New approach for gamma-hadron separation at the IceCube Neutrino Observatory

TeVPA 23 - Napoli Italy

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for the IceCube collaboration

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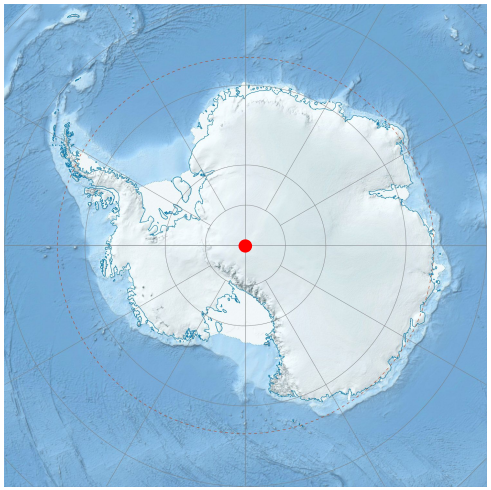
IceCube Neutrino Observatory

- IceCube Neutrino Observatory is located at the Amundsen–Scott South Pole Station in Antarctica
- The successor of Antarctic Muon And Neutrino Detector Array (AMANDA)



Source: https://icecube.wisc.edu/

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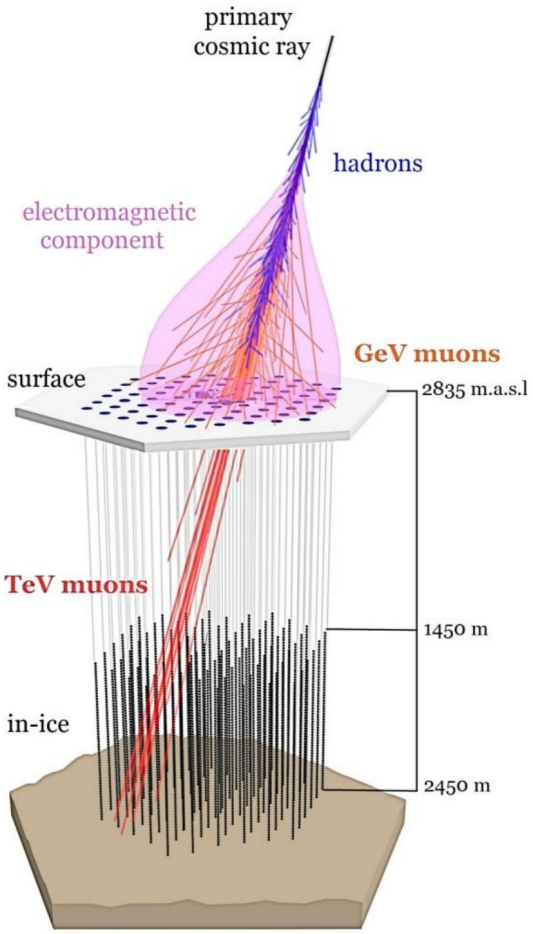
IceCube Neutrino Observatory

A three-dimensional cosmic ray detector:

- IceTop is a 1 km2 array of ice-Cherenkov detectors on the surface that serve:
  - as a partial veto for the down-going background of penetrating muons created by cosmic-ray interactions in the atmosphere
  - to detect and reconstruct cosmic-ray air showers (primary energy, mass and direction)

- IceCube 1 km3 in-ice array:
  - Measure high-energy muon (E > 400 GeV) generated by high energy cosmic rays interacting with the atmosphere
  - Muons generated by neutrino in-ice interaction



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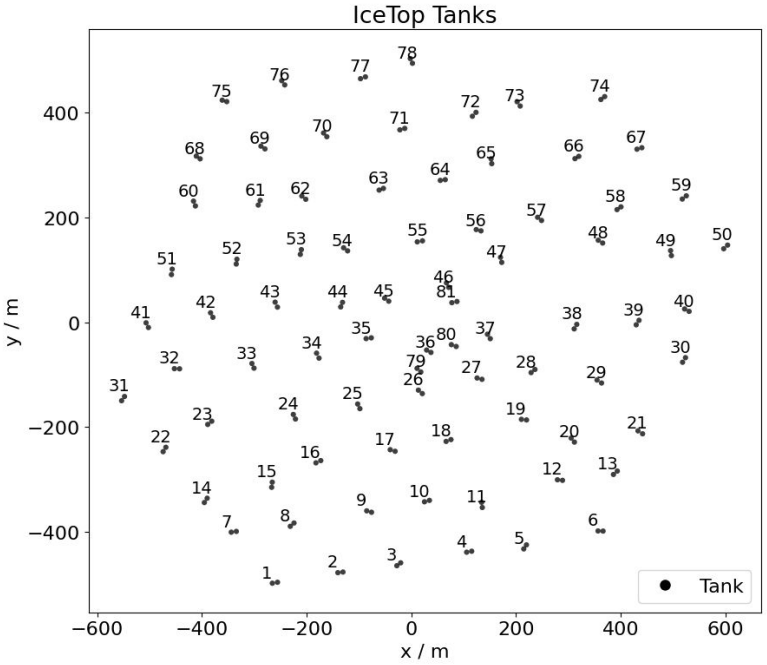
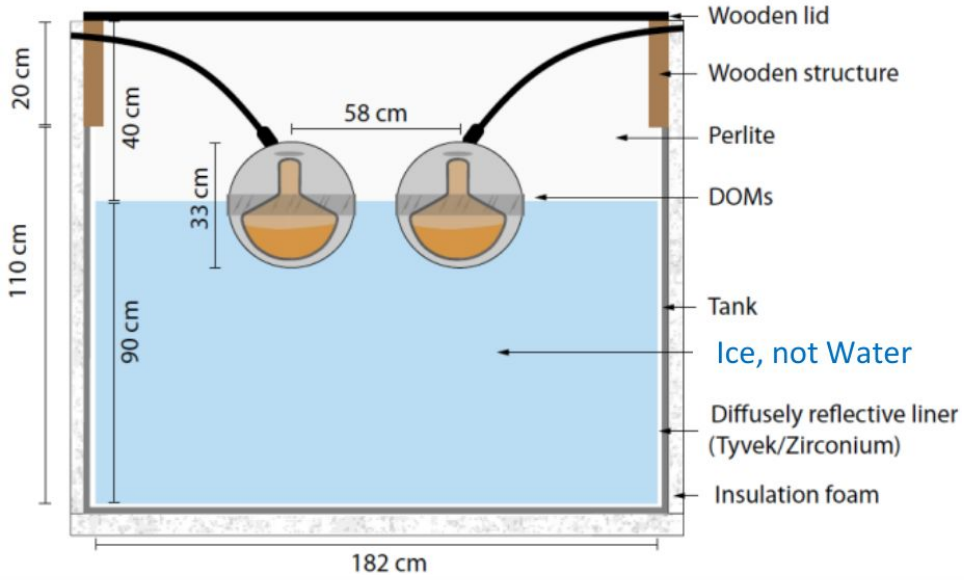
IceTop: Surface array

- Cosmic ray energies: 1 PeV to 1 EeV
- 81 stations with 2 tanks each (2 DOMs per tank)
- Eg. 1 PeV:
  - Angular resolution ~ 1 degree
  - Energy resolution 0.1 in $\log_{10}(E / GeV)$
  - Timing resolution 3 ns





HLC hit: both tanks in a station have registered a hit

SLC hit: a single tank in a station has registered a hit

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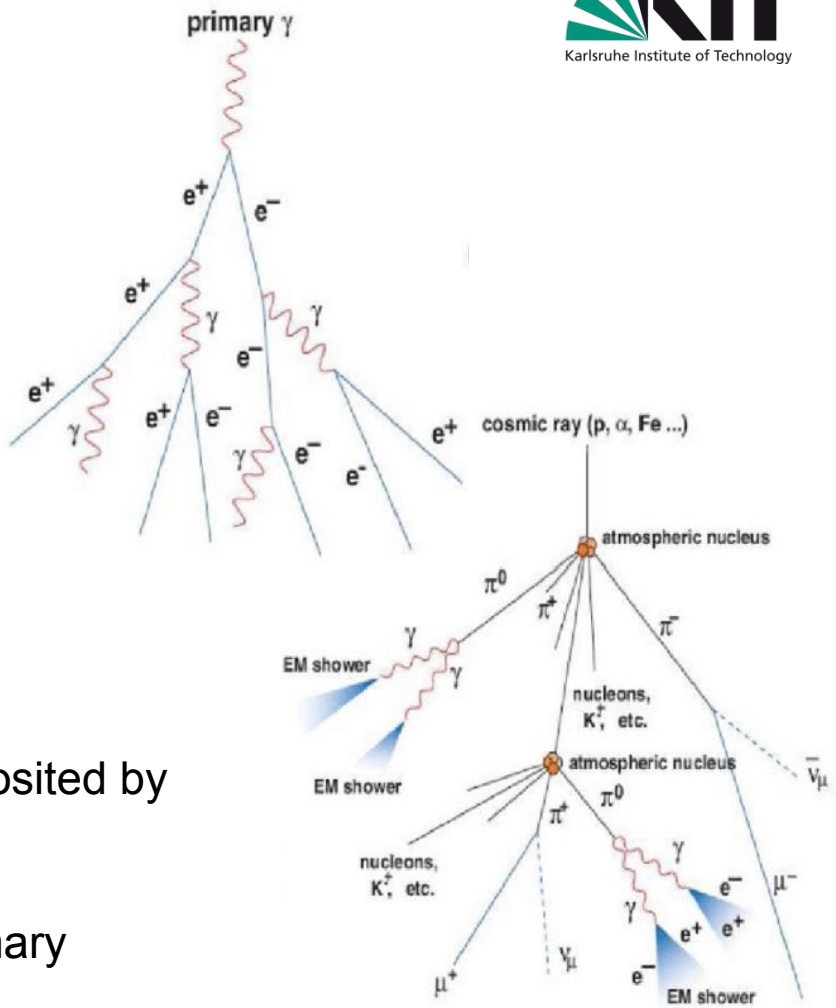
Gamma hadron separation

- Gamma-ray induced air showers:
  - fewer muons
  - less shower-to-shower fluctuation
  - narrower lateral spread

- Hadronic air showers:
  - more muons
  - more shower-to-shower fluctuation
  - wider lateral spread

- How to separate them:
  - Calculating the total in-ice charge deposited by high energy muon
  - Reconstructed energy of the primary
  - Reconstructed zenith angle of the primary



Images source: doi: 10.13140/RG.2.1.4140.4969

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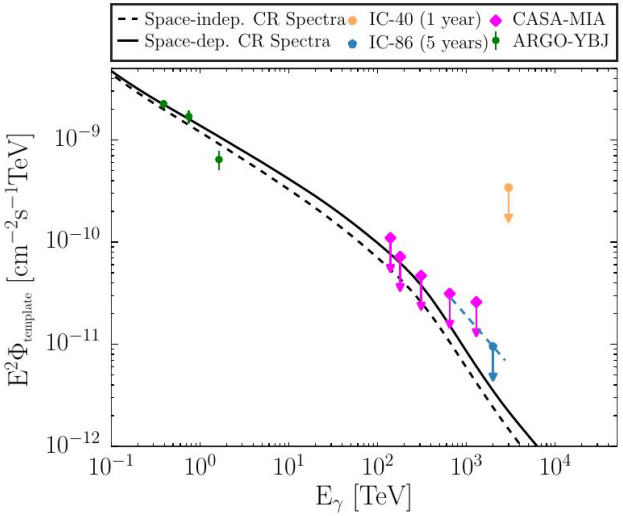
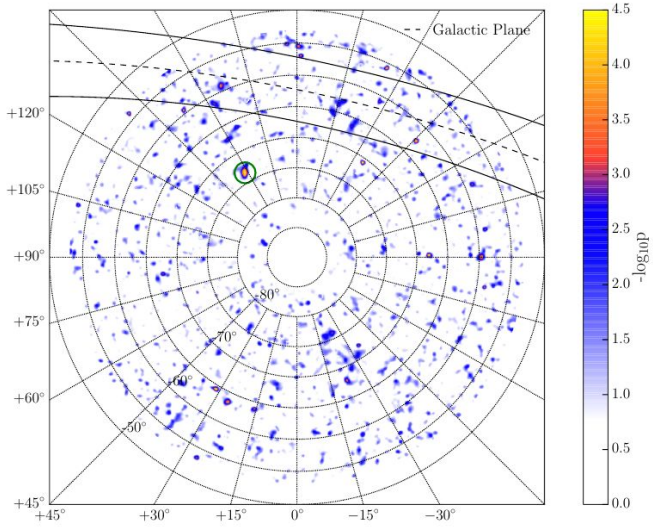
Previous work

- The IceCube 90% confidence level upper limit on the gamma-ray flux at 2 PeV from the Galactic plane in IceCube field of view

- After the photon selection, a sky search for gamma-ray point sources was performed
  The hottest spot in the sky: pre-trial p-value of 4×10^{-5}
  The post-trial p-value is consistent with background expectation





IceCube Collaboration, ApJ 891 (2020) 9: Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Years of Data from the IceCube Observatory

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What now?

Current goal:

- Investigate lower energies enabled by a new reconstruction approach (< 1 PeV)
- Different* gamma/hadron separation using deep learning

Search for gamma-ray sources:

- IceTop used for the air-shower reconstruction
- In-ice used for measuring the total charge of high energy muon (not yet implemented)

Next Goal:

- search for gamma-ray sources
- study the emission from the galactic plane

AI humor by ChatGPT

*IceCube Collaboration, ApJ 891 (2020) 9: Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Years of Data from the IceCube Observatory

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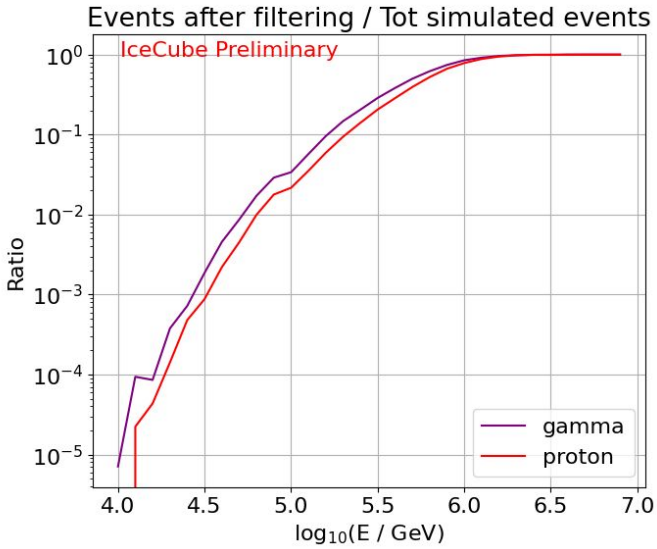
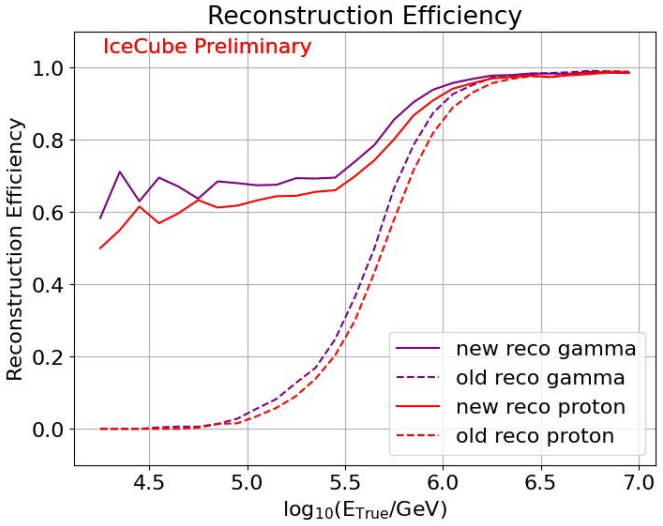
Low energy reconstruction

- Trigger and filtered (upper right)
- Filtered to reconstructed (lower right)

- Total detected events:
  - simulated radius < 500 m
  - simulated zenith < 38 deg

- Reconstructed events:
  - simulated radius < 500 m
  - simulated zenith < 38 deg
  - successful reconstruction
  - reconstructed radius < 500 m
  - reconstructed zenith < 38 deg
  - 1.9 < beta < 4.5 (slope of the lateral distribution)





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The Gamma-Proton discrimination

- The study is performed using Sibyll 2.3d Gamma and Proton simulations for the year 2012
- The discrimination is done combining the output of 2 Convolutional Neural Networks (CNN) followed by a Fully Connected Network (FCN)

Approach inspired by the previous work*. Here, probability maps instead of CNN were used

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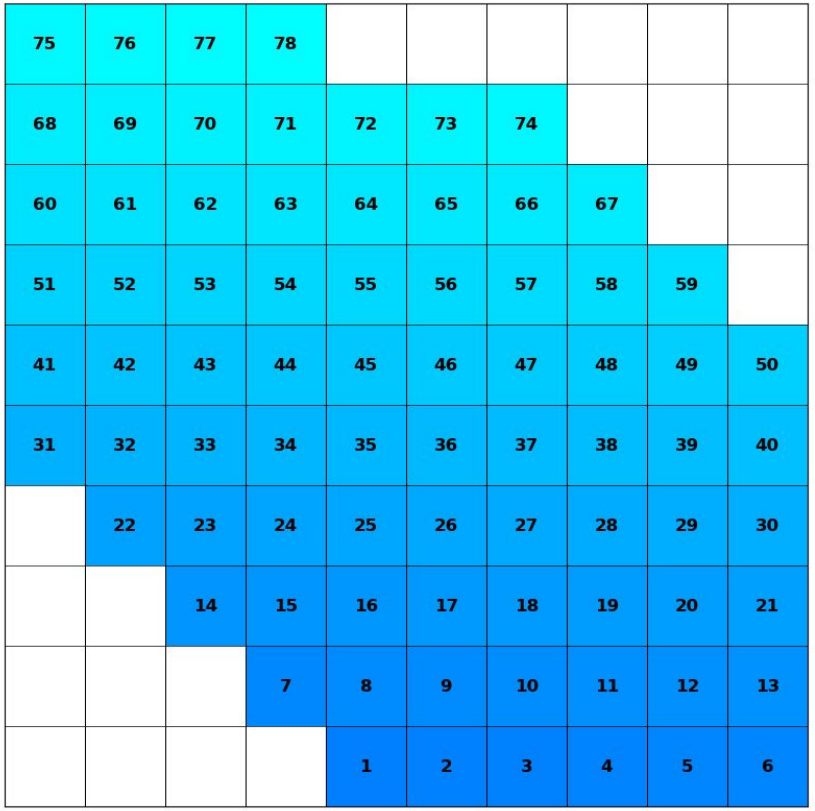
The Gamma-Proton discrimination

- CNN used for charge and time analysis:
  - Two input maps are created using the charge and time information

- FCN input:
  a. Output of CNN charge map
  b. Output of CNN time map
  c. $\log_{10}(S_{125})$ (energy proxy)
  d. zenith angle
  e. Beta (slope of the reconstructed lateral distribution function)
  f. Sum SLC charge hits
- Weighted spectrum with index = -3

- Output between [0, 1]



Note: In-ice signal is neglected at the moment

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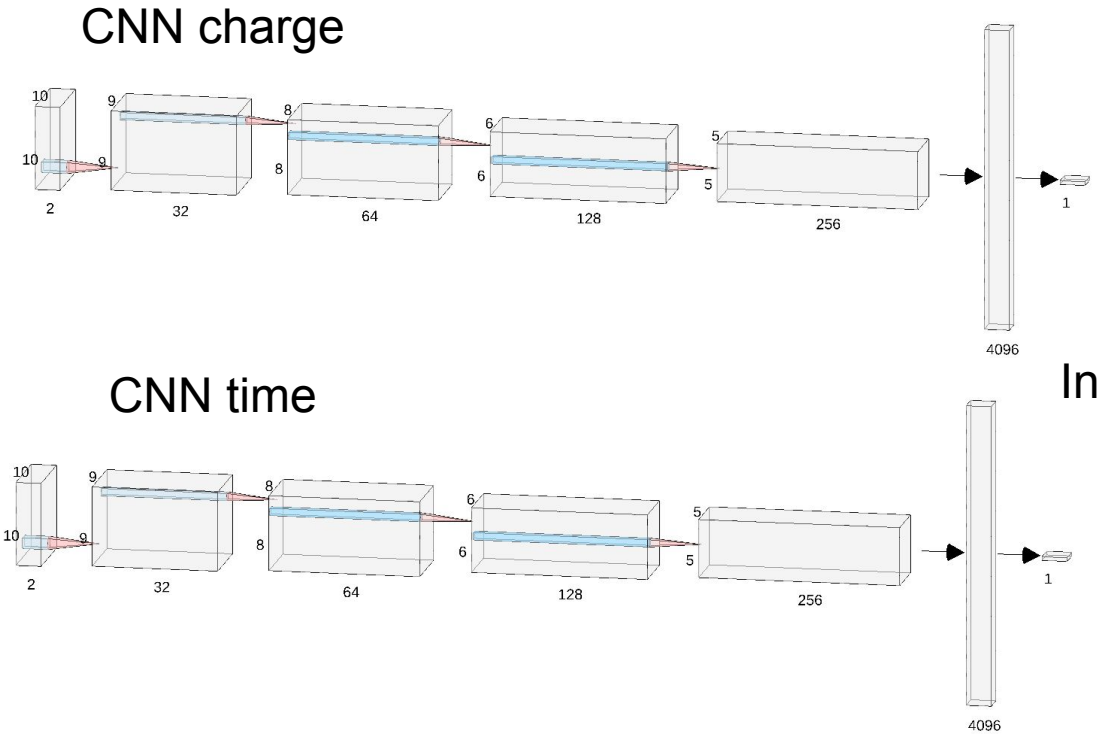
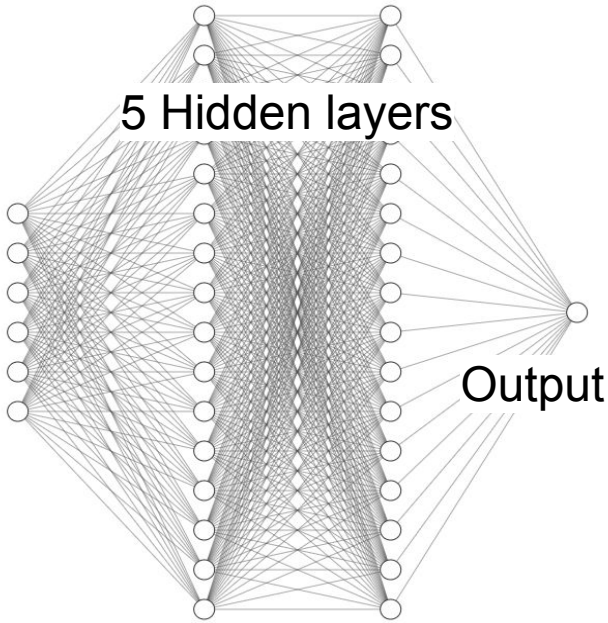
Simplified view of the model



Input



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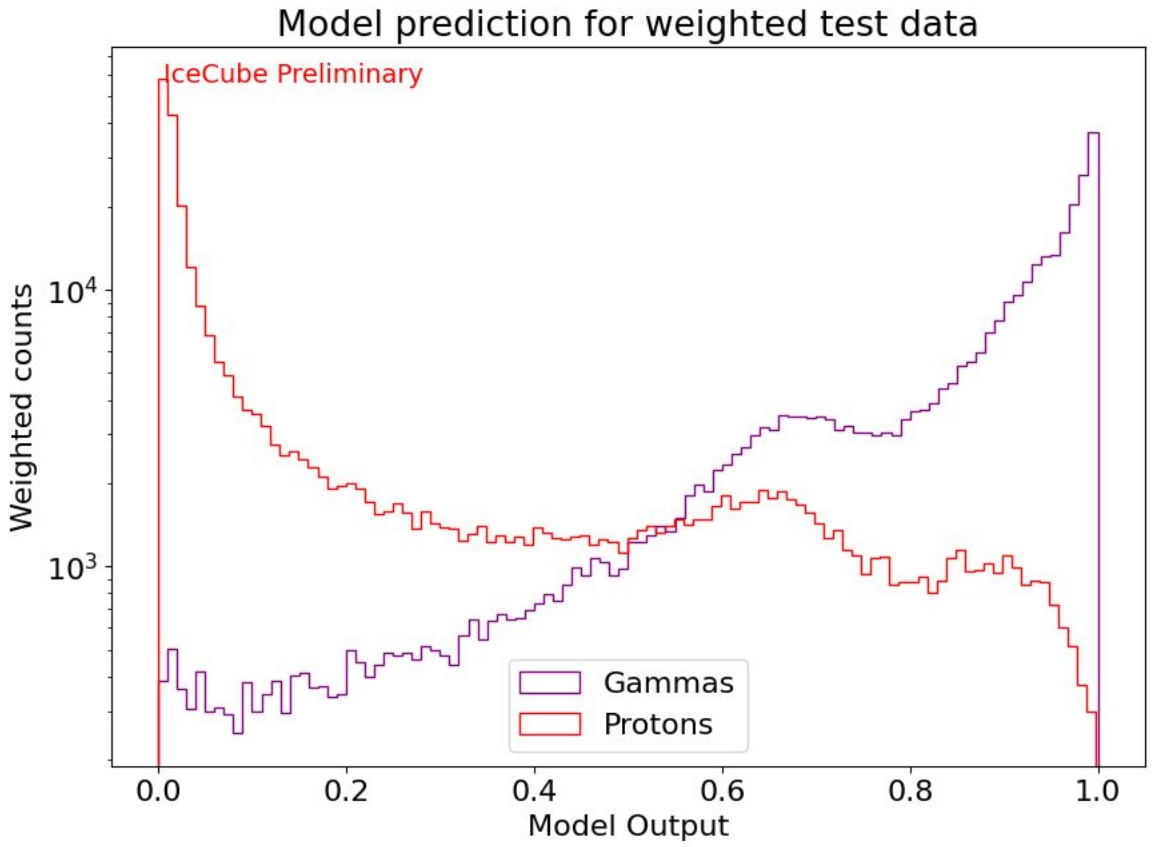
Training results

- Prediction of the trained model on the test sample
- Depending on the cut of the model output we have different selections of events



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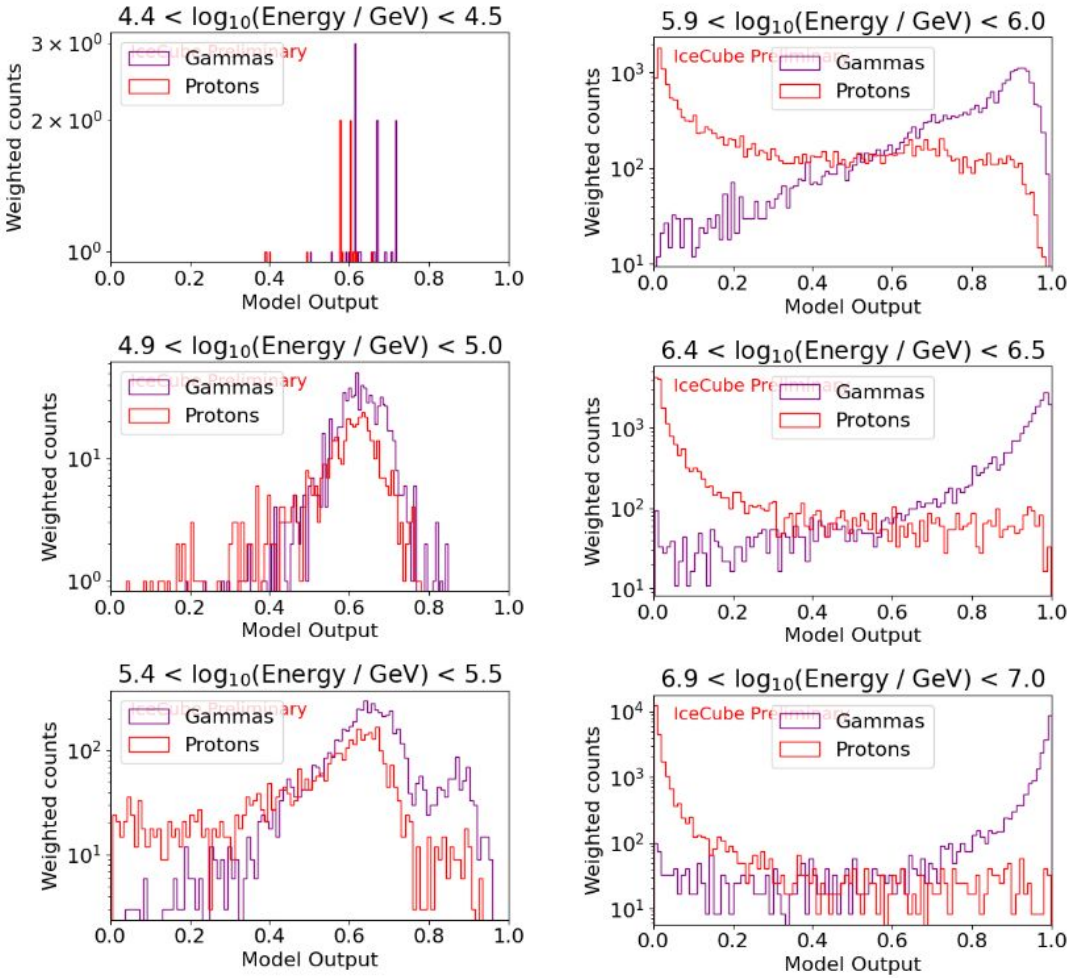
Training results

- Prediction of the trained model on the test sample
- Depending on the energy we have a different selections of events
- The current goal is to improve on the separation at low energies



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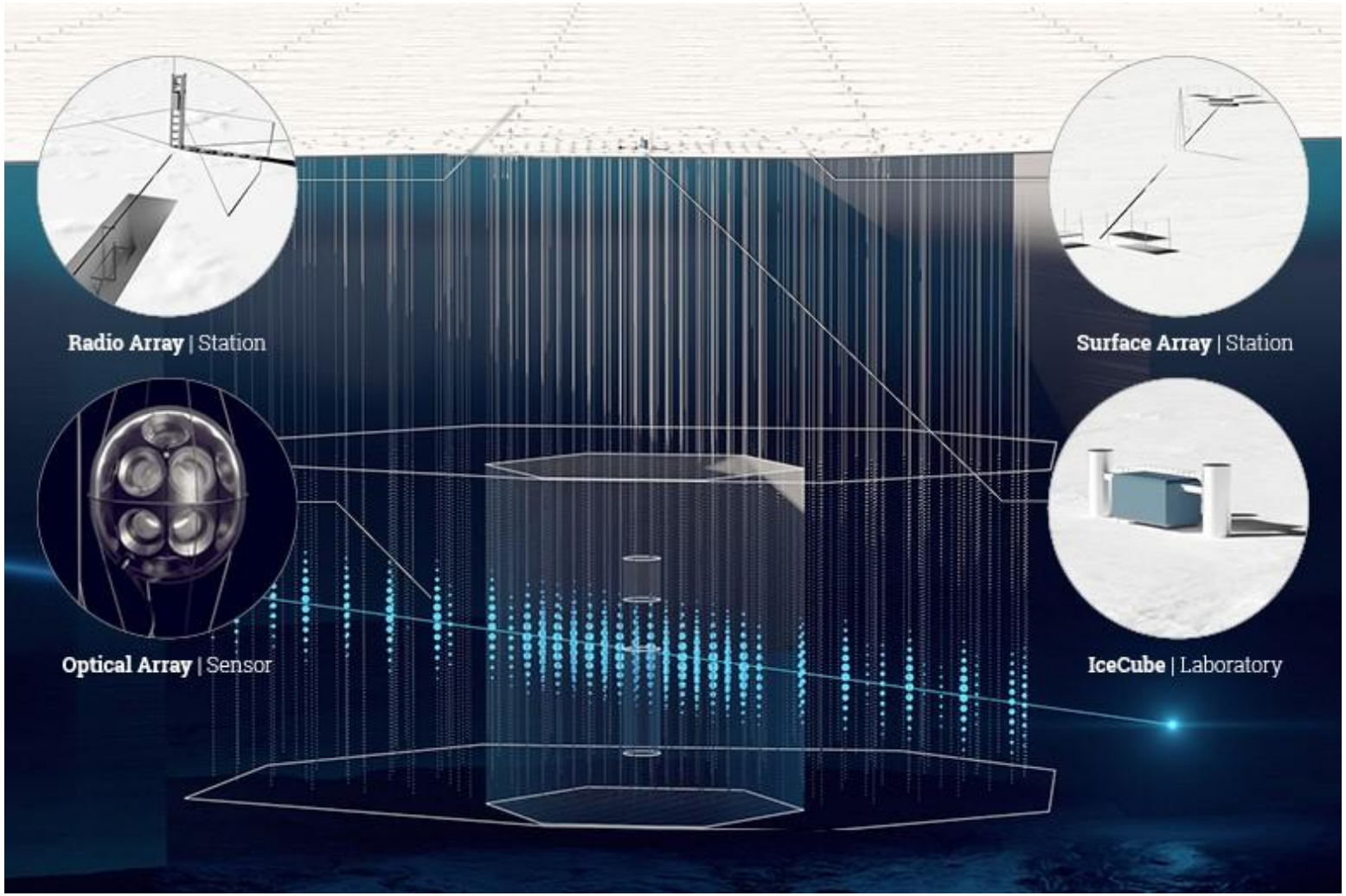
IceCube-Gen2



IceCube-Gen2 Collaboration, JHEAp 36 (2022) : High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

Source: https://www.icecube-gen2.de

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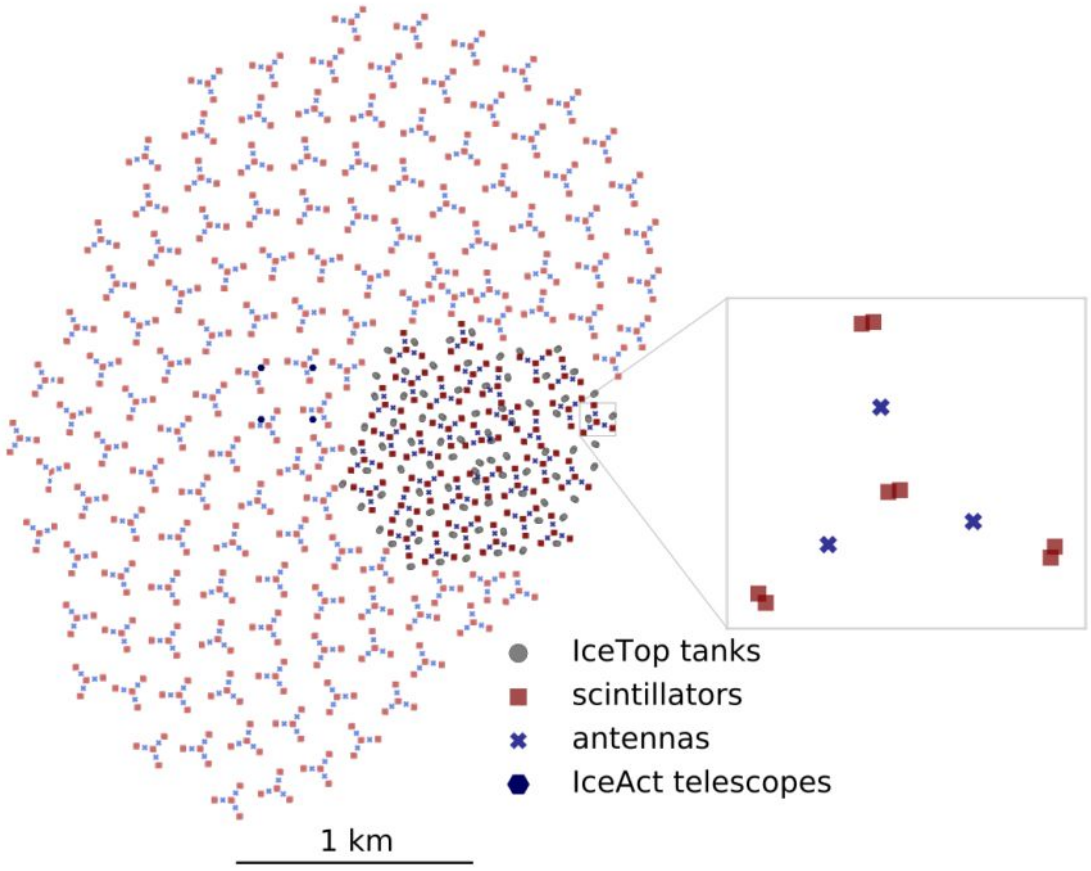
IceCube-Gen2 Surface array

- Each station composed by:
  - 8 scintillator panels
  - 3 antennas

- 8x more statistics through larger surface area
- 30x total increase in statistics for surface-deep coincidences

- IceCube-Gen2 Surface array will improve the gamma-hadron separation via:
  - ice cherenkov tanks
  - scintillator panels
  - antennas



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IceTop enhancement station

ICRC, 2023 (342): Status and plans for the instrumentation of the IceCube Surface Array Enhancement

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Summary & Outlook

- The IceCube Neutrino observatory is successfully used for the study of cosmic rays
- IceTop used for the air-shower reconstruction and the in-ice used for measuring the charge deposited by high energy muon

- Gamma/hadron separation can be performed using deep learning methods

- Next step:
  - include the in-ice information to improve the separation at low energies
  - identify gamma-ray sources in the southern sky
  - study the galactic plane emission

- IceCube-Gen2 will also increase the field of view and the number of detected events
- The combination of all three detectors can be used for the gamma/hadron separation

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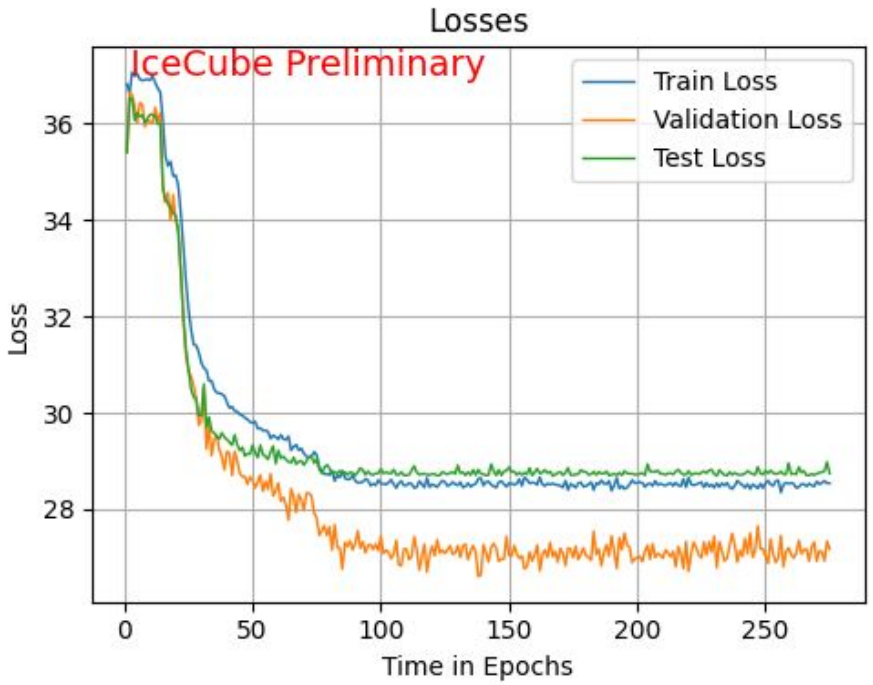
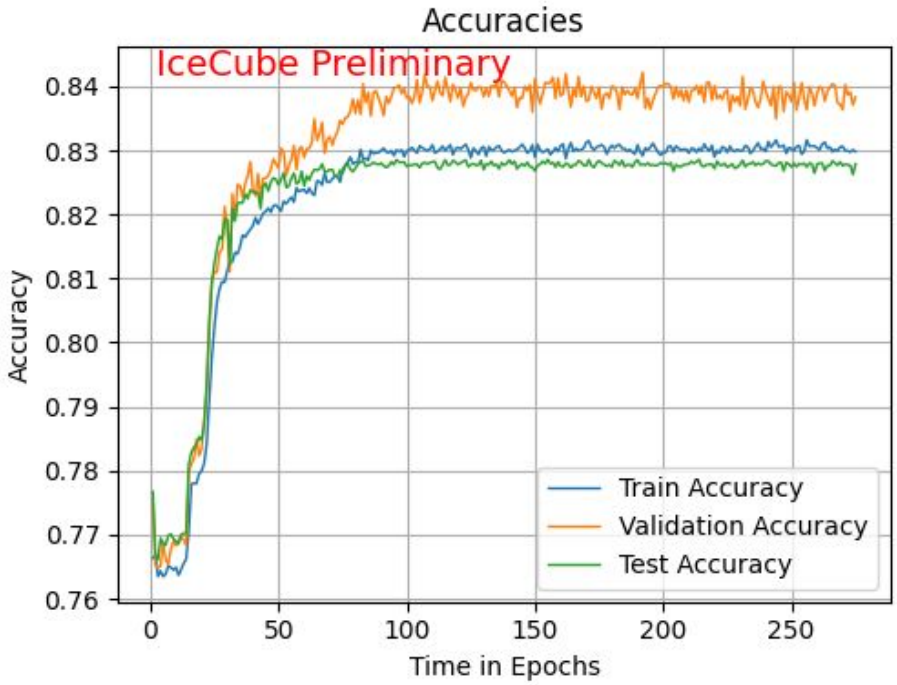
Training results





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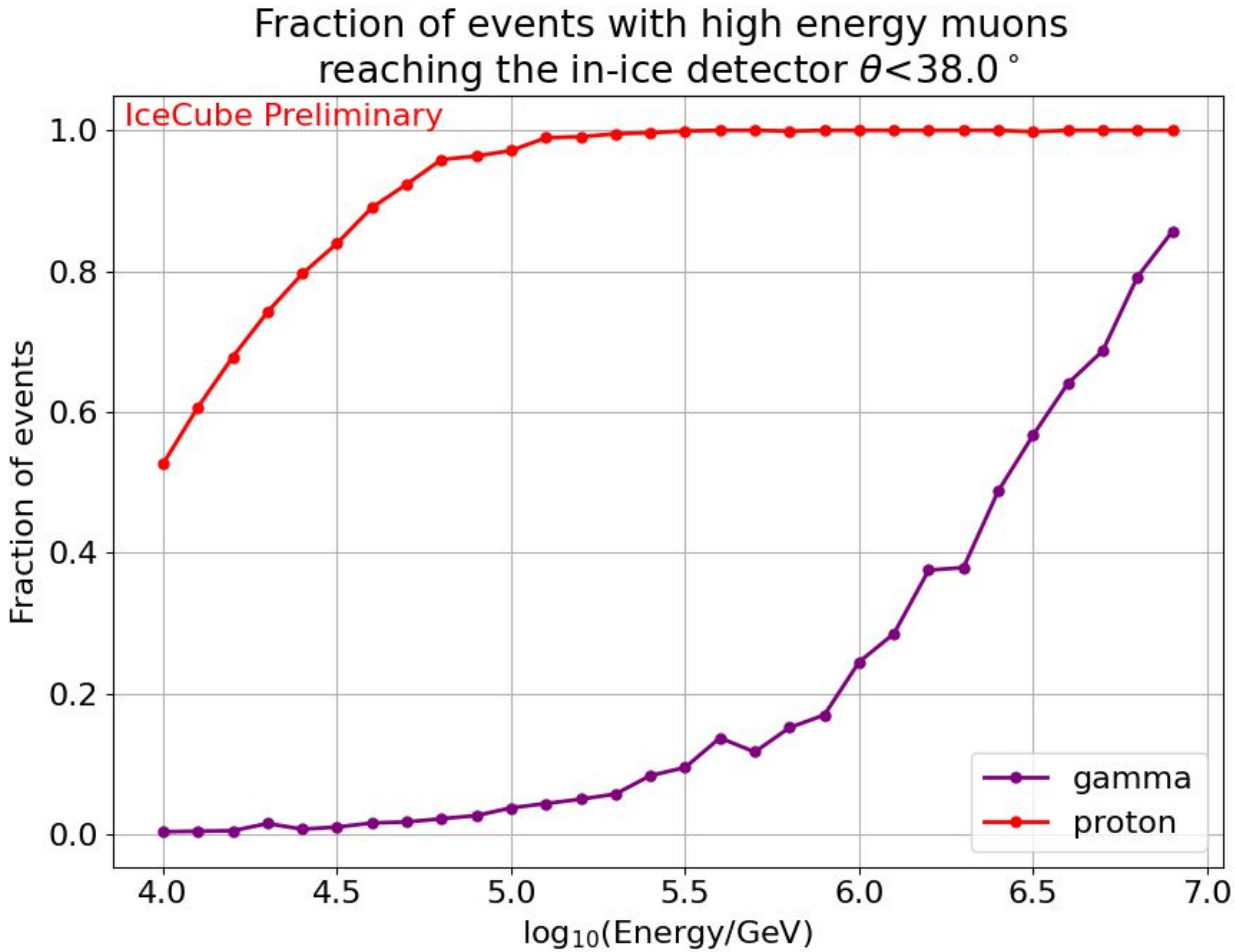
Muons reaching the in-ice detector

- The fraction of events containing at least one high-energy muon E > 273 GeV



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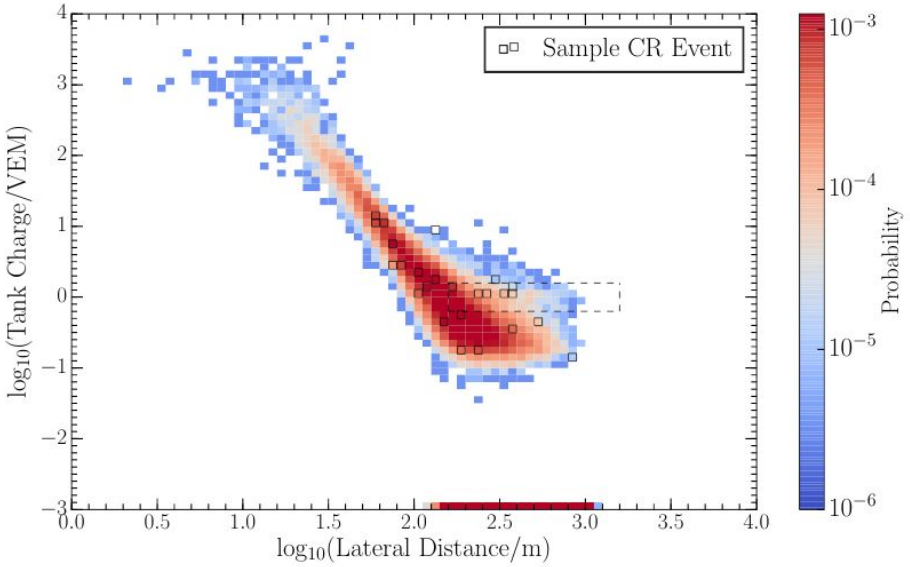
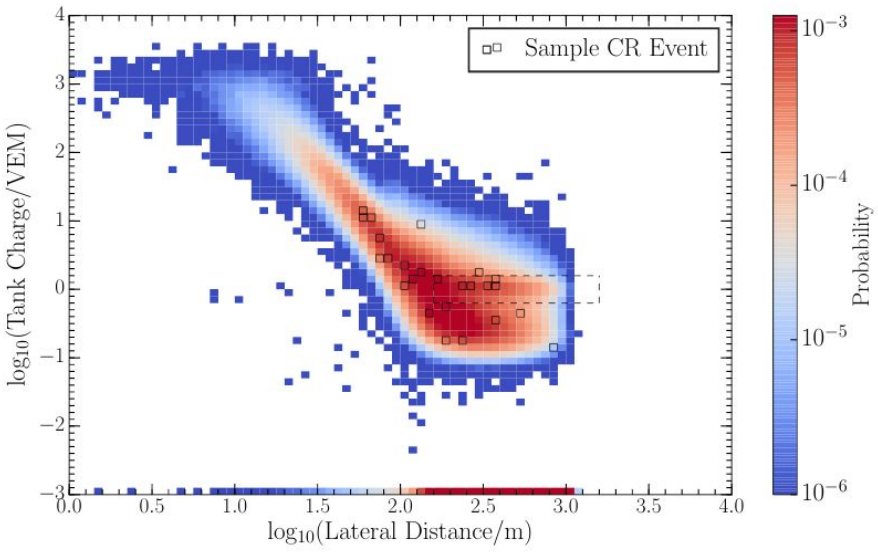
Log likelihood ratio



(a) Lateral PDF for gamma rays.



(b) Lateral PDF for cosmic rays.

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