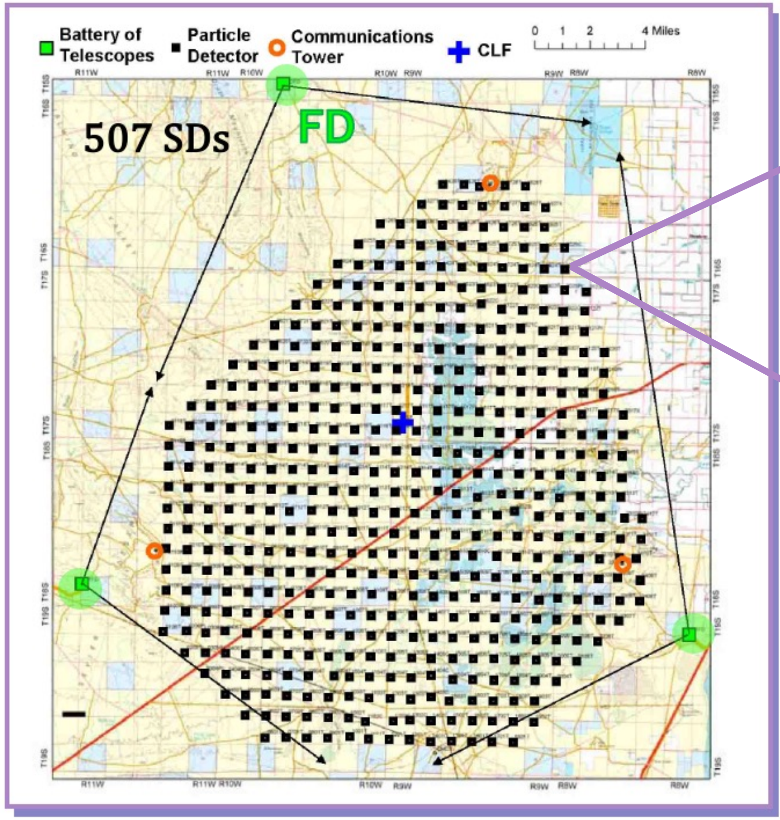
Toward EeV Neutrino Search with the TA Surface Detector Array

ICRR Kaoru Takahashi

Telescope Array

Location: Utah, USA (Longitude 113° W, latitude 39°N)
Area Covered: 700 km^2
Operation Period: Since May 2008 – Present
Type: Surface detector array (Scintillator-based)

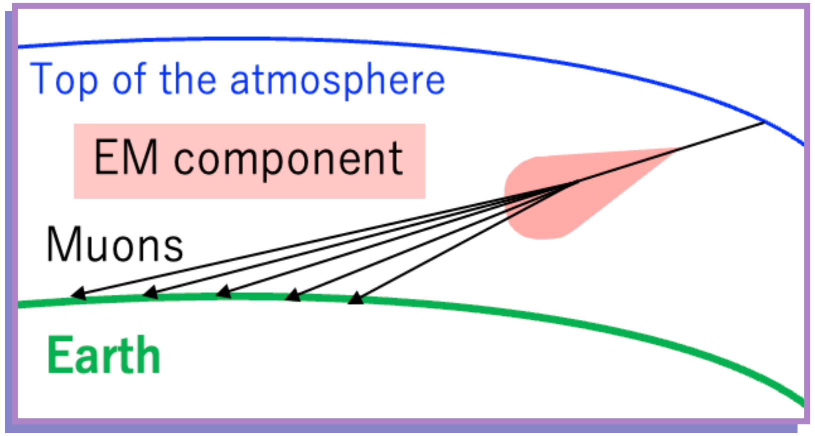
The largest surface detector array in the Northern Hemisphere!



Surface detector (SD)

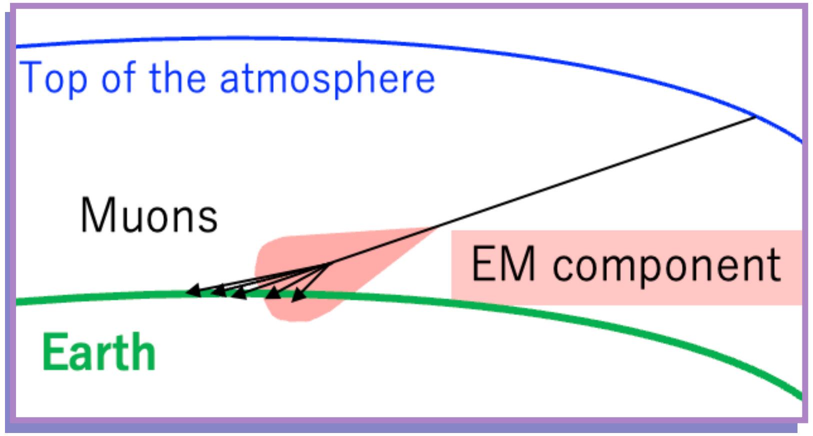
507 scintillation detector arrays ($3m^2$) placed at 1.2km intervals.

Neutrino × Inclined



Proton inclined showers

・First interaction occurs in the **upper atmosphere**.
・ Because of the **long path length** that the shower particles travel, many particles in the shower **do not survive** to reach the ground.



Neutrino inclined showers

・The first interaction also occurs in the **lower atmosphere**.
・Because of the **short path length** that the shower particles travel, shower may leave a **large footprint** even in the large zenith angle region.

Due to their small cross section, neutrinos can start interaction near the ground at large zenith angles, enabling better discrimination from proton-induced backgrounds.

Scope of This Talk

・Full study includes：

✔ **Development of inclined neutrino analysis method**

We developed a **new method** by **considering the asymmetry of shower arrival times** in the upstream and downstream of neutrino low-altitude development showers.

⇨ **The new method improves the pointing accuracy of neutrino-induced events.**

✔ **Discrimination**

✔ **Sensitivity calculation**

We calculated the **sensitivity to neutrinos** (ν_e, CC) in the previous observations (16 years) by TA SD.

・This talk covers：

👉 **Discrimination and Sensitivity calculation only**

📝 **For details on the reconstruction method, please ask me anytime**

MC dataset

CORSIKA ver.：corsika-76900
Interaction model：FLUKA, QGSJET II -04

Proton：

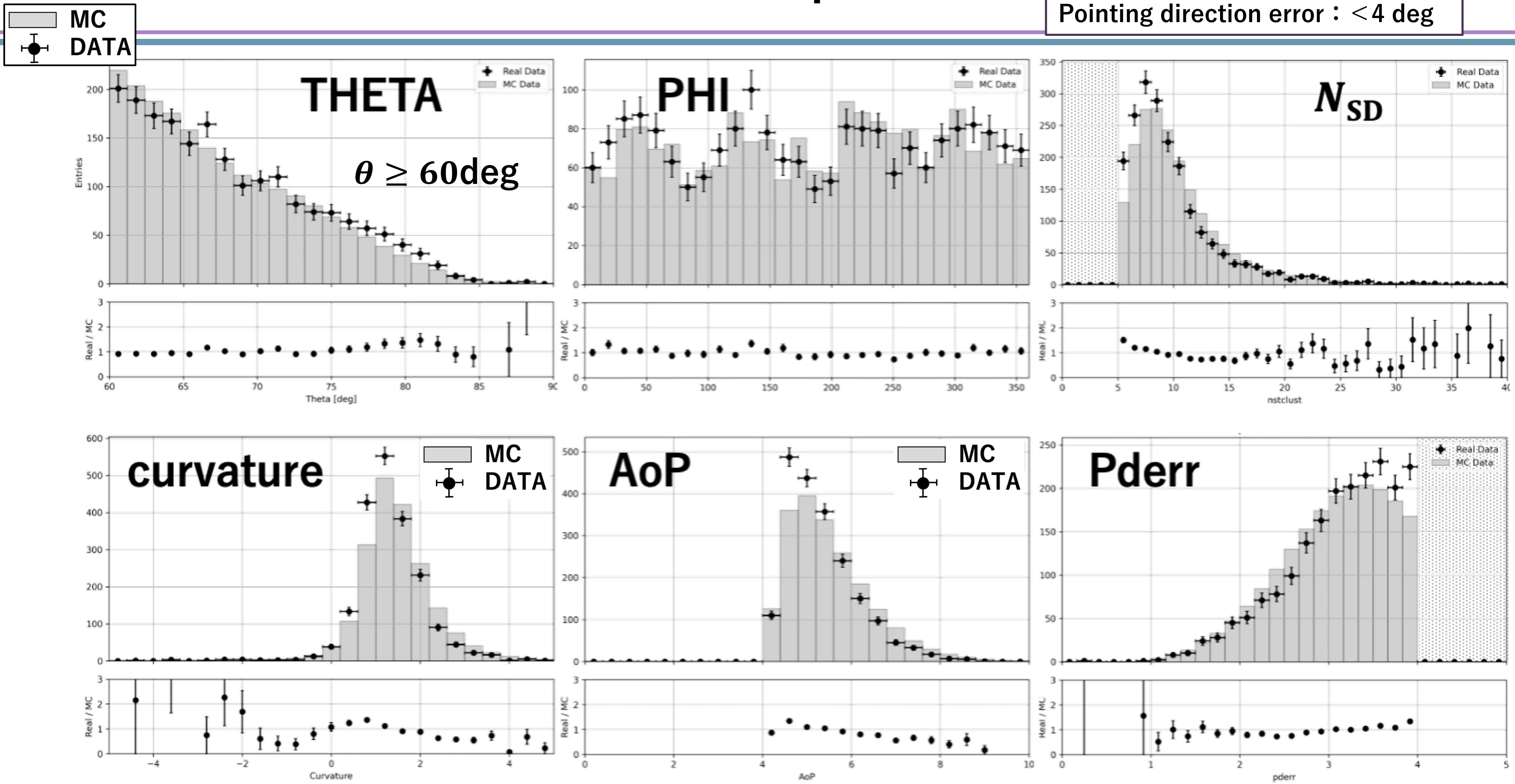
Energy	10^{18}eV ~$10^{20.5}$eV
Zenith Angle	50 deg ~ 90 deg
Azimuth Angle	0~360 deg
Spectrum index	-1

Neutrino：

Energy	$10^{16.5}$eV ~10^{19}eV
Zenith Angle	50 deg ~ 90 deg
Azimuth Angle	0~360 deg
Flavor	ν_e
1st interaction	Charged Current
Spectrum index	-1

Proton DATA(2009~2010)/MC comparison

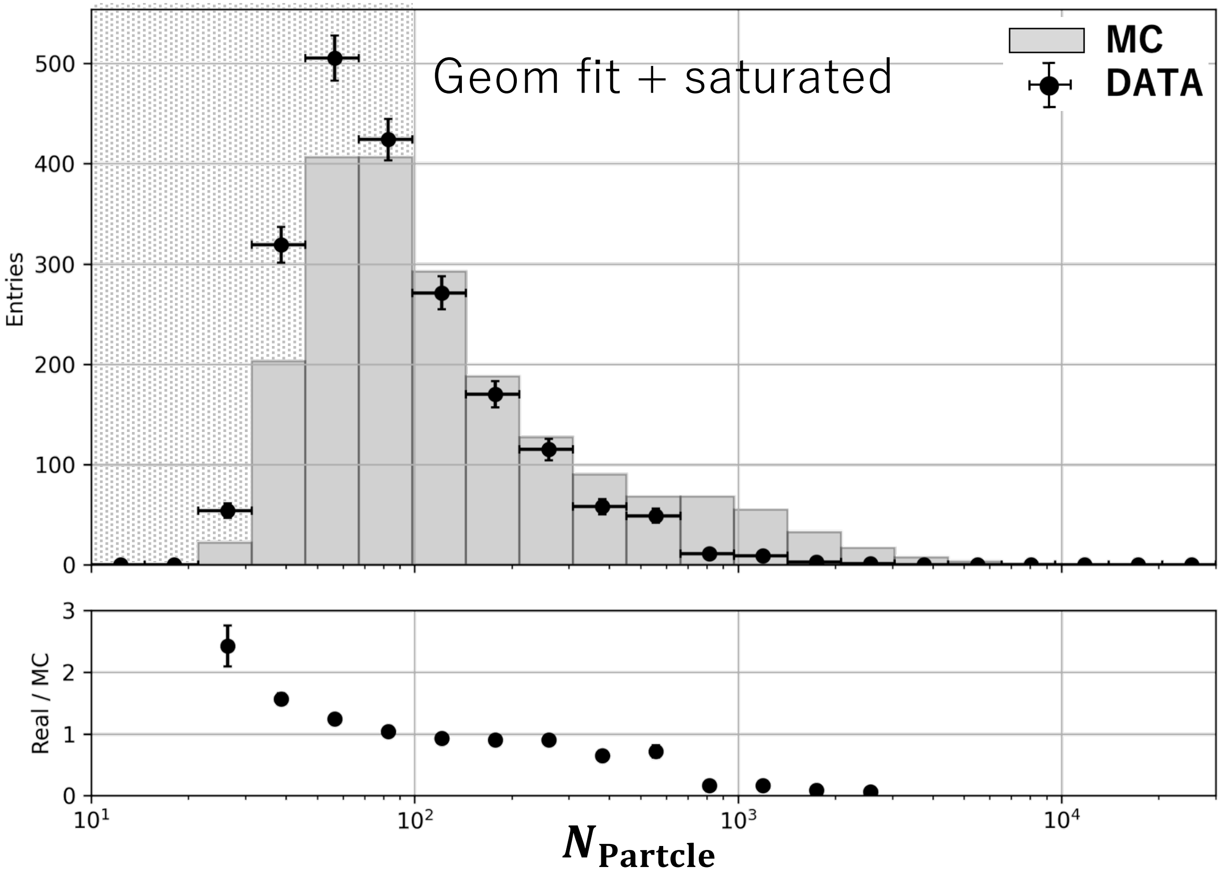
DATA selection criteria：
N_{sd} ：≥ 5
Pointing direction error：＜4 deg



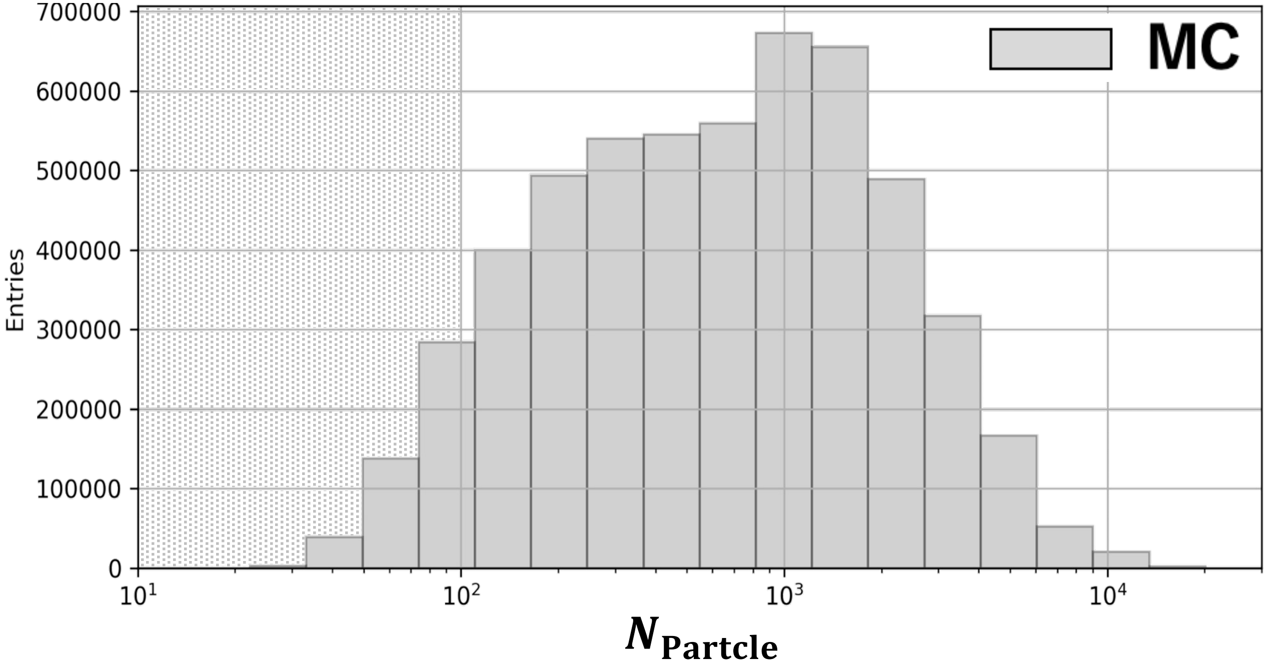
Proton DATA(2009~2010)/MC comparison

DATA selection criteria：
N_{sd} ：≥ 5
Pointing direction error：＜4 deg
$N_{Partcle}$ ： ≥ 100

Proton

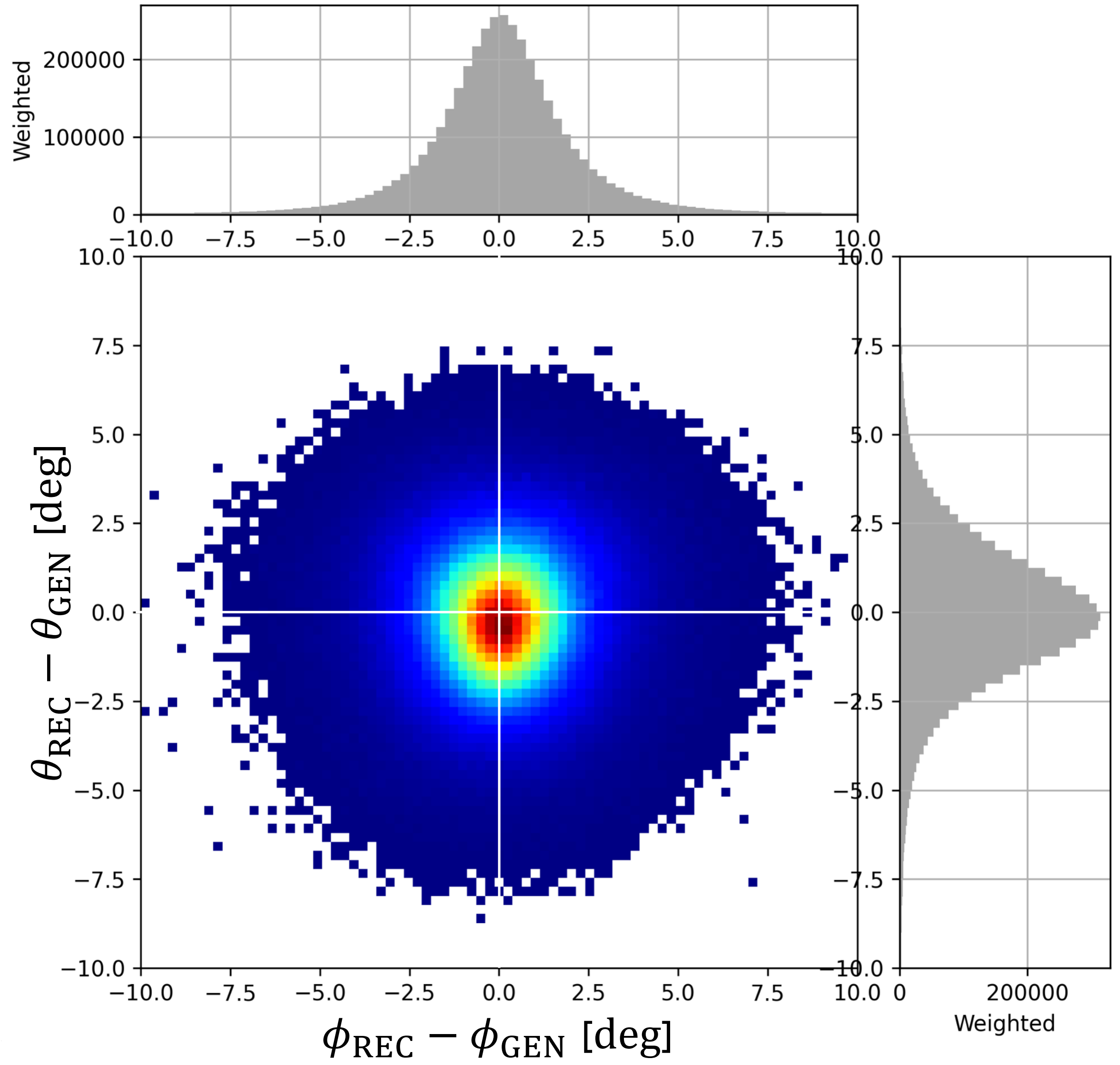


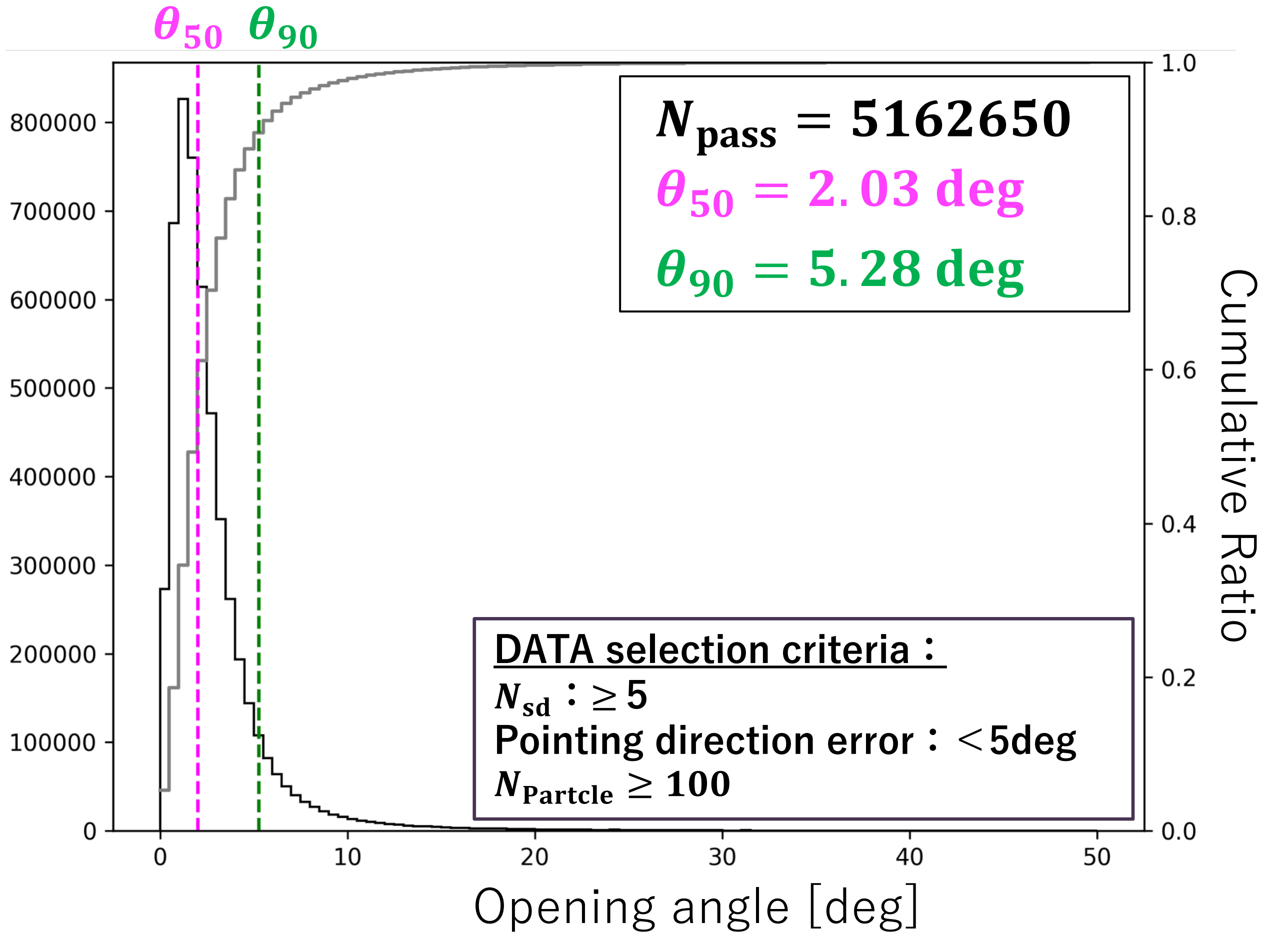
Neutrino



To exclude events with small proton footprints while preserving as many neutrinos as possible, a $N_{Partcle}$ cut is introduced. We used data only $N_{Partcle} \geq 100$.

Angular resolution for inclined neutrino showers



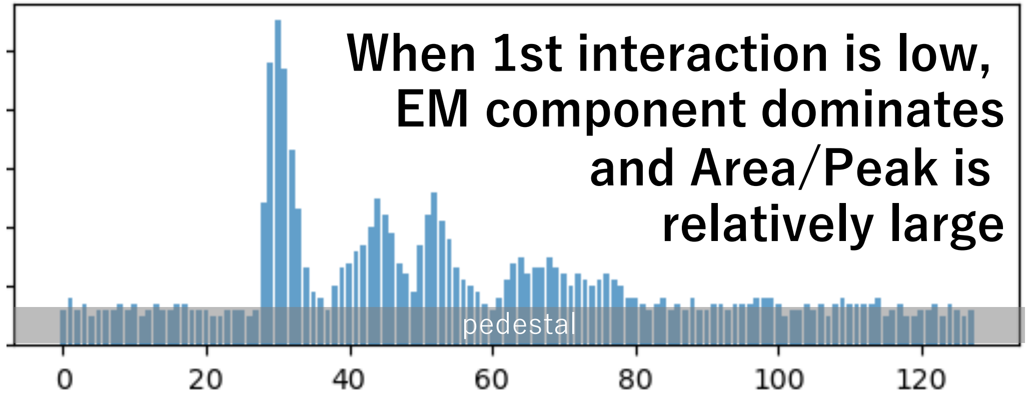


Discrimination parameter

Area over Peak (AoP)

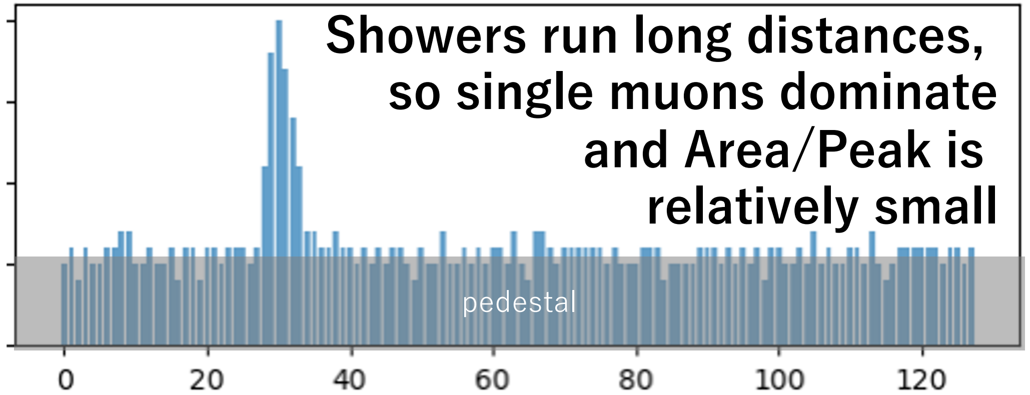
[3] PhysRevD.91.092008, Pierre Auger Collaboration

Schematic of waveform of Neutrino Shower



When 1st interaction is low, EM component dominates and Area/Peak is relatively large

Schematic of waveform of Proton Shower

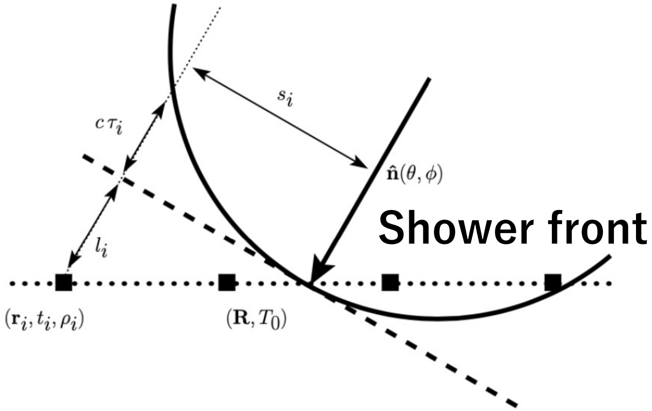


Showers run long distances, so single muons dominate and Area/Peak is relatively small

Curvature parameter a

One of the fit parameter of shower front

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



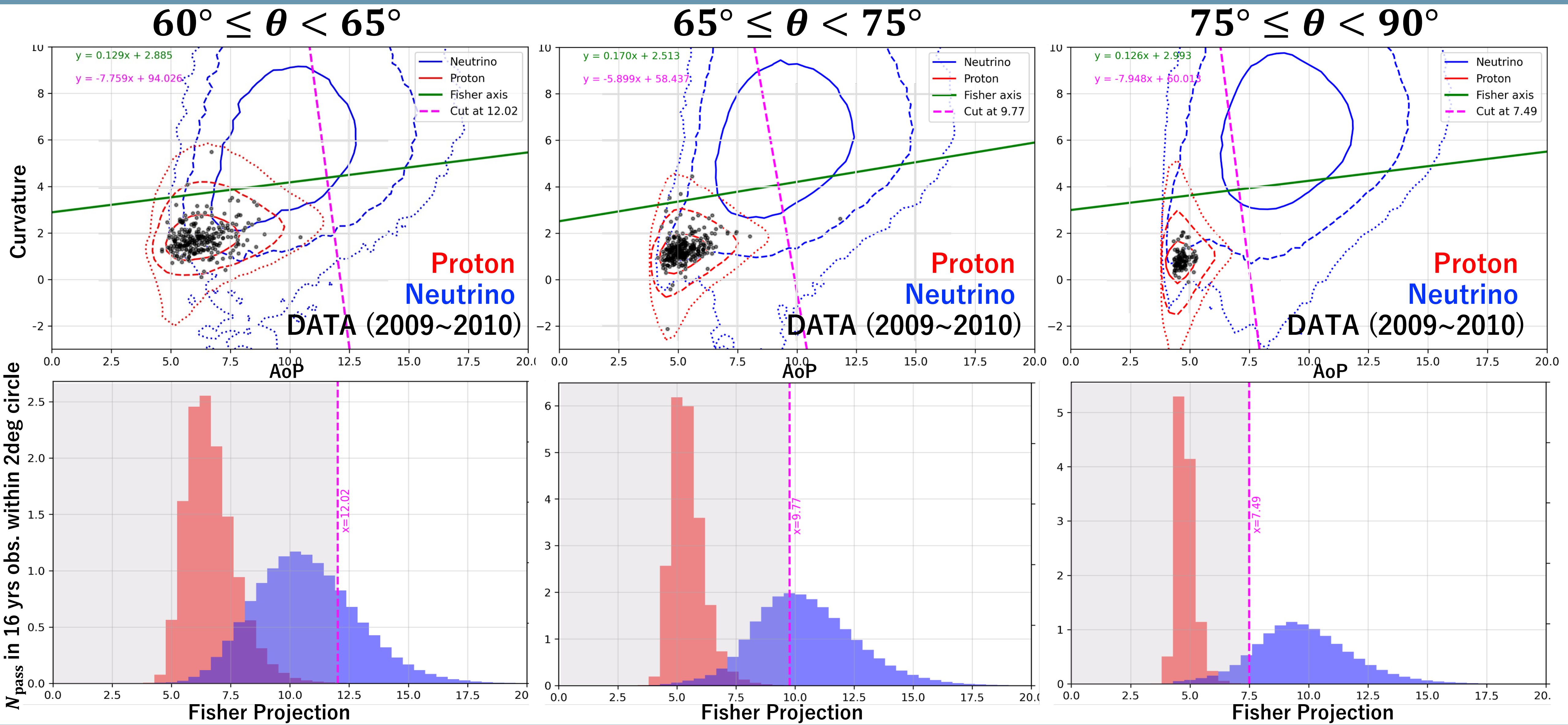
Large a

⇒ shower front with strong curvature

Due to their smaller interaction cross-section, neutrinos tend to interact at deeper, producing showers with smaller curvature radius and thus larger a.

Discrimination

DATA selection criteria：
N_{sd} ：≥ 5
Pointing direction error：＜4 deg
$N_{Partcle}$ ： ≥ 100



Discrimination

DATA selection criteria：
N_{sd} ：≥ 5
Pointing direction error：< 4 deg
$N_{Partcle}$ ： ≥ 100

$60° \leq \theta < 65°$ | $65° \leq \theta < 75°$ | $75° \leq \theta < 90°$

Discrimination Line and Search Radius

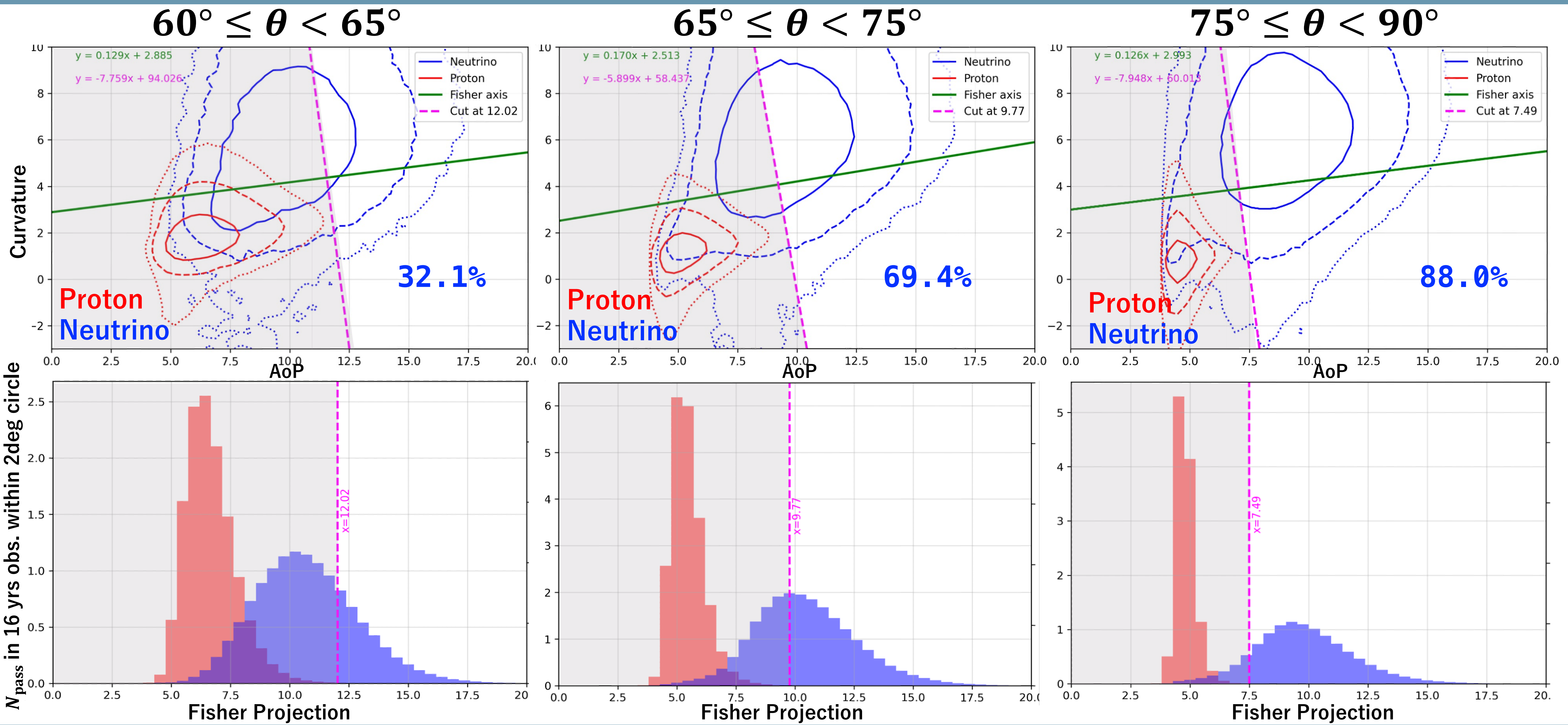
・The discrimination line was set so that the expected background within a **2deg circle** is < **0.01 events**.

・For the analysis, a **5deg search radius** was used, matching the angular resolution that includes **>90% of the events**.

・From the area ratio, the background increases by about **6.25**×, giving roughly **0.06 background events** within a 5deg circle.

Discrimination

DATA selection criteria：
N_{sd}：≥ 5
Pointing direction error：<4 deg
$N_{Partcle}$：≥ 100

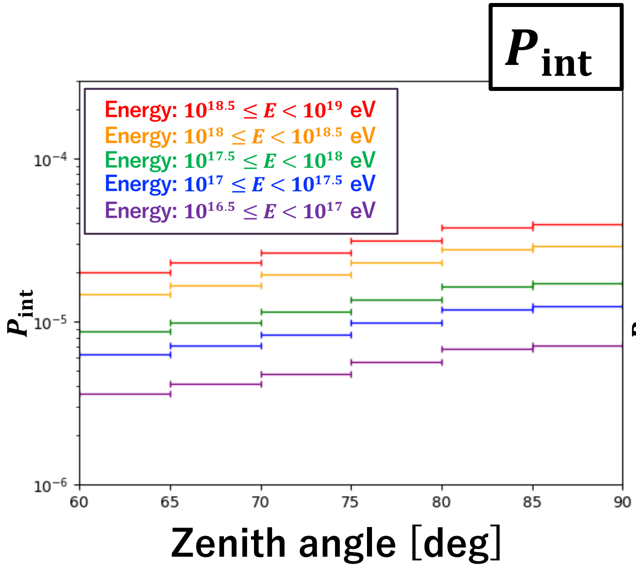


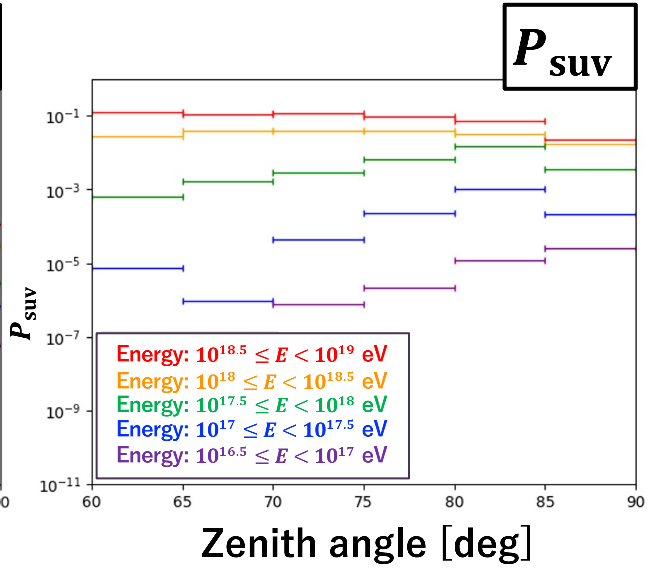
Sensitivity calculation

Calculation of effective area

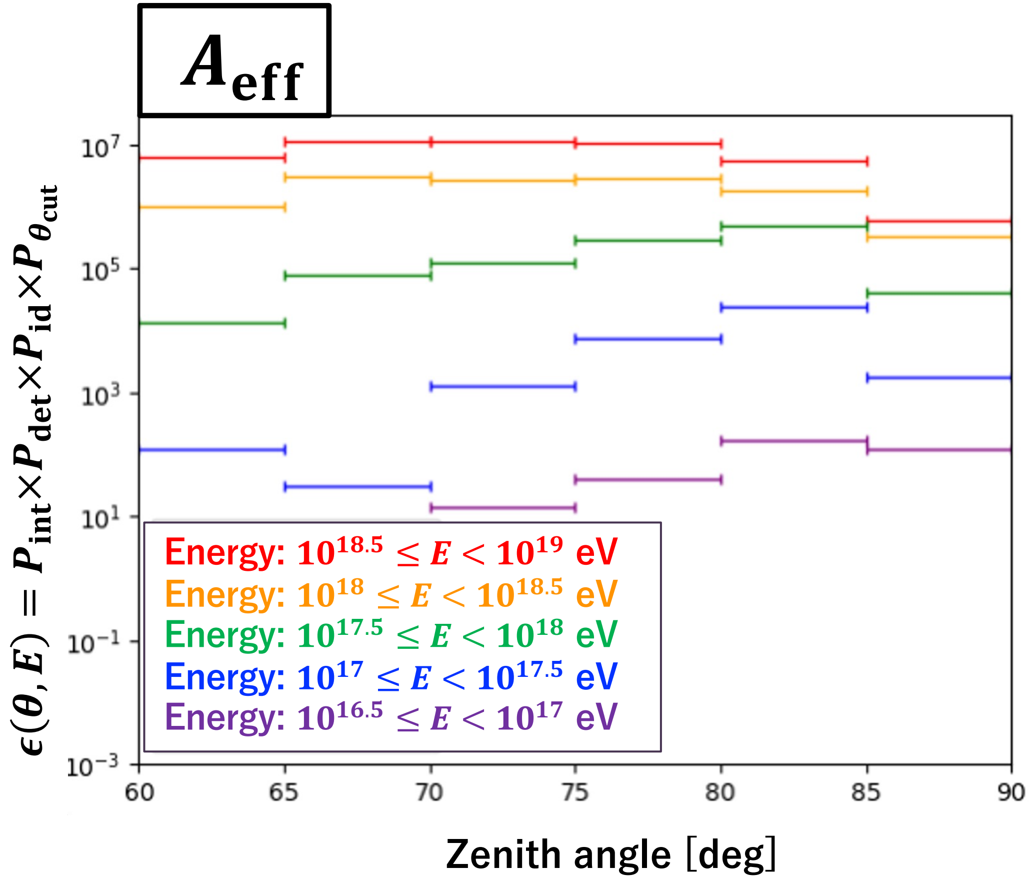
$$A_{\mathrm{eff}} = \left(\sum P_{\mathrm{int}} \times P_{\mathrm{suv}} \times P_{\mathrm{id}} \times P_{\theta_{\mathrm{cut}}}\right) \times S \cdot \cos\theta$$

P_{int}: Interaction probability
P_{suv}: Survival probability after reconstruction
P_{id}: Identification probability after discrimination
$P_{\theta_{\mathrm{cut}}}$:0.908





$$A_{\mathrm{eff}} = \epsilon(\theta, E) S \cos\theta$$



Sensitivity calculation

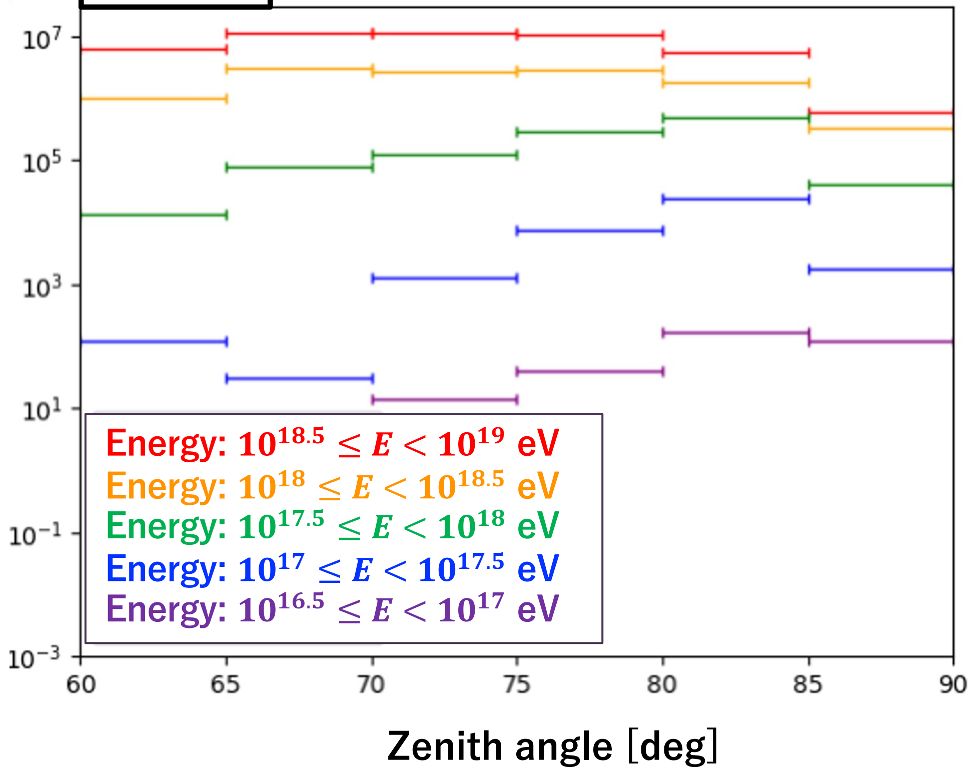
Total exposure as a function of declination is calculated by integrating the effective area x visible time.

$A_{\mathrm{eff}} = \epsilon(\theta, E) S \cos\theta$

$\epsilon(\theta, E) = P_{\mathrm{int}} \times P_{\mathrm{det}} \times P_{\mathrm{id}} \times P_{\theta\mathrm{cut}}$

A_{eff}

Effective Area $[\mathrm{cm}^2]$



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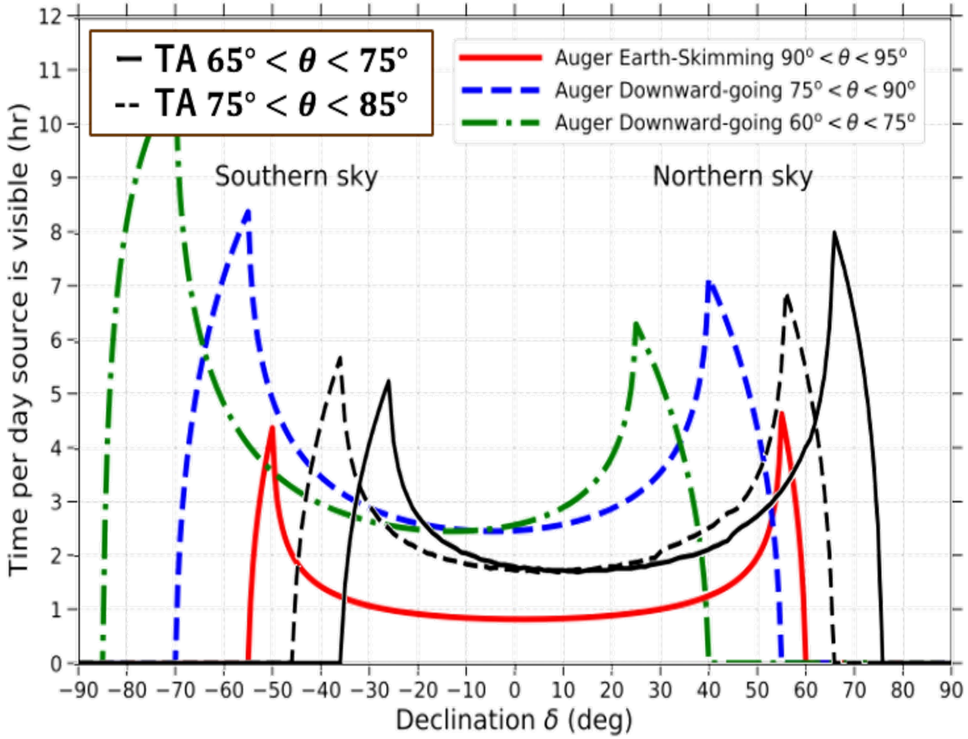
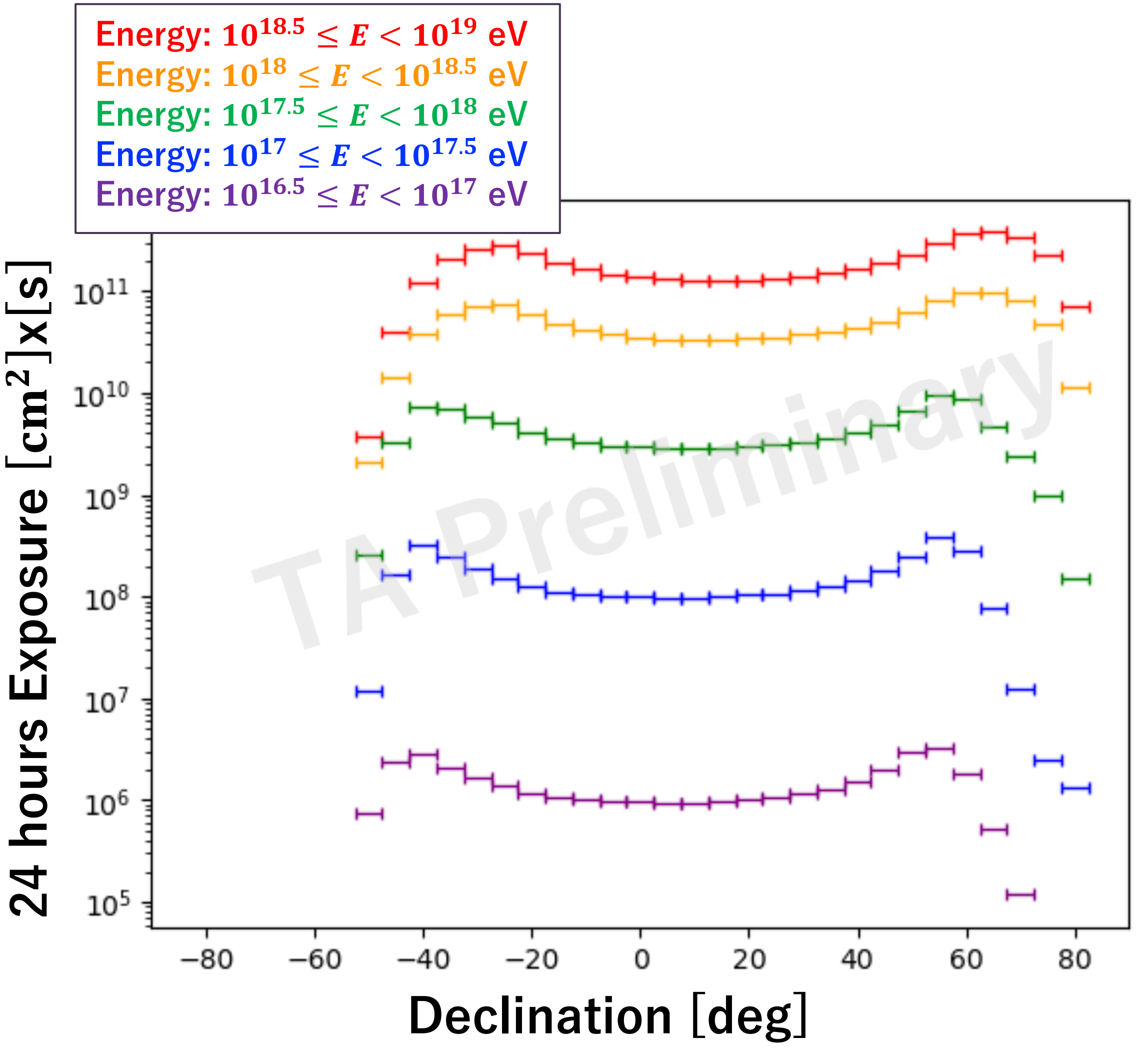
Visible Time by declination/day



Citation A. Aab *et al* JCAP11(2019)004

Sensitivity calculation

Exposure in 24hours by TA SD : $\varepsilon(E)$



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Assuming spectrum index and N_{exp}, neutrino sensitivity can be calculated for each declination by 16 years of TA SD observations.

@Each declination

$$N_{\mathrm{exp}} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \frac{dN}{dE} \times \varepsilon(E) \times 365 \times 16 \, dE$$

Assumed neutrino spectrum

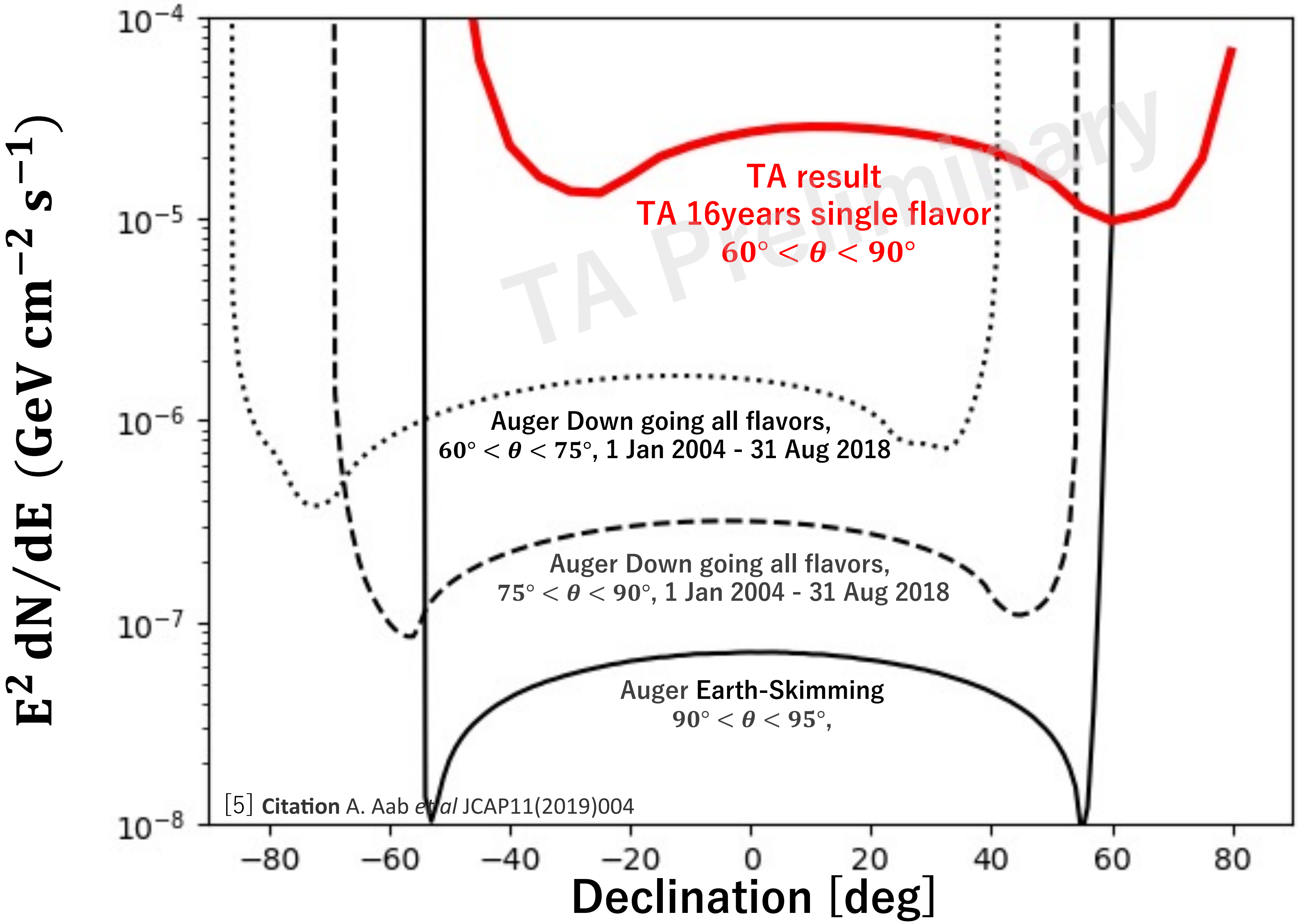
$$\frac{dN}{dE} = \phi_0 E^{-2}$$

$$N_{\mathrm{exp}} = 2.44, \ (N_{\mathrm{BG}} = 0, \ N_{\mathrm{det}} = 0)$$

Calculated by Feldman-Cousins approach. 90% confidence level for BG=0.

[4] G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998)

Sensitivity calculation



Summary and prospects

・DATA/MC comparison

✔ Good agreement for inclined proton showers.

Angular resolution for neutrino inclined air shower is , $\theta_{50} = 2.03$ deg.

・Discrimination

✔ **Survival rate of neutrinos after discrimination**

$60° \leq \theta < 65°$: 32.1%, $65° \leq \theta < 75°$: 69.4%, $\theta \geq 75°$: 88.0%

・Neutrino sensitivity by each declination

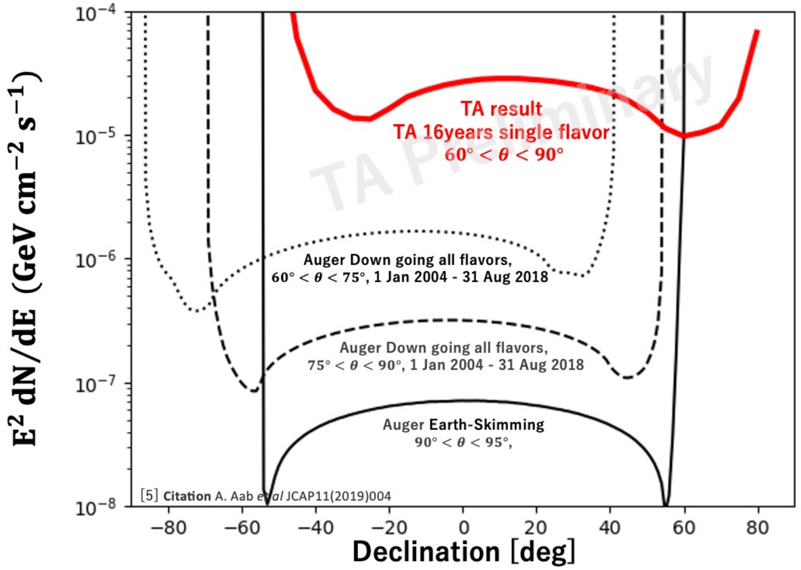
✔ For the large zenith angle region (ν_e CC $60° < \theta < 90°$), the neutrino sensitivity of the TA SD 16-year observation was calculated.

Those were assumed.

$$\frac{dN}{dE} = \phi_0 E^{-2}, \qquad N_{exp} = 2.44$$

DATA SELECTION

N_{sd} : ≥ 5
Pointing direction error : ≤4 deg
$N_{Partcle} \geq 100$



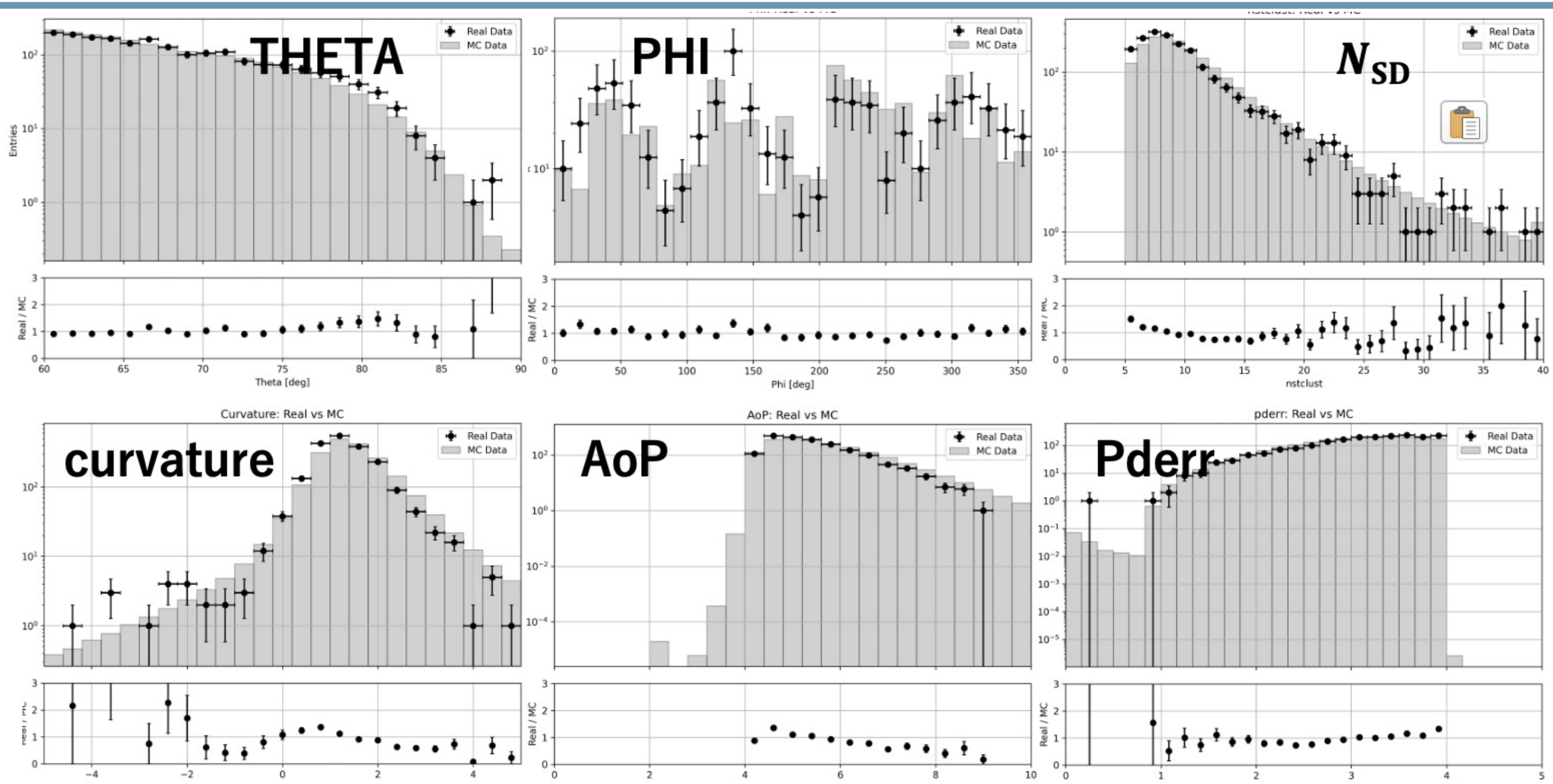
TA ν_e CC $60° < \theta < 90°$
16years (2008~2024)
90% confidence level
(calculated by Feldman-Cousins)

Prospects

👉 **Open 16 years data of TA SD**

Appendix

Proton DATA/MC comparison log

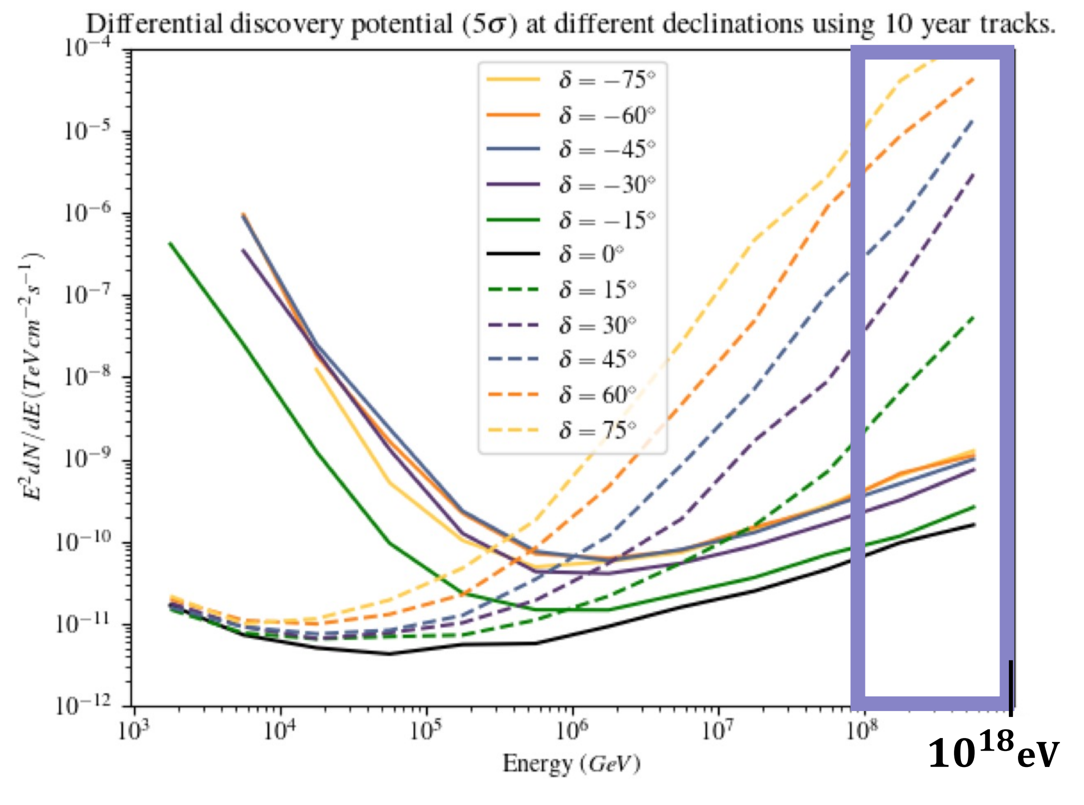


Comparison with IceCube sensitivity by latitude

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

The Northern sky is less sensitive to higher energies than the Southern sky because the signal necessary for a 5σ discovery is higher.

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.**

Neutrino cross section

Predictions for high energy neutrino cross-sections from the ZEUS global PDF fits

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1 Keble Road, Oxford OX1 3NP, UK

(Dated: October 29, 2018)

Referred also by Pierre Auger
high energy neutrino search

The paper showed H1 and ZEUS combined data collected in the years 1994–2000
and extrapolated to high energies.

Feldman-Cousins approach

TABLE IV. 90% C.L. intervals for the Poisson signal mean μ, for total events observed n_0, for known mean background b ranging from 0 to 5.

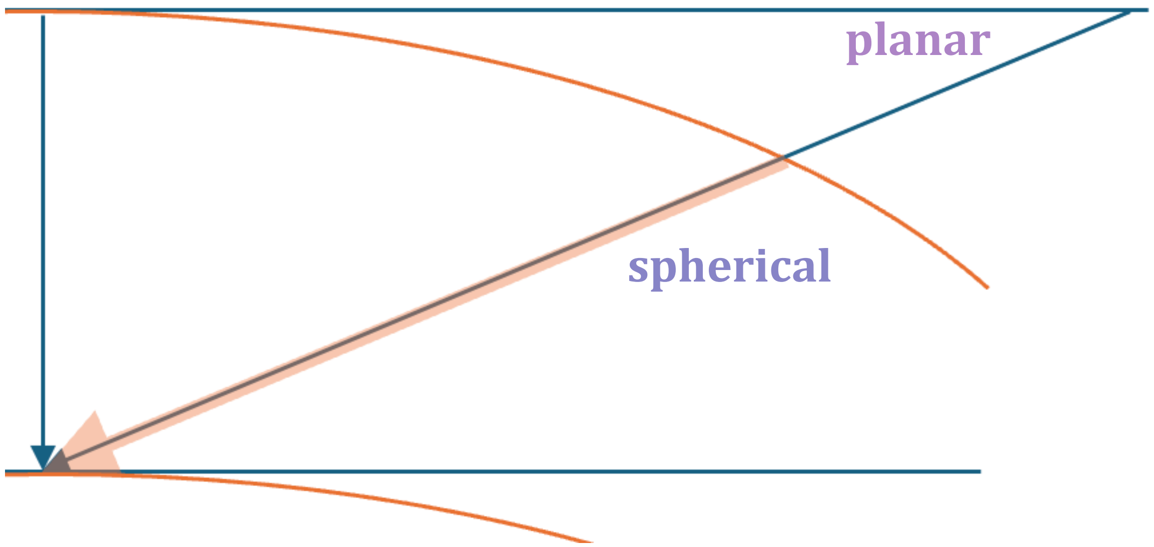
$n_0 \backslash b$	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
0	0.00, 2.44	0.00, 1.94	0.00, 1.61	0.00, 1.33	0.00, 1.26	0.00, 1.18	0.00, 1.08	0.00, 1.06	0.00, 1.01	*0.00, 0.98*
1	0.11, 4.36	0.00, 3.86	0.00, 3.36	0.00, 2.91	0.00, 2.53	0.00, 2.19	0.00, 1.88	0.00, 1.59	0.00, 1.39	0.00, 1.22
2	0.53, 5.91	0.03, 5.41	0.00, 4.91	0.00, 4.41	0.00, 3.91	0.00, 3.45	0.00, 3.04	0.00, 2.67	0.00, 2.33	0.00, 1.73
3	1.10, 7.42	0.60, 6.92	0.10, 6.42	0.00, 5.92	0.00, 5.42	0.00, 4.92	0.00, 4.42	0.00, 3.95	0.00, 3.53	0.00, 2.78
4	1.47, 8.60	1.17, 8.10	0.74, 7.60	0.24, 7.10	0.00, 6.60	0.00, 6.10	0.00, 5.60	0.00, 5.10	0.00, 4.60	0.00, 3.60
5	1.84, 9.99	1.53, 9.49	1.25, 8.99	0.93, 8.49	0.43, 7.99	0.00, 7.49	0.00, 6.99	0.00, 6.49	0.00, 5.99	0.00, 4.99
6	2.21,11.47	1.90,10.97	1.61,10.47	1.33, 9.97	1.08, 9.47	0.65, 8.97	0.15, 8.47	0.00, 7.97	0.00, 7.47	0.00, 6.47
7	3.56,12.53	3.06,12.03	2.56,11.53	2.09,11.03	1.59,10.53	1.18,10.03	0.89, 9.53	0.39, 9.03	0.00, 8.53	0.00, 7.53
8	3.96,13.99	3.46,13.49	2.96,12.99	2.51,12.49	2.14,11.99	1.81,11.49	1.51,10.99	1.06,10.49	0.66, 9.99	0.00, 8.99
9	4.36,15.30	3.86,14.80	3.36,14.30	2.91,13.80	2.53,13.30	2.19,12.80	1.88,12.30	1.59,11.80	1.33,11.30	0.43,10.30
10	5.50,16.50	5.00,16.00	4.50,15.50	4.00,15.00	3.50,14.50	3.04,14.00	2.63,13.50	2.27,13.00	1.94,12.50	1.19,11.50
11	5.91,17.81	5.41,17.31	4.91,16.81	4.41,16.31	3.91,15.81	3.45,15.31	3.04,14.81	2.67,14.31	2.33,13.81	1.73,12.81
12	7.01,19.00	6.51,18.50	6.01,18.00	5.51,17.50	5.01,17.00	4.51,16.50	4.01,16.00	3.54,15.50	3.12,15.00	2.38,14.00
13	7.42,20.05	6.92,19.55	6.42,19.05	5.92,18.55	5.42,18.05	4.92,17.55	4.42,17.05	3.95,16.55	3.53,16.05	2.78,15.05
14	8.50,21.50	8.00,21.00	7.50,20.50	7.00,20.00	6.50,19.50	6.00,19.00	5.50,18.50	5.00,18.00	4.50,17.50	3.59,16.50
15	9.48,22.52	8.98,22.02	8.48,21.52	7.98,21.02	7.48,20.52	6.98,20.02	6.48,19.52	5.98,19.02	5.48,18.52	4.48,17.52
16	9.99,23.99	9.49,23.49	8.99,22.99	8.49,22.49	7.99,21.99	7.49,21.49	6.99,20.99	6.49,20.49	5.99,19.99	4.99,18.99
17	11.04,25.02	10.54,24.52	10.04,24.02	9.54,23.52	9.04,23.02	8.54,22.52	8.04,22.02	7.54,21.52	7.04,21.02	6.04,20.02
18	11.47,26.16	10.97,25.66	10.47,25.16	9.97,24.66	9.47,24.16	8.97,23.66	8.47,23.16	7.97,22.66	7.47,22.16	6.47,21.16
19	12.51,27.51	12.01,27.01	11.51,26.51	11.01,26.01	10.51,25.51	10.01,25.01	9.51,24.51	9.01,24.01	8.51,23.51	7.51,22.51
20	13.55,28.52	13.05,28.02	12.55,27.52	12.05,27.02	11.55,26.52	11.05,26.02	10.55,25.52	10.05,25.02	9.55,24.52	8.55,23.52

[G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998)]

Considering about spherical geometry

Comparison of slant depths for planar and spherical atmosphere

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



zenith angle degree	planar distance km	planar slant depth g/cm^2	spherical distance km	spherical slant depth 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

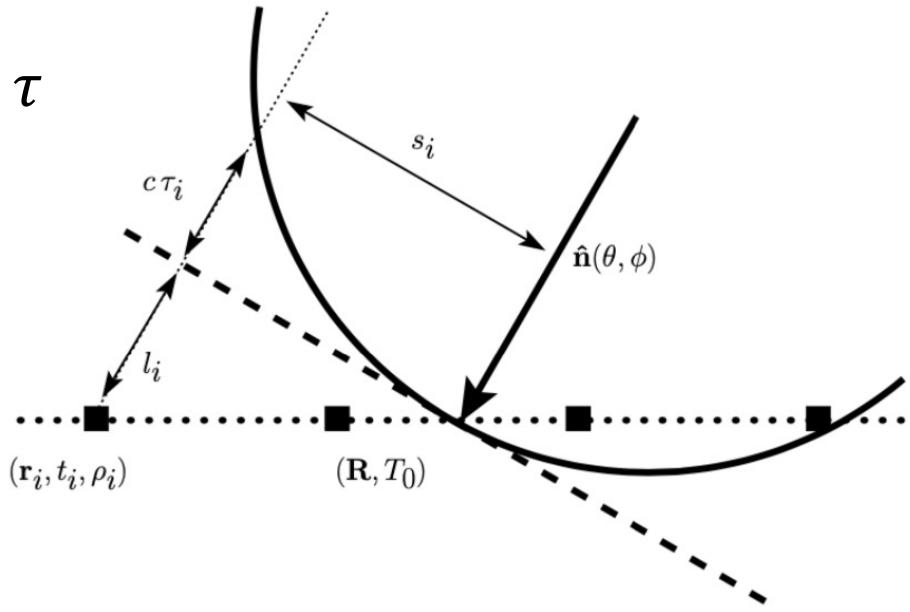
Slant depths in planar and spherical geometry, calculated the Linsley parametrization of the U.S. standard atmosphere.

The difference is more than 1000g/cm^2 at 70deg.

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

Original reconstruction method for TA SD

$$\chi_G{}^2 = \sum_{i=0}^{N} \frac{(t_i - t_i{}^{FIT})^2}{\sigma_{ti}{}^2} + \frac{\boldsymbol{R} - \boldsymbol{R}_{cog}{}^2}{\sigma_{Rcog}{}^2} \quad , \quad t^{FIT} = T_0 + \frac{l}{c} + \tau$$



Step1：Modified Linsley Fitting

$$\tau = (8\times10^{-4}\mu S)a(\theta)\left(1.0 + \frac{s}{30m}\right)^{1.5} \rho^{-0.5}$$

Step2：Plane Fitting

Step3：Linsley's with free "a"

$$\tau = a\left(1 - \frac{l}{12\times10^3 m}\right)^{1.05} \left(1.0 + \frac{s}{30m}\right)^{1.35} \rho^{-0.5}$$

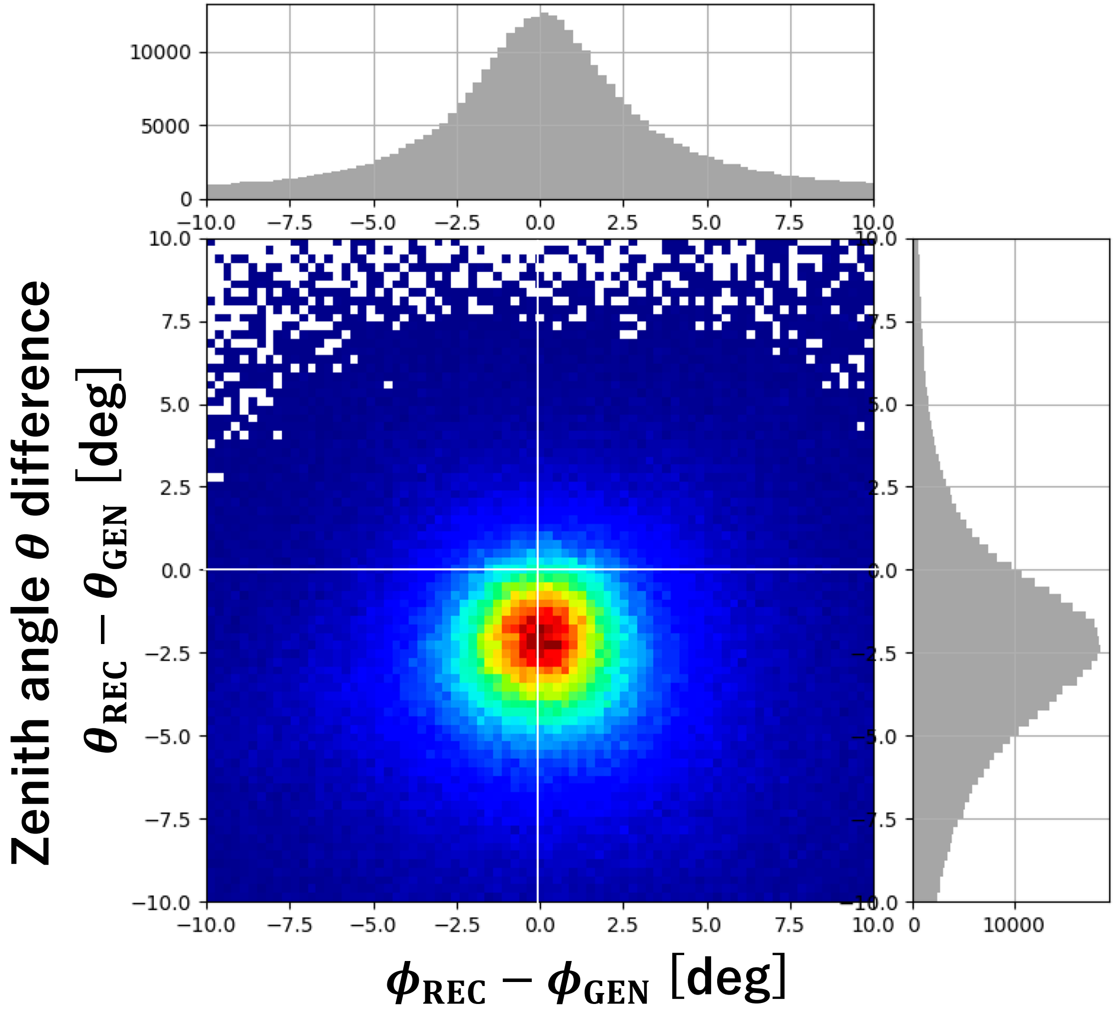
$$a(\theta) = \begin{cases} 3.3836 - 0.01848\,\theta & \theta < 25^o \\ c_3\,\theta^3 + c_2\,\theta^2 + c_1\,\theta + c_0 & 25^o \le \theta < 35^o \\ \exp(-3.2\times10^{-2}\,\theta + 2.0) & \theta > 35^o \end{cases}$$

$c_0 = -7.76168\times10^{-2}$, $c_1 = 2.99113\times10^{-1}$,

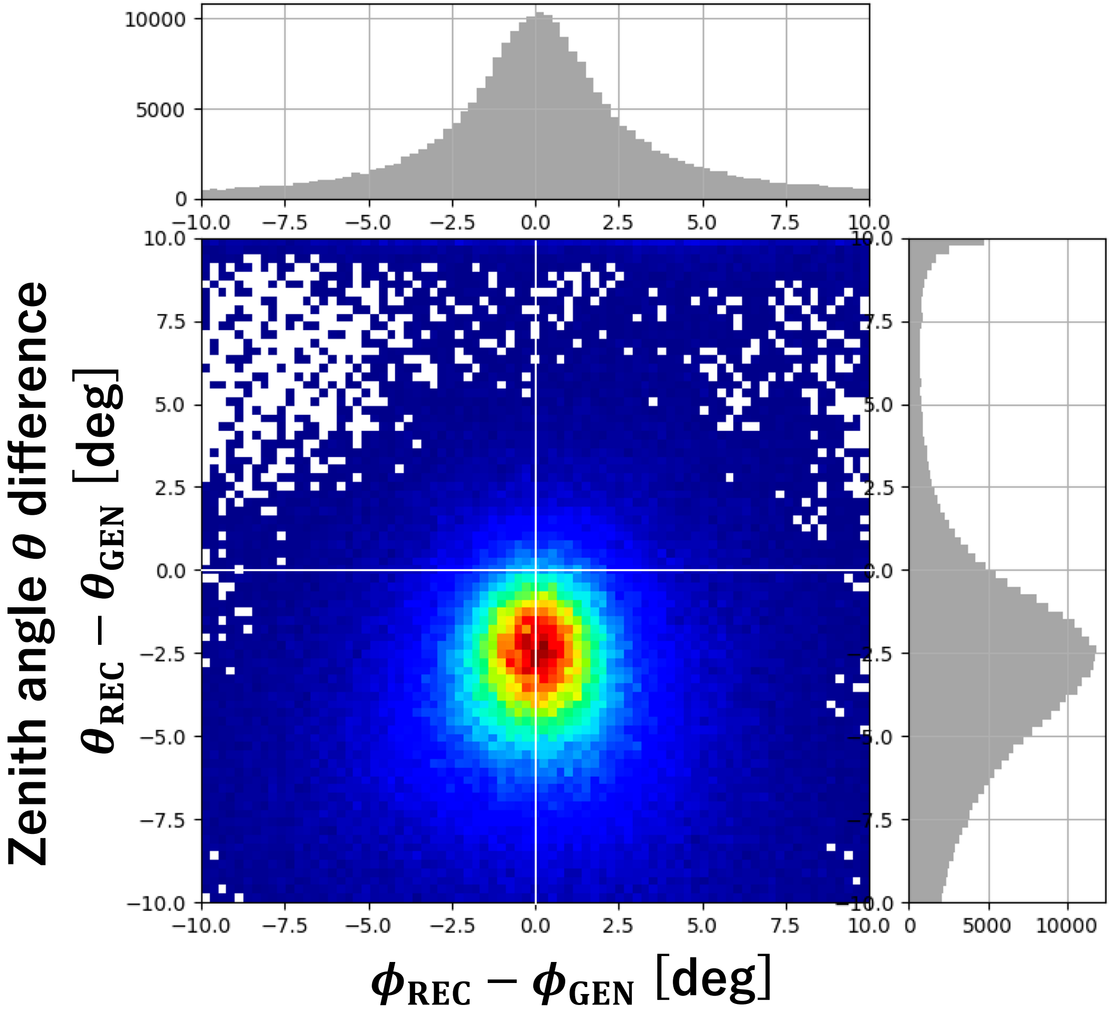
$c_2 = -8.79358\times10^{-3}$, $c_3 = 6.51127\times10^{-5}$

Applying the original reconstruction method to inclined neutrino shower

$\theta_{\mathrm{GEN}} = 70$ [deg]



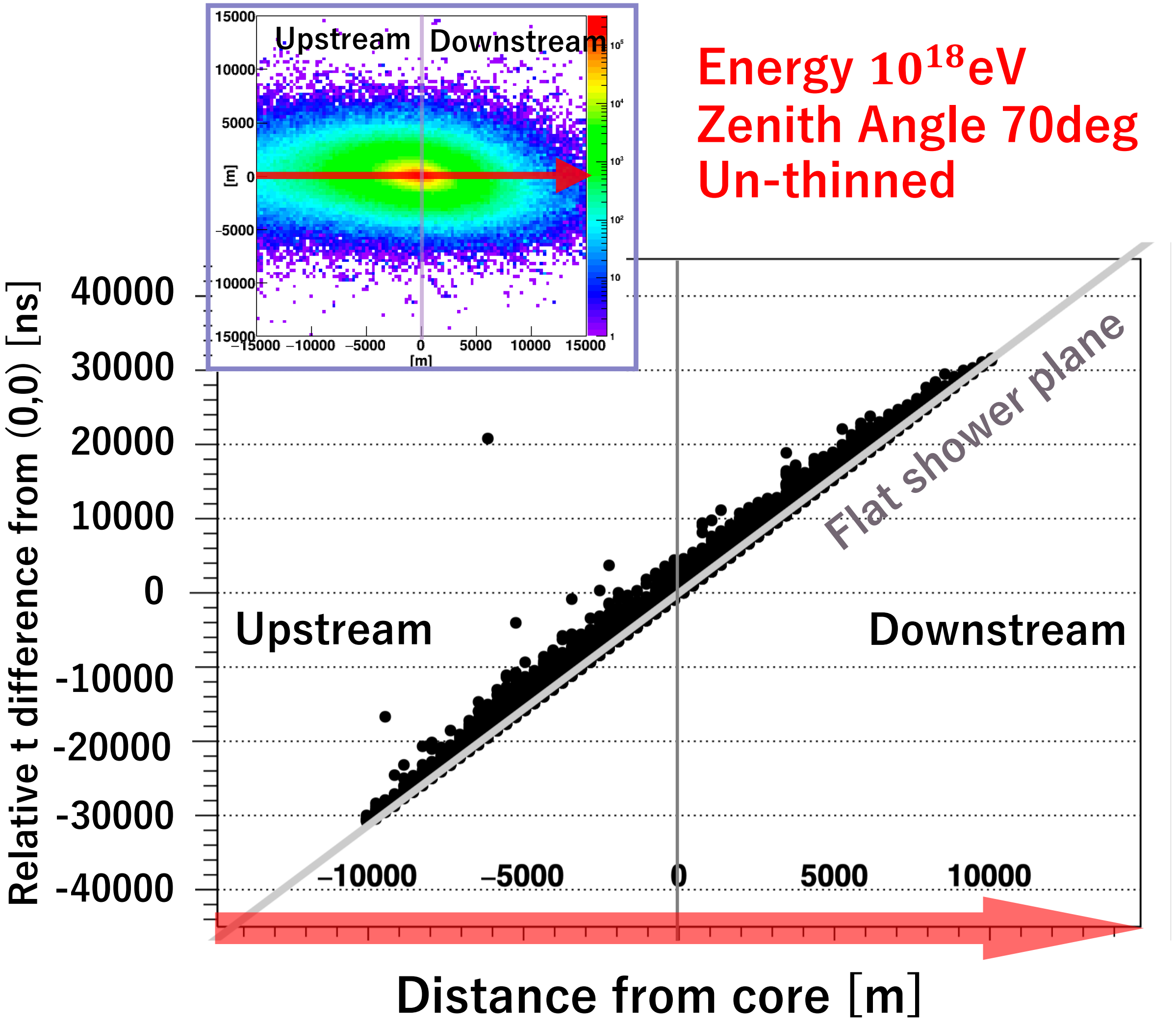
$\theta_{\mathrm{GEN}} = 80$ [deg]



Shower plane investigation (timing delay)

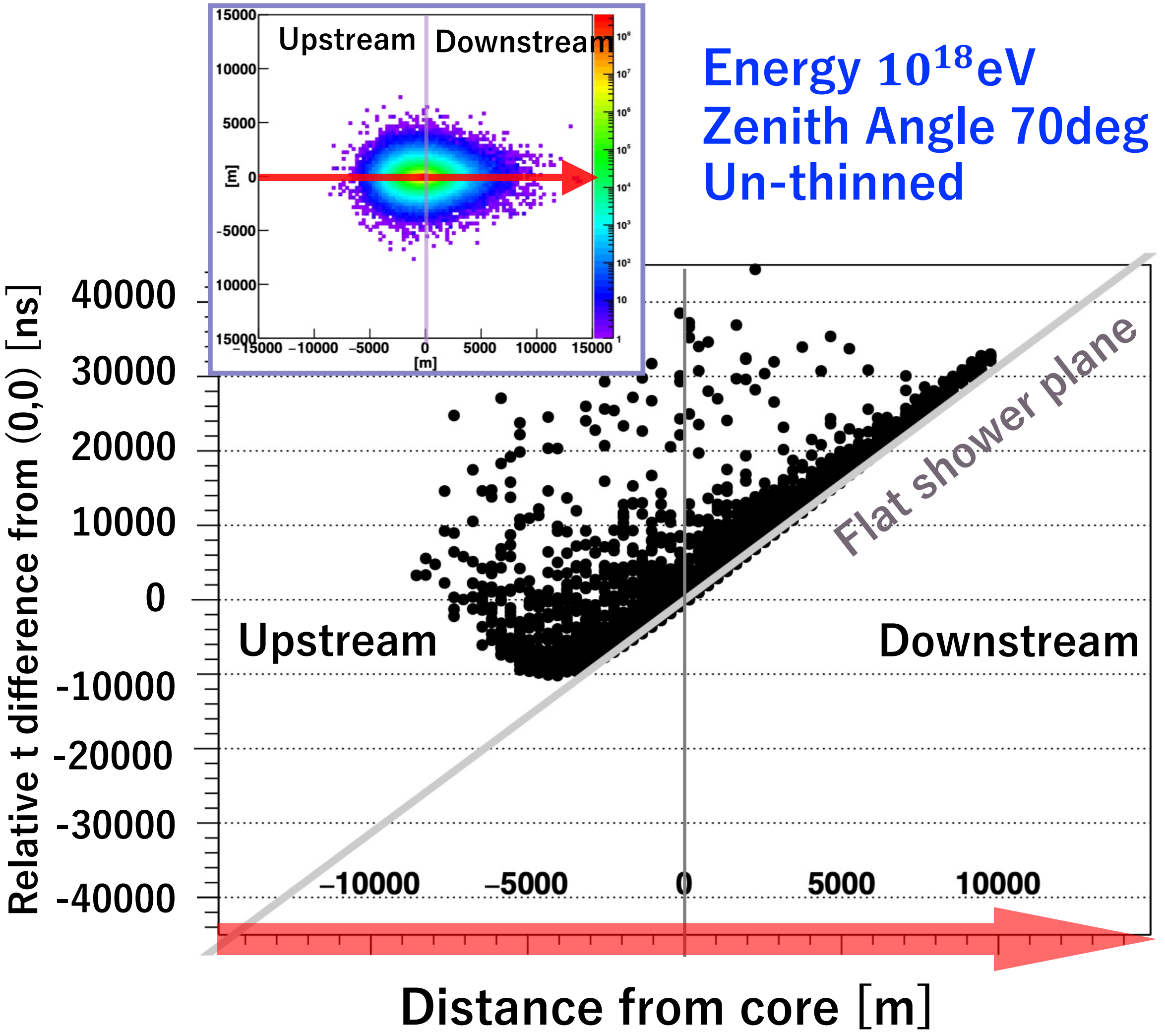
Proton

Energy 10^{18}eV
Zenith Angle 70deg
Un-thinned



Neutrino

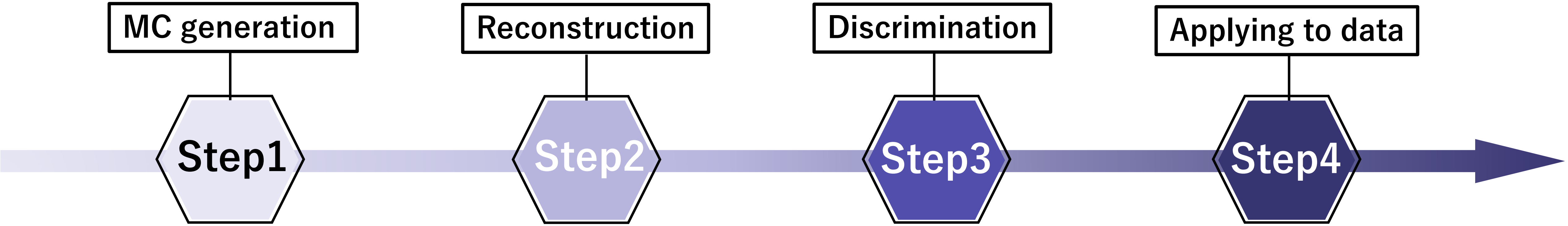
Energy 10^{18}eV
Zenith Angle 70deg
Un-thinned

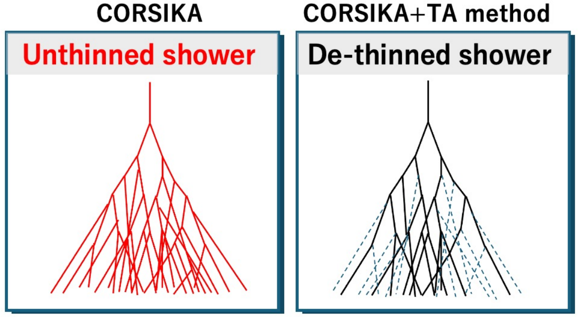


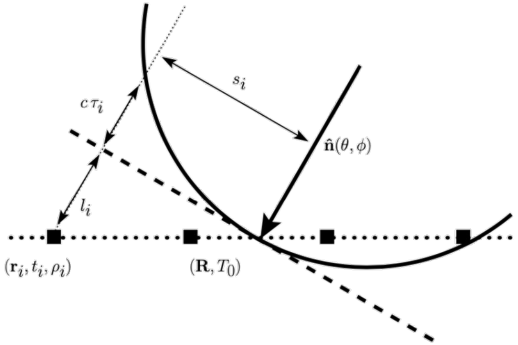
Neutrino × Inclined

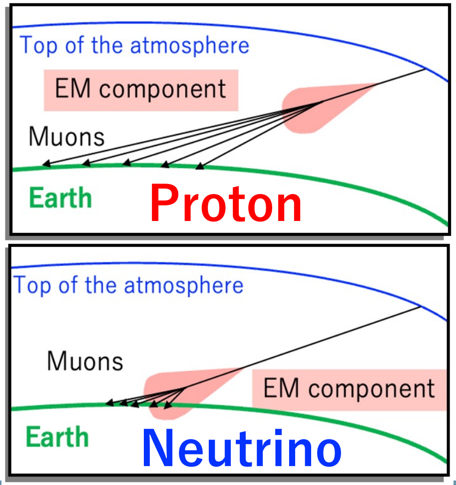
Issues to be Addressed to search inclined neutrinos

Each step must be investigated.







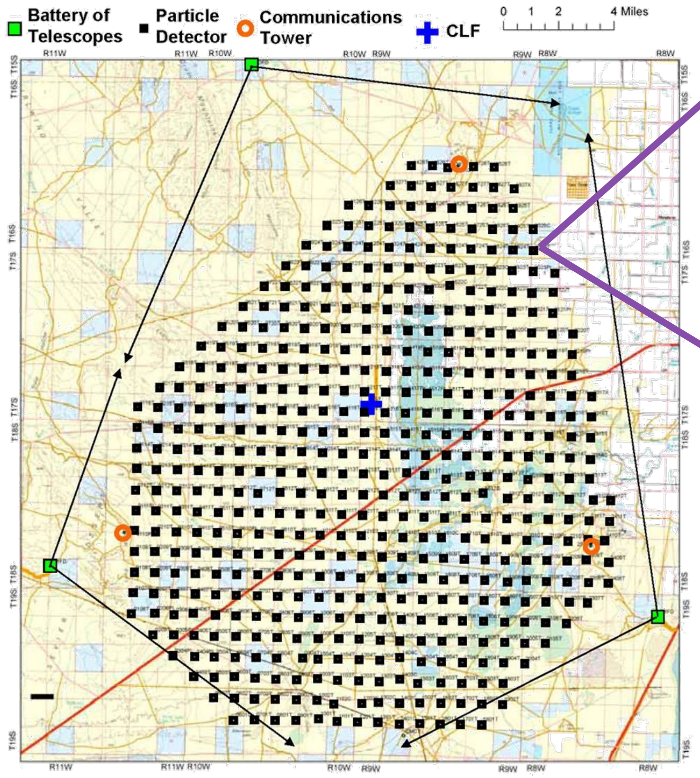


Open treasure box!!!

Telescope Array experiment (TA)

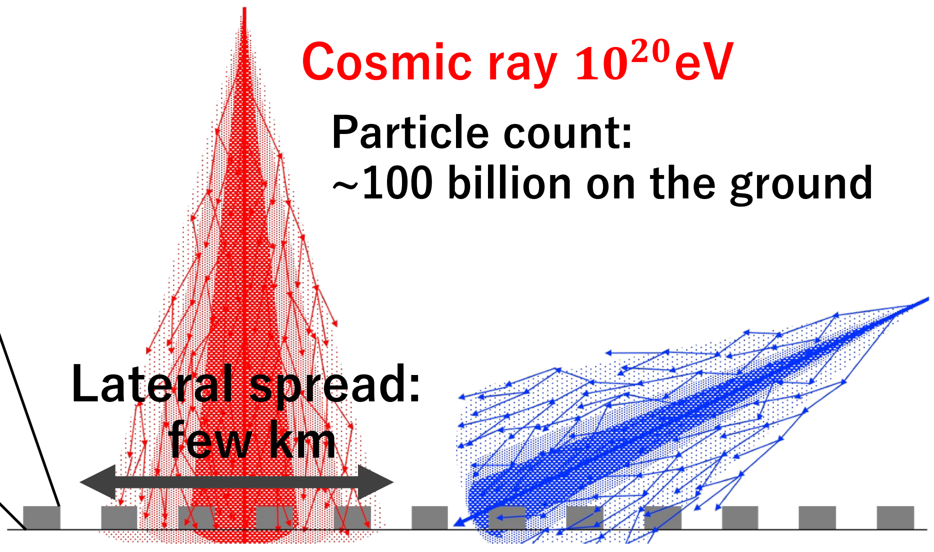
Location: Utah, USA (latitude 39°N, Longitude 113° W)
Area Coverage: 700 km^2
Operation Period: May 2008 – Present
Type: Surface detector array (Scintillator-based)

The largest air shower array in the Northern Hemisphere!



Surface detector (SD)
507 scintillation detector arrays ($3m^2$) placed at 1.2km intervals.

Air shower



Primary cosmic rays interact with the atmosphere, **creating cascades of secondary particles** that reach the detectors. From these signals, the arrival direction and energy of the original cosmic ray are reconstructed.