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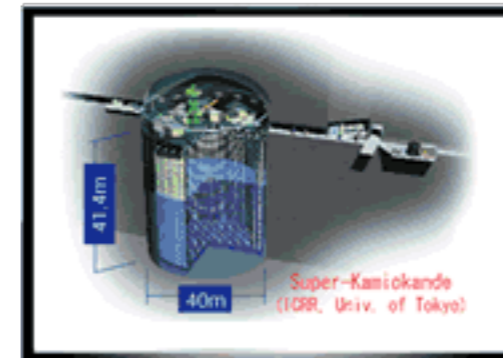
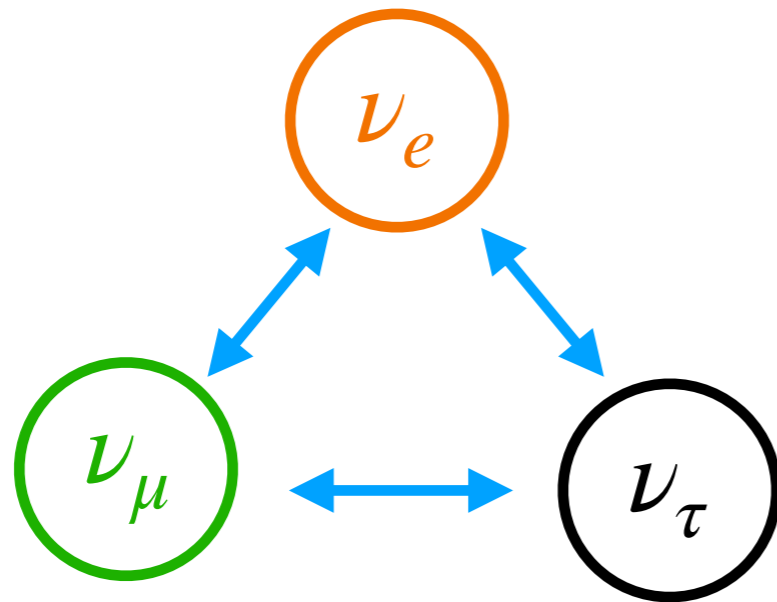
Demonstration of Two Dimensional Muon Profile Measurements by Electron Multiplier Tubes in the T2K Experiment

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Kobayashi Sota

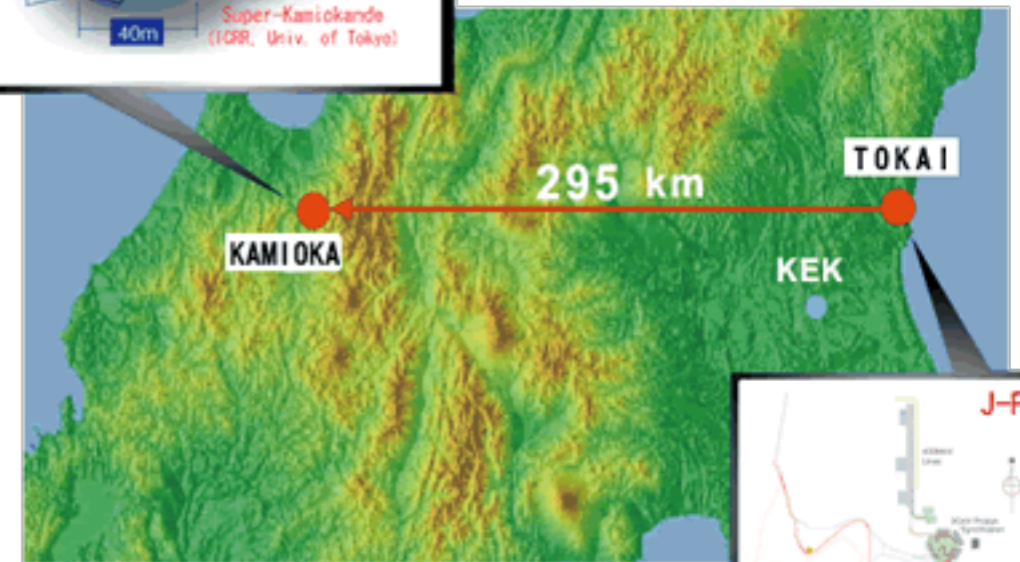
2026/5/27 NPN2026

Neutrino CP violation

Neutrino Oscillation

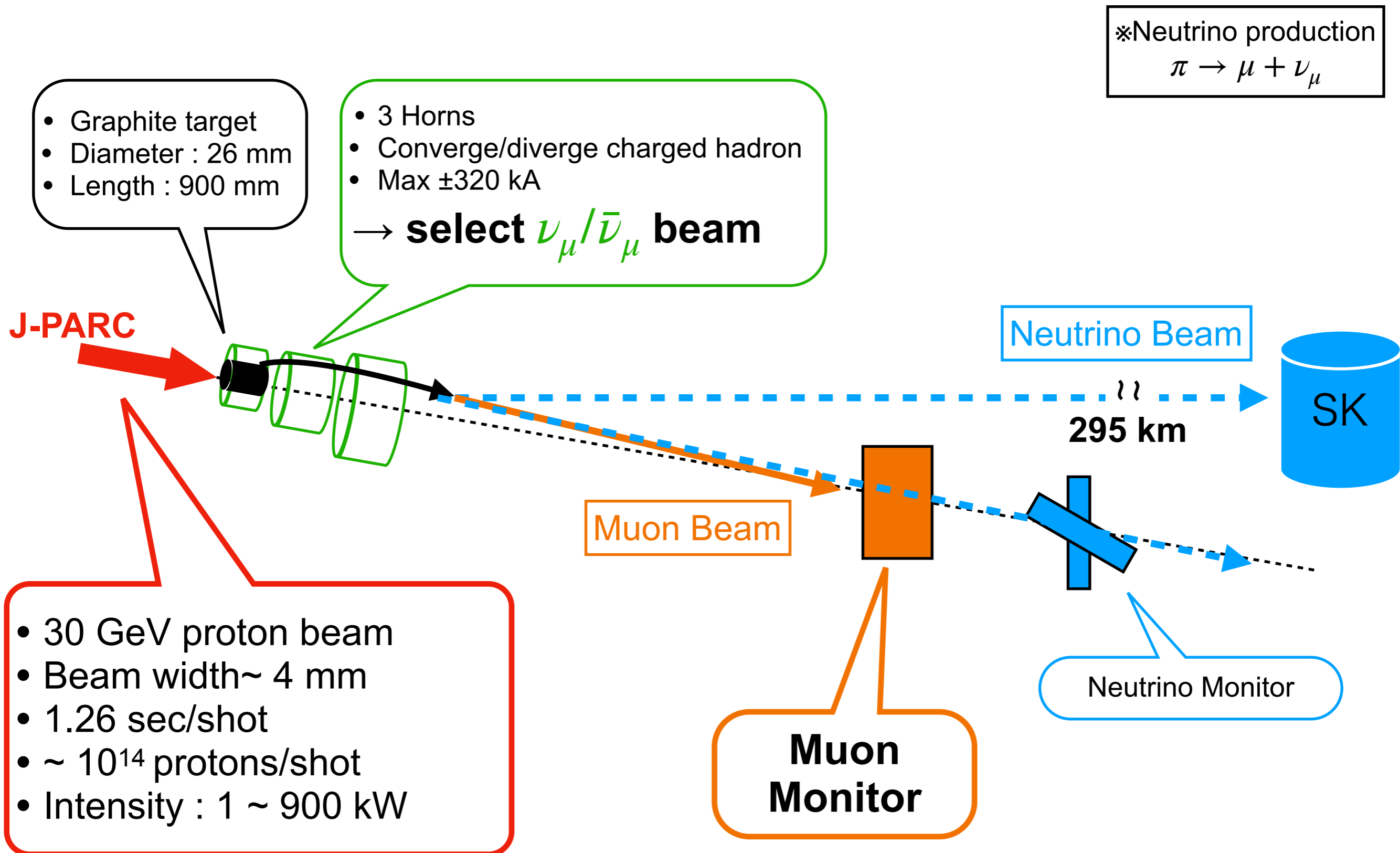


T2K experiment



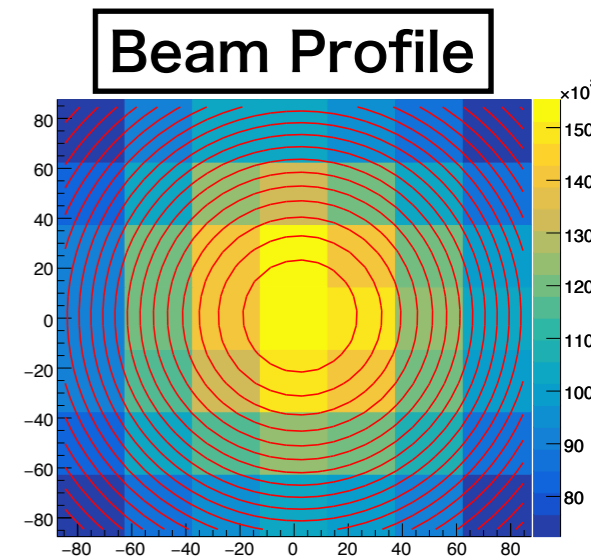
- Neutrino Oscillation
 - Neutrino can change Flavor, such as $\nu_\mu \rightarrow \nu_e$
- CP violation in Neutrino
 - Oscillation probability would be different btw ν and $\bar{\nu}$
- T2K experiment
 - Accelerator neutrino from J-PARC \rightarrow Measure at Super-Kamiokande.
- ❖ Exclude CP conservation at 90% confidence level

T2K experiment scheme



Muon Monitor(MUMON)

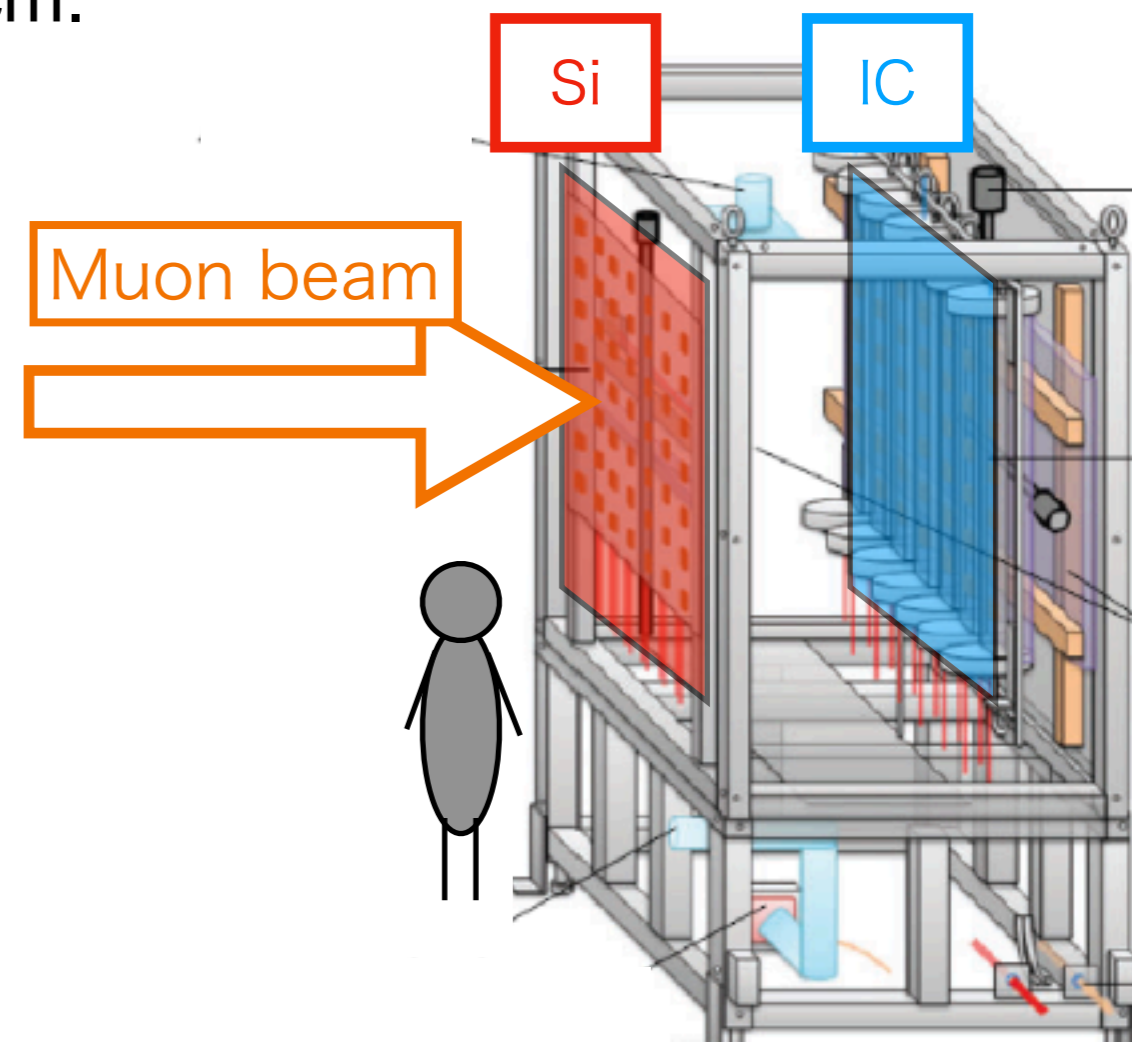
- 100m downstream
- In 1.5 m×1.5 m area, $7 \times 7 = 49$ sensors
- Silicon (Si) and Ion Chamber (IC)
- Beam Center and Width from Charge.
- Measurement precision
 - **3.3 cm (0.28 mrad)**, requirement is 3.5 cm.



[Current Issue is ...]

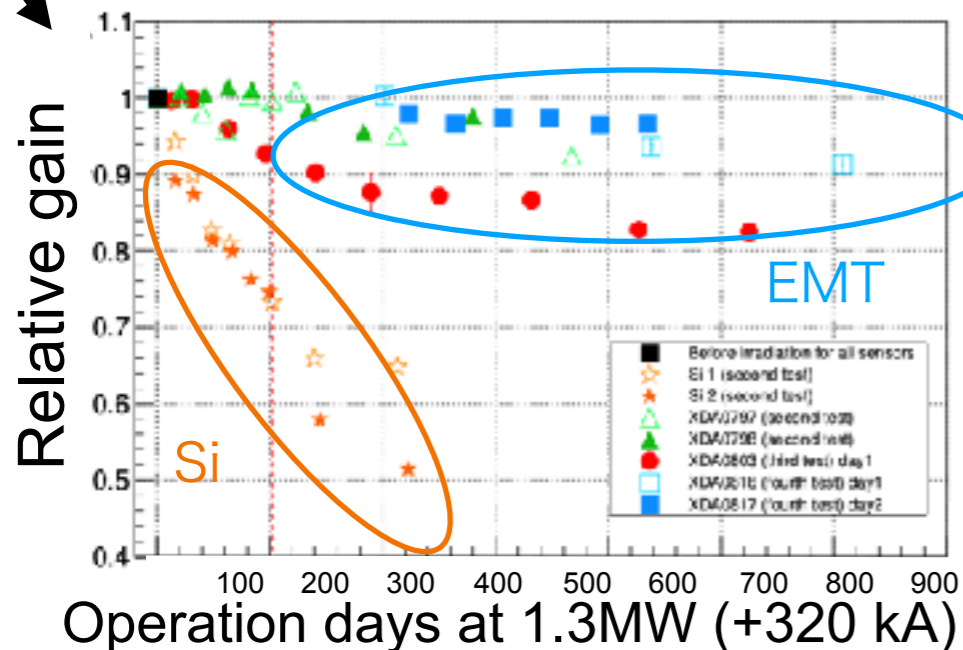
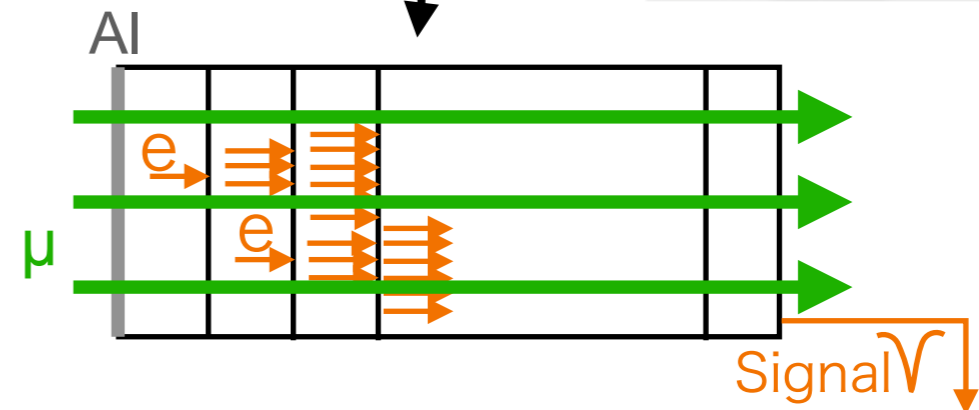
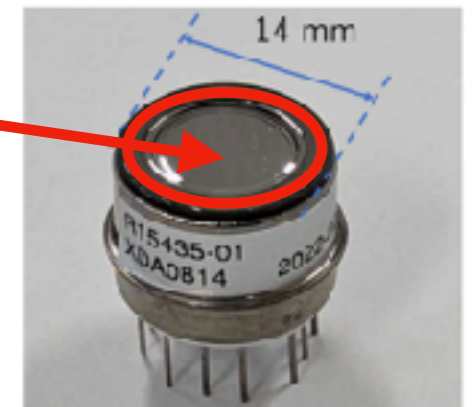
- Difficulty in future 1.3 MW
- High Radiation Tolerance
and Good Linearity

→ **New Sensor “EMT”**



Electron Multiplier Tube (EMT)

- Aluminum is vapor-deposited onto the **PMT's cathode** instead of photocathode material.
- When **muon** pass, Secondary electrons are emitted.
- 2019~2022, Beam test @ Tohoku Univ. ELPH(electron beam)
 - ✓ High radiation tolerance
 - ✓ Linearity even in 1.3MW.

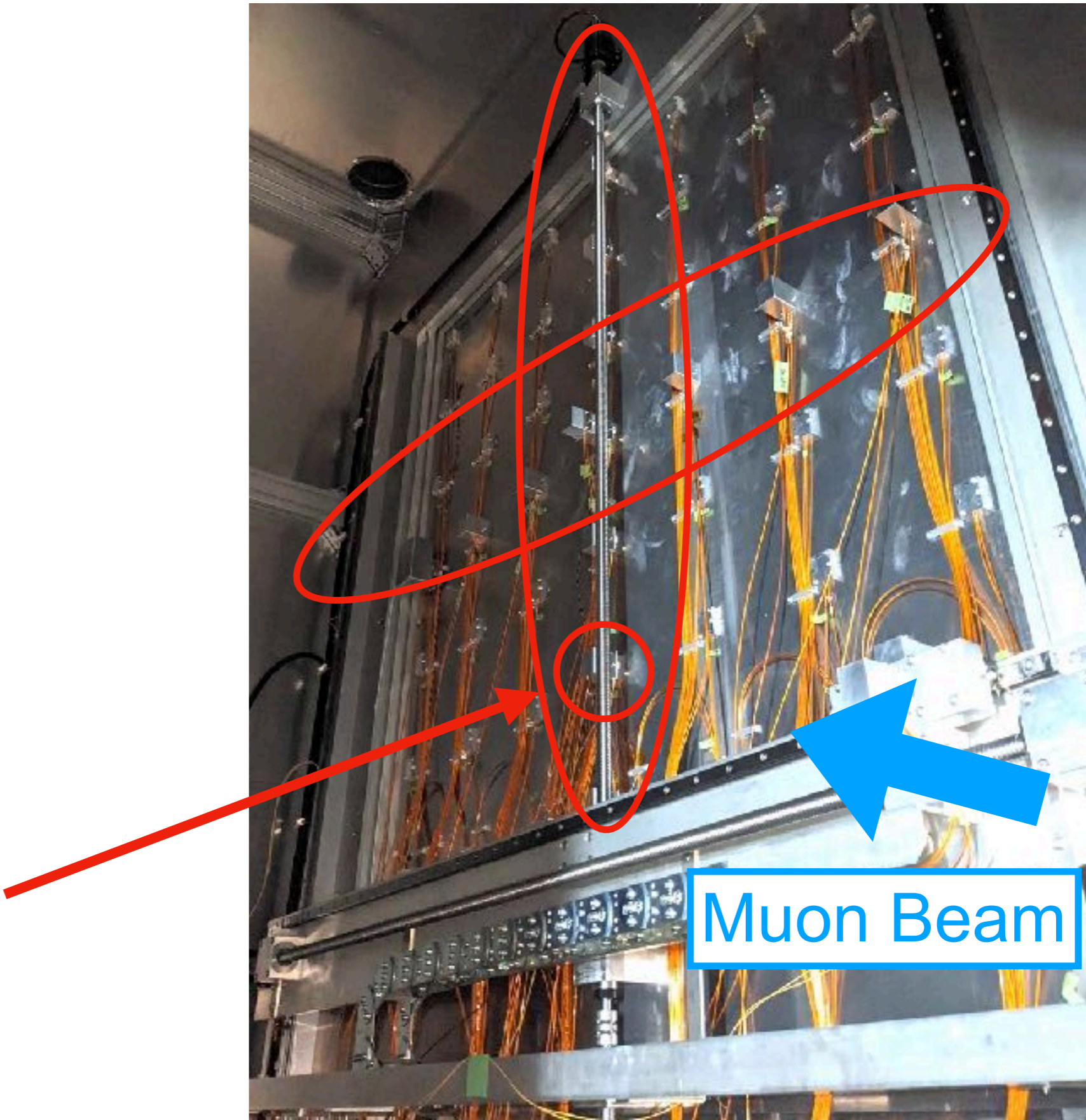
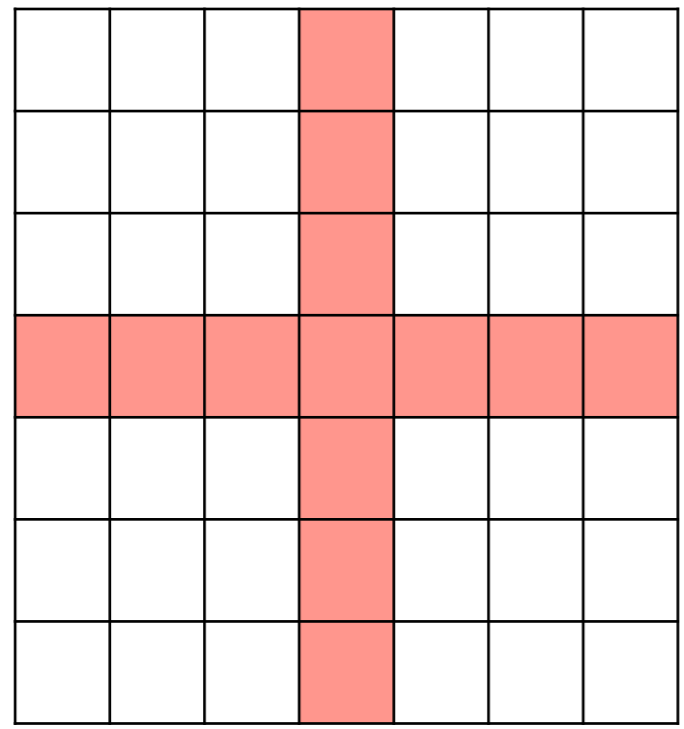


[Install History]

- 2023 : Horizontal, 7ch.
- 2024 : Plus shape, 13ch.
↑ Mainly discussed
- 2025 : Star shape, 25ch.
- 2026 (?) : Full 49 ch.

2024 Plus shape installed

Plus Shape

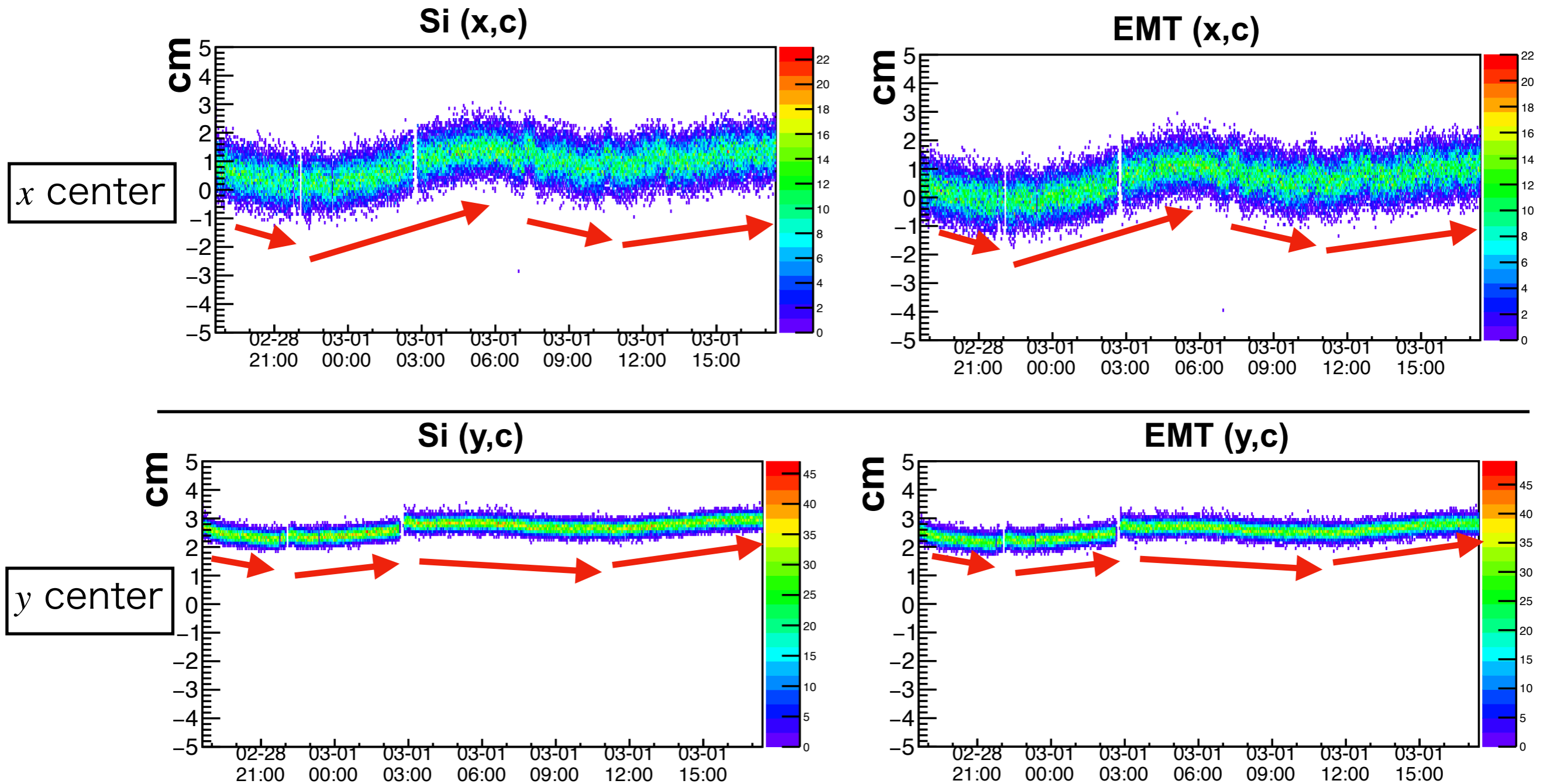


Muon Beam

High Intensity Beam Measurement

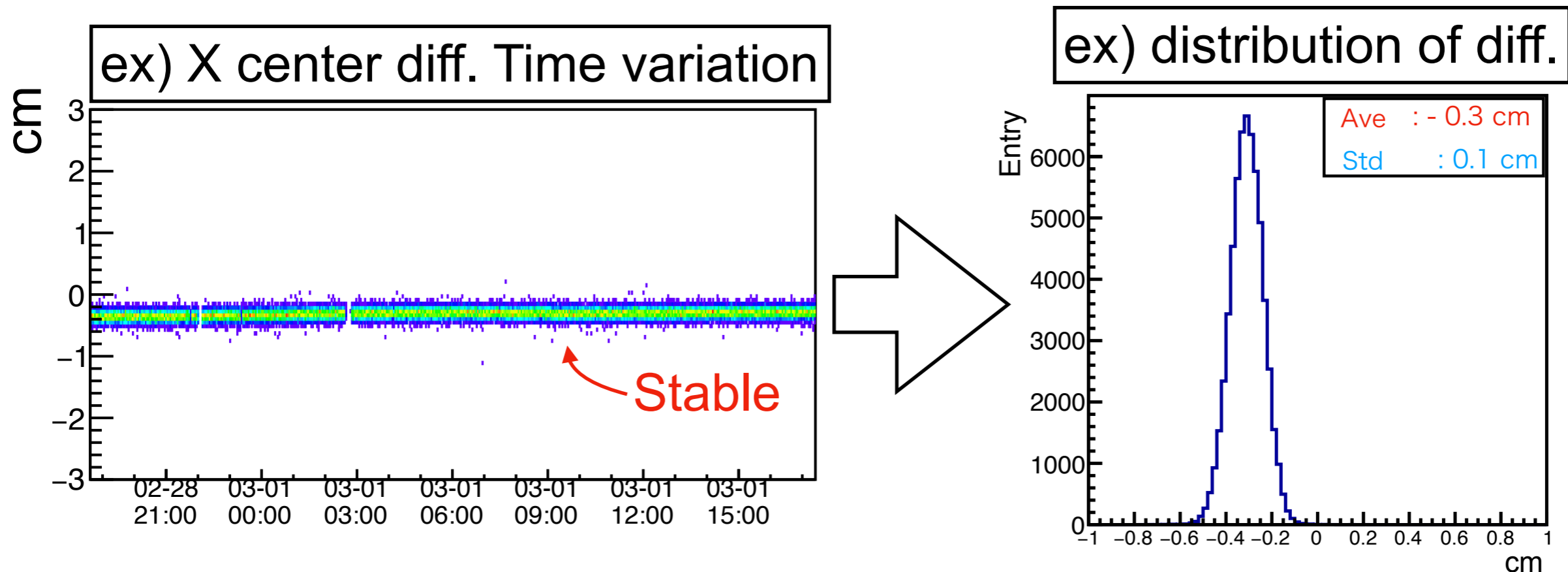
- Roughly more than 100 kW.
- Mainly used as Physics data.
- Better than 3.5 cm(0.3 mrad) accuracy is required.

Sensitivity to Time Variation at Beam Center



✓ Consistent time variations btw Si and EMT.

Difference btw Si and EMT (EMT-Si)



[cm]	Diff. Average	Diff. Std.
X center	-0.3	0.1
Y center	-0.1	0.1
X width	2.3	0.1
Y width	1.1	0.1

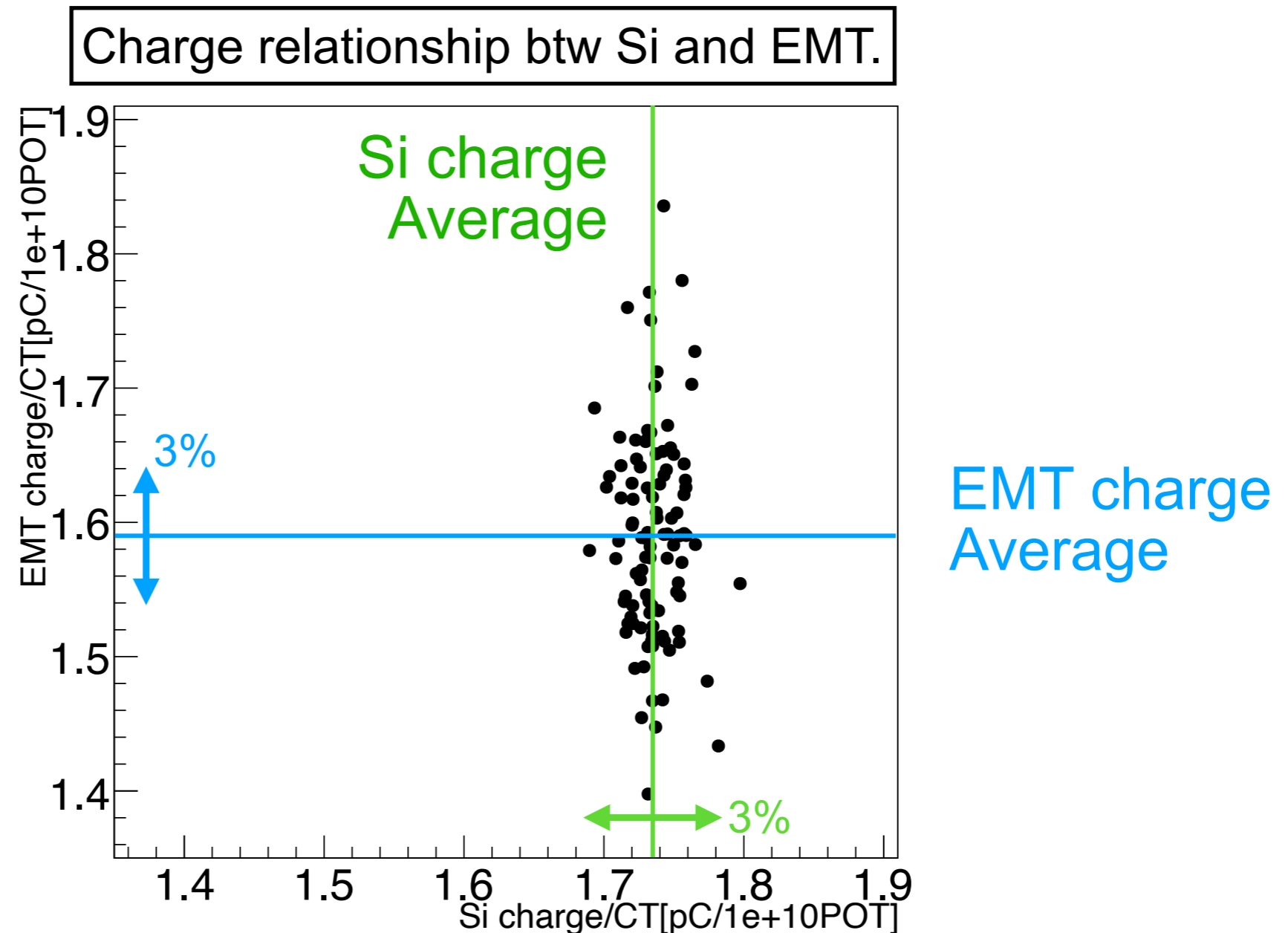
Less than MUMON
Sys. Error (3.3 cm)
✓ Satisfy requirement.

Not large diff. compared to
beam width (~ 85 cm).
✓ Key Points for Future.

Low Intensity Beam Measurement

- Precise measurement is required even at $\sim 1\text{kW}$.
 - Tune beam from low intensity beams.
 - The, gradually increase.

Charge measurement in Low beam.



Relationship btw EMT and Si at MUMON center

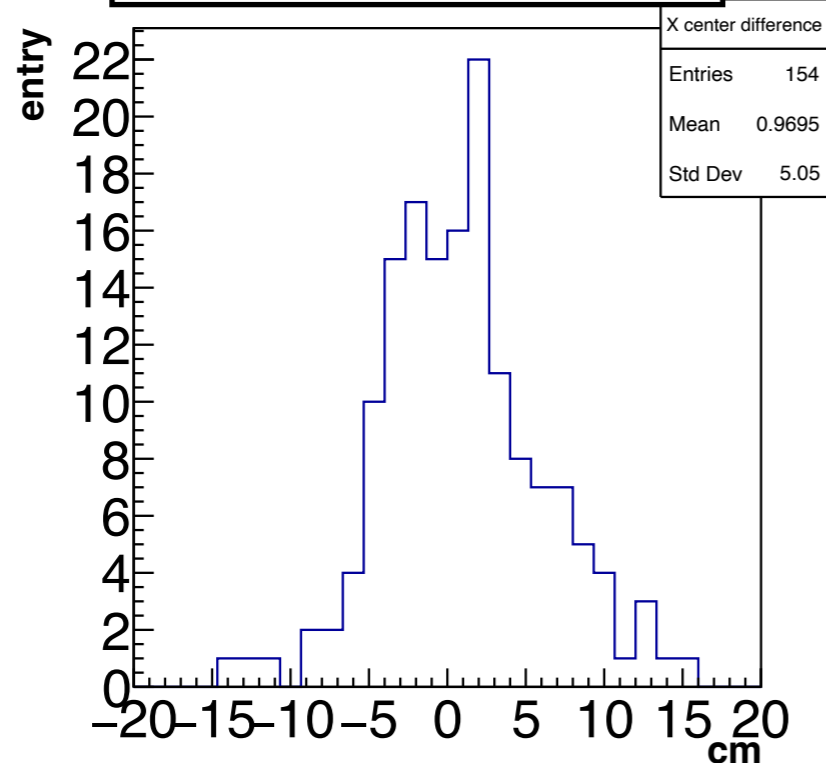
➔ EMT charge **fluctuate largely** shot by shot.

❖ Main reason is Secondary Electron Statistic fluctuation.

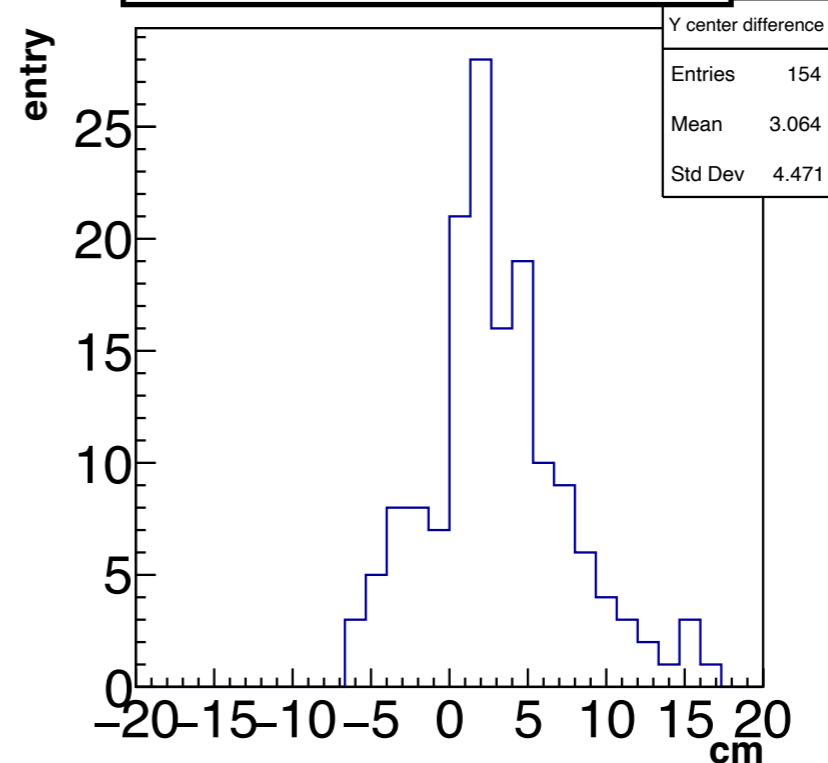
→ See Backup

Difference btw Si and EMT (EMT-Si)

ex) X center diff.



ex) Y center diff.



[cm]	Diff. Average	Diff. Std.
X center	1.0	5.1
Y center	3.1	4.5
X width	1.1	8.0
Y width	0.9	9.3

Unstable by about 5 cm relative to Si.
 ※ ± 1.5 cm stability is required

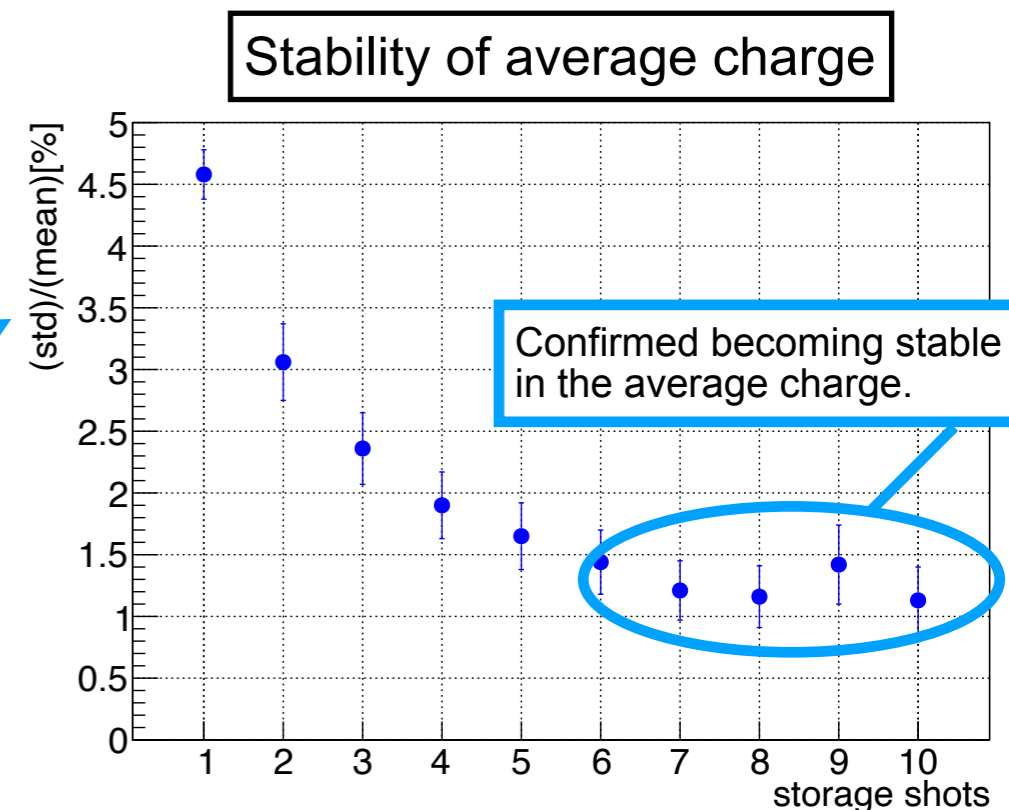
Two Countermeasures

- Issue : Charge fluctuation shot by shot

[Countermeasure]

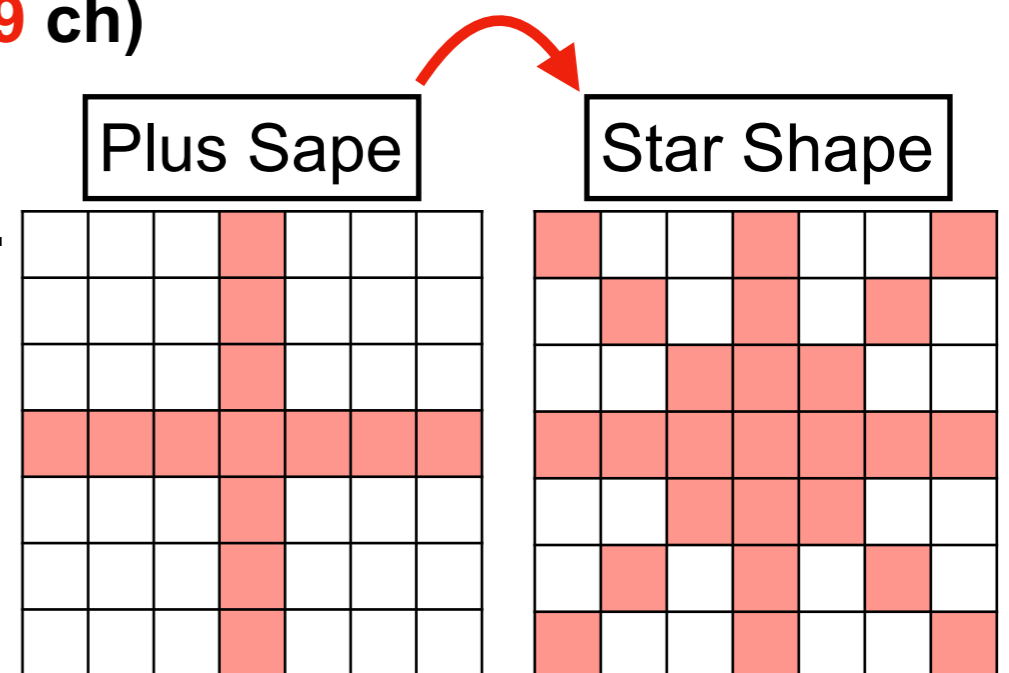
1. Take Average charge

- Average charge value is more stable.
- Take several shots continuously.
- Reconstruct beam profile and fit.



2. Install more channels

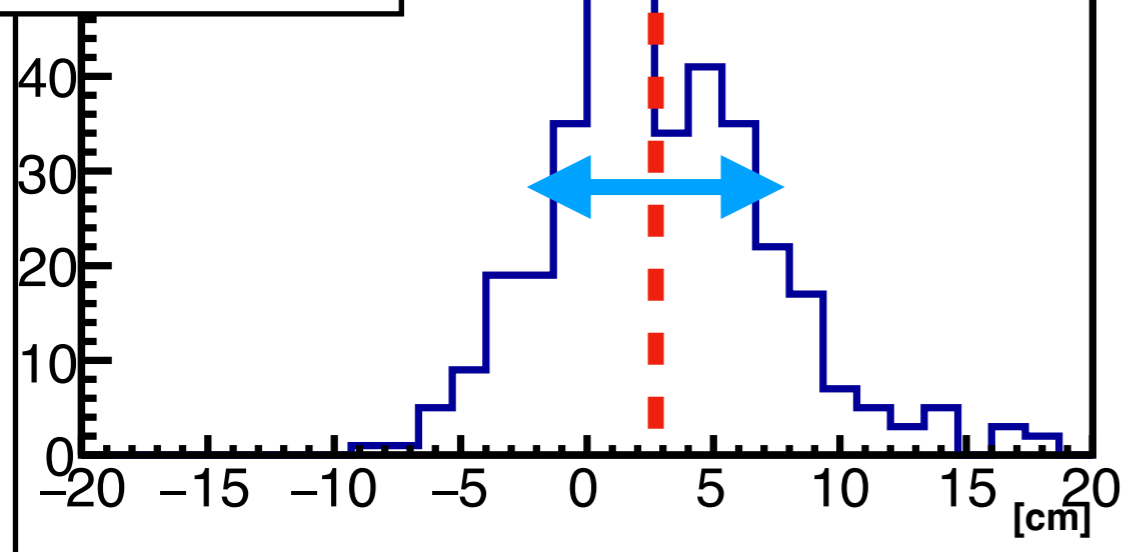
- Only **13** channels in plus shape (**final goal : 49 ch**)
- Add to diagonal area, call star shape.
- Profile measurement would be more stable.



Ex) Measurement by 4 shots average charge.

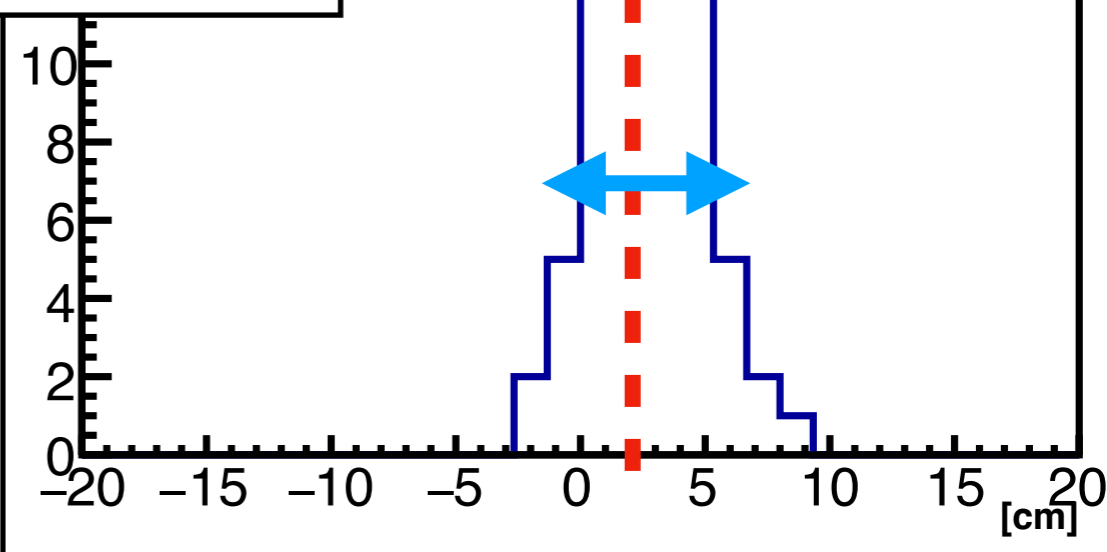
EMT-Si per 1 shot at the y center

Ave : 2.8 cm
Std : 4.3 cm



EMT-Si per 4 shots at the y center

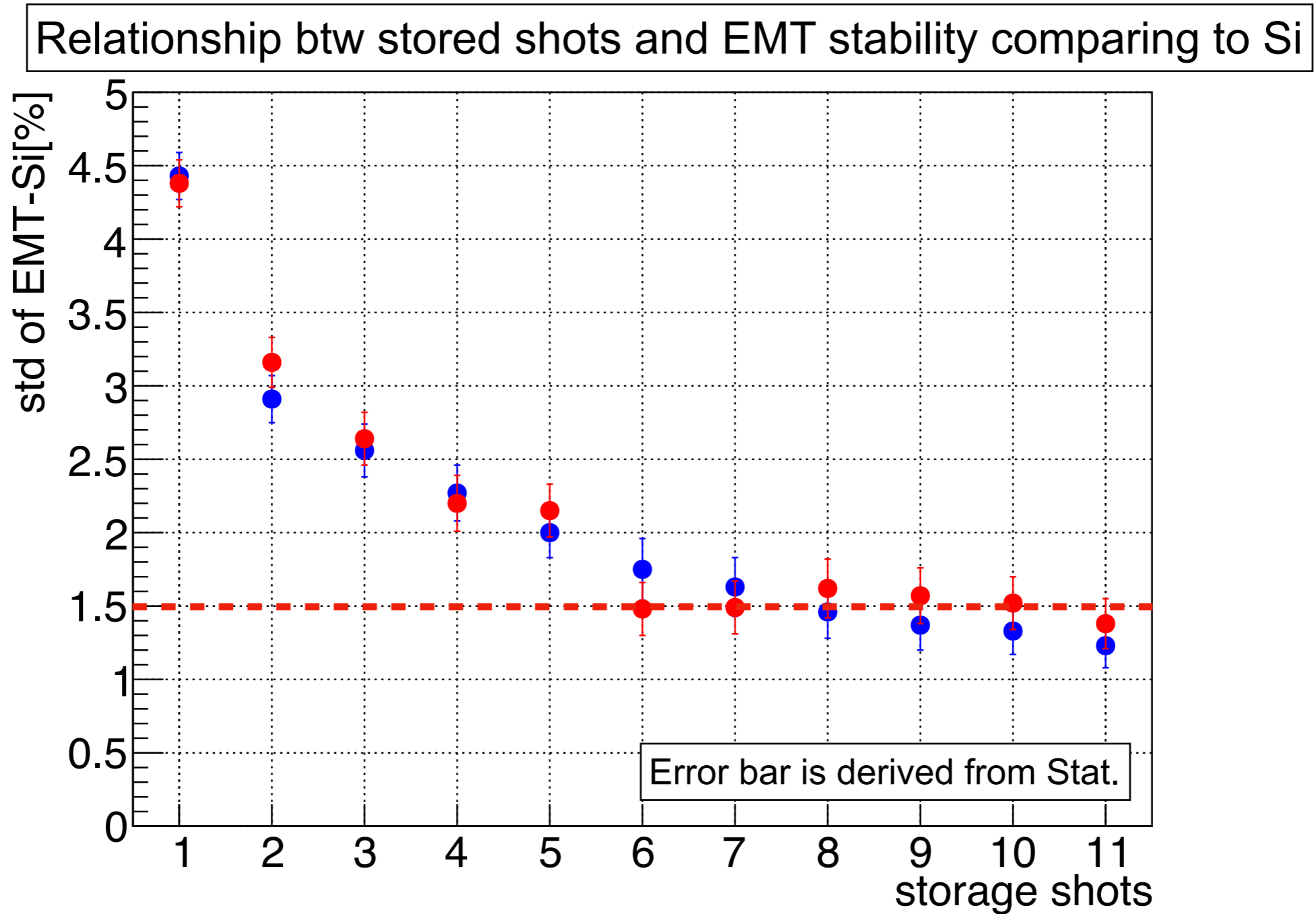
Ave : 2.7 cm
Std : 2.2 cm



Std of EMT - Si decreased by approximately 50%.

✓ This method can be counter-plan.

Average Shot num and Std of Difference

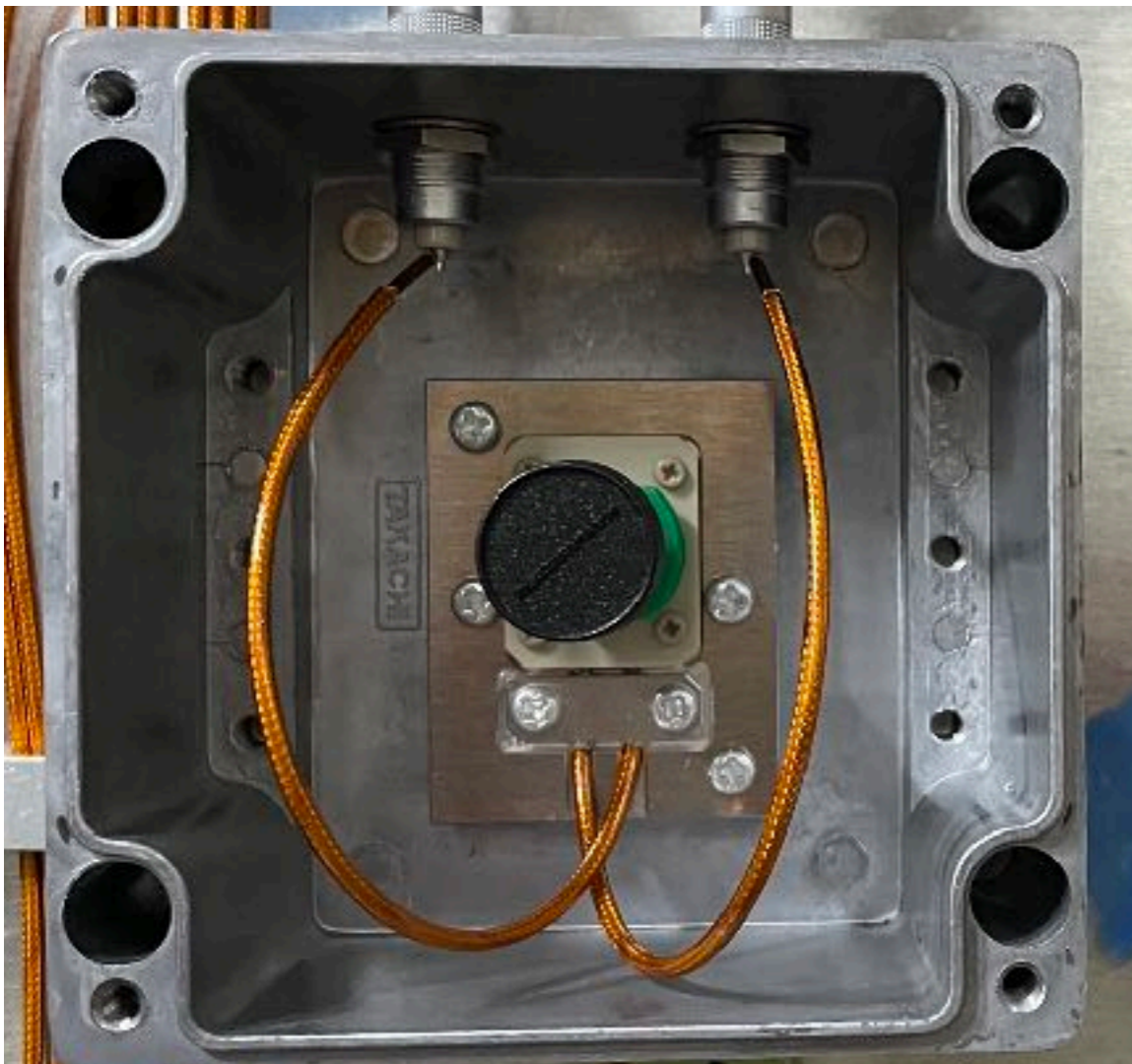
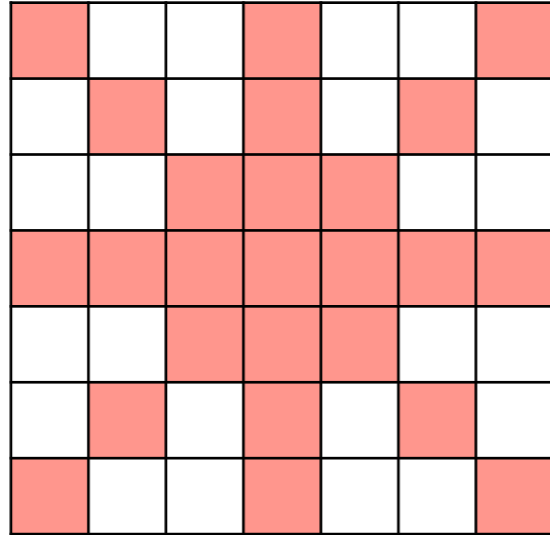


± 1.5 cm stable measurement is required.

✓ ~7 shots average satisfies required precision.

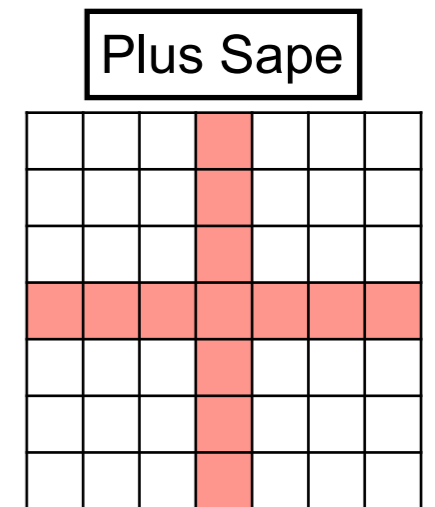
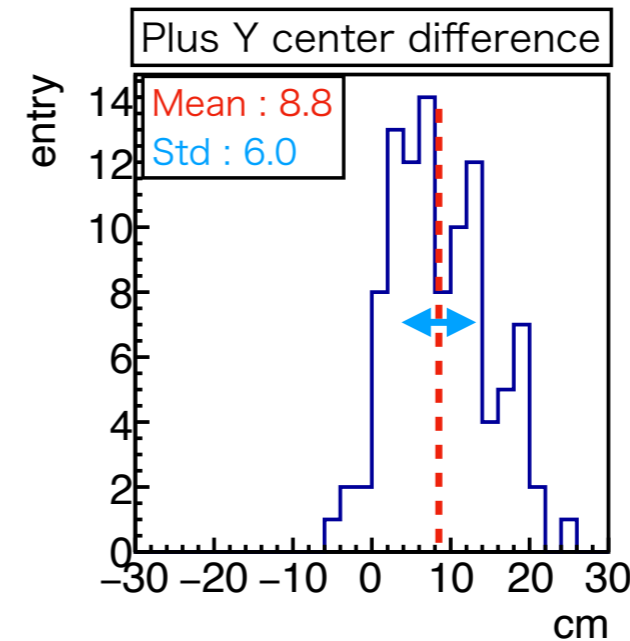
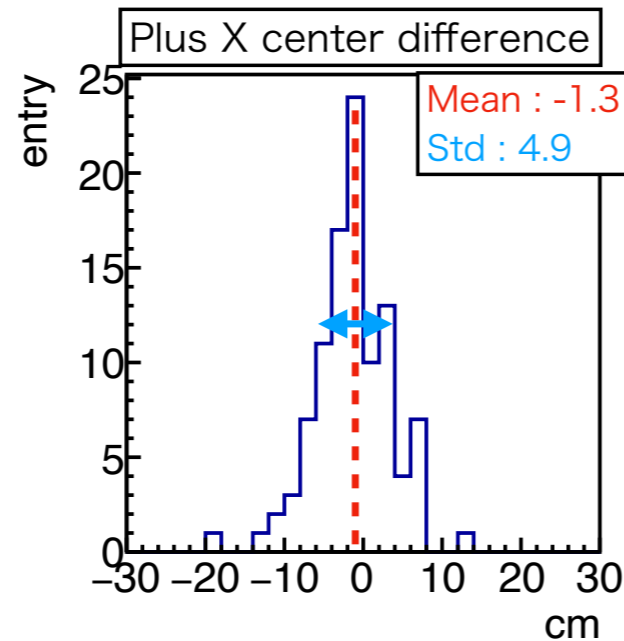
2 : More EMTs install

- 2025 Nov.
- Star Star

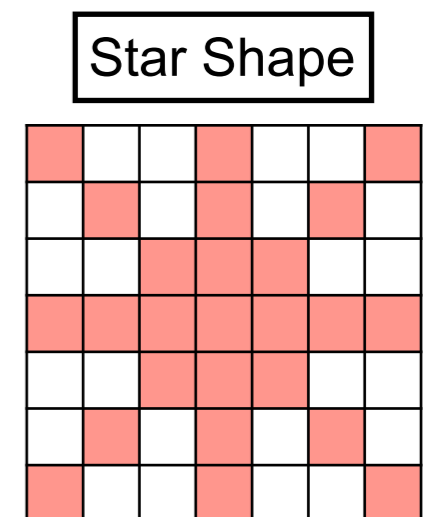
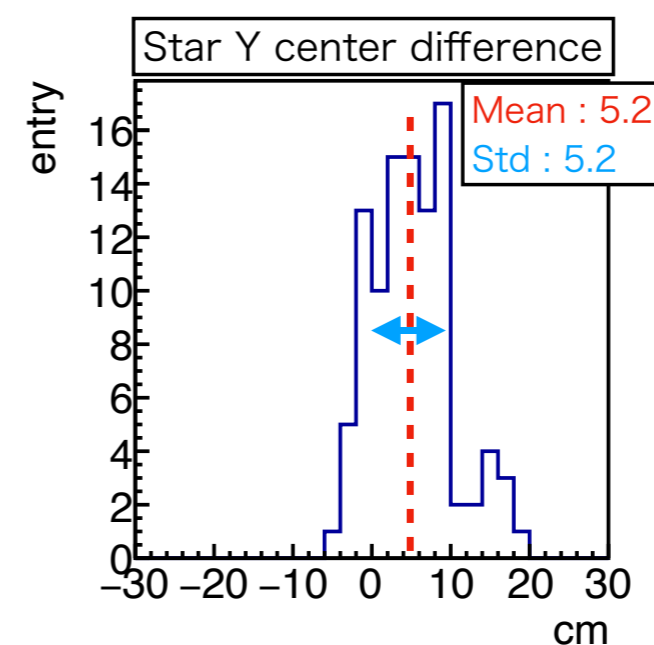
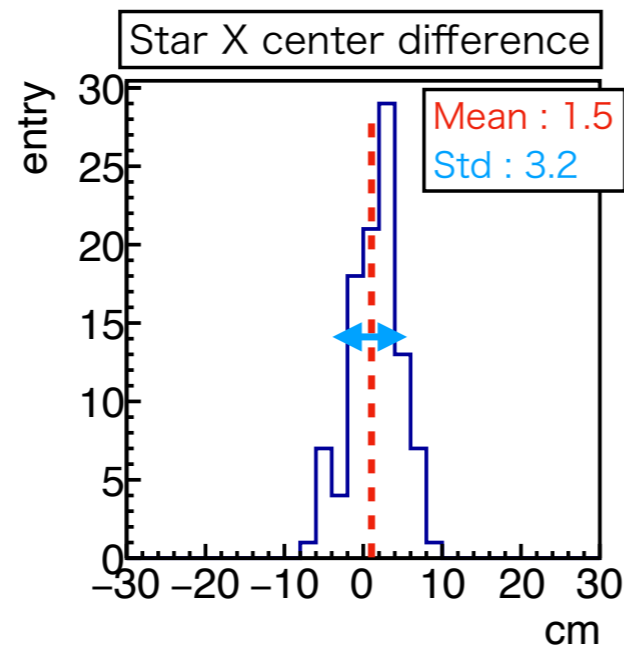


“Plus - Si” vs “Star - Si”

Plus - Si
(per shots)



Star - Si
(per shots)



Compare Si 49ch measurement and Plus, Star.

✓ Star Shape is more stable by **~1 cm**.

➡ The installation of all EMT channels is expected to improve accuracy.

Summary

- T2K experiment
 - Long base line neutrino oscillation experiment.
 - Searching CP violation in neutrino.
 - 1.3MW beam is planned.
 - —> More radiation tolerant sensor is necessary.
- New sensor : Electron Multiplier Tube, EMT
- High intensity beam measurement
 - **Good consistent** to current sensor, Si.
- Low intensity beam measurement
 - **Unstable measurement** shot by shot.
 - Average charge —> ~7 shots average seems enough.
 - More sensors —> good prospect in Full channel era.

Backup

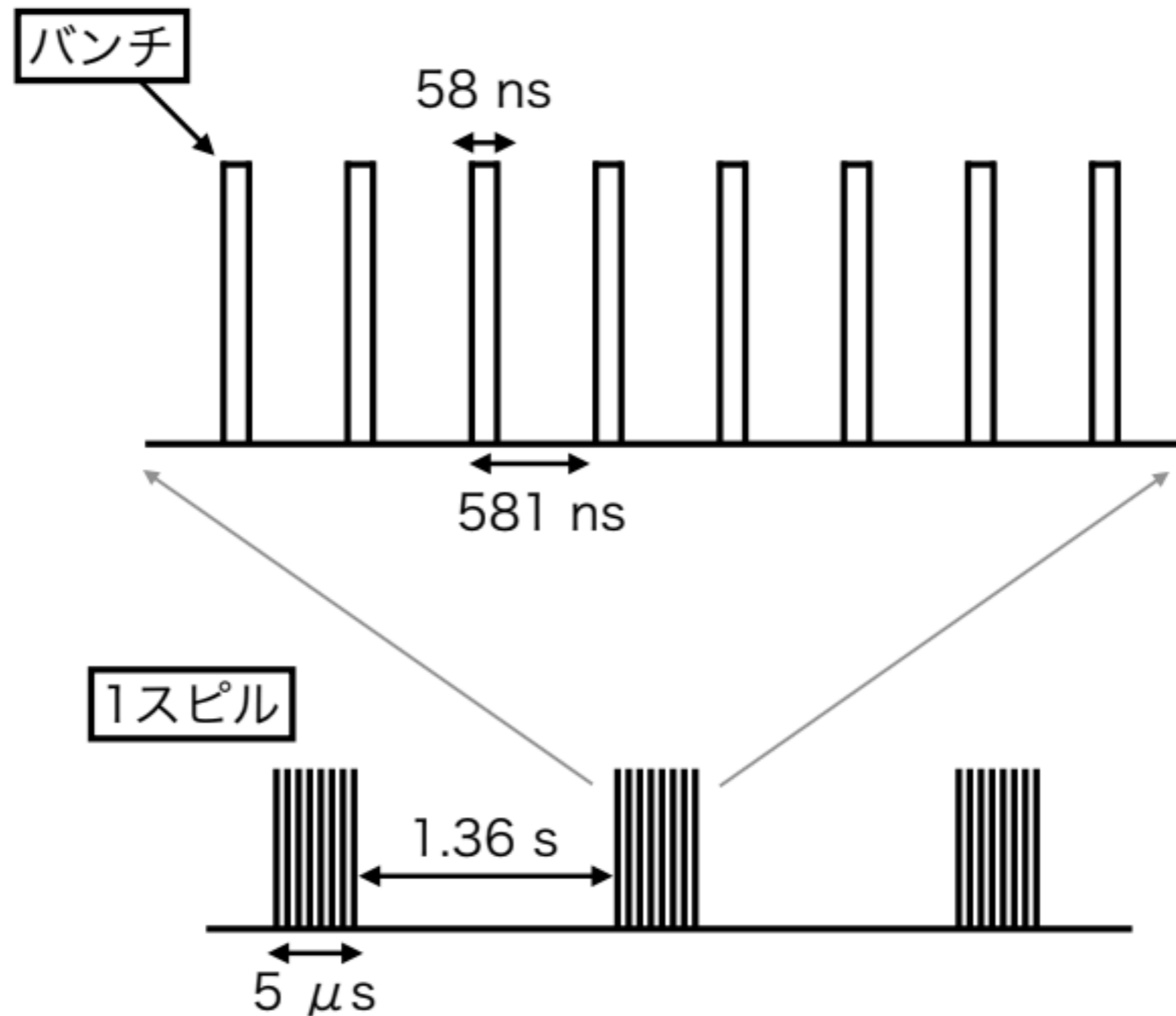
Neutrino Oscillation Prob.

$$\begin{cases} \Delta m_{jk}^2 = m_j^2 - m_k^2 \\ J_{\text{CP}} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin \delta_{\text{CP}} \end{cases}$$

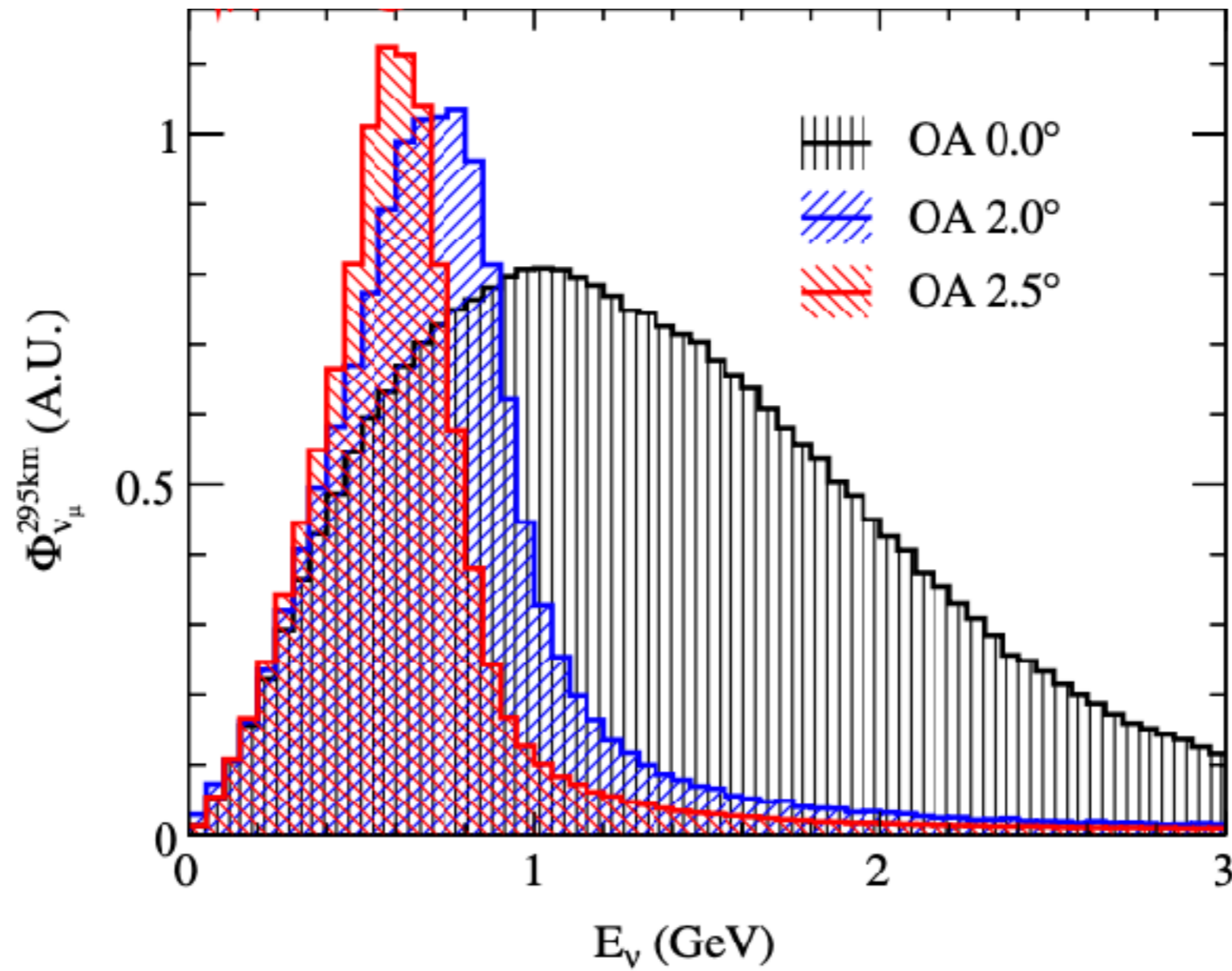
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right) \mp \frac{1.27 \Delta m_{21}^2 L}{E} 8J_{\text{CP}} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \times (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right)$$

J-PARC Beam bunch structure



Neutrino flux



MUMON configuration

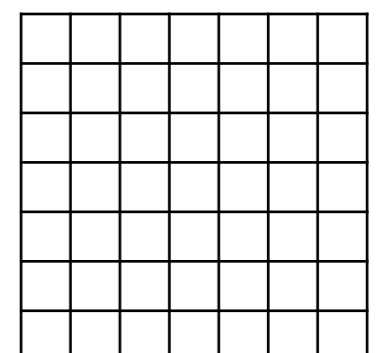
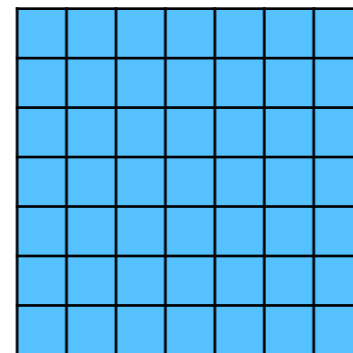
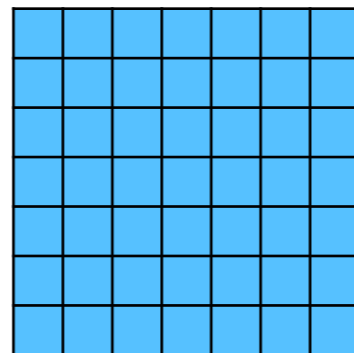
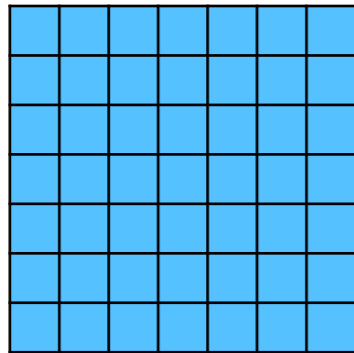
2024

2025

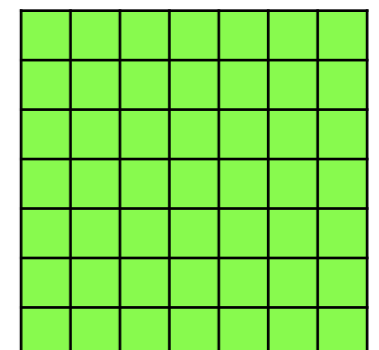
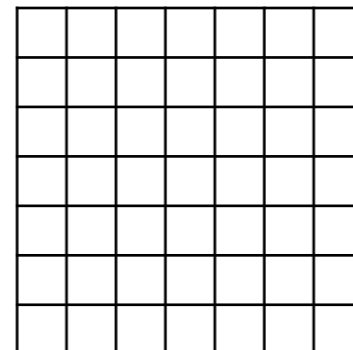
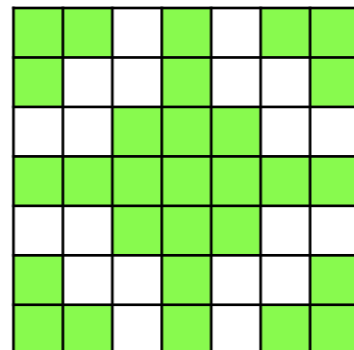
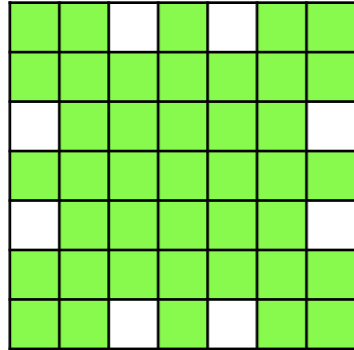
Full EMT test

HK era

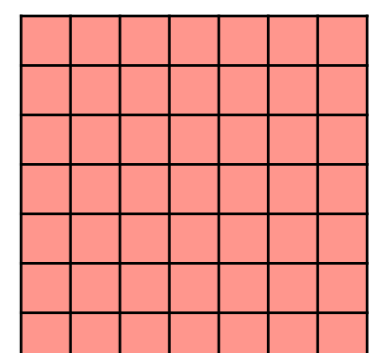
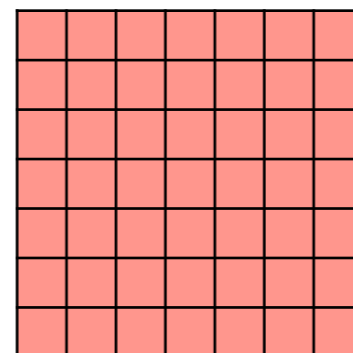
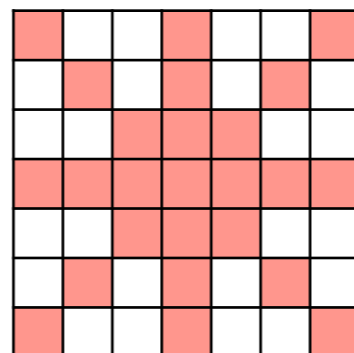
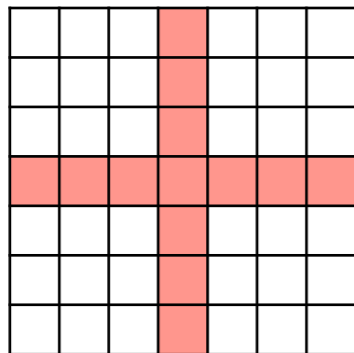
Si



IC

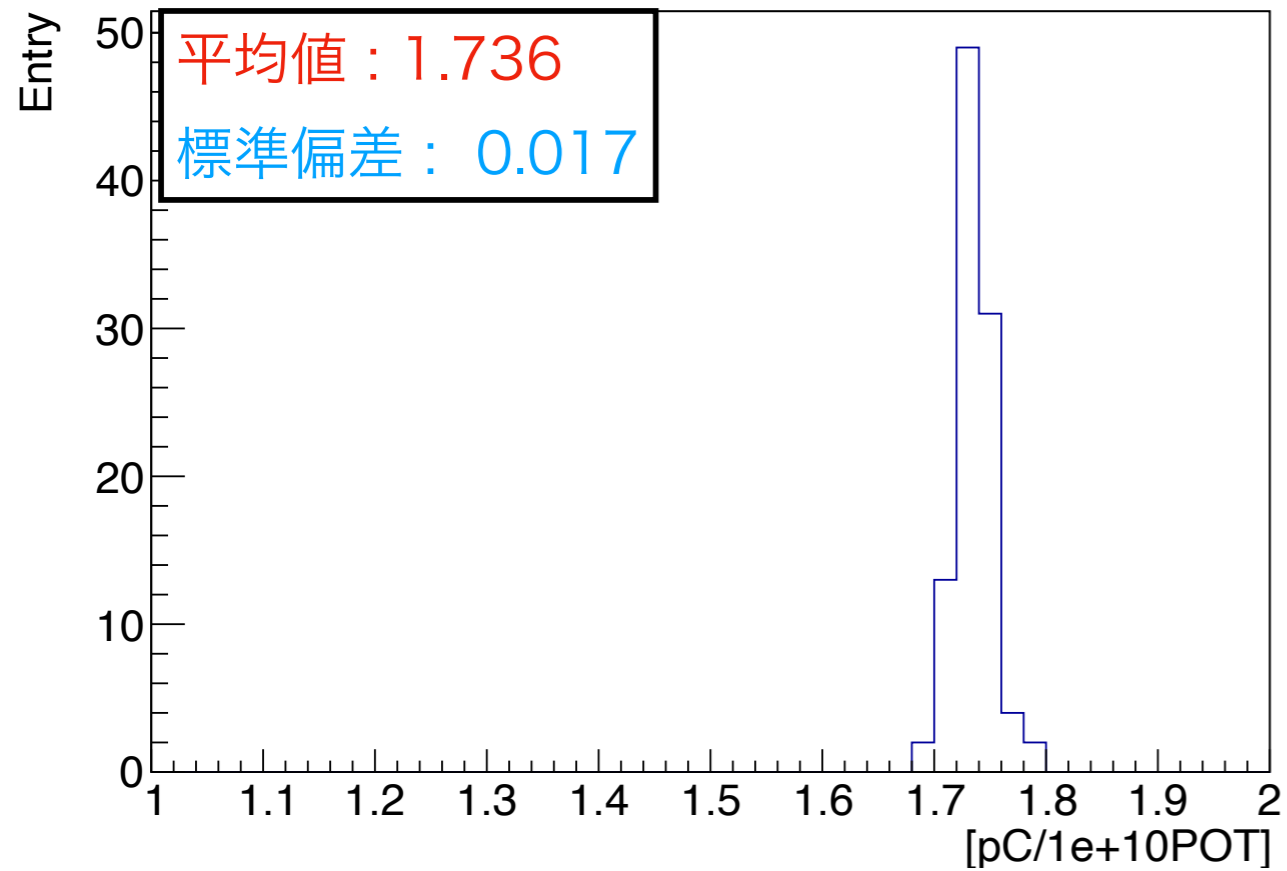


EMT

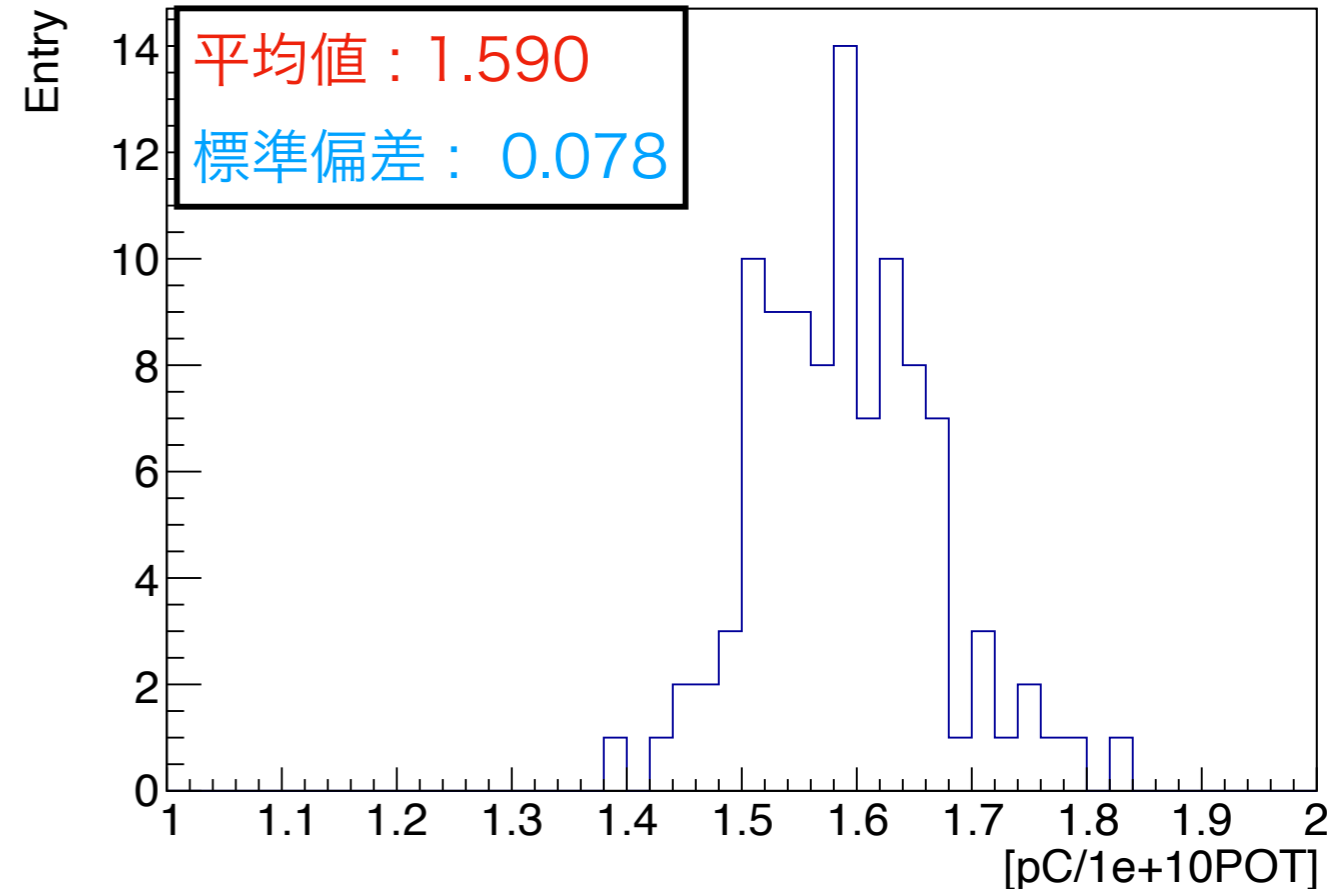


Si and EMT Charge (Low Int.)

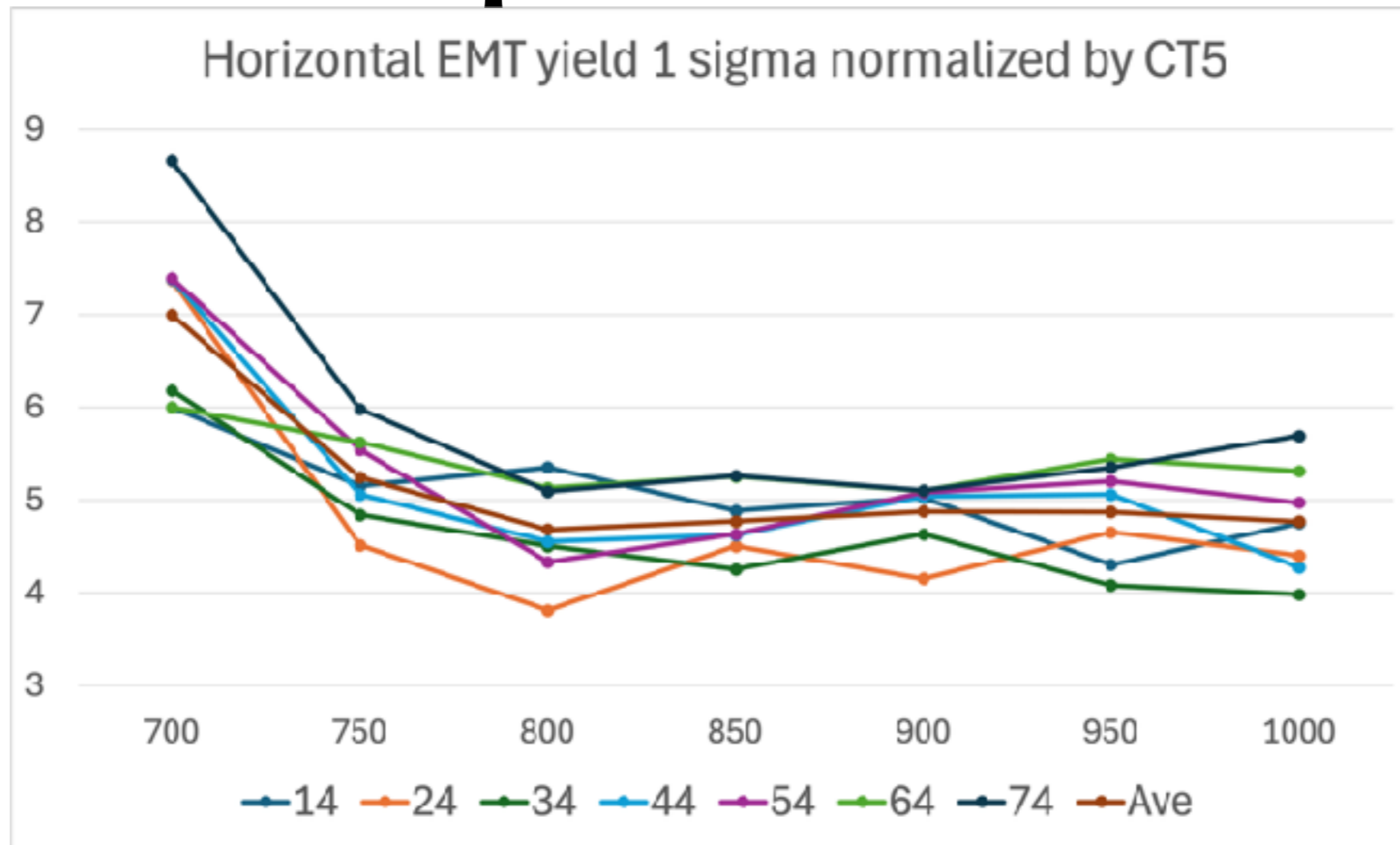
Si 4-7



EMT 4-7

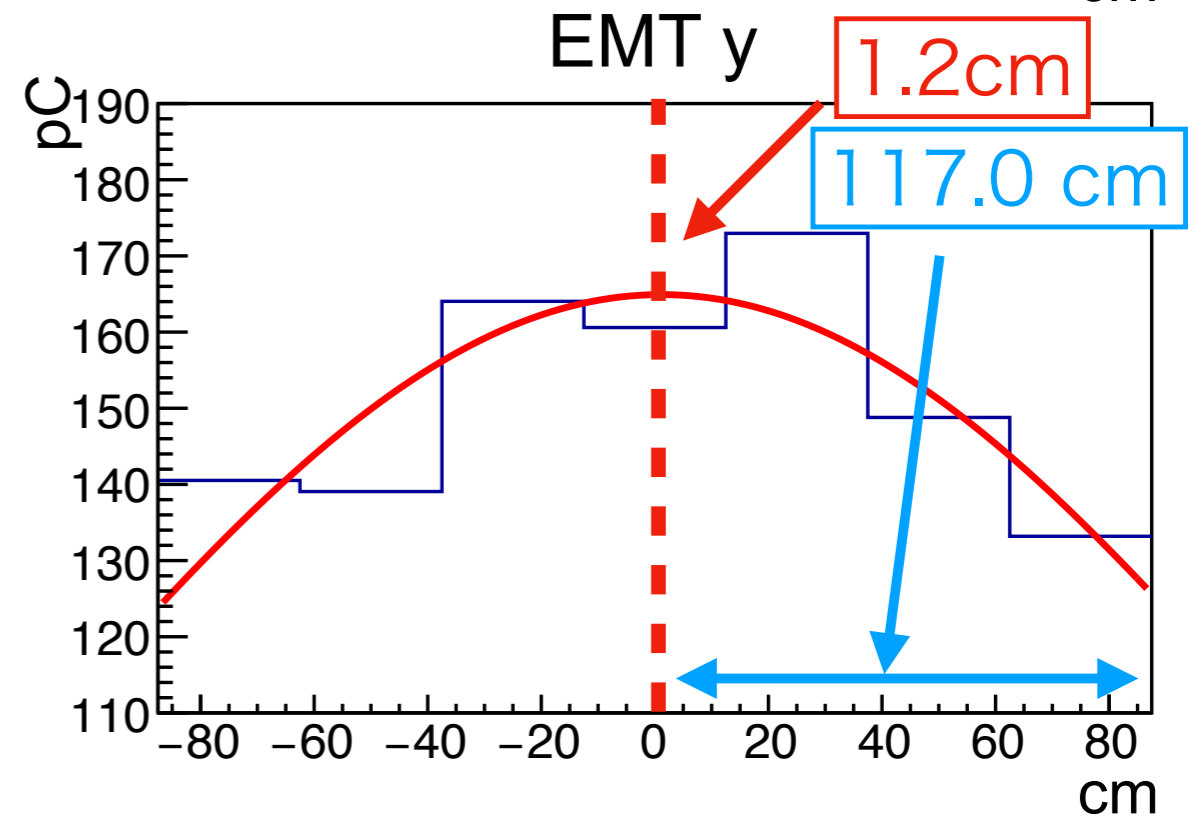
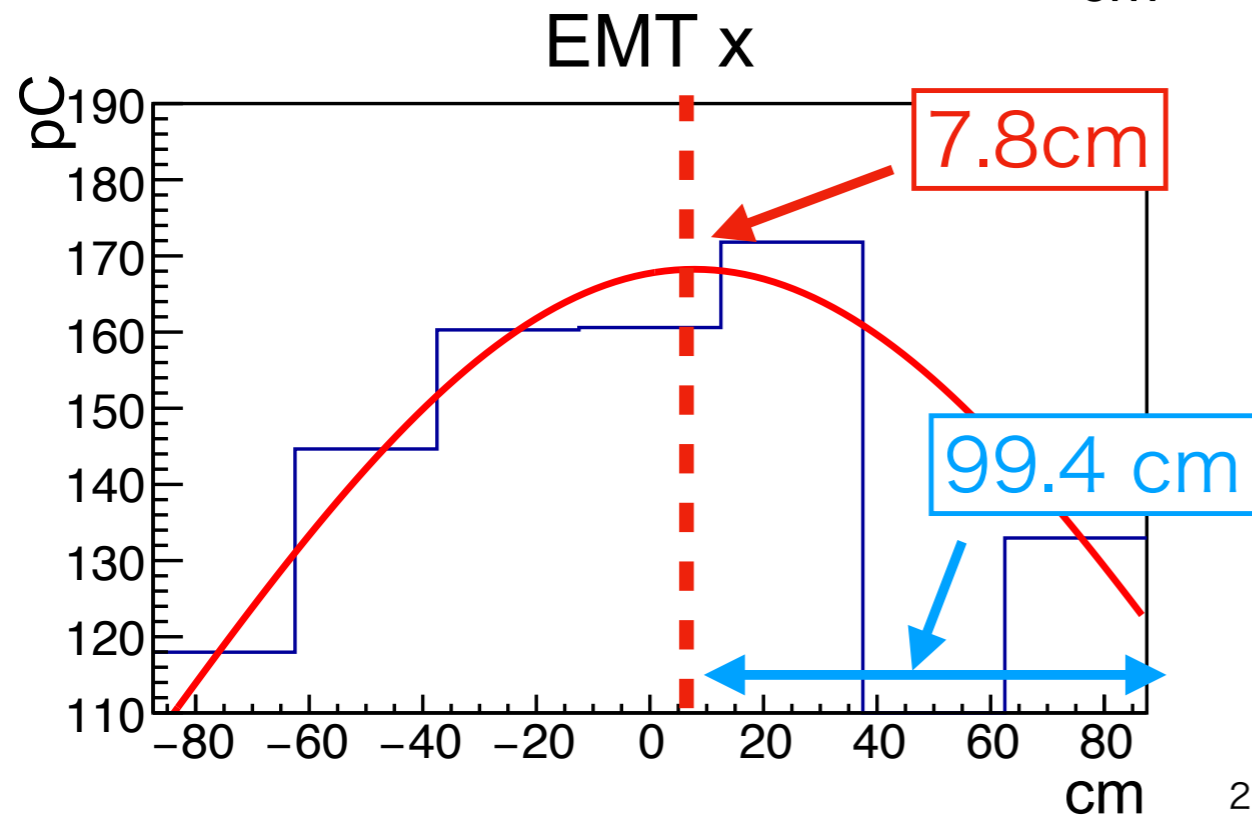
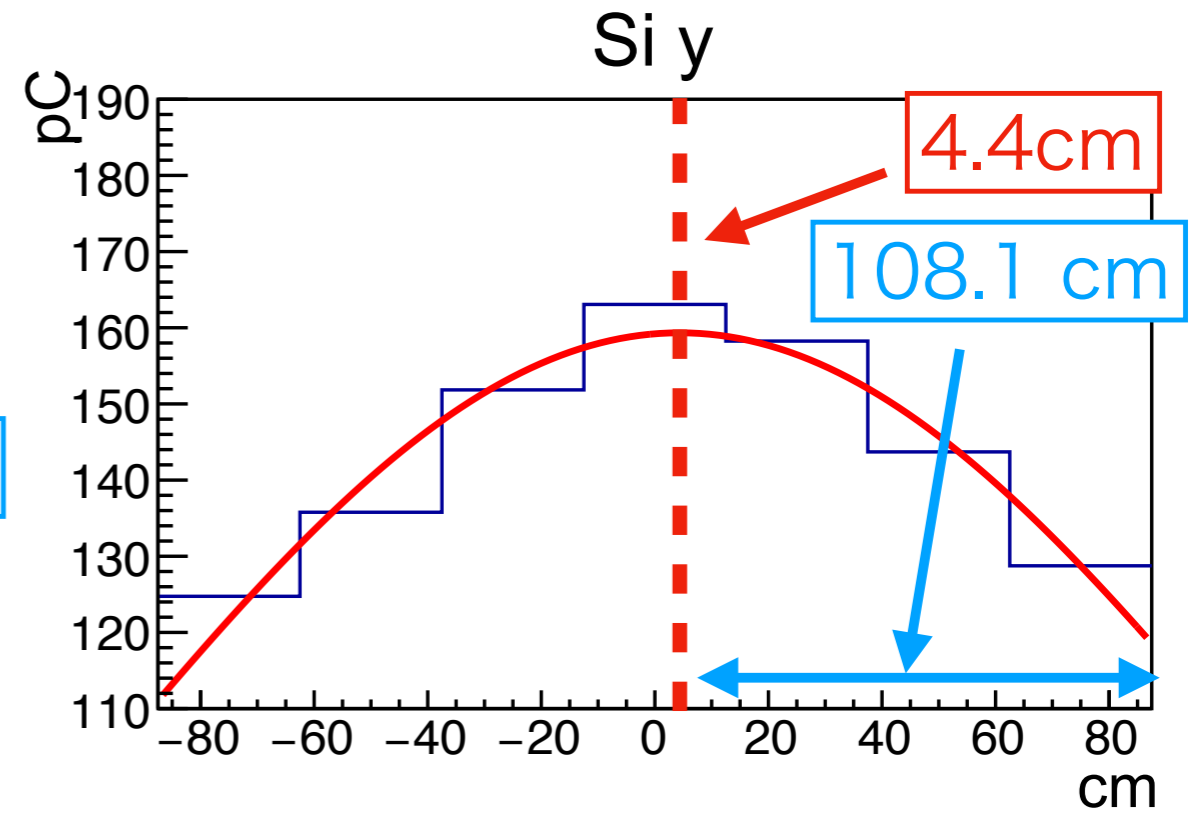
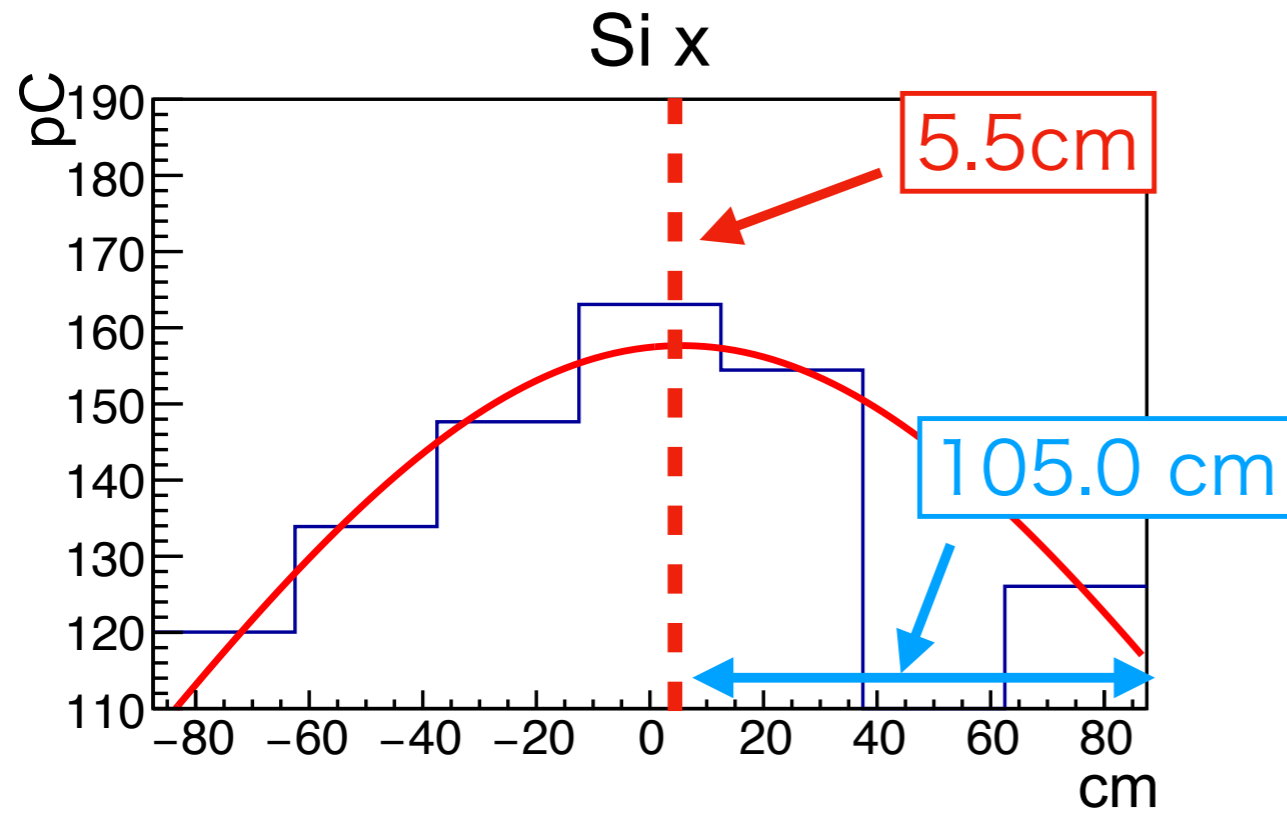


Relationship btw HV and Q



- Above 800V, charge fluctuation is same magnitude.
- S/N ratio is not the main cause.

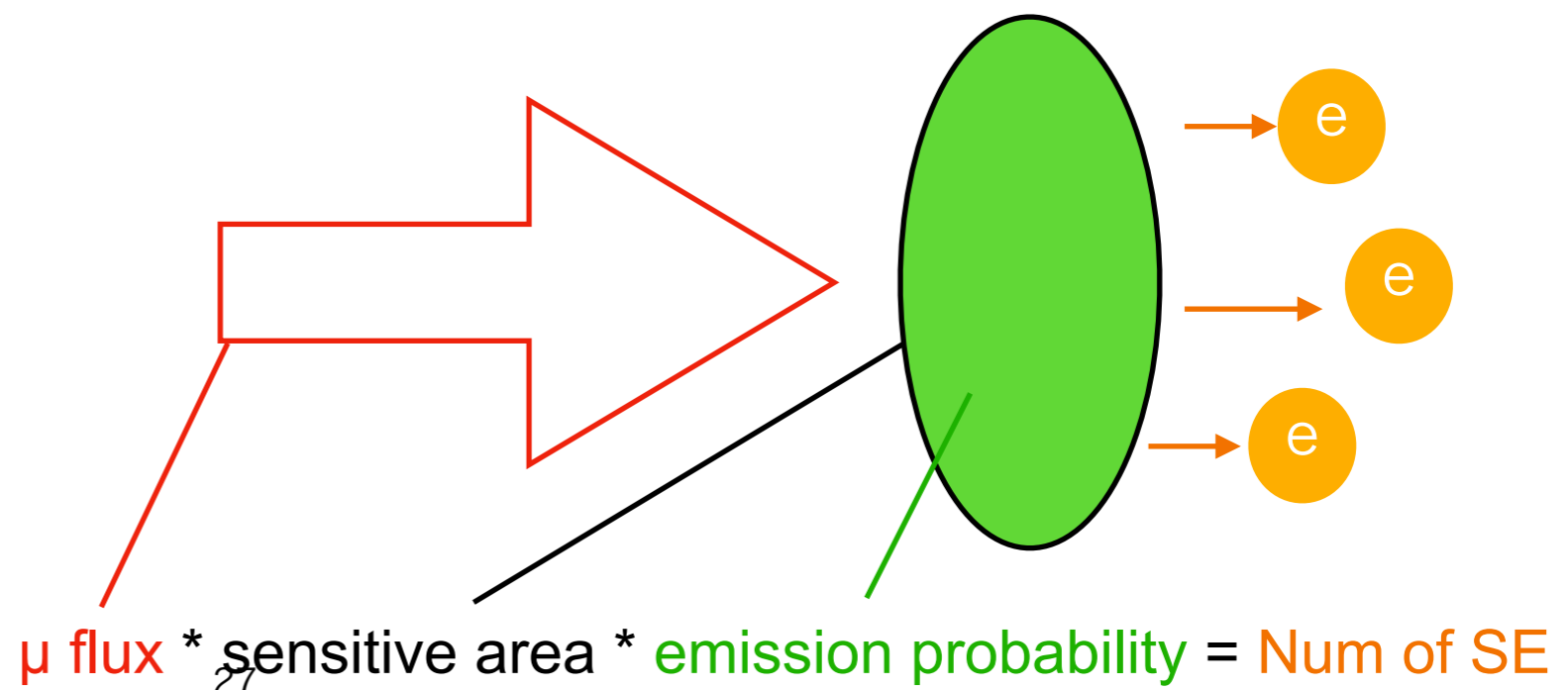
Beam Profile at Low, Si vs EMT



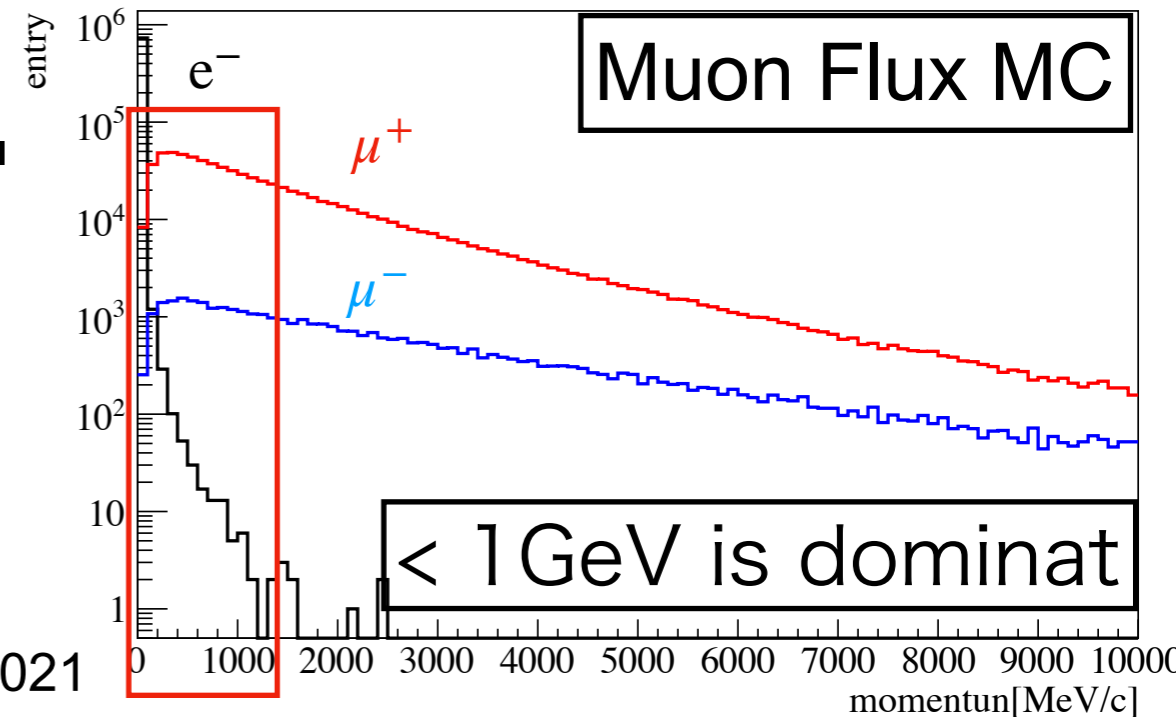
Low intensity Charge Fluctuation

- Secondary electron in per bunch is **353** electrons.
- Stat. fluctuation : $1/\sqrt{353} * 100 = \mathbf{5.3\%}$
- The Horizontal (Vertical) EMTs Charge fluctuation per bunch : **6.62 (5.74)%**
- Charge Fluctuation would be explained by Initial SE fluctuation.

μ flux	$1.1 * 10^4 / [\text{cm}^2] / 10^{11} [\text{proton on target}]$
sensitive area	0.5[cm ²]
SE emission prob.	0.065 @ 0.5GeV
Proton on target	$7.9 * 10^{11}$
Num. of SE	353



Muon/Al Se Prob.



David R Winn and Yasar Onel 2012 J. Phys.: Conf. Ser. 404 012021

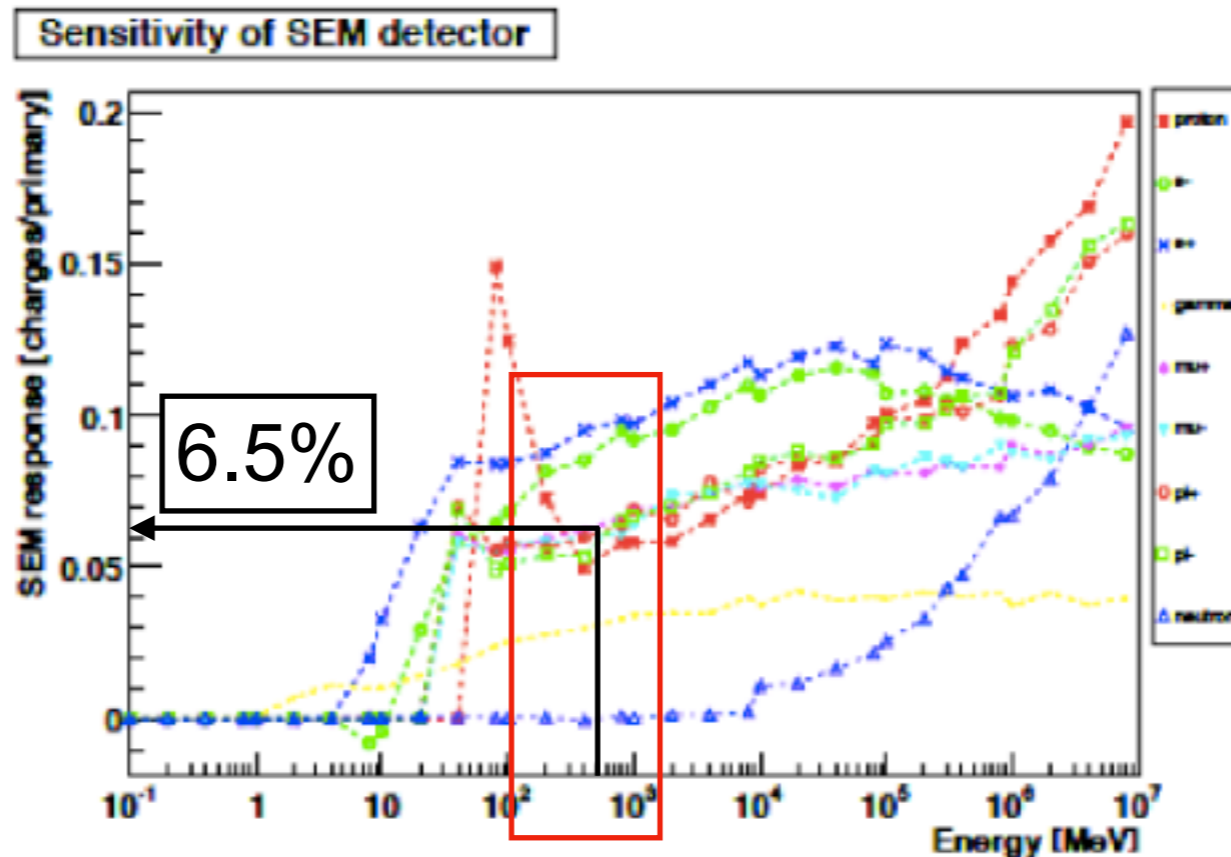
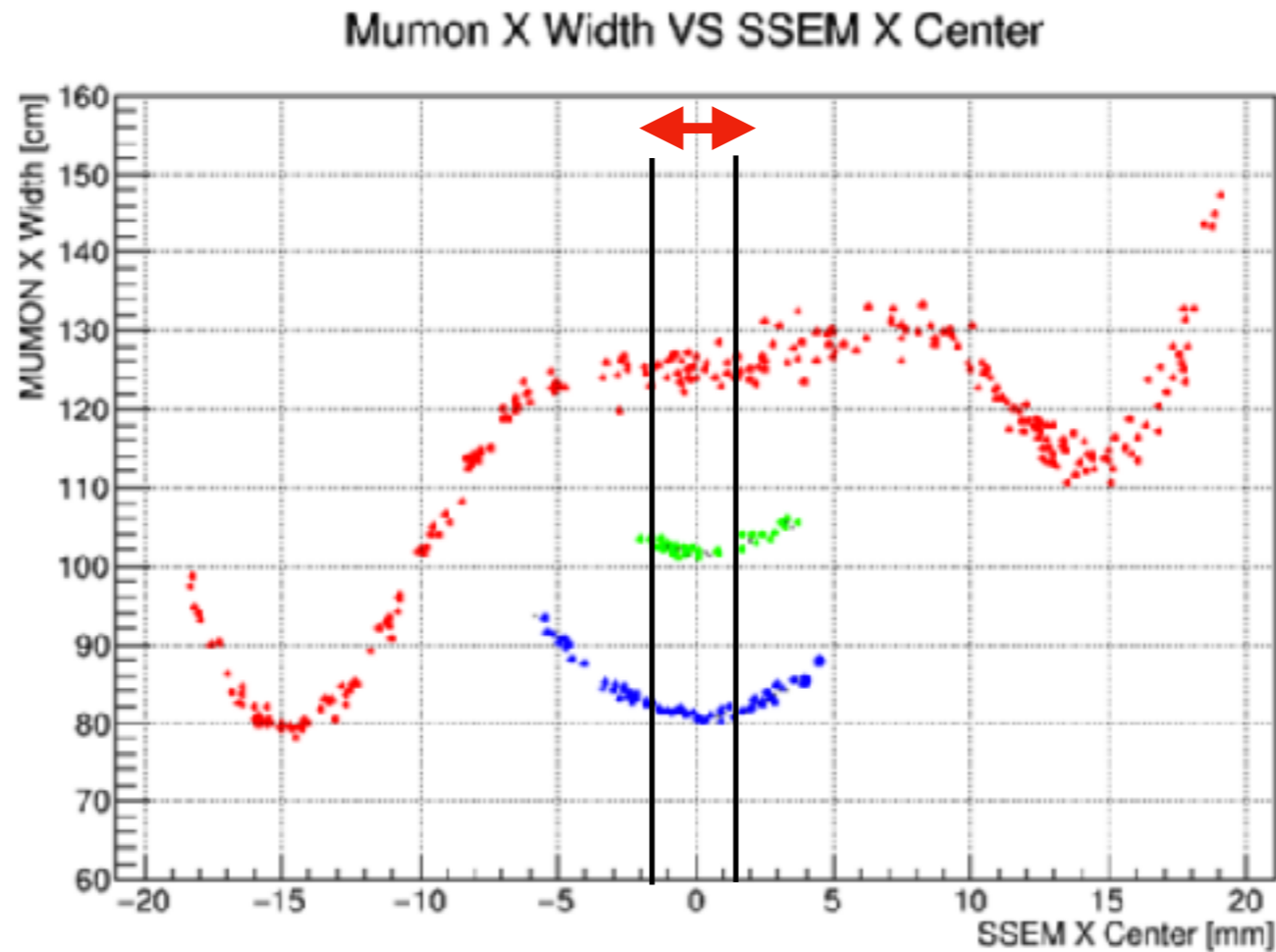


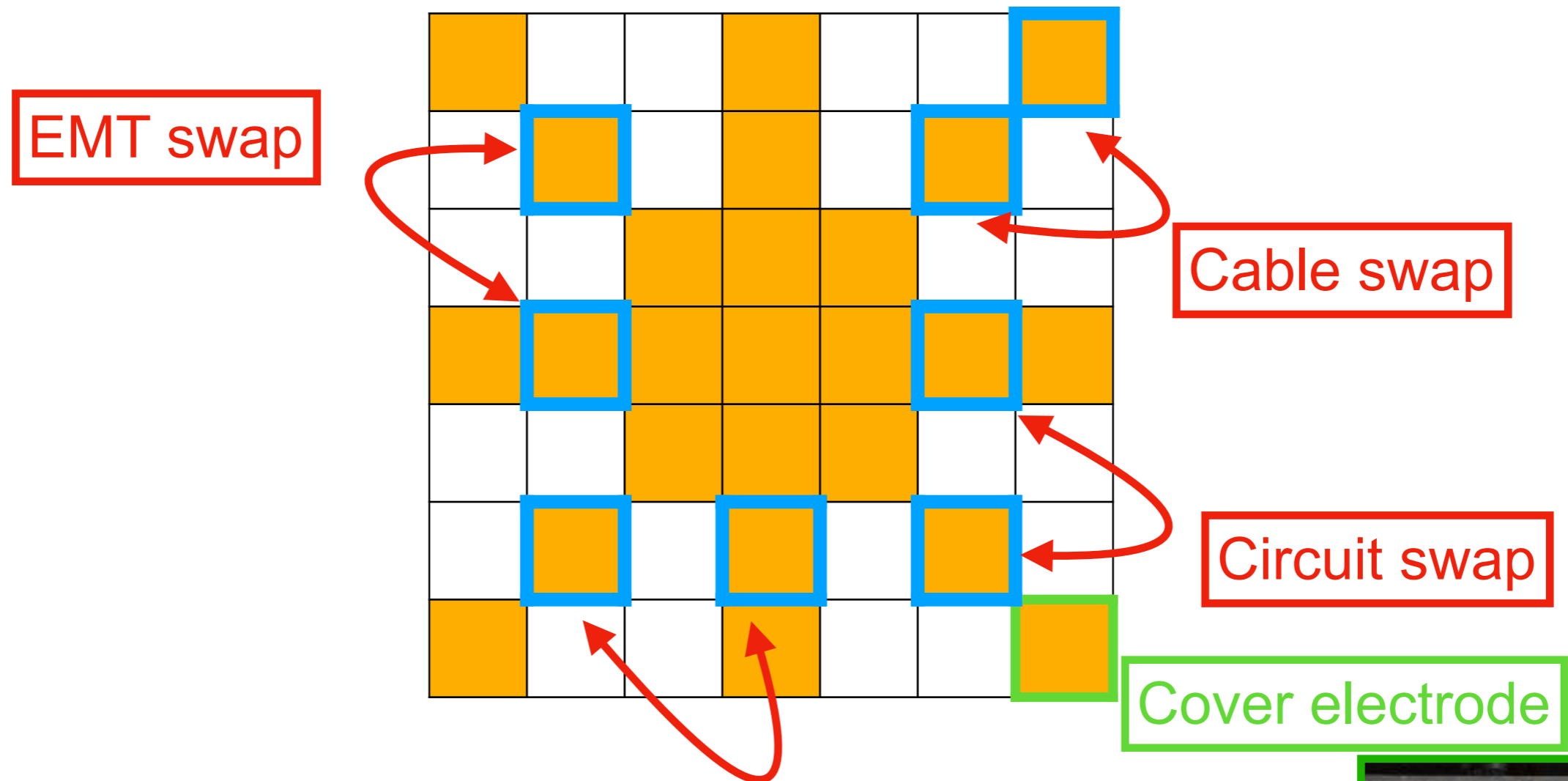
Fig. 6: The number of SE electrons per primary collected in the CERN BLMS system cell (alumina) vs primary energy- p(red square), e-, e+(green-solid, blue-x), μ^+ , μ^- (purple, magenta), π^+ , π^- (red-circle, green-open box), n(blue triangle), gamma(yellow) primaries. The high yields above ~ 10 GeV are speculated to be from delta-rays. From Ref⁷: B. Dehning et al. The energy bins $< \sim 10$ MeV have a threshold from the thick metal entrance window. (NB: negative signal at 8 MeV is absorption of e- inside the signal electrode).

Beam width sensitivity



- Proton Beam hit outside of Target —> Muon width change largely.
- ± 1.5 mm shift —> muon width ± 1 cm

Remind : EMT swap



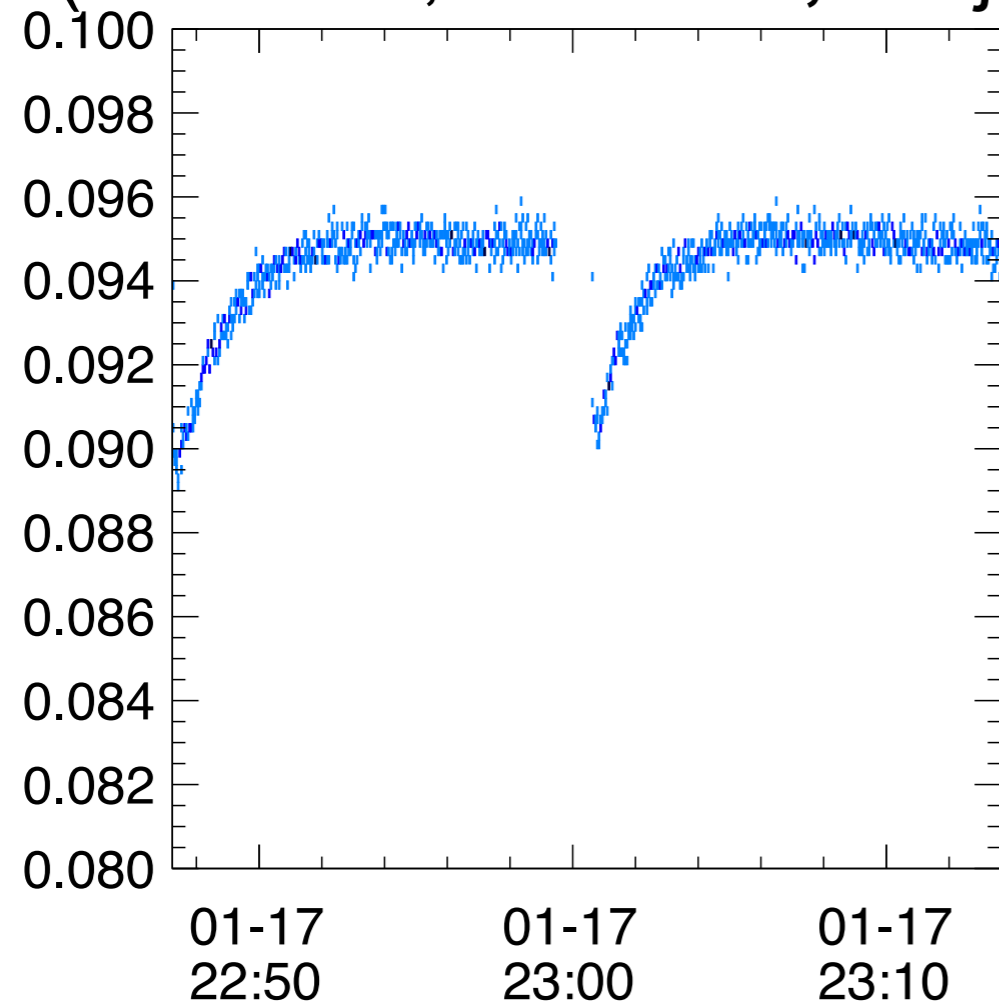
- Swapping
 - HV and Sig Cable : 7-7 \longleftrightarrow 6-6
 - EMT itself : 2-6 \longleftrightarrow 2-4
 - Bleeder circuit : 6-2 \longleftrightarrow 6-4
 - EMT + Bleeder : 2-2 \longleftrightarrow 4-2
- Data : run0930254 (physics run after MUMON calib).



EMT swap

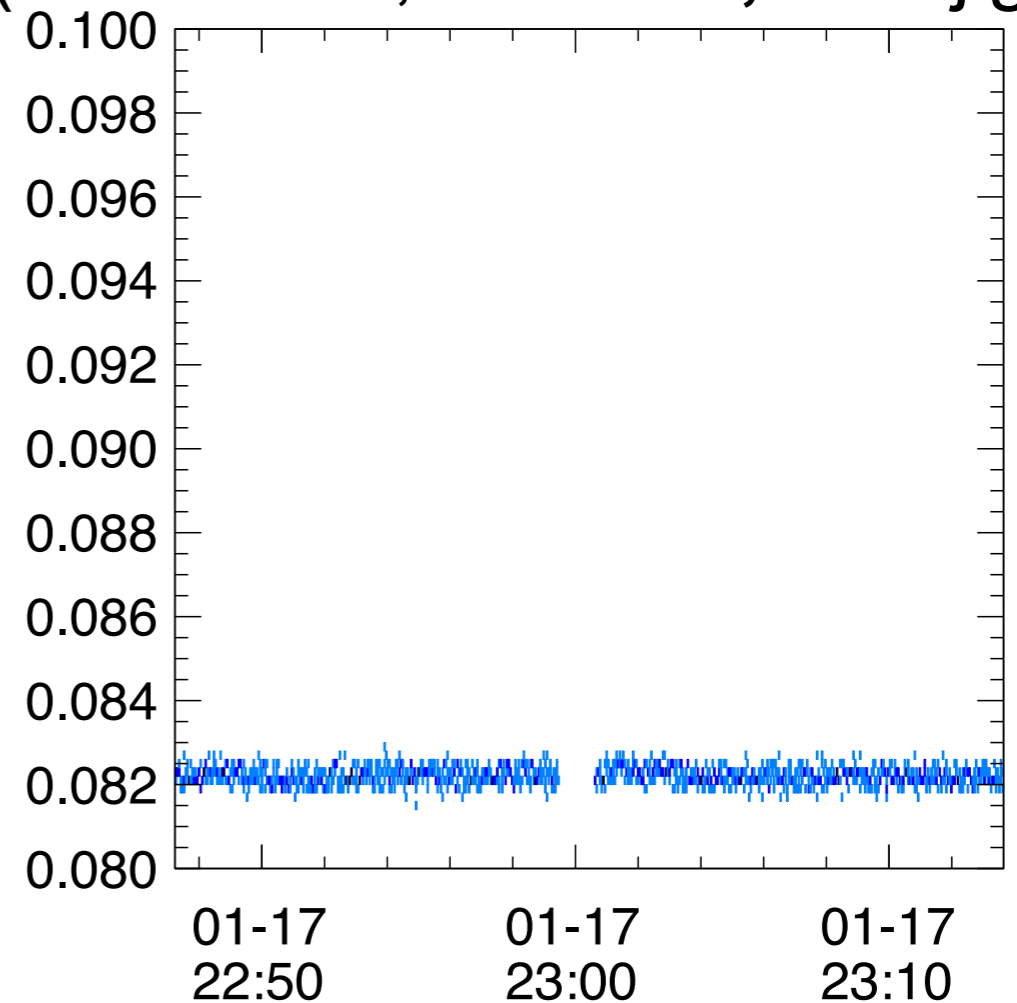
EMT 2-4

(old circuit, **new EMT**, old jig)



EMT 2-6

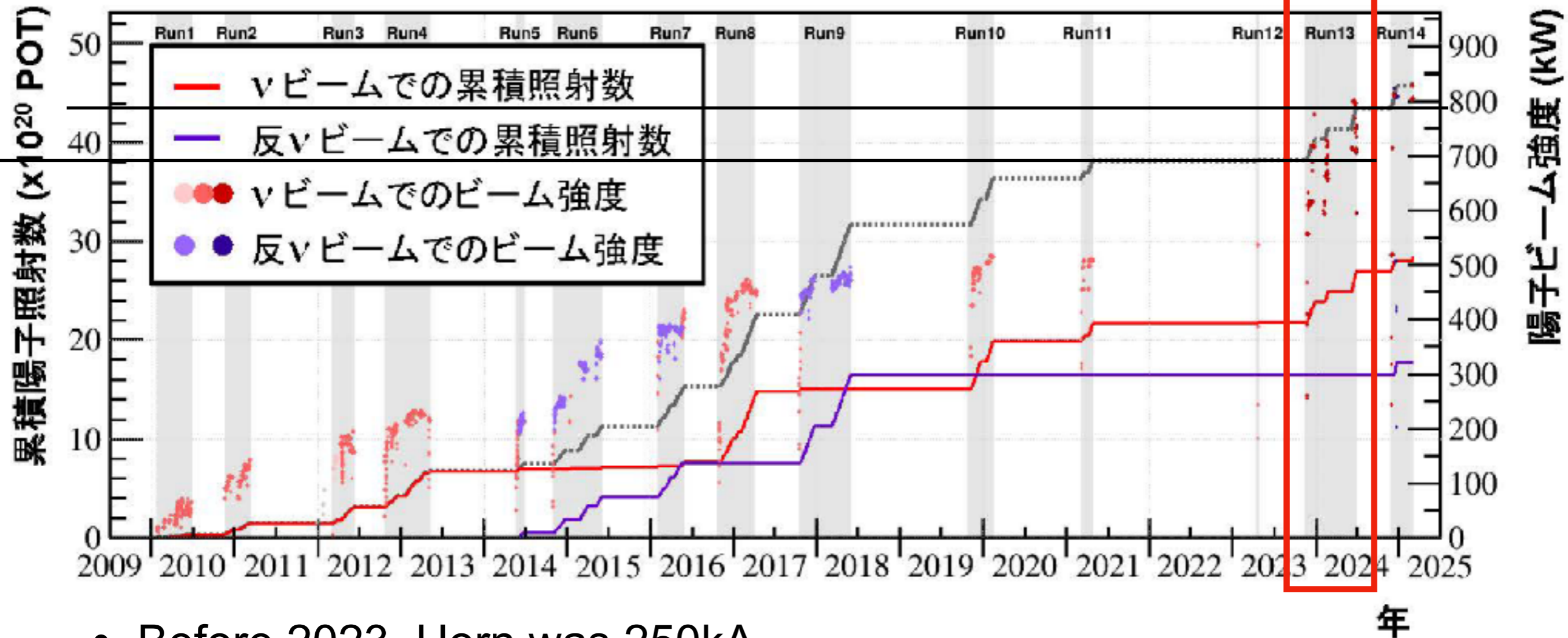
(new circuit, **old EMT**, new jig)



- New EMT has instability again.
- Old EMT does not have.
- ➔ **EMT itself is probably the cause.**
- ➔ **Jig is not.**

T2K POT

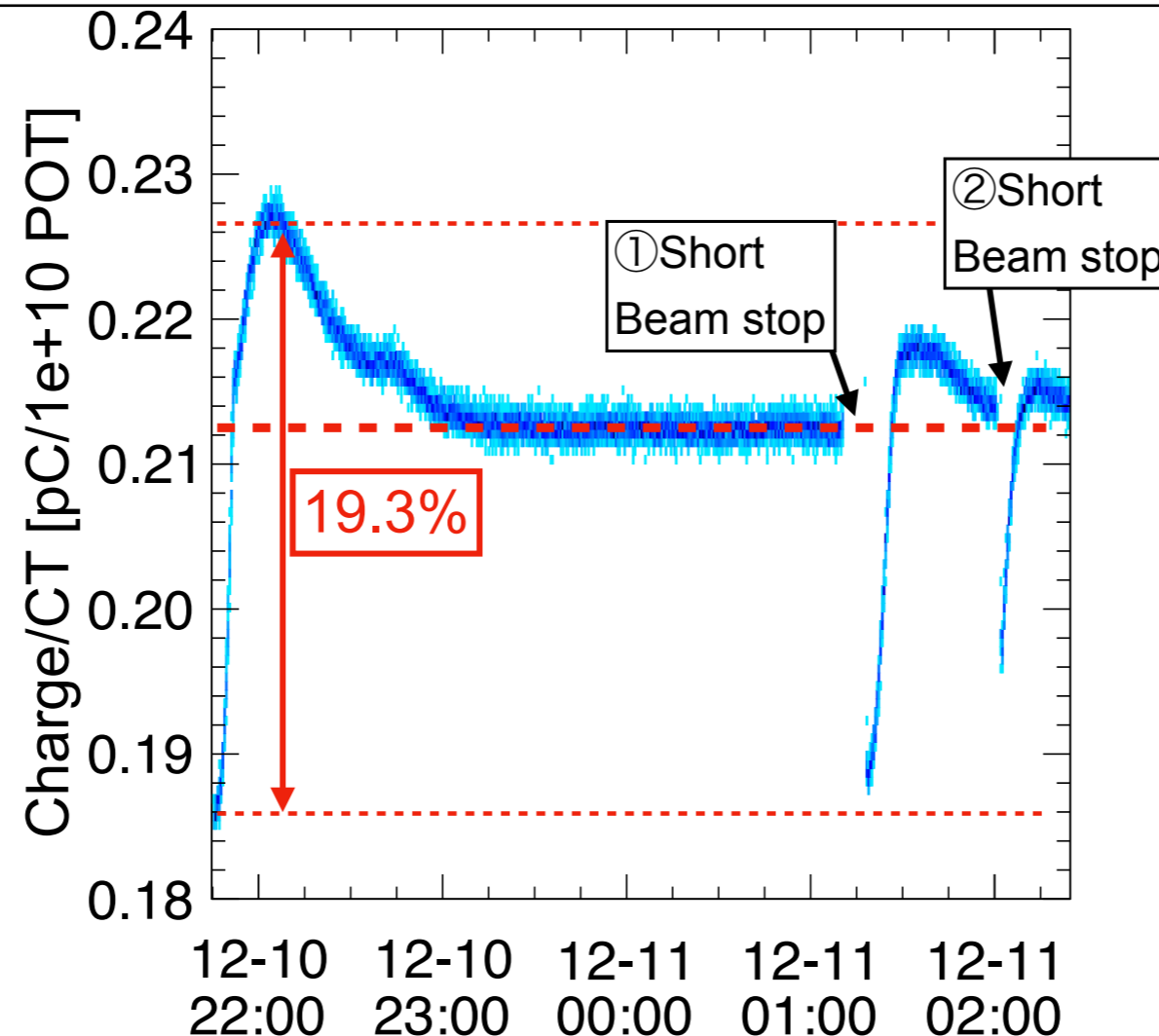
38→44*1e+20 Proton On Target
6/38 = 15.7%



- Before 2023, Horn was 250kA.
- 250 to 320 kA, neutrino flux increase about 10%.
- (44-38=)6*1e20 POT is comparable to 6.6POT, 17%.

New EMT instability

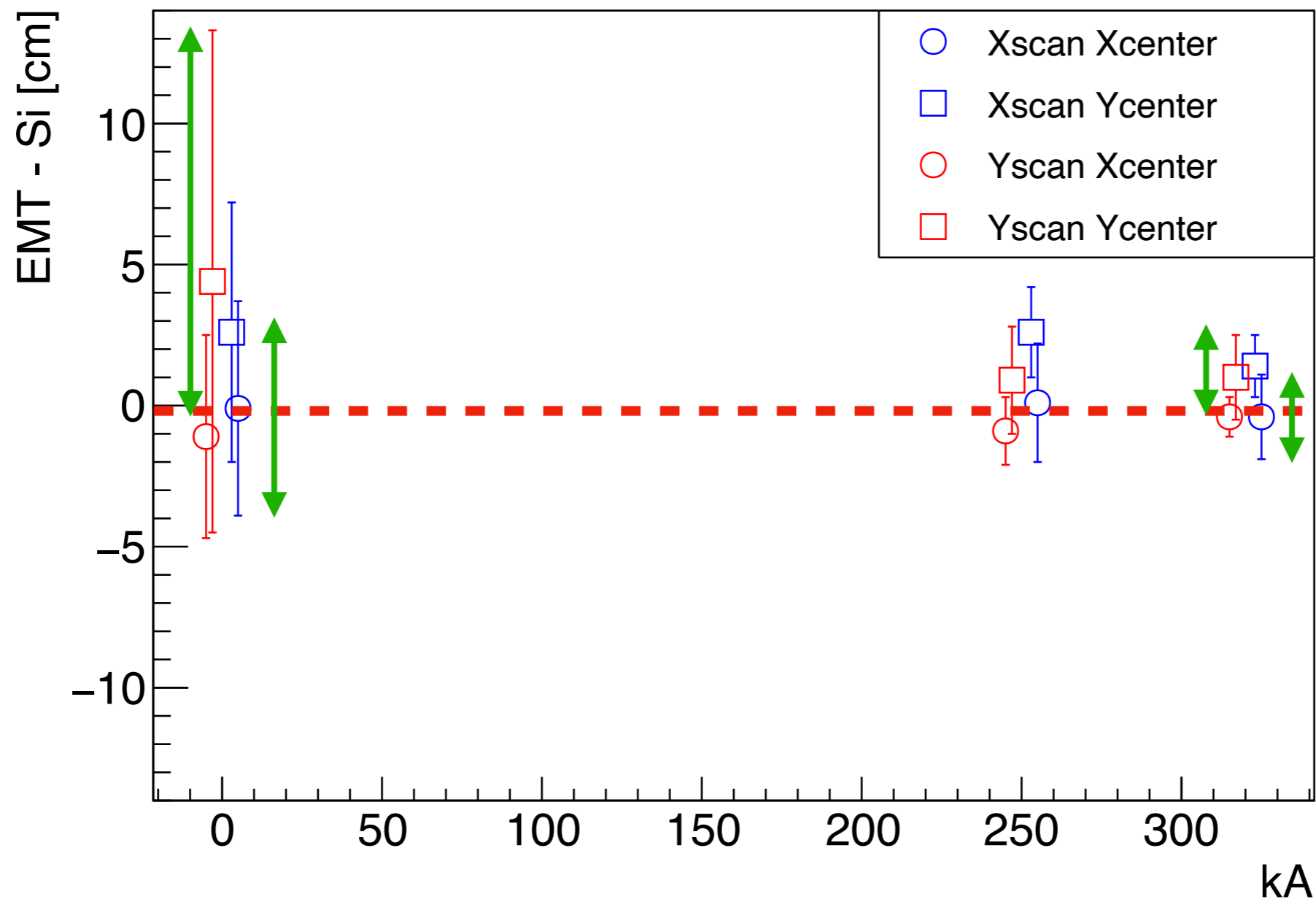
Time Variation of Charge in the EMT Introduced in 2025



- New EMTs have extremely unstable charge.
- Cable, jig, circuit, and other various swapping.
- ➔ **EMT itself may have some problems.**
- ➔ More investigation is ongoing.

Precision dependency on Horn

- Beam Scan, center data.
 - Plot (EMT) - Si, Error bar is its std.
- w/320kA, Std is less than 1.5cm (required value).
 - w/320kA : muon flux increase by ~6times.



Horn Scan

- Beam Scan, width data.
 - Plot (EMT) - Si, Error bar is its std.
- With Horn 320kA, Std is less than 3.0cm.

