Deep Learning Measurement of Non-Fiducial Electrons Cosmic Rays Using on the DAMPE Experiment

Young Researchers' Day:

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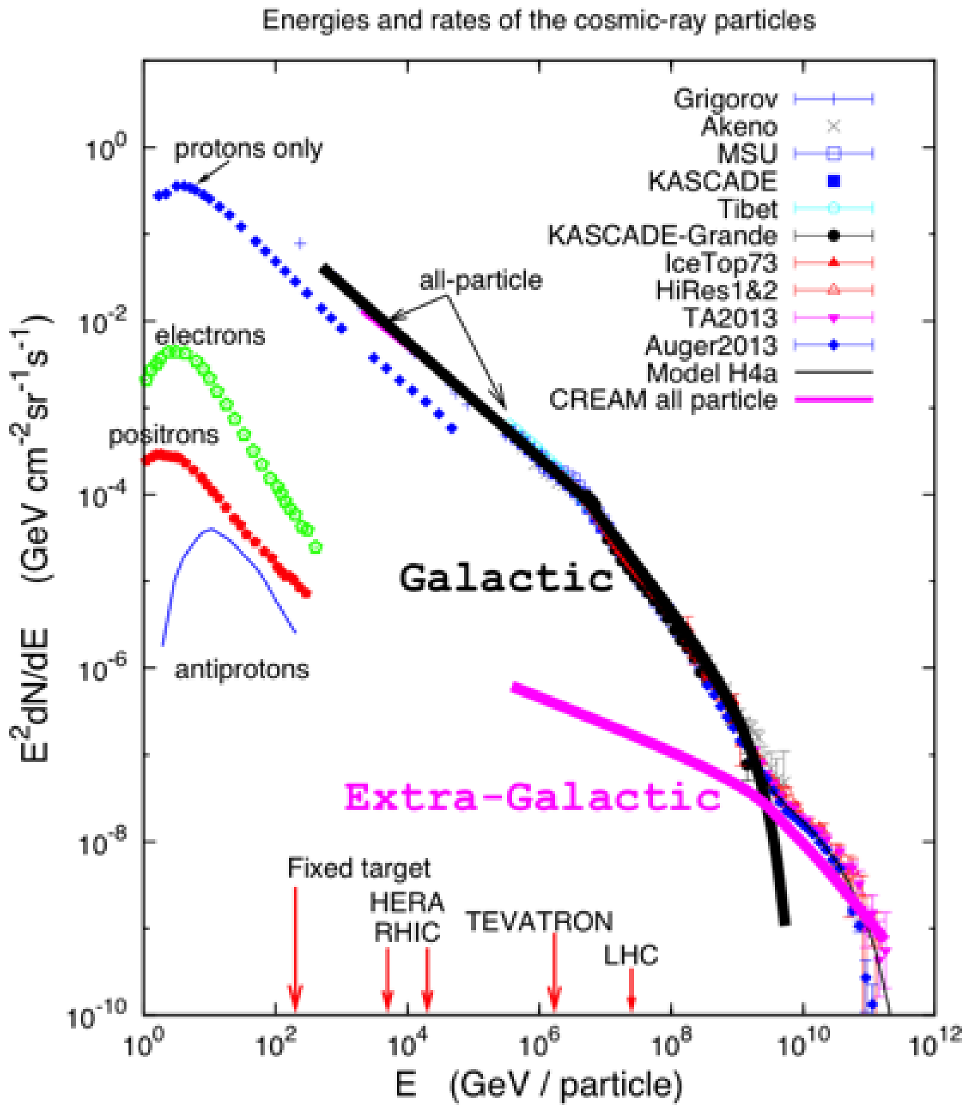
Outline

- Cosmic Rays.
- DAMPE experiment.
- Cosmic Ray Electrons (CREs).
- Motivation for a non-fiducial analysis.
- Events Selection.
- A Convolutional Neural Network (CNN) classifier.
- Assessing efficiency of models.

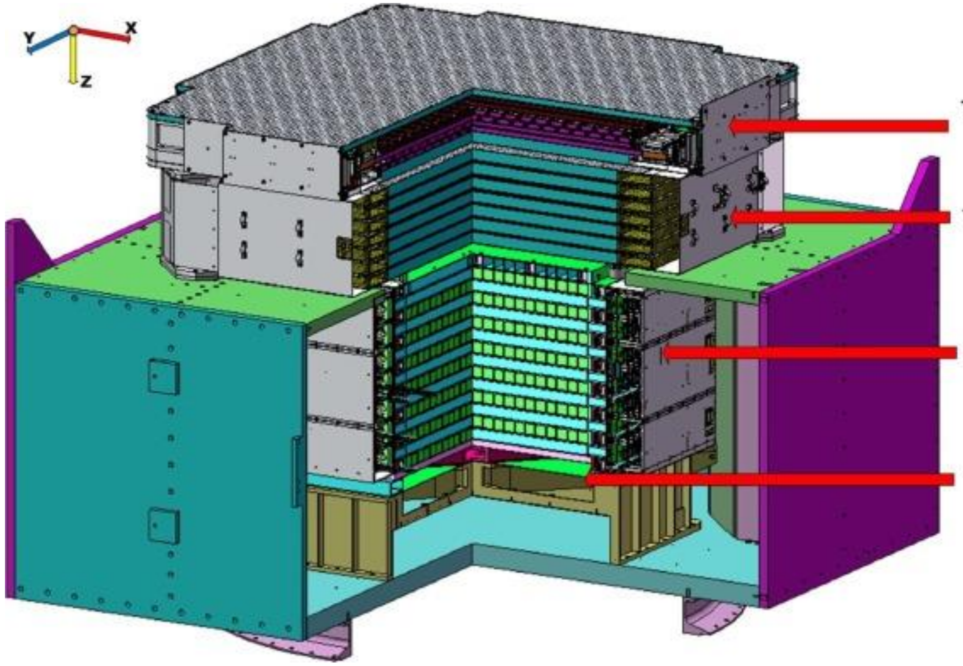
Cosmic Rays:

- Cosmic Rays are particles from space composed of protons, ions and electrons.
- Produced and accelerated in extreme environments such as e.g., supernovae, pulsar wind nebulae, AGN, etc.
- Potentially from Dark Matter annihilation/decay.
- Therefore, their understanding will allow to understand the mechanisms behind it.

[1] https://masterclass.icecube.wisc.edu/fr/analyses/le-spectre-denergie-des-rayons-cosmiques



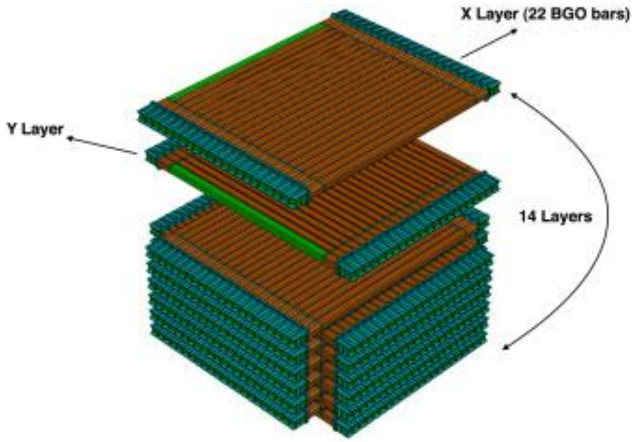
DAMPE Experiment:



[2]: J.Chang et al., The DArk Matter Particle Explorer mission. https://doi.org/10.1016/j.astropartphys.2017.08.005

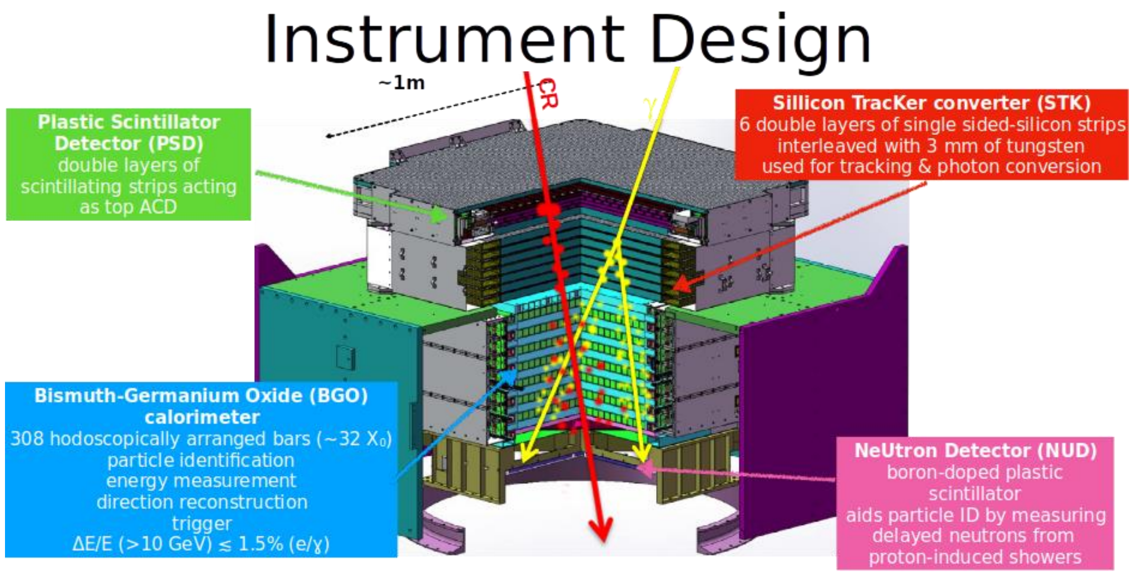
- DAMPE was launch in 2015.
- Collaboration between China, Italy and Swiss.
- Main objectives are the study of:
    - Cosmic Rays up to 100 TeV. (cf. Arshia Ruina presentation)
    - Cosmic Rays Electrons (CREs) and Gamma Rays between 5 GeV to 10 TeV.

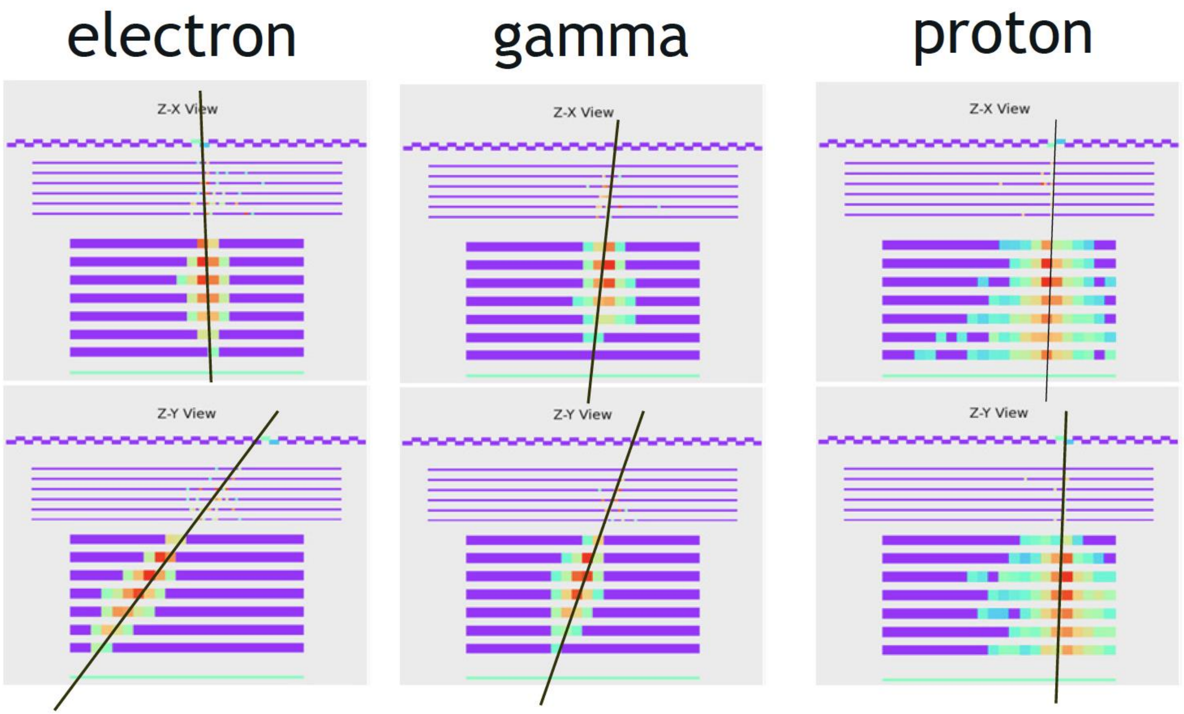
•BGO (Bismuth Germanium Oxide) calorimeter is composed of 14 layers each with 22 bars.



[3] Y.Wei et al. , Nuclear Inst. and Methods in Physics Research, A 922 (2019) 177–184

DAMPE Experiment: Particle interaction in the calorimeter.





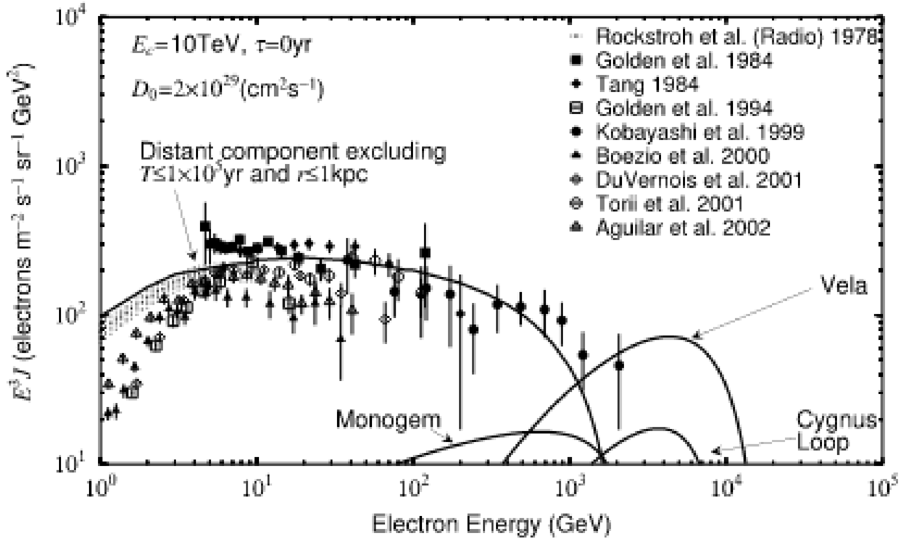
[4] S.Zimmer, TEVPa 2017, Colombus, Ohio,USA.

Cosmic Rays Electrons (CREs):

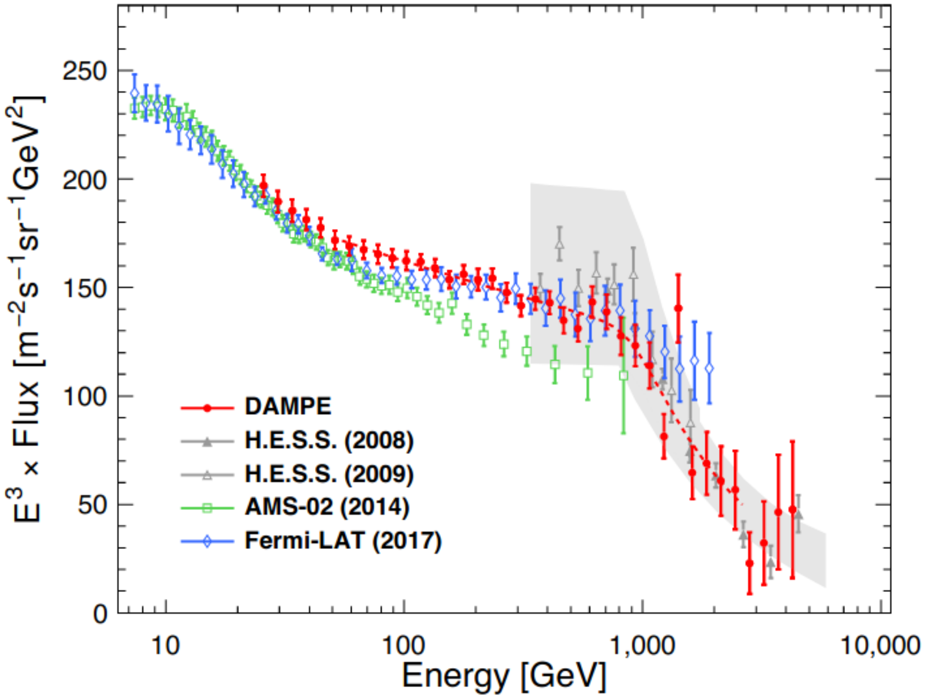
- CREs (electrons + positrons) are an interesting key to study galactic HE process.
- May prove Dark Matter annihilation/decay.
- Different experiments spaced/ground base experiments have studied CREs up to ~5TeV.
- A break at the TeV scale was observed by H.E.S.S [4] and confirmed by DAMPE (2017 nature).

[4] Aharonian, F. et al. (The H.E.S.S. Collaboration). Energy Spectrum of Cosmic-Ray Electrons at TeV Energies. Phys. Rev. Lett., 101, 261104 (2008).

Motivation For A Non-fiducial Analysis



[5]T. Kobayashi *et al.* 2004 *ApJ* **601** 340.

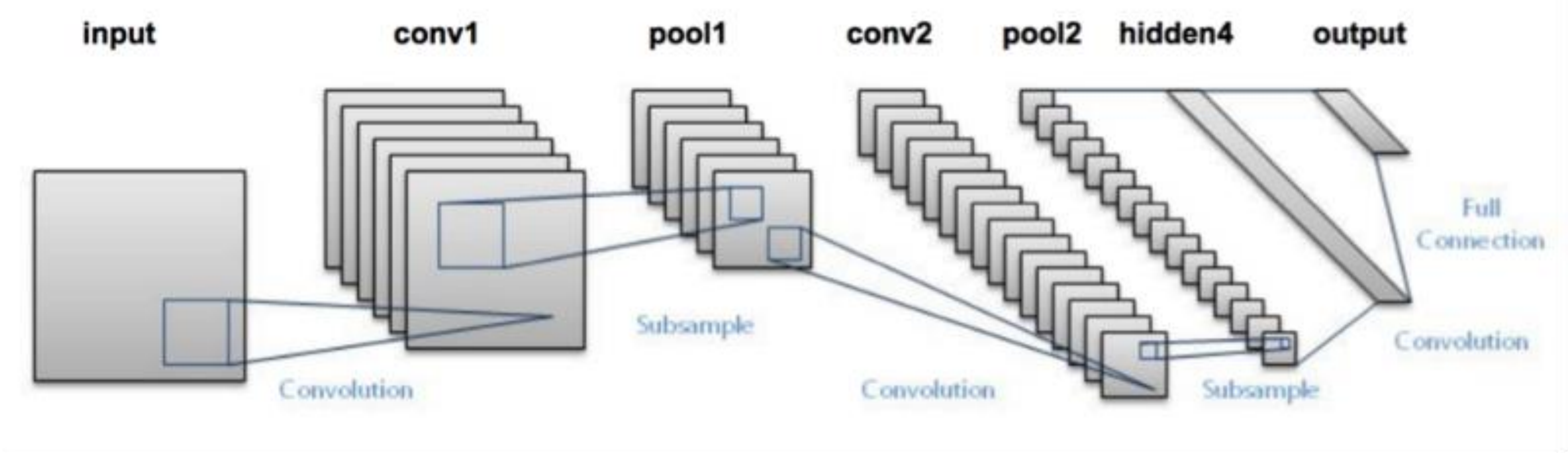


[6]G. Ambrosi et al. Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons. Nature, 552:63–66, 2017.

- Model suggest a hardening above the TeV => Low number of events.
- Increasing the acceptance of DAMPE => An increase of statistic.
- However, each events are less "clean" since there is no necessarily a PSD/STK signal and are not well contained on BGO.
- These requires advanced analysis techniques, e.g., deep learning.

A Convolutional Neural Network (CNN) classifier

Deep Learning techniques, wildly used in image recognition and computer vision.



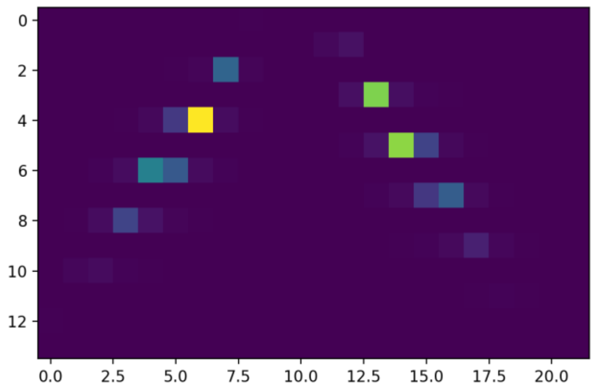
[7] https://towardsdatascience.com/a-simple-2d-cnn-for-mnist-digit-recognition-a998dbc1e79a

CNN take as an input an image, then applies some transformation of the image. After we flatten the subsample into a 1D array that will be given, as an input, to a neural network compose of a few layers of neurons and finally the output neuron.

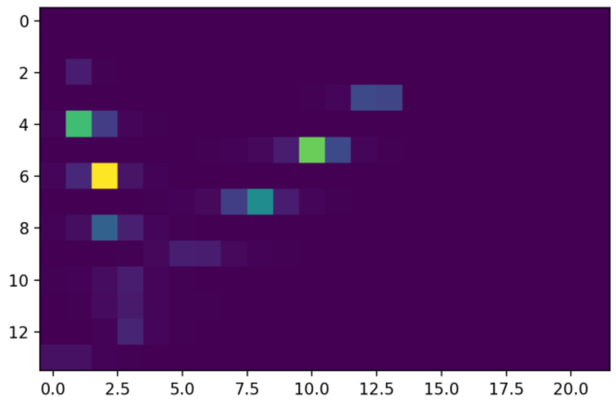
A Convolutional Neural Network (CNN) classifier

- From BGO calorimeter we can obtain an "Image" of X-Y (14x22 pixels) of the shower produced by the incoming particle.
- Both projections of the shower are correlated => Combine images allow to store more information in one image.

MC electron, 17 TeV

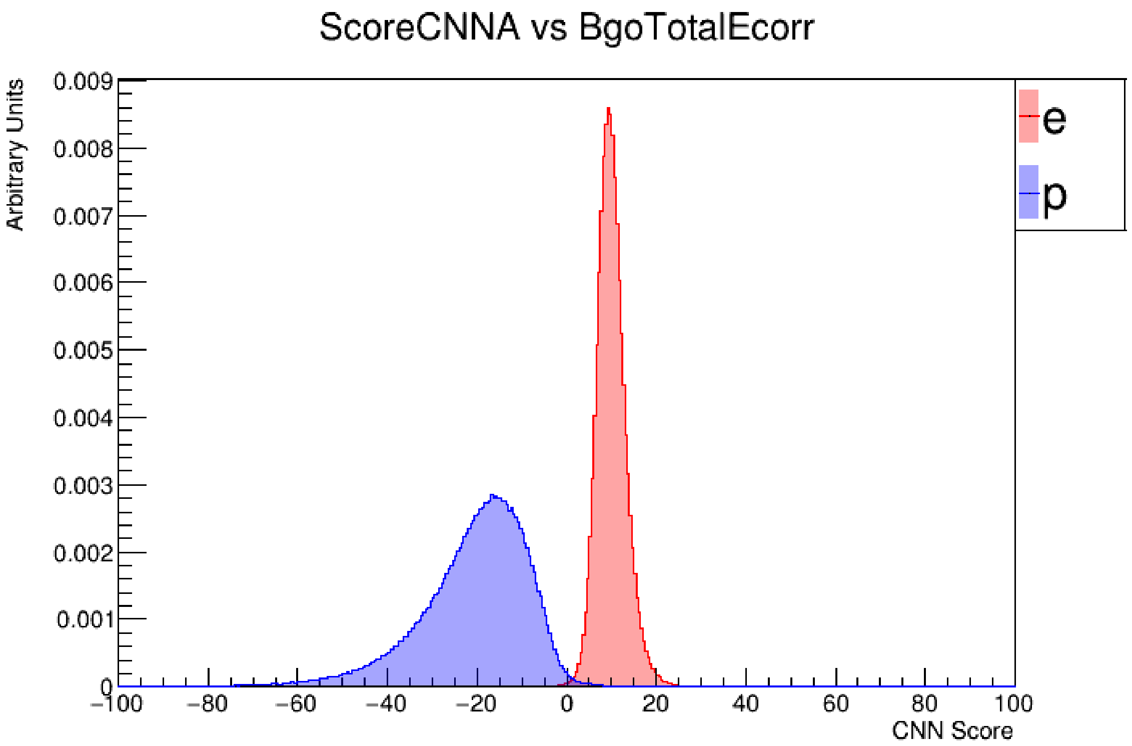


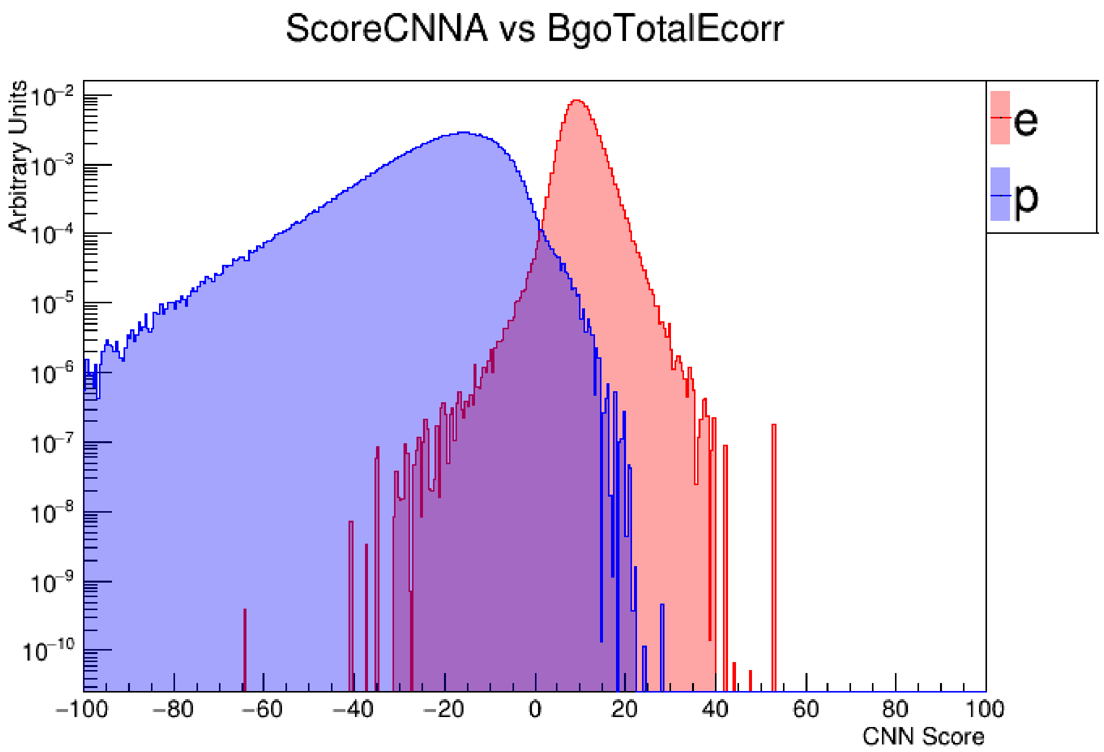
MC proton, 13 TeV



- This images are used as input for the different CNNs.

CNN score for MC protons and electrons:

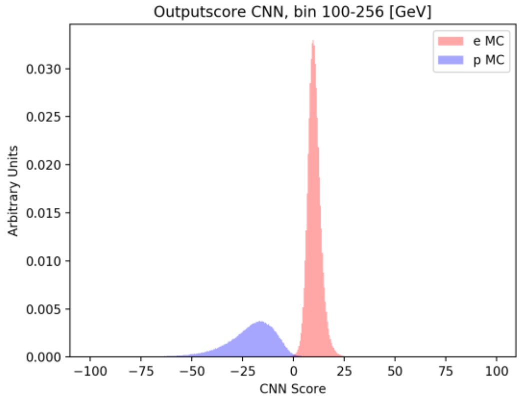


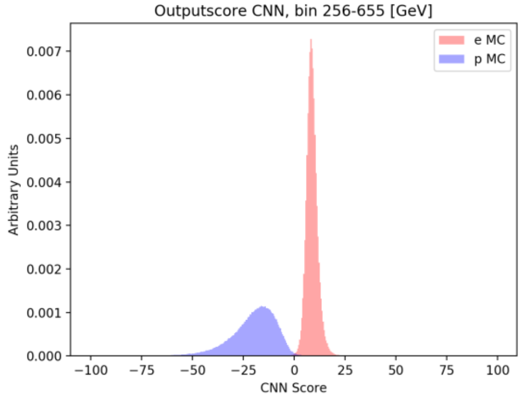


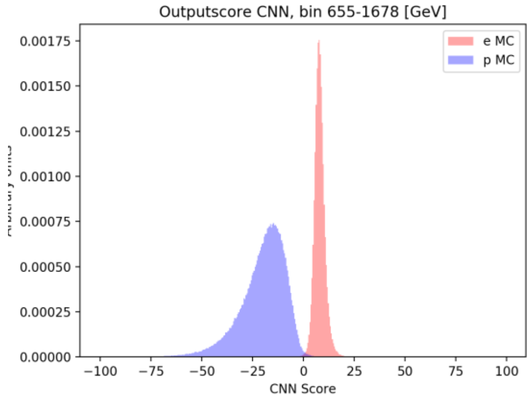
Not a normal output for a neural network, see D. Droz *et al.* 2021 *JINST* **16** P07036 for more details.

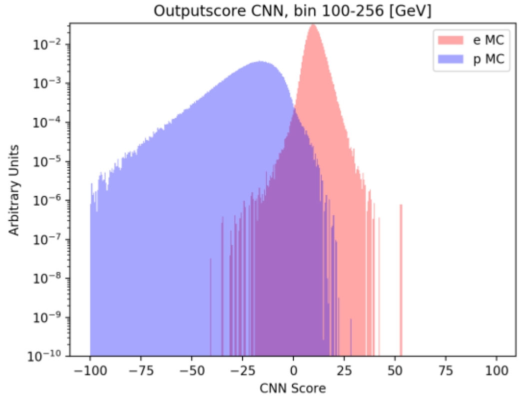
CNN Score For Different Energy Bins:

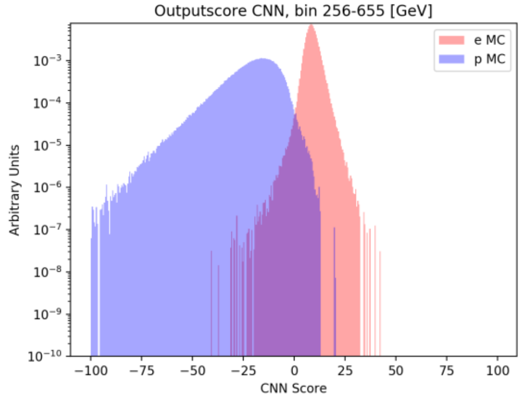
Linear scale

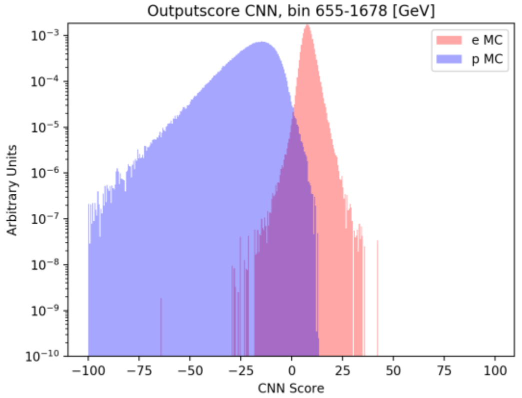








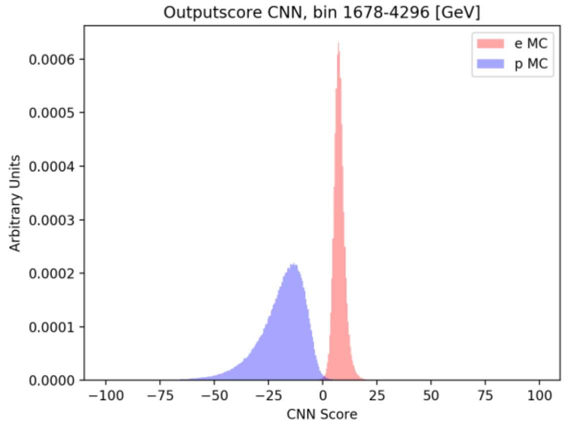


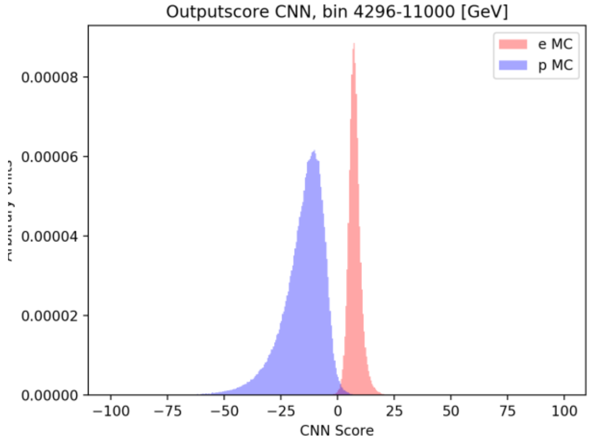


Log scale

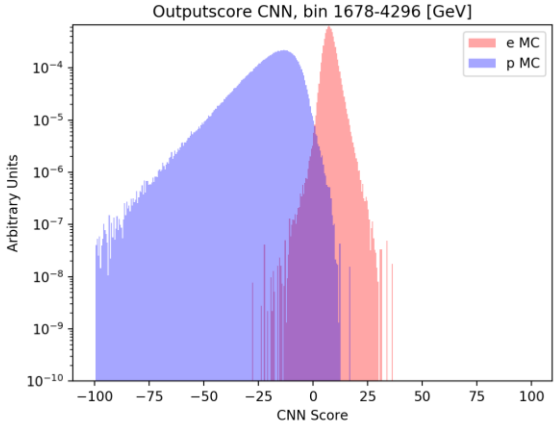
CNN Score For Different Energy Bins:

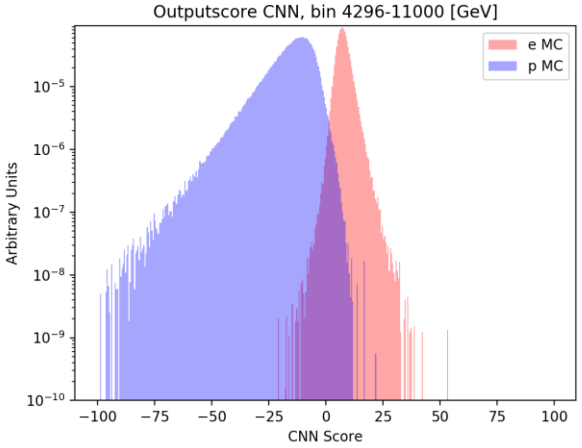
Linear scale





Log scale

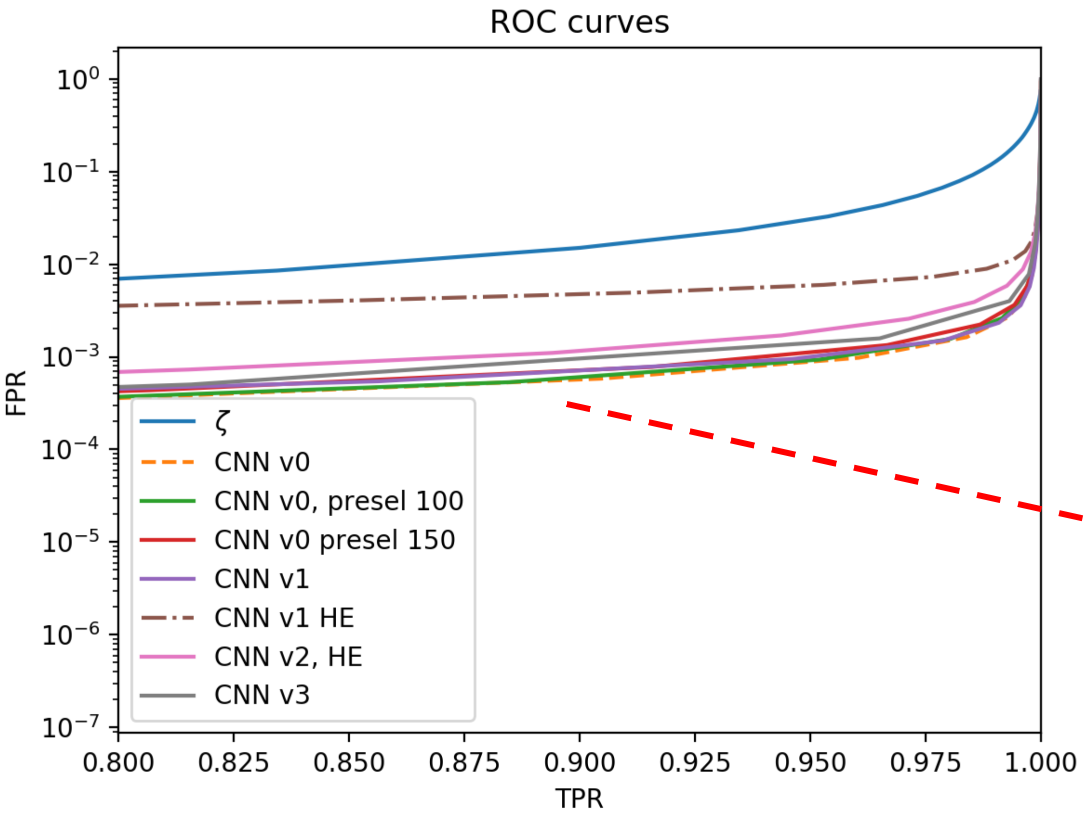




CNN Efficiency And Background Rejection:

- ROC curves define by getting True Positive Rate (TPR) and False Positive Rate (FPR):
  - $TPR = \frac{Number\ of\ electrons\ that\ pass\ the\ CNN\ score\ cut}{Total\ number\ of\ electrons} = Signal\ efficiency$
  - $FPR = \frac{Number\ of\ protons\ that\ pass\ the\ CNN\ score\ cut}{Total\ number\ of\ protons} \approx Background\ rejection$

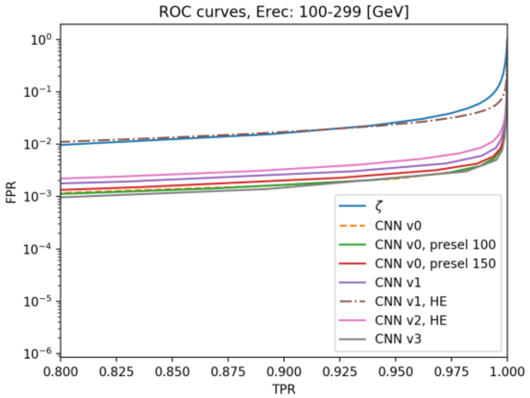
A low curve => better performances.

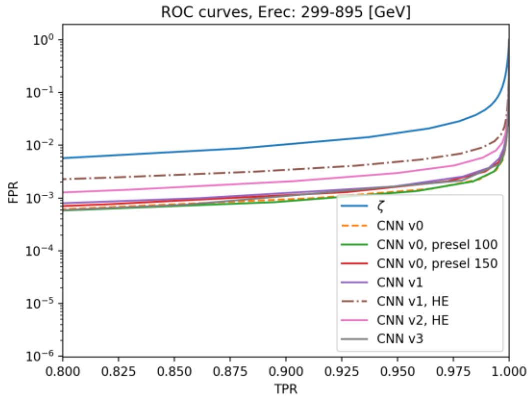


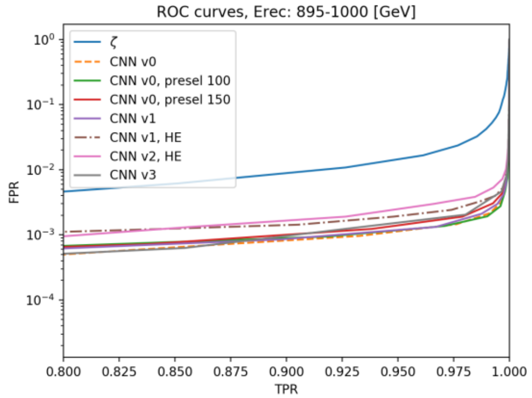
At 80/90% efficiency => ~1 order of magnitude better!!

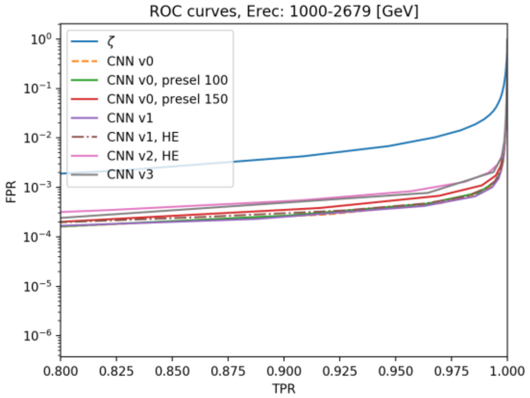
CNN Efficiency And Background Rejection Per Energy Bin:

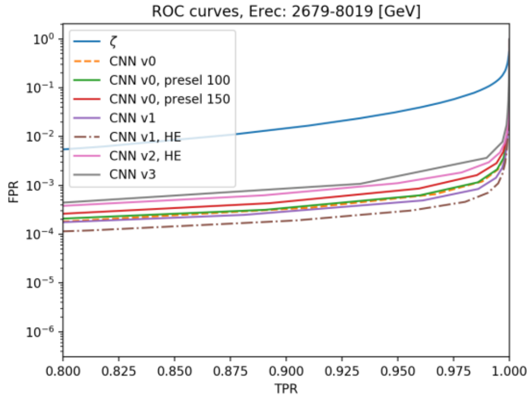
100 GeV to 1 TeV

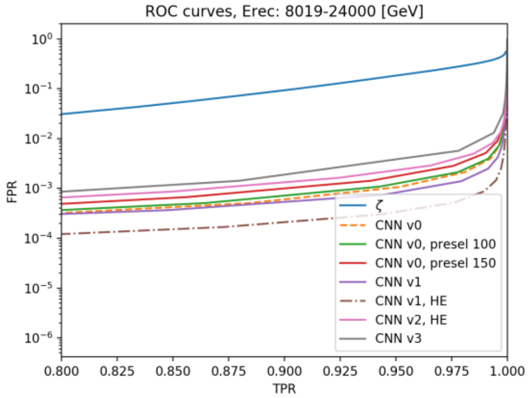












Above 1 TeV.

Summary:

- The motivation behind a non-fiducial analysis is the increase of statistics by opening the acceptance.
- While classical methods may have a low efficiency at high energy, the use of deep learning techniques can improve the selection of signal events.
- It was shown that CNN separate well electrons from background at all energies.
- However, this is based on MC data. The technique must now be validated on real data.

Thank you !

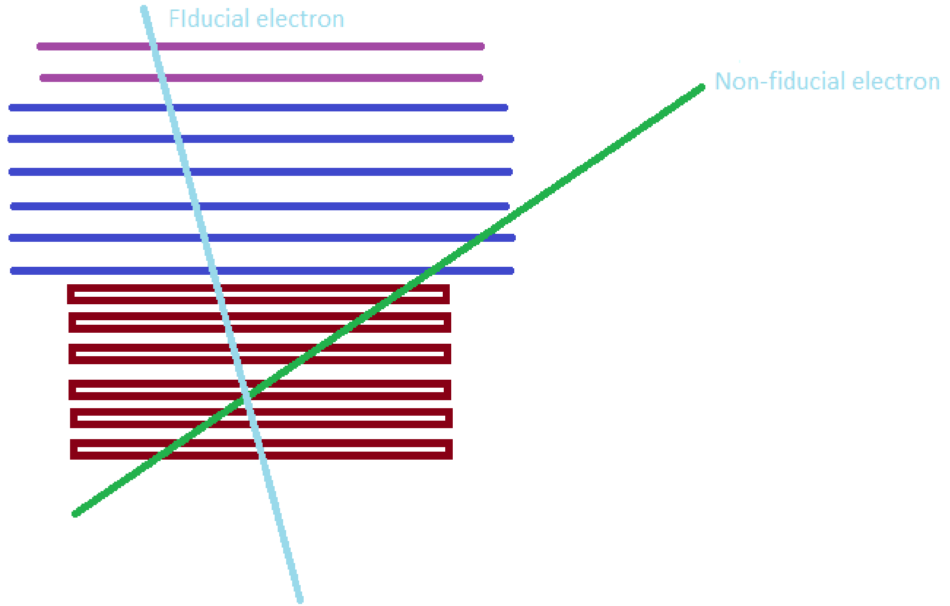
Backup Slide 1: Events selection.

- We selected events that have a reconstructed energy (Erec) above 100 GeV.
- Energy fraction of maximum energy layer < 0.35.
- Maximum energy in the first 3 layers not at the edges.
- Events where the projections of the BGO direction to the top/bottom is NOT within 280 mm from the center.
- For energies above 1 TeV, select events have a $\zeta < 100\ \mathrm{mm}^4$.

$$\zeta = \frac{\left(\sum_i^{layers}(RMS)_i\right)^4 \times \mathcal{F}_{Last}}{8 \cdot 10^6}$$

Backup Slide 2: Events Selection.

- Events > 100 GeV.
- Side and back entering events are removed.
- Events are **NOT** within BGO acceptance.
- Short and narrow showers above 1 TeV (Using ζ classifier, used in Nature,2017[6]) .



$$\zeta = \frac{\left(\sum_i^{layers}(RMS)_i\right)^4 \times \mathcal{F}_{Last}}{8 \cdot 10^6}$$

Backup Slide 3: Details on models.

- CNN v0 => Model train with full MC samples, images normalized by the max deposited energy in each layer.
- CNN v0, presel 100 => Model train with events that have a zeta below 100 (Select events' shower that are narrow and short).
- CNN v0, presel 150 => Same as previous but different event selection.
- CNN v1 => Model train with full MC samples, images normalized by the reconstructed energy.
- CNN v2, HE => Model train with full MC samples, images normalized by the maximum energy deposited in one bar. Train for events > 1TeV.
- CNN v0, HE => trained events have a reconstructed energy a > 1TeV.
- CNN v1, HE => Same as CNN v1, using events above 1TeV.
- CNN v3, Model training with events that pass new cuts.

Backup Slide 4: Calorimeter Resolution

Particle	Resolution [%]
Electrons, photons	1.5 at 100 GeV
Cosmic Rays	40 at 800 GeV