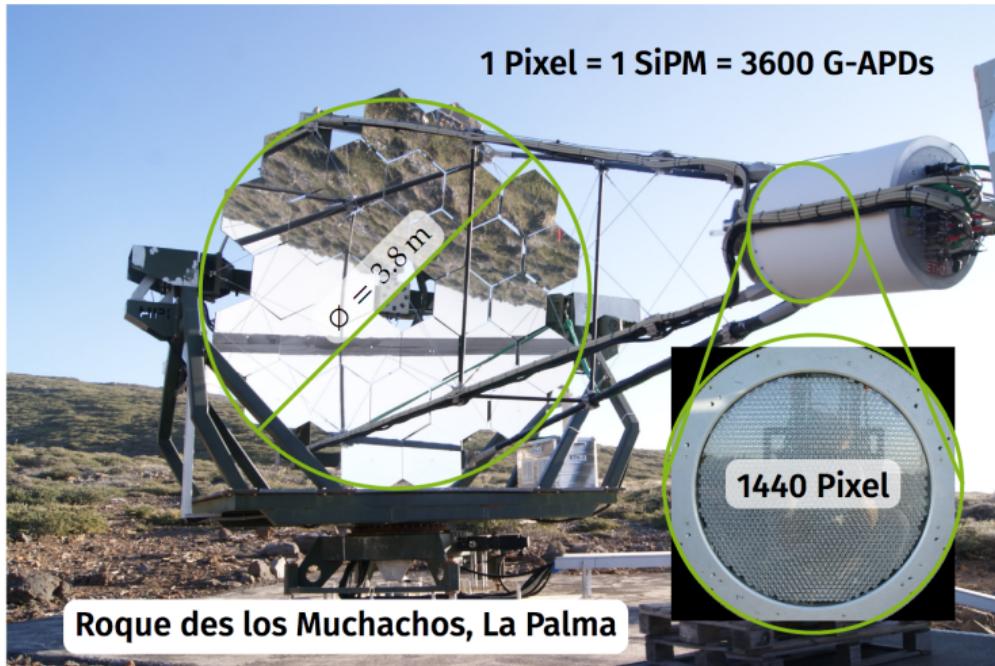


Analysis Of The Crab Nebula Using FACT's Photon Stream Data

Kevin Sedlaczek for the FACT-Collaboration

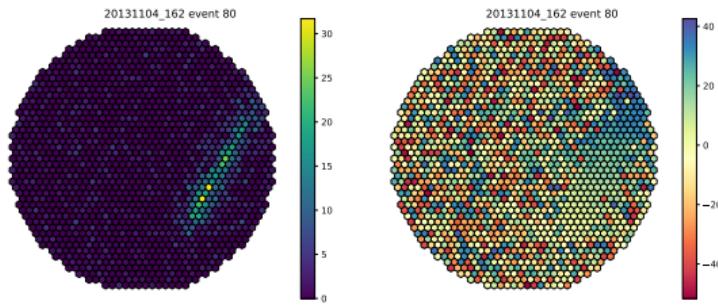
November 2, 2018

The First G-APD Cherenkov Telescope



data formats

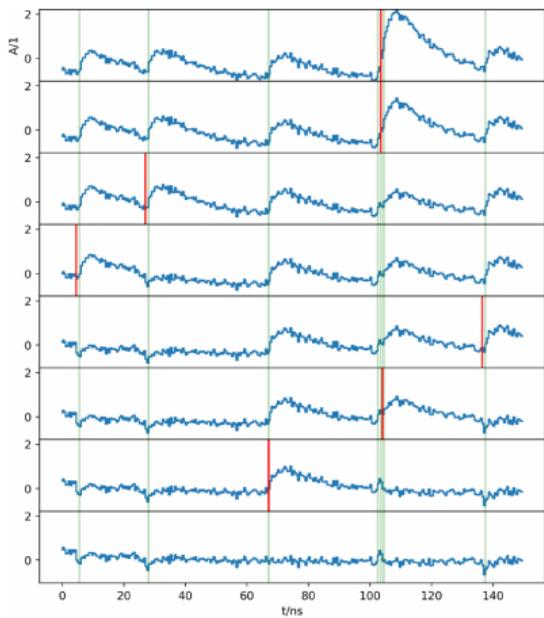
Largest pulse representation



- FACT records data in format close to readout hardware
- superposition of multiple photon signals in time series
- data describing electric pulses instead of photons
- 2 attributes:
 - **c** charge integral / p.e.
 - **t** arrival times / ns
- shower: largest pulse along **t**-axis

→interpretation of sensor response instead of photons

Photon Stream



- extracting single photons from time series of sensor responses
- list of arrival times of **single** photons / pixel
- 3 attributes:
 - c_x first spatial coordinate
 - c_y second spatial coordinate
 - c_t arrival time
- shower: extraction from 3-dimensional objects
- decoupled from hardware

→interpretation of observables of single photons

Photon Stream

$\left[\begin{array}{c} [59, 84] \\ [93, 102, 103] \\ [58] \\ [65, 79, 97] \\ [] \\ [43, 68, 125] \\ [102] \\ [68, 100, 123] \\ [77, 88, 99, 111] \\ [42, 142, 157] \\ [99] \\ [111, 132] \\ \dots \end{array} \right]$

- extracting single photons from time series of sensor responses
- list of arrival times of **single** photons / pixel
- 3 attributes:
 - c_x first spatial coordinate
 - c_y second spatial coordinate
 - c_t arrival time
- shower: extraction from 3-dimensional objects
- decoupled from hardware

→interpretation of observables of single photons

data preparation / cleaning

Largest pulse

1. search for high photon density along time axis (large pulses) t
2. integrate time series to estimate number of photons
3. estimate arrival time from fit of polynomial to rising edge

Cleaning

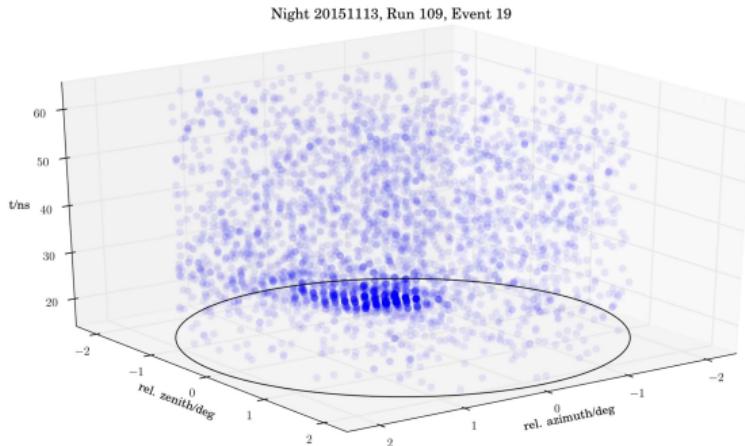
1. Find pixels containing more photons than an upper threshold t_1 (5 p.e.)
2. Remove pixels with less than 2 neighbors above t_1
3. Add neighbors of remaining pixels that are above lower threshold t_2 (2.5 p.e.)
4. Remove pixels that have less than 2 neighbors arriving in 5 ns time window
5. Remove single pixels with less than 2 neighbors
6. Remove pixels that have less than 2 neighbors inside 5 ns time window

Photon Stream

density based algorithm for discovering clusters with noise (DBSCAN)

- assign each photon to night-sky-background or cluster
- multiple clusters can be found
- no assumption of shape of clusters
- 2 parameters:
 - minimal number of photons a dense cluster must contain (20)
 - maximum distance between each photon to be considered dense ($0,45^\circ$)
- all observables taken into account simultaneously

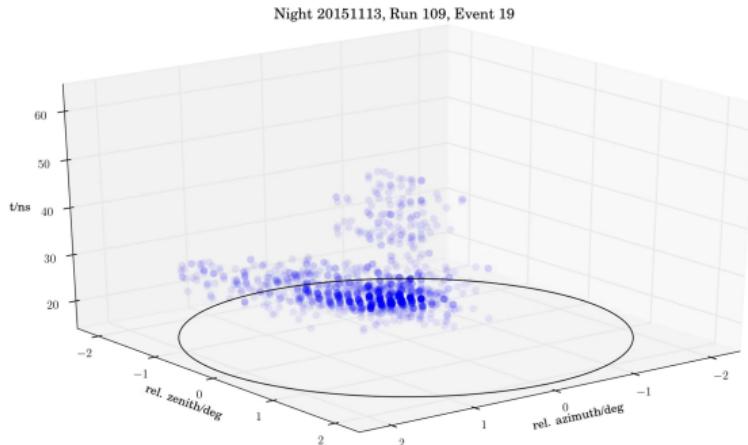
DBSCAN



Algorithm:

1. loop over photons to find a dense cluster ($\mathbf{x}, \mathbf{y}, t$)
2. add photons within ϵ or via *dense chain*
3. if nothing to add to cluster continue with left over photons
4. photons without cluster assignment: background

DBSCAN



Algorithm:

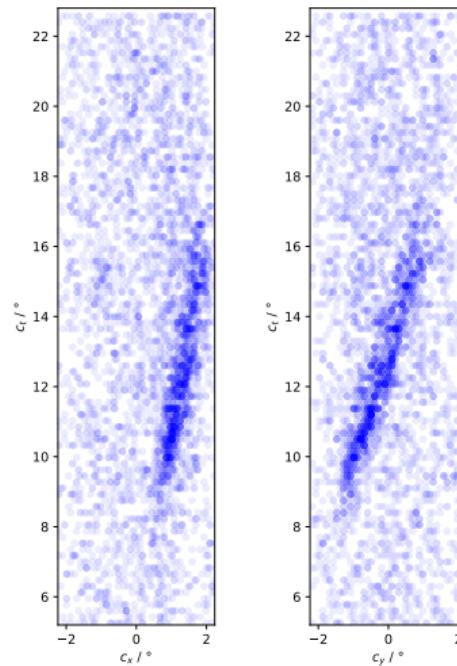
1. loop over photons to find a dense cluster ($\mathbf{x}, \mathbf{y}, t$)
2. add photons within ε or via *dense chain*
3. if nothing to add to cluster continue with left over photons
4. photons without cluster assignment: background

DBSCAN

What about the metric?

- $c_t = \alpha \cdot t$
- chosen to have similar distributions along all dimensions for typical photon rates
- $\alpha = 0,35 \cdot 10^9 \text{ } \circ/\text{s}$

In total 3 parameters: α, ε, m



Comparison of methods: Number of found air-shower

	Gamma-rays			Protons		
	DBSCAN	LP	DBSCAN \in LP	DBSCAN	LP	DBSCAN \in LP
After triggers	8725	8725	8725	2134	2134	2134
found air-shower	8300	5103	5078	1668	739	726

Table: Number of found air-showers for different cleanings on Proton and Gamma simulations.

- 63 % more gamma events in DBSCAN
- 126 % more proton events in DBSCAN

Comparison of methods

$$\delta_{1,2} = \arccos \left(\frac{I_1 \cdot I_2}{\|I_1\| \cdot \|I_2\|} \right) \quad D_{1,2} = \|I_1 - I_2\|$$

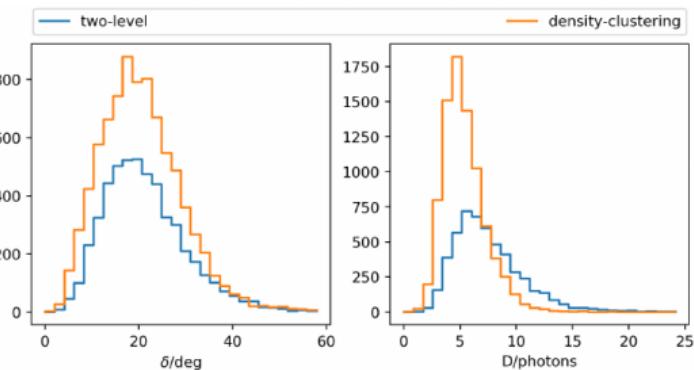


Figure: Gammas

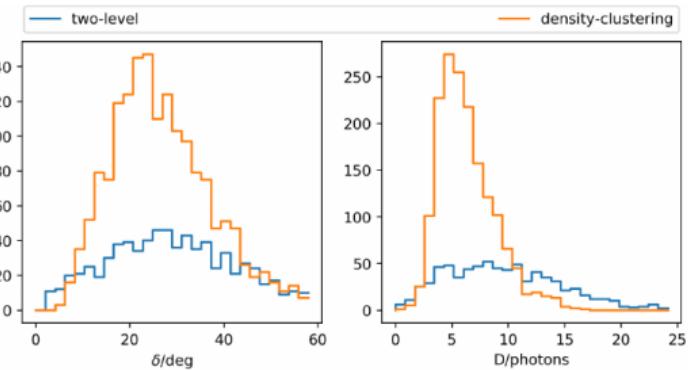


Figure: Protons

Comparison of methods

$$\delta_{1,2} = \arccos \left(\frac{\mathbf{I}_1 \cdot \mathbf{I}_2}{\|\mathbf{I}_1\| \cdot \|\mathbf{I}_2\|} \right) \quad D_{1,2} = \|\mathbf{I}_1 - \mathbf{I}_2\|$$

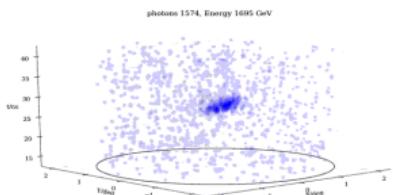
metric	Gamma-rays		Protons	
	DBSCAN	LP	DBSCAN	LP
mean δ/deg	22.6	23.3	29.3	31.4
mean $D/\text{p.e.}$	6.2	8.4	7.2	10.5
on overlap events				
mean δ/deg	18.6	23.3	22.8	31.3
mean $D/\text{p.e.}$	6.8	8.4	8.0	10.6

Data Set

The Data set: FACT open data crab sample

Photon-Stream (phs)

Single photon event representation for Imaging Atmospheric Cherenkov Telescopes (IACTs)



Public

Crab Nebula

High quality observations of the Crab Nebula in November 2013. Free to use for everyone. Please cite our [photon-1](#) on [GitHub](#).

Simulations (sim)

The FACT responses to simulated air-shower observations. This is the diffuse [ceres_12_rc](#) simulation pass.

Private

Observations (obs)

All observed air-shower events of FACT. About 1e9 air-shower records containing about 3e12 single photons. See [2](#)

About

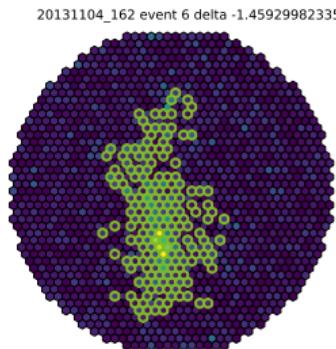
- [ICRC2017 proceeding](#)
- [photon-stream Python](#)
- [photon-stream C++](#)
- [production tools](#)

FACT collaboration, Sebastian A. Mueller, 2017

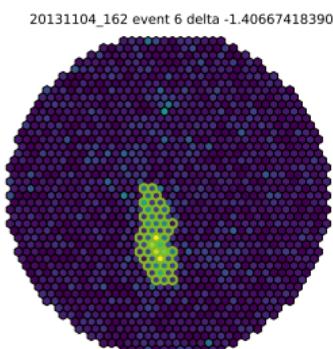
- <https://fact-project.org/data>
- Crab Nebula observations from November 2013
- including gamma-ray and proton simulations
- 17.7 hours of observations

Images on data

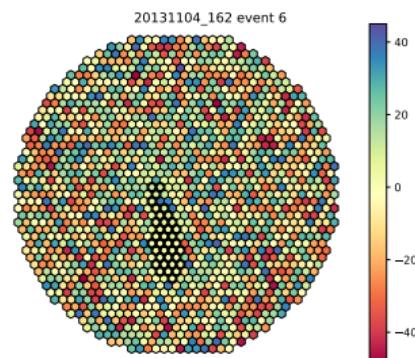
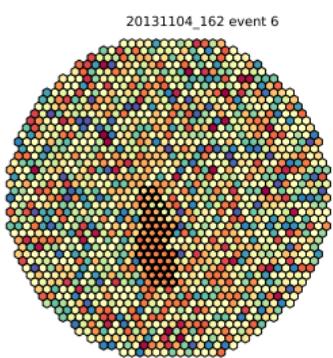
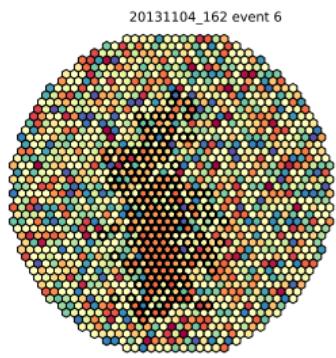
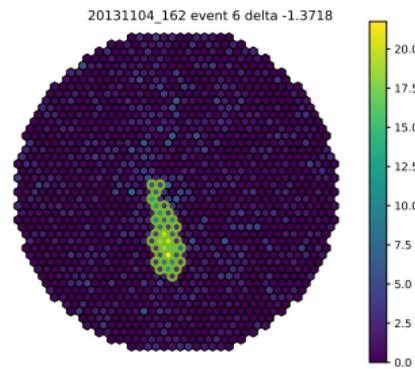
DBSCAN



Thresholds on phs

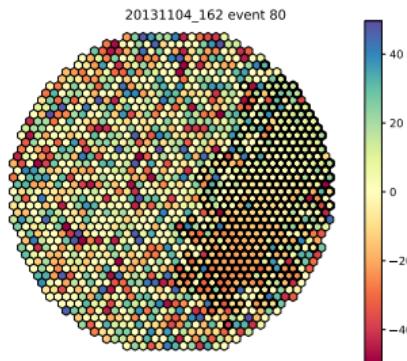
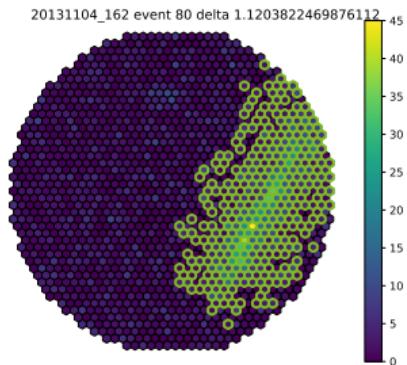


FACTtools

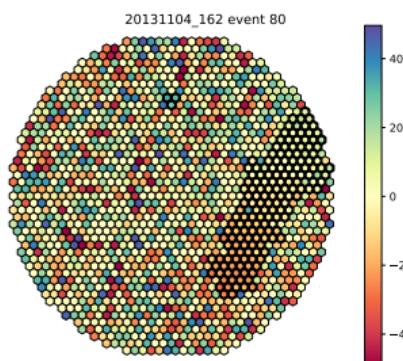
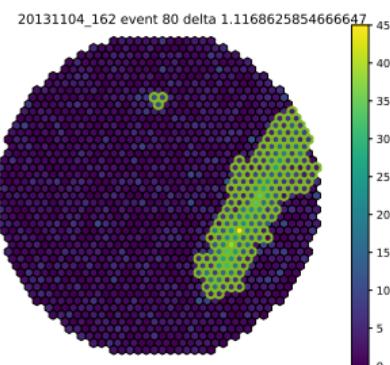


Images on data

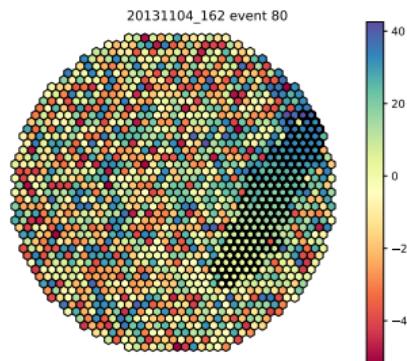
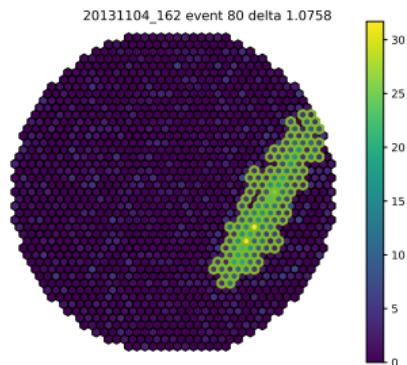
DBSCAN



Thresholds on phs

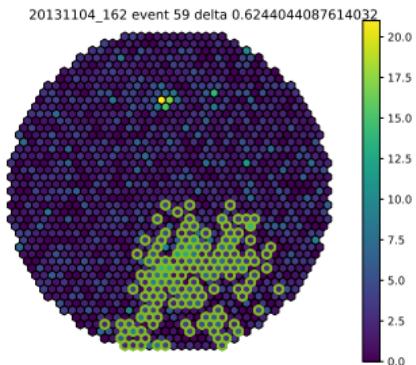


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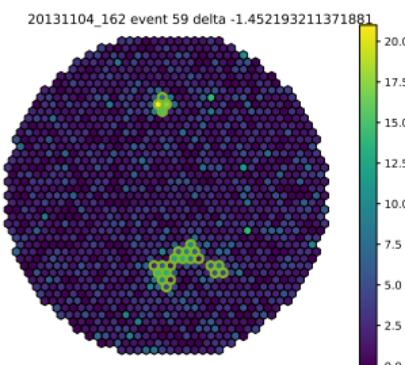


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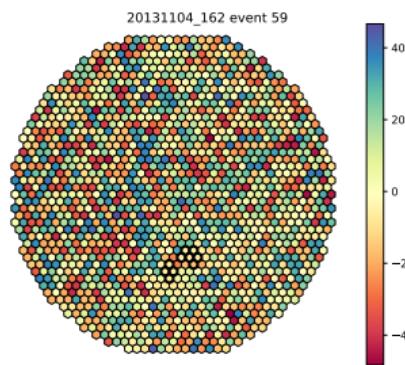
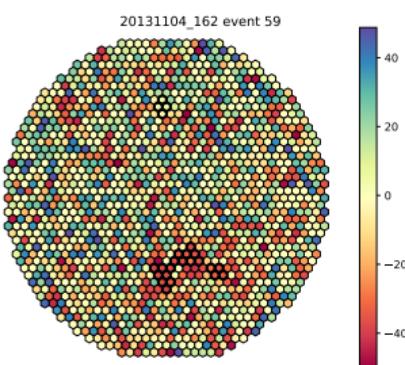
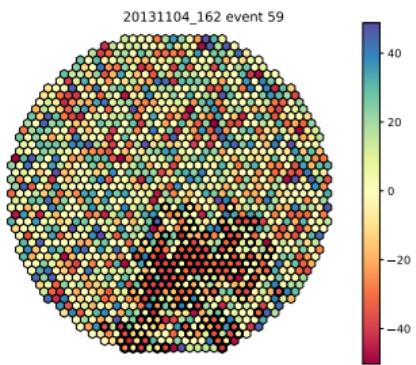
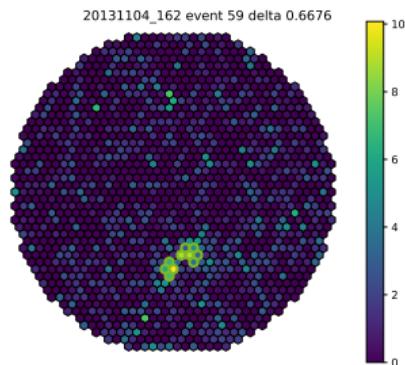
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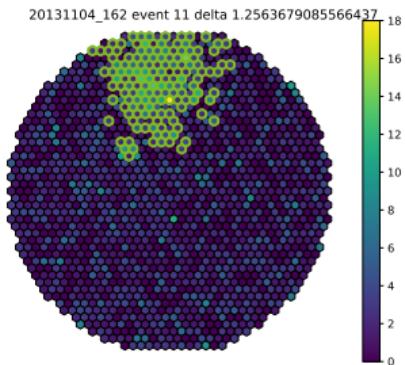
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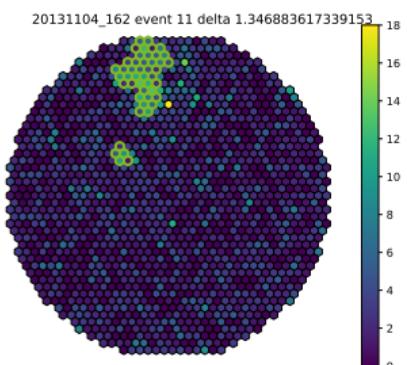
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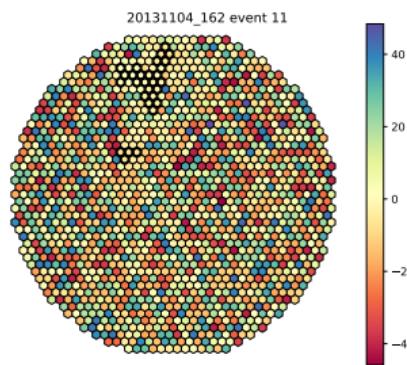
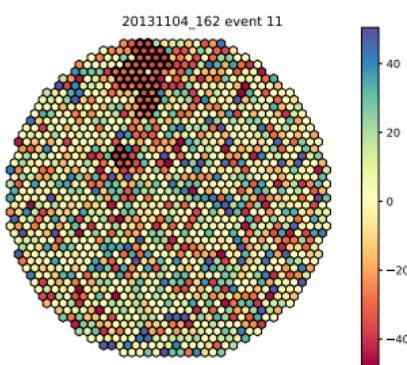
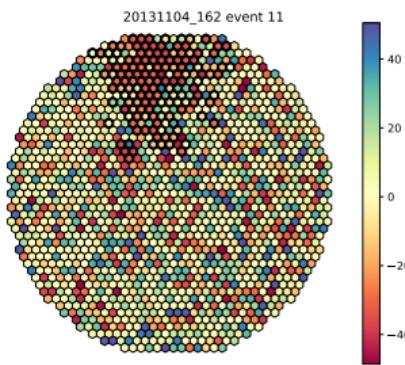
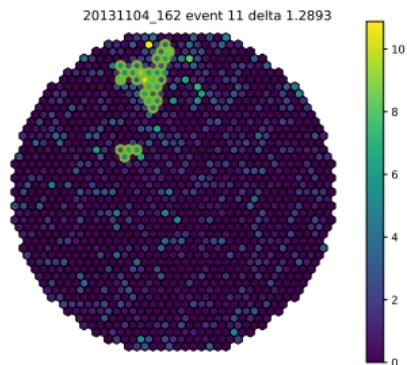
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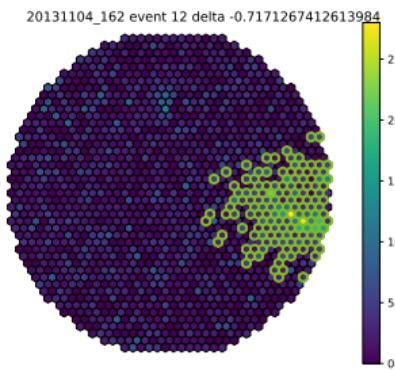
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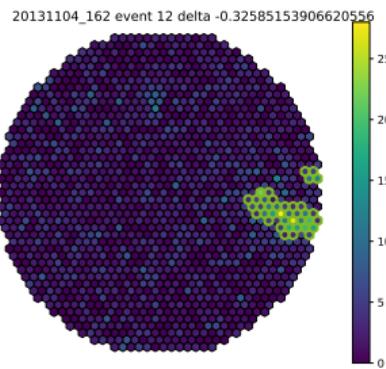
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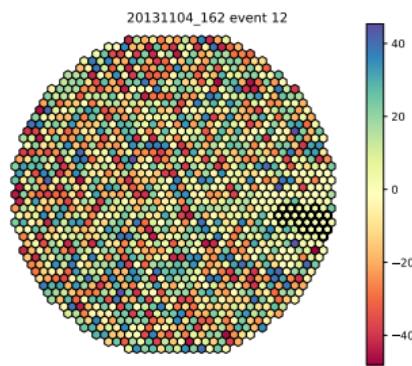
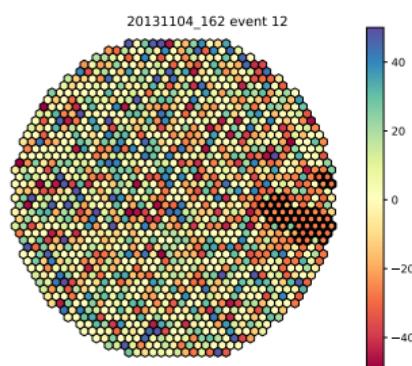
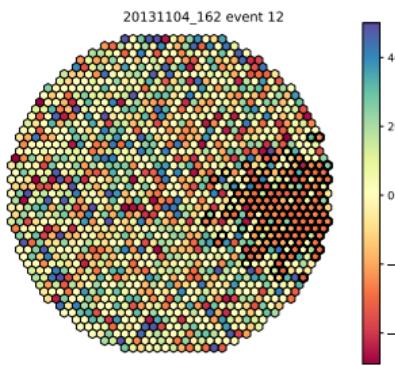
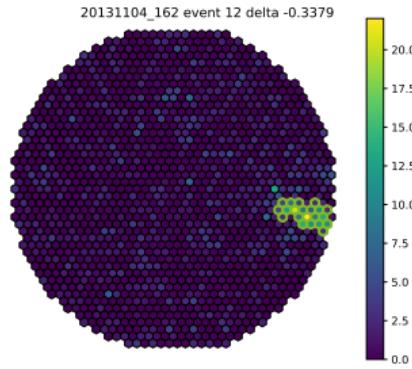
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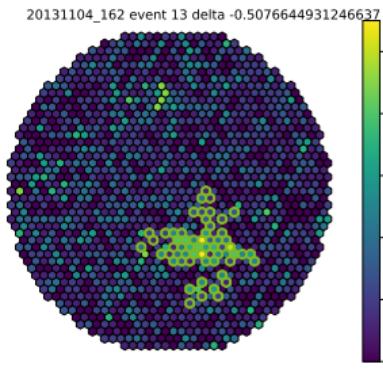
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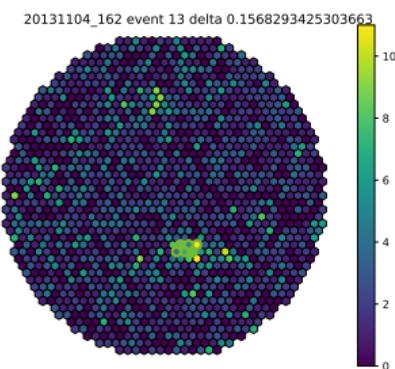
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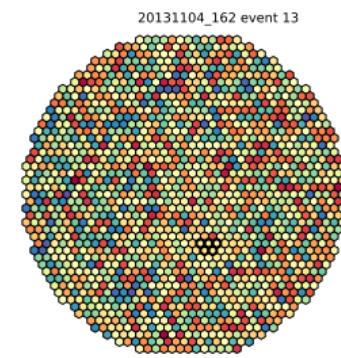
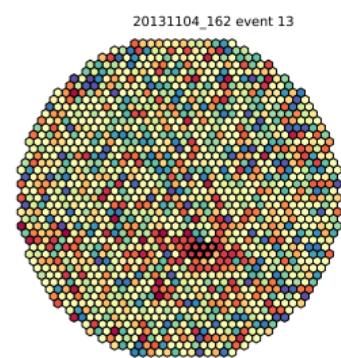
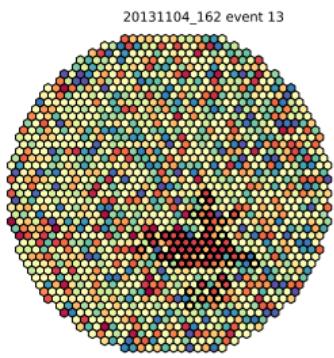
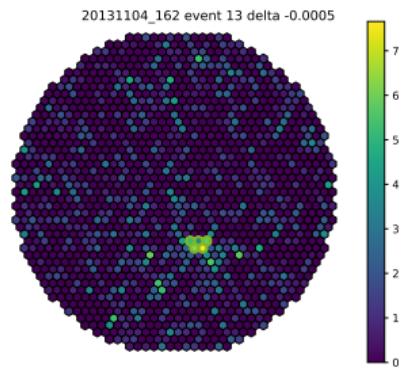
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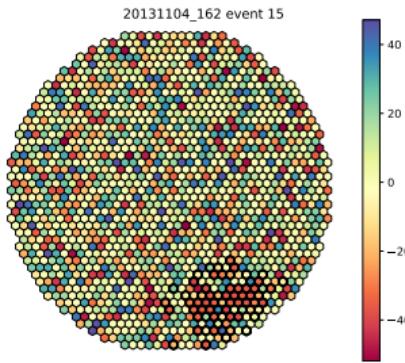
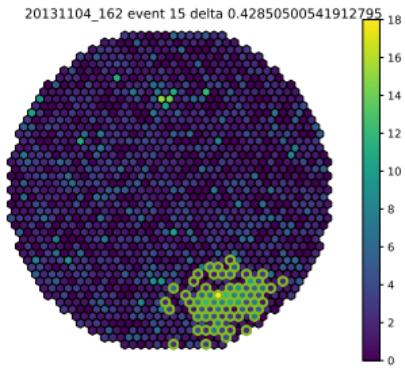
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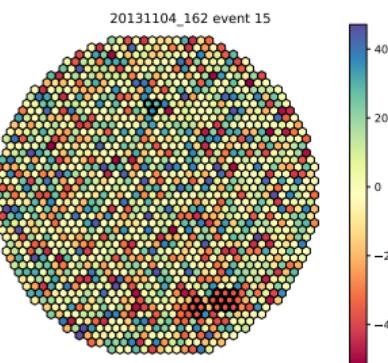
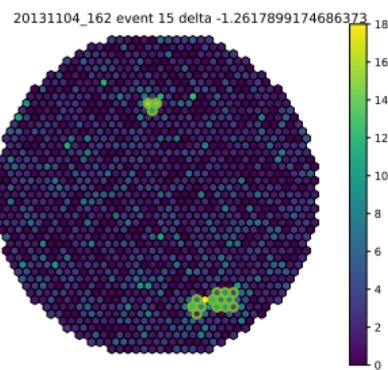
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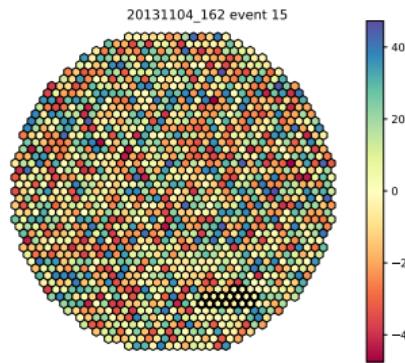
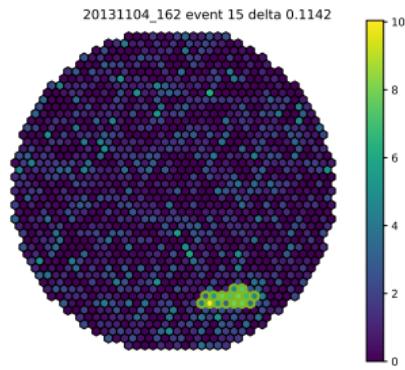
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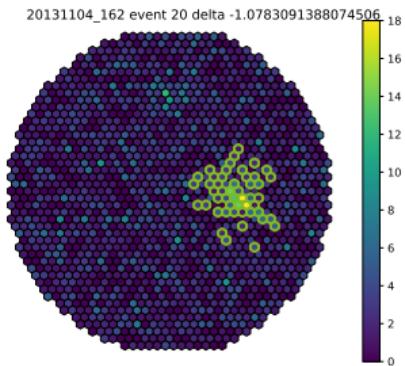


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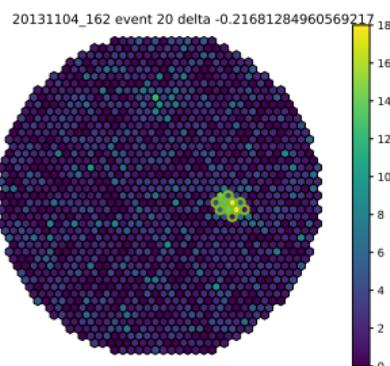


Images on data

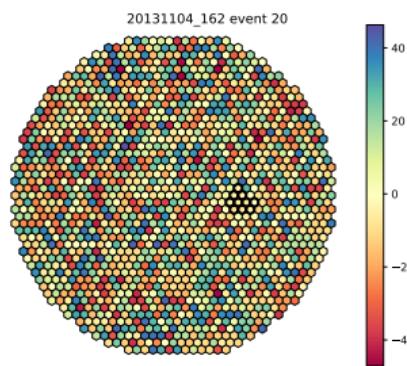
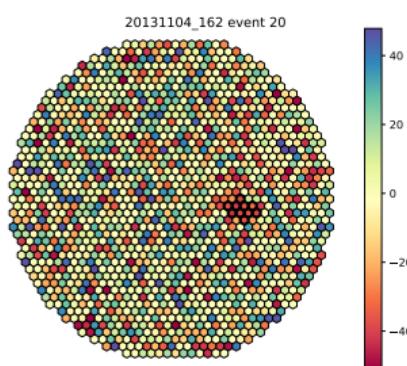
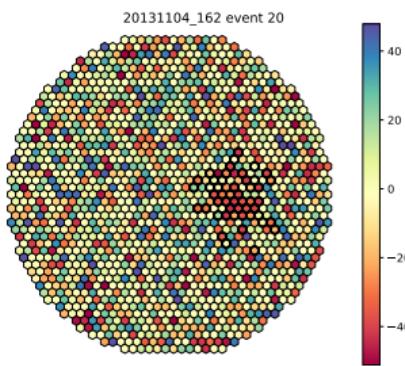
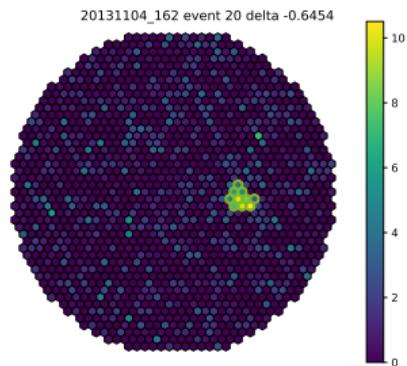
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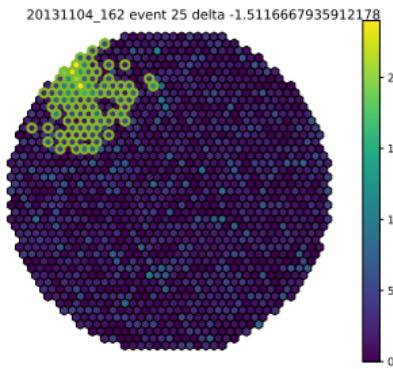
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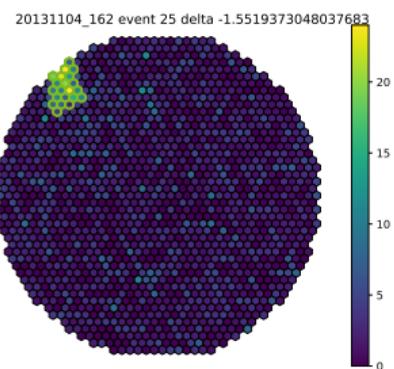
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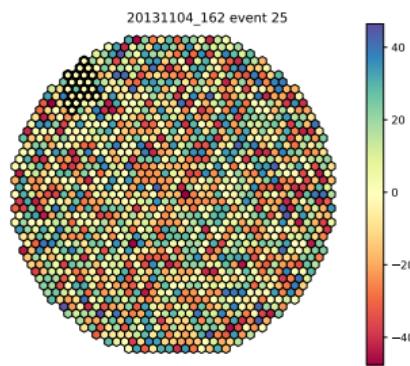
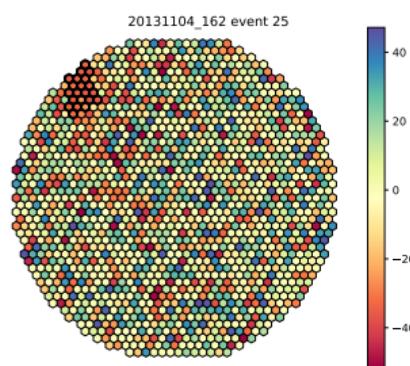
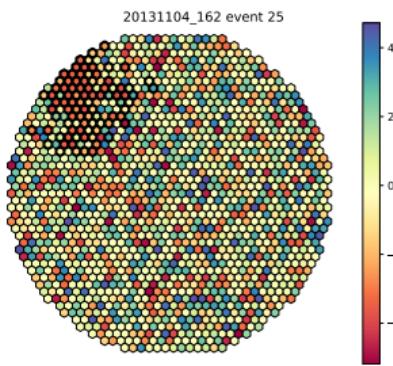
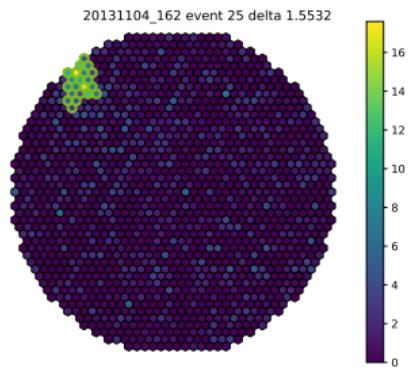
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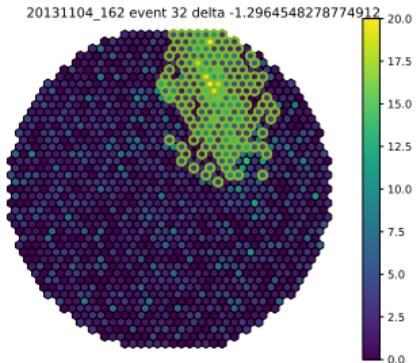
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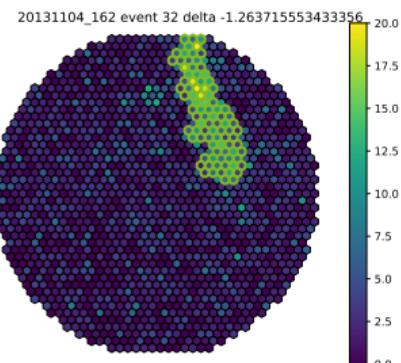
FACTtools



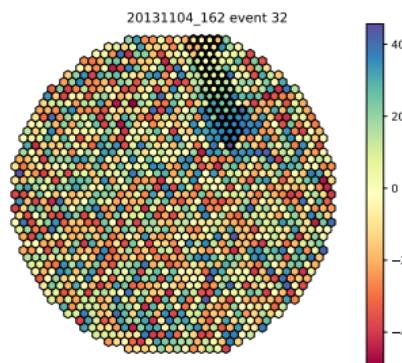
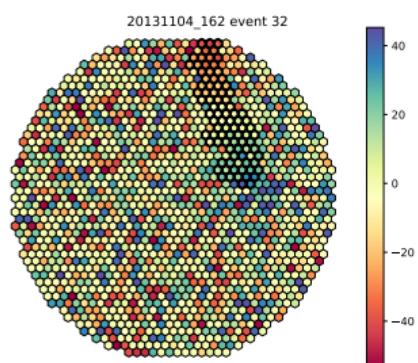
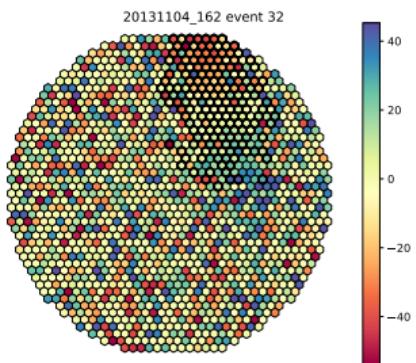
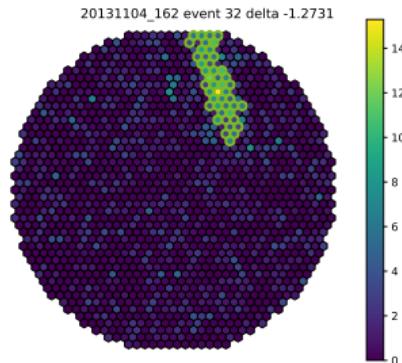
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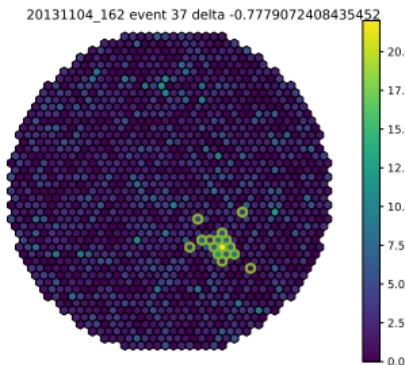
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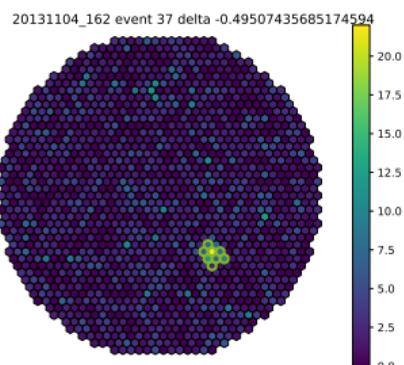
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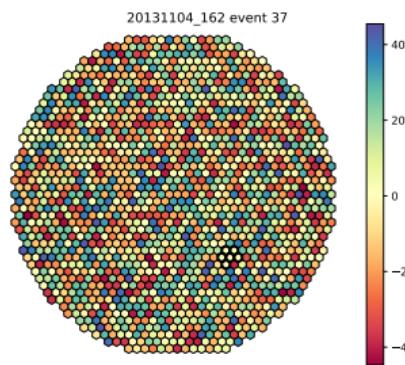
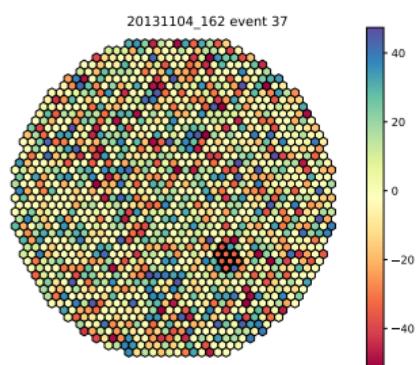
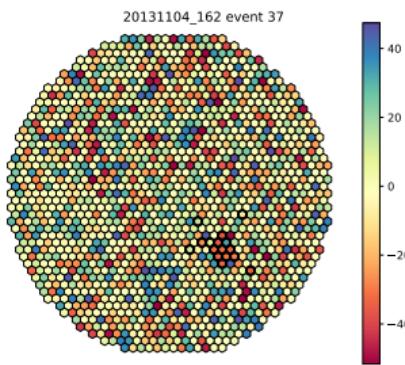
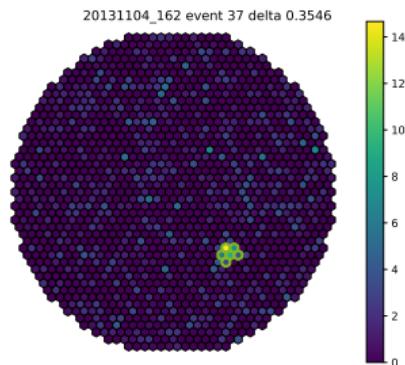
DBSCAN



Thresholds on phs

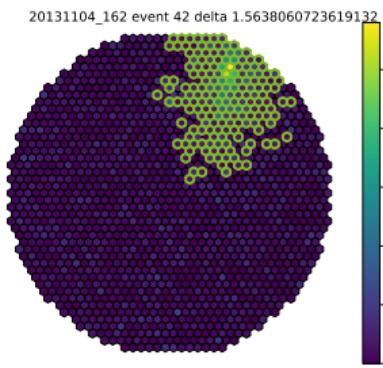


FACTtools

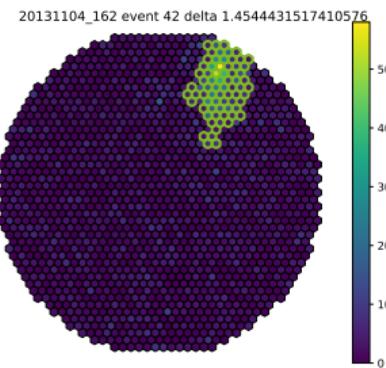


Images on data

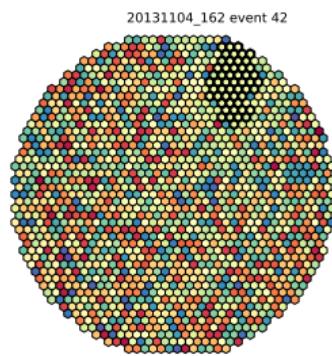
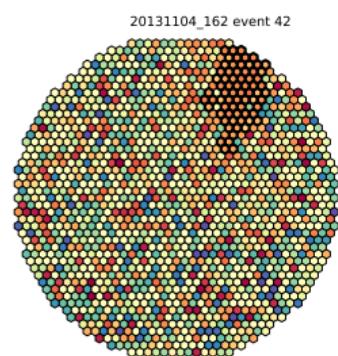
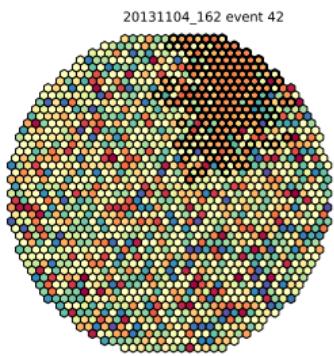
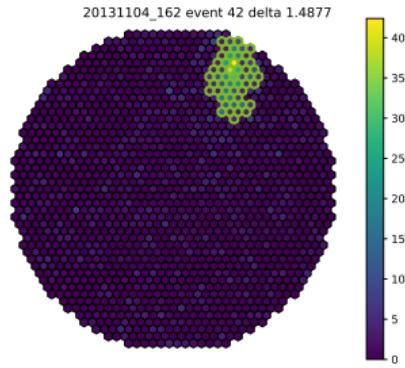
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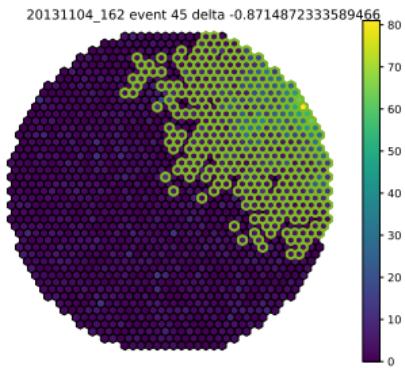
Thresholds on phs



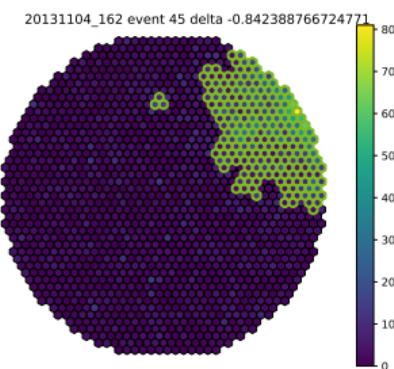
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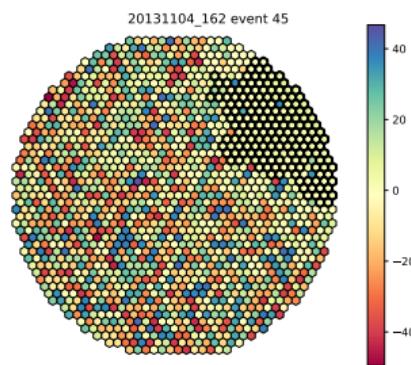
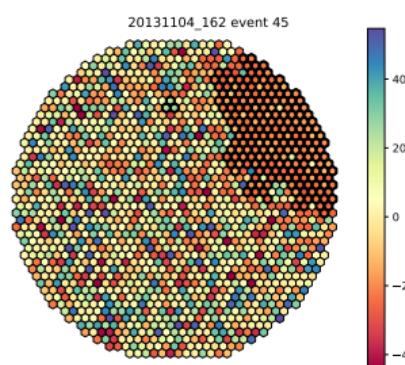
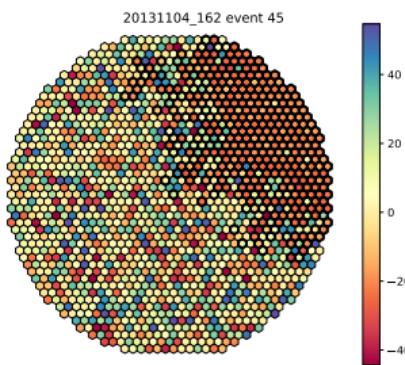
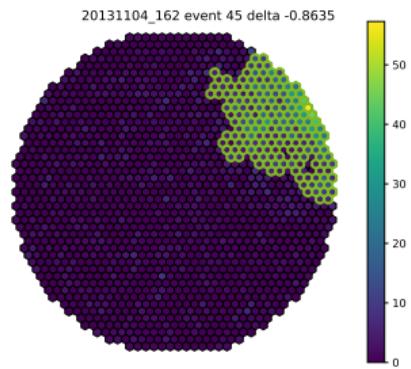
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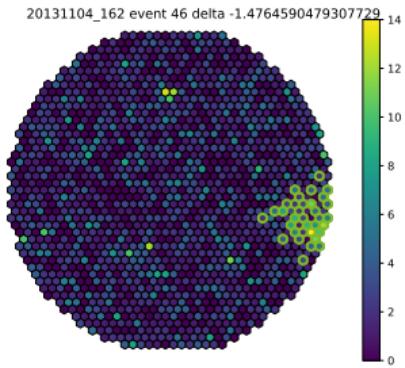
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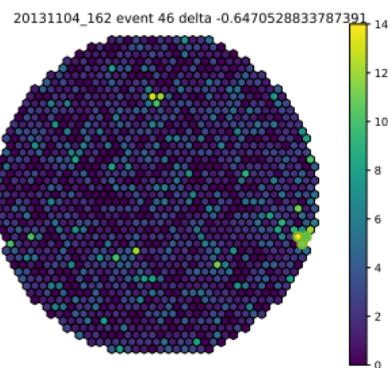
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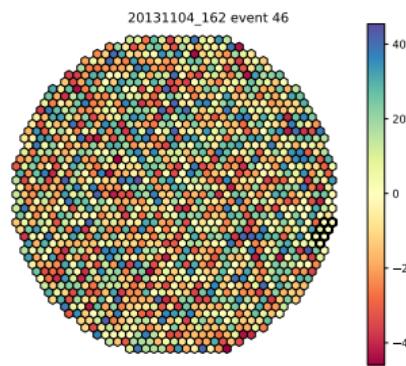
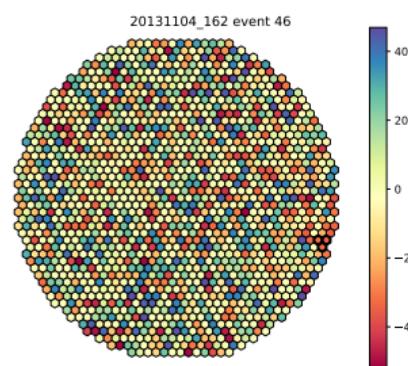
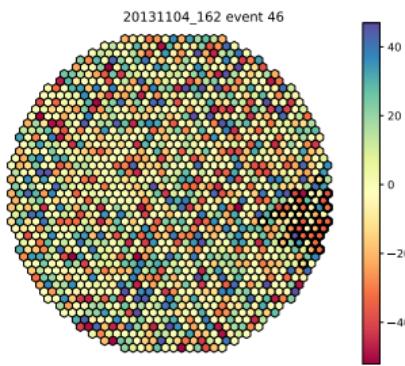
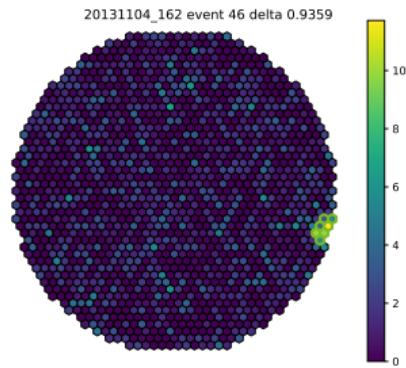
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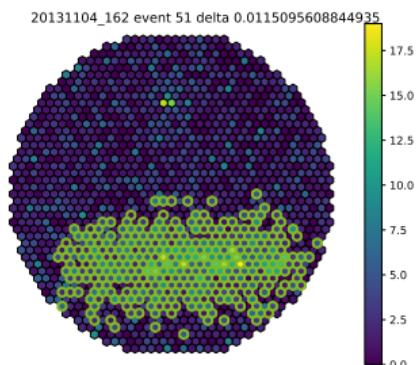
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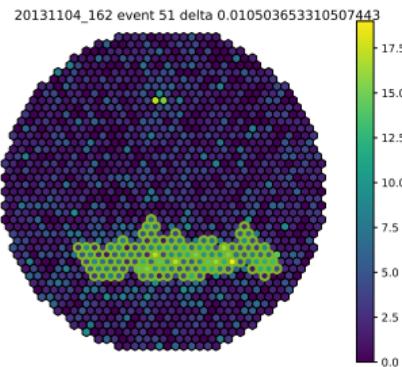
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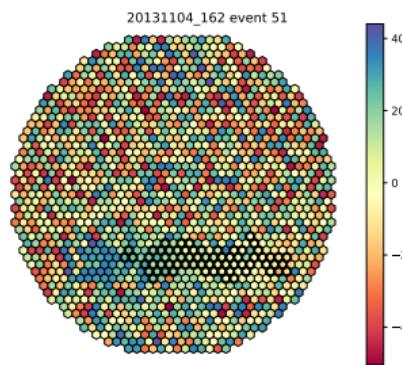
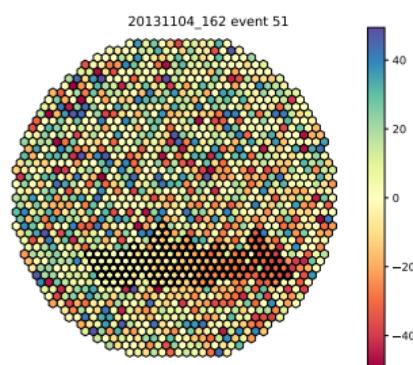
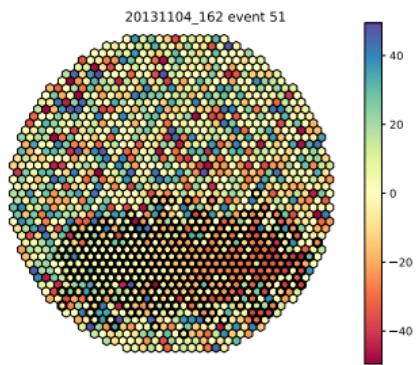
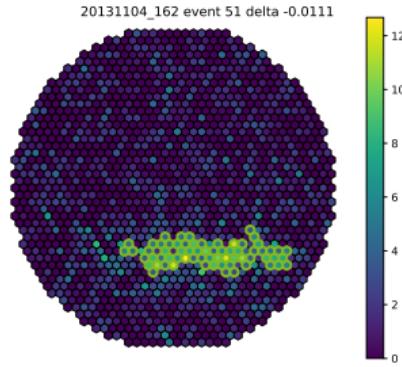
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Thresholds on phs

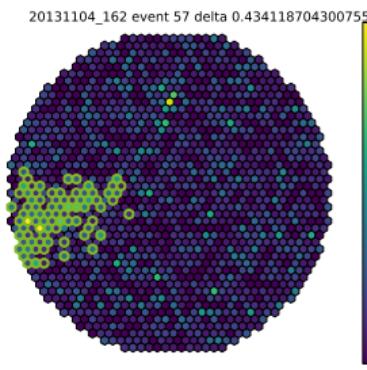


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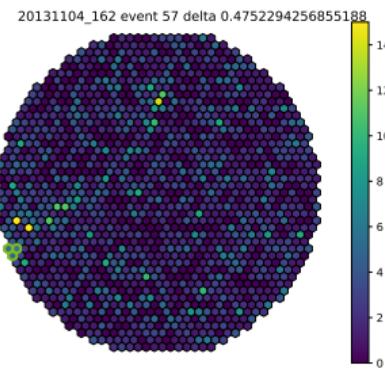


Images on data

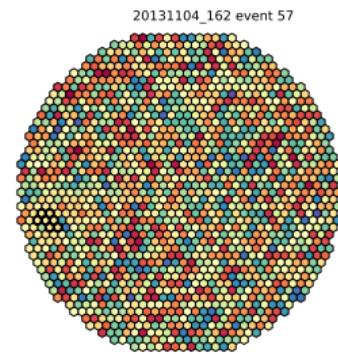
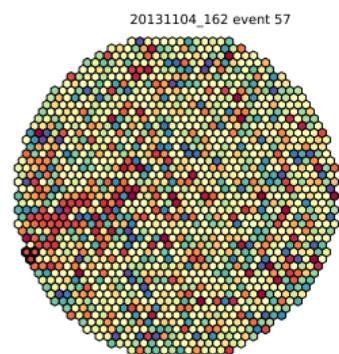
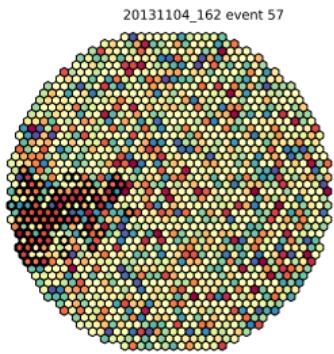
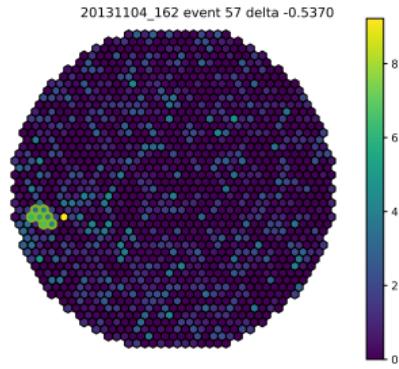
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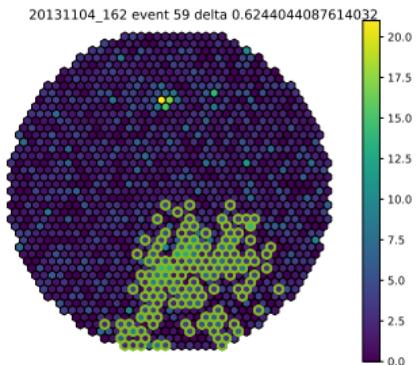
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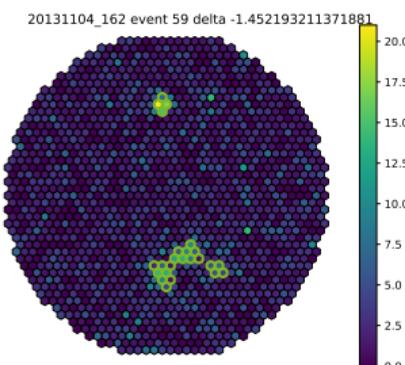
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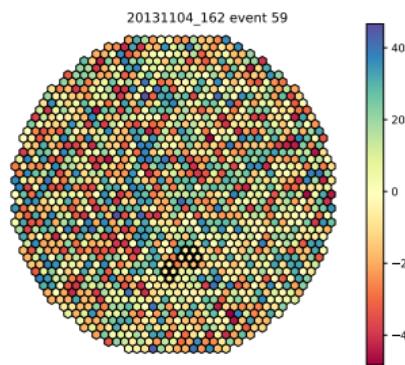
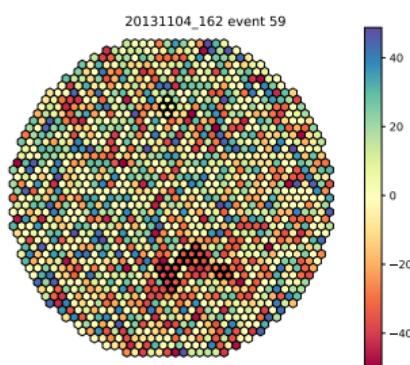
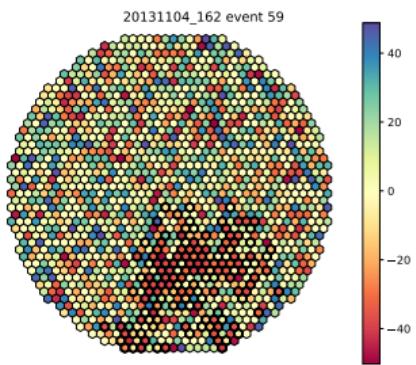
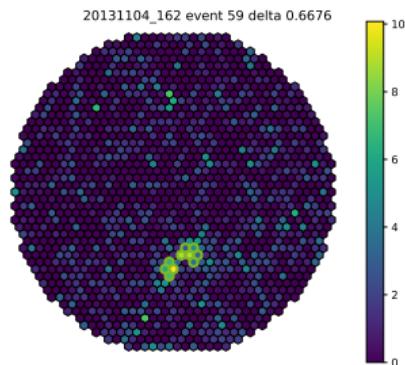
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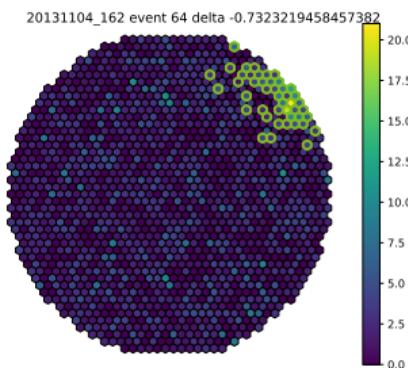
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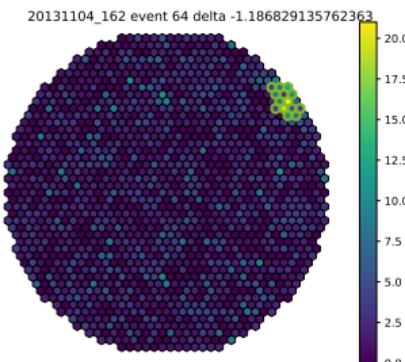
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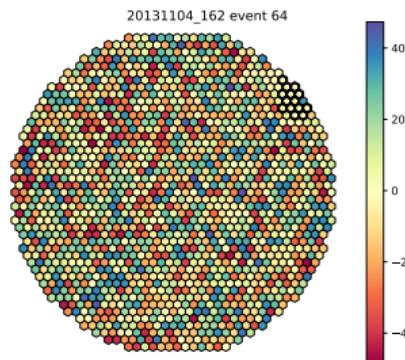
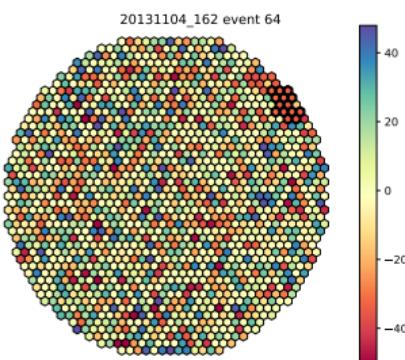
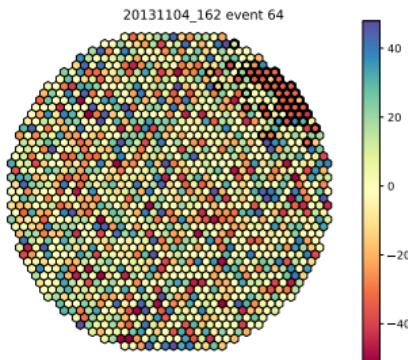
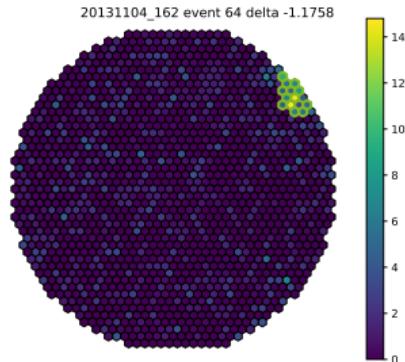
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Thresholds on phs

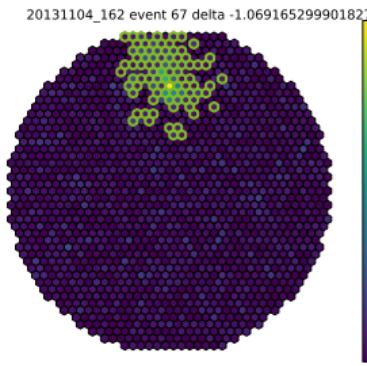


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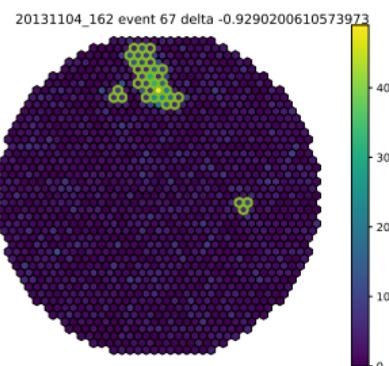


Images on data

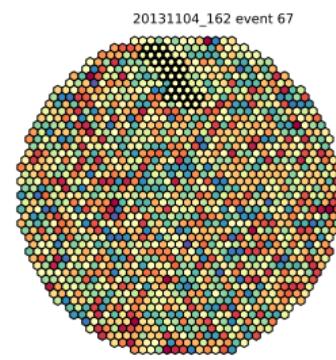
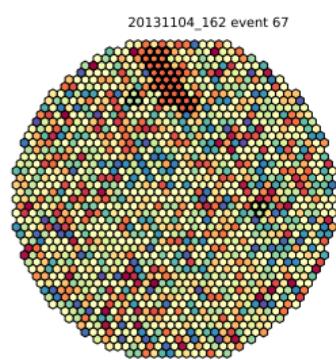
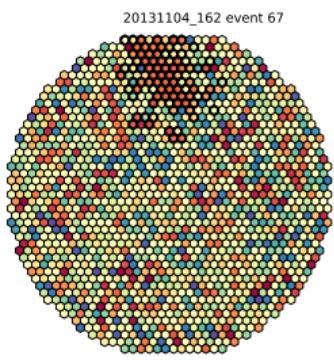
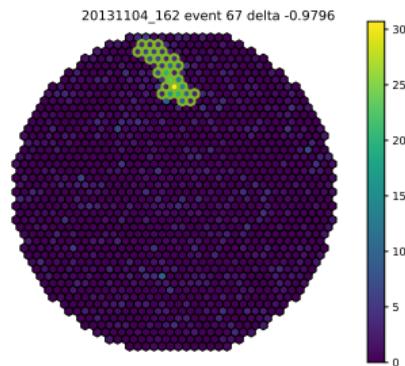
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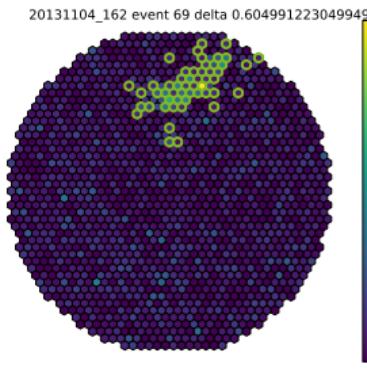
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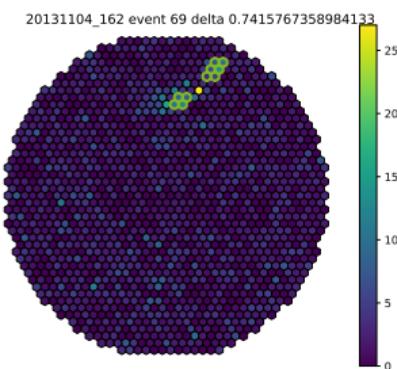
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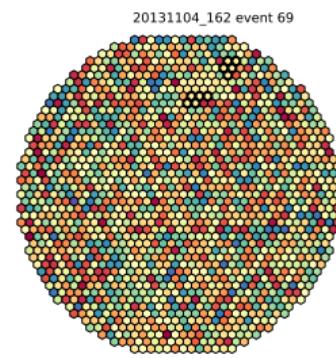
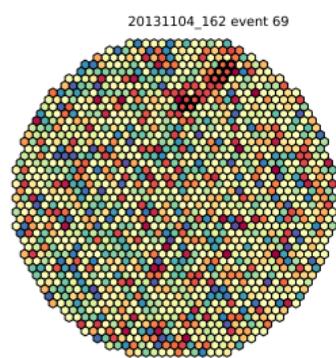
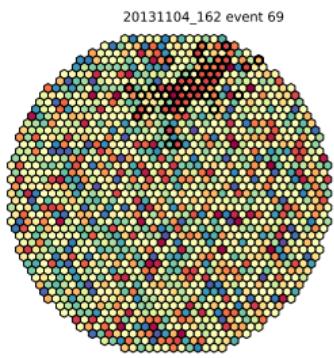
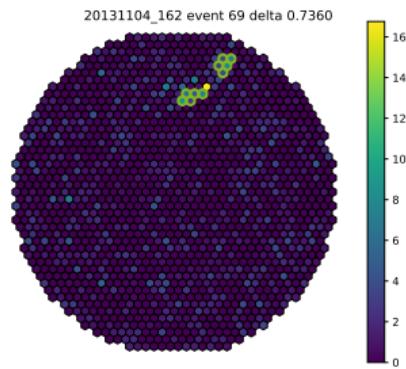
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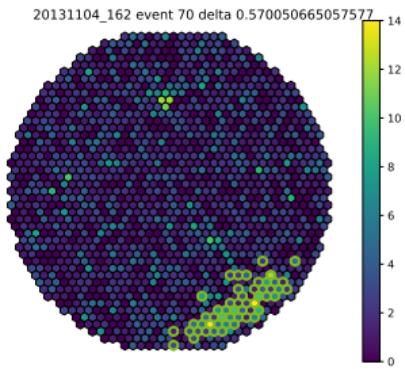
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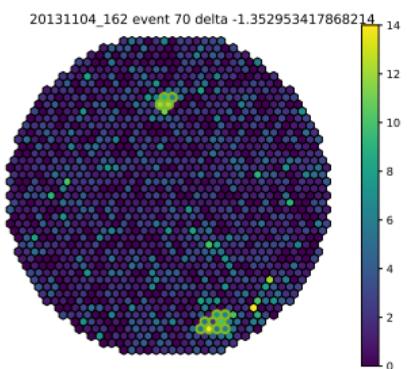
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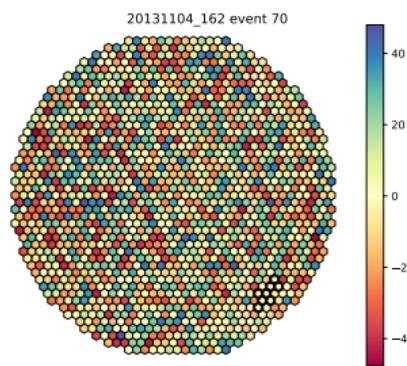
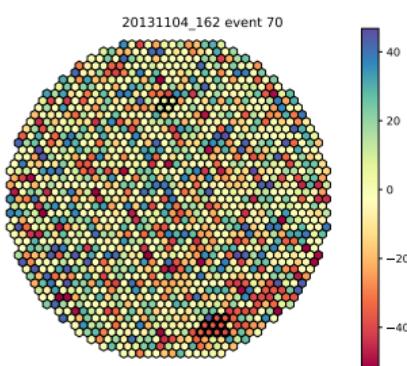
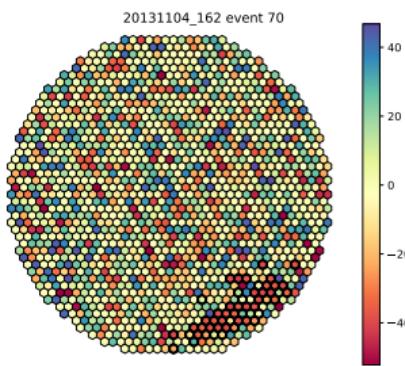
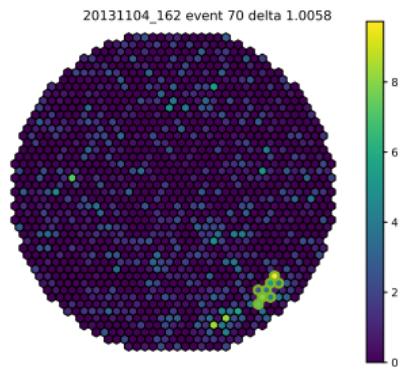
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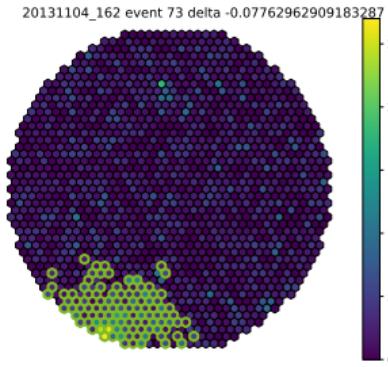
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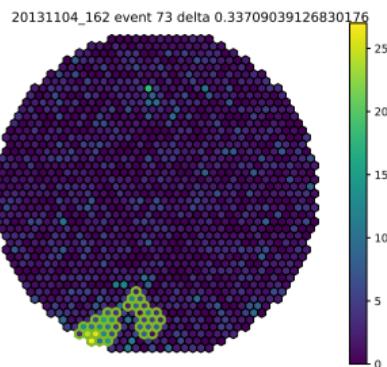
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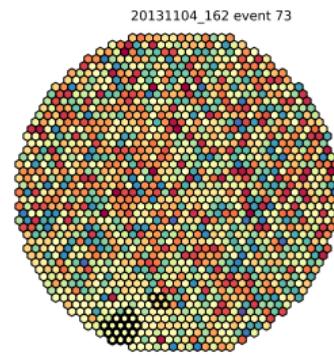
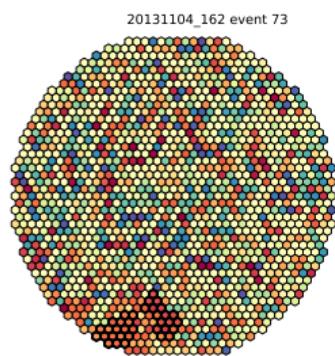
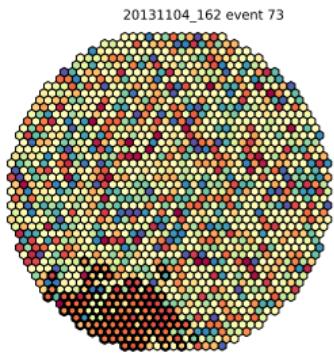
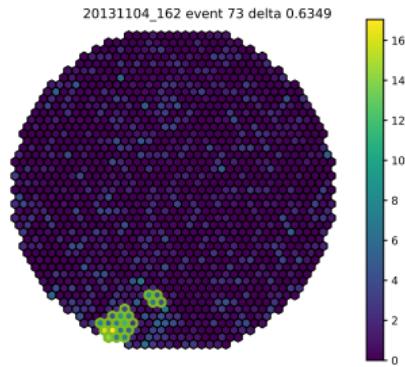
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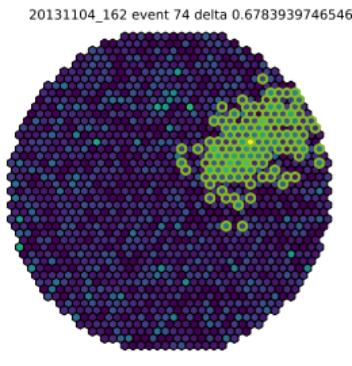
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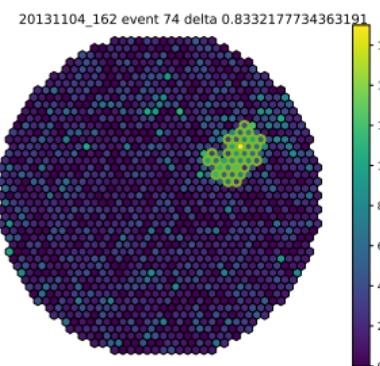
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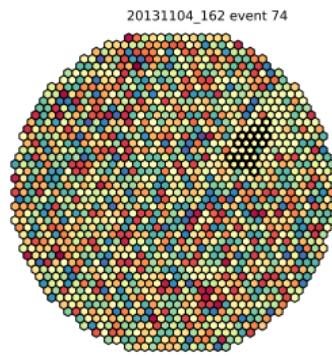
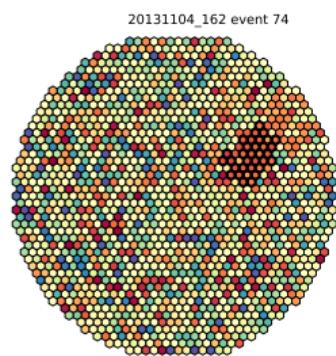
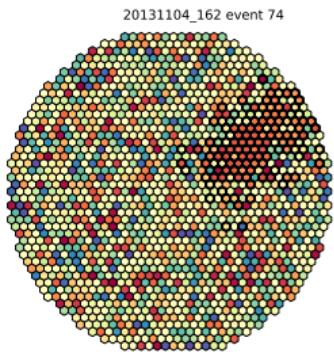
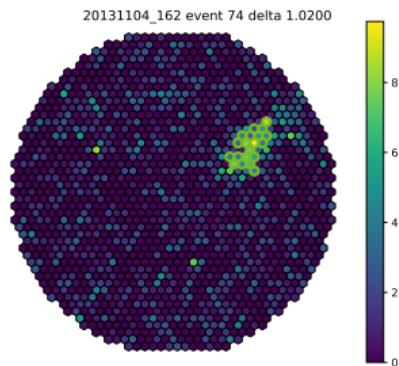
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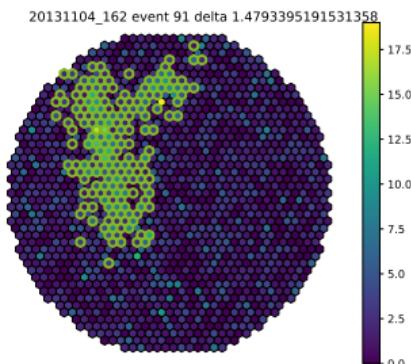
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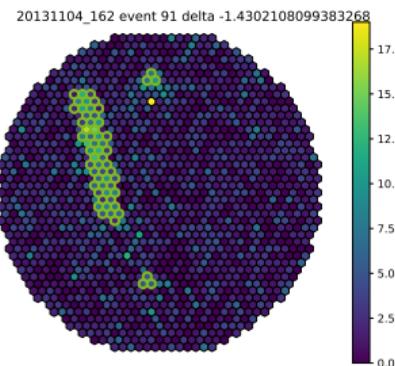
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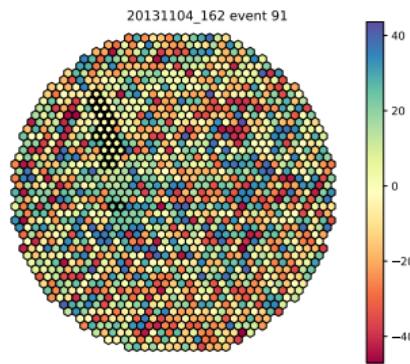
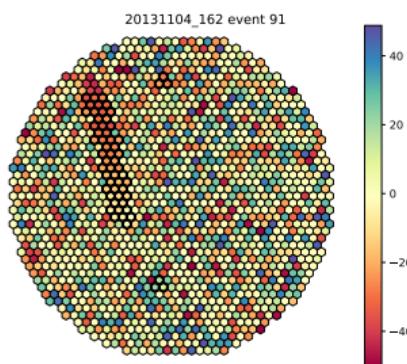
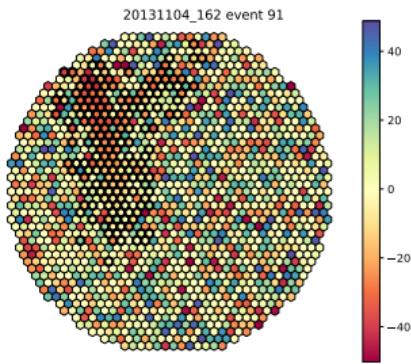
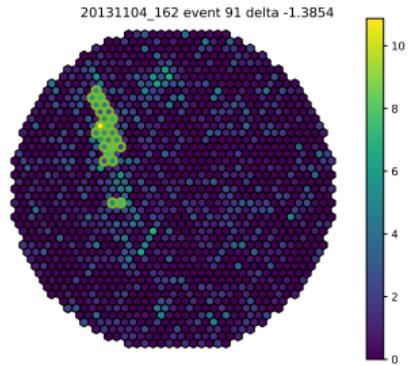
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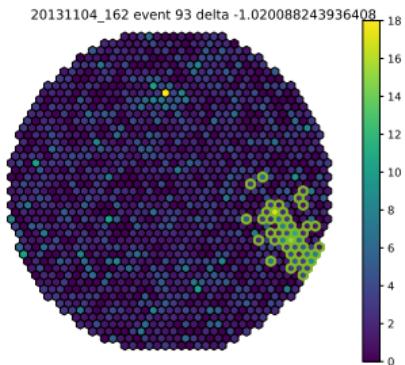
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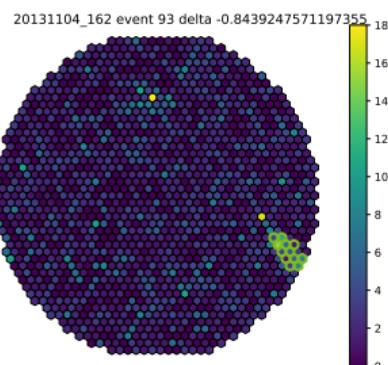
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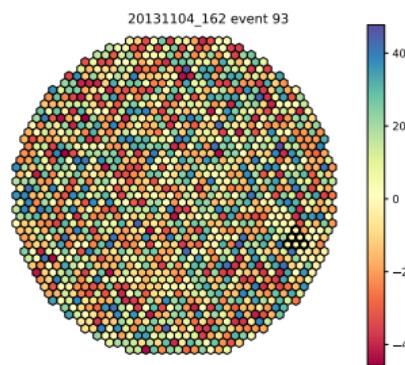
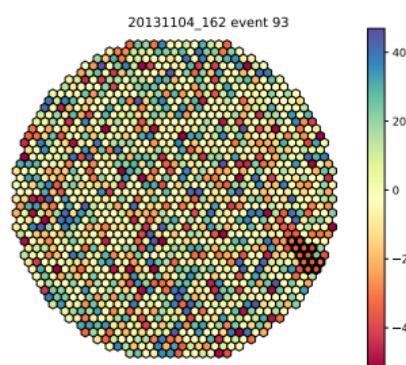
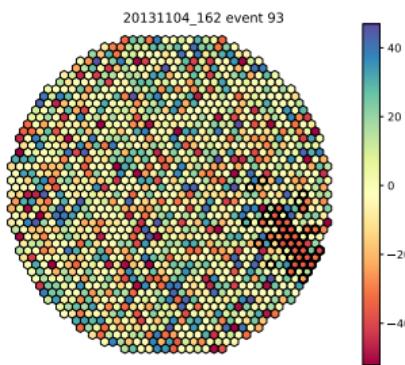
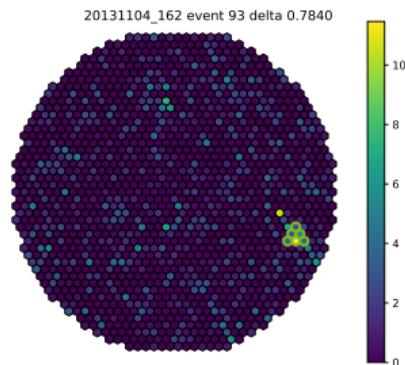
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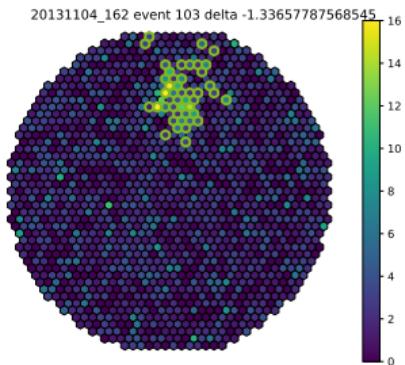
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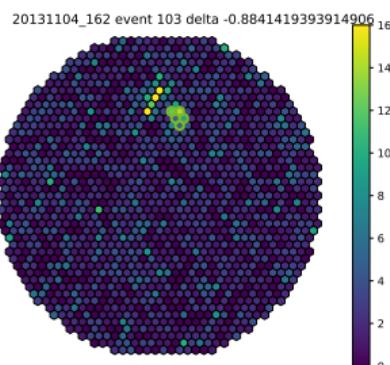
FACTtools



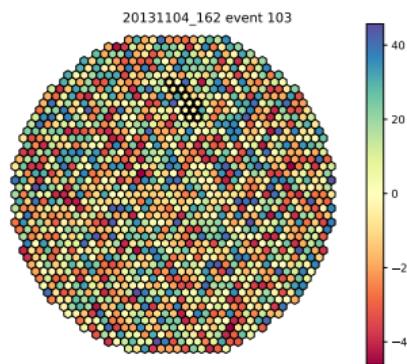
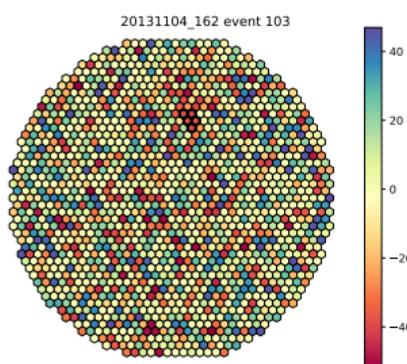
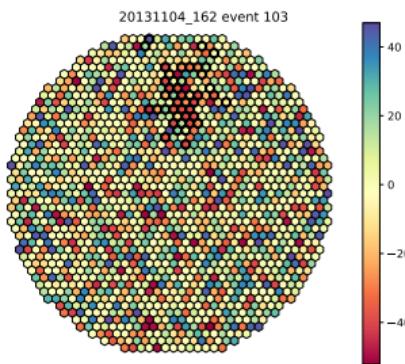
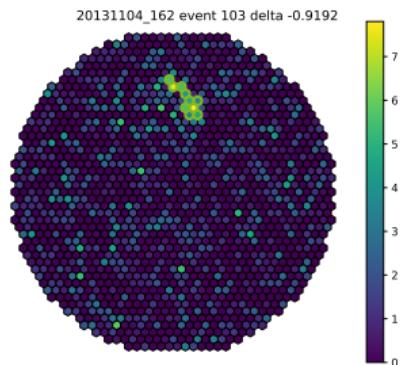
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Thresholds on phs

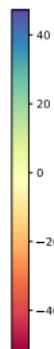
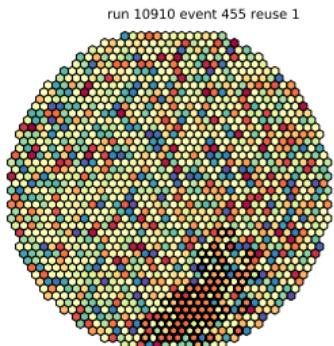
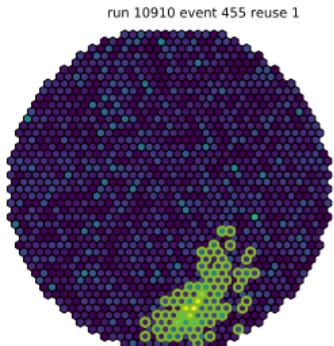


FACTtools

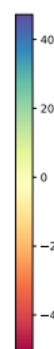
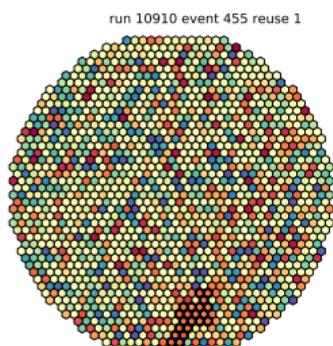
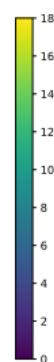
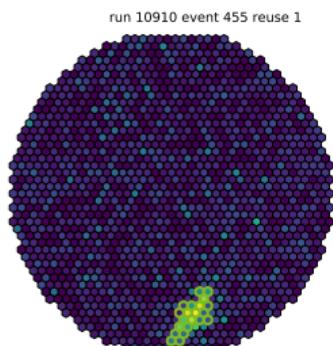


Images on Gamma MC

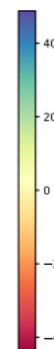
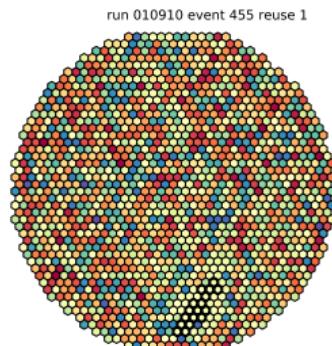
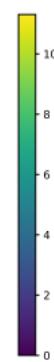
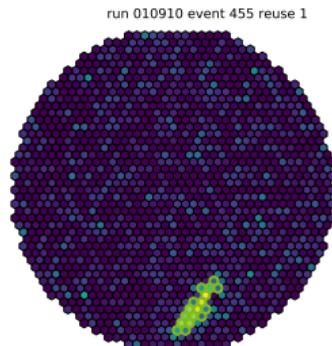
DBSCAN



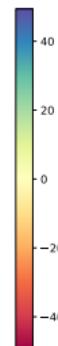
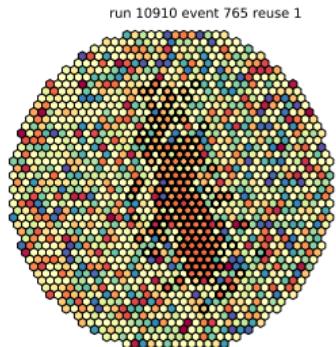
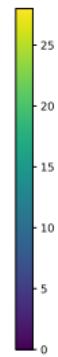
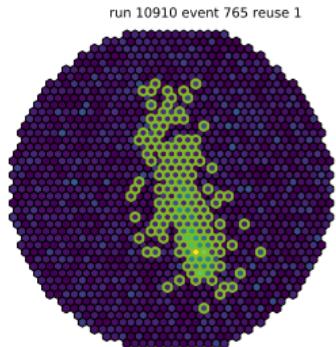
Thresholds on phs



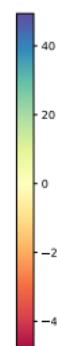
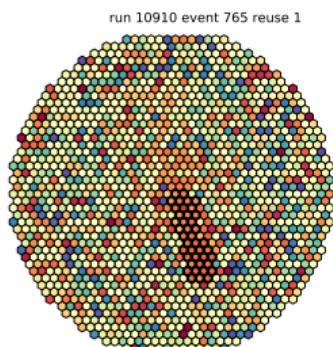
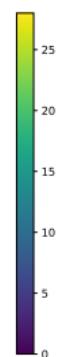
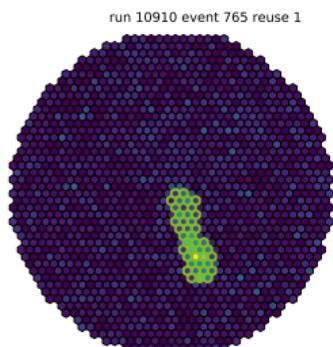
FACTtools



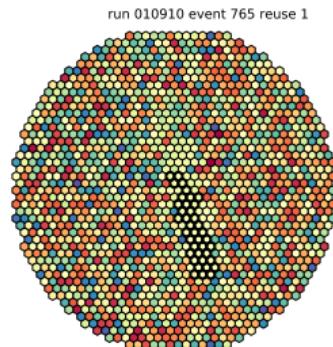
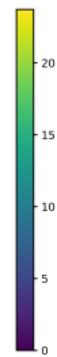
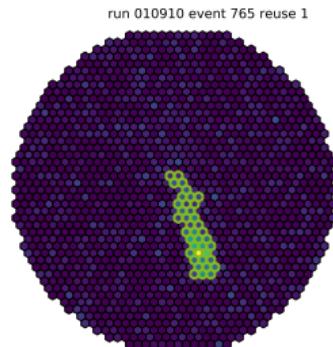
DBSCAN



Thresholds on phs

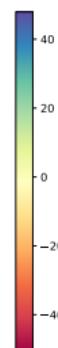
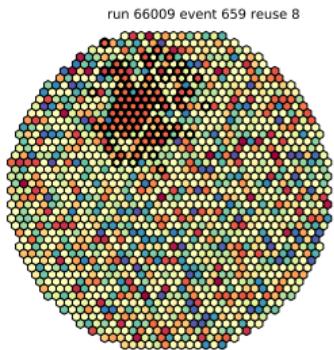
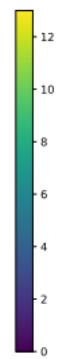
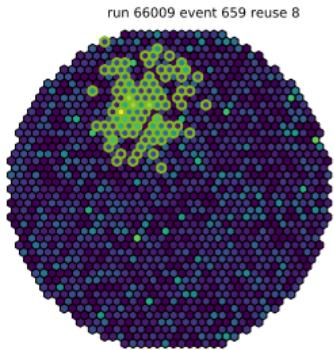


FACTtools

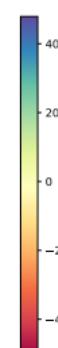
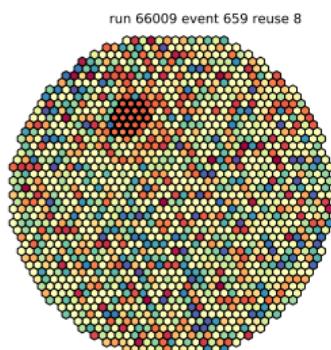
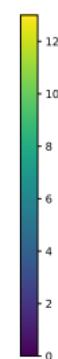
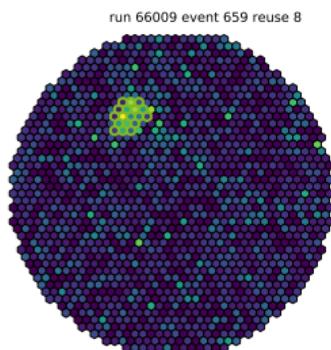


Images on Proton MC

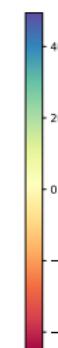
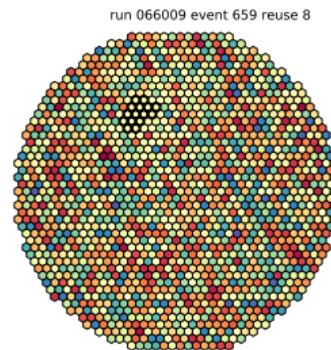
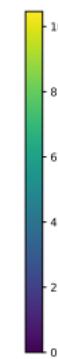
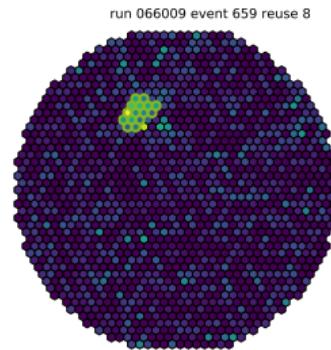
DBSCAN



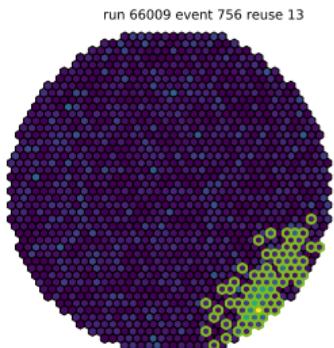
Thresholds on phs



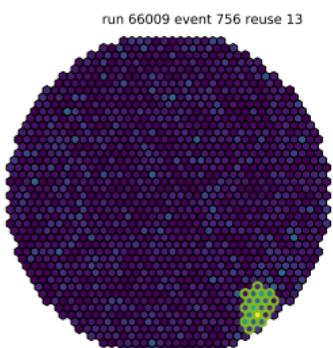
FACTtools



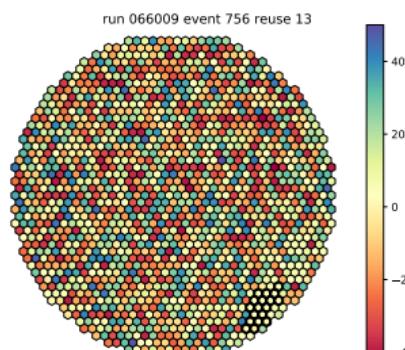
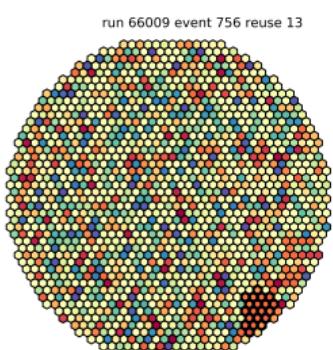
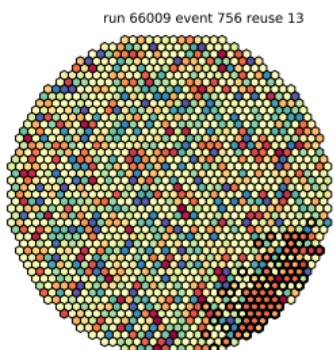
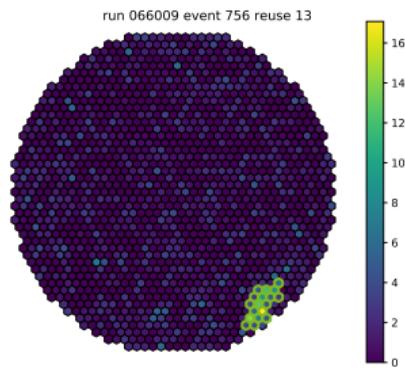
DBSCAN



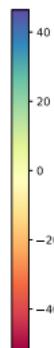
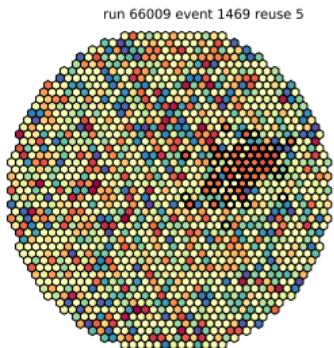
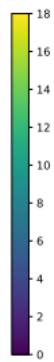
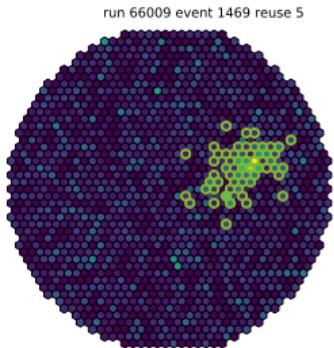
Thresholds on phs



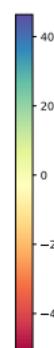
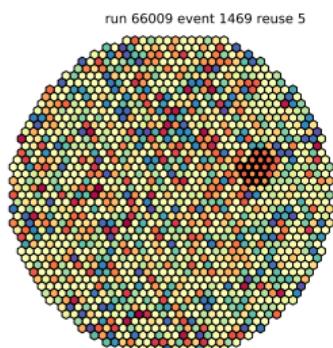
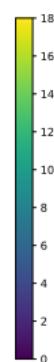
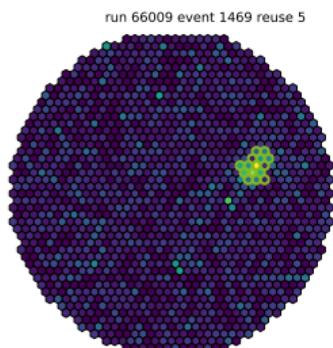
FACTtools



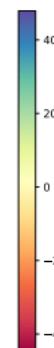
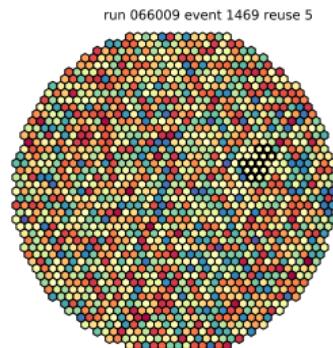
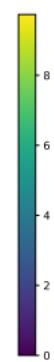
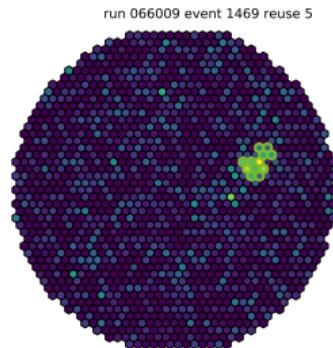
DBSCAN



Thresholds on phs



FACTtools



Analysis

Analysis

aim proof of concept: generate physics results

Crab Nebula well measured source of cosmic gamma rays → standard candle analysis

Photon Stream Analysis chain

calibration extracting single photons

image cleaning DBSCAN

parametrization parameter set A

separation IACT tools

reconstruction IACT tools

Standard Analysis chain

calibration identifying large pulses

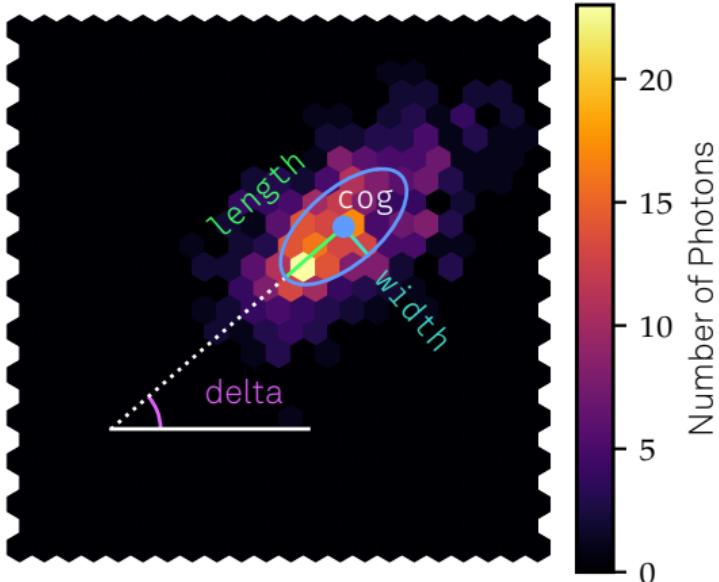
image cleaning time and pixel thresholds

parametrization parameter set B

separation IACT tools

reconstruction IACT tools

Parameterization

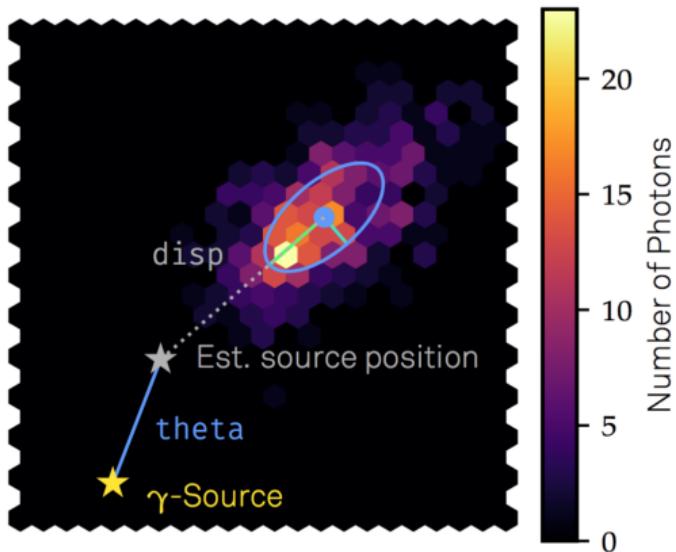


Analysis

Hillas parameters (projected back to 2D):

- size** number of photons in cluster
- length** std. dev. along long half-axis
- width** std. dev. along short half-axis
- delta** angle between length and disp
- skewness/ kurtosis** higher order statistical moments along half-axes in cluster system

Parameterization



Source position reconstruction via
disp-method:

|displ| distance from centre of gravity to
target

sgn(displ) Head/Tail-Disambiguation

theta distance between reconstructed
and true origin

IACT tools

Cuts: size > 30

Machine learning with Random Forrests, using 5-fold cross validation.

Energy estimation:

- random forest regressor (**size, length, width, n_pixel, delta, kurtosis_long, kurtosis_trans, skewness_long, skewness_trans**)

Gamma-hadron-separation:

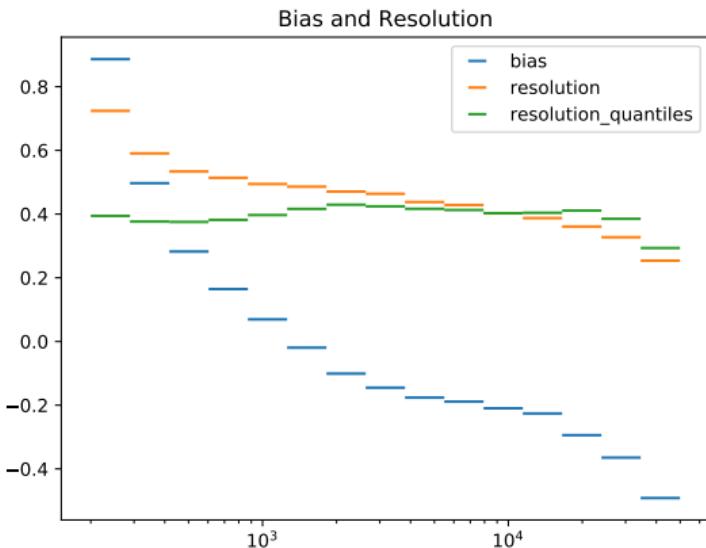
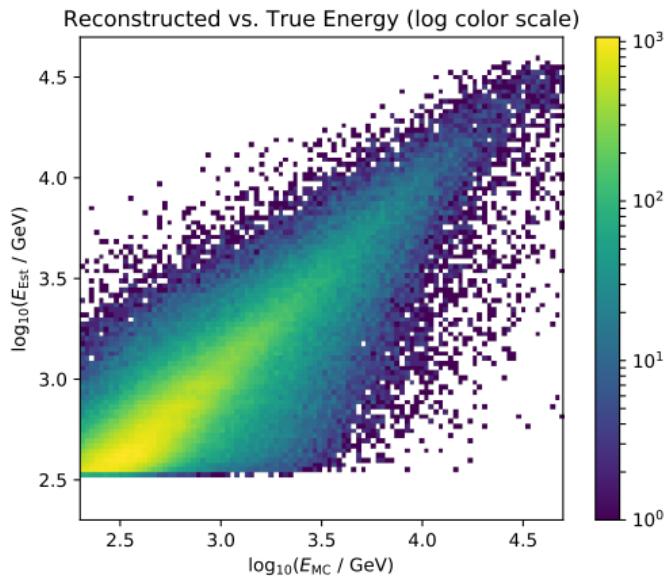
- random forest classifier (**clusters, cluster_size_ratio, n_pixel, size, length, width, kurtosis_long, kurtosis_trans, skewness_long, skewness_trans**)

Origin reconstruction:

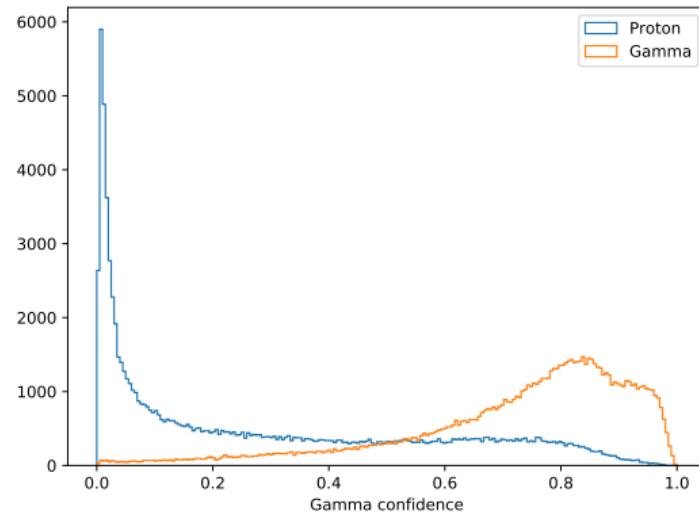
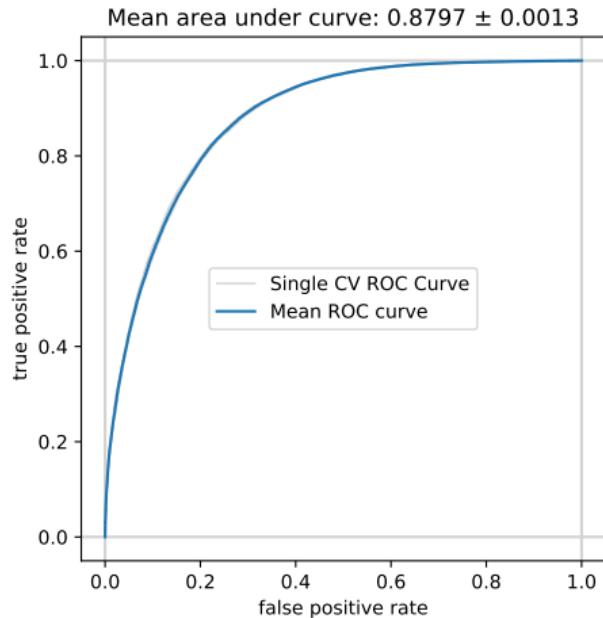
- two step task: regression of $|disp|$ and classification of $\text{sgn}(disp)$
- random forest regressor and classifier (**length, width, skewness_long, kurtosis_long**)

Results

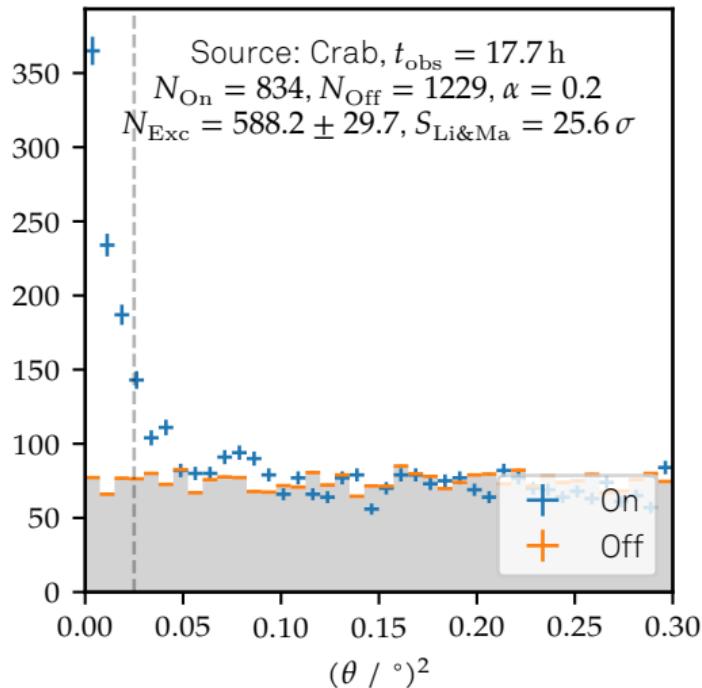
Energy estimation R^2 -score = 0.740



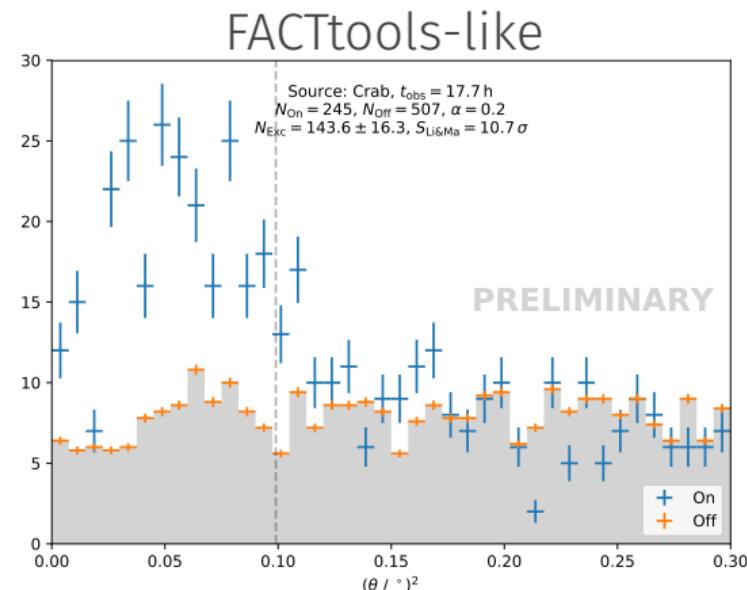
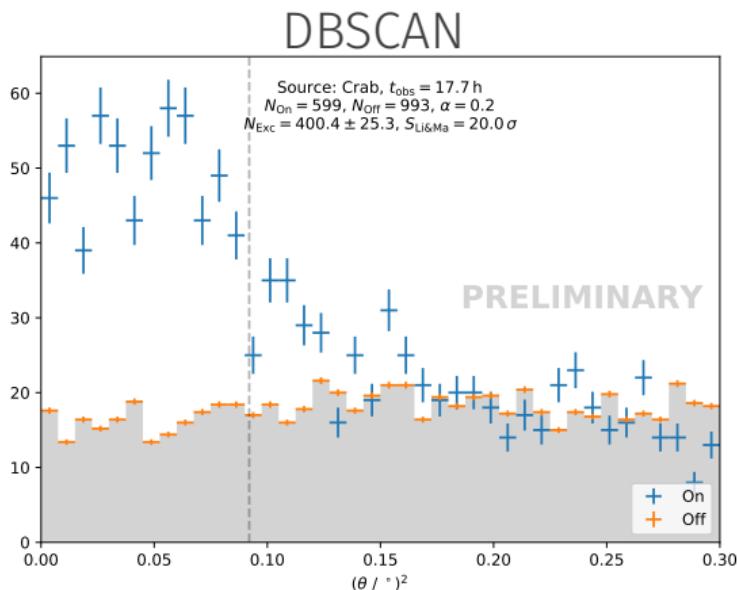
Separation



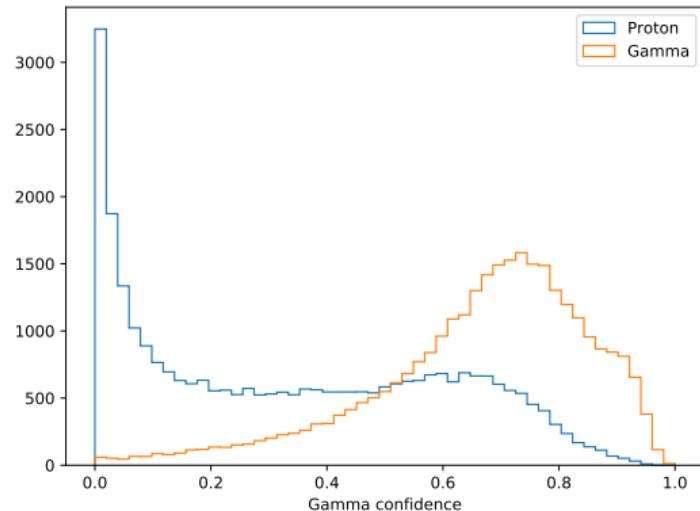
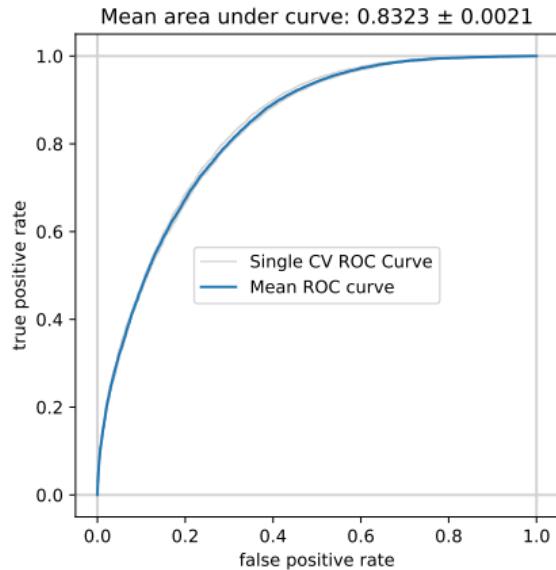
Origin reconstruction (FACTtools)



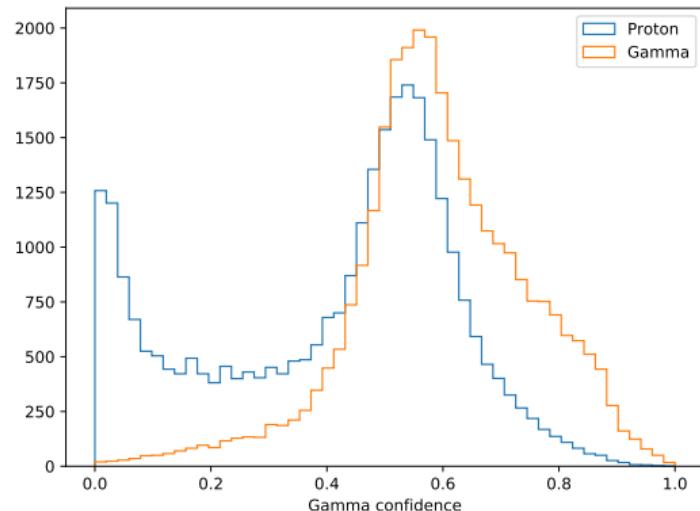
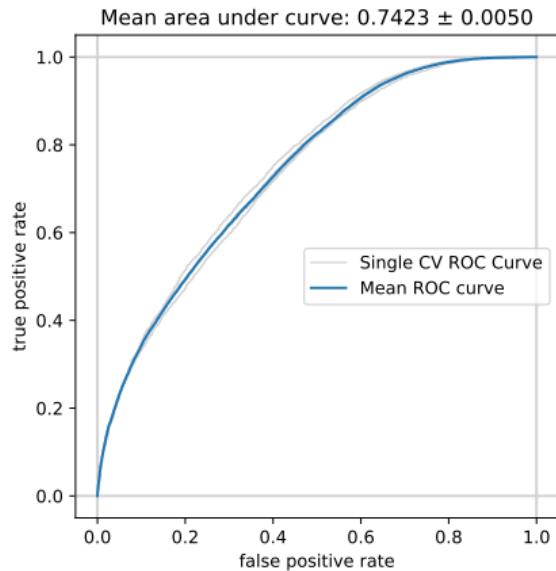
Origin reconstruction (PhotonStream)



Separation (DBSCAN)

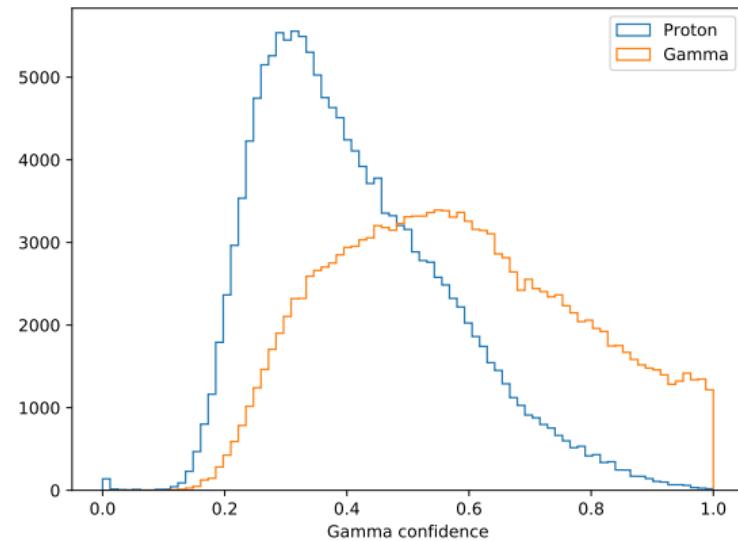
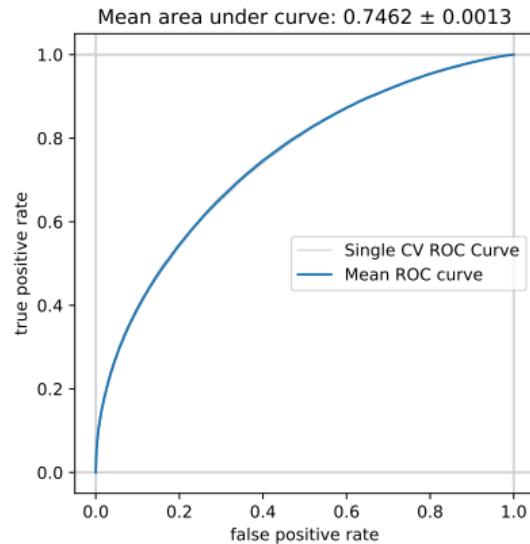


Separation performance (pixel based)

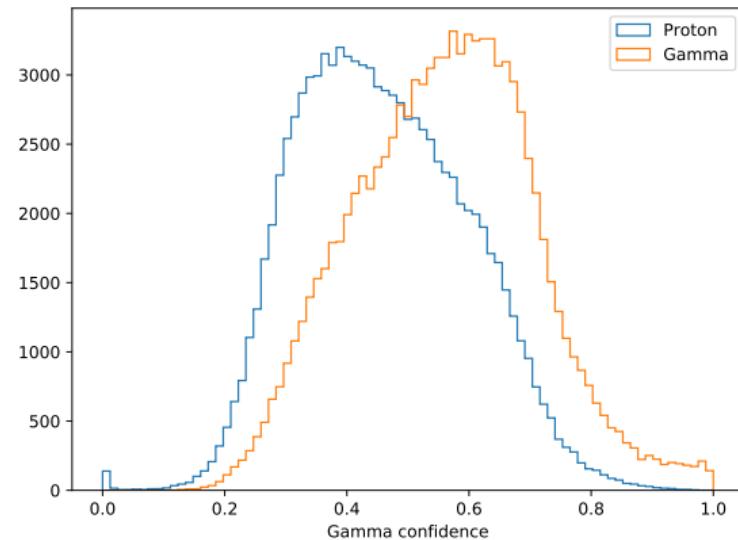
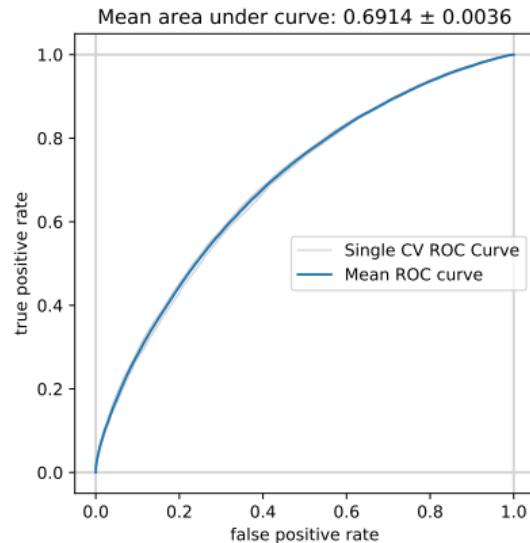


Data-Simulation mismatches

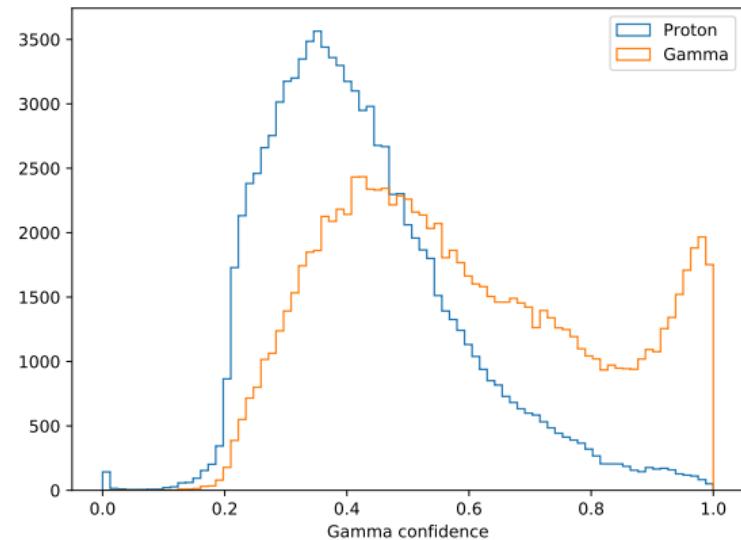
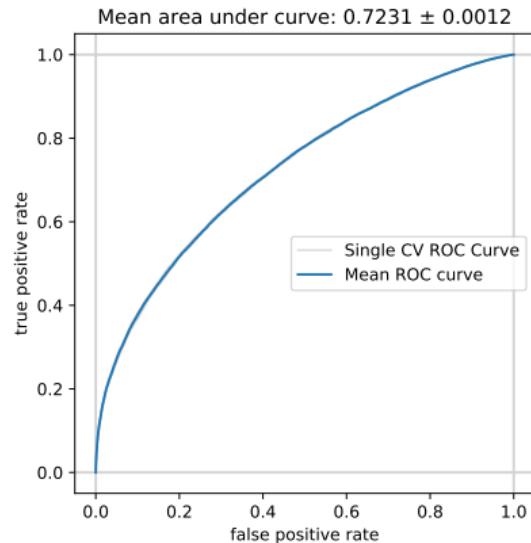
Data-Simulation mismatches: Random Forest (DBSCAN)



Data-Simulation mismatches: Random Forest (DBSCAN cuts)

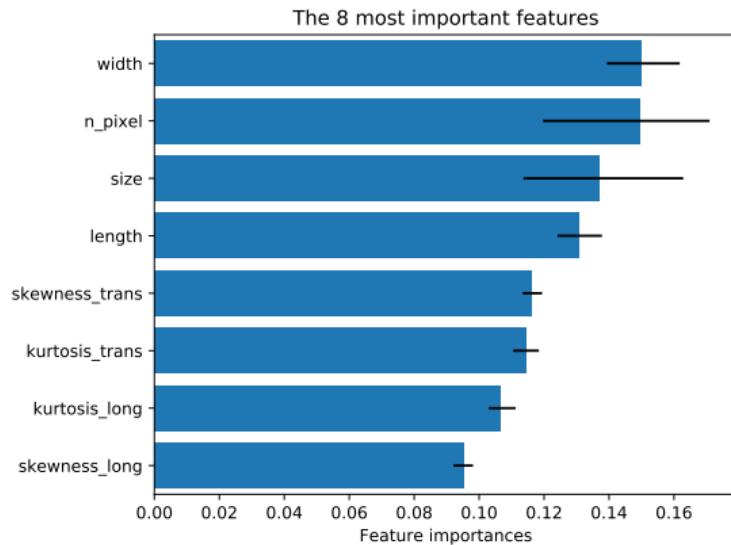


Data-Simulation mismatches: Random Forest (thresholds)

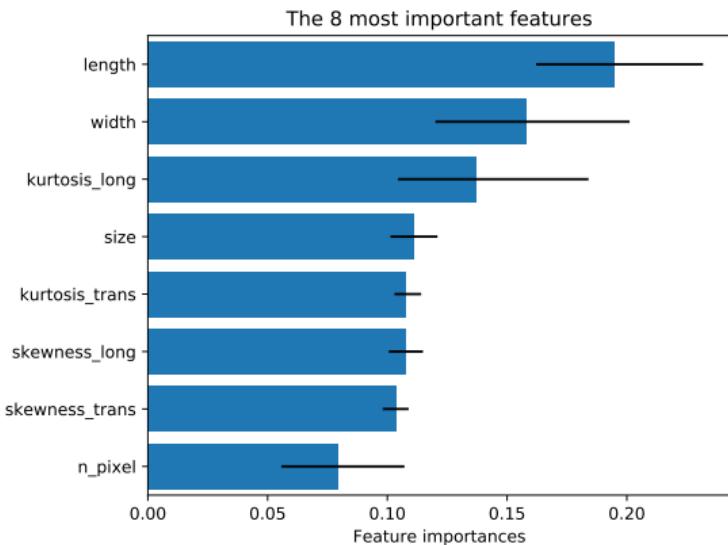


Data-Simulation mismatches: Random Forest

DBSCAN

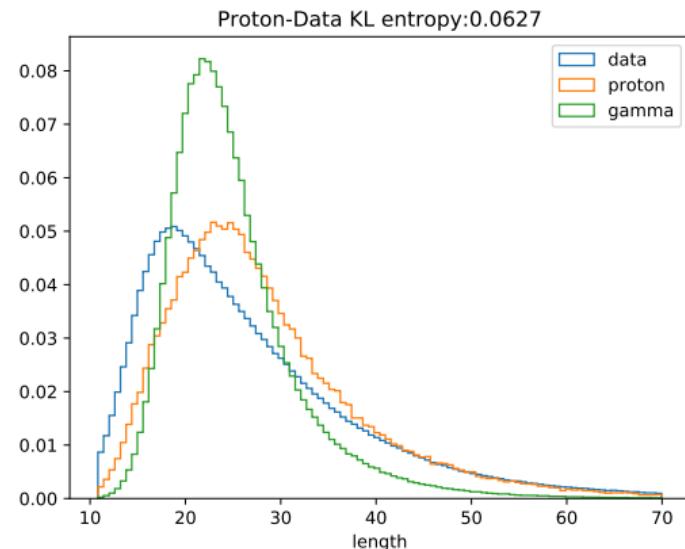
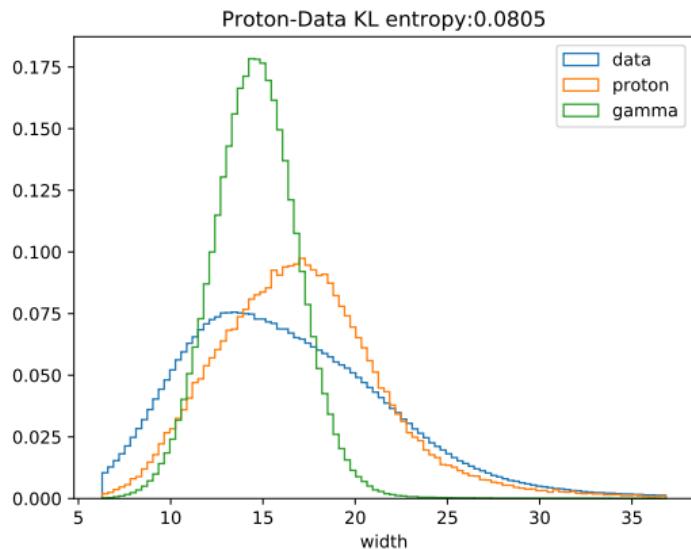


FACTtools



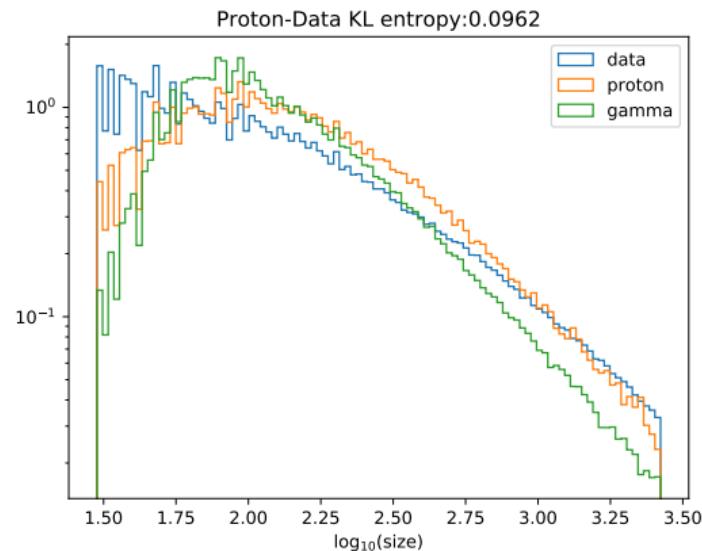
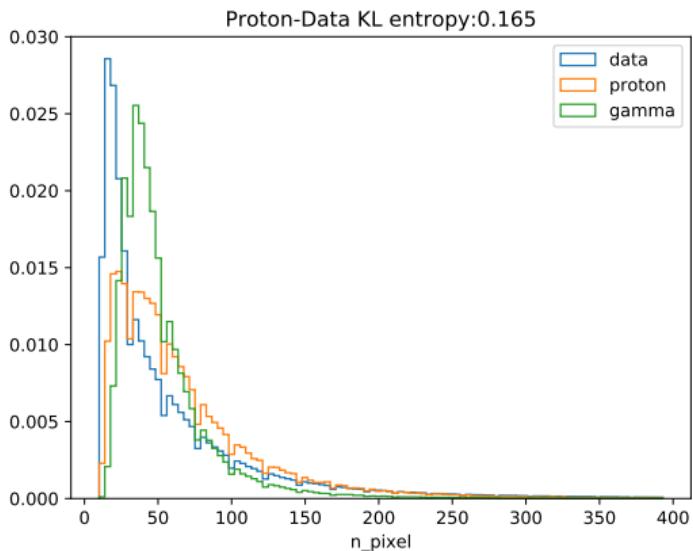
Data-Simulation mismatches

DBSCAN



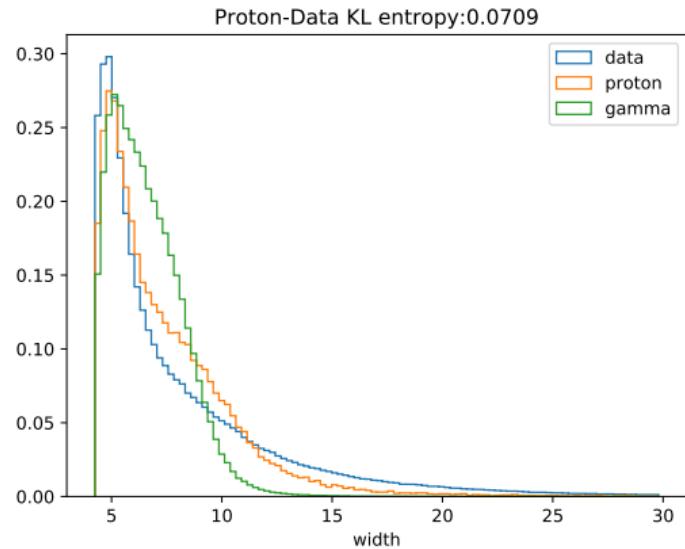
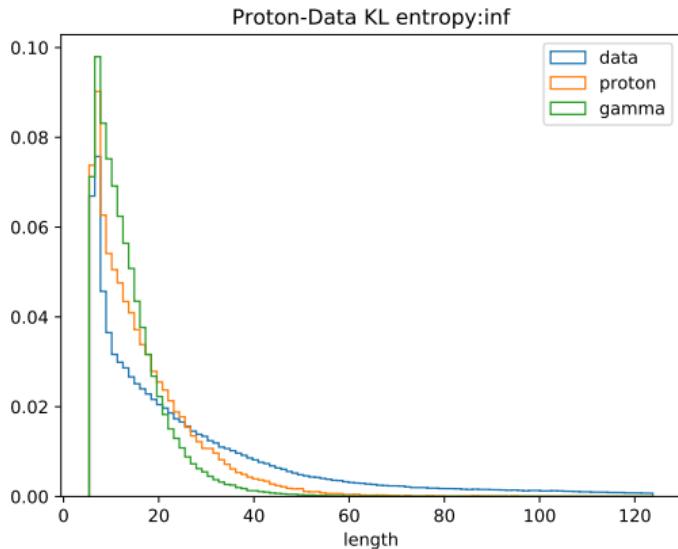
Data-Simulation mismatches

DBSCAN



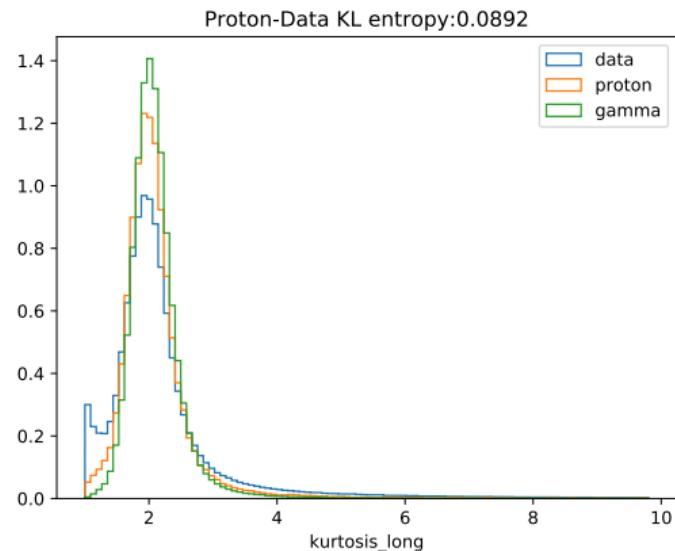
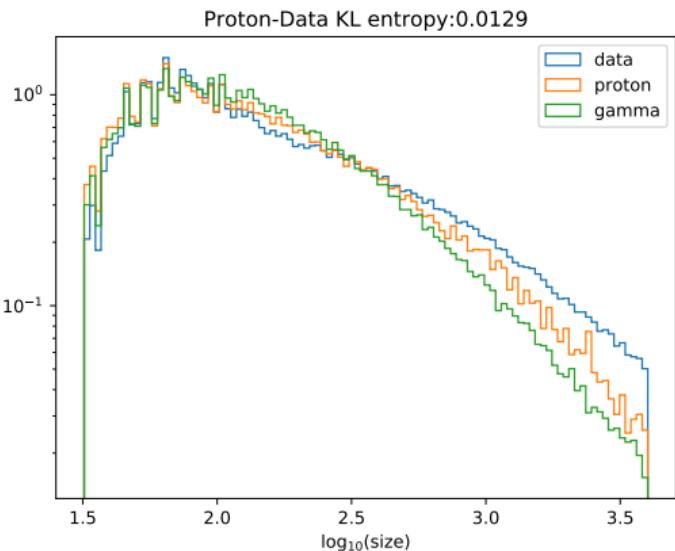
Data-Simulation mismatches

FACTtools cleaning



Data-Simulation mismatches

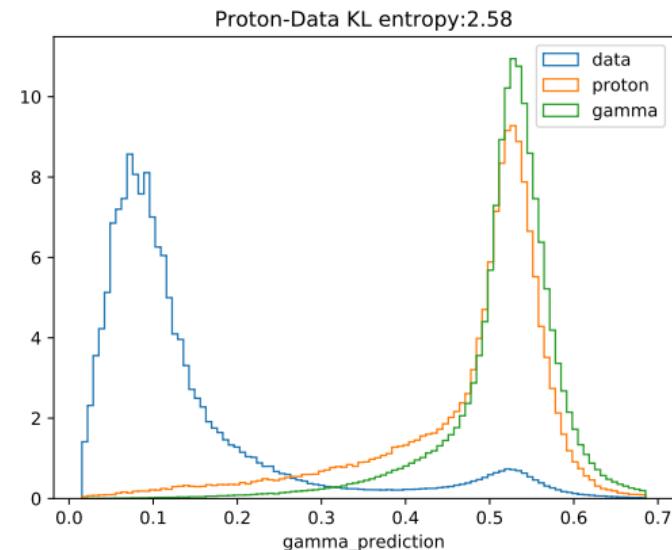
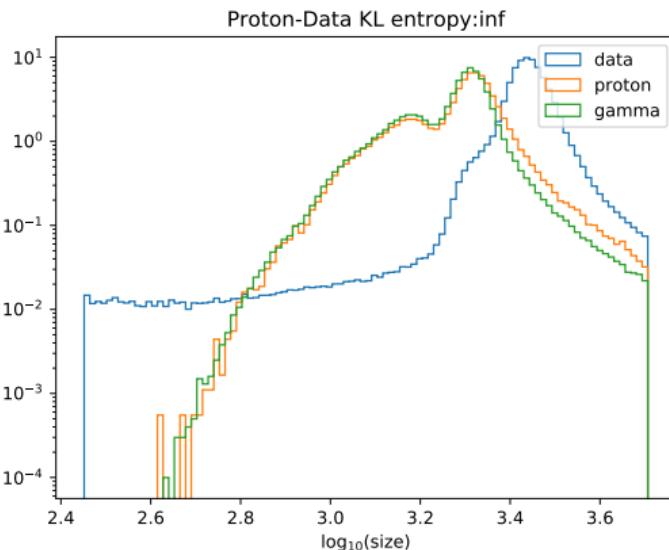
FACTtools cleaning



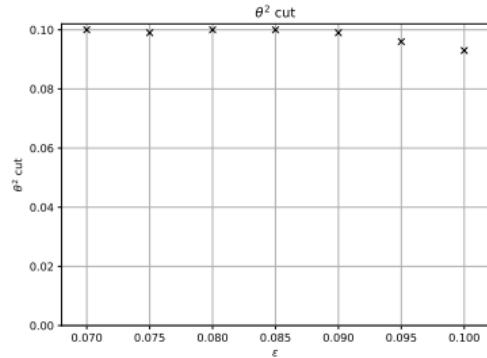
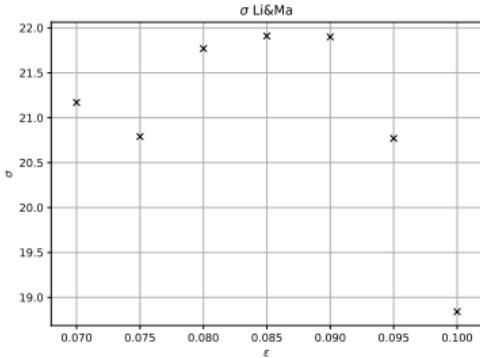
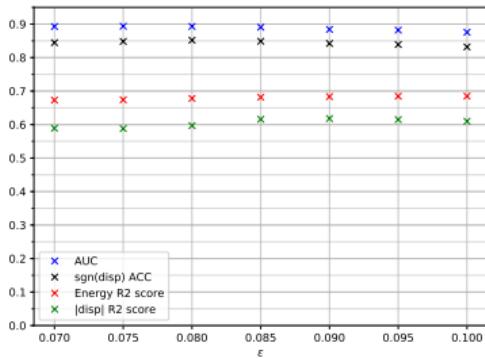
Effects of DBSCAN parameters

ε maximum distance between each photon to be considered dense

$$0.1 \rightarrow 0.175$$



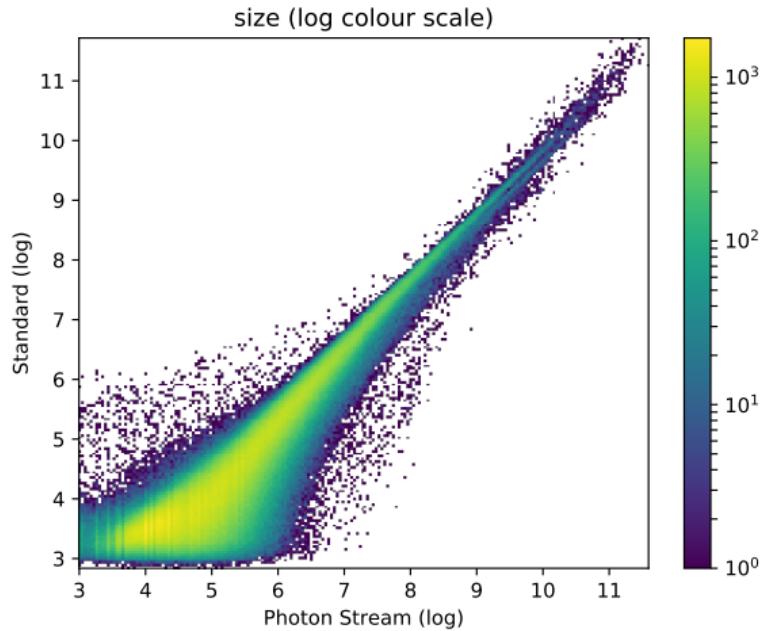
Effects of DBSCAN parameters



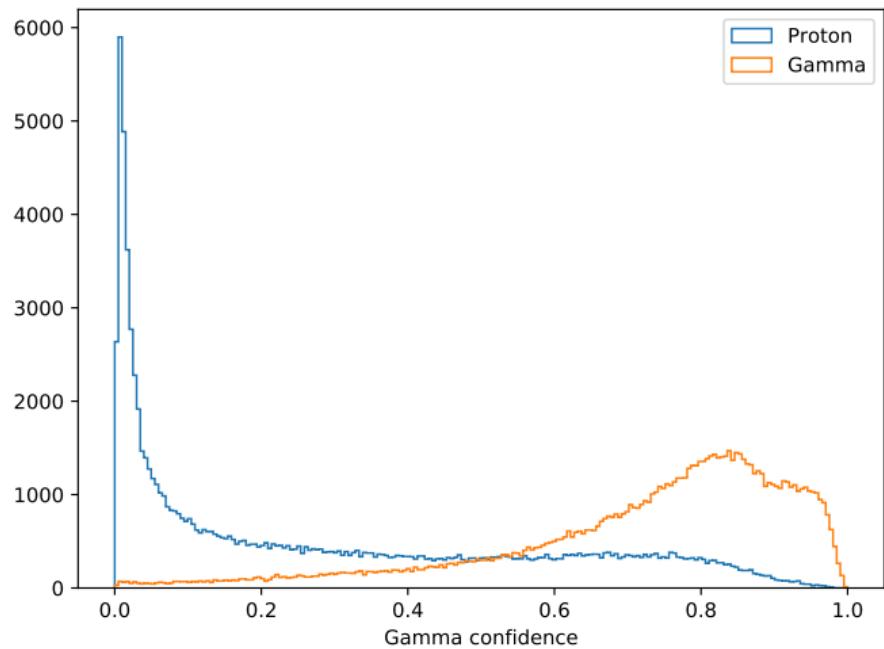
Back up

Rare photo of an experiment with no issues
in their Monte Carlo event generator

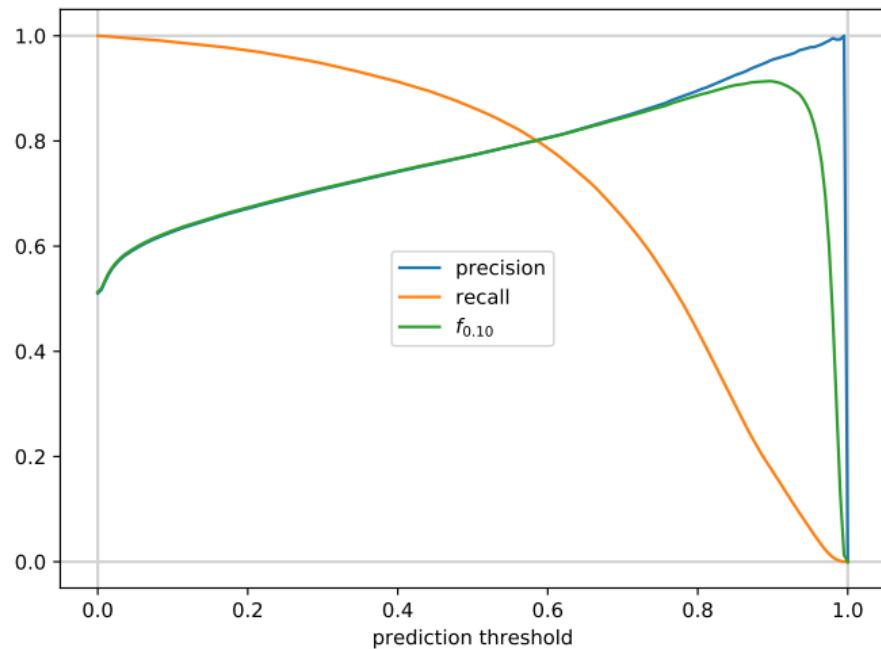




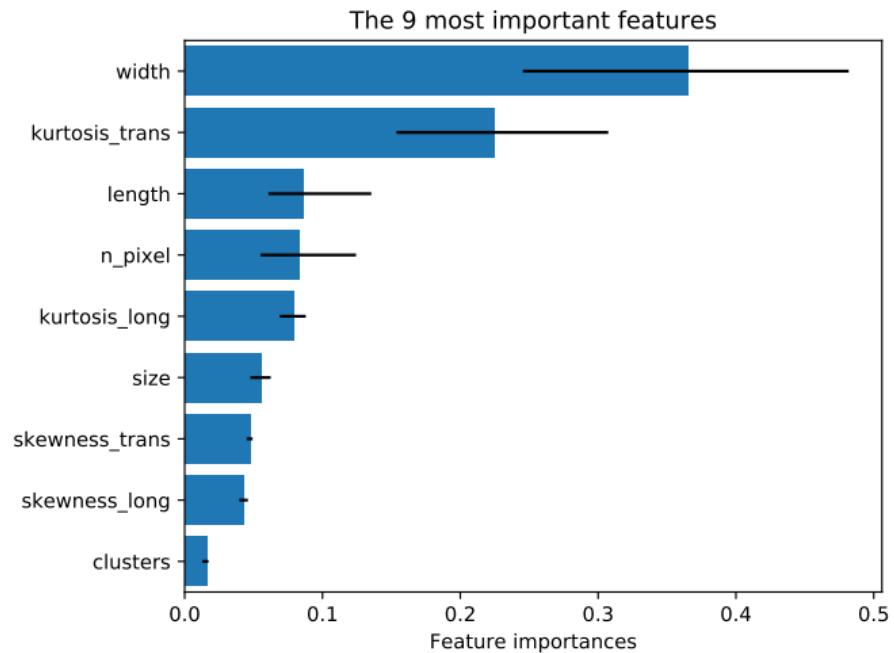
Separation



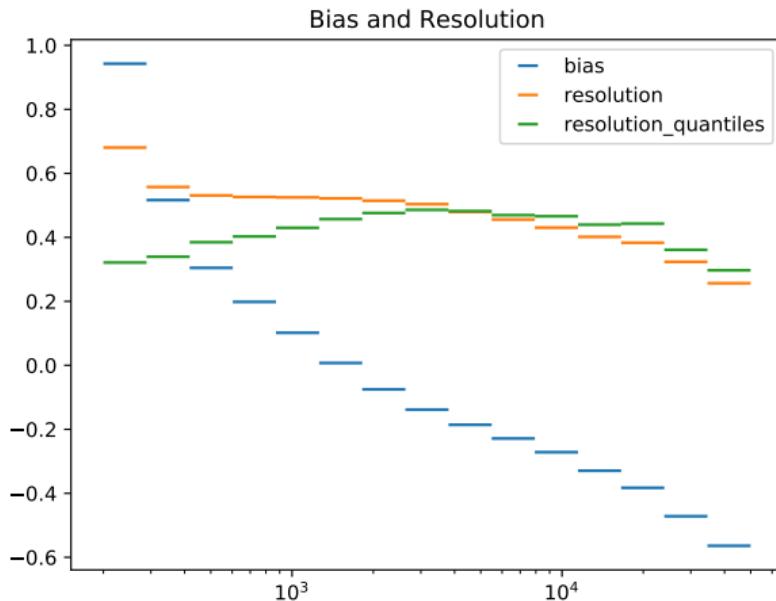
Separation



Separation



Energy



Energy

