Improving the gamma-hadron separation for air showers at the IceCube Neutrino Observatory

Machine Learning workshop @ Delaware University

Karlsruher Institut für Technologie (KIT)
Institut für Astroteilchenphysik (IAP)

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ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Previous works

2 PhD students from Delaware University (USA):

- SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY
  Zachary Dean Griffith
  ➔ Focused on ML techniques for Gamma Hadron discrimination

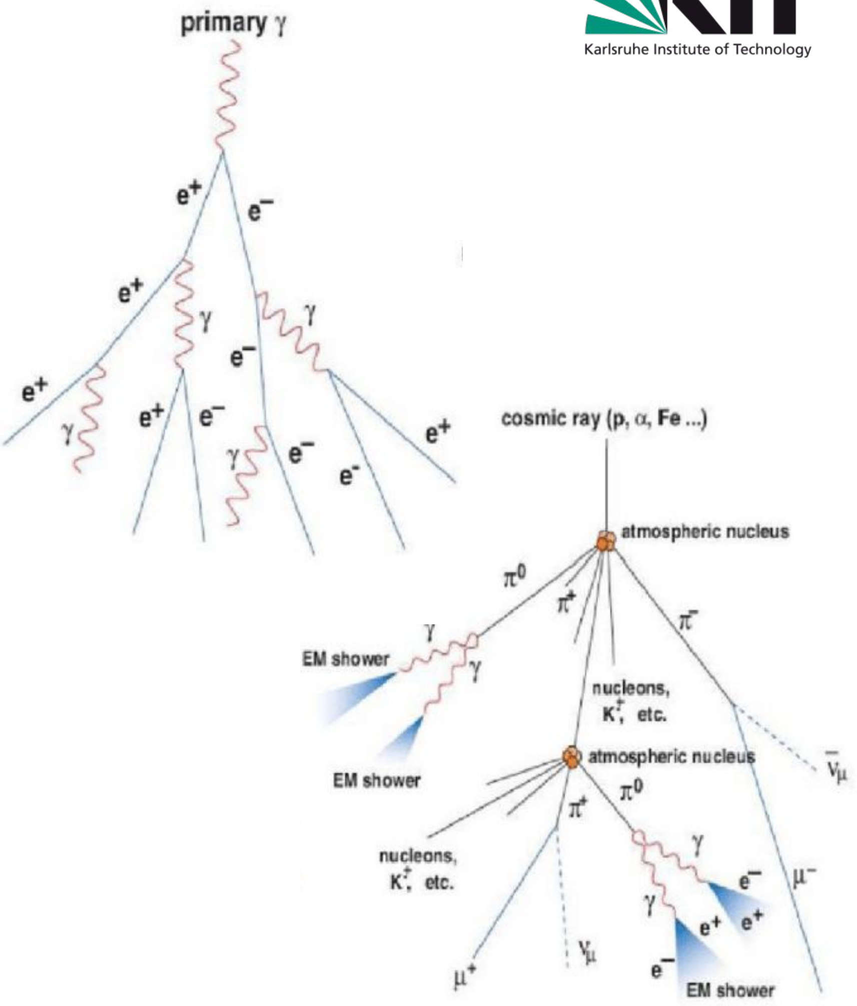
- SEARCH FOR PEV GAMMA RAYS AND ASTROPHYSICAL NEUTRINOS WITH ICETOP AND ICECUBE
  Hershal Pandya
  ➔ Developed Log Likelihood Ratio parameter

Gamma hadron separation

- Production of air showers:
  - gamma-ray primary
  - hadronic primary

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

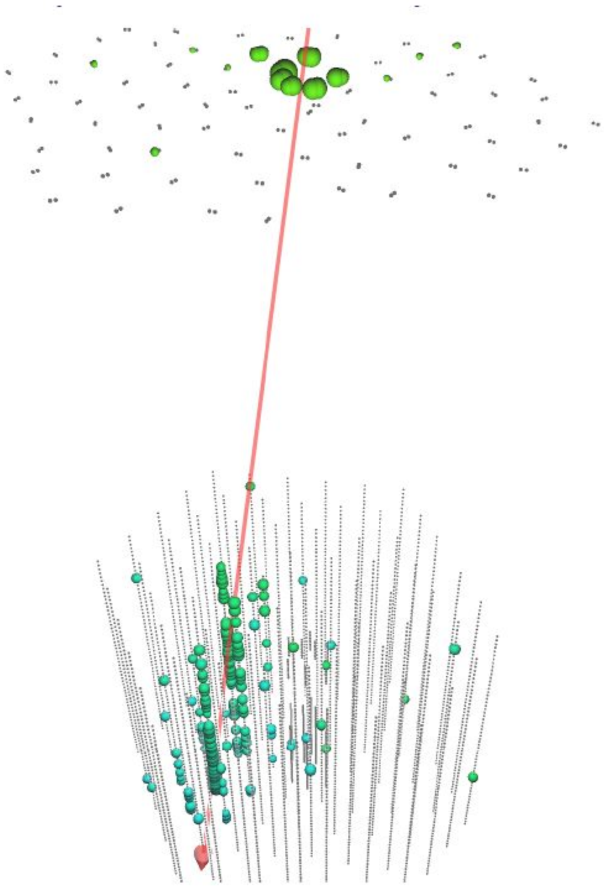
- Hadronic air showers:
  - richer in muon content
  - more shower fluctuations
  - wider lateral spread



Images source: Multi-year Campaign of the Gamma-Ray Binary LS I +61◦ 303 and Search for VHE Emission from Gamma-Ray Binary Candidates with the MAGIC Telescopes
doi: 10.13140/RG.2.1.4140.4969

IceCube Neutrino Observatory

- Ice-Top:
  - 1 km2
  - 162 Cherenkov tanks
  - measurement of the electromagnetic component of the shower
- In-ice:
  - 1 km3
  - 86 strings with in-ice with 60 DOMs each
  - measurement of the high energy muons



A cosmic-ray air shower event with a shower axis that passes through both components of the detector. (Z. Griffith)

Source: SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY, Zachary Dean Griffith

IceCube Neutrino Observatory

- Ice-Top:
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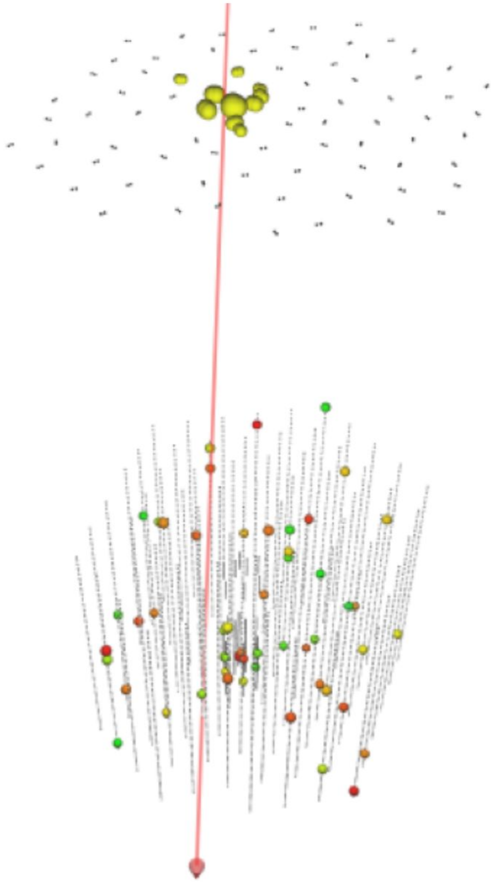


An event from the 2012 point source sample dataset with one of the ten highest Random Forest scores. (Z. Griffith)

Source: SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY, Zachary Dean Griffith

Find Gamma ray sources

1. Data (burning sample) and Sim (Sibyll 2.1) .i3 -> .hdf5
2. Cleaning & selection
3. Train Random Forest
4. Data selection with the Random Forest -> Gamma selection
5. Background creation
6. All sky search
7. Test statistic
8. P-value
9. Final plot

Completed for year 2012, 2013, 2014 and 2015
burning sample year 2011 is now available

Simulations:
https://wiki.icecube.wisc.edu/index.php/Cosmic-ray_IC86_Datasets

Data and Sim Cleaning & selection

- Quality cuts:
  - Number of triggered Station >= 5
  - Fraction Containment < 1.0 (contained in the in the surface array)
  - Laputop zenith < arccos(0.8)
  - log10(S125) > -0.25
  - Laputop Beta > 1.4 & Laputop Beta < 9.5
  - log10(Energy / GeV) < 8.0

- Features for Random Forest:

1. charges: total in-ice charge
2. Laputop in-ice FractionContainment
3. Laputop log10(s125)
4. sin(dec)
5. LLH_Ratio: log-likelihood parameter (Hershal PhD thesis)

Log likelihood ratio

The log-likelihood ratio is constructed for each event via 3 PDFs

e.g. The log-likelihood ratio for charge Q and lateral distance R:

$$\Lambda_{QR} = \log_{10}\left(\frac{L_{QR}(\text{event}|H_\gamma)}{L_{QR}(\text{event}|H_{CR})}\right), \qquad L_{QR}(\text{event}|H) = \prod_{\mathrm{i}=1}^{162} P\left(Q_\mathrm{i},\ R_\mathrm{i}|\,H\right),$$

with P (Qi, Ri | H) being the probability of observing a tank with measured charge Qi and at lateral distance Ri, for the hypothesis H.

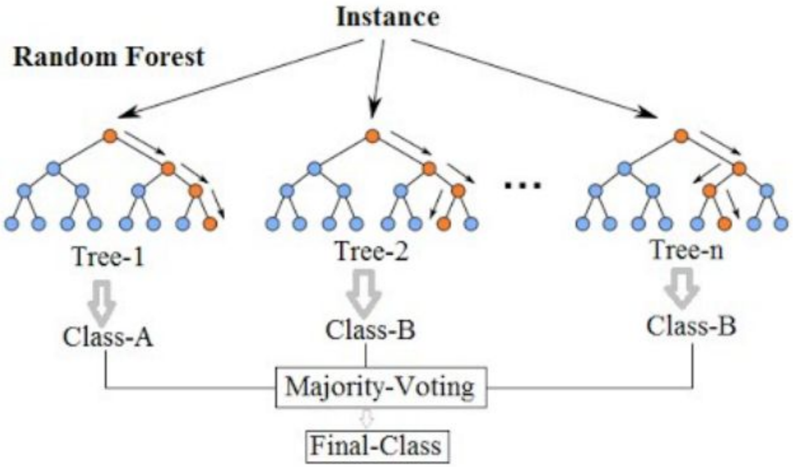
Total log-likelihood ratio is defined by the sum of all three log-likelihood ratios

$$\Lambda = \Lambda_{QR} + \Lambda_{Q\Delta T} + \Lambda_{\Delta TR}$$

Source: SEARCH FOR PEV GAMMA RAYS AND ASTROPHYSICAL NEUTRINOS WITH ICETOP AND ICECUBE, Hershal Pandya

Random Forest

The Random Forest: open-source
Python package Scikit-Learn



A Random Forest classifier consists of
a combination of many simple decision trees

Each tree acquires its n events from
the training sample, such that
each tree trains on a different set of events every time

The splitting condition: minimization of the Gini impurity in the child nodes

$$I_G = 1 - \frac{w_S^2 + w_B^2}{(w_S + w_B)^2}$$

wS and wB are the total weights in a node
for the signal and background classes

“probability of misclassification”:
all of the weight in the node is in one class IG = 0
an even split in the node results in IG = 0.5.

Source: https://scikit-learn.org/stable/

Random Forest

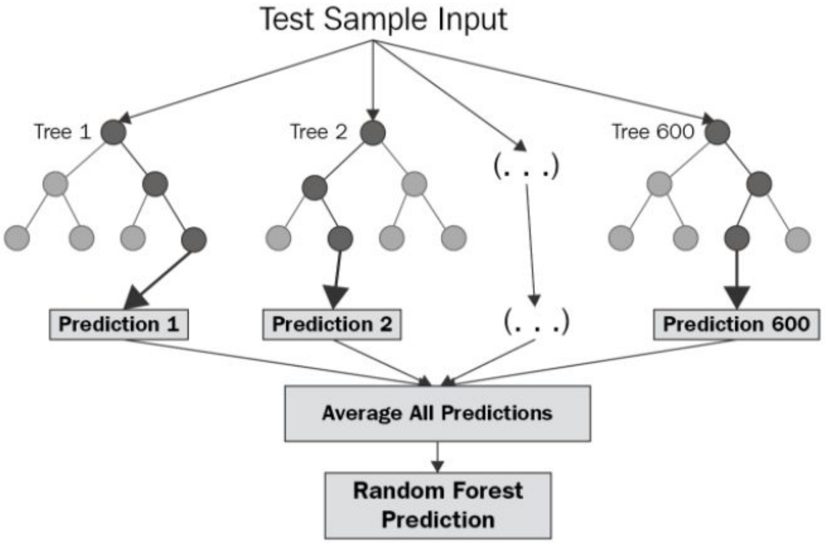
The Random Forest: open-source Python package Scikit-Learn

A Random Forest regressor consists of a combination of many simple decision trees

The splitting condition: minimization of the Mean Square Error (MSE)

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$$

MSE	= mean squared error
n	= number of data points
Y_i	= observed values
$\hat{Y}_i$	= predicted values



Source: https://scikit-learn.org/stable/

Training & Testing

- Training sample:
  - about 80.000 Gamma MC
  - about 80.000 Data as background
- Test sample:
  - about 20.000 Gamma MC
  - the complete burn sample about 4 Millions event

- Note: a different forest was trained for each year (snow accumulation)

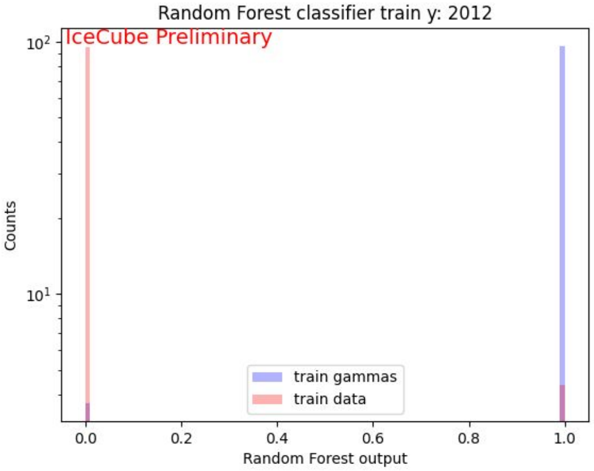
```
RandomForestClassifier(n_estimators=100,
                       random_state=0,
                        n_jobs=5, verbose=0,
                        max_depth=6)
```

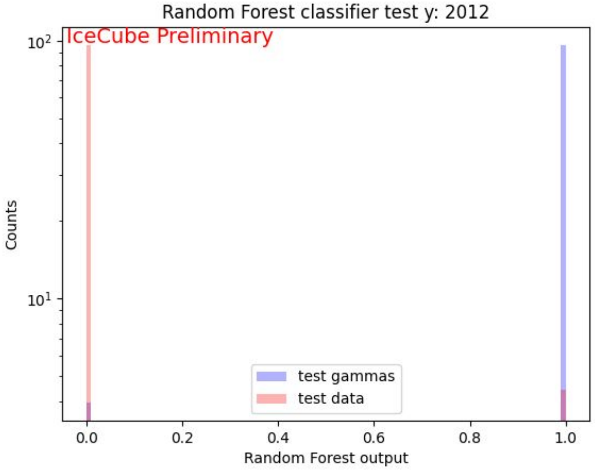
cut value=0.7

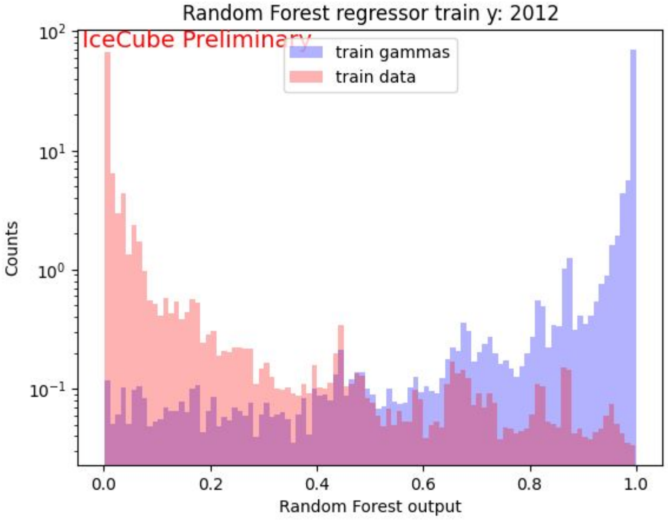
```
RandomForestRegressor(n_estimators=100,
                      random_state=0,
                      n_jobs=5, verbose=0,
                      max_depth=8)
```

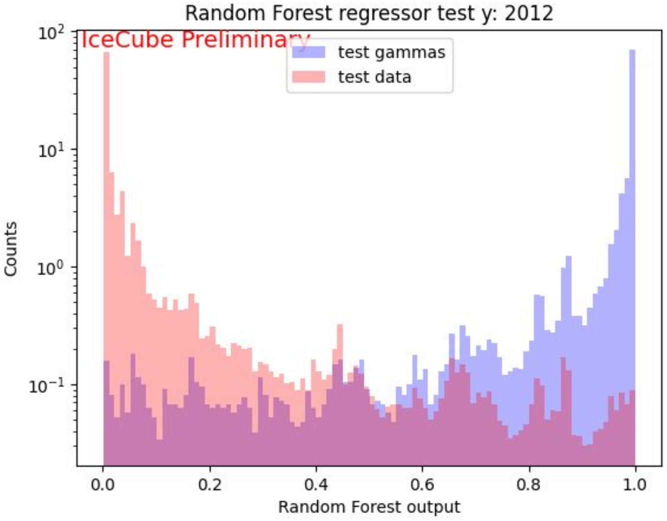
cut value=0.99

Training & Testing year 2012



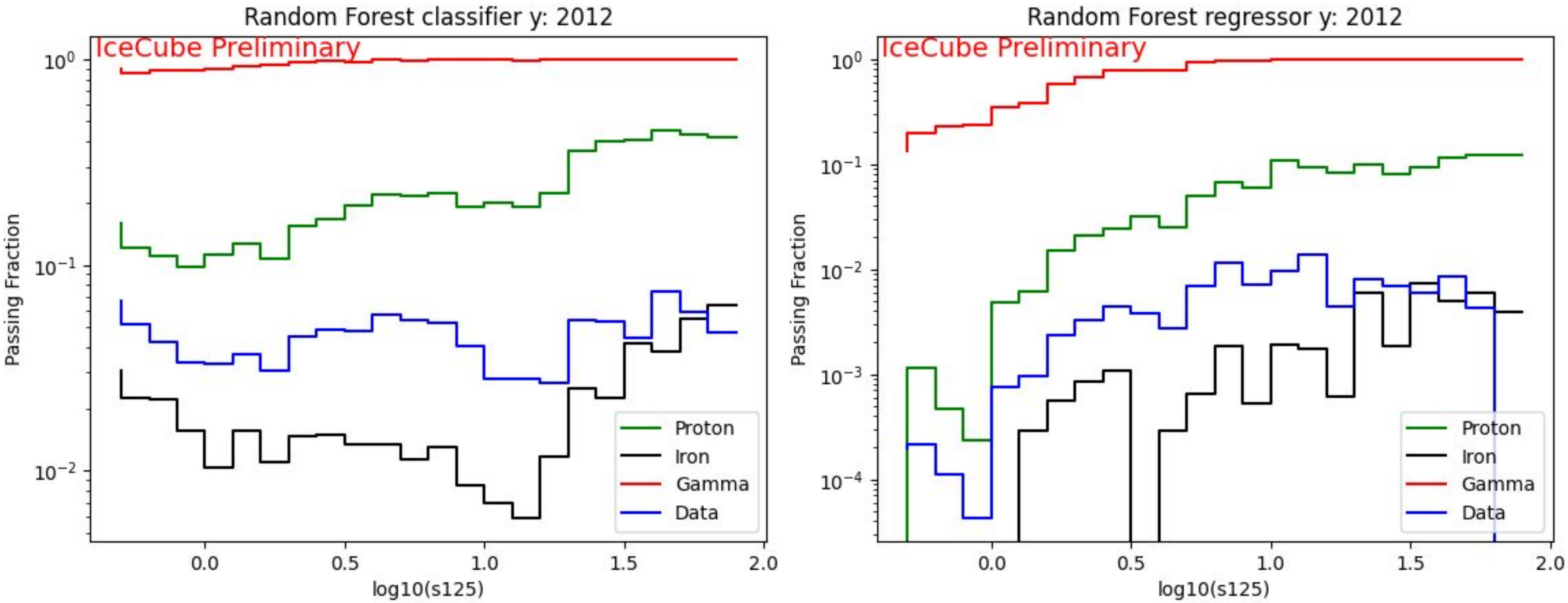






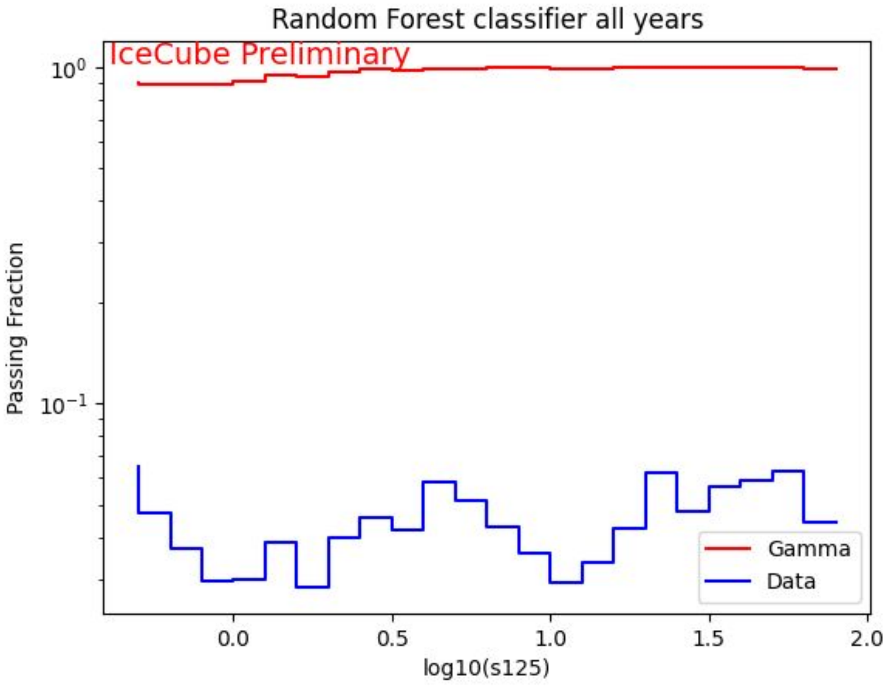
Passing fraction year 2012

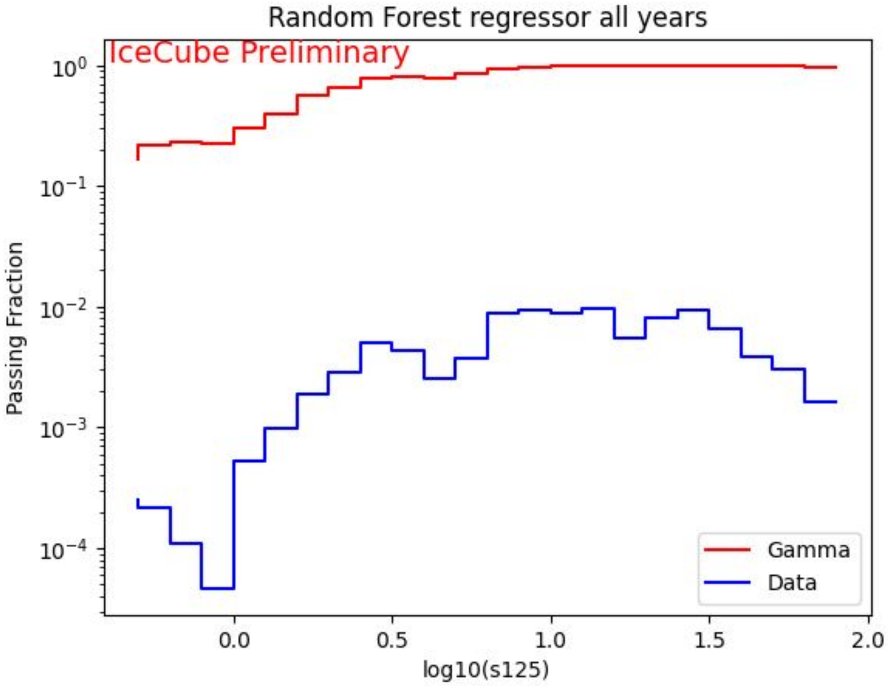
- event that passed the prediction cut / Total event
- plotted as function of energy



Passing fraction all years

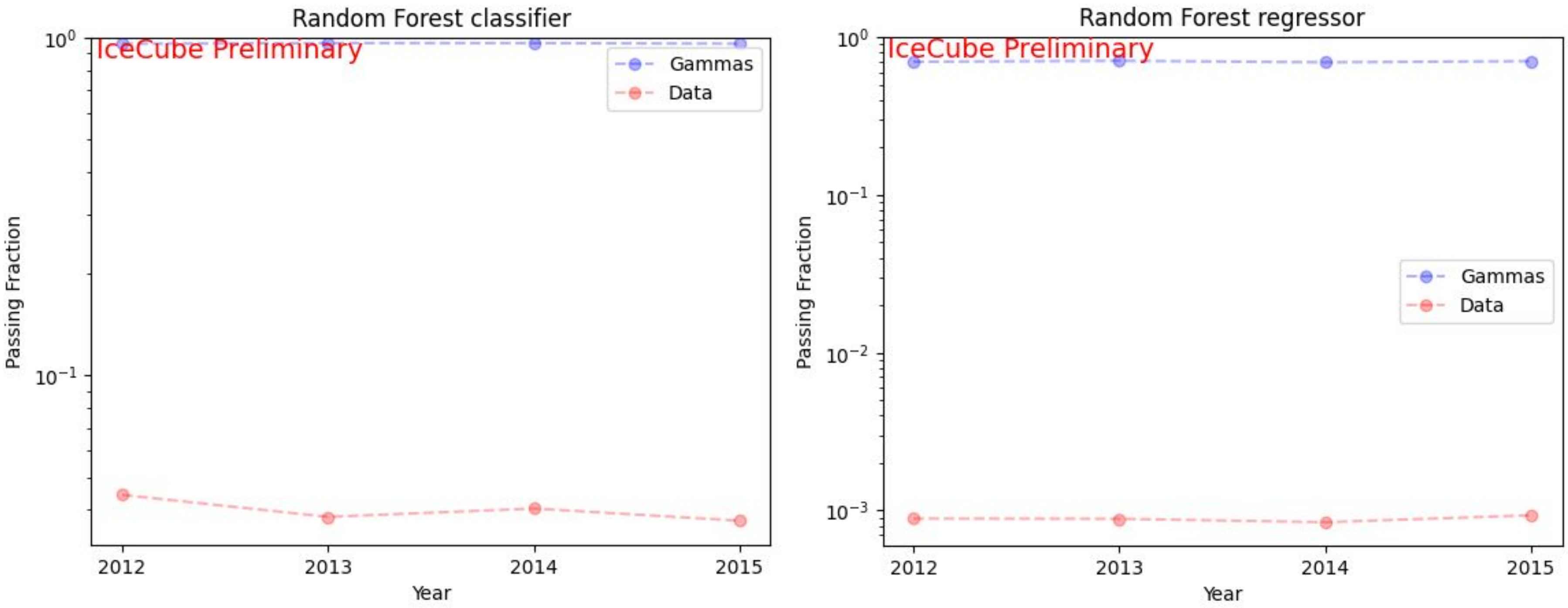
- event that passed the prediction cut / Total event
- plotted as function of energy





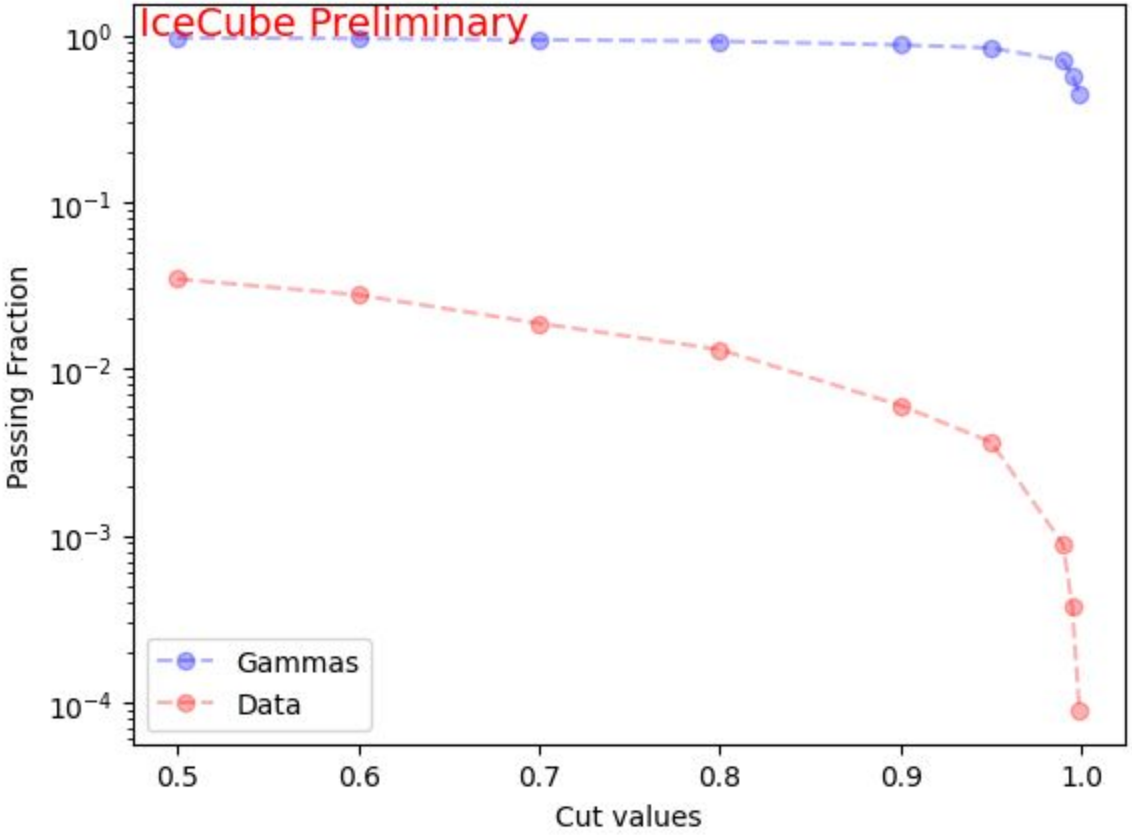
Passing fraction all years

- event that passed the prediction cut / Total event

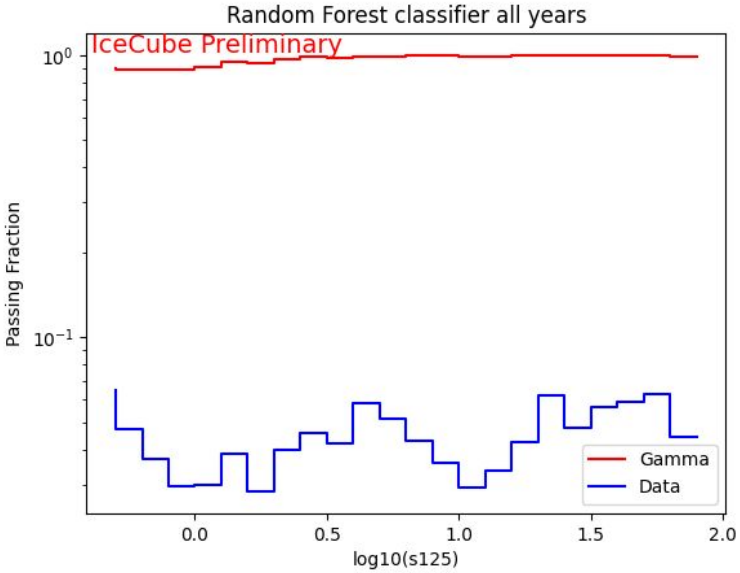


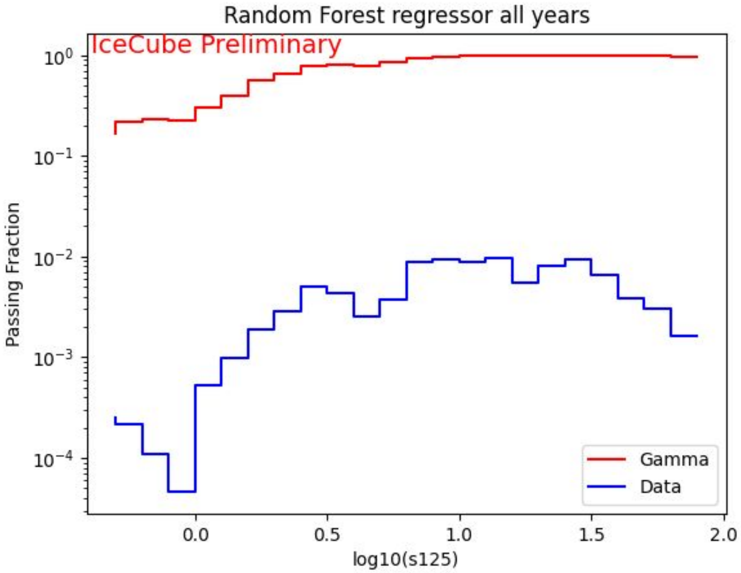
Passing fraction regressor all years

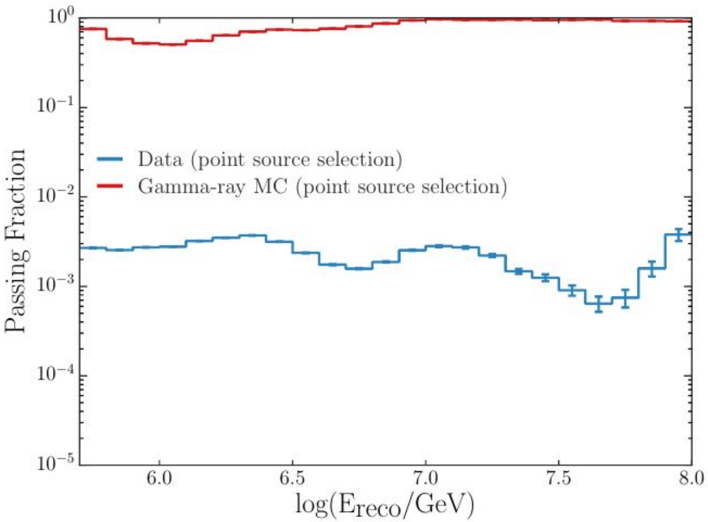
- Passing fraction for different cut values: [0.5,0.6,0.7,0.8,0.9,0.95,0.99,0.995,0.999]



Comparison with Zach’s results



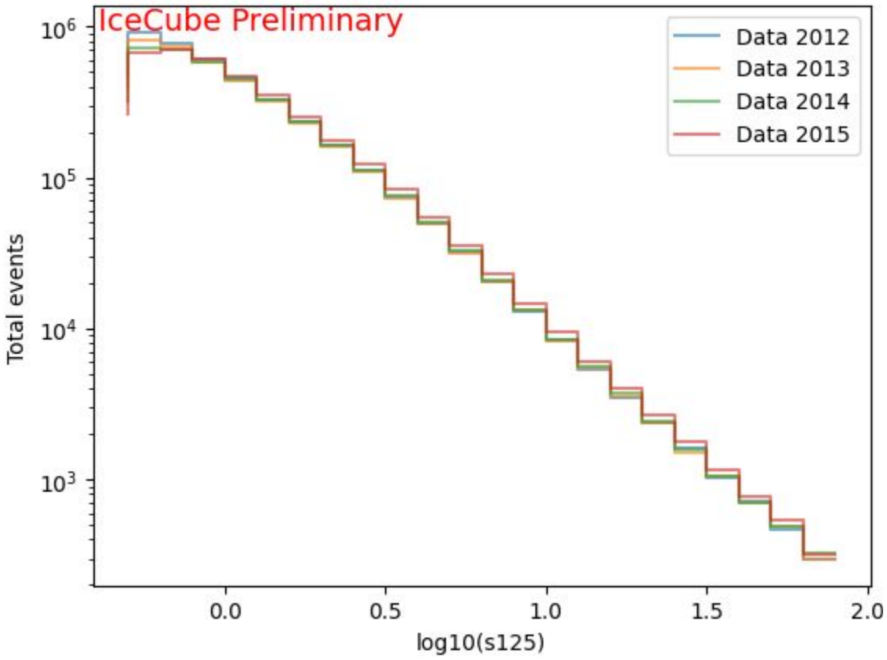


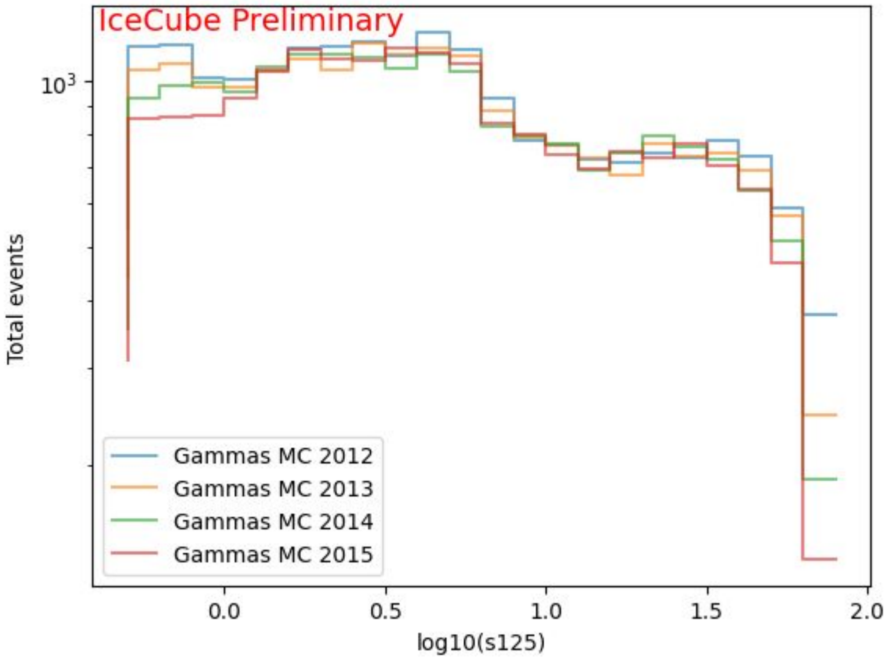


Source: SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY, Zachary Dean Griffith

Data and Sim Cleaning & selection

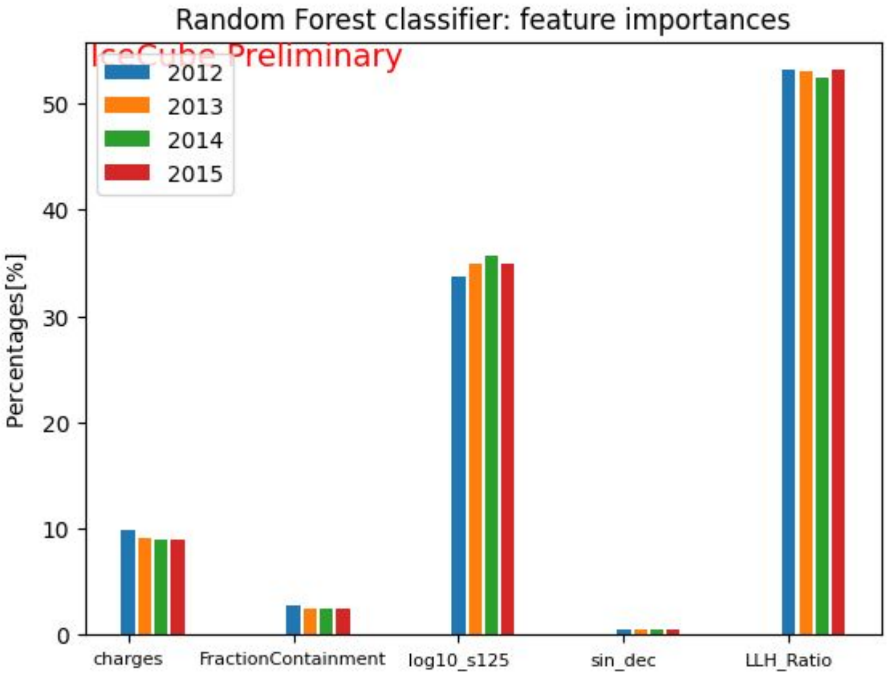
Sim and Data do not have the same steepness

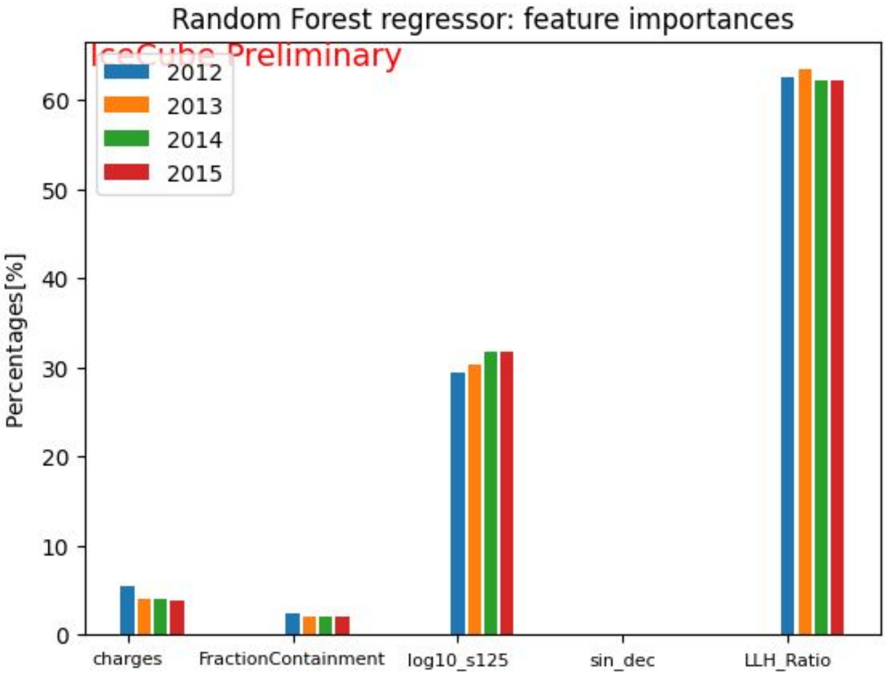




Feature importance all years

Each of the input feature has a different importance.
For each year, here they are plotted in percentages and sum up to 1

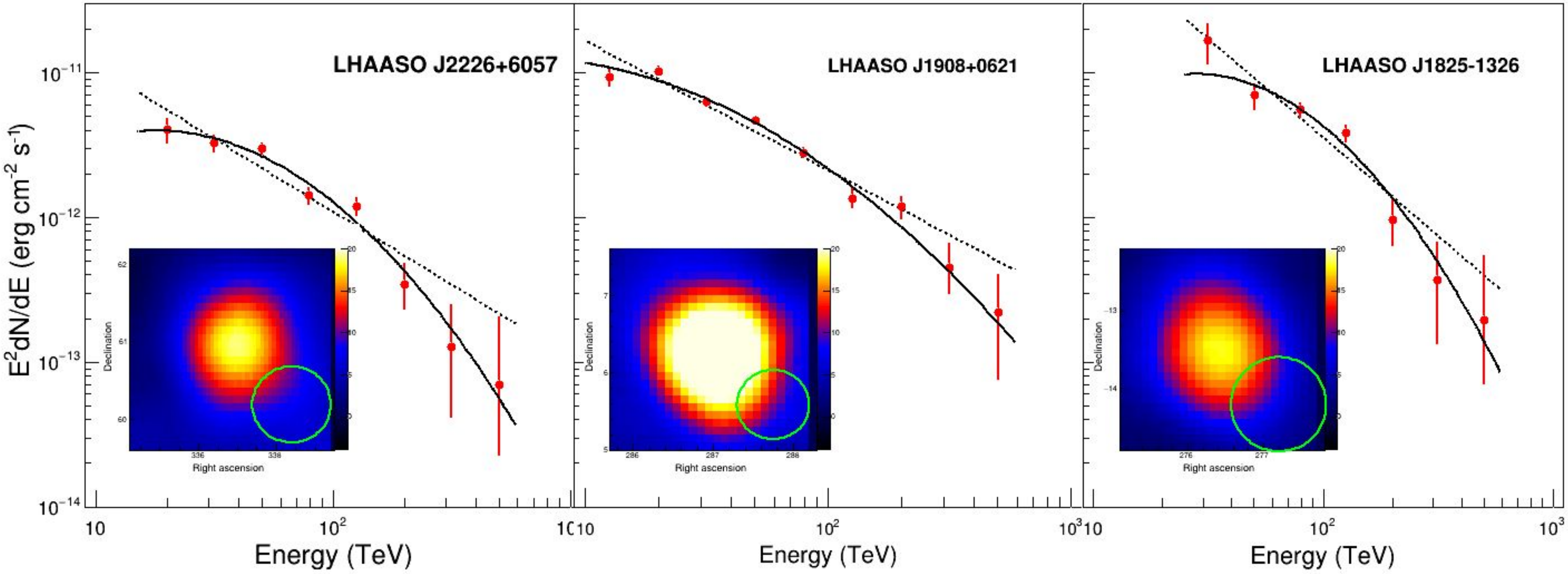




LHAASO sources

- Ultra High-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

- Is IceCube able to detect a LHAASO like UHE photon source?

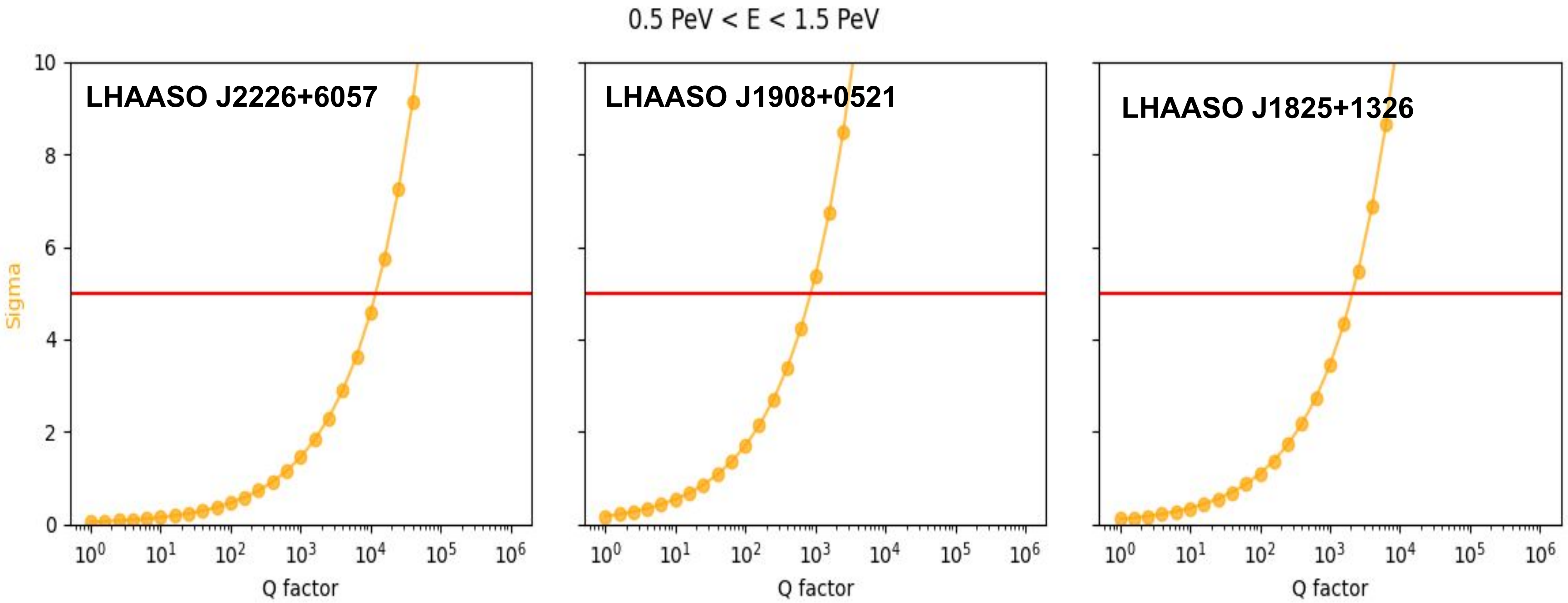


Source: https://www.nature.com/articles/s41586-021-03498-z

Sigma and Q-factor

- Q-factor indicates how good the CR background can be rejected
- A Q-factor between $10^3 \div 10^4$ is required for signal bg separation for a 5 sigma observation

- # sigma = signal / bg**0.5



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Summary & Outlook

- The classifier and the regressor are two different approaches
- Better gamma hadron separation for lower energies probably due to lower statistics for data at higher energies
- The declination is almost irrelevant for the final selection
- Regressor and Classifier depend on the cut value selected

Coming next:

- Correct the energy bias between simulation and data
- Search for gamma sources in the sky
- Use Deep Learning neural networks for the classification

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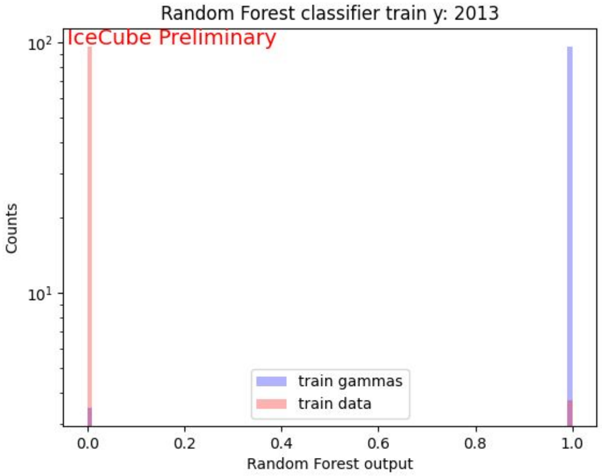
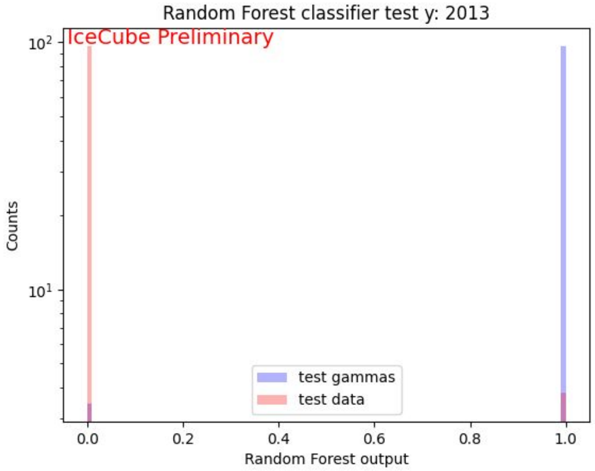
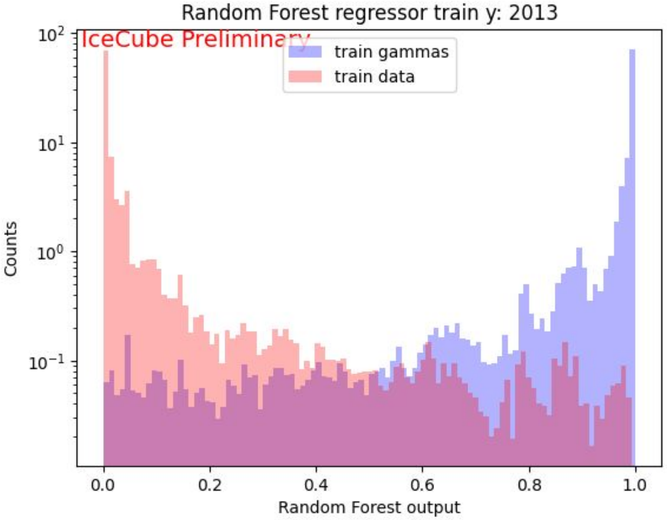
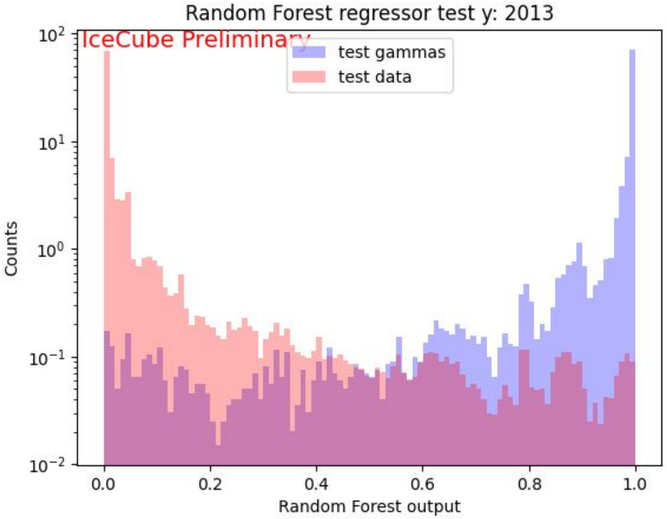
SOUTH POLE NEUTRINO OBSERVATORY

Training & Testing year 2013



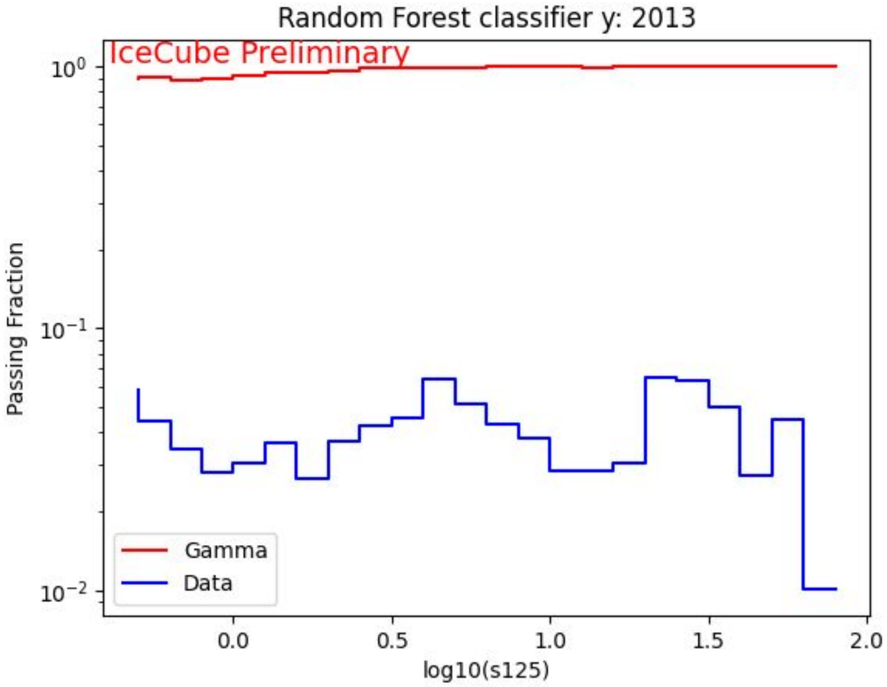


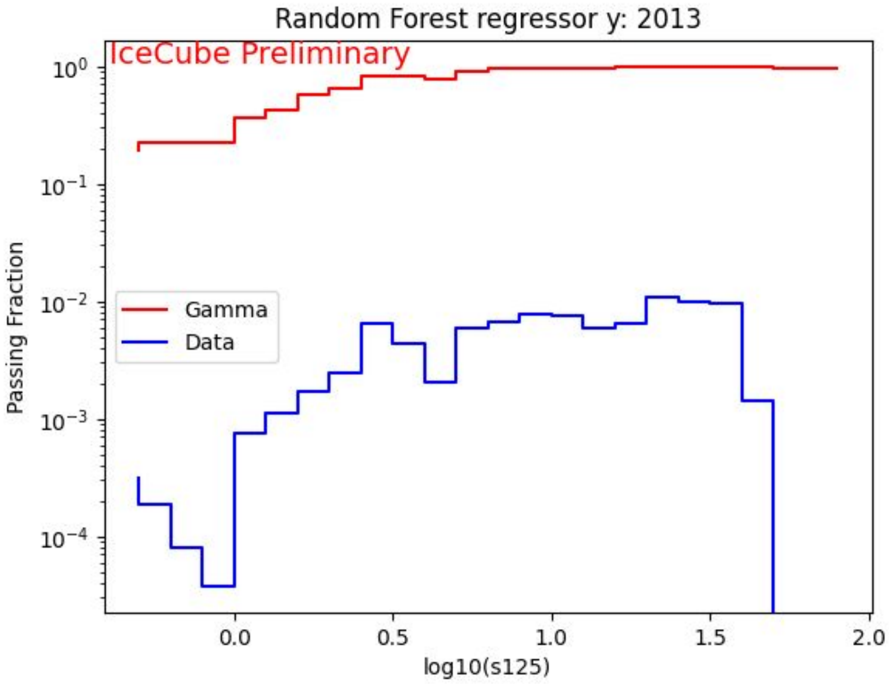




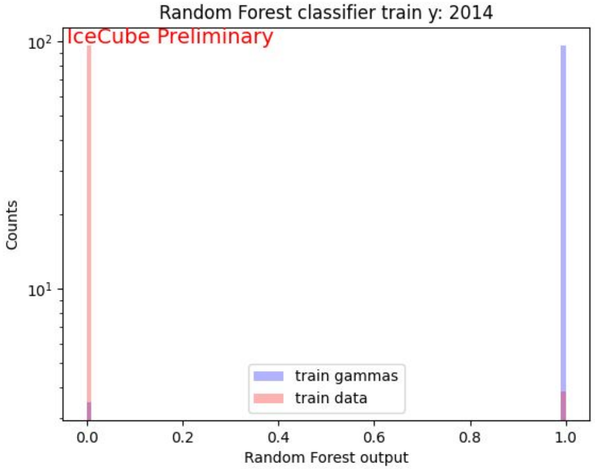
Passing fraction year 2013

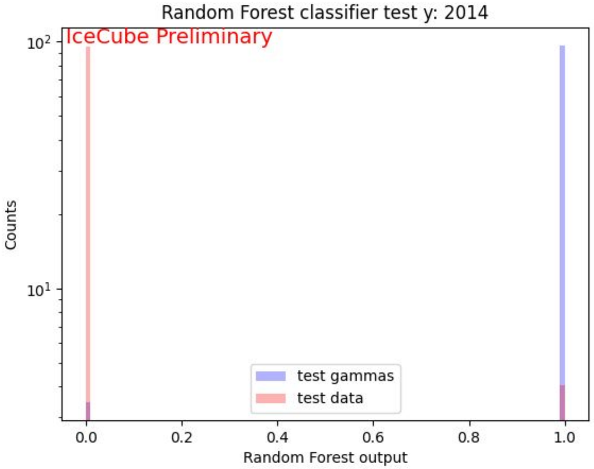
- event that passed the prediction cut / Total event
- plotted as function of energy

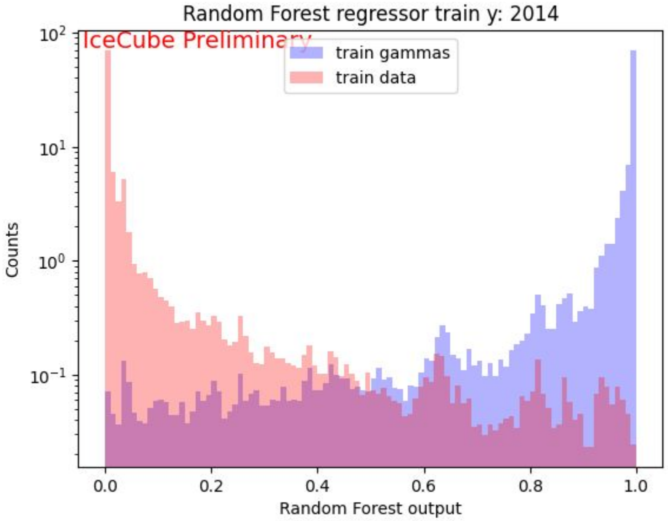


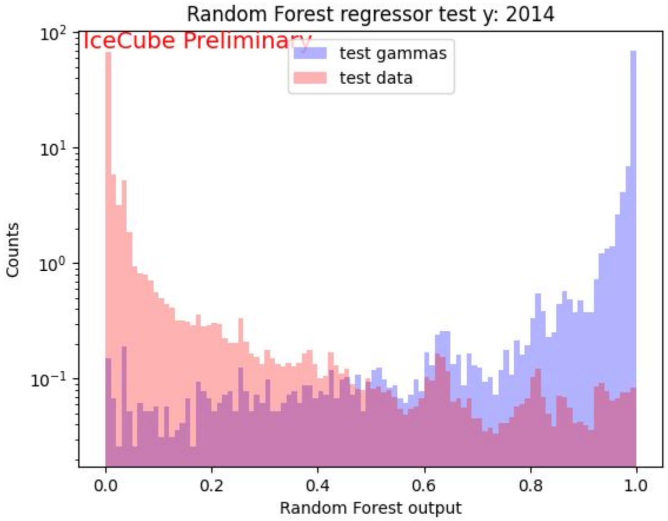


Training & Testing year 2014


Random Forest classifier train y: 2014

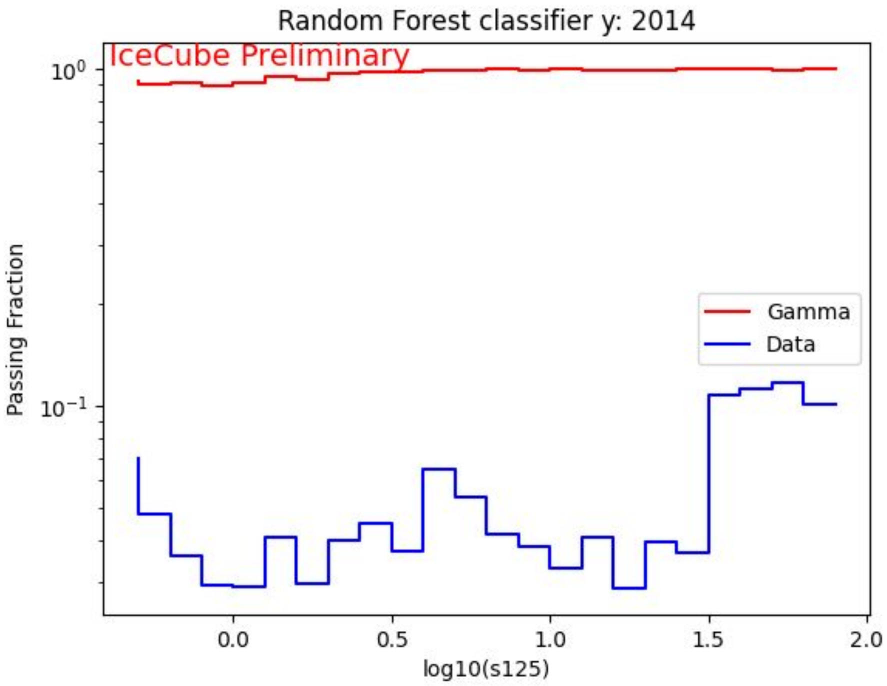

Random Forest classifier test y: 2014

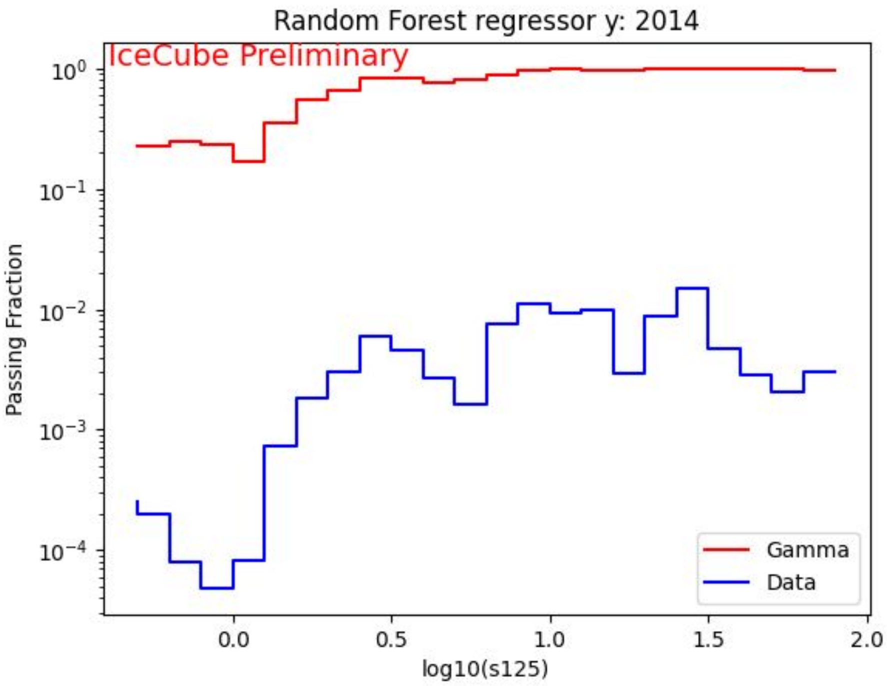

Random Forest regressor train y: 2014


Random Forest regressor test y: 2014

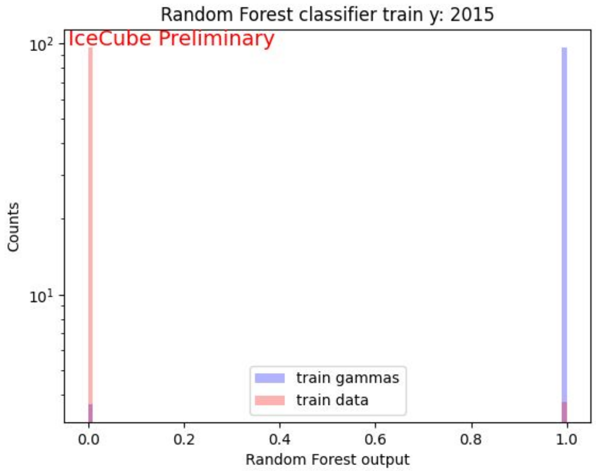
Passing fraction year 2014

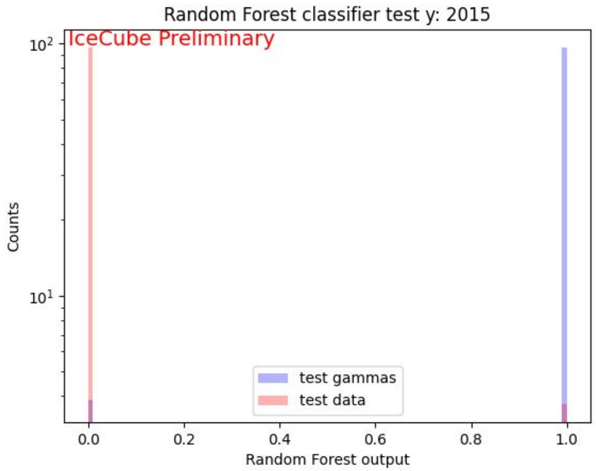
- event that passed the prediction cut / Total event
- plotted as function of energy

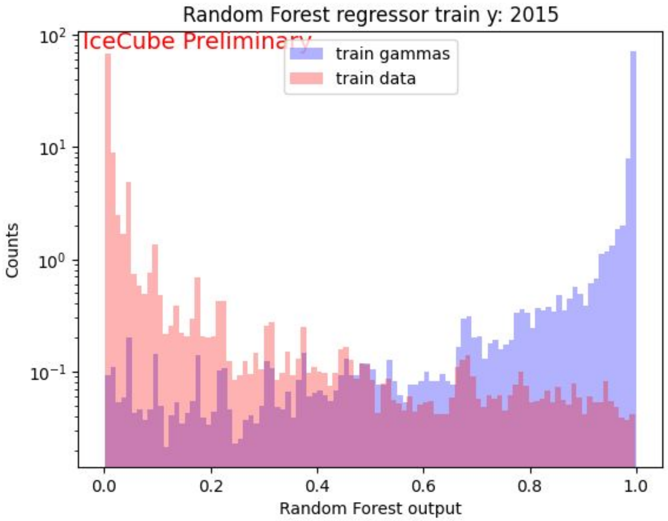


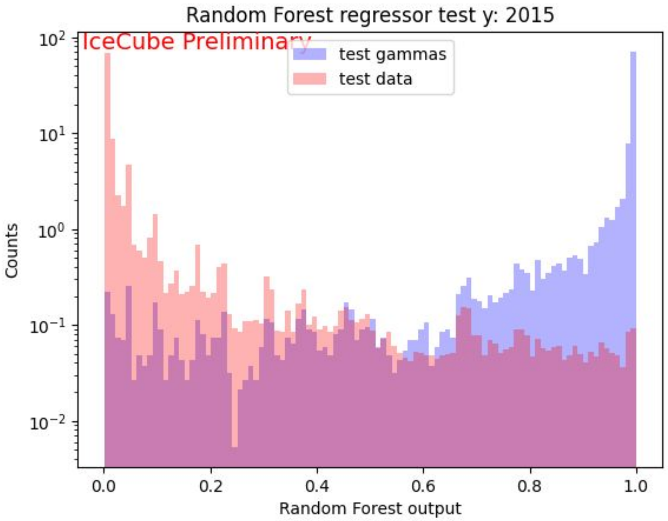


Training & Testing year 2015


Random Forest classifier train y: 2015

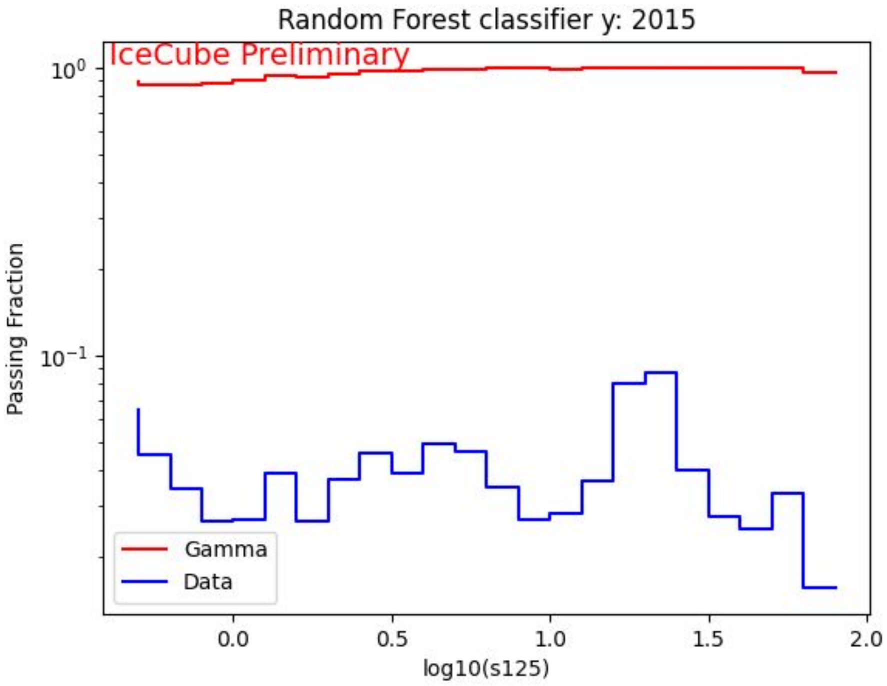

Random Forest classifier test y: 2015

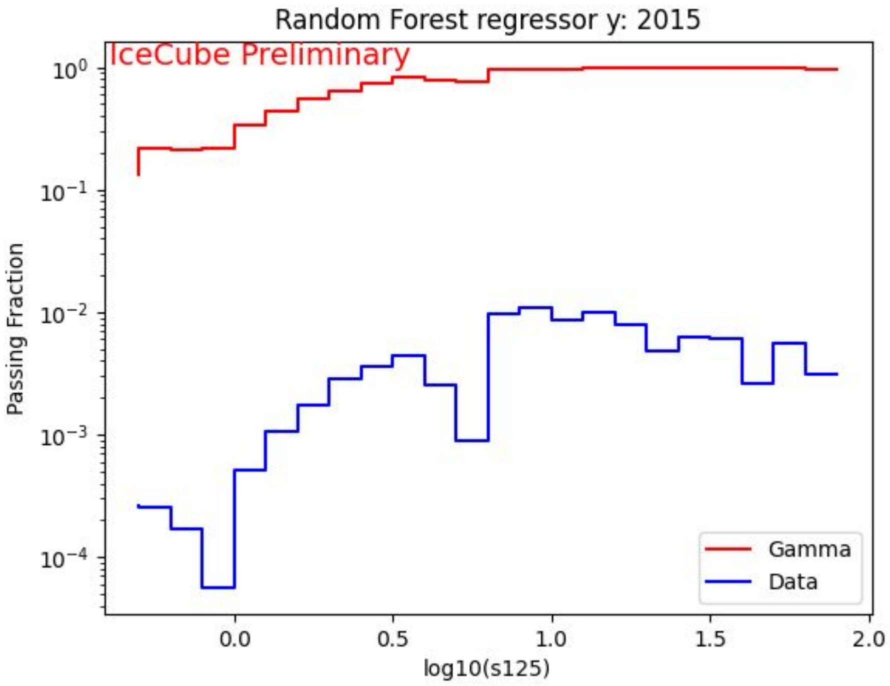

Random Forest regressor train y: 2015


Random Forest regressor test y: 2015

Passing fraction year 2015

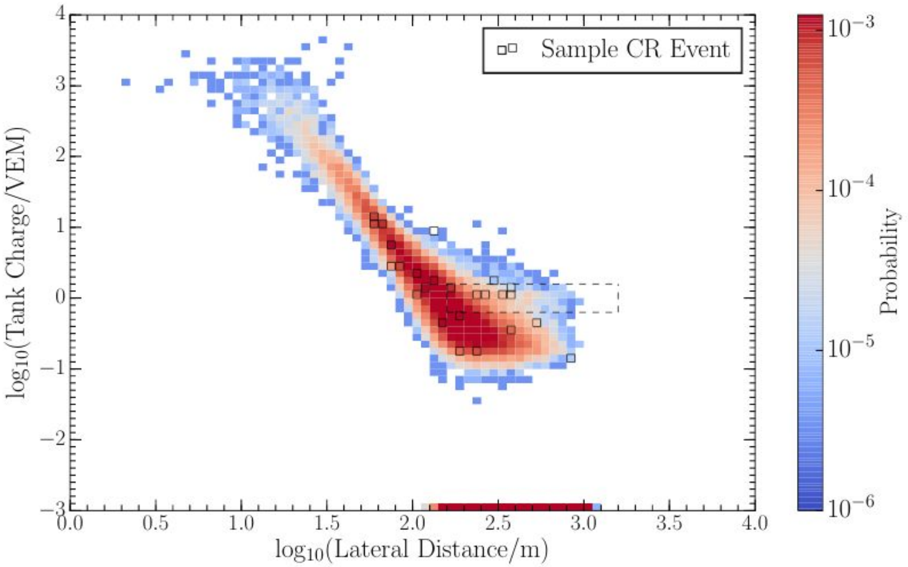
- event that passed the prediction cut / Total event
- plotted as function of energy



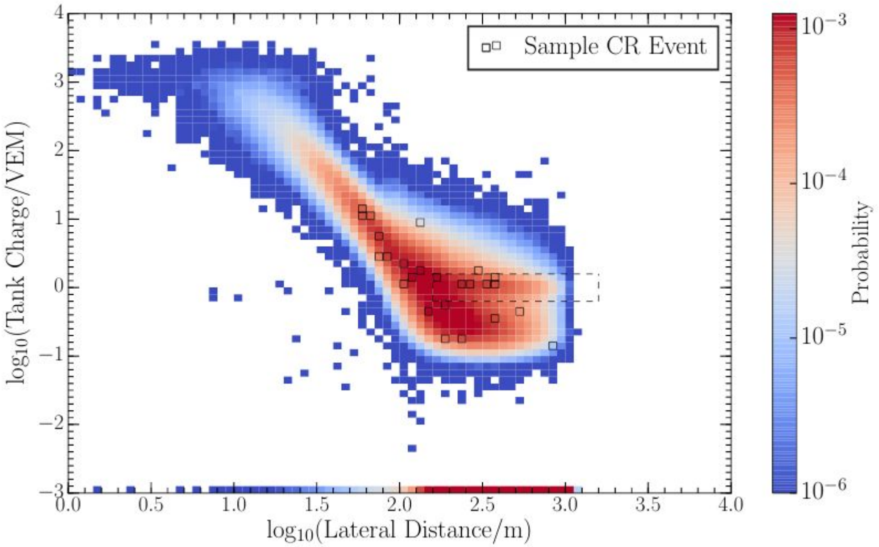


Log likelihood ratio

- example of a photon and CR background probability map



(a) Lateral PDF for gamma rays.



(b) Lateral PDF for cosmic rays.

Source: SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY, Zachary Dean Griffith