

Analysis of Inclined Air Showers with the TA Surface Detector Arrays

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2nd PEPS workshop

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TA and TA×4

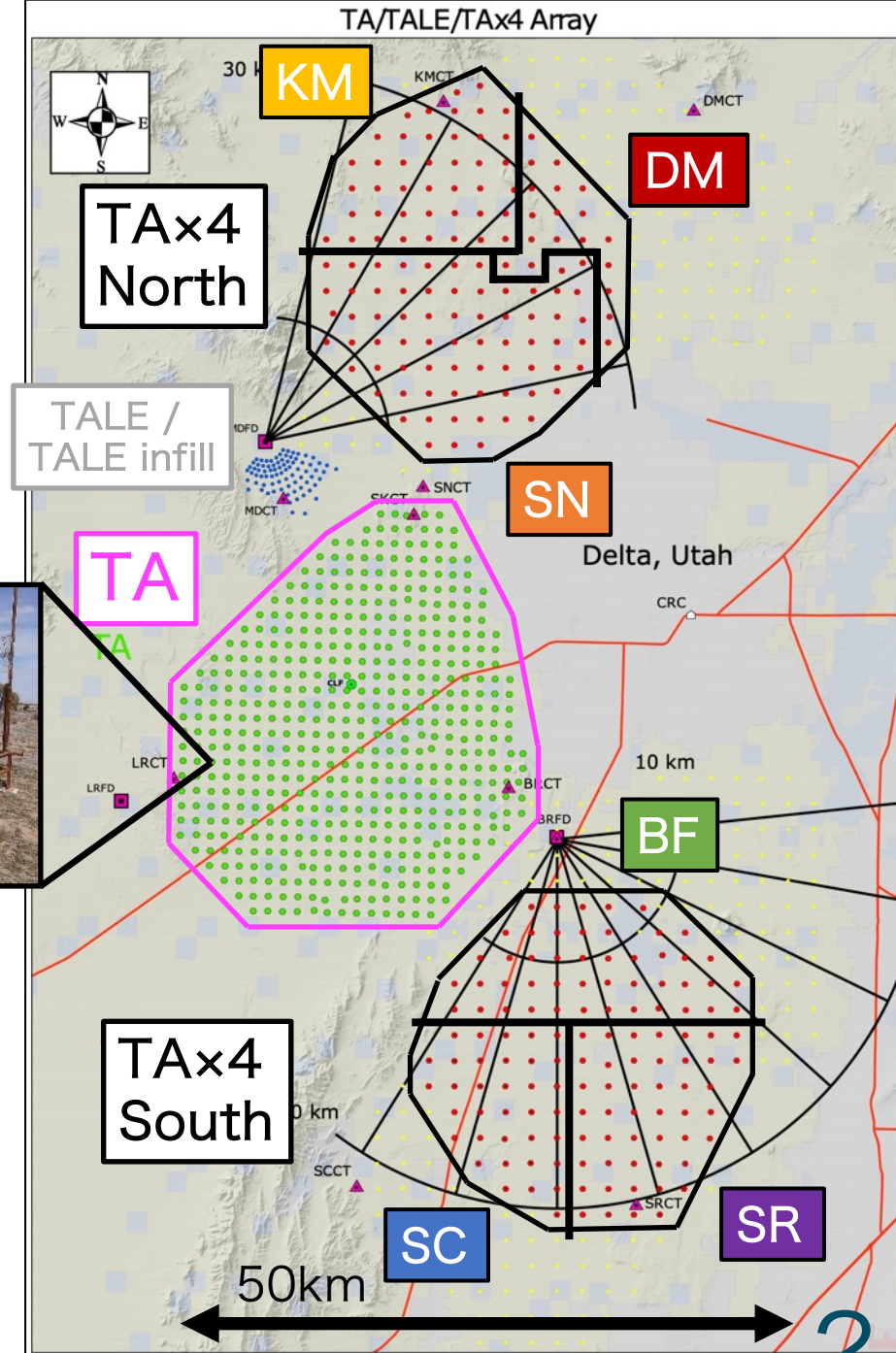
Telescope Array (TA) has been observing extended air showers with both surface detector (SD) arrays and fluorescence detectors (FDs) for 18 years to reveal the origin of ultra high-energy cosmic rays (UHECRs).

TA SD array contains **507 SDs** spaced 1.2km apart. Each SD consists of 2 layers of plastic scintillation detector (3m² and 1.2cm thick).

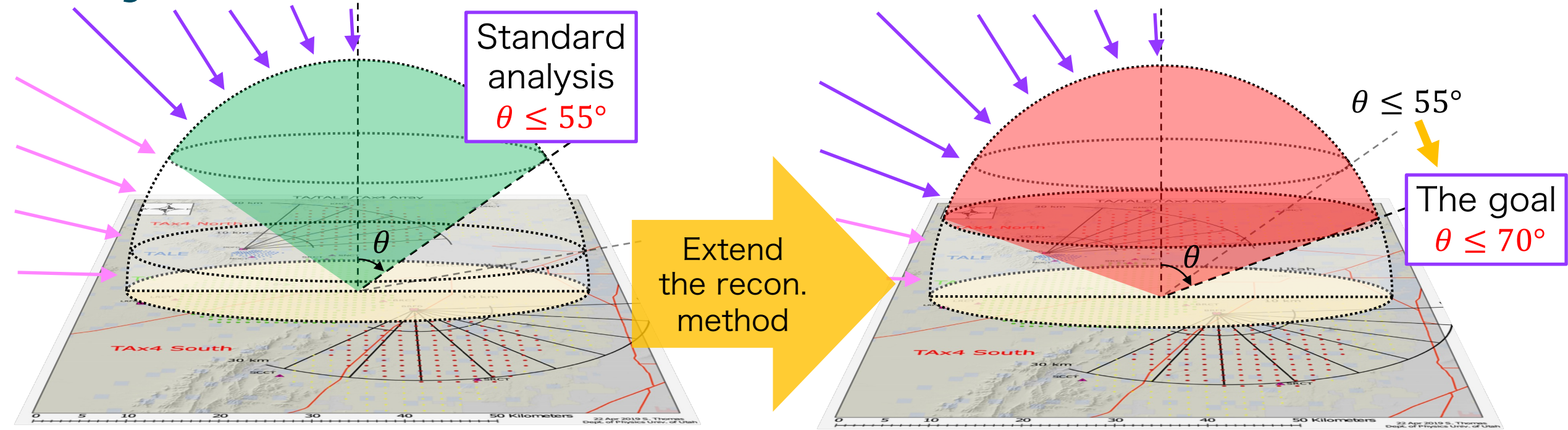


TA×4 Expansion

- Expand the TA SD by a factor of 4 with additional detectors spaced 2.08km apart ⇒ Increase the number of events
- Consists of **6 sub-arrays** (3 each in north & south) and the TA SD
- Deployed **257 SDs** in 2019 (red dots →)
- Planning to cover ~3000km² with 500 SDs



Why Inclined Events?



If extended from 55deg to 70deg, $\sim 1.3\times$ aperture of surface detector array
= Retroactively increase the number of events for UHECRs observation.

- TA \times 4 SD 6.5yr observation \rightarrow TA \times 4 SD ~ 8.5 yr observation equivalent
- TA SD 18yr observation \rightarrow TA SD ~ 23 yr observation equivalent

Visible region on the sky expands to lower dec. \rightarrow Com. dec. band w/ Auger expands

Muon component is dominant \rightarrow Suitable for study on muon excess

Standard Reconstructions with SDs

Geometry fitting

5 fitting parameters: $T_0, R_x, R_y, \theta, \phi$

To minimize

$$\chi_G^2 = \sum_{i=0}^N \frac{(t_i - t_i^{\text{FIT}})^2}{\sigma_{t_i}^2} + \frac{(\mathbf{R} - \mathbf{R}_{\text{COG}})^2}{\sigma_{\mathbf{R}_{\text{COG}}}^2}$$

where,

$$t^{\text{FIT}} = T_0 + \frac{l}{c} + \tau$$

$$\sigma_t = \sqrt{\sigma_e^2 + \sigma_\tau^2}$$

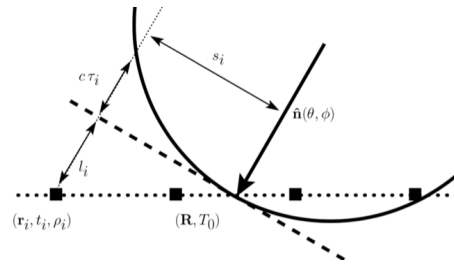
$$\tau = (8 \times 10^{-4} \mu\text{S}) a(\theta) \left(1.0 + \frac{s}{30\text{m}}\right)^{1.5} \rho^{-0.5}$$

$$\sigma_\tau = (7 \times 10^{-4} \mu\text{S}) a(\theta) \left(1.0 + \frac{s}{30\text{m}}\right)^{1.5} \rho^{-0.3}$$

$$a(\theta) = \begin{cases} 3.3836 - 0.01848 \theta & \theta < 25^\circ \\ c_3 \theta^3 + c_2 \theta^2 + c_1 \theta + c_0 & 25^\circ \leq \theta < 35^\circ \\ \exp(-3.2 \times 10^{-2} \theta + 2.0) & \theta > 35^\circ \end{cases}$$

$$c_0 = -7.76168 \times 10^{-2}, c_1 = 2.99113 \times 10^{-1},$$

$$c_2 = -8.79358 \times 10^{-3}, c_3 = 6.51127 \times 10^{-5}$$



② Fit counter signal size to find lateral distribution

LDF fitting

3 fitting parameters: R_x, R_y, A

To minimize

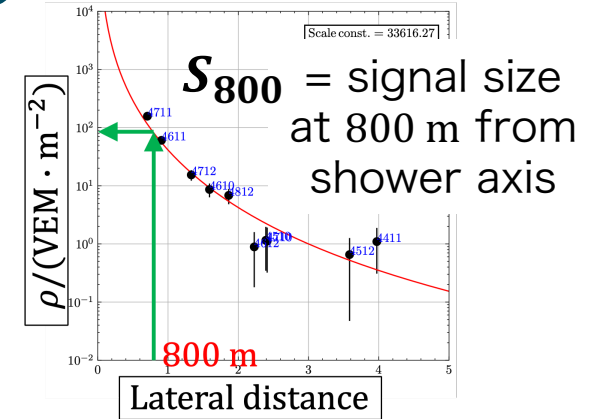
$$\chi_{\text{LDF}}^2 = \sum_{i=0}^N \frac{(\rho_i - \rho_i^{\text{FIT}})^2}{\sigma_{\rho_i}^2} + \frac{(\mathbf{R} - \mathbf{R}_{\text{COG}})^2}{\sigma_{\mathbf{R}_{\text{COG}}}^2}$$

where,

$$\rho = A \left(\frac{s}{91.6\text{m}}\right)^{-1.2} \left(1 + \frac{s}{91.6\text{m}}\right)^{-(\eta(\theta)-1.2)} \left(1 + \left[\frac{s}{1000\text{m}}\right]^2\right)^{-0.6}$$

$$\eta(\theta) = 3.97 - 1.79 [\sec(\theta) - 1]$$

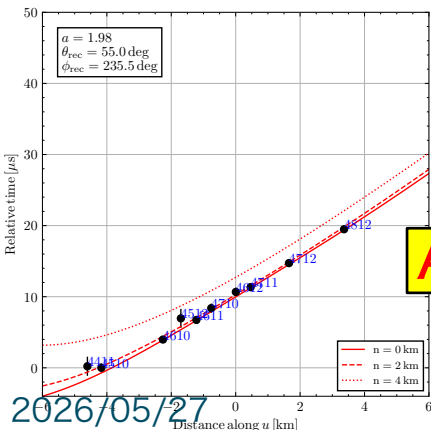
$$\sigma_\rho = \sqrt{0.56 \rho + 6.3 \times 10^{-3} \rho^2}$$



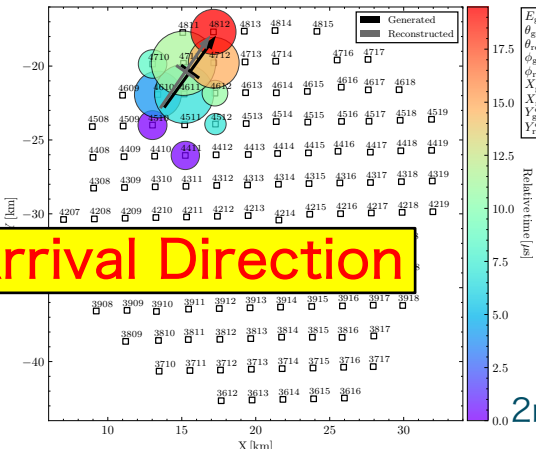
① Use detectors location and timing to determine shower core and direction

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$$c_2 = -8.79358 \times 10^{-3}, c_3 = 6.51127 \times 10^{-5}$$

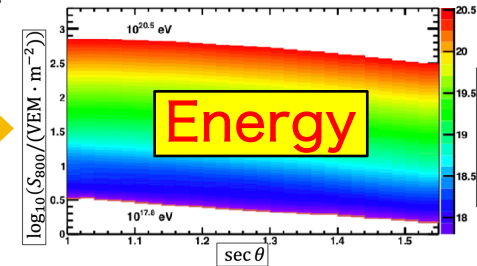


Arrival Direction



Energy determination

$$S_{800} \equiv \rho(800\text{m})$$



$$E = E_{\text{CORSIKA,SD}}/1.27$$

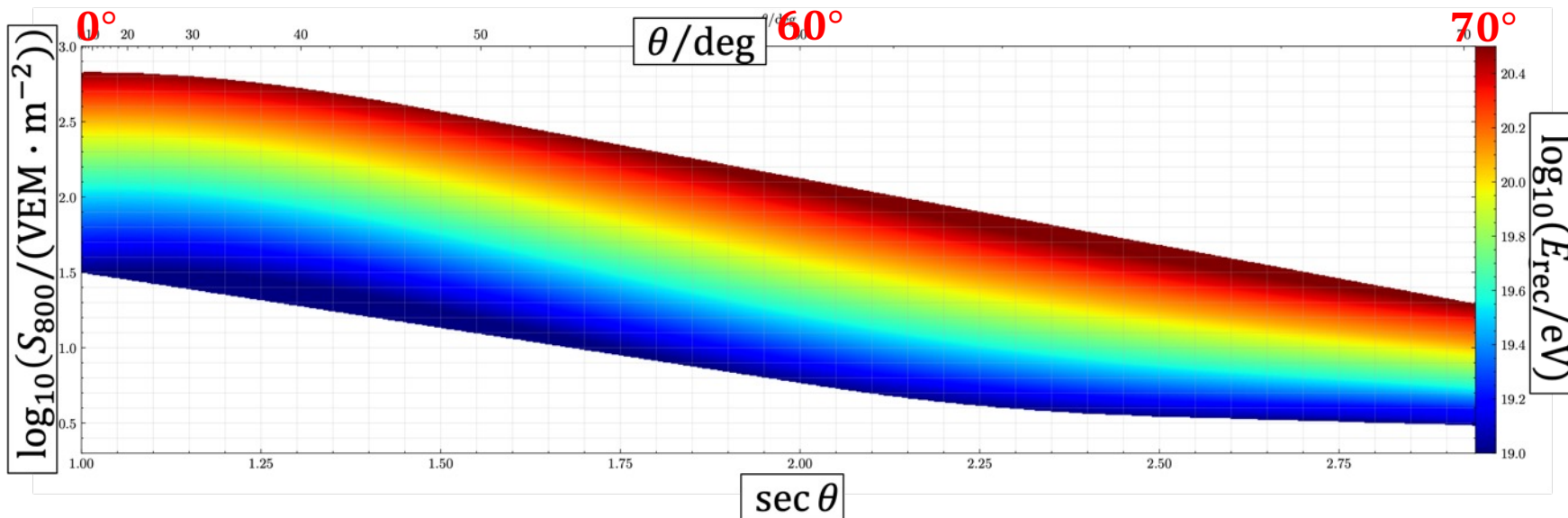
③ Use S_{800} and zenith angle to look up energy (from energy estimation table generated from MC)

Extension of Energy Estimation Table

TA×4 SD



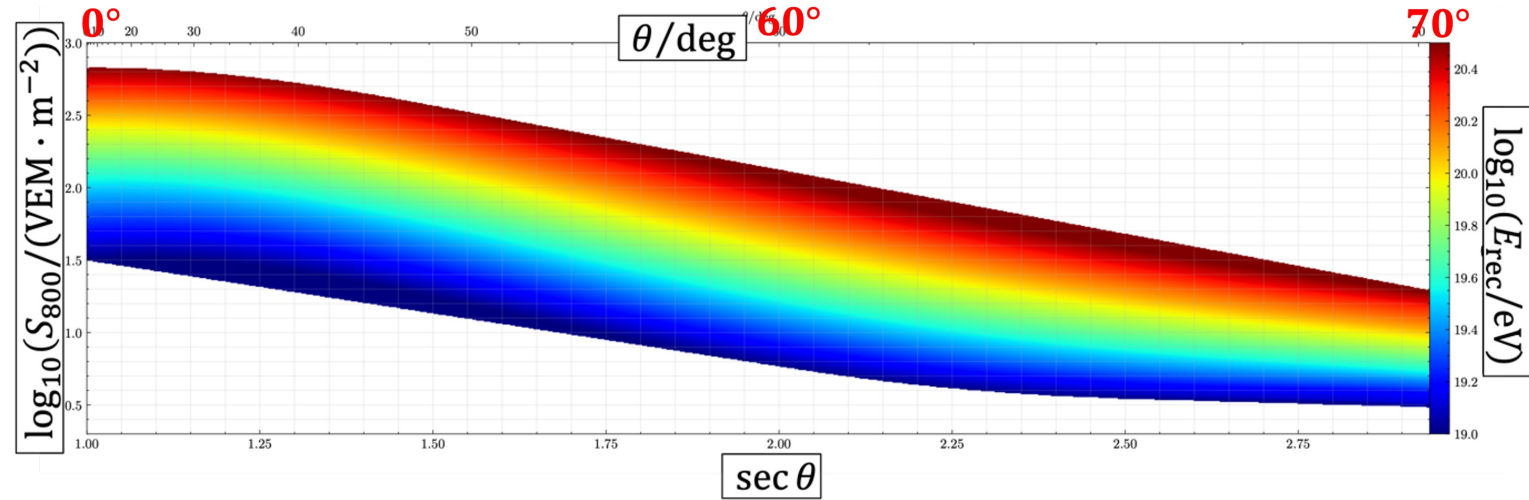
It was necessary to extend the **energy estimation table** generated from the MC sim. (w/ QGSJETII-04, p) to the large zenith angle region for reconstructing inclined evts. Using an enhanced method, we have extended it up to 70deg.



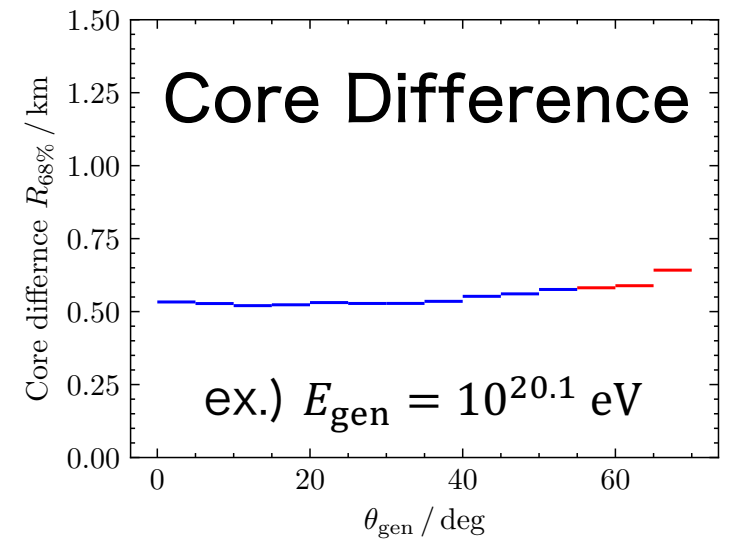
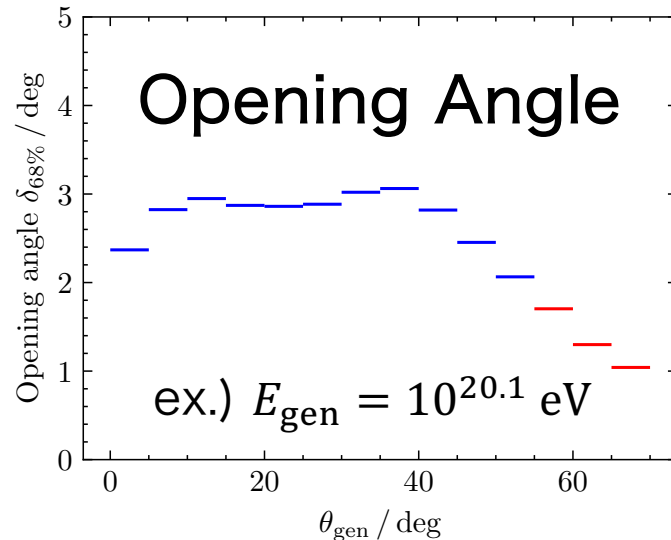
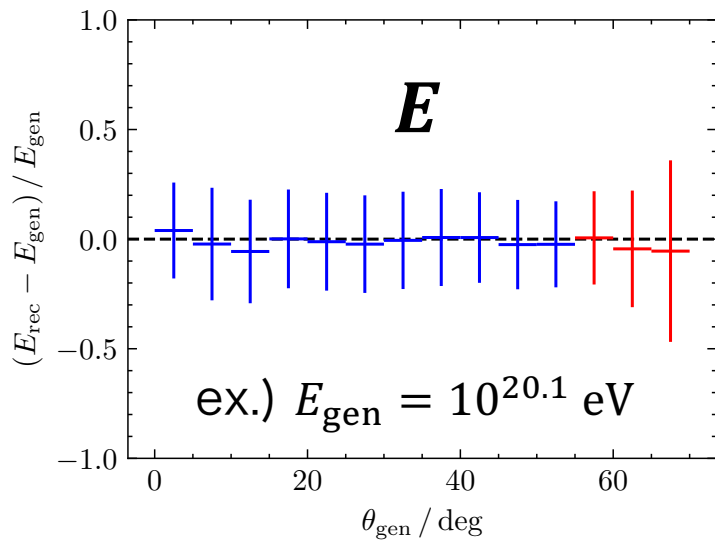
- Selection criteria
- $N_{\text{SD}} \geq 5$
 - $\theta_{\text{rec}} \leq 70^\circ$
 - $D_{\text{border}} \geq 400 \text{ m}$
 - $\chi^2/\text{ndf} \leq 4$
 - $\sigma_{\text{point direction}} < 8^\circ$
 - $\sigma(S_{800})/S_{800} < 0.5$

This extended table for the TA×4 SD enables the energy reconstruction of the primary cosmic ray in the range from 0deg to 70deg in zenith angle.

Evaluation of Reconstruction Accuracy TA \times 4 SD



Reconstruction accuracies of each parameter have been evaluated for each zenith angle. \Rightarrow **Accuracies preserved** for large zenith angle events



Data/MC Comparison

$E_{\text{rec}} \geq 10^{18.8}$ eV Flux normalize

TAx4 SD

Period

- Oct. 2019 to Oct. 2022

Selection criteria

- $N_{\text{SD}} \geq 5$

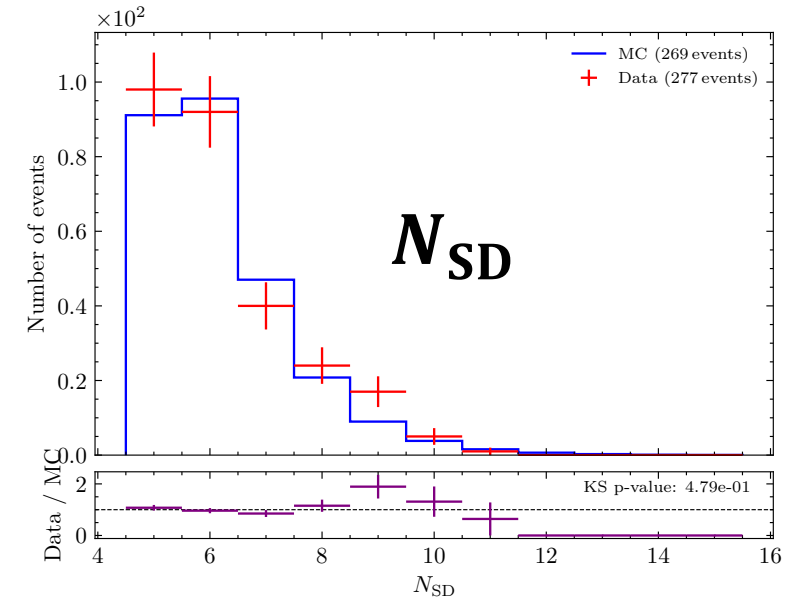
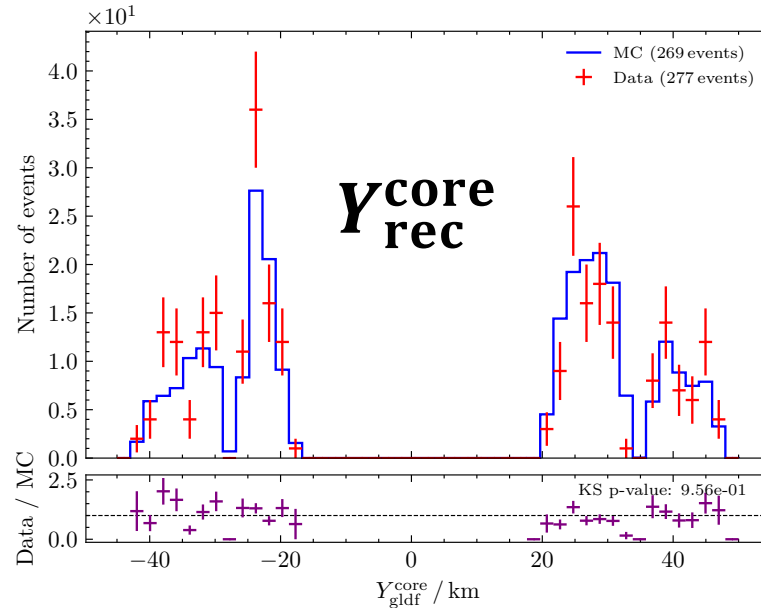
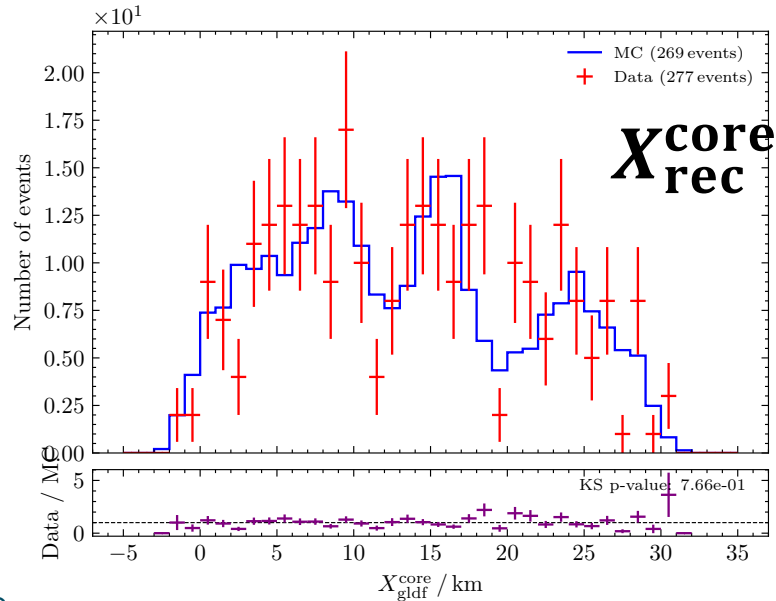
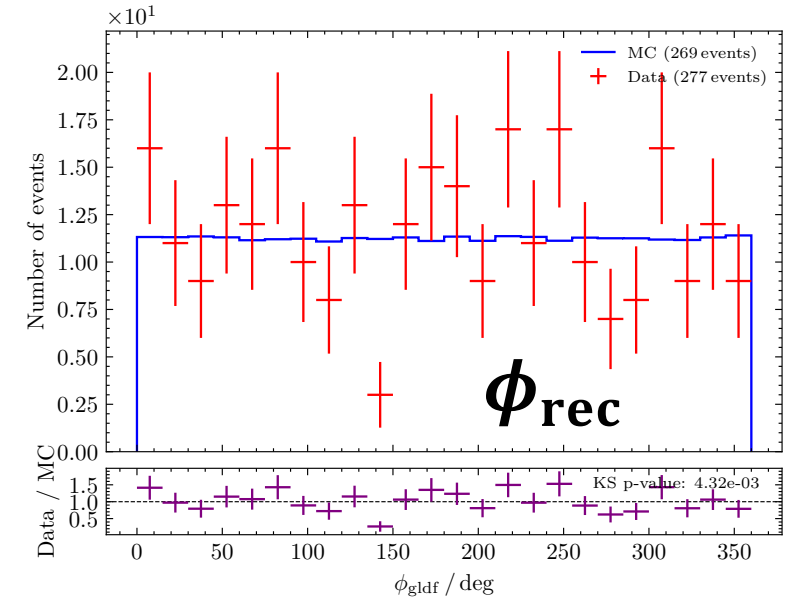
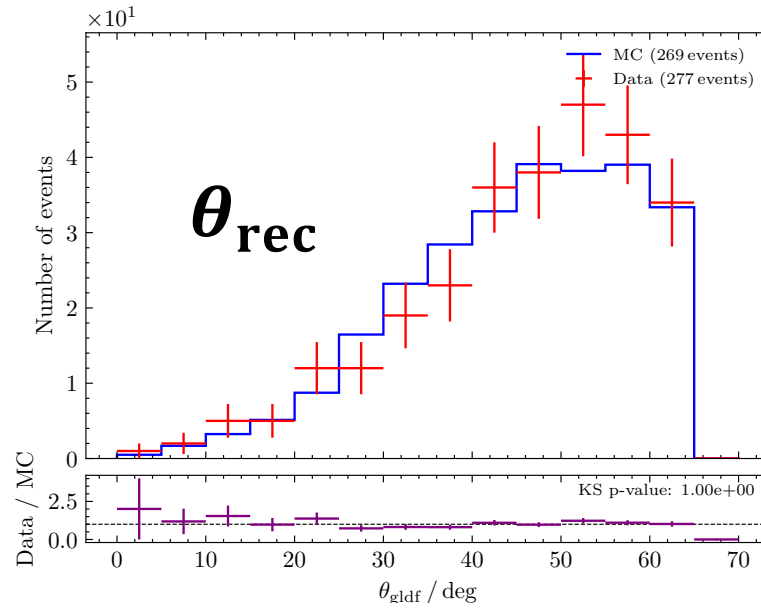
- $\theta_{\text{rec}} \leq 65^\circ$

- $D_{\text{border}} \geq 400$ m

- $\chi^2_{\text{rec}}/\text{ndf} \leq 4$

- $\sigma_{\text{point direction}} < 8^\circ$

- $\sigma(S_{800})/S_{800} < 0.5$



Data/MC Comparison

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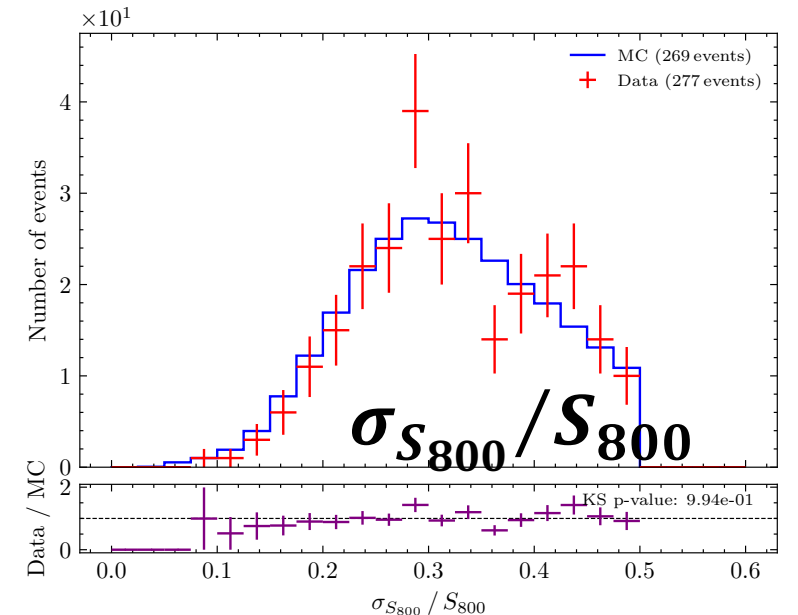
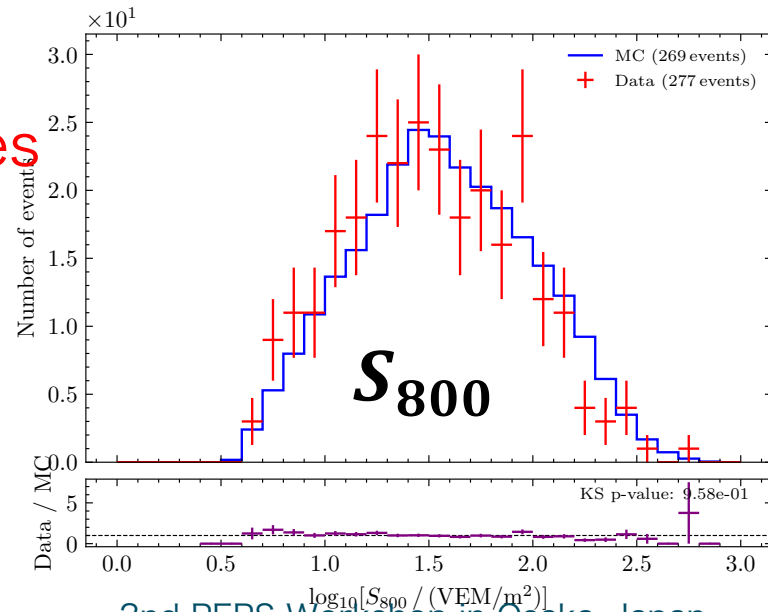
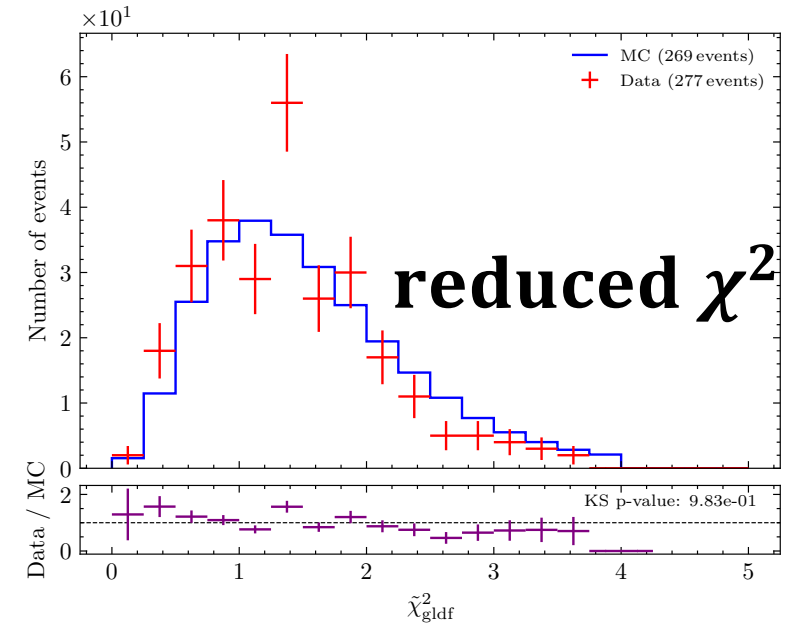
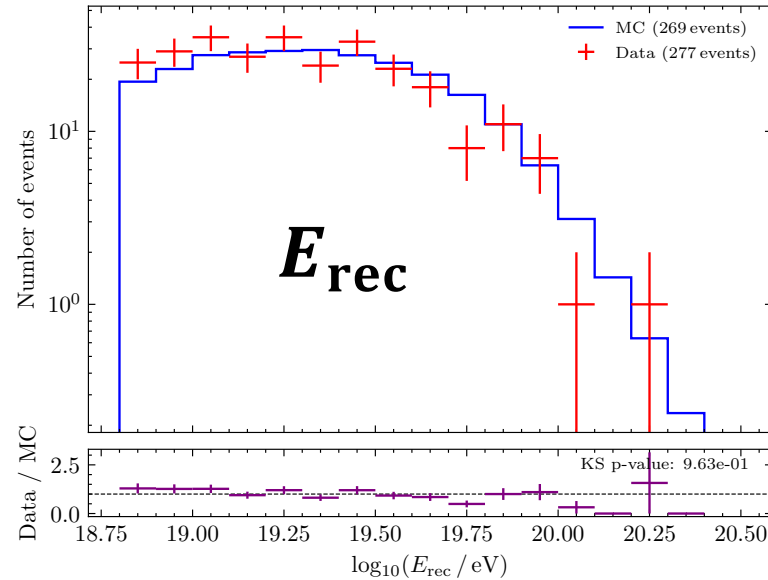
- $D_{\text{border}} \geq 400$ m

- $\chi^2_{\text{rec}}/\text{ndf} \leq 4$

- $\sigma_{\text{point direction}} < 8^\circ$

- $\sigma(S_{800})/S_{800} < 0.5$

No significant discrepancies
between observed data
and MC simulation

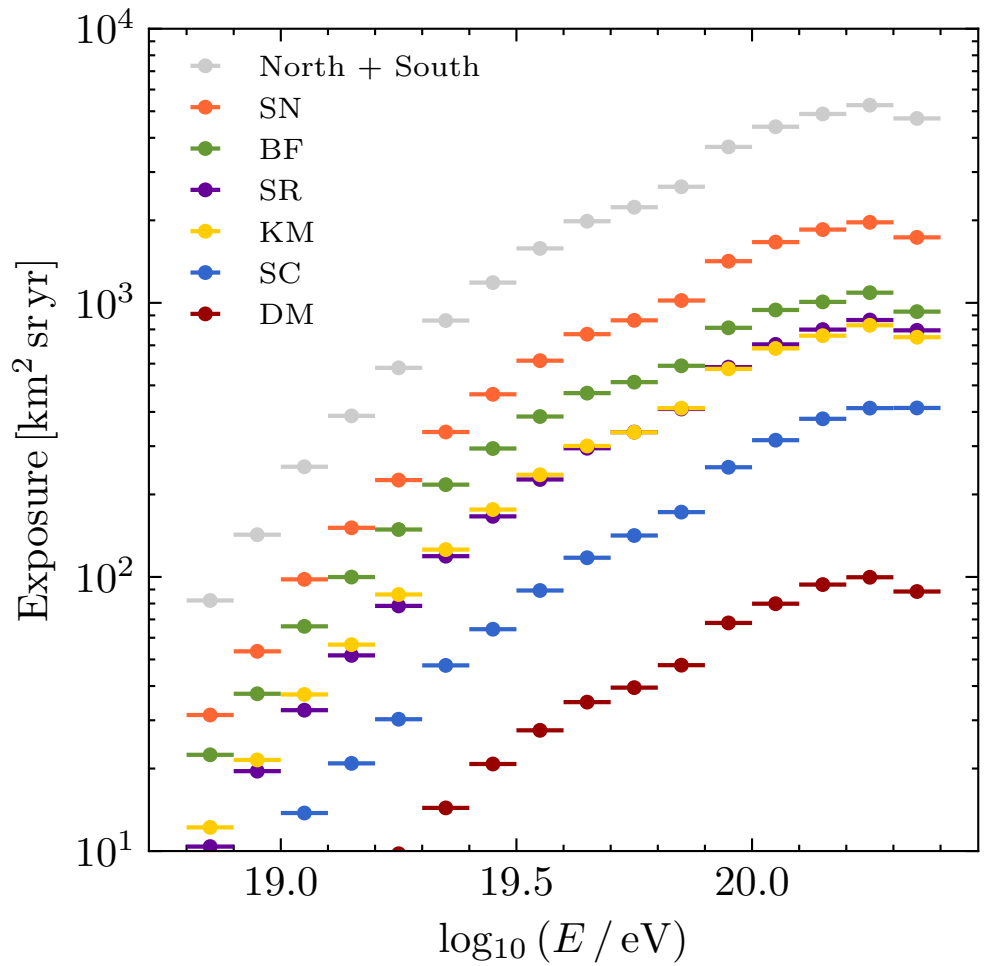


Effective Exposure

$$J_i = \frac{\sum_{\text{s.a.}} \frac{(N_{\text{rec}}^{\text{Data}})_i}{\Delta E_i}}{\sum_{\text{s.a.}} \left[\frac{(N_{\text{rec}}^{\text{MC}}(E_{\text{rec}}))_i}{(N_{\text{gen}}^{\text{MC}}(E_{\text{gen}}))_i} A_{\text{gen}} \Omega_{\text{gen}} T \right]}$$

Effective exposure considering bin-to-bin migration

	TAx4 North array			TAx4 South array		
Sub-array	KM	DM	SN	BF	SR	SC
MC Area A_{gen} [km ²]	~120	~40	~230	~150	~140	~110
Duration T [days]	1120	1102	1120	1093	1120	1120



Exposure values were smaller in the highest E bin than in the lower E bins, because the highest E of the energy estimation table is too low.

Energy Spectrum

$$J_i = \frac{\sum_{\text{sub-arrays}} \frac{(N_{\text{rec}}^{\text{Data}})_i}{\Delta E_i}}{\sum_{\text{sub-arrays}} \left[\frac{(N_{\text{rec}}^{\text{MC}})_i}{(N_{\text{gen}}^{\text{MC}})_i} A_{\text{gen}} \Omega_{\text{gen}} T \right]}$$

Comparison on the numbers of events of observed data $N_{\text{rec}}^{\text{Data}}$ above $10^{18.8}$ eV

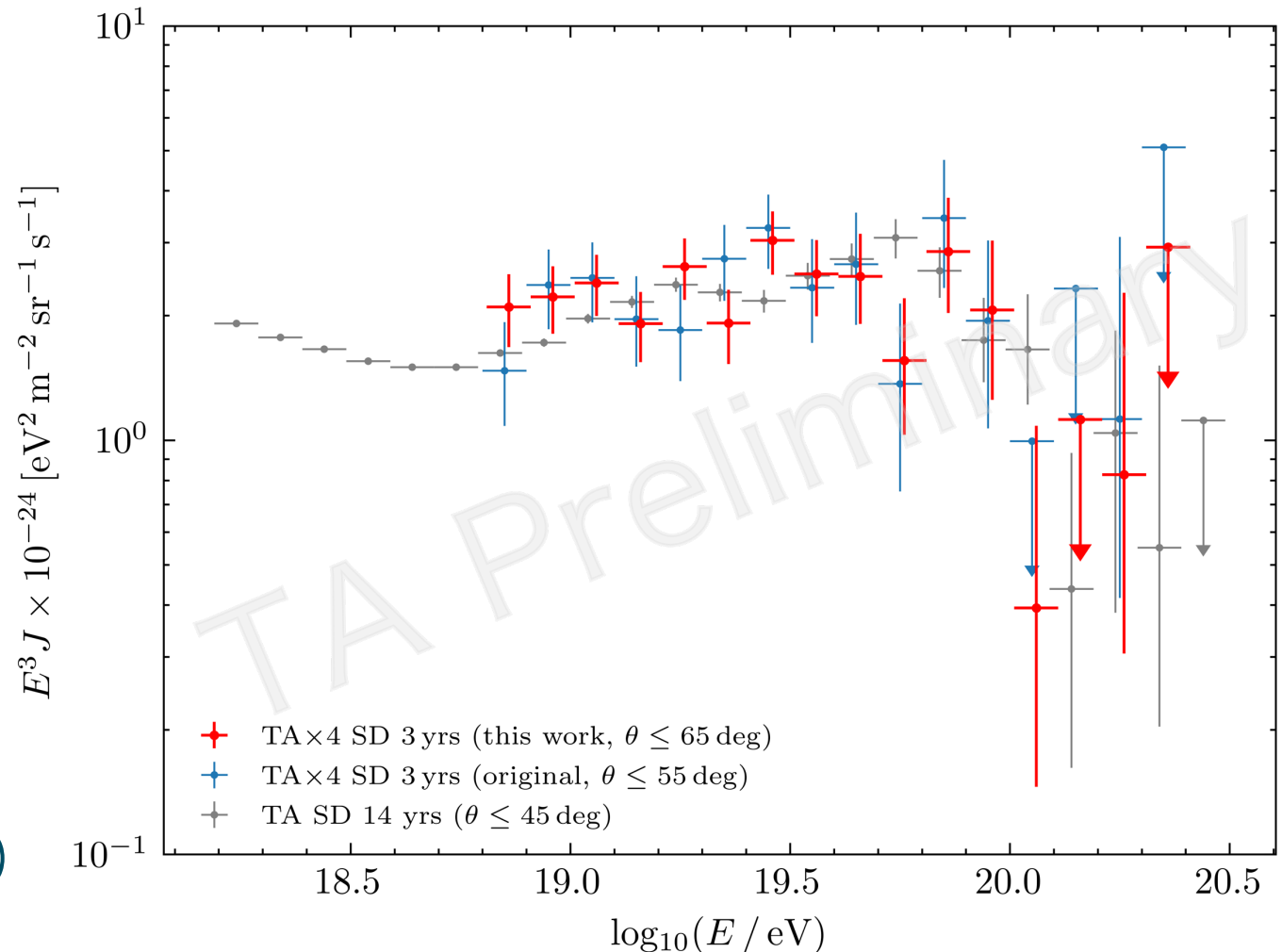
TAx4 SD
original analysis
(Criteria : $\theta \leq 55^\circ$)

$$N_{\text{rec}}^{\text{Data}} = 186$$

$\sim 1.5\times$ increase

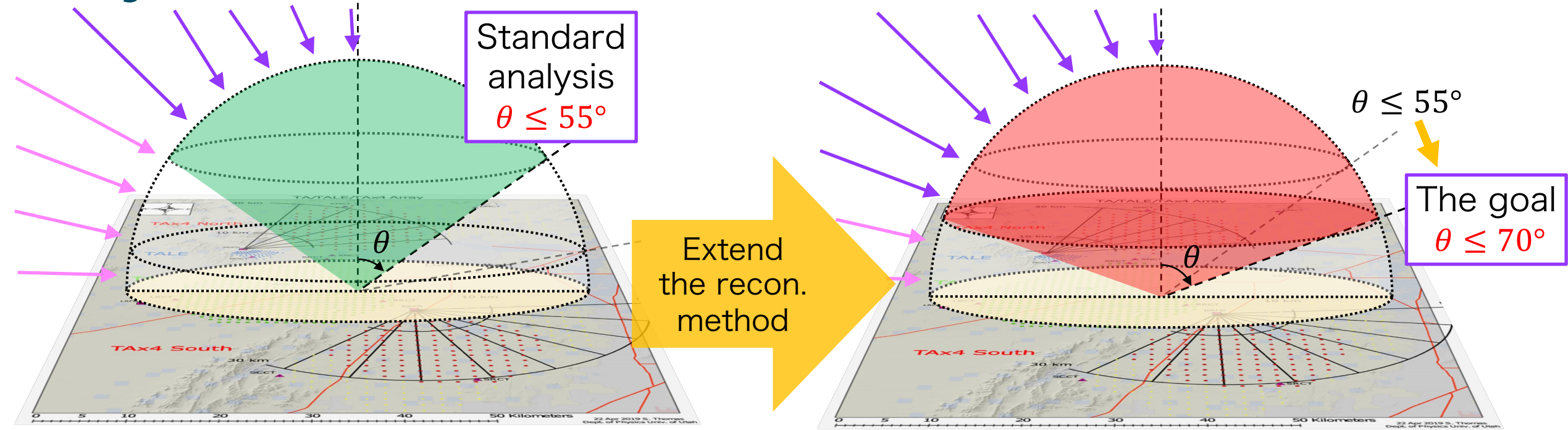
This work
(Criteria : $\theta \leq 65^\circ$)

$$N_{\text{rec}}^{\text{Data}} = 277$$



This is higher than expected increase from expansion of aperture ($\sim 1.2\times$) because events in the low-energy region are more likely to be reconstructed in the large zenith angle region.

Why Inclined Events?



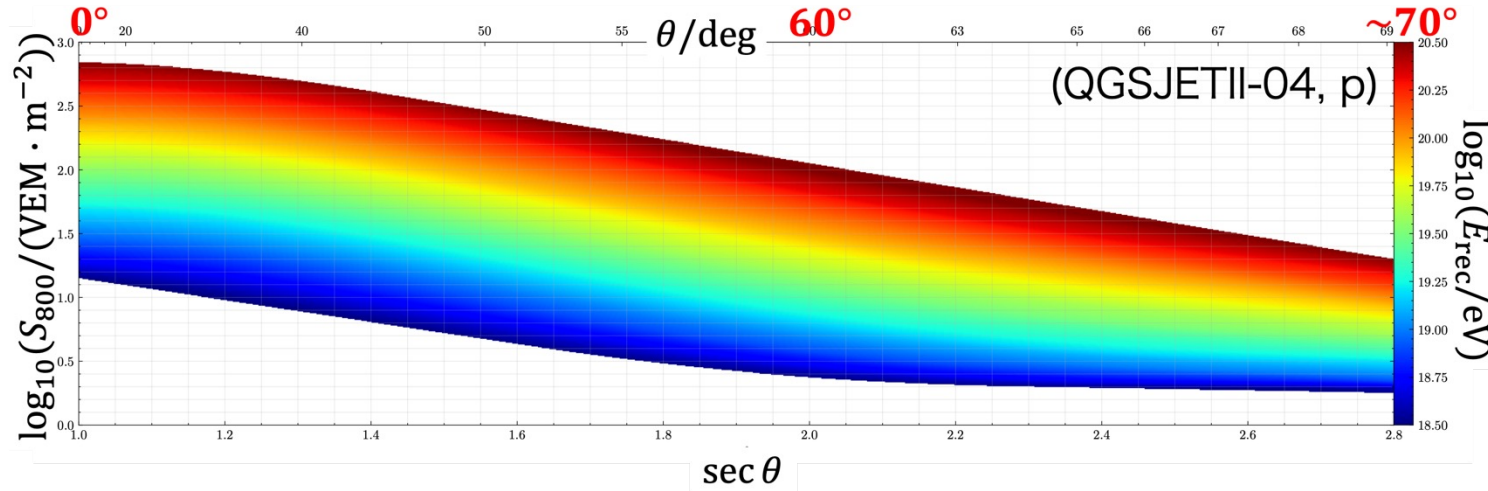
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- TA SD 18yr observation \rightarrow TA SD ~ 23 yr observation equivalent

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Muon component is dominant \rightarrow Suitable for study on muon excess

Extension of E est. & Evaluation of Accuracy

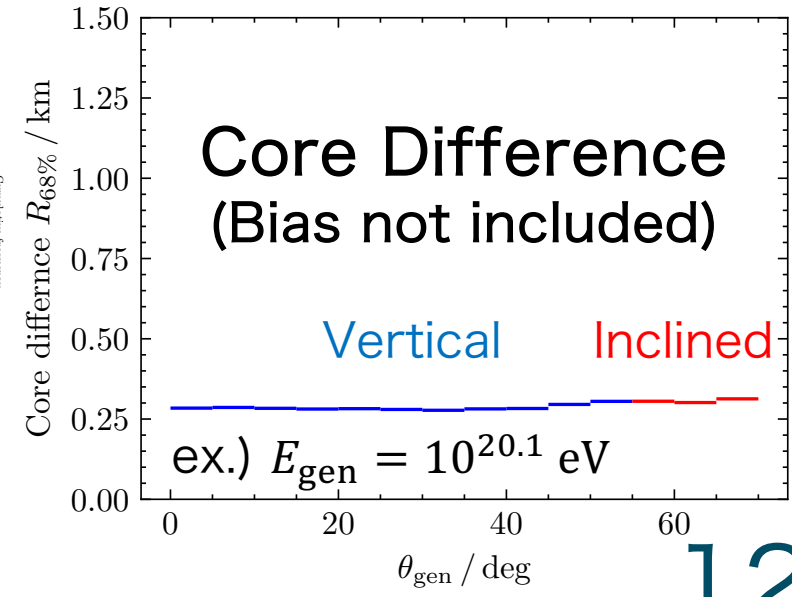
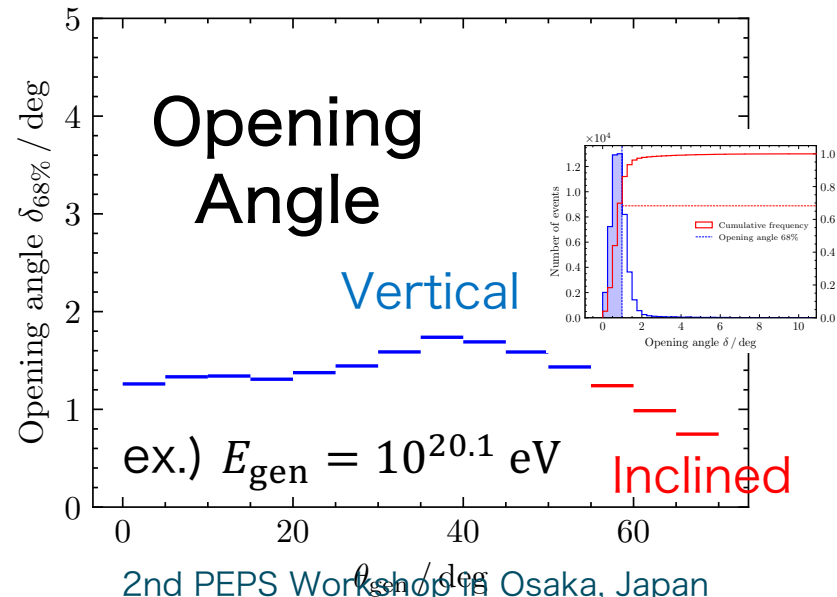
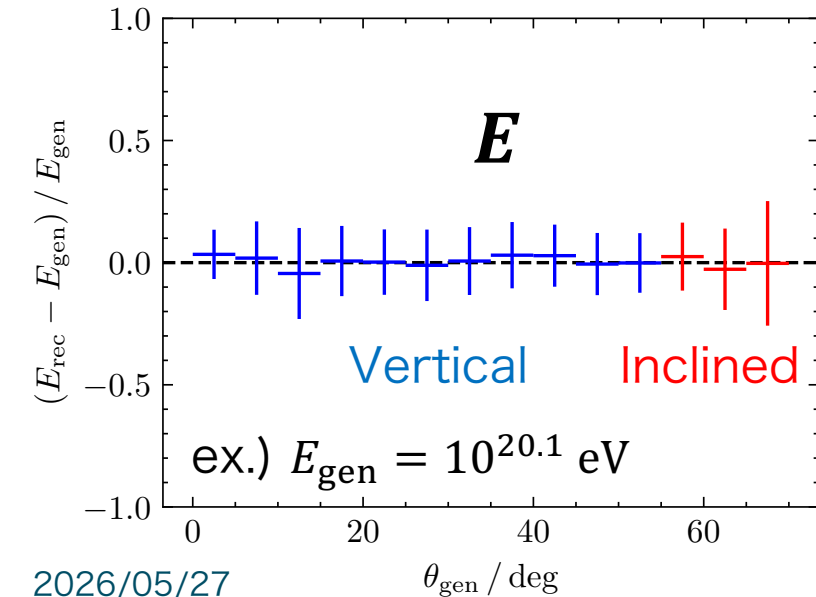


TA SD

p lookup table

Model
- QGSJETII-04

Reconstruction accuracies of each parameter were also evaluated for each Zd.
 ⇒ Accuracies preserved for large zenith angle events



Data/MC Comparison

Area normalize

p lookup table

TA SD

Period

- May 2008 to May 2024

Selection criteria

- $E_{tbl} \geq 10^{19.0}$ eV

- $N_{SD} \geq 5$

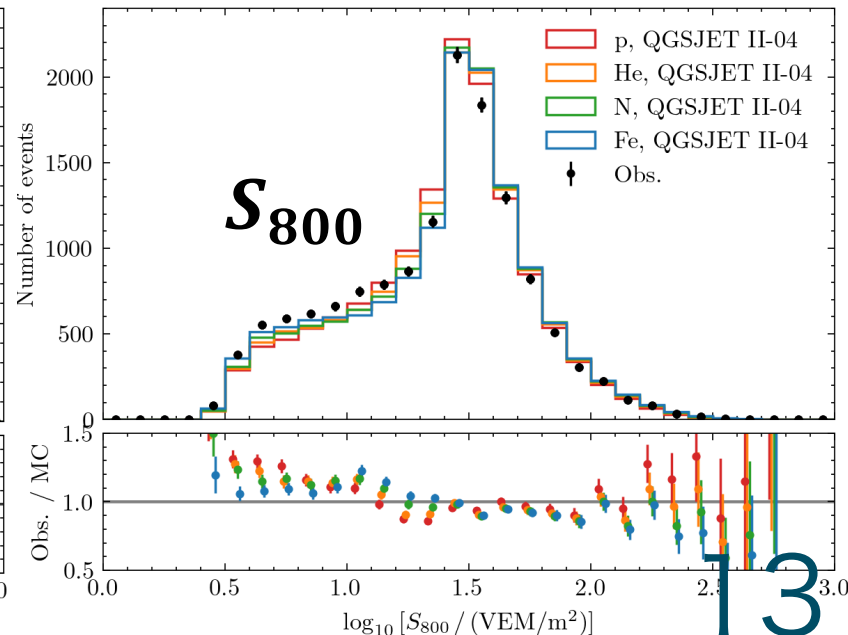
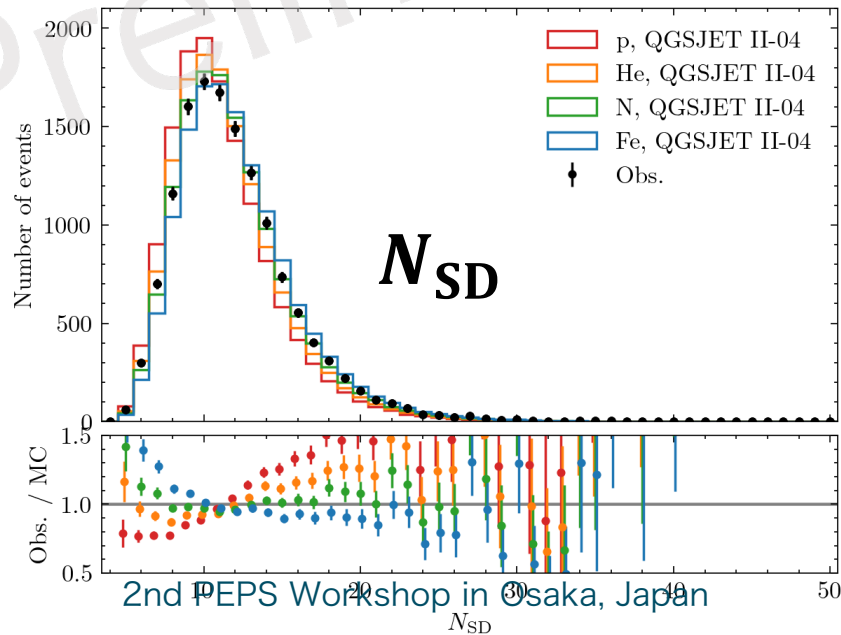
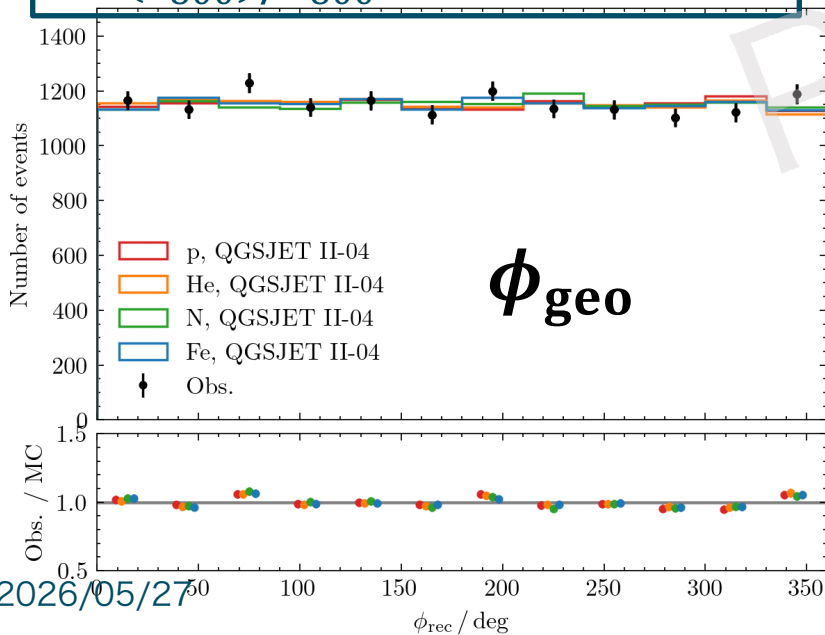
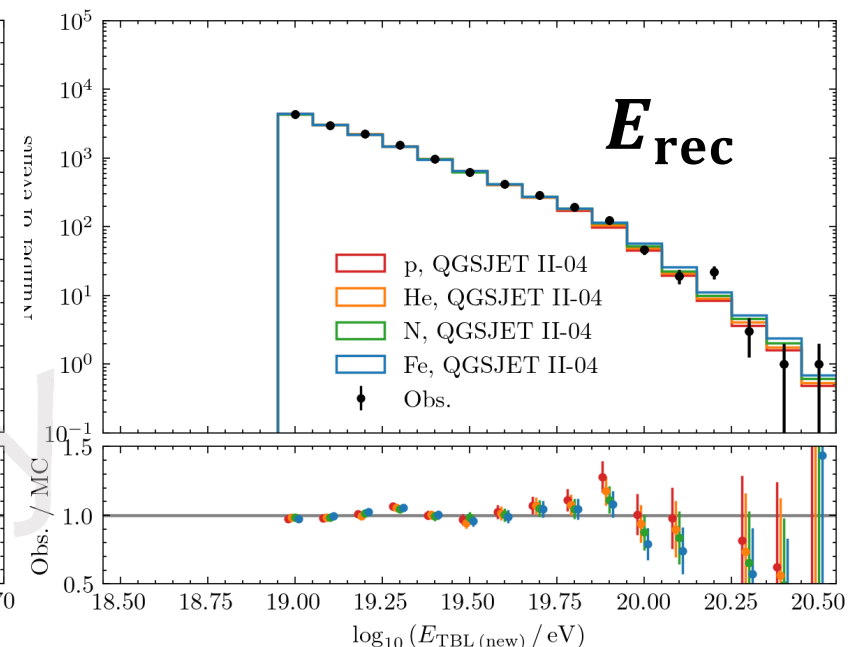
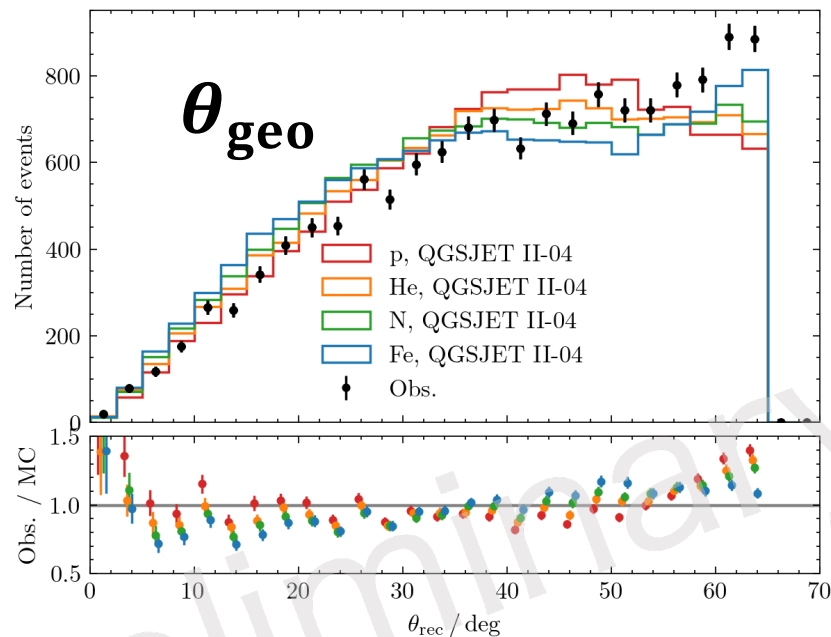
- $\theta_{geo} \leq 65^\circ$

- $D_{border} \geq 1.2$ km

- $\chi_{geo}^2/ndf \leq 4 \cap \chi_{LDF}^2/ndf \leq 4$

- $\sigma_{pointing\ direction} < 5^\circ$

- $\sigma(S_{800})/S_{800} < 0.25$



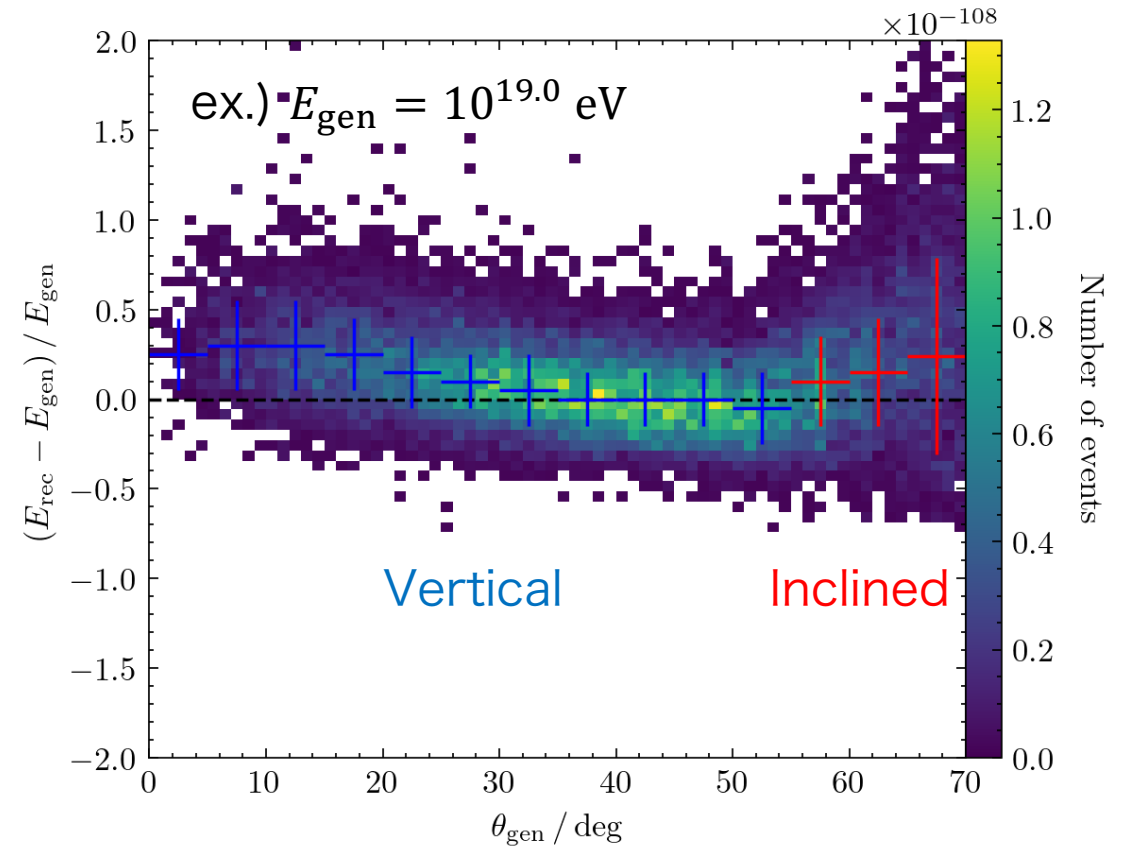
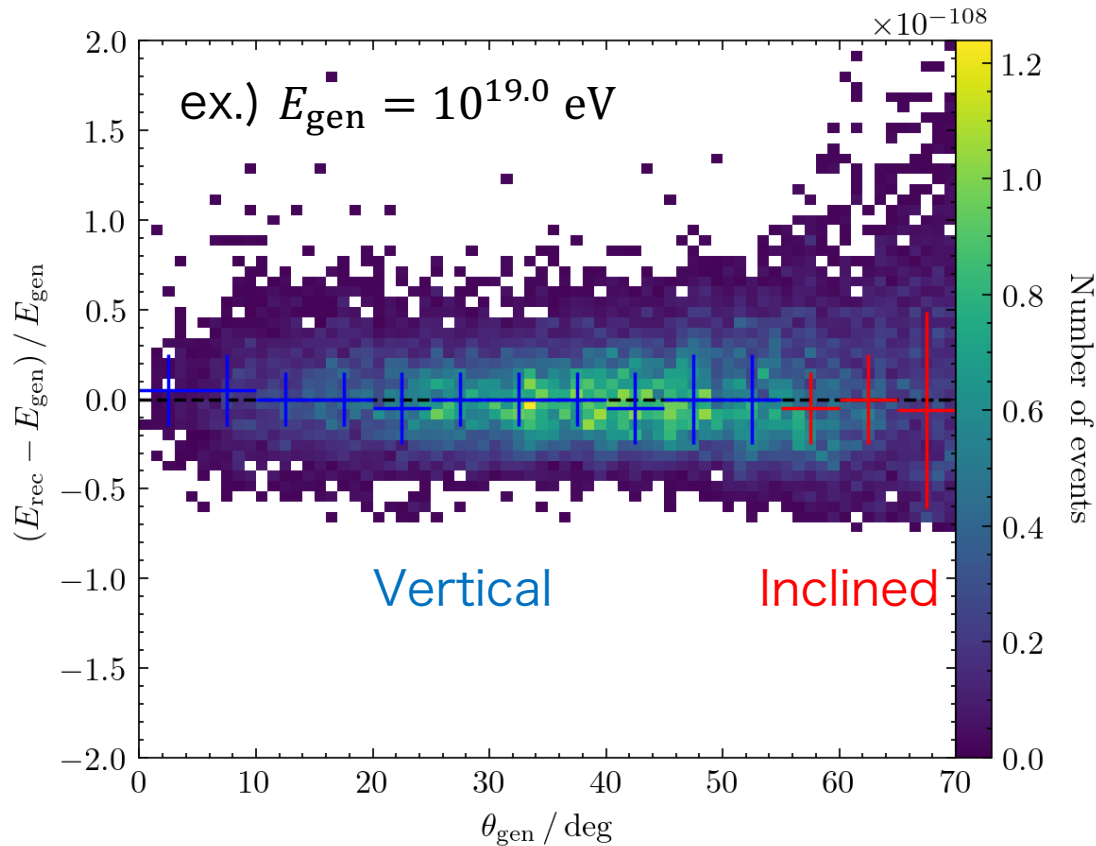
Energy Accuracies vs. Zenith Angles

TA SD

p lookup table

p MC by p (new) lookup table

Fe MC by p (new) lookup table



Increase the number of events with zenith angle above $\sim 50\text{deg}$ in heavier (Fe) MC distributions derives from events with overestimated energy due to using the **proton** energy lookup table.

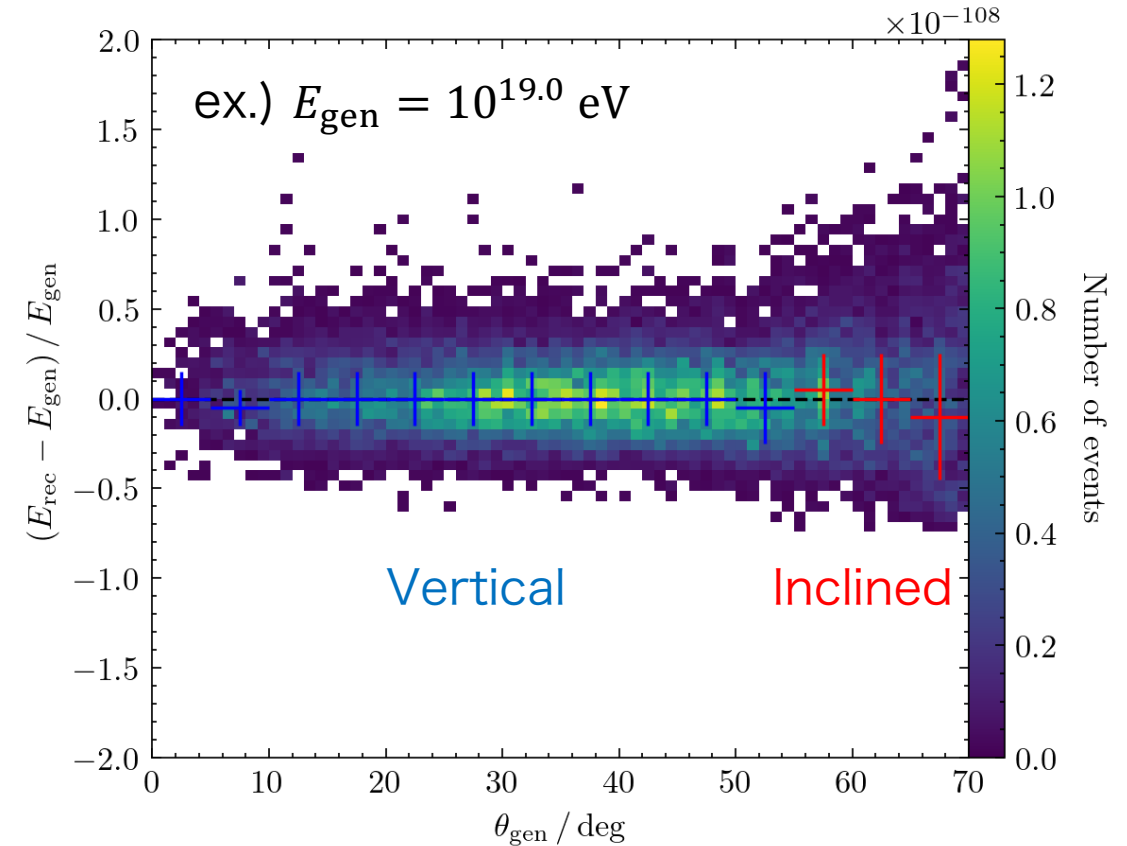
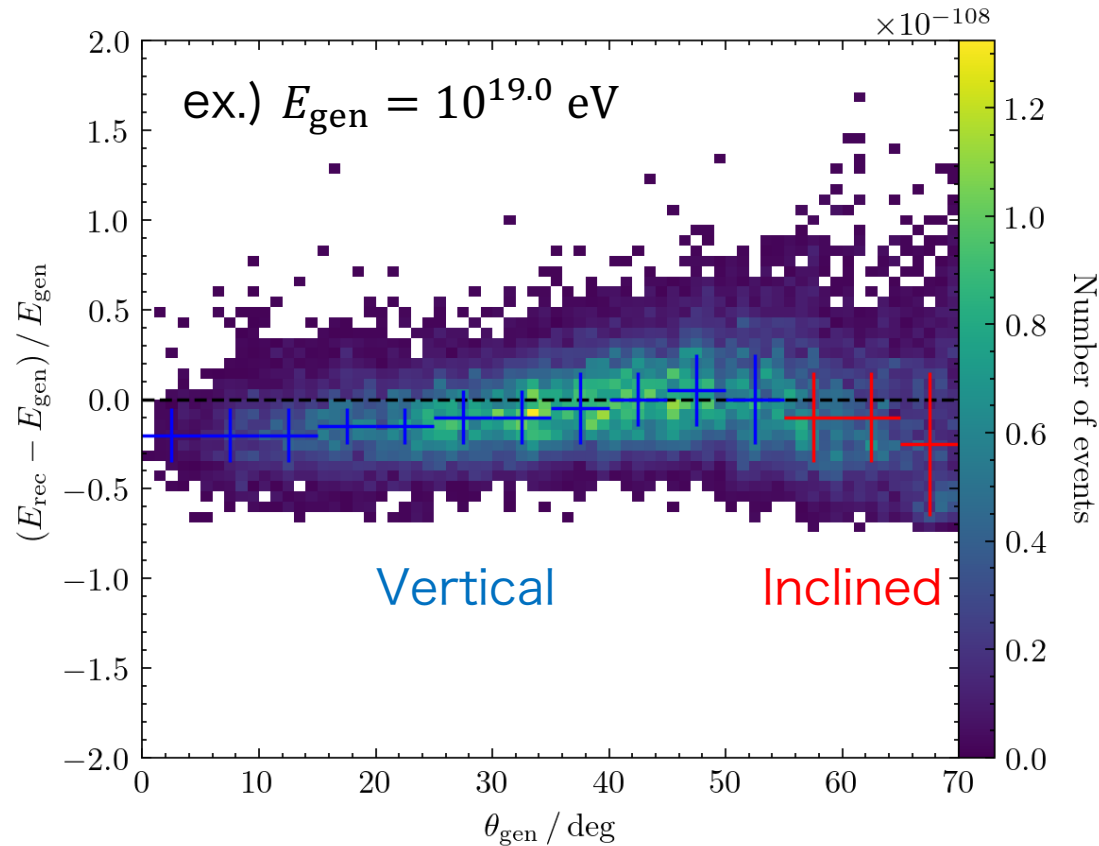
Energy Accuracies vs. Zenith Angles

TA SD

Fe lookup table

p MC by Fe lookup table

Fe MC by Fe lookup table



Reconstruction accuracies of energy were evaluated for each zenith angle.
⇒ **Opposite trends** to p lookup table case

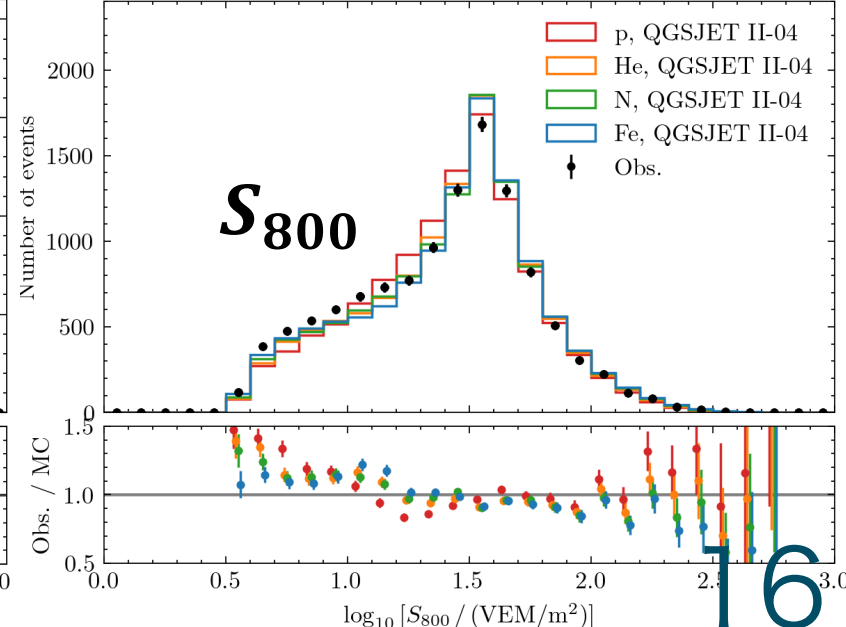
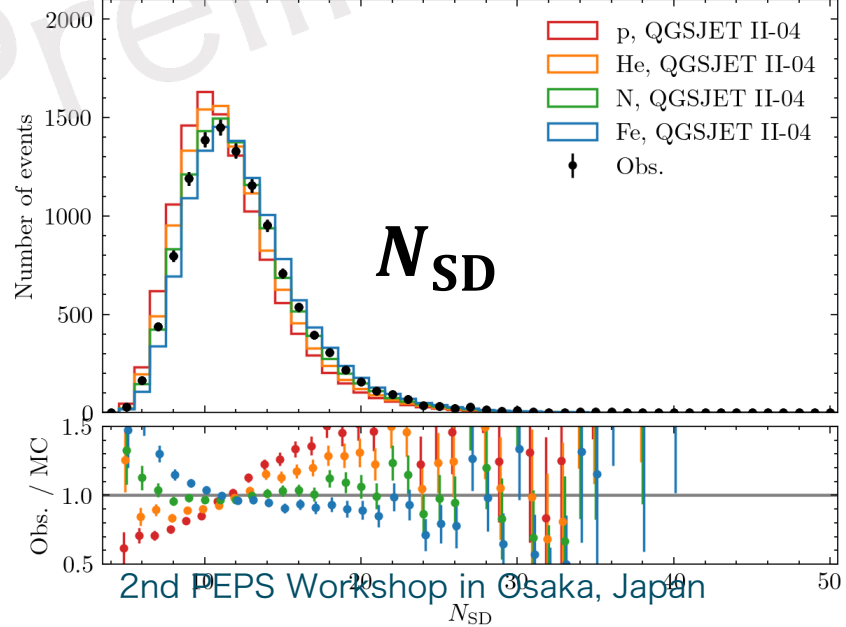
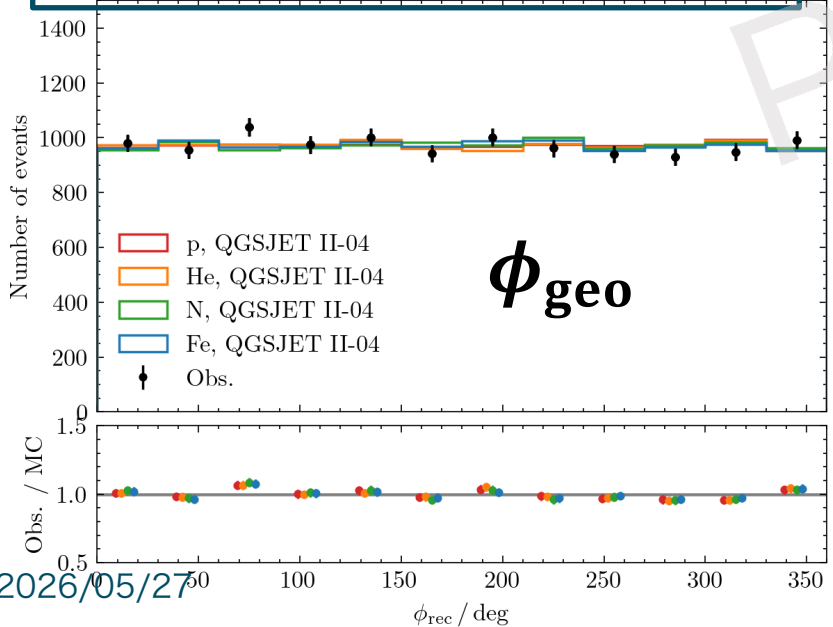
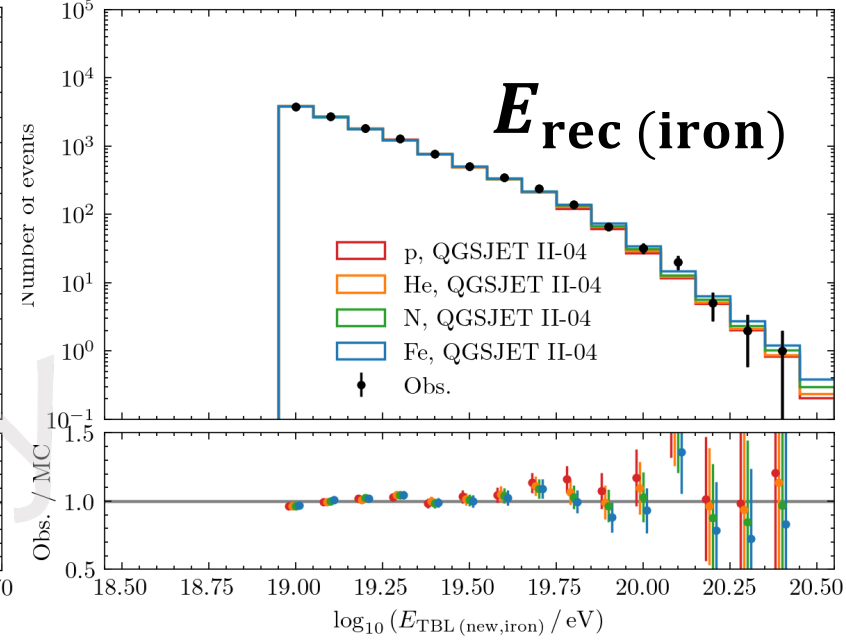
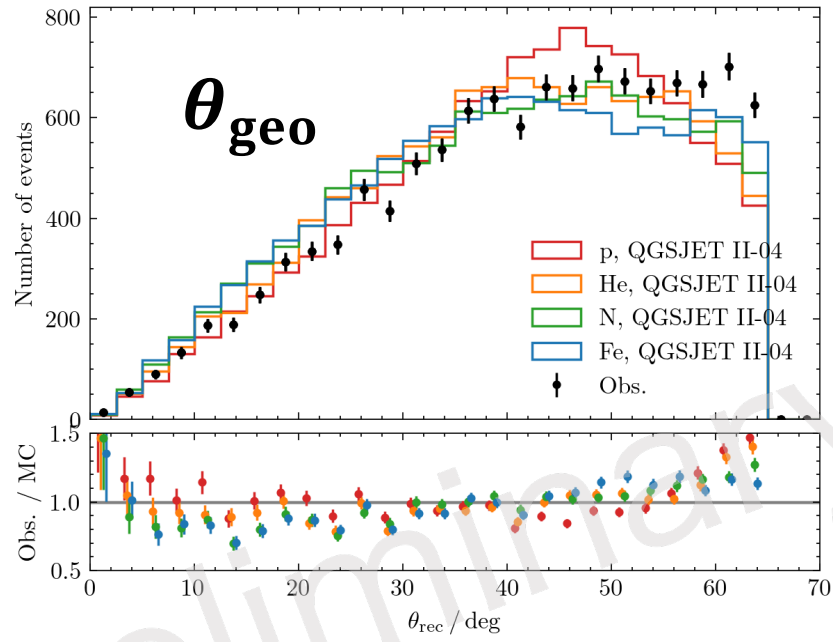
Data/MC Comparison

Area normalize

Fe lookup table

TA SD

- Period
 - May 2008 to May 2024
- Selection criteria
- $E_{tbl} \geq 10^{19.0}$ eV
 - $N_{SD} \geq 5$
 - $\theta_{geo} \leq 65^\circ$
 - $D_{border} \geq 1.2$ km
 - $\chi^2_{geo}/ndf \leq 4 \cap \chi^2_{LDF}/ndf \leq 4$
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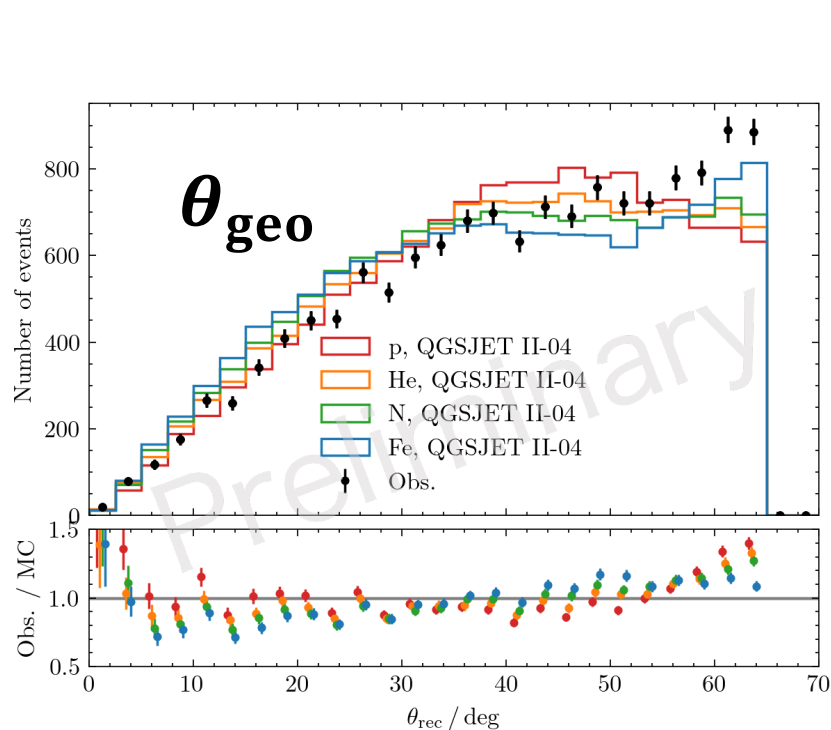


2026/05/27

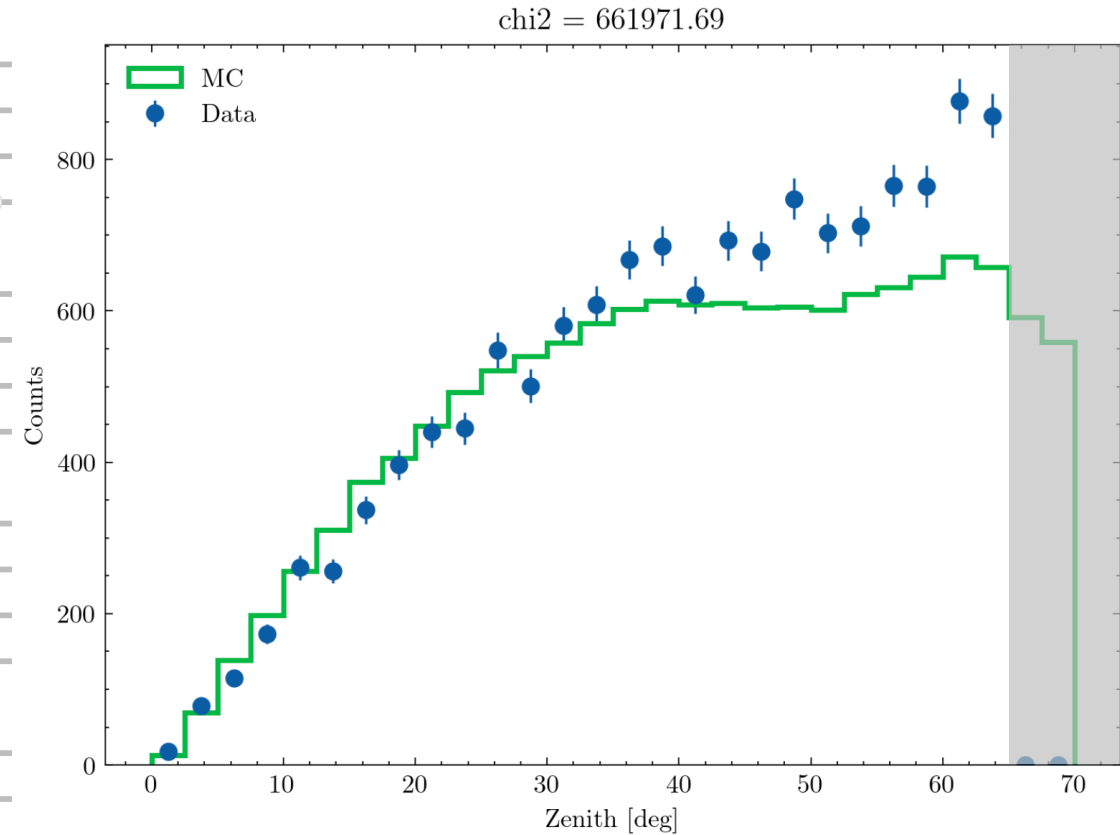
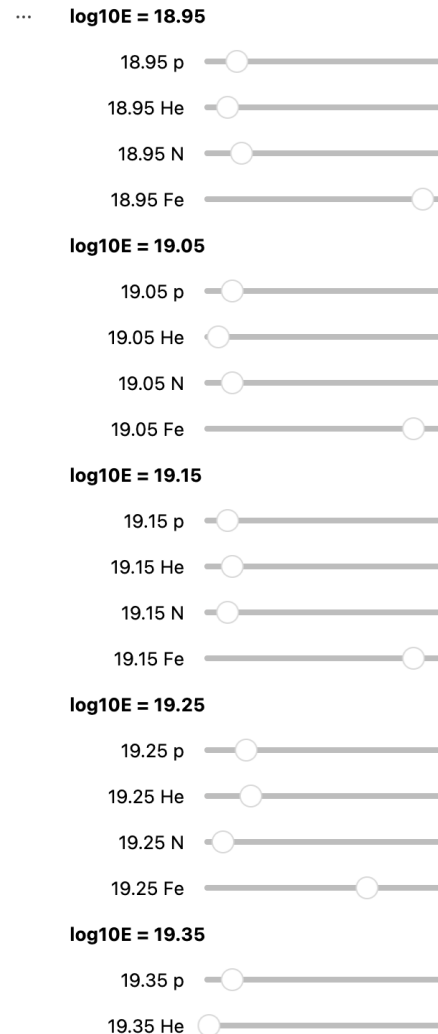
2nd PEPS Workshop in Osaka, Japan

Mass fractions fitting

Mass fractions of each energy were fitted based on the agreement of Data/MC



Comparing observed data to pure composition MCs



No mass fractions for each energy likely exists that would properly reproduce observed data.

Data/MC Comparison

Area normalize

QGSJETII-04
p table

TA SD

Period

- May 2008 to May 2024

Selection criteria

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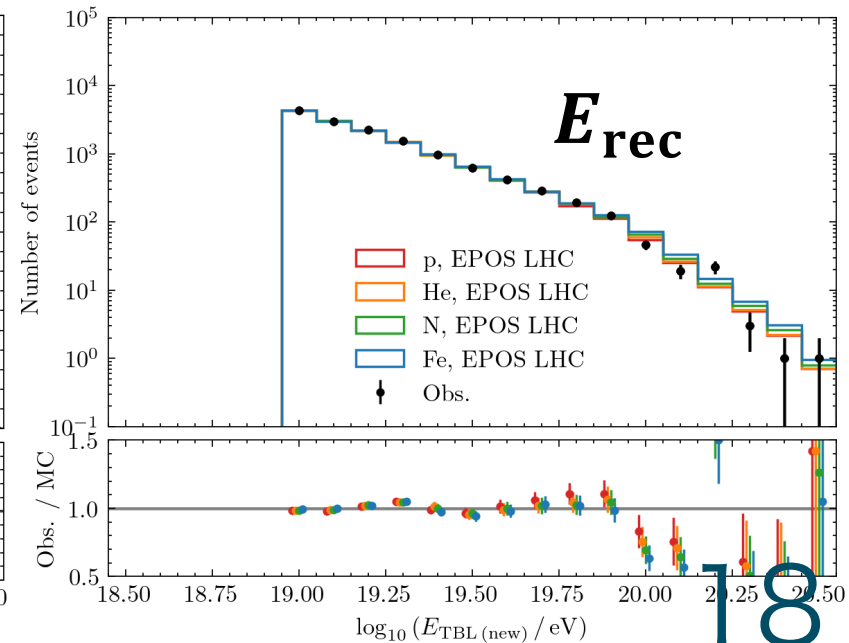
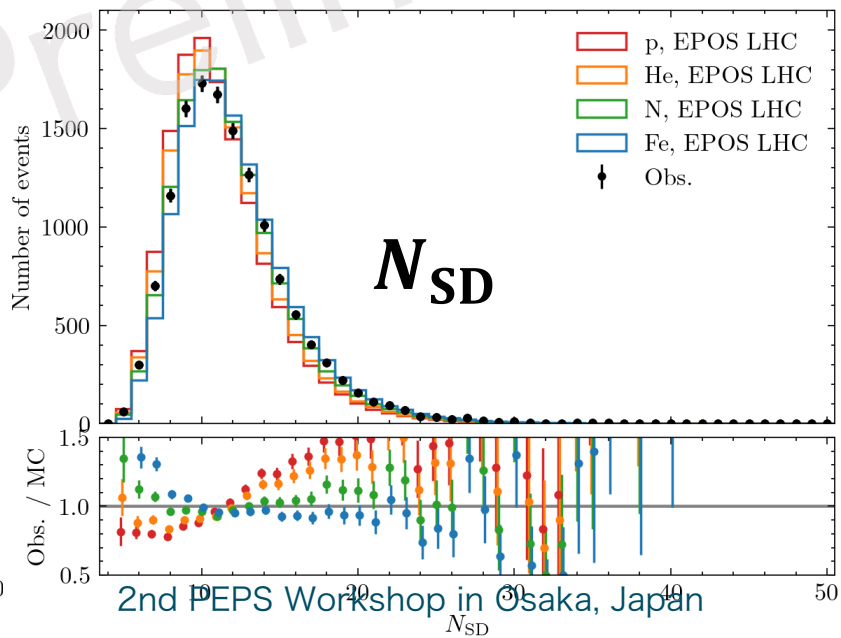
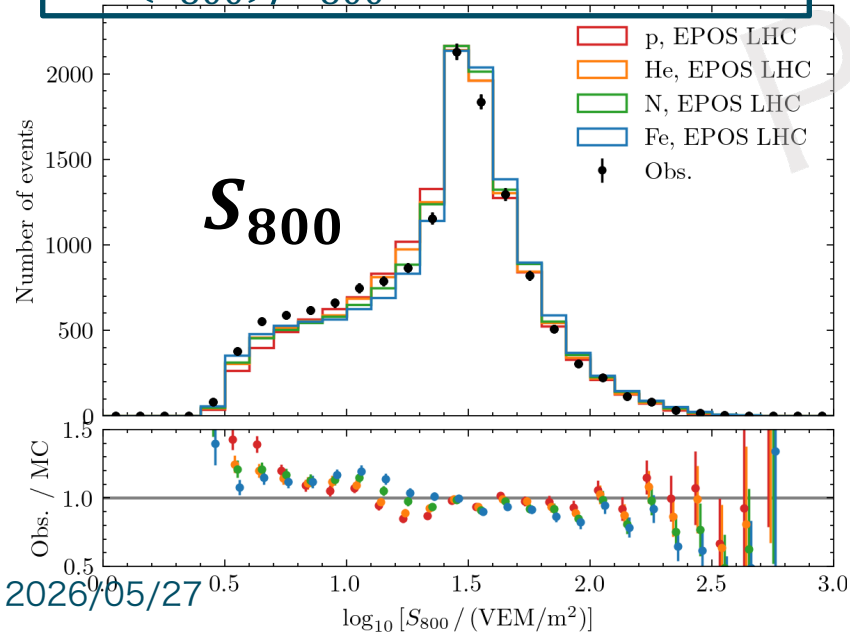
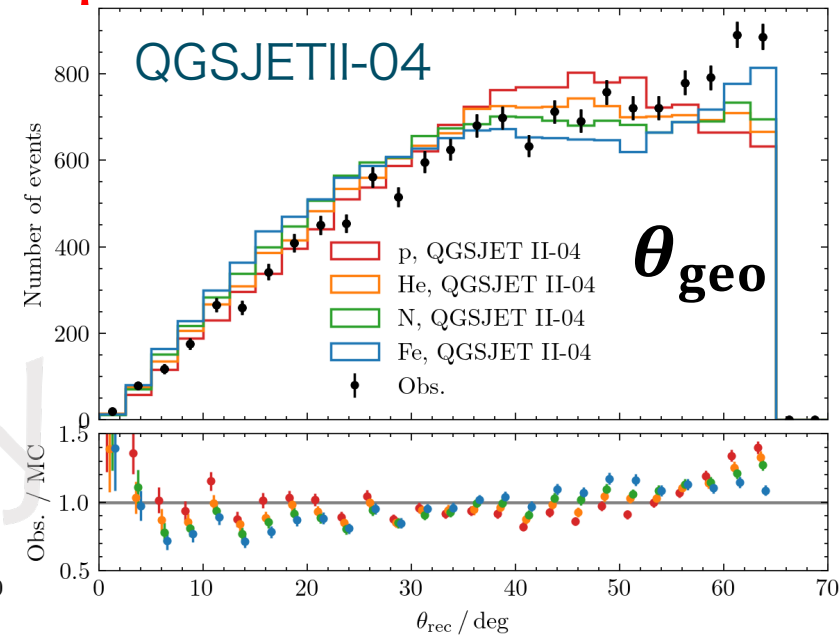
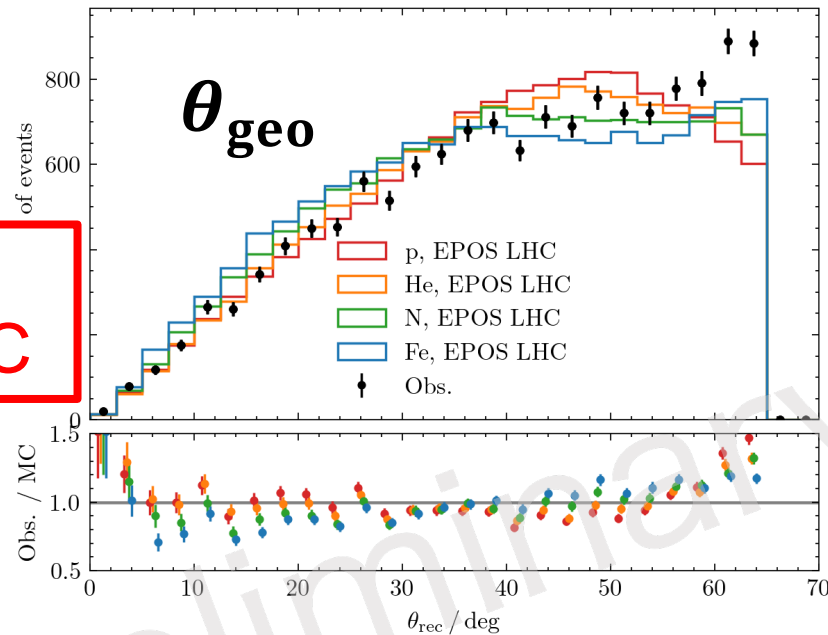
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- $\sigma(S_{800})/S_{800} < 0.25$

Model
- EPOS LHC



Summary

TA×4 SD

- The energy estimation was extended and Data/MC comp. were performed.
⇒ No significant discrepancies between observed data and MC
- Energy spectrum by TA×4 SD with inclined events was measured.
⇒ Good agreement with the previous analyses and achieved **~1.5× statistics**

TA SD

- Similar analysis for TA SD (Data/MC comparison w/ 4 primaries & 2 models)
⇒ Heavier (Fe) MCs show better agreement with observed data in Zd dist.
However, Zd distribution of observed data still shows excess in large Zd.
No mass fractions for each energy that would reproduce observed data.

To do

- Data/MC comparison using MC with much higher muon content?
- Try a different method for estimating energy → **CIC method**