Allpix^2 Simulations of Particle Interactions in Cell Phone Sensors for DECO

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May 10th 2022 on Allipx^2 user workshop

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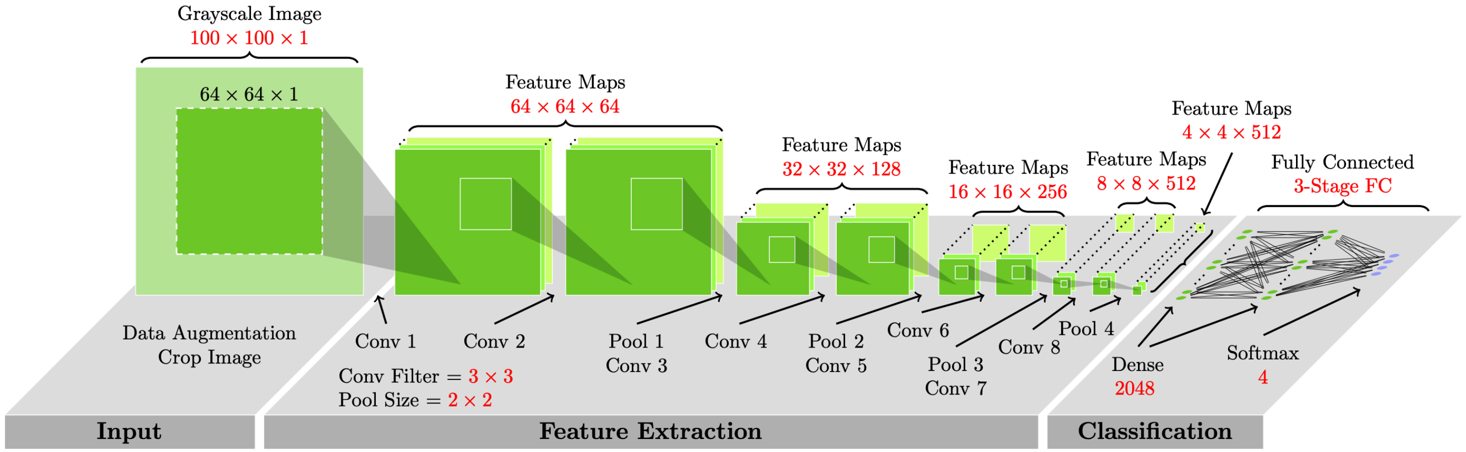
DECO
Distributed Electronic Cosmic-ray Observatory

Distributed Electronic Cosmic-ray Observatory (DECO)

- DECO is a cell phone app which uses its silicon camera image sensor (CMOS) to detect cosmic-ray particles or particles from radioactive decay, which provides a nice tool for citizen science and general education.
- When a charged particle from cosmic-ray / radioactive decay passes through the camera image sensor in cell phone, the ionization loss creates electron and hole pairs that drift and get deposited on pixels. This image will be captured by cell phone camera, and one sample image from DECO is shown.

Sample Image Taken by DECO

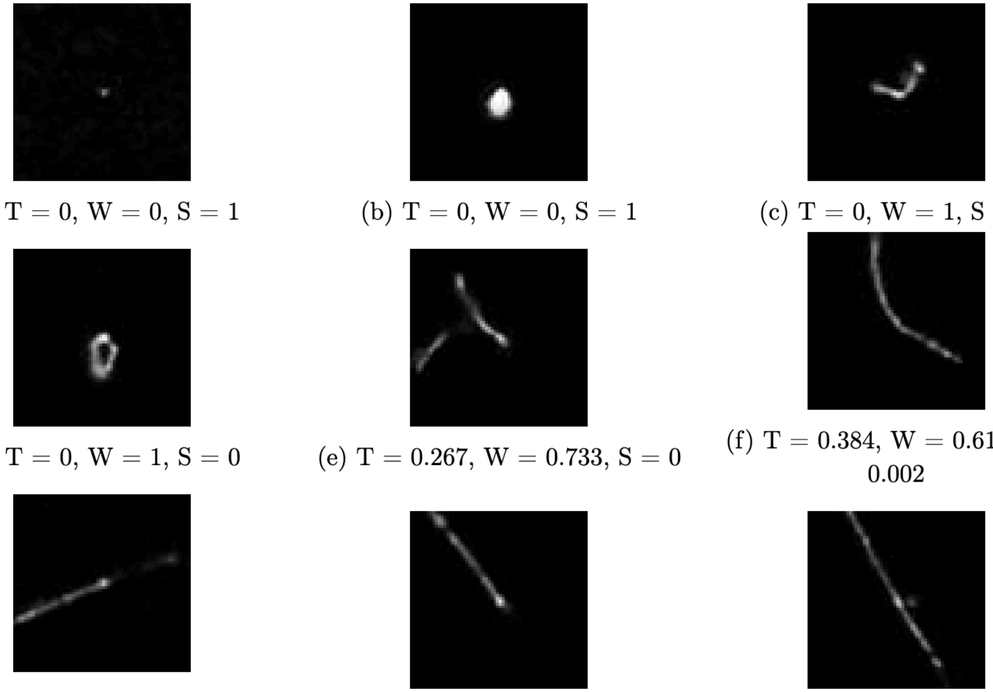


CNN Used to Classify DECO Events

- A Convolutional Neural Network shown is used to classify images taken by DECO according to their morphologies as tracks, worms, spots, and noise.
- More details about previous research in DECO can be found on https://wipac.wisc.edu/deco/research

Motivation

- Currently the CNN used in DECO is trained by human-labeled data events. Since those labels are only based on the image morphology, our CNN can only classify events as tracks / worms / spots / noises instead of particle type / energy / direction



(a) T = 0, W = 0, S = 1
(b) T = 0, W = 0, S = 1
(c) T = 0, W = 1, S = 0
(d) T = 0, W = 1, S = 0
(e) T = 0.267, W = 0.733, S = 0
(f) T = 0.384, W = 0.613, S = 0.002
(g) T = 0.626, W = 0.368, S = 0.003
(h) T = 0.951, W = 0.048, S = 0
(i) T = 0.967, W = 0.033, S = 0

Sample Images taken by DECO with CNN classification

- If we are able to simulate images of particles from cosmic-ray / radioactive decay recorded by DECO close enough to data events collected by DECO, then we could train the CNN by simulated events. These simulated events contains exact info about particle type / energy / direction, so the CNN will be able to classify those labels as well.

Outline

1. Simulation of individual events using Allpix2
    1. Simulation parameters
    2. Simulation results
    3. Post image processing and examples of simulated events and data events
2. Monte-Carlo simulation
    1. Monte-Carlo simulation setup
    2. Data / Monte-Carlo comparison
3. Conclusion and next step

Simulation of Individual Events

Simulation Parameters

- In order to simulate charged particles in cell phone camera image sensor, we use Allpix^2 with modules adjusted so that they are close to those of HTC Wildfire, the cell phone we used to install DECO and collect events.

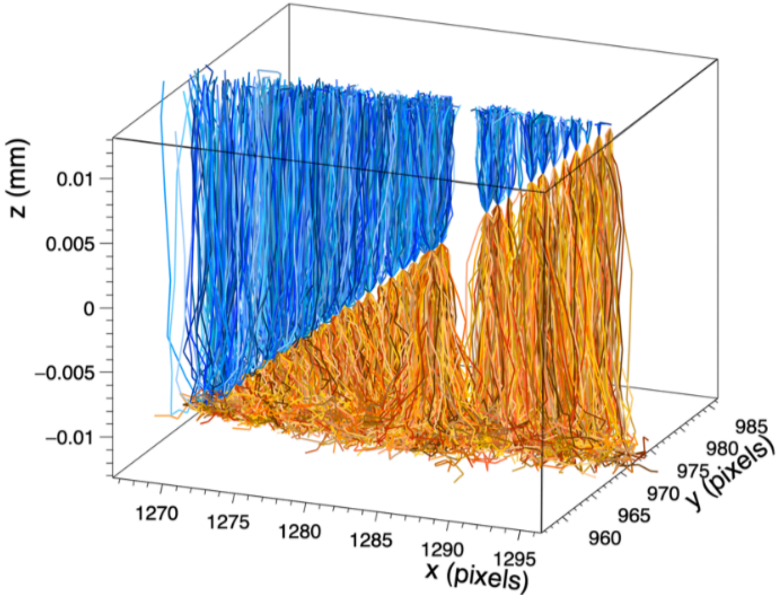
Parameter	Value
Number of Pixels	2592×1944 (5,038,848)
Pixel Size	0.9μm $\times 0.9$ μm
Depletion Thickness	26.3 μm
Temperature	293 K
Surrounding Material	Vacuum
Electric Field Model	Linear
Bias Voltage	-25 V
Integration Time	50 ns
Max Step Size	1 μm
Charge Creation Energy	3.62 eV
Charge Threshold as Hit	1 e
QDC Resolution	8 bits
QDC Slope	0.5 e
QDC Smearing	0 e

Simulation parameters based on previous works in DECO *

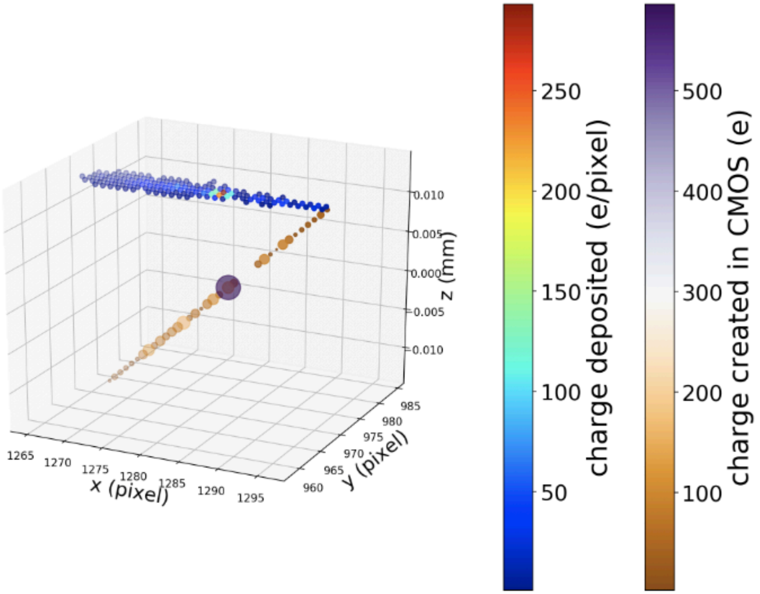
* arXiv:1511.00660

Simulation Results

- Simulation of a 4GeV μ^+ interacting with the camera image sensor with parameters listed before. Those 2 plots below represents the same event.



Propagation of each individual charges / holes created during simulation, under the bias voltage. Blue lines represent charge and orange lines represent holes



Charges created during propagation and charges deposited on the pixel bins at image sensor top surface.

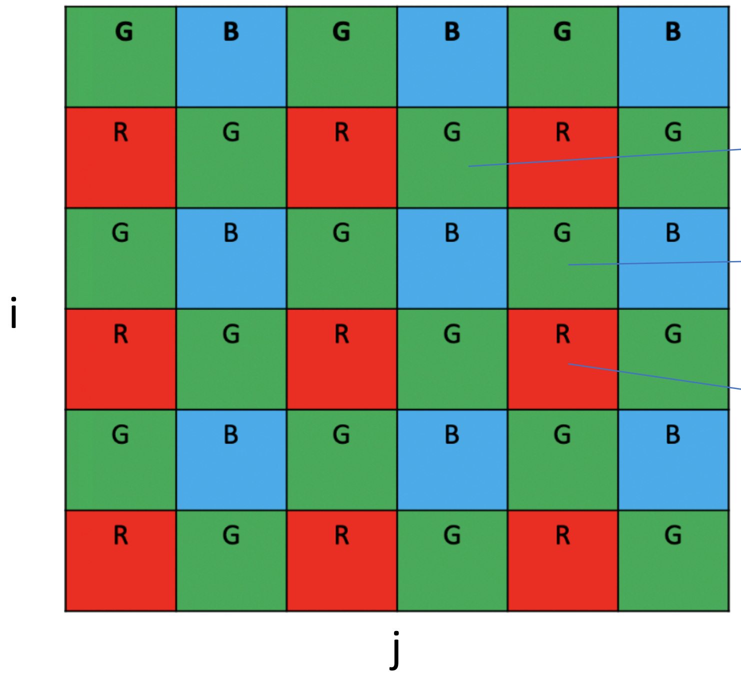
- QDC converter will convert charge on pixel into signal on pixel, so what we have is a 2592x1944 image

Post Image Processing

- What we have here is trying to reproduce what actually happens in the image processing of HTC Wildfire

- In order to convert signal on pixels of size 2592x1944x1 into RGB colored image of size 2592x1944x3, an interpolation with Bayer filter is applied.

- Here the interpolation we use is a simple averaging over neighbors, due to the lack of information about what is actually used in commercial cell phones



$$\left(\frac{L_{i,j-1}+L_{i,j+1}}{2}, L_{i,j}, \frac{L_{i-1,j}+L_{i+1,j}}{2}\right)$$

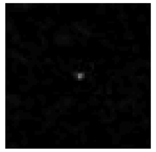
$$\left(\frac{L_{i-1,j}+L_{i+1,j}}{2}, L_{i,j}, \frac{L_{i,j-1}+L_{i,j+1}}{2}\right)$$

$$\left(L_{i,j}, \frac{L_{i-1,j}+L_{i+1,j}+L_{i,j-1}+L_{i,j+1}}{4}, \frac{L_{i-1,j-1}+L_{i+1,j+1}+L_{i+1,j-1}+L_{i-1,j+1}}{4}\right)$$

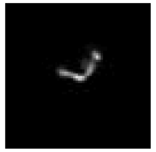
- After interpolation, we have an RGB colored image of size 2592x1944x3. Then white balancing and background addition is applied to mimic the image produced by HTC Wildfire

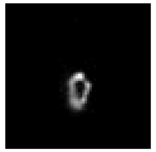
Examples of Simulated Events and Data Events

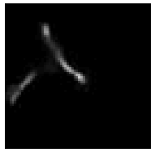
Data Events Collected by DECO


(a) T = 0, W = 0, S = 1

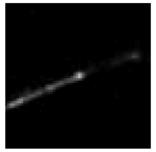

(b) T = 0, W = 0, S = 1


(c) T = 0, W = 1, S = 0


(d) T = 0, W = 1, S = 0


(e) T = 0.267, W = 0.733, S = 0

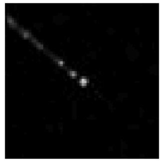

(f) T = 0.384, W = 0.613, S = 0.002


(g) T = 0.626, W = 0.368, S = 0.003


(h) T = 0.951, W = 0.048, S = 0


(i) T = 0.967, W = 0.033, S = 0

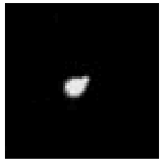
Simulated muons at different kinetic energy / zenith angle with bias voltage -25V


(a) 100 keV, $\theta = 20°$, T = 0.741, W = 0.257, S = 0.002


(b) 100 keV, $\theta = 50°$, T = 0.655, W = 0.342, S = 0.003


(c) 100 keV, $\theta = 80°$, T = 0.506, W = 0.492, S = 0.003

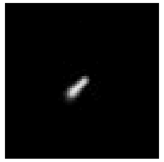
Muon decay region. An energetic minimum ionizing electron is produced.


(d) 1 MeV, $\theta = 20°$, T = 0.005, W = 0.009, S = 0.976


(e) 1 MeV, $\theta = 50°$, T = 0.701, W = 0.295, S = 0

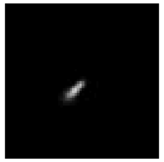

(f) 1 MeV, $\theta = 80°$, T = 0.175, W = 0.645, S = 0

1MeV corresponds to largest ionizing energy loss of muon, and possible muon decay in the end


(g) 10 MeV, $\theta = 20°$, T = 0.837, W = 0.161, S = 0.002


(h) 10 MeV, $\theta = 50°$, T = 0.998, W = 0.018, S = 0


(i) 10 MeV, $\theta = 80°$, T = 0.998, W = 0.002, S = 0


(j) 100 MeV, $\theta = 20°$, T = 0.908, W = 0.089, S = 0.002


(k) 100 MeV, $\theta = 50°$, T = 1, W = 0, S = 0


(l) 100 MeV, $\theta = 80°$, T = 0.017, W = 0.983, S = 0

A delta ray is produced

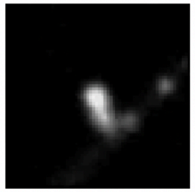
Examples of Simulated Events and Data Events

- In order to see the effect of different bias voltages, we choose 6 events to run under different values of bias voltage

Simulated muons with bias voltage -5V

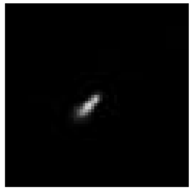
(a) 100 MeV, $\theta = 20°$, T = 0.153, W = 0.393, S = 0.447

(b) 100 MeV, $\theta = 50°$, T = 0.816, W = 0.184, S = 0



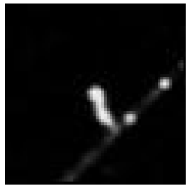
(c) 100 MeV, θ=80°, T = 0, W = 0, S = 0

Simulated muons with bias voltage -25V



(j) 100 MeV, $\theta = 20°$, T = 0.908, W = 0.089, S = 0.002

(k) 100 MeV, $\theta = 50°$, T = 1, W = 0, S = 0



(l) 100 MeV, $\theta = 80°$, T = 0.017, W = 0.983, S = 0

Simulated muons with bias voltage -100V

(a) 100 MeV, $\theta = 20°$, T = 0.981, W = 0.019, S = 0

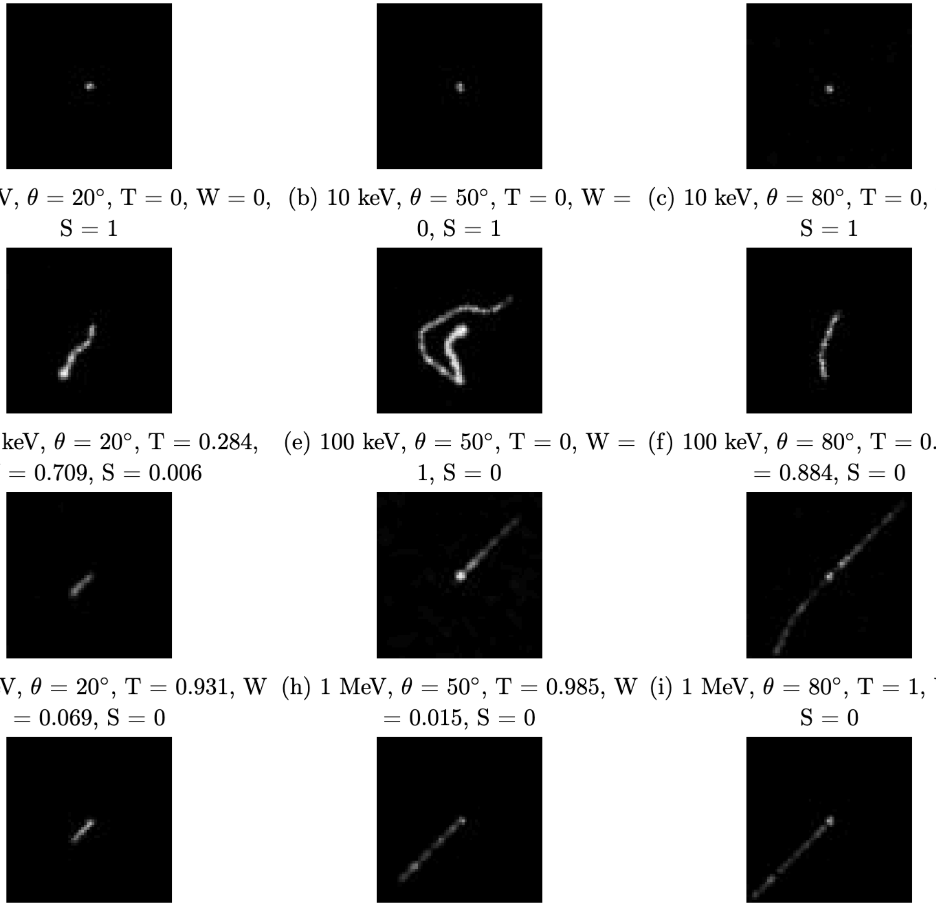
(b) 100 MeV, $\theta = 50°$, T = 1, W = 0, S = 0

(c) 100 MeV, $\theta = 80°$, T = 0.06, W = 0.940, S = 0

- Larger bias voltage causes smaller charge spread on pixels, which makes image brighter and narrower. Track rate also increases with larger bias voltage.

Examples of Simulated Events and Data Events

Simulated electrons at different kinetic energy / zenith angle with bias voltage -25V



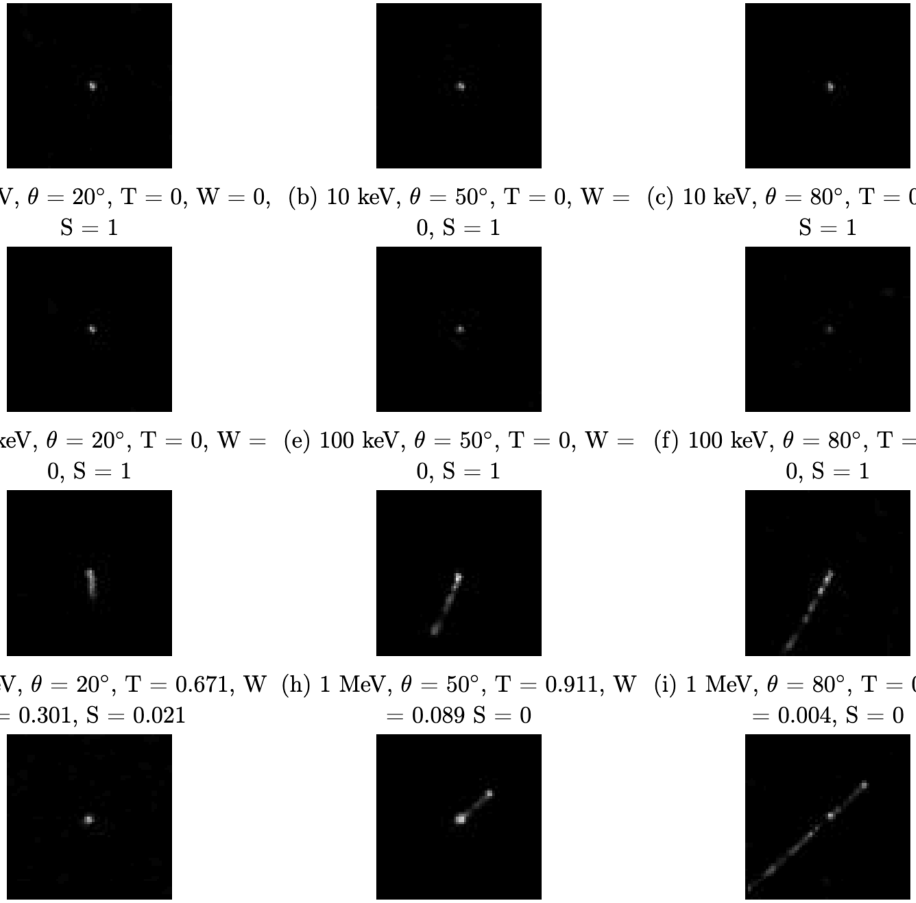
(a) 10 keV, $\theta = 20°$, T = 0, W = 0, S = 1 (b) 10 keV, $\theta = 50°$, T = 0, W = 0, S = 1 (c) 10 keV, $\theta = 80°$, T = 0, W = 0, S = 1

(d) 100 keV, $\theta = 20°$, T = 0.284, W = 0.709, S = 0.006 (e) 100 keV, $\theta = 50°$, T = 0, W = 1, S = 0 (f) 100 keV, $\theta = 80°$, T = 0.116, W = 0.884, S = 0

(g) 1 MeV, $\theta = 20°$, T = 0.931, W = 0.069, S = 0 (h) 1 MeV, $\theta = 50°$, T = 0.985, W = 0.015, S = 0 (i) 1 MeV, $\theta = 80°$, T = 1, W = 0, S = 0

(j) 10 MeV, $\theta = 20°$, T = 0.987, W = 0.013, S = 0 (k) 10 MeV, $\theta = 50°$, T = 0.998, W = 0.002, S = 0 (l) 10 MeV, $\theta = 80°$, T = 0.999, W = 0.001, S = 0

Simulated photons at different kinetic energy / zenith angle with bias voltage -25V



(a) 10 keV, $\theta = 20°$, T = 0, W = 0, S = 1 (b) 10 keV, $\theta = 50°$, T = 0, W = 0, S = 1 (c) 10 keV, $\theta = 80°$, T = 0, W = 0, S = 1

(d) 100 keV, $\theta = 20°$, T = 0, W = 0, S = 1 (e) 100 keV, $\theta = 50°$, T = 0, W = 0, S = 1 (f) 100 keV, $\theta = 80°$, T = 0, W = 0, S = 1

(g) 1 MeV, $\theta = 20°$, T = 0.671, W = 0.301, S = 0.021 (h) 1 MeV, $\theta = 50°$, T = 0.911, W = 0.089 S = 0 (i) 1 MeV, $\theta = 80°$, T = 0.996, W = 0.004, S = 0

(j) 10 MeV, $\theta = 20°$, T = 0, W = 0, S = 1 (k) 10 MeV, $\theta = 50°$, T = 0.708, W = 0.292, S = 0 (l) 10 MeV, $\theta = 80°$, T = 0.999, W = 0.001, S = 0

Since all observed events produced by photons are electrons from photoelectric effect / Compton scattering / pair production, their morphologies look similar with electrons on the left

Monte-Carlo Simulation

Monte Carlo Simulation Setup

- With procedure of simulating individual events as described before, we perform a Monte Carlo simulation by randomly generating muons according to the atmospheric muon flux *:

$$\frac{dN}{dEd\Omega dAdt} = E^{-2.7}\left(\frac{1}{1+1.11\frac{Ecos\theta}{115GeV}} + \frac{0.054}{1+1.11\frac{Ecos\theta}{850GeV}}\right)\left(\frac{E}{E+\frac{2GeV}{cos\theta}}\right)^{2.7} * cos\theta$$

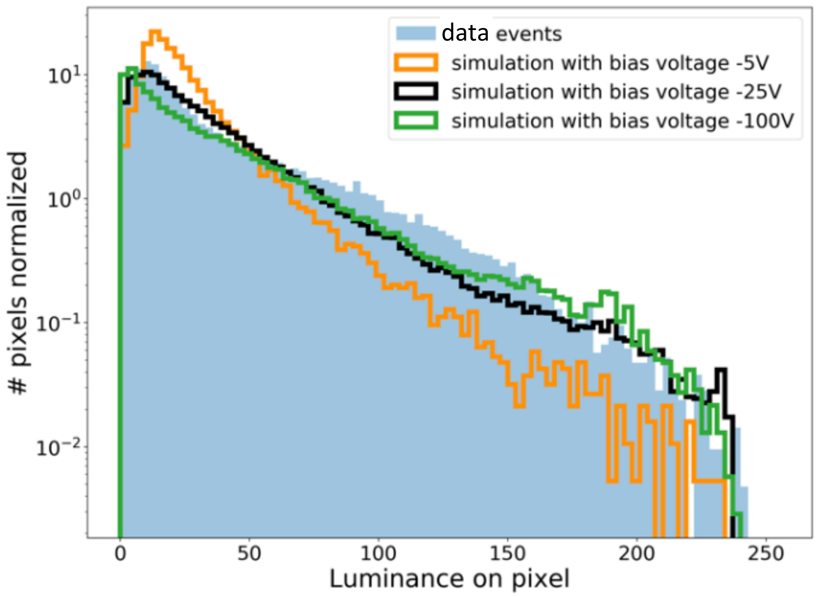
- All events are put into the CNN to be classified, and those with $P_{track} > 50\%$ are collected.

- Several parameters are extracted from both simulated images and DECO data images with $P_{track} > 50\%$.

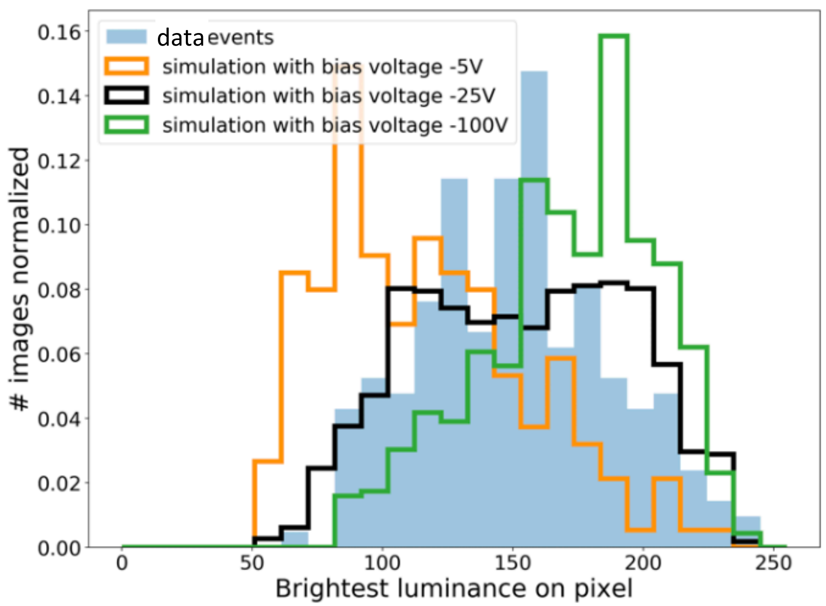
* T. K. Gaisser, et.al, Cosmic Rays and Particle Physics.

Data/Monte Carlo Comparison

- All following analysis are done with both simulated images with 3 different bias voltage values and data events, use CNN to select those with $P_{track} > 50\%$



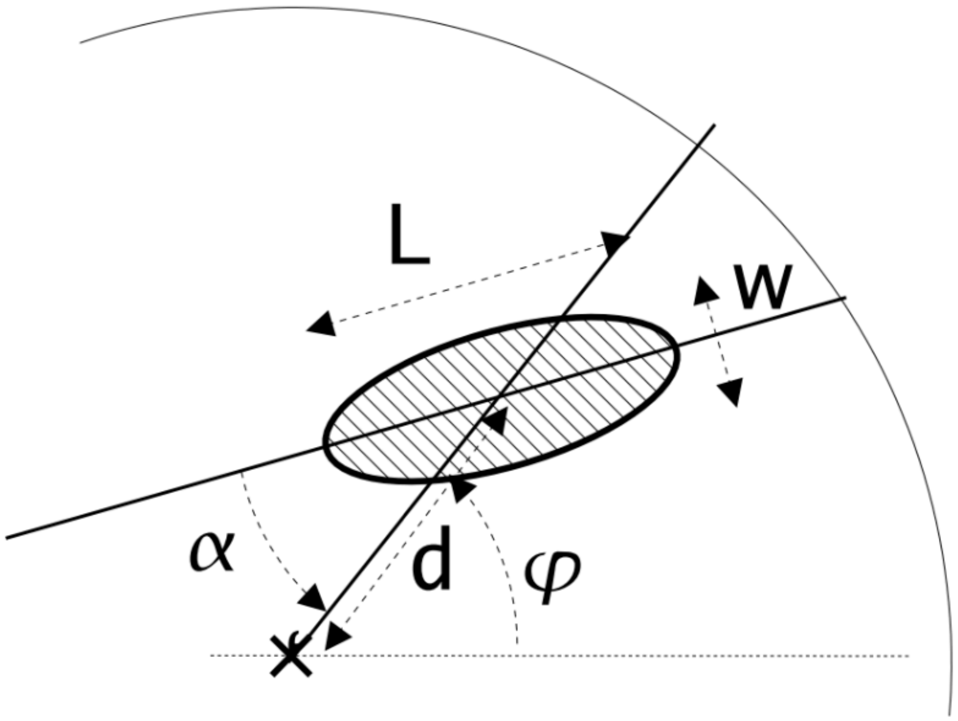
Distribution of luminance on image pixels.



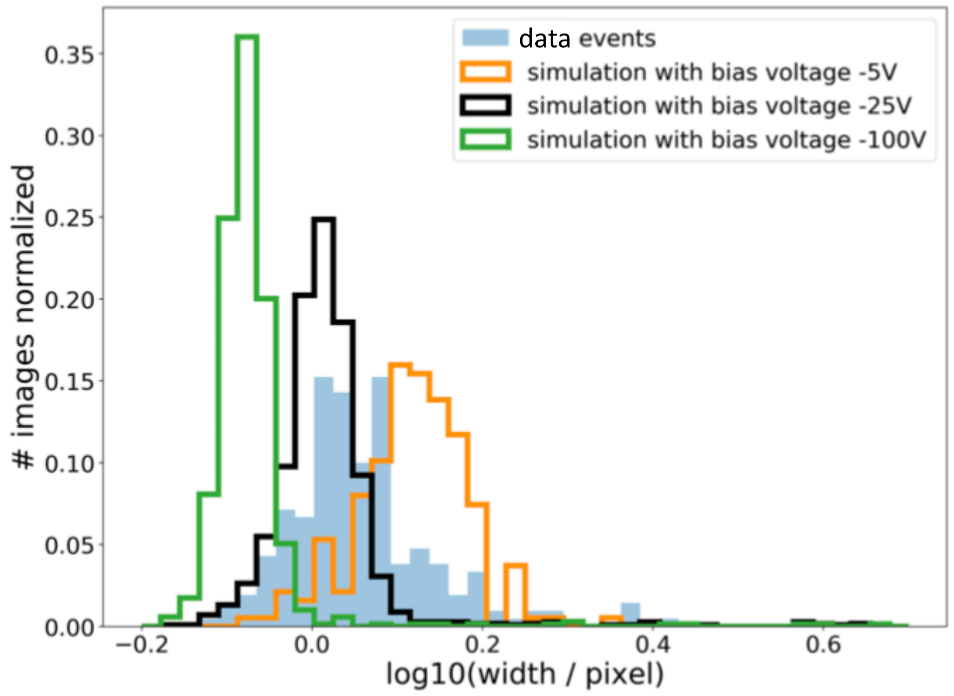
Distribution of brightest pixel luminance on image.

- With larger bias voltage, charge spread will be smaller and the number of pixels with large luminance will increase
- The best match with data events we have is using -25V bias voltage
- Remaining discrepancy could be caused by field model / interpolation method / electron-muon ratio

Data/Monte Carlo Comparison



Hillas parameters *



Distribution of Hillas width.

- With larger bias voltage, charge spread will be smaller so the Hillas width tends to be larger

* arXiv:astro-ph/0305308

Conclusion and Next Step

- DECO is a cell phone app which uses its silicon camera image sensor (CMOS) to detect cosmic-ray particles or particles from radioactive decay, which provides a nice tool for citizen science and general education.

- In order to train the CNN in DECO such that it is able to classify particle type / energy / direction, we are working on building a simulation tool that produces similar images as DECO data events

- Although current simulation produces results similar with DECO events in many parameter tests, there are some discrepancies remaining, which could be caused by the simplified model of electric field, color interpolation algorithm, or image processing algorithms.

- We are still working on improving our Data / Monte-Carlo agreement. Once it is done, we will begin training the CNN with simulated data.

- Possible next steps: Using raw image, asking manufacturer about electric field setup and image processing method, switching to unsupervised learning …….