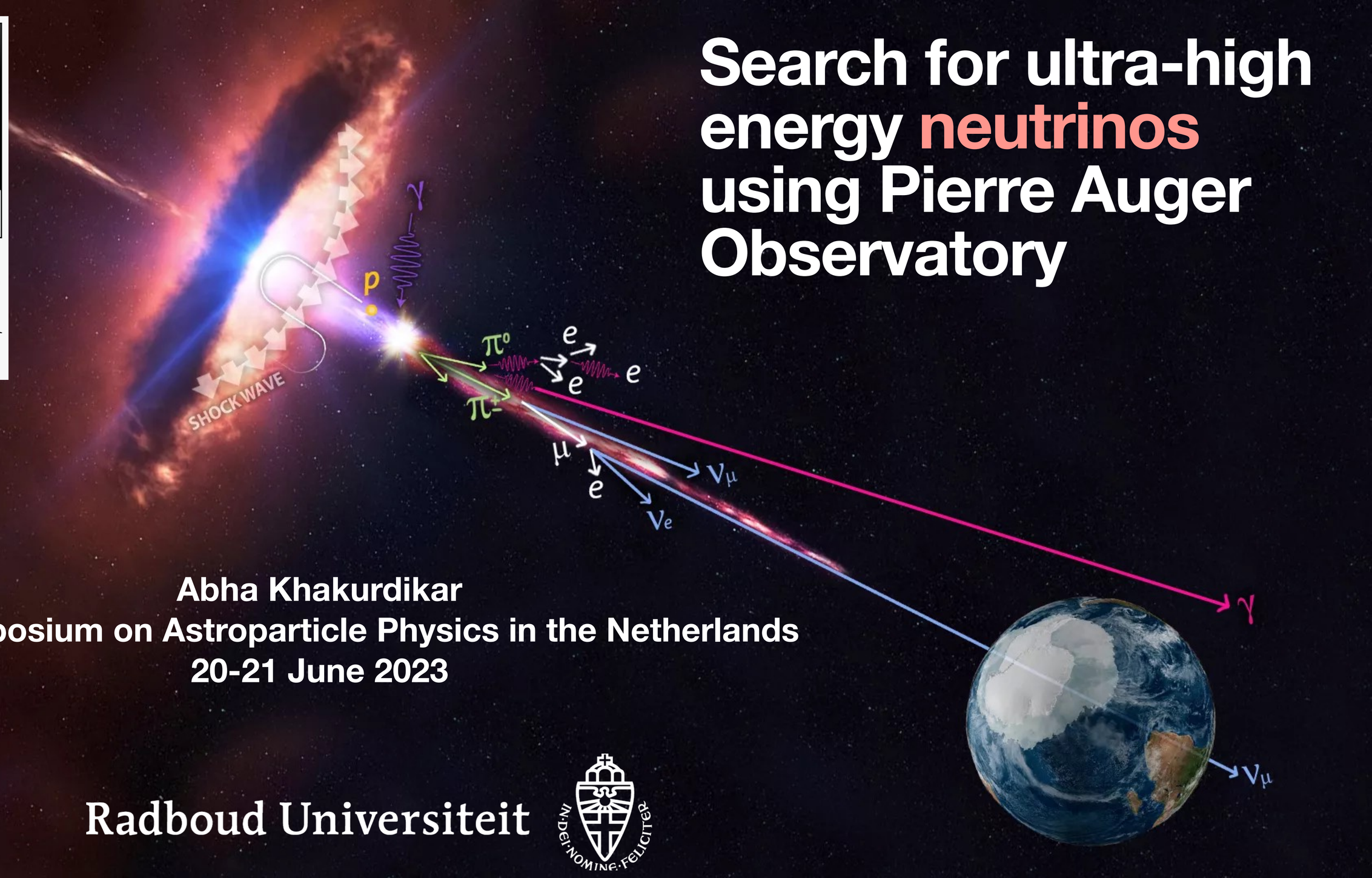
Search for ultra-high energy neutrinos using Pierre Auger Observatory



Abha Khakurdikar

27th Symposium on Astroparticle Physics in the Netherlands

20-21 June 2023

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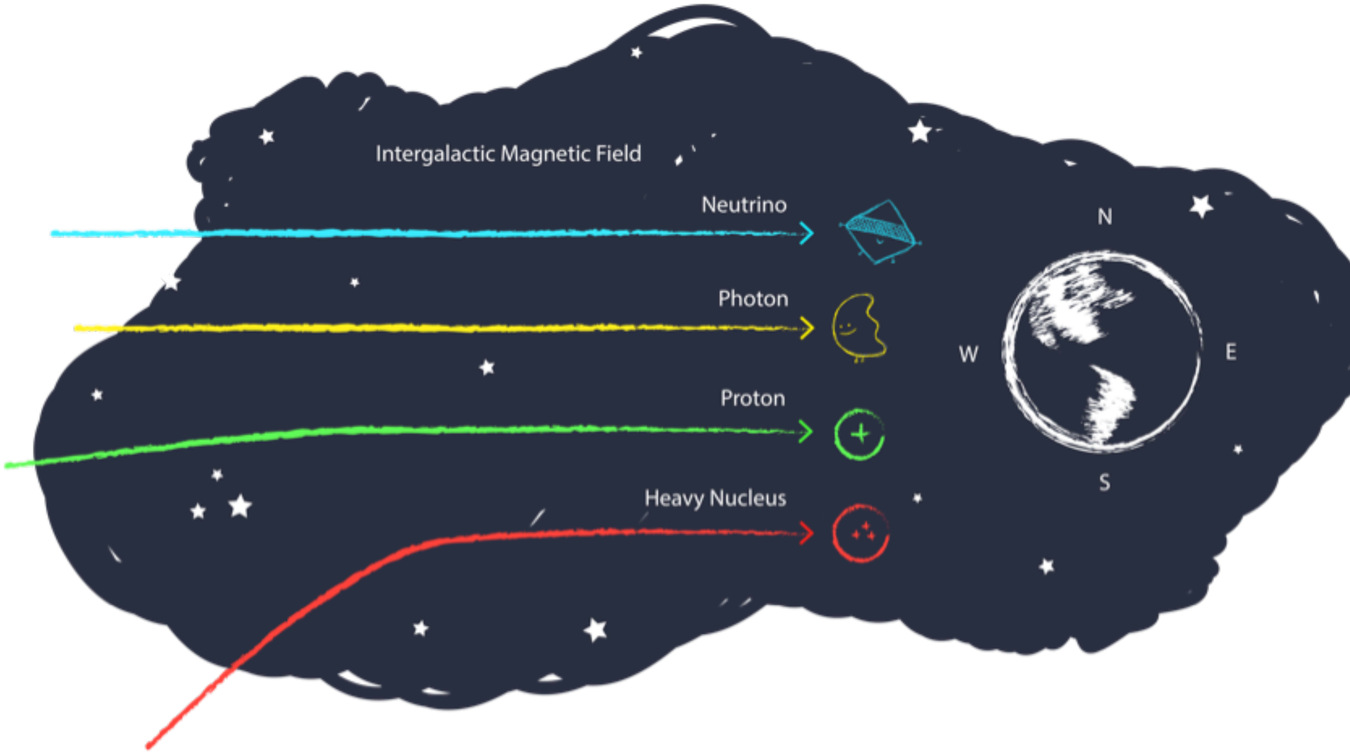
Why ultra-high energy neutrinos ?

- Key role in understanding the origin of the ultra-high energy cosmic rays (UHECR).
- Their observation should open a new window to the universe, otherwise hidden by large amounts of matter.
- Neutrinos are not deviated by the magnetic field -> point back to the sources.
- In the EeV range, neutrinos are expected to be produced in the same sources where the UHECR are thought to be accelerated.



Source: https://subarutelescope.org/subaru20anniv/assets/files/Shigeru_Yoshida.pdf

1 eV = 1.6 x 10^{-19} J

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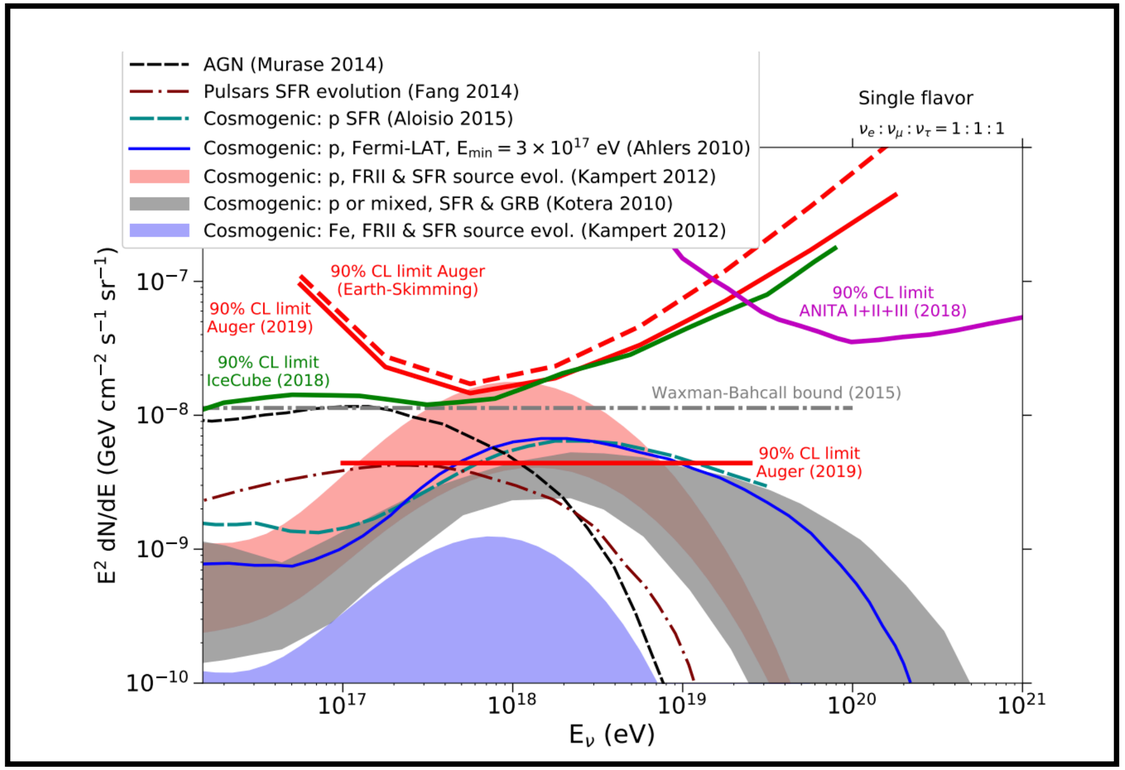
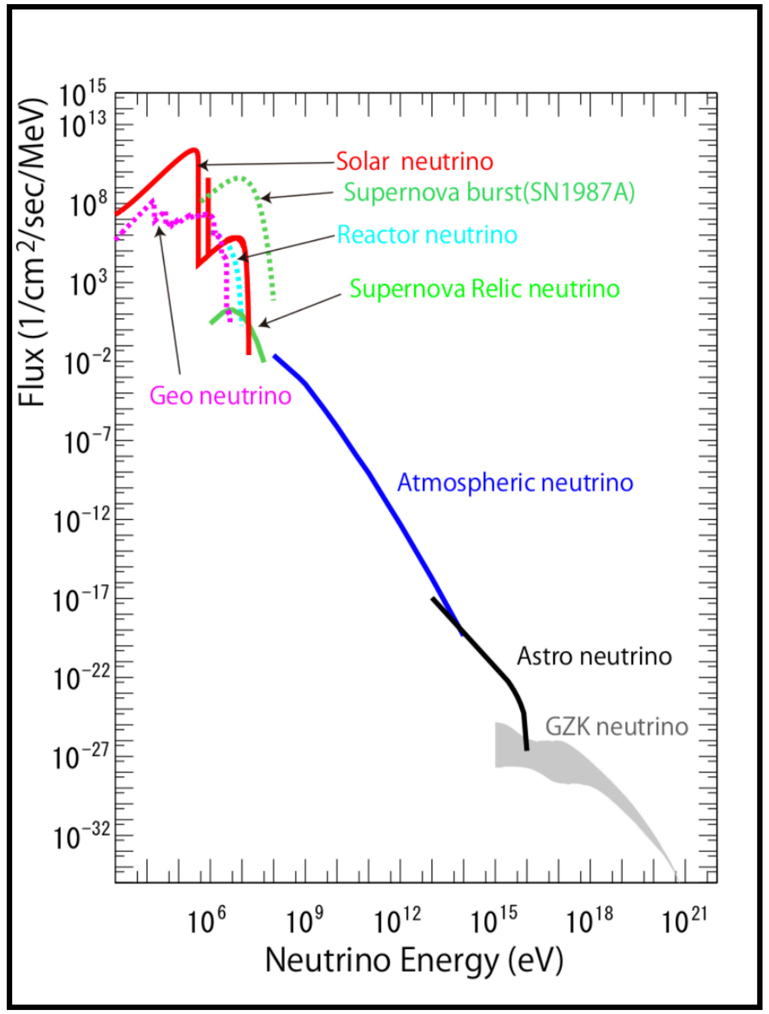
Search for ultra-high energy neutrinos

- A big challenge for the ultra-high energy neutrinos is that their flux is very low.
- We need a large detector for the detection and to get significant statistics.



The expected neutrino fluxes for Pierre Auger Observatory, several cosmogenic and astrophysical models of neutrino production,
as well as the Waxman-Bahcall bound.
Source: JCAP10(2019)022



Source: https://subarutelescope.org/subaru20anniv/assets/files/Shigeru_Yoshida.pdf

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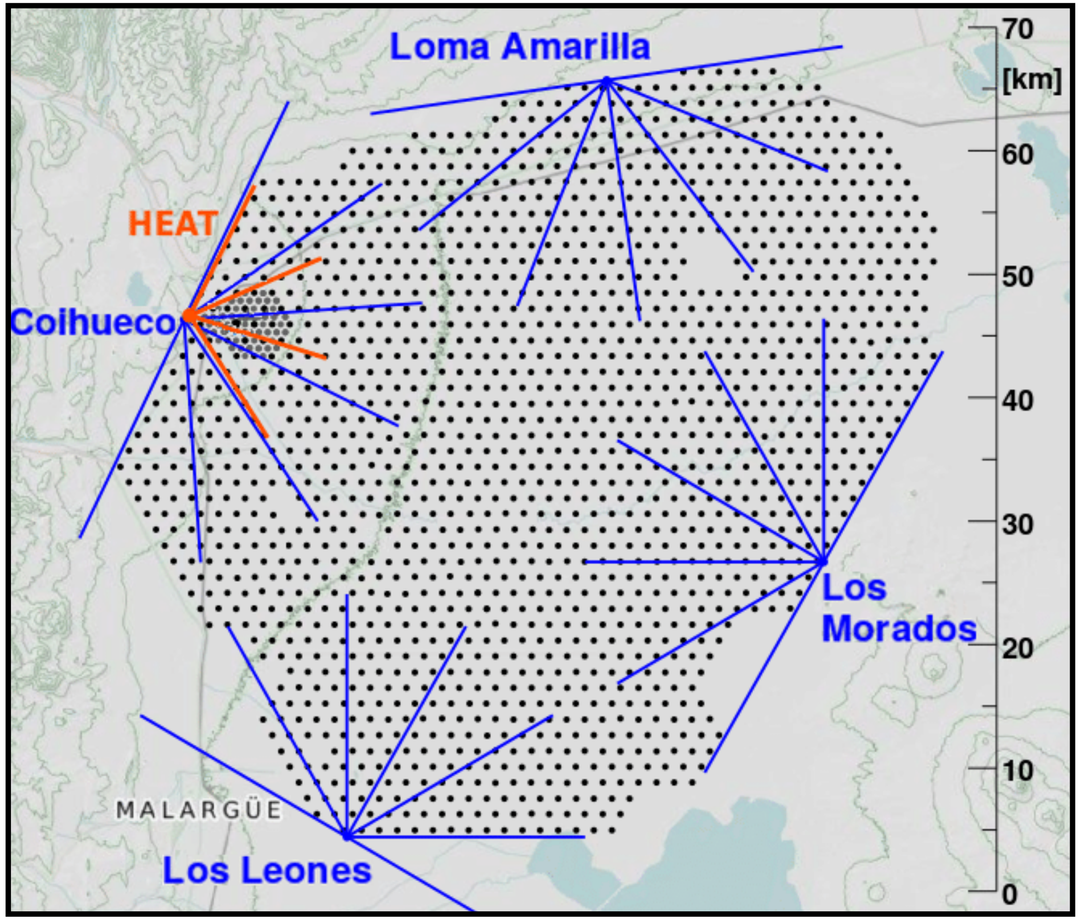
Pierre Auger Observatory



A schematic of the Pierre Auger Observatory where each black dot is a water Cherenkov detector.

Radio antenna on top of the particle detector

- Located in Mendoza Province, Argentina
- 1660 Water Cherenkov detectors (**WCD**)
- Surface area - 3000 km^2
- **Upgrade**: Radio antenna (**RD**) on top of each surface detector.

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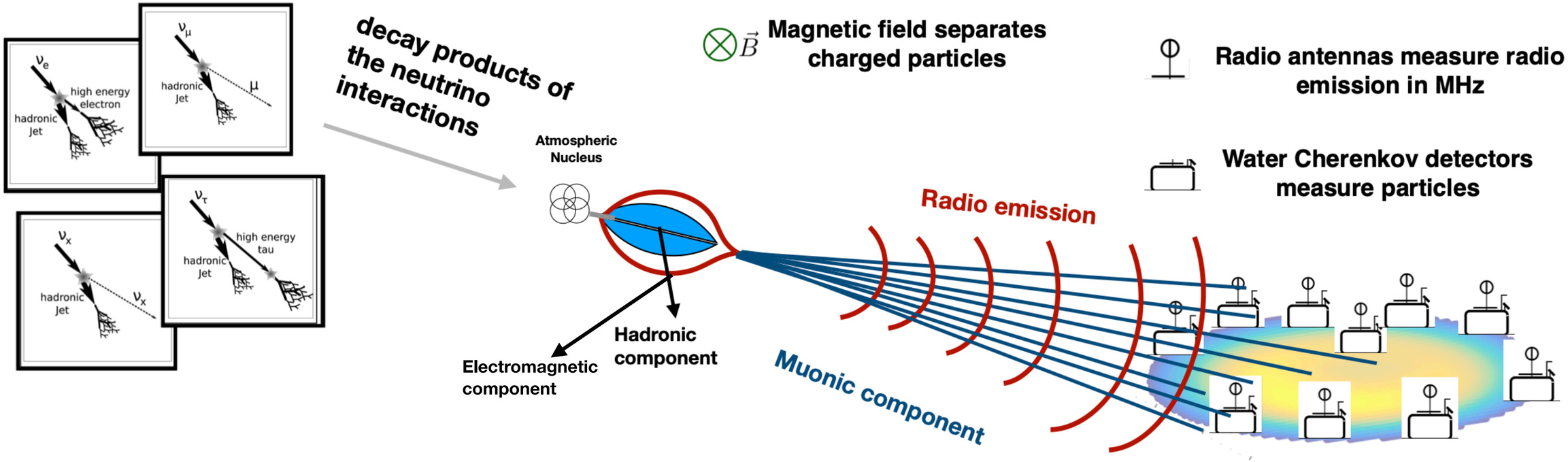
Ultra-high energy neutrinos

- All flavors of neutrinos with Energy E > 0.1 EeV
- Highly inclined extensive air showers (EAS) induced by the **neutrinos** : $75^\circ \lesssim \theta \lesssim 85^\circ$



Schematic diagram of the development of pipeline to detect the air showers induced by the the ultra-high energetic neutrinos

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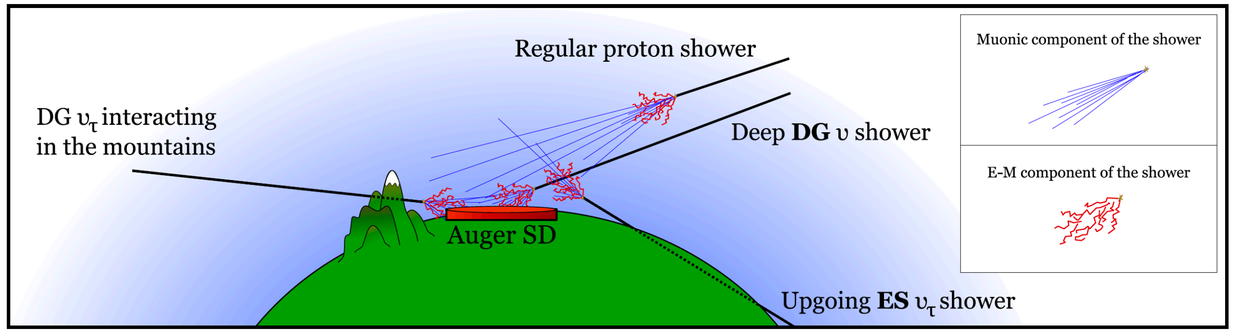
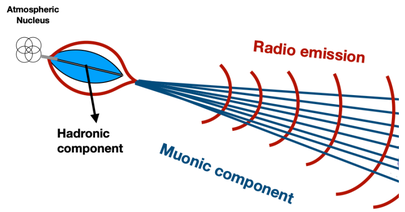
EAS RD simulations

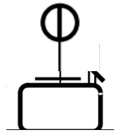


Simulate the ν-nucleon interactions to obtain the decay products

Simulate the air showers induced by the decay products

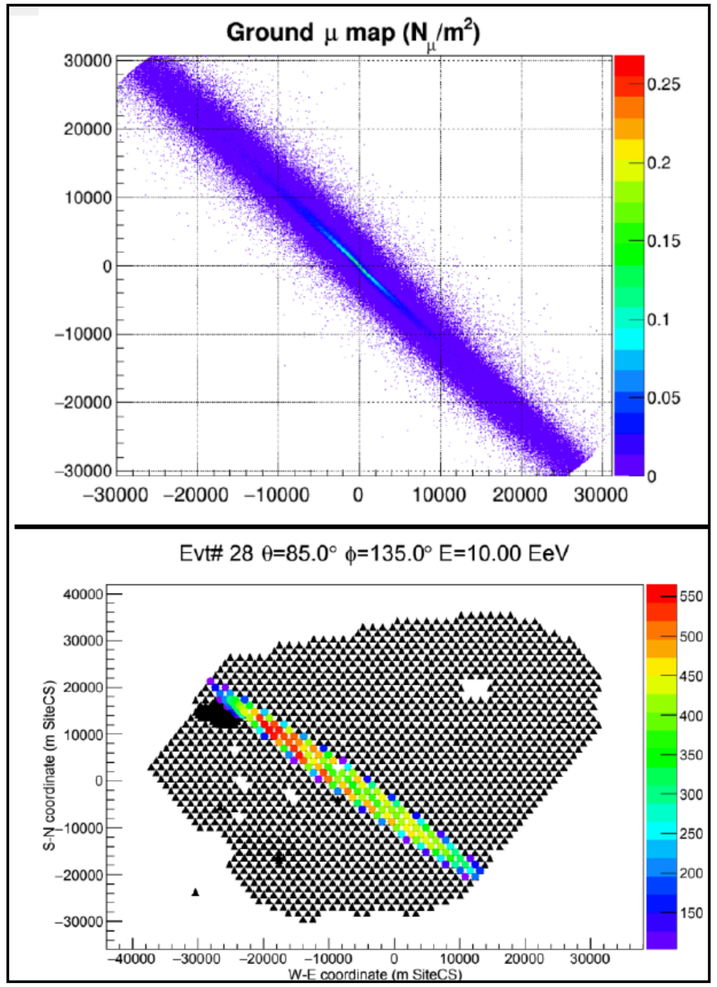


Detector simulation
(Hybrid reconstruction - WCD + RD)



Muonic part measured by WCD

Radio part measured by RD



EAS footprint after the detector simulation using the RDSim framework

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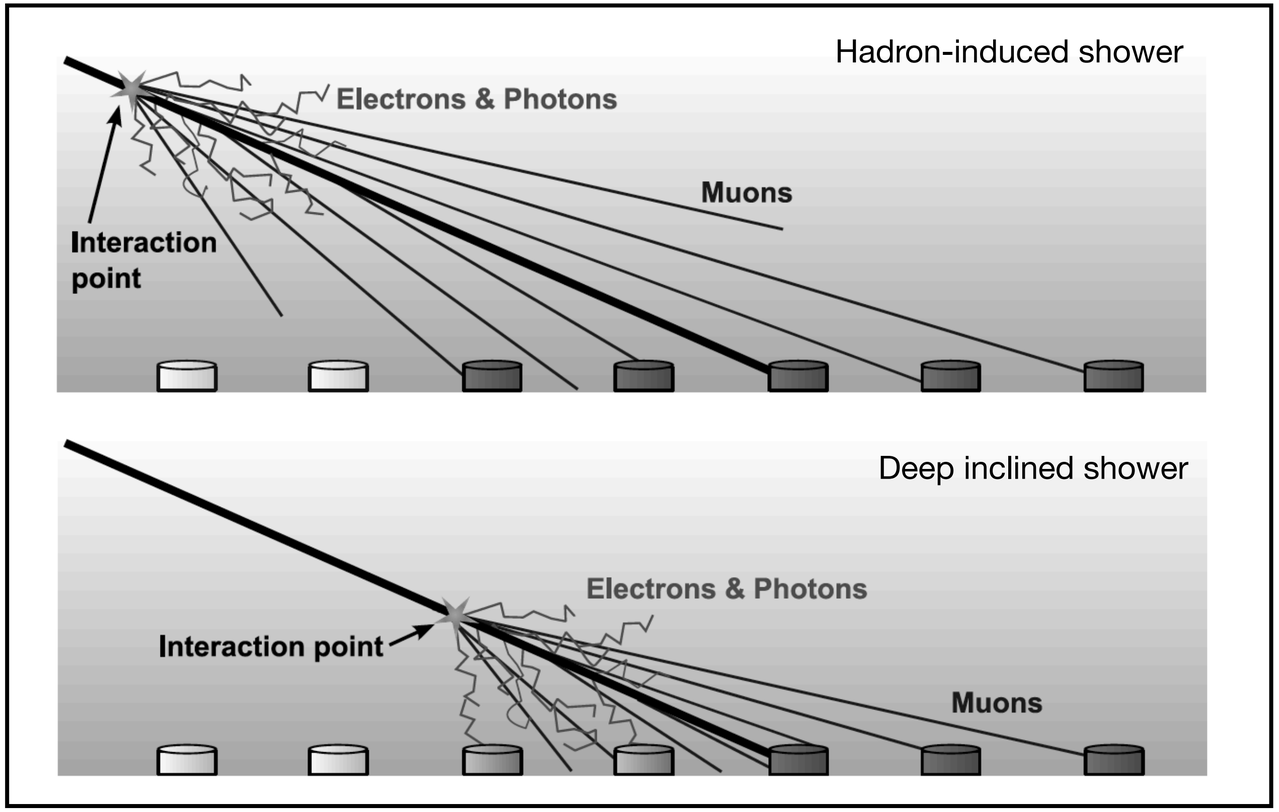
Identify the neutrino induced EAS

- The main challenge in detecting the UHE neutrinos is to identify a neutrino-induced shower (signal) in the background of showers initiated by UHERCRs.

EM component is absorbed and only the muons reach the detector

Significant EM component at the detector level



Source: arXiv:1202.1493

- RD upgrade will increase the sensitivity of the neutrino detection due to the significant EM component.

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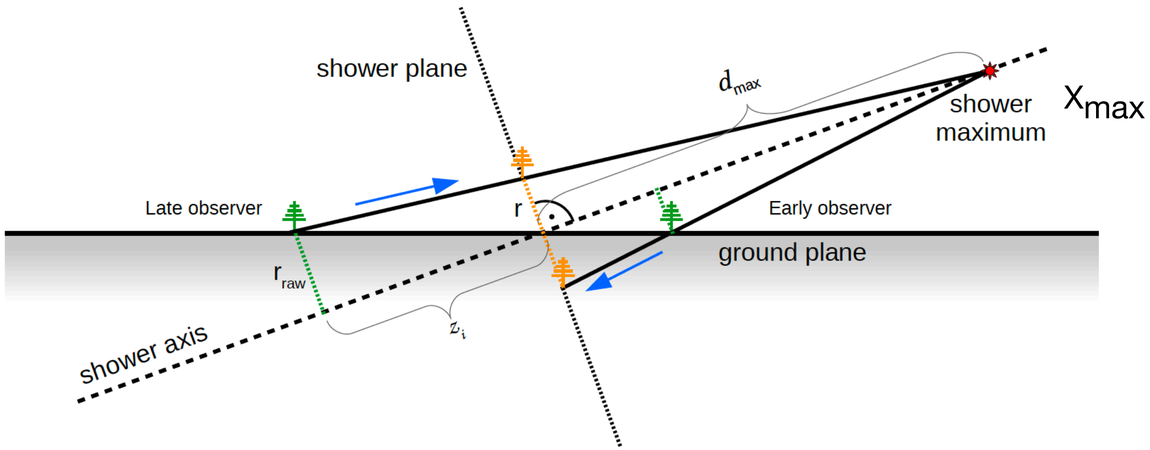
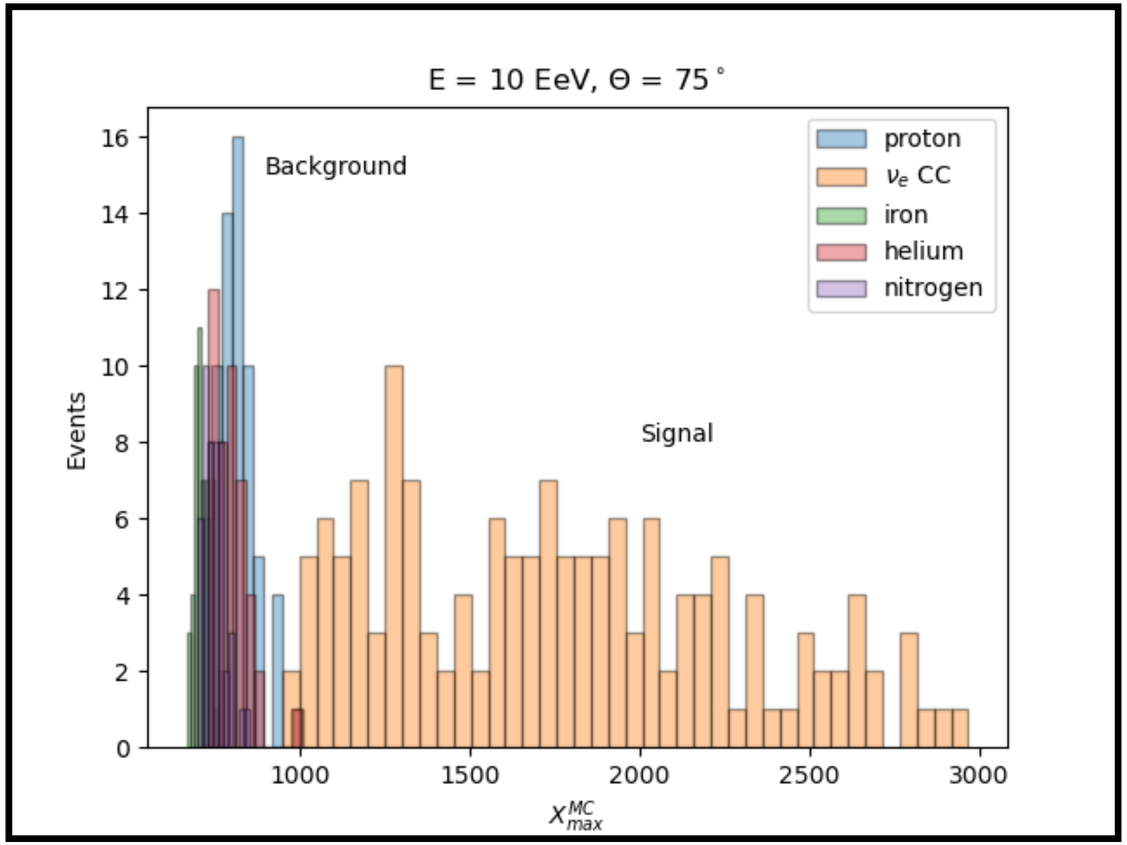
Identify the neutrino induced EAS

- The main challenge in detecting the UHE neutrinos is to identify a neutrino-induced shower (signal) in the background of showers initiated by UHERCRs.

- Several RD observables are investigated to differentiate between the background and the signal.



1. dmax (Xmax): An air shower observable, the geometrical distance along the shower axis (the extrapolated trajectory of the primary particle) between the ground/observation plane and the **shower maximum**.



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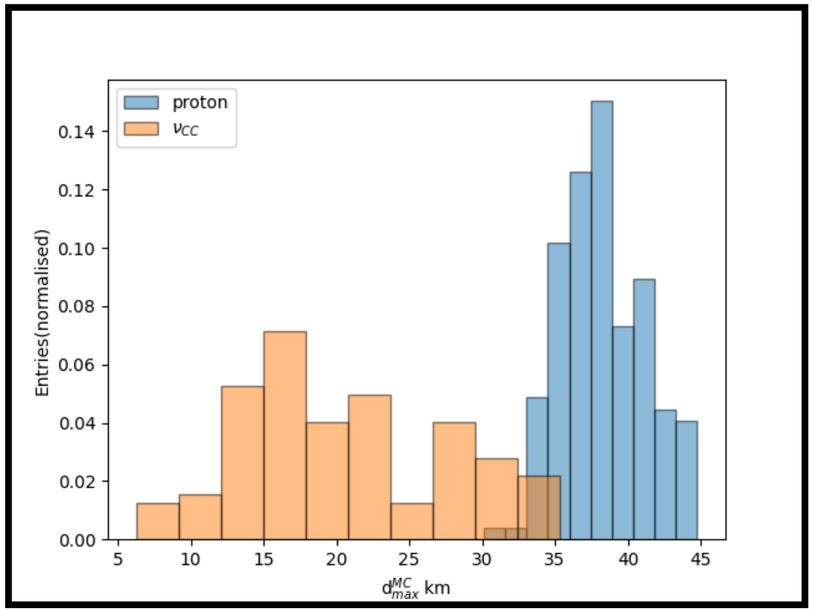
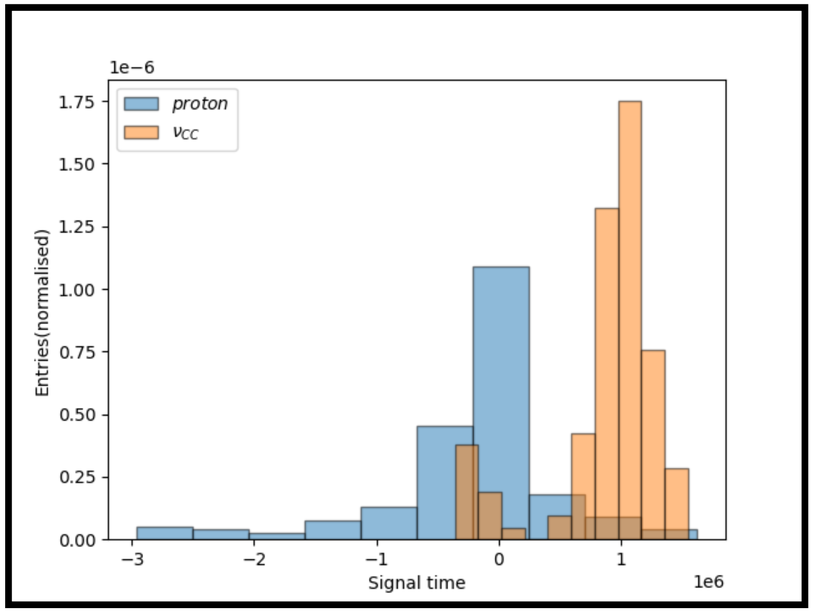
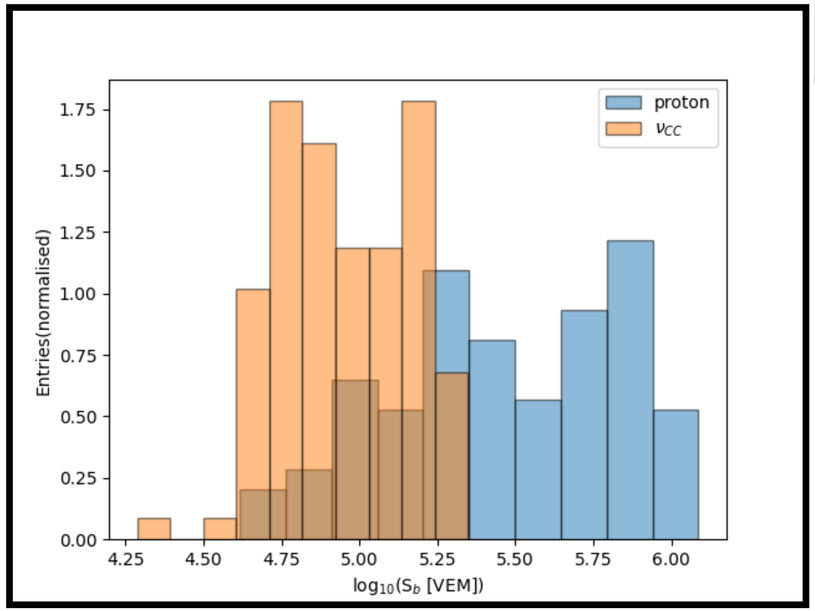
Identify the neutrino induced EAS

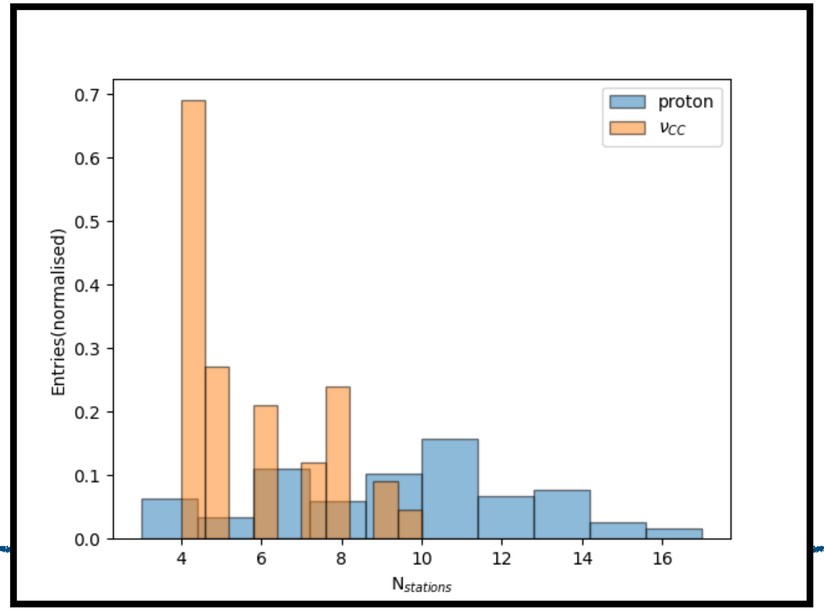




Signal time is measured by RD



Total Signal measured by the WCD



Number of stations triggered by the WCD + RD

- Separation of Signal (neutrino induced air showers) and Background (hadron induced air showers) using the RD observables - dmax and Nstations, Signal Time measured by the RD.
- Advantage of hybrid detection - use the signal measured by the WCD for the separation of the neutrino induced air shower from the background.

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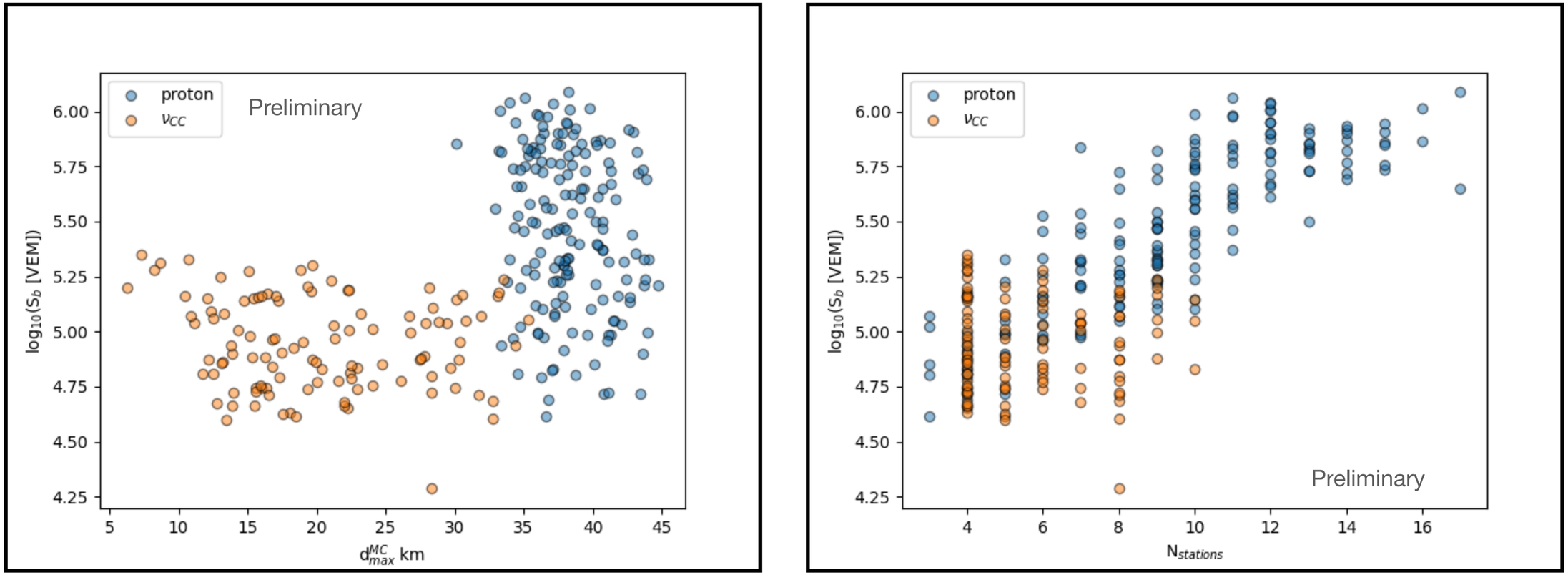
Identify the neutrino induced EAS



- Scatter plots of Sb and the RD observables which will be used in the hybrid search of neutrinos for simulated protons and neutrinos.

$$S_b = \sum_i S_i \times \left(\frac{R_i}{1000\ \mathrm{m}}\right)^b$$, S_i is the measured signal in the WCD at distance R_i

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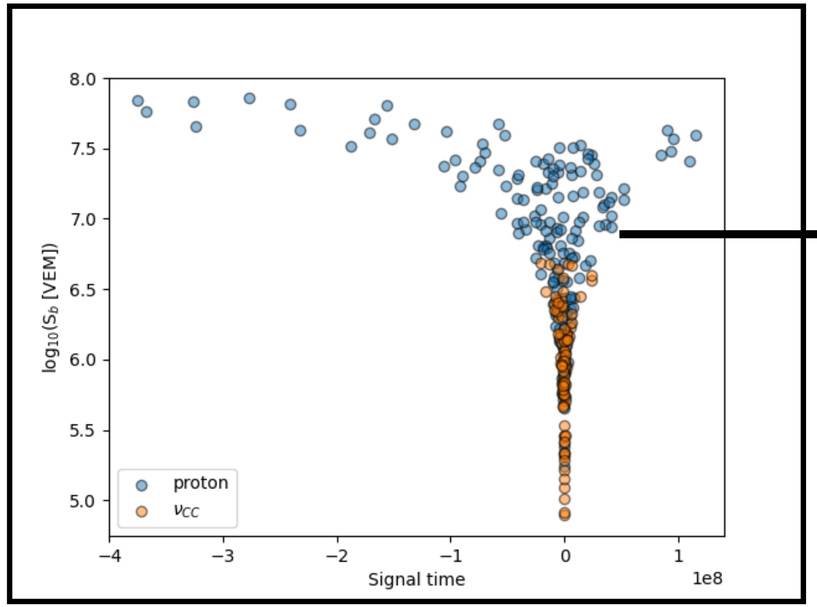
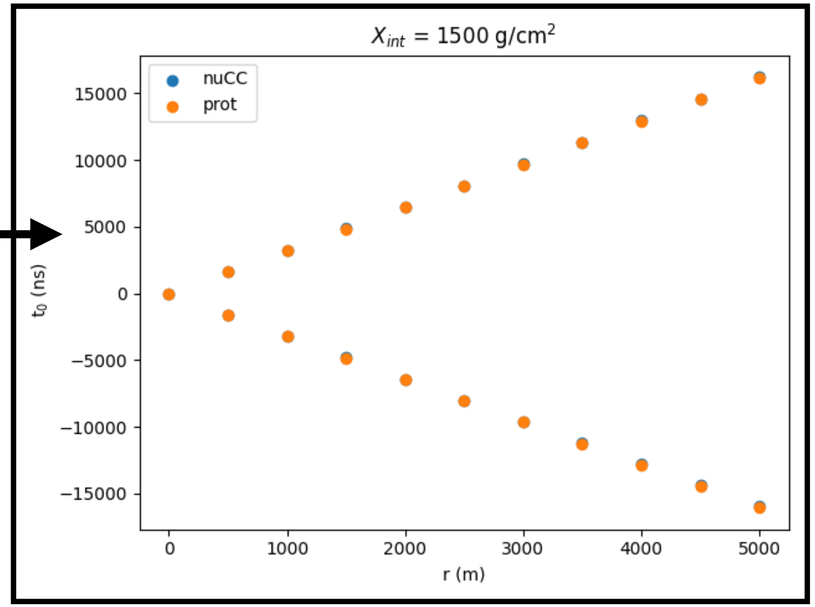
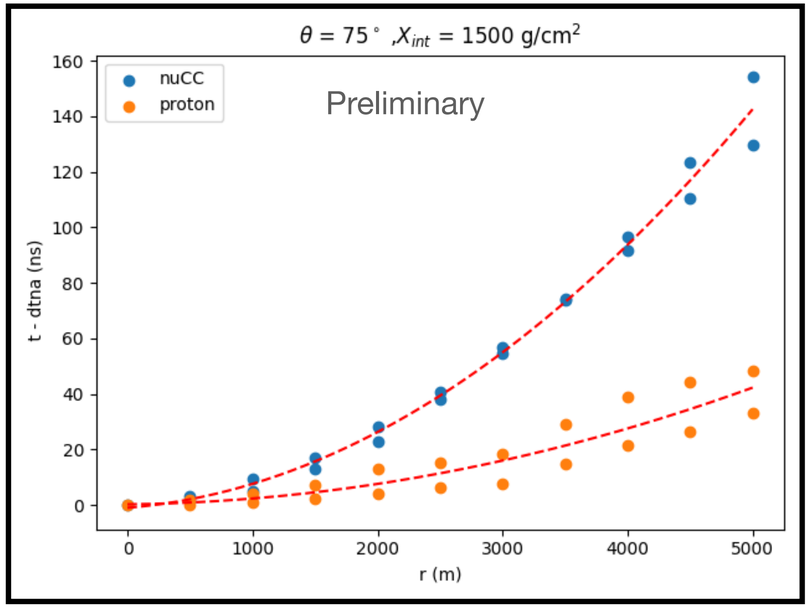
Identify the neutrino induced EAS





Signal time measured with respect to the distance of the RD station for a single event.



Corrected time signal with respect to the distance of the RD station.

- Due to geometrical reasons, the arrival of the first particles at lateral distance r from the axis is expected to be delayed with respect to planar shower front.
- We calculate the time delay and get a structure of shower front from the corrected time signal.
- Neutrino showers are in general much closer to the ground and hence the wavefront will be more curved as compared to hadron induced showers.

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Summary

- Ultra-high energy neutrinos play a key role in understanding the origin of UHECRs.
- RD upgrade will increase the sensitivity of the neutrino detection due to the significant EM component.
- Hybrid reconstruction of the particle detector and the radio antennas help to differentiate between the background and the signal.
- Geometry of the radio footprint of the showers is the main difference in the hadron- induced showers and the neutrino-induced showers
- RD observables and the Signal measured by the WCD will be used to do the hybrid search for neutrinos.

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Back-up

WCD + RD analysis

- Currently we can only use simulations for our background-like events. So, we can keep in mind the kinks in the background events.

1. The uncertainties on hadronic models,
2. The ignorance of unknown physical processes
3. The unpredictable detector effects may make very unreliable estimation of the background.
4. Also, the minimum number of simulated showers that would require to properly populate the tails of the distributions with a statistically significant number of entries was unaffordable.

Step 1: Background-like and Signal-like events

Simulations available:
Signal-like events: CoREAS showers

- Force Model: Sibyll2.3d
- Type: Electron Neutrino
- CC and NC interactions
- E = 1.0EeV, 10.0EeV
- $\theta = 66^\circ, 75^\circ$
- For varying Interaction lengths - 50 simulations per Xint

Background-like events: CoREAS showers

- Primaries: proton, helium, nitrogen and iron
- E = 1.0 - 120 EeV
- $\theta = 65^\circ - 85^\circ$, Uniform distribution in $\sin\theta\cos\theta$
- 2000 simulations per primary (Around 8000 simulations - there are some corrupt events)

Step 2: Reconstruction done with SdHAS + RD with 7.22 SNR threshold

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Back-up

WCD only analysis

- After training the Fisher method, a good discrimination was found when using the following ten variables:

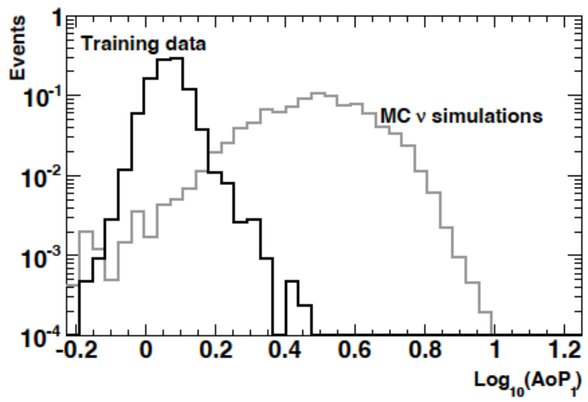
1.the **AoP of the four earliest triggered stations** in each event,

2. their squares - **the square of the AoP** because when the distribution of the input variables is not gaussian the addition of a non-linear combination of them improves the discrimination power.

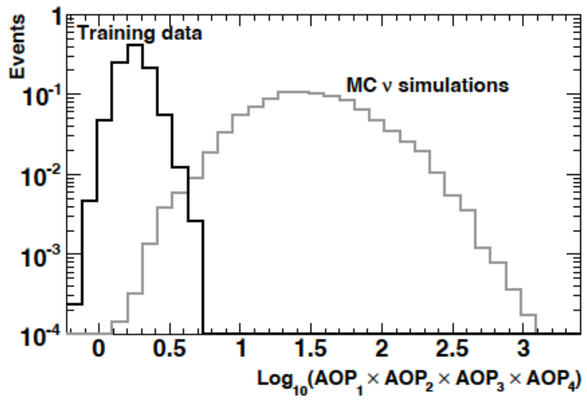
3. their product - **the product of the AoP** of the earliest four stations in the event aims at minimizing the relative weight of an accidentally large AoP produced.

4. a global early-late asymmetry parameter of the event- the early-late asymmetry parameter is a global observable of the event defined as the difference between the mean AoP of the earliest and latest stations in the event.

5. And observables characterizing the time spread of the signals, such as the **rise-time** (between 10% and 50% of the integrated signal) or the **fall-time** (between 50% and 90%), or including local observables of the stations that trigger last in the event, do not bring about significant improvements in the discrimination.



Distributions of the AoP of the earliest station



Distribution of product of the first four AoP

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Back-up

Reconstruction of shower front using the signal time

t_o: time at which the signal was found, relative to the event start time

$r_{ant} = \sqrt{x_{ant}^2 + y_{ant}^2}$

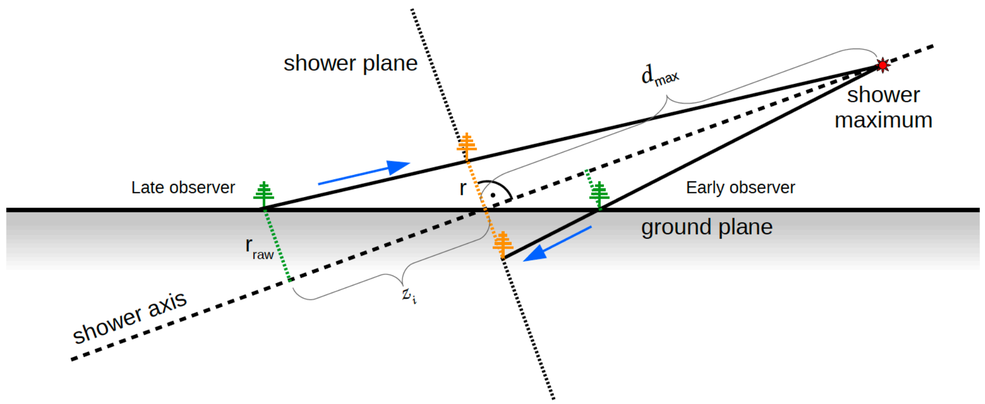
ϕ_{ant} = atan2(y , x)

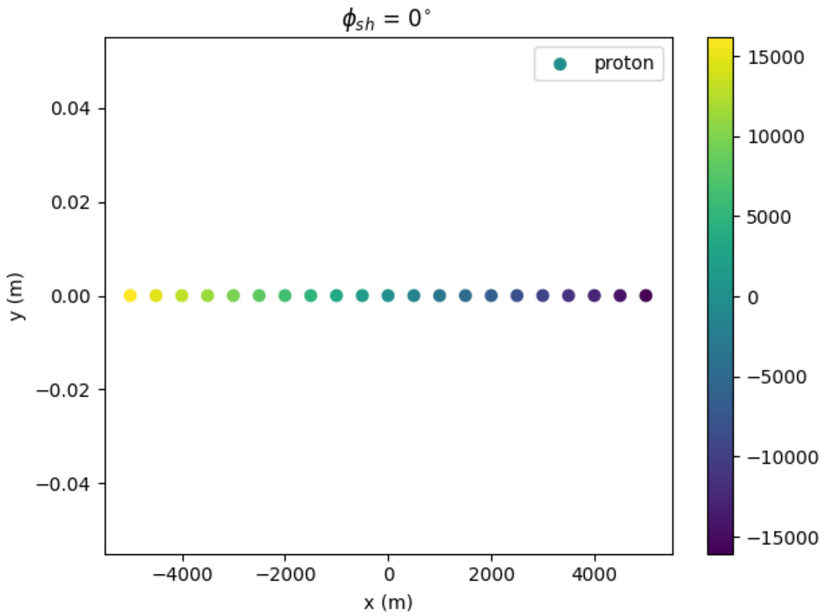
angle = $|\phi_{MC} - \phi_{ant}|$

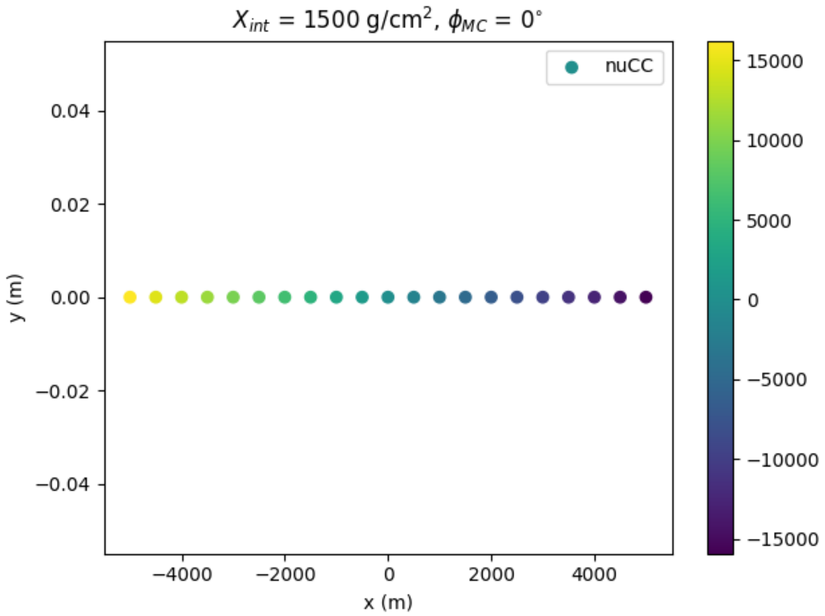
$r_{proj} = r_{ant} *$ cos(angle)

Delay in time due to the curvature of the air shower front

$$dtna = -(r_{proj} \sin(\theta_{MC})) / c$$







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