Development of an analysis method for neutrino-induced air showers with the Telescope Array surface detectors

ICRR, The University of Tokyo
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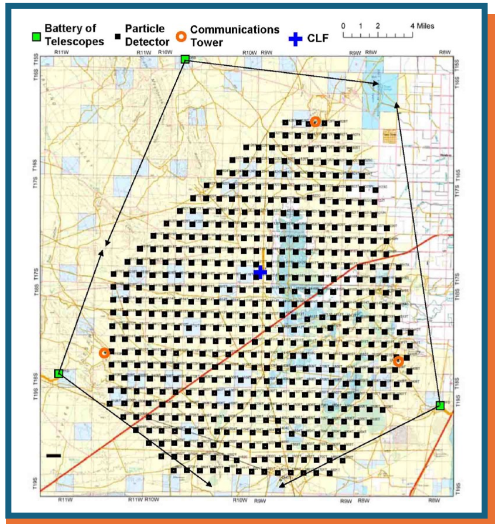
for the Telescope Array collaboration

Searching for high energy neutrino by TA SD

Final purpose：

To identify the source of the ultra high energy cosmic rays (UHECR).

Telescope Array Experiment



Surface detector (SD)

An array of 507 scintillation detectors ($3\ m^2$ each) placed at 1.2 km intervals.

Upper and lower double-layered scintillator

Neutrino

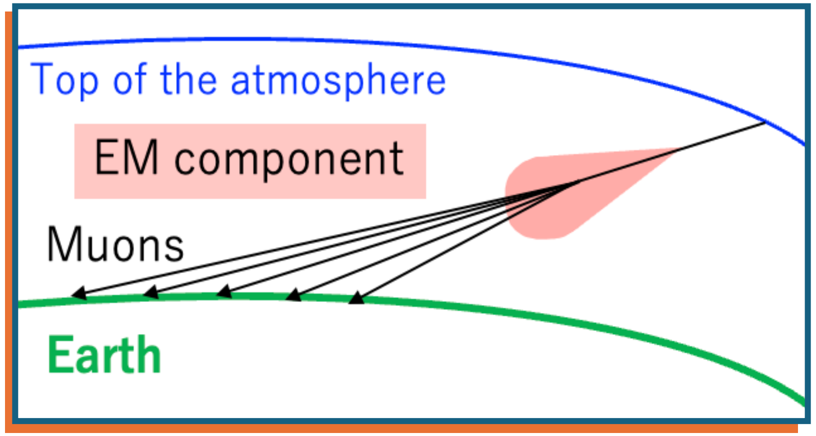
- ✓ Neutrinos are **neutral particles** and cannot be bent by magnetic fields.
- ✓ Neutrinos have **small interaction cross sections**, so they can arrive from extragalactic sources.

Searching for high energy neutrino by TA SD

Final purpose：

To identify the source of the ultra high energy cosmic rays (UHECR).

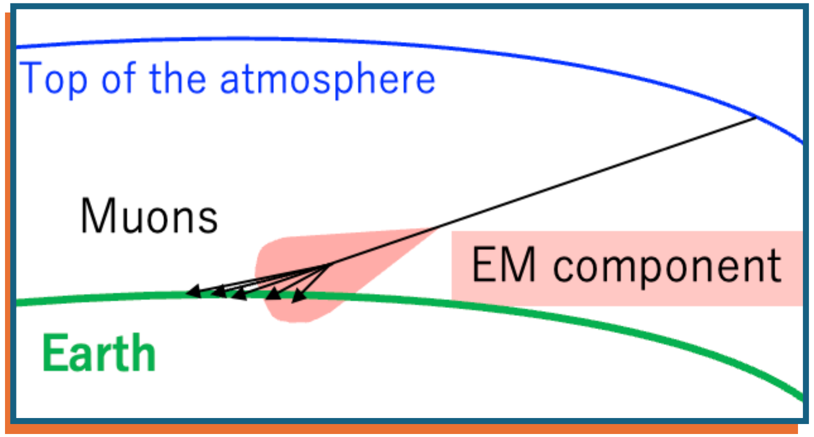
Large zenith angles



Proton inclined showers

・First interaction occurs in the **upper atmosphere**.

・ Because of the **long trajectory** that the shower takes, many particles in the shower **do not survive** to reach the ground.



Neutrino inclined showers

・The first interaction occurs in the **lower atmosphere**.

・Because of the **short trajectory** that the shower takes, shower may leave a **large footprint** even in the large zenith angle region.

Final purpose :

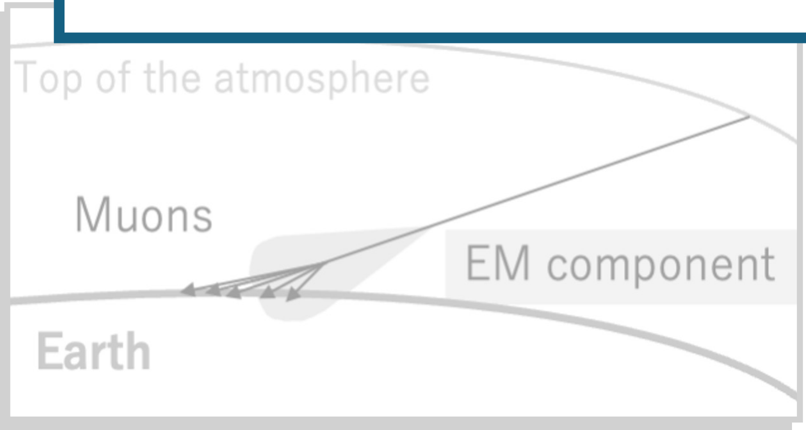
To identify the source of the ultra high energy cosmic rays (UHECR).

Large zenith angle neutrino search

・The standard analysis uses zenith angles up to 60 degrees, and the analysis method has not been established.

・Spherical atmosphere must be considered.

→ New method is needed to analyze inclined showers.



Neutrino inclined showers

・The first interaction occurs in the **lower atmosphere**.

・Because of the **short trajectory** that the shower takes, shower may leave a **large footprint** even in the large zenith angle region.

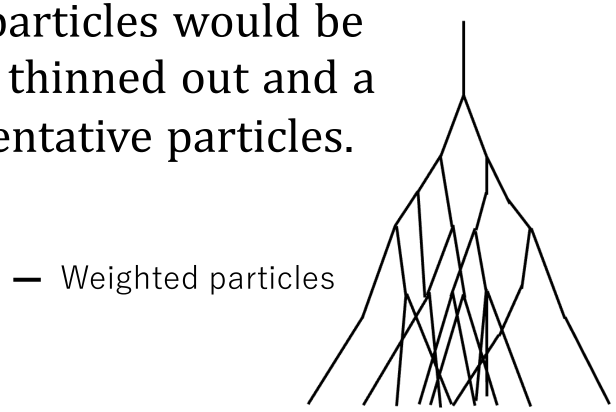
Thinning and De-thinning

Step1 by CORSIKA

THINNED shower generation
w/ spherical geometry

Thinning

Since following the trajectories of all particles would be very time consuming, the particles are thinned out and a weighted particles are hold as representative particles.

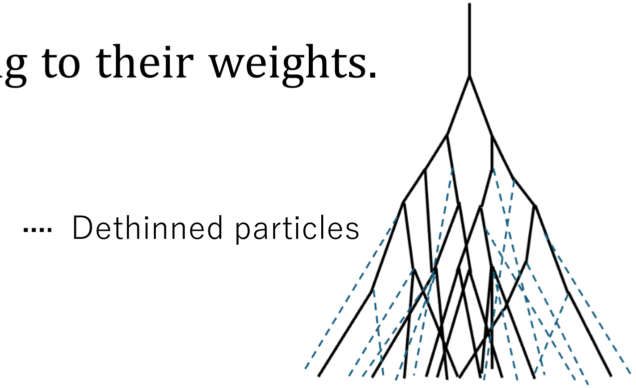


Step2 by TA method

DETHINNED shower generation
w/ spherical geometry

De-thinning

Thinned particles are returned according to their weights.



We need to make sure that the de-thinning process is returning the particles correctly.

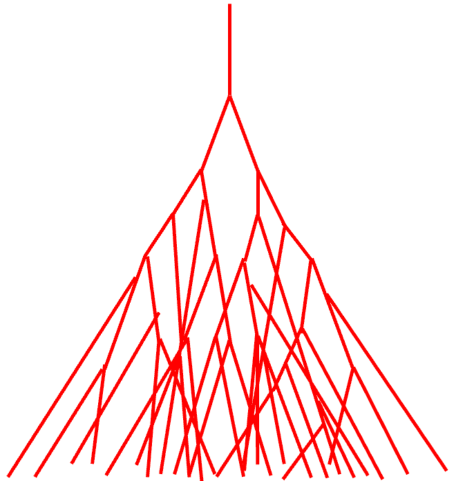
How to check the de-thinning process?

Using MULTITHIN option of CORSIKA

We can generate exactly the same shower for Unthinned and Thinned shower.

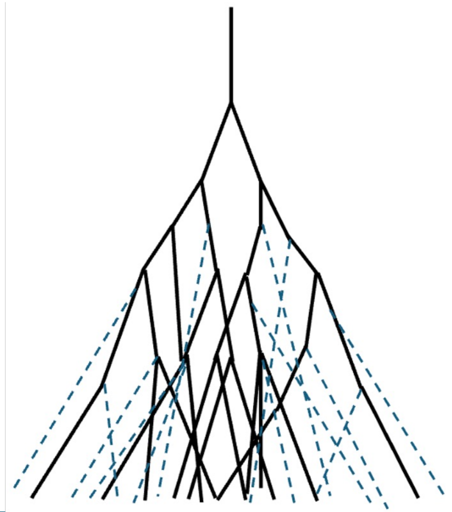
Unthinned shower

All particles are traced.



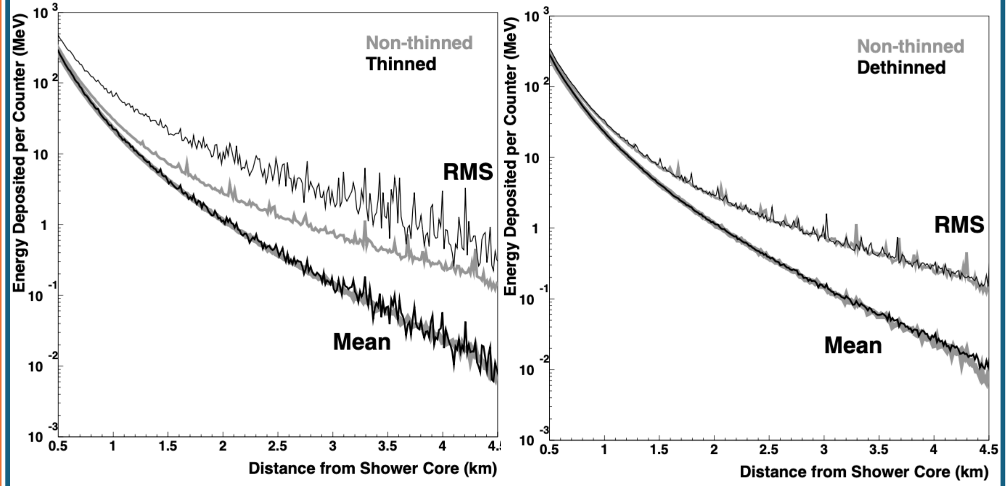
Thinned+TA de-thinning De-thinned shower

A reproduction of the original shower by regenerating the thinned particles.



Less than 60 deg

Comparison for standard analysis have already investigated.



(a) (b)

Dmitri Ivanov, Ph.D. - October 2012

The de-thinning process can be verified by comparing an **Unthinned shower** with a **Dethinned shower**.

How to check

CORSIKA

VERSION : corsika-76900 (QGSJET II -04, FLUKA)

OPTION : CURVED, **MULTITHIN**

UNTHINNED and THINNED shower can be generated simultaneously, so DETHINNING can be investigated combining with the TA method.

MC data set

Primary : ν_e

First interaction : Charged Current

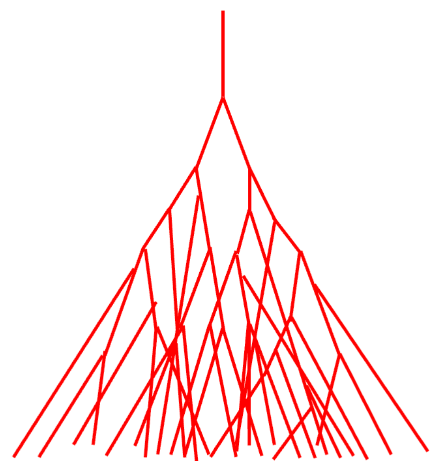
Zenith angle : 70deg and 80deg

Energy : 10^{16}eV,10^{17}eV,10^{18}eV

1st interaction height : 3km, 5km, 7km

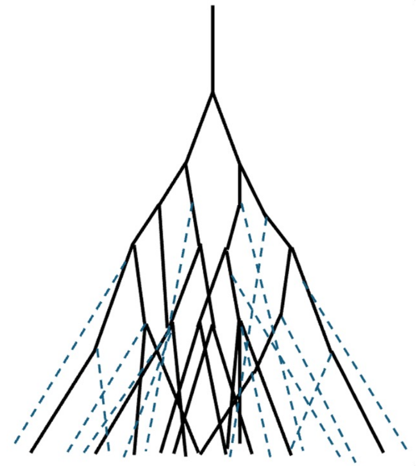
CORSIKA

Unthinned shower



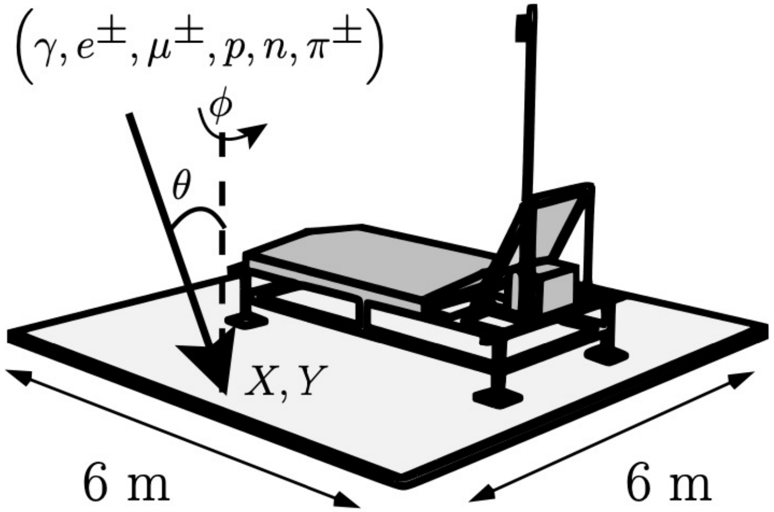
CORSIKA+ TA method

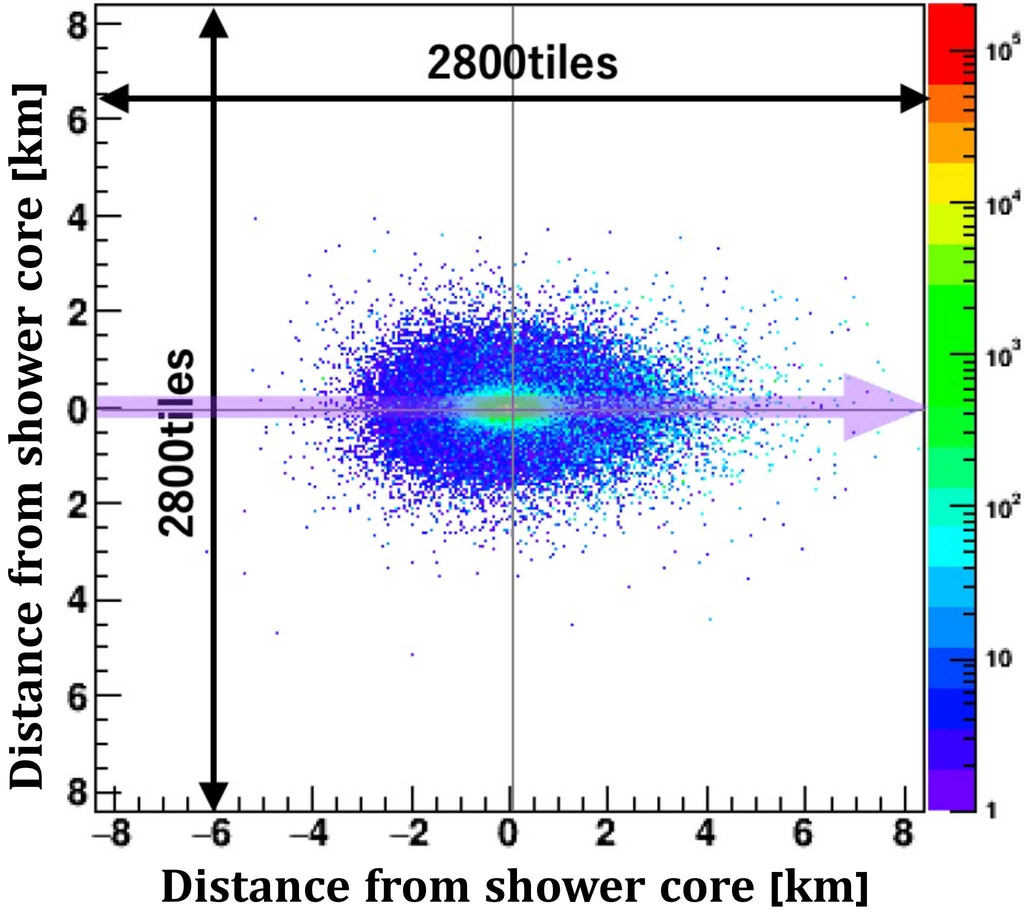
De-thinned shower



Calculation setup

Response of a virtual array filled by 6 m ×6 m tiles is simulated. Each tile contains a 3 m^2 TA SD at the center.





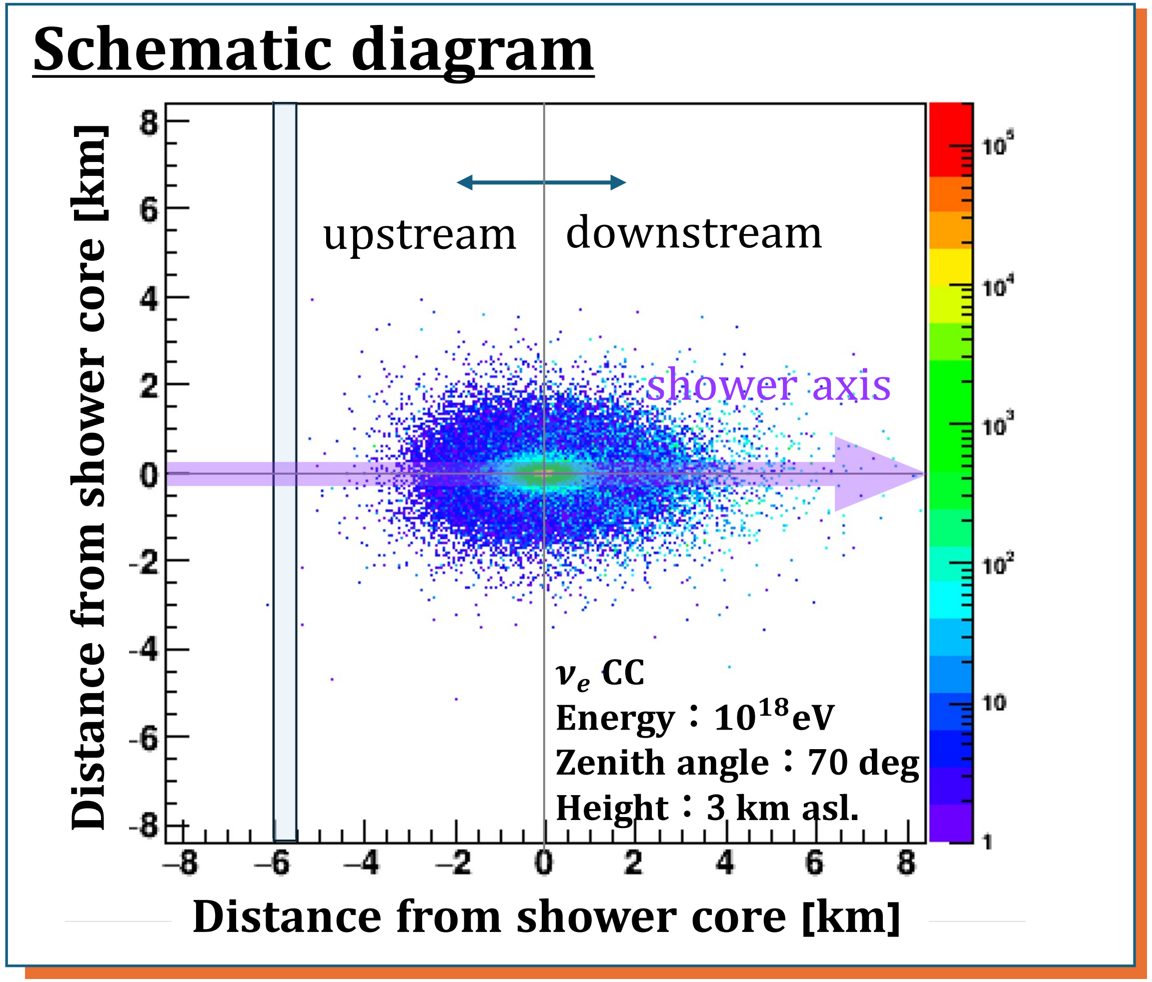
The layout consists of 2,800 tiles laid out in the x-axis and y-axis directions, respectively.

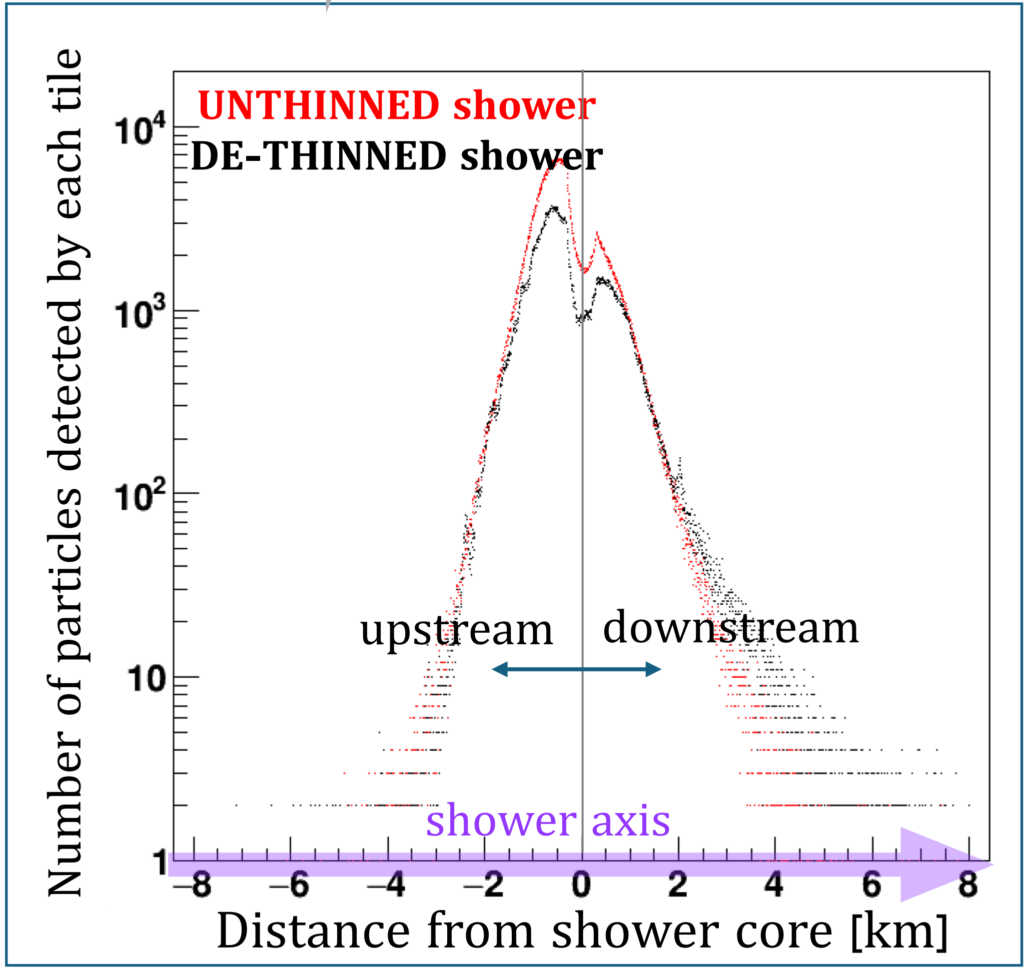
Thinning and DE-thinning comparison for inclined neutrino shower

Compare number of particles projected onto the shower axis

$$\frac{\int \text{DETHINNED}}{\int \text{UNTHINNED}} = 0.62$$

DE-thinning underproduces the number of particles by 38%

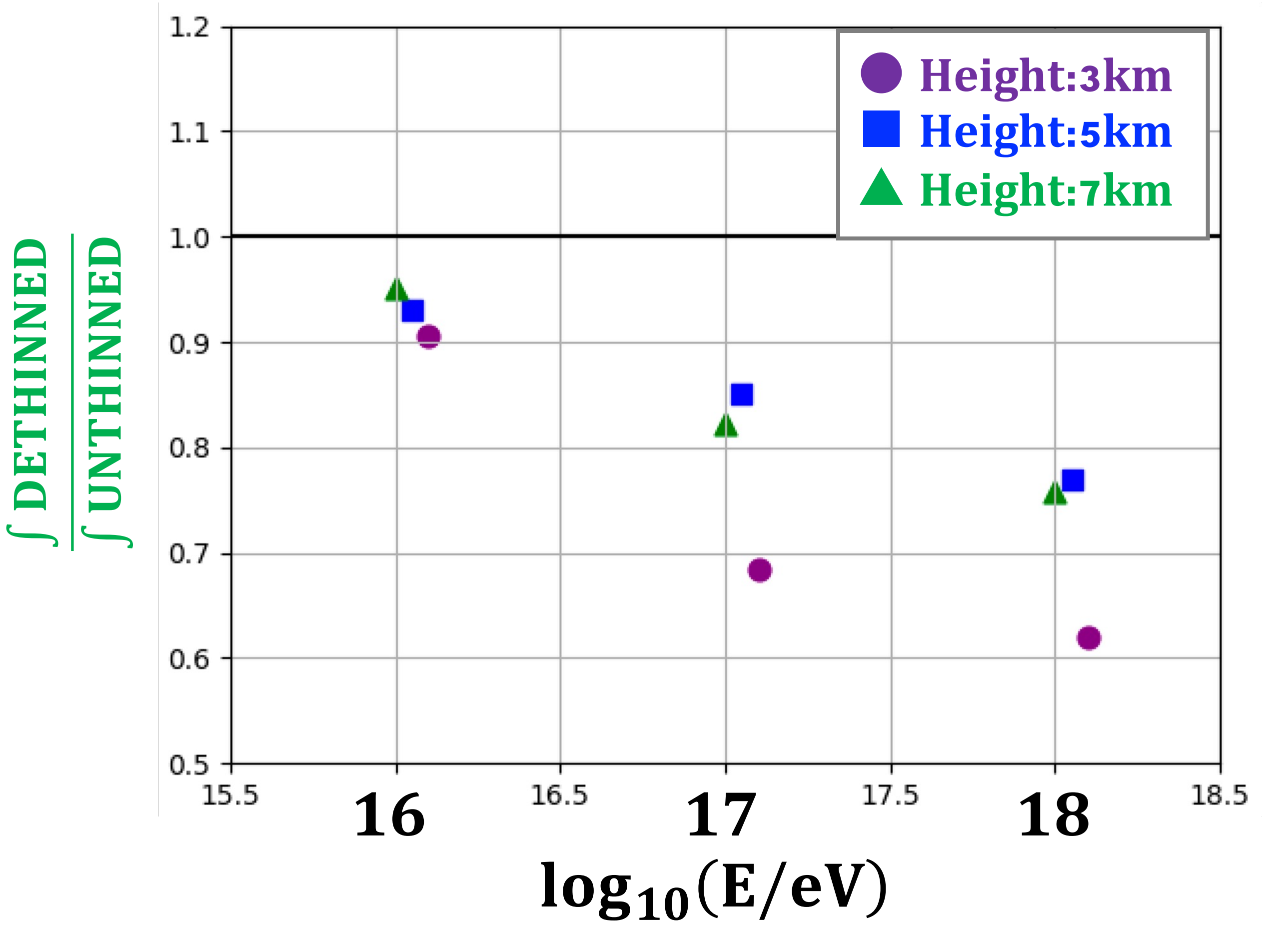




Thinning and DE-thinning comparison for inclined neutrino shower

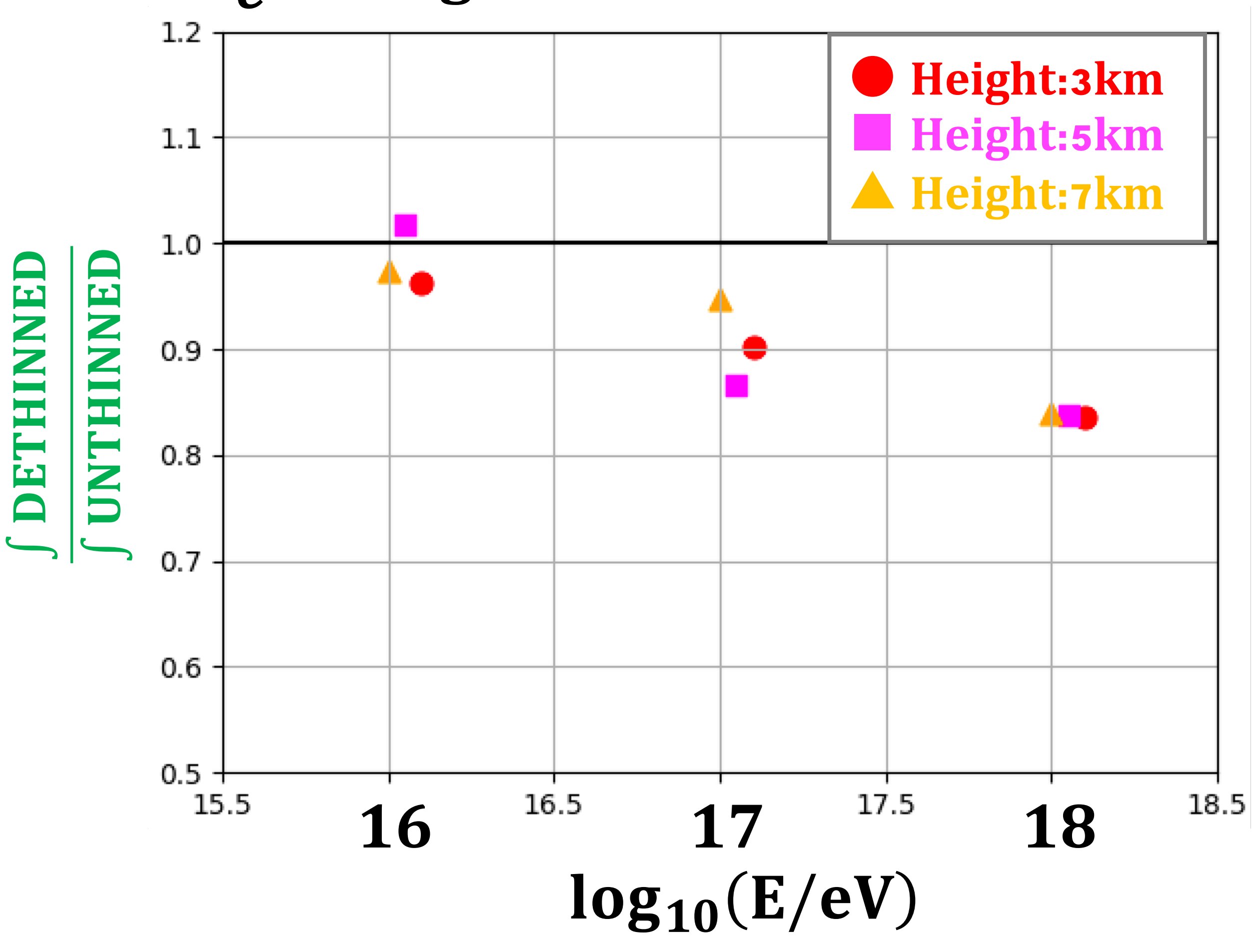
Zenith angle：70deg

ν_e (charged current)



Zenith angle：80deg

ν_e (charged current)

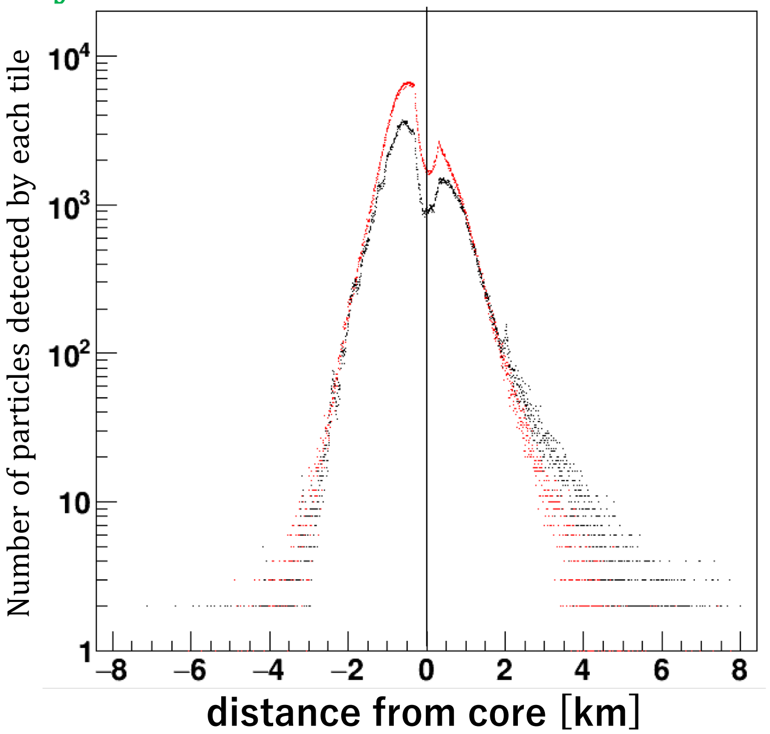


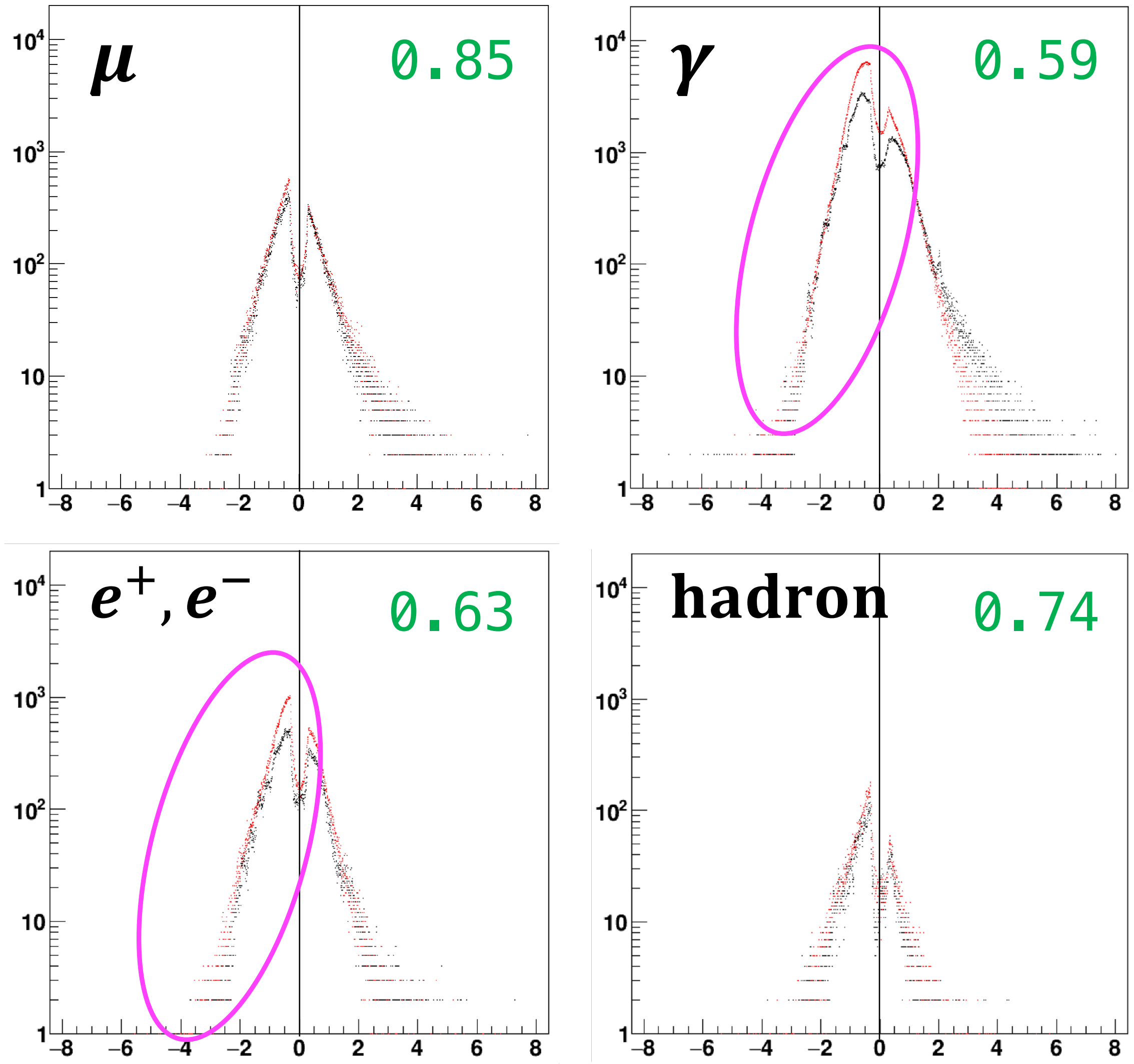
Systematic underestimation with the current De-thinning

Reason and solution

Shower example	
Primary Particle	: ν_e
Primary Energy	: 10^{18} eV
Primary Zenith angle	: 70 deg
1^{st} interaction height	: 3km asl.
1^{st} interaction	: Charged Current

$$\frac{\int \text{DETHINNED}}{\int \text{UNTHINNED}} = 0.62$$





* Poor agreement in the electromagnetic component.
* Similar trends were observed in other showers.

Reason and solution

Tuning for $\mathbf{W_{max_{em}}}$(**the maximum number of particles that can be represented by THINNING**) for the **electromagnetic component** in CORSIKA shower generation.

Original

Upper weight limit on the electromagnetic component can be **up to 100 times higher than the hadronic component**

$$\text{WEIGHT RATE} = \frac{W_{max_{em}}}{W_{max_{had}}} = 100$$

After modification

Match the upper weight limit of the electromagnetic component with that of the hadronic component.

$$\text{WEIGHT RATE} = \frac{W_{max_{em}}}{W_{max_{had}}} = 1$$

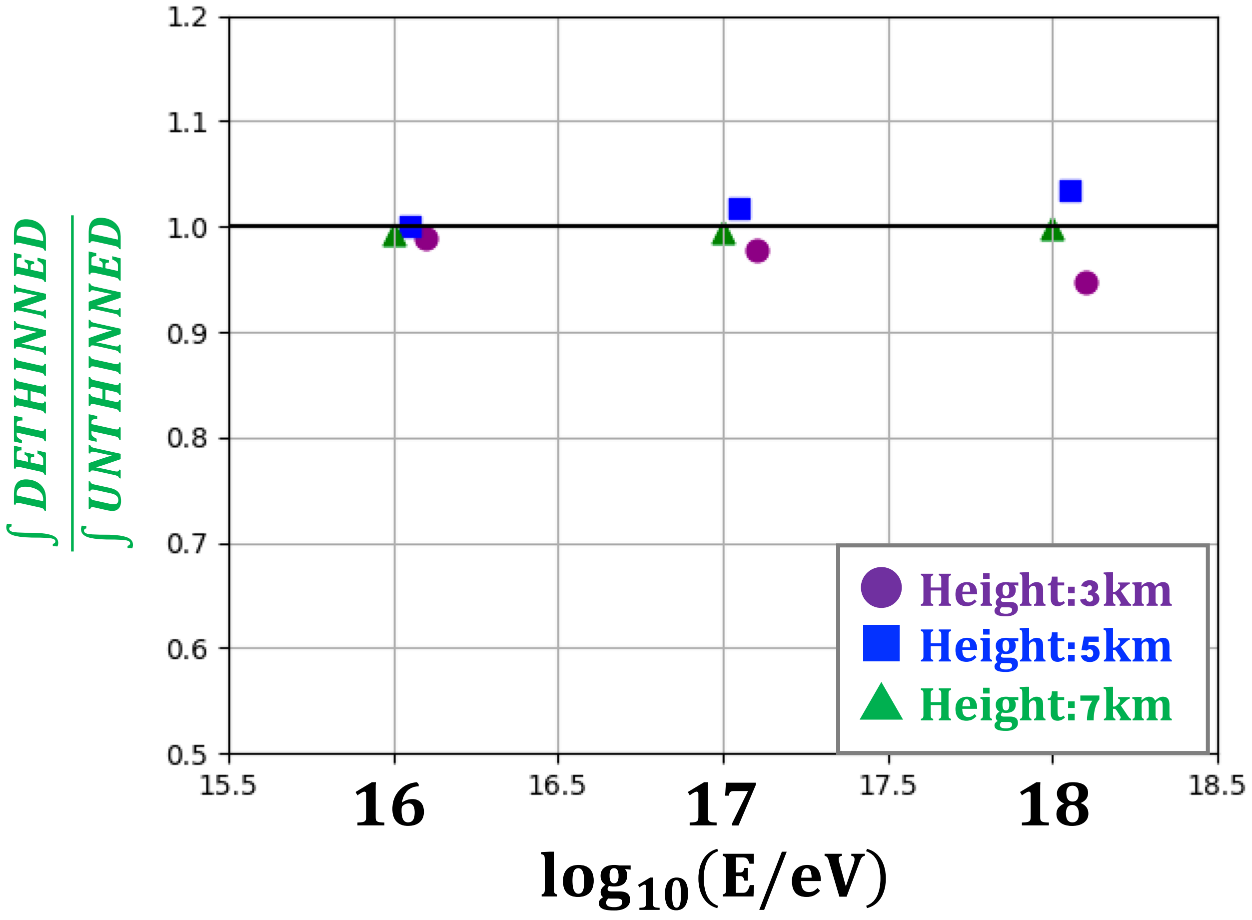
CPU time doubles, but acceptable.

The maximum weight for EM has been decreased.

After weight modification

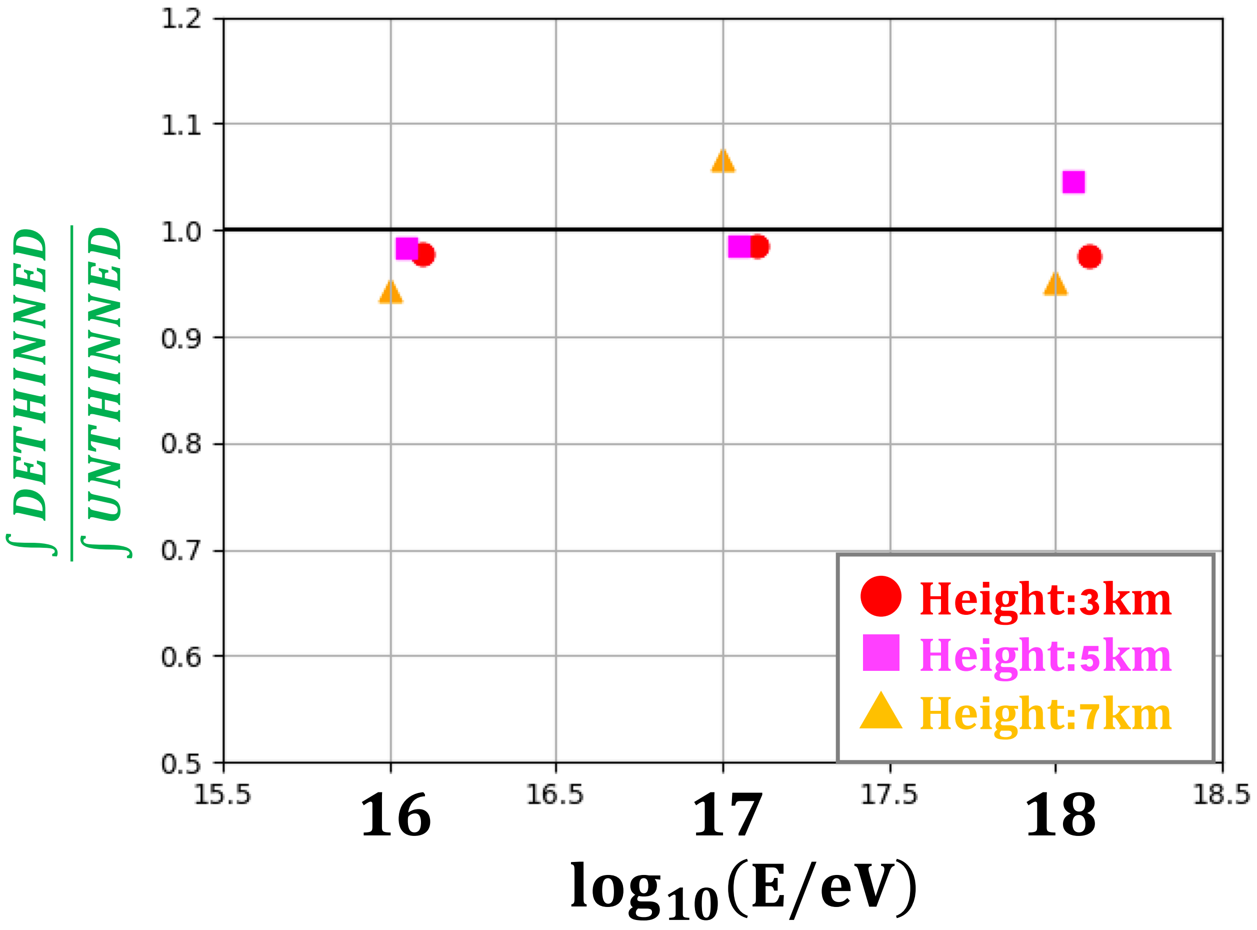
Zenith angle：70deg

ν_e (charged current)



Zenith angle：80deg

ν_e (charged current)

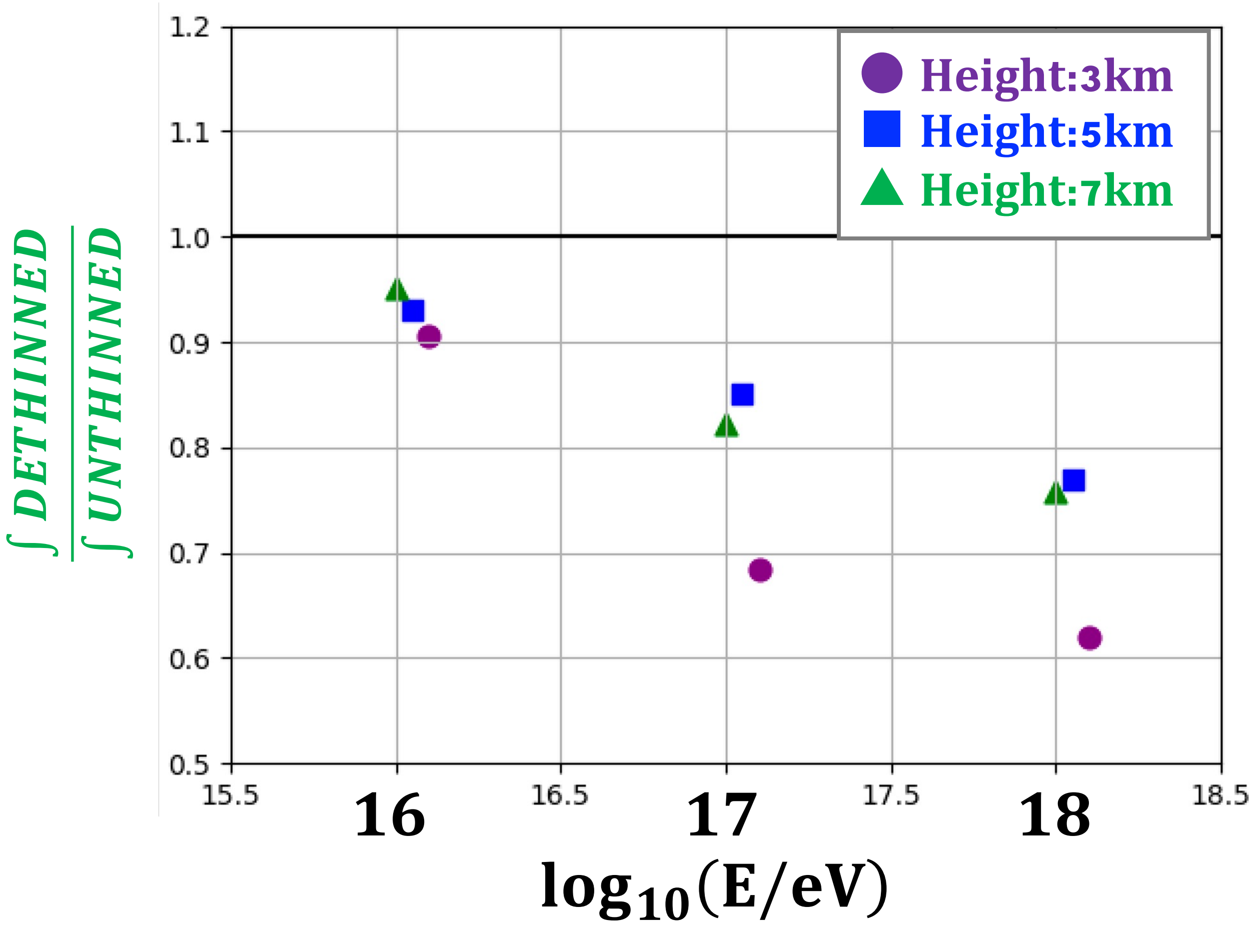


The values for all showers are distributed around 1, indicating good agreement.

Thinning and DE-thinning comparison for inclined neutrino shower

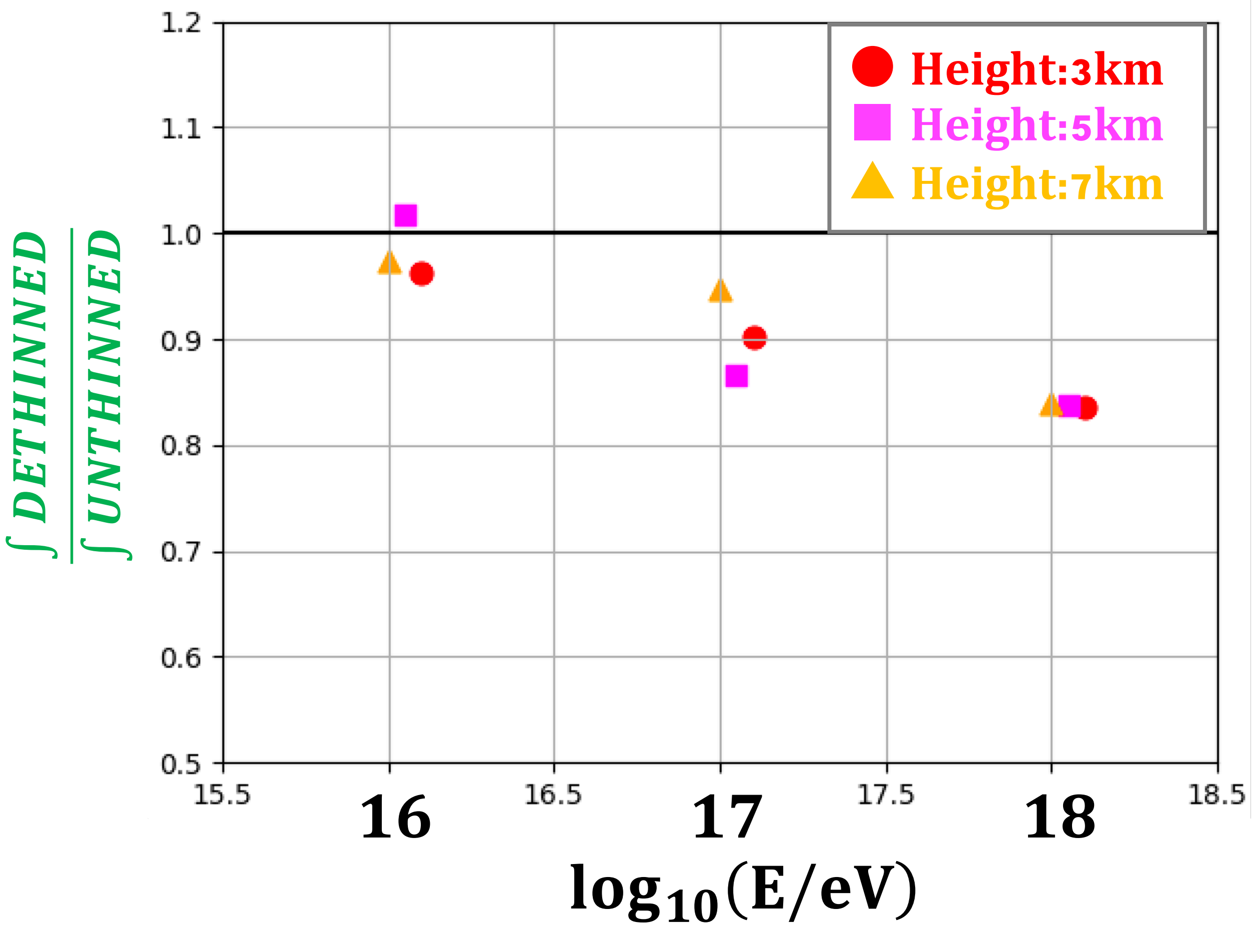
Zenith angle：70deg

ν_e (charged current)



Zenith angle：80deg

ν_e (charged current)



Systematic underestimation with the current DE-thinning

CR shower rejection

We will now discuss the discrimination parameters.

Neutrino

* **Energy : 10^{18}eV**
* **Zenith Angle : 70deg, 80deg**
* **Azimuth Angle : random**
* **Height : 3km, 4km, 5km, 6km, 7km, 8km**

30 showers each bin
$1 \times 2 \times 6 \times 30 = 360$ CORSIKA showers

Proton

* **Energy : $10^{18.5}$eV, 10^{19}eV, $10^{19.5}$eV, 10^{20}eV, $10^{20.5}$eV**
* **Zenith Angle : 70deg, 80deg**
* **Azimuth Angle : random**

30 showers each bin
$5 \times 2 \times 30 = 300$ CORSIKA showers

CORSIKA shower Reuse Conditions

Azimuth Angle : same as CORSIKA shower, fixed
Core position : Random within a 25 km radius circle containing the TA SD array
Number of generation : 8000 times for each shower

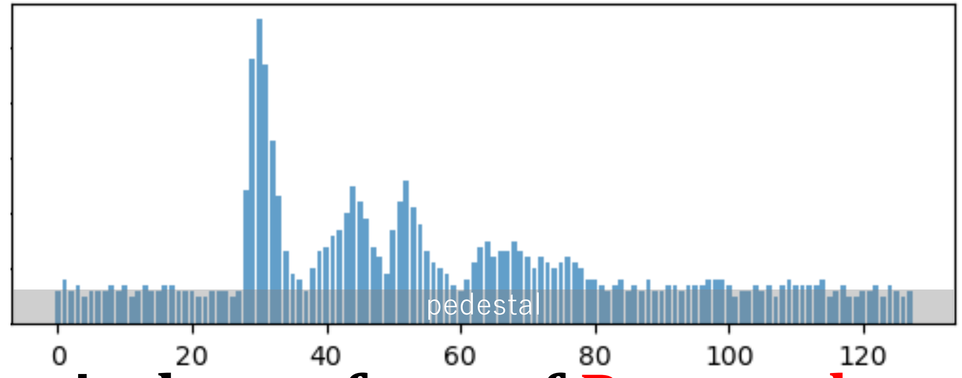
Comparison of shower parameters for neutrino and proton

Area over Peak (AoP)

PhysRevD.91.092008, Pierre Auger Collaboration

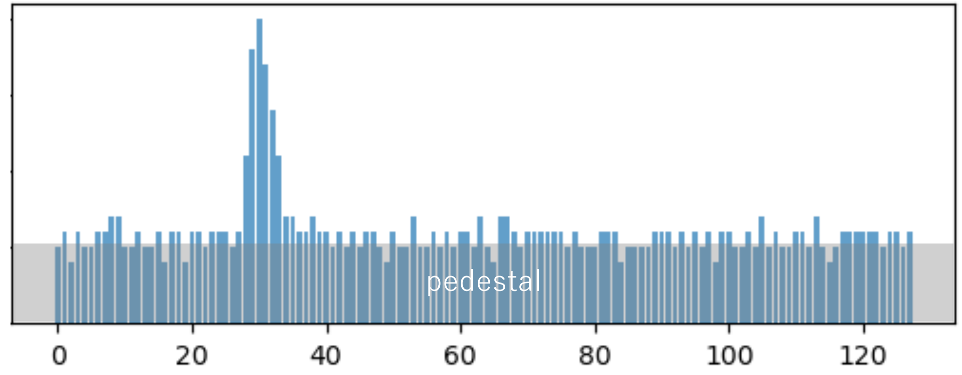
For large zenith angles

Typical waveform of Neutrino shower



When the 1st interaction point is low, the shower has much electromagnetic component and the Area/Peak is relatively large.

Typical waveform of Proton shower



Since the shower runs a long distance to reach the ground, there are many muons and the Area/Peak is relatively small.

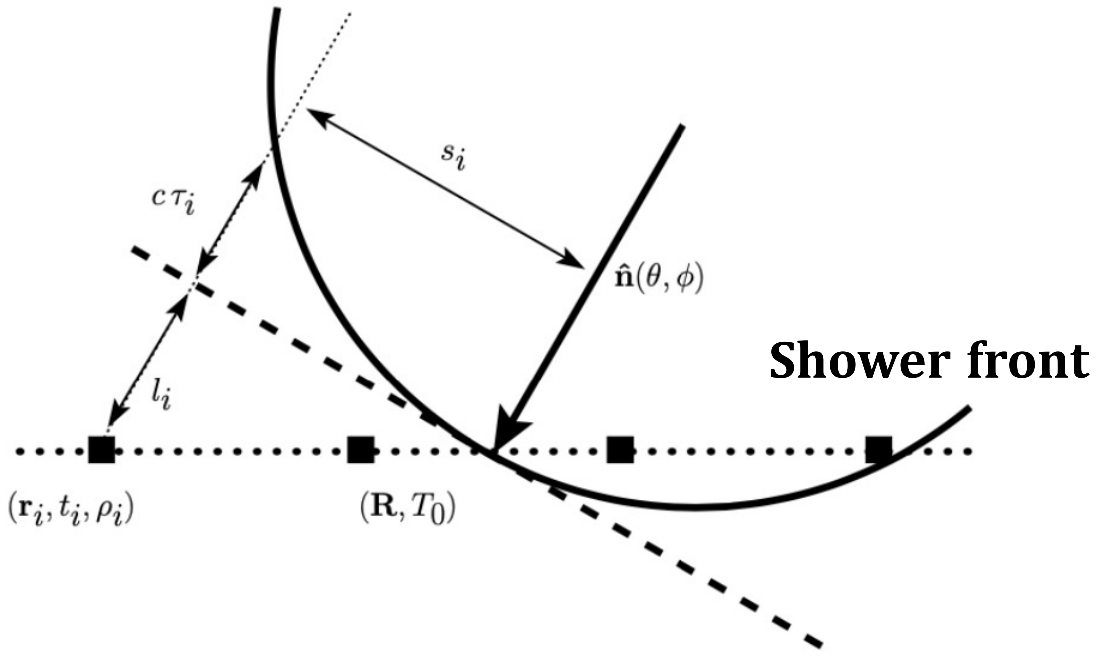
Average of upper and lower for the AoP of the largest signal SD had been used.

Comparison of shower parameters for neutrino and proton

Curvature parameter a

One of the fit parameters for shower fronts

$$\tau = a\left(1 - \frac{l}{12 \times 10^3 m}\right)^{1.05}\left(1.0 + \frac{s}{30m}\right)^{1.35} \times \rho^{-0.5}$$



Proton：

1st interaction point is high, so the shower has a large curvature radius

→ Shower front is close to a flat surface.

→ a is small.

Neutrino：

For the shower that has low 1st interaction point, so the shower has a small curvature radius

→ Shower fronts are curved.

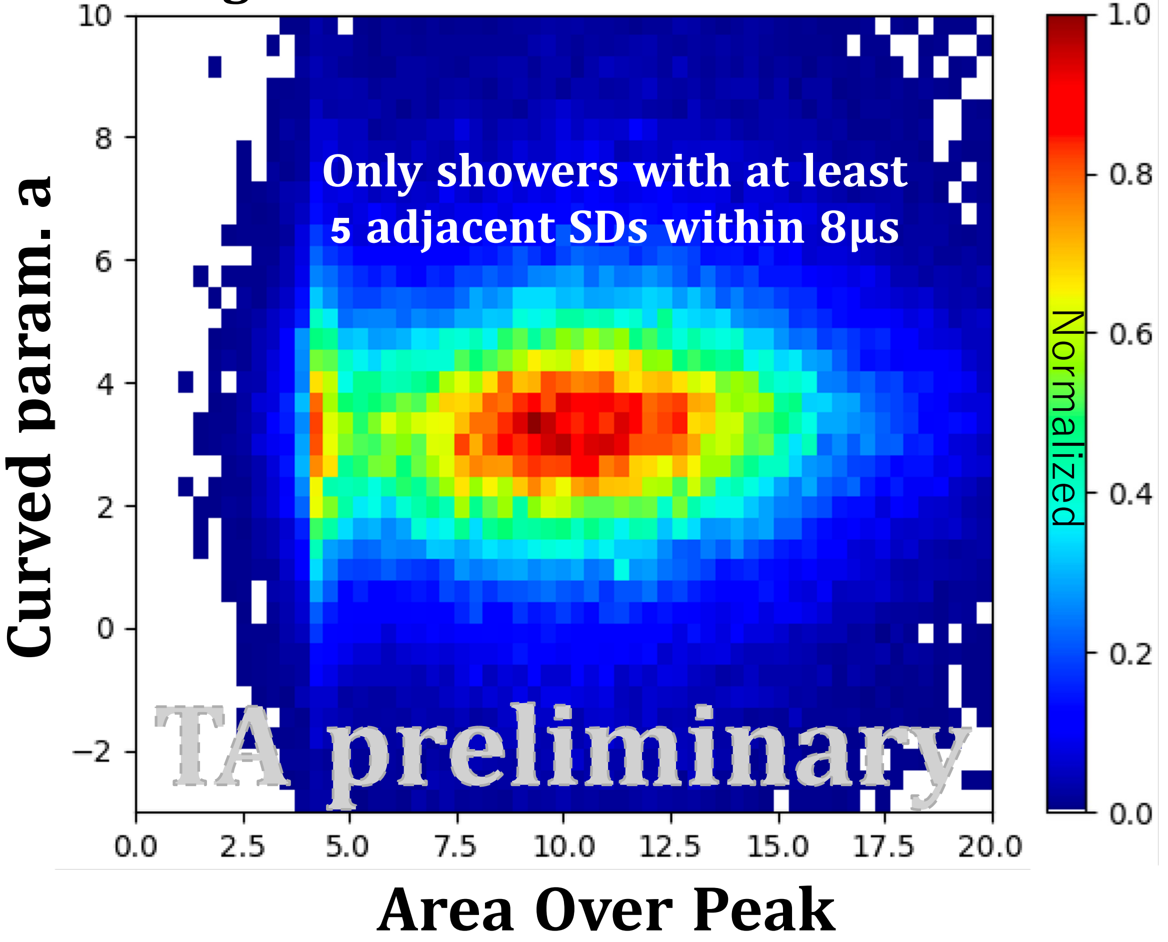
→ a is large.

Because of this property, we can distinguish between the two.

Comparison of shower parameters for neutrino and proton

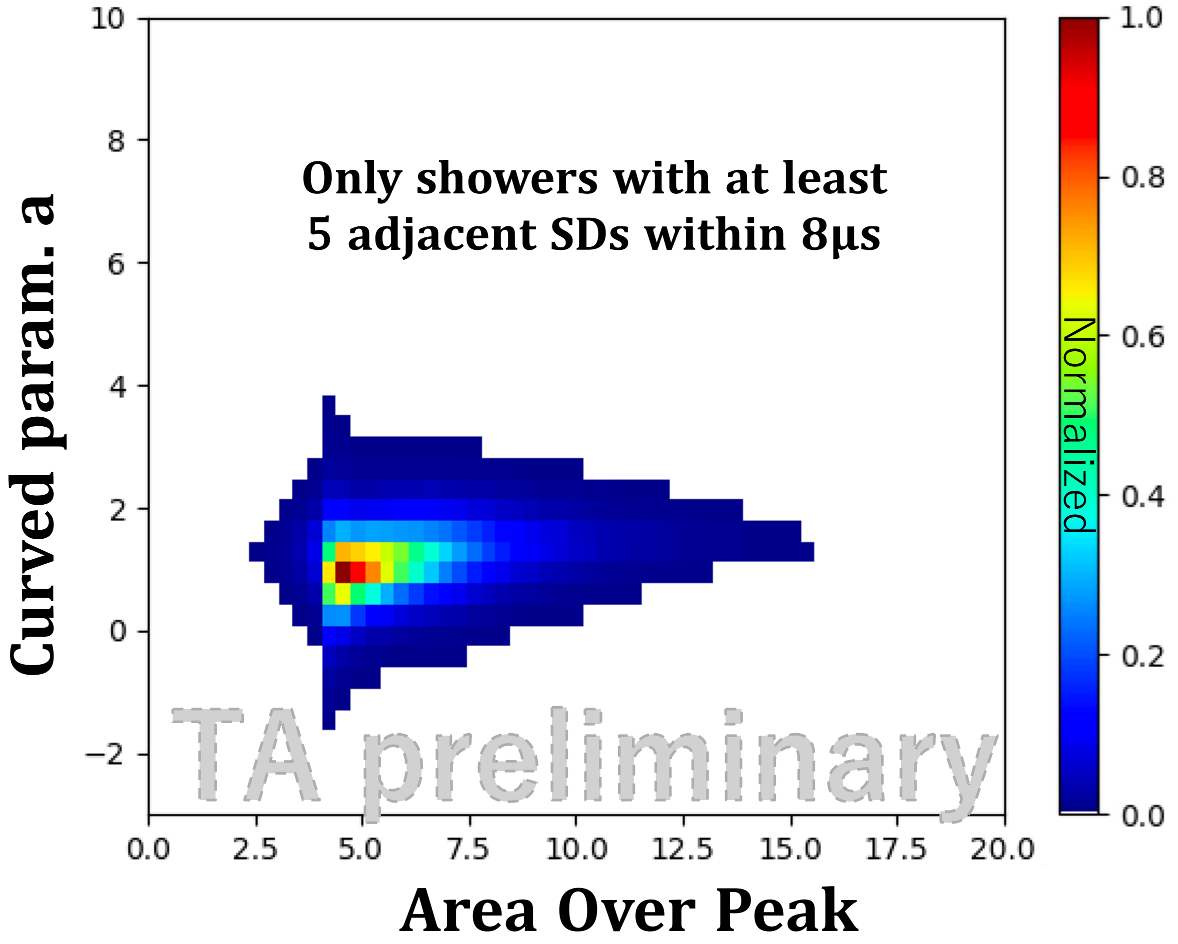
Neutrino shower

Energy : 10^{18}eV
Zenith angle : 70, 80 deg
Height : 3, 4, 5, 6, 7, 8 km asl.



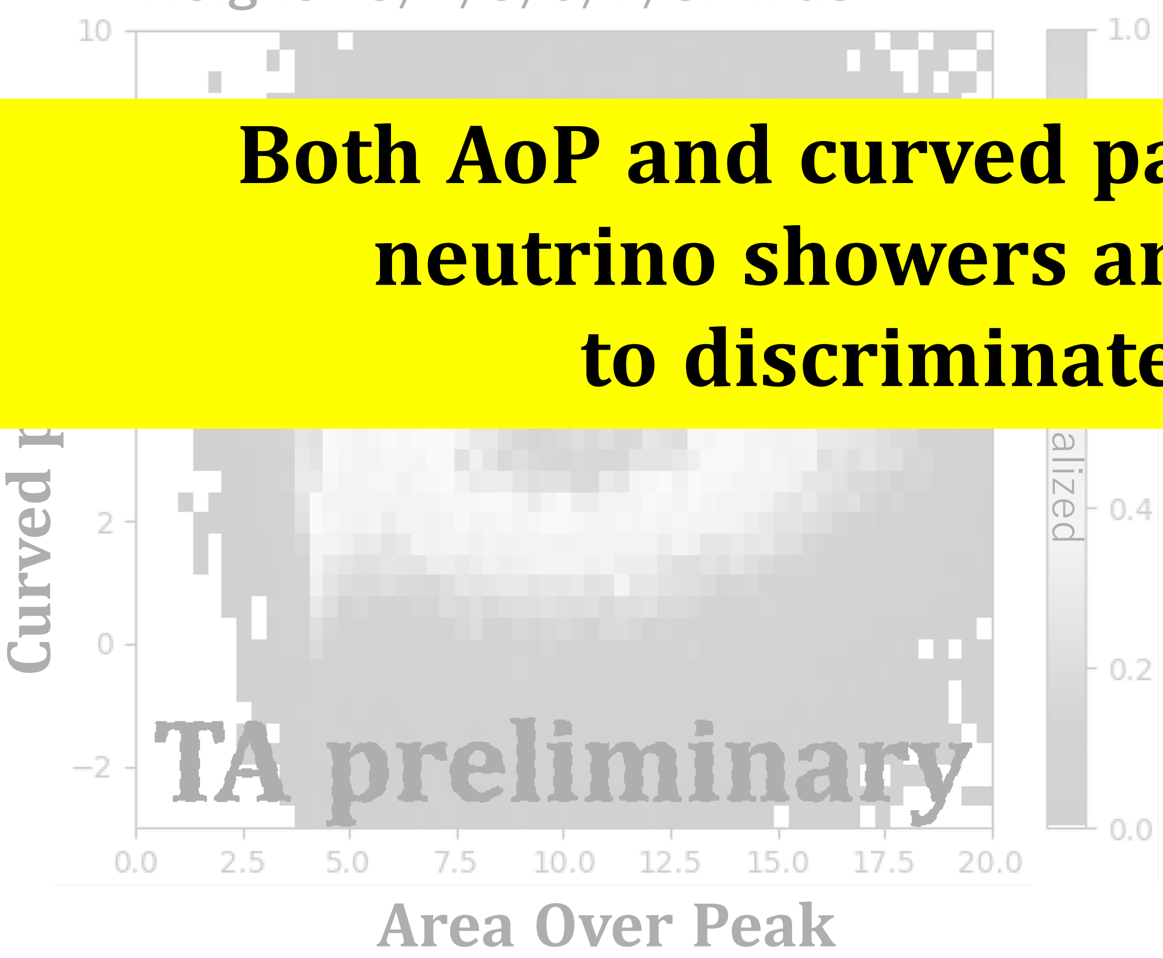
Proton shower

Energy : $10^{18.5}$, 10^{19}, $10^{19.5}$, 10^{20}, $10^{20.5}$eV
Zenith angle : 70, 80 deg

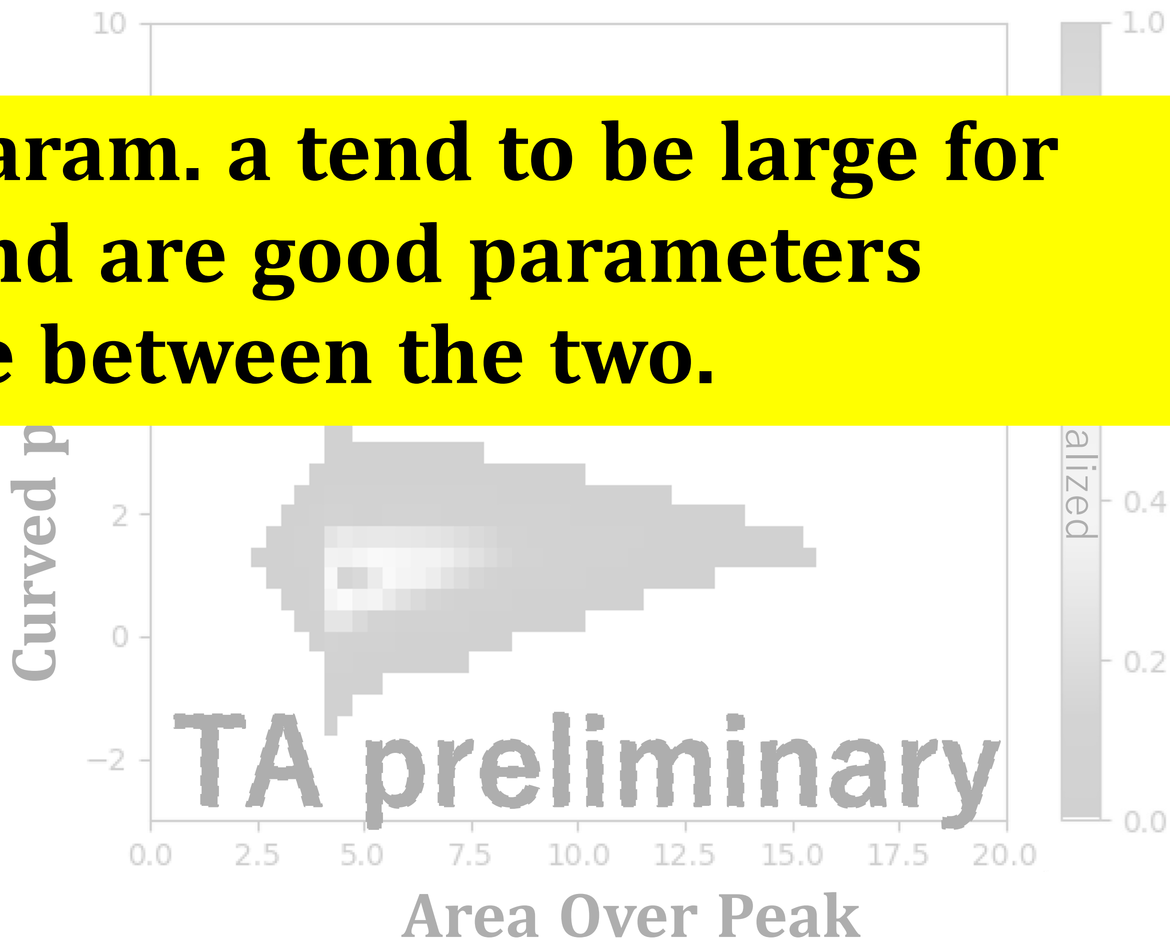


Comparison of shower parameters for neutrino and proton

Neutrino shower
Energy：10^{18}eV
Zenith angle：70, 80deg
Height：3, 4, 5, 6, 7, 8km asl.



Proton shower
Energy：$10^{18.5}, 10^{19}, 10^{19.5}, 10^{20}, 10^{20.5}$eV
Zenith angle：70, 80deg

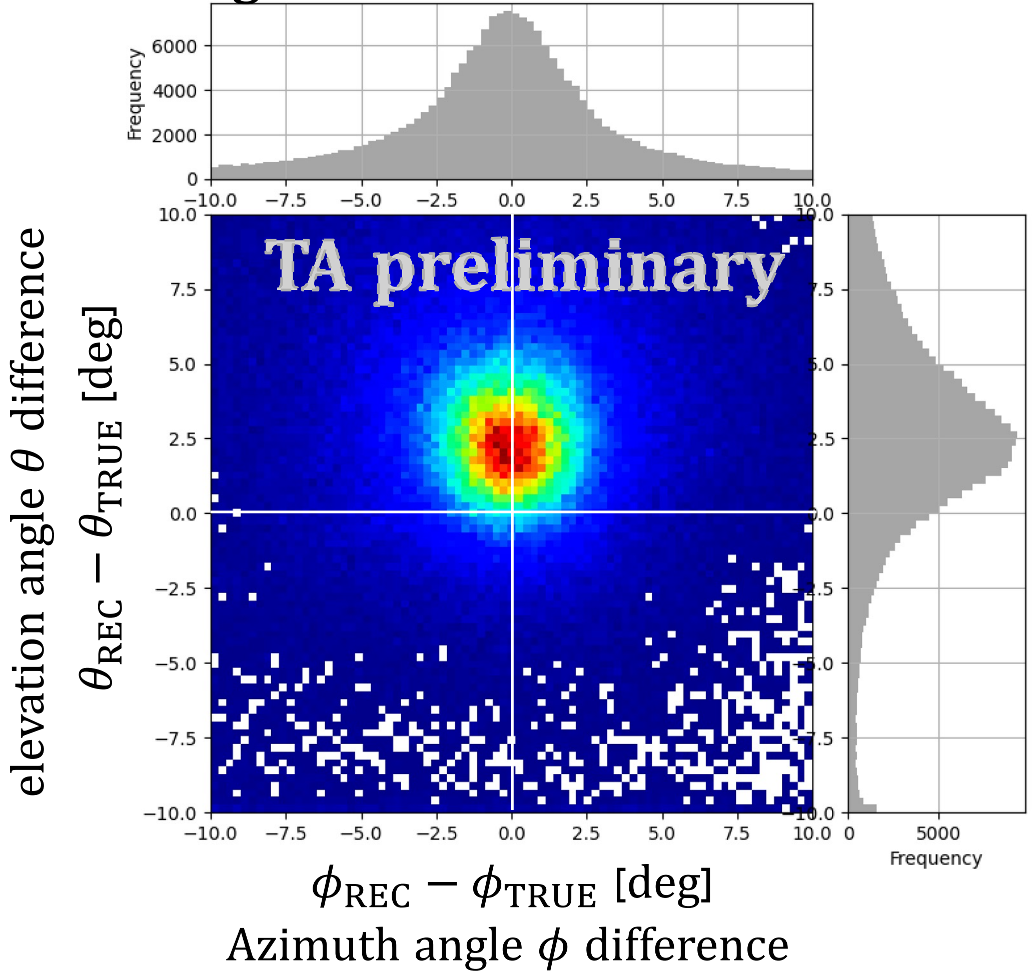


Both AoP and curved param. a tend to be large for neutrino showers and are good parameters to discriminate between the two.

Reconstruction of arrival direction

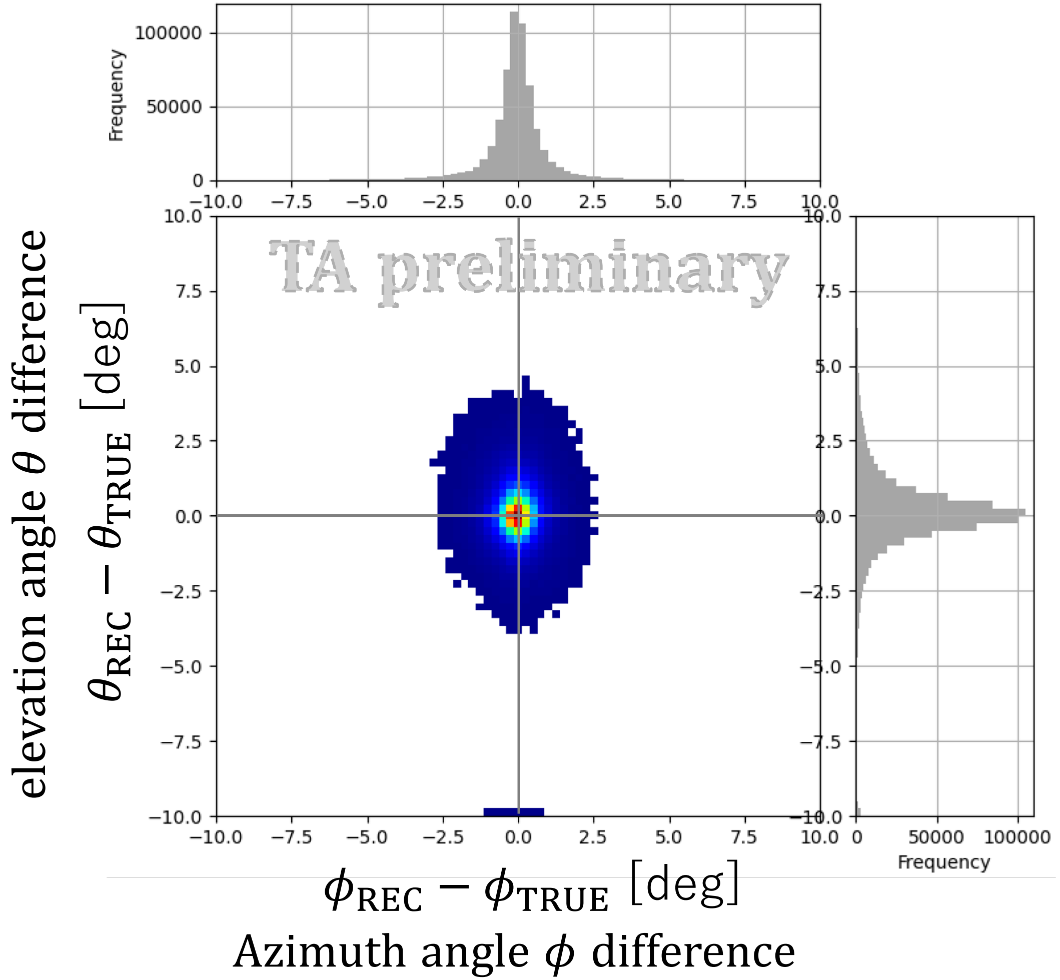
Neutrino shower

Energy : 10^{18}eV
Zenith angle : 70, 80 deg
Height : 3, 4, 5, 6, 7, 8 km asl.



Proton shower

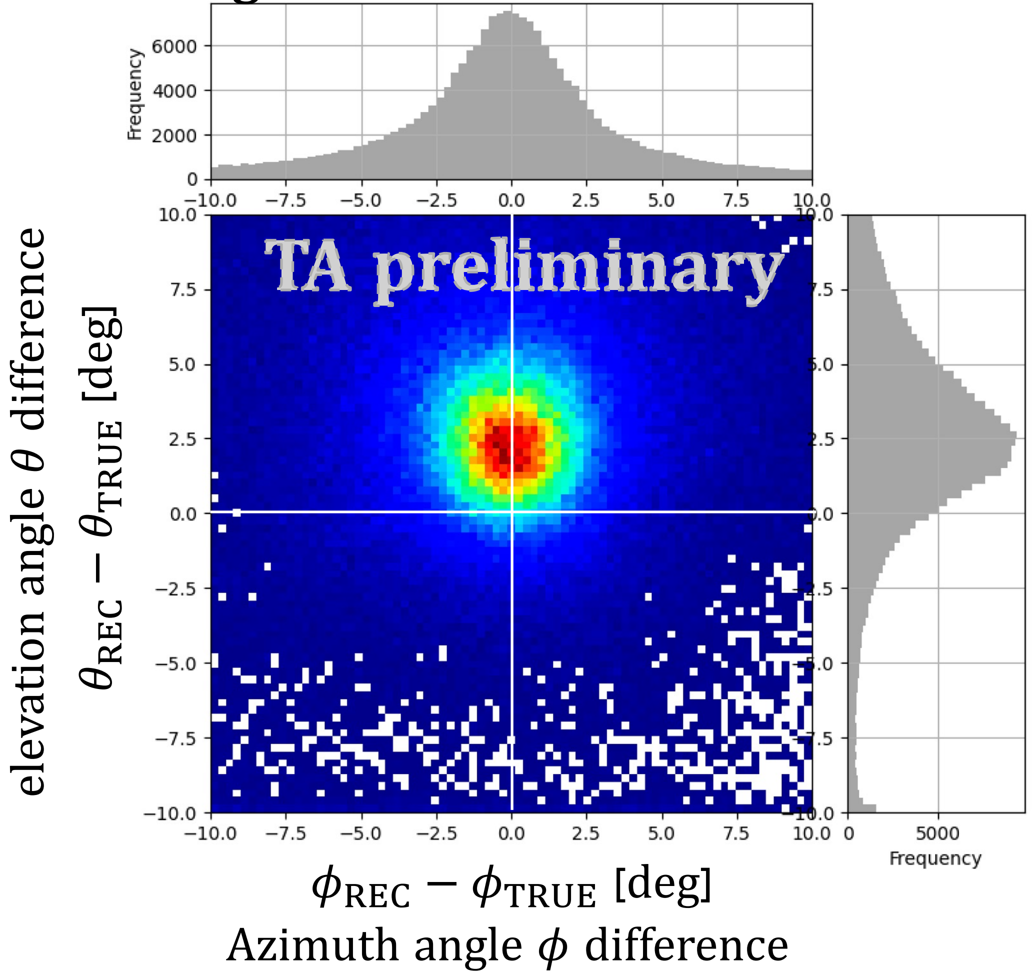
Energy : $10^{18.5}, 10^{19}, 10^{19.5}, 10^{20}, 10^{20.5}$eV
Zenith angle : 70, 80 deg



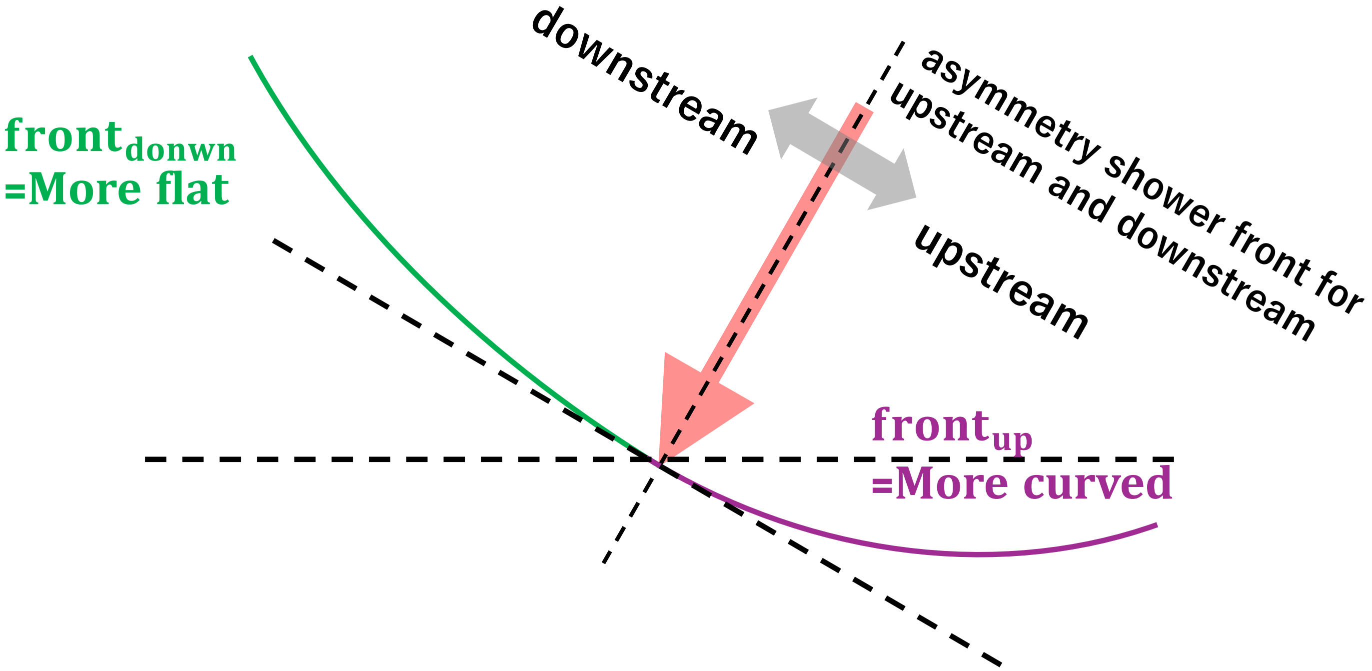
Reconstruction of arrival direction

Neutrino shower

Energy : 10^{18}eV
Zenith angle : 70, 80 deg
Height : 3, 4, 5, 6, 7, 8 km asl.



The asymmetry of the shower causes an overall estimate of about 2.5 degrees larger for the elevation angle.



Whether to revisit the reconstruction method or revise the reconstruction value by 2.5 deg is under consideration.

Summary and prospects

Summary

* The MC generation method for large zenith angle neutrino showers was verified.
* The DETHINNING method was improved by reducing the $W_{max_{em}}$.
* Observational parameters for neutrinos and protons in the large zenith angle region are compared and AoP and curved param. seemed to be available for discrimination.

NEXT

* More detailed study of the discrimination parameters between neutrinos and protons in the large zenith angle region
* Study of reconstruction methods
* Neutrino search using real TA SD data

Appendix

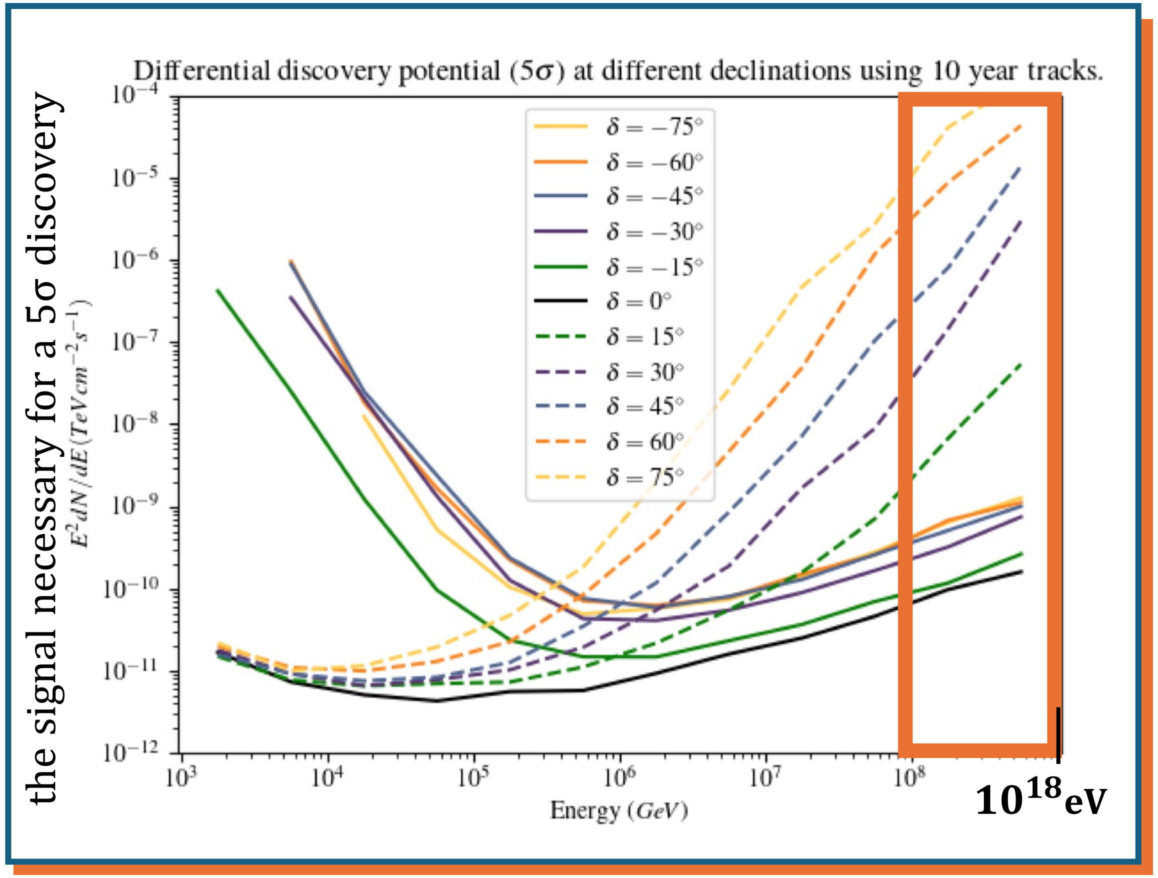
Why TA?

Comparison with IceCube sensitivity by latitude

The solid lines：Southern sky / The dashed lines：Northern sky

The Northern sky is less sensitive to higher energies than the Southern sky because neutrinos interact while passing through the earth.

TA is located in the northern hemisphere and is a detector **for looking at UHECR**.
It is very useful to search for neutrinos by TA.



[1] K. Ghiassi and J. Salwén, 'Neutrino Hotspots in the Universe: a Sensitivity Study Using the IceCube Neutrino Observatory', Dissertation, 2023.

Neutrino flavor and 1st interaction

Charged Current interaction

Charged leptons take most of the energy.

Neutral Current interaction

Almost all energy is retained by neutrinos.

$\nu_e, \overline{\nu_e}$

They basically emits electron.
This produces an electromagnetic shower.
It may collide with atoms in the atmosphere and emit pion.
There may also be pion produced when the gamma produced by ν_e reacts with nuclei.
This may result in the presence of hadrons in the shower.

$\nu_\mu, \overline{\nu_\mu}$

For muons with high energy (>100 GeV), **bremsstrahlung becomes dominant** and an electromagnetic component is produced, creating an **electromagnetic shower**.

The electromagnetic component is emitted by the electric field of the atoms, and **most of the energy is taken by the muons**; **it is not expected to be as large a shower as ν_e.**

$\nu_\tau, \overline{\nu_\tau}$

The tau first becomes a hadronic shower because about **60% of the energy is transferred to hadrons.**
The time spent in tau is long (several tens of kilometers), but **eventually it becomes an electromagnetic shower, so it may be observable.**

Comparison between AoP and Curved param. a

AoP ： It can be calculated from **each wave form**.
Curved param. A ： It can be calculated from **each shower**.

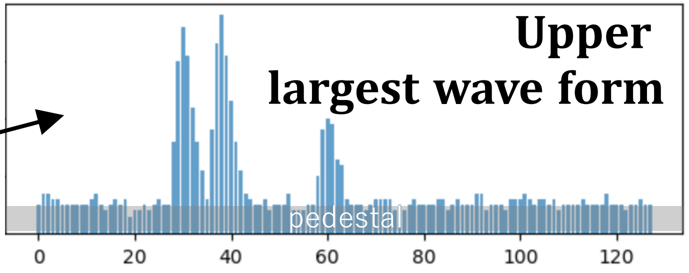
To get both values from one shower. . .

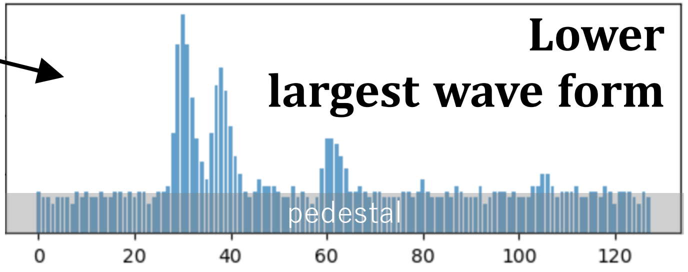
TA SD

Upper scintillator

Lower scintillator

Largest wave form selection
(compared by pulse area in VEM/
pedestal subtracted)



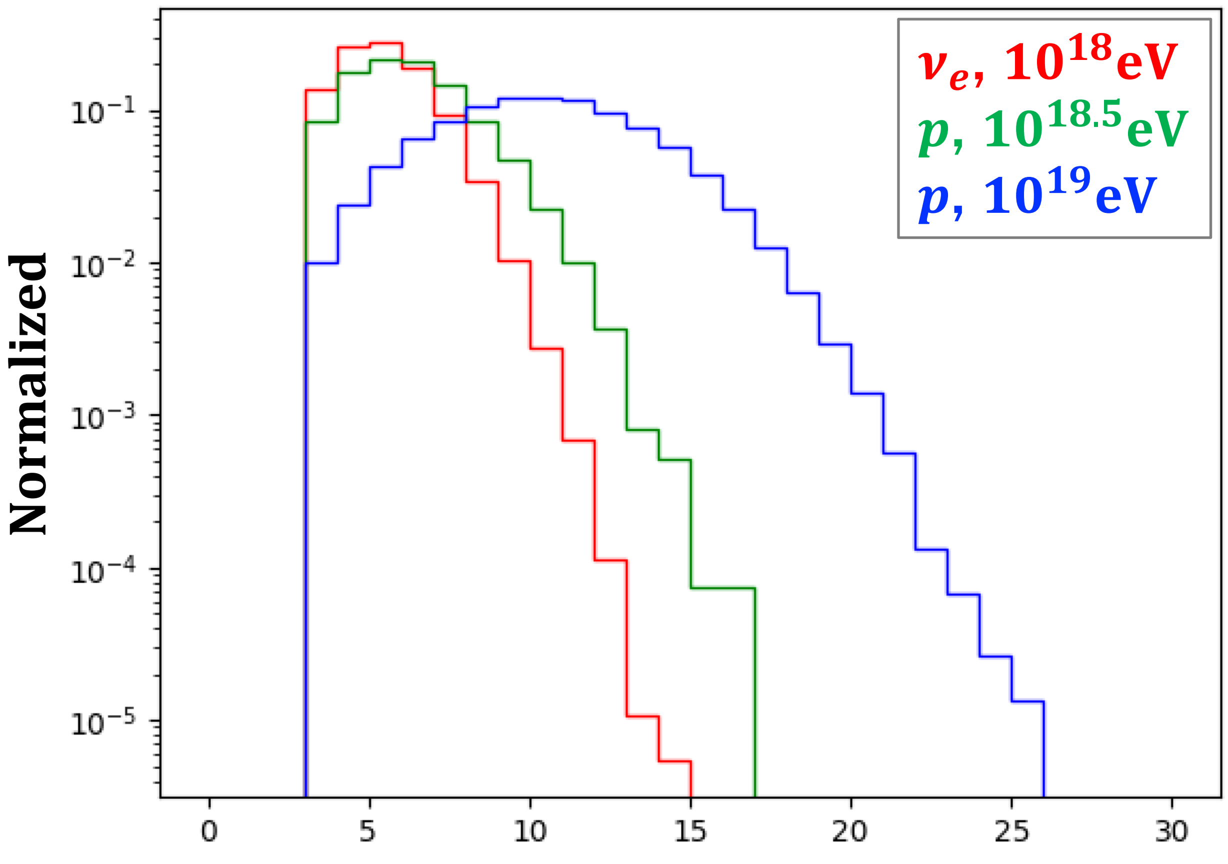


AoP is calculated for upper and lower largest wave form.

$$\mathbf{AoP_{shower}} = \frac{\mathbf{AoP_{upper}} + \mathbf{AoP_{lower}}}{\mathbf{2}}$$

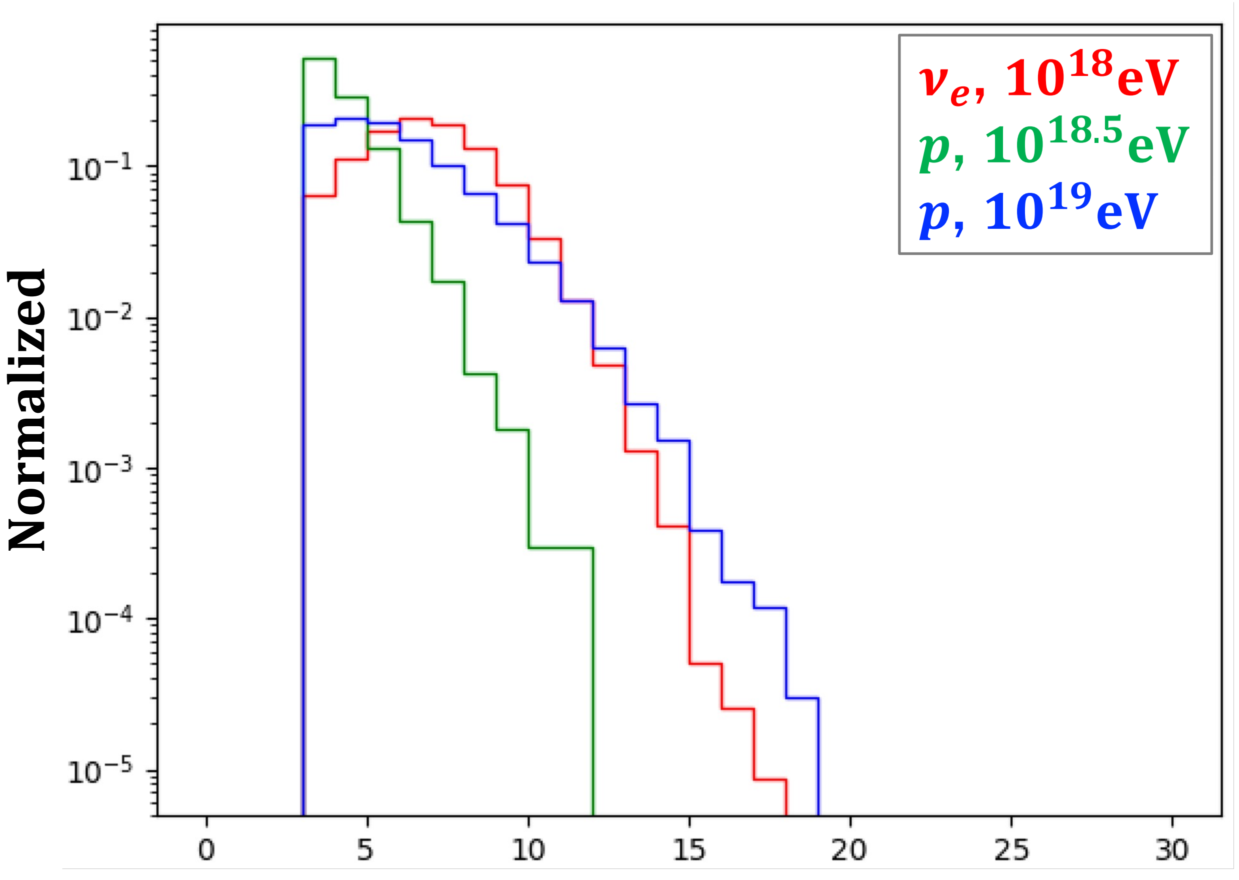
Number of hit SDs for proton and neutrino showers

Zenith Angle 70deg



Number of hist SDs (after space time cluster cut)

Zenith Angle 80deg

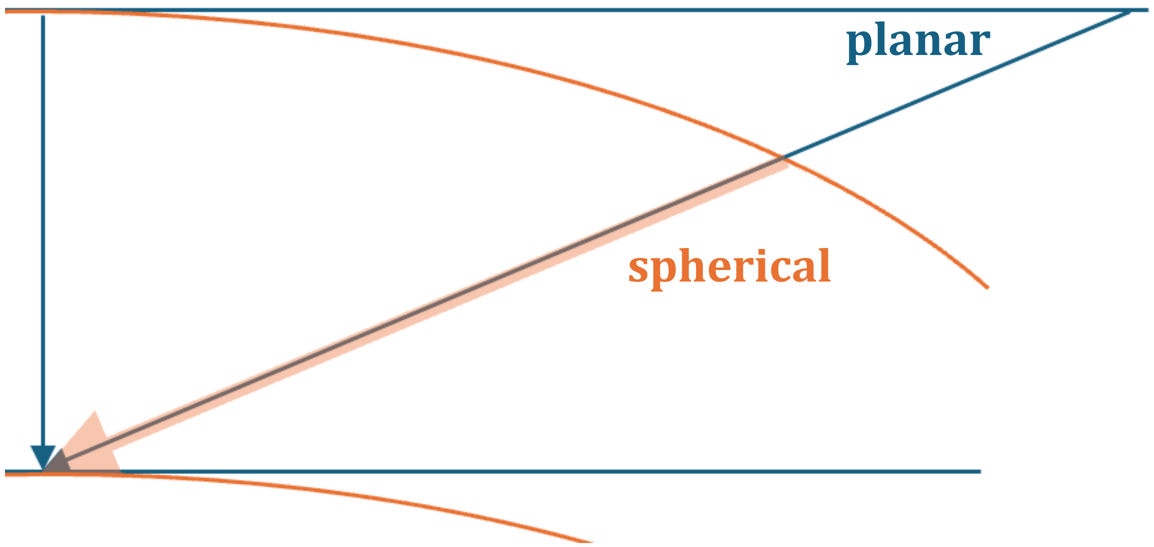


Number of hist SDs (after space time cluster cut)

Considering about spherical geometry

Comparison of slant depths for planar and spherical atmosphere

The larger the zenith angle, the greater the curvature effect.



The difference is more than 1000g/cm² at 70deg.

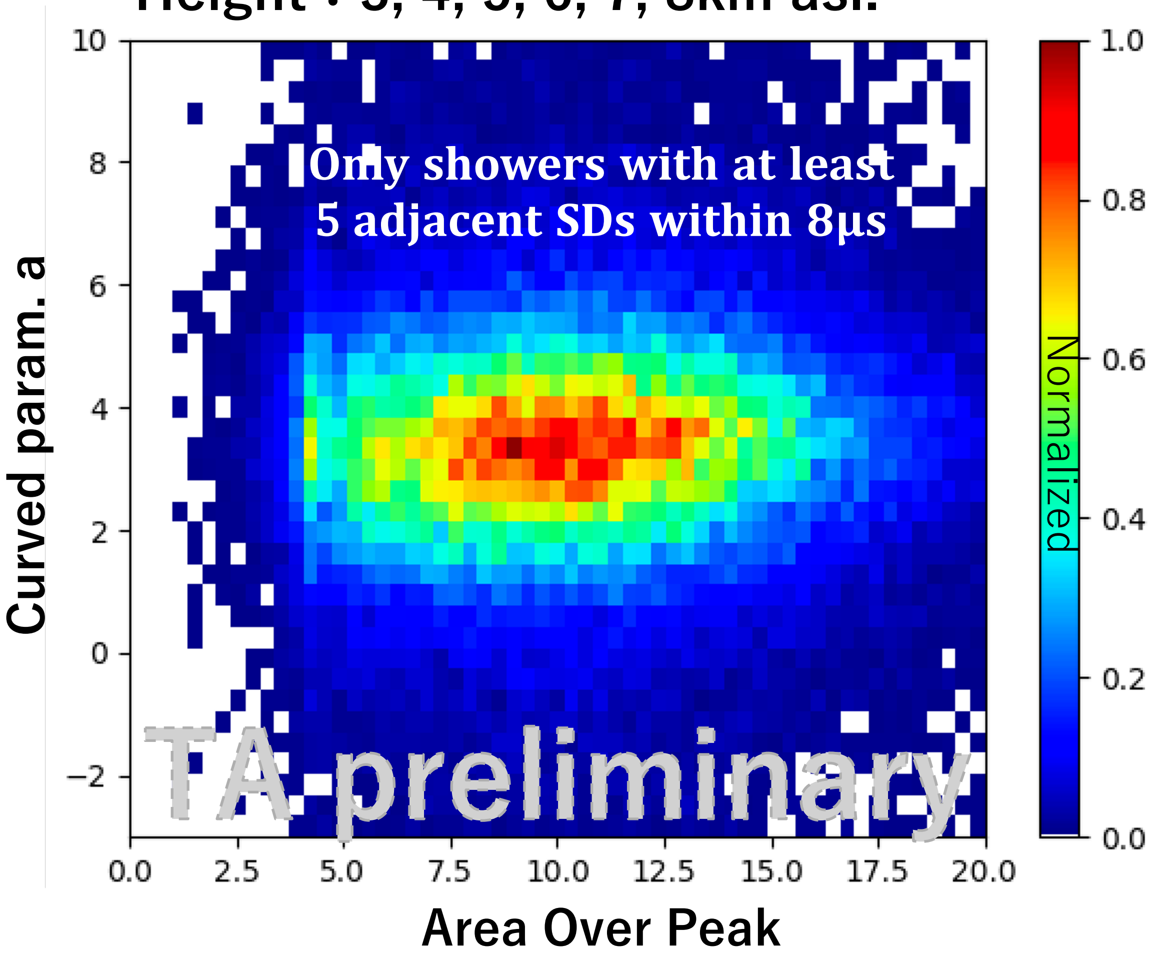
zenith angle	planar distance	planar slant depth	spherical distance	spherical slant depth
degree	km	g/cm^2	km	g/cm^2
0	112.8	1036.1	112.8	1036.1
30	130.3	1196.4	129.9	1196.0
45	159.6	1465.3	158.2	1463.7
60	225.7	2072.2	220.1	2065.3
70	329.9	3029.4	310.7	3003.9
80	649.8	5966.7	529.0	5765.9
85	1294.6	11887.9	770.9	10572.1
89	6465.0	59367.2	1098.3	25920.4
90	∞	∞	1204.4	36481.8

Slant depths in planar and spherical geometry, calculated the Linsley parametrization of the U.S. standard atmosphere.

[2] D. Heck, 'The CURVED version of the air shower simulation program CORSIKA', FZKA-6954, 2004.

Discrimination parameter of neutrino shower

Neutrino shower
Energy : 10^{18}eV
Zenith angle : 70deg
Height : 3, 4, 5, 6, 7, 8km asl.



Neutrino shower
Energy : 10^{18}eV
Zenith angle : 80deg
Height : 3, 4, 5, 6, 7, 8km asl.