TAx4 SD analysis

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Outline

- TAx4 SD Data/MC comparison
  - Data period : 1.5 years(TAx4 North SD) + 2 years(TAx4 South SD)
  - Determining temporally energy scale in terms of Data/MC event number
  - Data & MC agree with energy scale=1.3 for E > 10^{19} eV

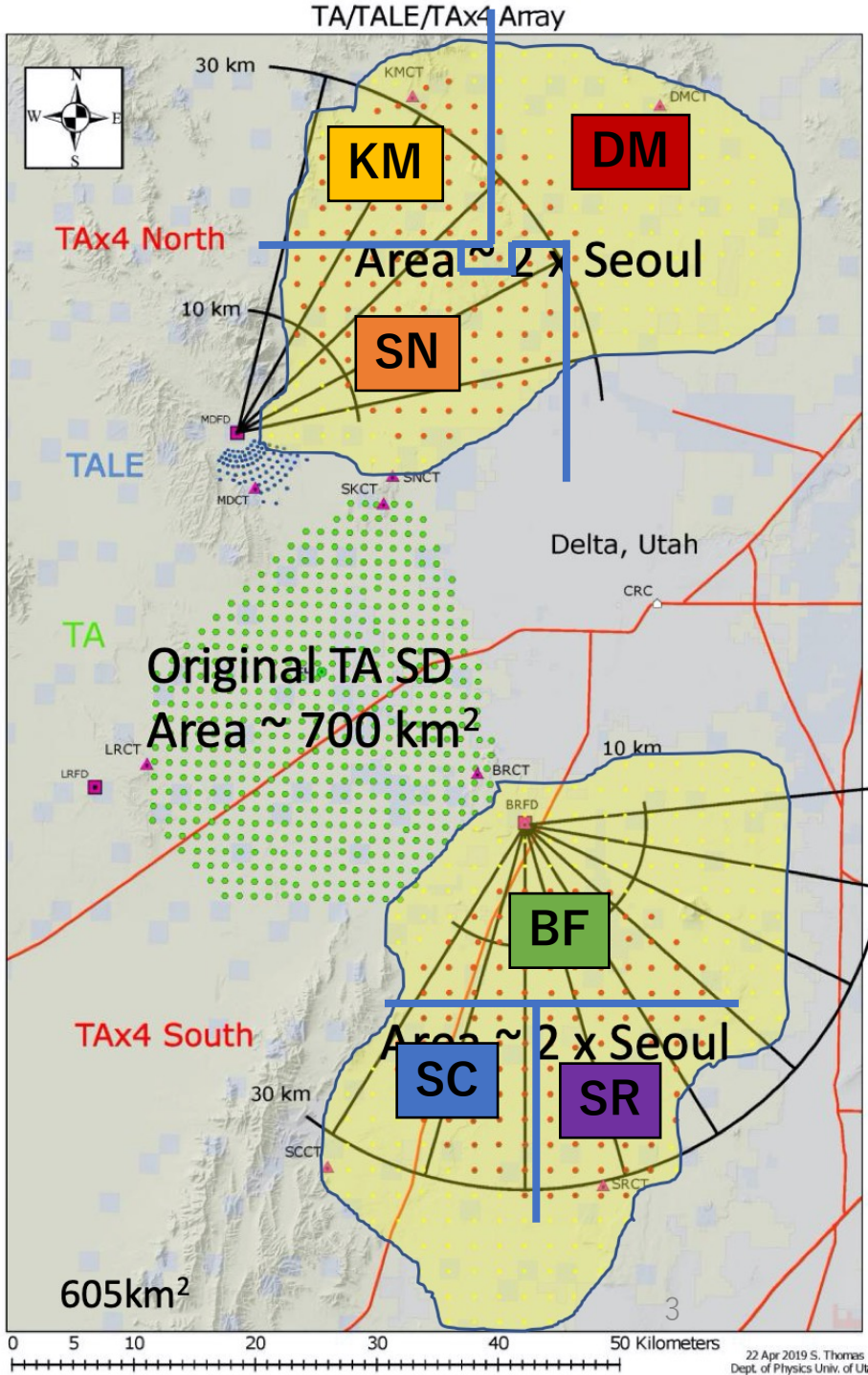
- TAx4 preliminary energy spectrum
  - For E > 10^{19} eV, the energy spectrum is consistent with TA SD 11 years energy spectrum
  - Validation of cut off

TAx4 SD Data set

	North array 1.5 years			South array 2 years		
	KM	DM	SN	BF	SC	SR
Duration <days>	191008-210430 <571>	191026-210521 <574>	191008-210428 <569>	191104-211007 <704>	191008-211007 <731>	191008-211007 <731>
Area [km²]	~120	~40	~230	~150	~105	~140
MC thrown area [km²]	330	251	486	354	283	345

- Currently, data acquisition & analysis are done for each sub-array individually.
  - Implementation of boundary trigger is ongoing.

- Reconstruction method :
  - Currently same as TA SD.



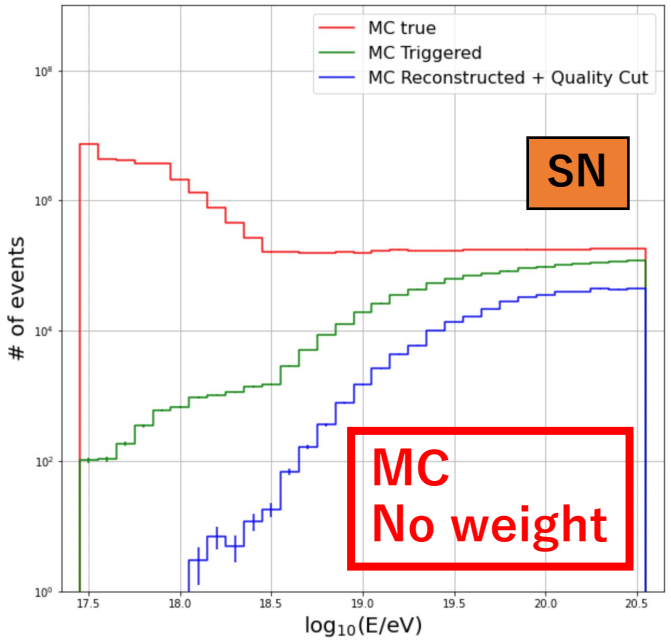
TAx4 SD MC simulation

CORSIKA shower input
- Hadronic interaction model : QGSJETII-04
- Primary particle : proton
- Energy : $10^{17.5}$ eV – $10^{20.5}$ eV
- Zenith angle : 0 - 60 deg (isotropic distribution)

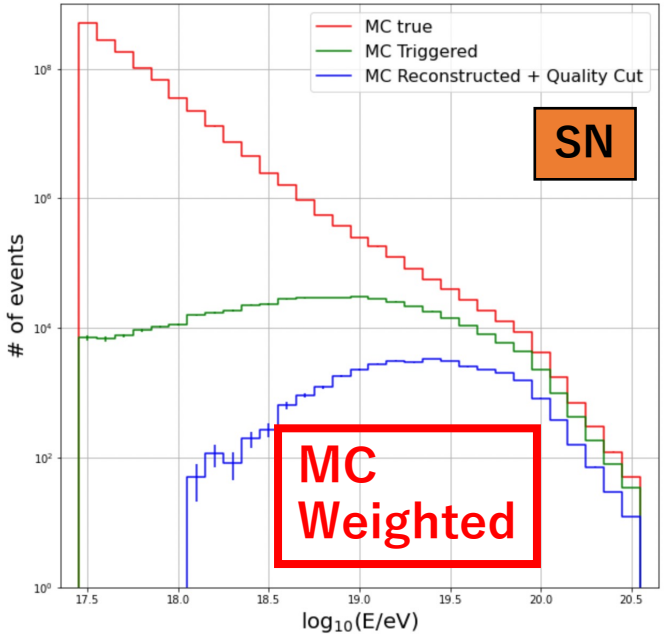
In MC simulation, real detector condition is implemented

After shower generation by CORSIKA, events are weighted to reproduce TA SD 11 years energy spectrum

(D. Ivanov, for the Telescope Array Collaboration, PoS. ICRC 2019)



weighting



Data/MC comparison

- Objective : checking if MC simulation reproduces real Data well
- Check if events which pass following quality cuts (QCs)

  (i) $\mathbf{N_{SD}}$ (Number of SDs which are used for reconstruction) >= **5**

  (ii) D (distance b/w rec. core position & array border) < **400 m**

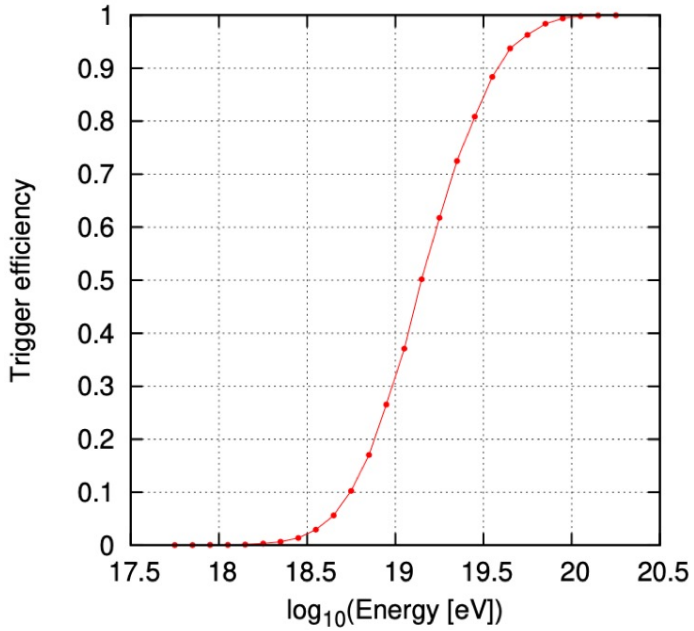
  (iii) $\theta_{\mathbf{rec}}(\mathbf{rec.\ zenith\ angle})$ < **55°**

  (iv) χ^2/dof < **4**

  (v) $\sigma_{\mathbf{dir}}$(uncertainty of rec. direction) < **8°**

  (vi) $\sigma_{\mathbf{S800}}$ /S800 < **0.50** (S800 : particle density at 800m from shower axis)

- Comparison for $\mathbf{E_{rec}}$ (rec. energy) $> 10^{19}$ eV



Abbasi R. U., *et al.* Surface detectors of the TAx4 experiment
Nucl. Instrum. Methods Phys. Res. A, 1019 (2021), 165726

Data/MC comparison – energy scale optimization

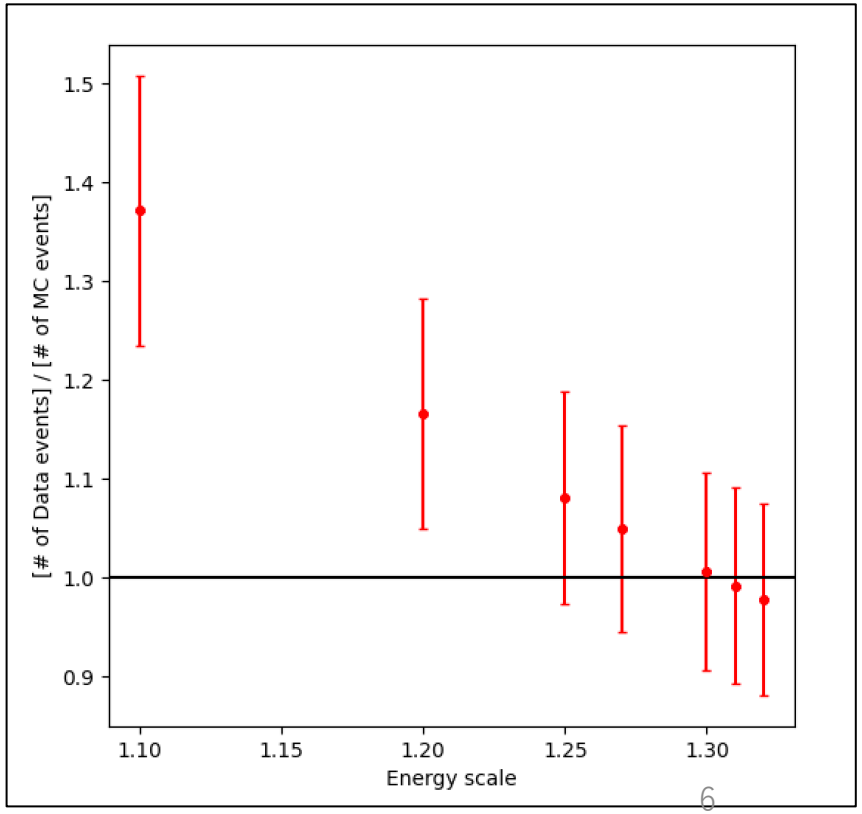
- MC normalization
  - MC events are weighed to reproduce the number of event expected from TA 11years energy spectrum.
    - The number of MC events depends on energy scaling factor
  - Energy scaling factor is determined to minimize

$$\left| \frac{[\text{The number of Data events (after QC) } E>10 \text{ EeV}]}{[\text{The number of MC events (after QC) } E>10 \text{ EeV}]} - 1 \right|$$

→ Energy scale factor = **1.3**

(Energy scale factor = 1.27 for TA SD, QGSJETII-03 proton)

(・It will be determined by FD/SD coincidence triggered event analysis)



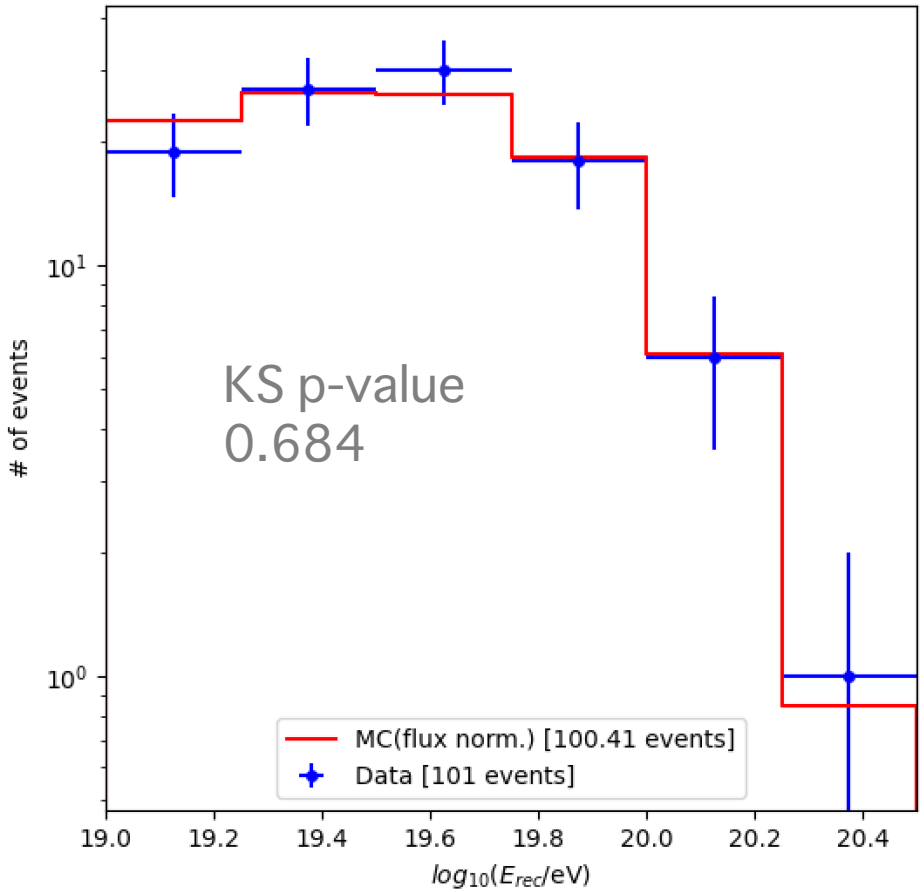
Data/MC comparison

(**Erec** $> 10^{19}$ **eV**)

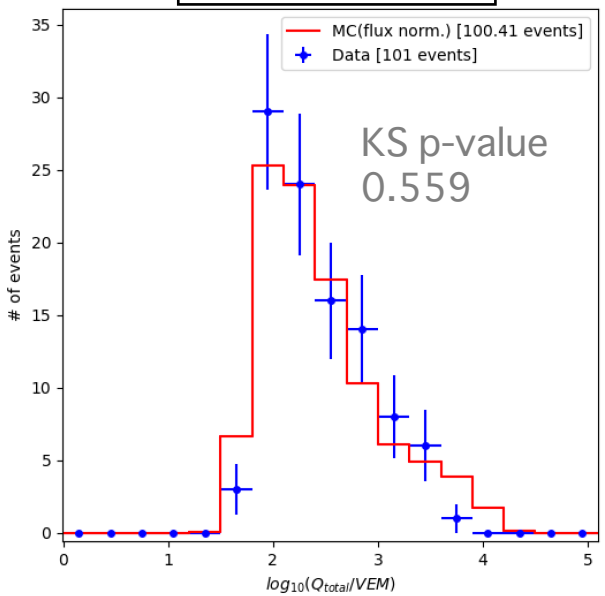
Red histogram	: simulation
Blue dots	: real data

Energy scale factor = **1.3**

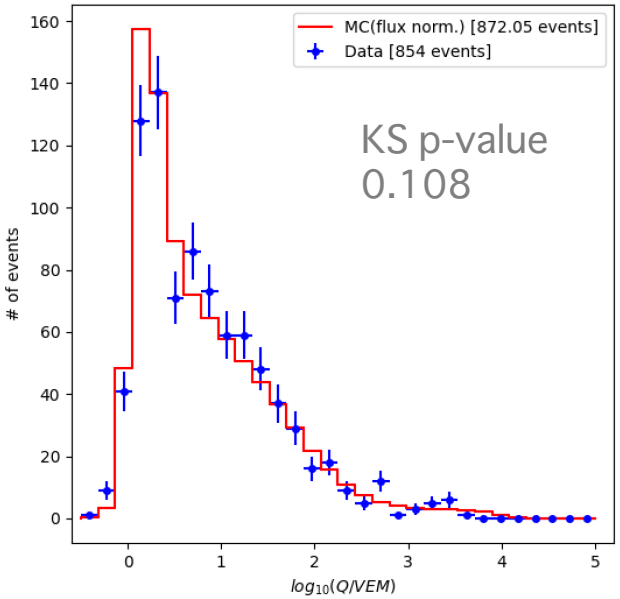
Reconstructed energy



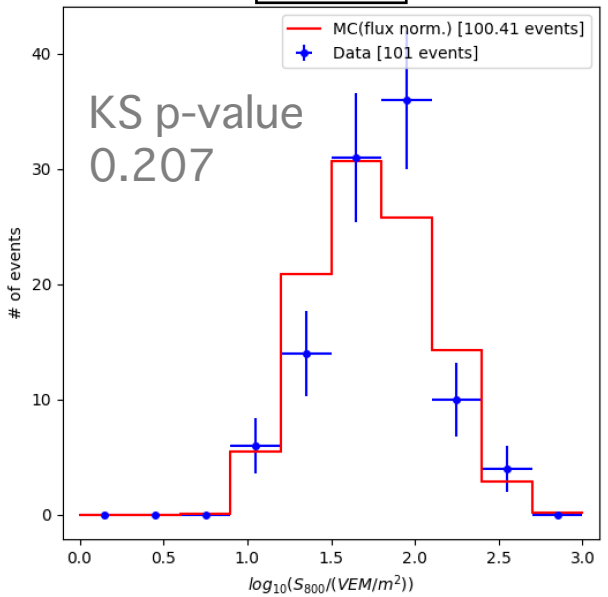
signal/event



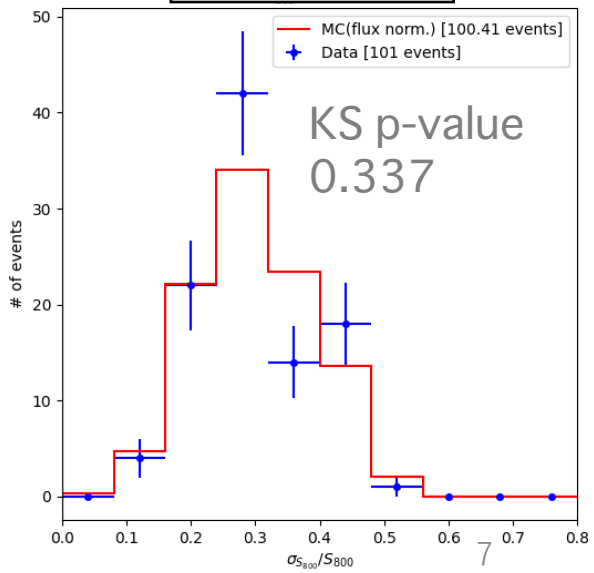
signal/detector



S800



σ_{S800}/S800

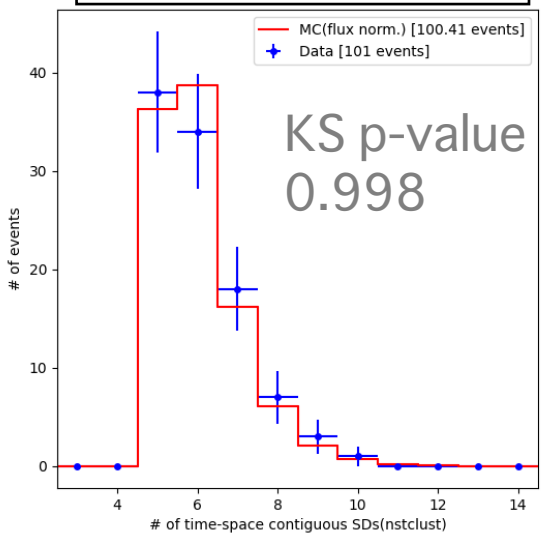


Data/MC comparison (Erec > 10^{19} eV)

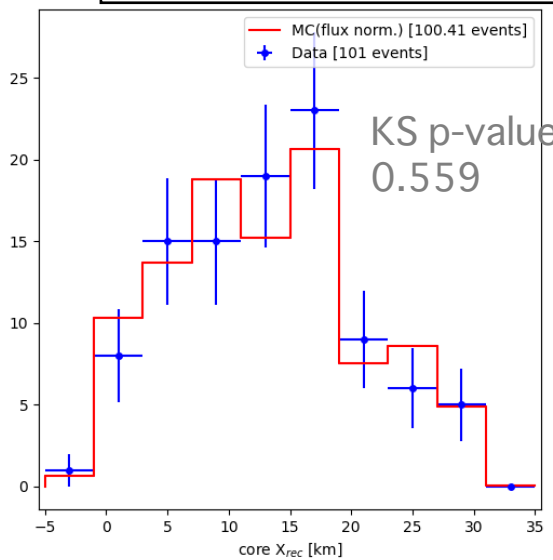
Red histogram : simulation
Blue dots : real data

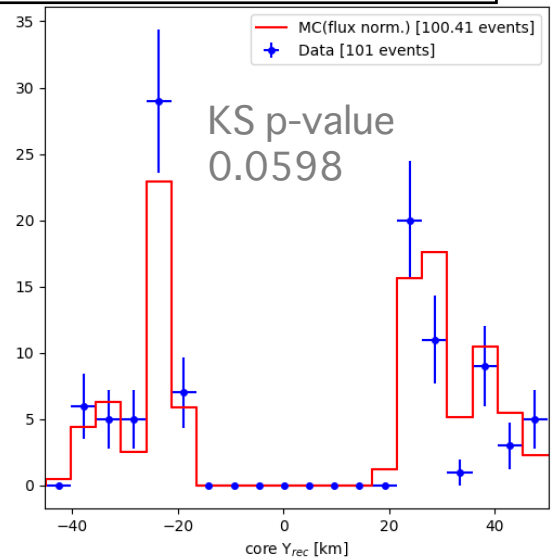
- They agree within statistical uncertainty

Number of hit SDs

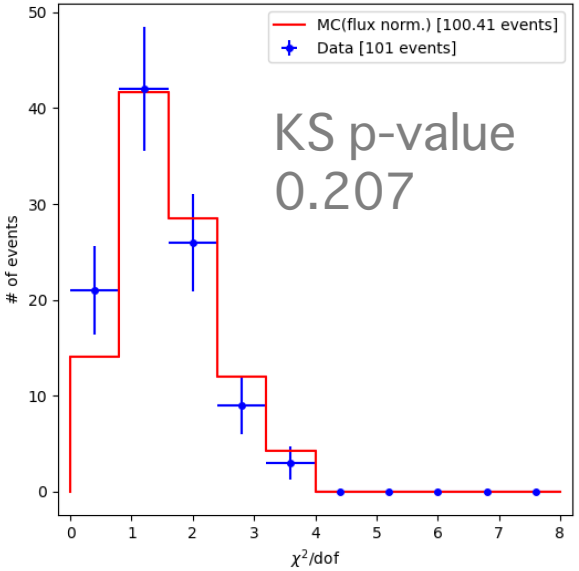


Rec. core position (West-east/South-north)

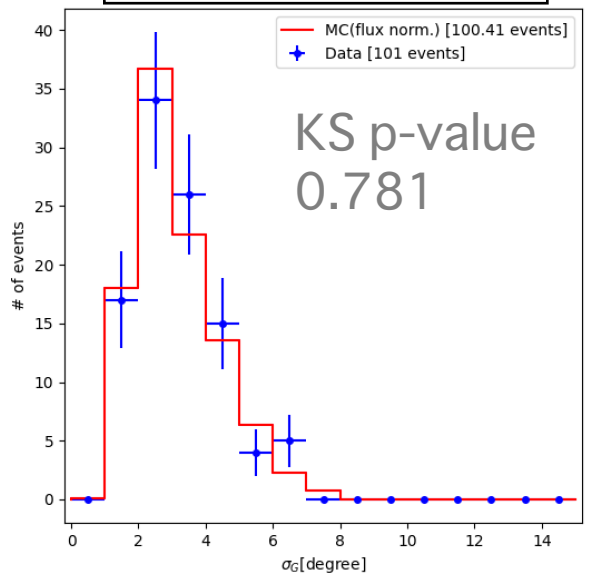




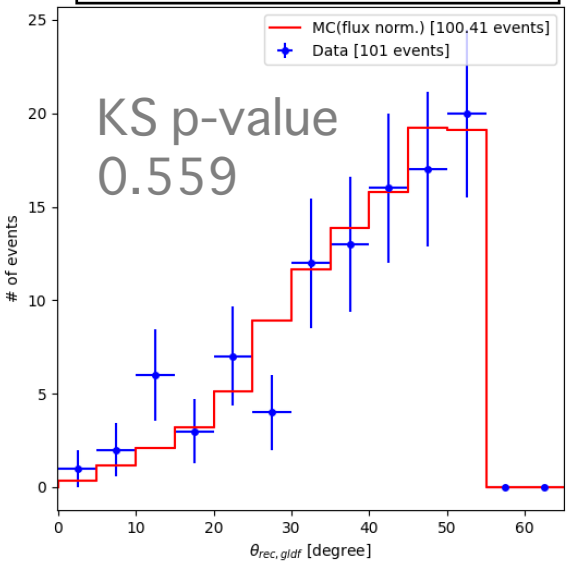
χ^2/dof



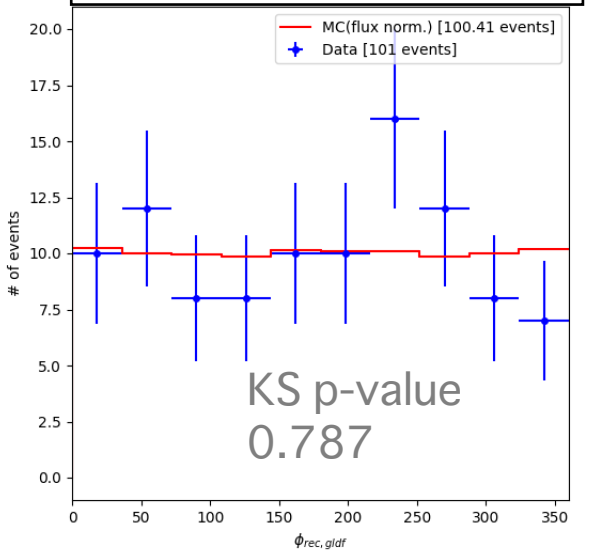
Uncertainty of reconstructed direction



Rec. zenith angle θ



Re. azimuth. angle ϕ



How to obtain energy spectrum

1) Calculating effective exposure for each sub-array using MC simulation
2) Combining $\mathrm{N}_{\mathrm{rec}}^{\mathrm{Data}}(\mathrm{E}_{\mathrm{i}}^{\mathrm{rec}})$ and effective exposures $\mathrm{A}\Omega T \times \mathrm{Rec.\,Eff.}\left(\mathrm{E}_{\mathrm{i}}^{\mathrm{rec}},\ \mathrm{E}_{\mathrm{i}}^{\mathrm{gen}}\right)$

   (This is bin-by-bin correction unfolding)
3) Calculating combined energy spectrum with the calculated values

$$\frac{\sum_{sub-array}[\mathrm{N}_{\mathrm{rec}}^{\mathrm{Data}}(\mathrm{E}_{\mathrm{i}}^{\mathrm{rec}})]}{\sum_{sub-array}[\mathrm{A}\Omega T \times \mathrm{Rec.\,Eff.}\left(\mathrm{E}_{\mathrm{i}}^{\mathrm{rec}},\ \mathrm{E}_{\mathrm{i}}^{\mathrm{gen}}\right)] \times \Delta \mathrm{E}_{\mathrm{i}}^{\mathrm{gen}}}$$

A=[MC throwing area], **Ω**=[MC throwing solid angle]=$3\pi/4$, **T**=[Duration]

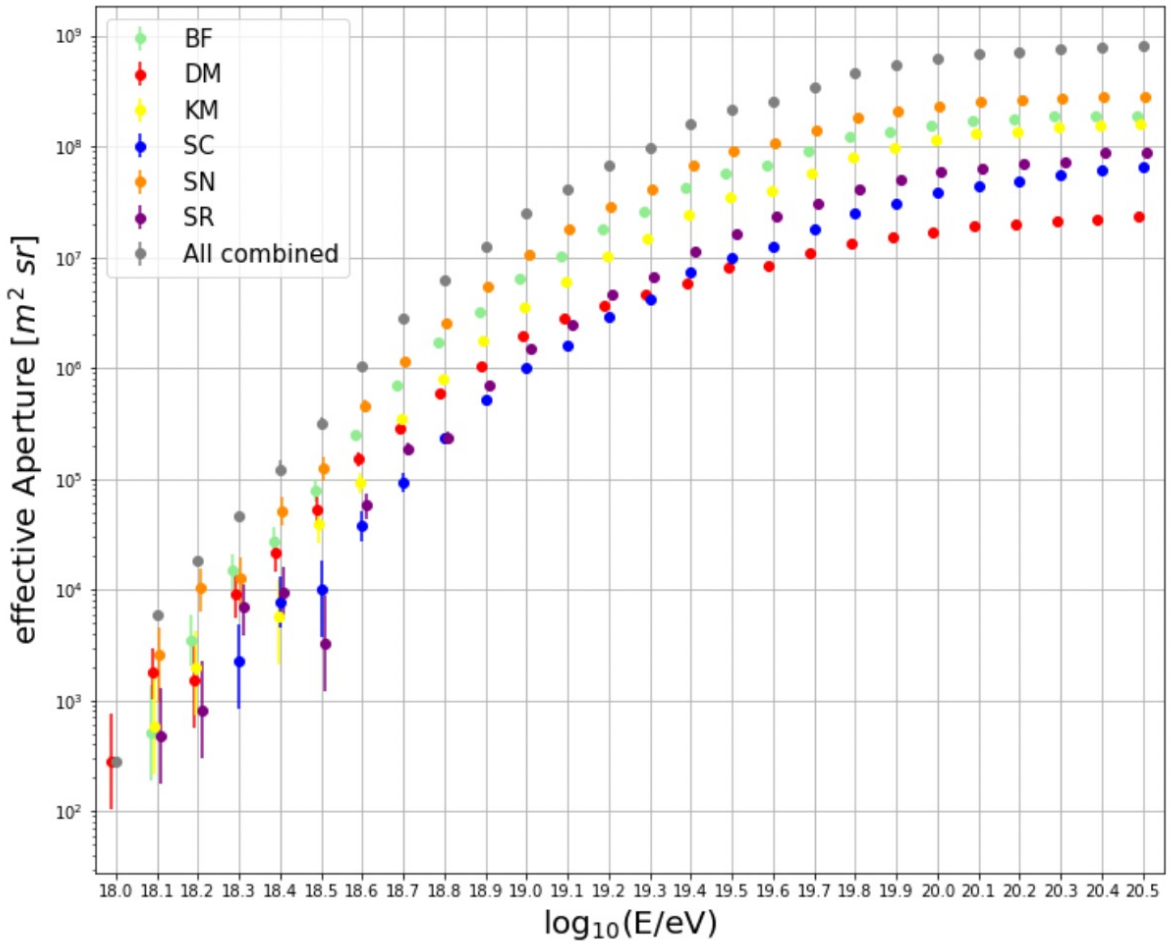
Rec.Eff.$(\mathbf{E}_{\mathbf{i}}^{\mathbf{rec}}, \mathbf{E}_{\mathbf{i}}^{\mathbf{gen}})$=[(# of QC passing events in $\mathrm{E}_{\mathrm{i}}^{\mathrm{rec}}$)/(# of all thrown events in $\mathrm{E}_{\mathrm{i}}^{\mathrm{gen}}$)]

$$= \mathbf{N}_{\mathbf{rec}}^{\mathbf{MC}}(\mathbf{E}_{\mathbf{i}}^{\mathbf{rec}}) / \mathbf{N}_{\mathbf{gen}}^{\mathbf{MC}}(\mathbf{E}_{\mathbf{i}}^{\mathbf{gen}})$$

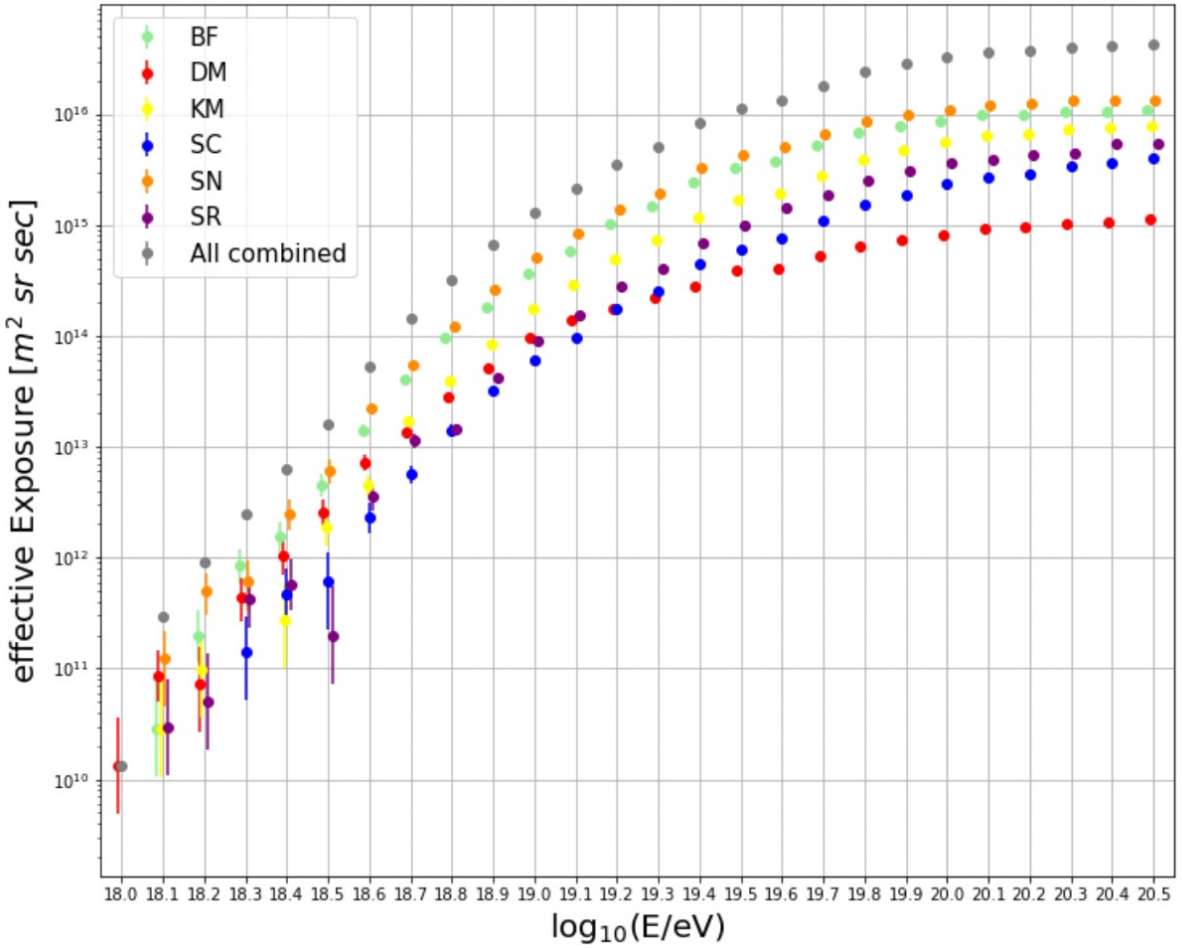
$\boldsymbol{\Delta}\ \mathbf{E}_{\mathbf{i}}$ = [width of ith bin]

Effective apertures & exposures

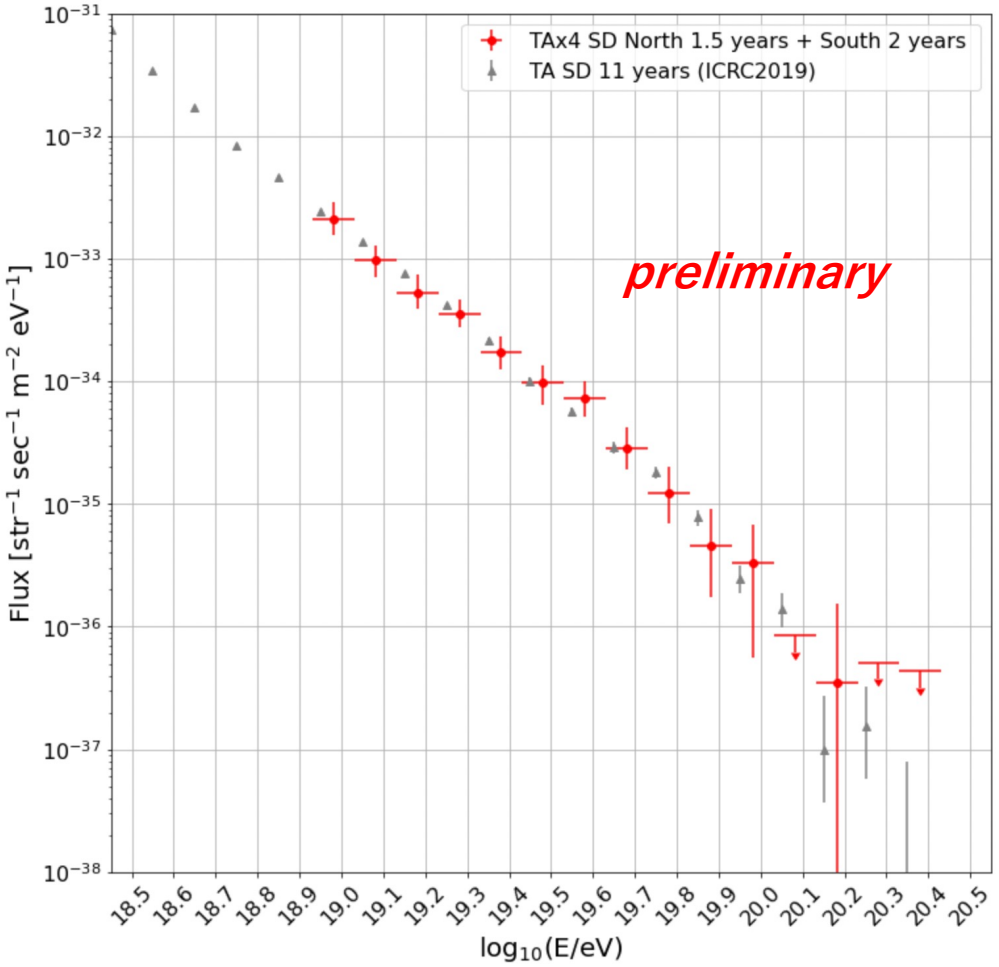
Aperture

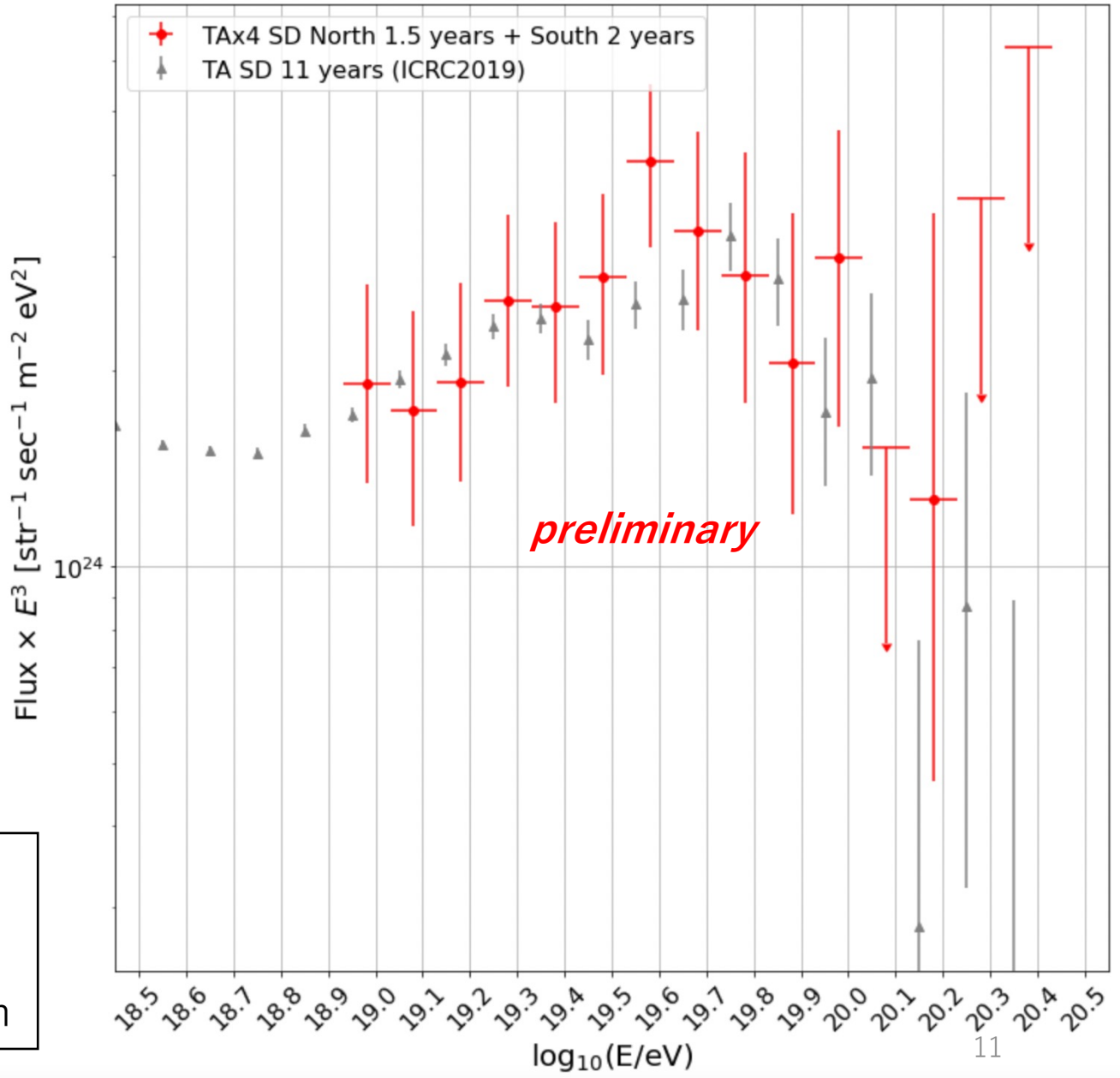


Exposure



TAx4 SD preliminary energy spectrum

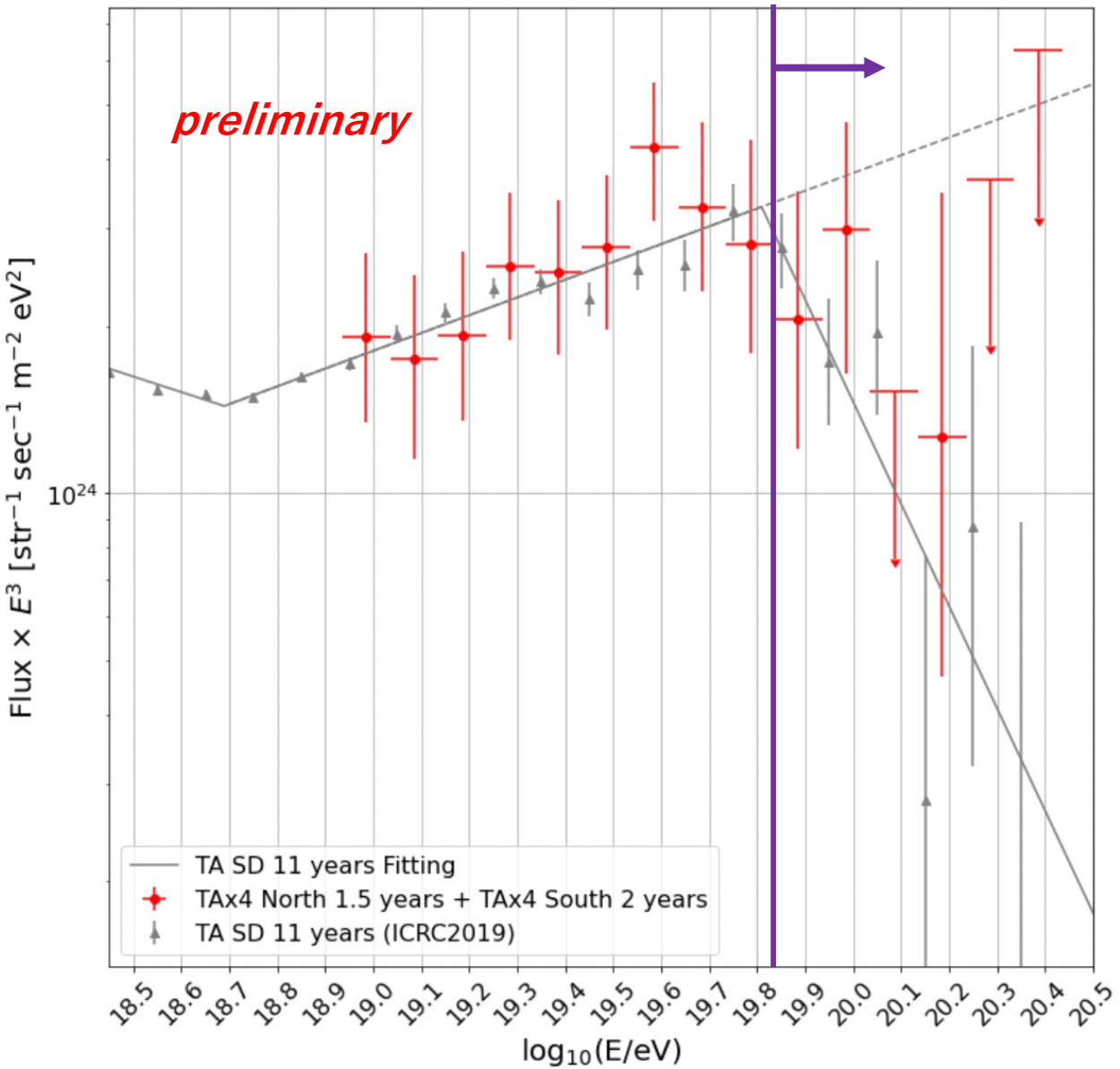




- TAx4 North 1.5 years + TAx4 South 2 years
- Energy scale=1.3
- Only $\sigma_{\text{Data stat}}$ (poisson distribution) is considered
- If 0 events in a raw bin, upper limit(90%) is drawn

TAx4 SD preliminary energy spectrum

Cut off significance



10 events are observed for E> $10^{19.84}$ eV

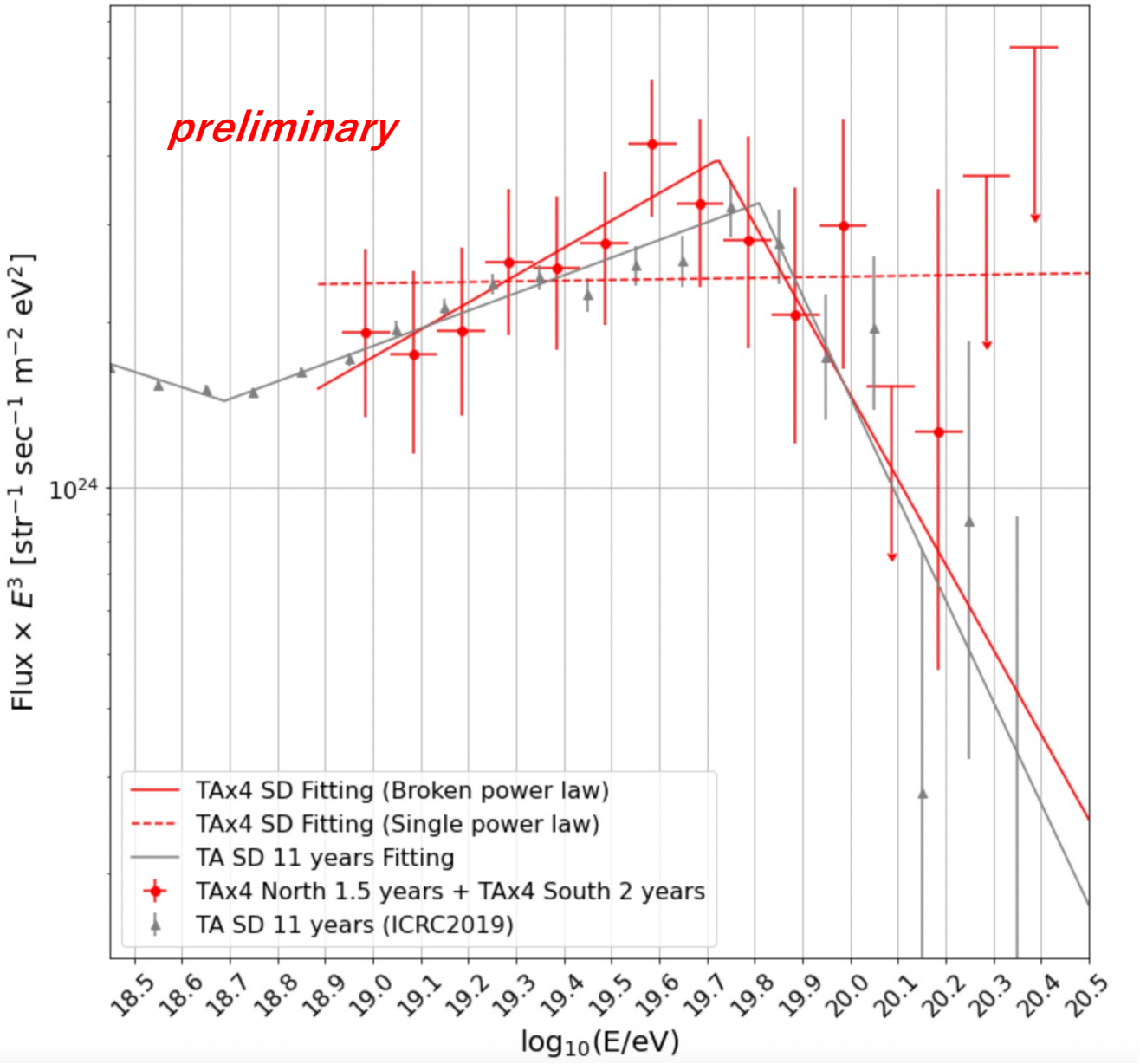
Expected number of events without cut off for E> $10^{19.84}$ eV : **27.16** events

$$\sum_{i=0}^{10} \mathrm{Poison}(27.16, i) = 1.48 \times 10^{-4}$$

It is approximately **3.6 σ**

TAx4 SD preliminary energy spectrum

Fitting with broken power law function



Broken power law :

$$F(E) = K_1[\ \theta(E_{break} - E)\left(\frac{E}{\mathrm{EeV}}\right)^{p_1} + \theta(E - E_{break})\left(\frac{E_{break}}{\mathrm{EeV}}\right)^{p_1 - p_2}\left(\frac{E}{\mathrm{EeV}}\right)^{p_2}\ ]$$

$\theta(x)$: step function

$$\begin{bmatrix} K_1 = 5.51\times10^{-31}\ [\mathrm{sr}^{-1}\mathrm{sec}^{-1}\ \mathrm{m}^{-2}\mathrm{eV}^{-1}] \\ E_{break} = 10^{19.72}[\mathrm{eV}] \\ p_1 = -2.51,\quad p_2 = -4.54 \end{bmatrix}$$

D /ndof = 6.82/11 = 0.62

Single power law :

$$F(E) = K\ (E/\mathrm{EeV})^p$$

$$\begin{bmatrix} K = 2.28\times10^{-30}\ [\mathrm{sr}^{-1}\mathrm{sec}^{-1}\ \mathrm{m}^{-2}\mathrm{eV}^{-1}] \\ p = -2.99 \end{bmatrix}$$

D /ndof = 17.4/13 = 1.34

Broken power law fit is preferred.

Summary

- TAx4 SD Data/MC comparison
  - Energy scaling factor is temporally determined to minimize the difference b/w the event number of observed Data and that of MC simulation.
  - Data/MC agree for E> 10^{19} eV.

- TAx4 SD preliminary energy spectrum (TAx4 North 1.5 years + TAx4 South 2 years)
  - For E> 10^{19} eV, TAx4 SD spectrum is consistent with TA SD 11 years energy spectrum.
  - Validation of cut off
    - Cut off chance probability is 3.6 σ
    - Broken power law is preferred.

- Further data set is under generating.

- Implementation of boundary trigger is ongoing.