JSPS Core-to-Core Program

東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

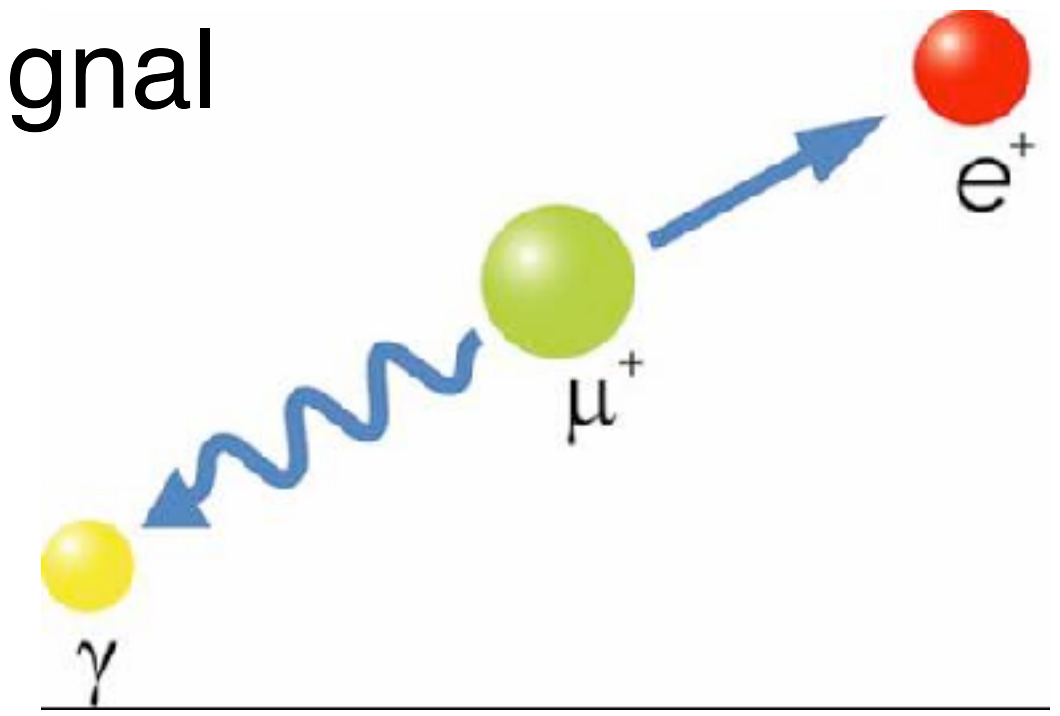
SiPMs in the liquid xenon gamma-ray detector for MEG II experiment

Toshiyuki Iwamoto
on behalf of the MEG II collaboration
The University of Tokyo

Nagoya Workshop on Technology and Instrumentation in Future Liquid Noble Gas Detectors
14–16 Feb 2024 @ Nagoya University

MEG II Experiment

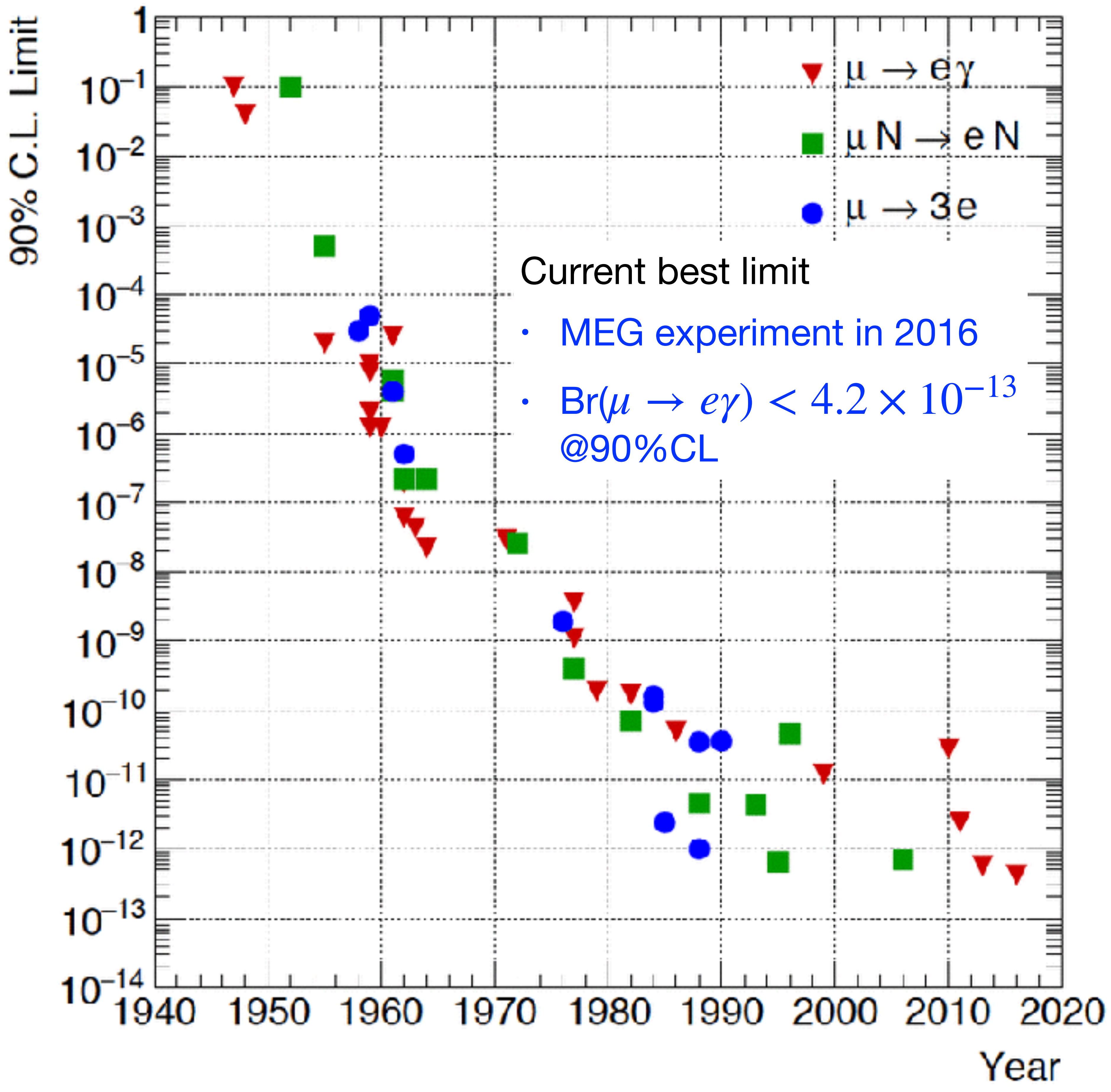
- Search for charged lepton flavor violating decay $\mu \to e\gamma$ as clear evidence of BSM physics
  - Current best limit: Br$(\mu \to e\gamma) < 4.2 \times 10^{-13}$ by MEG experiment
  - Goal of MEG II sensitivity: $(5-6) \times 10^{-14}$
- $\mu \to e\gamma$ signal



$$E_\gamma, E_e \sim 52.8\ MeV$$

$$\Theta_{e\gamma} = 180^\circ, T_\gamma = T_e$$

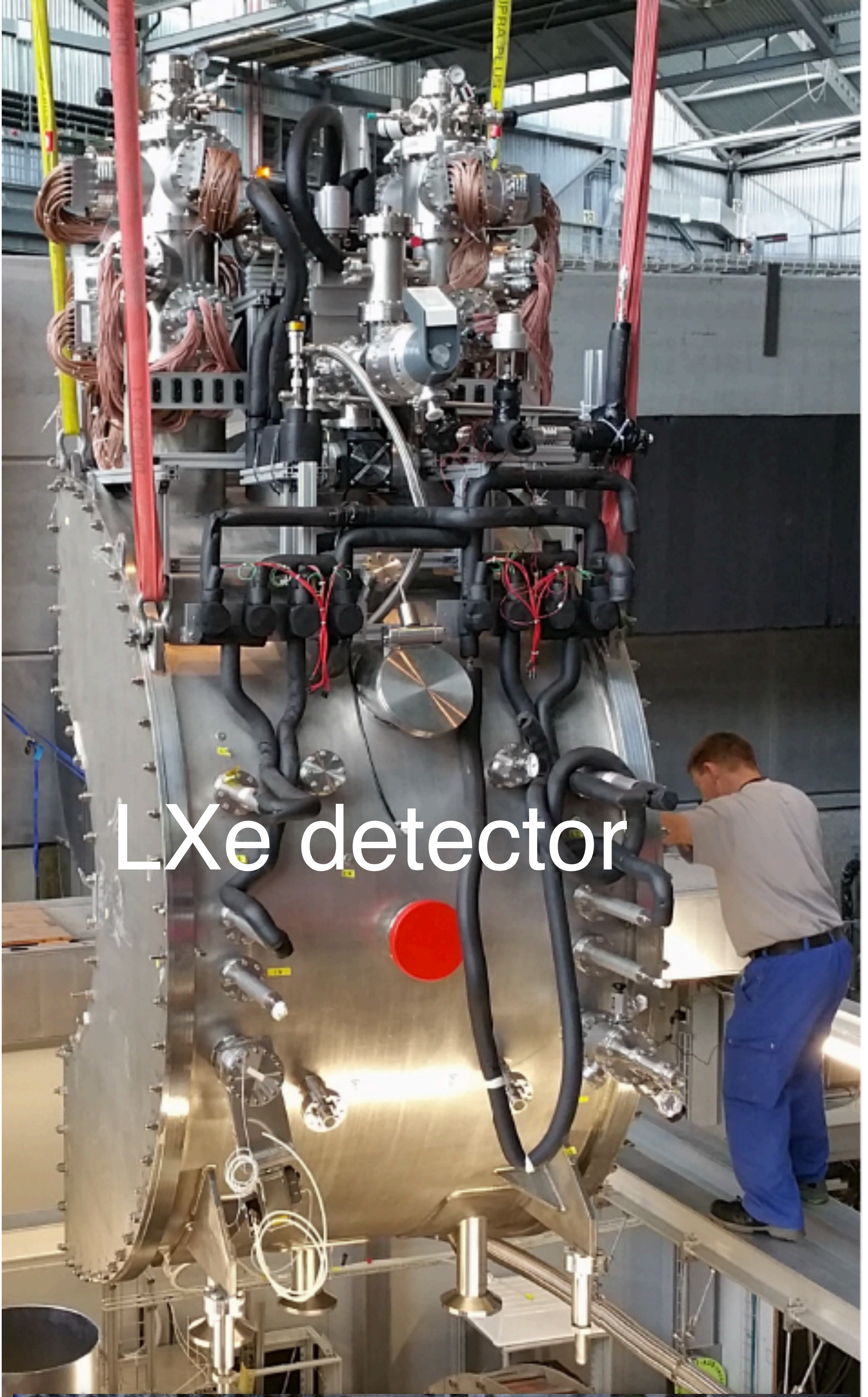
- Background
  - Accidental background is our dominant source
- Sensitivity improvement
  - High intensity muon beam (large statistics)
  - Good detector resolution (low background)

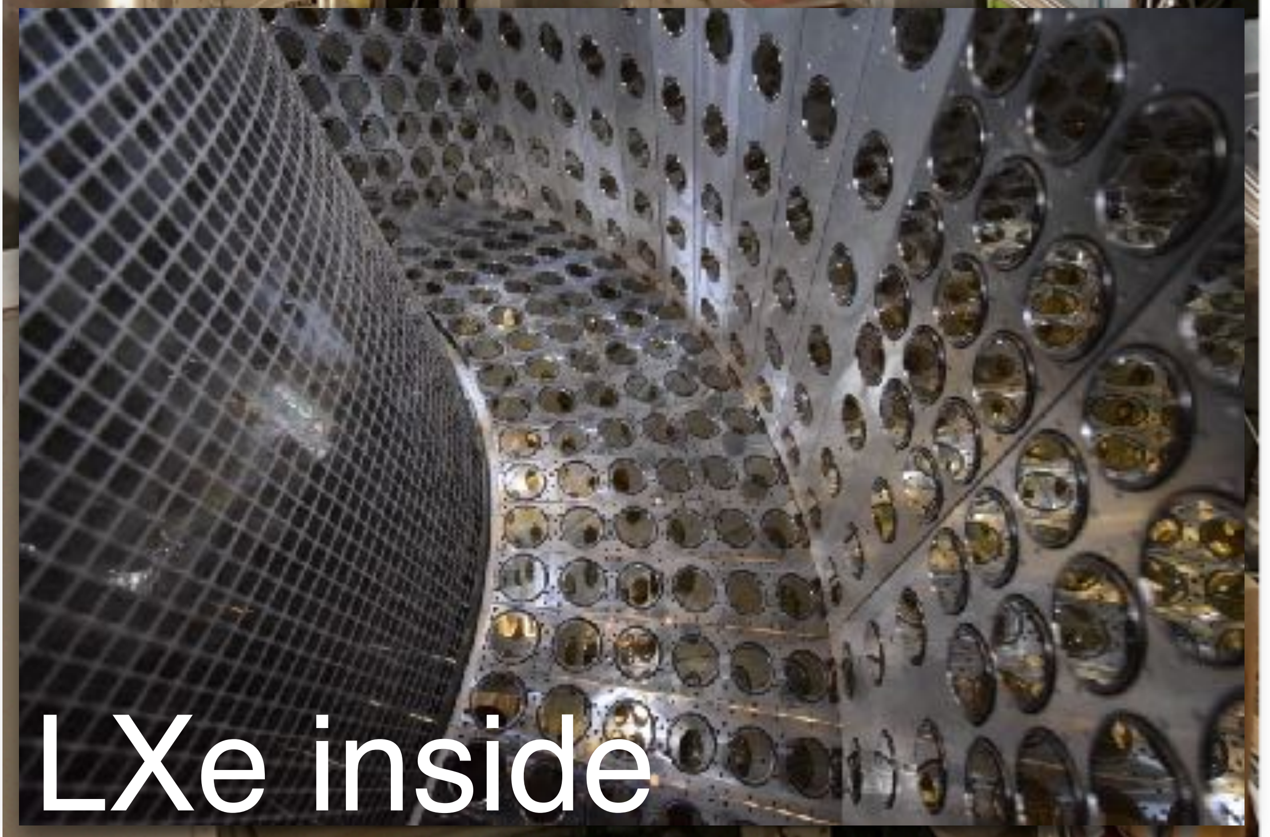


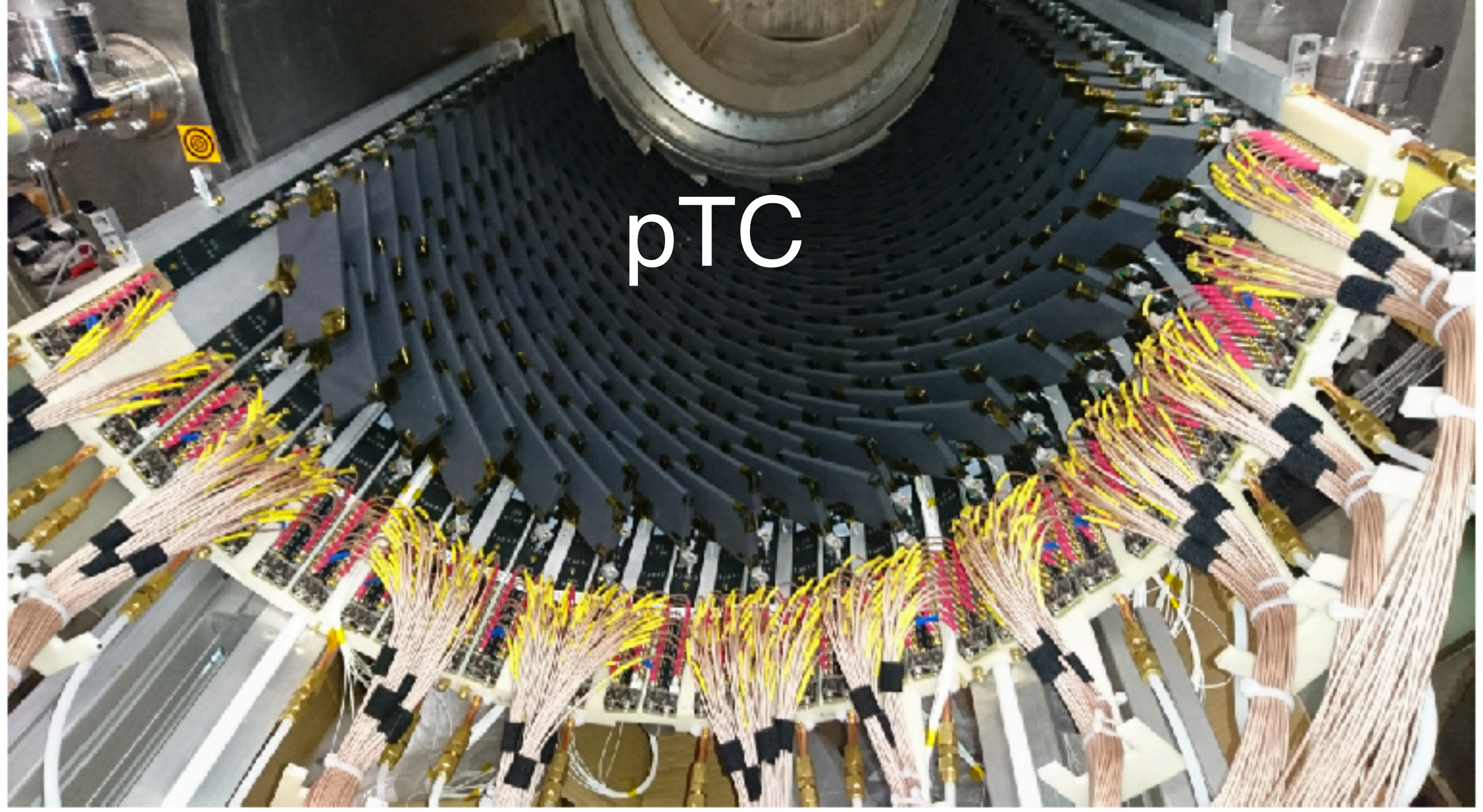
Paul Scherrer Institute in Switzerland

590 MeV 2.4mA proton ring cyclotron

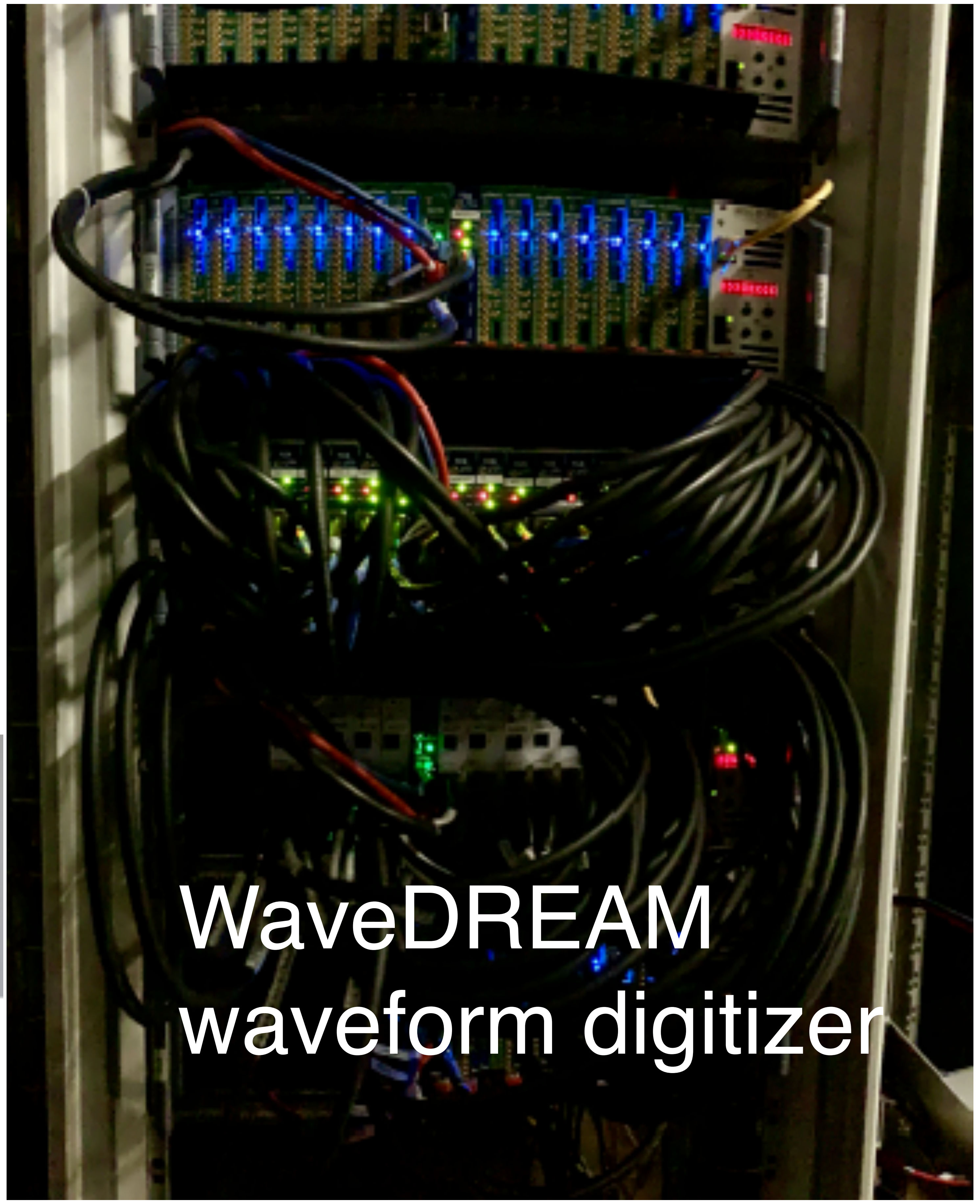
MEG II Experiment

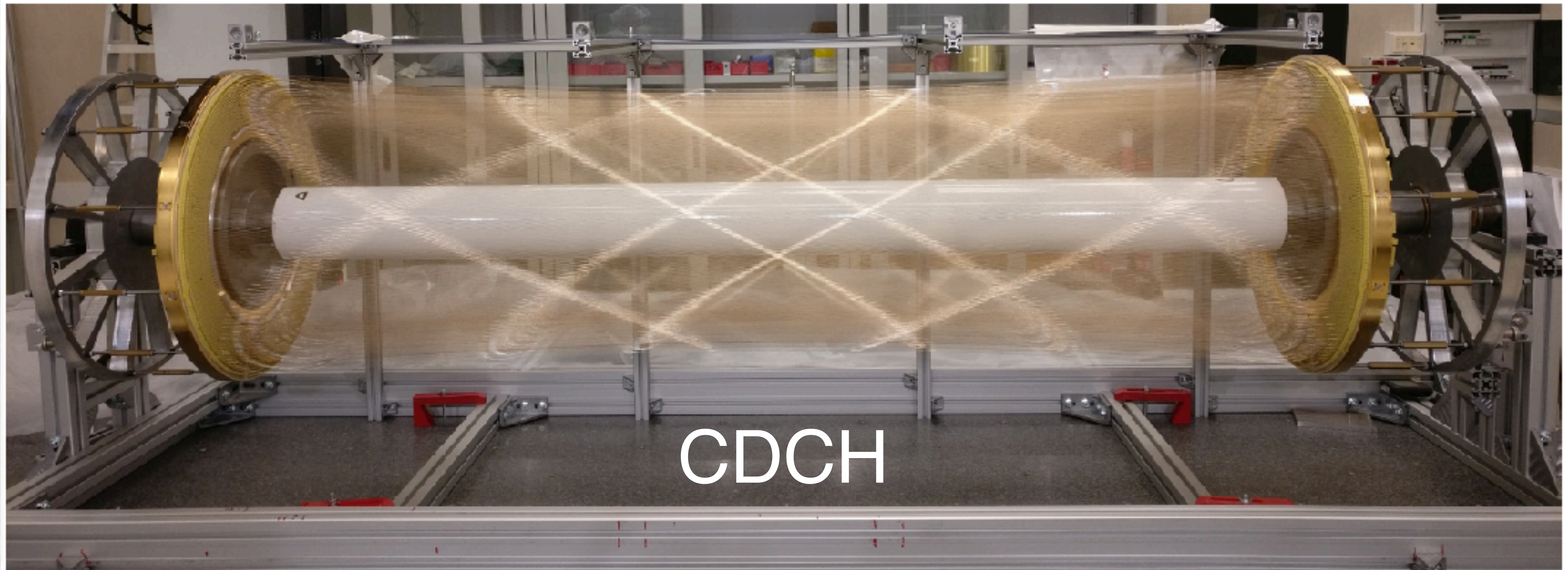


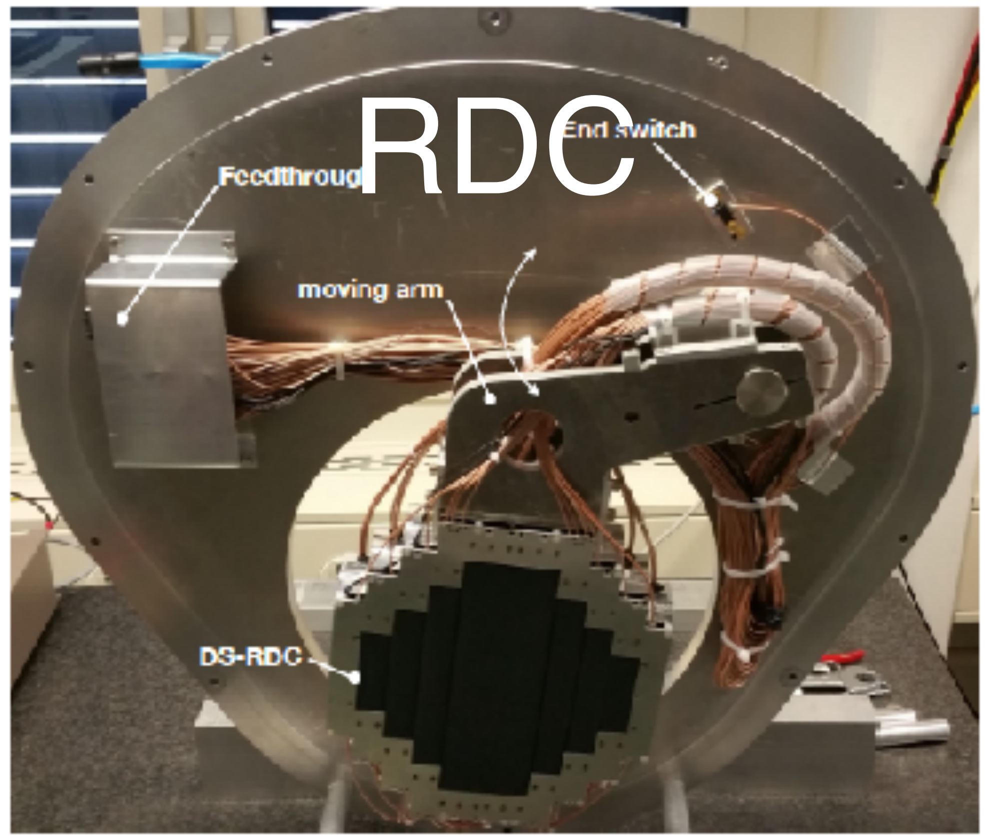




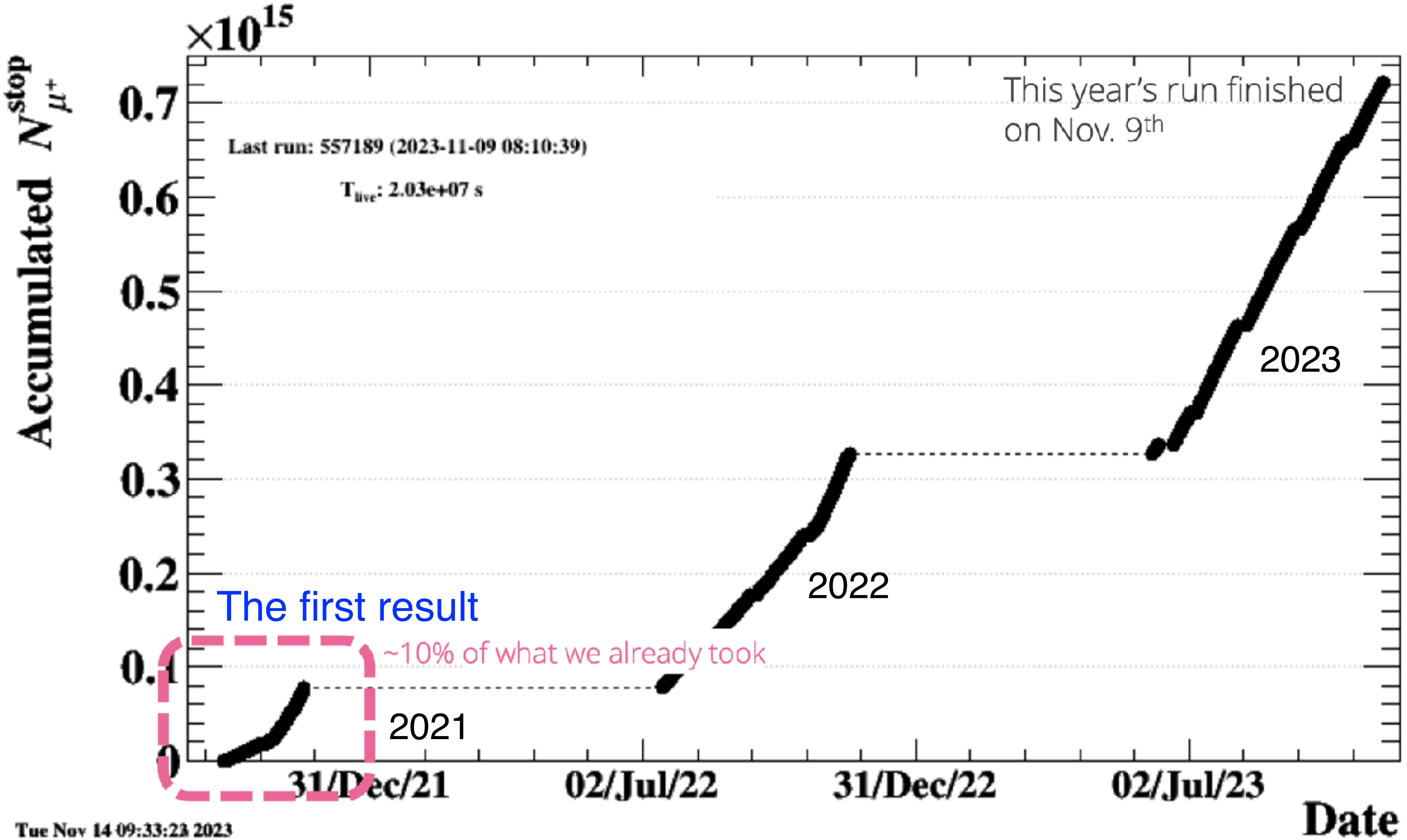
MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-



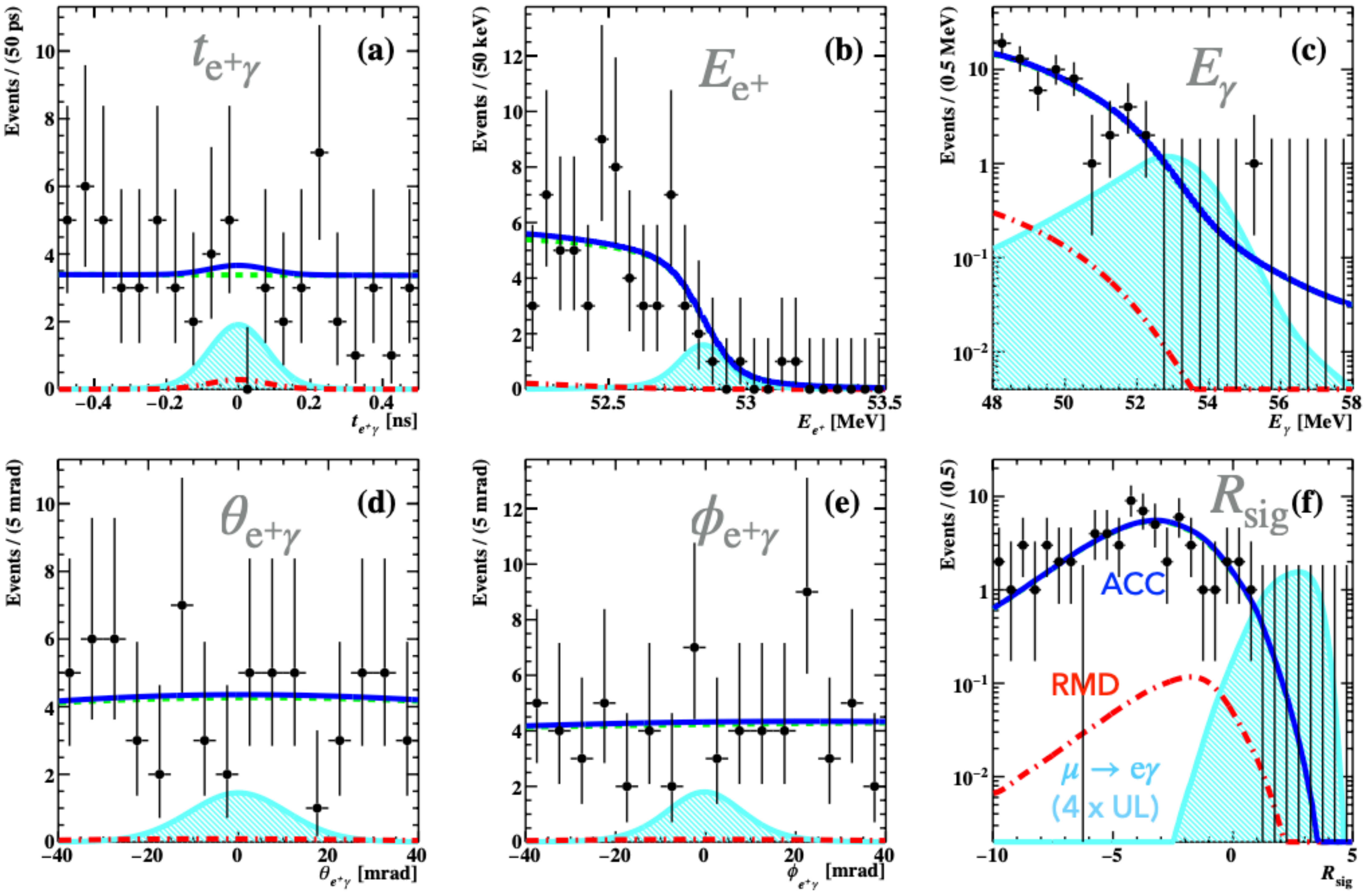




MEG II data


×10^15
Accumulated $N_{\mu^+}^{stop}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Last run: 557189 (2023-11-09 08:10:39)
T_{live}: 2.03e+07 s
This year's run finished on Nov. 9th
2023
2022
The first result
~10% of what we already took
2021
31/Dec/21
02/Jul/22
31/Dec/22
02/Jul/23
Date
Tue Nov 14 09:33:23 2023

Data & fit results



- Maximum likelihood analysis to estimate N_{sig}
  - Signal and RMD PDFs from resolution measurements
  - Accidental BKG PDFs from sidebands (fully data-driven)
- No excess was observed with the first 7-week data in 2021
- Set the upper limit @90%CL $\mathscr{B}(\mu \to e\gamma) < 7.5 \times 10^{-13}$ with sensitivity of 8.8×10^{-13}
- Combined result of MEG and MEG II 2021 provides the most stringent limit on the Branching ratio $\mathscr{B}(\mu \to e\gamma) < 3.1 \times 10^{-13}$

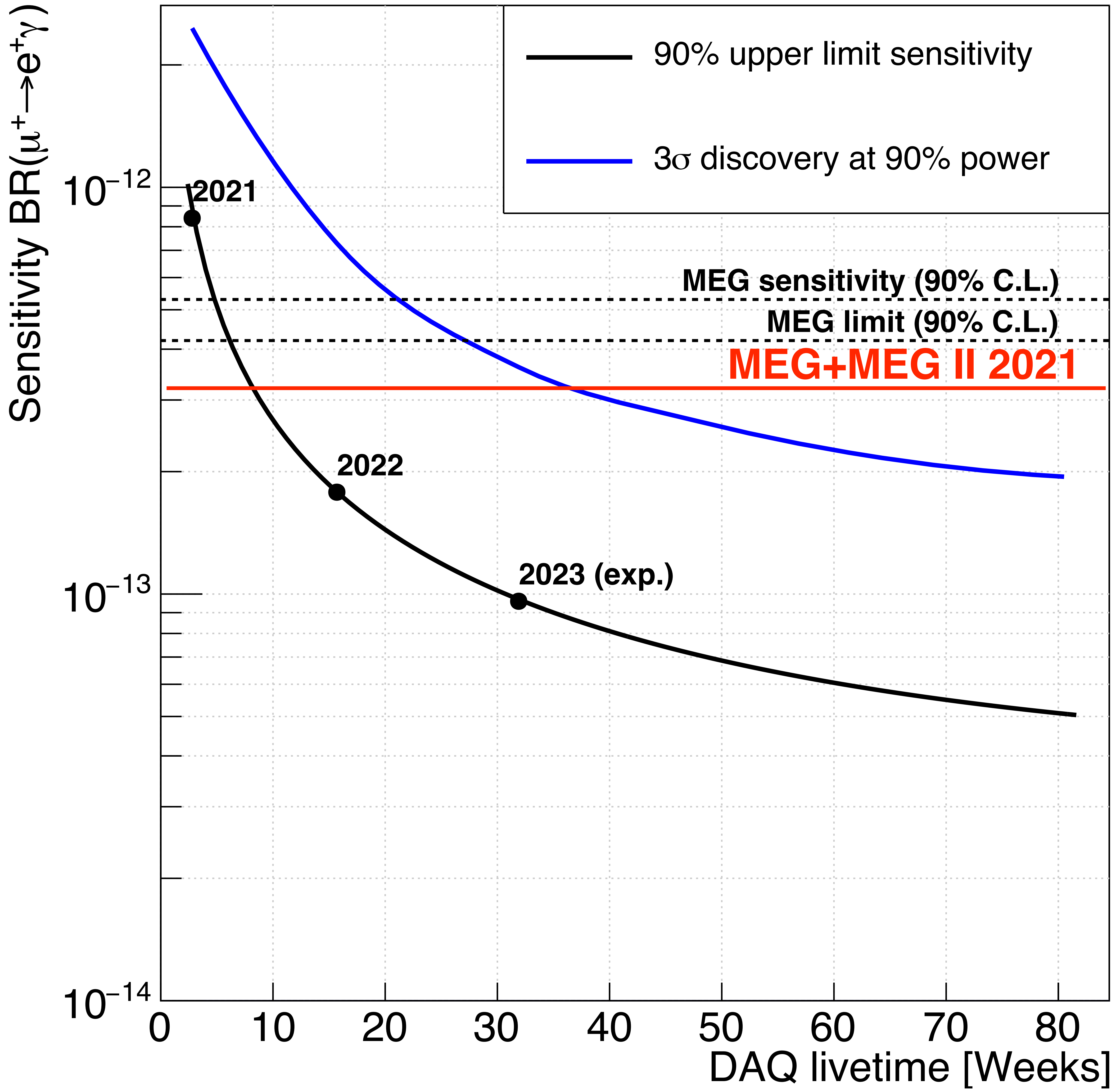
(f) Relative signal likelihood

$$R_{\rm sig} = \log_{10}\left(\frac{S(x_i)}{f_{\rm RMD}R(x_i) + f_{\rm ACC}A(x_i)}\right)$$

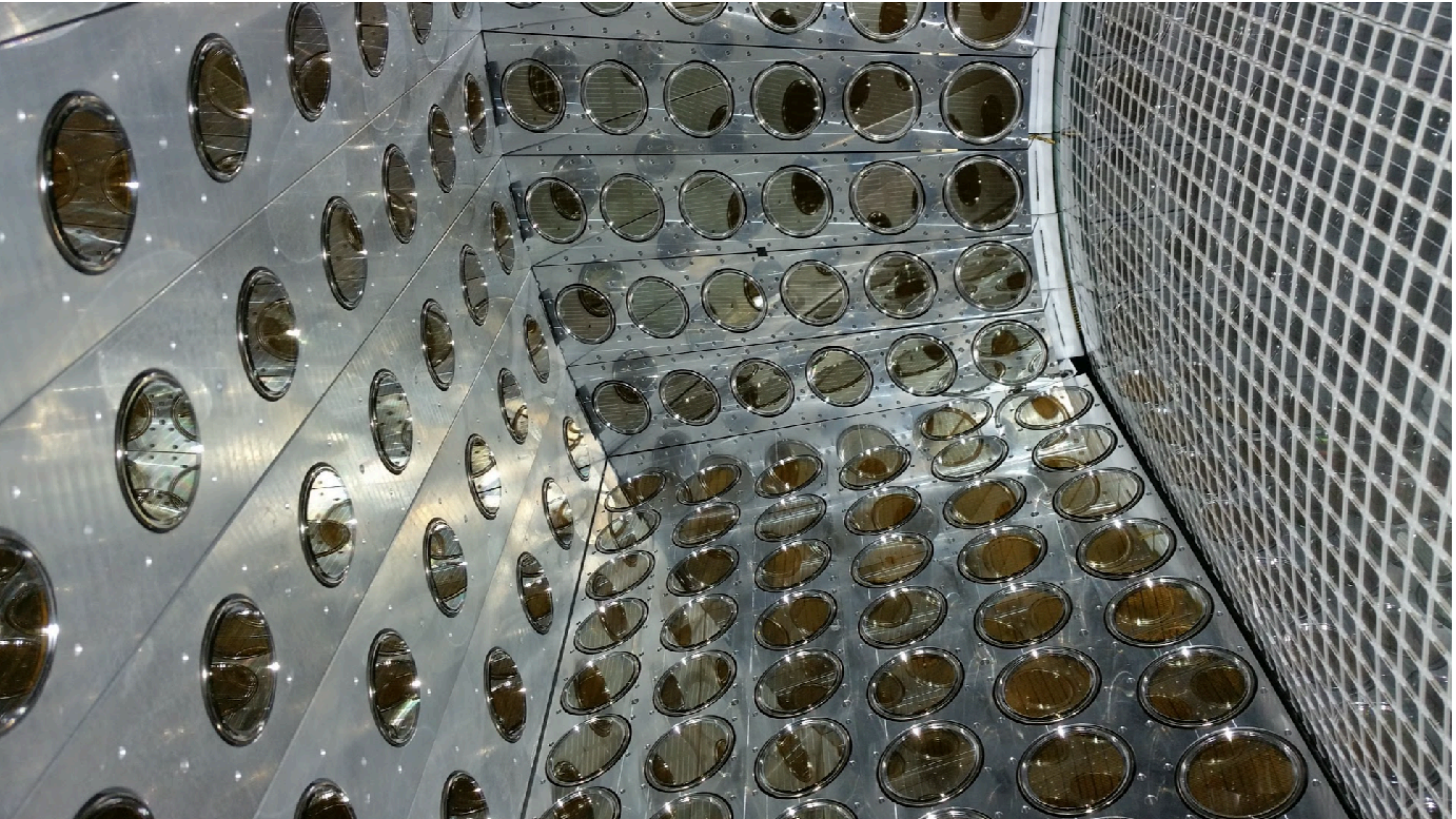
$$f_{\rm RMD} = 0.02,\ f_{\rm ACC} = 0.98$$

MEG II prospects

- MEG II experiment will accumulate the physics data several years at least until 2027
  - The PSI accelerator beam line has an upgrade plan (HiMB) to have the beam intensity of 10^{10} μ/s starting from 2027
  - The PiE5 beamline will be shared with Mu3e experiment
- The sensitivity of the MEG II experiment will reach Br(μ→eγ) ~(5–6)×10^{-14} @90%C.L. by then
- In parallel, 2022 analysis is ongoing. The results will be published this year which will have better sensitivity than MEG



MEG II Liquid Xenon Detector

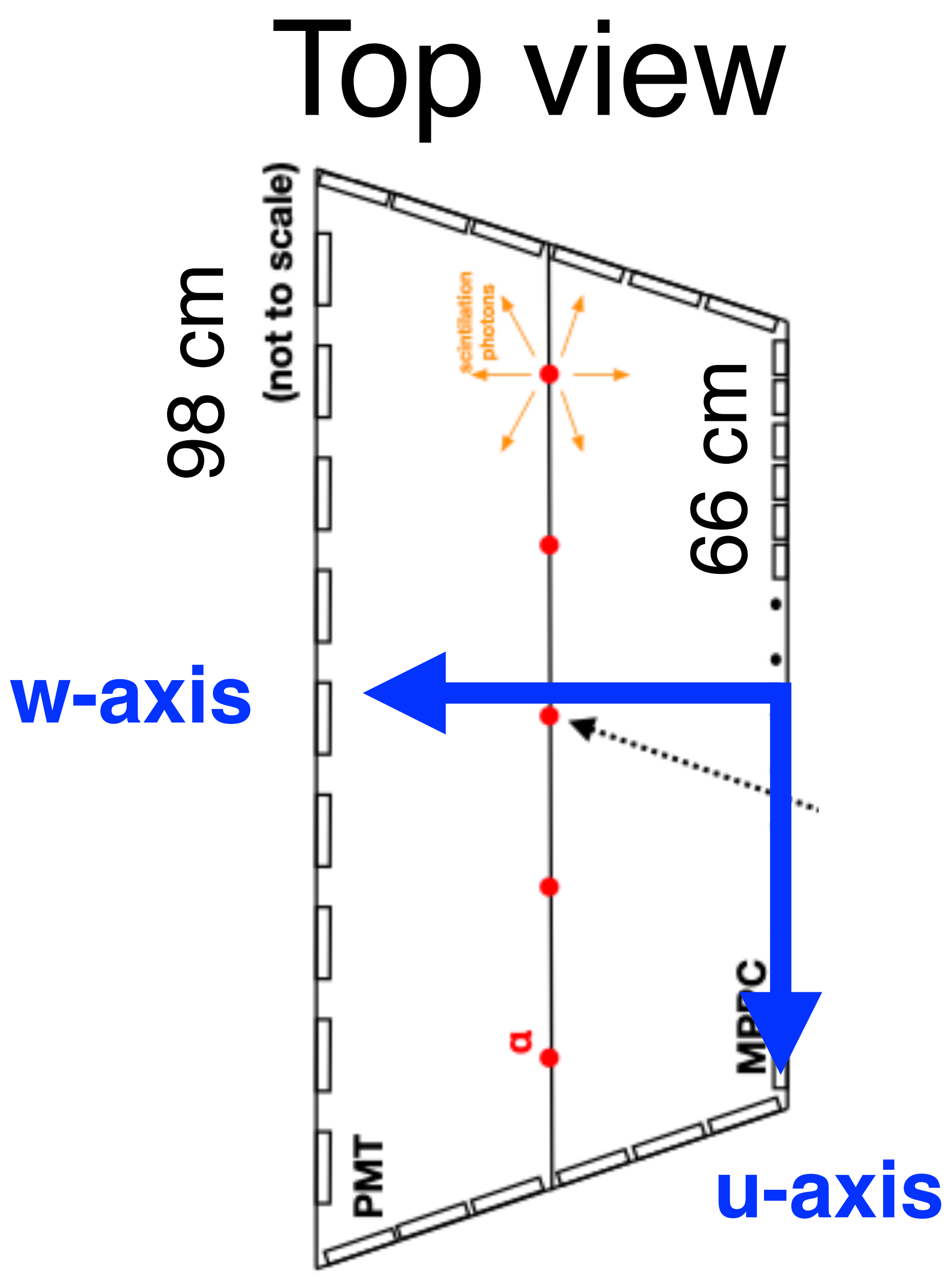


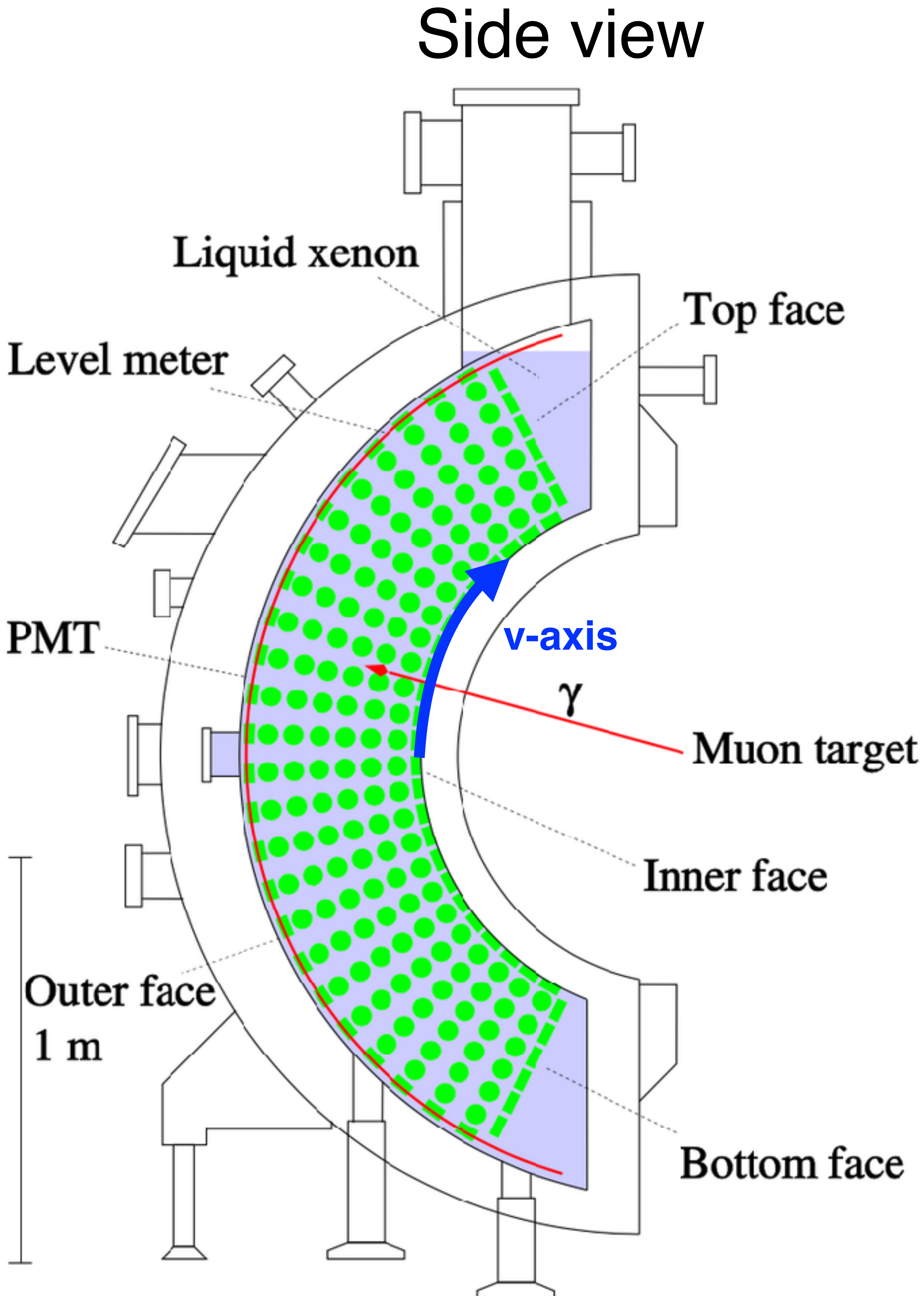
MEG II Liquid Xenon Detector

- Position, timing, energy measurements of 52.8 MeV γ
  - C-shape to fit the cylindrical shape of the superconducting magnets
  - Thin entrance window for γ (honeycomb structure) : $0.075X_0$
    - 66 cm (horizontal) × 140 cm (arc)

- Detector medium : 900 l LXe
  - Homogeneous
  - Heavy ($3\ g/cm^3$) : high γ efficiency
  - High light yield (only scintillation light readout)
  - decay time : 45ns (γ)
  - Depth 38.5cm ($\sim 13X_0$)

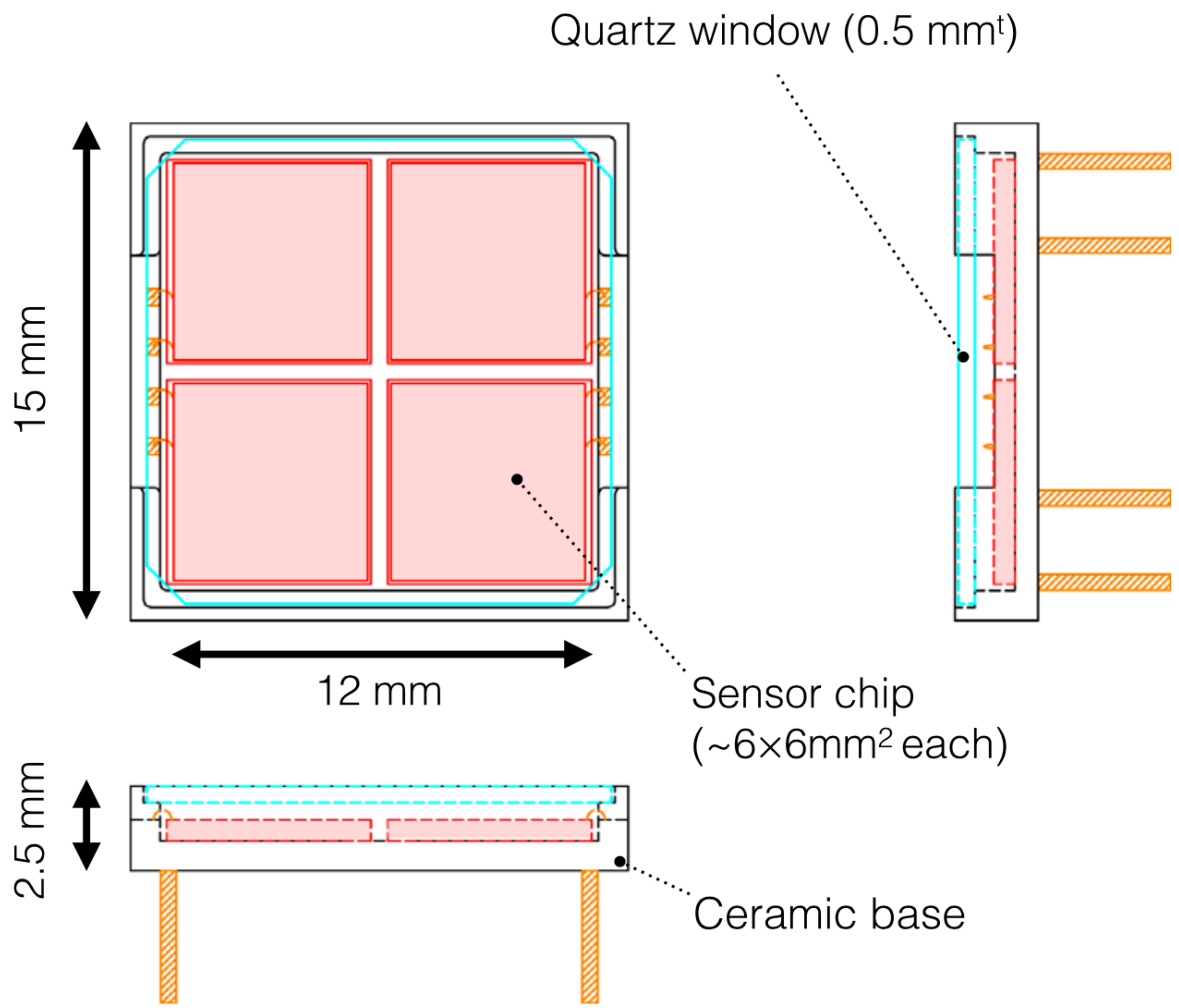
- Scintillation readout : 4092 MPPC ($15\times15mm^2$) + 668 PMTs (51mmϕ)
  - immersed in LXe ($0.029X_0$ from MPPC)
  - Sensitive to VUV-light (175nm)
  - Operational at 165K
  - All the waveforms are recorded by WaveDREAM (DRS4)

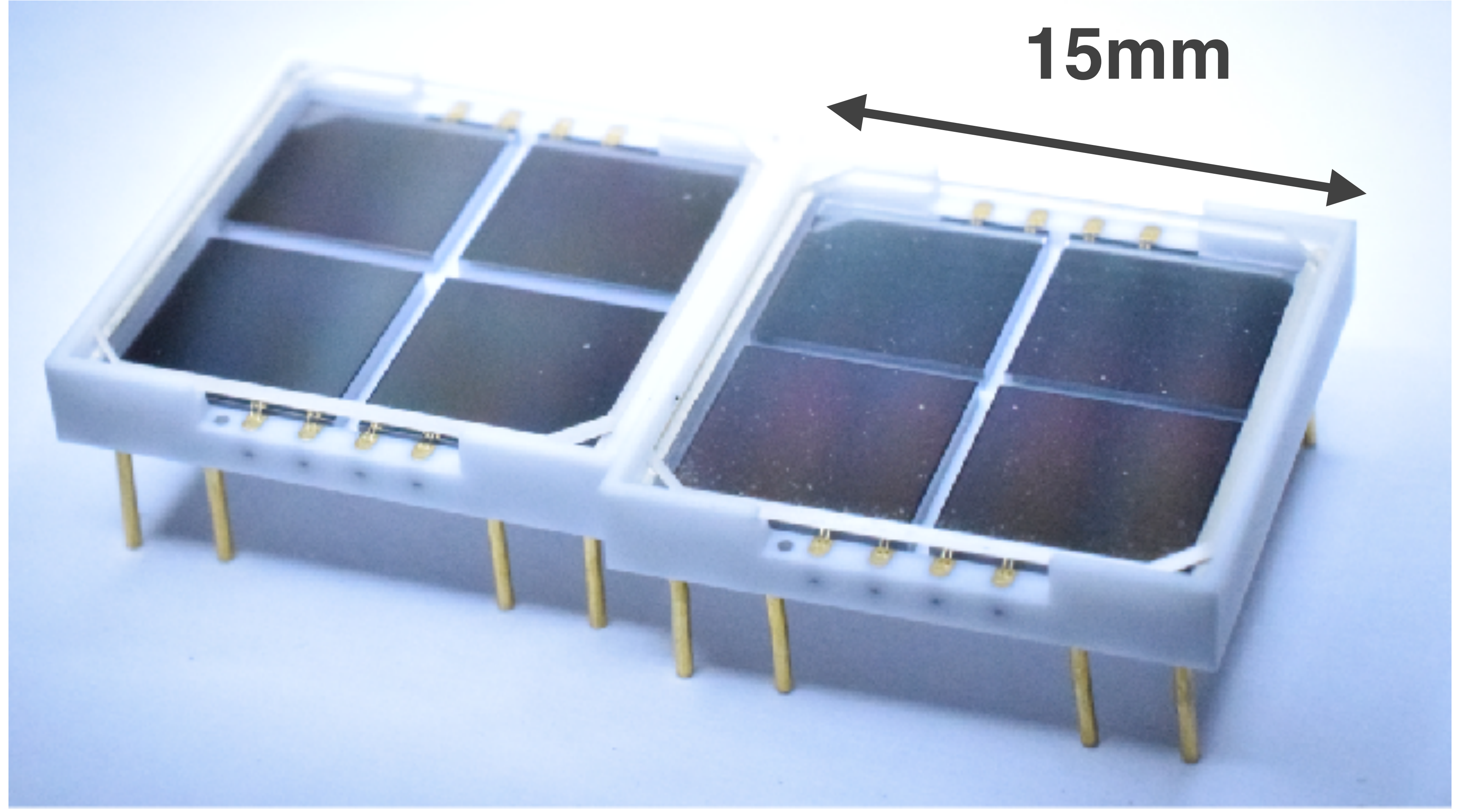




New SiPM development

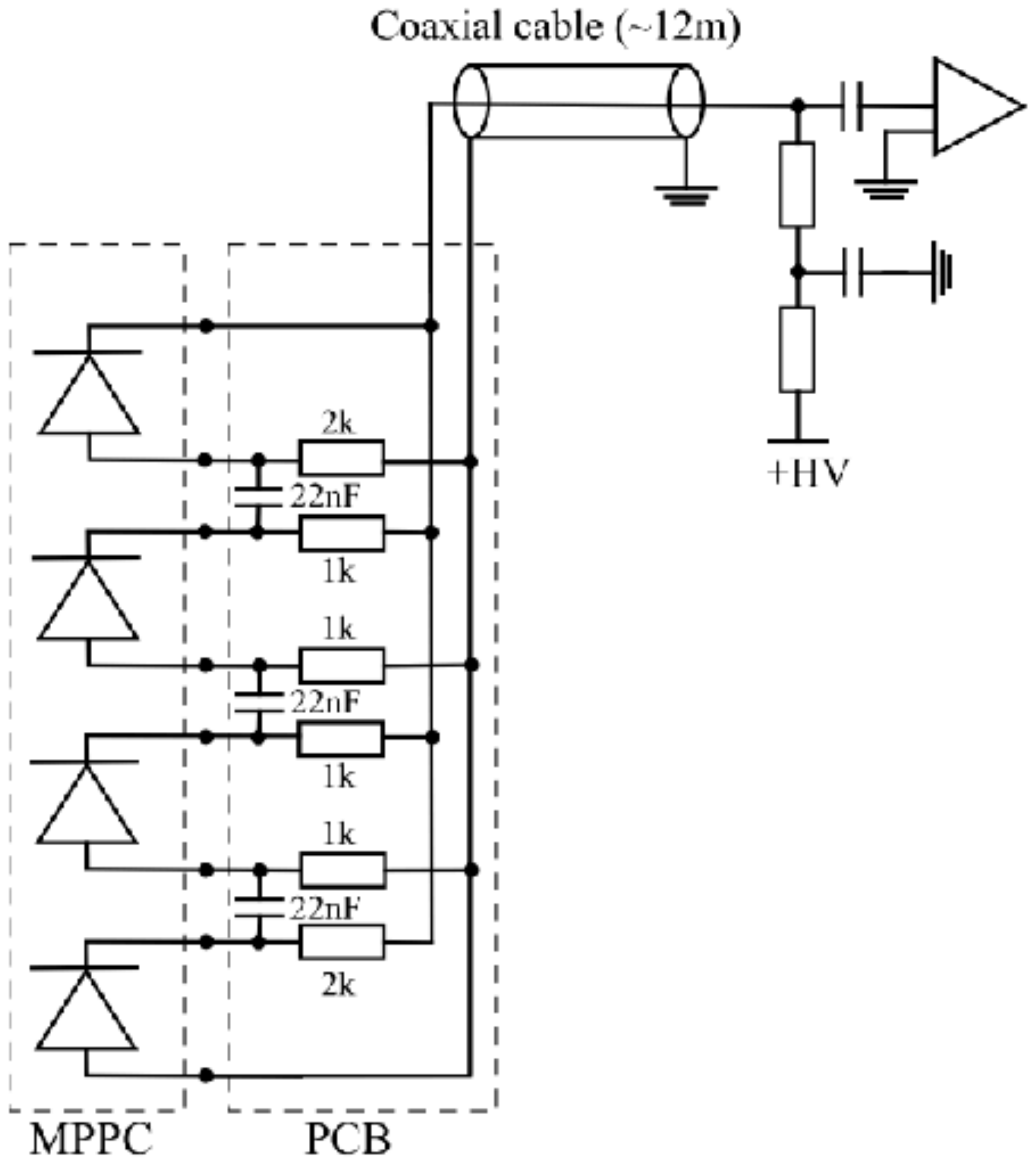
- LXe detector widely used for many applications
  - LFV experiment, dark matter search, double beta decay search, medical applications
- 2” diameter PMT (Hamamatsu, R9869)
  - working in LXe, developed for MEG in collaboration with Hamamatsu. QE ~ 15%
- SiPM is a good candidate to replace PMT
  - 1p.e. peak resolution, insensitive to magnetic field, thin, lower bias voltage etc.
- MPPC for MEG II (Hamamatsu, S10943-4372)
  - MPPC is one of SiPMs produced by HPK
  - Four 6x6 mm^2 chips, ceramic package, 50μm pixel pitch, VUV-sensitive, quartz window in front of SiPM, metal quench resistor

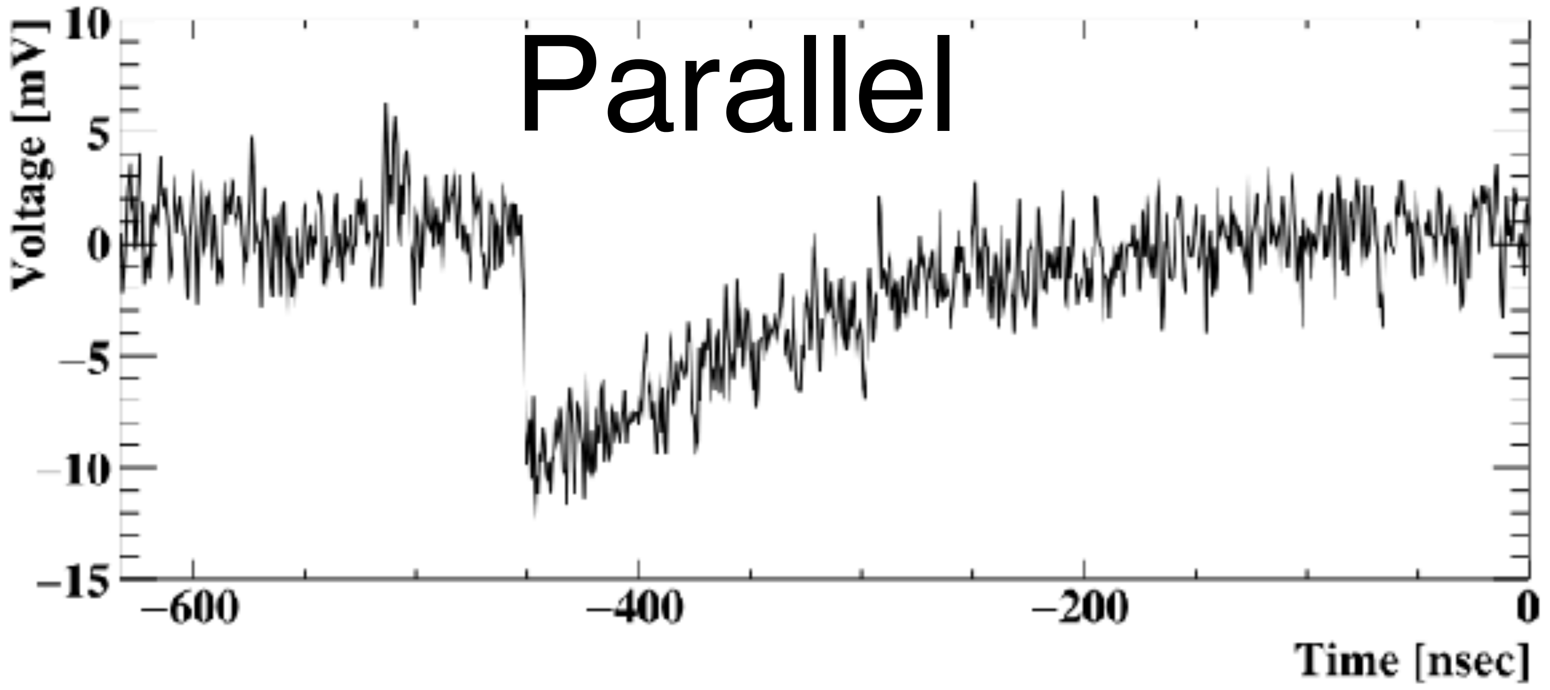


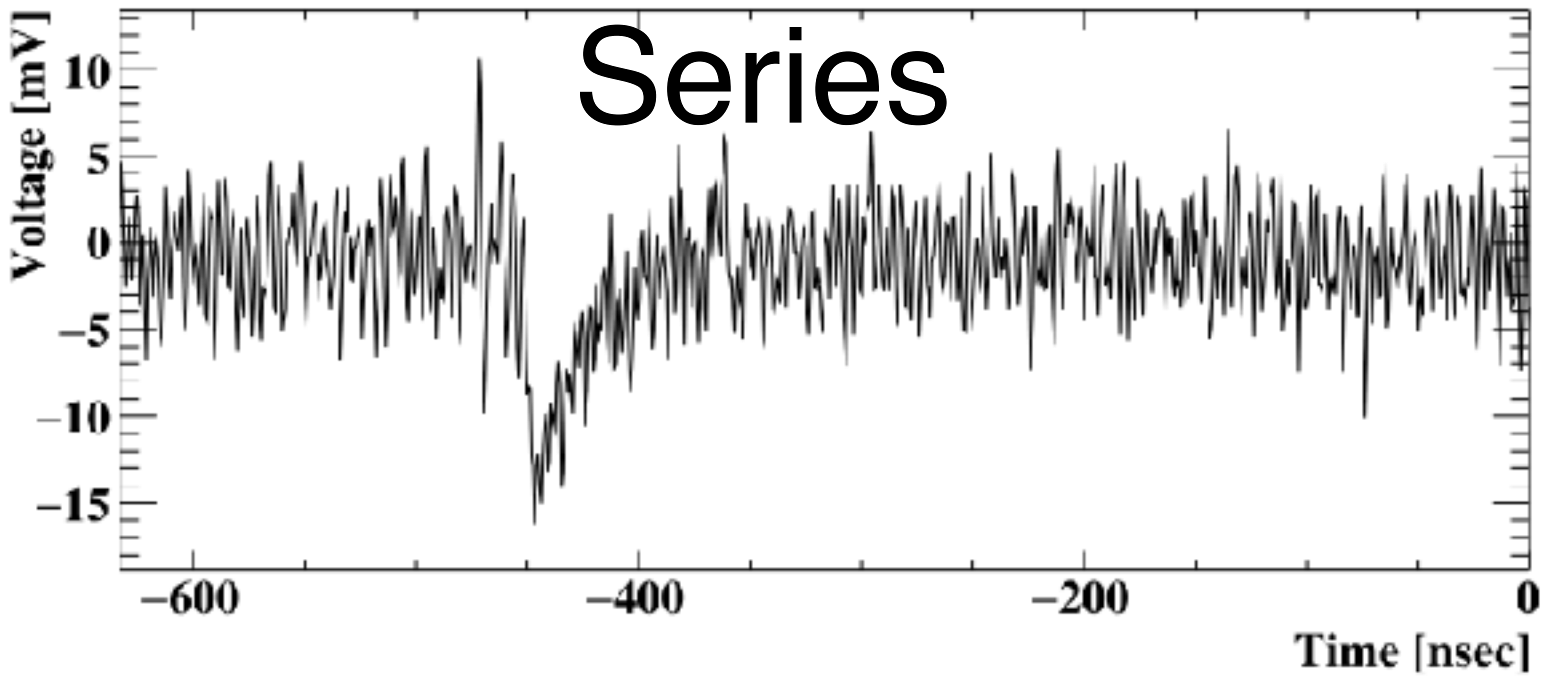


Large Area SiPM

- Large area SiPM in general has
  - large capacitance, long signal tail
  - large dark rate (no problem at LXe T)
- Our solution (to make a single ch. 12x12mm^2 MPPC)
  - Segmented into 4 chips, which are connected in series for signal readout line, in parallel for voltage supply line
    - Avoid large capacitance, manageable signal tail is realized (<50ns)
    - Common bias voltage (~65V)
  - Dark noise suppressed at low temperature
  - Single photoelectron peak can be resolved

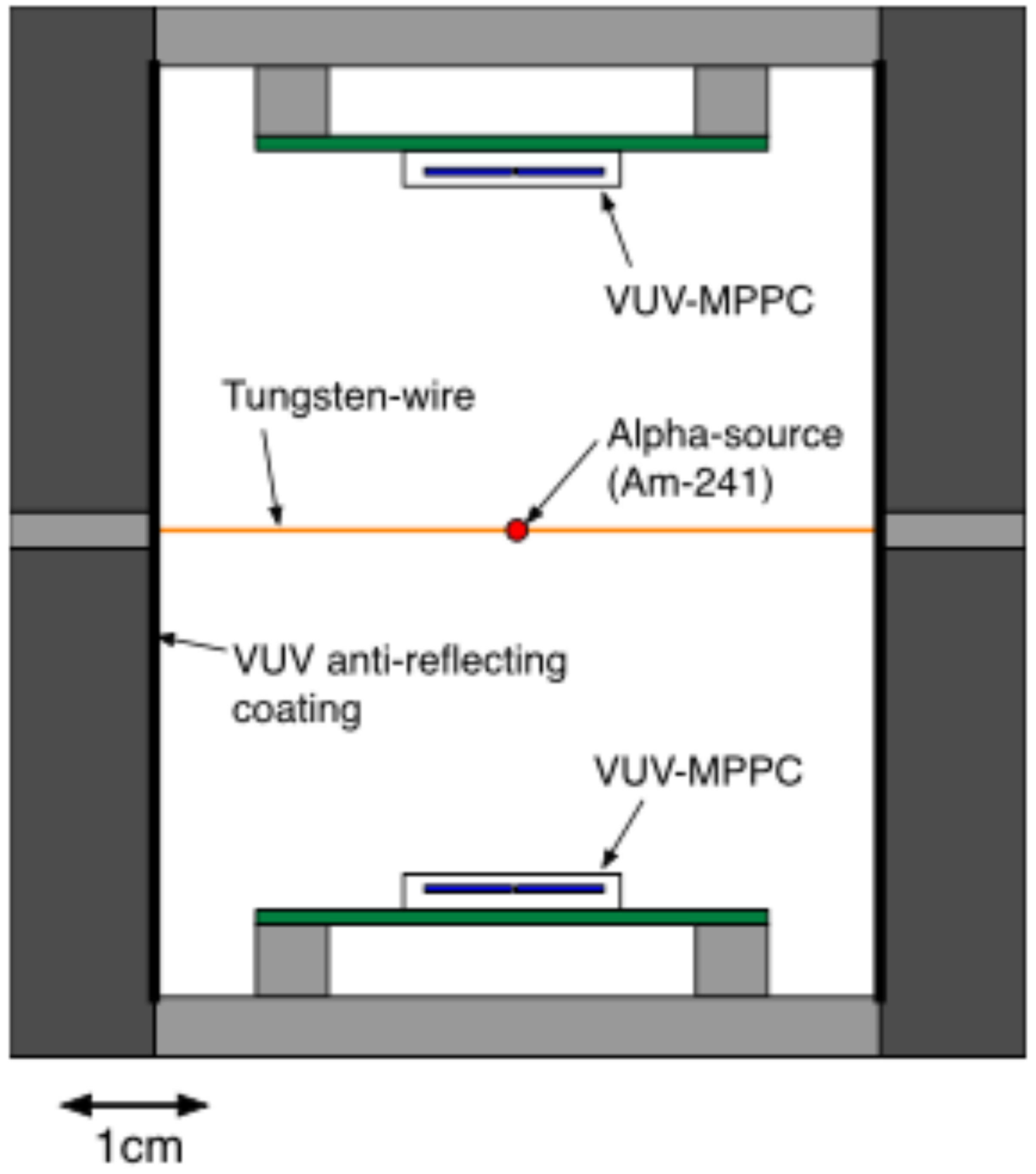


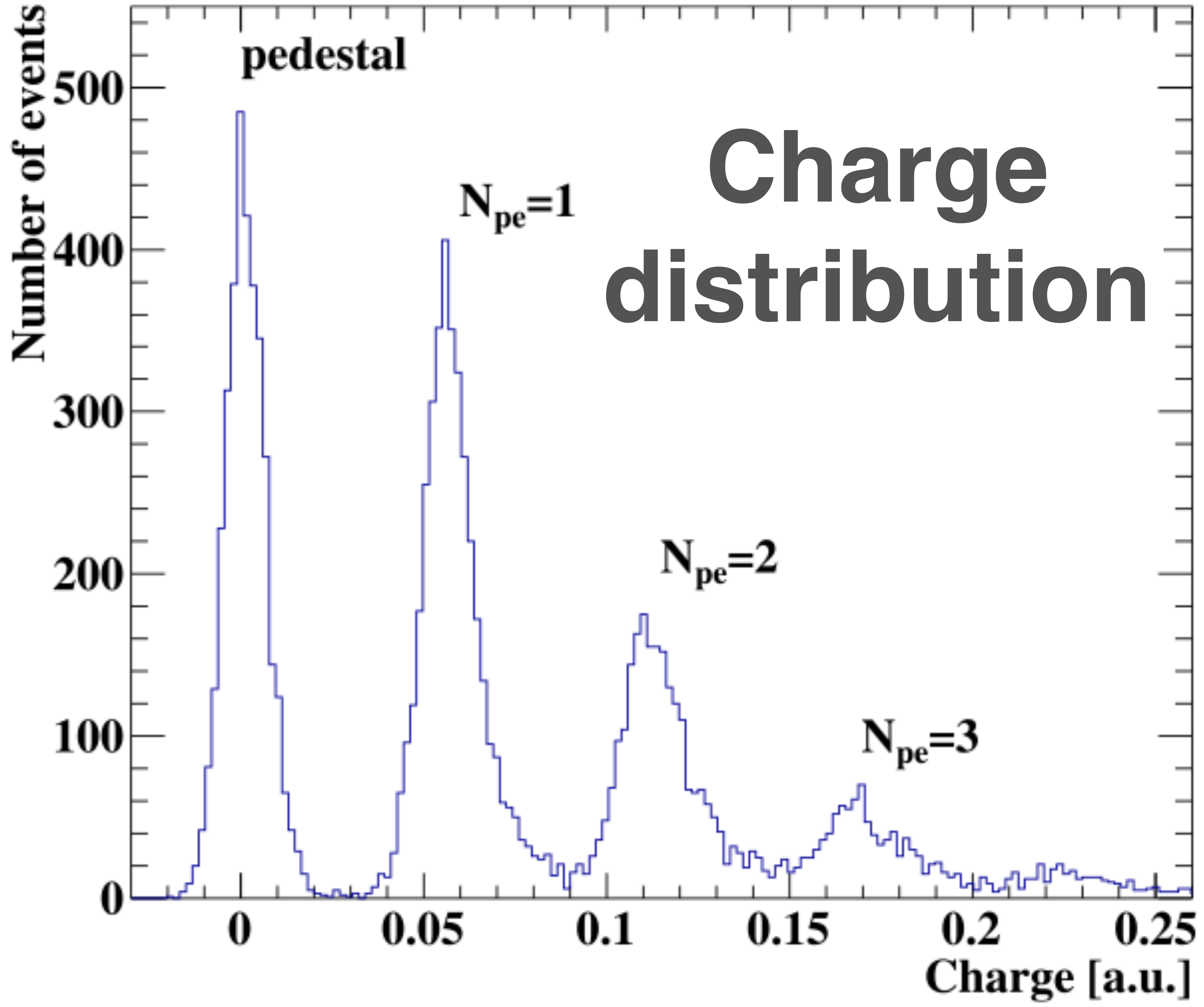


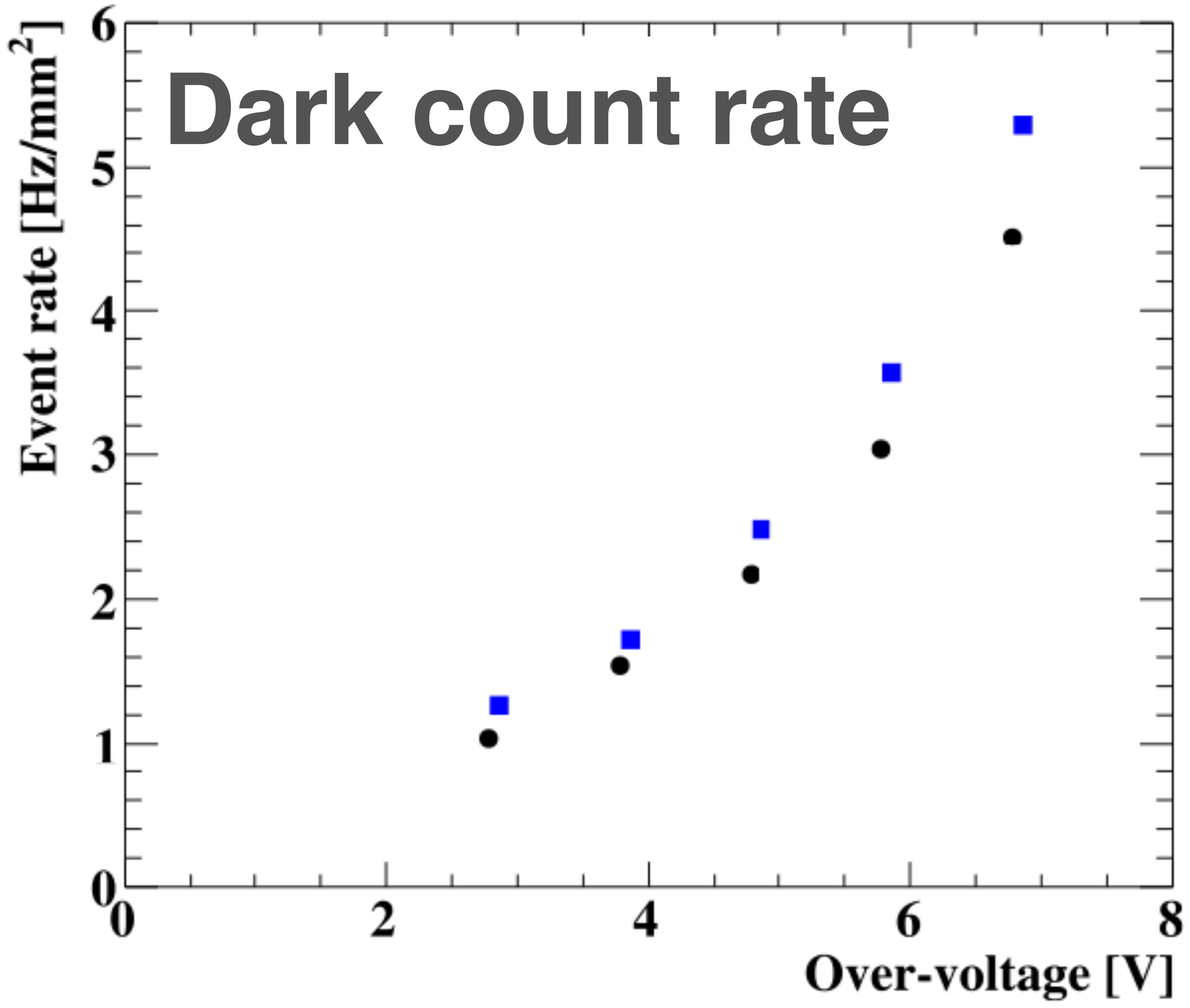


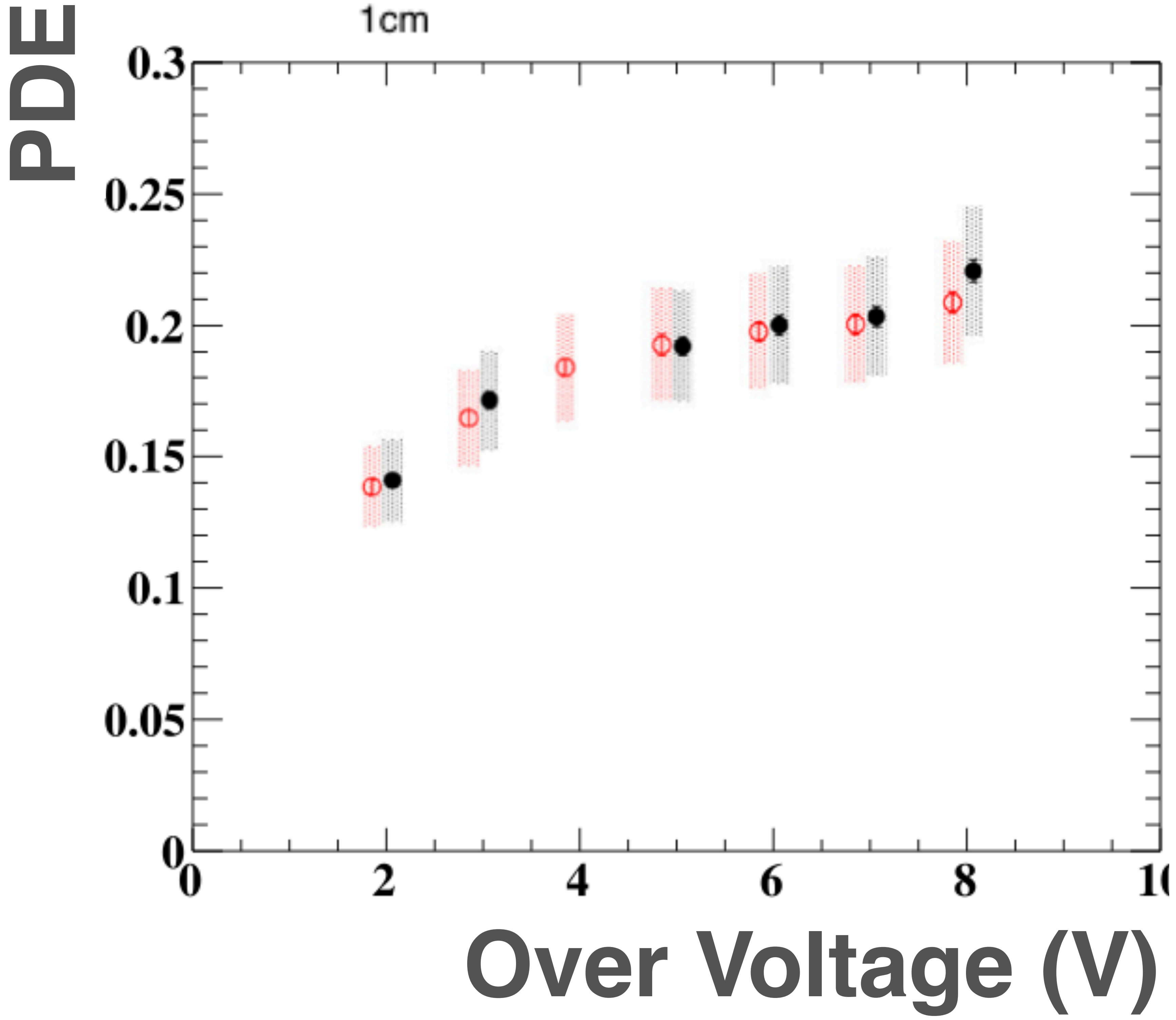
Performance

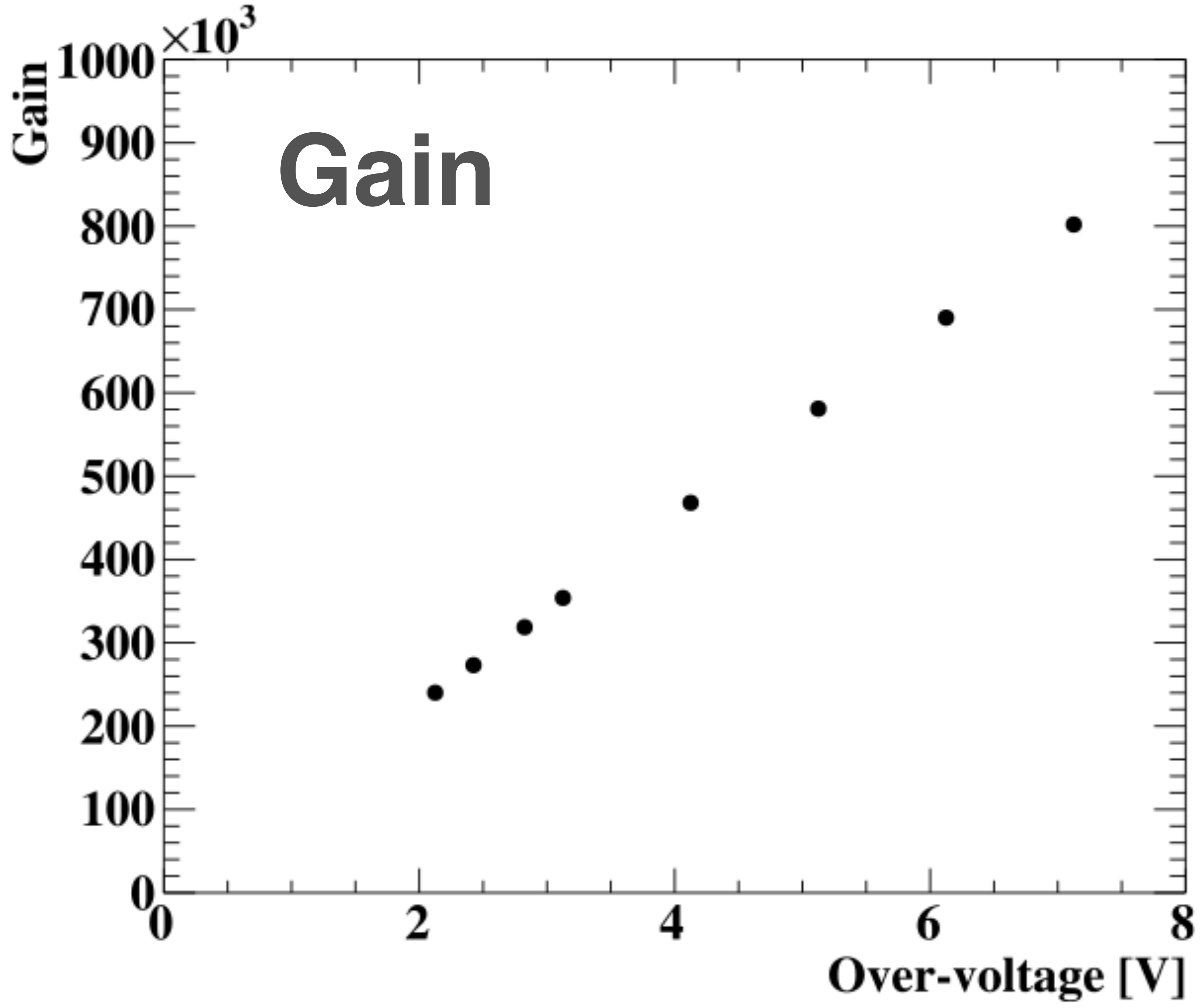
- Evaluated in the lab.
- Vover ~ 7V
- Single photoelectron peak resolved
- Gain: 8×10^5, PDE>~15%, Signal decay time: 30ns





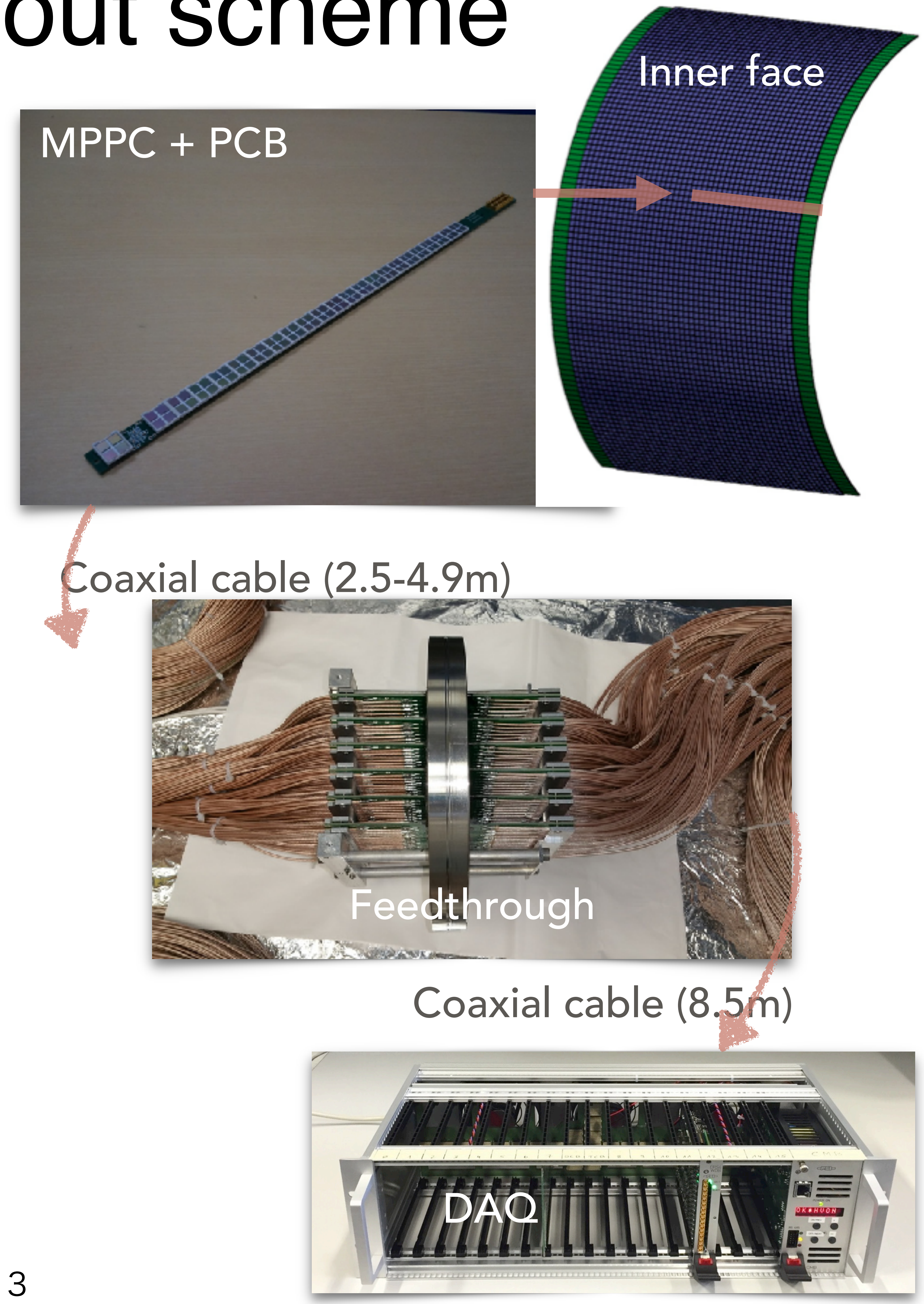




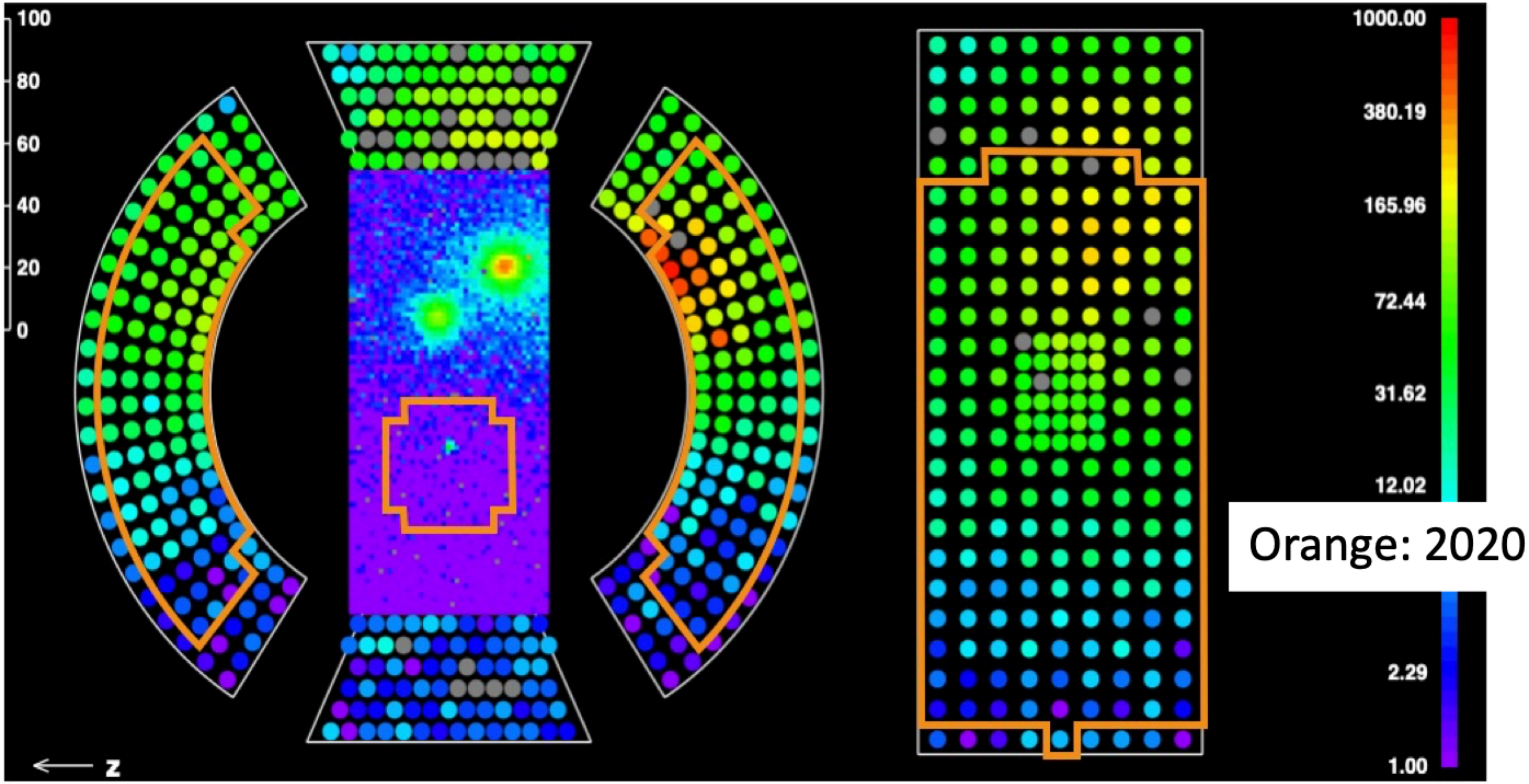


Signal readout scheme

- MPPCs plugged on assembly PCB
  - Series connection for four chips on PCB
  - 22 MPPCs on a PCB, two PCB on a row, 93 lines result in 4092 MPPCs
- MPPC signal transmitted over long cable (11-13.4m) w/o amplifier
- High density PCB-based feedthrough
  - PCB with coaxial-like signal line, 50Ω impedance, high noise immunity
  - High density 72ch x 6 PCB x 10 flanges
- Waveform digitizer
  - Fully integrated DAQ board including bias supply for SiPM, waveform digitizer, FPGA-based trigger (WaveDREAM)



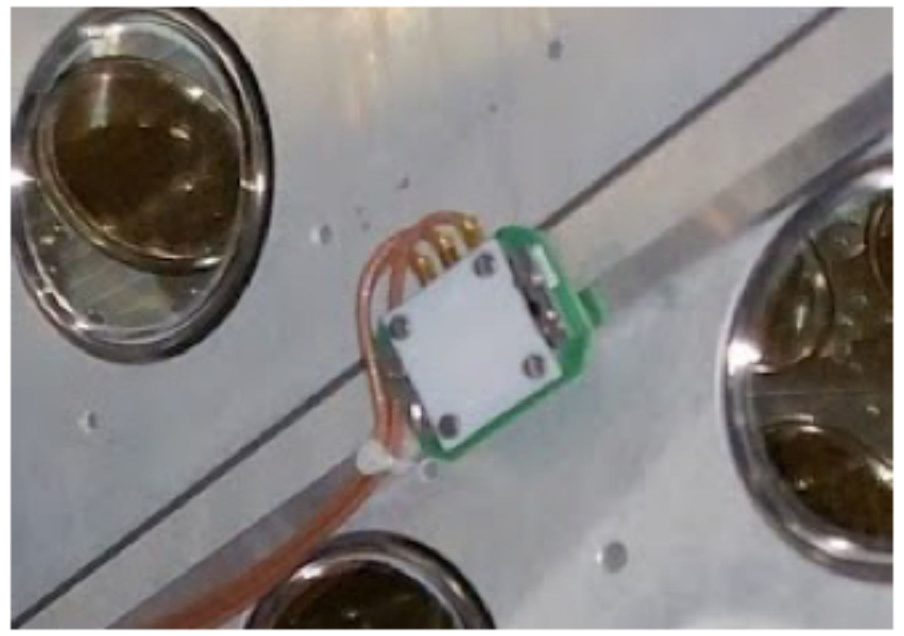
LXe detector commissioning

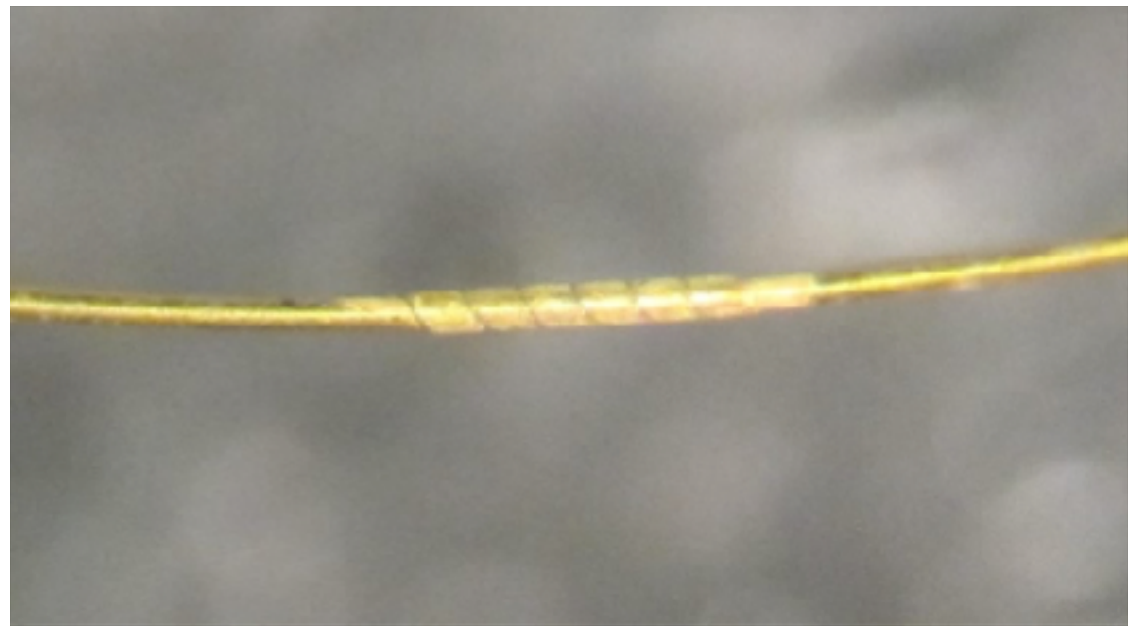


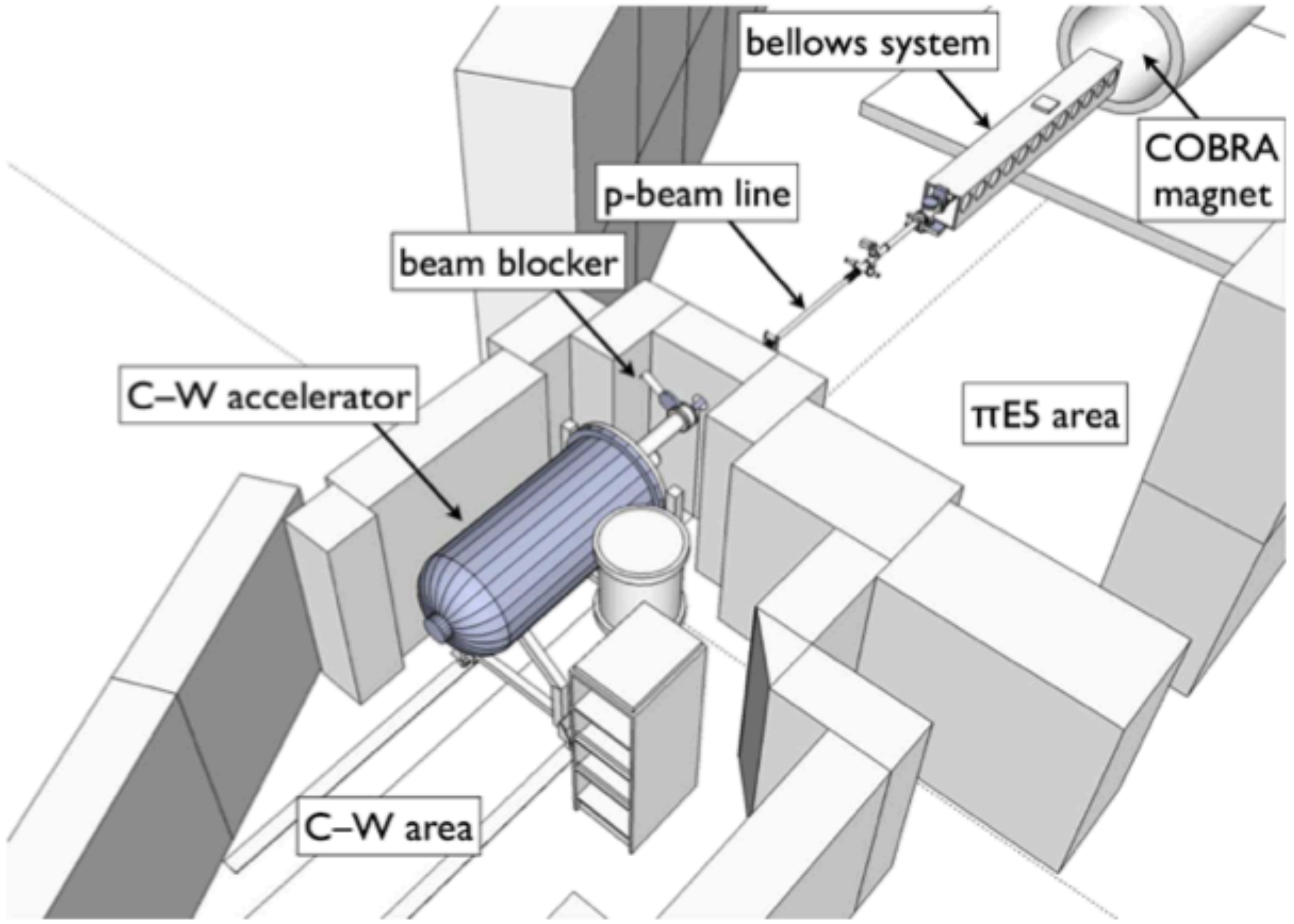
- 2017 Detector construction completed
  - sensor calibration, muon beam run with reduced number of readout sensors
- 2021 Full electronics ready, detector performance evaluation work started

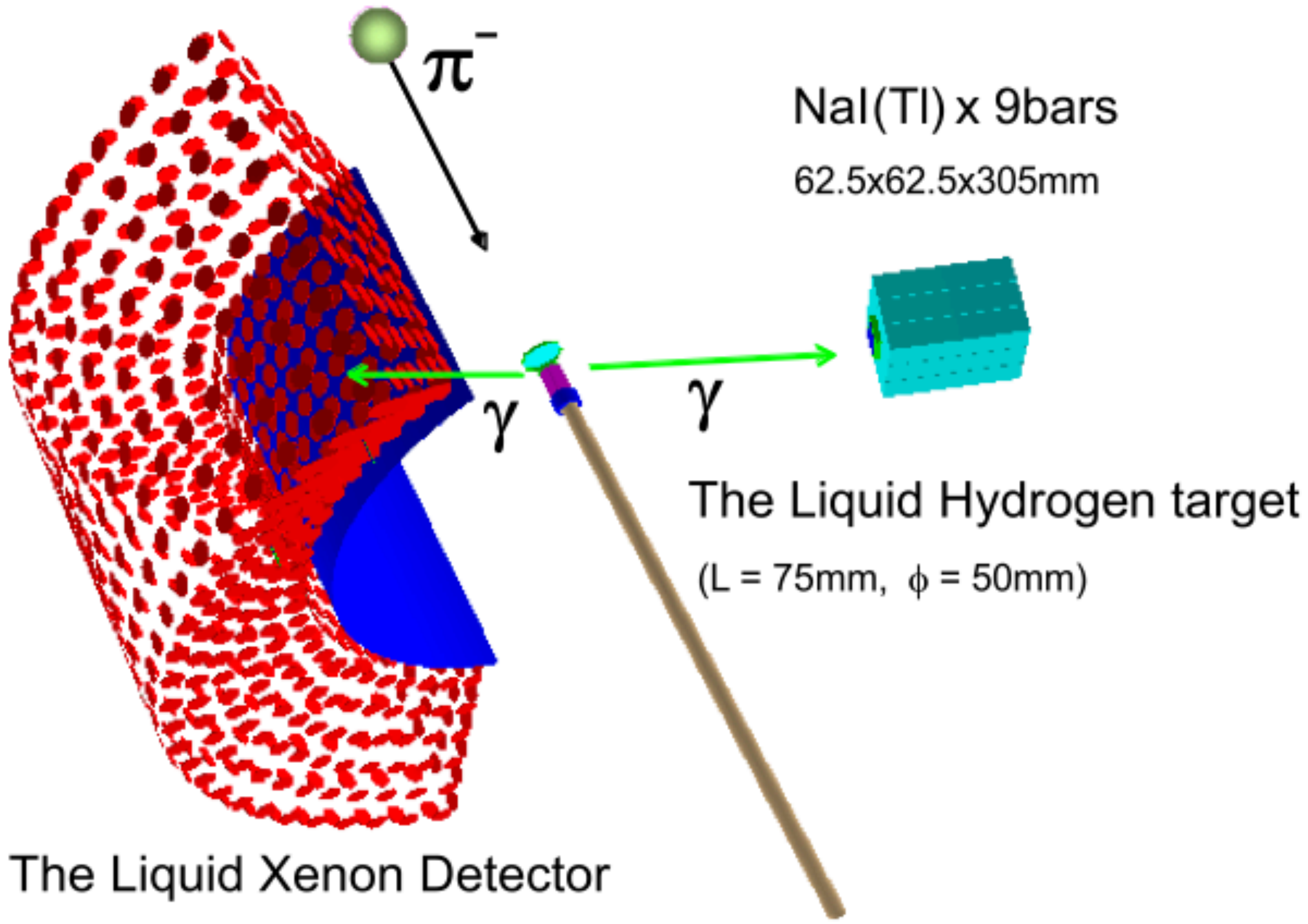
LXe detector event reconstruction & calibration

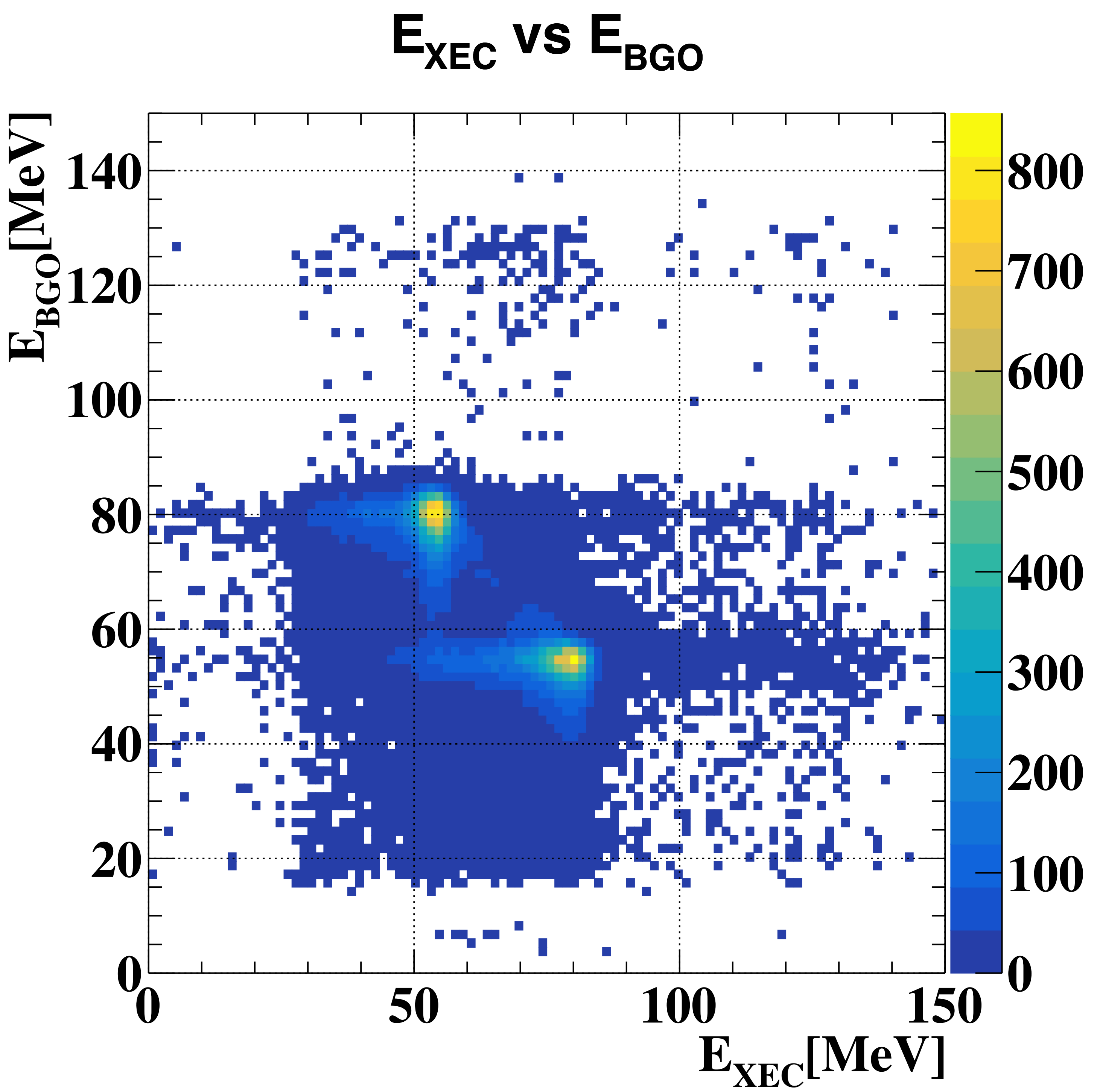
- 5-D reconstruction
  - Energy : sum of MPPC/PMT charges
  - Position (3D) : MPPC/PMT charge distribution
  - Time : average MPPC/PMT time
- Calibration
  - LED for gain, ^{241}Am for PDE, QE
  - 17.6 MeV γ from ^{7}Li(p,γ)^{8}Be reaction
  - 55, 83 MeV γ from $\pi^{-}p \rightarrow \pi^{0}n$ reaction







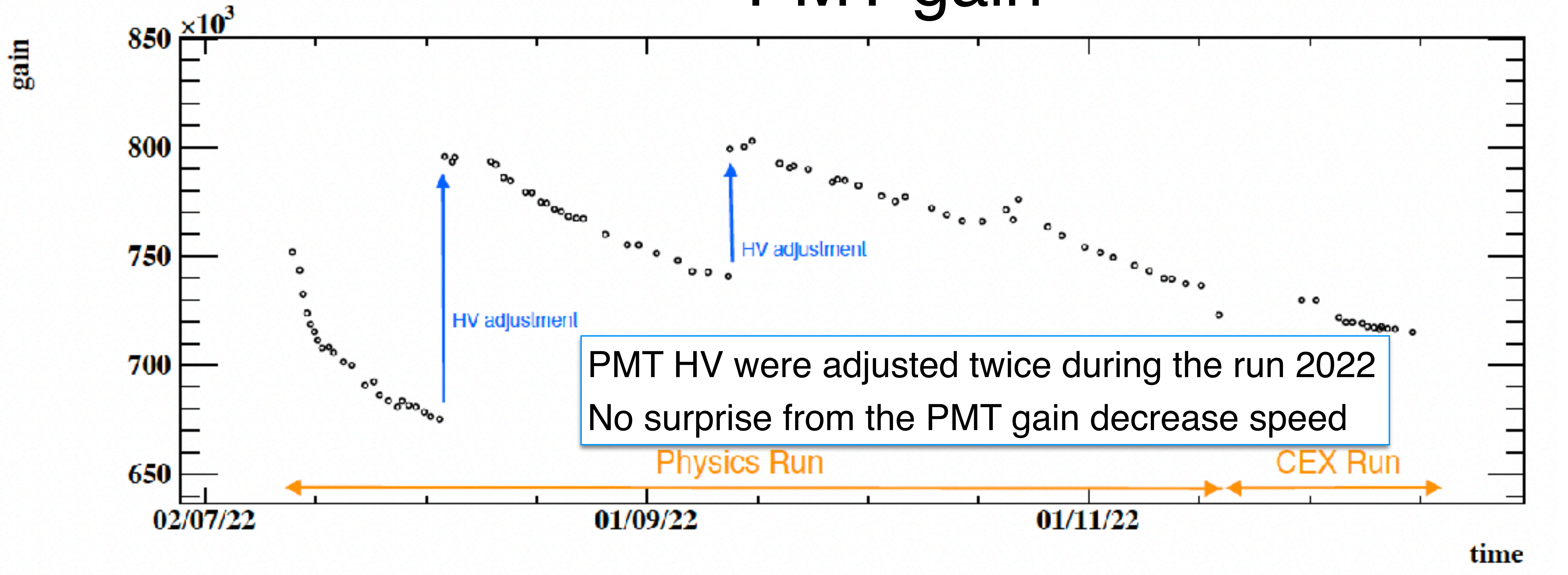




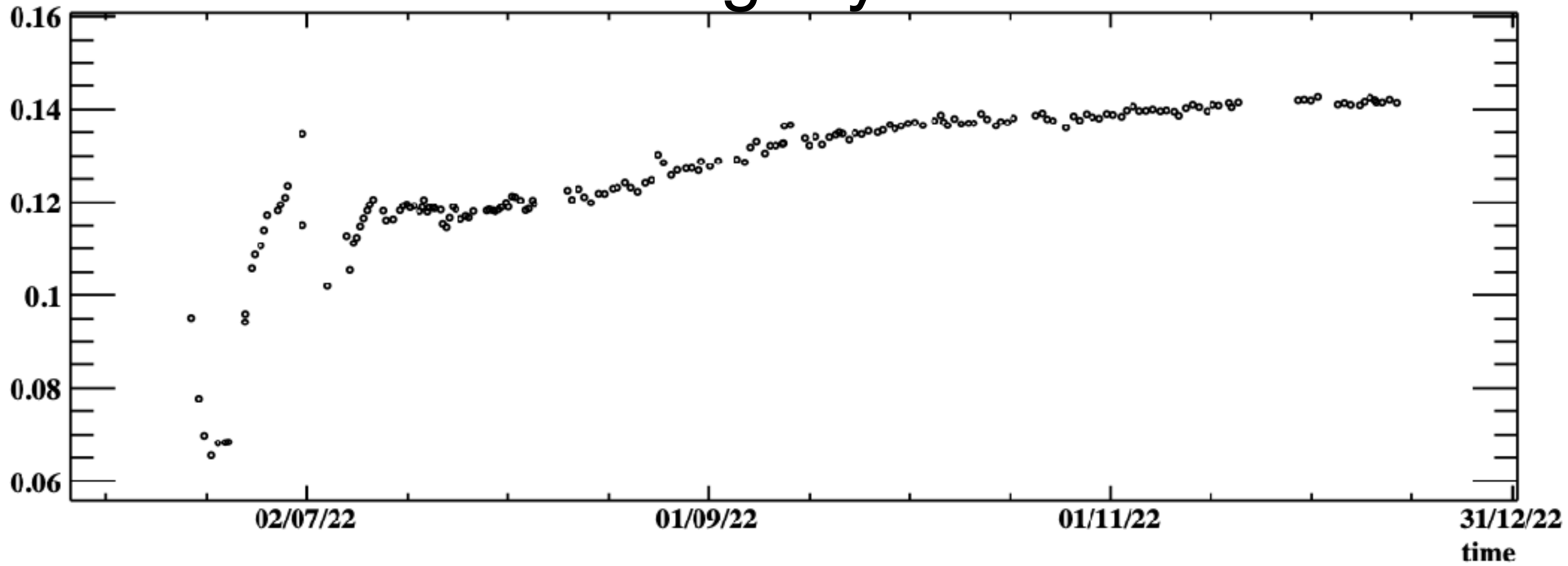
Detector monitoring

- PMT Gain
  - Absolute PMT gain is calculated with LED
  - Constantly gain is decreased under muon beam
  - Twice HVs were adjusted during run 2022
- LXe light yield
  - Monitored by α events by PMTs
  - Assumption of constant PMT QE
  - During the run, the gaseous purification is always on with getter
  - At the beginning, liquid purification with molecular sieves also performed

PMT gain



Light yield

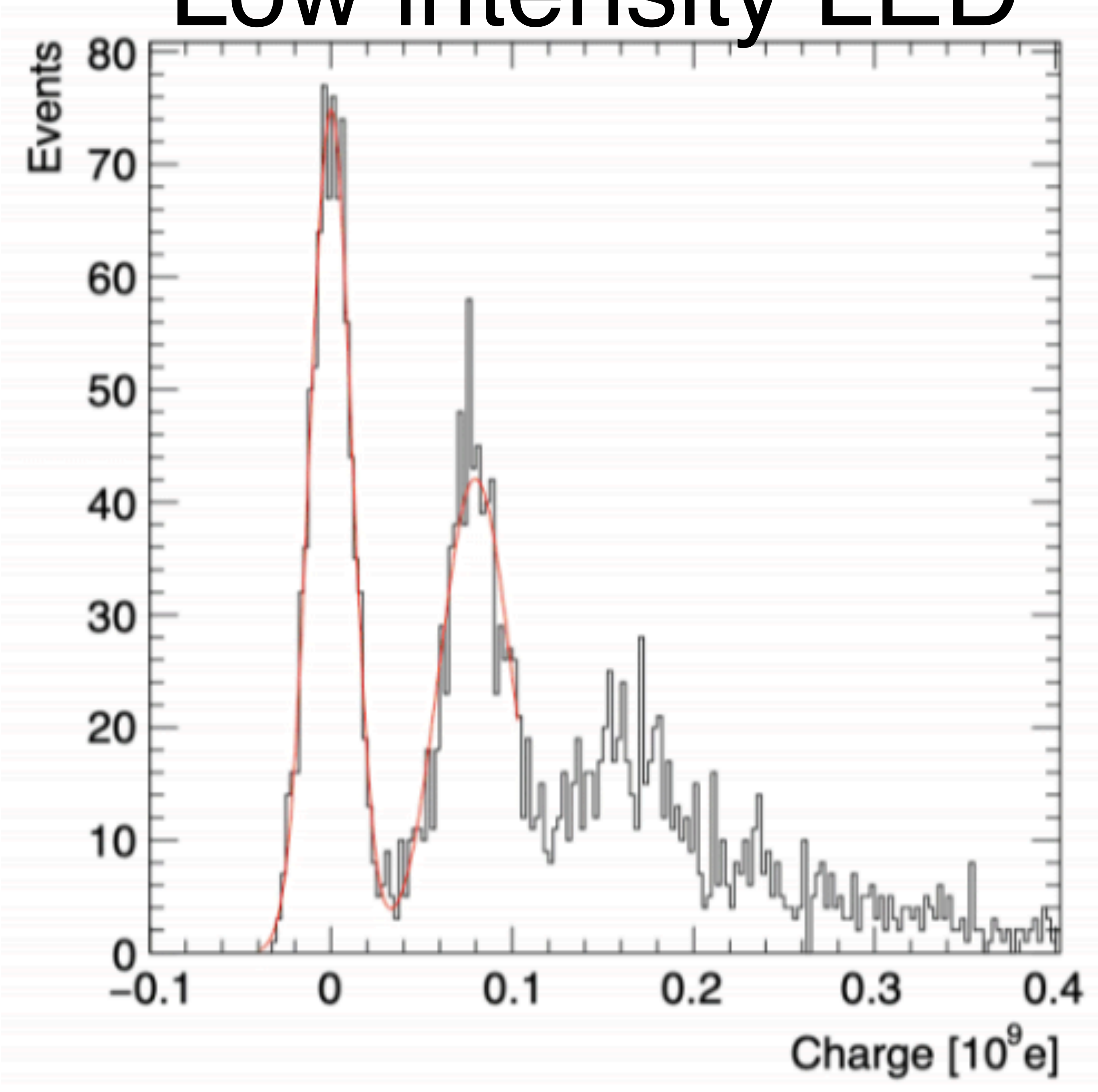


Monitored by α events by PMTs

MPPC calibration

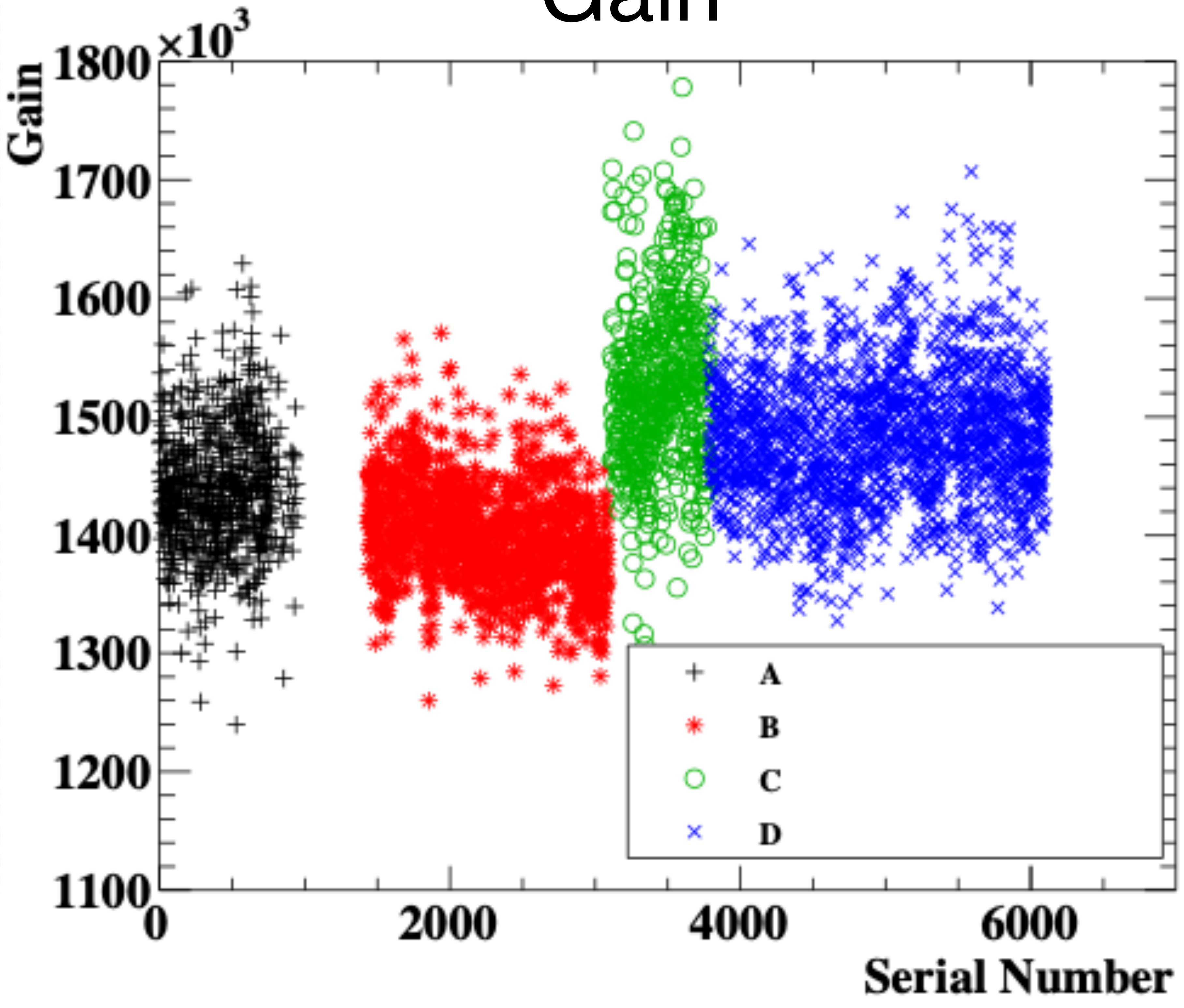
- Measured gain and ECF of MPPCs as a function of serial numbers
- Production lot dependences observed

Low intensity LED

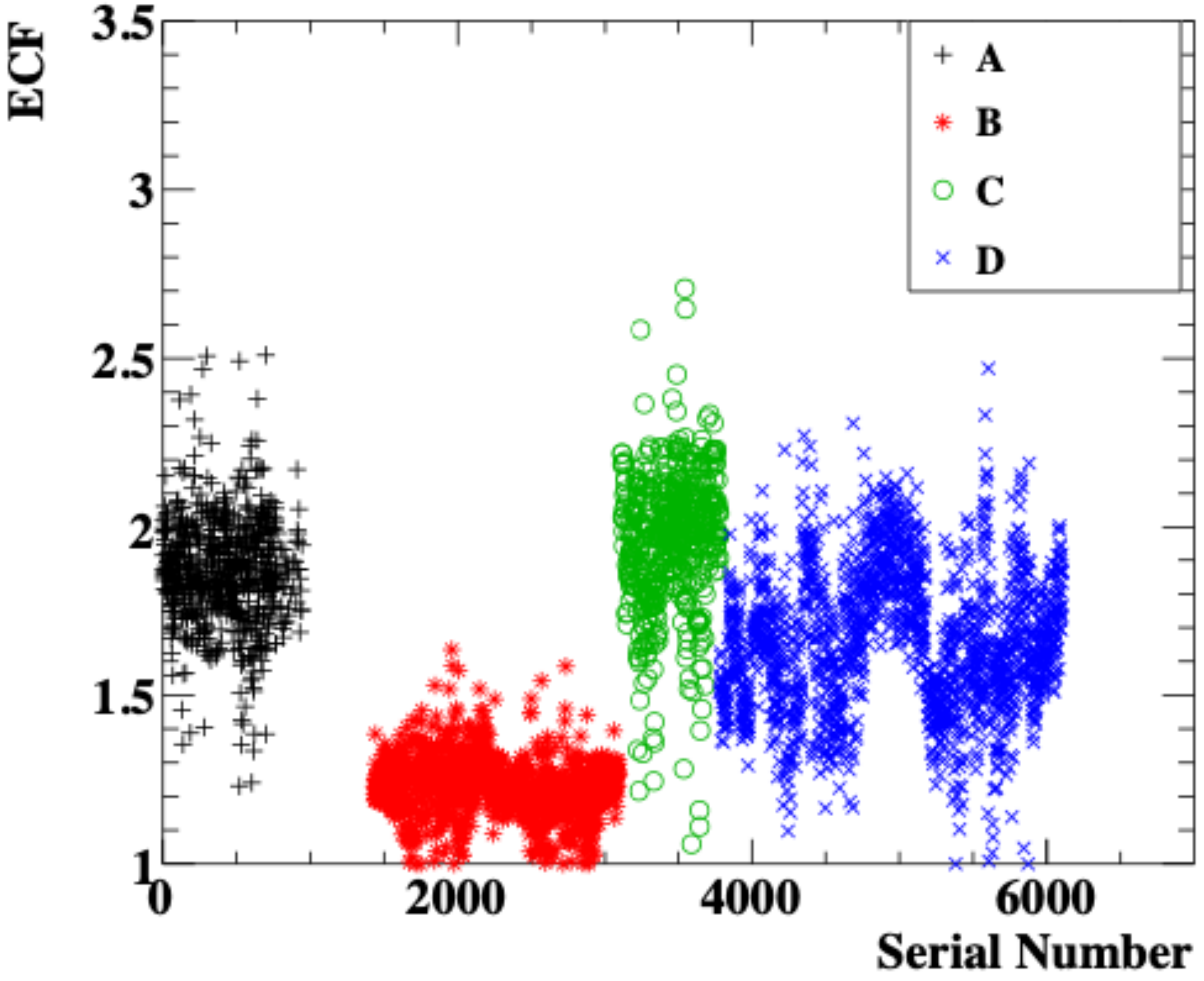


Excess charge factor (ECF) from charge increase by cross-talk and after-pulse from the poisson mean

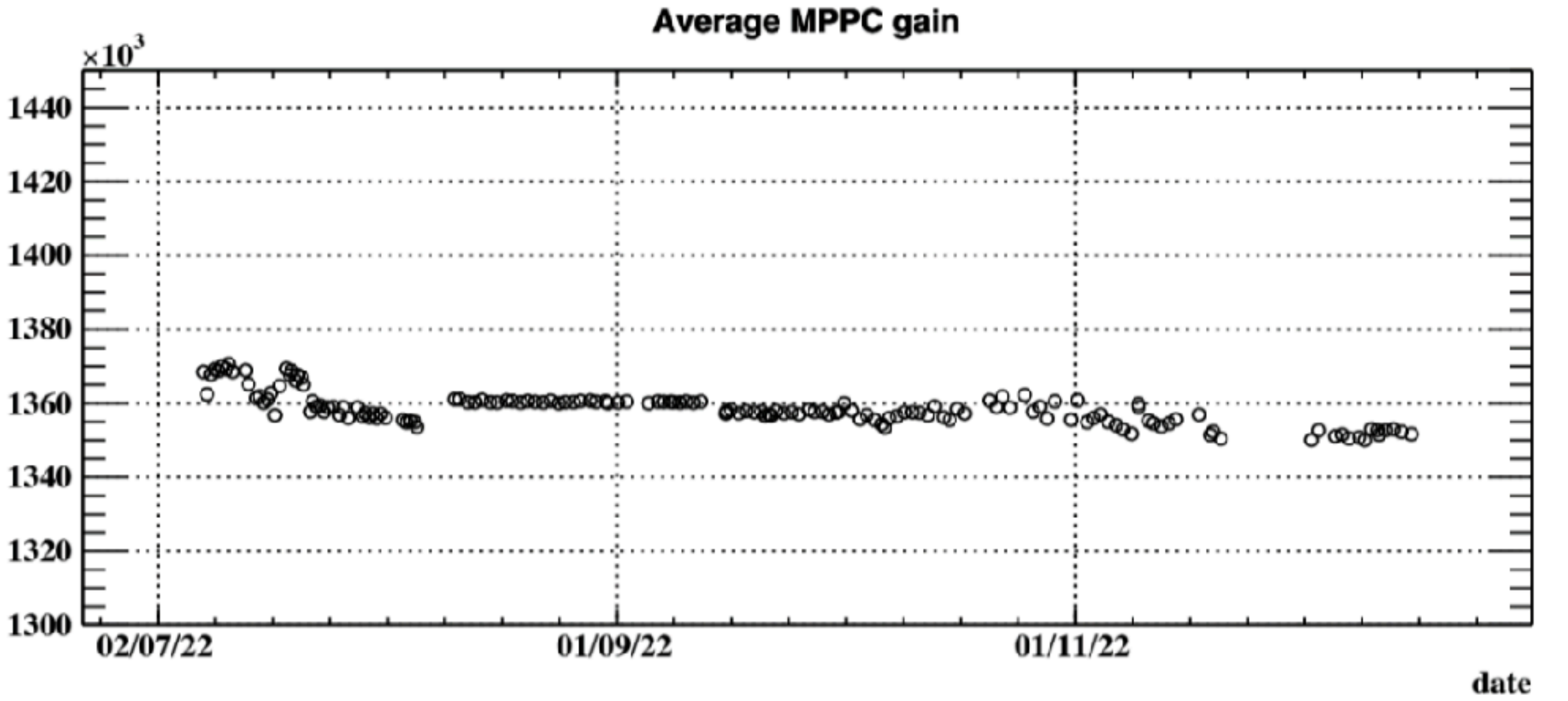
Gain

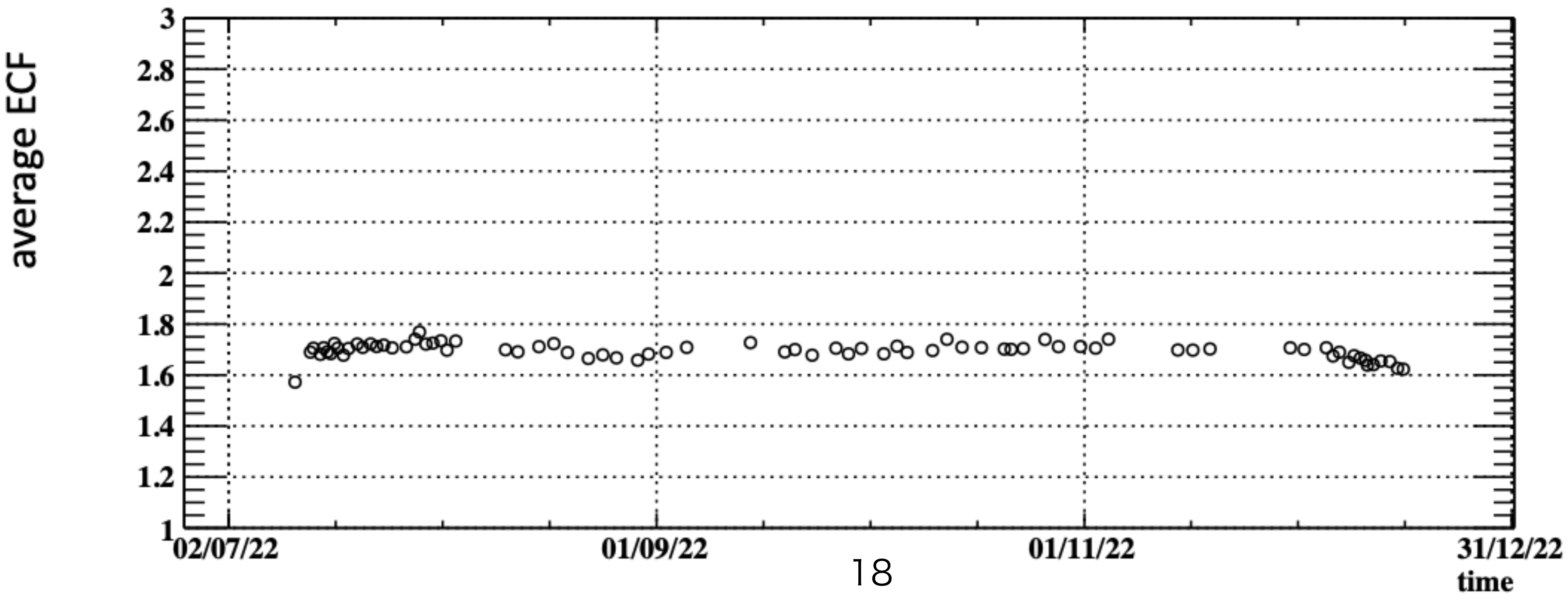


ECF



MPPC monitoring

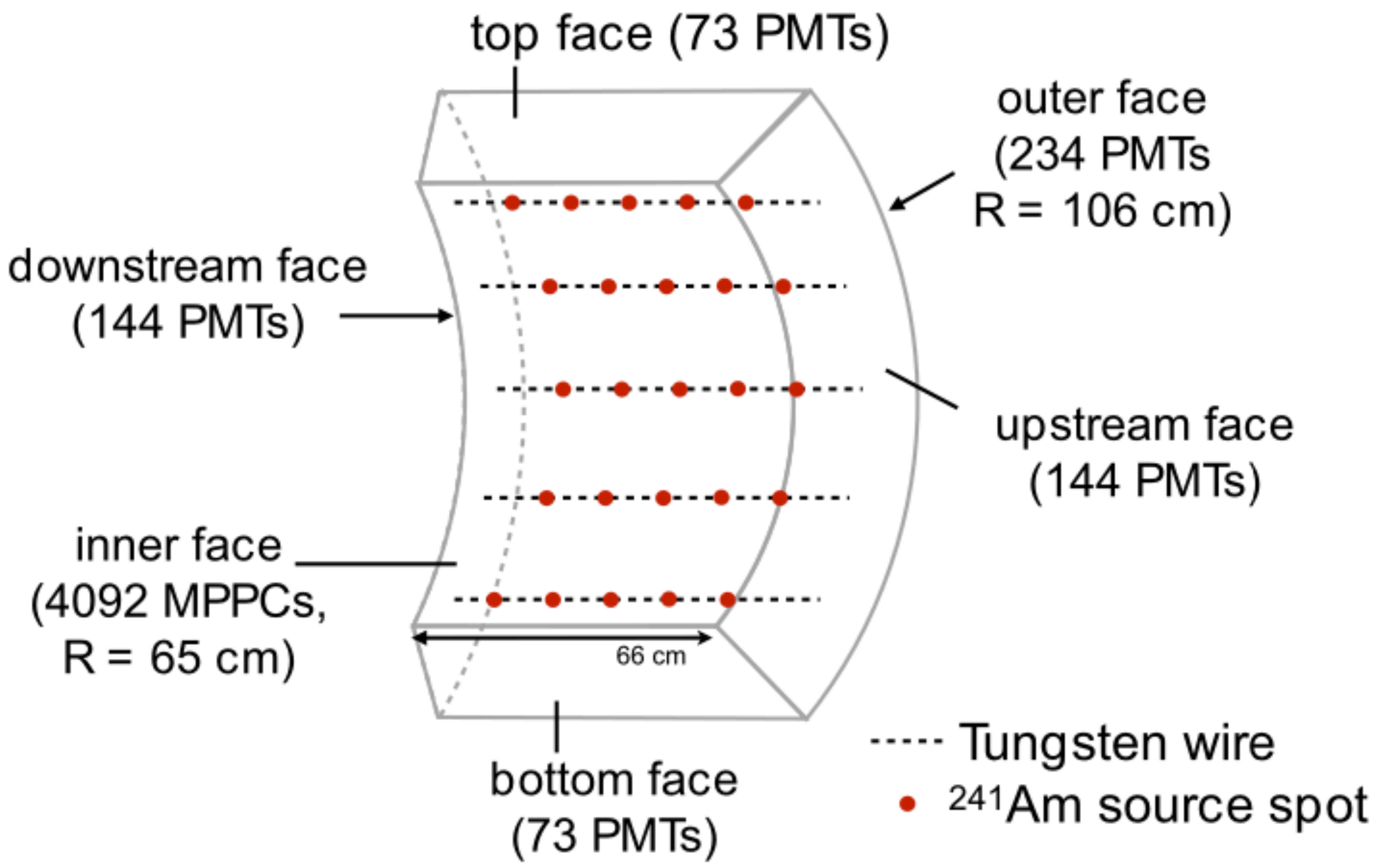


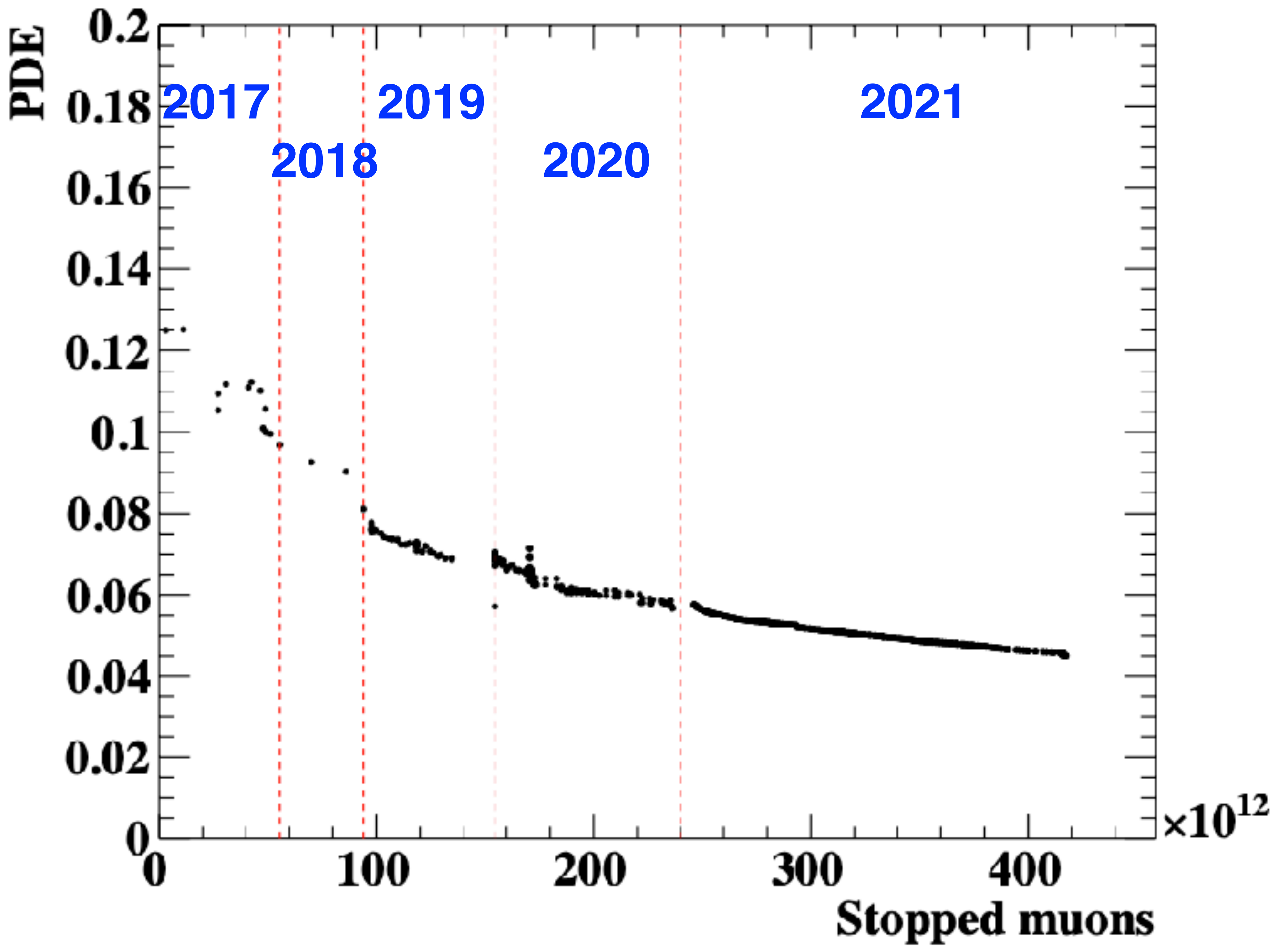


Gain and ECF are sufficiently stable

V_{bd}: 56mV/K
ΔV_{bd}~ 1%
@ΔT_{LXe}~1K

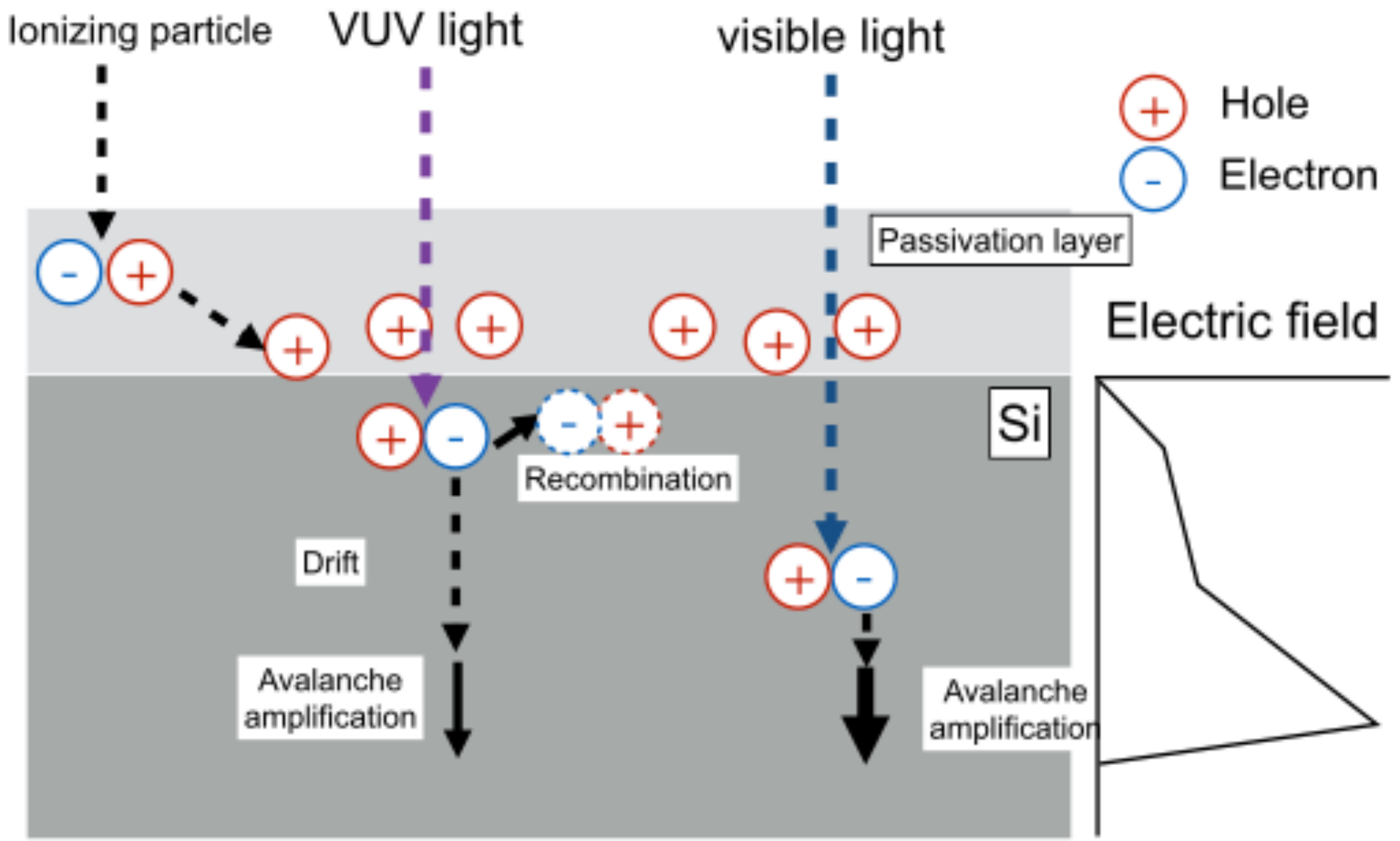
MPPC PDE decrease





- MPPC PDE monitored by α peaks.
- PDE decrease was observed when we started using muon beam, and was not stopped

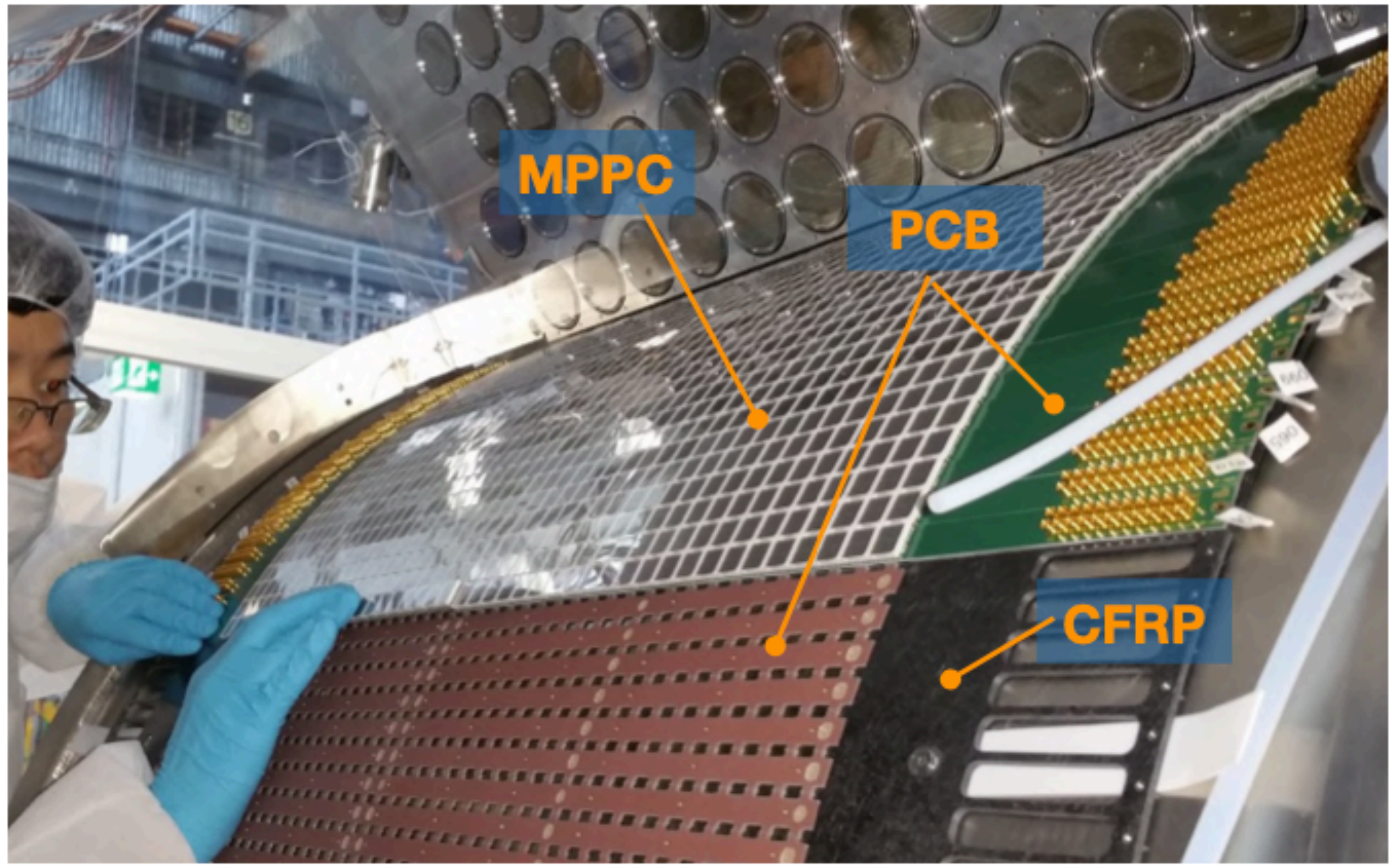
PDE decrease mechanism



Particle	Dose/Fluence	
Gamma-ray	1×10^{-4} Gy	<< 240Gy
Neutron	3×10^{6} cm^{-2} (1 MeV equivalent)	<< 10^9 cm^{-2}
VUV photon	6×10^{10} mm^{-2}	

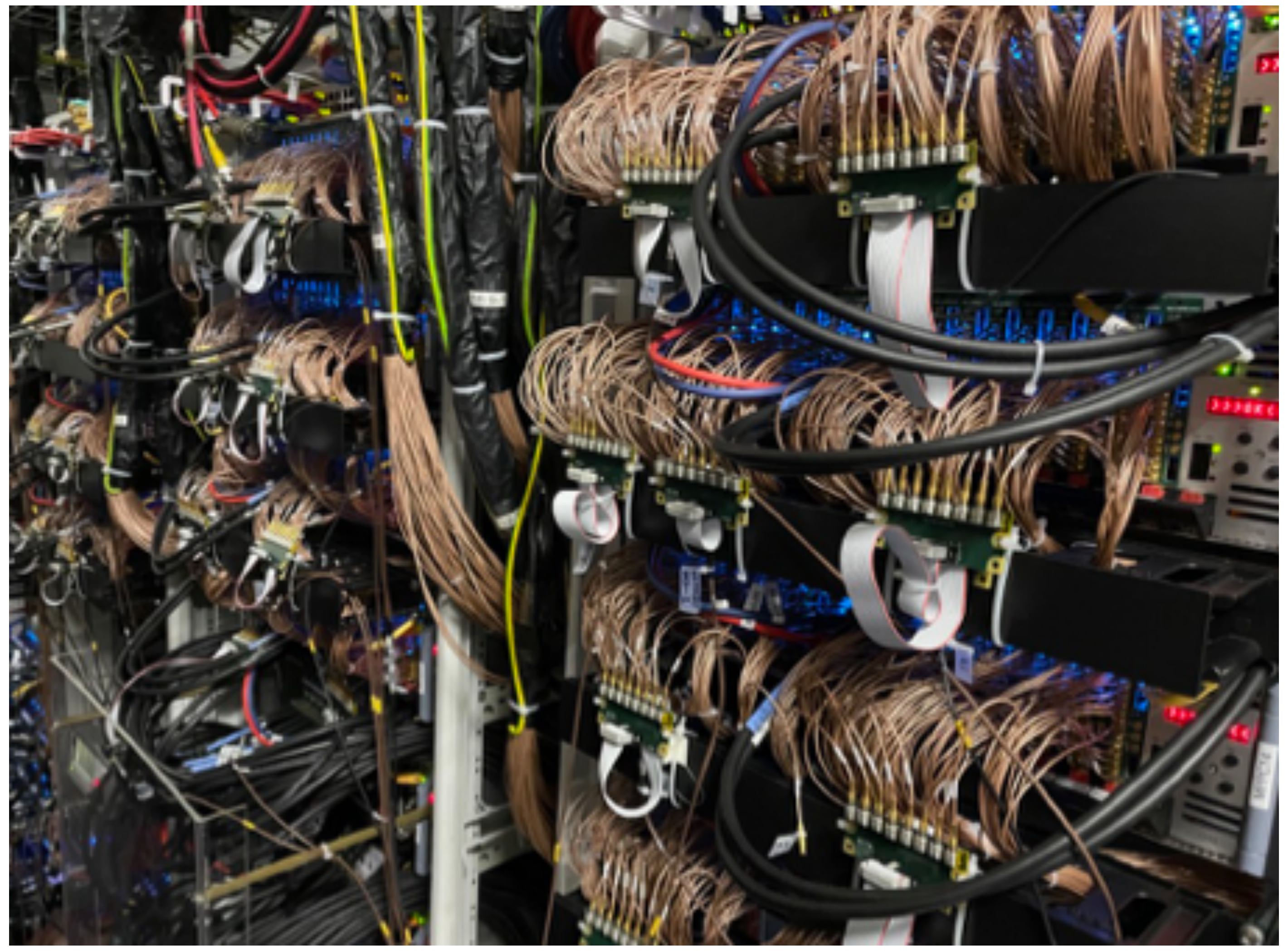
- Possible cause
  - Surface damage by VUV-light
    - Electron-hole pair generated in SiO2 by VUV light
    - Holes are trapped at interface SiO2-Si
    - Accumulated positive charge will reduce electric field near Si surface, reducing collection efficiency of charge carrier
  - Similar phenomena are known for UV photo diode
    - Degradation happens only with much larger amount of light at room temperature
    - Degradation seems accelerated at low temp.
- We haven't reproduced the PDE decrease in lab. measurement yet

Solution for PDE decrease

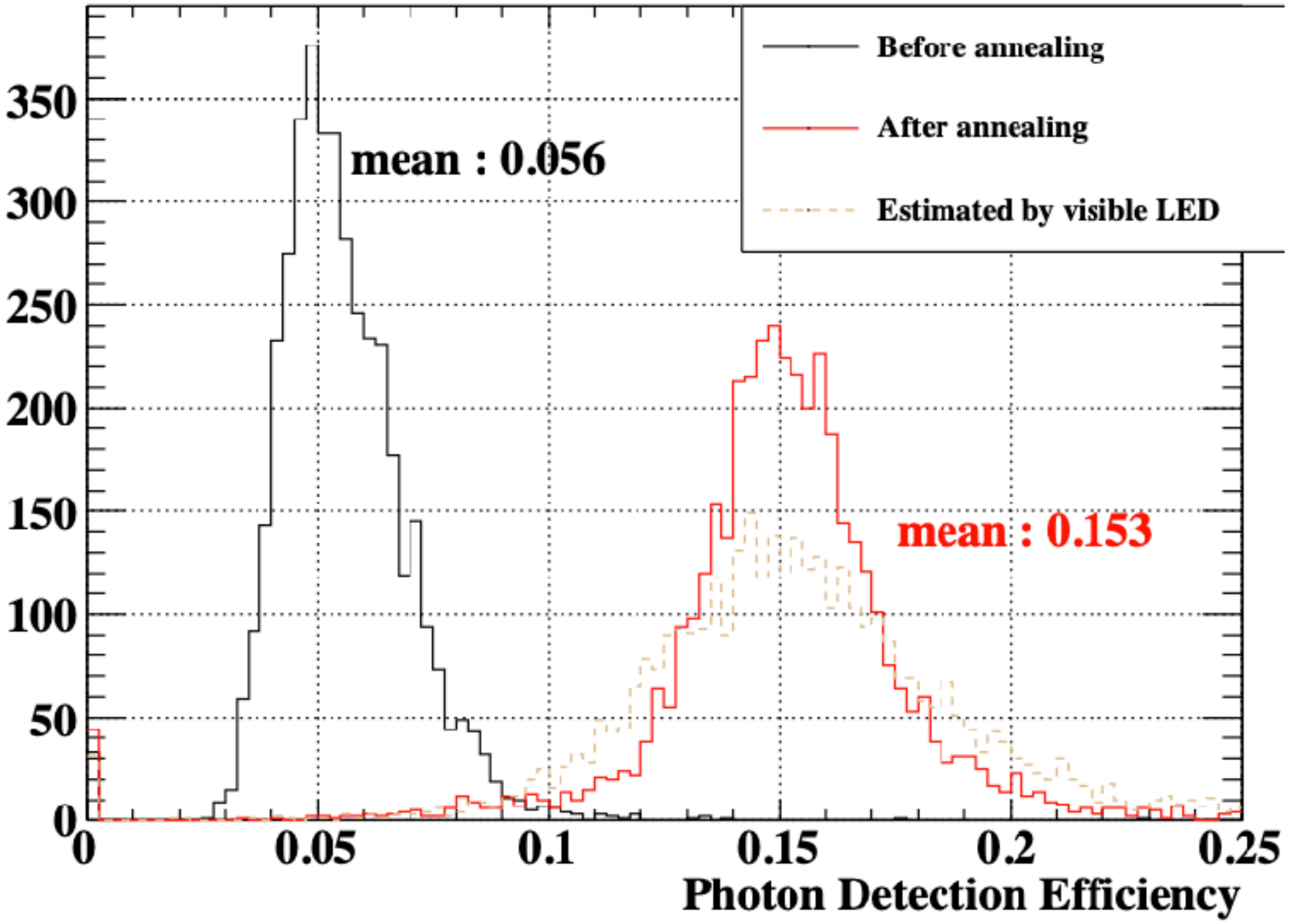


- Temperature limit
  - MPPC: 100°C
  - PCB: 120°C
  - CFRP: 45°C
  - Glue: 65°C

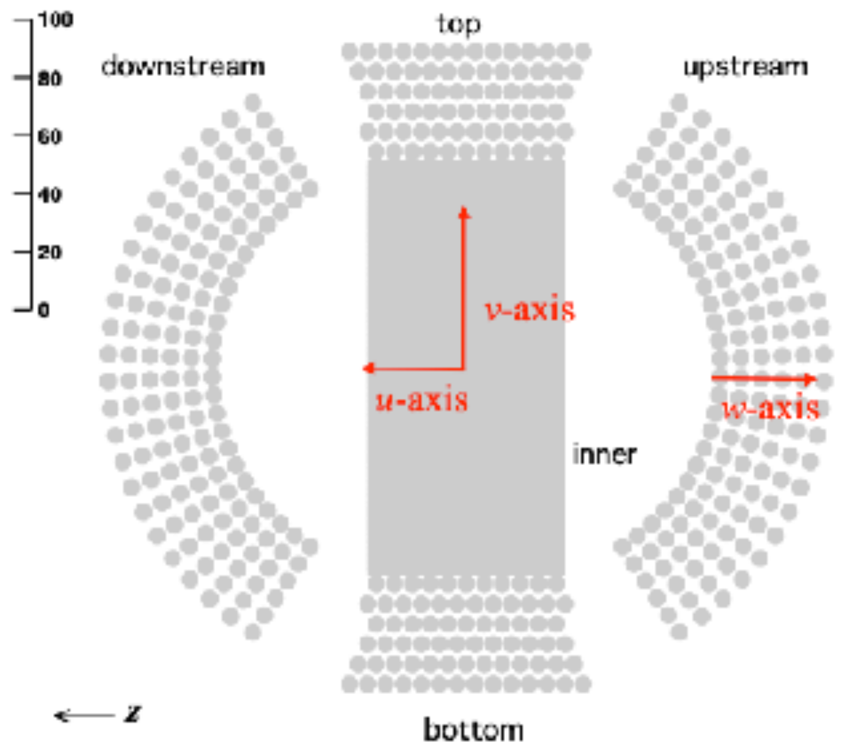
- Joule annealing method
  - Supply ~1.7W per MPPC using high current and LED light
- Annealing power supply
  - 30 outputs. Each connected to 8ch → 240ch/set
  - 4092 MPPCs → 17 sets of annealing repeated
- 30 hours annealing / set + cabling work ~ 3 days / set → 1.5 month annealing

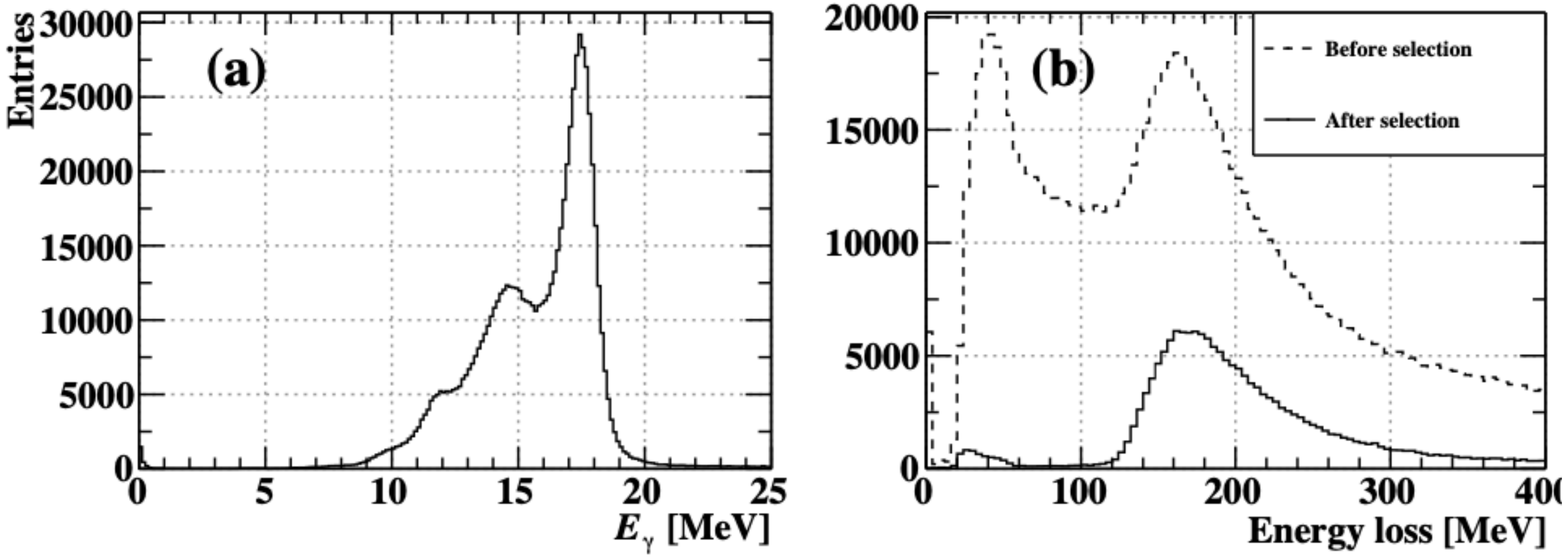


PDE before/after the annealing with LY correction (after annealing)

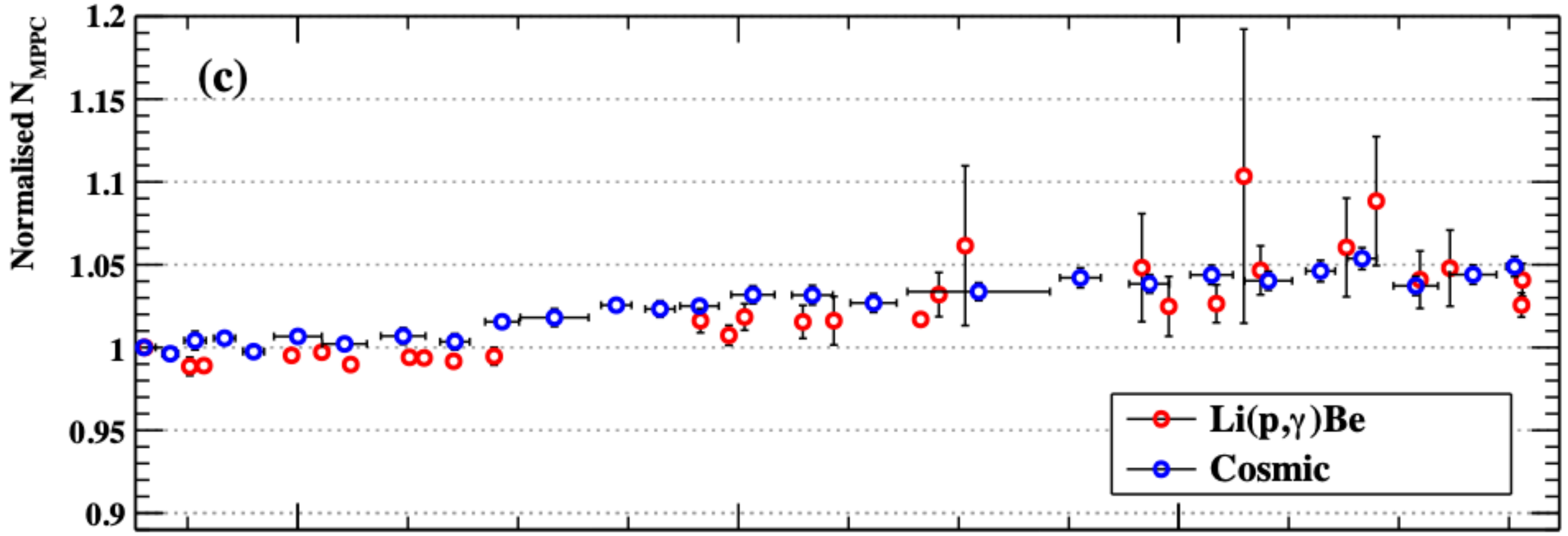


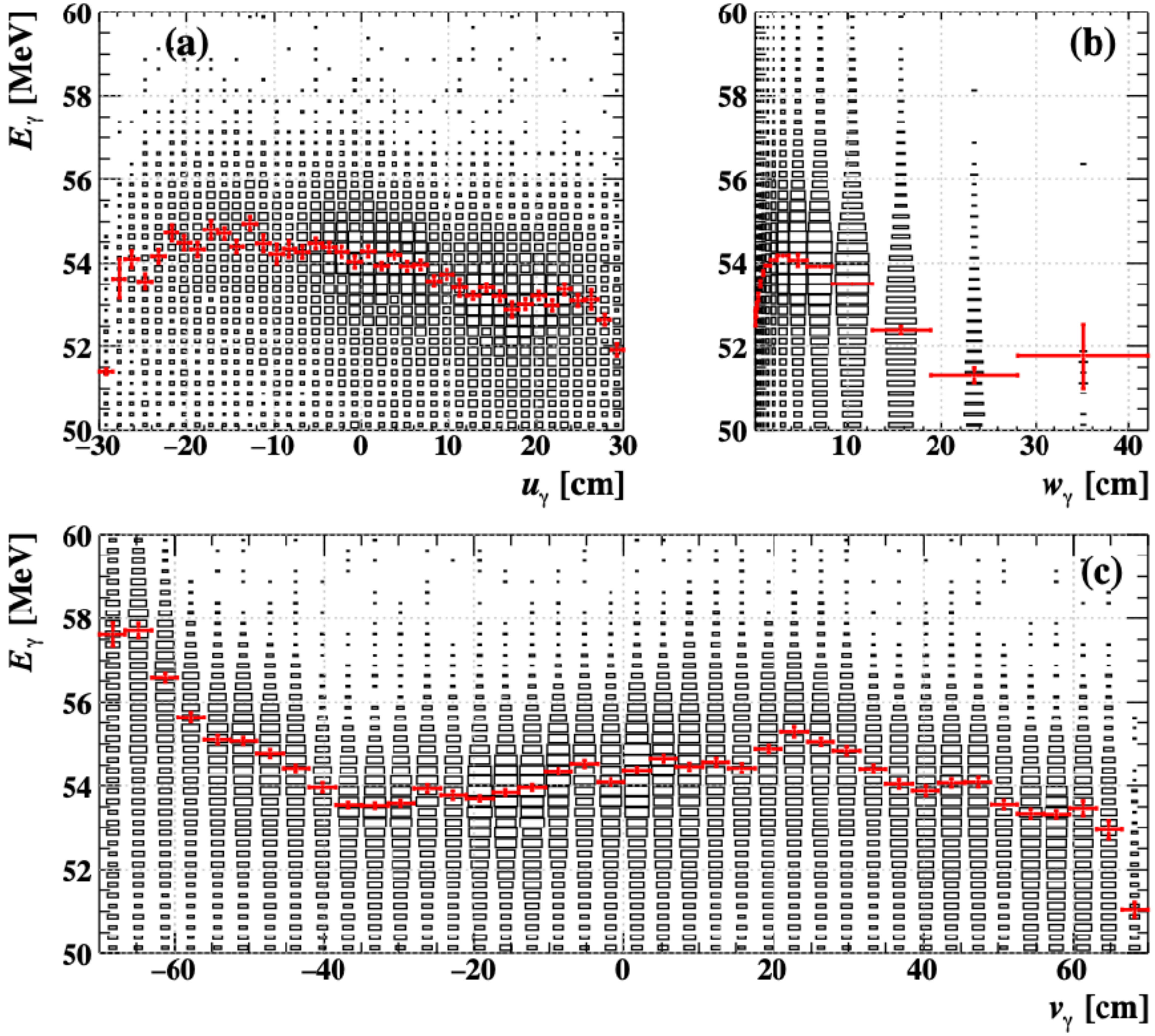
LXe detector stability and uniformity





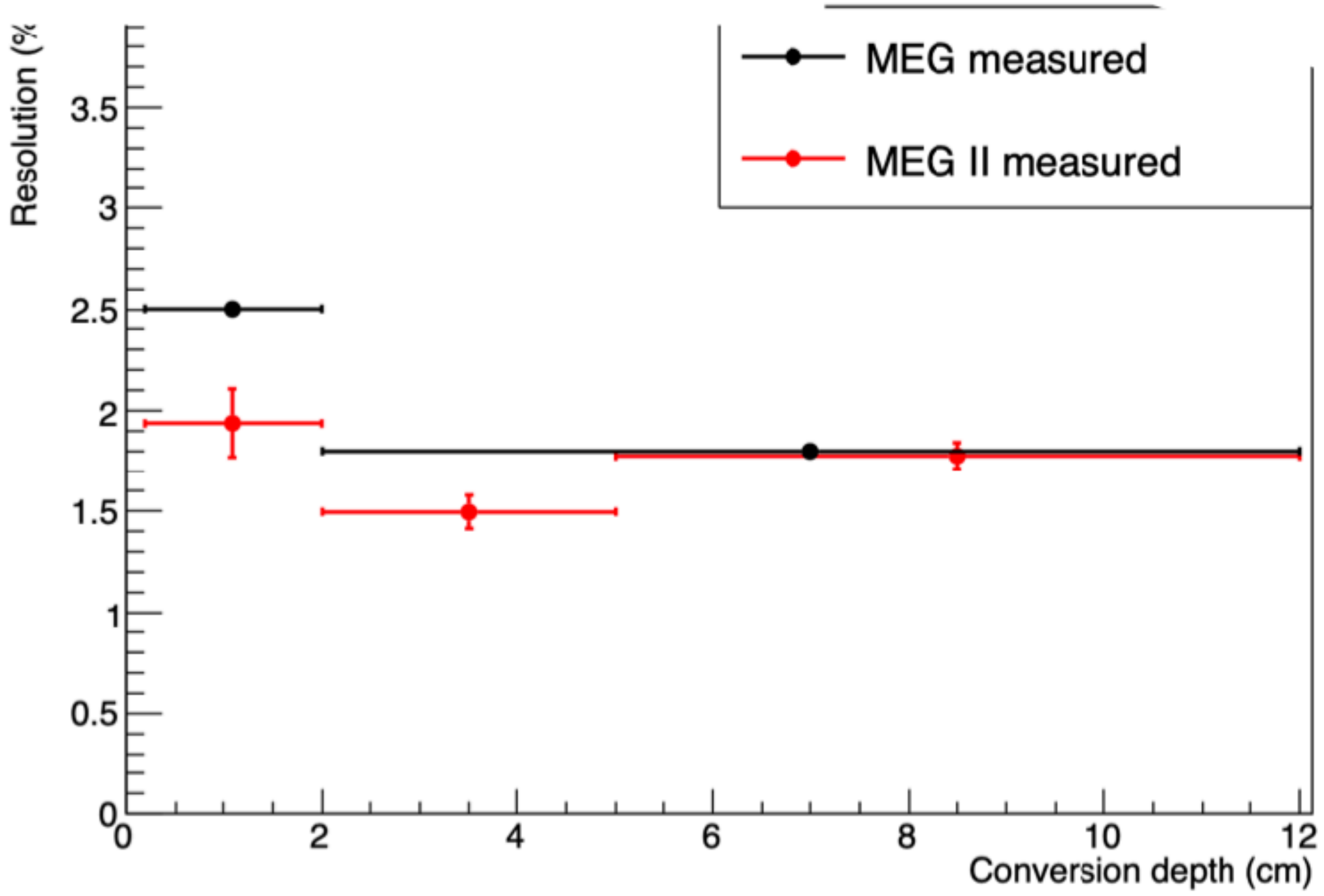
MPPC Q sum



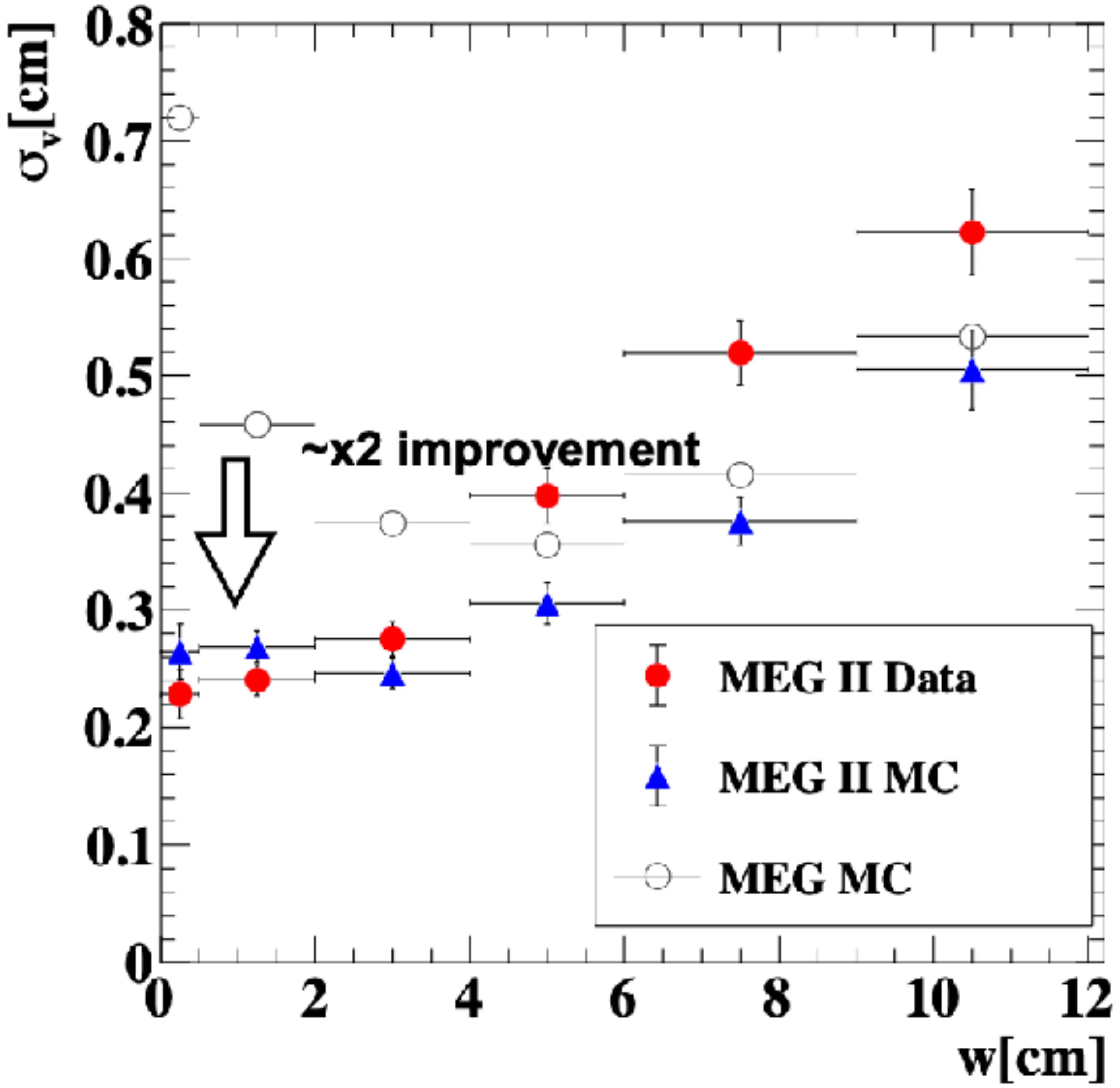


The LXe detector performance evaluation

Energy resolution (for 53MeV γ) vs depth



Position resolution



	MEG (measured)	MEG II (measured)
position resolution $(u/v/w)$(mm)	5/5/6	2.5/2.5/5.0 mm
energy resolution (%)($w < 2\,\mathrm{cm}/w > 2\,\mathrm{cm}$)	2.4/1.8	2.0/1.8 %
timing resolution (ps)	62	~ 65 ps
efficiency (%)	63	62

Summary

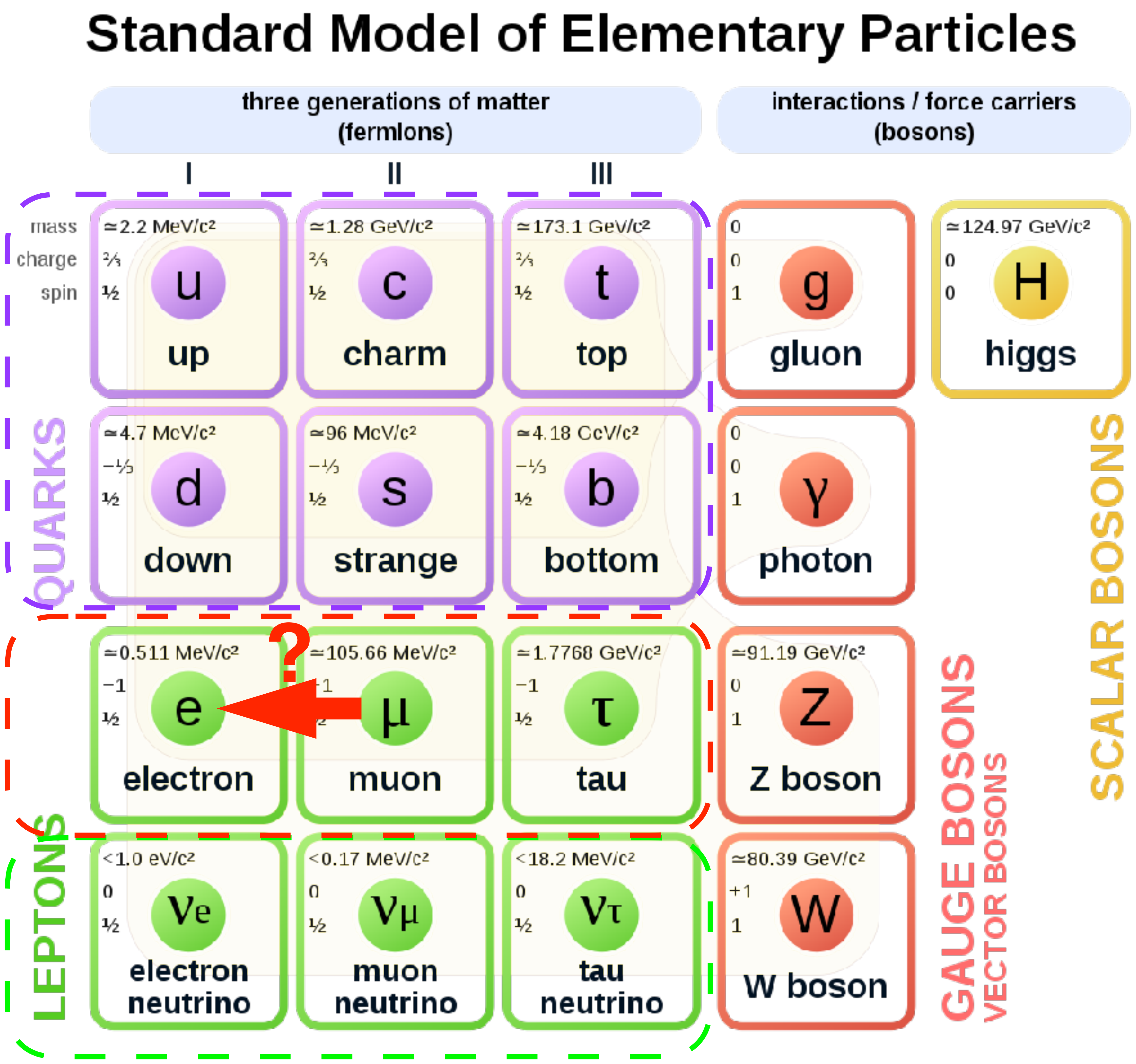
- The MEG II experiment looks for new physics beyond the standard model by studying the $\mu^+ \to e^+\gamma$ decay with the target sensitivity of 6×10^{-14} before 2027. The MEG II experiment started physics data taking in 2021, and the first results with 2021 data were presented last year.
- The 900 l liquid xenon detector is used for the γ detection, and 4092 VUV-sensitive MPPCs are newly installed in the detector. The full readout of all the photo sensors has been started since 2021.
- The sensor calibration and monitoring methods are established, and the detector performances are evaluated for the physics data analysis.
- The reason of the PDE decrease has to be understood, but the remedy to recover the PDE has been established by Joule annealing method.

Charged Lepton Flavor Violation

CKM matrix

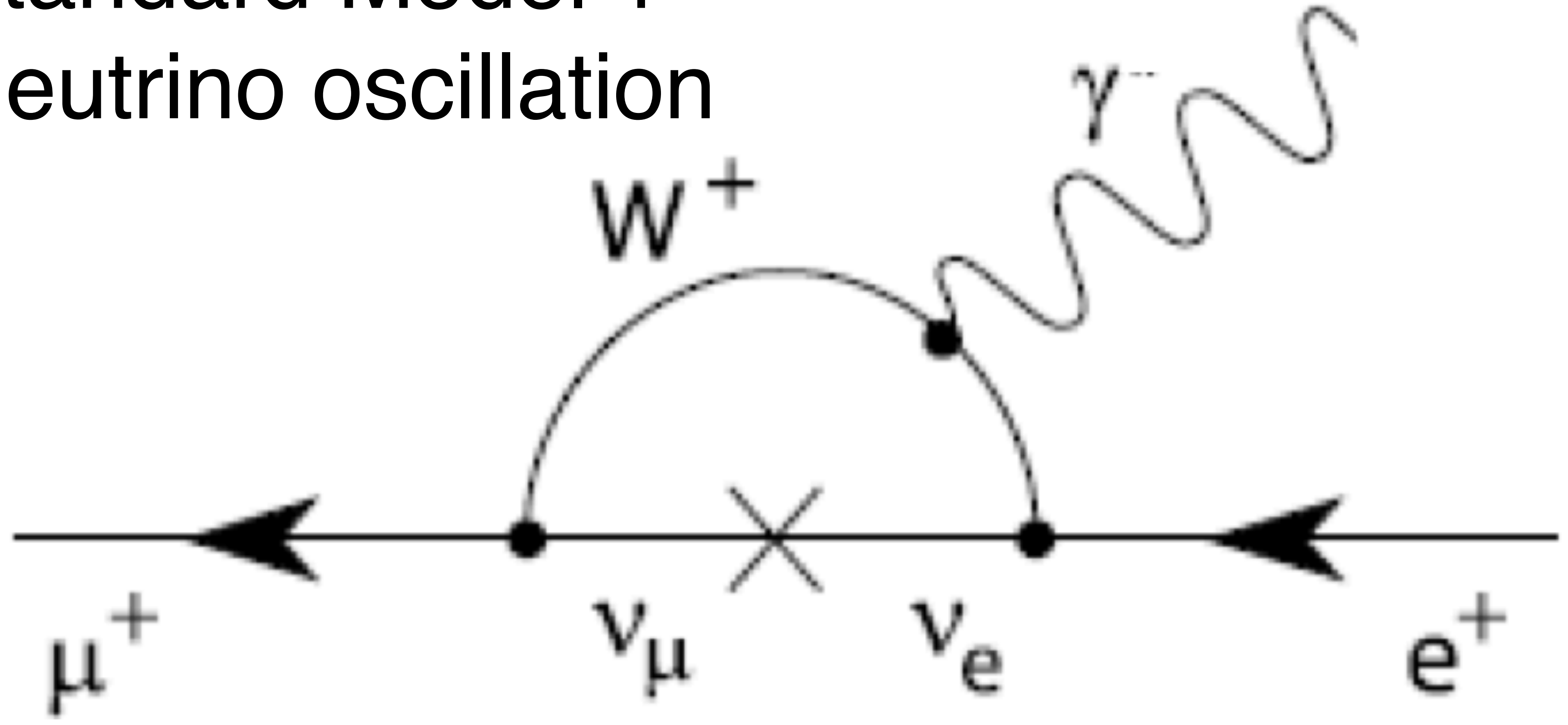
CLFV

Neutrino Oscillation



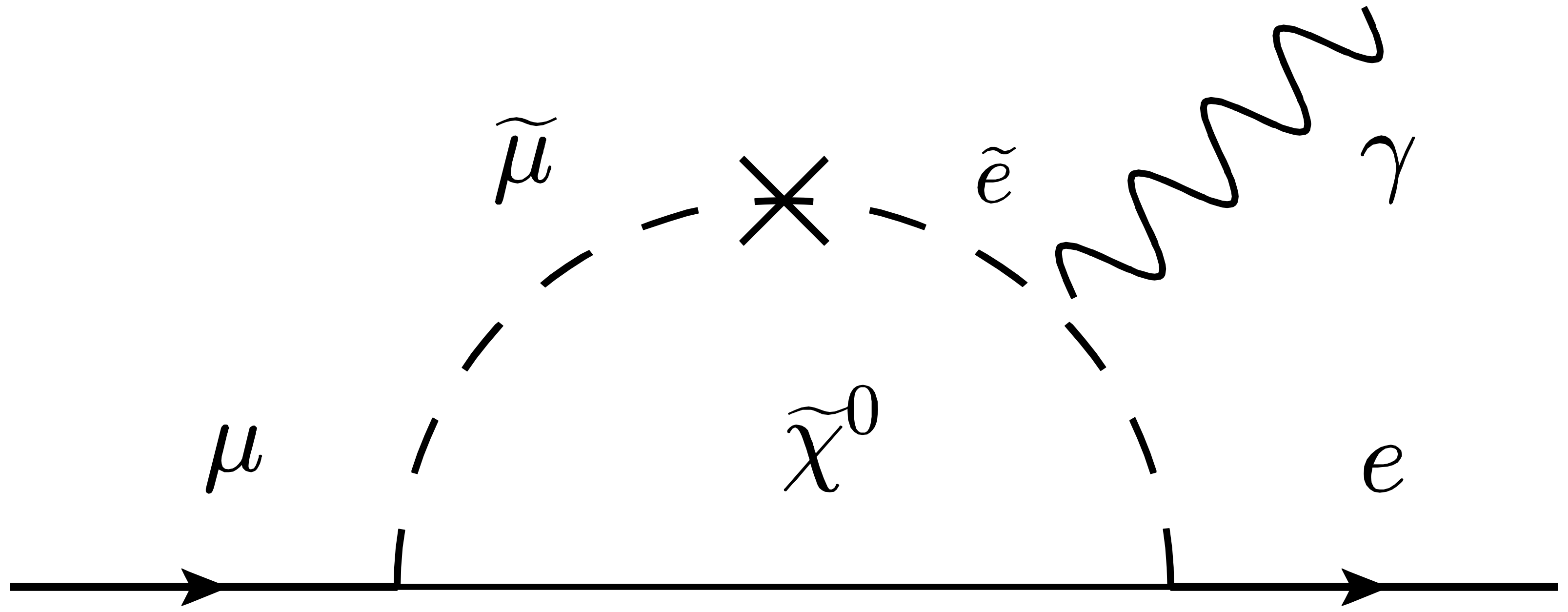
From Wikipedia

Standard Model +
Neutrino oscillation



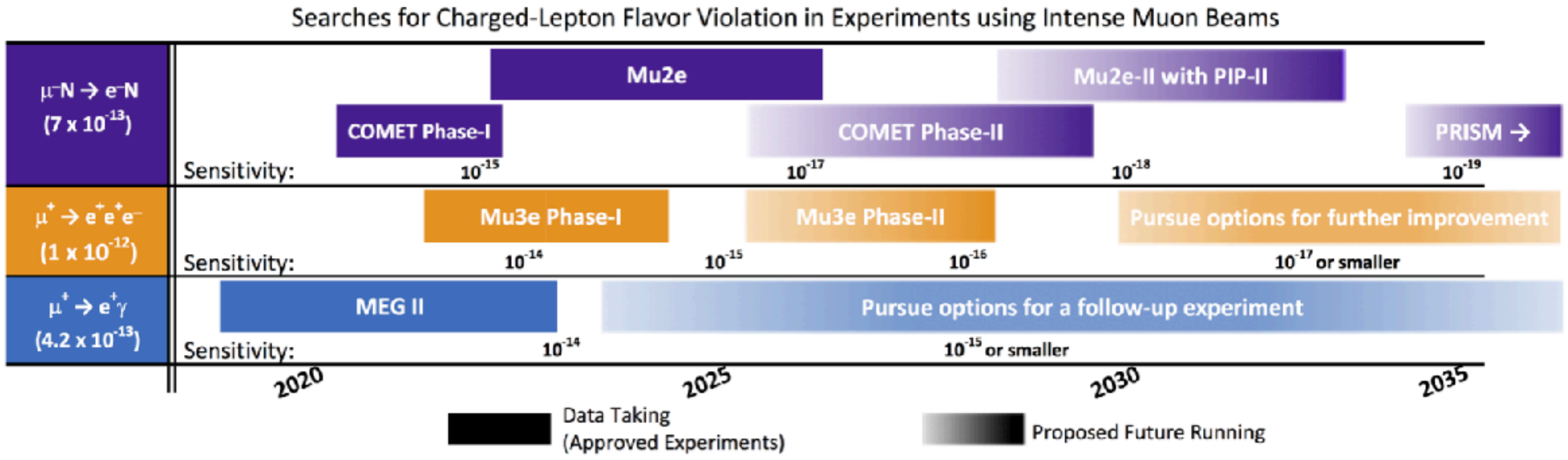
Br(μ→eγ) ~ 10^{-54}

New physics predictions
(SUSY-GUT, SUSY-Seesaw etc.)



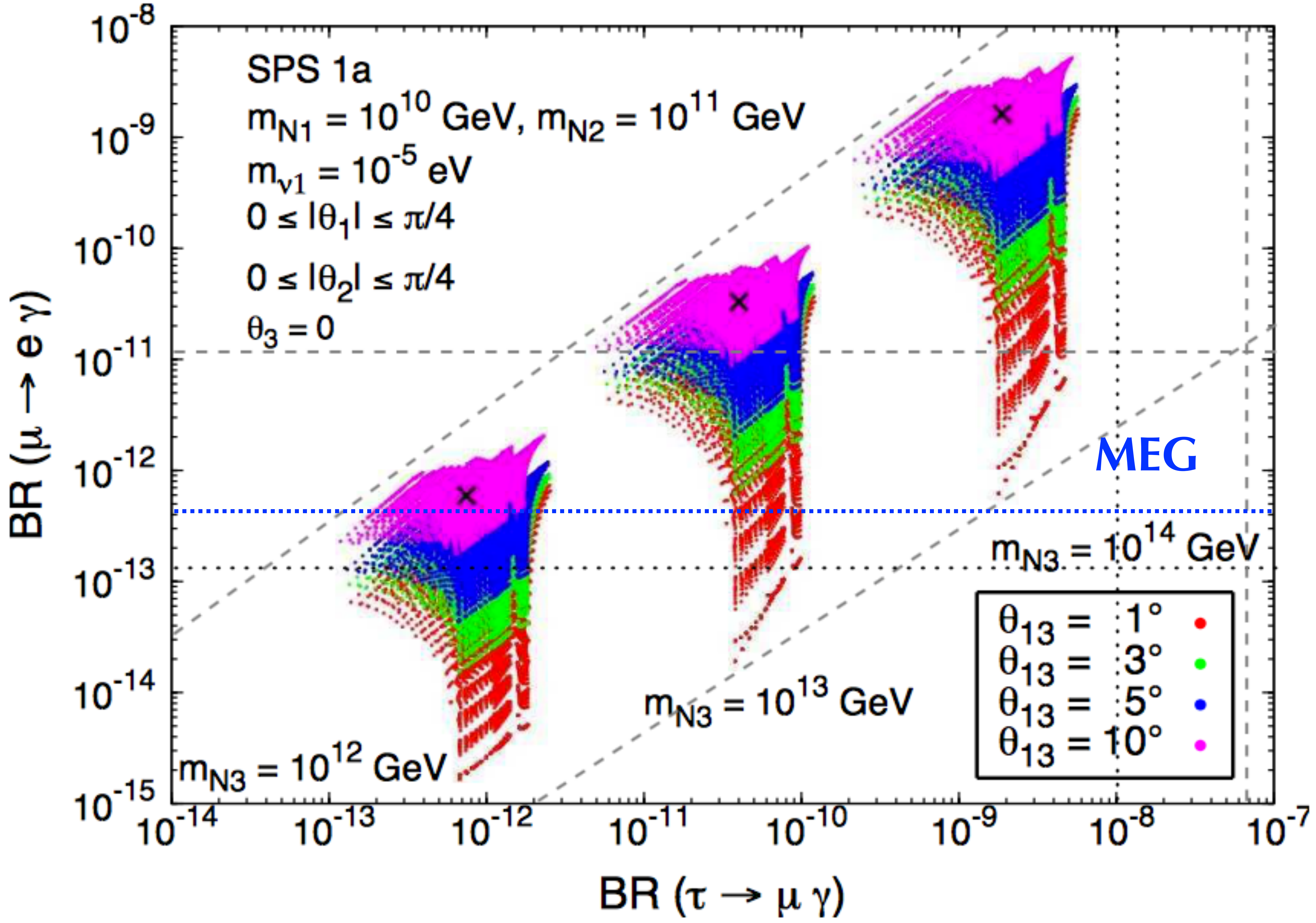
Br(μ→eγ) ~ 10^{-14}

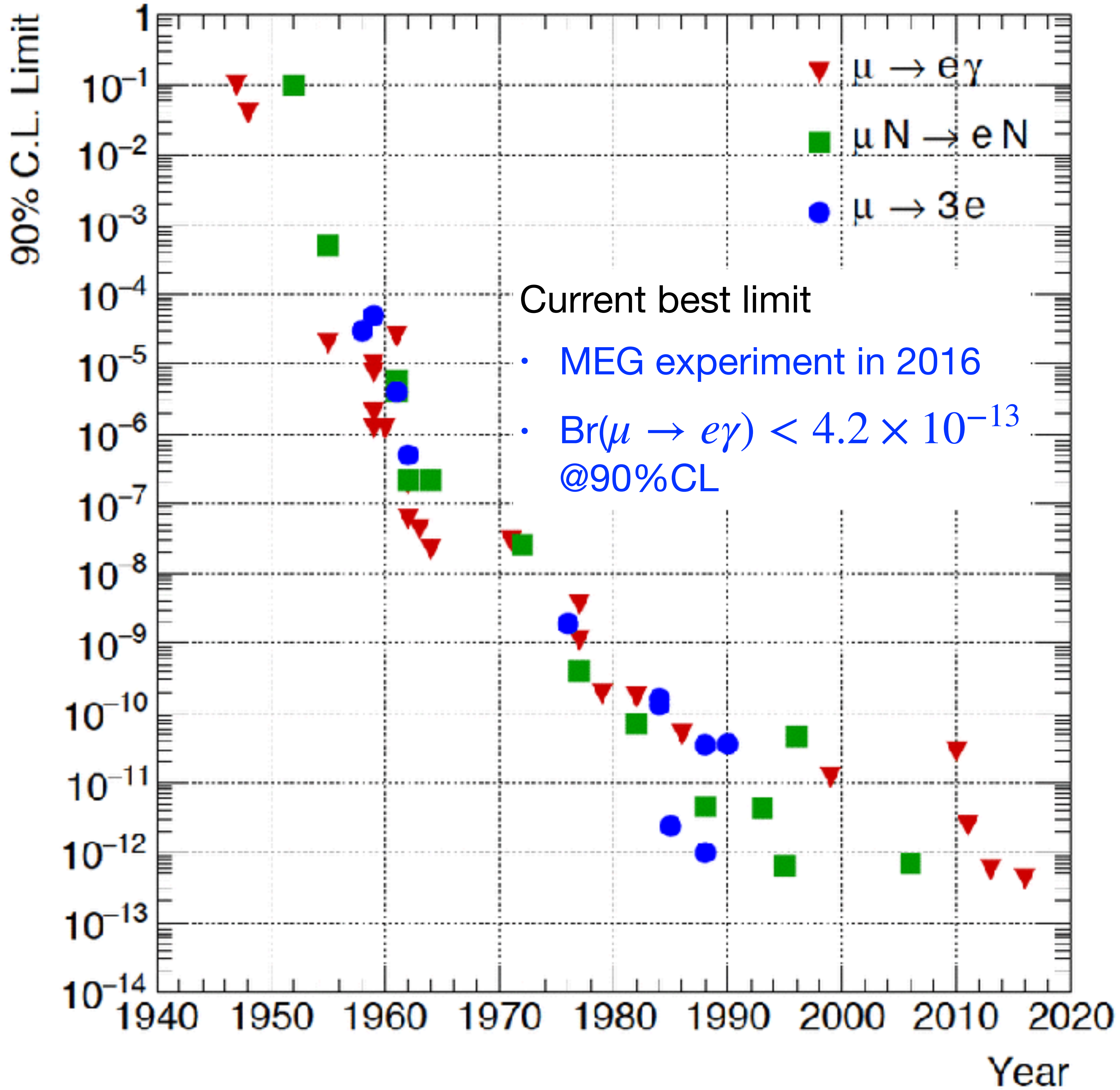
$$\mu^+ \rightarrow e^+\gamma$$



S. Antusch et al, JHEP 0611:090(2006)

SUSY-Seesaw

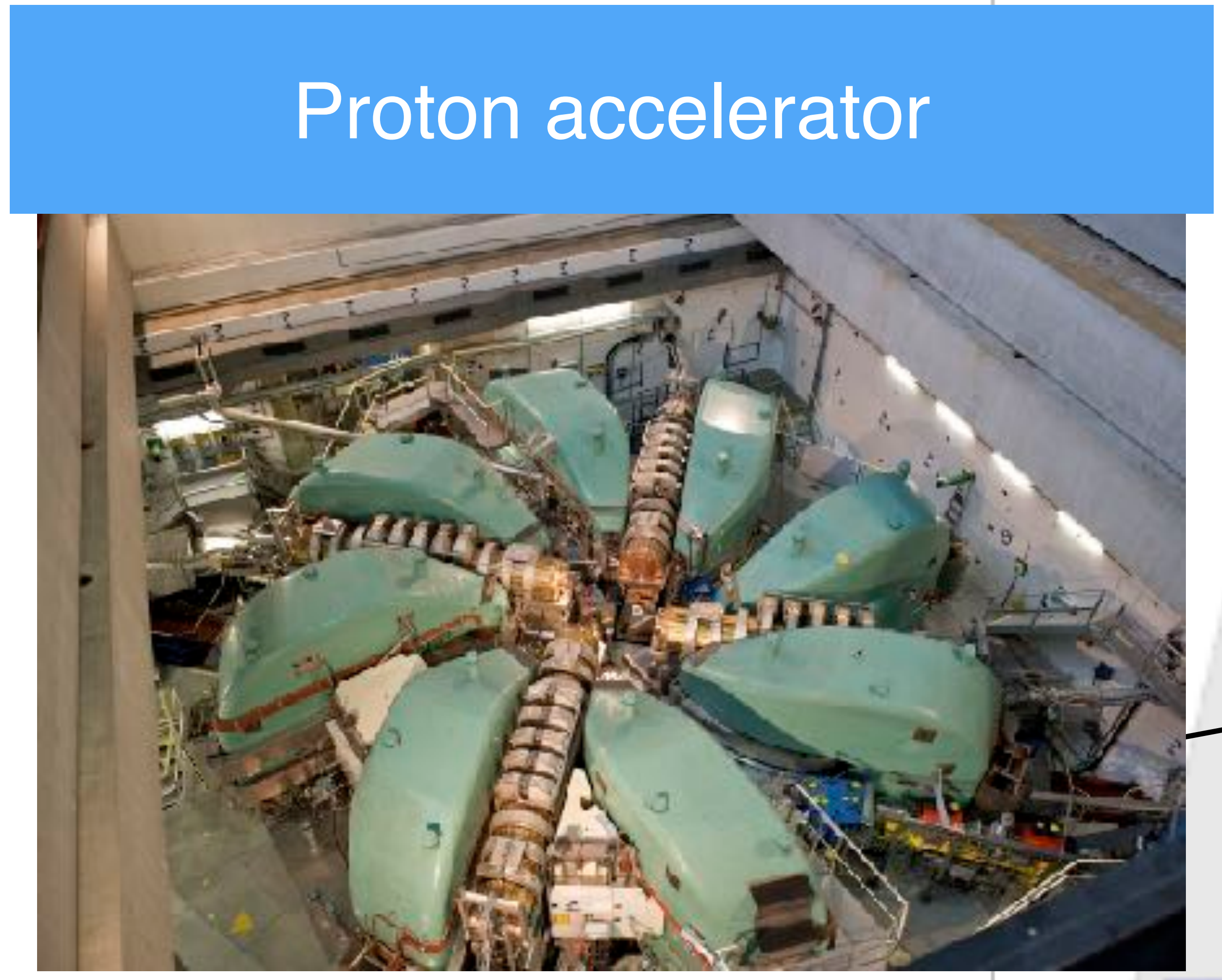


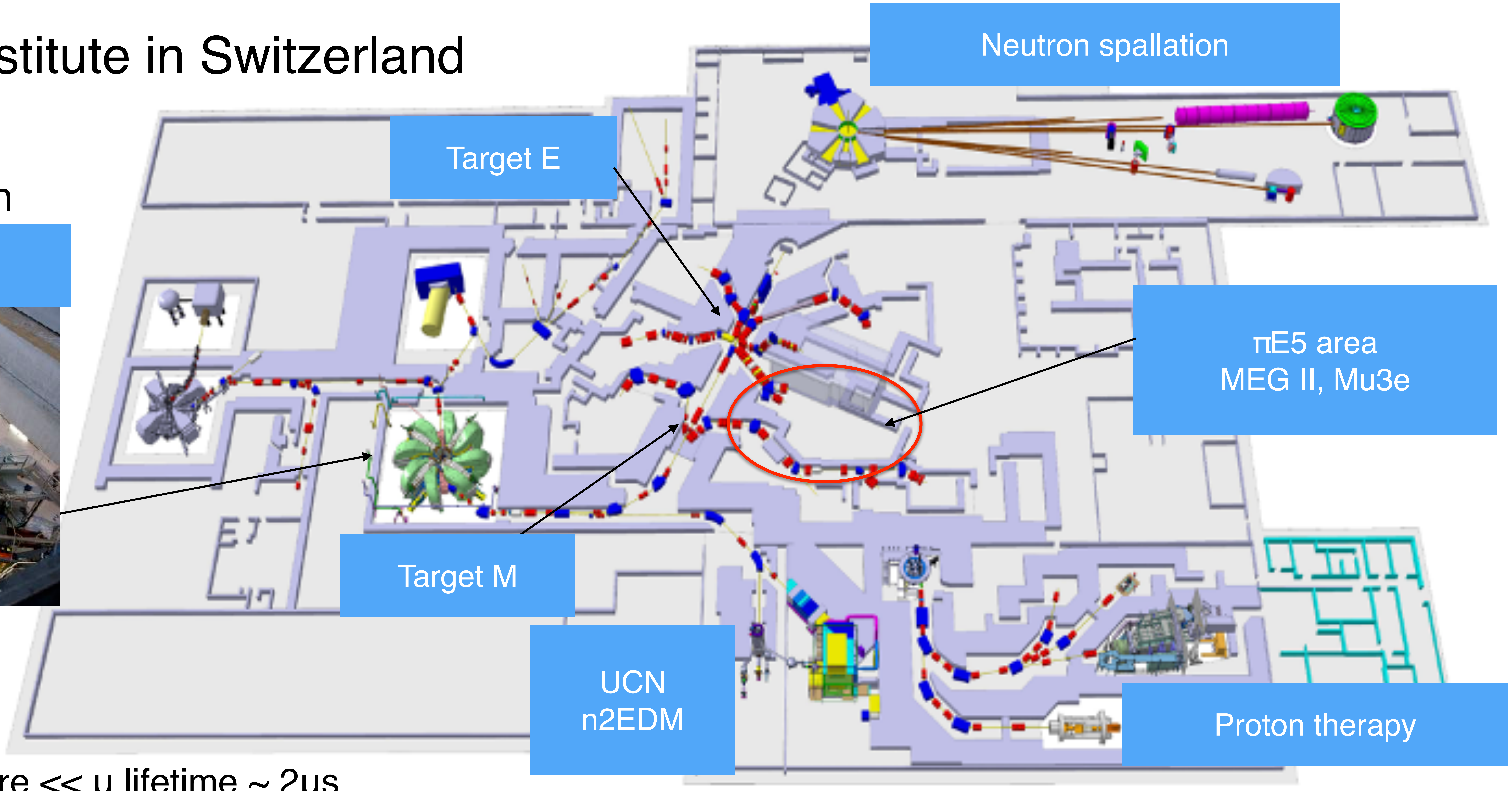


High intensity muon beam (DC)

Paul Scherrer Institute in Switzerland

590 MeV 2.4mA
proton ring cyclotron



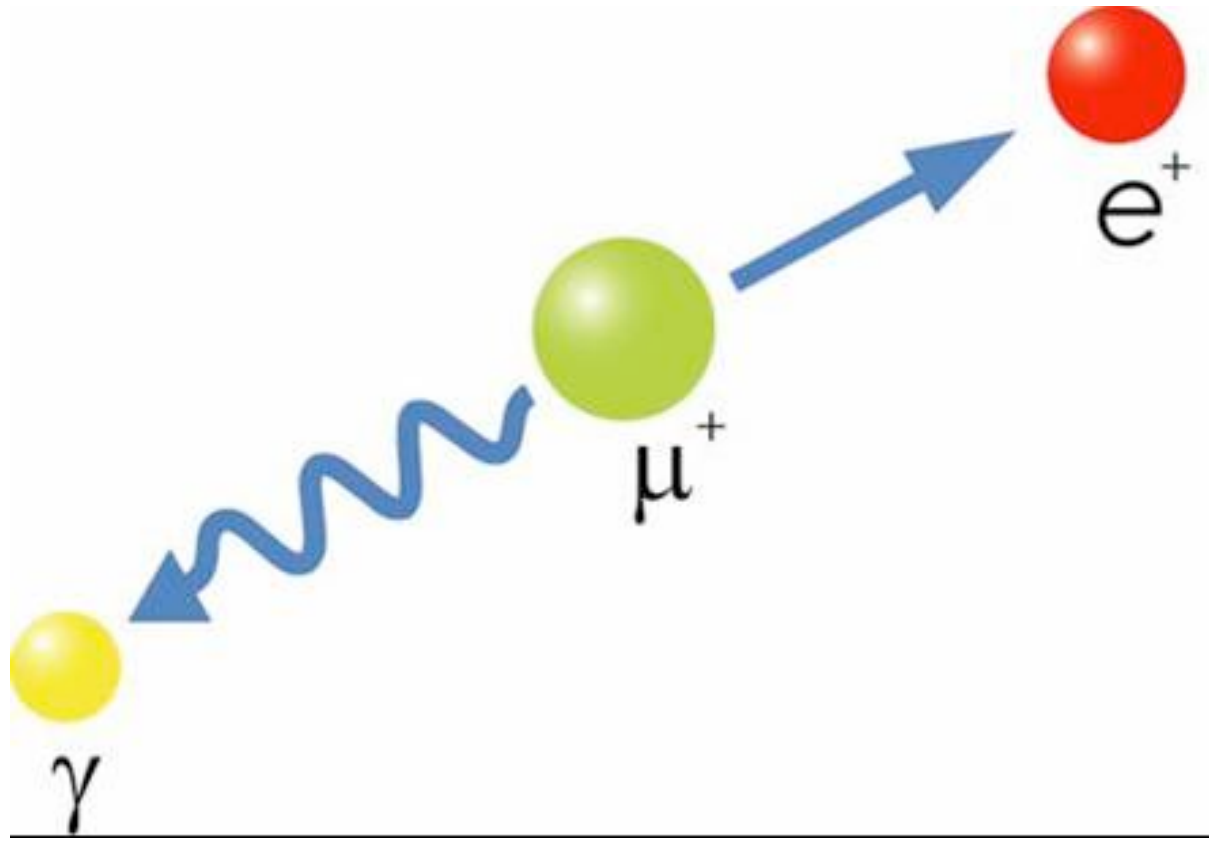


50 MHz RF time structure << μ lifetime ~ 2μs
No time structure in muon decay (continuous)

World most intense DC muon beam > 10^8 μ/s
Surface muon beam ~ 29 MeV/c

$\mu \to e\gamma$ signal and background

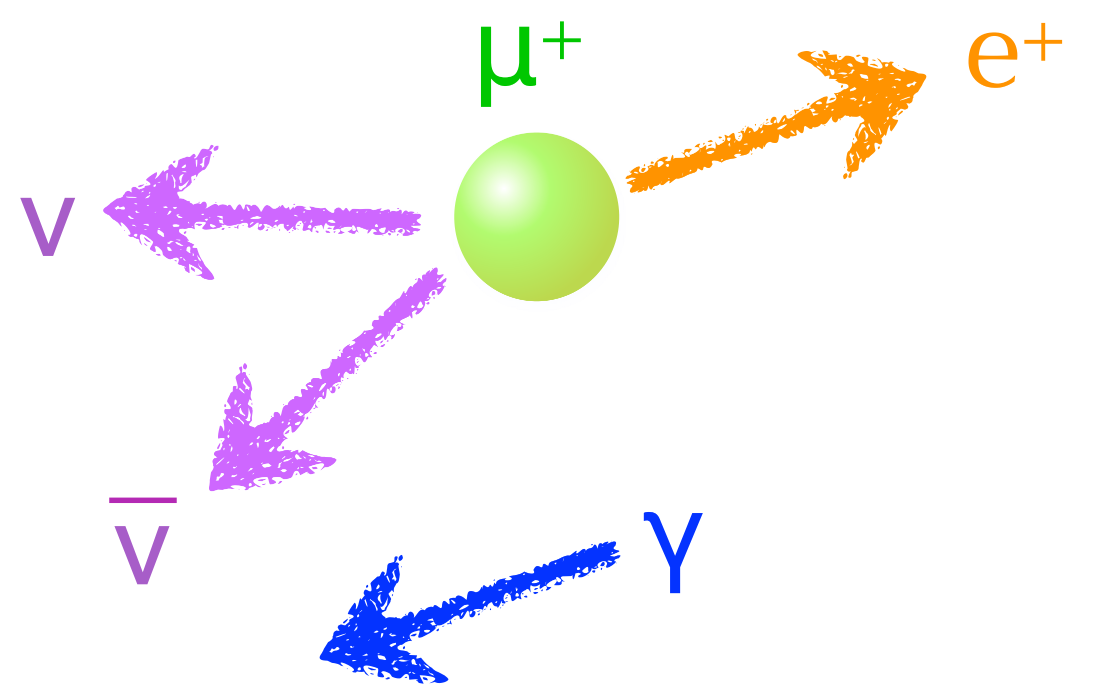
Signal



$$E_\gamma, E_e \sim 52.8\ MeV$$
$$\Theta_{e\gamma} = 180^\circ, T_\gamma = T_e$$

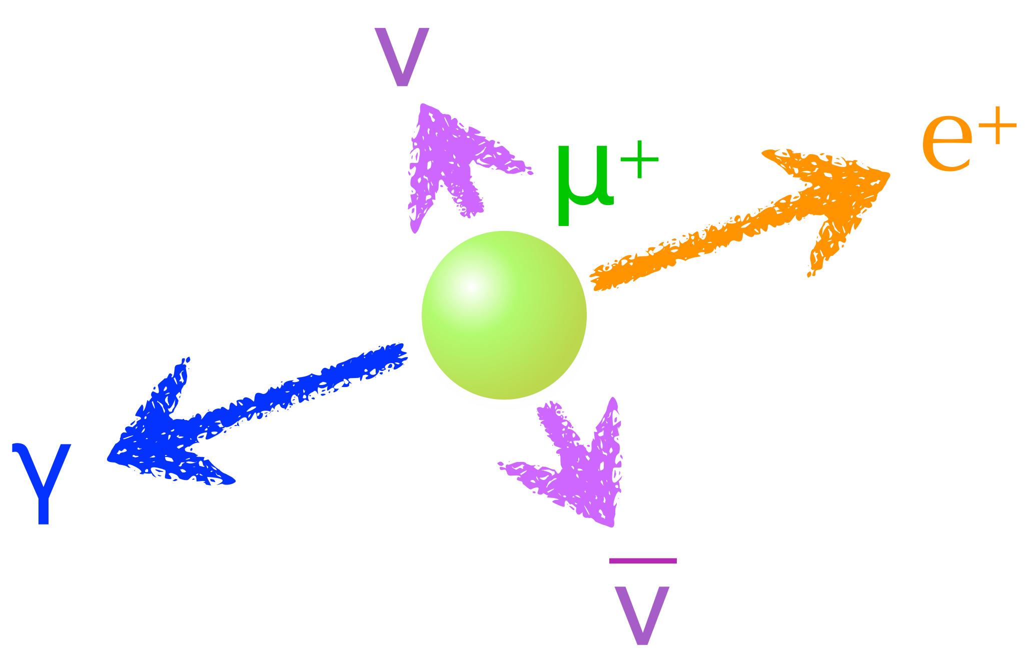
Background

Accidental Dominant BG



Michel e^+ + random γ from RMD/ AIF

Radiative Muon Decay



e^+-γ timing coincident

$$N_{acc} \propto (R_\mu)^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma} \times T$$

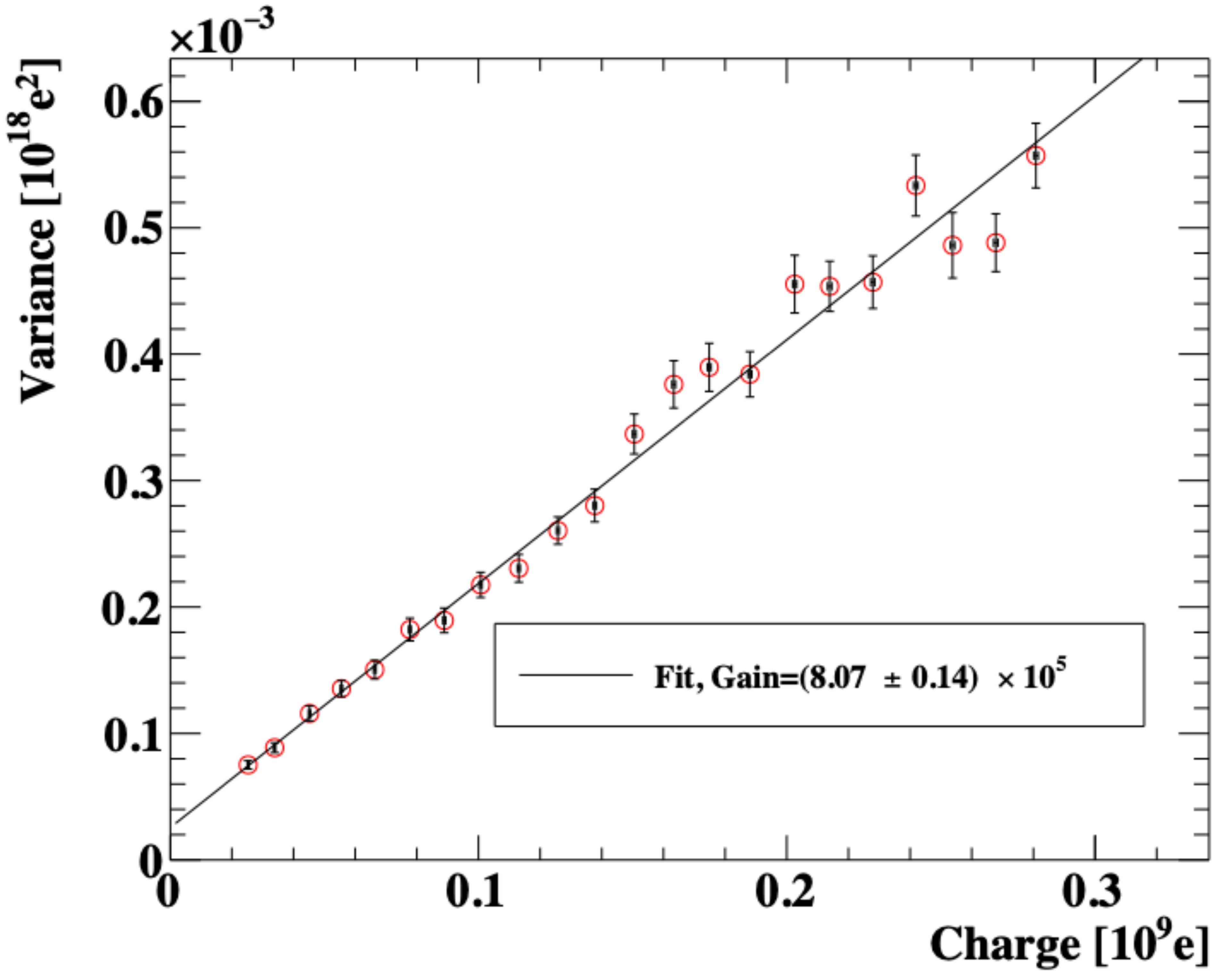
- High statistics: High intensity muon beam
- Low background:
  - Lower instantaneous muon beam rate (DC muon beam, not pulse beam)
  - Good detector resolutions

PMT gain calculation

- Photon statistics relations

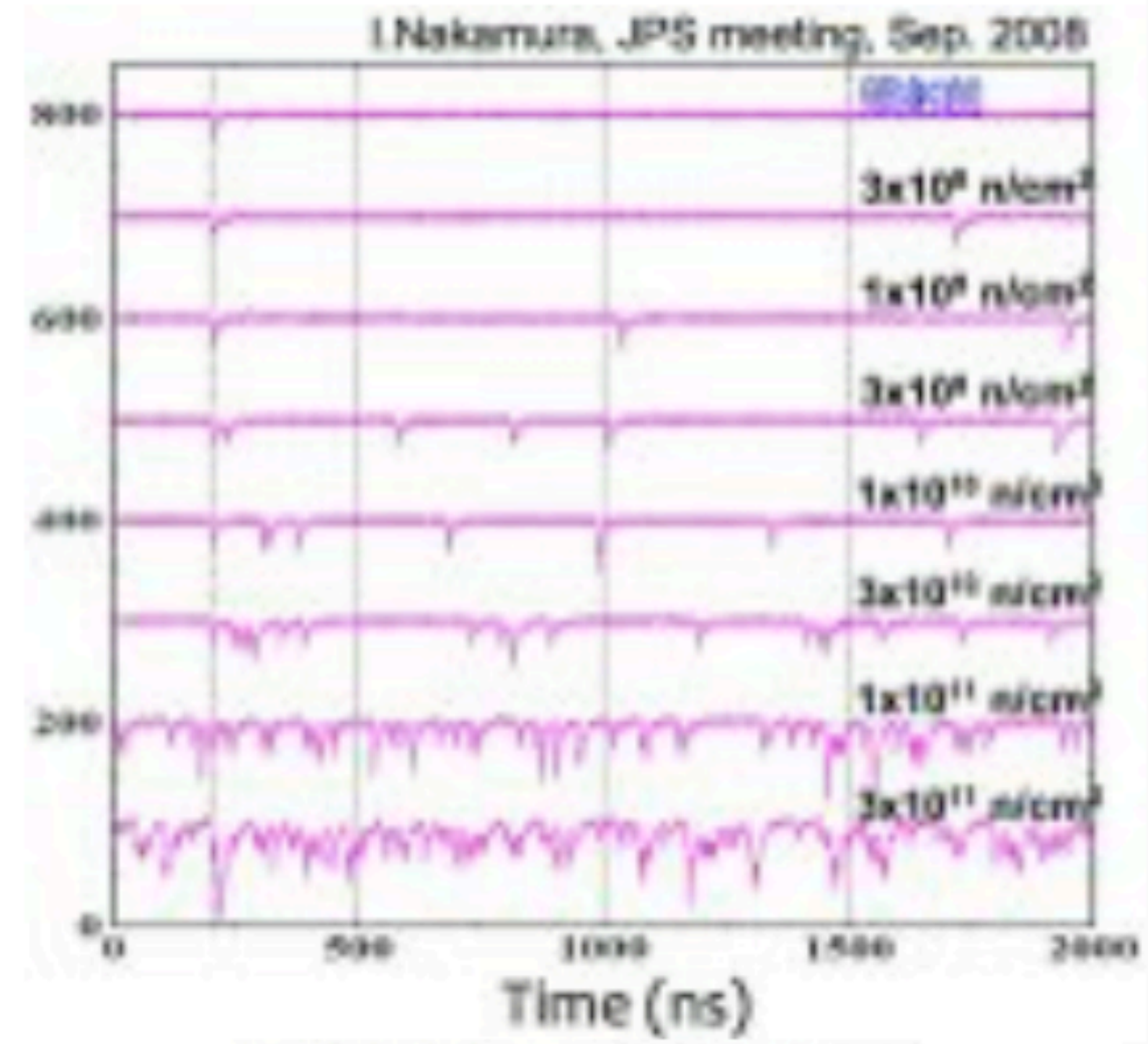
$$\sigma_Q^2 = G \cdot e \cdot \overline{Q} + \sigma_0^2$$

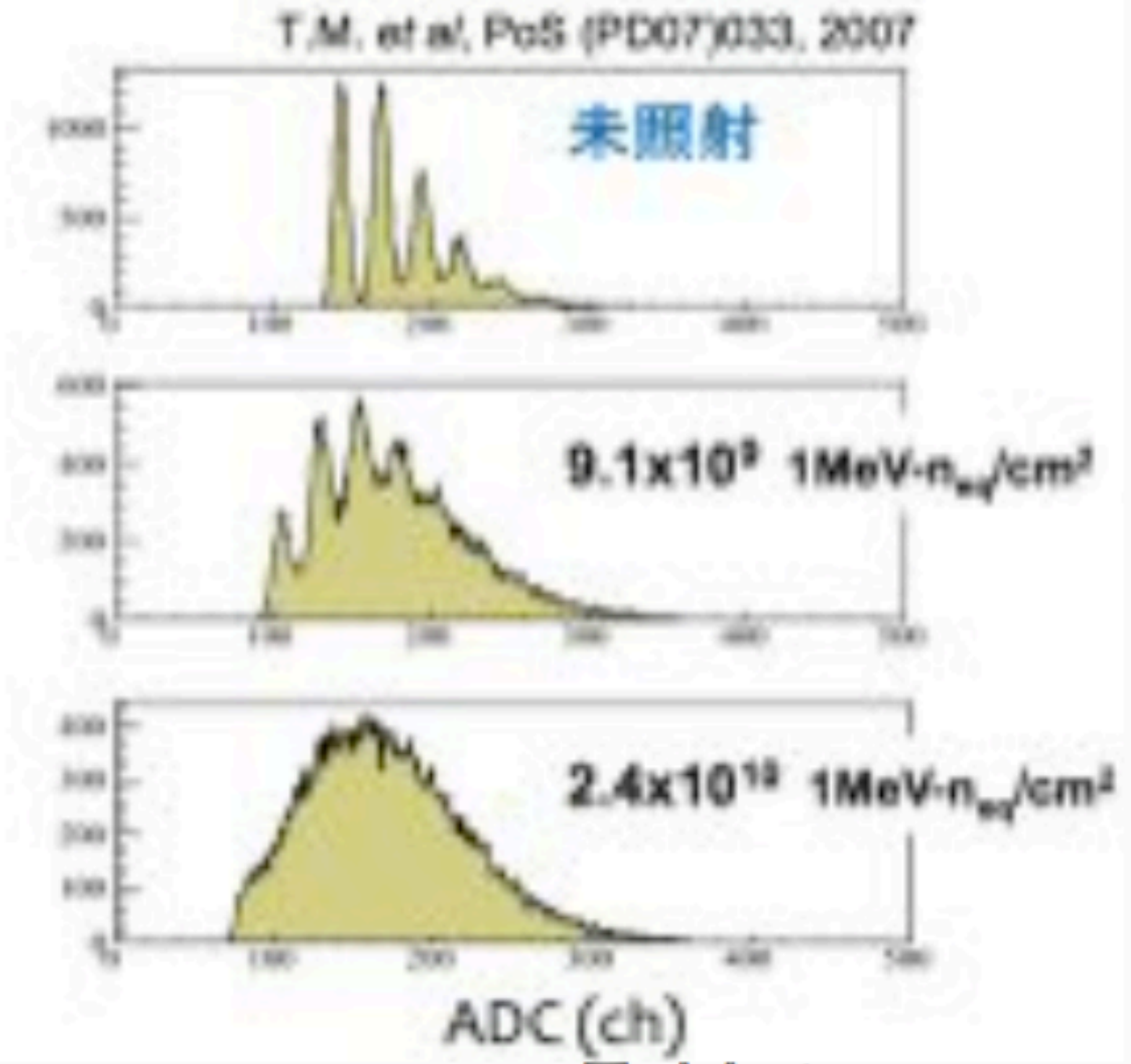
- σ_Q^2: spread of integrated charge distribution
- G: gain
- e: elementary charge
- $\bar{Q}$: mean of integrated charge



Radiation hardness

- Radiation produces defect in silicon bulk or Si/SiO_2 interface
  - Dark count rate, leakage current, PDE, ...
- Fast neutron
  - $>10^8$ n/cm^2 Increase of dark count rate
  - $>10^{10}$ n/cm^2 Loss of single p.e. detection capability
  - <1 n/s/cm^2(>0.1MeV) ~ $<1.6\times10^8$ n/cm^2 for full 5-years operation in πE5 area in PSI
  - ~3.5n/s/cm^2 ~ 10^7 n/cm^2 for one week CEX run per year for 5-years
- γ-ray
  - 200Gy Increase of leak current
  - MC: 0.58Gy with 10^8 μ/s for 5-years for MEG
- Radiation damage might not be an issue for MEG.

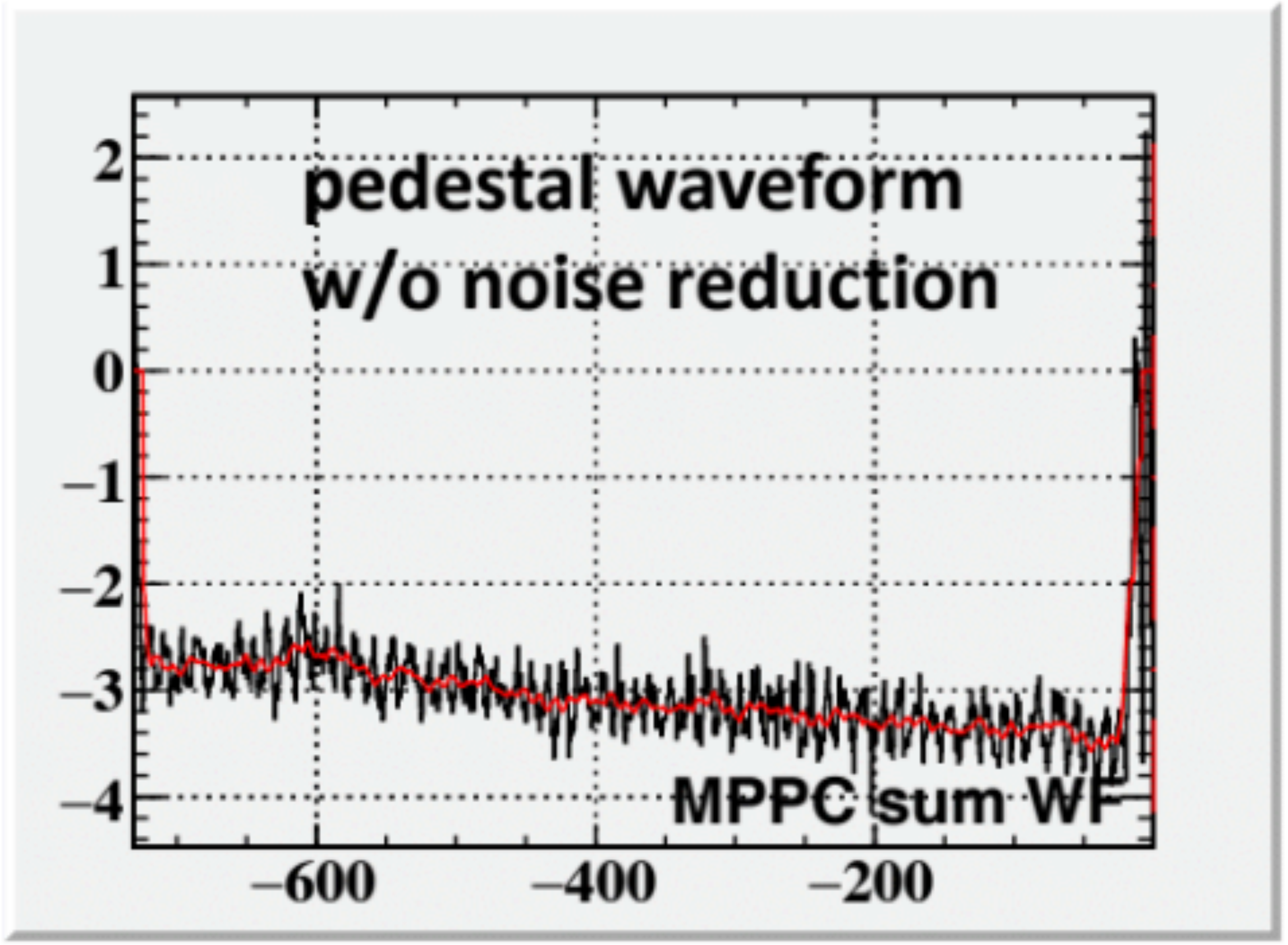


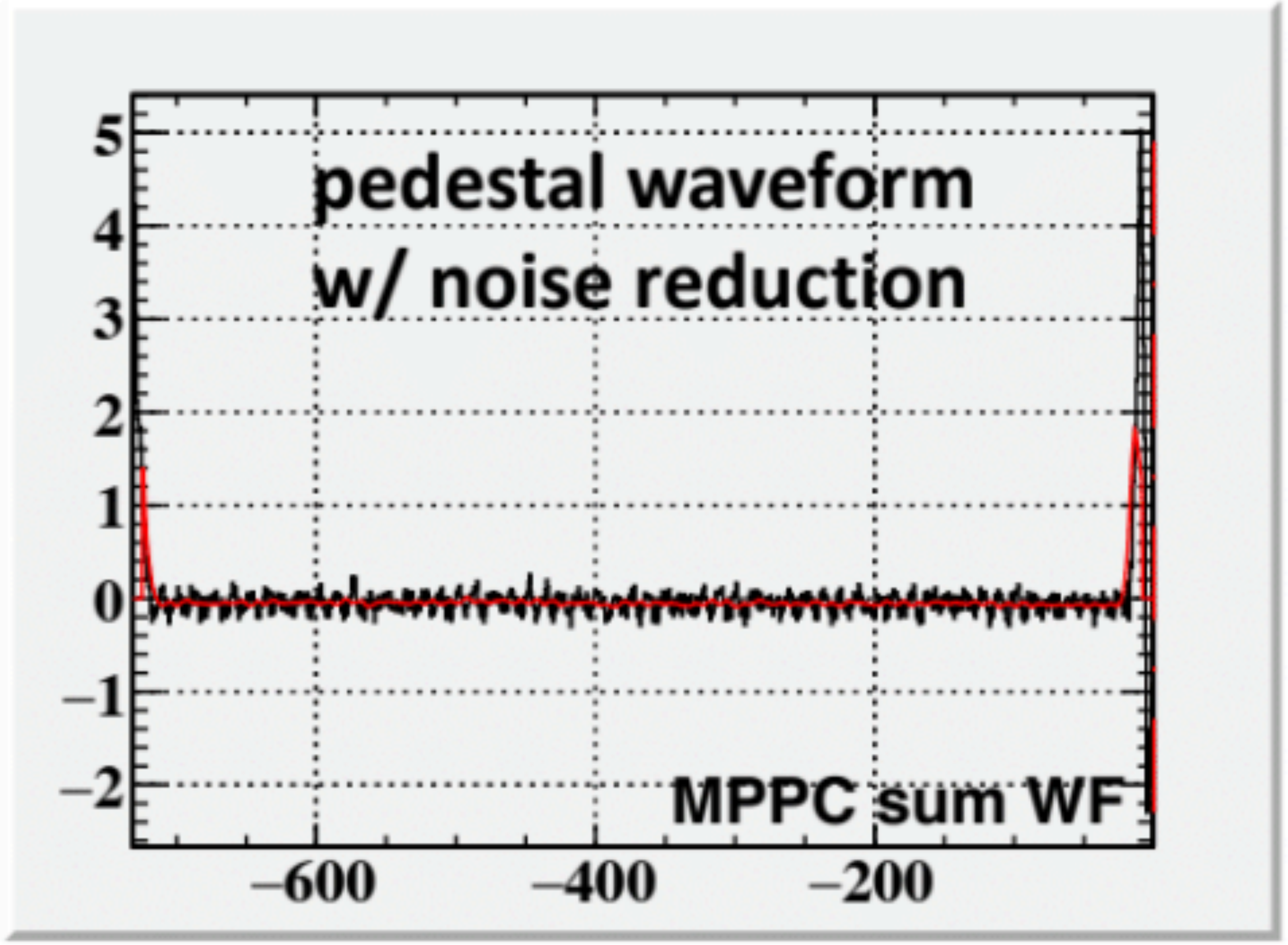


T. Matsumura et al.

Noise reduction

- Temperature dependent template (slope from waveform digitizer)
- Readout electronics voltage offset template
- High frequency noise template (clock signal in waveform digitizer)
- The first cell dependent noise template





MPPC alignment

- MPPC position alignment
  - Direct optical alignment at room temperature
  - Collimated γ beam to the detector with LXe
    - To take into account thermal expansion of MPPC supports (CFRP, PCB)
- Combined result
  - position uncertainty 0.6mm in z and 0.75mrad in ϕ