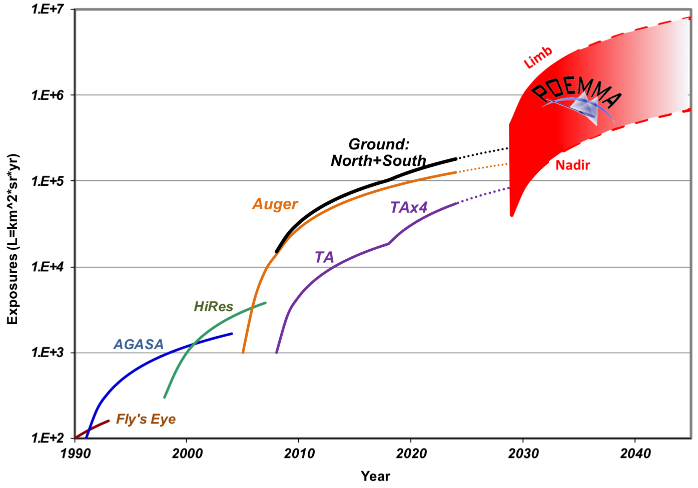
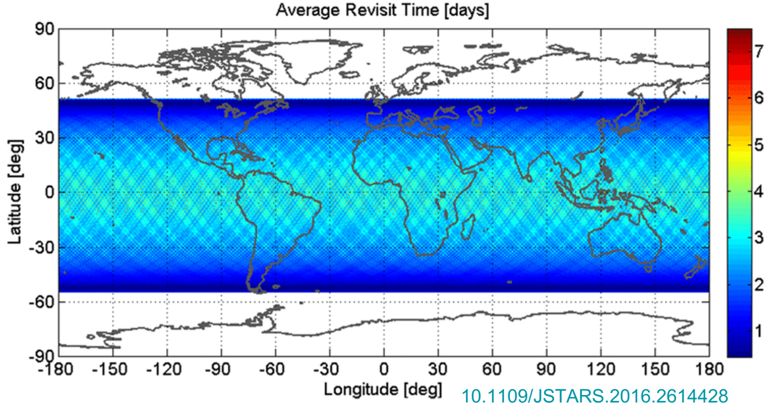
Neural Network Approaches for Event Classification Onboard EUSO-SPB2

G. Filippatos

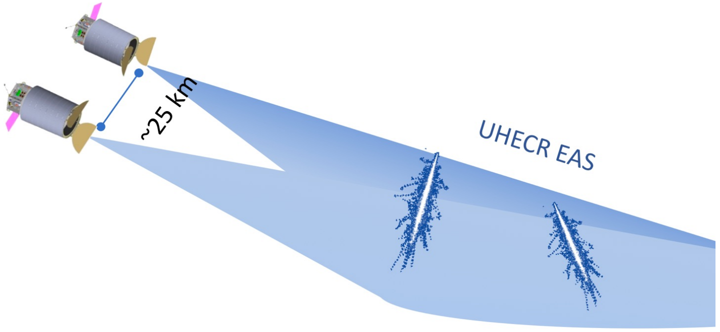
Space Based Observations of UHECRS: Why?





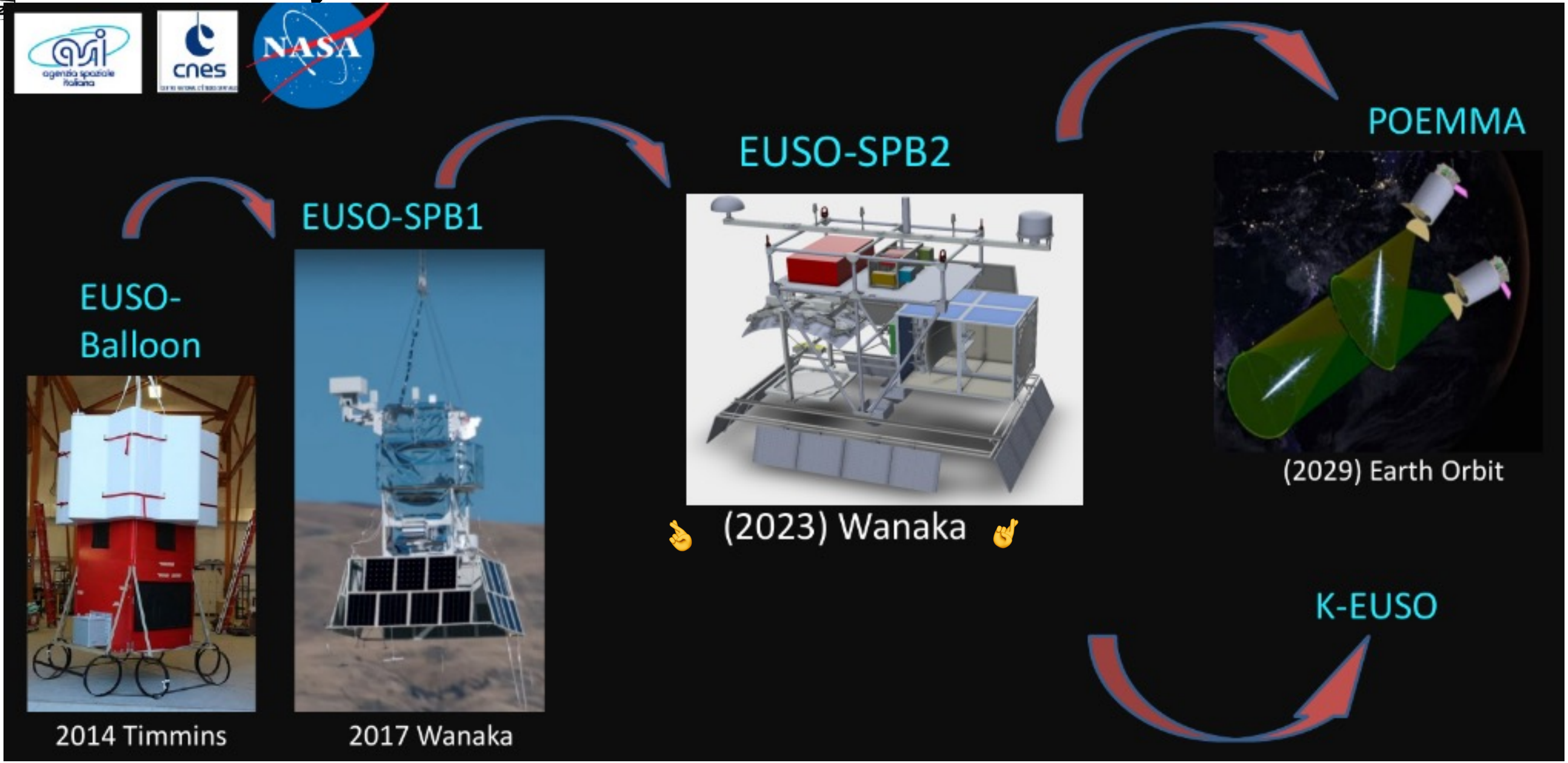
10.1109/JSTARS.2016.2614428

- Large aperture
- Full sky coverage
- X-Max -> composition dependent anisotropy possible

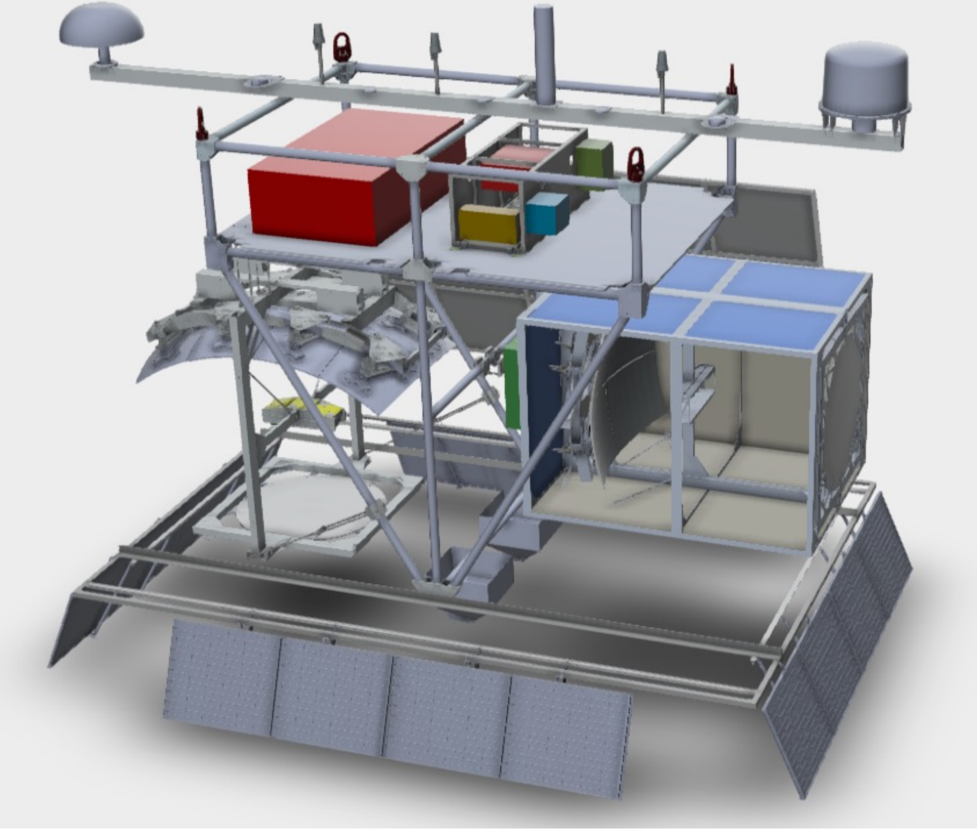


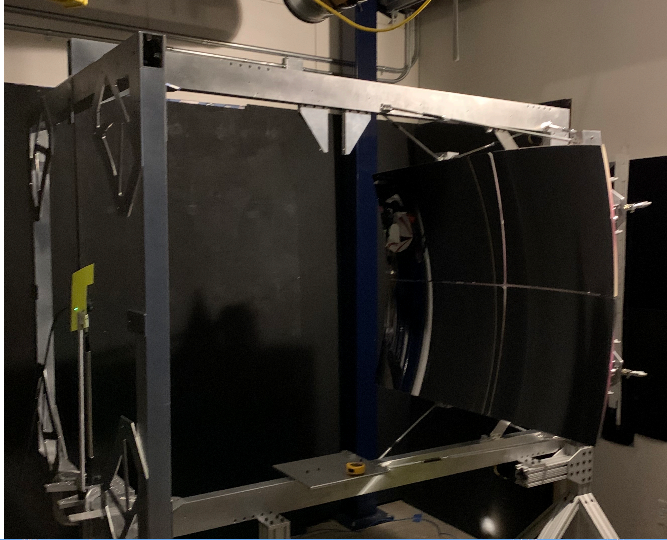
arXiv:2012.07945

The story so far . . .



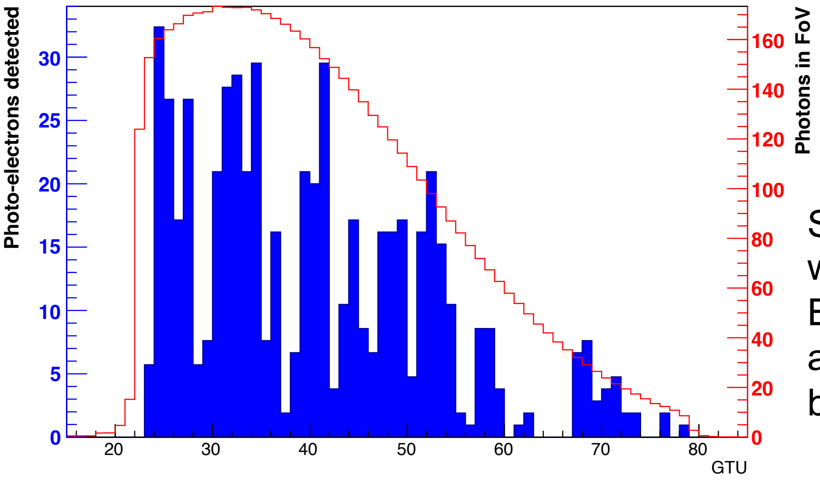
EUSO-SPB2



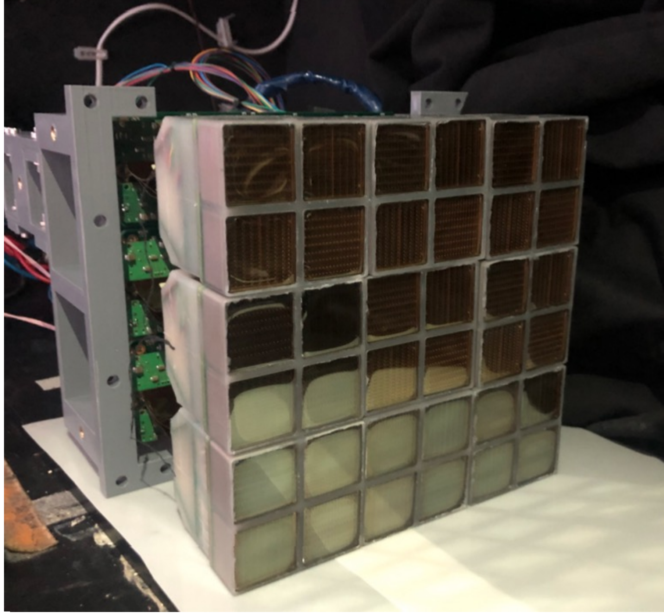


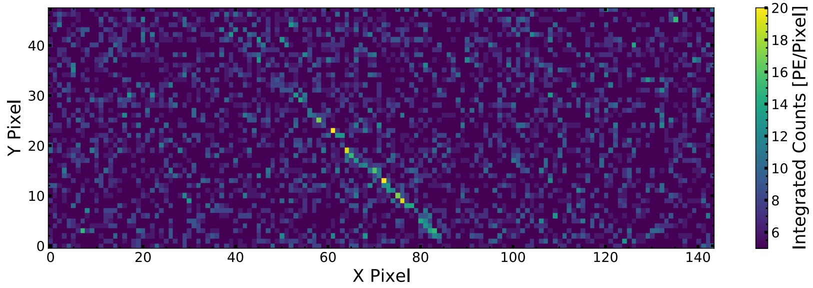
The Fluorescence Camera

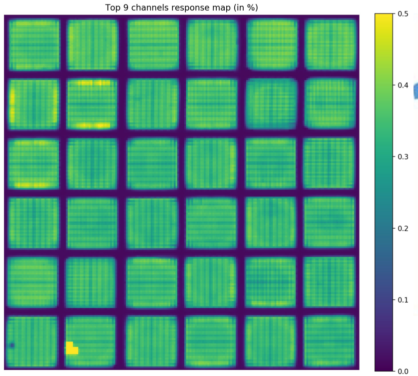
Example Event

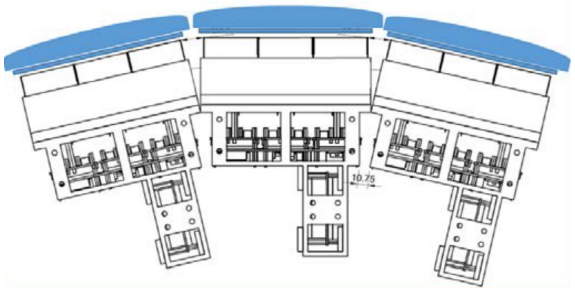


Simulated shower with Energy E = 3 EeV, θ = 57^{o}, and ideally placed below detector









Technical Challenges

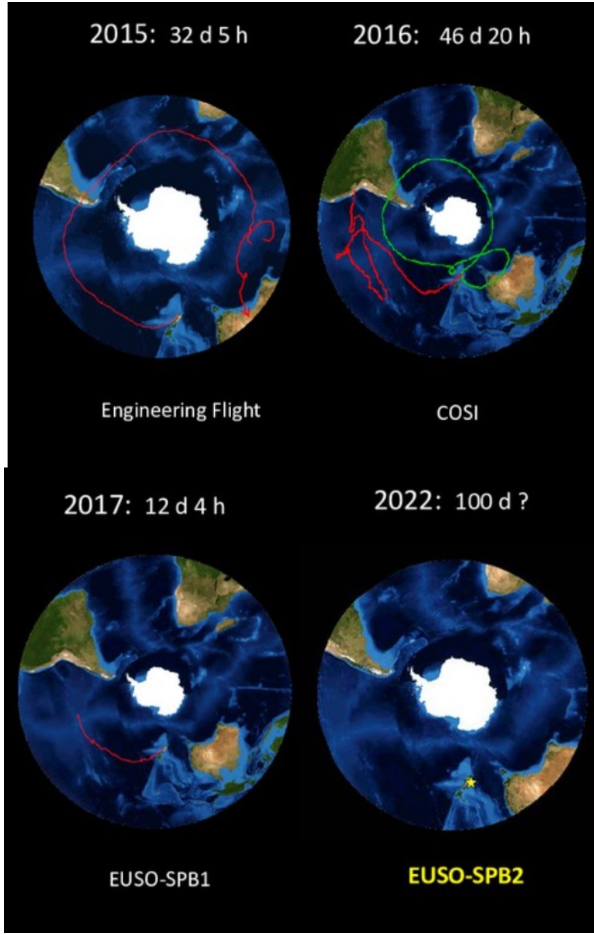
No guarantee of recovery

Limited telemetry to be shared with two telescopes + housekeeping/operations

~1-5% of recorded FT events will be downloaded

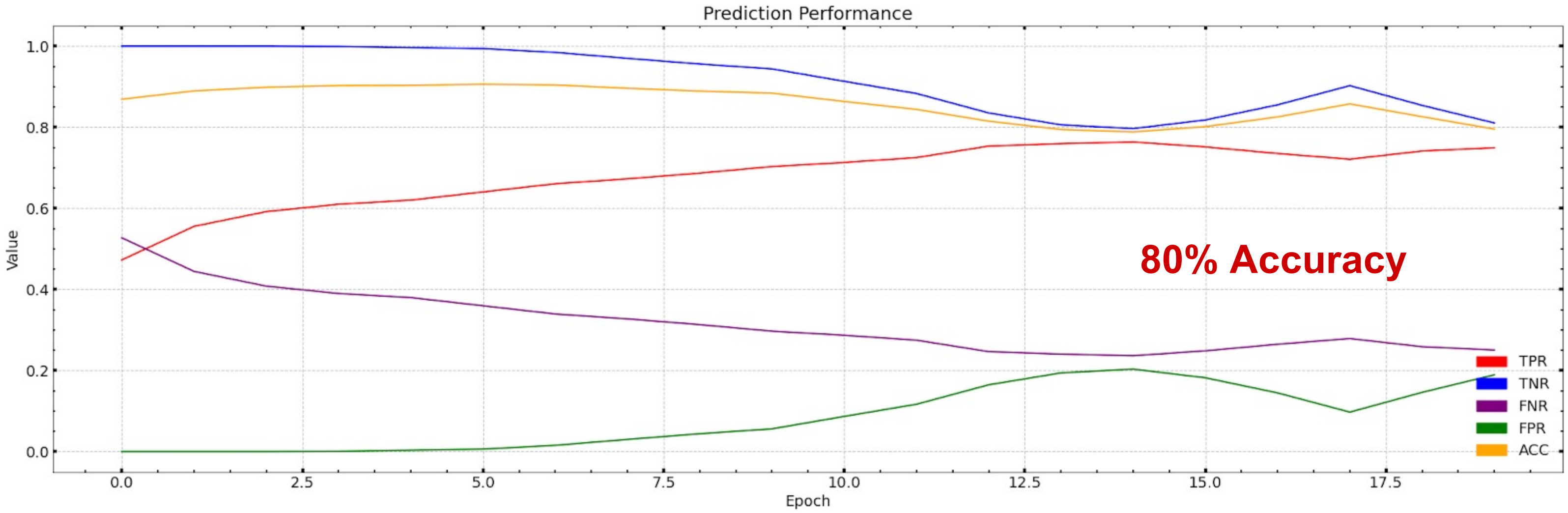
<<1% of recorded events will be EAS

Want a robust, computationally efficient way to identify events for high priority download.

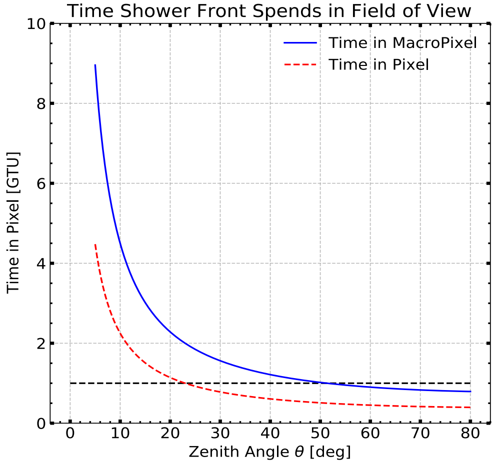


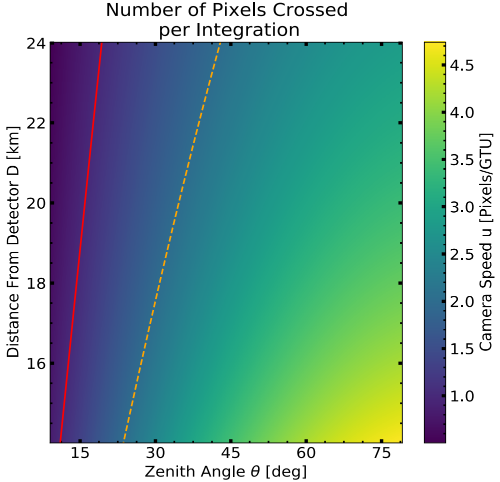
Convolutional Neural Network

- Binary classifier trained on simulated EAS and simulated noise, ~10^4 of each
- First attempt trained on entire event, averaging prediction of each frame to assign a prediction label



The “Macro-Pixel”





1	4	1	1	2	3	3	2	4	1	3	2	2	1	0	1
0	2	1	2	1	3	5	5	2	2	1	0	2	0	3	1
3	2	1	2	5	7	2	3	0	2	0	3	1	1	0	4
5	0	3	2	1	4	2	4	5	2	1	2	0	0	2	1
0	1	2	6	3	3	2	3	2	1	1	4	2	1	1	0
3	1	3	4	1	1	0	1	1	1	0	2	1	2	1	2
1	5	2	1	2	3	1	1	1	5	2	1	2	0	3	2
0	1	1	2	4	1	0	2	0	1	1	2	4	1	2	6
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1	1	0	1	3	1	3	1	1	0	1	1	2	1	1	1
3	1	3	4	1	0	0	2	0	2	1	1	2	0	0	2
1	5	2	1	3	1	3	1	1	1	2	1	1	2	1	1
0	1	1	2	1	0	2	0	0	1	1	2	1	1	2	1

4 MAPMTs at pixel level

7	5	9	15	9	6	5	5
10	8	17	11	9	6	2	7
5	15	8	6	5	7	6	4
7	6	10	4	7	6	7	13
6	8	2	4	10	6	4	6
11	8	3	10	8	8	4	10
6	8	5	6	3	4	5	4
7	6	5	6	3	6	5	5

The same 4 MAPMTs at MacroPixel level

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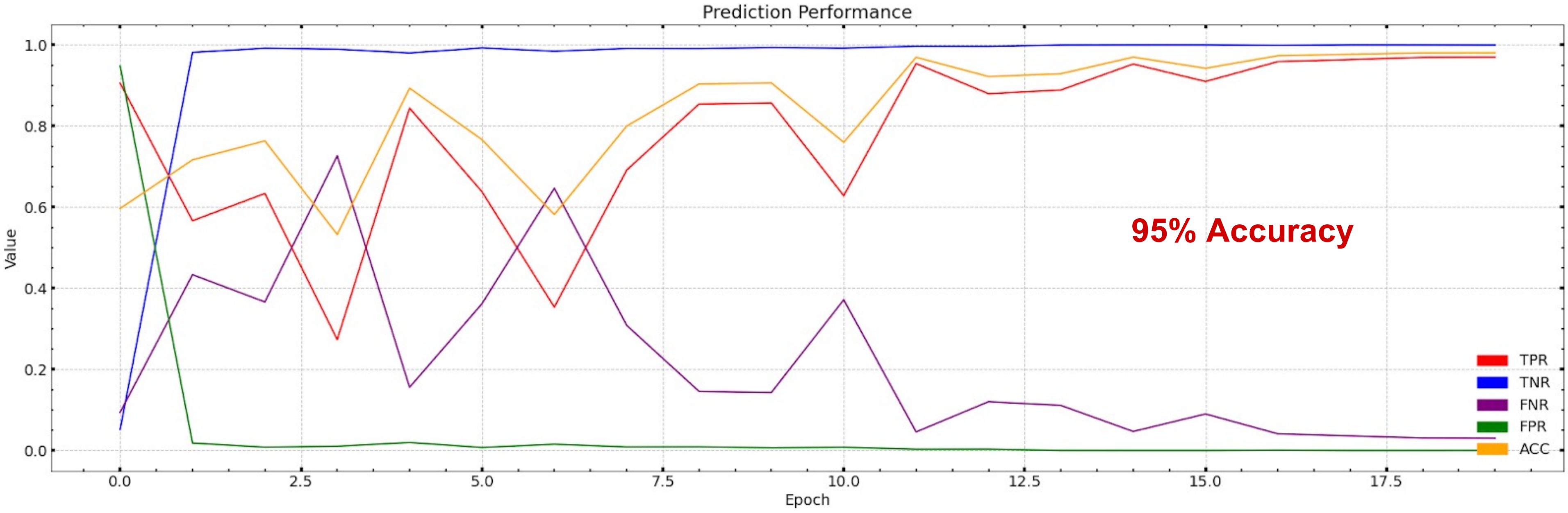
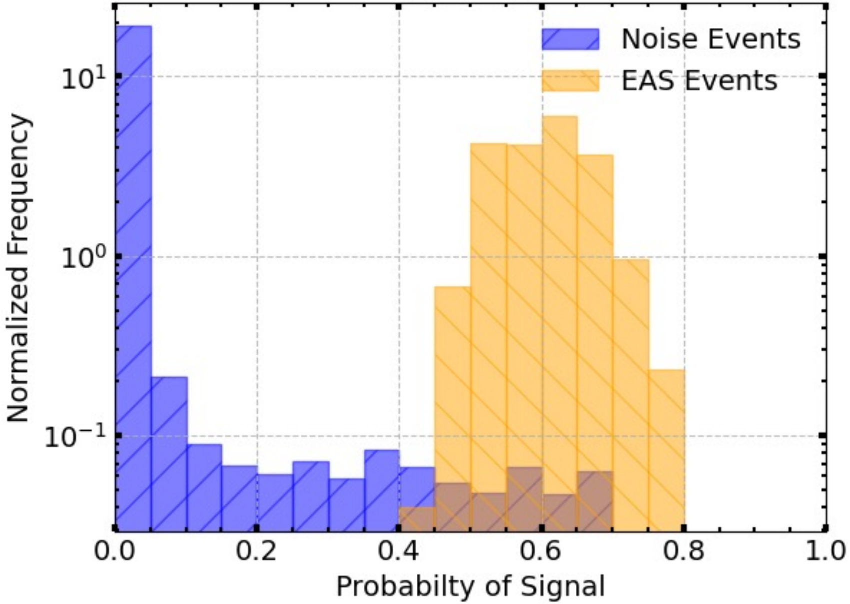
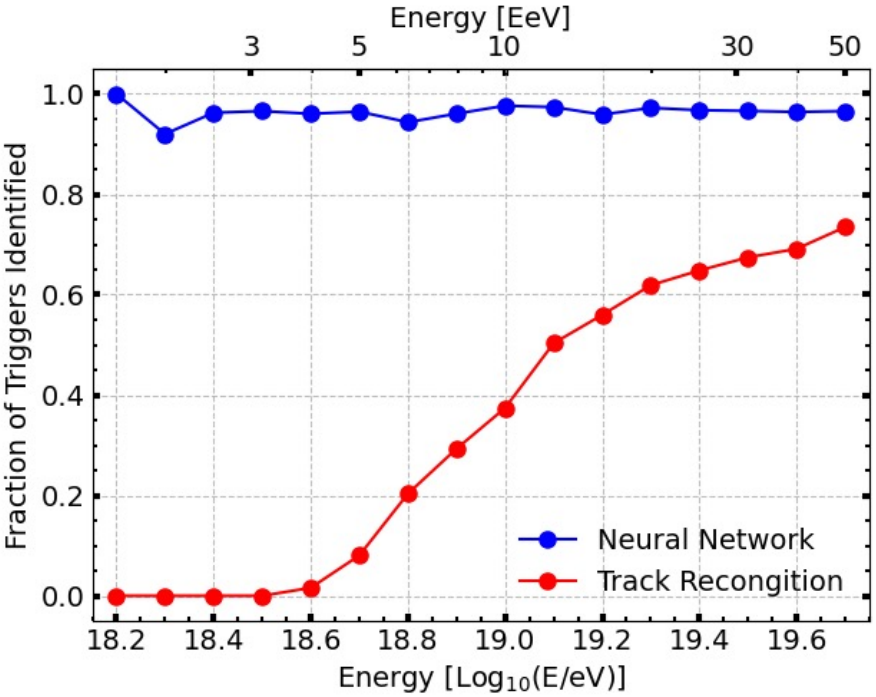
Convolutional Neural Network – Macro-Pixels



Convolutional Neural Network – Macro-Pixels

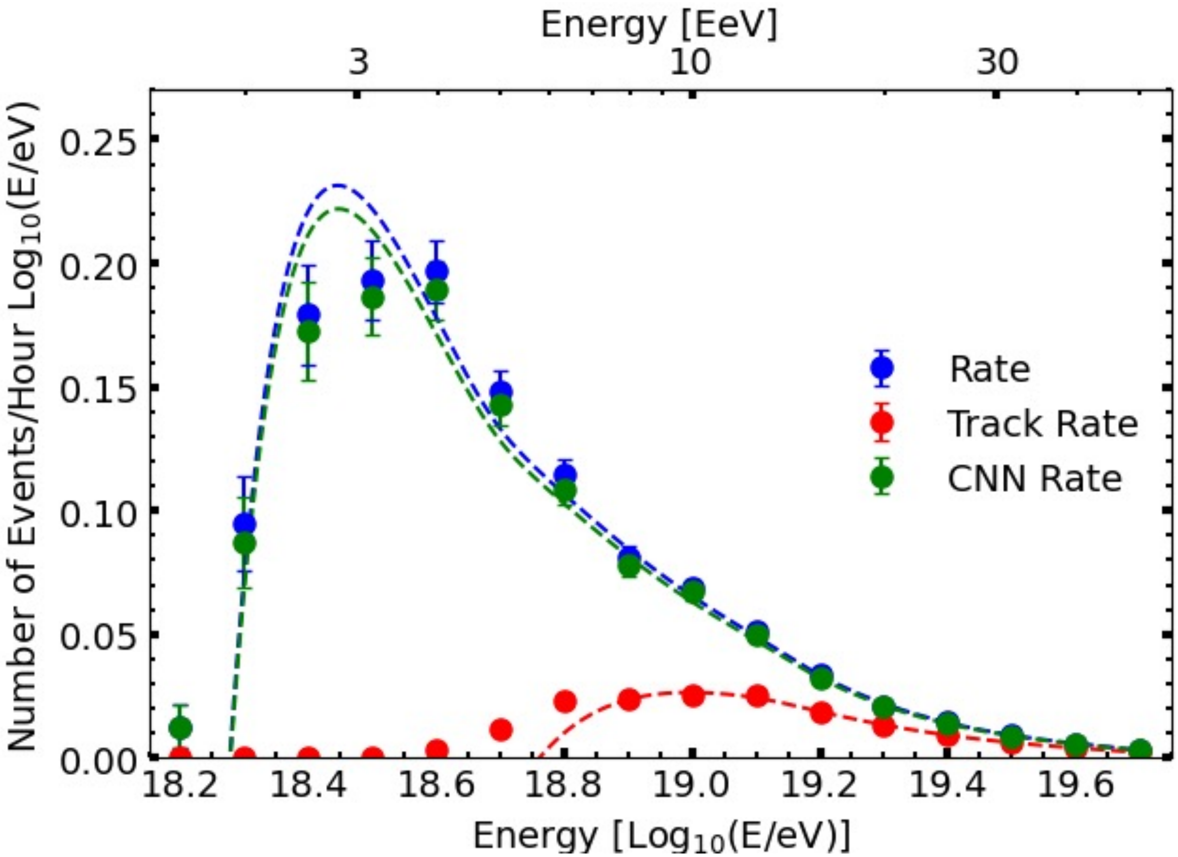




- Specifics: 5-layer CNN, Adam's optimizer, LR 0.001, L2 penalty of 0.01, 20 epochs, 20% dropout rate

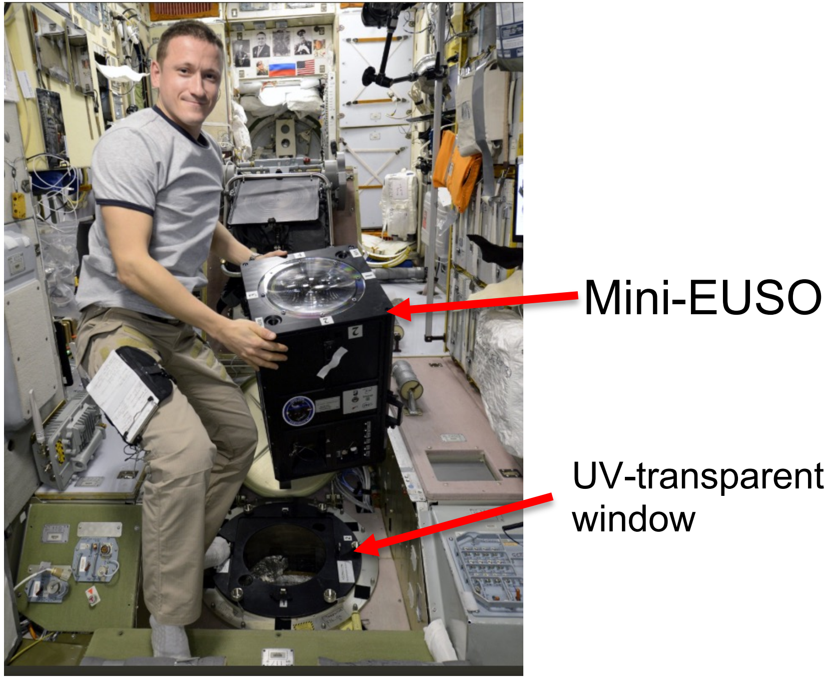
https://doi.org/10.22323/1.395.0405

Impact on recorded event rate

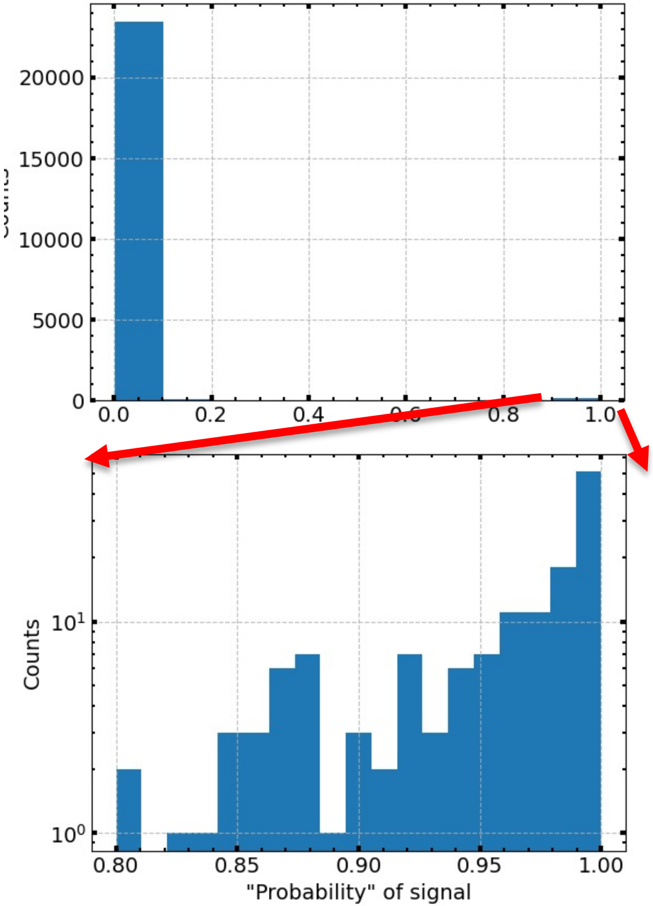


Using NN to classify Mini-EUSO Data

ISS

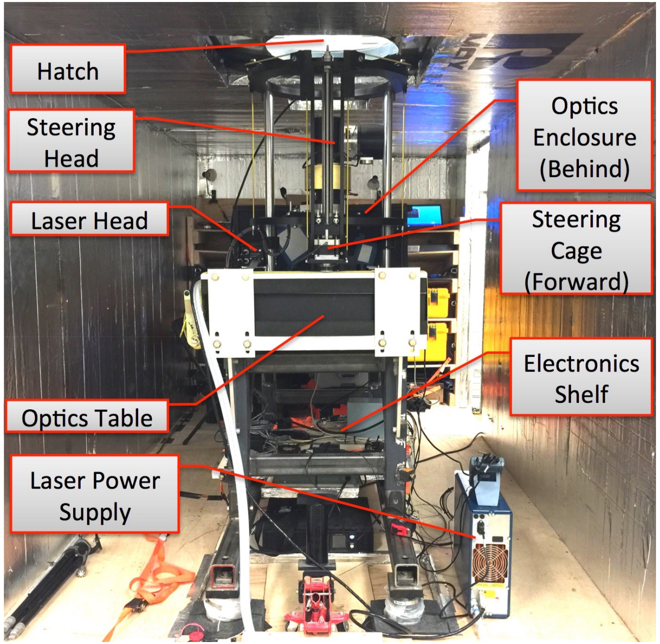


https://twitter.com/KudSverchkov/status/1342023781854961665?s=20

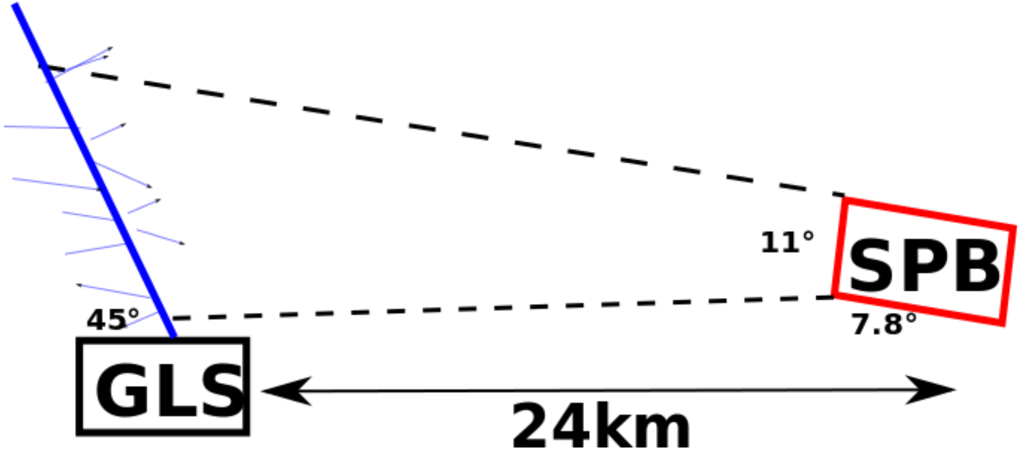


Field Tests

10.22323/1.236.0626



Steerable laser:
355 nm
0.25-80 mJ (5% acc.)
Pointing acc. 0.2°



Convolutional-Recurrent NN

Input shape: [-1, 2, 20, 48, 48]
  - -1 denotes batch size
  - 2 represents the two records of the <u>same angle</u> (should be described similarly)

Convolutional module processes every frame in each record
  - Output shape: [-1, 2, 20, 784]
  - One 784-dimension vector to describe each <u>frame</u> of input

RNN module processes frame vectors sequentially
  - Output shape: [-1, 2, 784]
  - One 784-dimension vector to describe each <u>sequence</u> in the input

Obtain sequence *projections* for each record
  - Output shape: [-1, 2, 36]

Calculate contrastive loss using projections

* Load pre-trained model weights *

Input shape: [-1, 20, 48, 48]
  - -1 denotes batch size

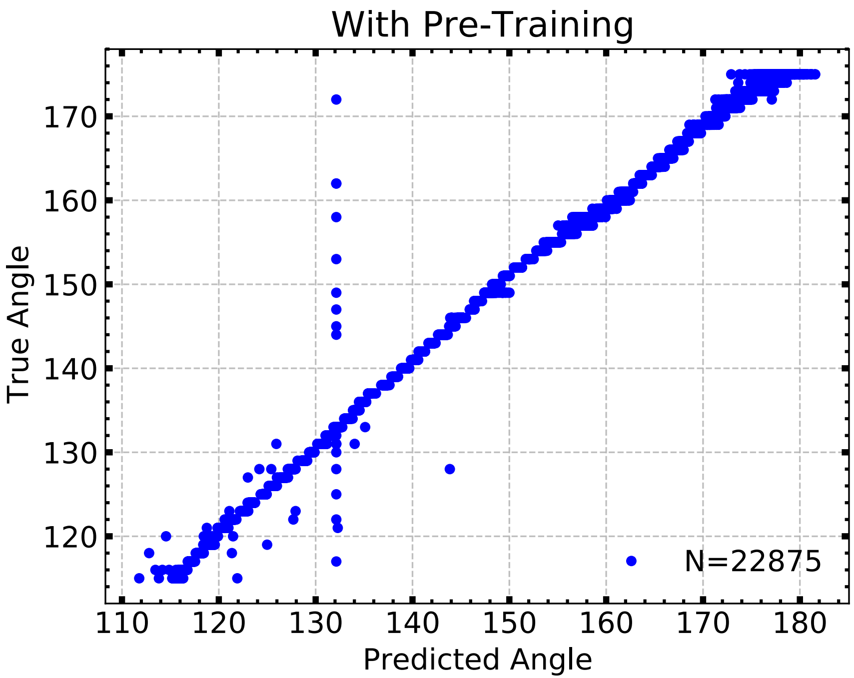
Convolutional module processes every frame in each record
  - Output shape: [-1, 20, 784]
  - One 784-dimension vector to describe each <u>frame</u> of input

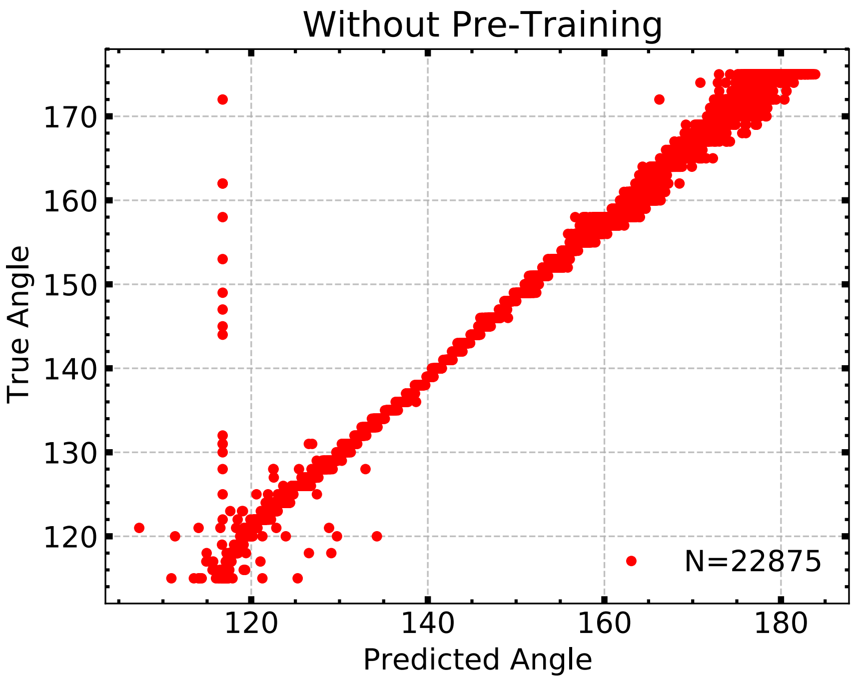
RNN module processes frame vectors sequentially
  - Output shape: [-1, 784]
  - One 784-dimension vector to describe each <u>sequence</u> in the input

Use sequence embeddings to predict the <u>angle</u> of the record

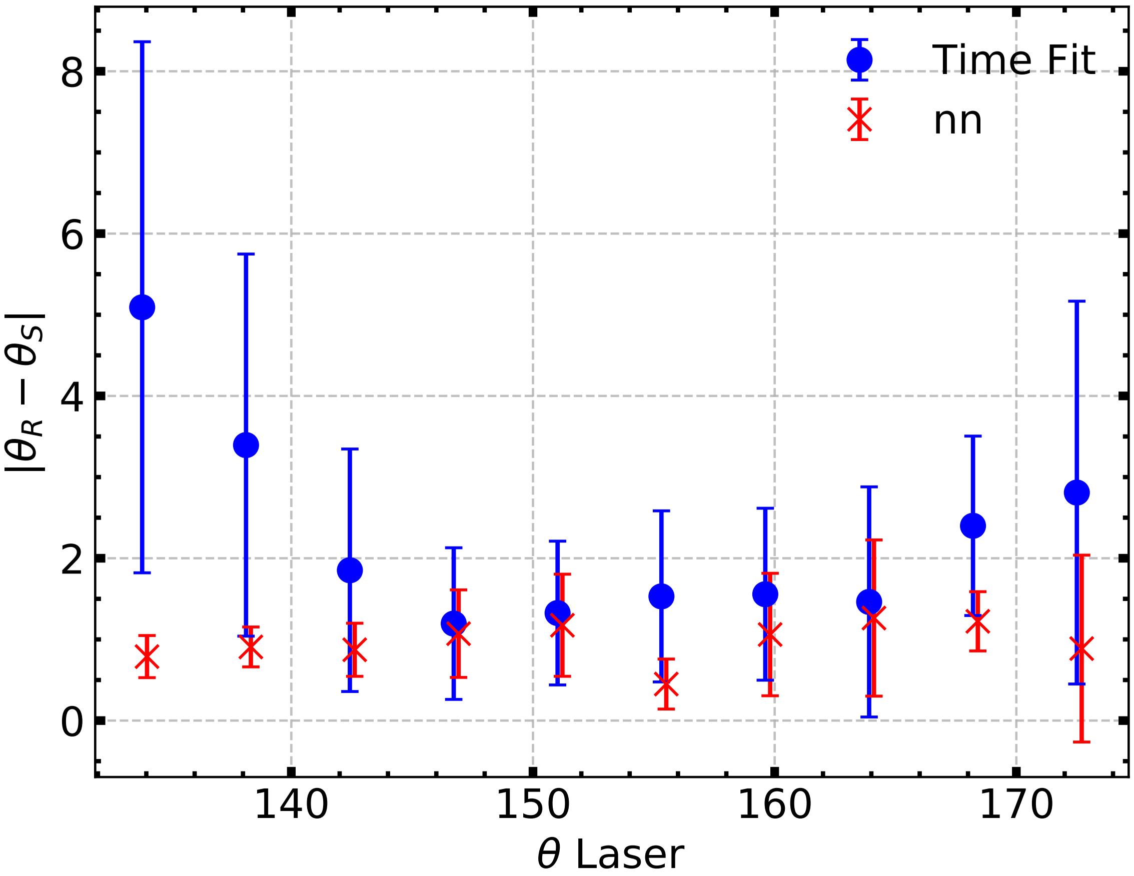
Minimize MSE(predictions, labels)

Impact of Pre-Training





Comparison with standard reconstruction



Conclusions

- CNN shows promise for onboard classification of EAS events for EUSO-SPB2
- More complex models show promise for offline analysis/event reconstruction
- Both techniques can be validated prior to flight during field tests using controlled laser shots

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Extras

Hardware Trigger

- Works at MacroPixel level (i.e. sum of a 2x2 square grid of pixels)
  - residence time in a pixel for medium to high inclined shower is less than 1μs. MacroPixels fully contain the signal.
- Adaptive threshold independent for each MacroPixel
  - Background estimated by the integral of 16ms of data (AVG_i)
  - Background values saved for exposure estimation
  - Threshold set n_σ [5] above the background level of each MacroPixel
  - Threshold updated every 500ms

$$AVG_i = \frac{1}{16384} \sum_{GTU=0}^{16383} \sum_{PXL=0}^{4} PXL_i(GTU)$$

$$THR_i = AVG_i + n_\sigma \sqrt{AVG_i}$$

https://doi.org/10.1016/j.asr.2021.12.028

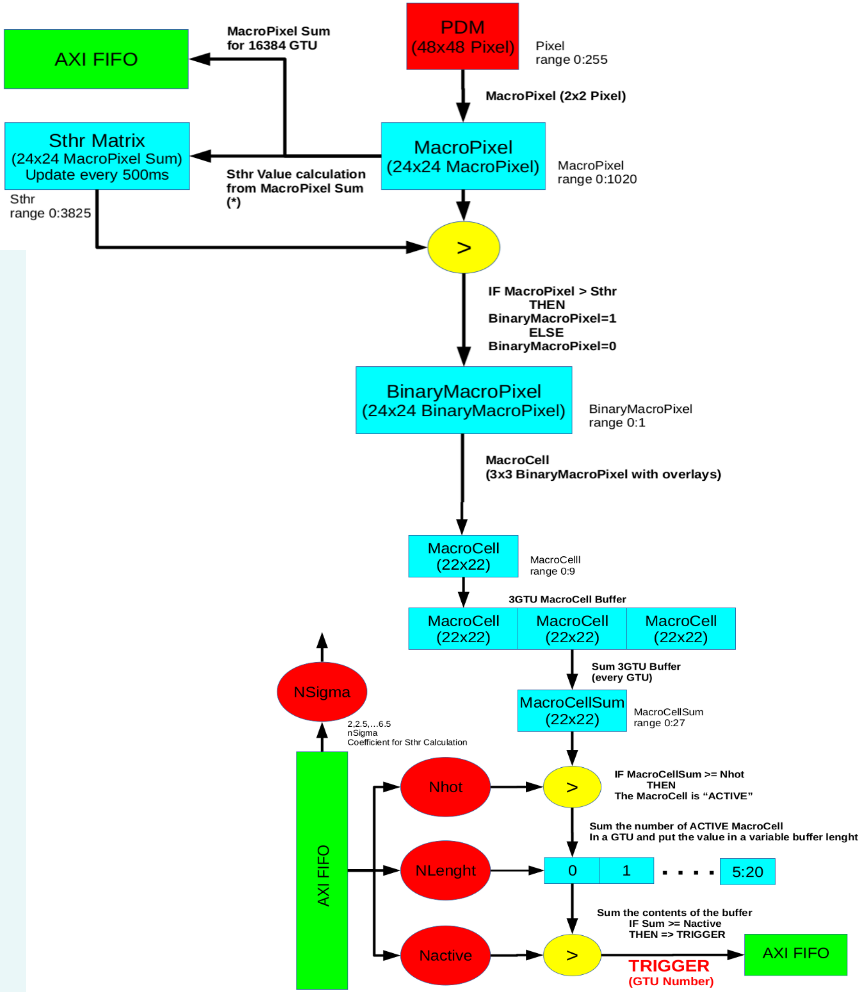
Hardware Trigger

The following operations are performed every GTU [1μs]:

1. Create a boolean matrix (**BinaryMacroPixel**) with "1" if the MacroPixel is above threshold, "0" otherwise
2. Count all the **MacroPixels above threshold in** a 3x3 grid over 3 consecutive GTUs. This 3x3x3 cell is called **MacroCell.**
   If the value of a MacroCell is ⩾ ***nHot*** [2], **the Macrocell is** considered **active**
3. Count how many **Active MacroCells** there are in the entire PDM in ***TriggerLength*** [20] **consecutive GTUs**. If ⩾ ***nActive***, a **trigger** is issued

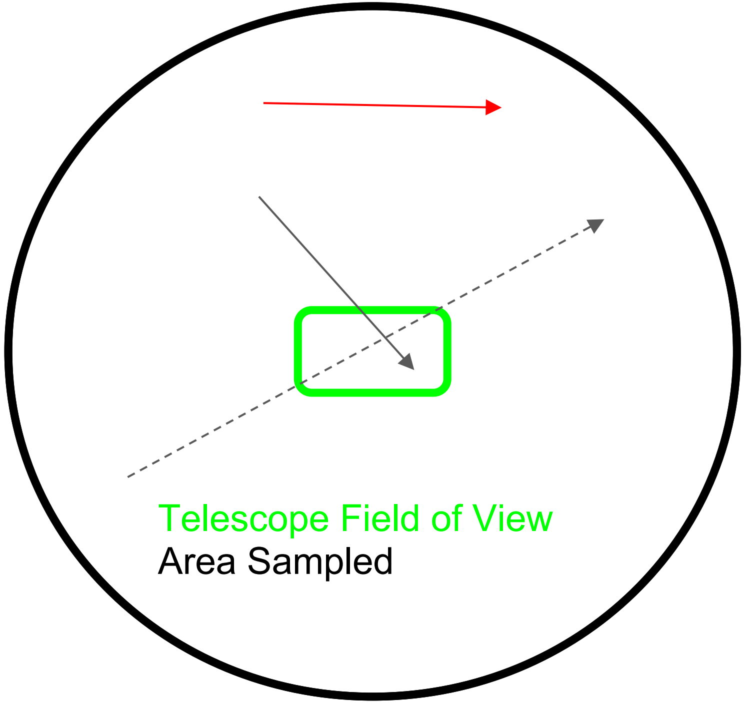
4 parameters to be set from outside: $\boldsymbol{n_\sigma}$, ***nHot***, ***nActive*** and ***TriggerLength.*** The values in square brackets are the best.

Upon the issue of a trigger, **128μs of data** are stored for all the 3 PDMs, 64 before and 64 after the trigger time.



Event Rate Calculation

- Showers simulated in Conex using EPOS-LHC
- Showers thrown isotropically over a 100 km disk
  - Zenith angles 0^{o}- 80^{o}
  - Energies from $10^{17.8}$-$10^{19.7}$ eV
  - 80k showers per energy
- Converted to event rate using the energy spectrum measured by Auger [*].
- Geant4 simulation of optics, parametric simulation of electronics in the JEM-EUSO OffLine framework



$$\text{Rate} = \left(\frac{\text{Showers Triggered}}{\text{Showers Thrown}}\right) A\Omega \int J(E)dE$$

[*] Pierre Auger Collaboration arXiv:2008.06486

Event Rate Calculation