Study of Muons with TA SD

Yuta Tange
M1 student, ICRR

2025/10/15

TA DAML workshop @ASIoP

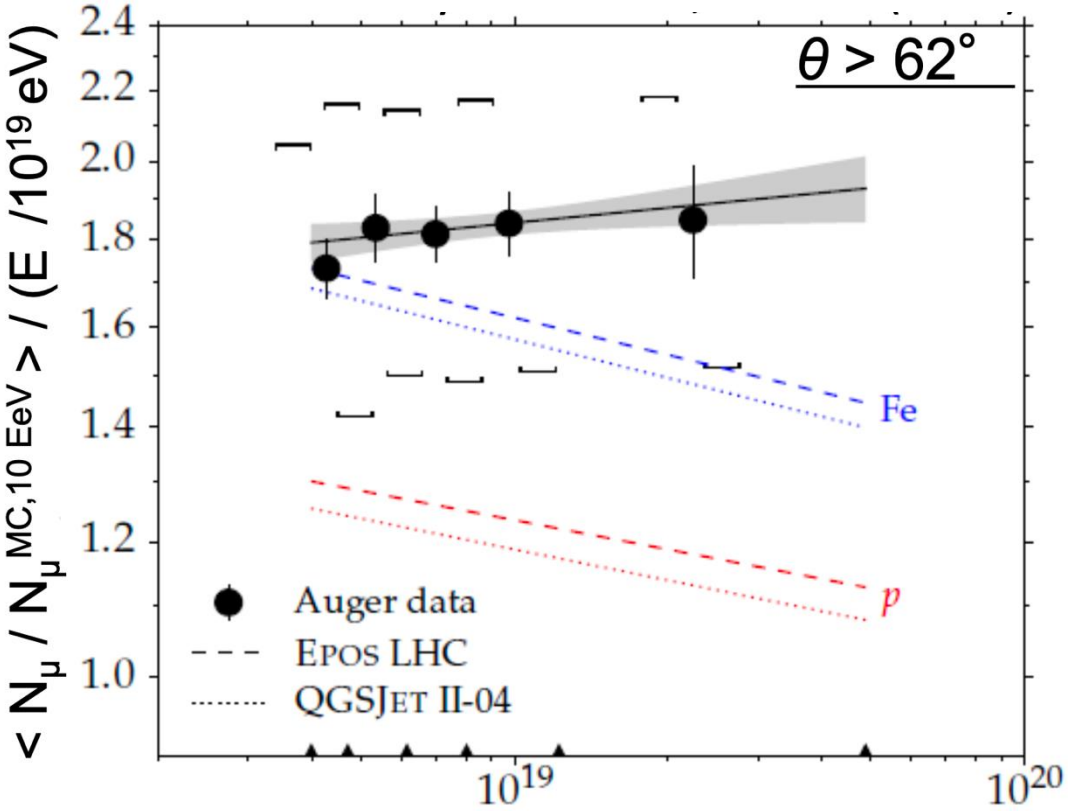
Muon Puzzle

The observed number of μ is larger than theoretical model predictions in UHECR.

by Auger obs.

$$N_\mu^{\mathrm{data}} \cong 1.8 N_\mu^{p,\,\mathrm{QGSJETII-03}}$$

⇒ Muon Puzzle



Phys. Rev. D91, 032003 (2015)

Z-factor

Muon Puzzle is reported from many studies,
but there're many difference between observatory, analysis method, etc…

➡ How to evaluate this deference ?

$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p},$$

Normalizing the number of muons in data by that in MC.

Using simulation to account for differences in observation.

Primary Particle : Fe ➡ $z = 1$

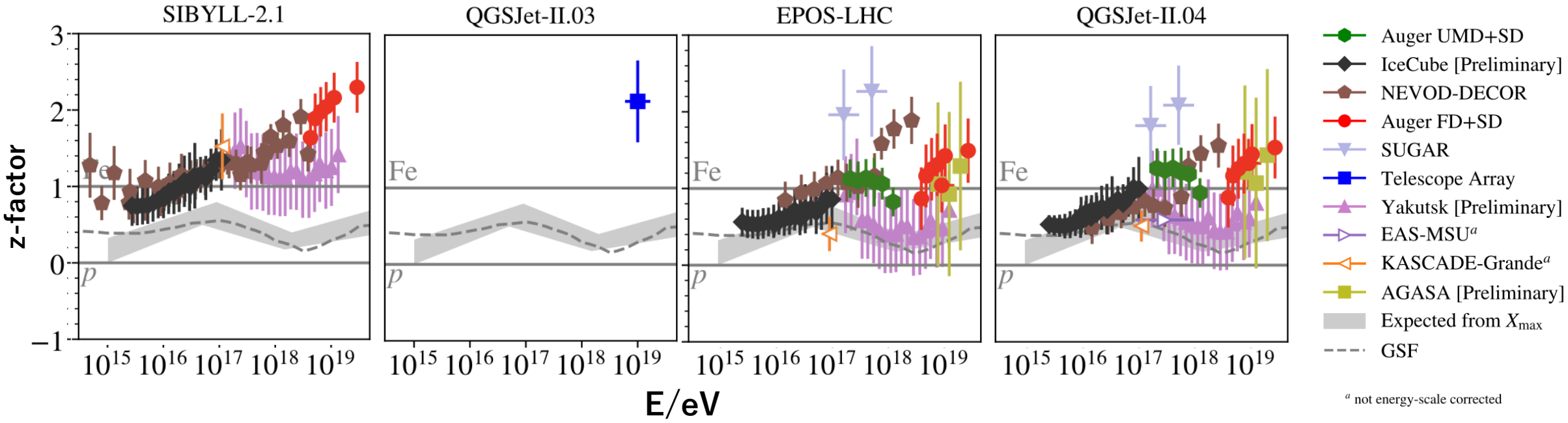
Primary Particle : p ➡ $z = 0$

(Muon count corresponding to)
Particles heavier than iron ➡ $\mathrm{z} > 1$

Muon Puzzle by various observations

$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p},$$

Normalizing the number of muons in data by that in MC.



z factors are larger than expected from $X_{\max}$ measurements

z factors are close to or exceeds 1 (i.e. heavier than Fe.)

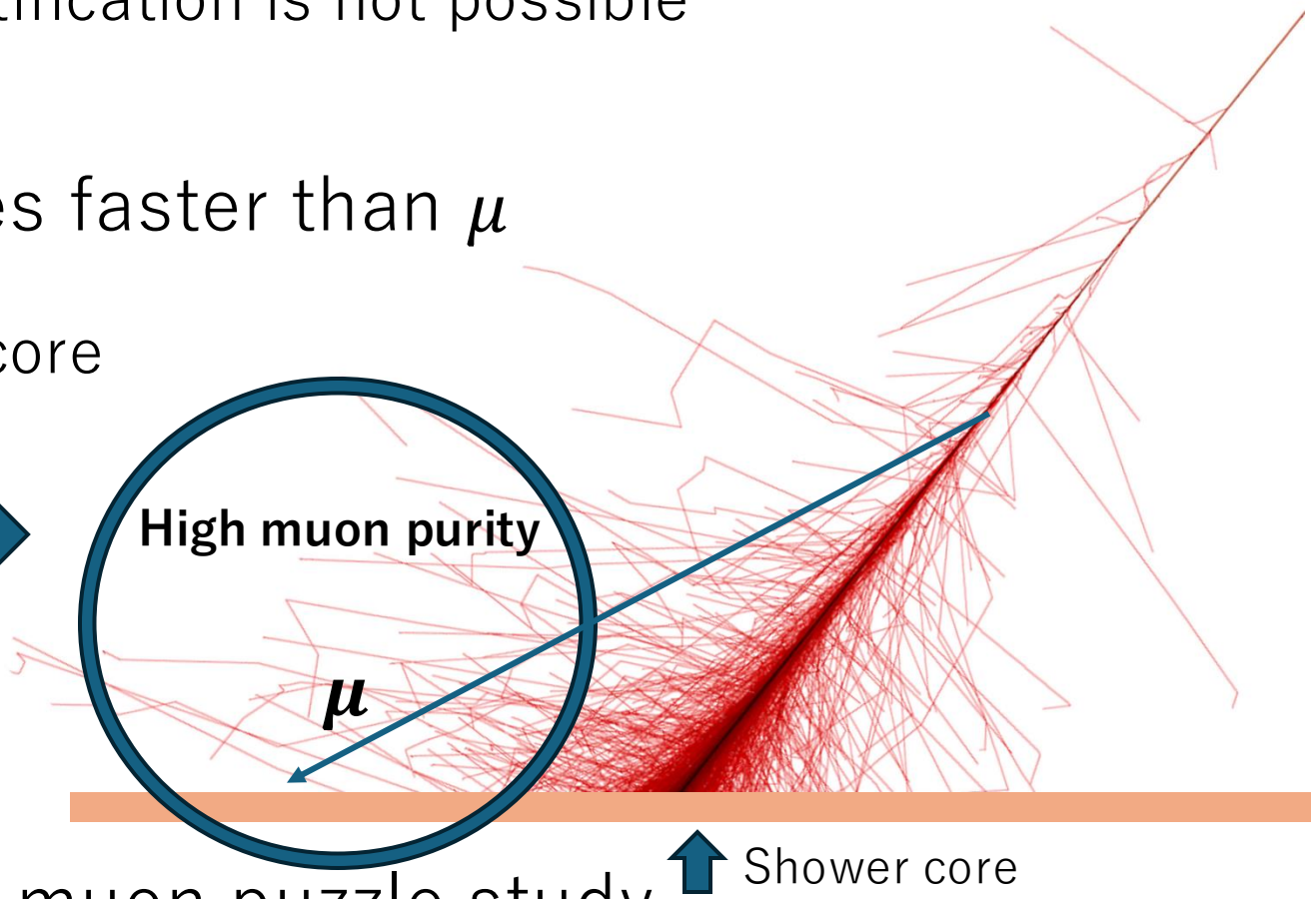
Analysis Framework (Takeishi-san)

How can we identify muons with the TA SD?

Direct particle identification is not possible

EM component → attenuates faster than μ

At large lateral distances from the core
(i.e., longer propagation paths)

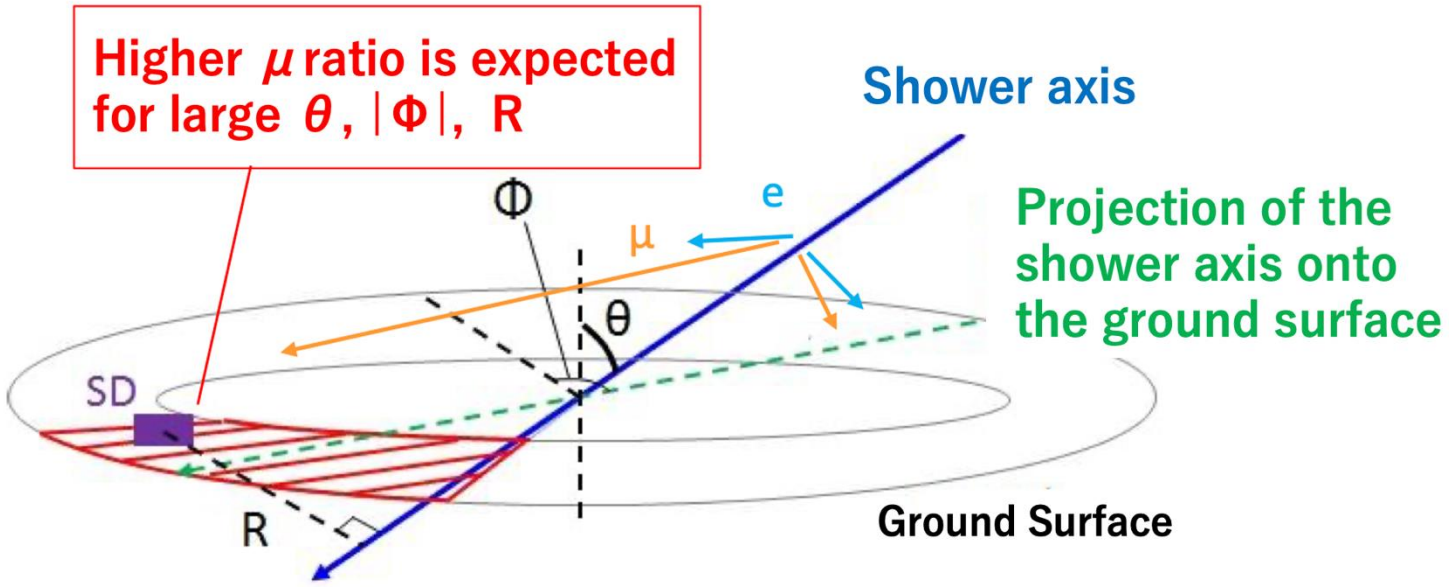


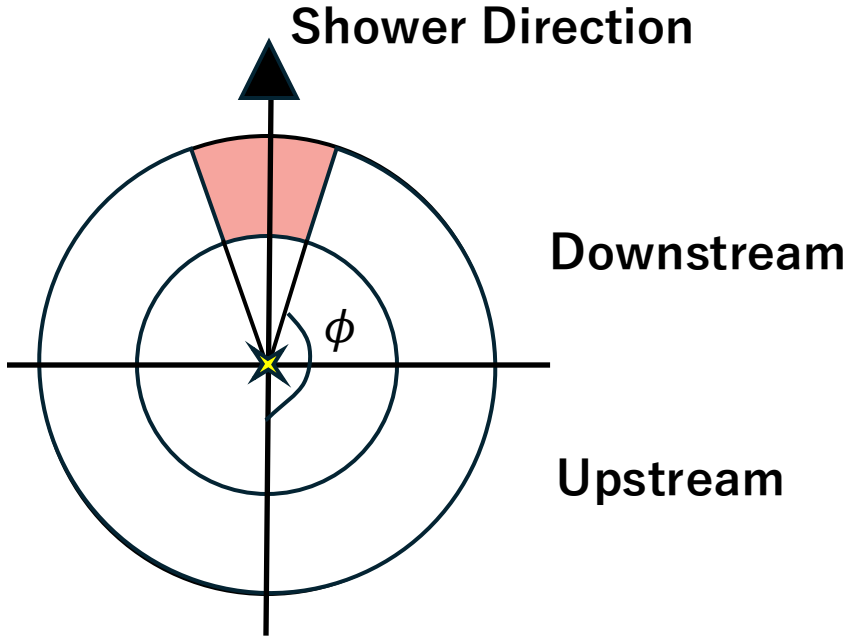
muons fraction becomes higher

That area can be used for muon puzzle study

Analysis Framework (Takeishi-san)

- High muon purity area:
  - shower with large zenith angle
  - opposite to the shower direction (i.e. downstream)
  - distant from shower core





Analysis Framework (Takeishi-san)

Dataset

Period: 7 years

$30° < \theta < 45°$

$150° < |\phi| < 180°$

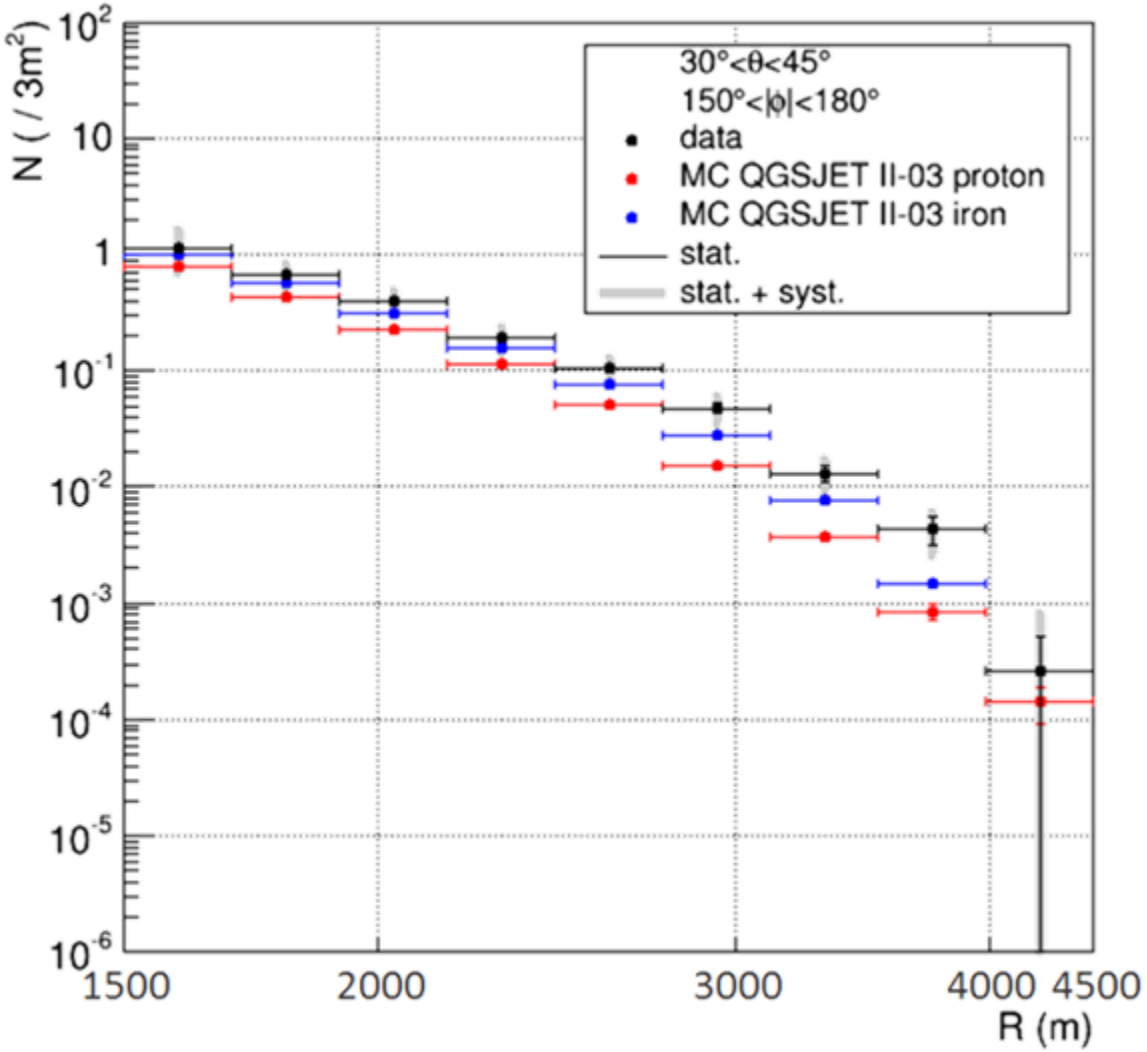
$10^{18.8} < E/\mathrm{eV} < 10^{19.2}$

More distant area (i.e. high muon purity)

$$S_{\mathrm{ave,data}} > S_{\mathrm{ave,MC}}$$

average lateral distribution

$(30° < \theta < 45°, 150° < |\phi| < 180°, 10^{18.8} < E < 10^{19.2})$



Plan

Step 0 Reproduction of Takeishi-san's analysis
(QGSJET II -03, p, $\mathbf{Fe}$, $\mathbf{10^{18.8} \leq E/eV \leq 10^{19.2}}$)

Step 1 Model: QGSJET II -03 (Proton, Fe) ⇒ QGSJET II -04, EPOS-LHC, SIBYLL (Proton, Fe)

Step 2 Energy: $\mathbf{10^{18.8} \sim 10^{19.2}\ eV}$ ⇒ (update) $E \leq 10^{18.8}\mathrm{eV}, 10^{19.2}\mathrm{eV} \leq E$ with TA SD
Higer/Lower energy with TAx4 TALE

Other Model ⇒ How does the result vary across different models?
How consistent are the results among different TA SD analyses?

Other Energy ⇒ What is the energy dependence of the muon puzzle?

My progress

Now: STEP 0

→ reproduce average lateral distribution

Dataset

MC:

Model	QGS Jet II -03
Primary Particle	proton
Energy Range	$10^{17.45} \leq E/\mathrm{eV} \leq 10^{20.55}$ (eV)
Zenith Range	$0° \leq \theta \leq 60°$

Data:

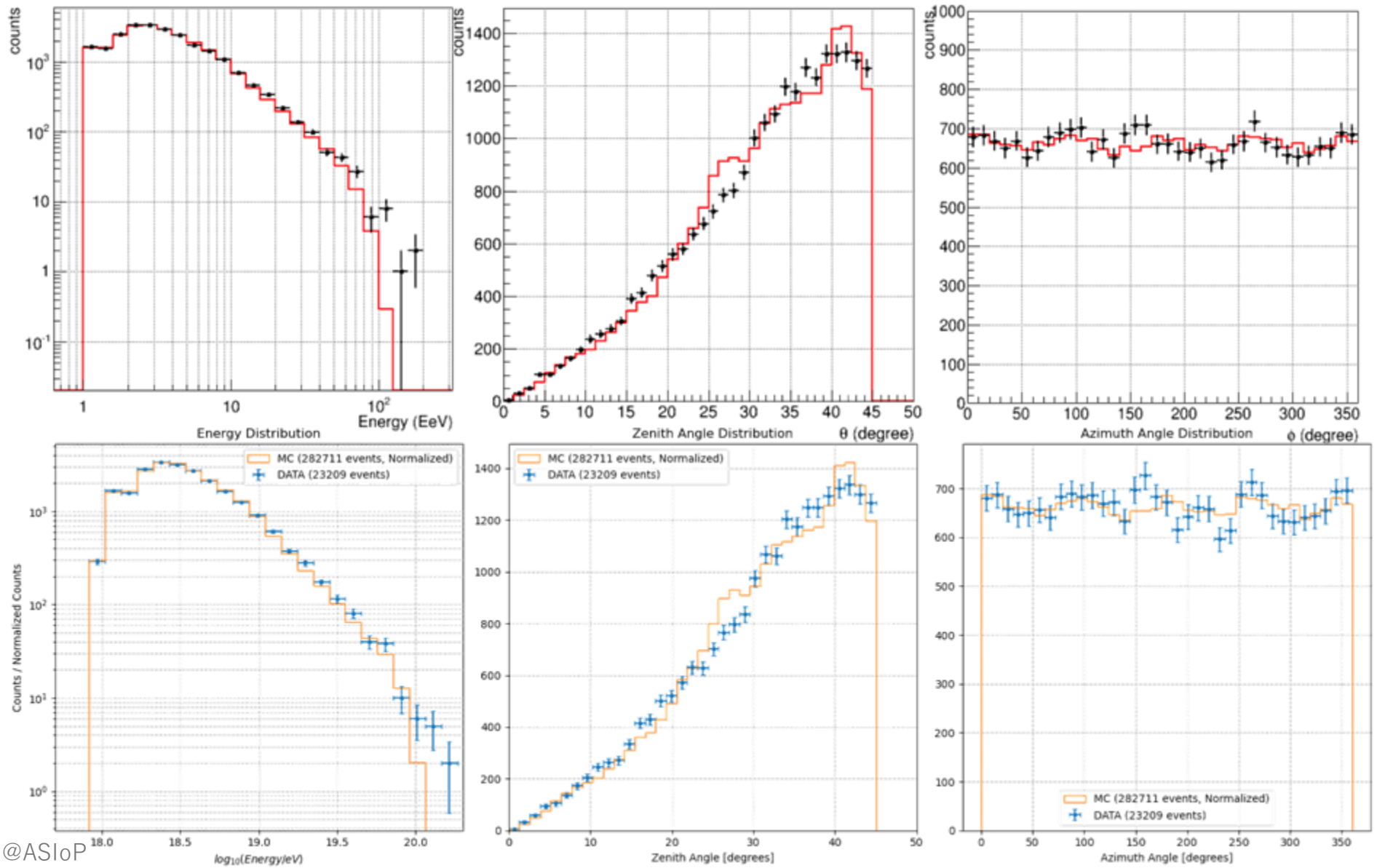
Period	7 years

DATA/MC Comparison

Reconstructed
DATA,MC events

DATA (Takeishi)
MC (Takeishi)

DATA (Tange)
MC (Tange)



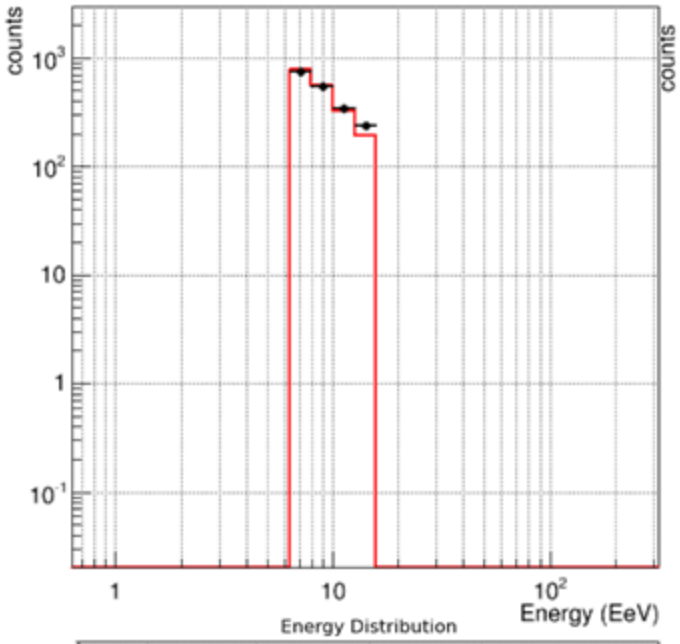
DATA/MC Comparison

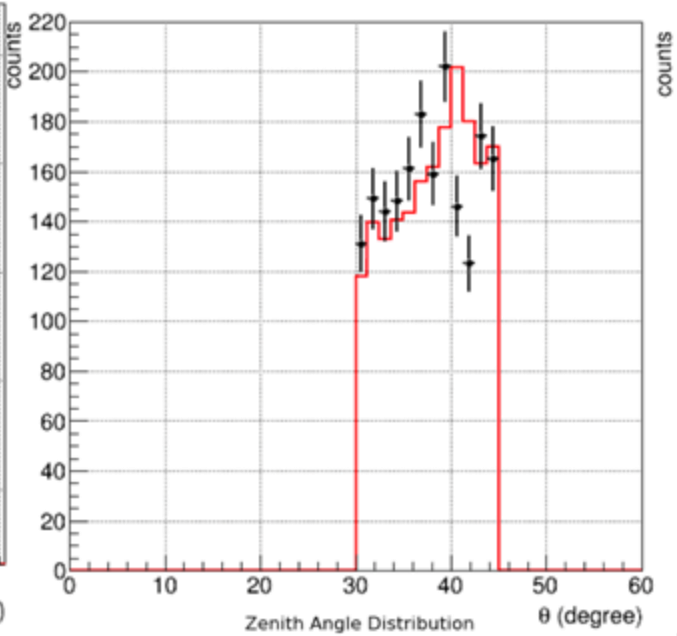
After selection

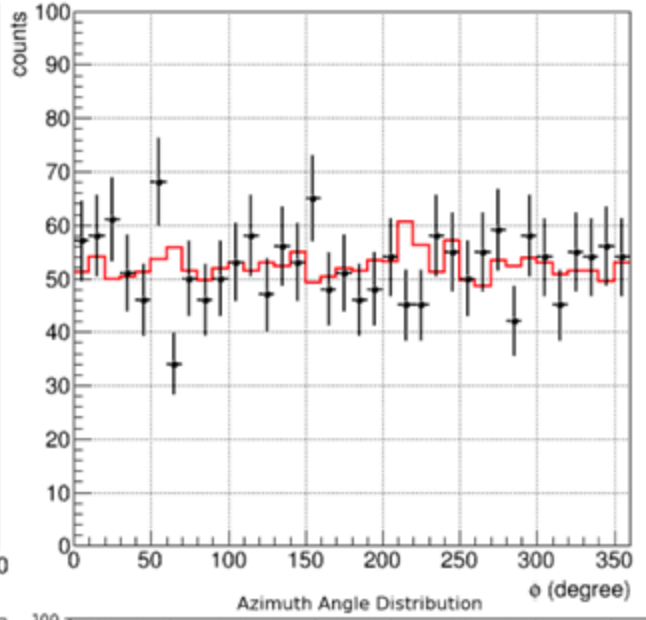
Data: 7 y
$30° < \theta < 45°$
$10^{18.8} < E < 10^{19.2}$

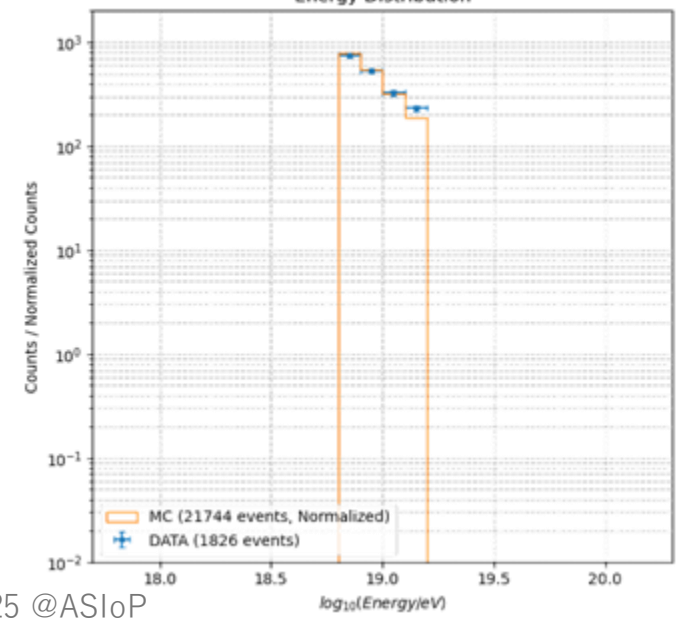
DATA (Takeishi)
MC (Takeishi)

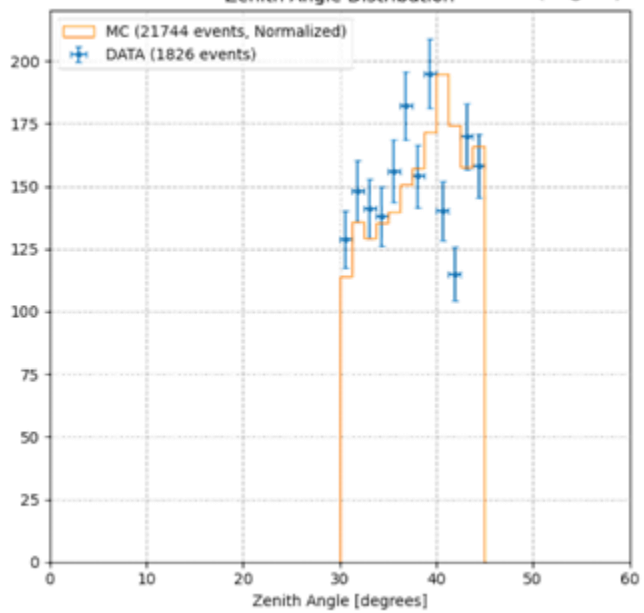
DATA (Tange)
MC (Tange)

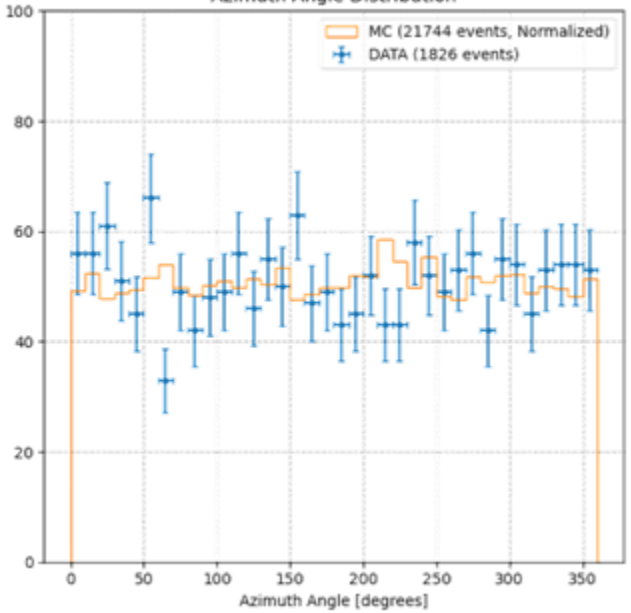






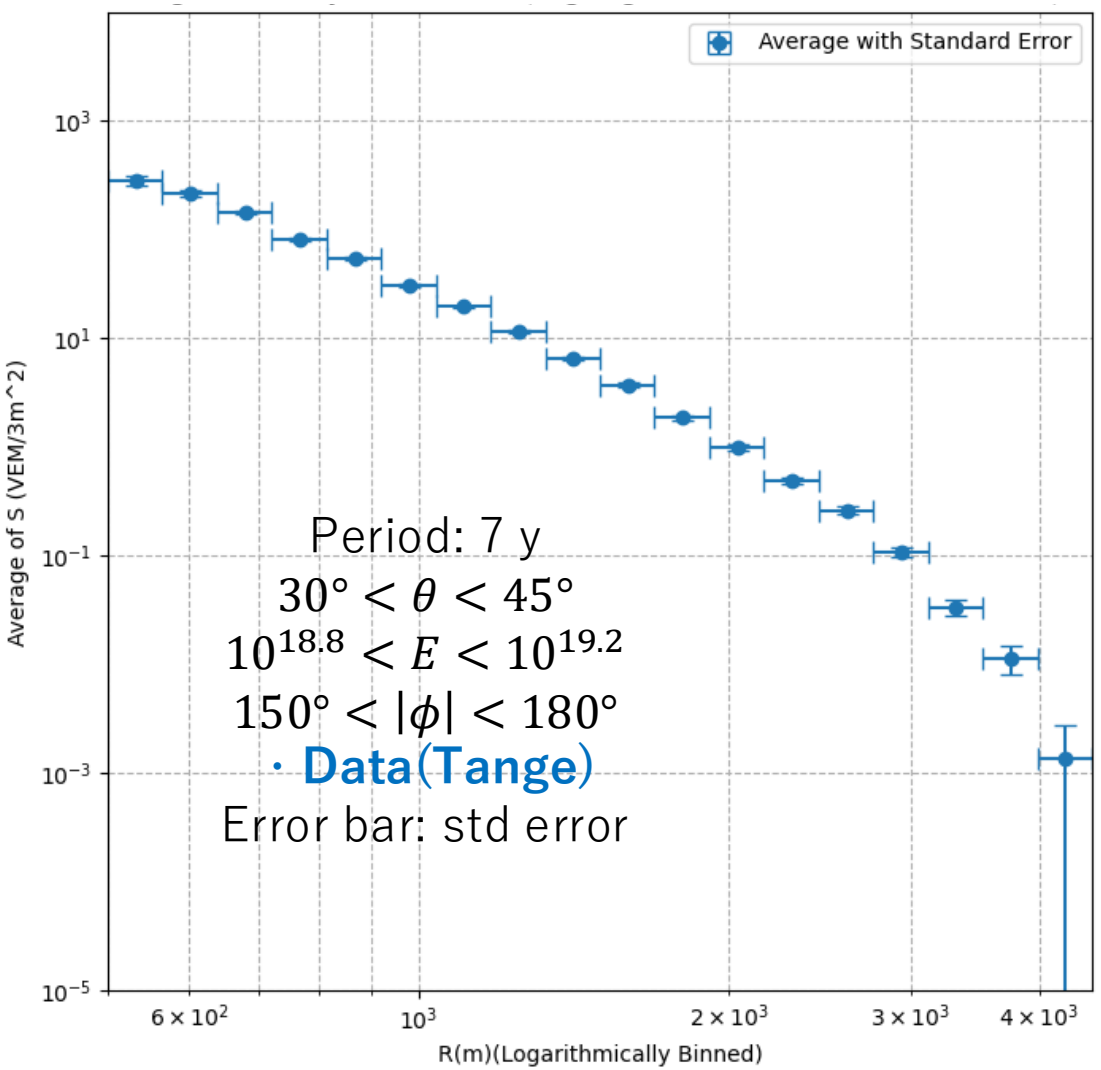




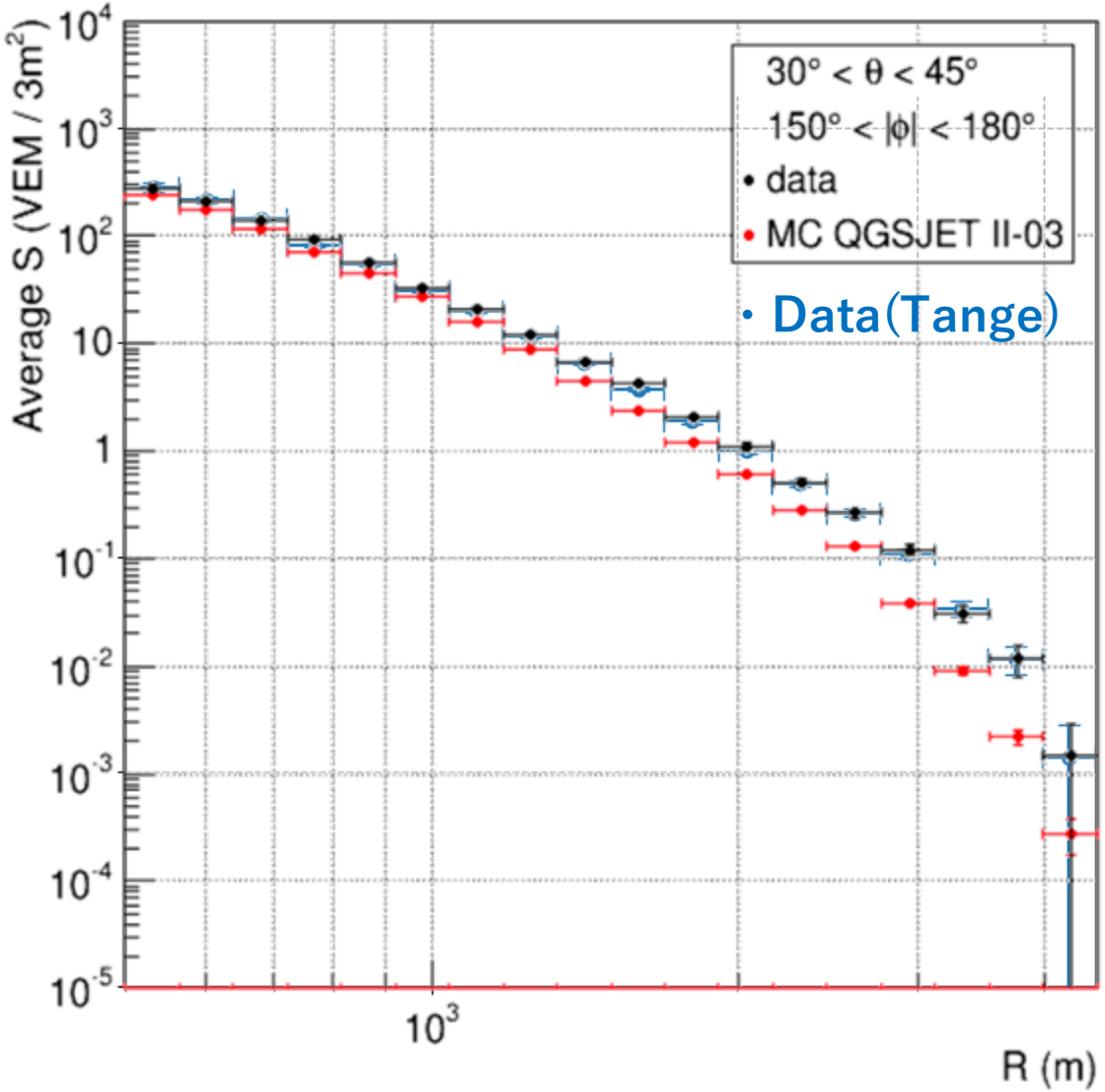


DATA

Lateral distributions: avg. signal size(DATA)



Compare with result of Takeishi-san



My result is <u>seemed to</u> agree with Takeishi analysis

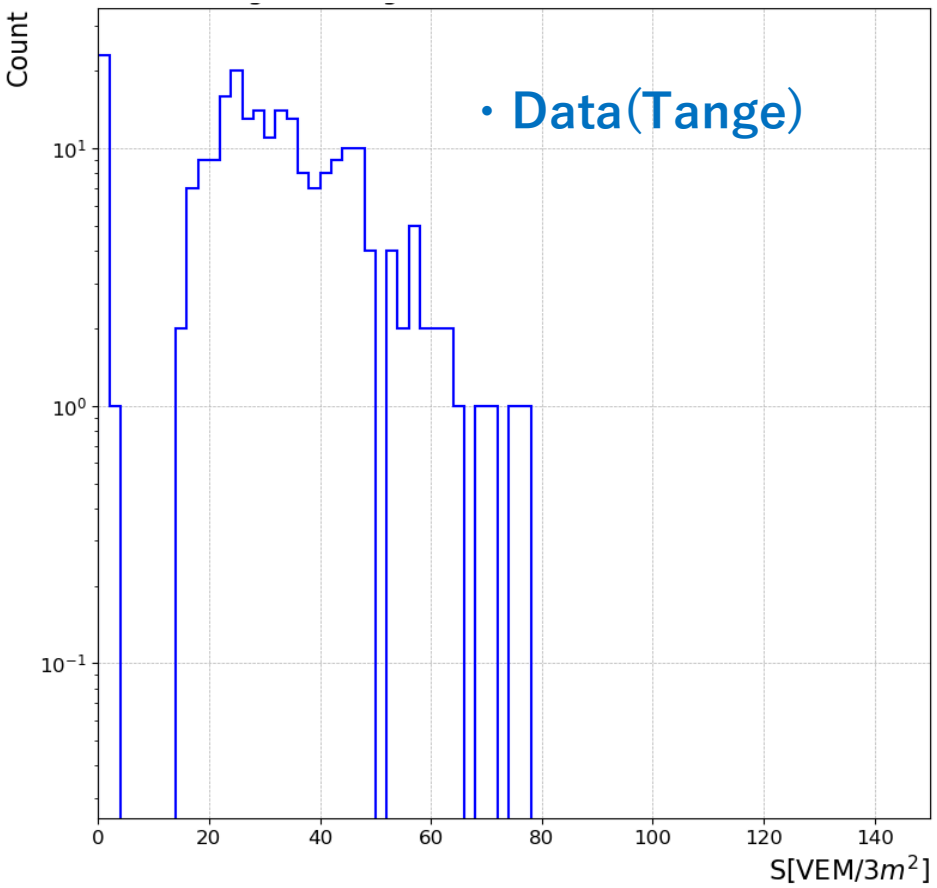
DATA

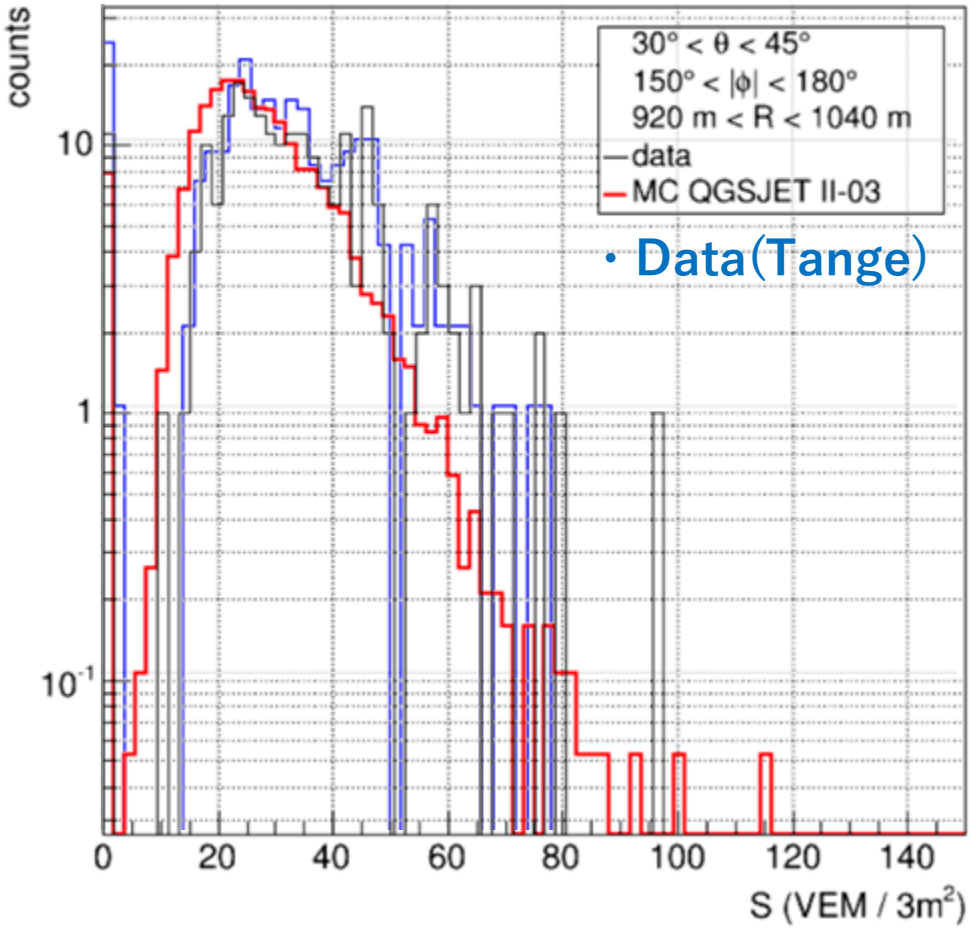
Distribution of signal sizes within each bin

slight differences depending on the analysis.

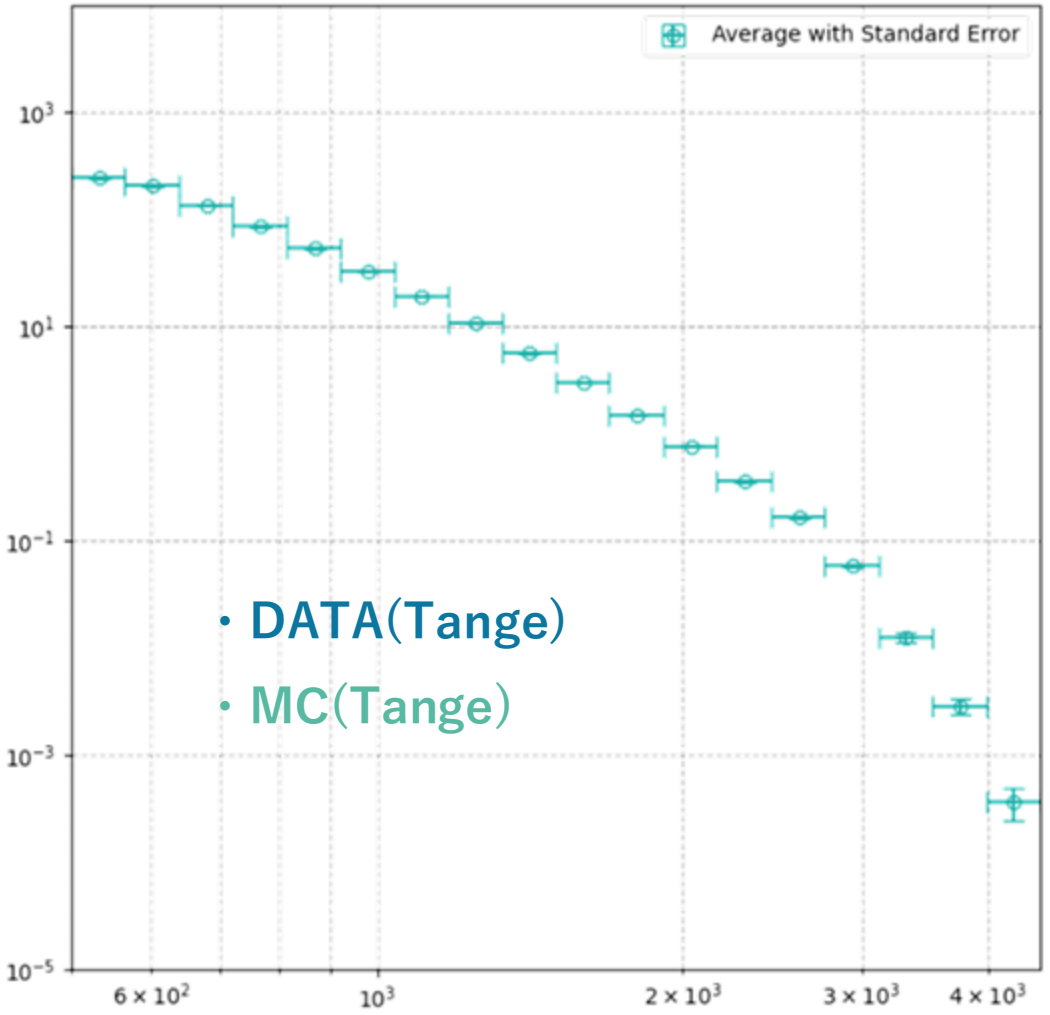
→ Difference in handling of offline SDs and working-but-zero-signal SDs?

Distribution of Signal Size $920\mathrm{m} \leq R \leq 1040\mathrm{m}$

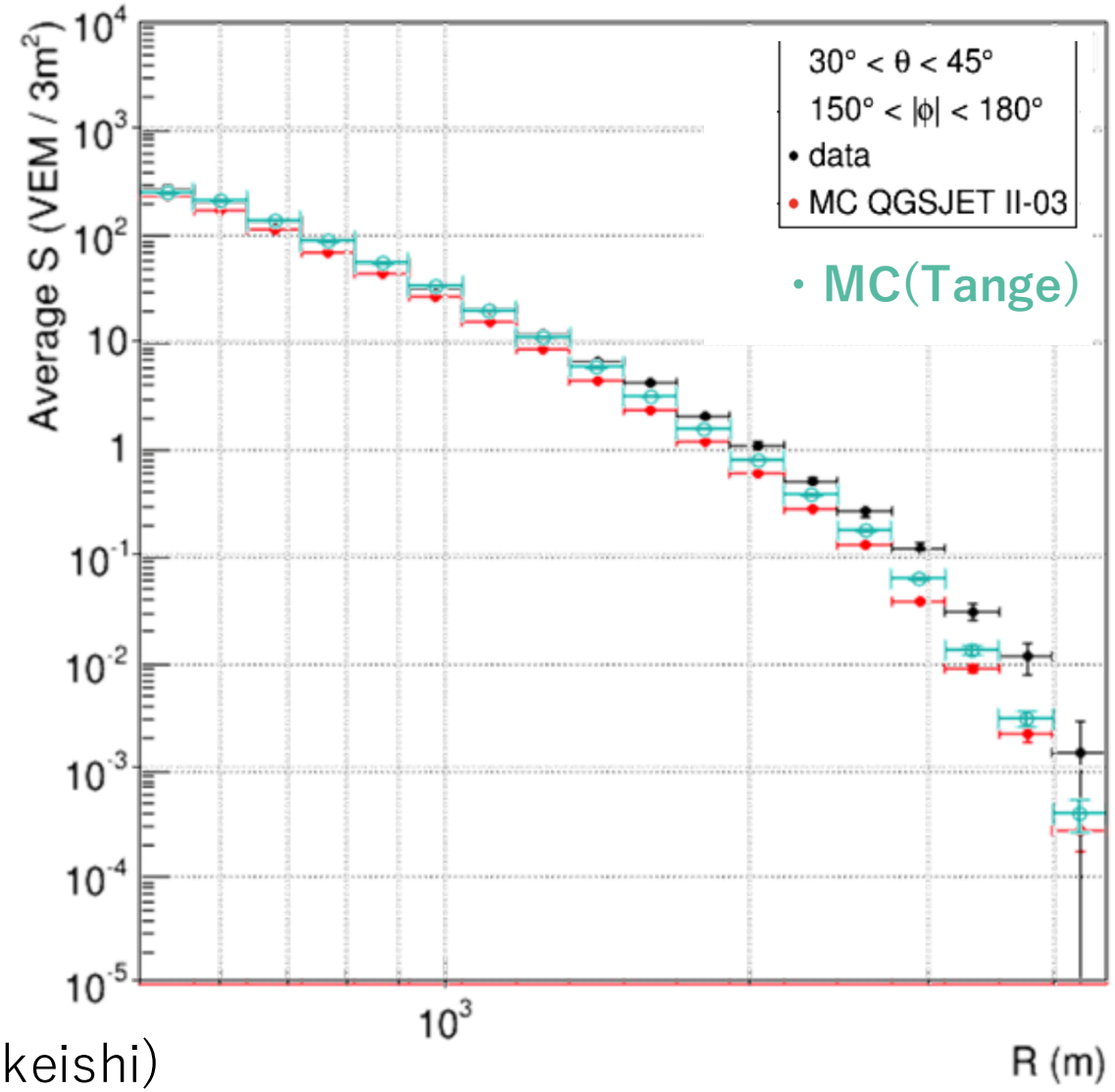




Lateral distributions: avg. signal size(MC)



Comparison with result of Takeishi-san

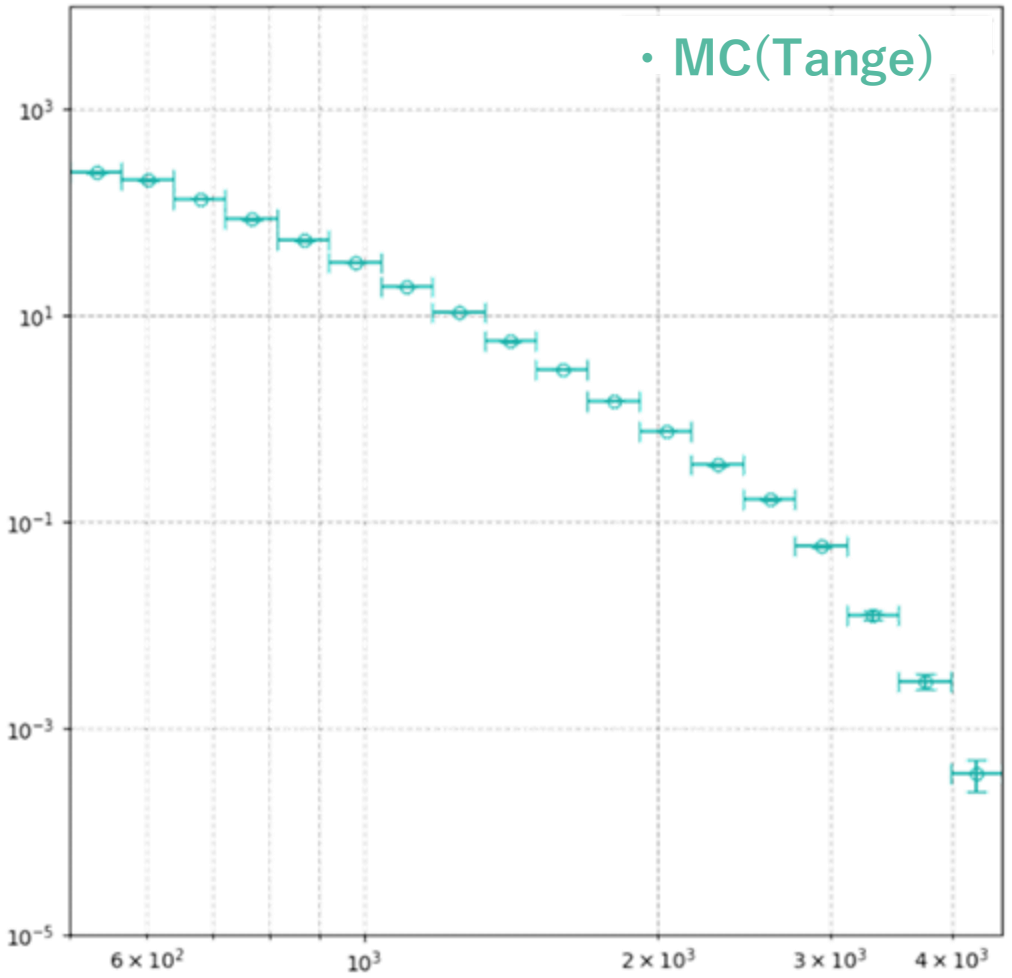


MC(Tange) has larger average S from MC(Takeishi)

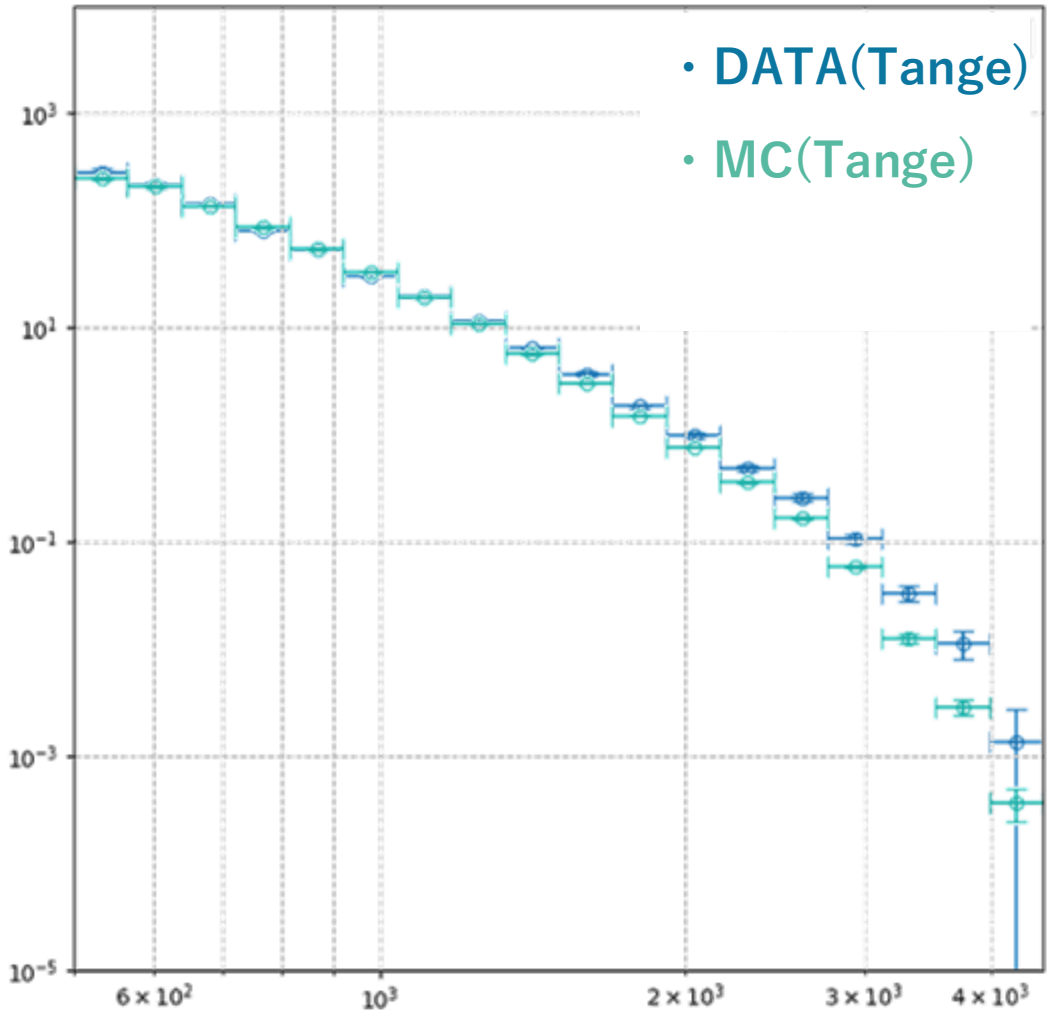
Not reproduced, need to find out and fix the causes

MC

Lateral distributions: avg. signal size(MC)



Compare with DATA(YTange)



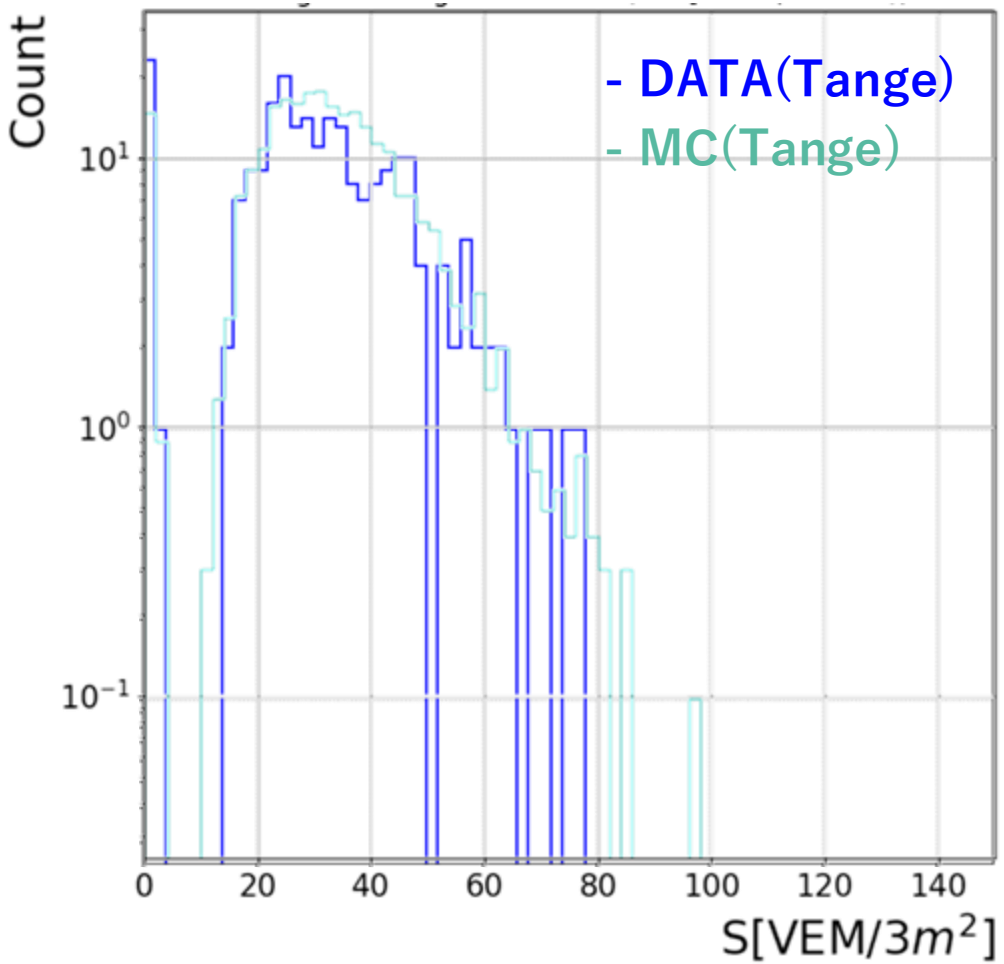
R is small → MC seem to agree with DATA

R is large → MC‘s signal size is smaller than that of DATA

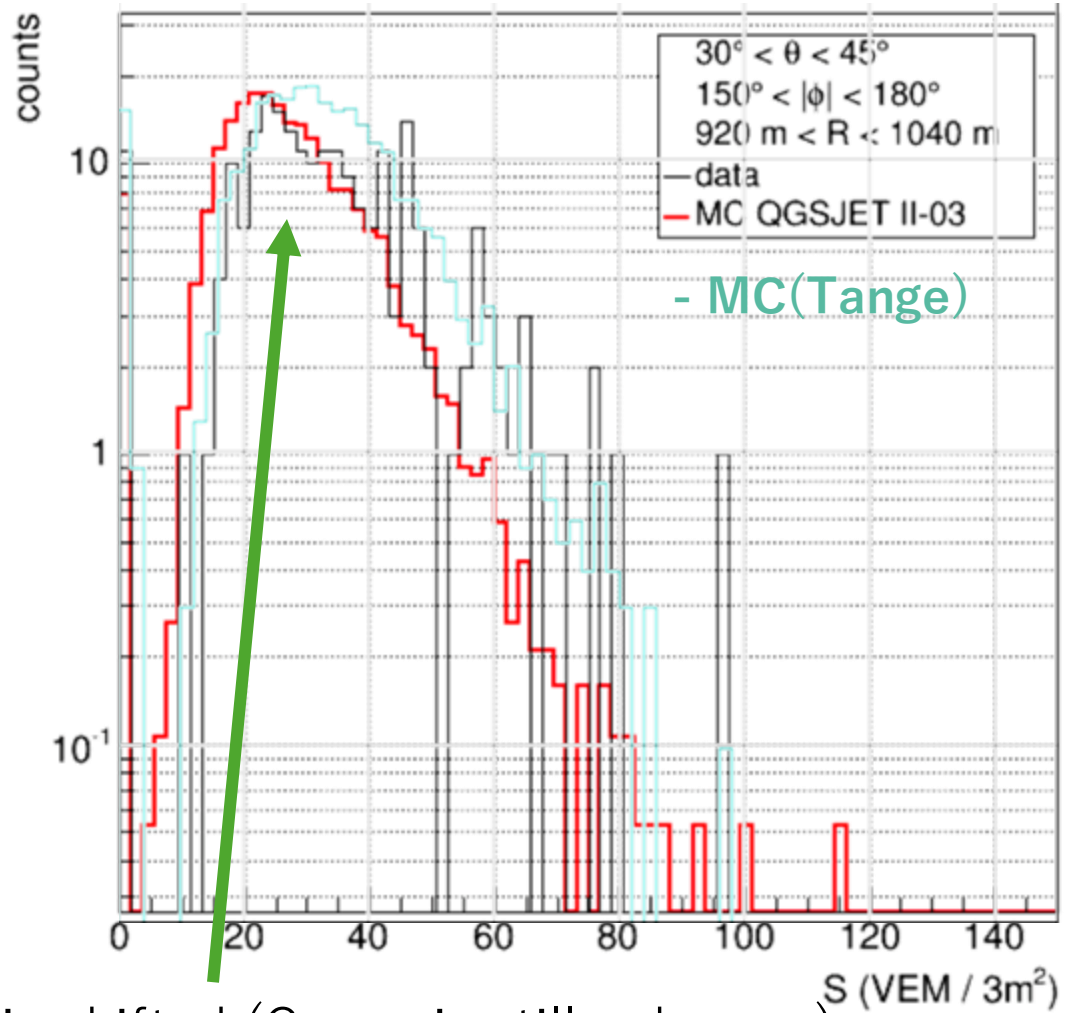
MC

Distribution of signal sizes within each bin

Signal Size distribution in $920\mathrm{m} \leq R \leq 1040\mathrm{m}$



Compere with result of Takeishi-san



Peak is shifted (Cause is still unknown)

Current Status

DATA
- Average lateral signal size → Shows a good agreement.
- Signal distribution per distance bin → Not an exact match.

MC
- Average lateral signal size →
- Signal distribution per distance bin →

Shows an overall shift toward larger values.

Possible Causes

Difference in MC data sets

Issues in event selection (minor differences may still exist)

summary

Now

reproduction of distribution of data
reproduction of lateral distribution of MC

Next

Update of MC model (QGSJET II -03 → -04, EPOS-LHC)

(Planning same energy range)

Other energy range

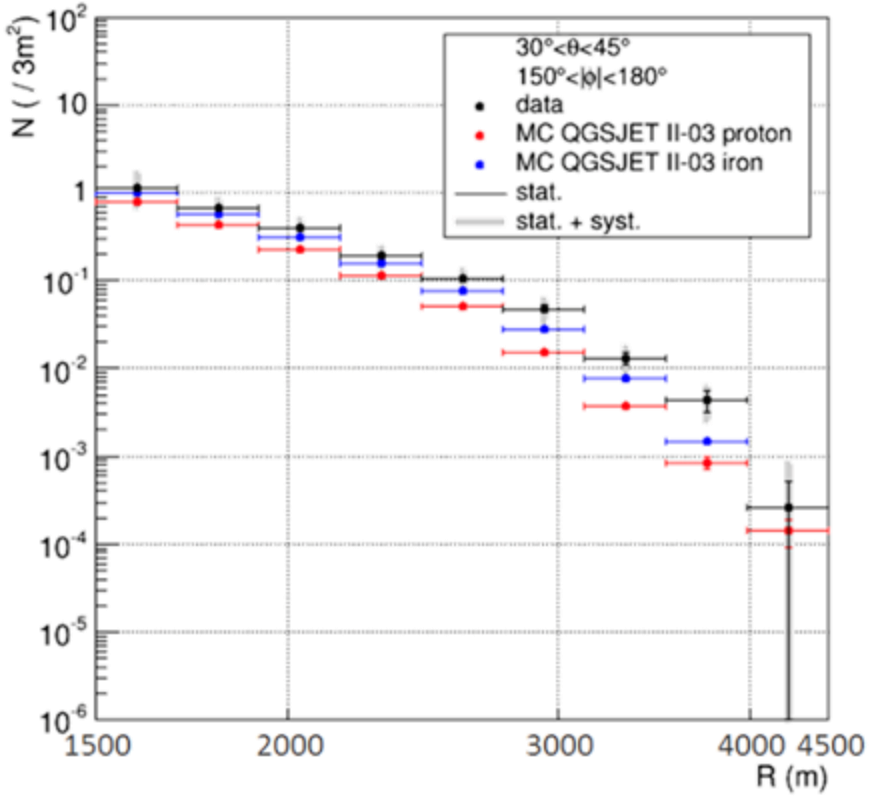
(Planning low-energy expansion with TA TALE or infill)

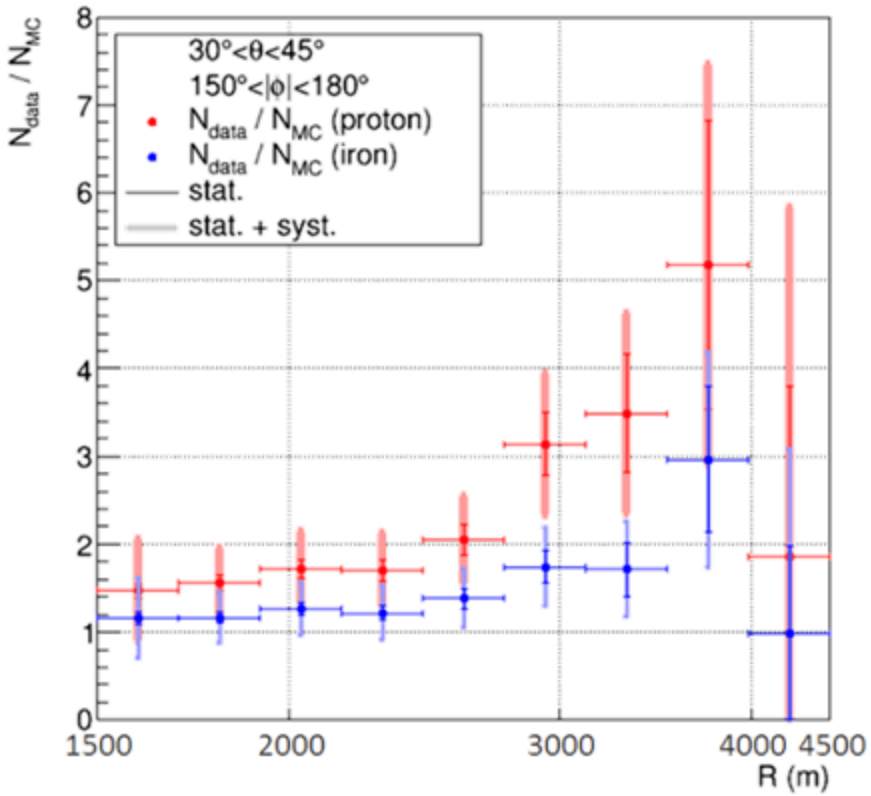
(or high-energy expansion with TAx4)

back up

Result by TA SD

Study with TA SD: QGSJet- II .03, $10^{18.8} < E < 10^{19.2}$ (Takeishi-san)





Analysis Framework (Takeishi-san)

How can muons be identified with the TA SD?

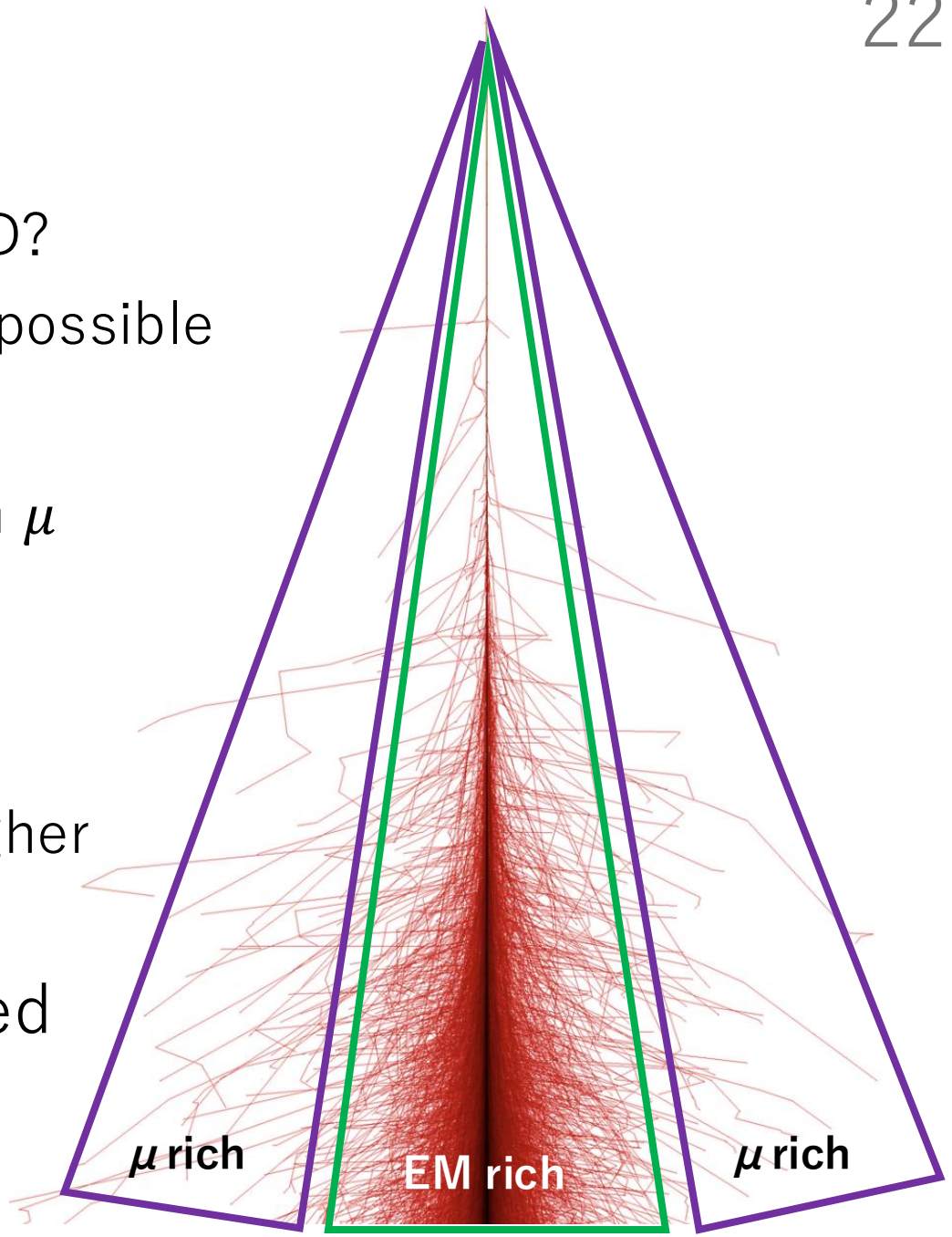
Direct particle identification is not possible

EM component → attenuates faster than μ

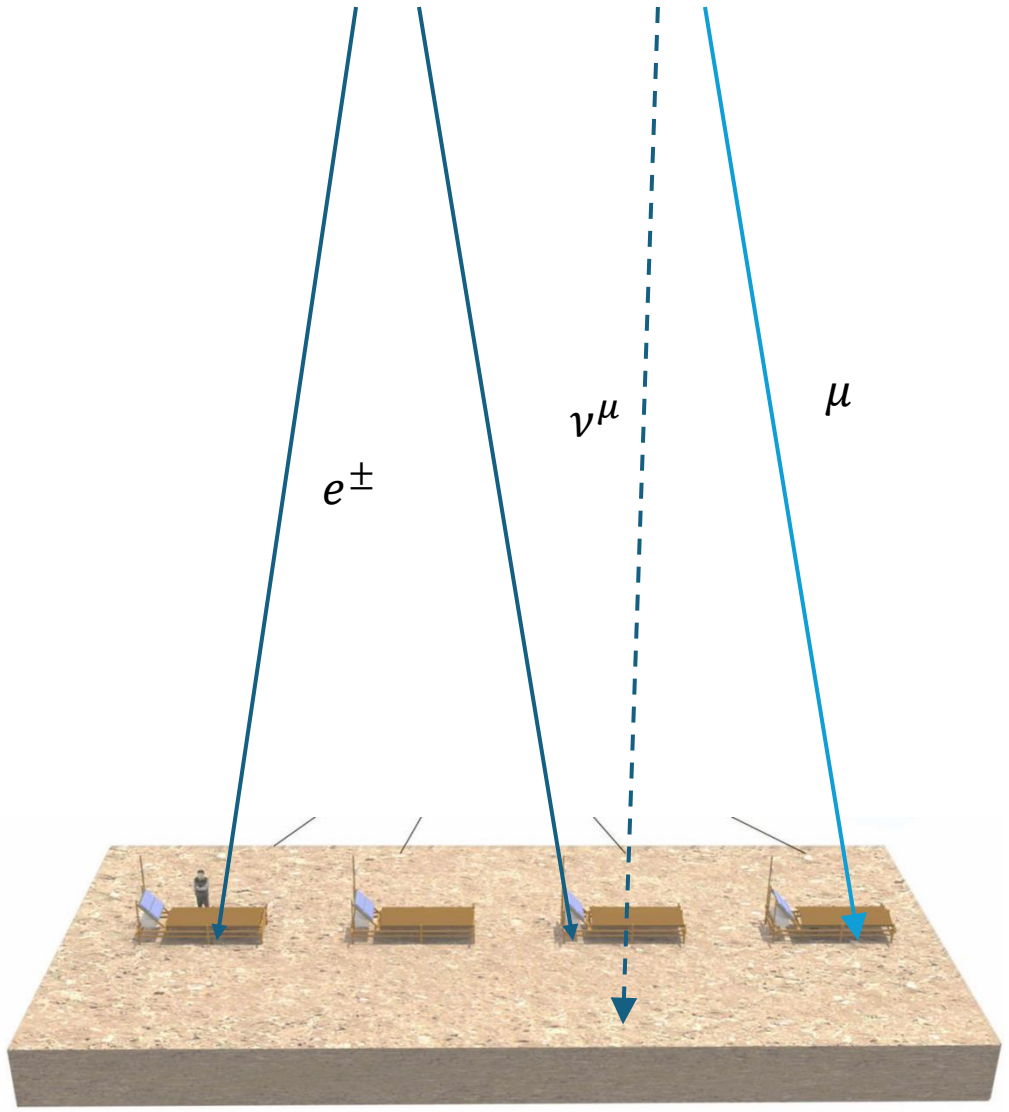
At large lateral distances from the core
(i.e., longer propagation paths)

→muons fraction becomes higher

➡ High putiyy muon can be observed



Air Shower(Detection)



How to Observe Muons with TA SD?

Auger → Uses water tanks

Direct μ measurement is possible via the Water Cherenkov effect.

TA SD → Uses plastic scintillators

At high energies, signals from EM and μ are (almost) indistinguishable.

→ μ cannot be measured directly.

How can we evaluate the impact of the Muon Puzzle?

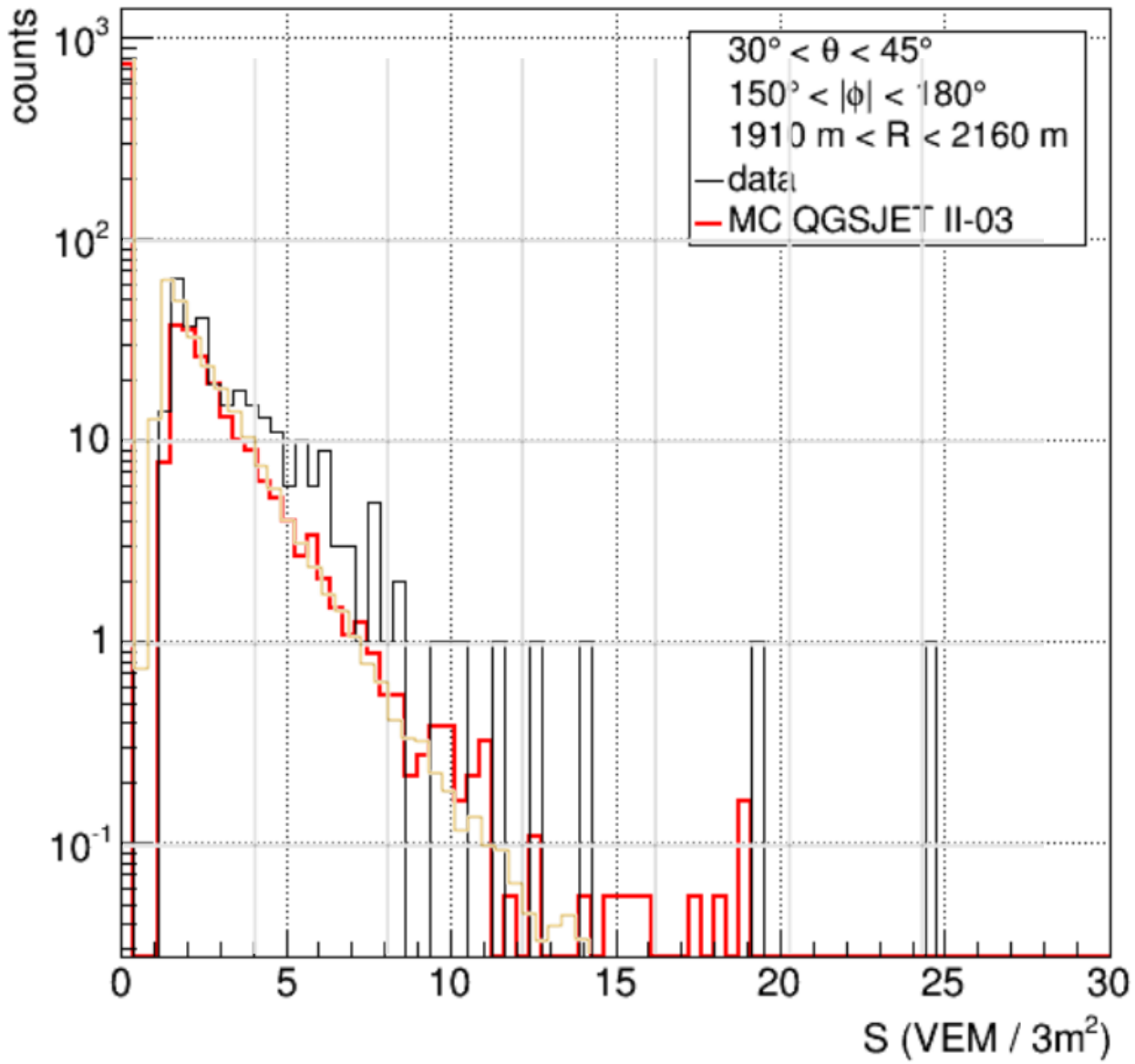
Analysis Framework (Takeishi-san)

Flag of SD

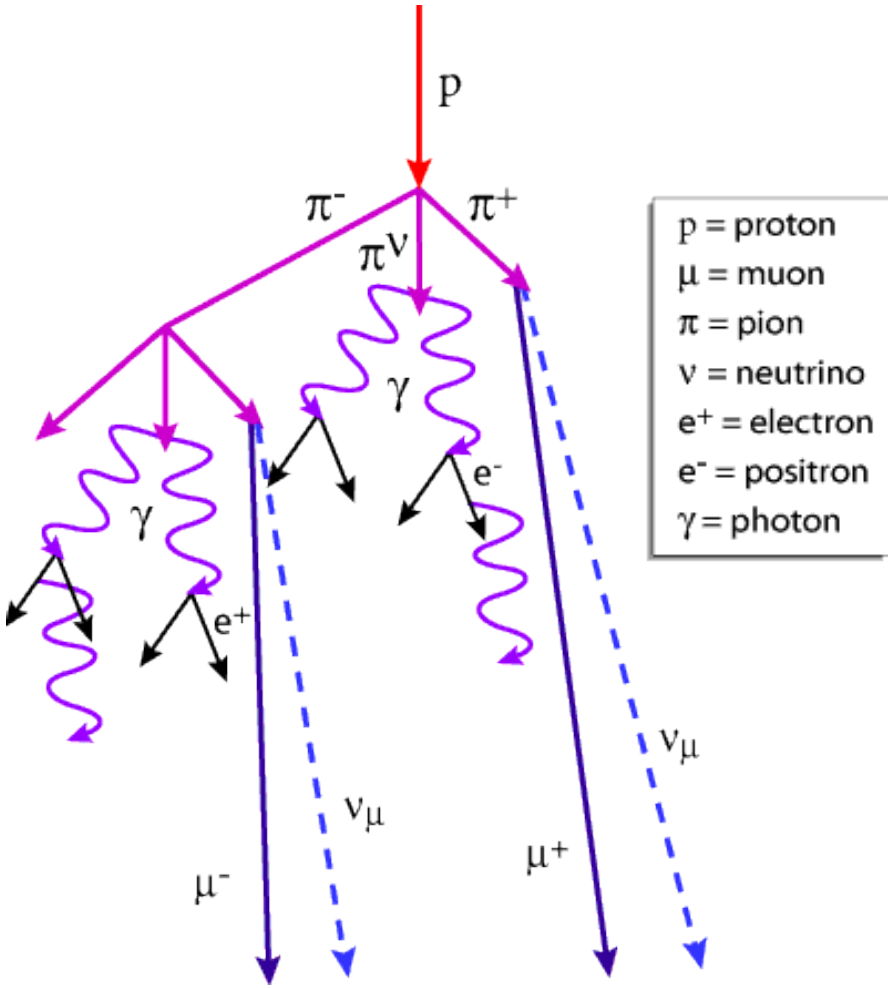
0. Dead SD
1. Not part of any cluster
2. Part of space cluster
3. Passed a roguh time pattern recognition

} Exclude from the average calculation

4. Part of event → Use the value as is
5. saturation → Exclude
(6). Other SD (Working but No Signal) → Fill with zero signal


counts
10^3
10^2
10
1
10^{-1}
0
5
10
15
20
25
30
S (VEM / 3m^2)
30° < θ < 45°
150° < |ϕ| < 180°
1910 m < R < 2160 m
data
MC QGSJET II-03

Air Shower



$$p + N \rightarrow p' + N' + \pi^{\pm} + \pi^{0} \cdots$$

First Interaction

$$\pi^{-} \rightarrow \pi^{+} + \pi^{-} + \pi^{-}$$

Hadron

$$\pi^{0} \rightarrow \gamma + \gamma \qquad \gamma \rightarrow e^{+} + e^{-}$$

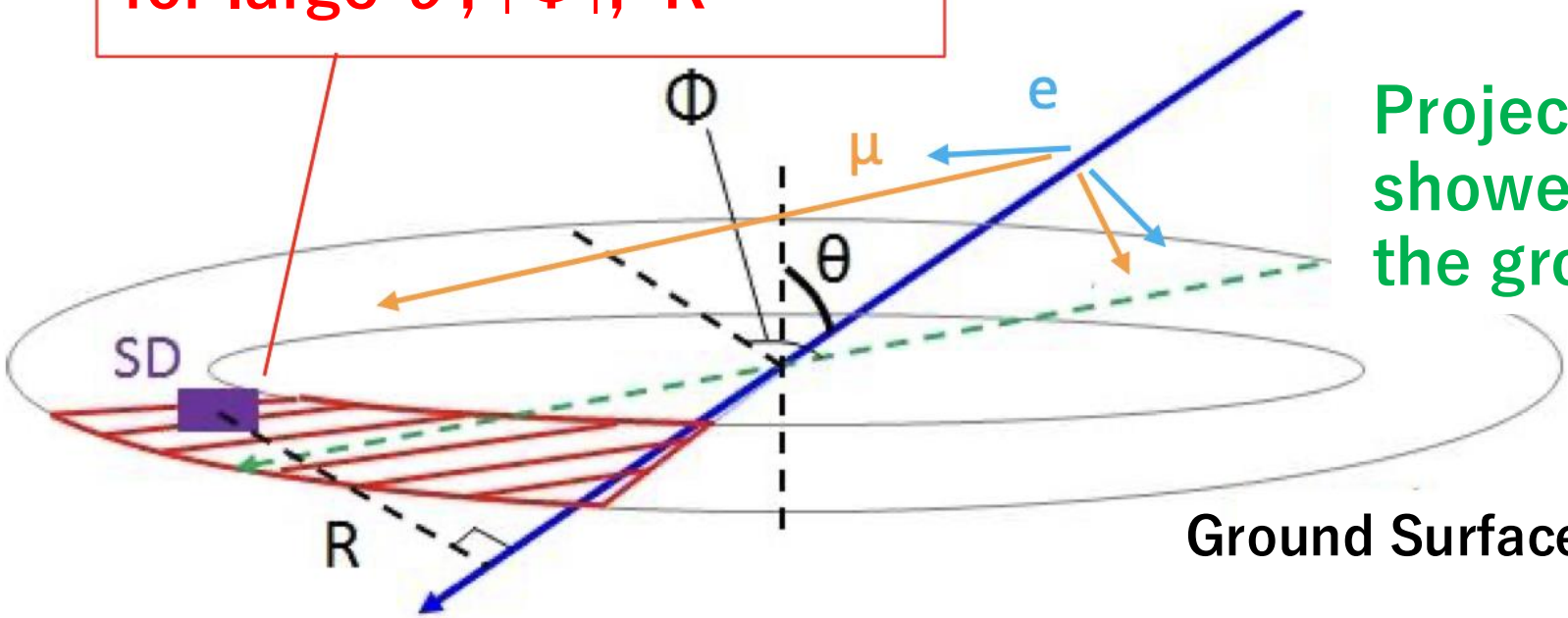
(e^{-} bremsstrahlung)

ElectroMagnetic

$$\pi^{+} \rightarrow \mu^{\nu} + \mu^{+}$$

muon

Higher μ ratio is expected for large θ, $|\Phi|$, R



Tange Analysis

0. Dead SD
1. Cluster
2. timing
3. location

→ 信号量0で埋める

4. In event
5. saturation

→ 値そのまま採用

その他のSD → 信号量0で埋める

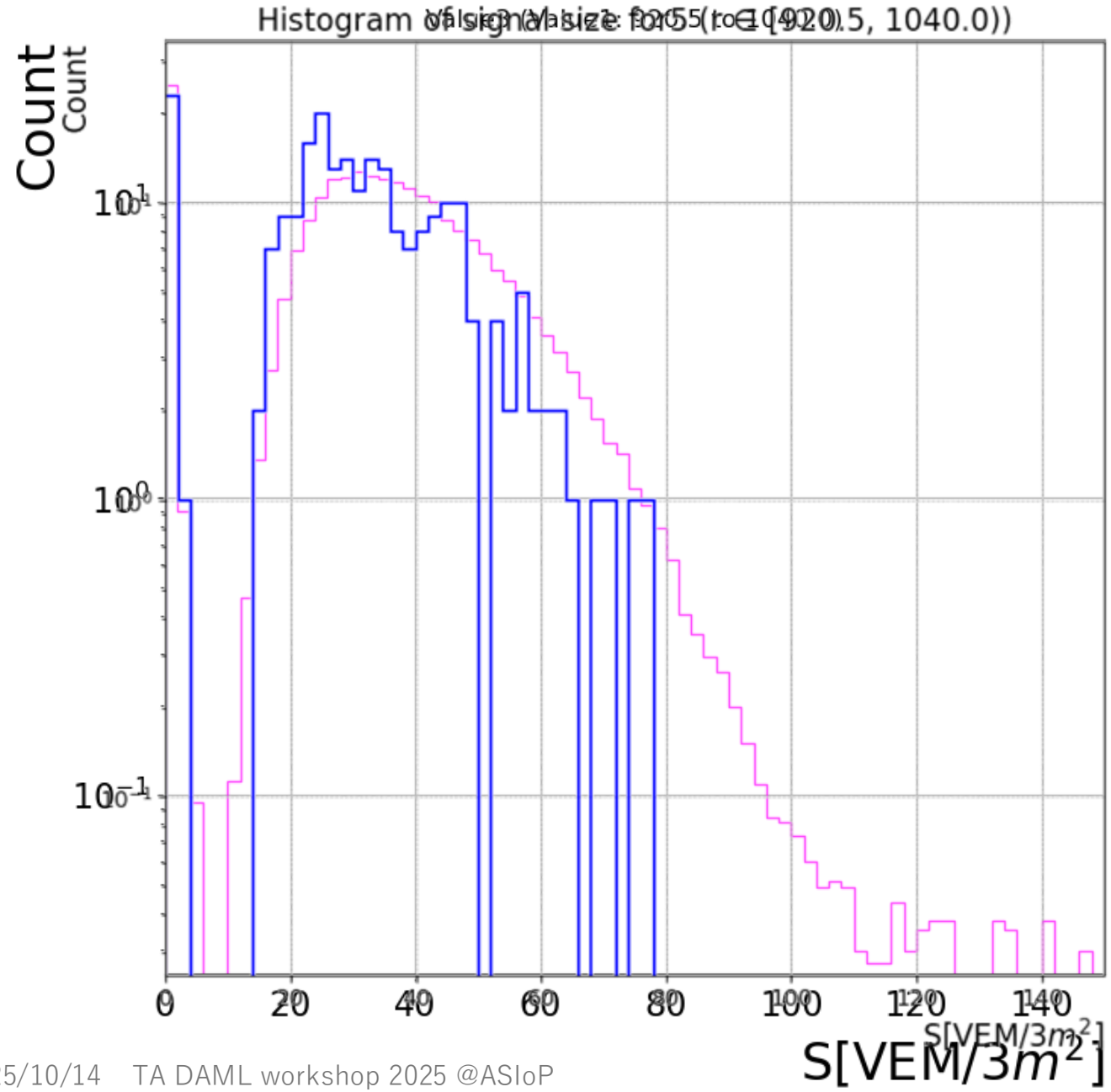
Takeishi Analysis

0. Dead SD
1. Cluster
2. timing
3. location

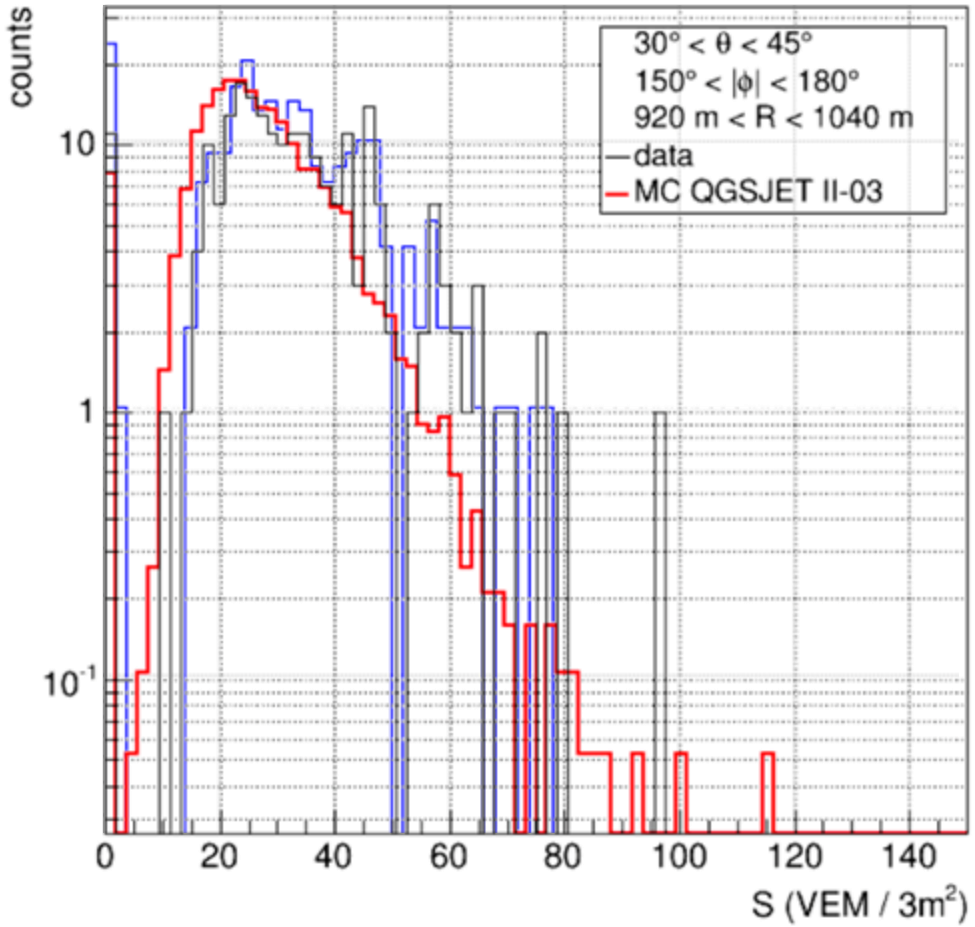
→ 統計から除外

4. In event → 値そのまま採用
5. saturation → ($500 \leq R$なので影響小)

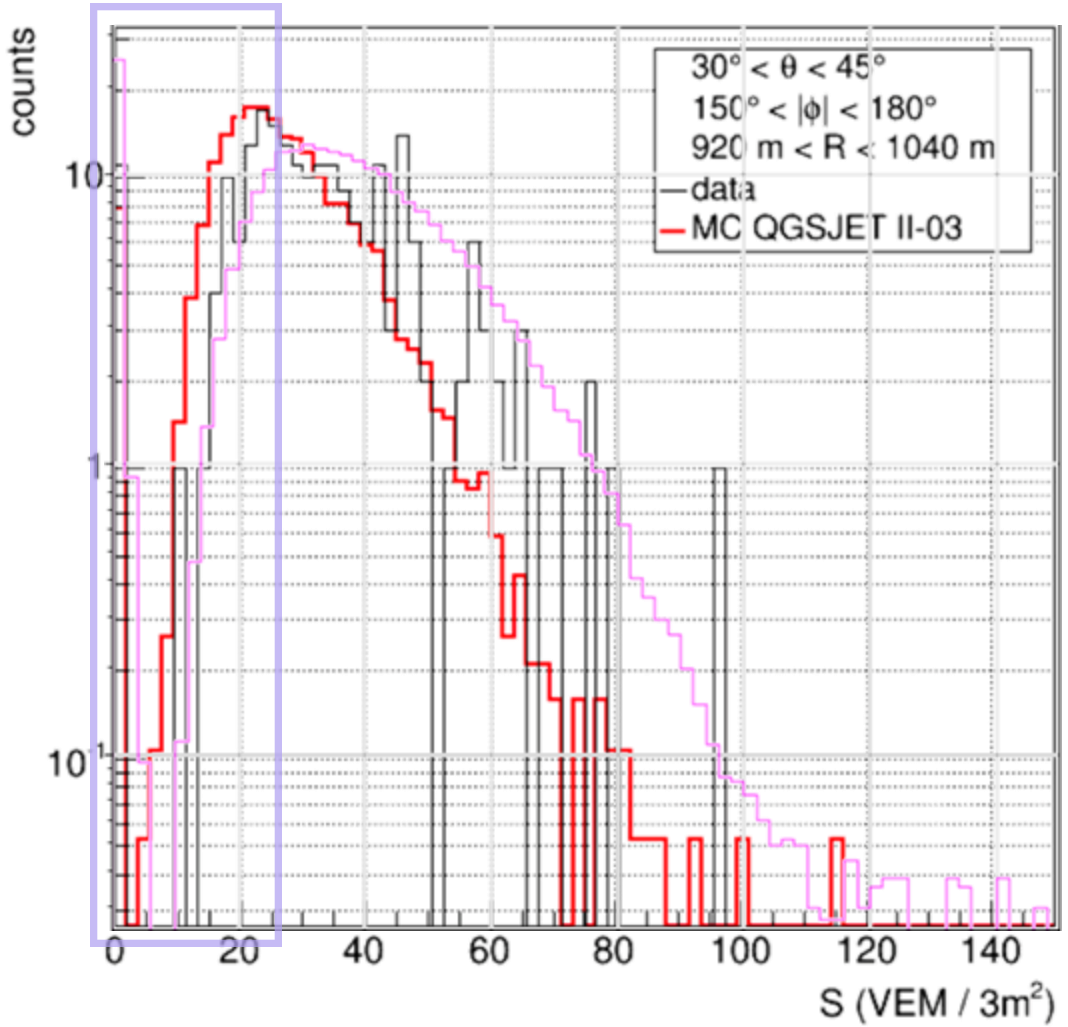
その他のSD → 信号量0で埋める


Histogram of signal size for S (r ∈ [920.5, 1040.0))
Count
10^{1}
10^{0}
10^{-1}
0
20
40
60
80
100
120
140
S[VEM/3m^2]

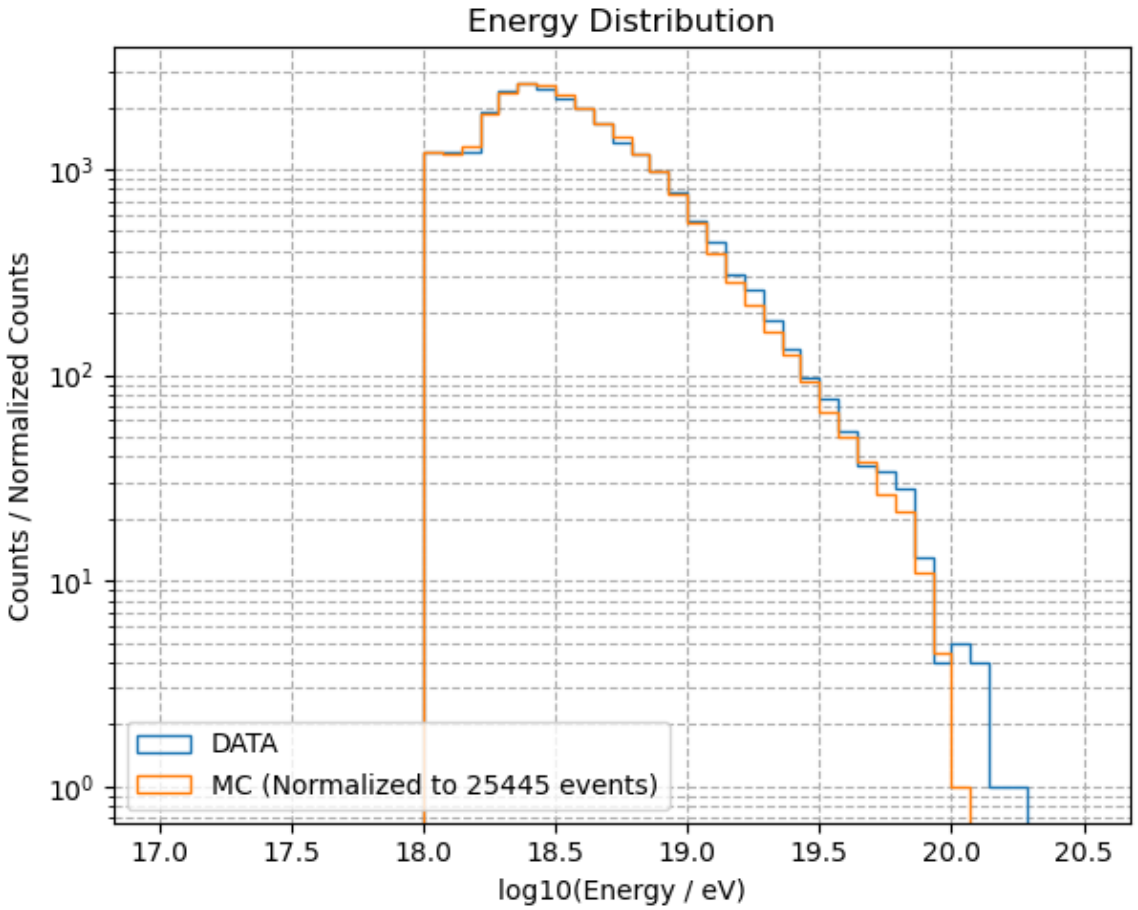
DATA

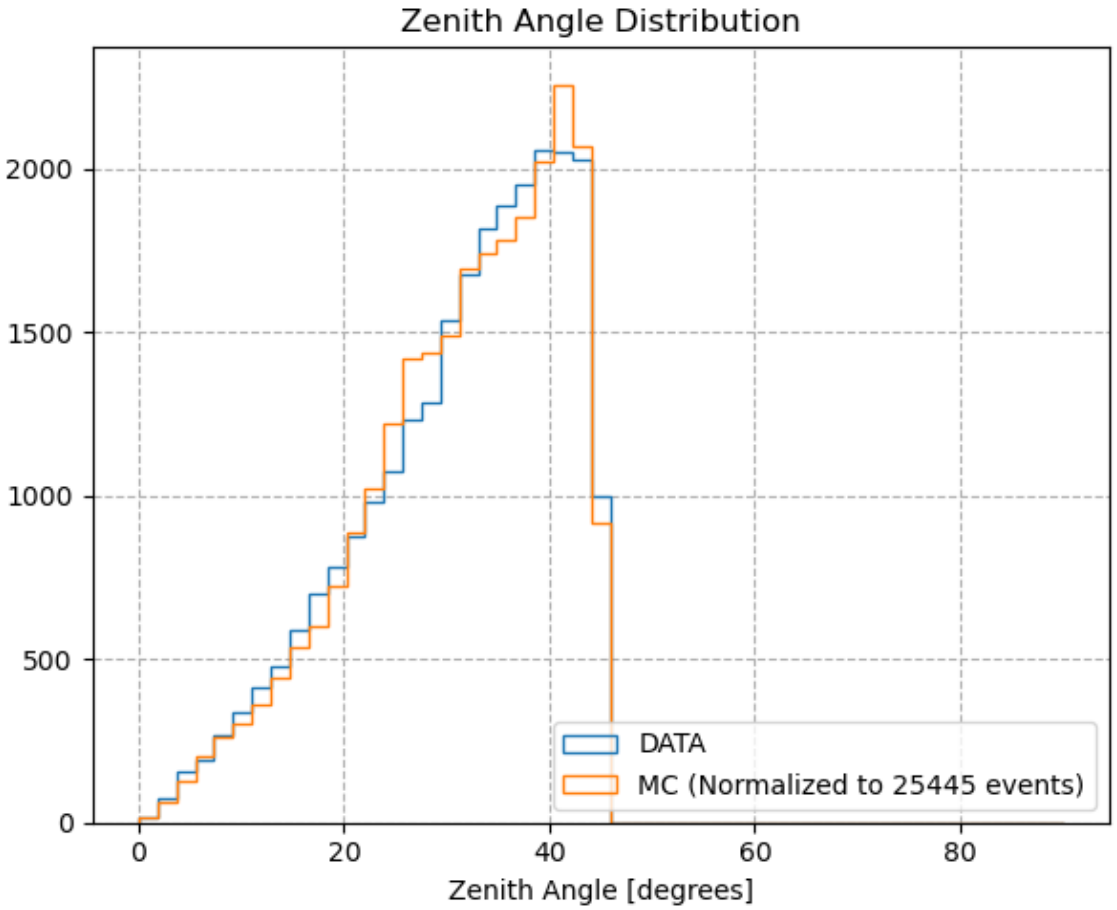

counts
10
1
10^{-1}
0
20
40
60
80
100
120
140
S (VEM / 3m^2)
30° < θ < 45°
150° < |ϕ| < 180°
920 m < R < 1040 m
data
MC QGSJET II-03

MC


counts
10
1
10^{-1}
0
20
40
60
80
100
120
140
S (VEM / 3m^2)
30° < θ < 45°
150° < |ϕ| < 180°
920 m < R < 1040 m
data
MC QGSJET II-03

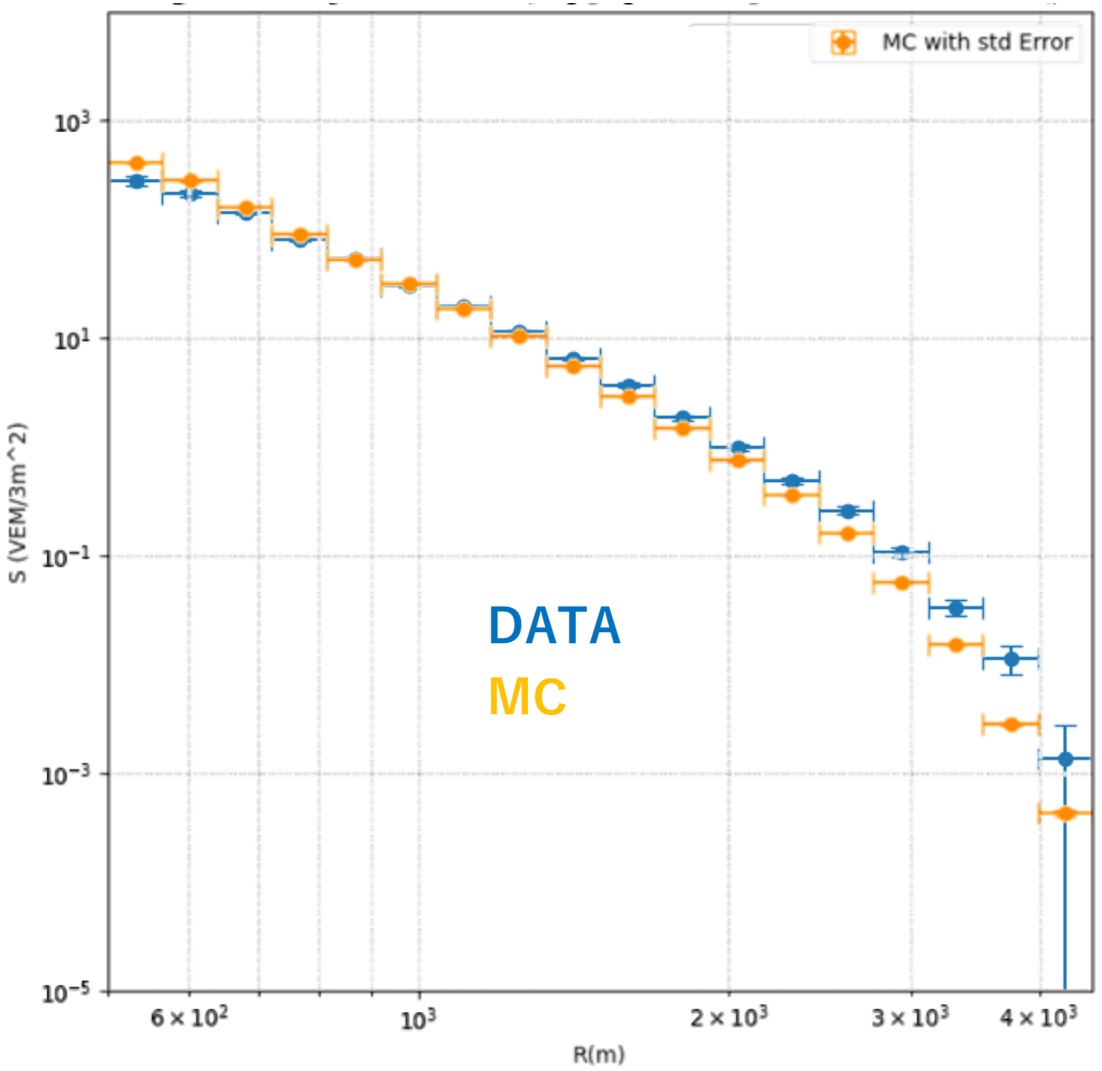
DATA, MC compalison





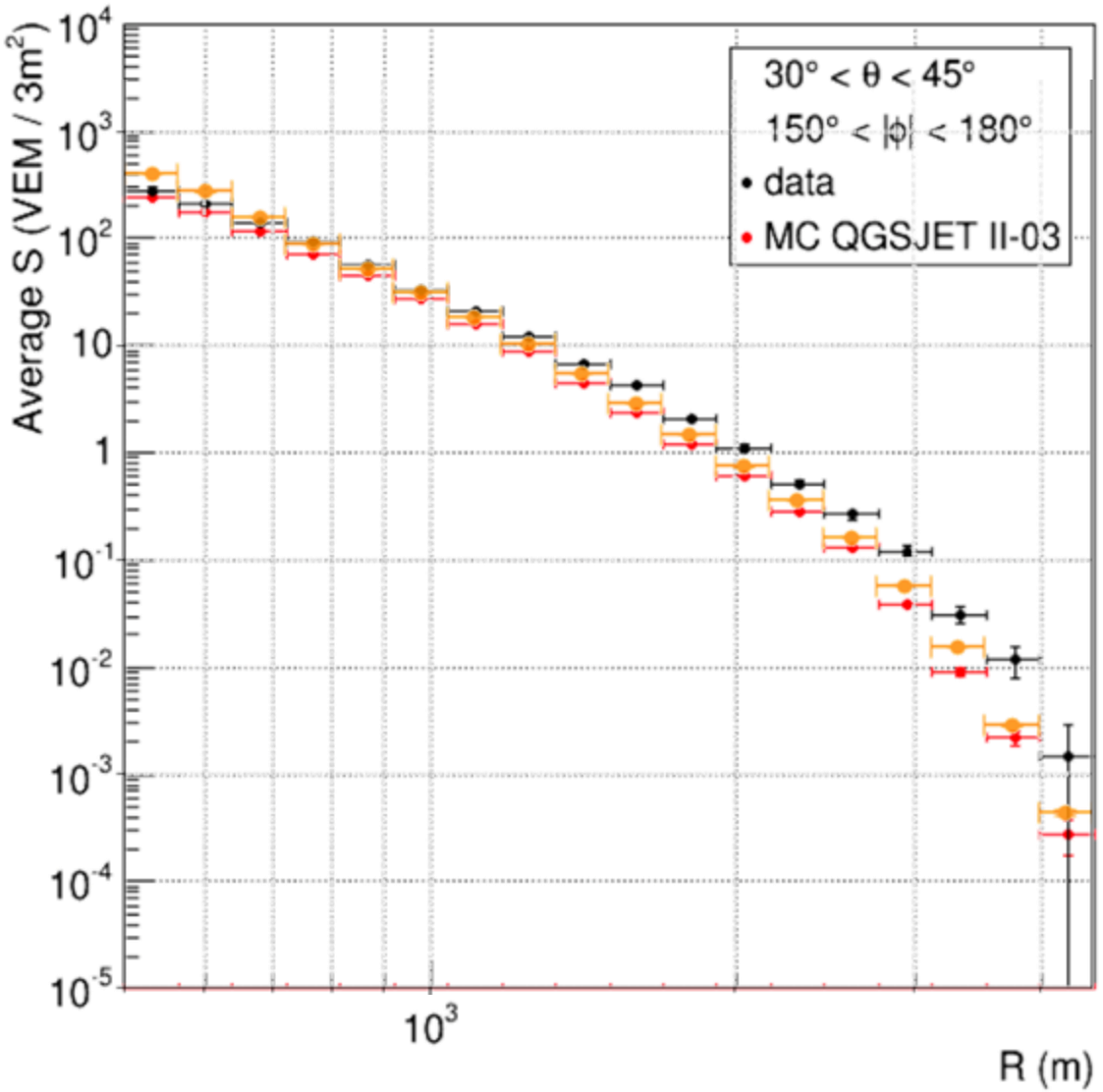
MC

Lateral distributions: avg. signal size(MC)



At small R, the data exceed the MC

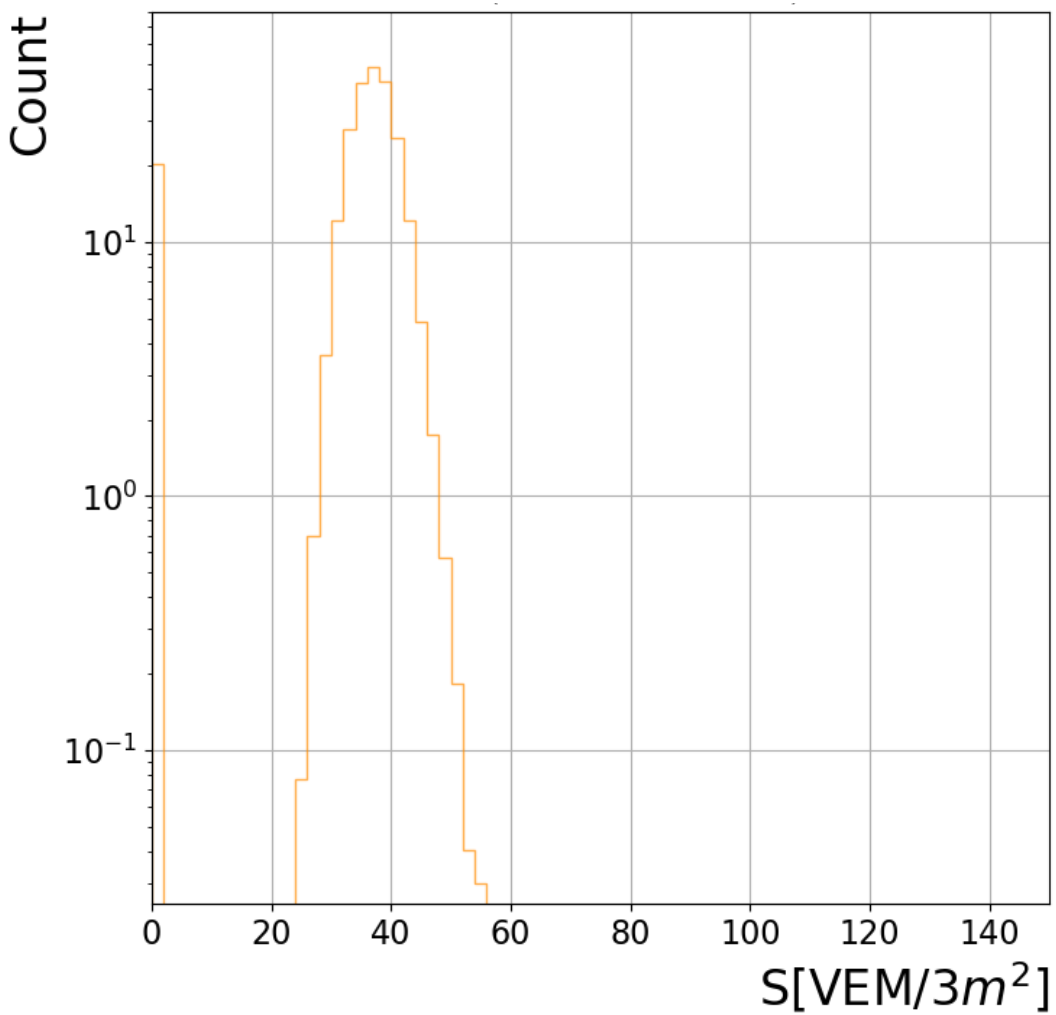
Compere with result of Takeishi-san



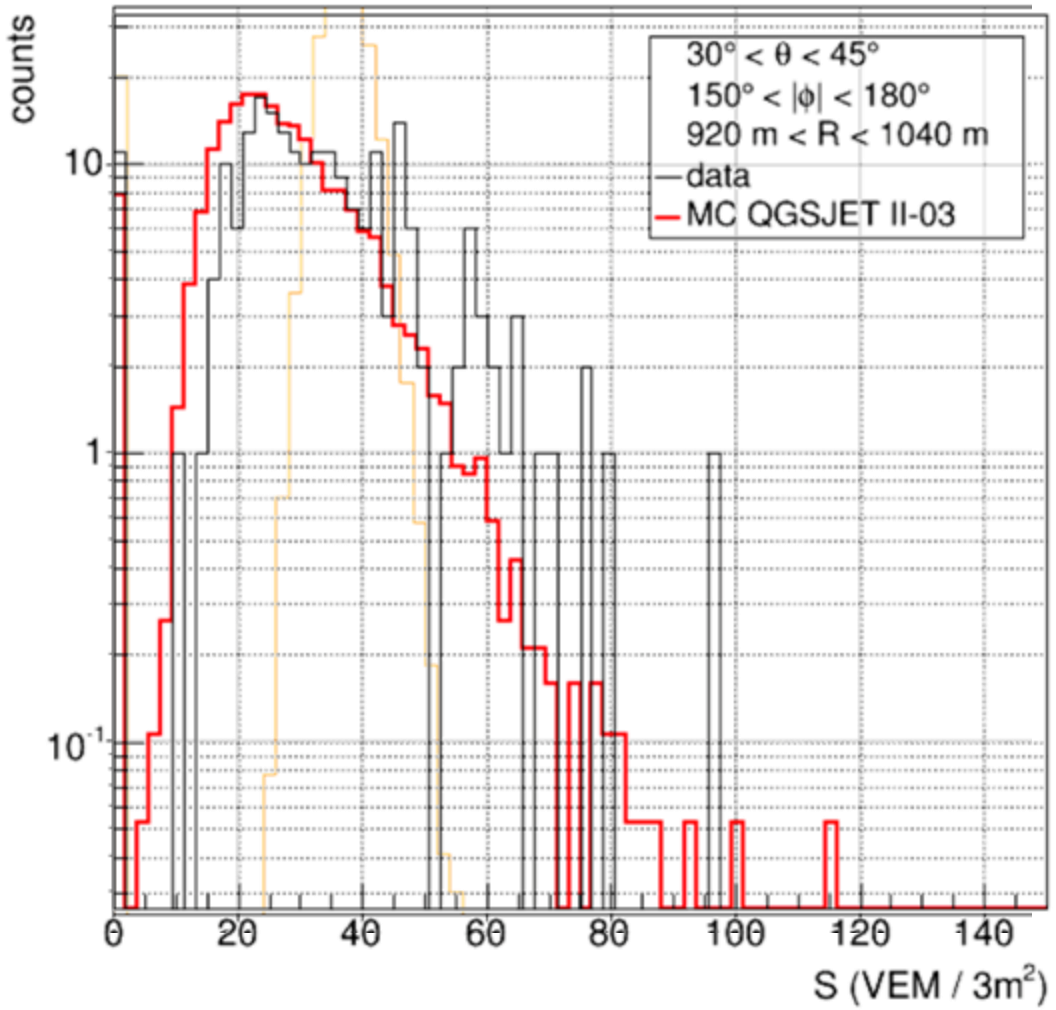
do not yet agree with Takeishi-san's results.

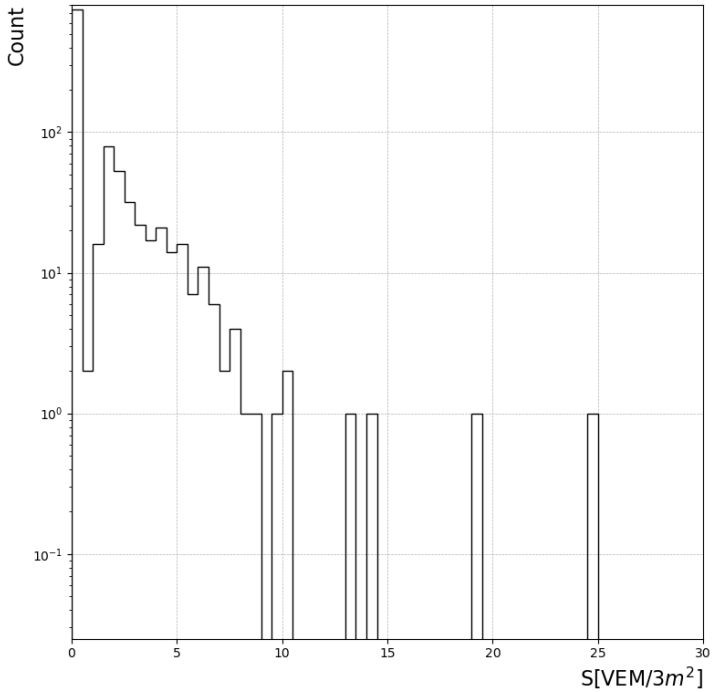
Distribution of signal sizes within each bin

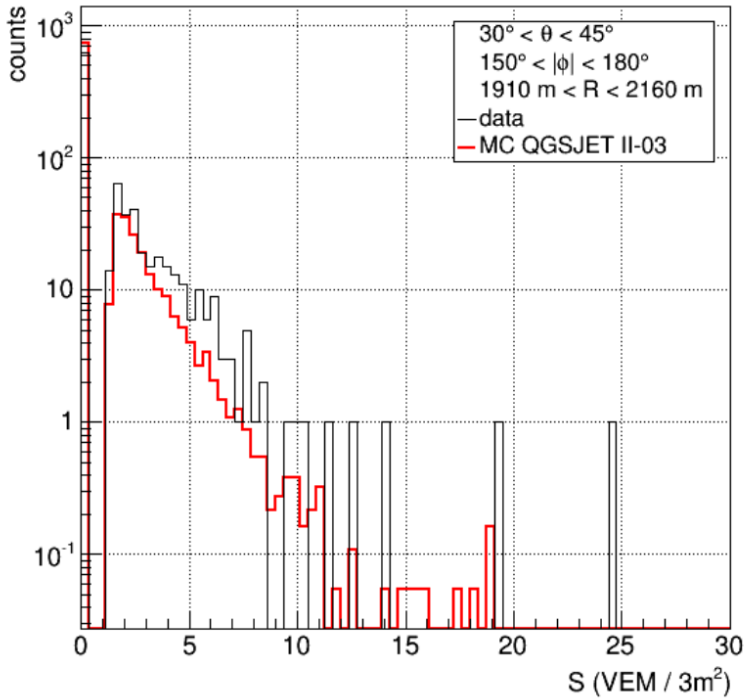
$920\mathrm{m} \leq R \leq 1040\mathrm{m}$ のSignal Size 分布

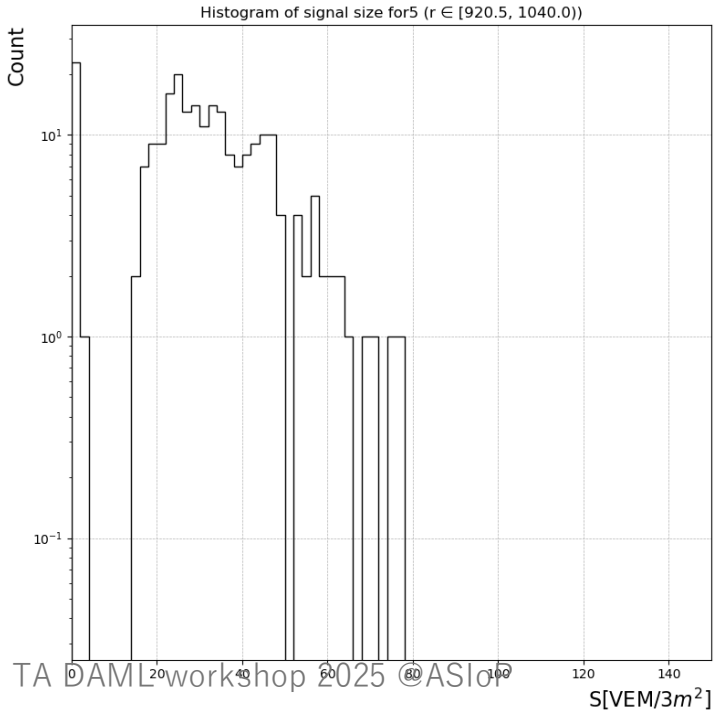


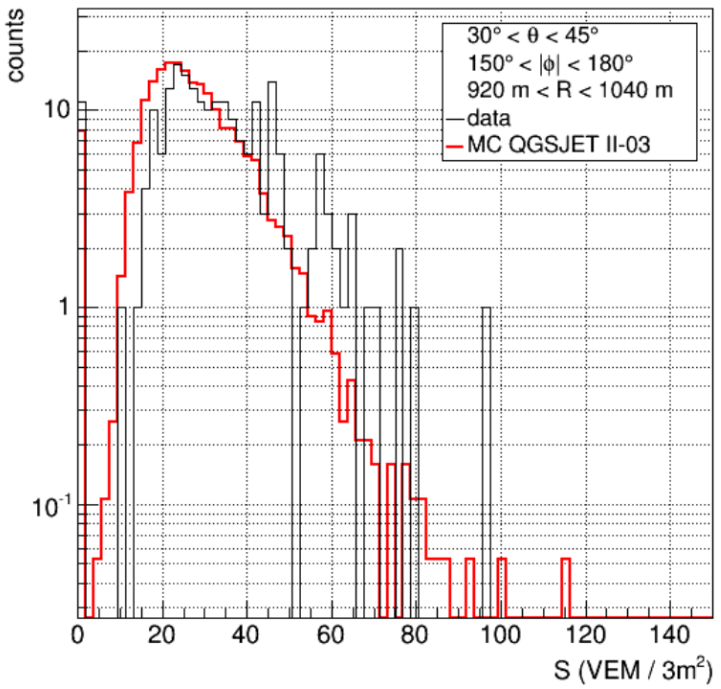
Compere with result of Takeishi-san




Count
S[VEM/3m^2]


counts
30° < θ < 45°
150° < |ϕ| < 180°
1910 m < R < 2160 m
data
MC QGSJET II-03
S (VEM / 3m^2)


Histogram of signal size for5 (r ∈ [920.5, 1040.0))
Count
S[VEM/3m^2]


counts
30° < θ < 45°
150° < |ϕ| < 180°
920 m < R < 1040 m
data
MC QGSJET II-03
S (VEM / 3m^2)

Analysis of SD data

Check with Amatersu particle

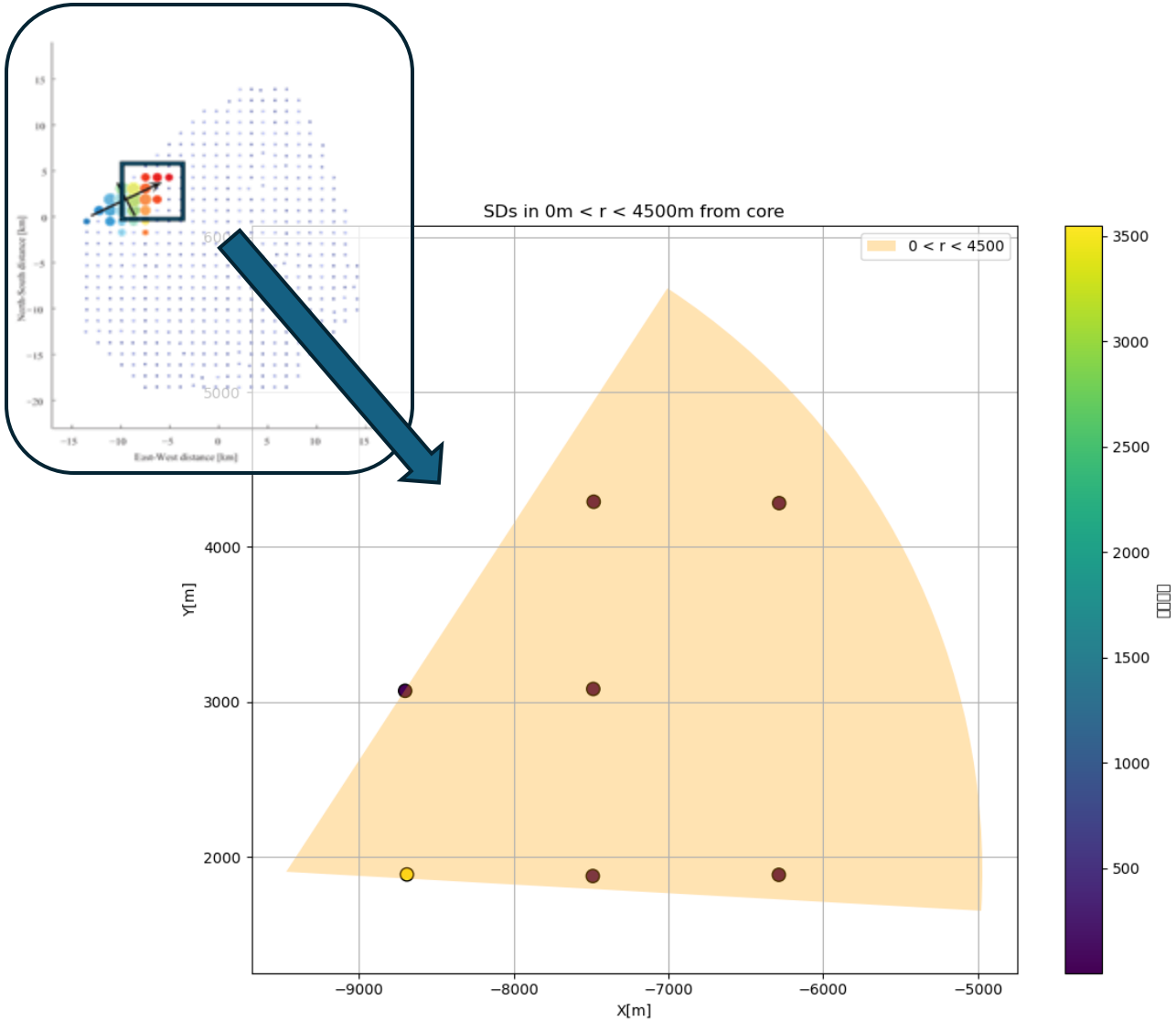
requirement

Zenith : $30 \leq \theta \leq 45$

Azimuth : $150 \leq \Delta\phi \leq 210$

Energy : $10^{20} \leq E \leq 10^{21}$

Radius : $500 \leq r \leq 4500$



SD in the fan-shaped area is the target!