PeV Cosmic-Ray Measurements with TALE infill SD array

2026/5/26-29 PEPS workshop @OMU

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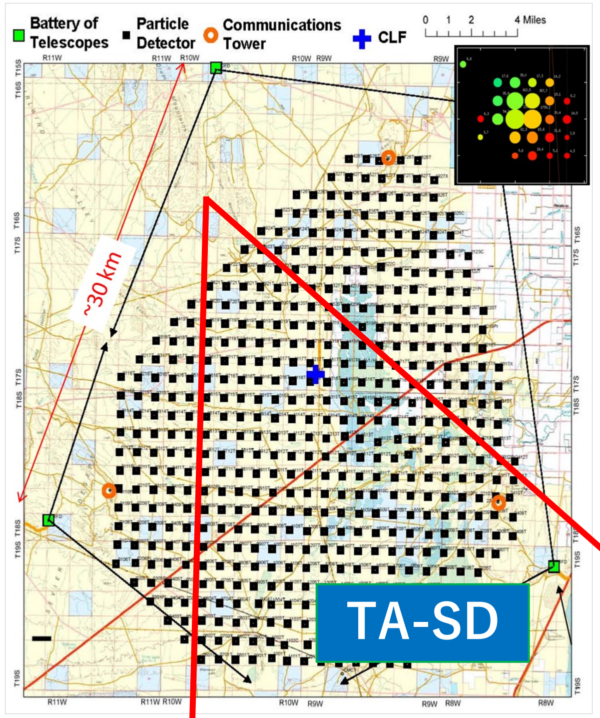
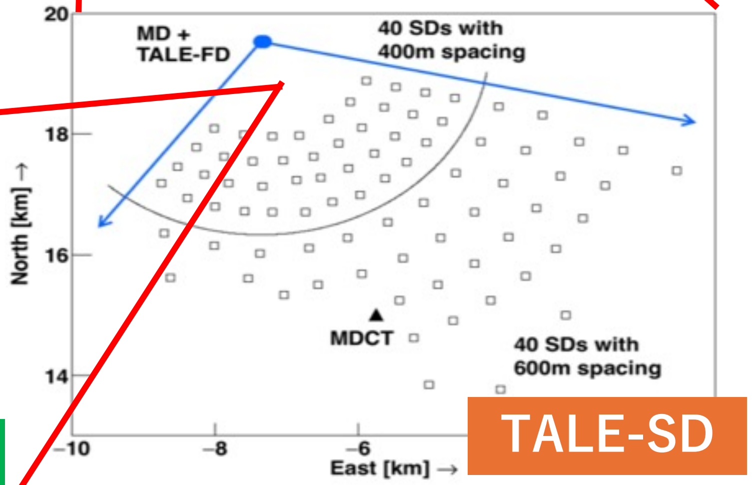
TALE infill

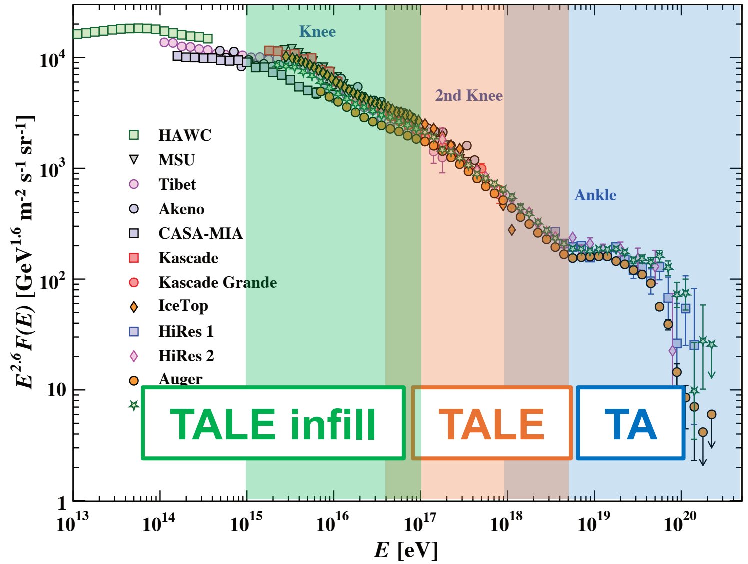
- Overview : A further low energy extension of **TALE**

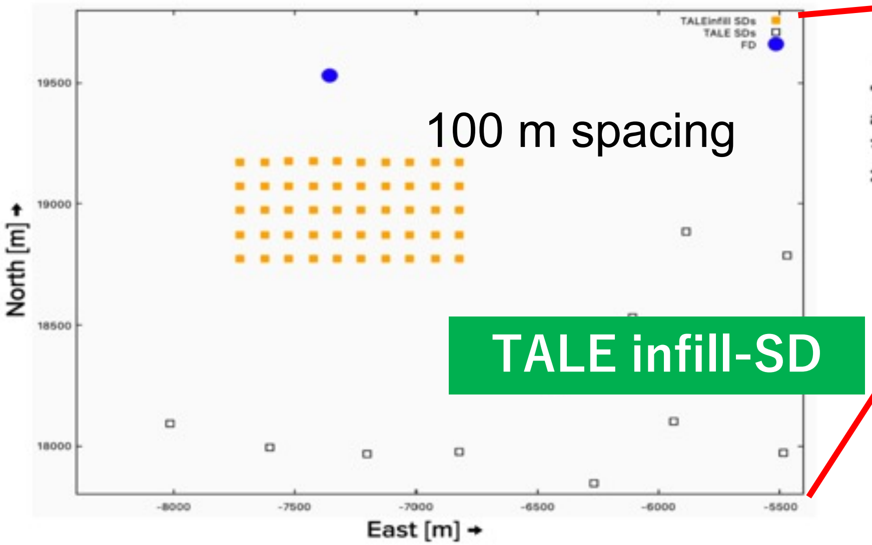
- Target : Cosmic rays with $E \geq 10^{15.0}$ eV

- Objective : Investigating the "knee" structure
  - Calculate energy spectrum
  - Analyze mass composition and anisotropy



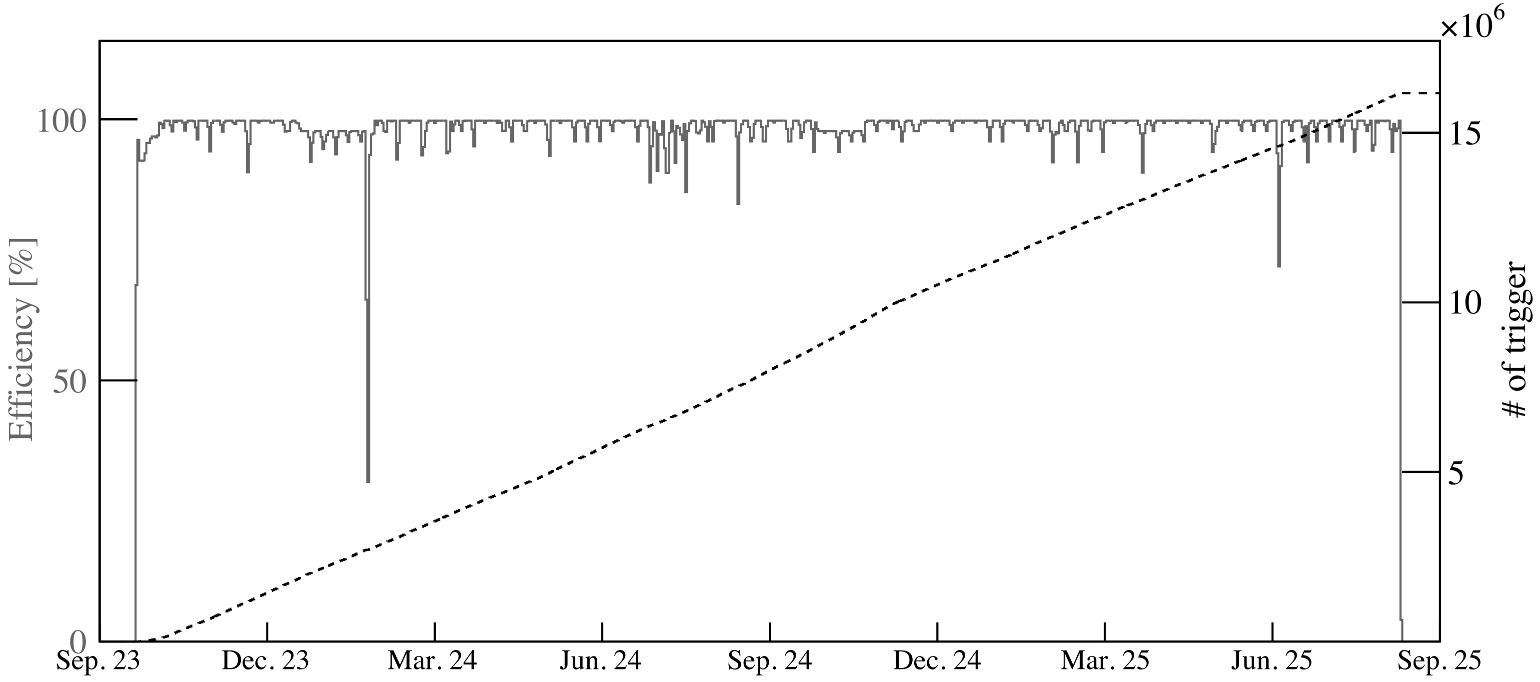


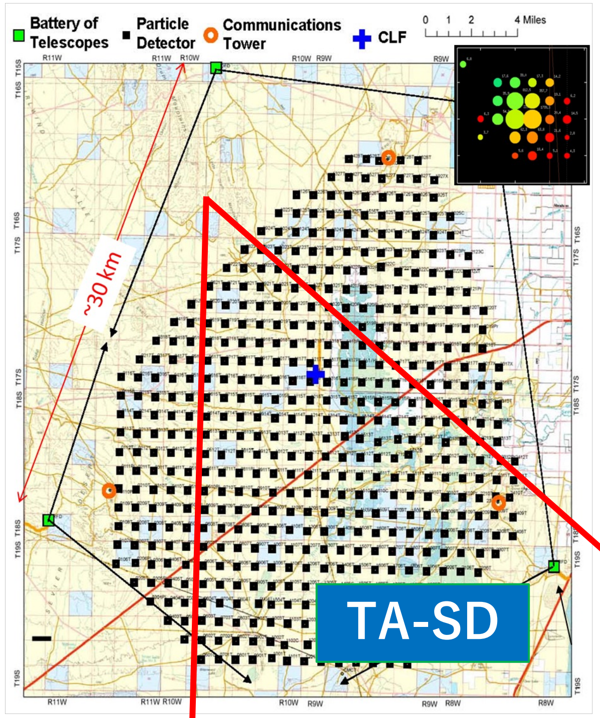


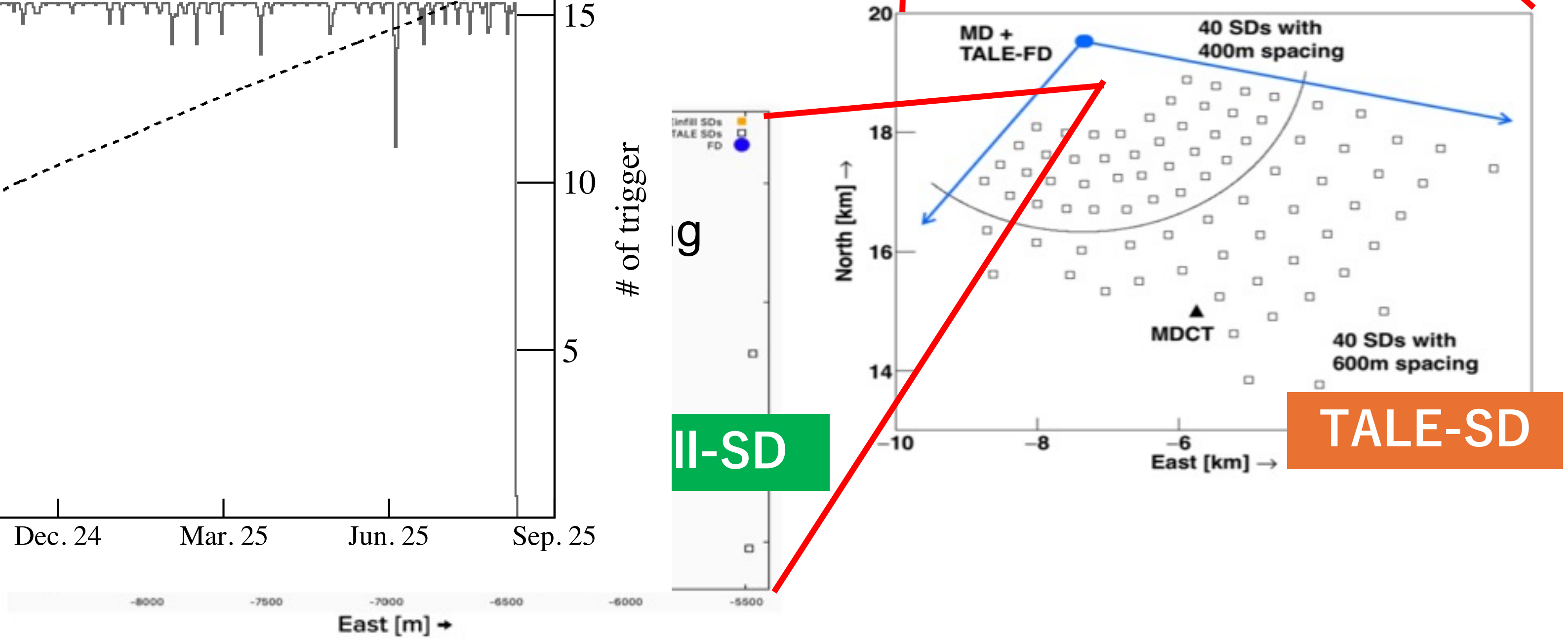


TALE infill

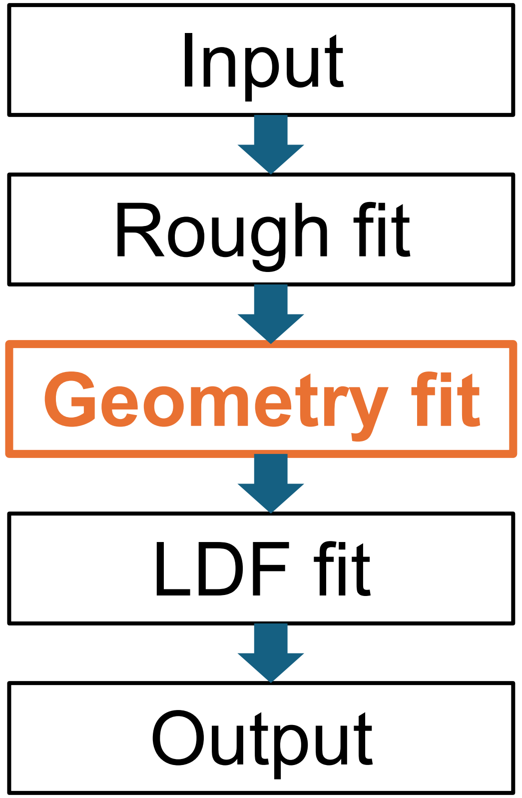
- Observation period : Nov. 2023 ~
- Duty cycle : 98.5 %
  → stable observation is ongoing.







Reconstruction process



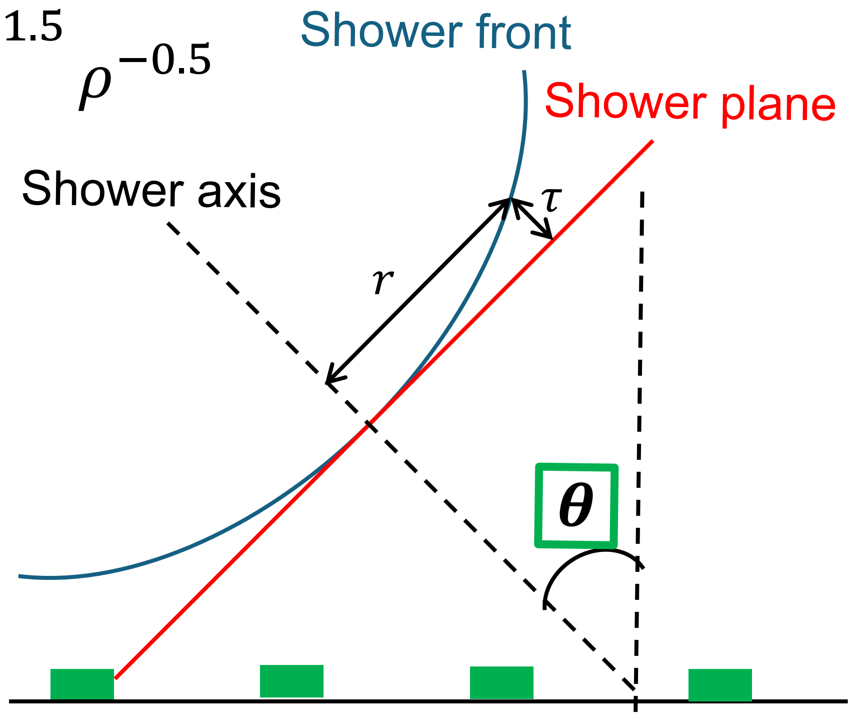
Geometry fit :

Determine geometrical parameters

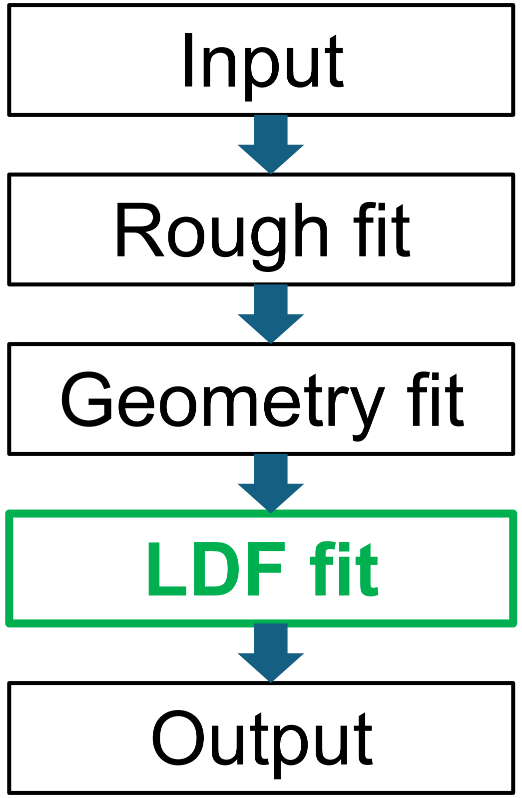
by fitting the following function :

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

- 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

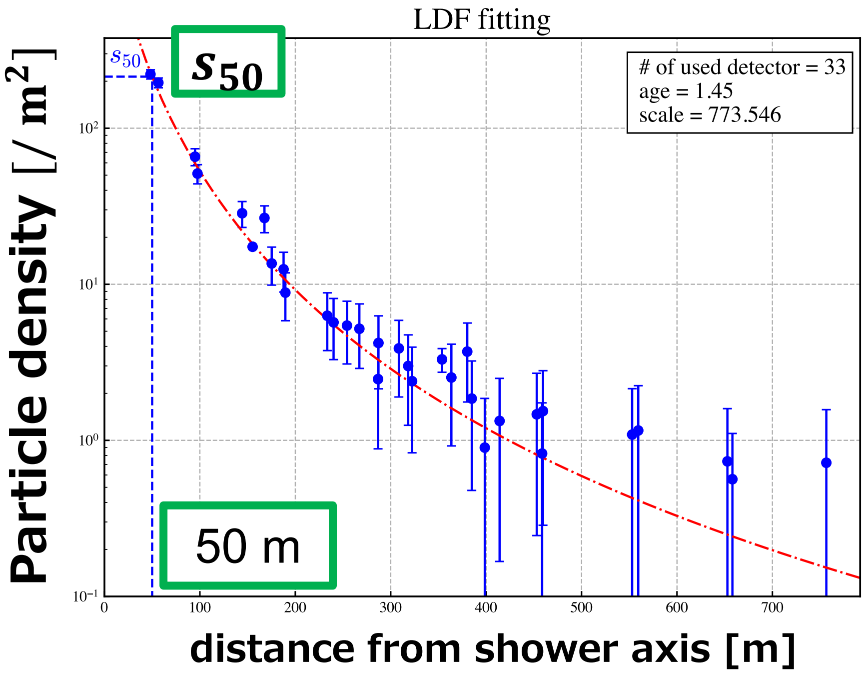


LDF fit :
Determine Core Pos. & Lateral Dist. of the shower
by fitting NKG function

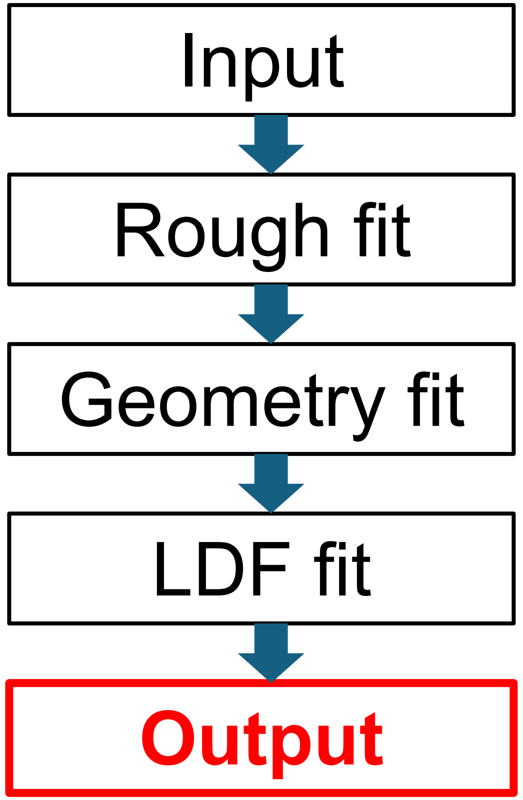
$$\rho^{\mathrm{fit}} = N\left(\frac{1}{r_M}\right)^2 \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4.5}$$

- 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

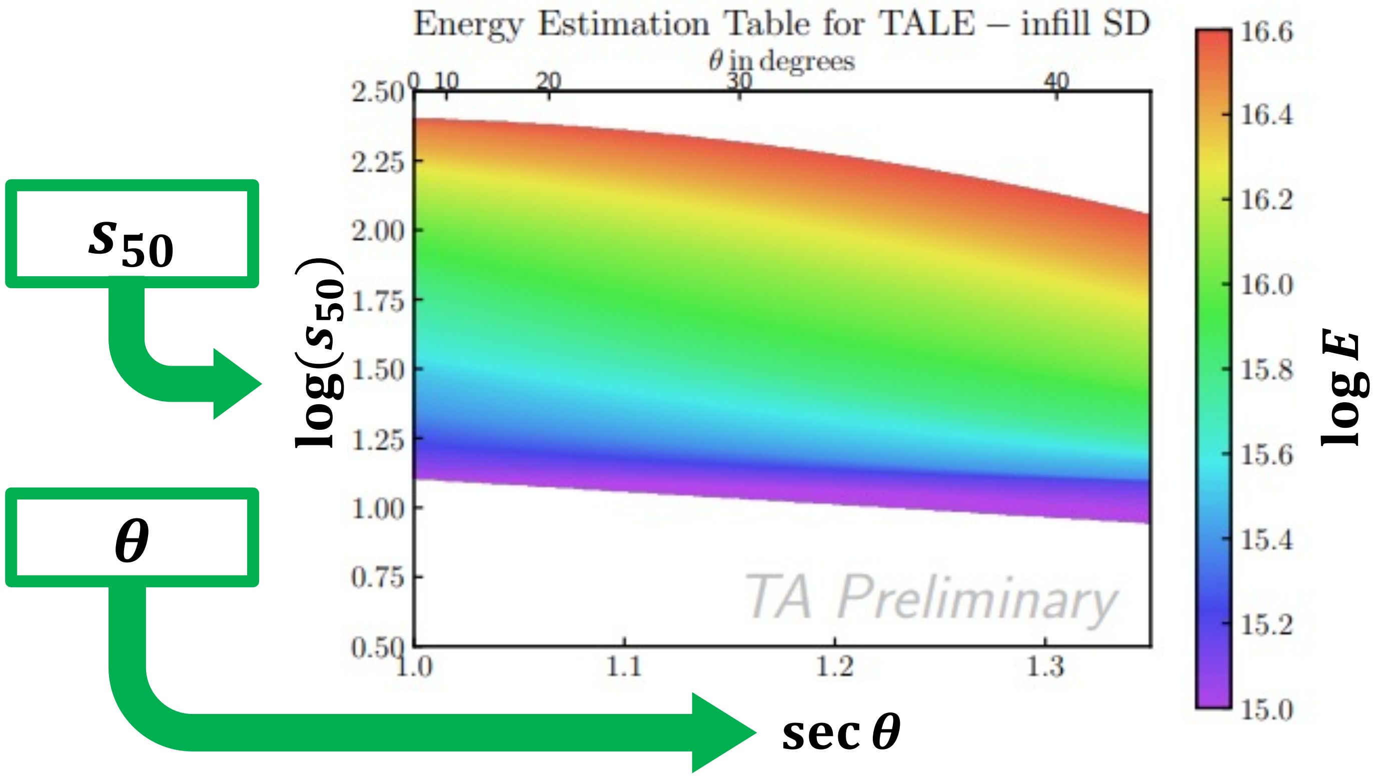
Primary energy E is estimated using energy estimation table with θ and s_{50}

Output below params:

$\boldsymbol{E}$

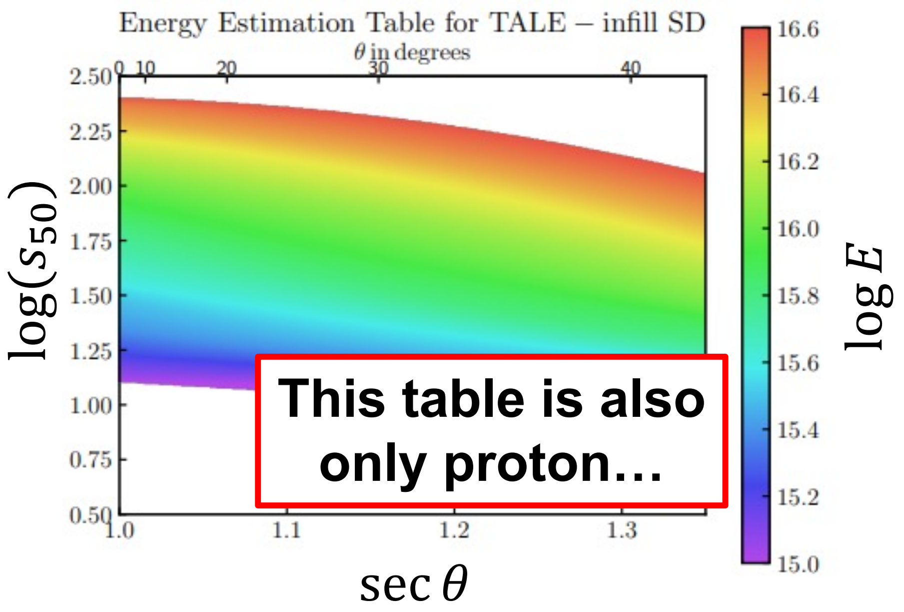
$(\boldsymbol{\theta}, \boldsymbol{\phi})$

$(\boldsymbol{x}, \boldsymbol{y})$

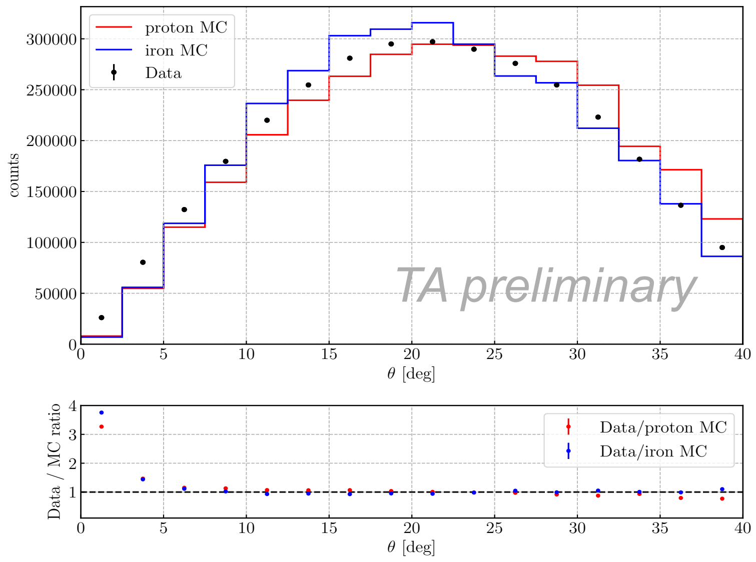


Outflow of this analysis

1. **Make energy lookup table**
   - MC events for infill is **only proton**
     → Multi-primary MC is important for analyzing knee region
     → MC of **heavier nuclei** should be prepared



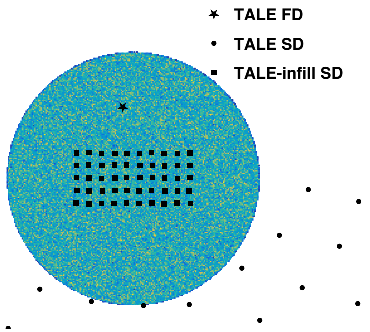
2. **Perform Data/MC comparison**
   - Check the consistency of MC dataset



3. **Measure an energy spectrum**

MC dataset for this analysis

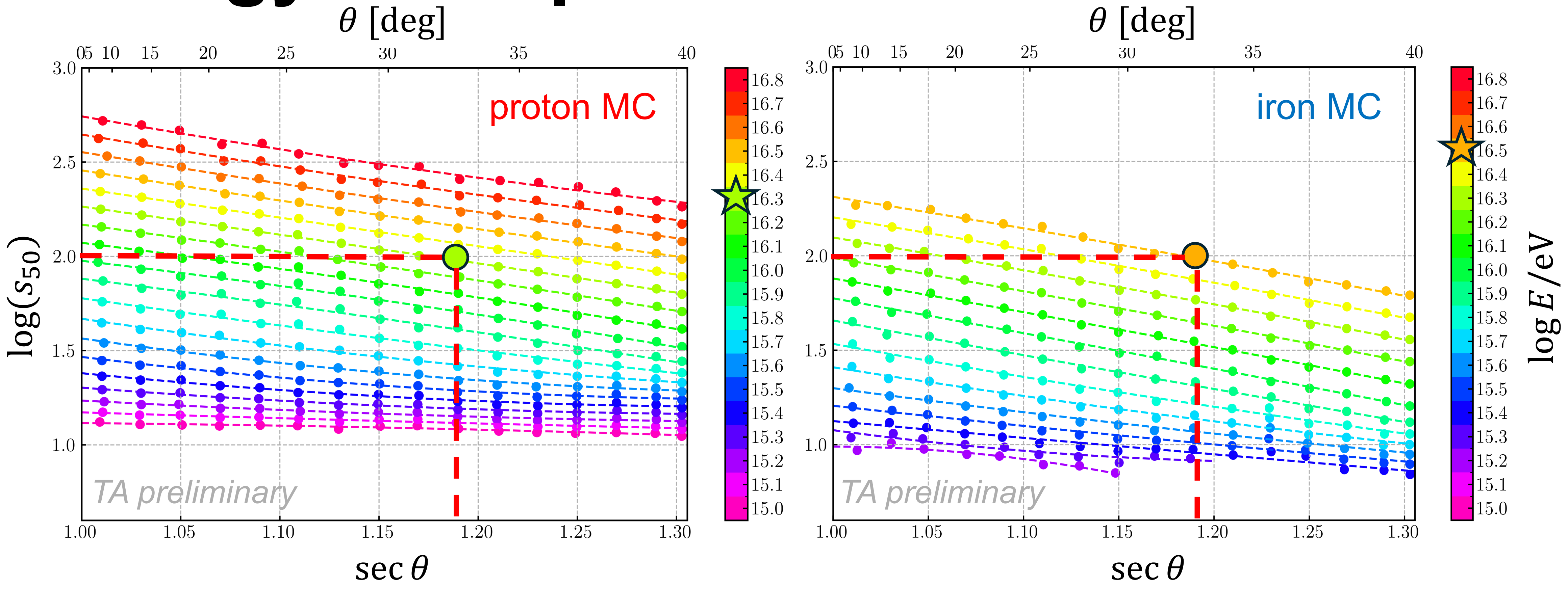
- Primary particle : proton, iron
- Hadron interaction model : QGSJETII-04
- Energy
  proton: $10^{15.0} \sim 10^{16.8}$ eV
  iron: $10^{15.0} \sim 10^{16.5}$ eV
- $[\theta, \phi] = [(0° \sim 65°), (0° \sim 360°)]$
- Range : circle with a radius of 1.0 km
- period: 2023/11/1-2025/10/8



Event selection criteria

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

1. Energy lookup tables



There are energy bias depending on the mass of primary particle.

ex.) the event with $(\sec\theta, \log s_{50}) = (1.04,\ 2.00)$

rainbow plot from proton MC : $\boldsymbol{E_{\mathrm{rec}}} \approx \mathbf{10^{16.3}\ eV}$

rainbow plot from iron MC : $\boldsymbol{E_{\mathrm{rec}}} \approx \mathbf{10^{16.5}\ eV}$

It's approximately 1.6 times larger!!

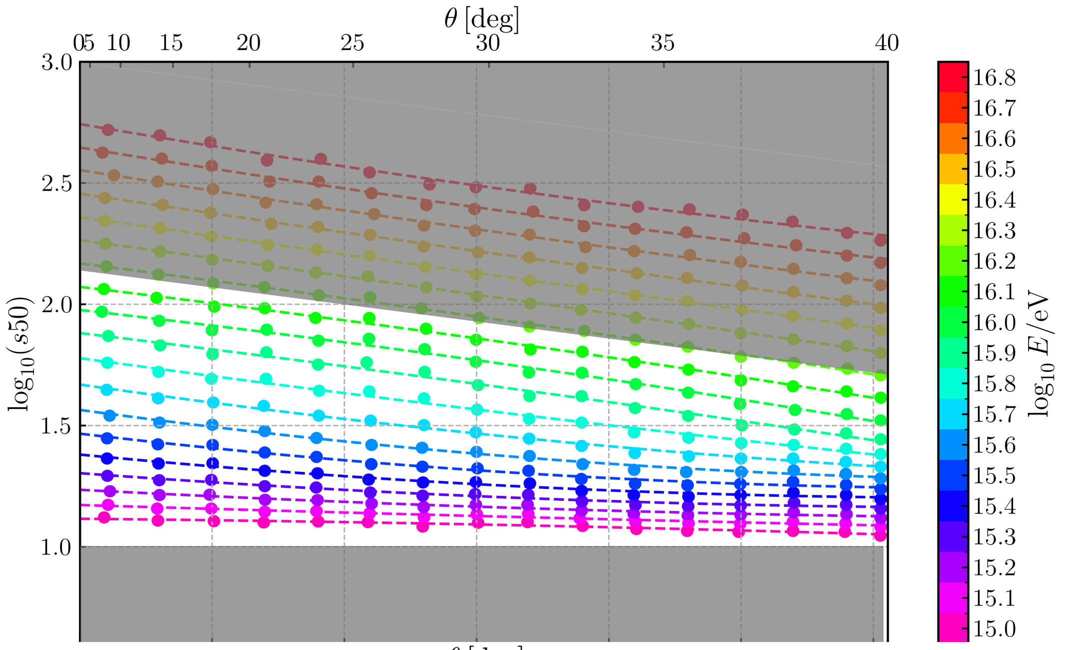
2. Data/MC

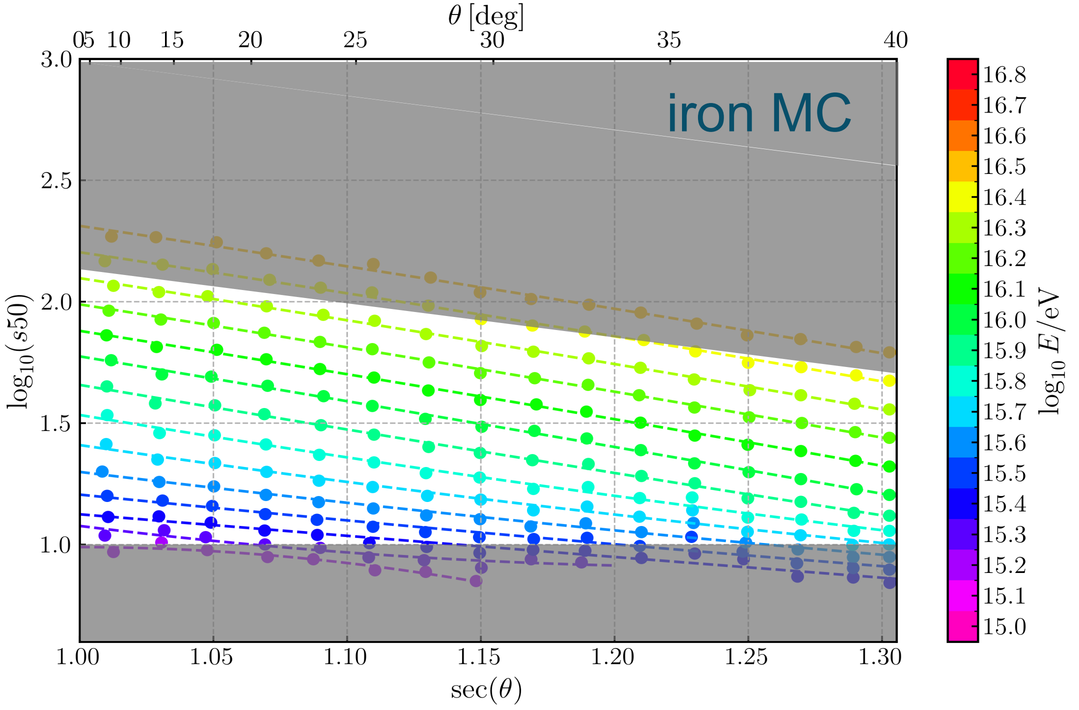
- Reconstruct data with new tables
  → Compare the results of data with
  the ones of proton, iron MC
  - period: 2023/11/1 ~ 2025/10/8

- Weight to MC data
  - E: assume the following spectrum

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

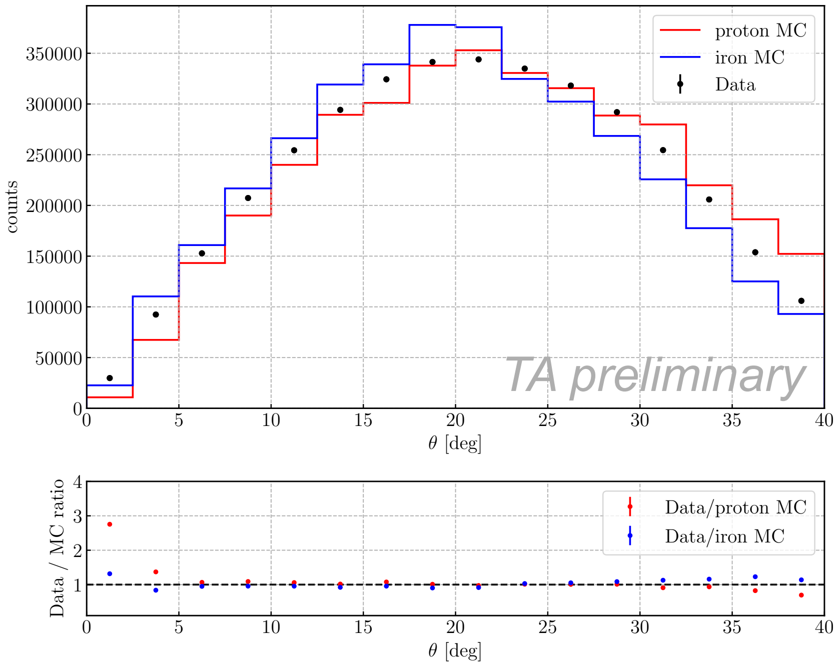
- Adapt additional event-selection
  $1.0 < \log s_{50} < f_{\mathrm{iron}}(\sec\theta\,, \log E = 16.4)$
  → get a common area of proton & iron MC

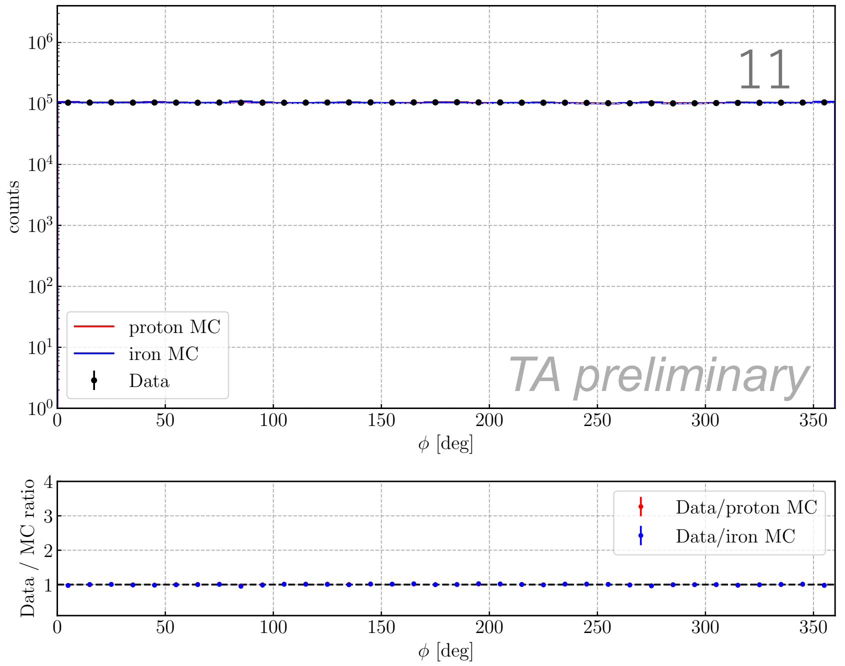




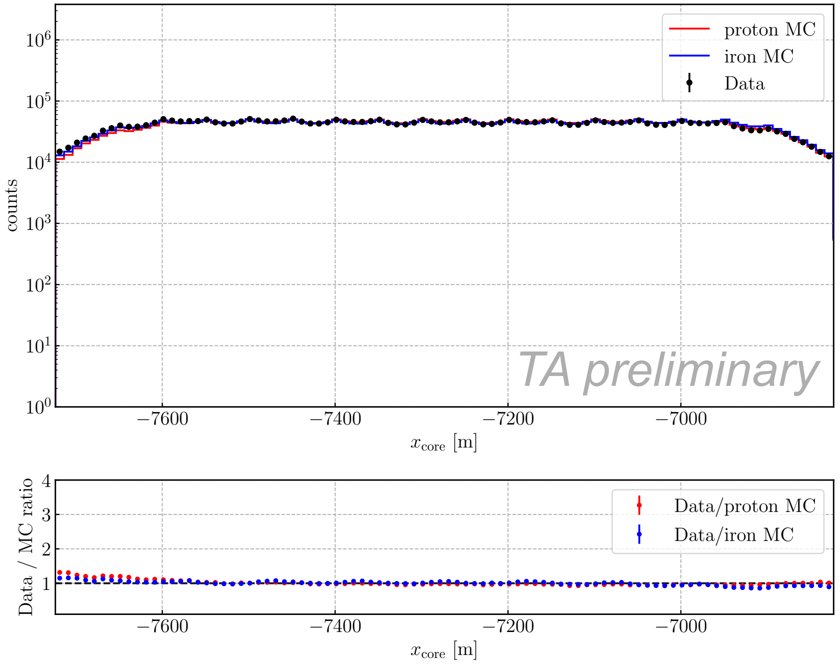
2. Data/MC

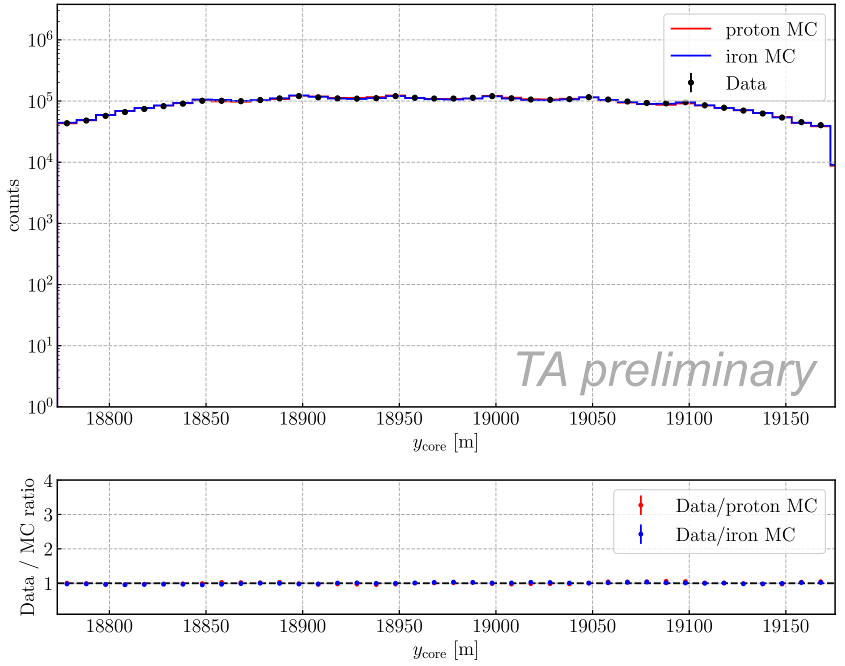
- θ:
  MC is consistent well with data **assuming the mixed composition**



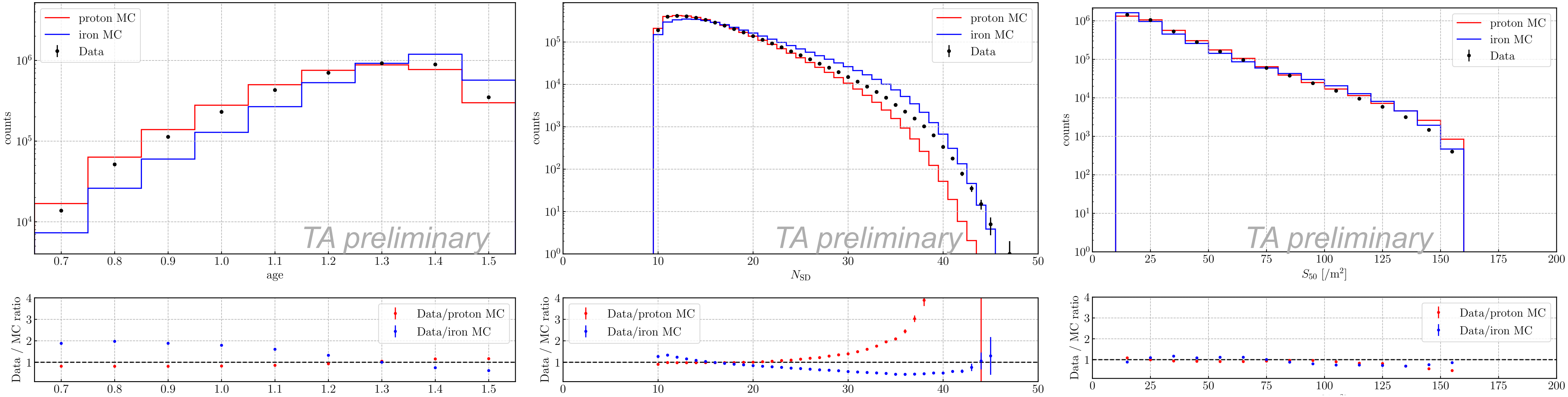


- Other parameters:
  MC is consistent well with data





2. Data/MC



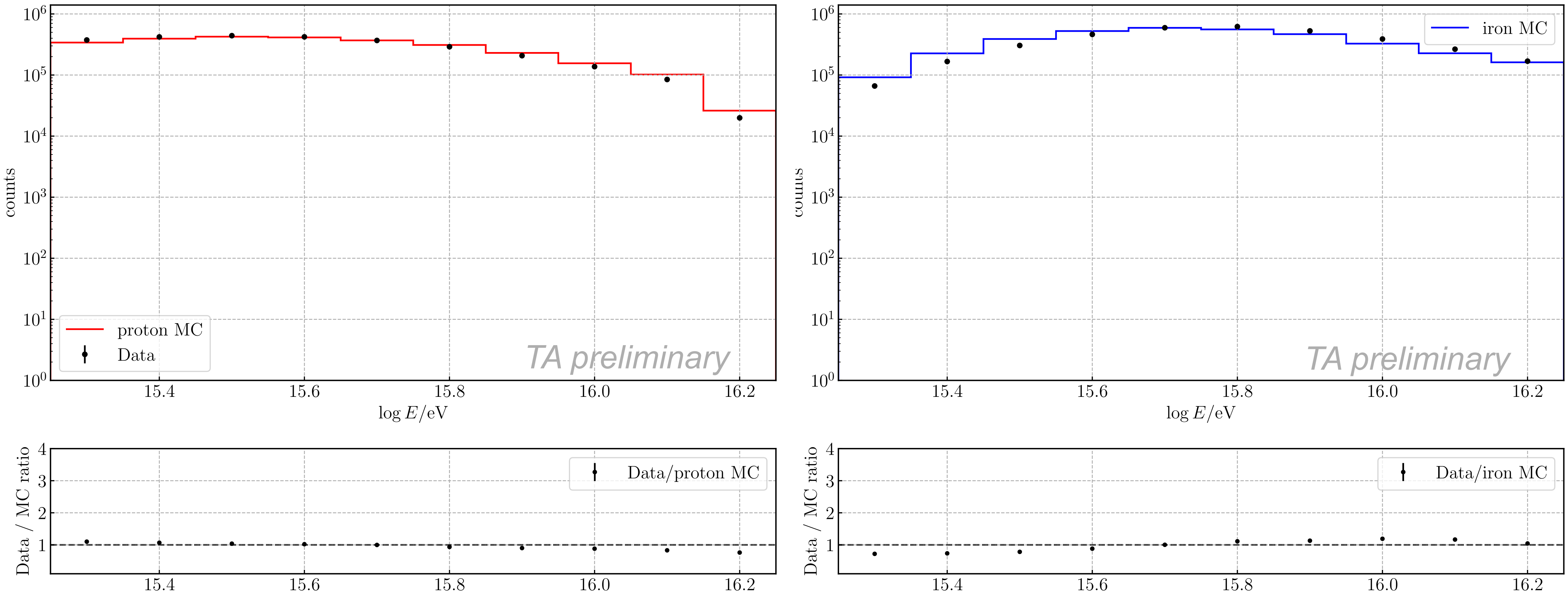
age

N_{SD}

s_{50} [/m^2]

- age: MC is consistent with Data **assuming the mixed composition**
- N_{SD}: MC is consistent with Data **assuming the mixed composition**
- s_{50}: MC is consistent well with Data

2. Data/MC



log E_{proton} /eV

log E_{iron} /eV

- MC is consistent well with Data

3. Energy spectrum measurements

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

- Calculate exposure

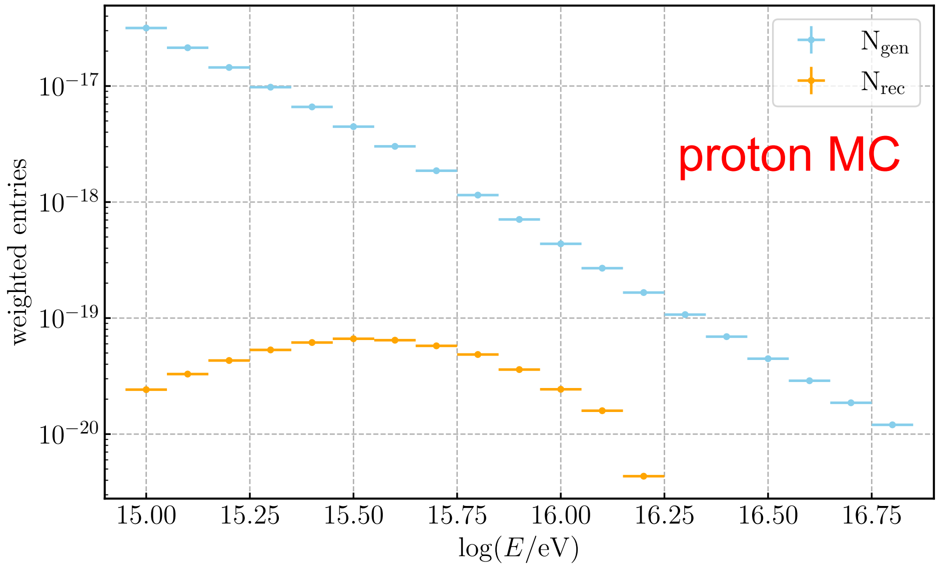
$$exp(E_i) = A \cdot \Omega \cdot T \cdot eff(E_i)$$

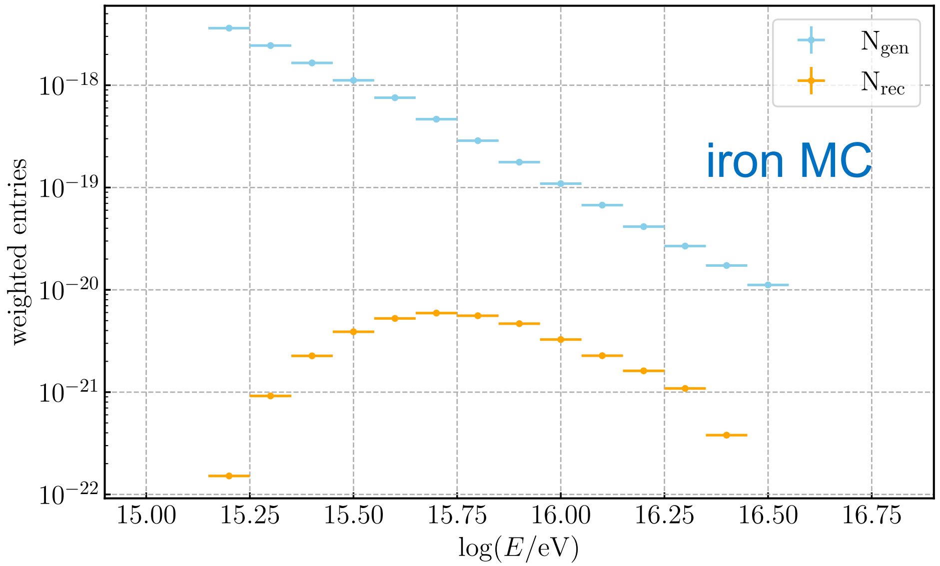
  - $A = \pi \times 1000^2\ \mathrm{m}^2$
  - $\Omega = \int_{0°}^{360°} \int_{0°}^{65°} \sin\theta \cos\theta \, d\theta d\phi$
  - $T = 707\ \mathrm{days} \times 24\ \mathrm{h} \times 60\ \mathrm{min} \times 60\ \mathrm{sec}$ (2023/11/1 – 2025/10/8)

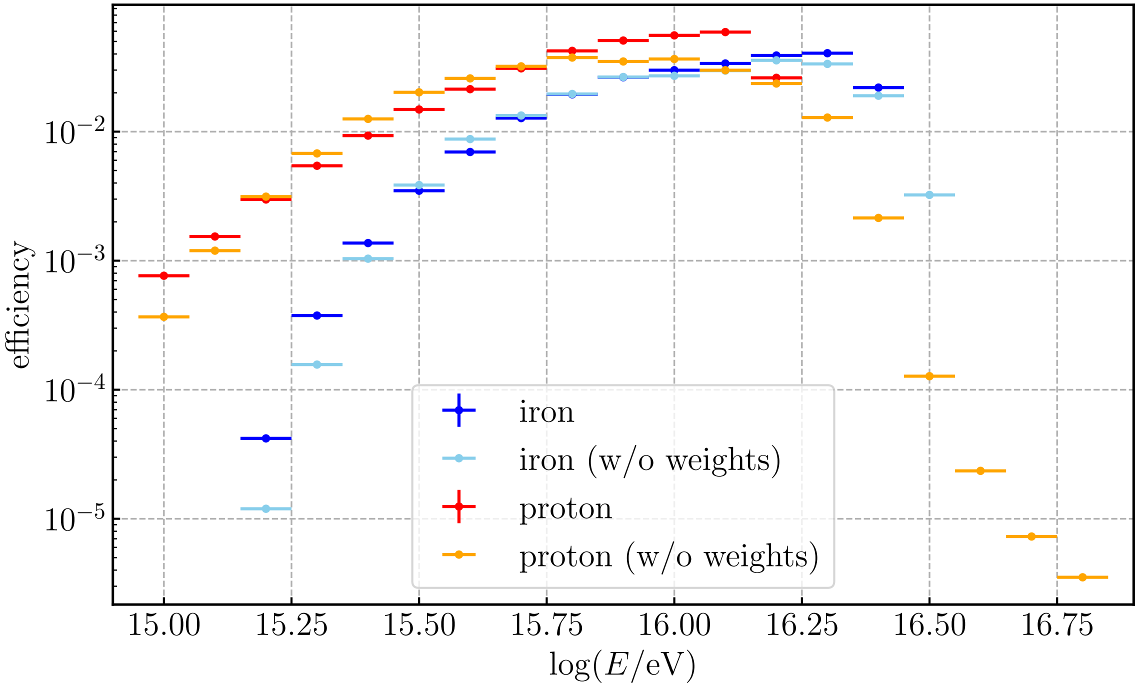
- Calculate spectrum

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

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



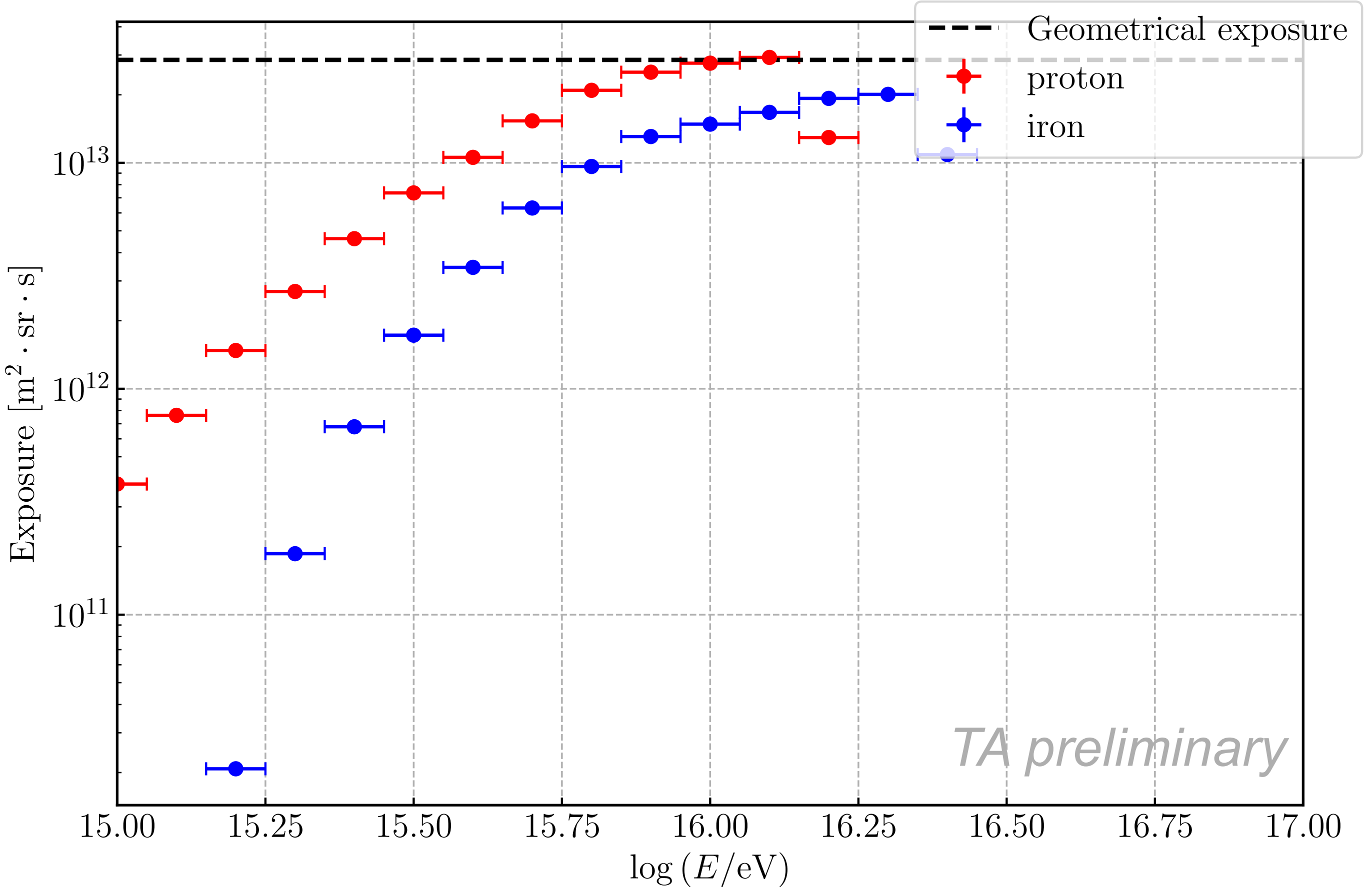




Exposure

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

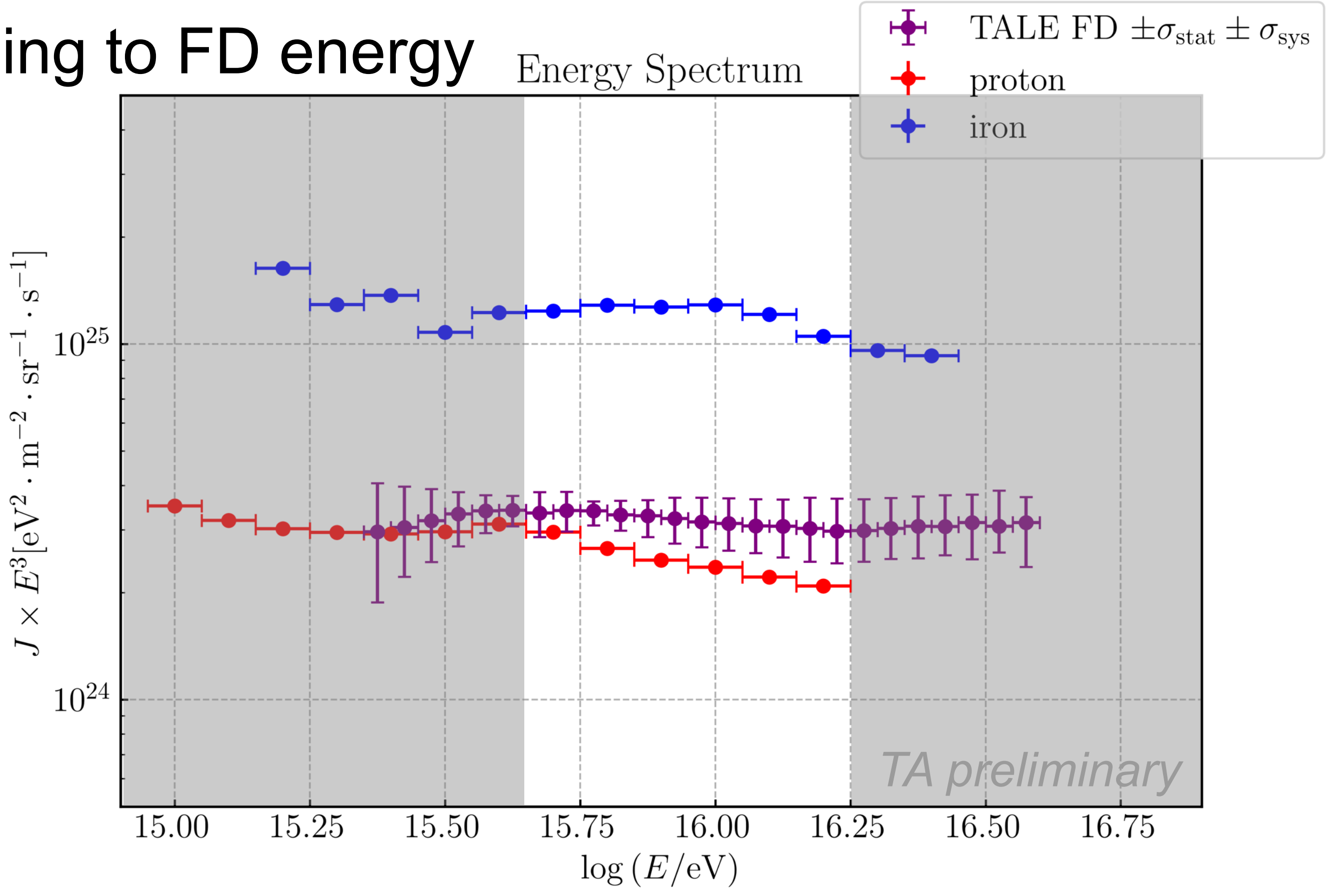
- It seems that geometrical exposure is too close to the data points…



Energy spectrum

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

- Not yet energy scaling to FD energy



Summary & To do

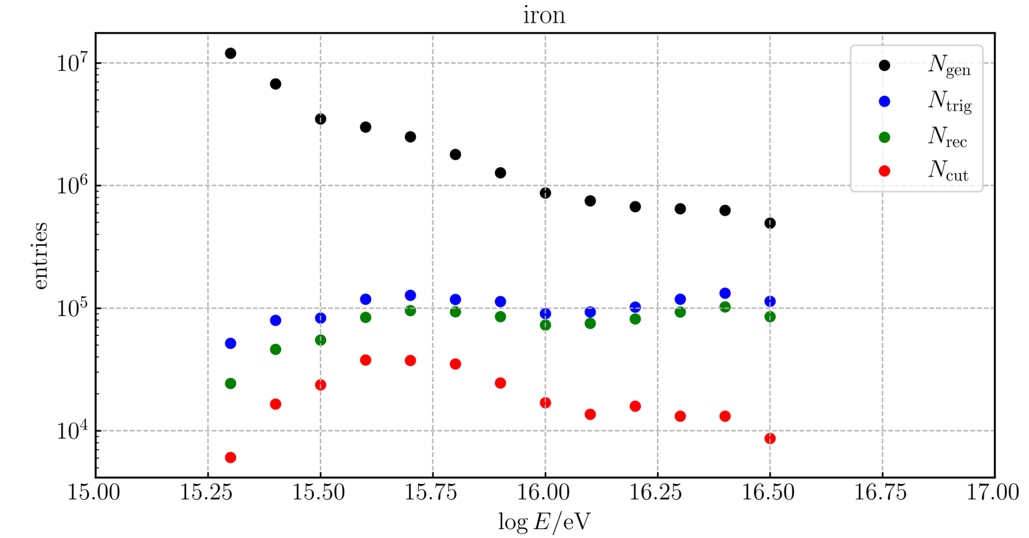
- **Summary:**
  - **Energy lookup table**
    Make the tables assuming pure proton & iron with large statistics of MC
    → **There are energy bias depending on the mass of primary particle**
  - **Data/MC**
    Compare the results of reconstruction of data & MC
    → **MC is consistent well with Data except for the area of small θ & large N_{SD}**
  - **Energy Spectrum**
    Display the first preliminary energy spectrum from TALE infill SD array

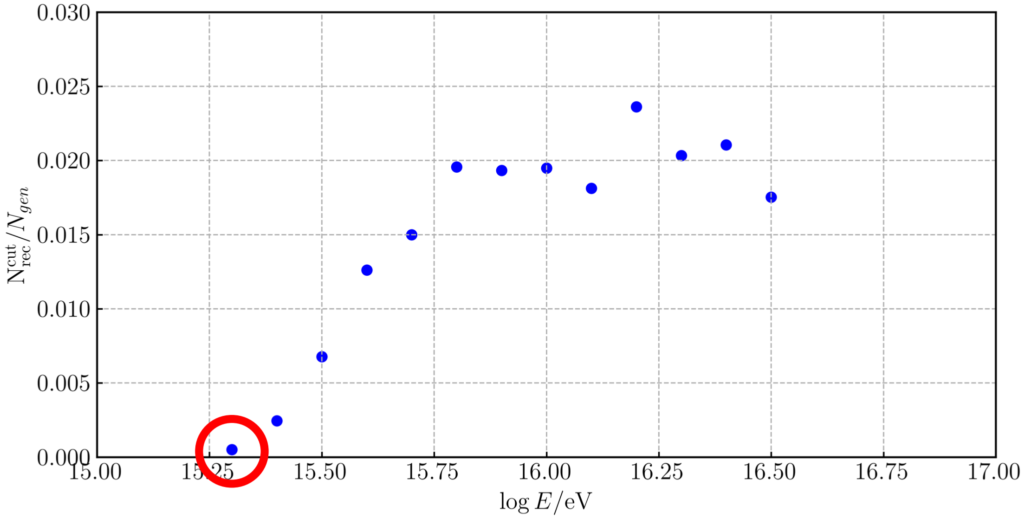
- **To do next:**
  - Calculate scaling factor to FD energy
  - Measure an energy spectrum with mixed composition

Back up

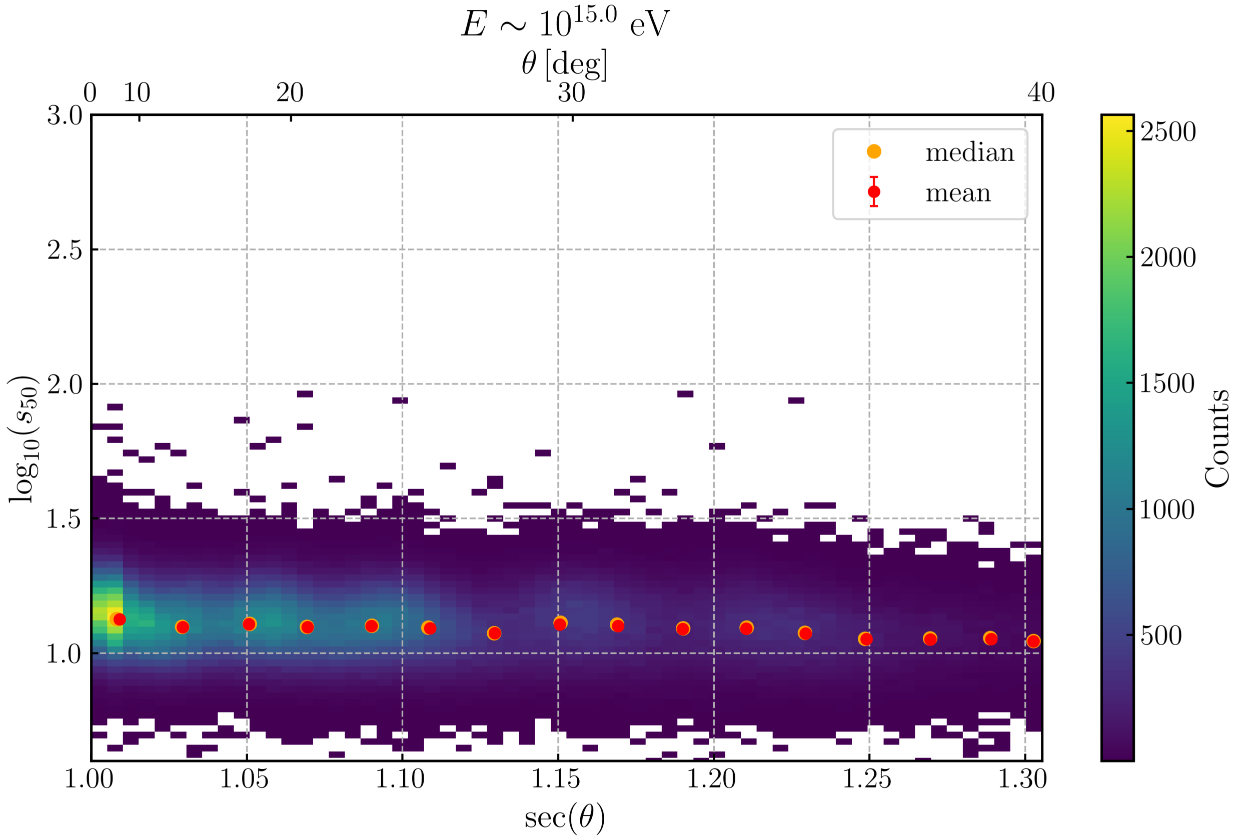
Efficiency of iron MC

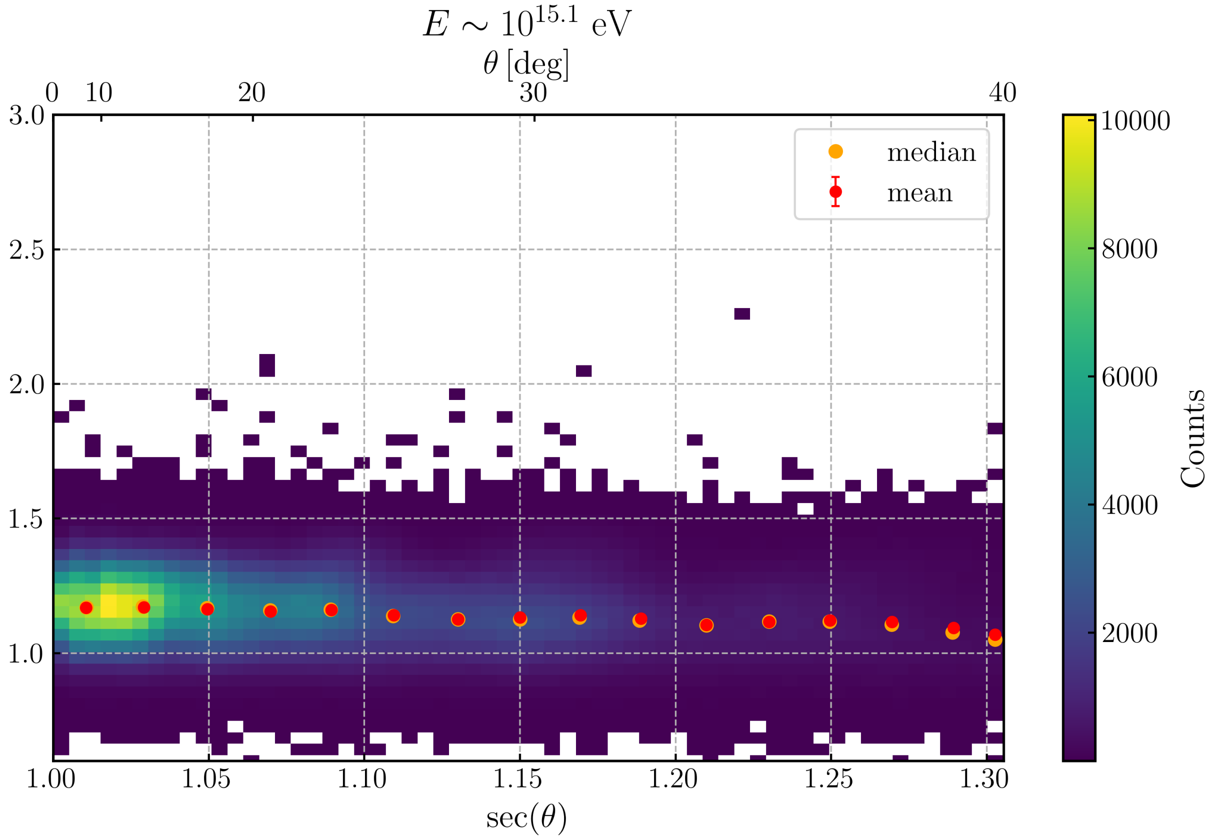
- Efficiency $\simeq 0$ at $\log E = 15.3$
  $\rightarrow$ MC events of $\log E = 15.0, 15.1$ is not made in this analysis



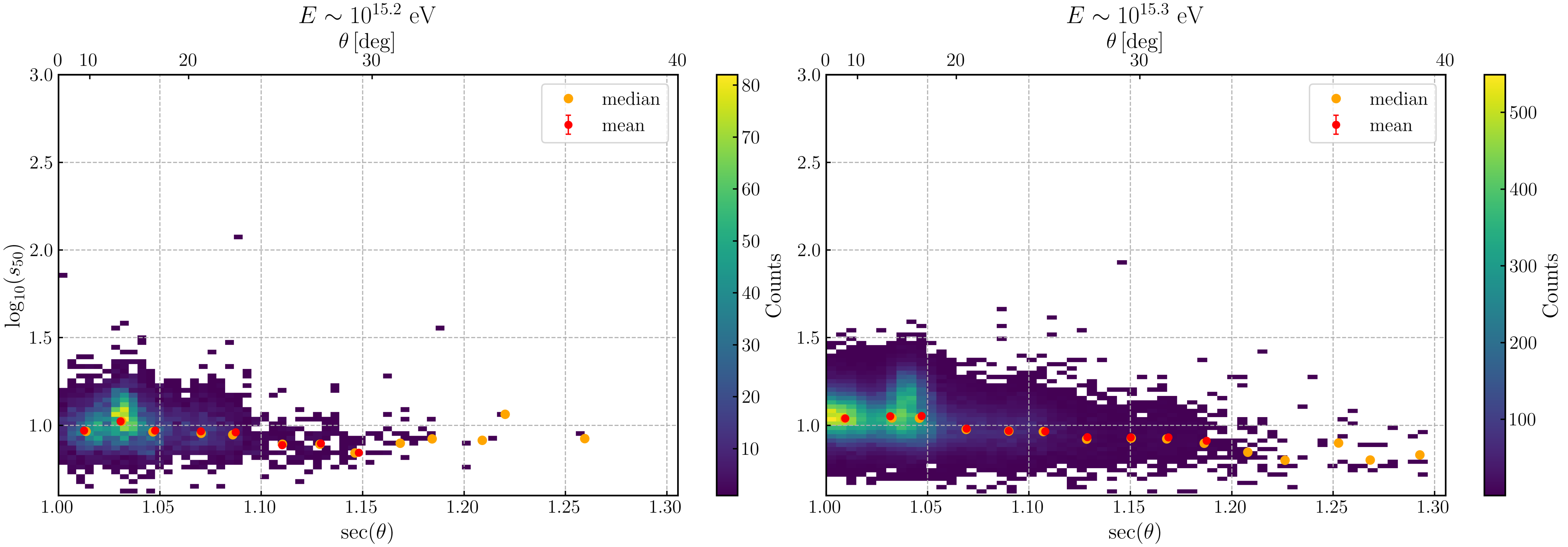


Proton MC events with low energy

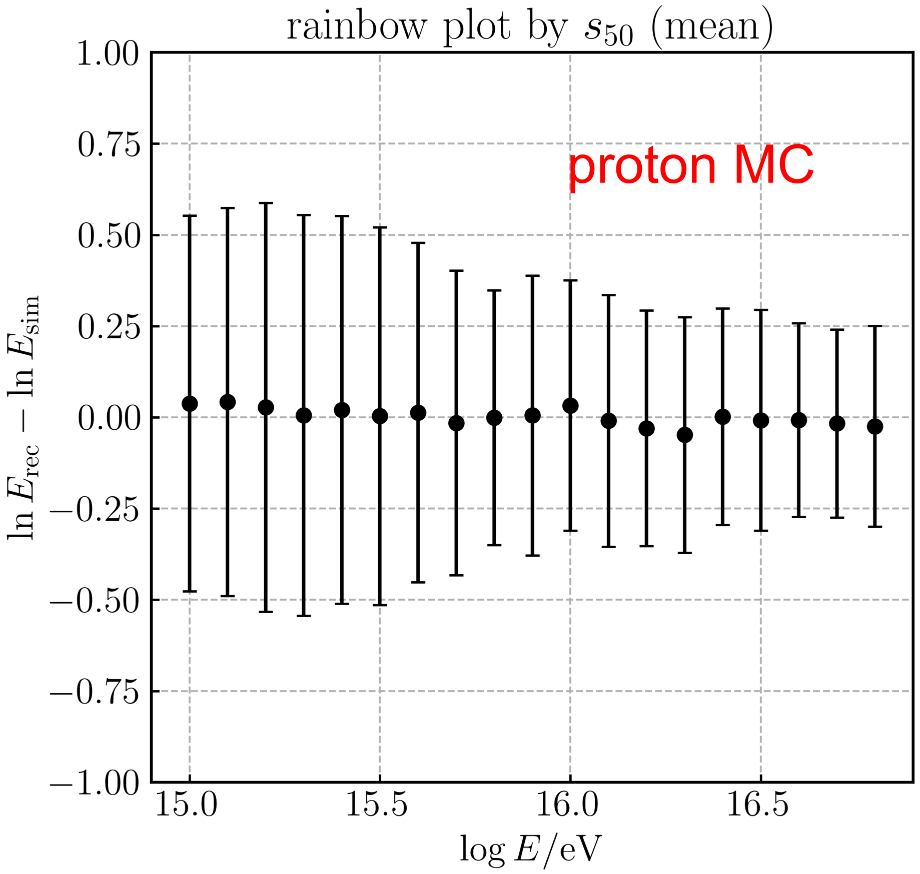


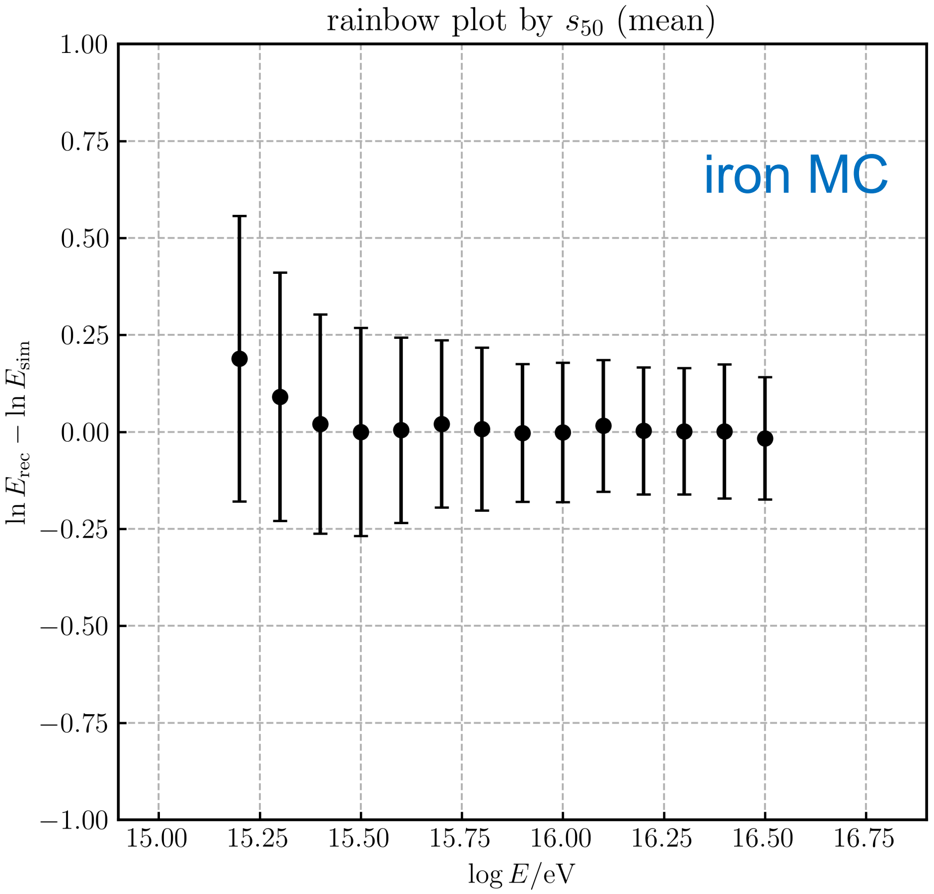


Iron MC events with low energy

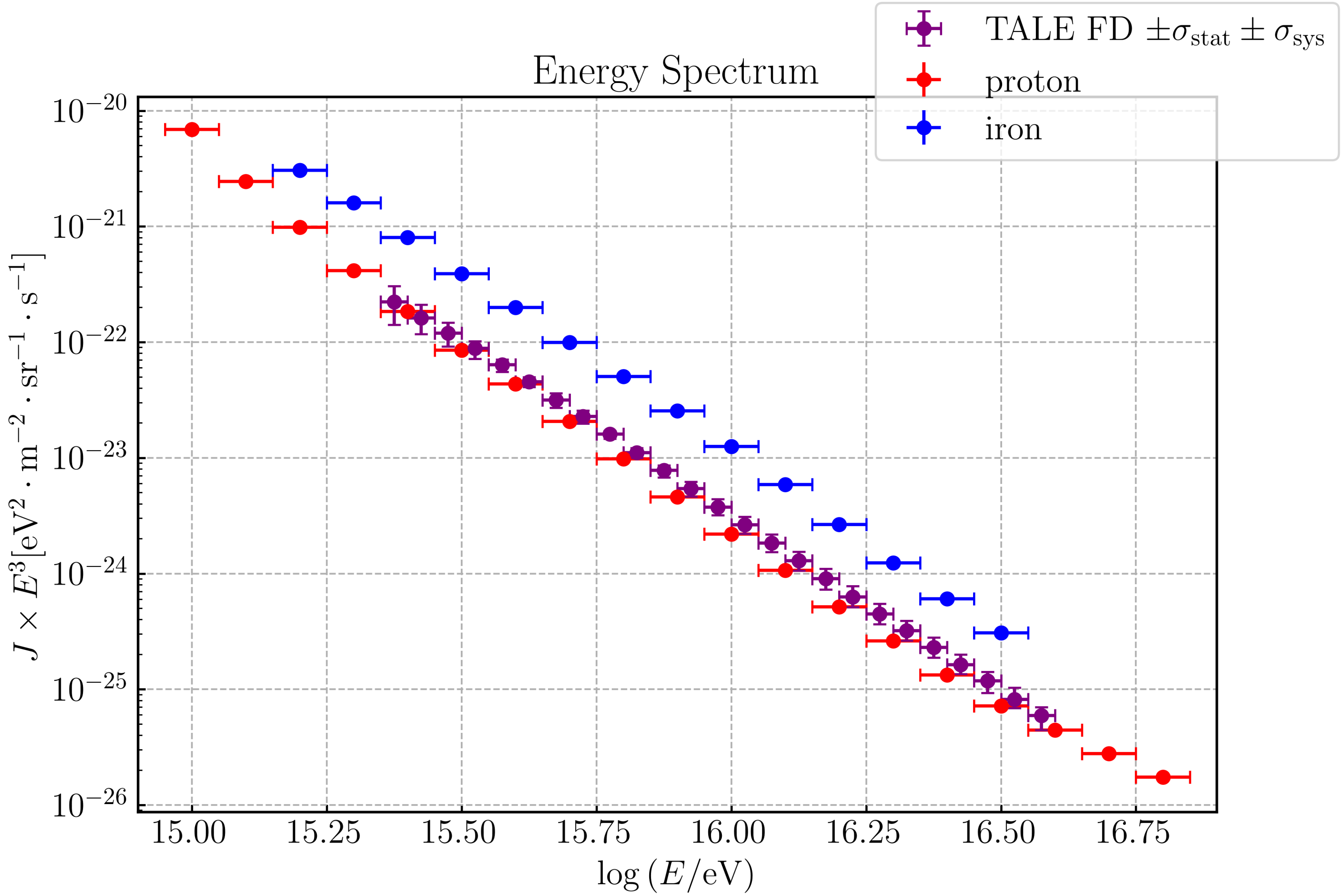


Energy resolution





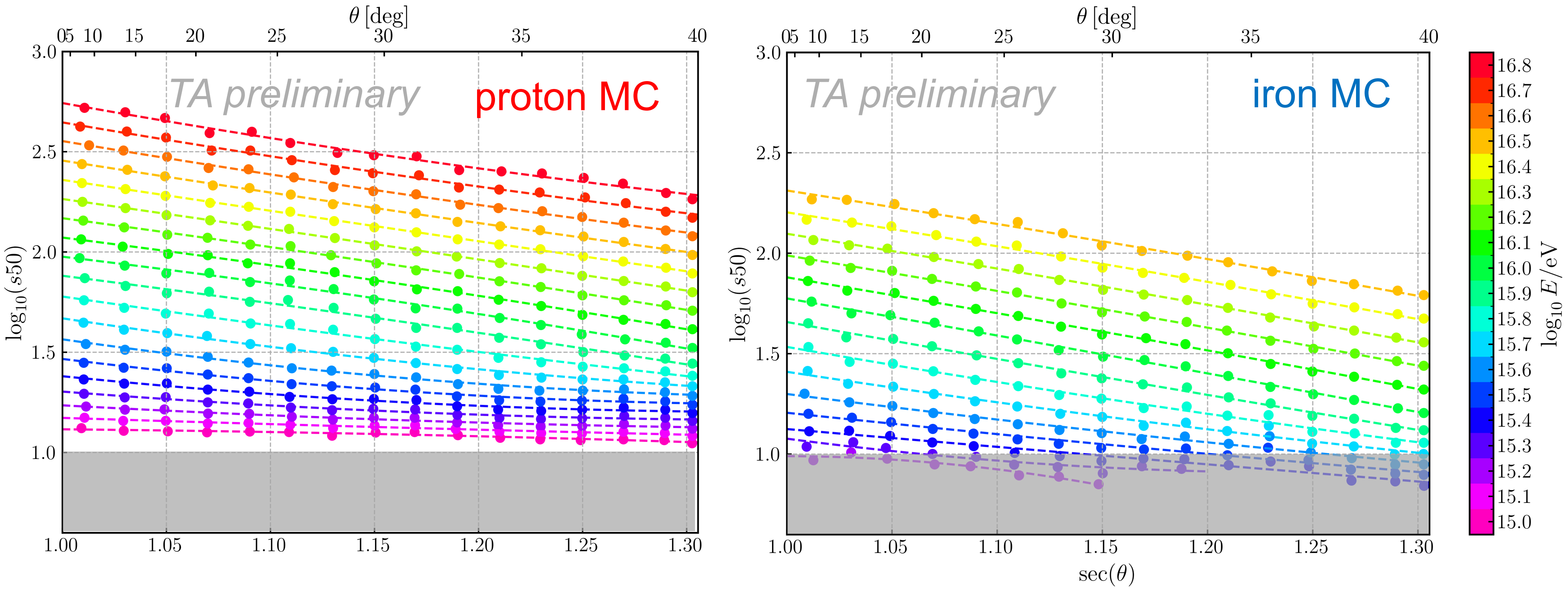
Spectrum



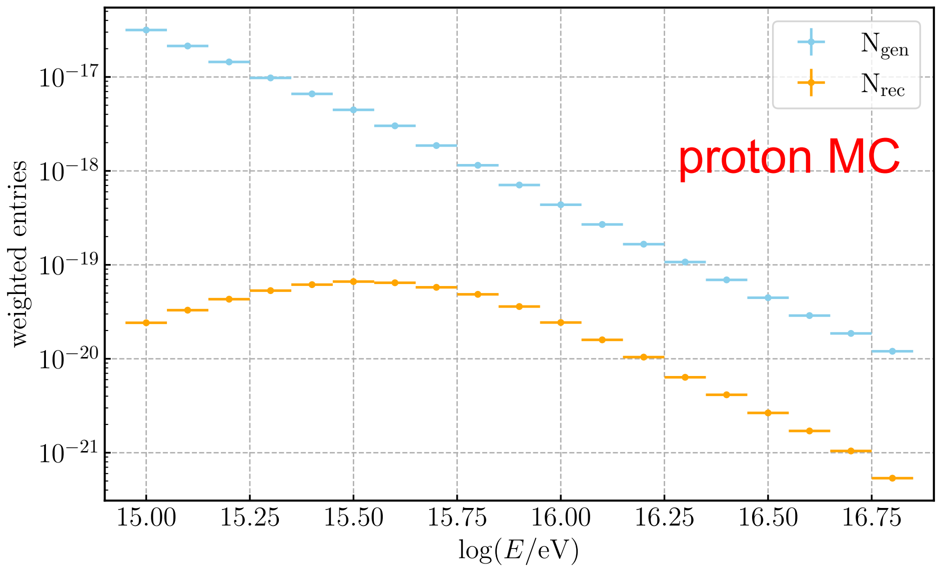
Energy Spectrum
TALE FD $\pm\sigma_{\rm stat} \pm \sigma_{\rm sys}$
proton
iron
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$J \times E^3 [\mathrm{eV}^2 \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{s}^{-1}]$
15.00
15.25
15.50
15.75
16.00
16.25
16.50
16.75
$\log(E/\mathrm{eV})$

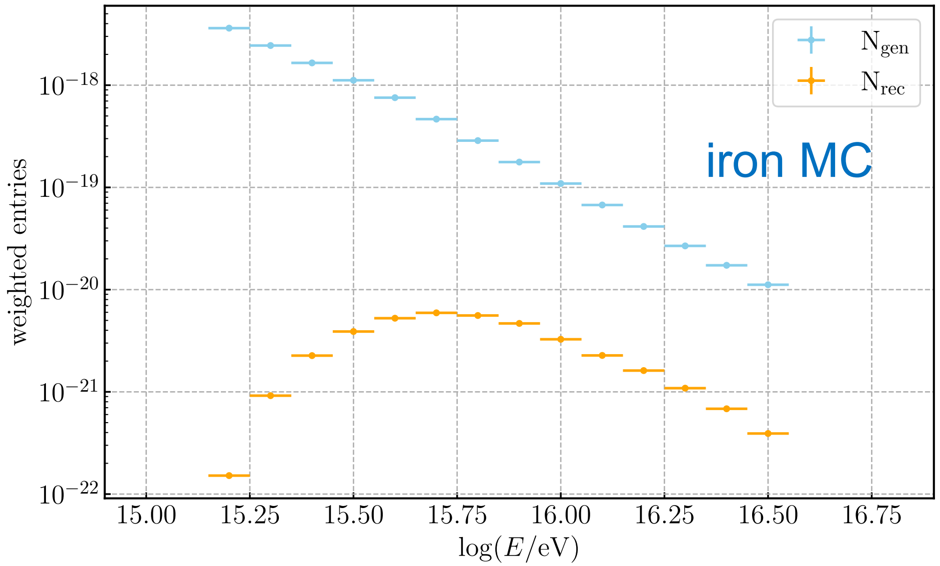
Event selection

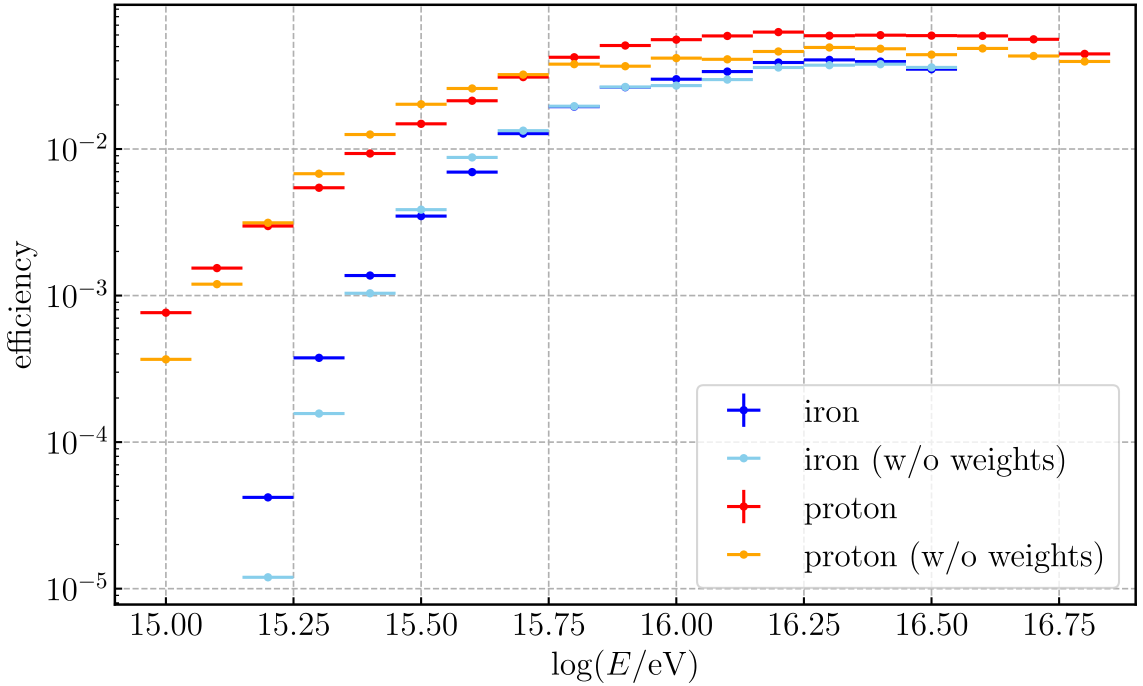
- $1.0 < \log s_{50}$
  → alternative selection of Energy cut



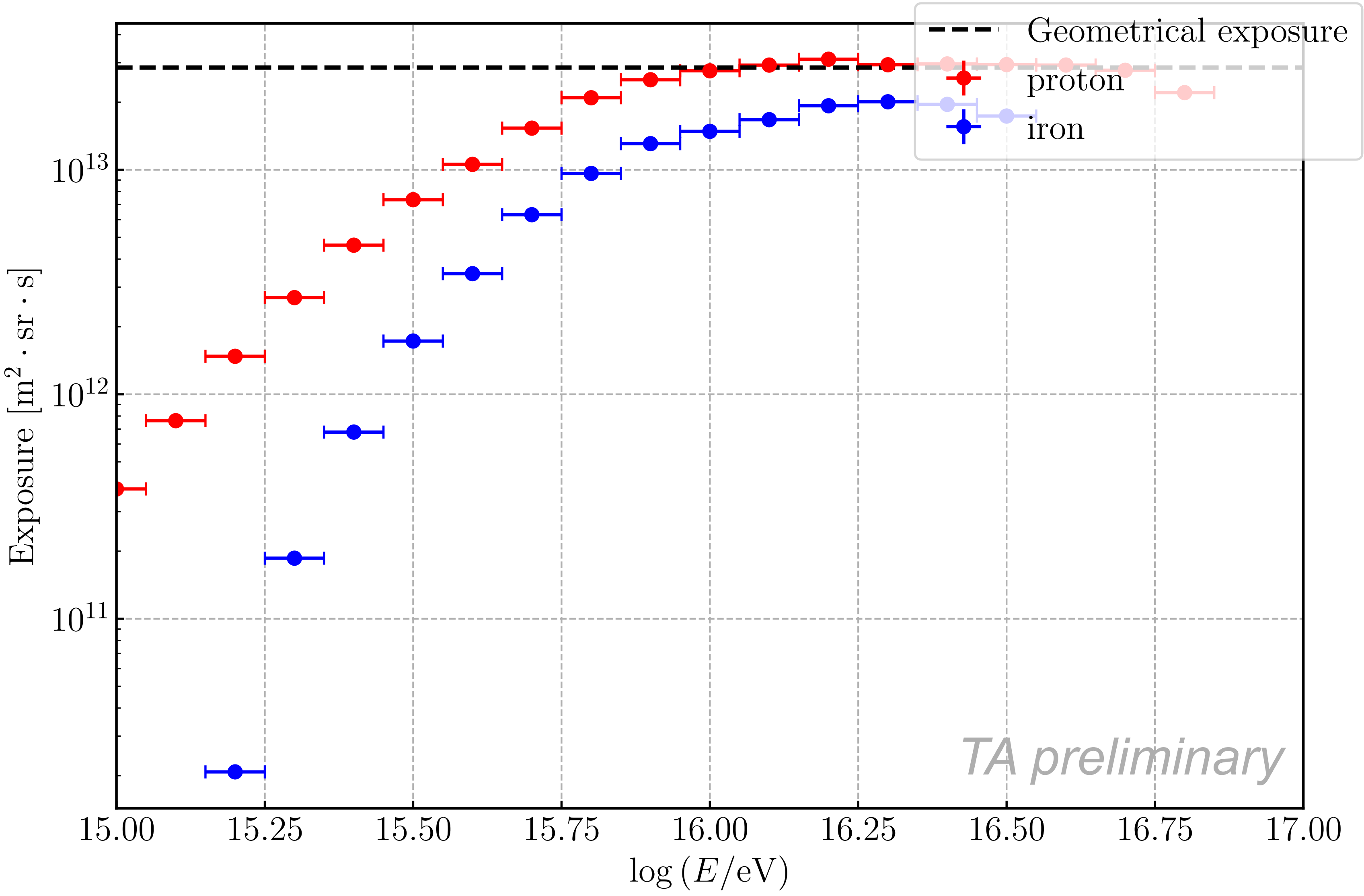
$$eff(E_i) = N_{\mathrm{rec}}(E_i^{\mathrm{rec}}) / N_{\mathrm{gen}}(E_i^{\mathrm{sim}})$$





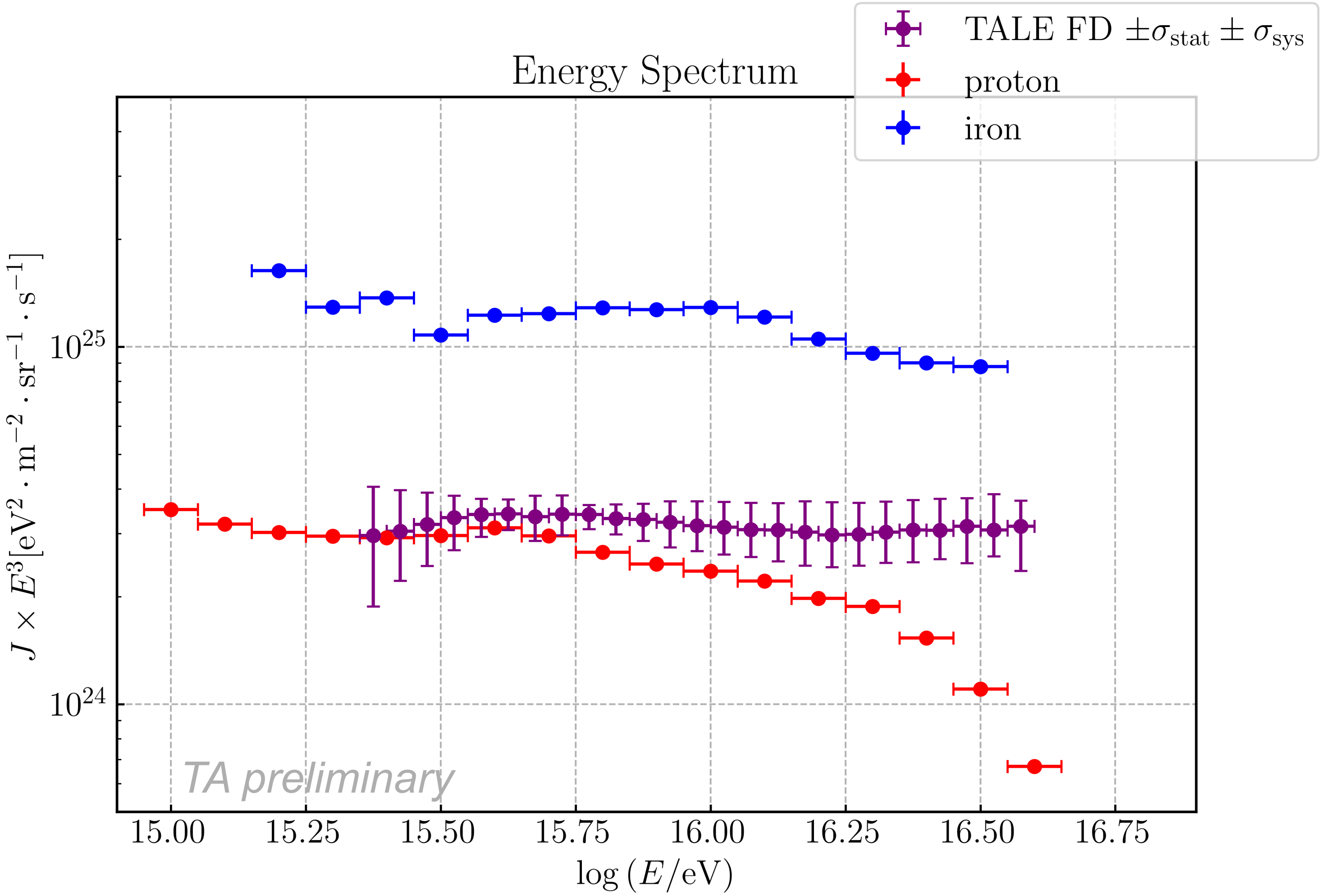


Exposure

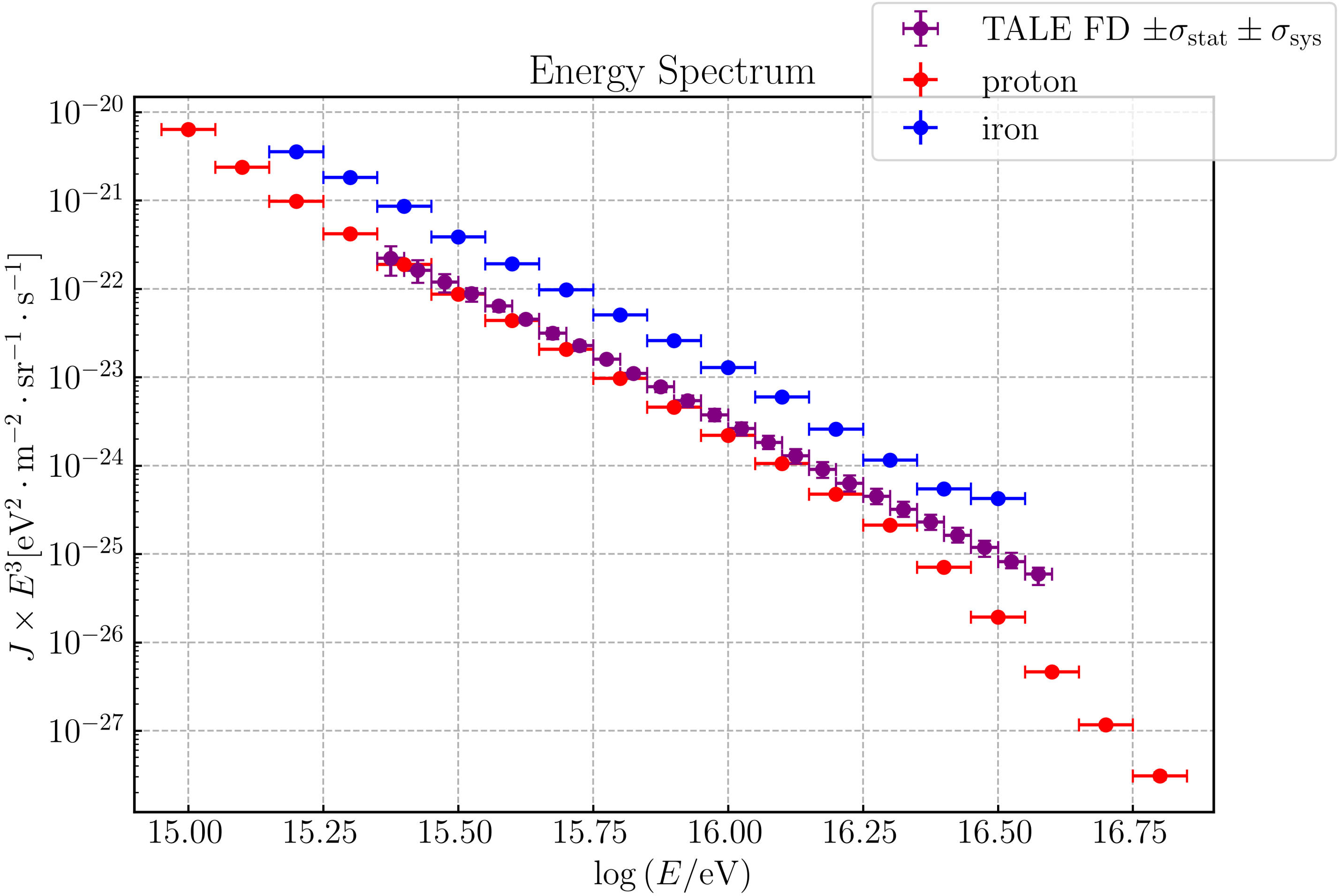

Geometrical exposure
proton
iron
TA preliminary
Exposure [m² · sr · s]
log (E/eV)
10^13
10^12
10^11
15.00
15.25
15.50
15.75
16.00
16.25
16.50
16.75
17.00

Spectrum

- Not yet energy scaling to FD energy



Spectrum



Energy Spectrum
TALE FD $\pm\sigma_{\rm stat} \pm \sigma_{\rm sys}$
proton
iron
$J \times E^3 [\mathrm{eV}^2 \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{s}^{-1}]$
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
15.00
15.25
15.50
15.75
16.00
16.25
16.50
16.75
$\log(E/\mathrm{eV})$

Response Matrix

- These matrix shows that events with $15.7 \leq \log(E/\mathrm{eV}) \leq 16.2$ can be unfolded correctly