



Demonstration of 2 dimensional measurement of T2K experiment beam direction using Electron Multiplier Tube

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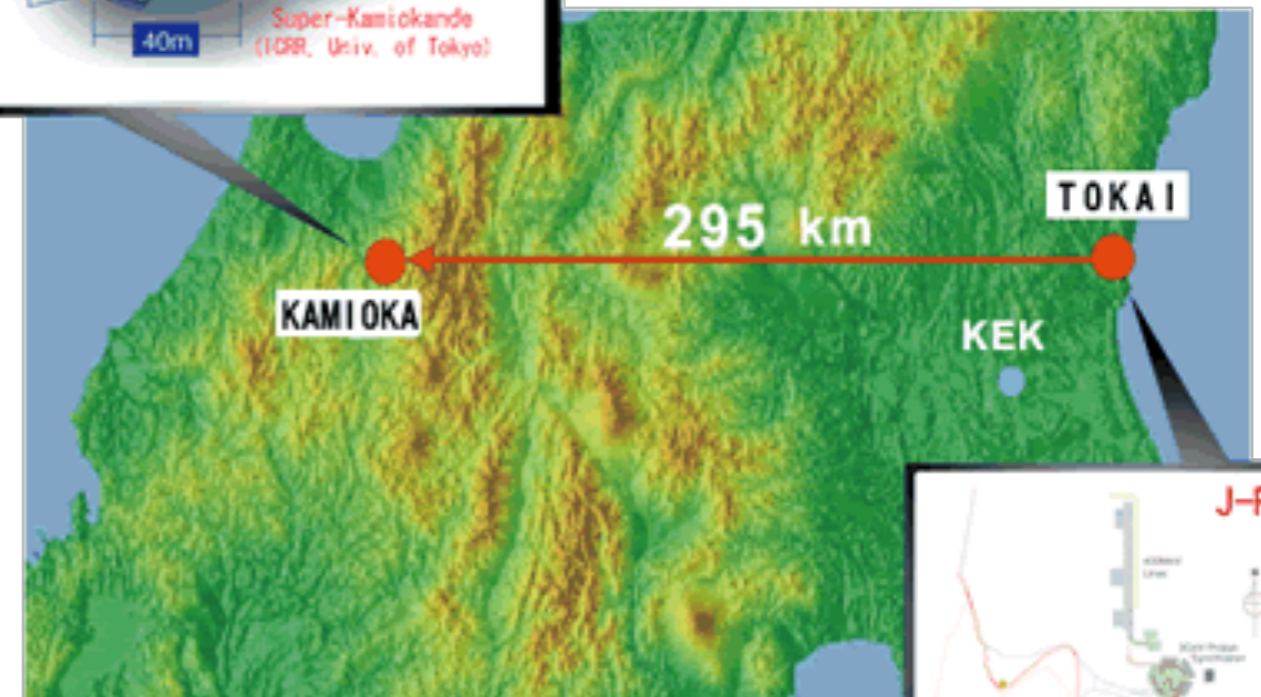
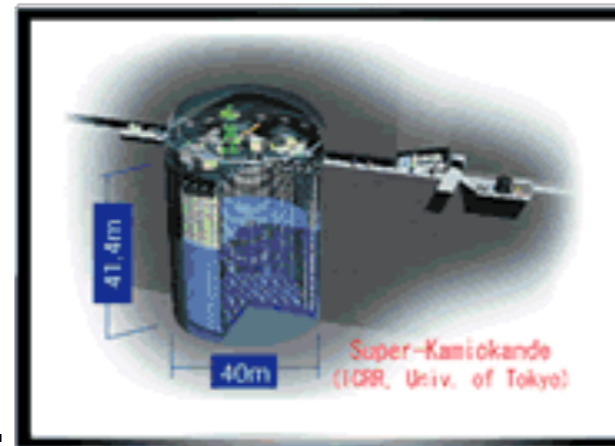
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 - New detector “ EMT ” as a Muon Monitor
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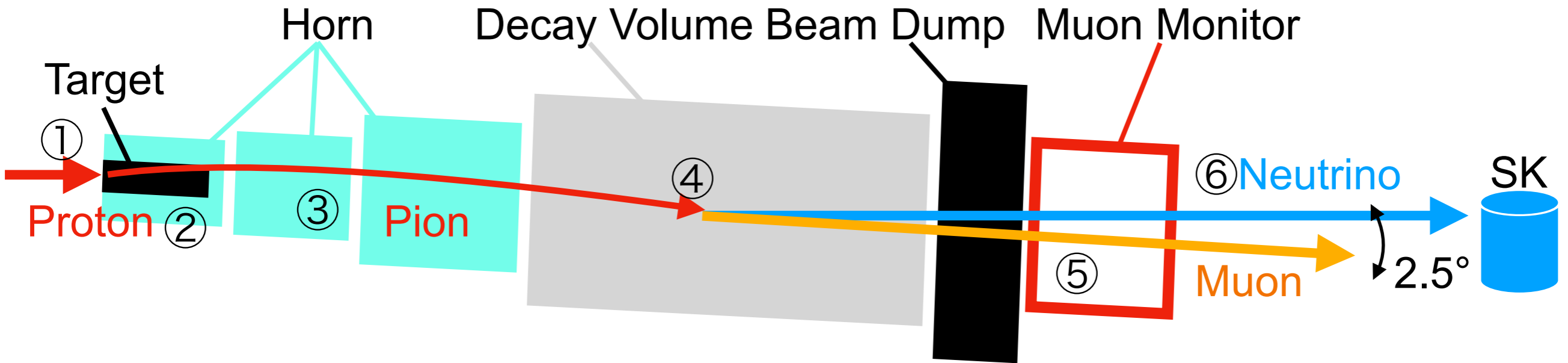
Introduction

T2K experiment schematic

- Long baseline Neutrino Oscillation experiment.
- Physics aim
 - Searching CP violation in neutrino.
 - Precise measurement of mixing parameters.
- Method
 - Observe $\nu_{\mu} \rightarrow \nu_e$ or $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ event at Super Kamiokande, huge water cherenkov detector.
- Future Plan
 - Hyper Kamiokande experiment will start in a few years.
 - About 10 times fiducial volume.
 - More beam intensity(830kW—> 1.3MW)



T2K neutrino beam line.



- ① Hit 30GeV proton on Target.
- ② Produce π^\pm .
- ③ Gather π^+/π^- by Horn current.
- ④ $\pi \rightarrow \mu + \nu$ in the Decay Volume.
- ⑤ μ higher than 5GeV reach to Muon Monitor.
- ⑥ ν goes to Super Kamiokande (SK).

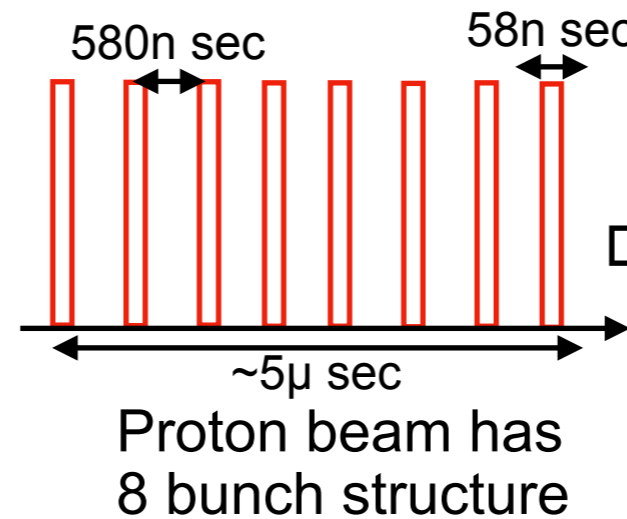
Make 2.5° offset angle with ν beam.
—> select specific $E_\nu \sim 0.6\text{GeV}$.



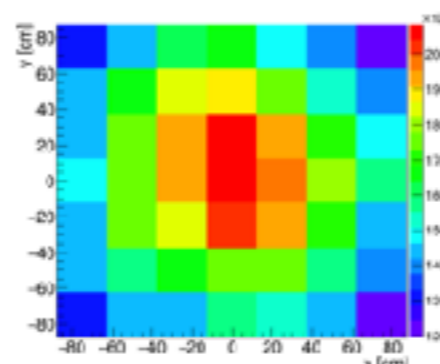
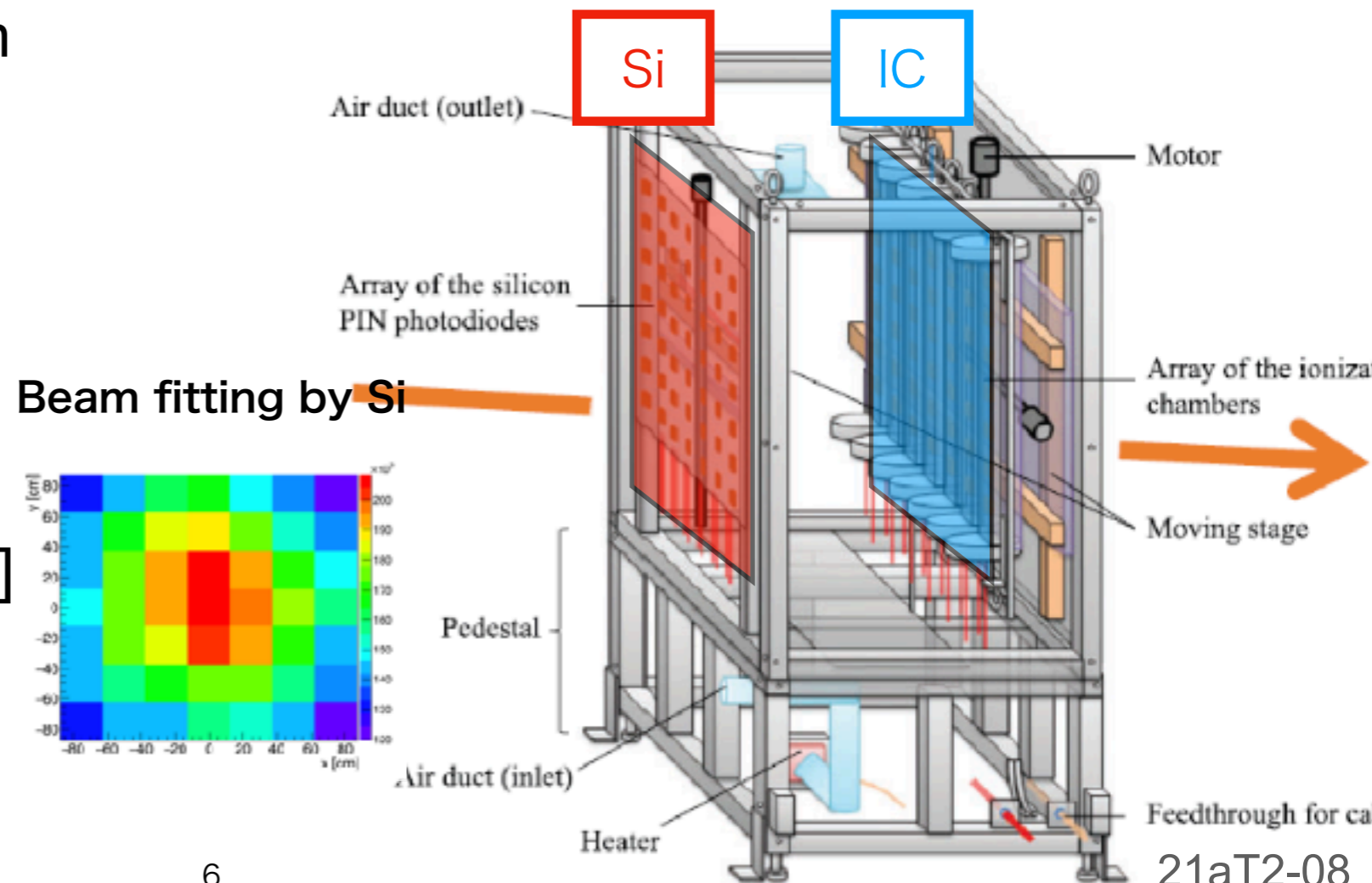
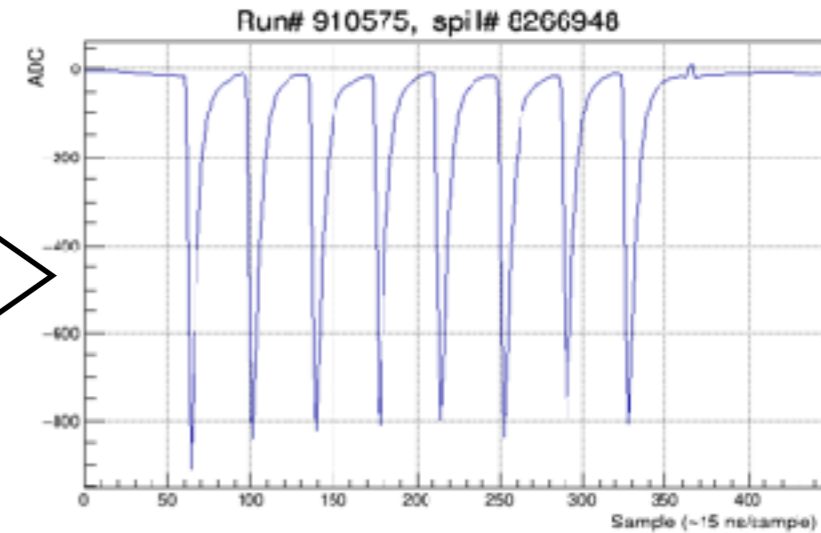
Monitoring beam angle is necessary.

Muon Monitor (MUMON)

- Monitoring μ beam bunch by bunch.
- 2 detectors.
 - Si and Ion Chamber.
- Configuration
 - At about 100m downstream from target station.
 - $7 * 7 = 49$ detectors.
 - 25 cm spacing in each detectors.
 - > 150cm * 150cm
- Required precision : 0.3m[rad]
- —> about 3cm.
- Estimated sys. Error : ~ 0.28 m[rad].



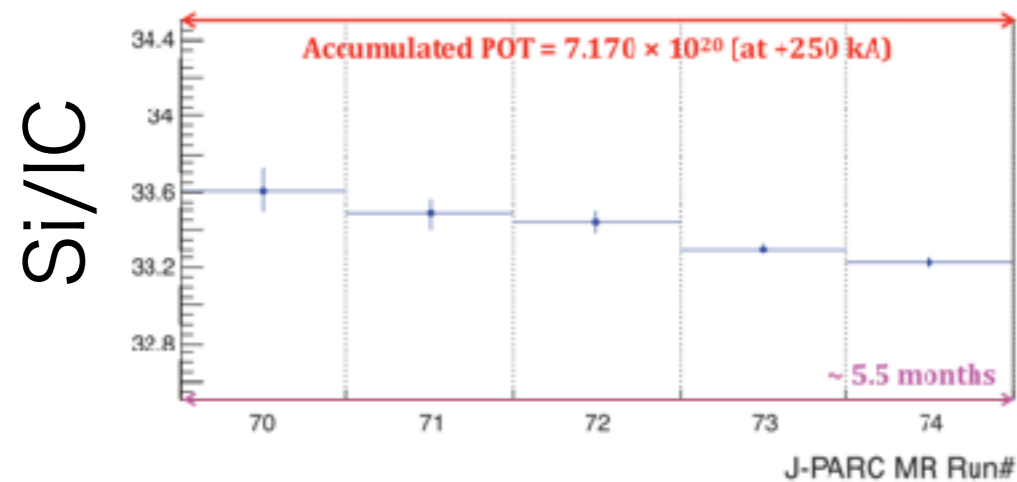
MUMON Waveform



Current situation

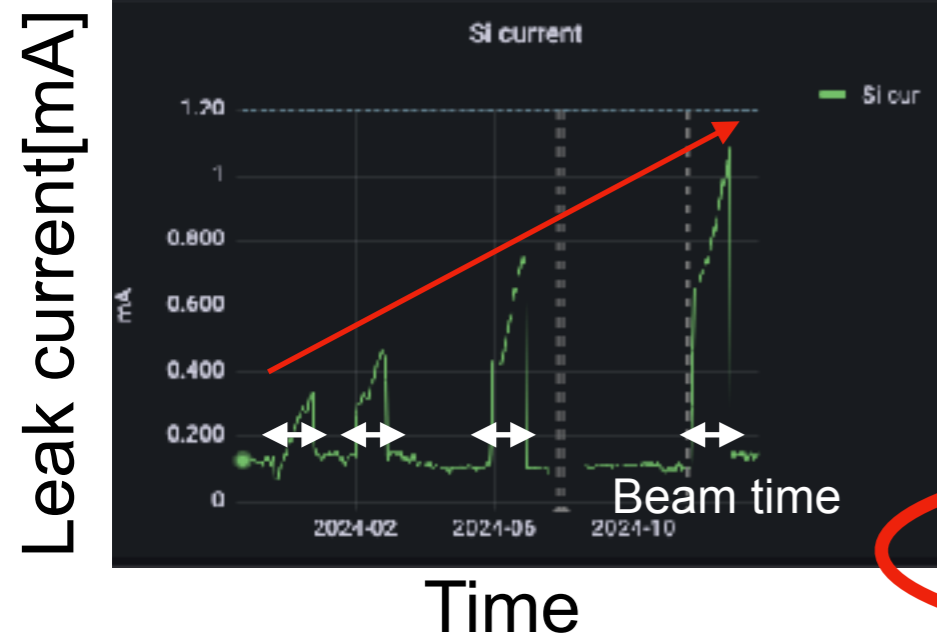
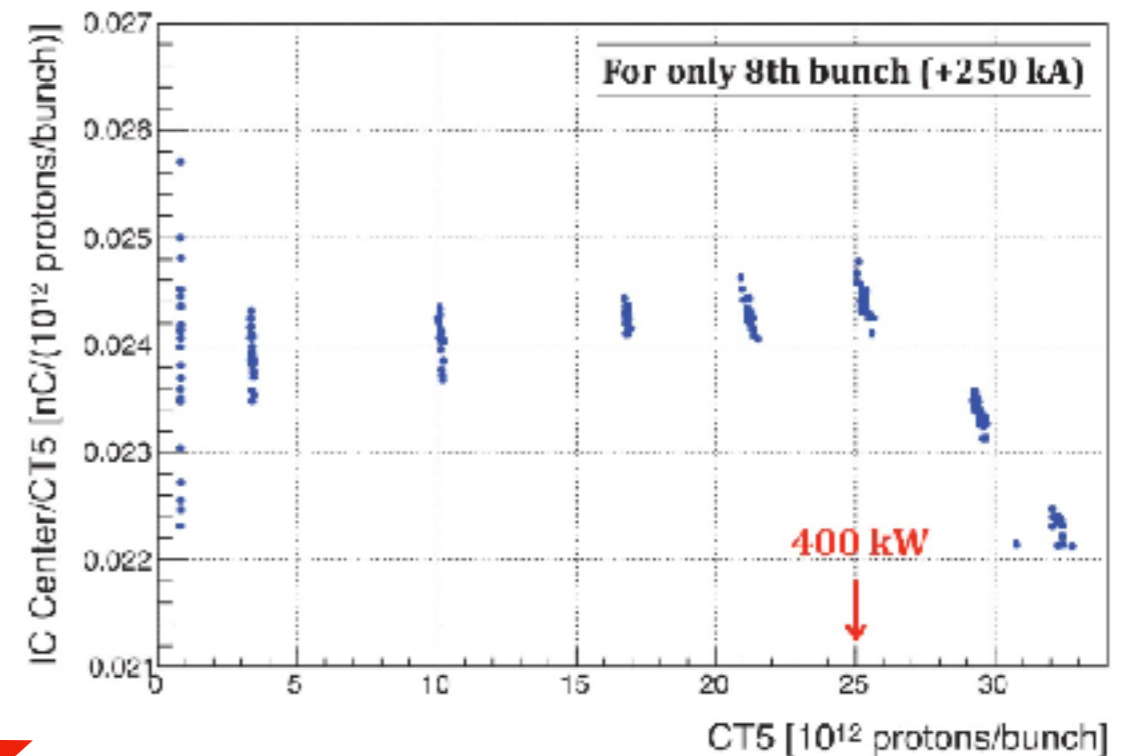
Si Problem

- Si is weak to radiation.
 - Yield become smaller .
 - Leak current increases due to radiation damage.
- But intensity increase is planed.
- In the 1.3MW intensity era, monthly change of Si may be needed.



IC Problem

- Space charge effect.
- IC yield becomes small in higher intensity.



New Detector is Needed !

Electron Multiplier Tube (EMT)

- Similar to PMT
 - Al is vapor deposited on window.
 - ① Charged particle go through EMT.
 - ② Electron is emitted from Al or dynodes.
 - ③ Occur Electron avalanche.
 - ④ Get Signal.
- Less radiation damage
- 7 EMTs were installed in 2023/01 Horizontally.

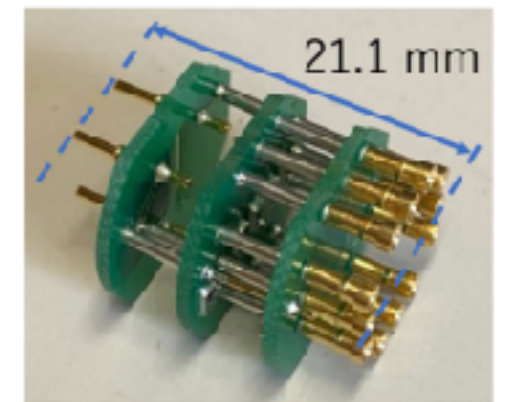
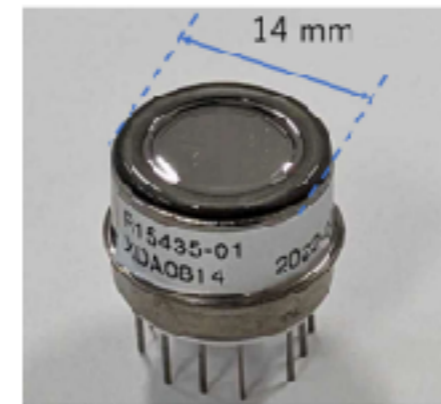
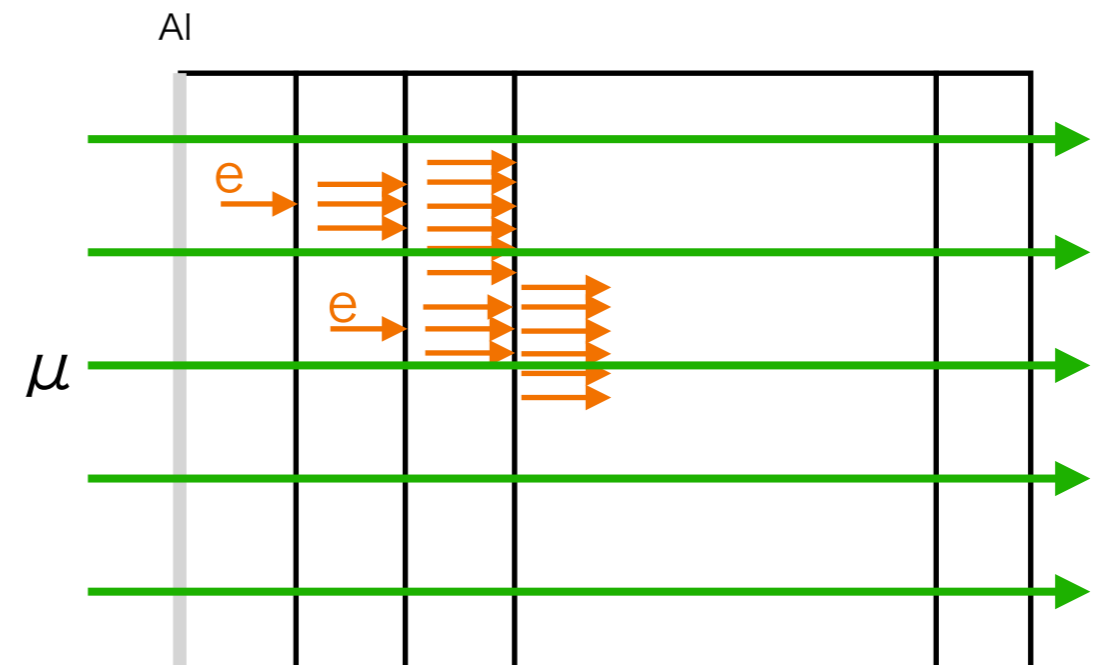
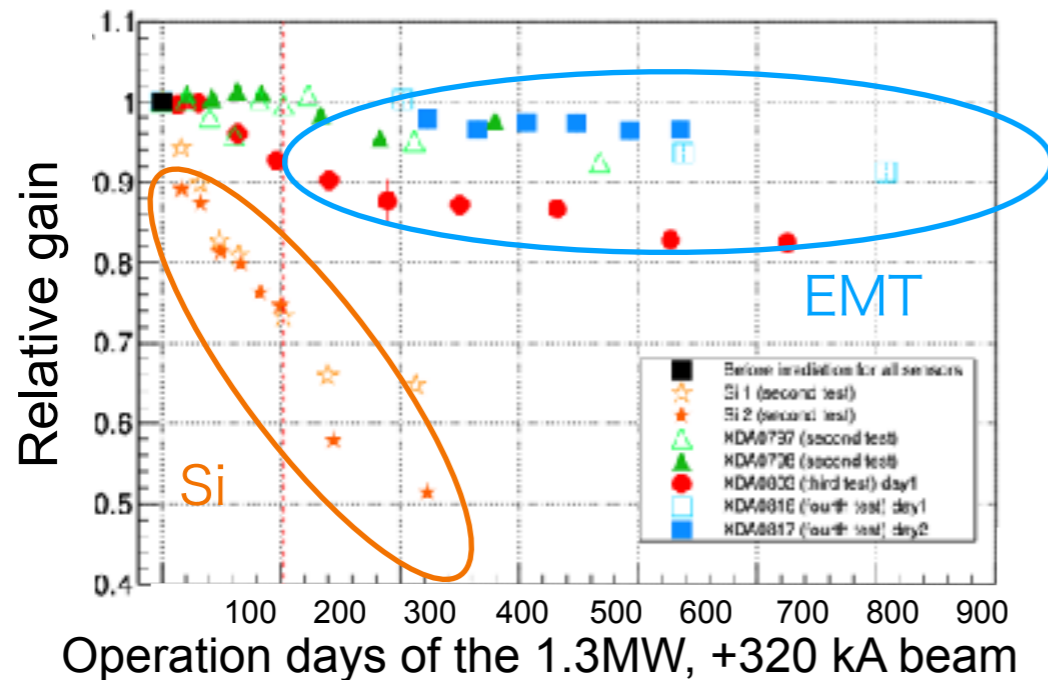
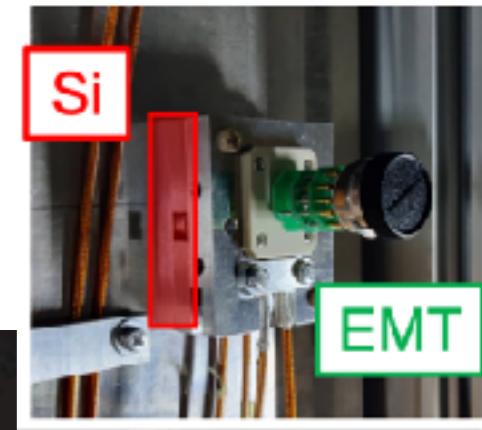


Fig. 1 Photograph of an EMT (left) and a bleeder circuit (right).

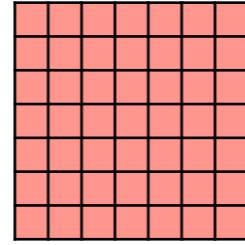


New EMT installation

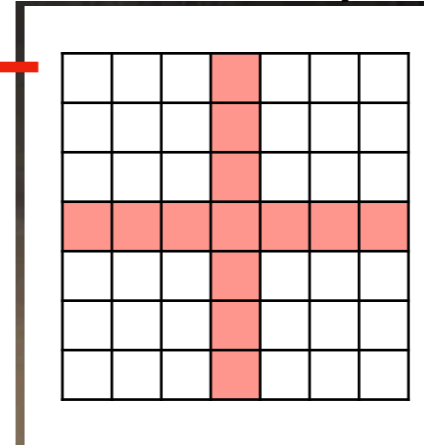
EMT installation in 2024/11



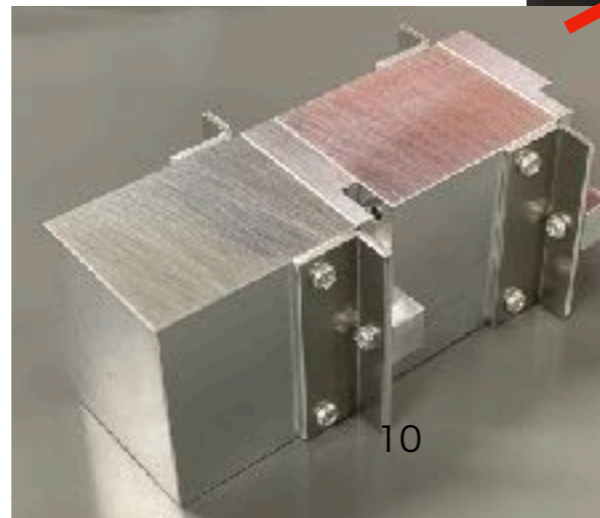
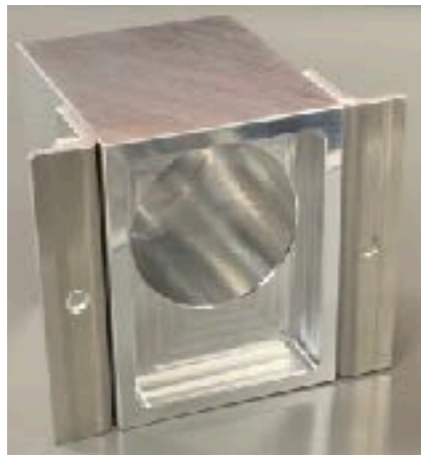
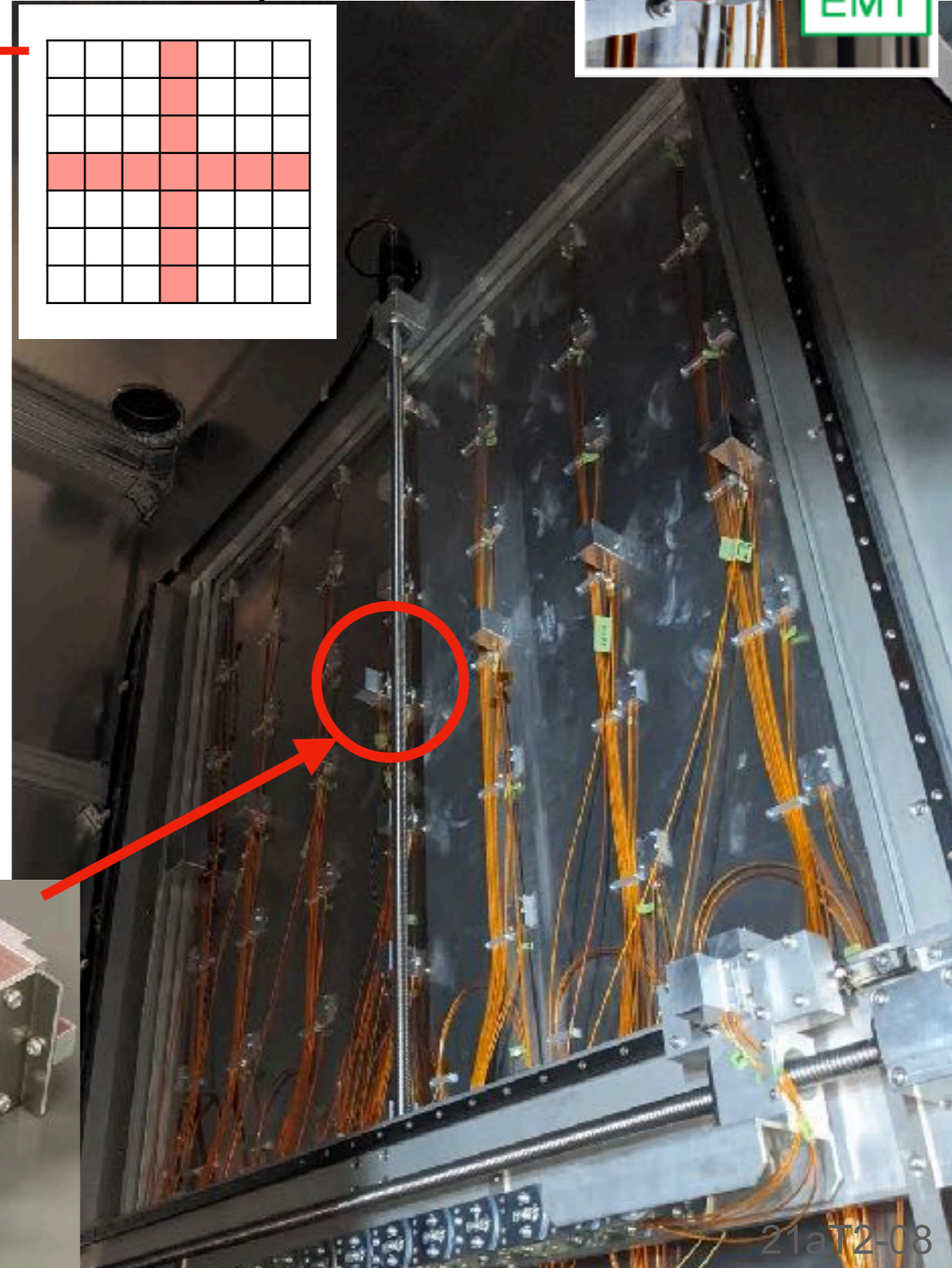
HK era, 49ch



Plus Shape



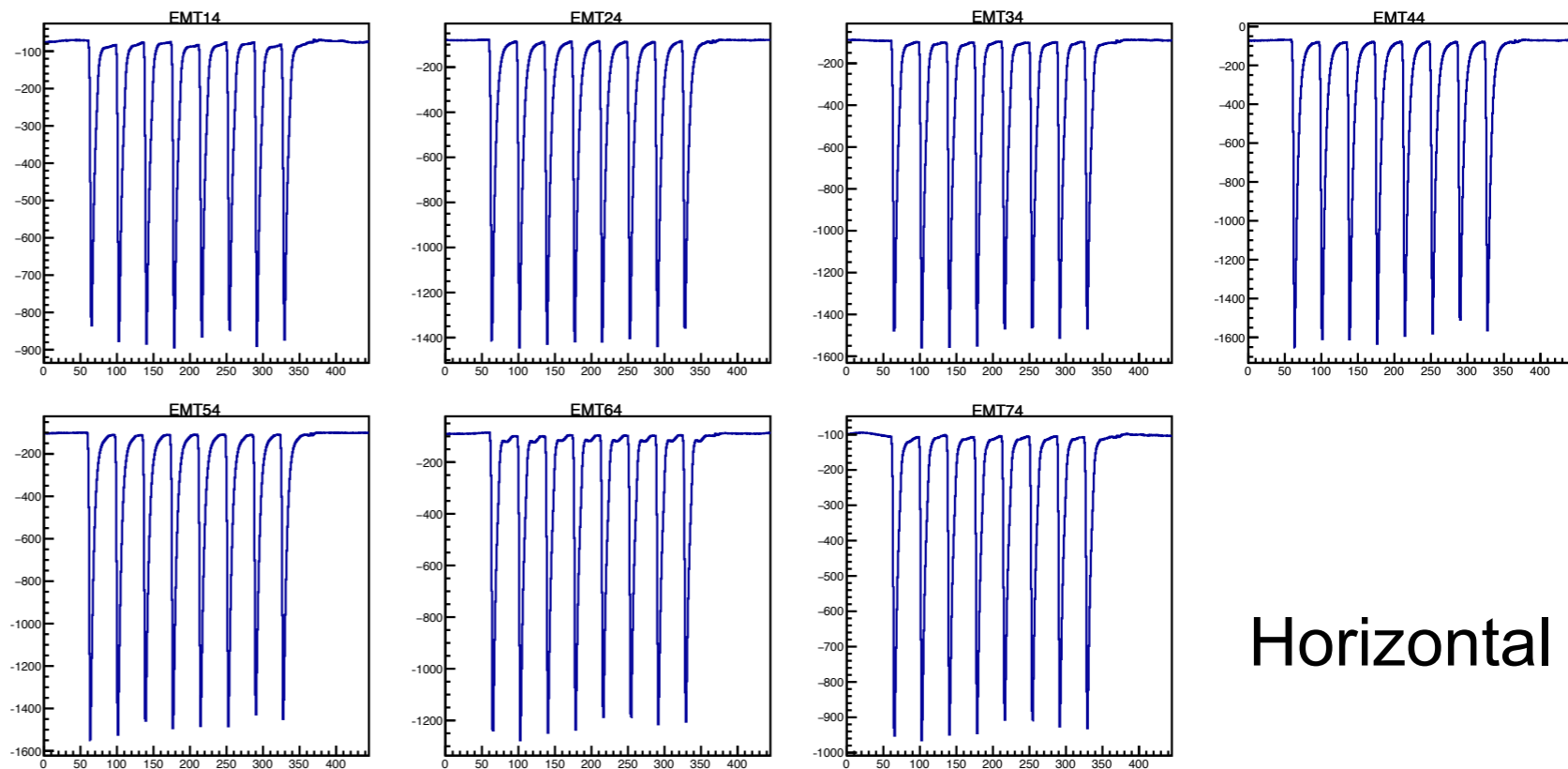
- Gradually install EMT.
 - (limitation of channel)
- Installed in plus shape.
 - Horizontals : installed in previous.
 - Verticals : Newly installed.
- Specific Things.
 - New thick jig (only New EMT)
 - To make noise smaller (previous one was just plate.)
 - Overlap EMT
 - Add EMT behind center EMT.



High intensity Operation result

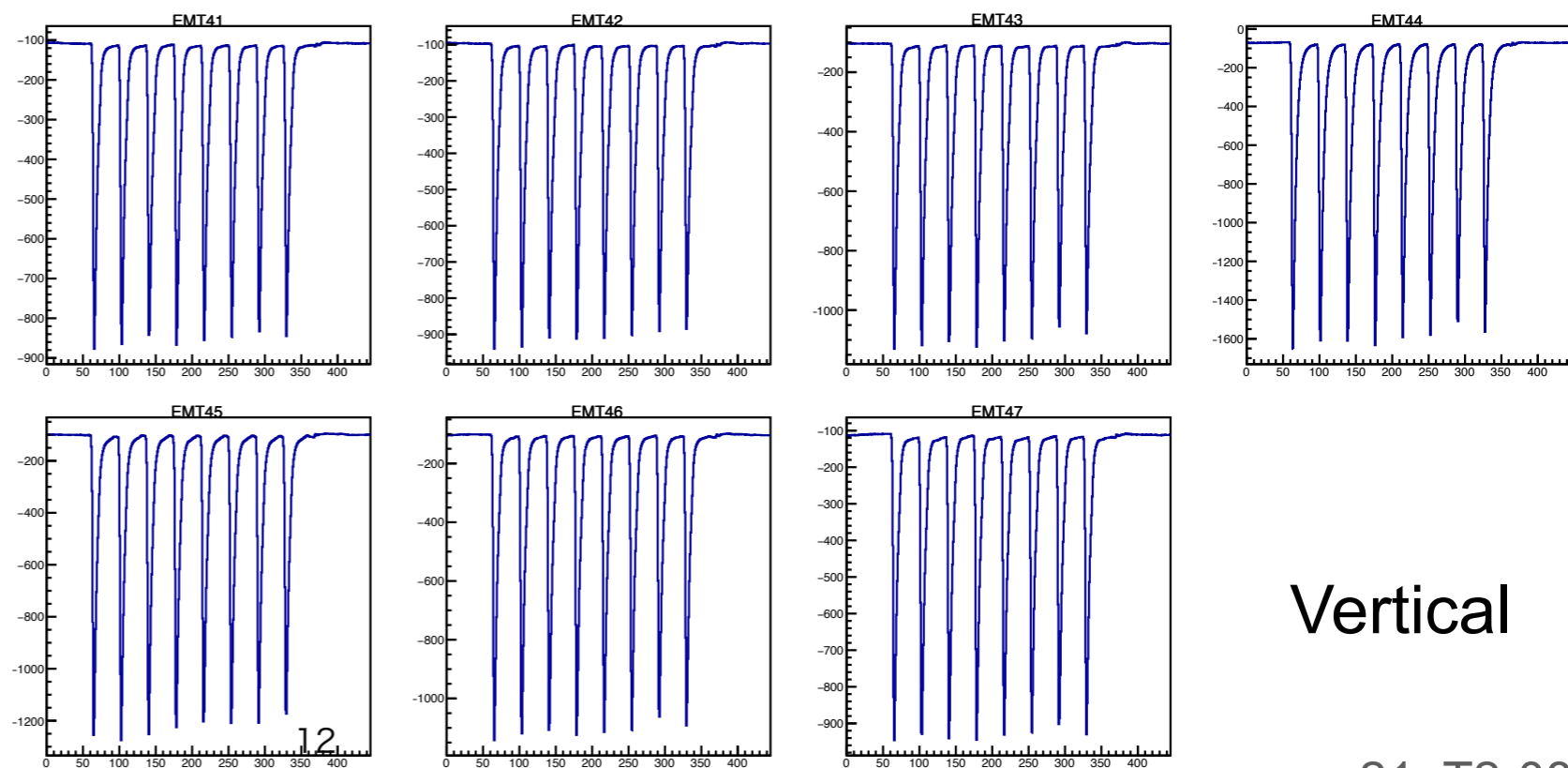
- High intensity beam
- Typically, several dozens ~ hundreds kW
- Mainly For : Physics Run.

Waveform



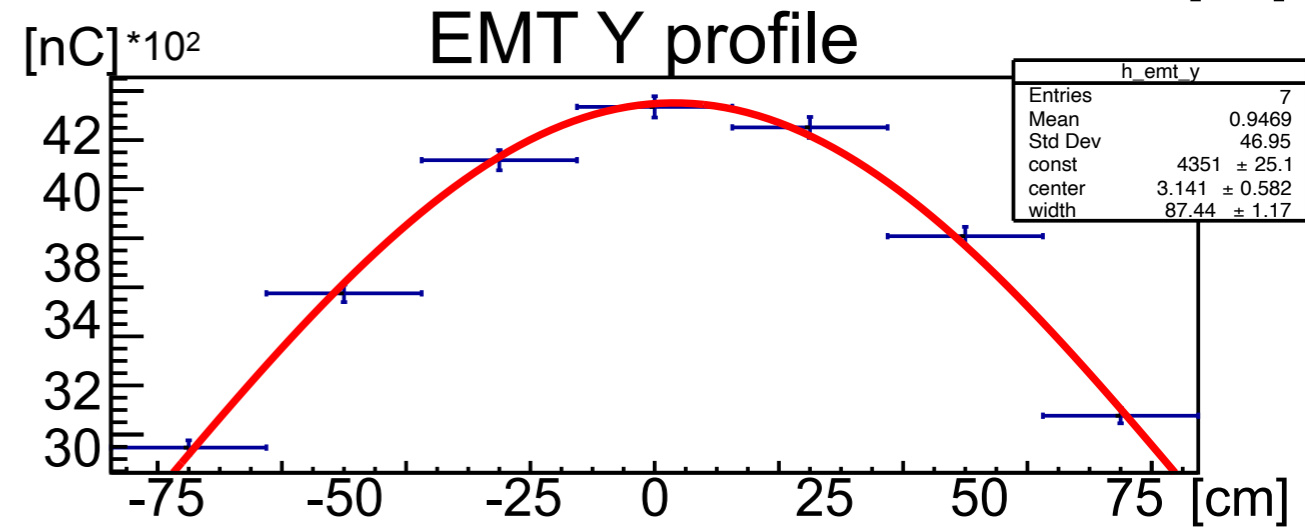
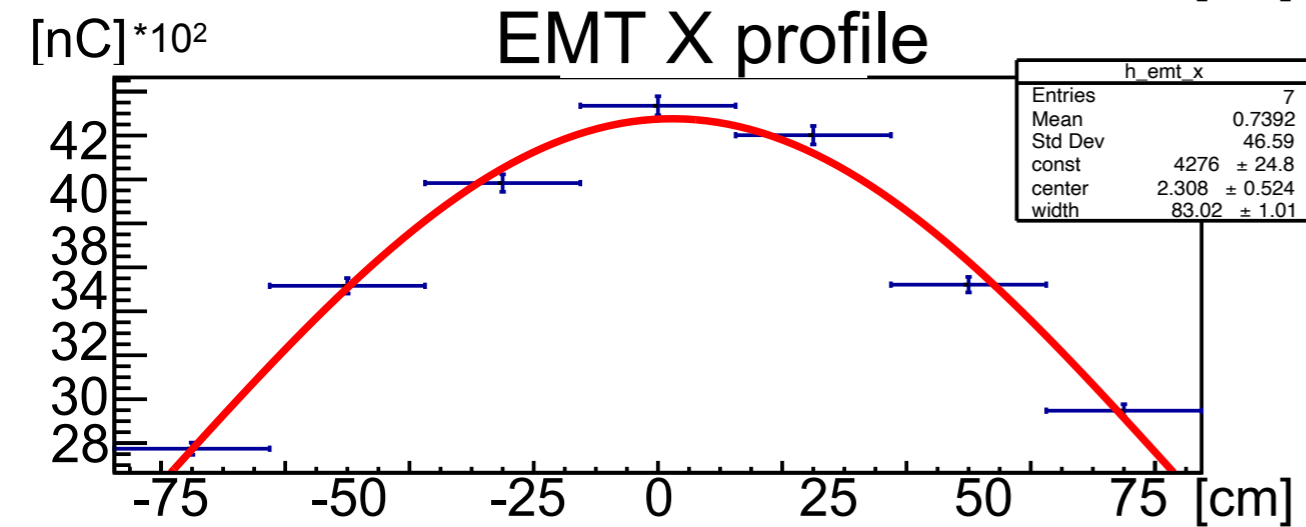
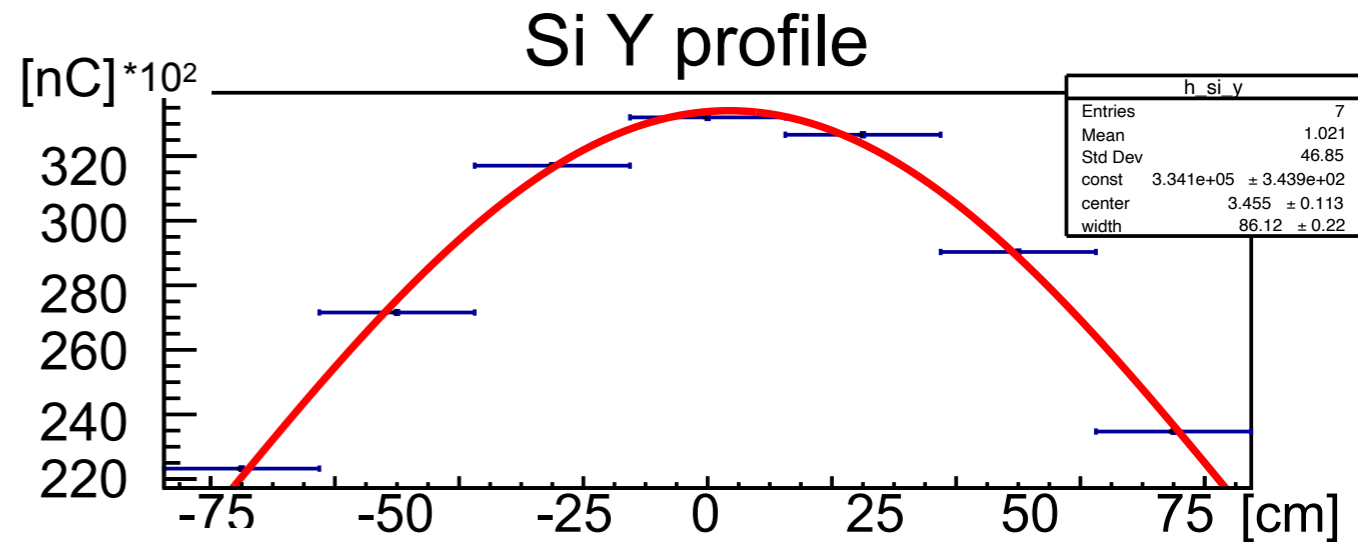
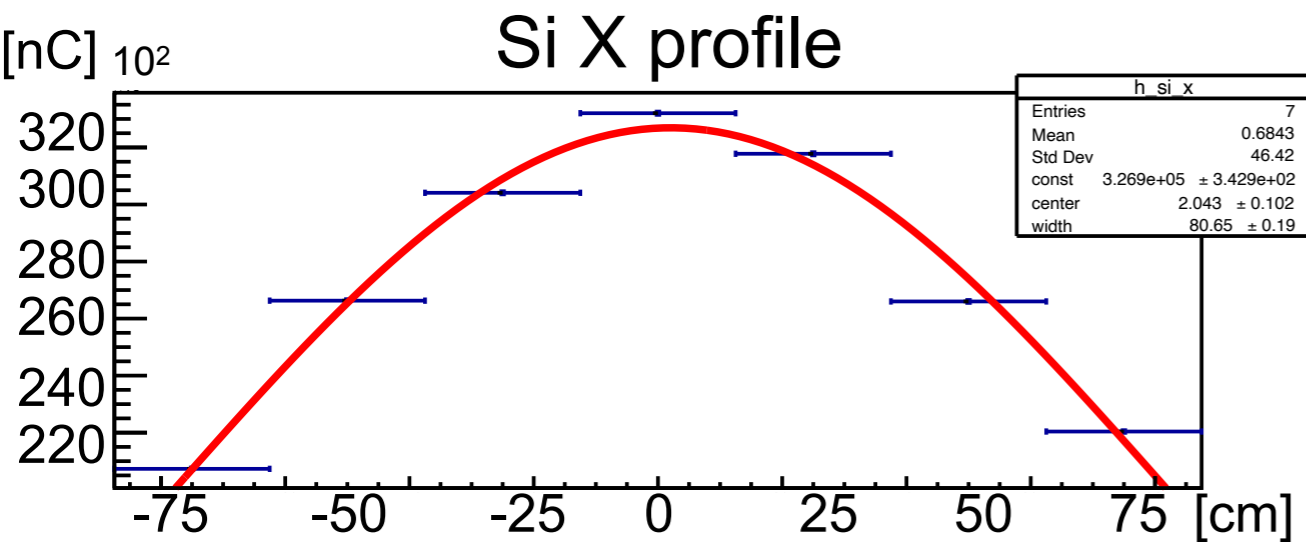
Horizontal

- Succeed to see clear 8 bunch structure.



Vertical

X & Y profile (1 typical shot)



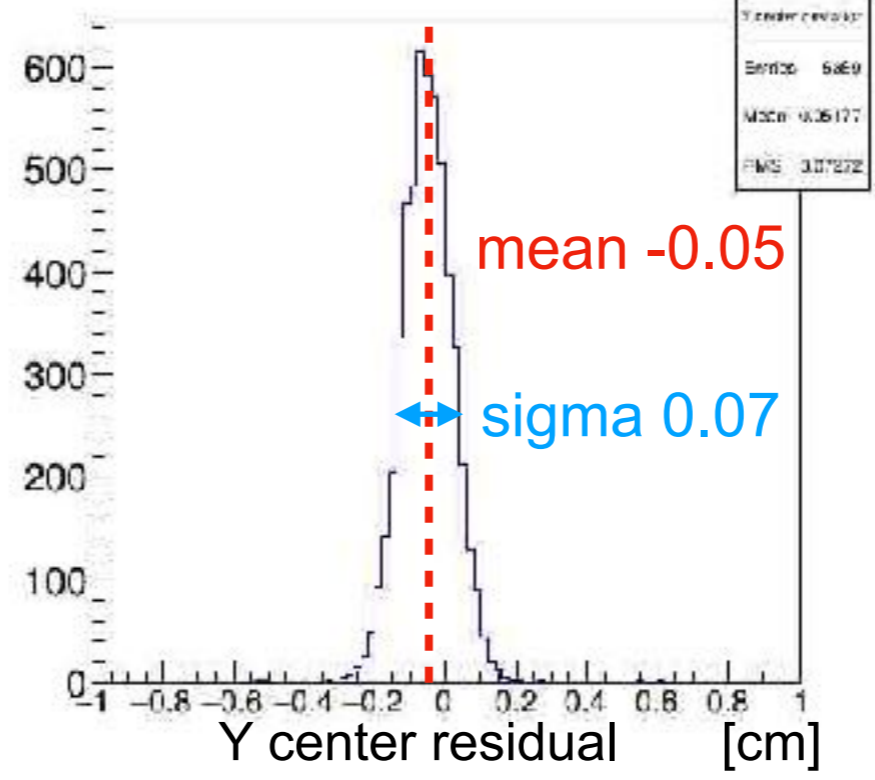
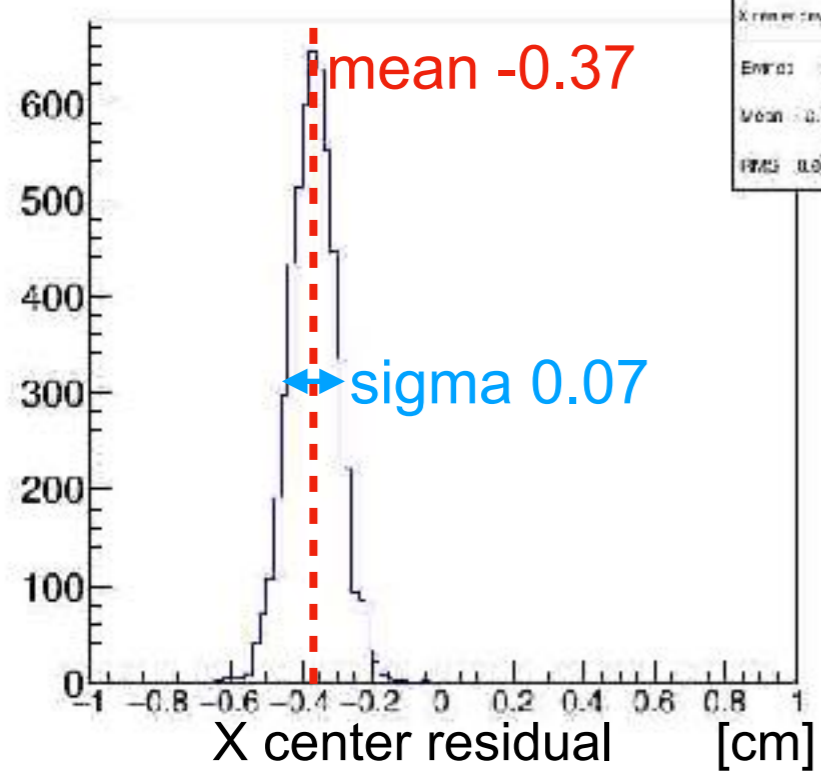
	X center[cm]	X width[cm]	Y center[cm]	Y width[cm]
Si	2.0 ± 0.1	80.7 ± 0.2	-0.4 ± 0.1	86.1 ± 0.2
EMT	2.3 ± 0.5	83.0 ± 1.0	-0.7 ± 0.6	87.4 ± 1.2

- EMT profile seems gaussian.

- Get EMT Y profile for the first time.

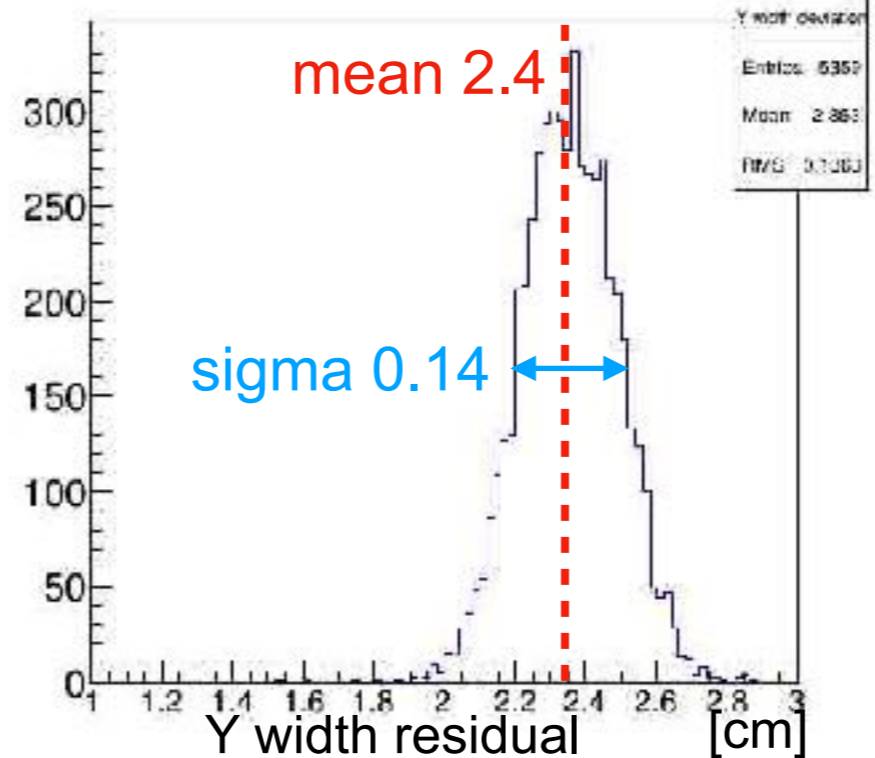
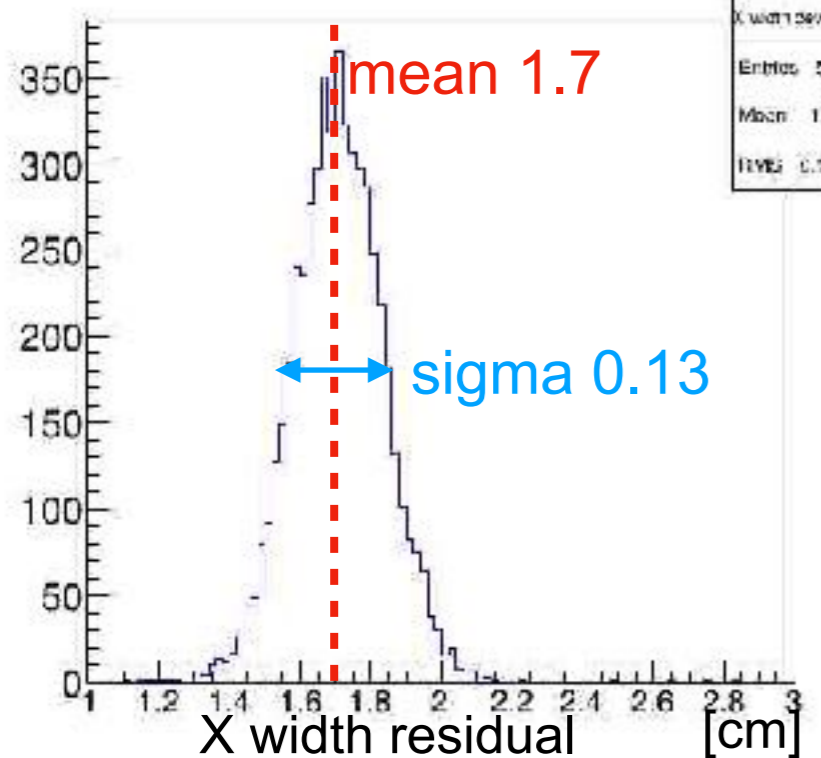
More shots, profile residual (EMT - Si)

Center residual



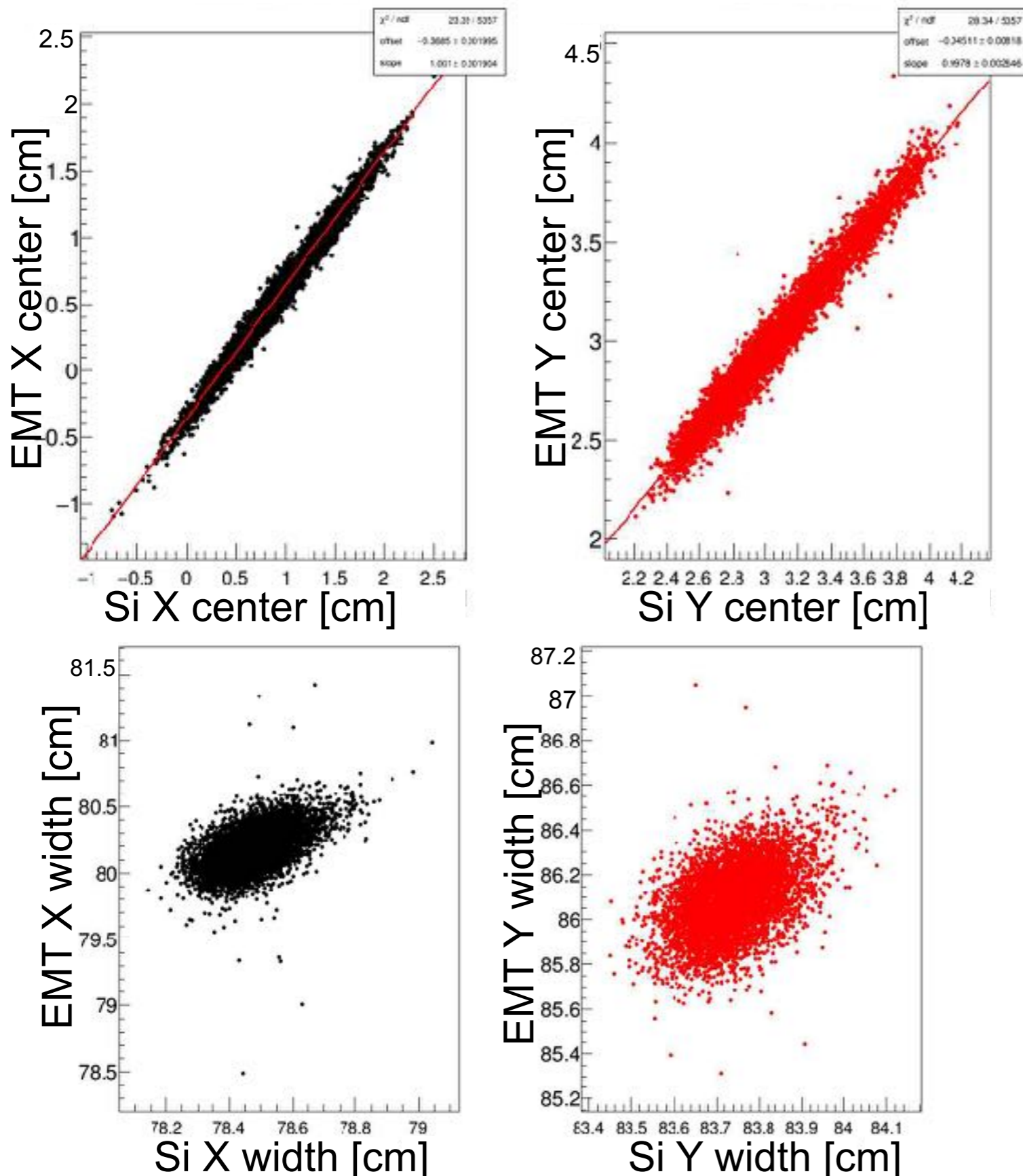
- There is very small offset in center.
- Also, small sigma (< 0.1 cm).

Width residual



- A few cm offset in width.
- But small sigma (~ 0.1 cm).

Correlation plot of Si and EMT



- Expectation
 - Profiles of Si and EMT has strong correlation.
 - Fit the plot by $y = ax + b$.
- Center
 - X's a is 1.001 ± 0.002
 - Y's a is 0.9978 ± 0.003

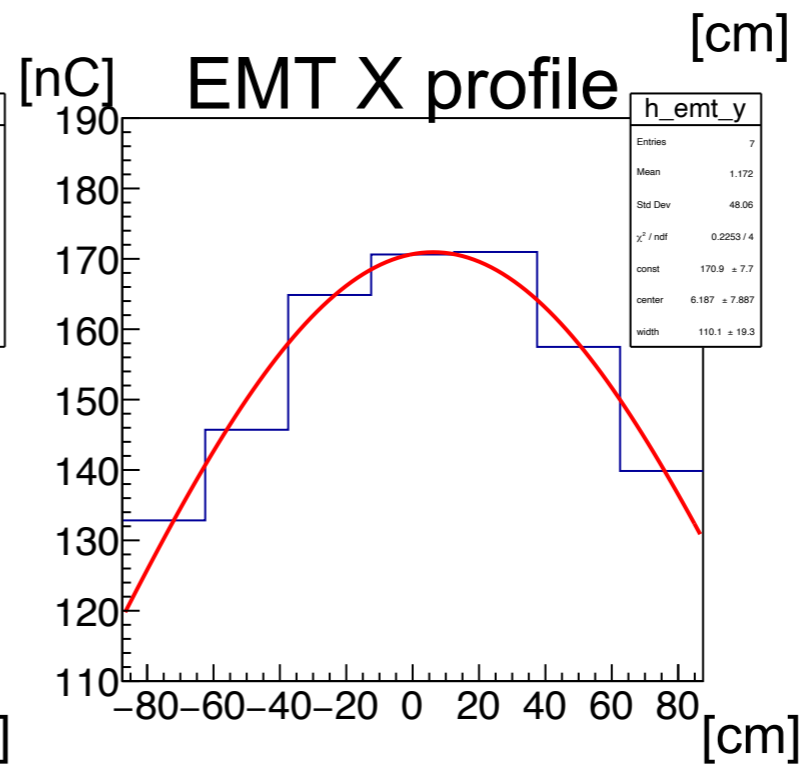
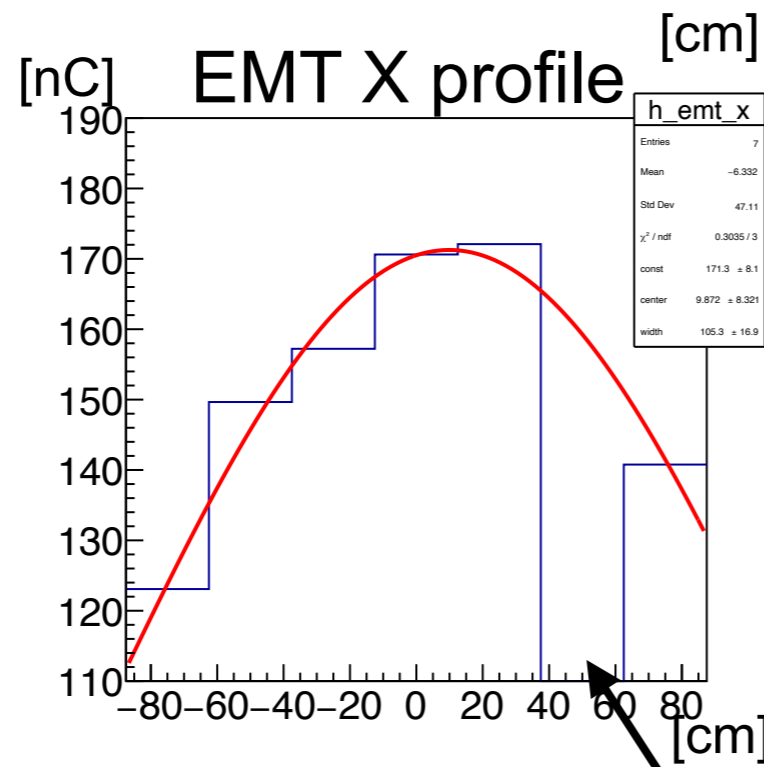
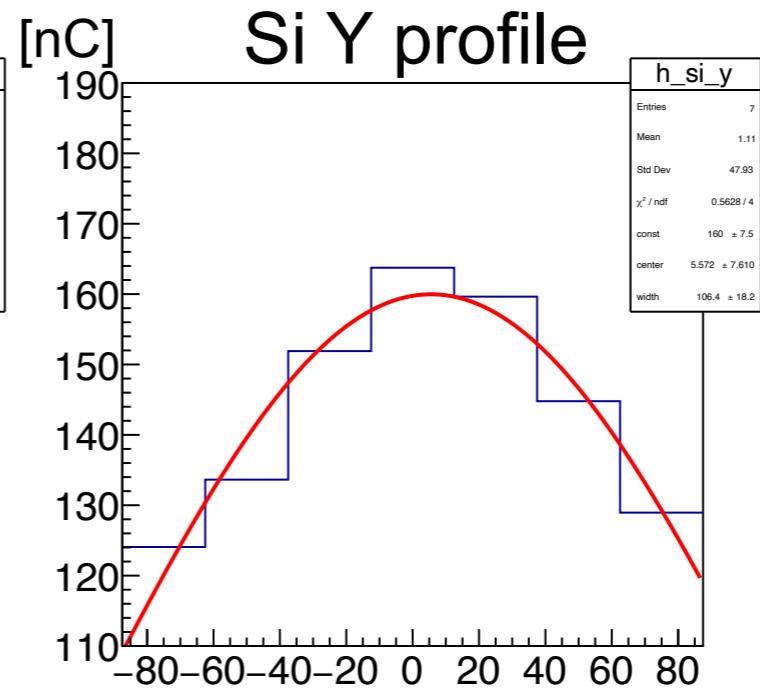
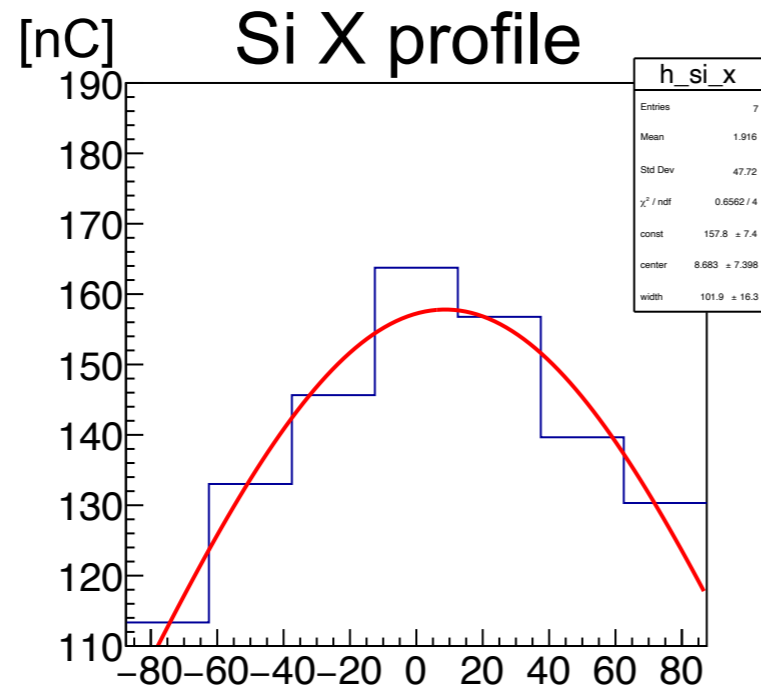
EMT is working as well as Si.

Low intensity Operation result

- Low intensity
- Typically, a few kW.
- Mainly For : Beam tuning at the beginning of each beam time.

- Necessity
 - In case of beam missing the target.
 - Reduce the damage

X & Y profile



Dead ch

- Shape difference (sometimes large) between Si and EMT was observed.
- Check with more shots (next slide).

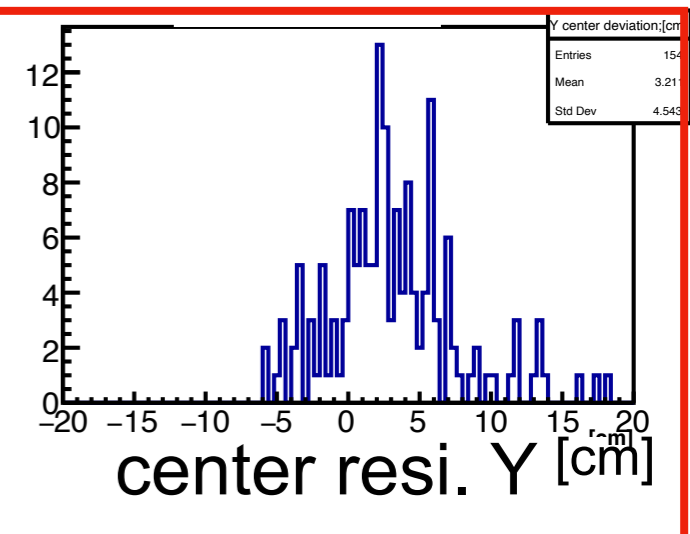
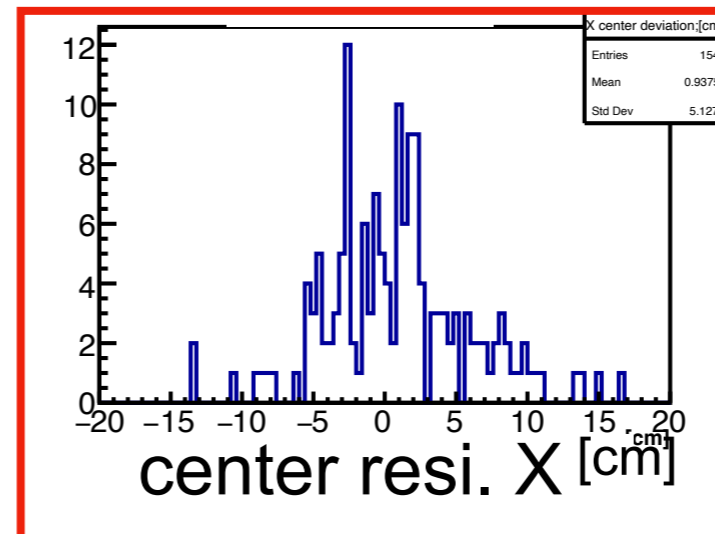
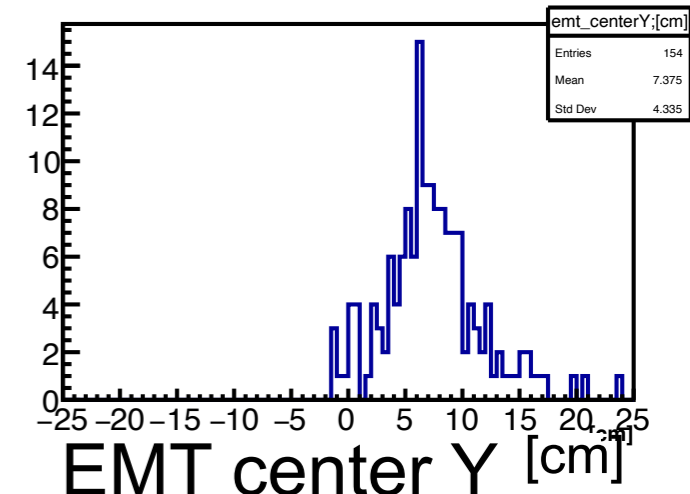
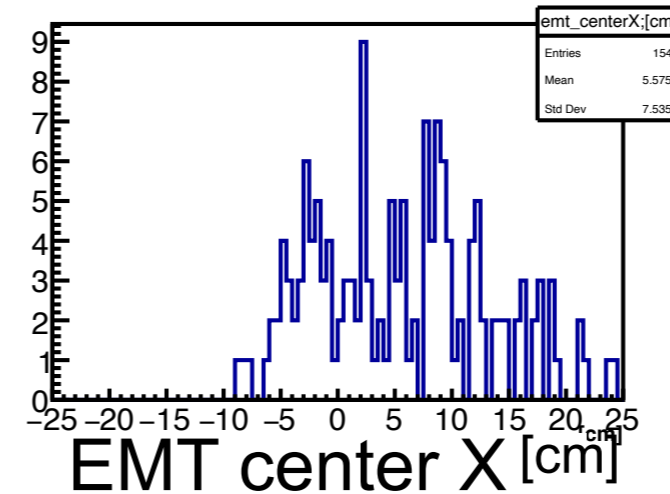
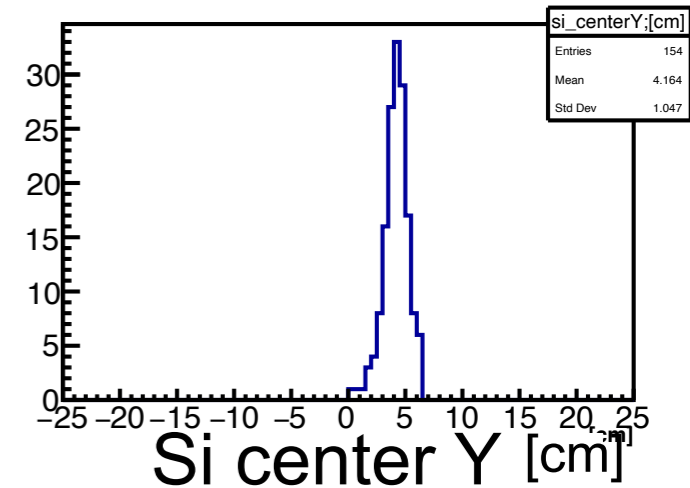
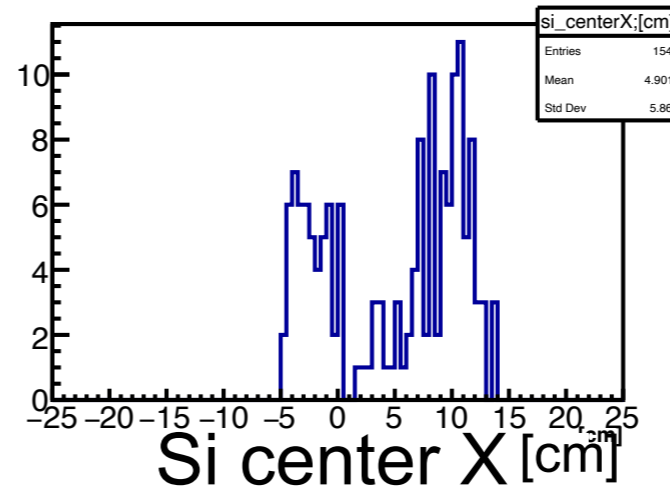
Low intensity center residual.

- Used Run
 - Moving proton beam in x direction.
- Fit Si and EMT profile.
 - Fill the center.
 - Fill EMT - Si.

Center [cm]	ΔX mean	ΔX σ	ΔY mean	ΔY σ
EMT-Si	0.94	5.1	3.2	4.5

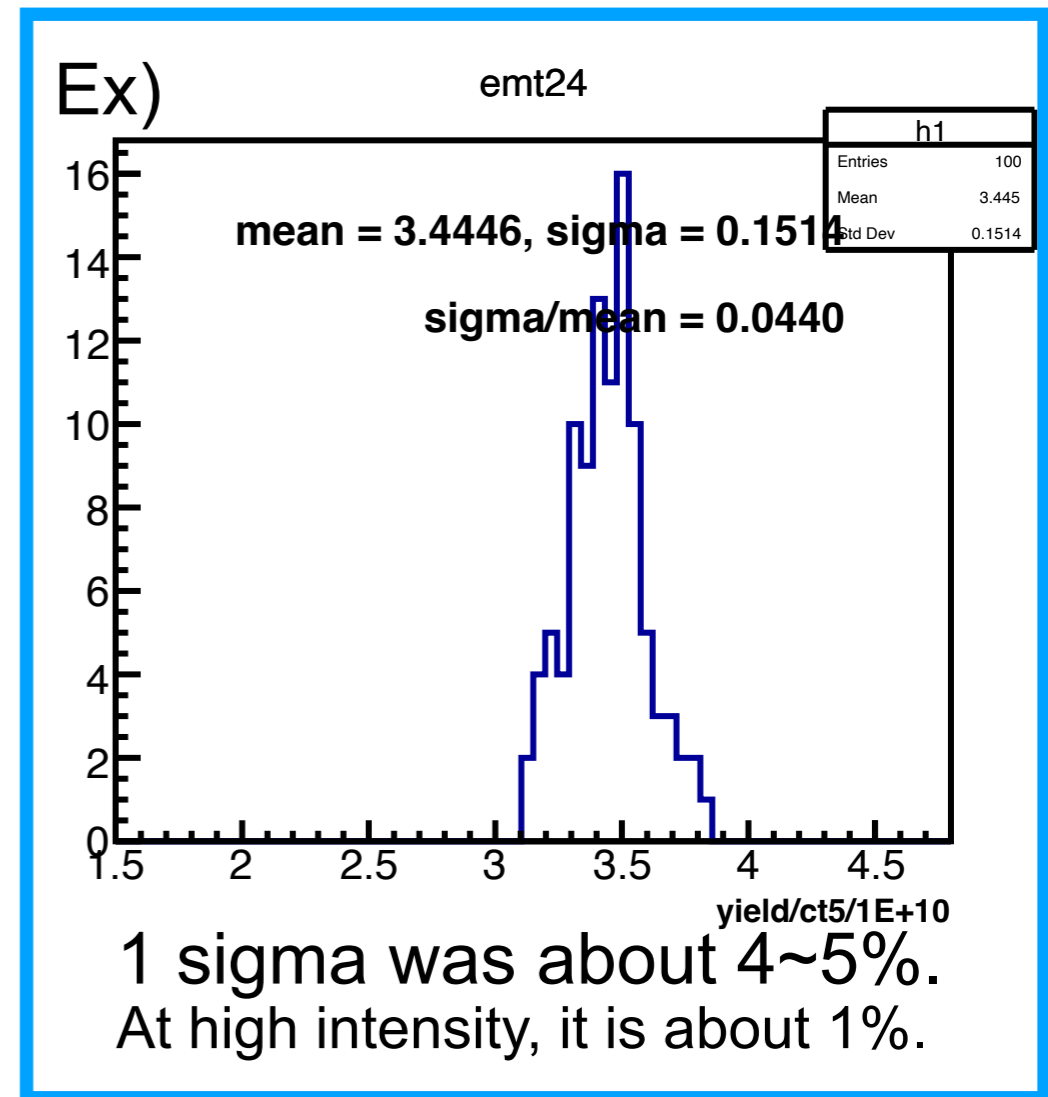
- Large offset and variation in center residual.

- Residual is bigger than MUMON requirement, 3cm.



Yield fluctuation

- Beam tuning is done shot by shot.
- Large offset and Large variation in center are crucial...
- Checked the EMT yield shot by shot.
- EMT yield has more fluctuation than Si and EMT yield of high intensity run.
- —> it prevents EMT from getting proper beam profile.
- Also, we get detector calibration constant by taking 10 shots in each detector.
- —> calibration constants have uncertainty, too.

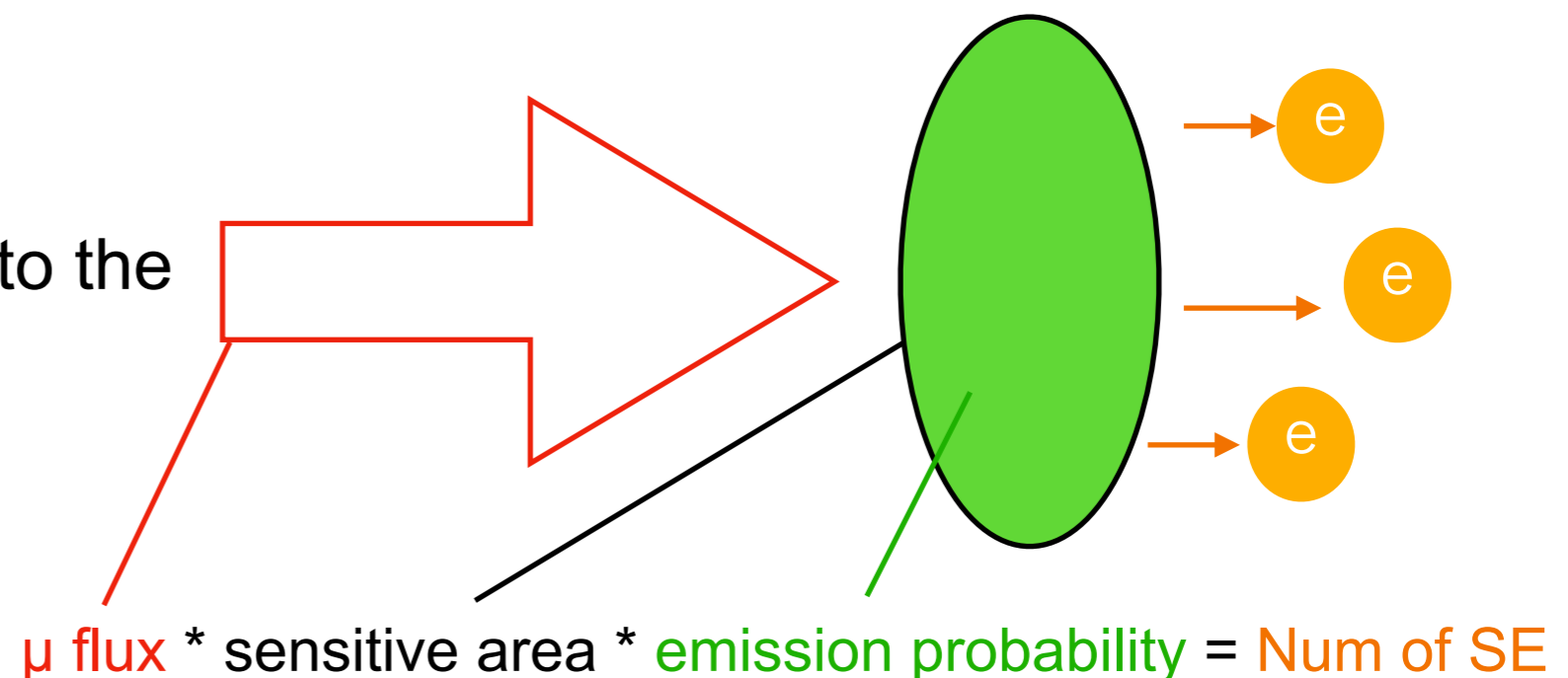


Pedestal RMS is about 1ADC count.
Peak heights in low int. is at least 120.
—> the effect of Ped. RMS is estimated roughly less than 1%

The source of yield fluctuation

- One of the source may be the number of secondary electron (SE).
- Secondary electron in per bunch is 435 electrons.
- The fluctuation $\rightarrow 1/\sqrt{435} * 100 = 4.8\%$.
- The Horizontal (Vertical) EMTs yield fluctuation per bunch $\rightarrow 6.62$ (5.74)%
- Then, remained fluctuation is ...
 $\sqrt{6.62^2 - 4.8^2} = 4.56[\%]$,
 $\sqrt{5.74^2 - 4.8^2} = 3.15[\%]$
- About half of fluctuation is due to the number of secondary electron.

μ flux	$1.1 * 10^4 / [\text{cm}^2] / 10^{11} [\text{proton on target}]$
sensitive area	$0.5 [\text{cm}^2]$
SE emission prob.	0.08
Proton on target	$7.9 * 10^{11}$
Num. of SE	435



Improvement possibility

- Usual low intensity beam is 2 bunch.
 - If use 8 bunch, 1 shot or 2 bunch, 4 shots,
 - Yield fluctuation will be divided by about 2.
 - Actually, EMT fluctuation change about 4.5% → 2.5%.
- On the Other hand,
Si yield fluctuation of 2 bunch is about 1%.
- The simulation with 49ch EMT.
 - Apply the yield fluctuation and reconstruct beam profiles.
 - Calculate reco. sigma in each yield fluctuation.
- It is one possibility for future EMT era.

	EMT 2 bunch	EMT 8 bunch, 1 shot Or 2bunch, 4shots	Si 2 bunch
Yield σ	~4.5%	~2.5%	1%
reco. σ MC prediction	~10mm	5.5mm	2.2mm

Even 3σ is about half of MUMON requirement (~ 3cm).

Conclusion

Conclusion

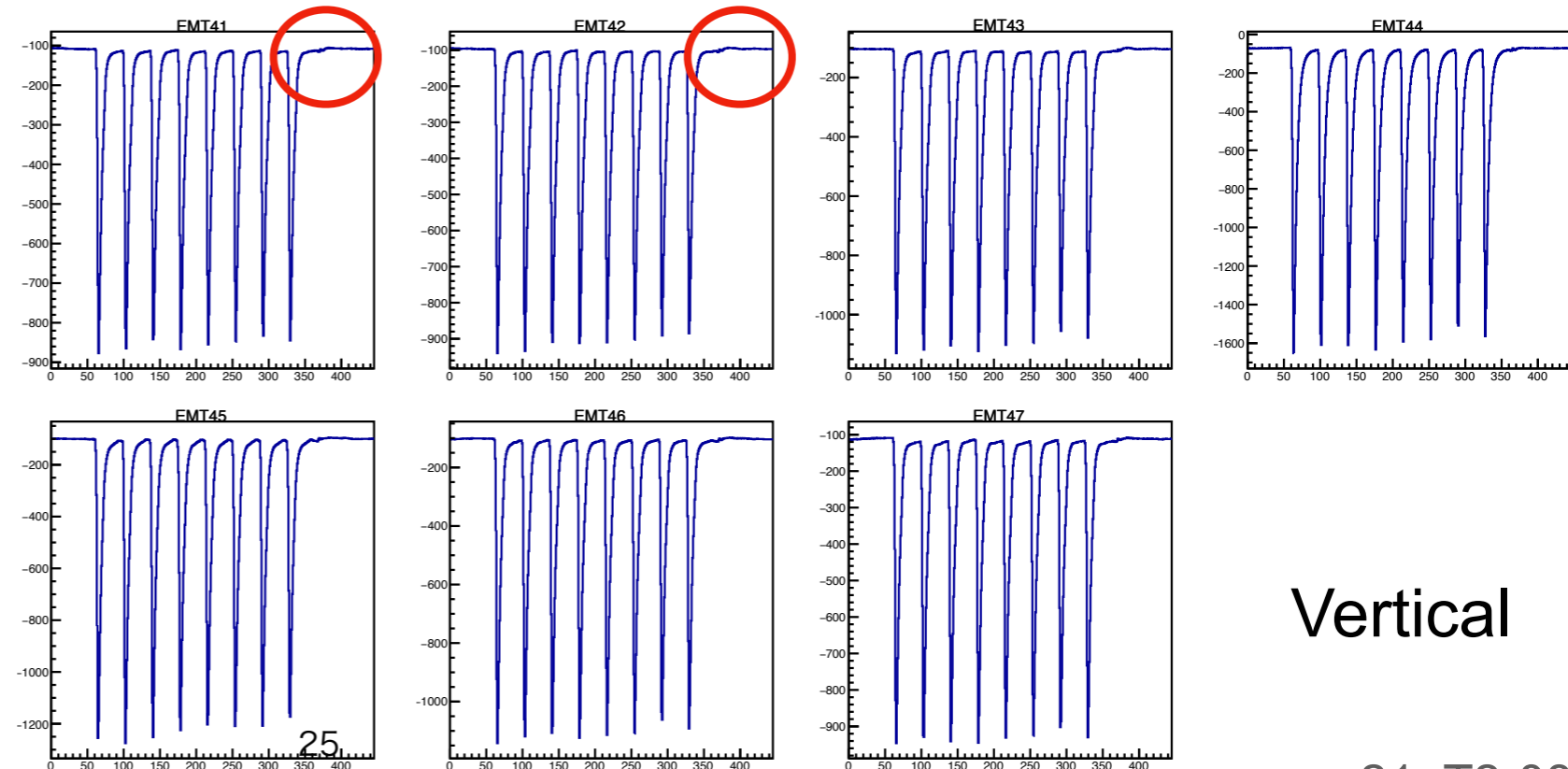
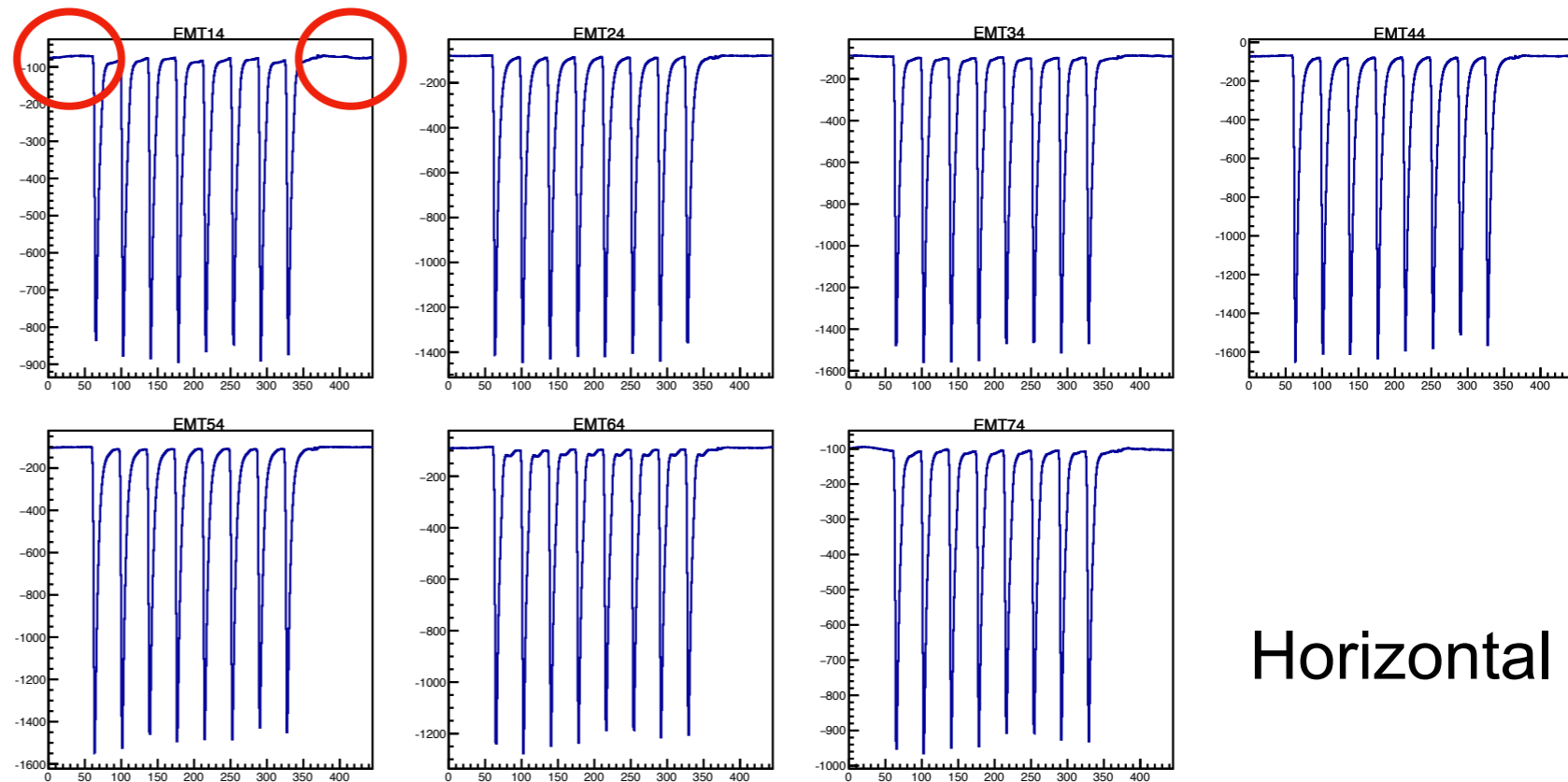
- T2K experiment is searching for CP violation in neutrino.
 - Plan to increase beam power and need new detector for muon monitor.
- EMT R&D is ongoing.
 - According to the past research, EMT may be able to take the place of Si or IC.
 - Added new EMTs from 2024/11 (plan to use 49ch at HK era).
 - It allows us to see vertical profile.
- Good result in high intensity.
 - Especially, reconstructed beam center is close to that of Si.
- There is one obstacle at low intensity.
 - Large yield fluctuation prevents beam reconstruction.
 - Depends on our ingenuity, we can break it.

Supplement

Waveform

- Succeed to see clear 8 bunch structure.
- Sometimes noise on pedestal.
- Both Vertical and Horizontal.
—> compare the pedestal RMS at that time.

- Average Pedestal RMS of Verticals was not reduced.
- —> No improvement.



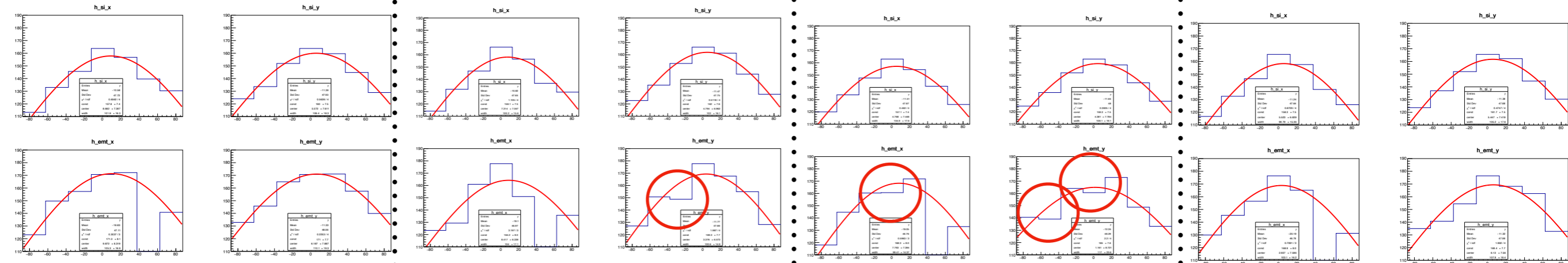
Low intensity - typical shot

Entry 1

Entry 2

Entry 3

Entry 4

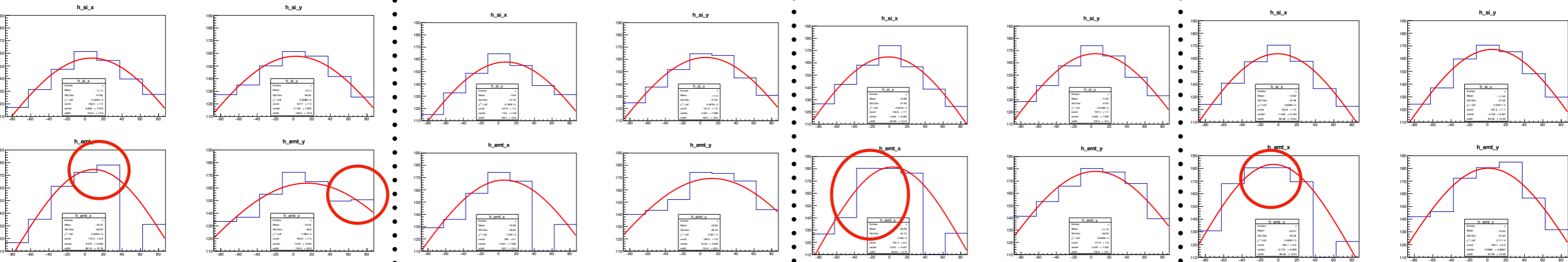


Entry 5

Entry 10

Entry 100

Entry 101

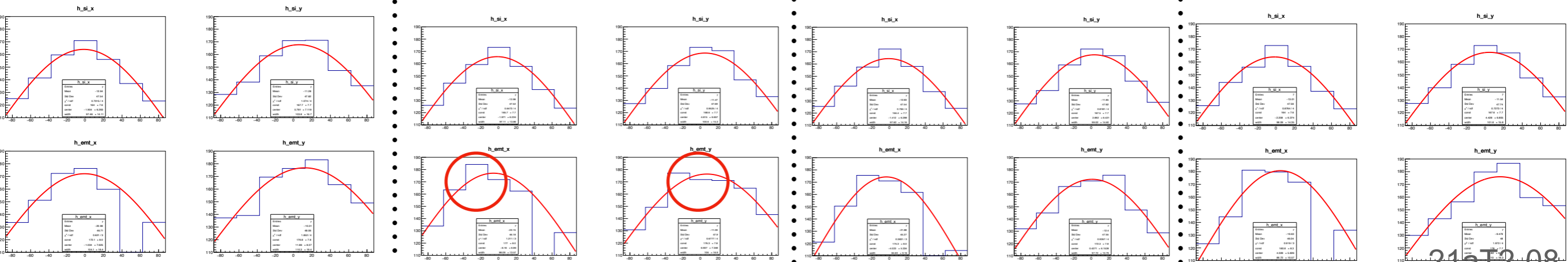


Entry 102

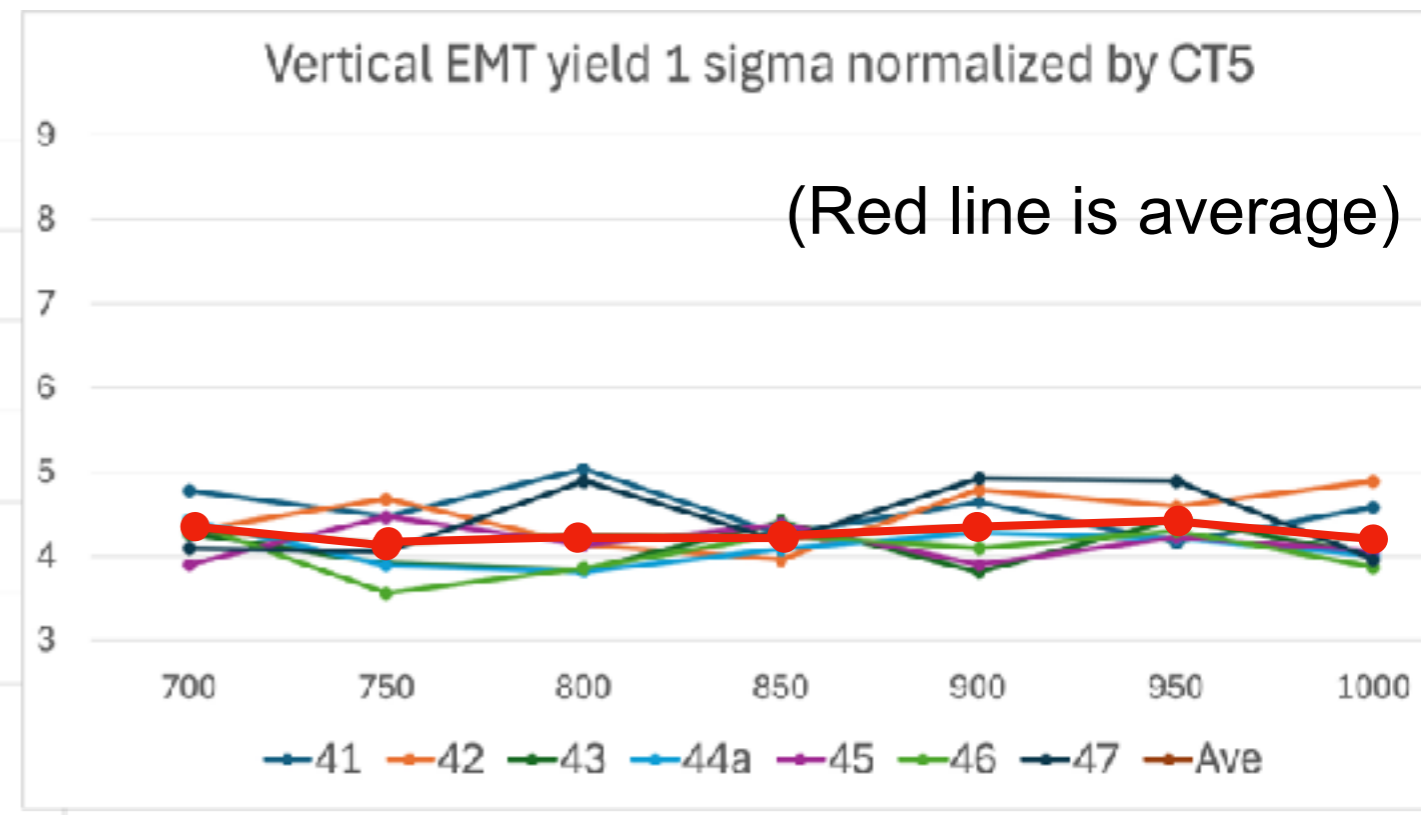
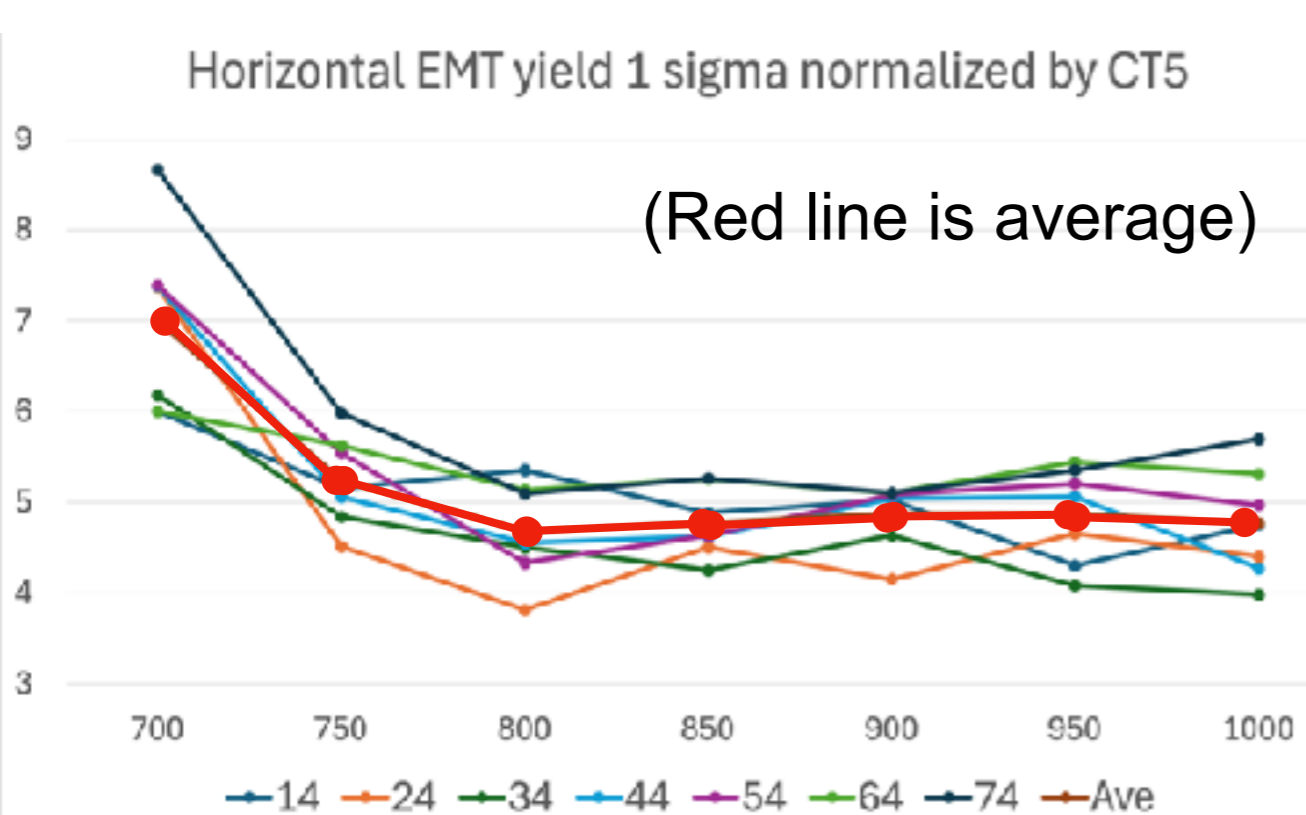
Entry 103

Entry 104

Entry 105



HV scan plot



- X axis : HV value
- Each colors : each EMTs.
- In Horizontal EMT, higher HV makes smaller sigma in the range of -700~-800V
- However, in both of EMT arrays, the sigma saturates below -800V.
- —> bigger signal dose not solve the fluctuation issue.

Waveform integration

- Waveform integration is also fluctuate.

- Ex) EMT44 & 44a of shot No.25.

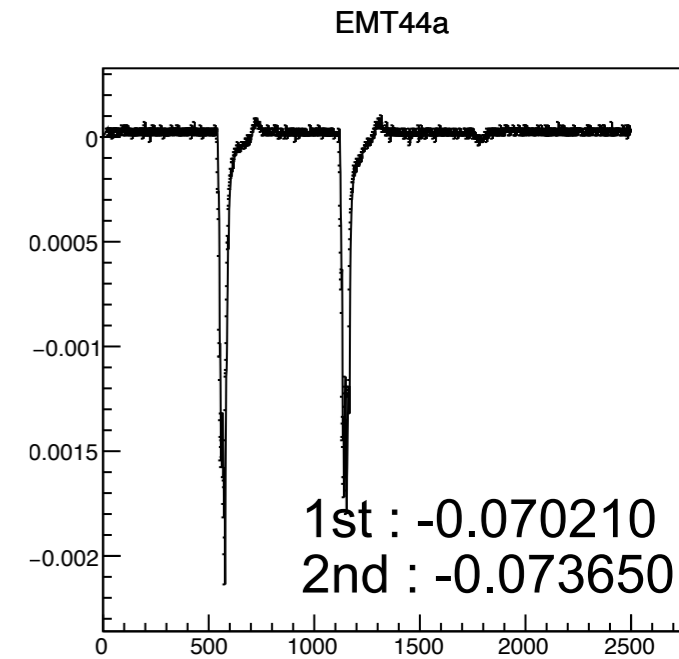
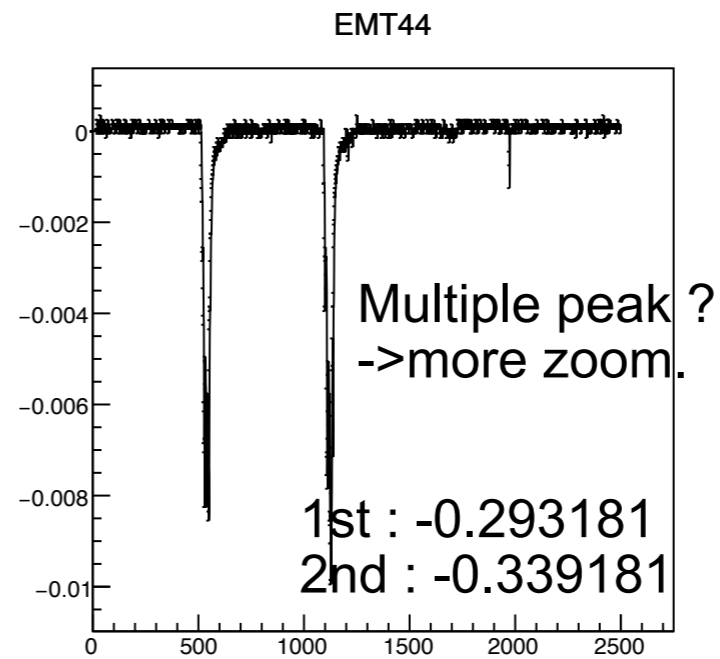
- Both of 1st bunch is smaller than 2nd bunch.
- OK.

- Ex) EMT44 & 44a of shot No.11.

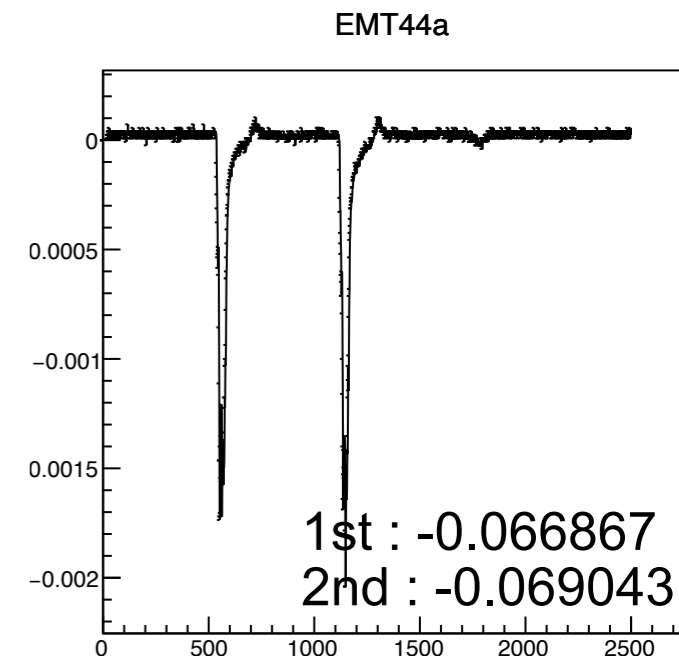
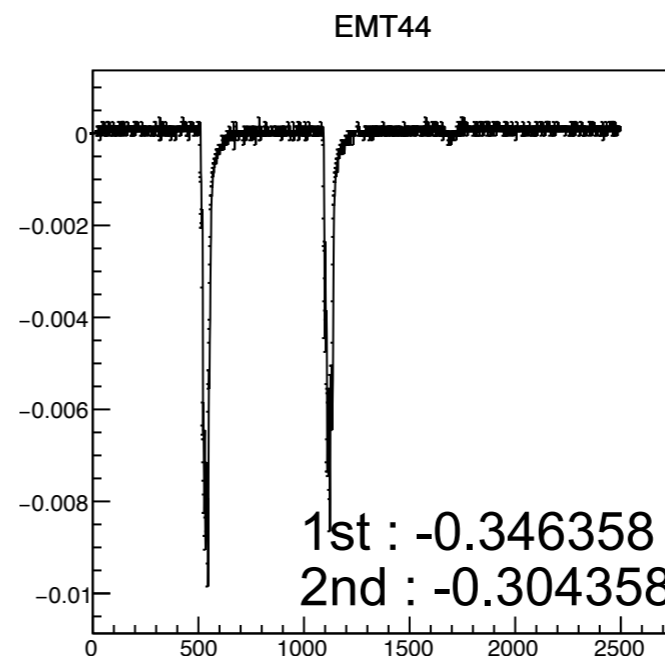
- 1st bunch in EMT44 is bigger than 2nd bunch.
- 1st bunch in EMT44a is smaller than 2nd bunch.
- Inconsistent.

- Anyway, fluctuation is caused in EMT itself.

No. 25



No.11



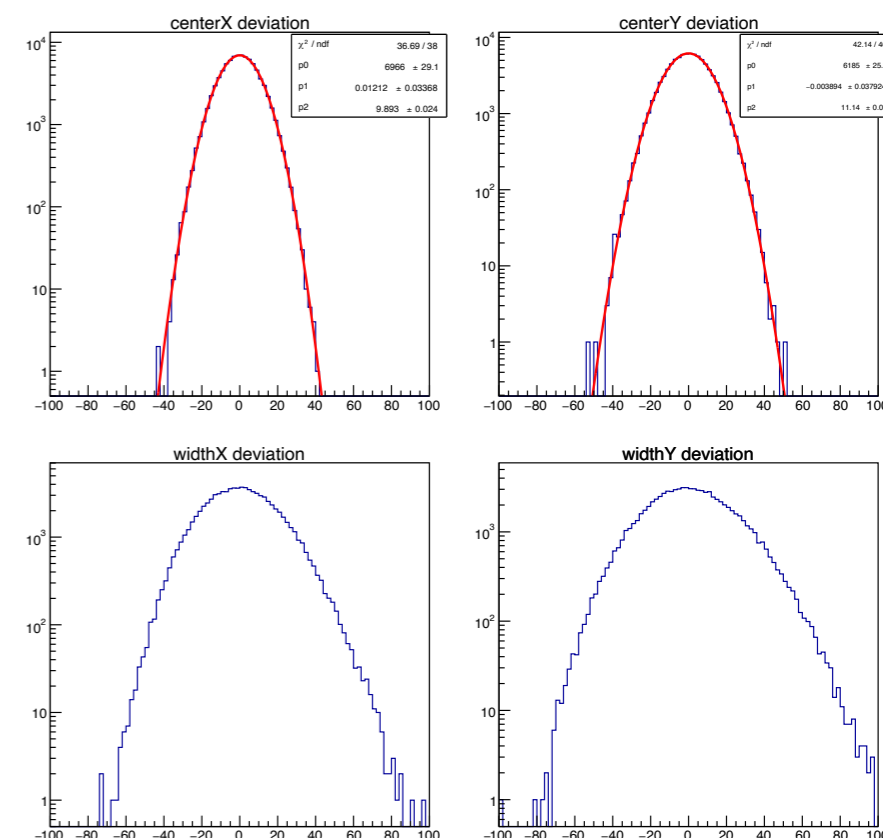
Yield Sigma influence to center reconstruction

- Make simple MC.
 - Shoot beam center (0,0), width (820, 870), typical profile.
 - Integral beam in each EMT areas (49 ch) and regard it as yield.
 - Change yield by gaussian distribution (mean is yield and sigma is inputted).
 - Fill and fit them.
 - Compare the center result to (0,0) and get and fill deviation.
 - Fit the deviation distribution.
 - **Get reconstruction sigma in each yield sigma.**

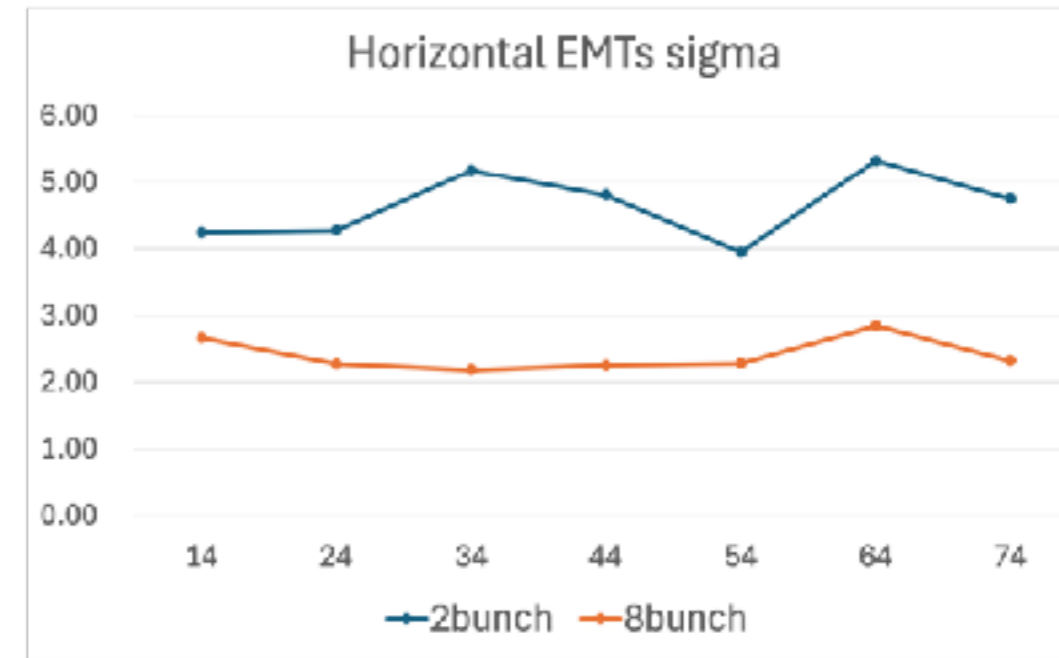
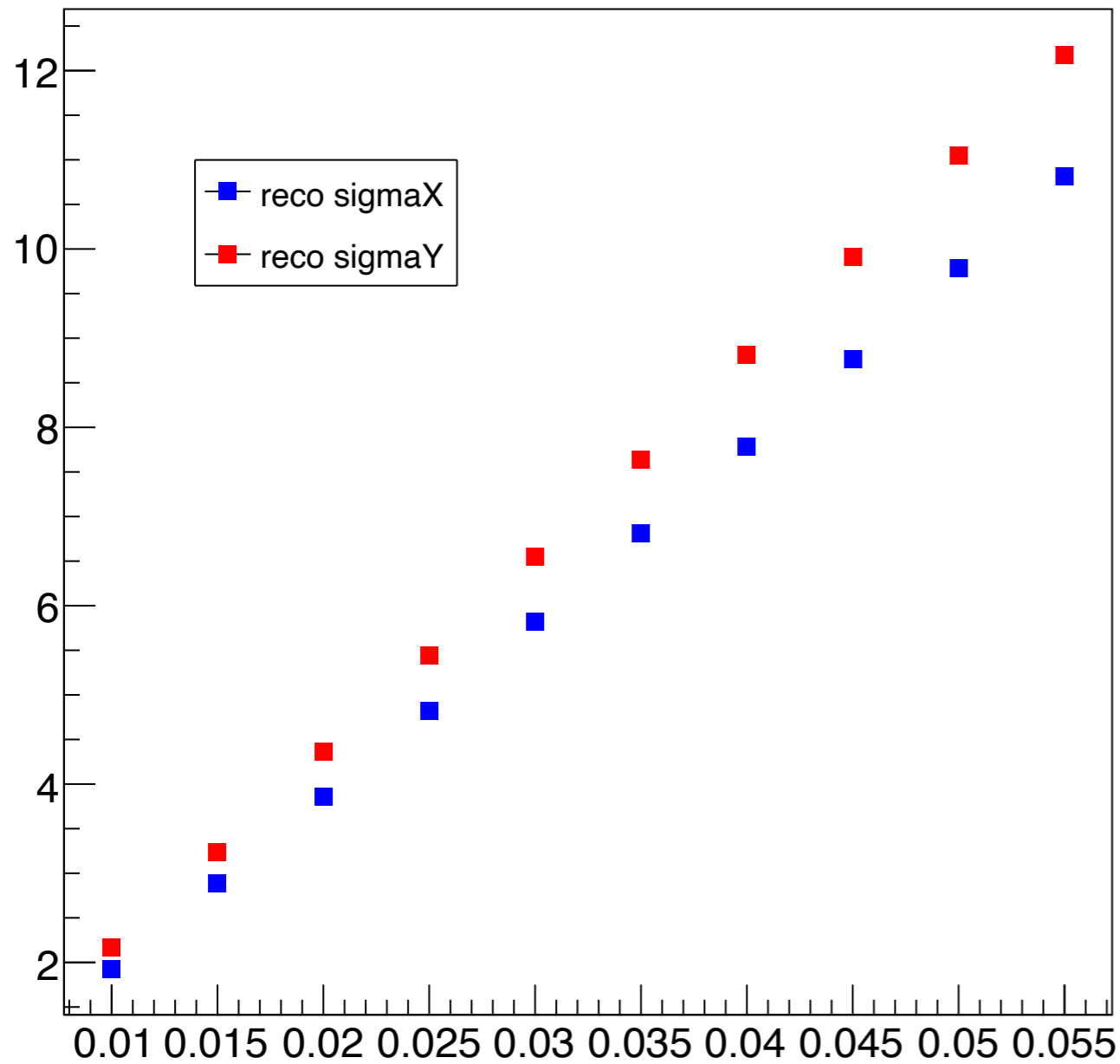
1 sigma of Horizontal EMTs

[%]	14	24	34	44	54	64	74
-700	6.0289	7.4237	6.3428	7.3351	7.487	6.0345	8.7528
-750	5.2692	4.573	4.8329	5.0576	5.5596	5.517	6.103
-800	5.475	3.8165	4.4471	4.5973	4.2009	5.087	4.957
-850	4.6792	4.4571	4.1494	4.6639	4.7181	5.1948	5.2361
-900	4.997	4.1085	4.615	4.9075	5.2041	4.9842	5.1394
-950	4.2442	4.7171	4.1307	5.151	5.1895	5.5051	5.3575
-1000	4.8972	4.3983	4.0924	4.2036	5.0343	5.2765	5.7027

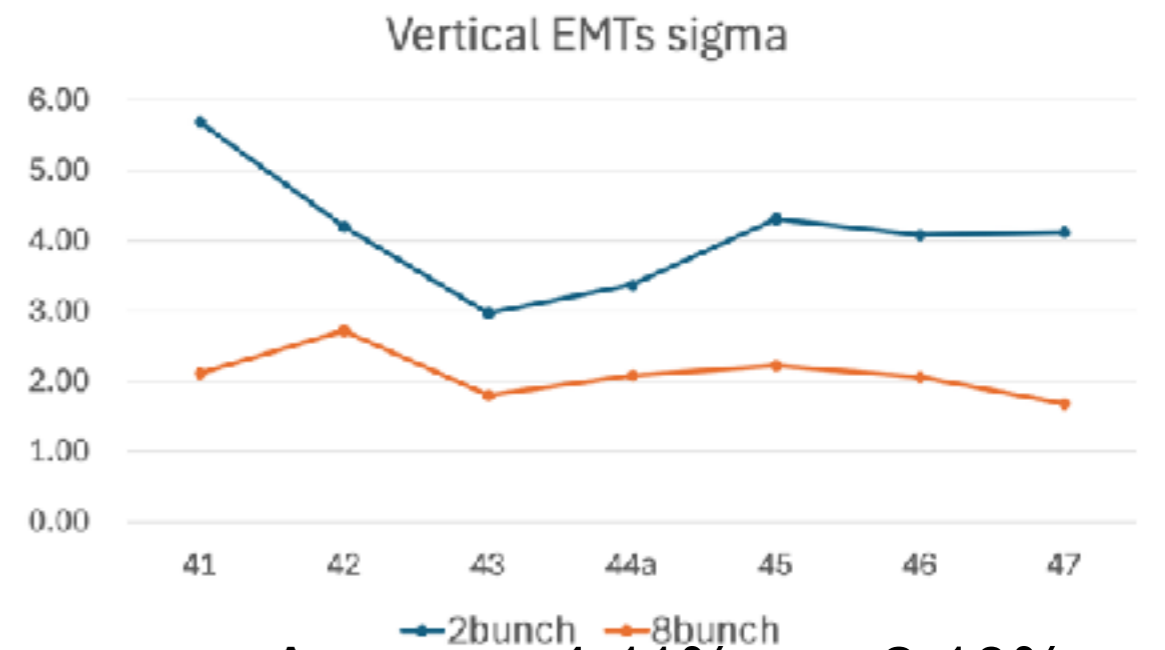
Ex. Yield sigma = 5%.



Reconstruction sigma



Average: 4.64% \rightarrow 2.60%



Average: 4.11% \rightarrow 2.10%