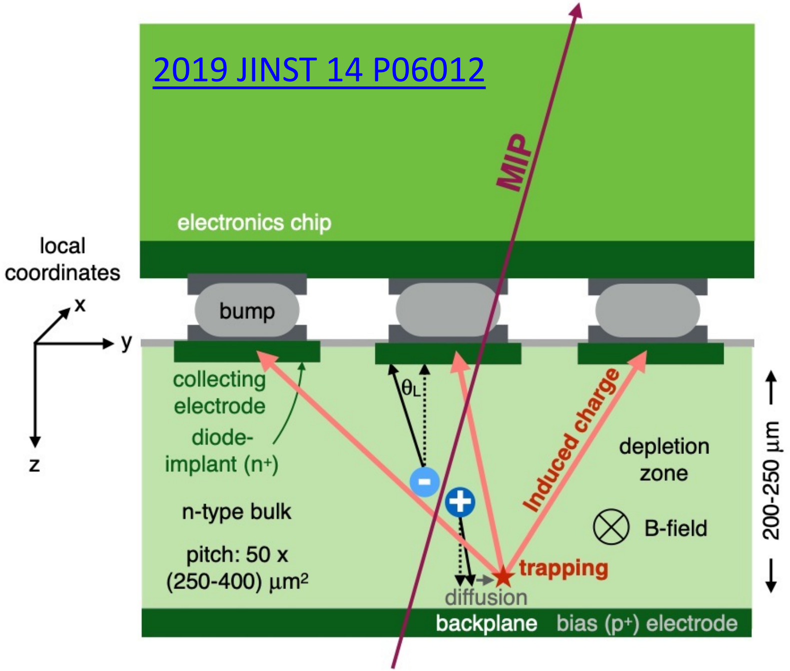
A lightweight algorithm to model radiation damage effects in Monte Carlo events for High-Luminosity LHC experiments

Marco Bomben & Keerthi Nakkalil

APC & UPC

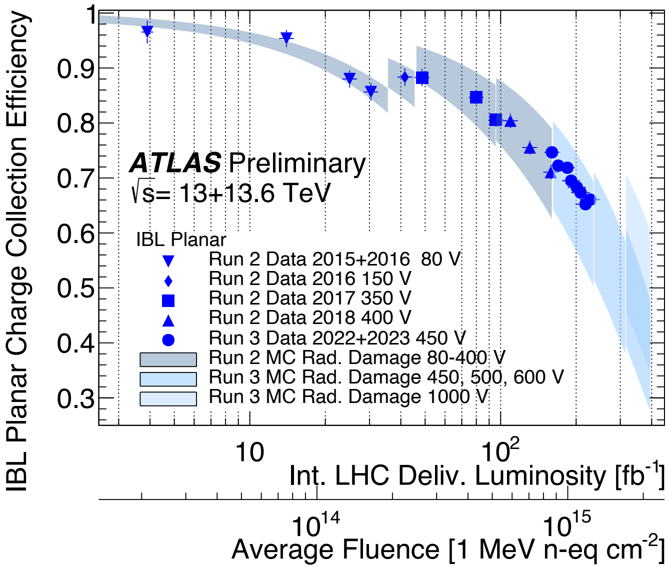
Radiation damage digitizer in ATLAS

[2019 JINST 14 P06012](#)



ATLAS has developed an algorithm to add radiation damage effects in MC events
It is the default digitizer for pixels in Run3

[PIX-2023-001](#), [EPS 2023](#)



As seen in previous [talk by M. Bindi](#)

✓ **Data vs MC: excellent agreement**

X **3x slower than standard digitizer**

(see also my poster tomorrow)

HL-LHC conditions

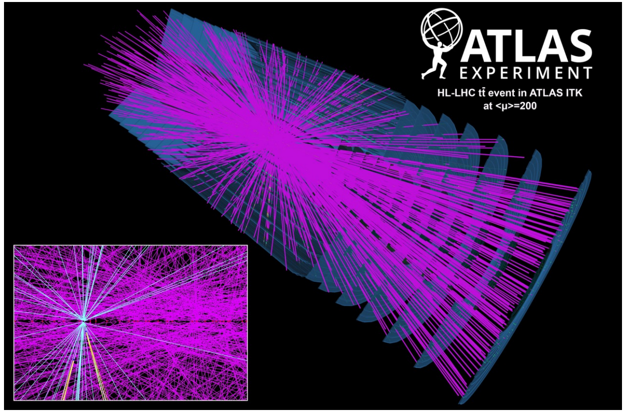
More information in Simone Monzani's talk

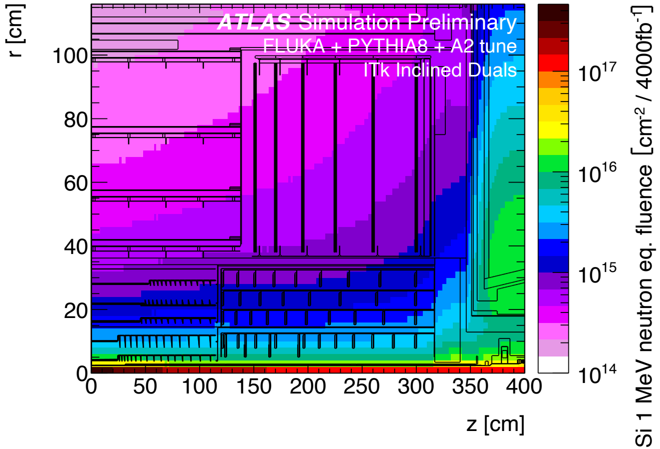
Increase in instantaneous and integrated luminosity from 4 to 8 with respect to the end of Run3

From 60 to 200 collisions per BC

Innermost pixel layers in ATLAS to receive 1-2x10^{16} n_{eq}/cm^2 after 2000 fb^{-1} , x10 more fluence than end of Run2 -> severe signal loss!

- Larger radiation damage effects than Run3
- Less computing resources than Run3
- **A faster yet as precise as possible radiation damage digitizer is needed**



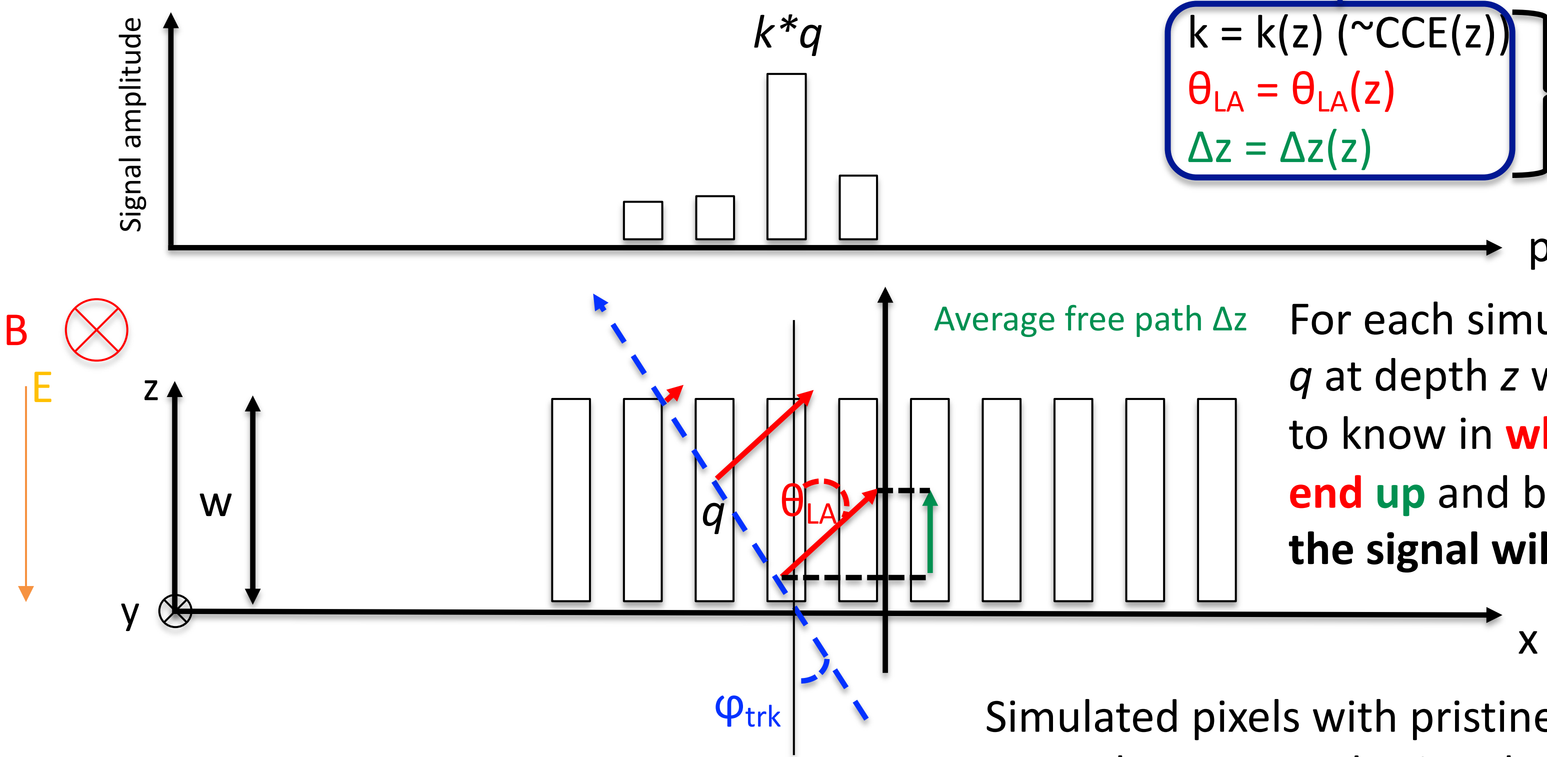


The Look-Up Table method

Lookup Tables (LUTs)

- $k = k(z)$ (~CCE(z))
- $\theta_{LA} = \theta_{LA}(z)$
- $\Delta z = \Delta z(z)$

Corrections depend on deposition depth z

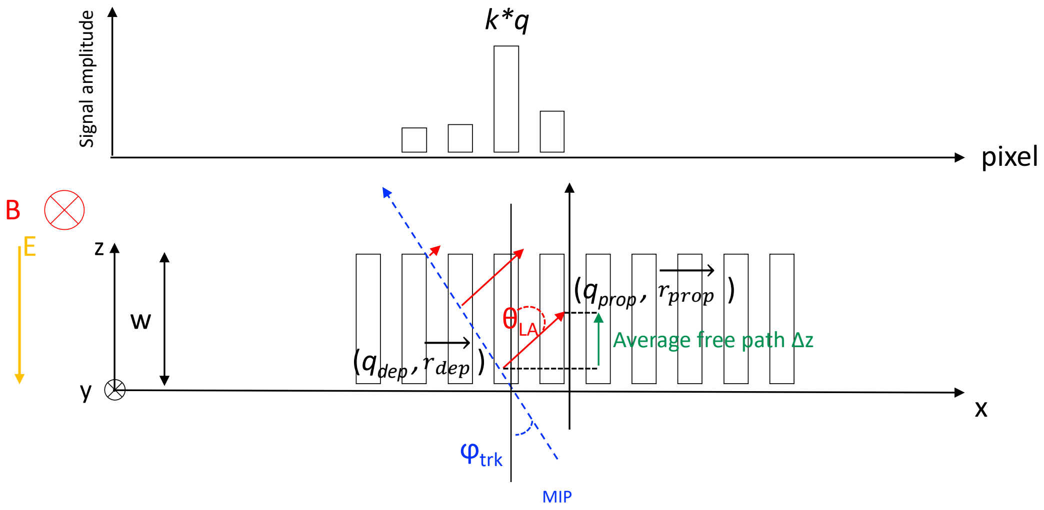


For each simulated charge *q* at depth *z* we want to know in **which pixel it will end up** and by how much (***k***) **the signal will be reduced**

Inspired by CMS "template method"

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

Calculating signal and position with LUTs



$$
\begin{cases}
x_{prop} &= x + [\tan(\theta_{LA}(z)) \cdot \Delta z(z)] + \Delta_x^{diff} \\
y_{prop} &= y + \Delta_y^{diff} \\
z_{prop} &= z + \Delta z(z) \\
q_{ind} &= k(z) \cdot q
\end{cases}
$$

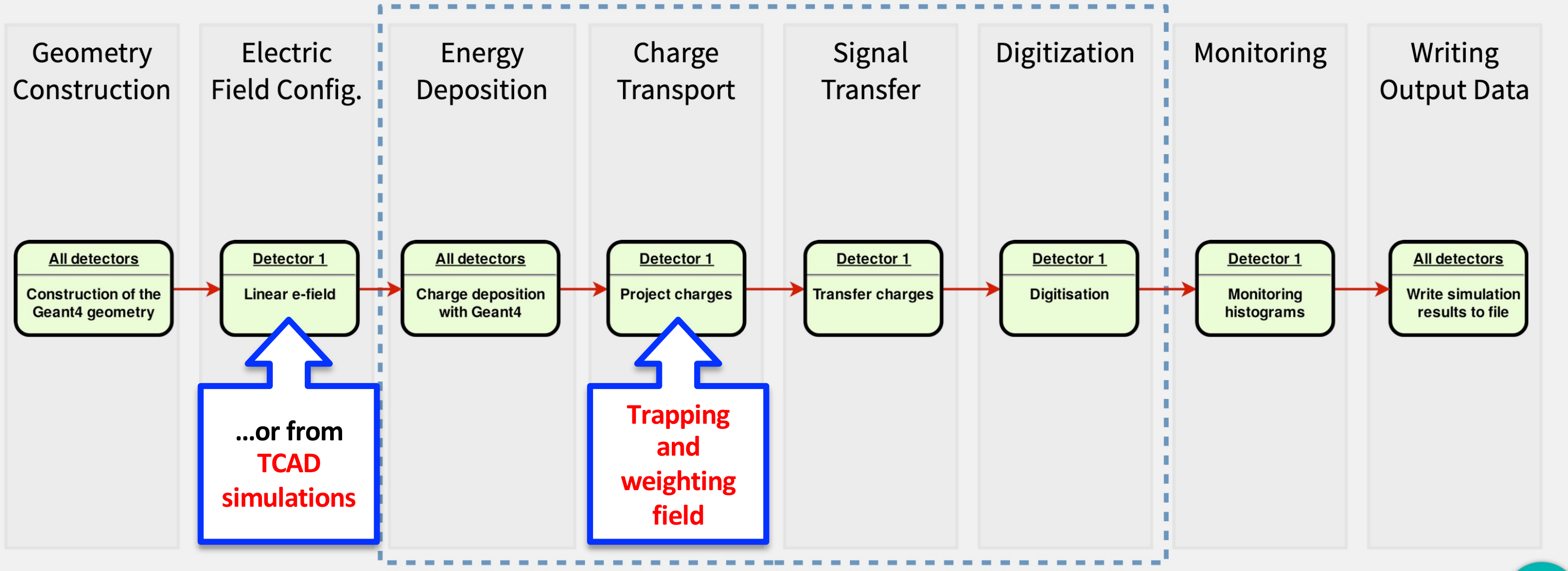
- Designed following ATLAS MC code structure (no cluster-level correction possible)
- Algorithmically very simple

- **Expected to be very fast**

LUTs calculated using Allpix2 together with TCAD

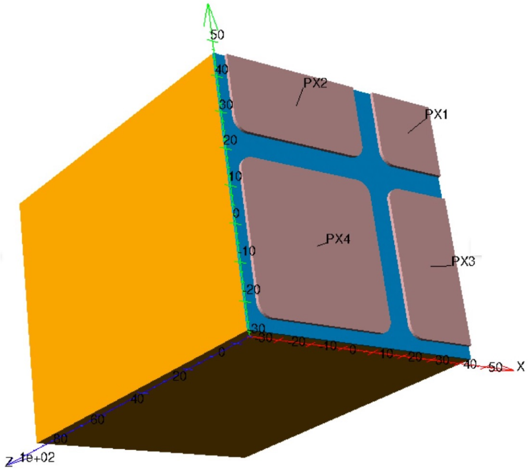
https://allpix-squared.docs.cern.ch/

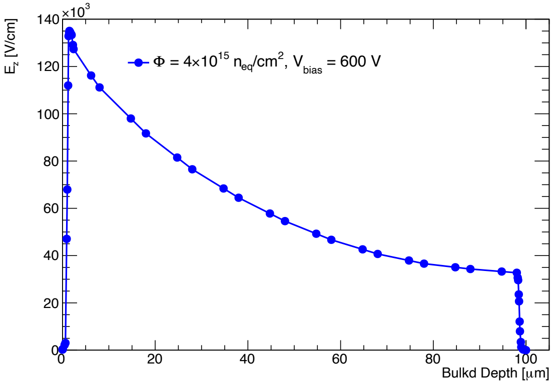
- Building blocks follow individual steps of signal formation in detector
- Algorithms for each step can be chosen independently



Inputs to Allpix^2

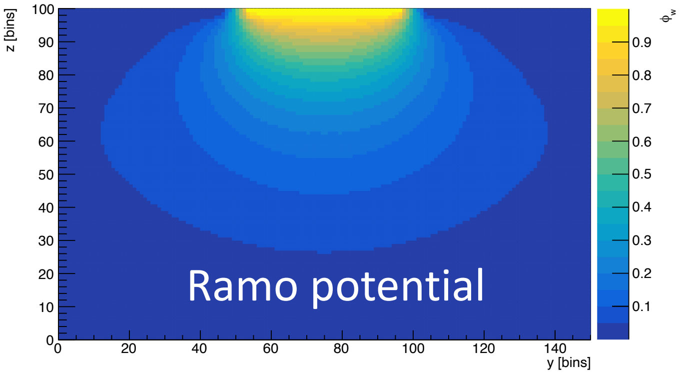
1/4 of 3x3
planar n-on-p
pixel matrix
50 x 50 µm^2
100 µm thick





$\Phi = 4\text{x}10^{15}\ n_{eq}/cm^2$
$V_{bias} = 600$ V

LHCb rad. 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]

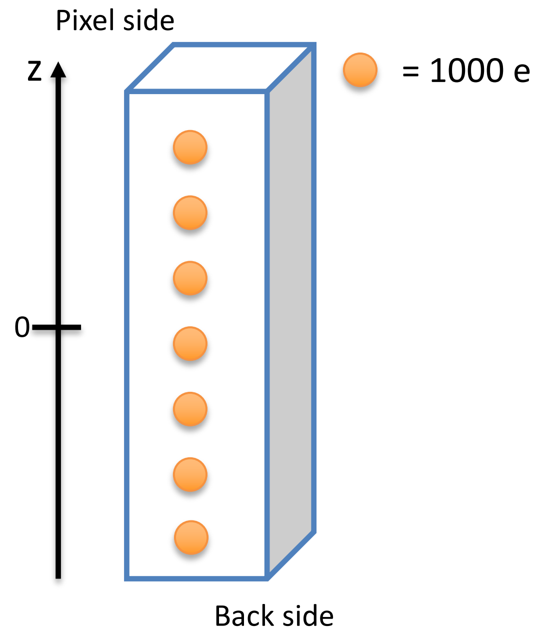
10.1016/j.nima.2017.08.042

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

Look-Up Tables calculation

In Allpix^2 deposit 1000e at different locations

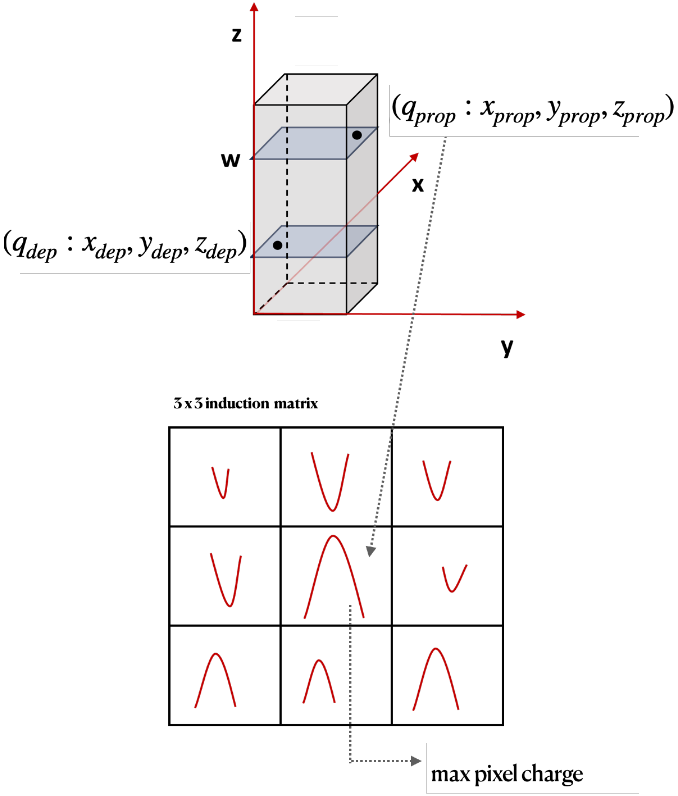


Look-Up Tables calculation

In Allpix^2 deposit 1000e at different locations

Let charges drift and note propagated position as a function of deposited one

See in a 3x3 matrix which is the pixel with the largest signal



Look-Up Tables calculation

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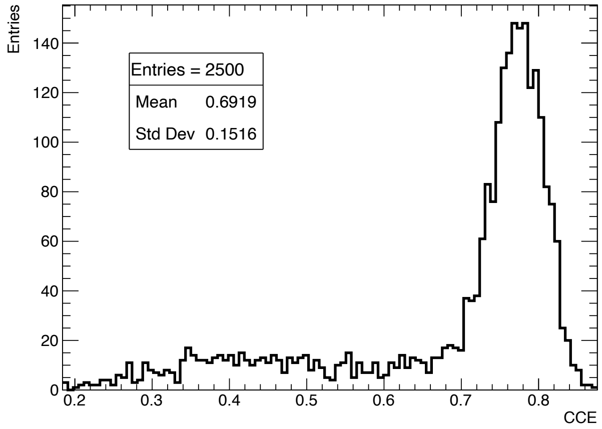
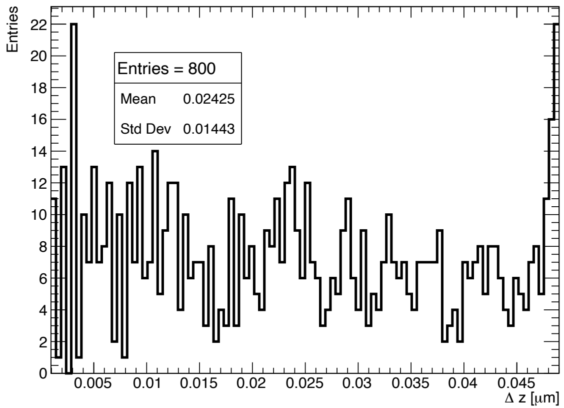
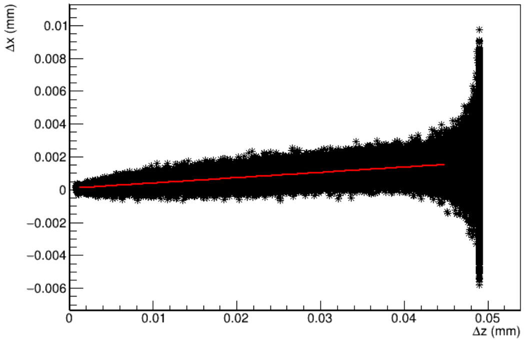
Calculate the fraction of induced charge *k*, the path Δz and the θ_{LA}







Look-Up Tables calculation

In Allpix^2 deposit 1000e at different locations

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See in a 3x3 matrix which is the pixel with the largest signal

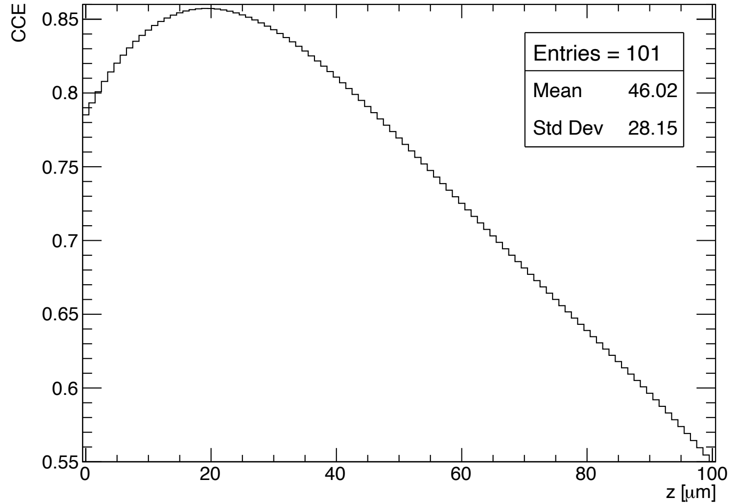
Calculate the fraction of induced charge *k*, the path Δz and the θ_{LA}

Average over all (x,y) positions for fixed z

$$\begin{cases} \Delta z(z)|_1 & = \sum_{x,y} \Delta z(x,y,z) / \sum_{x,y} \\ \theta_{LA}(z)|_1 & = \sum_{x,y} \theta_{LA}(x,y,z) / \sum_{x,y} \\ k(z)|_1 & = \sum_{x,y} k(x,y,z) / \sum_{x,y} \end{cases}$$

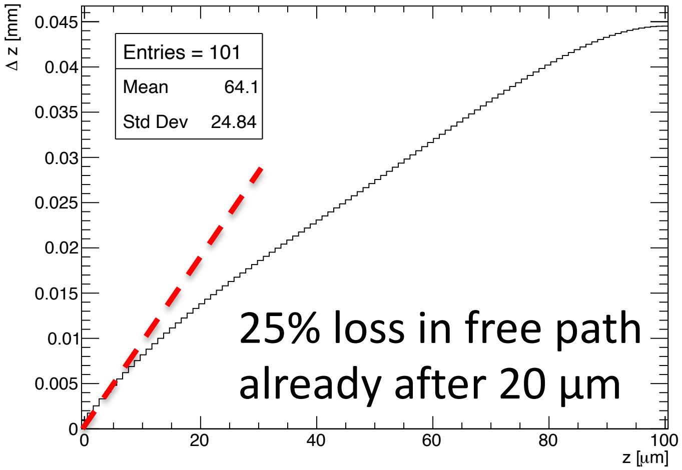
Repeat

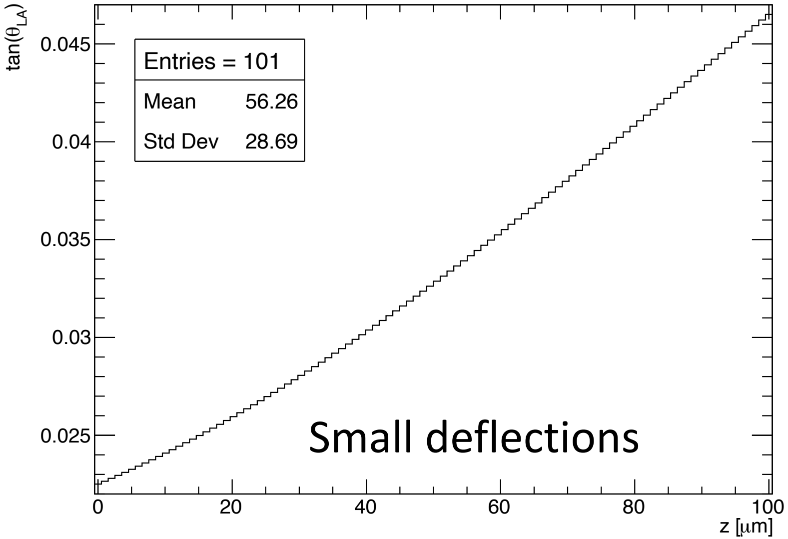
Look-Up Tables



Max CCE at ~ 20 μm

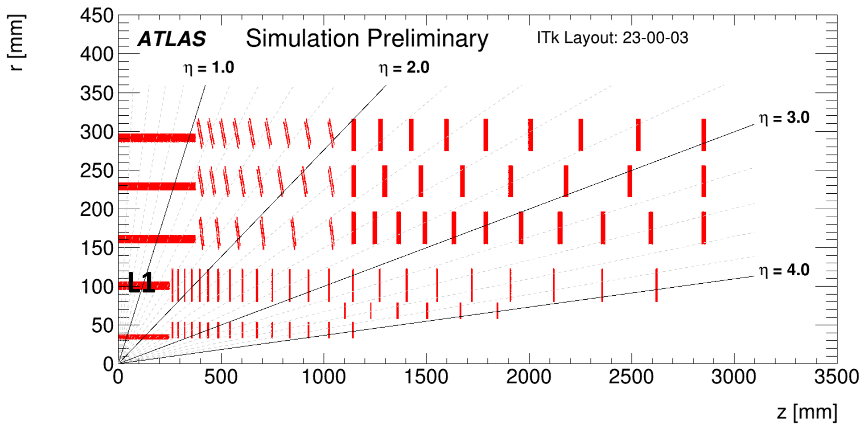
Effect of holes clearly visible





Validation

No data from testbeam data available, so we performed a closure test



We tested a range in η between 0 and 1.4 (like in barrel L1)

Modules were tilted in ϕ by 0.25 rad

We compared Full Simulation (FS) events with LUT ones

We compared cluster charge and sizes in both projections

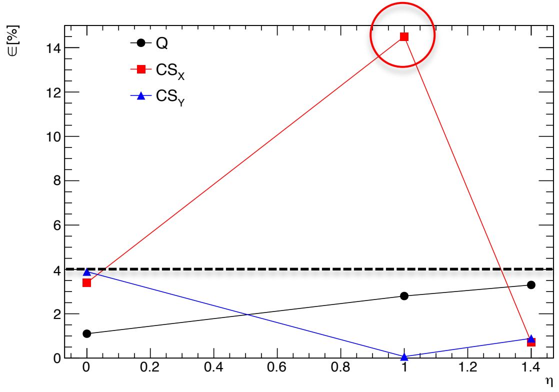
We simulated pions with p_T = 1, 10 & 100 GeV/c

Want to know more?

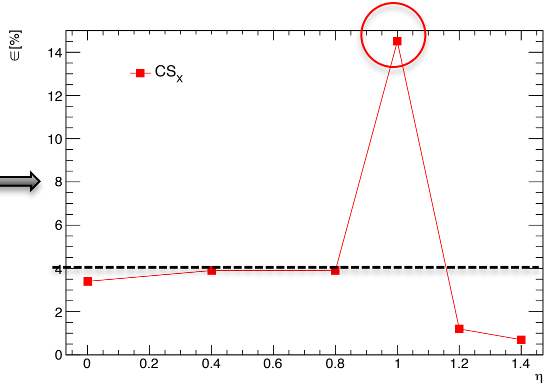
Read our article!

[Sensors 2024, 24(12), 3976; https://doi.org/10.3390/s24123976](https://doi.org/10.3390/s24123976)

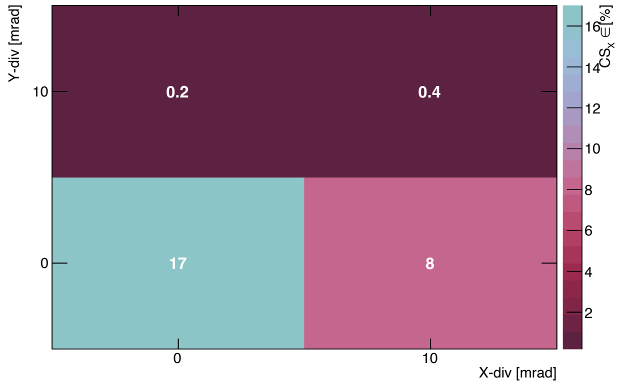
Selection of results - p_T = 100 GeV/c

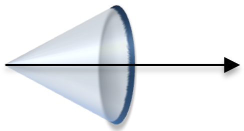


Agreement at few % level but for transverse cluster size at η = 1



Detailed study indicated the discrepancy is limited to a very narrow range around η = 1





Slightly increasing the beam divergence in y brings the agreement back to an excellent level

Relative difference between LUT-based and fully simulated events indicate an agreement at the level of very few % in cluster charge and projected cluster sizes

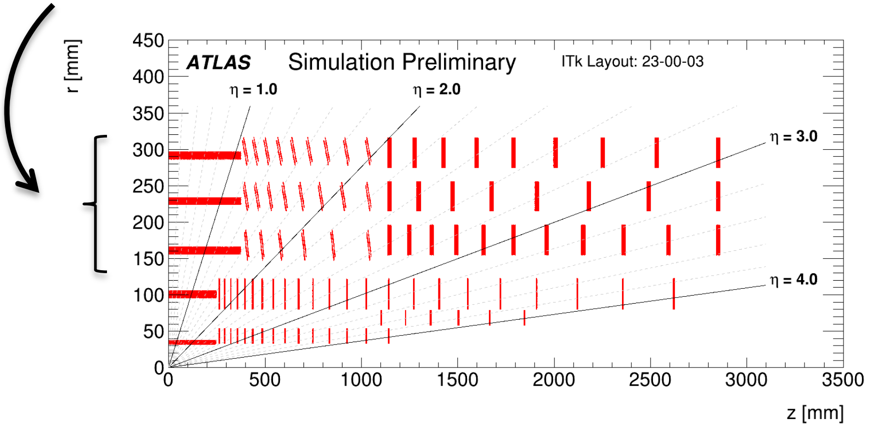
At η = 1 a larger than expected difference is observed but it is limited to a very narrow range
Harmless anyway as the track density at LHC is flat in η between -2 and 2

New geometry: 150 µm thick sensor

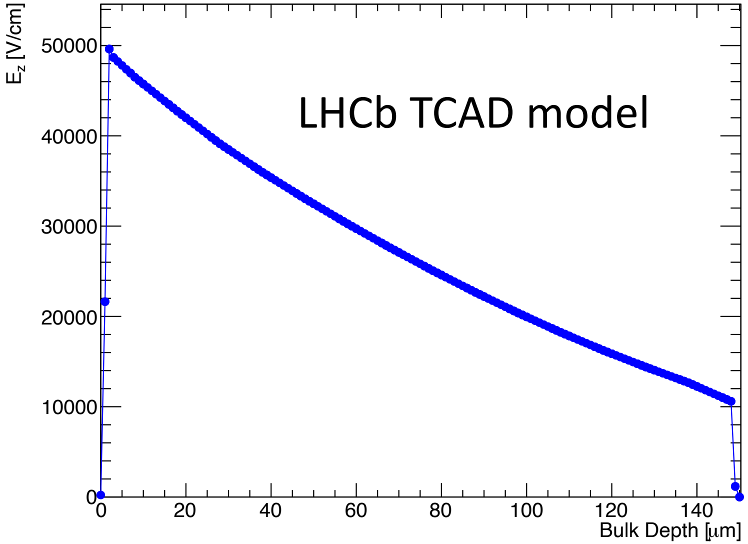
New sensor simulated:

- 150 µm thick n-on-p, 50x50 µm^2 pitch
- ϕ = 1x10^{15} n_{eq}/cm^2
- 400 V

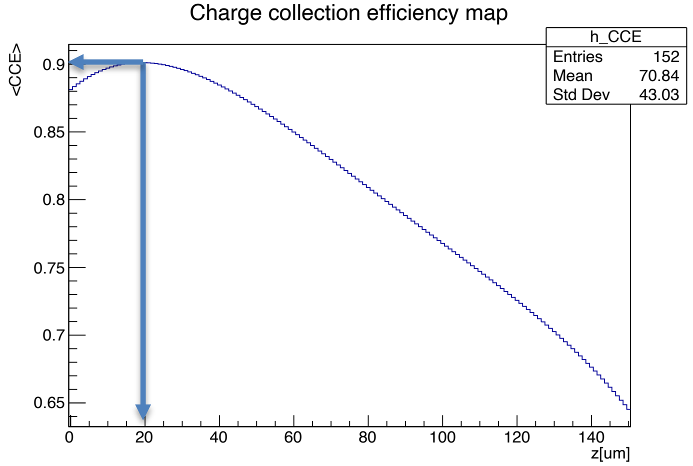
Case for L2-L4 in ITk pixels

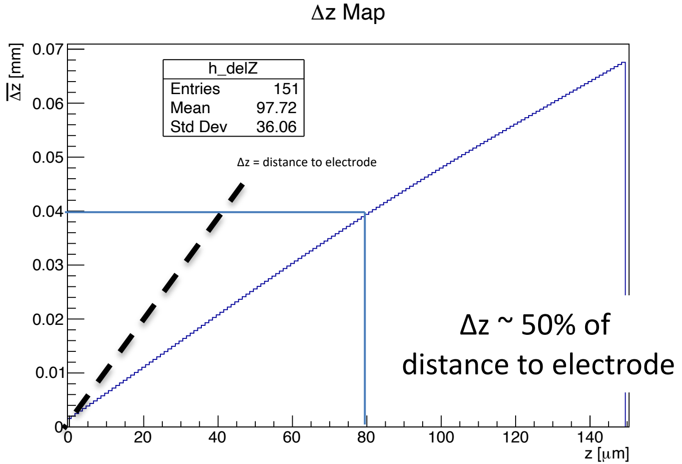


Electric field profile in the centre of a pixel

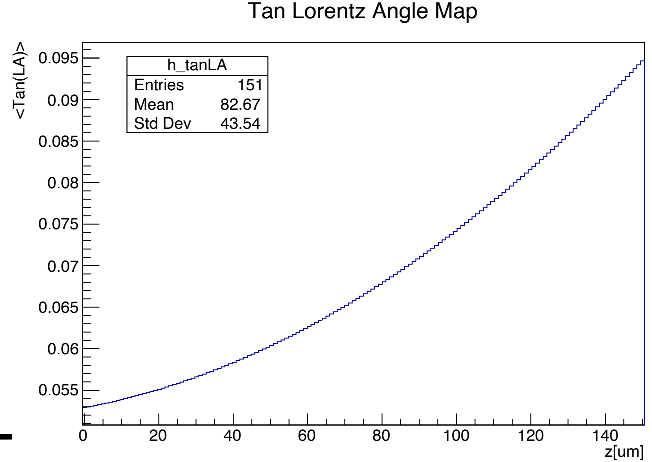


Look-up tables



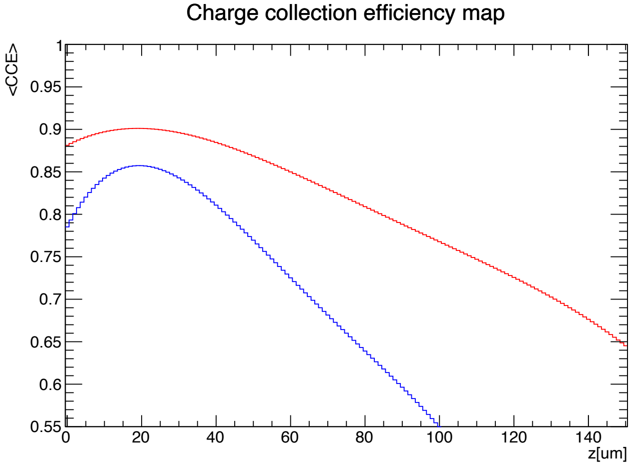


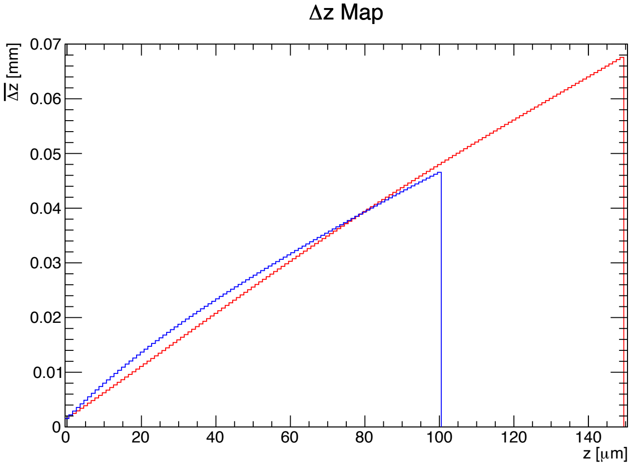
As for 100 μm the max CCE is ~ 20 μm below the pixel implant



Largest deflection ~ 7 μm

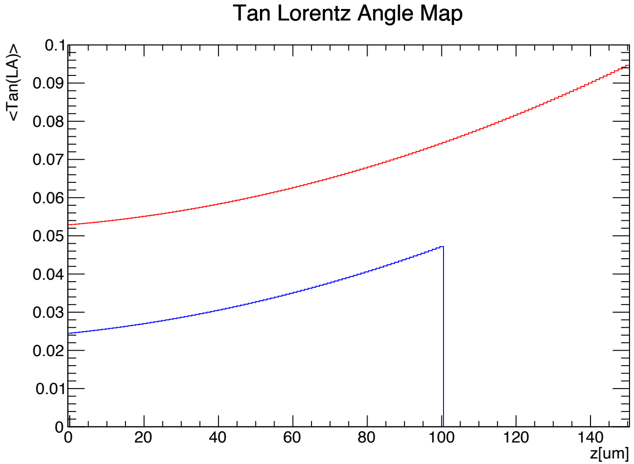
Comparison of LUTs for the two cases



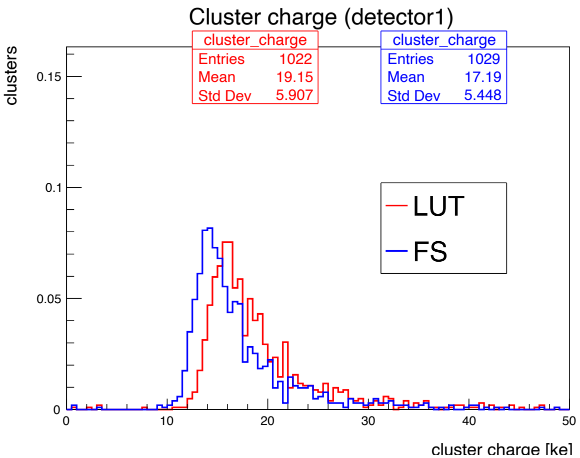


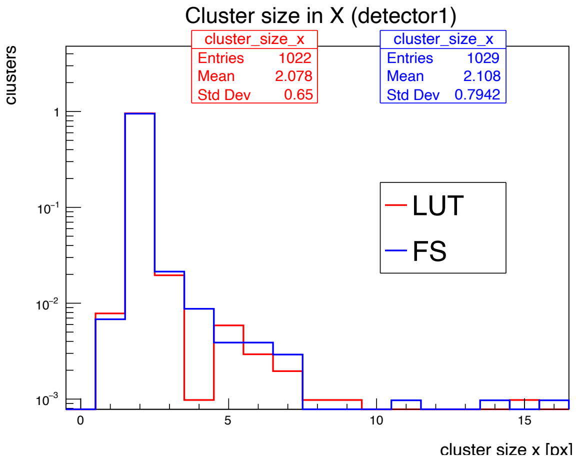
150 μm, 1x10^{15} n$_{eq}$/cm^{2} , 400 V

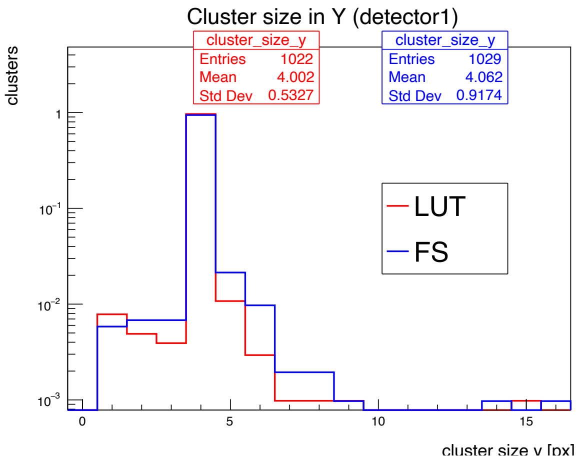
100 μm, 4x10^{15} n$_{eq}$/cm^{2} , 600 V



150 µm, example form closure test - η = 1



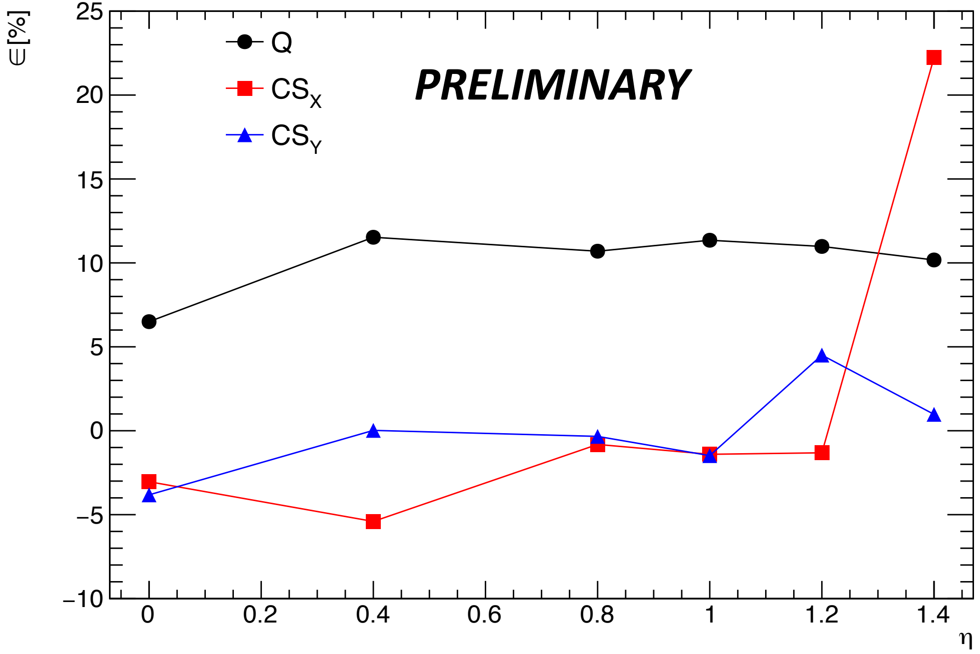




~ 10 % larger charge with LUT method

Very good agreement in both longitudinal and transverse cluster size

Closure tests for pions of 120 GeV



- ~ 10% more charge in LUT
- Agreement within 5% for both longitudinal and transverse cluster size but for $\eta = 1.4$
- More tests are planned

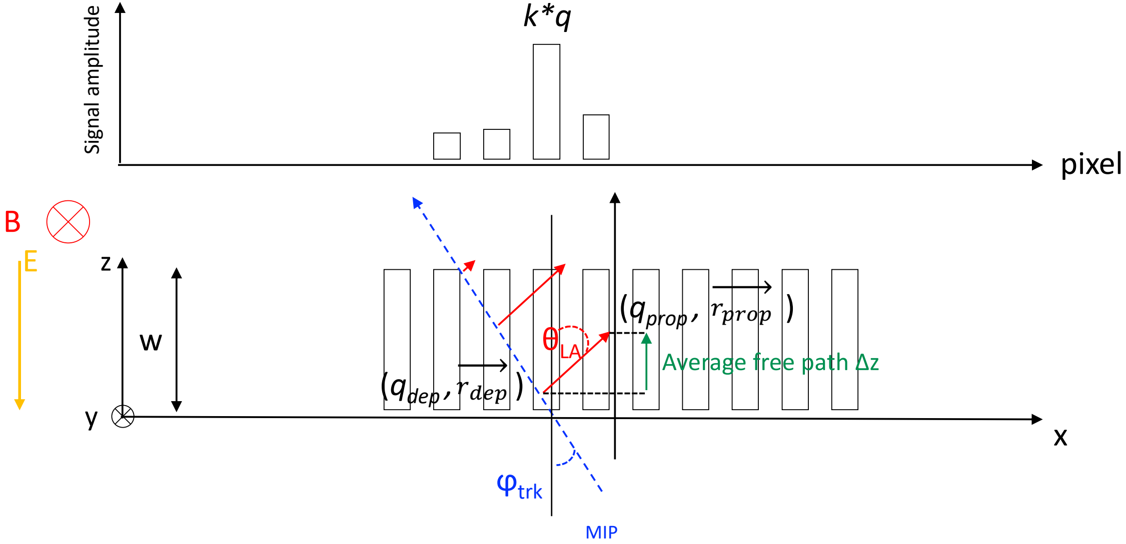
Computing performance – preliminary results

Without radiation damage effects we use these equations:

$$\begin{cases} x_{prop} & = x + [\tan(\theta_{LA}(z)) \cdot \Delta z(z)] + \Delta_x^{diff} \\ y_{prop} & = y + \Delta_y^{diff} \\ z_{prop} & = z + \Delta z(z) \\ q_{ind} & = k(z) \cdot q \end{cases}$$

but with:

- $k = 1$
- $\Delta z = w - z$
- $\theta_{LA} = \text{const.}$



Computing performance – preliminary results

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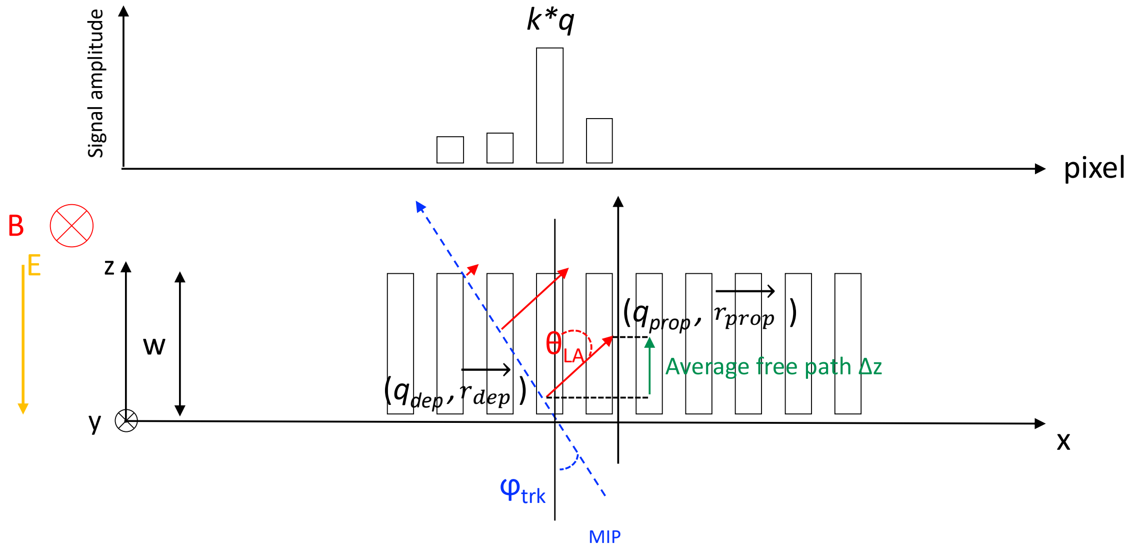


➢ Same algorithmic complexity, just different numbers

➢ **Indeed first tests indicate no difference in performance when radiation corrections are applied**

Conclusions & Outlook

- HL-LHC conditions pose stringent constraints on pixel detectors but on computing resources too
- Need for an algorithm to mimic radiation damage effects that is **faster than Run3 one but as precise as possible**
- **LUT method promises to fulfil both tasks**
- It works also for strips and soon for 3D pixels too
- **Next: validate on data**
- **Code is on gitlab, plan to integrate it in Allpix^2**
- **It was great to work with Allpix^2 – we got great support! Thank you!**

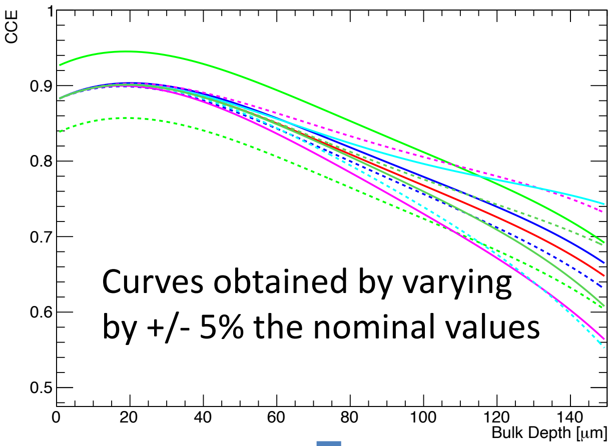
Want to know more?
Read our article!
Sensors 2024, 24(12), 3976;
https://doi.org/10.3390/s24123976

Interested in collaborating? Conctact us!

One last thing

At this point it is crucial to have testbeam data from irradiated modules to fully validate the method

Since the LUTs are smooth functions we can fit them with a polynomial and play with parameters till we get the best agreement with data



Very fast

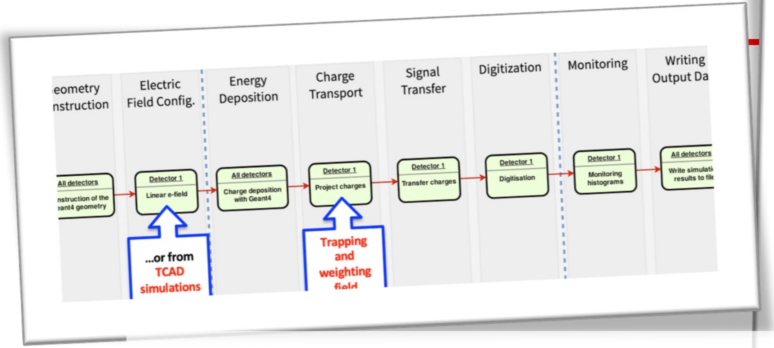
LUT simulated data

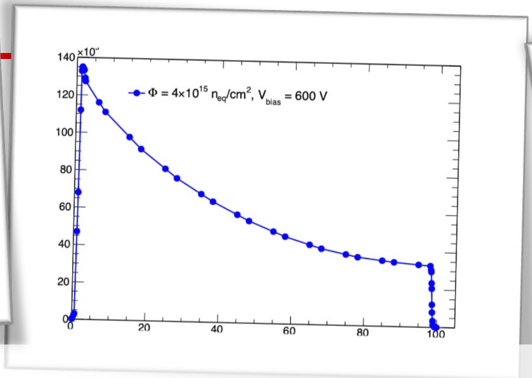
Testbeam data

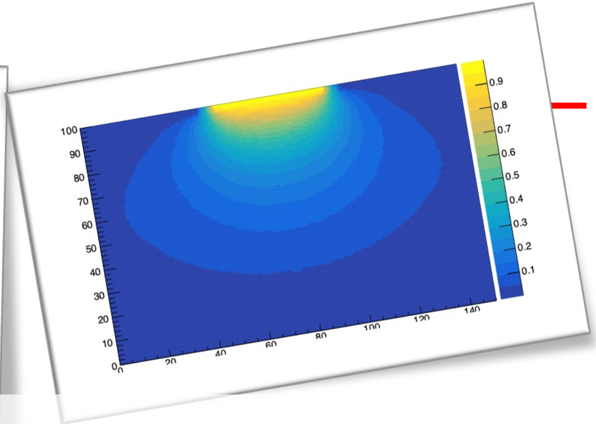
ML tool

Best LUTs from interpolation

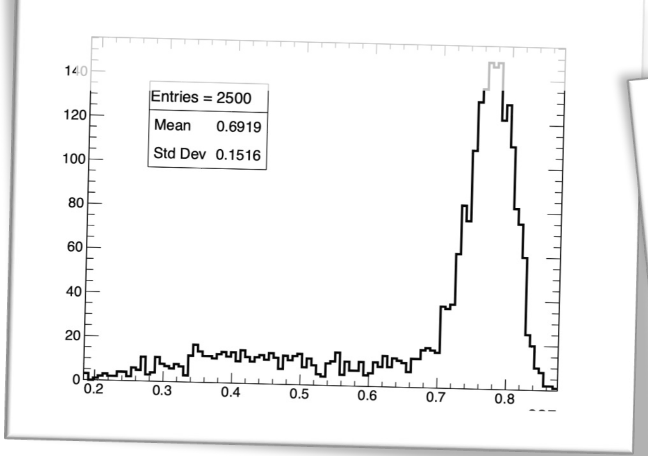
➢ Let Machine Learning do the hard work!

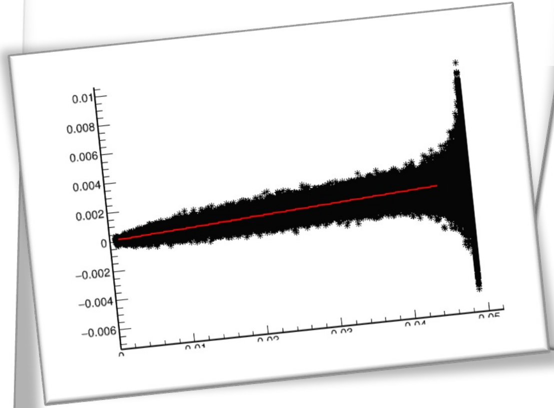


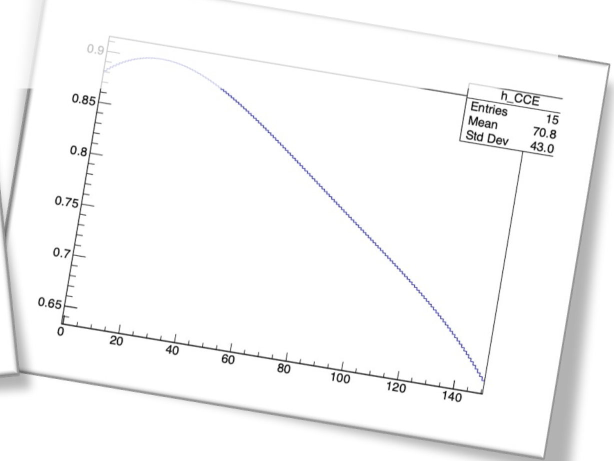




THANK YOU FOR YOUR ATTENTION!

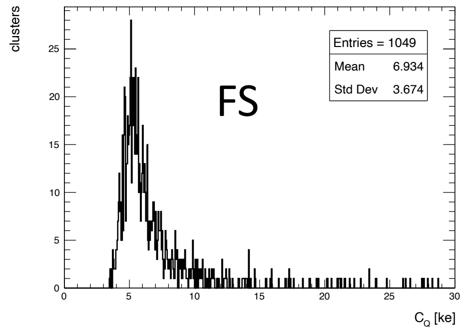


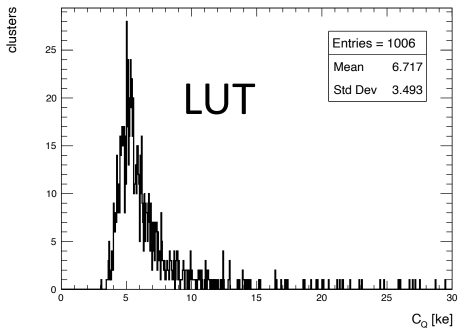




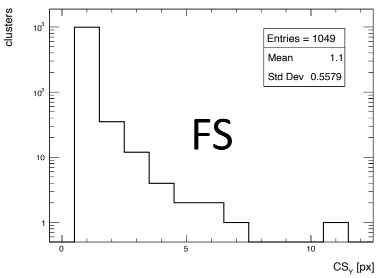
Backup

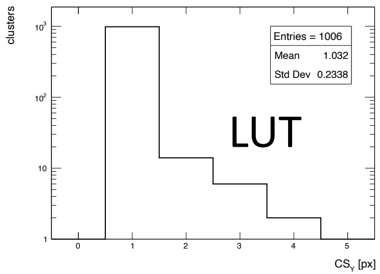
Selection of results - $\eta = 0$, $p_T = 100$ GeV/c



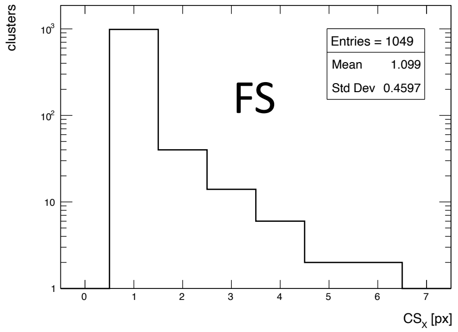


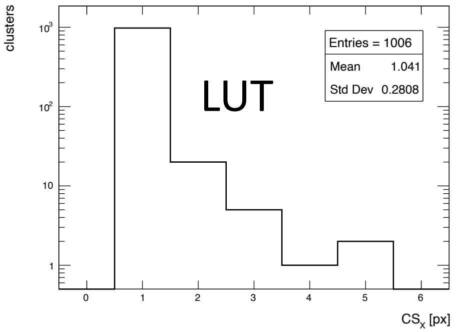
Charge





Longitudinal cluster size





Transverse cluster size

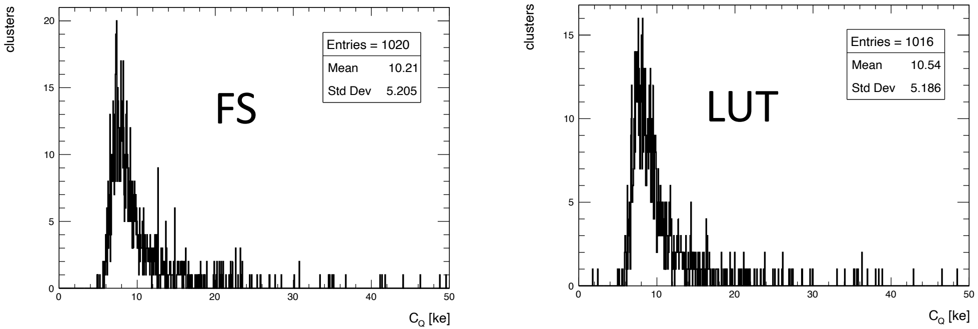
Summary

η	CS_X			CS_Y			C_Q [ke]		
	FS	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]
0	1.099	1.041	5.3	1.1	1.032	6.2	6.957	6.741	3.1

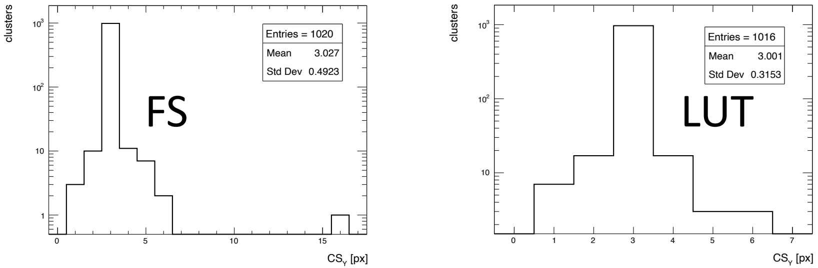
Agreement at few % level

Same for all p_T values

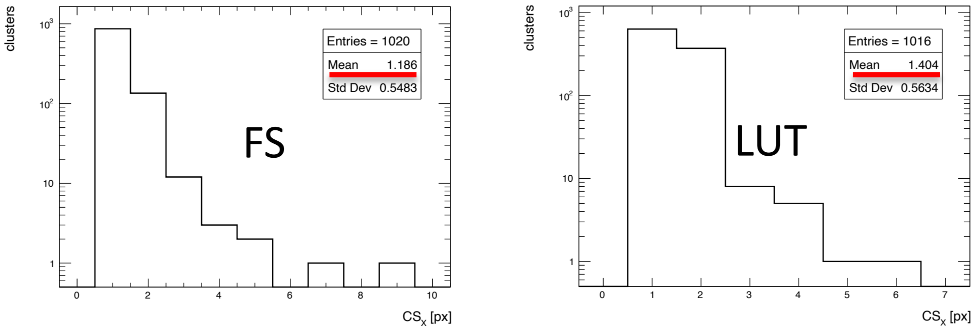
Selection of results - η = 1, p_T = 1 GeV/c



Charge



Longitudinal cluster size



Transverse cluster size

Summary for η = 1

p_T [GeV/c]	CS_X			CS_Y			C_Q [ke]		
	FS	LUT	ϵ [%]	FS	LUT	ϵ [%]	FS	LUT	ϵ [%]
1	1.186	1.404	18.38	3.027	3.001	0.86	10.25	10.54	2.8
10	1.217	1.422	16.8	3.023	2.988	1.2	10.37	10.95	5.6
100	1.243	1.424	14.5	3.011	3.013	0.07	10.39	10.68	2.8

Same situation for all p_T values

Investigation of discrepancy at η = 1

For $p_{T=}$ 100 GeV/c we scanned the η range with a finer granularity

	cs_X		
η	**FS**	**LUT**	ϵ [%]
0	1.079	1.042	3.4
0.4	1.09	1.047	3.9
0.8	1.117	1.073	3.9
1	1.243	1.424	14.5
1.2	2.042	2.018	1.2
1.4	2.068	2.053	0.72

Agreement at few % level for all η values tested **but not for η =1**
(only for transverse cluster size)

Further investigation – beam divergence

For p_T = 100 GeV/c and η = 1 we increased slightly the beam divergence in full simulation
This divergence corresponds to a range of η of [0.99,1.01]

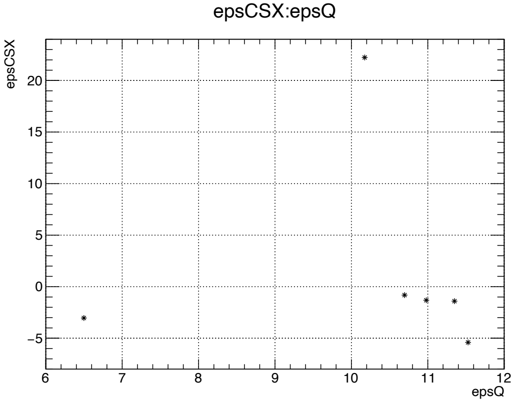
Results

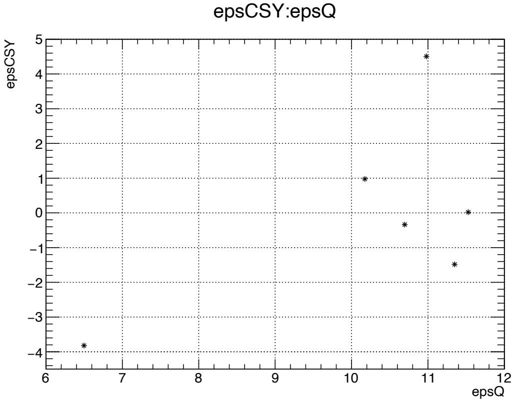
	CS_X		
Beam Divergence (x, y) (mrad)	**FS**	**LUT**	ϵ [%]
0, 0	1.224	1.428	17
10, 0	1.344	1.449	8
0, 10	1.547	1.551	0.2
10, 10	1.548	1.554	0.4

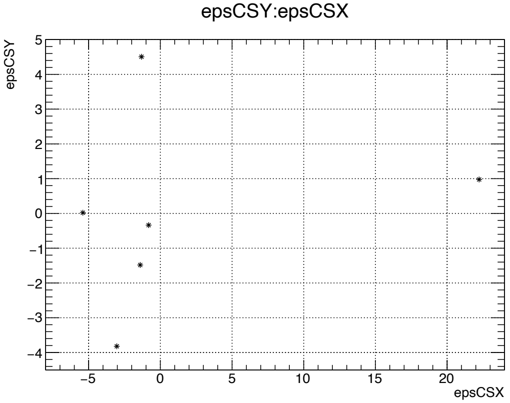
N.B. Charged particles produced in pp collisions are uniformly distributed in η within [-2,2]

Conclusions: this discrepancy is appearing in a very limited η range and should pose no problem in ATLAS MC simulated events

150 μm

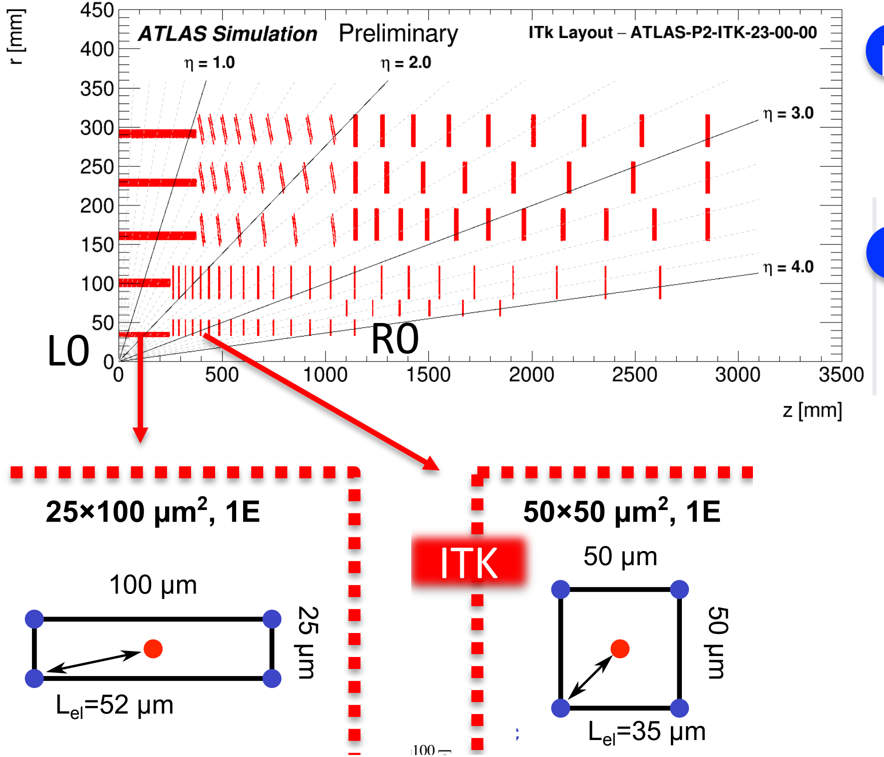


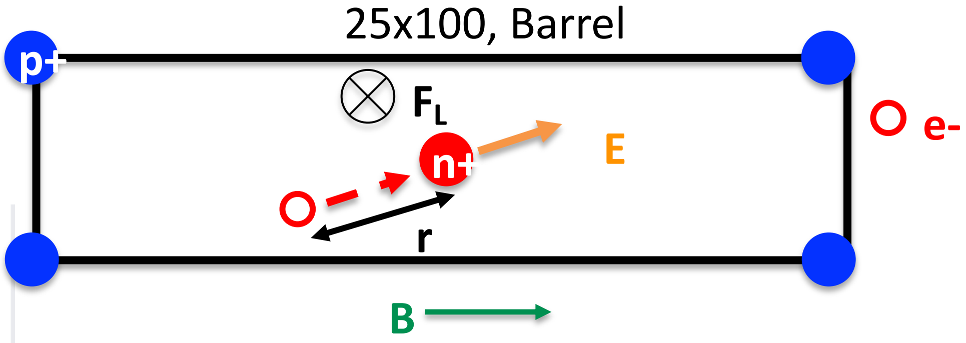


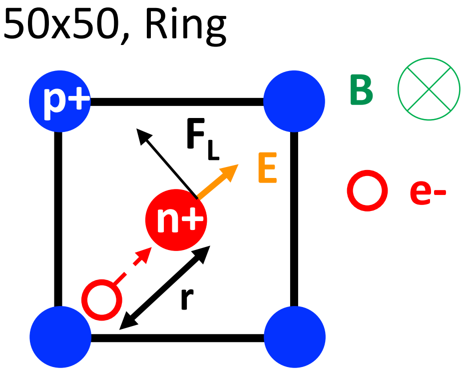


No clear correlation (but very limited statistics)

3D sensors

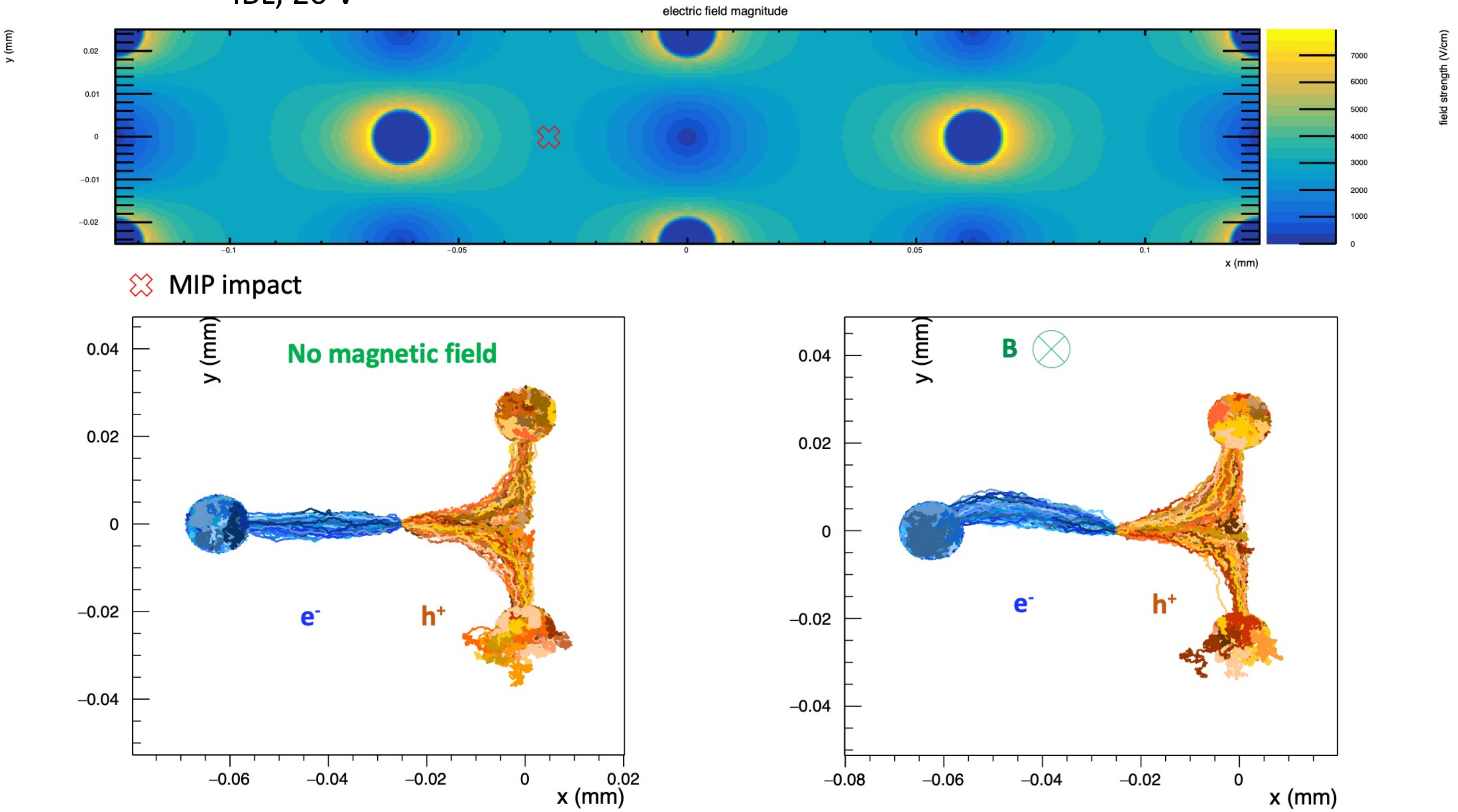






Conclusion: CCE(r) is the only needed LUT

IBL, 20 V



... yes, they do ☺

Comparison of electric field