Reconstruction of energy of EUSO-TA events with ANNs. Current status

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Brief reminder

Two artificial neural networks (ANNs) for EUSO-TA were developed/tuned in 2024 (basing on those for EUSO-SPB2):

1. A convolutional encoder-decoder (CED) for recognition of EAS tracks
2. A convolutional neural network (CNN) for reconstruction of energy and arrival directions (as well as the distance from EUSO-TA to EAS cores)

The same ANNs work both for EUSO-TA and EUSO-SPB2. The only difference is the representation of data: integrated tracks for EUSO-SPB2 and stacks of focal surface images for EUSO-TA.

All ANNs were trained on simulated data obtained with CONEX and Offline[1] for the elevation angle 10°, 5–100 EeV, background 1 c./p./GTU

All details can be found in: arXiv:2408.02440 (published) and arXiv:2501.02311 (in press)

Our goal in 2025: try to reconstruct energy of UHECRs registered with EUSO-TA in 2015

[1] Thanks a lot to Francesca B., George, Johannes, and Zbigniew!

EUSO-TA events

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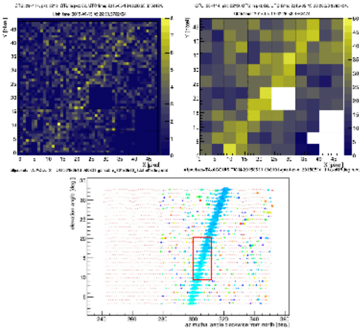
Table A.5
Parameters of the nine detected events from measurements with the external trigger from TA-BRM-FDs. In order from left to right: elevation angle of EUSO-TA during the operation; energy reconstructed by TA, zenith angle θ; azimuth angle ϕ measured from east counterclockwise; the impact parameter R_p; the energy rescaled based on this analysis $E_{eq,atm}$; the distance of the shower measured along the telescope optical axis.

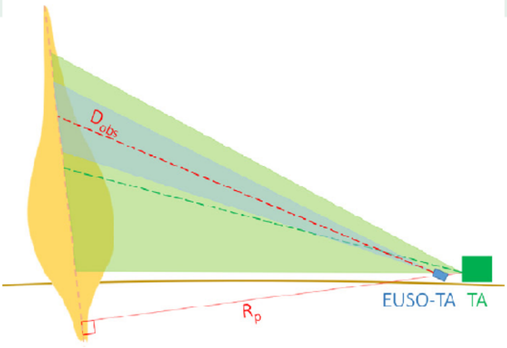
elev. (deg)	E_{recTA} (eV)	θ (deg)	ϕ (deg)	R_p (km)	$E_{eq,atm}$ (eV)	D (km)
25	4.90×10^{18}	56.9	15.7	8.3	2.09×10^{18}	8.66
15	1.15×10^{18}	34.5	82.8	2.5	3.27×10^{18}	2.88
25	1.58×10^{18}	62.9	27.0	0.8	6.98×10^{18}	1.04
21	1.12×10^{18}	29.5	254.9	5.0	5.61×10^{17}	5.12
20	3.24×10^{18}	60.4	169.3	9.1	1.88×10^{18}	19.80
10	2.40×10^{18}	41.2	114.8	6.7	3.51×10^{17}	10.03
15	3.31×10^{18}	40.6	210.5	9.0	2.17×10^{18}	10.07
10	5.13×10^{17}	10.6	130.5	1.7	3.10×10^{17}	2.12
15	2.63×10^{18}	8.1	8.0	2.6	2.08×10^{18}	2.76

Information on energy, θ, ϕ was provided by the Telescope Array collaboration.
Accuracy of energy estimation by TA FDs: **17%**.

Important: every elevation angle needs its own training data set prepared with $\overline{\text{Off}}\underline{\text{line}}$.
This is time-consuming. We considered $10^\circ, 15^\circ, 25^\circ$ but then focused on 15° (3 events).

Difficulties of energy reconstruction for EUSO-TA





- a small field of view ⇒ only a part of an EAS is registered
- coarse time resolution in comparison with the Auger, TA FDs (2.5 μs vs. 0.01 μs) ⇒ all events registered at the elevation angle of 15° have a single hit GTU
- a whole number of pixels didn't function properly
- not quite clear PMT gains

```
allpackets-TA-ACQUISITION-20150512-081249-gaintable_20150510_1.txt-el25deg.root
allpackets-TA-ACQUISITION-20150513-080301-gaintable_20150510_1.txt-el15deg.root
allpackets-TA-ACQUISITION-20150516-054449-gaintable_20150510_1.txt-el25deg.root
allpackets-TA-ACQUISITION-20150912-035814-gaintable_20150516.txt-CLF21deg0358.root
allpackets-TA-ACQUISITION-20150918-053906-gaintable_20150516.txt-Laser20deg0539.root
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allpackets-TA-ACQUISITION-20151016-090337-gaintable_20150516.txt-TA_EXT_10Degrees.root
allpackets-TA-ACQUISITION-20151107-091314-gaintable_20150516.txt-Cosmic15degTA.root
```
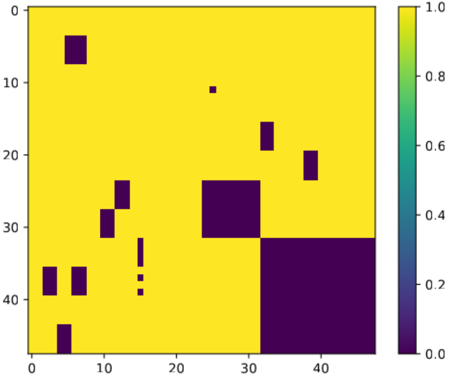

Taking into account “bad” pixels and other puzzles

We can apply the mask

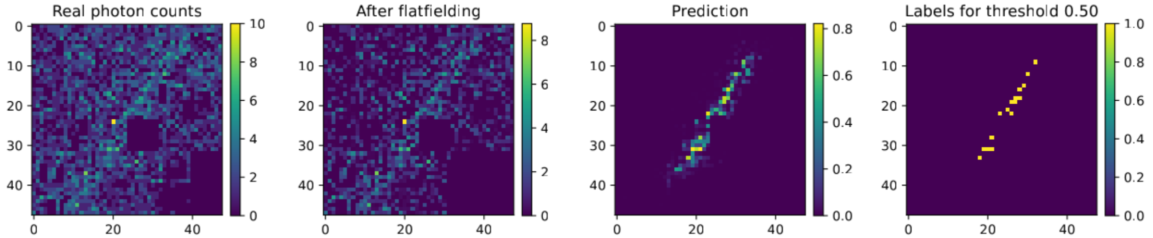
- at the stage of training a model for track recognition (CED)
- at the stage of training a model for energy reconstruction (CNN)
- at both stages
- just at the stage of working with EUSO-TA events



Mask extracted from PMT gains (as of 2015-05-23) found in $\overline{\rm Off}\underline{\rm line}$ (17% dead)

An unexpected puzzle: segmentation models that are the best in terms of performance metrics usually result in reconstruction models with lower MAPE. **However**, the best reco models do not necessarily give the best estimates for the energy of EUSO-TA events ⇒ **Ensembles of CNNs**

2015-05-13, E=1.15 EeV

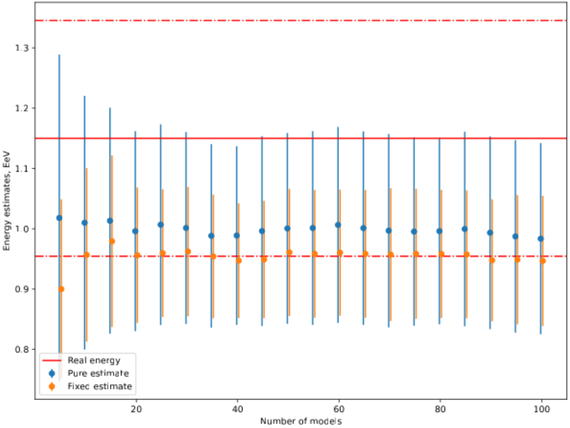


Flat-fielding: just extract mean counts calculated during previous 256 GTUs (and zero negatives)

10 segmentation models were trained with the mask applied. The best one (in terms of performance metrics) was chosen

$\theta = 34.5^\circ$, $\phi = 82.5^\circ$ (almost orthogonal to the line of sight).
We don't have an event with similar ϕ for close values of (E, θ) in the training dataset
(neither triggered nor non-triggered event)

2015-05-13, E(TA)=1.15 EeV. Energy Reconstruction with an Ensemble



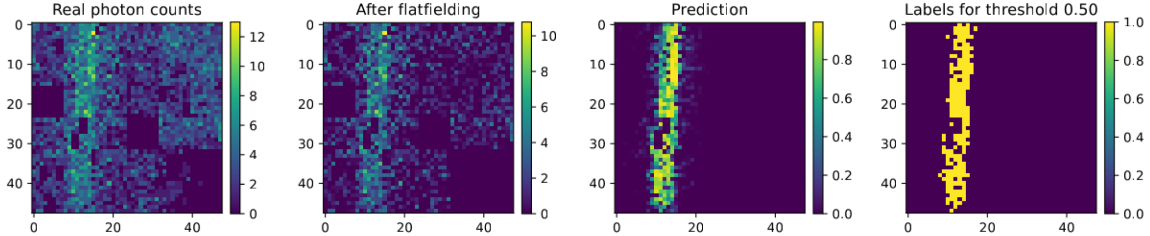
100 CNN models were trained using the mask.

$\bar{E} = 0.98$ EeV, $\sigma(E) = 0.16$ EeV ($\sim 16\%$)

Exclude outliers with the Tukey fence[2]: $\bar{E} = 0.95$ EeV, $\sigma(E) = 0.11$ EeV ($\sim 12\%$)

[2]Keep data within [Q1 - k(Q3-Q1); Q1 + k(Q3-Q1)], $k = 1.5$

2015-11-07; E(TA) = 2.63 EeV

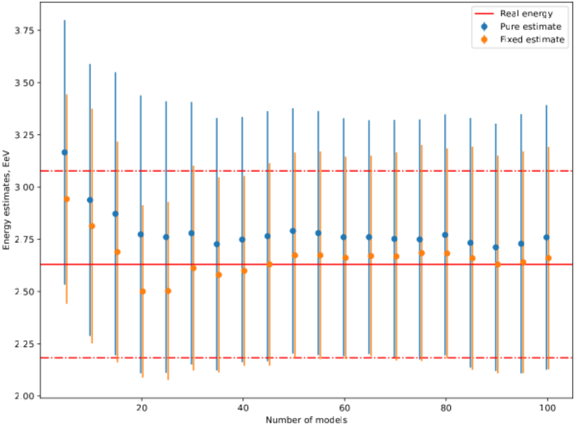


Different segmentation models select slightly different tracks that do not strongly influence estimations of energy. The same segmentation model is used here.

$\theta = 8.1^\circ$, $\phi = 8.0^\circ$. No such events in the initial dataset.
The event is bright $\Rightarrow$ overestimated energy (~ 4 EeV)

We complemented the training dataset with nearly vertical but nearby events (within 3 km from EUSO-TA) to avoid overestimation of the energy

2015-11-07; E(TA) = 2.63 EeV. Energy Reconstruction

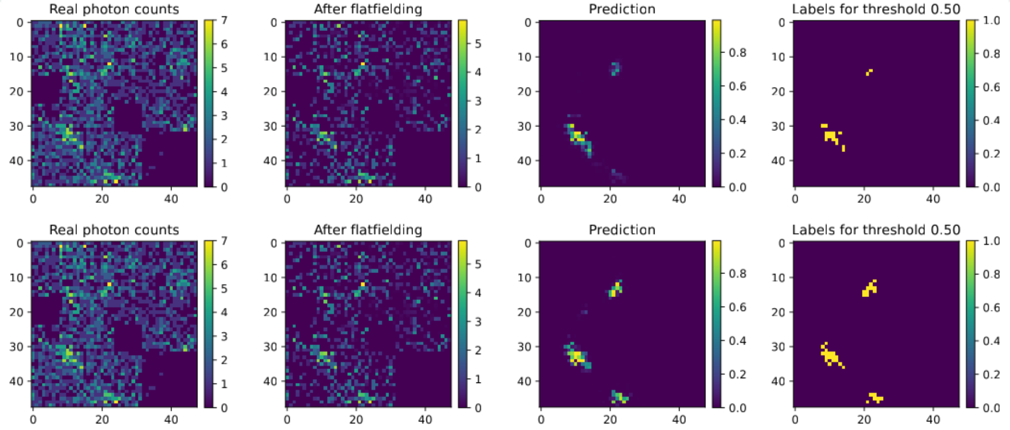


100 CNN models trained with the same segmentation model as above but with an updated dataset

$\bar{E} = 2.80$ EeV, $\sigma(E) = 0.71$ EeV ($\sim 25\%$)

Exclude outliers with the Tukey fence: $\bar{E} = 2.67$ EeV, $\sigma(E) = 0.58$ EeV ($\sim 22\%$)

2015-10-15; E(TA) = 3.31 EeV



Top: the same segmentation model. Bottom: a model trained w/o the mask

Top: $\bar{E} = 1.48$ EeV, $\sigma(E) = 0.25$ EeV. **The energy is strongly underestimated!**

Bottom: $\bar{E} = 2.94$ EeV, $\sigma(E) = 0.81$ EeV (reco models trained w/o the mask; if we employ the mask while training CNNs, the energy estimation decreases)

Key takeaways

- One can reconstruct energy of an UHECR having a single hit GTU but the procedure isn't straightforward (yet) and some questions remain
- Try to prepare a dataset with all possible combinations of E, θ, ϕ, D you can think about. CONEX doesn't provide uniform distribution vs. $\thema$, thus quasi-vertical and highly inclined showers can by under-represented (NB: Offline doesn't necessarily produce a trigger.)
- Using ensembles of models is recommended
- The root of some predictions is still unclear even for simulated events. It would be interesting to try so called "explainable ML models" (see, e.g., arXiv:1705.07874, arXiv:2505.06815)
- There are more ANN-based tools that can be tested:
  - more sophisticated ensemble learning methods
  - reconstruct energy with graph neural networks (e.g., arXiv:2502.07421)
  - generative adversarial networks to complement Offline or to simulate non-uniform backgrounds similar to real ones to avoid artefacts in reconstructed tracks
  - "infill" data for malfunctioning pixels and gaps between PDMs, complement partial tracks at the edges of the FoV
- Our scripts are available at the collaboration repository at gitlab. No README yet but a lot of comments in the code. Don't hesitate to let me know if you have questions/ideas or find bugs!

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Thank you for your attention! Merci pour votre attention !