Viability of SOIPIX INTPIX8 as a beam monitor for J-PARC muon g-2/EDM experiment

JPS annual meeting (online)

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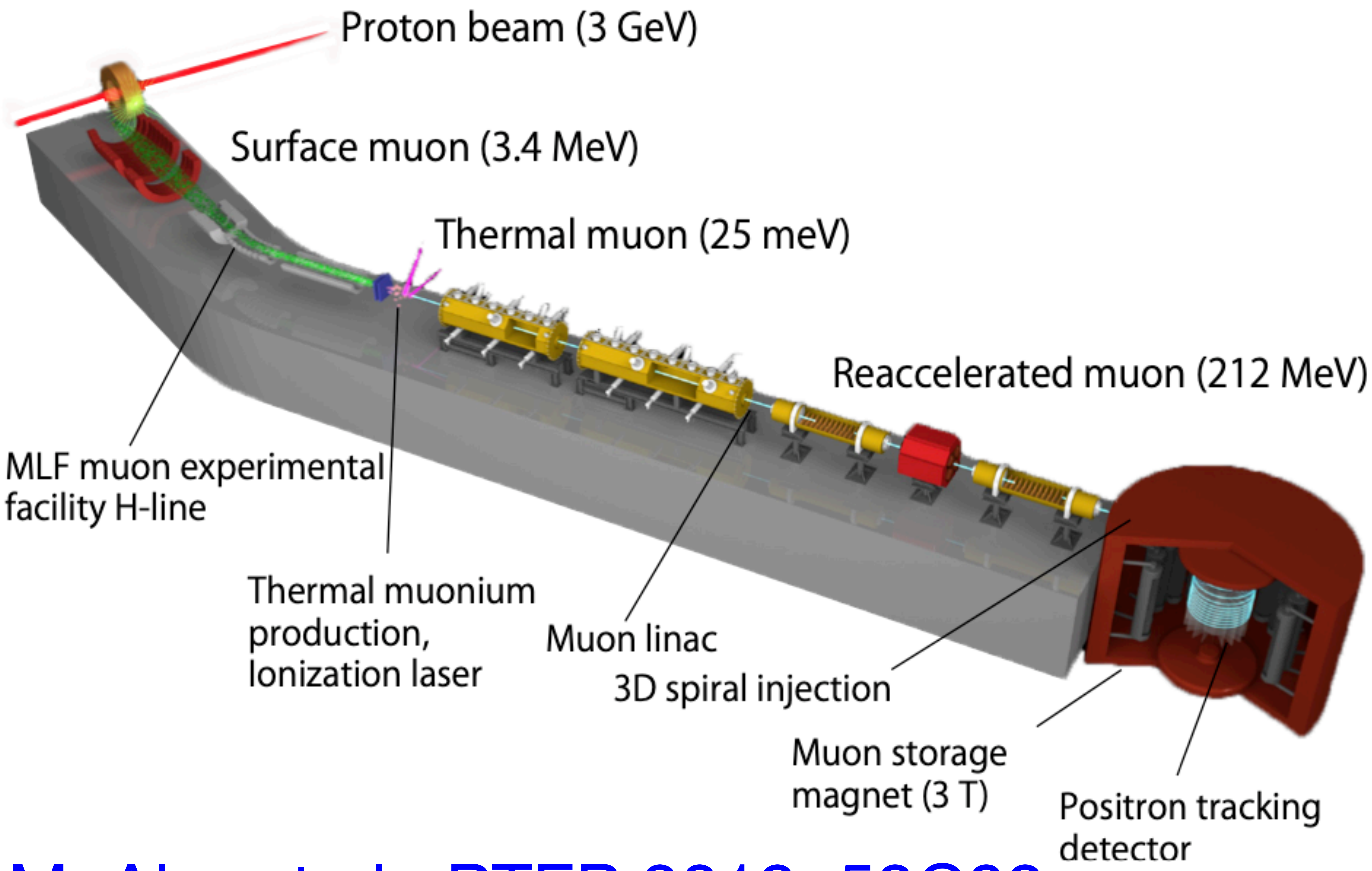
Muon g-2/EDM experiment at J-PARC

- A 3.7σ discrepancy in muon g-2 between theory and experiment
- Could be an indication of new physics beyond the Standard model



[M. Abe et al., PTEP 2019, 53C02]

- **Completely independent measurement with a novel muon beam.**
- **Target precision**
  - 0.1 ppm for g-2
  - 10^{-21} e•cm for EDM
- **An appropriate muon beam monitoring system** is necessary.

Beam monitor with SOIPIX INTPIX8

Muon beam characteristics

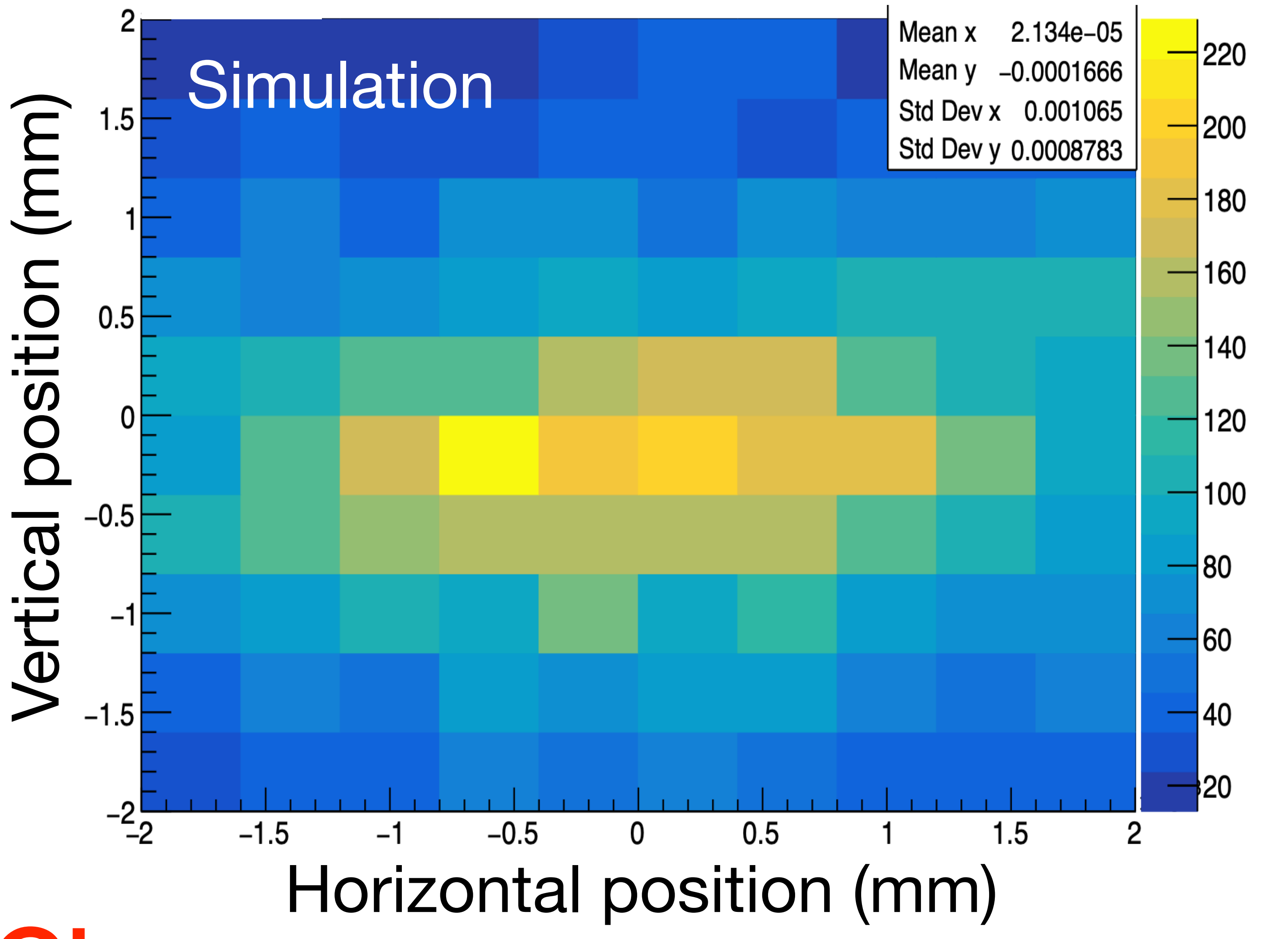
- Pulsed beam : 25 Hz, 3 bunches per 10 ns spill
- Intensity : 4×10^4 muon/pulse
- Beam energy : 25 meV → 212 MeV
- Beam size : a few mm

SOIPIX INTPIX8

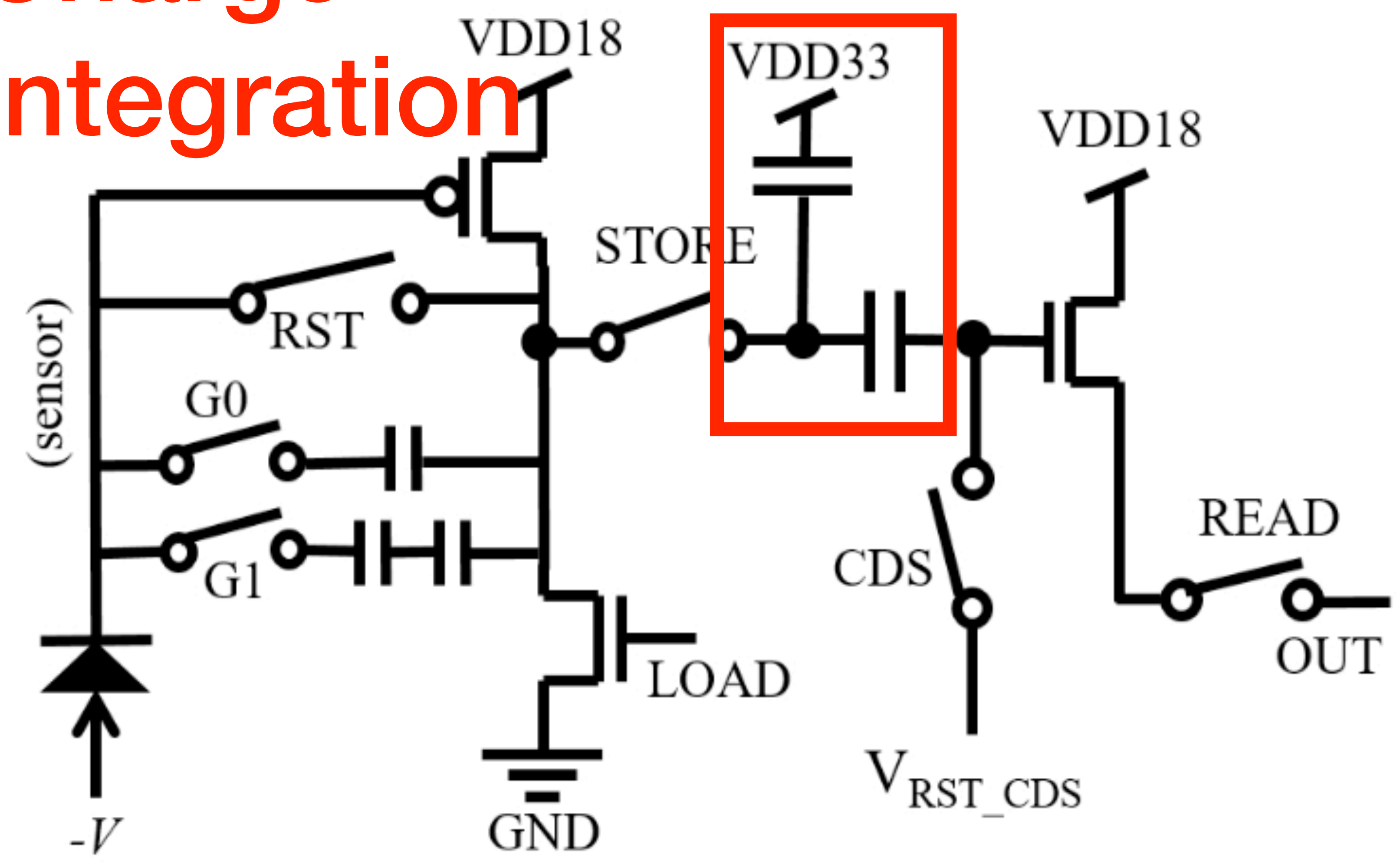
Presented in
JPS 2019 Spring
JPS 2020 Fall

- Active area : 10.9 mm x 17.4 mm
- Pixel size : 16 μm x 16 μm
- Num. pixels : 1024 x 640
- Gain : 7 mV / 1000 e^- (lowest setting)
- e-h pairs @ 4.5 MeV : 17k (22um, partial depletion)
- e-h pairs @212 MeV : 2.5k (22um, partial depletion)
- noise : ~200 e^- (22um, partial depletion)

Simulated beam profile @ 4.5 MeV



Charge integration



Beam monitor with SOIPIX INTPIX8

	Requirement	SOIPIX INTPIX8
Size of sensitive region	10 x 10 mm^2	10.9 x 17.4 mm^2
Spatial resolution	0.1 mm	~ 0.01 mm
Readout Time	25 Hz	Capable of 25 Hz
Exposure time	>10 ns, as short as possible	Minimum of 40 ns
Dynamic Range	A few to 10^4 muons	?
Tolerance against radiation from RF cavity	?	?

Issues and scope of this talk

- Issue 1: Dynamic Range
  - Single muon response has been evaluated
  - Expected multi-muon hits in the real experiment
  - Multi-muon hits are emulated from single muon data

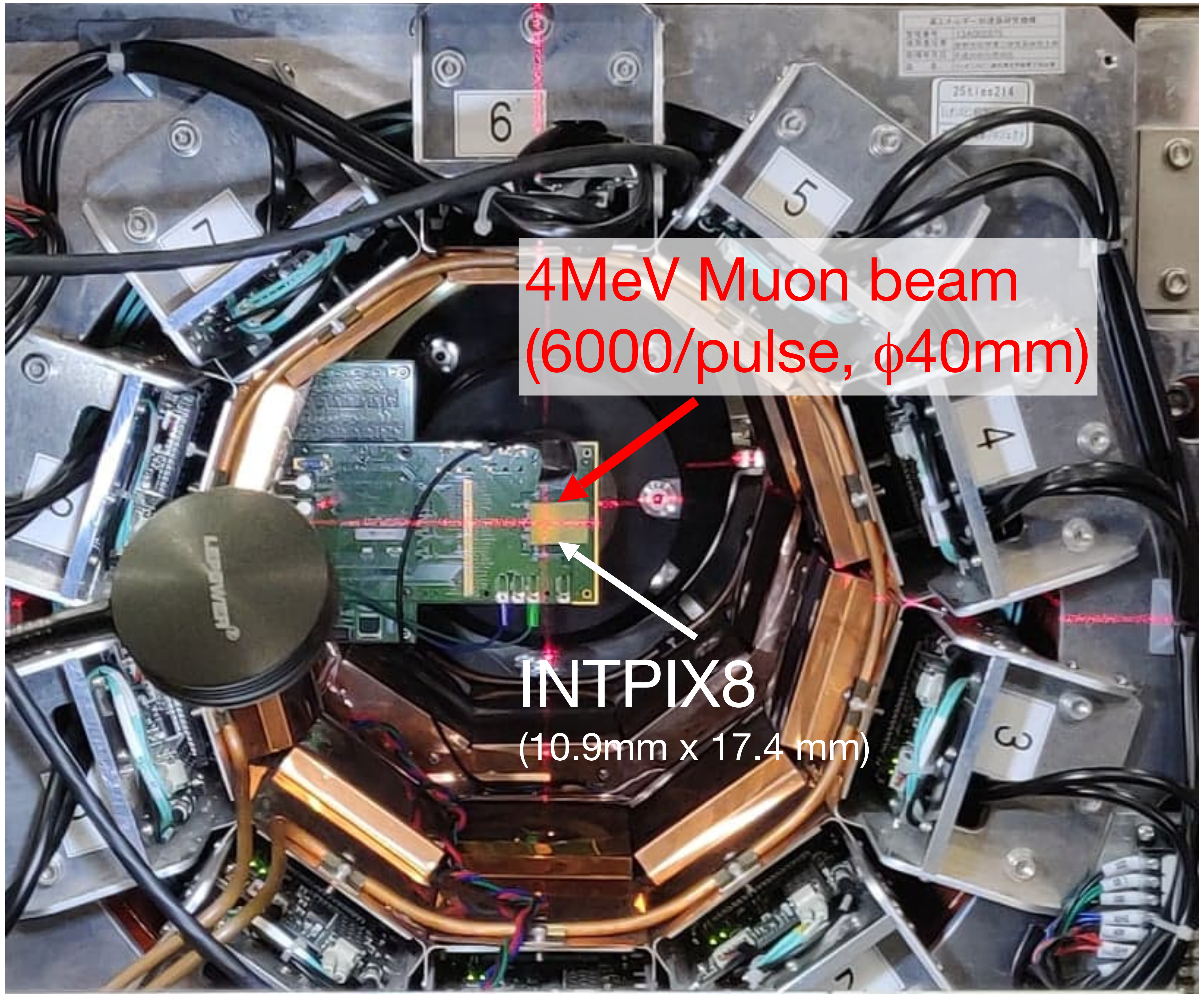
- Issue 2: Radiation from RF cavities
  - The radiation dose is unknown
  - The response of the sensor to the radiation untested

Single muon response (1)

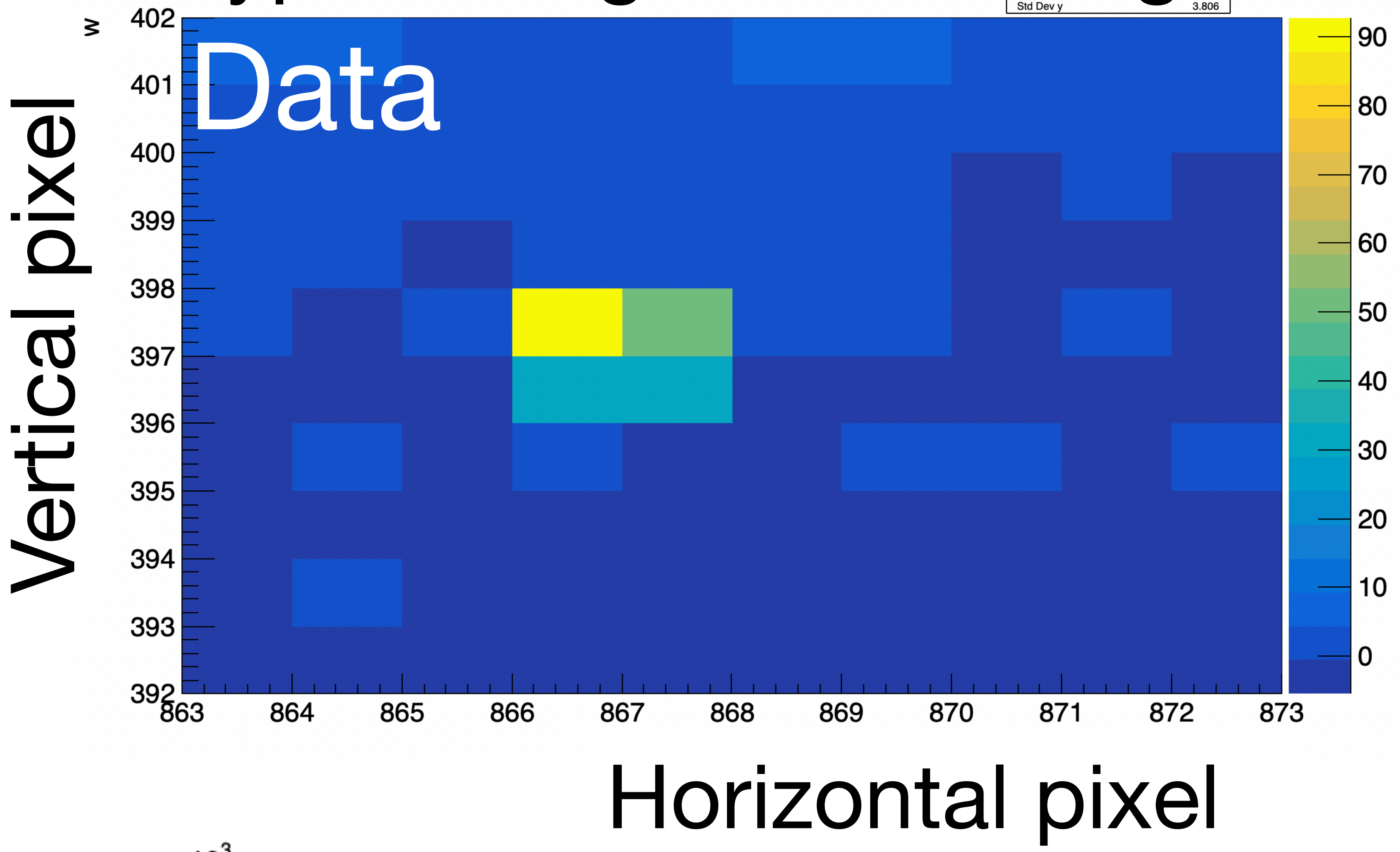
Presented in JPS 2020 Fall

Evaluated at J-PARC MLF S1 area in Mar 2020

View from back

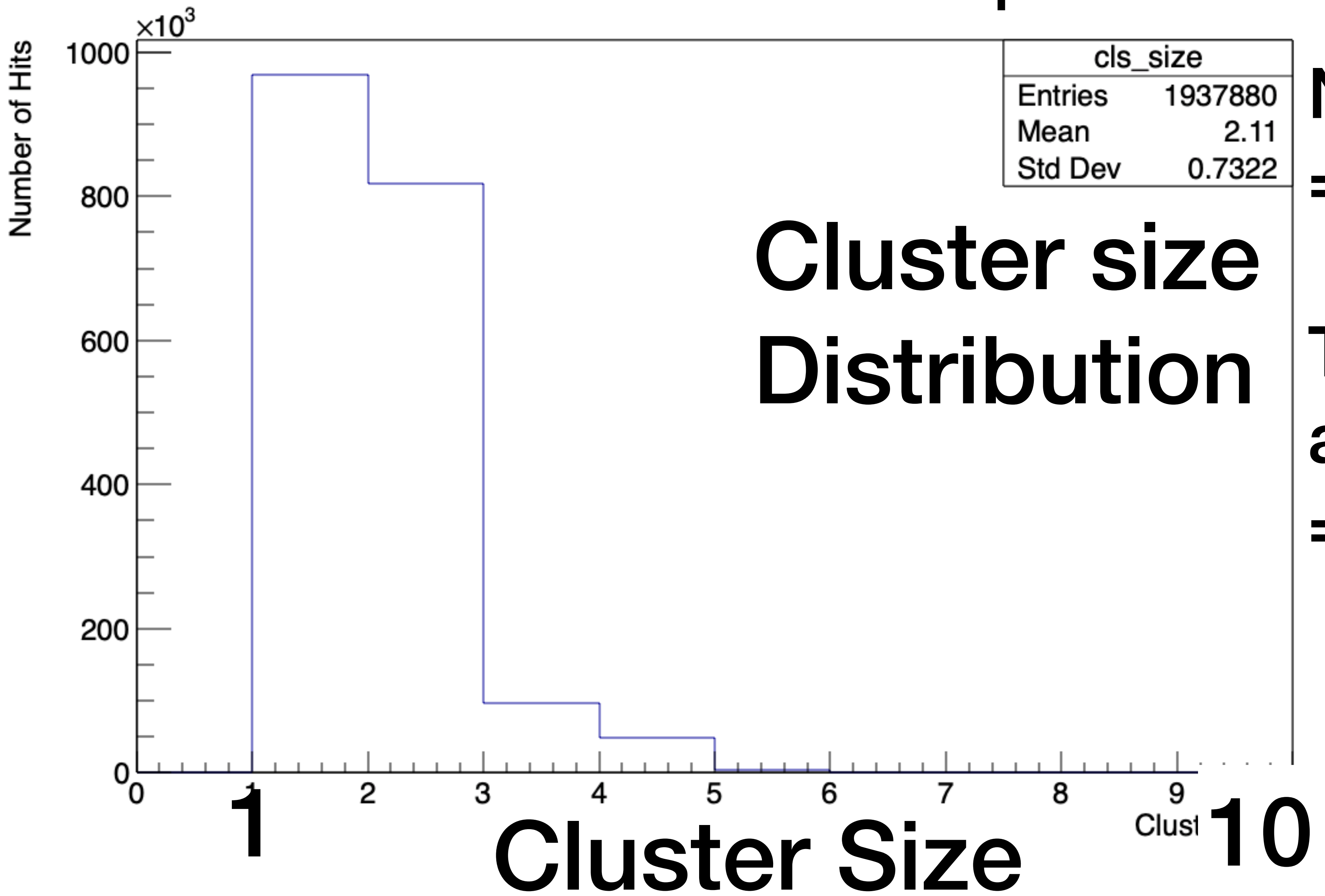


Typical single muon image



DSOI
Vbias = 5V

Integration time = 200ns



Noise level = 1.4 mV

Threshold on a pixel was = 10 mV

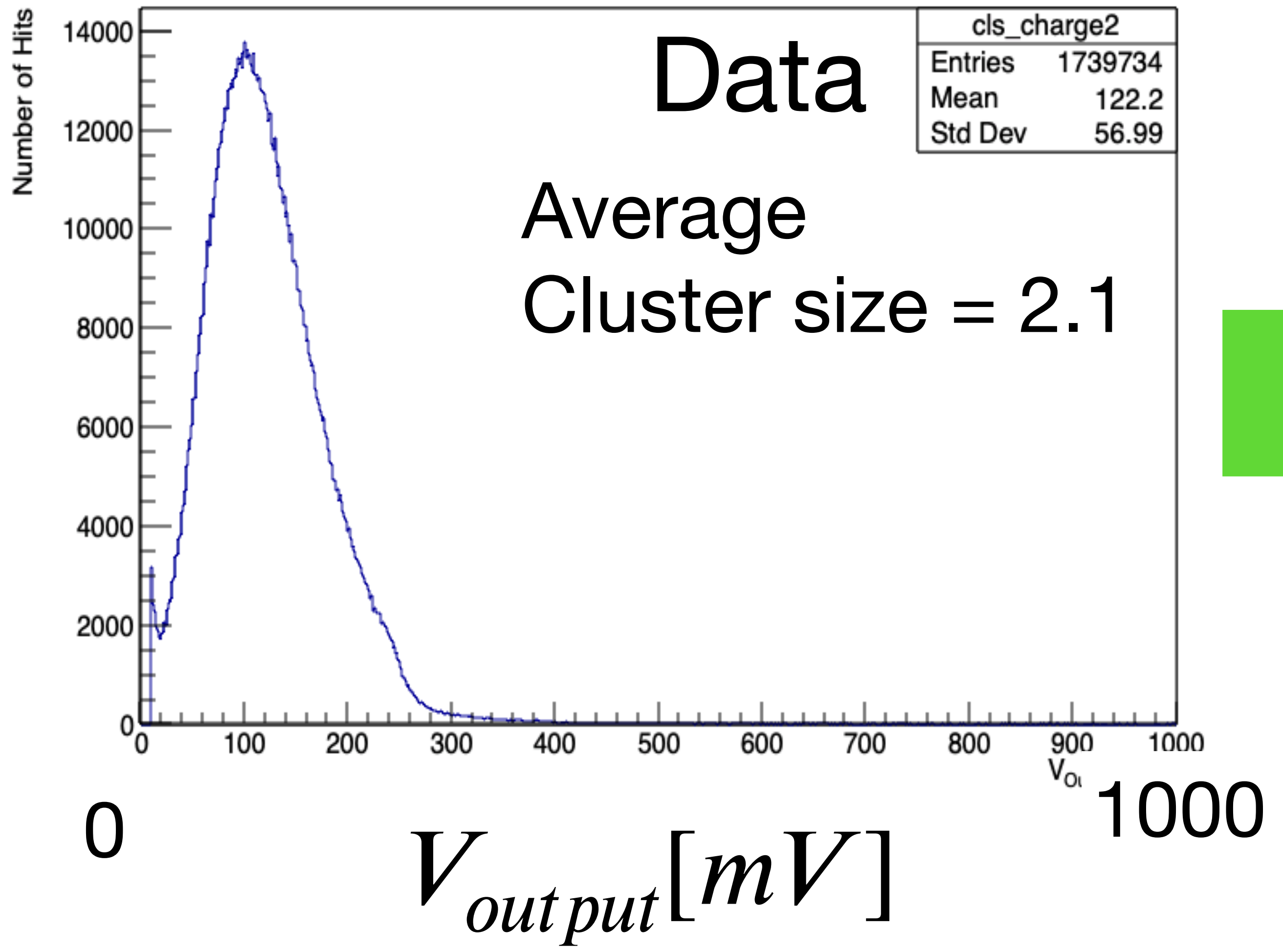
Single muon response (2)

DSOI

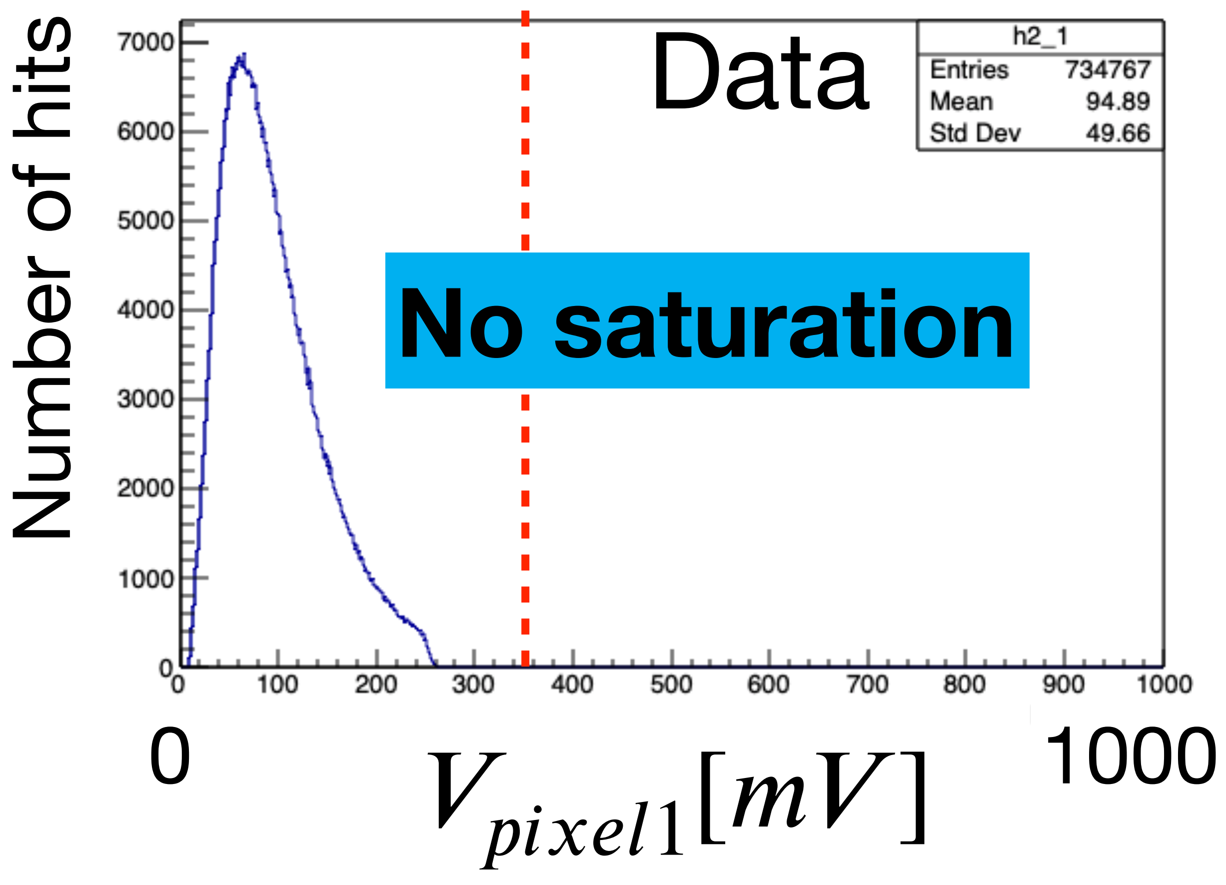
$V_{bias} = 5V$

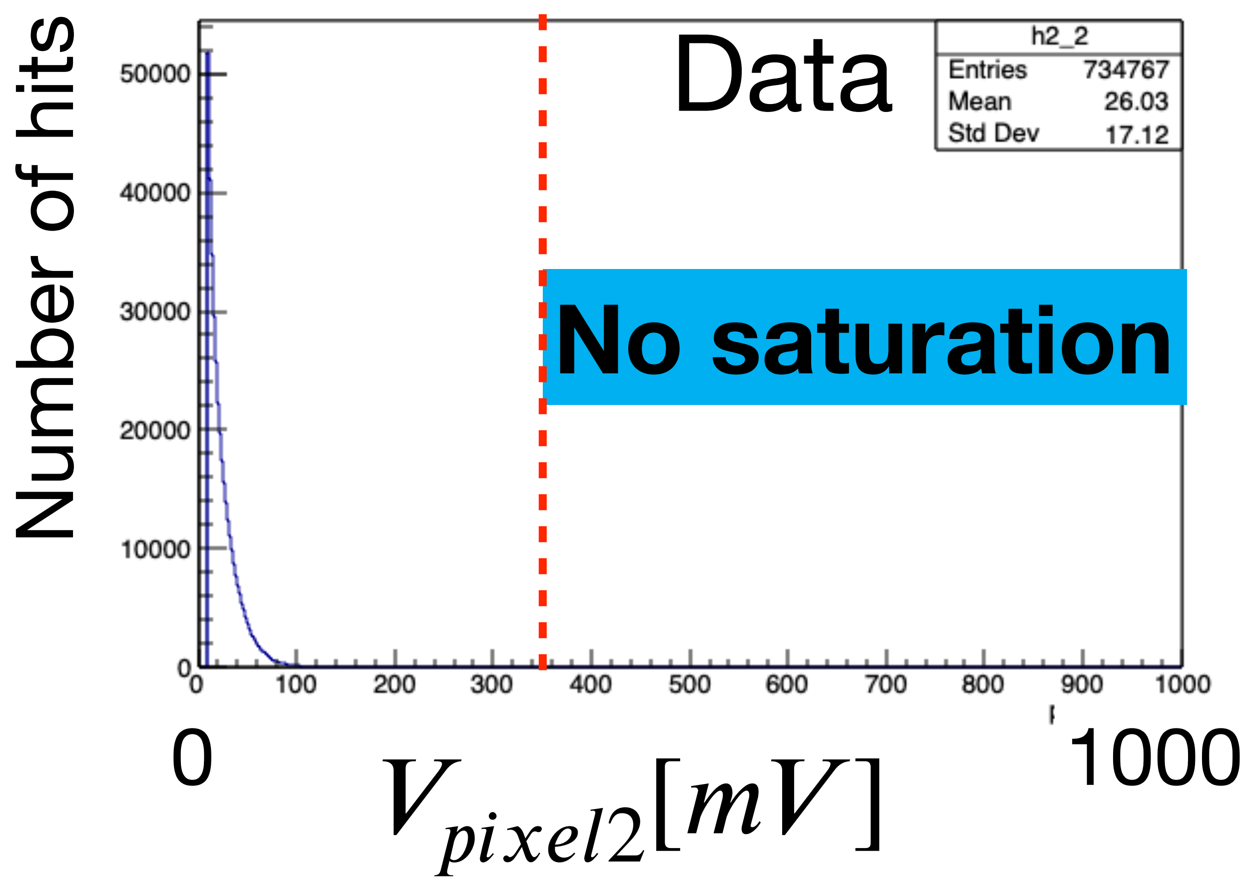
(depletion 22μm)

Cluster charge



Pixel charge (cluster size=2, $V_{pixel1}>V_{pixel2}$)

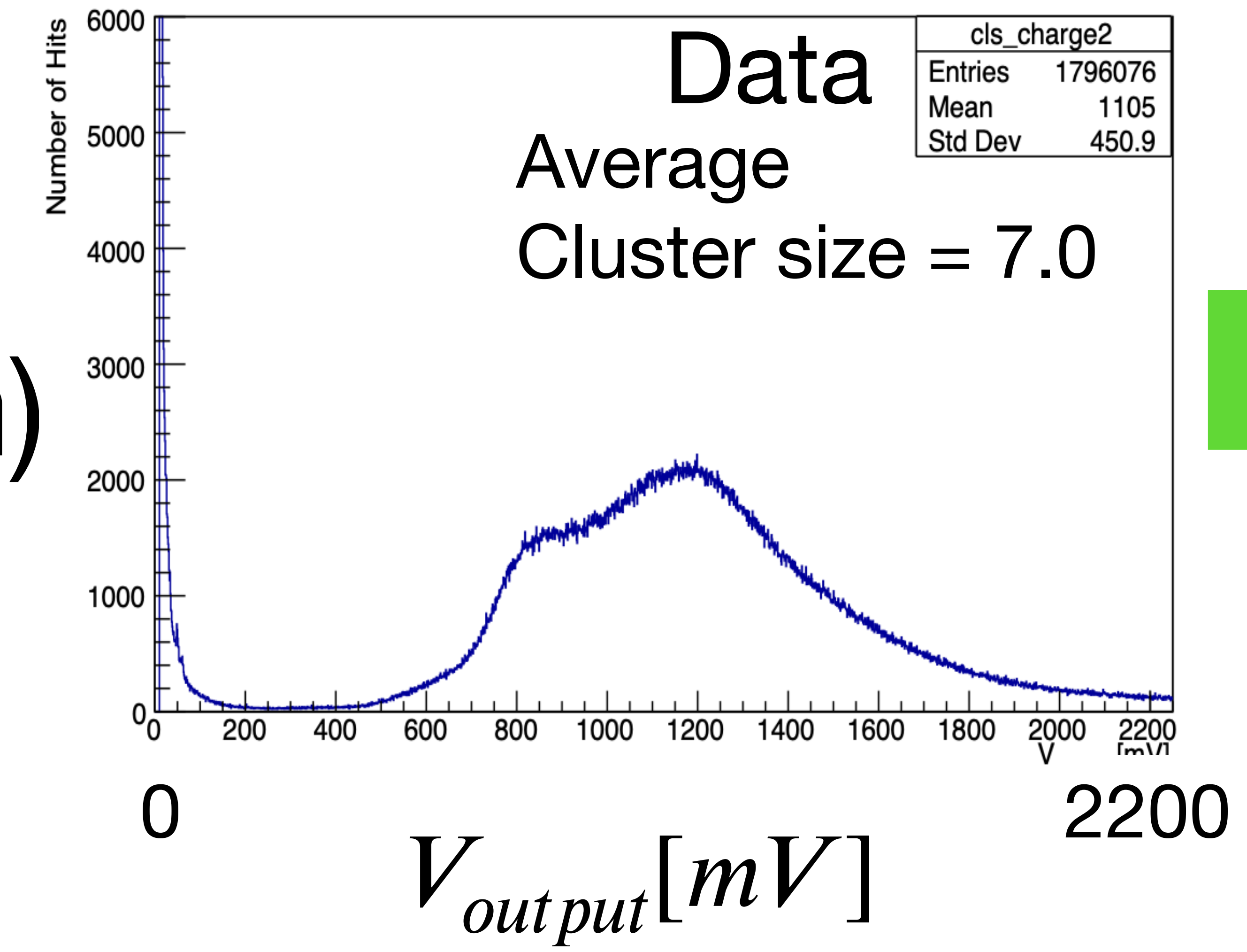




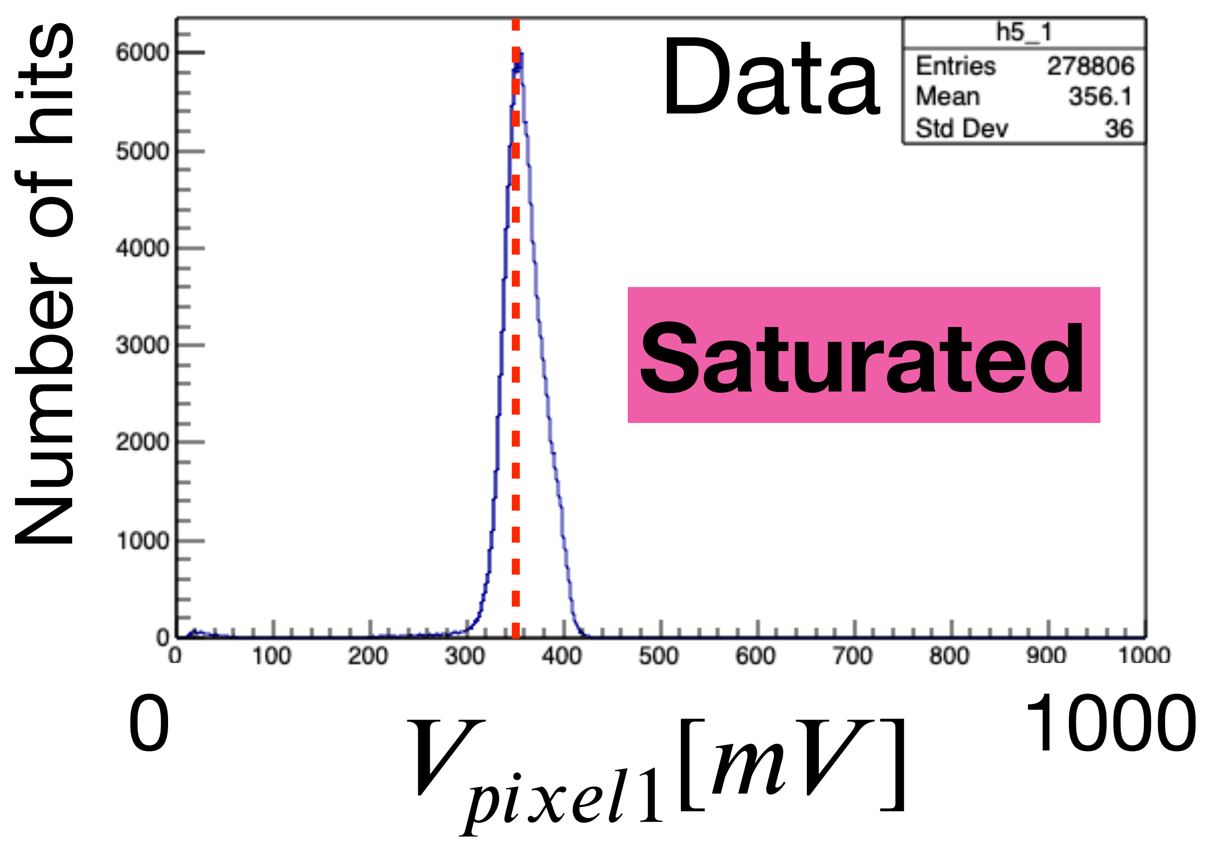
$V_{bias} = 400V$

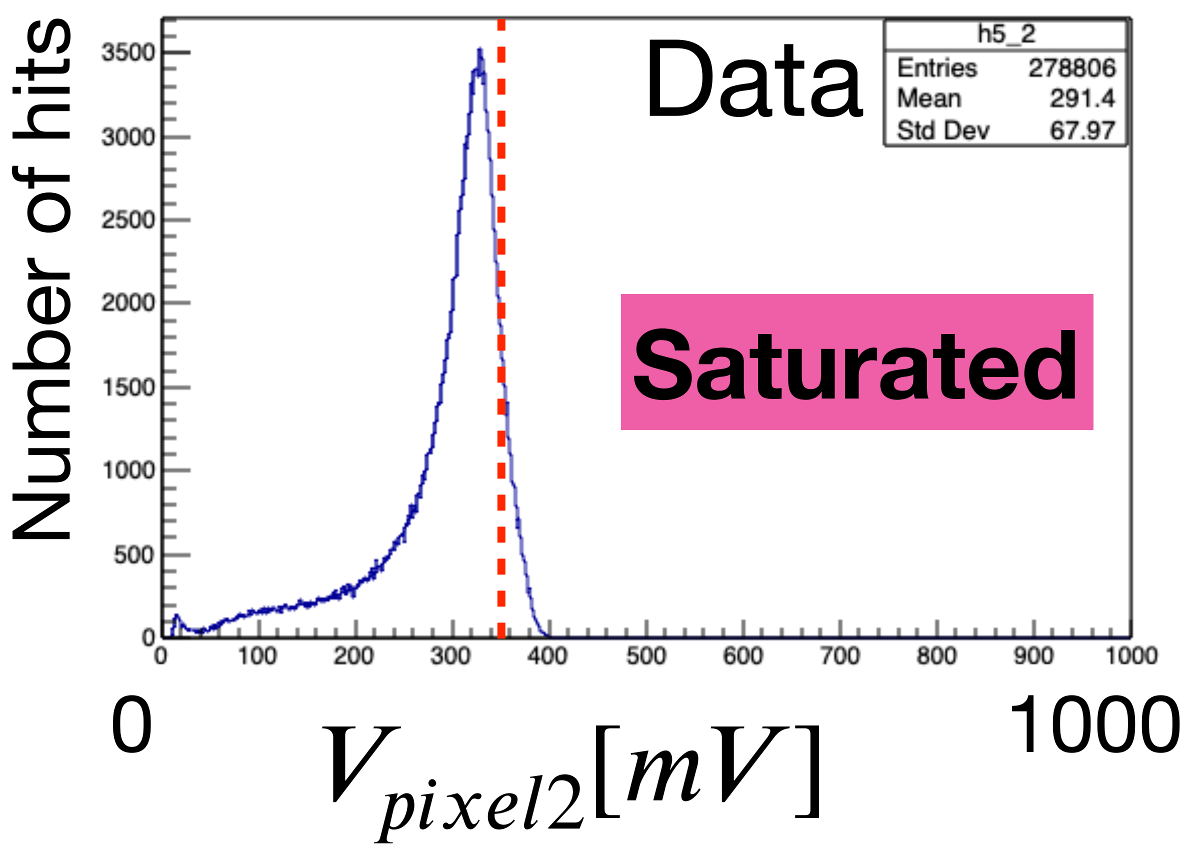
(depletion 200μm)

Cluster charge



Pixel charge (cluster size=5, $V_{pixel1}>V_{pixel2}>V_{pixel3}$)

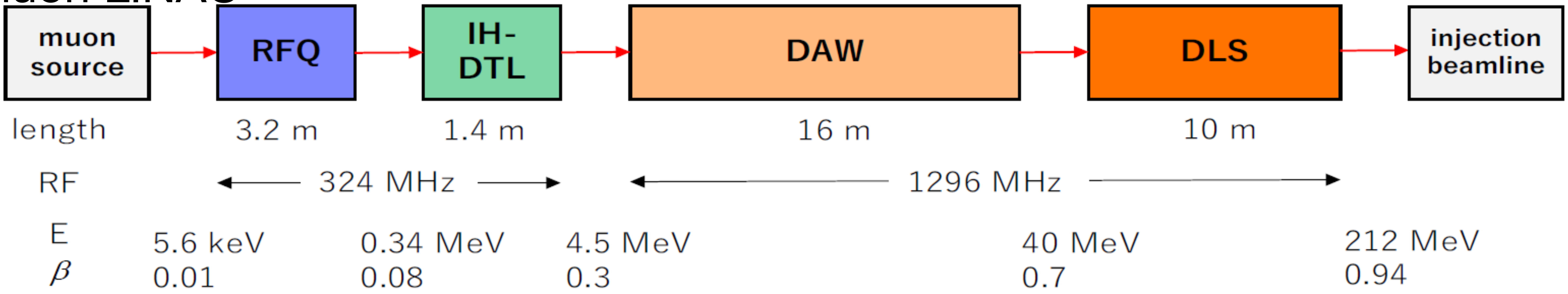




Saturation was also confirmed by SPICE simulation.
Dynamic range of the pixel : 350 mV (**50k e-h pairs**)

Estimation of multi-muon response (1)

muon LINAC



Multi-muon simulation

Average $N_{e\text{-}h \text{ per cluster per } \mu}$	18k	3.8k	2.5k
N_{μ} range to cover 97% Number of muon hit per pixel	4	6	8
Estimated $N_{e\text{-}h \text{ per } N_{\mu}}$ (Cluster size is not accounted for.)	72k (larger than 50k)	21.6k	20k

Single muon data at 4 MeV

Average $N_{e\text{-}h \text{ per pixel}}$ 19k

An estimation suggests saturation at lower energies.
A more realistic estimation is studied by using single muon data.

Estimation of multi-muon response

The pixel charge for the multi-muon hits in a pixel is estimated with 4 MeV single muon data.

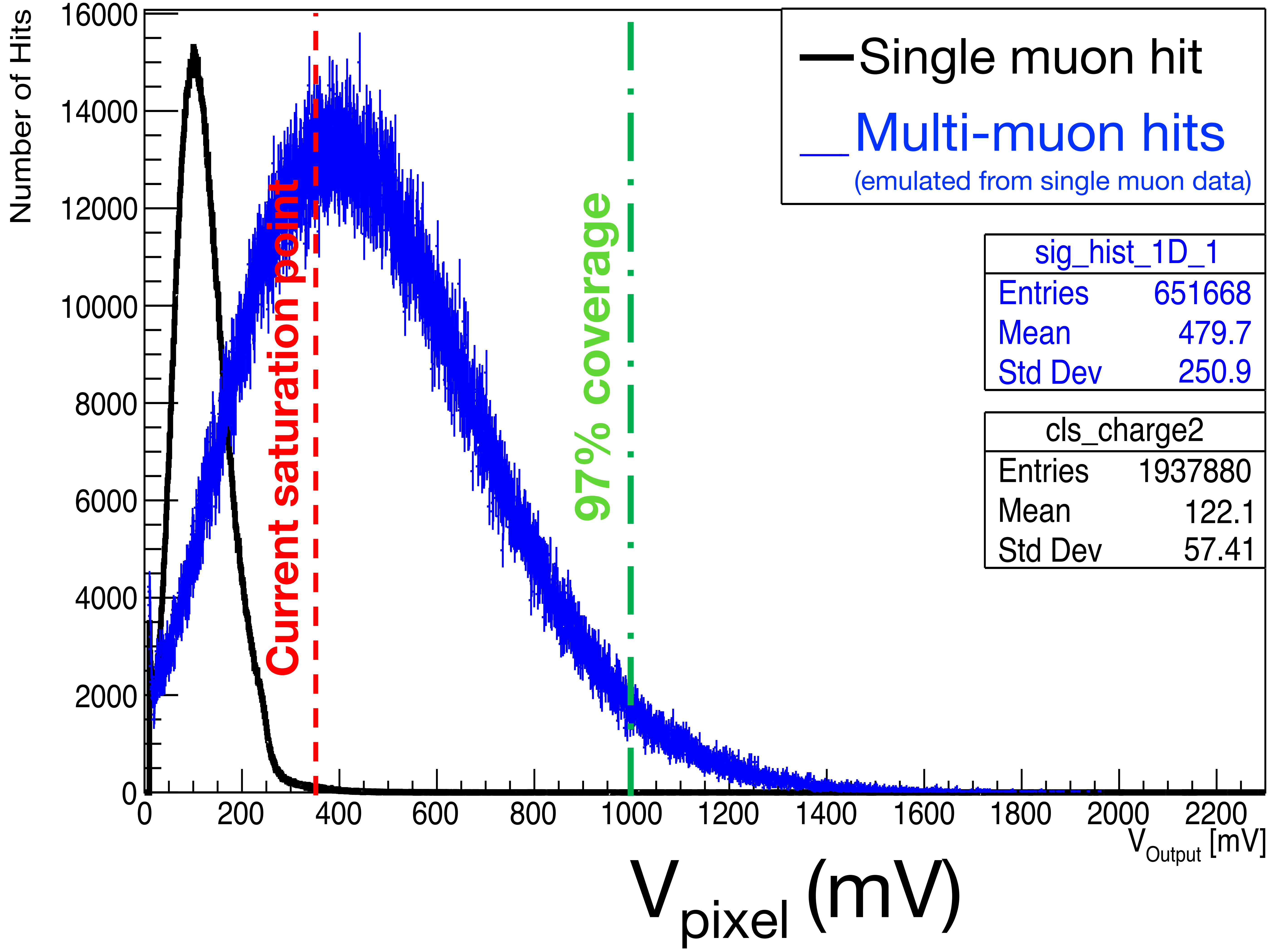
Average number of single muon cluster per beam pulse: $N_{cluster} = 2000$

Number of pixel: $N_{pixel} = 655{,}360$

Hit occupancy: $N_{cluster}/N_{pixel} = 3 \times 10^{-3}$

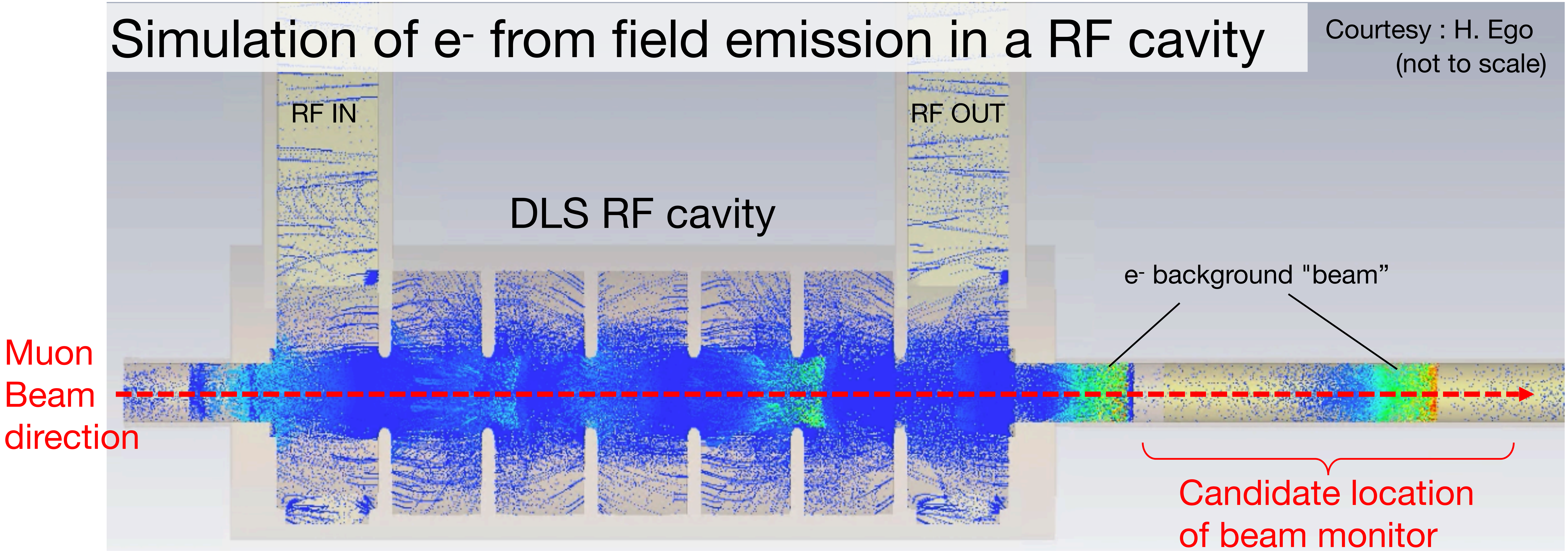
Therefore, pixel charge for multi-muon (n_μ=4) is estimated as

$$V_{pixel}(n_\mu=4) = \Sigma_{i=0,1334} V_{pixel}(i)$$



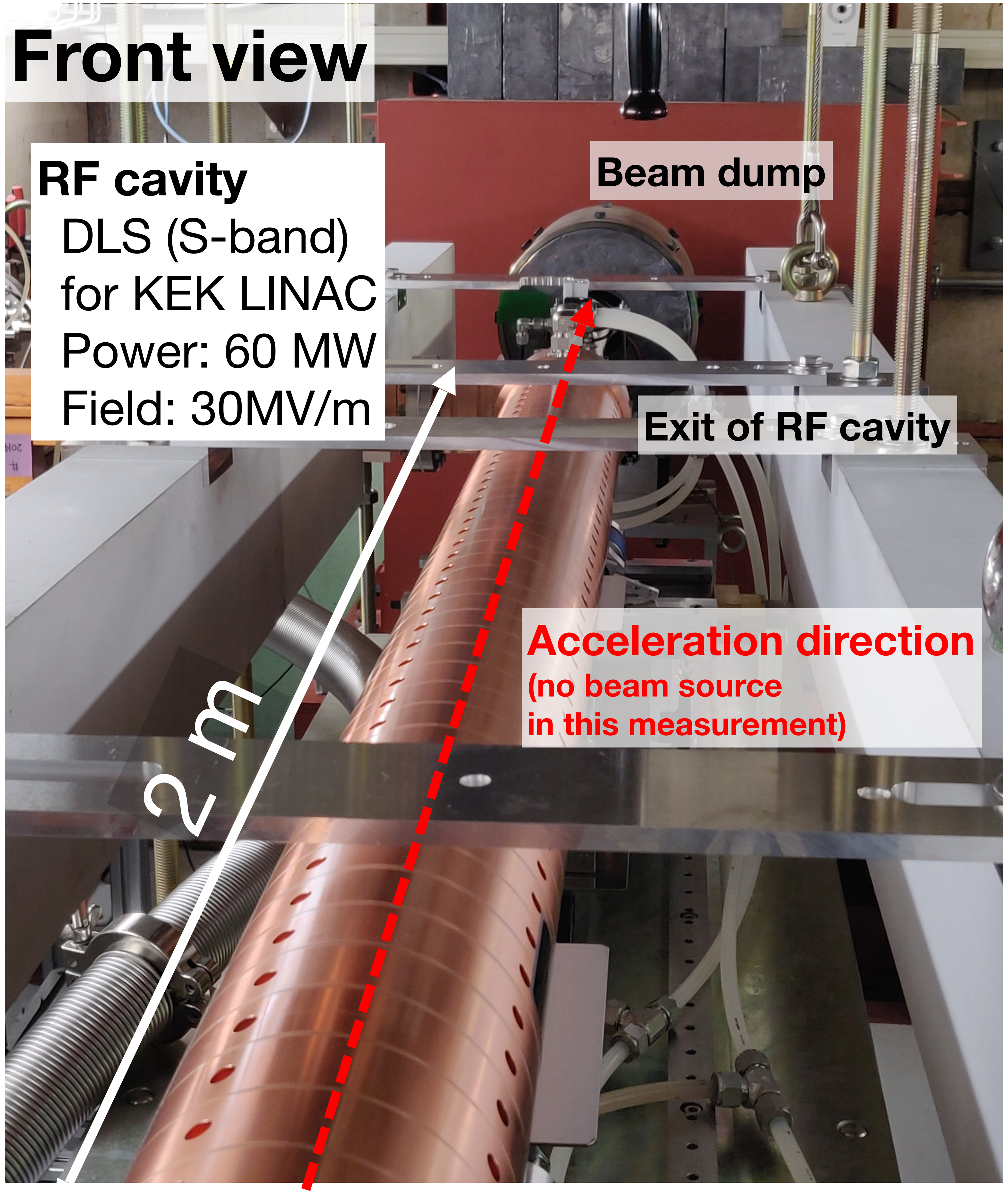
Gain must be reduced by a factor of 1000 mV / 350 mV = 2.9

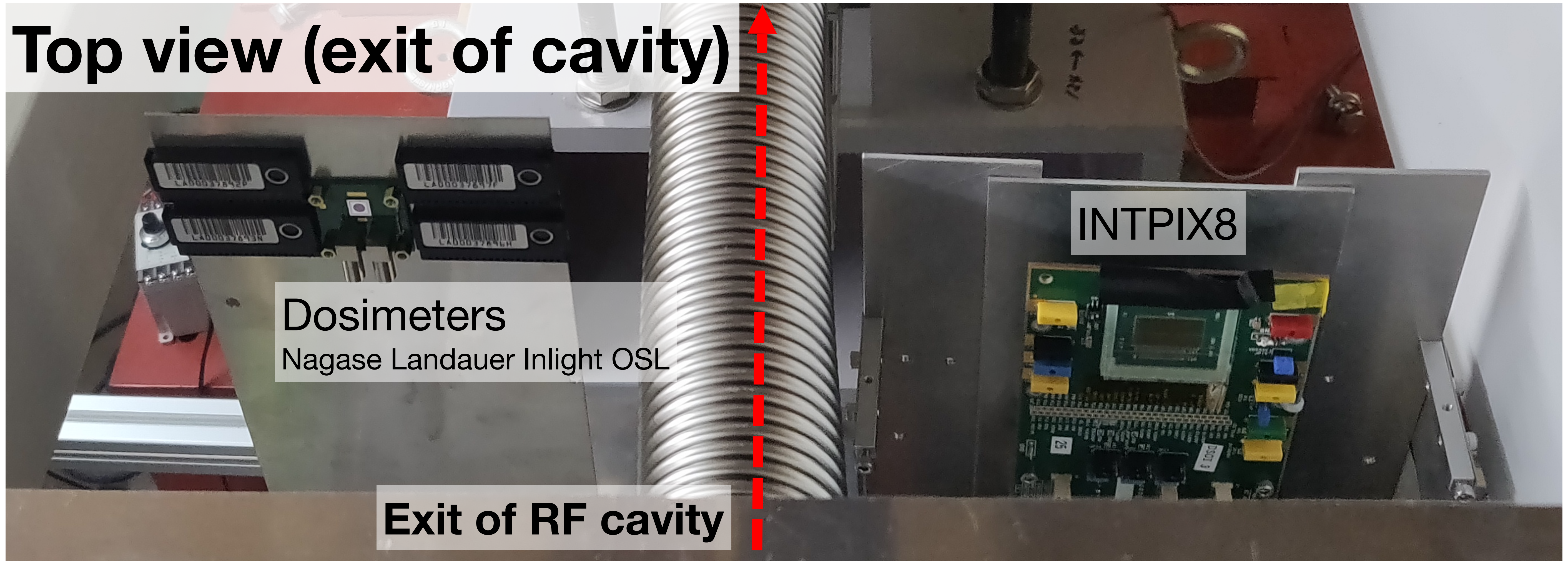
Radiation from RF cavities (1)

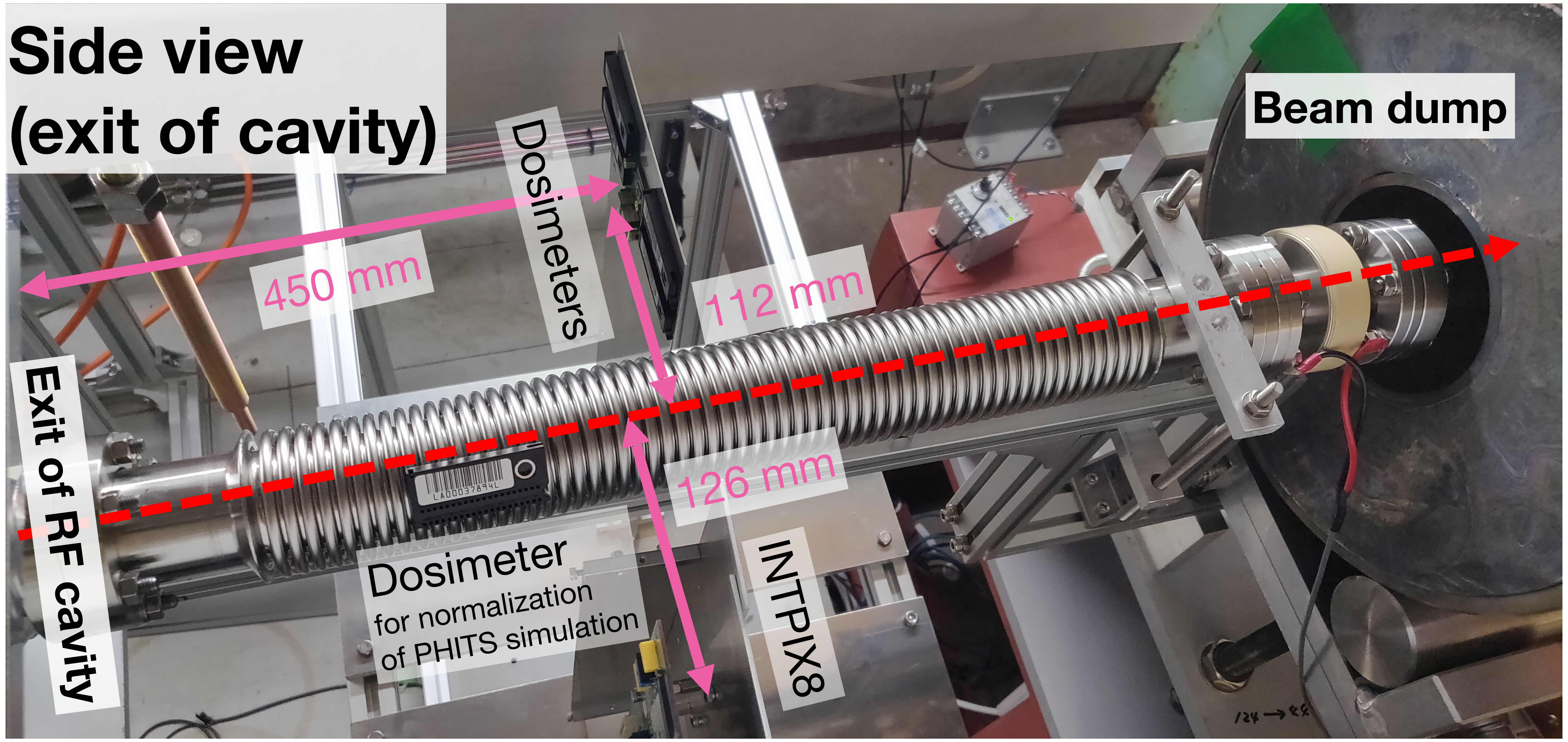


- RF cavities generate radiation due to field emission on the cavity surface.
- The radiation from the Disk-Loaded Structure cavity and response to INTPIX8 were evaluated.

Radiation from RF cavities (2)

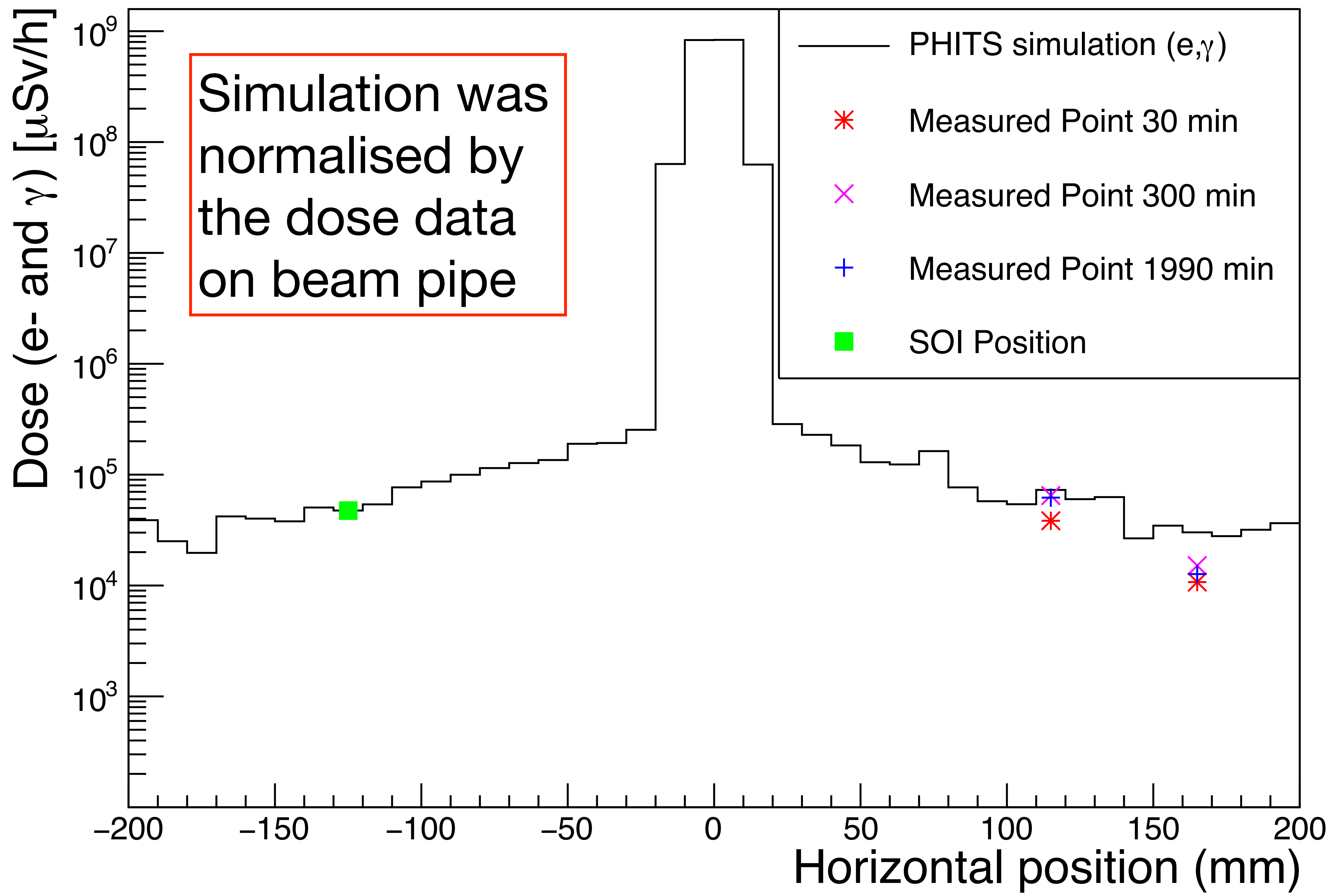




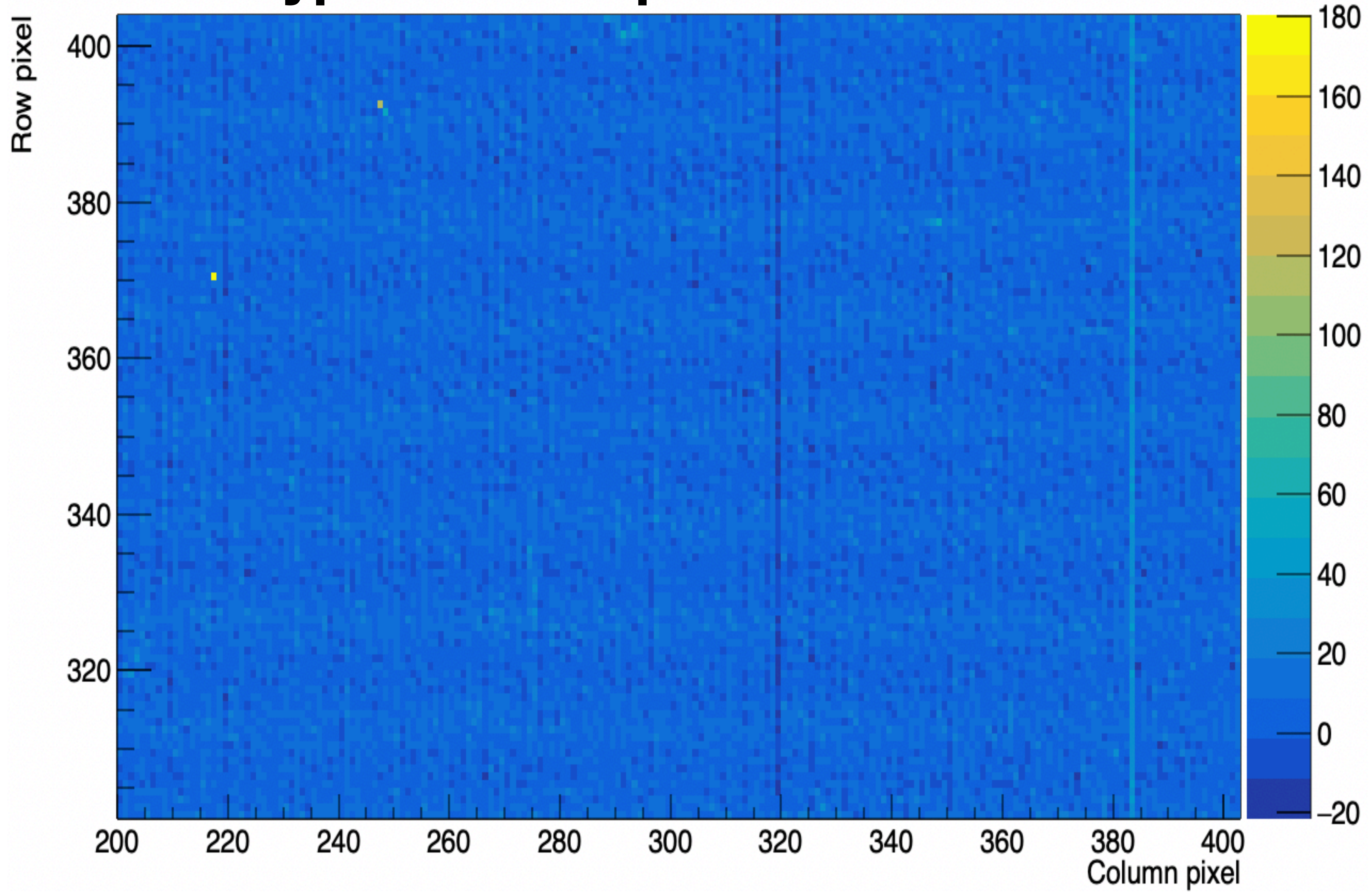


Radiation from RF cavities (3)

Dose measurements and simulation (PHITS)



Typical hit map for DSOI V_{bias} = 5V



- Expected 1k Sv/h (= 1k Gy/h for e^-,γ) on beam axis.
- Radiation tolerance ~1MGy for DSOI * → Challenging for long-term operation.
- Data analysis is ongoing

* K. Hara, et al., NIMA 924, 426 (2019)

Summary

- The J-PARC muon g-2/EDM experiment relies on a novel muon beam obtained by re-acceleration of thermal muons.

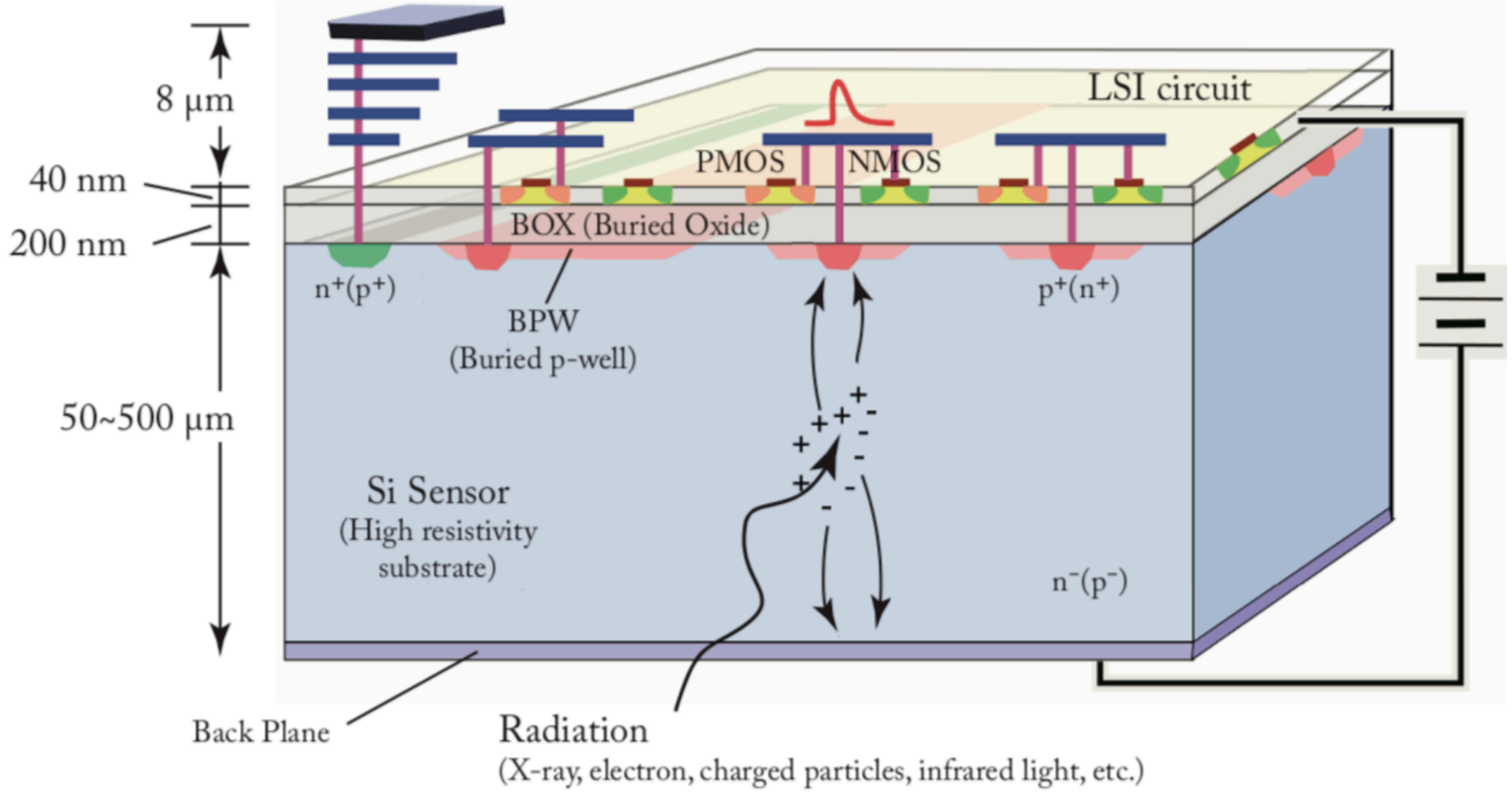
- The INTPIX8 was evaluated as a sensor for a muon beam profile monitor.

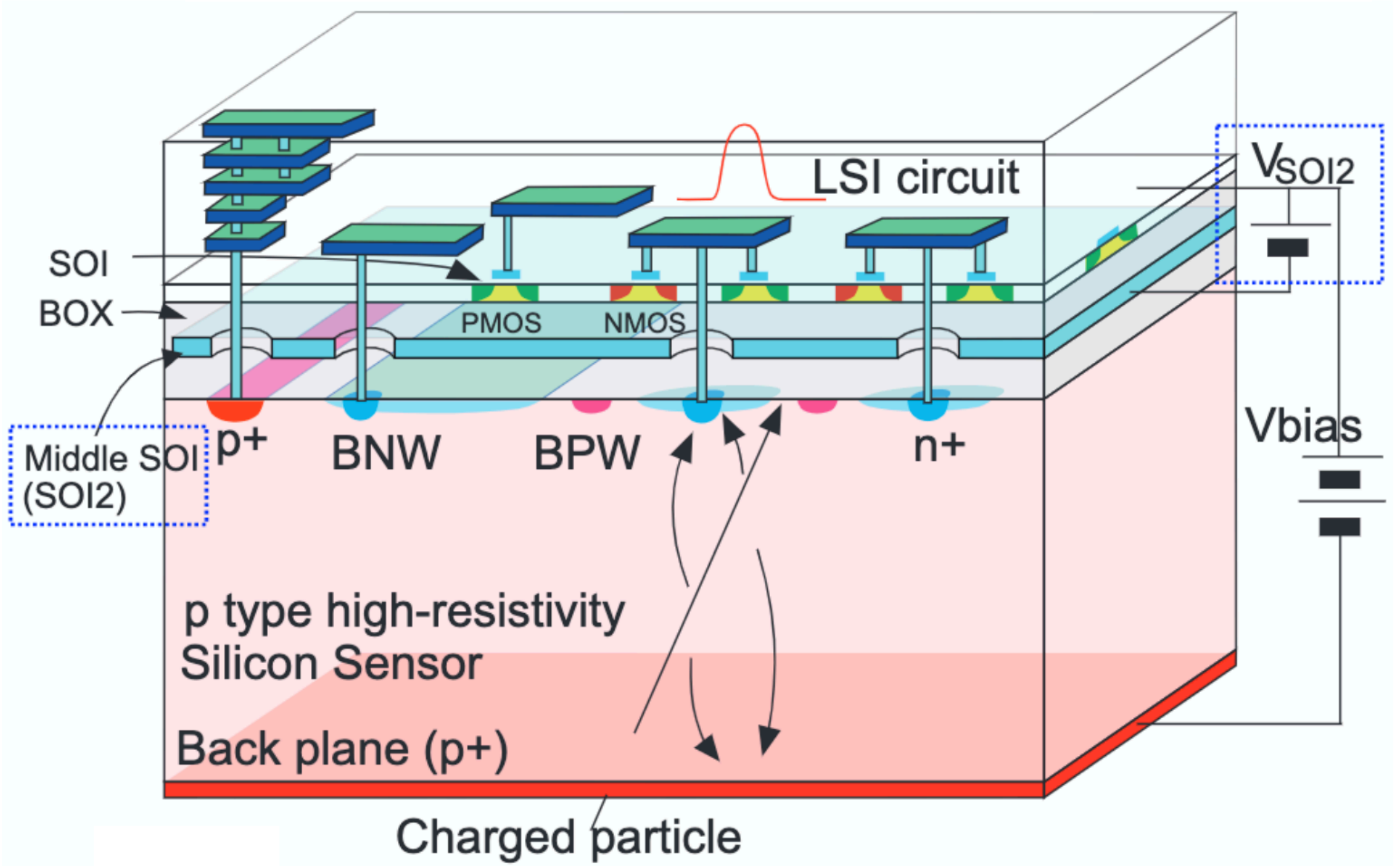
- Reduction of gain is necessary at the energy region at around 4 MeV.

- Operation in the vicinity of a DLS-type RF cavity was tested. At the peripheral location, the sensor was functional after the exposure. Radiation dose at the on-beam location is challenging.

Back up

SSOI vs DSOI

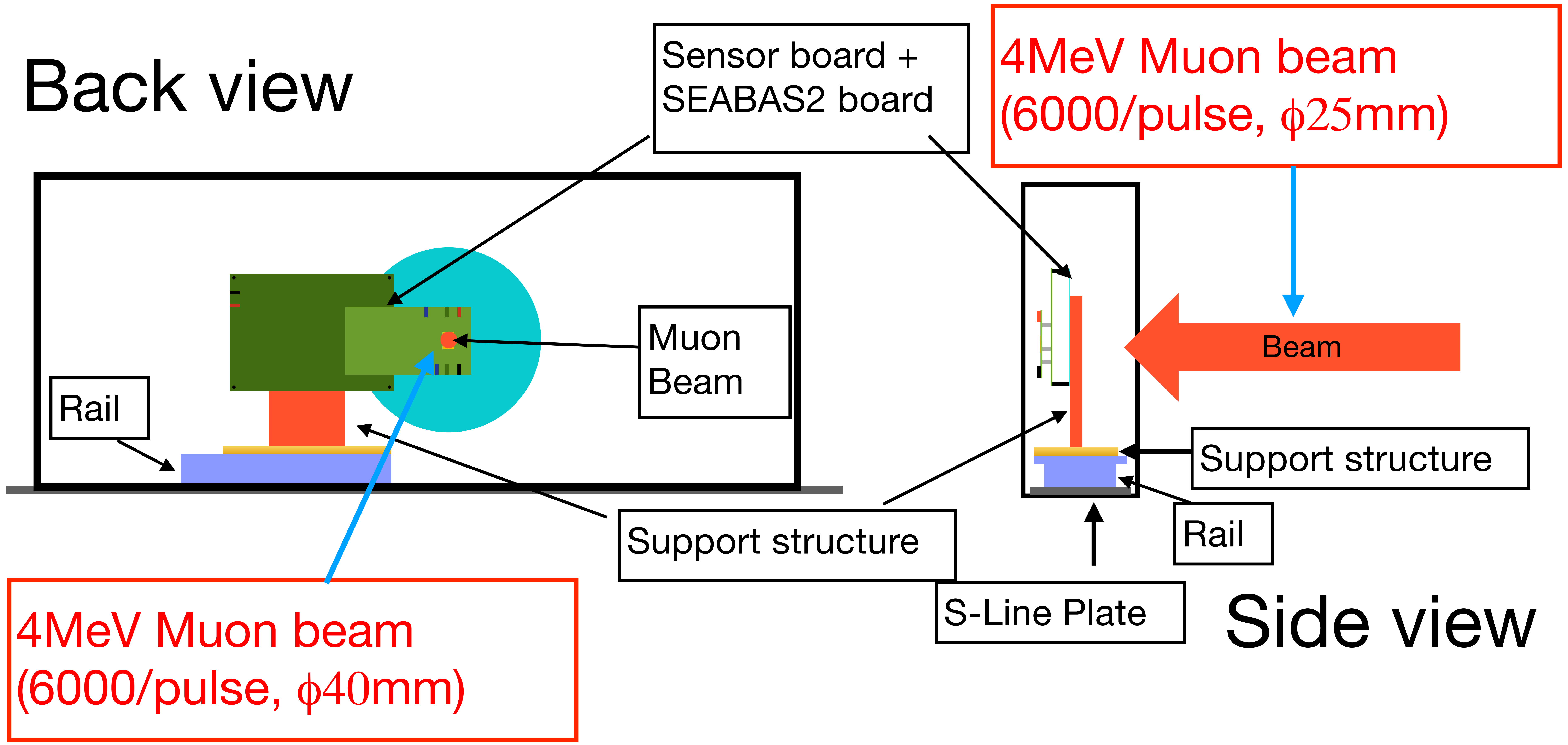




	SSOI	DSOI
Thickness	500 μm	300 μm
Full depletion	Can be reached	Can not be reached before brake down
Pros	• Cheap to manufacture • Commercially available wafer	• Second Si layer suppresses the cross talk effect • Radiation hardened
Cons	• Can't handle high radiation • Cross talk effect	• Custom wafer • Expensive

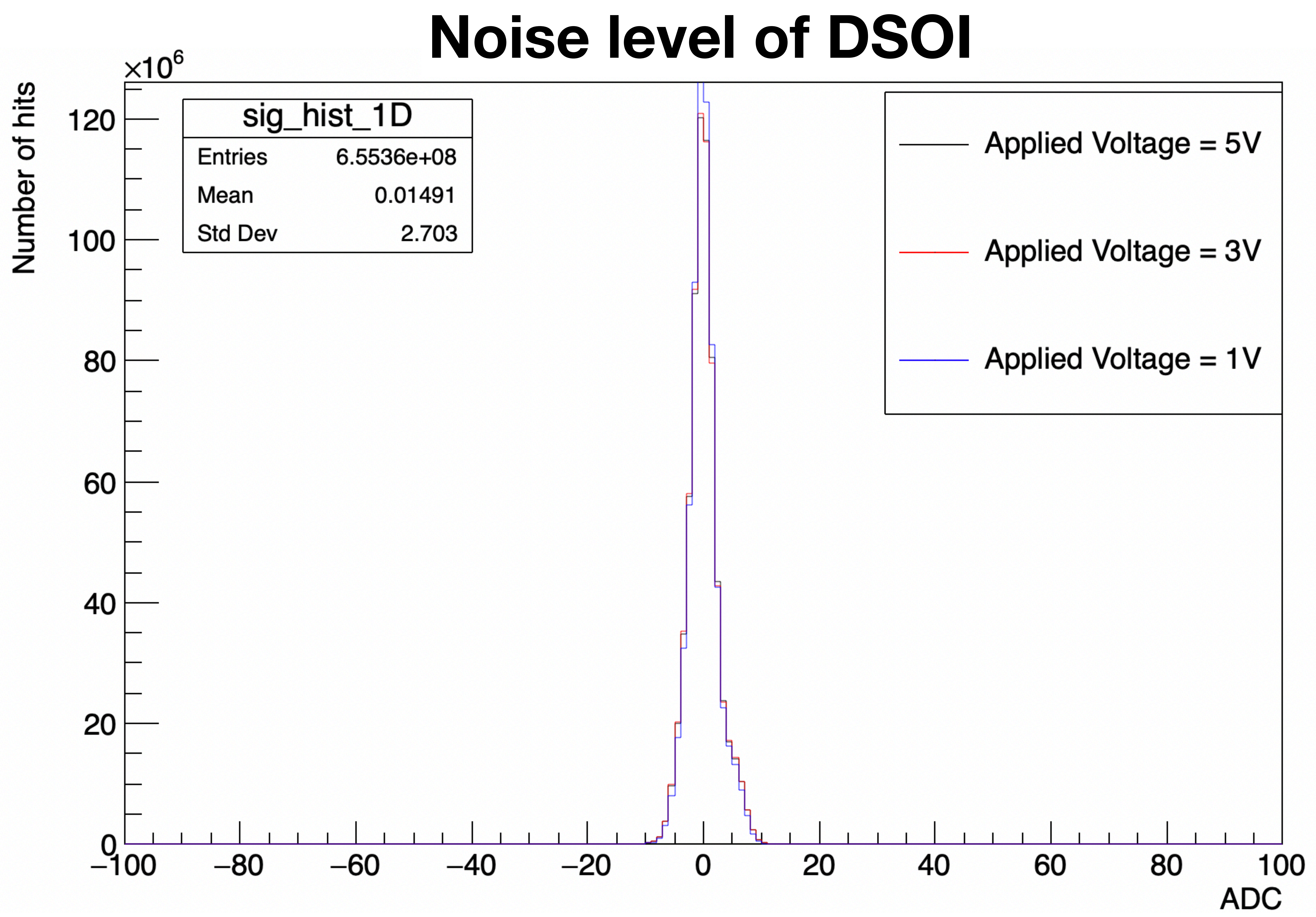
Single muon response (1)

Illustration of Set up



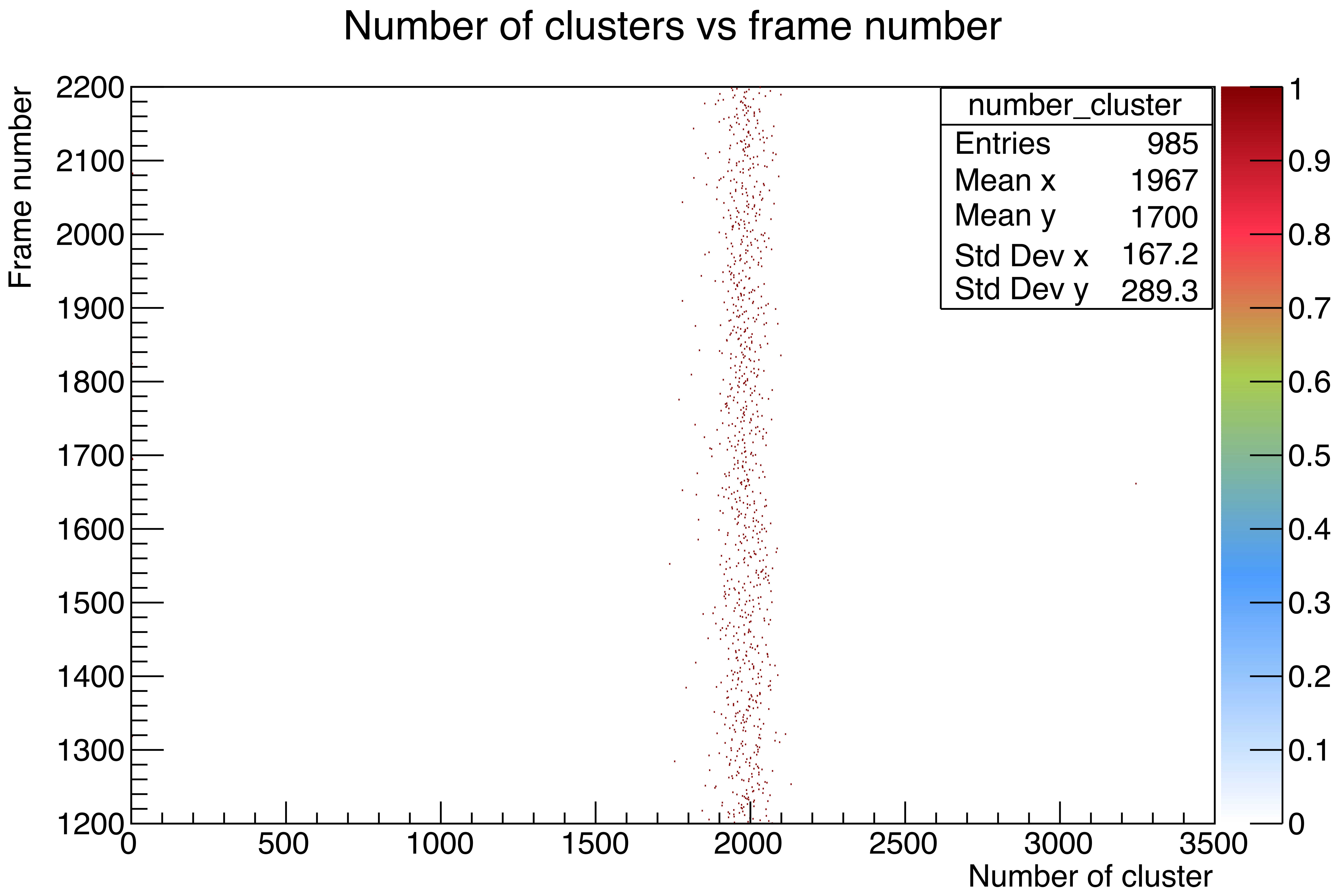
DOSI Noise level

- The noise signal is at the level of 2.7 ADC (1.4 mV) DSOI
- However there was some noisy pixels
- A threshold was set higher to reduce the effect of noise
  - 20 ADC (10 mV) DSOI

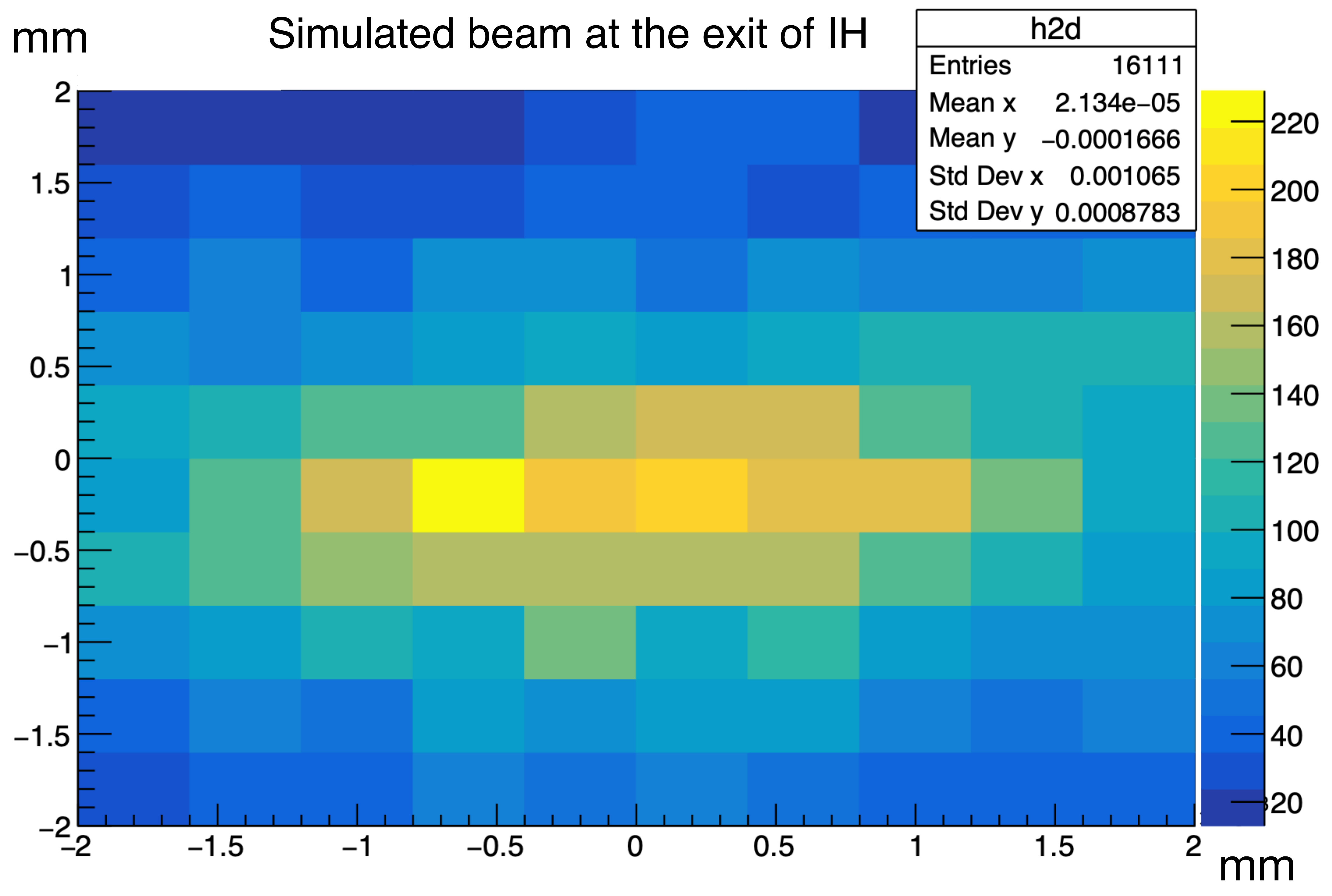


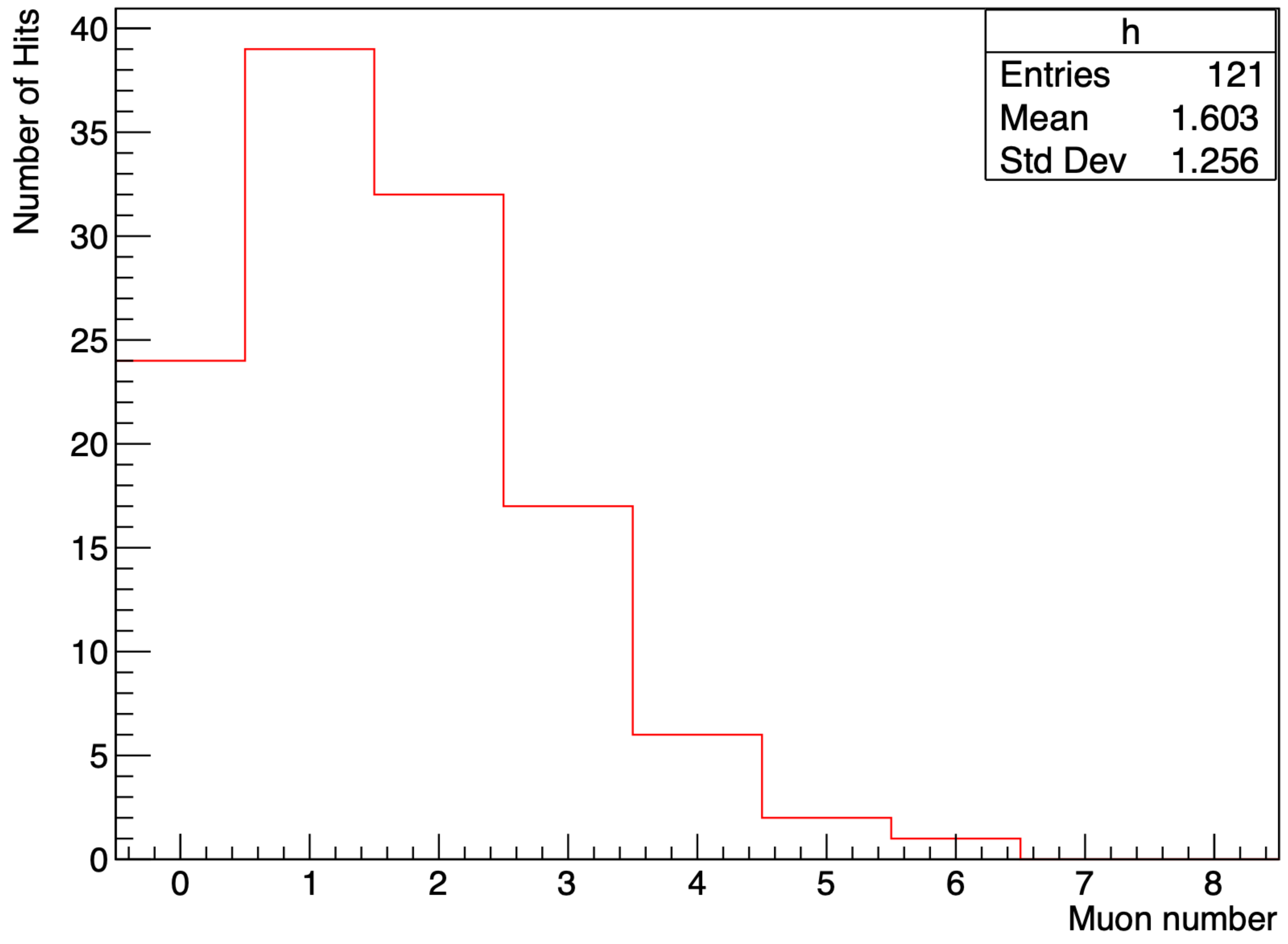
Single muon response (1)

DSOI 5V
Average number of clusters per frame
2000



Estimation of number of muon per pixel

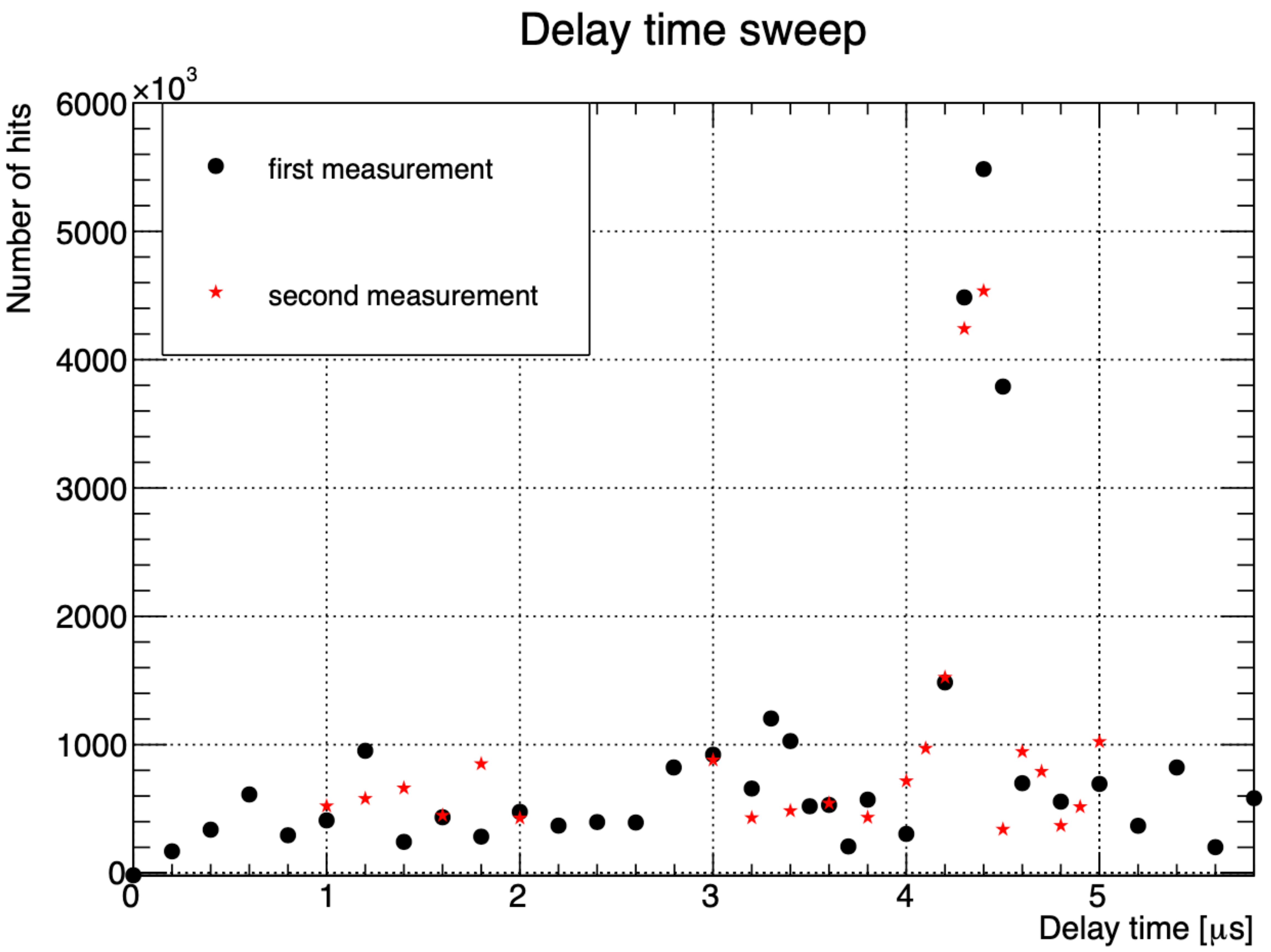


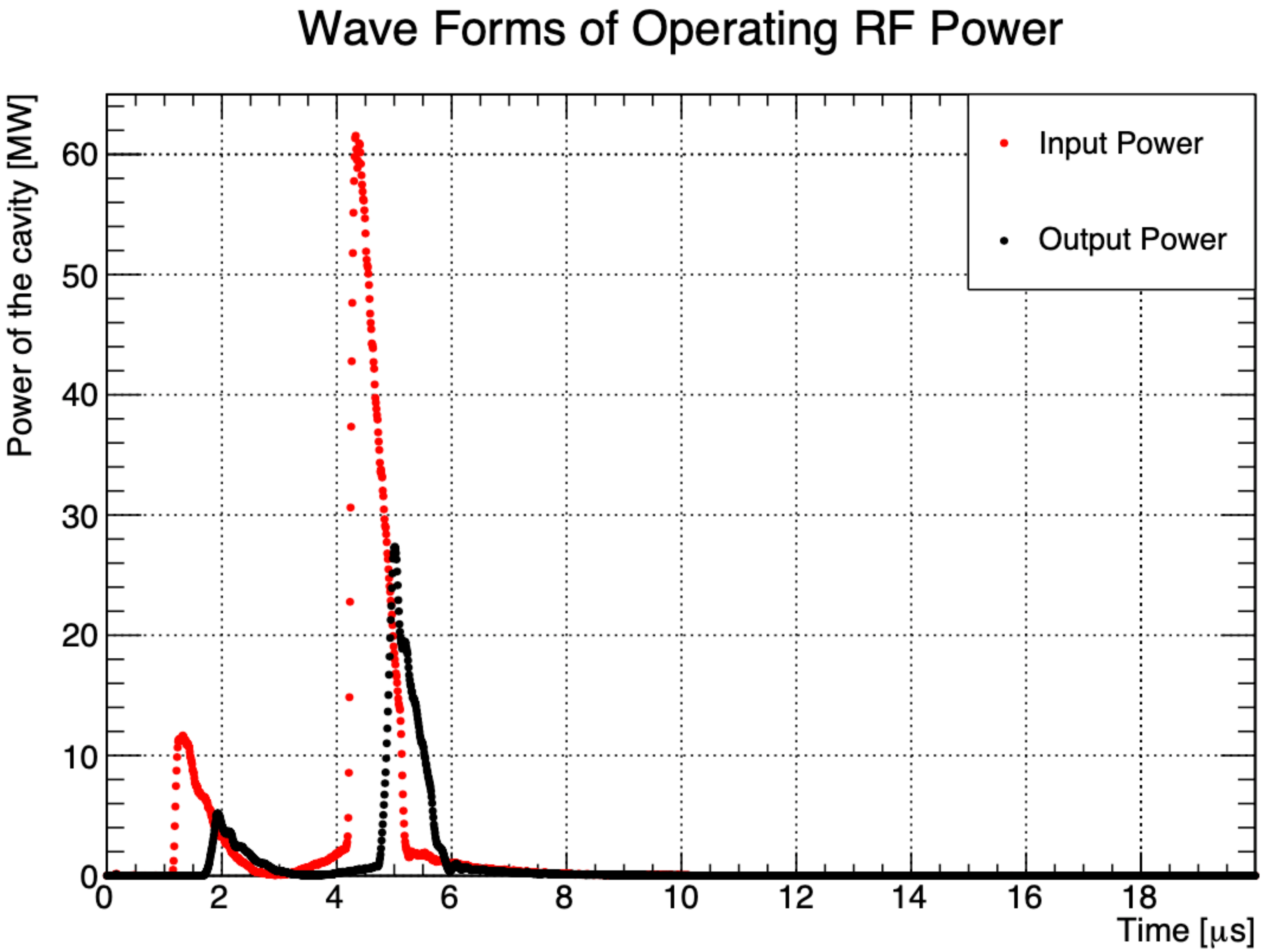


- The muon distribution in a bin follows Poisson distribution
- The simulated beam has a lower intensity than the muon LINAC (4×10^4 per spill)
  - Used Poisson distribution to plot
- To detect 97% of the beam, the number of muons per pixel should be 4
- Similar estimation was done for beam at the end of DLS and DAW
  - The number of muons per pixel at DAW 6
  - The number of muons per pixel at DLS 8

Simulated Data provided by Masashi Otani

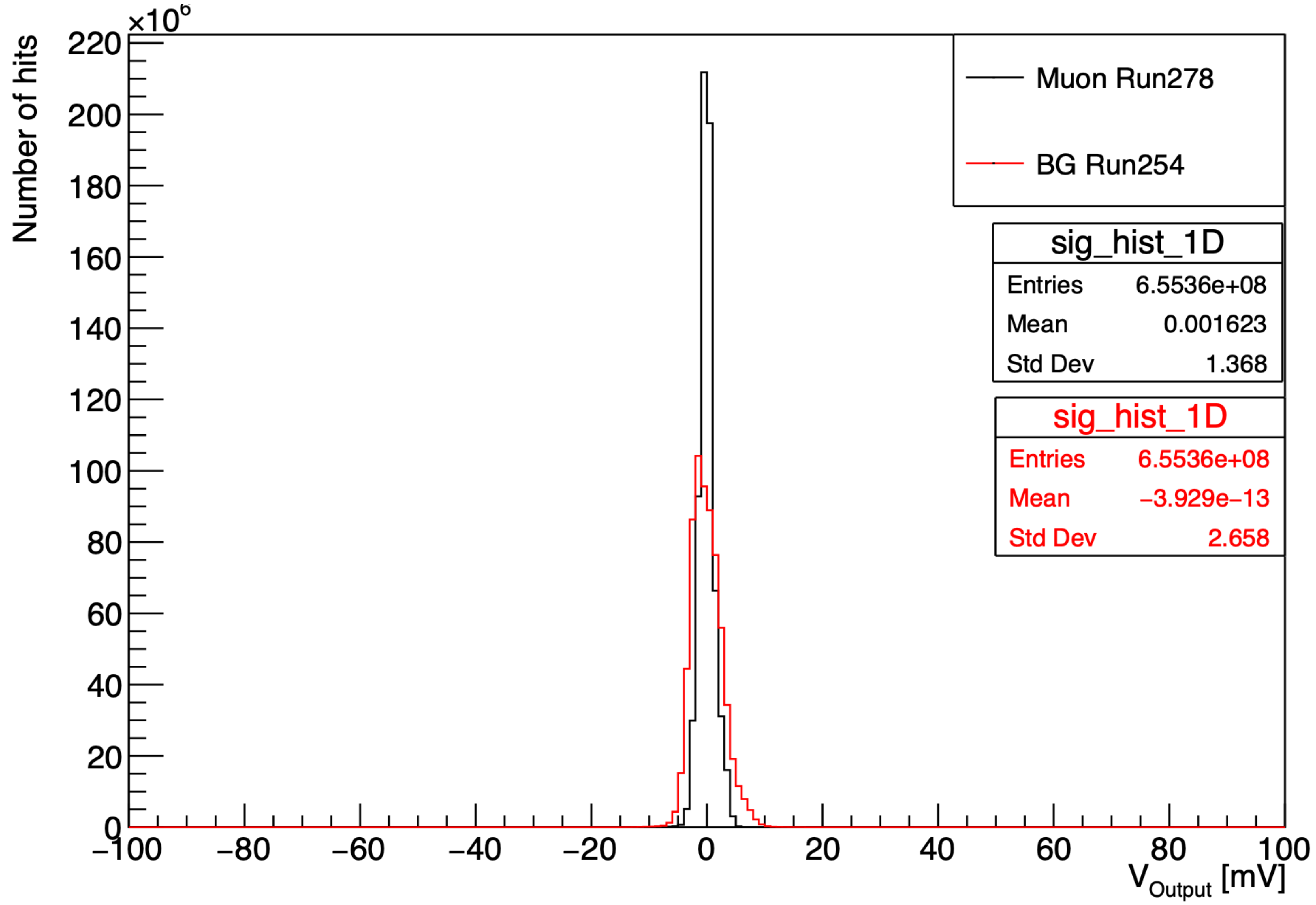
Radiation from RF cavities

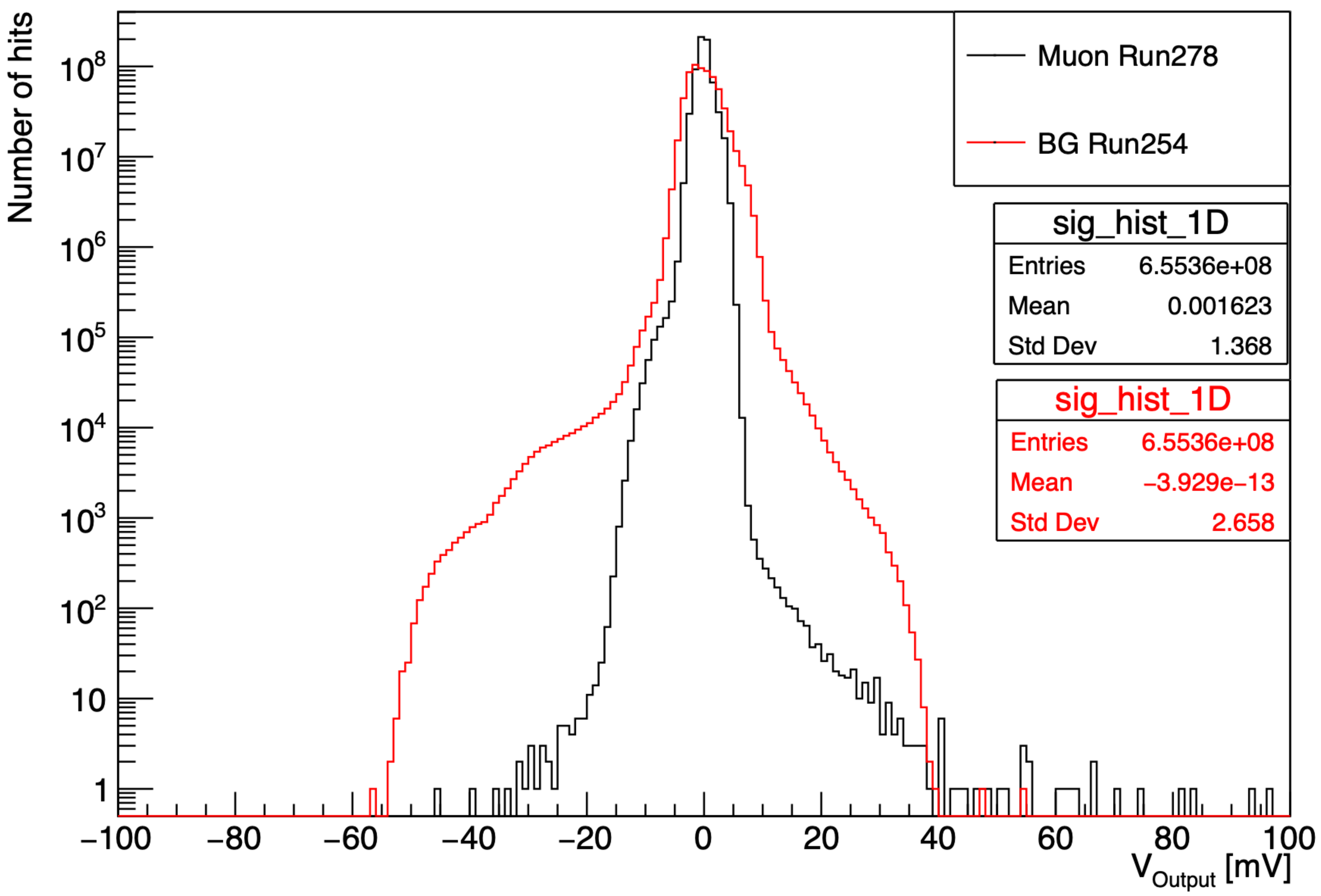




Background measurements Noise

DSOI, 5V bias voltage
Irradiated for 7 hours





- The background measurement noise level is ~ 2 times higher then the muon beam test (reason unknown)
  - This is still well below the muon signal observed during the muon beam test