

Analysis of Inclined Air Shower Events Observed by the TA × 4 SD



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Introduction

Telescope Array (TA) experiment observes extended air showers to reveal the origin of Ultra High Energy Cosmic-Rays (UHECRs).

TA × 4 experiment

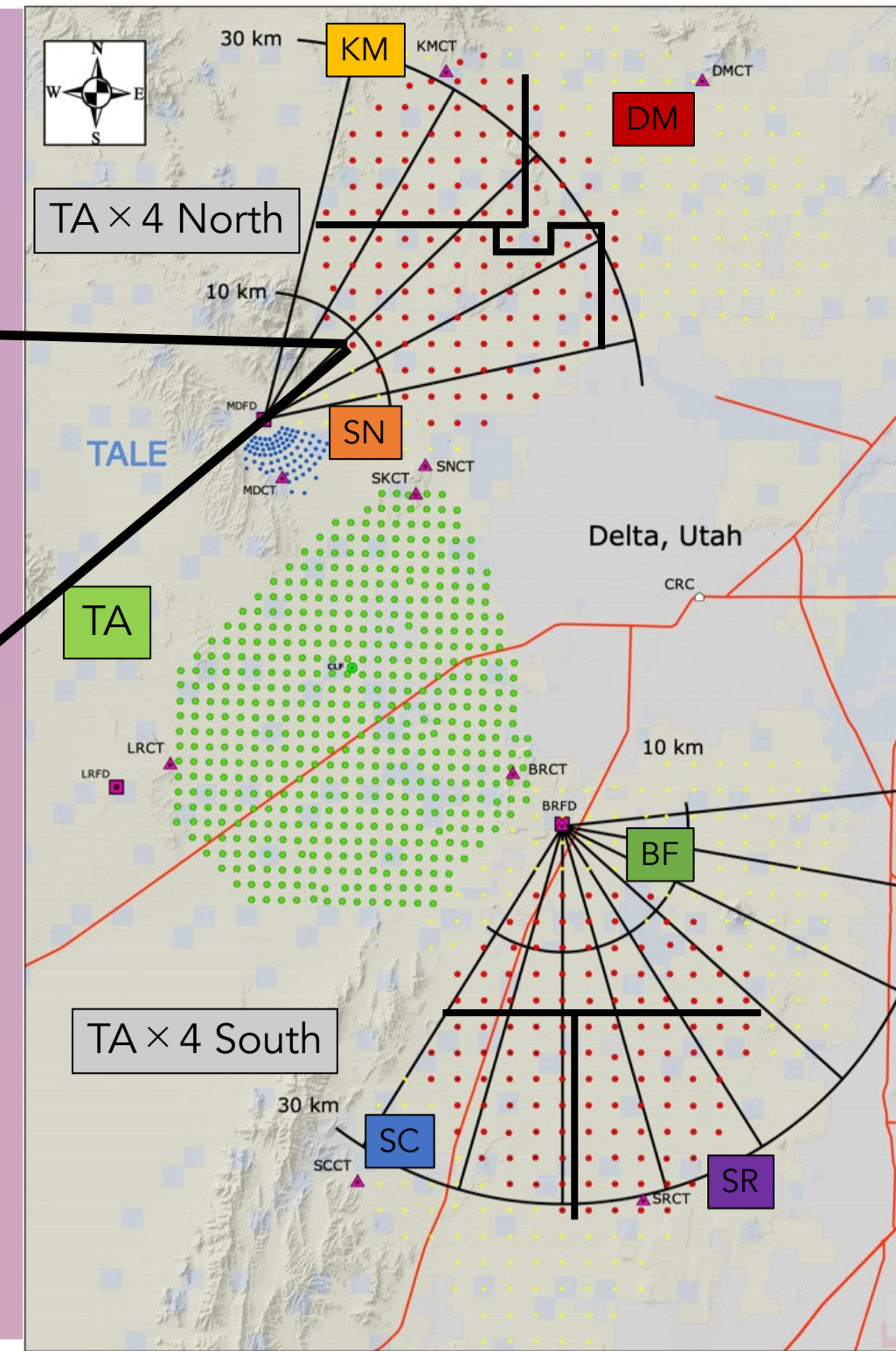
Expand TA experiment by a factor of 4 in array area

→ Increasing the number of events

TA × 4 SD array

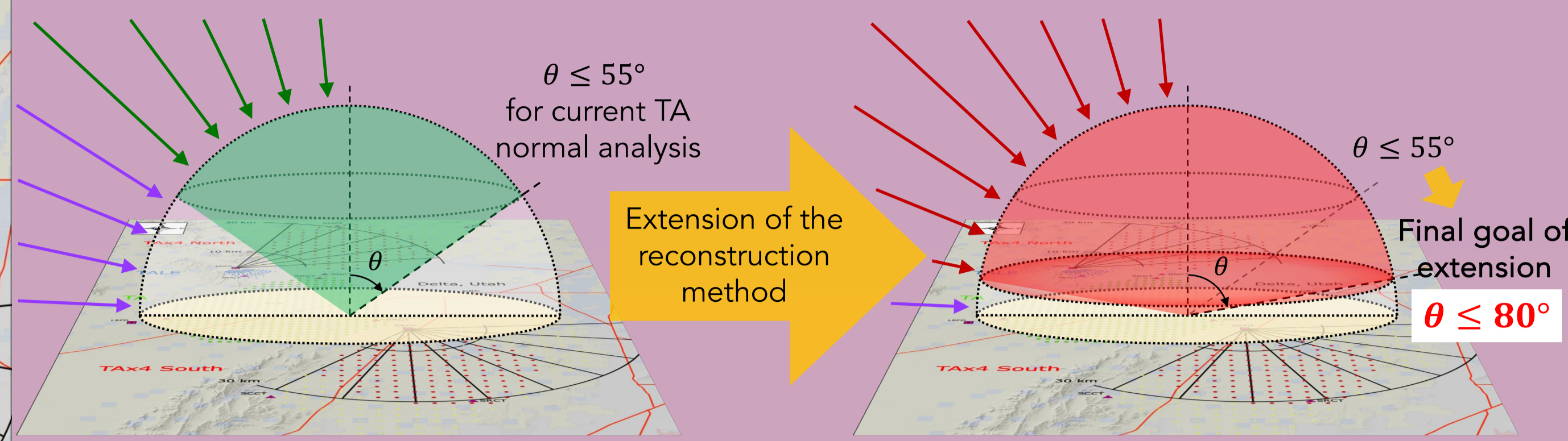
- Add 500 detectors spaced 2 km apart
- Consists of 6 sub-arrays (3 each in north and south, here we refer to these as **TA × 4 North and South array**) and TA SD array
- Covers 3000 km² on its completion
- Deployed 257 detectors in 2019 (red dots in the right figure)

TA × 4 SD
 2 layers plastic scintillation detector, 3 m² and 1.2cm thick



Why inclined showers?

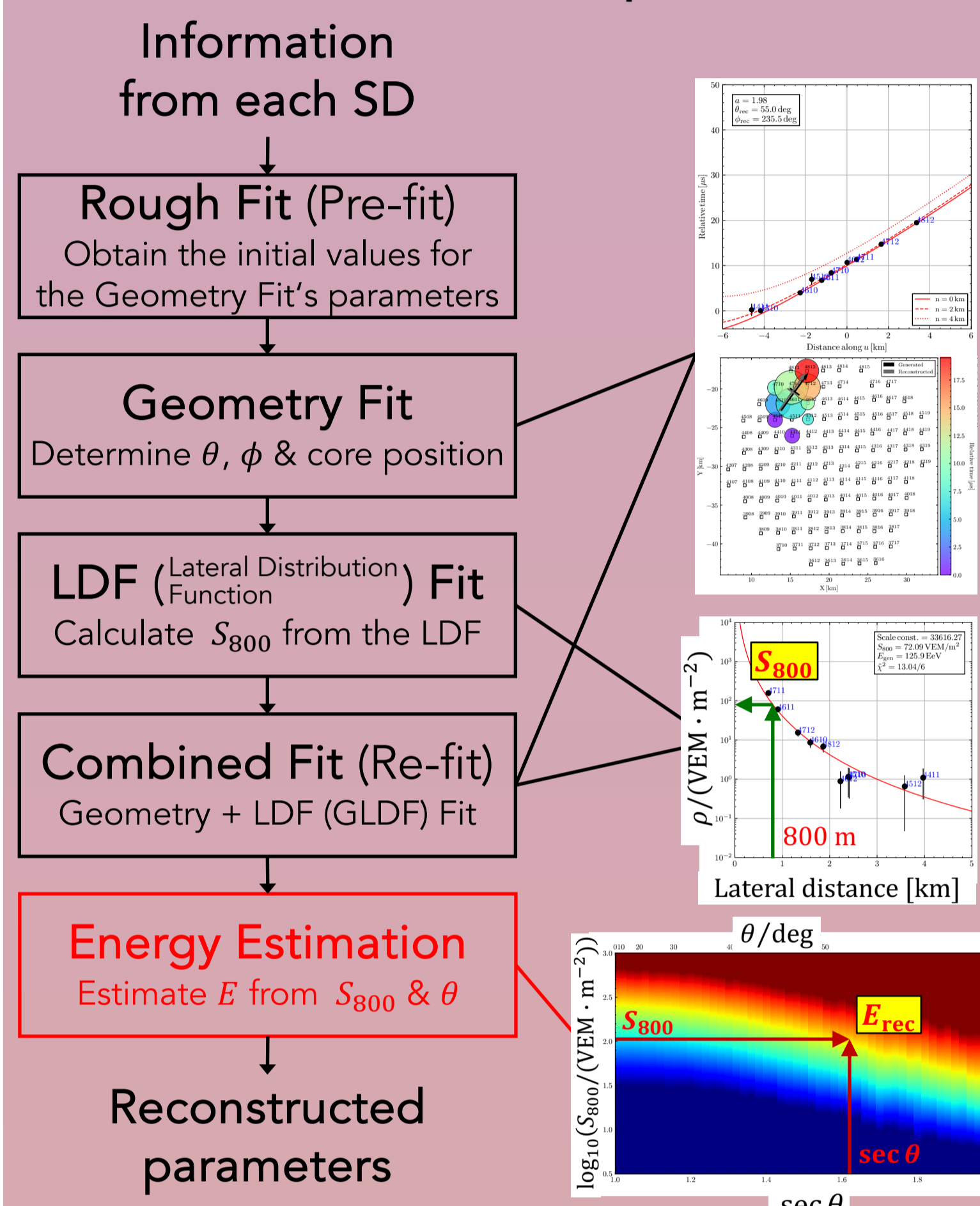
It is important to ensure larger statistics for UHECRs observation.
 → Extend the reconstruction method to the large zenith angle region



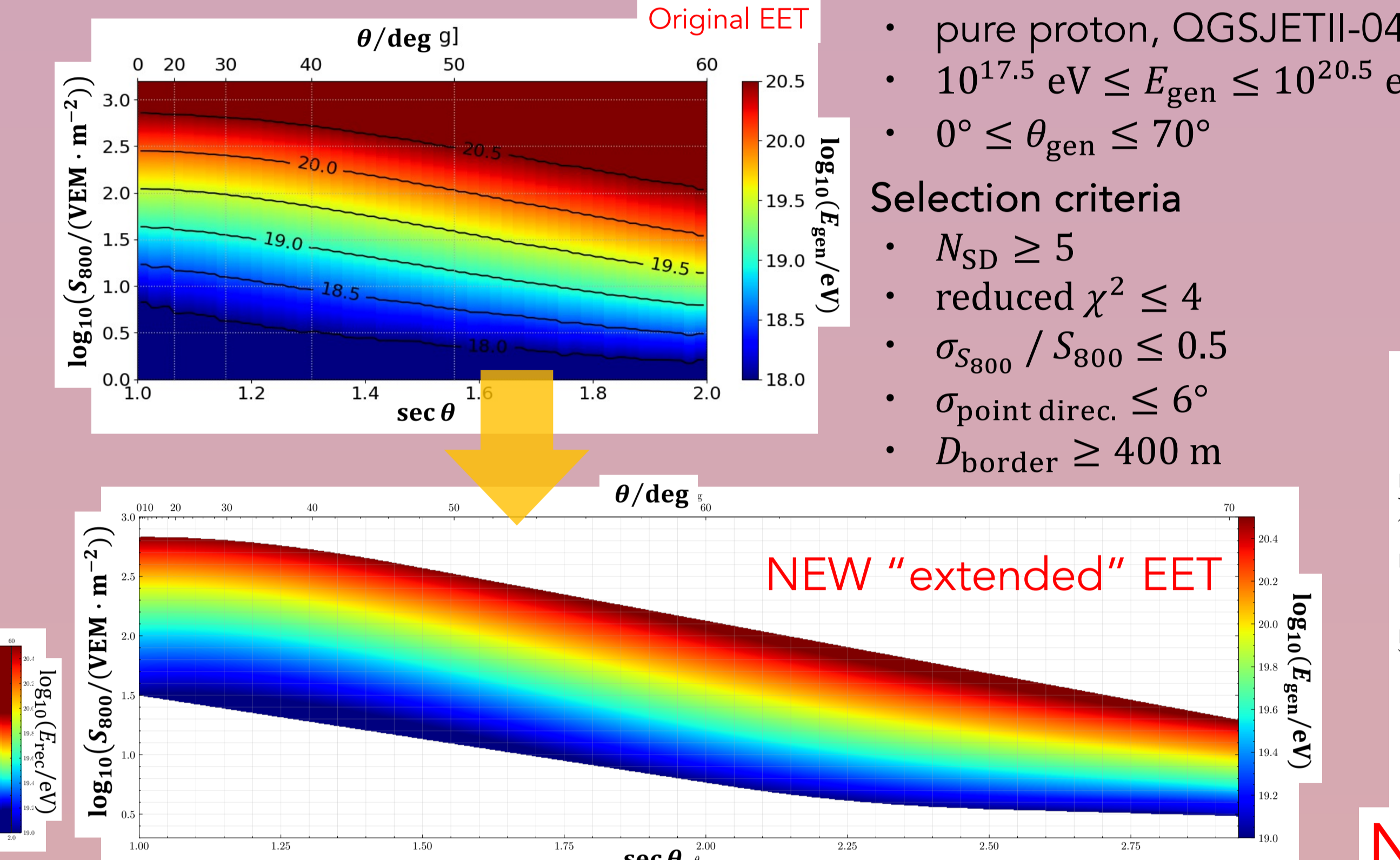
If extended from 55° to 80°, ~1.5 × aperture for TA × 4 → ~6 × of TA
 We can apply to **past data** as well ⇒ TA × 4 4yr → ~TA × 4 6yr equiv.
 If we apply to **TA SD data**, ⇒ TA 15.5yr → ~TA 23yr equivalent

Extension of the reconstruction method

Event reconstruction process



It was necessary to extend the **Energy Estimation Table (EET)** used to the large zenith angle region for reconstructing inclined events. Using an enhanced method, we extended the EET generated from the MC simulation to $\theta = 70^\circ$.



MC simulation dataset

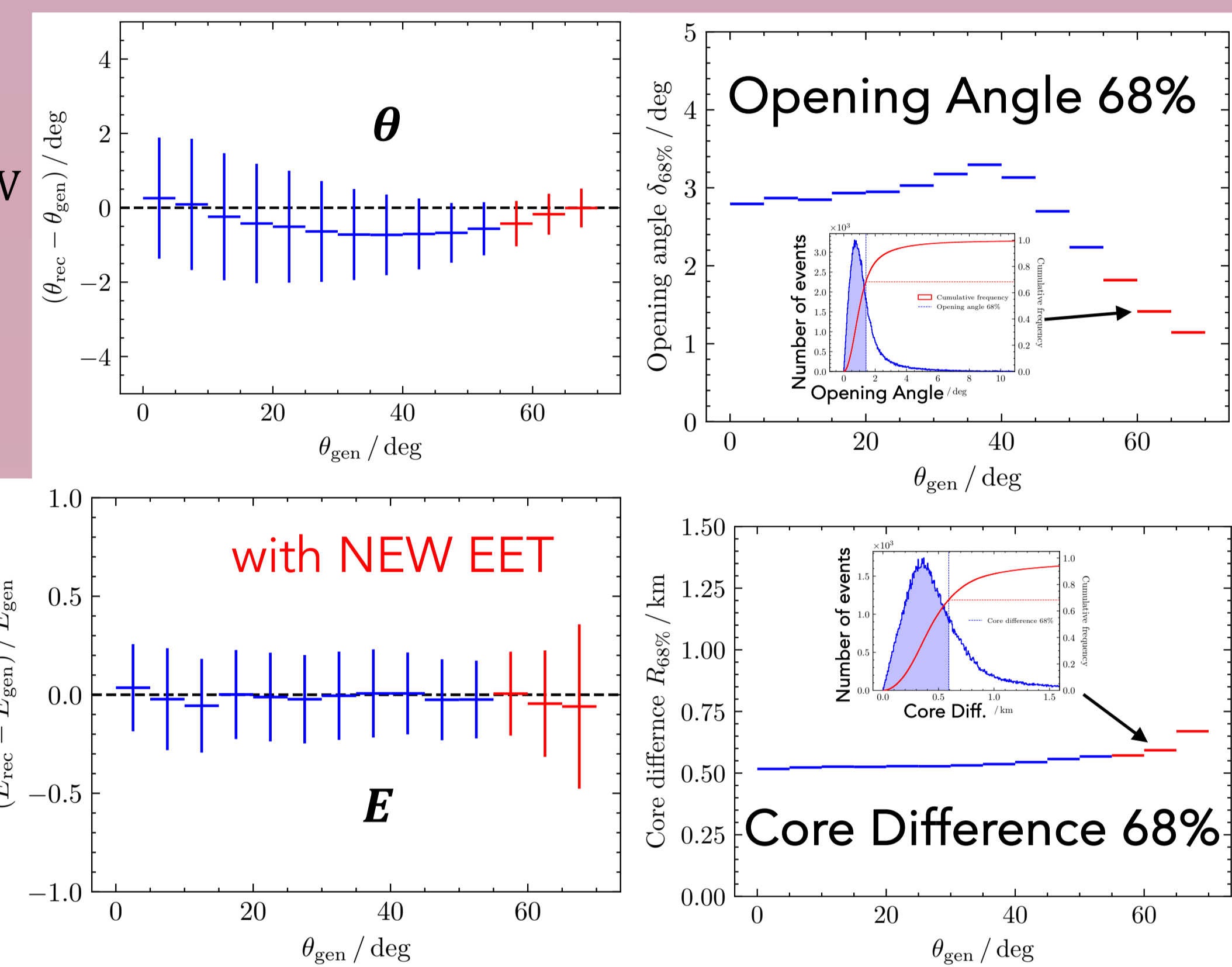
- pure proton, QGSJETII-04
- $10^{17.5} \text{ eV} \leq E_{\text{gen}} \leq 10^{20.5} \text{ eV}$
- $0^\circ \leq \theta_{\text{gen}} \leq 70^\circ$

Selection criteria

- $N_{\text{SD}} \geq 5$
- reduced $\chi^2 \leq 4$
- $\sigma_{S_{800}} / S_{800} \leq 0.5$
- $\sigma_{\text{point direc.}} \leq 6^\circ$
- $D_{\text{border}} \geq 400 \text{ m}$

Evaluation of reconstruction accuracies

Reconstruction accuracies of each parameter are evaluated for each zenith angle (Below are ex. of $10^{20.1} \text{ eV}$).



No significant bias in the large zenith angle region

Data/MC comparisons

Observed data

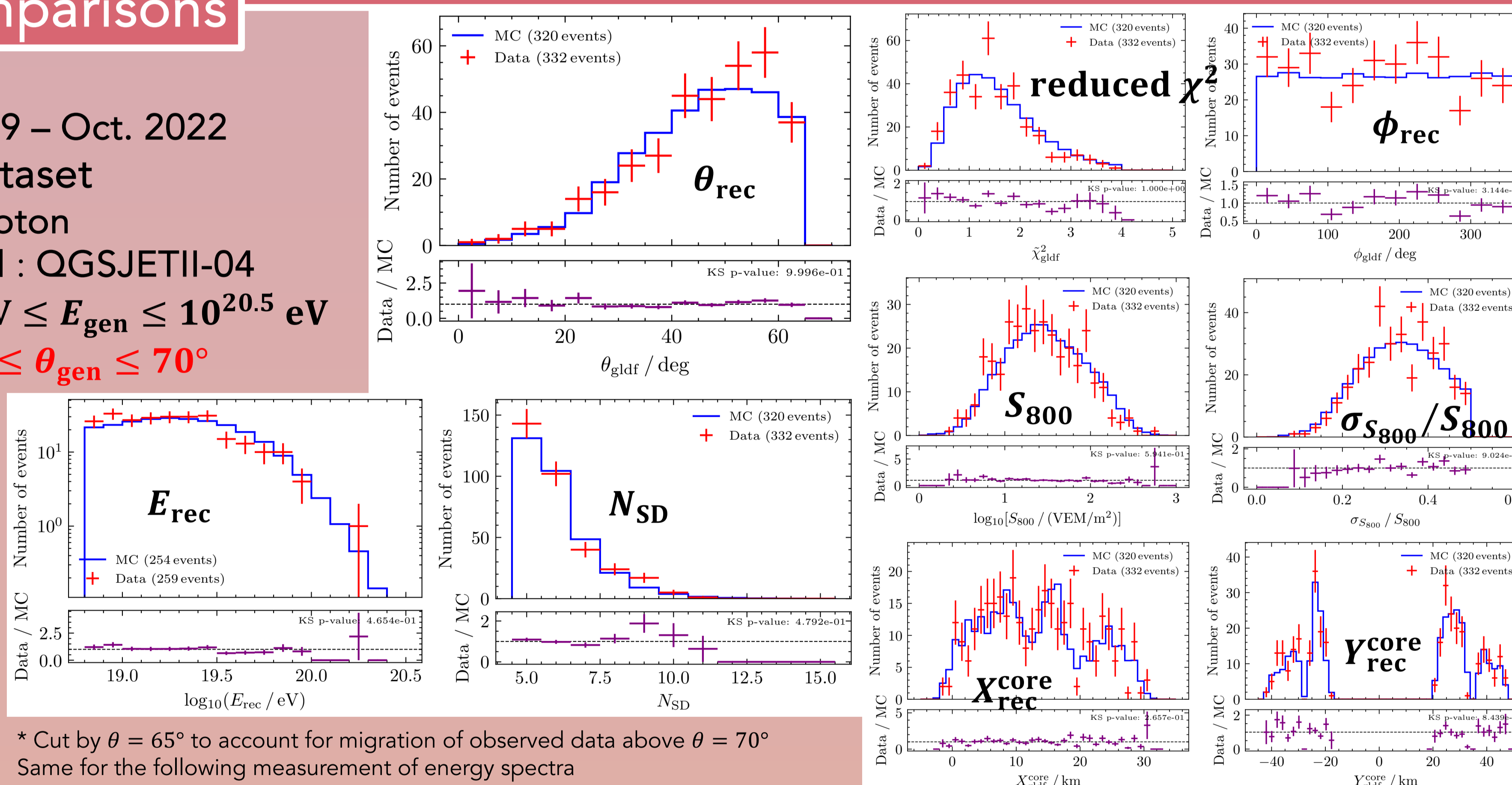
• Period : Oct. 2019 – Oct. 2022

MC simulation dataset

- Primary : pure proton
- Interaction model : QGSJETII-04
- Energy : $10^{17.5} \text{ eV} \leq E_{\text{gen}} \leq 10^{20.5} \text{ eV}$
- Zenith angle : $0^\circ \leq \theta_{\text{gen}} \leq 70^\circ$

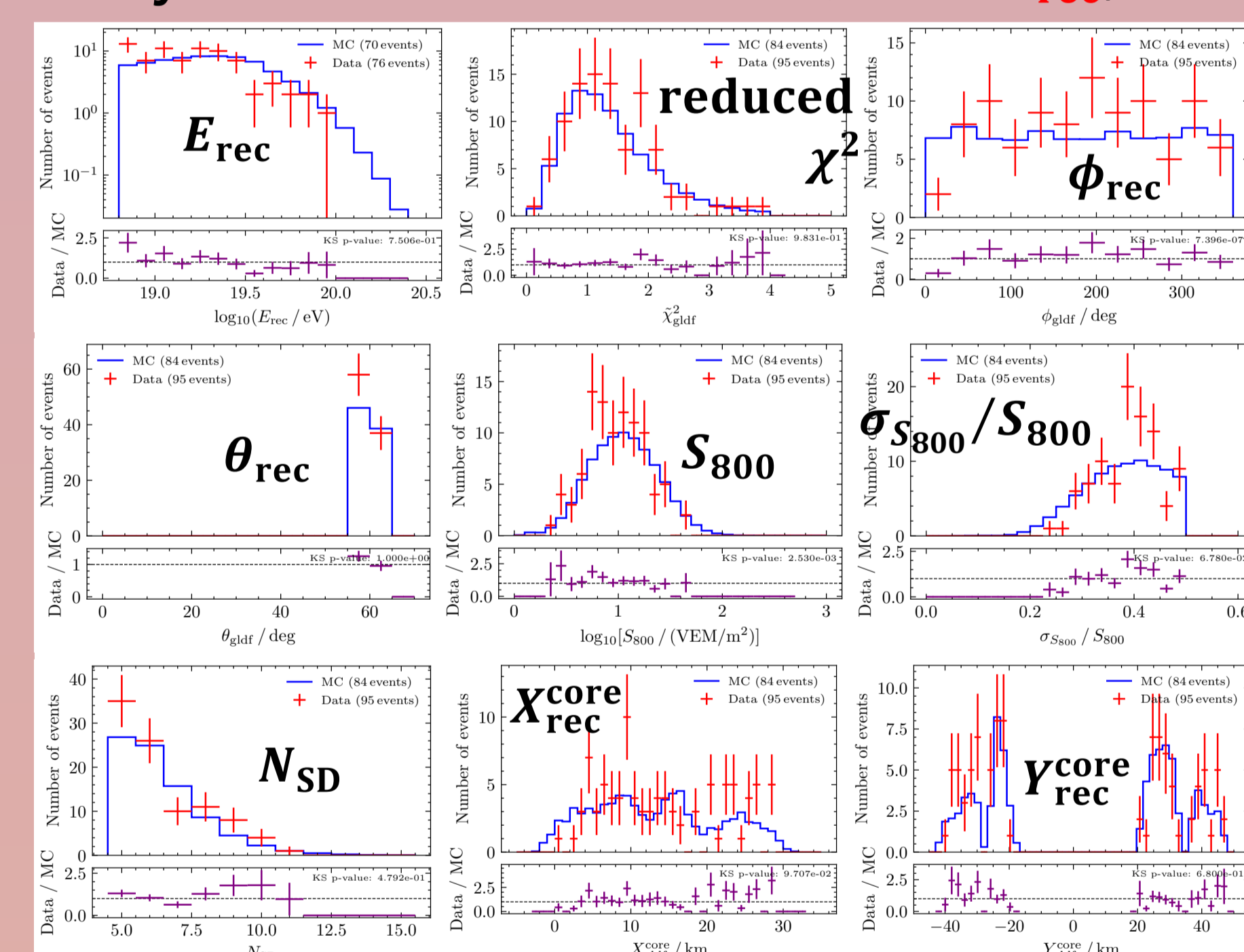
Selection criteria

- $0^\circ \leq \theta_{\text{rec}} \leq 65^\circ$
- $E_{\text{rec}} \geq 10^{18.8} \text{ eV}$
- $N_{\text{SD}} \geq 5$
- reduced $\chi^2 \leq 4$
- $\sigma_{S_{800}} / S_{800} \leq 0.5$
- $\sigma_{\text{point direc.}} \leq 6^\circ$
- $D_{\text{border}} \geq 400 \text{ m}$



* Cut by $\theta = 65^\circ$ to account for migration of observed data above $\theta = 70^\circ$
 Same for the following measurement of energy spectra

Only with inclined events ($55^\circ \leq \theta_{\text{rec}}$)



No significant discrepancies between them even in the large zenith angle region

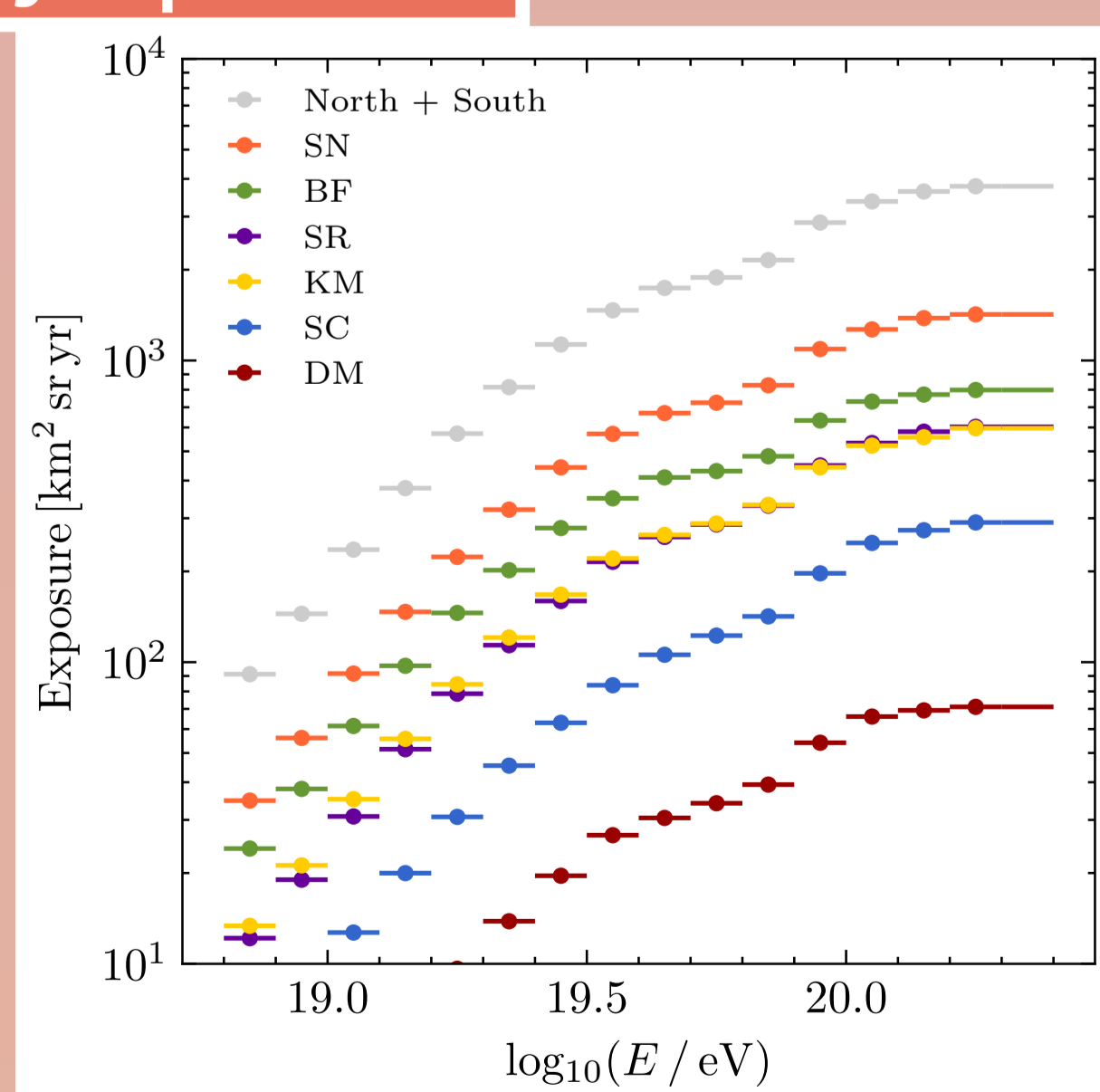
Measurement of energy spectra

Cosmic Ray Flux

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

Effective exposure considering bin to bin migration (TA 11yr spectra was assumed)

Sub-array	TA × 4 North array	TA × 4 South array
	KM DM SN BF SR SC	
Array area [km ²]	~120 ~40 ~230 ~150 ~140 ~110	
# of days T [days]	1120 1102 1120 1093 1120 1120	



Exposure values were smaller in the highest energy bin than in the lower energy bin, so extrapolated values are used assuming flat exposure.

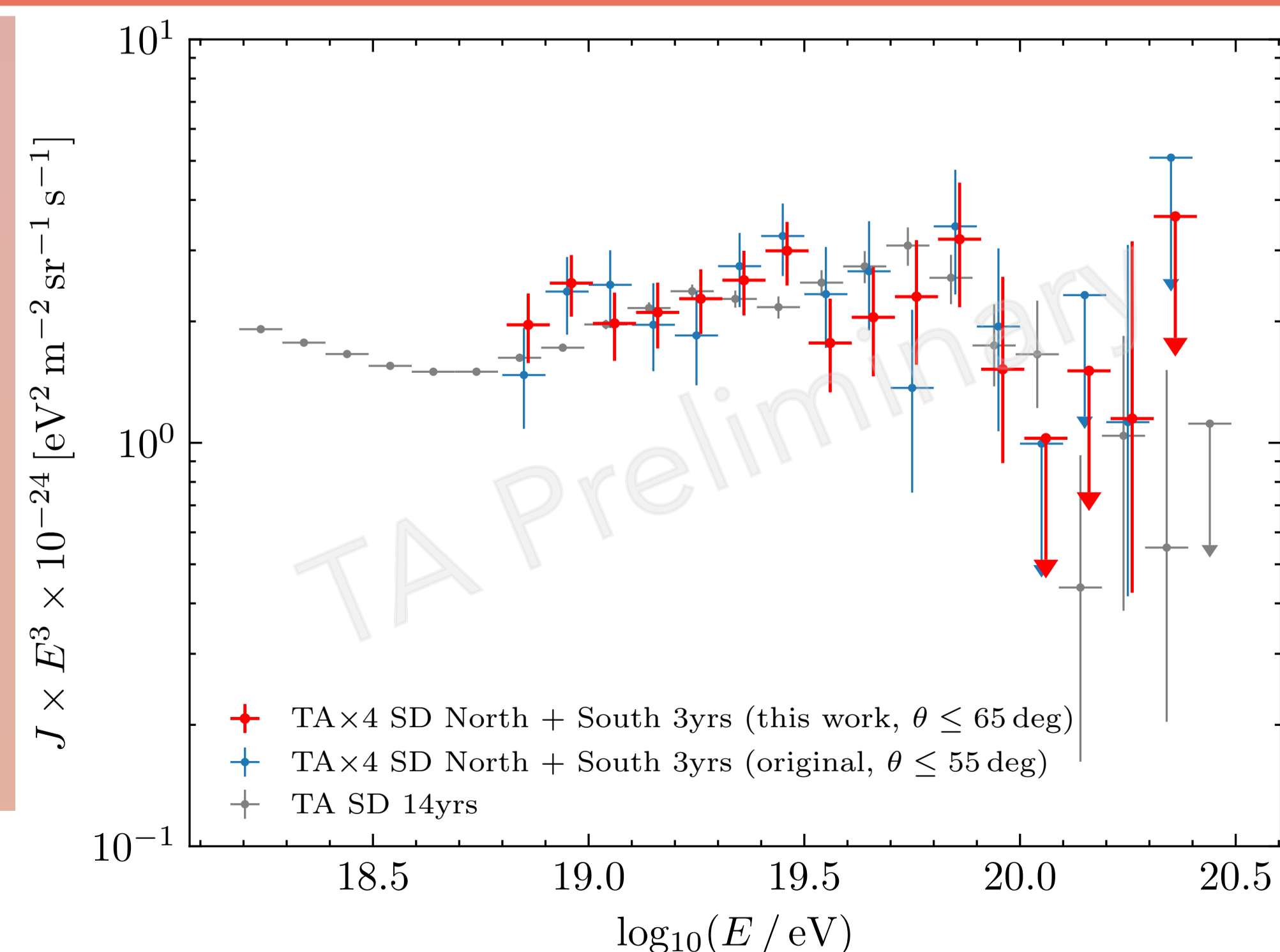
Comparison on the numbers of events of observed data $N_{\text{rec}}^{\text{Data}}$ with $E \geq 10^{18.8} \text{ eV}$

TA × 4 SD original analysis (Criteria : $\theta \leq 55^\circ$) $N_{\text{rec}}^{\text{Data}} = 186$
This work (Criteria : $\theta \leq 65^\circ$) $N_{\text{rec}}^{\text{Data}} = 259$

1.4 × increase in statistics**

** This is larger than expected increase from expansion of the aperture associated with extension of the zenith angle. (By extension from $\theta = 55^\circ$ to 65° , aperture expands ~1.2 × larger) This is because that events in the low-energy region where the reconstruction efficiency is not 100% are more likely to be reconstructed in the large zenith angle region.

Good agreements with previous analysis



Summary & prospects

- ✓ Extended the energy estimation table for TA × 4 to $\theta = 70^\circ$ ⇒ **No significant bias** in the large zenith region
- ✓ Compared observed data and MC simulation dataset including large zenith angle events ⇒ **No significant discrepancies** even in the large zenith angle region
- ✓ Initial measurement of energy spectra using inclined air shower events observed by the TA × 4 SD ⇒ **1.4 × increase** in statistics and **good agreement** with previous analysis

NEXT

- Apply this method (extension up to 70°) to TA SD analysis (now in progress)
- Extend the zenith angle region up to 80° (Validation of the TA de-thinning process of MC simulation is necessary)