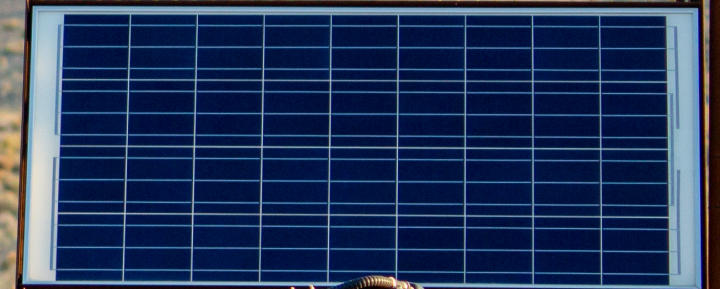


First Results with TALE infill SD Array for a PeV Cosmic-Ray Energy Spectrum Measurement

2026/8/30-9/4 TeVPA

**Graduate School of Science, Osaka Metropolitan Univ.
Haruto Matsushita for the TA collaboration**



Contents

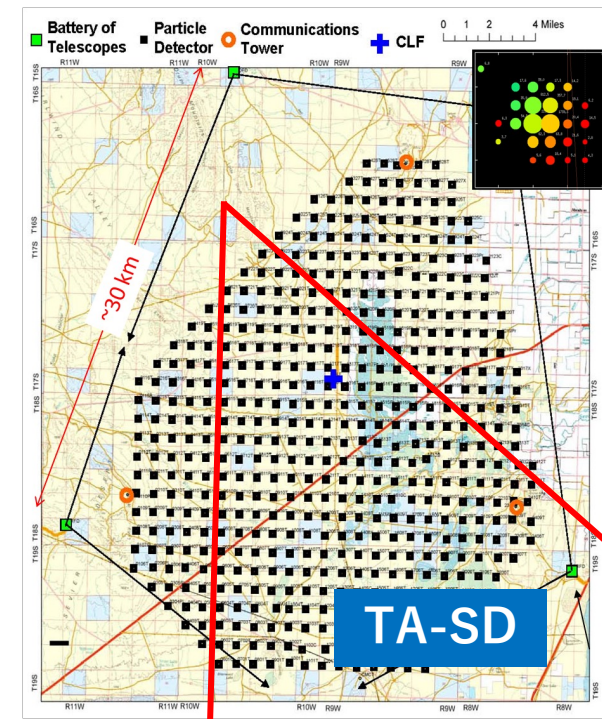
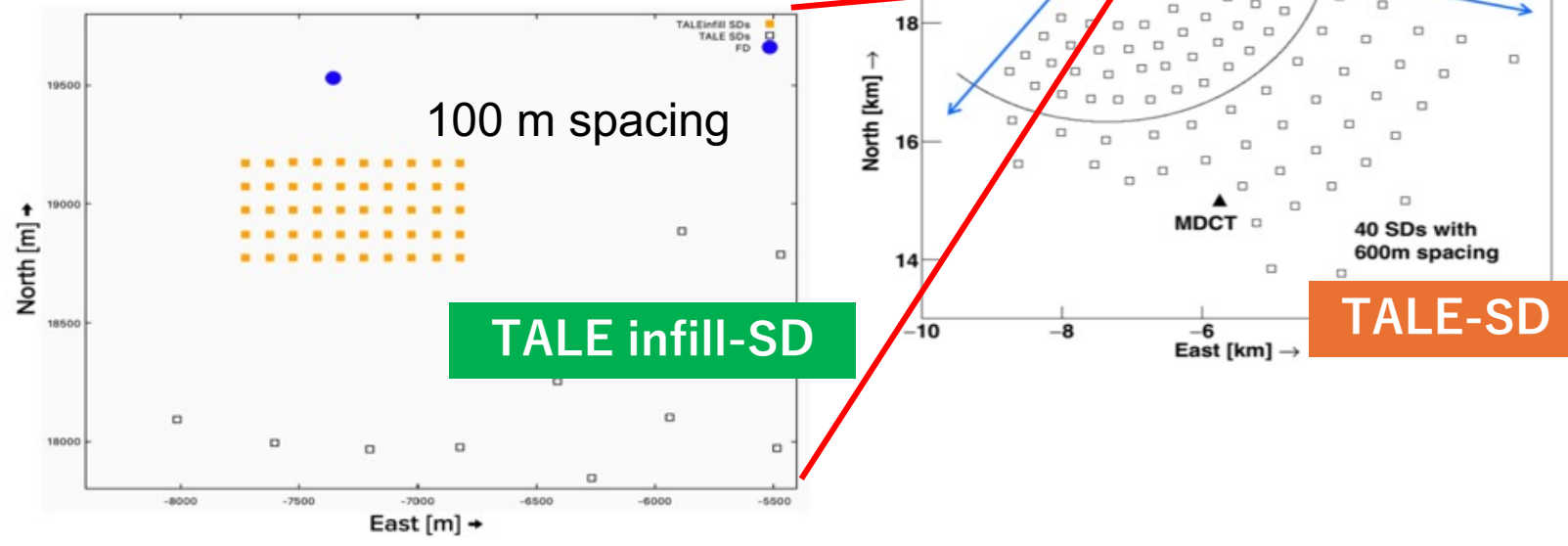
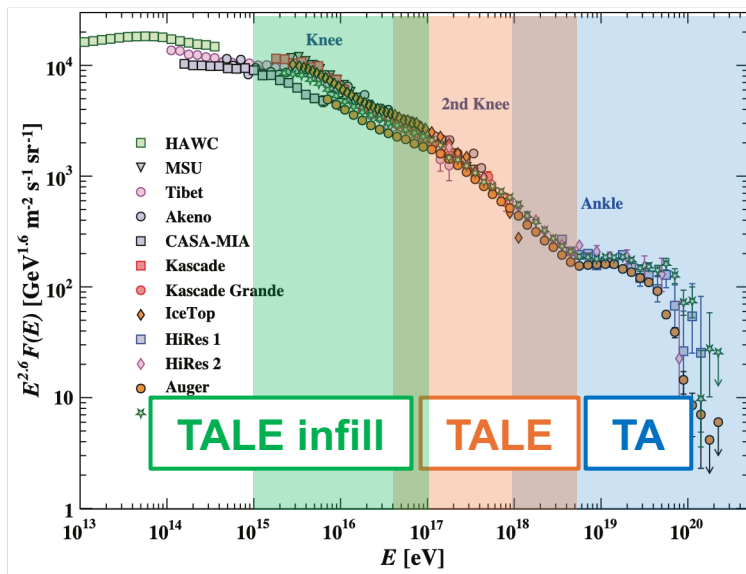
1. Introduction of TALE infill SD array
2. Reconstruction method & performance
3. Data/MC comparison
4. Spectrum measurements

Contents

- 1. Introduction of TALE infill SD array**
2. Reconstruction method & performance
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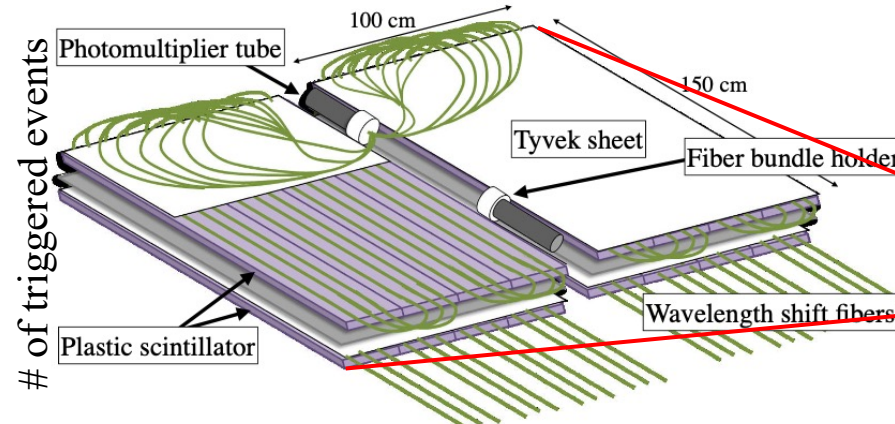
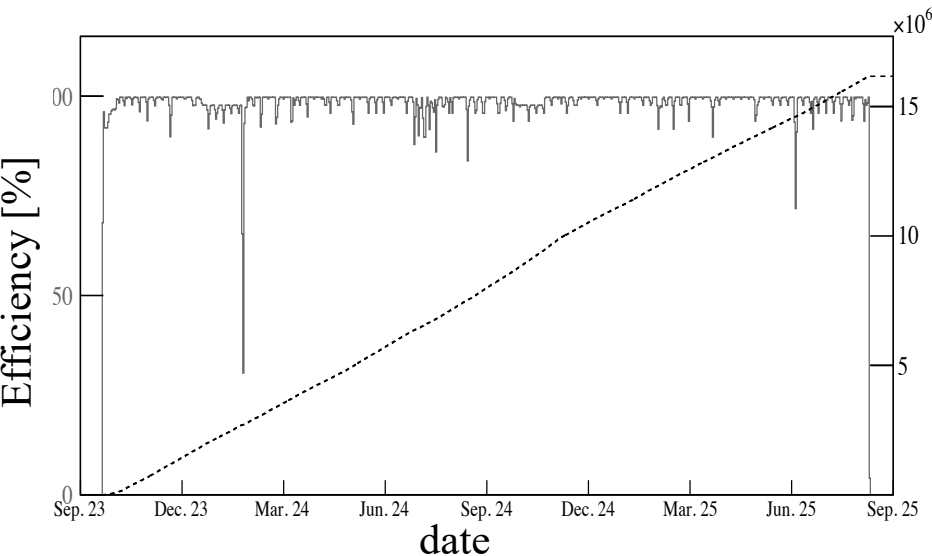
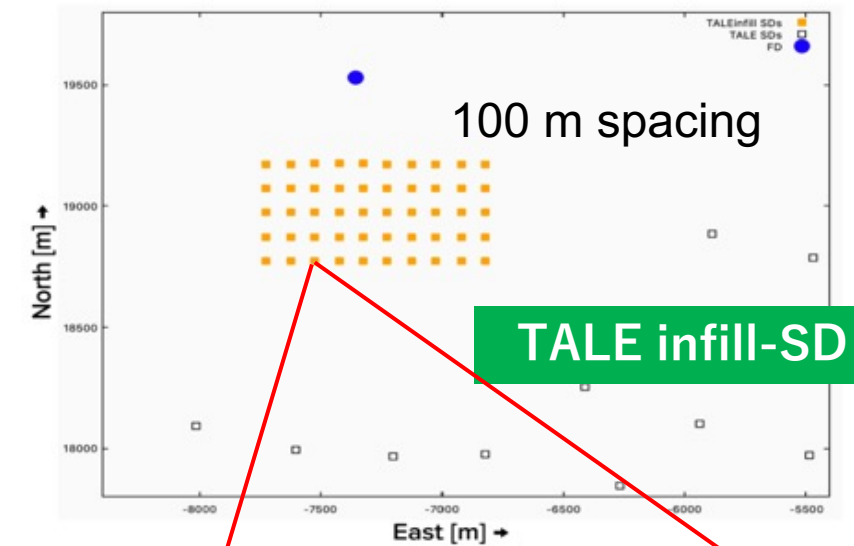
TALE infill

- Overview : A further low energy extension of **TALE** (Telescope **A**rray **L**ow-energy **E**xtension)
- Target : Cosmic rays with $E \geq 10^{15.0}$ eV
- Objective : Investigating the “knee” structure
 - Measure an energy spectrum
 - Measure mass composition and anisotropy



TALE infill

- SDs of TALE infill have two layers of plastic scintillators
- Trigger condition of TALE infill SD array:
 - 5 adjacent SDs coincidence within $3\mu\text{s}$
- Number of triggered events in 2 years is $> 10^7$



Credit: T. Abu-Zayyad et al. (Telescope Array Collaboration),
 "Surface detectors of the TAx4 experiment,"
Nucl. Instrum. Methods Phys. Res. A 1019, 165726 (2021).



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Reconstruction method

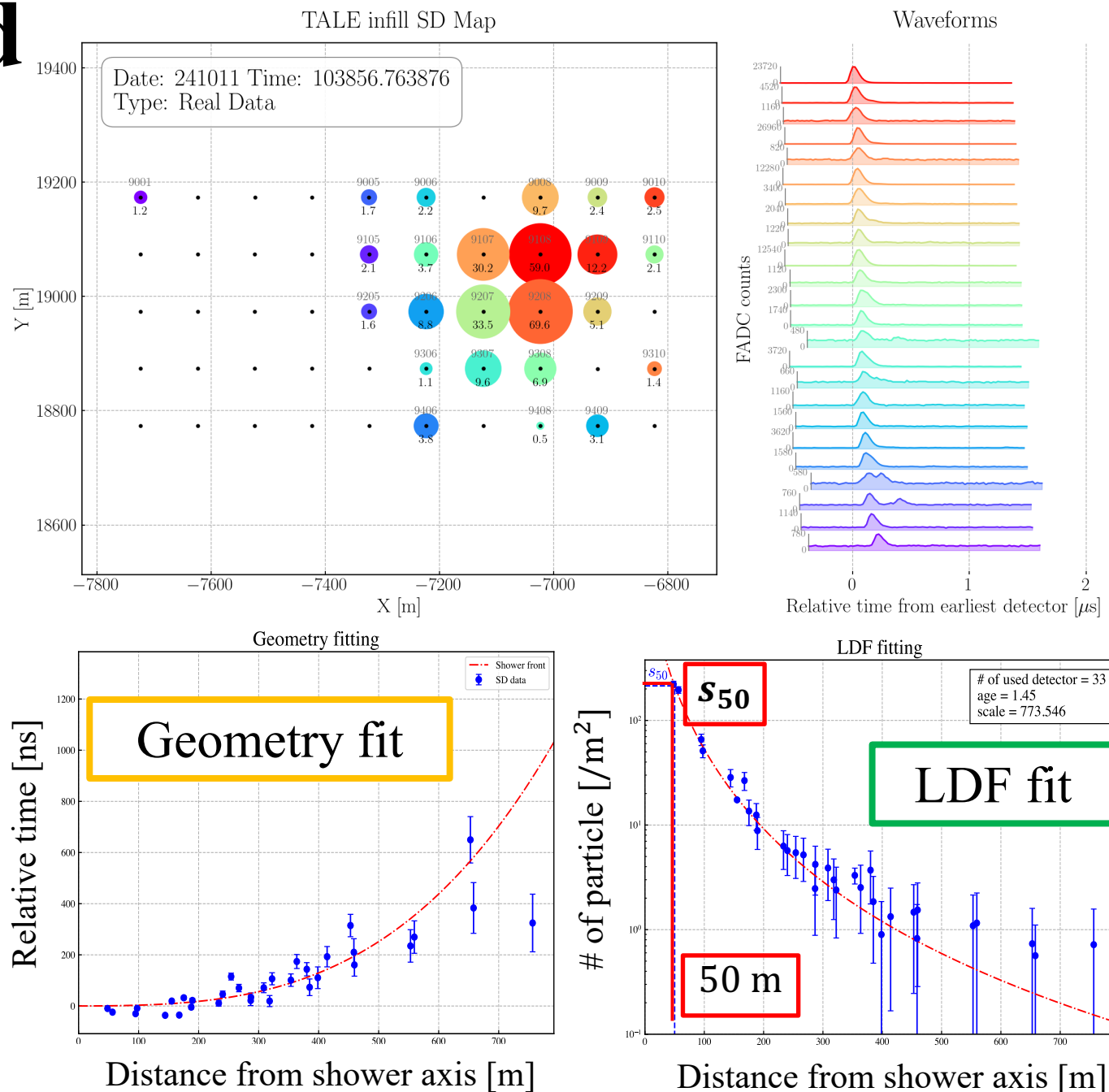
Get information of waveform a & time

Determine arrival direction (θ, ϕ)
using time information

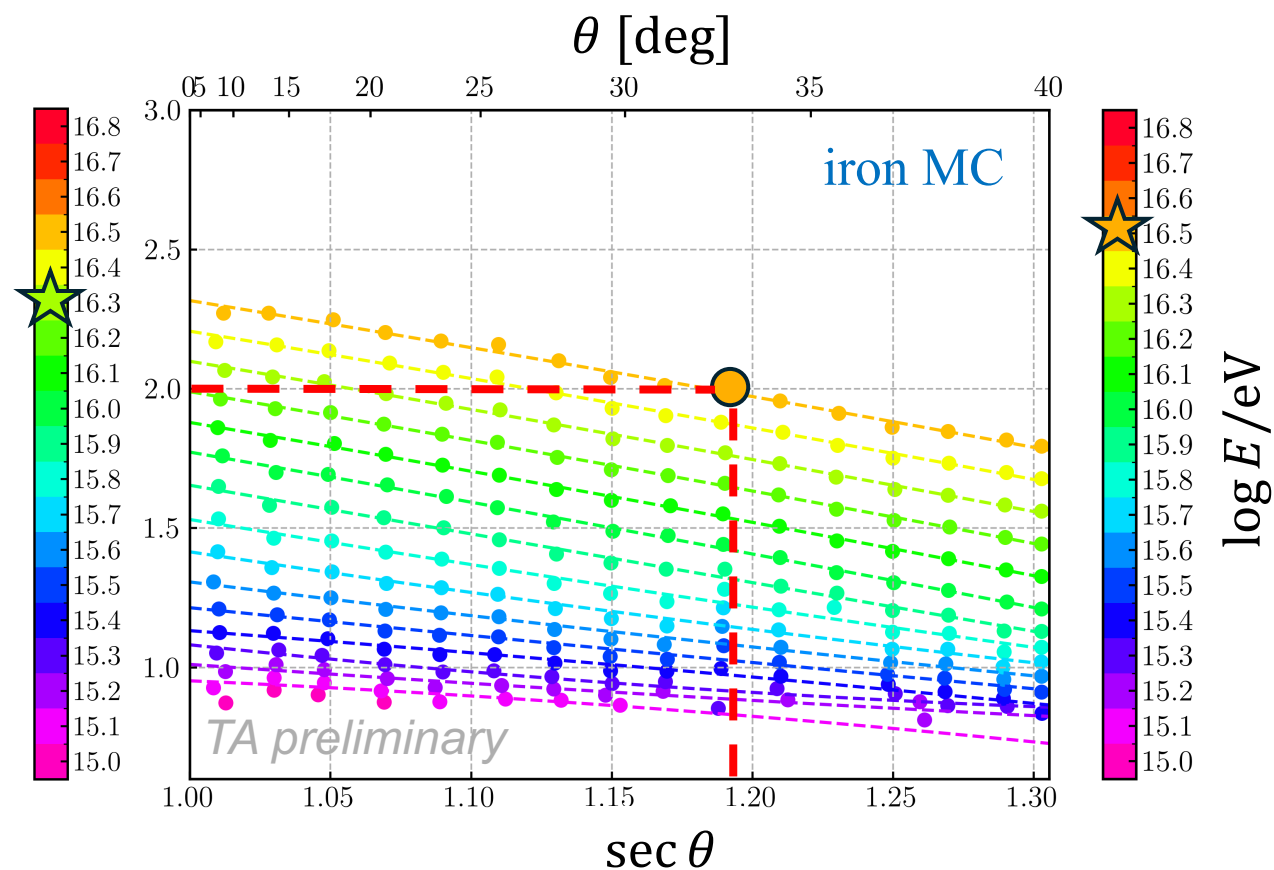
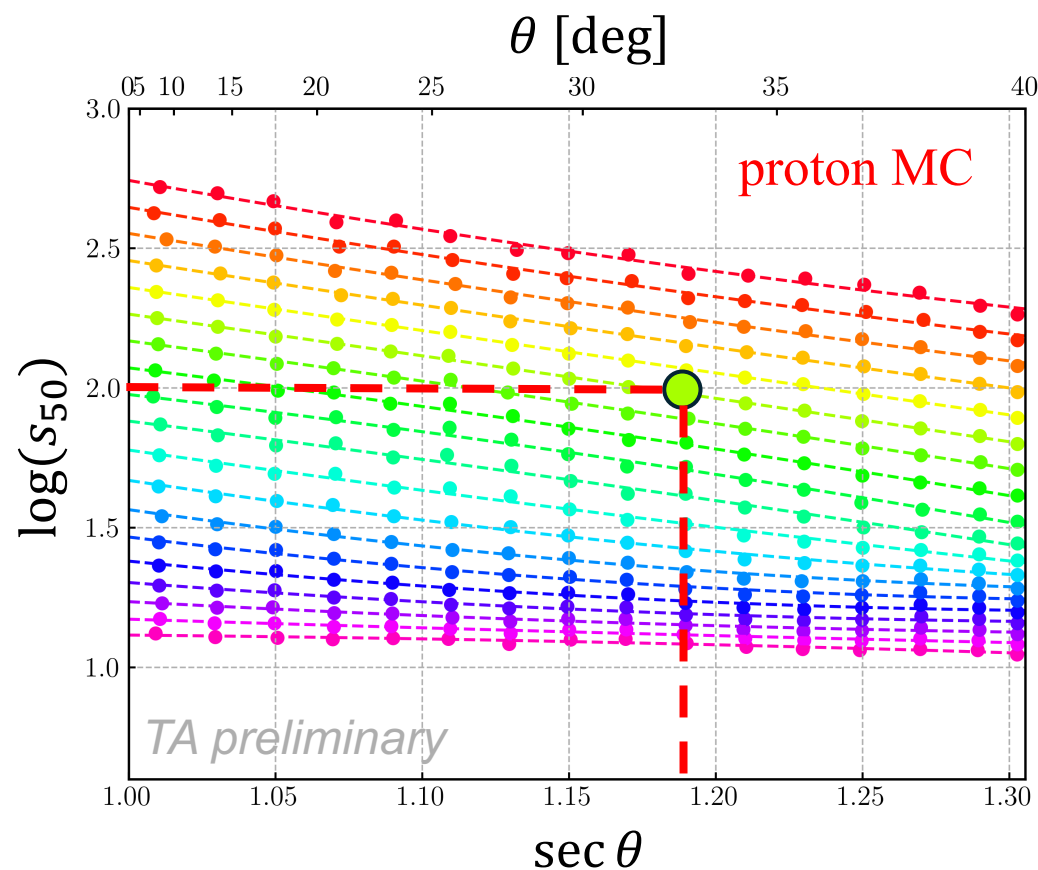
Determine core pos. ($x_{\text{core}}, y_{\text{core}}$) & s_{50}
from lateral distribution fitting using
waveform information

Estimate energy(E) from energy-lookup
table using θ & s_{50}

Output reconstructed parameters



Energy estimation



There are energy bias depending on the mass of primary particle

ex.) the event with $(\sec \theta, \log s_{50}) = (1.19, 2.00)$

Lookup table from **proton MC** : $E_{\text{rec}} \approx 10^{16.3} \text{ eV}$

Lookup table from **iron MC** : $E_{\text{rec}} \approx 10^{16.5} \text{ eV}$

It's approximately 1.6 times larger!!

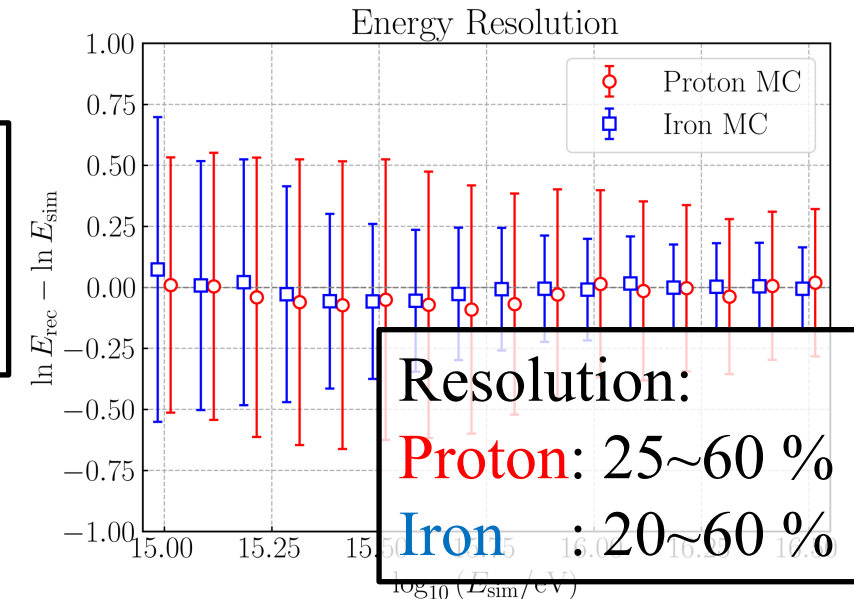
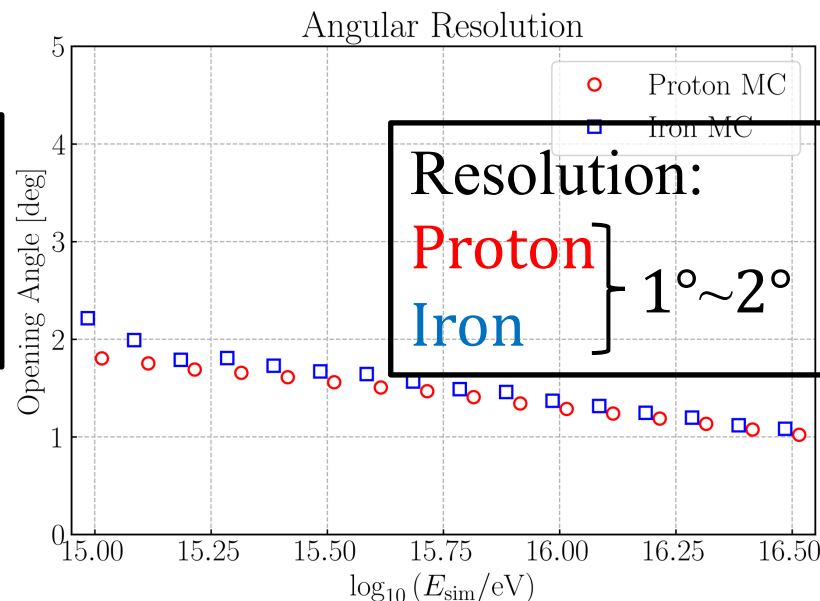
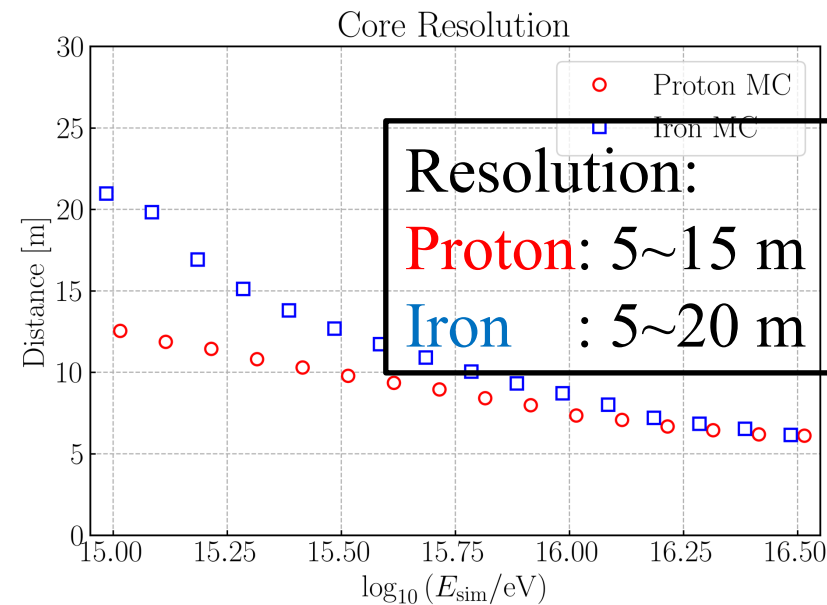
Reconstruction performance

MC dataset for this analysis

- Primary particle: **proton**, **iron**
- Hadron interaction model: QGSJETII-04
- Energy
proton: $10^{15.0} \sim 10^{16.5}$ eV
iron: $10^{15.0} \sim 10^{16.5}$ eV
- $[\theta, \phi] = [(0^\circ \sim 65^\circ), (0^\circ \sim 360^\circ)]$
- period: 2023/11/1-2025/10/8

Event selection criteria

- Boundary cut
 - Core_{rec} is in array
- Hottest SD cut
 - $\text{SD}_{\text{MIPmax}}$ is not located on the edge of the array
- $N_{\text{SD}} \geq 10$
- $|\text{Core}_{\text{LDF}} - \text{Core}_{\text{Rough}}| \leq 200$ m
- $0 \leq \theta \leq 40^\circ$
- $0.7 \leq \text{age} \leq 1.5$
- $\chi_{\text{LDF}}^2 < 1$ & $\chi_{\text{geom}}^2 < 15$



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Preparation for Data/MC

- Compare the results of observed data with the ones of proton & iron MC dataset
→ Check the consistency of MC with observed data
 - period: 2023/11/1 ~ 2025/10/8 (707 days)

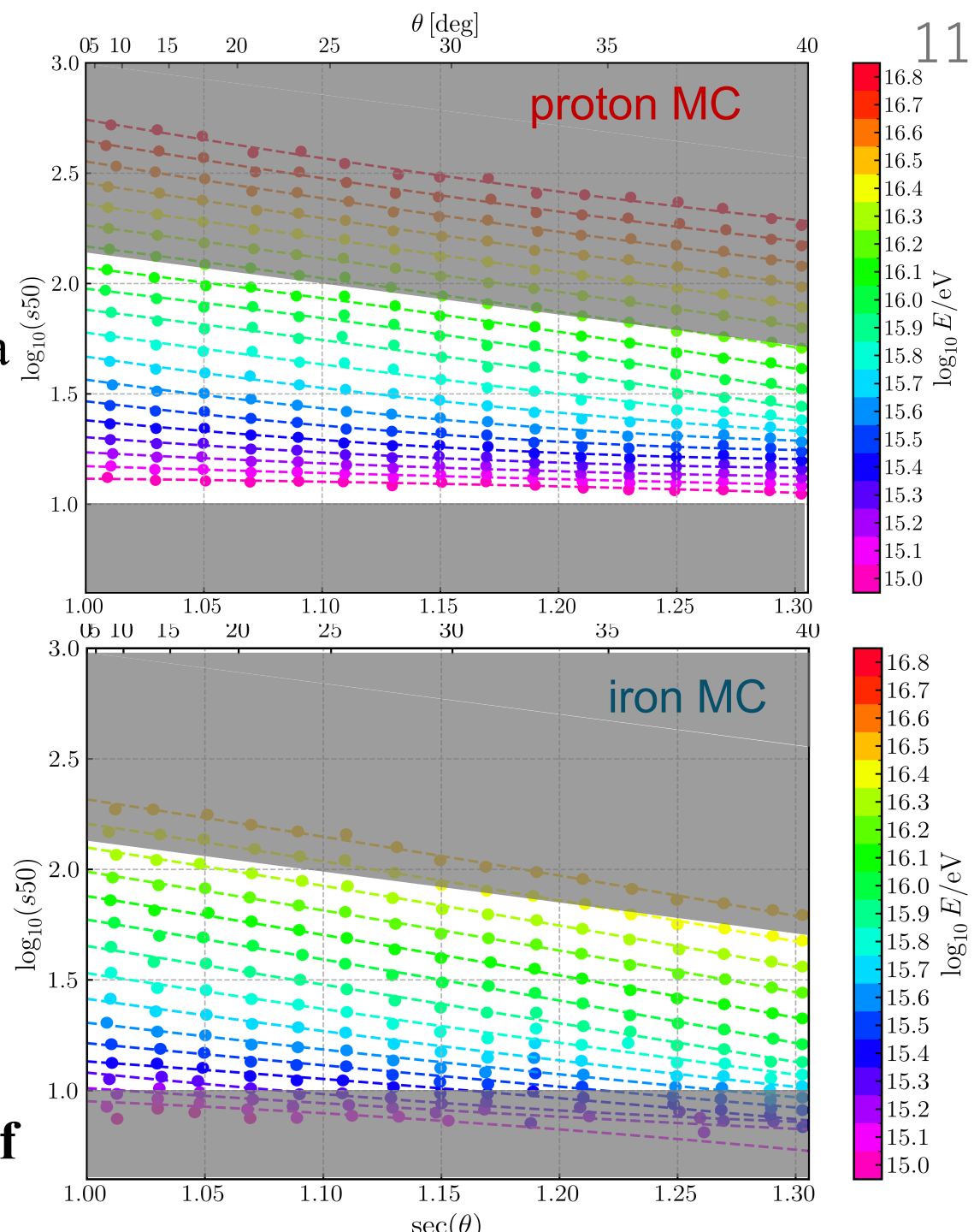
- Spectrum weighting to MC data

$$J = \begin{cases} E^{-2.7} & (\log(E/\text{eV}) < 15.6) \\ E^{-3.1} & (15.6 \leq \log(E/\text{eV}) < 16.2) \\ E^{-2.9} & (16.2 \leq \log(E/\text{eV})) \end{cases}$$

R. U. Abbasi et al. (Telescope Array Collaboration), *ApJ* 865, 74 (2018).

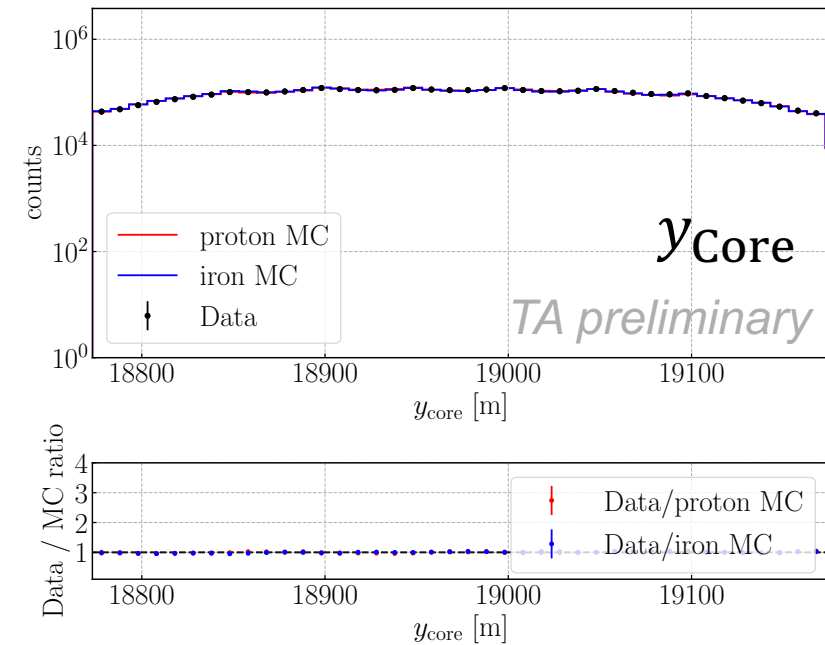
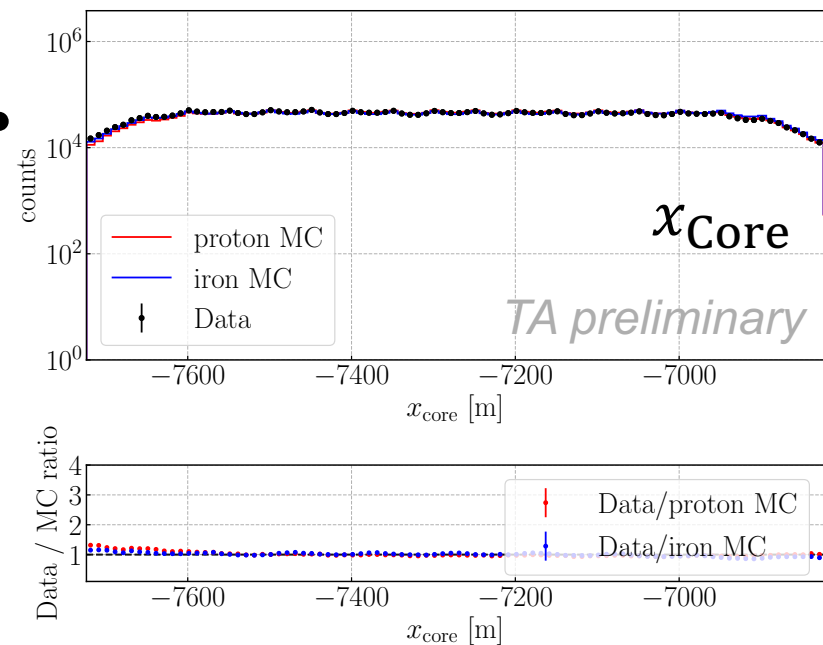
- Adapt additional event-selection:

$$1.0 < \log s_{50} < f_{\text{iron}}(\sec \theta, \log E = 16.4)$$
 - Large energy recon. bias exists depending on the primary mass
→ **Extract events from common phase space of both MC & observed data for comparison**

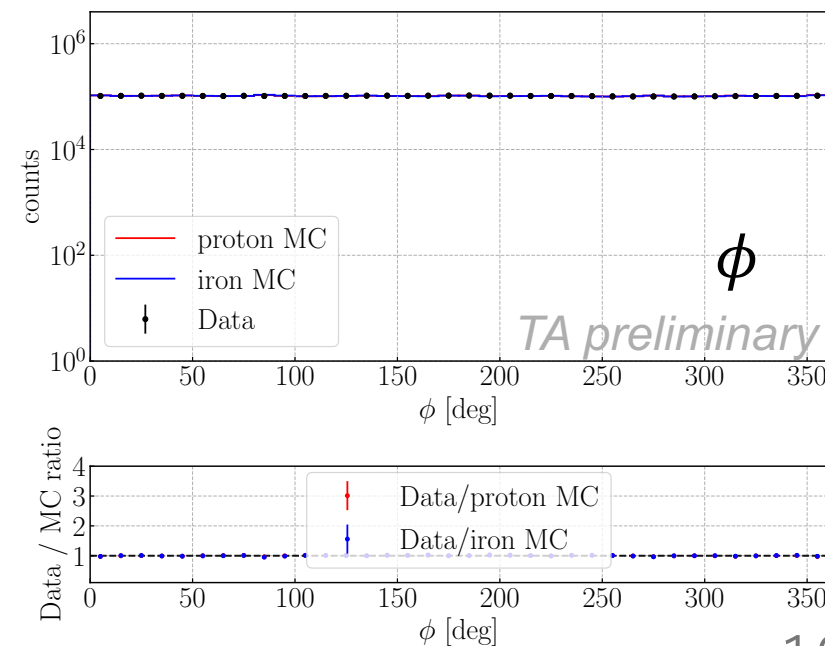
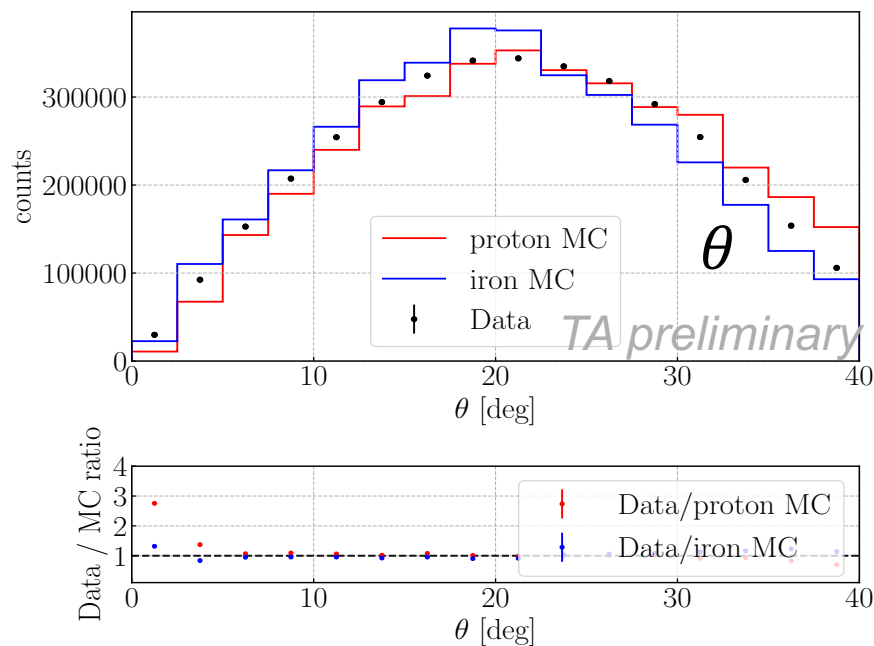


Data/MC comp.

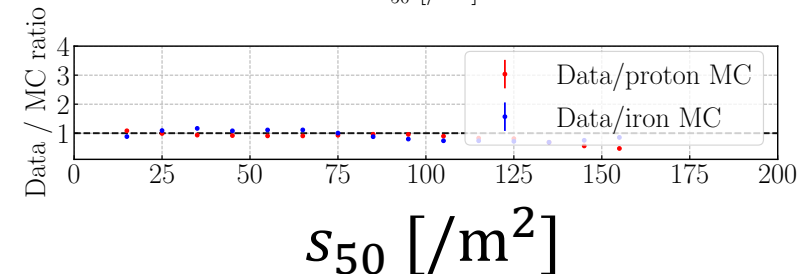
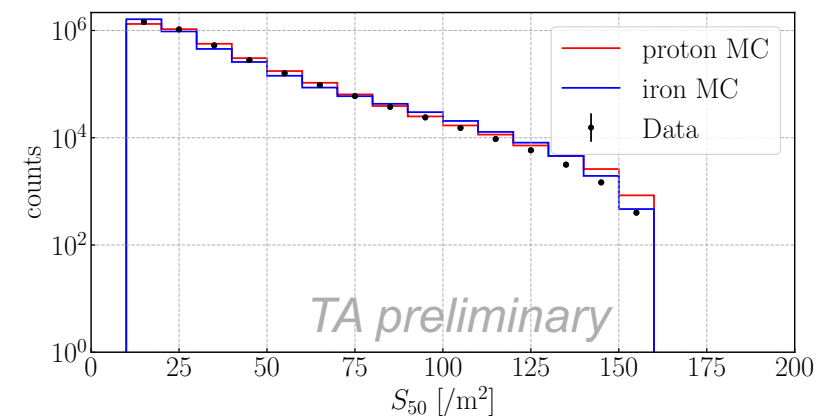
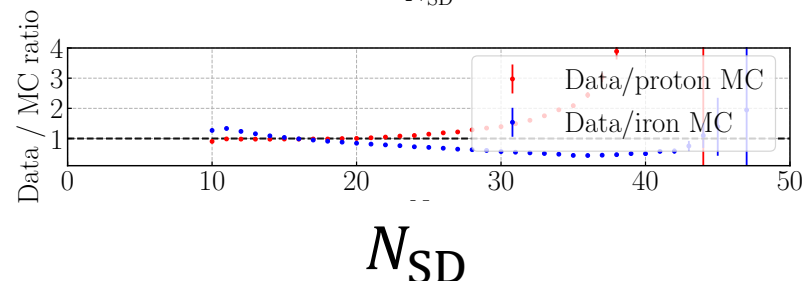
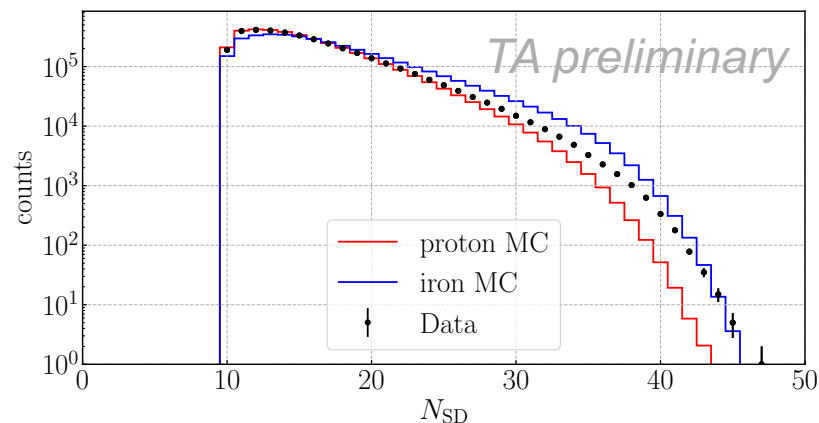
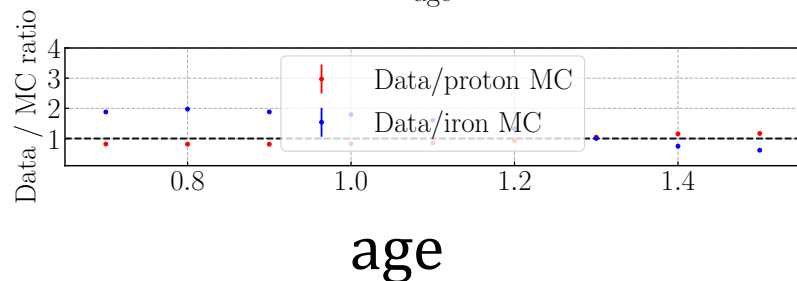
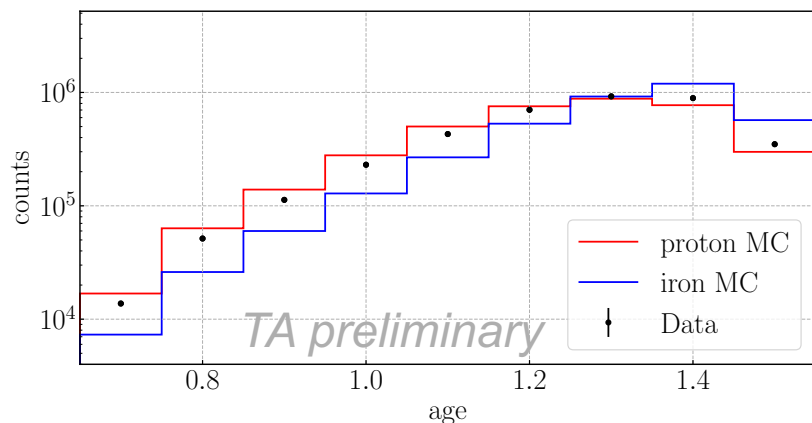
- θ :
Mostly MC is consistent
with observed data
**under the mixed
composition assumption**



- Other parameters:
MC is consistent with
observed data



Data/MC comp.



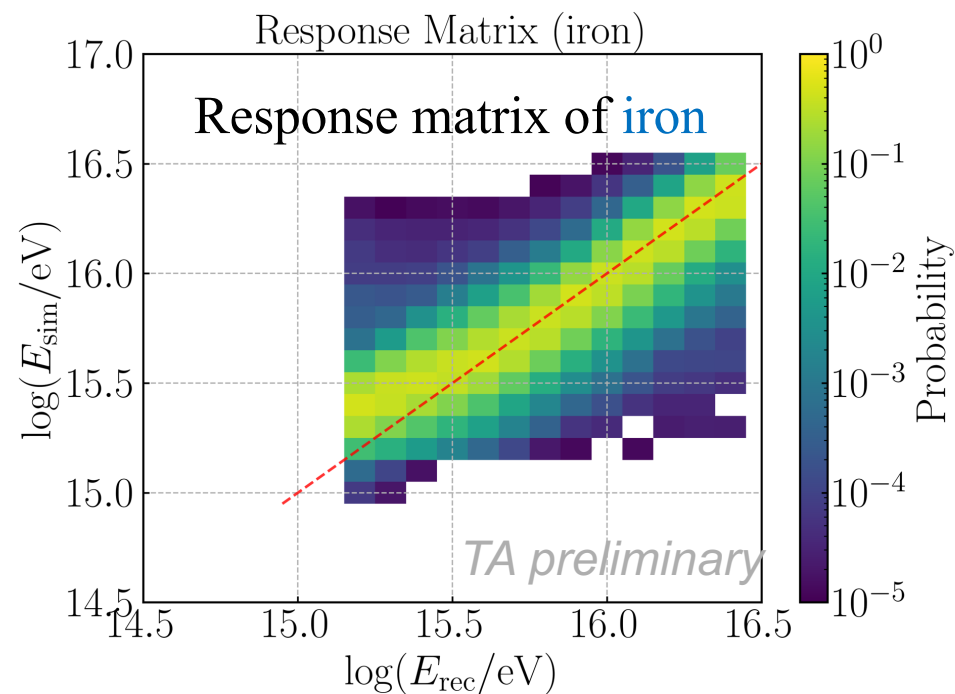
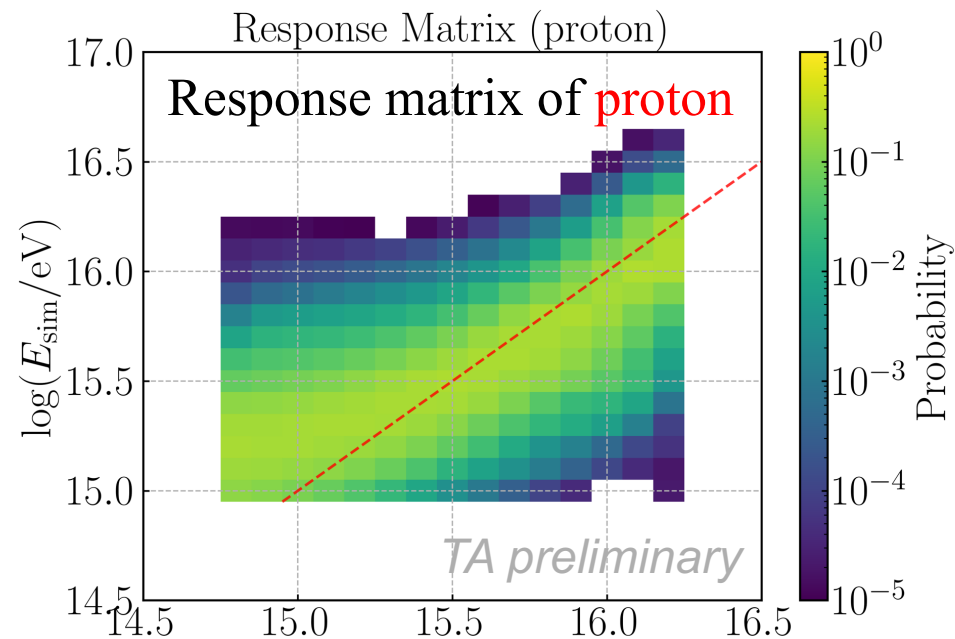
- age: MC is consistent with observed data **under the mixed composition assumption**
- N_{SD} : MC is consistent with observed data **under the mixed composition assumption**
- s_{50} : MC is consistent with observed data

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Spectrum measurements

- Data/MC comparison shows good agreements
→ Move on to measuring an energy spectrum
- Period of measurements: 2023/11/1~2025/10/8
- Method to measure:
 - Get exposure from MC events
 - Unfold energy distribution of observed data using response matrix
→ Estimate the true energy distribution of observed data
 - Measure an energy spectrum using exposure & unfolded energy distribution of observed data



Exposure

- Calculate exposure

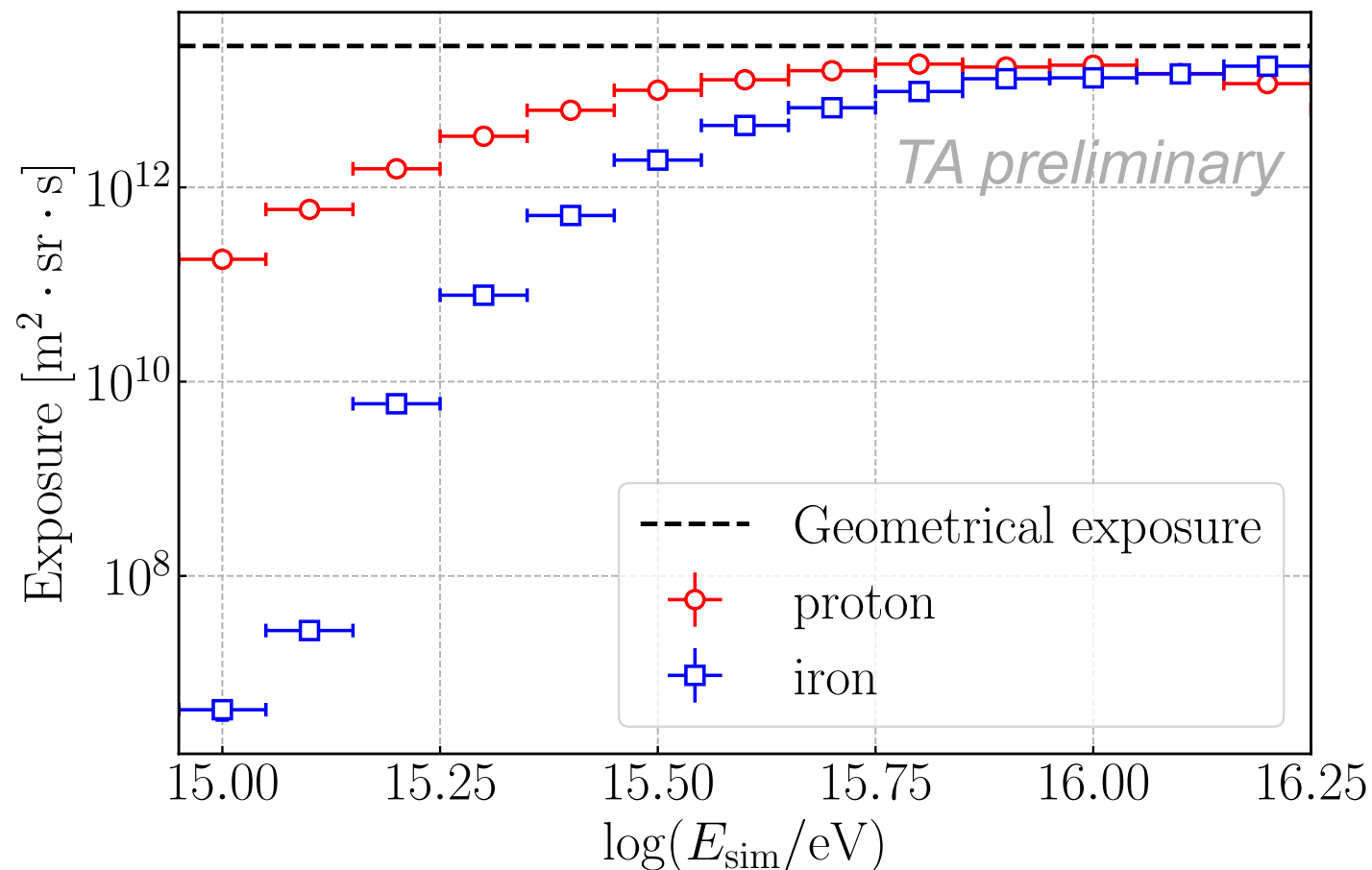
$$\exp(E_i) = A \cdot \Omega \cdot T \cdot \frac{N_{\text{rec}}^{\text{cut}}(E_i^{\text{sim}})}{N_{\text{gen}}(E_i^{\text{sim}})}$$

- $A = \pi \times 1000^2 \text{ m}^2$
- $\Omega = \int_{0^\circ}^{360^\circ} \int_{0^\circ}^{65^\circ} \sin \theta \cos \theta d\theta d\phi$
- $T = 707 \text{ days} \times 24 \text{ h} \times 60 \text{ min} \times 60 \text{ sec}$
(2023/11/1 – 2025/10/8)

- geometrical exposure

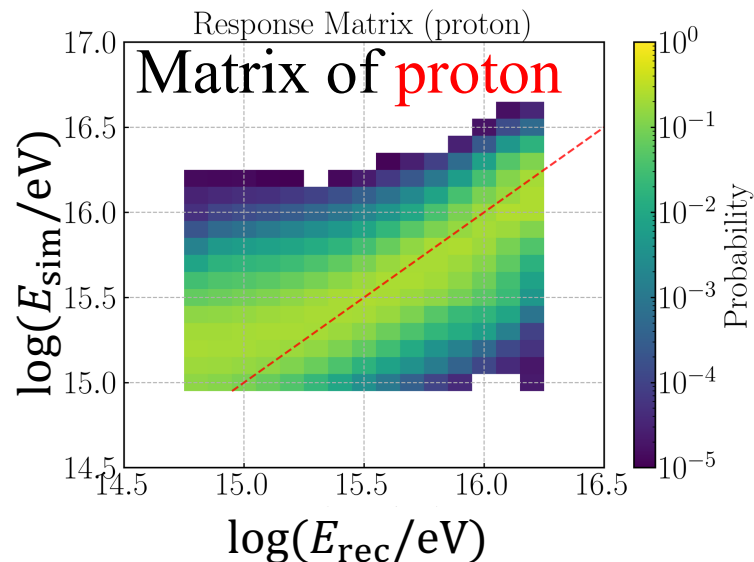
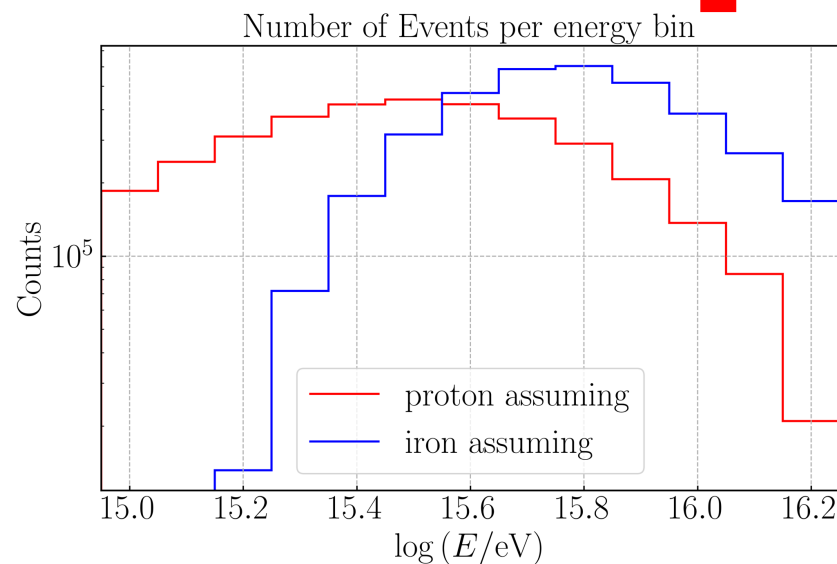
$$= A_{\text{geom}} \cdot \Omega_{\text{geom}} \cdot T$$

- $A_{\text{geom}} = 400 \text{ m} \times 900 \text{ m}$
- $\Omega = \int_{0^\circ}^{360^\circ} \int_{0^\circ}^{40^\circ} \sin \theta \cos \theta d\theta d\phi$

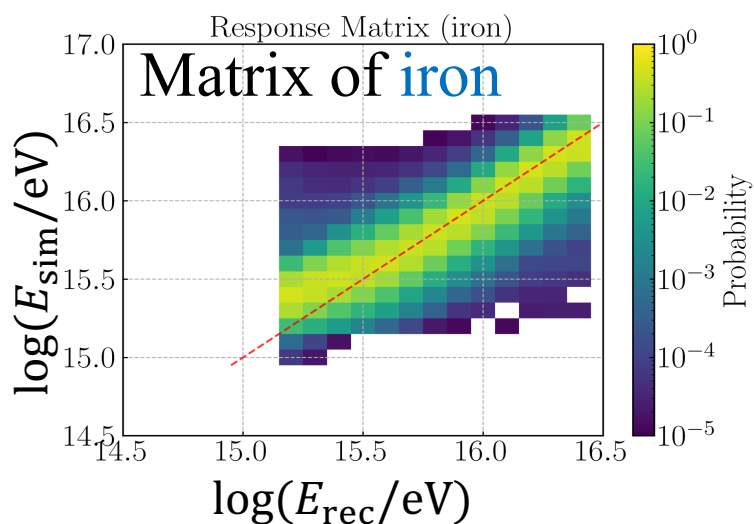
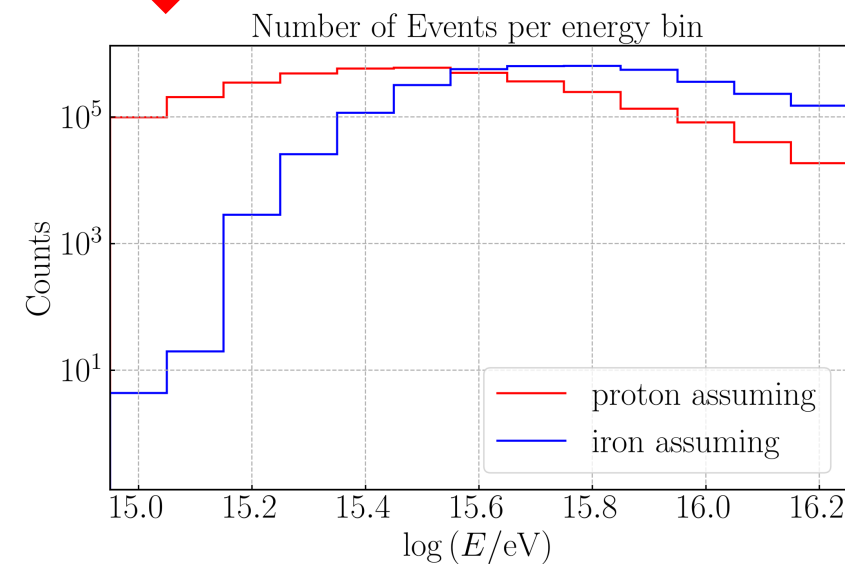


Estimate true energy dist. by unfolding

Before unfolding



After unfolding



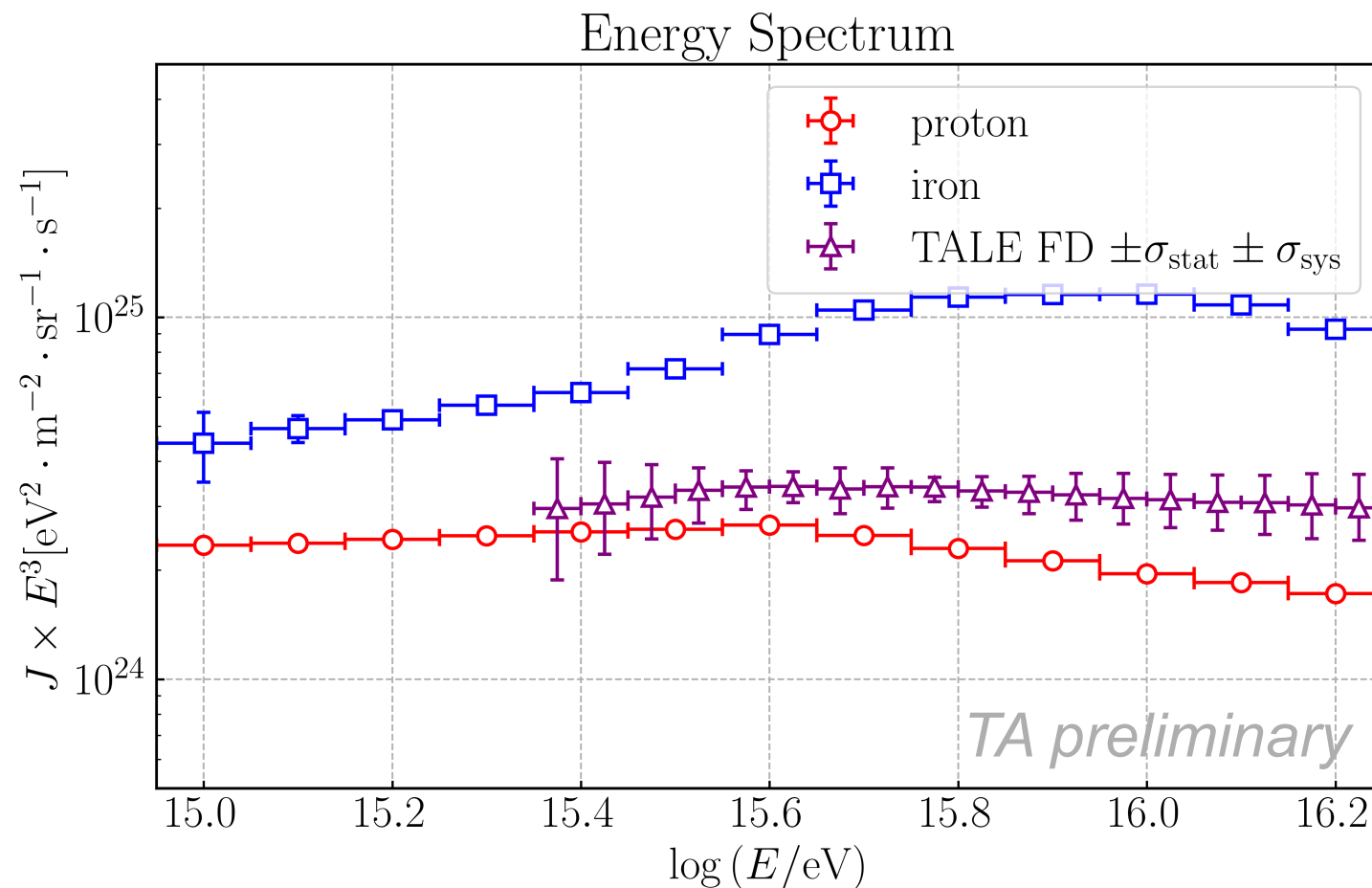
Energy spectrum assumed pure composition

- Measure an energy spectrum

$$J(E_i) = \frac{N_{\text{unfolded}}(E_i)}{\exp(E_i) \cdot \Delta E}$$

- ΔE : bin width (here, $\Delta E = 10^{0.1}$ eV)

- This is the first preliminary results of energy spectrum measurements from TALE infill SD array



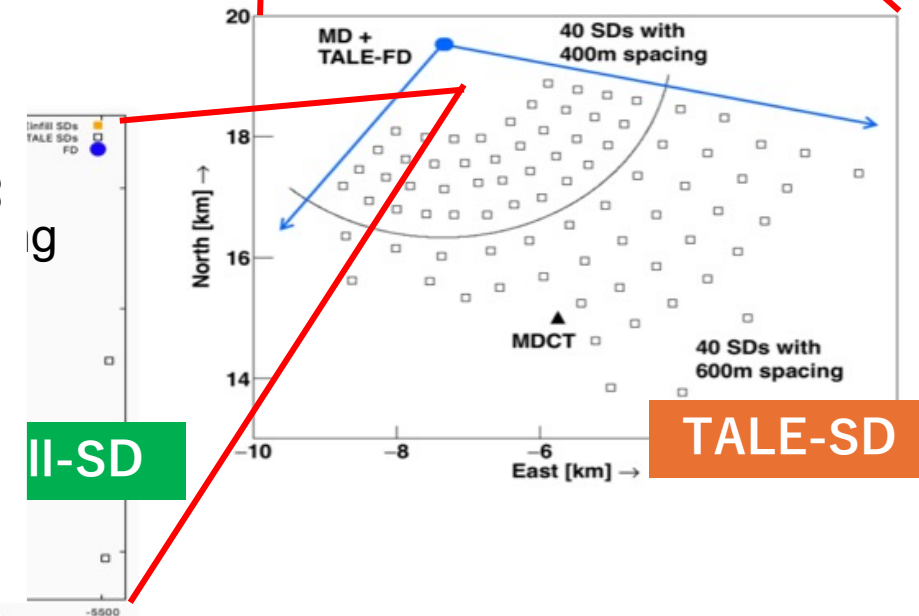
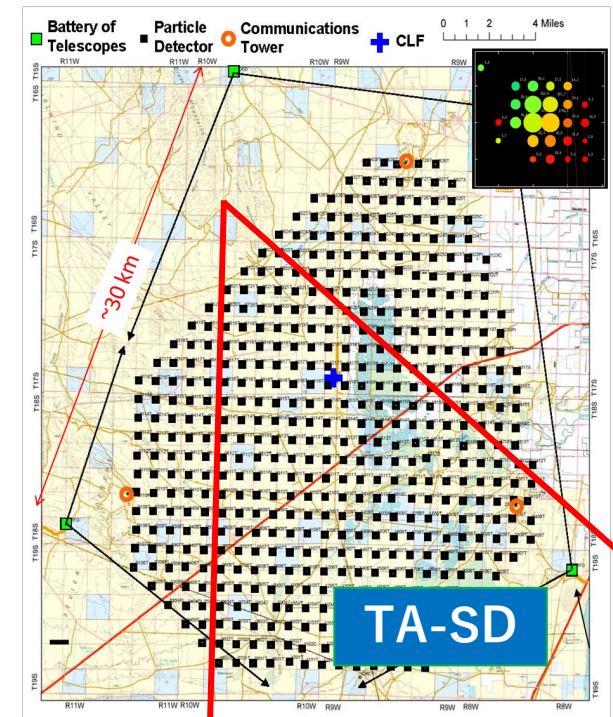
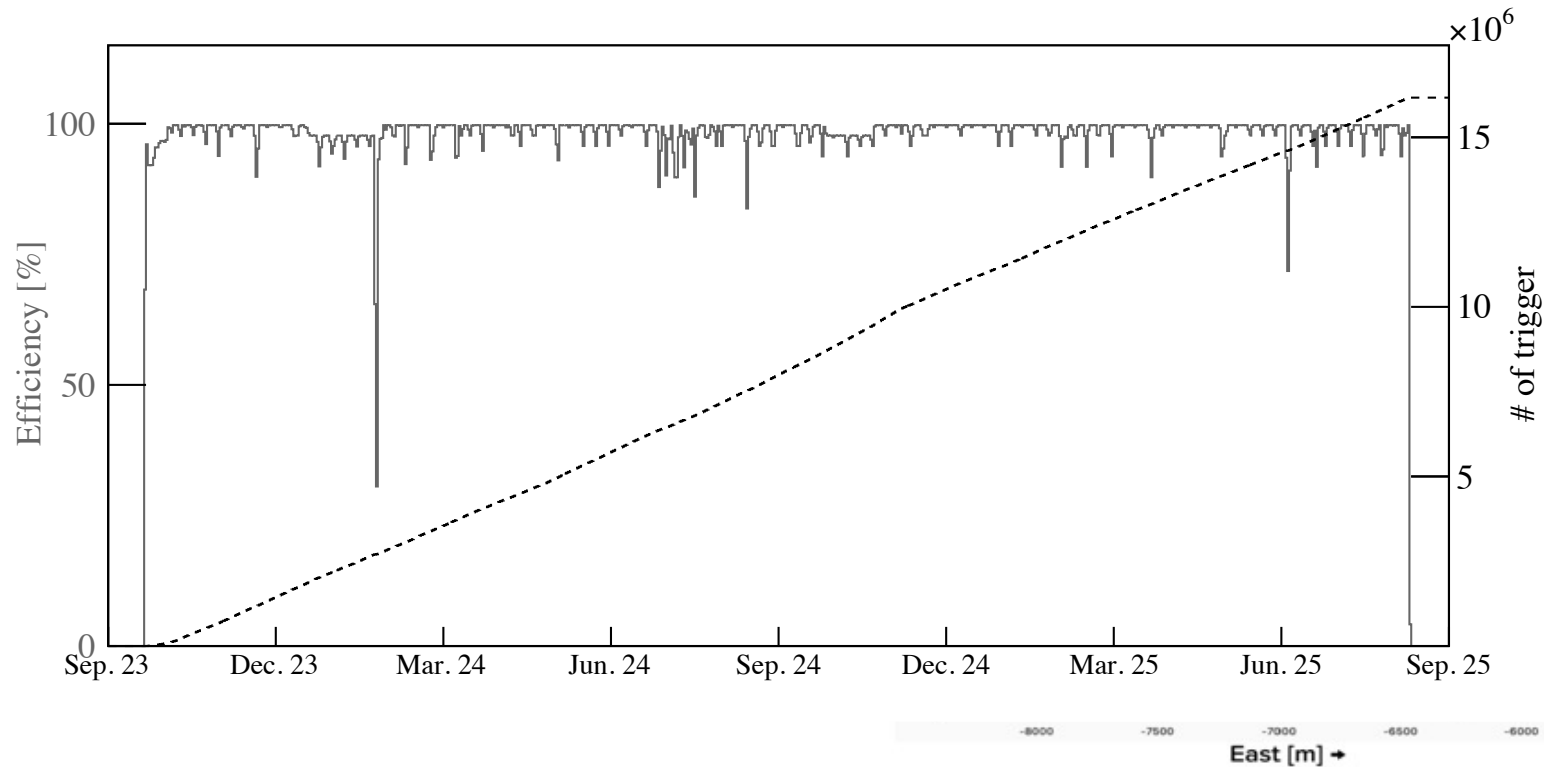
Summary

- Reconstruction performance
 - Core pos. resolution: 5~20 m
 - Angular resolution : $1^{\circ}\sim 2^{\circ}$
 - Energy resolution : 20~60%
 - **It is confirmed there are energy bias depending on the kind of primary particles**
- Data/MC
 - We compare the results of reconstruction of data & MC
 - **MC dataset is consistent with observed data under mixed composition assumption**
- Spectrum
 - Measured energy spectra assuming pure-primary (proton or iron)
 - **Showed the first preliminary results of energy spectrum from TALE infill SD array**

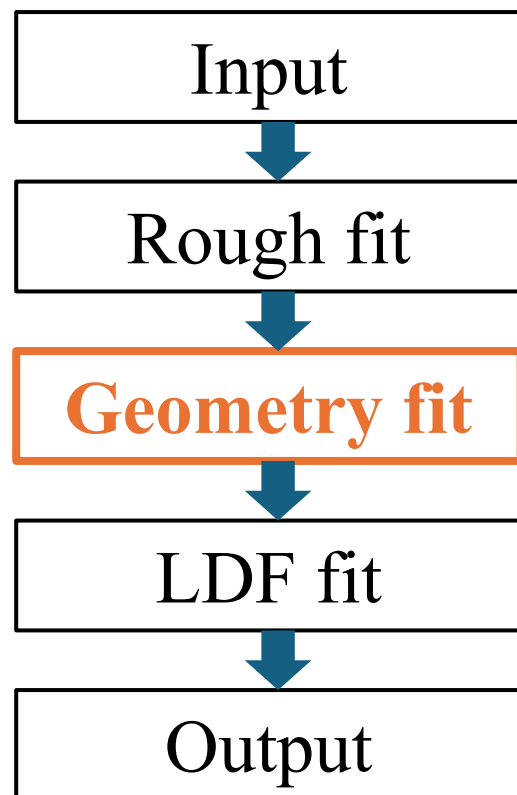
Back up

TALE infill

- Observation period : Nov. 2023 ~
- Duty cycle : 98.5 %



Reconstruction process

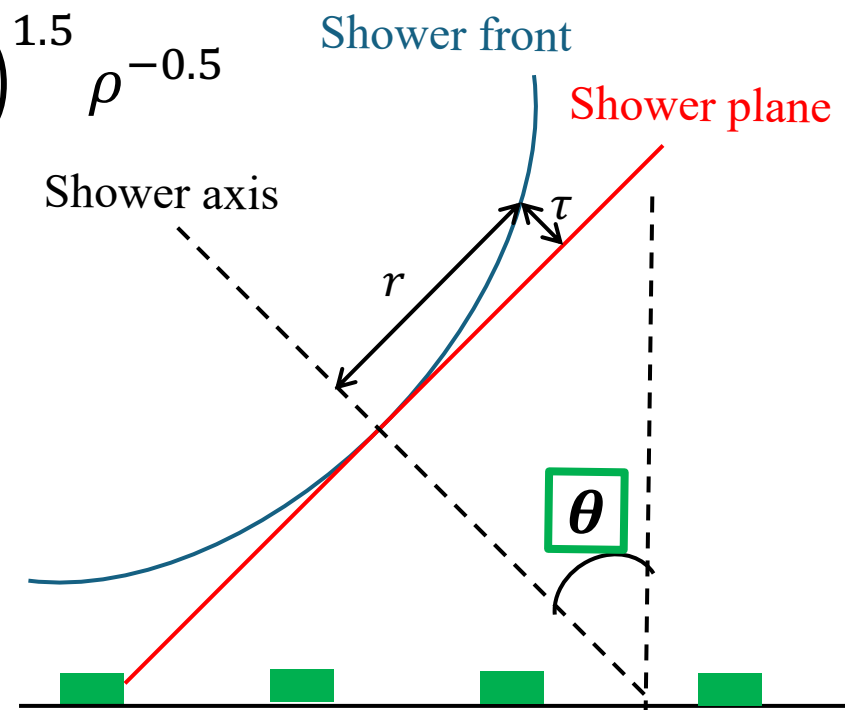


Geometry fit :

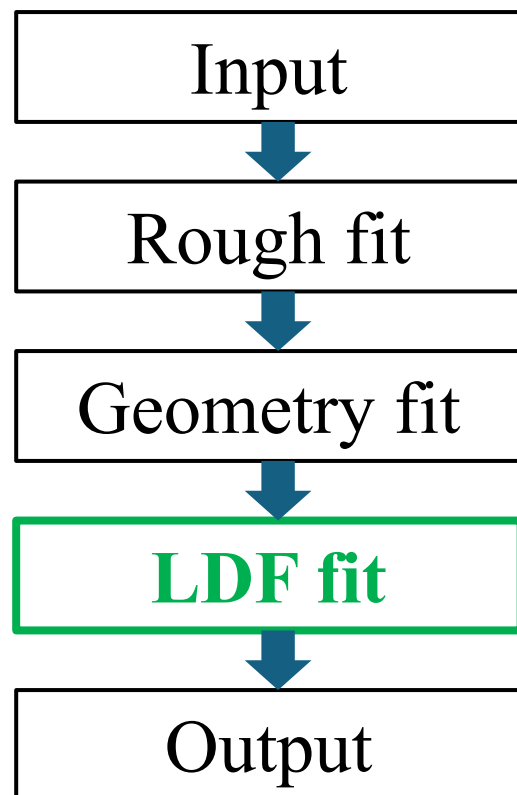
Determine geometrical parameters
by fitting the following function :

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

- τ : the time delay from shower plane
- r : the distance from shower axis
- ρ : the particle density
- $a(\theta)$: the shower curvature parameter



Reconstruction process



LDF fit :

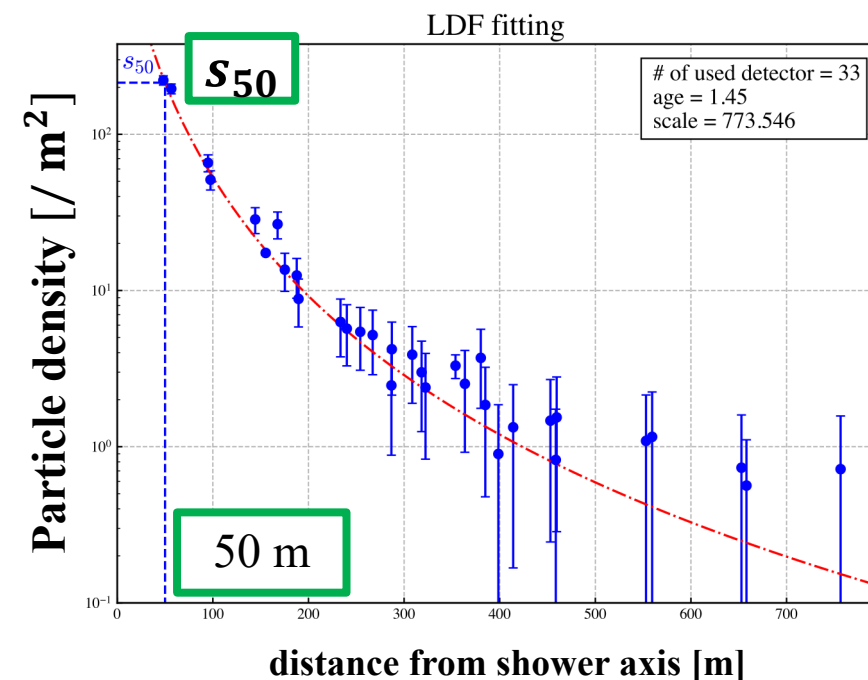
Determine Core Pos. & Lateral Dist. of the shower

by fitting NKG function

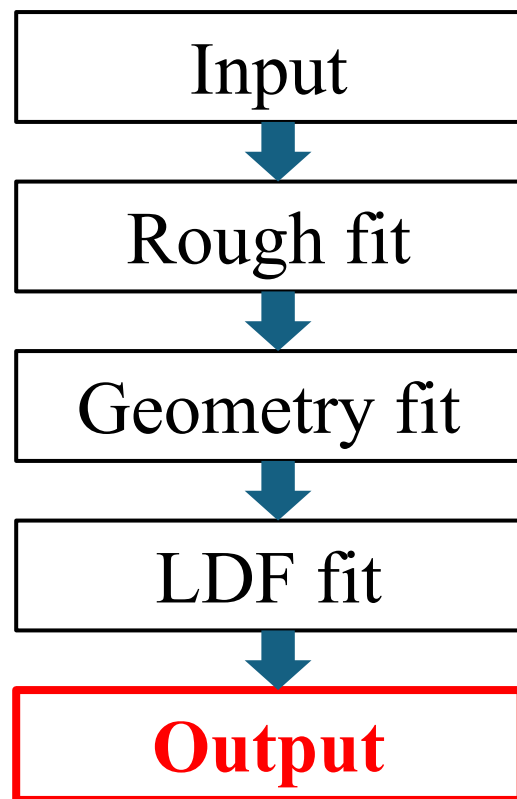
$$\rho^{\text{fit}} = N \left(\frac{1}{r_M} \right)^2 \left(\frac{r}{r_M} \right)^{s-2} \left(1 + \frac{r}{r_M} \right)^{s-4.5}$$

- r_M : Moliere radius (for infill: ~ 77 m)
- N : scale factor
- s : shower age

then, calculate s_{50} , which is the particle density 50 m from the shower axis



Reconstruction process



Output

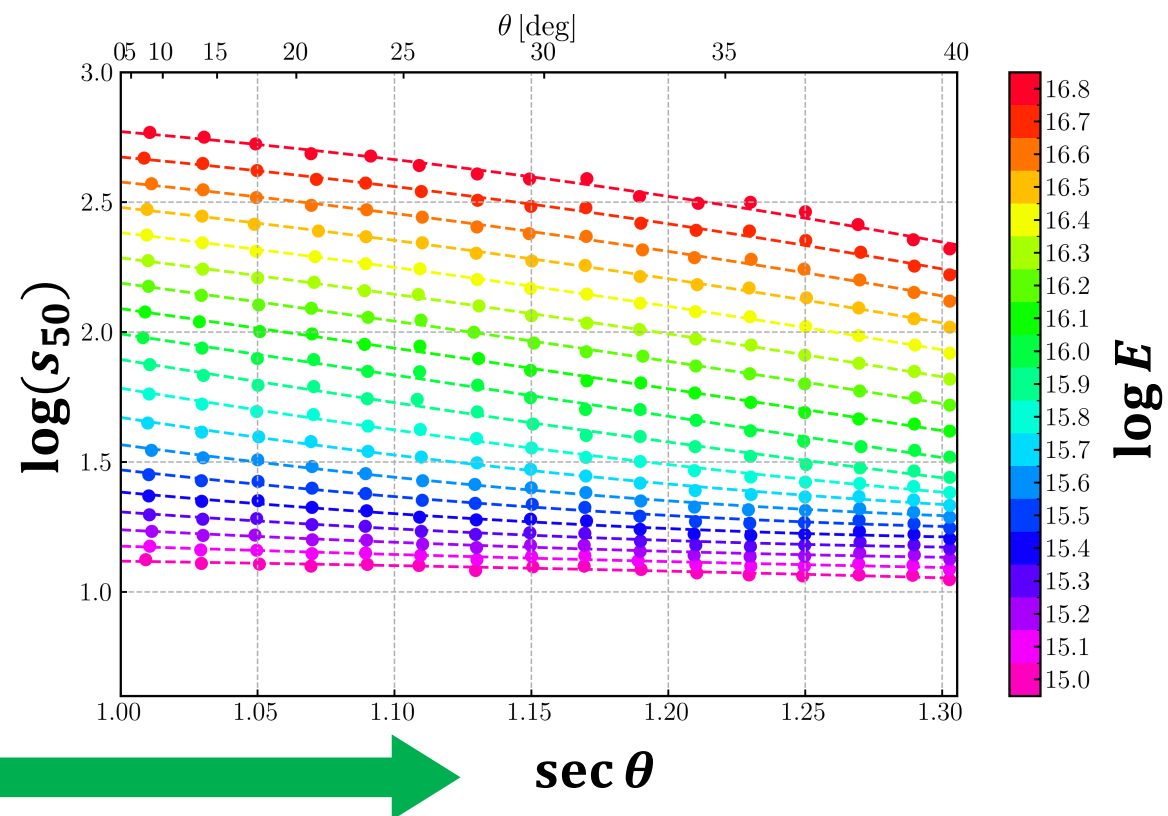
Primary energy E is estimated using energy estimation table with θ and s_{50}

Output below params:

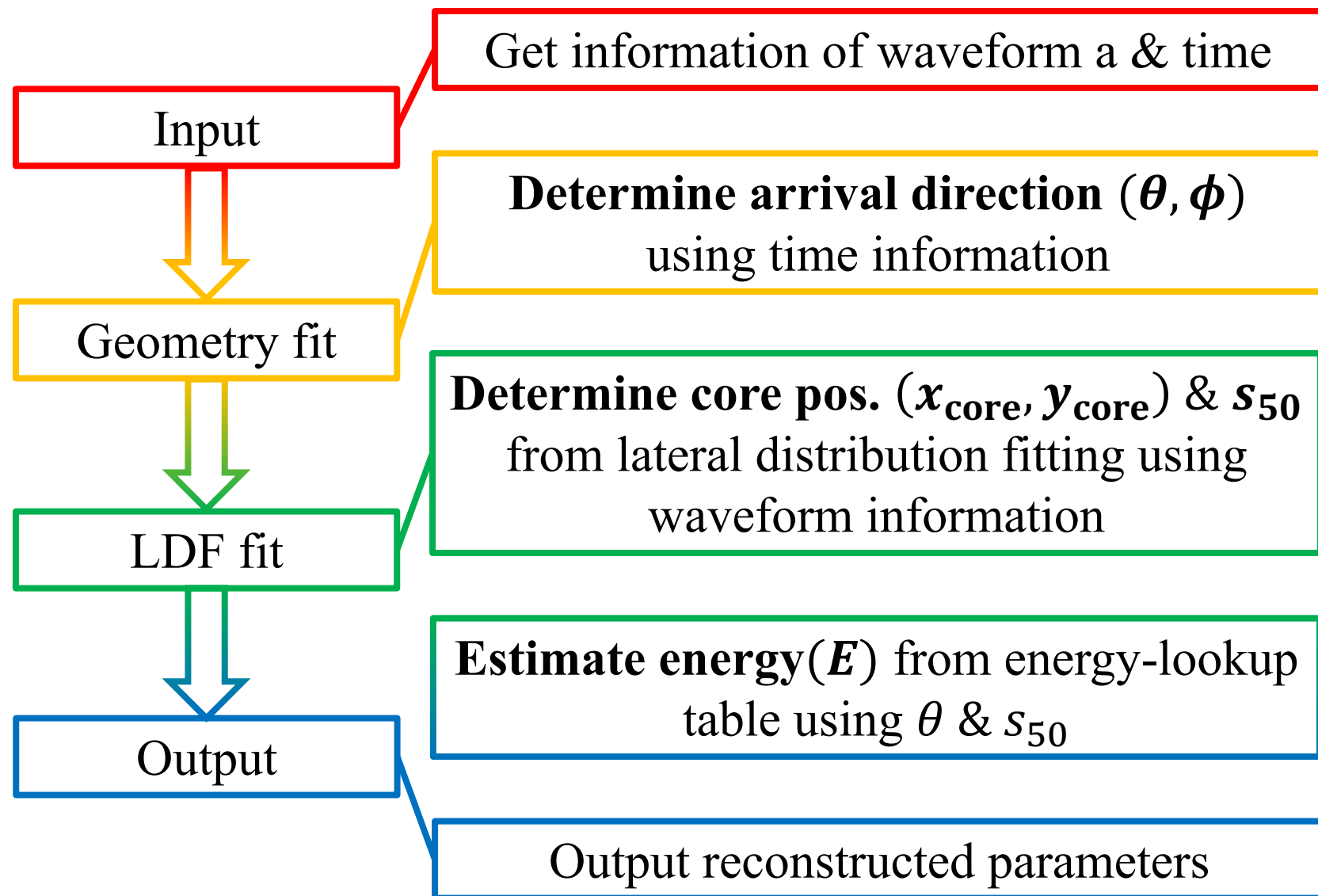
E
 (θ, ϕ)
 (x, y)

s_{50}

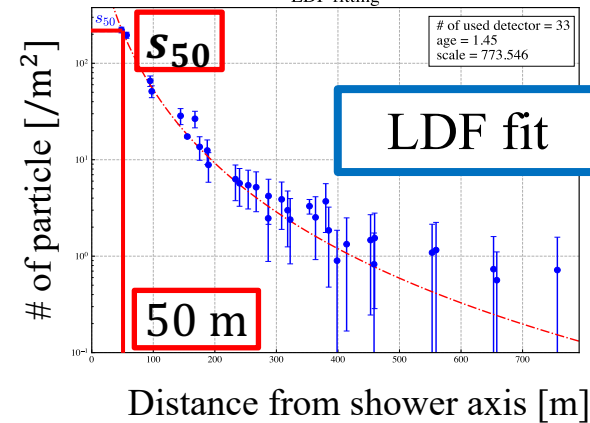
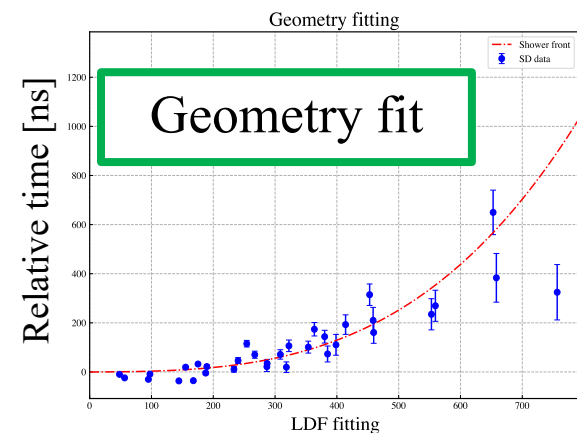
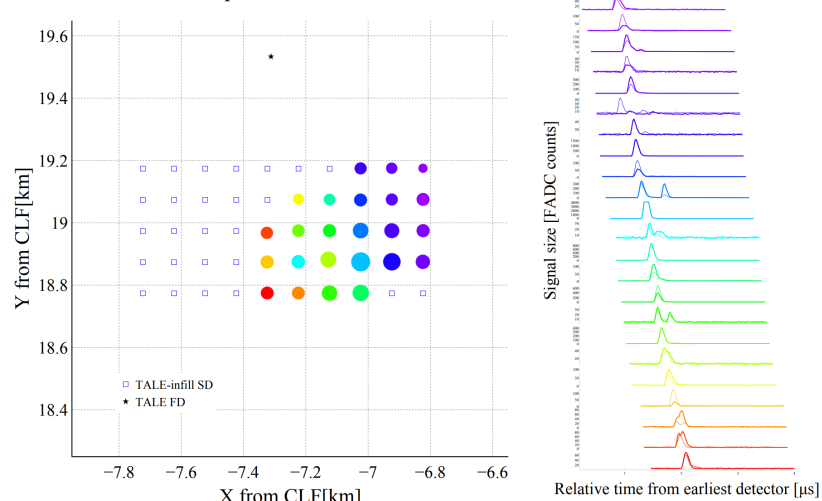
θ



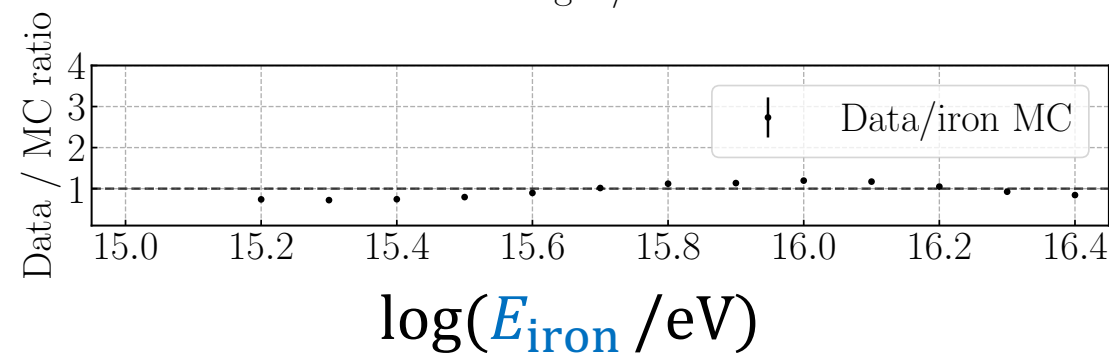
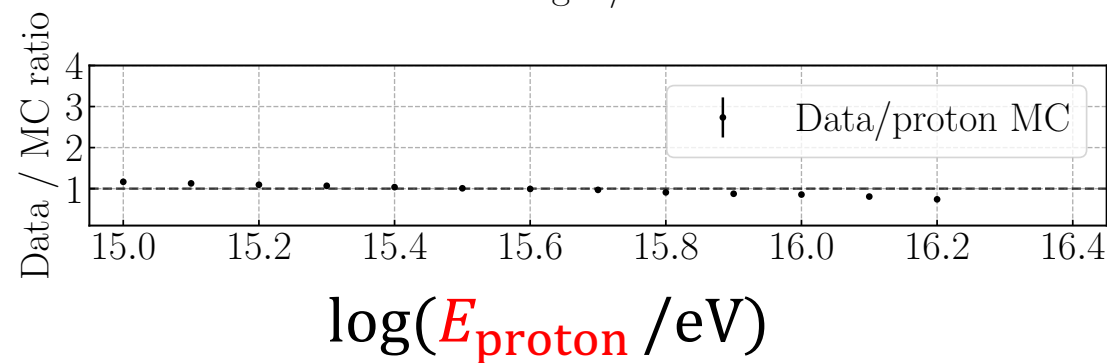
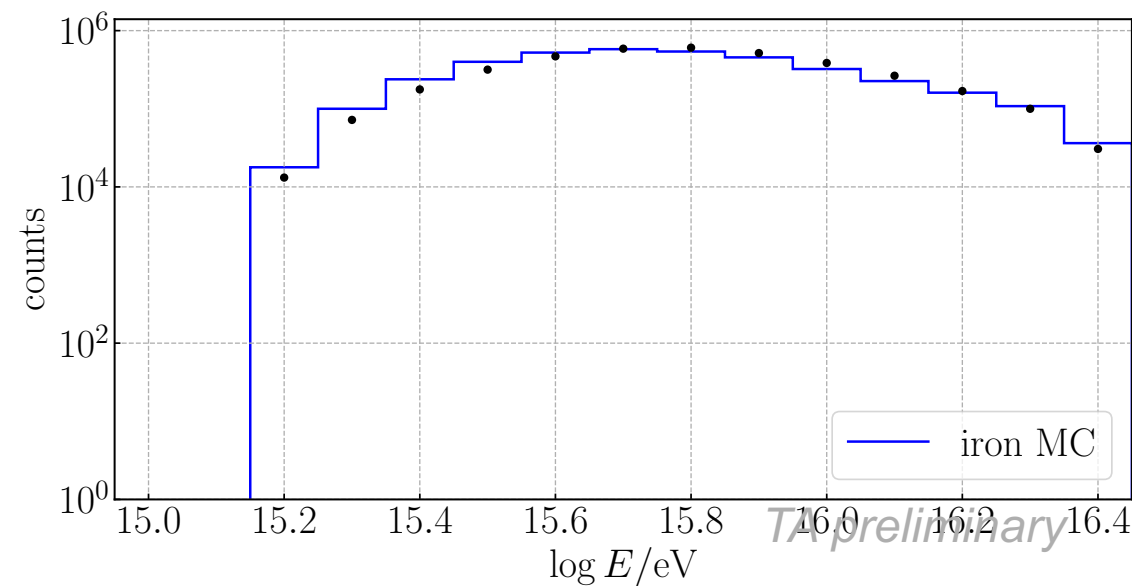
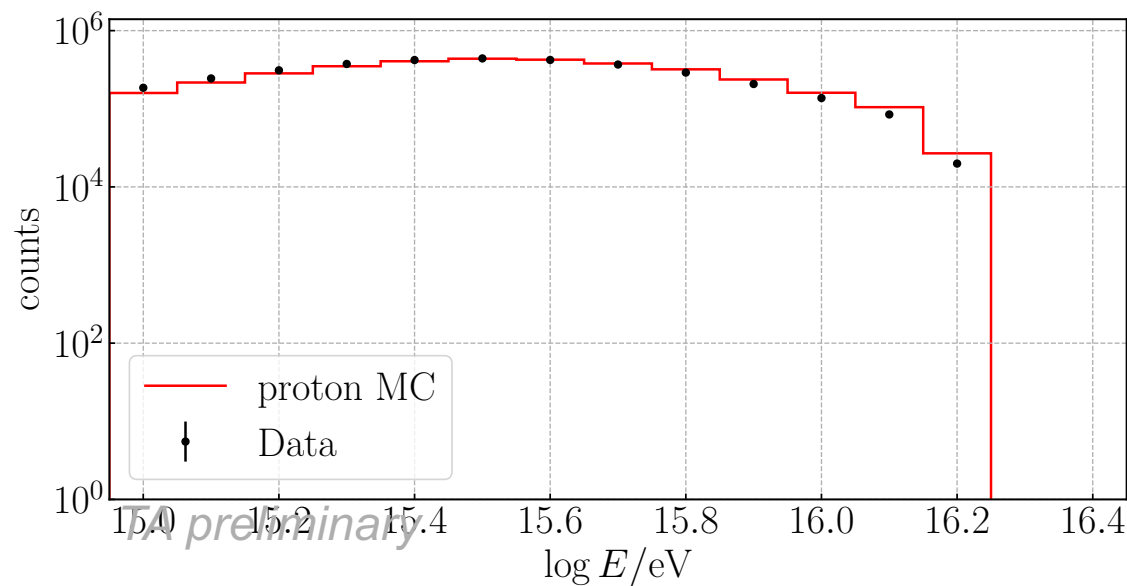
Reconstruction method



TALE-infill SD map: MC data event



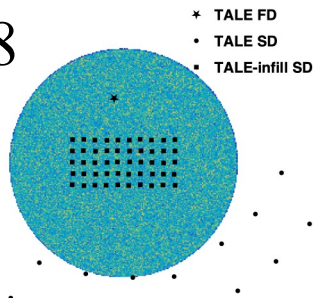
Data/MC comp.



- MC is consistent with observed data

MC dataset for this analysis

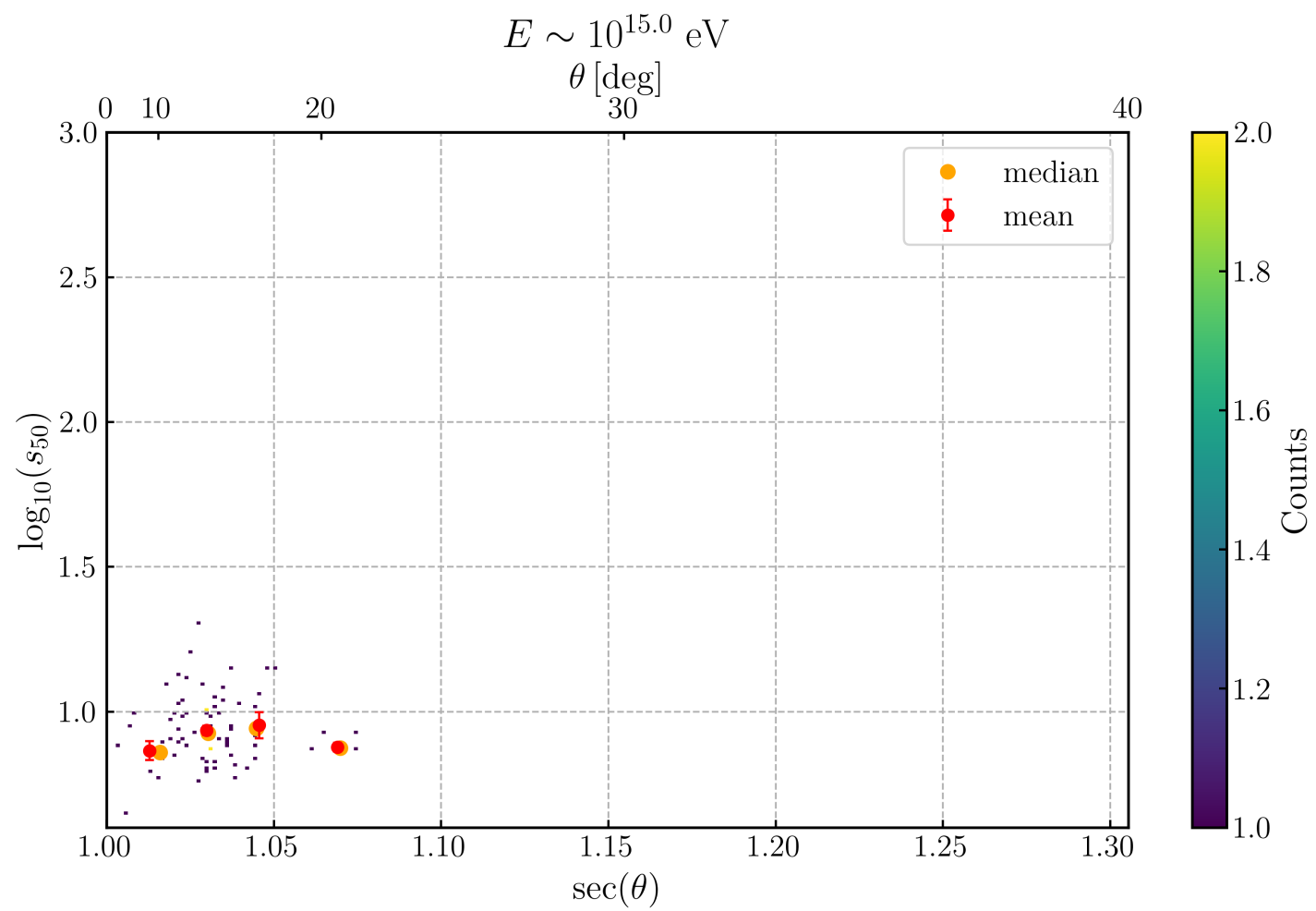
- Primary particle: **proton**, **iron**
- Hadron interaction model: QGSJETII-04
- Energy
proton: $10^{15.0} \sim 10^{16.8}$ eV
iron : $10^{15.0} \sim 10^{16.5}$ eV
- $[\theta, \phi] = [(0^\circ \sim 65^\circ), (0^\circ \sim 360^\circ)]$
- Range: circle with a radius of 1.0 km
- period: 2023/11/1-2025/10/8



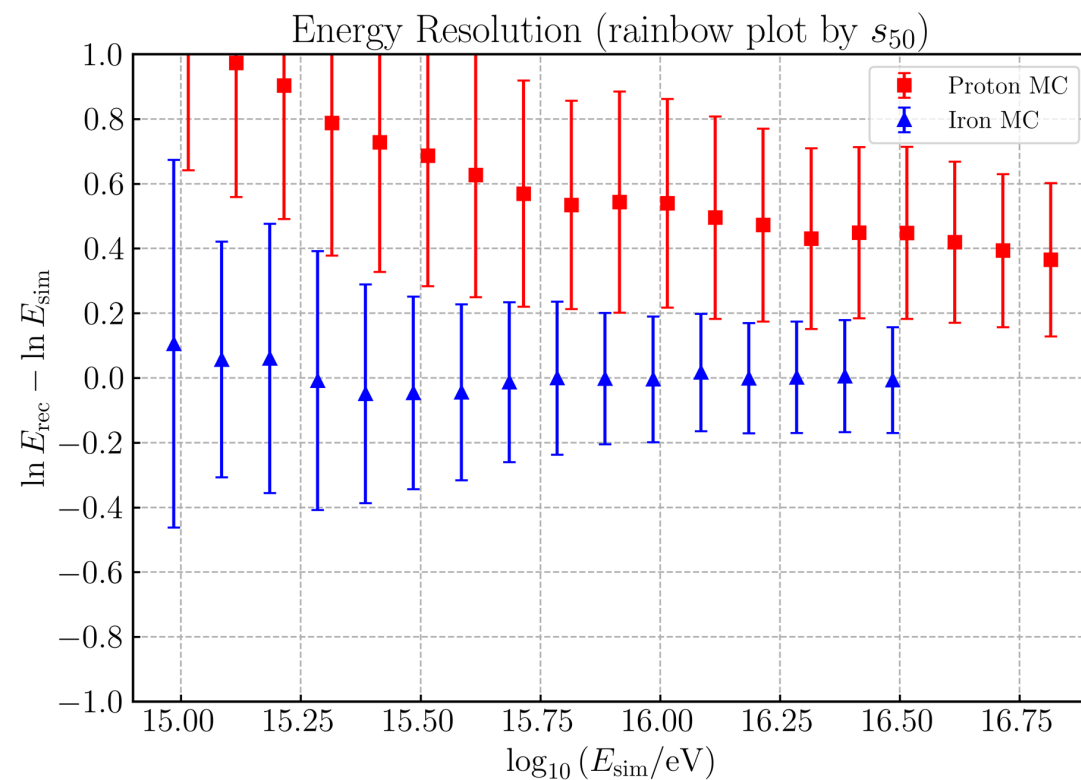
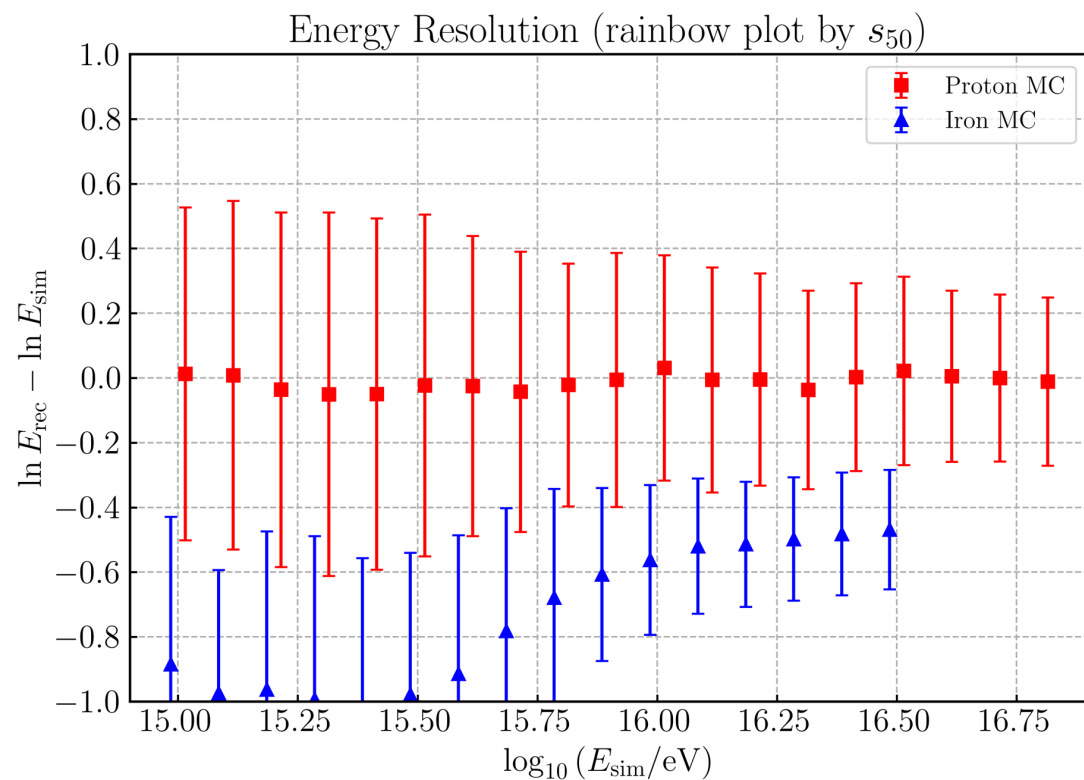
Event selection criteria

- Boundary cut
 - Core_{rec} is in array
- Hottest SD cut
 - $\text{SD}_{\text{MIPmax}}$ is not located on the edge of the array
- $N_{\text{SD}} \geq 10$
- $0 \leq \theta \leq 40^\circ$
- $|\text{Core}_{\text{LDF}} - \text{Core}_{\text{Rough}}| \leq 200$ m
- $0.7 \leq \text{age} \leq 1.5$
- $\chi^2_{\text{LDF}} < 1$ & $\chi^2_{\text{geom}} < 15$

Iron MC ($\log E = 15.0$)



Reconstruction bias



The method used in TA collaboration traditionally

- Calculate $eff(E_i) = N_{\text{rec}}^{\text{cut}}(E_i^{\text{rec}}) / N_{\text{gen}}(E_i^{\text{sim}})$

- Calculate exposure

$$exp(E_i) = A \cdot \Omega \cdot T \cdot eff(E_i)$$

- $A = \pi \times 1000^2 \text{ m}^2$

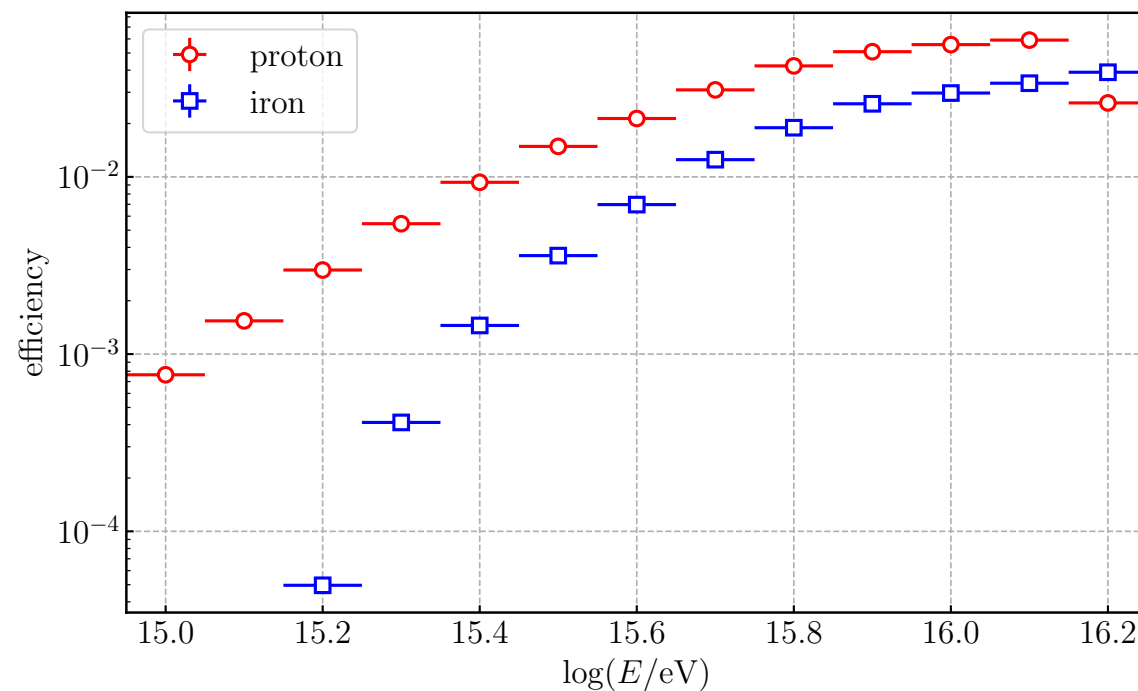
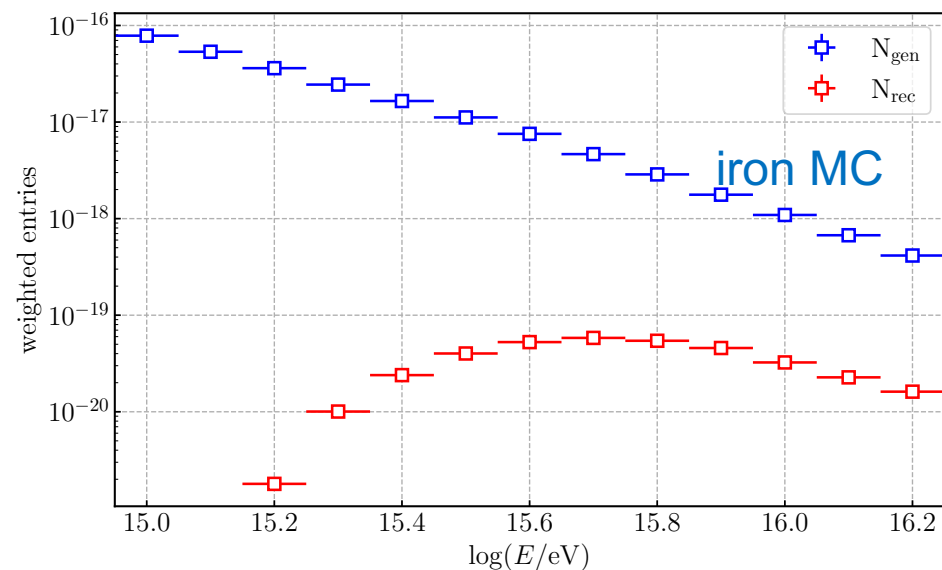
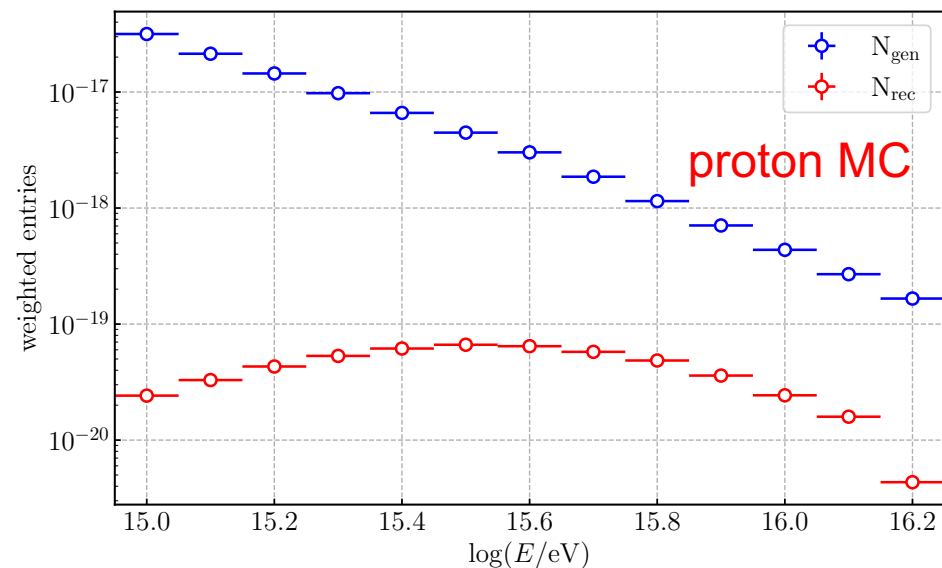
- $\Omega = \int_{0^\circ}^{360^\circ} \int_{0^\circ}^{65^\circ} \sin \theta \cos \theta d\theta d\phi$

- $T = 707 \text{ days} \times 24 \text{ h} \times 60 \text{ min} \times 60 \text{ sec} (2023/11/1 - 2025/10/8)$

- Calculate spectrum

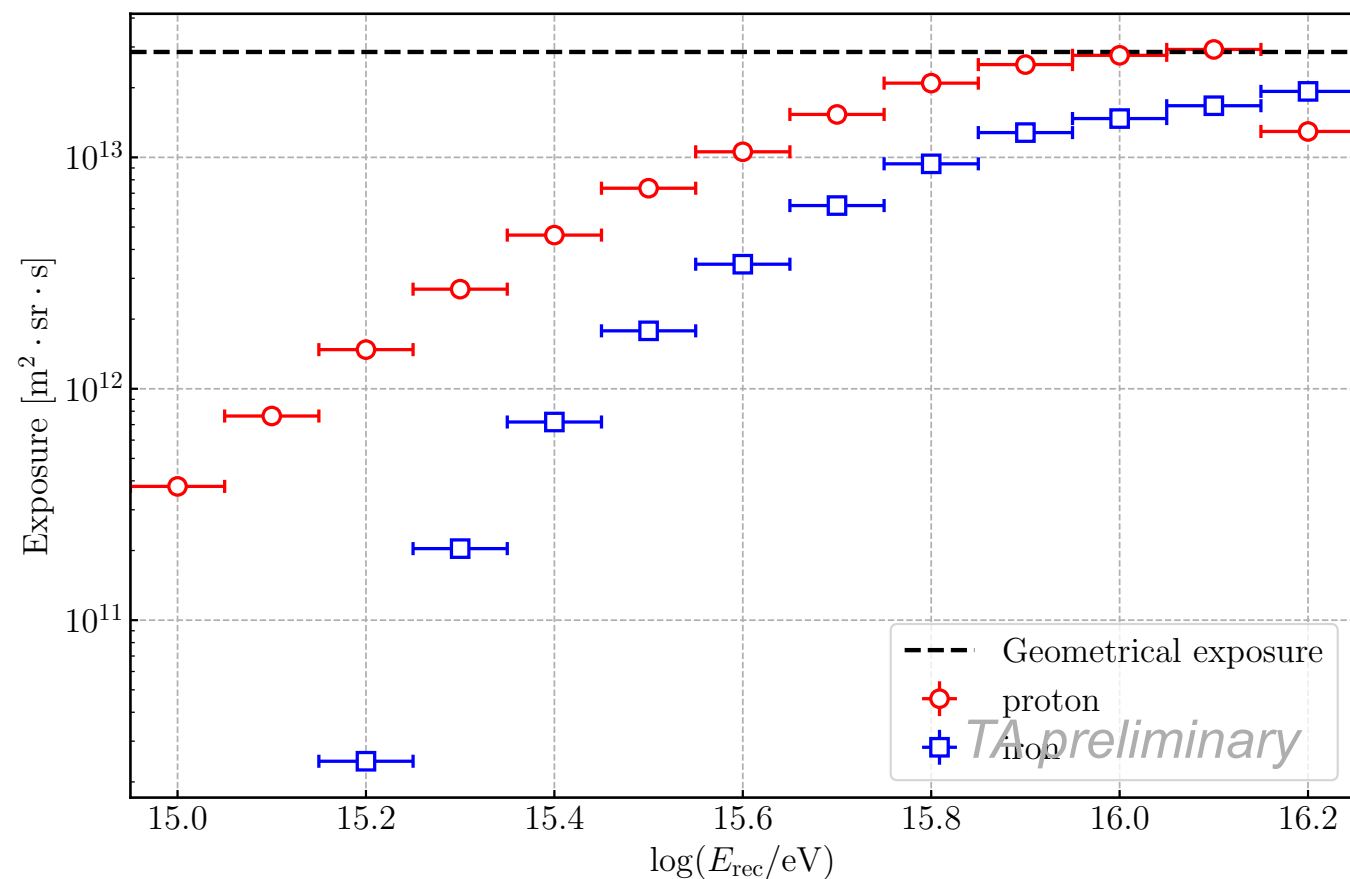
$$J(E_i) = \frac{N(E_i)}{exp(E_i) \cdot \Delta E}$$

$$eff(E_i) = N_{\text{rec}}^{\text{cut}}(E_i^{\text{rec}}) / N_{\text{gen}}(E_i^{\text{sim}})$$

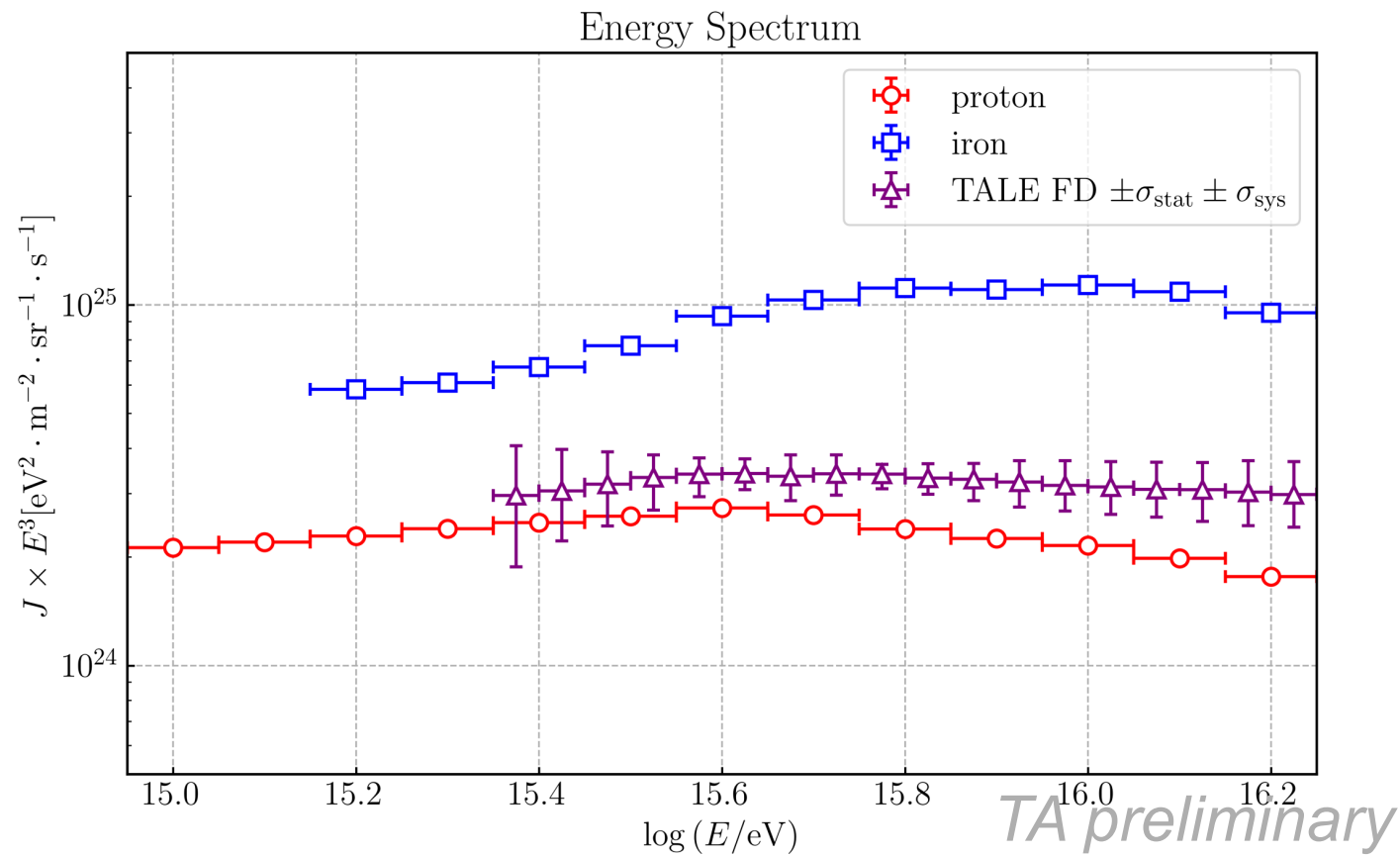


Exposure

- geometrical exposure = $A_{\text{geom}} \cdot \Omega_{\text{geom}} \cdot T$
 - $A_{\text{geom}} = 400 \text{ m} \times 400 \text{ m}$
 - $\Omega = \int_{0^\circ}^{360^\circ} \int_{0^\circ}^{40^\circ} \sin \theta \cos \theta d\theta d\phi$



Spectrum



PyUnfold

- This is a python library which performs Bayesian-statistics based **iterative** unfolding

- Steps of unfold are below:

1. $N(E_i^{\text{rec}})$ is converted into an estimate of the true distribution $N(E_i^{\text{sim}})$ using Response Matrix

2. The cumulative distributions are calculated:

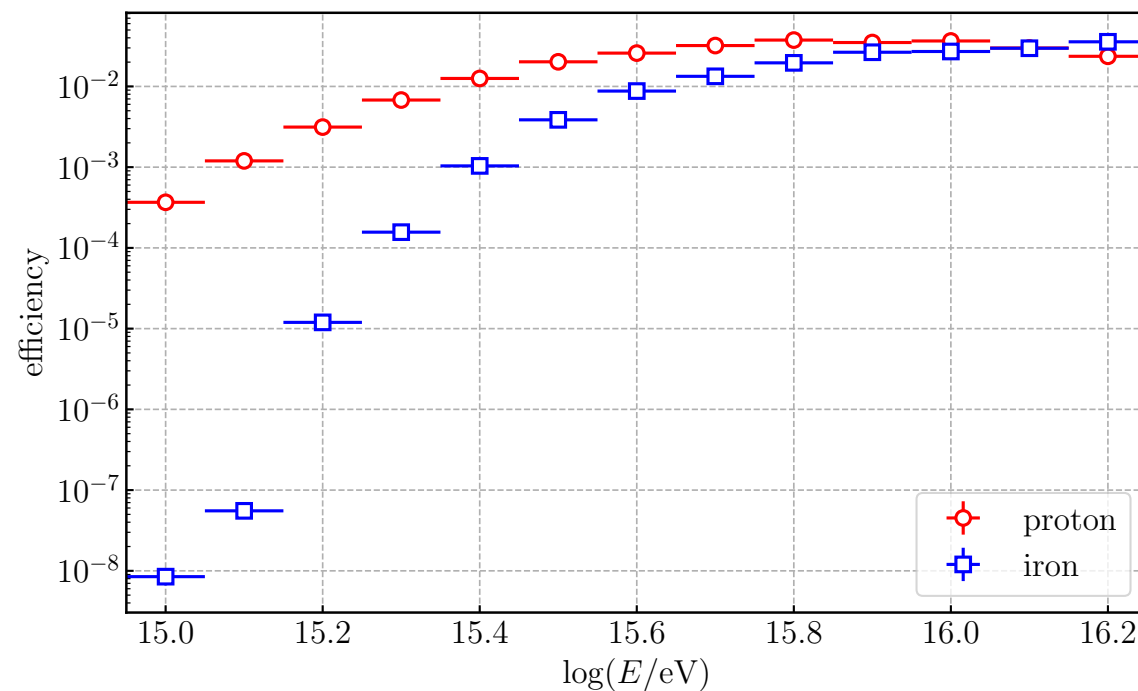
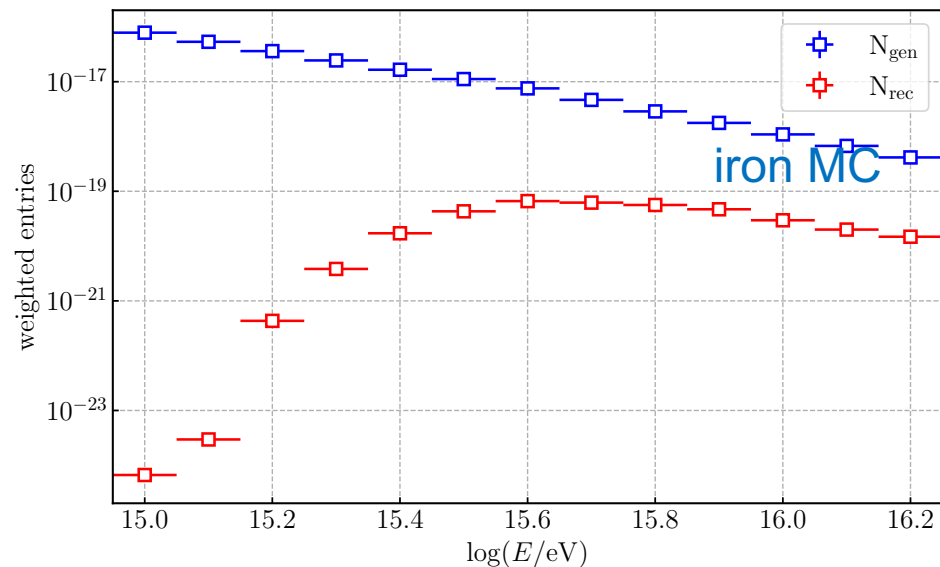
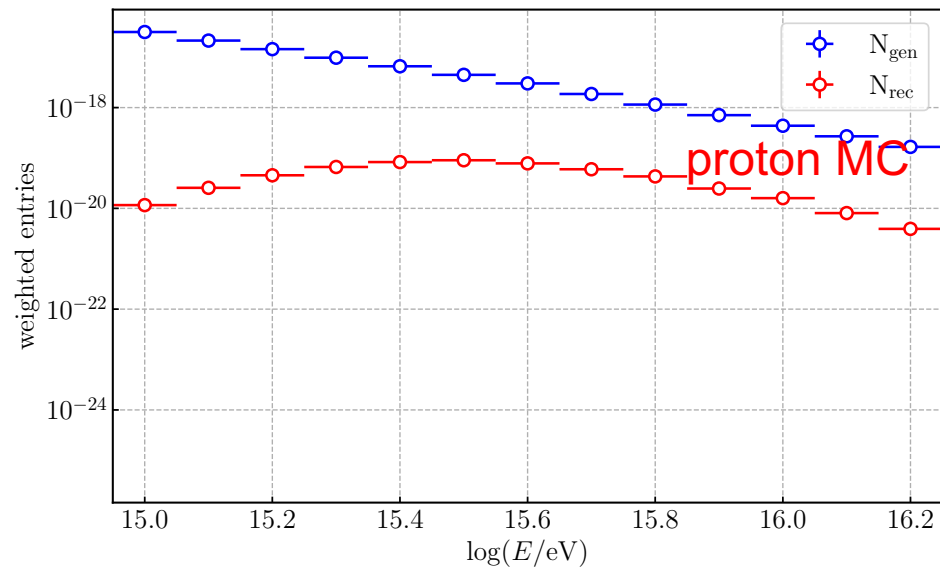
$$F_k(E_i) = \frac{\sum_{j \leq i} N_k(E_j)}{\sum_i N_k(E_i)} \quad (k: \text{current iteration, } i: \text{energy bin})$$

3. The test statistics is defined as below:

$$TS = \max |F_k(E_i) - F_{k-1}(E_i)|$$

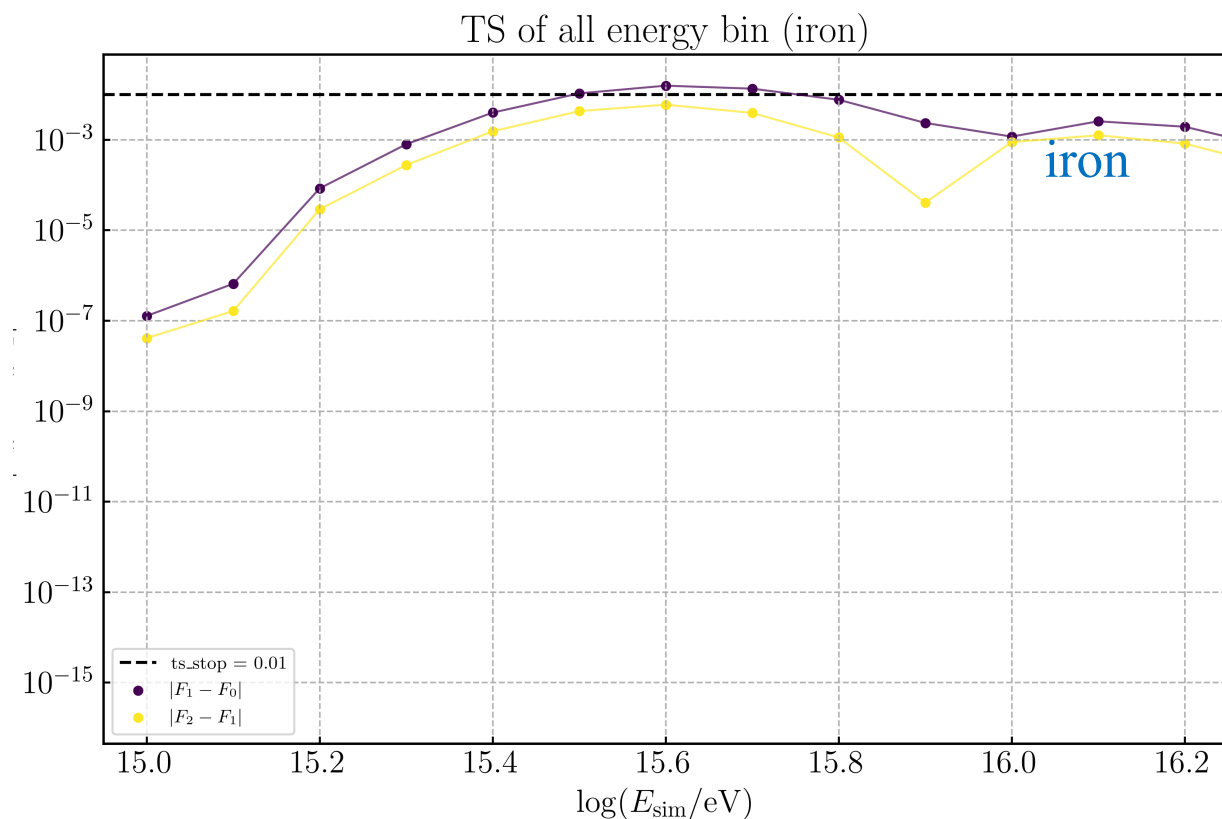
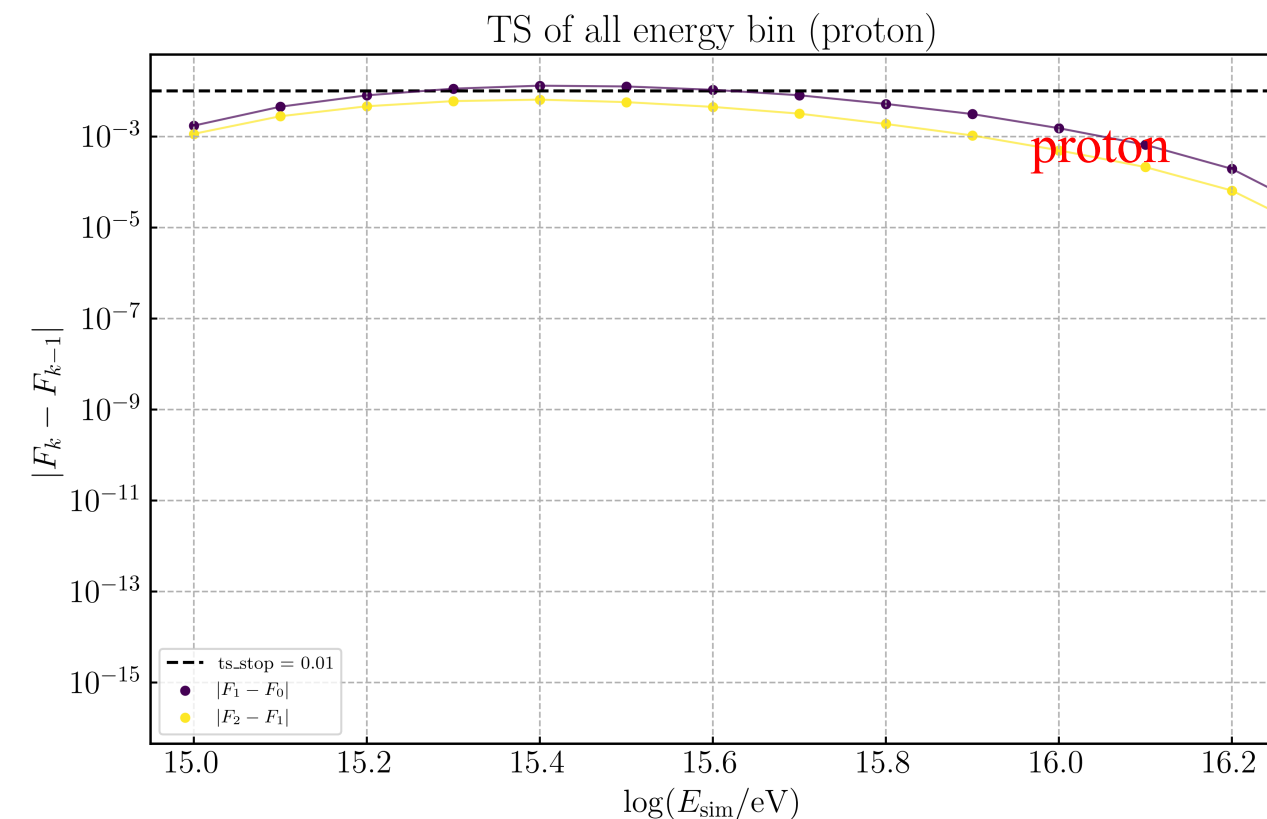
4. If TS becomes smaller than a chosen threshold (this analysis: 0.01), the iteration is stopped
otherwise, unfold procedure is repeated

$$eff(E_i) = N_{\text{rec}}^{\text{cut}}(E_i^{\text{sim}}) / N_{\text{gen}}(E_i^{\text{sim}})$$



TS values in each iteration

$$F_k(E_i) = \frac{\sum_{j \leq i} N_k(E_j)}{\sum_j N_k(E_j)} \quad (k: \text{current iteration, } i: \text{energy bin})$$



Compare energy dist. of before/after unfolding

