On-orbit Calibration with Penetrating Proton and Helium

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Calibration on the ISS orbit

- For continuous high performance of the detector, on-orbit calibration considering detector condition is required.
- We use the measured response to MIP (Minimum Ionizing Particle) for the calibration. Applicability of the basic method has been confirmed in beam tests using muons.
- There are few muons in space, so we use protons and helium nuclei for on-orbit calibration.

We should confirm following points:

- number of penetrating events obtained during 1 orbit ← previous TIM
- efficiency and accuracy of off-line event selection ← this work
- expected calibration error ← this work

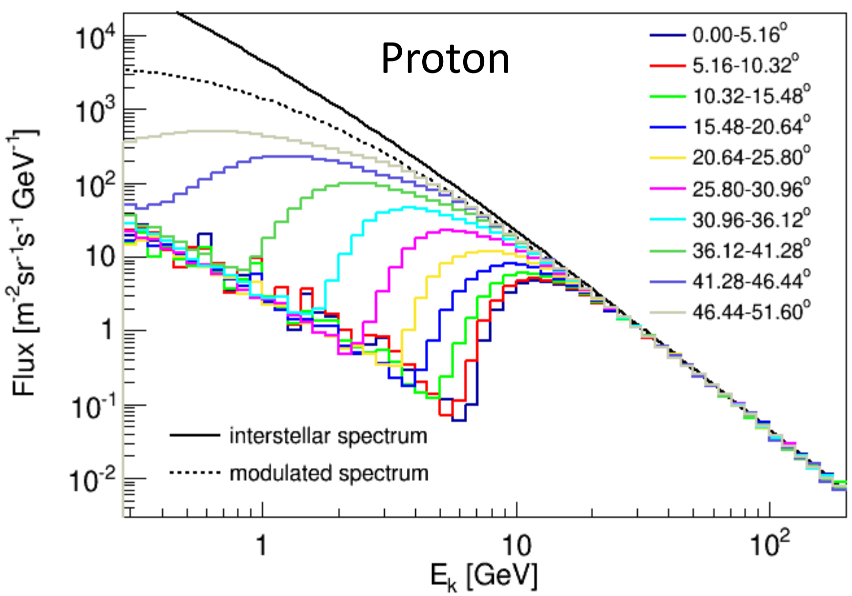
1. Number of penetrating events obtained on orbit

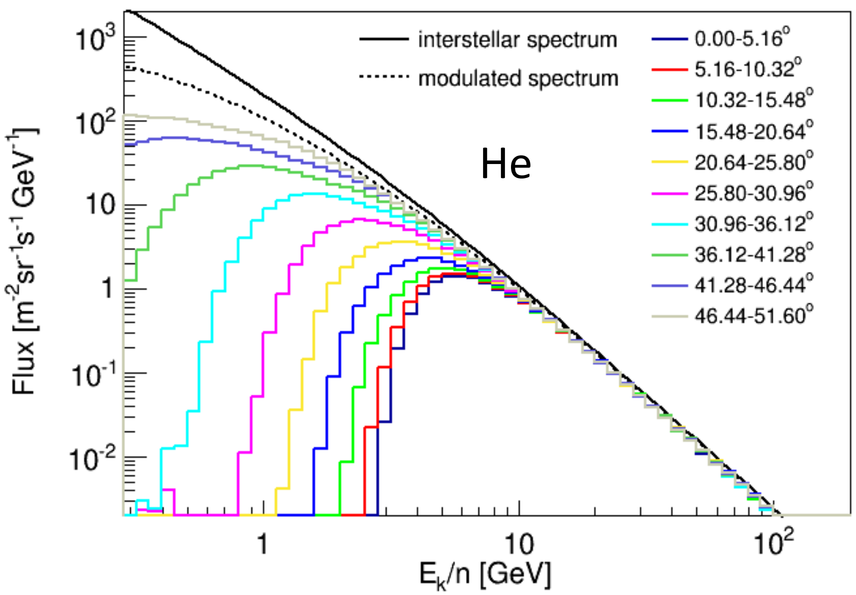
1.1. Calculation of proton & Helium spectra on ISS orbit

- As interstellar spectra:
  use AMS-01 data (June 1998, altitude: 320-390 km)

- Solar modulation:
  calculate based on Force Field approximation
  assuming modulation factor Φ = 0.4 GV

- Effect of geomagnetic field & interaction with atmosphere:
  calculate using ATMNC3





1. Number of penetrating events obtained on orbit

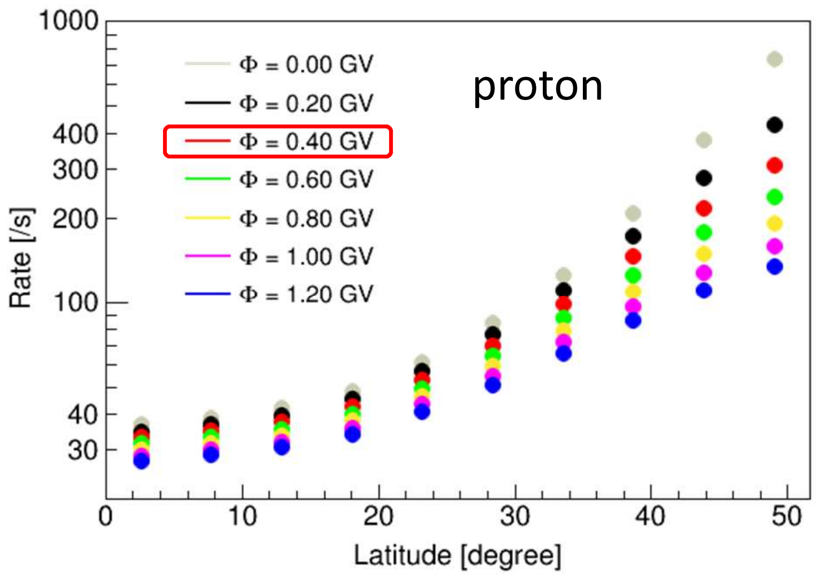
1.1. Rate of triggered events

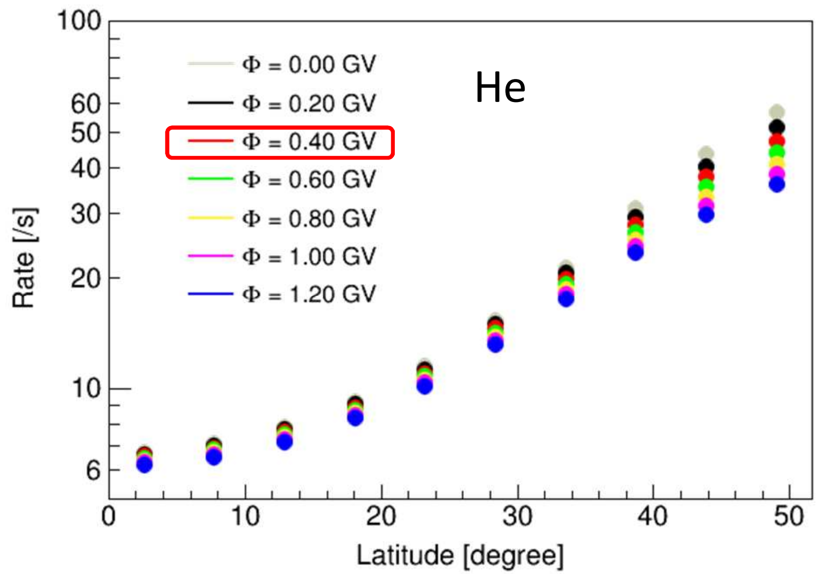
- interaction in the detector:
  calculate using EPICS (EPICS version: 9.161, detector config.: CAD rev.21)

- trigger mode: Single

- average trigger rate: 170 Hz
  proton: 7.8×10^5 events /orbit
  He nuclei: 1.3×10^5 events /orbit
  (when Φ = 0.4 GV)

	High Energy Shower	Low Energy Shower	**Calibration**
CHD each lay.	-	> 0.7 MIP	**> 0.7 MIP**
IMC 1-6th lay.	-	> 0.7 MIP	**> 0.7 MIP**
IMC 7-8th lay.	> 7.5 MIP	> 2.5 MIP	**> 0.7 MIP**
TASC 1st lay.	> 55 MIP	> 7 MIP	**> 0.7 MIP**





1. Number of penetrating events obtained on orbit

1.1. Rate of single penetrating events

According to EPICS calculation…

- 20% of triggered events pass through the detector from the top to the bottom without escaping through the side … (A)
- 96 % of (A) reach to the bottom without stopping inside the detector … (B)
- {19% (p), 11% (He)} of (B) penetrate the detector without creating shower particles … (C)

⇒ (C) / triggered events

$$= 0.2 \times 0.96 \times \begin{Bmatrix} 0.19\ (p) \\ 0.11\ (He) \end{Bmatrix} = \begin{Bmatrix} 3.6\%\ (p) \\ 2.1\%\ (He) \end{Bmatrix}$$

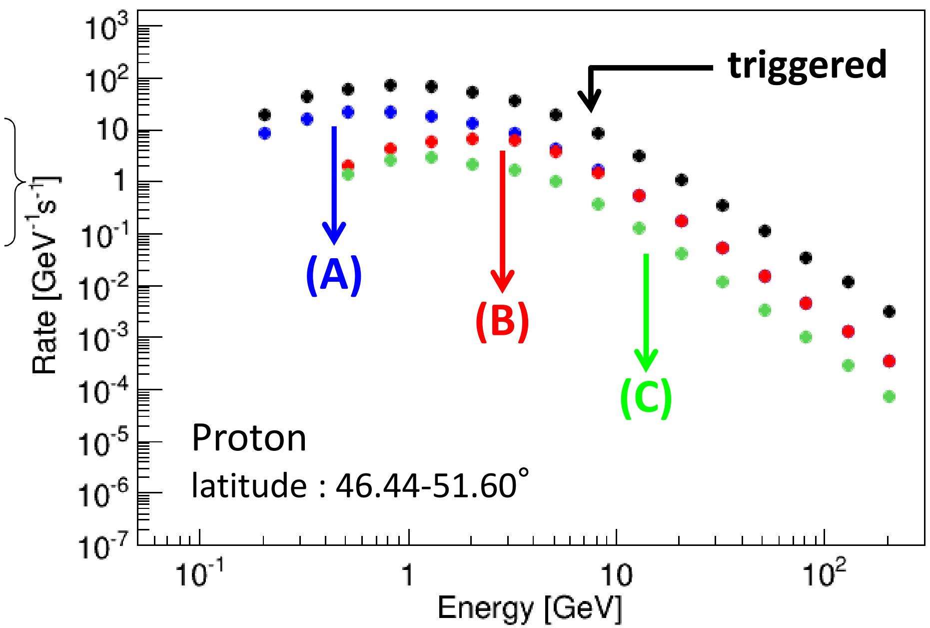
※ exact rate depends on latitude

average penetrating event rate: 6.5 Hz

proton: 2000 events /orbit /log

He nuclei: 150 events /orbit /log

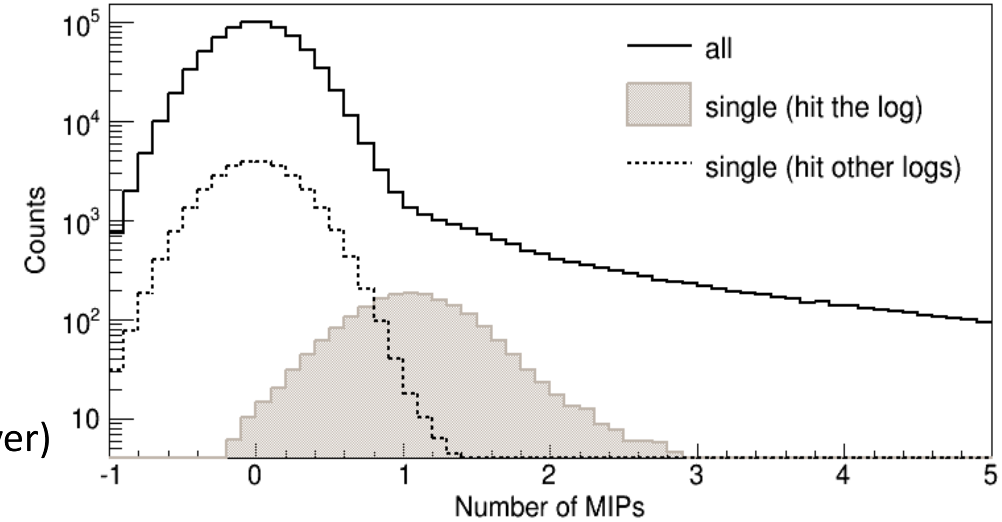
(when Φ = 0.4 GV)



2. Off-line analysis for event selection

Without any event selection…

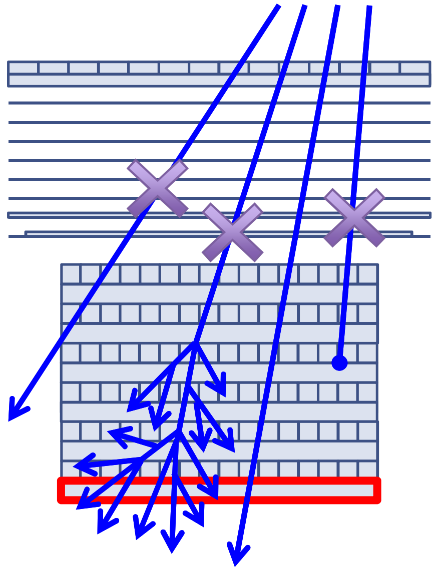
(when S/N = 3)



Signal distribution of
1 PWO log (bottom layer)

Basic idea of selection

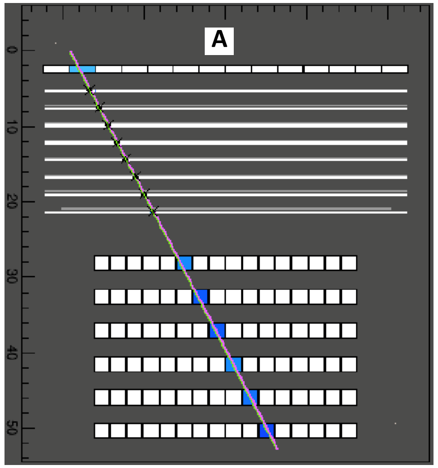
1. reject events which escape through the side and identify the hit PWO by track reconstruction
2. reject events which create shower particles using total deposited energy in TASC
3. reject events which stop inside the detector using likelihood parameter



2. Off-line analysis for event selection

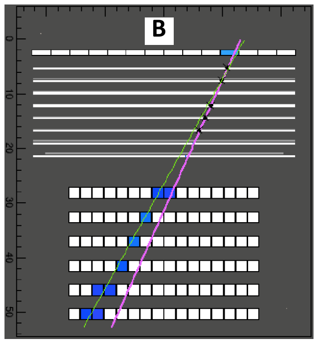
2.1 Track reconstruction

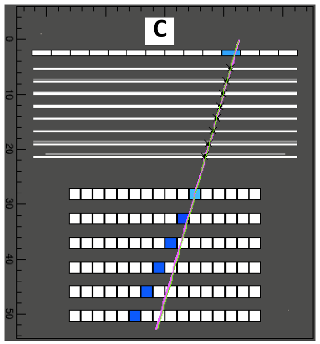
least-squares fit of the most luminous fiber in each IMC layer



hit PWO in the TASC bottom layer can be correctly identified for almost 77% of single penetrating protons -> Fig. A

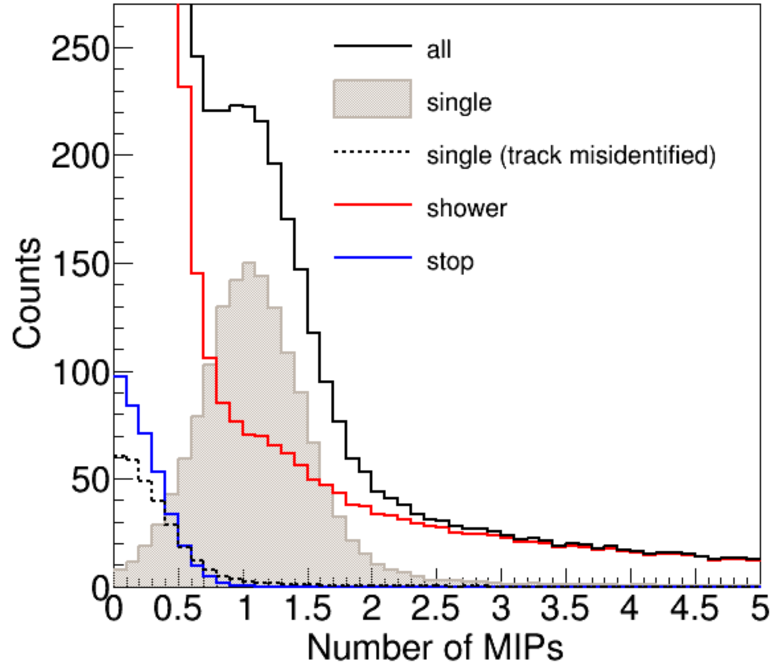
The other events are affected by
- reconstruction errors (3%) -> Fig. B
- elastic scattering (20%) -> Fig. C





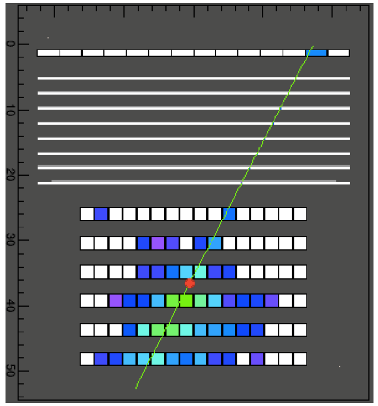
incident direction
reconstructed track

Signal distribution of 1 PWO log (bottom layer) after the selection



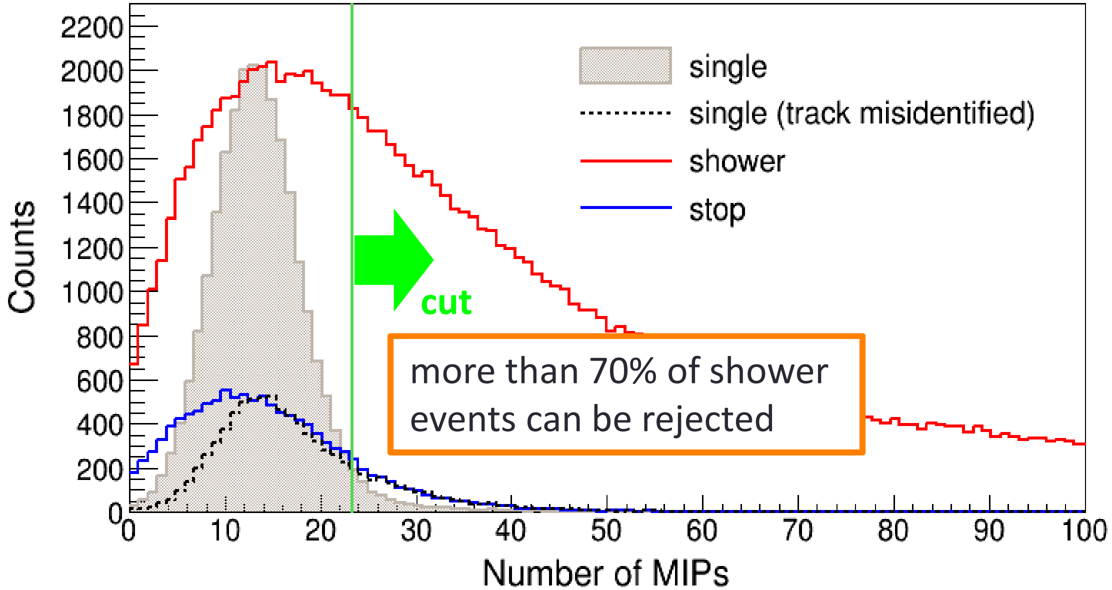
2. Off-line analysis for event selection

2.2 Selection using total deposited energy in TASC

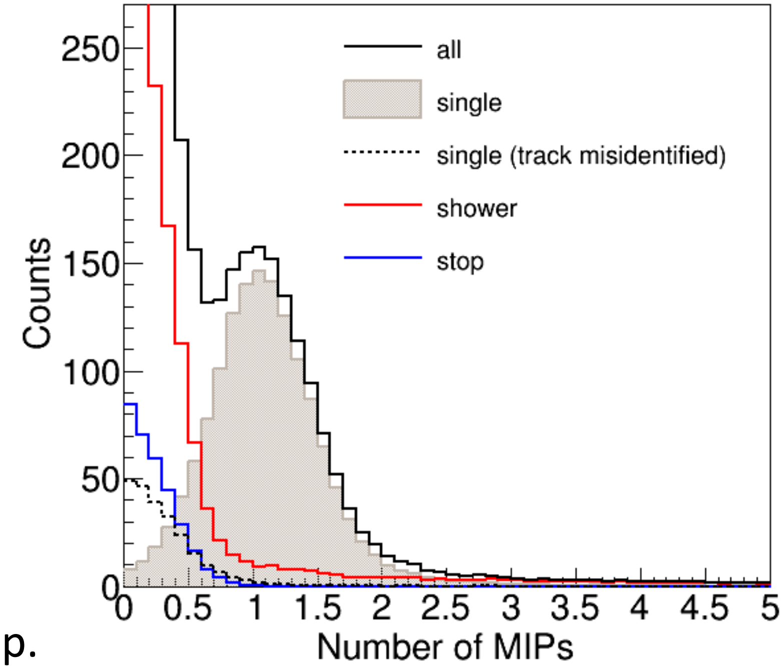


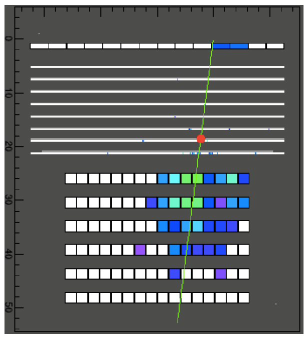
Shower events which make a large energy deposition (Fig. A) can easily be cut by the distribution below.

Distribution of total deposited energy in TASC



Signal distribution of 1 PWO log (bottom layer) after the selection





※ Shower events which fade out before reaching the bottom layer (Fig. B) are rejected in the next step.

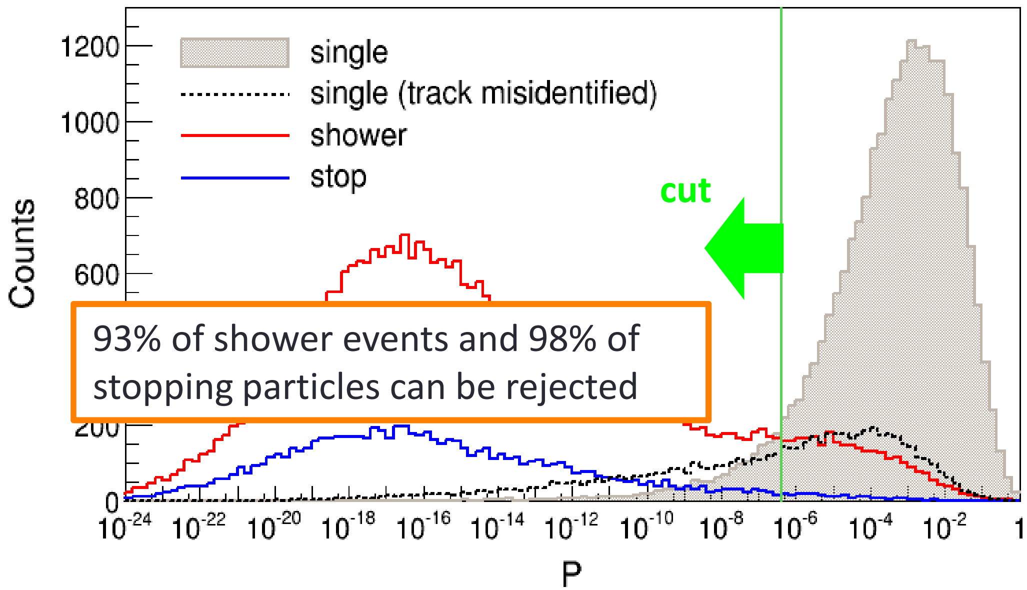
2. Off-line analysis for event selection

2.3 Selection using likelihood parameter

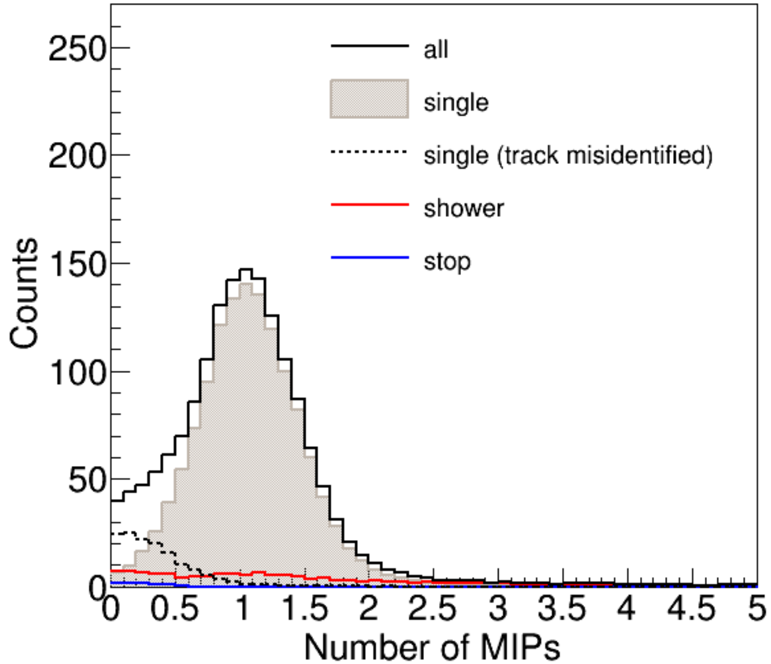
Template signal distribution of penetrating particles: *F(s)*
Likelihood of penetrating a layer as a single particle: $p(s) = F(s) / \int F(s)\,ds$
Likelihood of penetrating the TASC as a single particle: $P(s_1, s_2, \ldots, s_{12}) = \prod_{i=1\sim12} p(s_i)$

We can use P as a selection parameter.

Distribution of likelihood parameter



Signal distribution of 1 PWO log (bottom layer) after the selection



2. Off-line analysis for event selection

2.4 Efficiency and purity in the final state

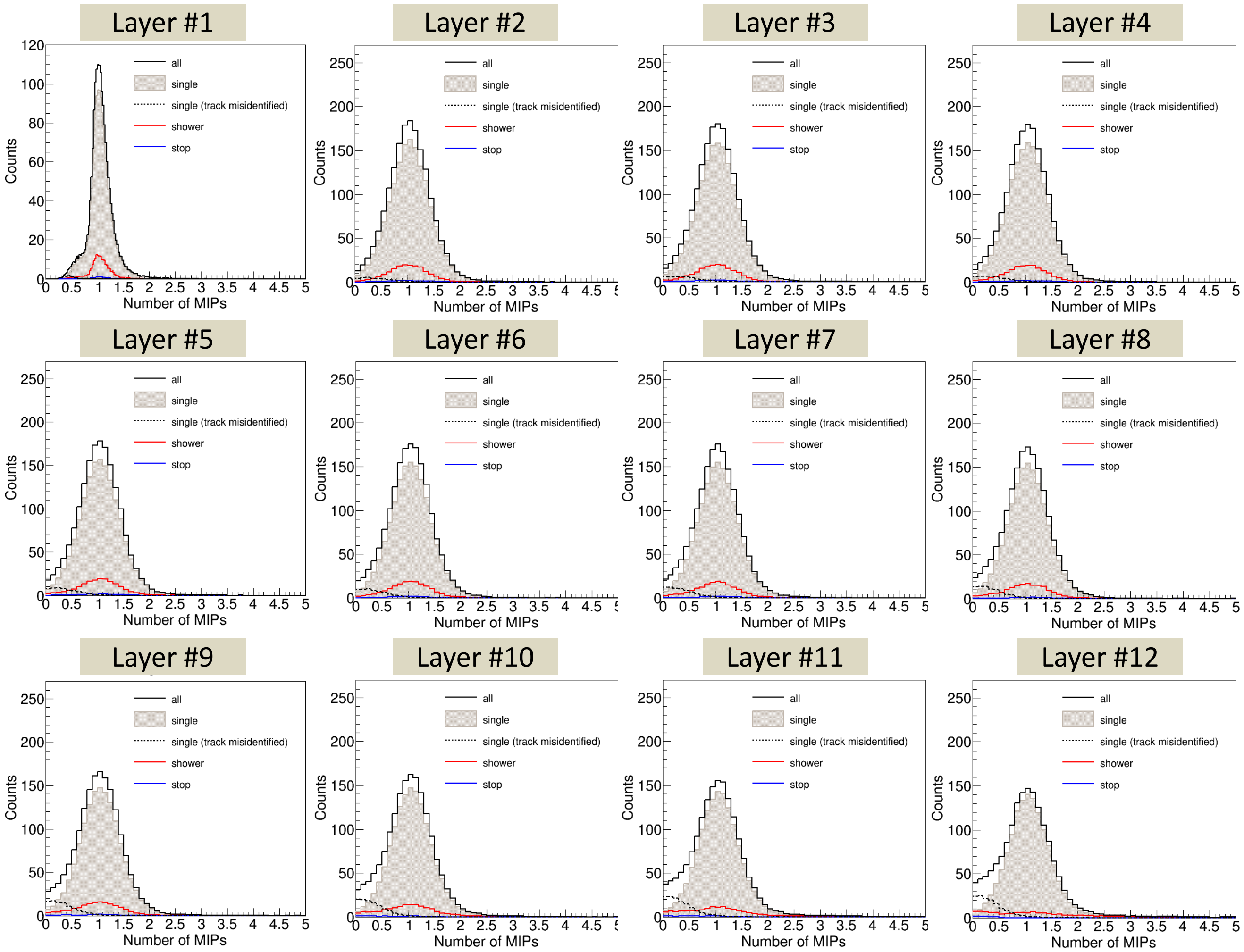
Efficiency $\equiv N_{select\ (single)} / N_{trig\ (single)}$

Purity $\equiv N_{select\ (single)} / N_{select}$

$N_{trig\ (single)}$: all triggered single events

$N_{select\ (single)}$: all selected single events

N_{select} : all selected events



Layer	Efficiency [%]	Purity [%]
1	77.3	87.9
2	76.2	86.4
3	75.7	85.8
4	75.5	85.4
5	74.8	84.6
6	74.3	84.0
7	73.3	82.9
8	72.6	82.0
9	71.4	80.6
10	70.2	79.4
11	68.6	77.7
12	67.1	76.4

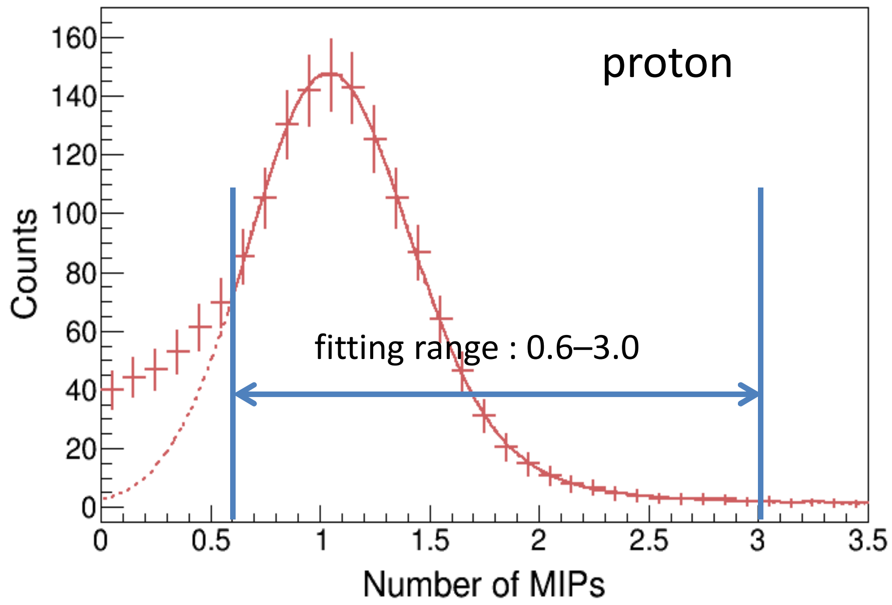
3. Expected calibration error

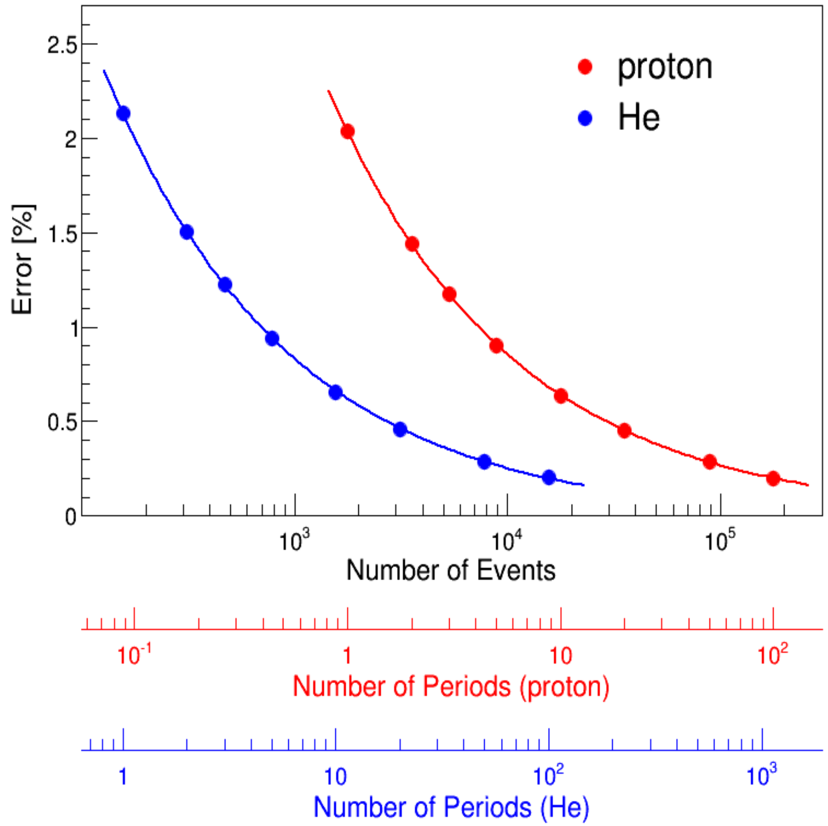
Fitting function: Landau Function convoluted with a Gaussian

Fitting error of the most probable value of the function:

proton (1 orbit) : 2.0%
Helium (1 orbit) : 2.1%   (when Φ=0.4 GV)

Error becomes smaller with higher statistics
(1% in 4 orbital periods)





Conclusions

We carried out Monte Carlo simulations and confirmed that we can calibrate the CALET detector on the ISS orbit using cosmic ray protons and helium nuclei with high accuracy within a reasonable amount of time.

Expected trigger rate:
170 Hz on average (Φ=0.4 GV) ※ depending on solar modulation

Expected number of single penetrating events:
proton: 2000 events /orbit /log
He nuclei: 150 events /orbit /log (Φ=0.4 GV) ※depending on solar modulation

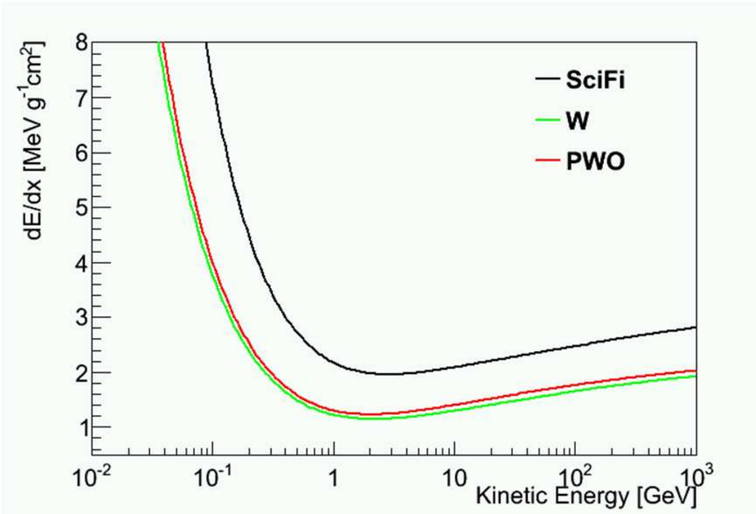
Expected calibration error:
2-3% within one orbit (90 min)
This can be reduced to below 1% within several orbital periods.

In this way, the energy resolution for high energy electrons is kept under a few %. Therefore, we can expect a precise measurement of GeV-TeV electrons with the CALET observation starting in 2015.

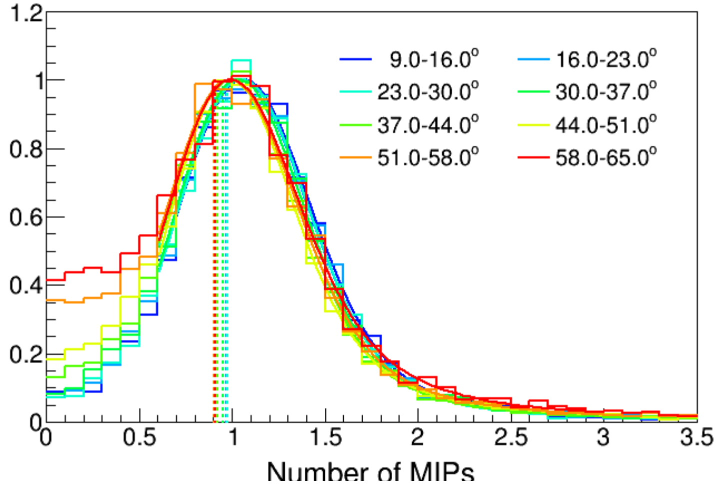
End

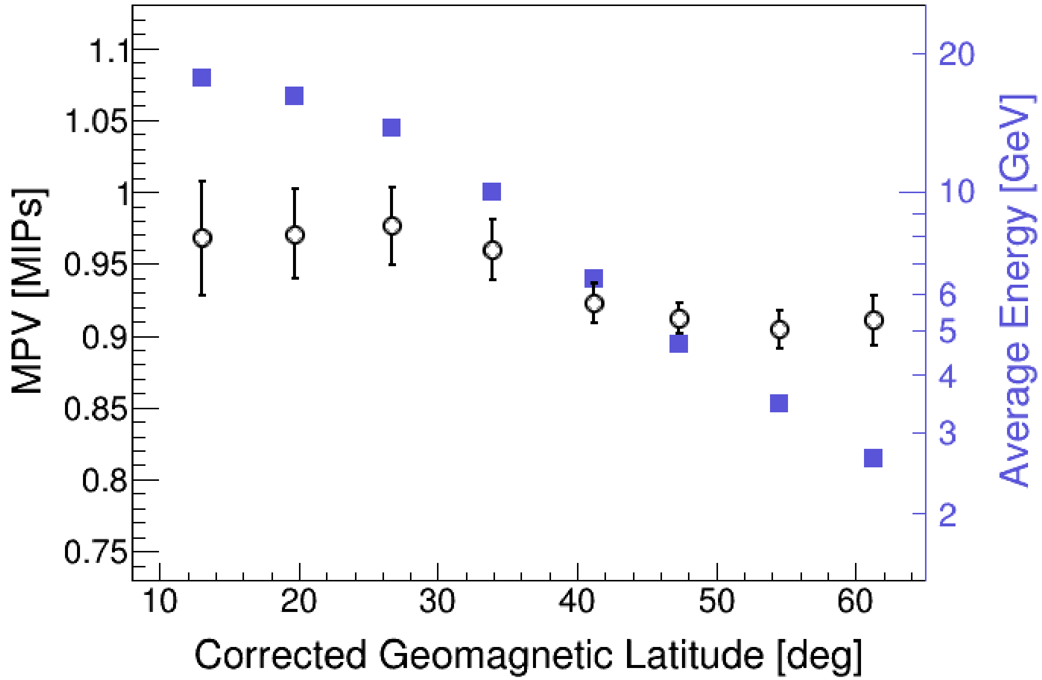
Correction of incident energy

Energy deposition vary with particle energy.



→ We can use the function (right figure) as a correction factor when we combine the data obtained at different geomagnetic latitudes.





Expected Event Rate

modulation factor: 0.6 GV

Latitude [deg]	proton [/s]		proton [/s] > 800MeV		He [/s]		He [/s] > 800MeV	
	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)
0.00-5.16	1.17	0.073	1.13	0.071	0.090	0.0056	0.090	0.0056
5.16-10.32	1.21	0.076	1.18	0.084	0.099	0.0062	0.099	0.0062
10.32-15.48	1.28	0.080	1.25	0.078	0.11	0.0069	0.11	0.0069
15.48-20.64	1.44	0.090	1.42	0.089	0.13	0.0080	0.13	0.0080
20.64-25.80	1.82	0.11	1.80	0.11	0.16	0.0099	0.16	0.0099
25.80-30.96	2.51	0.16	2.50	0.16	0.22	0.014	0.22	0.014
30.96-36.12	3.69	0.23	3.68	0.23	0.33	0.021	0.33	0.021
36.12-41.28	5.36	0.34	5.35	0.33	0.51	0.032	0.47	0.030
41.28-46.44	7.67	0.48	7.56	0.47	0.69	0.043	0.60	0.038
46.44-51.60	10.1	0.63	0.67	0.60	0.85	0.053	0.71	0.044
Counts / period	26666	1667	25962	1623	2316	145	2055	128

Expected Event Rate

modulation factor: 0.2 GV

Latitude [deg]	proton [/s]		proton [/s] > 800MeV		He [/s]		He [/s] > 800MeV	
	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)
0.00-5.16	1.29	0.080	1.24	0.078	0.092	0.0058	0.09 2	0.0058
5.16-10.32	1.34	0.084	1.31	0.082	0.10	0.0063	0.10	0.0063
10.32-15.48	1.42	0.089	1.39	0.087	0.11	0.0071	0.11	0.0071
15.48-20.64	1.62	0.10	1.61	0.10	0.13	0.0082	0.13	0.0082
20.64-25.80	2.10	0.13	2.08	0.13	0.17	0.010	0.17	0.010
25.80-30.96	3.01	0.19	3.00	0.19	0.24	0.015	0.24	0.015
30.96-36.12	4.68	0.29	4.67	0.29	0.36	0.023	0.36	0.022
36.12-41.28	7.38	0.46	7.37	0.46	0.57	0.035	0.52	0.032
41.28-46.44	11.9	0.74	11.5	0.72	0.79	0.049	0.67	0.042
46.44-51.60	17.1	1.07	15.5	0.97	0.98	0.061	0.79	0.050
Counts / period	4071 6	2545	38326	2395	2605	163	2260	141

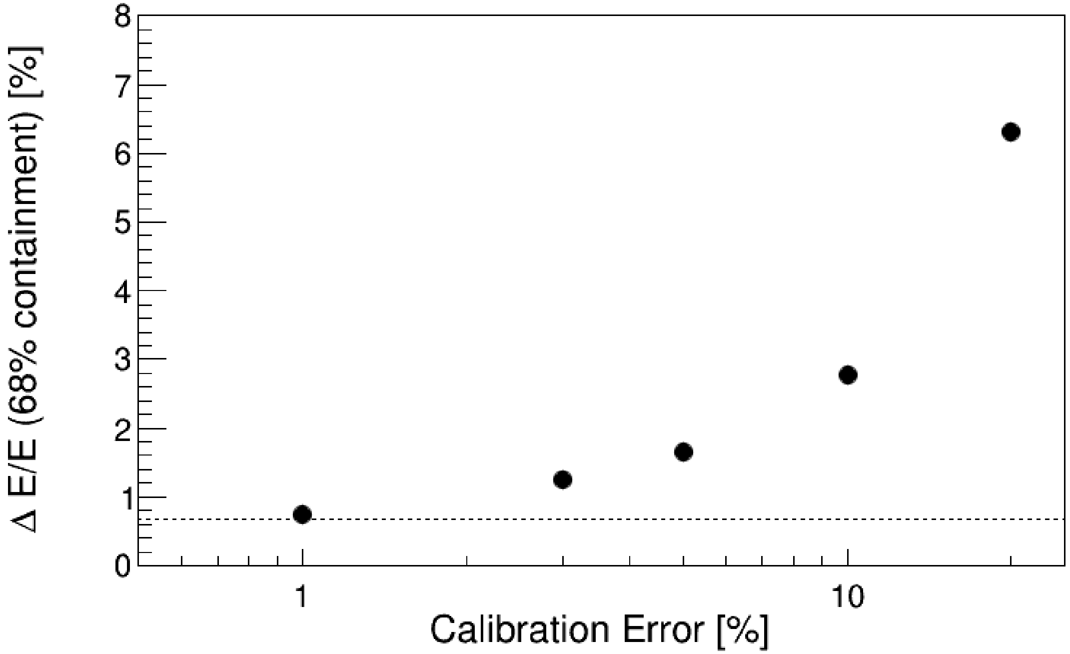
Expected Event Rate

modulation factor: 1.2 GV

Latitude [deg]	proton [/s]		proton [/s] > 800MeV		He [/s]		He [/s] > 800MeV	
	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)	per layer	per log (average)
0.00-5.16	1.02	0.064	0.98	0.061	0.087	0.0054	0.087	0.0054
5.16-10.32	1.05	0.066	1.03	0.064	0.095	0.0059	0.095	0.0059
10.32-15.48	1.10	0.069	1.08	0.067	0.11	0.0067	0.11	0.0067
15.48-20.64	1.22	0.076	1.20	0.075	0.12	0.0076	0.12	0.0076
20.64-25.80	1.49	0.093	1.48	0.092	0.15	0.0094	0.15	0.0094
25.80-30.96	1.97	0.12	1.96	0.12	0.21	0.013	0.21	0.013
30.96-36.12	2.71	0.17	2.70	0.17	0.30	0.019	0.30	0.019
36.12-41.28	3.65	0.23	3.64	0.23	0.44	0.027	0.41	0.026
41.28-46.44	4.77	0.30	4.74	0.30	0.58	0.036	0.52	0.032
46.44-51.60	5.84	0.37	5.73	0.36	0.70	0.044	0.60	0.038
Counts / period	17169	1073	16946	1059	1979	124	1800	113

Required accuracy

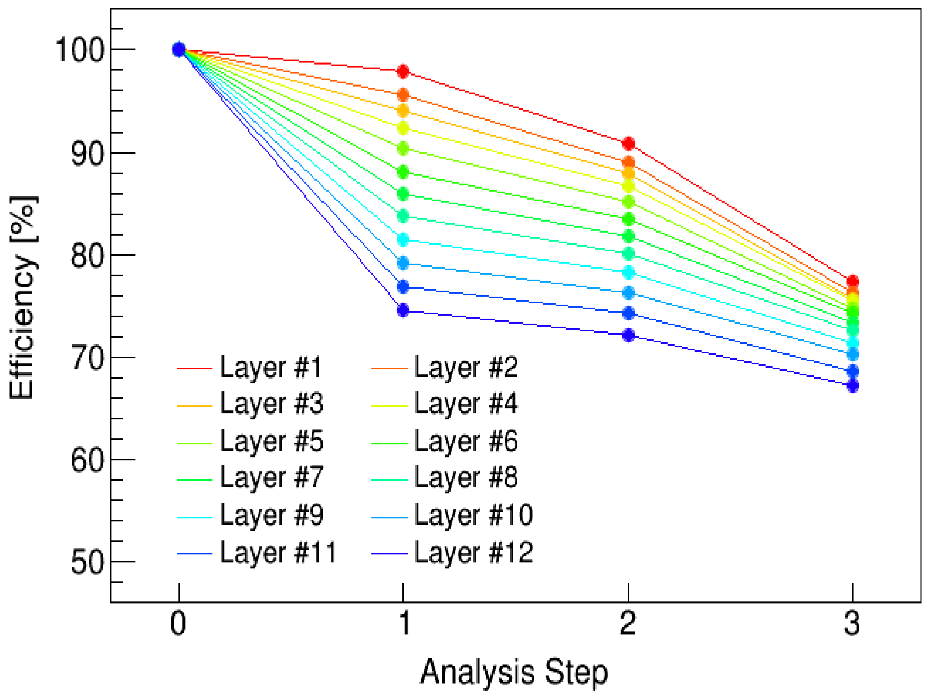
Calibration error vs. energy resolution for 1 TeV electrons

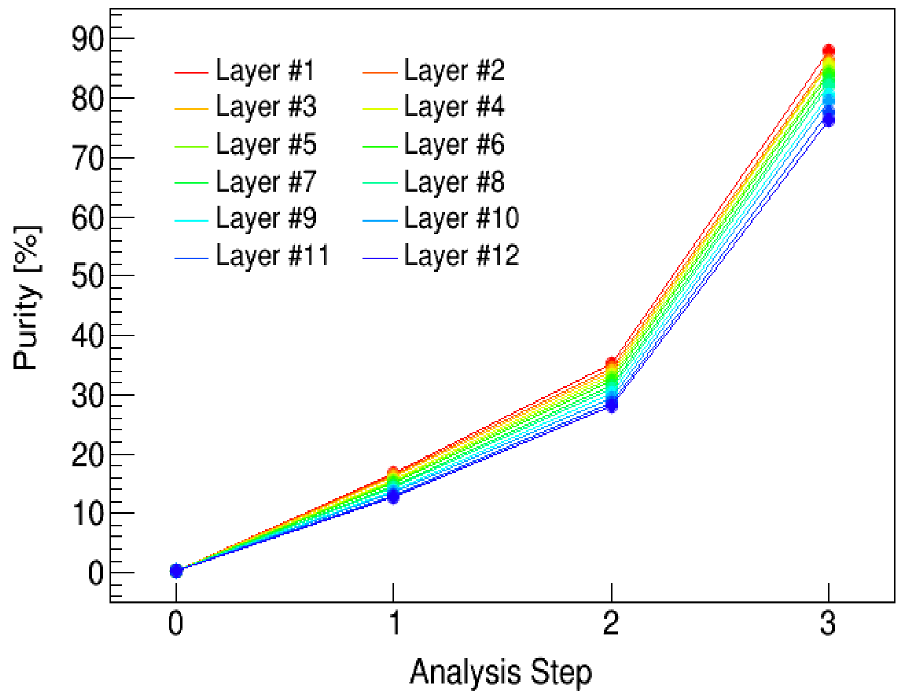


Energy resolution can be kept under 3 % with calibration error less than 10 %

Efficiency and purity in each analysis step

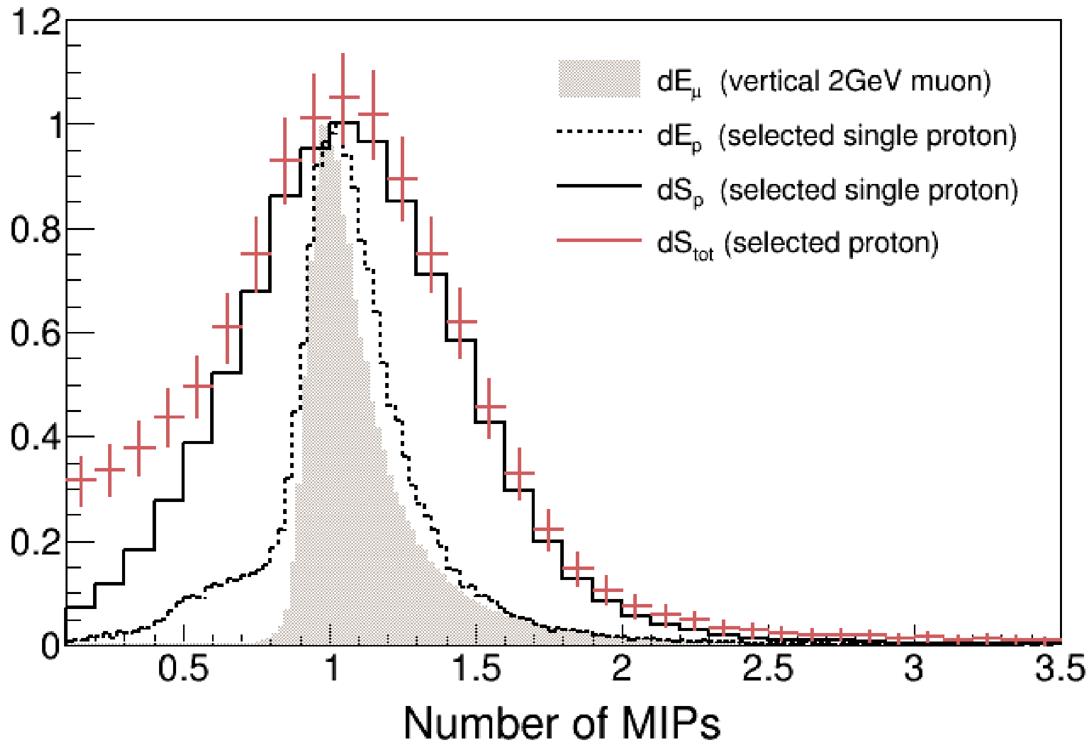
0. before selection
1. after track reconstruction
2. after the cut by total deposited energy in TASC
3. after the cut by likelihood parameter



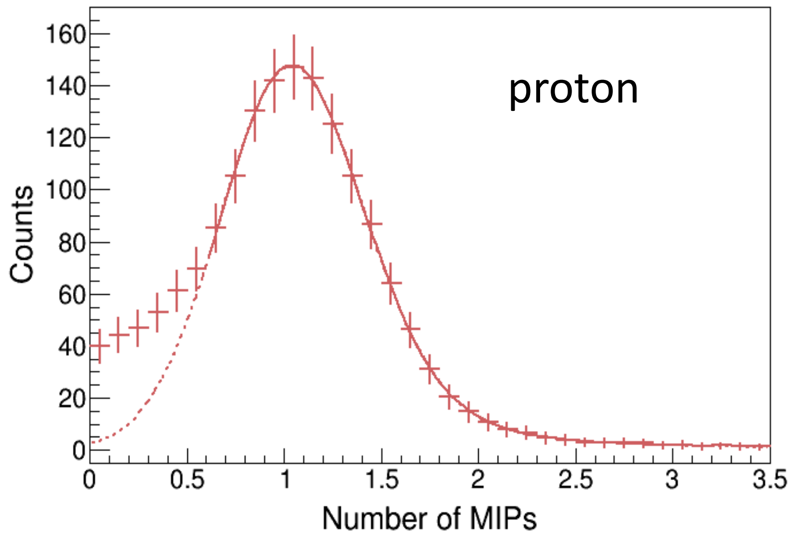


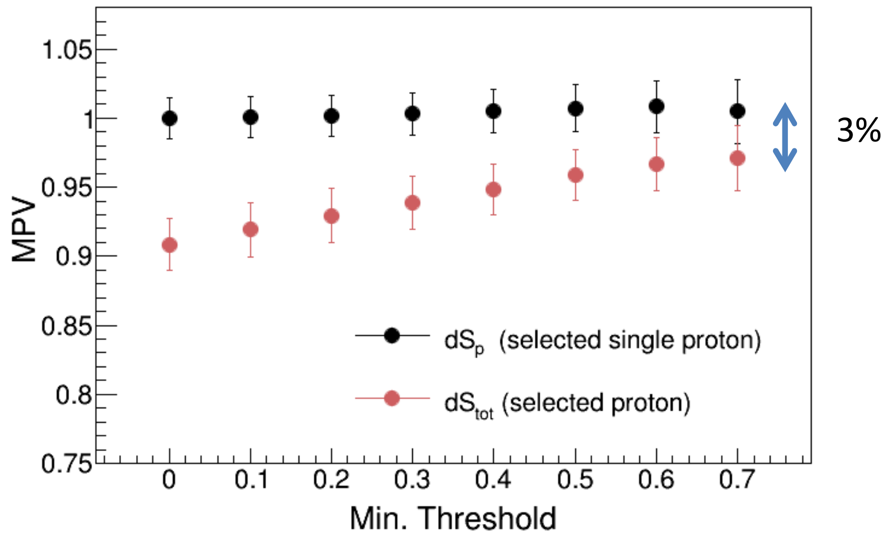
Comparison of distributions

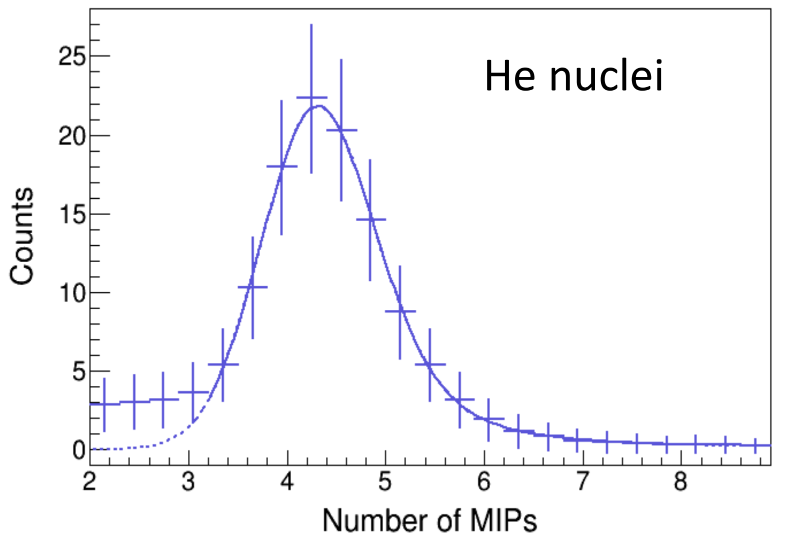
- vertically incident 2 GeV muons (energy deposition)
- selected single protons on orbit (energy deposition)
- selected single protons on orbit (with electronic noise, S/N=3)
- selected protons on orbit (with electronic noise; S/N=3)

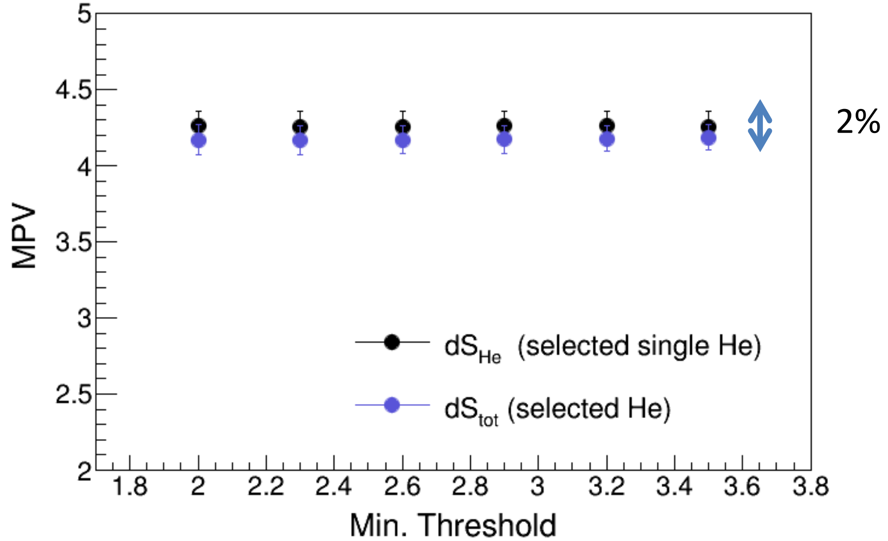


MPV and fitting range



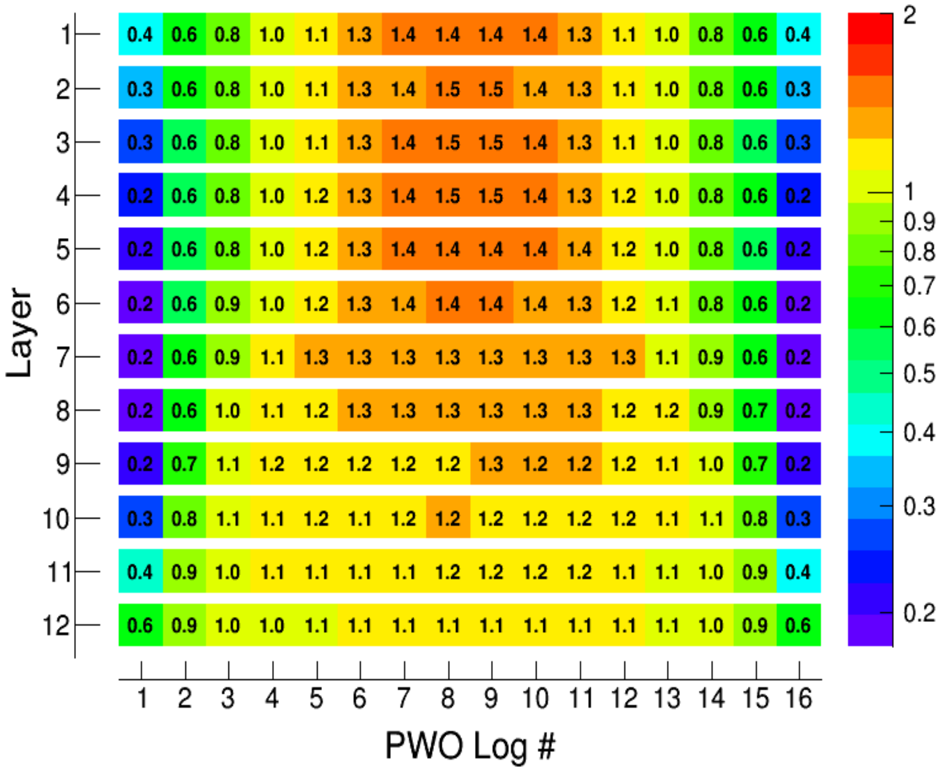




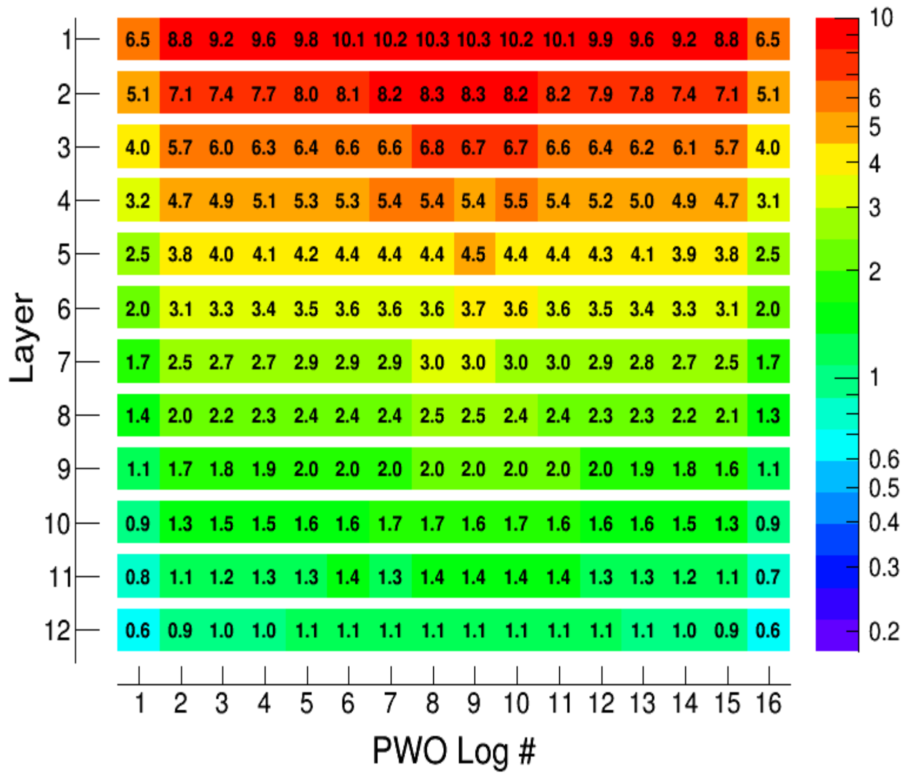


Event rate for each PWO

Geometrical condition: from top to the bottom

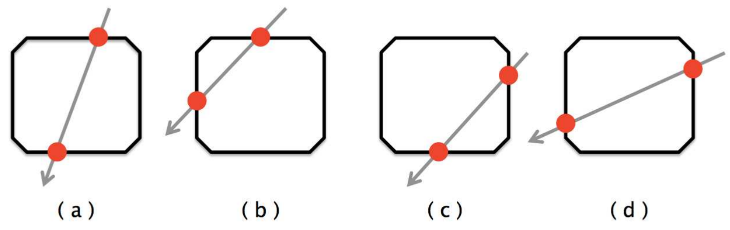


Geometrical condition: from top to each layer



※ normalized by averaged number of events we can get for 1 PWO log in the bottom layer (i.e. proton 2, 000 events, He 150 events)

Correction of incident angle



Path length in each log depends on geometrical condition.

→ 1. calculate path length and apply as a correction factor

2. select events which pass the log from the top side to the bottom side .. (a)

Calibration error can be reduced a little (2.0% -> 1.6%) by applying both 1 & 2, but required calibration time increase (1 orbit -> 1.2 orbit).