Analysis of Inclined Air Showers with the TA Surface Detector Array

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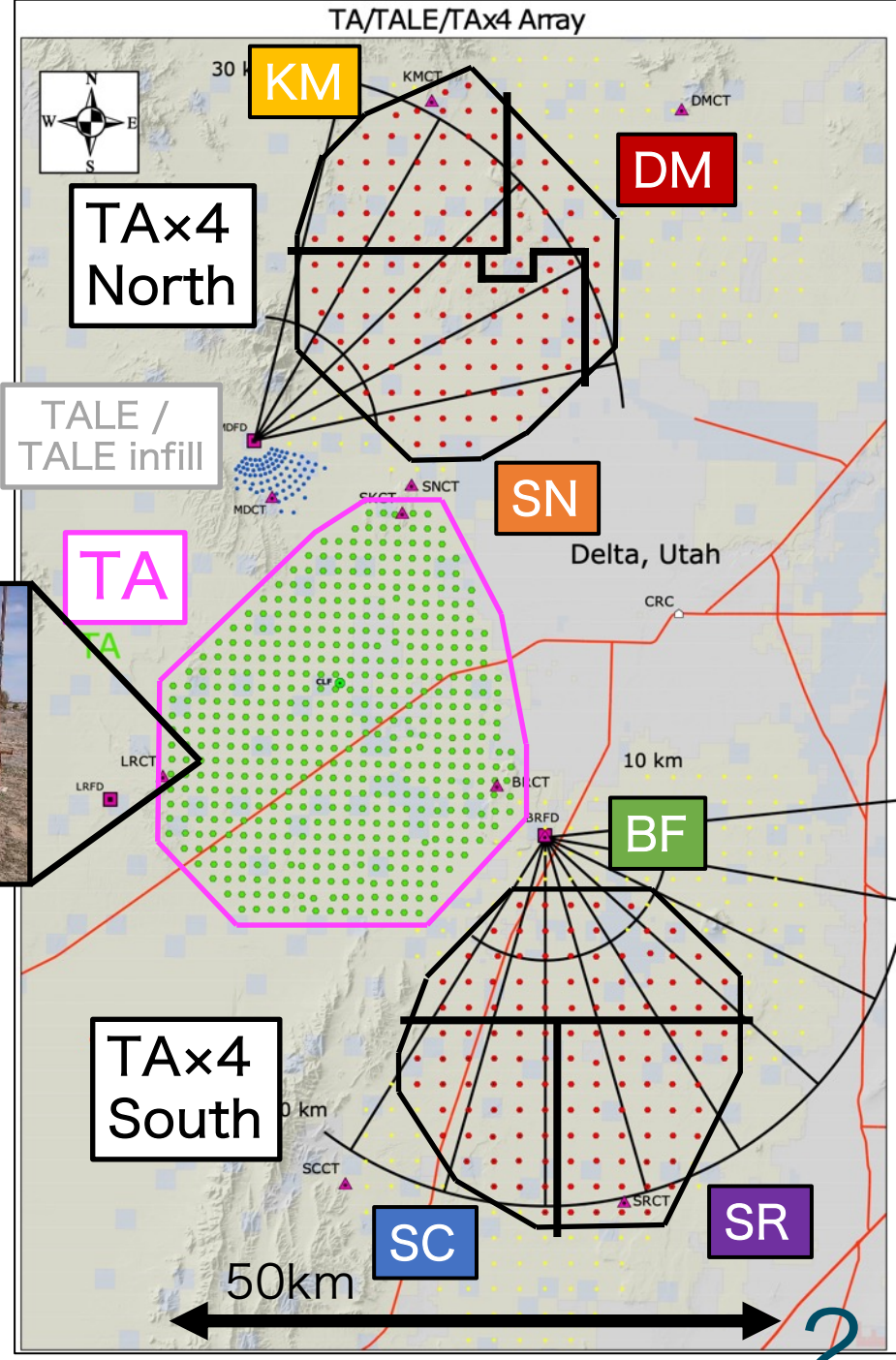
TA and TA×4

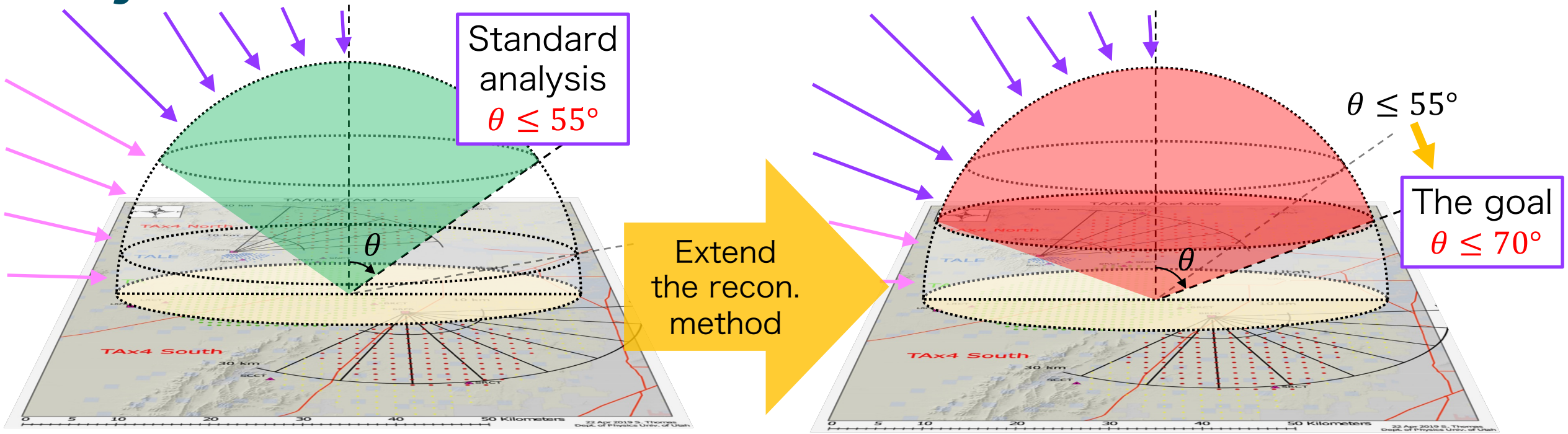
Telescope Array (TA) has been observing extended air showers with both surface detector (SD) arrays and fluorescence detectors (FDs) for 17 years to reveal the origin of ultra high-energy cosmic rays (UHECRs).
TA SD array contains 507 SDs spaced 1.2km apart.
Each SD consists of 2 layers of plastic scintillation detector (3m^2 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 ~3000km^2 with 500 SDs



Why Inclined Events?



If extended from 55deg to 70deg, ~1.3× aperture of surface detector array
= Retroactively increase the number of events for UHECRs observation.
- TA×4 SD 6yr observation → TA×4 SD ~8yr observation equivalent
- TA SD 17.5yr observation → TA SD ~23yr observation equivalent

Visible region on the sky expands to lower declination.

Muon component is dominant → Suitable for study on muon excess

Ongoing Analysis and Future Plan

Telescope Array has been observing UHECRs using SD array since 2008.

Much higher statistics are required especially for UHECRs to identify their origin.
→ TA×4 expansion (expand array area) and
Inclined air showers analysis (retroactively enlarge aperture)

This talk!

Inclined Air Showers Analysis for TA×4 SD → Achieved ~1.5× increase in stat.
Similar Analysis for TA SD is now being performed. → Increasing furthermore

We are trying to estimate UHECR mass using a DNN, from SD data (~10× stat. of FD)

If join inclined analysis and DNN analysis,
→ Obtain energy, arrival direction and mass together in the highest statistics ever
→ We can select highest and lighter events.

⇒ Charged particles “astronomy” in the future

cf.) Magnetic deflection of UHECR
$\sim 10^\circ\, Z \left(\frac{E}{10^{19}\ \mathrm{eV}}\right)^{-1}$ in several hundreds Mpc

Standard Reconstructions with SDs

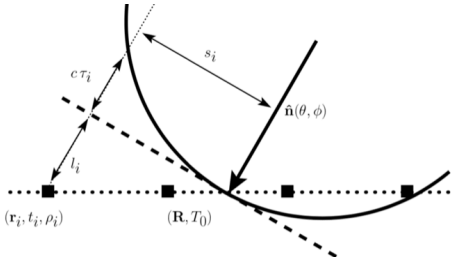
① Use detectors location and timing to determine shower core and direction

Geometry fitting

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

To minimize

$$\chi^2_{\rm G} = \sum_{i=0}^{N} \frac{(t_i - t_i^{\rm FIT})^2}{\sigma_{t_i}^2} + \frac{(\mathbf{R} - \mathbf{R}_{\rm COG})^2}{\sigma^2_{\mathbf{R}_{\rm COG}}}$$



where,

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

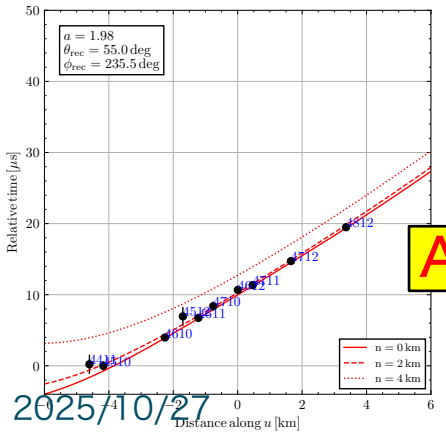
$$\sigma_t = \sqrt{\sigma_e^2 + \sigma_\tau^2}$$

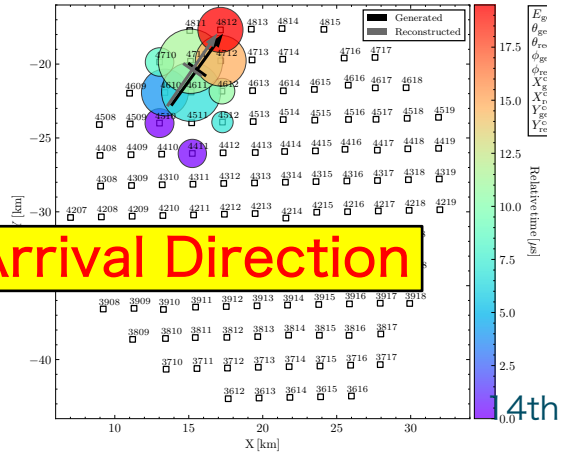
$$\tau = (8 \times 10^{-4}\mu{\rm S})\, a(\theta) \left(1.0 + \frac{s}{30{\rm m}}\right)^{1.5} \rho^{-0.5}$$

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

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

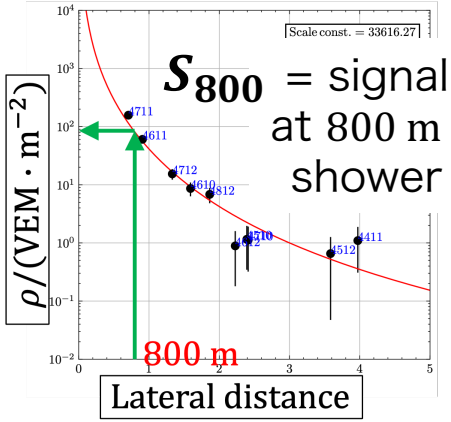
$$c_0 = -7.76168 \times 10^{-2},\ c_1 = 2.99113 \times 10^{-1},$$
$$c_2 = -8.79358 \times 10^{-3},\ c_3 = 6.51127 \times 10^{-5}$$





Arrival Direction

② Fit counter signal size to find lateral distribution



S_{800} = signal size at 800 m from shower axis

LDF fitting

3 fitting parameters: R_x, R_y, A

To minimize

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

where,

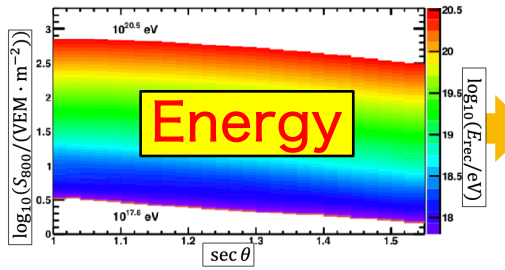
$$\rho = A \left(\frac{s}{91.6{\rm m}}\right)^{-1.2} \left(1 + \frac{s}{91.6{\rm m}}\right)^{-(\eta(\theta)-1.2)} \left(1 + \left[\frac{s}{1000{\rm m}}\right]^2\right)^{-0.6}$$

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

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

Energy determination

$$S800 \equiv \rho(800{\rm m})$$



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

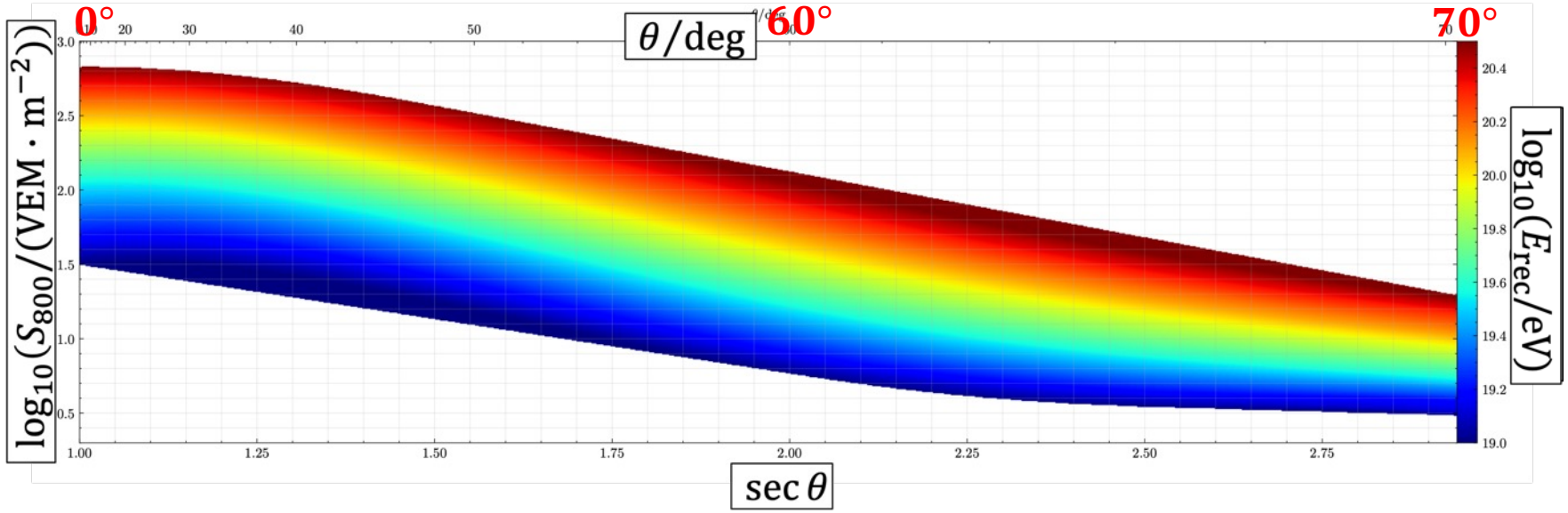
③ Use S_{800} and zenith angle to look up energy (from energy estimation table generated from MC)

Extension of Energy Estimation Table

TA×4 SD

Information from each SD → **Geometry Fit** Calculate θ, ϕ and core position → **LDF Fit** Determine S_{800} from the LDF → **Energy Estimation** Estimate E from S_{800} and θ using E est. table → Reconstructed parameters

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.

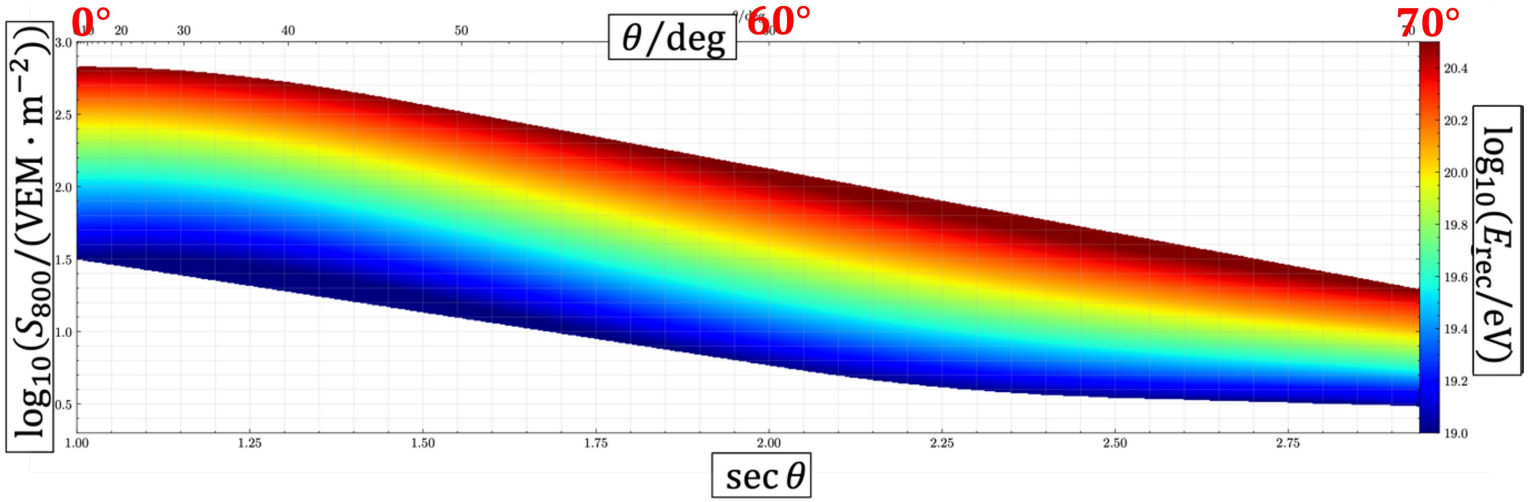


Selection criteria
- $N_{\mathrm{SD}} \geq 5$
- $\theta_{\mathrm{rec}} \leq 70°$
- $D_{\mathrm{border}} \geq 400\ \mathrm{m}$
- $\chi^2/\mathrm{ndf} \leq 4$
- $\sigma_{\mathrm{point\ direction}} < 8°$
- $\sigma(S_{800})/S_{800} < 0.5$

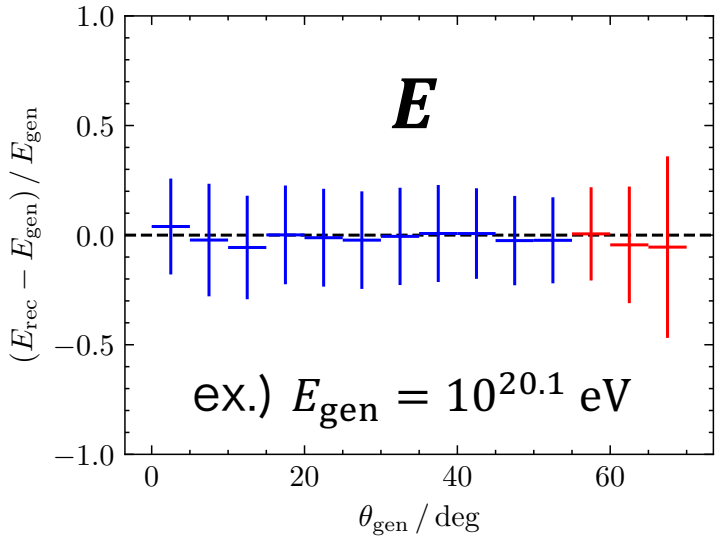
This extended table for the TA×4 SD enables the energy reconstruction of the primary cosmic ray in the range from 0deg to 70deg in zenith angle.

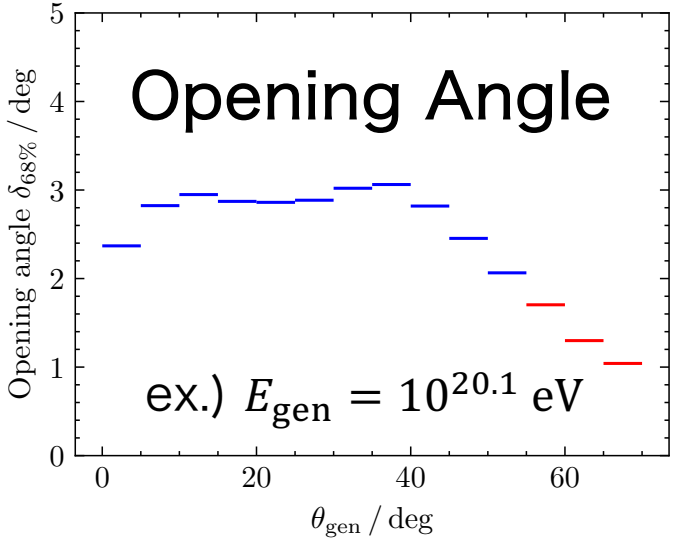
Evaluation of Reconstruction Accuracy

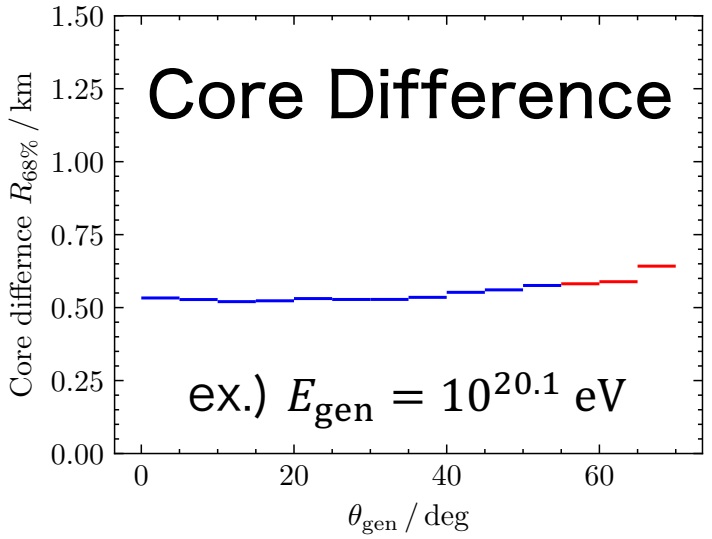
TA×4 SD



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





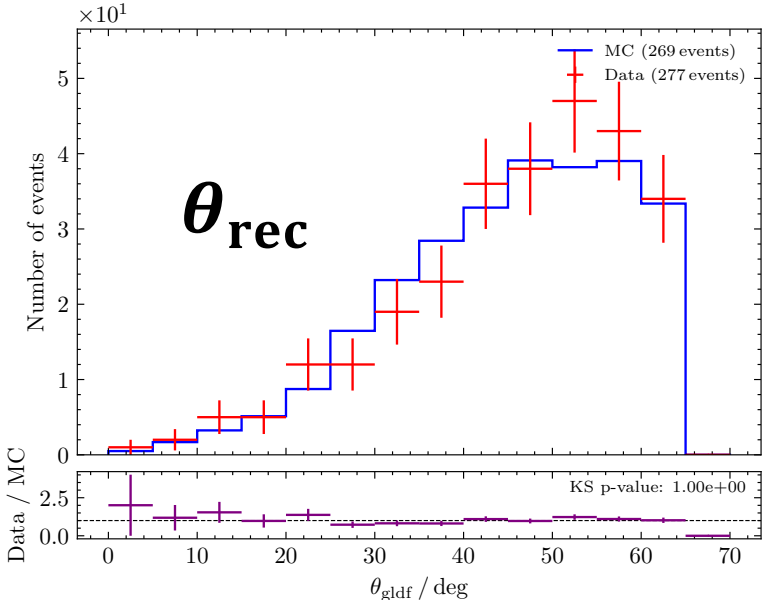


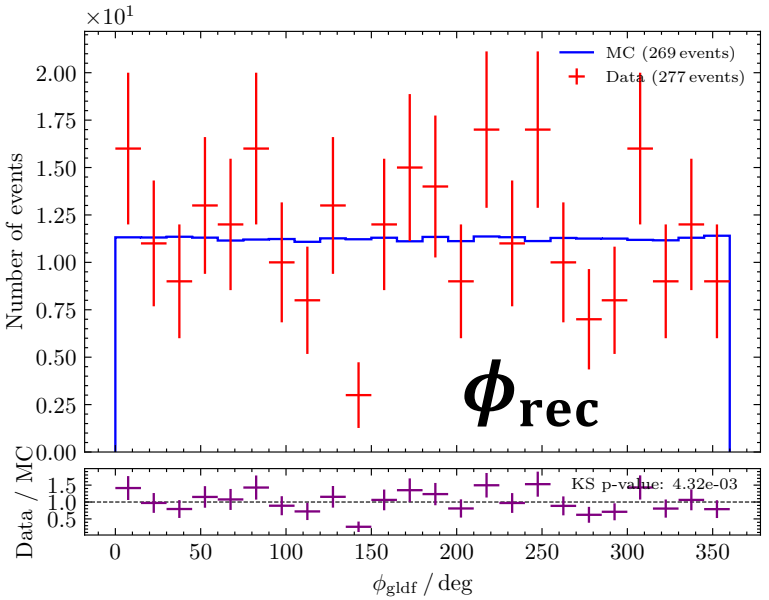
Data/MC Comparison

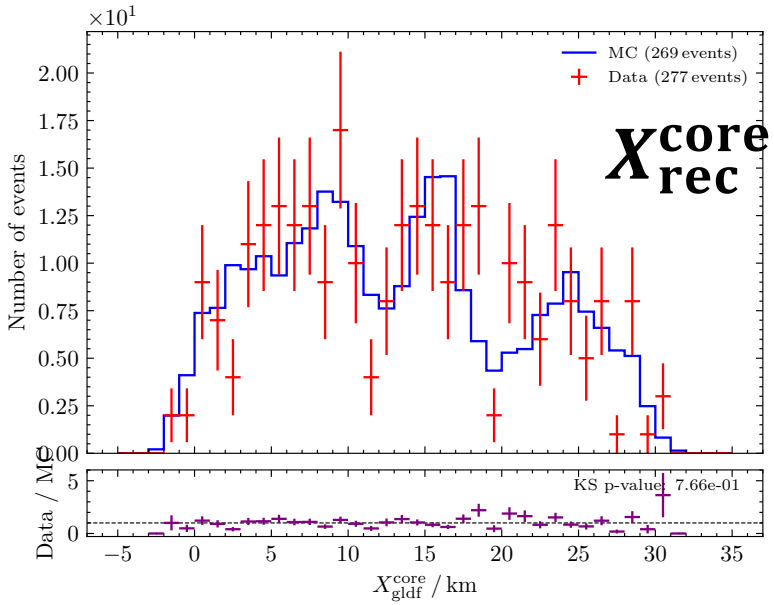
$E_{\mathrm{rec}} \geq 10^{18.8}$ eV Flux normalize **TA×4 SD**

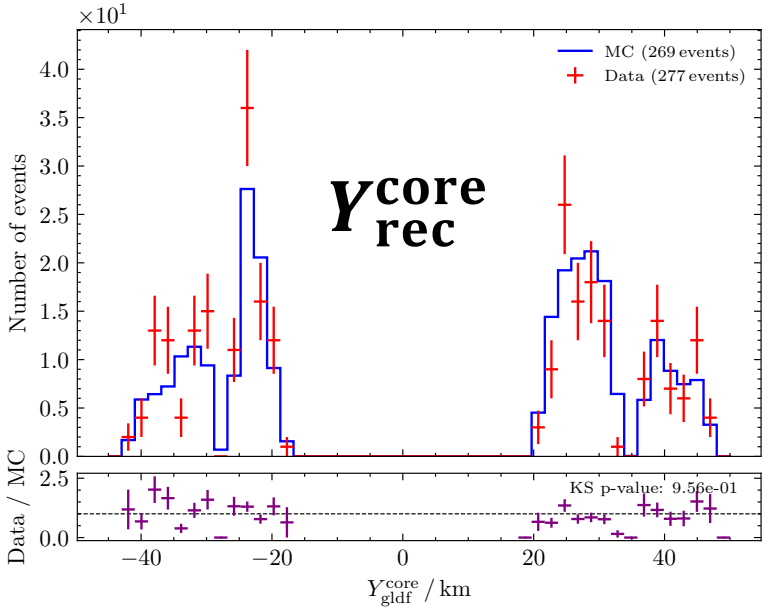
Period
- Oct. 2019 to Oct. 2022

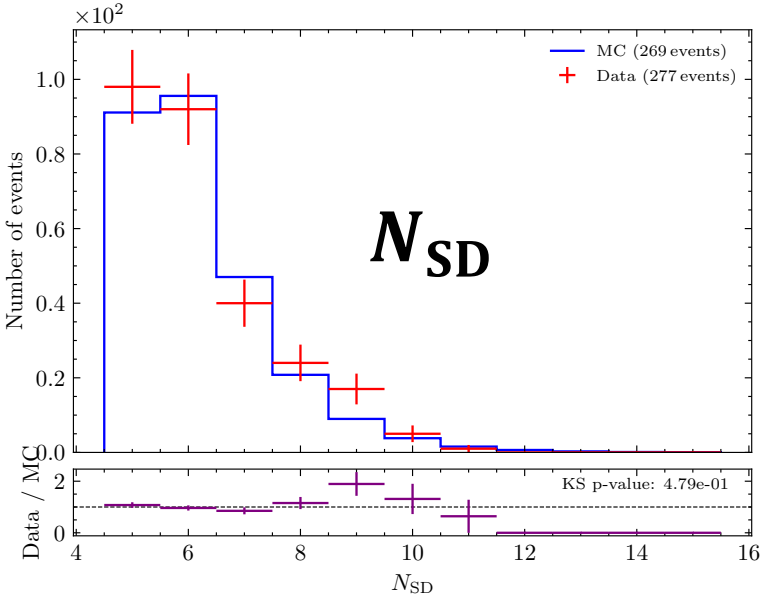
Selection criteria
- $N_{\mathrm{SD}} \geq 5$
- $\theta_{\mathrm{rec}} \leq 65°$
- $D_{\mathrm{border}} \geq 400$ m
- $\chi^2_{\mathrm{rec}}/\mathrm{ndf} \leq 4$
- $\sigma_{\mathrm{point\ direction}} < 8°$
- $\sigma(S_{800})/S_{800} < 0.5$











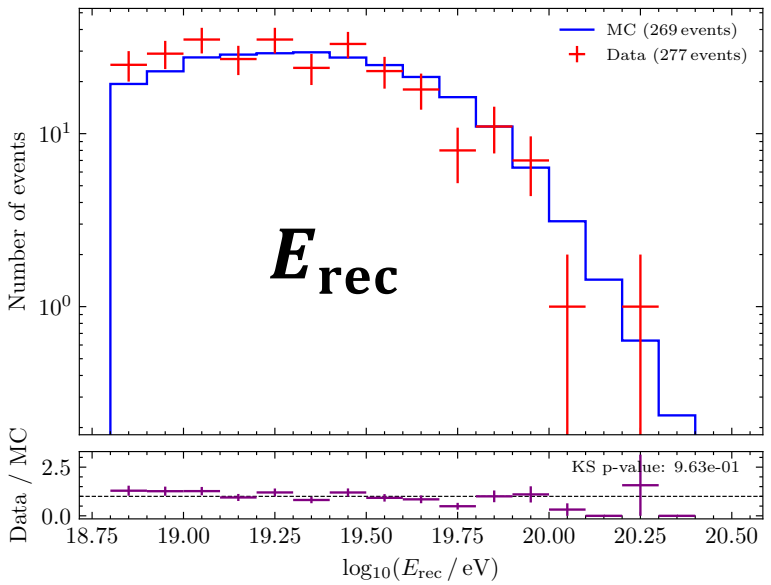
Data/MC Comparison

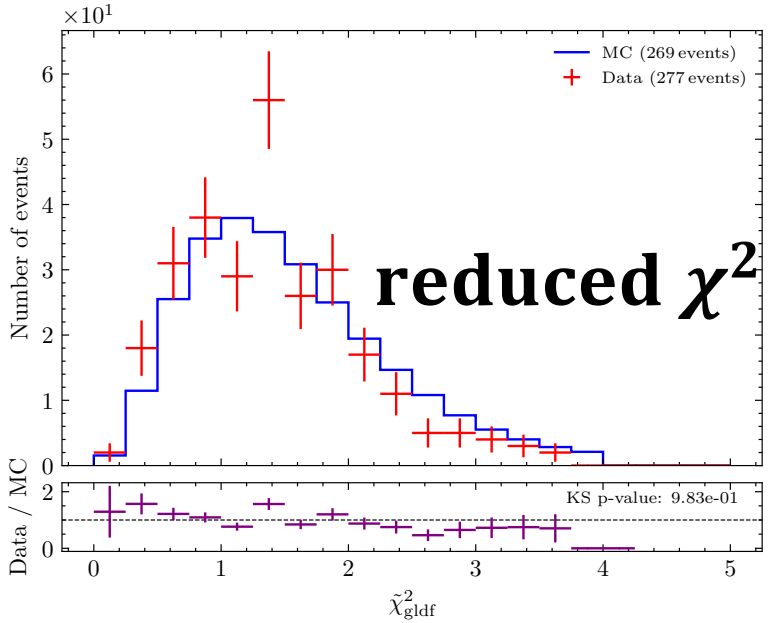
$E_{\mathrm{rec}} \geq 10^{18.8}$ eV Flux normalize **TA×4 SD**

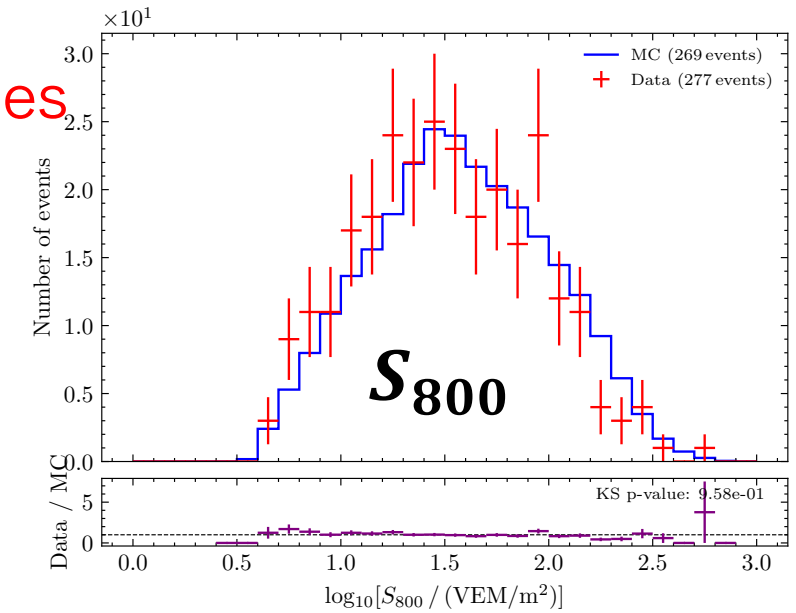
Period
- Oct. 2019 to Oct. 2022

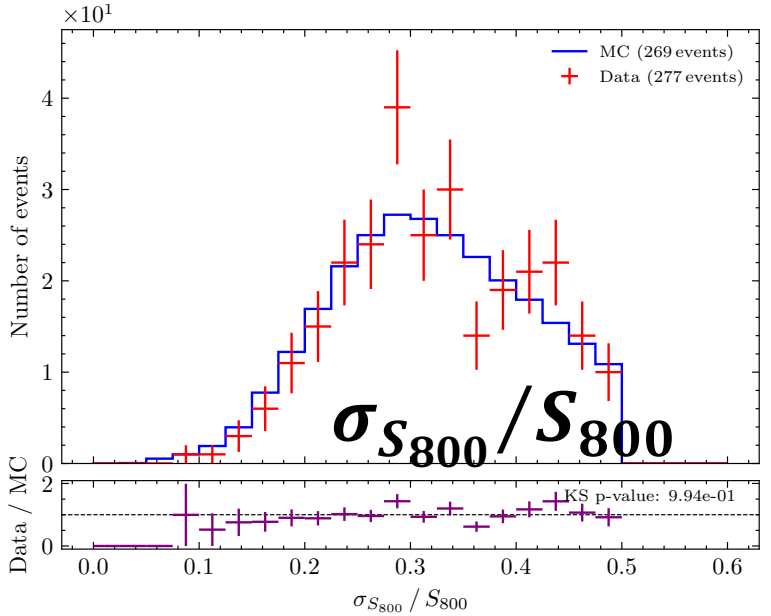
Selection criteria
- $N_{\mathrm{SD}} \geq 5$
- $\theta_{\mathrm{rec}} \leq 65°$
- $D_{\mathrm{border}} \geq 400$ m
- $\chi^2_{\mathrm{rec}}/\mathrm{ndf} \leq 4$
- $\sigma_{\mathrm{point\ direction}} < 8°$
- $\sigma(S_{800})/S_{800} < 0.5$

No significant discrepancies between observed data and MC simulation









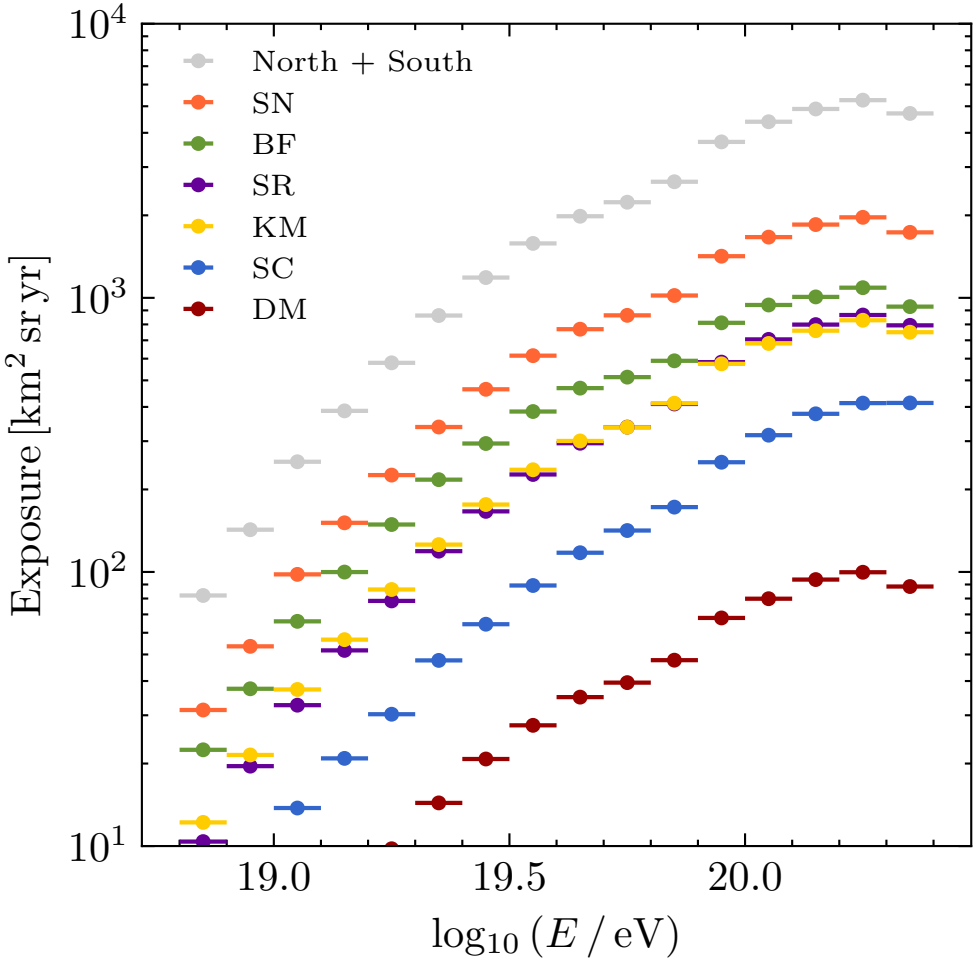
Effective Exposure

TA×4 SD

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

Effective exposure considering bin-to-bin migration

	TA×4 North array			TA×4 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

TA×4 SD

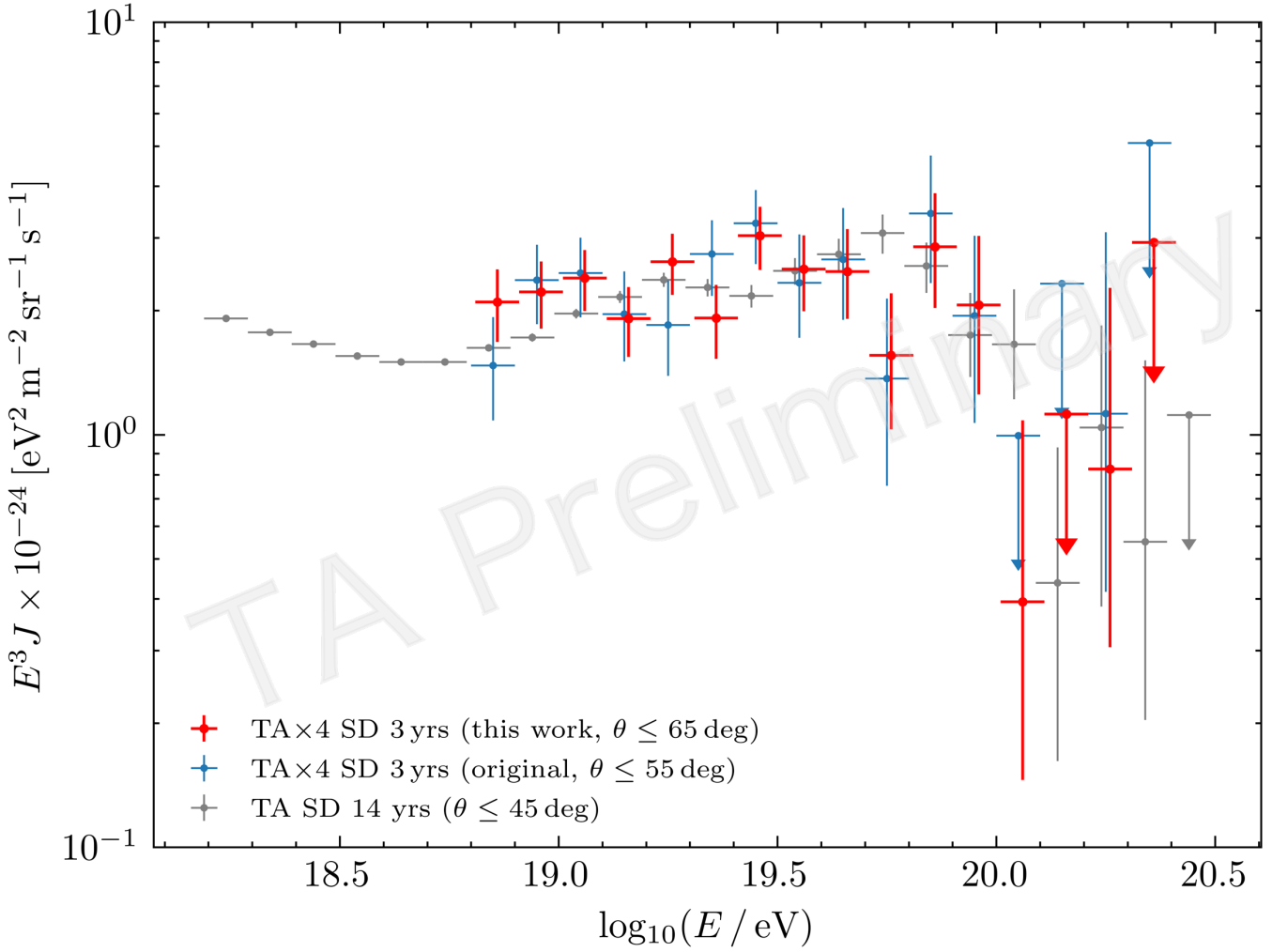
$$J_i = \frac{\sum_{\text{sub-arrays}} \frac{\left(N_{\text{rec}}^{\text{Data}}\right)_i}{\Delta E_i}}{\sum_{\text{sub-arrays}} \left[\frac{\left(N_{\text{rec}}^{\text{MC}}\right)_i}{\left(N_{\text{gen}}^{\text{MC}}\right)_i} A_{\text{gen}} \Omega_{\text{gen}} T\right]}$$

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

TA×4 SD
original analysis
(Criteria : $\theta \leq 55°$)
$N_{\text{rec}}^{\text{Data}} = 186$

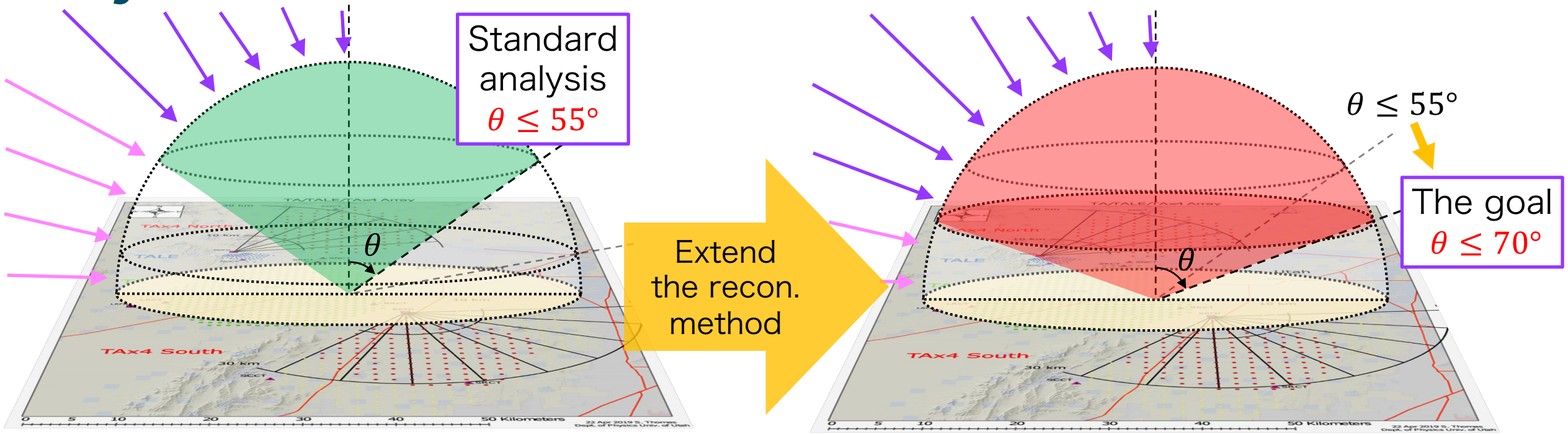
~1.5× increase

This work
(Criteria : $\theta \leq \mathbf{65°}$)
$N_{\text{rec}}^{\text{Data}} = 277$



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

Why Inclined Events?



If extended from 55deg to 70deg, ~1.3× aperture of surface detector array
= Retroactively increase the number of events for UHECRs observation.
- TA×4 SD 6yr observation → TA×4 SD ~8yr observation equivalent
- TA SD 17.5yr observation → TA SD ~23yr observation equivalent

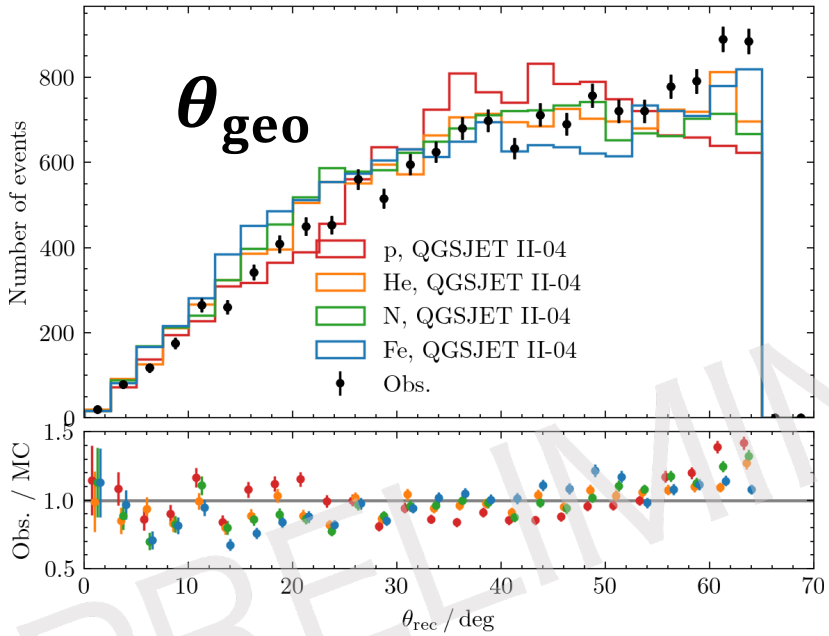
Visible region on the sky expands to lower declination.

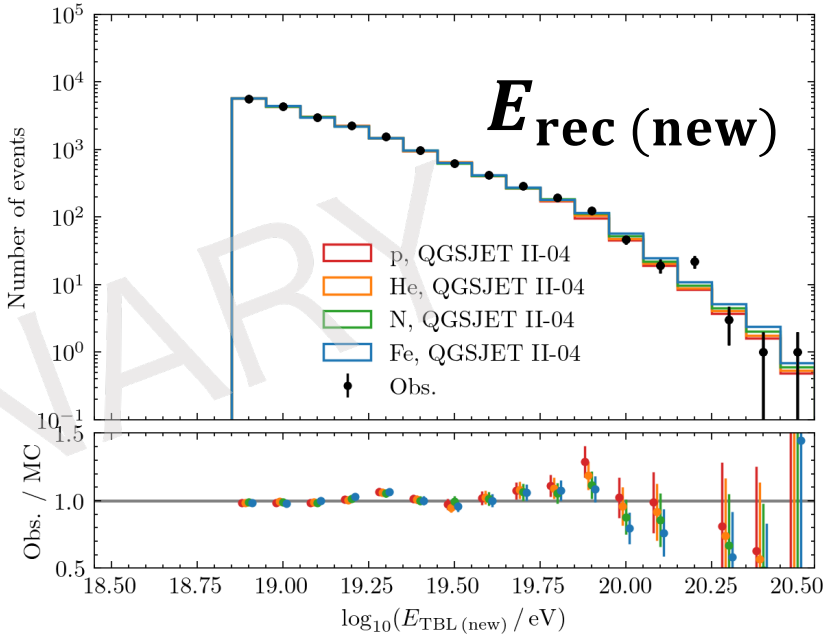
Muon component is dominant → Suitable for study on muon excess

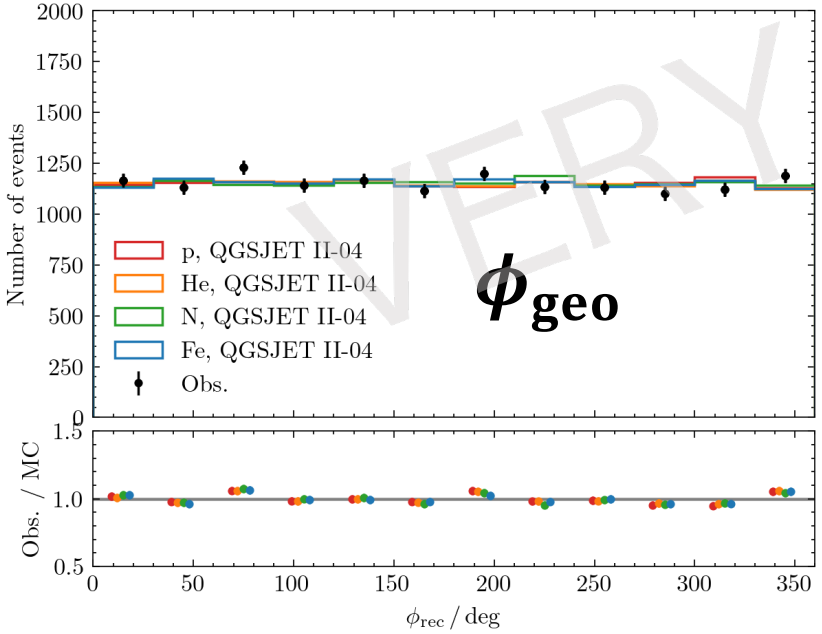
Data/MC comparison $E_{\mathrm{rec}} \geq 10^{18.9}$ eV Area normalize TA SD

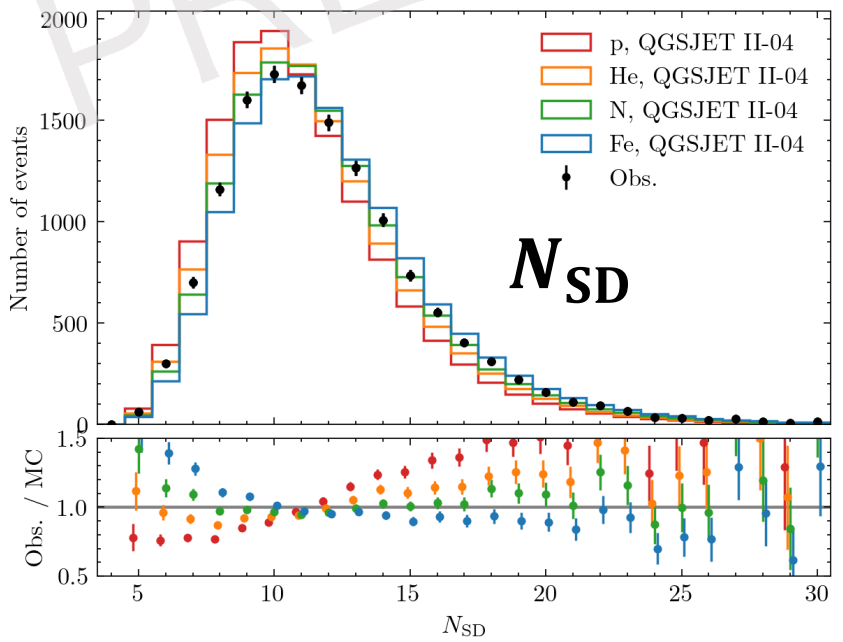
Period
- May 2008 to May 24

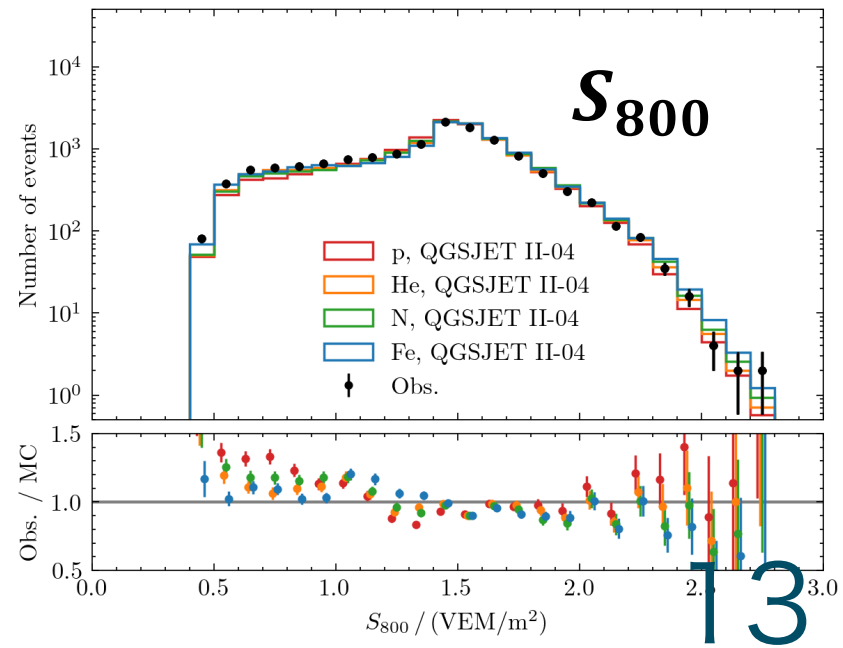
Selection criteria
- $N_{\mathrm{SD}} \geq 5$
- $\theta_{\mathrm{SD}} \leq 65^{\circ}$
- $D_{\mathrm{border}} \geq 1.2$ km
- $\chi^2_{\mathrm{geo}}/\mathrm{ndf} \leq 4 \cap \chi^2_{\mathrm{LDF}}/\mathrm{ndf} \leq 4$
- $\sigma_{\mathrm{point\ direction}} < 5^{\circ}$
- $\sigma(S_{800})/S_{800} < 0.25$











Summary

Inclined air showers analysis with TA Surface Detector Array

- 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 w/ inclined events was measured.
  ⇒ Good agreement with the previous analyses and achieved ~1.5× statistics
- Similar analysis for TA SD is now ongoing

To do

- Compare More precisely with other primary particles than proton in MC
- Develop a machine learning method to improve event selection