Upgrade of the ATLAS Inner Tracker and related physics perspectives of the Higgs boson decay into two b quarks

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PhD thesis, Friday October 26th, amphithéâtre Charpak (LPNHE)

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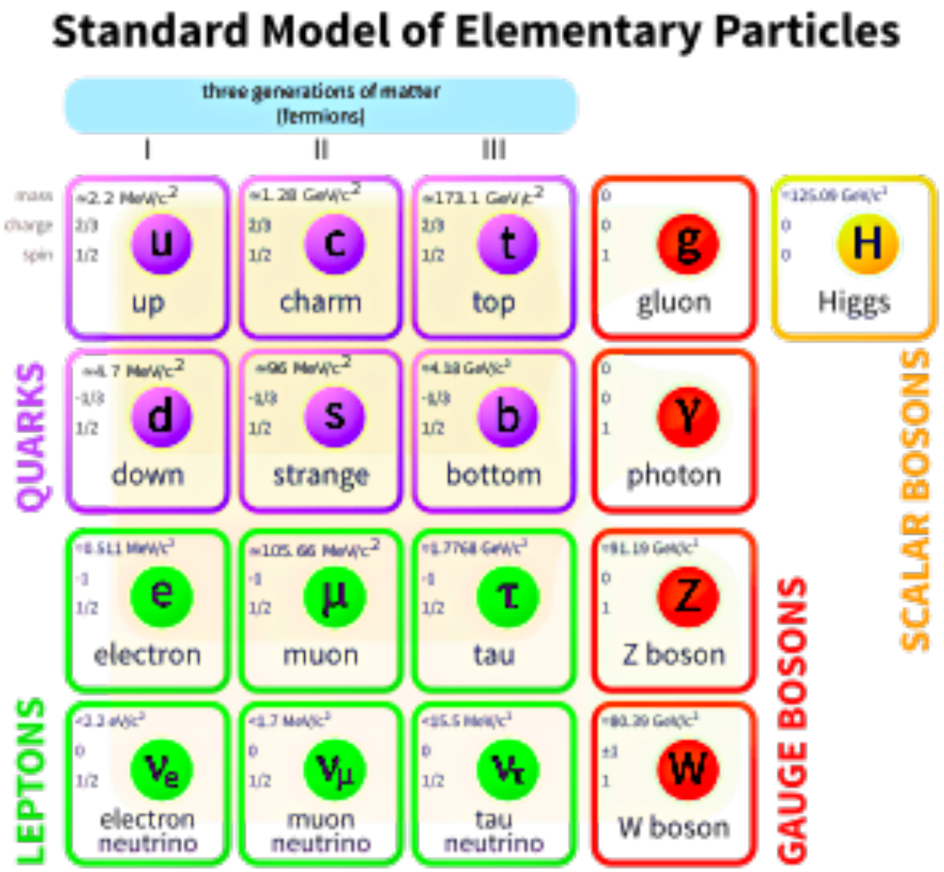
Standard Model

Particles

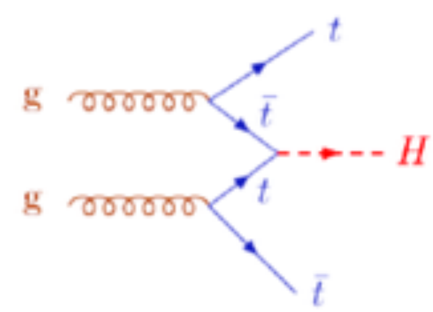


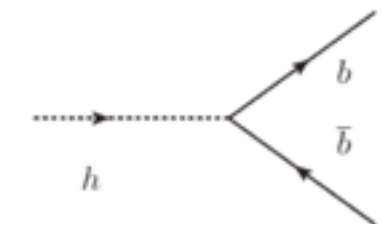
Interactions

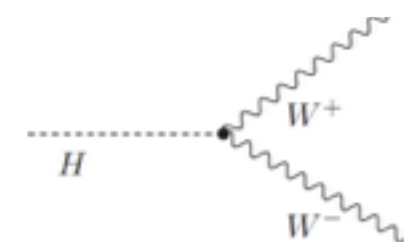
- **Electromagnetism (γ)**
- **Weak interaction (W, Z bosons)**
- **Strong interaction (gluons)**
- ~~Gravitation~~

Higgs boson

- Higgs couplings to massive particles (quarks, W, Z, e, μ, τ)







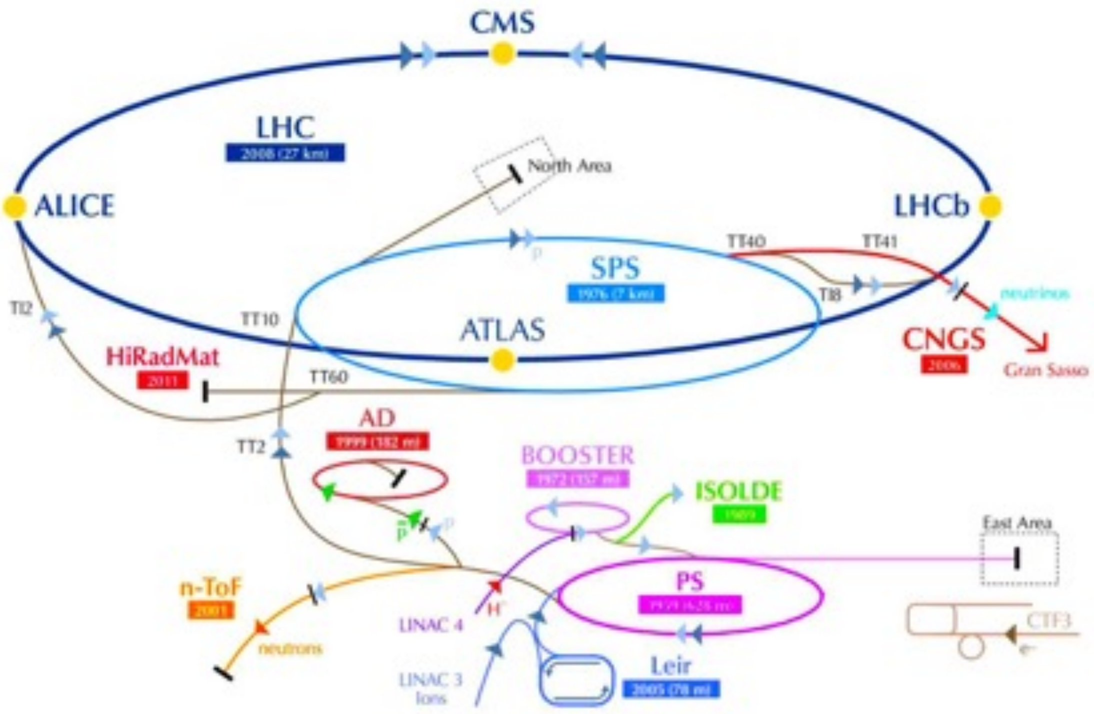
- Higgs boson mass

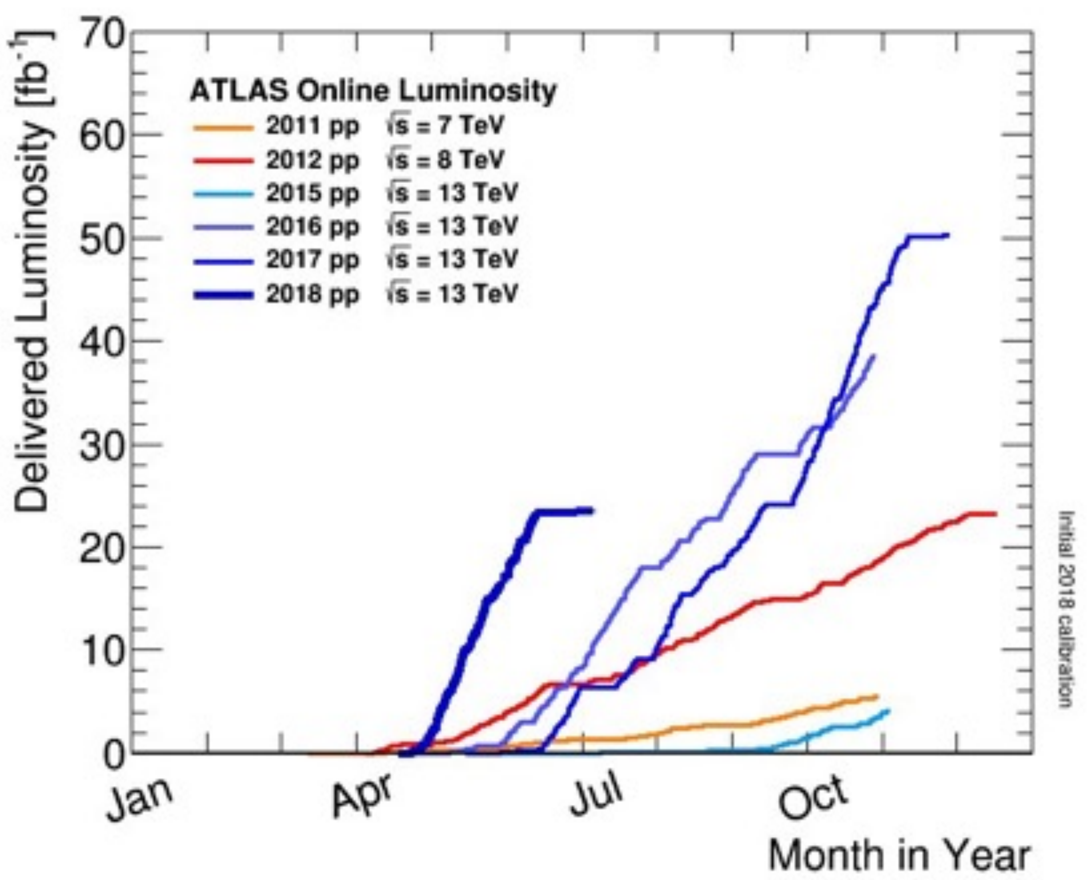
Beyond the standard model

- Dark matter
- Mass Hierarchy problem
- Gravitation

➡ BSM models: SUSY, gravitons…

LHC - Large Hadron Collider





CERN accelerator, current world largest particle accelerator:

- **proton-proton collisions** at (now) **$\sqrt{s}$ = 13 TeV,** target luminosity: **300 fb-1**
- LHC experiments: **ATLAS & CMS** (general purpose experiments), **LHCb** (b physics), **ALICE** (strong interaction)
- ATLAS experiment recorded luminosity:
  - **Run1 ($\sqrt{s}$ = 7 and 8 TeV): 30 fb^{-1} accumulated**
  - **Run2 ($\sqrt{s}$ = 13 TeV): 136 fb^{-1} accumulated**

Physics results - State of the art

- Higgs discovery in 5 channels
- Higgs mass and couplings characterization (recently b and t)
- Electroweak measurements
- Cross section measurements
- top mass and couplings measurement
- BSM searches

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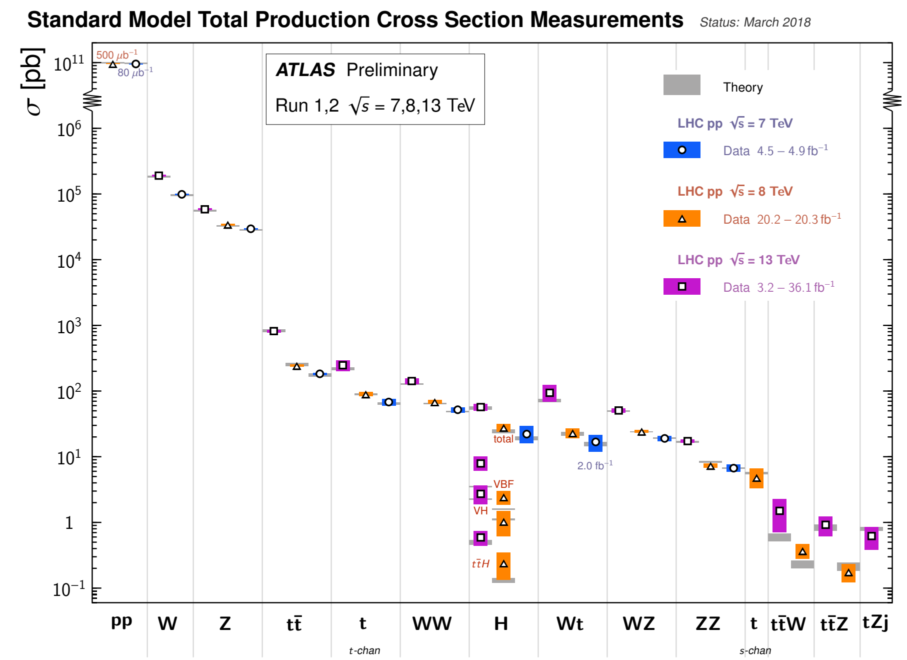
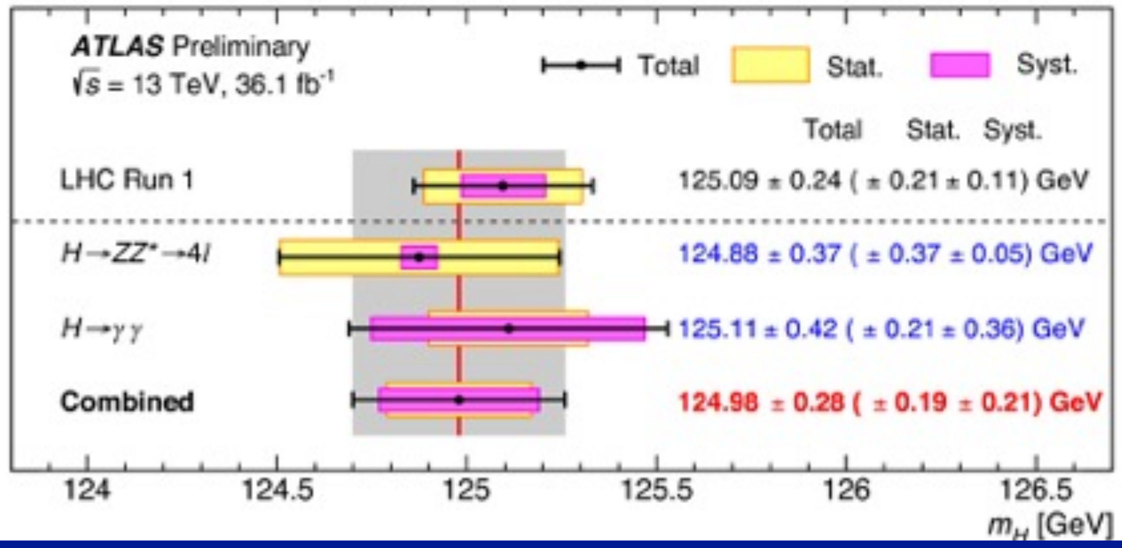




Next:

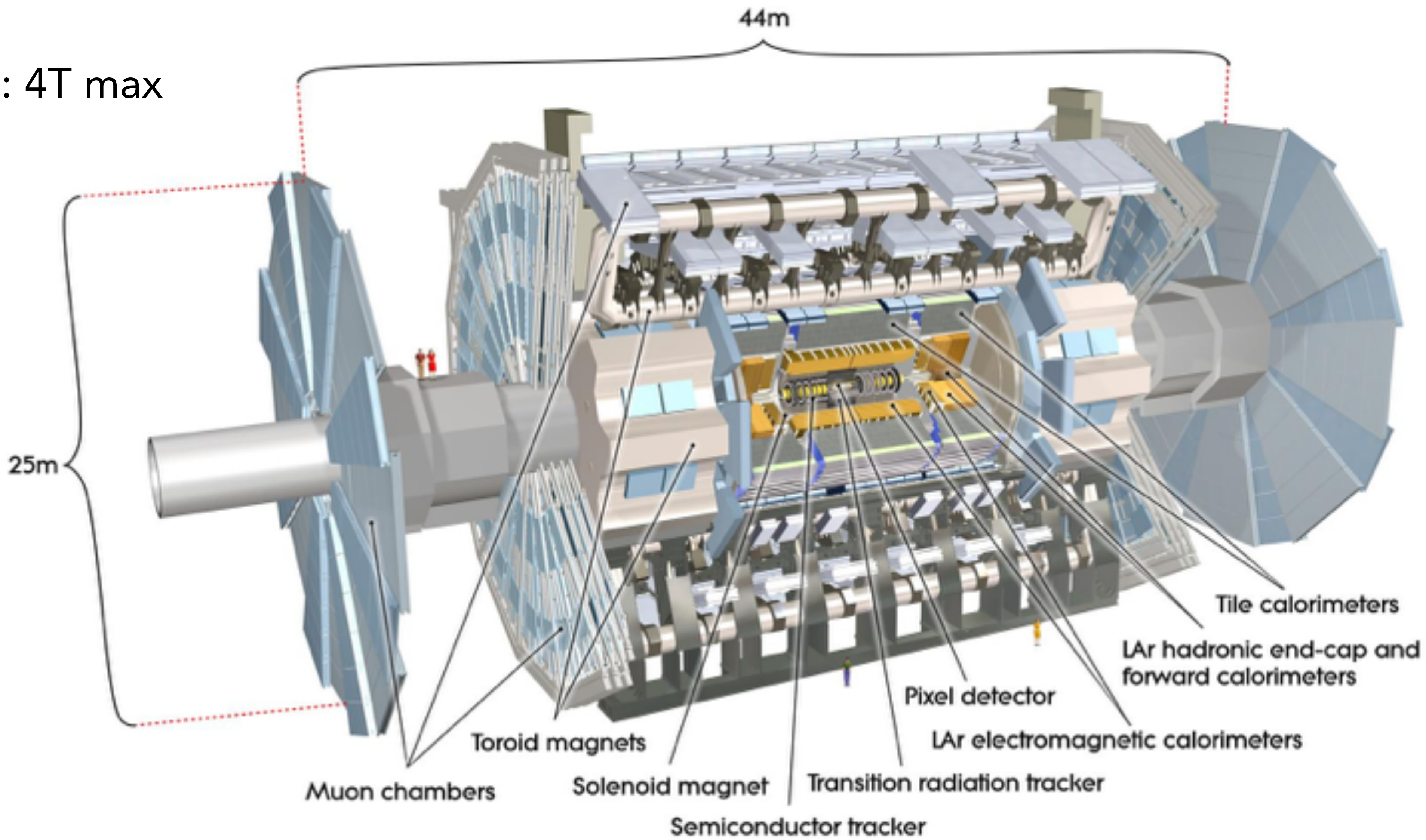
- Higgs couplings to second generation family
- Higgs self couplings
- Higgs boson in BSM physics ?

…

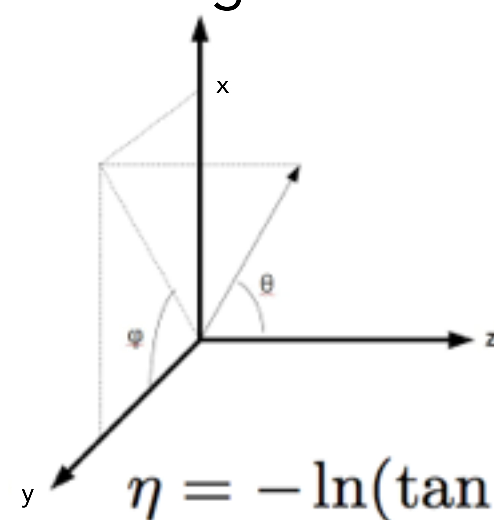
Good b-tagging and tracking (hence good sensors) are fundamental

ATLAS detector

B: 4T max



Cylindrical geometry, ~4 π angular coverage



$$\eta = -\ln(\tan(\theta/2))$$
$$p_T = \mathrm{p}\ \sin(\theta)$$

Trigger

40 MHz

Level 1 - input from Calo and MS

100 kHz

HLT - selection of interesting events

1 kHz

DETECTORS

- **Inner detector**: measurement of **tracks & vertices reconstruction**
- **Electromagnetic calorimeter**: reconstruction of electrons and photons energy
- **Hadronic calorimeter:** measures hadrons energy
- **Muon spectrometer**: records **muon trajectories**

ATLAS Inner Detector

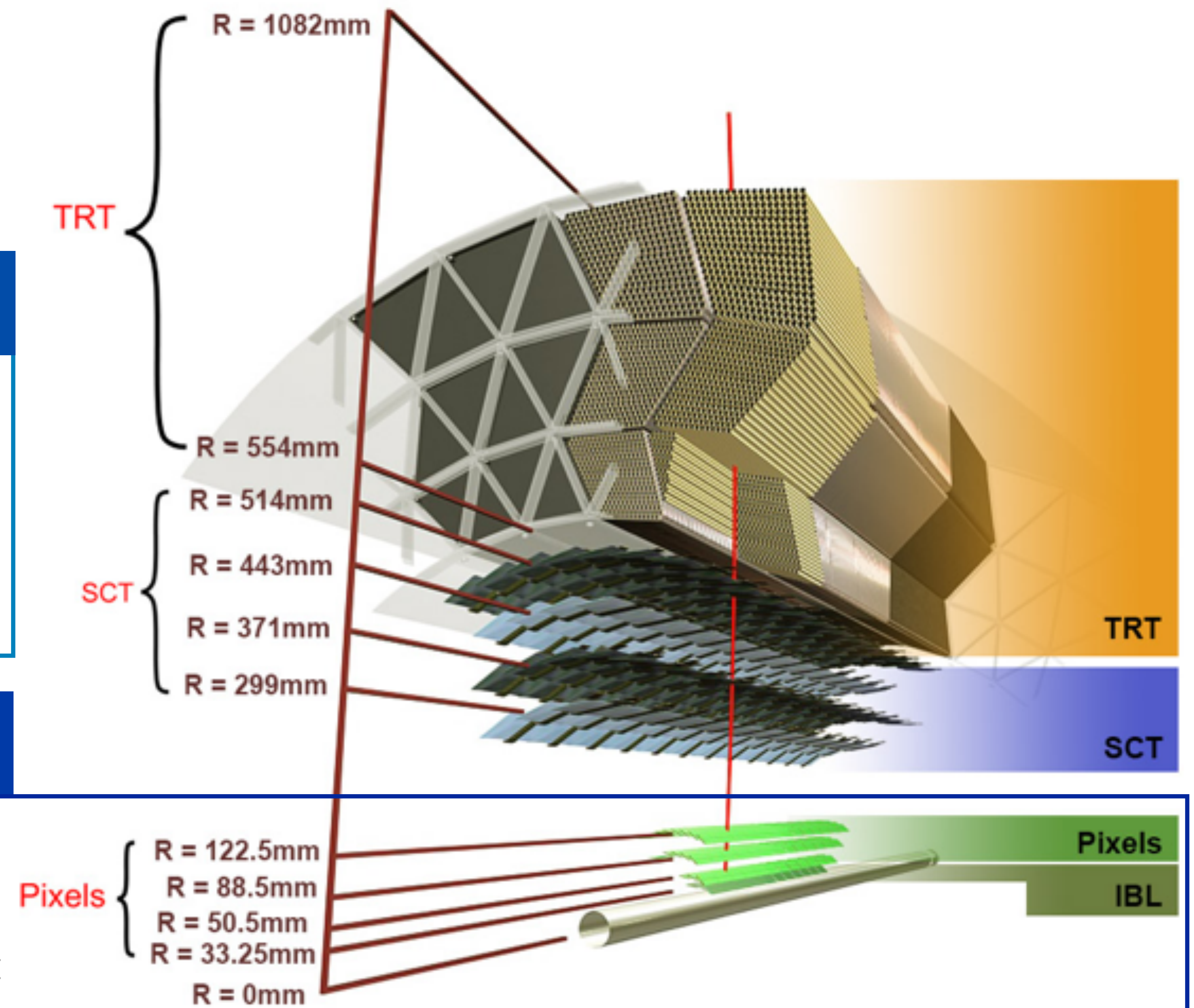
- Tracks and vertices reconstruction

Momentum resolution:

$$\frac{\sigma(p_T)}{p_T} \simeq 3.8 \times 10^{-4} p_T \text{ (GeV)} \oplus 0.015.$$

TRT & SCT

- **TRT**: proportional drift tubes, up to 36 points/track.
- **SCT**: silicon micro-strips detector



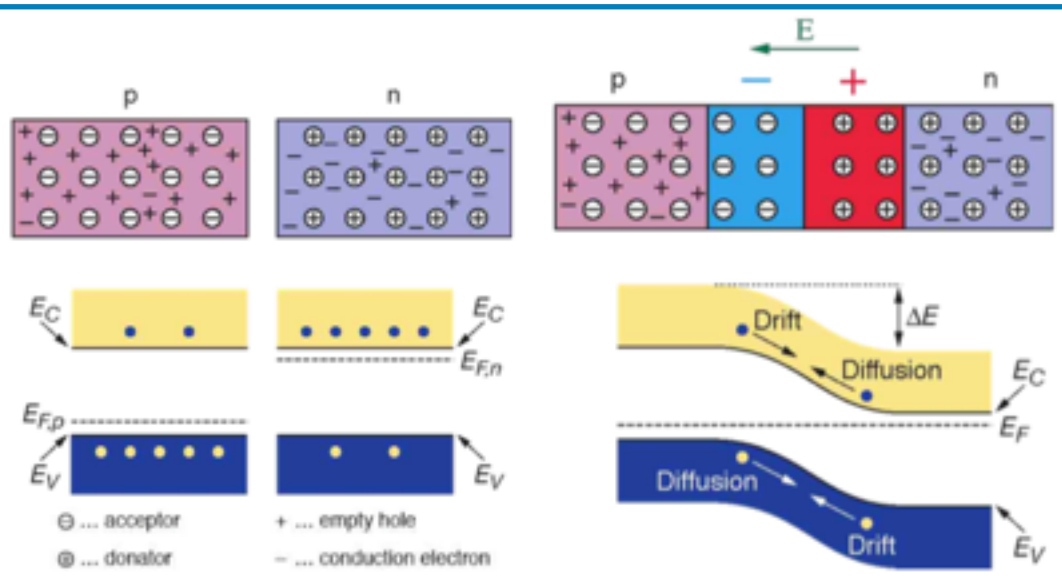
Pixels

Closest detector to the beam pipe,

composed of a barrel and two end caps:

- **4 pixel barrel layers** (IBL, BLayer, L1 & L2), IBL inserted in 2015 to allow a better reconstruction of b-objects
- IBL cell size **50 μm x 250 μm** ; BLayer/L1/L2 cell size **50 μm x 400 μm**
- Overall **spatial resolution**: ~**10 μm** in the r-ϕ direction, ~**100 μm** in the z direction

Silicon sensors

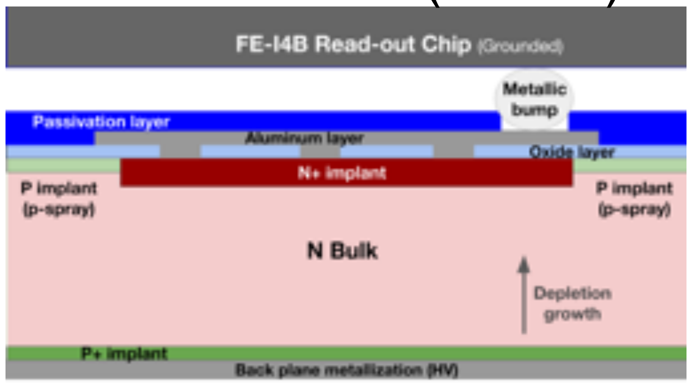


- **P/N junction** $V_{dep} = \frac{q|N_{eff}|d^2}{2\epsilon\epsilon_0}$
- **Drift** of carriers following electric Field E
- **Diffusion**
- **Lorentz angle:** deflection angle caused by B

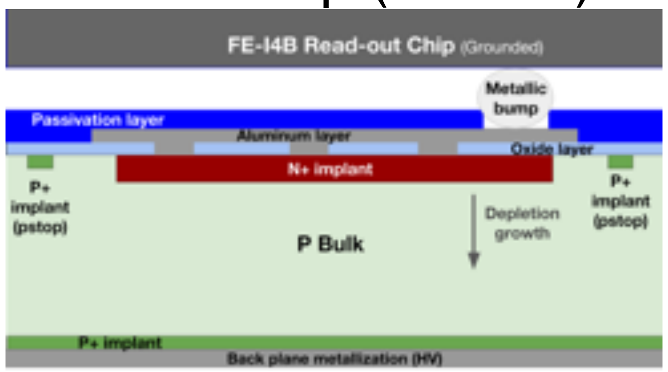
Silicon pixel sensors

- **Planar:** highly doped implant on top of a low-doped Si bulk n-in-n (ID-like), n-in-p (ITk), **medium radiation hardness, less costy than 3D, HEP classic sensors**
- **3D:** highly doped Si columns through low-doped Si bulk -> **high radiation hardness**, **low yield**
- **CMOS: industrial mature technology, « low cost »**, **less radiation hard**

Planar n-in-n (ID like)

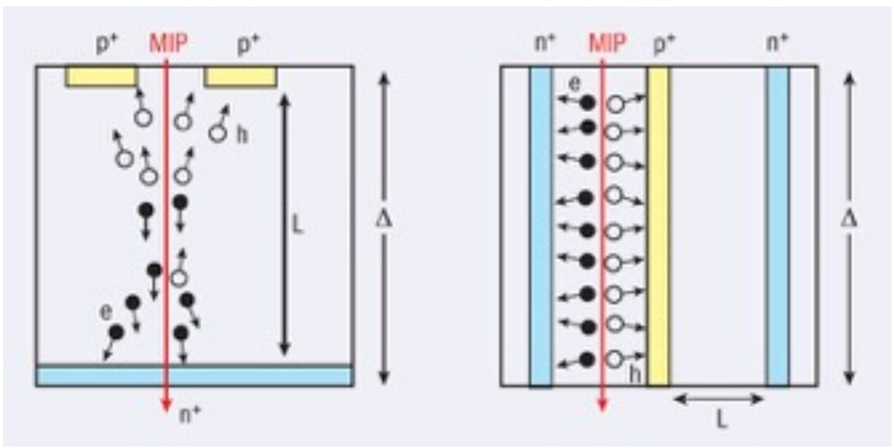


Planar n-in-p (ITk like)



Planar

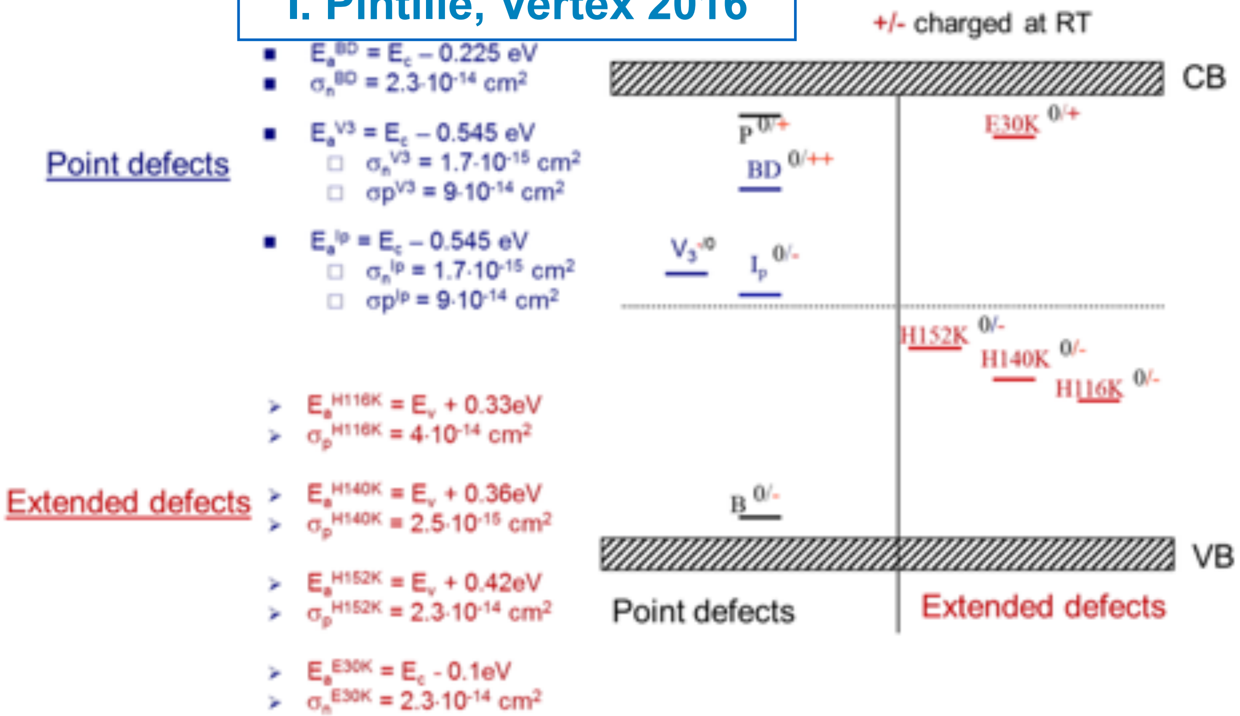
3D ←Used in IBL



Silicon - Radiation damage

Non Ionizing Energy Loss ➔ **microscopic defects ➔ macroscopic effects**:

I. Pintilie, Vertex 2016



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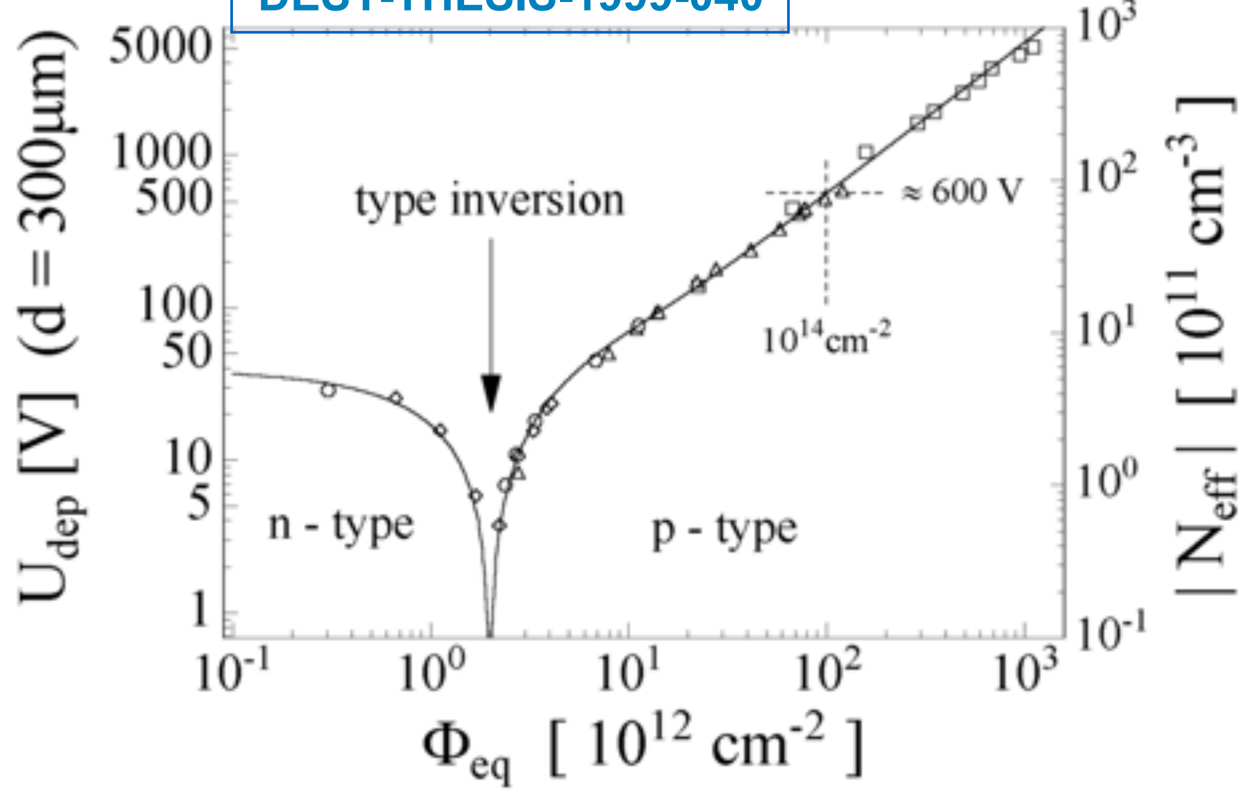


- **Charge trapping:** electrons or holes trapped in defect centers
- **Change in operational bias voltage**
- **Type inversion** of n-type bulk in p-type bulk
- Increase in leakage current

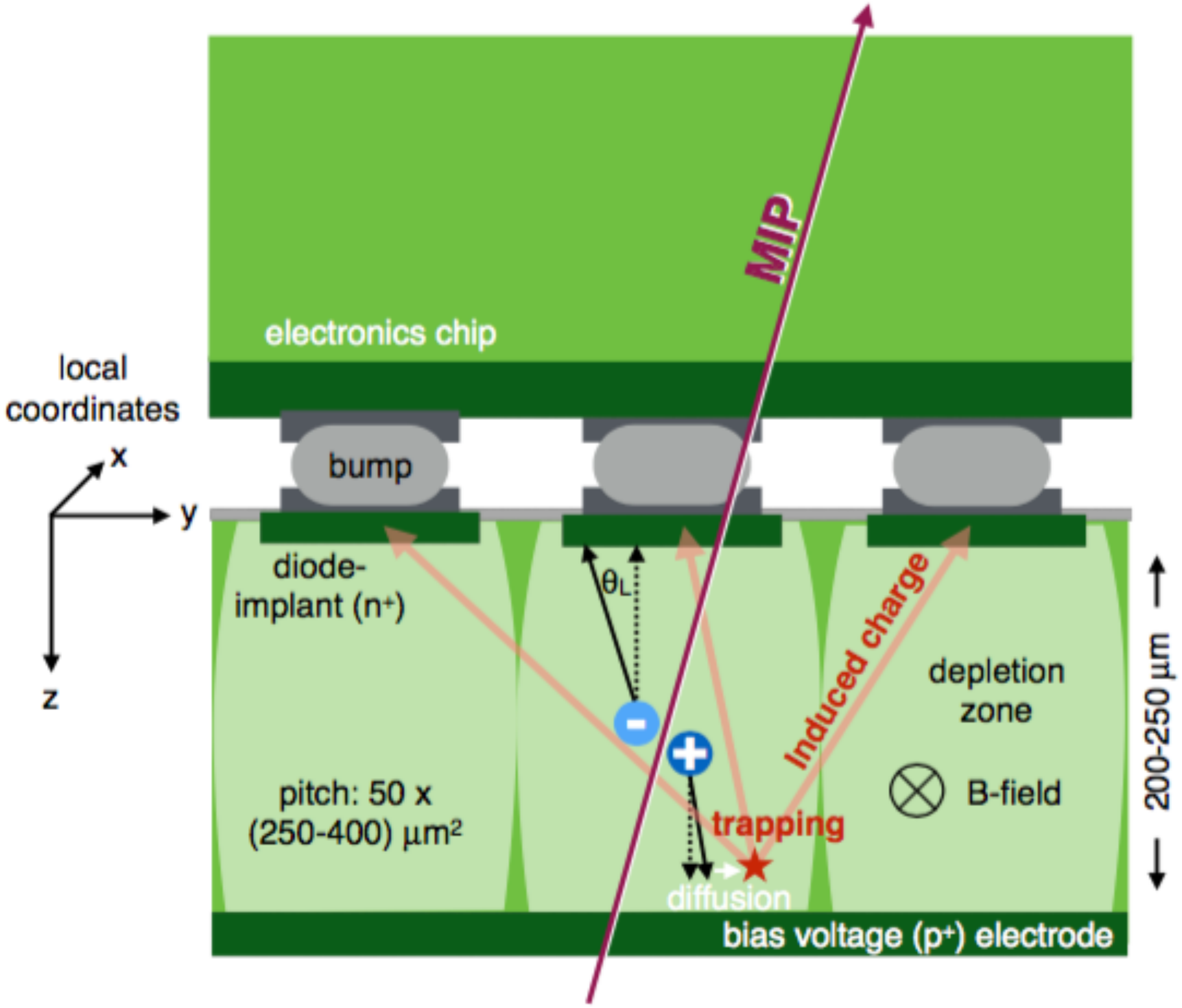
$$\Delta I(\Phi,T,t) = I(\Phi,T,t) - I_0 = \alpha(t,T)\mathcal{V}_{dep}\Phi$$

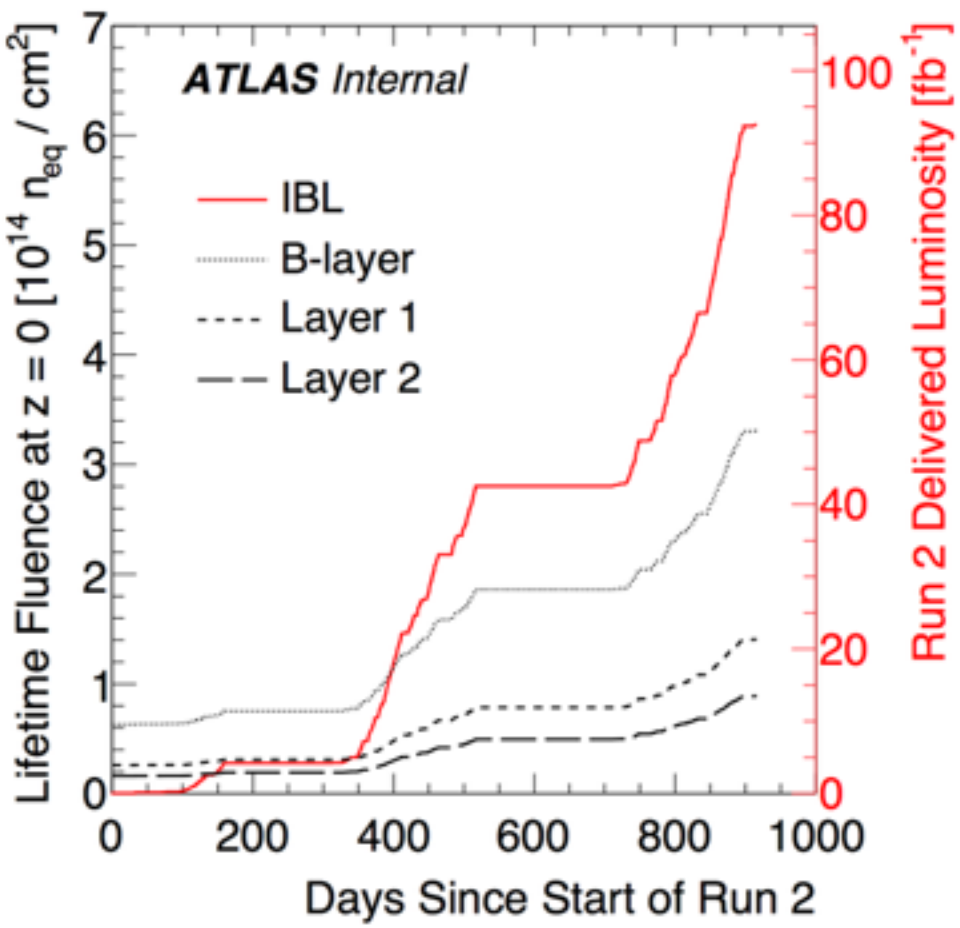
Annealing: Evolution of defects with T and t

Radiation damage digitizer

- **Production of electric field maps**
- Evolution of cluster size vs temperature and bias voltage
- **Charge collection efficiency, comparison to data**
- **Cluster & Track properties variations**

Radiation damage digitizer





JINST 13 C03046 (2018)

ID pixel layers are **irradiated** which implies:

- **Charge collection efficiency drops due to charge trapping**
- **Modification of the depletion voltage**
- **Evolution of the Lorentz angle** with the fluence and operational bias voltage

➡ Implementation in MC simulations at the digitization level of the fluence and its effect on pixel layers

Radiation damage digitizer

1. Production of electric field maps for various fluence and bias voltage

2. Validation: Charge collection efficiency, comparison to data

3. Prediction: impact of radiation damages on Cluster & Track properties

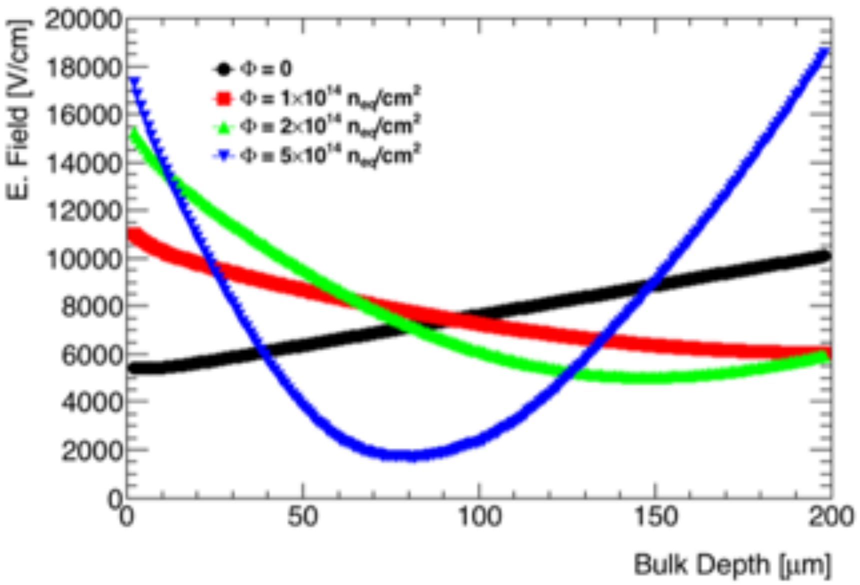
Benchmarks	0		1		2		3		4		5		6	
Luminosity (Run2)	$0 fb^{-1}$		$0 fb^{-1}$		$15 fb^{-1}$		$30 fb^{-1}$ end 2016		$30 fb^{-1}$ end 2016		$75 fb^{-1}$ end 2017		$130 fb^{-1}$ end 2018	
Φ (10^{14} n_{eq}/cm^2) V (V)	Φ	V	Φ	V	Φ	V	Φ	V	Φ	V	Φ	V	Φ	V
IBL	0	80	0	80	1	80	2	80	2	150	5	350	8.7	400
BLayer	0	150	0.7	150	1.2	150	1.7	150	1.7	350	3.1	350	4.6	400
Layer 1	0	150	0.3	150	0.5	150	0.7	150	0.7	250	1.3	250	2.1	250
Layer 2	0	150	0.2	150	0.3	150	0.4	150	0.4	150	0.8	150	1.3	150

7 benchmarks considered (corresponding to Run2 benchmarks)

Use of tracks from Z➔$\mu\mu$ samples

Electric field maps

Chiochia model of radiation damage used to simulate **E field maps** of the **ID planar pixel sensors**:

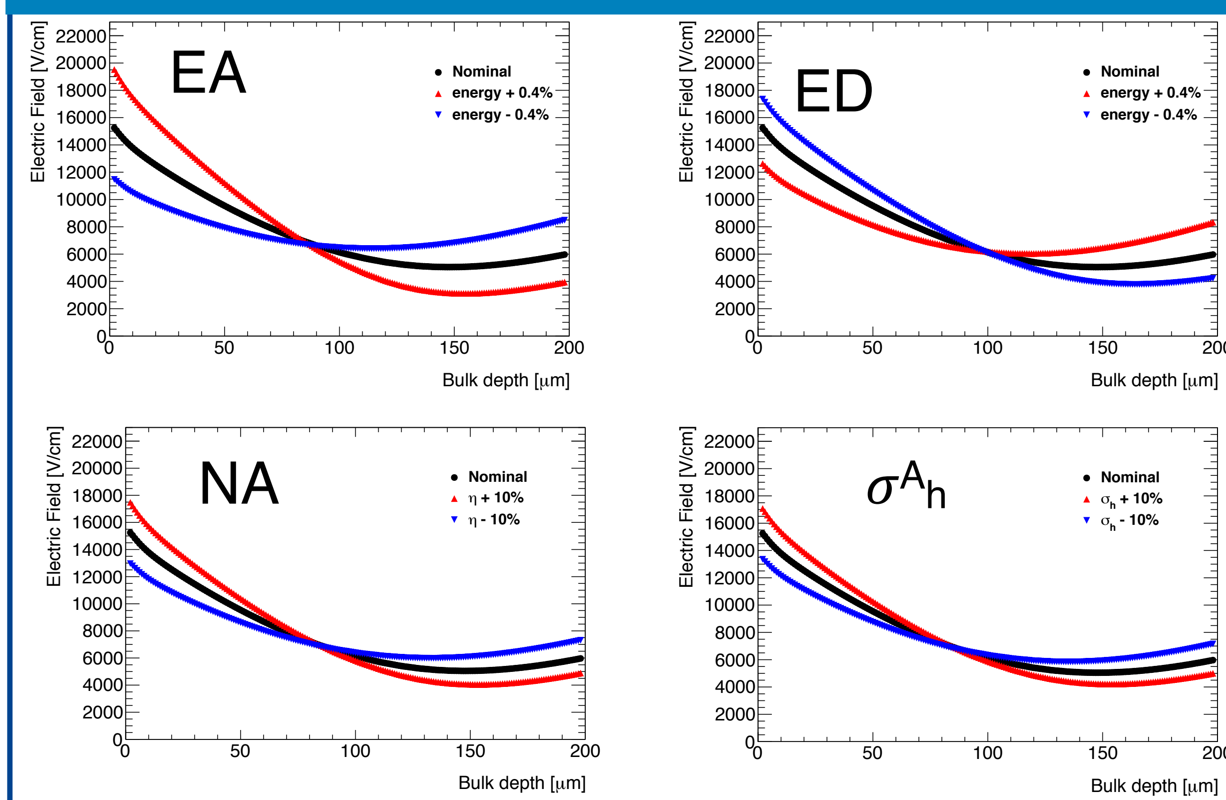


Parameters: traps energy **EA** and **ED**, effective concentration **NA** and **ND** and **electron and hole capture cross sections**

NIMA 568 (2006) 51–55

Fluence (10^{14} n_{eq}/cm^2)	E_T^A (eV) $\pm 0.4\%$	E_T^D (eV) $\pm 0.4\%$	N_A (10^{14} cm^{-3}) $\pm 10\%$	N_D (10^{14} cm^{-3}) $\pm 10\%$	$\sigma_e^{A,D}$ & σ_h^D (10^{-15} cm^2) $\pm 10\%$	σ_h^A (10^{-15} cm^2) $\pm 10\%$
1			3.6	5		
2	E_C-0.52eV	E_V+0.48eV	6.8	10	6.60	1.65
5			14	34		

Parameters variations

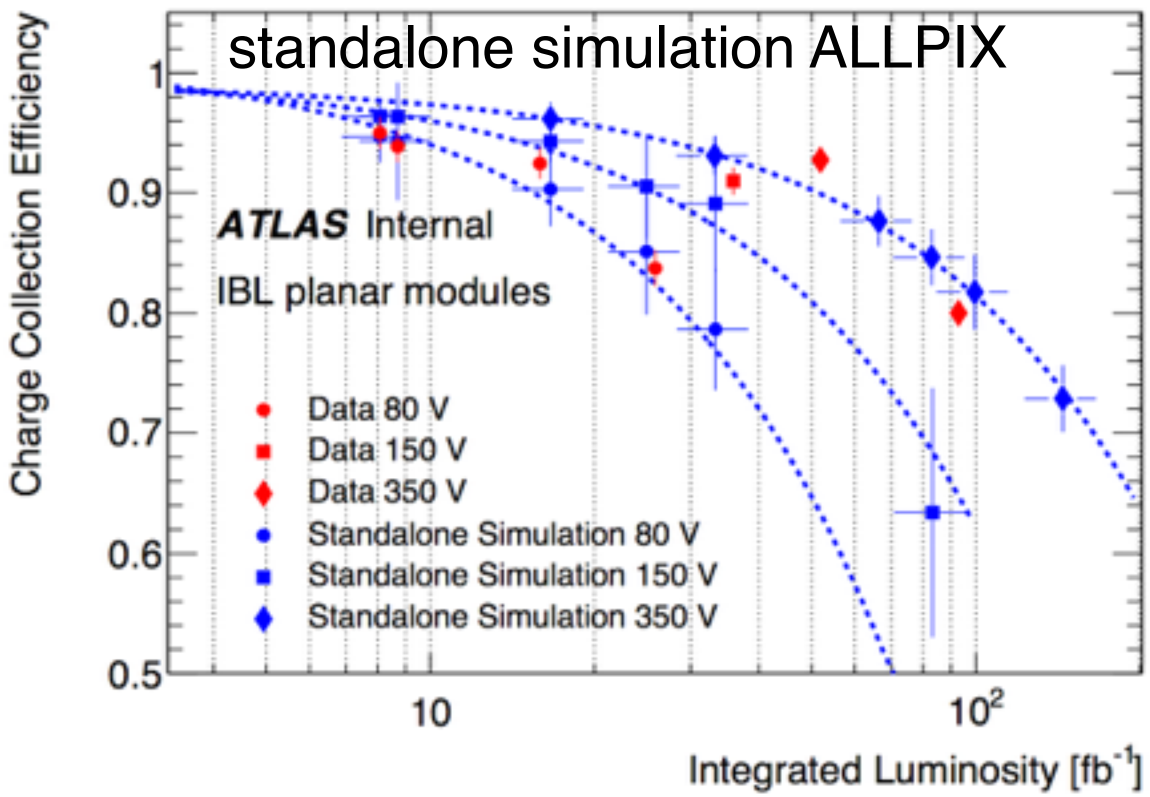


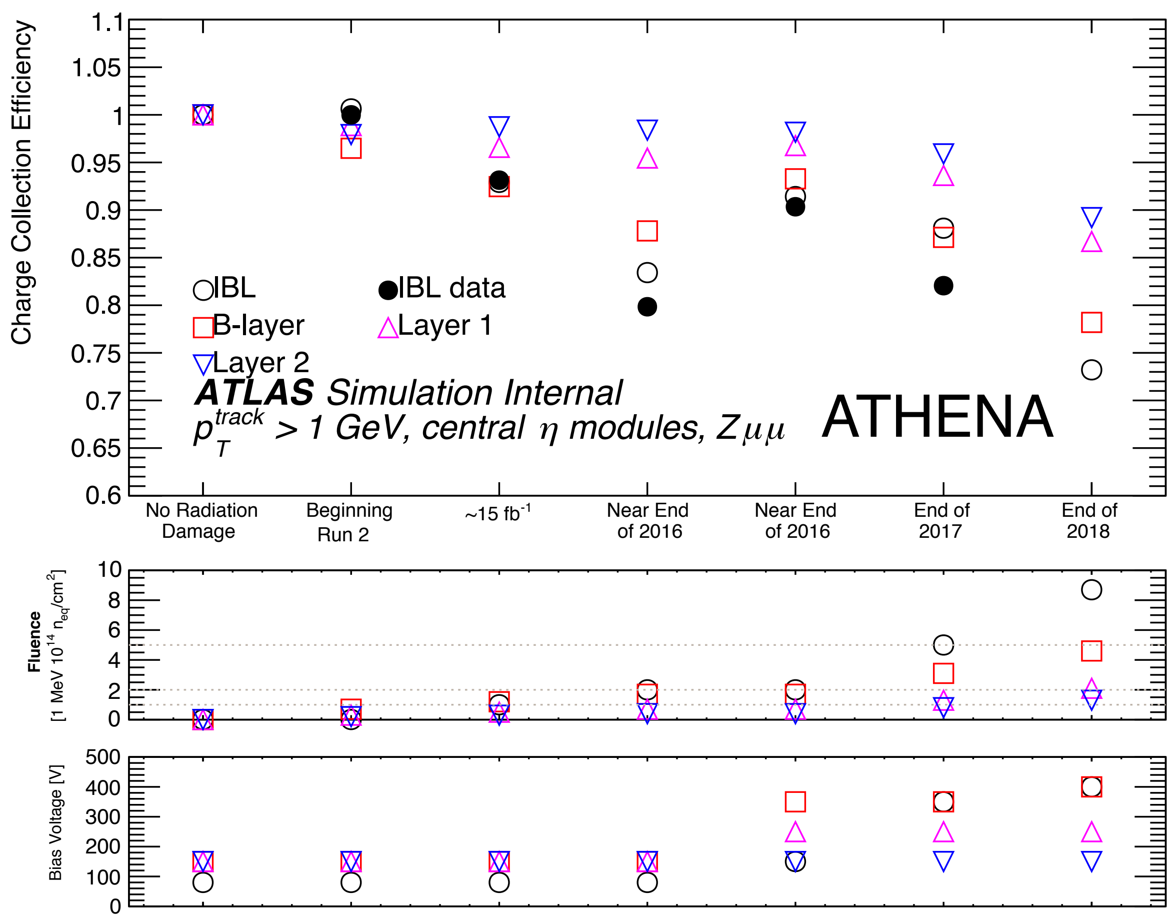
- **Highly sensitive** to modifications in the **trap energy**
- **Moderately sensitive** to the **defect concentration variation**
- **Slightly sensitive** to **the capture cross section variations**

➡ **Variations on acceptor observables give larger variation in E field compared to variation of donor observables**

A=Acceptor ; D=Donor ; h = holes ; e = electrons

Charge collection efficiency





CCE = average charge after irradiation / before irradiation

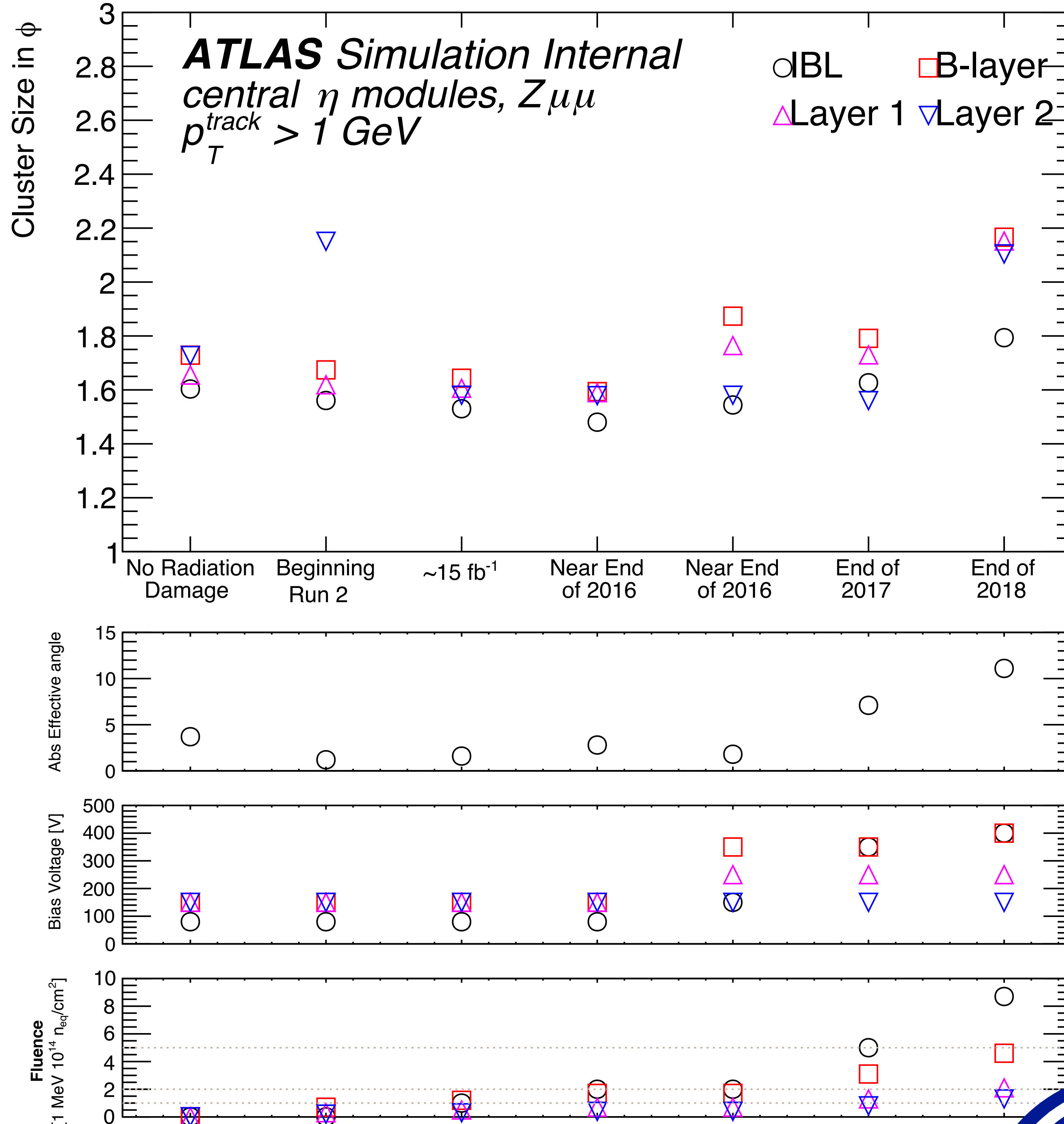
Validation of the **radiation damage digitizer model** ➔ Comparison of **CCE from** simulations and data:

- **Charge collection efficiency: good level of agreement between simulations and data**
- Caveat: variations in terms of threshold, tuning, temperature and annealing not yet implemented. Systematic errors not represented in ATHENA validation plot

Cluster size

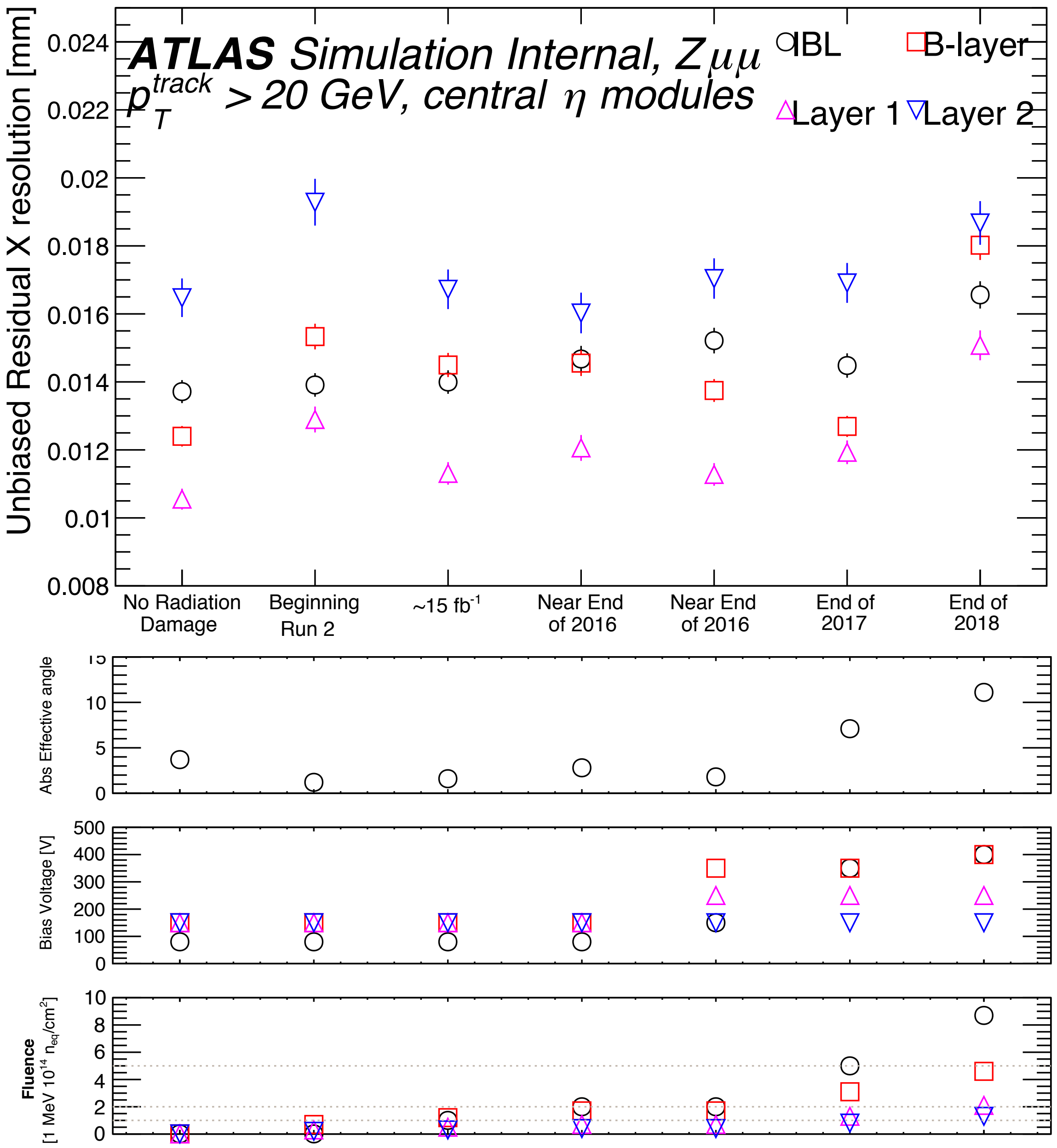
Cluster size in ϕ

- **Highly sensitive to fluence, moderately sensitive to change in bias voltage**
- **Sensitive to the modification in Lorentz angle**
- Between the end of 2017 and the end of 2018, Cs in ϕ increases of more than **20%** (BLayer, L1 and L2) and **10%** for IBL



Tracking properties

Unbiased residuals resolution



Cut on tracks: p_T >20GeV required to mitigate multiple scattering

- **Degradation of the spatial resolution with fluence**
- IBL: Degradation by **20%** / **6%** in the **short** / **long** pixel direction between the beginning of Run2 and the predictions for the end of Run2

Next:

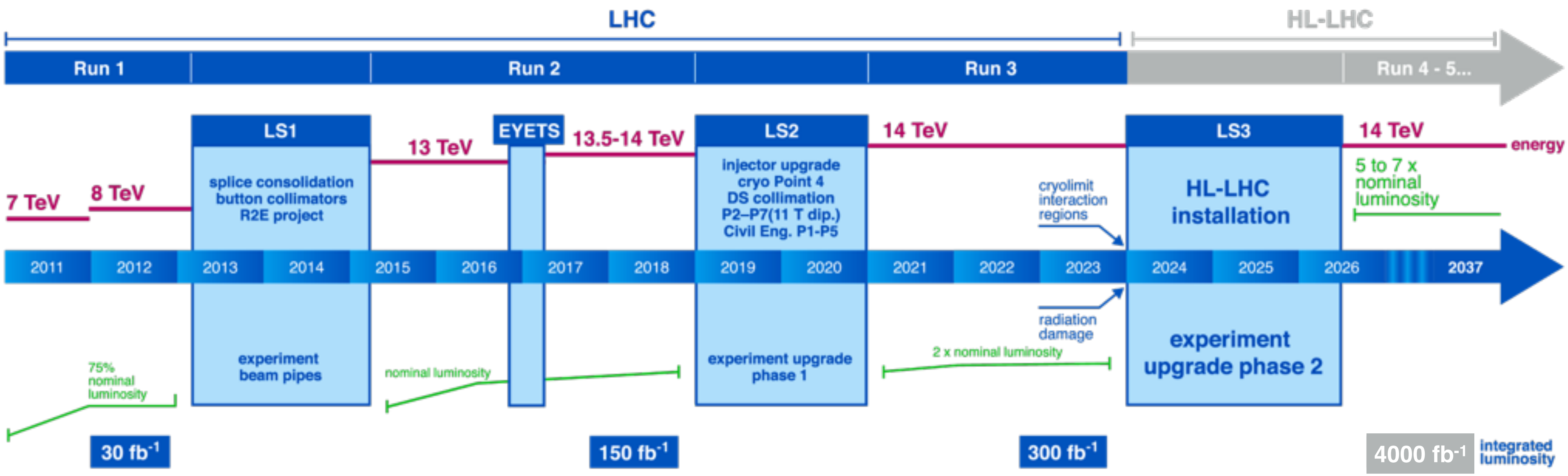
- Use of higher p_T samples and higher statistics (ttbar and Vh, h ➔ bb samples)
- Quantify impact on b-tagging and higher level physics objects

ITk pixels LPNHE R&D
Sensors performance

- LPNHE ITk pixel sensor productions
- Biasing options comparison
- Performance of thin and irradiated planar pixel sensors
- Performance of active edge sensors

HL-LHC

LHC / HL-LHC Plan



The LHC will be upgraded in high luminosity LHC (**HL-LHC**) and the data taking will start in 2026:

- Goal: integrated luminosity of **4000 fb-1**
- Need to **upgrade** accelerators and experiments
- **ATLAS Inner Tracker upgrade (ITk - pixels)**

ATLAS HL-LHC Physics goals:

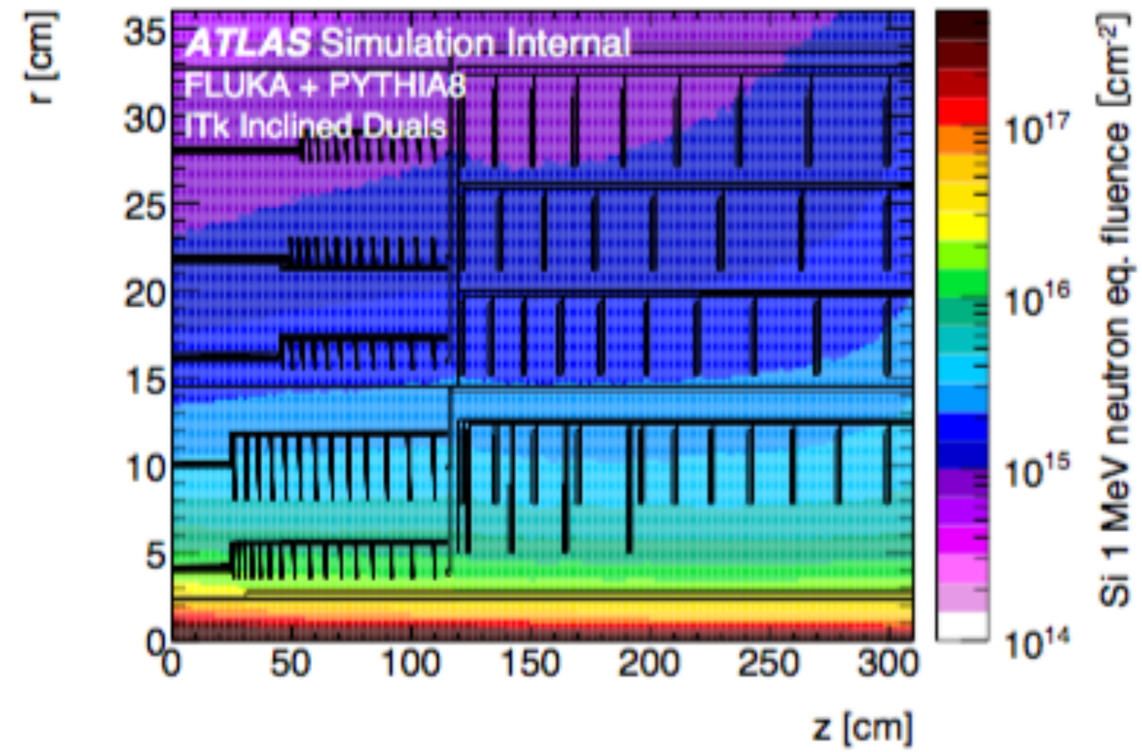
- Precision measurements
- Measurement of Higgs boson self couplings
- BSM physics searches

...

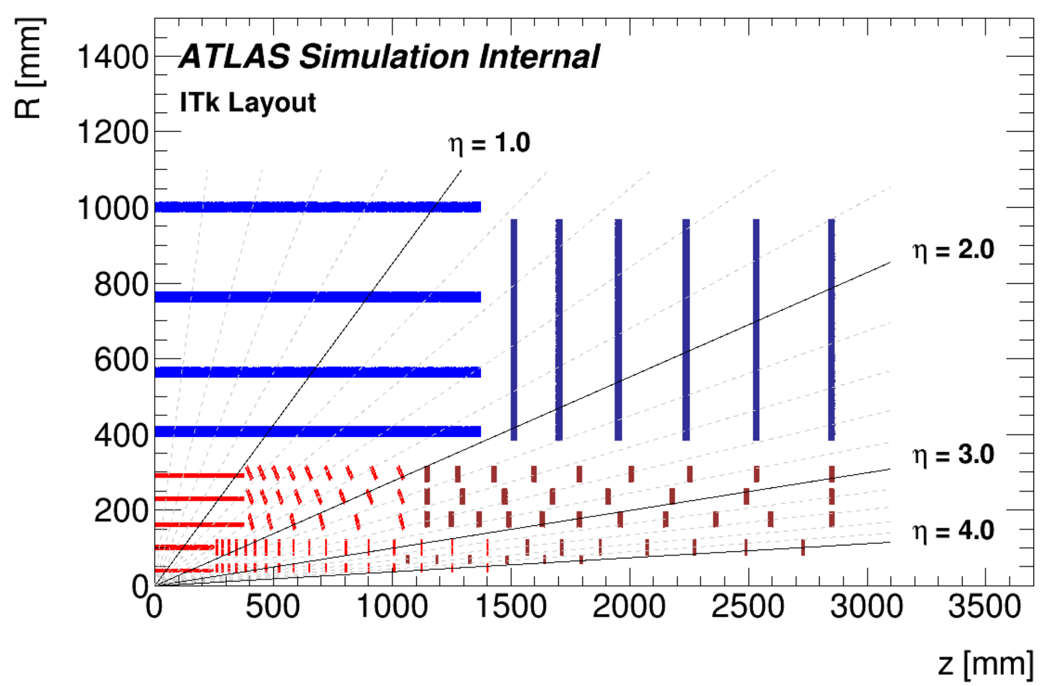
Inner Tracker upgrade

ATLAS data taking phase in HL LHC conditions:

- Peak luminosity of L_{inst} ~7.5 x $10^{34}cm^{-2}s^{-1}$
- 200 inelastic pp collisions per bunch crossing
- Maximum fluence in inner tracker 2.5 x 10^{16} n_{eq}/cm^2 (5 times IBL fluence)



Inner Tracker (ITk)



All silicon tracker (pixels + strips) to cope with radiation level

ITk pixels:

- Instrumented up to $|\eta|<4$
- Less material budget and 1 additional layer compare to Run2 thanks to the inclined layout
- Increase in tracking and b-tagging performance compared to Run2

ITK pixels challenges

Radiation hardness

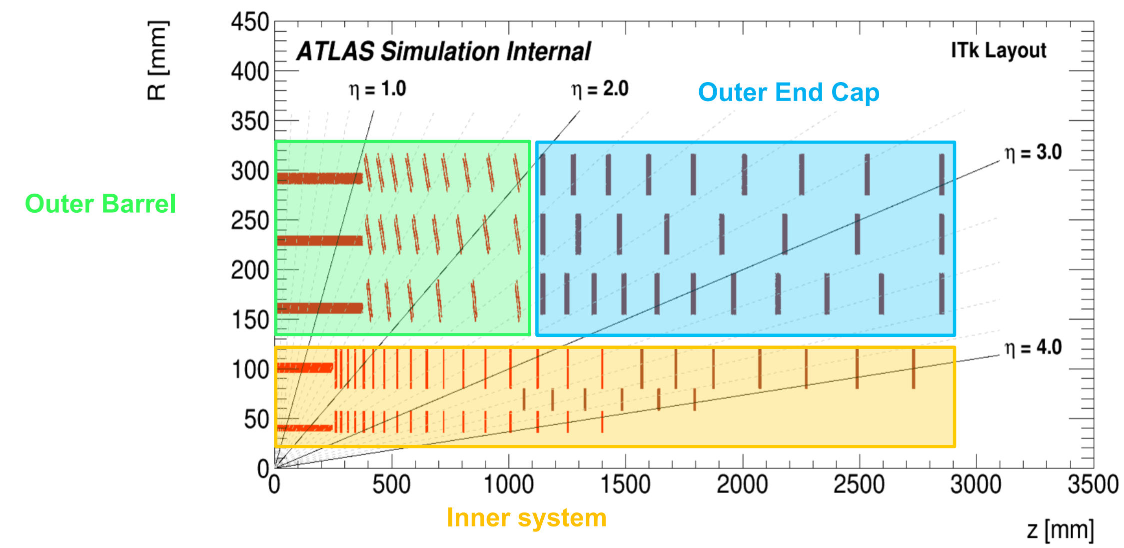
Goal: 97% hit-efficiency with a fluence up to 1.3 x 10^{16} n_{eq}/cm^2 for innermost layer (to be replaced once)

- Problem: Radiation induced charge trapping and decrease in the collected signal
- Solution: Radiation harder sensors
  - ➡ 3D sensors for innermost layer (perpendicular drift, smaller collection distance)
  - ➡ **Thinner planar sensors** for the outermost layers: **LPNHE thin sensors**

Pile up compliance

- Granularity: **50 μm x 50 μm** or **25 μm x100 μm** pitch instead of 50 μm x 250 μm
- **New chip RD53**: 50 μm x 50 μm to deal with high data rate at HL-LHC

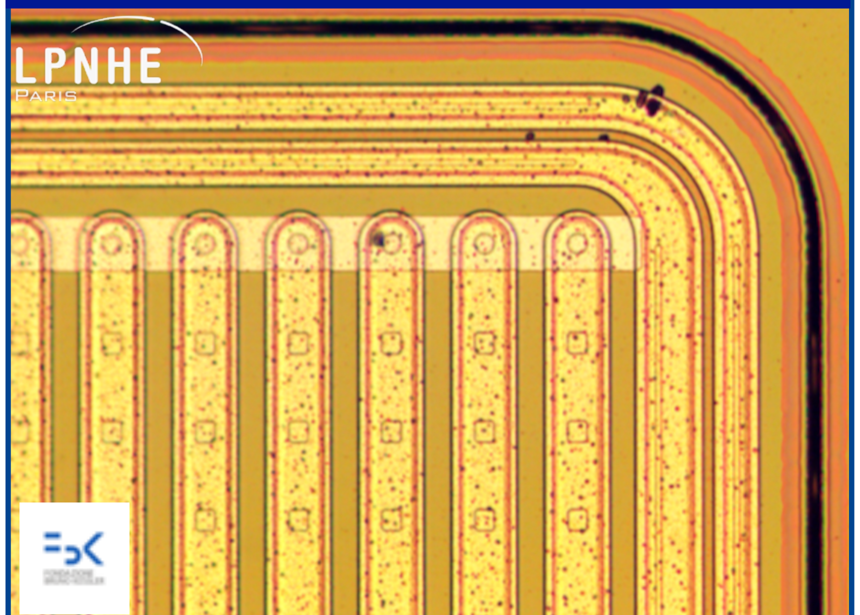
Geometrical acceptance increase



- Instrument at high eta, cf Inclined layout
- **Reduction of dead area ➔ Active edge sensors**

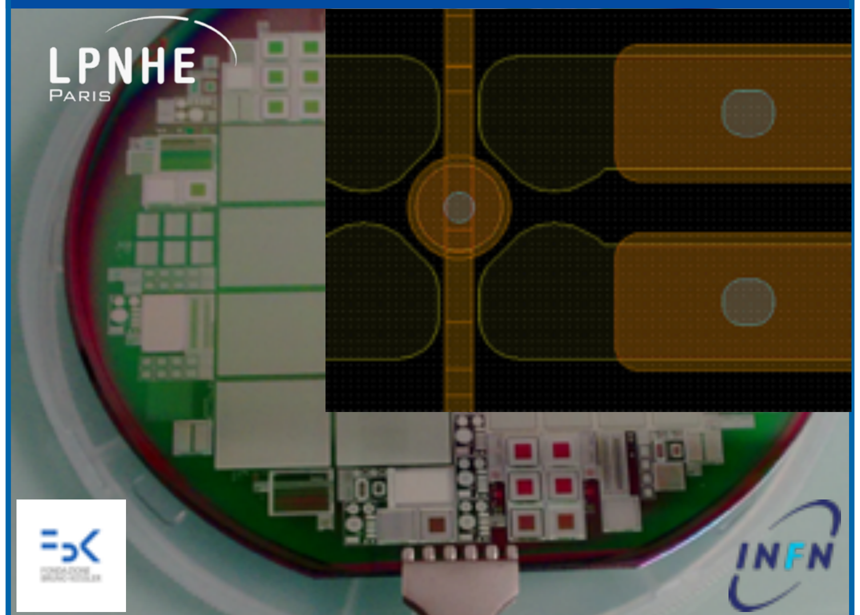
LPNHE n-in-p productions

Production 1
Active Edge (AE) sensors



- **Active edge**, DRIE process
- 100 μm pixel to trench, 0-2 Guard Rings (GR)
- 200 μm thick
- **Temporary metal**
- Not irradiated

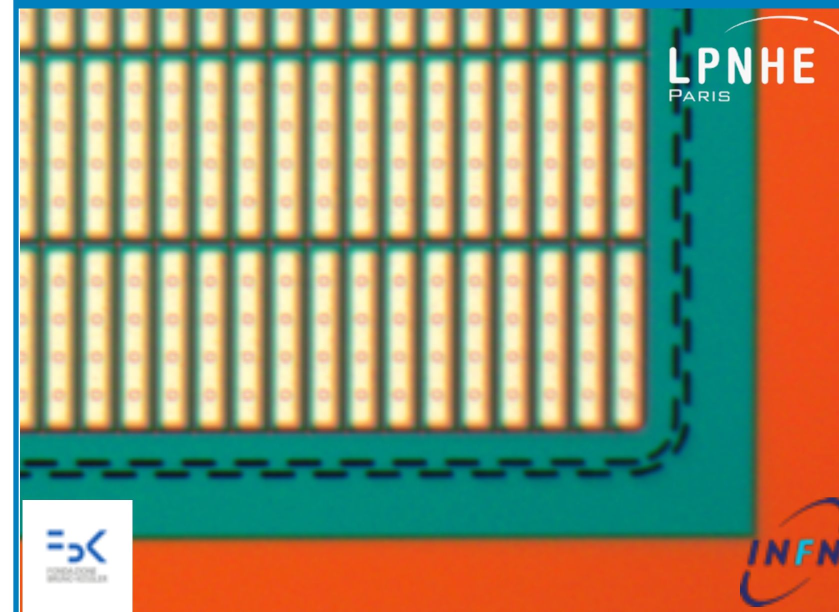
Production 2
Thin sensors



- Standard edge
- **130 μm thick**
- **Bias dots** (punch-through mechanism)
- Non-uniform **irradiation**: Average $1\text{x}10^{16}$ n_{eq}/cm^2

  Peak at $1.4\text{x}10^{16}$ n_{eq}/cm^2

Production 3
AE & Thin sensors



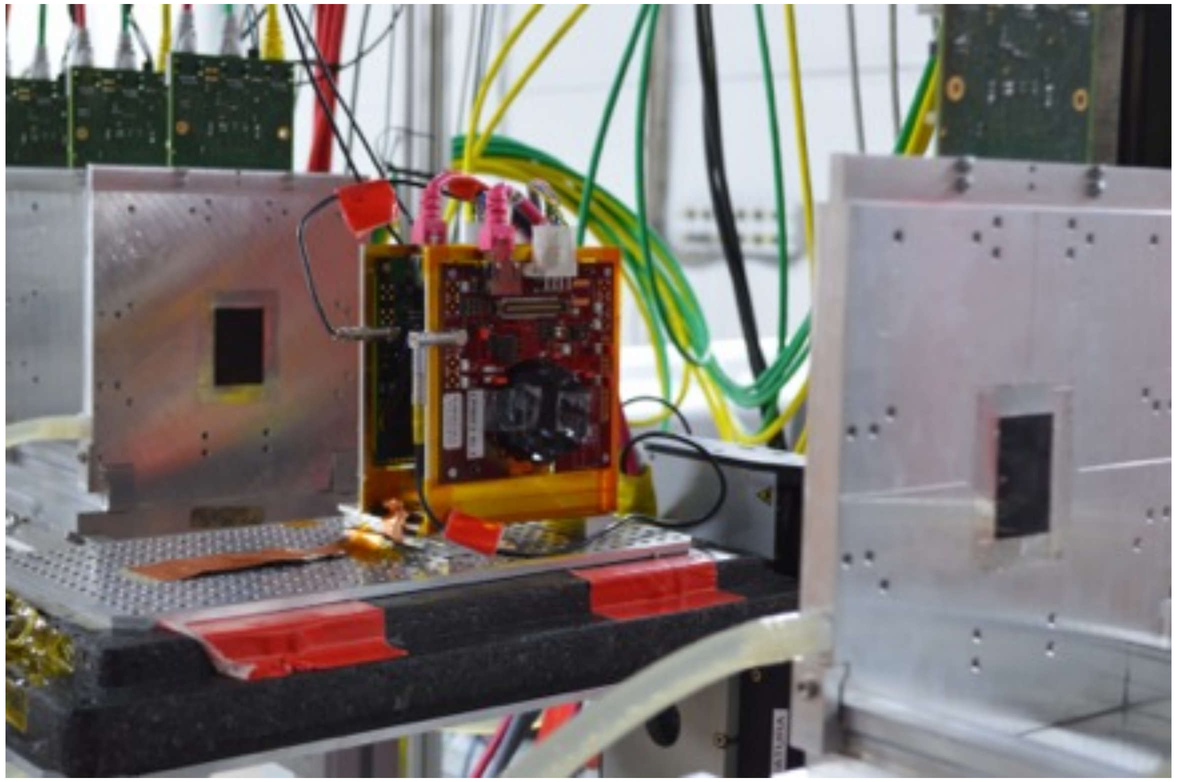
- **Active staggered edge**
- 50 -75 μm pixel to trench, 0-1 GR
- **130 μm thick**
- **Temporary metal**
- **Irradiated** uniformly at $3\text{ x}10^{15}$ n_{eq}/cm^2

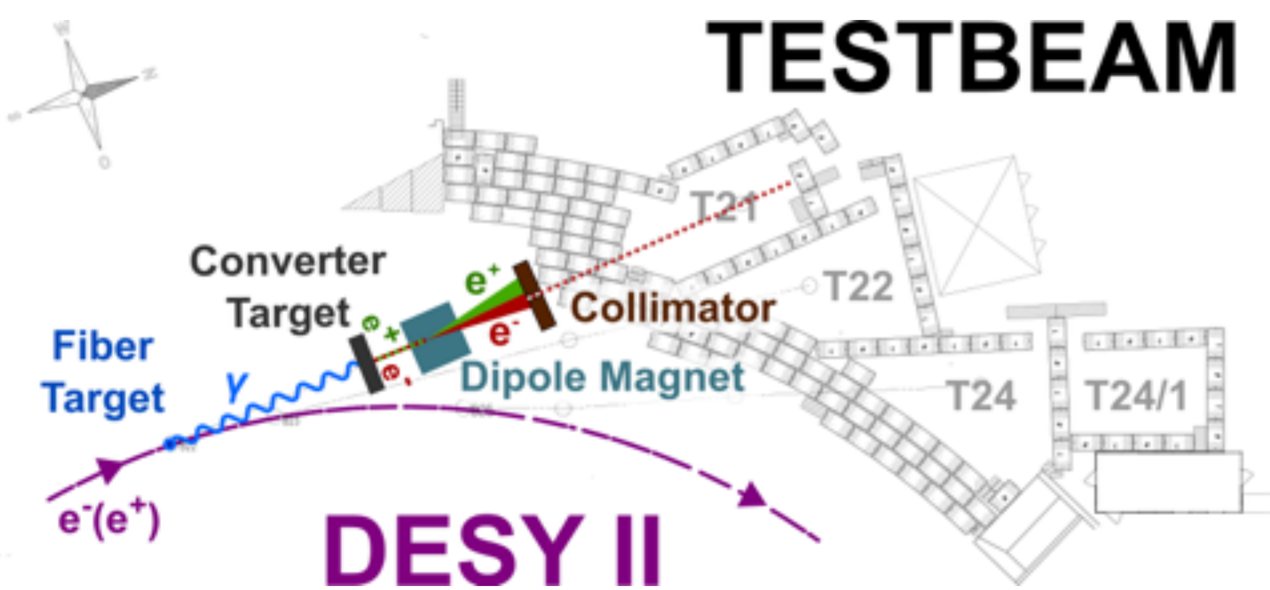
Testbeams

Test of sensors in particle beams (Testbeams):

- **DESY**: 4 GeV/c electrons beam, important **multiple scattering** contribution on spatial resolution (~30 µm)
- **CERN-SPS:** 120 GeV/c pions beam, small multiple scattering contribution on spatial resolution (~4µm)
- **EUDET telescope:** 6 planes of mimosa sensors (pixel size 18.4 µm x 18.4 µm), 1 reference FEI4 DUT for temporal coincidence, 2 scintillators for trigger

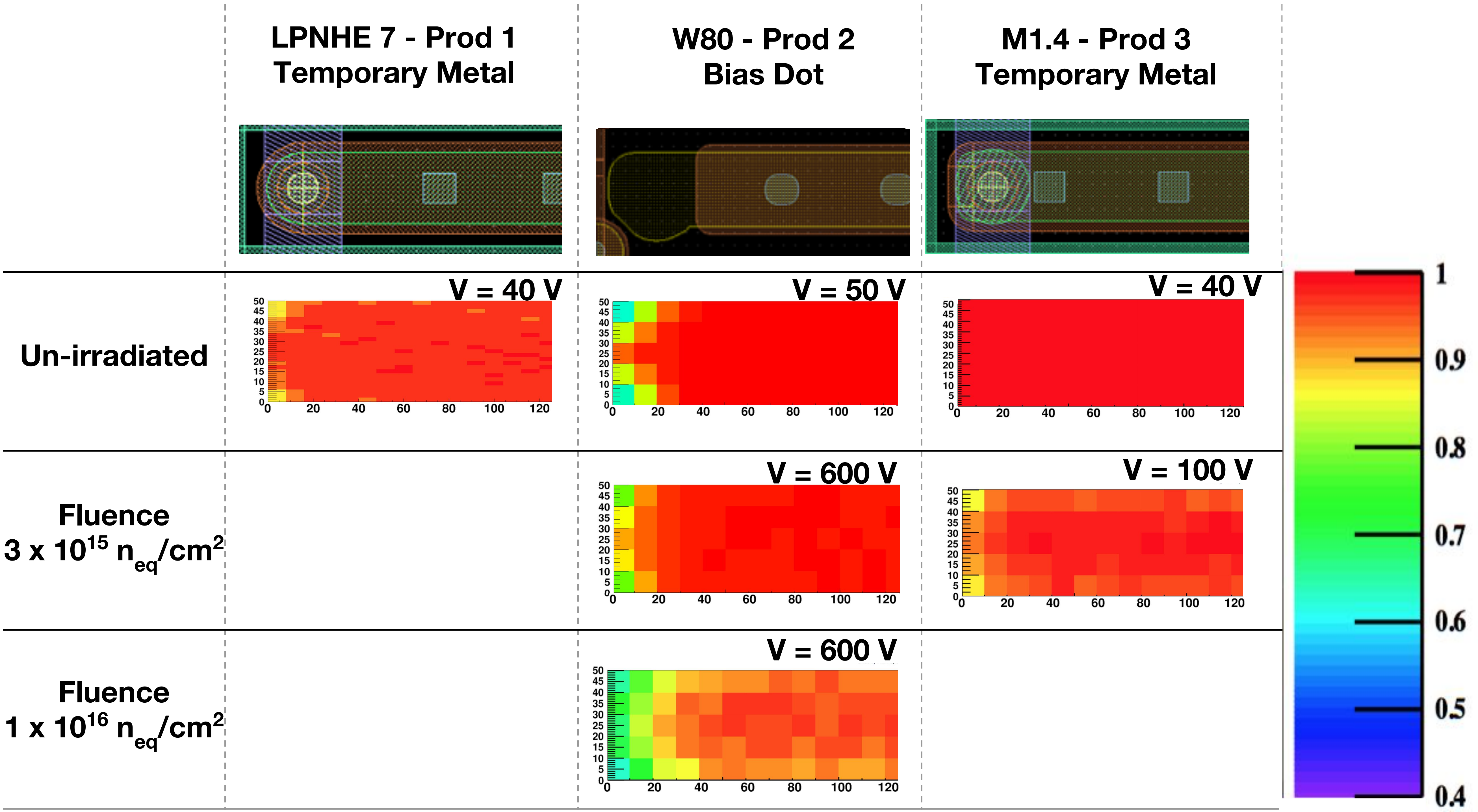
- 11 testbeams, 3 LPNHE productions tested
- **Sensors irradiated at CERN Irrad facilities or KIT**





Thin and irradiated sensors performance

R&D biasing structures



In pixel hit efficiency (half pixels considered):

arXiv:1810.07279 (October 2018)

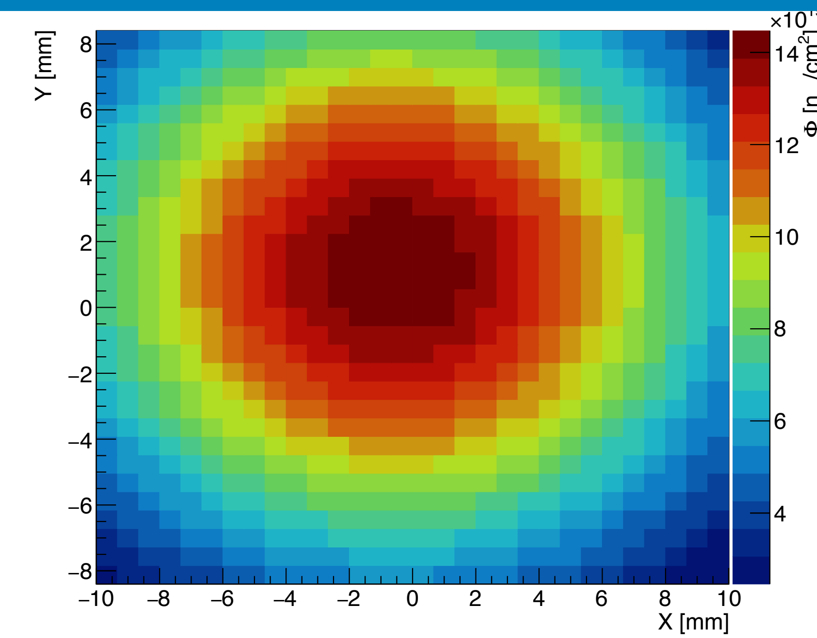
- **Degradation** of efficiency in the corner with **bias dot**
- More **uniform** efficiency for **temporary metal,** even after irradiation

Thin sensors (Production 2)

Thin sensor - W80

arXiv:1810.07279 (October 2018)

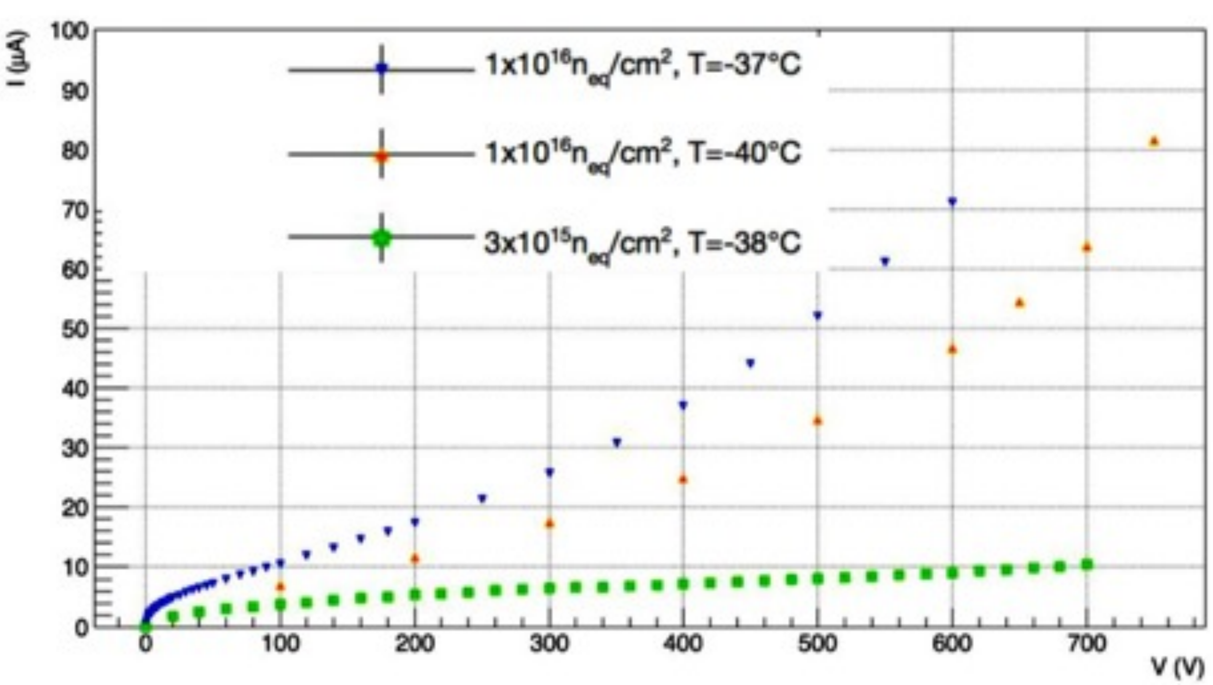
- Thickness: 130 μm
- Biasing system: bias dot
- Classic edge, 2 Guard rings
- Irradiated non uniformly in two times at CERN irradiation facility: peak fluence 1.4 x 10^{16} n_{eq}/cm^2



Leakage current and power dissipation

Sensor power dissipation at -25°C ~40mW/cm^2 → 4 times more than 3D sensors

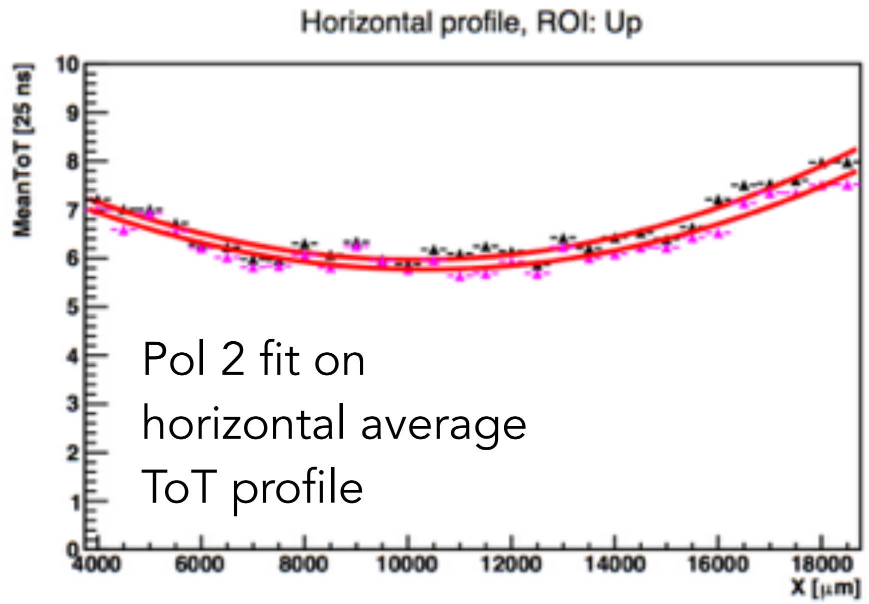
(V_{3D} 4x smaller)



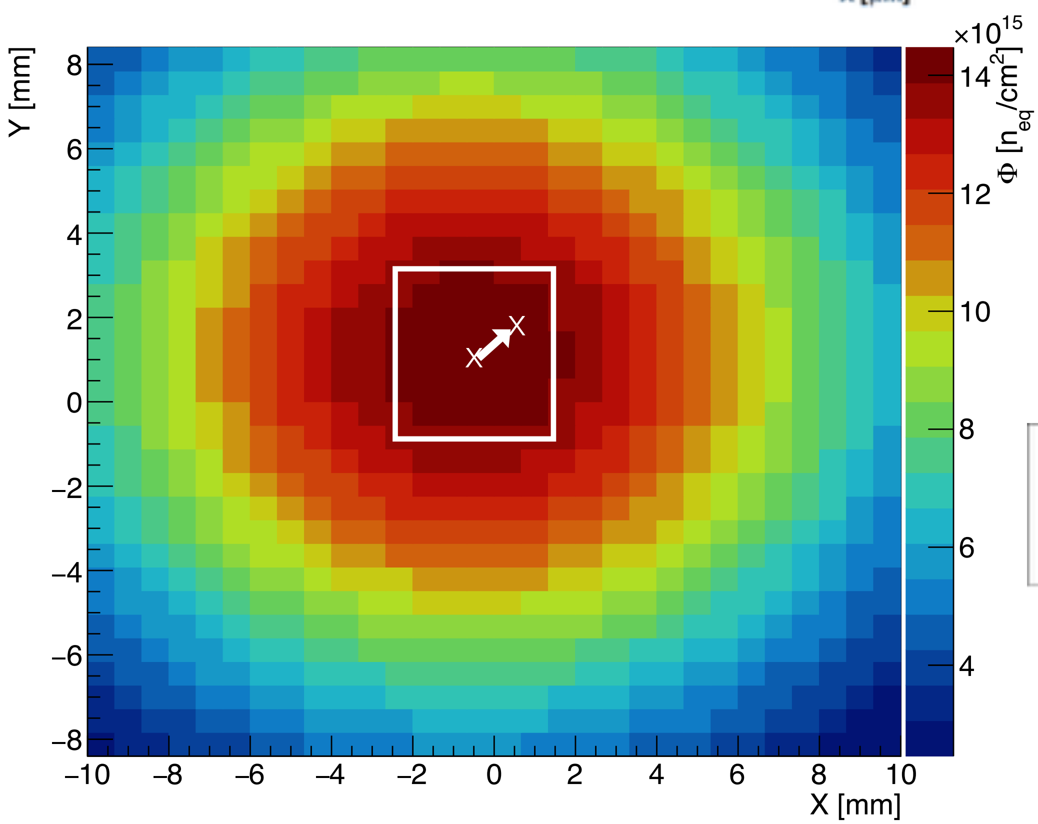
Current related damage rate α: $\Delta I = \alpha V \Phi$

- **Compatible with literature value at 3x 10^{15} n_{eq}/cm^2** (α=4.0 10^{-17} A/cm)
- **Higher value** (α=8.0 10^{-17} A/cm) for **highest fluence due to impact ionisation and limited annealing**

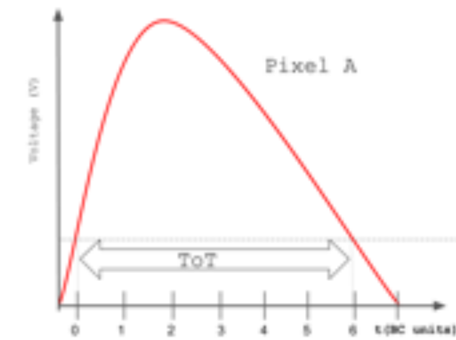
Irradiation



Pol 2 fit on horizontal average ToT profile

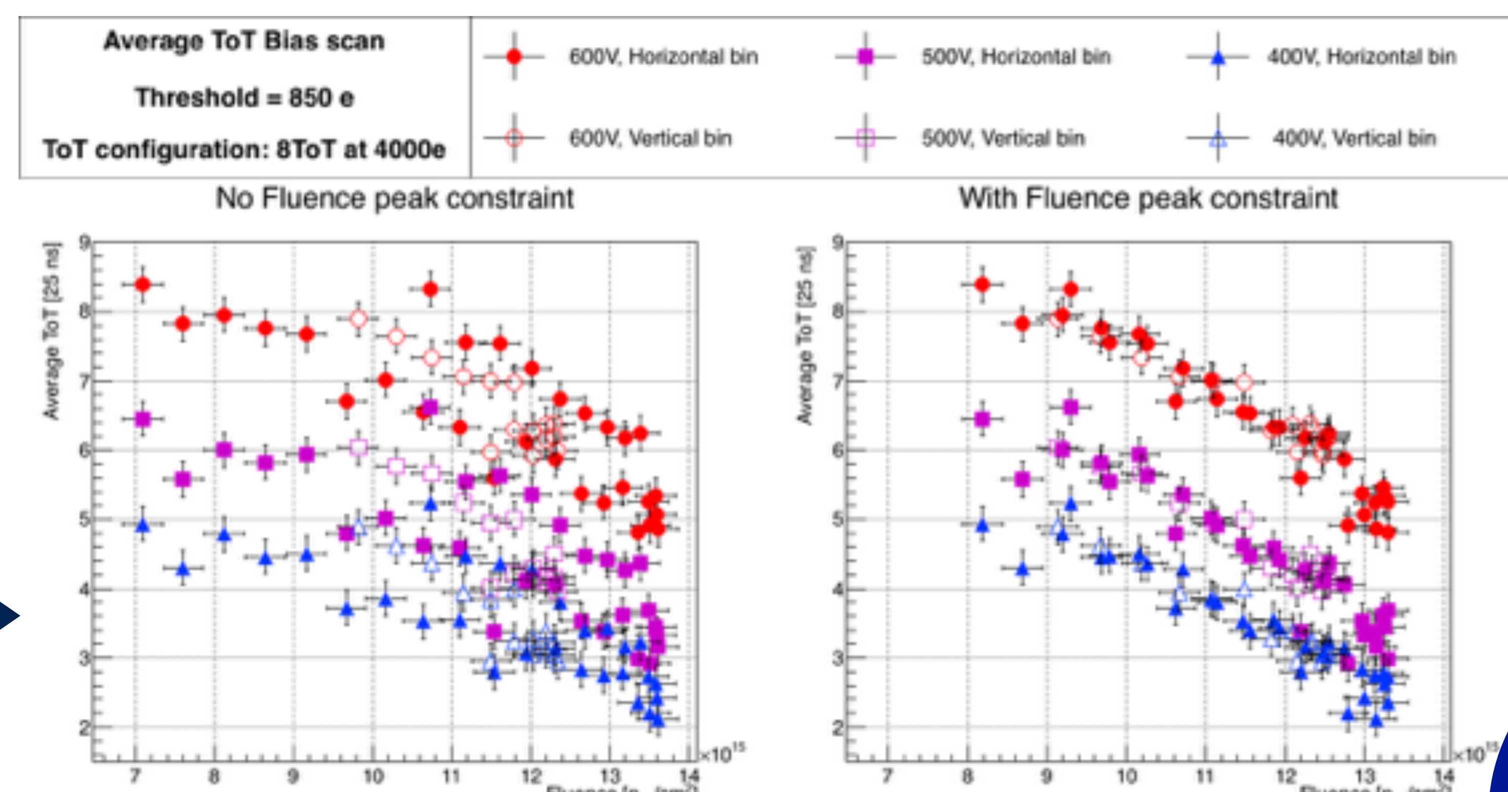


Data from CERN irradiation facility: **2D gaussian fluence profile, +/- 2 mm uncertainty on fluence peak position.** To obtain a more constraint peak position:



- Plot the average ToT (Time-over-Threshold) vertical and horizontal profiles for several configurations,
- Fit with a pol2 function and extract the minimum position (X and Y), use it as the new fluence peak

As a result: Less dispersion of ToT for same fluence →

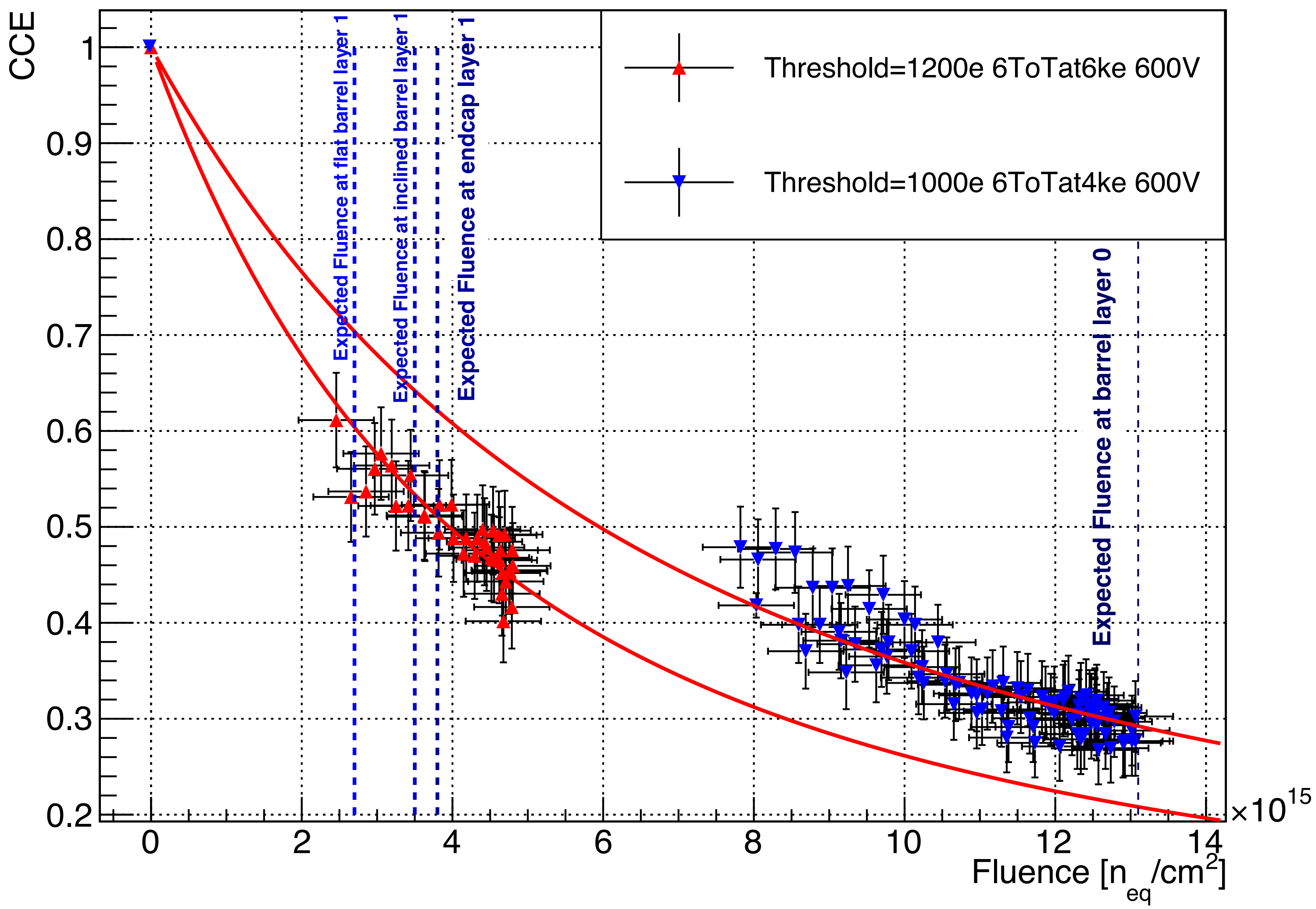


arXiv:1810.07279 (October 2018)

Charge collection efficiency

CCE = average charge after irradiation/ before irradiation

Hecht fit - > extraction of β the effective trapping constant



	Fluence (10^{15} n_{eq}/cm^2)			
	2.7	3.5	3.8	13.1
Thr=1200e, 6ToT at 6000e, CCE =	61%	53%	51%	21%
Thr=1000e, 6ToT at 4000e, CCE =	71%	64%	62%	29%

- **CCE highly dependent of the threshold target**
- **CCE drops drastically with the fluence (<30% at 1.3 x 10^{16} n_{eq}/cm^2)**

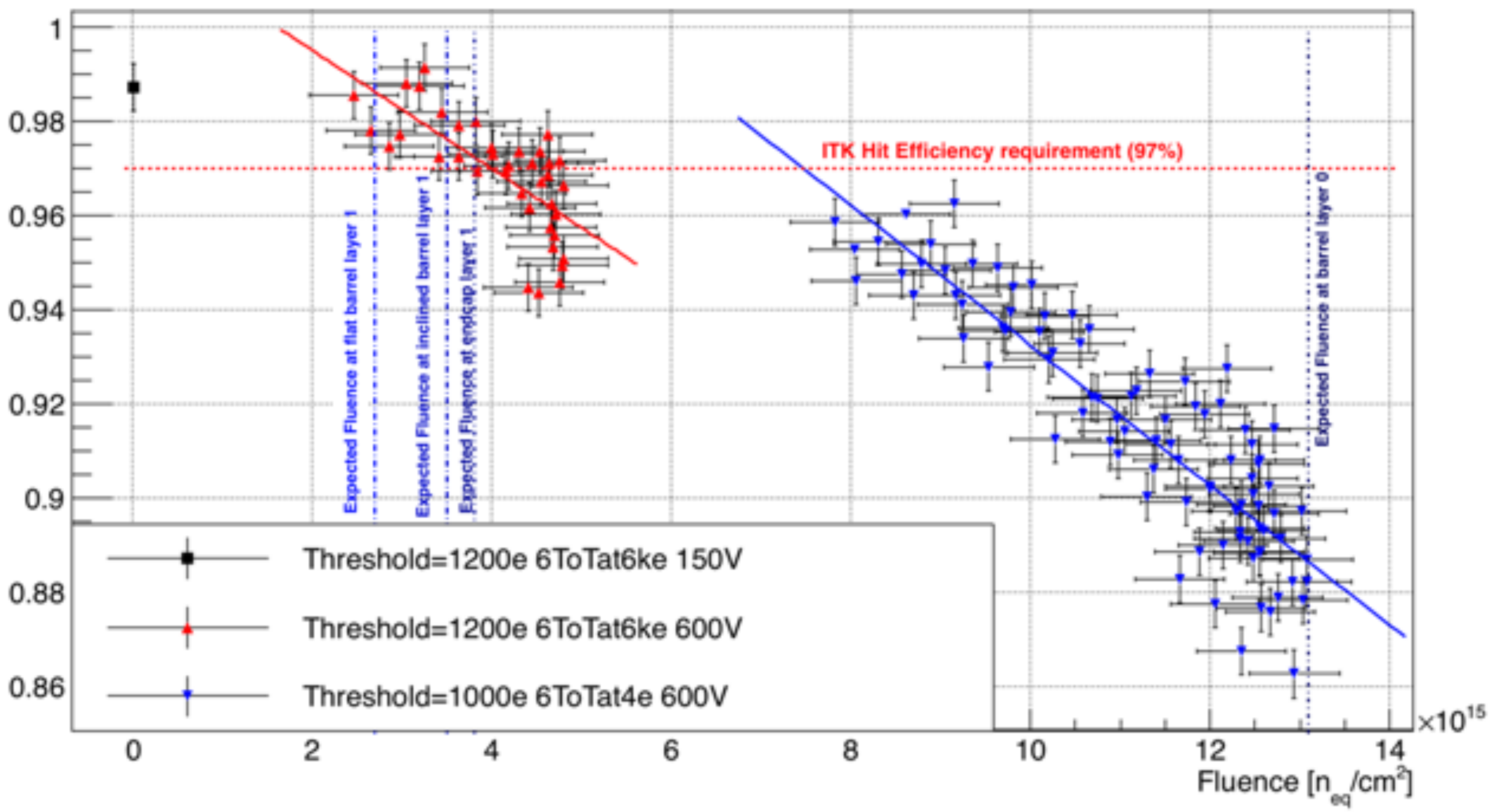
➡ **This data will be used to compare with radiation damage digitization at high (ITk-like) fluence**

- Reference $\beta e = 6.6 \pm 0.3 \times 10^{-16} cm^2/ns$ and $\beta h = 10.1 \pm 0.3 \times 10^{-16} cm^2/ns$ (from Kramberger et al ATL-INDET-2002-006)
- Lower values found (different tuning, annealing, approximations used …):
  - at intermediate fluence: $\beta e = \beta h = 5.5 \pm 0.2 \times 10^{-16} cm^2/ns$
  - at high fluence: $\beta e = \beta h = 3.6 \pm 0.1 \times 10^{-16} cm^2/ns$

arXiv:1810.07279 (October 2018)

Hit Efficiency

Efficiency higher than 97% up to **4 x 10^{15} n_{eq}/cm^2** for the red configuration and **7.5 x 10^{15} n_{eq}/cm^2** for the blue one



Fluence (10^{15} n_{eq}/cm^2)	2.7	3.5	3.8	7.45	13.1
Threshold (electrons)	1200	1200	1200	1000	1000
ToT tuning (ToT corresponding to electrons)	6at6	6at6	6at6	6at4	6at4
Extrapolated Hit Efficiency (% ± 0.5%)	**98.6**	**97.6**	**97.2**	**97.0**	**88.6**

- Large **impact of threshold** settings
- Negative **impact of bias dots** on efficiency
- **Thin sensor of production 2 suited for Layer 1 and outermost layers** (hit efficiency >97% up to max fluence received)

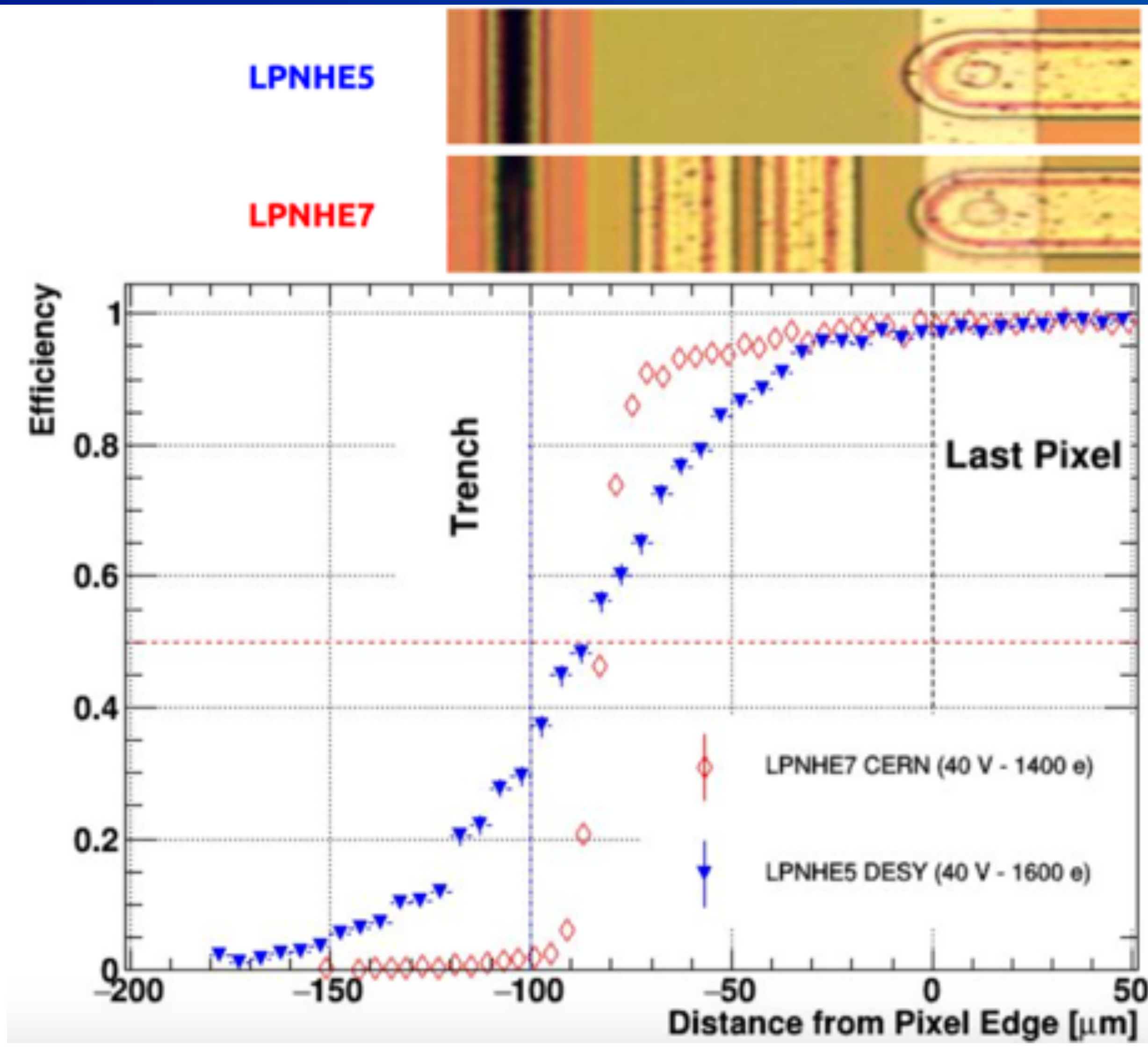
➡ As expected, **not suited for innermost layer** (low hit efficiency and too high sensor power dissipation)

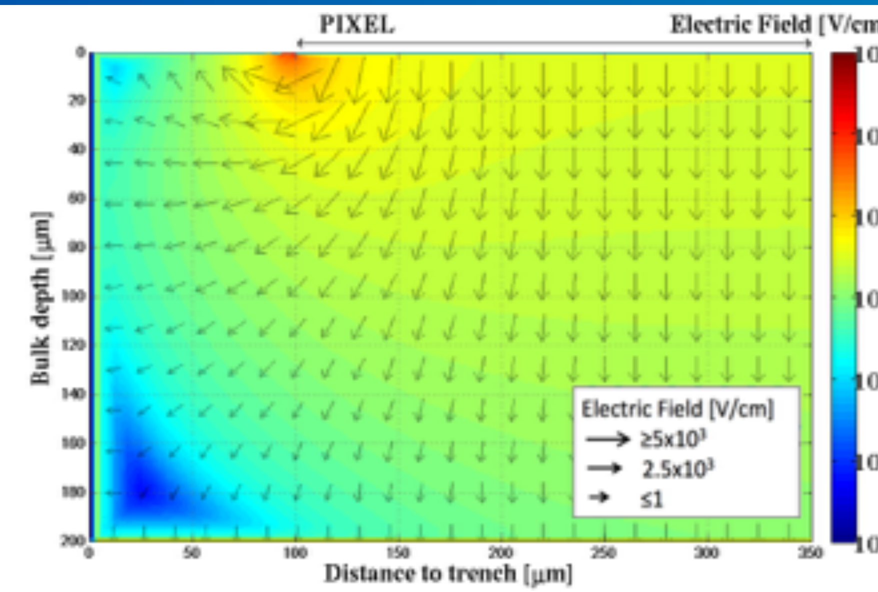
arXiv:1810.07279 (October 2018)

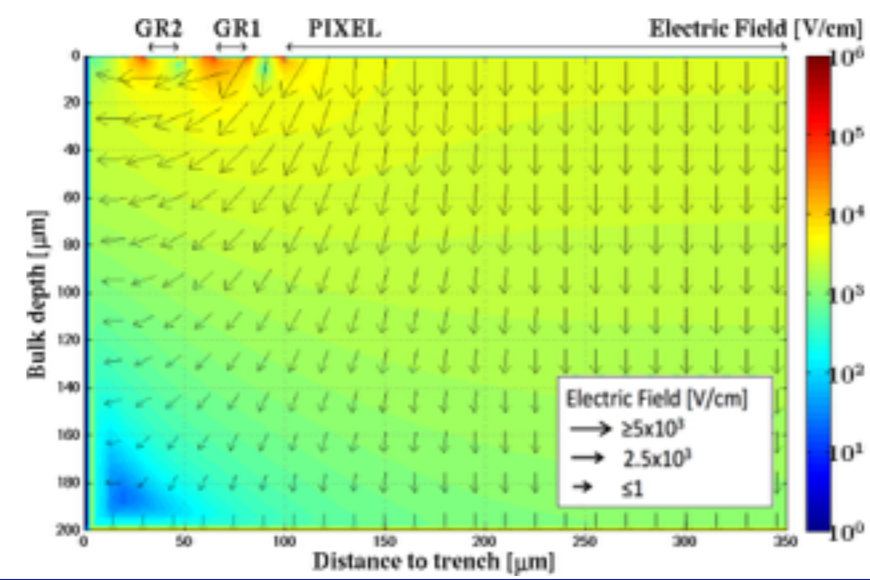
Thin and Edgeless sensors, unirradiated & irradiated

Active edge sensors

Standard Active edge (Production 1)





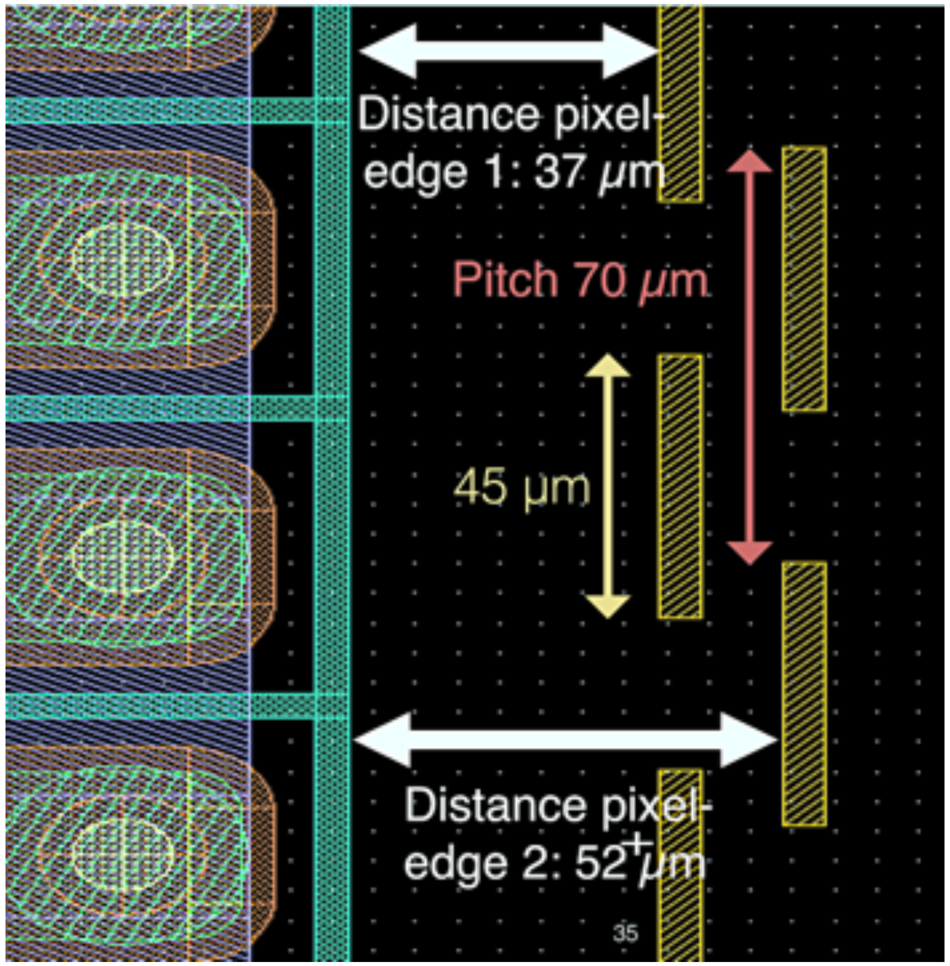


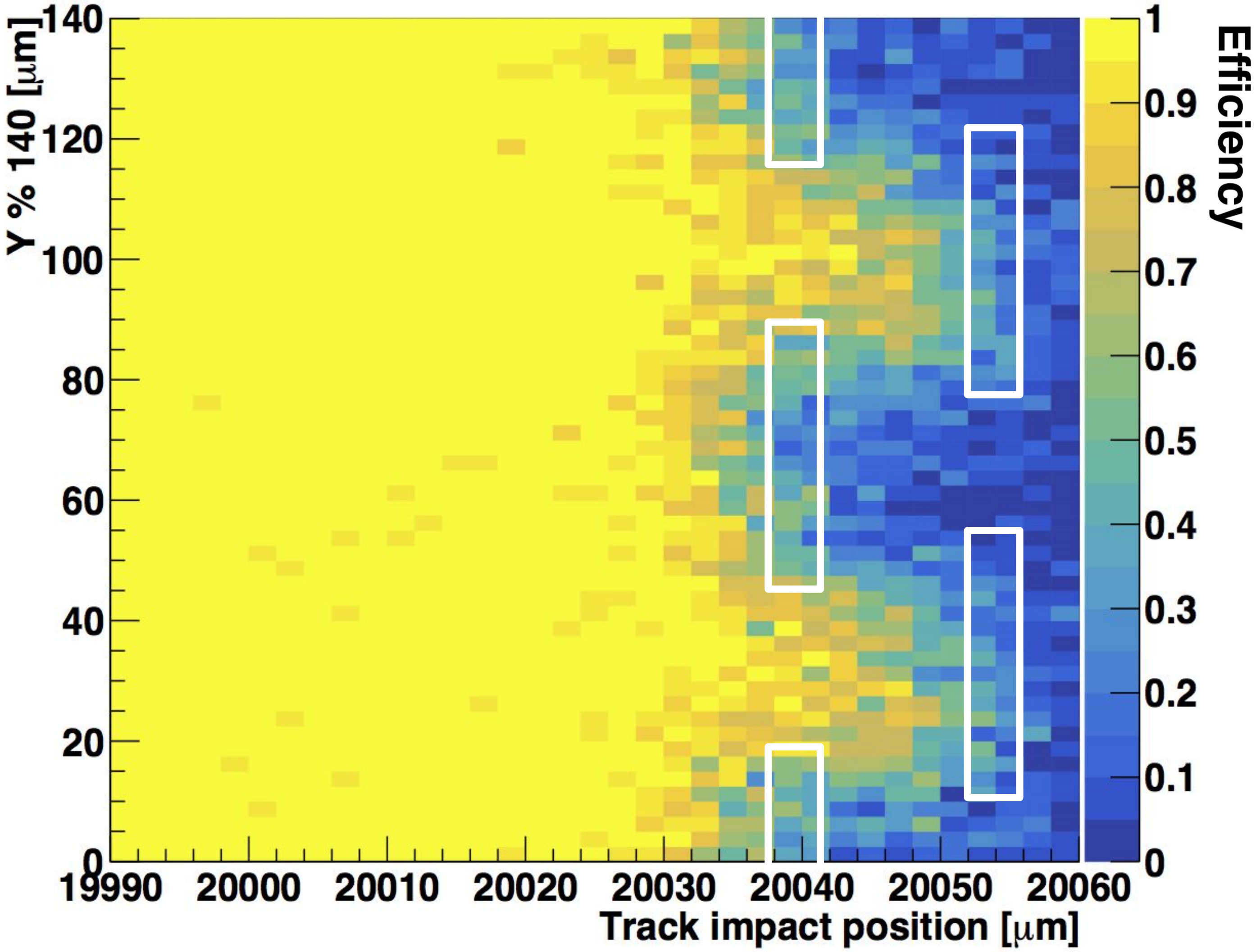
Efficiency in the edge area:

JINST 12 P05006 (2017)

- Efficiency higher than 80% up to 75 μm from last pixel
- Blue triangles (DESY low energetic e), multiple scattering smear the spatial resolution
- GR don't influence efficiency, supported by TCAD simulations

Staggered edge design (Production 3)





M1.4 sensor, staggered edge, 0 GR, ~50 μm last pixel to last edge, 130 μm thick, before irradiation:

➡ 2 fences of discontinued edges (such sensors do not require a support wafer)

➡ **The efficiency follows the edge pattern**

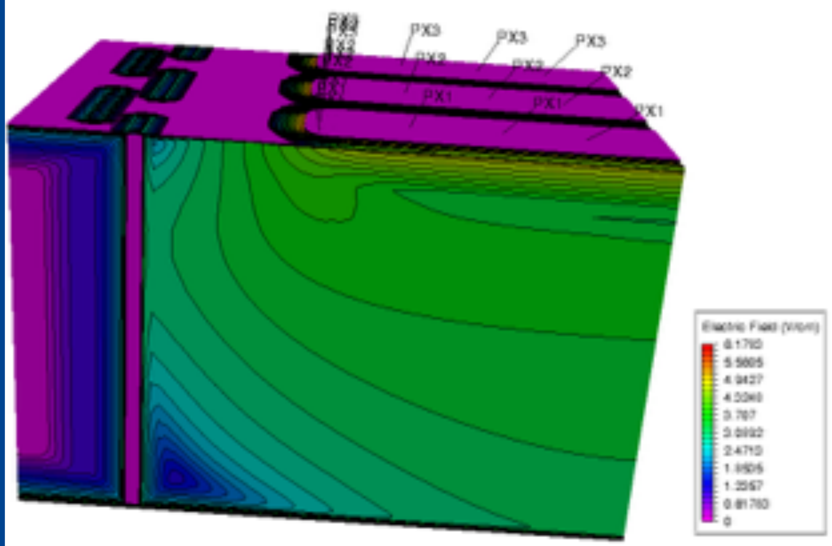
➡ **The efficiency is higher than 50% up to 44 μm from the last pixel**

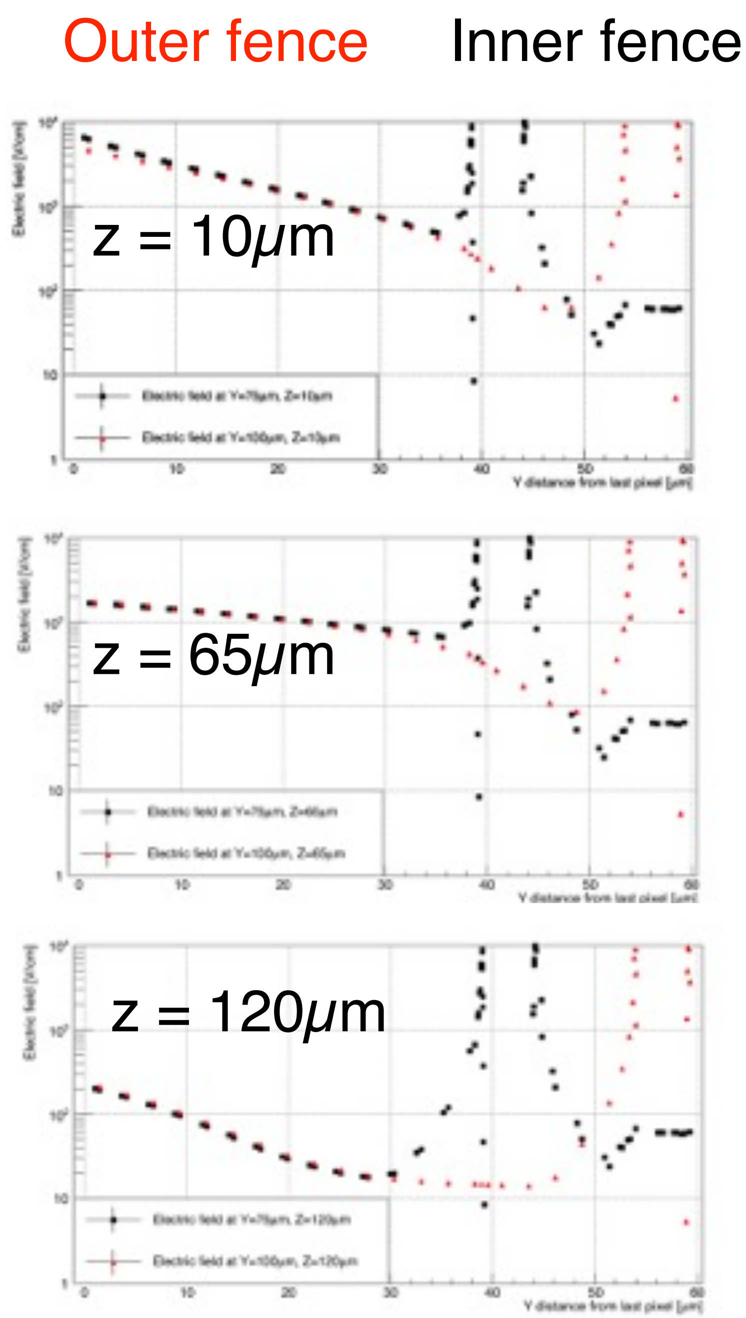
Comparison with TCAD

TCAD Simulations - Electric field

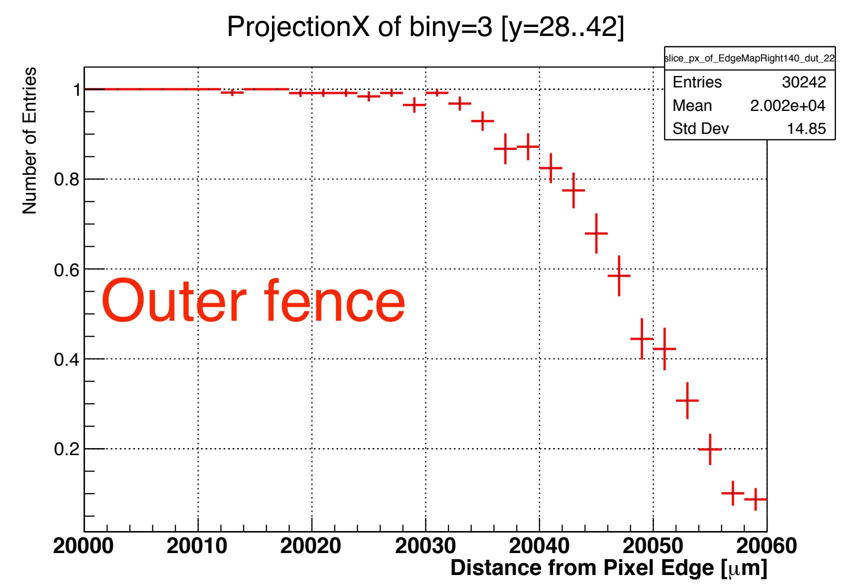
Simulation of the electric field for several depth z in the sensor:

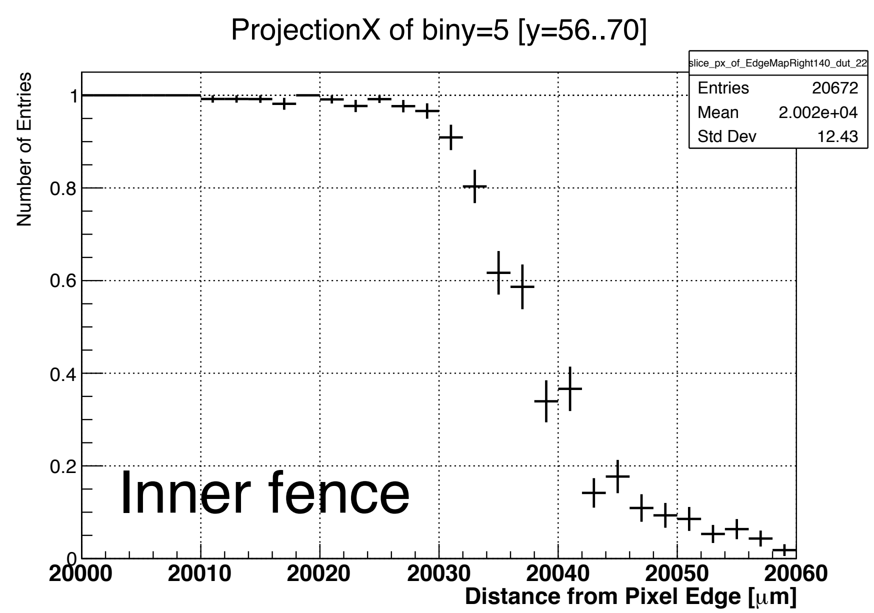
- E drops at 0 when at edge position
- low E in the bottom corner close to the edge.





Edge Efficiency

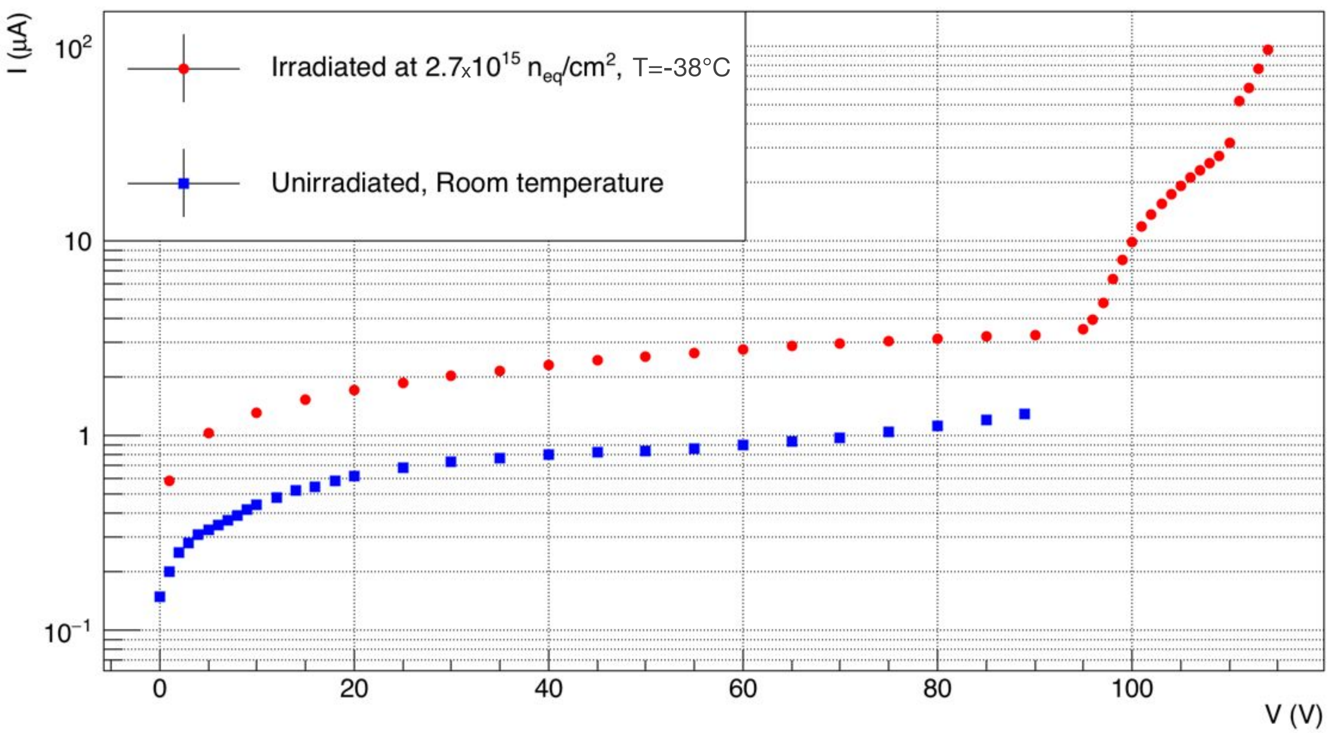


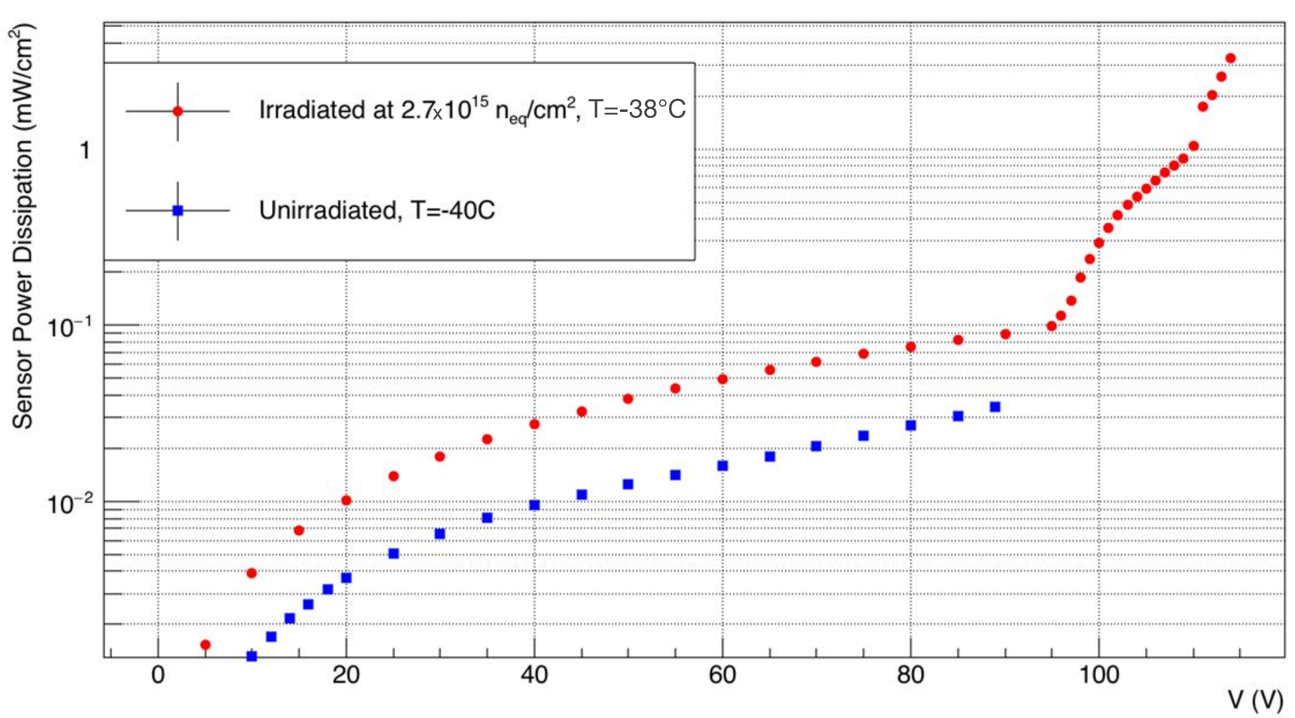


Efficiency drop matches the Electric field drop in the vicinity of the edge

Active edge sensors

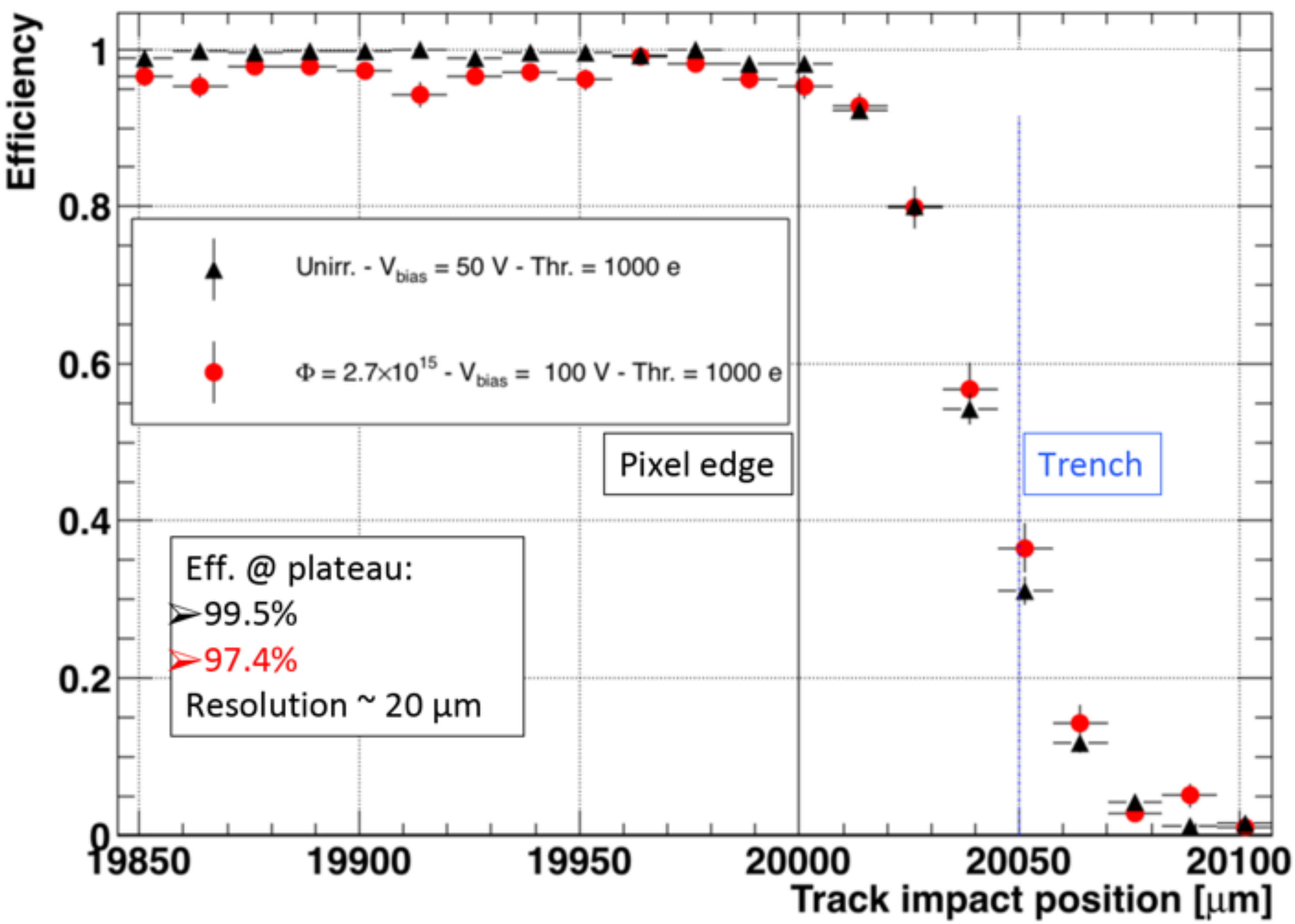
Staggered Active edge - Irradiated





- M1.4 **irradiated uniformly at 2.7 x 10^{15} n_{eq}/cm^2**
- **Early soft breakdown** around 90V (observed by other ITk group)
  - ➡ discharges at the edge of the sensor between the sensor and the chip
- Estimation of α value ($\alpha = 1.4 \pm 0.2 \times 10^{17}$ A/cm), **compatible with partial depletion of the sensor**
- At 100-110 V and -25°C Sensor power dissipation is 0.4 mW/cm^2

Staggered trench edge efficiency after irradiation



Edge efficiency after irradiation + in soft BD conditions:

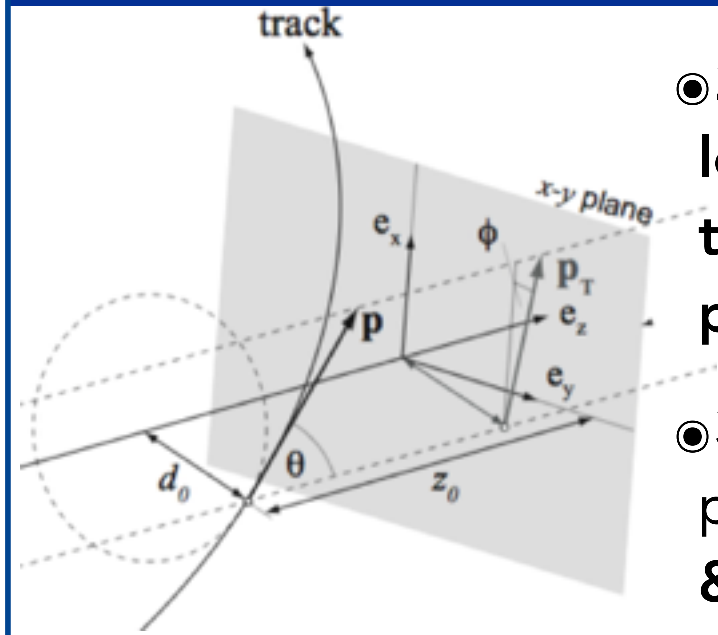
- **Comparable to unirradiated performance**
- **Efficiency higher than 80% up to 25 *μ*m from last pixel**
- Plateau Efficiency: 97.5%

b-tagging upgrade for ITk

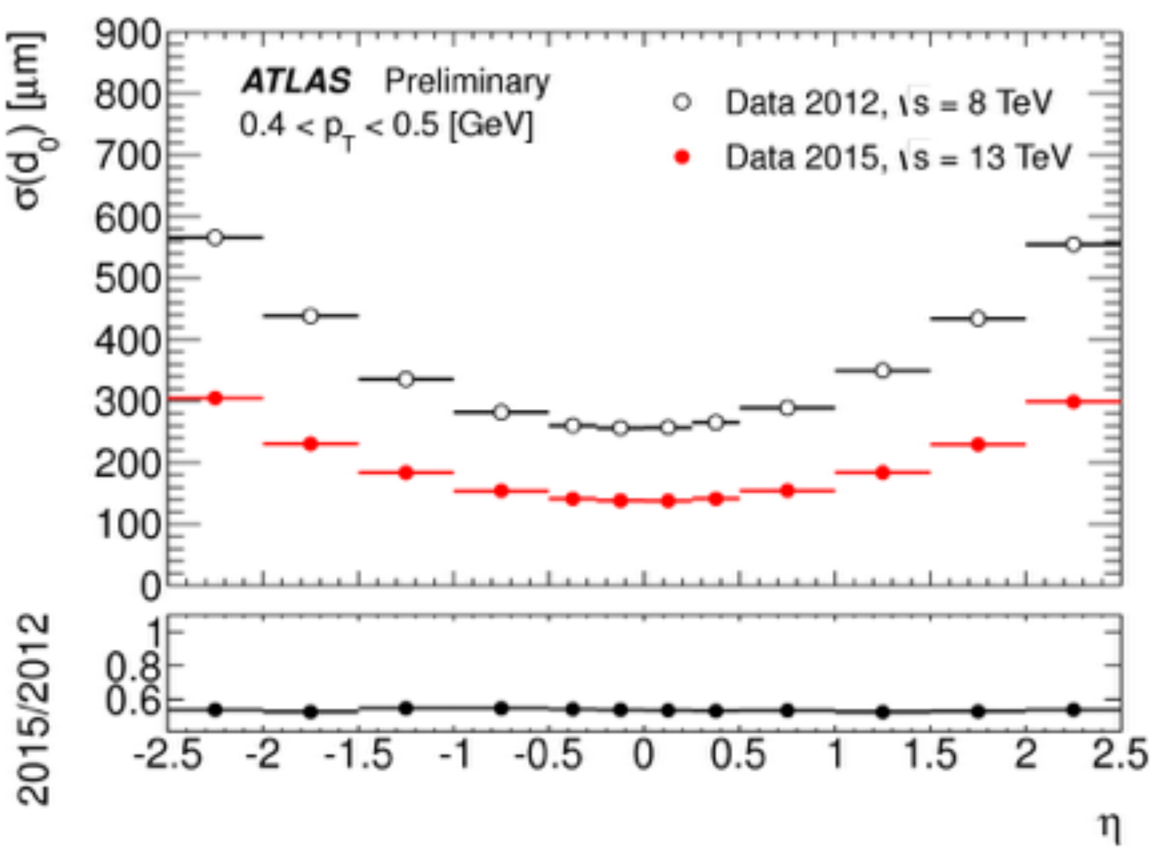
- **b-tagging at ITk**
- **SV1 Optimization**
- b-tagging extrapolation at high pT

ATLAS: From tracks to b-jets

Tracking



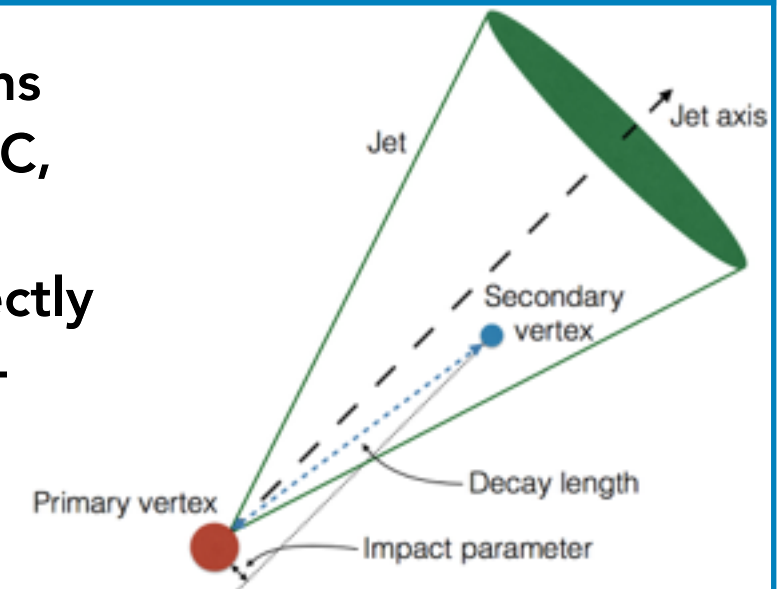
- 2 local parameters: **longitudinal and transversal impact parameters d0 & z0**
- 3 global parameters: **q/pT, ϕ & θ**



The addition of the IBL helped to improve the tracking performance

b-tagging

Massive b-hadrons production at LHC, essential to reconstruct correctly jets containing b-hadrons (b-jets)



Long b-hadrons lifetime (~1.5 ps), b-jets are characterized by:

- **Displaced secondary vertex** at several hundreds of μm from the primary vertex - **SV1**
- **Large impact parameters - IP3D**
- **Decay topology involving c hadrons:** dominant decay channel b→cW - **JetFitter**

b-tagging algorithms combined using multivariate techniques to optimize the b-tagging

b-tagging upgrade

b-tagging

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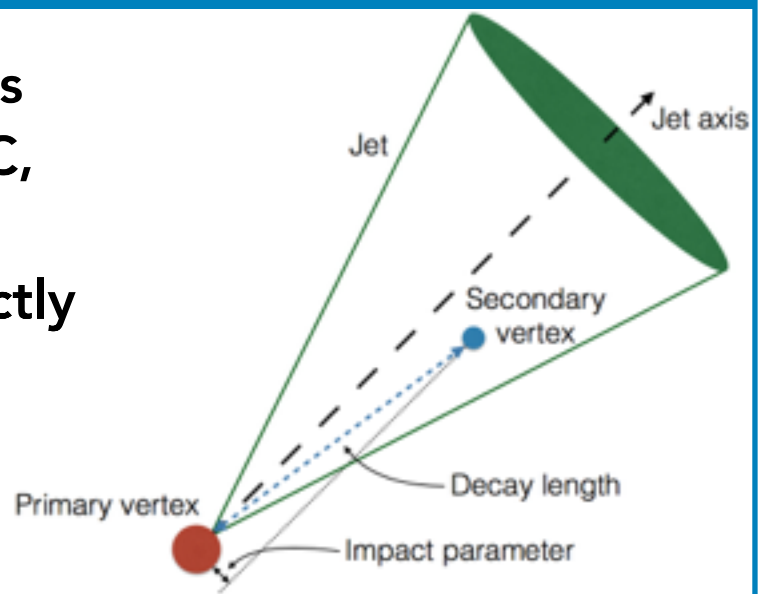

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b-tagging algorithms combined using multivariate techniques to optimize the b-tagging

Algorithms upgrade for ITk

b-tagging at ITk:

- crucial ingredient in a large number of analysis including hh → bbbb and hh → bbγγ channels …
- have to be upgraded to deal with HL-LHC conditions and ITk geometry

- IP3D - already optimized (ITk pixel TDR)
- **SV1 - Optimization study presented in next slides**
- JetFitter and Multivariate techniques: effort ongoing

Other studies:

- **ITk layouts comparison**
- b-tagging performance at high pT using Z′ samples

SV1 Optimization

Secondary vertex finder algorithm (SVF)

Goal: Create a pool of secondary vertices (SV) passing a set of criteria. Afterwards the SV1 algorithm classifies the SV from b, c and light jets.

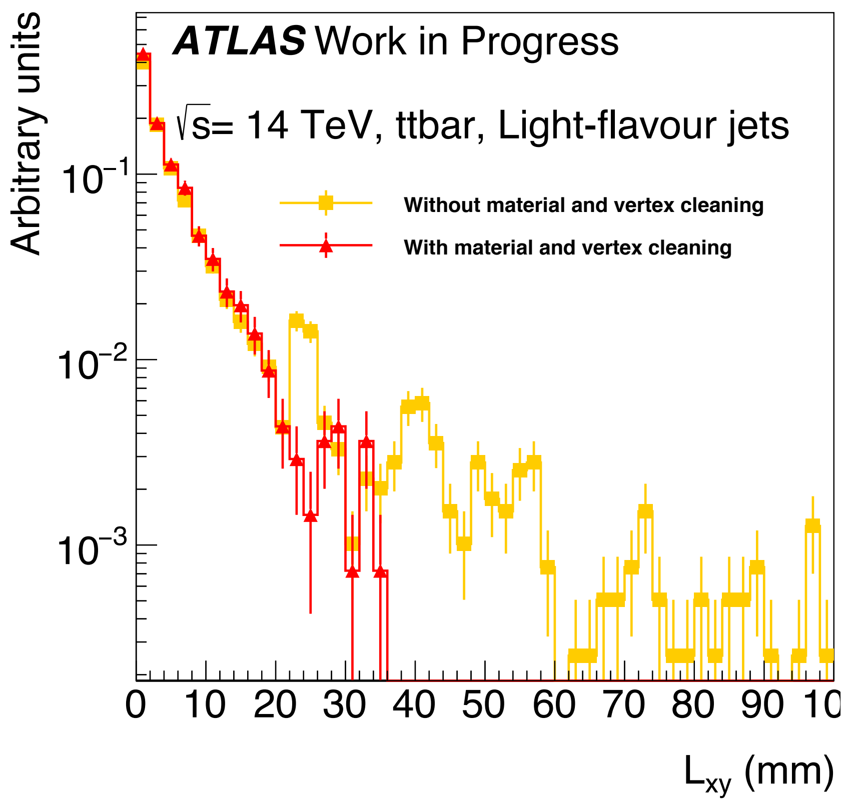
1. **Tracks selection inside a jet: Cuts on silicon hits, on track p_T …**
2. **Formation of all possible 2-track vertices**
3. **Selection on the 2-track vertices: Vertex cleaning disentangle true SV from long lived particles (K_s or Λ) decay vertices, photon conversion vertices and vertices from hadronic interaction with matter (material rejection).**
4. **Merging of the 2-track vertices into multi-tracks vertices**

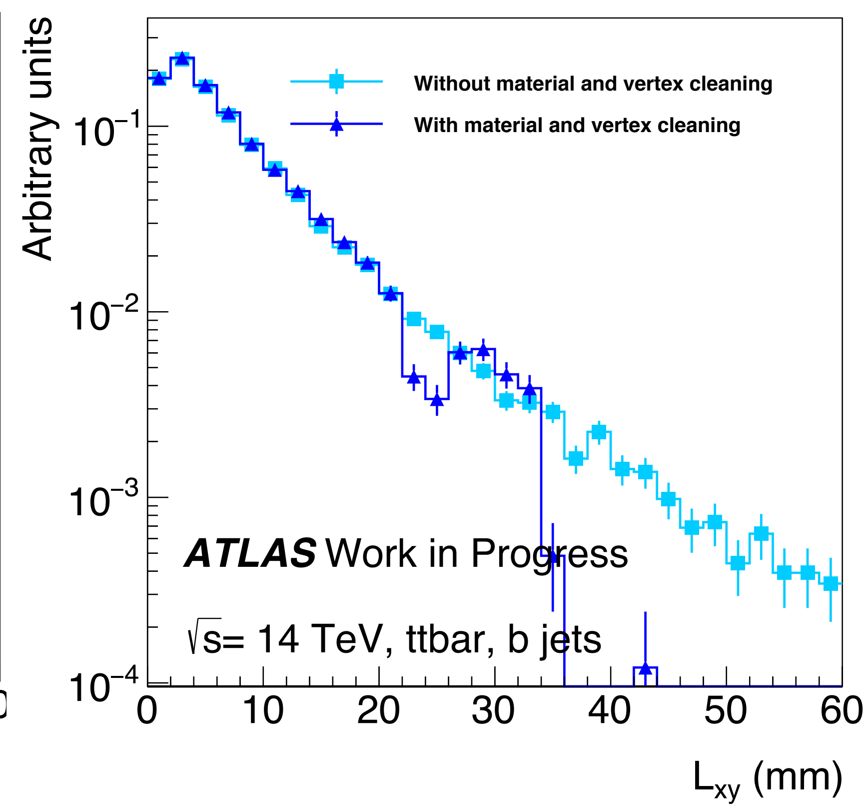
Optimization studies

- **Material rejection:** Update the SVF algorithm to obtain a material rejection which matches the ITk geometry
- **p_T cuts and Silicon hit cuts optimization**

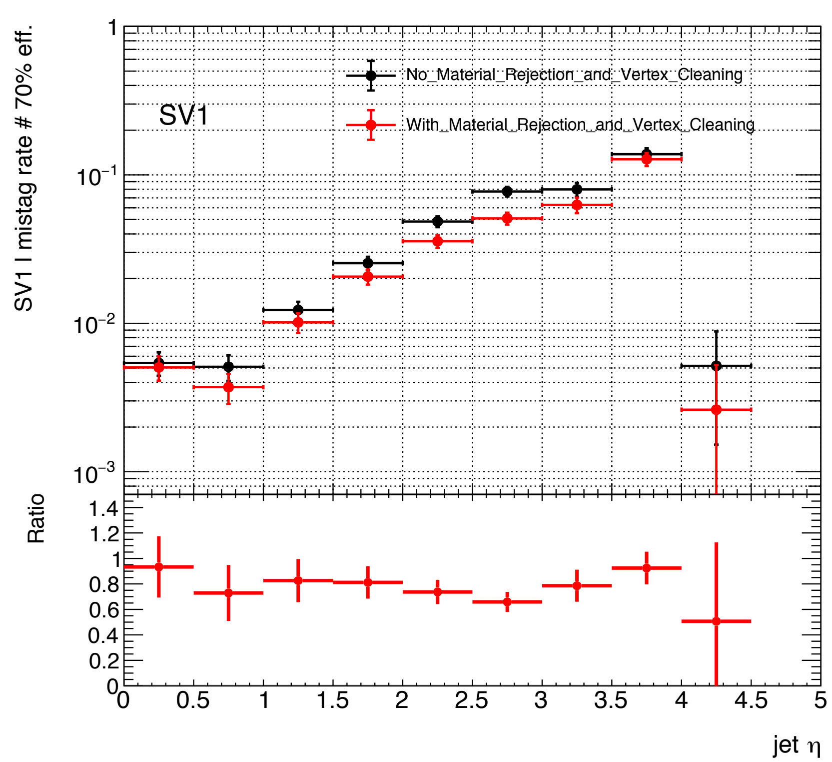
SV1: Material cleaning

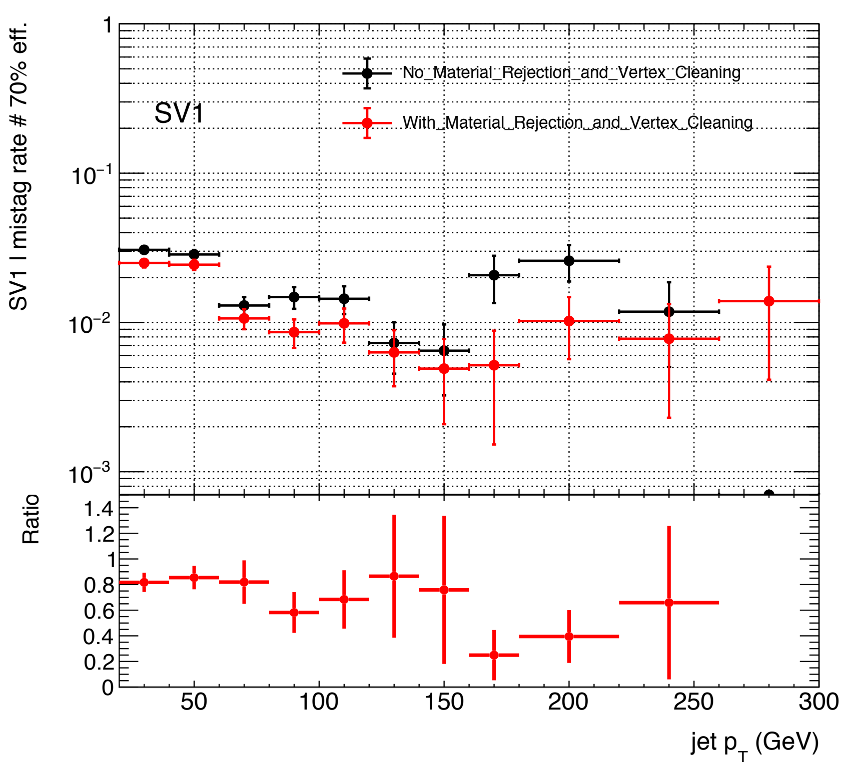
Lxy: transverse distance between the secondary vertex and the primary vertex





- Yellow spikes correspond to light jets created by hadronic interaction with beam pipes or pixel layers
- Using material rejection allow to discard a lot of light SV from hadronic interaction but also discard some good b-SV, cuts to be refined

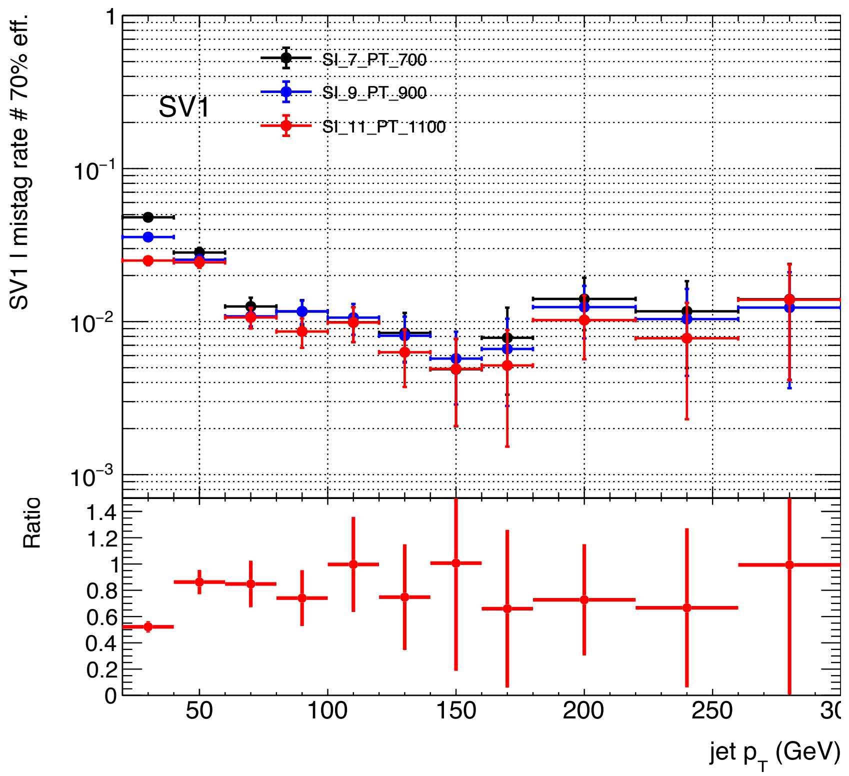


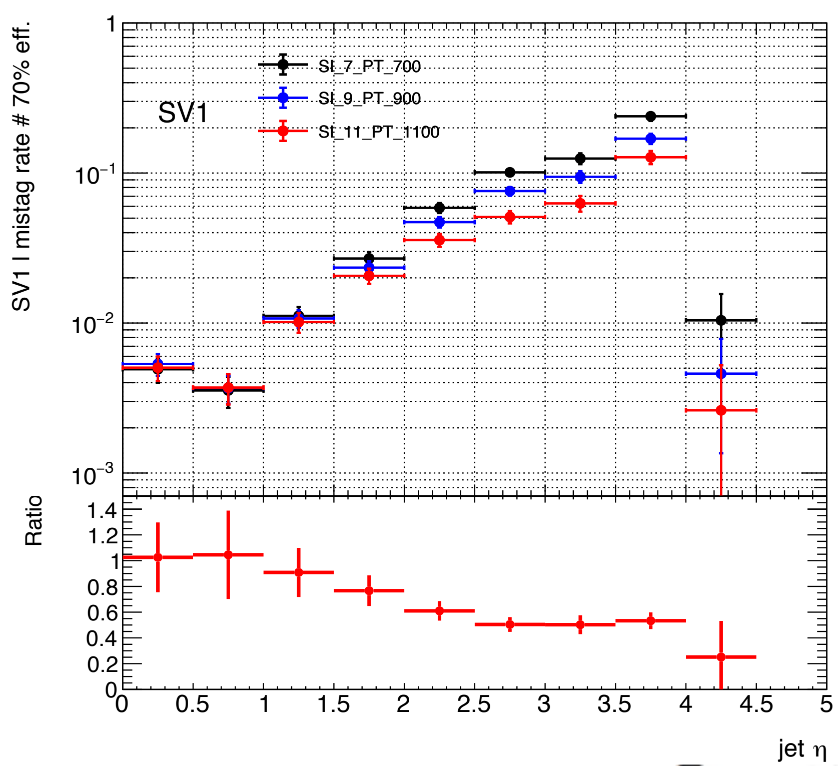


➡ **The light-jet mis-tag rate is diminished by at least 20 % over the jet pT spectrum and 20-40 % for 0.5 < |η| < 3.5**

SV1: p_T and Si Hits Cuts

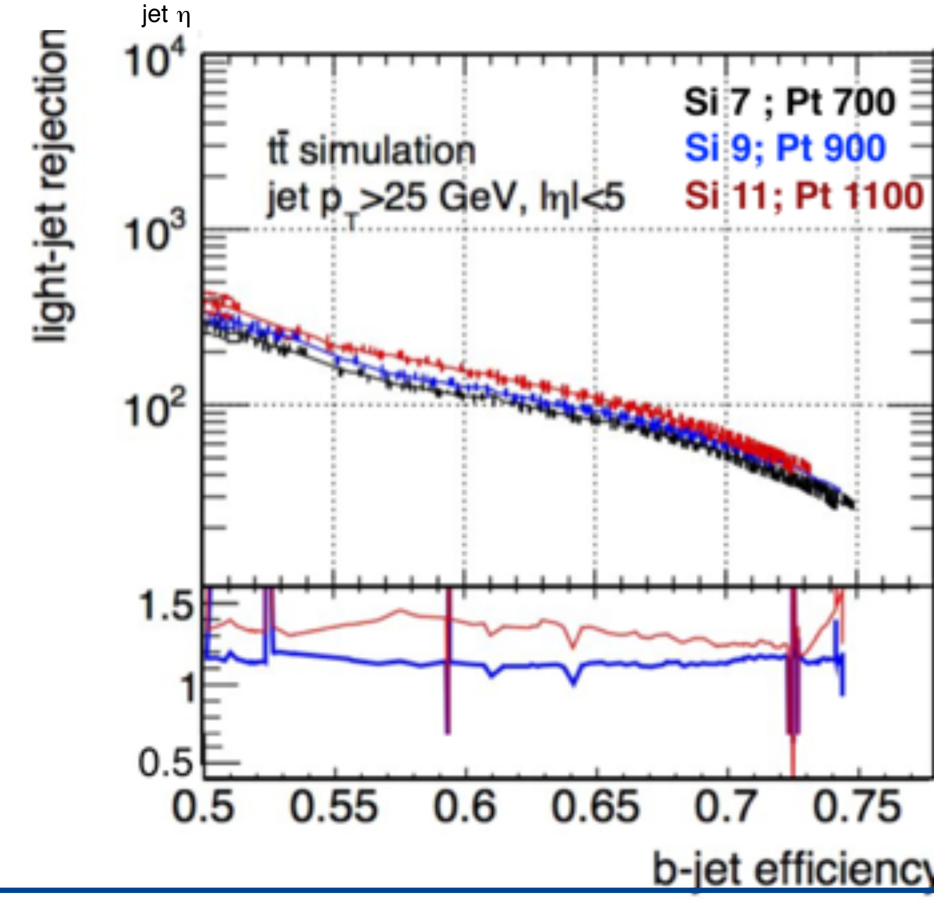
Several p_T cut options (700, 900 and 1100 MeV) and cuts on the number of silicon hits (7,9 and 11) investigated





- The most stringent selection (1100 MeV, Si Hits Cut=11) gives better results (lower l-mistag rate) at medium and high η and along the full p_T range.

- The configuration (1100 MeV, Si Hits Cut=11) results in an **increase of the Light-flavour jet rejection of roughly 30%** compared to the (700 MeV, Si Hits Cut=7) configuration



Conclusions

Thin and irradiated sensors

- **Good Hit-Efficiency for thin sensors at ITk outermost layer fluences**
- The **temporary metal option** results in **more uniform and higher hit efficiency** even **after irradiation**
- Charge collection efficiency: **drops drastically with the fluence:** To be used to validate radiation damage model at ITk like fluence
- Active edge: **Edge efficiency** recovered for 2 edge designs and for **irradiated sensor** in soft breakdown regime

Next: **Test of irradiated small pitch pixels modules** + tests on **irradiated standard active edge** modules.

ITk decision on design features: early 2019

Radiation damage digitizer

- Evaluation of the impact of Chiochia model parameters variations
- **Validation of radiation damage digitizer** on **charge collection efficiency**
- **Impact of fluence and bias voltage on tracks and clusters**

Next: Redo the study with higher pT samples and higher statistics, quantify impact on b-tagging and higher level physics objects using ttbar and Vh, h→bb samples

b-tagging for ITk

- SV1 optimization using updated material rejection and stringent tracks criteria: **increase of light-flavour jet rejection**