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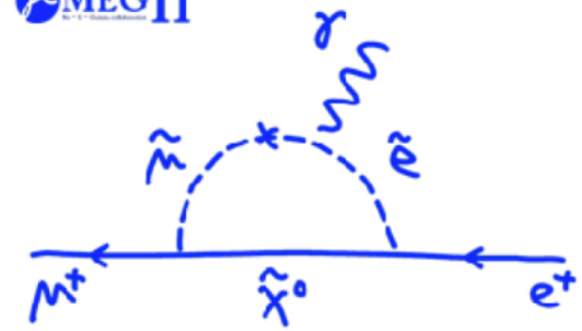

MEG II experiment and Future μ→eγ search

Sei BAN (ICEPP), for the MEG II collaboration
22nd Oct. 2025, BRIDGE2025, UTokyo

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Charged Lepton Flavor Violation (cLFV)

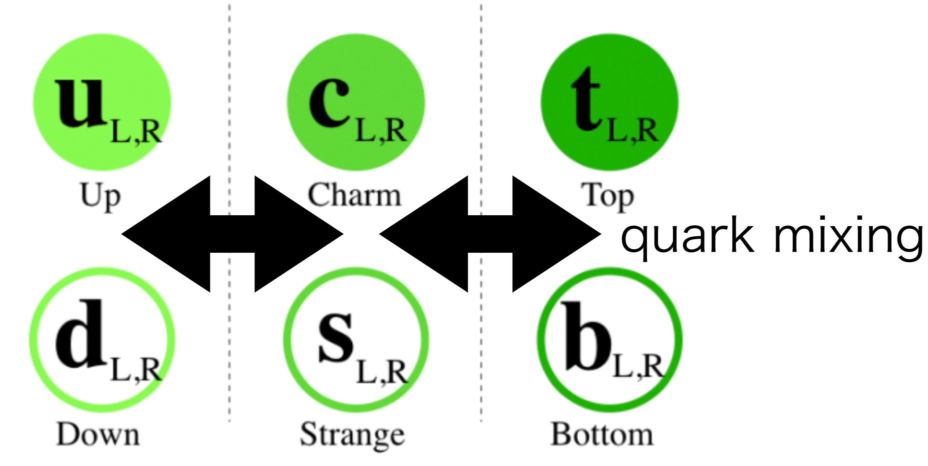
MEG II experiment

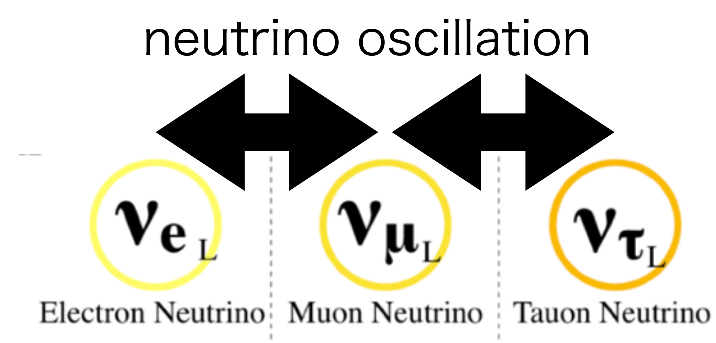
Future $\mu \to e\gamma$ search

Summary

Charged Lepton Flavor Violation

- In quark and neutrino (neutral lepton) sector, the flavor violates in SM





- Some theories BSM predict flavor violation in the charged lepton sector
  - In the Standard Model (+ν osci.), it is practically prohibited : Br(μ→eγ)=10^{-54}
  - In BSM, Br(μ→eγ) ~ O(10^{-14}) is predicted (not observed yet)

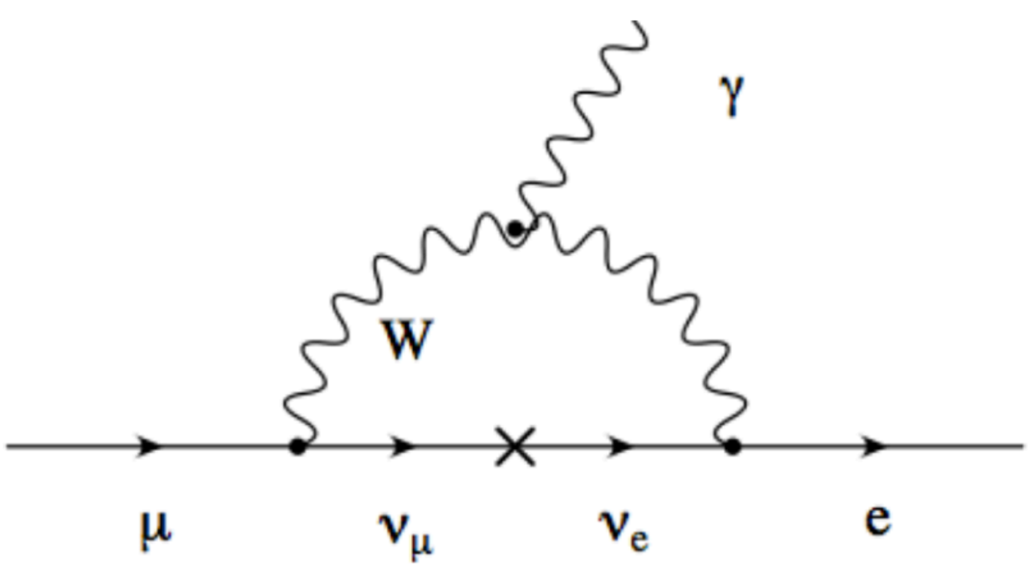
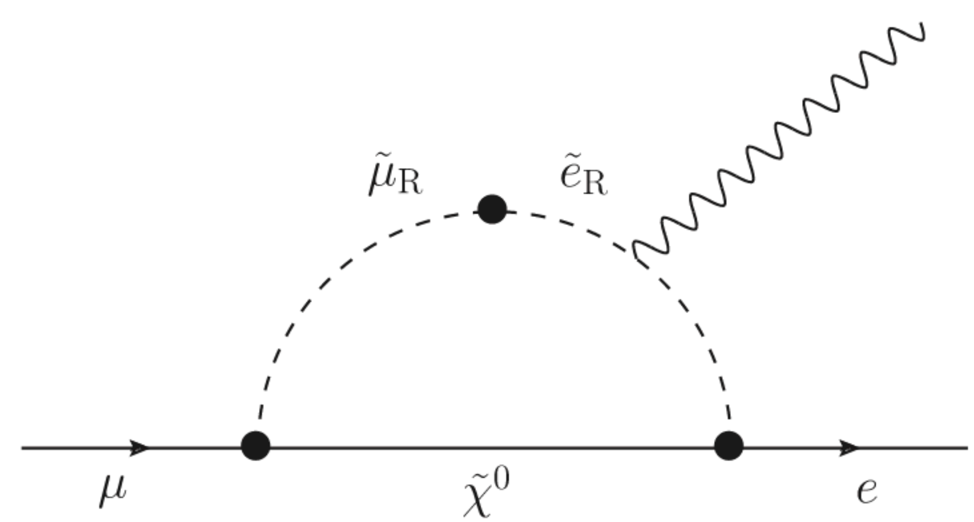


Diagram in the SM + neutrino oscillation

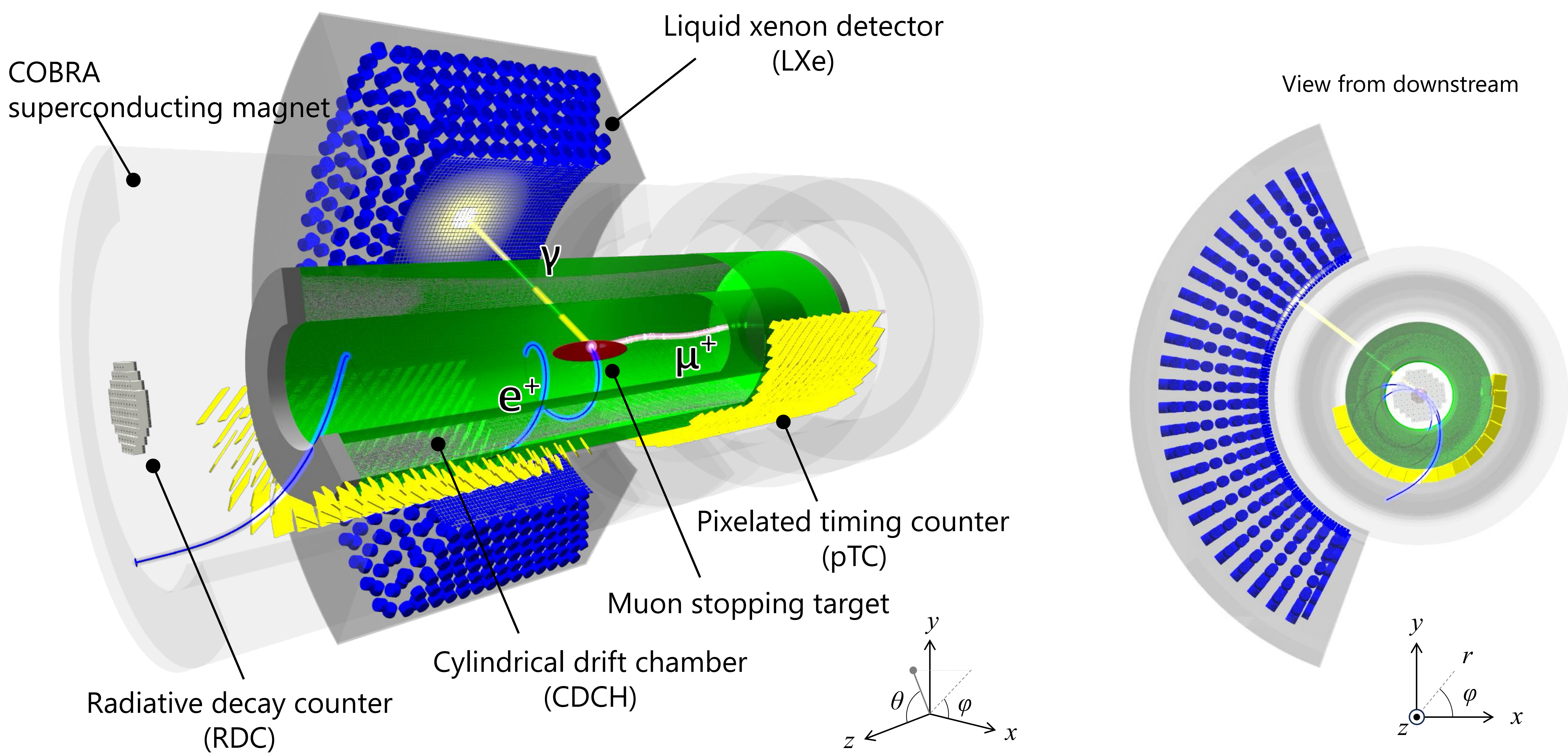


Possible diagram in SUSY-GUT senario

MEG II experiment

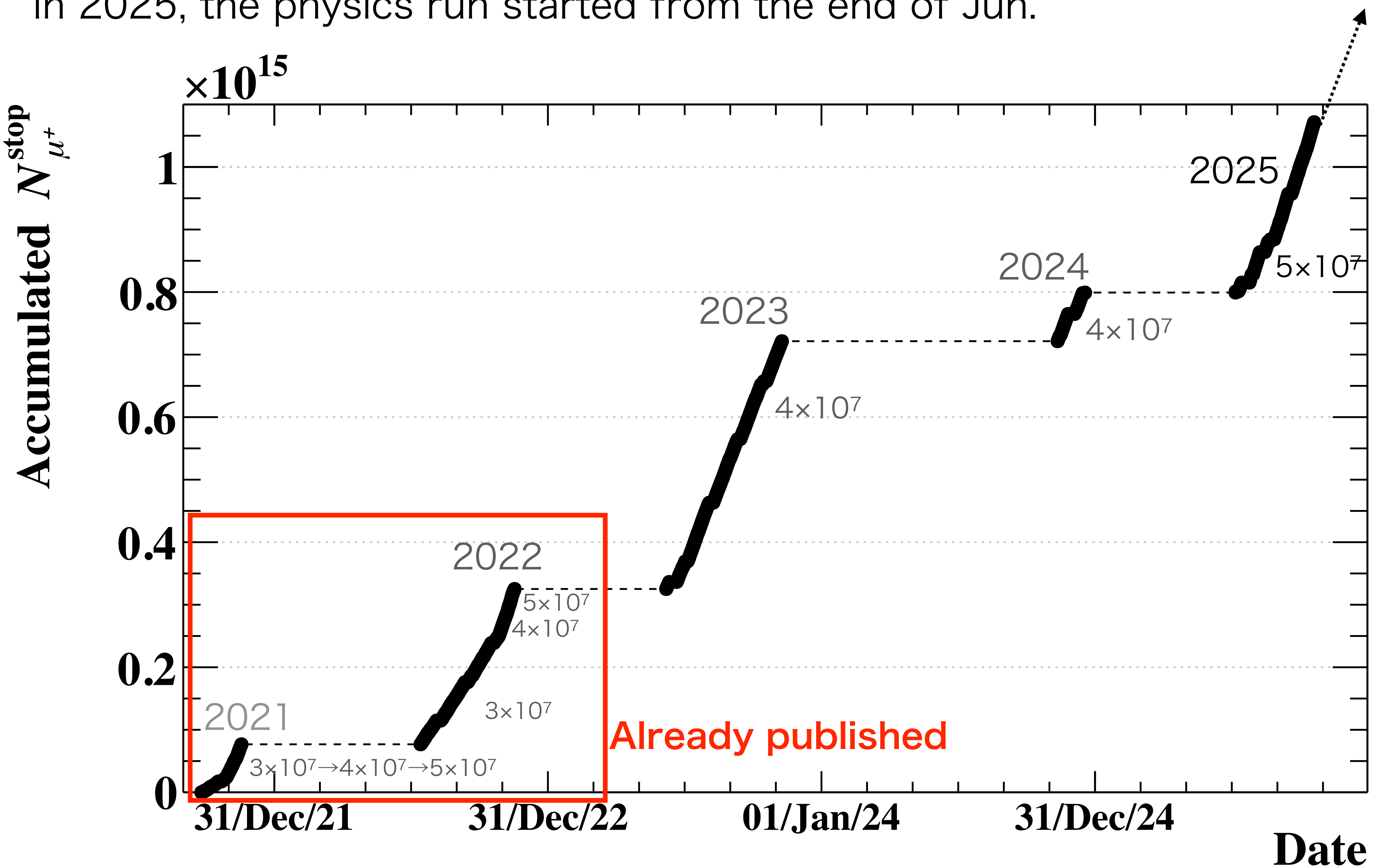
MEG II experiment

- MEG II experiment aims to search for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$
  - with higher sensitivity by one order of magnitude compared to the MEG
- Consists of LXe detector for γ-ray, drift chamber & timing counter for e^+
- Physics run started since 2021, and will continue to 2026
  - Target sensitivity : $Br = 6\times10^{-14}$



MEG II experiment

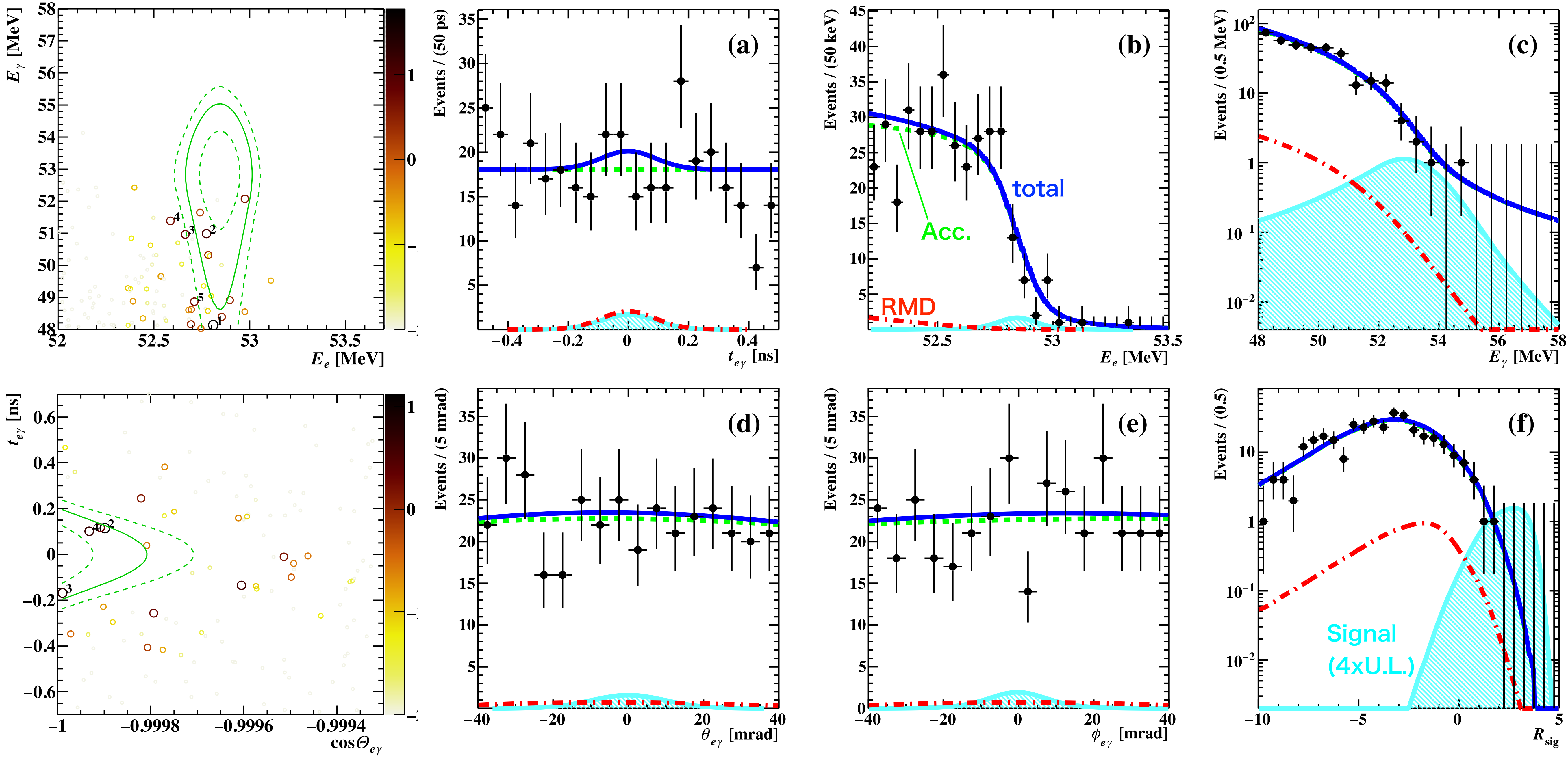
- Physics run started since 2021, and will continue to 2026
  - Result using 2021+2022 data : arXiv.2504.15711 (accepted by EPJC letter)
  - Analysis using 2021-2024 data is ongoing
  - In 2025, the physics run started from the end of Jun.



MEG II experiment : Likelihood fit

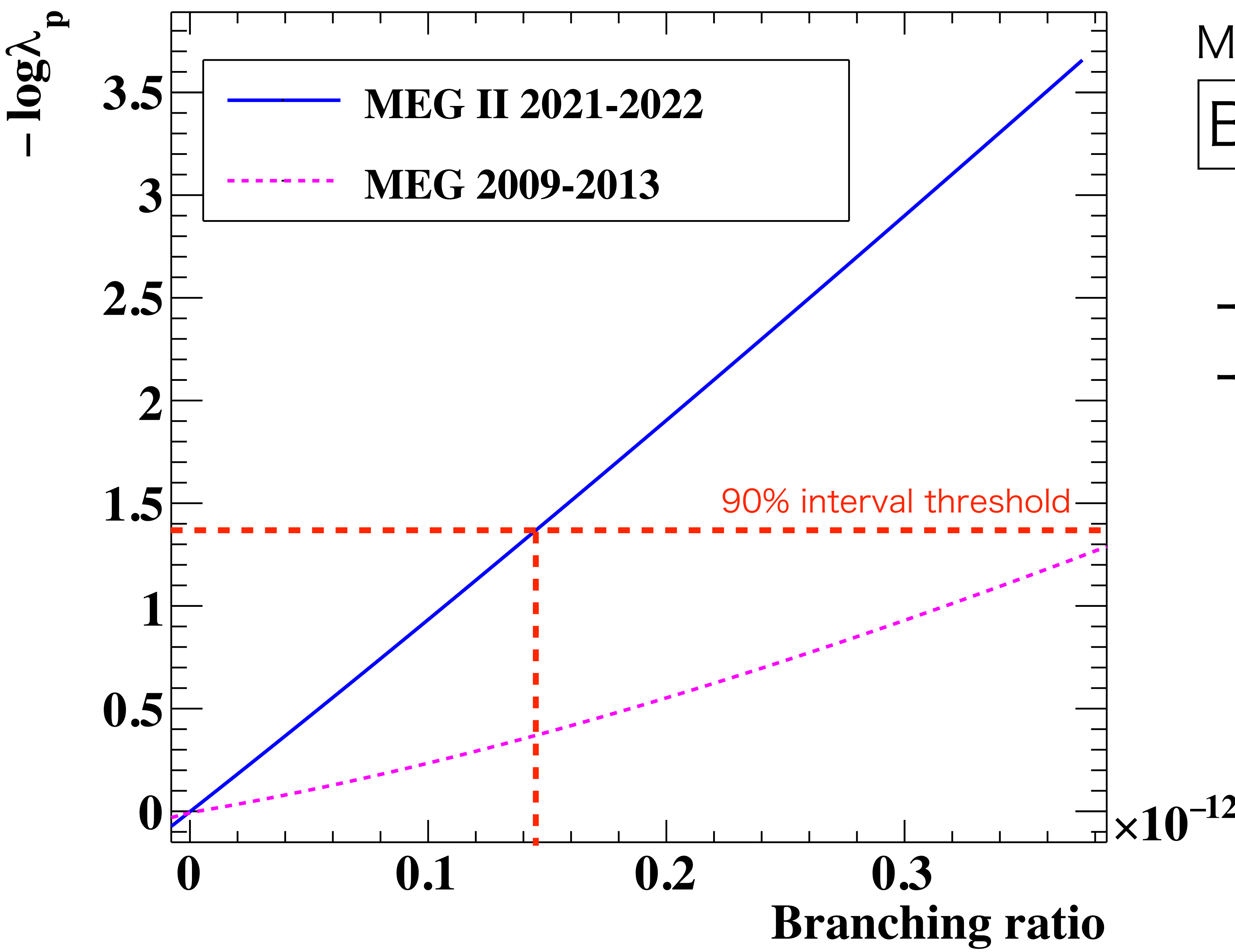
- Best fit : $\mathbf{N_{sig} = -5.1}$ ← No signal excess
- converted into branching ratio
  - $Br(\mu \to e\gamma) = N_{sig}/N_{\mu} = -5.1/1.34\times10^{13} = \mathbf{-3.8\times10^{-13}}$ (Best Fit)

1D-projections of fitting result for signal window



MEG II experiment : the latest result

- Confidence interval by Feldman-cousins method with likelihood ratio ordering
- **Most stringent upper limit in cLFV is set by MEG II 2021+2022**
- Dominant systematic uncertainty comes from
    - alignment of the muon stopping target, energy scale of gamma-ray



MEG II 2021+2022 :

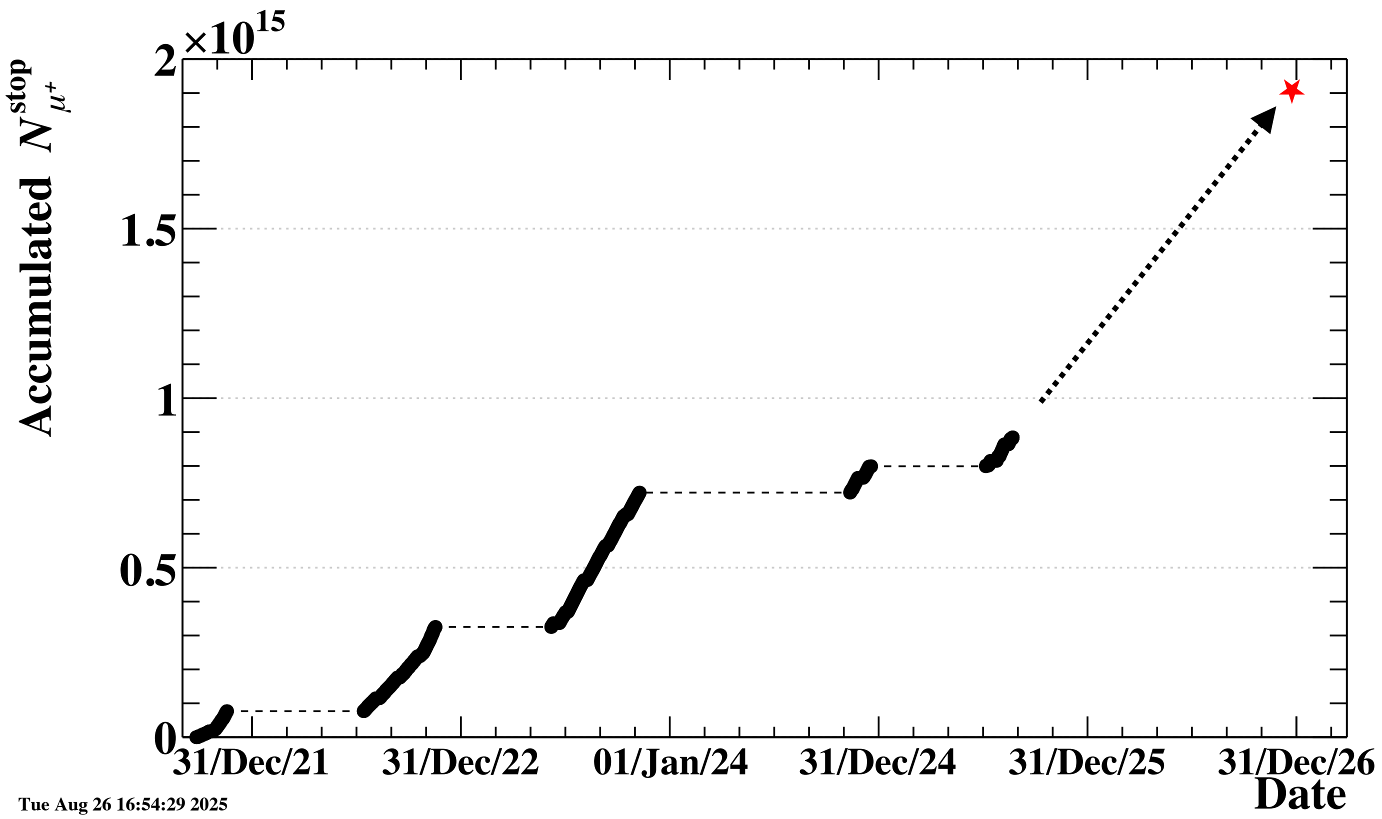
$\boxed{Br(\mu^+ \to e^+\gamma) < 1.5\times10^{-13}}$

(90% C.L.)

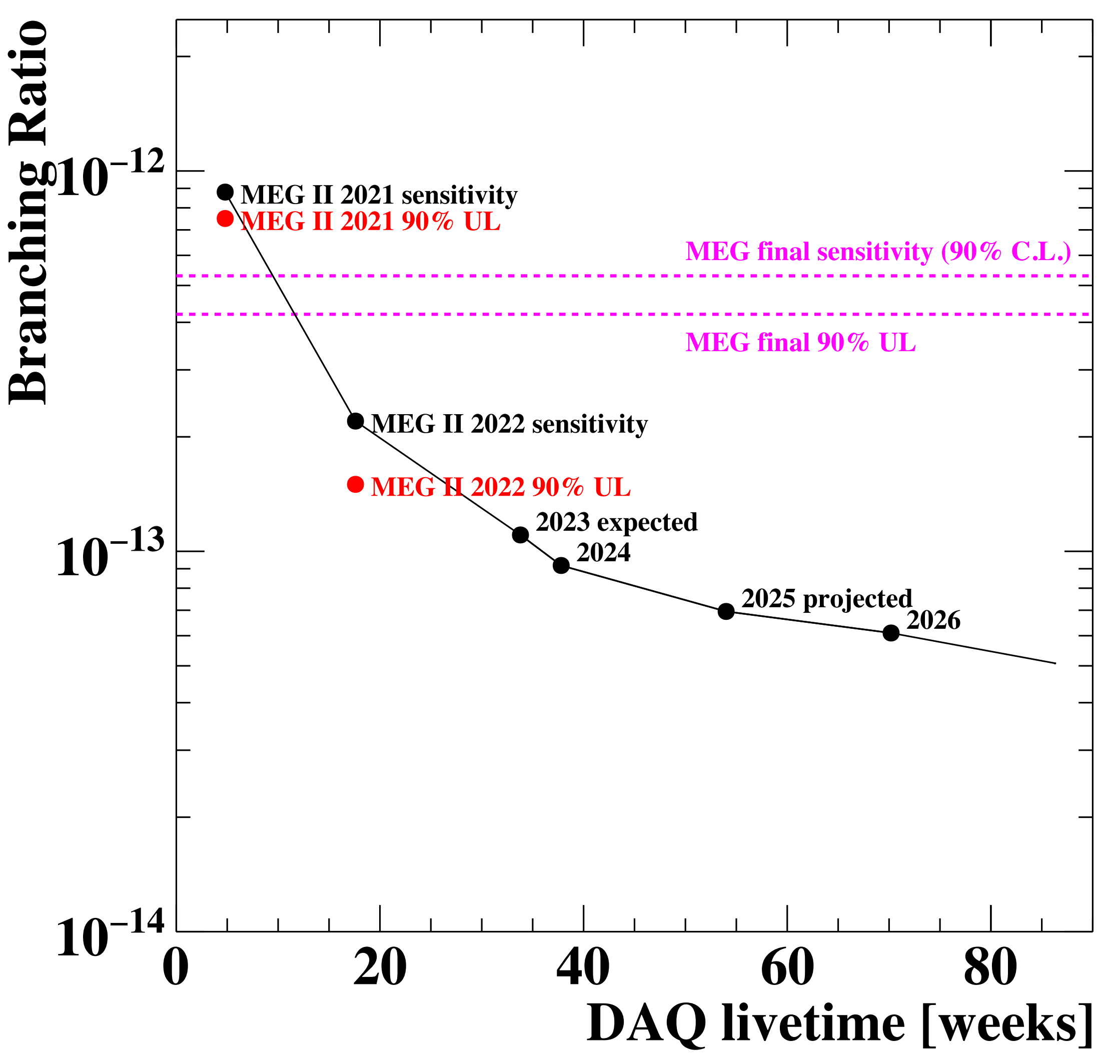
- arXiv.2504.15711
- Accepted by EPJC letter

MEG II experiment : prospects

- Expected sensitivity with
  - assigned beam time in 2025
  - assuming 20 weeks of DAQ in 2026
  - Analysis with the performance in 2021+2022 result
- Final sensitivity will be **~6×10^{-14}**
  - Still have some room for improvement
    - Tracking efficiency improvement
    - E_γ resolution improvement



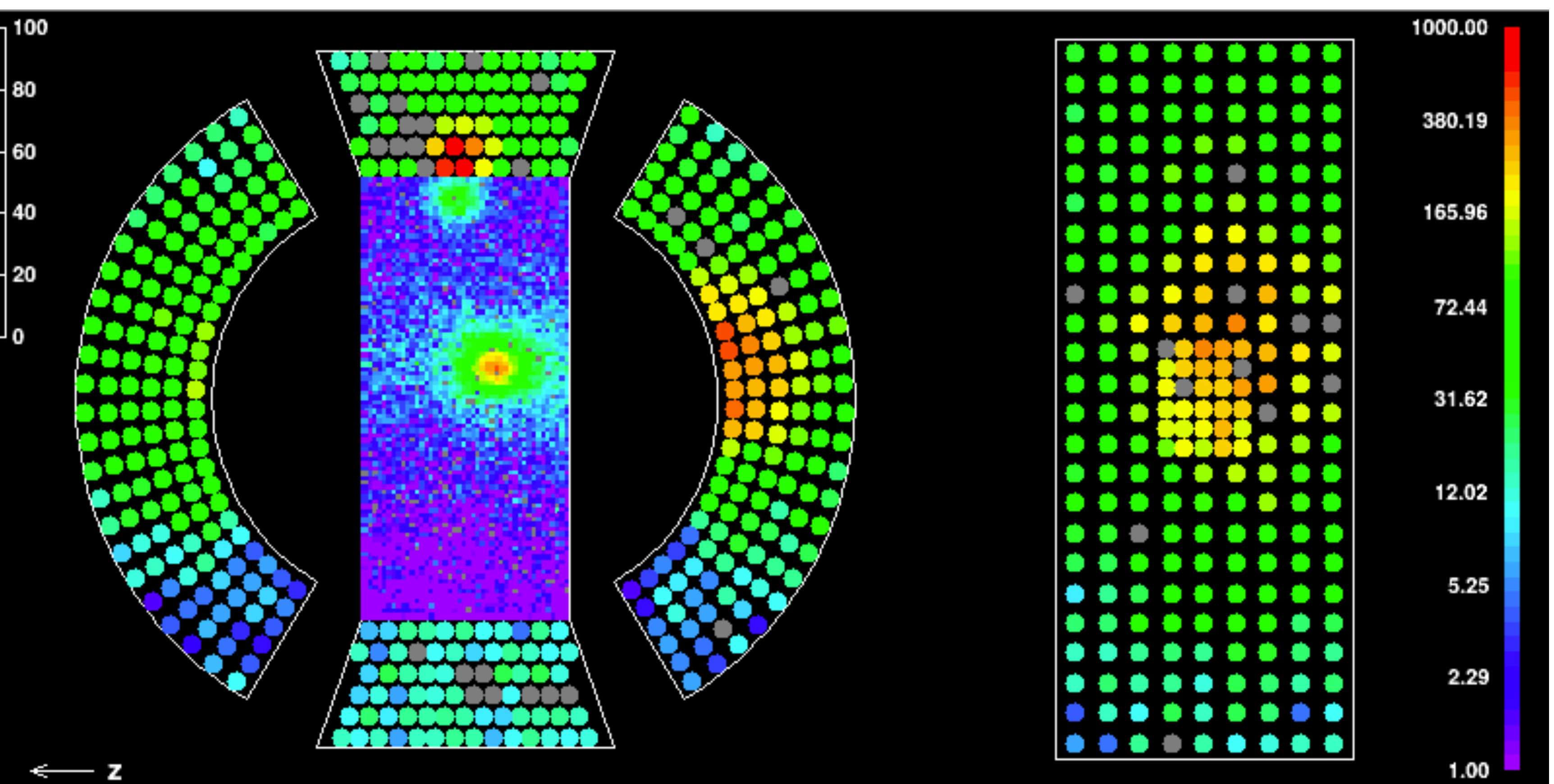
MEG II expected sensitivity

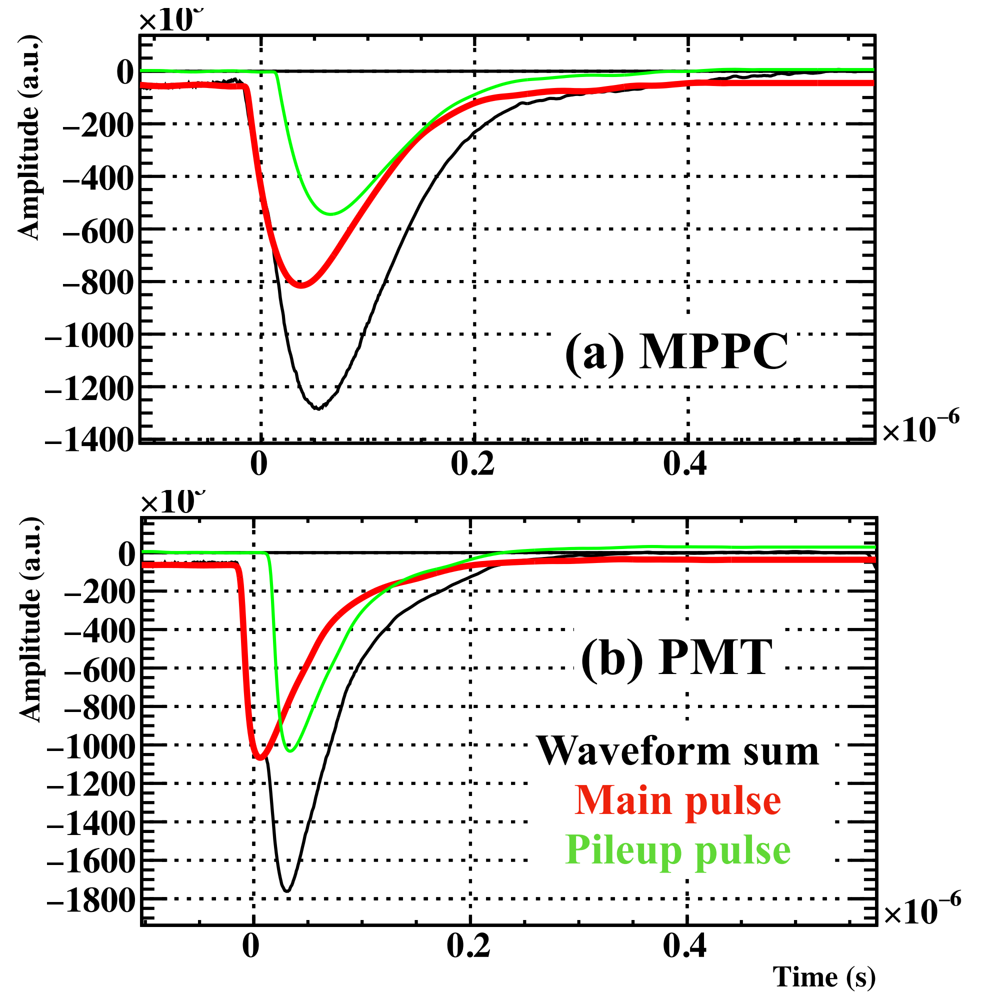


MEG II experiment : LXe detector and pileup unfolding

- Liquid xenon detector to measure energy, position, and timing of gamma-rays
- Homogeneous liquid xenon (900L) sensitive volume
- 4,092 VUV-sensitive MPPCs on the entrance face
- 668 VUV-sensitive PMTs on the other faces

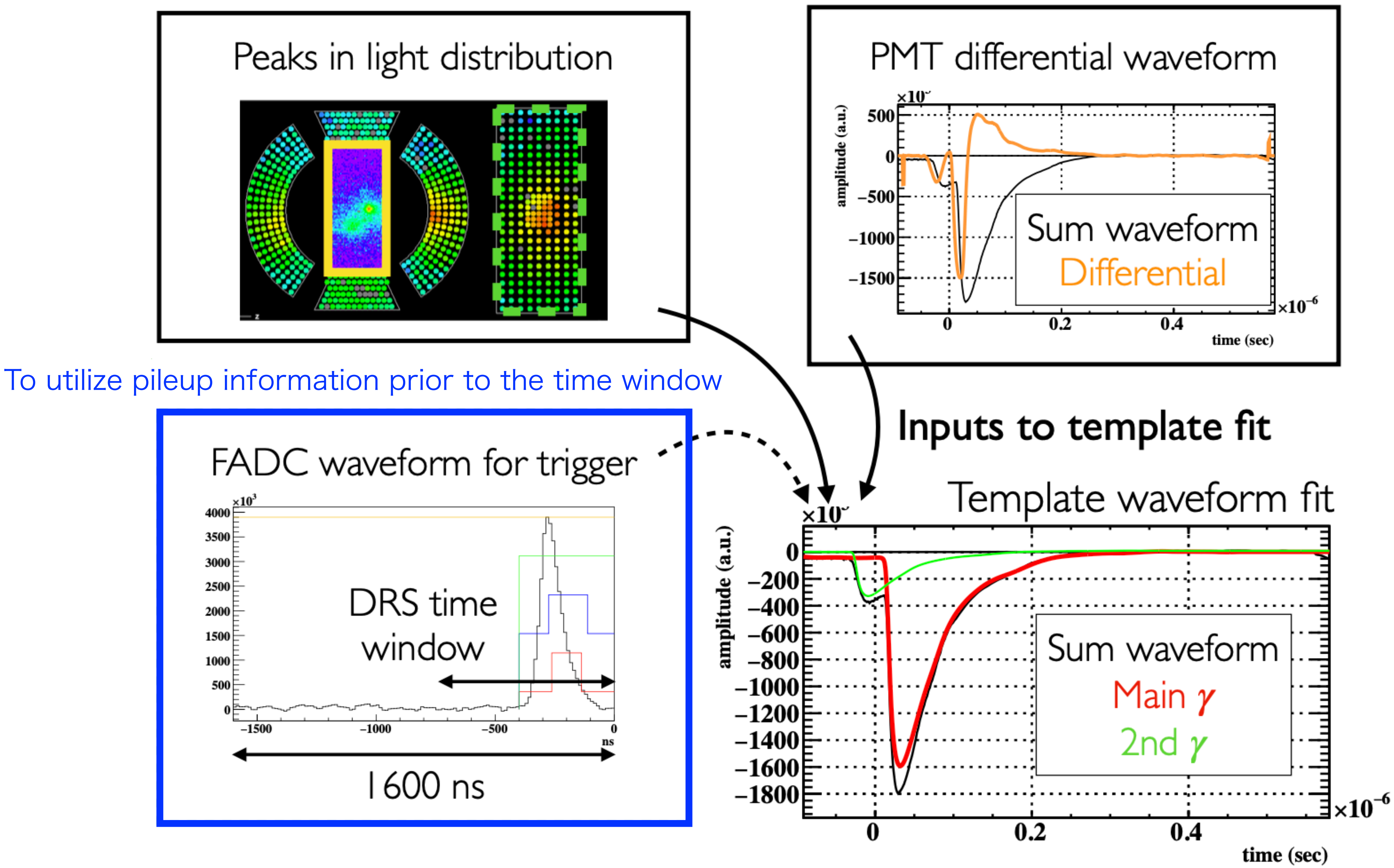
- High rate muon beam causes pileup event
- Pileup analysis with spacial distribution in MPPCs and timing information
  - Efficiency : 94.2± 0.5% (3e7 μ/s)





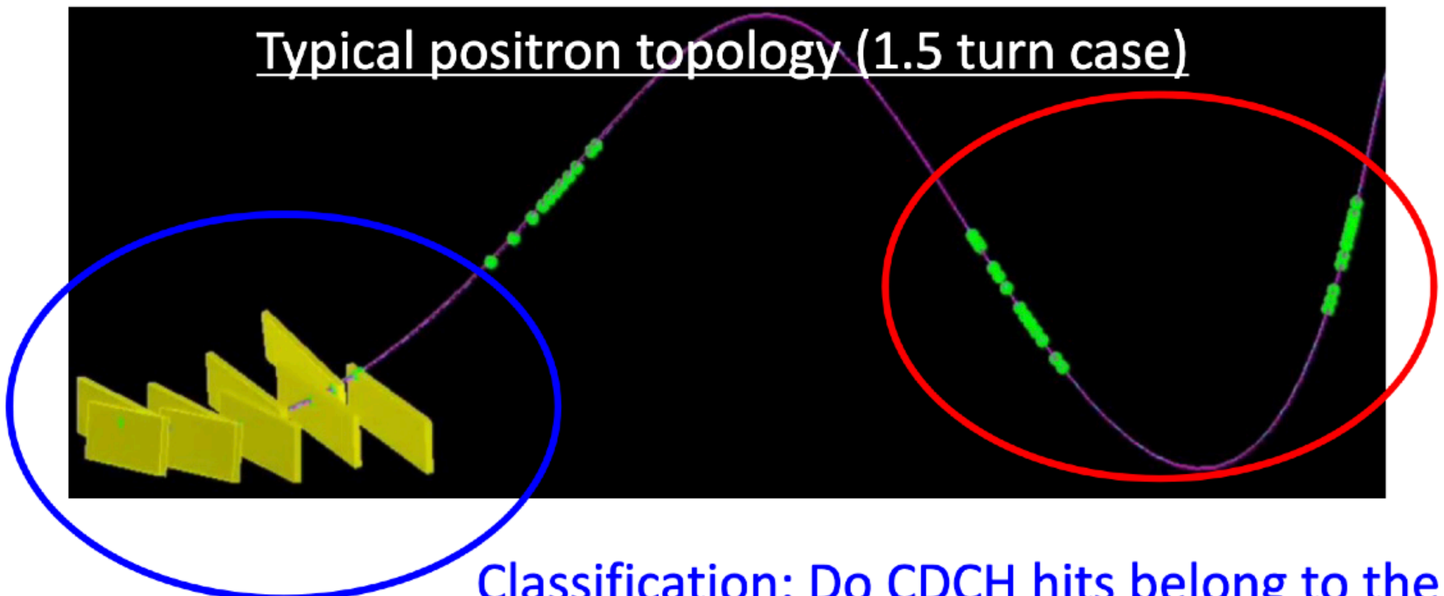
MEG II experiment : LXe detector and pileup unfolding

- Pileup search and unfolding
  - Using information of spacial clustering and #pulses in sum waveform
  - Then unfold the sum waveform by template waveform fit
  - Simultaneous fit to both PMT and MPPC sum waveform is performed



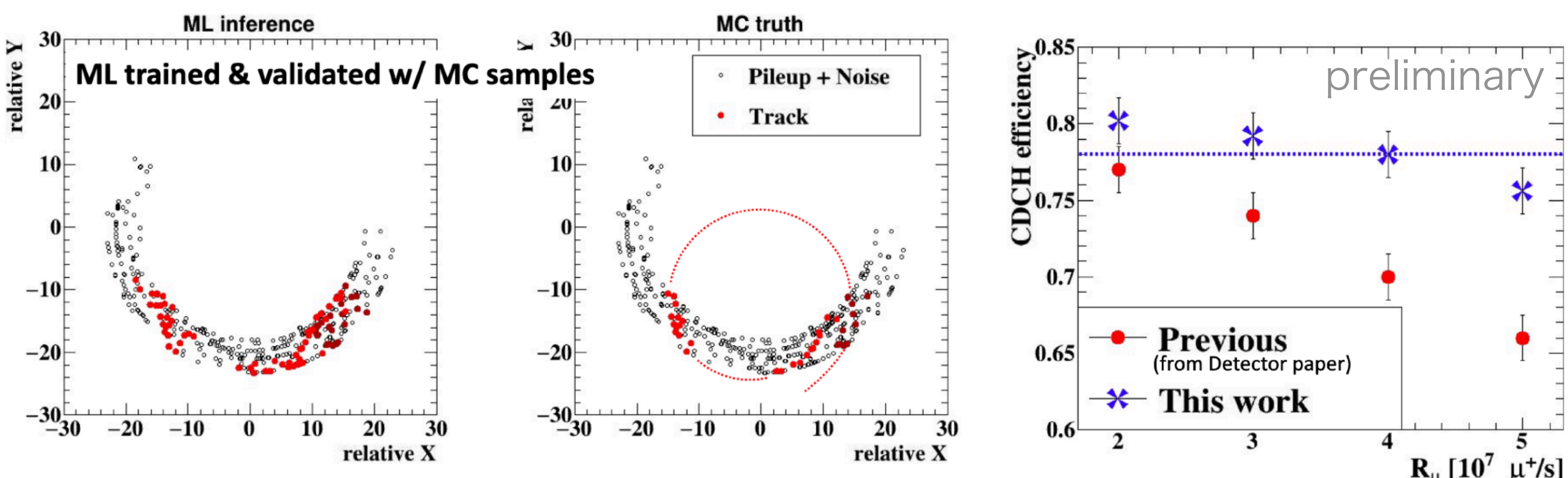
MEG II experiment : ML technic for positron tracking

- New machine learning method for positron reconstruction
  - Using transformer-method to filter out pileup hits
  - Improve tracking efficiency with O(10%) -> higher beam rate can be chosen
    - → 5e7 μ/s beam in 2025 run (by 2024 run, 4e7 μ/s beam was chosen)
- Not yet applied to 21+22 analysis



Attention mechanism tries to connect different CDCH hits belonging to the same track

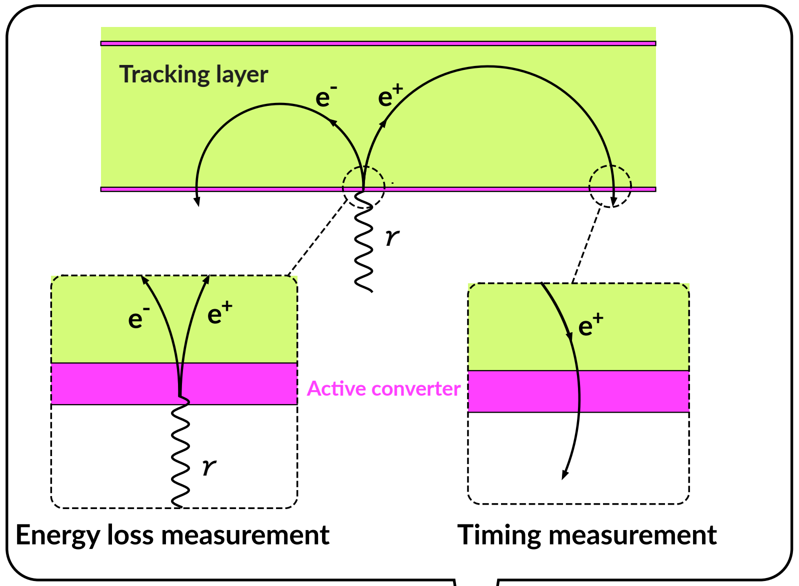
Classification: Do CDCH hits belong to the same track as timing counter hits?

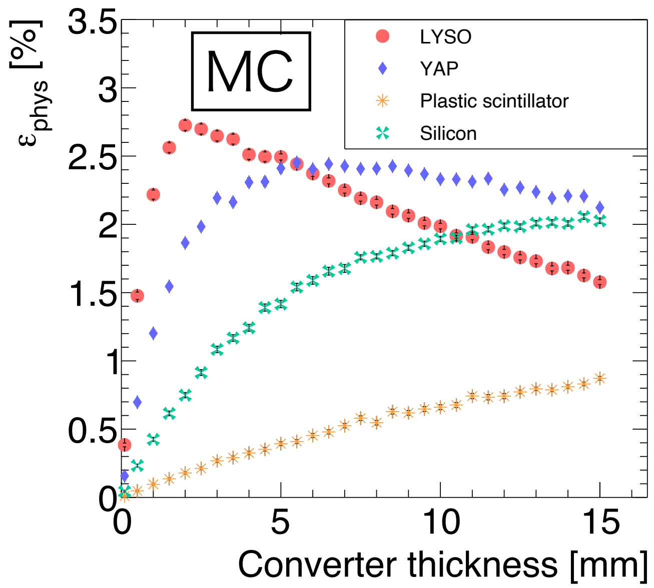


Future $\mu \to e\gamma$ search

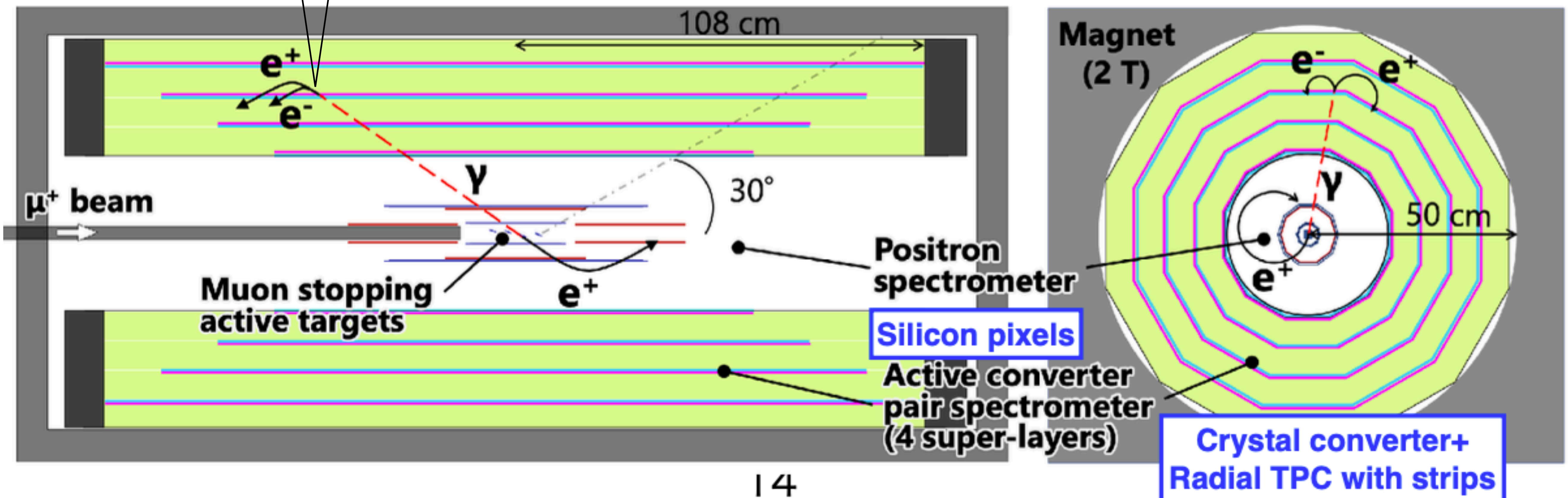
Future cLFV search

- Utilize large statistic thank to the HiMB
- Photon spectrometer with active convertor to achieve high energy resolution, rate capability, and to get angle information
- Positron spectrometer based on Si detector for higher rate capability



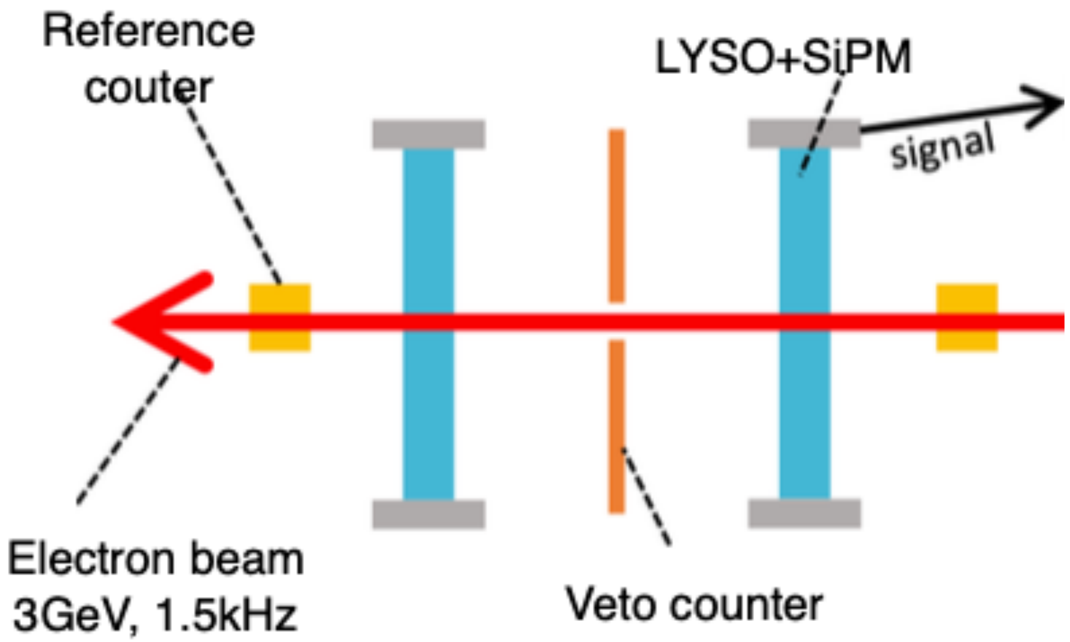


- LYSO is one of a promising candidate for active convertor

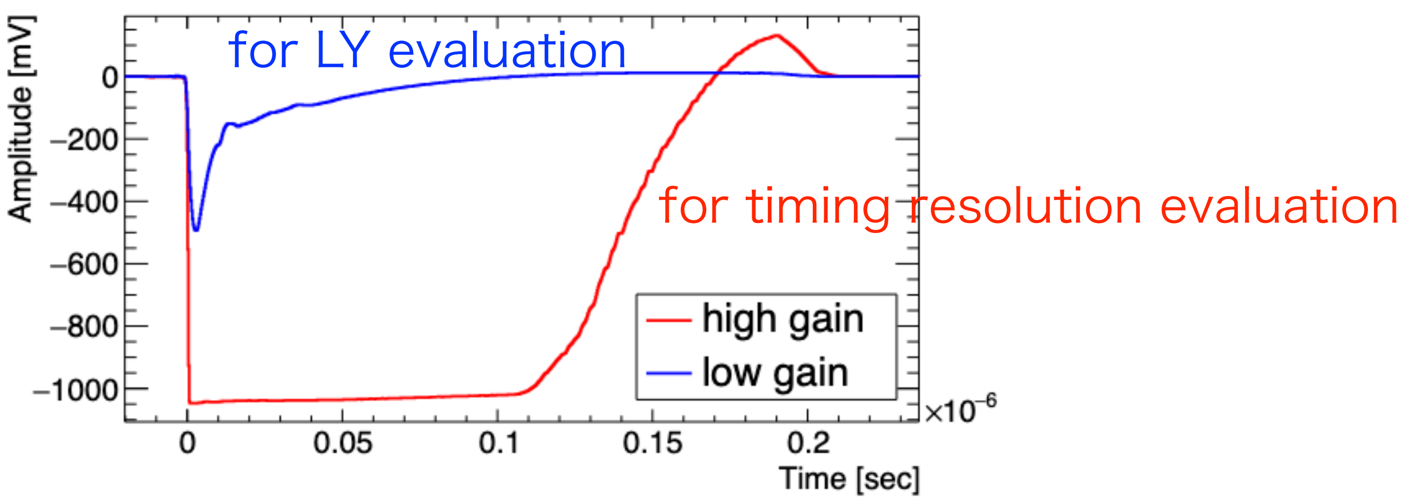


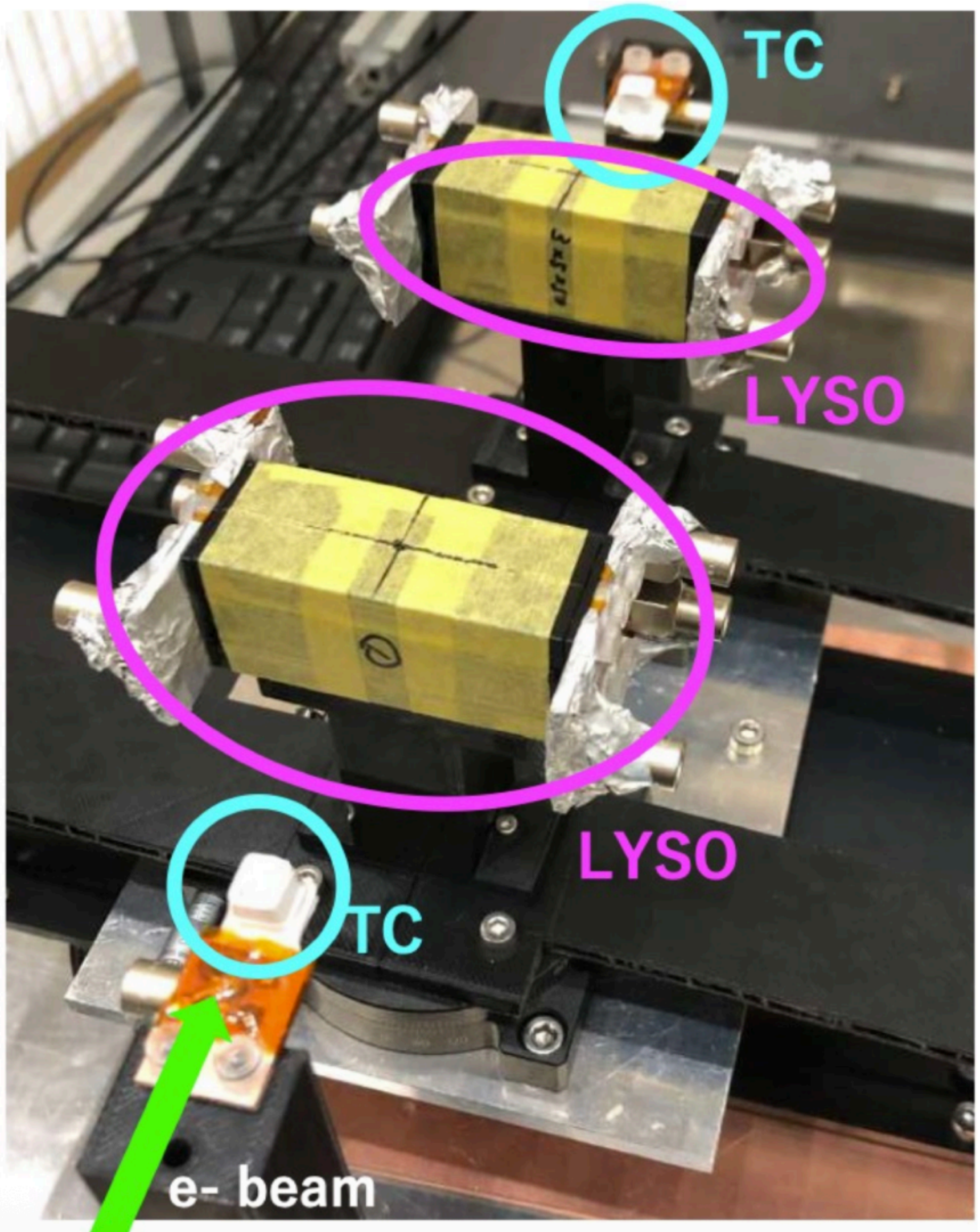
Future cLFV search

- Evaluation of LYSO active convertor prototype by electron beam
  - at KEK test beam line of the PF-AR
  - momentum of 3 GeV, frequency of 4.5 kHz
- Read out by SiPM from both side of the LYSO



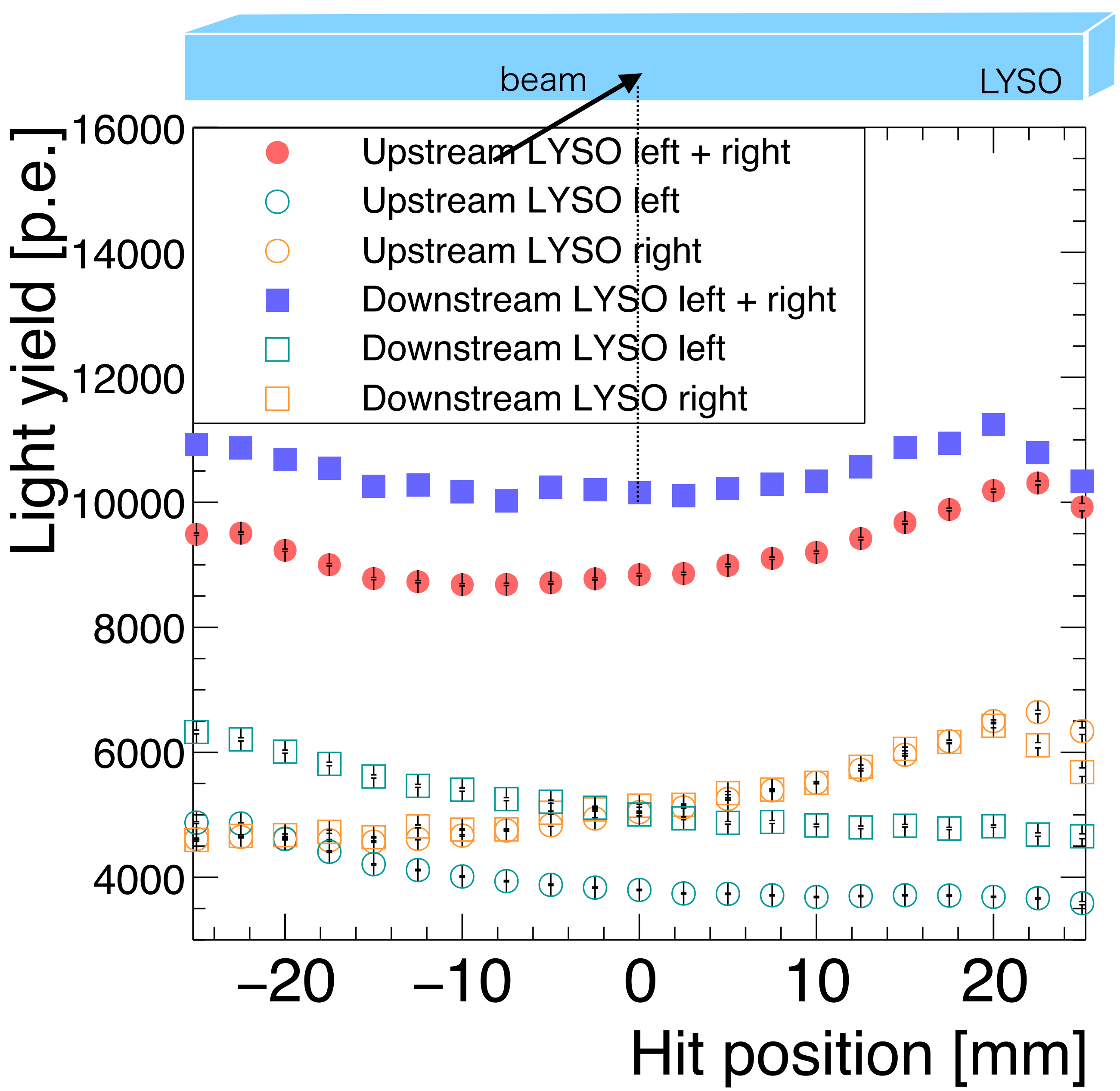
- Read out with high/low amplifier gain
  - WaveDREAM board (DRS4 chip x2)

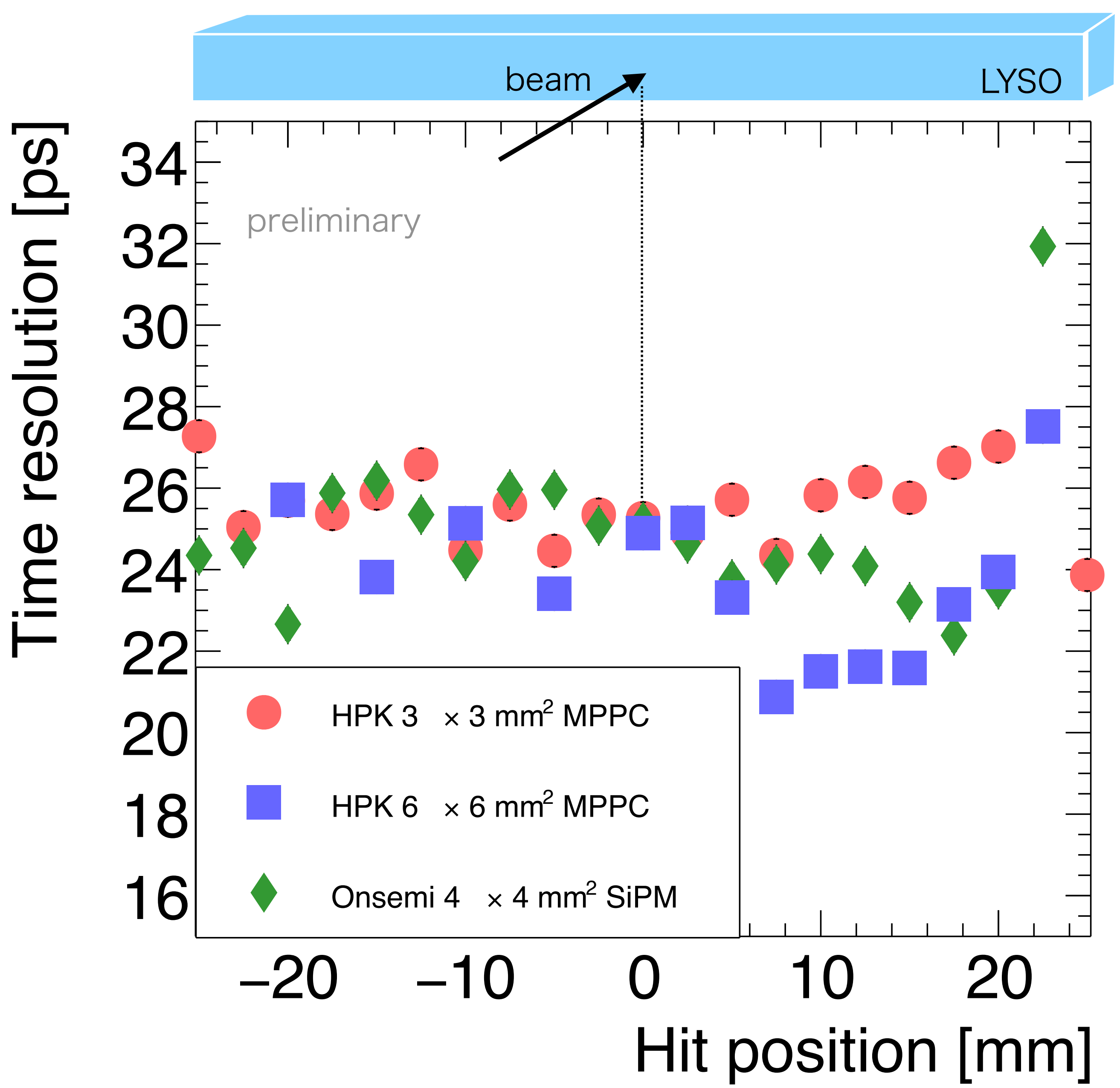




Future cLFV search

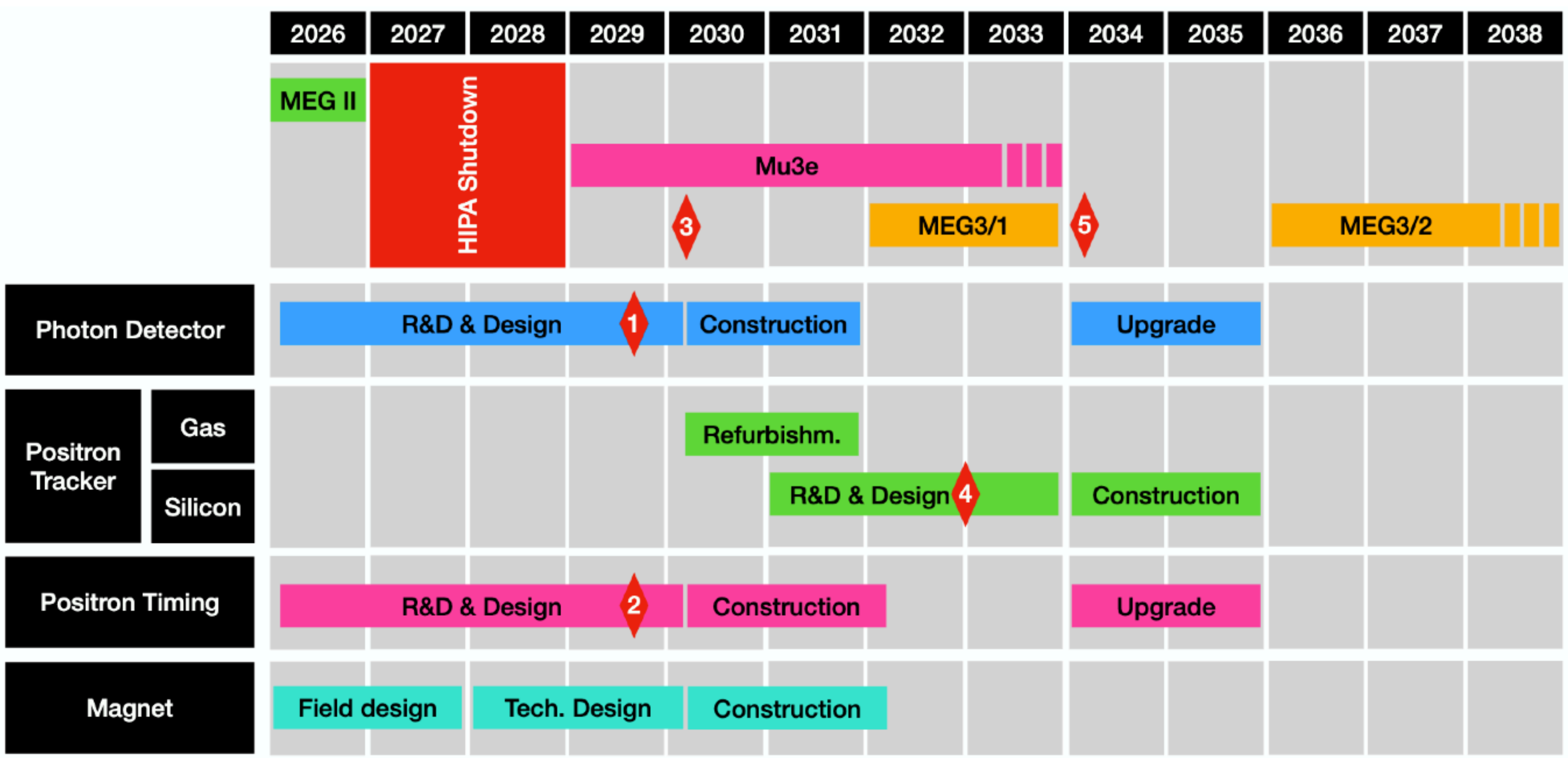
- Evaluation of LYSO active convertor prototype by electron beam
- Minimum requirement to achieve good performance : 2,500 photons (10 MeV)
  - For all region of the LYSO crystal, obtained light yields are above 2,500 ph.
- Designed timing resolution : 40 ps
  - Along entire region, the timing resolution is better than the target value





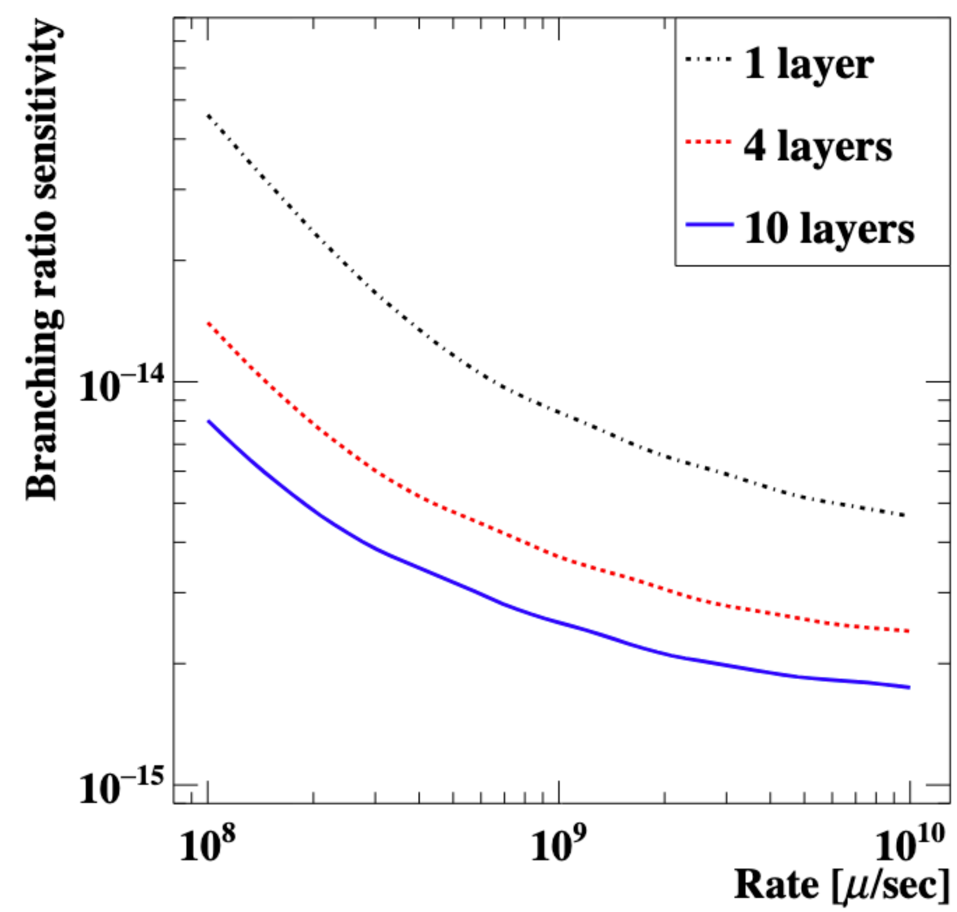
Future cLFV search

- Prospect of future cLFV search (called MEG3 temporarily here)
  - Stepped approach with Phase-I and Phase-II
  - In Phase-I, running with 10^8 μ/s beam to target a few 10^{-14} sensitivity
  - In Phase II, using $>10^{10}$ μ/s beam, aiming to reach $O(10^{-15})$ sensitivity



◆1: Photon converter proof of principle (CEX with converter + tracker in the MEG COBRA magnet)
◆2: Decision about positron timing technology
◆3: phase-I approval by PSI and funding agencies
◆4: Decision about positron tracker technology for phase-II
◆5: phase-II approval by PSI and funding agencies

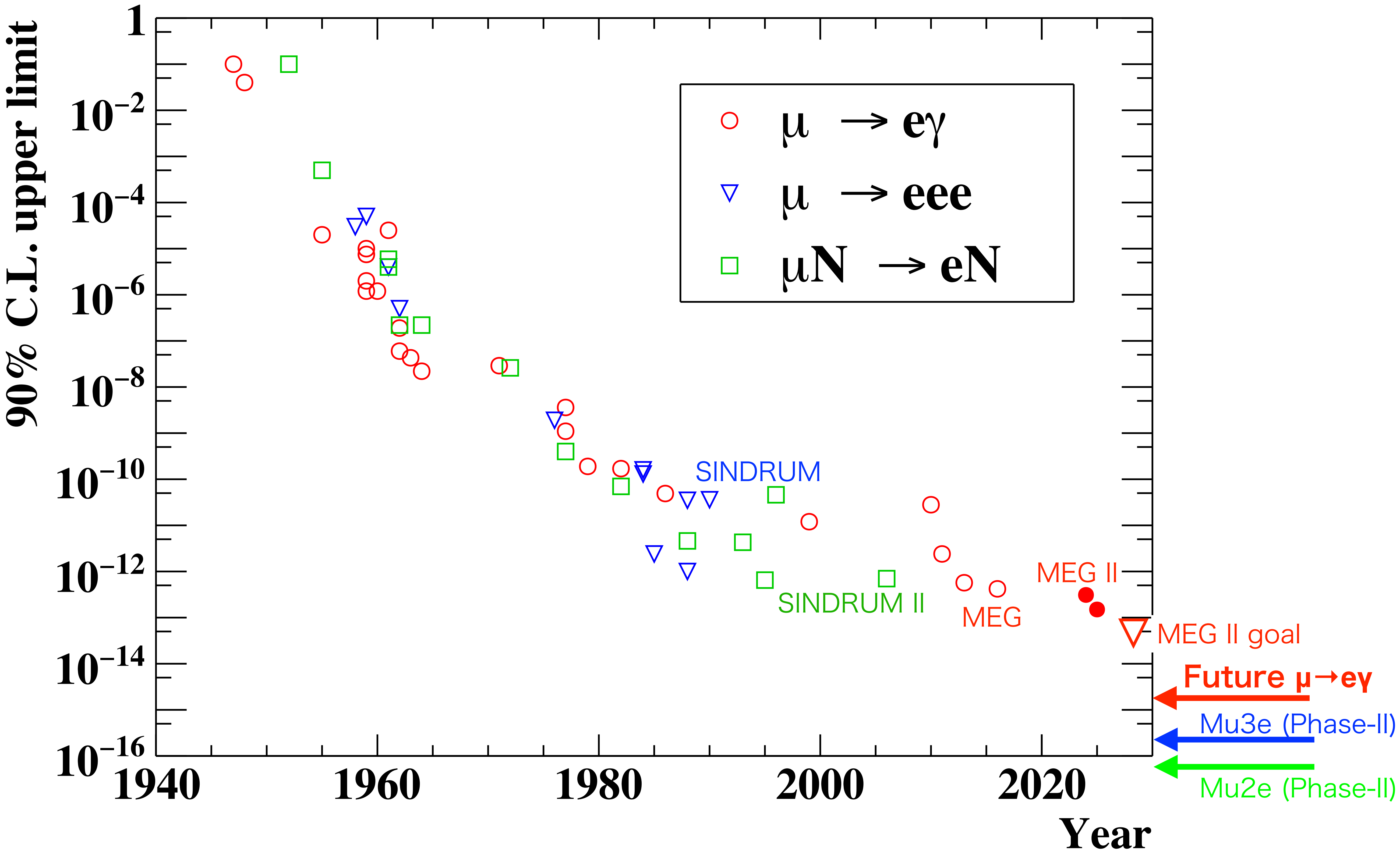
Projected sensitivity with 3-year run
Three scenarios with different number of photon conversion layer is shown



For more detail, see 'Future prospects for μ→eγ searches', arXiv.2504.18831

Prospect of charged Lepton Flavor Violation

- History and prospects of cLFV search



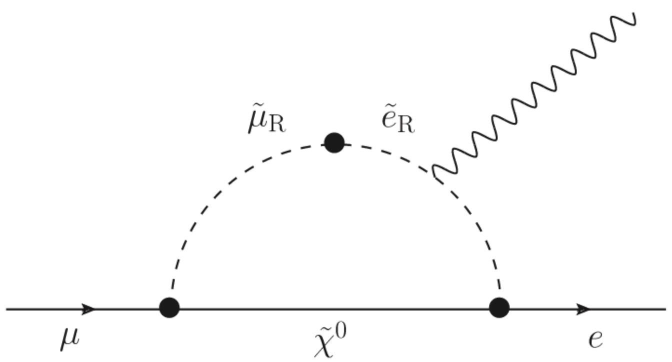
Summary

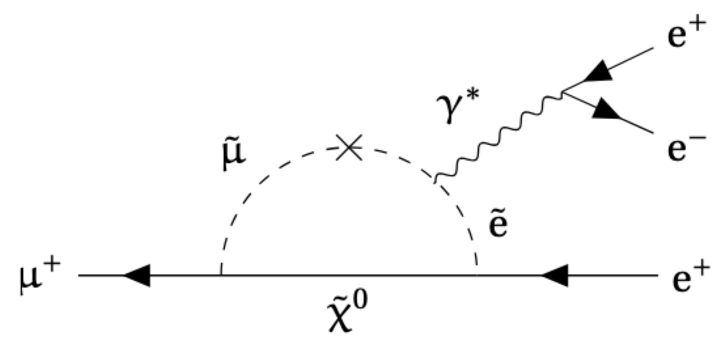
- Charged Lepton Flavor Violation (cLFV) is good probe to search New Physics
  - Theoretically back ground free, thus strong evidence of NP if it is found
- MEG II shows the best limit for cLFV
  - $Br(\mu^+ \rightarrow e^+\gamma) < 1.5\times10^{-13}$ (90% C.L.) with MEG II 2021+2022
  - (Analysis of 2021-2024 data is ongoing)
- Future $\mu^+ \rightarrow e^+\gamma$ search project is proposed
  - with High intensity Muon Beam (HiMB) at PSI → 10^8 - 10^{10} μ/s on the target
  - using active photon convertor for pair photon spectrometer
- **Many exciting results from cLFV search are expected in 2030s and 2040s !!**

Supplements

Charged Lepton Flavor Violation

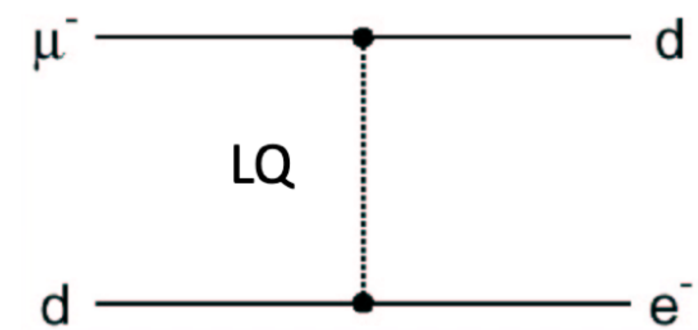
- What new physics ?

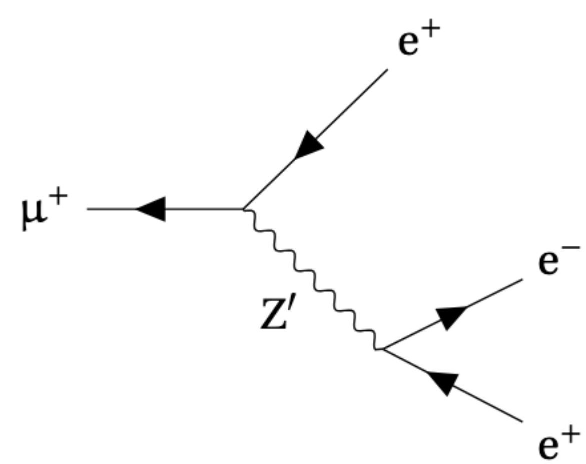




μ→eγ/μ→eee with Flavor mixing in sleptons

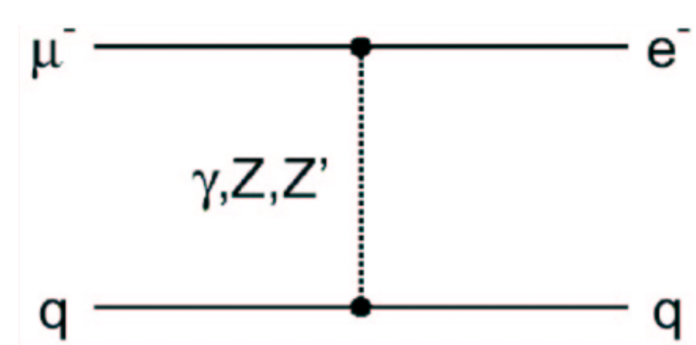
Leptoquarks



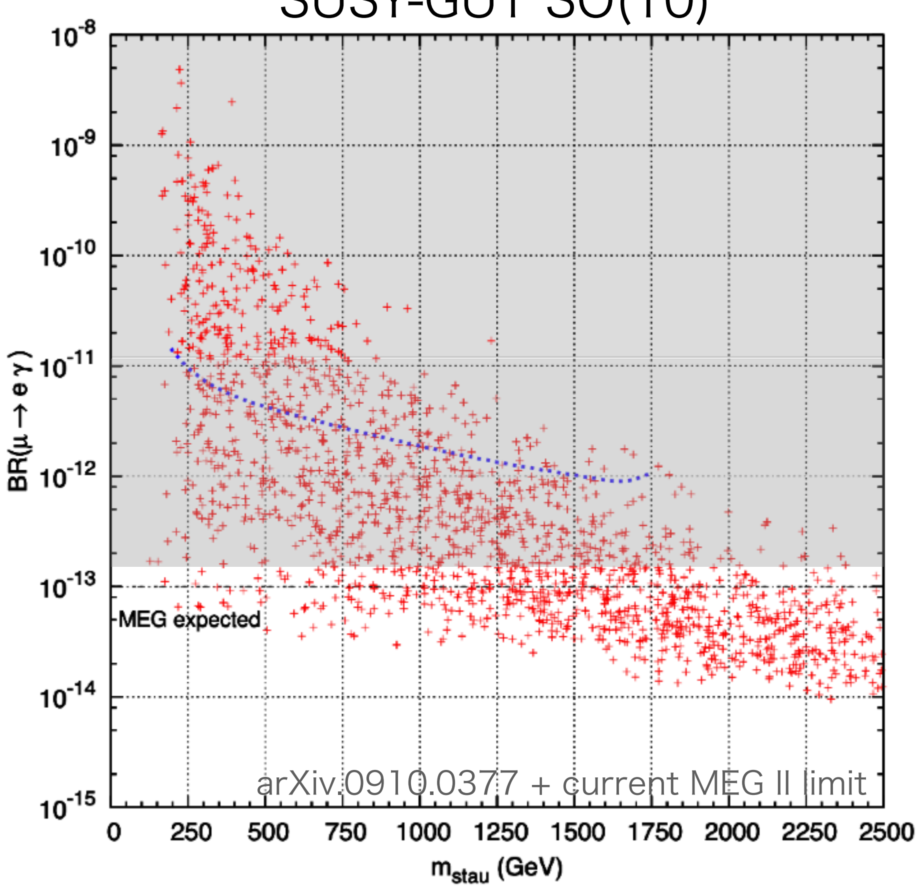


Heavy Z'

Heavy Z', Anomalous boson couplings

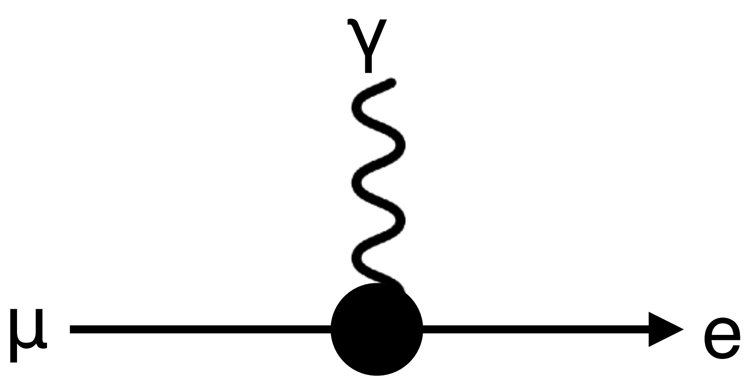


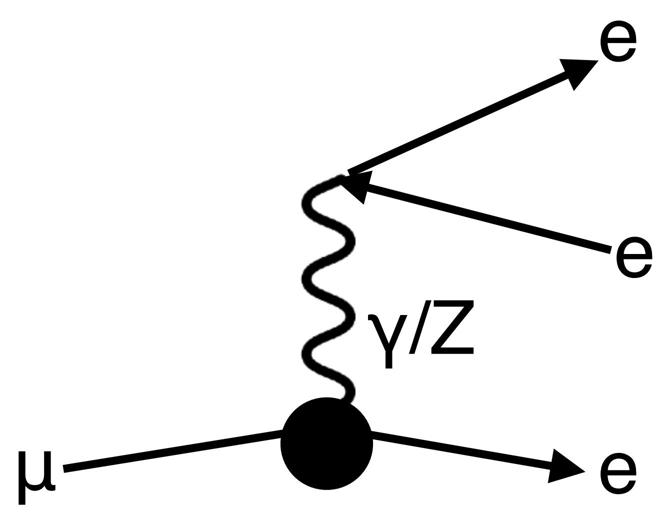
SUSY-GUT SO(10)

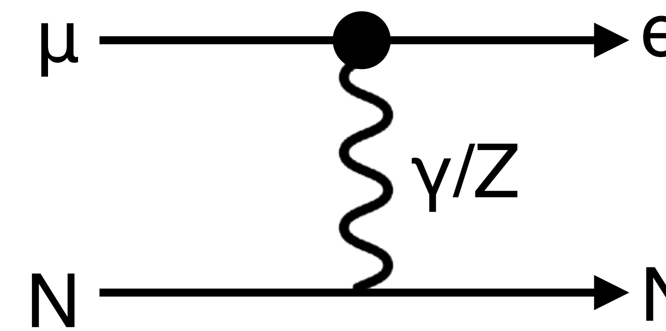


Charged Lepton Flavor Violation

$\mu \to e\gamma$	$\mu \to eee$	$\mu N \to eN$







Dipole dominant

1 : 1/170 : 1/390

Current limit (90% C.L.)

$\mu \to e\gamma$	$\mu \to eee$	$\mu N \to eN$
1.5×10^{-13} (MEG II [1])	1.0×10^{-12} (SINDRUM[2])	6.1×10^{-13} (SINDRUM II [3])

Ongoing projects

$\mu \to e\gamma$	$\mu \to eee$	$\mu N \to eN$
MEG II	Mu3e	Mu2e COMET

[1] K. Afanaciev, et al. New limit on the μ+->e+γdecay with the MEG II experiment., arxiv.2504.15711 (submitting to journal)

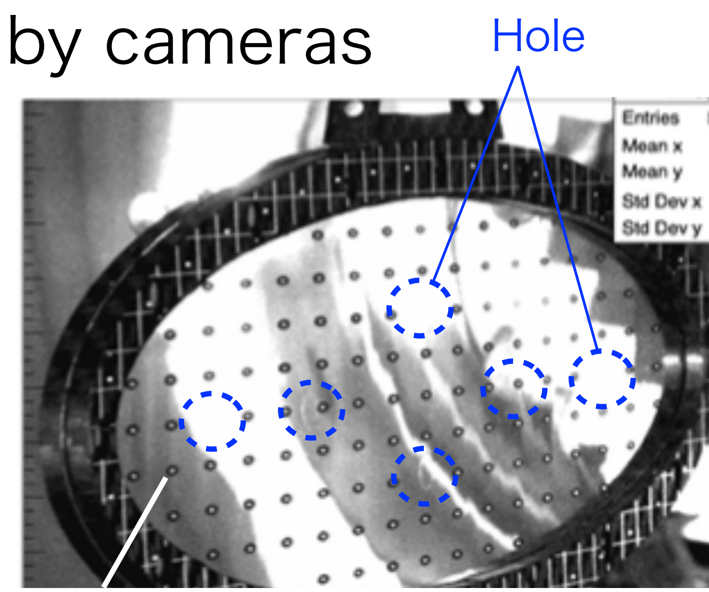
[2] Bellgardt, U.; Otter, G.; Eichler, R.; Felawka, L.; Niebuhr, C.; Walter, H.; Bertl, W.; Lordong, N.; Martino, J.; Egli, S.; et al. Search for the decay $\mu^+ \to e^+ e^- e^+$. Nucl. Phys. B 1988, 299, 1–6.

[3] Dohmen, C.; Groth, K.D. Test of lepton-flavour conservation in $\mu \to e$ conversion on titanium. Phys. Lett. B 1993, 317, 631–636.

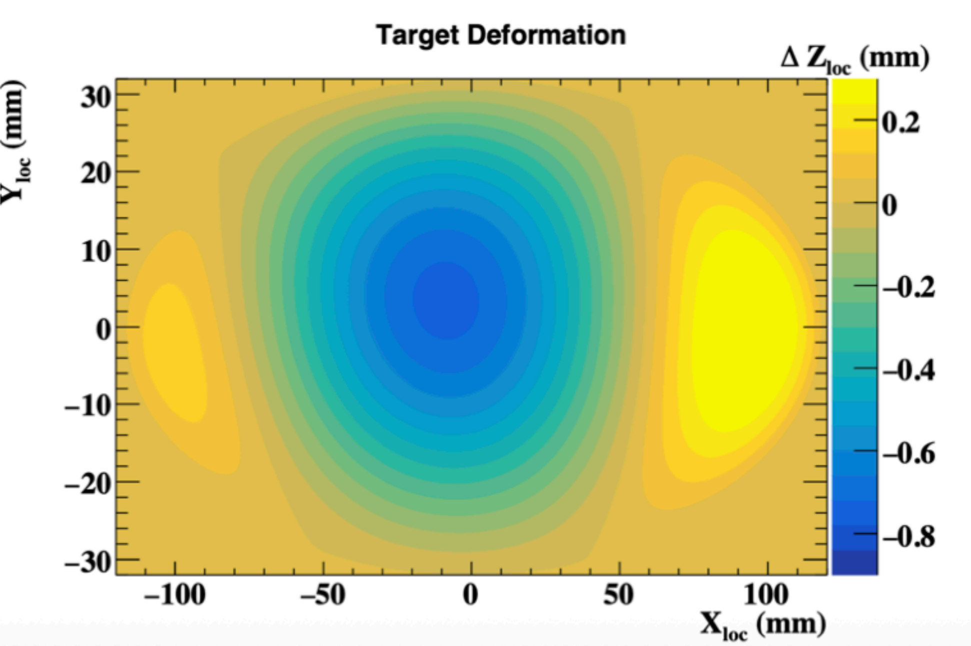
MEG II experiment

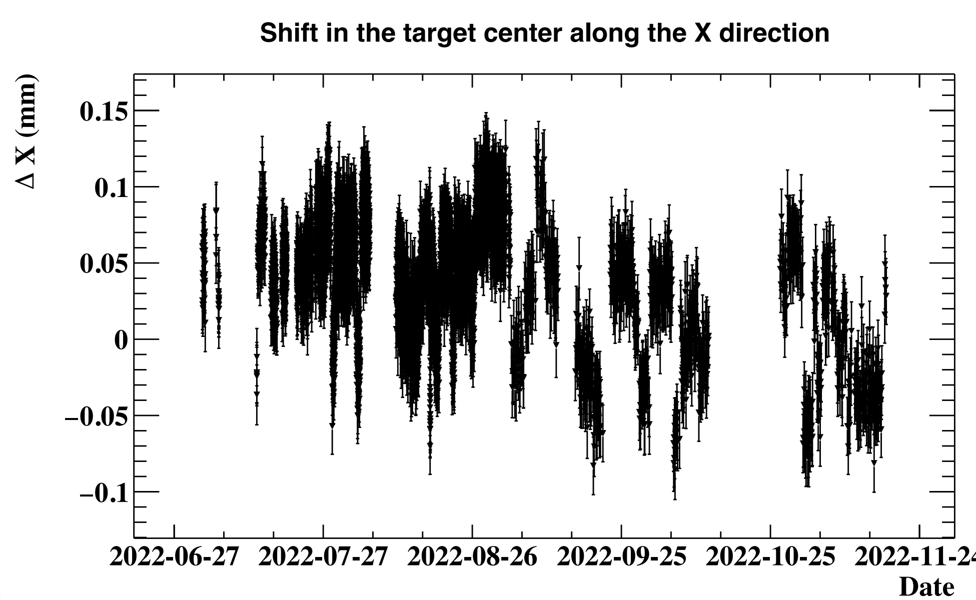
- Muon stopping target : 174±20μm thickness polyvinyltoluene (scinti. material)
- In MEG experiment, the largest uncertainty came from target deformation
- In MEG II experiment, it is monitored by Camera

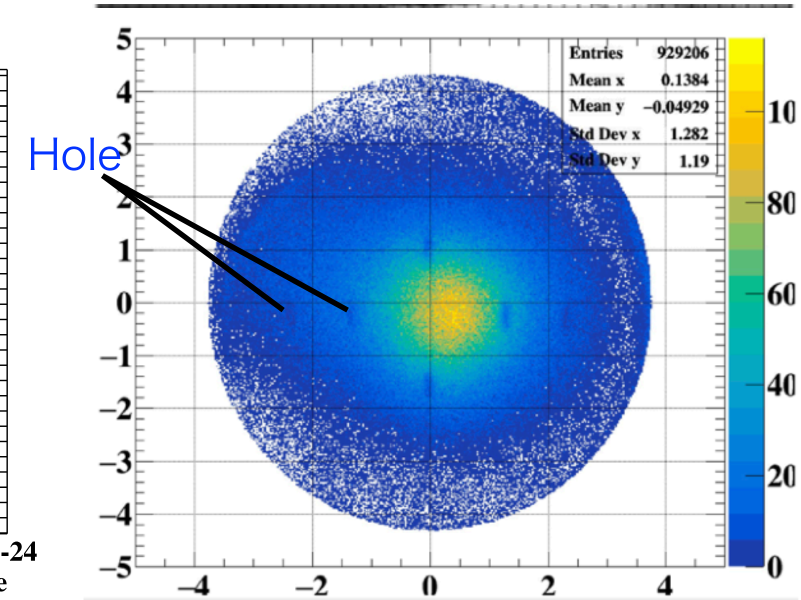
- Marker analysis
  - monitored the target position/rotation and deformation by cameras
  - -> implemented into event reconstruction
- Hole analysis
  - Hole reconstruction by positron tracks



analyze marker (dot) position



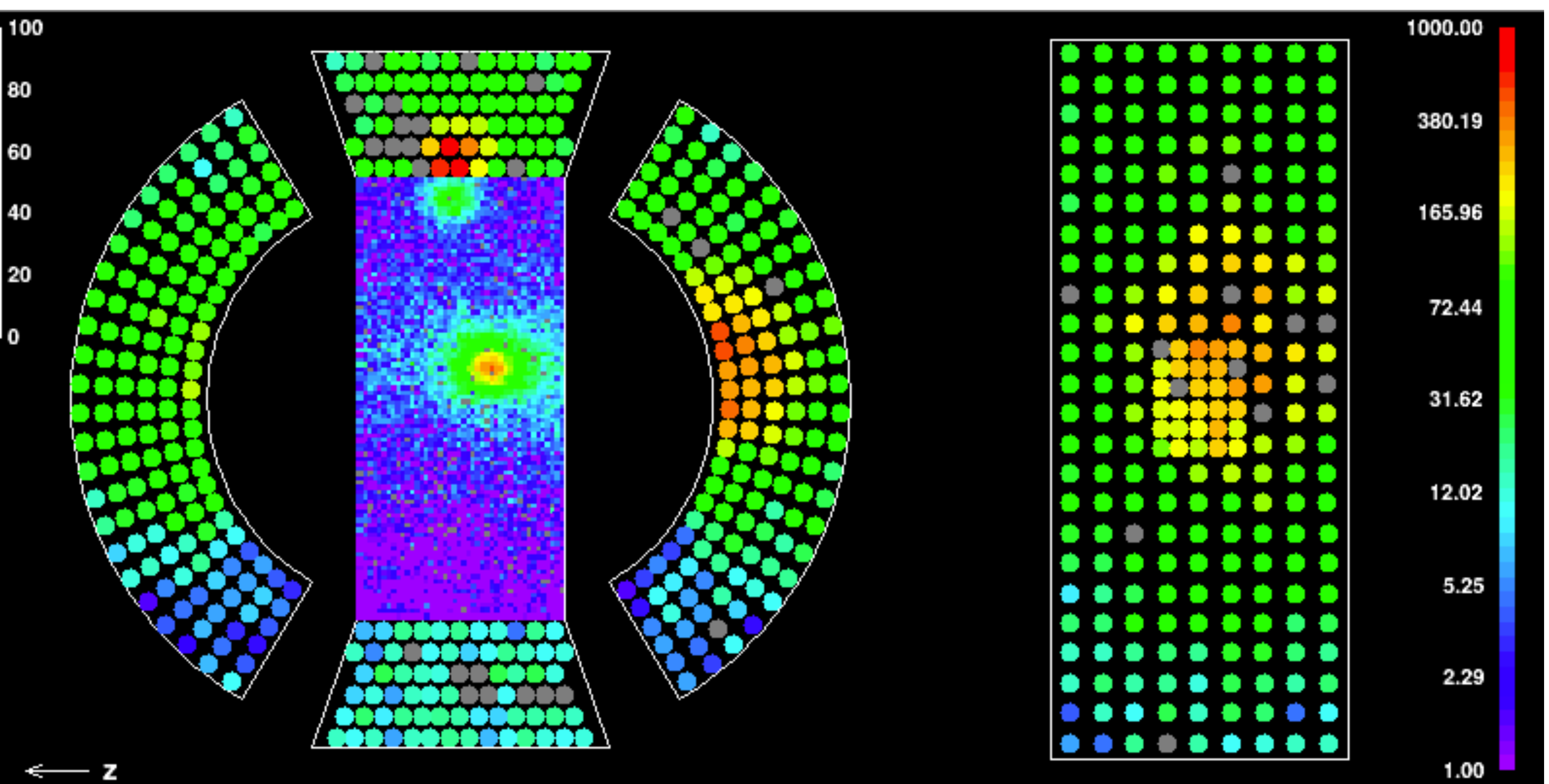


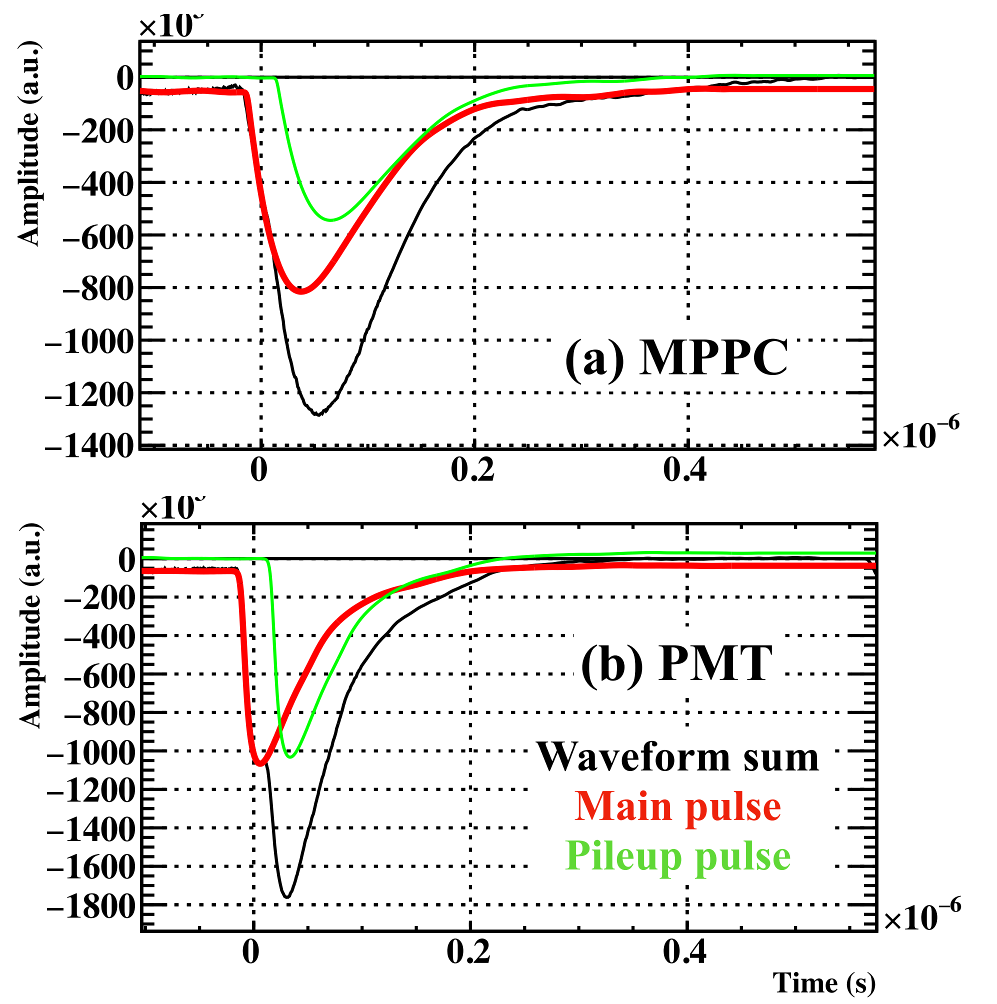


MEG II experiment

- Liquid xenon detector to measure energy, position, and timing of gamma-rays
- Homogeneous liquid xenon (900L) sensitive volume
  - Large stopping power, emit VUV (λ~175nm) scintillation lights
- 4,092 VUV-sensitive MPPCs on the entrance face
- 668 VUV-sensitive PMTs on the other faces

- Pileup analysis with spacial distribution in MPPCs and timing information
  - Efficiency : 93.4 ± 0.4% (3e7 μ/s)

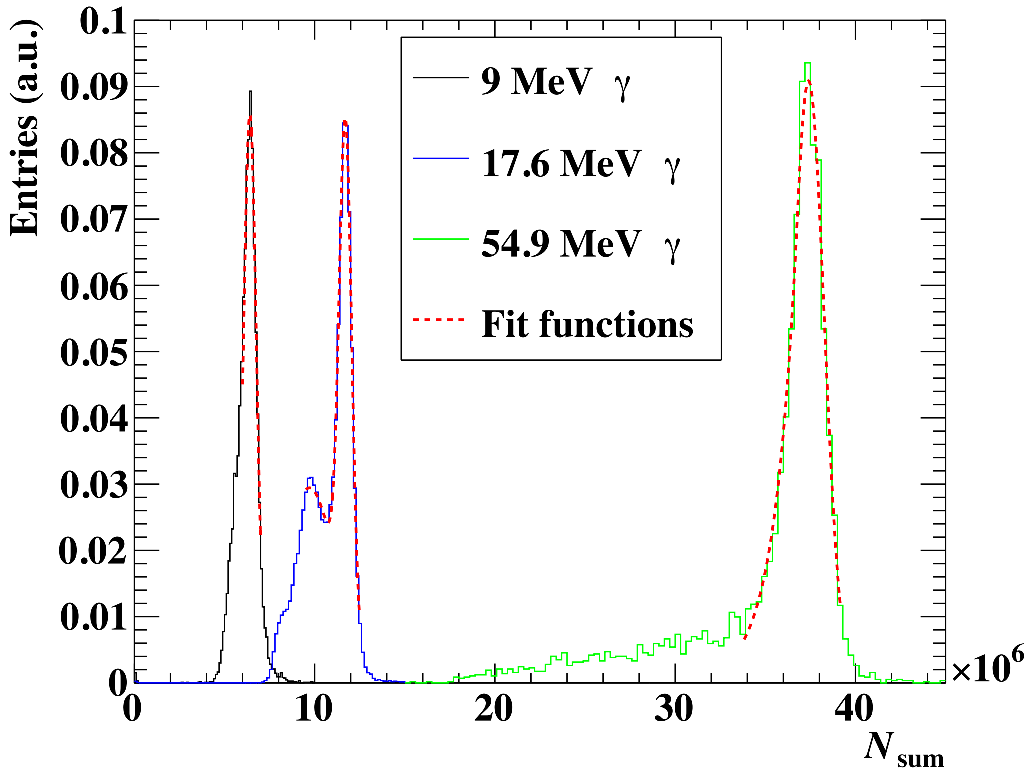




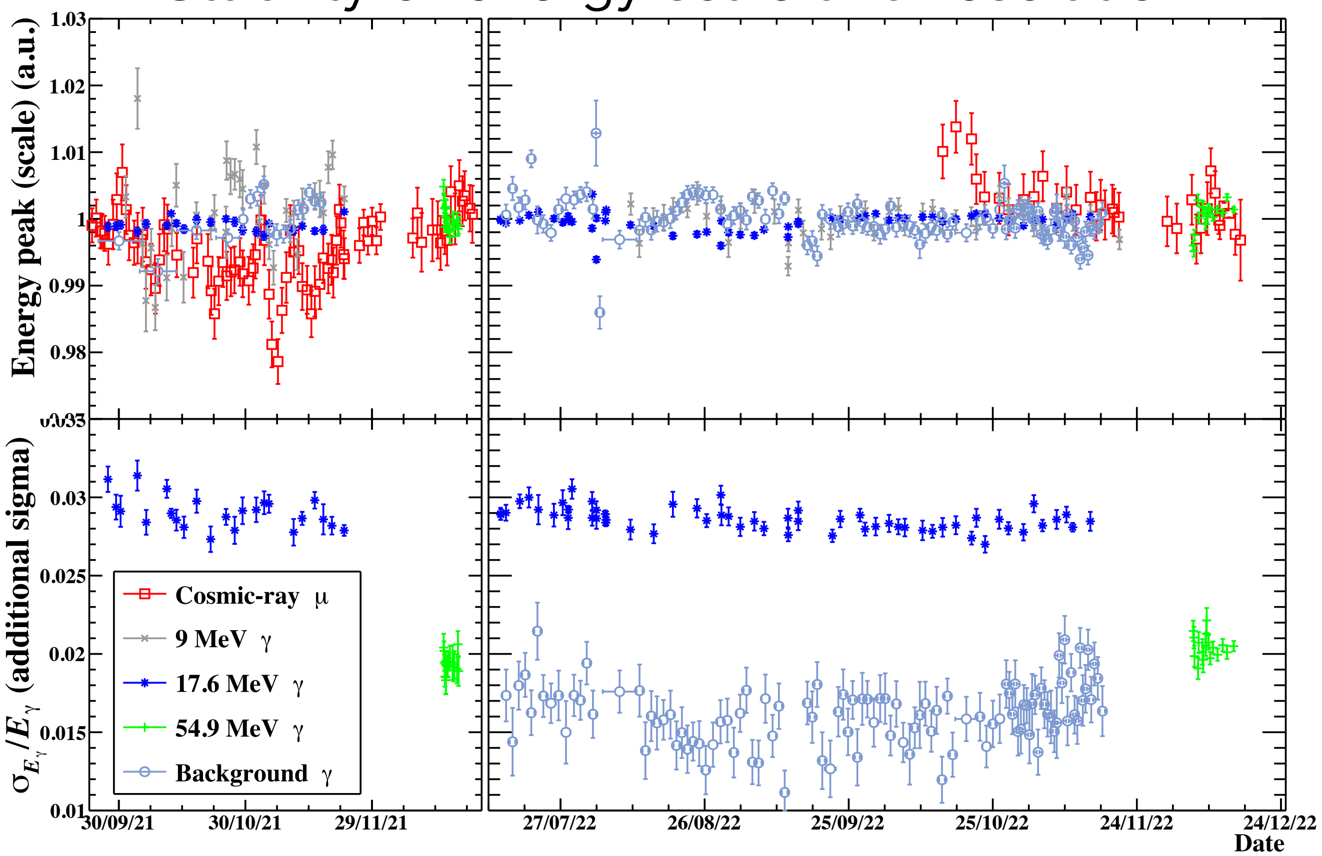
MEG II experiment

- Energy scale is monitored and calibrated with some calibration sources
  - 17.6 MeV gamma-ray : p (CW acc.) + Li (target) → $^{7}Li(p, \gamma)^{8}Be$
  - 9 MeV gamma-ray : neutron capture in nickel nuclei $^{58}Ni(n, \gamma)^{59}Ni$
  - Cosmic-ray (typically ~120 MeV)
  - Background spectrum
  - 54.9 MeV gamma-ray by charge exchange reaction of π^{+} and H_2 → π^0
    - Dedicated calibration campaign with 2~3 weeks

Energy spectrum of each calibration source

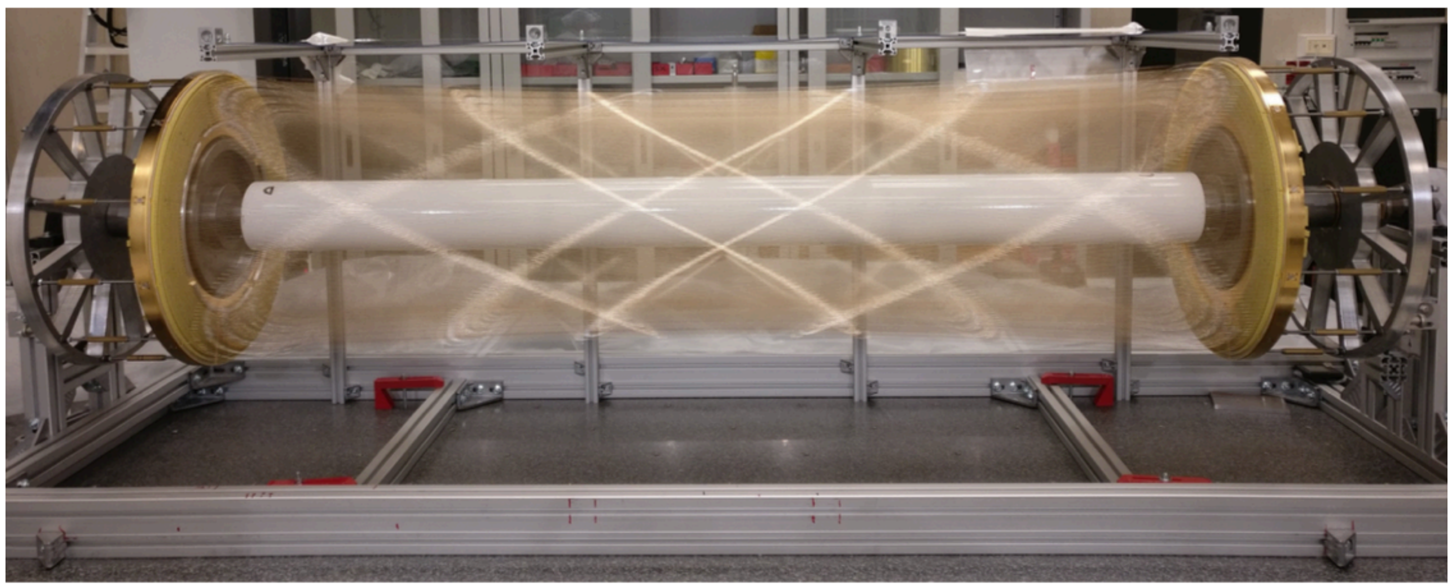


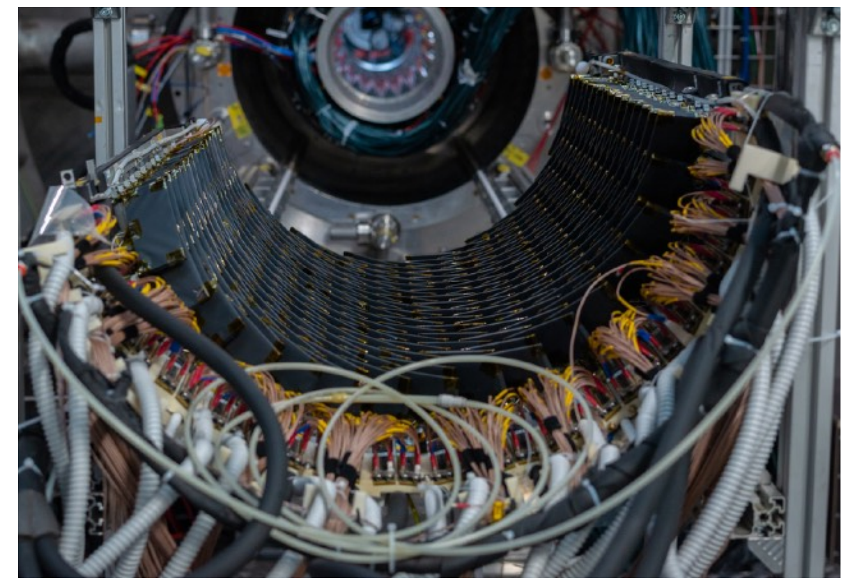
Stability of energy scale and resolution

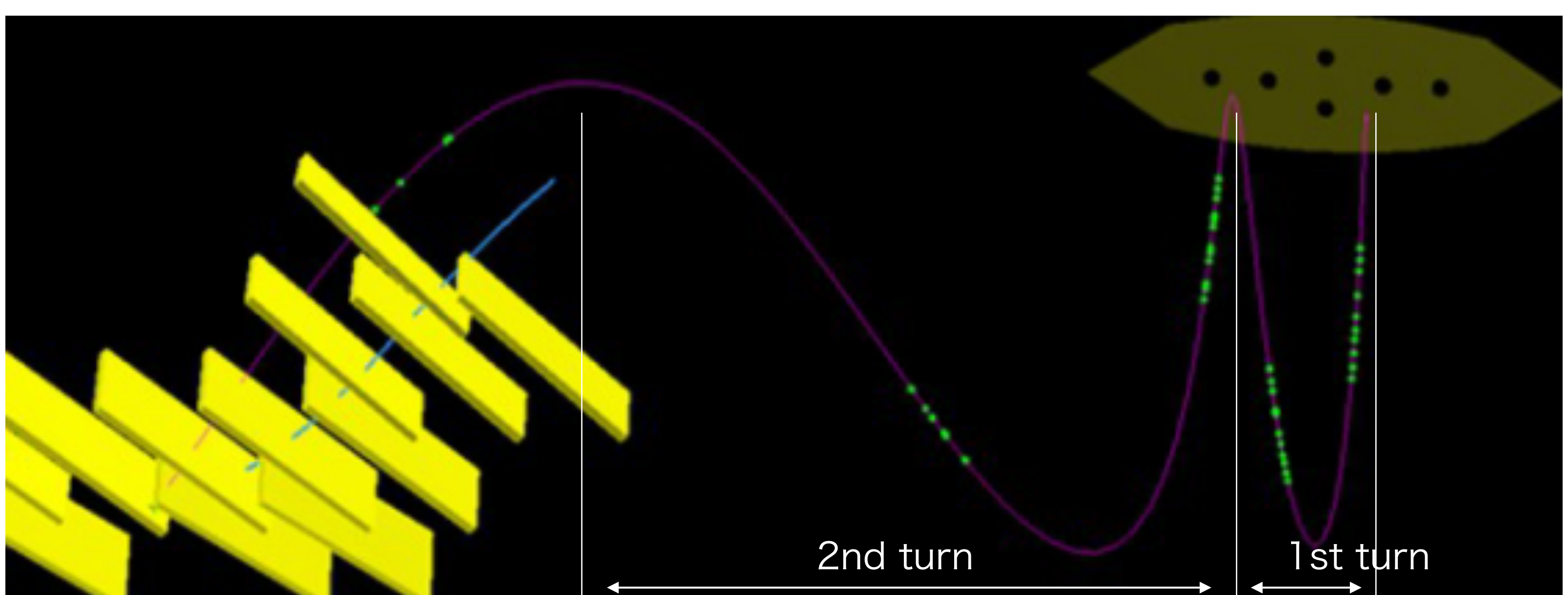


MEG II experiment

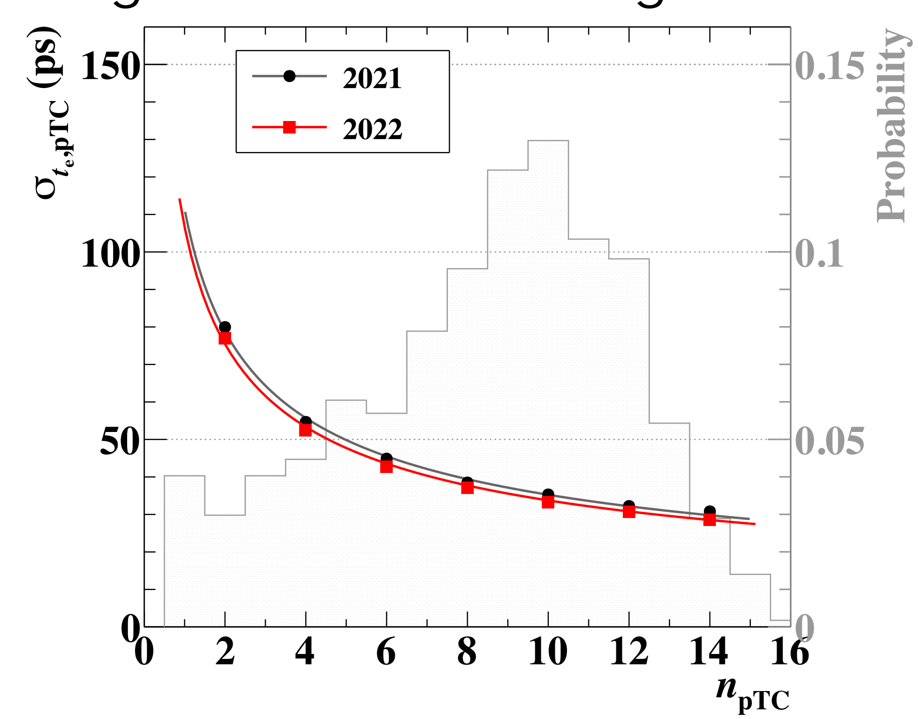
- Positron spectrometer : COBRA magnet + Drift chamber + Timing counter
  - Gradient magnetic field by COBRA magnet (1,27T @center, 0.49T @end)
  - Drift chamber with low material to reconstruct positron track
  - Pixelized timing counter to measure positron timing







Timing resolution in timing counter

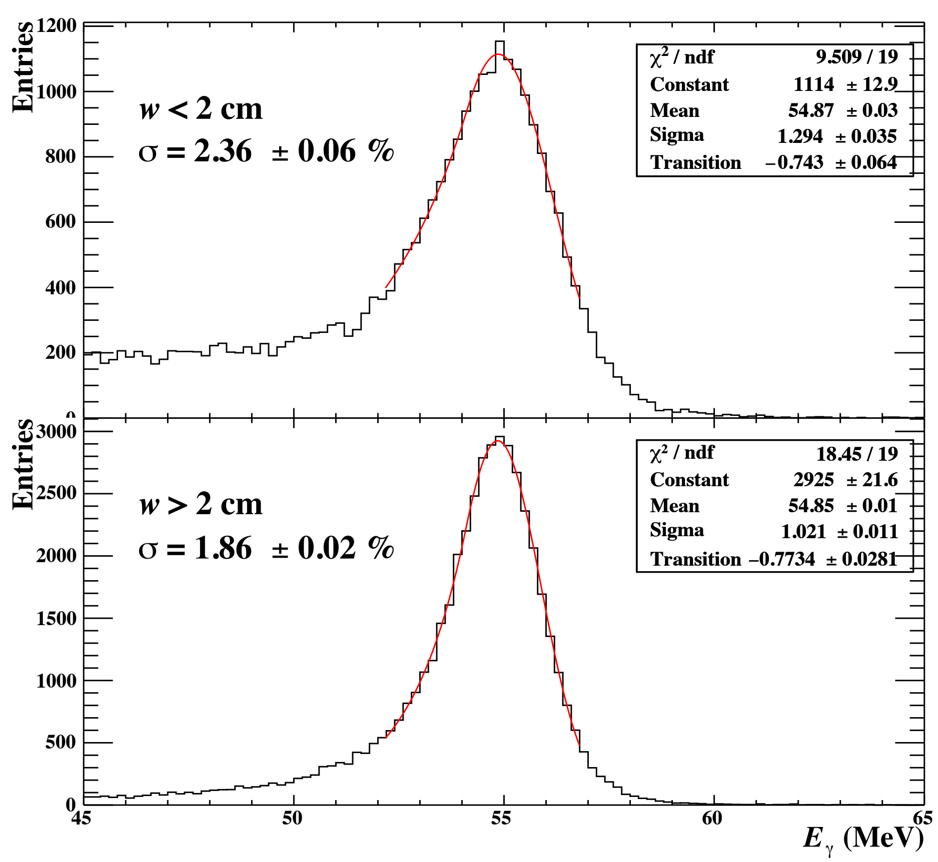


MEG II experiment

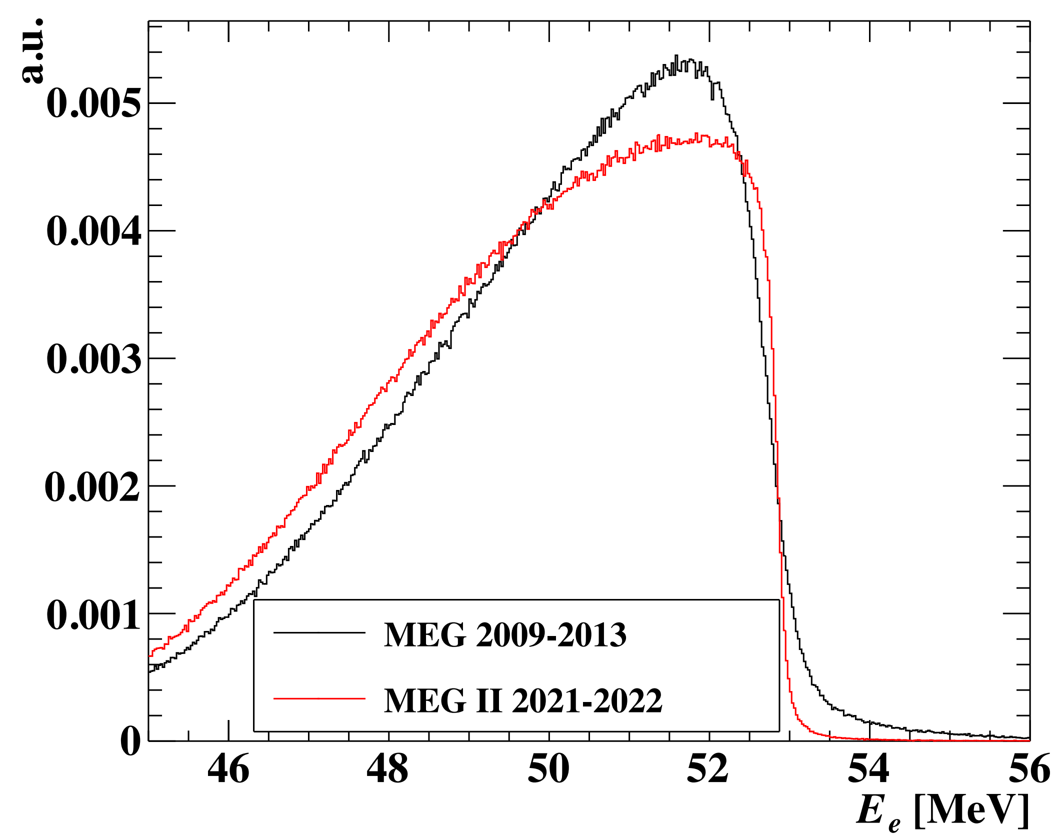
- Summary of the detector performance

	P_e	θ_e	E_γ	$Position_\gamma$	$T_{e\gamma}$	ε_e	ε_γ
MEG	380 keV/c	9.4 mrad	2.4%/1.7%	5 mm	122 ps	30%	63%
2021 (3e+7)	89 keV/c	7.2 mrad	2.0%/1.8%	2.5 mm	78 ps	67%	62%
2022 (3e+7)	89 keV/c	6.2 mrad	2.4%/1.9%	2.5 mm	78 ps	67%	62%

Energy spectrum of gamma-ray (2022)

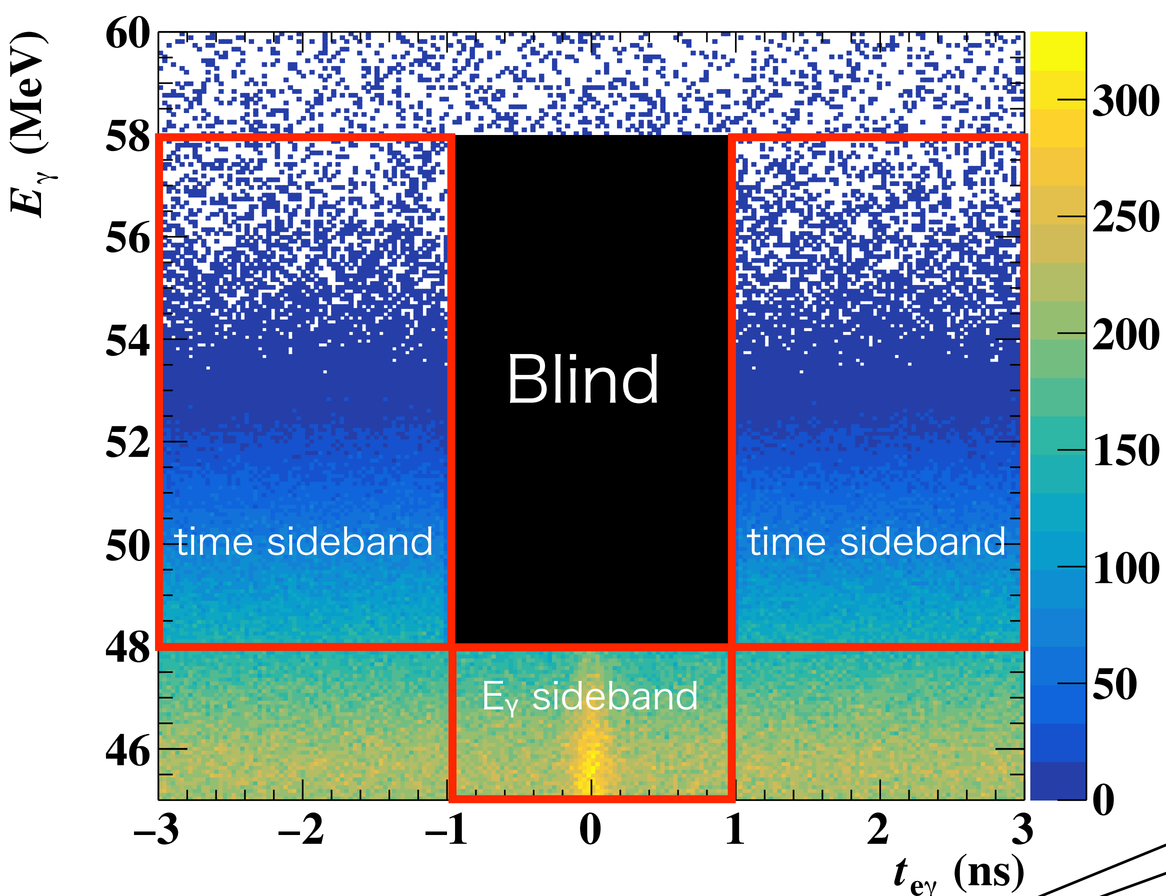


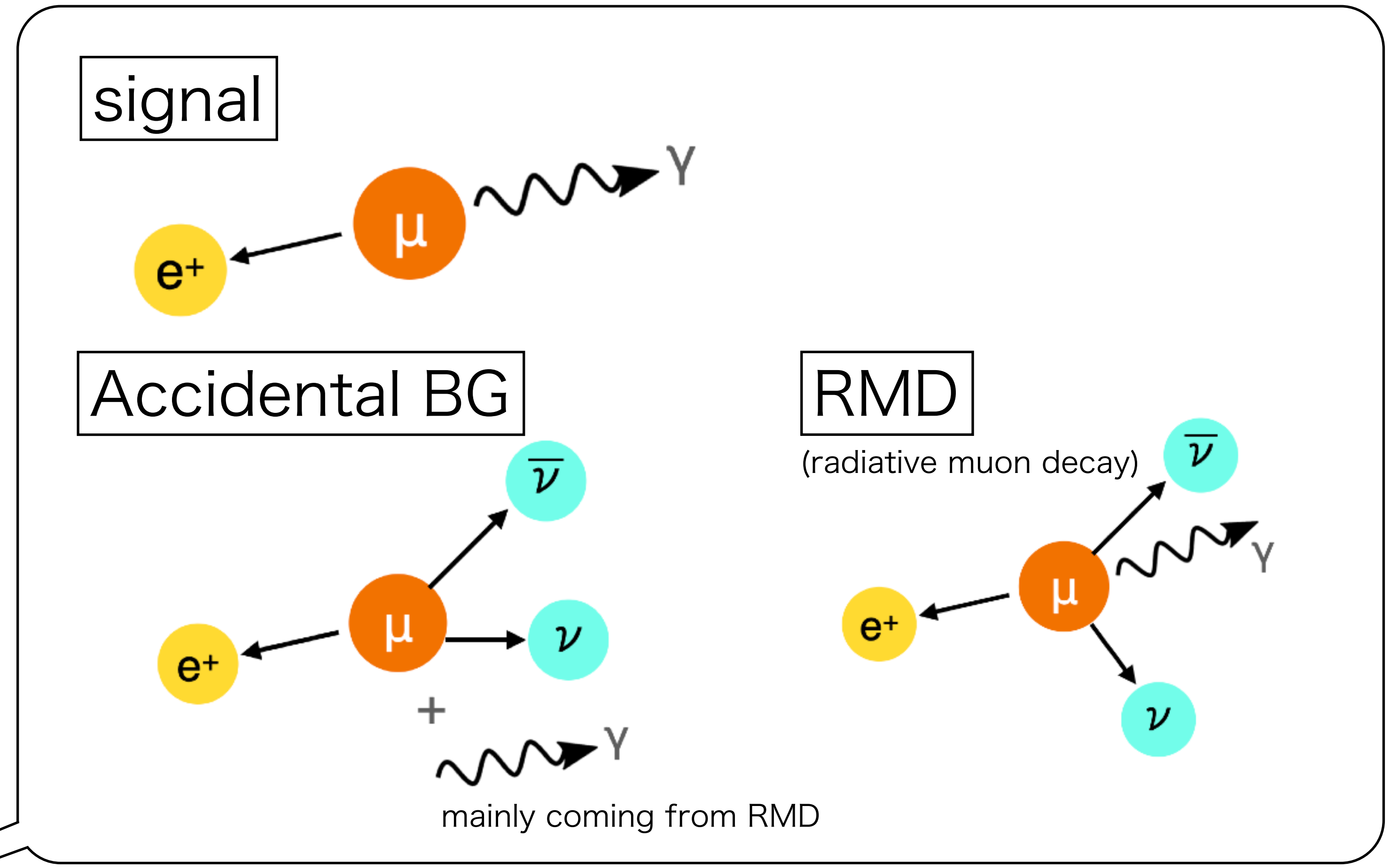
Reconstructed momentum of positron



MEG II experiment : Likelihood analysis

- Blind analysis : [48, 58] MeV for E_γ, [-1,1] ns for $t_{e\gamma}$
    - Time/Energy sidebands are set for extraction of PDFs and analysis check





- Likelihood analysis using per-event PDF

constraint term with $N_{acc,\ exp.}$ = 364, $N_{RMD,exp.}$ = 10.1
(estimated from sideband)

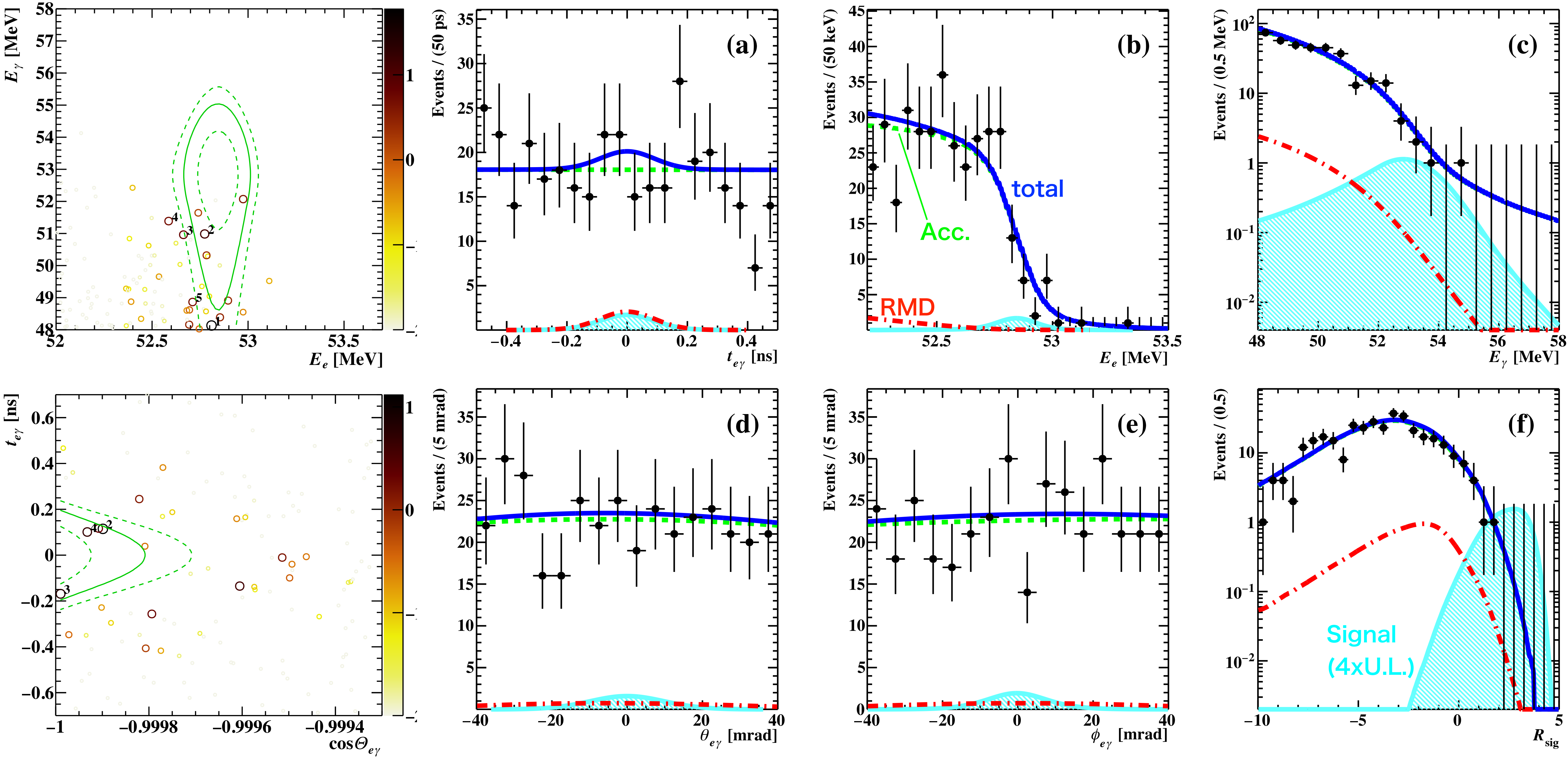
$$L(N_{\rm sig}, N_{\rm acc}, N_{\rm RMD}|\mathbf{X}) = \exp\left(-\frac{(N_{\rm acc}-N_{\rm acc,expected})^2}{2\sigma^2_{\rm acc,expected}}\right)\times\exp\left(-\frac{(N_{\rm RMD}-N_{\rm RMD,expected})^2}{2\sigma^2_{\rm RMD,expected}}\right)$$
$$\times\frac{e^{-N}}{N_{\rm obs}!}\prod_i^{N_{\rm obs}}\left(N_{\rm sig}P(x_i)+N_{\rm acc}A(x_i)+N_{\rm RMD}R(x_i)\right)$$

Probability Density Function (PDF) of each components

MEG II experiment : Fit result

- Best fit : **N_{sig} = -5.1** ← No signal excess
- converted into branching ratio
  - $Br(\mu\rightarrow e\gamma)=N_{sig}/N_{\mu}$ = -5.1/1.34×10^{13} = **-3.8×10^{-13}** (Best Fit)

1D-projections of fitting result for signal window

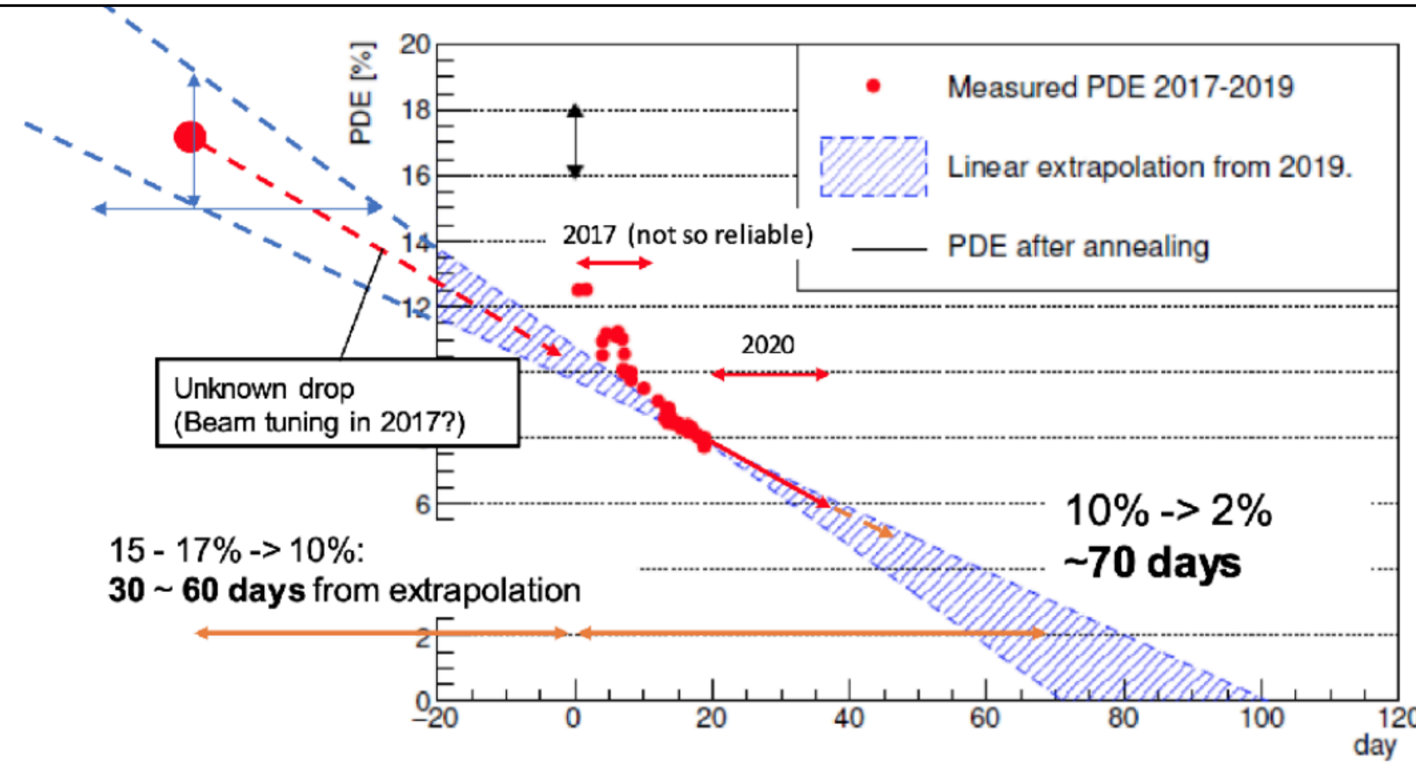


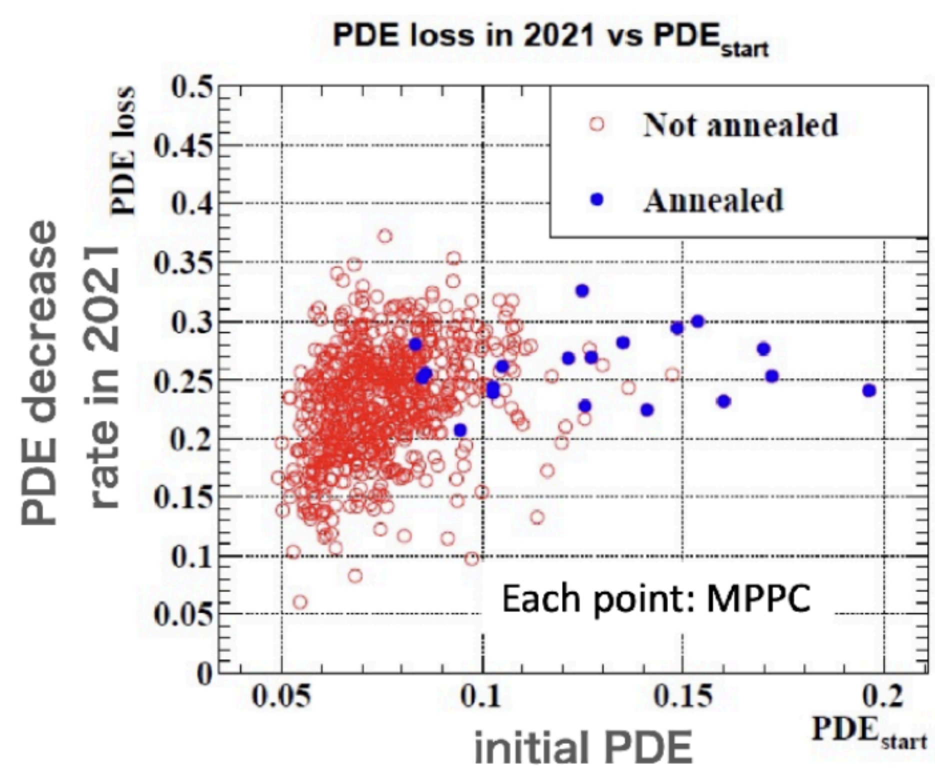
PDE decrease

Slide from T. Iwamoto (JPS Mar. 2021, talk: 15aA562-4)

γ detector (LXe) Issue

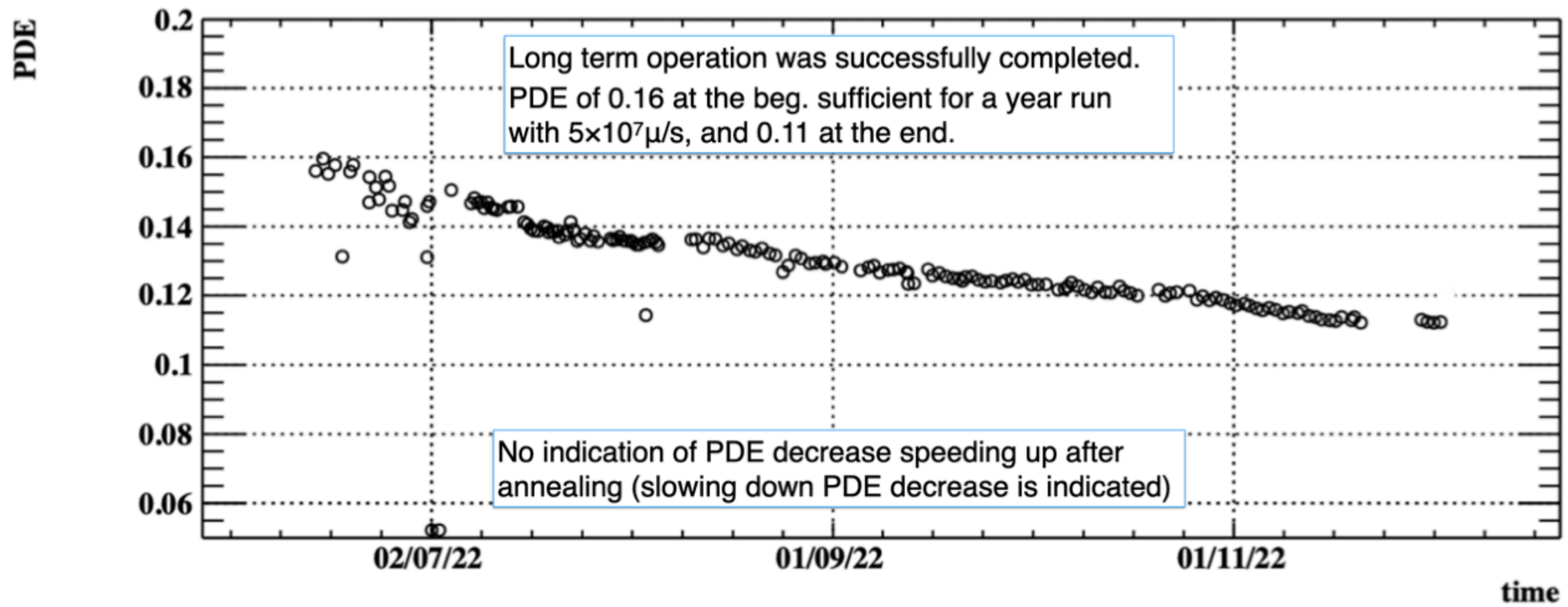
- MPPC PDE decrease
  - observed in 2017 under muon beam
  - The cause to be investigated
  - Based on 2021 operation, PDE will change from 16% to 2% in ~100 days MEG II intensity
  - Annealing recovers PDE fully
- Strategy for run 2022
  - LXe MPPC can sustain ~ 120 days with 5×10⁷ μ/s
    - Beam intensity optimization necessary
  - Annealing for all MPPCs during accelerator winter shutdown period





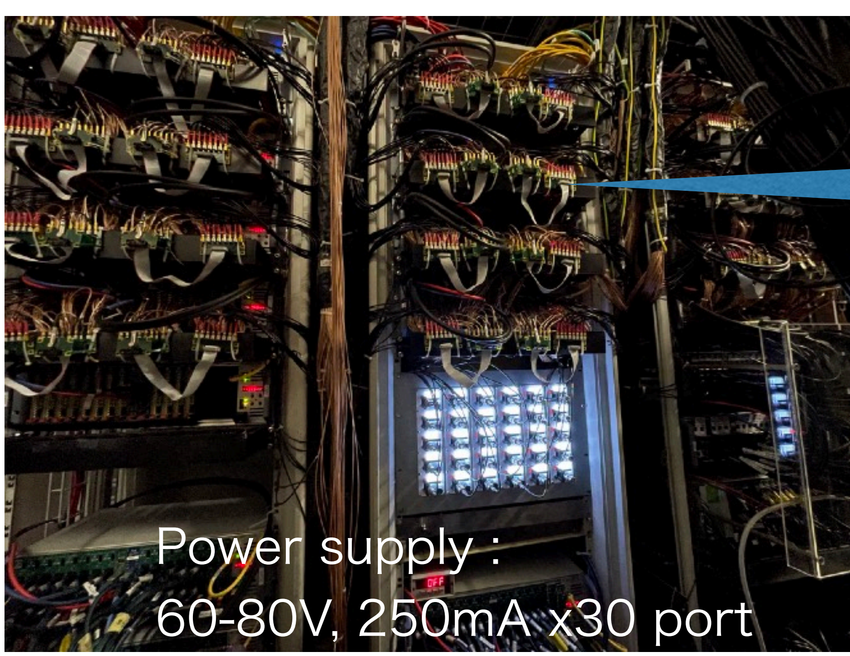
PDE decrease in 2022 run and Annealing 2023

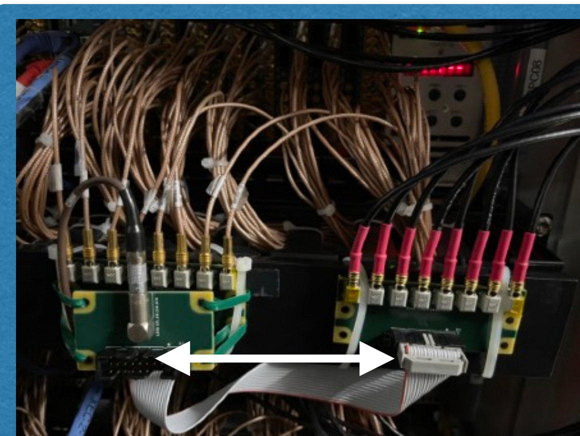
- Averaged Photon Detection Efficiency (PDE) monitoring during 2022 run
  - It decreased gradually because of radiation damage (known problem)



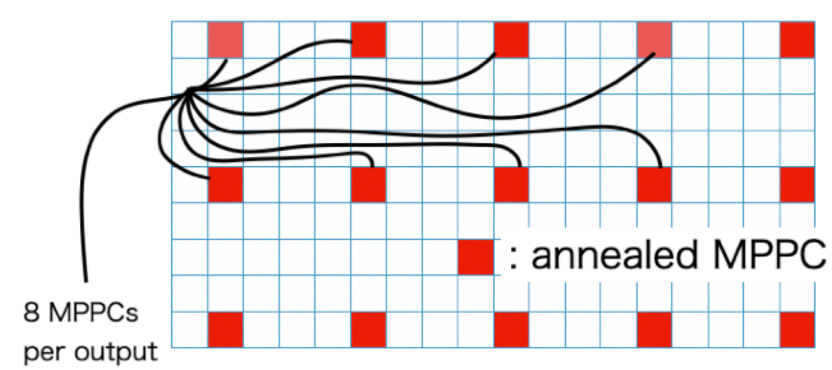
Rough calibration during run time
(precise calib. is on goling)

- Annealing of MPPCs by Joule heating to recover the PDE
  - ~70V × ~25mA = ~1.75W /MPPC -> 30h/MPPC annealing was done (Jan.-Mar.)
  - Monitoring by LED in intervals of annealing in a set : to see degree of recover





easily switch :
annealing ⇄ meas. mode

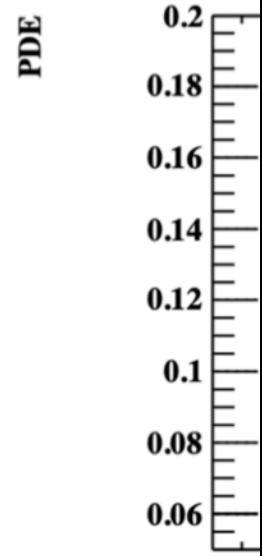


-> 256 MPPCs are annealed at once
-> 16 set in total

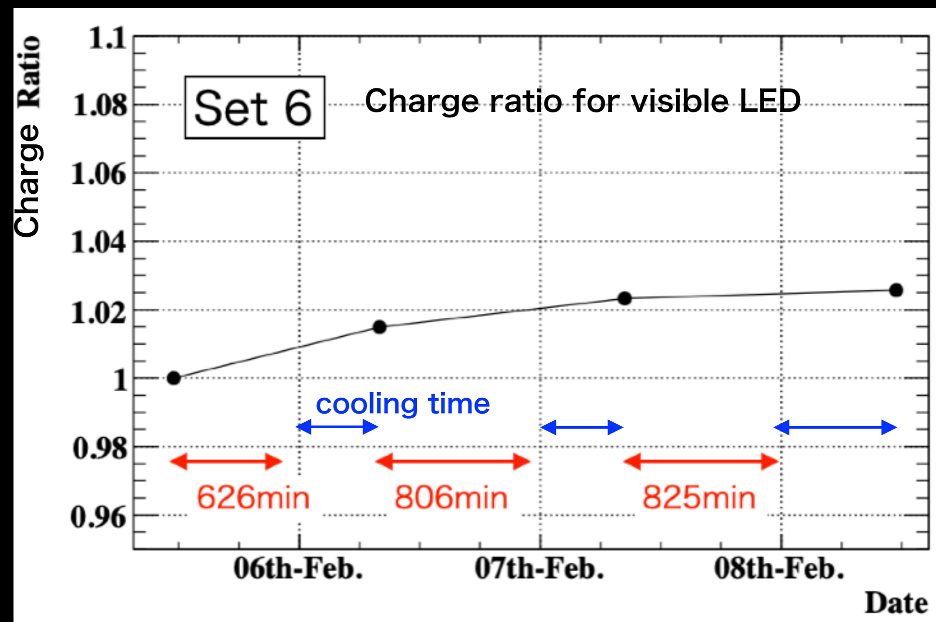
Blue LED

PDE decrease in 2022 run and Annealing 2023

- Averaged Photon De
  - It decreased gradu



- Empirical relation :
  - [Recovery ratio for VUV] = 10 * [Recovery ratio for visible]
  - e.g. : (relatively) 5% recovery for visible light -> relatively 50% recovery for VUV



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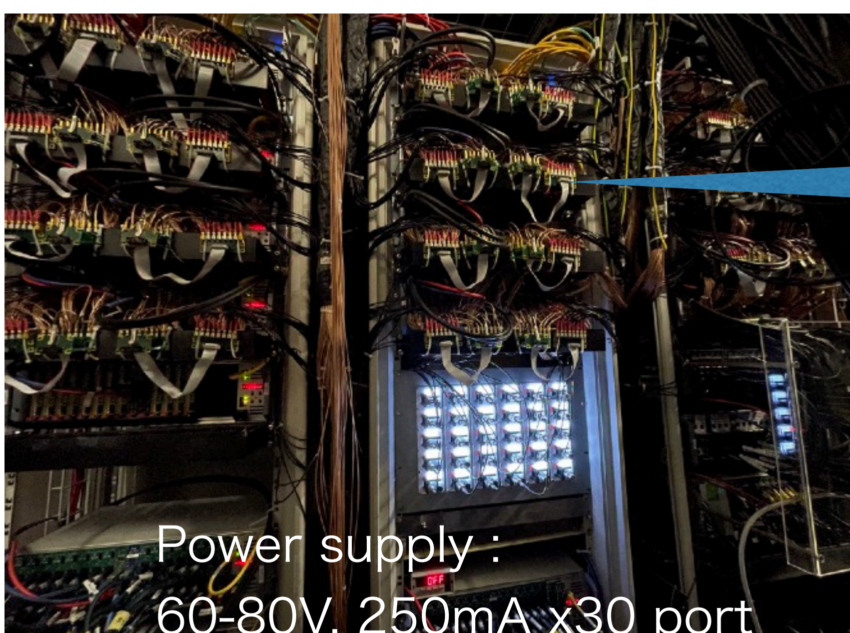
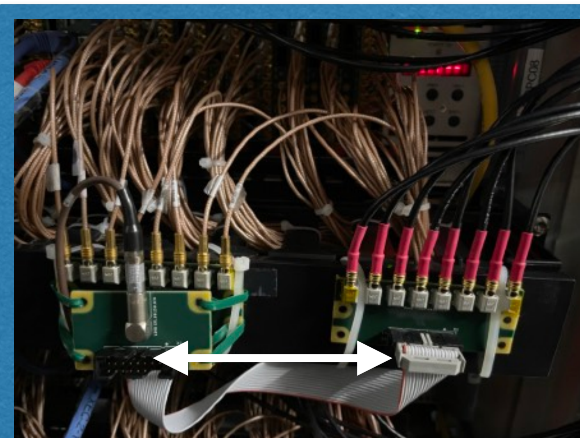
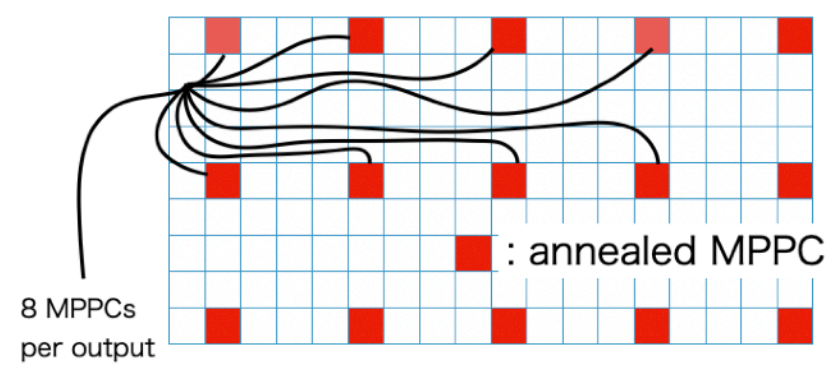




easily switch :
annealing ⇄ meas. mode

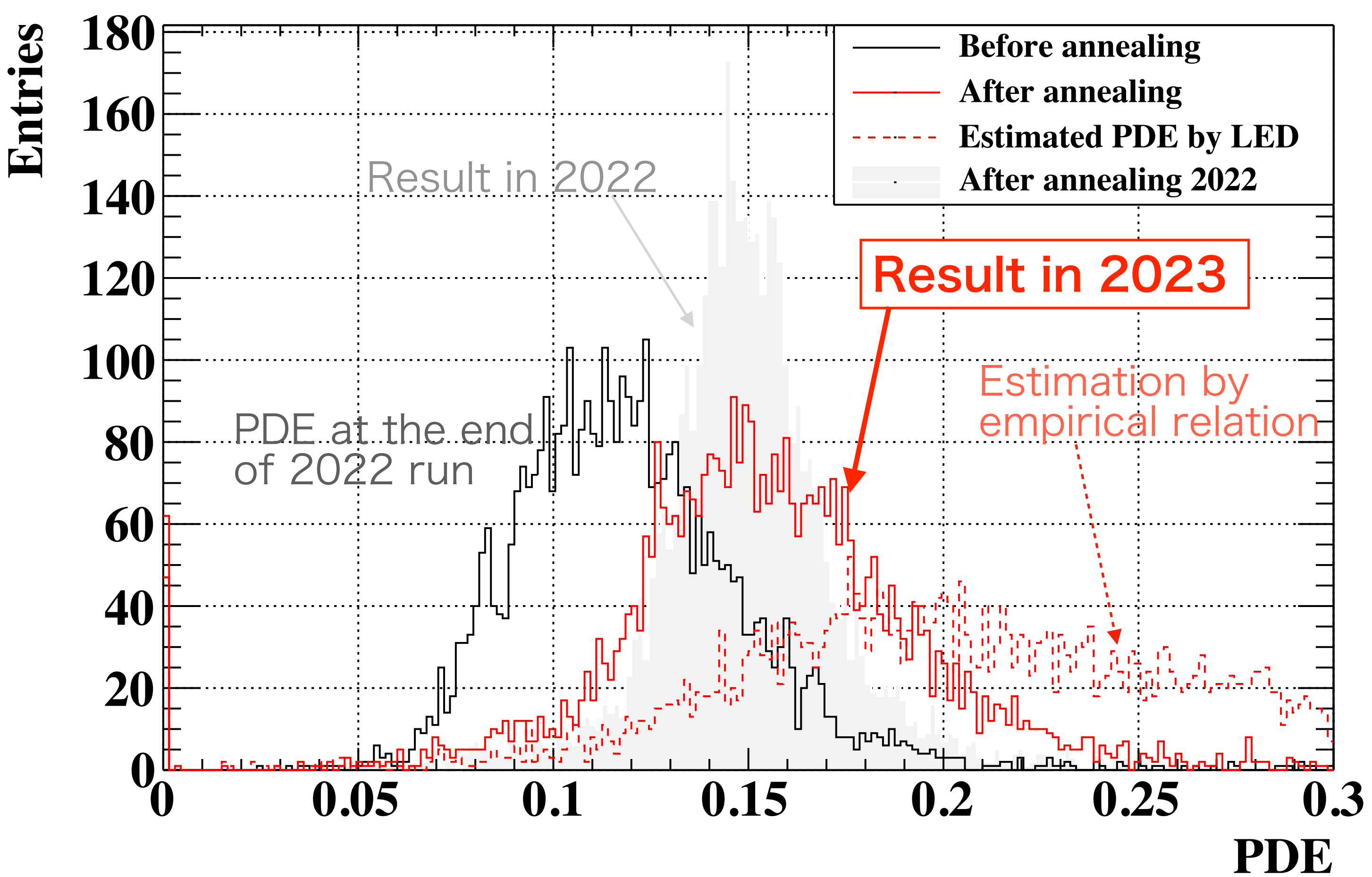


-> 256 MPPCs are annealed at once
-> 16 set in total

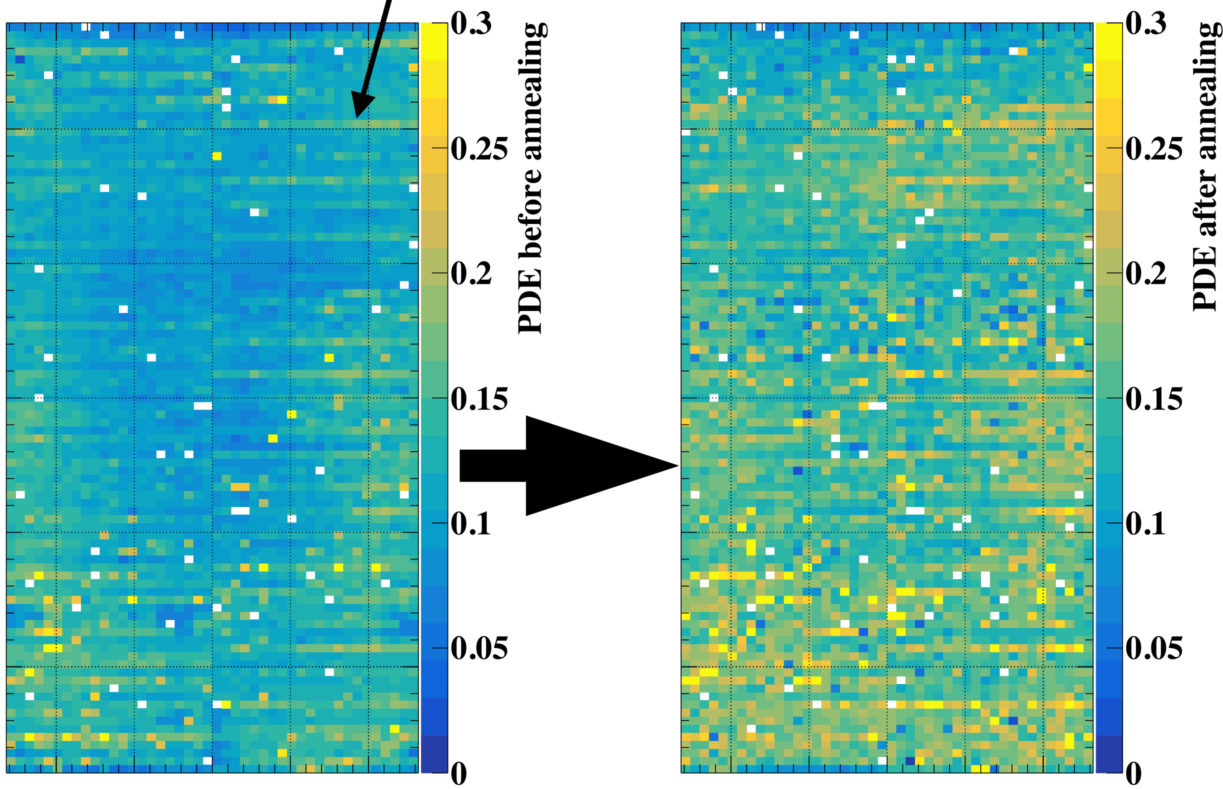
Blue LED

Annealing result at the beginning of 2023

- Annealing recovered MPPC PDE from ~11% (in avg.) to ~15% (in avg.)
  - Spread of PDE distribution became wider than 2022
  - Large discrepancy between result and estimation by visible LED
    - Causes are under investigation
  - PDE decrease and recovery seem to depend on production Lot strongly
  - At the top region, not significance recovery is observed
    - should be improved for the next annealing in 2024



same MPPC production Lot is aligned in one line bordering in the center



Charged Lepton Flavor Violation

- History and prospects of cLFV search