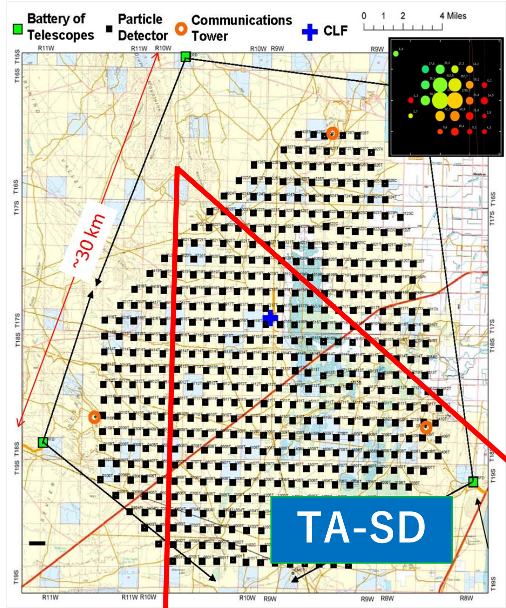
TALE infill SD reconstruction

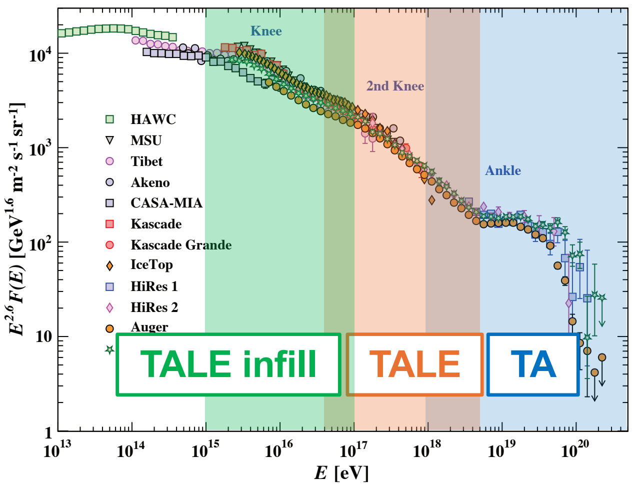
TADAML 2025 @Academia Sinica

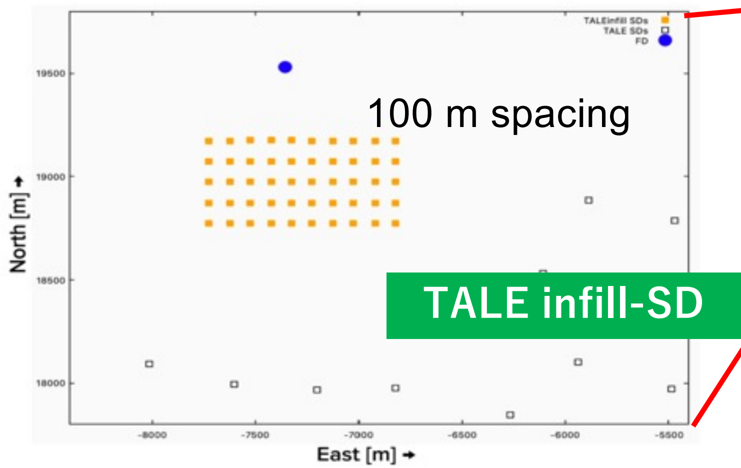
graduate school of science, Osaka Metropolitan Univ.
Haruto Matsushita

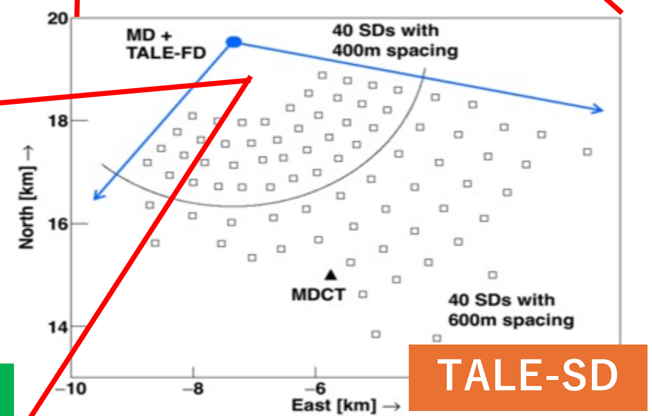
TALE infill

- 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



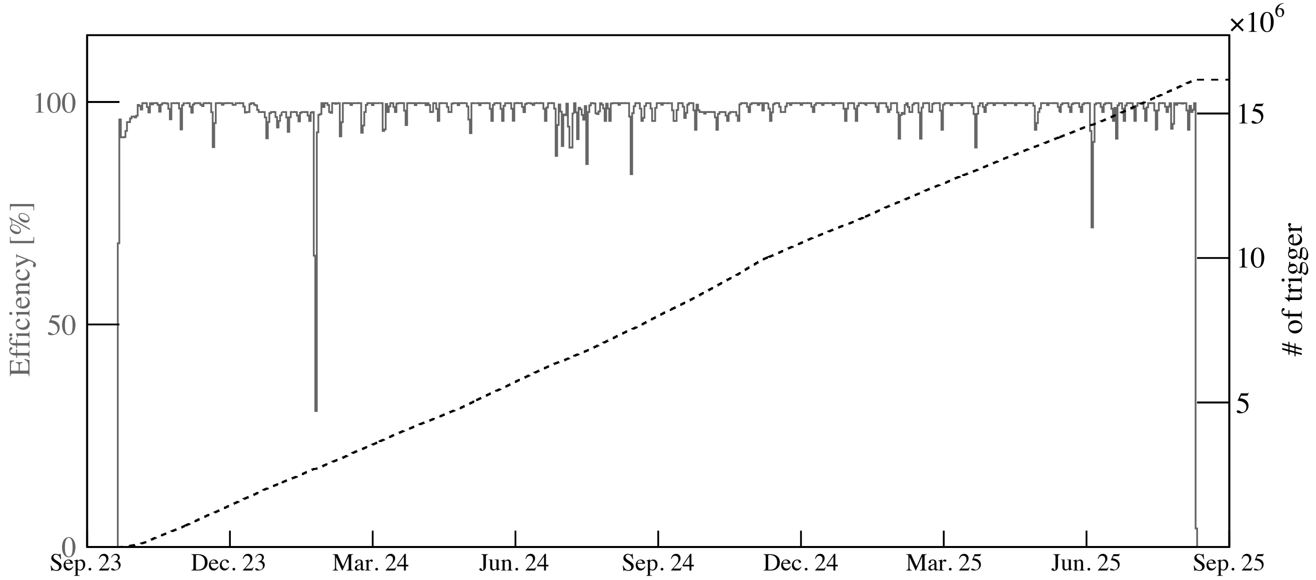


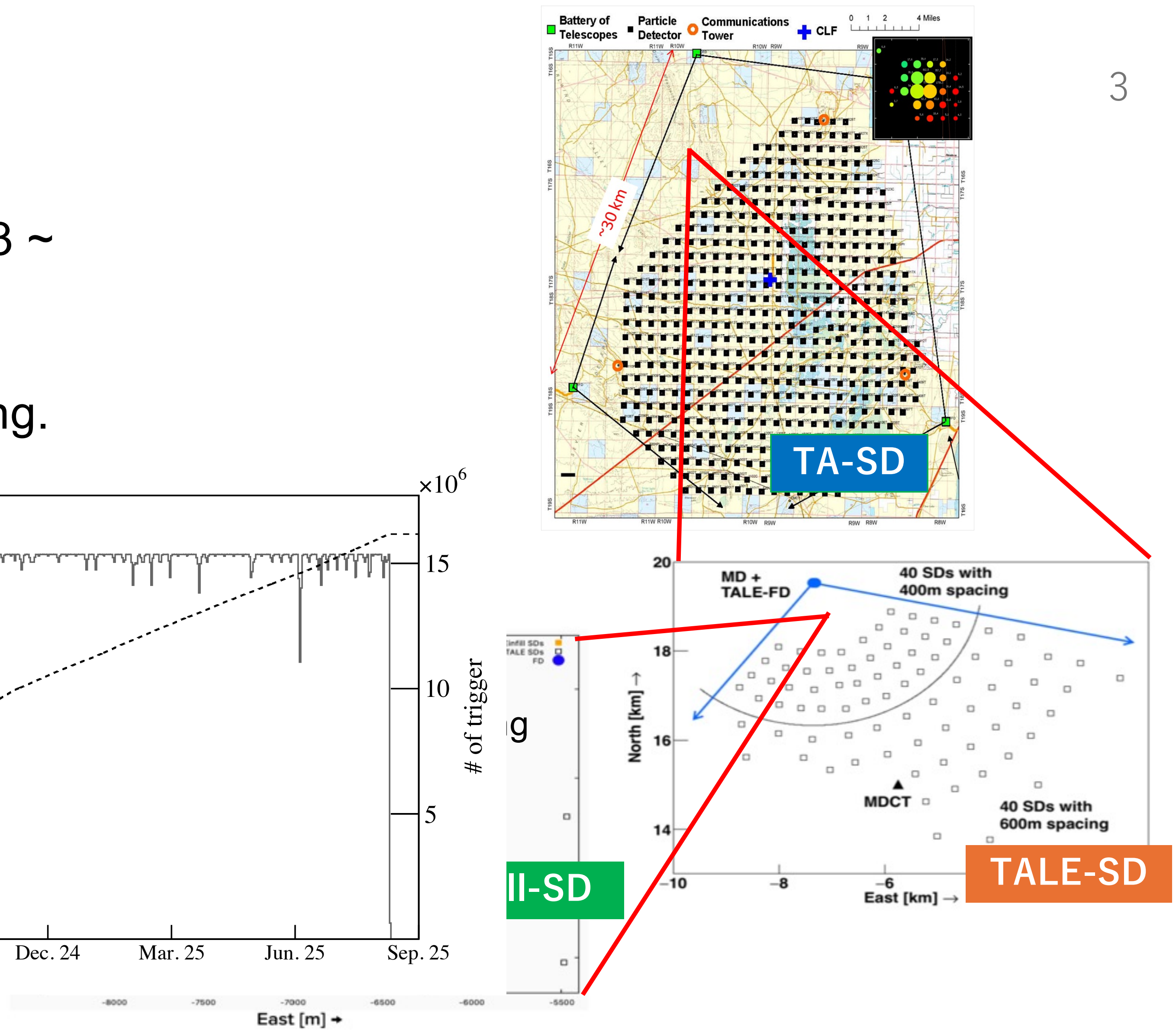




TALE infill

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





Reconstruction process

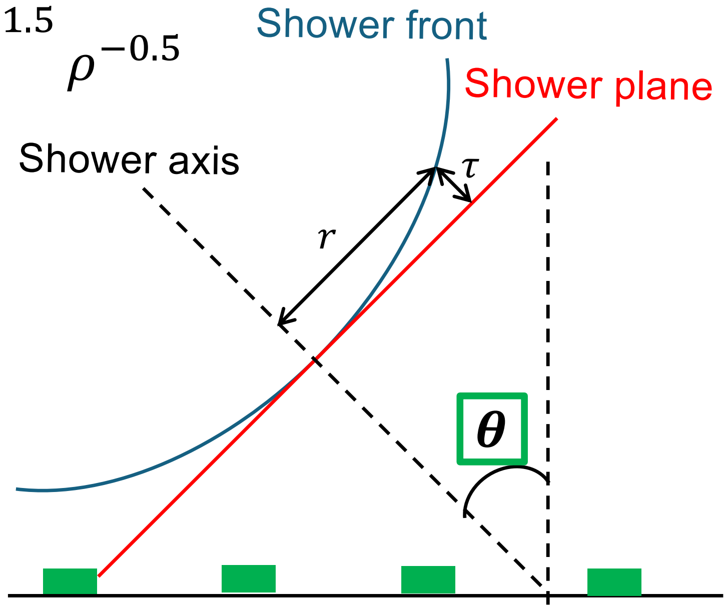
Input
↓
Rough fit
↓
Geometry fit
↓
LDF fit
↓
Output

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

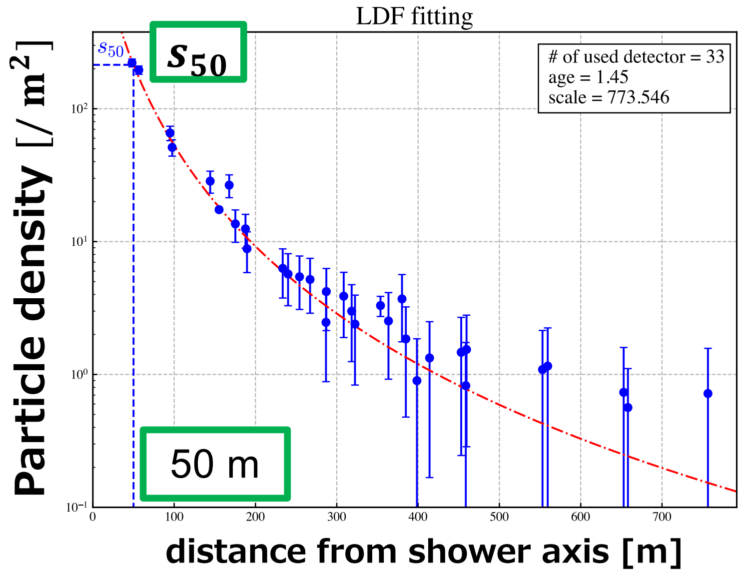
Input
↓
Rough fit
↓
Geometry fit
↓
LDF fit
↓
Output

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

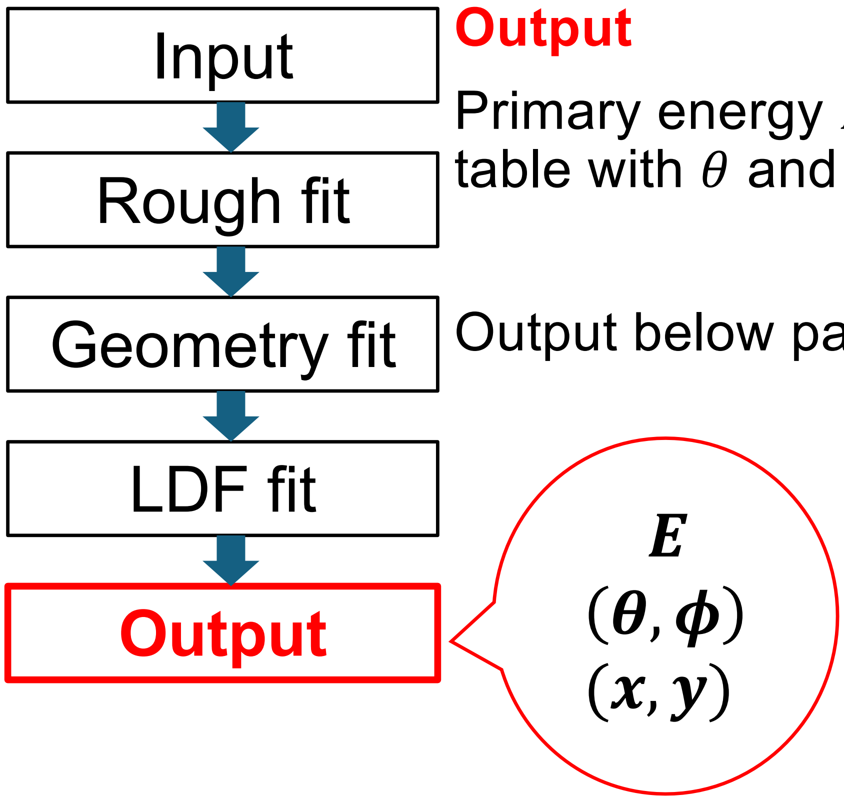
$$\rho^{fit} = N\left(\frac{1}{r_M}\right)^2\left(\frac{r}{r_M}\right)^{s-2}\left(1 + \frac{r}{r_M}\right)^{s-4.5}$$

- 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



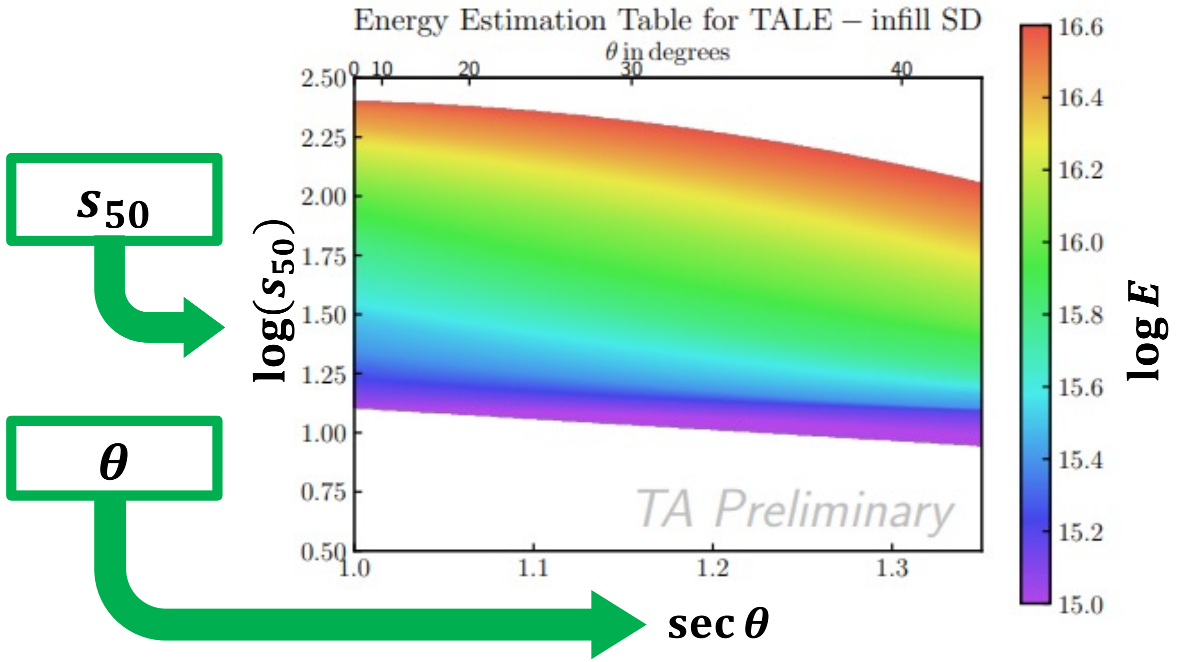
Reconstruction process



Output

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

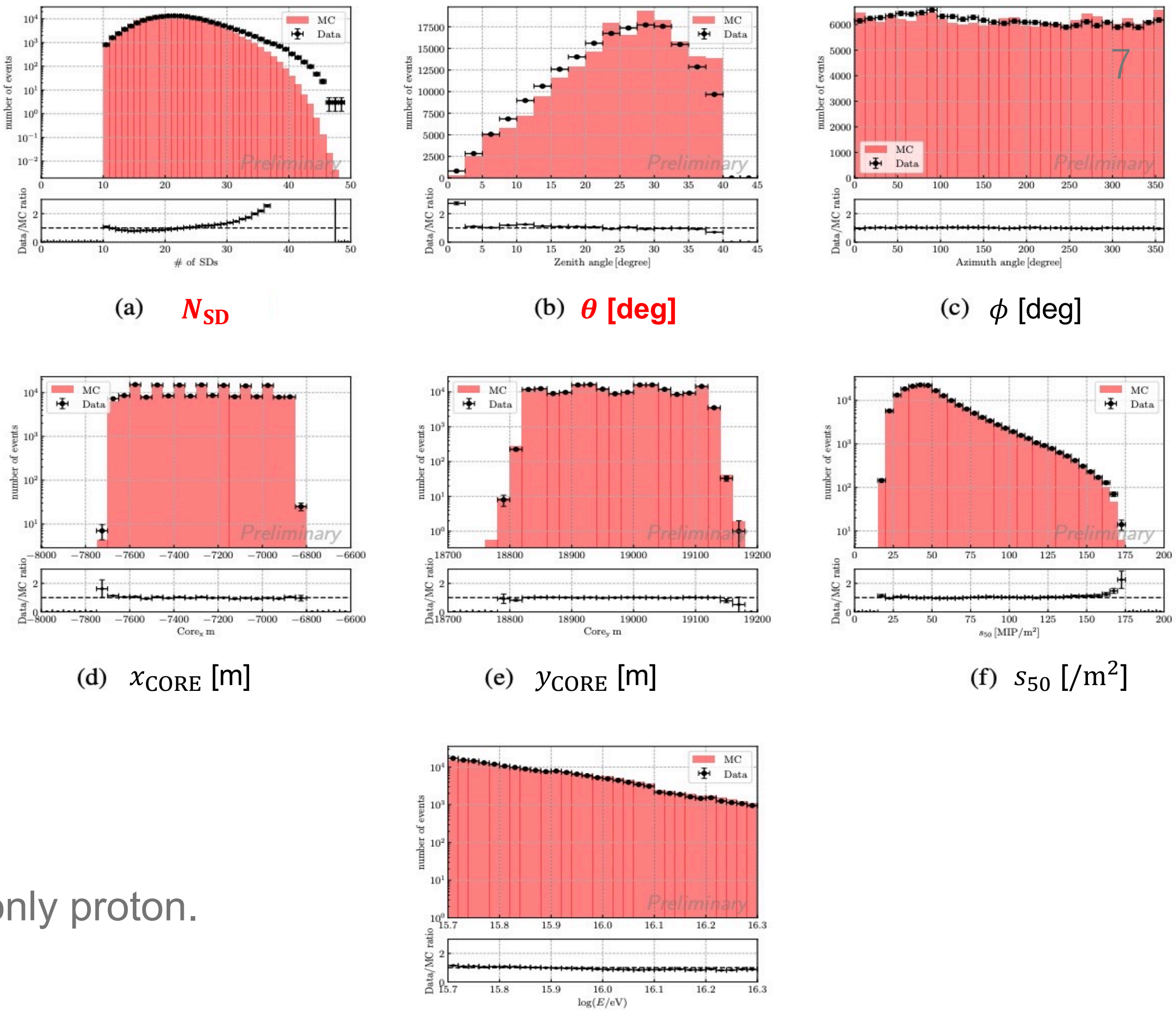
Output below params:



Current analysis

- **Data / MC comparison (period : 2023/11/1 ~ 2024/6/28)**
  - good agreements except for N_{SD} and Zenith angle θ

- **Possible reasons**
  - N_{SD}
    Lateral particle density distribution at positions far from the shower axis in the CORSIKA shower does not match reality.
  - Zenth angle θ
    Primary particle of MC simulation is only proton.
    Number of showers is not enough.



(a) N_{SD} (b) θ [deg] (c) ϕ [deg]
(d) x_{CORE} [m] (e) y_{CORE} [m] (f) s_{50} [/m^2]
(g) log(E/eV)

Credit : Kawachi, Masters Thesis (2025)

Current analysis

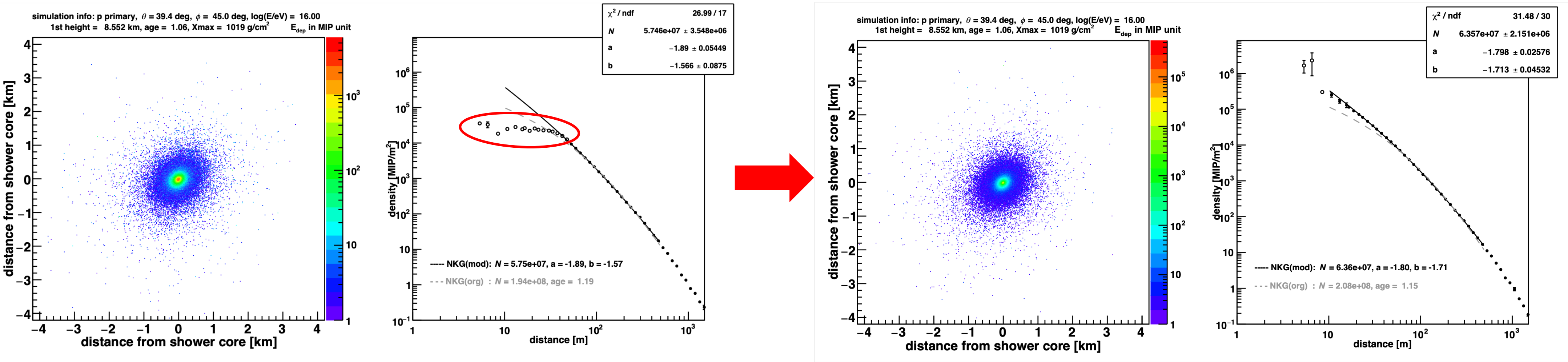
- **Energy resolution**
  - TALE　　　: 25% ($10^{17.0}$ eV)
  - TALE infill : **40%** ($10^{15.6} \sim 10^{16.7}$ eV)

- **Energy bias**
  - TALE　　　: a few % ($10^{17.0}$ eV)
  - TALE infill : a few % ($10^{15.6} \sim 10^{16.7}$ eV)

- **Angular resolution**
  - TALE　　　: 2.5° ($10^{17.0}$ eV)
  - TALE infill : 1.6° ($10^{15.6} \sim 10^{16.7}$ eV)

Problem of generating MC events

- Number of particles in a shower with a distance from the shower axis < 100m are saturated (now modified by K.Fujita).
  → make MC events using modified MC programs (undergoing…)



While waiting for new MC events…

- make rainbow plot, compare Data/MC, calculate energy spectrum as a practice using already prepared dataset.
  → After finished generating MC events, replace the data.

- At first, I try to make the rainbow plot

SD MC data reconstruction

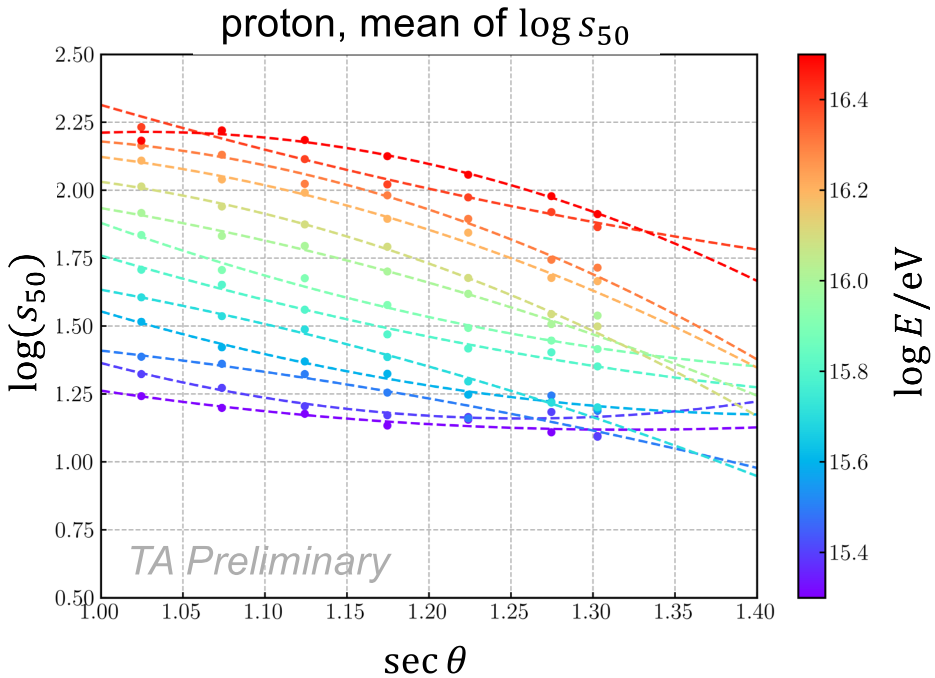
- period：2023/11 ~ 2024/6 (Only dates on which hybrid observation was conducted)

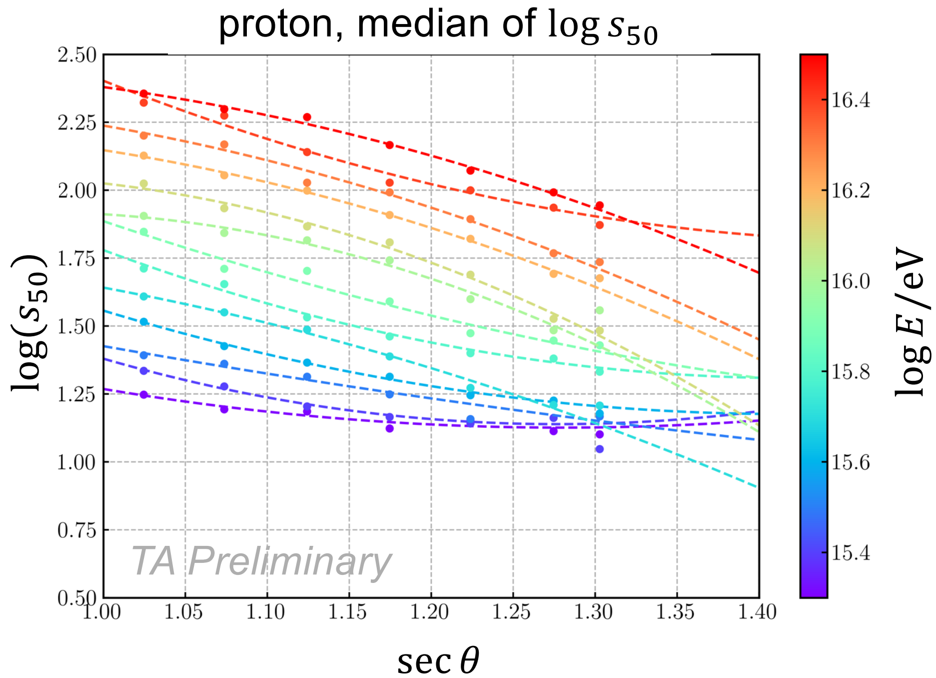
- 2 types of primary particles (proton, iron)
  proton：reconstruction done
  iron：reconstruction done

Quality cut

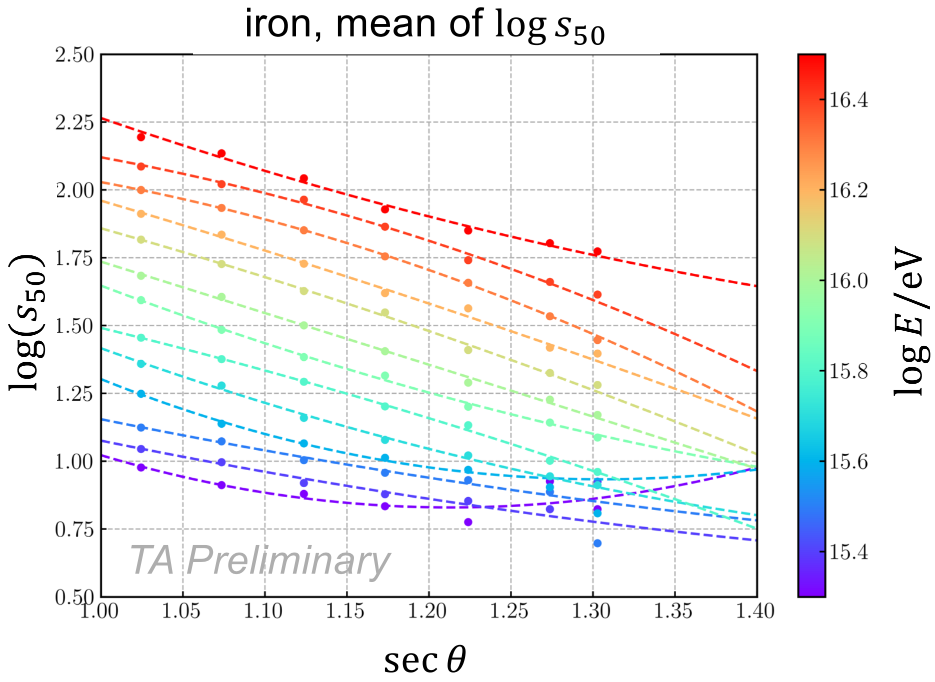
- Boundary cut
  - $\mathrm{Core_{rec}}$ is in array
- Hottest SD cut
  - $\mathrm{SD_{MIPmax}}$ is not located on the edge of the array
- $N_{SD} \geq 10$
- $0 \leq \theta \leq 40°$
- $\left|\mathrm{Core_{LDF}} - \mathrm{Core_{Rough}}\right| \leq 200\ \mathrm{m}$
- $0.2 \leq \mathrm{age} \leq 1.9$
- $|\mathrm{SD_{closest}} - \mathrm{axis}| \leq 70\ \mathrm{m}$
  - The distance between the shower axis and the closest SD used in LDF fit ≤ 70 m

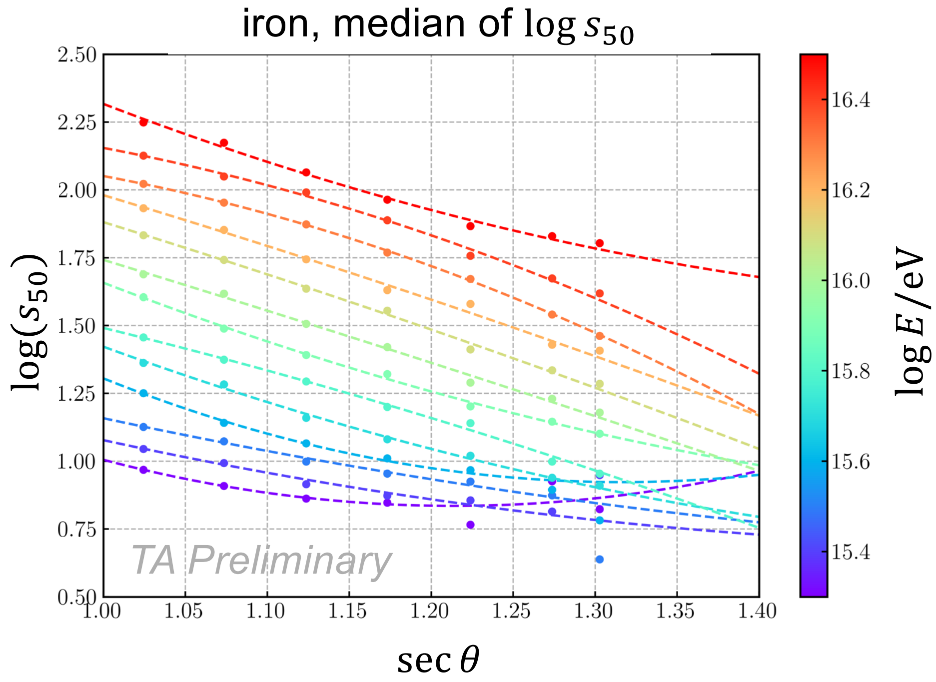
Progress of rainbow plot (proton)



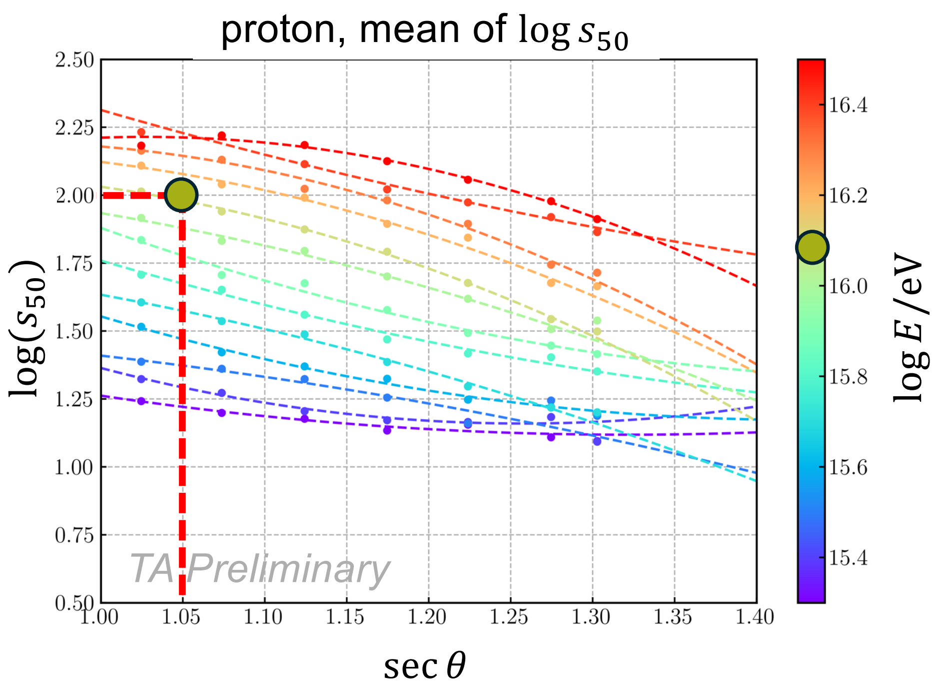


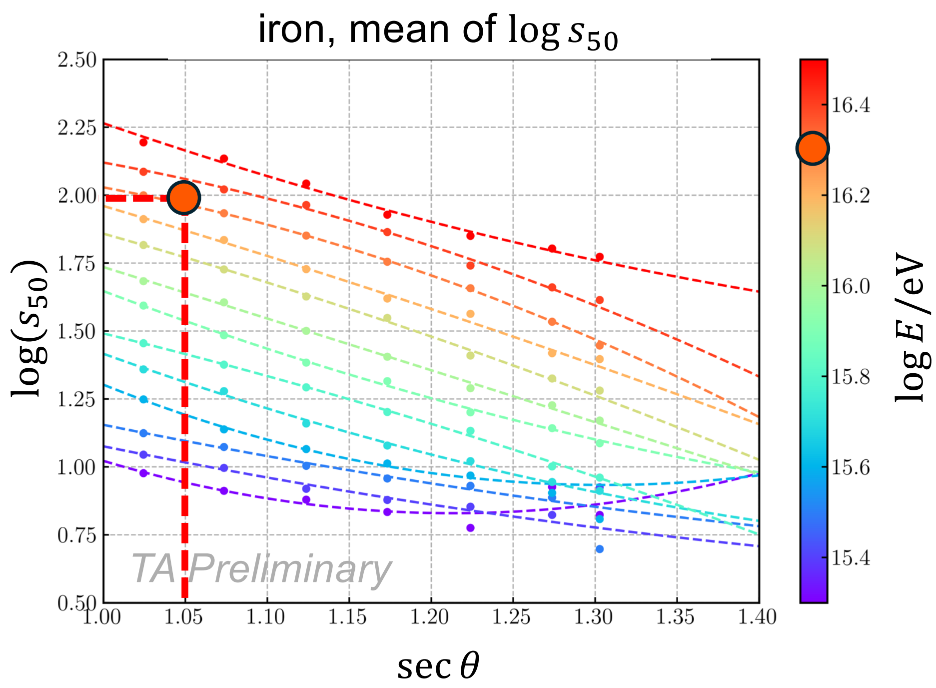
Progress of rainbow plot (iron)





Comparison (mean)





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

ex) the event with $(\sec\theta, \log s_{50}) = (1.05,\ 2.00)$

rainbow plot from proton MC : $\boldsymbol{E_{\mathrm{rec}}} \approx \mathbf{10^{16.1}\ eV}$

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

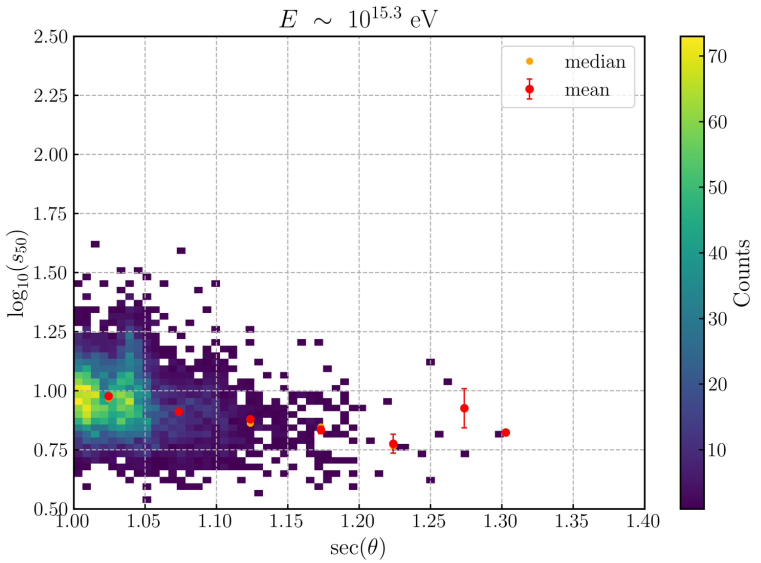
It's approximately 1.6 times larger!!

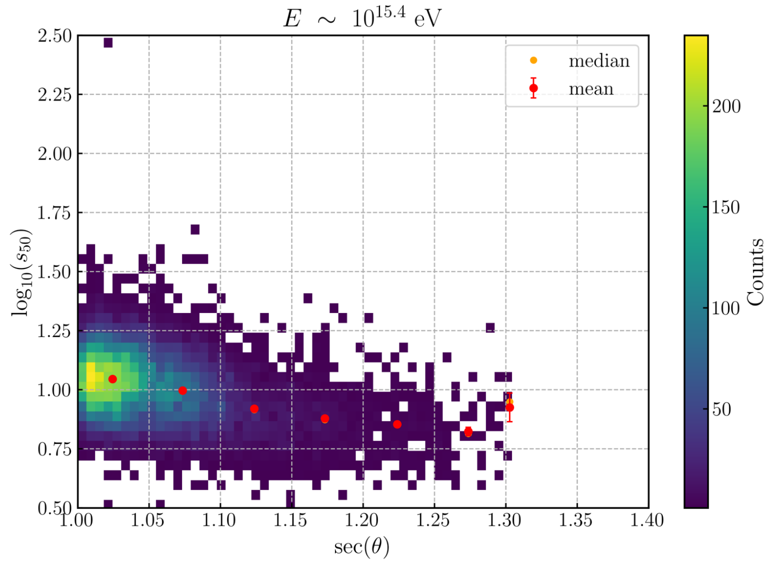
Result & Summary

- The current rainbow plot has too many overlapping energy bins, making it unusable.
  → It is necessary to devise a method, such as excluding data points with too few entries in each $sec(\theta)$ bin from the fit.

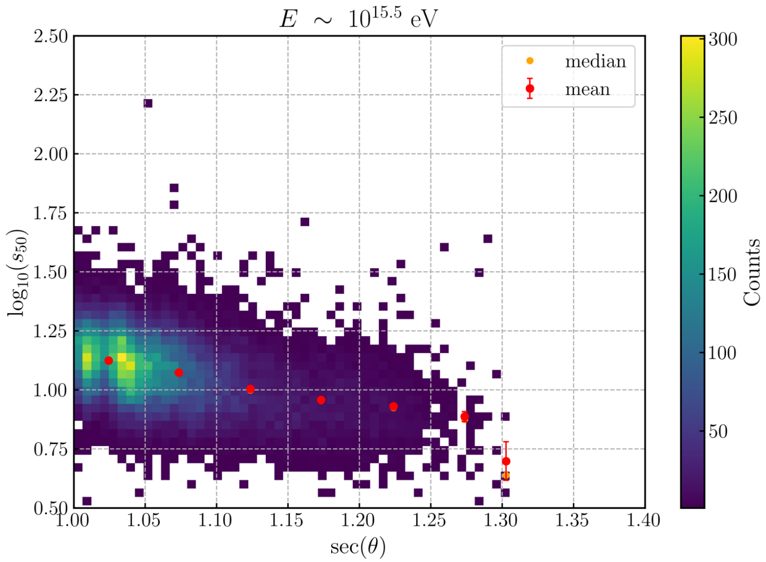
- There is an energy bias depending on the mass composition.
  → When determining primary energy, it is necessary to take the mass of the primary particle into account.
  → By using a machine learning approach that learns from MC events of various primary particles, it may be possible to estimate the energy more accurately (and even infer the mass of the primary particle).

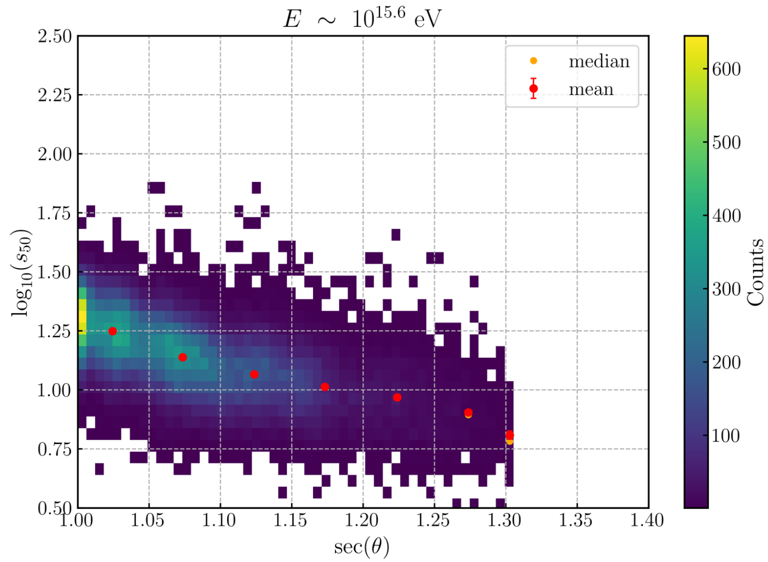
Back up

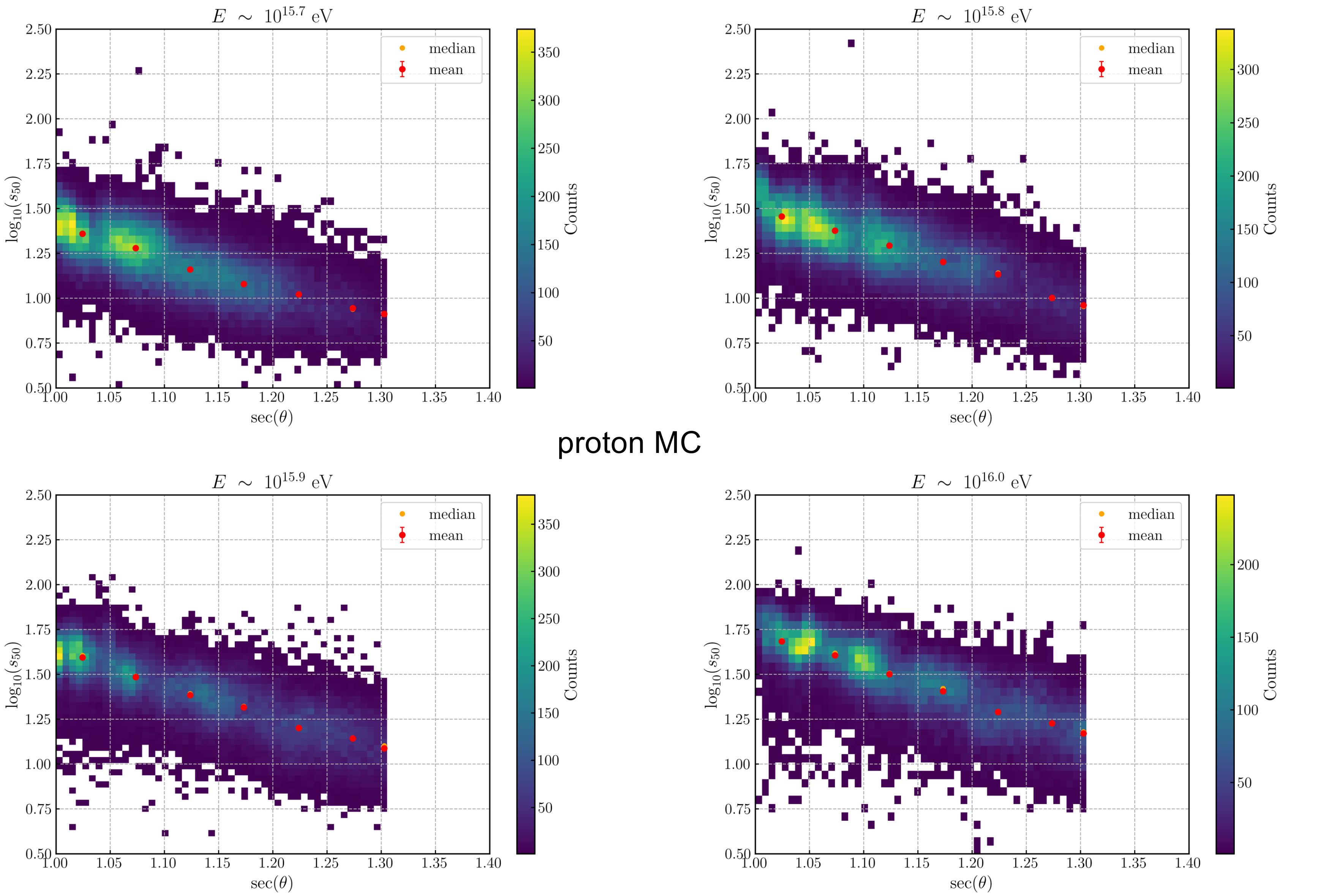

$E \sim 10^{15.3}$ eV
median
mean
Counts
$\log_{10}(s_{50})$
$\sec(\theta)$


$E \sim 10^{15.4}$ eV
median
mean
Counts
$\log_{10}(s_{50})$
$\sec(\theta)$

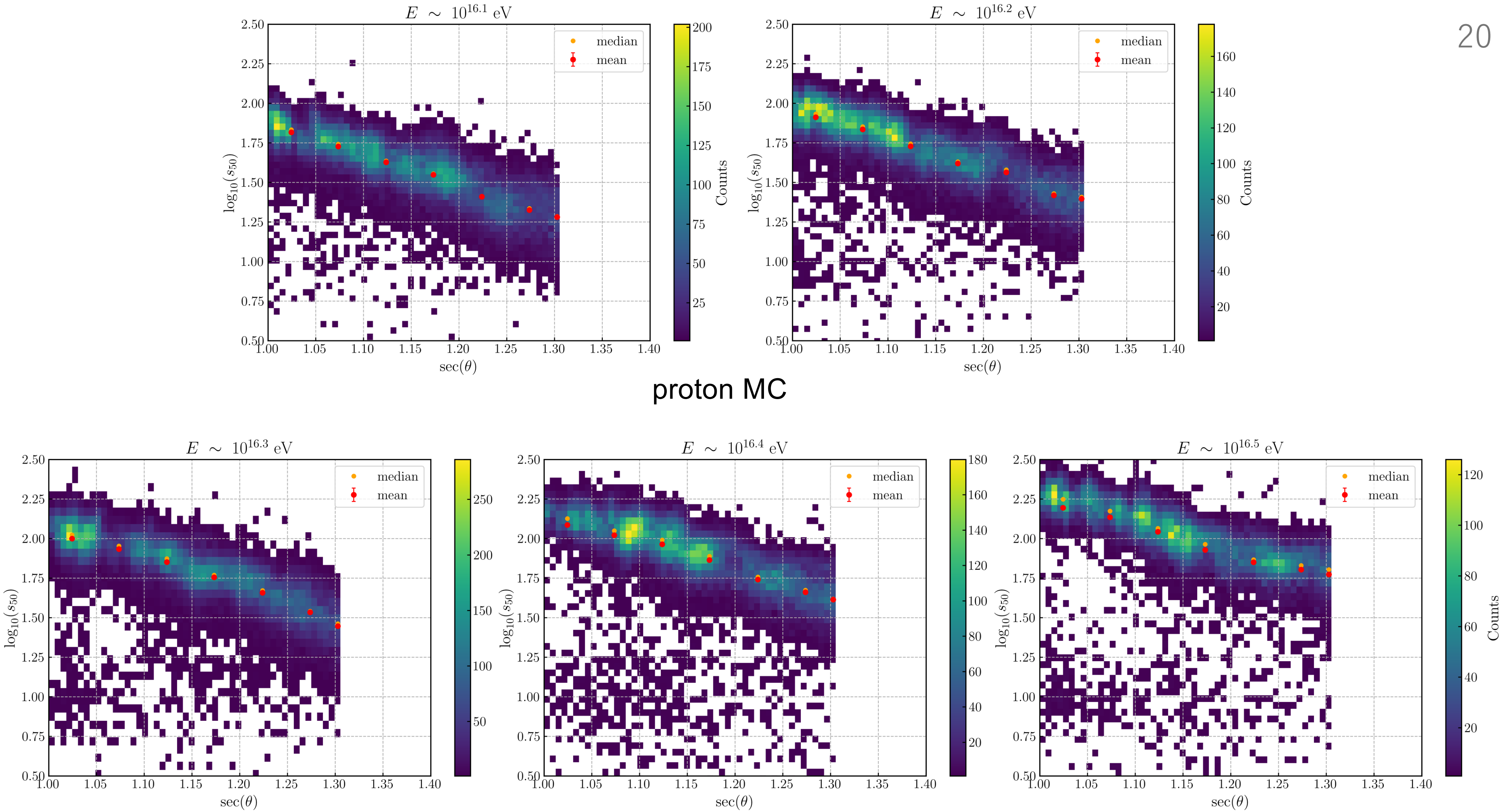
proton MC


$E \sim 10^{15.5}$ eV
median
mean
Counts
$\log_{10}(s_{50})$
$\sec(\theta)$


$E \sim 10^{15.6}$ eV
median
mean
Counts
$\log_{10}(s_{50})$
$\sec(\theta)$

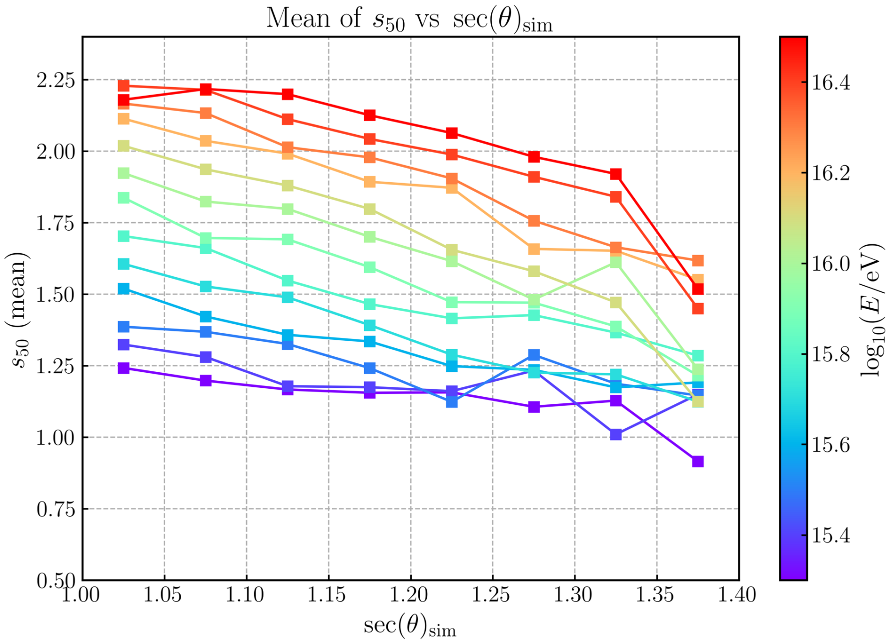

$E \sim 10^{15.7}$ eV
$E \sim 10^{15.8}$ eV
$E \sim 10^{15.9}$ eV
$E \sim 10^{16.0}$ eV
median
mean
$\log_{10}(s_{50})$
$\sec(\theta)$
Counts

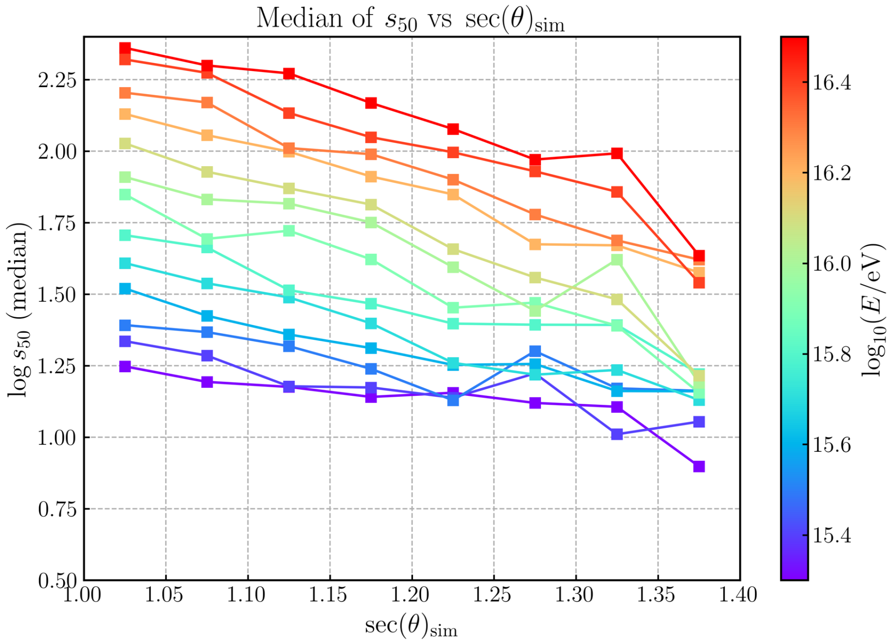
proton MC



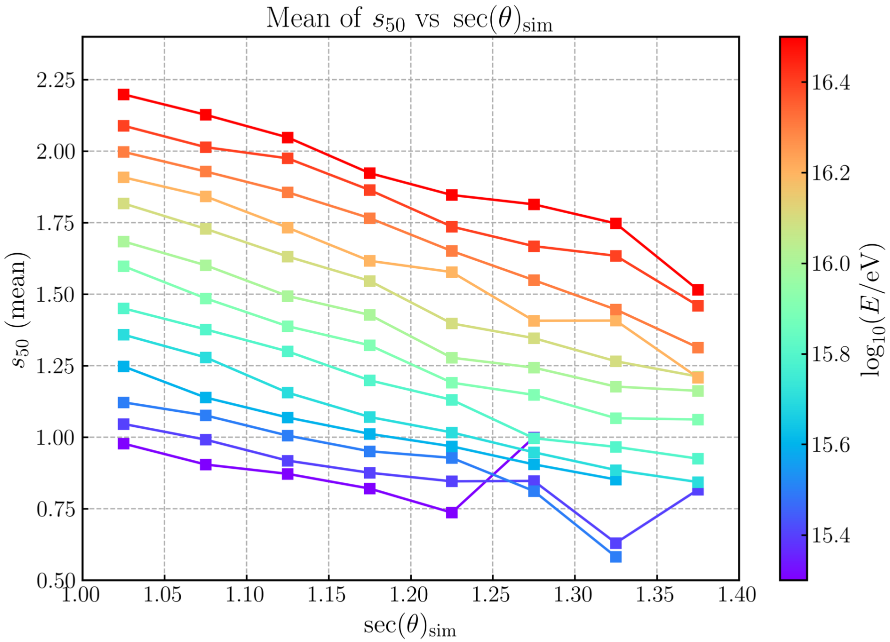
$E \sim 10^{16.1}$ eV
$E \sim 10^{16.2}$ eV
median
mean
$\log_{10}(s_{50})$
$\sec(\theta)$
Counts
proton MC
$E \sim 10^{16.3}$ eV
$E \sim 10^{16.4}$ eV
$E \sim 10^{16.5}$ eV

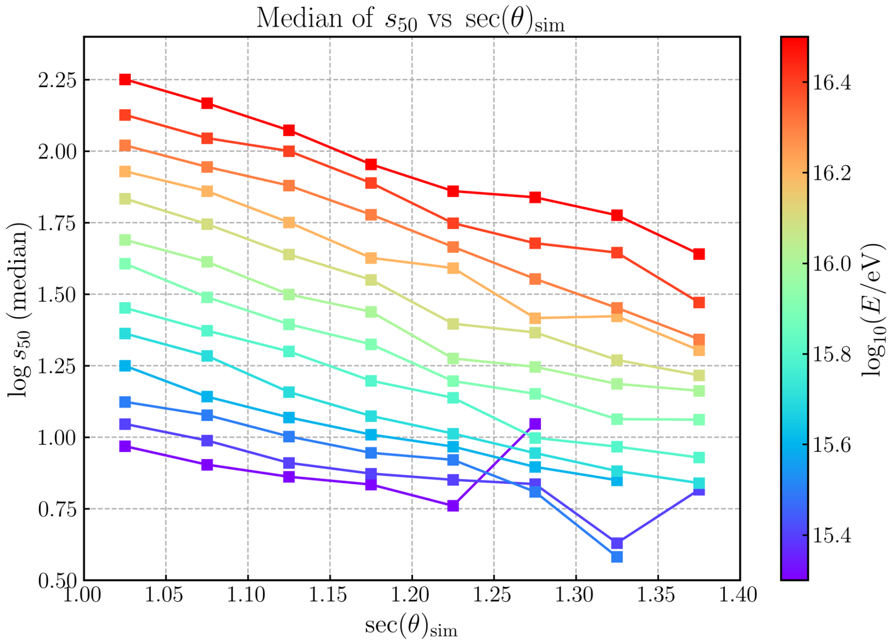
Progress of rainbow plot (proton)





Progress of rainbow plot (iron)





Reconstruction program

Input

Rough fit

Geometry fit

LDF fit

Output

LDF fit :

Determine Core Pos. & Lateral Dist. of the shower

fitted using NKG function

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

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

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