

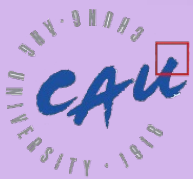


HAWL & HAWLU

Hankuk Atmospheric muon Wide Landscaping



From Tunnel Overburden Reconstruction
  **to Tidal Measurements**
via atmospheric muons



Jiwon Seo

Department of Physics, Chung-Ang University

On behalf of the Rare Event Search Lab.(RESL)

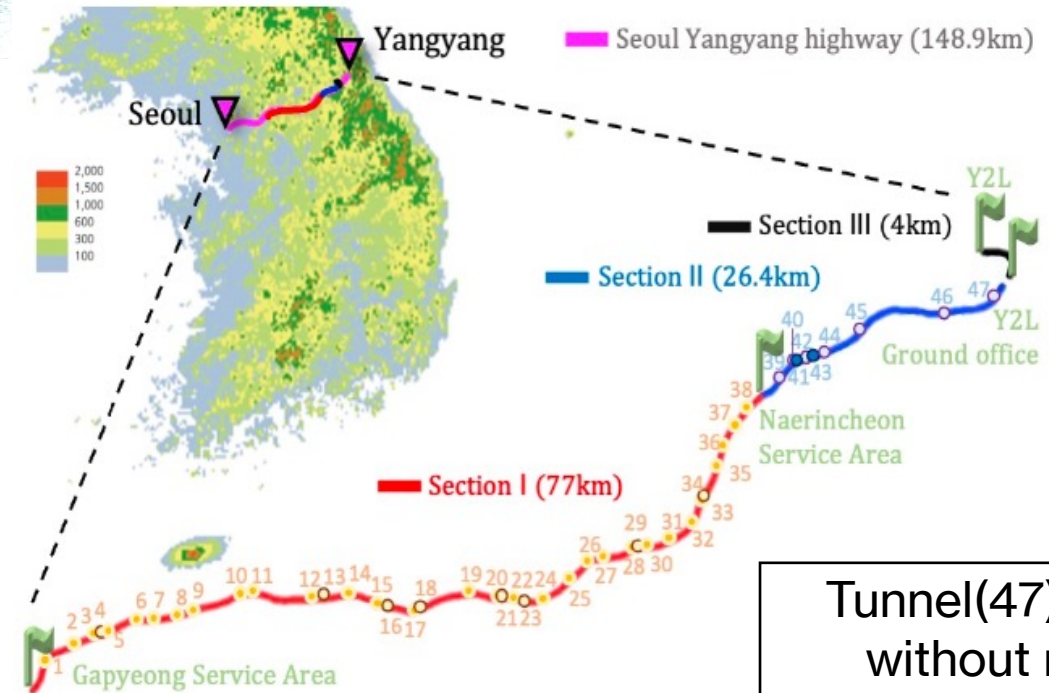
2026 Muographers. 2026.06.03

1. Real-time Portable Muography

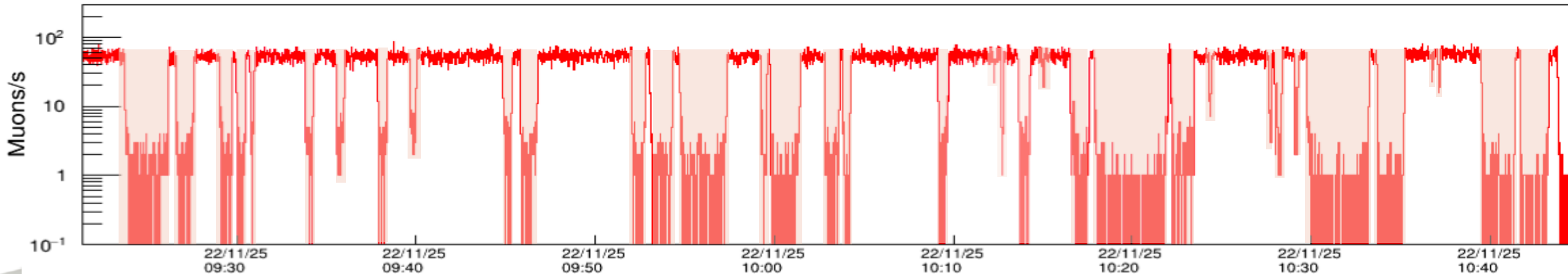
A fast scan over hundred kilometers within a few hours has been achieved for the first time.



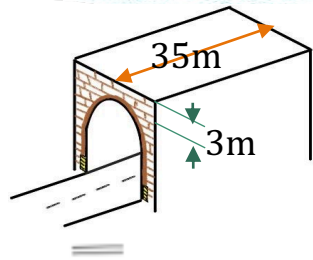
Driving
~55km/h



Tunnel(47) mapping without missing!

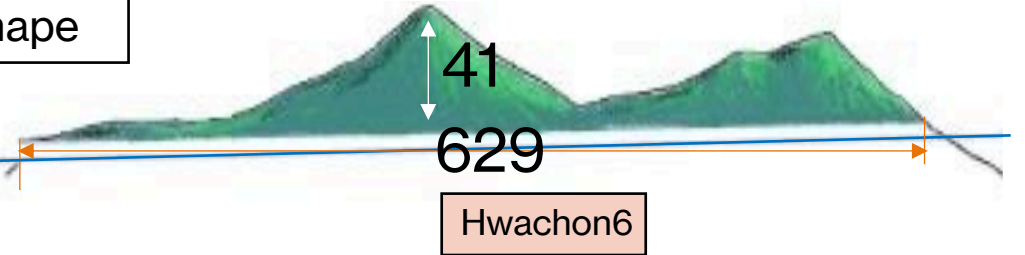
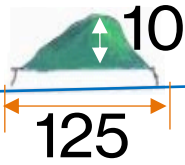


1. Real-time Portable Muography



Mapping 3m tunnel while moving (~55km/h)!!

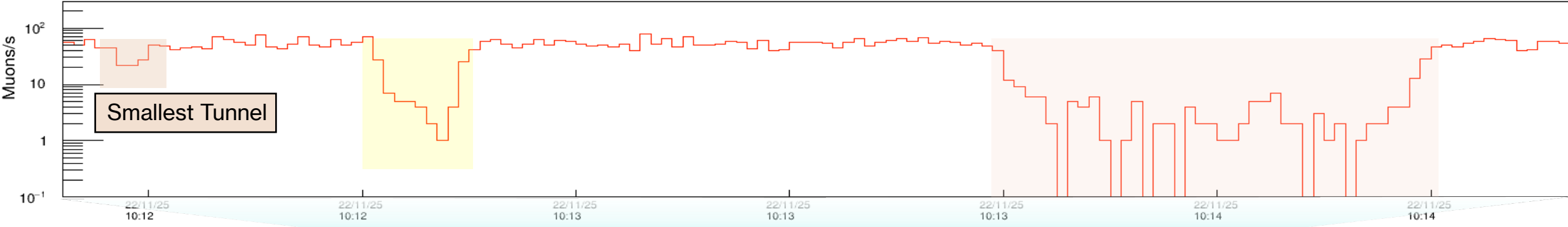
HAWL measured detail mountain shape



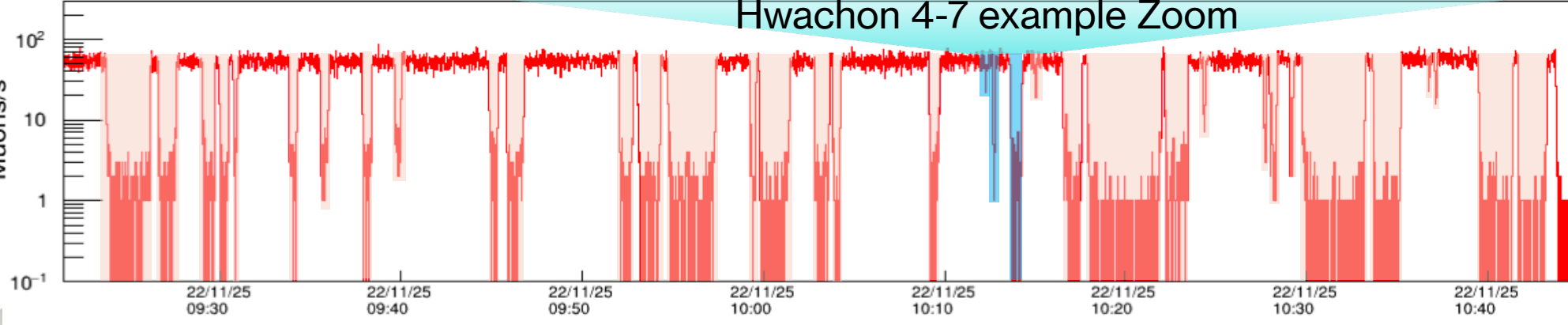
Hwachon4

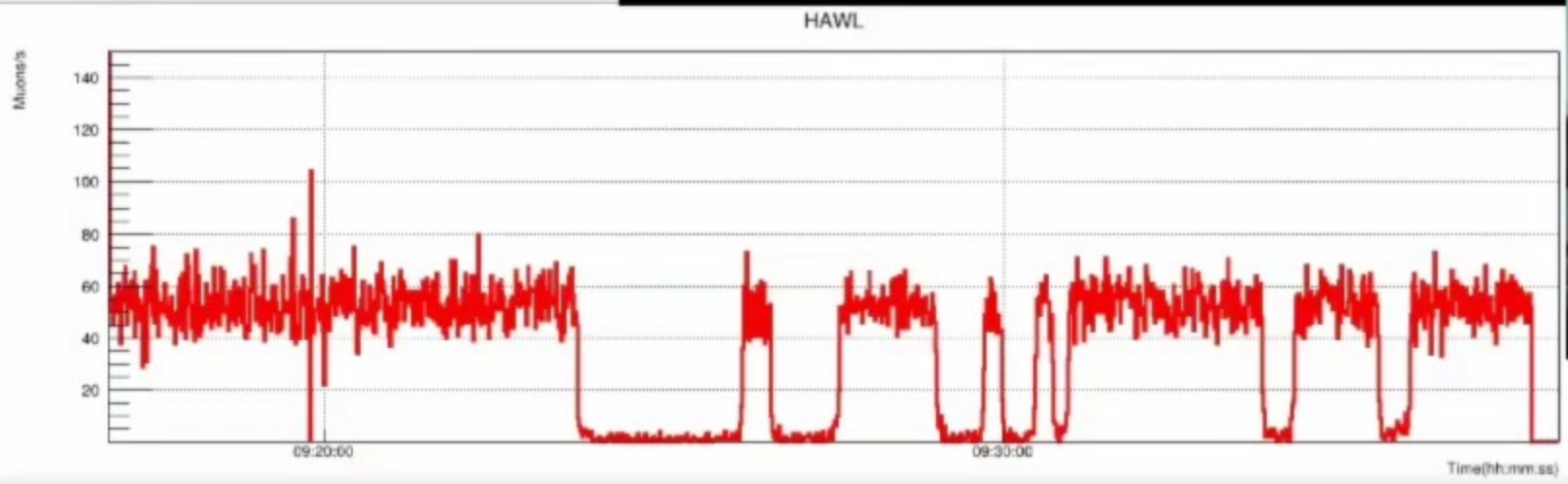
Hwachon5

Hwachon6

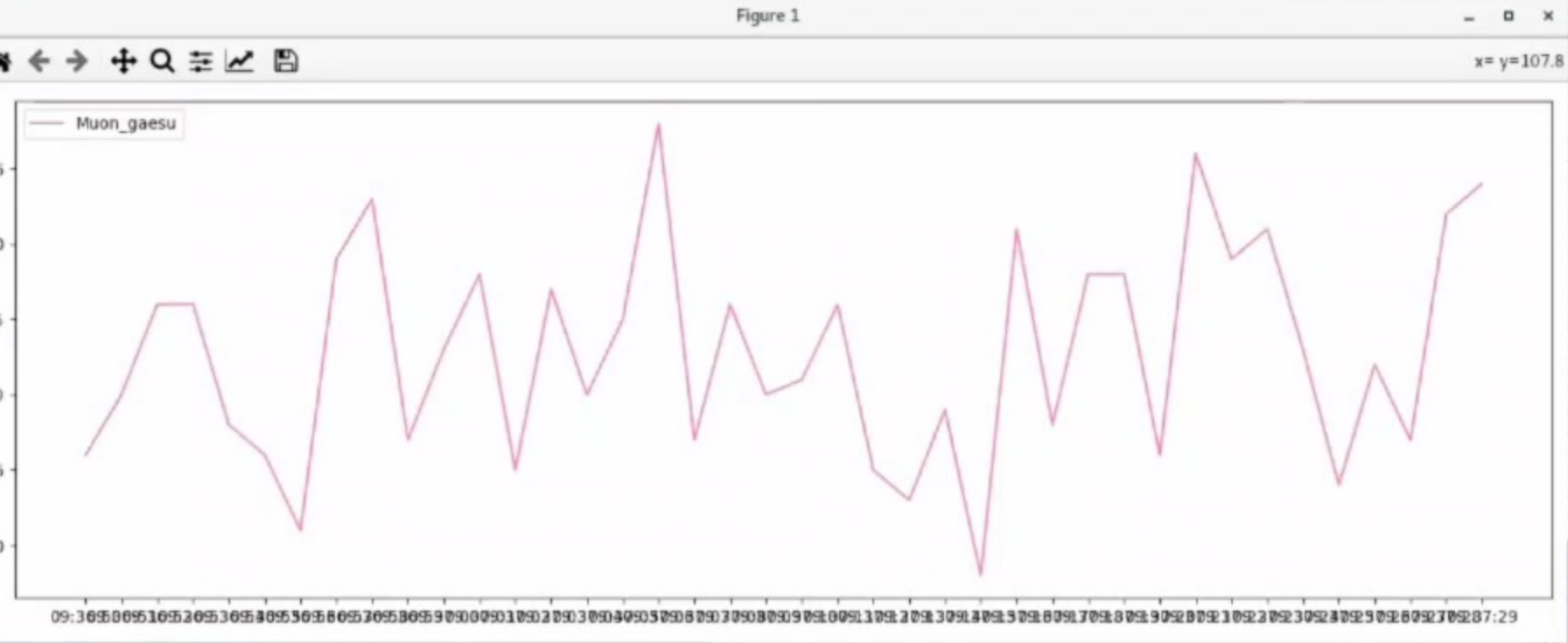


Hwachon 4-7 example Zoom



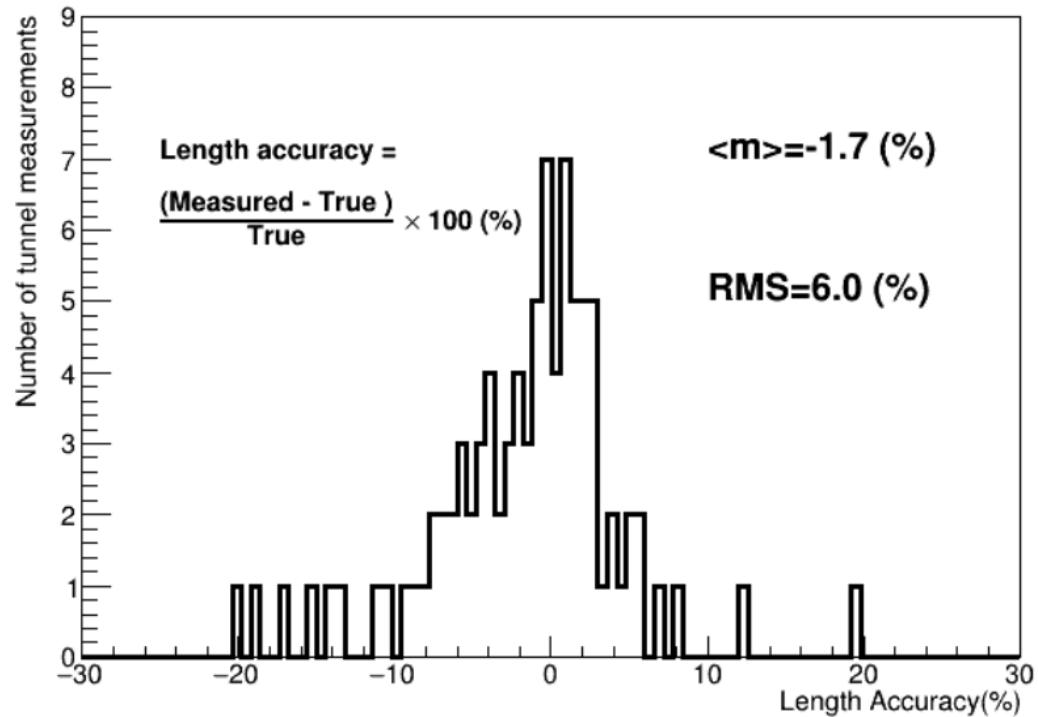


1669336631	T(local) = 1221	Muon Counts/sec = 56
1669336632	T(local) = 1222	Muon Counts/sec = 45
1669336633	T(local) = 1223	Muon Counts/sec = 43
1669336634	T(local) = 1224	Muon Counts/sec = 49
1669336635	T(local) = 1225	Muon Counts/sec = 38
1669336636	T(local) = 1226	Muon Counts/sec = 61
1669336637	T(local) = 1227	Muon Counts/sec = 48
1669336638	T(local) = 1228	Muon Counts/sec = 58
1669336639	T(local) = 1229	Muon Counts/sec = 58
1669336640	T(local) = 1230	Muon Counts/sec = 46
1669336641	T(local) = 1231	Muon Counts/sec = 66
1669336642	T(local) = 1232	Muon Counts/sec = 59
1669336643	T(local) = 1233	Muon Counts/sec = 61
1669336644	T(local) = 1234	Muon Counts/sec = 53
1669336645	T(local) = 1235	Muon Counts/sec = 44
1669336646	T(local) = 1236	Muon Counts/sec = 52
1669336647	T(local) = 1237	Muon Counts/sec = 47
1669336648	T(local) = 1238	Muon Counts/sec = 62
1669336649	T(local) = 1239	Muon Counts/sec = 64
1669336650	T(local) = 1240	Muon Counts/sec = 54
1669336651	T(local) = 1241	Muon Counts/sec = 47
1669336652	T(local) = 1242	Muon Counts/sec = 62
1669336653	T(local) = 1243	Muon Counts/sec = 62
1669336654	T(local) = 1244	Muon Counts/sec = 60
1669336655	T(local) = 1245	Muon Counts/sec = 49
1669336656	T(local) = 1246	Muon Counts/sec = 53
1669336657	T(local) = 1247	Muon Counts/sec = 59
1669336658	T(local) = 1248	Muon Counts/sec = 57
1669336659	T(local) = 1249	Muon Counts/sec = 50
1669336660	T(local) = 1250	Muon Counts/sec = 58
1669336661	T(local) = 1251	Muon Counts/sec = 56
1669336662	T(local) = 1252	Muon Counts/sec = 46
1669336663	T(local) = 1253	Muon Counts/sec = 51
1669336664	T(local) = 1254	Muon Counts/sec = 46
1669336665	T(local) = 1255	Muon Counts/sec = 57
1669336666	T(local) = 1256	Muon Counts/sec = 46



2. Detector ability

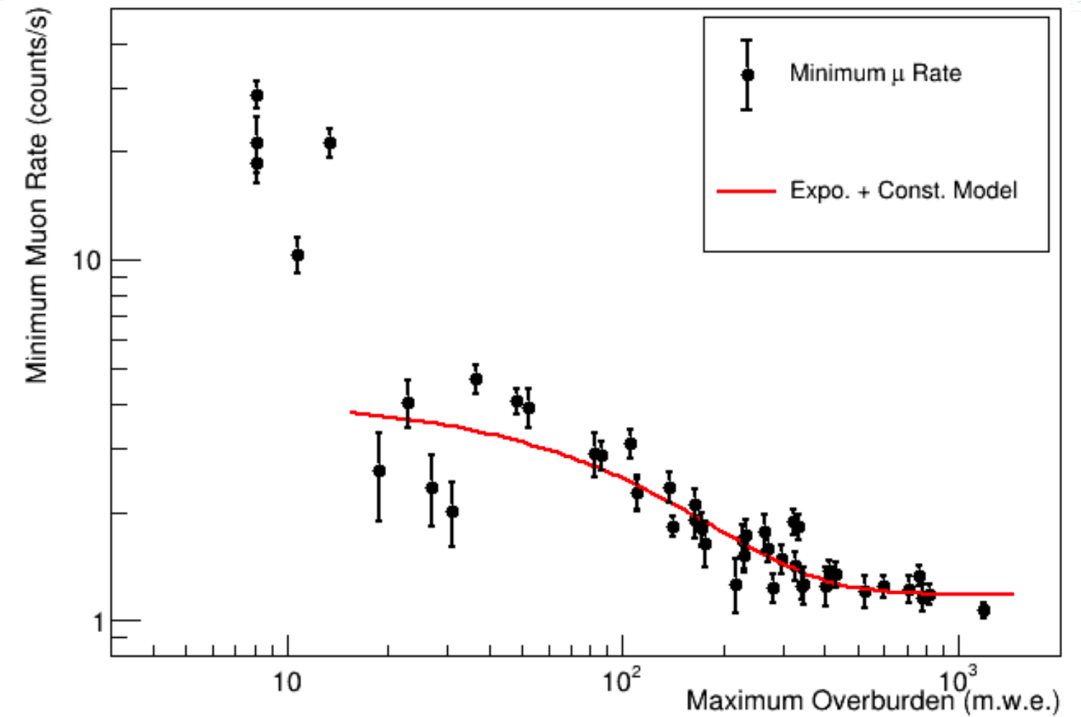
Length Accuracy



* Assuming constant speed (55km/h and 51km/h)

Outliers: mostly short tunnels

Overburden



* Assuming rock contents ($\rho = 2.7 \text{ g/cm}^3$)

Outliers: Animal tunnels

Tunnel length accuracy of 6.0%
, with a detectable overburden range spanning from 8 to 400 (m.w.e.)

HAWL paper

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journal homepage: www.elsevier.com/locate/radphyschem



Real-time portable muography with Hankuk Atmospheric-muon Wide Landscaping : HAWL

J. Seo ^a, N. Carlin ^b, D.F.F.S. Cavalcante ^b, J.S. Chung ^a, L.E. França ^b, C. Ha ^{a,*}, J. Kim ^a, J.Y. Kim ^a, H. Kimku ^a, B.C. Koh ^a, Y.J. Lee ^a, B.B. Manzato ^b, S.W. Oh ^a, R.L.C. Pitta ^b, S.J. Won ^a

^a Department of Physics, Chung-Ang University, Seoul, 06974, Republic of Korea

^b Physics Institute, University of São Paulo, São Paulo, 05508-090, Brazil

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Keywords:

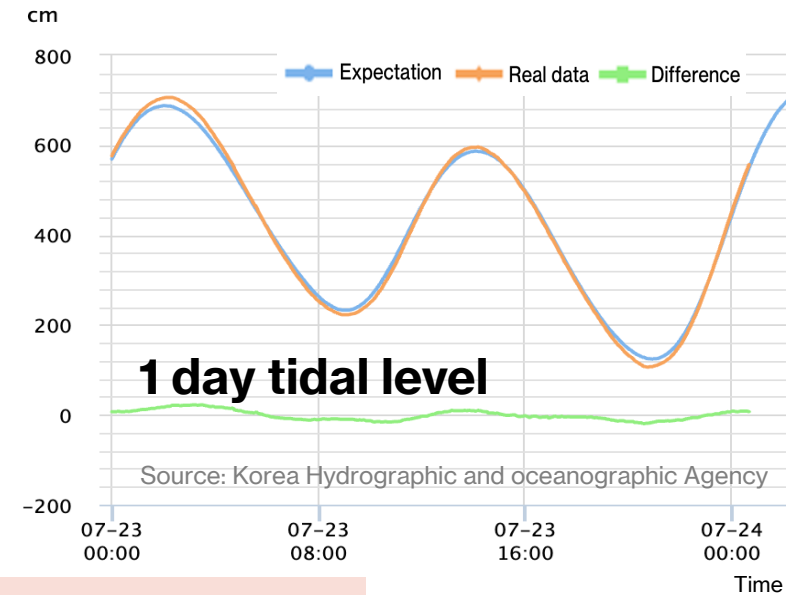
Muon tomography
Plastic scintillator
Portable radiation detector

ABSTRACT

Cosmic ray muons prove valuable across various fields, from particle physics experiments to non-invasive tomography, thanks to their high flux and exceptional penetrating capability. Utilizing a scintillator detector, one can effectively study the topography of mountains situated above tunnels and underground spaces. The Hankuk Atmospheric-muon Wide Landscaping (HAWL) project successfully charts the mountainous region of eastern Korea by measuring cosmic ray muons with a detector in motion. The real-time muon flux measurement shows a tunnel length accuracy of 6.0%, with a detectable overburden range spanning from 8 to 400 meter-water-equivalent depth. This is the first real-time portable muon tomography.

3. Measure the tides

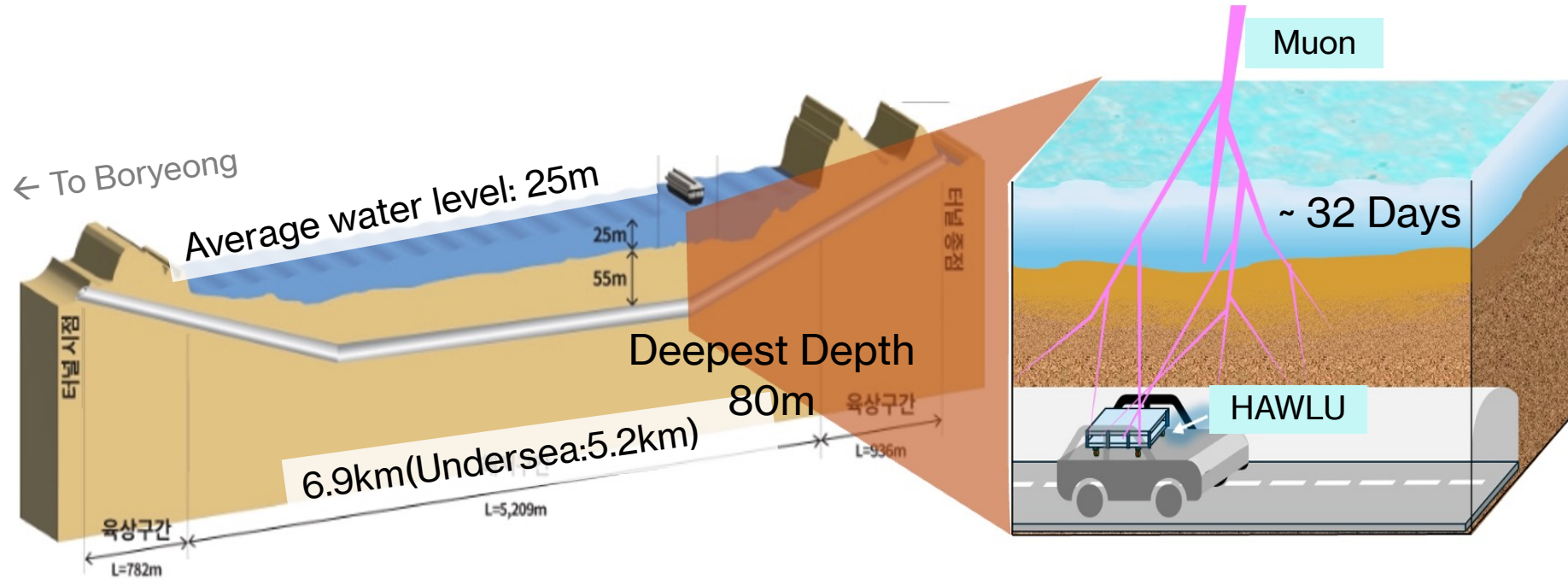
West sea of Korea is **perfect place to measure tides!**



- Tidal difference(7.56m)
- Two tides per day, 2nd order oscillation 24.8 -> 12.4hr
- Disaster Monitoring(Tsunami, Typhoon, Sinkhole)

3. Measure the tides

West sea of Korea is **perfect place to measure tides!**



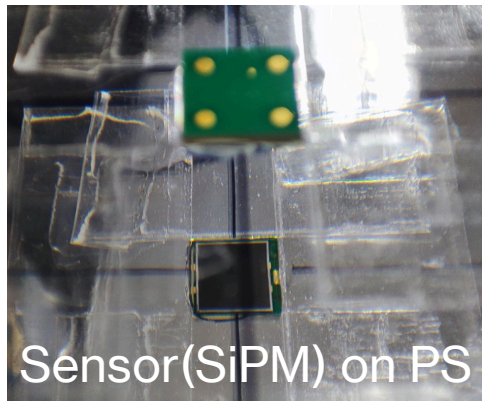
→ The world's 5th longest tunnel ➤ Wave variation is little!

3. Measure the tides

- 1. Light yield increasing : Direct attaching
- 2. Convolutional Neural Network (CNN)

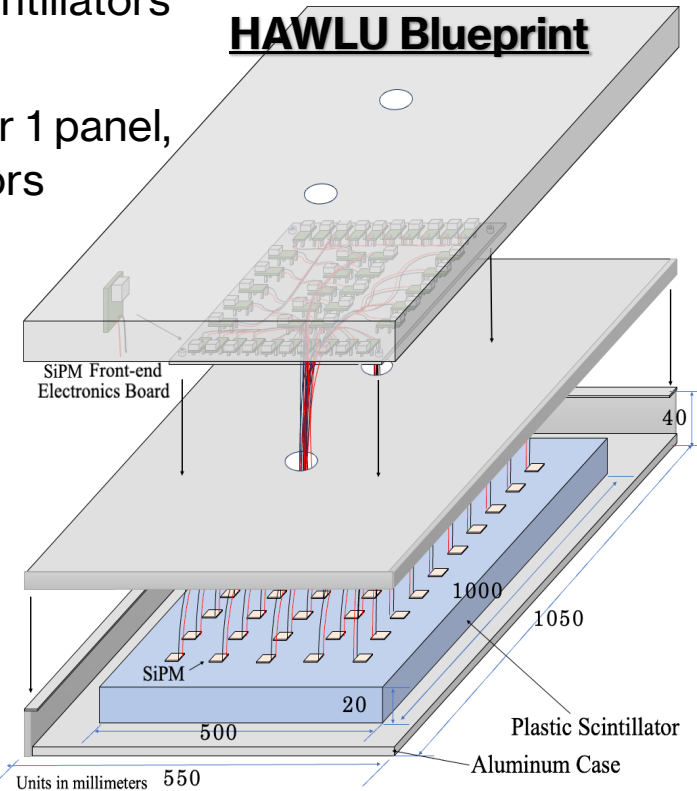
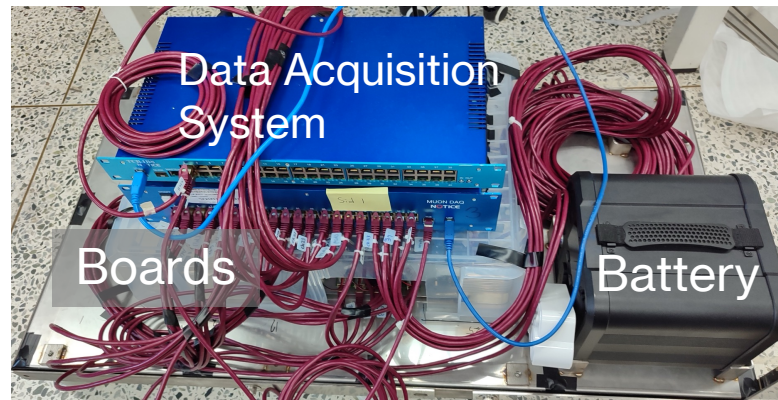
3. Two panel coincidence

- Gamma Noise and Muon Separation well
- Overburden range will improve.
- Trajectory reconstruction

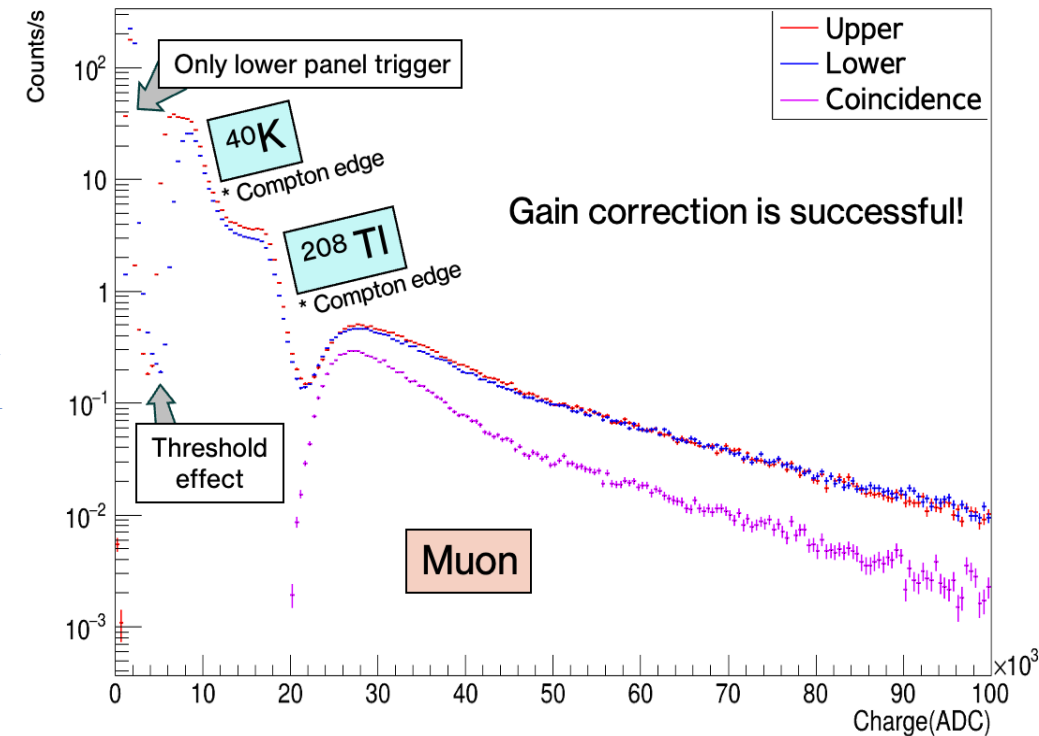


Two plastic scintillators

40 Sensors per 1 panel,
Total 80 Sensors



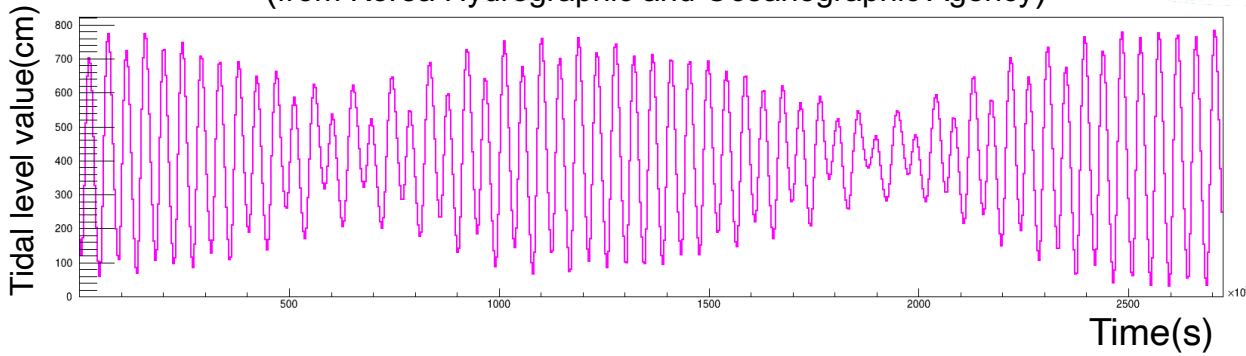
Muon Coincidence



3. Measure the tides

Tidal level value

(from Korea Hydrographic and Oceanographic Agency)



$$\text{Muon Model} = p0 - p1 * \text{wave level}(x - p2)$$

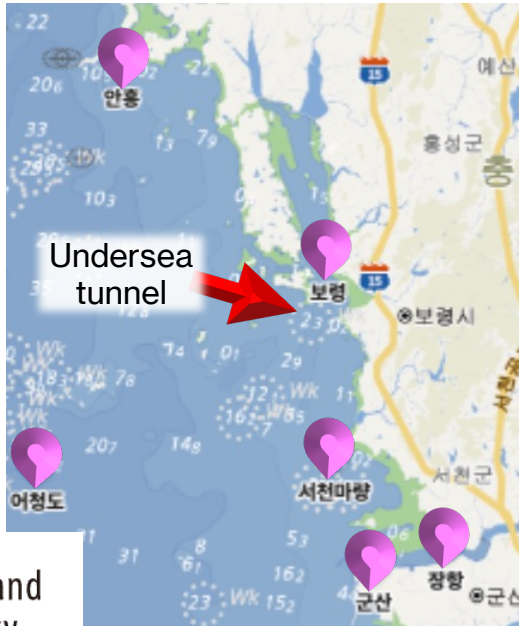
P0: Mean muon count

P1: Change in muon count per unit water-level variation [counts/m]

P2: Time delay between water level and muon count variation

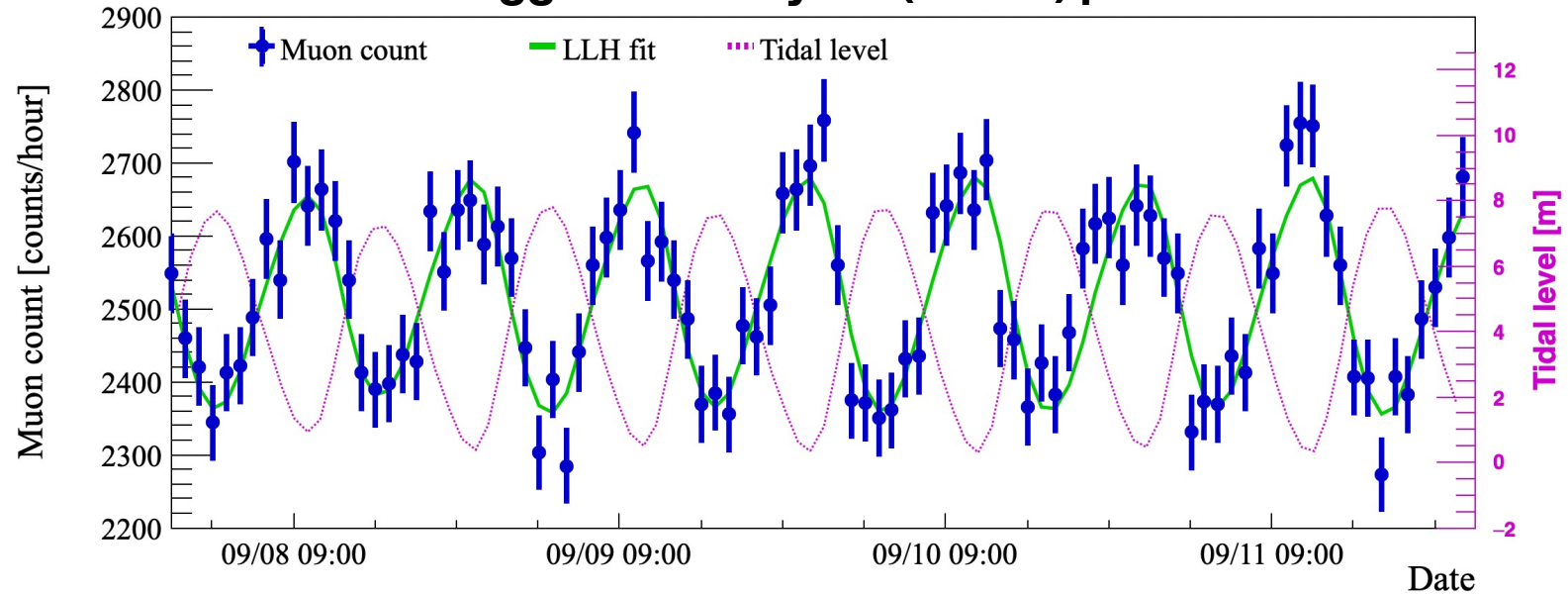


Tide level Measurement place



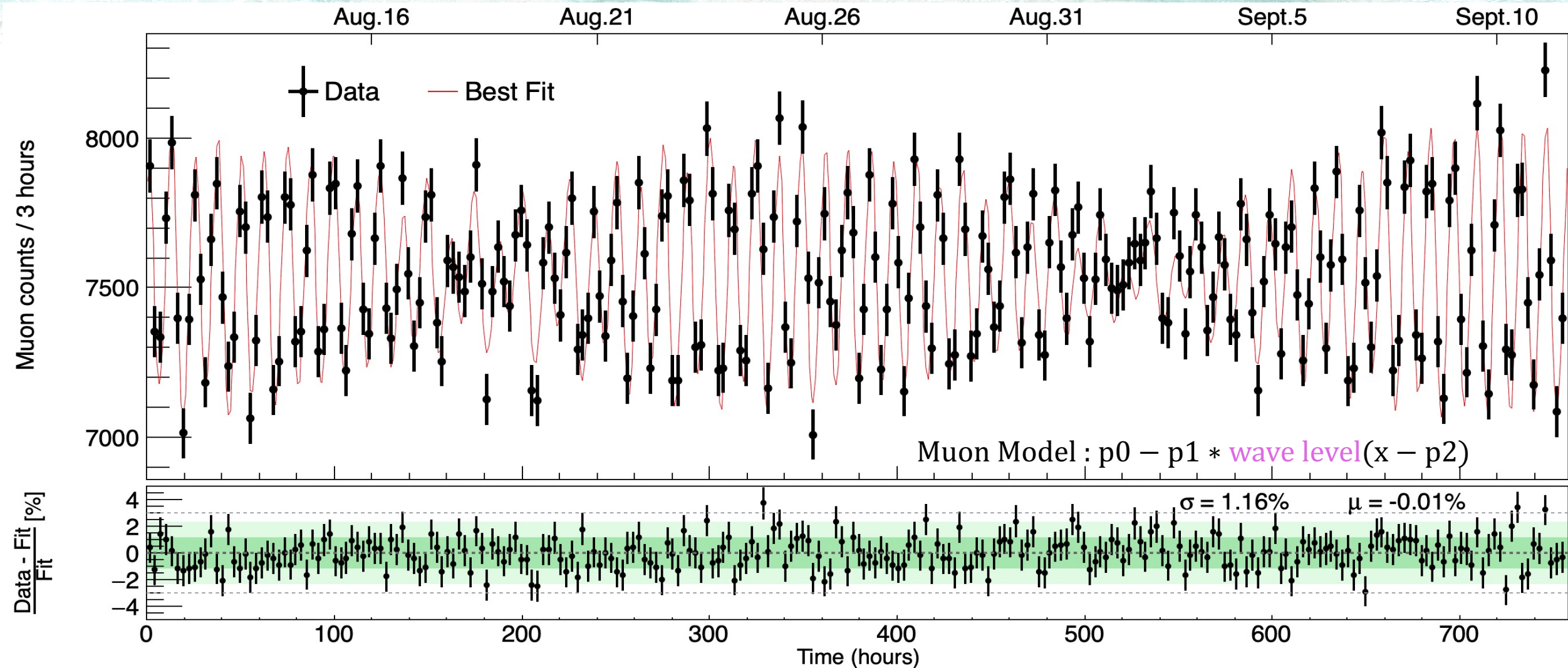
Undersea tunnel

The Biggest of the year (756cm) period Data



~32 days 2025 8/11 (10:03:10) ~ 9/12 (00:05:53)

3. Measure the tides



Fitting well with Wave level

$\chi^2/\text{ndf} = 768.1/755 = 1.02$, P-value = 0.36
Residual RMS = 50.67

P0(Offset)	2514.64 ± 1.82
P1(Amplitude)	43.21 ± 0.95
P2(Time shift)	-413.67 ± 157.01

4. Detector sensitivity

The detector achieves a sensitivity of **>4 σ per meter for a 24-hour**

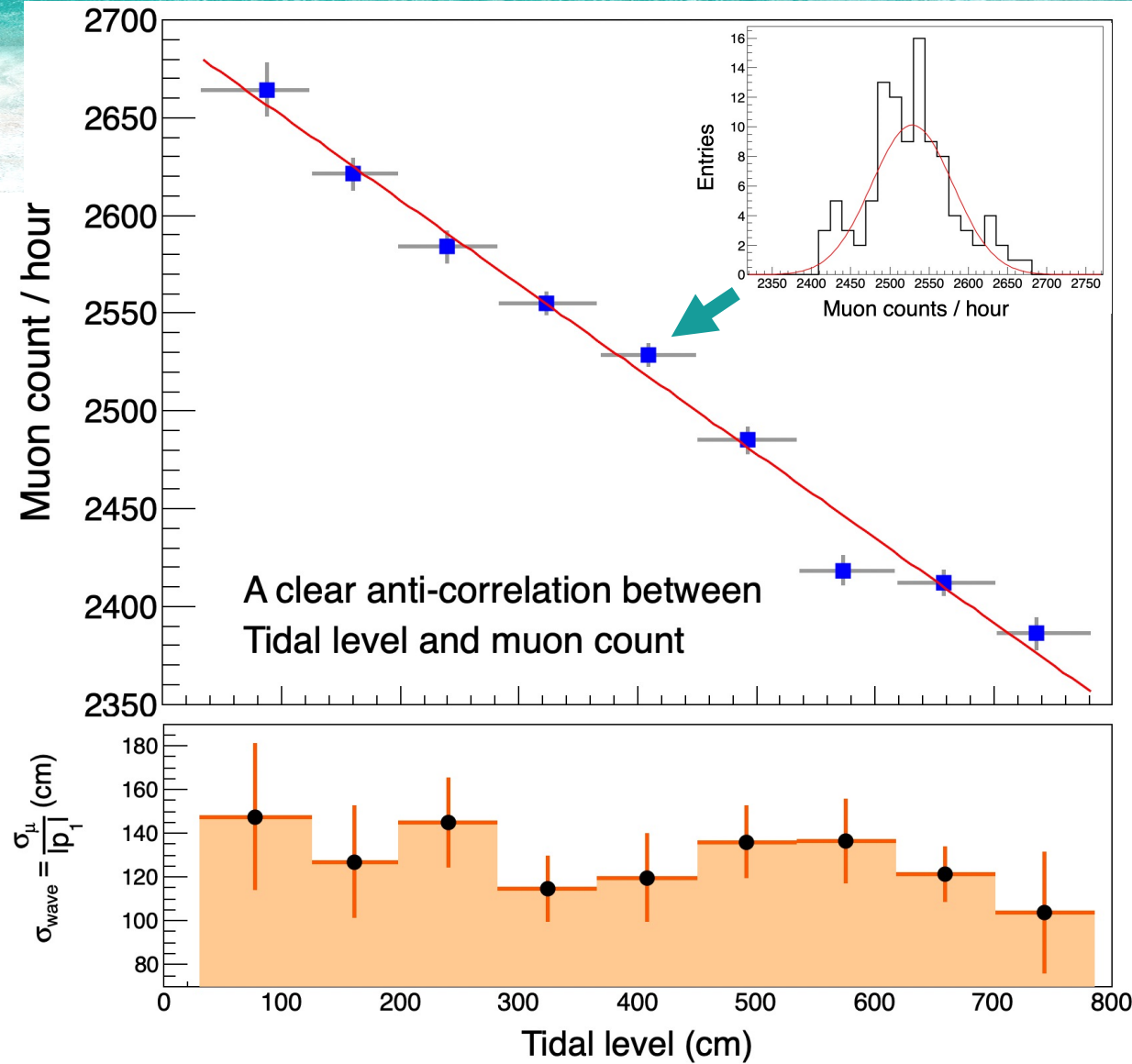
$$\text{Muon model} = P_0 - P_1 * \text{water level variation}(t - \Delta T)$$

$$\text{Significance} = \frac{p_1}{\sqrt{p_0}} / m = 0.86 \sigma/m/\sqrt{\text{hour}}$$

Significance increases with measurement time: $\sigma \propto \sqrt{T}$

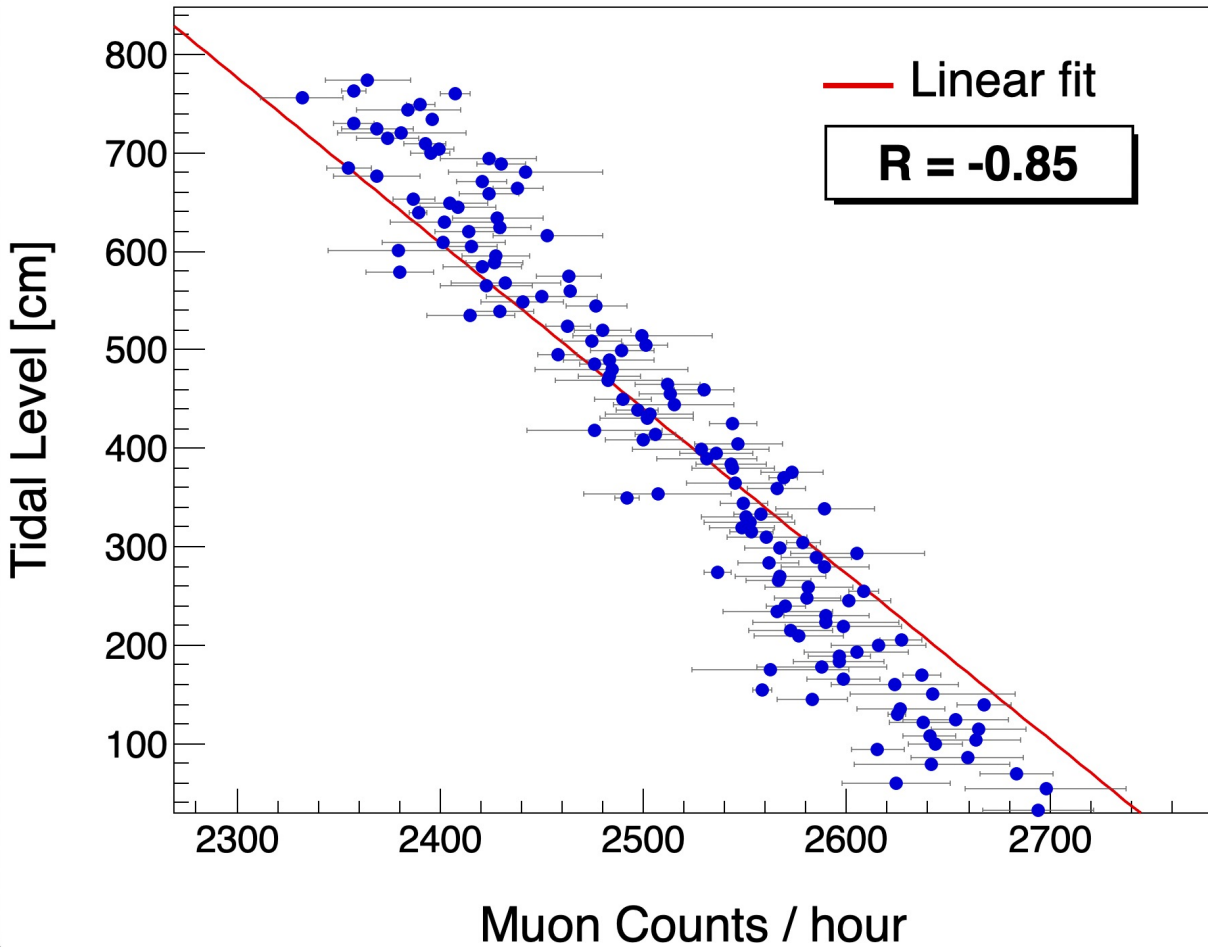
$$\text{24-hour sensitivity} = 0.86 \times 24 \approx 4.2 \sigma/m$$

The detector achieved a **tidal timing resolution** of **± 2.63 minutes** (For all six locations)



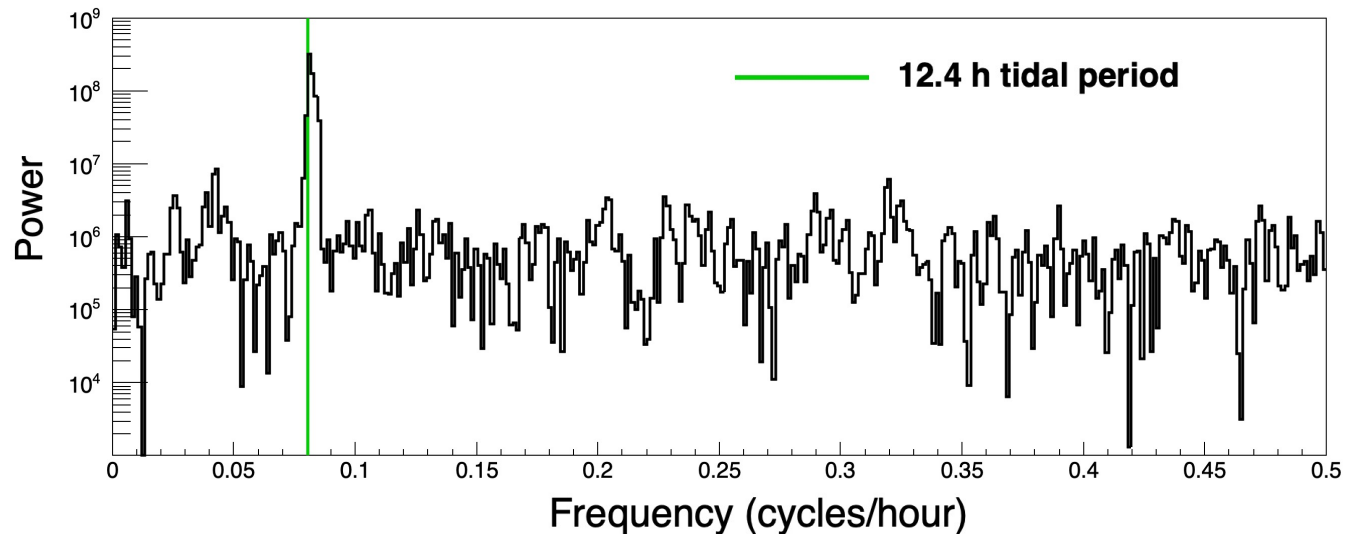
The reconstructed water-level uncertainty at the meter scale over the full range

4. Detector sensitivity

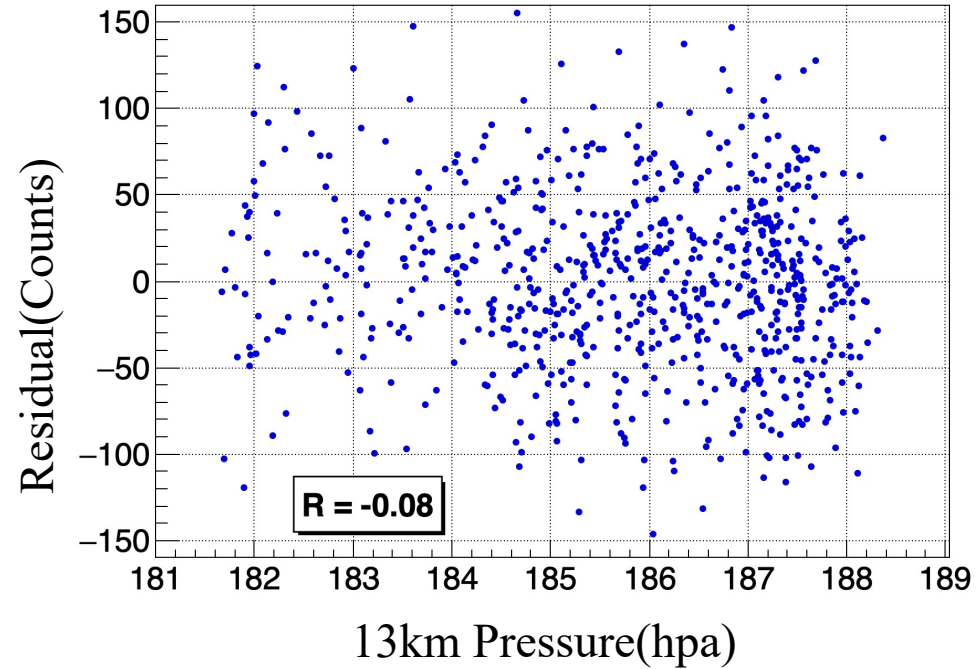
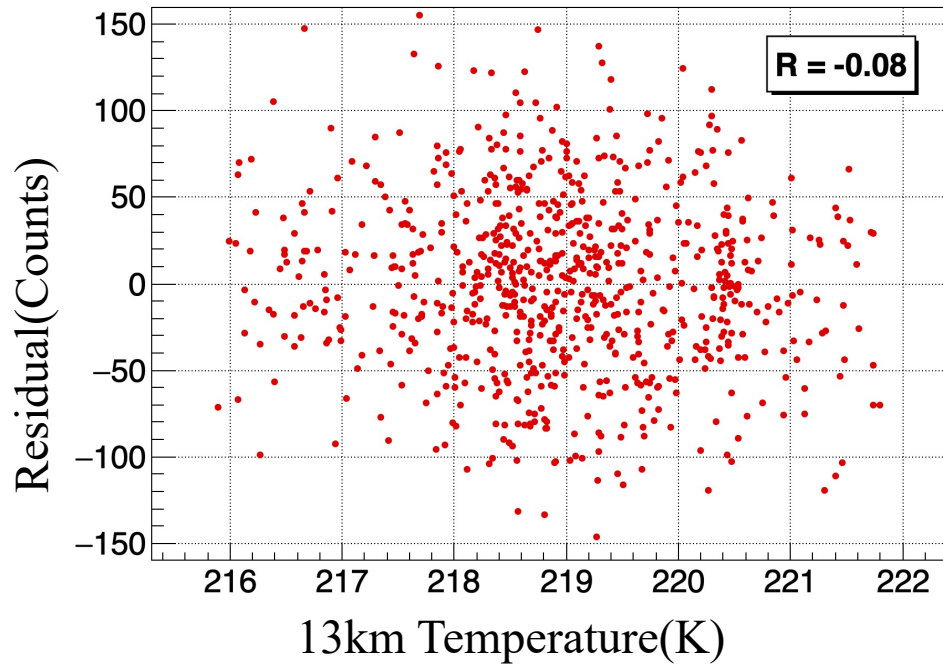


Increased seawater overburden producing additional attenuation of cosmic-ray muons

- A strong anti-correlation ($r = -0.85$)
- attenuation response: -0.456 ± 0.01 counts $\text{h}^{-1} \text{cm}^{-1}$
- A strong peak at 12.4 hours in the FFT result.



5. Environment



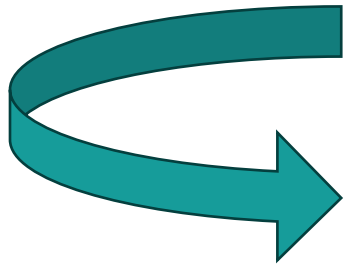
No significant correlation

About Ground
10km, 13km, 16km

$$\text{Muon Model} = p_0 - p_1 * \text{wave level}(x - p_2) + p_3 * T + p_4 * P \quad \rightarrow \mathbf{P : 1.69\sigma, T : 1.59\sigma}$$

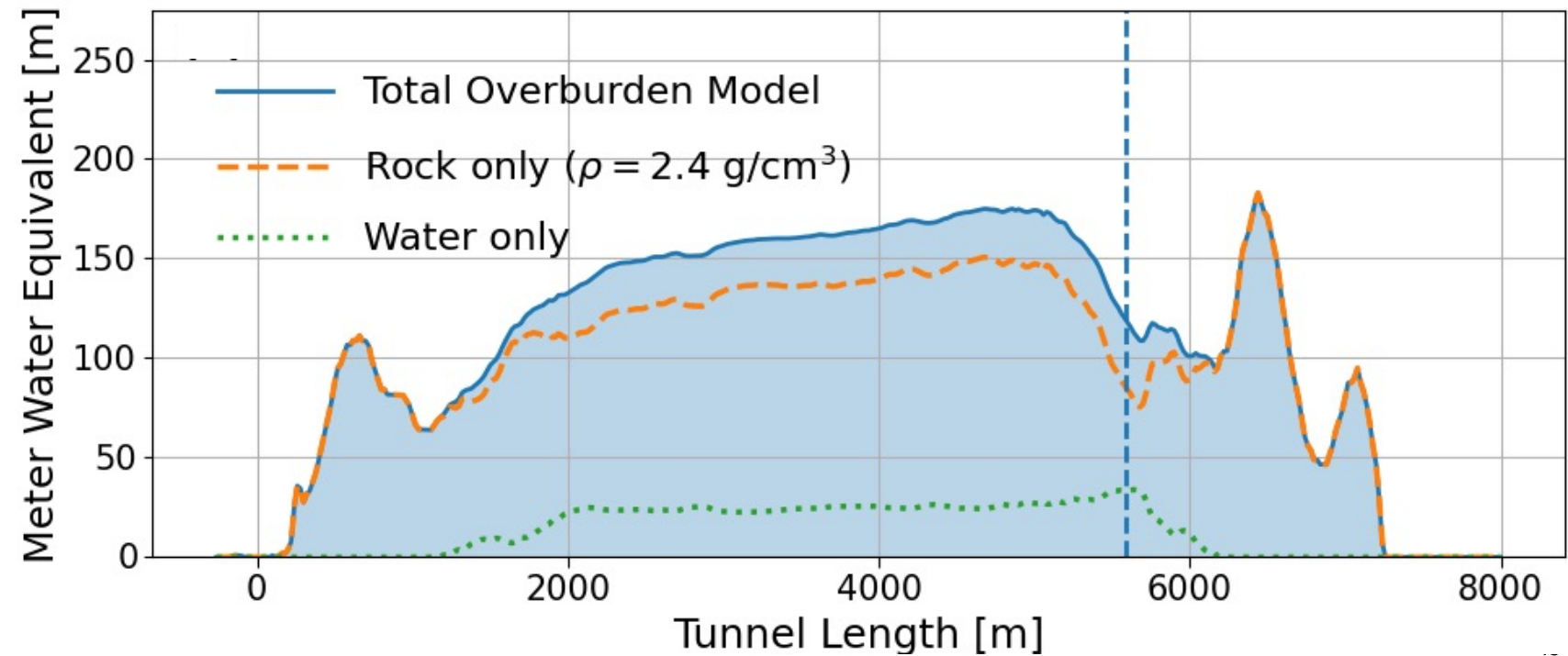
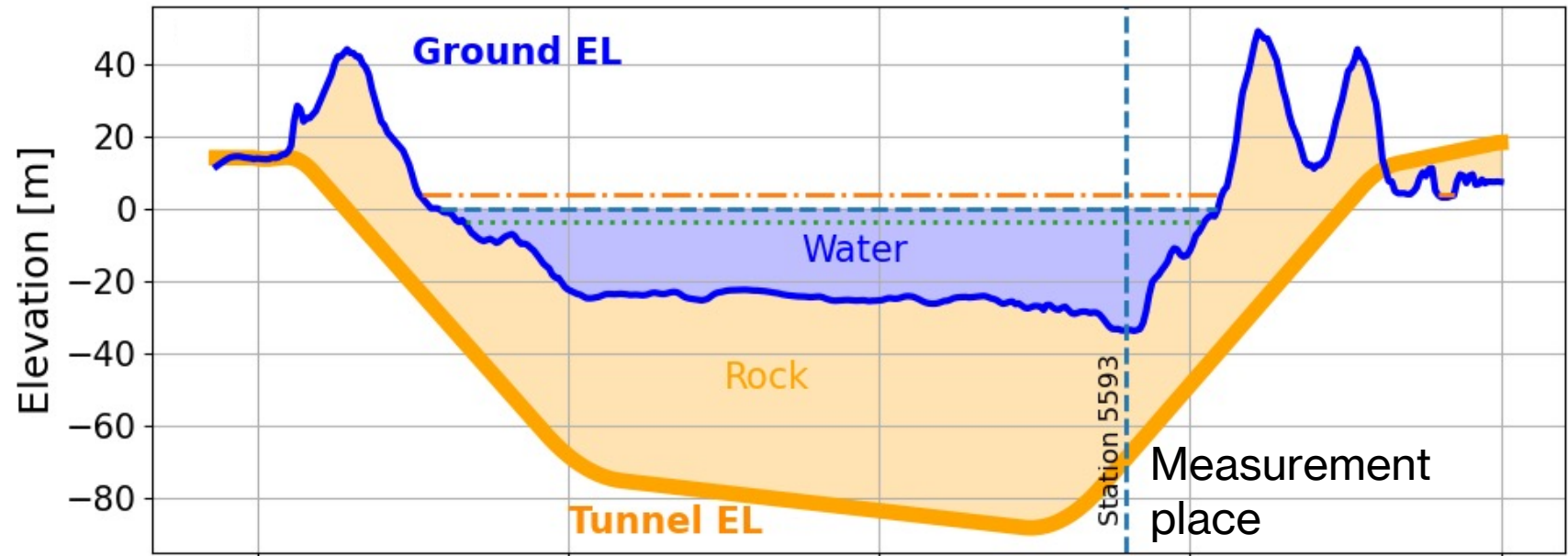
HAWLU Muon Modulation is **dominated by seawater overburden variations** rather than by **atmospheric Temperature and Pressure**

6. Real-time Portable Muography : undersea Tunnel



Blueprint of Undersea tunnel

➔ Meter water equivalent

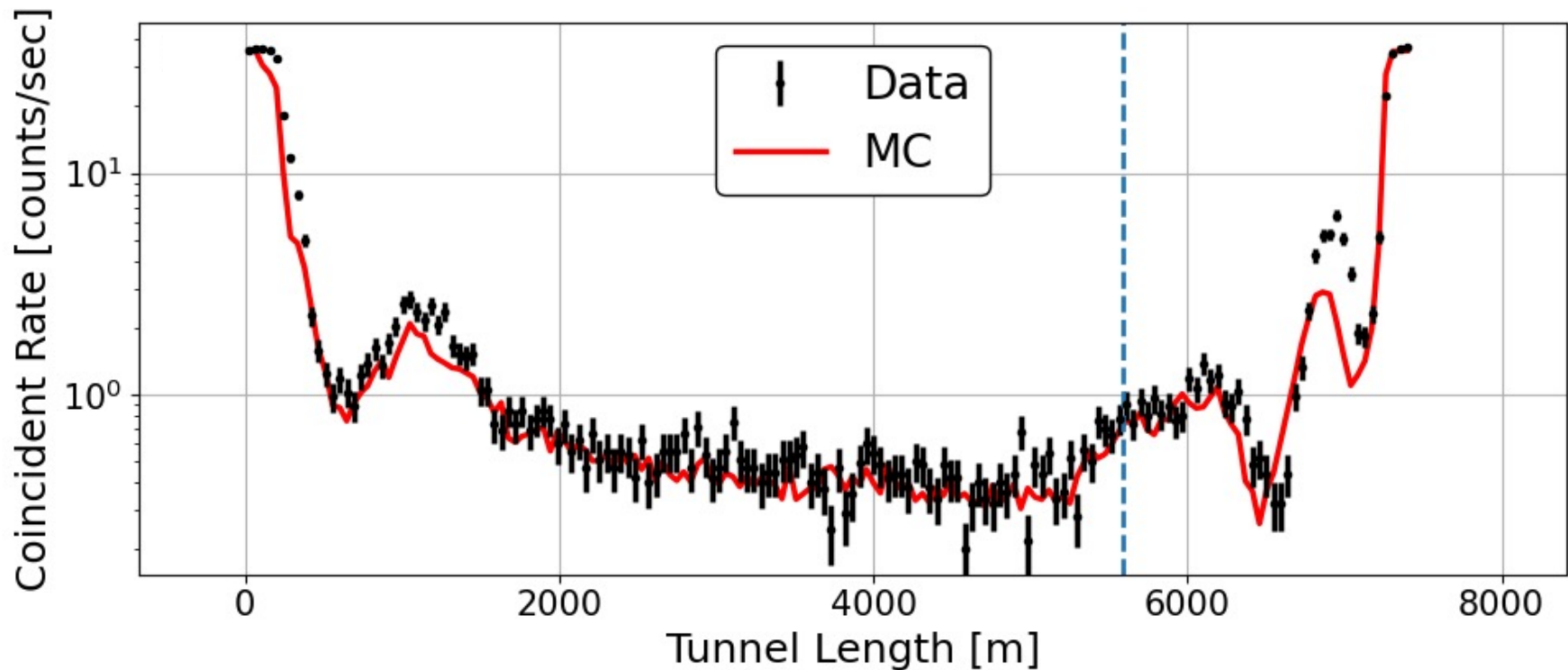
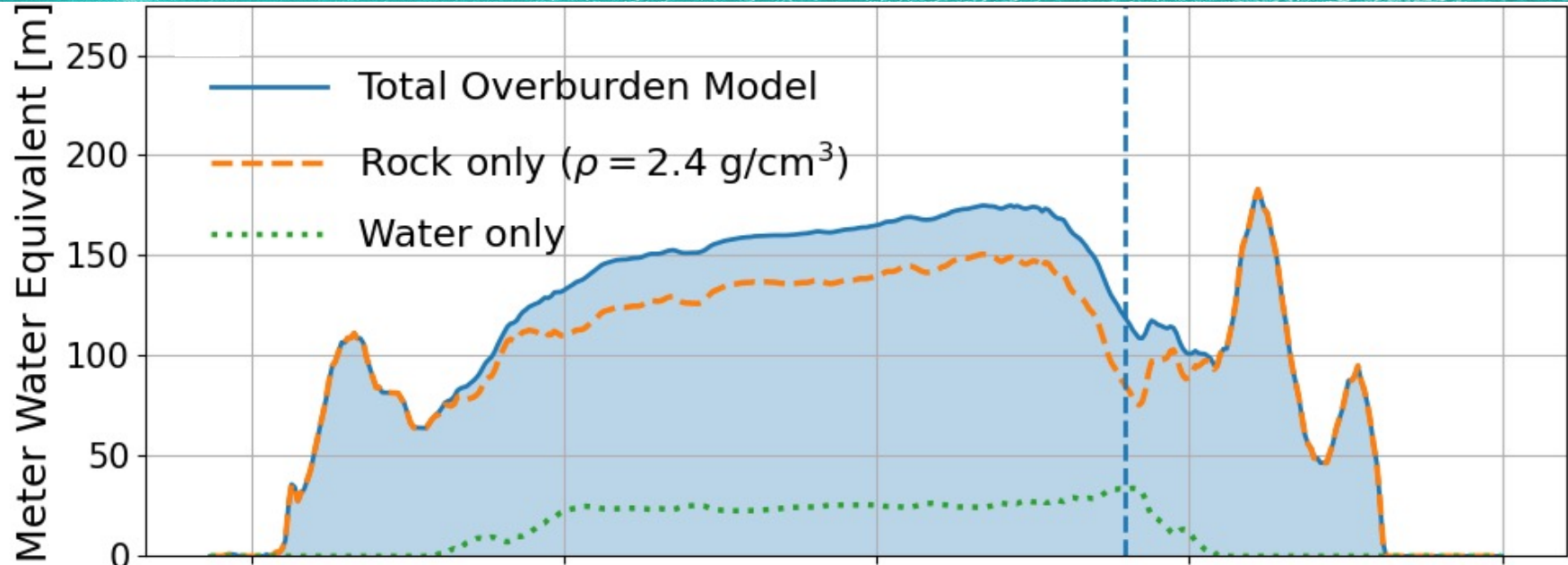


6. Real-time Portable Muography : undersea Tunnel

CRY 1D simulation

Combine 10 times measurement Data

Good agreement between data and simulation!



Summary

- **HAWL: First real-time portable muography & quick covering wide area**
- **Length accuracy $\langle m \rangle = -1.7$, rms = 6.0% & Overburden 3~150m**
- **24-hour sensitivity $\approx 4.2 \sigma/m$**
- **The detector achieved a tidal timing resolution of ± 2.63 minutes**
- **HAWLU Muon modulation by seawater overburden variations \gg Temperature and Pressure**
- **The coincidence data from 10 tunnel measurements were consistent with the simulation**
- **Disaster Monitoring(Tsunami, Typhoon, Sinkhole)**



BACK UP



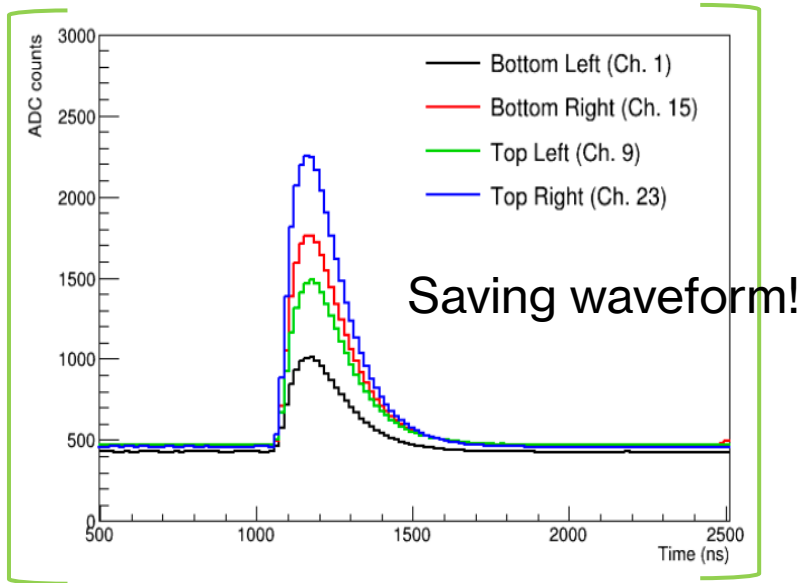
1. Real-time Portable Muography

1. Robust, cost-effective

- Fabrication, maintenance cost↓

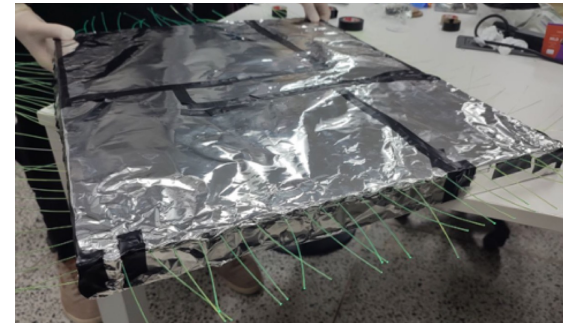
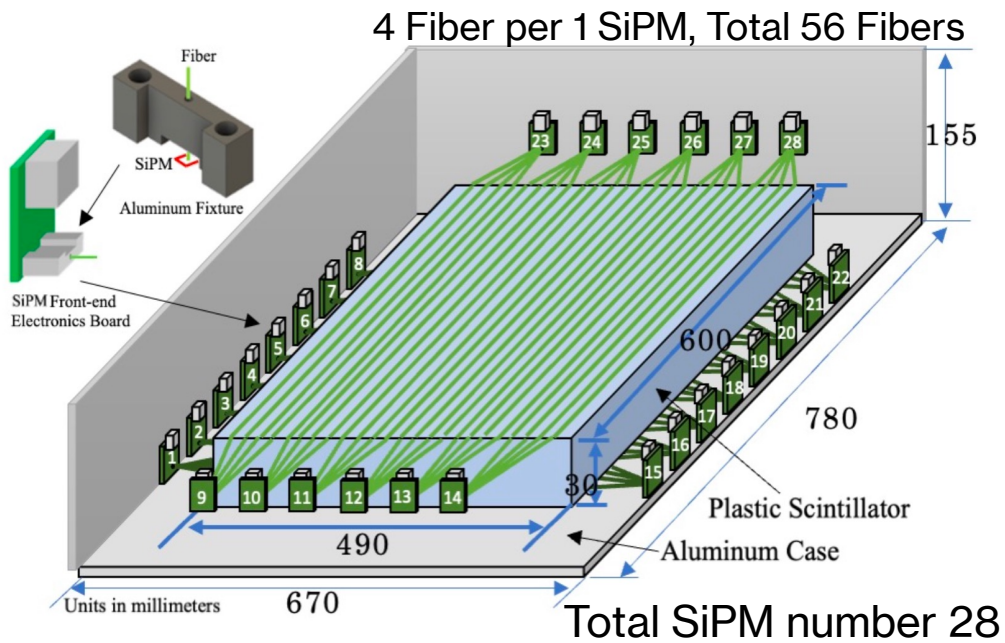
3. Compact design

- 0.3m² sized detector



2. Moveable DAQ system

- Many channels(~80ch)
- Low power consumption(68W)



1. Real-time Portable Muography

1. Robust, cost-effective

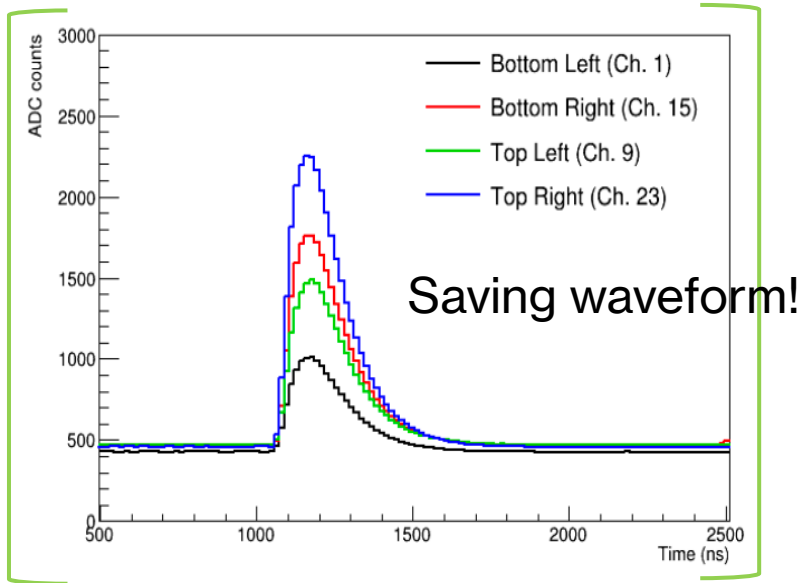
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3. Compact design

- 0.3m² sized detector

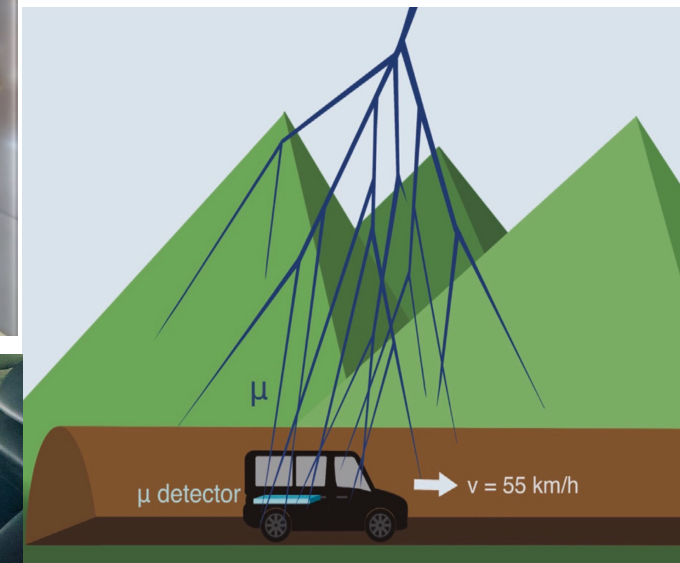
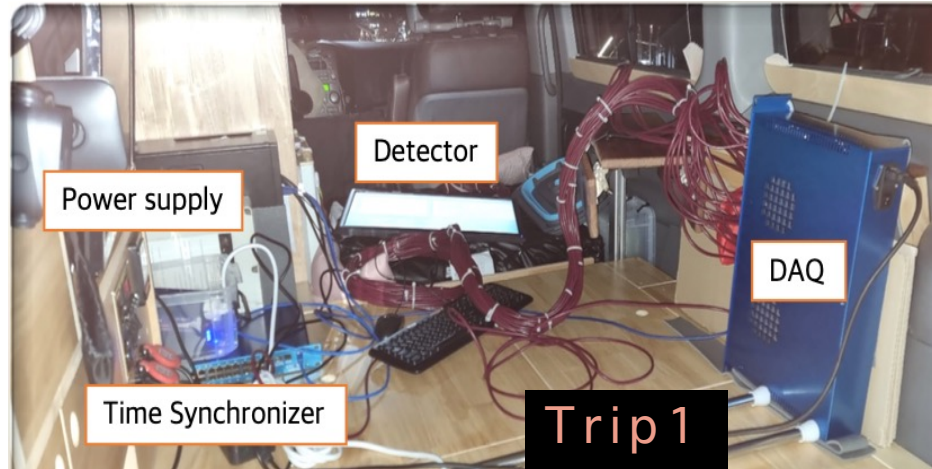
→ Muography in car with high speed(55km/h)

- Real-time Monitoring via WIFI

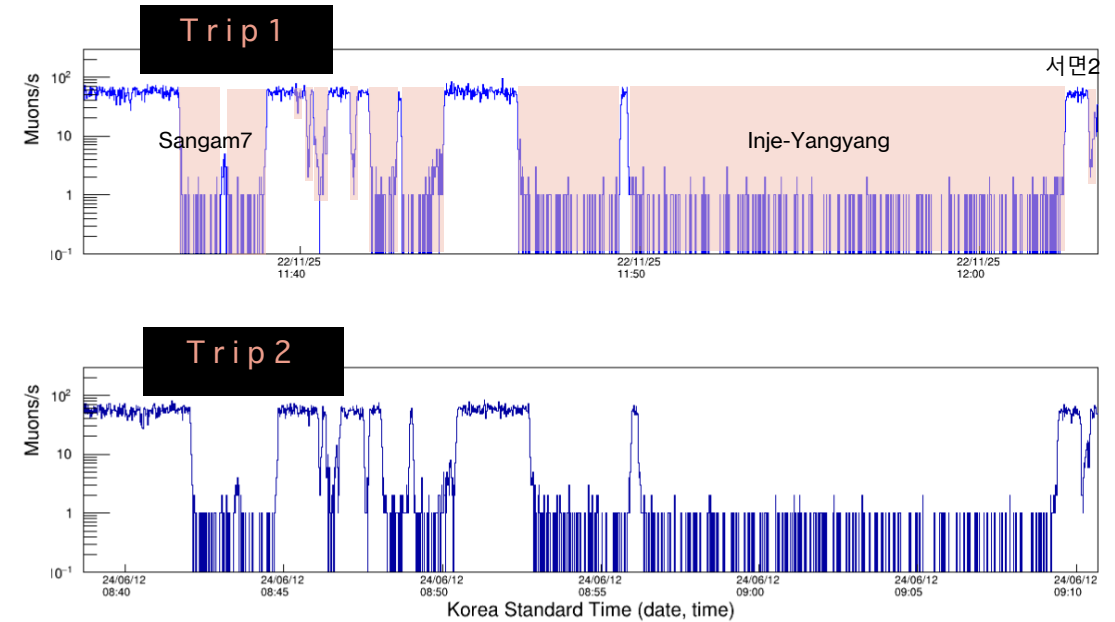
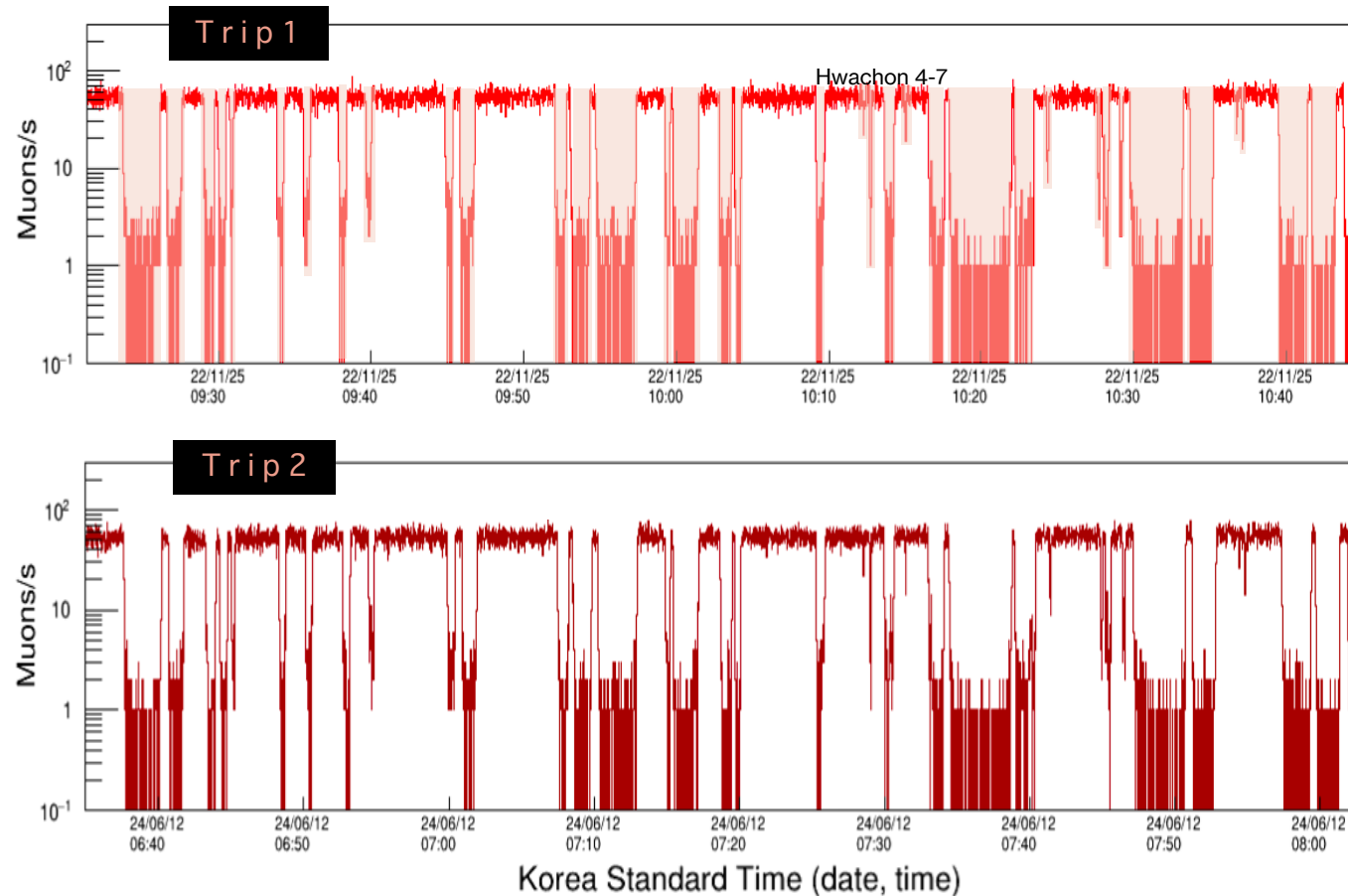


2. Moveable DAQ system

- Many channels(~80ch)
- Low power consumption(68W)



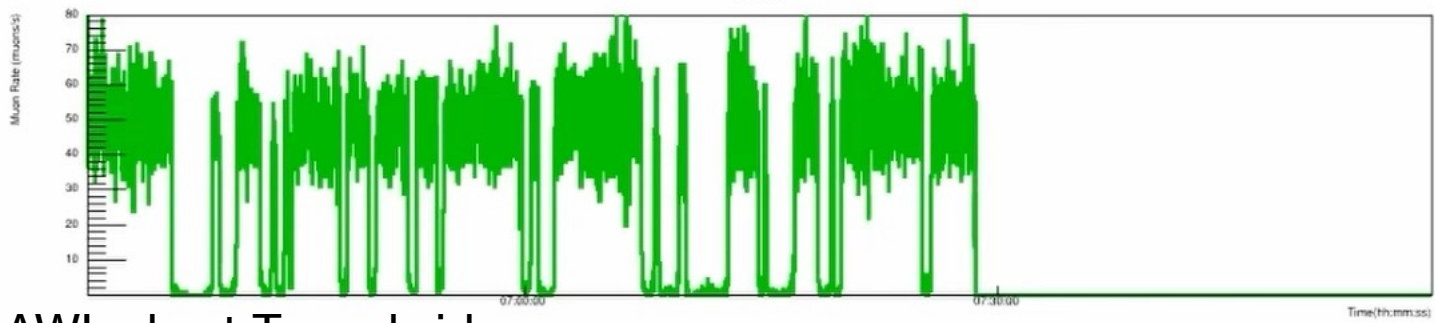
1. Real-time Portable Muography



Sections divided by geographical uniqueness!

- Section 1 : many tunnels of varying lengths and types
- Section 2 : includes the longest tunnel
- Section 3 : Yangyang underground laboratory (Y2L)(700m)

HAWL



HAWL short Tunnel video

HAWL

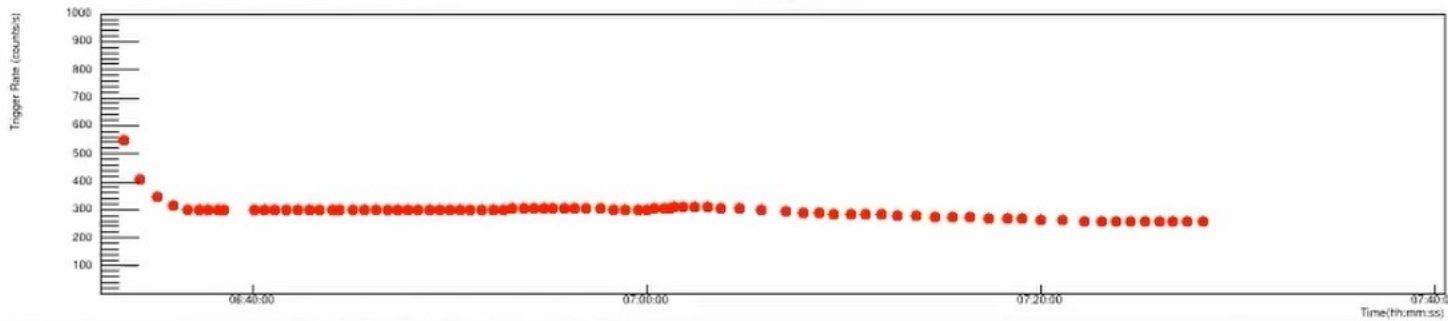
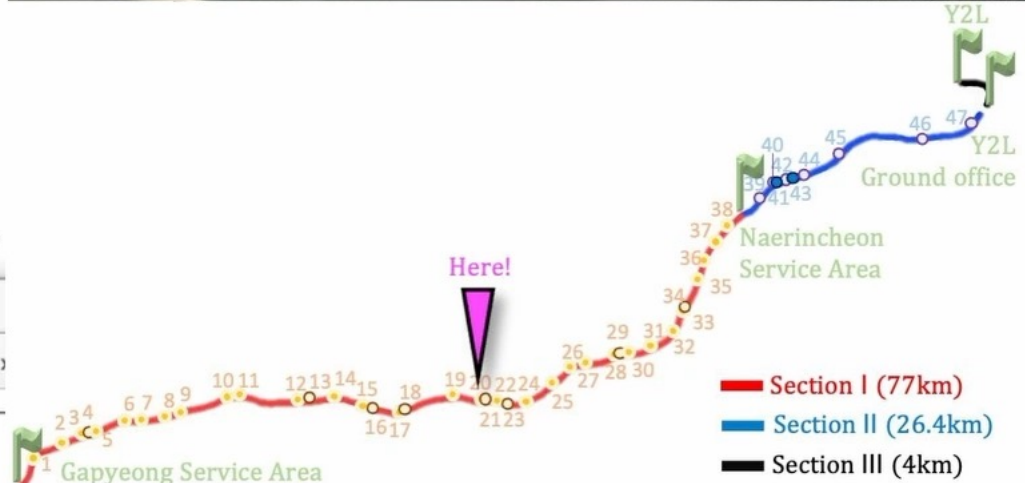
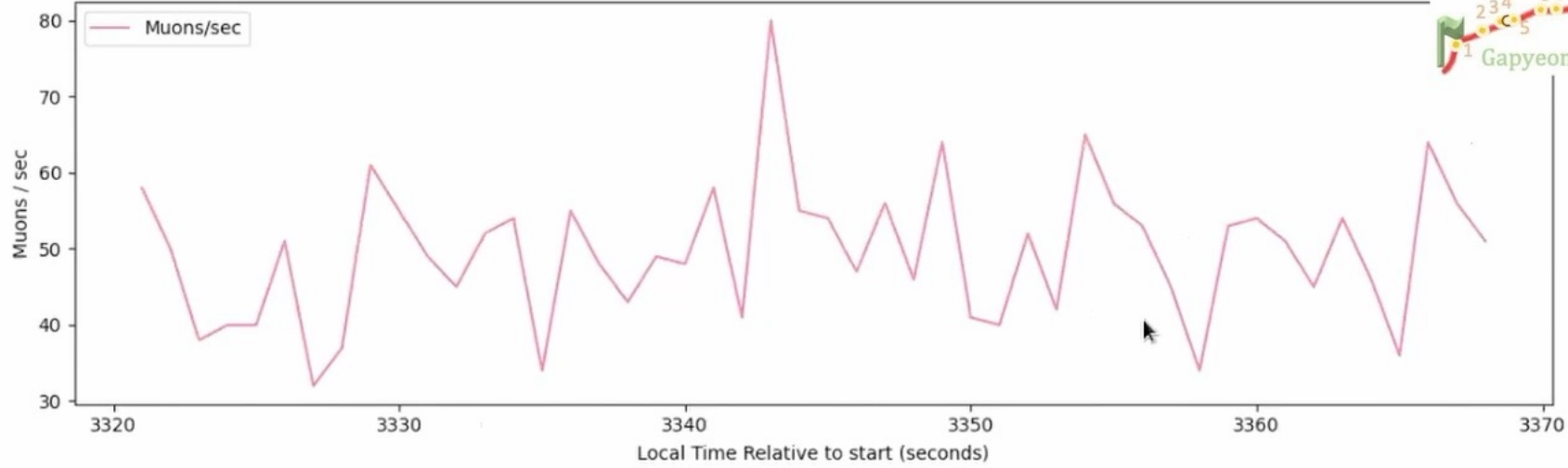


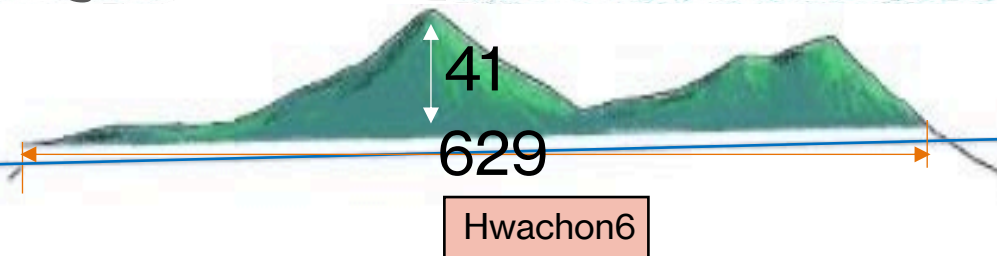
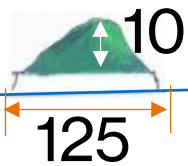
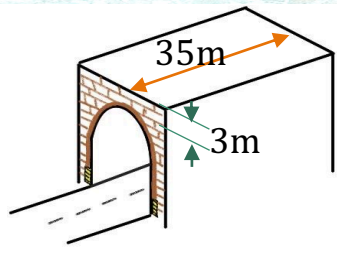
Figure 1



- Section I (77km)
- Section II (26.4km)
- Section III (4km)

T = 1718144904	T (local) = 3370	Muon Counts/sec = 71
T = 1718144905	T (local) = 3371	Muon Counts/sec = 46
T = 1718144906	T (local) = 3372	Muon Counts/sec = 47
T = 1718144907	T (local) = 3373	Muon Counts/sec = 51
T = 1718144908	T (local) = 3374	Muon Counts/sec = 45
T = 1718144909	T (local) = 3375	Muon Counts/sec = 46
T = 1718144910	T (local) = 3376	Muon Counts/sec = 42
T = 1718144911	T (local) = 3377	Muon Counts/sec = 25
T = 1718144912	T (local) = 3378	Muon Counts/sec = 13
T = 1718144913	T (local) = 3379	Muon Counts/sec = 36
T = 1718144914	T (local) = 3380	Muon Counts/sec = 57
T = 1718144915	T (local) = 3381	Muon Counts/sec = 55
T = 1718144916	T (local) = 3382	Muon Counts/sec = 47
T = 1718144917	T (local) = 3383	Muon Counts/sec = 43
T = 1718144918	T (local) = 3384	Muon Counts/sec = 51
T = 1718144919	T (local) = 3385	Muon Counts/sec = 52

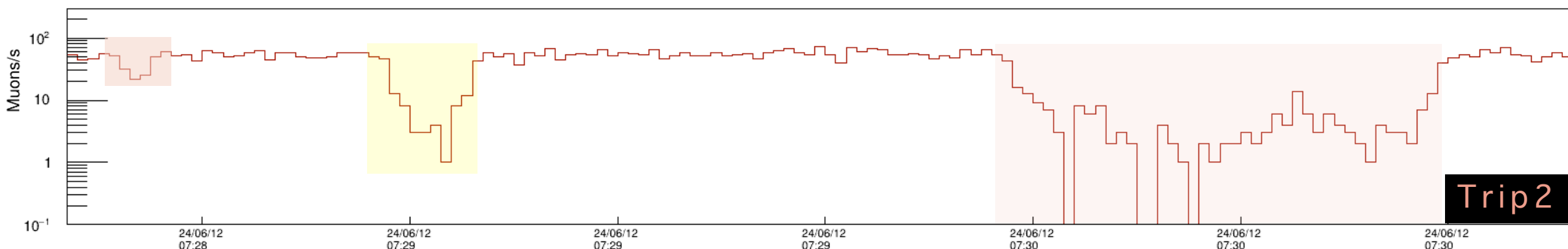
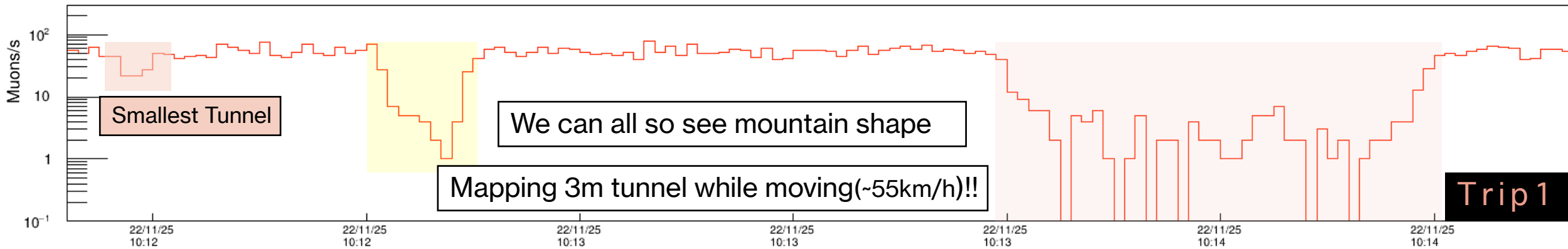
1. Real-time Portable Muography : Tunnel mapping examples



Hwachon4

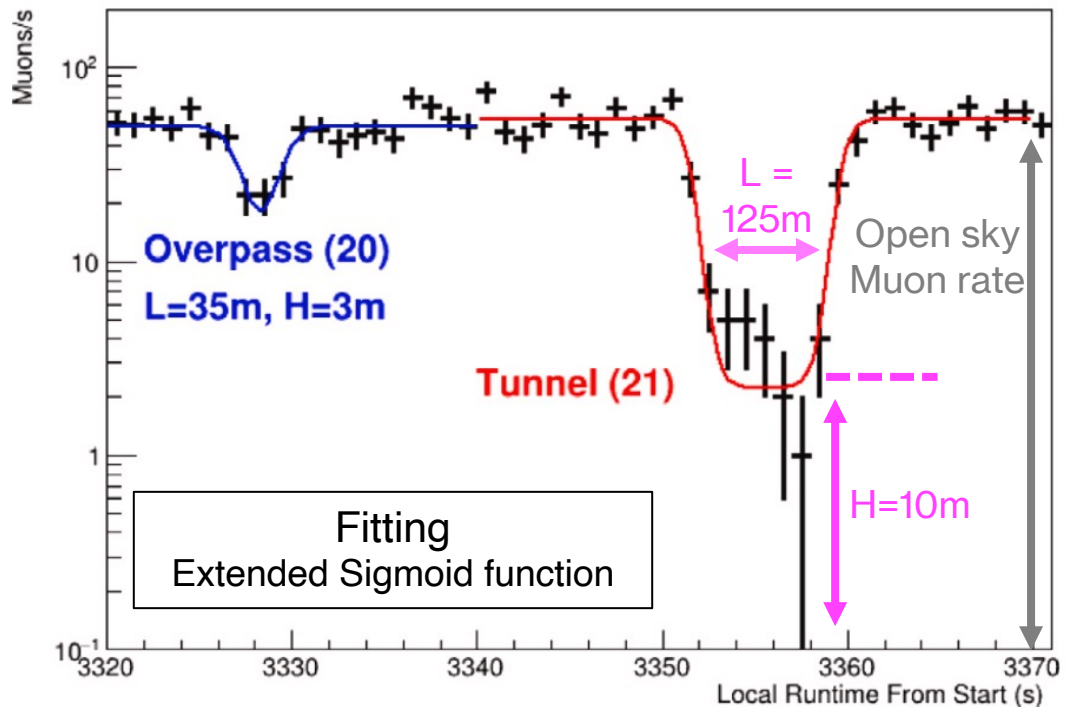
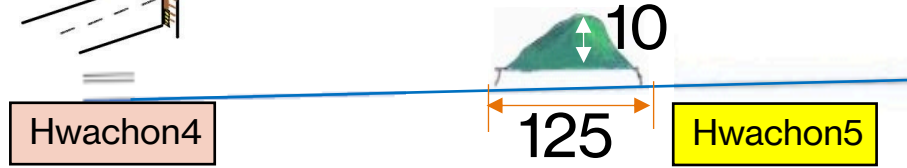
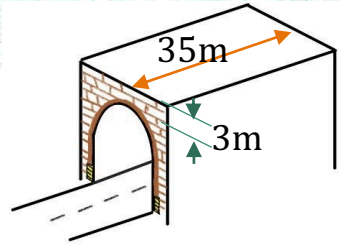
Hwachon5

Hwachon6



Korea Standard Time (date, time)

1. Real-time Portable Muography : Tunnel mapping examples



Time to pass through the tunnel
↔ **Length**

Minimum muon rate
↔ **Maximum Overburden**

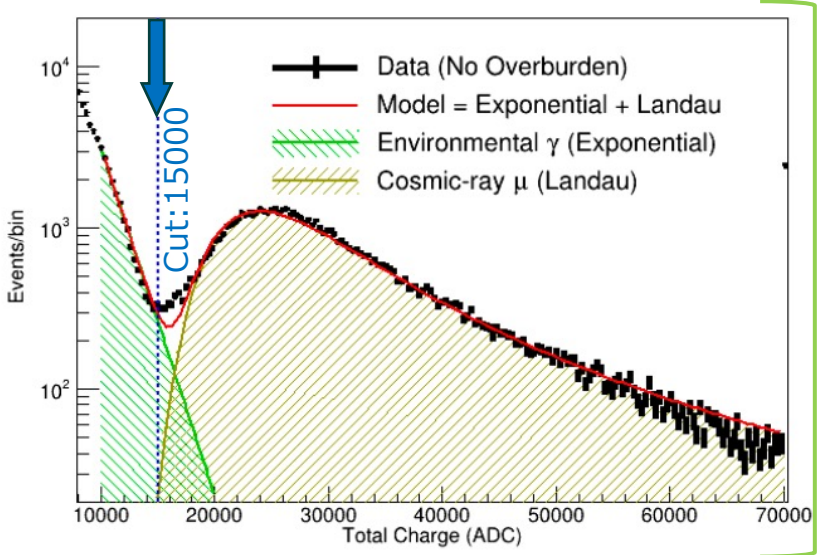
2. Detector verification

: Charge spectrum

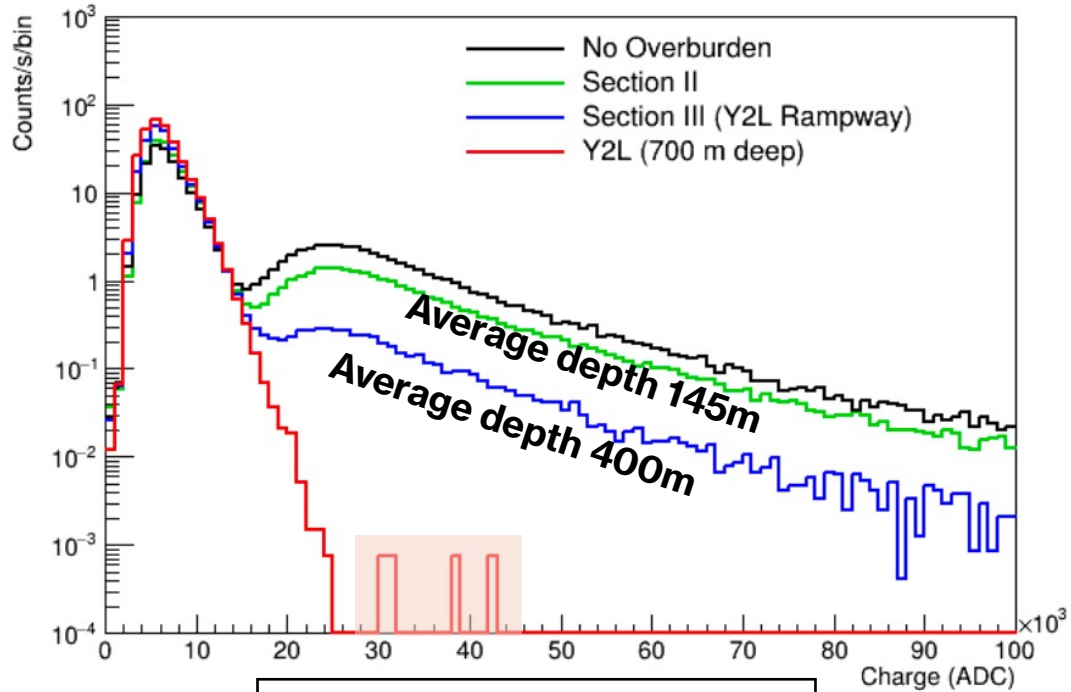
Detector Works very well!

Muon selection

Signal efficiency	99%
Gamma contamination	2%

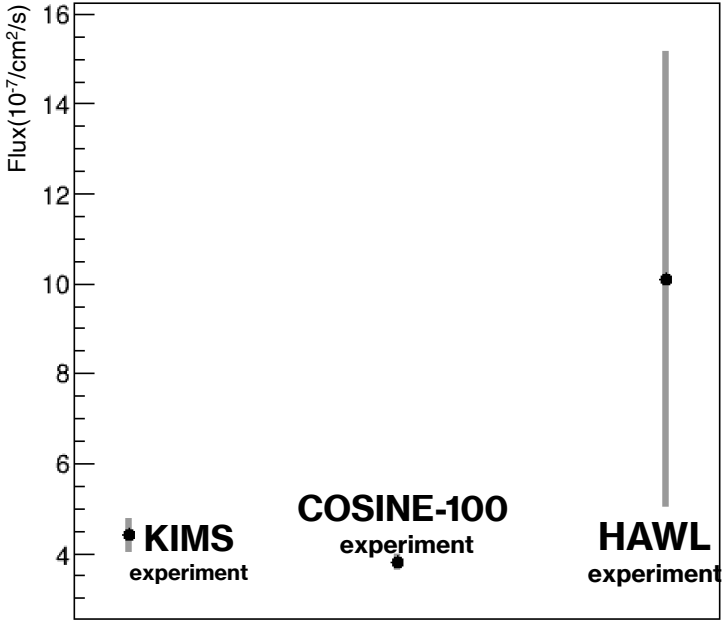


Reduction in muon rates



Clear reduction in muon rates

Y2L Muon Flux



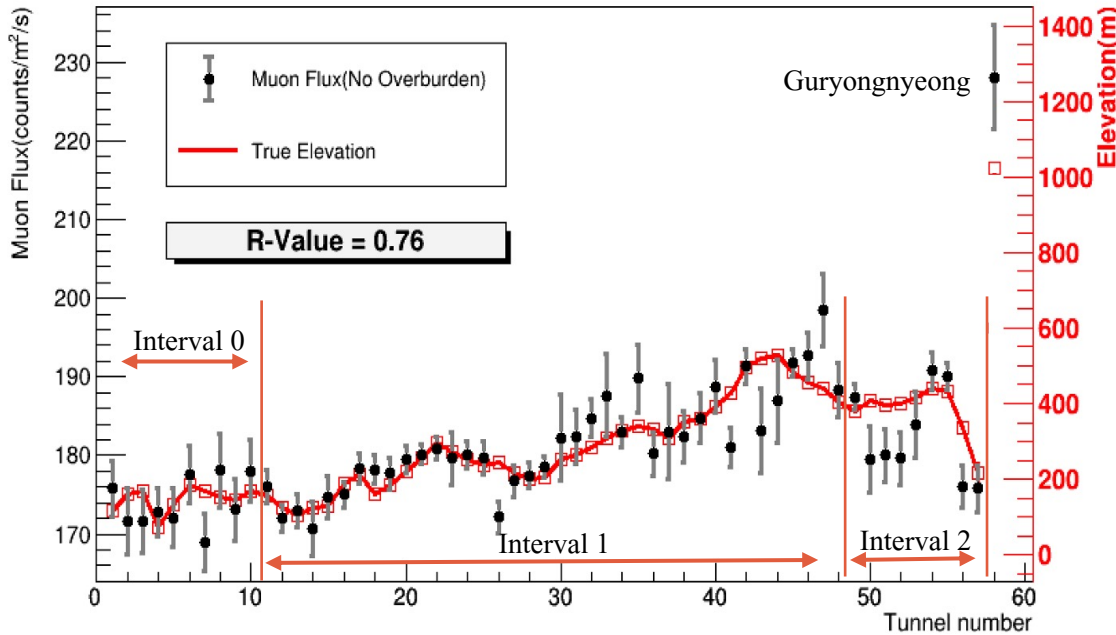
Consistence with KIMS and COSINE-100

2. Detector verification

: Open sky Muon Flux with Elevation



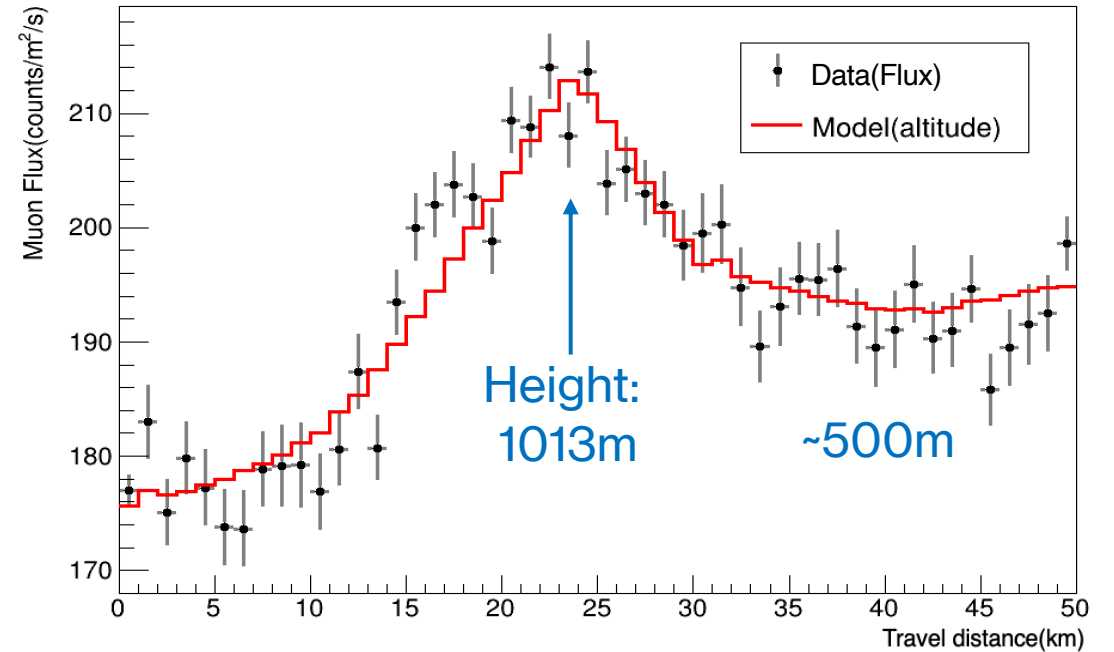
Tunnel Fitting data



Taebek Mountain range
→ 100km 2~3h mapping

The fitting data is reliable

Guryongnyeong



$\chi^2/ndf = 74.316/48$, P-value = 0.0088

Muon rate and Elevation fit well!

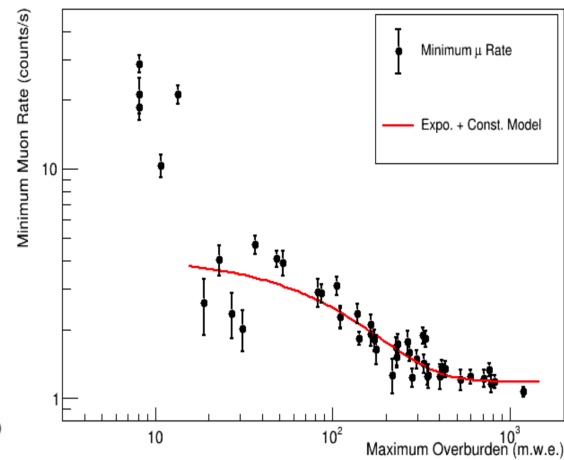
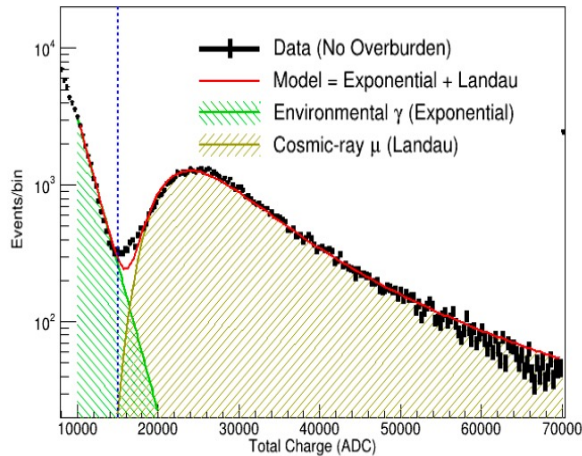
Dynamic Portable measurement was successful !

3. Detector R&D

What to Improve at HAWL

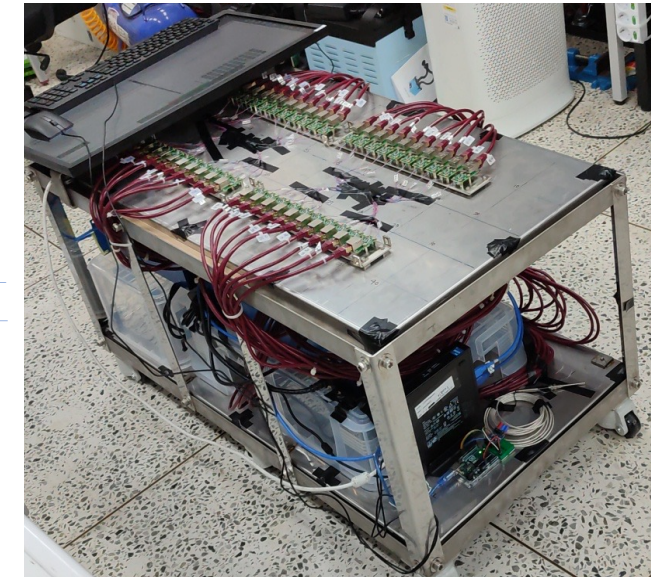
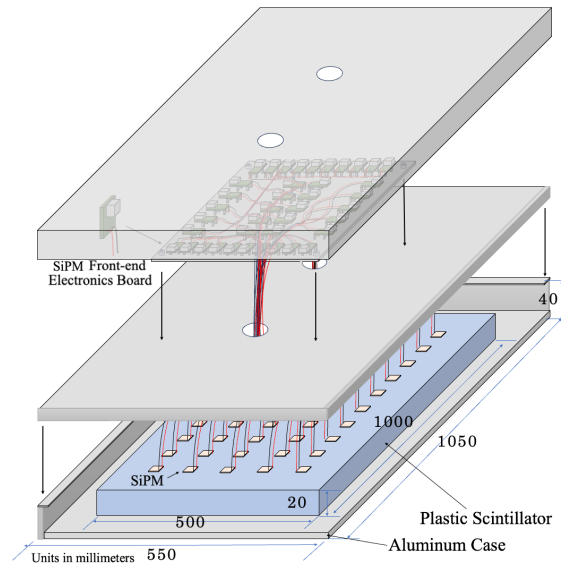
Upgrade : HAWLU

- 1. Gamma separation
→ Detectable Overburden accuracy



- 1. Light yield increasing : Direct attaching!
&: Two panel coincidence

- Gamma Noise and Muon Separation well
- Overburden range will improve.



- 2. Two panel → Trajectory reconstruction

3. Detector R&D

What to Improve at HAWL

Upgrade : HAWLU

3. Reflector(For Pattern recognition)

4. The dataset is small.

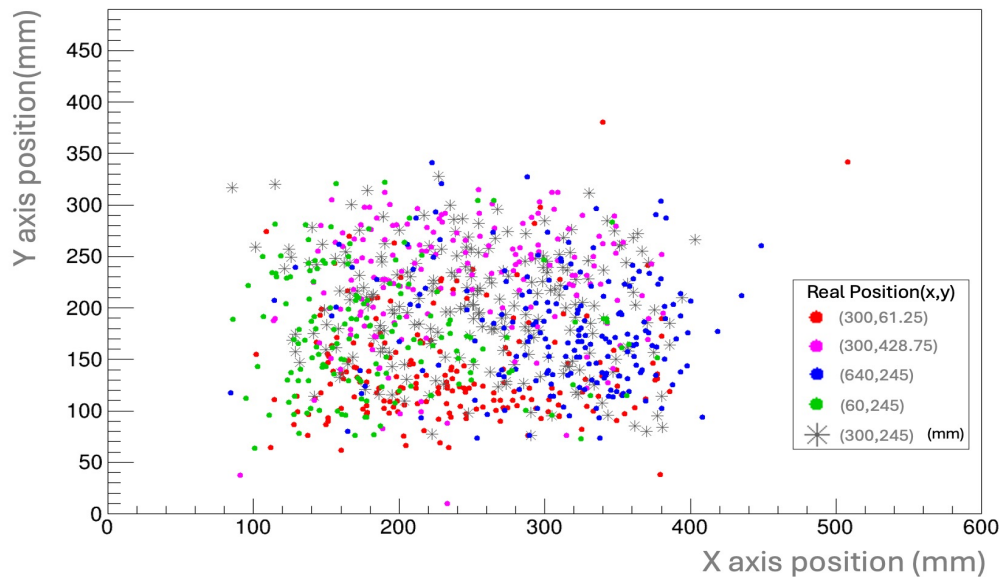
5. Position resolution is not good

3. Tyvek sheet(Diffuse) → ESR film(Total reflection)

4. PS size -> 1.5times & At slower speed

5. Convolutional Neural Network (CNN)

Position Detection

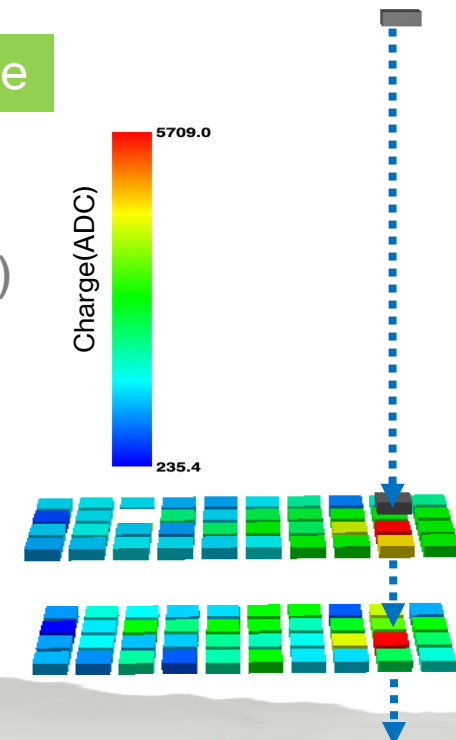


X Resolution: 61.88 ± 1.54 mm,

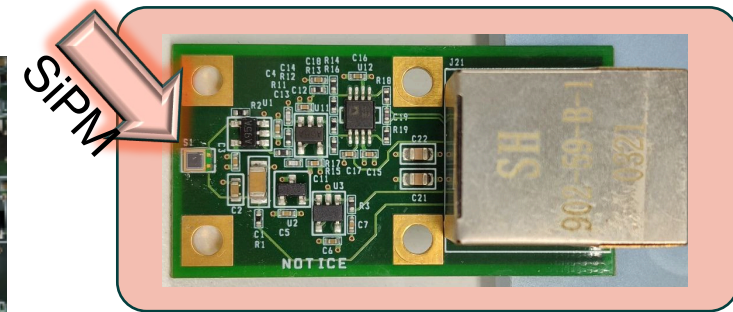
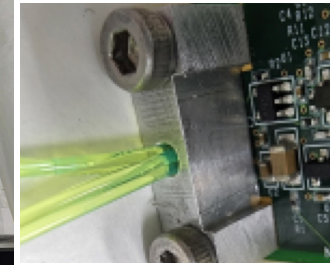
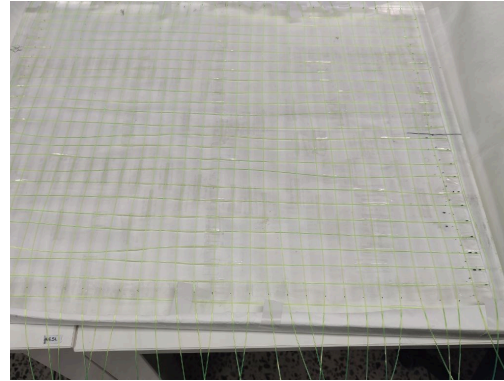
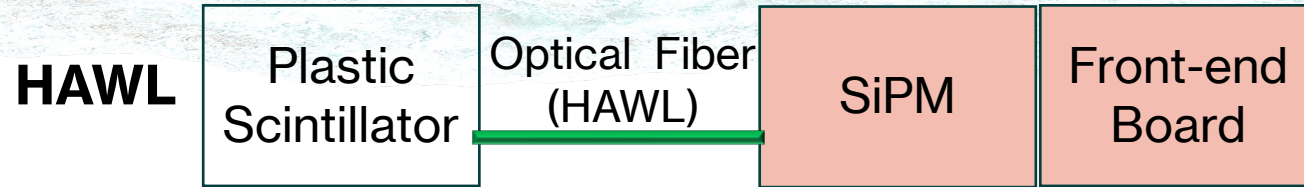
Y Resolution: 54.09 ± 1.46 mm

Each channels Charge

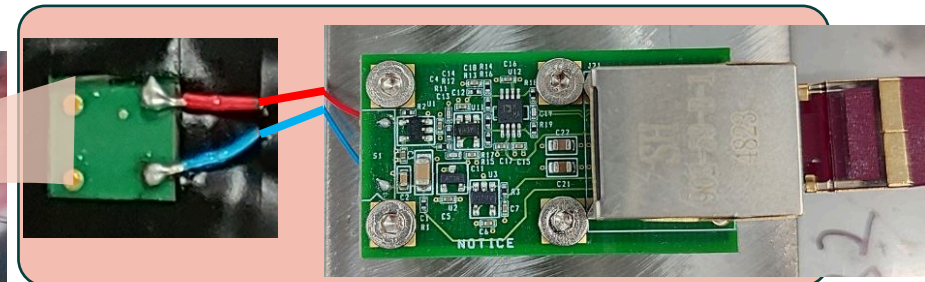
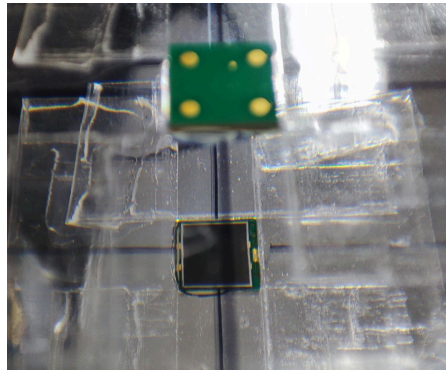
Real Data
(Event number: 26104)



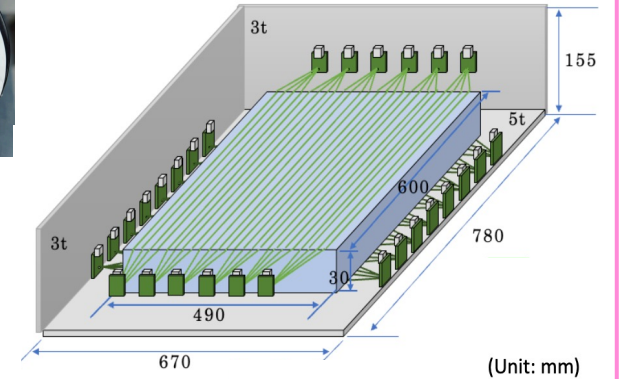
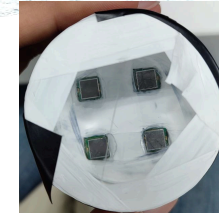
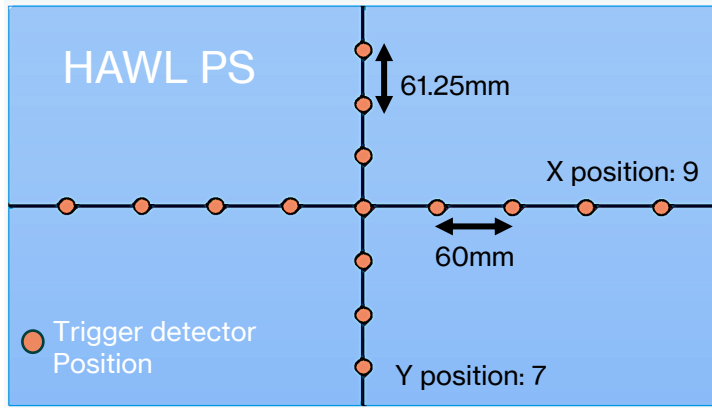
3. Detector R&D



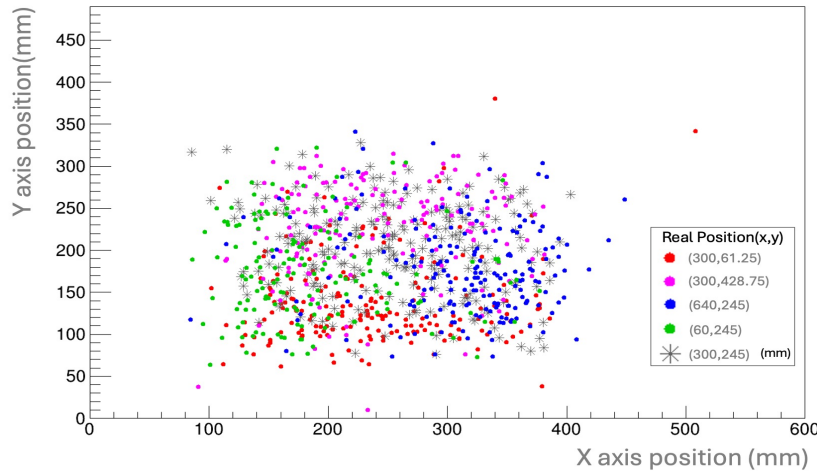
Directly attaching the SiPM on the PS



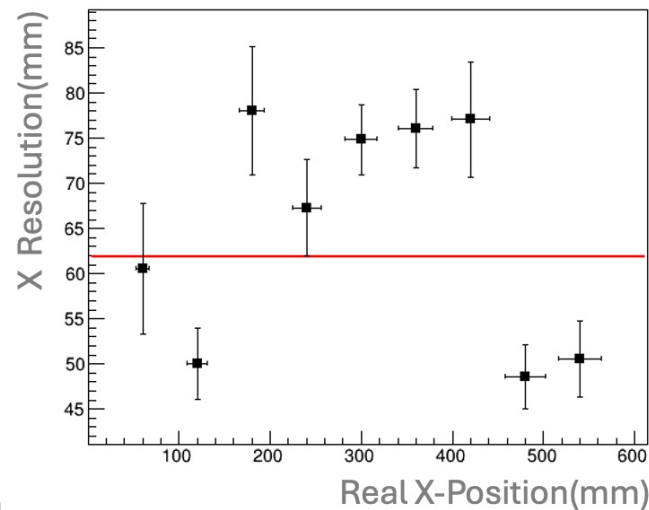
4. Position Resolution_HAWL



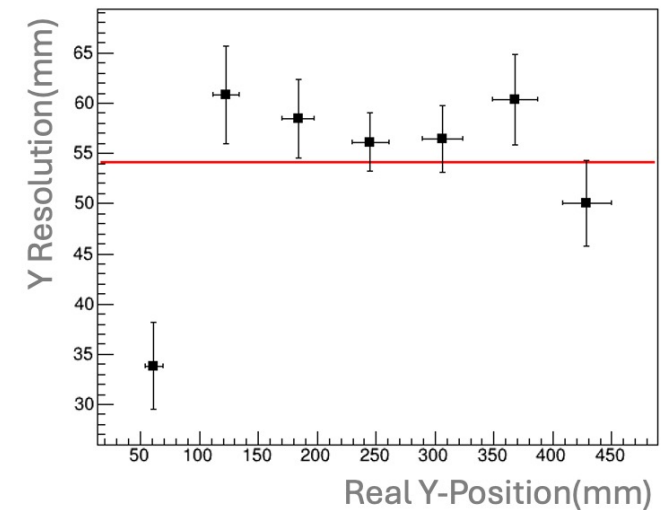
Position Detection



X Resolution



Y Resolution



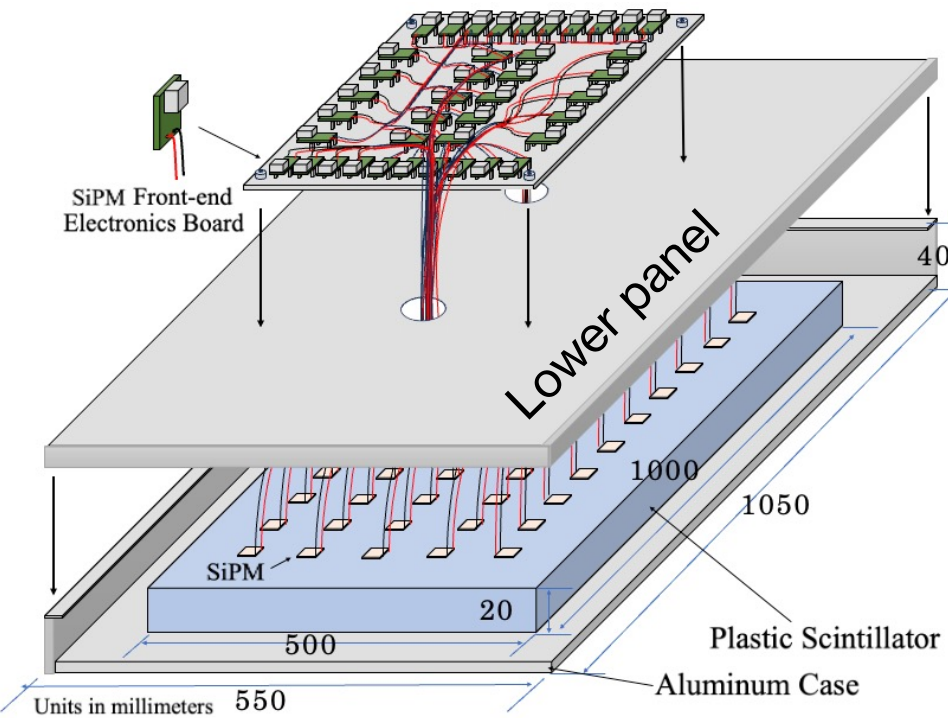
X Resolution: 61.88 ± 1.54 mm,

Y Resolution: 54.09 ± 1.46 mm

4. HAWLU Detector

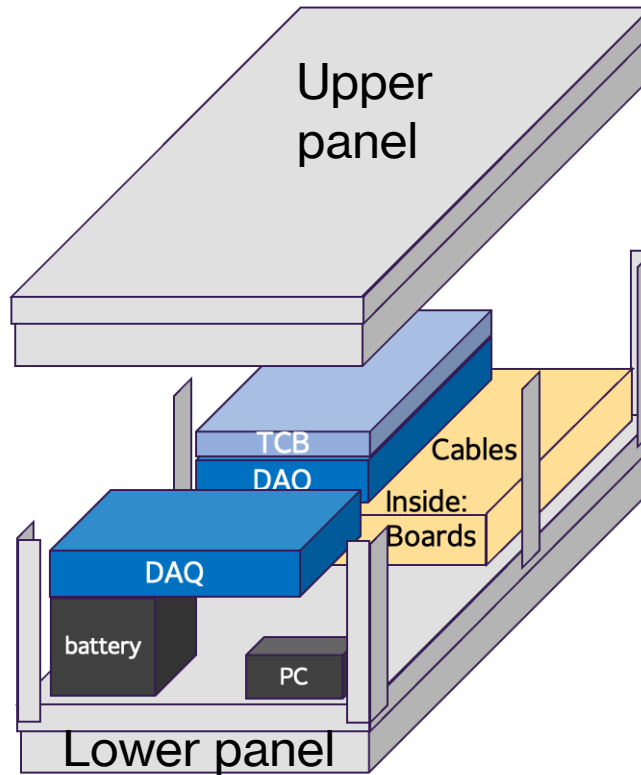
SiPM	Hamamatsu, MPPC, S13360-6075 PE Photosensitive area: 6 X 6(mm ²)
PS Scintillator	Eljen-200(PVT), 1000X500X20(mm ³)
Reflector	Vikuiti(ESR(Enhanced Specular Reflector) Film)
Data acquisition sys.	NOTICE Muon DAQ, NOTICE TCB(Trigger-clock board), PC

HAWLU Blueprint



40 SiPMs per 1 panel,
Total 80 SiPMs

DAQ sys.



Two plastic panels



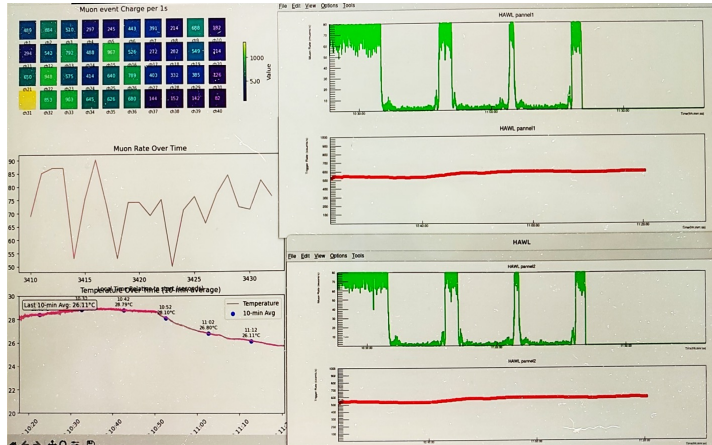
5. Data taking

1st 10-times measurement

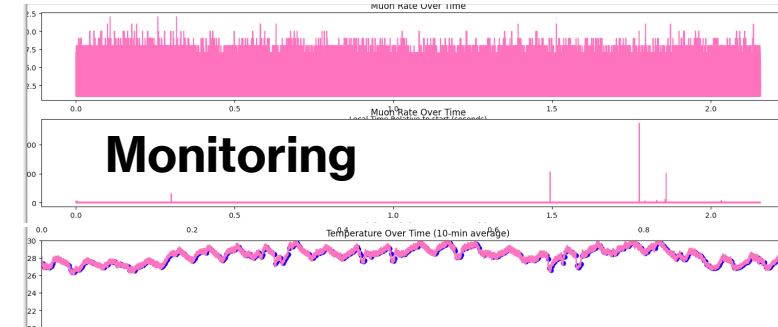
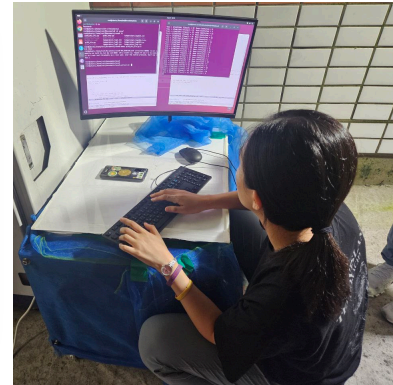


Data: 2025.6.30
Speed: 31km/h

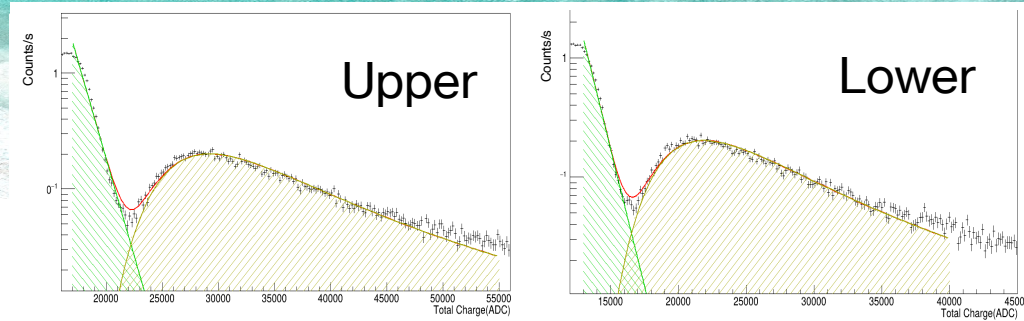
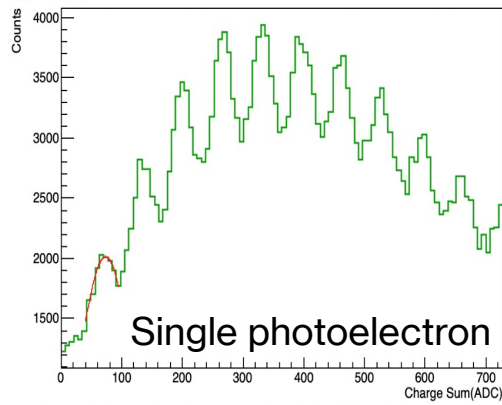
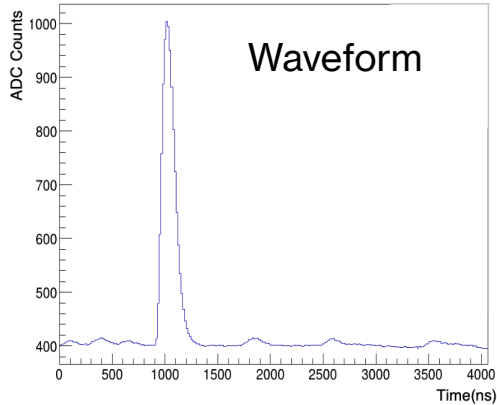
Threshold	0.5MeV
Trigger rate	550Hz
HV (Over voltage)	56.5(4)V
Total Power Consumption	163W



2nd Longterm data Taking

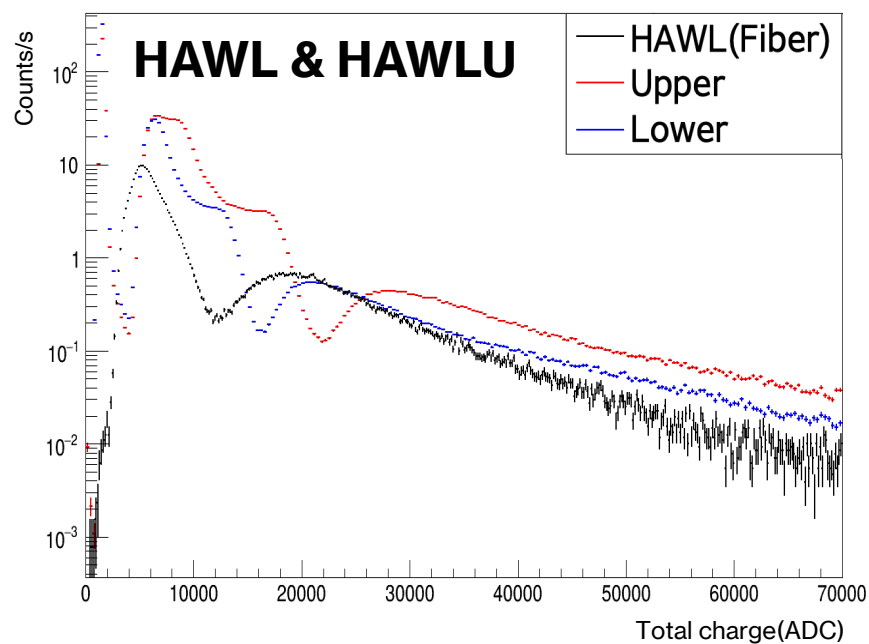
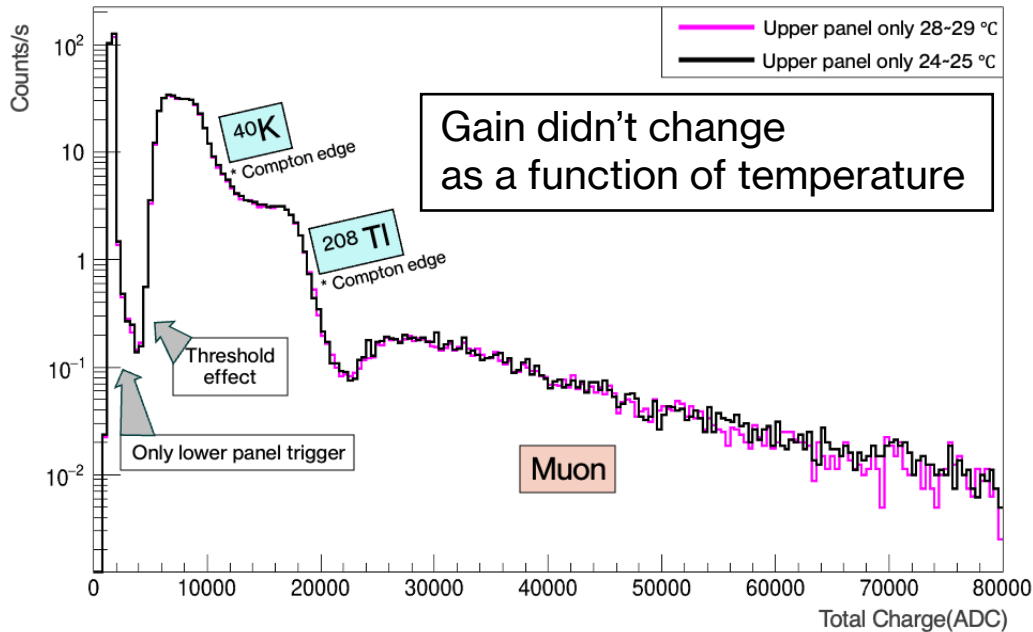


5. Data taking



Both panel efficiency is good!

Panel	Muon Efficiency	Contamination	Open sky Muon Flux
Upper	0.99	0.0595	169.47600
Lower	0.99	0.0524	162.77200



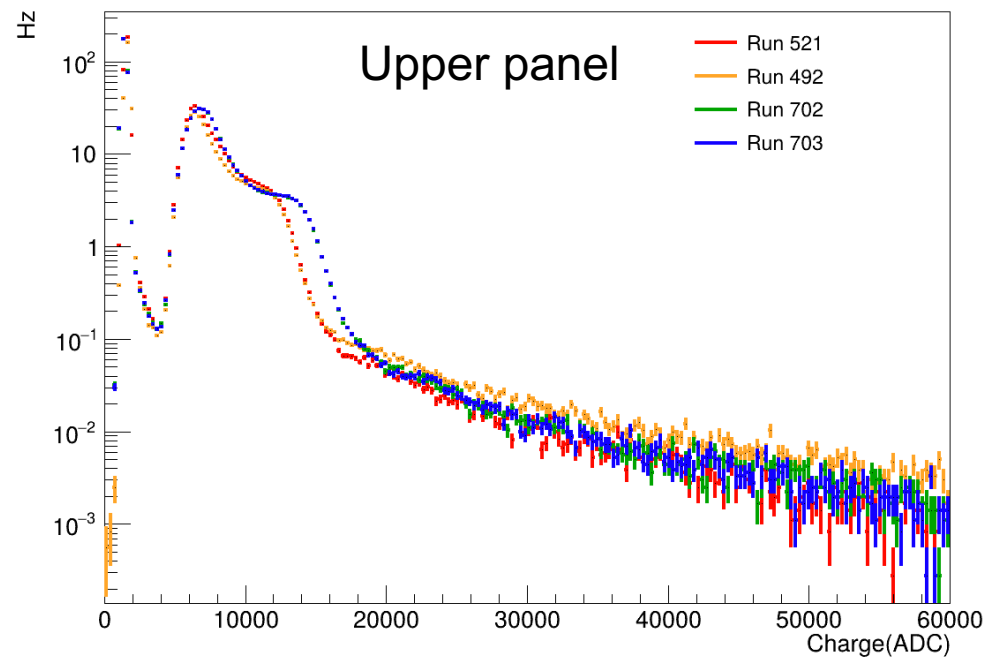
➤ HAWLU gain is better than HAWL.

➤ Upper panel gain > Lower panel gain

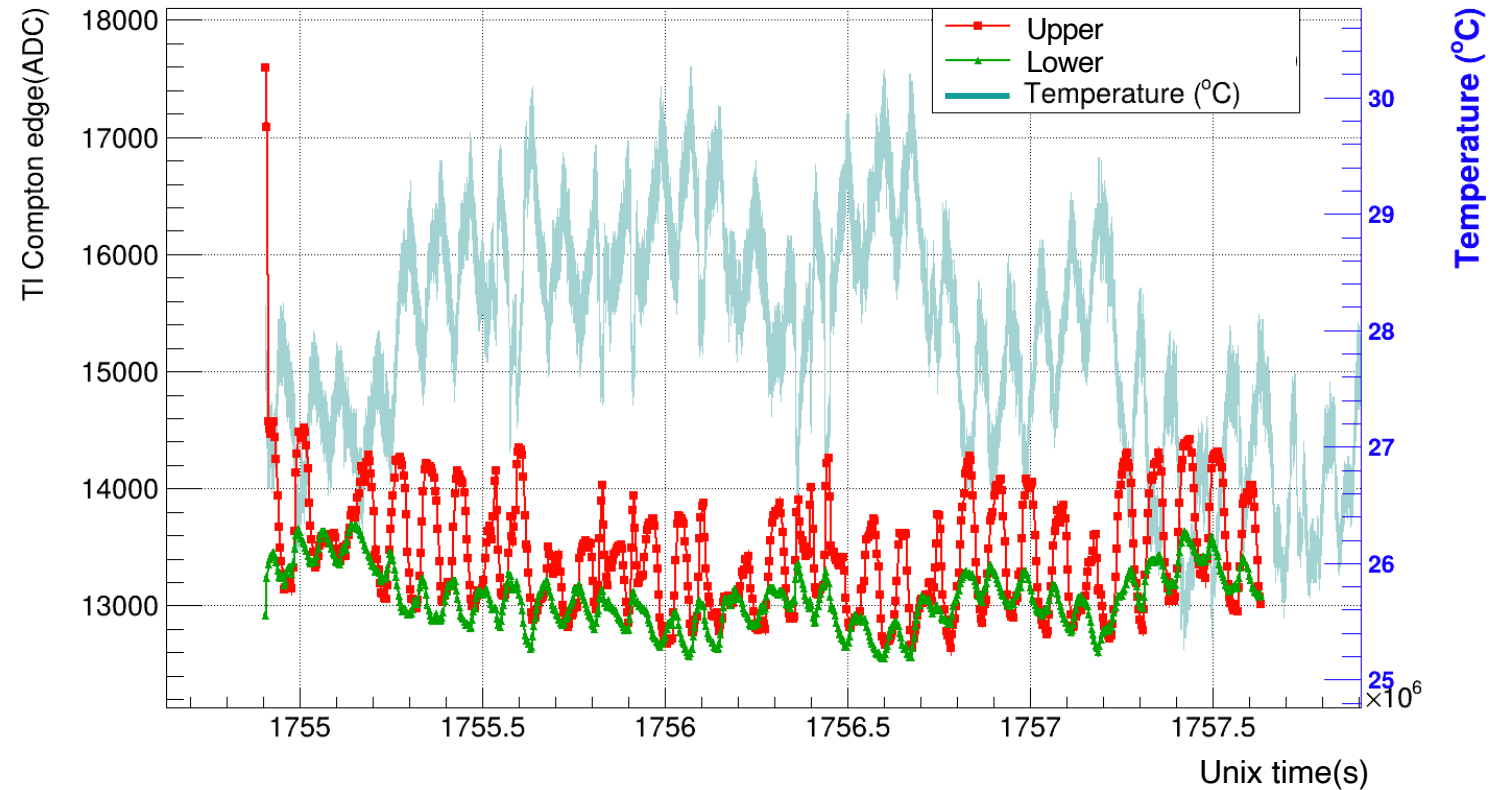
Light coupling between PS and SiPM
→ Panel gain difference

5. Data taking

Charge spectrum



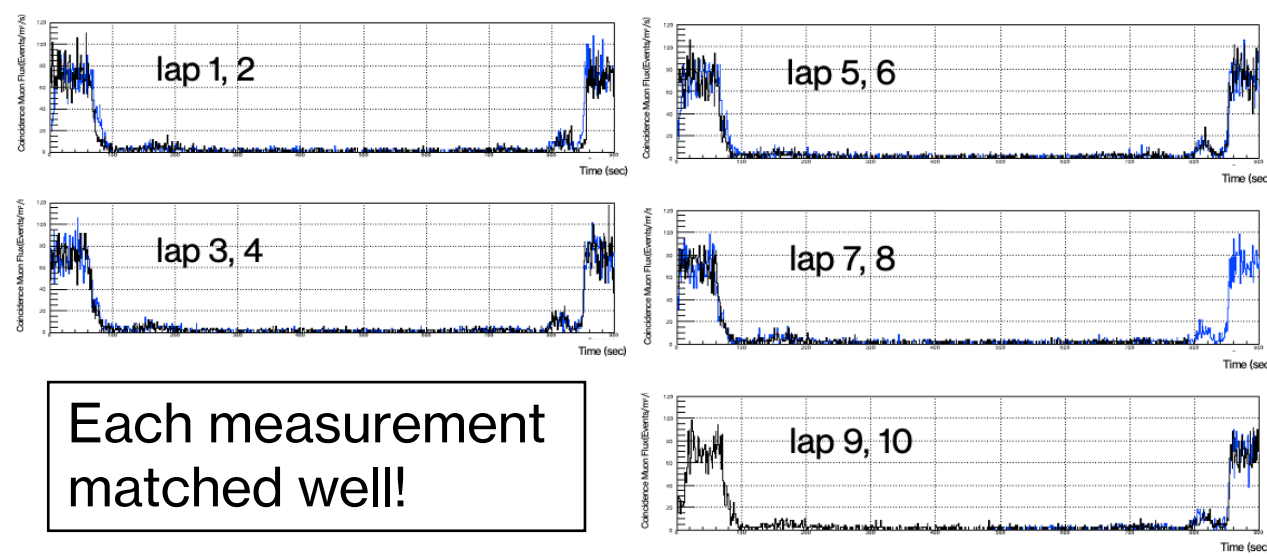
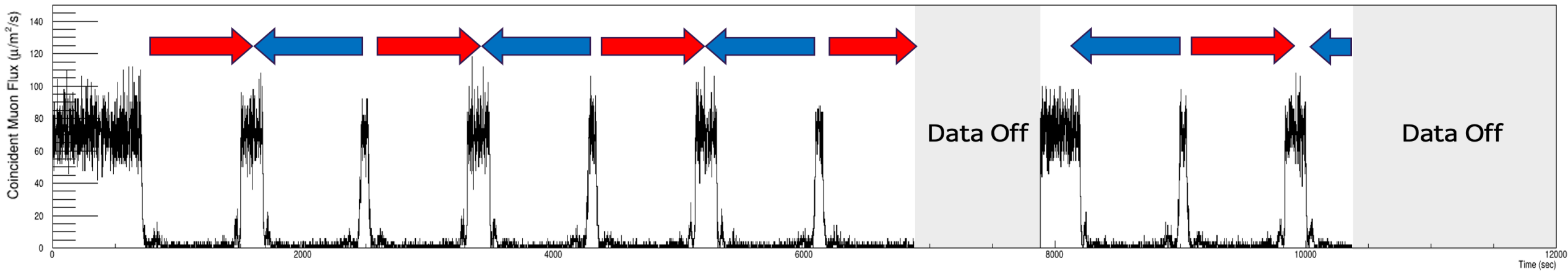
Gain Graph



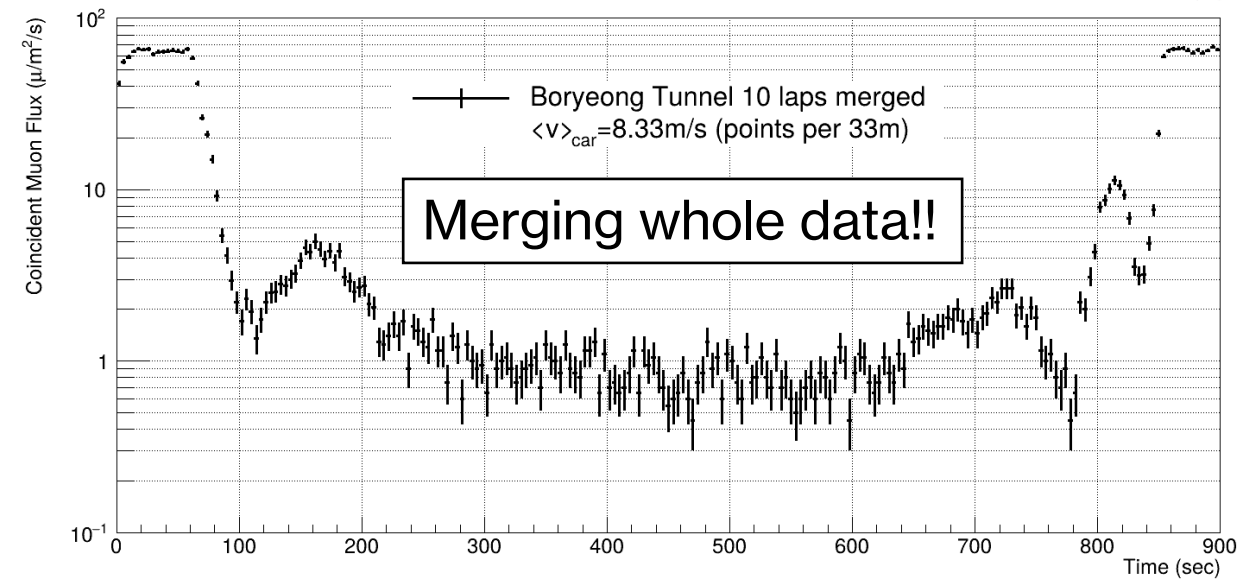
Over long-term measurements, **the gain (each panel) varied!!**
→ HAWLU uses **Coincidence events & gain matching**

6. 10 times measurement

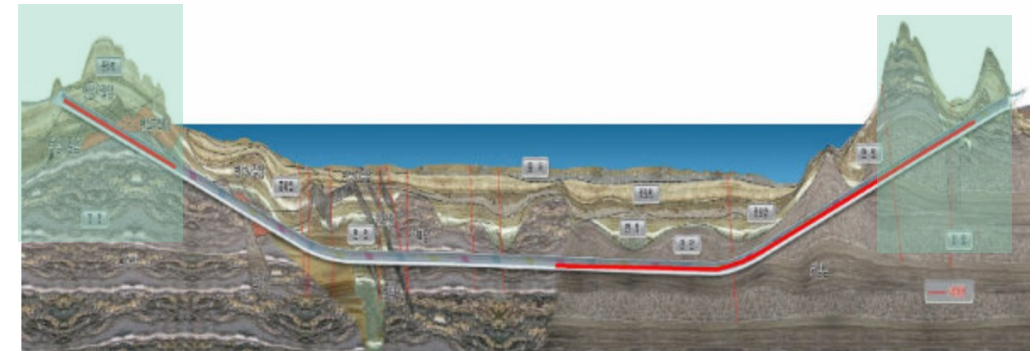
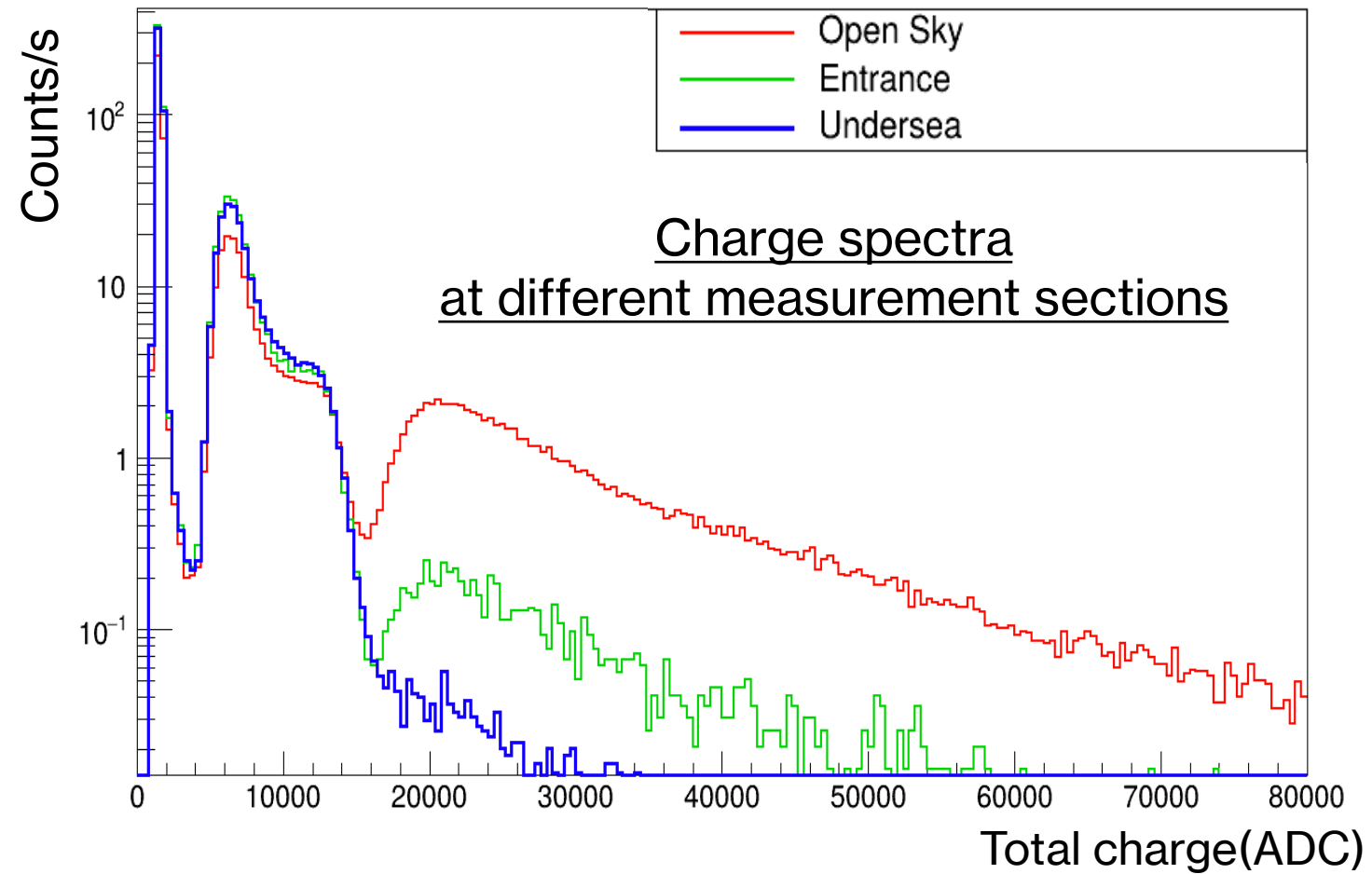
Two panel coincidence Undersea Tunnel 10 measurement



Each measurement matched well!



6. 10 times measurement

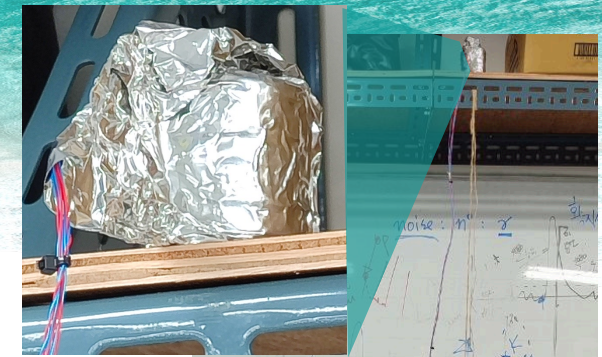
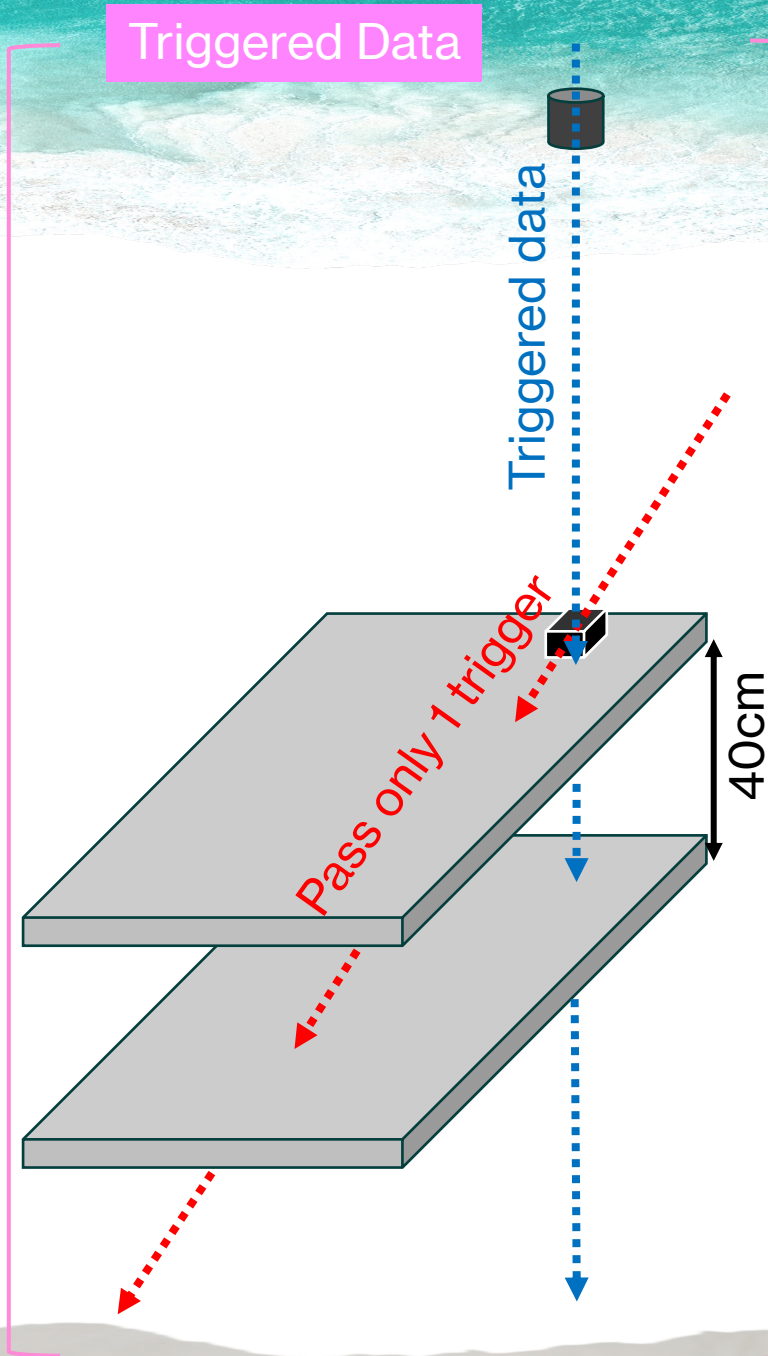
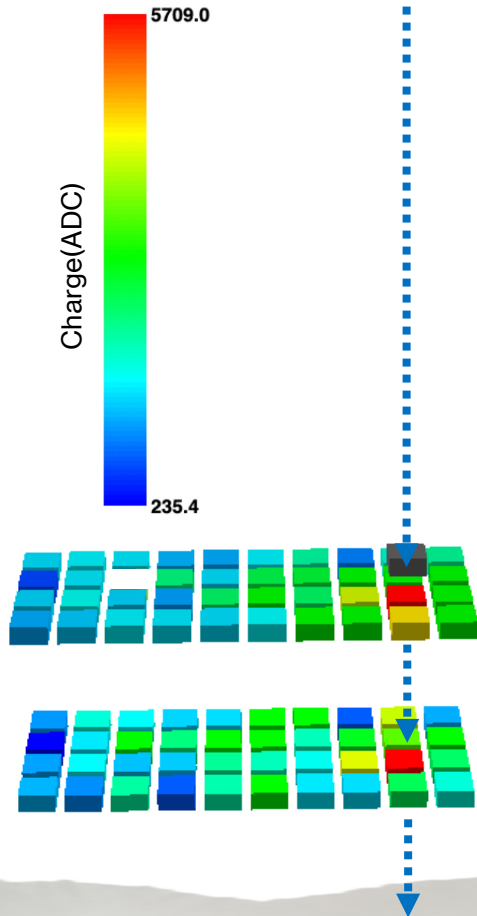


Clear reduction at different sections

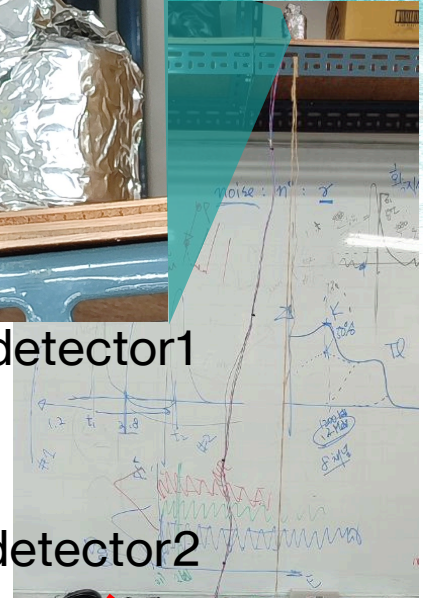
7. Positioning

Each channels Charge

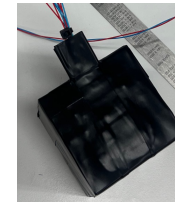
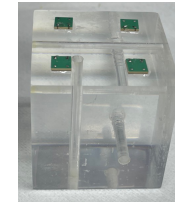
Real Data
(Event number: 26104)



Trigger detector1



Trigger detector2



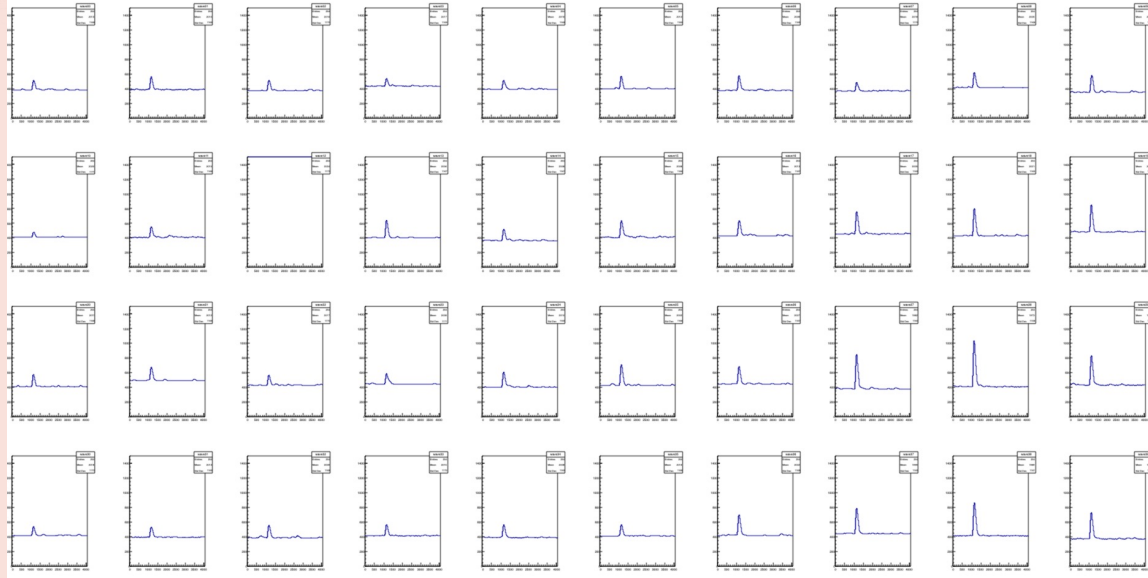
45cm

200cm

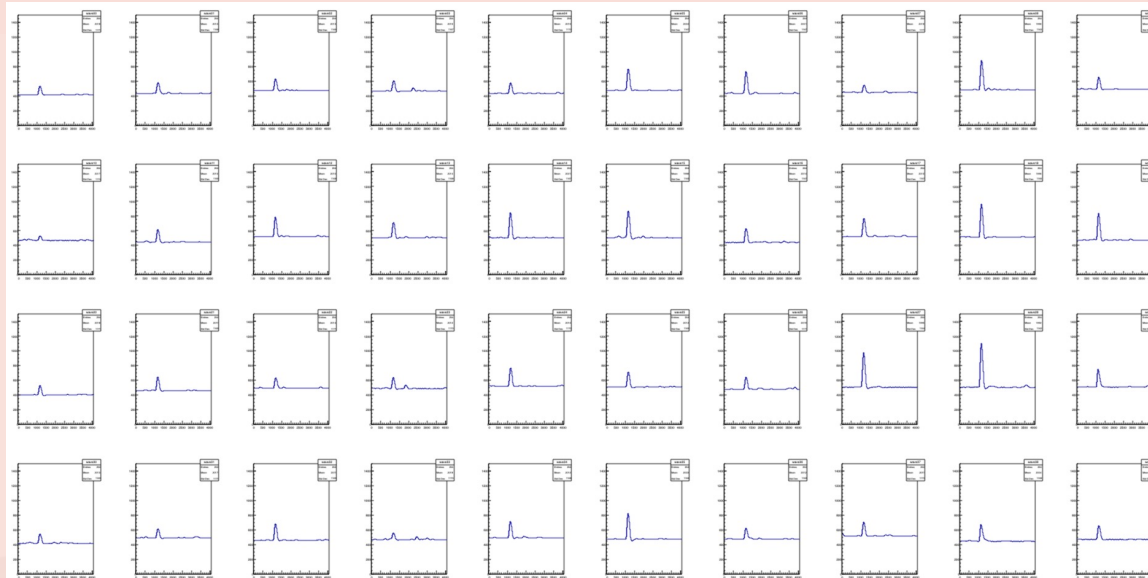
7. Positioning

HAWLU

Upper panel

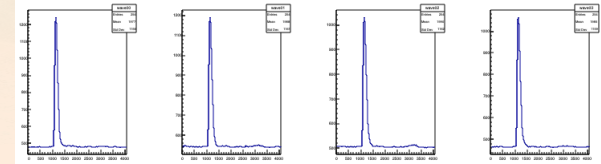


Lower panel

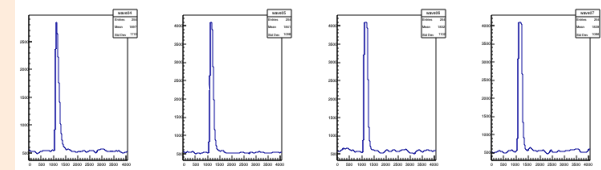


Trigger detector

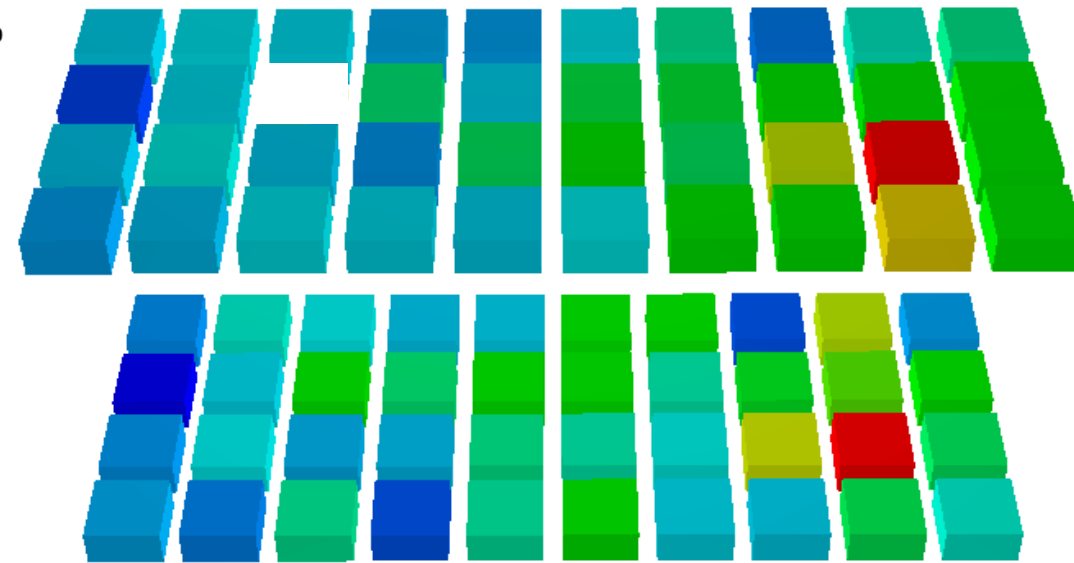
Trigger 1



Trigger 2



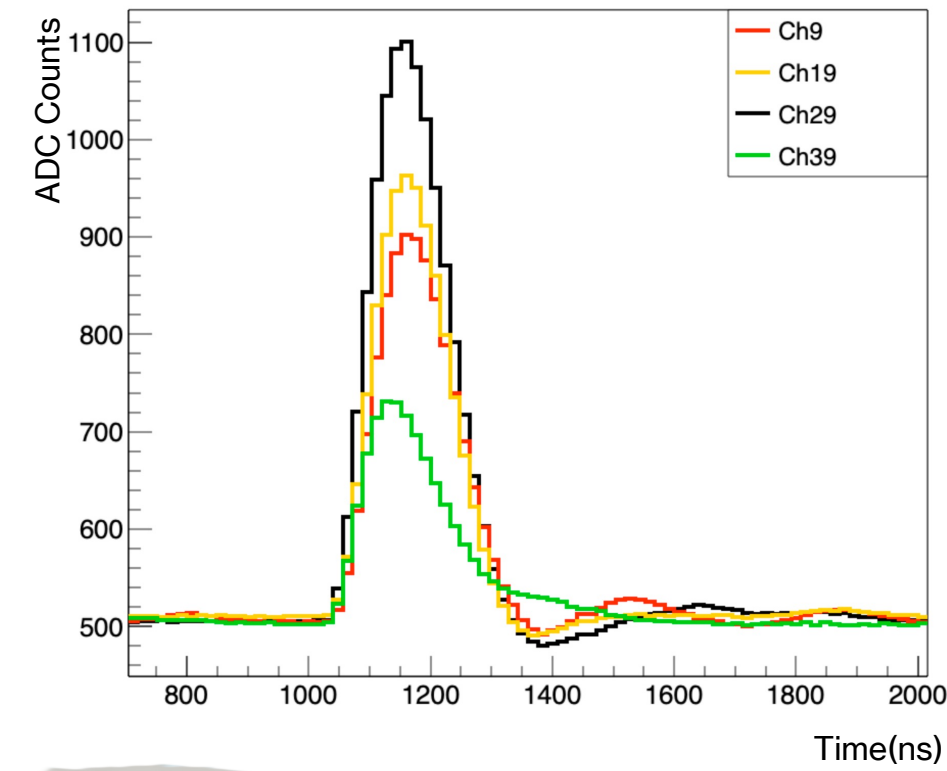
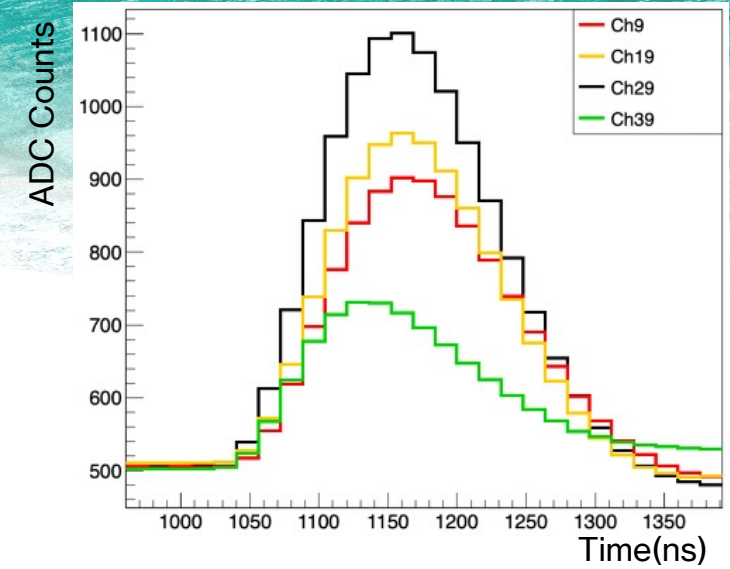
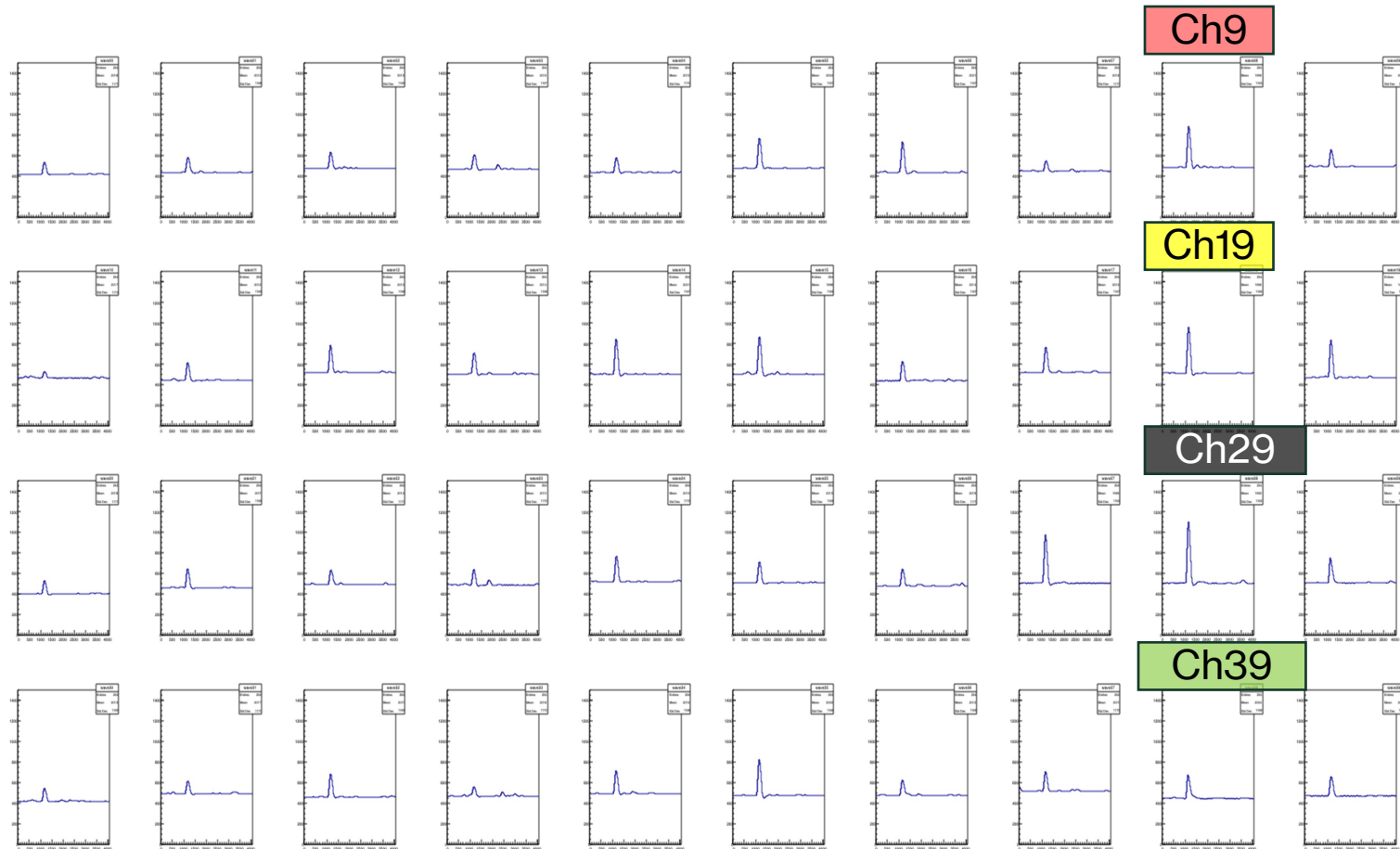
Upper panel



Lower panel

7. Positioning

Lower Panel Example: Vertical



7. Positioning

Lower Panel Example: Horizontal

