Including radiation damage effects in ATLAS MonteCarlo simulations:

status and perspectives

M. Bomben, APC & UPC

on behalf of ATLAS Pixels

Motivation

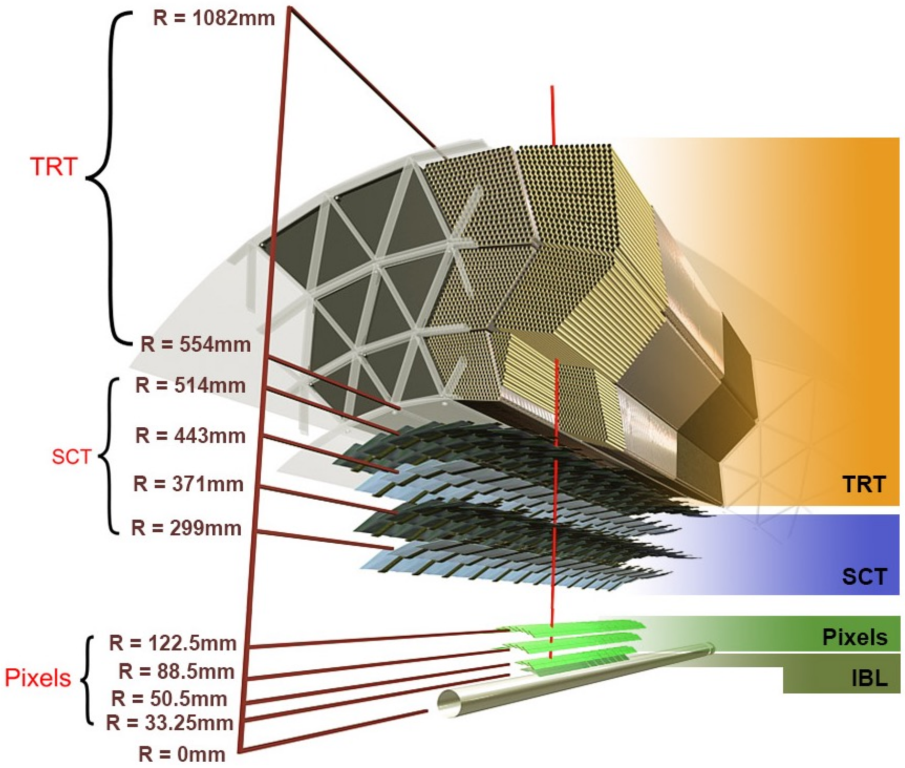
Signal reduction is the most important radiation damage effect on performance of IBL and pixels detectors in ATLAS

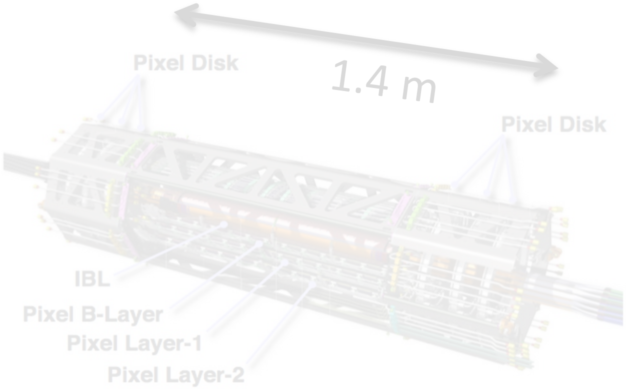
Adjusting sensor bias voltage and detection threshold can help in mitigating the effects

…but it is important to have simulated events that model the evolution of performance with the accumulation of luminosity

ATLAS collaboration developed and implemented an algorithm that reproduces signal loss and changes in Lorentz angle due to radiation damage

ATLAS Insertable B-Layer and Pixels



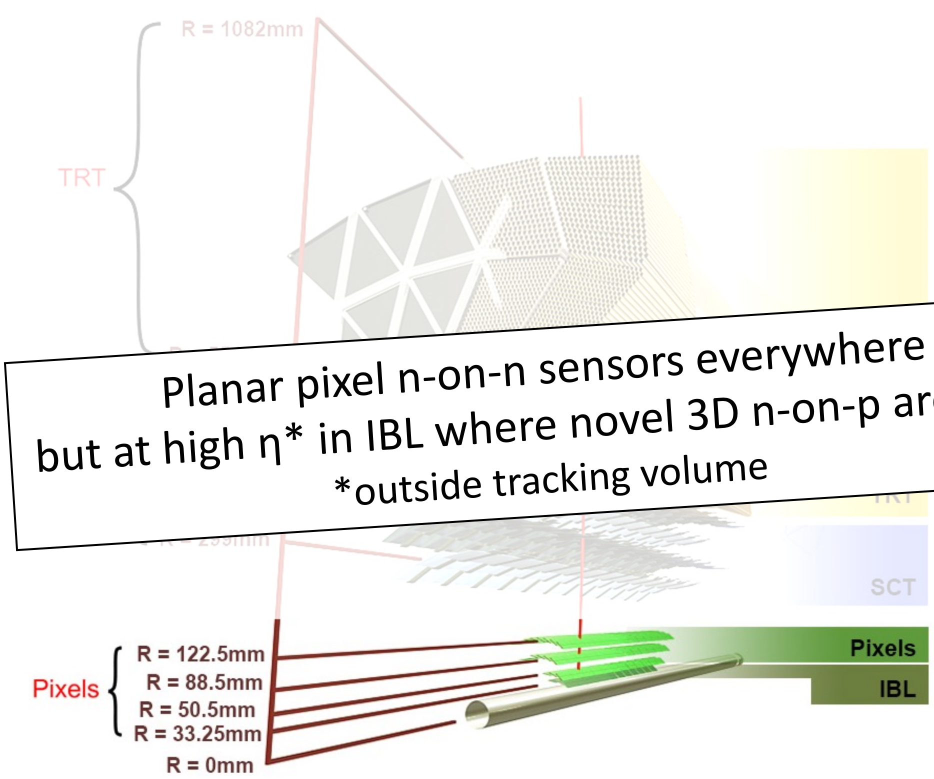


4 Pixel barrel layers

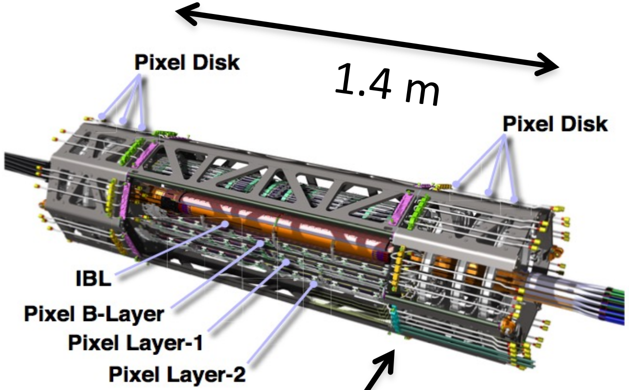
3 Outermost:
250 μm thick
50x400 μm^2 pitch

Innermost layer: IBL
Inserted for Run2
200 μm thick
50x250 μm^2 pitch

ATLAS Insertable B-Layer and Pixels



Planar pixel n-on-n sensors everywhere
but at high η* in IBL where novel 3D n-on-p are used
*outside tracking volume



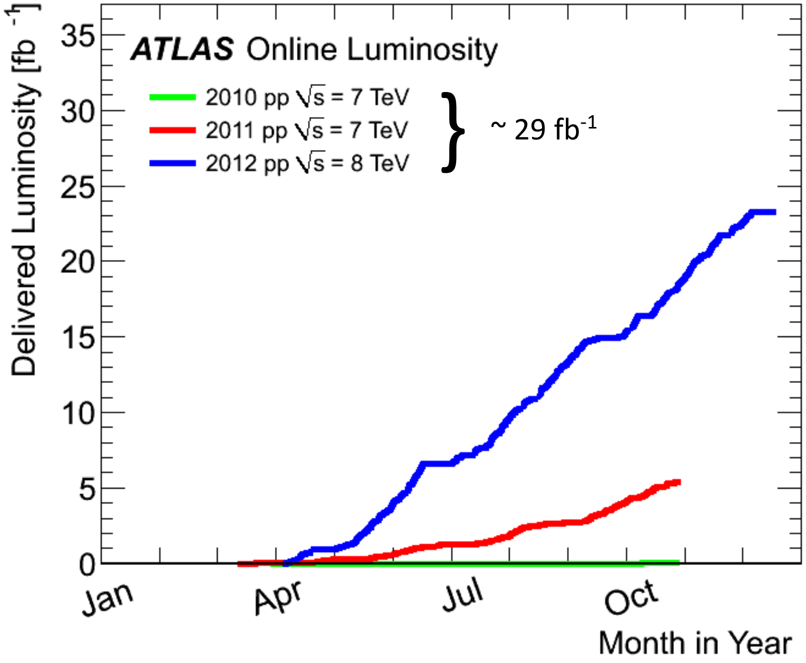
4 Pixel barrel layers

3 Outermost (and disks):
250 μm thick
50x400 μm^2 pitch

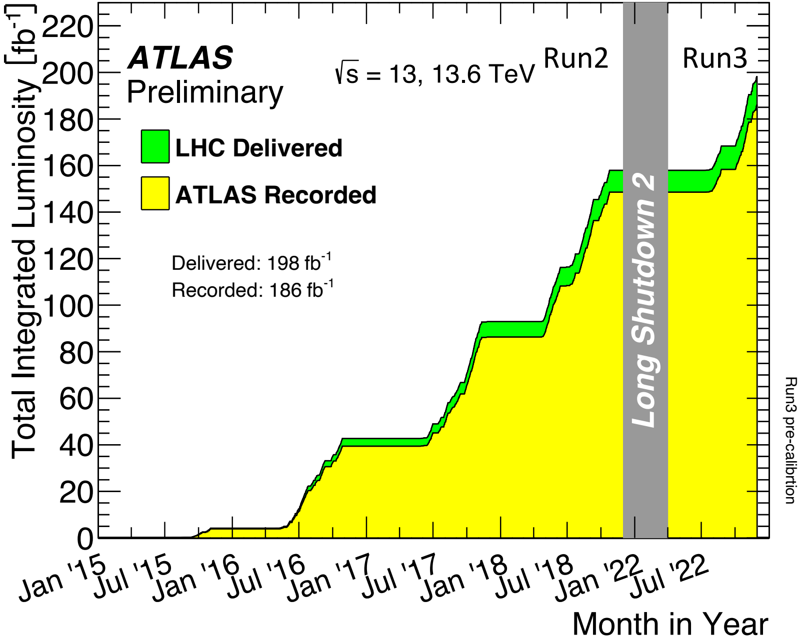
Innermost layer: IBL
Inserted for Run2
200 μm thick
50x250 μm^2 pitch

RADIATION DAMAGE MEASUREMENTS

Luminosity



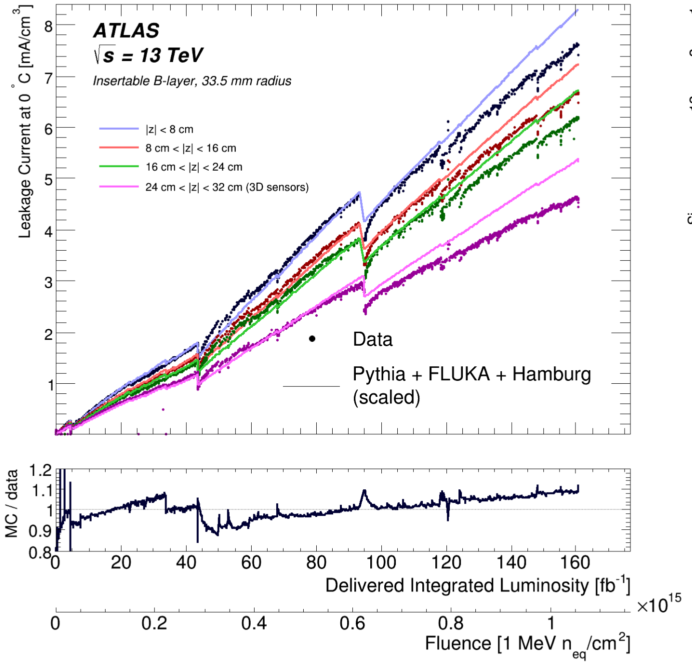
~ 29 fb^{-1}

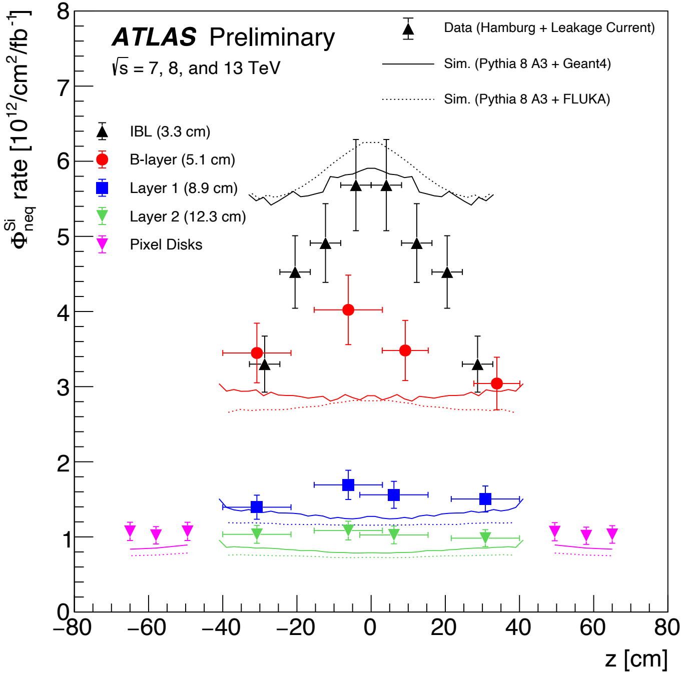


Predictions for Run 3: collect 200-300 fb^{-1}

Radiation damage measurements

Measurements of sensor radiation damage in the ATLAS inner detector using leakage currents





Unexpected fluence profile for IBL

Still an open question

Rescaling predictions:

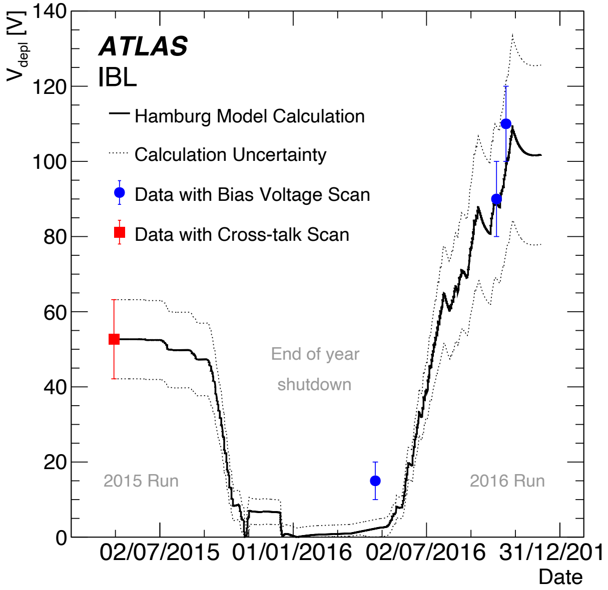
IBL

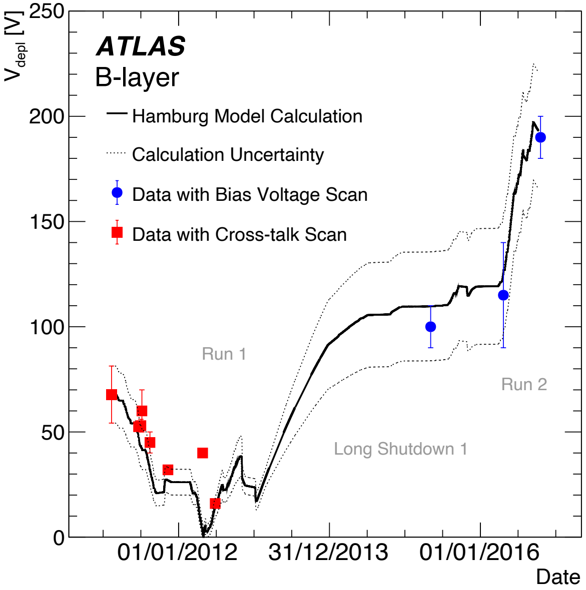
z Bin	Mean SF
32 cm > $\|z\|$ > 24 cm	0.56 ± 0.06
24 cm > $\|z\|$ > 16 cm	0.77 ± 0.08
16 cm > $\|z\|$ > 8 cm	0.84 ± 0.09
8 cm > $\|z\|$ > 0 cm	0.97 ± 0.10

SF = scale factor

Radiation damage measurements

Modelling radiation damage to pixel sensors in the ATLAS detector





Several measurements per year

After type inversion a different technique is used

Voltage of plateauing of charge as a proxy to depletion voltage

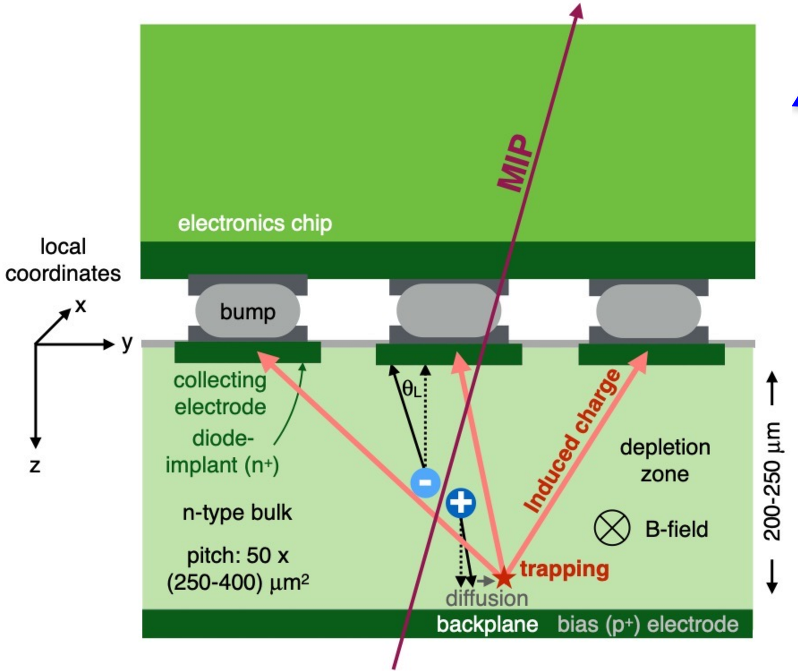
Parameter	IBL [$\times 10^{-2}$cm^{-1}]	*B*-layer [$\times 10^{-2}$cm^{-1}]	ROSE Coll. [$\times 10^{-2}$cm^{-1}]
g_A	1.4 ± 0.5	1.4 ± 0.5	1.4 (*n*)
g_Y	6.0 ± 1.6	6.0 ± 1.6	2.3 (*p*), 4.8 (*n*)
g_C	1.1 ± 0.3	0.45 ± 0.1	0.53 (*p*), 2.0 (*n*)

3rd RD48 status report

RADIATION DAMAGE SIMULATION IN RUN2-3

Simulation radiation damage effects in ATLAS MC

Modelling radiation damage to pixel sensors in the ATLAS detector



All this included in
ATLAS MonteCarlo digitization*

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**)

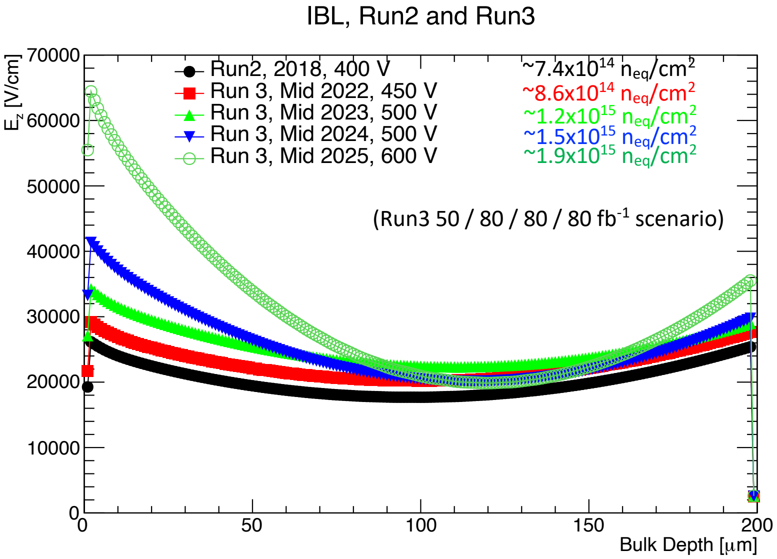
Total induced charge is then digitized and clustered

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

Ingredients

Modelling radiation damage to pixel sensors in the ATLAS detector

Electric field from TCAD simulations



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

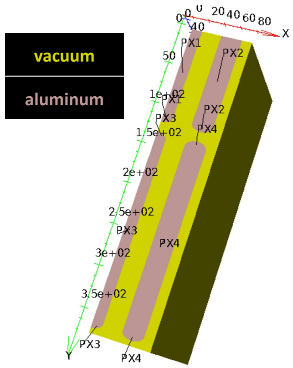
TNS, VOL. 52, NO. 4, AUGUST 2005

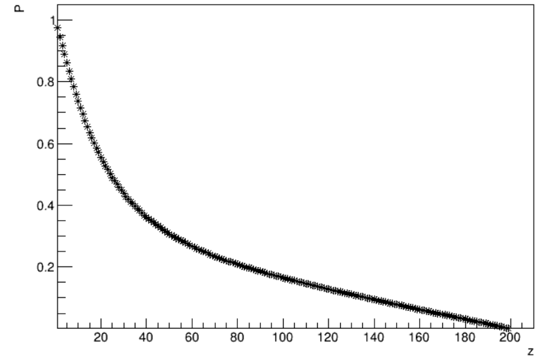
NIM A 568 (2006) 51–55

W. Adam *et al* 2016 *JINST* **11** P04023

All inspired by EVL 2 levels model

Ramo potential from TCAD simulations



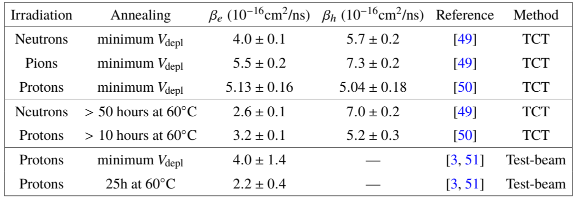


Trapping from literature:

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

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

based on these inputs:

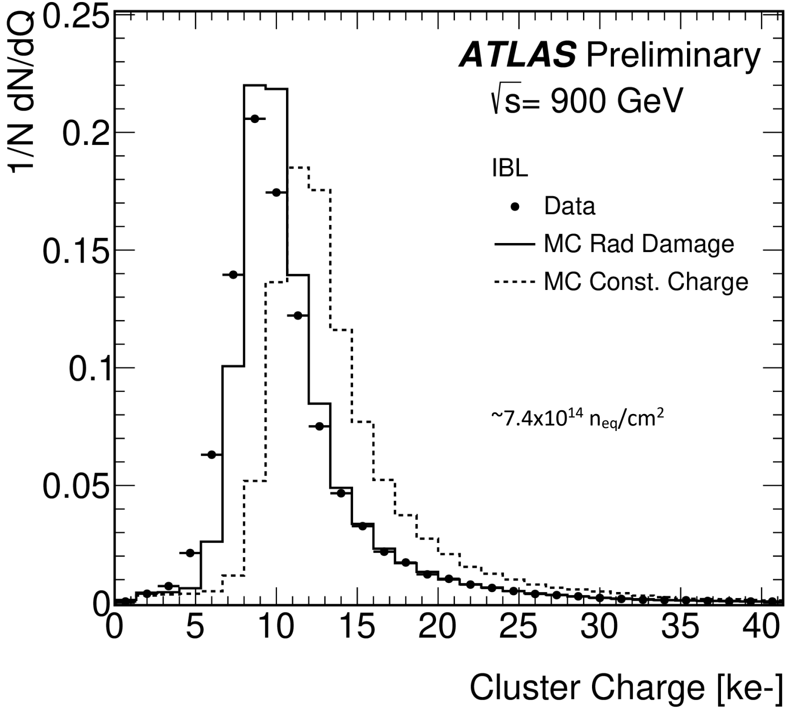


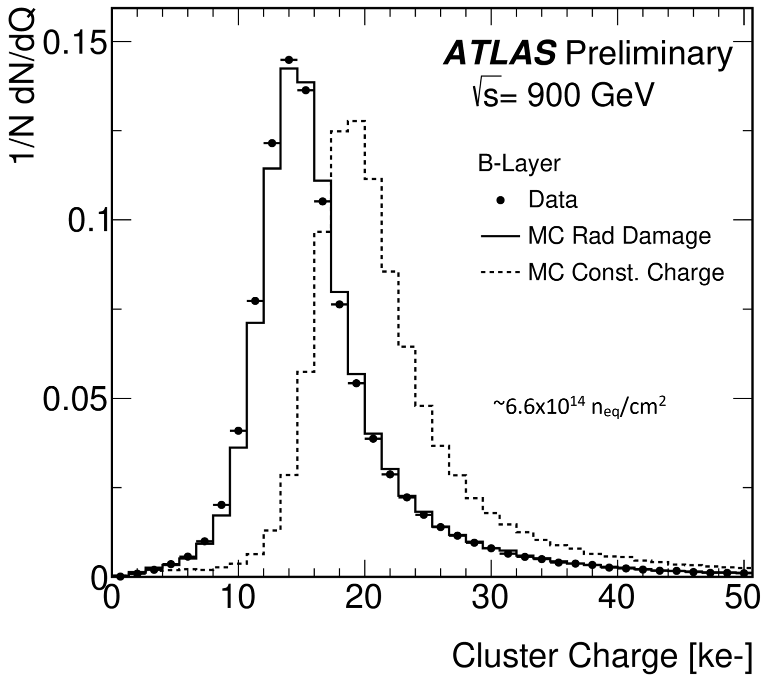
Irradiation	Annealing	β_e (10^{-16}cm^2/ns)	β_h (10^{-16}cm^2/ns)	Reference	Method
Neutrons	minimum V_{depl}	4.0 ± 0.1	5.7 ± 0.2	[49]	TCT
Pions	minimum V_{depl}	5.5 ± 0.2	7.3 ± 0.2	[49]	TCT
Protons	minimum V_{depl}	5.13 ± 0.16	5.04 ± 0.18	[50]	TCT
Neutrons	> 50 hours at 60°C	2.6 ± 0.1	7.0 ± 0.2	[49]	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

DATA VS MONTECARLO

Early Run3 data vs MonteCarlo

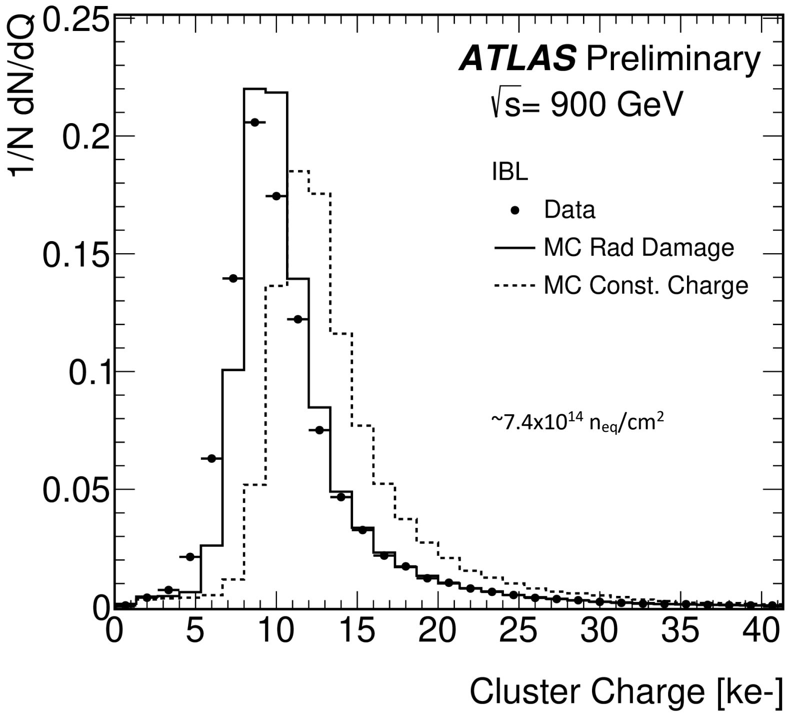
Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at $s\sqrt{}=900$ GeV





MPV match at % level

Early Run3 data vs MonteCarlo



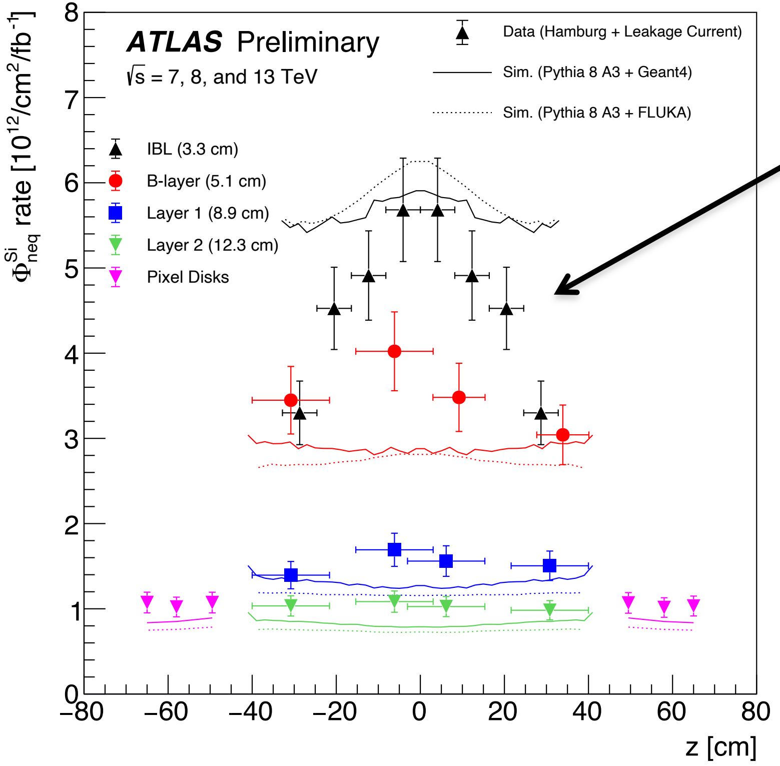
It seems for IBL there is a somewhat less satisfactory agreement

From detailed analysis it seems ~ +20-25% 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

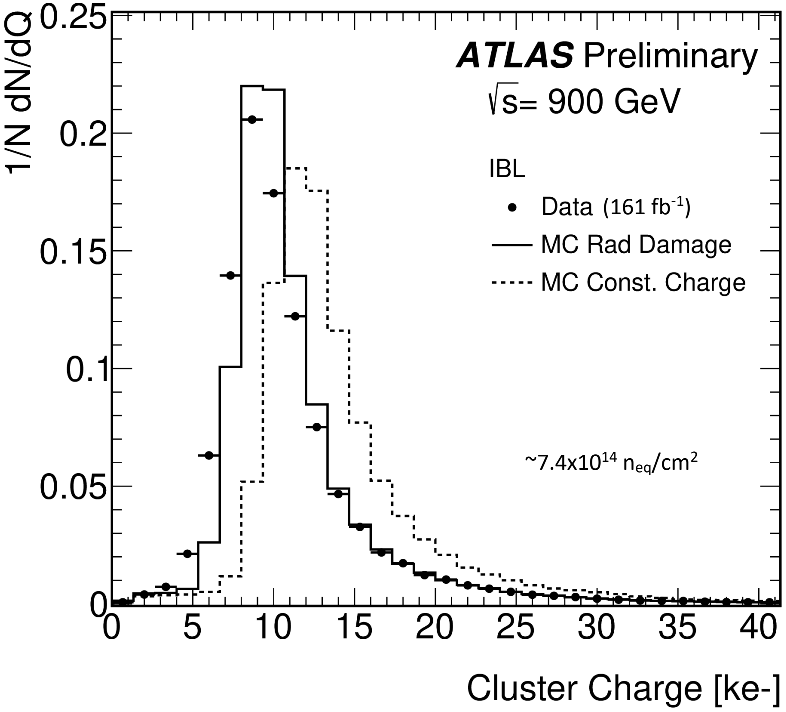
Reminder



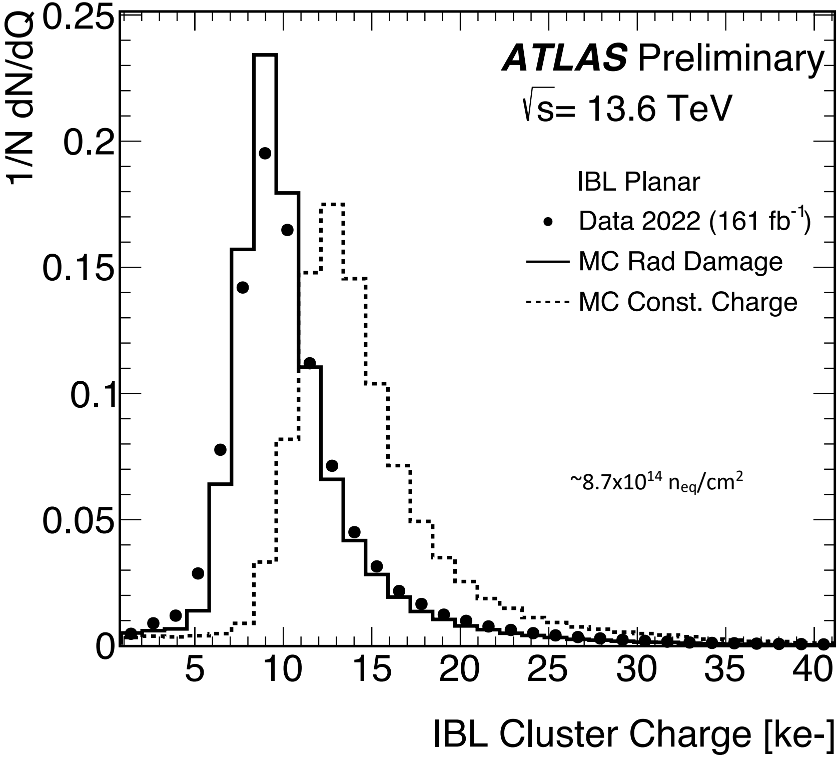
IBL fluence profile across stave is non uniform

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

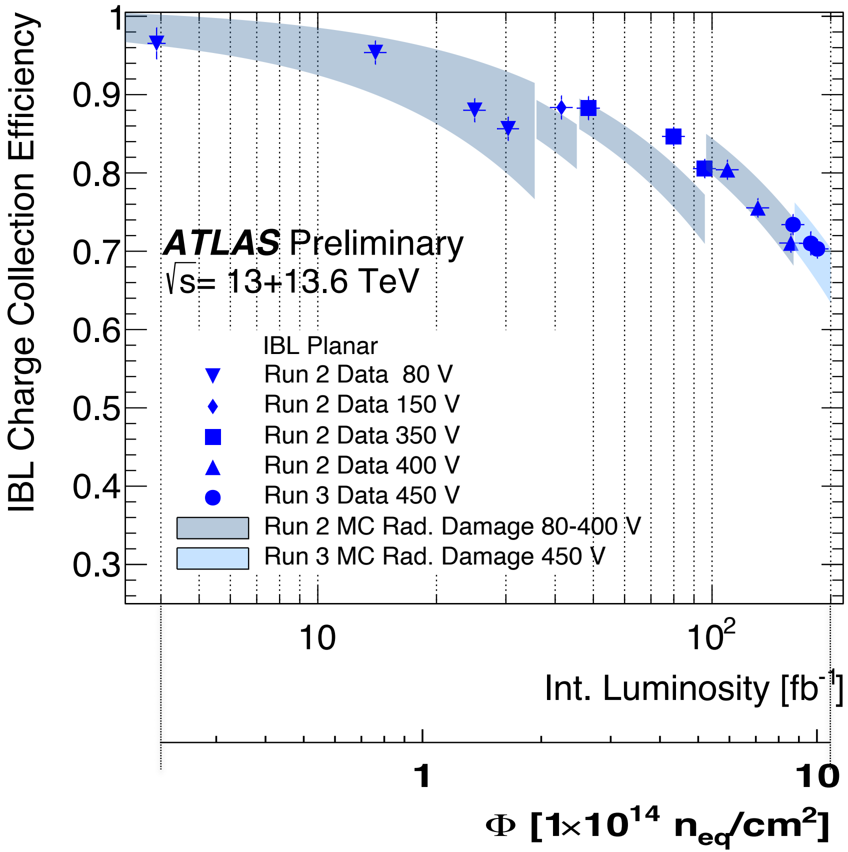
Answer: +20%



ATL-COM-INDET-2022-027



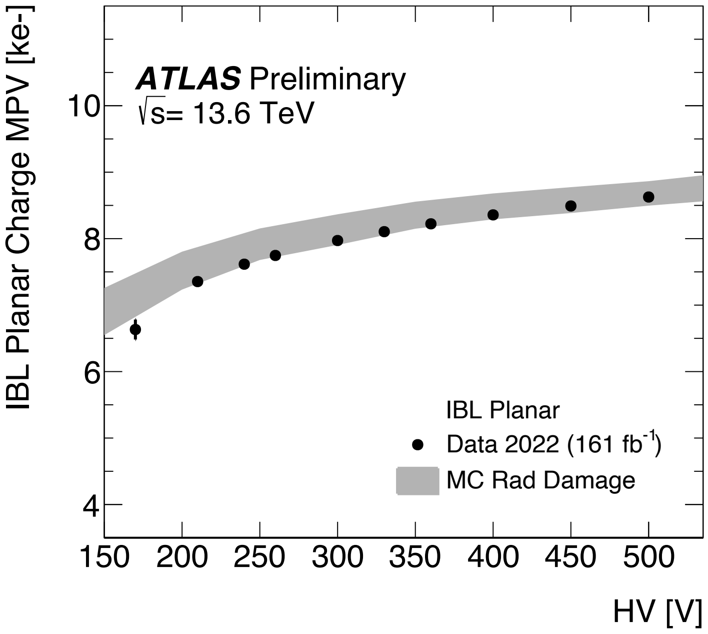
Charge collection efficiency vs luminosity

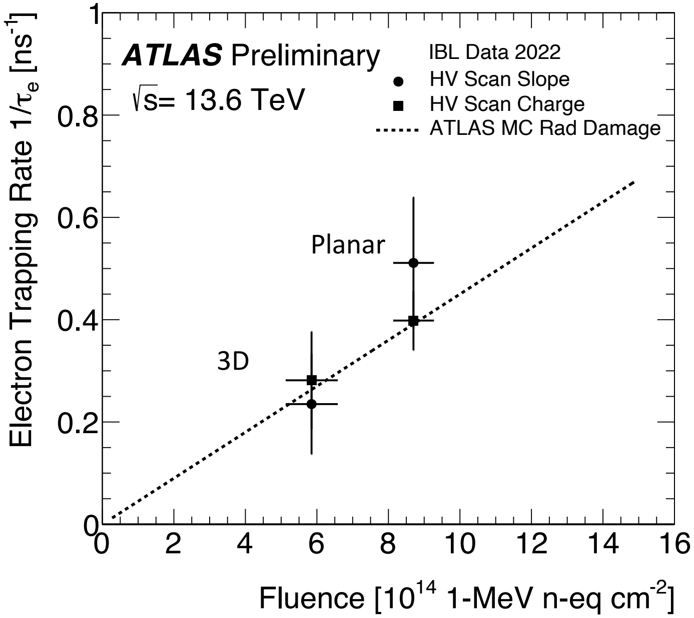


track z averaged fluence

Excellent agreement over almost two order of magnitudes of fluence

Charge vs bias voltage, trapping rate



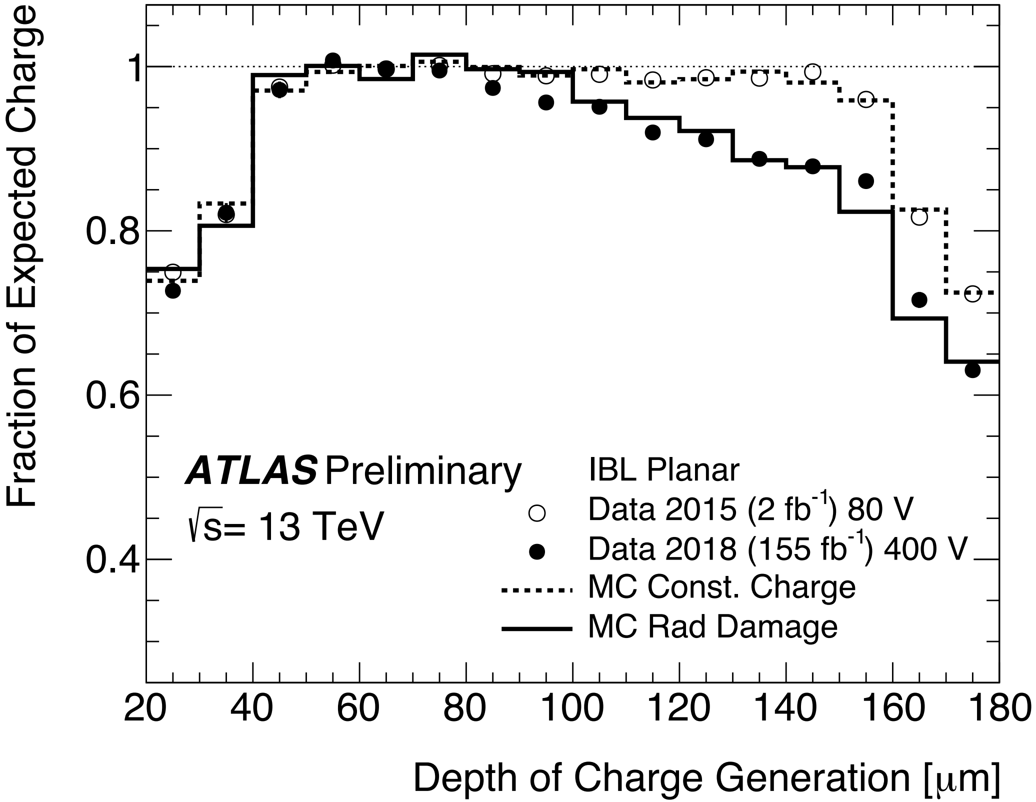


Good agreement also before depletion

Trapping rate consistent with our simulations

Simulations now used to estimate depletion voltage for operations

Charge vs deposition depth



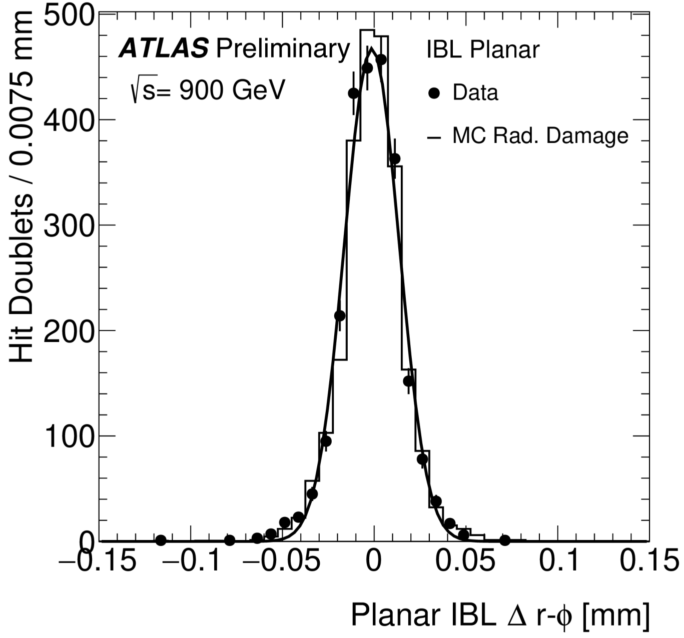
Precise modeling of electric field and of all derived quantities as a function of depth in the bulk

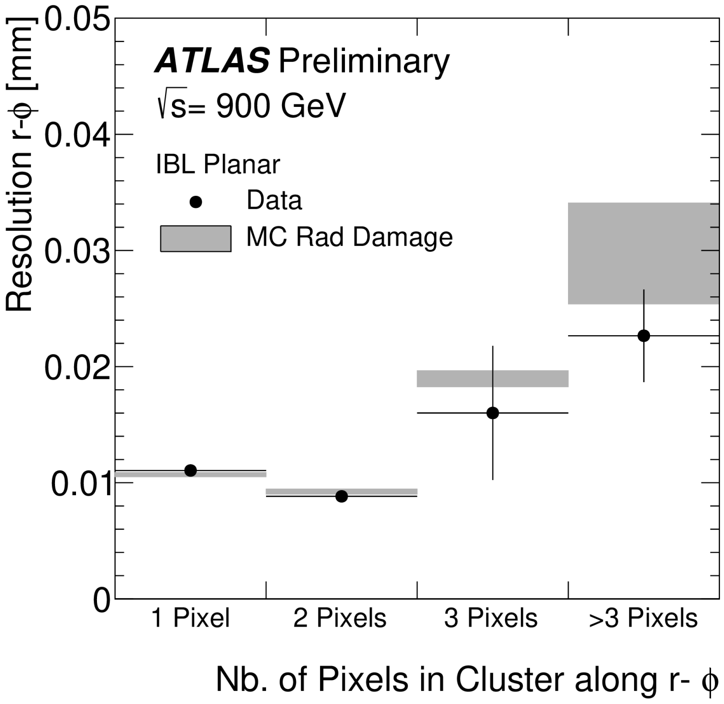
Thanks to this level of agreement Neural Networks trained on radiation damage MC samples give excellent space point resolution when used with Run3 data

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

Pixel hit spatial resolution

Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at s√=900 GeV

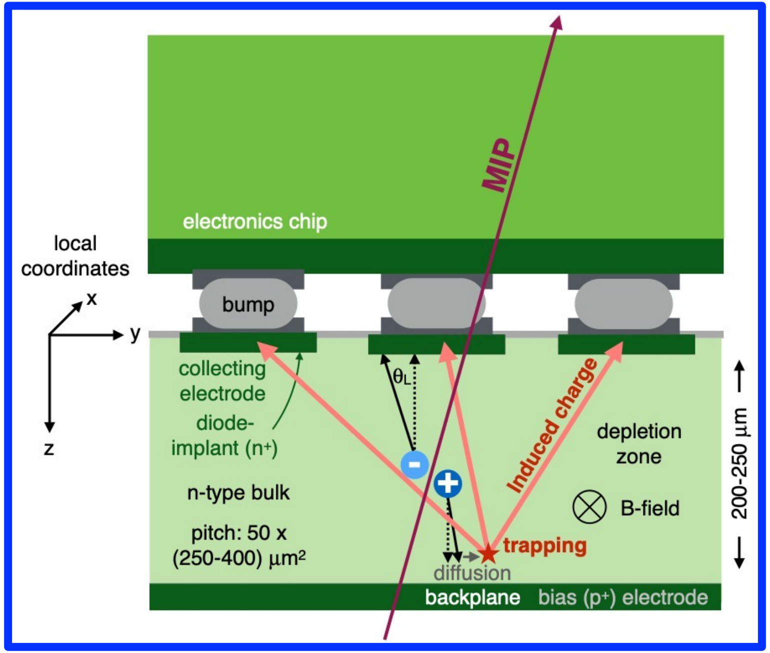




RADIATION DAMAGE SIMULATION FOR HL-LHC

Simulation radiation damage effects in ATLAS MC

Run 2 & 3



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

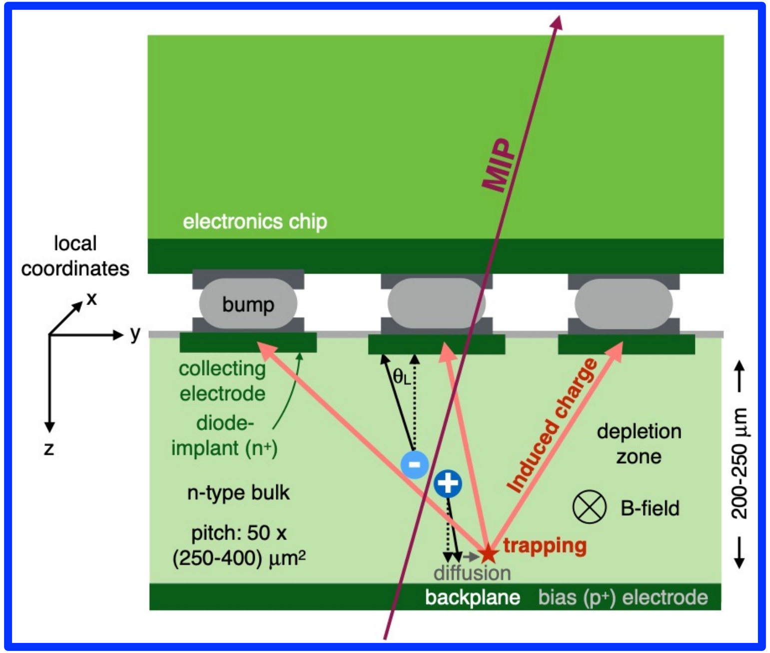
Modified pixel digitizer to include radiation damage effects is now the default for Run3

Excellent agreement with data

But too slow for HL-LHC

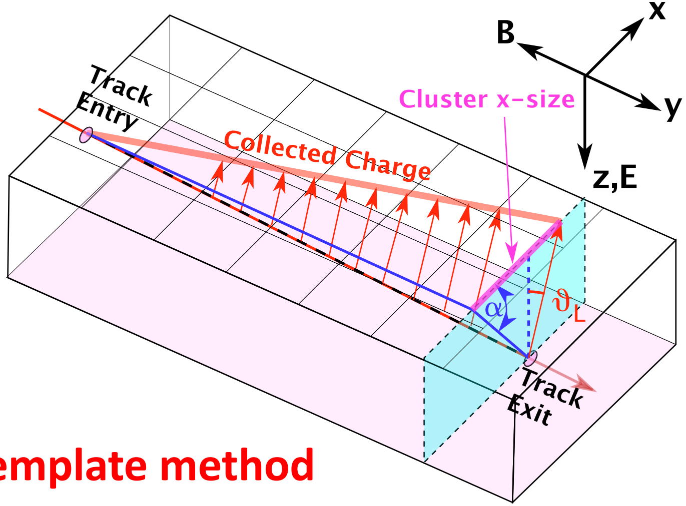
Radiation damage MC for ITk

Run 2 & 3



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

ITk



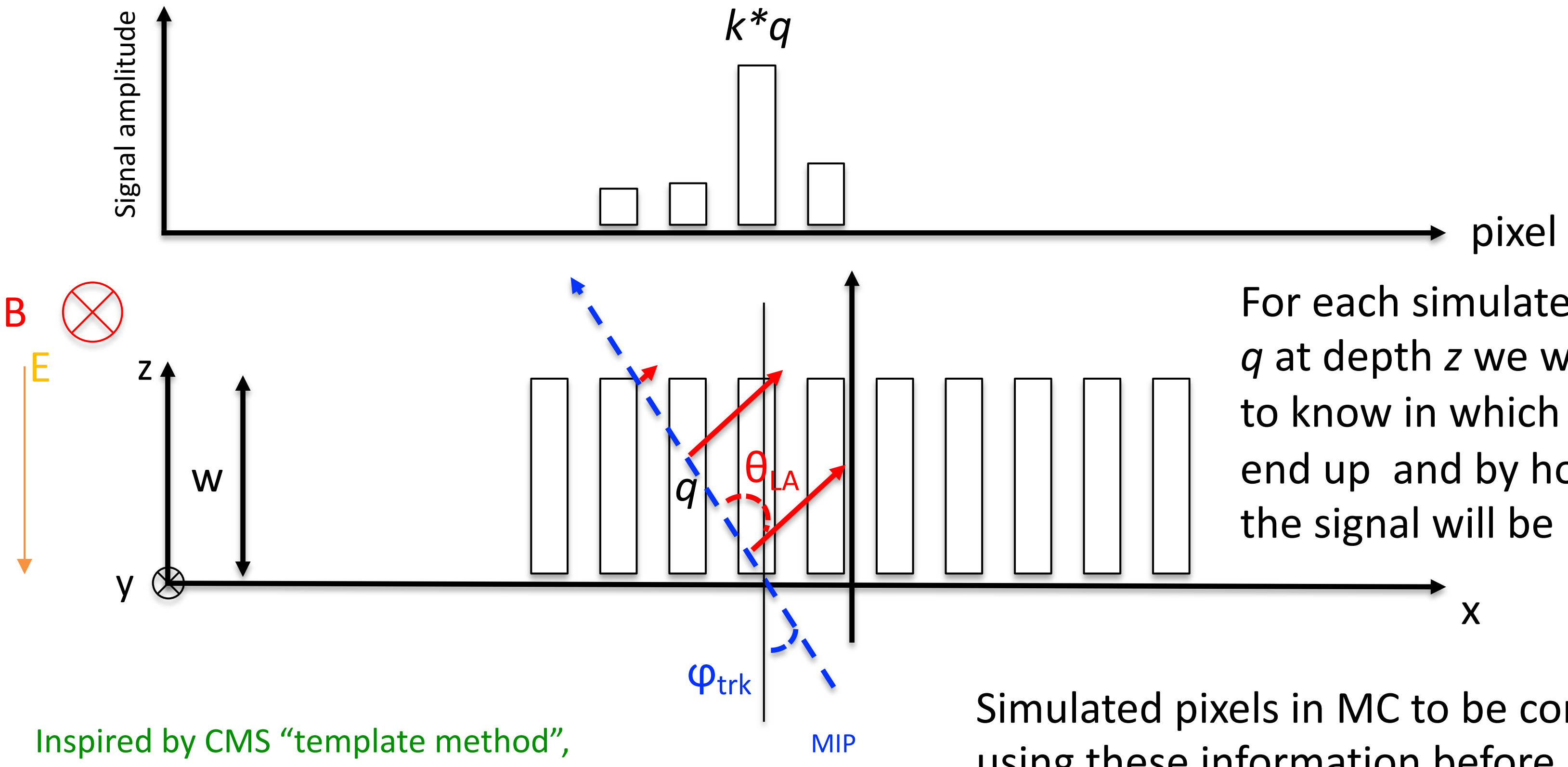
Template method

For each group of charges the corresponding correction is calculated.

Corrections through "templates"

Inspired by CMS approach

Strategy for High Luminosity LHC phase



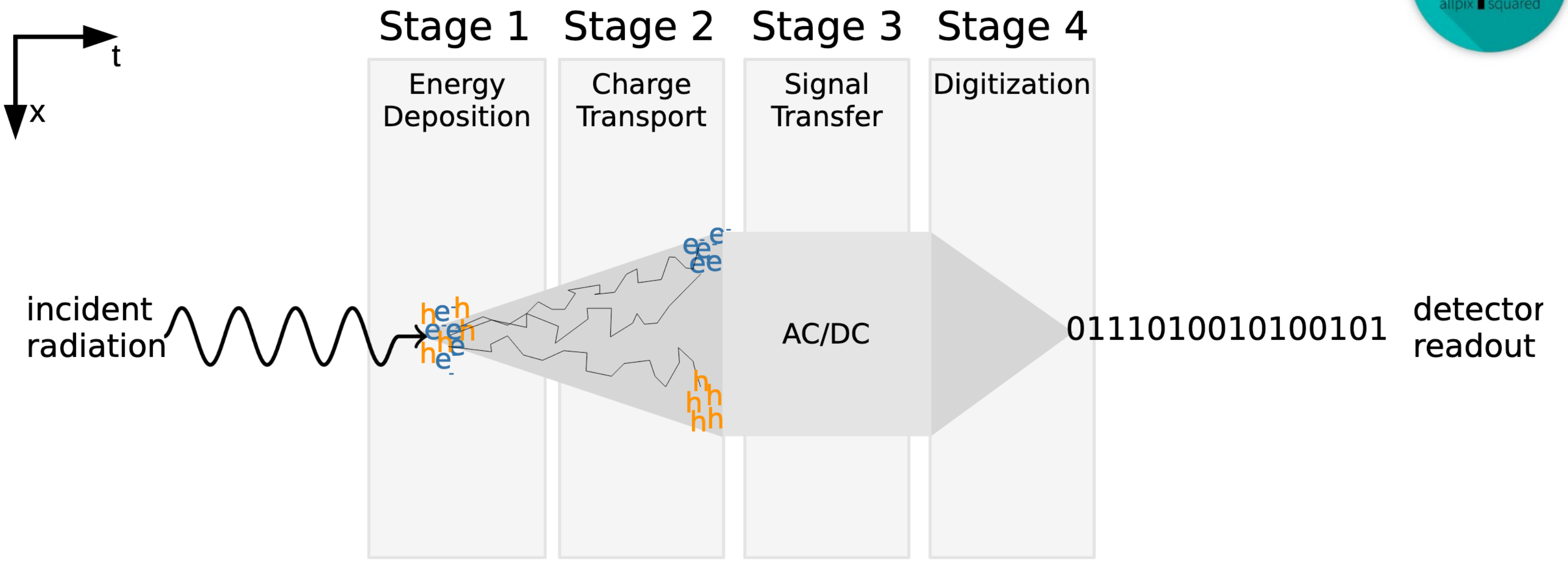
For each simulated charge q at depth z we want to know in which pixel it will end up and by how much (k) the signal will be reduced

Simulated pixels in MC to be corrected using these information before digitization

Inspired by CMS "template method",
PoS VERTEX2007 (2007) 035

Allpix^2 for radiation damage digitizer

- To implement such a correction scheme we have thought Allpix^2 is the perfect tool



Allpix^2 for radiation damage digitizer

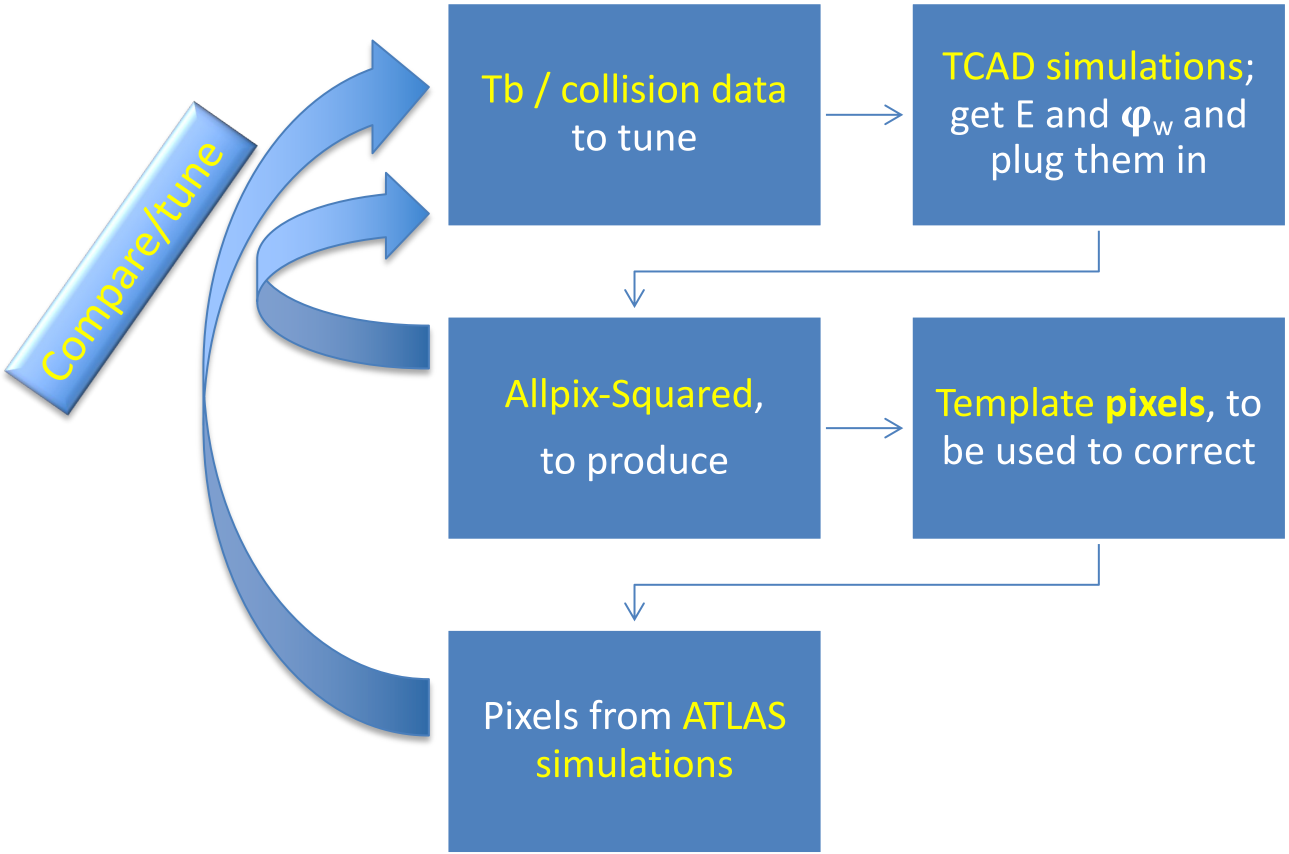
- To implement such a correction scheme we have thought Allpix^2 is the perfect tool

➢ Simulate sensors before and after irradiation, per geometry and per fluence

➢ Save the ratio of after-over-before irradiation collected charge for a pixel struck at a certain depth z

➢ Evaluate Lorentz angle deflection too as a function of initial z position

Project workflow



Compare/tune

Tb / collision data to tune

TCAD simulations; get E and $\boldsymbol{\varphi}_w$ and plug them in

Allpix-Squared, to produce

Template **pixels**, to be used to correct

Pixels from ATLAS simulations

Let's talk about inputs…

Input variables: Φ, V, T, z_{entry}

LHCb TCAD radiation damage model

Development of a silicon bulk radiation damage model for Sentaurus TCAD

Å. Folkestad [a,*,1], K. Akiba [b], M. van Beuzekom [c], E. Buchanan [e], P. Collins [a], E. Dall'Occo [c], A. Di Canto [a], T. Evans [d], V. Franco Lima [f], J. García Pardiñas [g], H. Schindler [a], M. Vicente [b], M. Vieites Diaz [g], M. Williams [a]

10.1016/j.nima.2017.08.042

Table 2
Parameters of the proposed radiation damage model. The energy levels are given with respect to the valence band (E_V) or the conduction band (E_C). The model is intended to be used in conjunction with the Van Overstraeten–De Man avalanche model.

Defect number	Type	Energy level [eV]	σ_e [cm^{-2}]	σ_h [cm^{-2}]	η [cm^{-1}]
1	Donor	$E_V + 0.48$	2×10^{-14}	1×10^{-14}	4
2	Acceptor	$E_C - 0.525$	5×10^{-15}	1×10^{-14}	0.75
3	Acceptor	$E_V + 0.90$	1×10^{-16}	1×10^{-16}	36

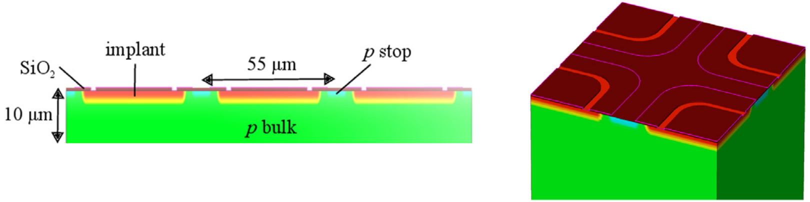


Fig. 1. Close-up of the pixel region of a (left) 2D geometry with three pixels and (right) a 3D geometry with four quarter pixels. The 2D mesh used in CCE simulations contains two additional pixels, i.e. a total of five.

Radiation damage model for n-on-p pixels

Tested up to 8x10^{15} n$_{eq}$/cm^2

Already used for preliminary estimations for ITk

Developed on Synopsys

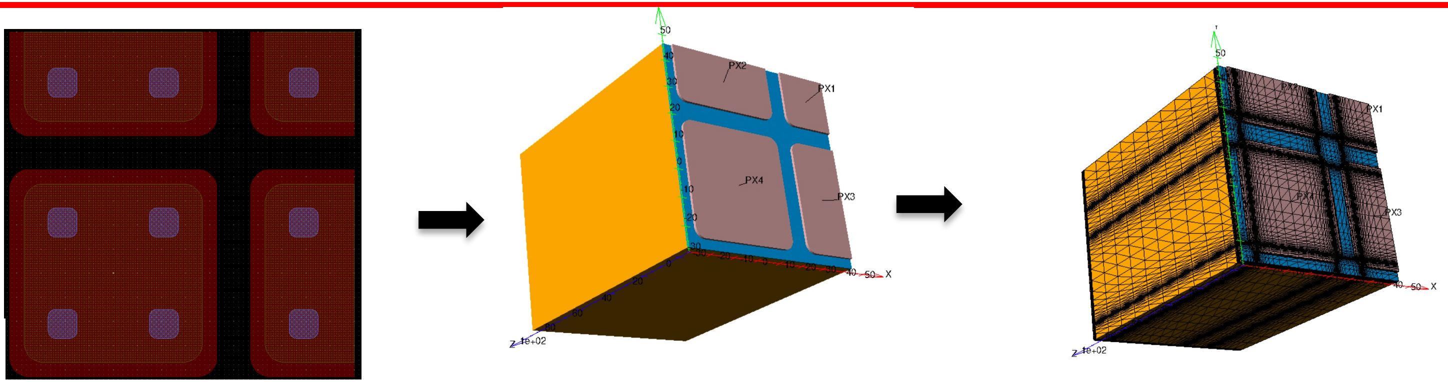
Trying to porting it in Silvaco

In the following: comparison of electric field simulations

ITk pixels simulations with TCAD

n-on-p
100 µm think
50 µm pitch

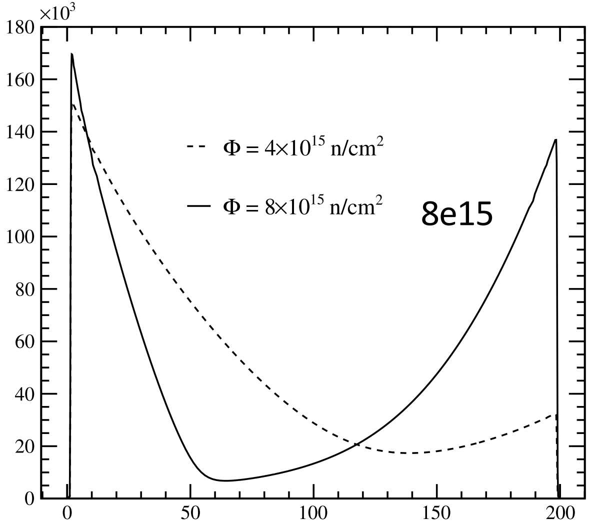
¼ of 3x3
pixels matrix

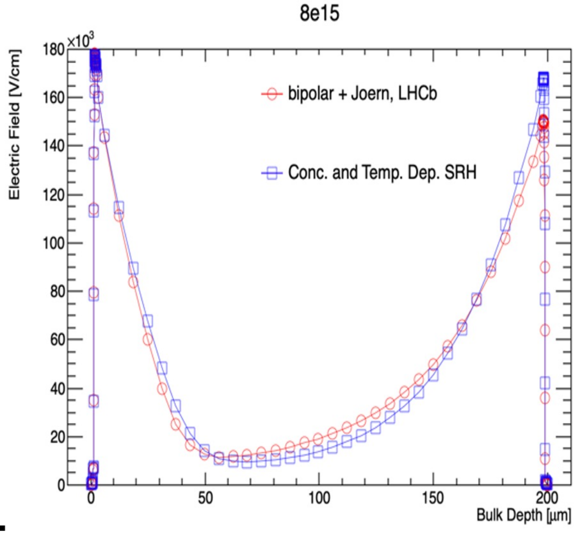


Full 3D simulation

Several models tested (mobility, recombination, bands…)

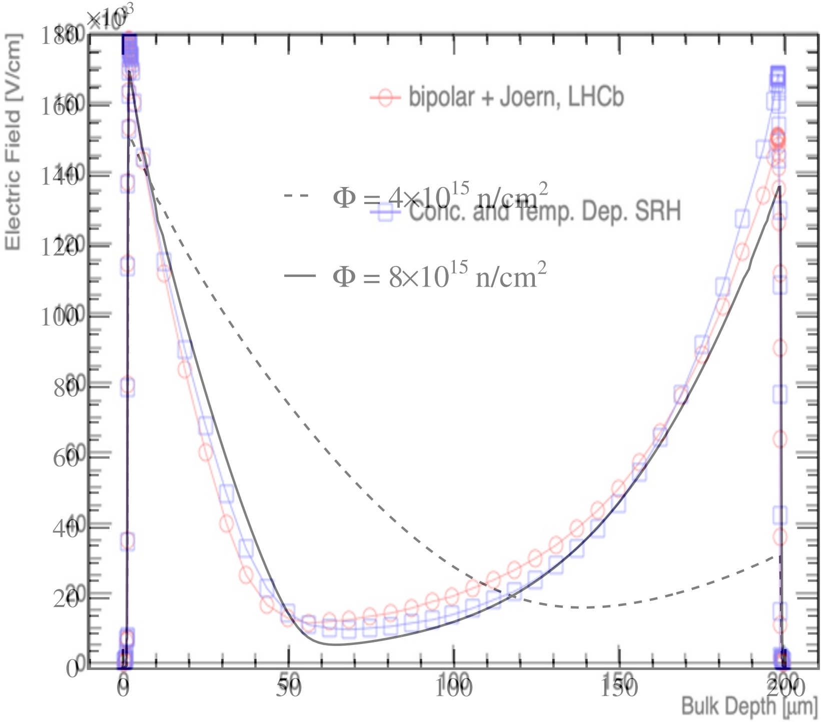
(validation done in 2D)





LHCb TCAD radiation damage model

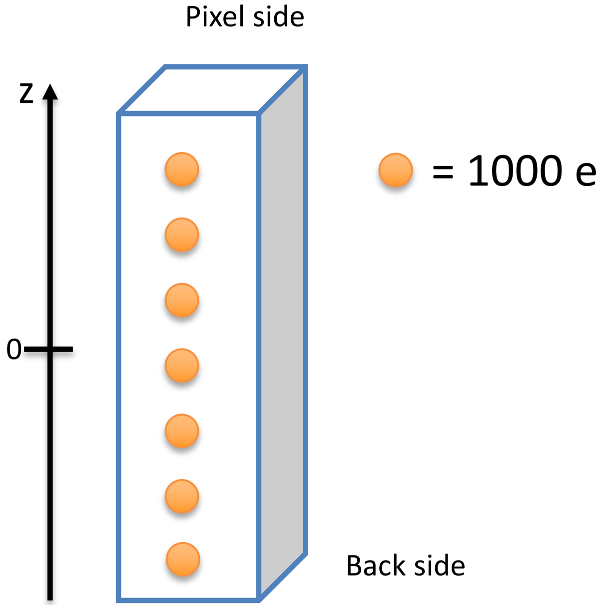
8e15



Good agreement!

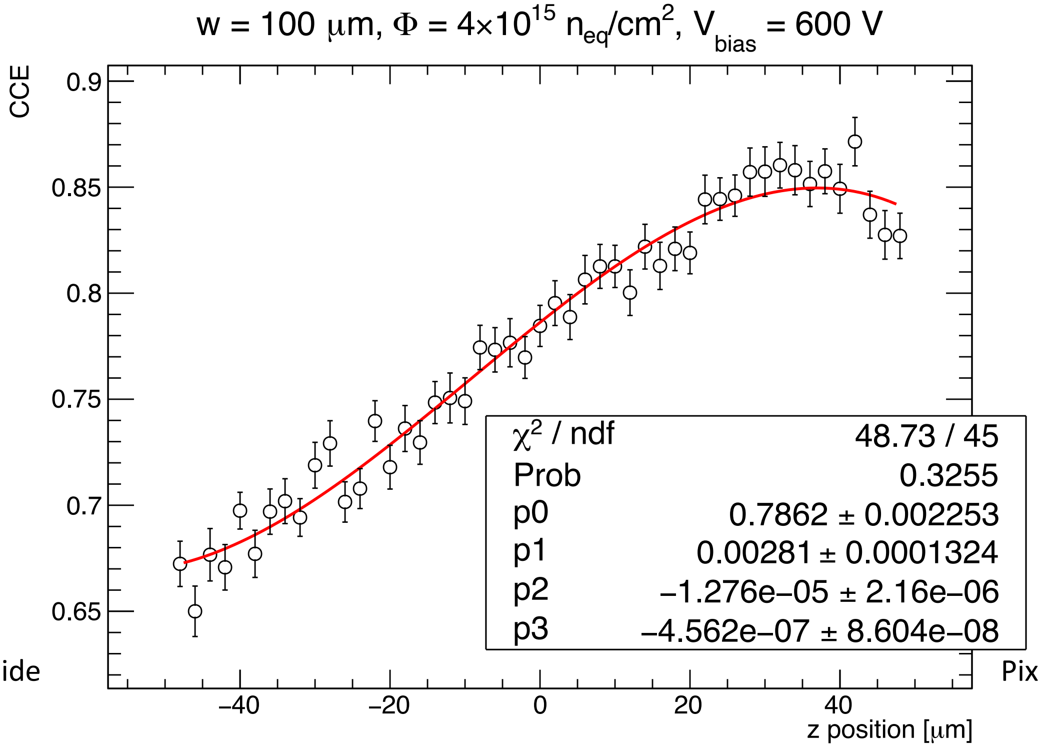
How to calculate CCE in Allpix^2

- Simulate point deposition at different z positions
  - 1 simulation per z position
- Get the fraction of induced charge
- Plot it vs z



- Details:
  - 100 events per z position
  - 1000e deposited per event
  - Scan from 2 µm below one surface to 2 µm the other, in 2 µm steps
  - Simulation for 100 µm thick sensor at 4×10^{15} n_{eq}/cm^2 and 600 V

Charge collection efficiency vs z



χ^2 / ndf	48.73 / 45
Prob	0.3255
p0	0.7862 ± 0.002253
p1	0.00281 ± 0.0001324
p2	−1.276e−05 ± 2.16e−06
p3	−4.562e−07 ± 8.604e−08

Back side

Pixel side

Pol3 seems enough
to describe the trend

CONCLUSIONS & OUTLOOK

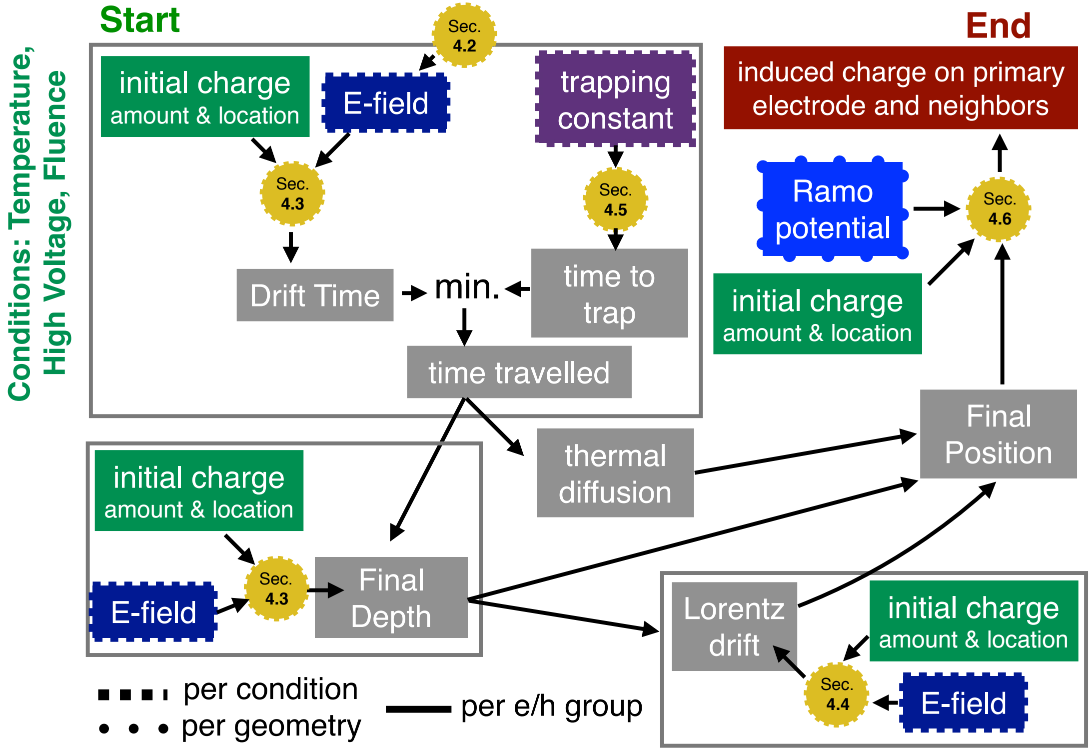
Conclusions & Outlook

- Precise electric field, mobility and trapping modeling makes possible to reproduce charge collection in ATLAS pixels at % level
- Simulations including radiation damage effects used as a tool for operation purposes 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 a faster – yet as precise as possible – algorithm is needed
- Joint ITk Pixel & Strip effort to make it possible, using DLTS data too
- Allpix^2 + TCAD will provide templates to correct simulations
- Simulations to be validated against testbeam data

Backup

Simulation radiation damage effects in ATLAS MC

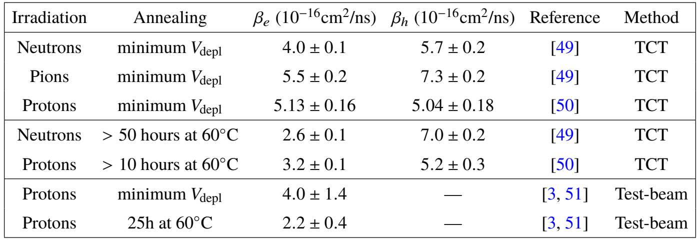
Modelling radiation damage to pixel sensors in the ATLAS detector



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}cm^2/ns)	β_h (10^{-16}cm^2/ns)	Reference	Method
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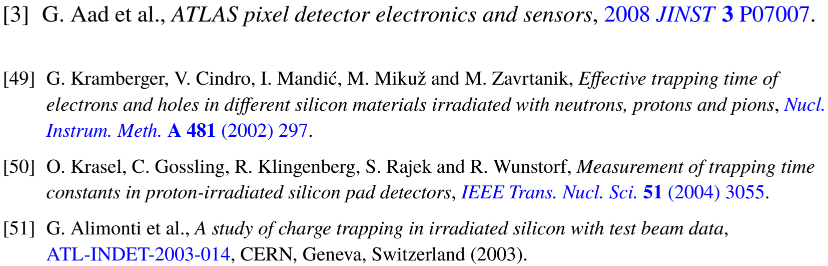


[3] G. Aad et al., *ATLAS pixel detector electronics and sensors*, 2008 *JINST* **3** P07007.

[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.

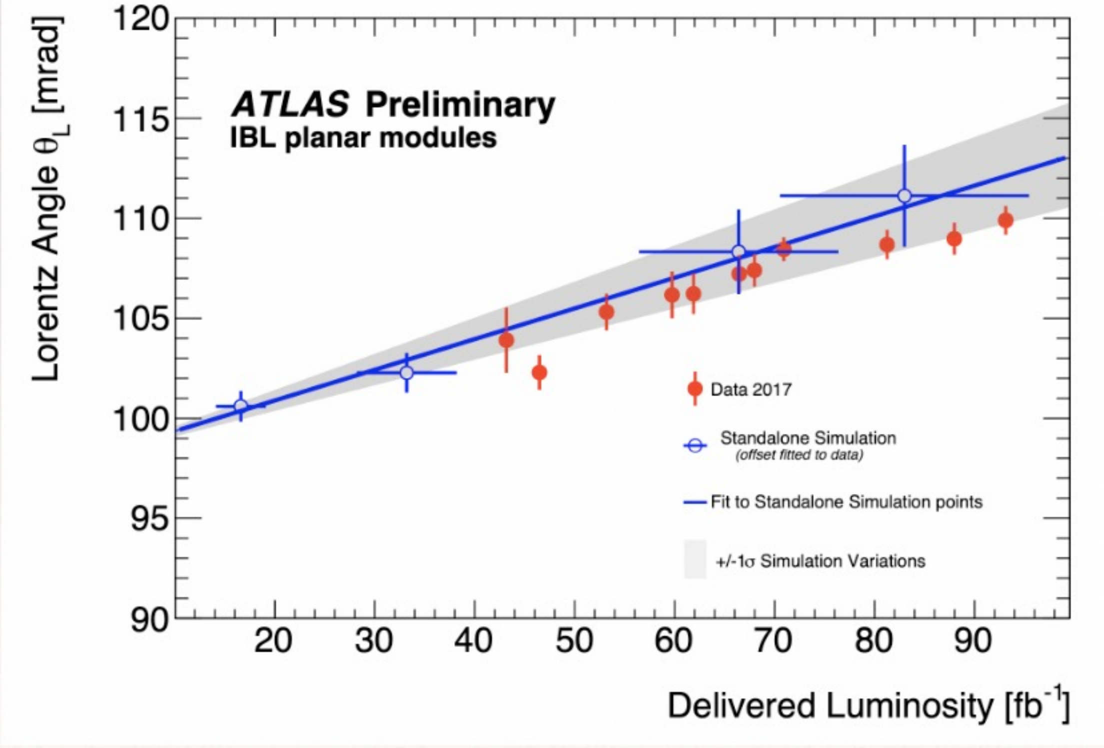
[51] G. Alimonti et al., *A study of charge trapping in irradiated silicon with test beam data*, ATL-INDET-2003-014, CERN, Geneva, Switzerland (2003).

The values we use in our modeling:

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

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

Lorentz Angle vs luminosity



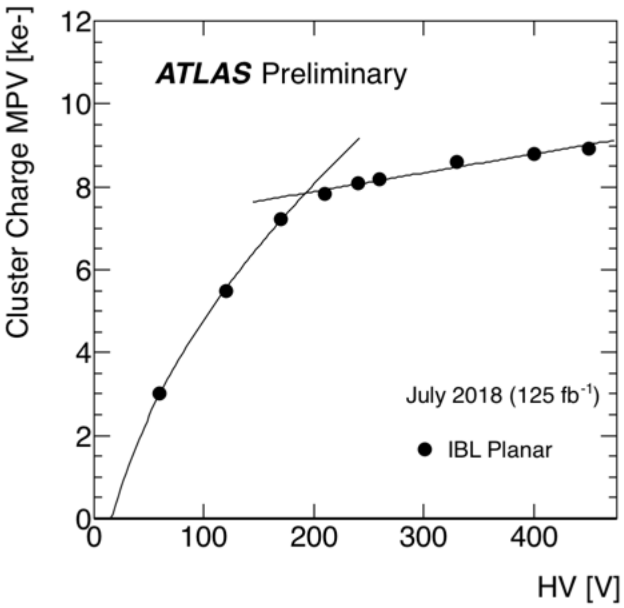
Fluence estimates – planar sensors

- Estimates for Run3 year by year
- 50 / 80 / 80 / 80 fb^{-1} scenario

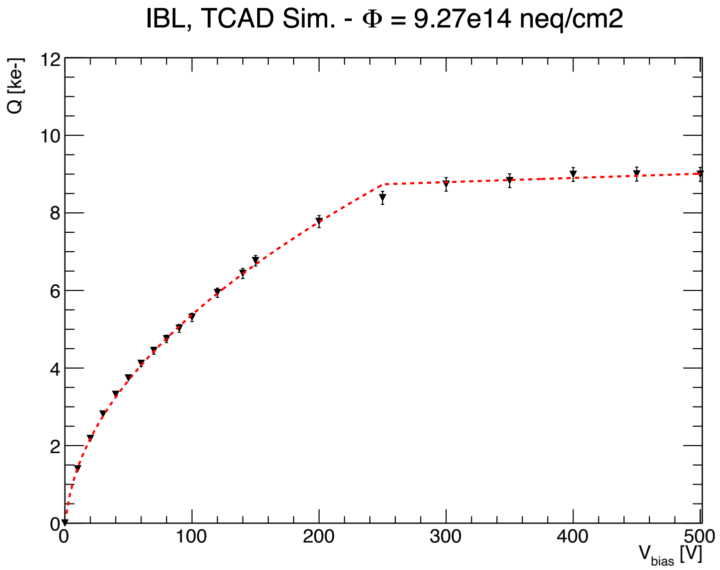
Layer / Fluence @	End Run2 [10^{14} n_{eq}/cm^2]	Mid 2022 [10^{14} n_{eq}/cm^2]	Mid 2023 [10^{14} n_{eq}/cm^2]	Mid 2024 [10^{14} n_{eq}/cm^2]	Mid 2025 [10^{14} n_{eq}/cm^2]
IBL	6.4	7.2	10	13	17.9
BL	5.86	6.8	9.2	12	14.8
L1	2.58	3	4	5.3	6.6
L2	1.73	2	2.7	3.6	4.5

- +/- 10-15% due to fluence conversion factors

Fitting depletion voltage

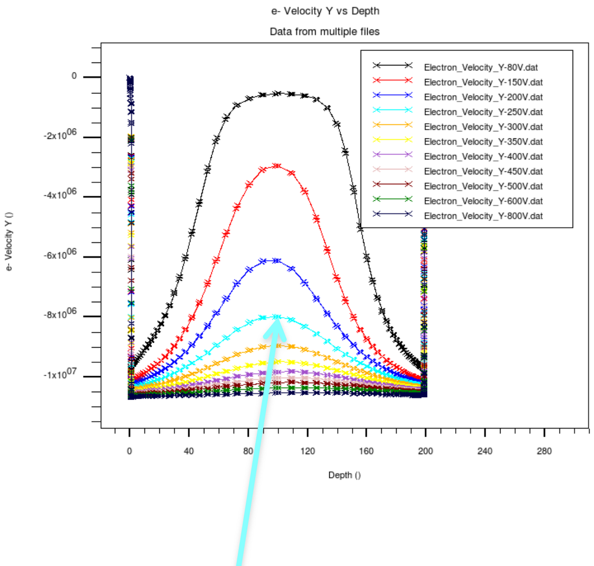


Fitted Depletion = (225 +/- 15) V

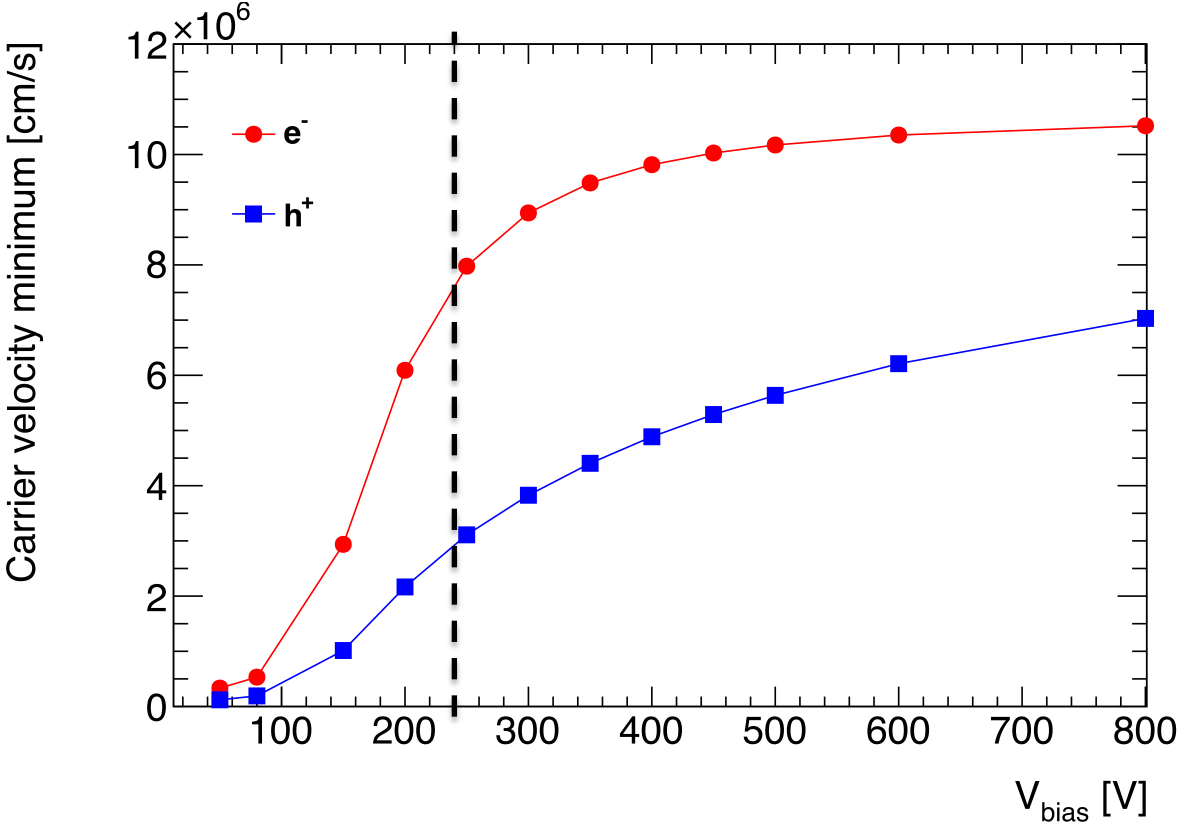


Fitted Depletion = (250 +/- 11) V

Minimum of carrier velocities vs bias

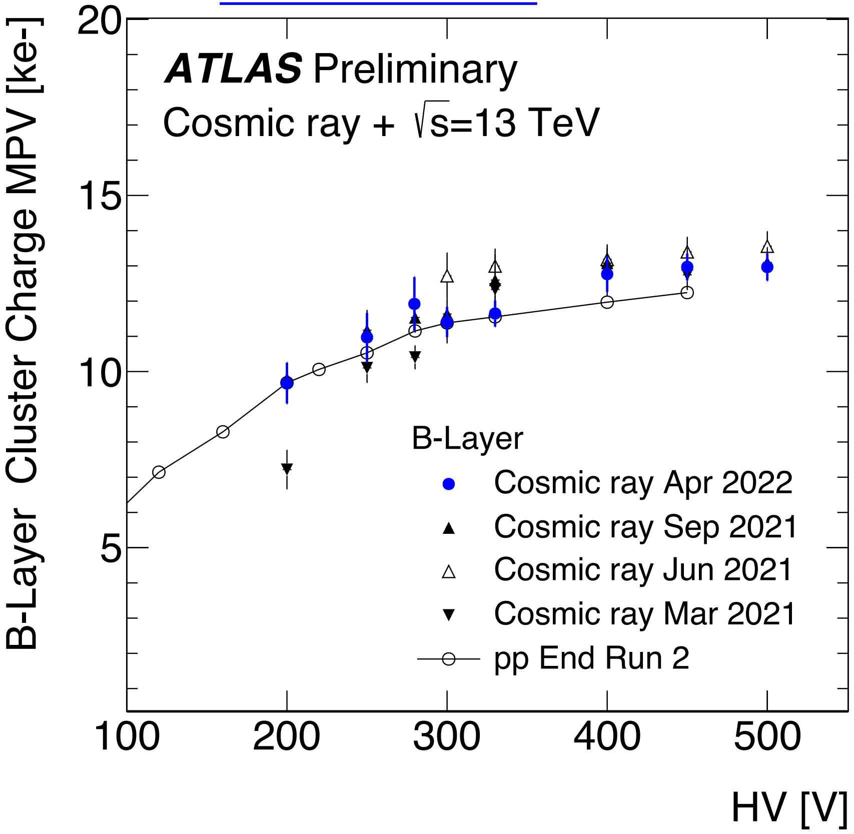


Vdepl ~ 250 V



Radiation damage measurements

ATL-INDET-INT-2022-001



Pixels were warm for 43 days during LS2

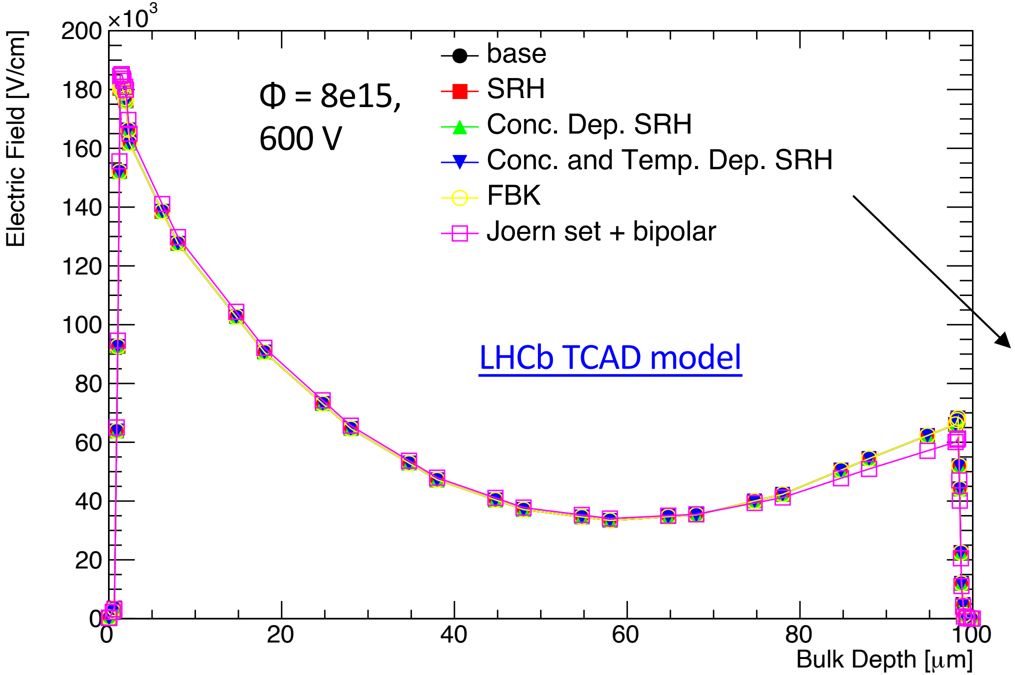
CR μ data taken during LS2, after lowering the analog thresholds to the settings chosen for Run 3

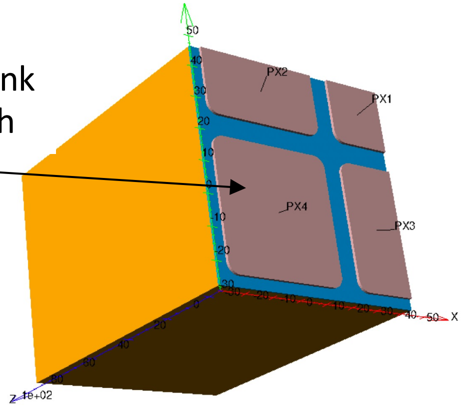
The cluster charge measured above the depletion voltage increases after the threshold decrease and remains constant, within uncertainties, over the last year of LS2

Structures and models

n-on-p
100 μm think
50 μm pitch

Electric field in the middle of PX4





base: models fermidirac fldmob trap.tunnel mass.tunnel=0.5 KLAASSEN print

SRH: base + SRH

Conc. Dep. SRH: SRH + Conc. Dep.

Conc. and Temp. Dep. SRH: you guess it ☺

FBK: set of models by FBK colleagues using Synopsys

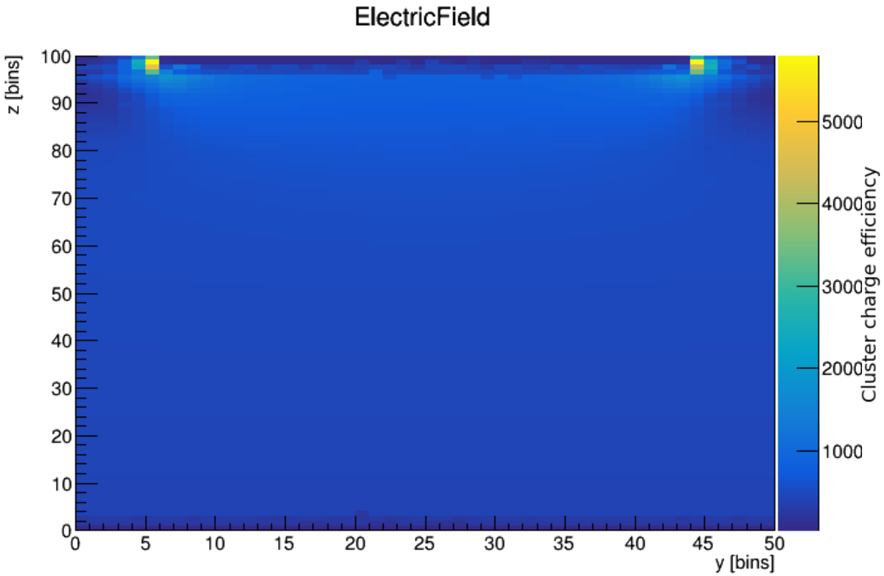
Joern set + bipolar: basic set of models for bipolar devices in Silvaco

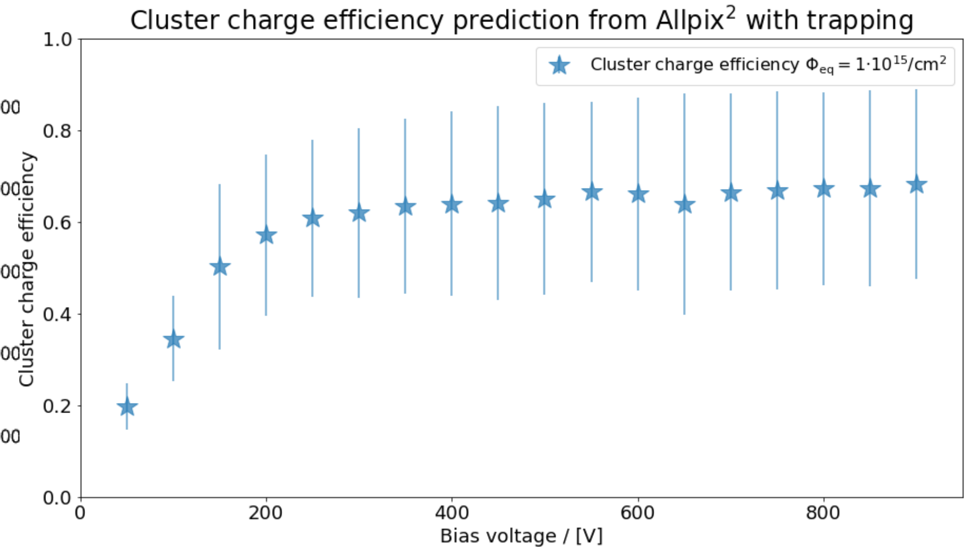
Conclusion: no difference apart for "Joern set + bipolar"

Enhancing Allpix^2 capabilities

New module to read field maps from Silvaco

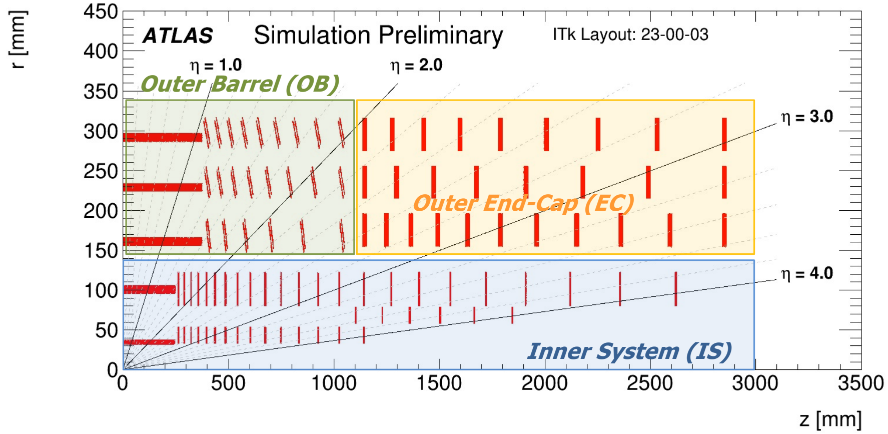
Trapping implemented too!





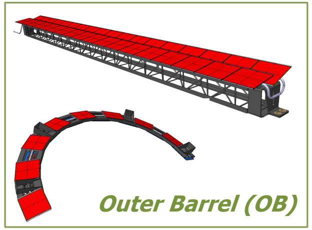
ITk Pixel Overview

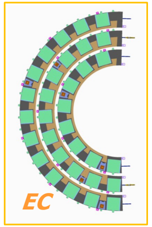
Calderini @ Vertex 2021

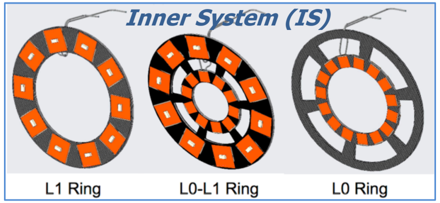


Inner system can be replaced at 2000 fb^{-1}
Outer system need to survive to 4000 fb^{-1}

Local supports

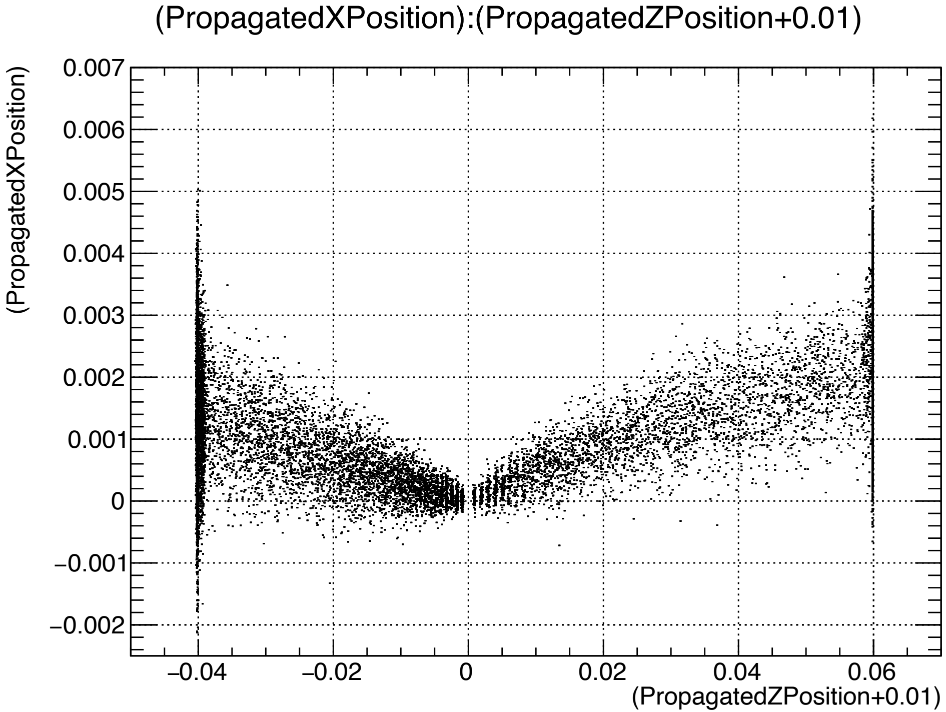




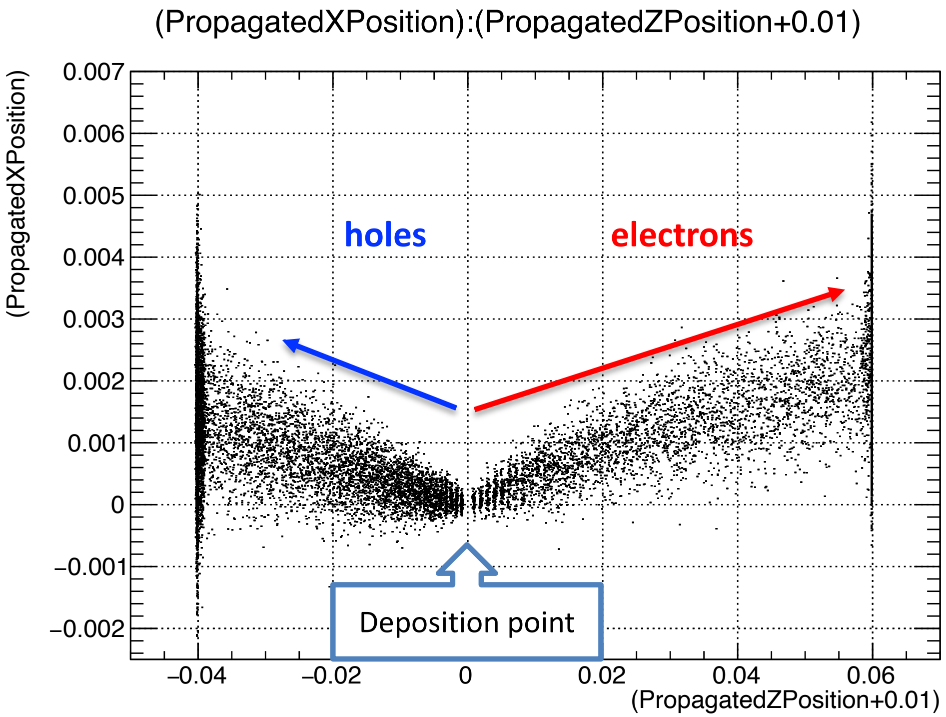


Layer	Sensor Type	Thickn. [μm]	Sensor Size [μm^2]	Module Type	Module installed	Replace-ment	Fluence w/ SF [1e15 n_{eq}/cm^2]
L0 barrel	3D n-in-p	150	25x100 1E	Triplet	288	Yes	18
L0 rings	3D n-in-p	150	50x50 1E	Triplet	900	Yes	18
L1	Planar n-in-p	100	50x50	Quad	1160	Yes	4
L2-4	Planar n-in-p	150	50x50	Quad	6816	No	4-1

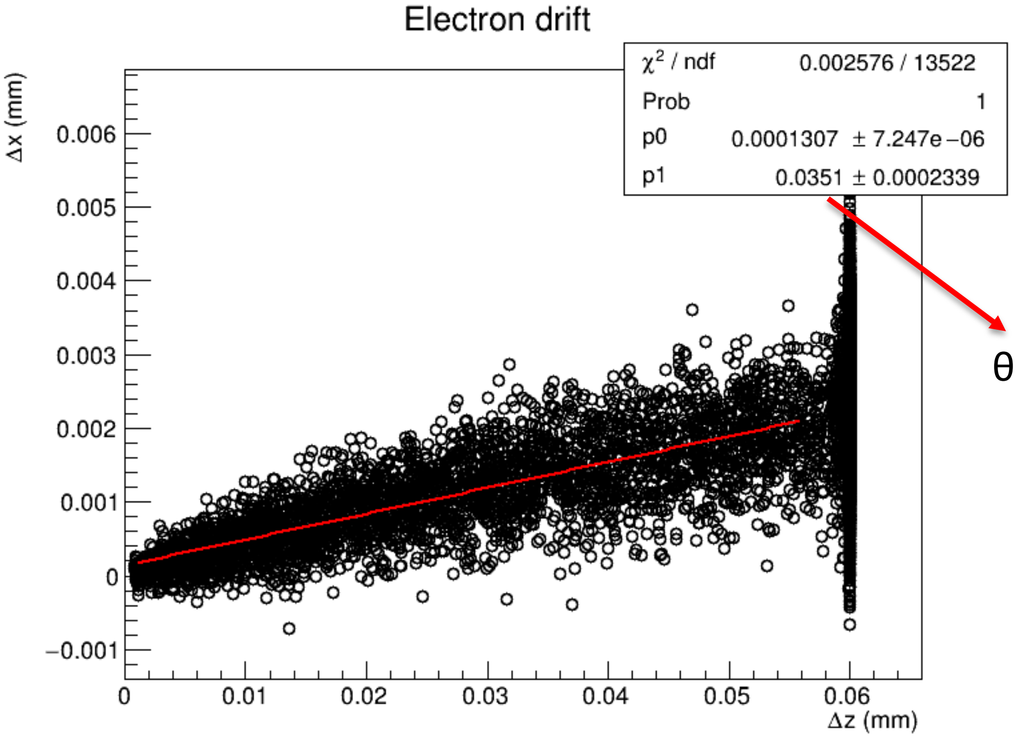
Lorentz angle studies – carriers drift



Lorentz angle studies – carriers drift

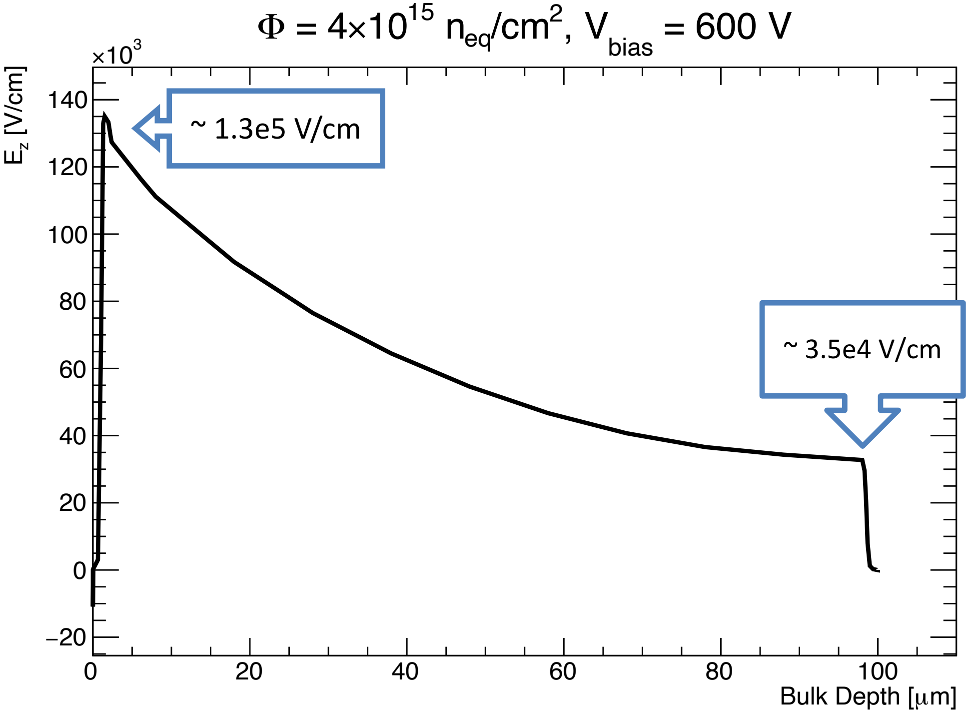


Average Lorentz angle deflection



θ_{LA} ~ 35 mrad

Electric field profile and mobility



T = 253 K

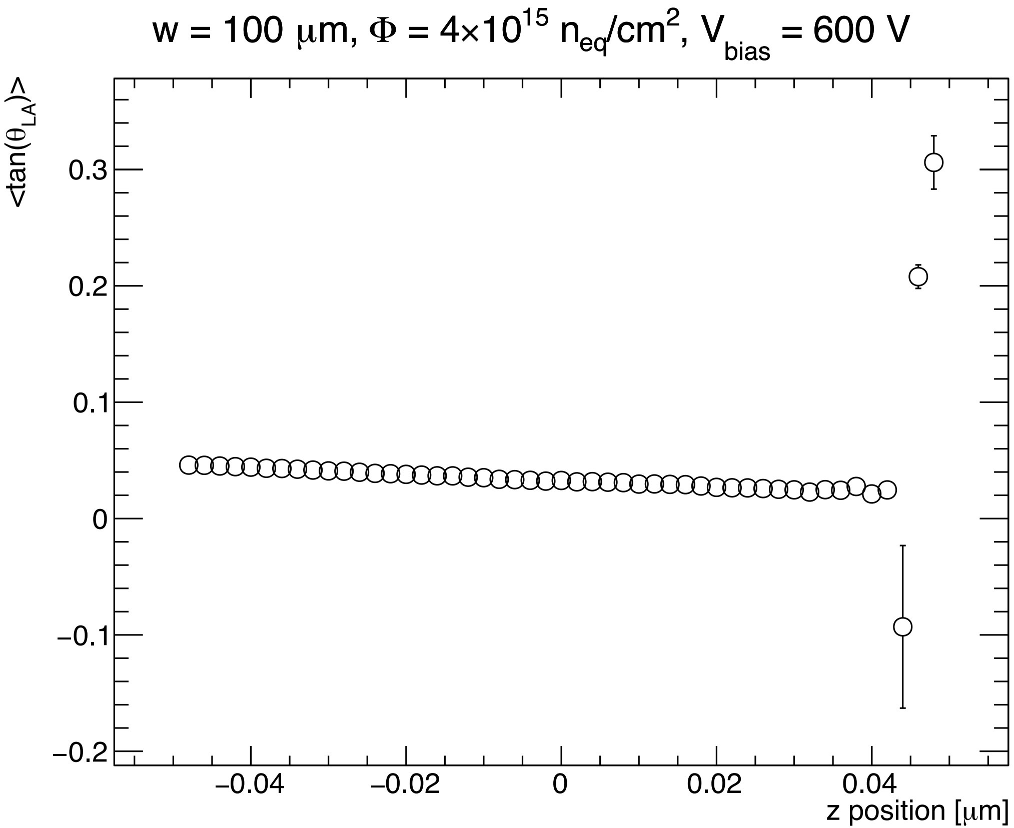
Highest electric field
μ_e = ~ 9e-3 m^2/V/s =>
θ_{LA} ~ 18 mrad

Lowest electric field
μ_e = ~ 30e-3 m^2/V/s =>
θ_{LA} ~ 60 mrad

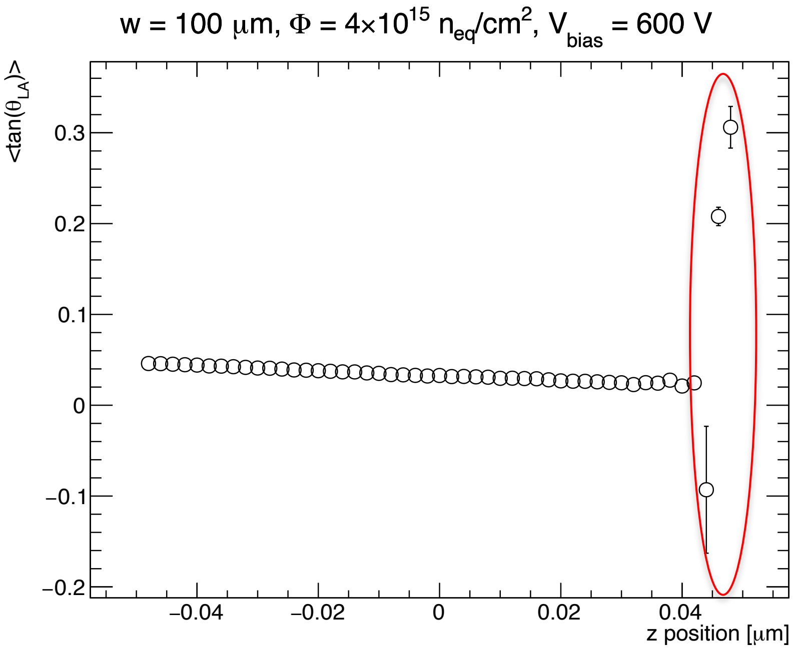
In previous slide:
θ_{LA} ~ 35 mrad

Ballpark!

Average Lorentz angle deflection vs z



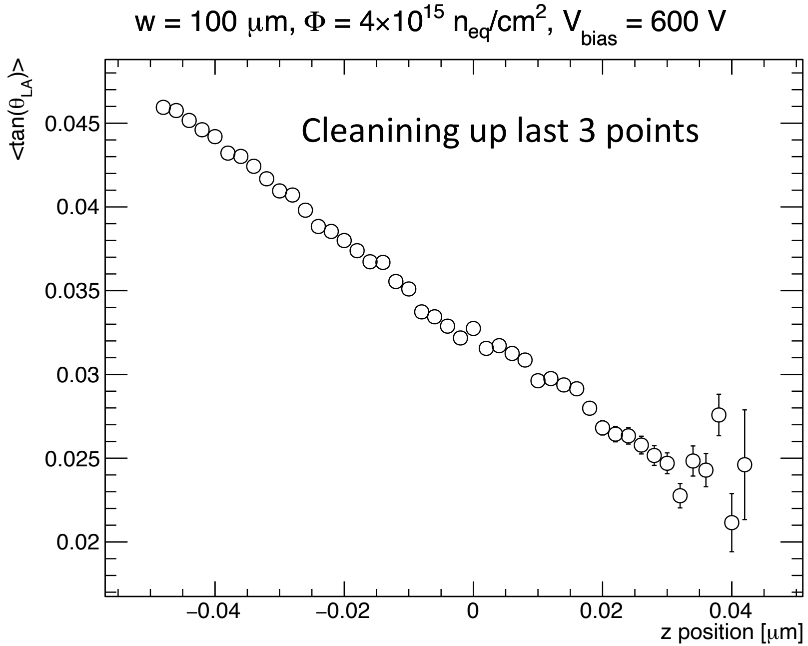
Average Lorentz angle deflection vs z

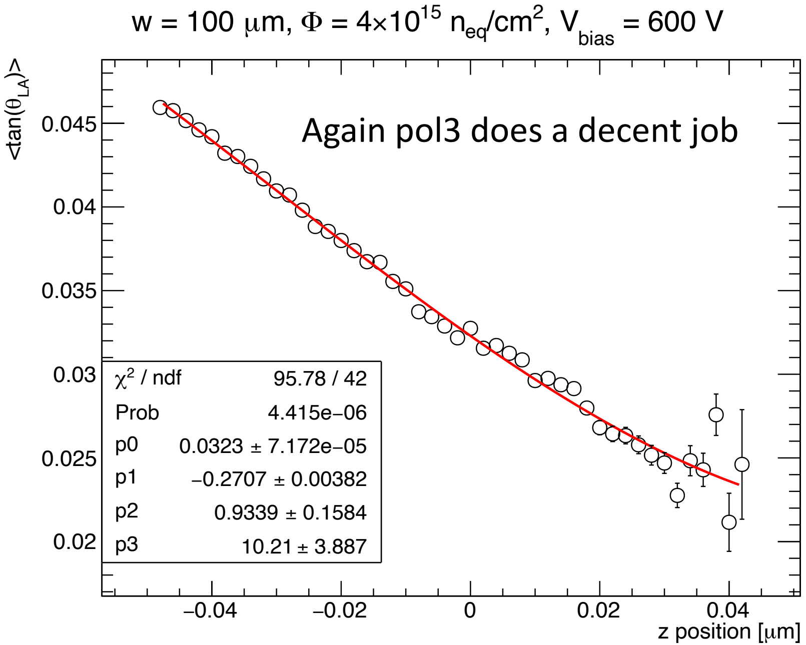


Coarse interpolation grid for implant zone

Not a problem as it is about 6 μm path so we do not expect a lot of deflection

Average Lorentz angle deflection vs z


Cleanining up last 3 points

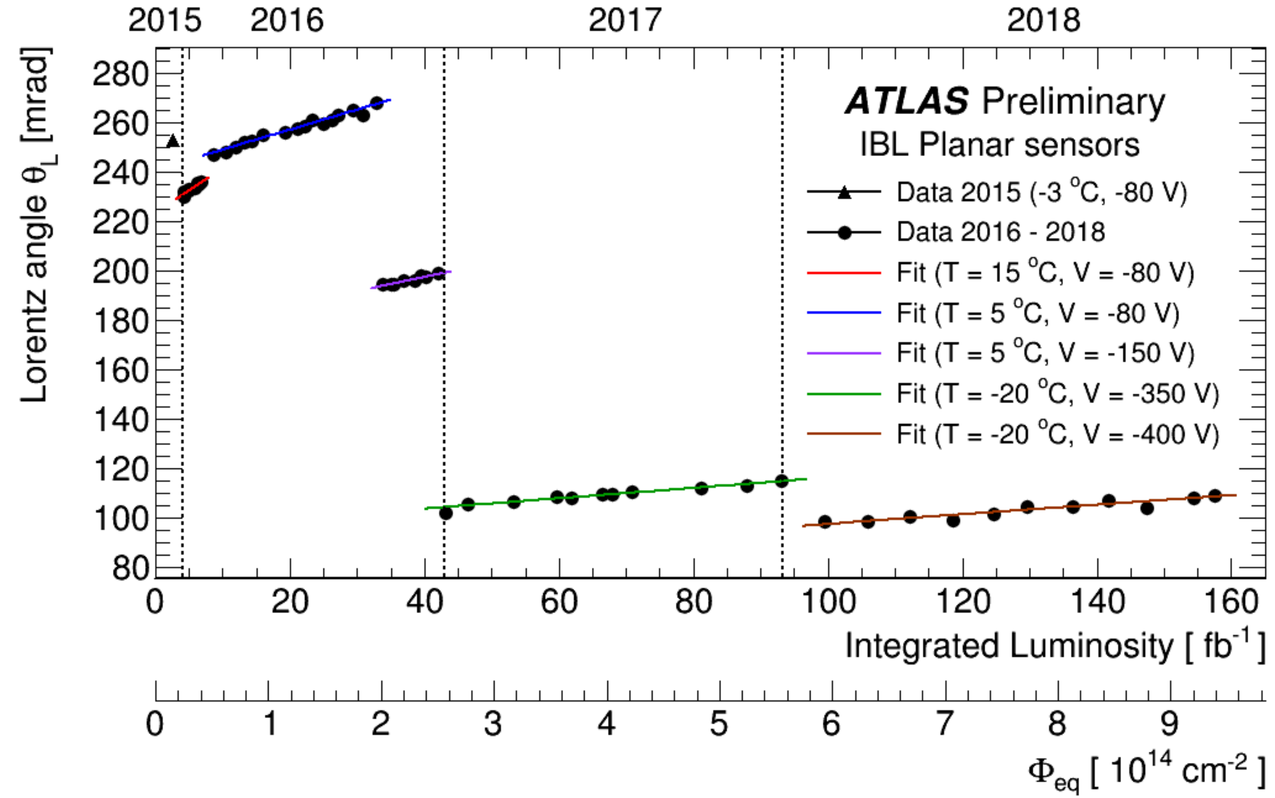

Again pol3 does a decent job

Since largest LA is ~ 45 mrad, even assuming maximal deflection the correction in the last 10 μm will be less than 1 μm

So, as for charge, we can “complete” the map for very short drift distances with a constant (25 mrad?) value

Comparison

[PIX-2017-005](PIX-2017-005)



T = 253 K

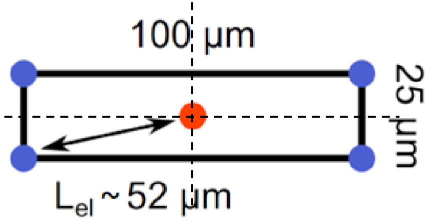
Highest electric field
μ_e = ~ 9e-3 m^2/V/s =>
θ_{LA} ~ 18 mrad

Lowest electric field
μ_e = ~ 30e-3 m^2/V/s =>
θ_{LA} ~ 60 mrad

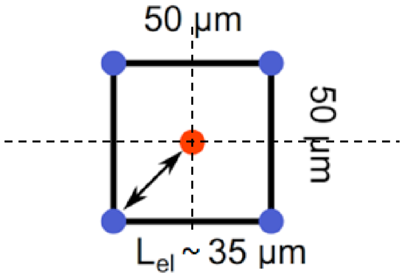
3D sensors for ITk

➢ What do we do with 3D sensors?

25×100 µm², 1E



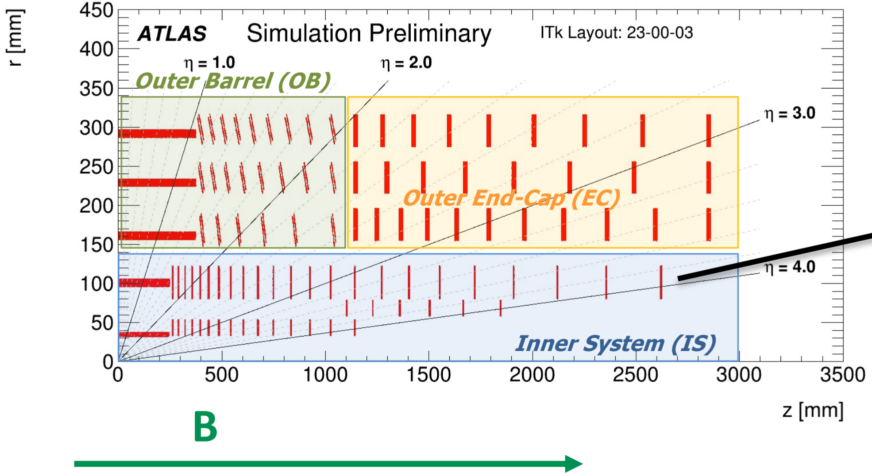
50×50 µm², 1E

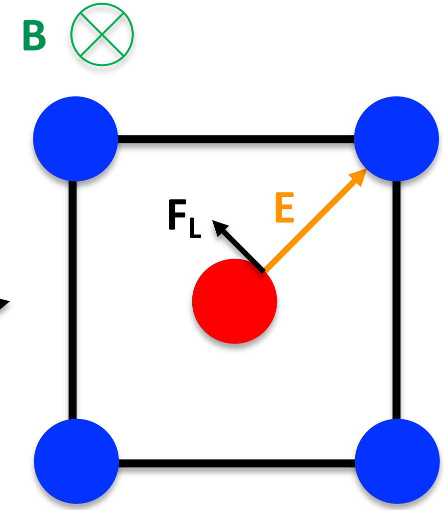


- **For groups of electrons:**
  1. Calculate distance *r* from central column
  2. Get from lookup table the fraction *k* of induced charge

- **For groups of holes** *(if needed)*:
  1. Determine the quadrant of the charge
  2. Calculate distance *r* from the collecting column
  3. Get from lookup table the fraction *k* of induced charge

Lorentz angle in rings

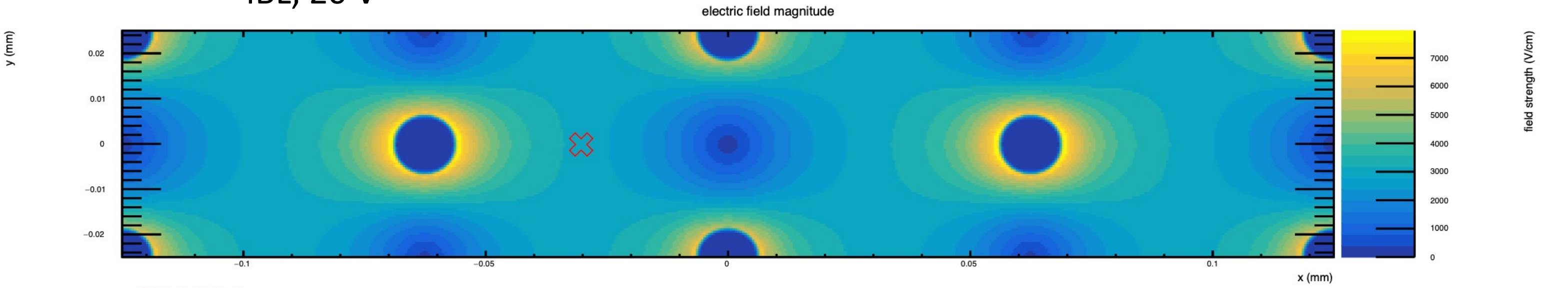




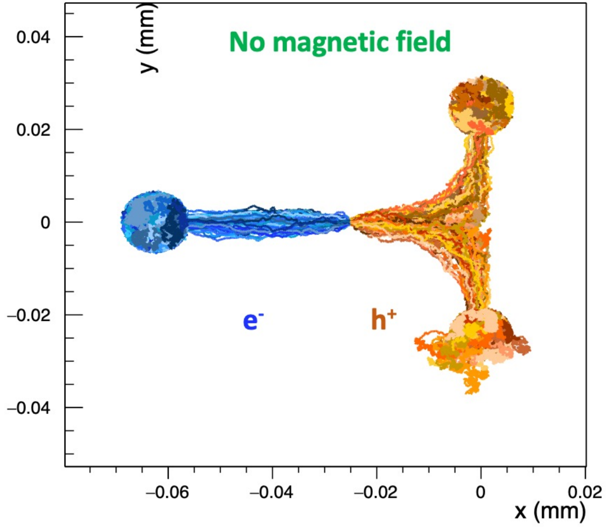
Do carriers **“curve”** inside the cell?

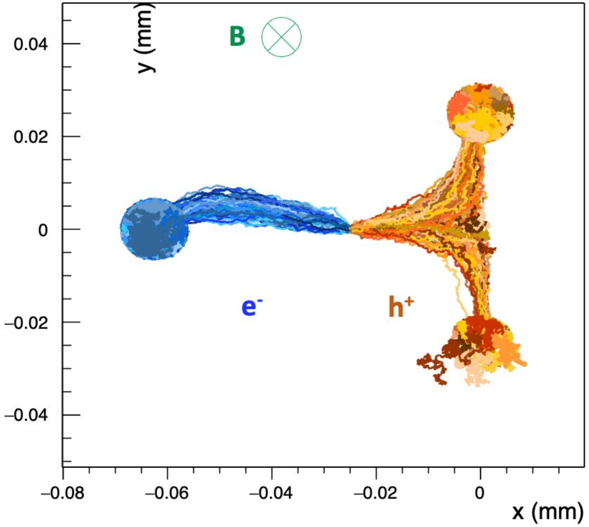
Discussed and tested with Allpix^2…

IBL, 20 V



✕ MIP impact

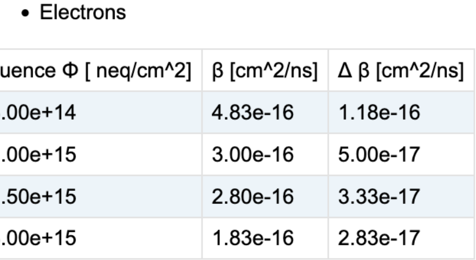




… yes, they do ☺

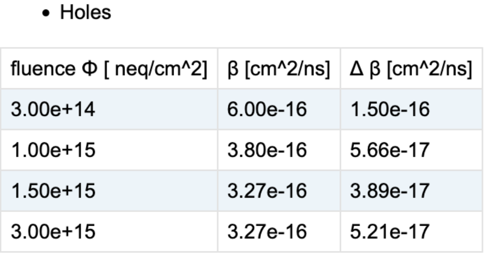
Simulation ingredients – trapping constants

Based on 2016 CMS paper



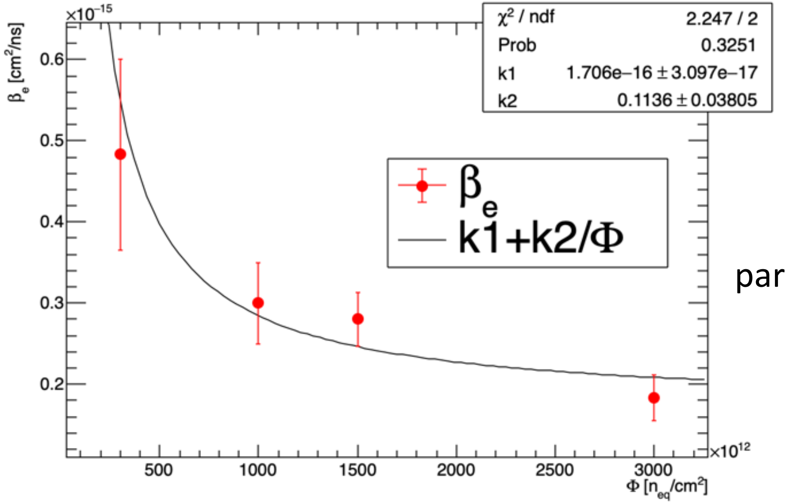
- Electrons

fluence Φ [neq/cm^2]	β [cm^2/ns]	Δ β [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]	Δ β [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