Silicon Pixel Sensor Simulation in CMS

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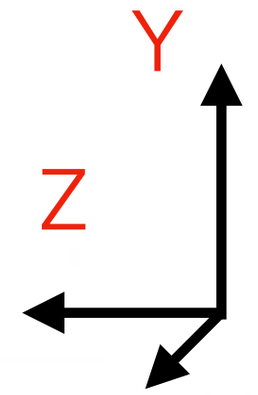
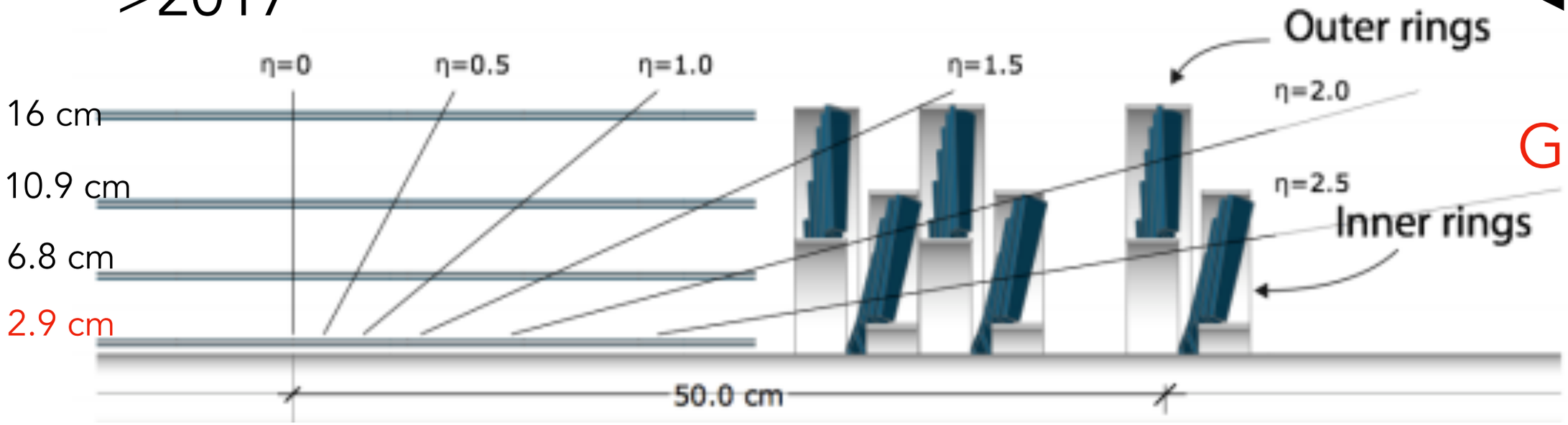
CMS Pixel Detector recap



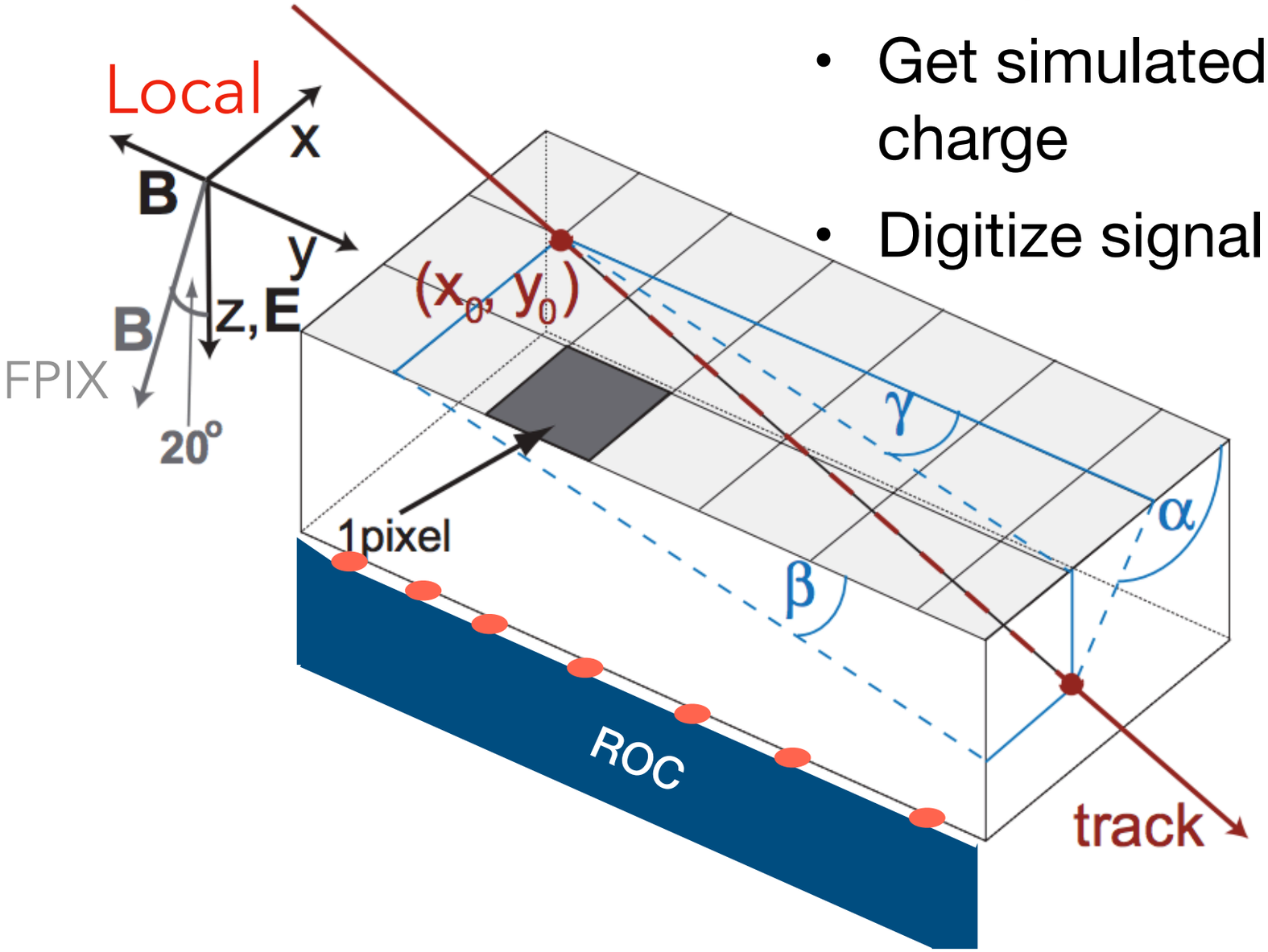
>2017



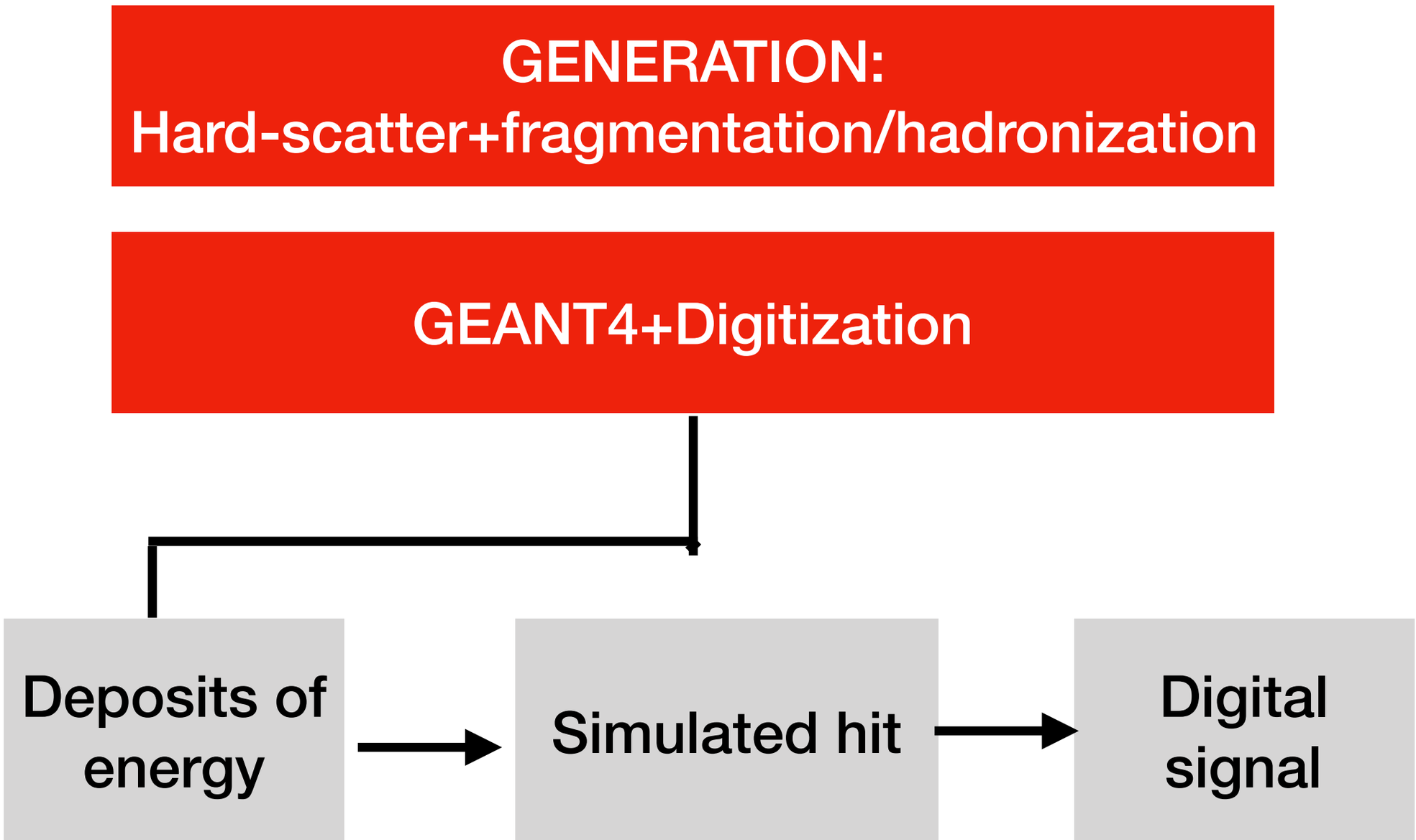
- Upgraded in 2017 to fully profit higher luminosities
  - Four barrel layers (one more than < 2017)
  - Three endcap disks
  - 2.9 cm from interaction point
  - Pixel size: 100 um x 150 um and 300um in depth

CMS Pixel Detector recap

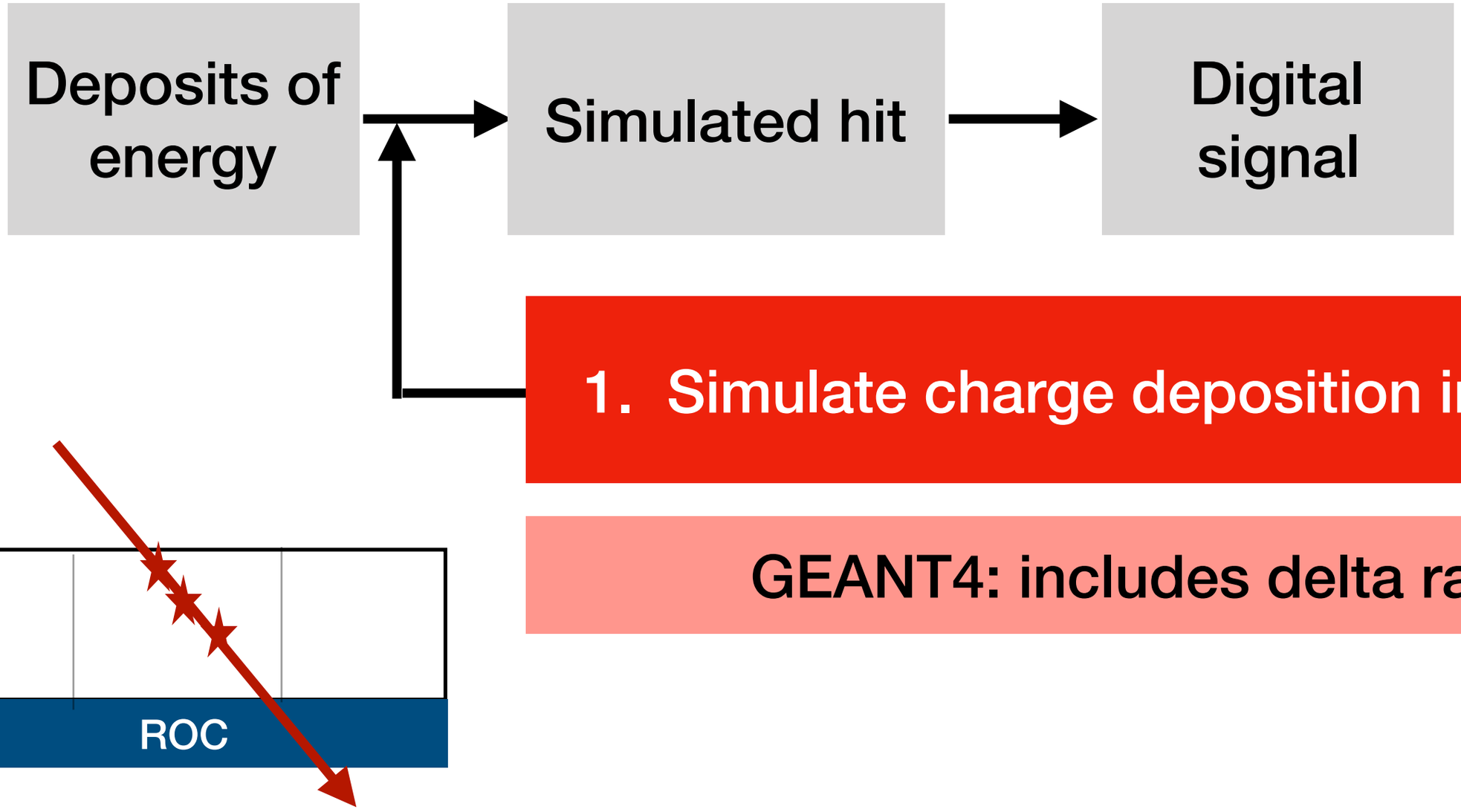
- Particle enters and deposits charge
- Charge transports to electrodes
- Get simulated hit position and cluster charge
- Digitize signal



Simulation Chain



Pixel Simulation Chain (CMSSW)



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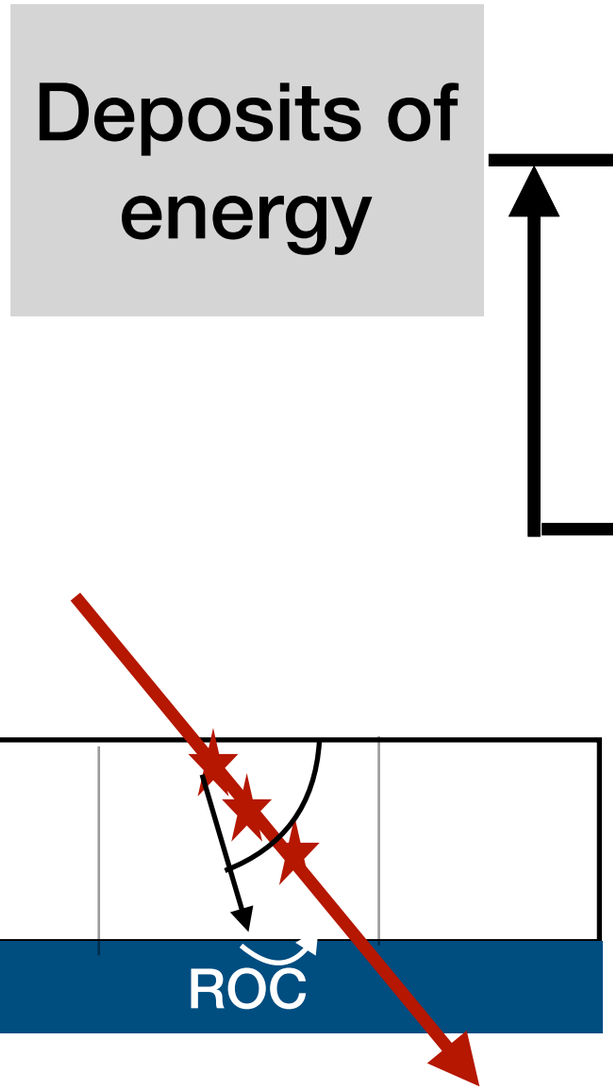


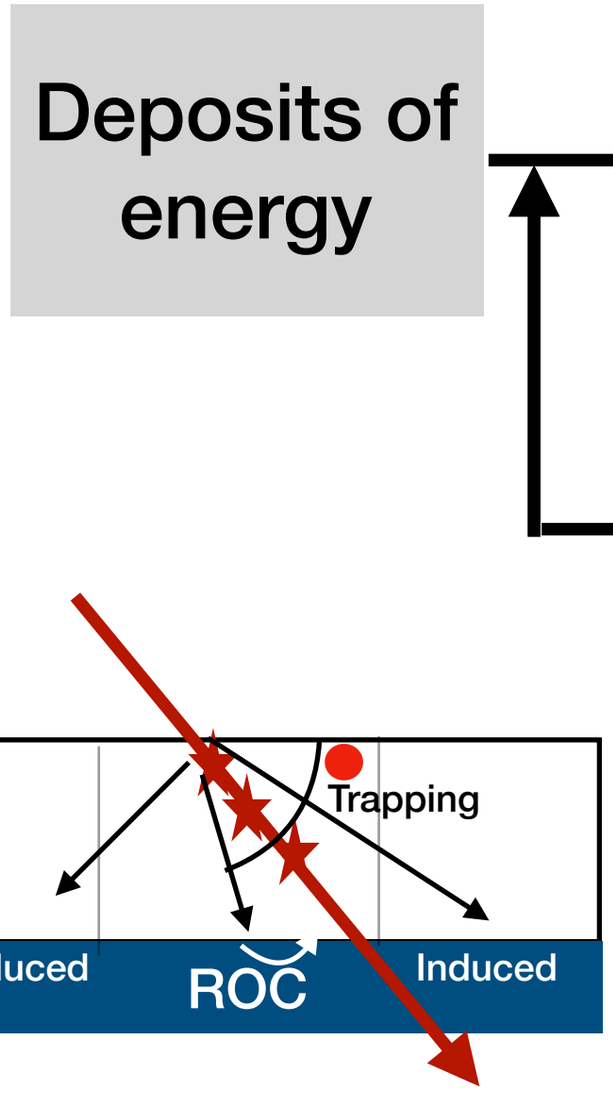
1. Simulate charge deposition in pixels

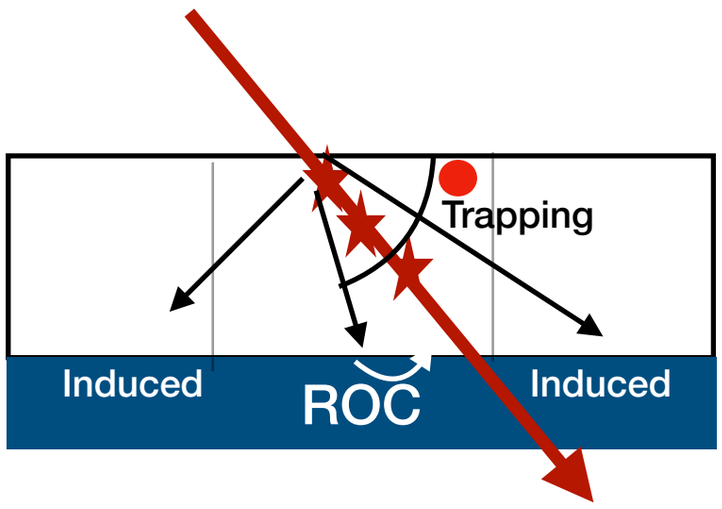
GEANT4: includes delta rays

Include carriers drift and diffusion

But assume uniform E field

Pixel Simulation Chain (CMSSW)





1. Simulate charge deposition in pixels

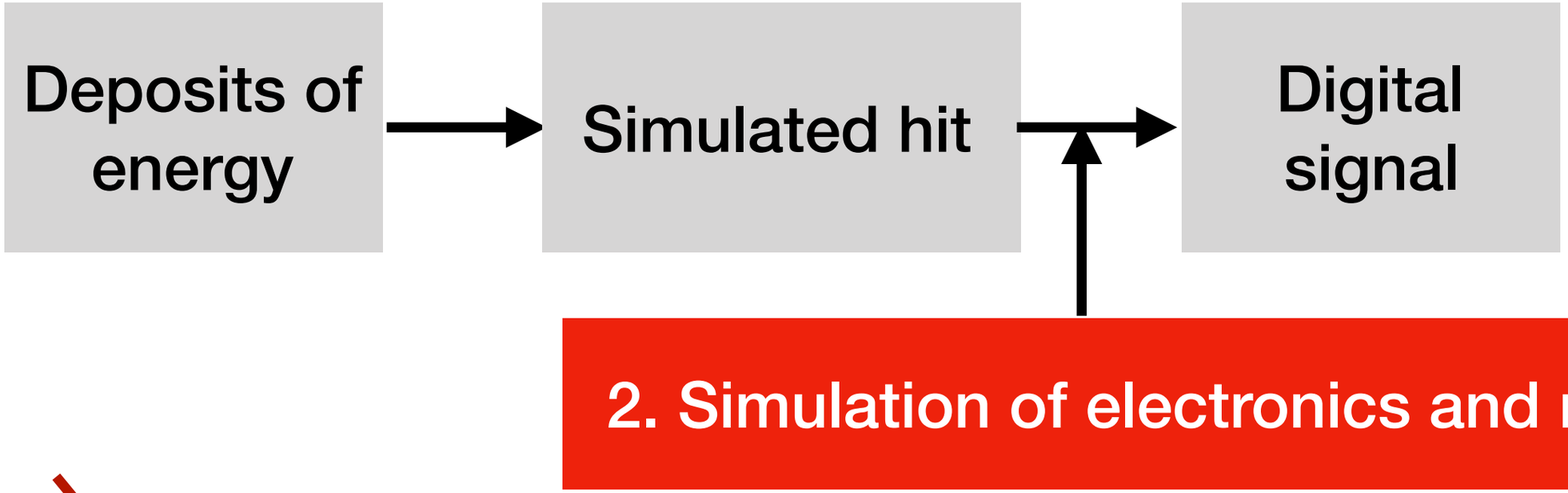
GEANT4: includes delta rays

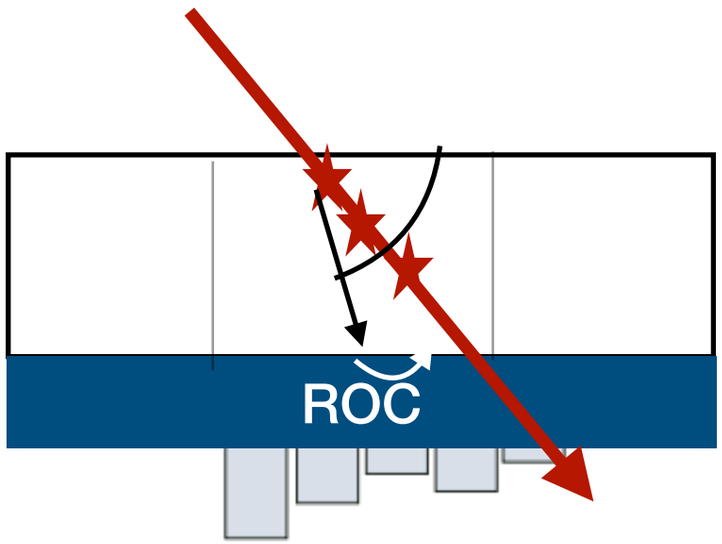
Include carriers drift and diffusion

But assume uniform E field

No Trapping or charge induction!

Pixel Simulation Chain (CMSSW)

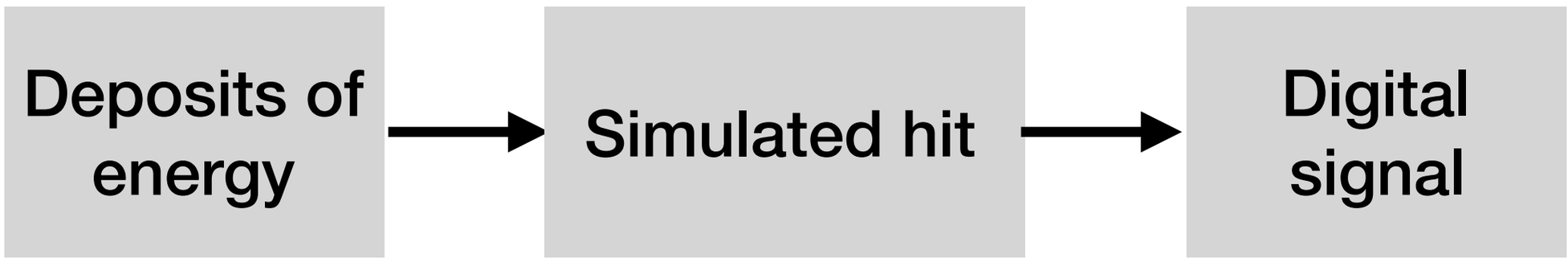




Include ROC thresholds and analog response

+ dynamic ROC inefficiencies and dead channels

Pixel Simulation Chain (CMSSW)



Default simulation: FAST but simplified

recent development:

This talk

NEW since 2018 MC!

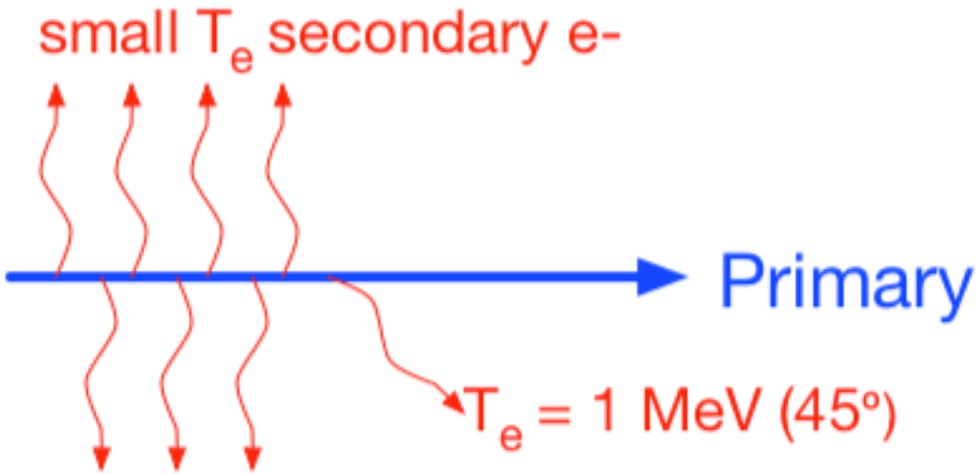
Use pre-determined cluster shapes including radiation effects(PIXELAV) to apply a correction factor on the cluster charge

PIXELAV: simulation

- Transport simulation of individual electrons through Si sensor
  - Generates electric field inside the sensor
  - Generates charge carriers and simulates their transport to electrodes
  - Accounts for readout chip electronics
- Used for Lorentz angle calibrations and generates template cluster shapes

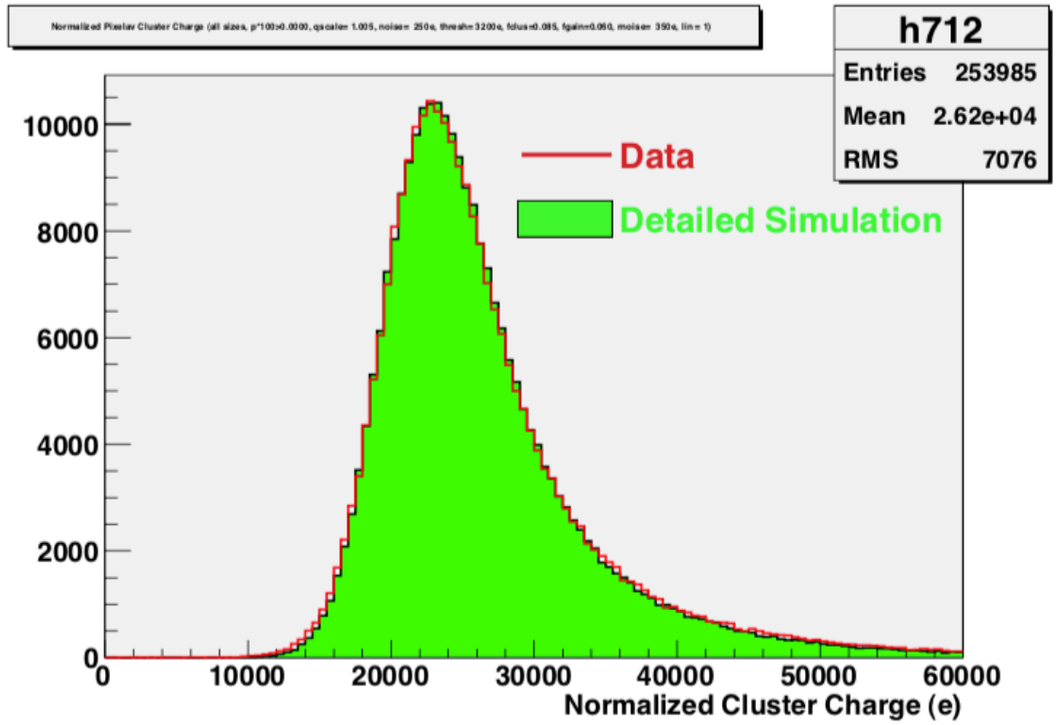
PIXELAV: simulation

1. Charge deposition model based on Bichsel π-Si x-sections



- Includes large delta rays:
  - Secondaries energies [8eV,1MeV]
  - Travel up to 1-2 mm
  - Stopping power taken from NIST ESTAR

Q/track length for a sample of pixel clusters



Model describes cluster charge distribution well

PIXELAV: simulation

2. Carrier transport from Runge-Kutta integration of saturated drift

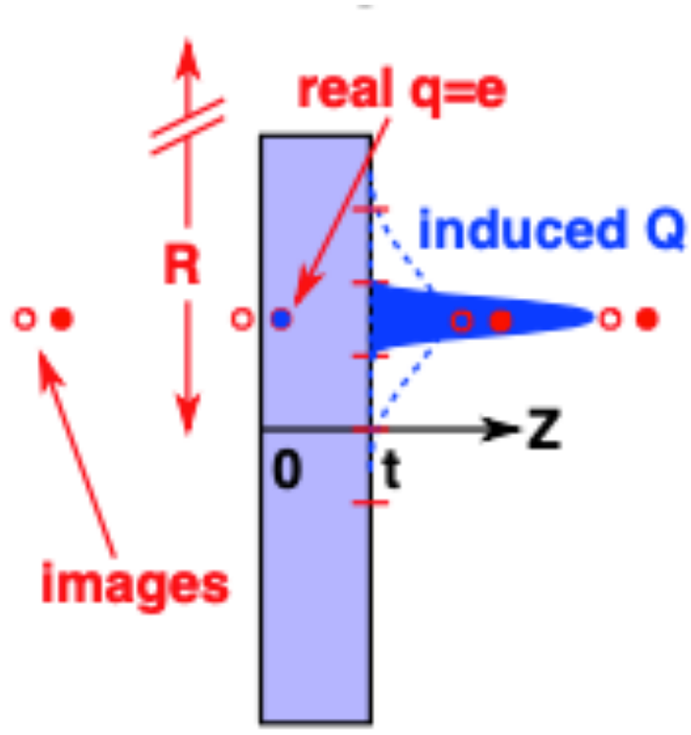
   - Electrons and holes propagated using electric field modeling using TCAD
   - Transport calculation from:

$$\frac{d\vec{r}}{dt} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E}\times\vec{B} + q\mu^2 r_H^2(\vec{E}\cdot\vec{B})\vec{B}\right]}{1+\mu^2 r_H^2|\vec{B}|^2}$$

   - Incorporates diffusion and trapping (Llubjana trapping rates)
   - N.B. simulation transports only 1/10 carriers to save time

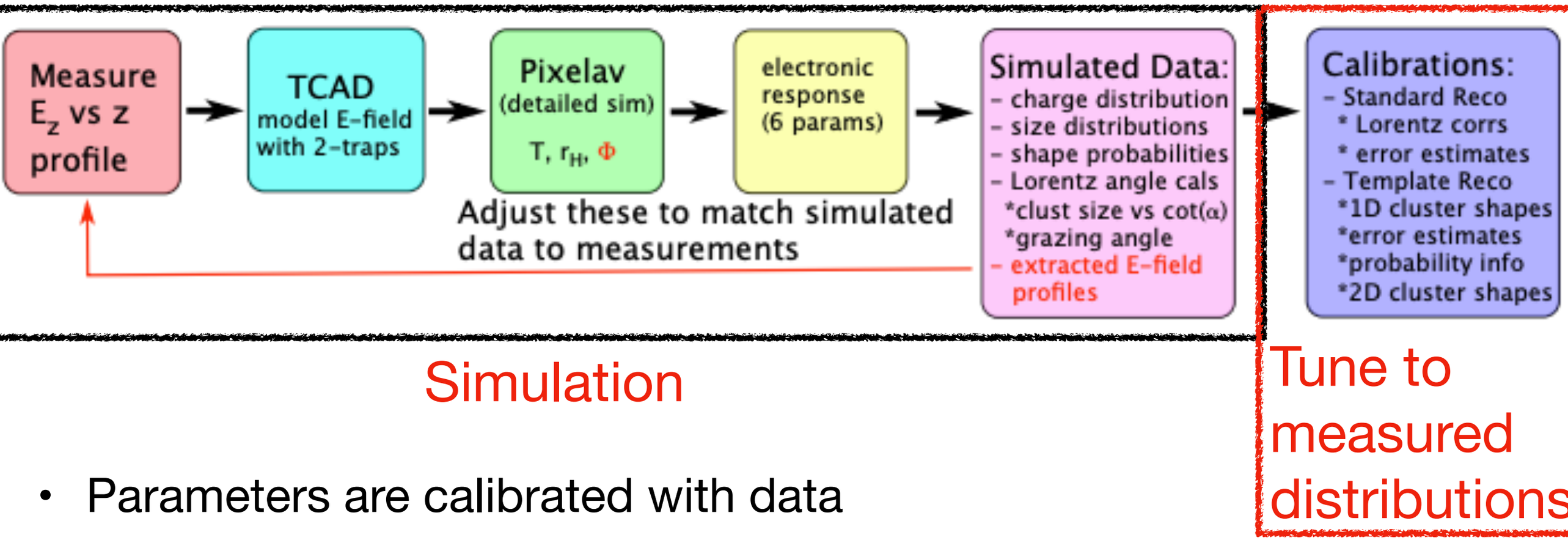
PIXELAV: simulation

3. Signal induction
   - Trapping: reduces net signal
     or produces adjacent signal
   - Induced signal is calculated from
     segmented parallel plate cap. model



4. Electronic simulation:
   - Includes noise
   - ROC thresholds + ROC response from measurements

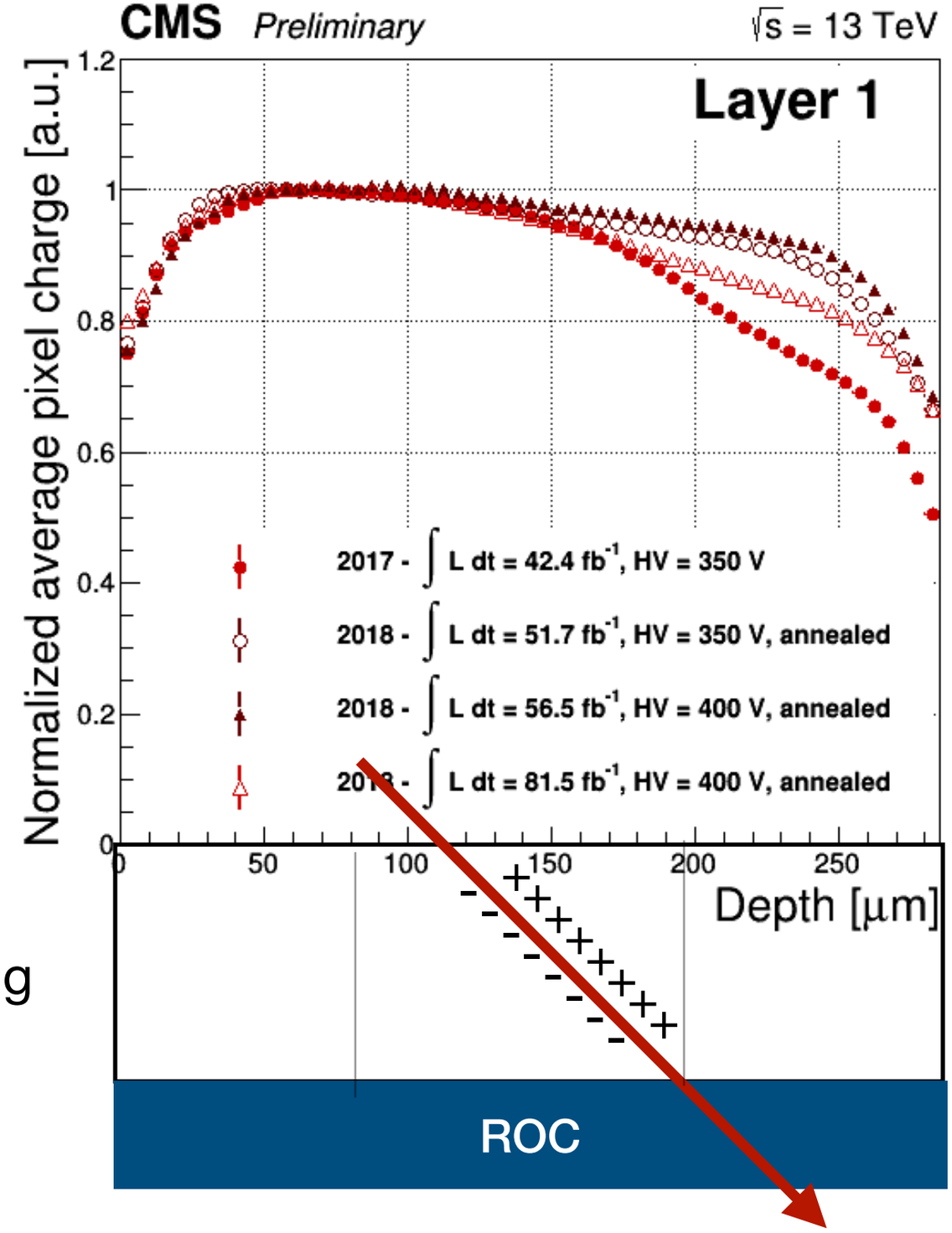
PIXELAV: Implementation



- Parameters are calibrated with data
  - Trapping parameters are adjusted to model Q/depth
  - TCAD modeling is adjusted to reproduce E-field profiles
- Usage:
  - Pixel hit reconstruction
  - Cluster charge re-weighting

Cluster charge re-weighting

- Charge collection efficiency:
  - For non-irradiated sensor: FLAT
  - For irradiated sensor: decreases with production depth
  - Fix:
    - Use PIXELAV to re-weight cluster charge
- N.B.:
  - between 2017 and 2018 (>10C) annealing flattens the charge profile
  - @2018 Higher bias voltage (350->400V) increases with charge collection eff.



Algorithm

Inputs
From CMSSW simulation:

Original[ix,iy] (Pixel charges)
[x,y] (Local coord hit)
[cotα,cotβ] (Local track angles)

From PIXELAV simulation:

Irradiated[ix,iy] : 2D template
Non-irradiated[ix,iy] : 2D template

Interpolate 2D templates
@ [x,y] and [cotα,cotβ]

Calculate output charge:

Signal[ix][iy] = (Irrad[ix][iy]/Non-irrad[ix][iy]) * Original[ix][iy]

This produces output clusters with the correct average shapes but reflecting the charge fluctuations of the input cluster

Implementation

$\Phi=1.2\times10^{15}$ neq/cm2, 600V, 263K

Original[ix,iy]

Non-irradiated[ix,iy]:

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

0	0	0	0	0	0	0	0	0	0	0
0	0	9590	7380	0	0	0	0	0	0	0
0	0	0	9140	12500	11140	11790	12330	1750	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	93	10696	5584	722	23	0	0	0	0	0
0	0	884	7398	12337	12963	12997	13042	1375	0	0
0	0	0	0	0	0	0	0	0	0	0

Irradiated[ix,iy]

- Average cluster shape for a damaged physical sensor

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

Weights

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

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

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0	0	0	0	0	125	477	582	258	40	0

Signal[ix,iy]

0	0	0	0	0	0	0	0	0	0	0
0	0	7773	7878	764	226	478	468	0	0	0
0	0	0	3583	7728	6169	5429	4516	865	0	0
0	0	0	0	0	0	433	550	0	0	0

Long drifting carriers

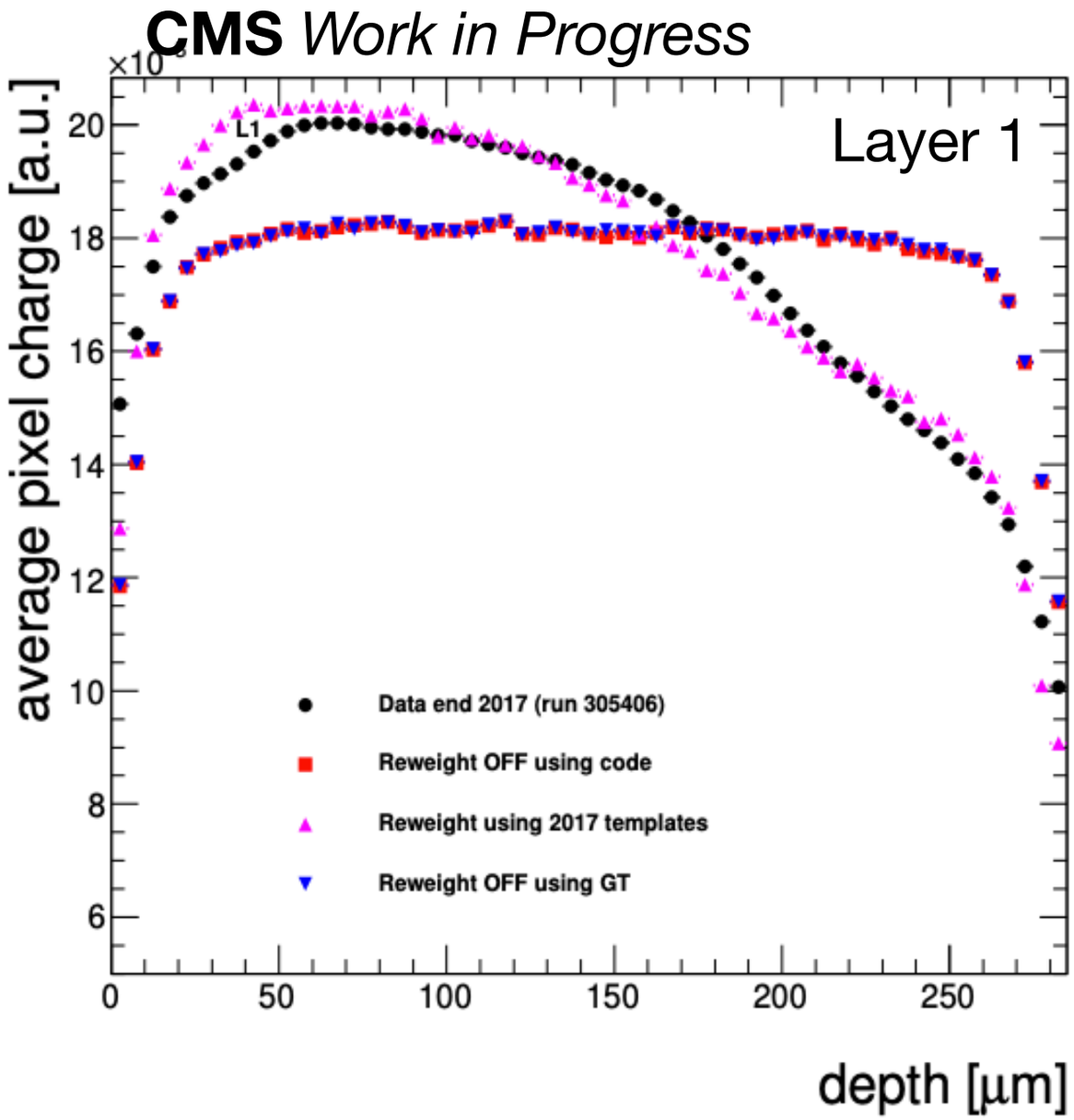
Might be < threshold but contribute to pixels with collected carriers

Output

Algorithm has already been implemented in central CMSSW simulation and will be used for full Run II MC.

Preliminary studies show good agreement between data and simulation.

Waiting for preliminary plots to come out soon when Run II legacy MC production starts



Conclusions

- Main CMSSW simulation FAST and simplified but re-weighted to include charge induction and trapping
- For Run II legacy MC CMS Pixel simulation incorporates radiation damage effects
- Pixelav standalone simulation is a key part of the pixel hit reconstruction algorithm
  - Parameters are tuned from data
  - Cluster shapes are necessary to include realistic effects on simulation
  - Can also be used for hit reconstruction to improve resolution after radiation damage
- With last changes we expect better data/MC agreement on cluster shape

Backup

Cluster reweighing details

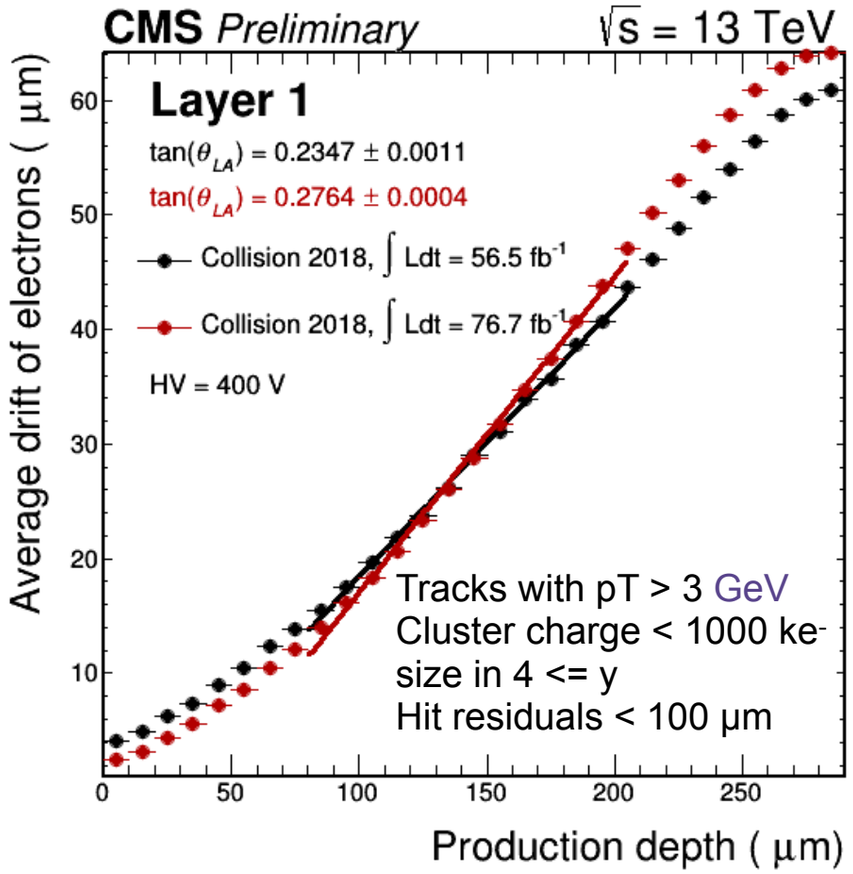
- Common LAs for non-irradiated templates: chosen to be the same or little larger than equivalent LAs from the irradiated templates
  - This makes all cluster size similar and weights ~ 1
- Sometimes size(original) > size(denominator), because e.g. delta rays
  - Apply weights from nearest pixel that does not have denominator =0
  - Same if charge < min value
- Irradiated template: there is focusing of the carriers at n+ implants but none in CMSSW (non-irradiated), also includes charge induced by trapped carriers

E field measurement and template LA calibration

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

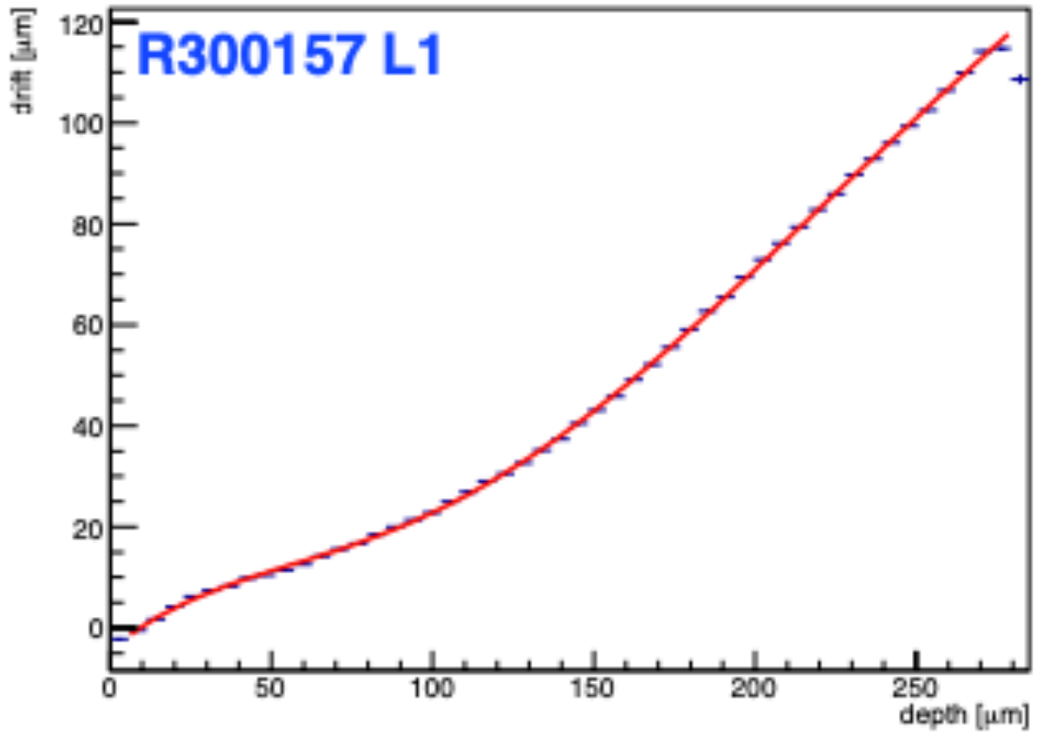
$$\tan\theta_L = \frac{dx}{dD} = r_H \mu(E) B_y$$

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

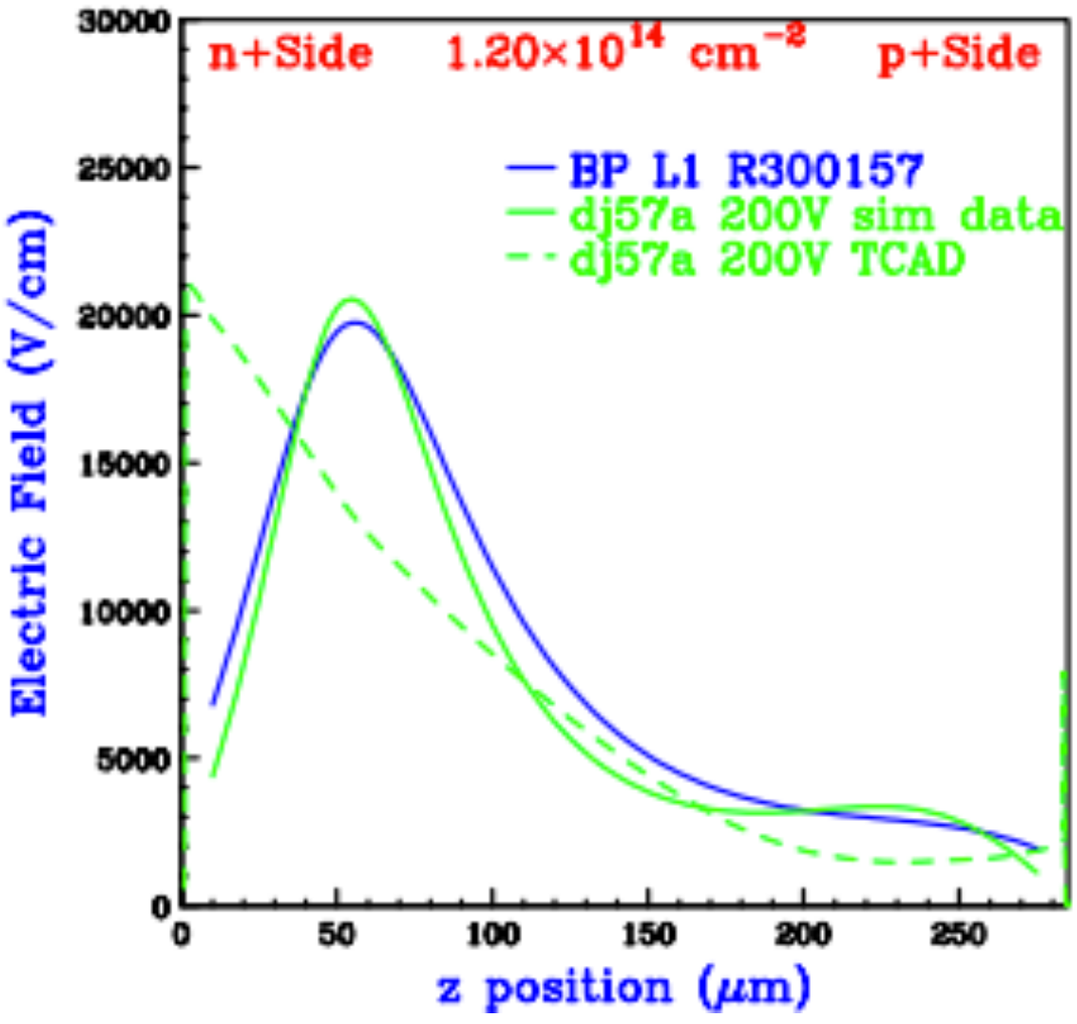


Increase of the measured LA and change of the shape of the drift vs depth curve is observed due to the detector irradiation

E field measurement and template LA calibration

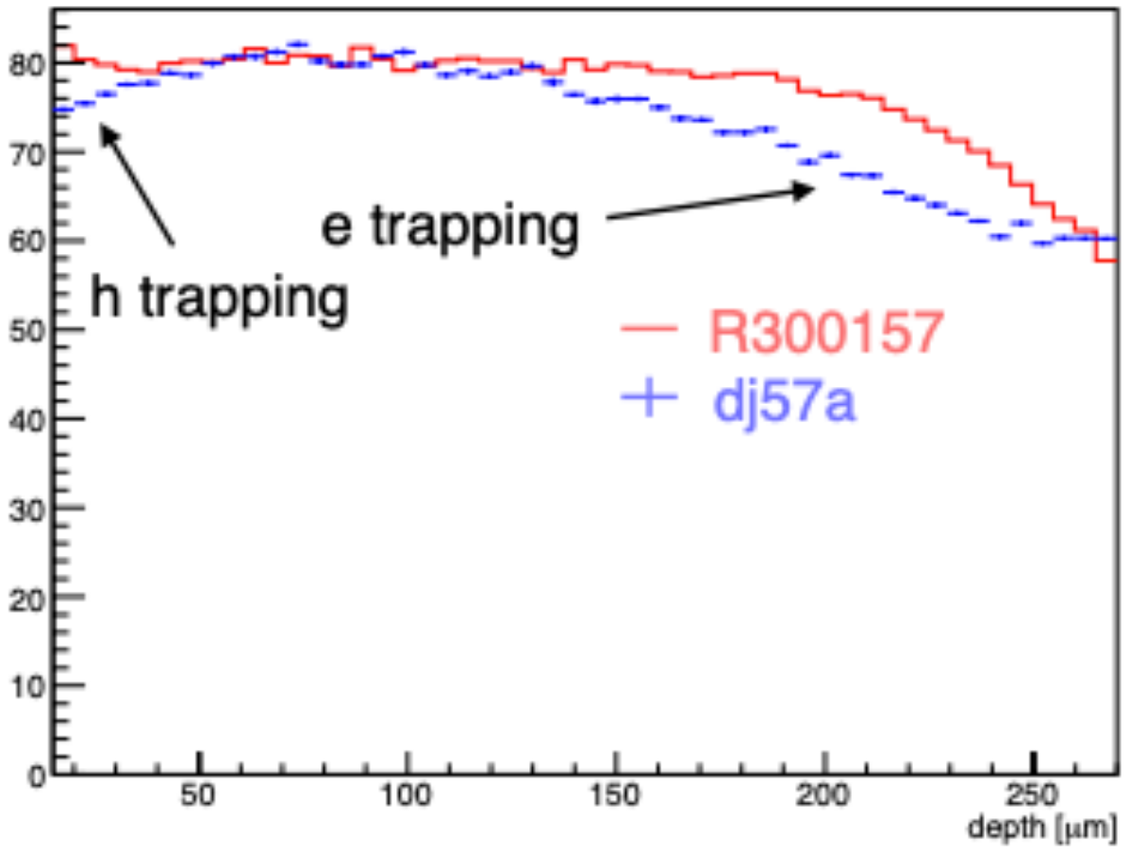


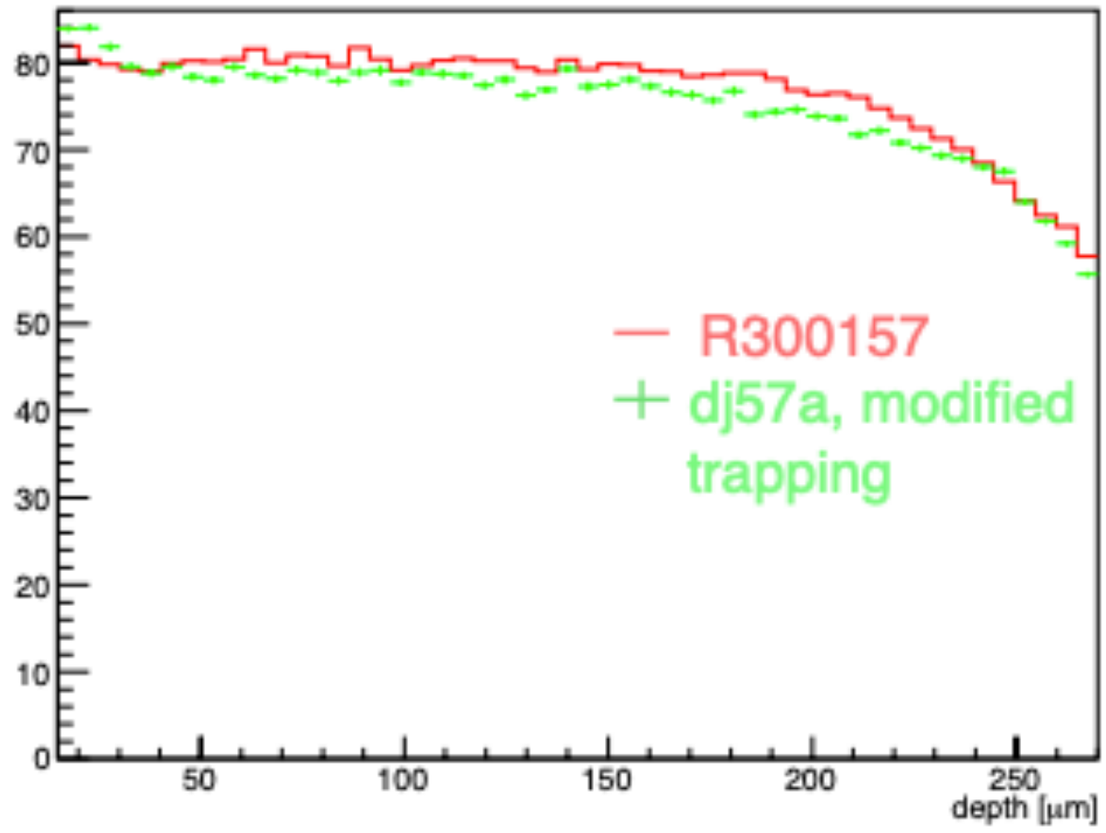
Run 300157 was taken after 11.8 fb-1: Φ_Q = 1.2x10^{14} cm^{-2}
the electric field is well described by our old model dj57a: it was from a sensor exposed to Φeq = 2x10^{14} cm^{-2}



The extracted electric field profile is distorted by focusing near the n+ implant and other systematic effects

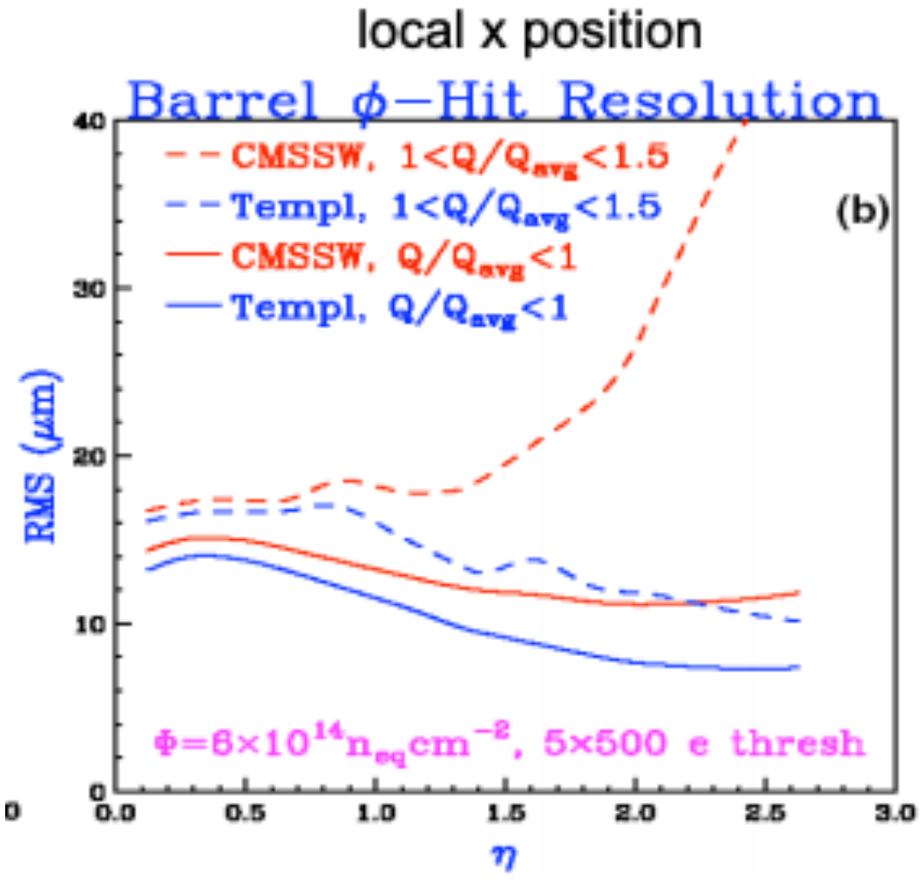
Trapping measurement





Comparing measured depth profile (red) with simulated profile (blue)
The slower evolution of the trapping rates has important consequences for the longevity of the detector

RECO: Pixel hit reconstruction

- Benefits from PIXELAV simulation:
  - Generic hit reconstruction:
    - With Lorentz drift corrections
  - Template hit reconstruction:
    - Given track angles, find cluster shape (template object)
    - Uses 1D cluster shapes (projections in x and y) or 2D
    - Determine hit position that minimizes χ2 between template and cluster
- Also provides error estimates

- After irradiation better hit resolution