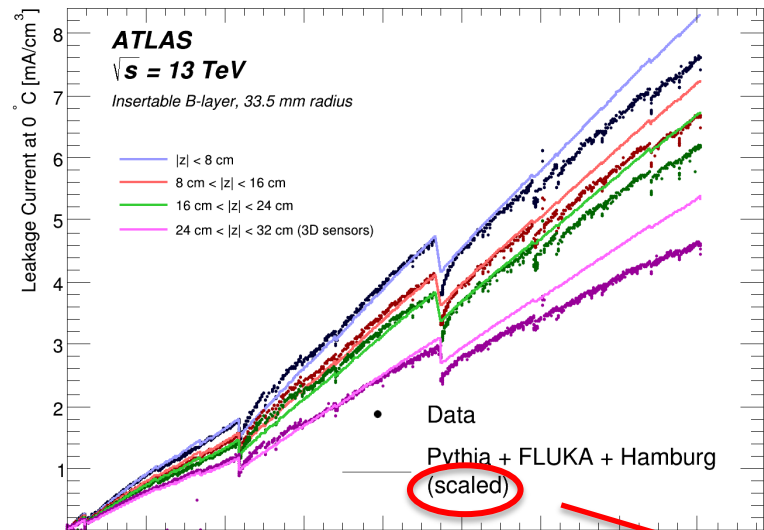
ITS subdetector	Radius	Maximum TID	Maximum hadron fluence Φ_{eq}
SPD	3.9 cm	19.3 krad	$3.2 \times 10^{11}/\text{cm}^2$
SDD	15 cm	1.65 krad	$4.0 \times 10^{10}/\text{cm}^2$
SSD	38 cm	0.37 krad	$1.8 \times 10^{10}/\text{cm}^2$





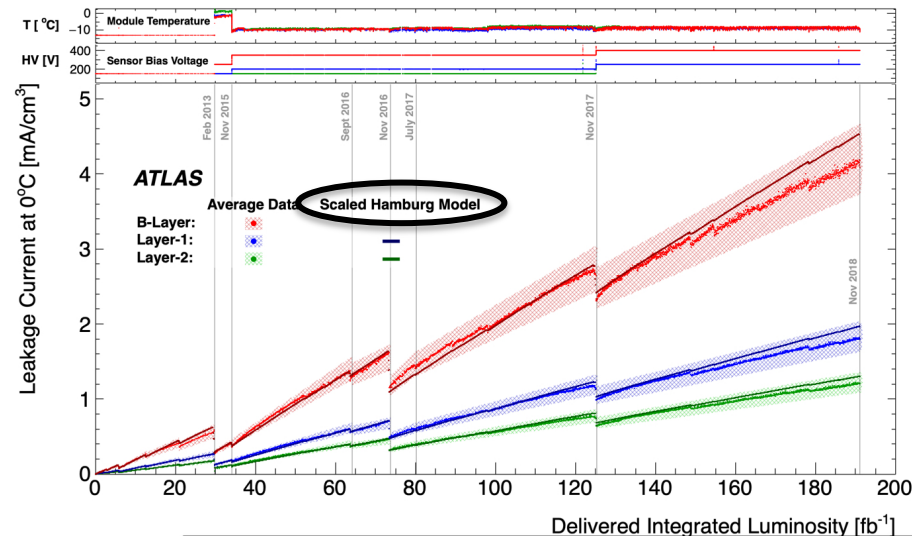
Leakage current – ATLAS Pixels

JINST 16 P08025



IBL scale factors

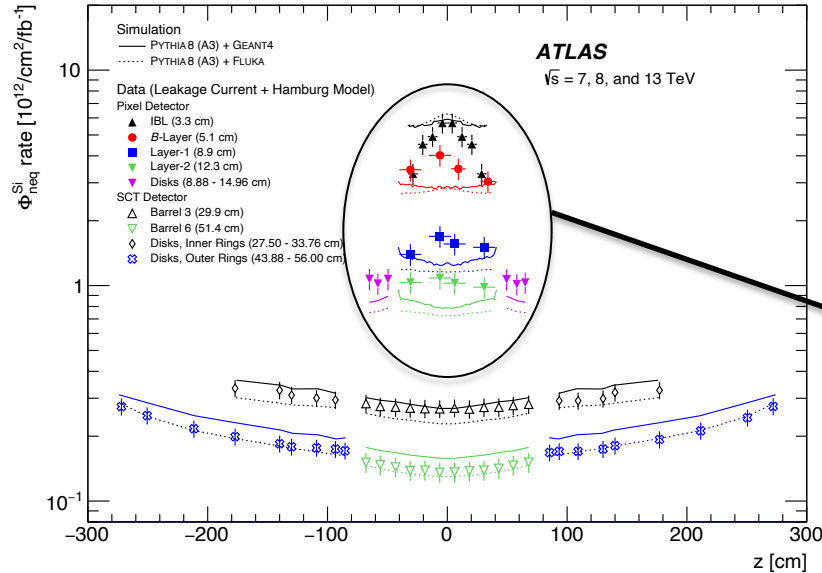
z Bin	Mean SF
$32 \text{ cm} > z > 24 \text{ cm}$	0.56 ± 0.06
$24 \text{ cm} > z > 16 \text{ cm}$	0.77 ± 0.08
$16 \text{ cm} > z > 8 \text{ cm}$	0.84 ± 0.09
$8 \text{ cm} > z > 0 \text{ cm}$	0.97 ± 0.10



Detector	Layer	r [cm]	Mean SF	Min. SF	Max. SF	SF uncert.
Pixel	B-Layer	5.10	1.28	1.11	1.47	0.15
	Layer-1	8.90	1.31	1.19	1.44	0.15
	Layer-2	12.30	1.39	1.32	1.46	0.16

Pixel scale factors

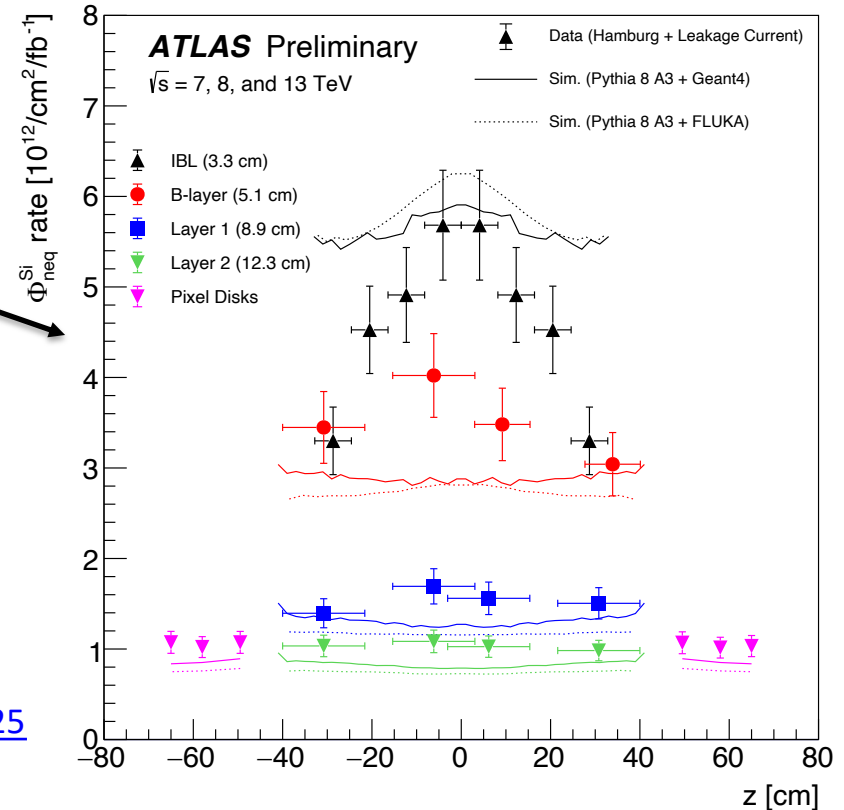
Fluence rates from leakage current - ATLAS



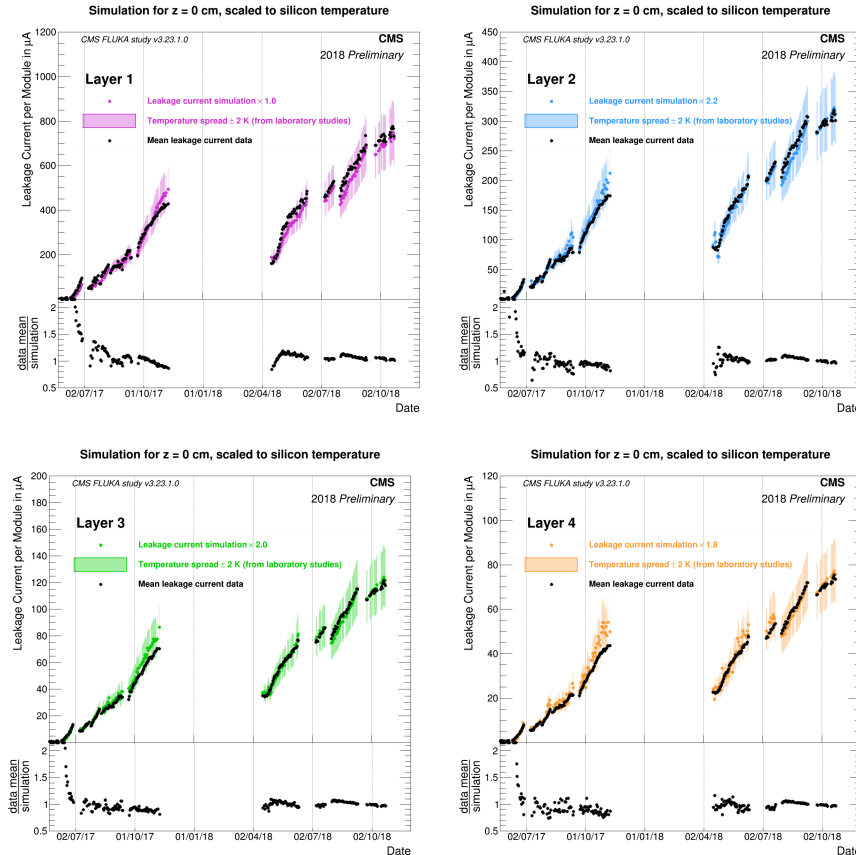
Unexpected fluence
 profile for IBL

Still an open question

[JINST 16 P08025](#)



Leakage current – CMS Pixels



Measurements for the detector inserted in 2016/17 ($\sim 118 \text{ fb}^{-1}$)

HV channels are grouped in z

Scale factors applied on the entire layer

L#	r [cm]	SF	Φ [$10^{14} n_{\text{eq}}/\text{cm}^2$]
1	2.9	1.0	7.9
2	6.8	2.2	1.8
3	10.9	2.0	0.9
4	16.0	1.8	0.5

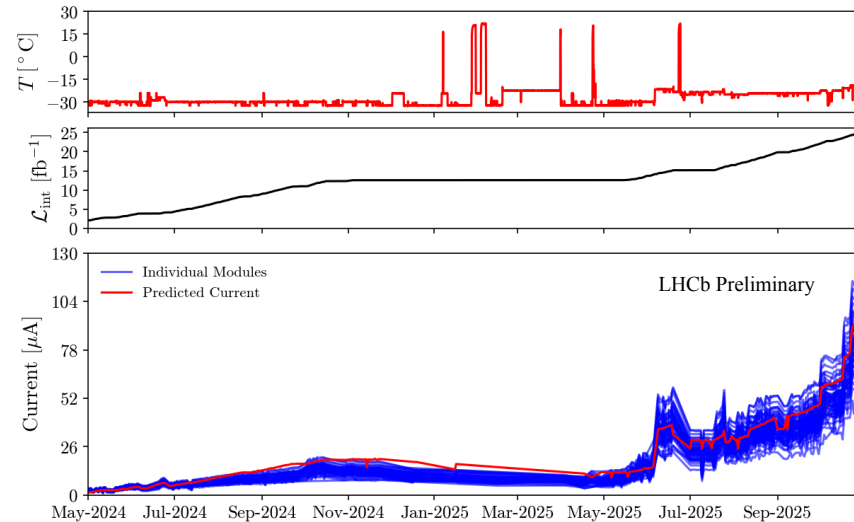
Leakage current – LHCb Velopix

Radiation damage studies

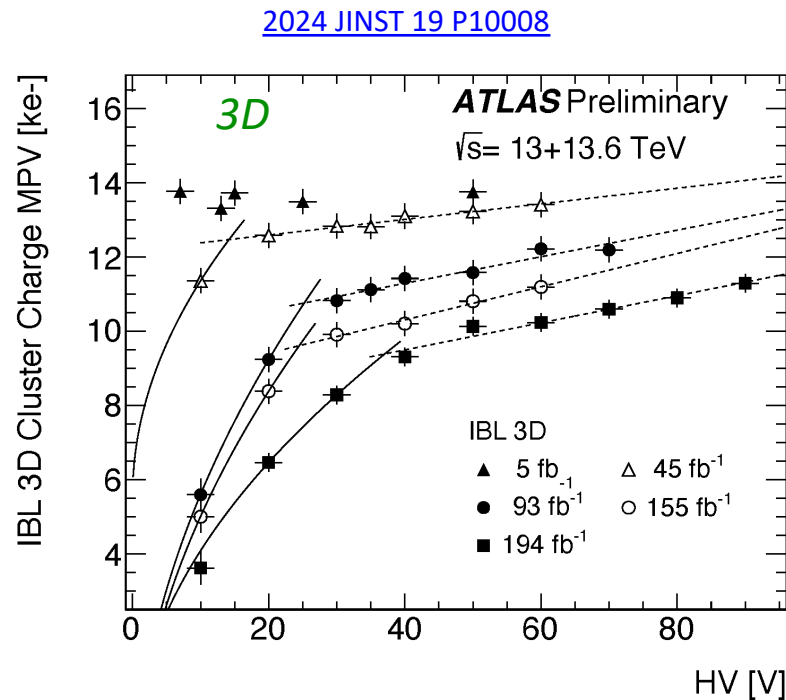
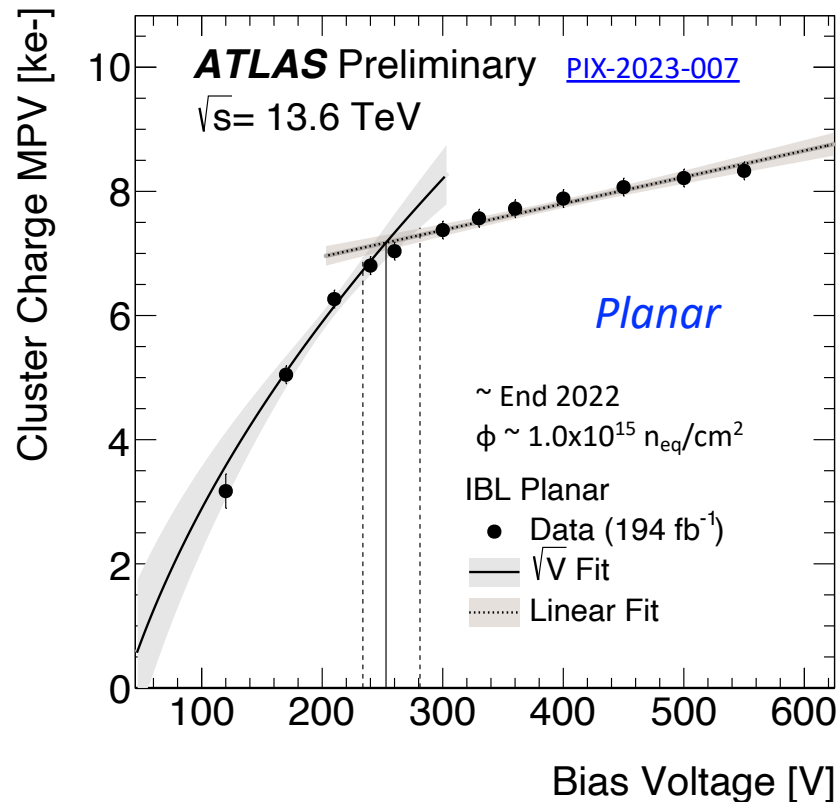
V. Zhovkovska, Tipp 2026

Estimation of Leakage Current

- Several GBTx show instabilities at -36°C => warming up (now to -23°C) helps
 - Possible increase of degradation from irradiation (depletion voltage)
- Feasibility studies of detector operation at higher temperature until the end of Run 4
 - Estimated leakage current, corrected for the sensor temperature
 - Compared to the actual value
 - **Impact from warm up is visible**

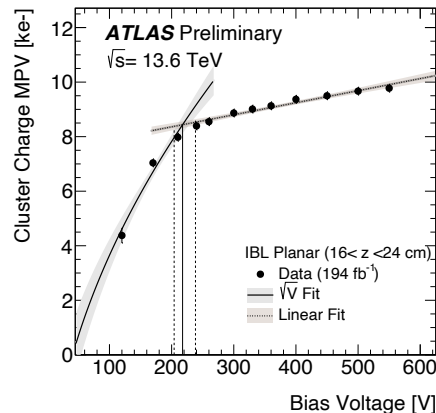
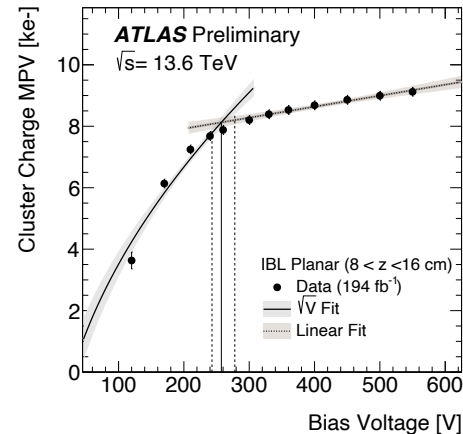
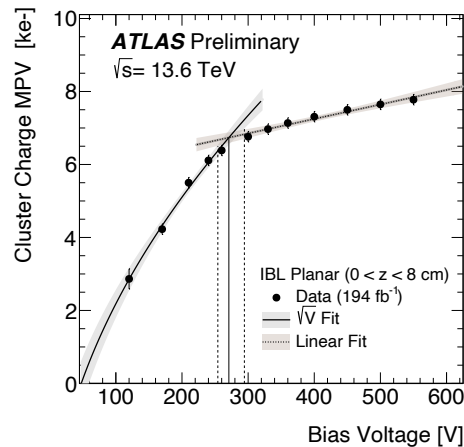
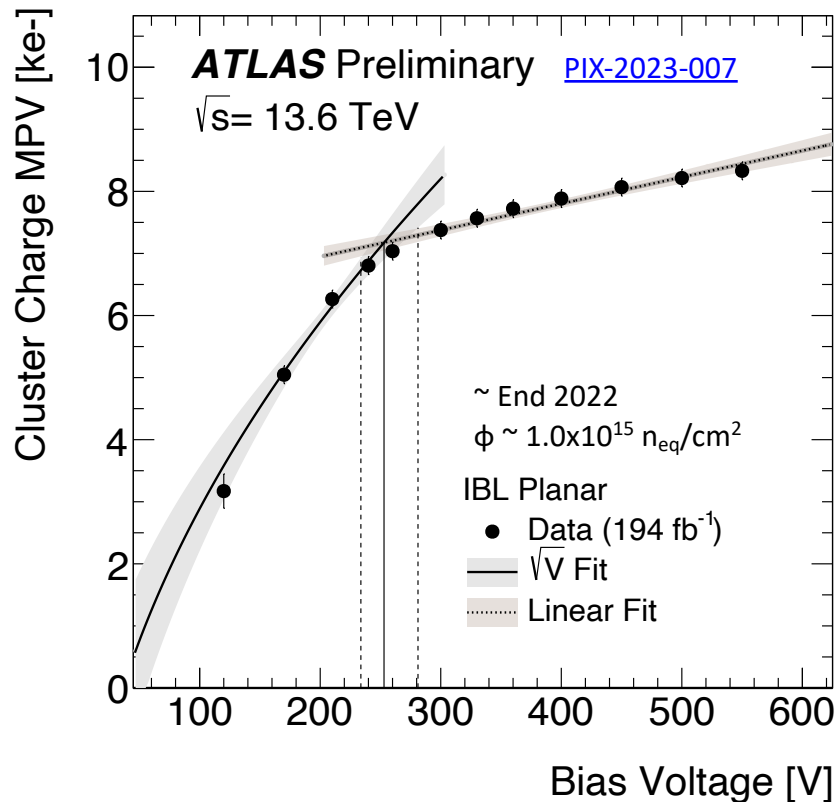


Depletion voltage – ATLAS IBL



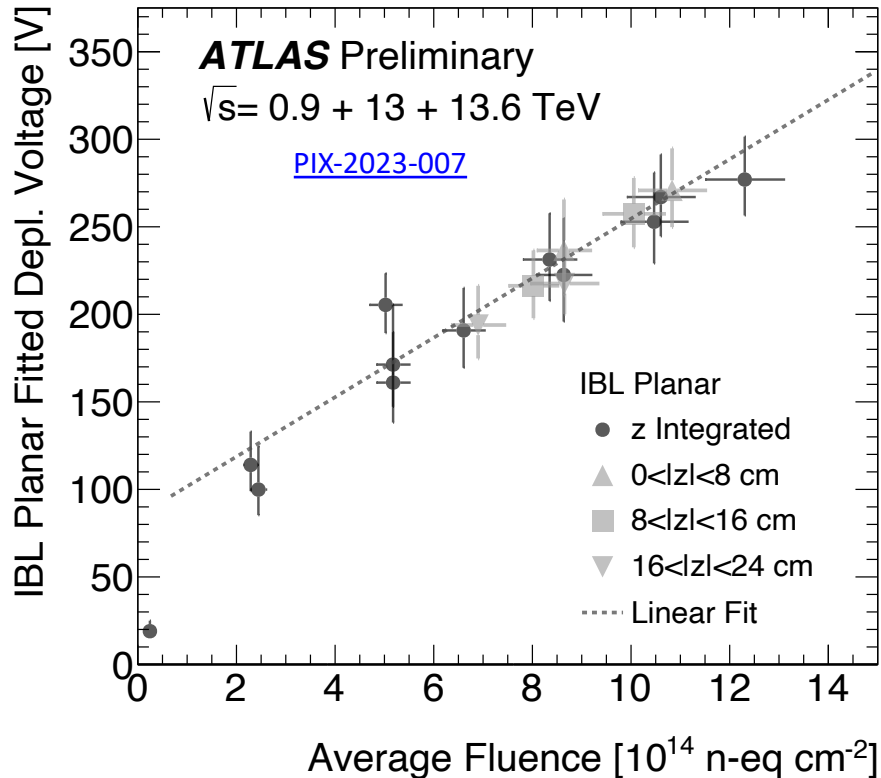
Depletion voltage inferred from
cluster charge vs bias voltage

Depletion voltage – ATLAS IBL



Repeat the analysis
per z-region

Depletion voltage – ATLAS IBL



IBL modules spent most of their time cold

No annealing effects are measurable

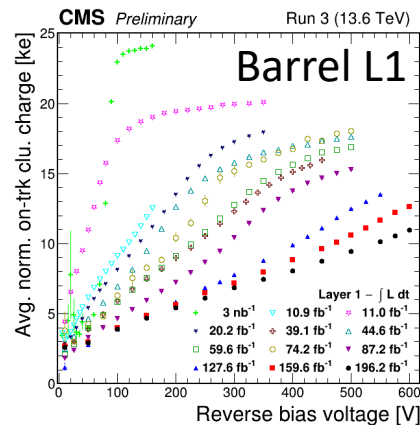
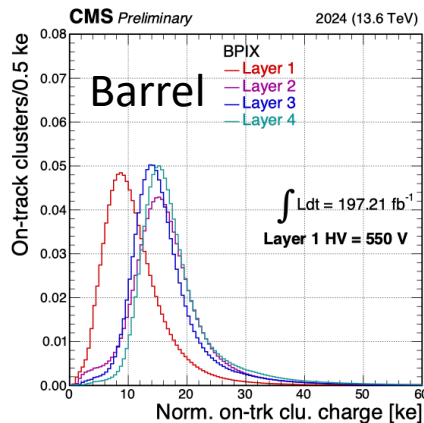
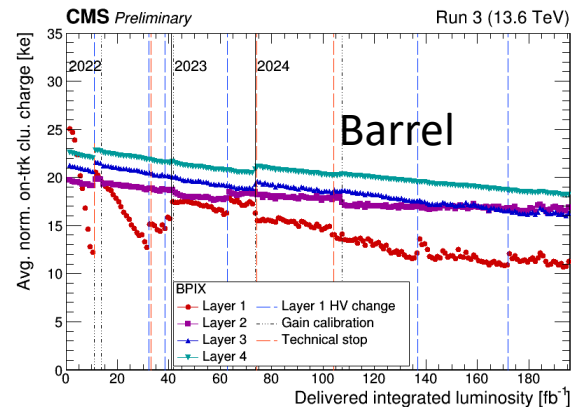
Linear fit does great job 😊

Note that also differential measurements line up well

We can extrapolate V_{depl} to end of Run3

Q vs V – CMS Pixels

M. Wulansatiti, Vertex 2025



Current settings:

Layer 1: 600 V

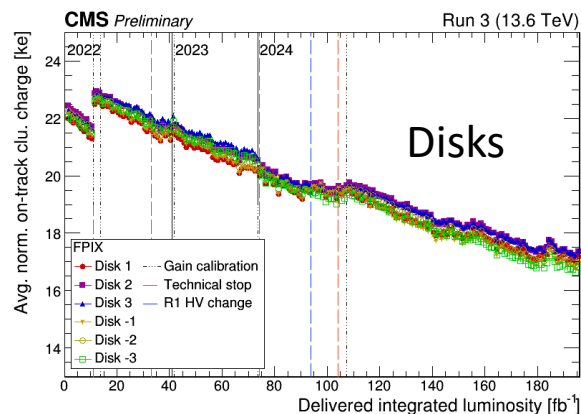
Layer 2: 450 V

Layer 3: 350 V

Layer 4: 300 V

Ring 1: 450 V

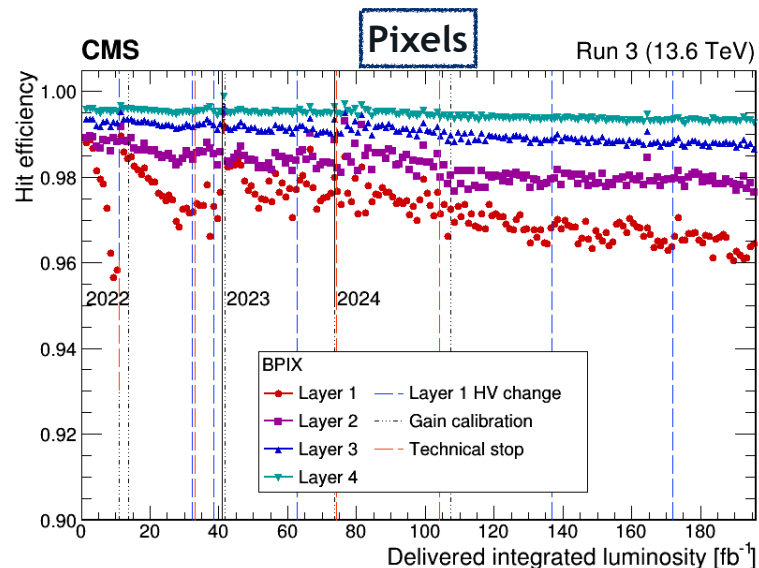
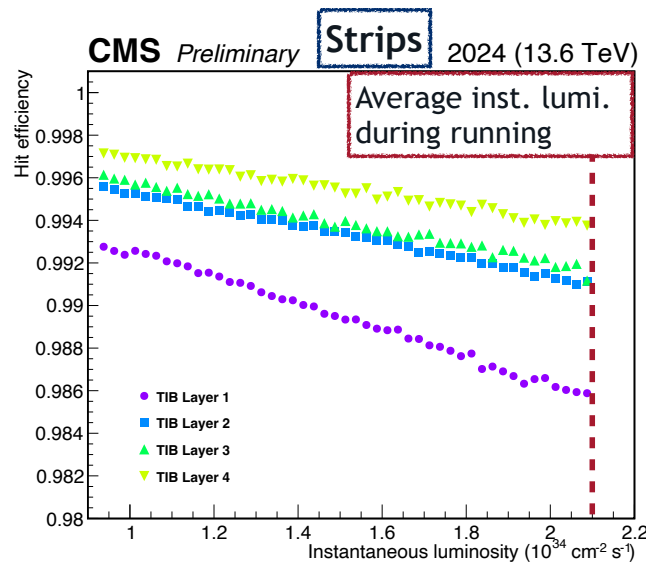
Ring 2: 350 V



- Layer 1 currently collecting 50% of the charge compared to unirradiated sensors
- Charge collection in FPix is also degrading, but more slowly
- Improvements come from beneficial annealing, increase of HV bias, updated gain calibrations
- HV bias scan performed regularly to monitor performance
→ **Layer 1 evolves rapidly**

Hit efficiency – CMS Pixels & Strips

M. Wulansatiti,
Vertex 2025



- High hit efficiency >98% for strips, scales linearly with instantaneous luminosity
- Pixels hit efficiency degrades with integrated luminosity, recovered by annealing, gain calibrations, and HV bias increase

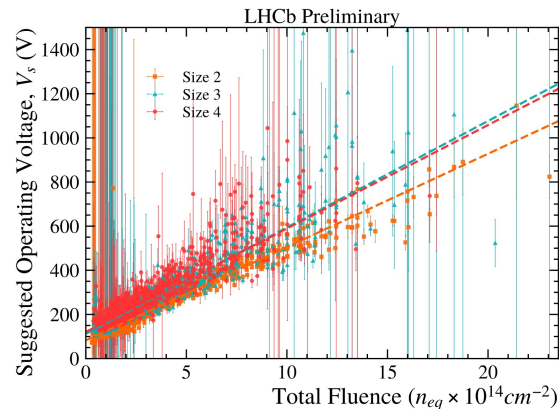
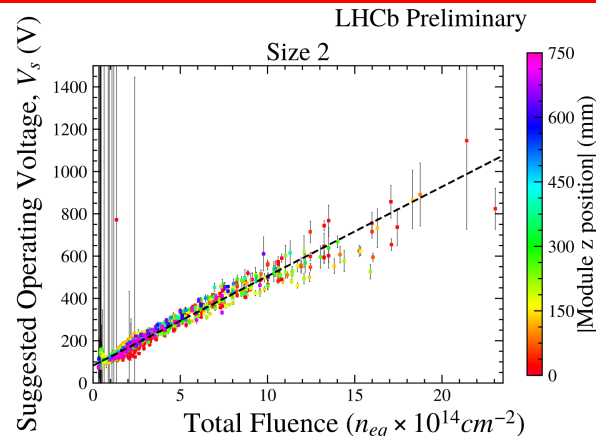
Operation voltage – LHCb Velopix

Cluster size studies

Operation Voltage

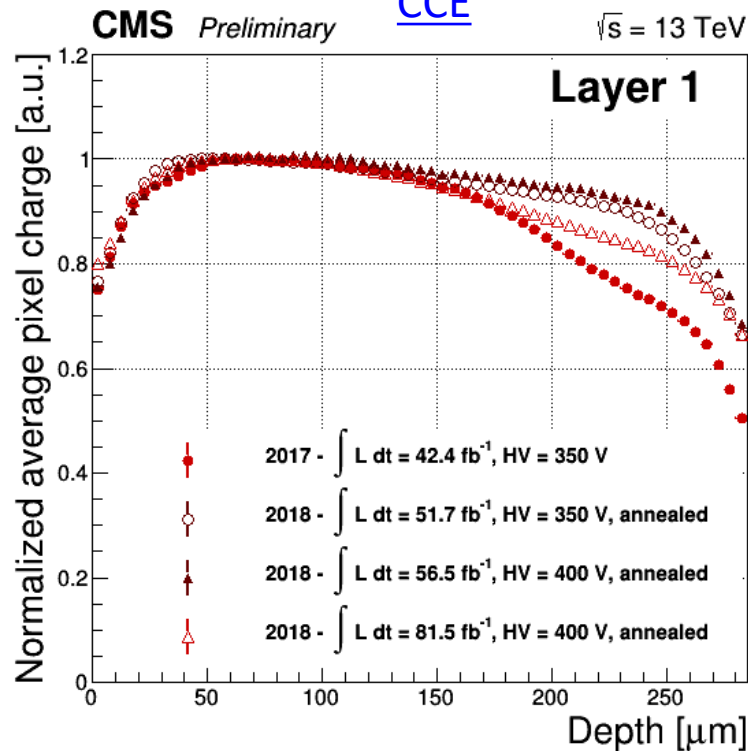
- Suggested operating voltage, V_s , extracted for every module vs radius looking at size 2, 3 and 4 clusters vs HV
- Values are extrapolated to $8 \times 10^{15} \text{ MeV } n_{eq}/\text{cm}^2$ (maximum expected fluence)
- Annealing is not included yet
- Strategy allows to predict operating voltage below threshold
 - For the end of 2025 it is 1270V for the most irradiated areas
 - Actual operating voltage was 400V: small impact on tracking

[V. Zhovkovska, Tipp 2026](#)

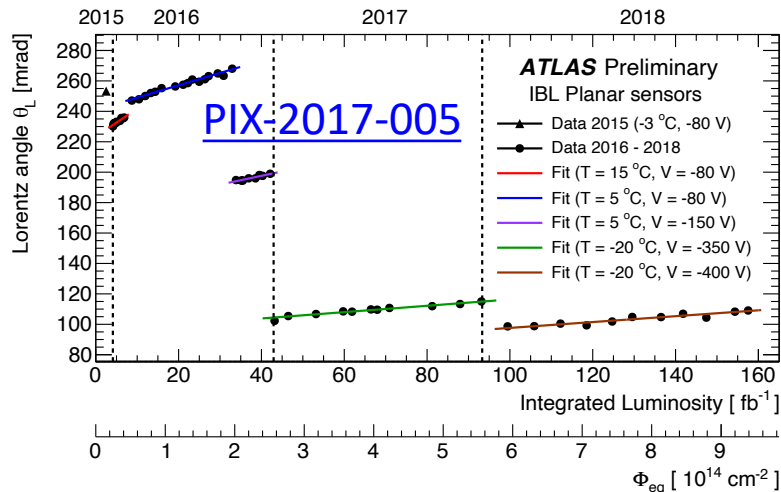


CCE, Lorentz Angle & Space point resolution

CCE

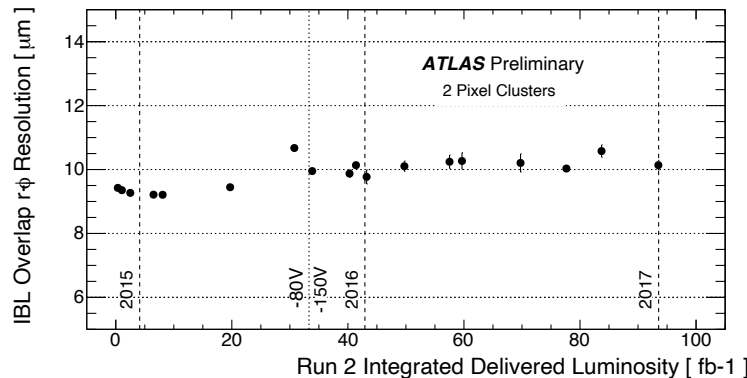


Effect of annealing clearly visible



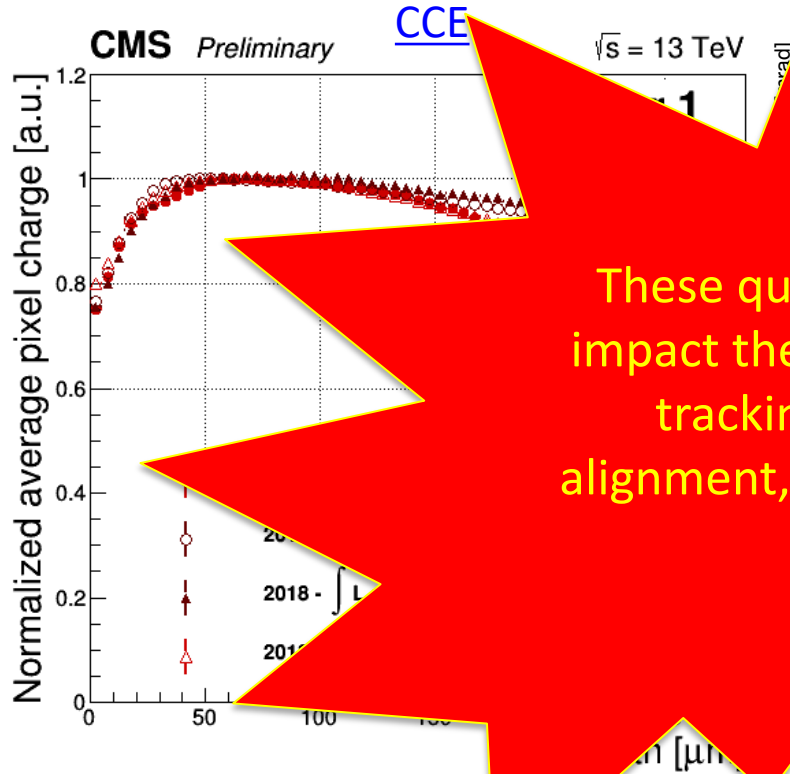
L.A.:

- increasing with fluence due to low electric field regions
- decreasing for larger bias voltage



Degradation due to less clusters with two pixel

CCE, Lorentz Angle & Space Point resolution



These quantities directly impact the performance of tracking, vertexing, alignment, flavour-tagging...

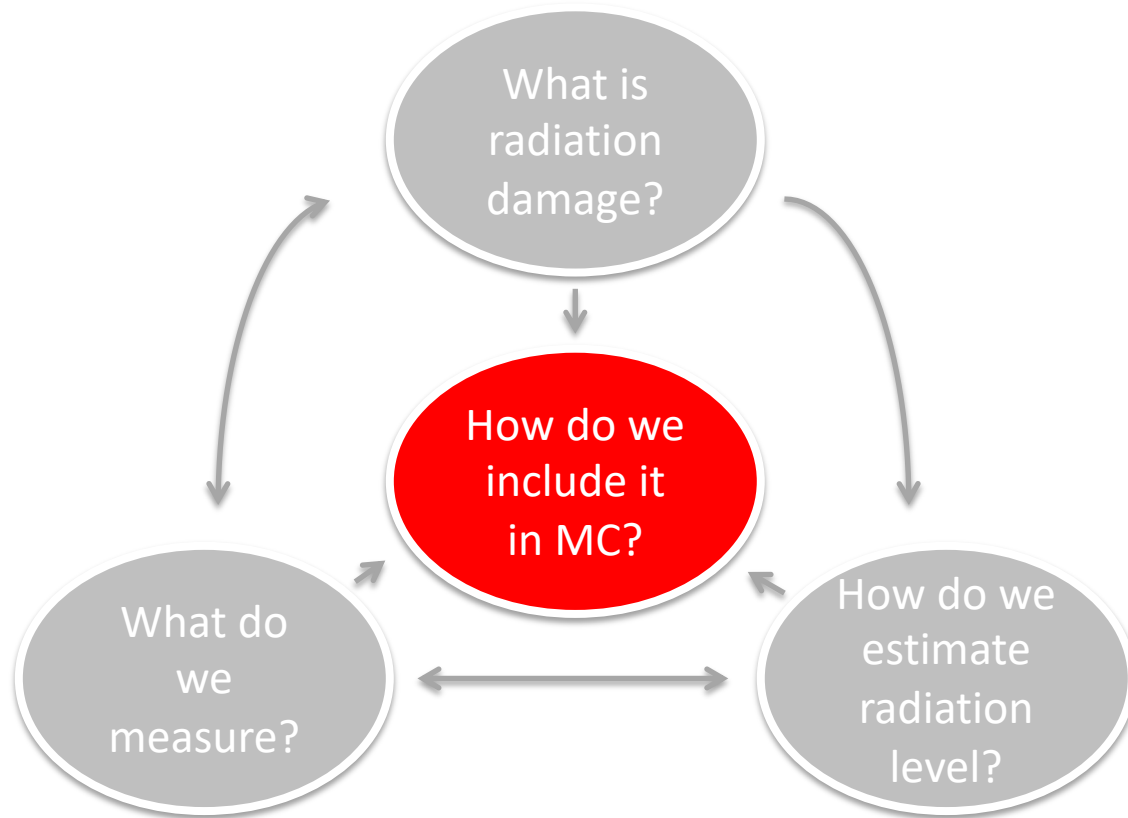
Effect of annealing clear visible



L.A.:

- increasing with fluence due to low electric field regions
- decreasing for larger bias voltage

Degradation due to less clusters with two pixel



Goals

Accurate MonteCarlo simulations should be able to

- Reproduce detector response evolution with accumulated luminosity
- Predict future detector conditions
- Improve reconstruction algorithms
- Be the training set for Machine-Learning tools

Strategies across experiments – Run3

			
Energy Deposition	Bichsel Model + G4 (δ -rays)	Pixelav (applied as correction to G4)	Geant4
Energy spreading	from Bichsel + chunking	from Bichsel + chunking	Uniform (space) + uniform/Gauss (E)
E-field/ Lorentz angle	TCAD (<u>Chiochia et al.</u>)	TCAD (tuned to data)	N/A
Diffusion	Einstein	Einstein	tuned
Noise	capacitive coupling + noise	readout noise	capacitive coupling + noise
Radiation damage	trapping + charge induction	trapping + charge induction	charge & 'diffusion' corrections

[B. Nachman](#)

Hard-scatter

*MadGraph 5 / aMC@NLO
POWHEG-BOX*



Fragmentation

Pythia, Herwig, Sherpa



Material Interactions

Geant 4



Digitization

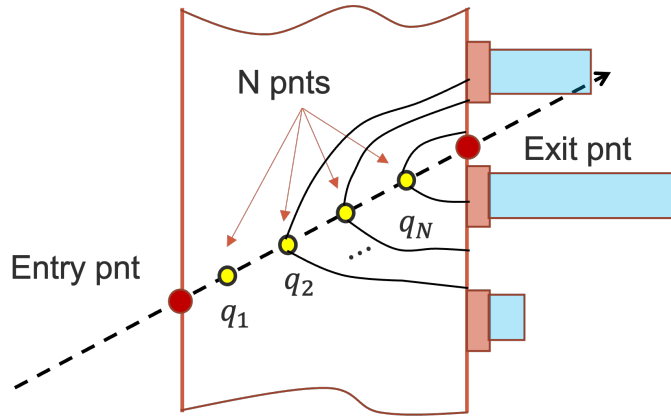
*Inspired by
Sherpa 1.1 paper*
Custom code

[B. Nachman](#)

*this is where rad.
damage goes.*

LHCb strategy for VELO

From Geant4 entry and exit point are evaluated



Total energy is divided in several points along the track

Charges are projected to surface

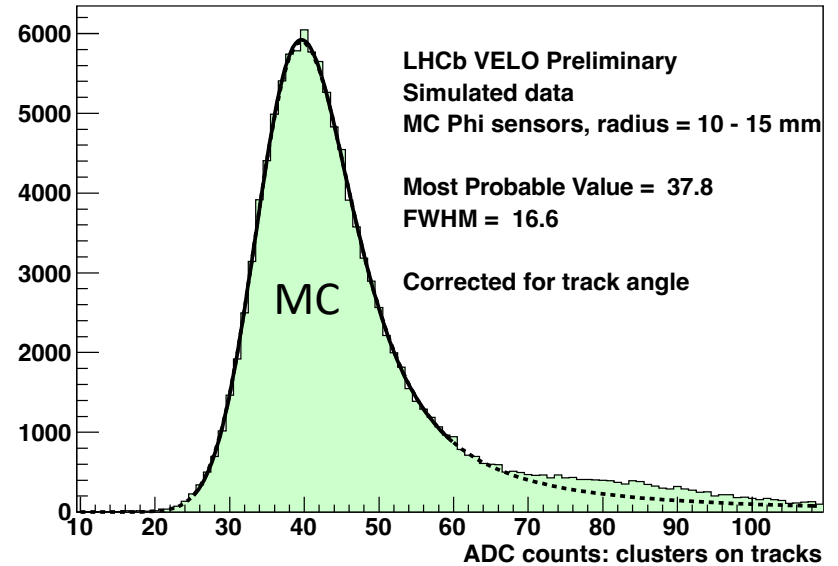
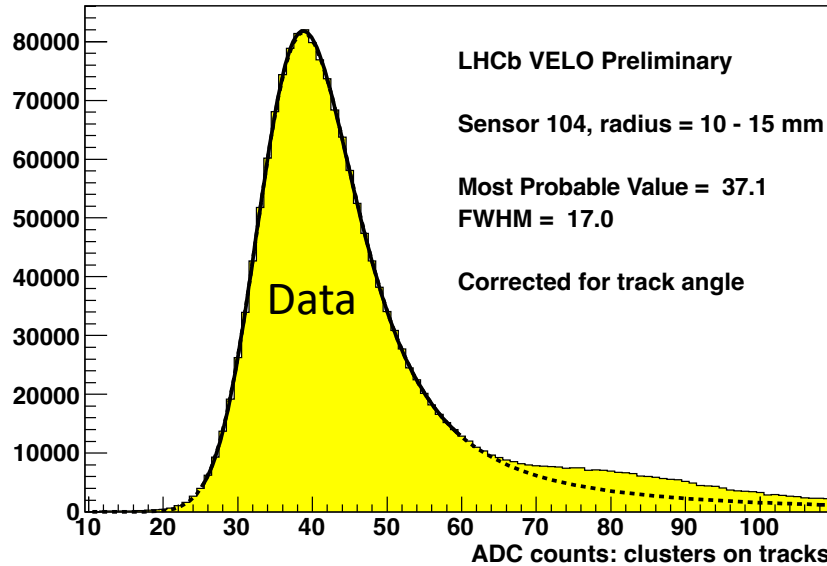
At this point radiation damage effects can be added

Using testbeam data:

- reduce collected charge
- increase diffusion length

to match observed distributions in tb data

LHCb results



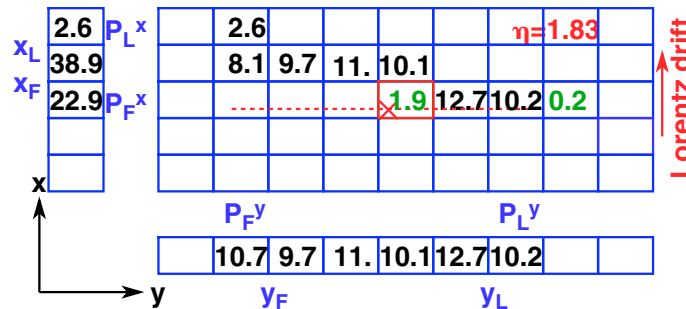
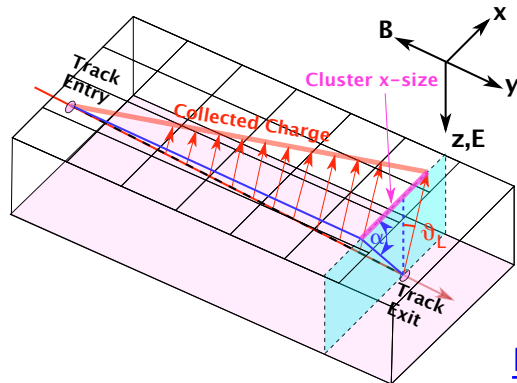
Excellent agreement between data and simulations

CMS strategy for pixel detector

MonteCarlo events are generated assuming pristine detector

Clusters shapes and charge are then corrected using **templates**

Templates are generated using a standalone tool called **Pixelav***



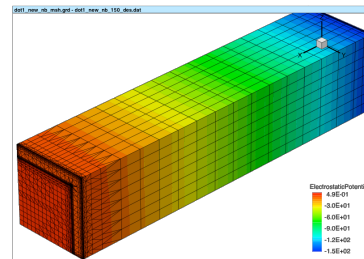
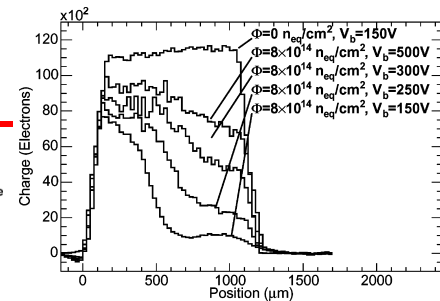
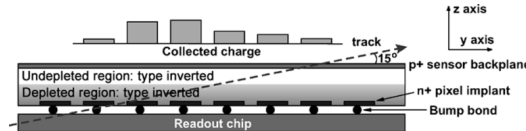
[M. Swartz et al. \(2007\)](#)

* used also in reco – not in today's talk

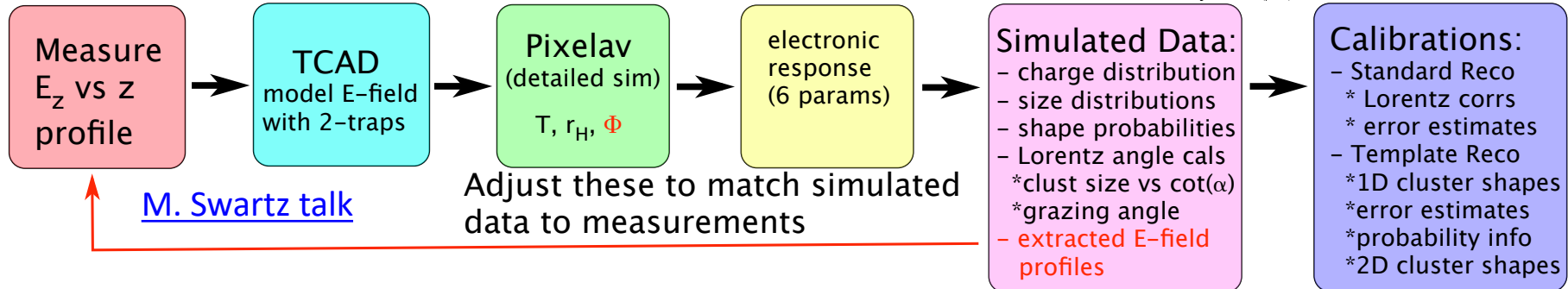
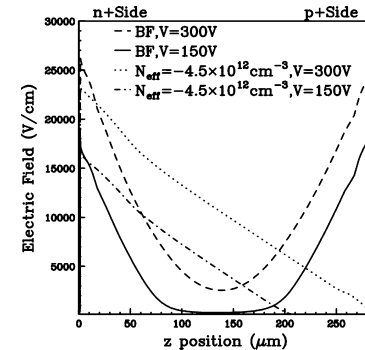
CMS Pixelav

SW created to interpret testbeam data from irradiated detectors, now used to compute **templates**

Based on **TCAD simulations** and **numerical simulations** for charge propagation and trapping

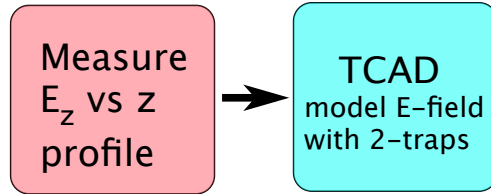


potential distribution



Intermezzo – TCAD simulations

M. Swartz talk

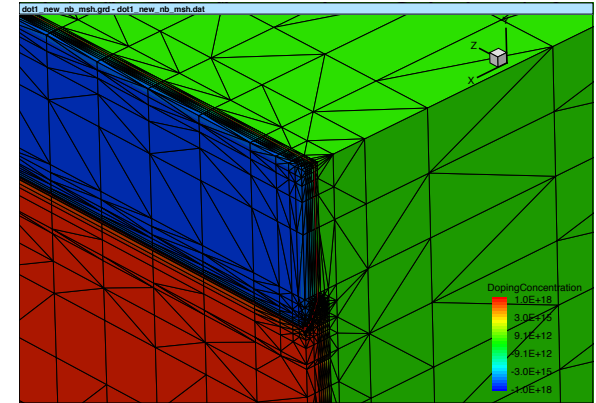


TCAD simulations: solve carriers continuity & Poisson equation on a mesh of points, taking into account several physics models (SRH, impact ionization, mobility, etc.)

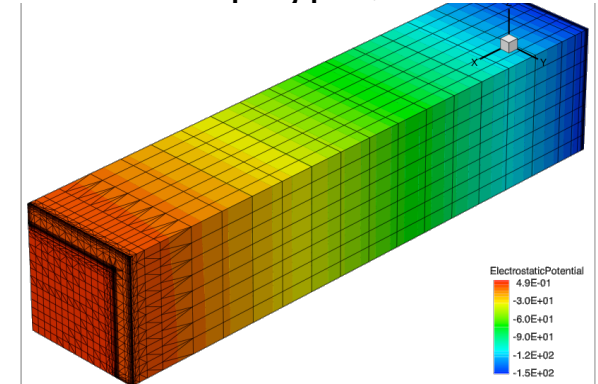
Possible to include (effective) deep defects

Input: geometry, doping profiles and conditions

Output: leakage current, carrier distribution, electric field, carrier distribution, ...

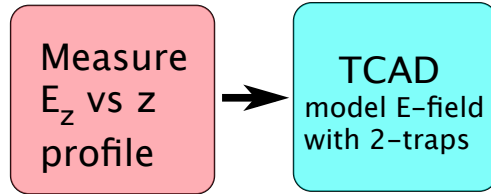


doping profiles



potential distribution

Intermezzo – TCAD radiation damage models

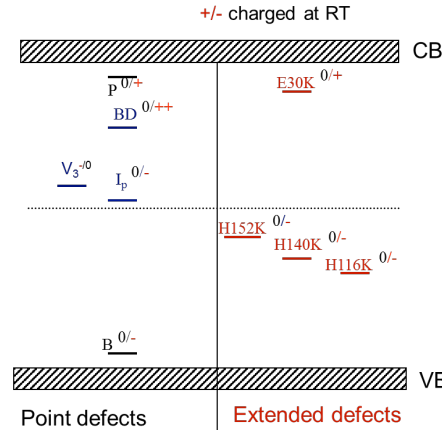


- Numerically impossible to simulate all measured defects
 - Plus: their properties are not all well known
 - Plus: there might be more defects to be identified

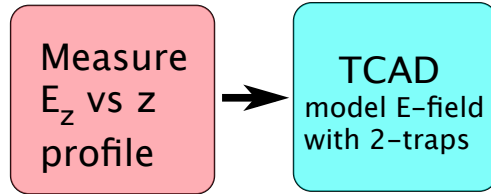
I. Pintilie (VERTEX 2016)

Measured defects

Point defects	
■ $E_a^{BD} = E_c - 0.225 \text{ eV}$	
■ $\sigma_n^{BD} = 2.3 \cdot 10^{-14} \text{ cm}^2$	
■ $E_a^{V3} = E_c - 0.545 \text{ eV}$	
□ $\sigma_n^{V3} = 1.7 \cdot 10^{-15} \text{ cm}^2$	
□ $\sigma_p^{V3} = 9 \cdot 10^{-14} \text{ cm}^2$	
■ $E_a^{Ip} = E_c - 0.545 \text{ eV}$	
□ $\sigma_n^{Ip} = 1.7 \cdot 10^{-15} \text{ cm}^2$	
□ $\sigma_p^{Ip} = 9 \cdot 10^{-14} \text{ cm}^2$	
Extended defects	
➢ $E_a^{H116K} = E_v + 0.33 \text{ eV}$	
➢ $\sigma_p^{H116K} = 4 \cdot 10^{-14} \text{ cm}^2$	
➢ $E_a^{H140K} = E_v + 0.36 \text{ eV}$	
➢ $\sigma_p^{H140K} = 2.5 \cdot 10^{-15} \text{ cm}^2$	
➢ $E_a^{H152K} = E_v + 0.42 \text{ eV}$	
➢ $\sigma_p^{H152K} = 2.3 \cdot 10^{-14} \text{ cm}^2$	
➢ $E_a^{E30K} = E_c - 0.1 \text{ eV}$	
➢ $\sigma_n^{E30K} = 2.3 \cdot 10^{-14} \text{ cm}^2$	



Intermezzo – TCAD radiation damage models

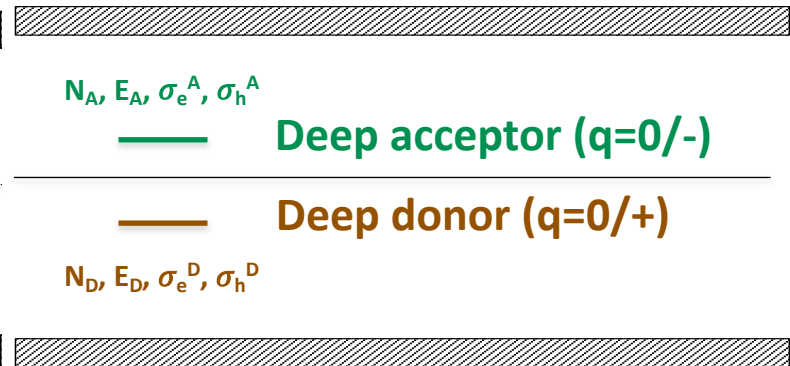
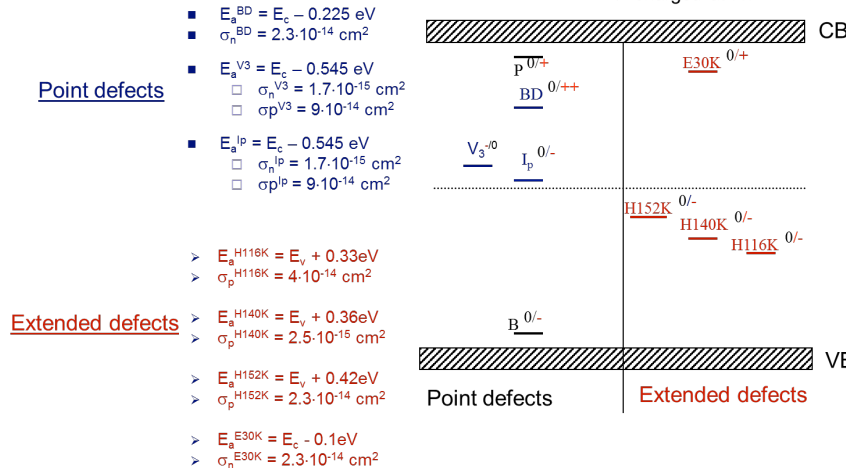


- Numerically impossible to simulate all measured defects
 - Plus: their properties are not all well known
 - Plus: there might be more defects to be identified
- **Instead use few (2-5) effective states**

I. Pintilie (VERTEX 2016)

Measured defects

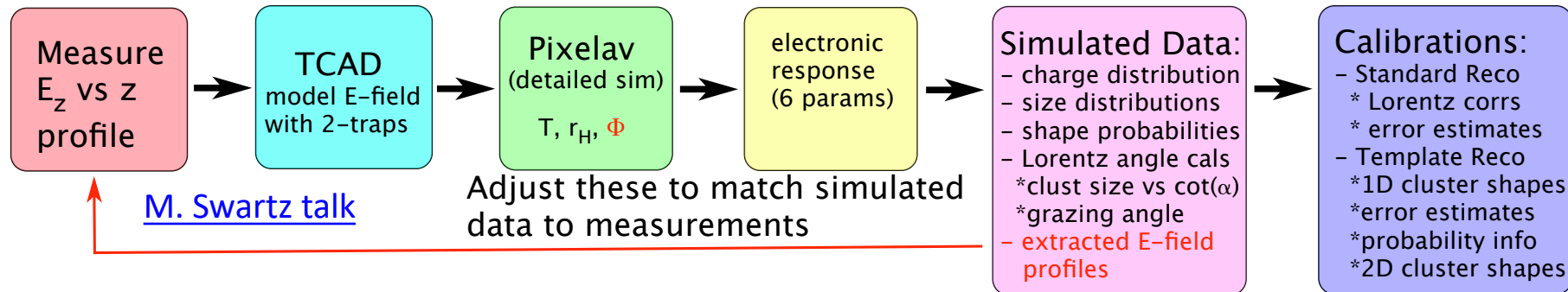
Simulated effective defects in TCAD



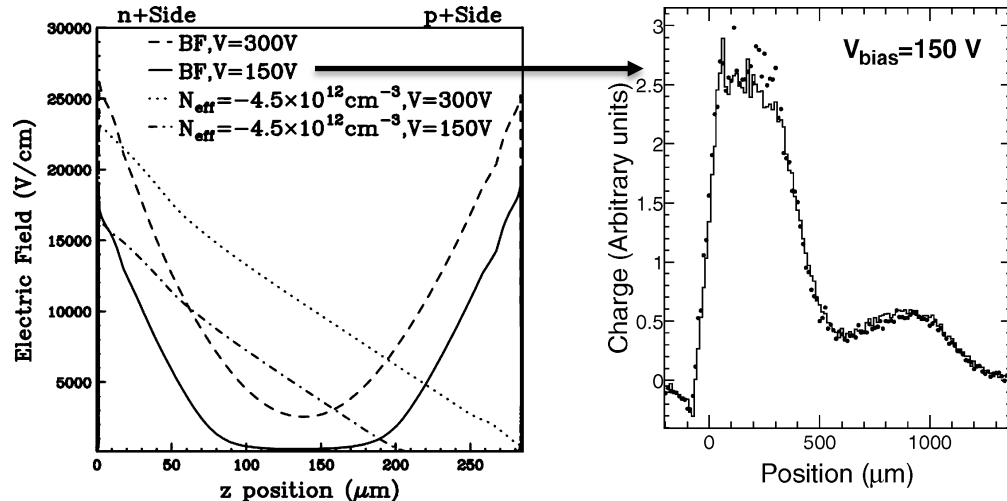
EVL (2002)

V. Chiochia et al. (2005)

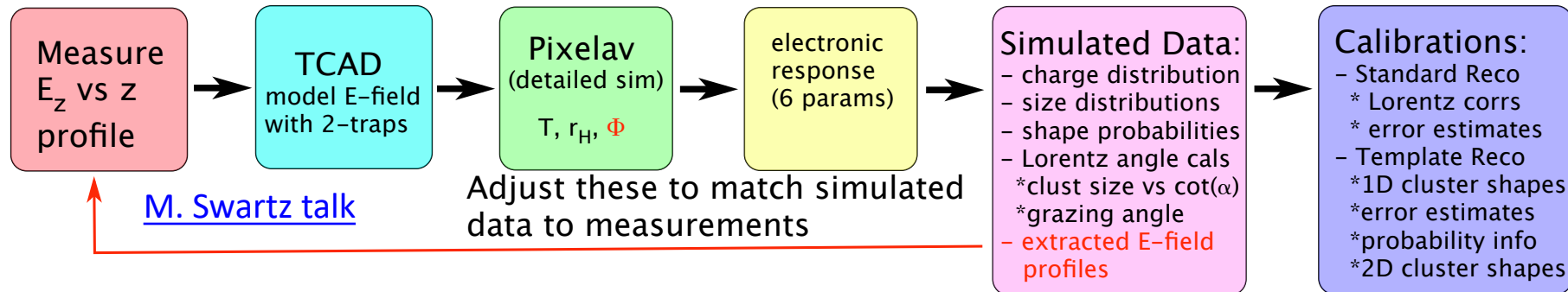
CMS Pixelav



SW tuned on testbeam data from irradiated detectors



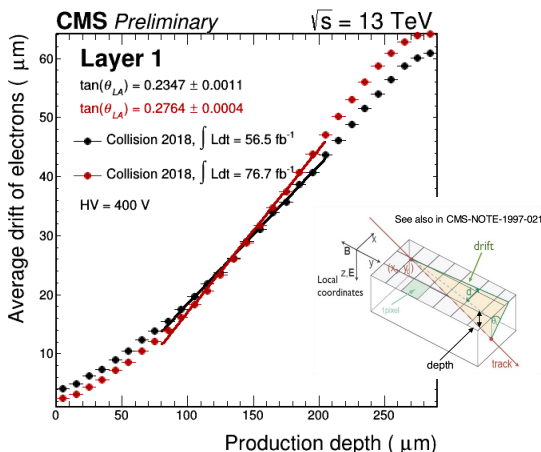
CMS Pixelav



SW tuned on **collision data too**

Templates produces ~
every 10 fb^{-1} after type inversion

Deflection and Lorentz Angle

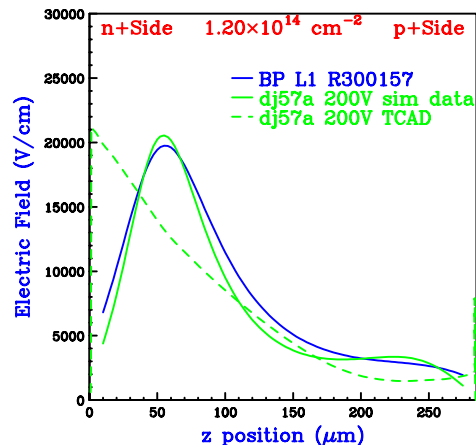
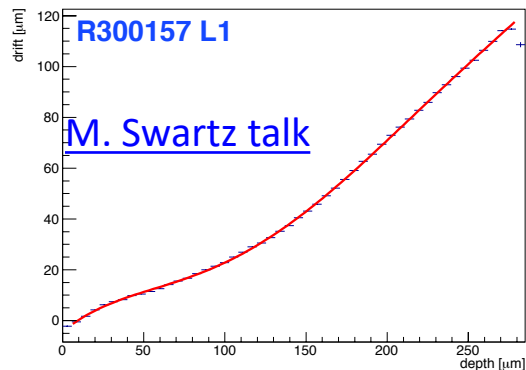


- Start from drift (x) vs Depth (D) data:
- Fit to a polynomial and calculate a local slope [Lorentz Angle] vs D.
- Then convert it to E vs D.

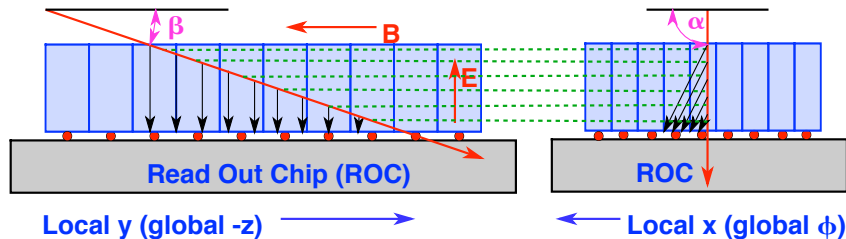
$$\tan \theta_L = \frac{dx}{dD} = r_H \mu(E) B_y$$

$$\rightarrow E = \mu^{-1} \left(\frac{1}{r_H B_y} \frac{dx}{dD} \right)$$

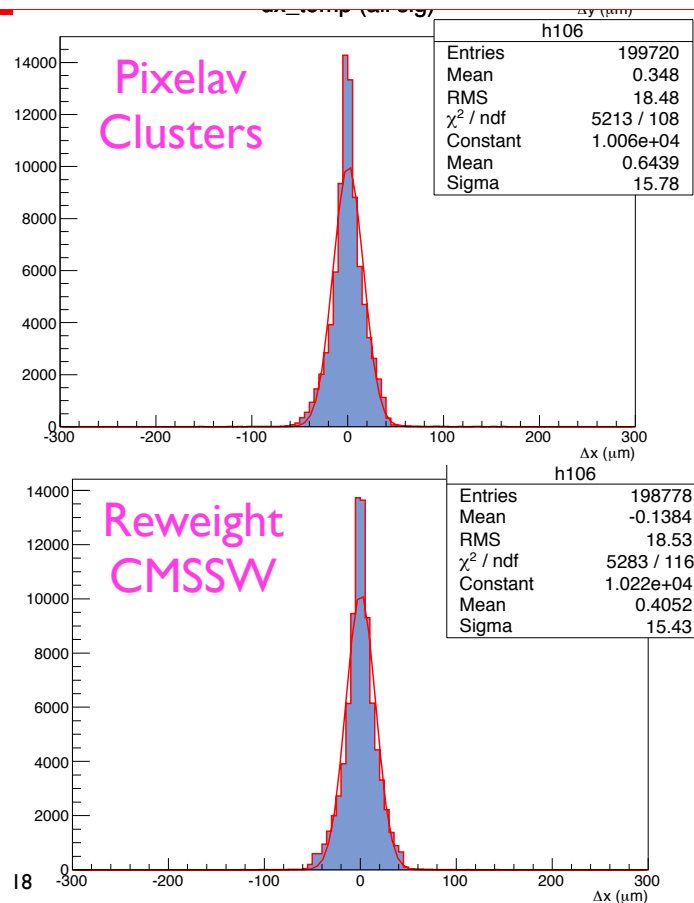
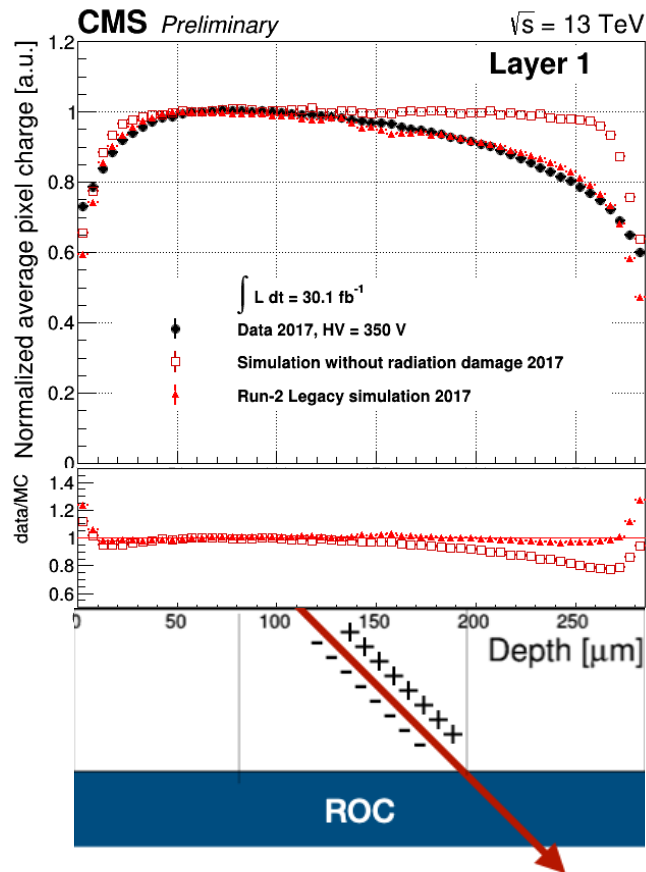
The extracted electric field profile is distorted by focusing near the n+ implant and other systematic effects. The good news is that we can simulate them [mostly]:



Using long clusters and the lateral drift they can reconstruct with great precision the electric field profile



CMS results

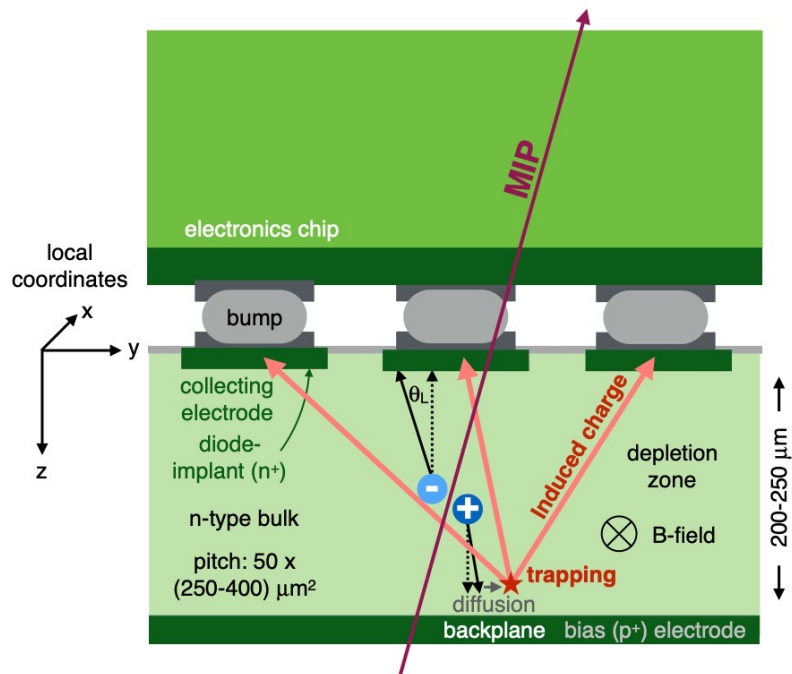


$$\Phi = 1.2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$$

Full simulated
vs
Reweighted
clusters

ATLAS strategy

[JINST 14 P06012, 2019](#)



All this included in ATLAS MonteCarlo digitization* for Run3

Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage**

Their path will be deflected by magnetic field (**Lorentz angle**) and **diffusion**

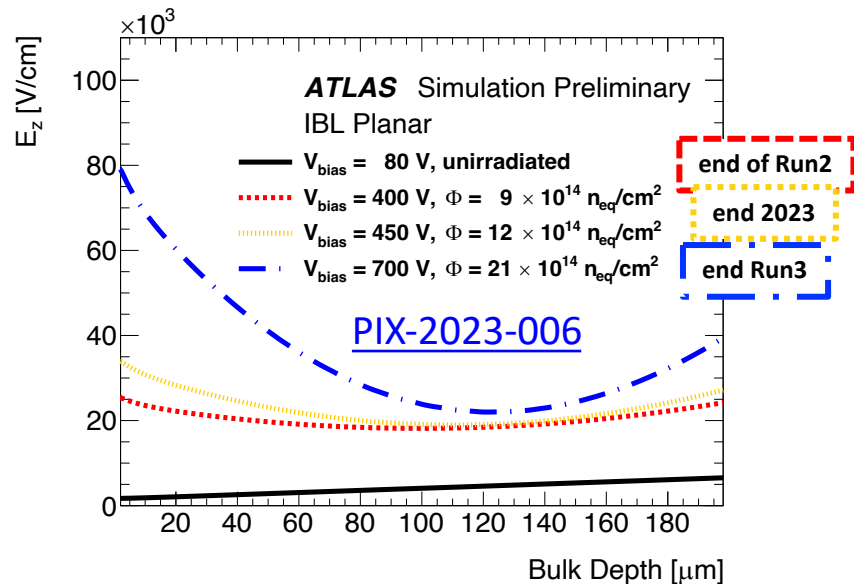
Due to **radiation damage** they can be **trapped** and induce/screen a fraction of their charge (**Ramo potential**)

Total induced charge is then digitized and clustered

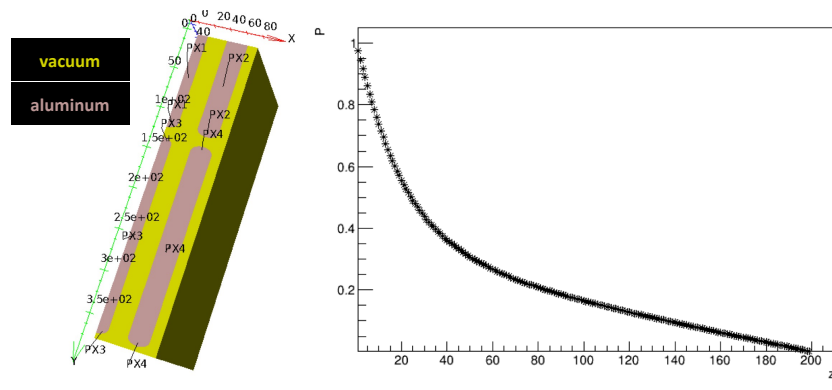
*Digitization happens after simulated charge deposition and before space point reconstruction

ATLAS radiation damage digitizer: ingredients

Electric field from TCAD simulations



Ramo potential from TCAD simulations



Trapping from literature:

[JINST 14 P06012, 2019](#)

$$\beta_e = (4.5 \pm 1.5) \times 10^{-16} \text{ cm}^2/\text{ns}$$

$$\beta_h = (6.5 \pm 1.5) \times 10^{-16} \text{ cm}^2/\text{ns}$$

based on these inputs:

Irradiation	Annealing	β_e ($10^{-16} \text{ cm}^2/\text{ns}$)	β_h ($10^{-16} \text{ cm}^2/\text{ns}$)	Reference	Method
Neutrons	minimum V_{depl}	4.0 ± 0.1	5.7 ± 0.2	[49]	TCT
Pions	minimum V_{depl}	5.5 ± 0.2	7.3 ± 0.2	[49]	TCT
Protons	minimum V_{depl}	5.13 ± 0.16	5.04 ± 0.18	[50]	TCT
Neutrons	> 50 hours at 60°C	2.6 ± 0.1	7.0 ± 0.2	[49]	TCT
Protons	> 10 hours at 60°C	3.2 ± 0.1	5.2 ± 0.3	[50]	TCT
Protons	minimum V_{depl}	4.0 ± 1.4	—	[3, 51]	Test-beam
Protons	25h at 60°C	2.2 ± 0.4	—	[3, 51]	Test-beam

The maps are the result of careful interpolation between several publications:

[TNS, VOL. 52, NO. 4, AUGUST 2005](#)

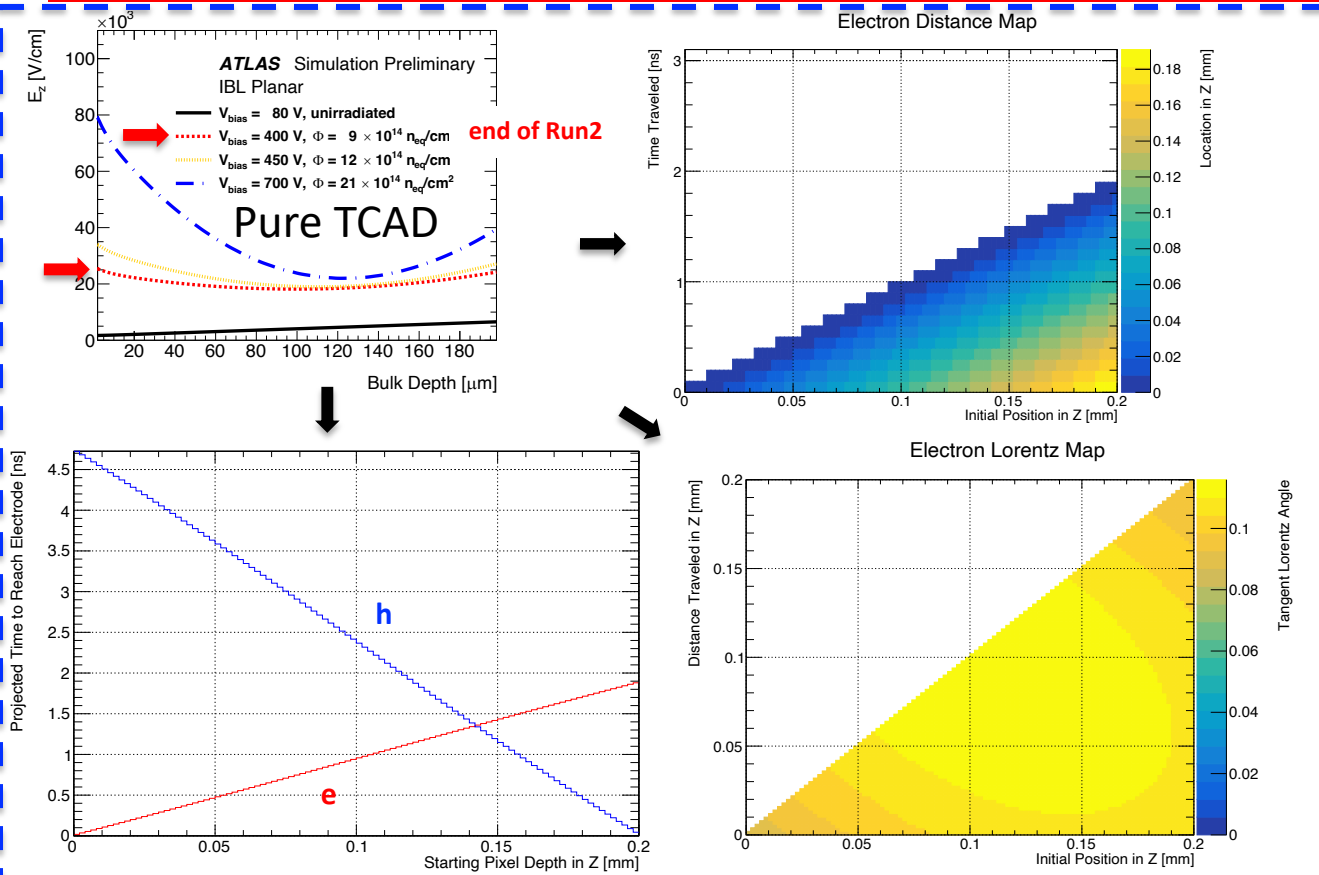
[NIM A 568 \(2006\) 51–55](#)

[W. Adam et al 2016 JINST 11 P04023](#)

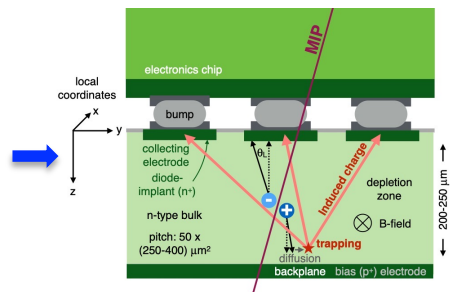
All inspired by [EVL 2 levels model](#)

Same model of CMS

What do we do with TCAD simulation?



Rad. Damage Digi

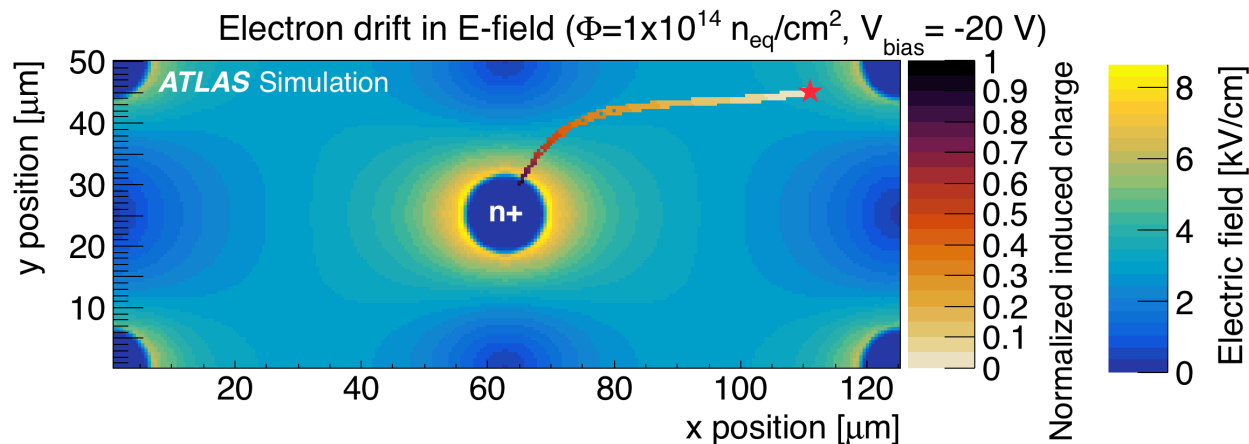
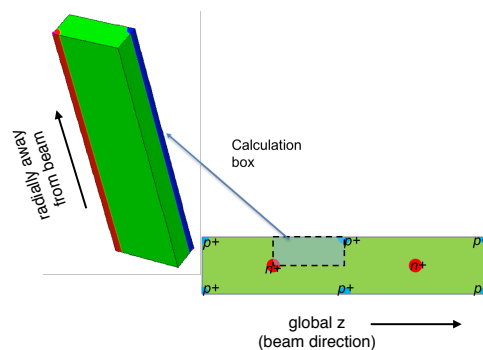


Example of maps

One set is representative of
1 year of operations

(Based on fluence
estimates for mid-year)

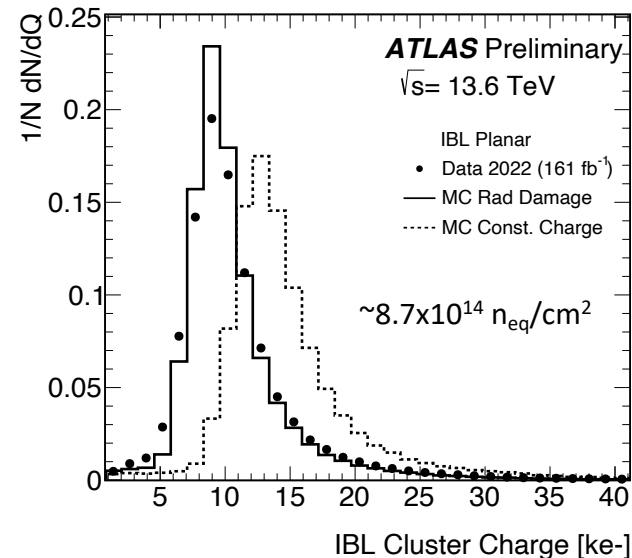
- ❑ With respect to planar, in 3D sensors the field is almost independent of the bulk depth (z) while it depends on the (x,y) position in the plane perpendicular to the columns
- ❑ With respect to planar the material is different – n-bulk vs p-bulk
- Different strategy and ingredients for simulating them in TCAD



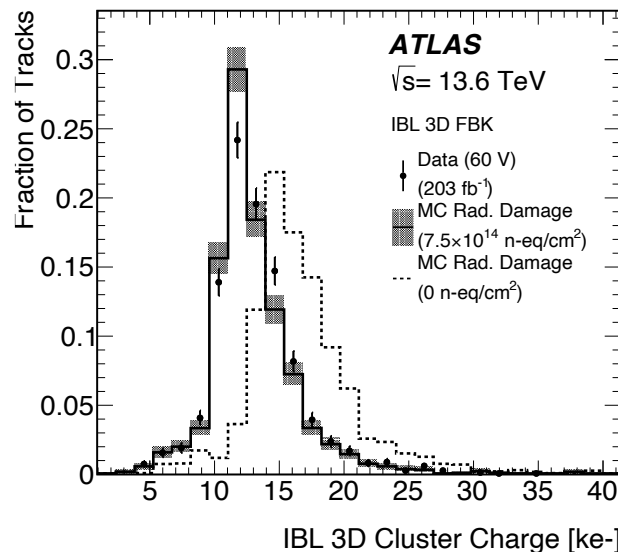
*Electric field &
Ramo potential*

Run3 data vs MonteCarlo – ATLAS

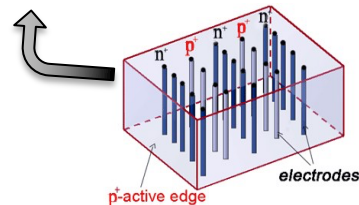
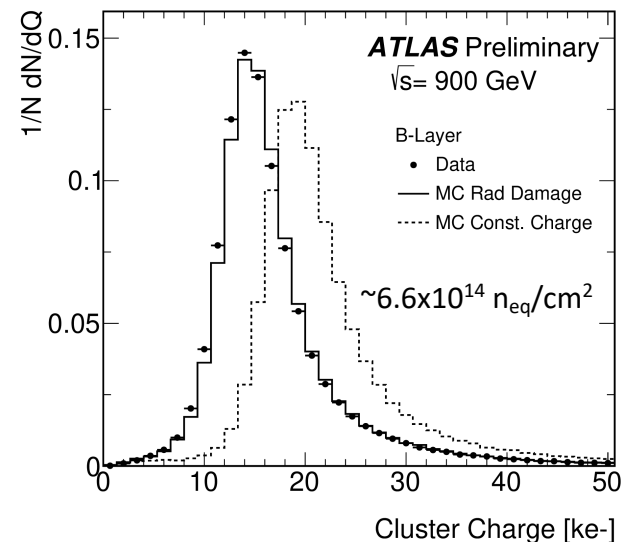
[ATL-COM-INDET-2022-027](#)



[2024 JINST 19 P10008](#)



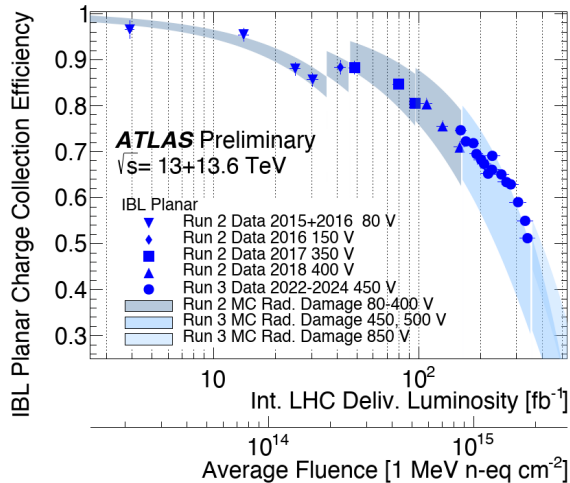
[ATL-PHYS-PUB-2022-033](#)



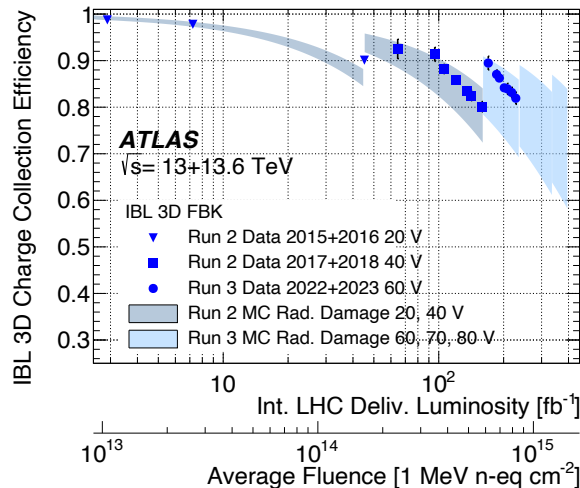
Most Probable Values match at 1 % level

Charge collection efficiency vs luminosity

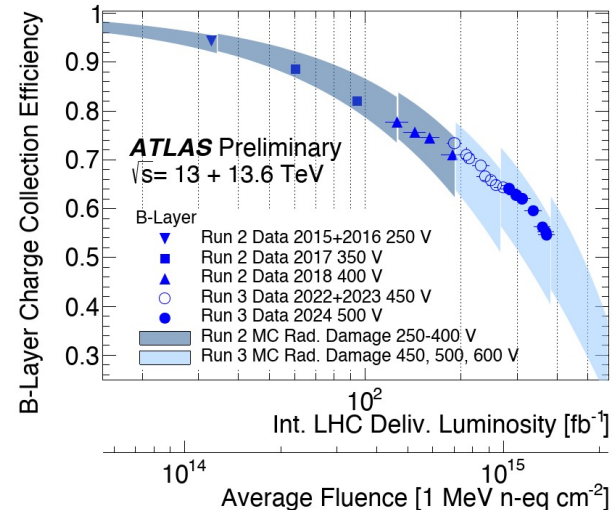
PIXE-2024-06



2024 JINST 19 P10008

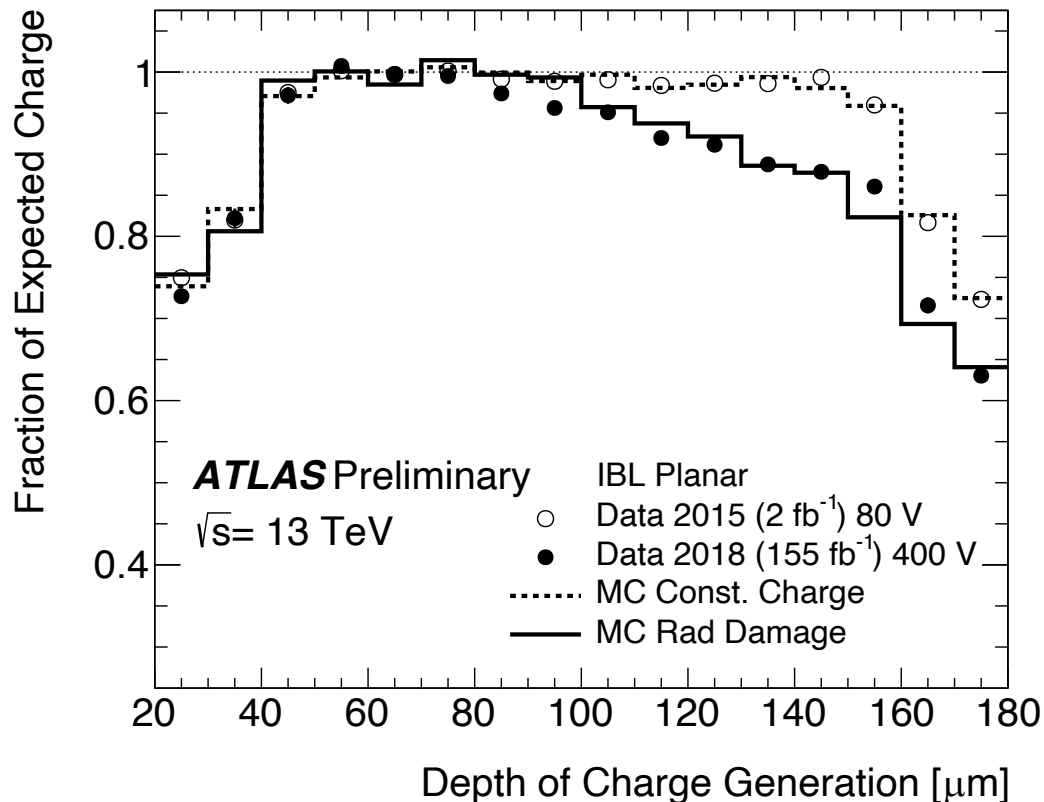


PIXE-2024-06



- ✓ Excellent agreement over almost two order of magnitudes of fluence
- ✓ Predictions indicate enough charge till the end of Run3 – and hit eff. too
- ✓ Nice agreement for 3D sensors too!
- *N.B. different material, device and radiation damage model ([Folkestad et al., NIM A \(2017\)](#))*

Charge vs deposition depth – ATLAS



Precise modeling of electric field and of all derived quantities as a function of depth in the bulk

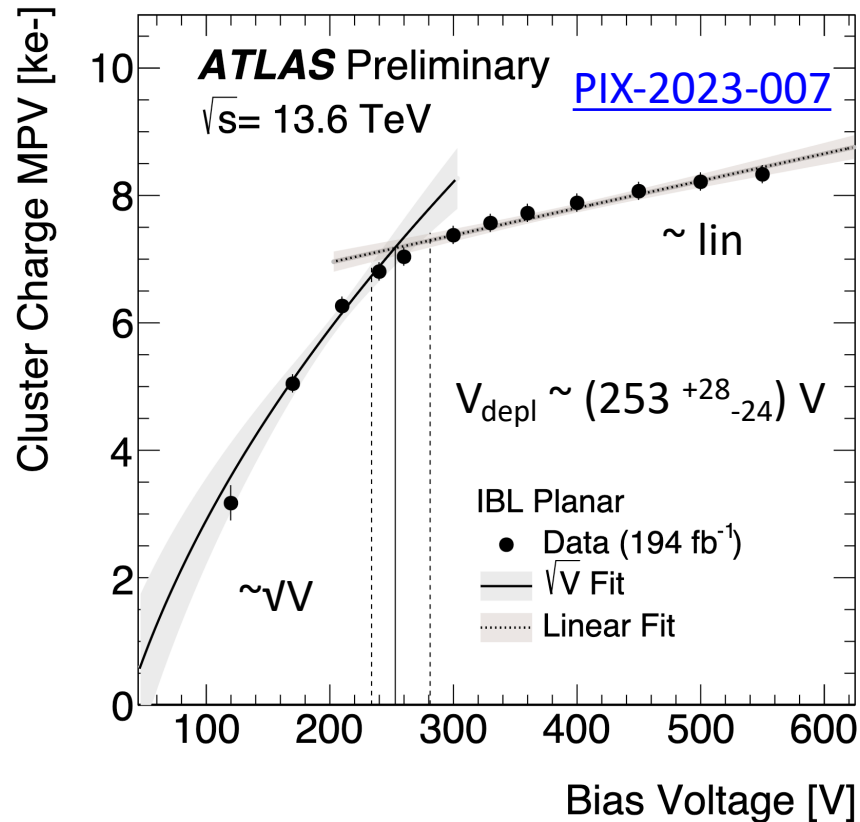
**Thanks to this level of agreement
Neural Networks trained on
radiation damage
MC samples give excellent
space point resolution when
used with Run3 data**

(Only tracks with $p_T > 3$ GeV
and at least 3 pixels in the
longitudinal projection are
considered to optimise the
resolution)

Once the modeling validated...

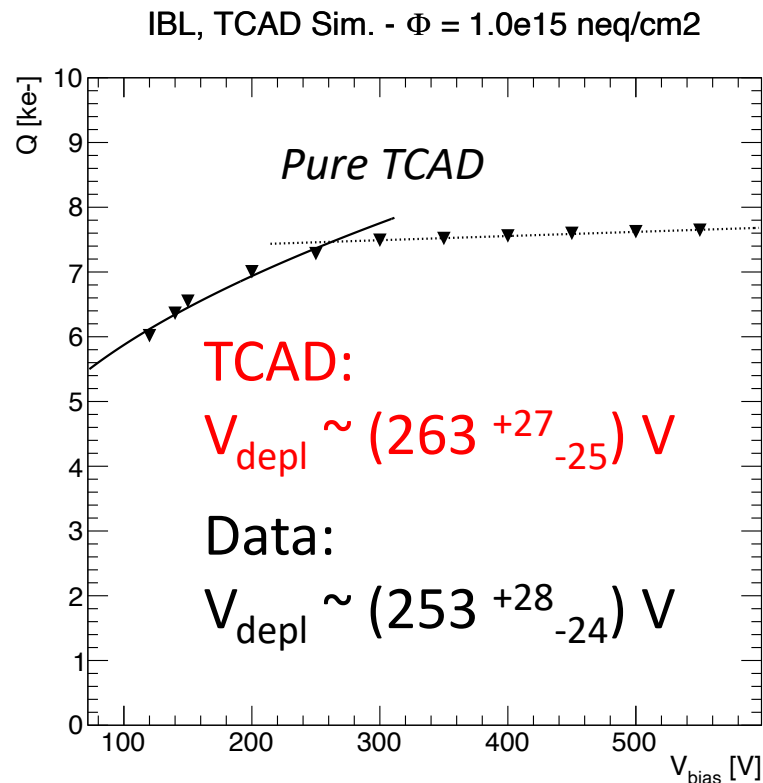
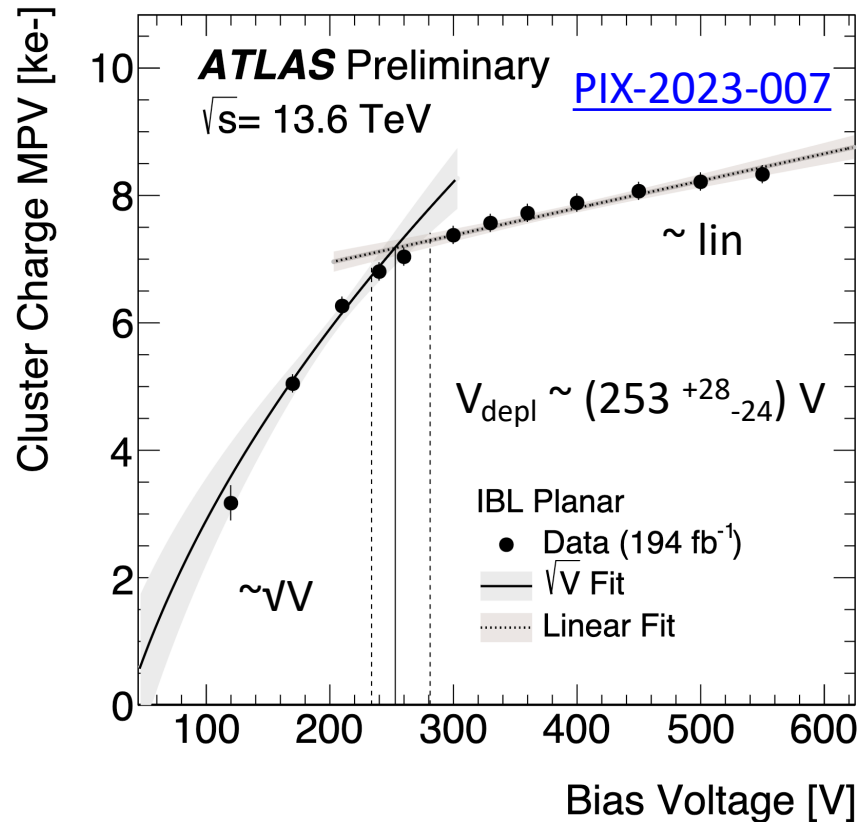
- We can make predictions
 - and of course, we do!
- **but we also get insight into observables otherwise difficult/impossible to access**
- In the following I will focus on "depletion voltage" and use TCAD results to try to shed light on the Q vs V dependence and indeed on " V_{depl} "
- All results for IBL planar at $1.0 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (end 2022)

ATLAS IBL - Q vs V

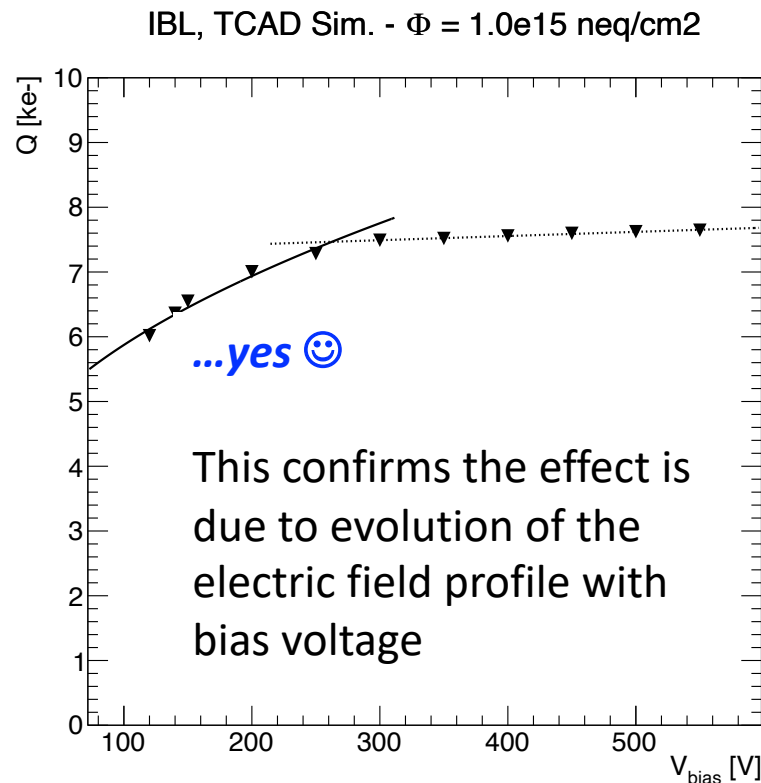
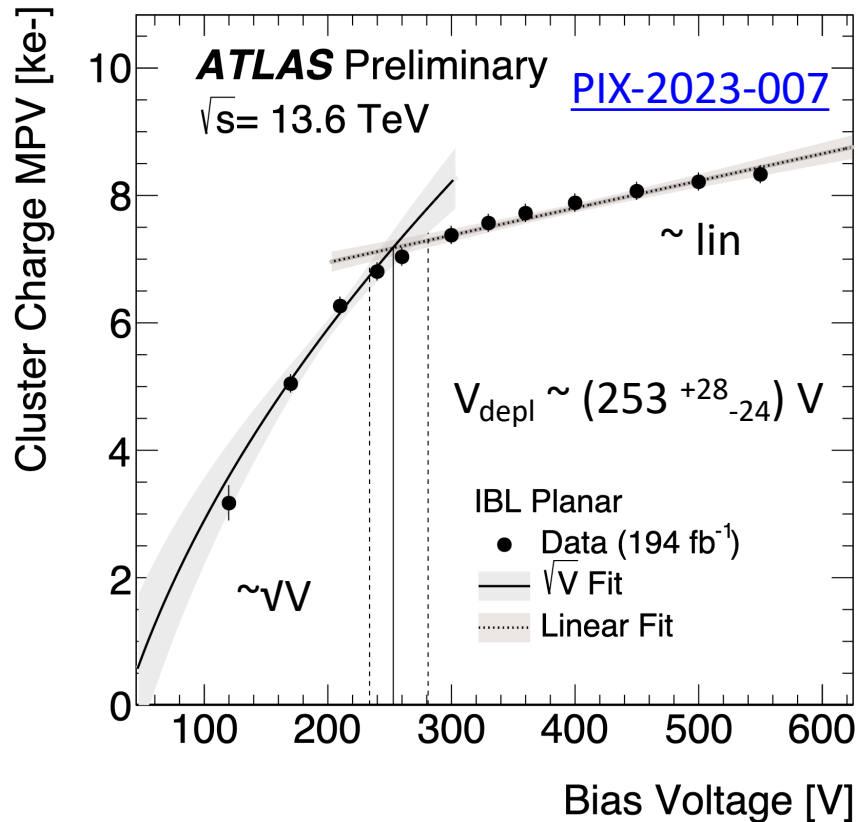


Do we see the same trends in TCAD?

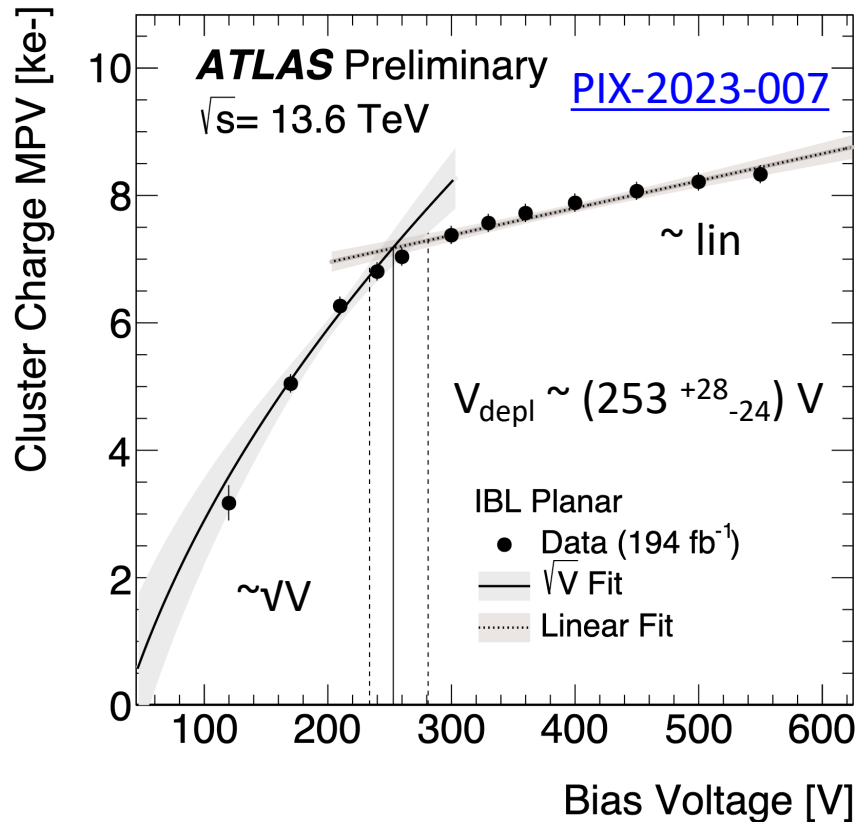
ATLAS IBL - Q vs V: data and TCAD



ATLAS IBL - Q vs V: data and TCAD



ATLAS IBL - Q vs V: data and TCAD



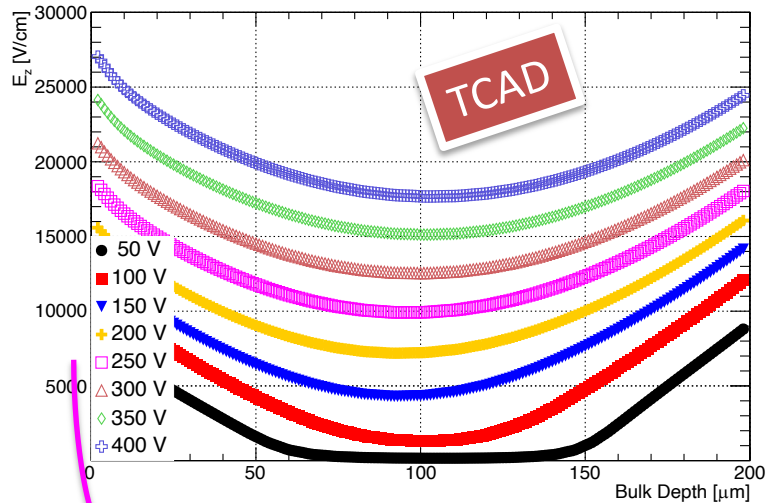
Well established behaviour of Q vs V

- below “depletion” $\rightarrow Q \sim \sqrt{V}$
- above “depletion” $\rightarrow Q \sim \text{lin}(V)$

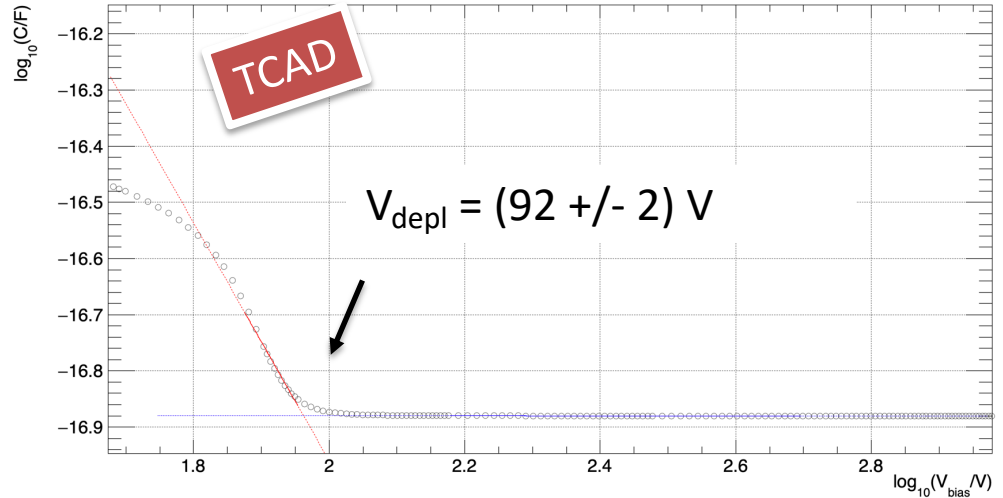
in both data and simulations

... but why?

Electric field and CV simulation

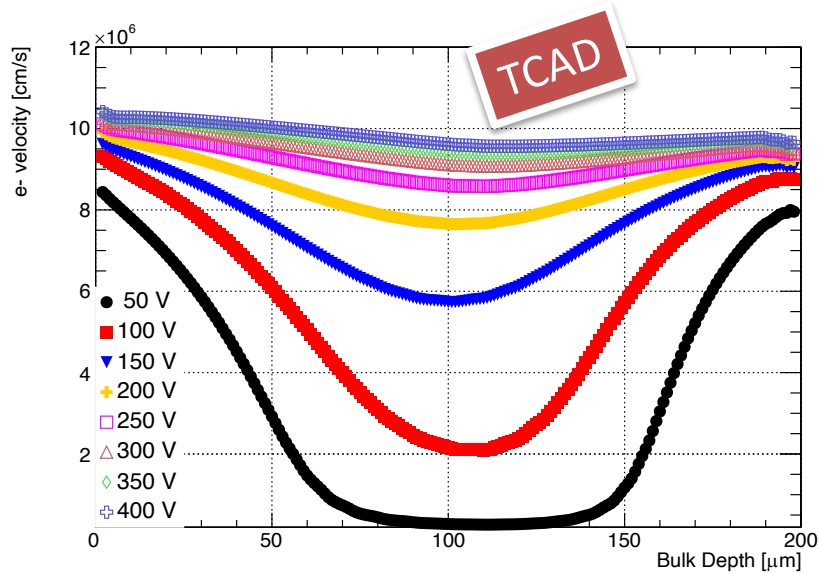


No major effect visible going from below 250 V to above that value



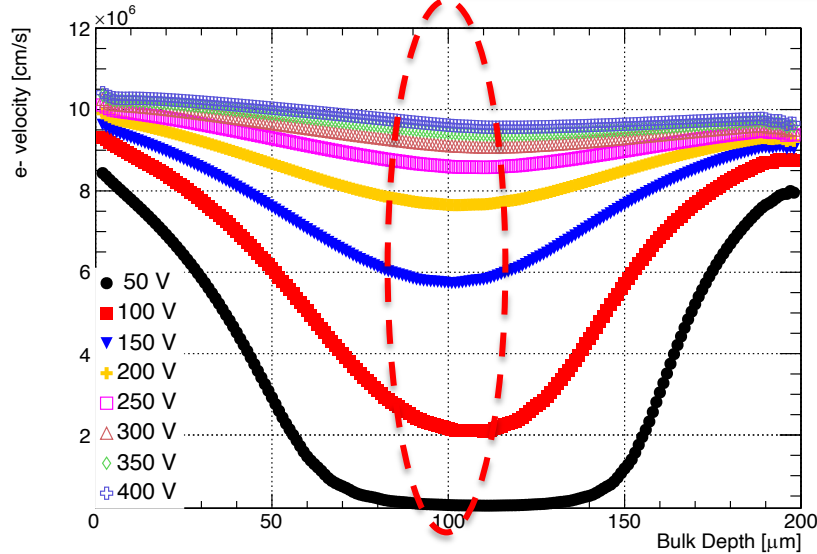
It is clear what we observe from Q vs V is not just an electric field effect

Electron velocity simulation



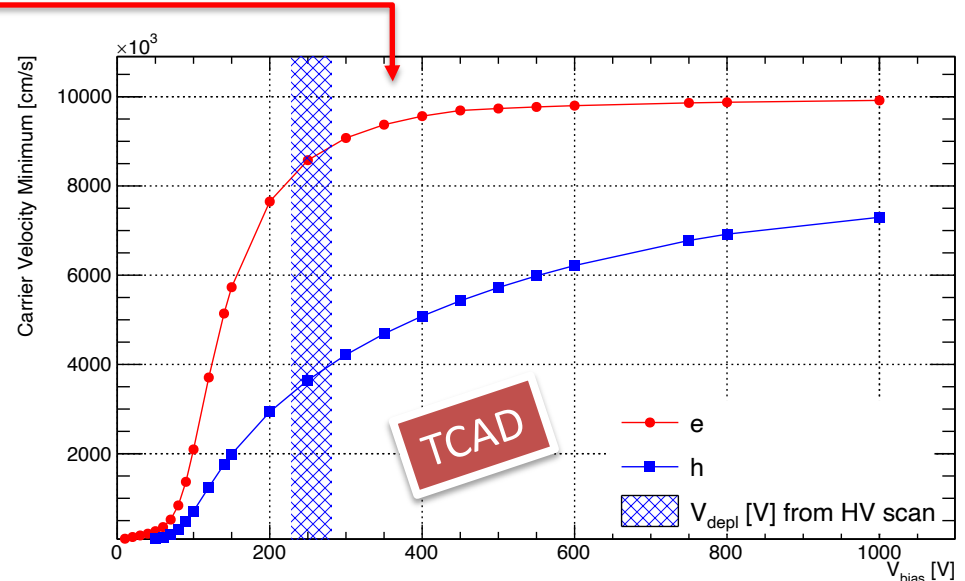
It seems the gradient is significantly reduced beyond 250 V

Electron velocity simulation



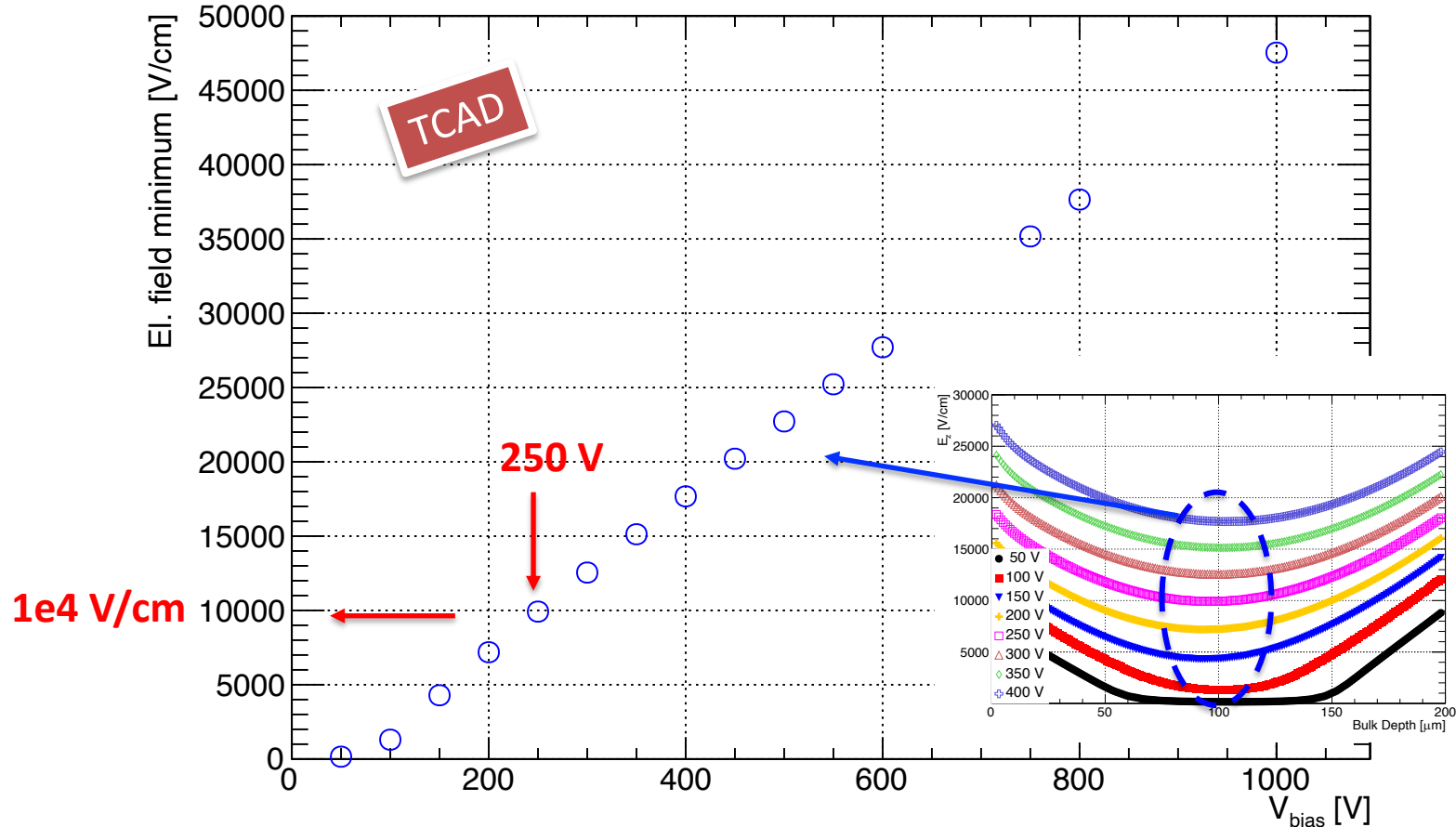
It seems the gradient is significantly reduced beyond 250 V

Let's focus on minima

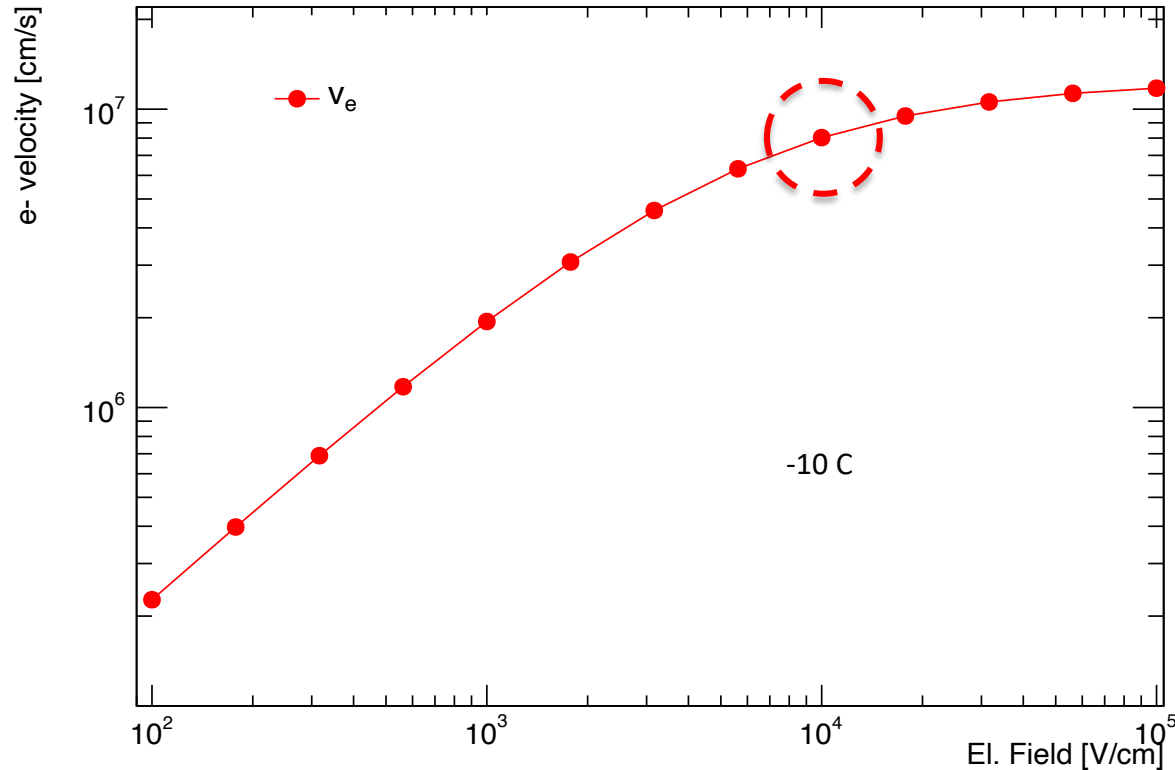


Depletion voltage is related to electron velocity saturation

Minimum of electric field vs bias

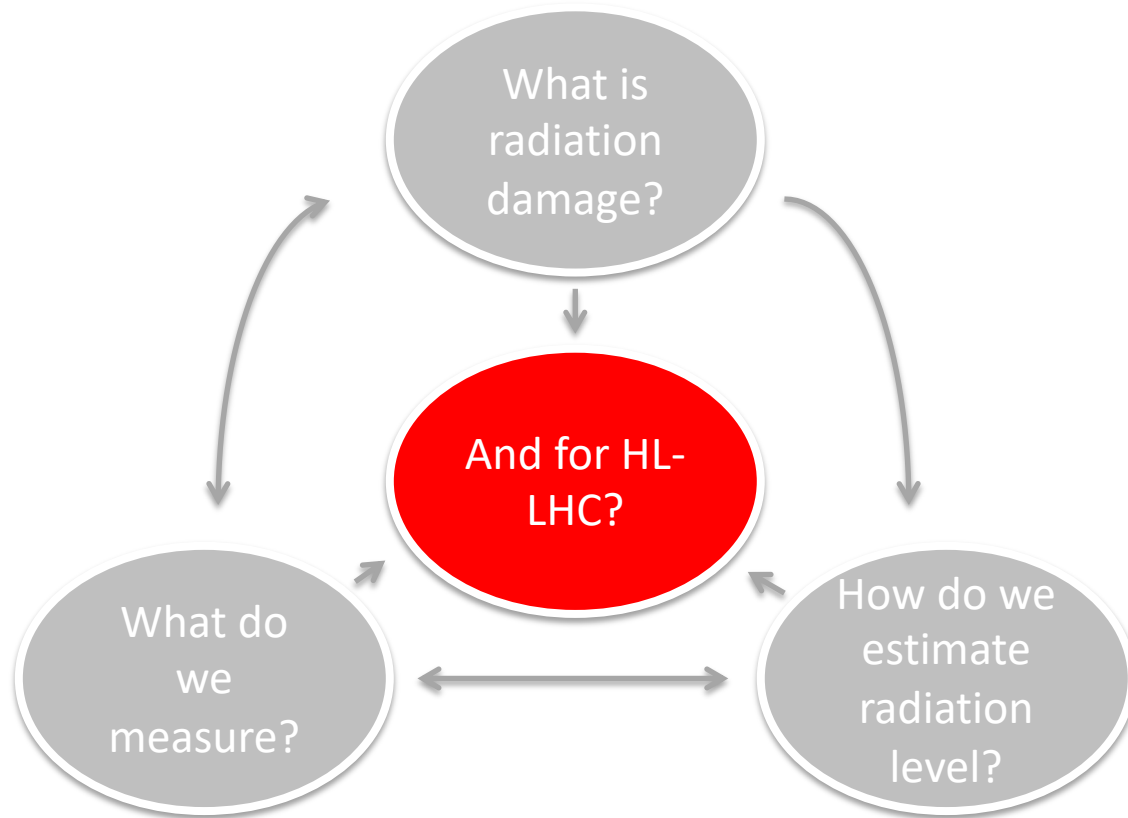


Electron velocity vs electric field

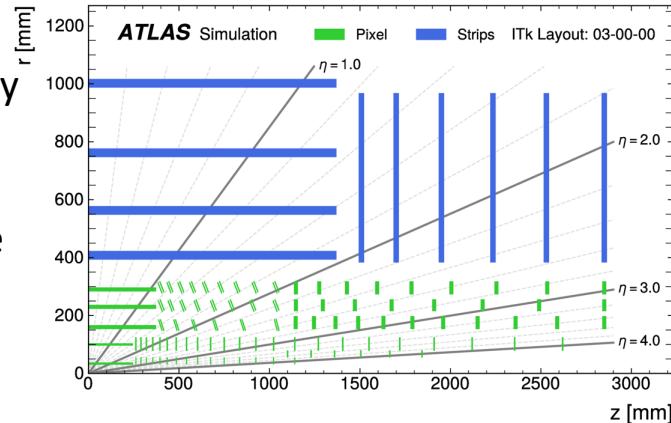
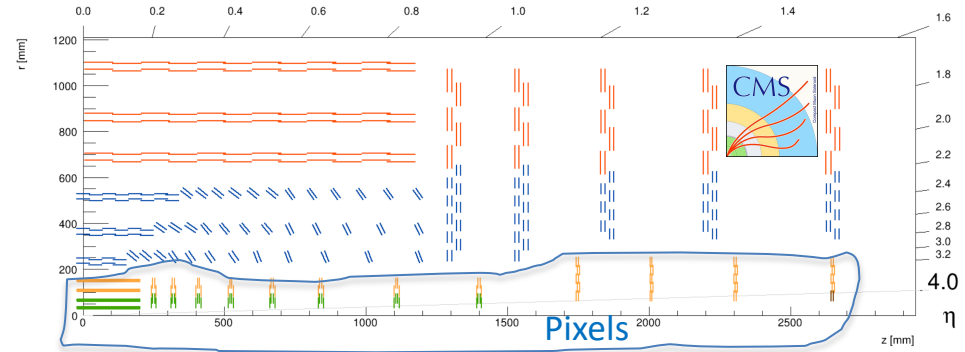
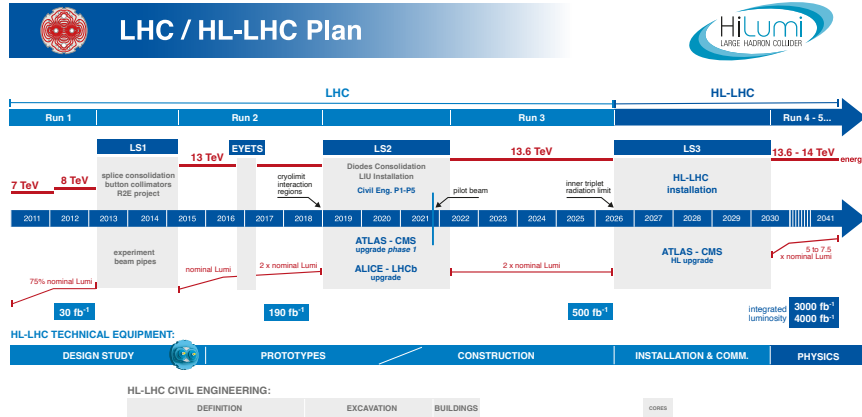


At ~ 250 V the electron velocity is close to saturation everywhere in the bulk

Mobility model (IBL&PIX default):
C. Canali, G. Majni, R. Minder and
G. Ottaviani, *IEEE Transactions on
Electron Devices* **22** (1975) 1045



High Luminosity LHC and trackers upgrades



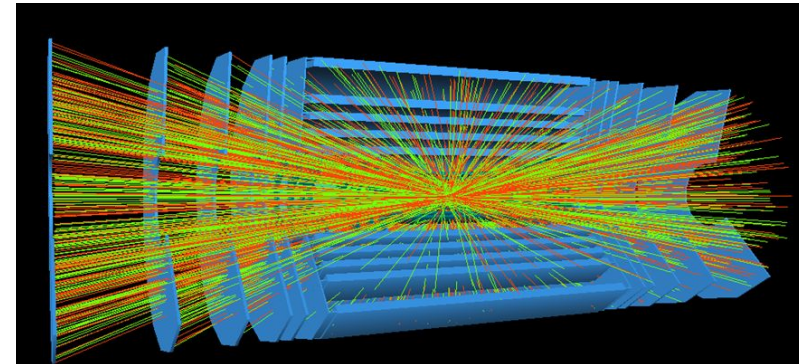
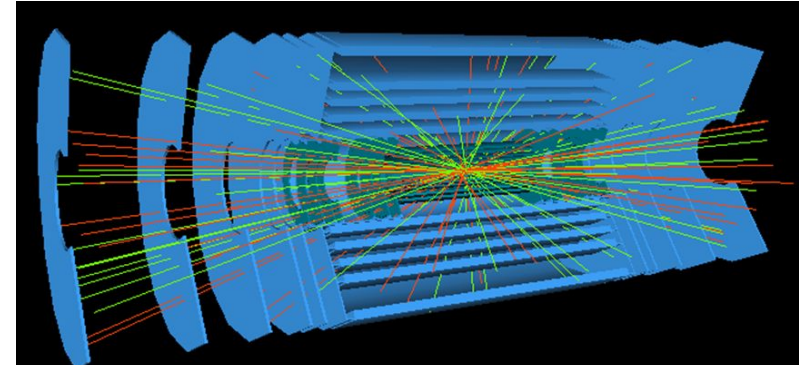
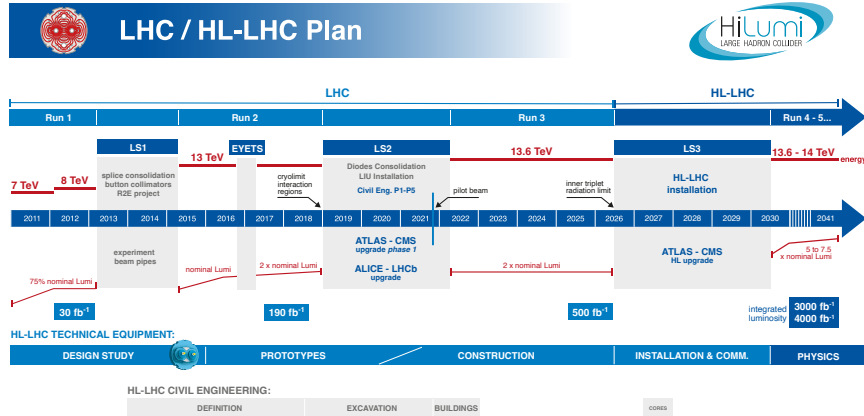
For both ATLAS and CMS:

- silicon only system
- down to $|\eta| = 4$
- more granular
- thinner sensors
- 3D pixel modules

Increase in instantaneous and integrated luminosity from 4 to 8 with respect to the end of Run3

Innermost pixel layers in ATLAS and CMS to receive $1-2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ after 2000 fb^{-1} , $\sim x10$ more fluence than end of Run2

High Luminosity LHC and trackers upgrades



Increase in instantaneous and integrated luminosity from 4 to 8 with respect to the end of Run3

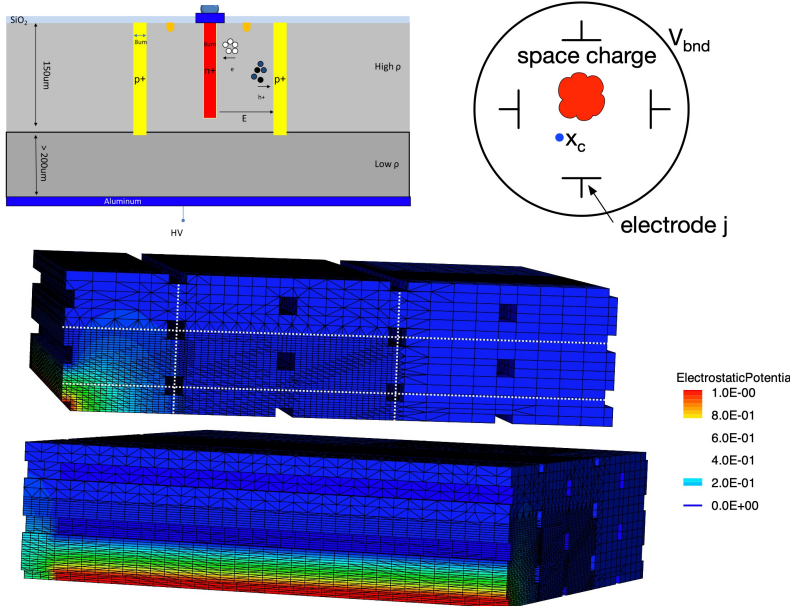
Innermost pixel layers in ATLAS and CMS to receive $1-2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ after 2000 fb^{-1} , $\sim \times 10$ more fluence than end of Run2, and pile-up by a factor 4

CMS Pixelav “upgrades”

T.A. Vami and M. Swart, 2023

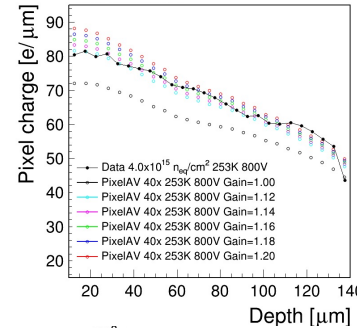
1) Physics models based on 2018 data scaled to HL-LHC fluences – see also [2016 CMS paper](#)

2) Simulation of 3D sensors

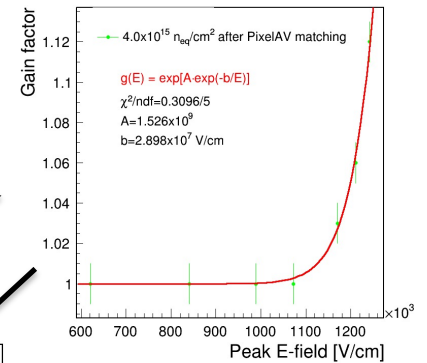


3) Simulation of gain

a) Tune gain on testbeam data

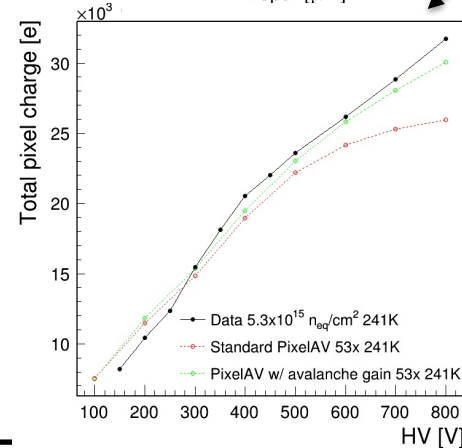


b) Fit gain constants



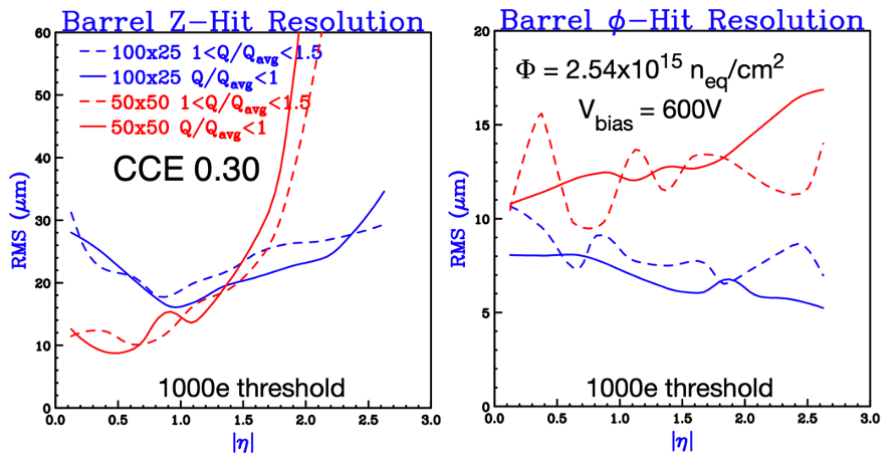
c) Compare **simulation** to data

Very good agreement at large voltage!



Pixelav used to decide on detector layout and technology based on simulated performance after radiation damage, e.g.

L2@3000 fb-1: 1000e threshold

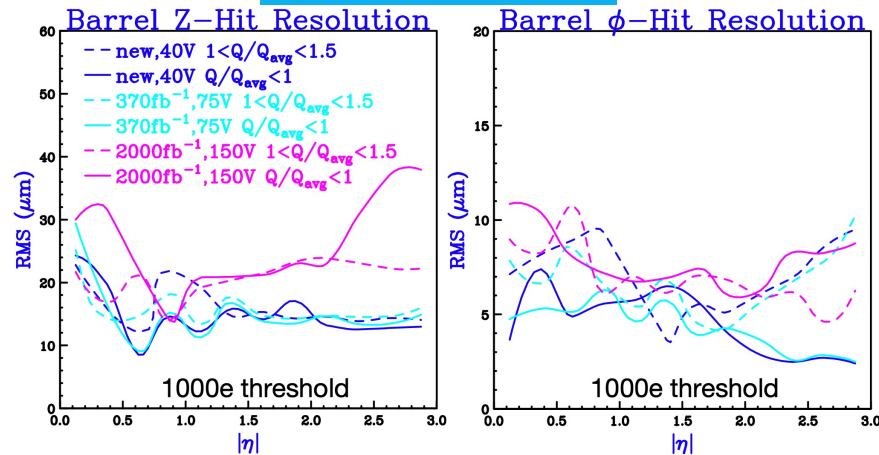


50x50 vs 100x25 pitch

50x50 better in z before irradiation

100x25 best after irradiation

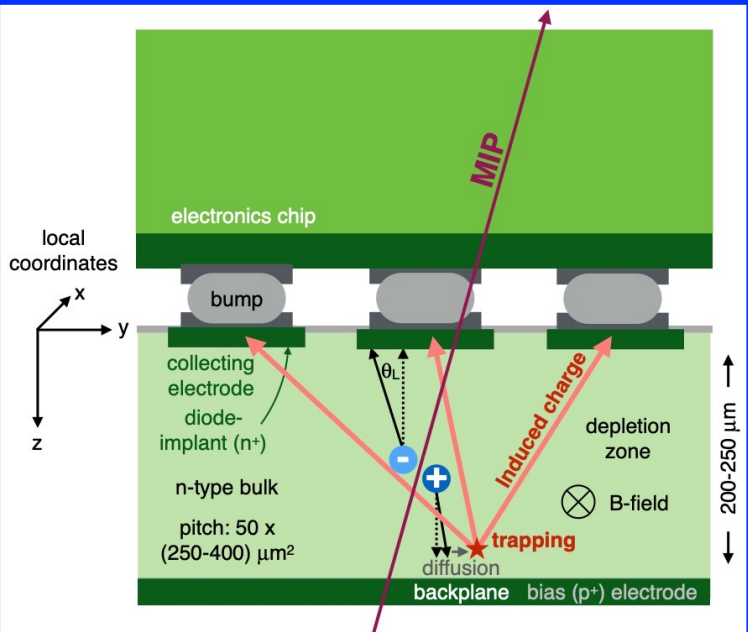
3D sensors in L1



Performance of 3D sensor after 370 fb⁻¹
 very close to pristine detector
 Effect of radiation damage clearly visible
 at 2000 fb⁻¹

ATLAS strategy & tools

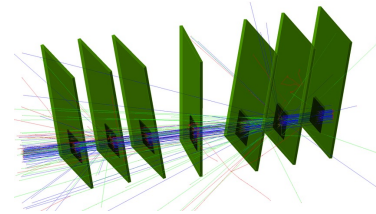
Run 2 & 3



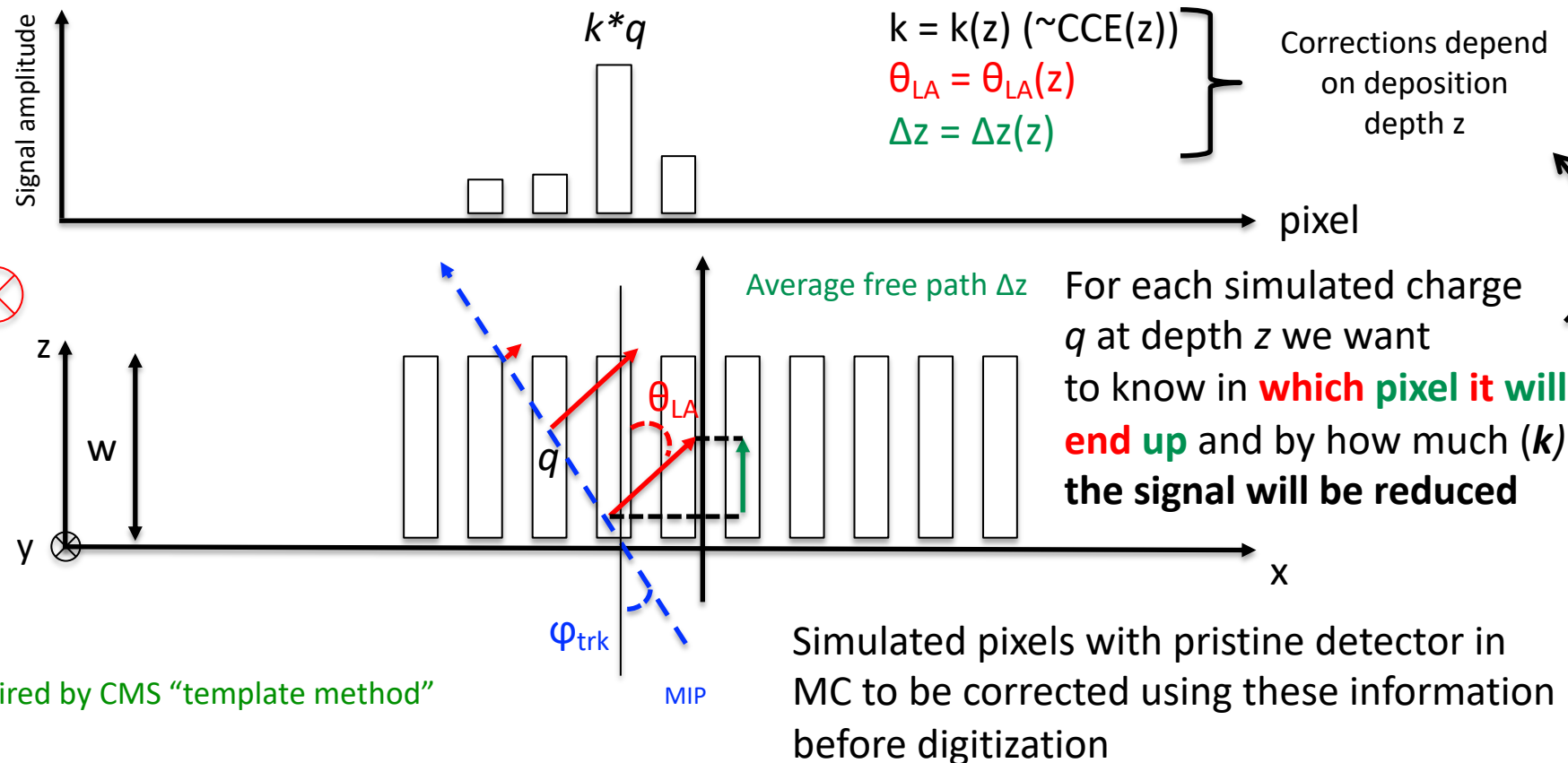
For each group of carriers the induced signal per pixel is evaluated

Modified pixel digitizer to include radiation damage effects is now the default for Run3

- ✓ As shown, **excellent agreement with data**
- **But too slow for HL-LHC**
- The idea is to use a “template” approach like CMS
- Templates to be produced using [Allpix²](#)

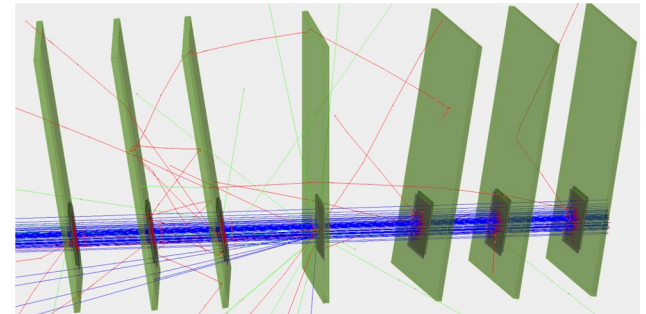
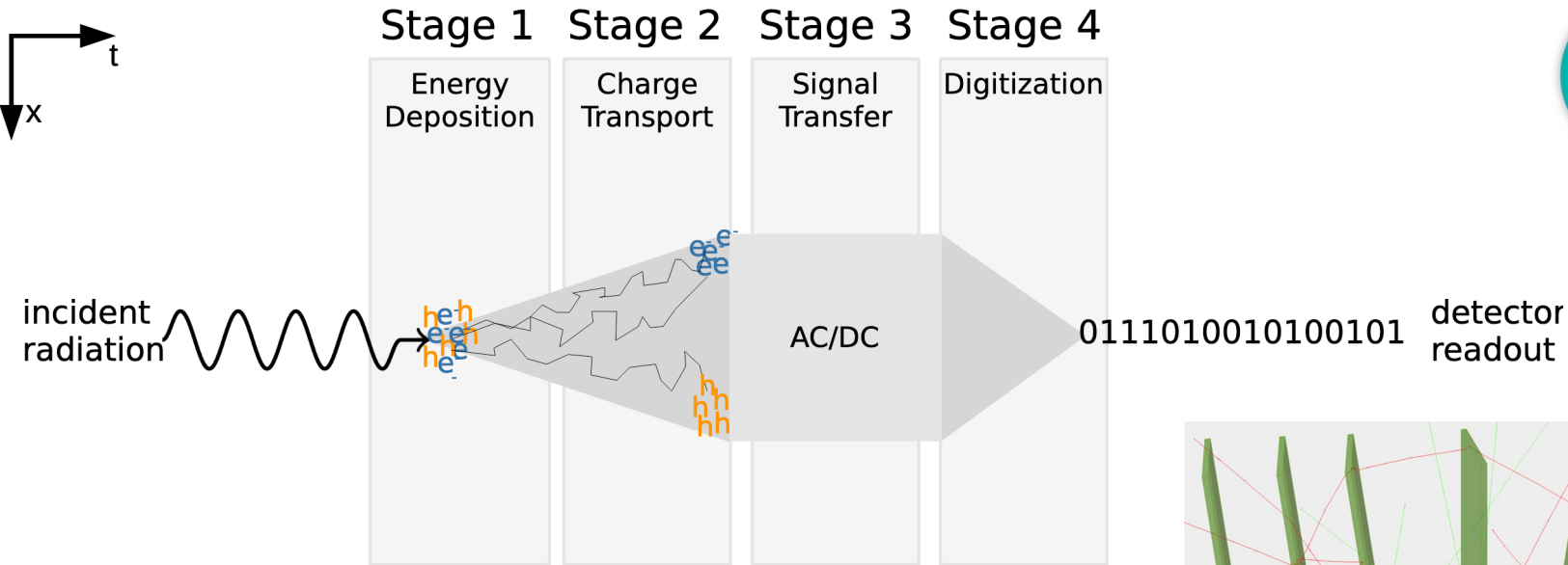


ATLAS strategy



Intermezzo: Allpix-Squared

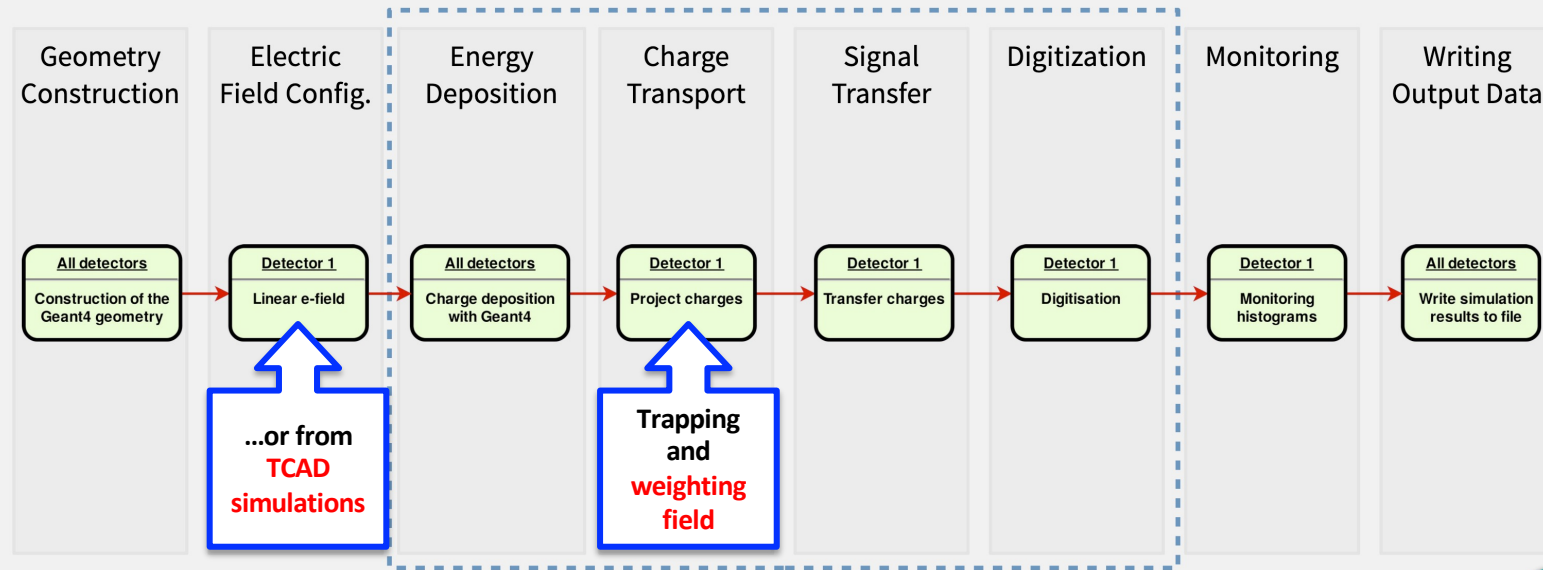
To implement such a correction scheme [Allpix²](#) is the perfect tool



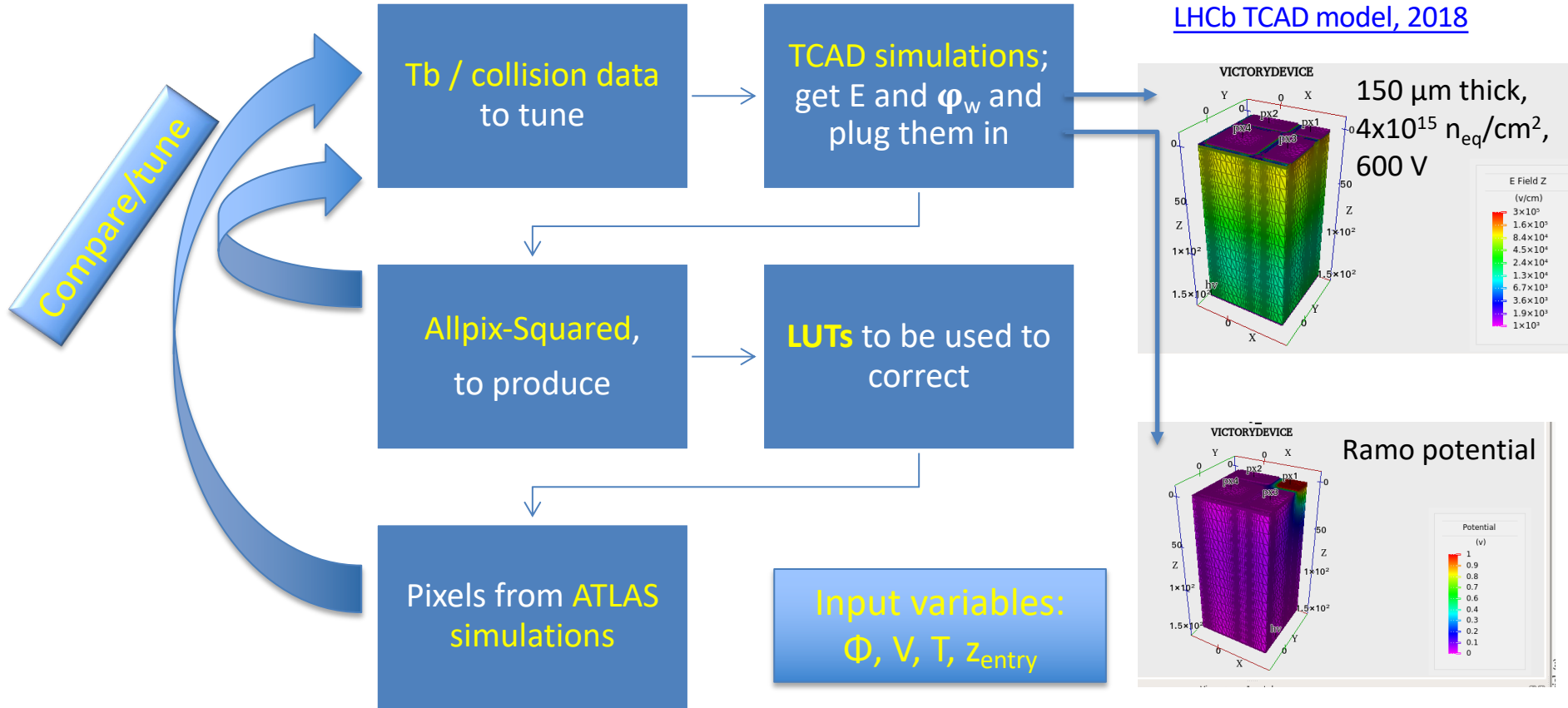
Intermezzo: Allpix-Squared

To implement such a correction scheme [Allpix²](#) is the perfect tool

- Building blocks follow individual steps of signal formation in detector
- Algorithms for each step can be chosen independently

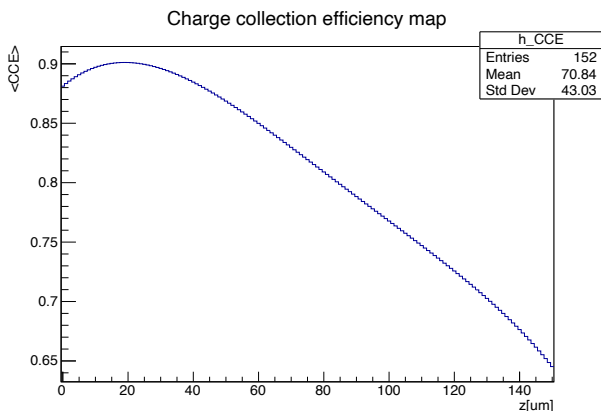


Project workflow

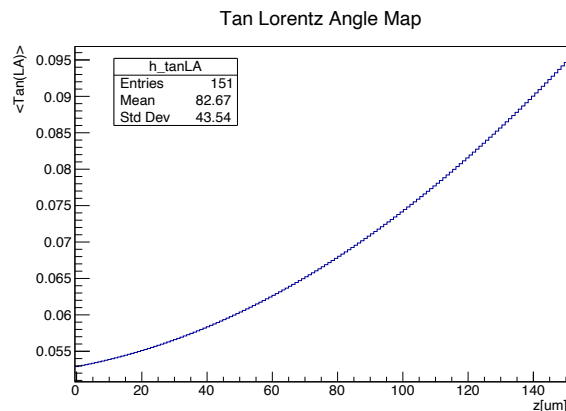


ATLAS ITk Pixels – Simulation results

150 μm thick sensor at $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ & 400 V; $z = 0$ (150) corresponds to the Pixel (Back) side, Voxels of $(1 \times 1 \times 2) \mu\text{m}^3$, 1000e in each one, calculating $\text{CCE}(z)$, $\tan(\theta_{\text{LA}})(z)$ and $\Delta z(z)$

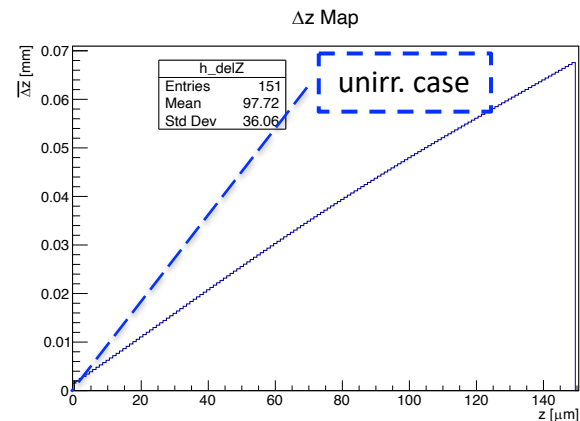


Decrease at frontside due to holes



L.A. ~ 50 -100 mrad

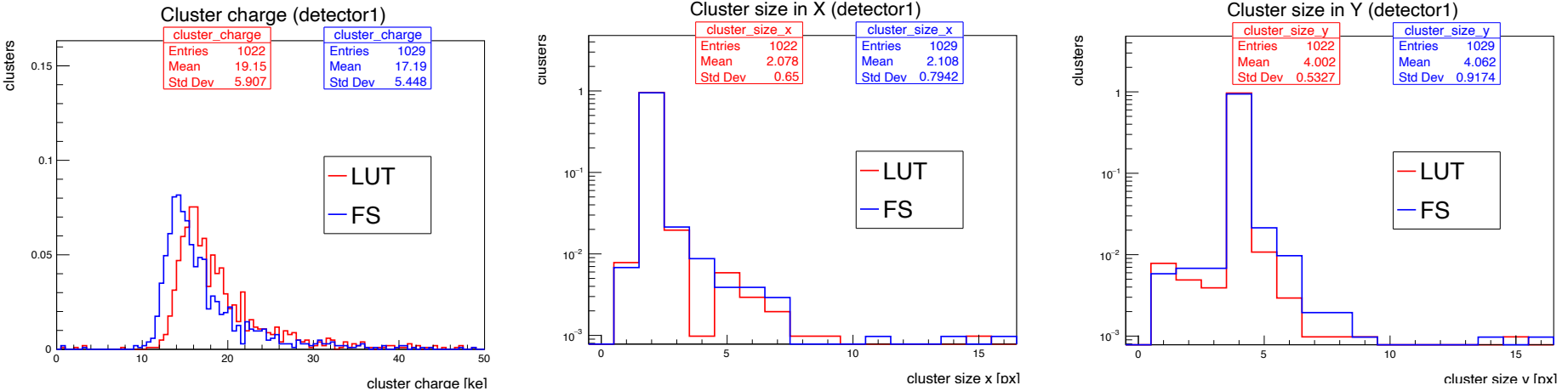
This is due to low temperature and large electric field



Trapping shortens free path

[M. Bomben and K. Nakalil, pixel 2024](#)

150 μm , example form closure test - $\eta = 1$



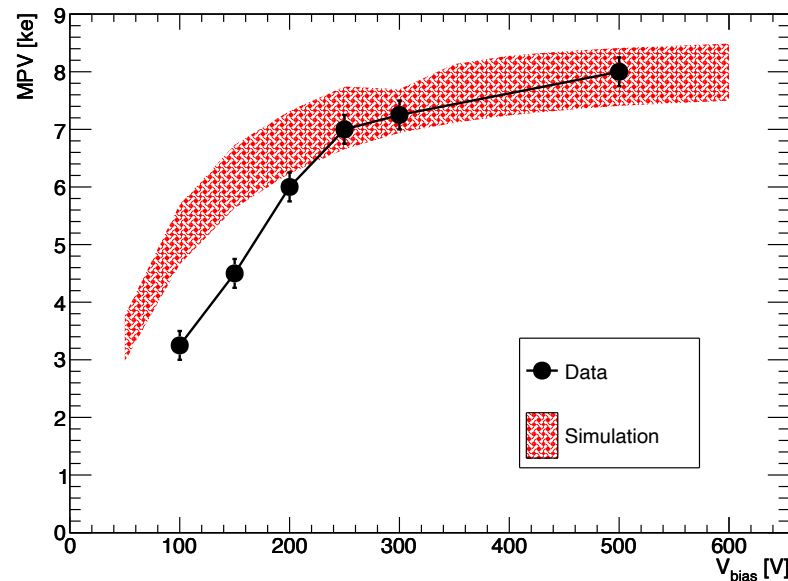
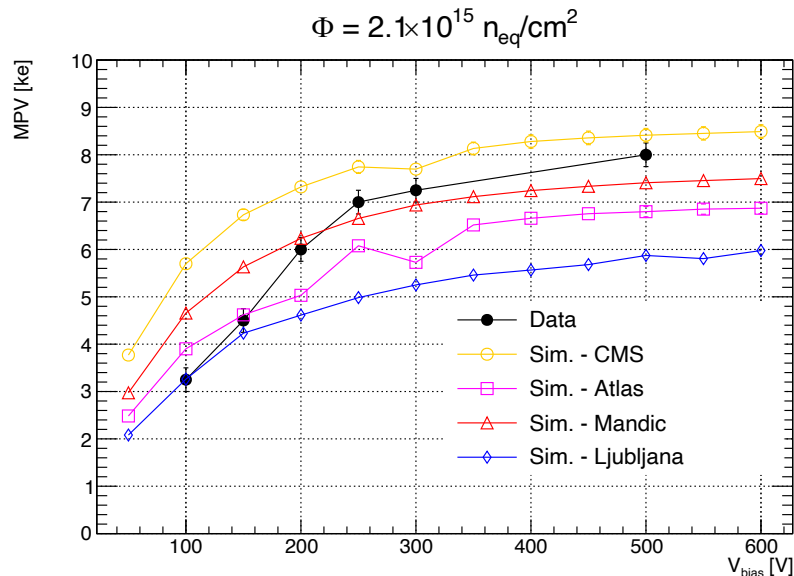
~ 10 % larger charge with LUT method

Very good agreement in both longitudinal and transverse cluster size

M. Bomben and K. Nakkalil, pixel 2024

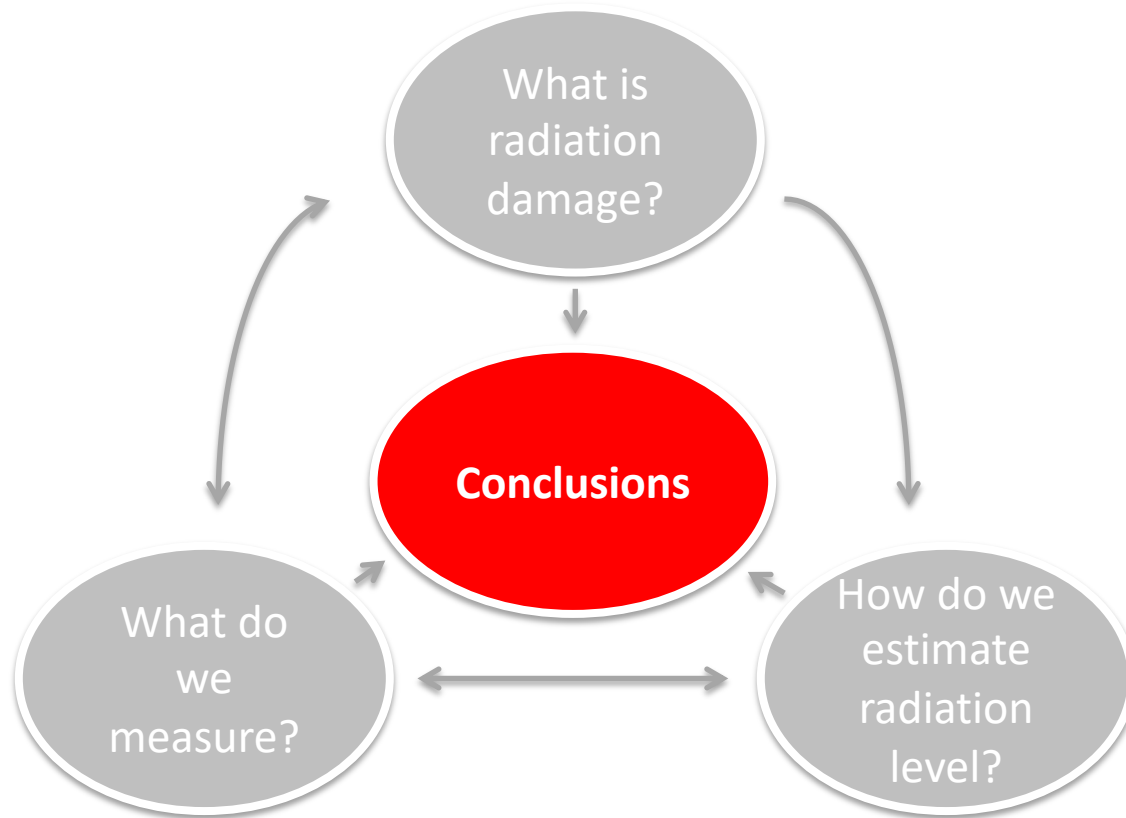
Validation with data

M. Bomben NIM A 2025



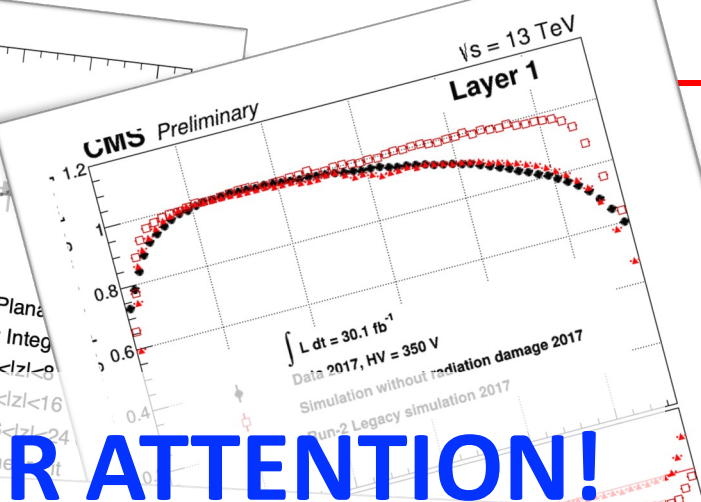
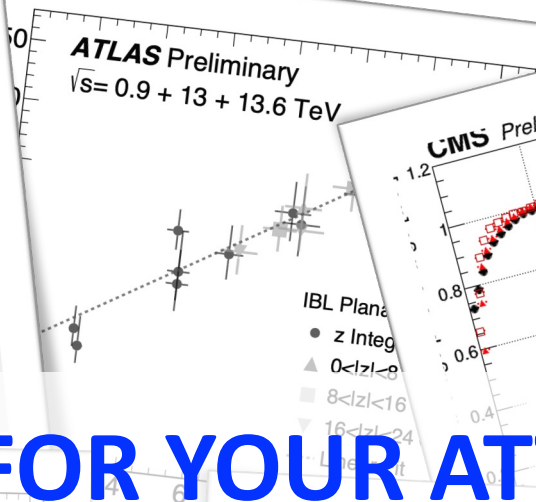
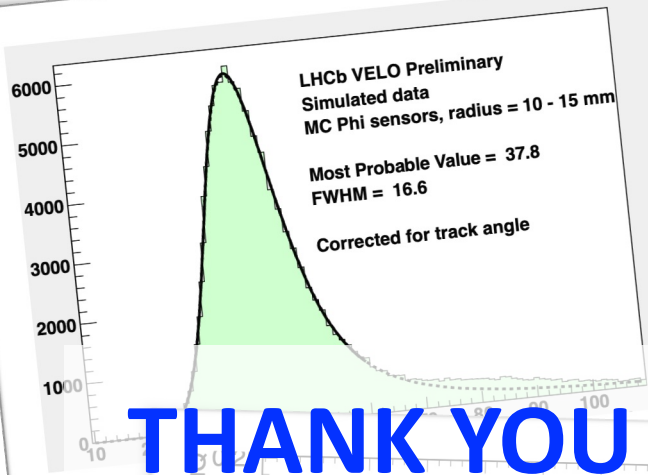
Comparison to CMS 150 μm thick sensors data
Electric field simulated using LHCb model
Simulation using Allpix²
Several trapping models tested

"Best model" is an average of CMS and Mandic
Next: test other electric field models
... and use ATLAS ITk prototypes data 😊

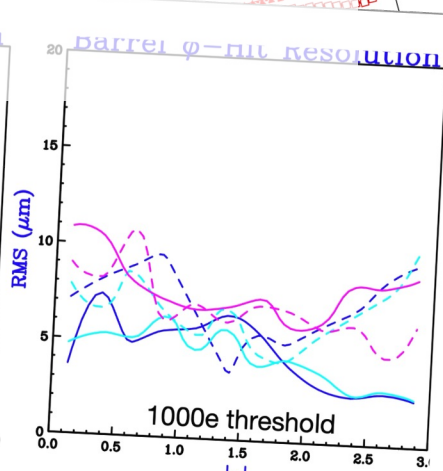
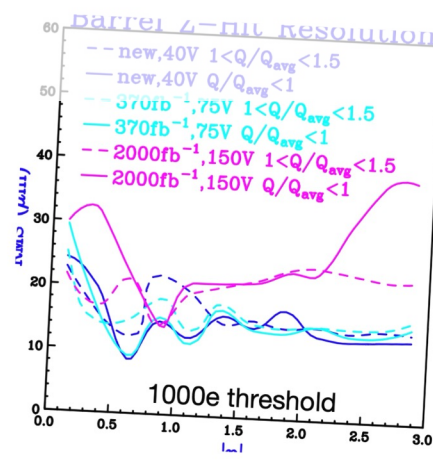
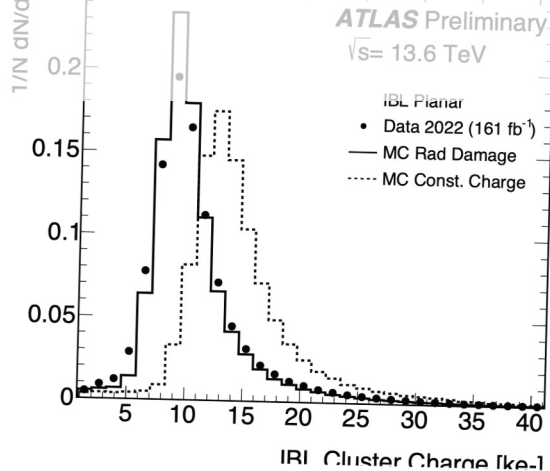


Summary & Perspectives

- Radiation damage effects are well visible and measured in LHC experiments tracking detectors
 - Predictions were most of the time respected but some intriguing deviations have been observed
- Precise electric field, mobility and trapping modeling makes possible to reproduce charge collection in pixels at % level
- Simulations including radiation damage effects used as a tool for operation purposes, performance predictions and tuning of reconstruction algorithms
- We are at the point in which we can use collision data to improve our modeling (*e.g.* fluence estimate) – *data-driven "era"*
- For HL-LHC faster – yet as precise as possible – algorithms are being tuned
- Testbeam data + TCAD + Pixelav/Allpix² is the way forward

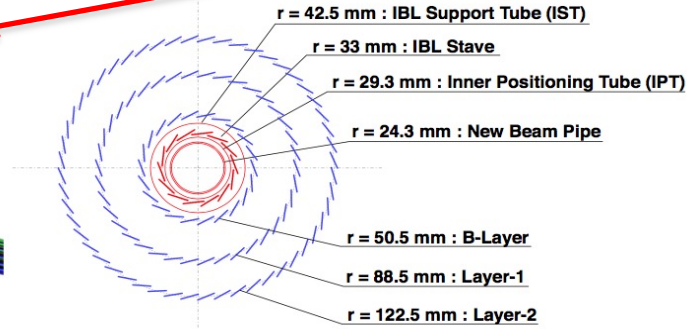
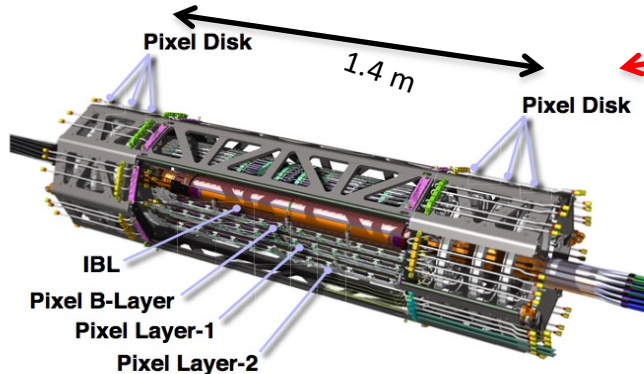
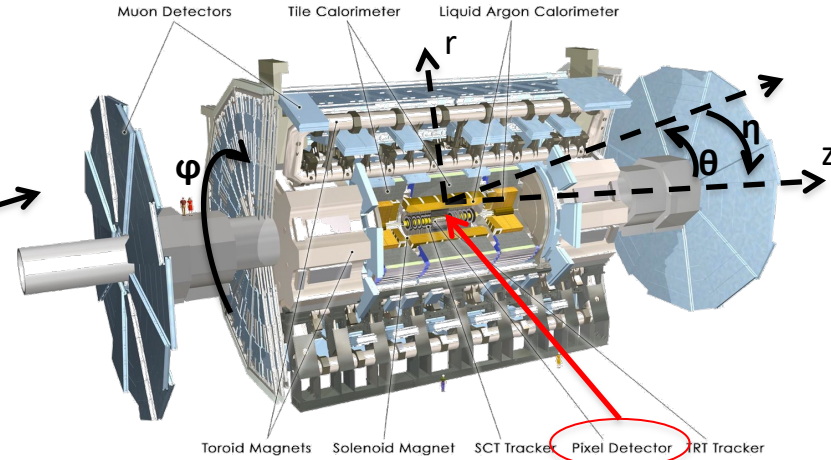
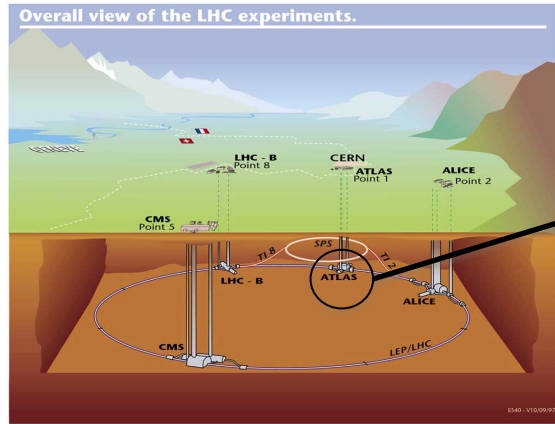


THANK YOU FOR YOUR ATTENTION!

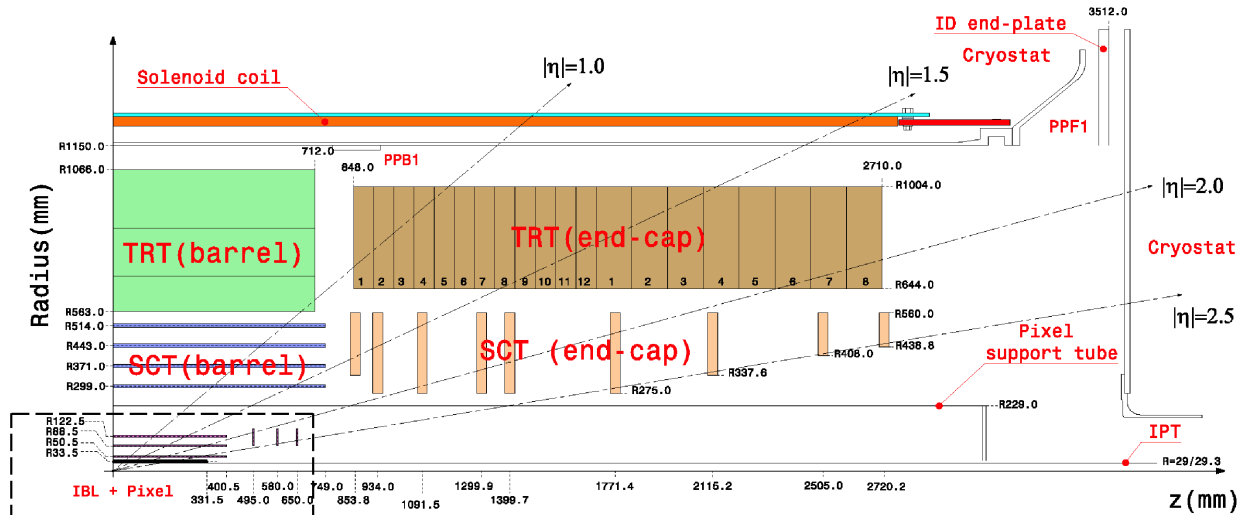


Backup

Current ATLAS detector @ CERN LHC

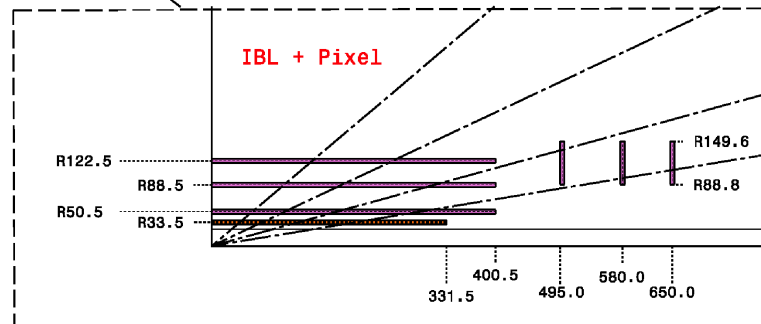


ATLAS Inner Detector



SCT

- p-in-n 285 μm thick sensors
- pitch is 80 μm



Detector envelopes (mm)

IBL	31<R<40
Pixel	42.5<R<242
SCT barrel	255<R<549
SCT end-cap	251<R<610
TRT barrel	554<R<1082
TRT end-cap	617<R<1106

IBL (PIX)

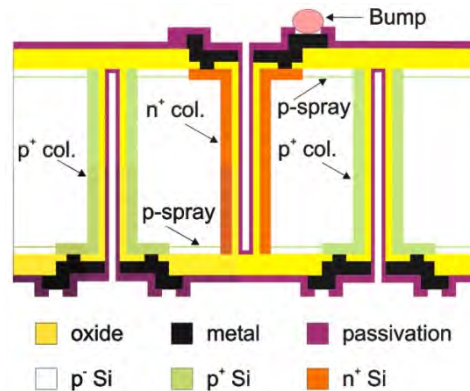
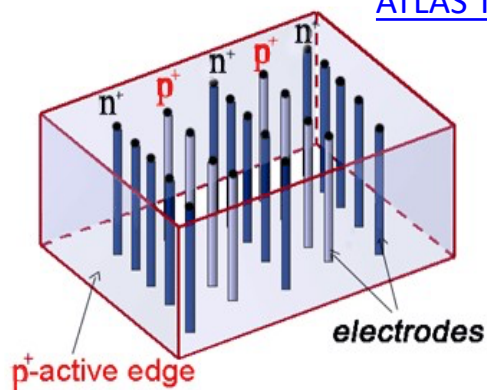
- n-in-n 200 (250) μm thick sensors
 - IBL has 3D n-in-p at high $|\eta|$
- pitch is 50x250(400) μm^2

ATLAS IBL & B-Layer - fluences and doses

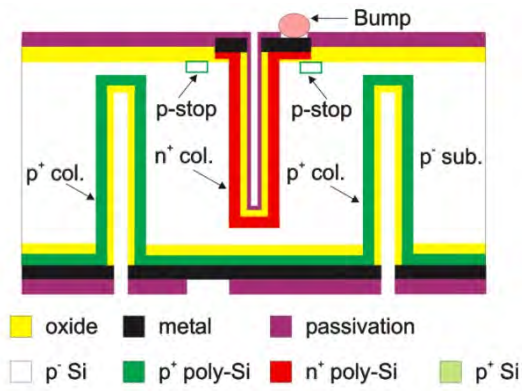
Layer	IBL			B-Layer		
time	Int. Lumi [fb ⁻¹]	Fluence [n _{eq} /cm ²]	Dose [Mrad]	Int. Lumi [fb ⁻¹]	Fluence [n _{eq} /cm ²]	Dose [Mrad]
End of Run2	161	~ 9x10 ¹⁴	~ 53	190	~ 7x10 ¹⁴	~ 28
Till now	230	~ 12x10 ¹⁴	~ 76	260	~ 10x10 ¹⁴	~ 38
End Run3 (proj.)	395	~ 21x10 ¹⁴	~ 130	425	~ 15x10 ¹⁴	~ 63
Max by design	-	~ 50x10 ¹⁴	~ 250	-	~ 10x10 ¹⁴	~ 50

ATLAS IBL 3D sensors

[ATLAS TDR 29](#)



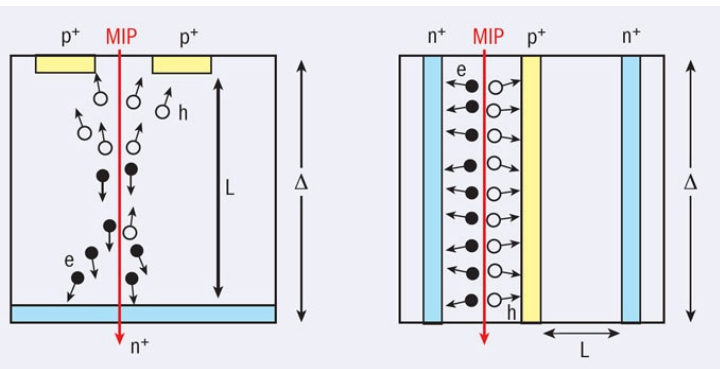
(a)



(b)

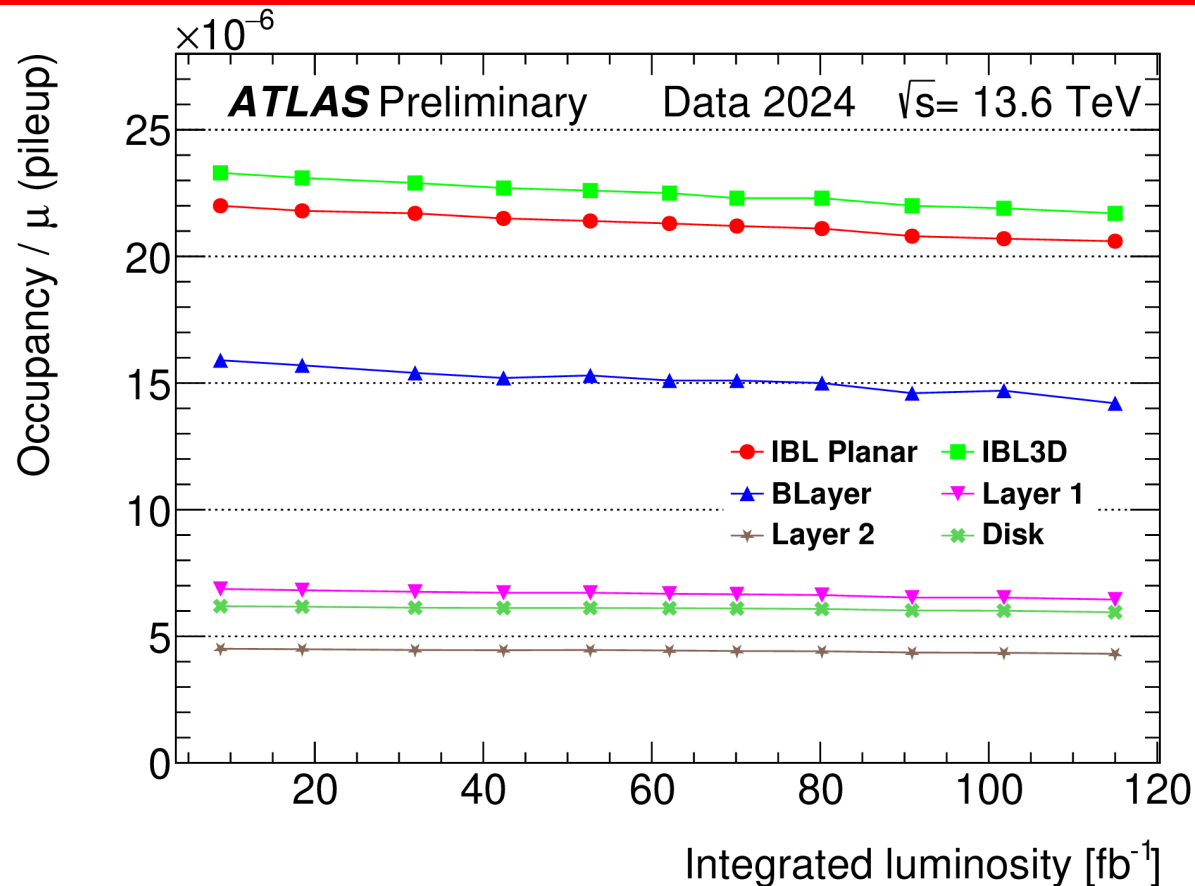
Figure 9. Design of the columns of (a) FBK and (b) CNM 3D sensors. This sketch is for illustration only and is not to scale.

[B. Abbott et al 2018 JINST 13 T05008](#)



ATLAS Hit-occupancy

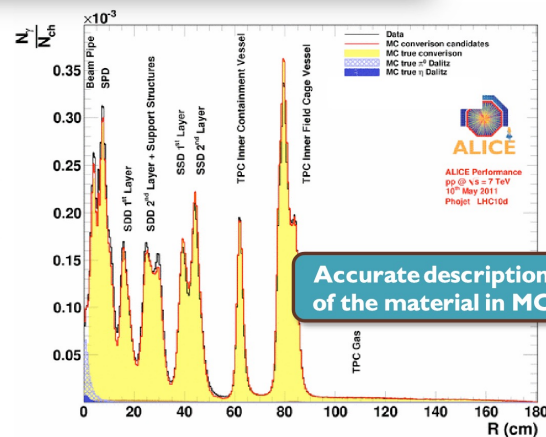
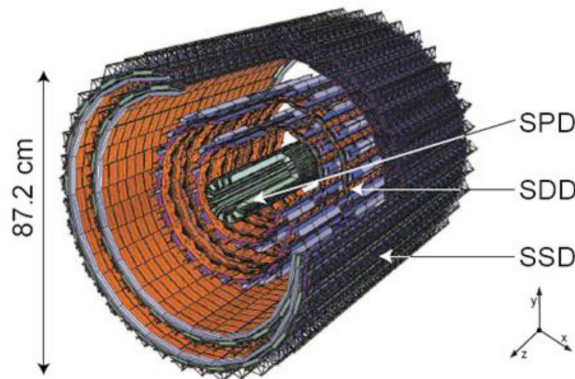
PIXE-2024-07



Hybrid pixels
Drift Detectors
 μ -Strip

The ITS parameters

Layer	Det.	Radius (cm)	Length (cm)	Surface (m ²)	Chan.	Spatial precision (mm)		Cell (μ m ²)	Max occupancy central PbPb (%)	Material Budget (% X_0)	Power dissipation (W)	
						rp	z				barrel	end-cap
1	SPD	3.9	28.2	0.21	9.8M	12	100	50x425	2.1	1.14	1.35k	30
2		7.6	28.2						0.6	1.14		
3	SDD	15.0	44.4	1.31	133 K	35	25	202x294	2.5	1.13	1.06k	1.75k
4		23.9	59.4						1.0	1.26		
5	SSD	38.0	86.2	5.0	2.6M	20	830	95x40000	4.0	0.83	850	1.15k
6		47.0	97.8						3.3	0.86		



Accurate description
of the material in MC

ALI-PRF-6268

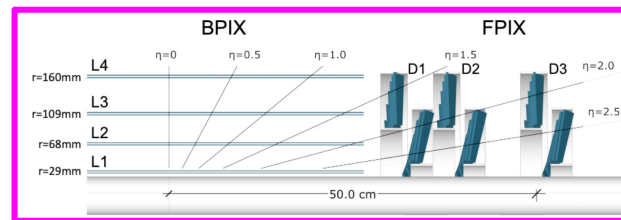
14/09/2011 G. Contin - PSD9

6

CMS Tracker



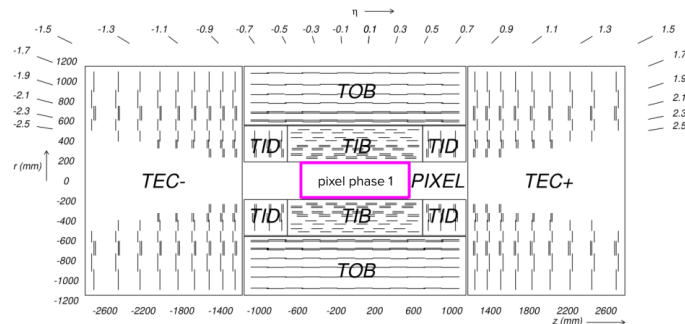
CMS Tracking system: Run 1 + Run 2 2010-2016



Since 2017

The tracking challenge at the LHC

- typically **30 charged particles** within the tracker acceptance per proton-proton collision and **~ 25-40 collisions** per event: **~O(1000) charged particles per event** need to be reconstructed.



Largest silicon tracker ever built

- active area: $\sim 200 \text{ m}^2$
- acceptance: $|\eta| < 2.5$
- immersed in a 3.8 T magnetic field

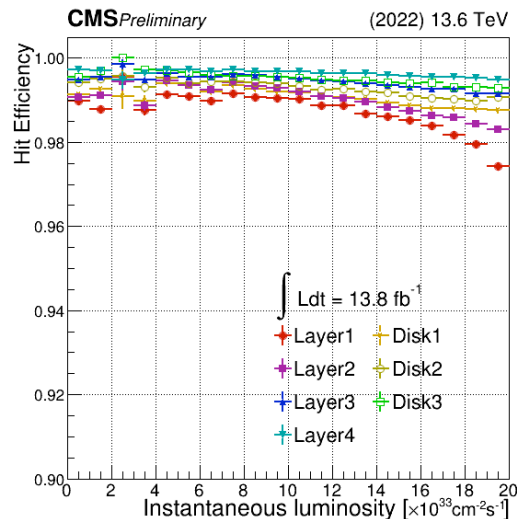
Strip detector [pitch: 80-180 μm^2]

- inner Barrel (**TIB**): 4 layers
- inner Disks (**TID**): 3 (x 2) layers
- outer barrel(**TOB**): 6 layers
- endcap (**TEC**): 9(x 2) disks.
- hit resolution: (10,40) x (230,530) μm
- 4 barrel layers.
- 3(x2) endcap disks.
- hit resolution: 10 x (20,40) μm

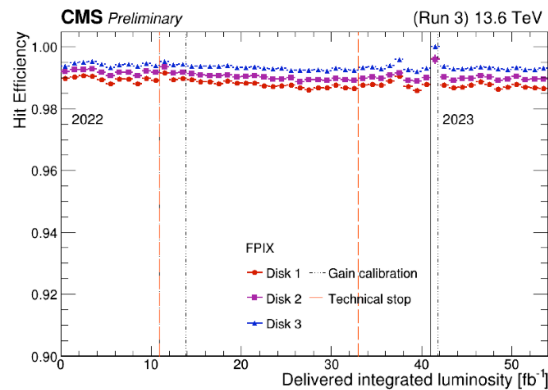
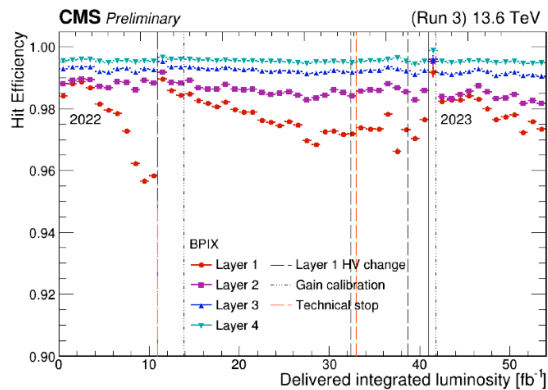


Beginning of Run 3

- Pixels refurbished and reinstalled in June 2021
- **Completely new layer 1** has significant improvements
 - ➡ Readout chip decreased dynamic inefficiency and reduced crosstalk
 - ➡ New TBM with additional delay option
 - ➡ New high density interconnect for more robust HV operation
- Some layer 2 modules replaced
- New DCDC converters
- Improved FPix cooling connections
- ➡ **Excellent performance in start of Run 3 in 2022**



Hit efficiency

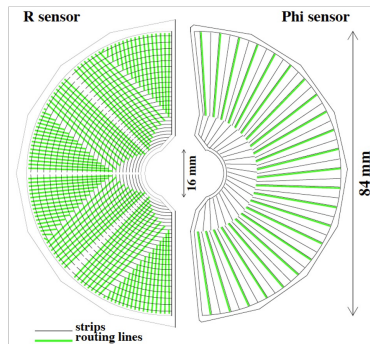


- Hit efficiency affected by gain calibration, HV setting, and annealing during technical stops
- ➔ High hit efficiencies for all layers and disks

LHCb tracker (Run1+Run2)

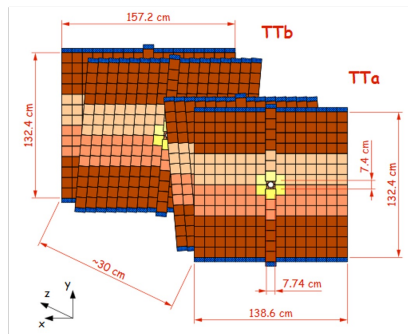
Current VELO

- Silicon (n^+ -on- n) micro-strip detectors
- 2x21 planes (R and ϕ)
- Floating pitch: $\sim 40 - 100 \mu m$, thickness: $300 \mu m$
- $\sim 180\,000$ readout channels
- Total silicon area $\sim 0.32 m^2$
- Detectors operate at $-8^\circ C$



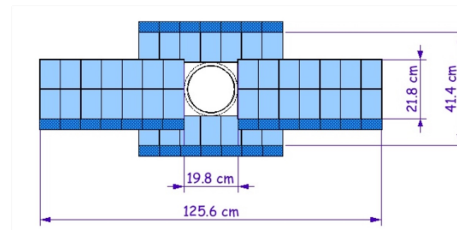
Current TT

- Silicon (p -on- n) micro-strip detectors
- Four planes ($0^\circ, +5^\circ, -5^\circ, 0^\circ$)
- Pitch: $183 \mu m$, thickness: $500 \mu m$
- Long readout strips (up to $37 cm$)
- $\sim 143\,000$ readout channels
- Total silicon area $\sim 8 m^2$
- Detectors operate at $5^\circ C$

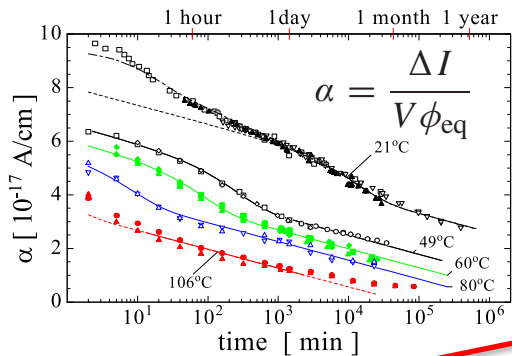


Current IT

- Silicon (p -on- n) micro-strip detectors
- Four boxes and four planes ($0^\circ, +5^\circ, -5^\circ, 0^\circ$)
- Pitch: $198 \mu m$, thickness: $320 \mu m$ and $410 \mu m$
- $\sim 130\,000$ readout channels
- Total silicon area $\sim 4.2 m^2$
- Detectors operate at $5^\circ C$



Annealing: leakage current and effective doping



Fluence rate
measured in
data

$$I_{leak} = \left(\Phi / L_{int} \right) \cdot \sum_{i=1}^n V_i \cdot L_{int,i} \left[\sum_{j=1}^{n_{states}} \alpha_j((T_i, t_i), (T_{i+1}, t_{i+1}), \dots, (T_n, t_n)) \right]$$

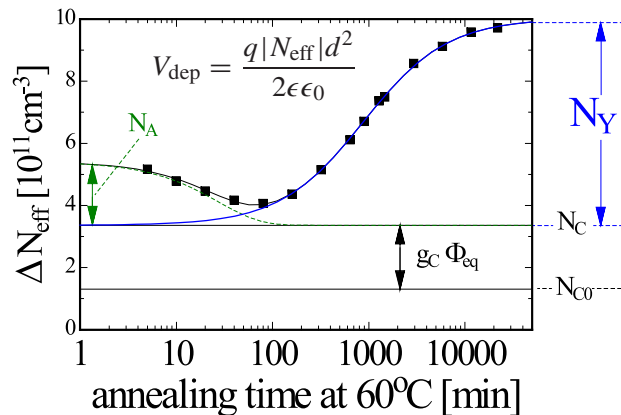
Some over time intervals t_i spent at temperature T_i

$$\alpha_1^A = \alpha_I \exp \left(- \sum_{j=i}^n \frac{t_j}{\tau(T_j)} \right)$$

$$\alpha_2^A = \alpha_0^* - \beta \log \left(\sum_{j=i}^n \frac{\Theta(T_j) \cdot t_j}{t_0} \right),$$

Parameter	Value	Units
α_I	$(1.23 \pm 0.06) \times 10^{-17}$	A/cm
$k_{I,0}$	$1.2^{+5.3}_{-1.0} \times 10^{13}$	Hz
E_I	1.11 ± 0.05	eV
α_0^*	7.07×10^{-17}	A/cm
β	3.29×10^{-18}	A/cm
E_I^*	1.30 ± 0.14	eV
t_0	1	min.
T_{ref}	21	°C

M. Moll, 2018



$$\Delta N_{eff}(t) = \underline{N_A(t)} + \underline{N_C} + \underline{N_Y(t)}$$

beneficial

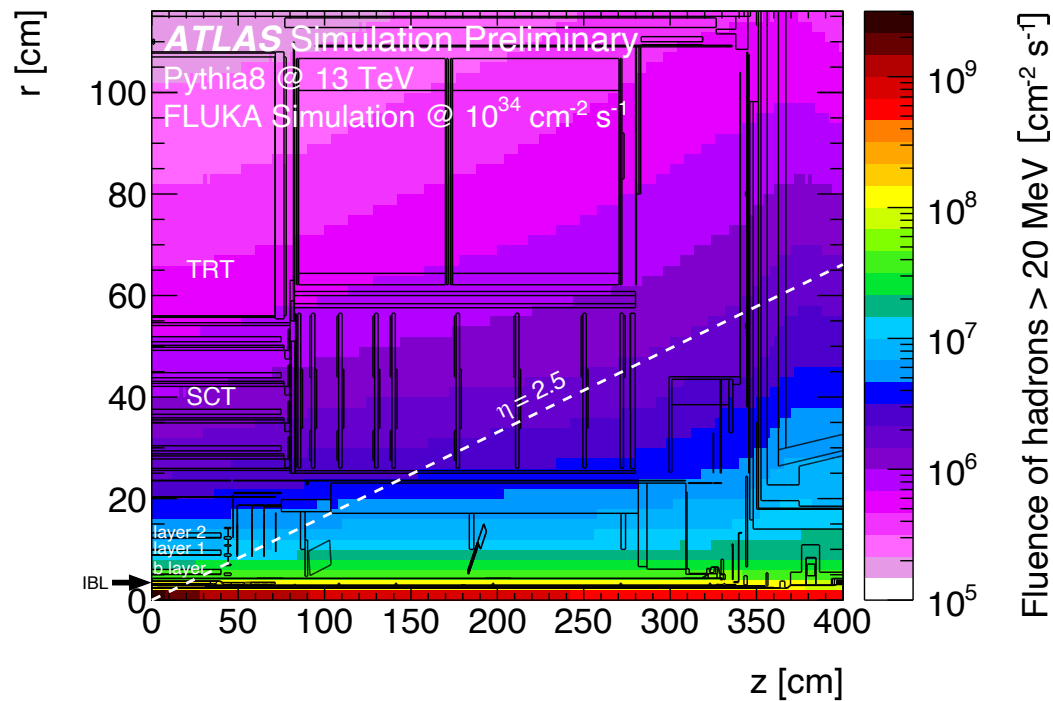
stable

reverse

$$\underline{N_A(t)} = g_a \phi_{eq} \exp(-t/\tau_a)$$

$$\underline{N_C} = N_{C,0}(1 - \exp(-c\phi_{eq})) + g_c \phi_{eq}$$

$$\underline{N_Y(t)} = g_y \phi_{eq}(1 - \exp(-t/\tau_y))$$



Radiation damage to electronics

Performance of micro-electronics is impacted by radiation damage in several ways:

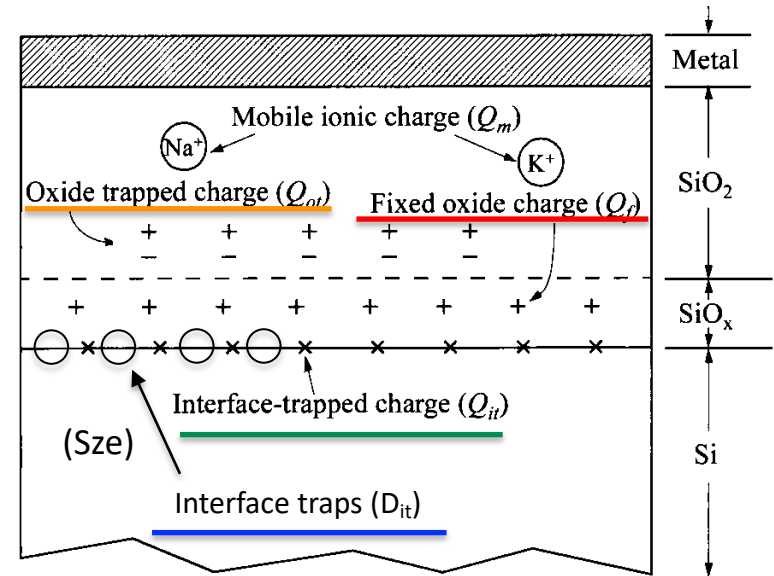
- **Total Ionising Dose (TID):** associated with the **build up of trapped charge states**, either in an oxide layer or at the oxide–bulk. TID measured in Gray (Gy) or rad (=0.01 Gy)
- **Single Event Effects (SEE):** **large charge deposition** in a sensitive node. The SEE sensitivity of a chip to radiation is defined by a cross-section (ratio of events rate and flux triggering them)
- (NIEL – not discussed today, less important for CMOS)

Radiation damage to Silicon Oxide & interface

Electronics sensitive to defects and charges in Oxide and Si-SiO₂ interface

Main actors:

- Interface traps and Trapped charges
 - located at Si-SiO₂ **interfaces**
 - states in Si forbidden gap
 - charge density is bias dependent
- Fixed oxide charges
 - near or at **interface**
 - immobile under applied electric fields
- Oxide trapped charges
 - distributed **inside the oxide** layer
- (Mobile ionic charges)



Total Ionizing Dose effects (TID) are associated with the build up of trapped charge states, either in an oxide layer or at the oxide–bulk

Single Event Effects (SEE) macroscopic effects

SEEs include

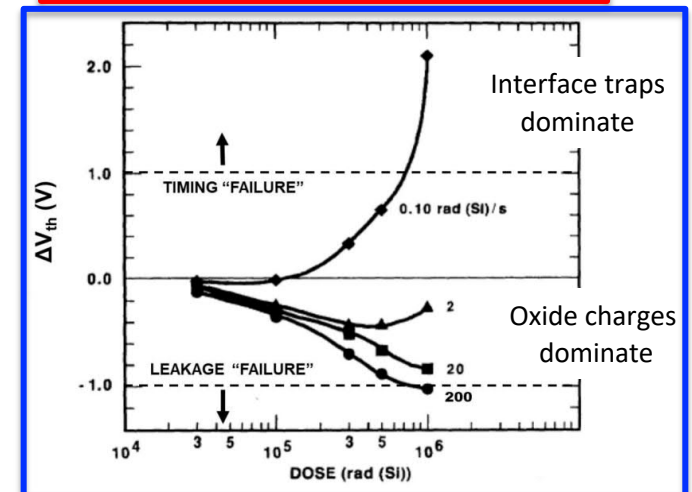
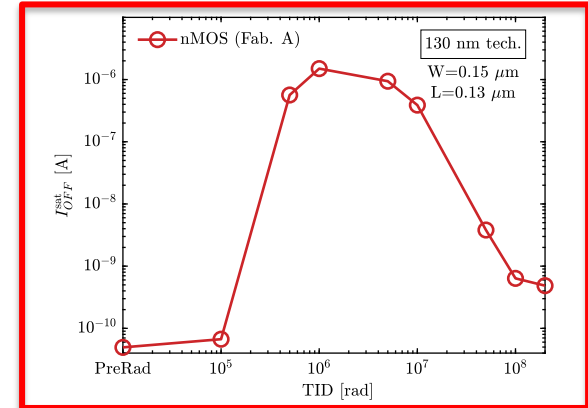
- soft SEEs (called soft Single Event Upsets (SEUs)): radiation induced bit-flips which can be recovered by reconfiguring the system
- hard SEEs (hard SEUs): permanent radiation induced bit-flips; e.g. bit stuck at '1' in a memory cell
- destructive SEEs: e.g. Single Event Latchup (SEL), which leads to permanent damage due to thermal destruction

TID related macroscopic effects

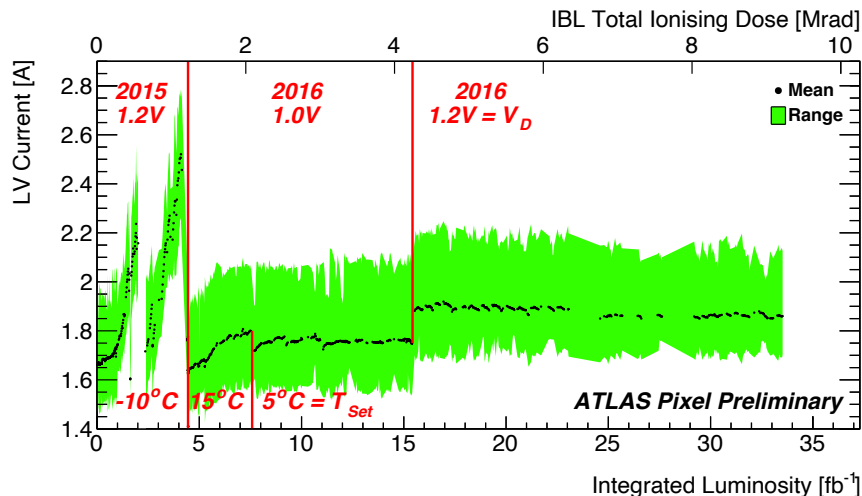
In the oxide the holes are less mobile than electrons so they get trapped in defects, resulting in an accumulation of positive charges under irradiation

This layer of charges determines a change in the electric field which in turn is responsible for a drift in the threshold voltage and of the increase of leakage current

These processes are temperature and dose rate dependent

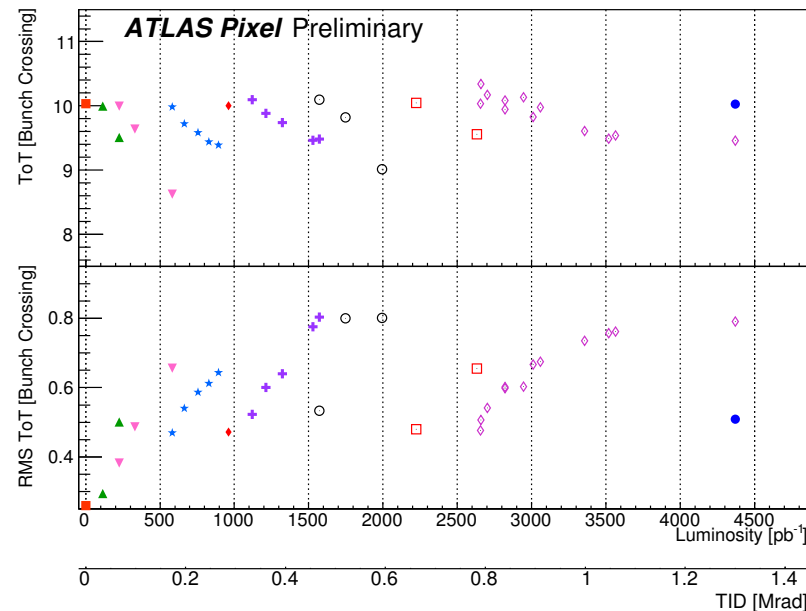


TID effects in ATLAS IBL



Drift of low voltage currents

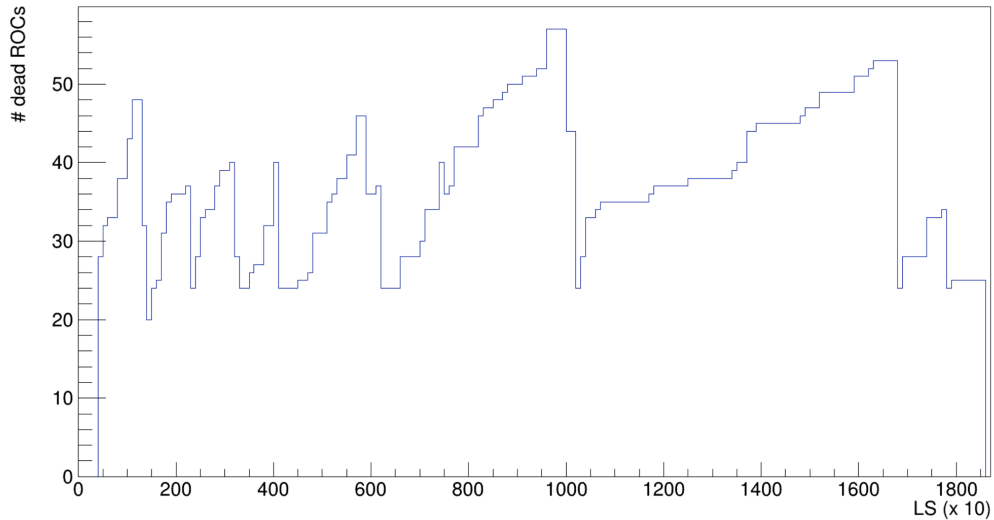
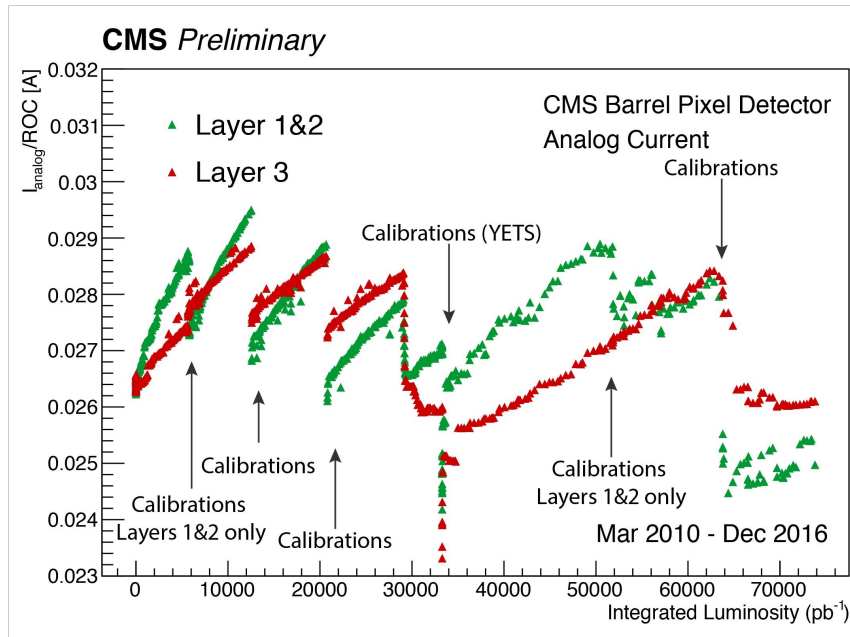
Temperature increase and voltage decrease helped in keeping currents within limits (3 A for 4 chips group)



Impact on gain and its dispersion

Regular retuning brought values back to normal

CMS TID & SEU effects



Inactive ROCs vs time in BPIX L1 in 2017

CMS Phase-0 analog current evolution

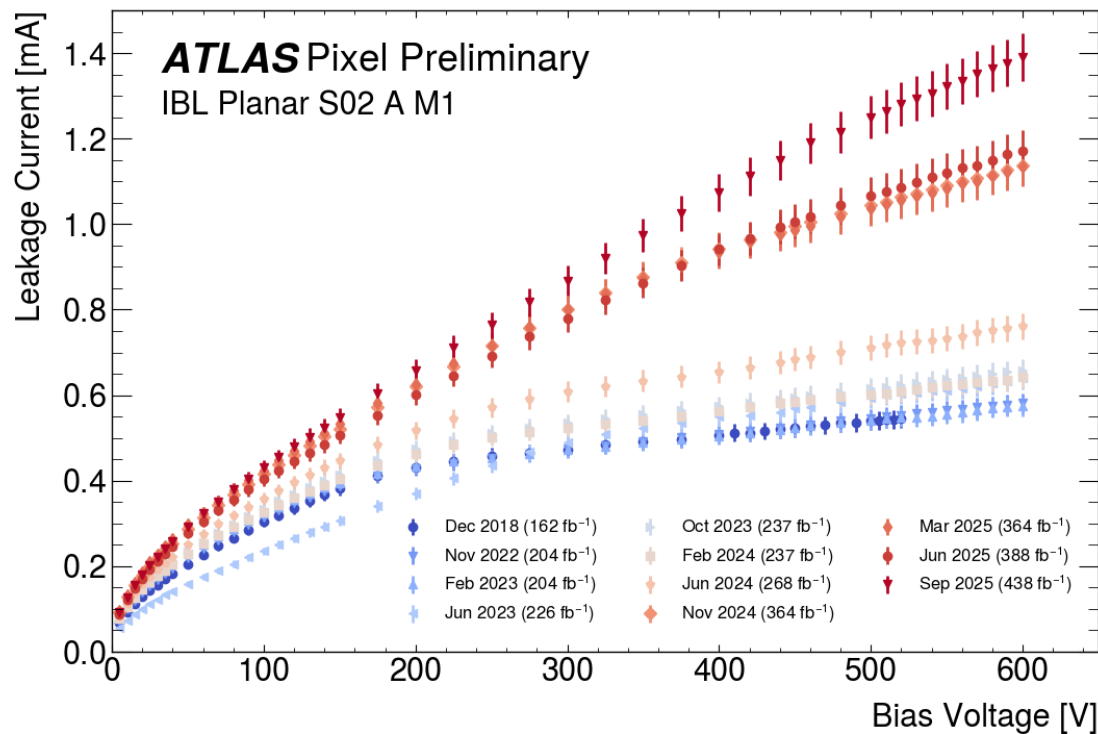
Recalibration of L1&L2 already after few fb^{-1}

SEU rate depends on instantaneous luminosity

(~ 1 inactive ROS/5 minutes @ $1.0 \times 10^{34} \text{ /cm}^2/\text{s}$)

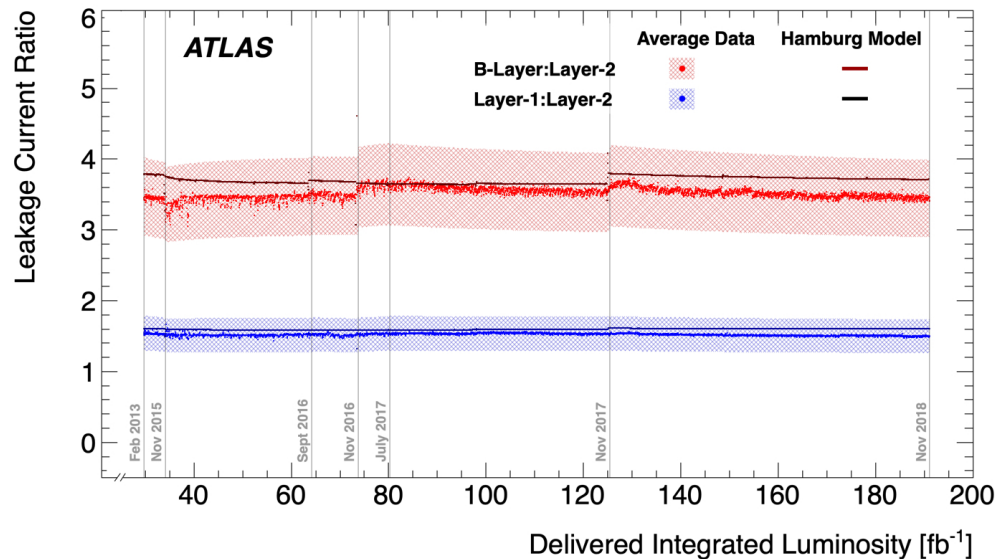
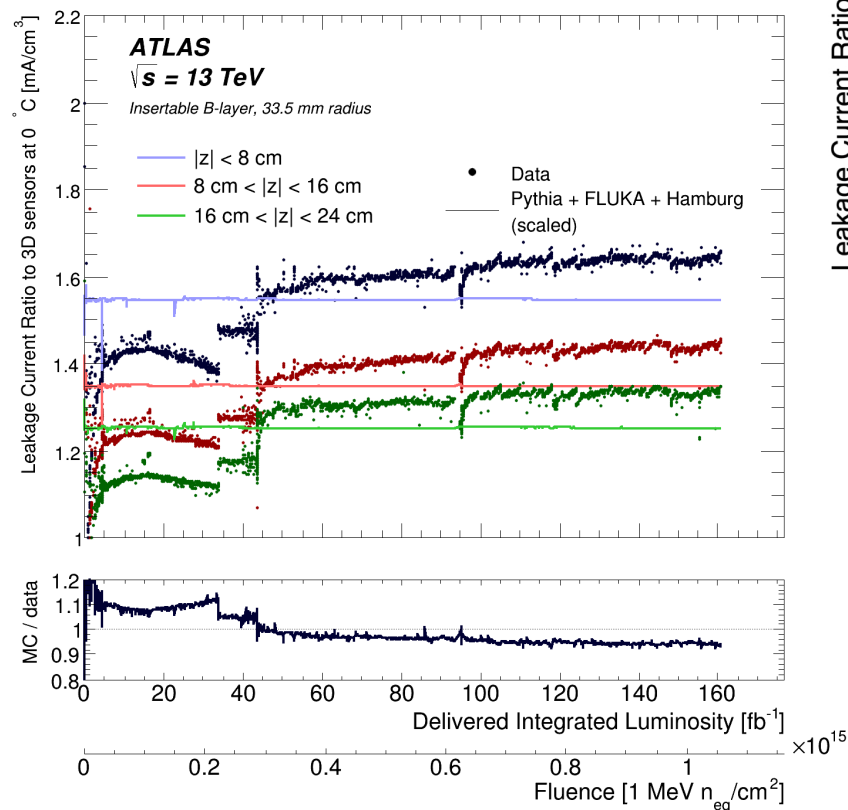
Leakage current ATLAS

[PIXE-2025-02](#)



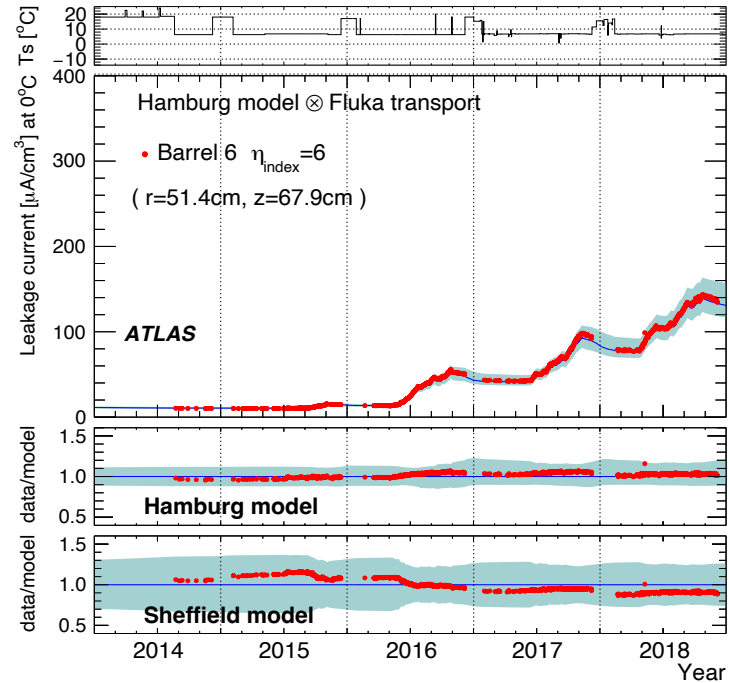
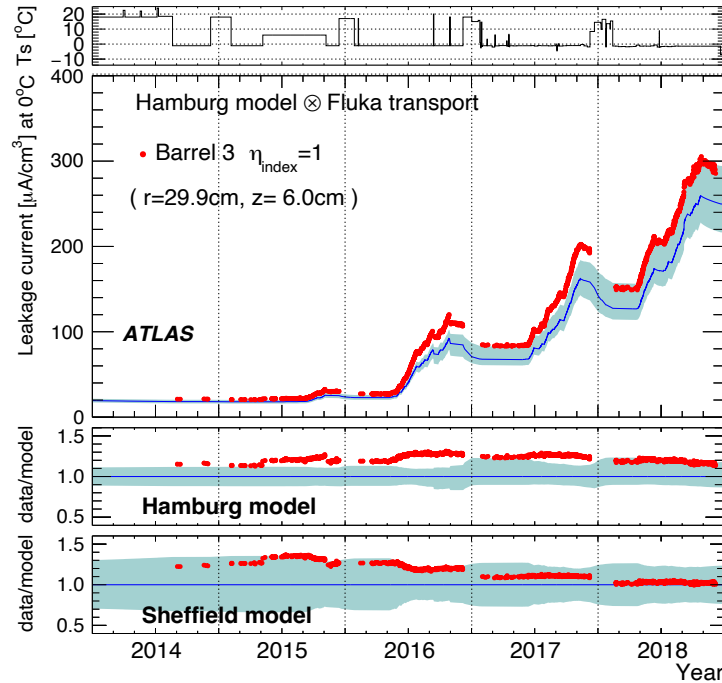
Leakage current ratios - ATLAS

JINST 16 P08025



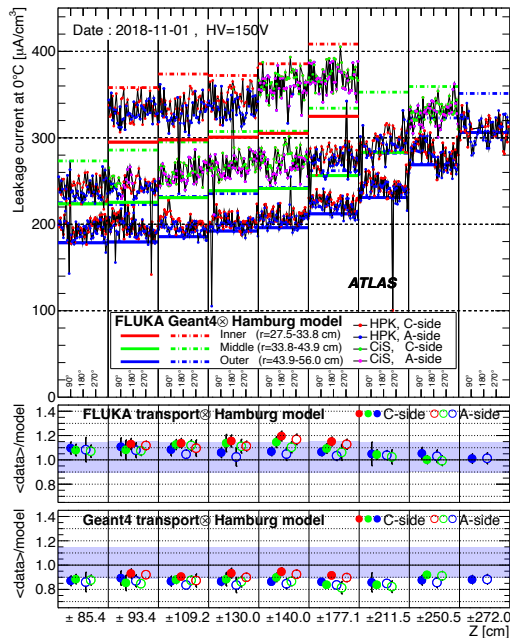
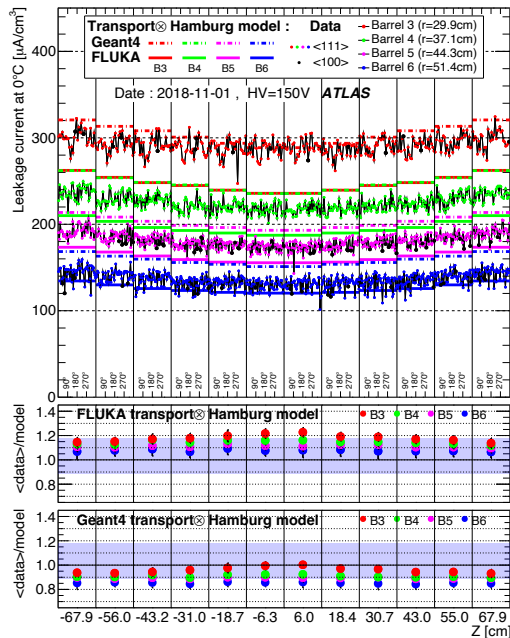
Leakage current – ATLAS SCT

JINST 16 P08025



Leakage current – ATLAS SCT

JINST 16 P08025

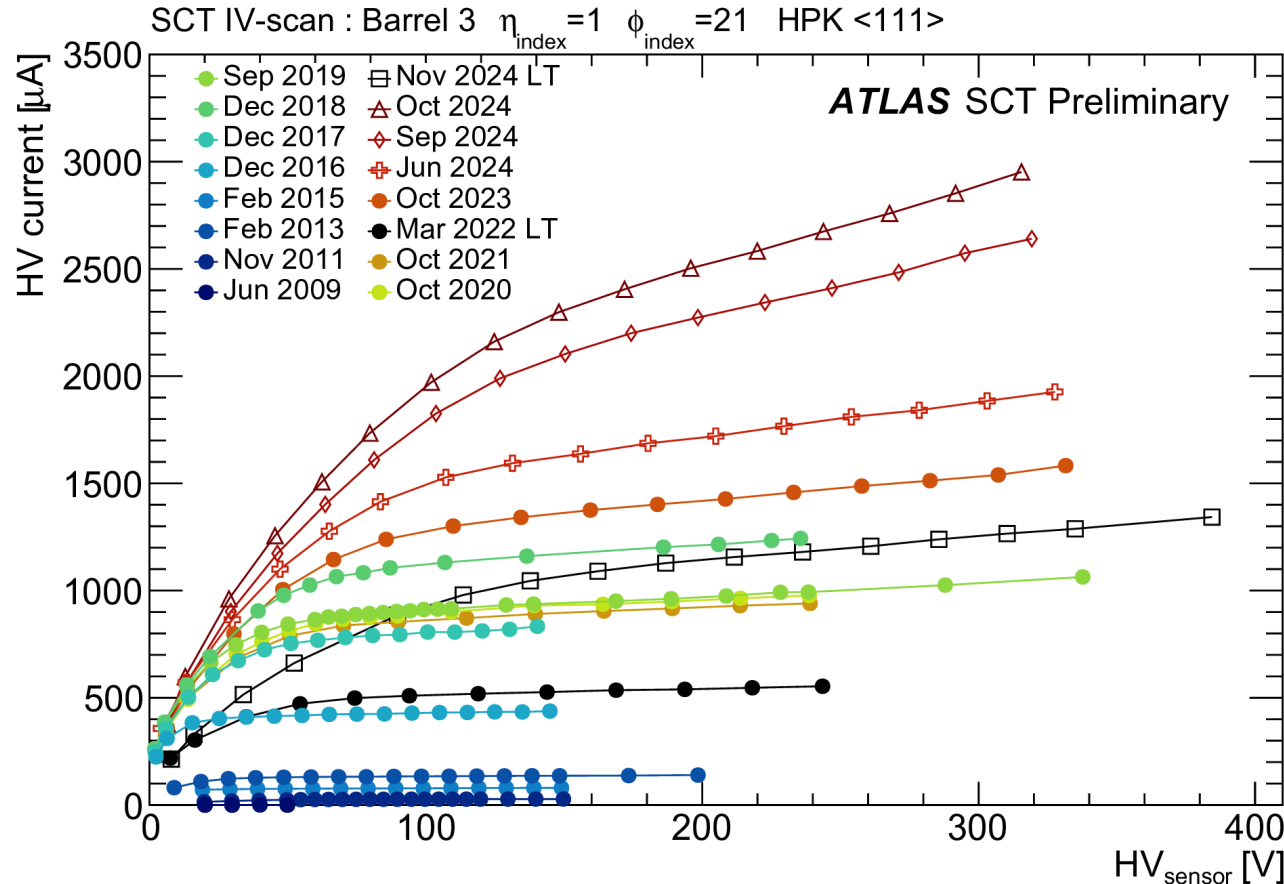


SCT scale factors

Detector	Layer	r [cm]	Mean SF	Min. SF	Max. SF	SF uncert.
SCT	Barrel 3	29.90	1.13	1.11	1.17	0.11
	Barrel 4	37.10	1.09	1.05	1.15	0.11
	Barrel 5	44.30	1.06	1.01	1.13	0.10
	Barrel 6	51.40	1.03	0.98	1.09	0.11

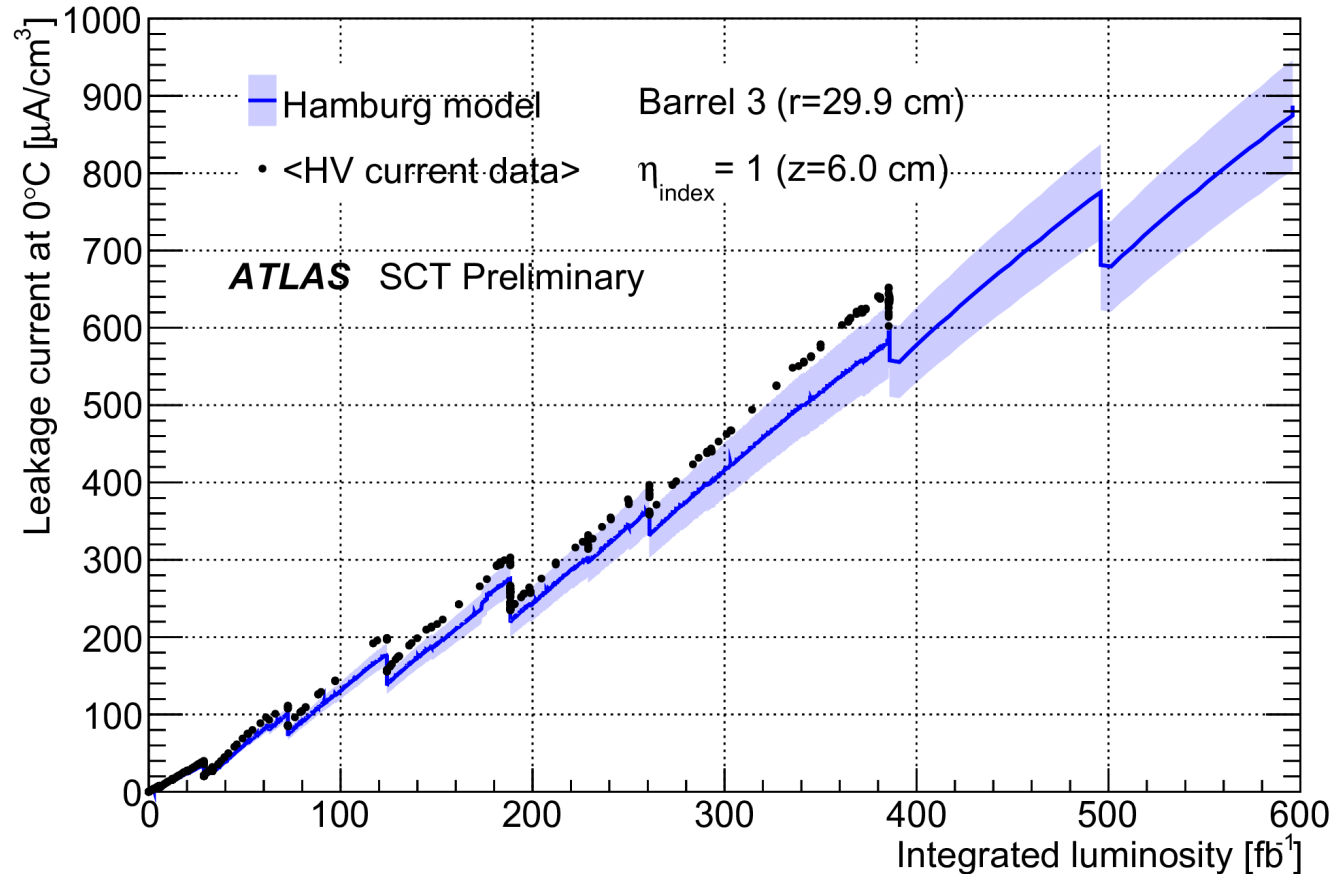
Leakage current – ATLAS SCT

SCT-2024-002



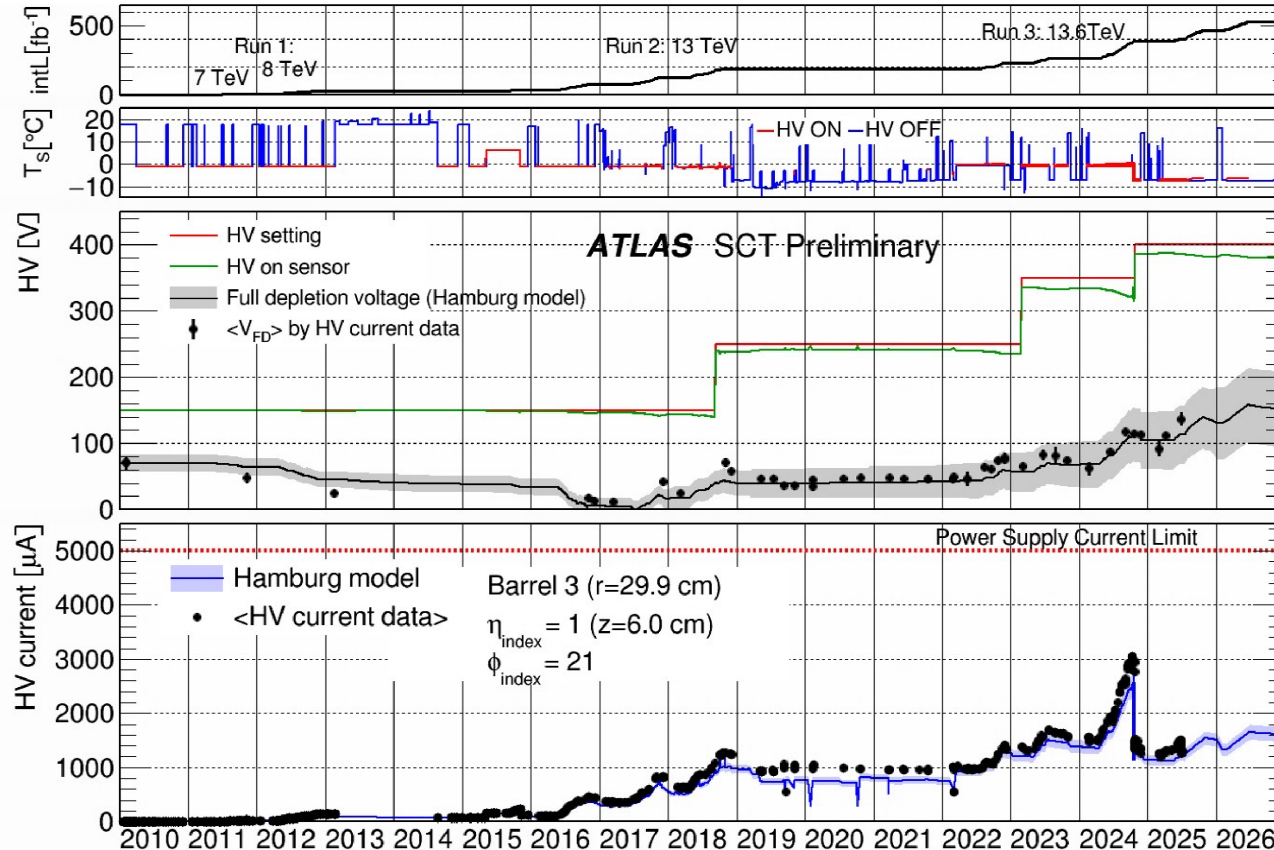
Leakage current – ATLAS SCT

[SCT-2024-002](#)

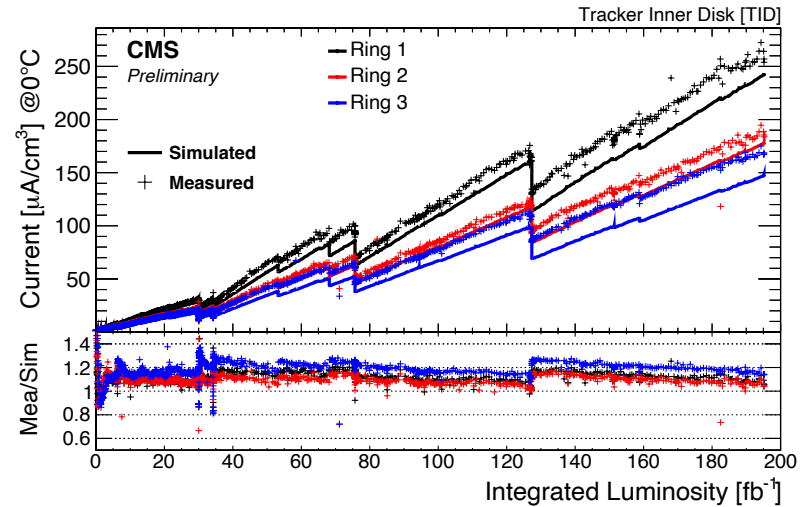
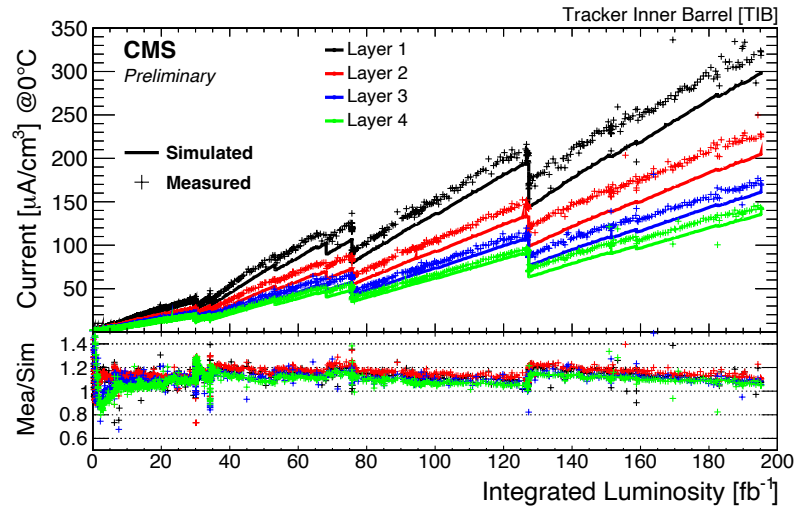


Leakage current – ATLAS SCT

SCTD-2025-02



Leakage current – CMS Strips



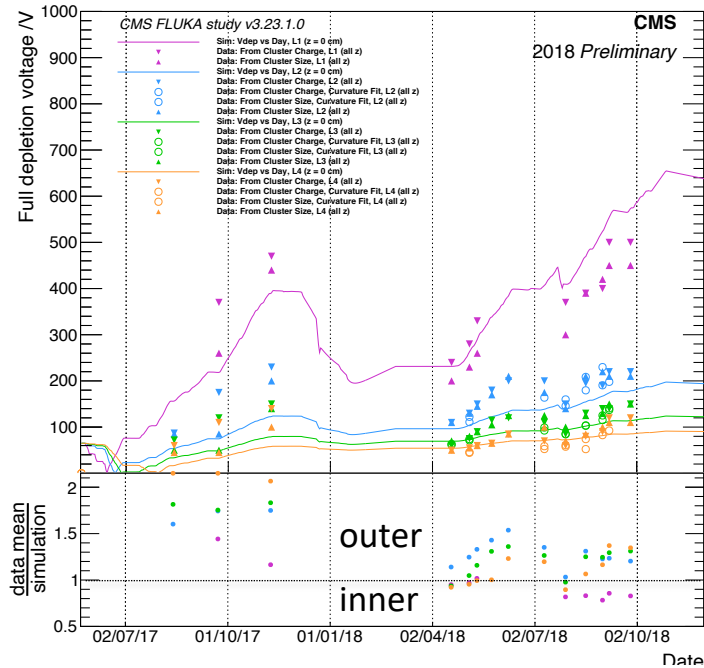
No scaling applied

Agreement within 20%

Compatible with uncertainties

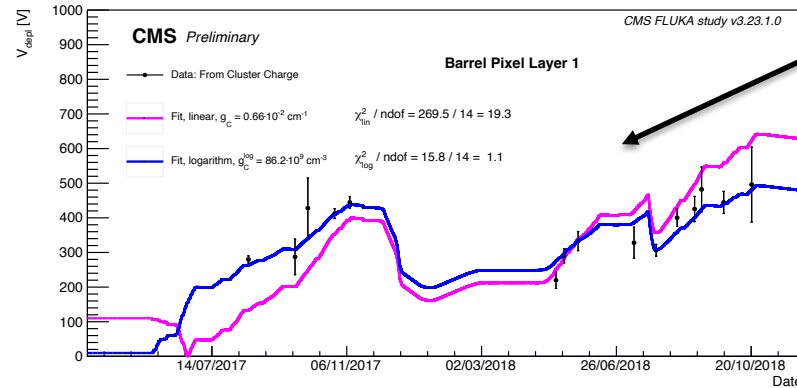
Depletion voltage – CMS Pixel and Strips

Phase-1 Pixel - Full depletion voltage vs days

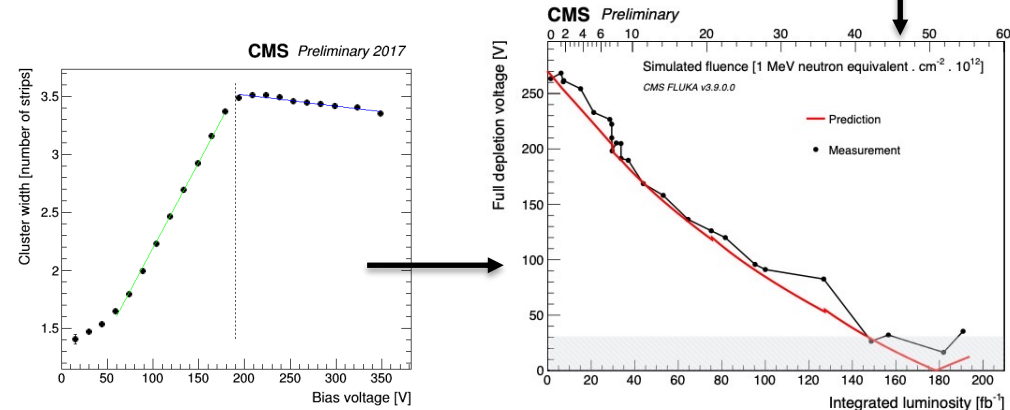


Depletion voltage inferred from cluster charge/size

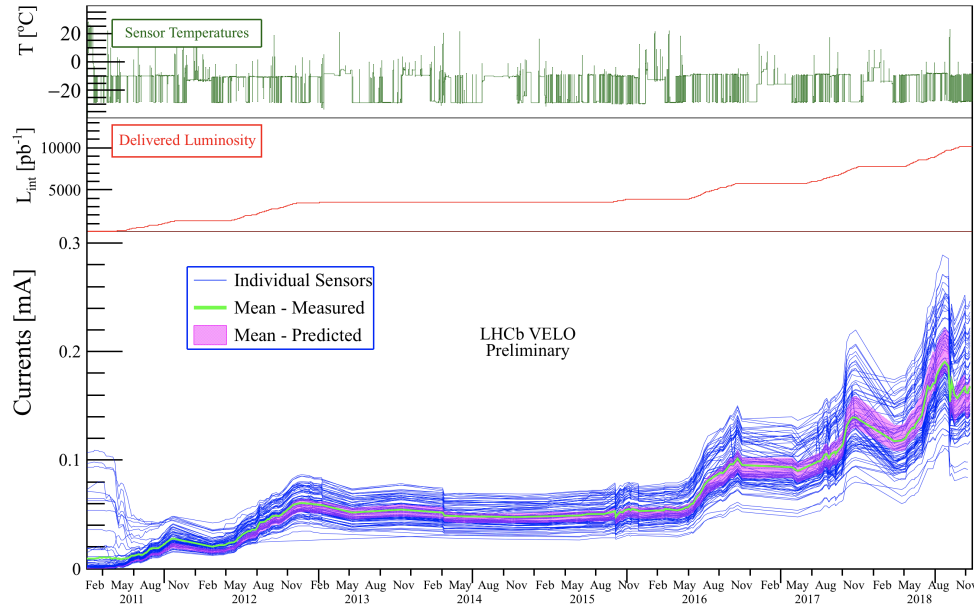
Phase-1 Barrel Pixel - Full depletion voltage vs day



Log. instead of lin. dep on fluence?
Excellent agreement with predictions

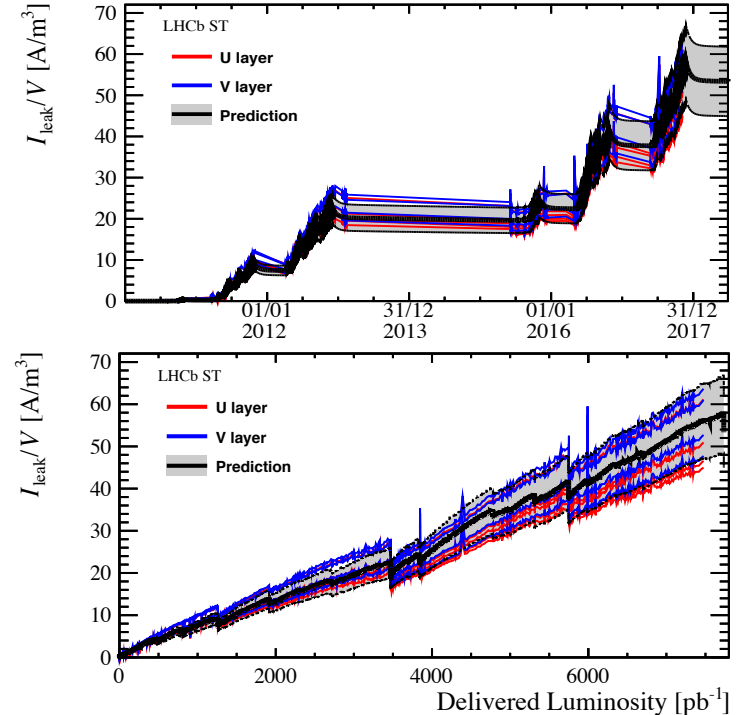


Leakage current – LHCb Velo & TT



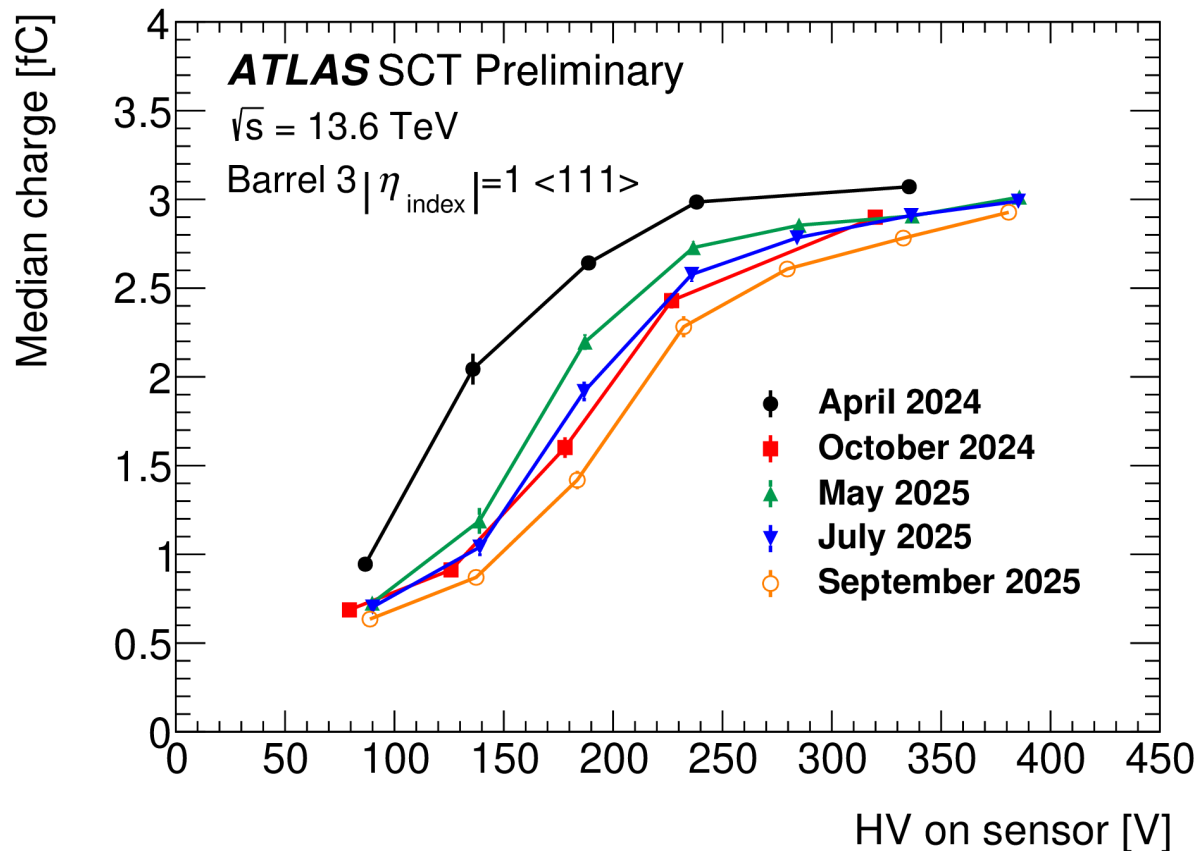
No scaling

Excellent agreement over the entire lifetime

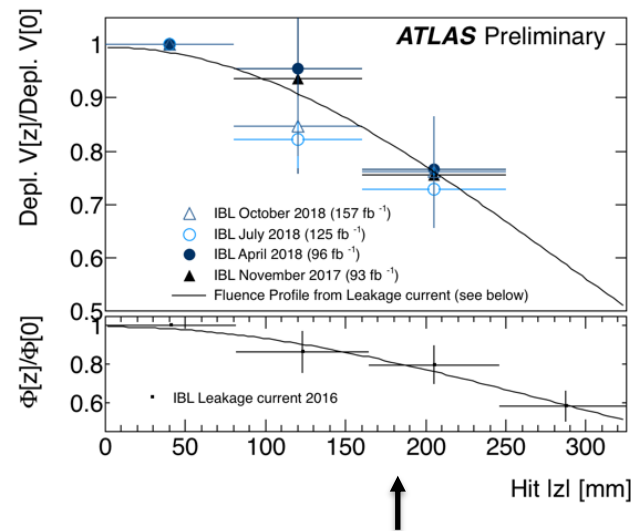
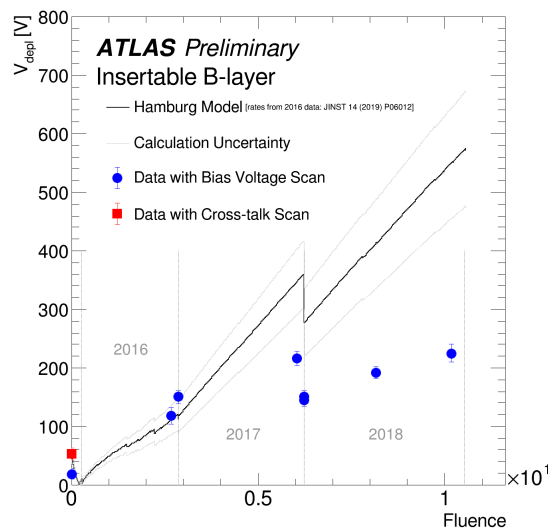
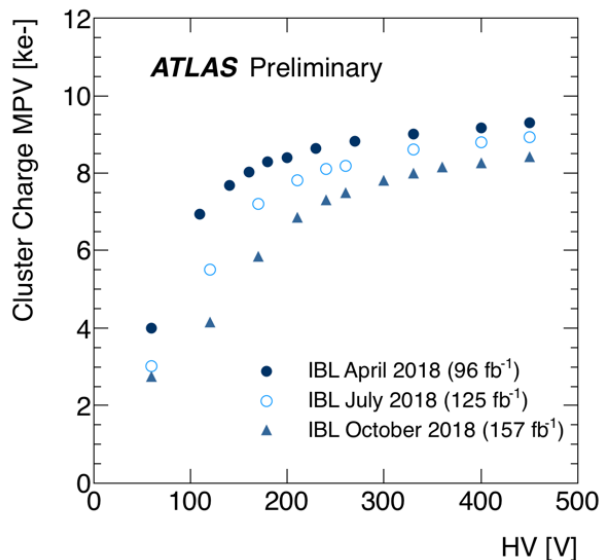


Depletion voltage – ATLAS SCT

[SCTD-2025-04](#)



Depletion voltage, CCE and annealing - ATLAS



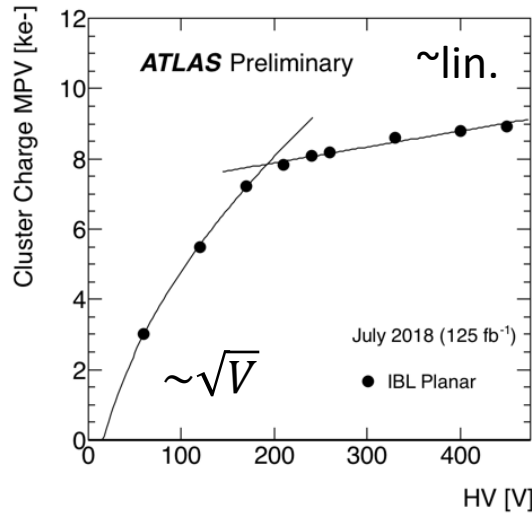
Modelling radiation damage to pixel sensors in the ATLAS detector

Parameter	IBL [$\times 10^{-2} \text{cm}^{-1}$]	B-layer [$\times 10^{-2} \text{cm}^{-1}$]	ROSE Coll. [$\times 10^{-2} \text{cm}^{-1}$]
g_A	1.4 ± 0.5	1.4 ± 0.5	1.4 (n)
g_Y	6.0 ± 1.6	6.0 ± 1.6	2.3 (p), 4.8 (n)
g_C	1.1 ± 0.3	0.45 ± 0.1	0.53 (p), 2.0 (n)

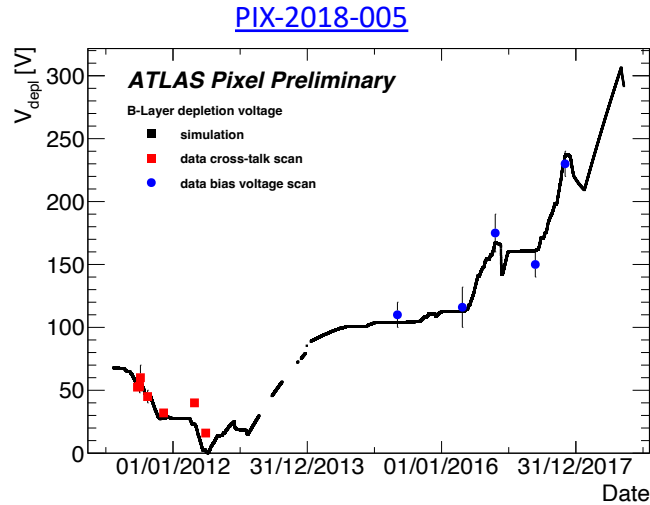
3rd RD48 status report

Fluence profile visible
also through depletion
voltage

Depletion voltage – ATLAS IBL, PIX & SCT

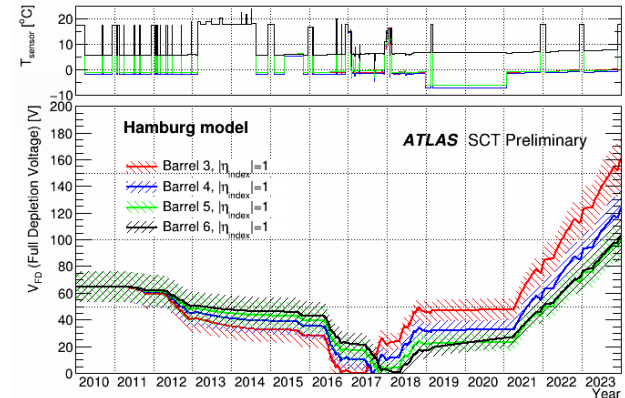
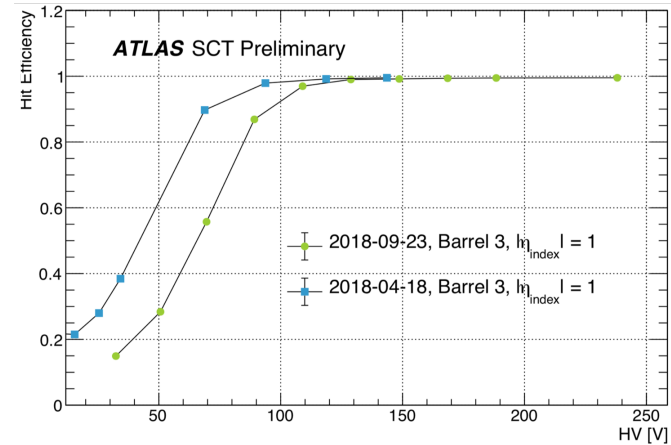


Depletion voltage inferred from cluster charge (IBL & PIX) and hit efficiency (SCT)



Hamburg model parameters adjusted on data

Inversion happened in 2016



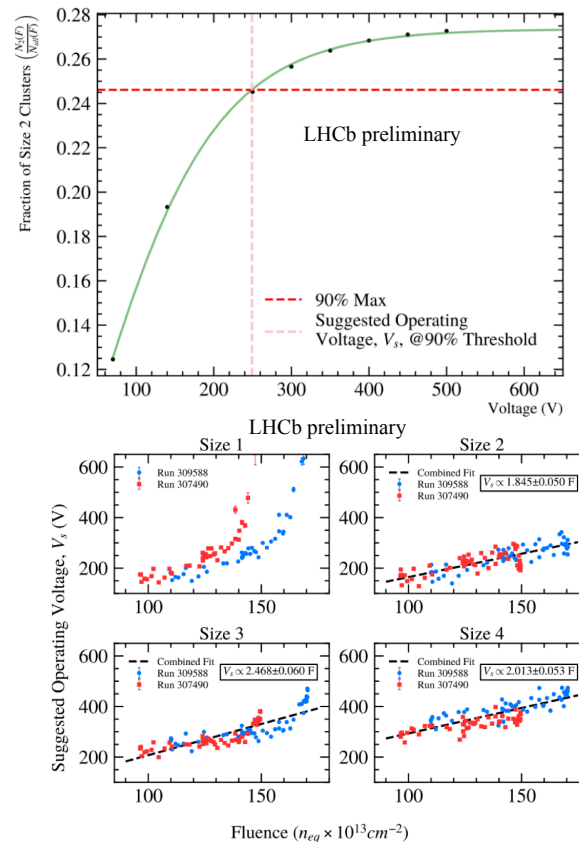
Operation voltage – LHCb Velopix

Operation voltage

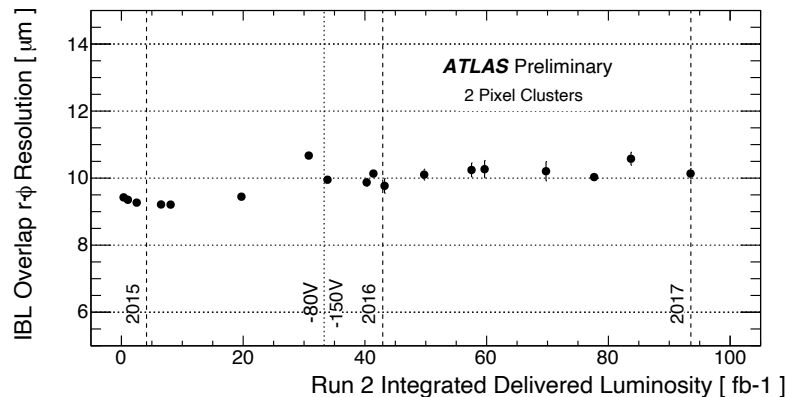
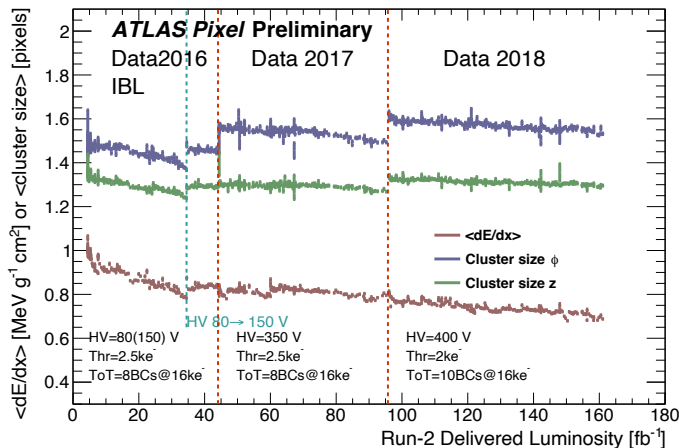
Baseline Strategy

- For every module, plot the fraction of size x clusters as a function of HV
- Extract a suggested operating voltage, V_s for every module
- Plot V_s vs (innermost) fluence module has been exposed to

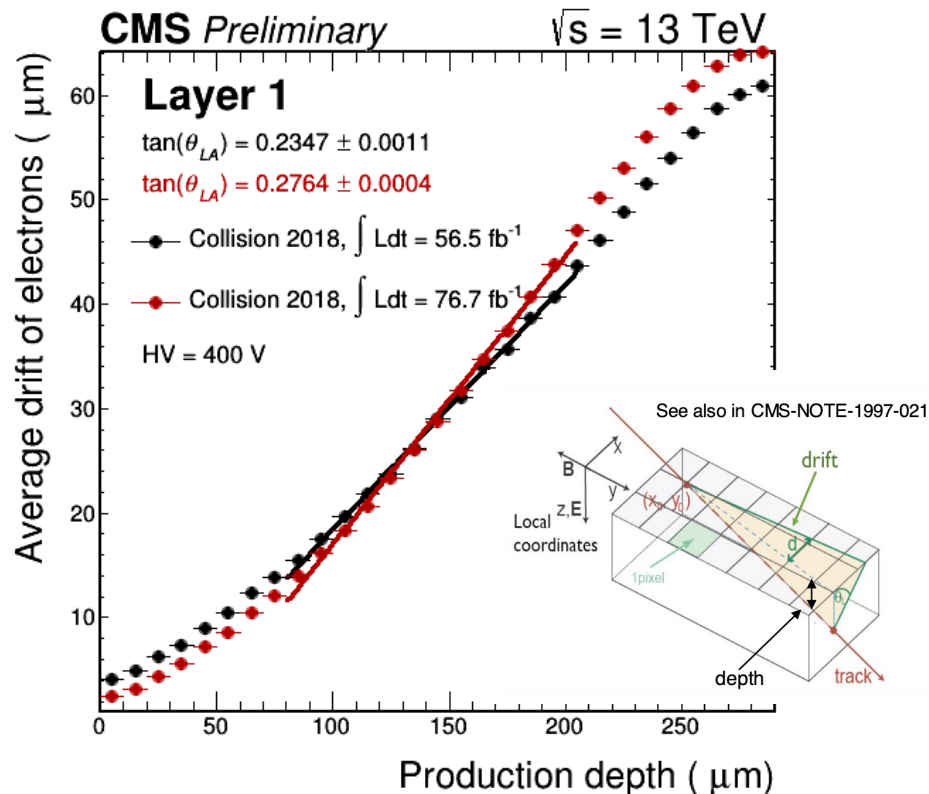
[V. Zhovkovska, Tipp 2026](#)



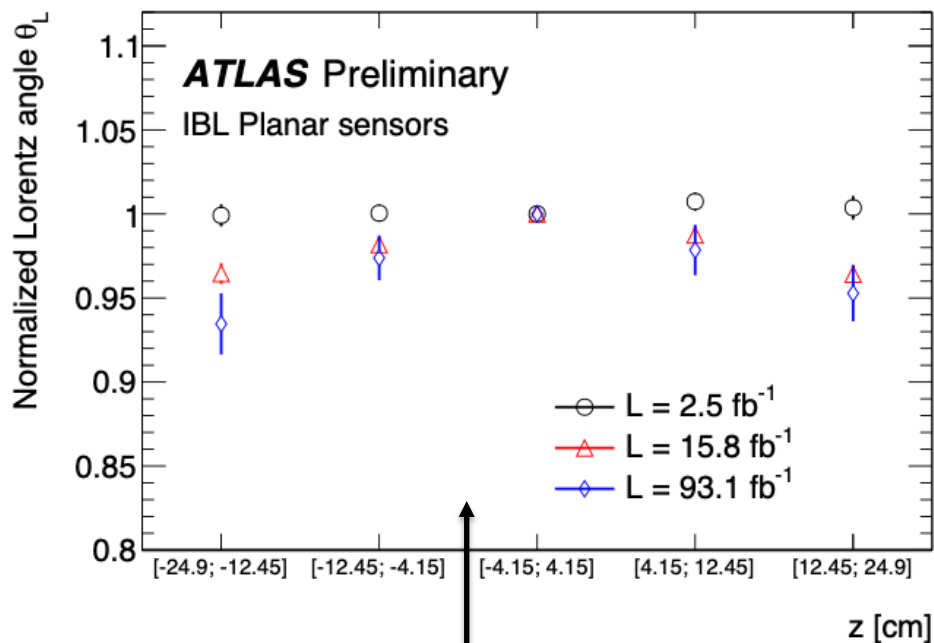
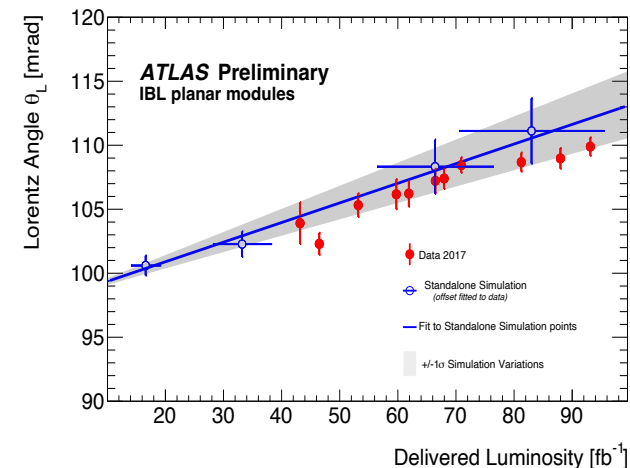
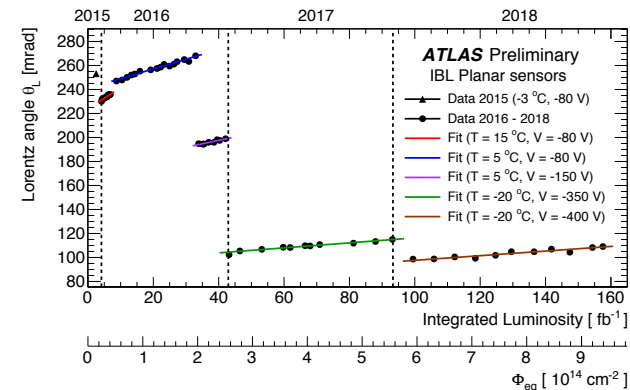
dE/dx, Lorentz Angle & Space point resolution



Deflection and Lorentz Angle

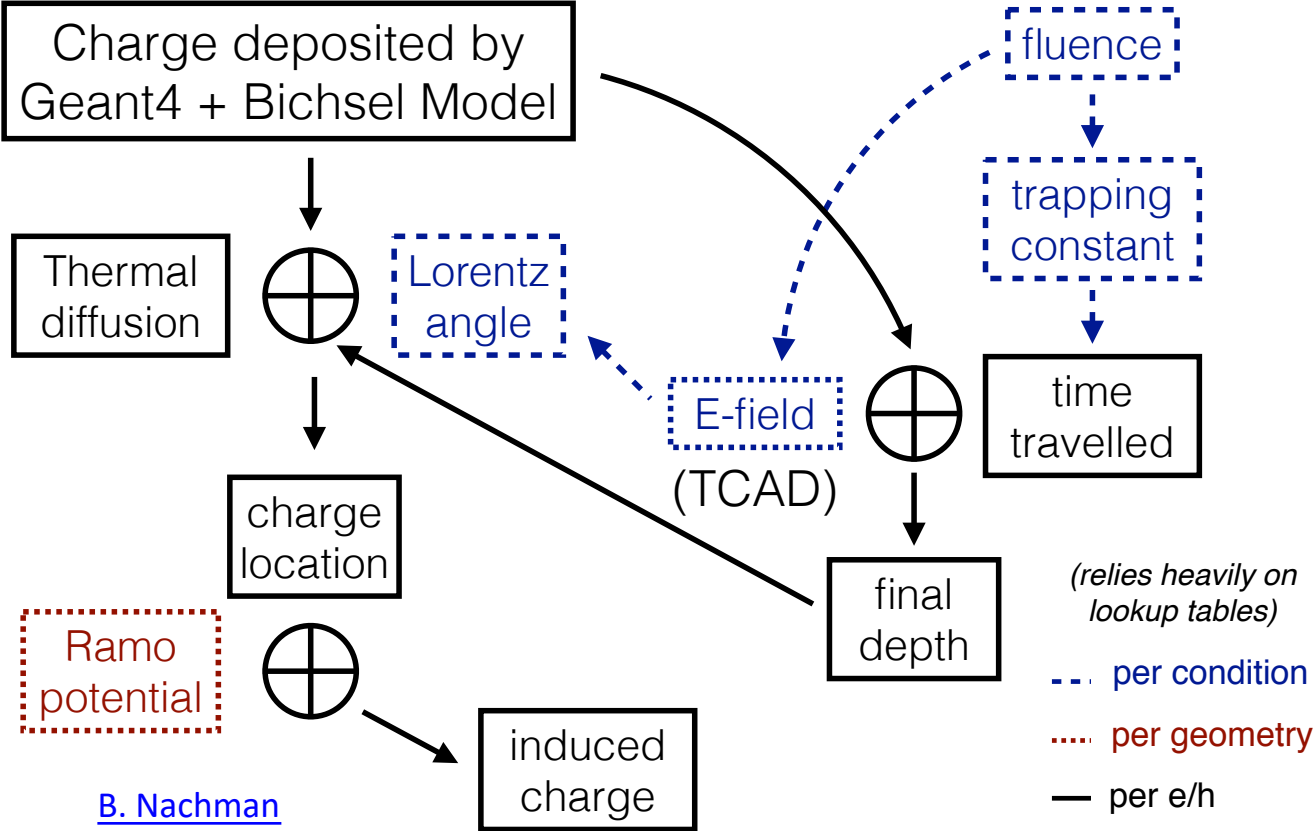


Lorentz Angle – ATLAS



Fluence profile visible also through Lorentz angle

ATLAS Radiation damage digitizer: implementation

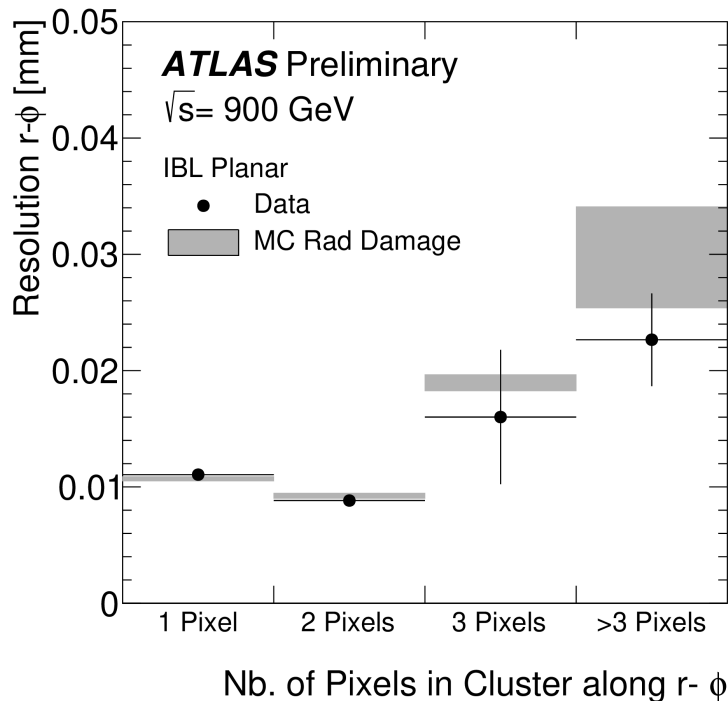
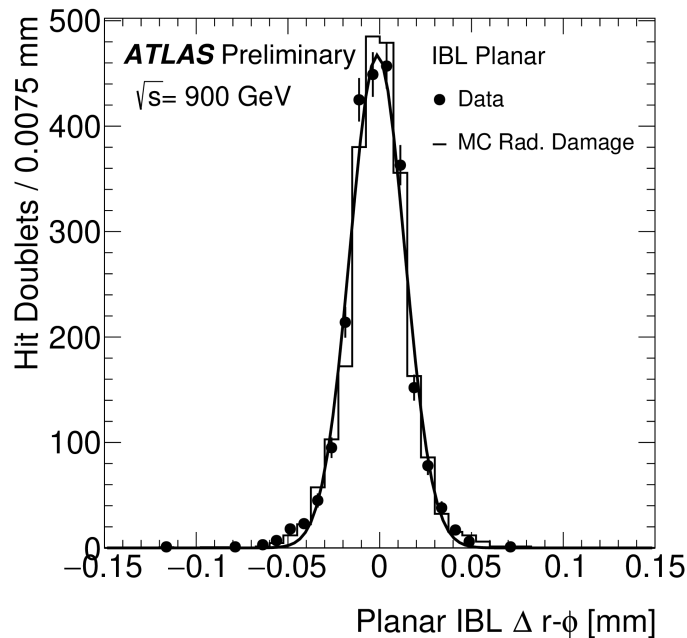


**Now part of
official ATLAS simulation**

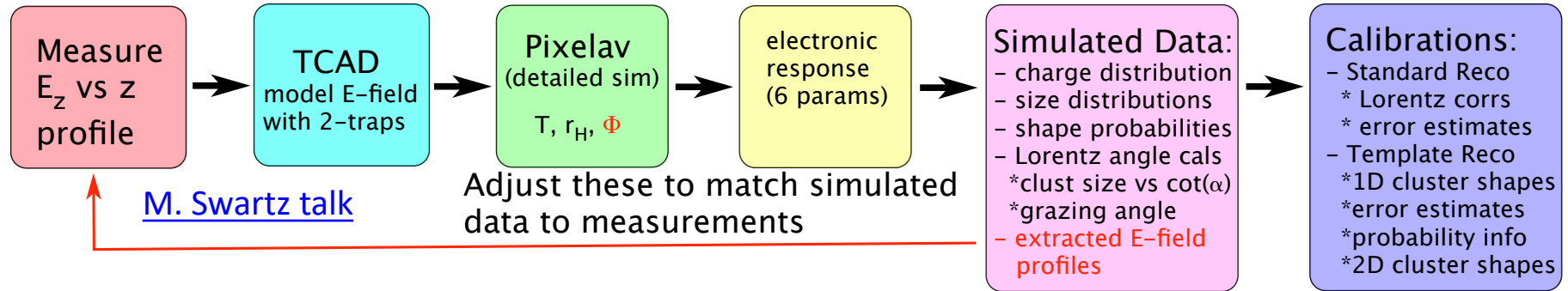
B. Nachman

ATLAS Pixel hit spatial resolution

Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at $\sqrt{s}=900$ GeV

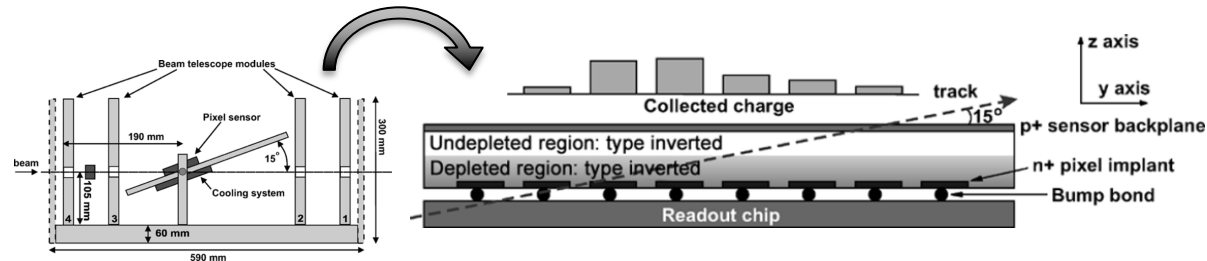


CMS Pixelav

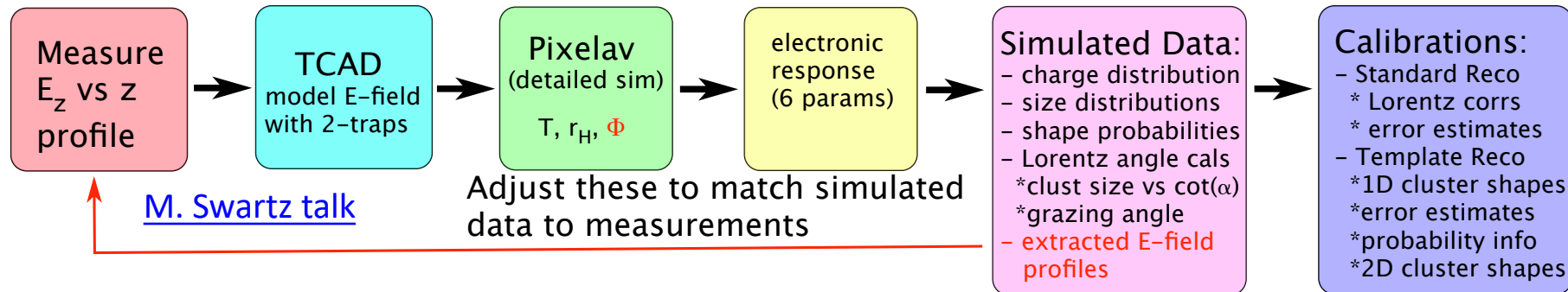


SW created to interpret testbeam data from irradiated detectors

Based on TCAD simulations and numerical simulations for charge propagation and trapping

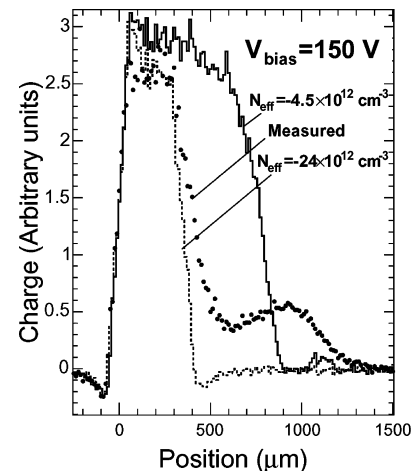
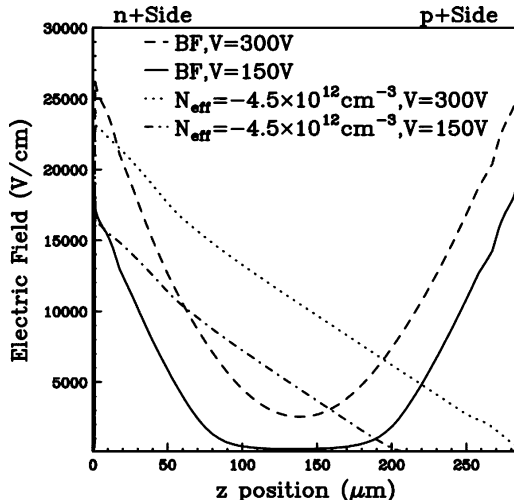


CMS Pixelav



SW created to interpret testbeam data from irradiated detectors

Based on TCAD simulations and numerical simulations for charge propagation and trapping



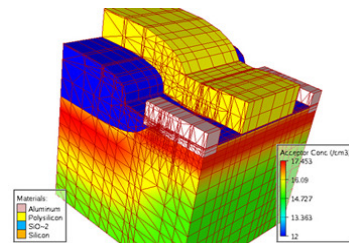
TCAD simulations

- Technology Computer Aided Design - TCAD
- Solve drift/diffusion & Poisson equations for electrons and holes:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} + G_n - R_n ; J_n = qn\mu_n E + qD_n \frac{\partial n}{\partial x}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} + G_p - R_p ; J_p = qn\mu_p E - qD_p \frac{\partial p}{\partial x}$$

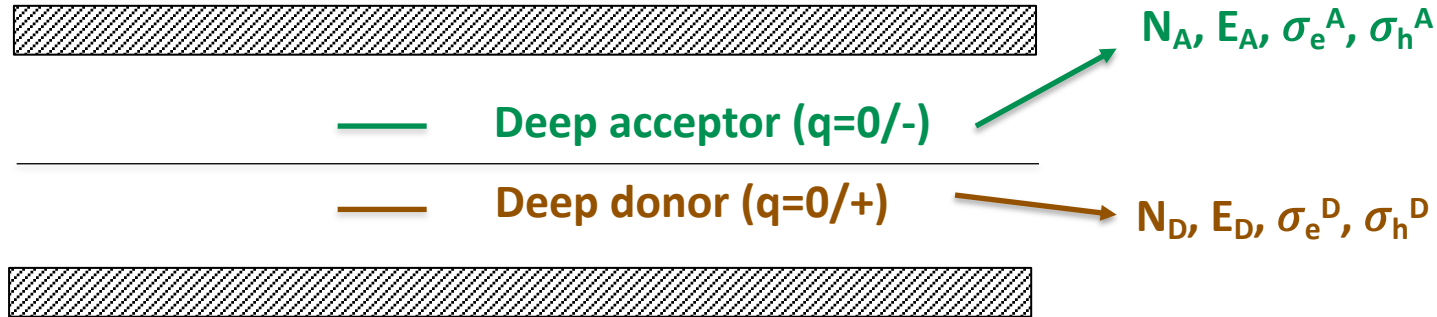
$$\frac{\partial^2 \psi}{\partial x^2} = -\frac{q}{\epsilon_{Si}\epsilon_0} (N_D + p(x) - n(x) - N_A)$$



- taking into account boundary conditions
 - Electrodes' potentials, interface charges, etc
- on a grid of points

SILVACO

Intermezzo – TCAD simulations



Trap	E (eV)
Donor	$E_V + 0.48$
Acceptor	$E_C - 0.525$

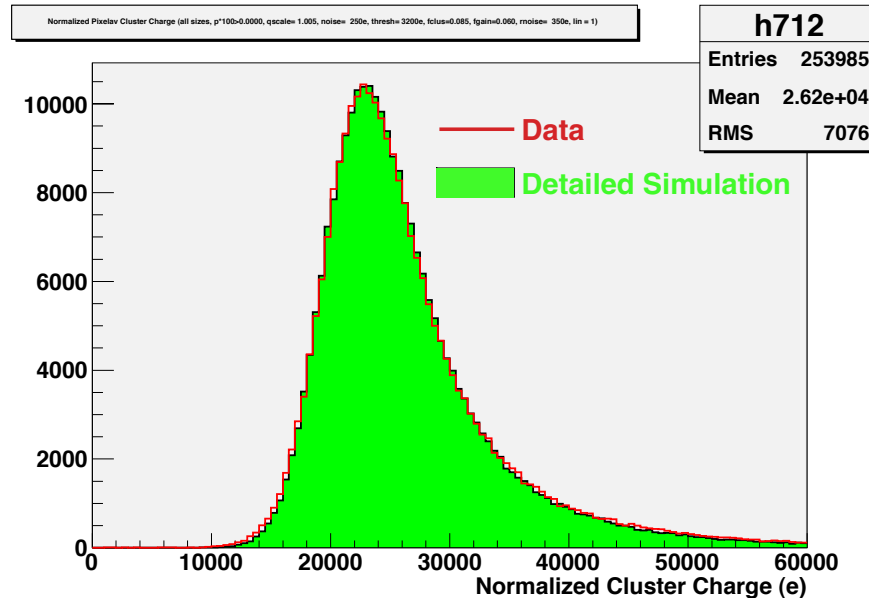
[V. Chiochia et al. \(2006\)](#)

Φ (n_{eq}/cm^2) ($\times 10^{14}$)	$N_A(cm^{-3})$ ($\times 10^{15}$)	$N_D(cm^{-3})$ ($\times 10^{15}$)	$\sigma_e^{A/D}(cm^2)$ ($\times 10^{-15}$)	$\sigma_h^A(cm^2)$ ($\times 10^{-15}$)	$(cm^2) \sigma_h^D$ ($\times 10^{-15}$)
0.5	0.19	0.25	6.60	1.65	6.60
2	0.68	1.0	6.60	1.65	6.60
5.9	1.60	4.0	6.60	1.65	1.65

CMS Pixelav: cluster charge

The high energy secondaries [“delta rays”] produce a “tail” at large charge. Plotting Q/track length for a sample of real pixel clusters

[M. Swartz talk](#)



- Model describes observed cluster charge distribution very well
- Charge scale [no free parameters] agrees with measured distribution to within a few x 0.1%

CMS Pixelav: cluster reweighting

Implementation

$\Phi=1.2 \times 10^{15}$ neq/cm2, 600V, 263I

Original[ix,iy]

0	0	0	0	0	0	0	0	0	0	0
0	0	9590	7380	0	0	0	0	0	0	0
0	0	0	9140	12500	11140	11790	12330	1750	0	0
0	0	0	0	0	0	0	0	0	0	0

Non-irradiated[ix,iy]:

- Generated in PIXELAV with uniform fields and the same LA as used by the CMSSW digitizer

0	0	0	0	0	0	0	0	0	0	0
0	93	10696	5584	722	23	0	0	0	0	0
0	0	884	7398	12337	12963	12997	13042	1375	0	0
0	0	0	0	0	0	0	0	0	0	0

Irradiated[ix,iy]

- Average cluster shape for a damaged physical sensor

0	0	0	0	0	0	114	159	87	23	0
0	0	8538	5871	754	263	527	495	208	41	0
0	0	48	2856	7512	7069	5894	4705	669	51	0
0	0	0	0	0	125	477	582	258	40	0

Weights

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.80	1.05	0.06	0.02	0.04	0.04	0.00	0.00	0.00
0.00	0.00	0.00	0.39	0.61	0.55	0.45	0.36	0.49	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.00	0.00

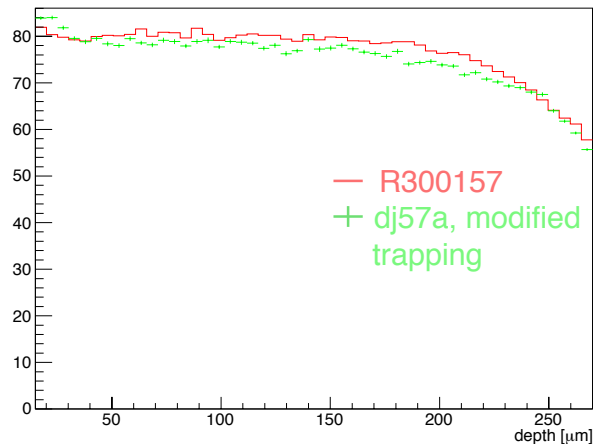
- PIXELAV: provides average cluster shape
- CMSSW sim: provides pixel-to-pixel fluctuation

[C. Mantilla Suarez, 2019](#)

CMS results

Trapping Measurement

Simulate the dj59a E-field with trapping rates corresponding to $0.6 \times 10^{14} \text{ cm}^{-2}$



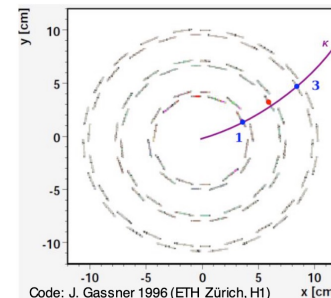
[M. Swartz talk](#)

- The electric field is evolving faster [differently] than expectations from the beam test models
- Trapping rates appear to be evolving according to the fluence calculation with a hardness factor of 0.6
- The slower evolution of the trapping rates has important consequences for the longevity of the detector

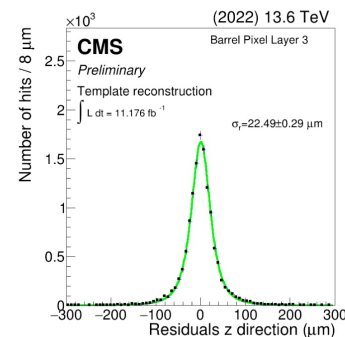
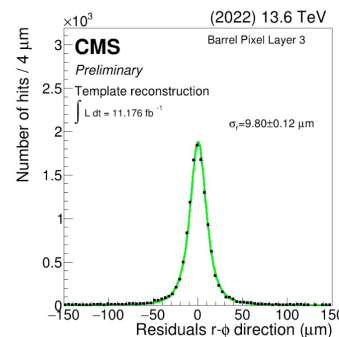
CMS Pixelav for reconstruction

Estimate of the resolution

- Triplet method:
 - $p_T > 12$ GeV tracks with hits in 3 layers are selected and refitted using hits in two of three layers
 - Trajectory extrapolated to remaining layer, residuals with the actual hit are calculated
 - Residual distribution fitted with the Student-t function
- Template: an algorithm based on detailed cluster shape simulations predicted by PixelAv [1,2]. Used in the final fit of each track in the offline reconstruction
- Example shows residual in layer 3: propagate from hits on layer 2 and 4
- Observed residual distribution is the sum of the intrinsic detector resolution and a track extrapolation error



[Pixel 2022](#)



- [1] M. Swartz, "CMS pixel simulations", Nucl. Instrum. Methods, A 511 (2003), 88-91
[2] M. Swartz and D. Fehling and G. Giurgiu and P. Maksimovic, "A new technique for the reconstruction, validation, and simulation of hits in the CMS pixel detector", PoS VERTEX2007 (2007), 035

TCAD radiation damage model

2016 CMS paper

Table 1. The key parameter values used in the Synopsys device simulation. These include: donor and acceptor concentrations, N_D and N_A , and their electron and hole capture cross sections, $\sigma_{D,A}^{e,h}$, for silicon sensors after irradiation with 23 GeV protons (top rows) [11], and for sensors after irradiation with 23 MeV protons (bottom rows) [8].

ϕ_{neq} [10^{14}neq/cm^2]	N_A [10^{14}cm^{-3}]	N_D [10^{14}cm^{-3}]	σ_A^e [10^{-15}cm^2]	σ_D^e [10^{-15}cm^2]	σ_A^h [10^{-15}cm^2]	σ_D^h [10^{-15}cm^2]
2 (23 GeV) [11]	6.8	10	6.6	6.6	1.65	6.6
6 (23 GeV) [11]	16	40	6.6	6.6	1.65	1.65
12 (23 GeV) [11, 18] ⁴	30	69	3.8	3.8	0.94	0.94
24 (23 GeV) [11, 18] ⁴	61	138	3.8	3.8	0.94	0.94
3 (23 MeV) [8]	4.2	13	10	10	10	10
10 (23 MeV) [8]	12.5	52	10	10	10	10

Simulation ingredients – trapping constants

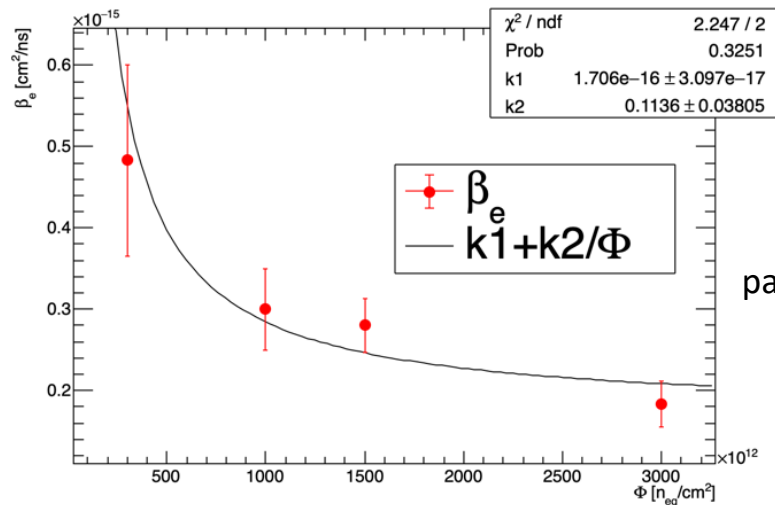
Based on [2016 CMS paper](#)

• Electrons

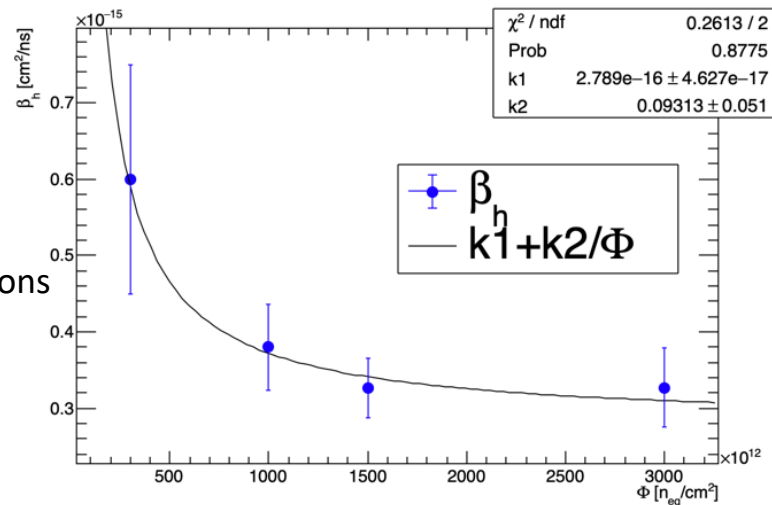
fluence Φ [neq/cm ²]	β [cm ² /ns]	$\Delta \beta$ [cm ² /ns]
3.00e+14	4.83e-16	1.18e-16
1.00e+15	3.00e-16	5.00e-17
1.50e+15	2.80e-16	3.33e-17
3.00e+15	1.83e-16	2.83e-17

• Holes

fluence Φ [neq/cm ²]	β [cm ² /ns]	$\Delta \beta$ [cm ² /ns]
3.00e+14	6.00e-16	1.50e-16
1.00e+15	3.80e-16	5.66e-17
1.50e+15	3.27e-16	3.89e-17
3.00e+15	3.27e-16	5.21e-17



Possible
parametrisations



Simulation radiation damage effects in ATLAS MC

Modelling radiation damage to pixel sensors in the ATLAS detector

Trapping from literature, based on these data:

Irradiation	Annealing	β_e ($10^{-16}\text{cm}^2/\text{ns}$)	β_h ($10^{-16}\text{cm}^2/\text{ns}$)	Reference	Method
Neutrons	minimum V_{depl}	4.0 ± 0.1	5.7 ± 0.2	[49]	TCT
Pions	minimum V_{depl}	5.5 ± 0.2	7.3 ± 0.2	[49]	TCT
Protons	minimum V_{depl}	5.13 ± 0.16	5.04 ± 0.18	[50]	TCT
Neutrons	> 50 hours at 60°C	2.6 ± 0.1	7.0 ± 0.2	[49]	TCT
Protons	> 10 hours at 60°C	3.2 ± 0.1	5.2 ± 0.3	[50]	TCT
Protons	minimum V_{depl}	4.0 ± 1.4	—	[3, 51]	Test-beam
Protons	25h at 60°C	2.2 ± 0.4	—	[3, 51]	Test-beam

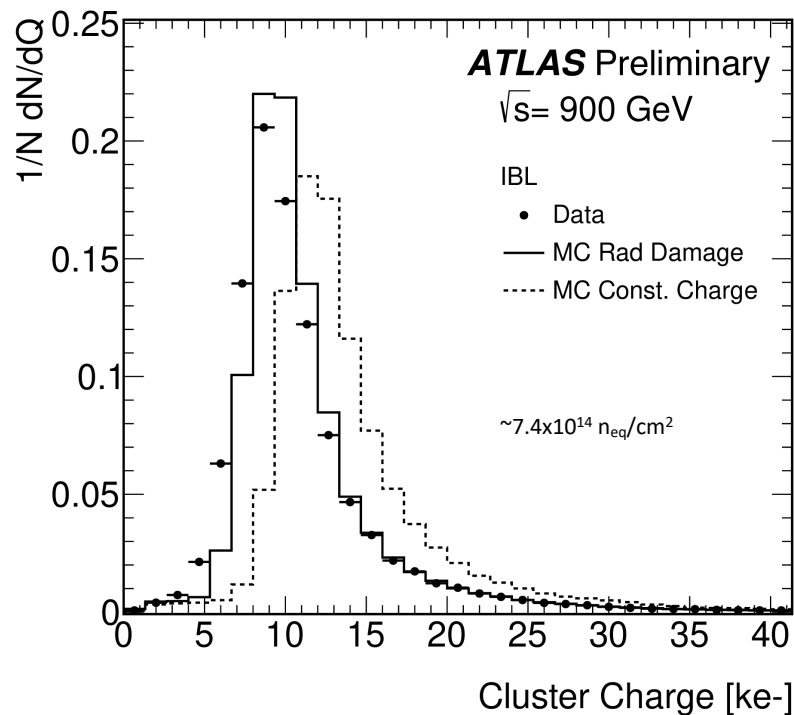
The values we use in our modeling:

$$\beta_e = (4.5 \pm 1.5) \times 10^{-16} \text{ cm}^2/\text{ns}$$

$$\beta_h = (6.5 \pm 1.5) \times 10^{-16} \text{ cm}^2/\text{ns}$$

- [3] G. Aad et al., *ATLAS pixel detector electronics and sensors*, [2008 JINST 3 P07007](#).
- [49] G. Kramberger, V. Cindro, I. Mandić, M. Mikuž and M. Zavrtanik, *Effective trapping time of electrons and holes in different silicon materials irradiated with neutrons, protons and pions*, [Nucl. Instrum. Meth. A 481 \(2002\) 297](#).
- [50] O. Krasel, C. Gossling, R. Klingenberg, S. Rajek and R. Wunstorf, *Measurement of trapping time constants in proton-irradiated silicon pad detectors*, [IEEE Trans. Nucl. Sci. 51 \(2004\) 3055](#).
- [51] G. Alimonti et al., *A study of charge trapping in irradiated silicon with test beam data*, [ATL-INDET-2003-014](#), CERN, Geneva, Switzerland (2003).

ATLAS results



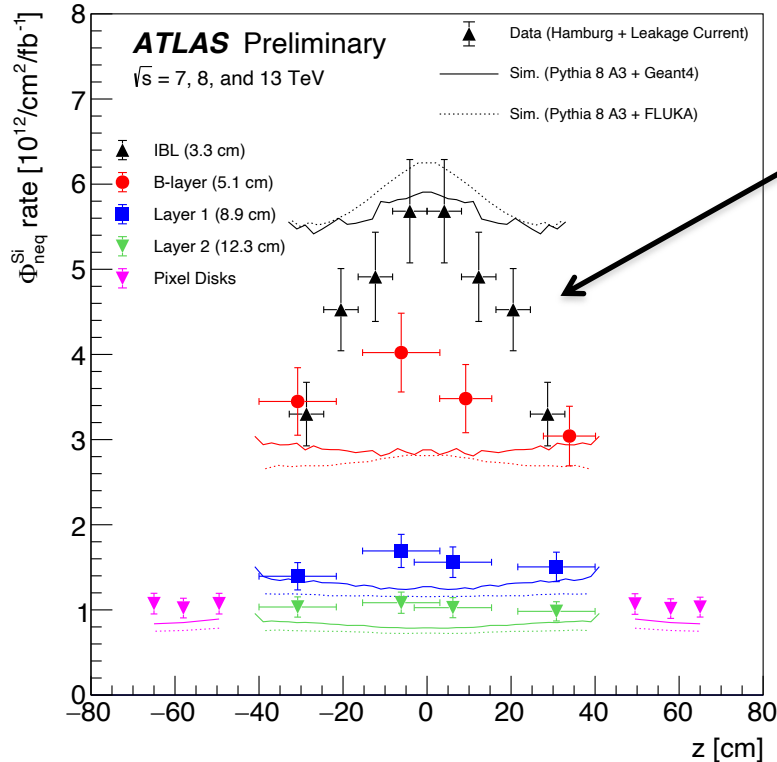
It seems for IBL there is a somewhat less satisfactory agreement

From detailed analysis it seems $\sim +20\text{-}25\%$ in trapping would make MC agree better with data

But trapping rate is the product of fluence and trapping constant...

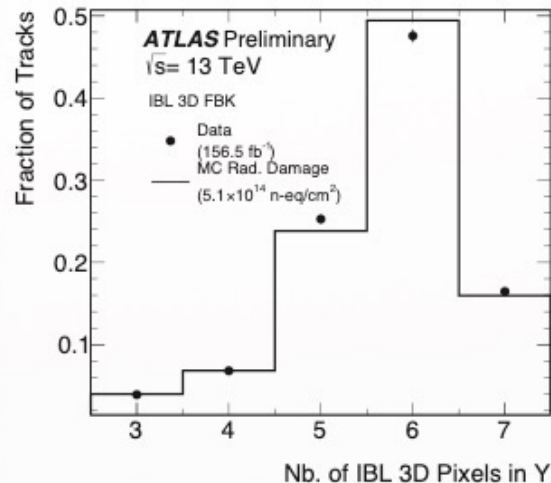
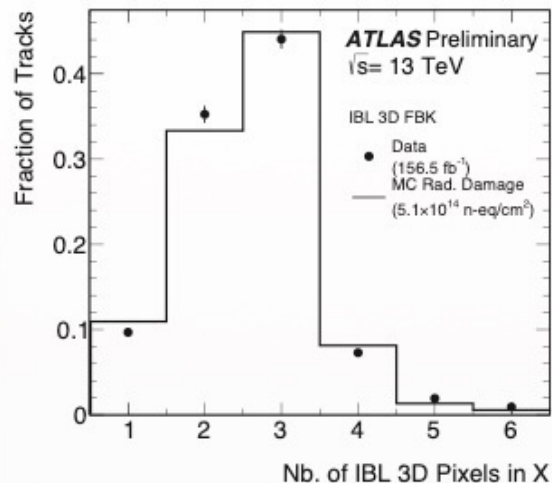
Fluence profile and charge collection

Reminder



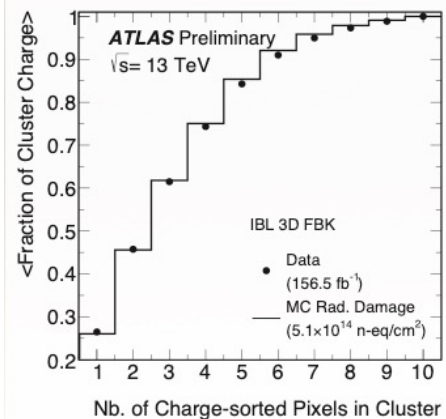
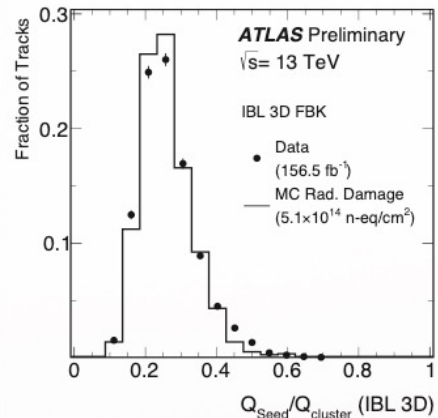
IBL fluence profile across stave is non uniform

How much does the fluence prediction change if you take a weighted average with the track distribution?

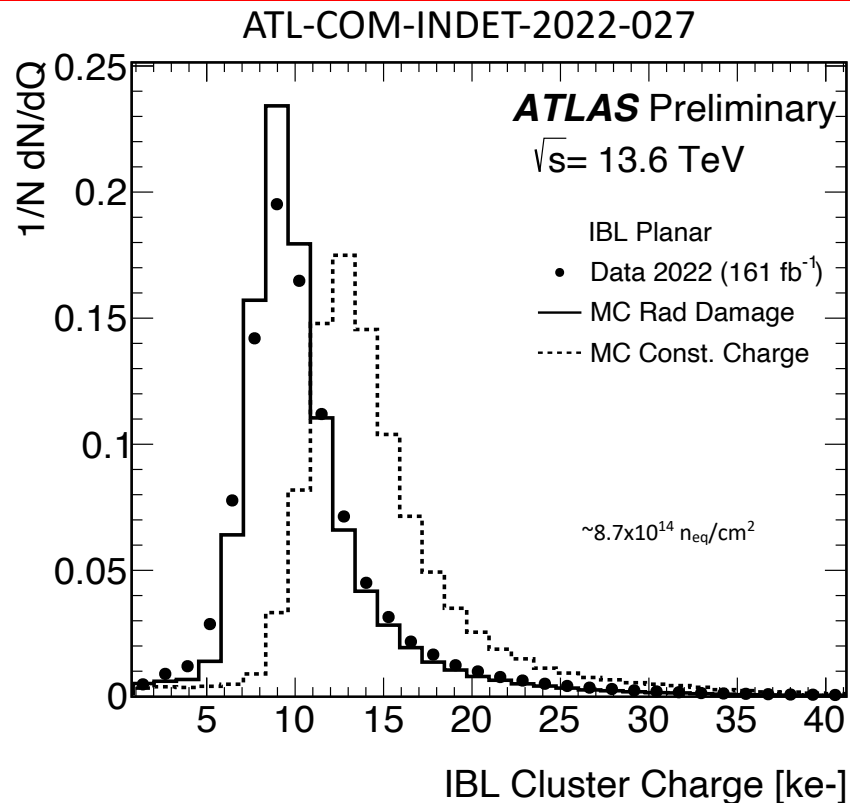
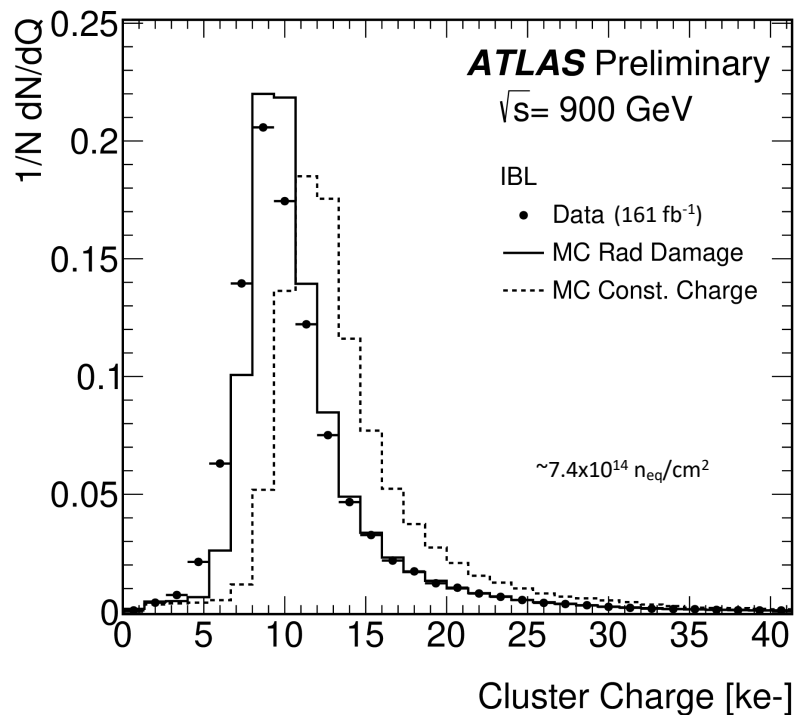


Excellent agreement

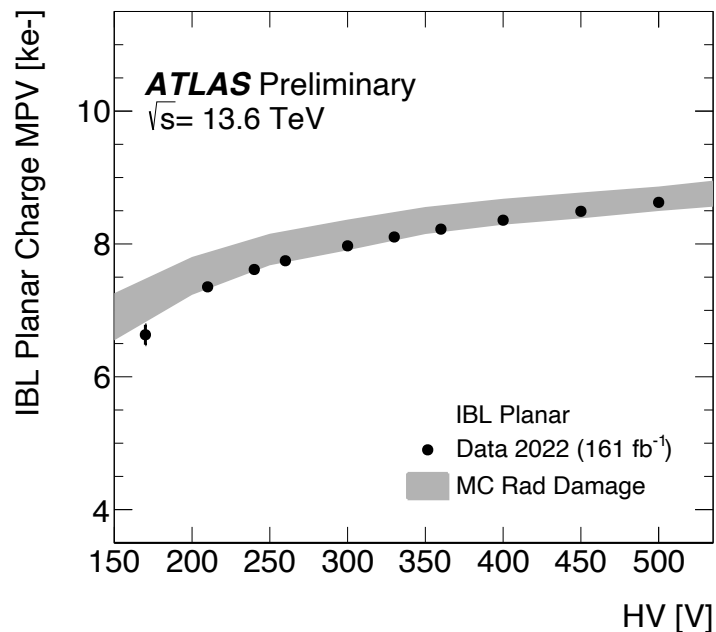
Excellent performance also for long clusters



Answer: +20%

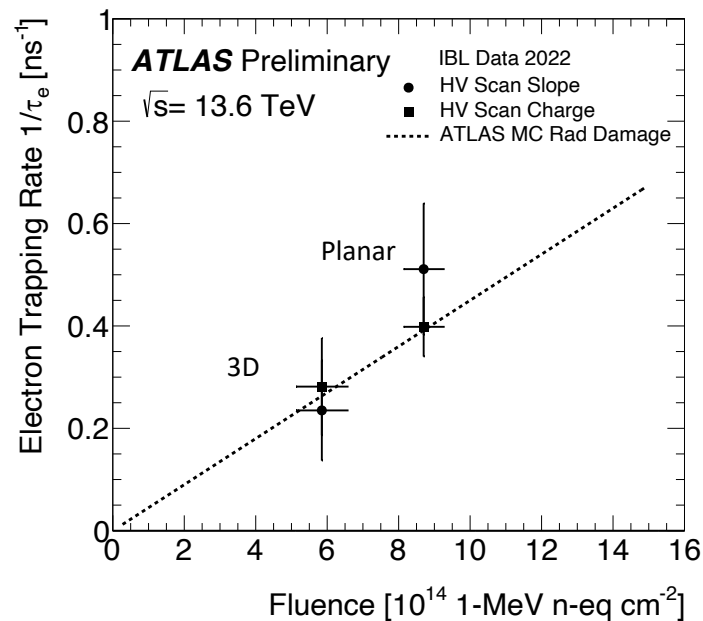


ATLAS Charge vs bias voltage, trapping rate



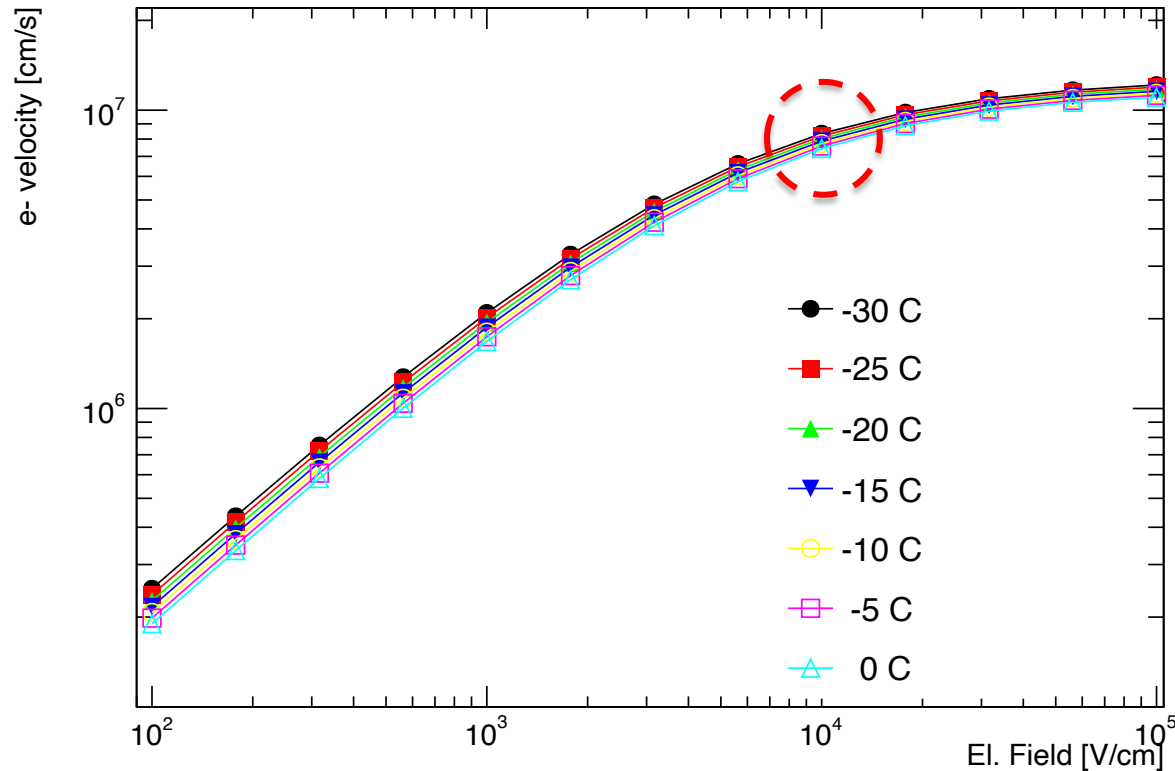
Good agreement also before depletion

Simulations now used to estimate depletion voltage for operations



Trapping rate consistent with our simulations

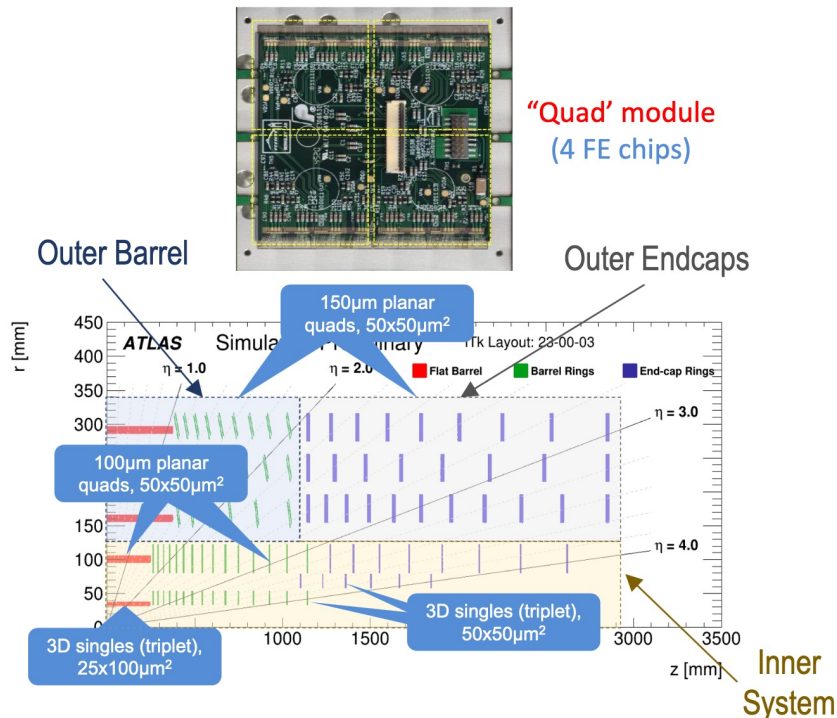
Electron velocity vs electric field



The result does not depend much on temperature

Mobility model (IBL&PIX default):
C. Canali, G. Majni, R. Minder and
G. Ottaviani, *IEEE Transactions on
Electron Devices* **22** (1975) 1045

Module Placement



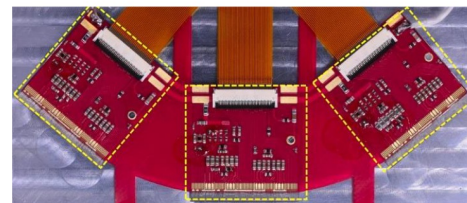
4 Dec 2023

HSTD13 - Vancouver (Canada)

Module type is region-dependent

- Innermost layer ("Layer 0"): 3D sensors
 - Higher radiation tolerance
 - Lower power consumption → easier servicing
 - Pixel size 50x50 μm² or 25x100 μm²
- Layer 1
 - 100μm thick planar Si
 - Pixel size 50x50 μm²
- Layers 2-4
 - 150μm thick planar Si, 50x50 μm² pixels

Innermost two layers will be replaced at half-lifetime (~2000 fb⁻¹)

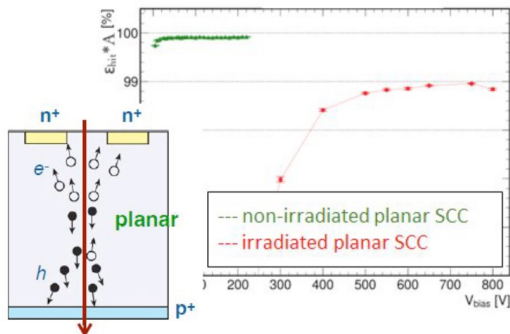


3 Single-chip modules
in a "triplet"

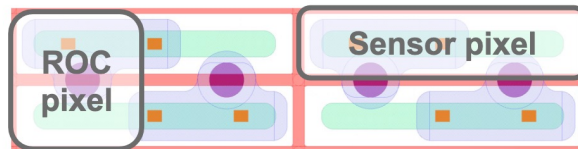
10

Sensors

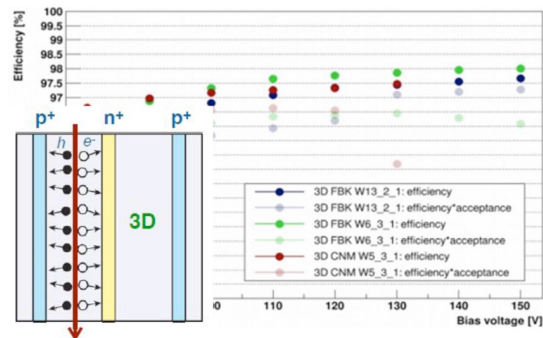
- Rectangular pixels (25 x 100 μm) everywhere
 - 100 μm in beam direction to match longer clusters in barrel mid-rapidity
 - Square pixels offer small to no improvement
- Planar (n-in-p, 150 μm bulk thickness)
 - **High hit efficiency (>99%)**
- 3D
 - Slightly less efficient (up to 98%)
 - **High margin for thermal stability**
 - **Lower bias voltage**
- Barrel layer 1 requires 3D sensors for thermal stability after irradiation
- Planar sensors are used everywhere else for higher efficiency



Hit efficiency after irradiation
($1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$)



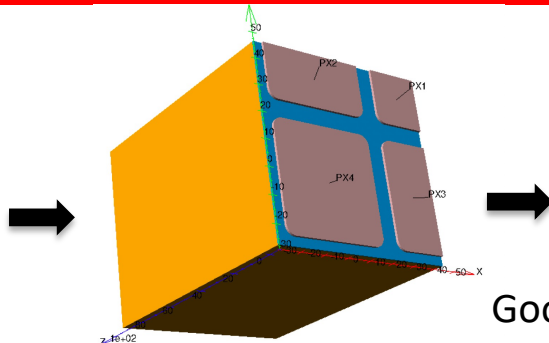
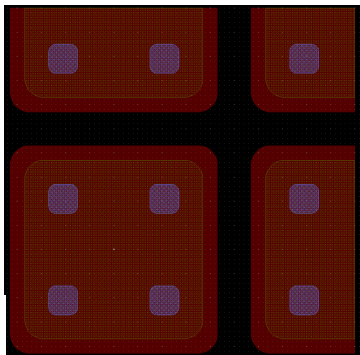
Rectangular sensor pixels are bump bonded to square ROC pixels according to this pattern



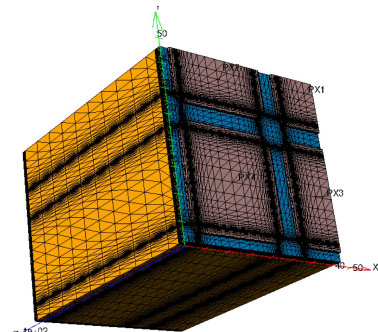
ITk pixels simulations with TCAD

n-on-p
100 μm thick
50 μm pitch

$\frac{1}{4}$ of 3×3
pixels matrix



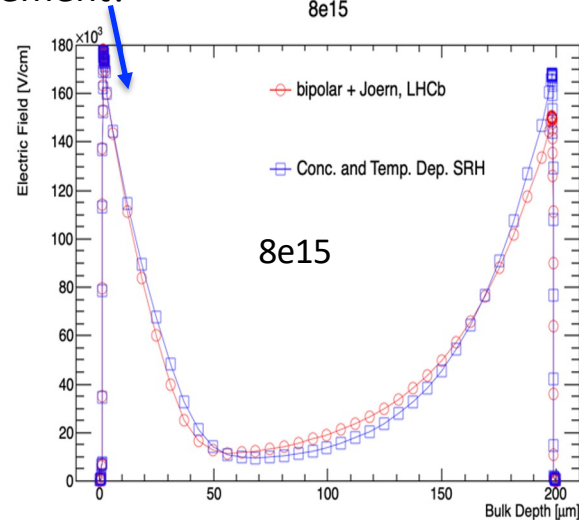
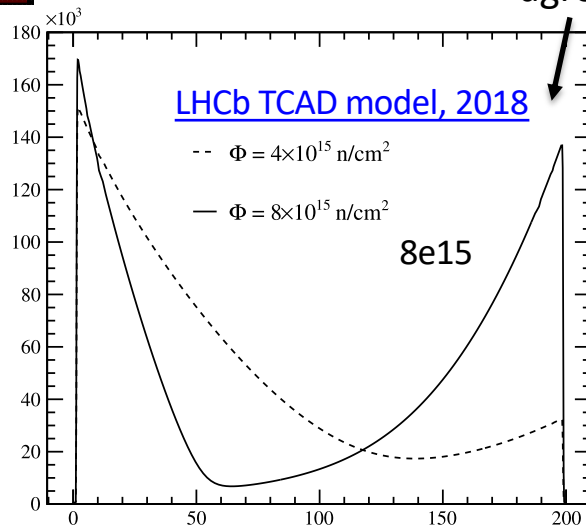
Good
agreement!



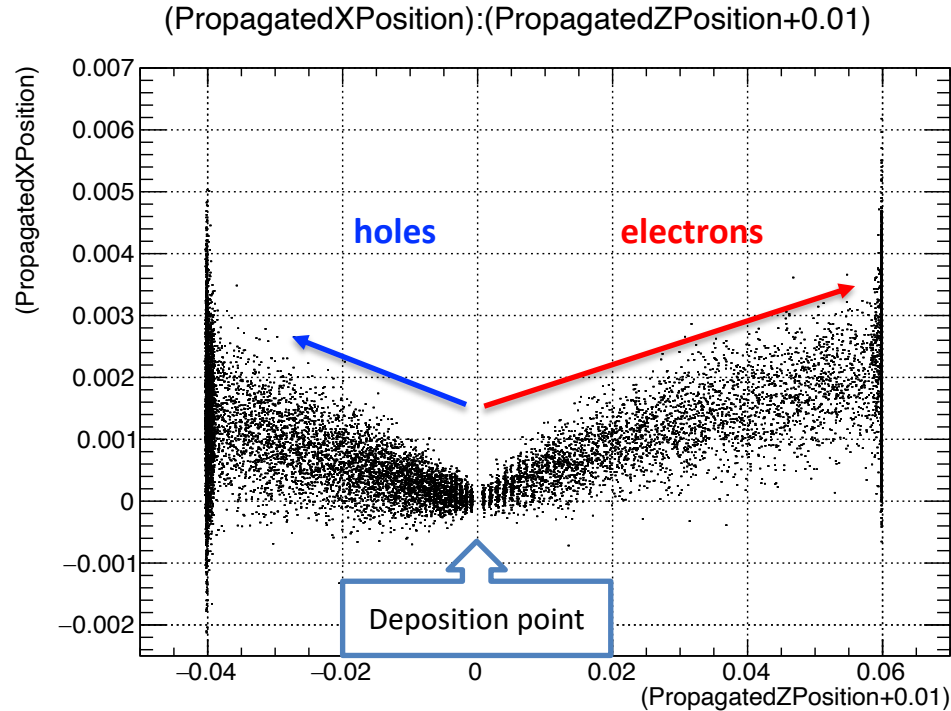
Full 3D simulation

Several models tested
(mobility, recombination,
bands...)

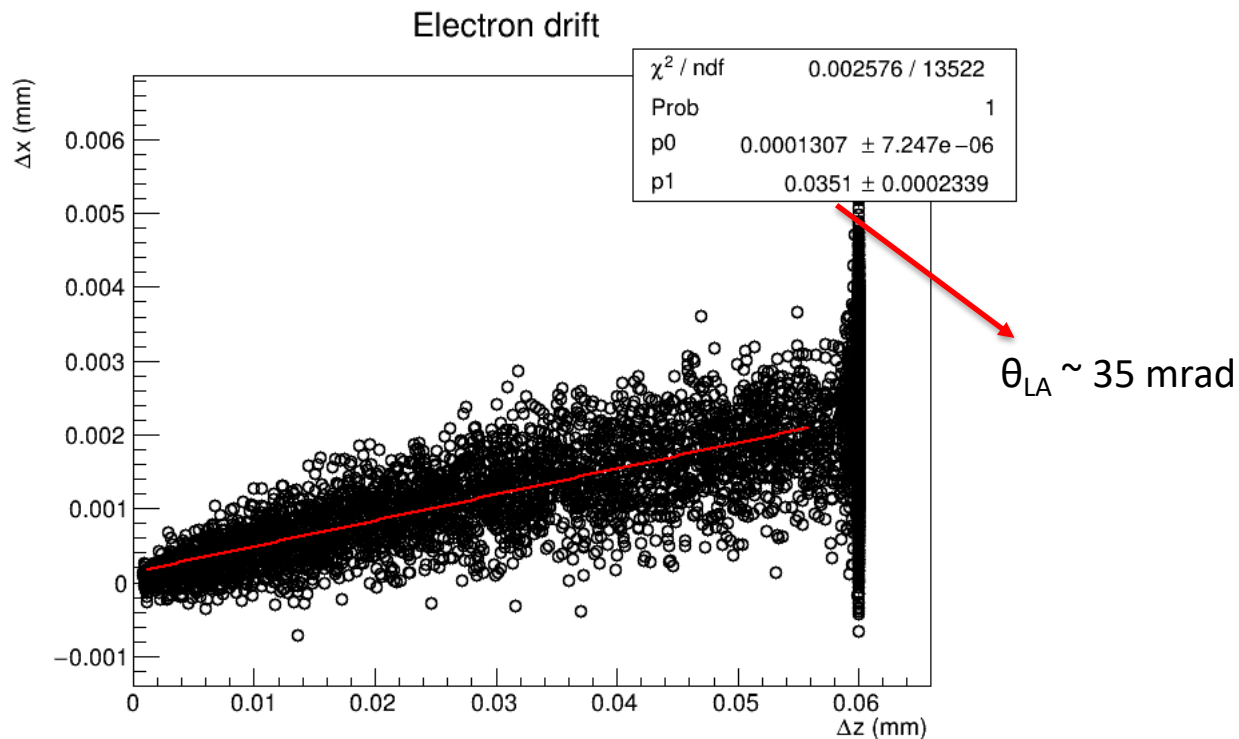
(validation done in 2D)



Lorentz angle studies – carriers drift

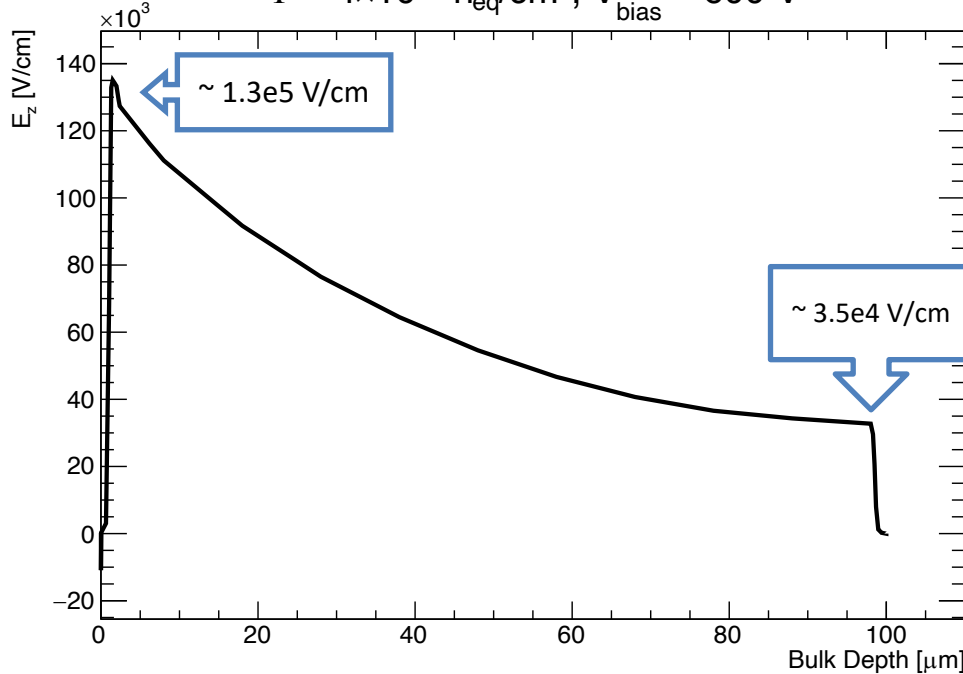


Average Lorentz angle deflection



Electric field profile and mobility

$$\Phi = 4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2, V_{\text{bias}} = 600 \text{ V}$$



$$T = 253 \text{ K}$$

Highest electric field

$$\mu_e = \sim 9 \times 10^{-3} \text{ m}^2/\text{V/s} \Rightarrow$$

$$\theta_{\text{LA}} \sim 18 \text{ mrad}$$

Lowest electric field

$$\mu_e = \sim 30 \times 10^{-3} \text{ m}^2/\text{V/s} \Rightarrow$$

$$\theta_{\text{LA}} \sim 60 \text{ mrad}$$

In previous slide:

$$\theta_{\text{LA}} \sim 35 \text{ mrad}$$

Ballpark!

MOSAIX key specifications

J. Lalic, Vertex 2025

Fill factor	93 % sensitive region
	0.7 % sensor area modularity
	144 tiles (independent units)
Pixel performance	$22.8 \times 20.8 \mu\text{m}^2$ pixel size
	Detection Efficiency >99 %
	Fake hit rate $<0.1 \text{ pixel}^{-1} \text{ s}^{-1}$
Data taking	4.4 MHz/cm^2 particle rate
	30.72 Gb/s off-chip data transmission
	minimum $2 \mu\text{s}$ integration time
Radiation performance	10^{13} NIEL ($1 \text{ MeV n}_{eq}/\text{cm}^{-2}$)
	10 kGray TID
	Triple modular redundancy
Power budget	40 mW/cm^2

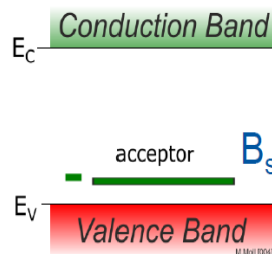
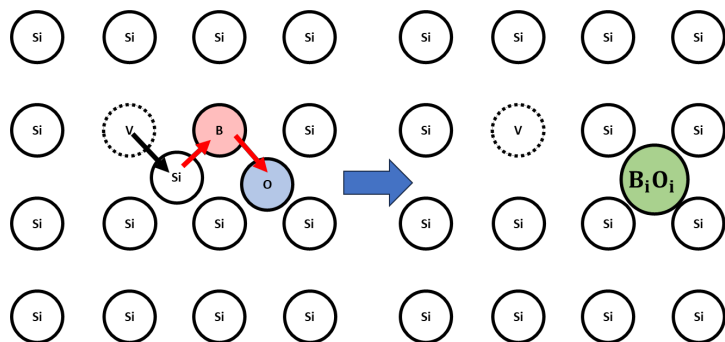


ALICE

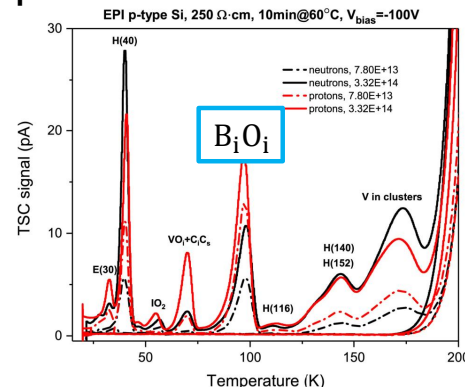
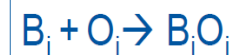
Principle of Acceptor Removal

- According to the measurement results of p-type silicon with acceptor concentration of $O(10^{12}) \text{ cm}^{-3}$, the microscopic mechanism is

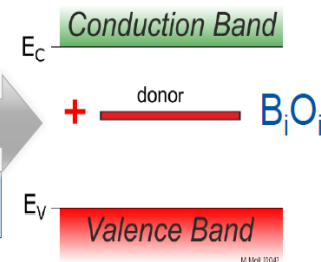
- NIEL damage creates interstitials Silicon (Si_i) and Vacancies (V)
- Si_i replace boron on the lattice (B_s) ($\text{B}_s + \text{Si}_i \rightarrow \text{B}_i$: boron inactivation)
- B_i bonds with O_i to become $\text{B}_i\text{O}_i \Rightarrow$ This creates donor level



Radiation Damage



■ TSC measurement



✓ Decrease in acceptors

✓ Formation of donor levels by B_iO_i

Main factors!!

[Y. Murayama, Vertex 2025](#)

- M.Moll, Acceptor Removal - Effects of displacement damage involving the shallow acceptor doping in p-type silicon devices, vertex2019
- Y.Gurinskaya et al., Radiation damage in p-type EPI silicon pad diodes irradiated with protons and neutrons, NIMA, in press. 2019.

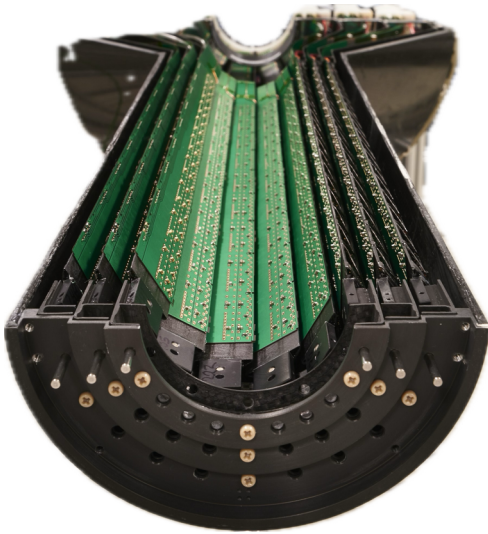


From ITS2 to ITS3

[L. Terlizzi, Vertex2025](#)

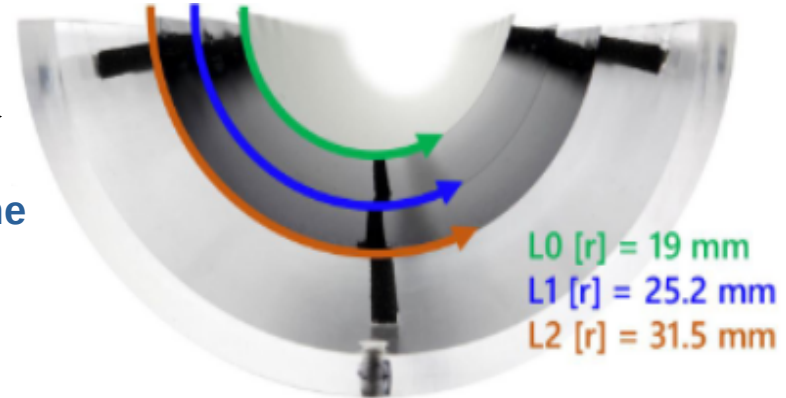
ALICE

- ITS2 was installed in 2021 and taking data since then:
 - Monolithic Active Pixel Sensor (MAPS)** $50\ \mu\text{m}$ Si sensors
 - average material budget of **0.36% X_0 per layer**
 - 1st layer radius **24 mm**

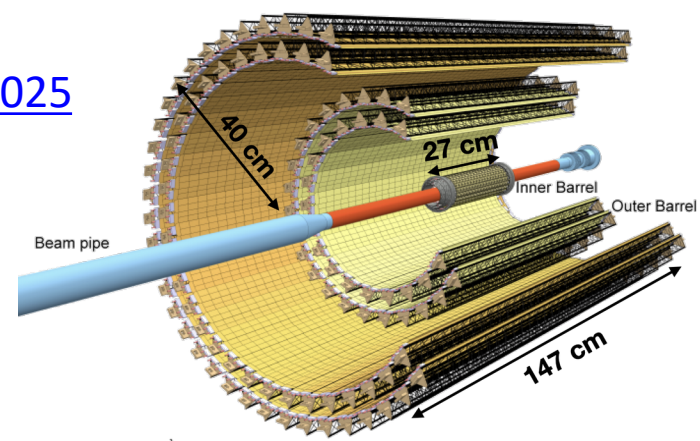


ITS2 half inner 3 layer

→
Replacement of the 3 innermost layers of the ITS2 for Run 4



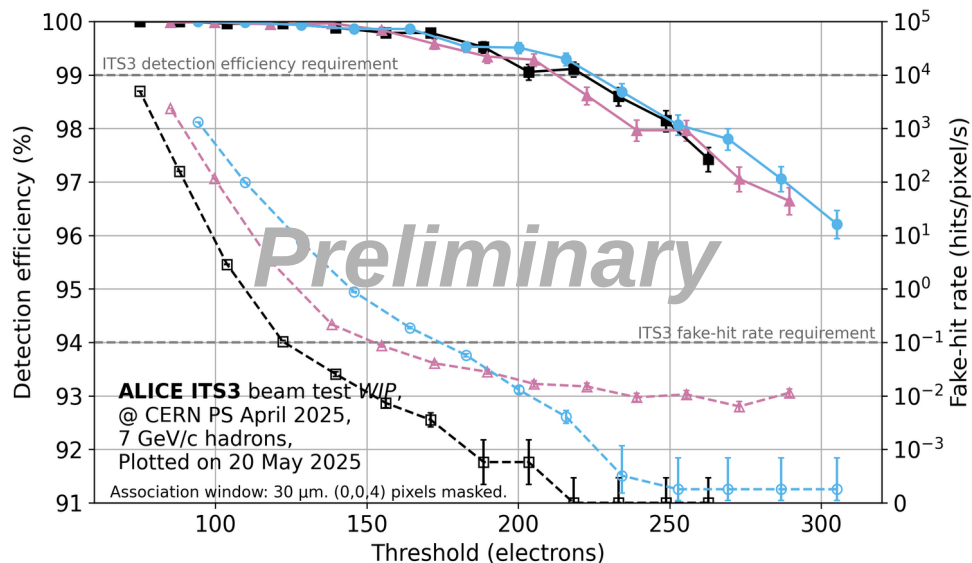
ITS3 half inner 3 layer



MOSS results

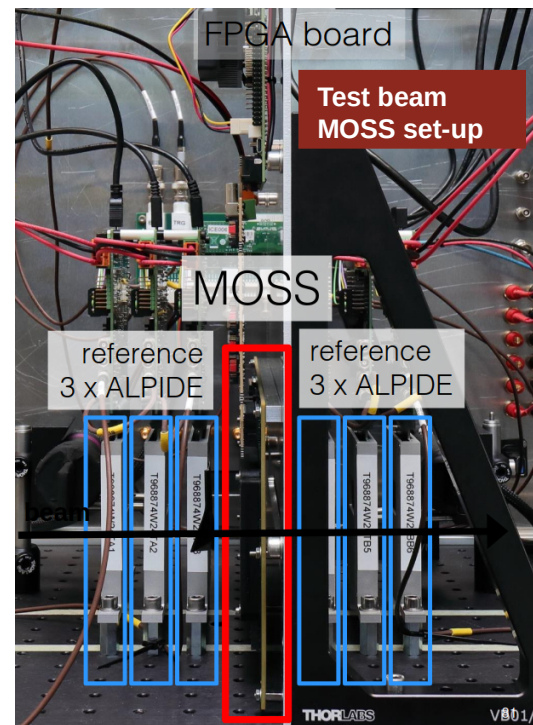
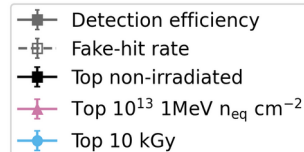
[L. Terlizzi, Vertex2025](#)

- The required ITS3 performance in terms of efficiency and fake-hit rate is **reached** also after irradiating the sensors with a dose higher than the one expected over the full ITS3 operational lifetime



Region 0

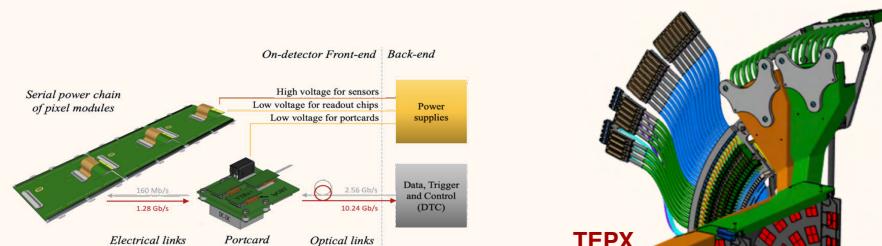
Type: 2.5 μm gap
 $I_{\text{bias}} = 62$ DAC
 $I_{\text{biasn}} = 100$ DAC
 $I_{\text{db}} = 50$ DAC
 $I_{\text{reset}} = 10$ DAC
 $V_{\text{shift}} = 145$ DAC
 $V_{\text{casn}} = 104$ DAC
 $V_{\text{psub}} = -1.2$ V
 Strobe length = 0.6 μs
 $T = 27^\circ\text{C}$



- chip is working well
 - stitched design validated and adopted for MOSAIX**

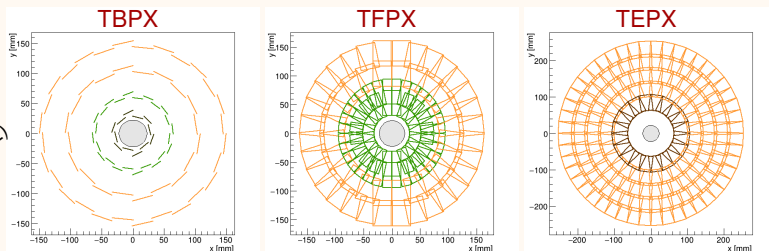
The CMS Inner Tracker for High-Luminosity LHC

- **Hybrid pixel detector** designed for high rate, pileup, and radiation dose
 - Electronics requirements: up to about 1 Grad and $2 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$
- **Multiple sensor technologies employed**
 - Innermost barrel layer: 3D sensors
 - Remaining barrel layers and endcap discs: planar sensors (n-in-p)
 - High granularity to cope with increased pileup: $25 \mu\text{m} \times 100 \mu\text{m}$ pixel size
 - Active thickness: $150 \mu\text{m}$
- **Instrumented with approximately 10^4 CMS Readout Chips (CROCs)**
 - 65 nm CMOS readout chip developed by the RD53 Collaboration
 - High hit rate operation: up to approximately 3 GHz cm^{-2}
- **Low material budget system**
 - Serial powering of detector modules
 - Carbon fibre + carbon foam mechanical structure; thin CO2 cooling pipes
 - Low-mass electrical links or flex PCBs for powering and readout

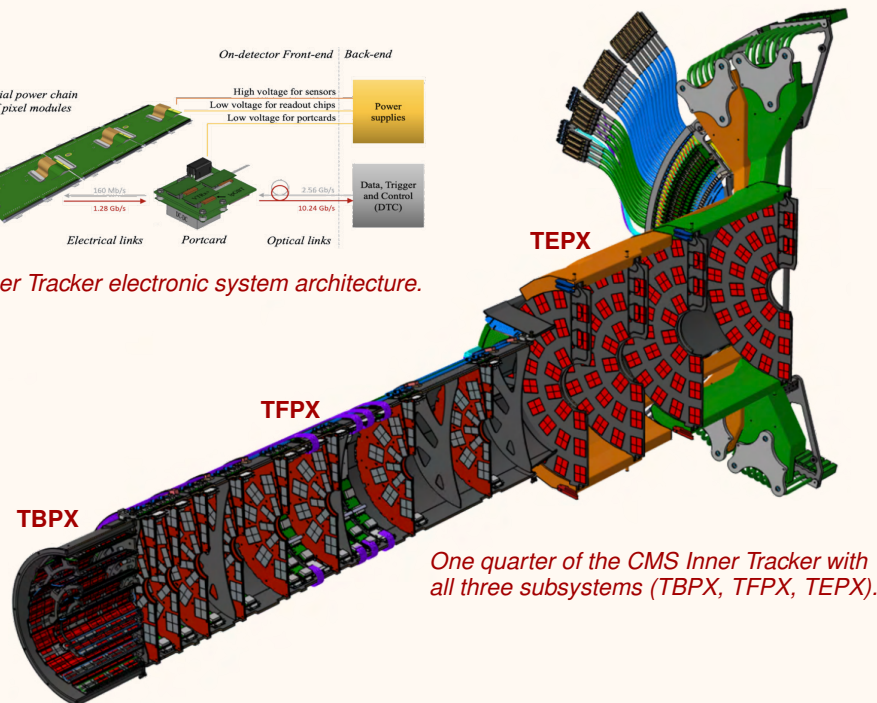


Inner Tracker electronic system architecture.

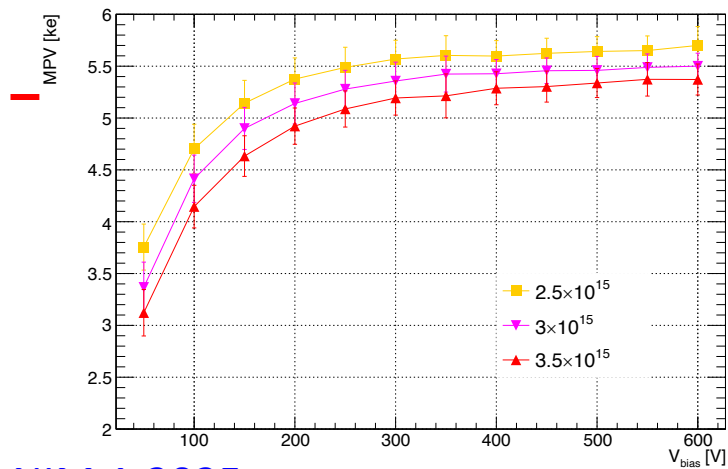
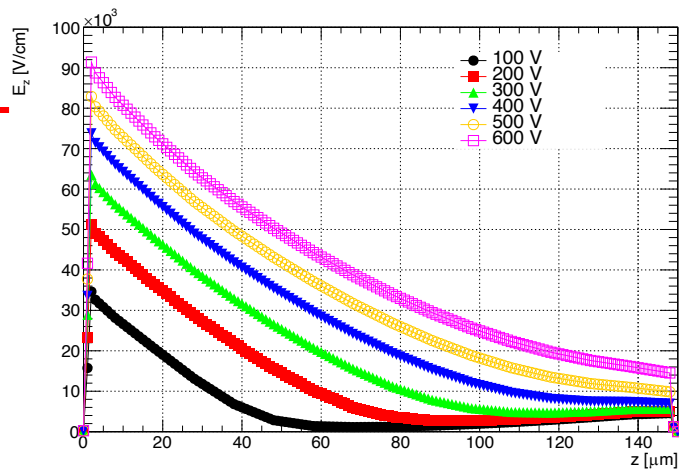
Planar (2x2)
Planar (1x2)
3D sensors (1x2)



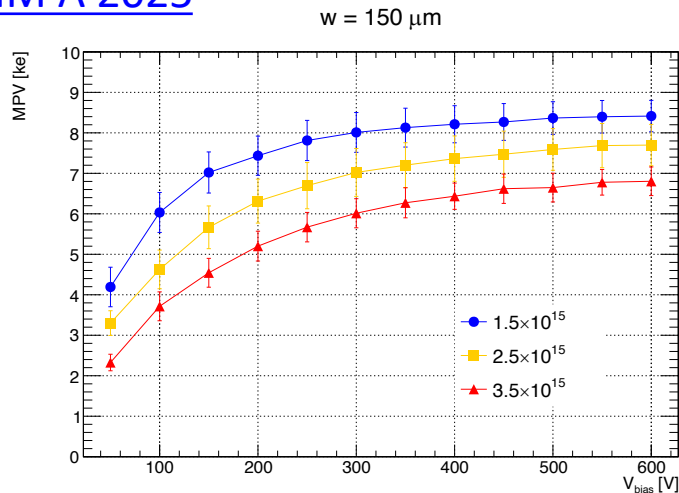
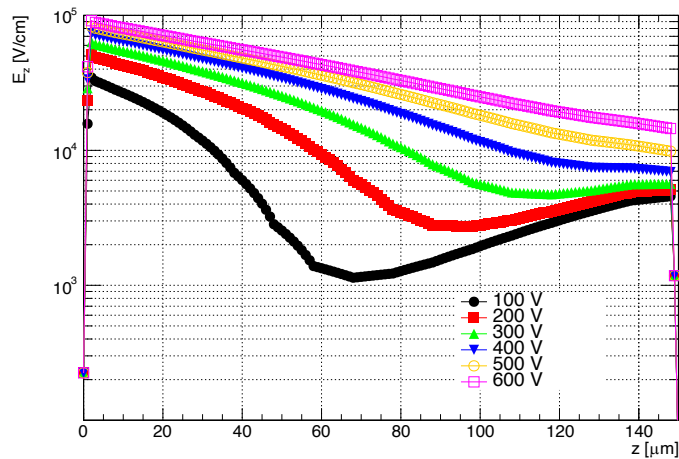
XY projections for TBPX, TFPX, TEPX. The colours highlight the different module types.



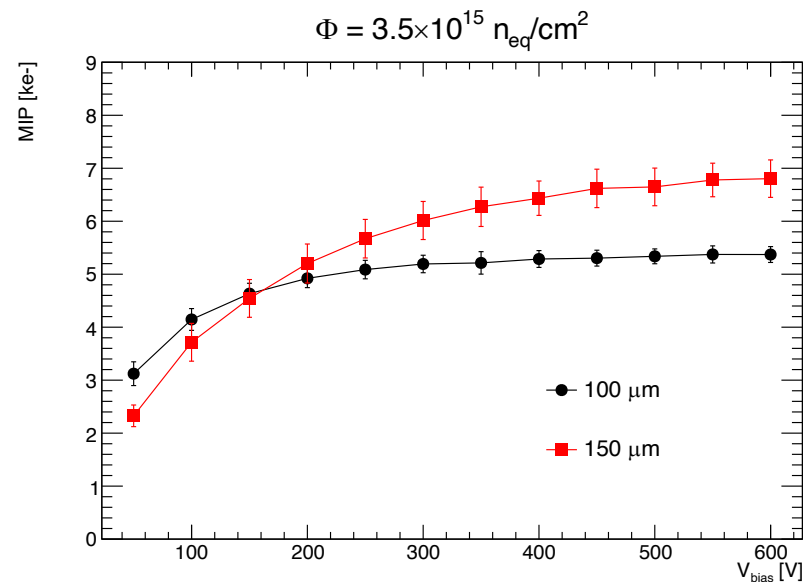
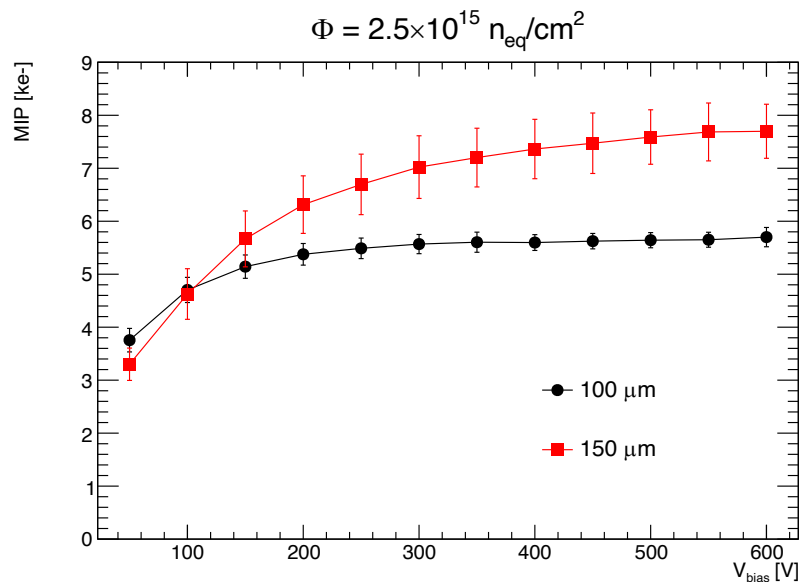
One quarter of the CMS Inner Tracker with all three subsystems (TBPX, TFPX, TEPX).



M. Bomben NIM A 2025



M. Bomben NIM A 2025



$w = 150 \text{ } \mu\text{m}$

[M. Bomben NIM A 2025](#)

