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

CHISATO KOYAMA for the Telescope Array Collaboration

Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha Kashiwa, Chiba, Japan

Introduction

Telescope Array (TA) experiment observes extended air showers to reveal the origin of Ultra High Energy Cosmic-Rays (UHECRs).
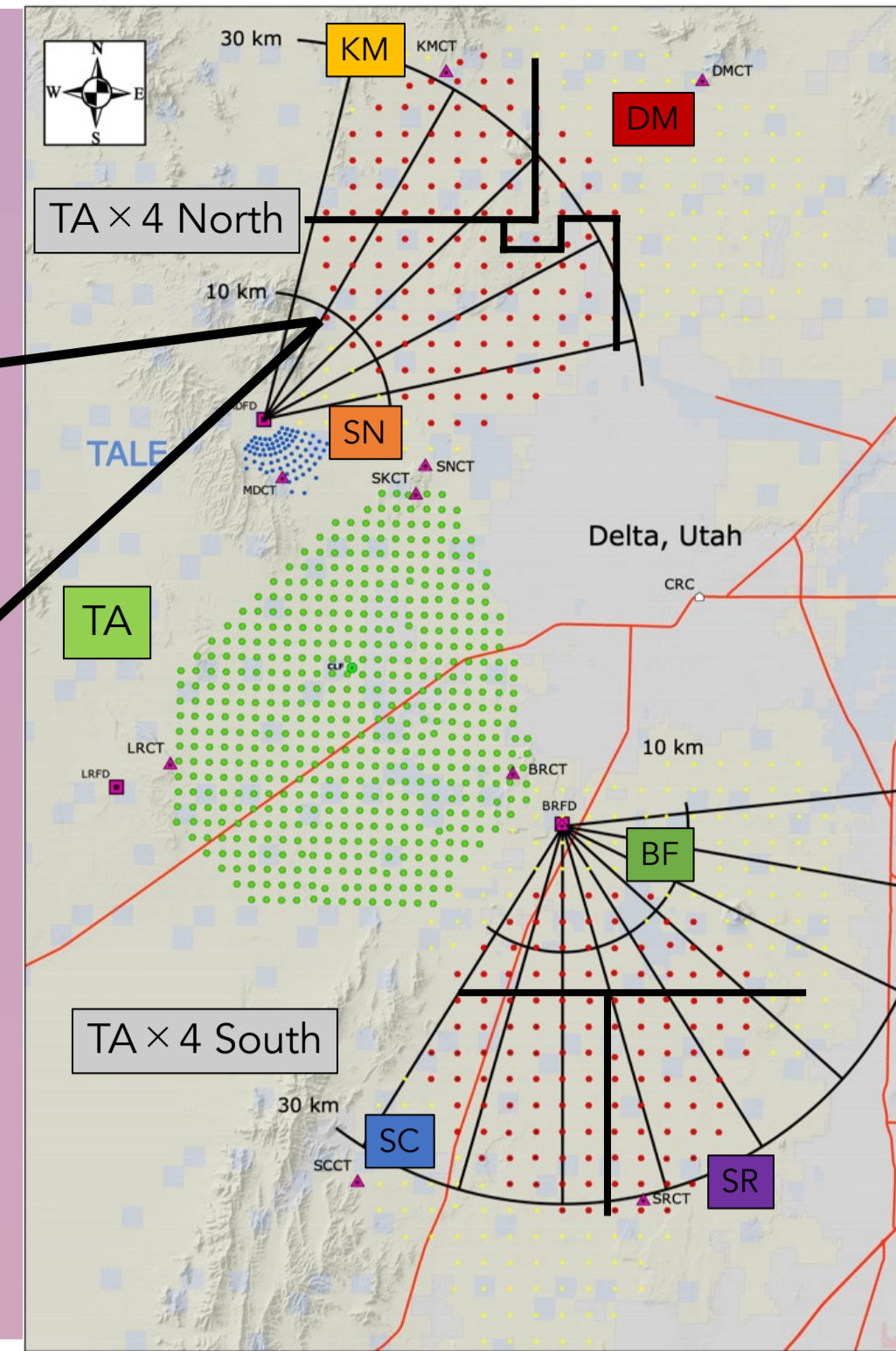
TA×4 experiment

Expand TA experiment by a factor of 4 in array area
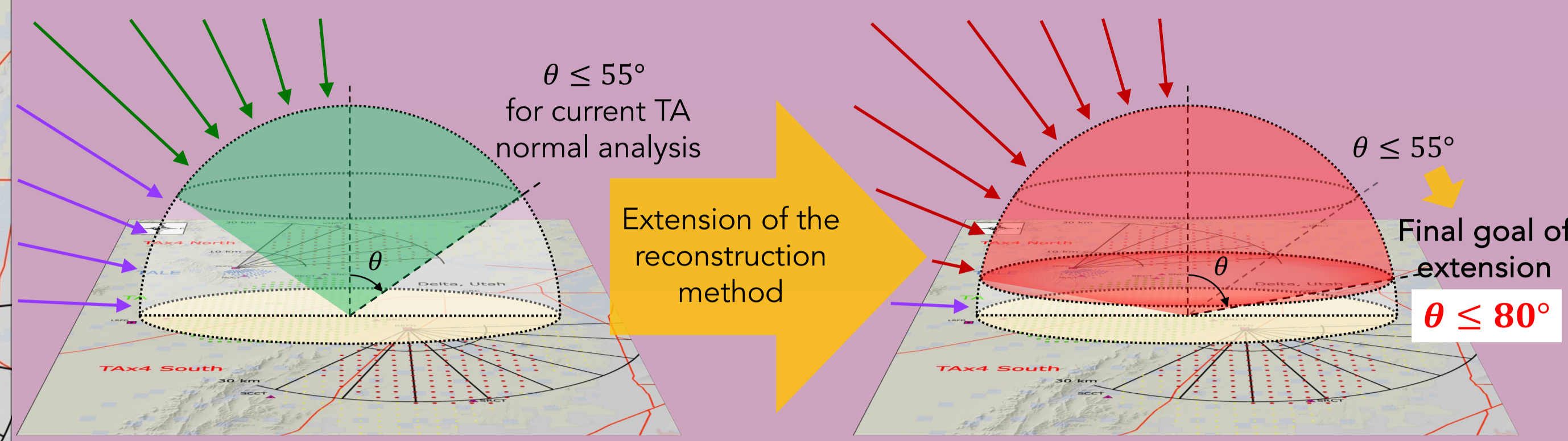→ Increasing the number of events

TA×4 SD array
- 500 detectors spaced 2 km apart
- Consists of 6 sub-arrays (3 each in north and south) and TA SD array
- Covers 3000 km² on its completion
- Deployed 257 detectors in 2019 (red dots in right figure)

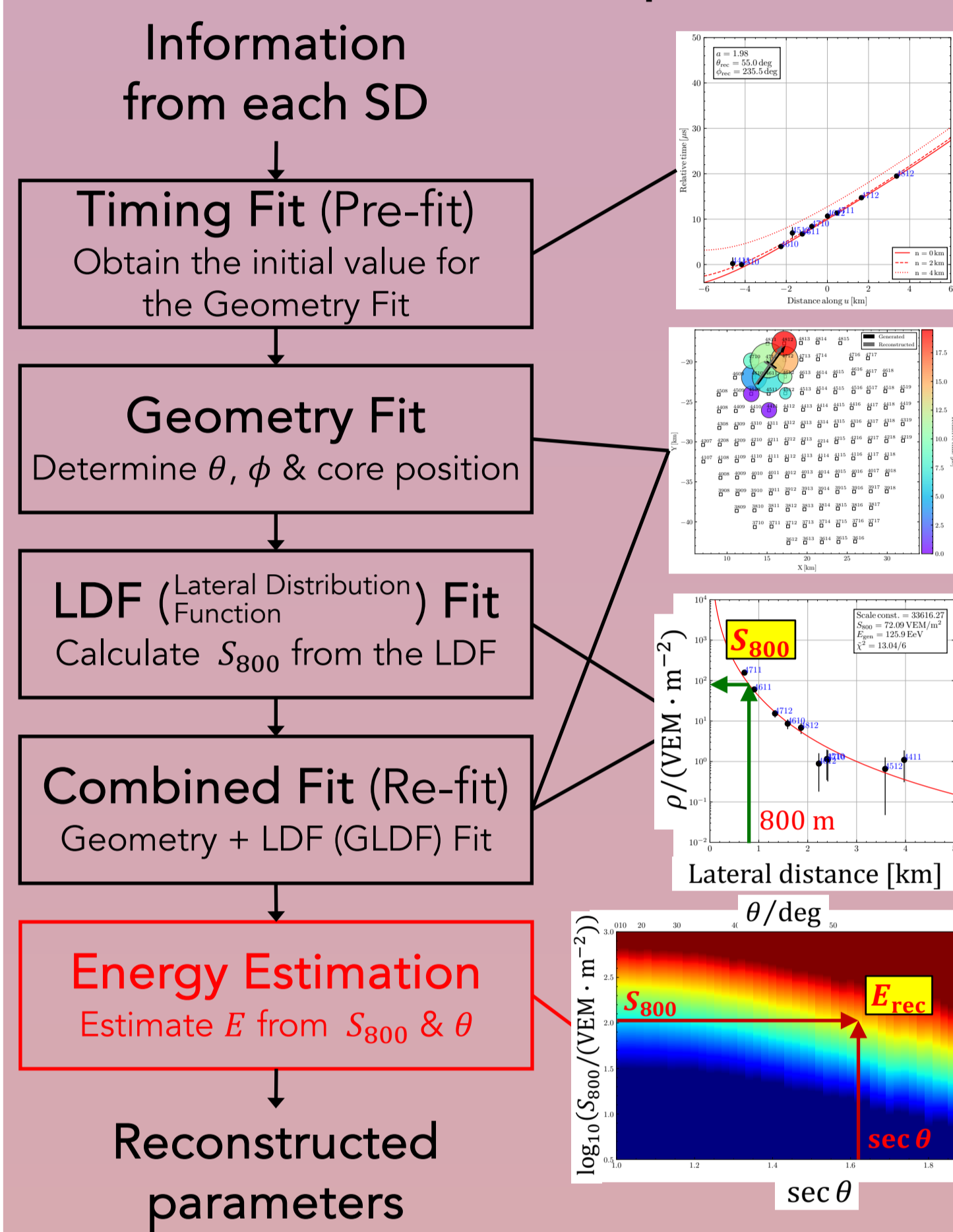**TA×4 SD** — 2 layers plastic scintillation detector, 3 m² and 1.2cm thick

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

$\theta \leq 55°$ for current TA normal analysis

Extension of the reconstruction method

$\theta \leq 55°$

Final goal of extension $\theta \leq 80°$

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

Information from each SD
↓
Timing Fit (Pre-fit) — Obtain the initial value for the Geometry Fit
↓
Geometry Fit — Determine θ, ϕ & core position
↓
LDF (Lateral Distribution Function) Fit — Calculate S_{800} from the LDF
↓
Combined Fit (Re-fit) — Geometry + LDF (GLDF) Fit
↓
Energy Estimation — Estimate E from S_{800} & θ
↓
Reconstructed parameters

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 $\theta = 70°$.
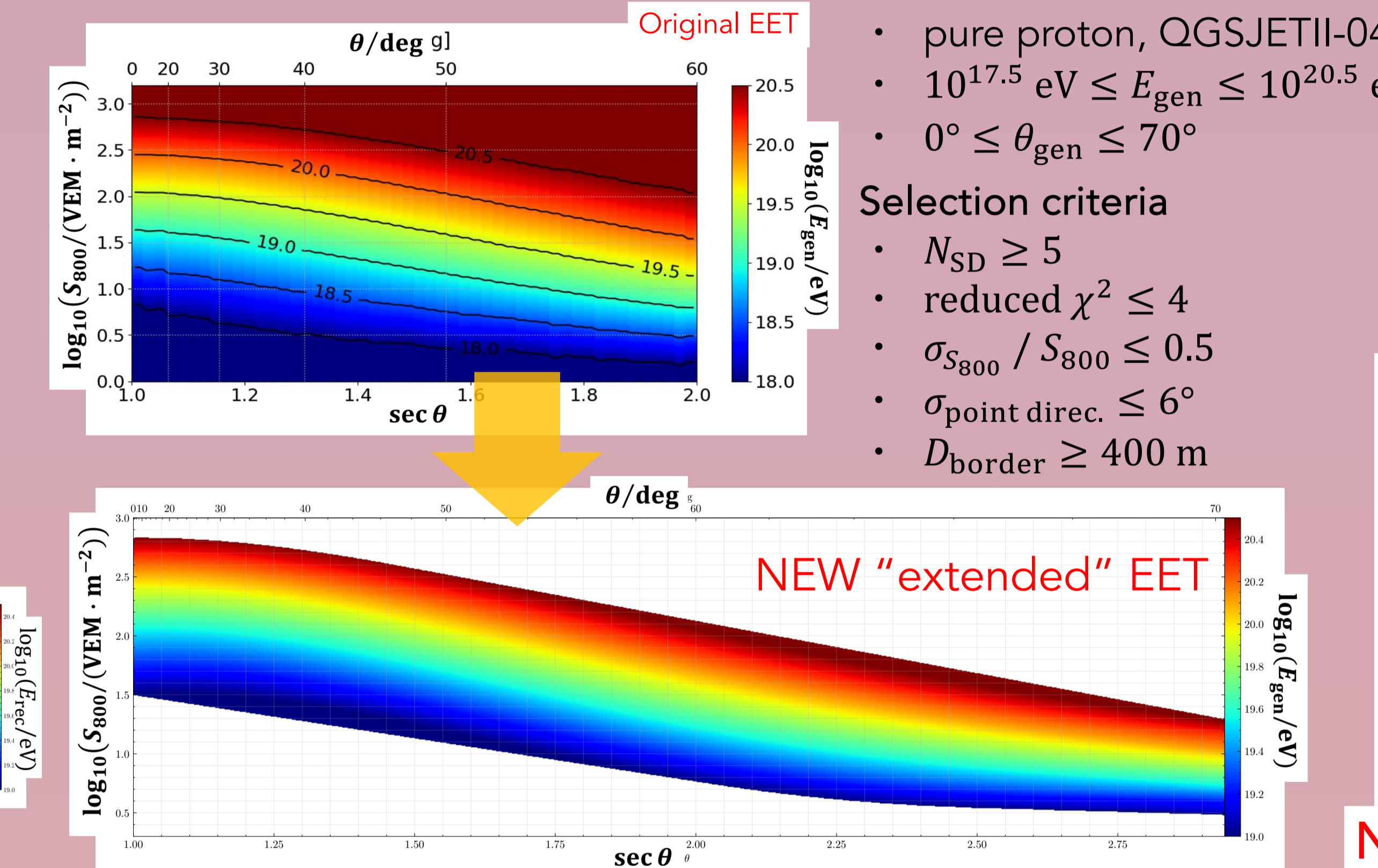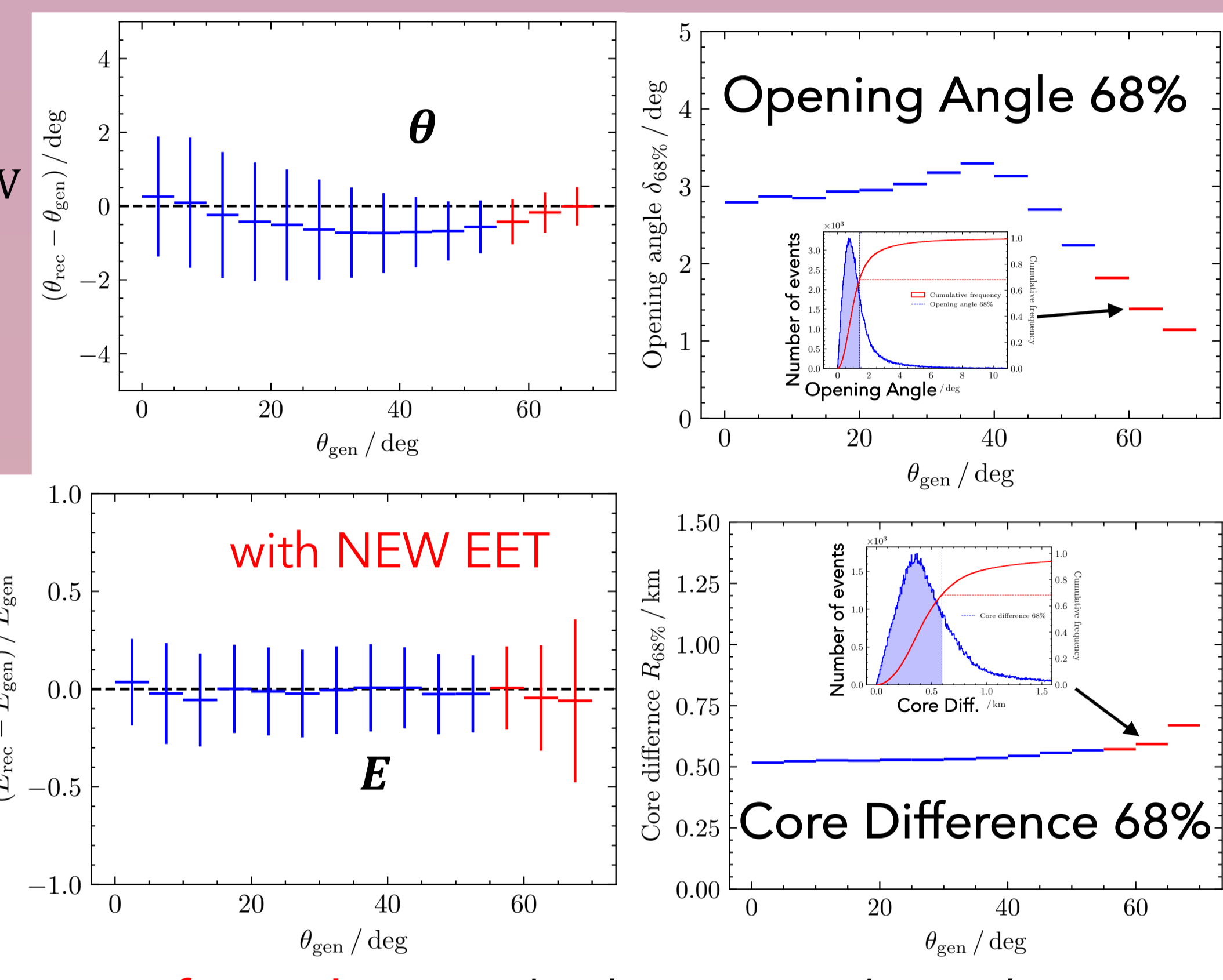
MC simulation dataset
- pure proton, QGSJETII-04
- $10^{17.5}$ eV $\leq E_{gen} \leq 10^{20.5}$ eV
- $0° \leq \theta_{gen} \leq 70°$

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

Original EET

NEW "extended" EET

Evaluation of reconstruction accuracies

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

θ — Opening Angle 68%

with NEW EET — E — Core Difference 68%

No significant bias in the large zenith angle region
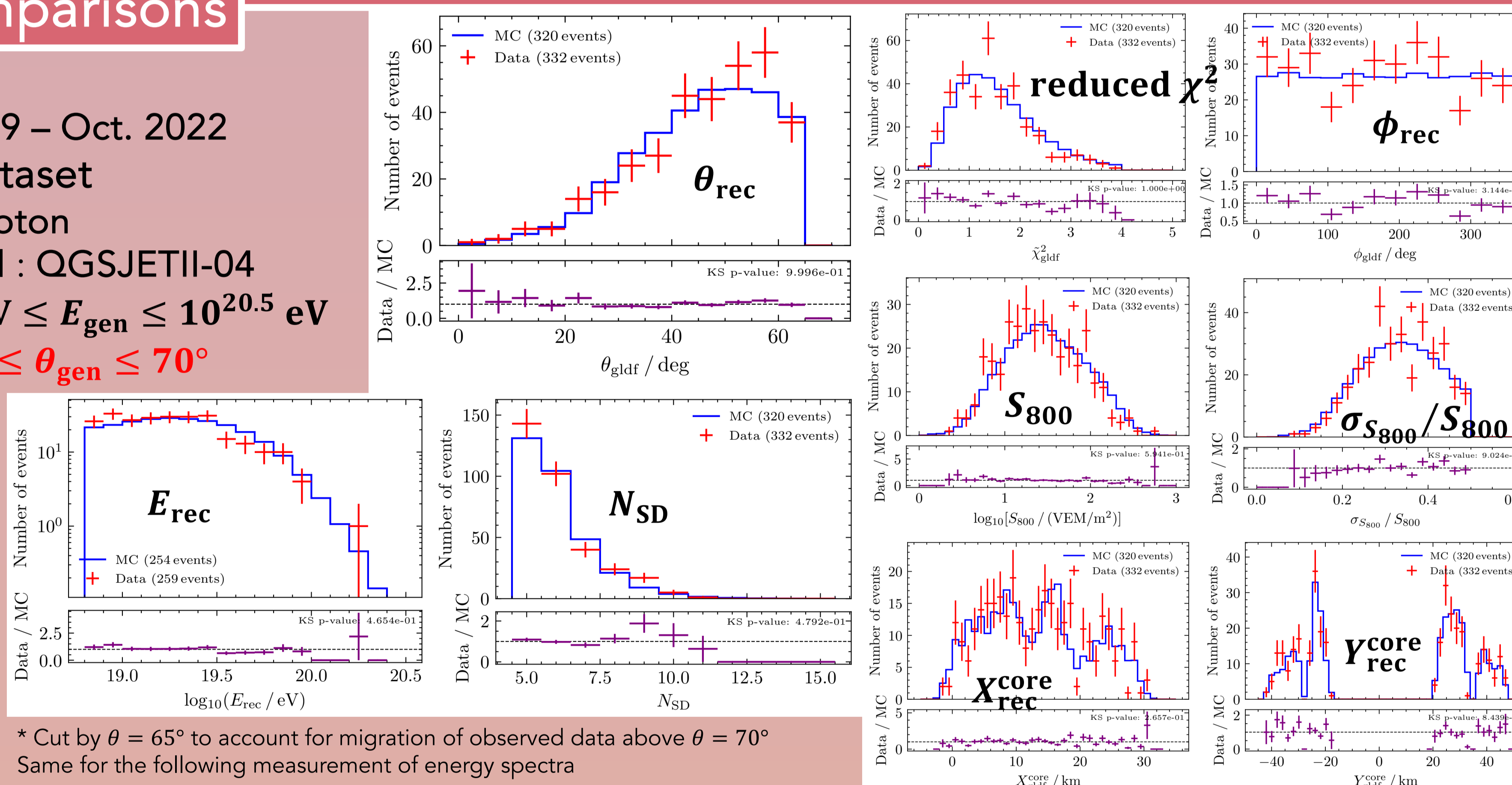
Data/MC comparisons

Observed data
- Period : Oct. 2019 – Oct. 2022

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

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

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

θ_{rec}, reduced χ^2, ϕ_{rec}, E_{rec}, N_{SD}, S_{800}, $\sigma_{S_{800}}/S_{800}$, X_{rec}^{core}, Y_{rec}^{core}

Only with inclined events ($\theta_{rec} \geq 55°$)

E_{rec}, reduced χ^2, ϕ_{rec}, θ_{rec}, S_{800}, $\sigma_{S_{800}}/S_{800}$, N_{SD}, X_{rec}^{core}, Y_{rec}^{core}
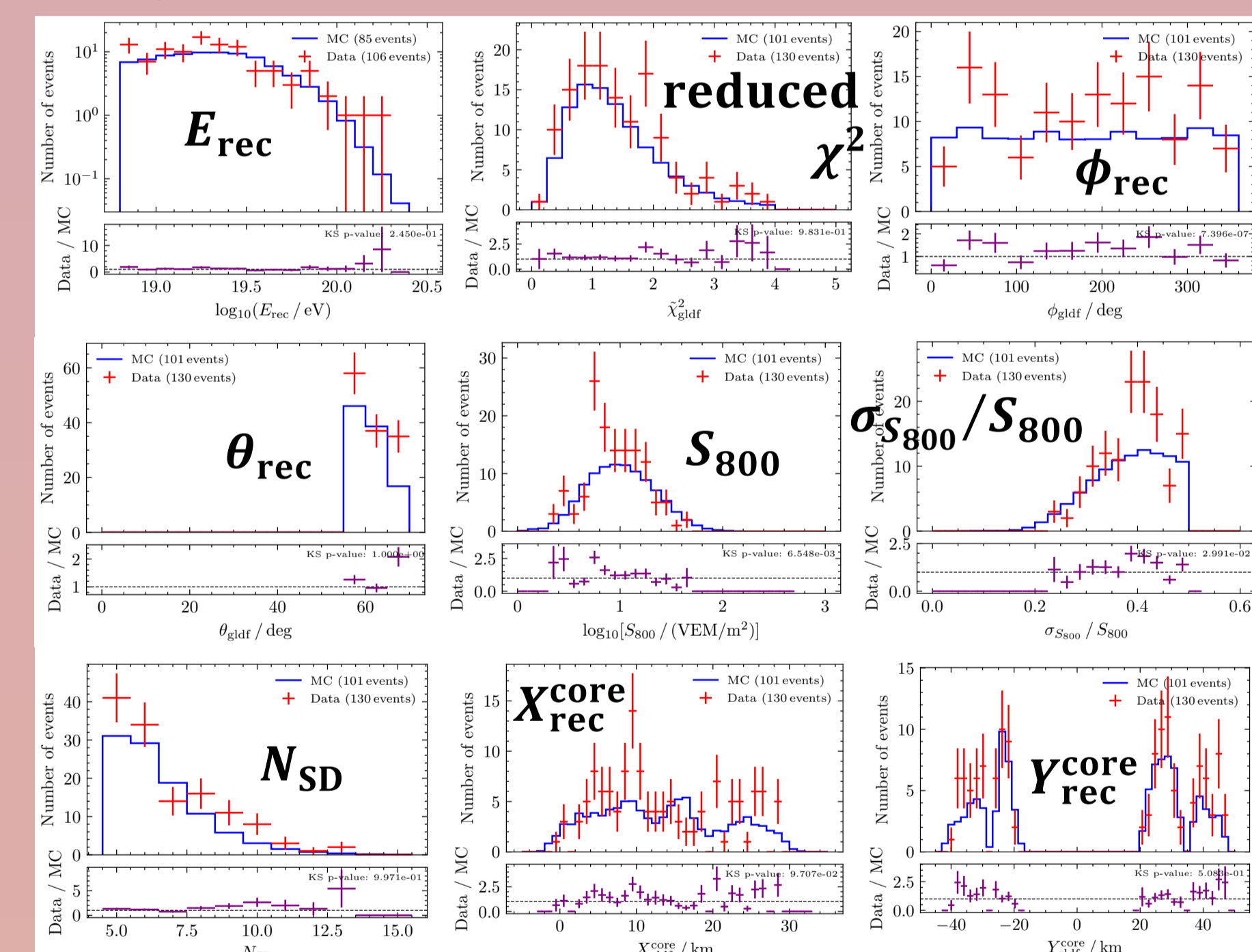
No significant discrepancies between them even in the large zenith angle region

Measurement of energy spectra

Cosmic Ray Flux

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

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 [km²]	~120	~40	~230	~150	~140	~110
# of days T [days]	1120	1102	1120	1093	1120	1120
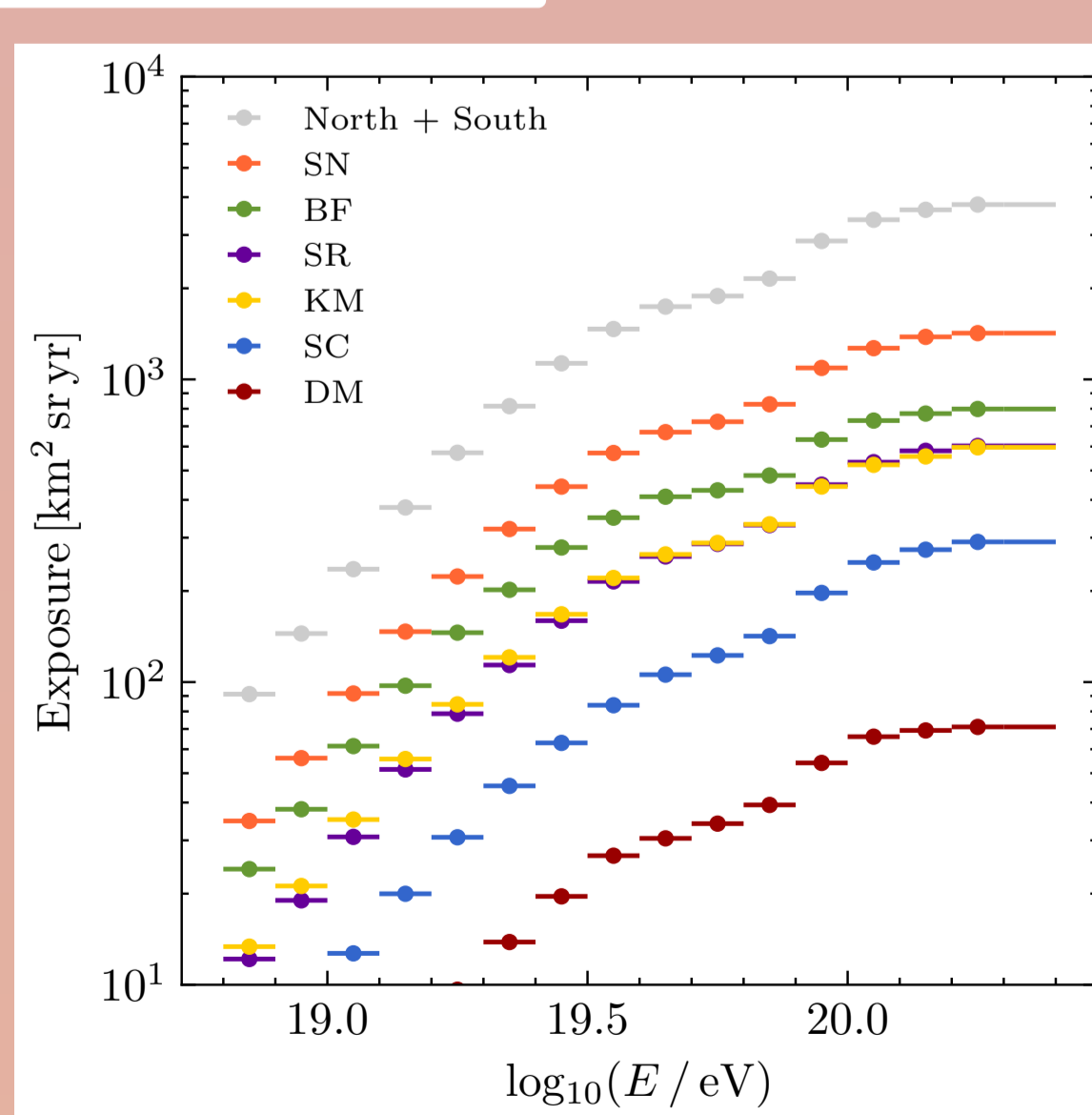
Exposure values were smaller in the highest energy bin than in the lower energy bins (Because the highest energy of the EET was too low, so that extrapolated values are used assuming flat exposure.

North + South, SN, BF, SR, KM, SC, DM

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

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

This work (Criteria : $\theta \leq 65°$) $N_{rec}^{Data} = 259$

1.4× increase in statistics **

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

Good agreements with previous analysis

TA Preliminary

- TA×4 SD 3yrs (this work, $\theta \leq 65$ deg)
- TA×4 SD 3yrs (original, $\theta \leq 55$ deg)
- TA SD 14yrs
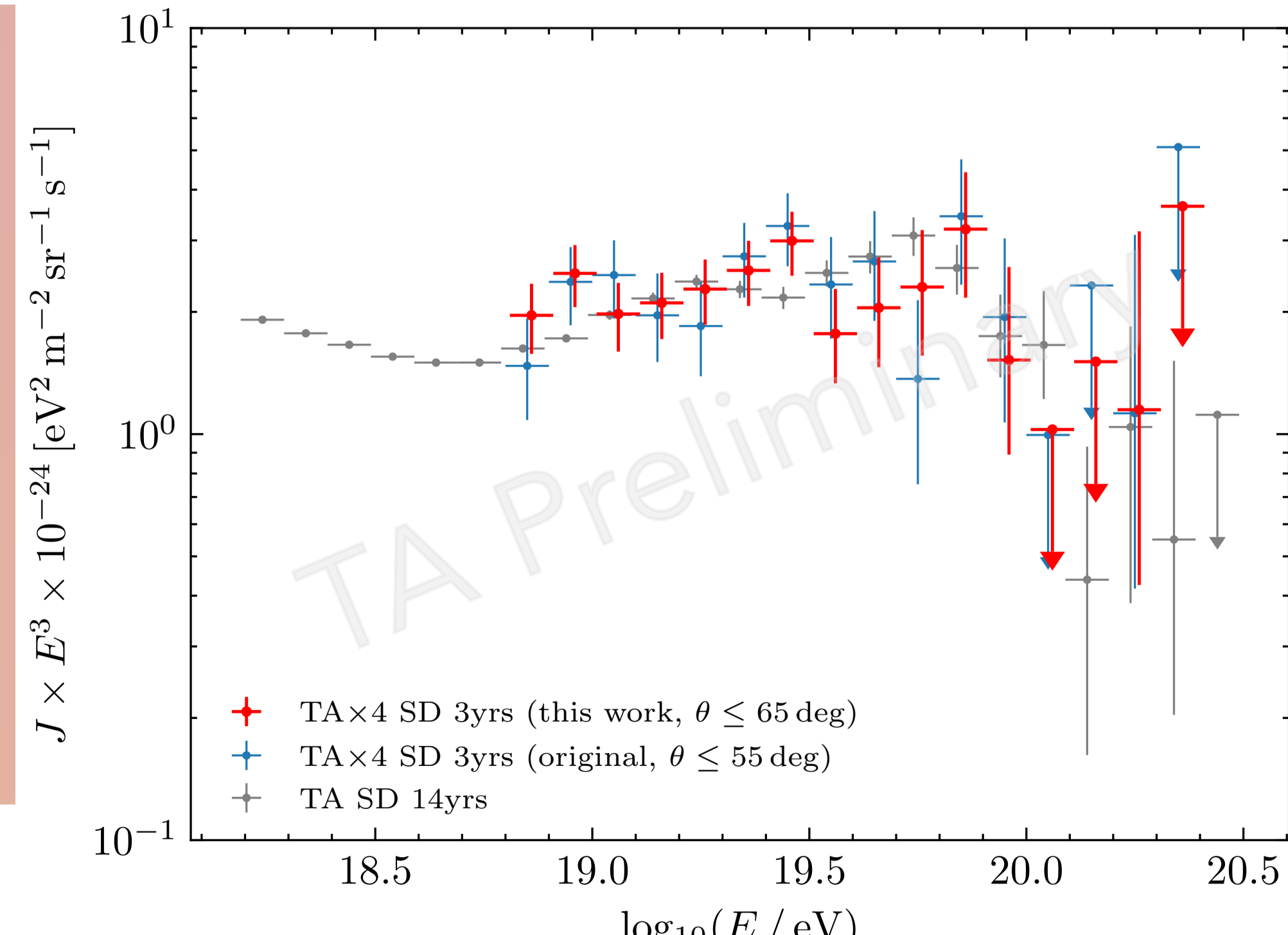
Summary & prospects

✓ Extended the energy estimation table for TA×4 to $\theta = 70°$ ⇒ **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)