

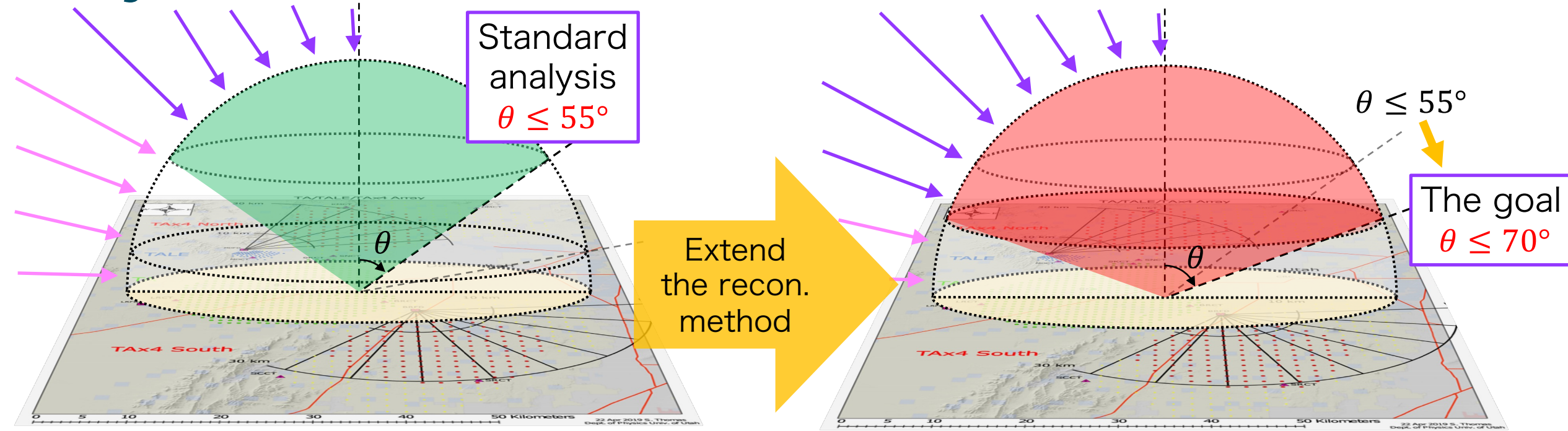
Analysis of Inclined Air Showers Observed by the Surface Detector Arrays of TA

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Why Inclined Events?



If extended from 55deg to 70deg, $\sim 1.3\times$ aperture of surface detector array
= Retroactively increase the number of events for UHECRs observation.

- TA $\times$ 4 SD 6yr observation $\rightarrow$ TA $\times$ 4 SD ~ 8 yr observation equivalent
- TA SD 17.5yr observation $\rightarrow$ TA SD ~ 23 yr observation equivalent

Visible region on the sky expands to lower dec. $\rightarrow$ Com. band with Auger expands.

Muon component is dominant $\rightarrow$ Suitable for study on muon excess

Ongoing Analysis and Future Plan

Telescope Array has been observing UHECRs using SD array since 2008.

Much higher statistics are required especially for UHECRs.

→ TA×4 expansion (expand array area) and

Inclined air showers analysis (retroactively enlarge aperture)

Inclined Air Showers Analysis for TA×4 SD → Achieved ~1.5× increase in stat.
Similar Analysis for TA SD is now ongoing. → Increasing furthermore

Now we can estimate UHECR mass **using a DNN, from SD data** (~10× stat. of FD)

If join inclined analysis and DNN analysis,

(Of course, this includes optimization of DNN method for inclined events.)

→ Obtain energy, arrival direction and mass together **in the highest statistics ever**

→ We can select highest and lighter events.

⇒ Charged particles “astronomy” in the future

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This talk!

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Previous Work

Inclined Air Showers Analysis for TAx4 SD has been performed.

We extended from 55deg to 65deg for TAx4 SD

- Extended the energy estimation table
- Data/MC comp. $\Rightarrow$ No significant discrepancies even in large zenith region
- Measured energy spectrum including inclined events
 $\Rightarrow$ increased $\sim 1.5\times$ in statistics

Similar Analysis for TA SD is now ongoing.

We have been extending from 55deg to 65deg for TA SD

- Updated the energy estimation table (w/ QGSJETII-04)
- Data/MC comparison

Event reconstructions with SDs

Geometry fitting

5 fitting parameters: $T_0, R_x, R_y, \theta, \phi$

To minimize

$$\chi_G^2 = \sum_{i=0}^N \frac{(t_i - t_i^{\text{FIT}})^2}{\sigma_{t_i}^2} + \frac{(\mathbf{R} - \mathbf{R}_{\text{COG}})^2}{\sigma_{\mathbf{R}_{\text{COG}}}^2}$$

where,

$$t^{\text{FIT}} = T_0 + \frac{l}{c} + \tau$$

$$\sigma_t = \sqrt{\sigma_e^2 + \sigma_\tau^2}$$

$$\tau = (8 \times 10^{-4} \mu\text{S}) a(\theta) \left(1.0 + \frac{s}{30\text{m}}\right)^{1.5} \rho^{-0.5}$$

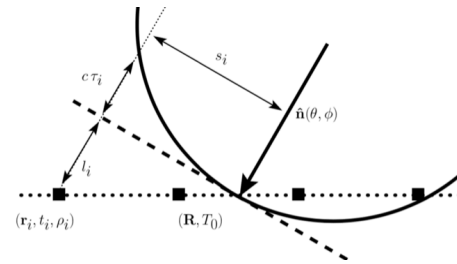
$$\sigma_\tau = (7 \times 10^{-4} \mu\text{S}) a(\theta) \left(1.0 + \frac{s}{30\text{m}}\right)^{1.5} \rho^{-0.3}$$

$$a(\theta) = \begin{cases} 3.3836 - 0.01848\theta & \theta < 25^\circ \\ c_3\theta^3 + c_2\theta^2 + c_1\theta + c_0 & 25^\circ \leq \theta < 35^\circ \\ \exp(-3.2 \times 10^{-2}\theta + 2.0) & \theta > 35^\circ \end{cases}$$

$$c_0 = -7.76168 \times 10^{-2}, c_1 = 2.99113 \times 10^{-1},$$

$$c_2 = -8.79358 \times 10^{-3}, c_3 = 6.51127 \times 10^{-5}$$

① Use detectors location and timing to determine shower core and direction



② Fit counter signal size to find lateral distribution

LDF fitting

3 fitting parameters: R_x, R_y, A

To minimize

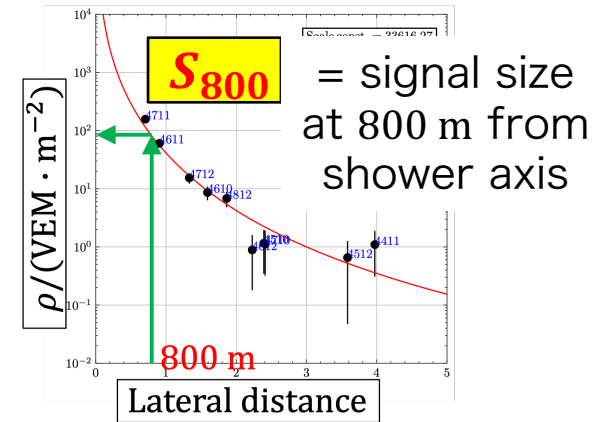
$$\chi_{\text{LDF}}^2 = \sum_{i=0}^N \frac{(\rho_i - \rho_i^{\text{FIT}})^2}{\sigma_{\rho_i}^2} + \frac{(\mathbf{R} - \mathbf{R}_{\text{COG}})^2}{\sigma_{\mathbf{R}_{\text{COG}}}^2}$$

where,

$$\rho = A \left(\frac{s}{91.6\text{m}}\right)^{-1.2} \left(1 + \frac{s}{91.6\text{m}}\right)^{-(\eta(\theta)-1.2)} \left(1 + \left[\frac{s}{1000\text{m}}\right]^2\right)^{-0.6}$$

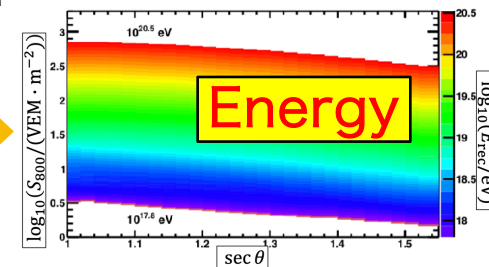
$$\eta(\theta) = 3.97 - 1.79 [\sec(\theta) - 1]$$

$$\sigma_\rho = \sqrt{0.56\rho + 6.3 \times 10^{-3}\rho^2}$$



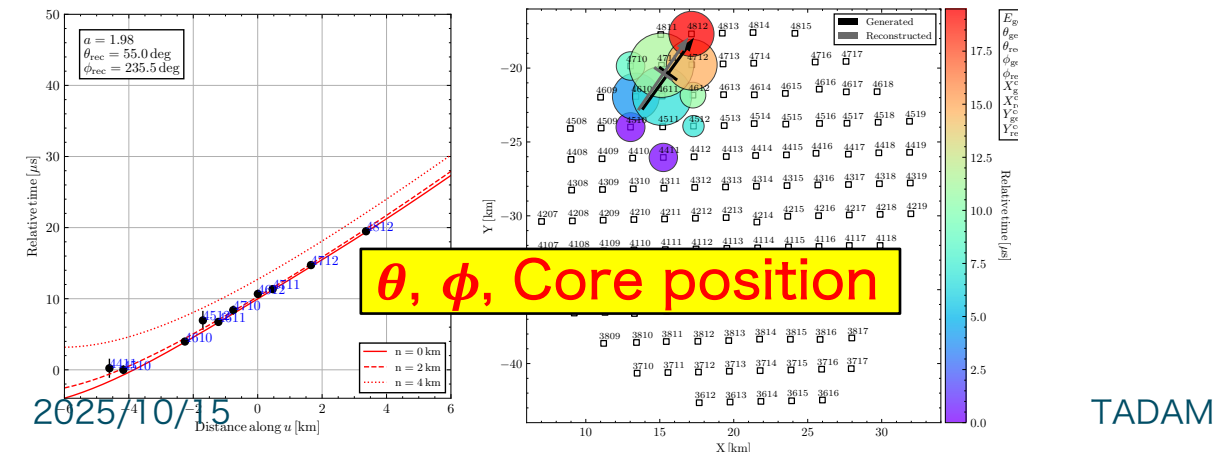
Energy determination

$$S_{800} \equiv \rho(800\text{m})$$



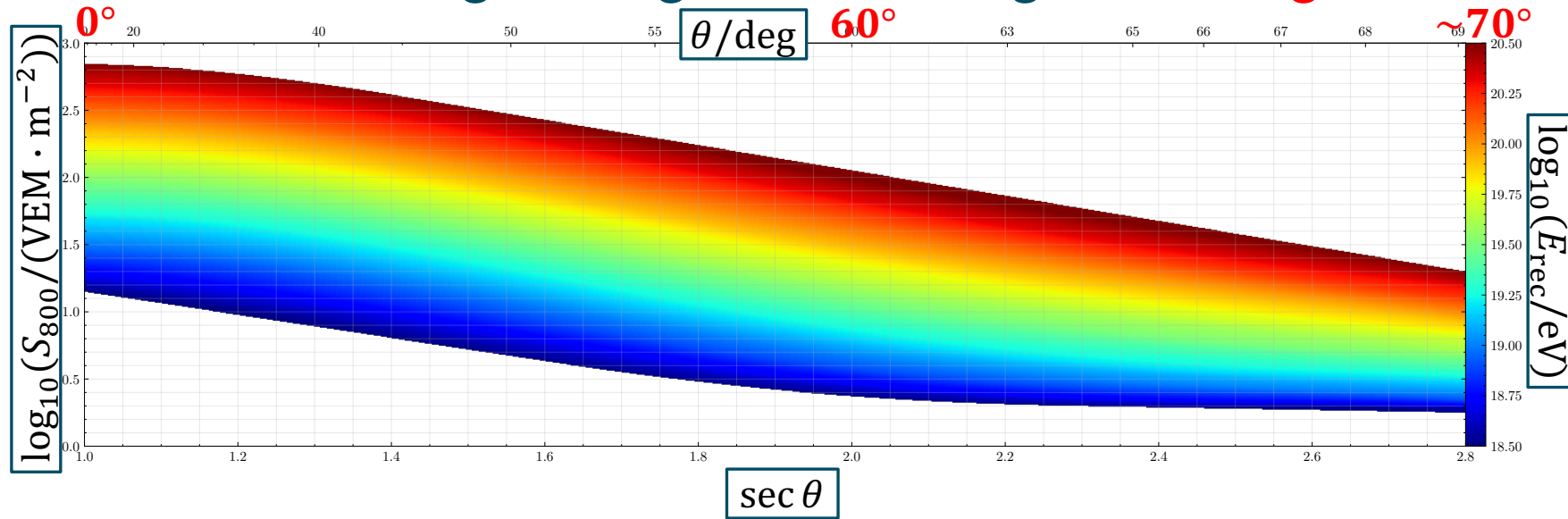
$$E = E_{\text{CORSIKA,SD}}/1.27$$

③ Use S_{800} and zenith angle to look up energy (from energy estimation table generated from MC)



Creation of Energy Estimation Table

A new energy estimation table for the TA SD has been created (w/ QGSJETII-04, p), enabling energy reconstruction in the zenith angle range from 0deg to 70deg.

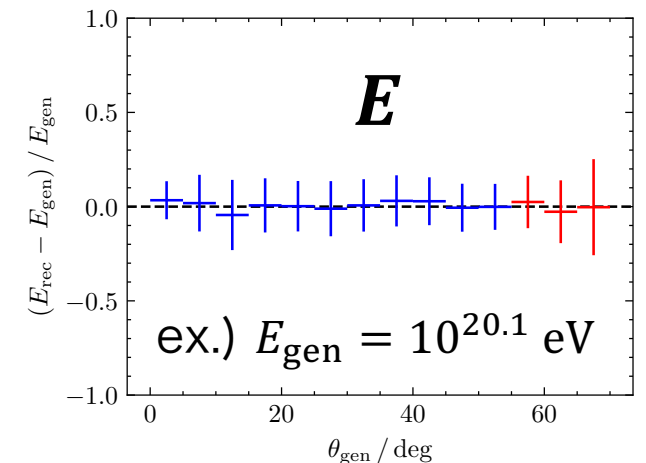


Selection criteria

- $N_{\text{SD}} \geq 5$
- $\theta_{\text{rec}} < 70^\circ$
- $D_{\text{border}} \geq 1.2 \text{ km}$
- $\chi^2_{\text{geo}}/\text{ndf} \leq 4$
- $\chi^2_{\text{ldf}}/\text{ndf} \leq 4$
- $\sigma_{\text{pointing direc.}} < 5^\circ$
- $\sigma(S_{800})/S_{800} < 0.25$

Reconstruction accuracies of each parameter have been evaluated for each zenith angle.

⇒ Accuracies preserved for large zenith angle events



Data/MC comparison

$$E_{\text{rec}} \geq 10^{19.0} \text{ eV}$$

Area normalize

Period

- May 2008 to May 24

Selection criteria

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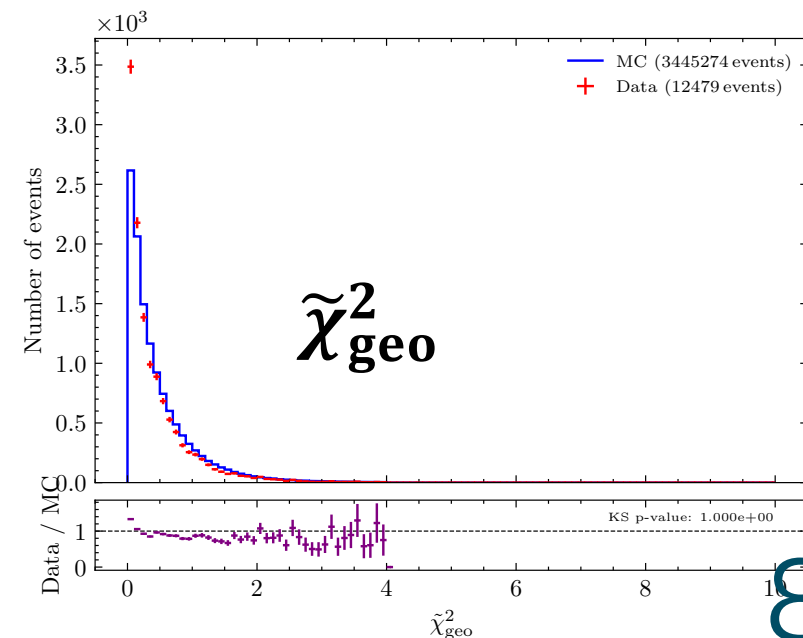
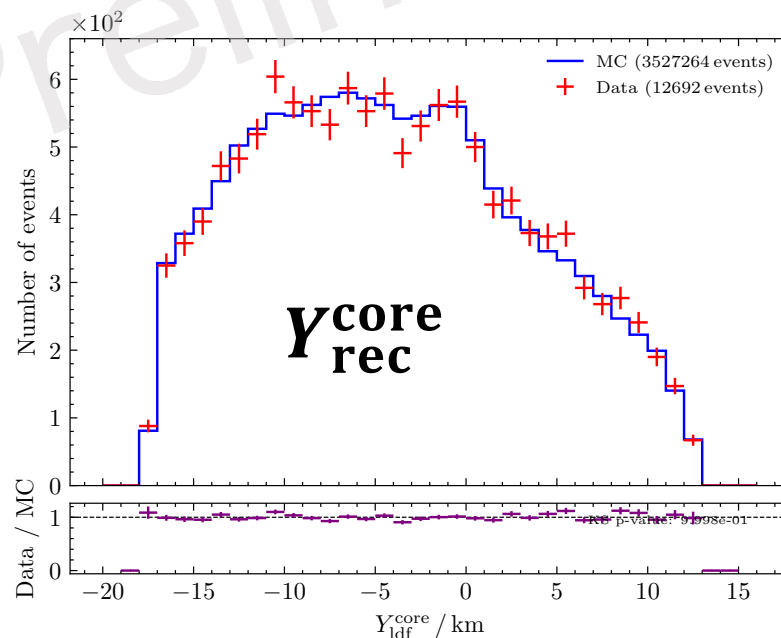
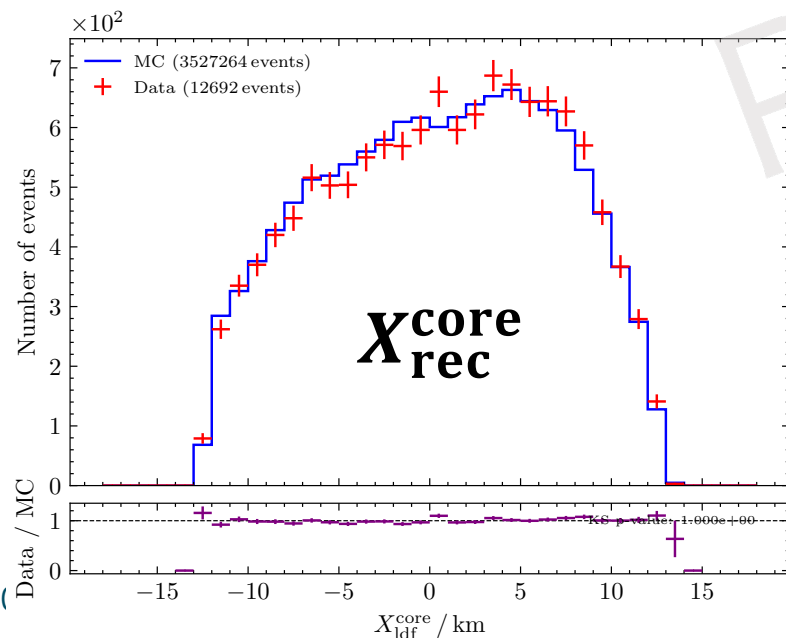
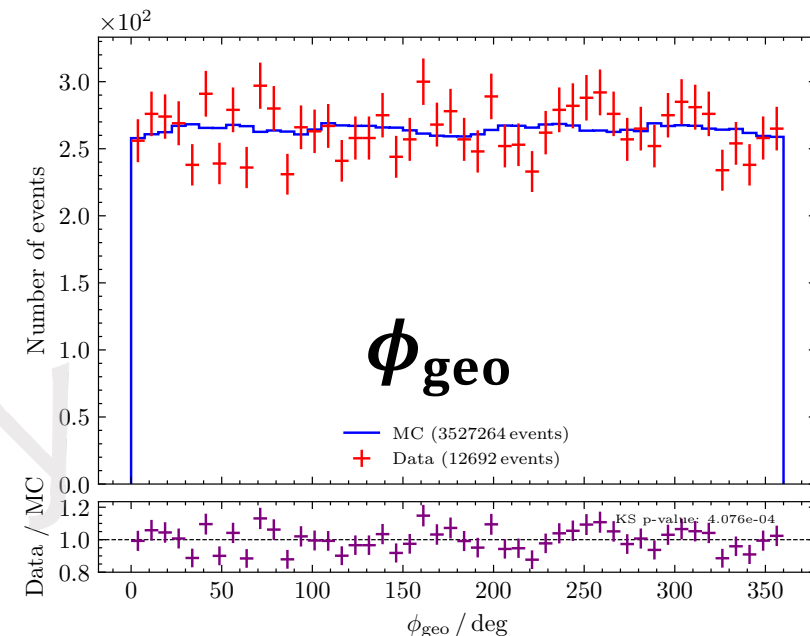
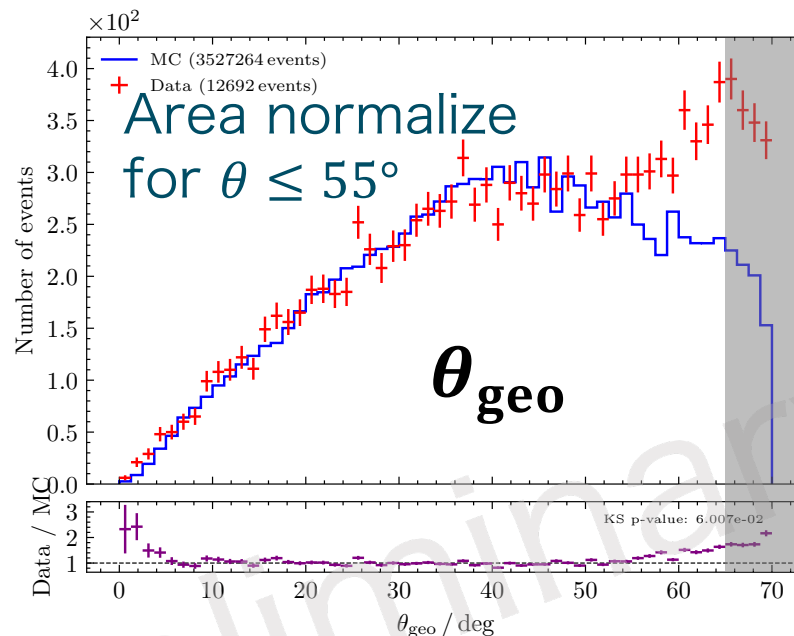
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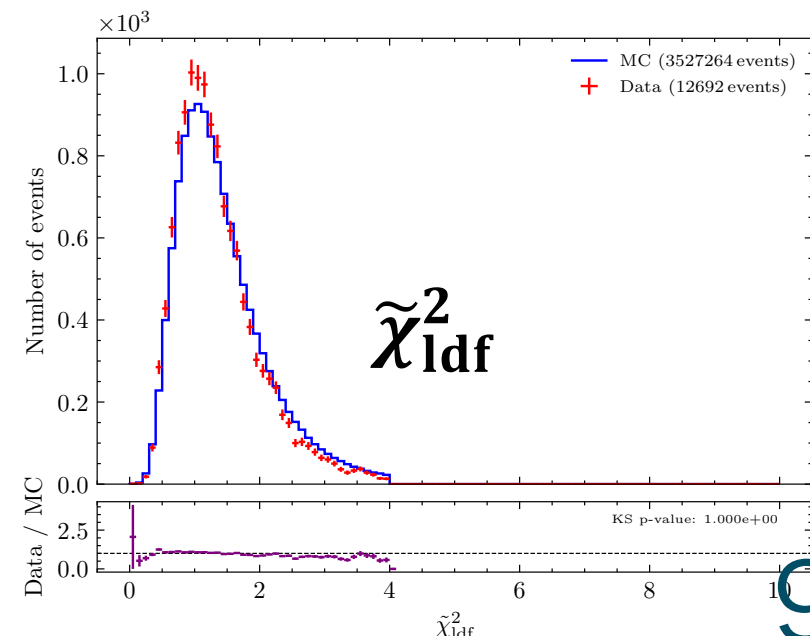
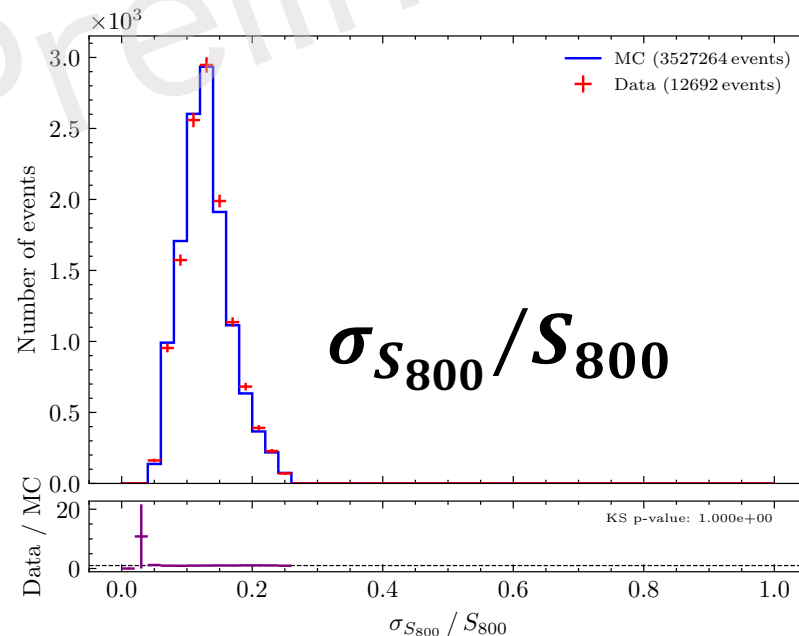
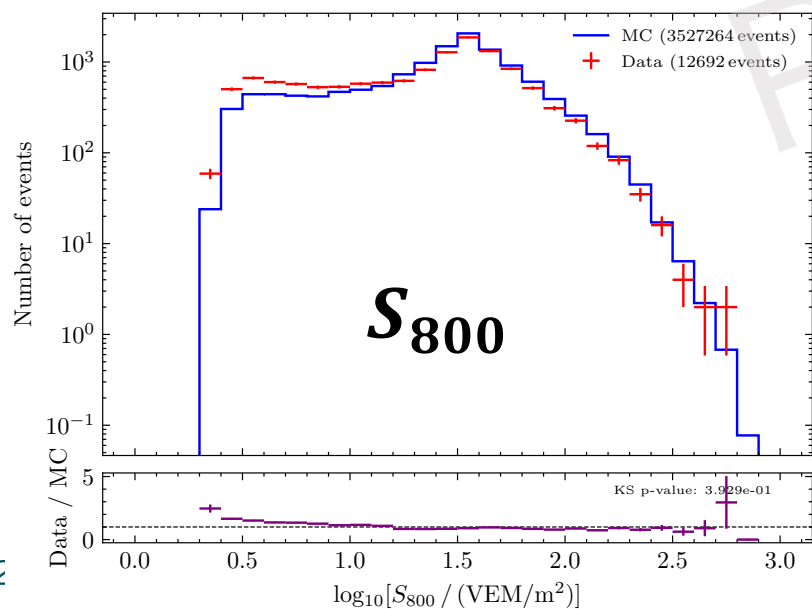
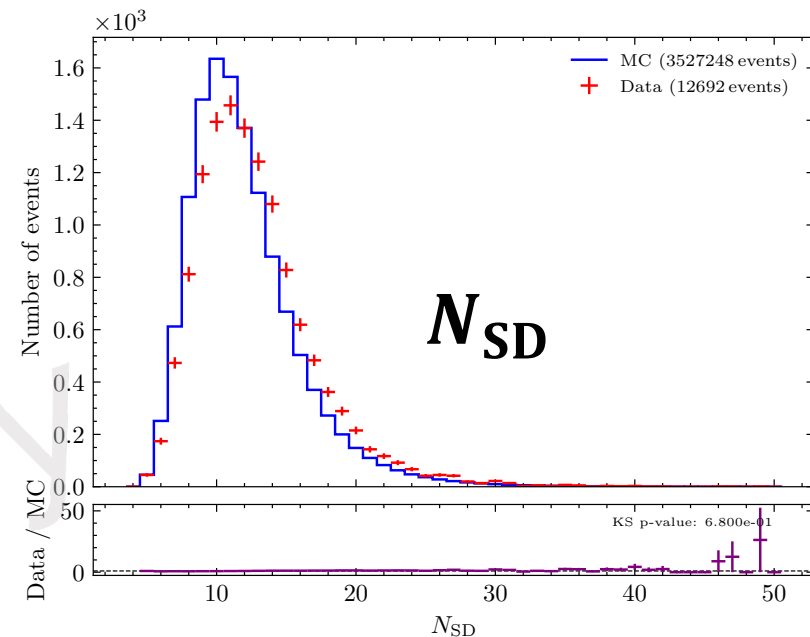
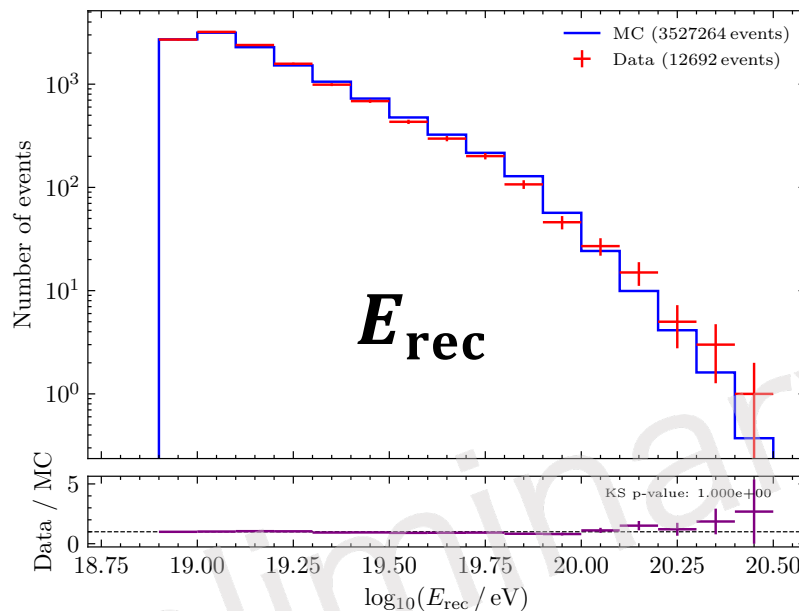
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New Analysis Database: HDF5

At this moment, many people using TXT file (convert from DST file) for analysis

HDF5: new database for TA analysis (especially for DNN)

- **Hierarchical structure**: organize data in groups and datasets (like directory, e.g. /MC/QGSJETII-04/proton/data)
- **High speed binary format**: faster read/write and smaller file size than TXT files.
- **Partial I/O**: load only necessary parts
- **Multi languages**: supported in python, C/C++, etc.

DST file converter to HDF5 file: **dstparser** (Hands-on Session tomorrow)

New TA SD dataset (HDF5 converted by K. Fujisue)

MC (**Differences from previous analysis**)

- Same period as observed data
- QGSJETII-04 p, **He, N, Fe**
- $\theta_{\text{gen}} \in [0^\circ, 70^\circ]$
- $E_{\text{gen}} \in [10^{18.0} \text{ eV}, 10^{20.5} \text{ eV}]$
- **1000 CORSIKA showers** for each energy bin

Observed data

From May. 11th, 2008 to Apr. 22nd, 2024
(16 years)

16 years of Obs. and MC data size
TXT file: >~20GB (After cut)
HDF5 file: <1GB (Before cut)

Data/MC comparison

$$E_{\text{tbl}} \geq 10^{19.0} \text{ eV}$$

Area normalize

Period

- May 2008 to May 24

Selection criteria

- $N_{\text{SD}} \geq 5$

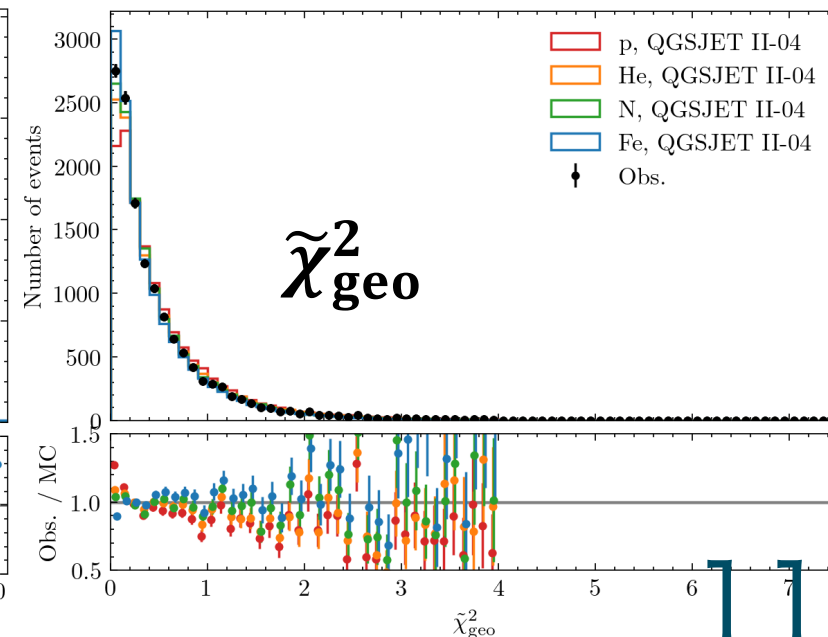
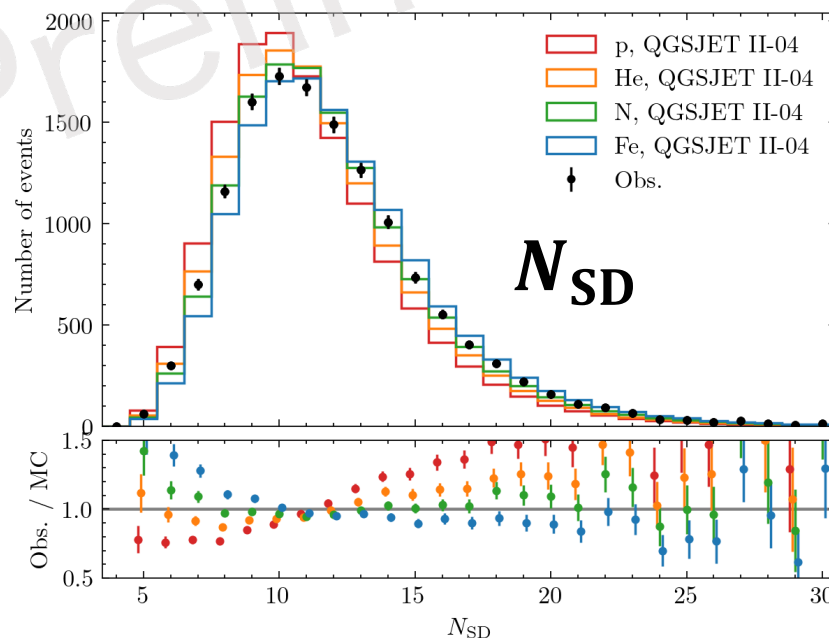
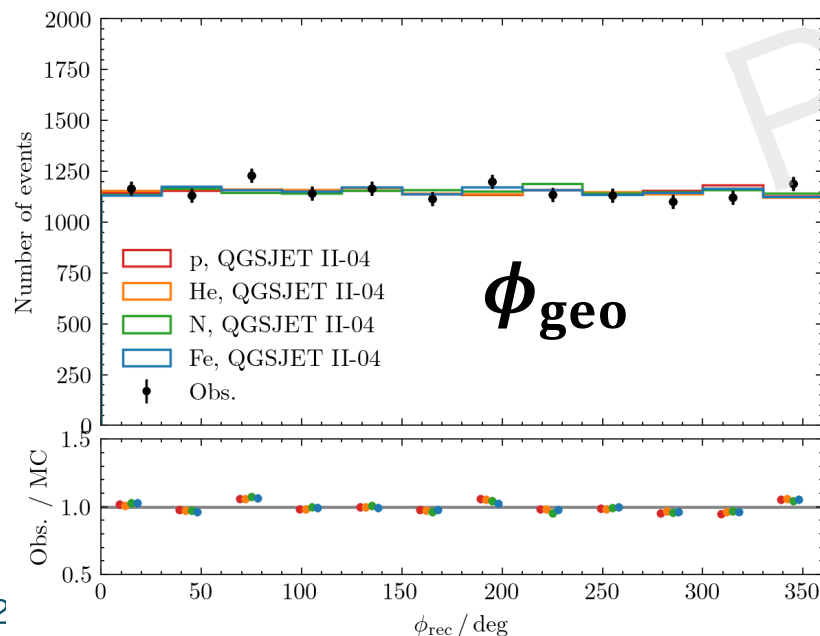
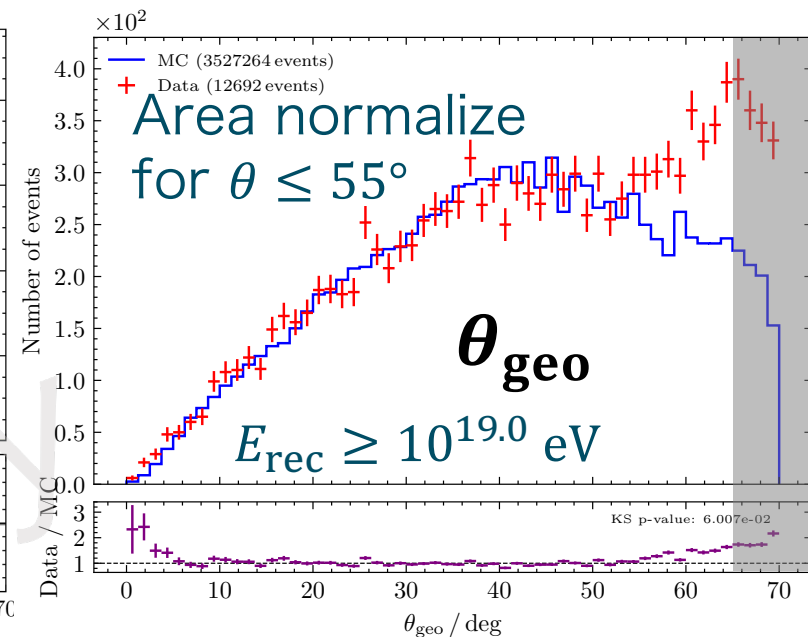
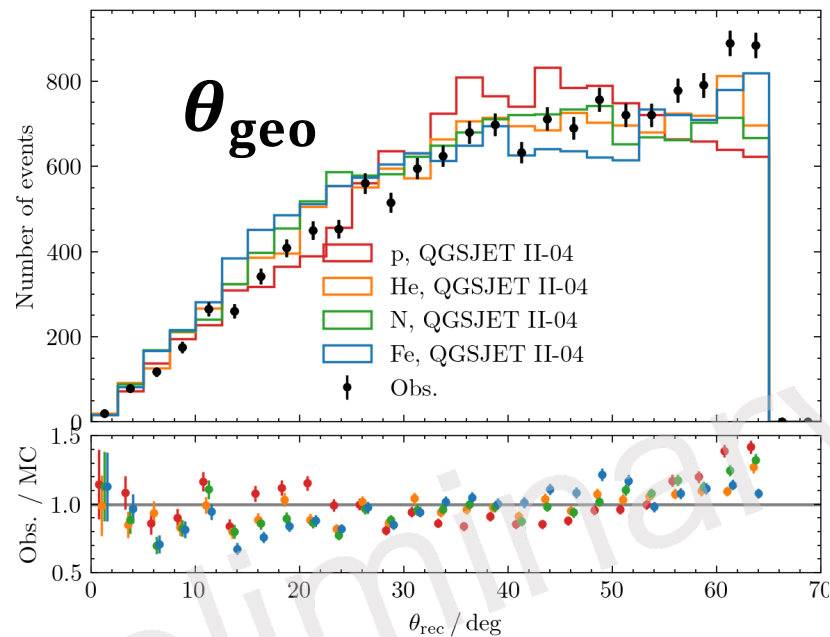
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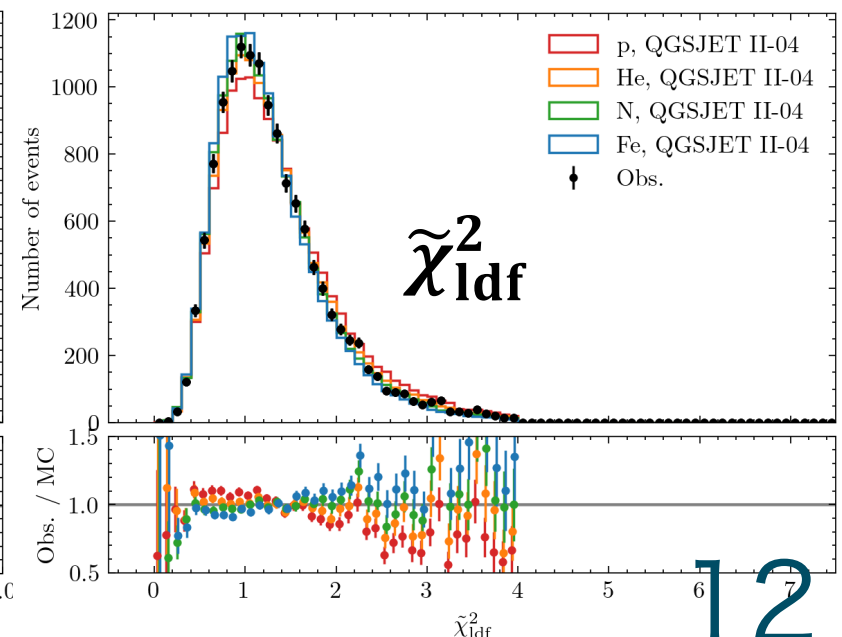
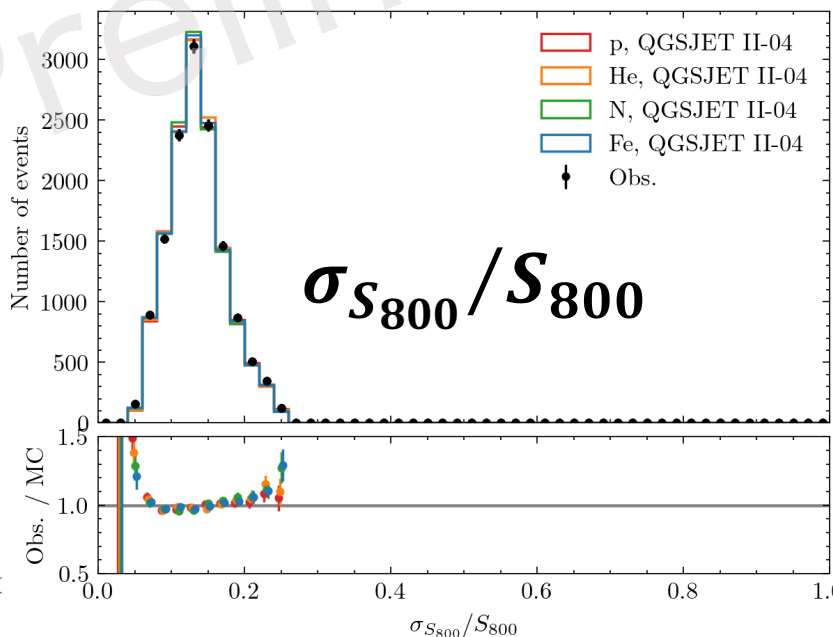
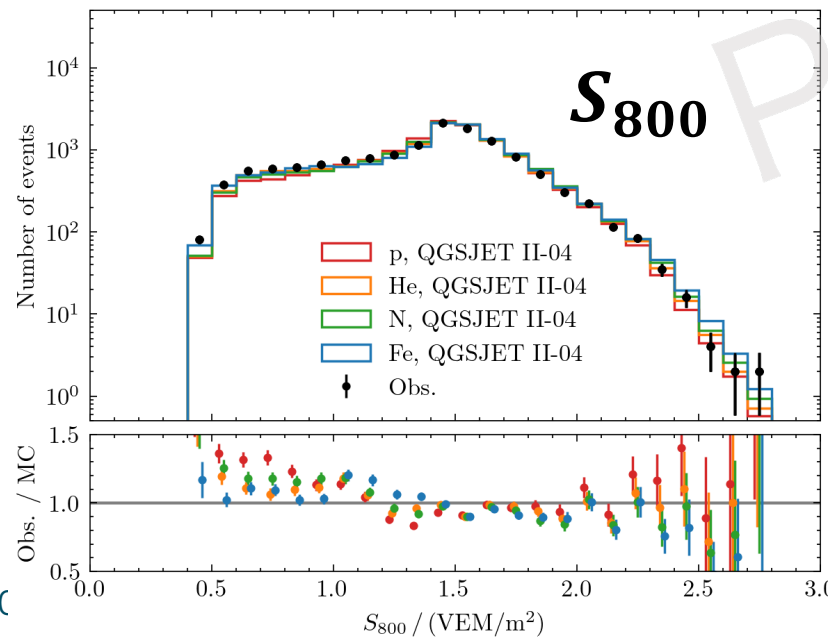
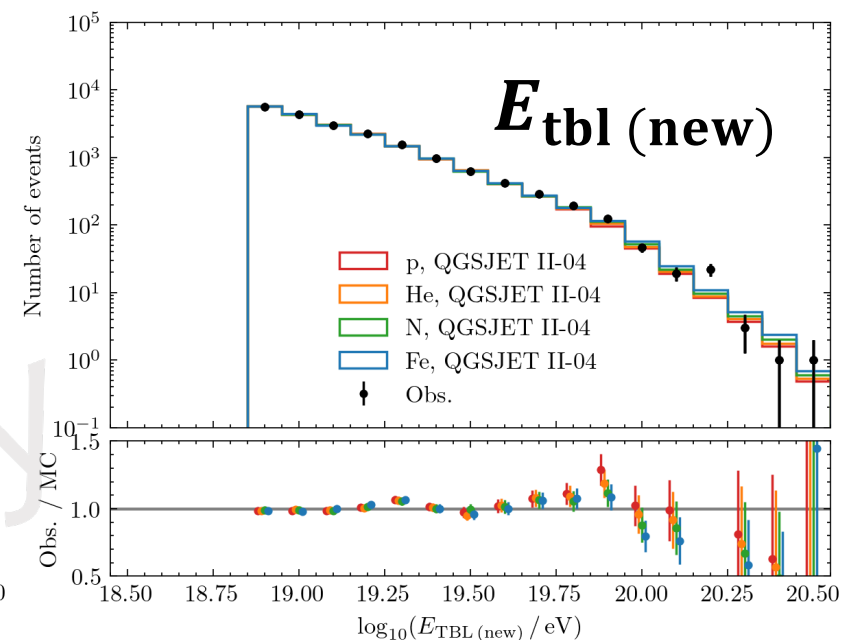
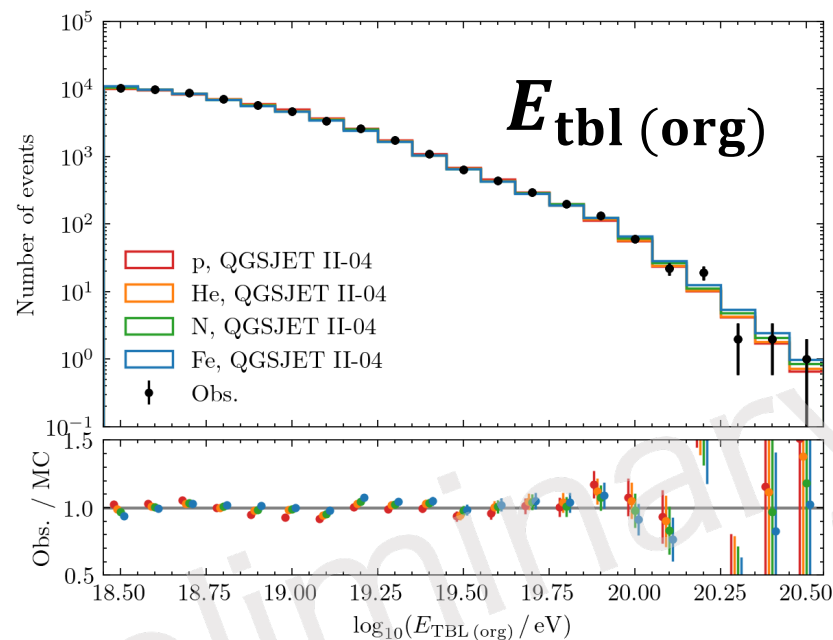
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- $\sigma_{\text{point direction}} < 5^\circ$

- $\sigma(S_{800})/S_{800} < 0.25$



Summary

Inclined air showers analysis with TA SD

We performed Data/MC comparison including large zenith angle events.
→ They have discrepancies in zenith angle distributions only with p MC.

Preliminary result of Data/MC comparison with HDF5 files including other primary particles than p in MC

⇒ They show better agreement in zenith angle distributions and even for other parameters.

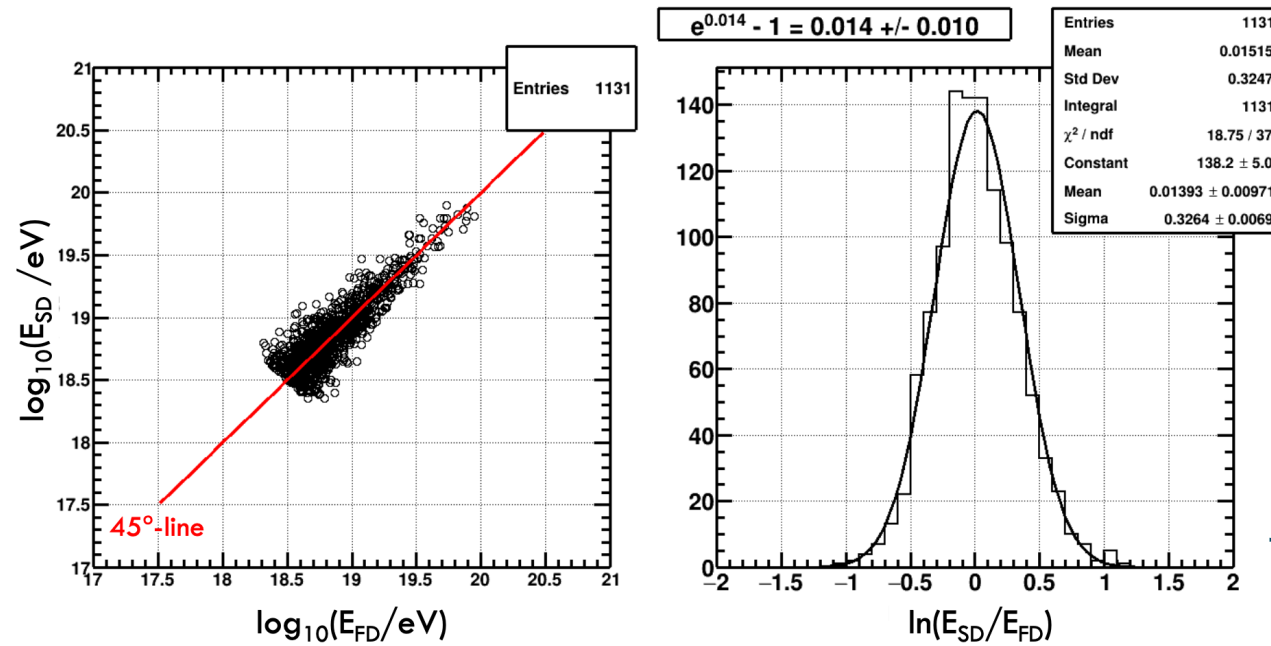
To do

- MC weighting with θ_{gen}
- More precise comparison for TA SD and TA×4 SD
- Join inclined analysis and DNN analysis → optimization required

Back up

Energy Calibration

The SD energy of the TA is scaled to the FD energy in the hybrid analysis. In the standard energy estimation table (w/ QGSJETII-03), the scaling constant was calculated to be 1.27 (recent study shows $1.27 \rightarrow 1.25?$).



from K. Ji Hyun, Analysis meeting, Apr. 2025

In this work, we newly created the energy estimation table using QGSJETII-04 as a hadronic interaction model.

⇒ We calculated the scale factor for the new energy estimation table.

Energy Calibration

TA hybrid (BR and LR) data of 12yr (up to Feb. 2020) observation are used for energy calibration

Selection criteria for hybrid dataset

- Good weather condition
- Number of hit PMTs of FD > 20
- $\theta_{\text{hybrid}} < 55^\circ$
- Shower core must be inside of the SD array.
- X_{max} must be observed.

Selection criteria for SD dataset

- $N_{\text{SD}} > 5$
- $\theta_{\text{SD}} < 55^\circ$
- Shower core must be 1.2 km far from border
- $\chi^2_{\text{geo}}/\text{ndf} < 4 \cap \chi^2_{\text{LDF}}/\text{ndf} < 4$
- $\sigma_{\text{dir}} < 5^\circ$
- $\sigma(S_{800})/S_{800} < 0.25$

The energy threshold is set to be $10^{19.0}$ eV because new table allows the energy reconstruction above $10^{18.5}$ eV.

A total of 265 events are reconstructed above $10^{19.0}$ eV

Energy Calibration

Energy scale factor	$E_{\text{rec}} \geq 10^{18.5} \text{ eV}$	$E_{\text{rec}} \geq 10^{19.0} \text{ eV}$
Standard energy estimation table (QGSJETII-03, $E_{\text{gen}} \gtrsim 10^{18} \text{ eV}$)	1.27 (1.25)	1.24
New energy estimation table (QGSJETII-04, $E_{\text{gen}} \gtrsim 10^{18.5} \text{ eV}$)	—	1.16

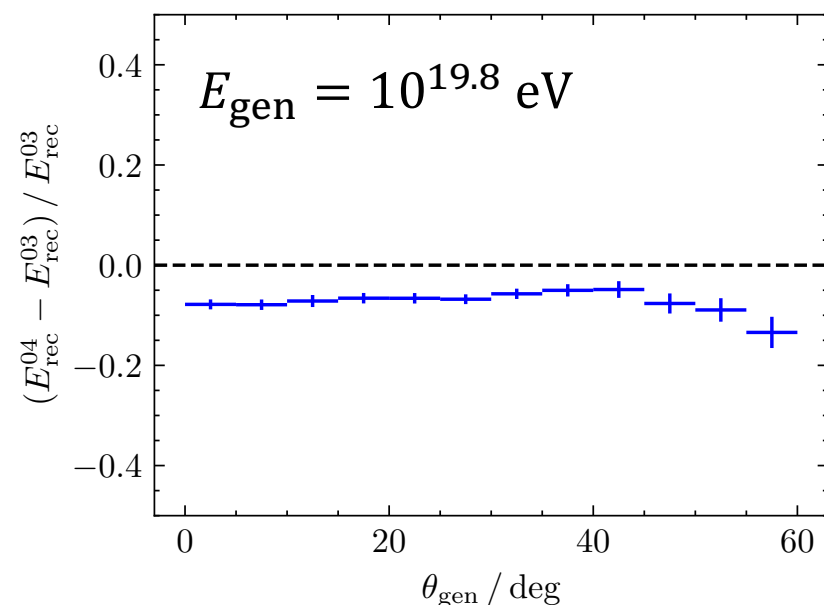
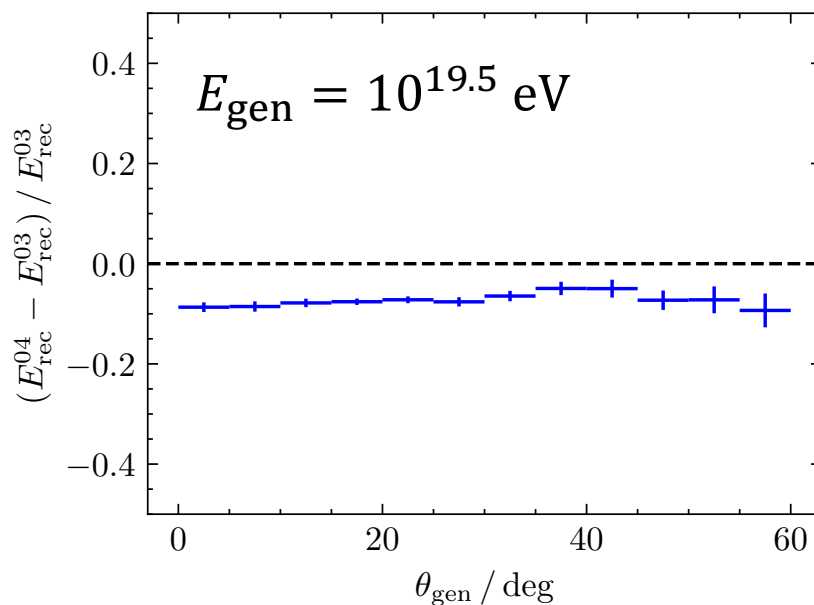
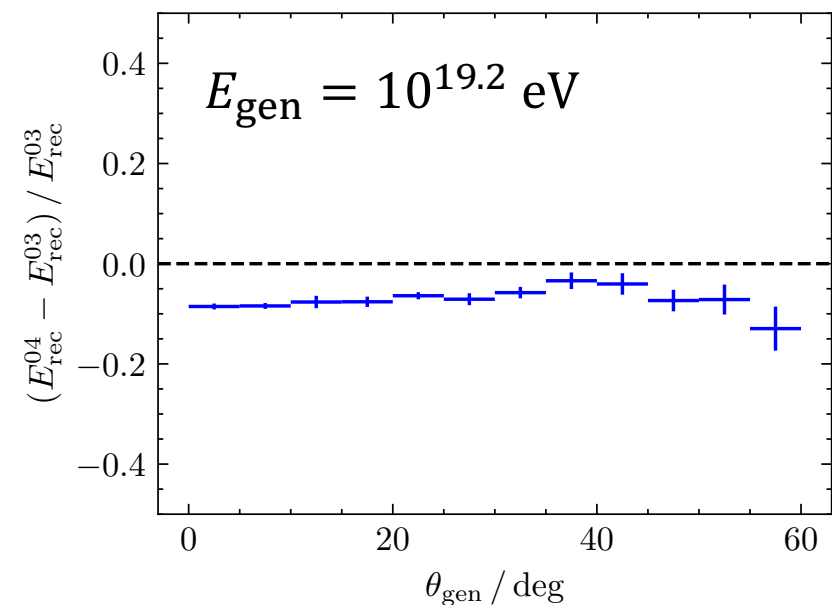
We calculated the energy scale factor for the new energy estimation table to be **1.16** (for $\geq 10^{19.0} \text{ eV}$).

This is smaller than 1.24 (for $\geq 10^{19.0} \text{ eV}$) for the standard energy est. table.
⇒ Possibly due to differences in hadronic interaction models

This tendency is qualitatively consistent with previous studies.

For this work, we will use the value 1.16 for the energy scale factor

QGSJETII-03 vs QGSJETII-04

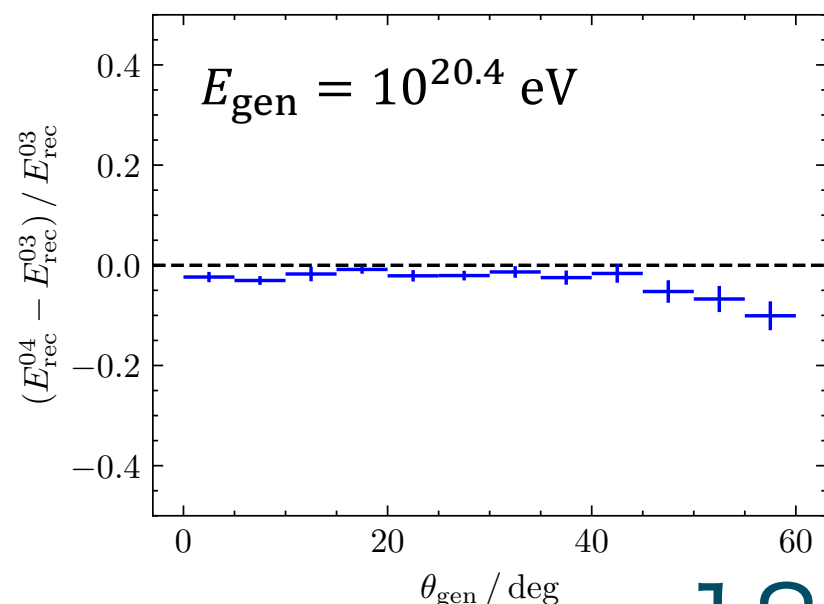
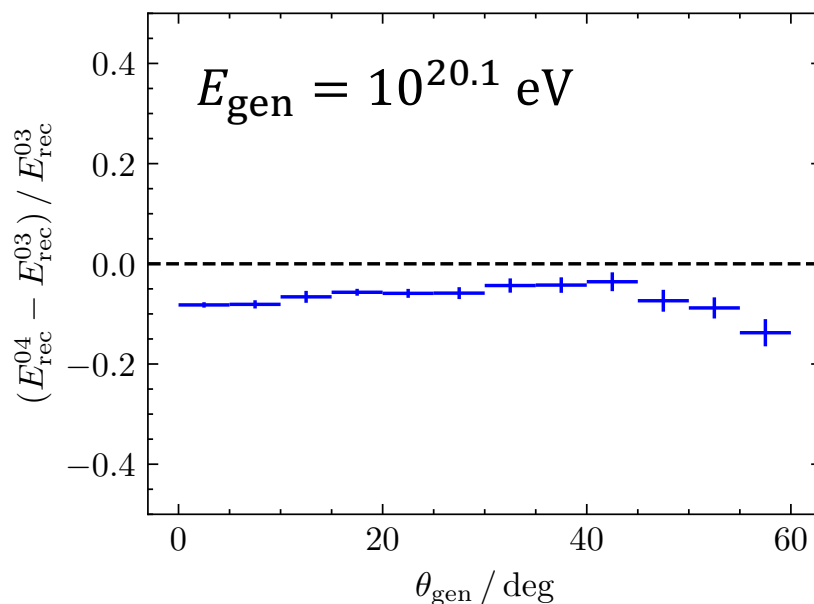


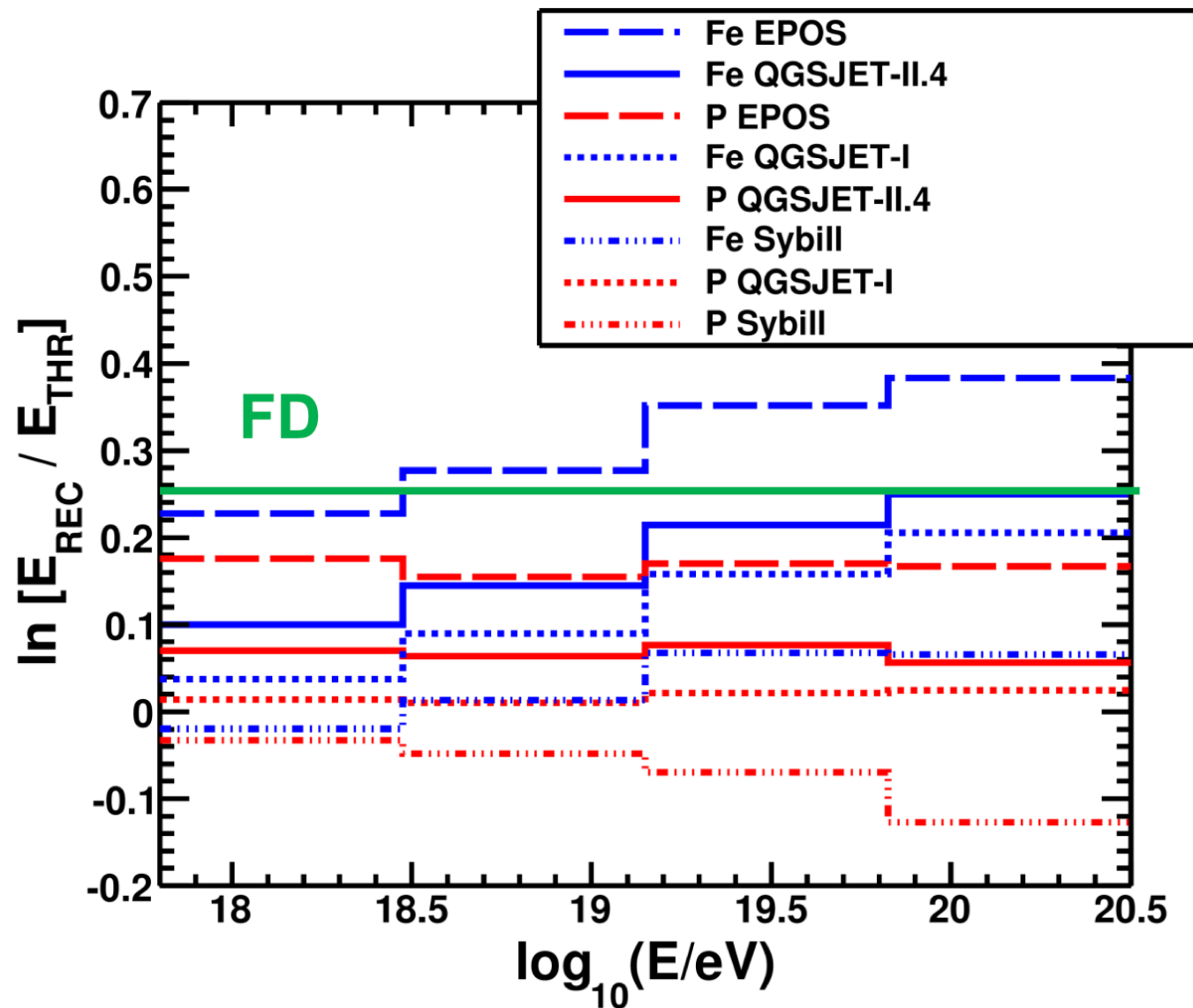
$$\frac{E_{\text{rec}}^{\text{QGSJETII-04}} - E_{\text{rec}}^{\text{QGSJETII-03}}}{E_{\text{rec}}^{\text{QGSJETII-03}}}$$

$E_{\text{rec}}^{\text{QGSJETII-03}}$: original table

$E_{\text{rec}}^{\text{QGSJETII-04}}$: new table

QGSJETII-04, p shower





from B. Stokes,
ICRC2013

TA SDの原子核種およびハドロン相互作用に対するエネルギースケールの違い
各シャワー (E_{THR}) をQGSJETII-03, protonのテーブルで再構成 (E_{REC}) している

Tentative energy scale calculation for QGSJET II-04 **p**, **Fe**

- For QGSJET II-03 **proton**, energy scale $s_{03,p}$ was determined using the hybrid data:

$$s_{03,p} = 1 / 1.27 \quad \text{T. Abu-Zayyad et al., ApJL 768, L1 (2013)}$$

$$E_{03,p}^{\text{rec}} = E_{03,p}^{\text{TBL}} \times s_{03,p} = E_{03,p}^{\text{TBL}} / 1.27$$

$$(E_{03,p}^{\text{TBL}} / 1.27) / (E_{03,p}^{\text{gen}} / 1.27) = 1 \quad (\text{on average})$$

$$E_{03,p}^{\text{rec}} / (E_{03,p}^{\text{gen}} / 1.27) = 1 \quad (\text{on average})$$

- $E_{03,p}^{\text{rec}} / (E_m^{\text{gen}} \times s_m)$ should equals to one on average.

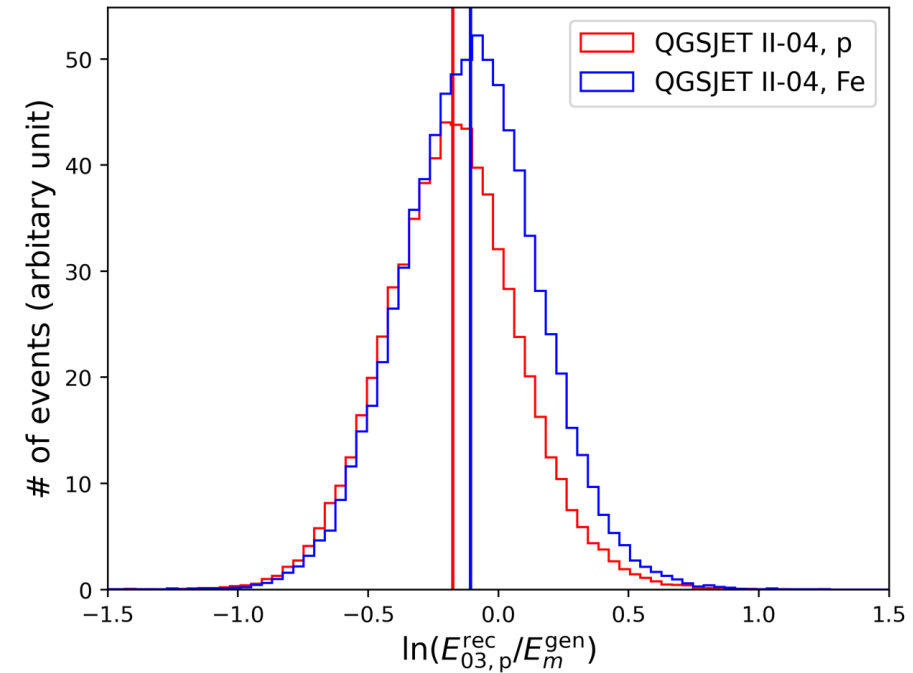
- MC events for $E_m^{\text{gen}} > 10^{18.3}$ eV
- Tentative calculation of energy scale using MC events:

$$s_m = \exp(\ln(E_{03,p}^{\text{rec}} / E_m^{\text{gen}}))$$

- Tentative energy scales:

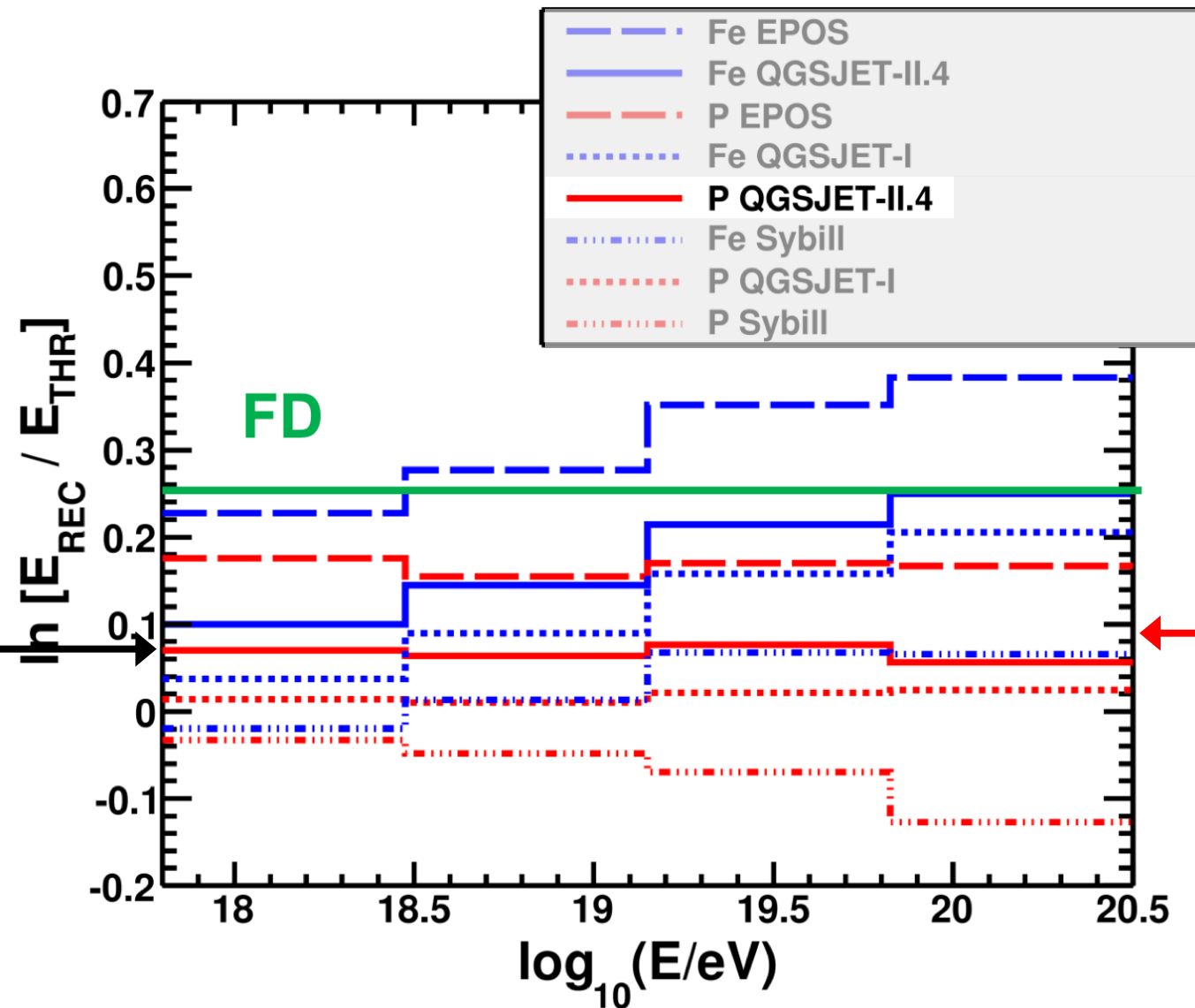
- QGSJET II-04 **proton** $s_{04,p} \sim 1 / 1.19$
- QGSJET II-04 **iron** $s_{04,Fe} \sim 1 / 1.11$

Caveat: these energy scales are tentative for this study



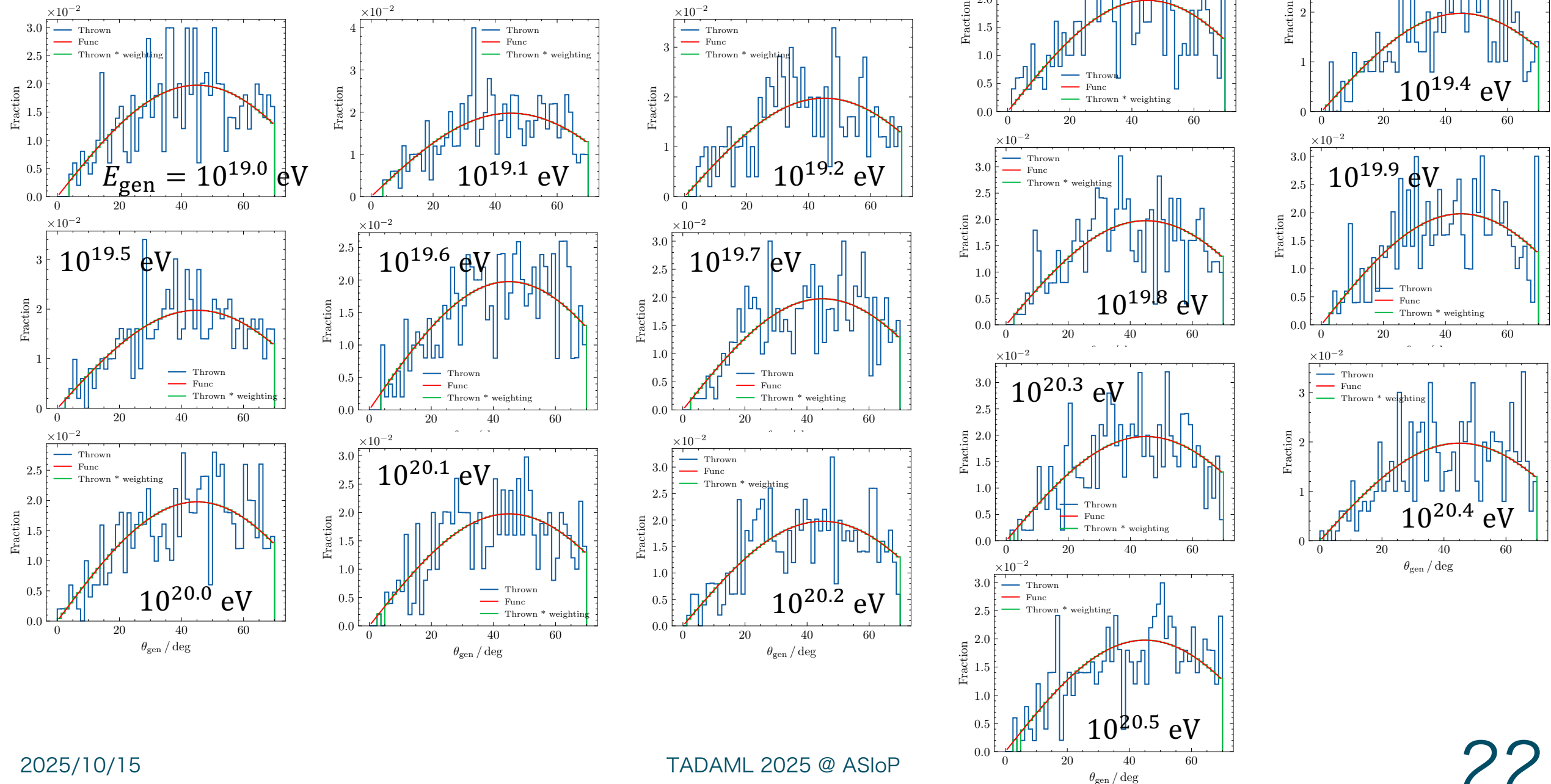
from K. Fujisue, Analysis meeting, Feb. 2025

$\ln(1.27/1.19) = 0.07$
 0.07 (1.19) K. Fujisue
 Analysis meeting,
 Feb. 2025

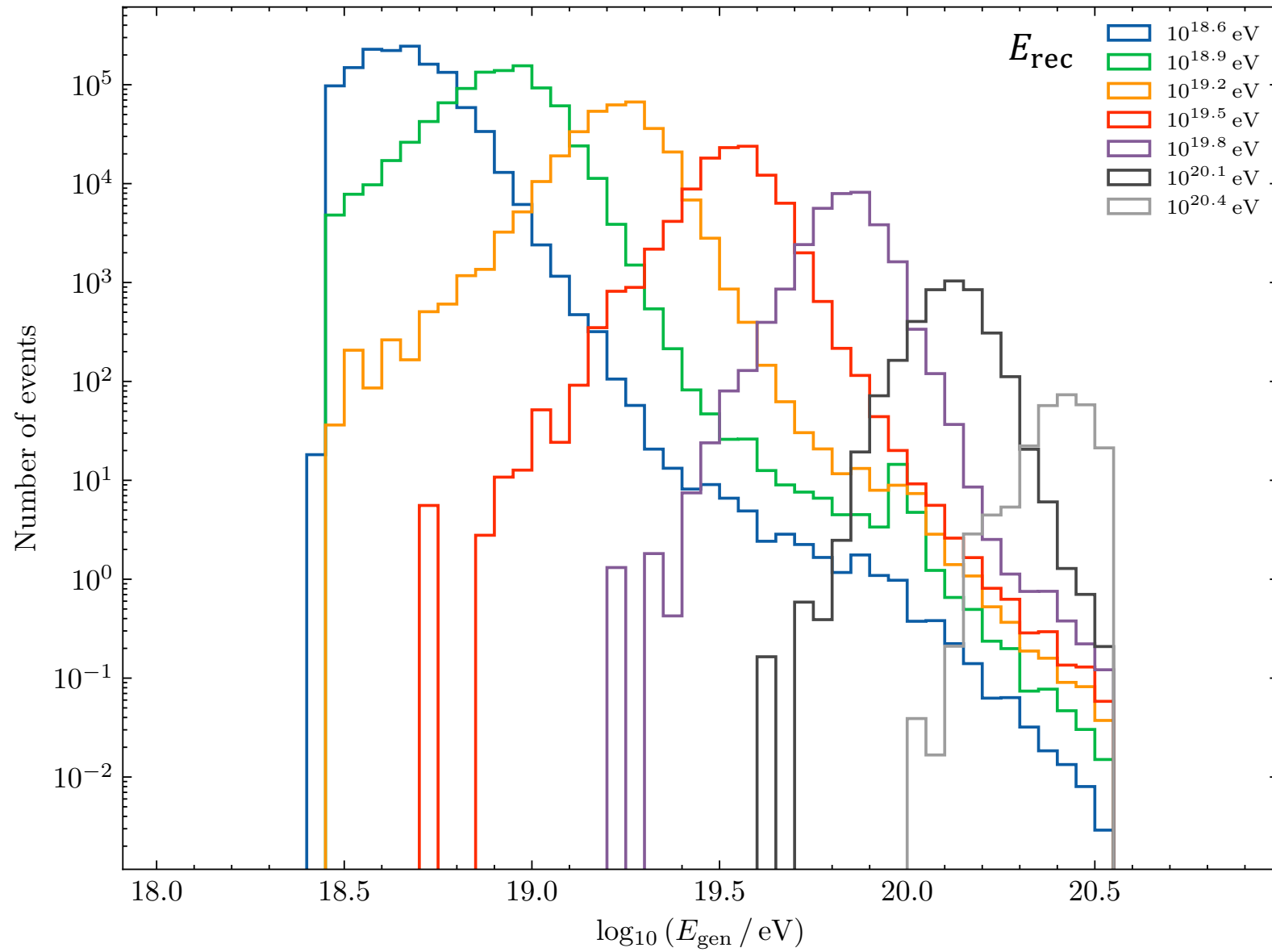


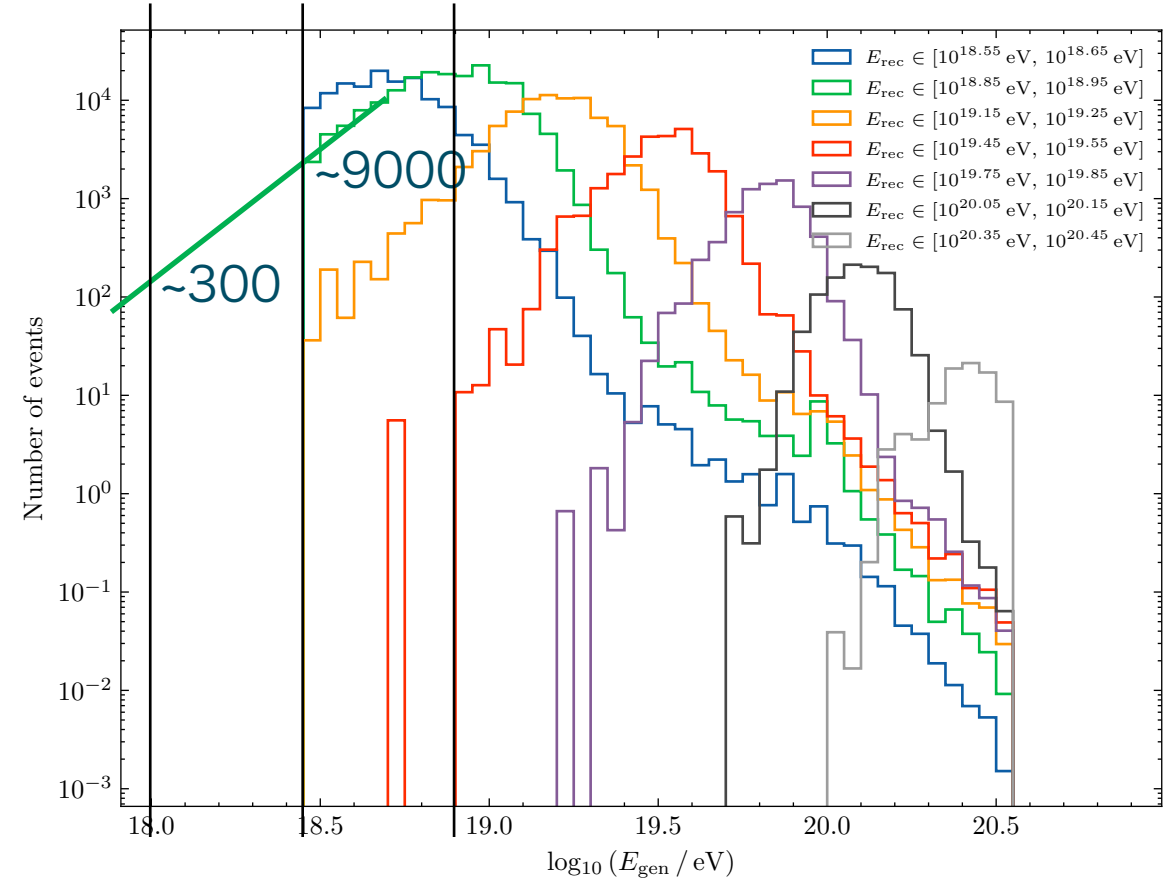
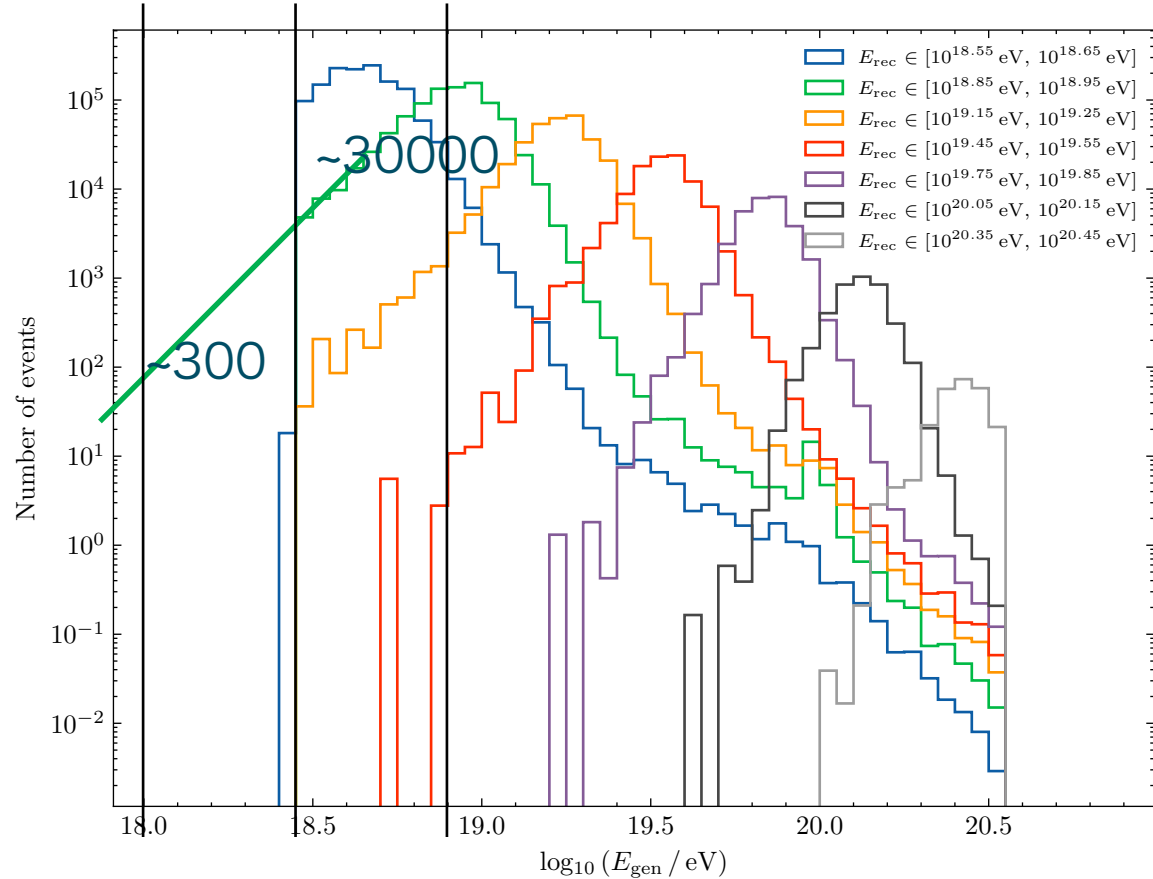
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MC Weighting

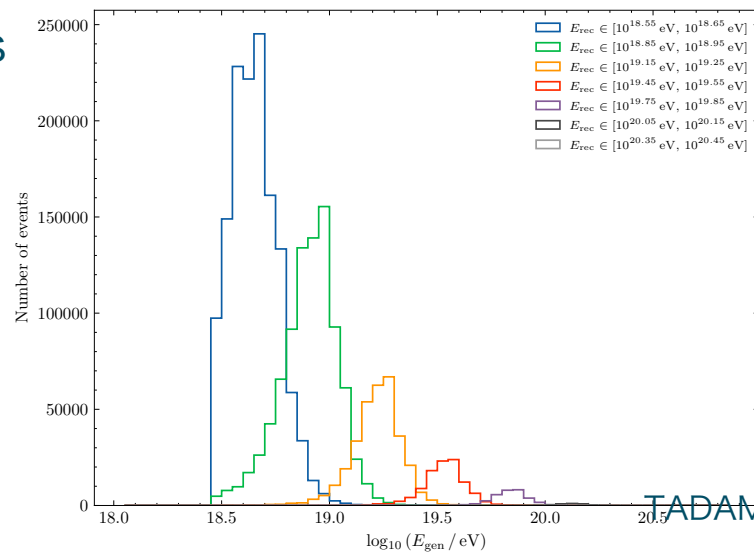


Energy Resolution

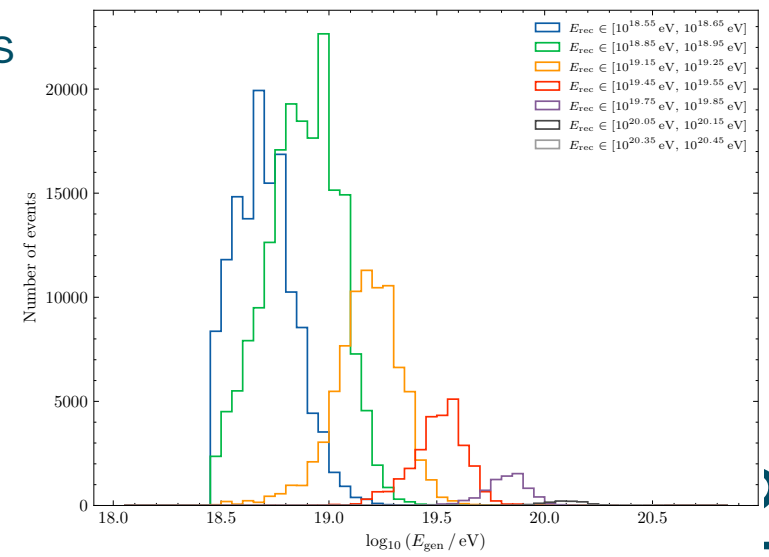




All events

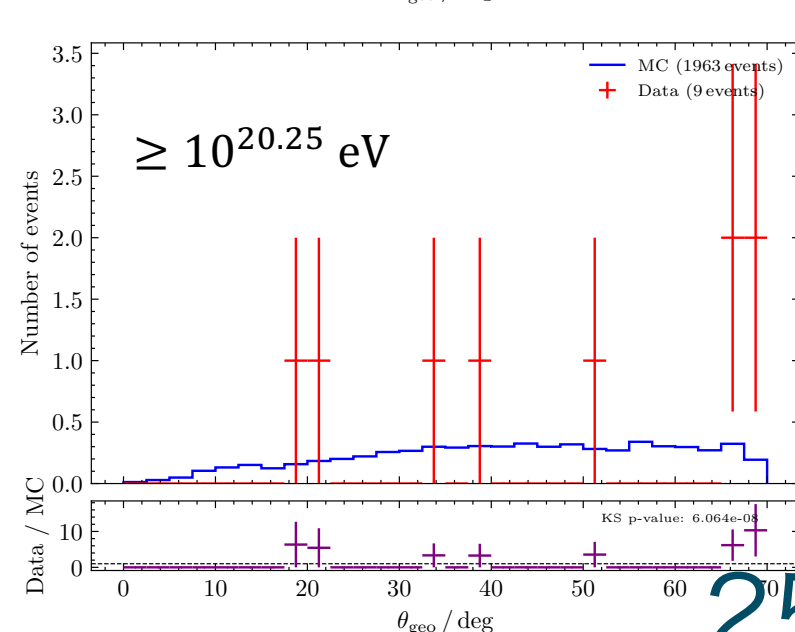
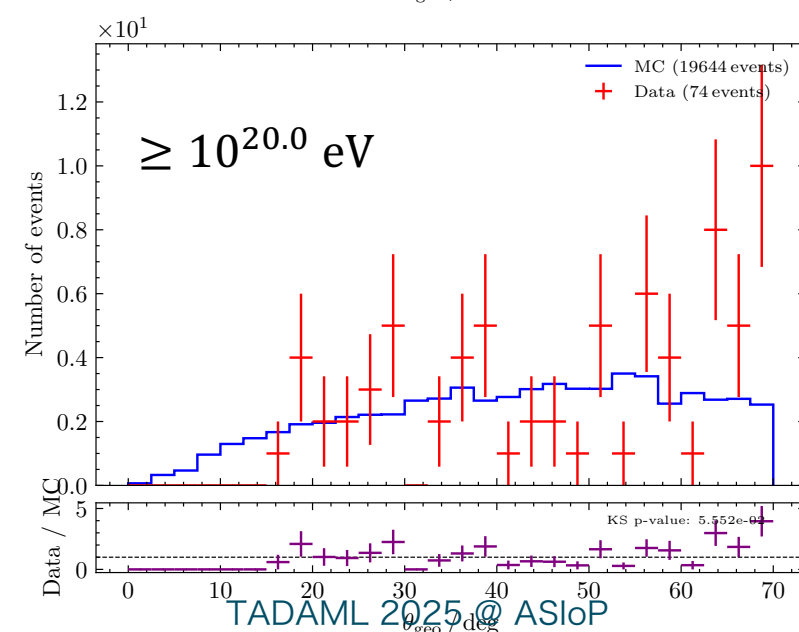
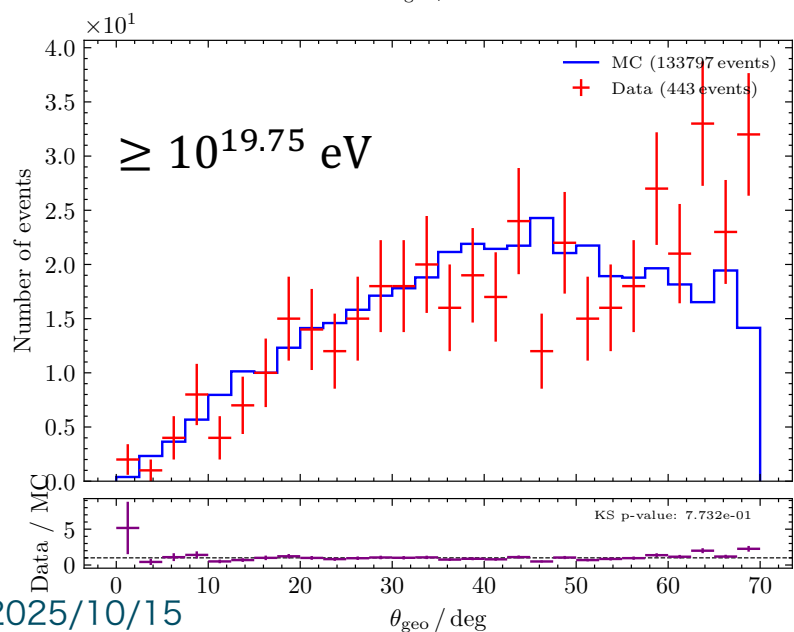
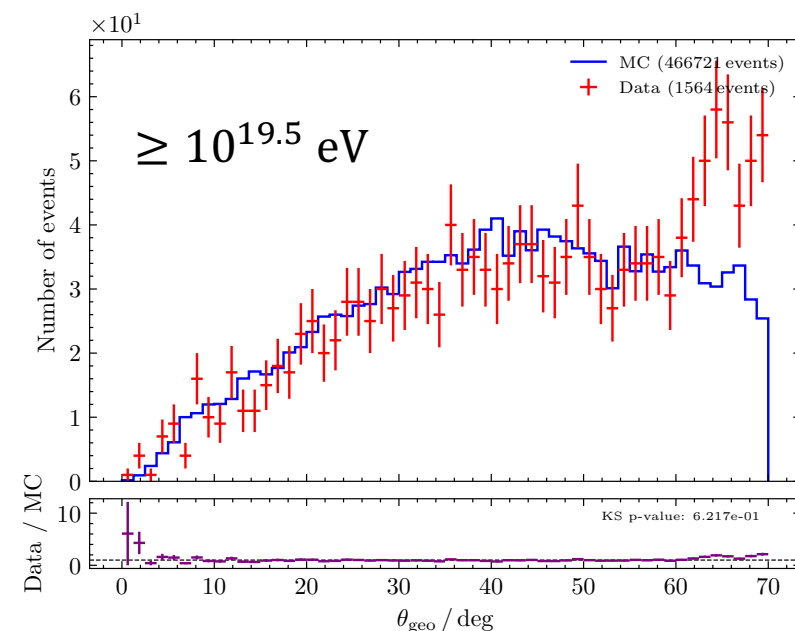
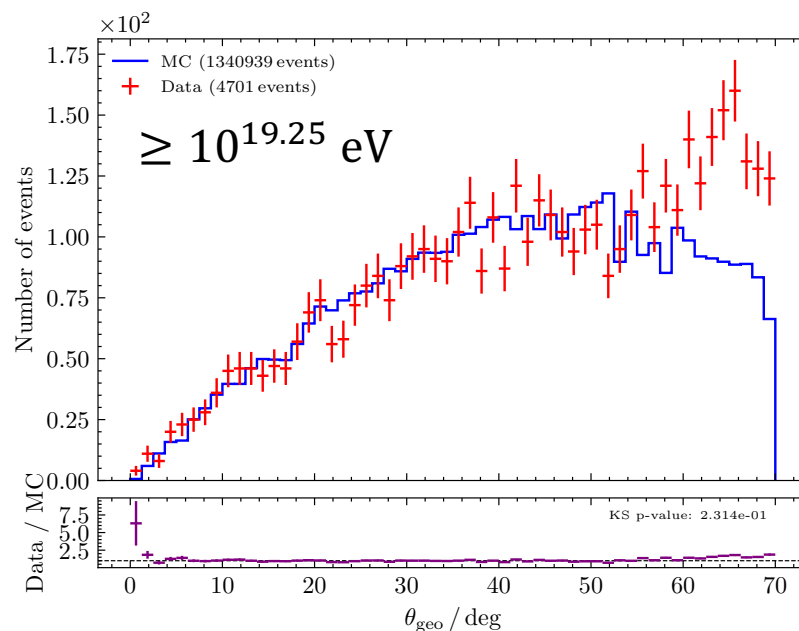
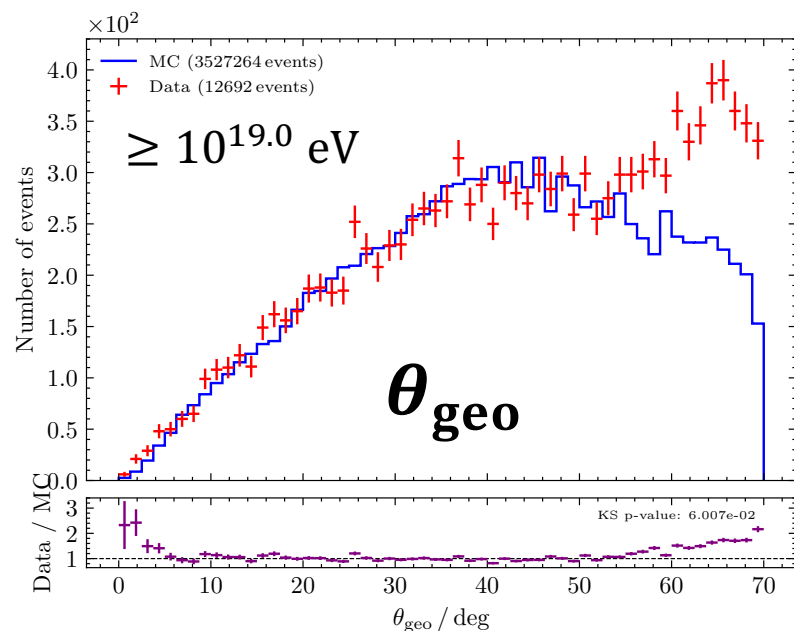


Inclined events

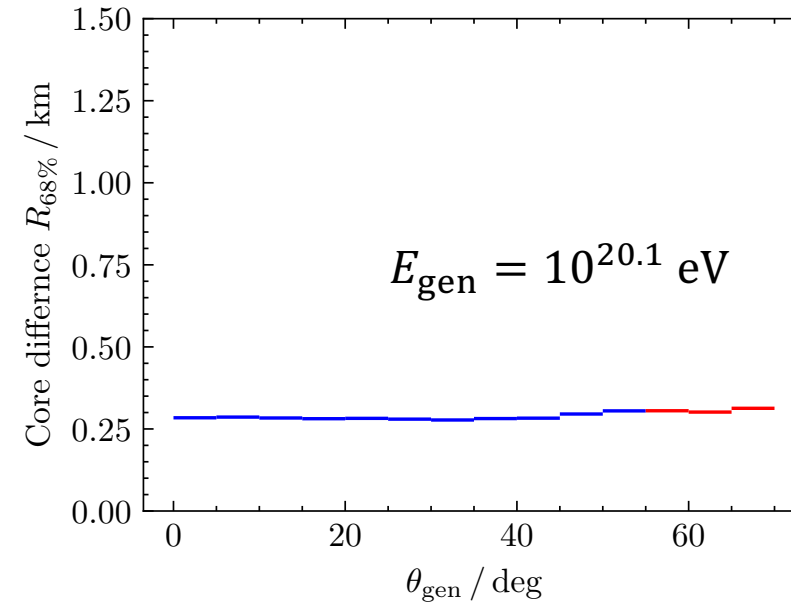
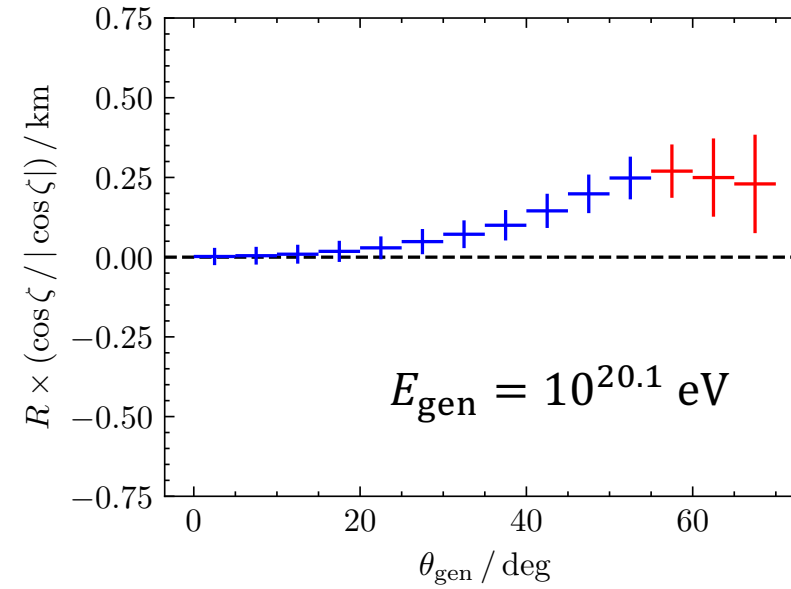
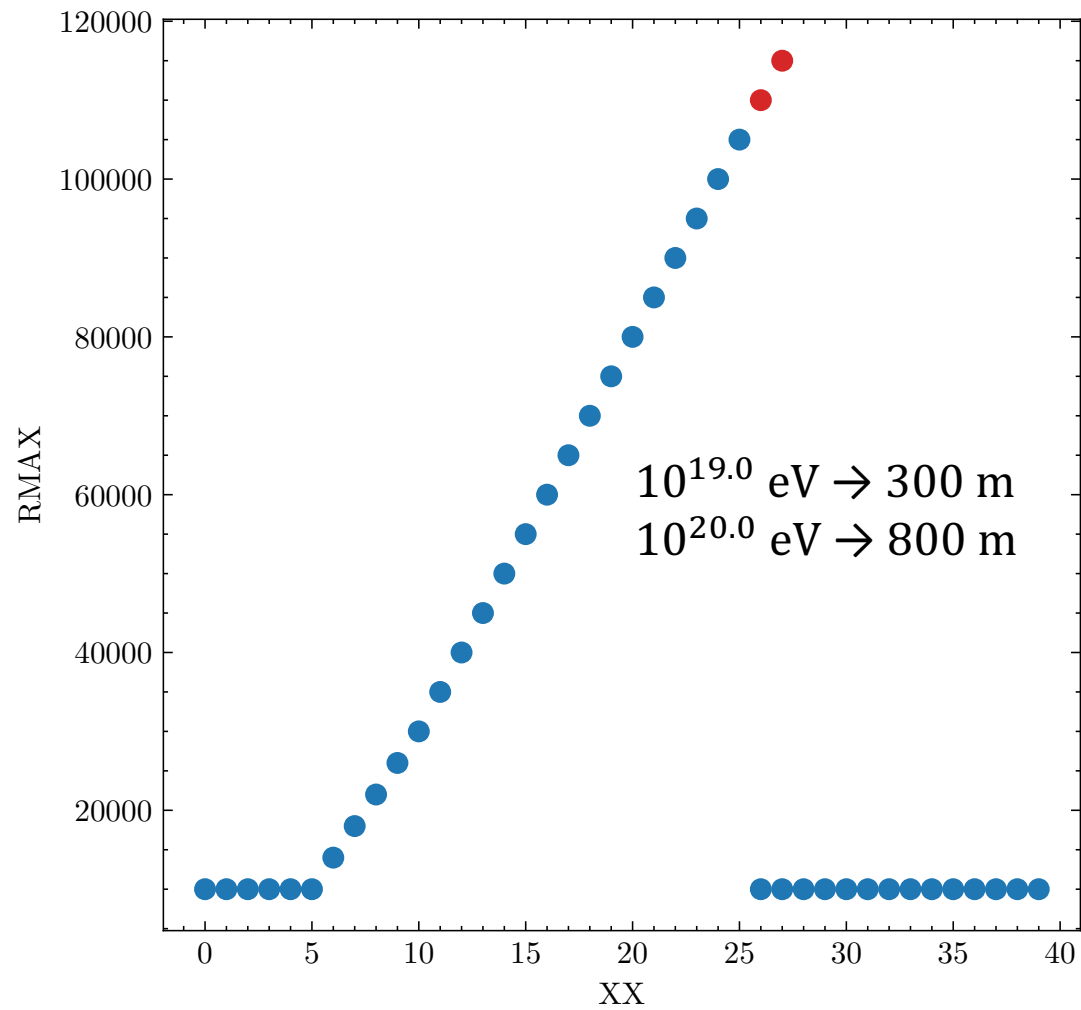


Data/MC comparison

Area normalize for $\theta \leq 55^\circ$



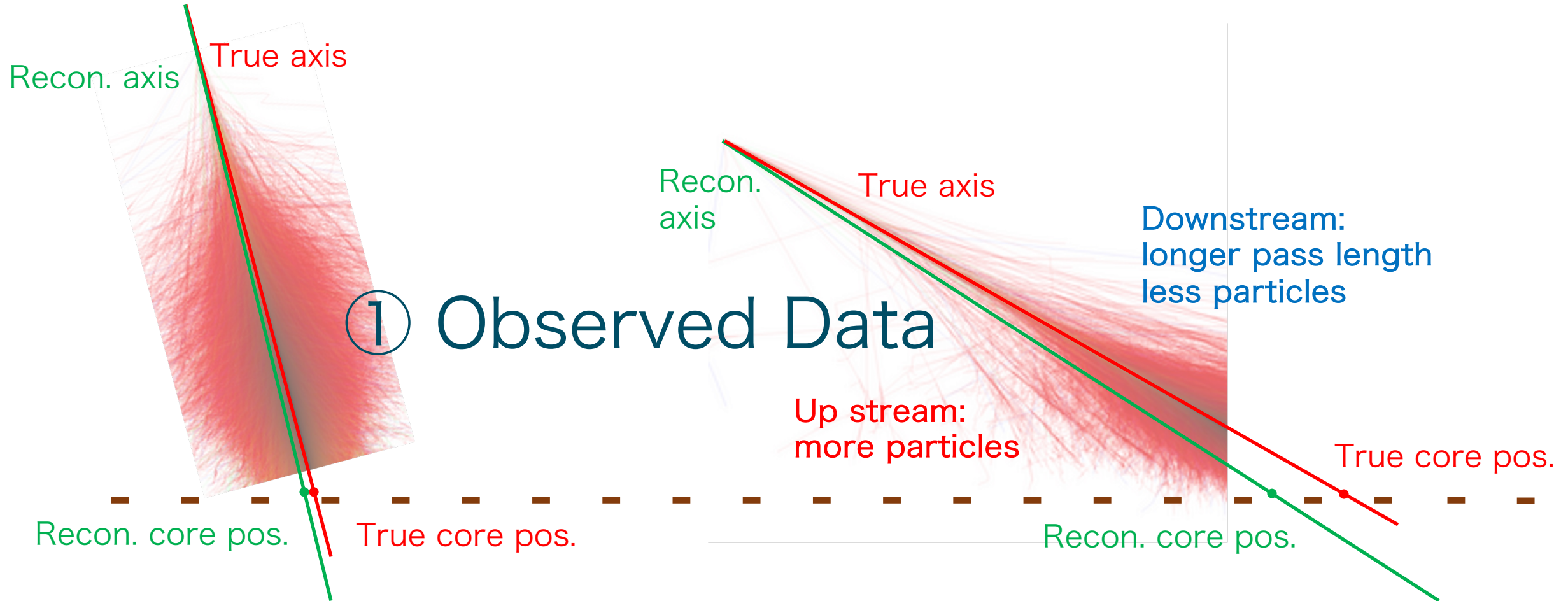
RMAX and Core Difference



Hypothesis of Difference in Lateral Dist.

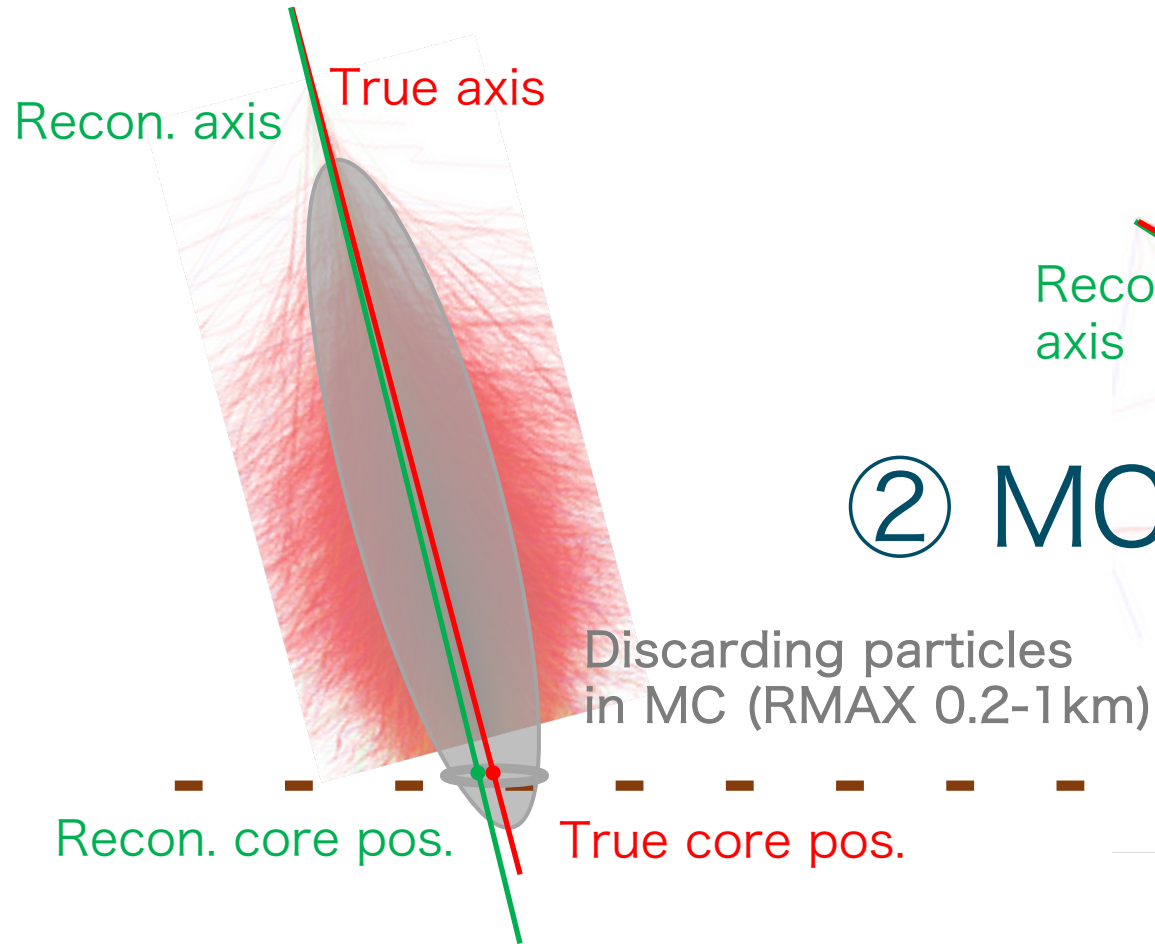
Vertical shower

Inclined shower

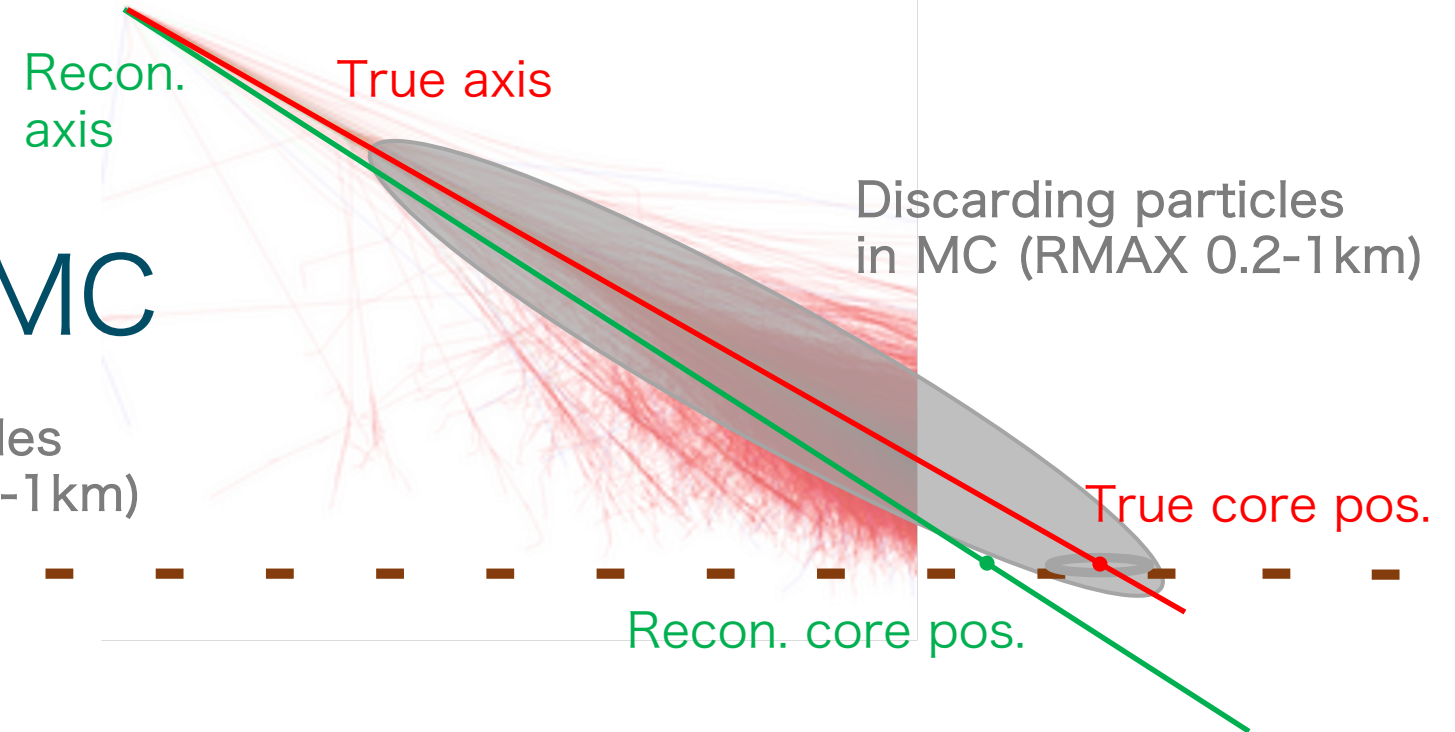


Hypothesis of Difference in Lateral Dist.

Vertical shower

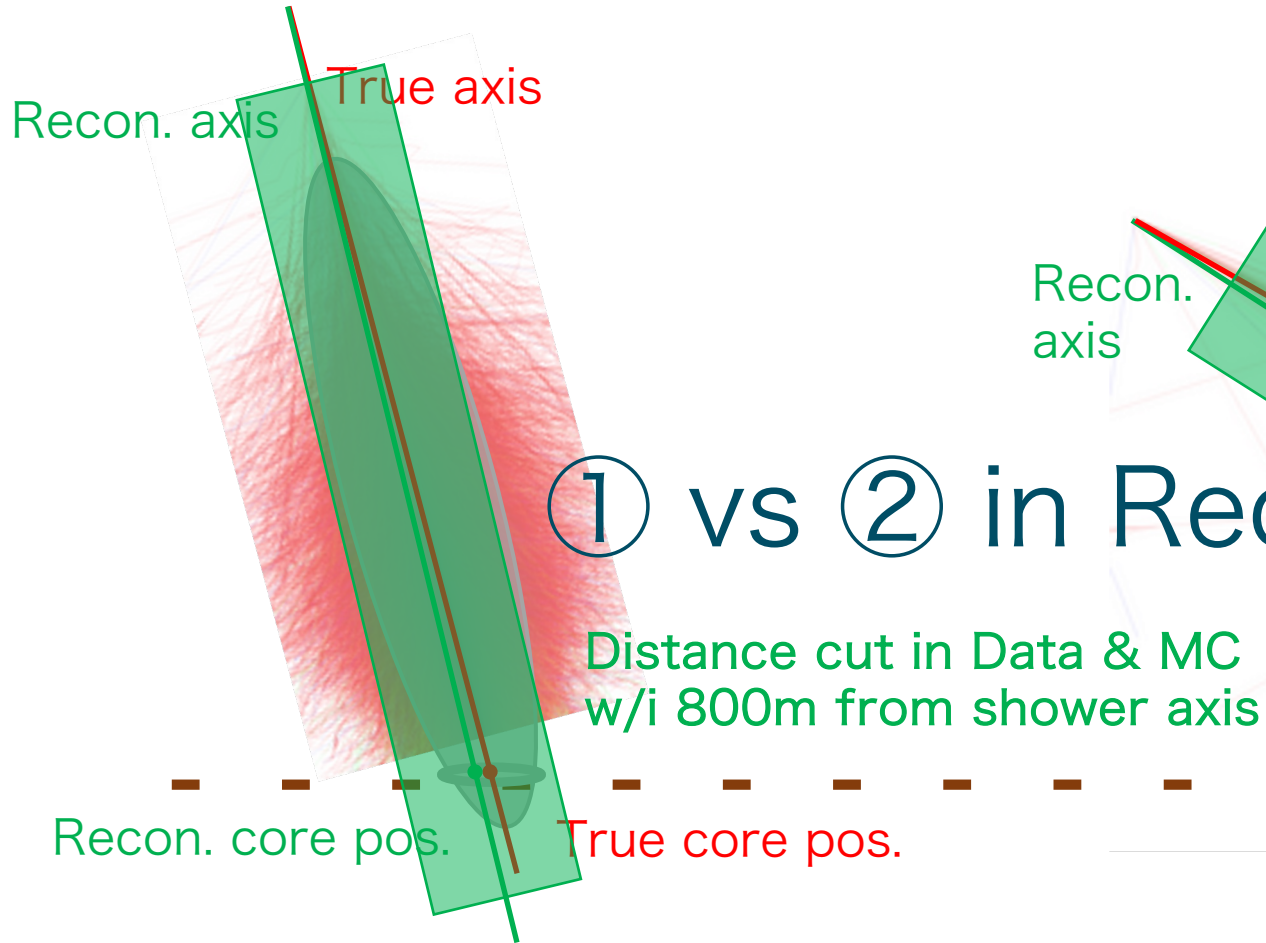


Inclined shower



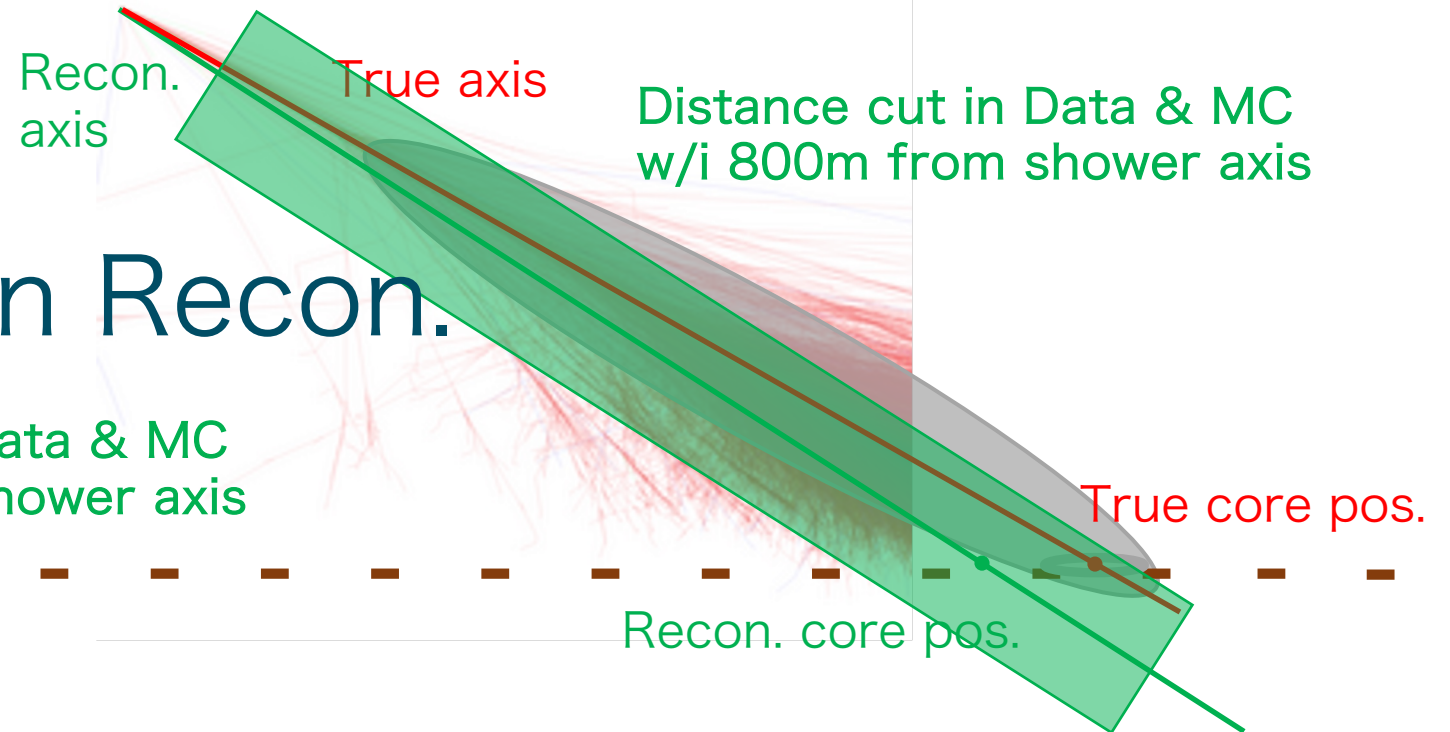
Hypothesis of Difference in Lateral Dist.

Vertical shower



No difference observed

Inclined shower

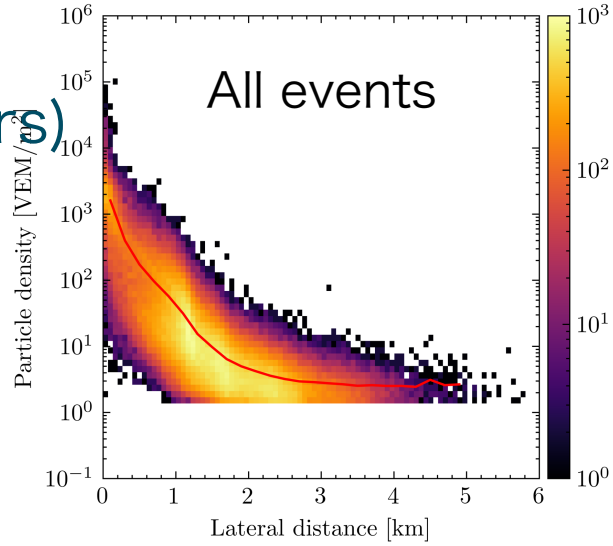


Difference occur downstream near core?

Comparison on Lateral Distribution $E_{\text{rec}} \geq 10^{19.0}$ eV

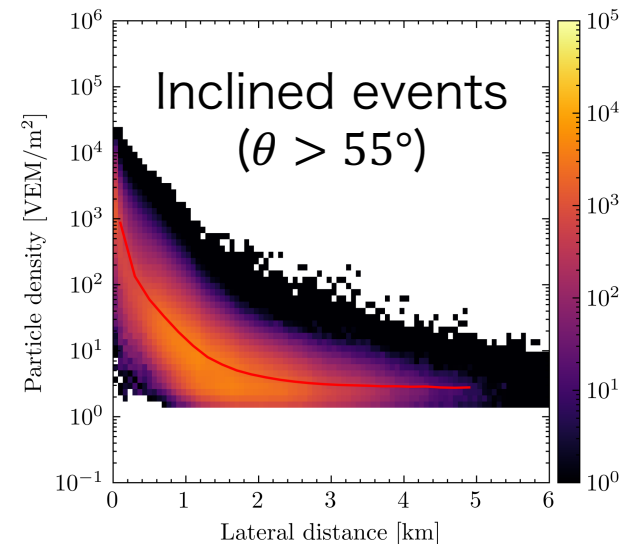
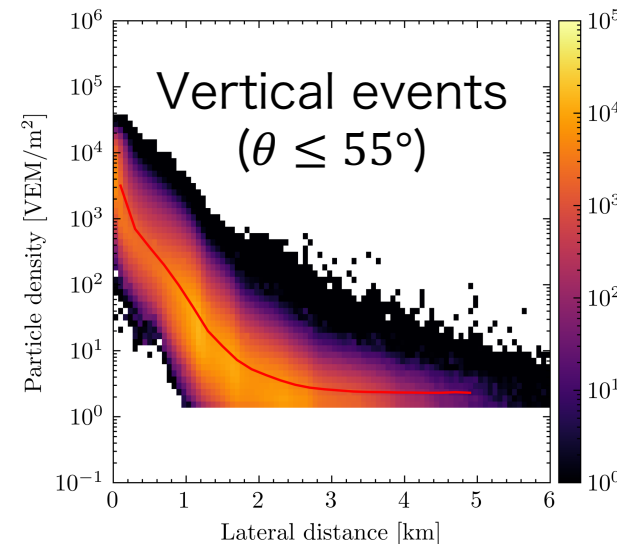
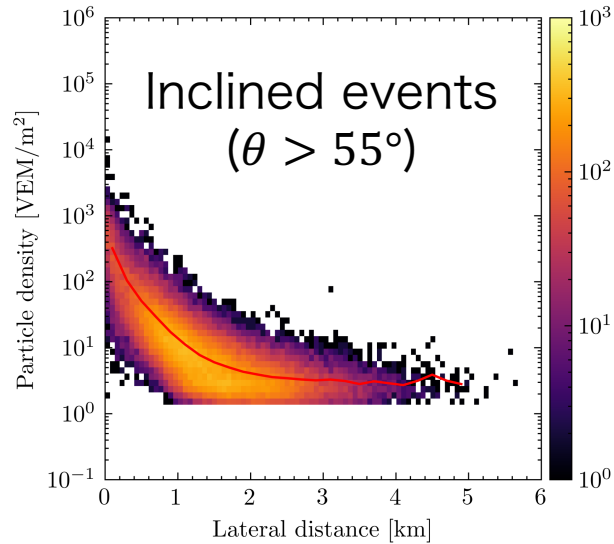
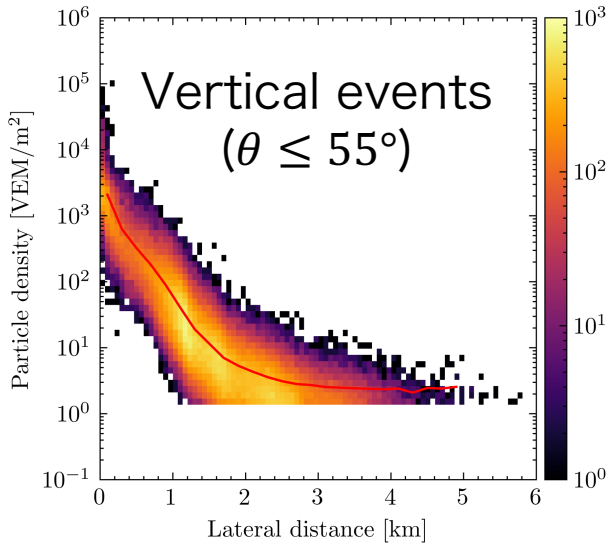
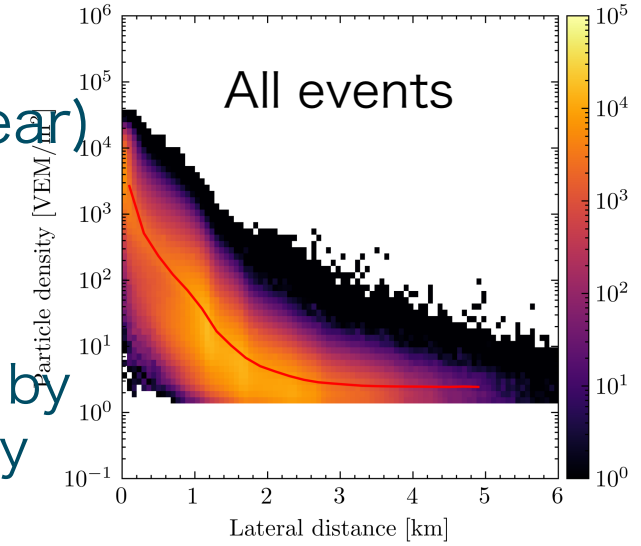
Particles density measured by all detectors used for reconstruction

Data
(16 years)



MC
(2nd year)

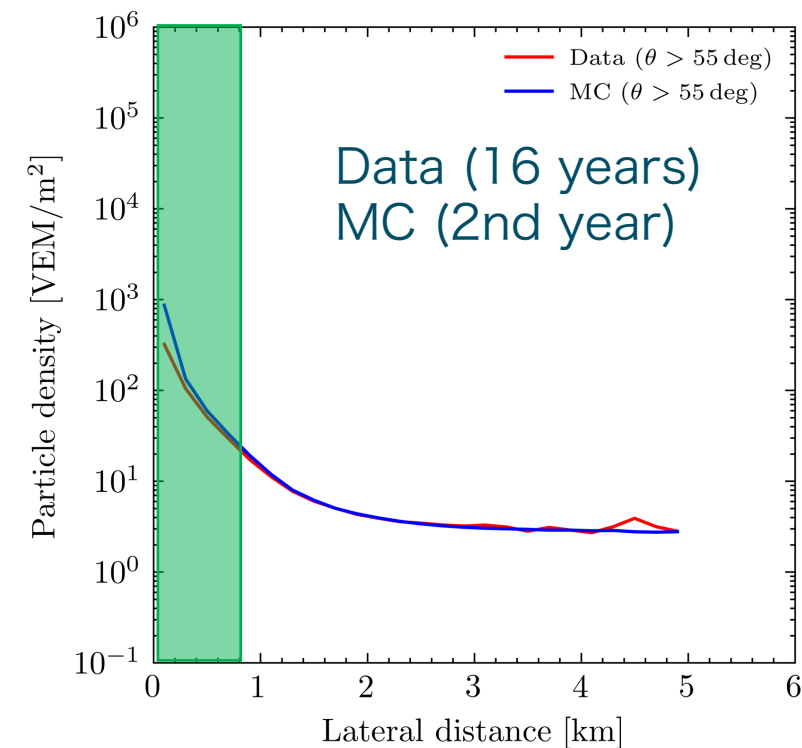
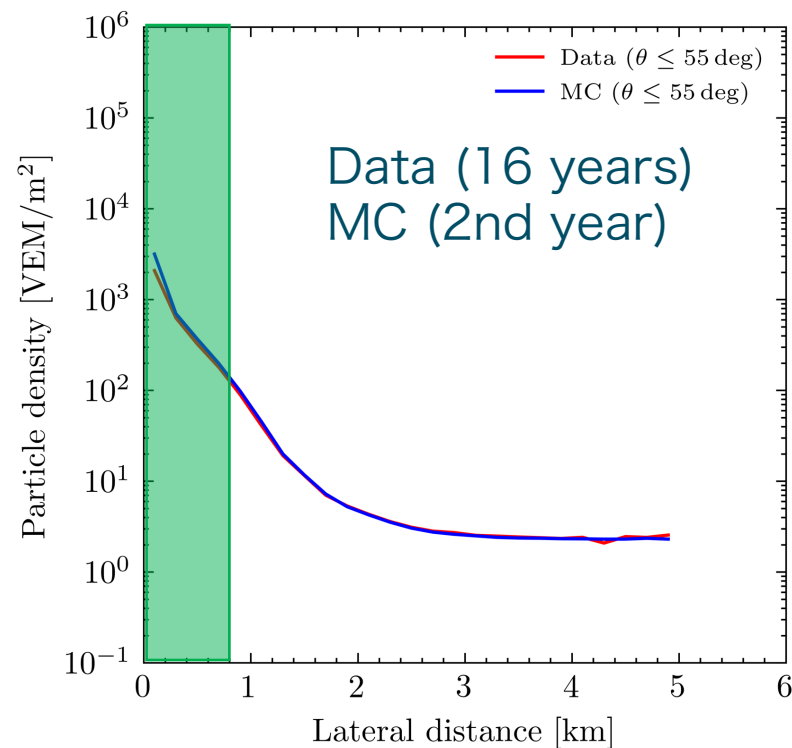
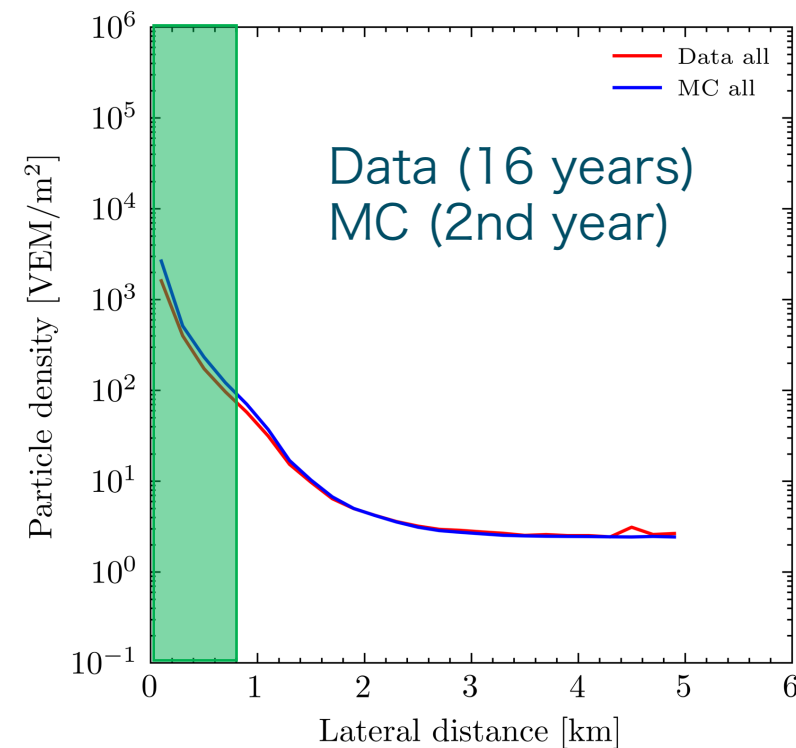
Weighted by
MC energy



Comparison on Lateral Distribution

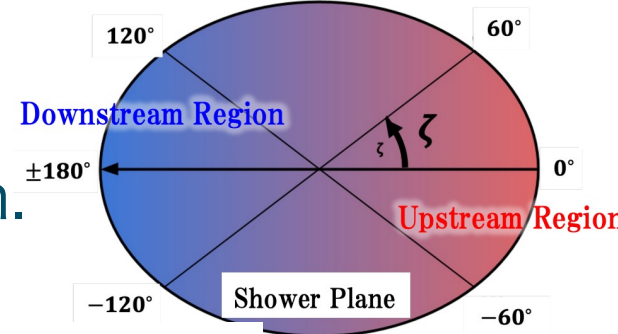
$$E_{\text{rec}} \geq 10^{19.0} \text{ eV}$$

Particles density measured by all detectors used for reconstruction
MC events are weighted by thrown energy.

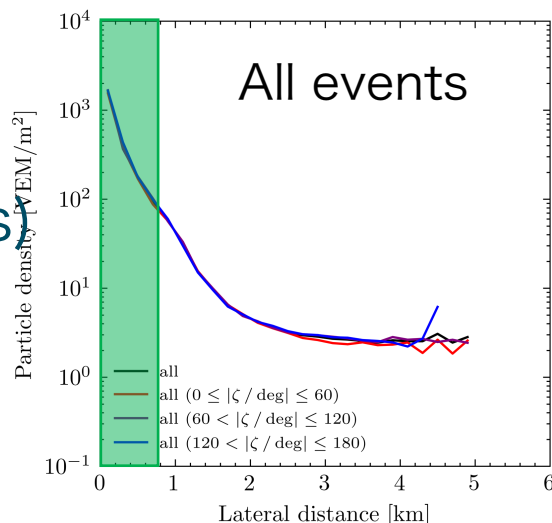


Comparison on Lateral Distribution

Particles density measured by all detectors used for recon.
Azimuthal asymmetry is introduced



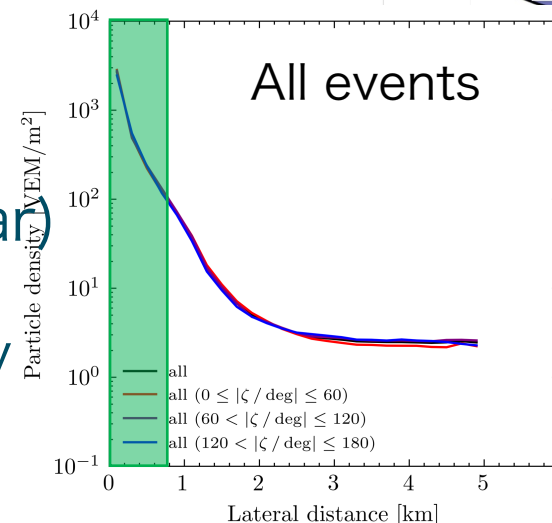
Data
(16 years)



$$E_{\text{rec}} \geq 10^{19.0} \text{ eV}$$

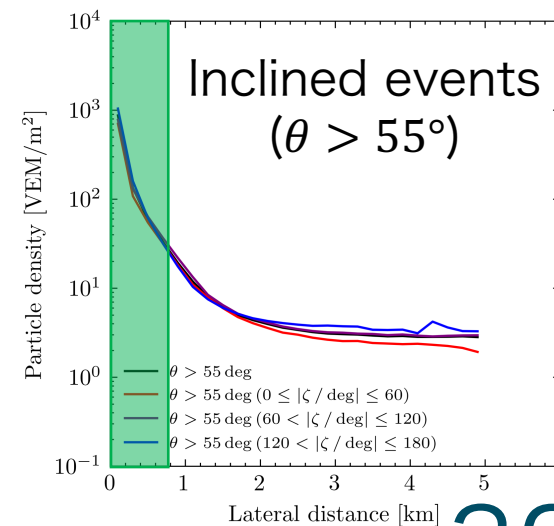
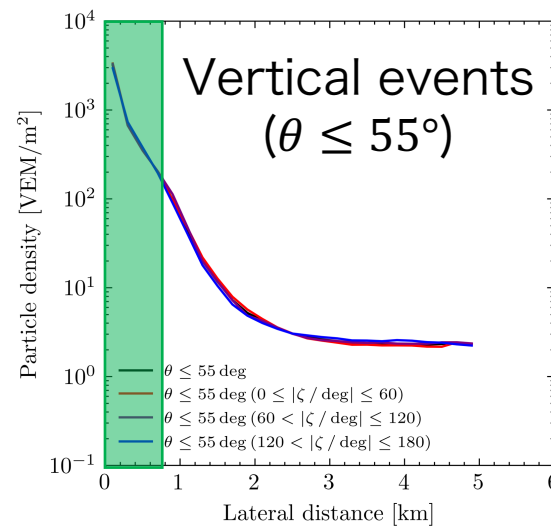
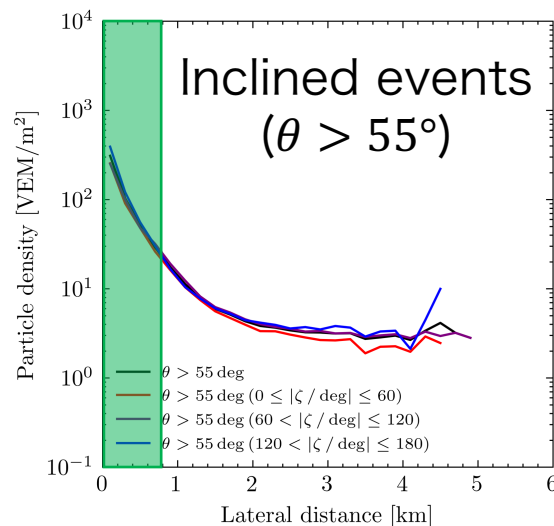
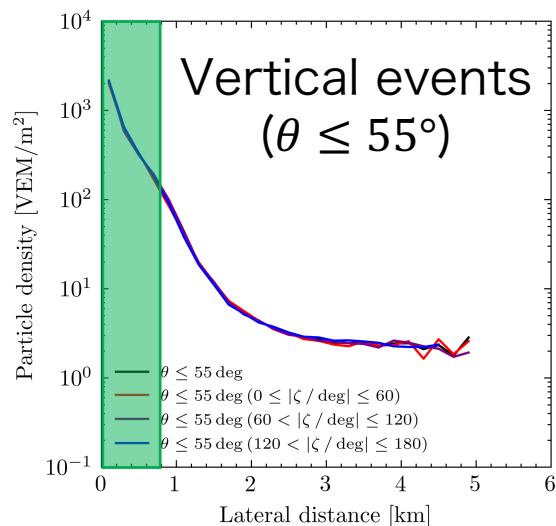
MC
(2nd year)

Weighted by
MC energy



from R. Sakamoto,
TA-JP, May 2025

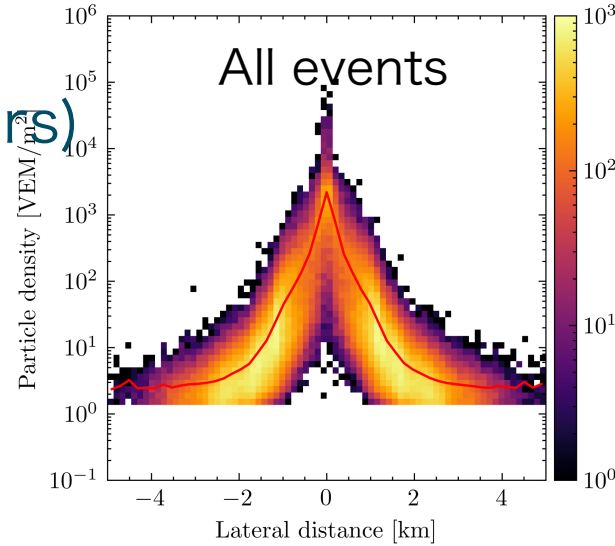
Same definition



Comparison on Lateral Distribution

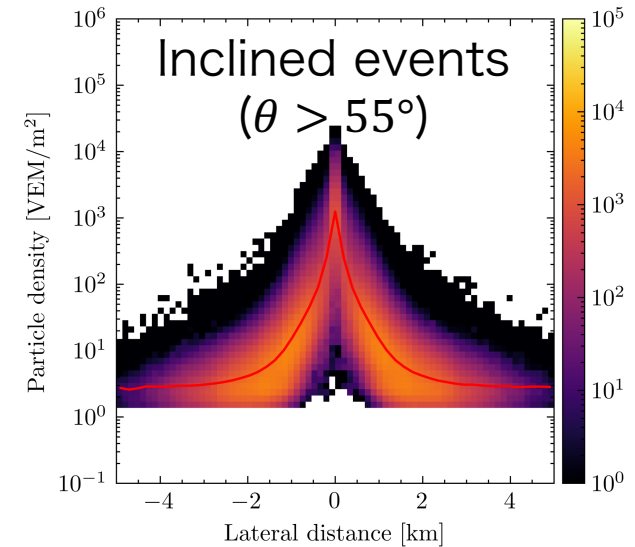
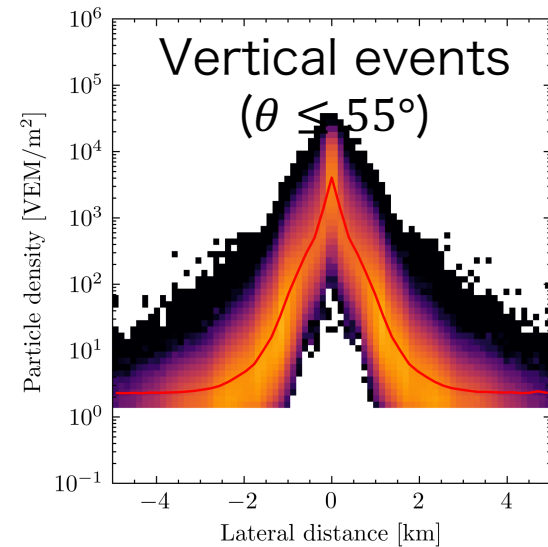
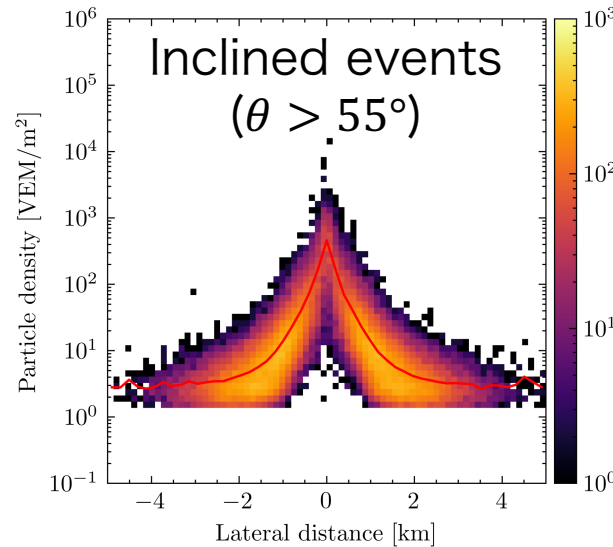
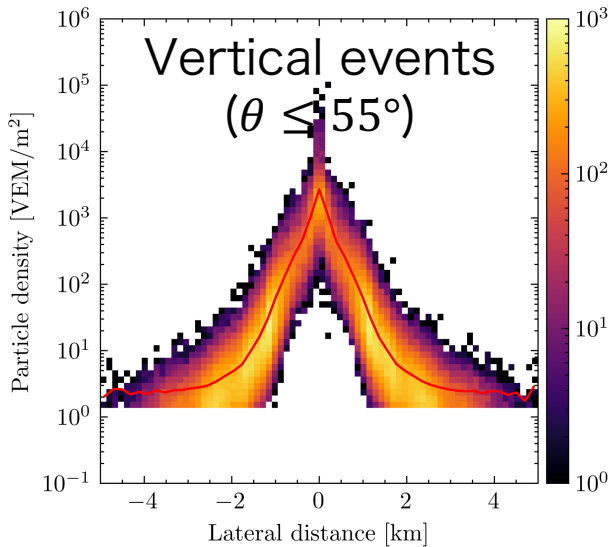
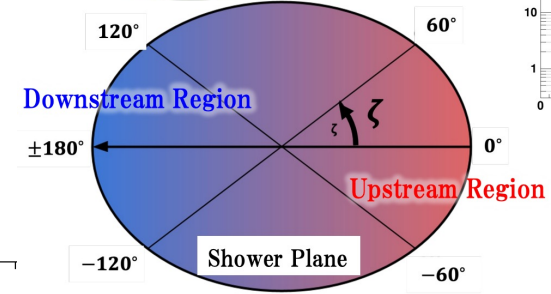
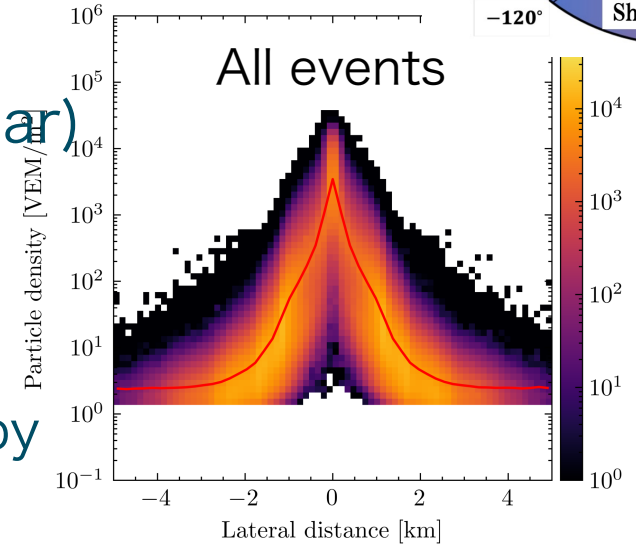
Particles density measured by all detectors used for recon.

Data
(16 years)



MC
(2nd year)

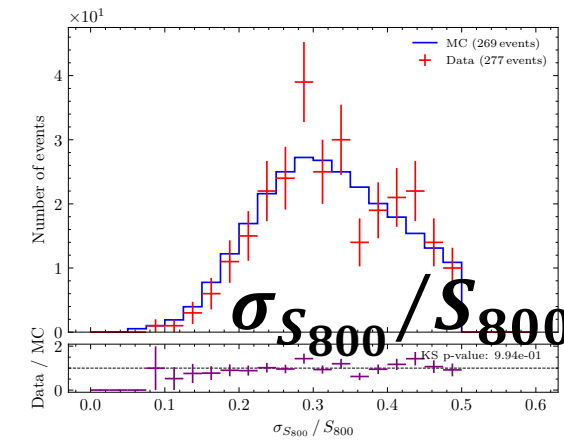
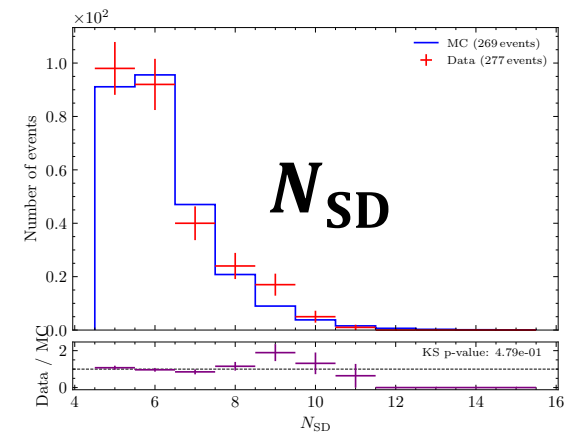
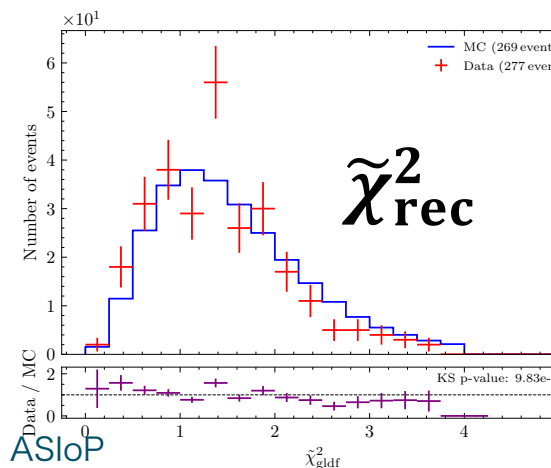
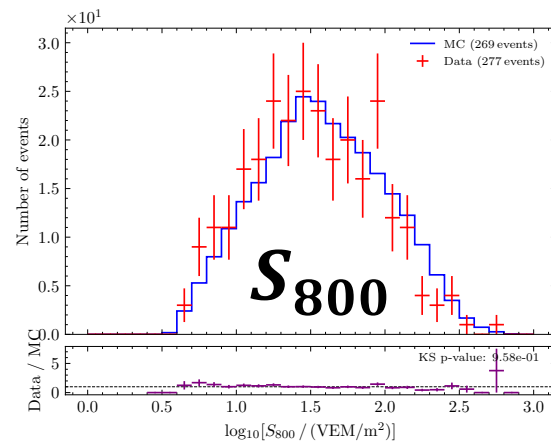
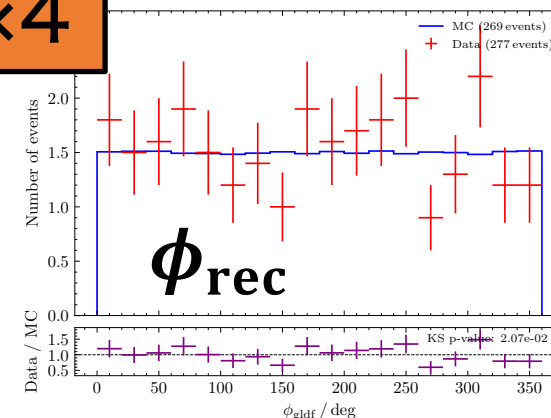
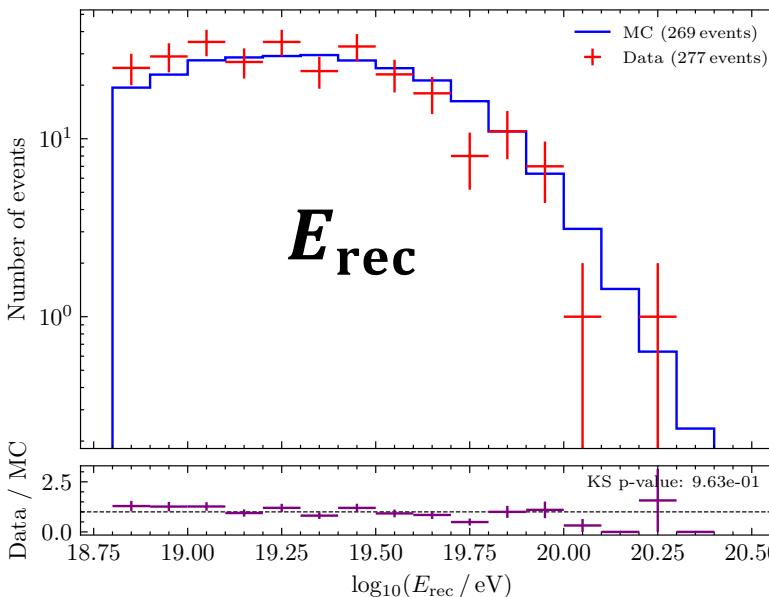
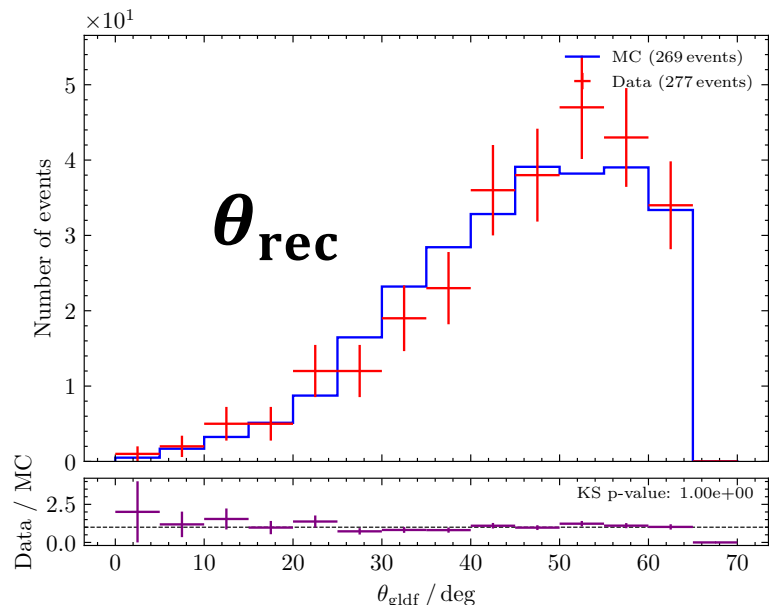
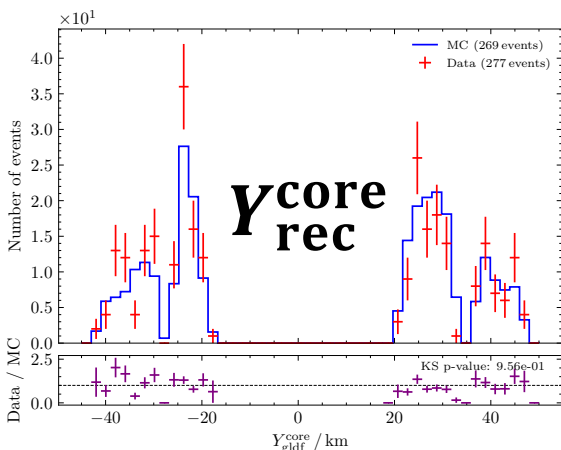
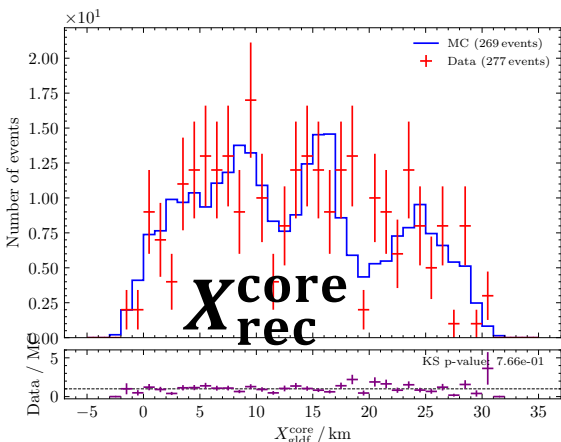
Weighted by
MC energy



Data/MC comparison

TA $\times$ 4

$\theta \leq 65^\circ$



大天頂角事象
を含めても
両者に有意な
差はない

6つのサブアレイ
のデータを足し
合わせて比較