1st DRD3 workshop – WG4, Simulations

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

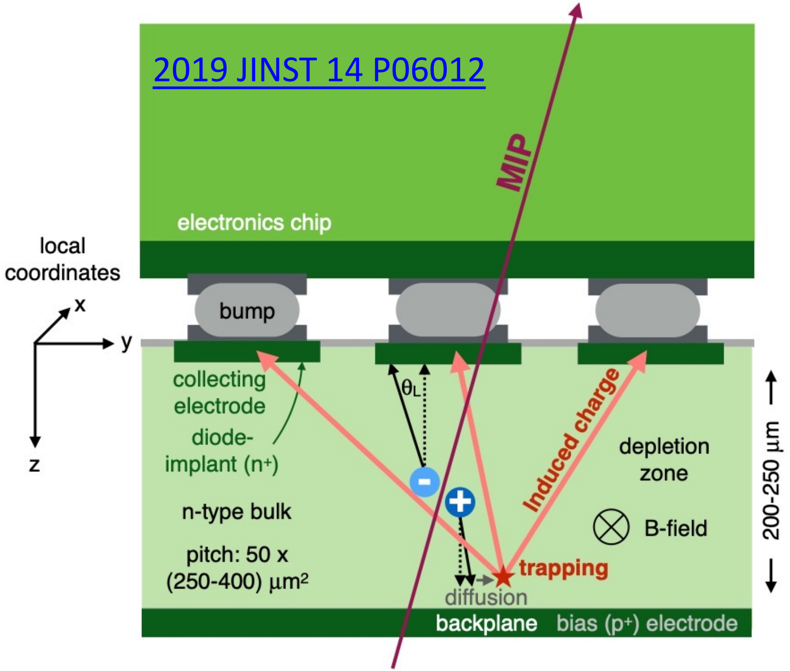
Marco Bomben & Keerthi Nakkalil

APC & UPC

Université Paris Cité

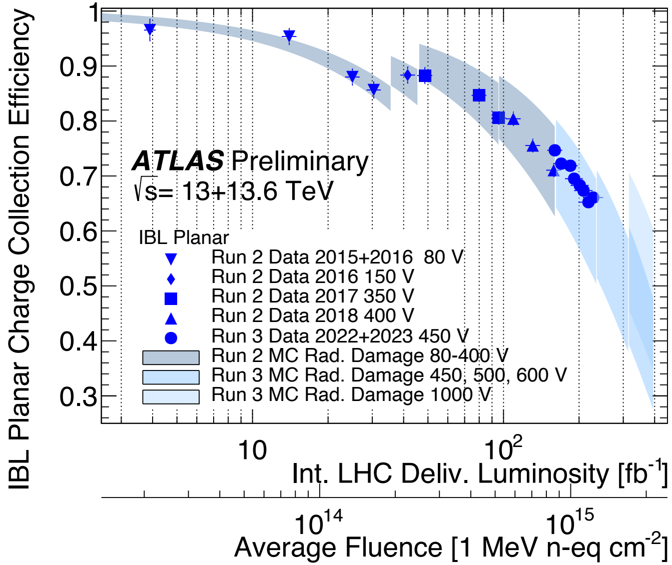
IN2P3
Les deux infinis

Radiation damage digitizer in ATLAS



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



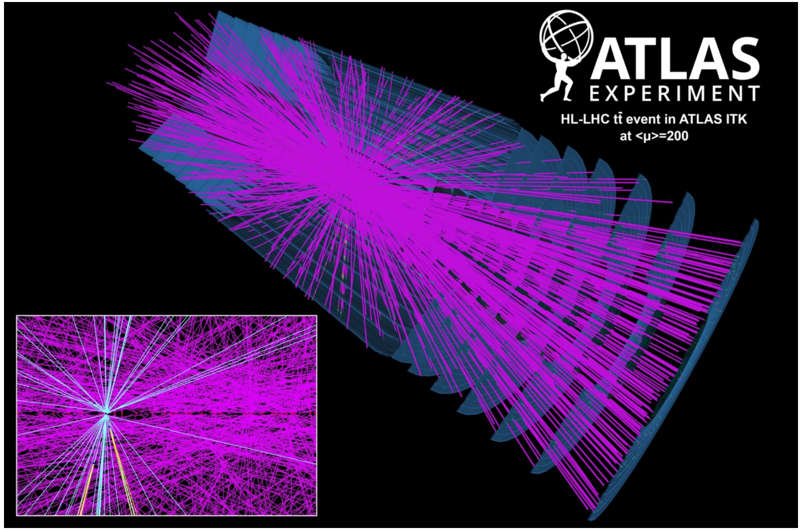
- ✓ Data vs MC: excellent agreement
- X 3x slower than standard digitizer

HL-LHC conditions

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

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!

From 60 to 200 collisions per BC



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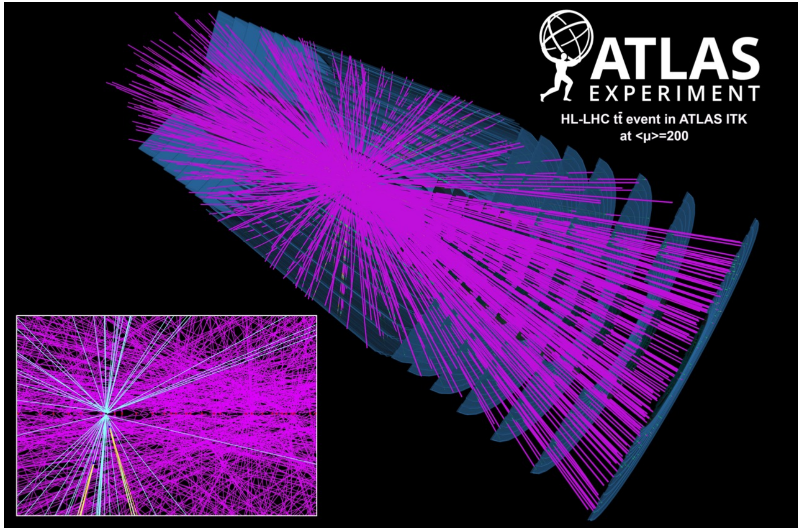


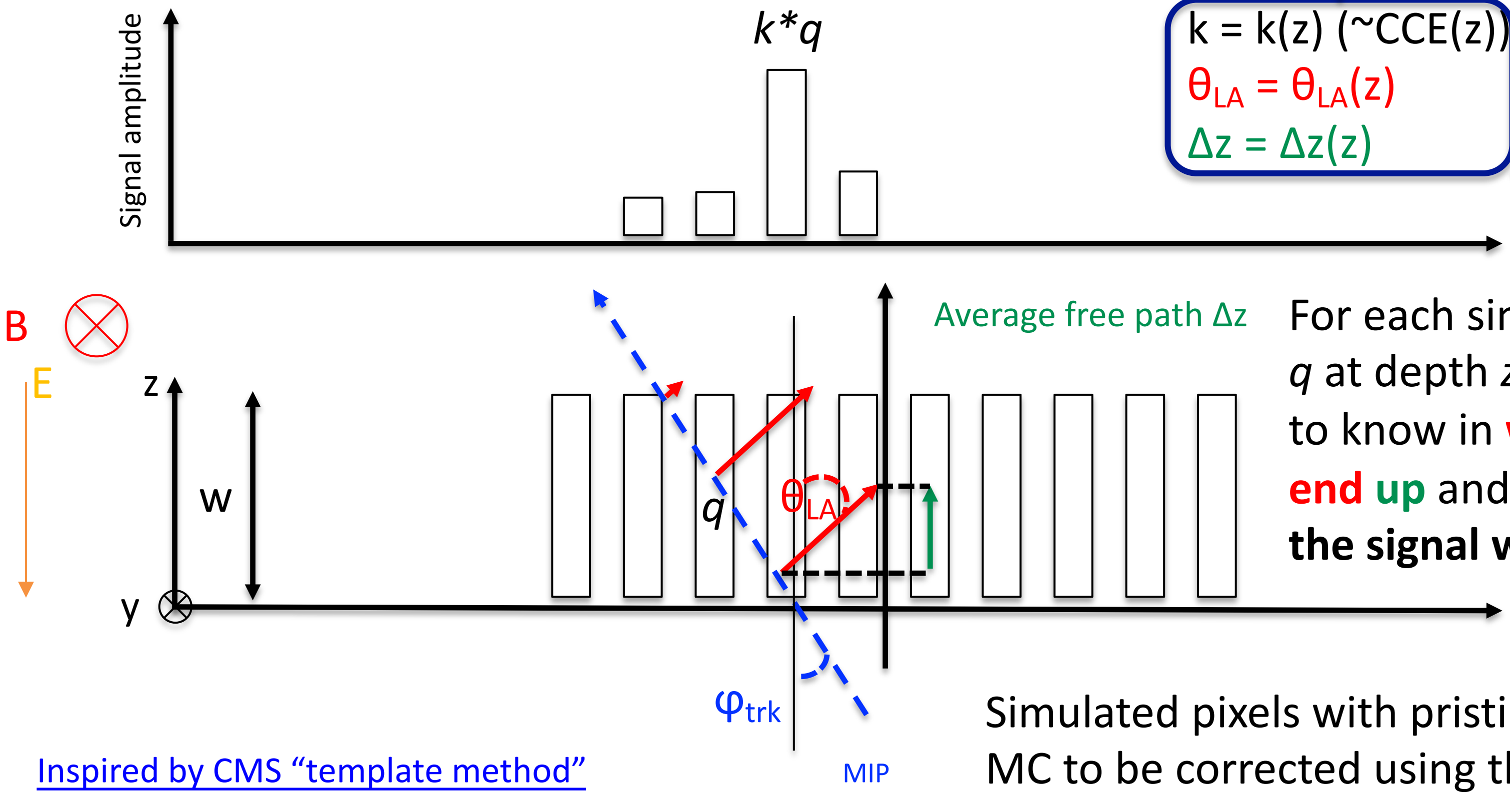
- Larger radiation damage effects than Run3
- Less computing resources than Run3
- **A faster yet as precise as possible radiation damage digitizer is needed**

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**

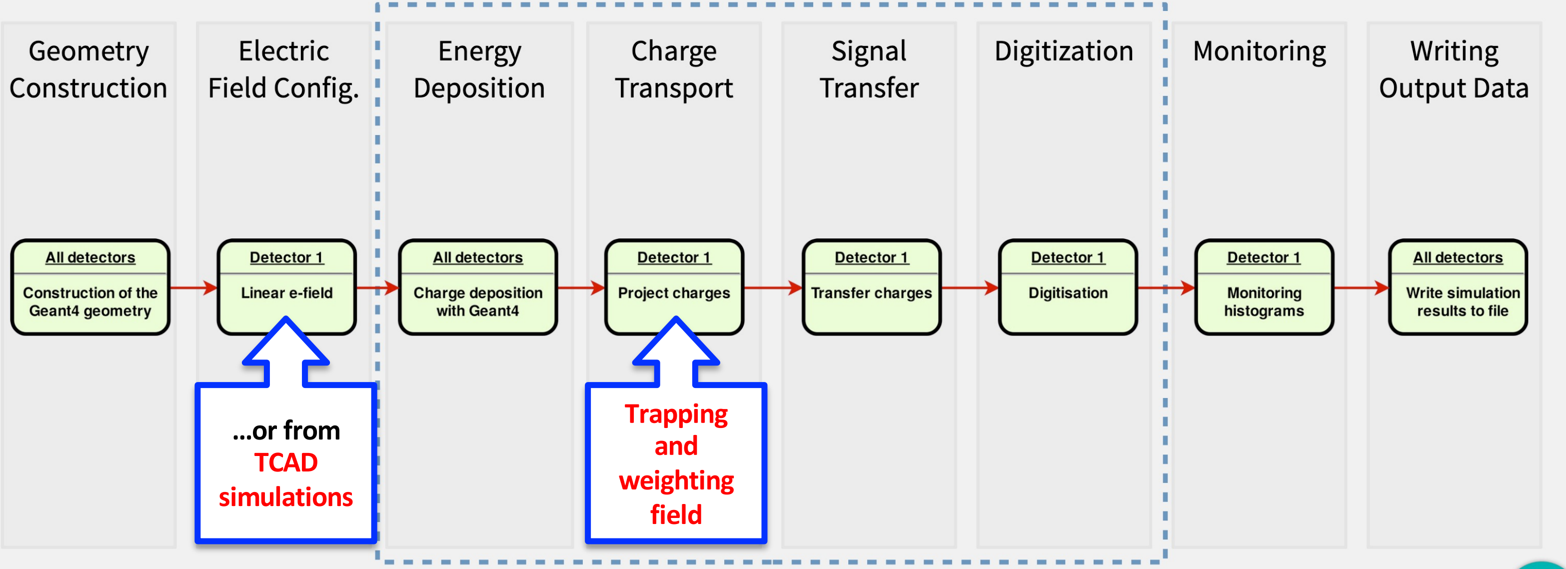
Inspired by CMS "template method"

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

LUTs calculated using Allpix2 together with TCAD

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

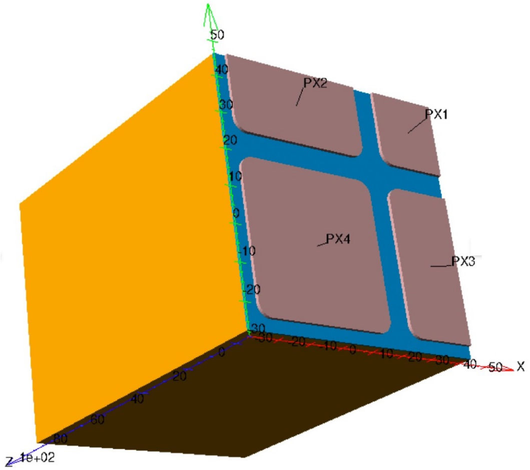
- Building blocks follow individual steps of signal formation in detector
- Algorithms for each step can be chosen independently

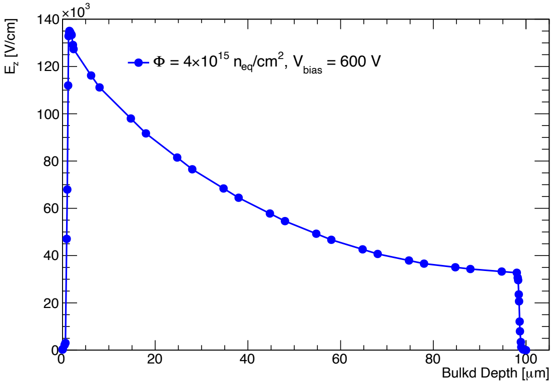


12 S. Spannagel, PIXEL22, Allpix Squared - Semiconductor Detector Monte Carlo Simulations 15/12/2022

Inputs to Allpix^2

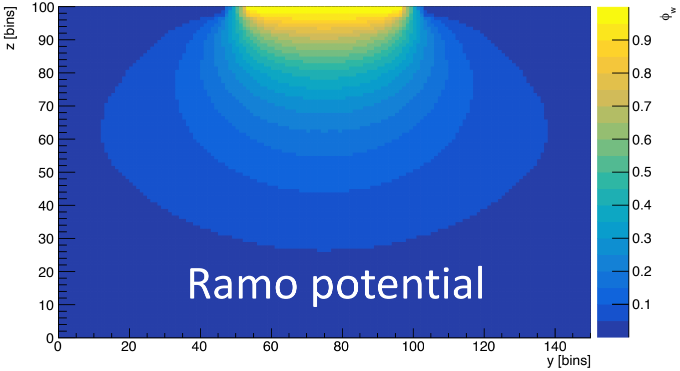
1/4 of 3x3 planar n-on-p pixel matrix
50 x 50 μm^2
100 μm thick





$\Phi = 4\text{x}10^{15}\ n_{eq}/cm^2$
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]

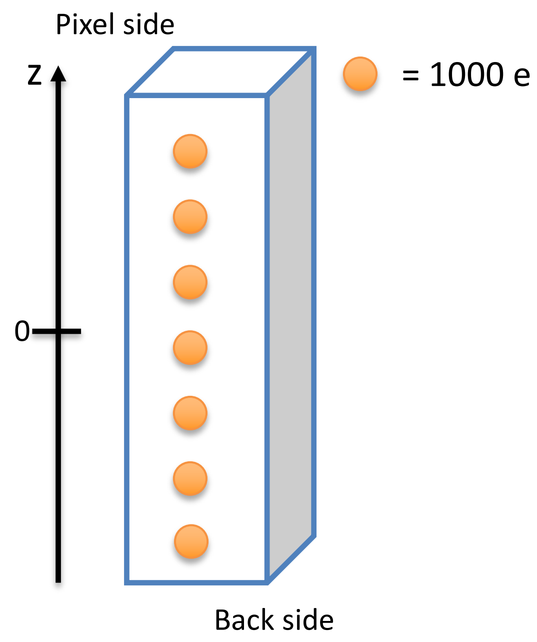
10.1016/j.nima.2017.08.042

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

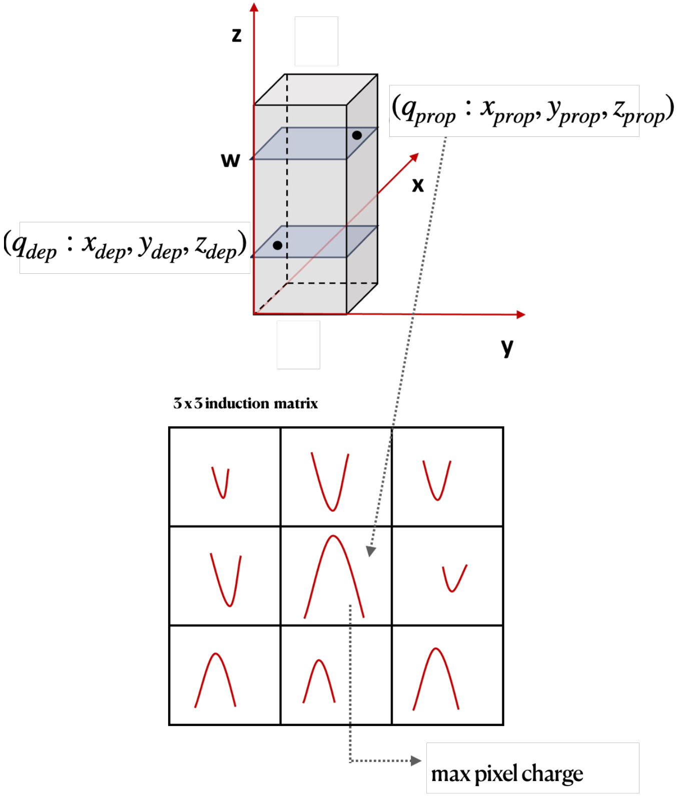


Look-Up Tables calculation

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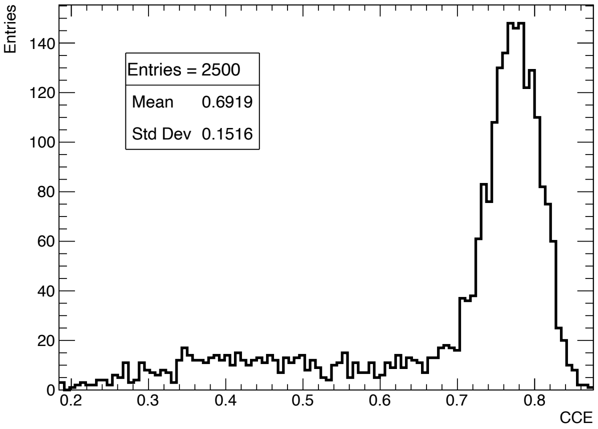
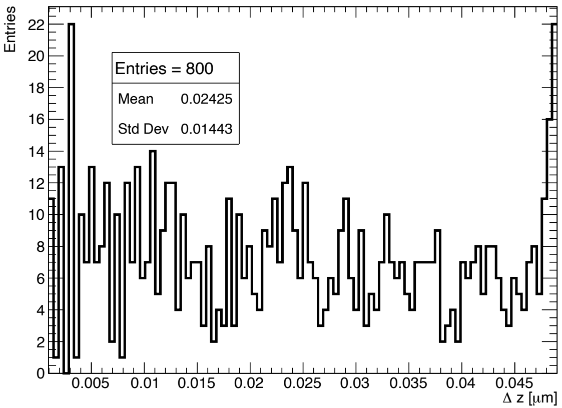
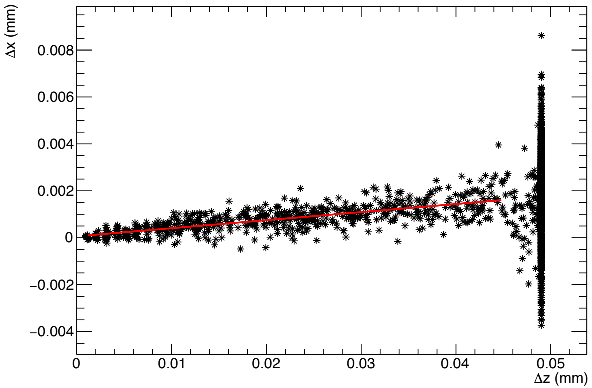
Calculate the fraction of induced charge *k*, the path Δz and the θ_{LA}







Look-Up Tables calculation

In Allpix^2 deposit 1000e at different locations

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

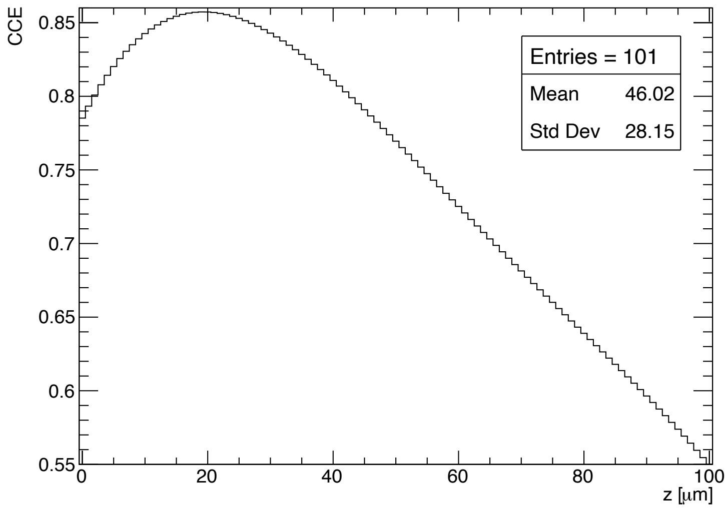
Calculate the fraction of induced charge *k*, the path Δz and the θ_{LA}

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

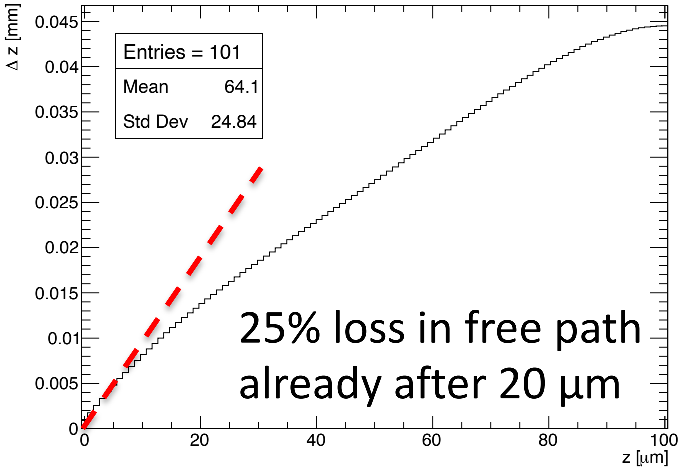
$$\begin{cases} \Delta z(z)|_1 & = \sum_{x,y} \Delta z(x,y,z) / \sum_{x,y} \\ \theta_{LA}(z)|_1 & = \sum_{x,y} \theta_{LA}(x,y,z) / \sum_{x,y} \\ k(z)|_1 & = \sum_{x,y} k(x,y,z) / \sum_{x,y} \end{cases}$$

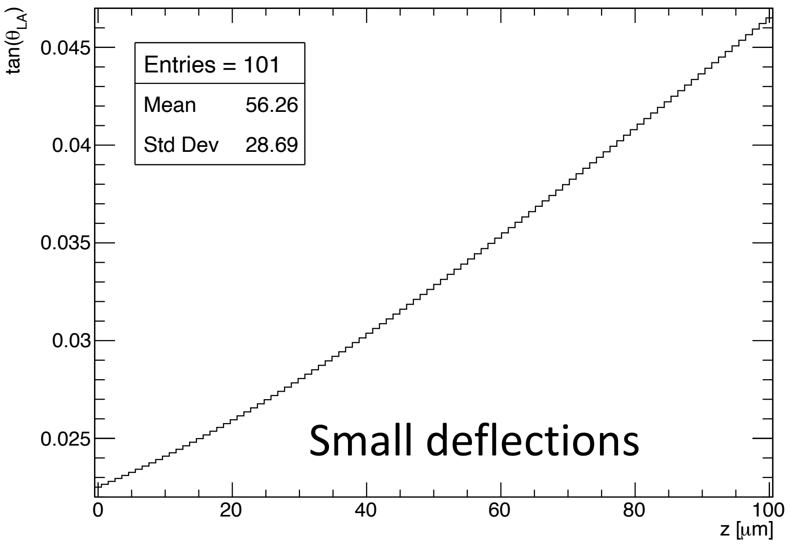
Repeat

Look-Up Tables



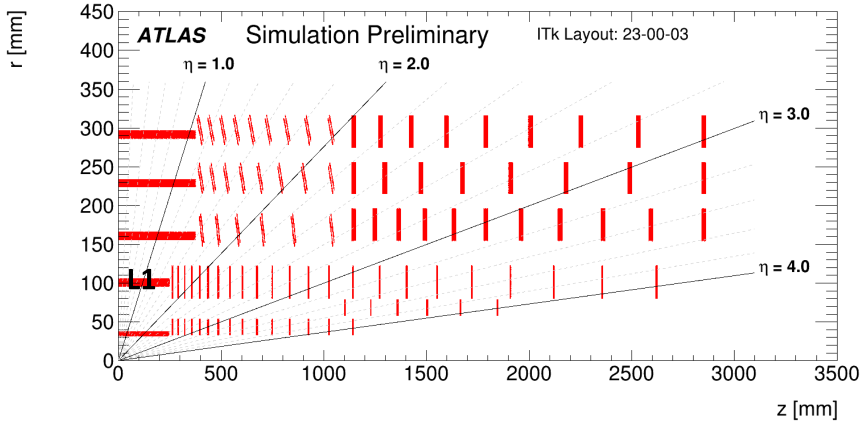
Max CCE at ~ 20 μm
Effect of holes clearly visible





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)

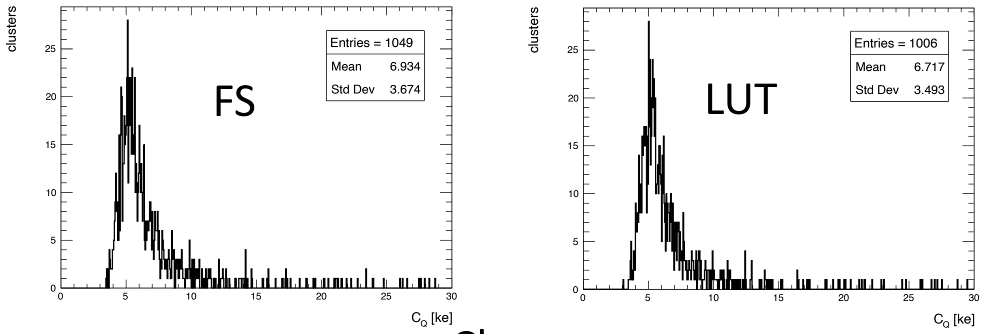
Modules were tilted in ϕ by 0.25 rad

We compared Full Simulation (FS) events with LUT ones

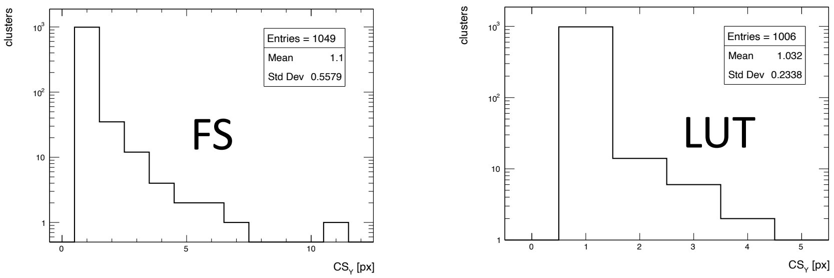
We compared cluster charge and sizes in both projections

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

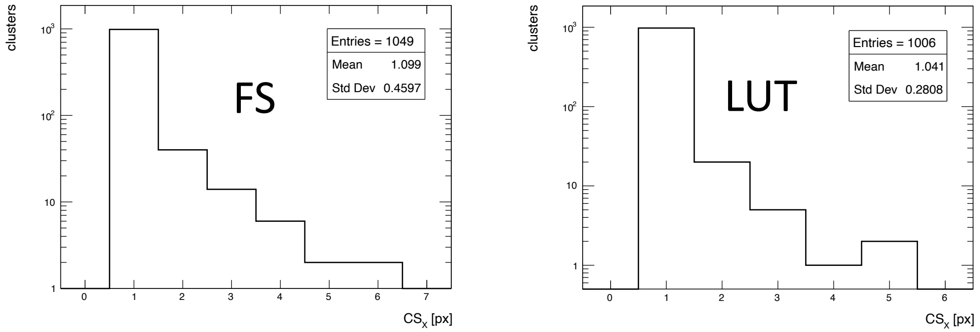
Selection of results - $\eta = 0$, $p_T = 1$ GeV/c



Charge



Longitudinal cluster size



Transverse cluster size

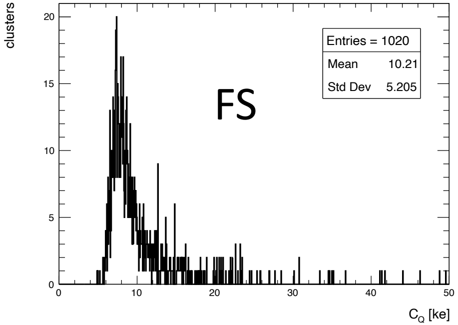
Summary

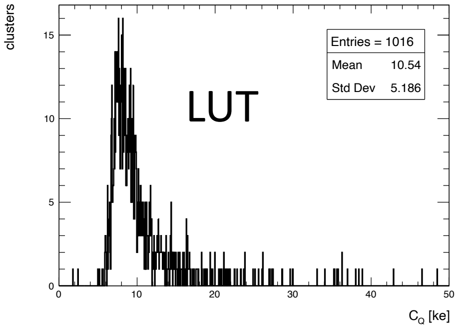
η	CS_X			CS_Y			C_Q [ke]		
	FS	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]
0	1.099	1.041	5.3	1.1	1.032	6.2	6.957	6.741	3.1

Agreement at few % level

Same for all p_T values

Selection of results - $\eta = 1$, $p_T = 1$ GeV/c





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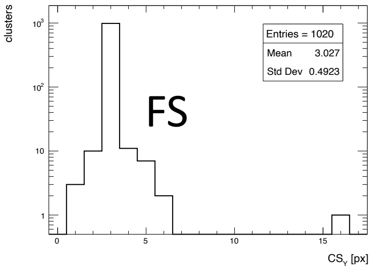
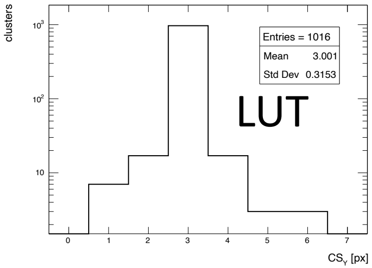
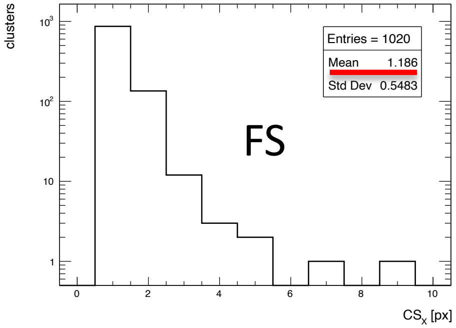
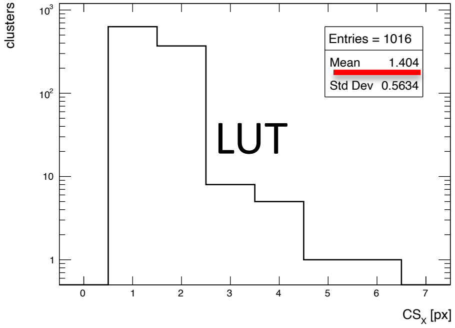




Longitudinal cluster size





Transverse cluster size

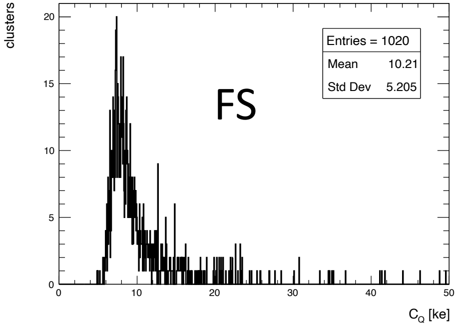
Summary

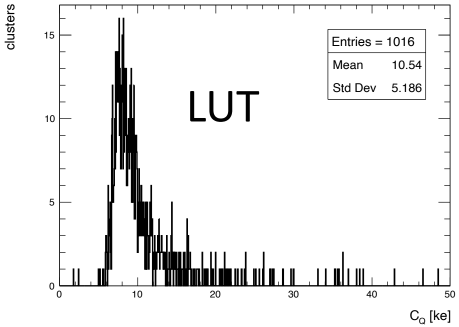
η	CS_X			CS_Y			C_Q [ke]		
	FS	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]	**FS**	**LUT**	ϵ [%]
0	1.099	1.041	5.3	1.1	1.032	6.2	6.957	6.741	3.1
1	1.186	1.404	18.38	3.027	3.001	0.86	10.25	10.54	2.8

Agreement at few % level

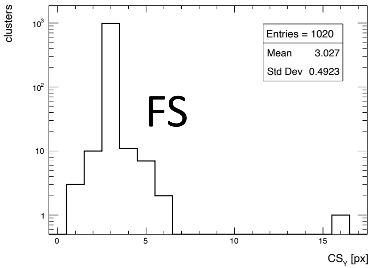
but not for transverse cluster size

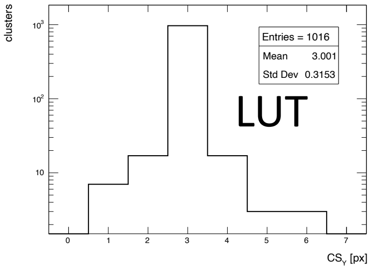
Selection of results - η = 1, p_T = 1 GeV/c



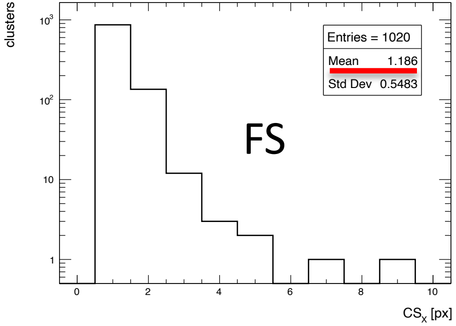


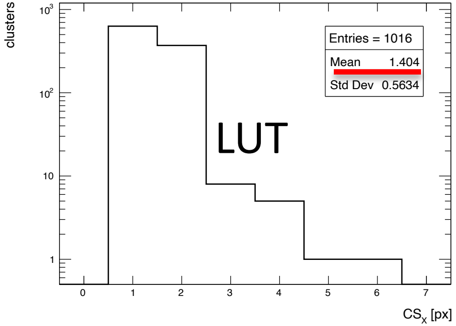
Charge





Longitudinal cluster size





Transverse cluster size

Summary for η = 1

p_T [GeV/c]	CS_X FS	CS_X LUT	CS_X ϵ [%]	CS_Y FS	CS_Y LUT	CS_Y ϵ [%]	C_Q [ke] FS	C_Q [ke] LUT	C_Q [ke] 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

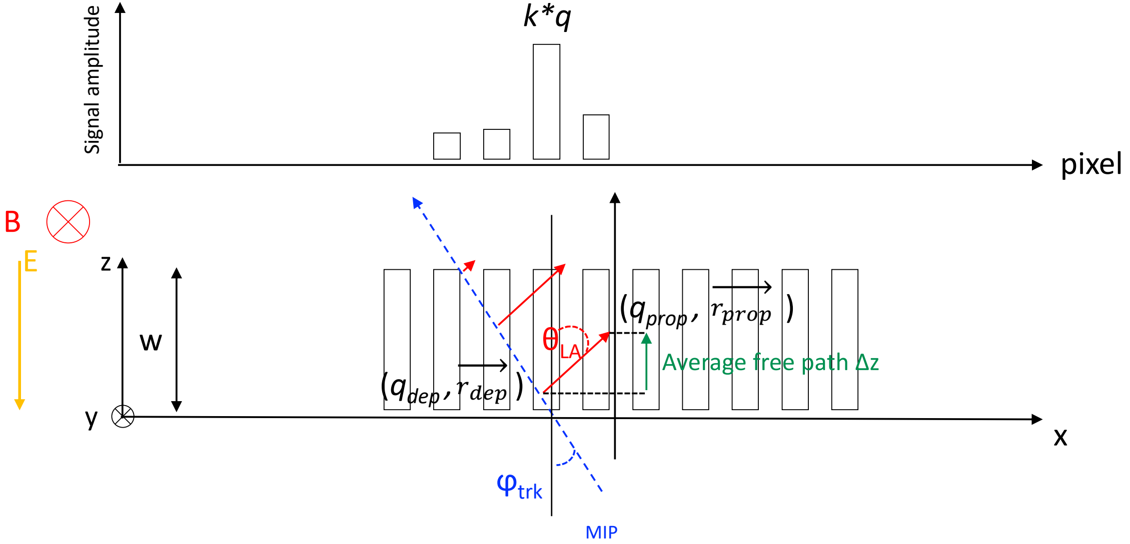
N.B. Charged particles produced in pp collisions are uniformly distributed in η within [-2,2]

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

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
- Δz = w-z
- θ_{LA} = const.

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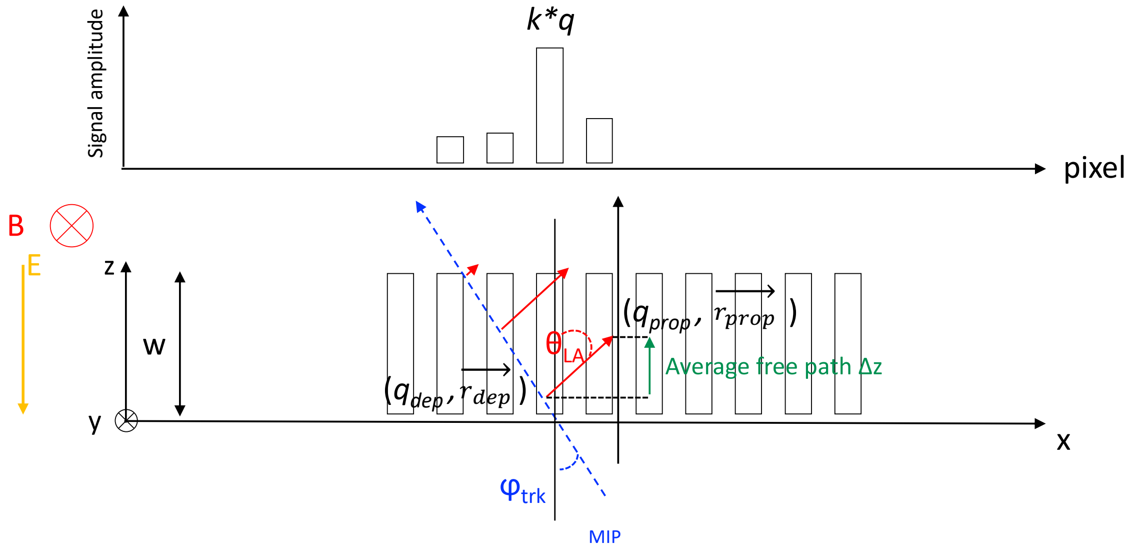

but with:

- k = 1
- Δz = w-z
- θ_{LA} = const.

- ➢ 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 is able 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!**

Interested in collaborating? Conctact us!

Conclusions & Outlook

- HL-LHC conditions pose stringent constraints on pixel detectors but on computing resources too
- Need for an algorithm to mimic … s that is **faster than Run3** …
- **LUT** …
- I…
- **N…**
- **Co… …egrate it in Allpix²**
- **It w… …work with Allpix² – we got great support! Thank you!**

Want to know more?

Read our article!

Sensors 2024, 24(12), 3976;

https://doi.org/10.3390/s24123976

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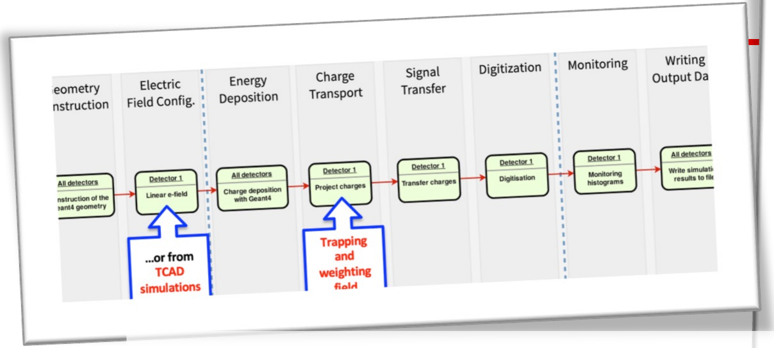
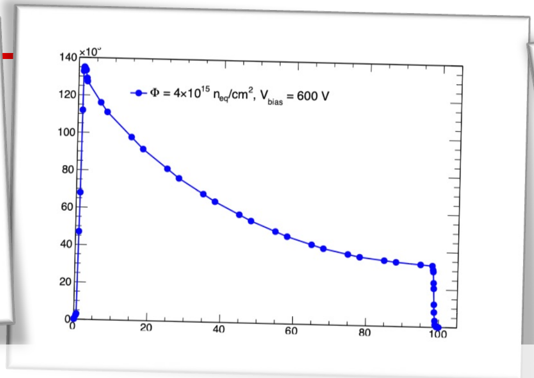
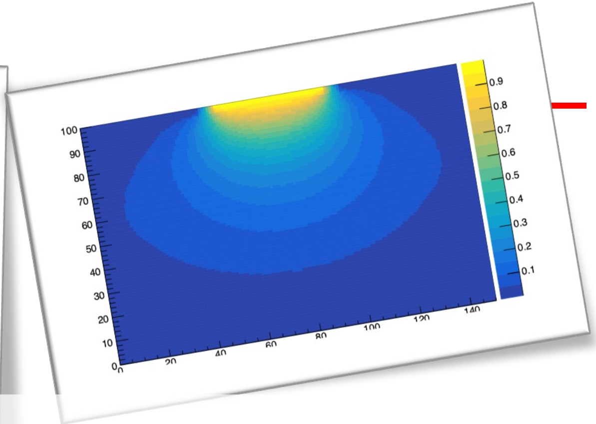
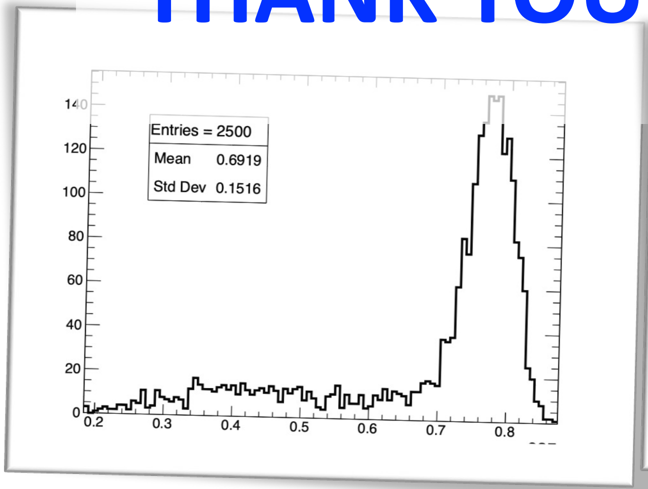
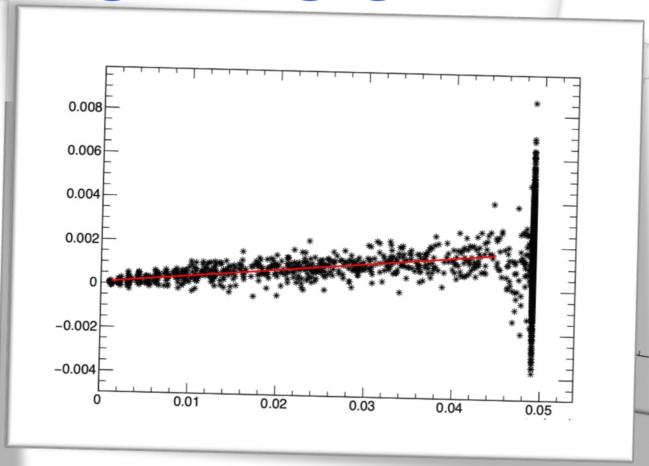


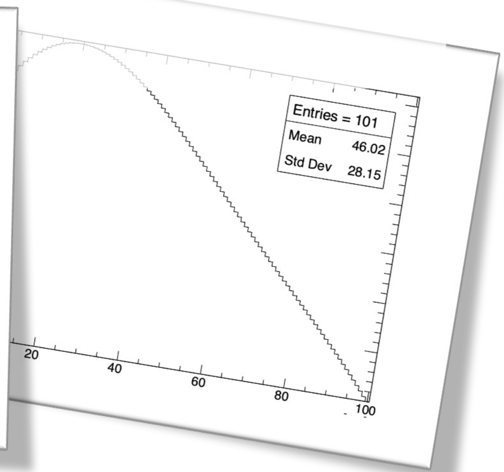




THANK YOU FOR YOUR ATTENTION!

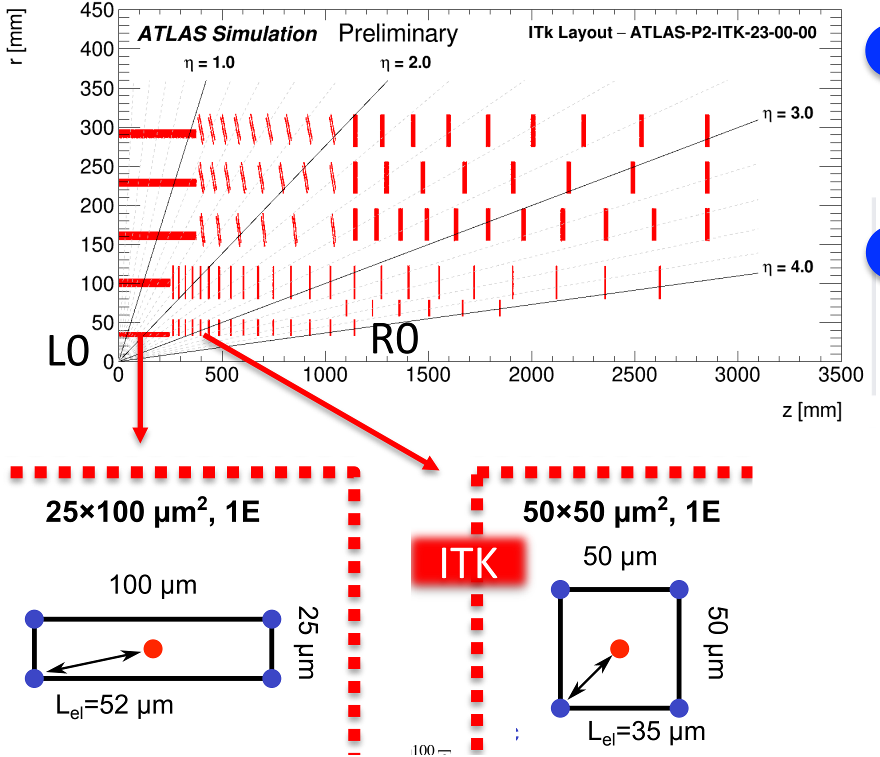


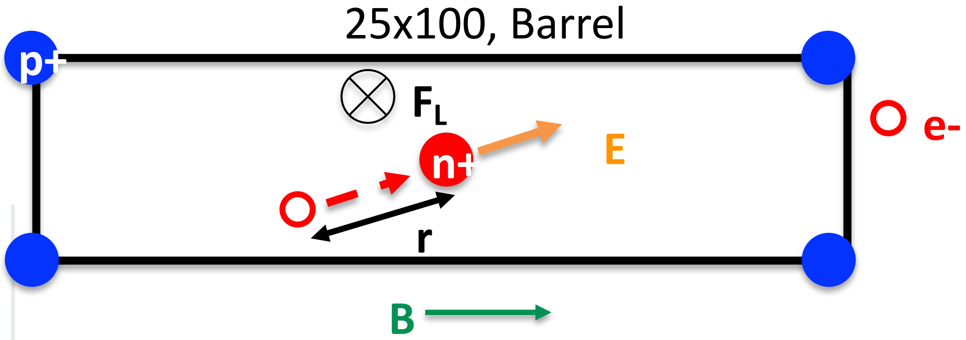


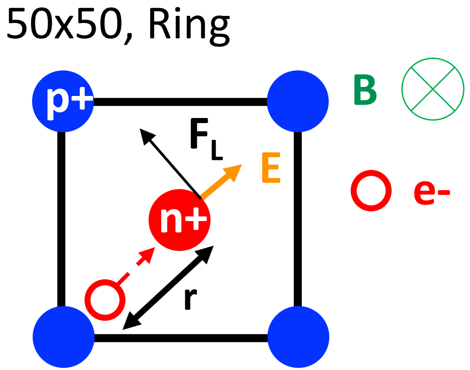


Backup

3D sensors

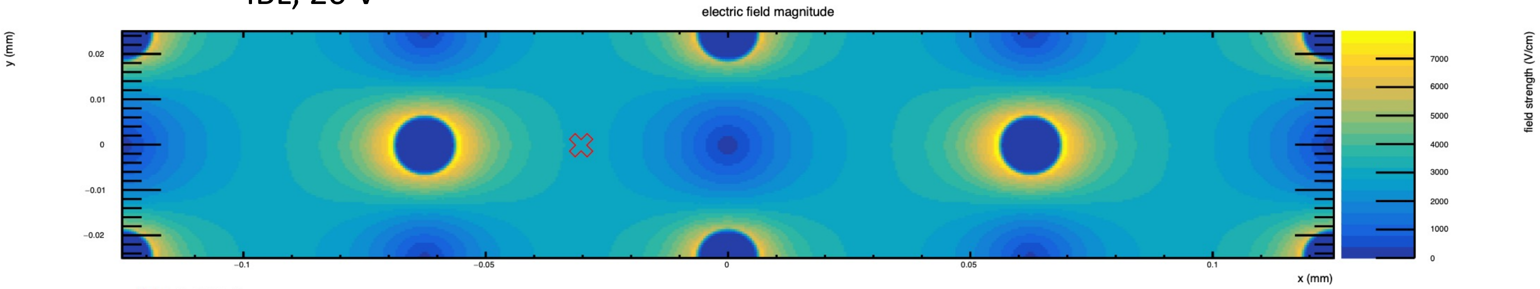




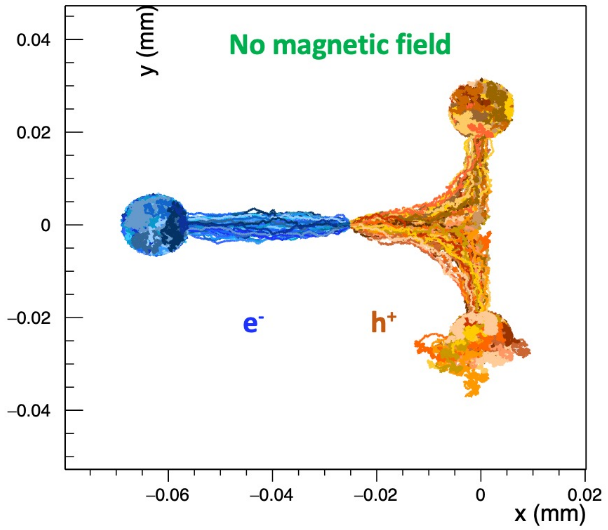


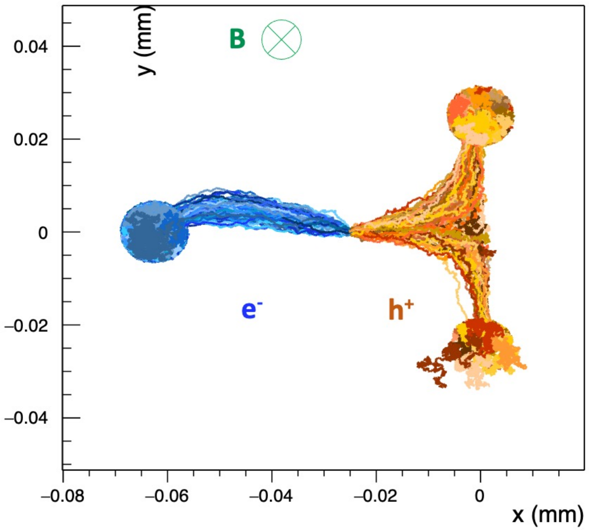
Conclusion: CCE(r) is the only needed LUT

IBL, 20 V



MIP impact





… yes, they do ☺