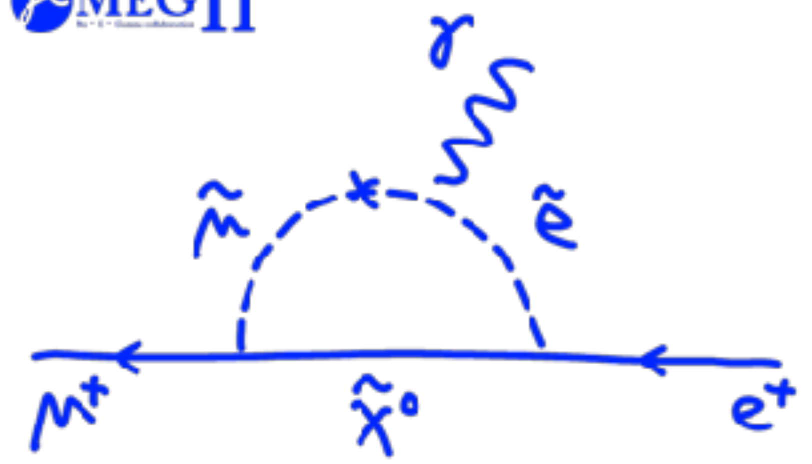
MEG II 実験 2021年物理ラン開始の報告と今後の実験計画

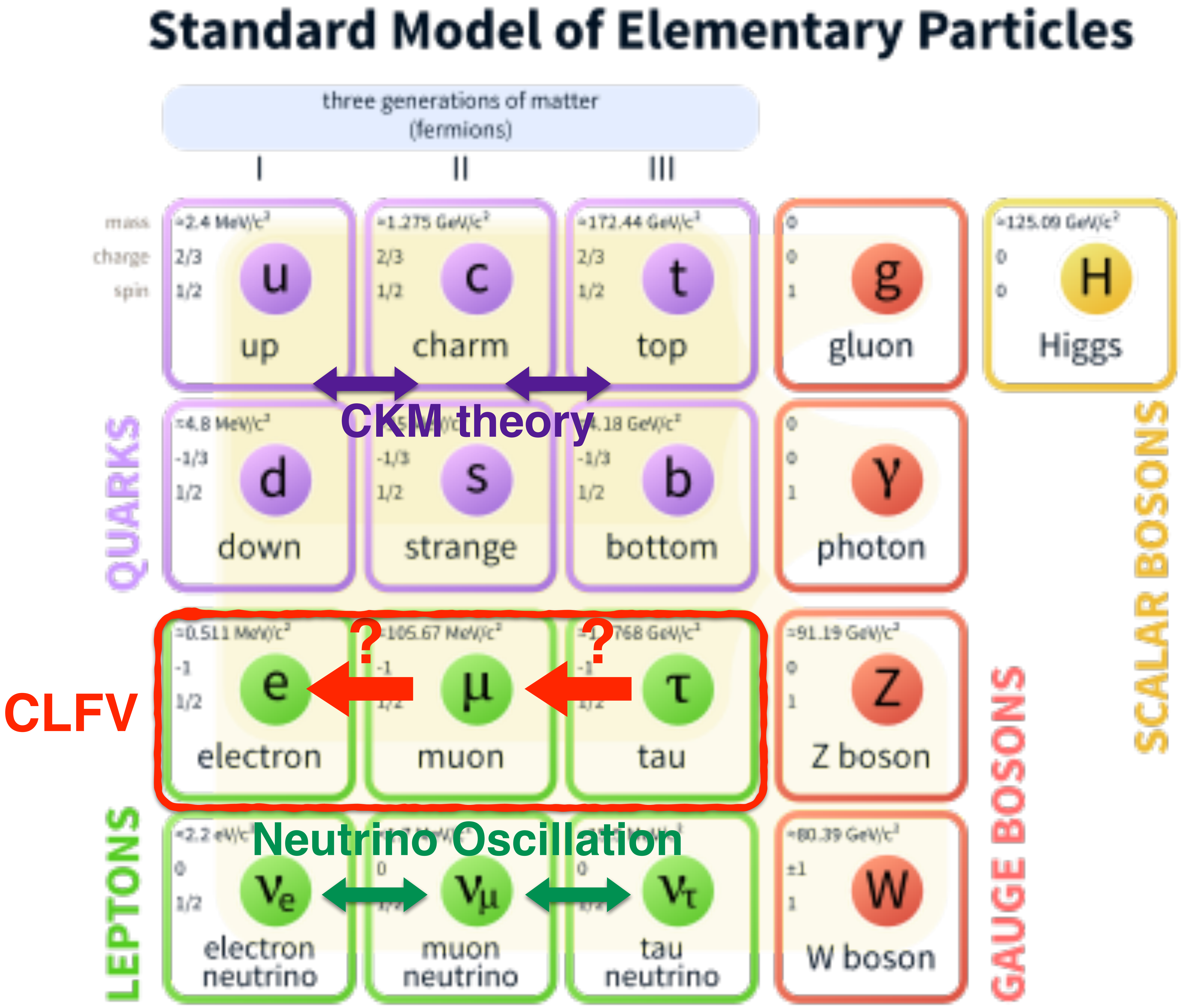
東京大学　素粒子物理国際研究センター
岩本敏幸　他MEG II コラボレーション



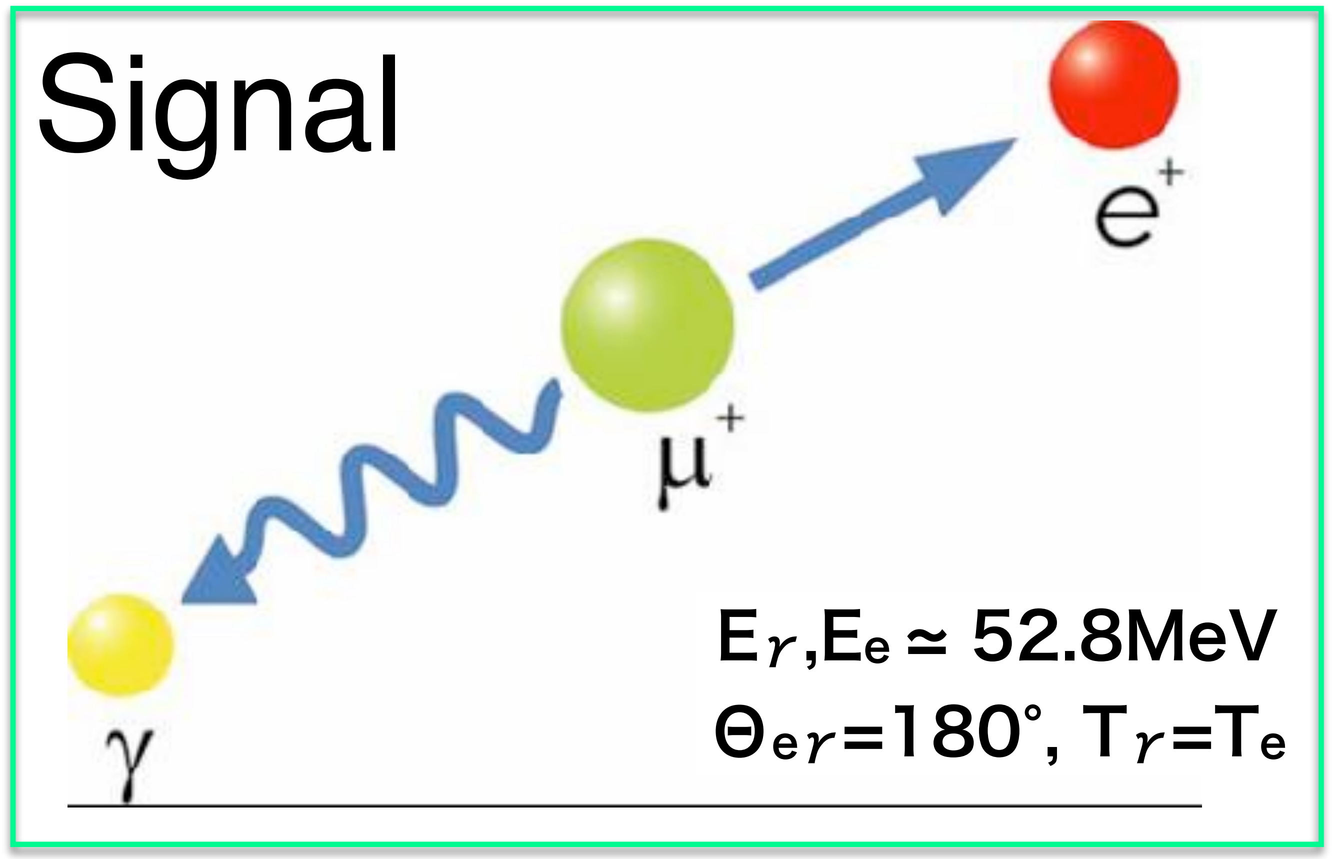
2022年3月15日
日本物理学会2022年第77回年次大会 岡山大学/岡山理科大学

Target of $\mu^+ \to e^+\gamma$ search

- Flavors in quark, neutrino sectors are violated in SM
- Charged Lepton Flavor Violation (CLFV)
  - practically never occurs in SM : $Br(\mu \to e\gamma) \sim 10^{-54}$
- CLFV is suitable to search for new physics
  - No background from SM
  - No reason to conserve flavors in new physics BSM
- Many new physics predictions in a measurable region
  - SUSY-seesaw, SUSY-GUT etc.: $Br(\mu \to e\gamma) \sim O(10^{-14})$
  - Reachable with the state-of-the-art experiments!

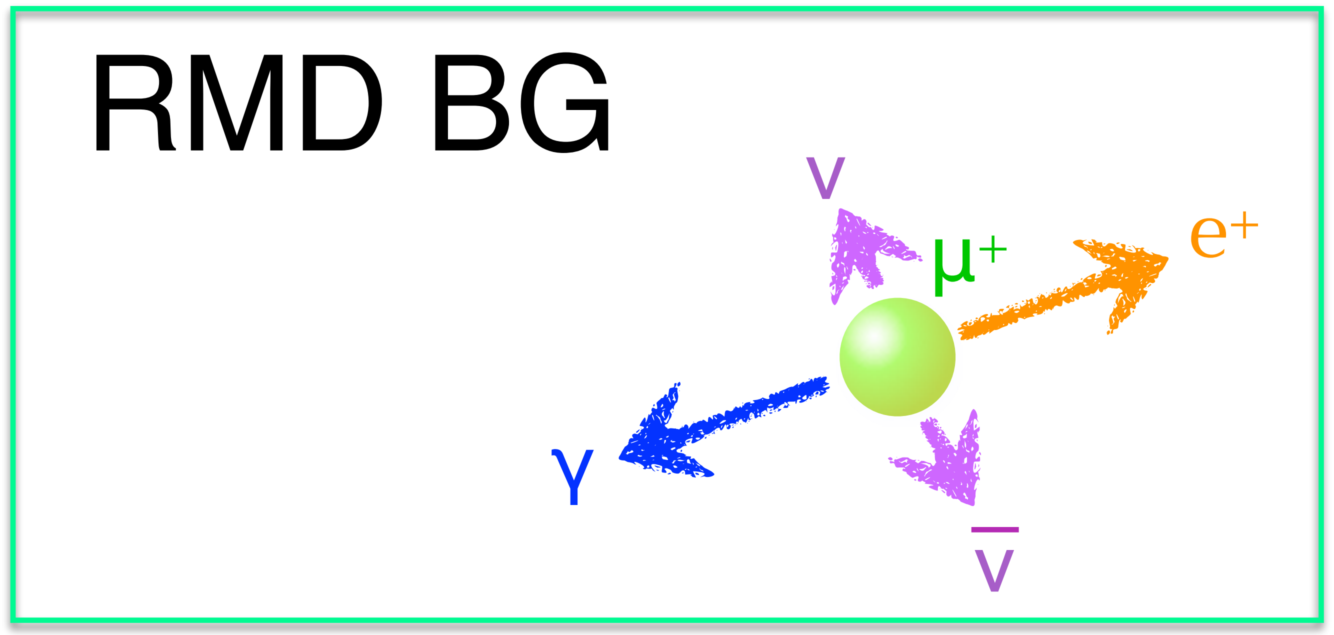


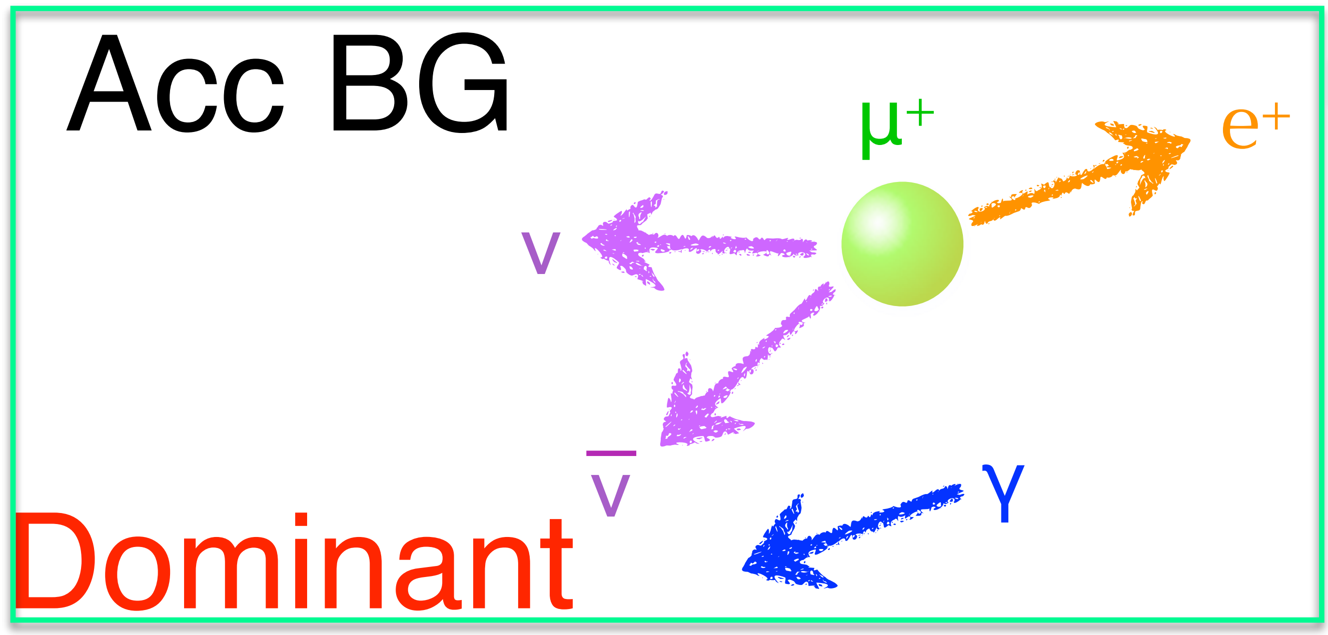
$\mu^+ \rightarrow e^+\gamma$ signal and backgrounds



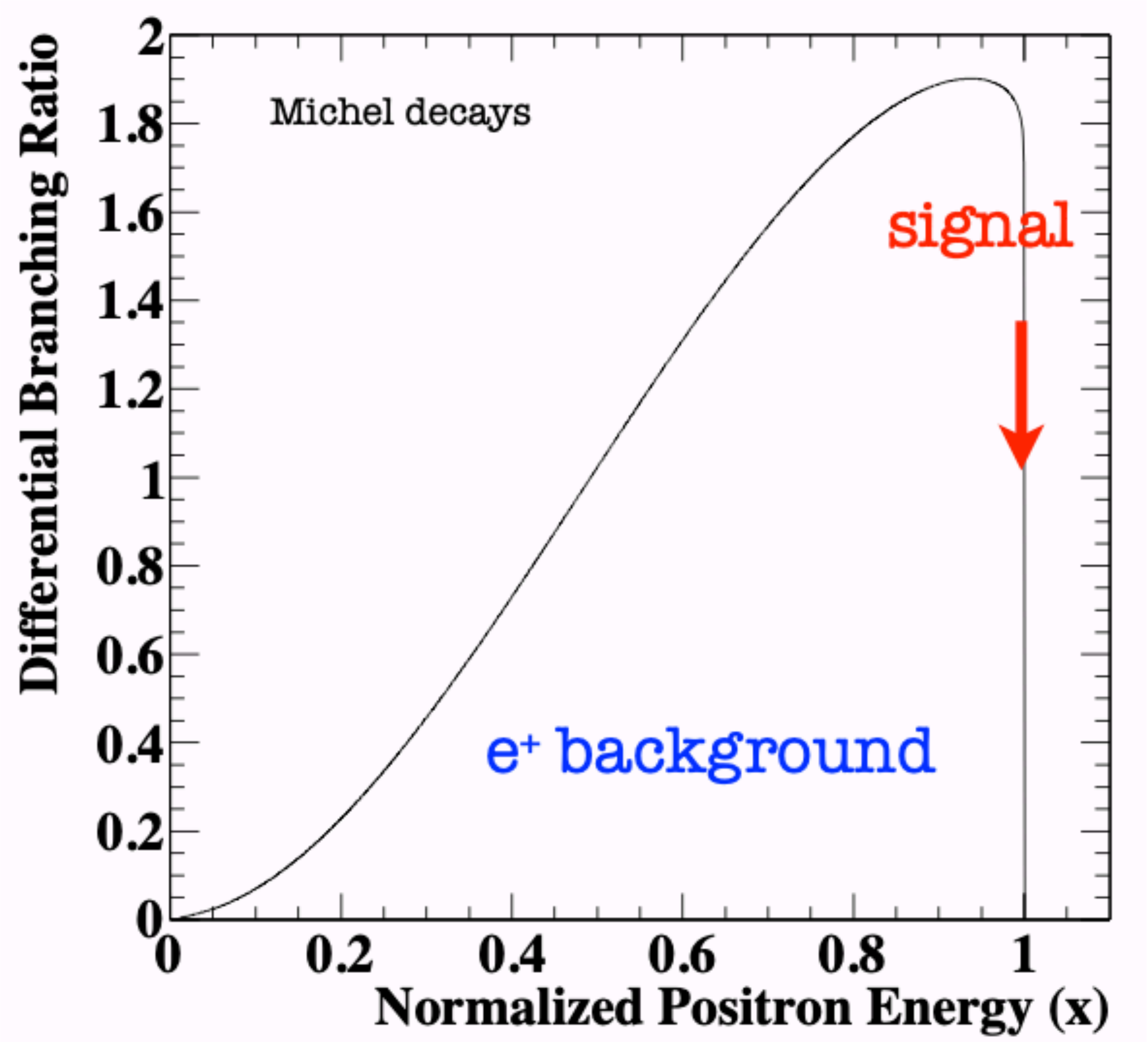
$E_\gamma, E_e \simeq 52.8$MeV

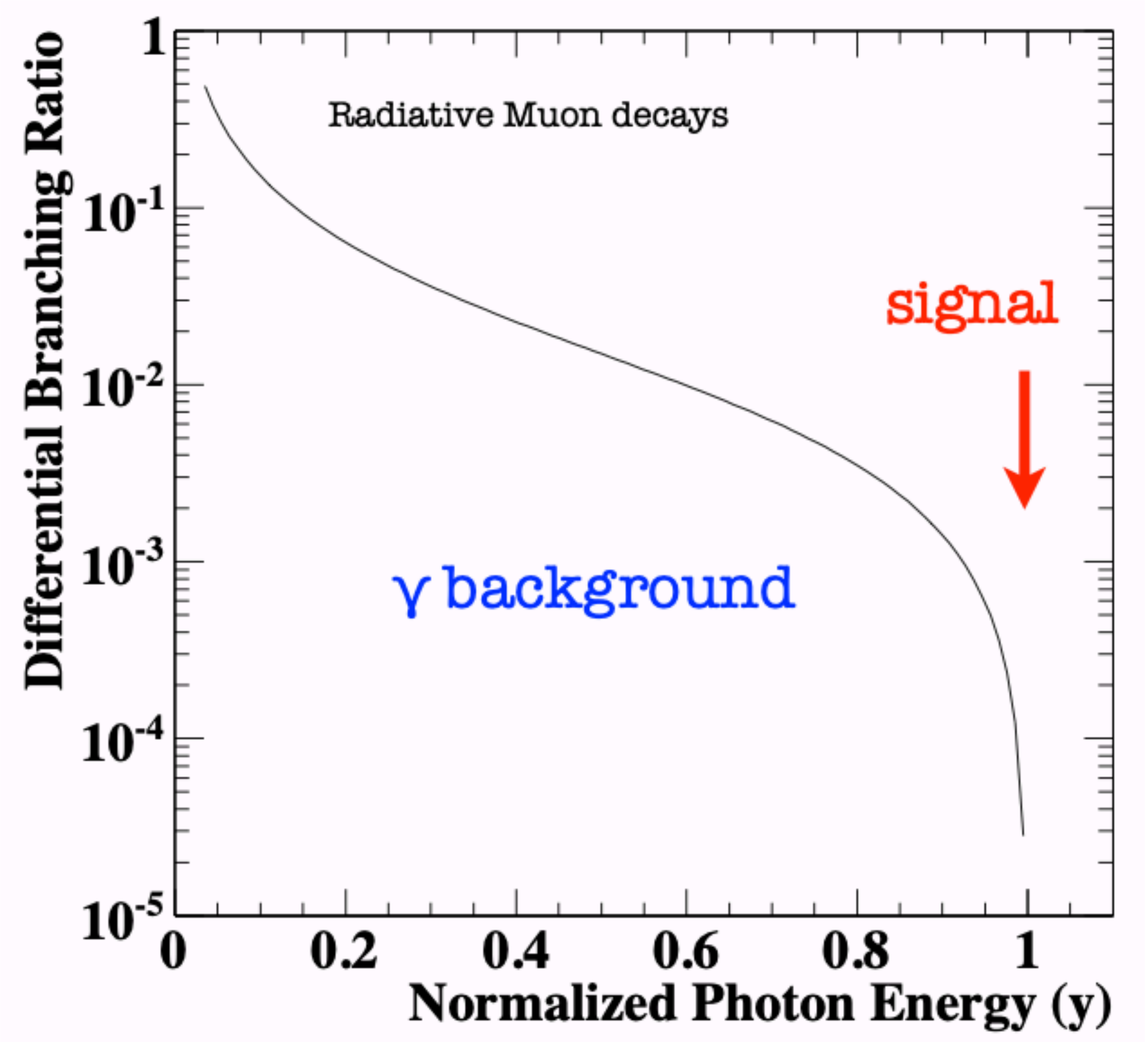
$\Theta_{e\gamma}=180^\circ$, $T_\gamma=T_e$





Dominant





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

Beam rate

Resolutions

Elapsed time

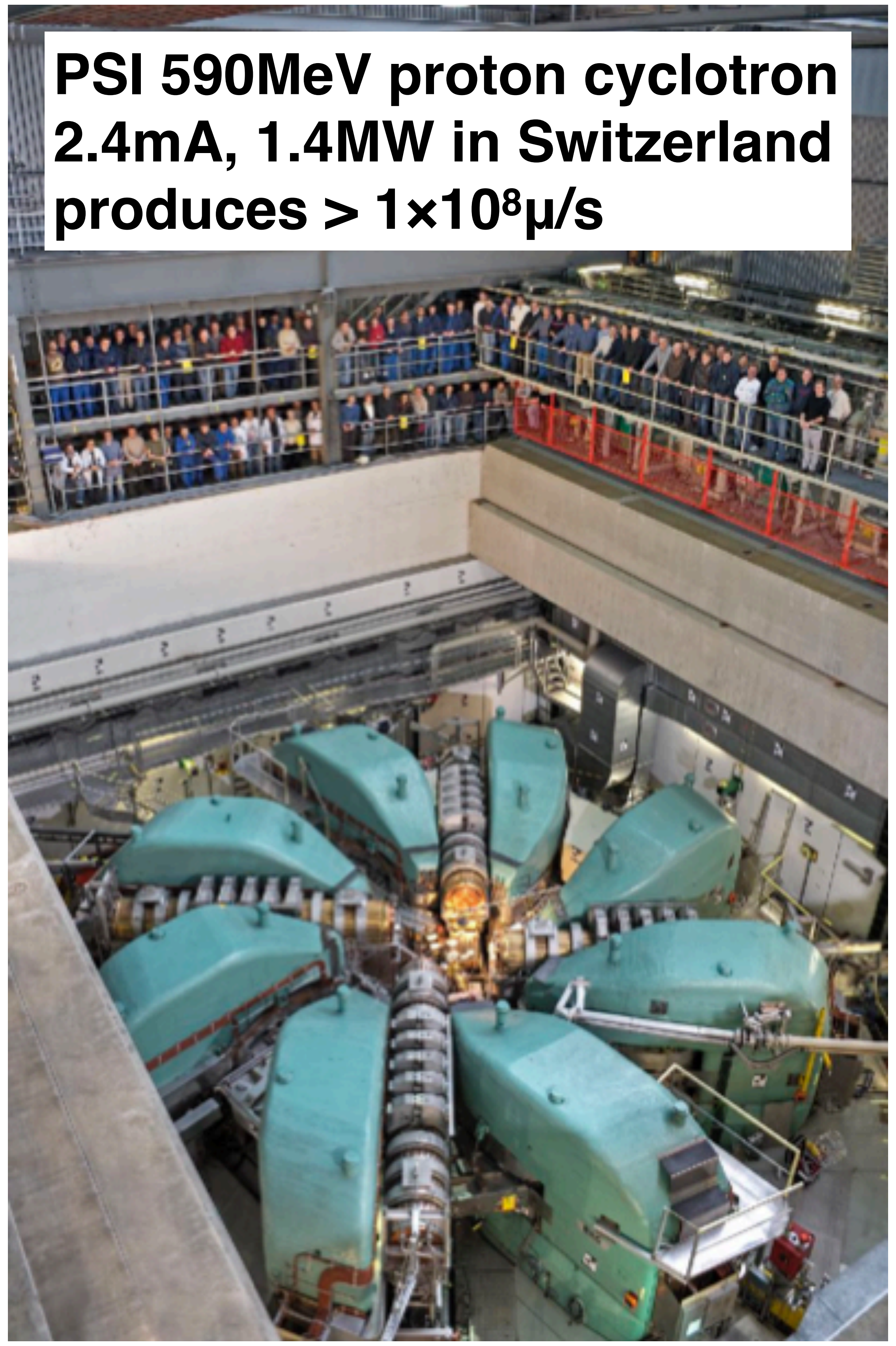
Good resolution crucial to lower the accidental background (N_{BG})

MEG II experiment

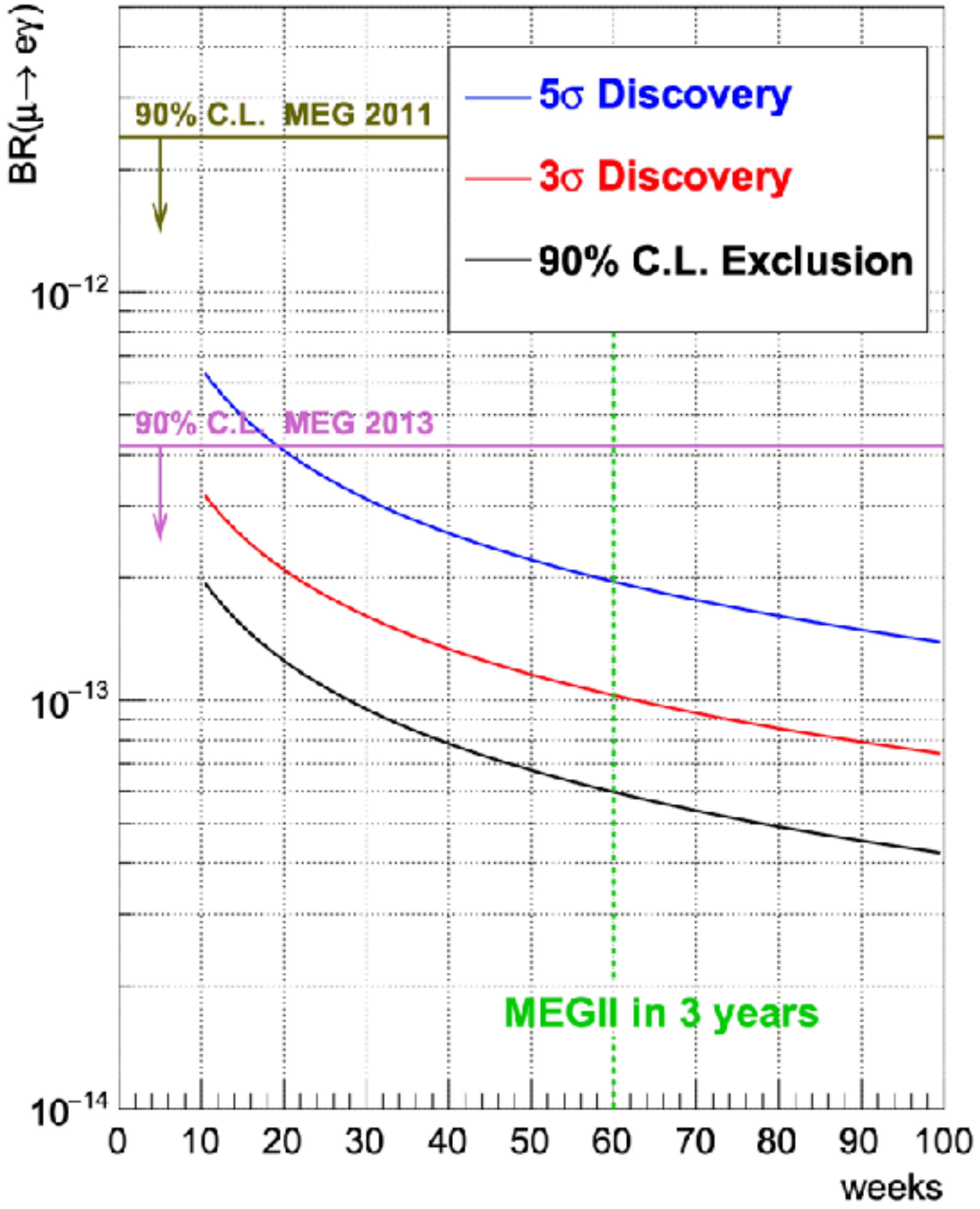
- MEG II experiment
  - Lepton flavor violating μ→eγ search
  - Intensity frontier experiment
  - Upgrade from MEG experiment

- MEG final result (2016)
  - Br(μ→eγ) < 4.2×10^{-13} @ 90%CL
(5.3×10^{-13} Sensitivity)

- MEG → MEG II upgrade concept
  - Intense muon beam
    - Up to 7×10^{7} μ^{+}/s stopping at target at PSI
  - Twice better resolutions for all detectors
  - Twice better detection efficiency

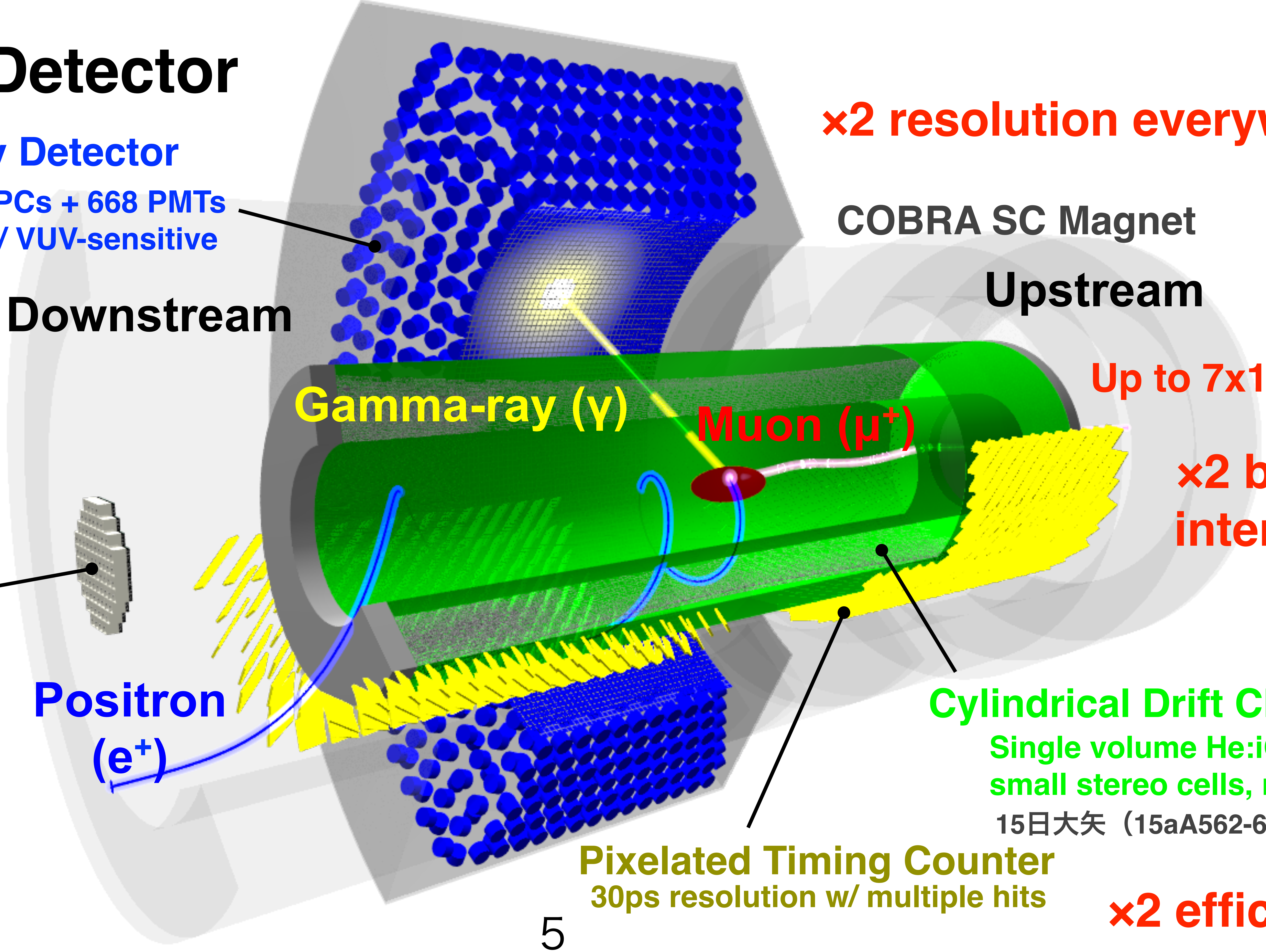


PSI 590MeV proton cyclotron
2.4mA, 1.4MW in Switzerland
produces > $1\times10^{8}\mu$/s



Search for Br(μ→eγ) ~ 6×10^{-14} (90% CL) in 3 year physics run

MEG II Detector



Liquid Xenon γ Detector

900L LXe, 4092 MPPCs + 668 PMTs
Better uniformity w/ VUV-sensitive
12x12mm^2 SiPM

15日小林(15aA562-5
連続講演)
16日松下(16aA573-9)
16日恩田(16pA573-2)
17日潘(17aA572-8)
17日吉田(17aA572-10)

Radiative Decay Counter

Further reduction
of radiative BG

15日高橋(15aA573-8)
山本(15aA573-9)

×2 resolution everywhere

Up to 7x10^7/s

×2 beam intensity

Cylindrical Drift Chamber

Single volume He:iC$_4$H$_{10}$
small stereo cells, more hits

15日大矢（15aA562-6 連続講演）

Pixelated Timing Counter

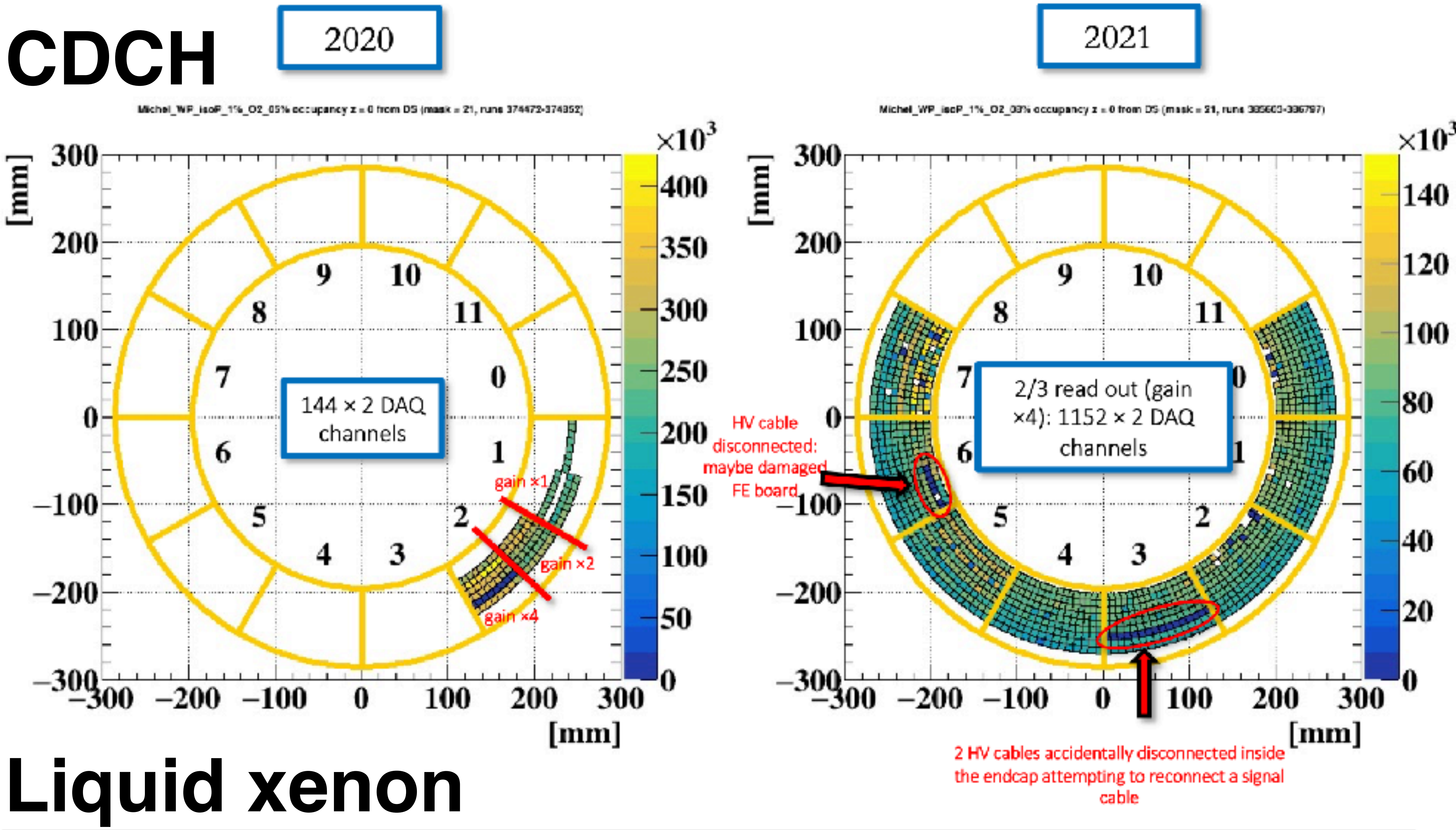
30ps resolution w/ multiple hits

×2 efficiency

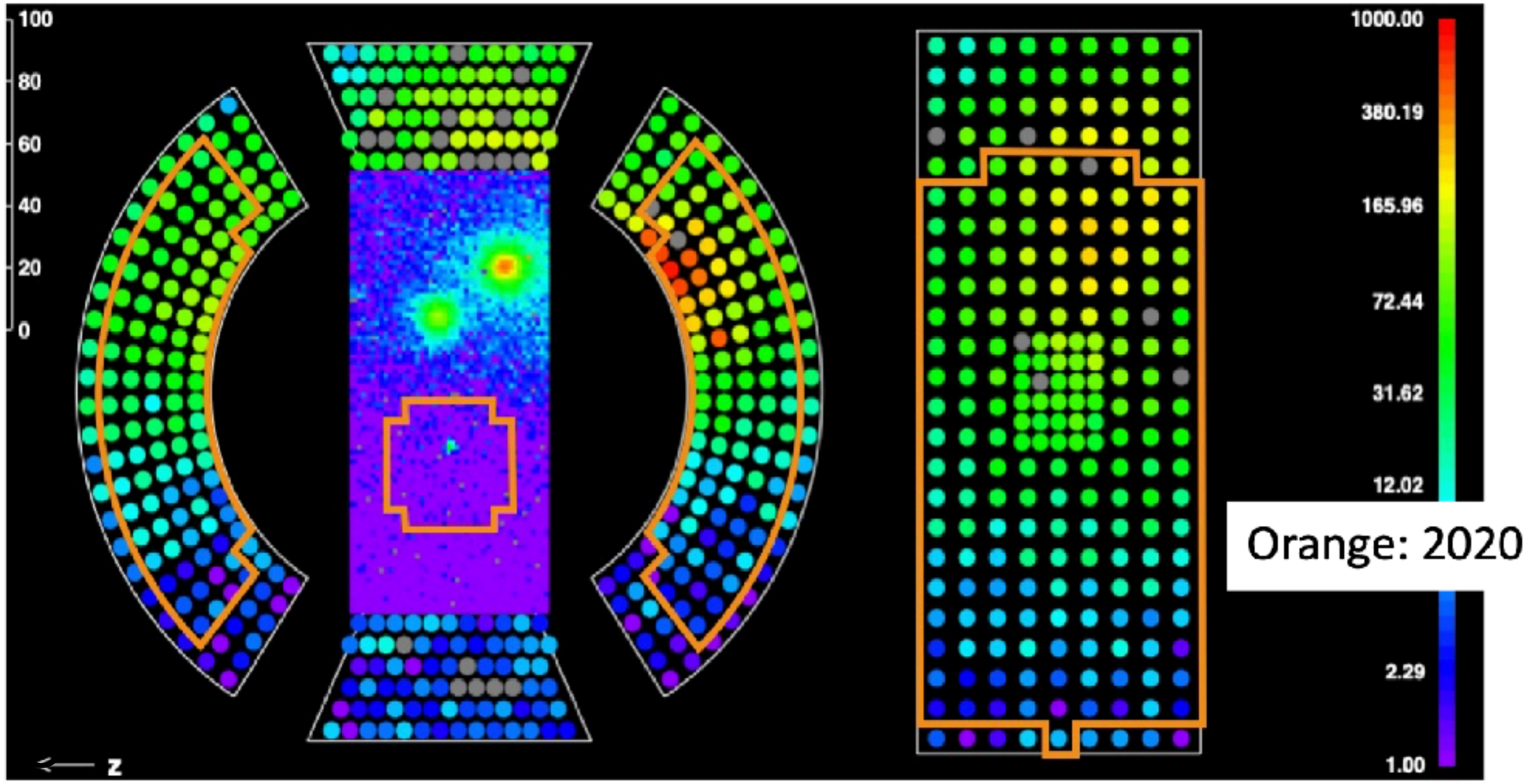
What’s new in 2021?

- All electronics channels provided for all the sub-detectors
    - Mass production, and the delivery finished in **March 2021**
- Sub-detector preparation (**May—July**)
    - Liquid xenon detector / Drift chamber /Timing counter / DS RDC : full channel readout, calibration, performance study
    - US RDC: R&D with RPC
- Trigger setup (**Aug—Sep**)
    - Self, time coincidence (12.5 ns window), direction match → muegamma trigger ready on **25th September**
- Physics run (**25/Sep — 22/Nov**)
    - TDAQ rate improvement by online data reduction (~20 to 5 MB/s)
    - Different beam intensity (3→4→5×10^{7}μ/s)
- CEX run (**Dec**)
    - Energy scale and performance study near signal region with pion beam with Liquid H_2

CDCH

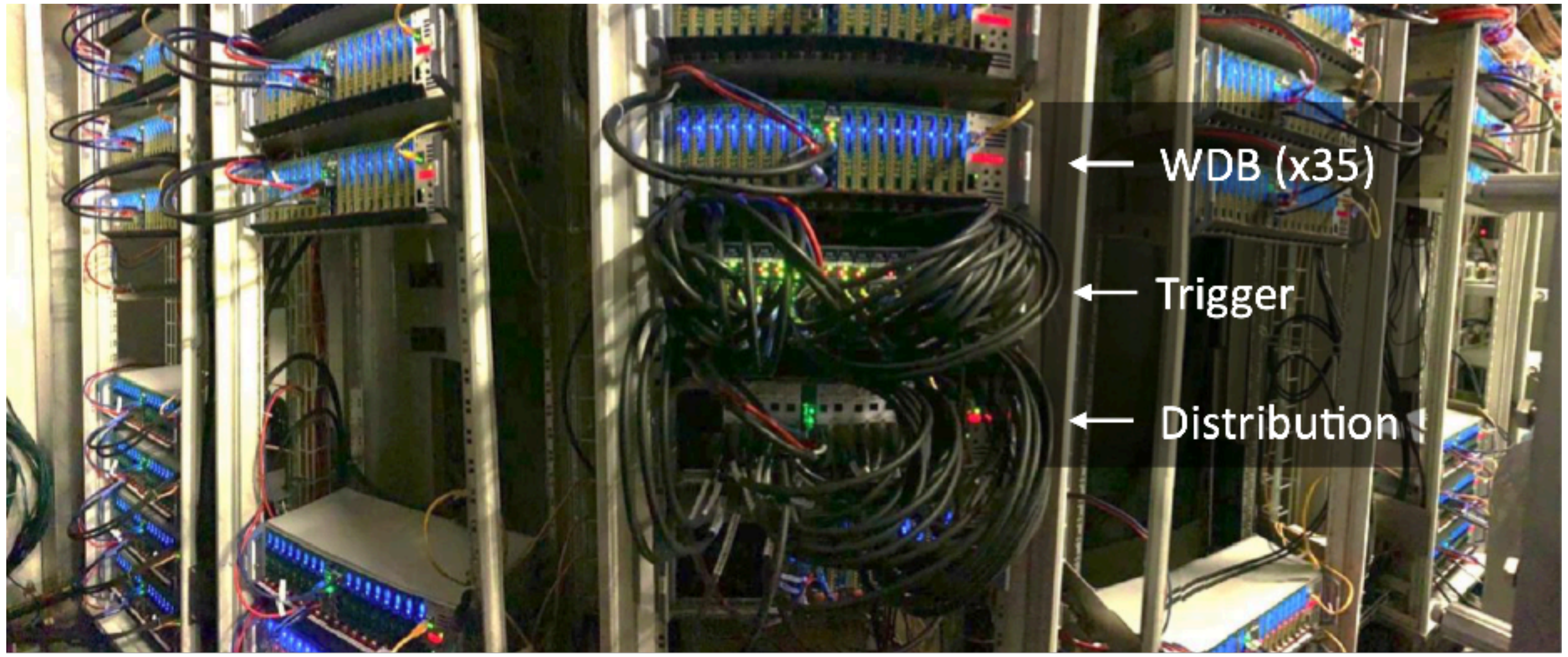


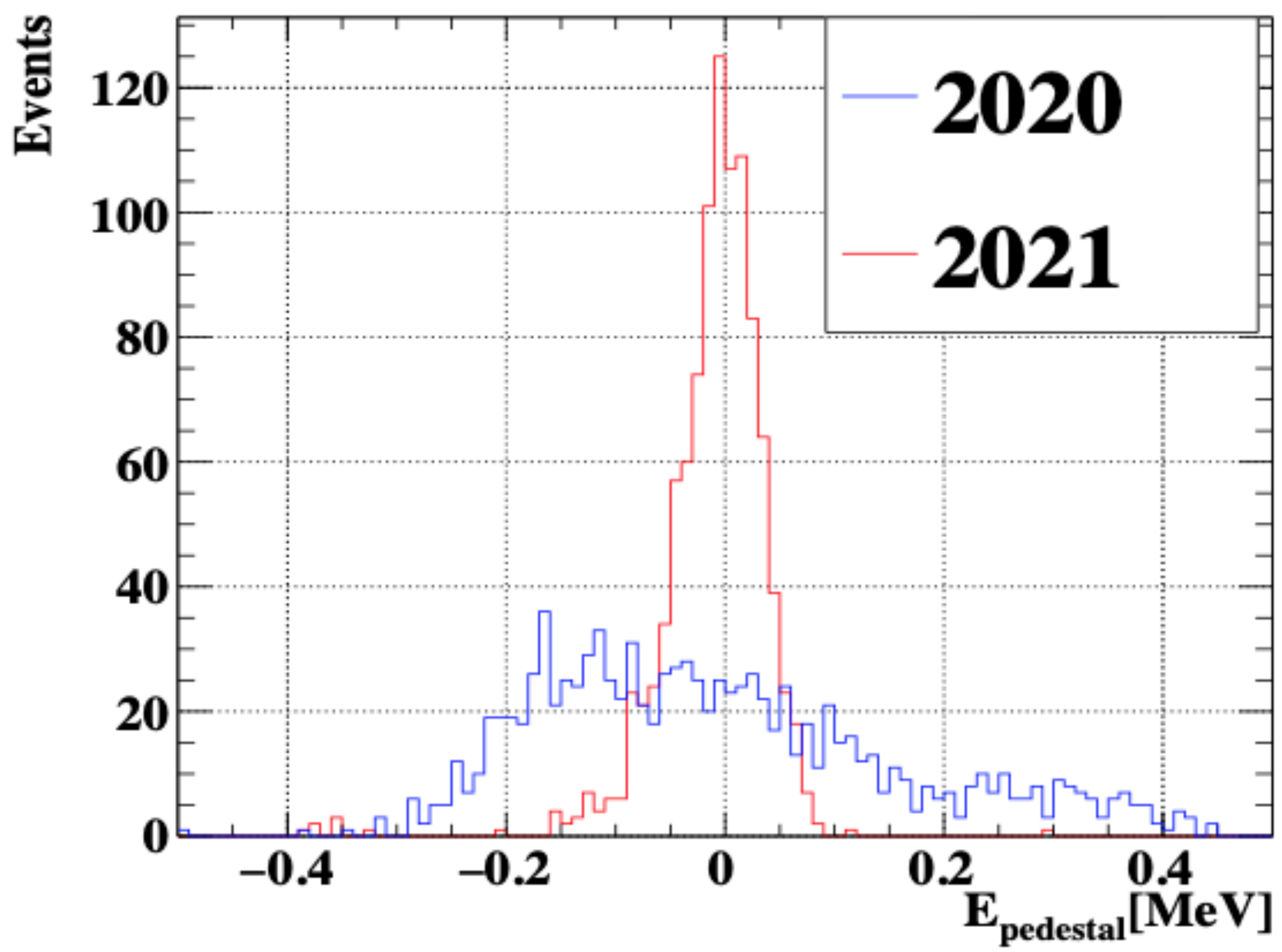
Liquid xenon



Full electronics preparation

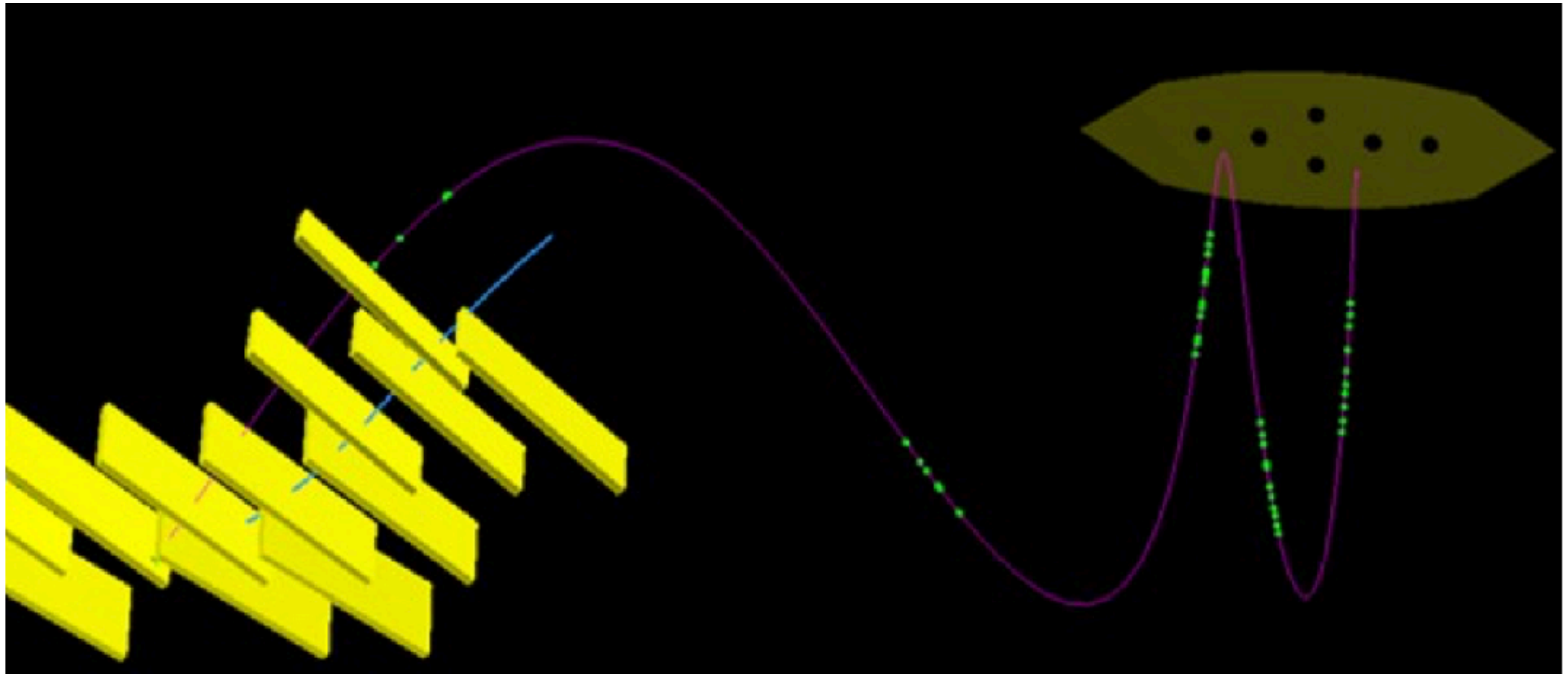
- WaveDREAM
  - Waveform digitizer for all the detectors ~ 9000 channels
- Hardware improvement
  - WaveDREAM final board (choke coil added)
  - Replacement of DC-DC converter, noise shield for crate controller, shielded network cables
  - Noise contribution to the energy resolution in LXe
    - Negligible: 0.1% at 52.8MeV
- Trigger logic
  - $E_\gamma > 40—45$ MeV
  - $|T_{e\gamma}| < 12.5$ ns
  - Direction match condition : e-γ hit positions correlation



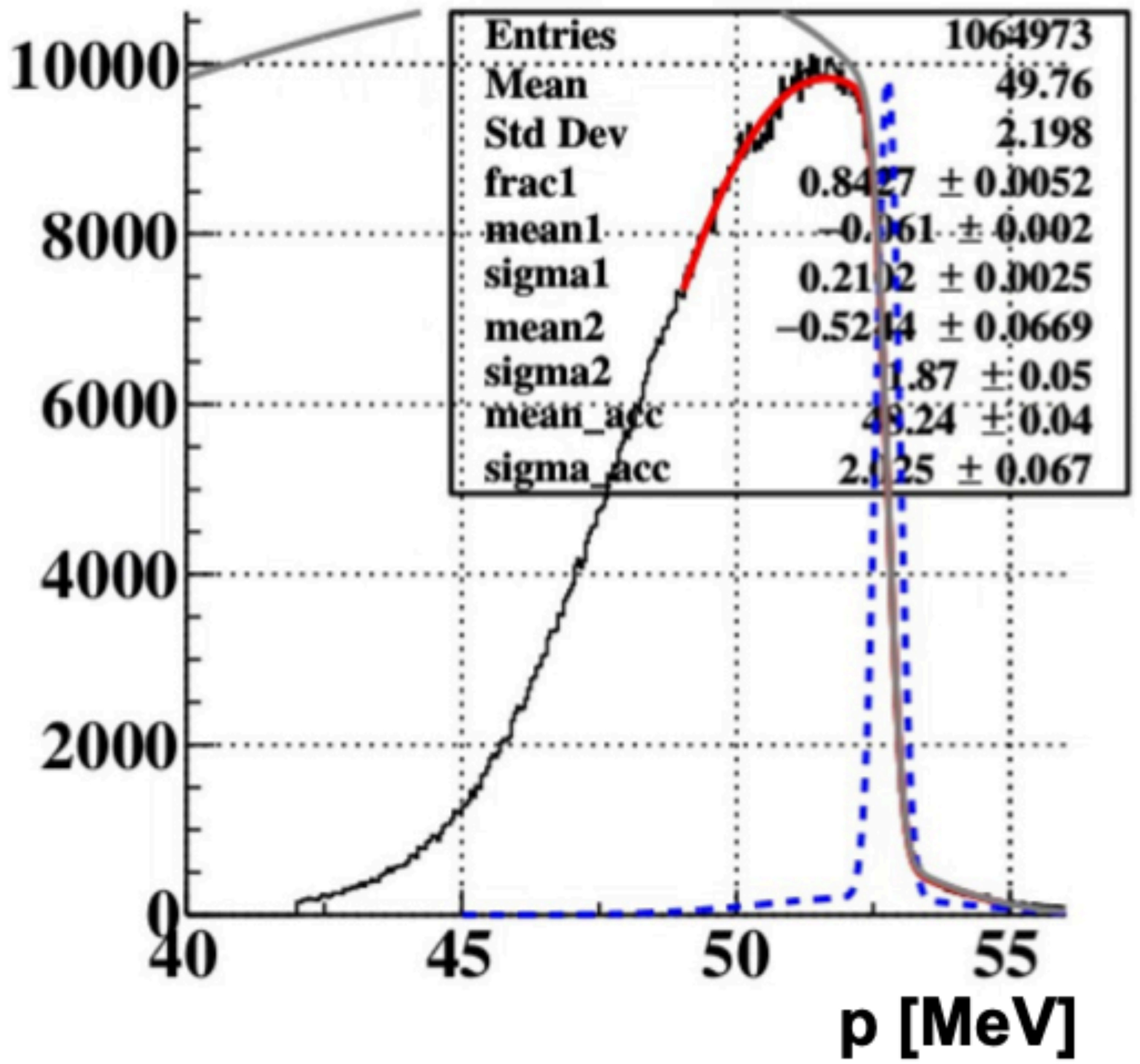

$E_{pedestal}$ distribution

CDCH operation

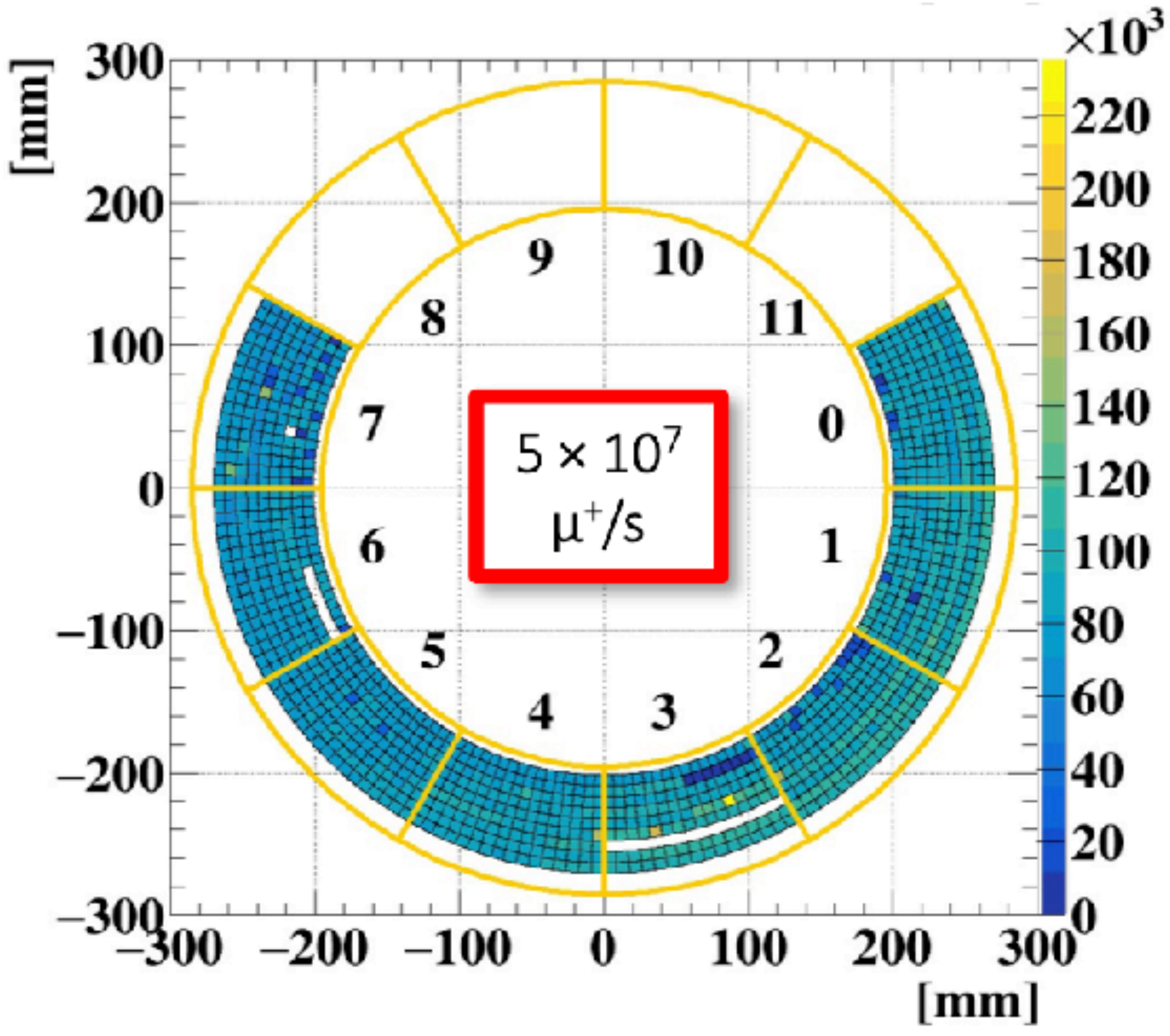
- Run 2021 conditions
  - Stable operation up to $5\times10^7\mu/s$
  - No broken wire
  - Detailed study for resolutions, efficiency possible with full channel readout for the first time
- Prospects
  - No re-opening CDCH
  - Bad channel investigation in the external volume
- Preparation of CDCH2
  - Better efficiency, stable operation
  - Thicker cathode wires: 50μm Al(Ag)
  - Delivery at PSI in time for 2023 run



e^+ momentum distribution

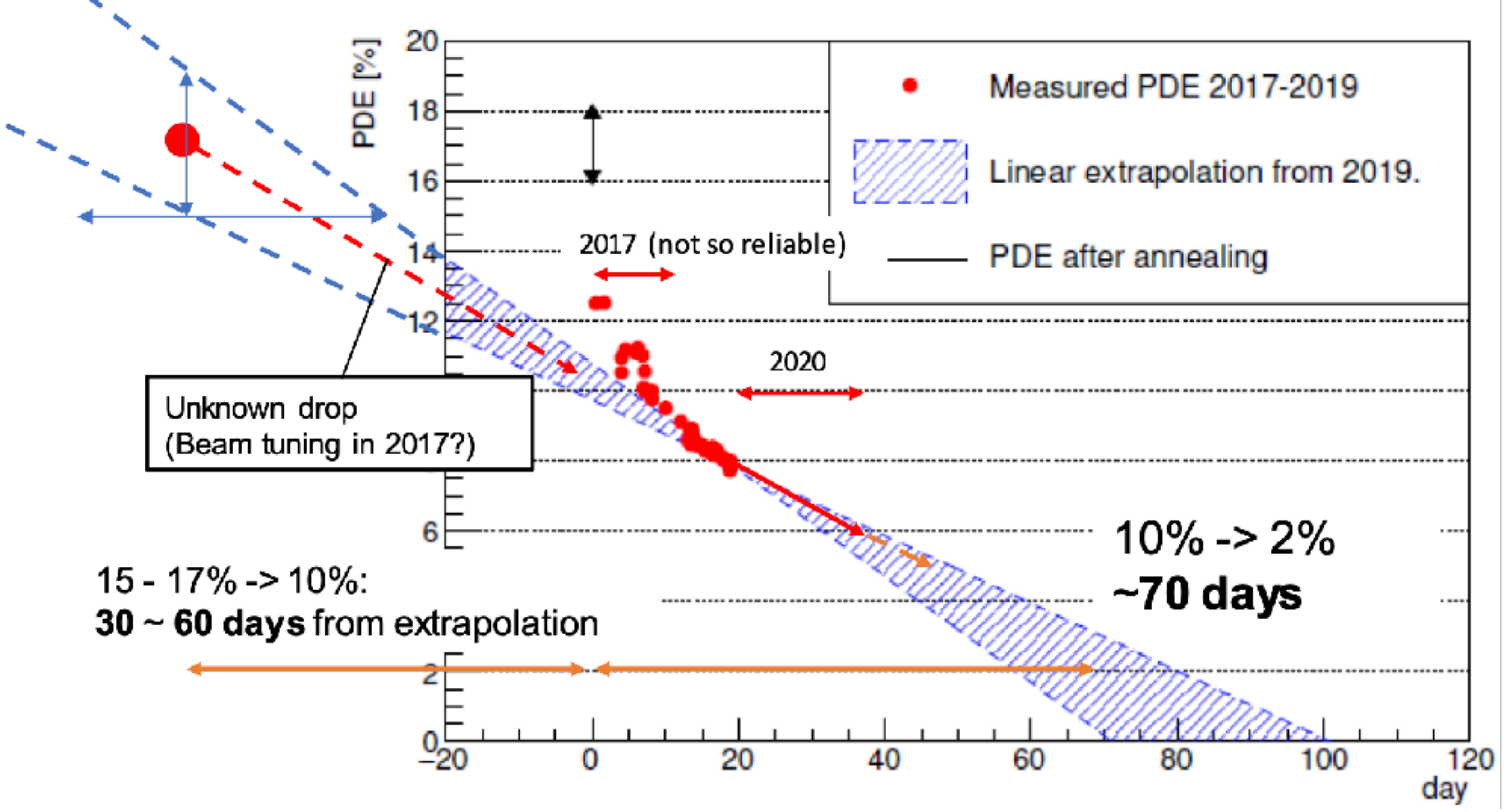


e^+ hit map



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

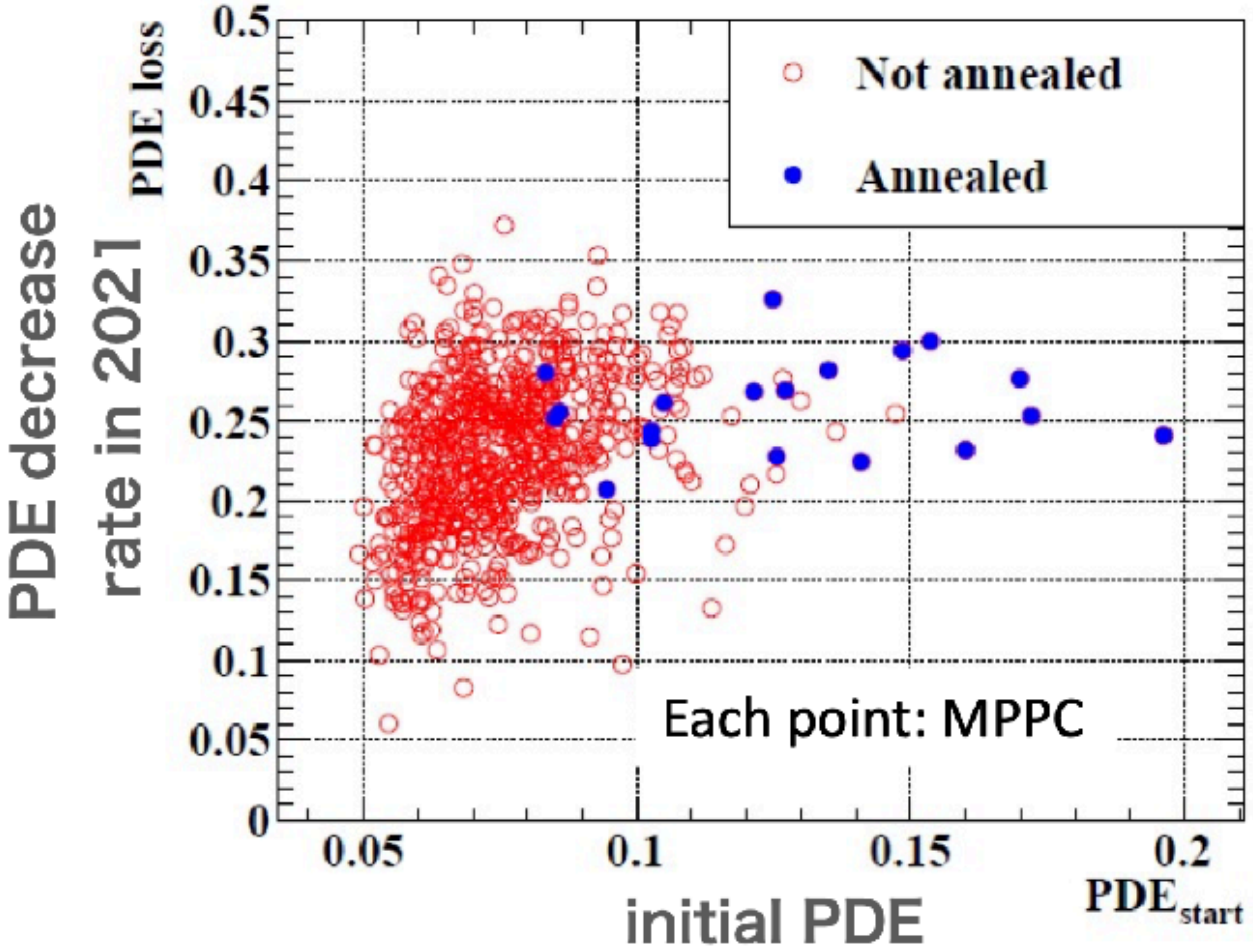


Unknown drop (Beam tuning in 2017?)

15 - 17% -> 10%:
30 ~ 60 days from extrapolation

10% -> 2%
~70 days

PDE loss in 2021 vs PDE$_{start}$



PDE decrease rate in 2021

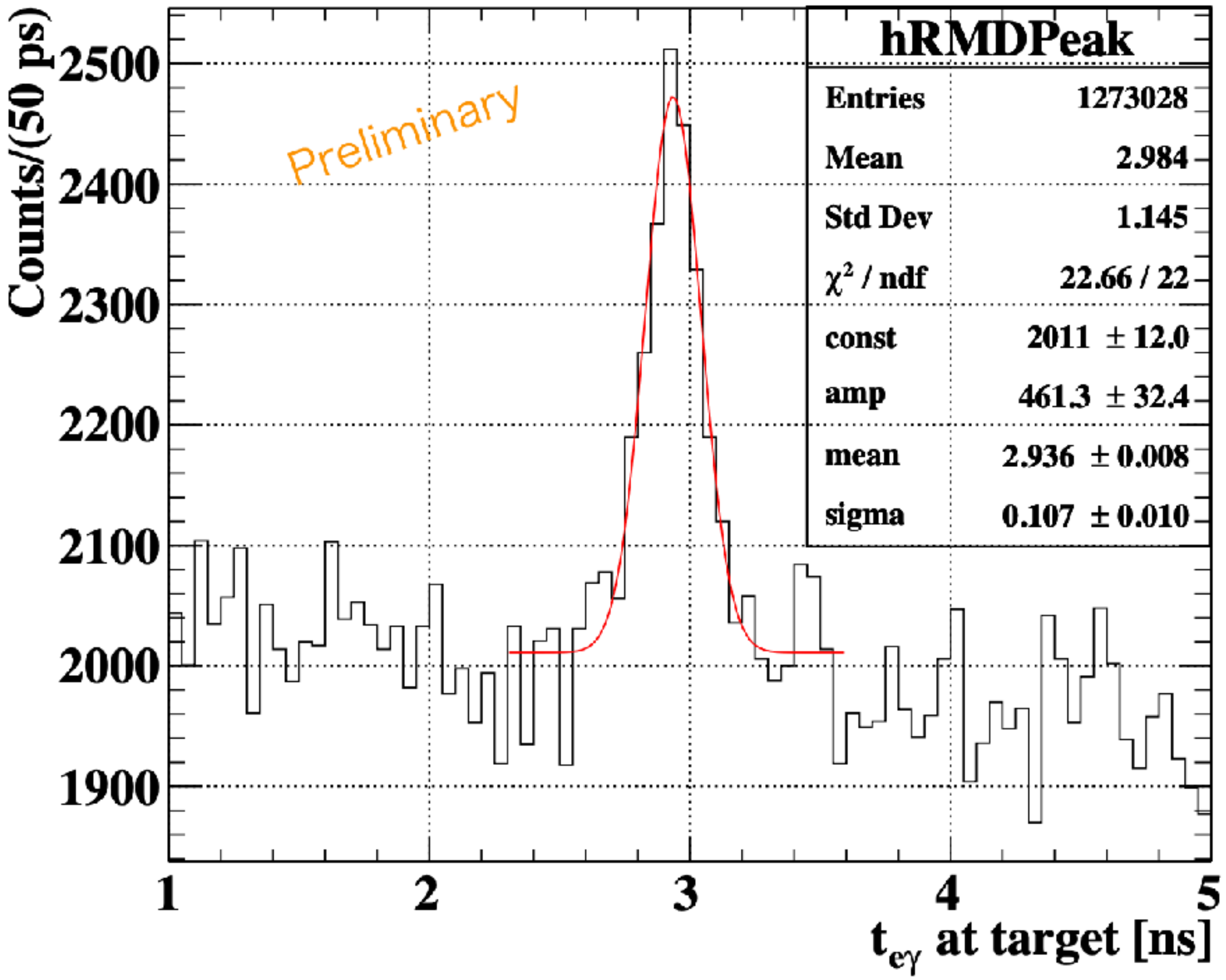
initial PDE

Each point: MPPC

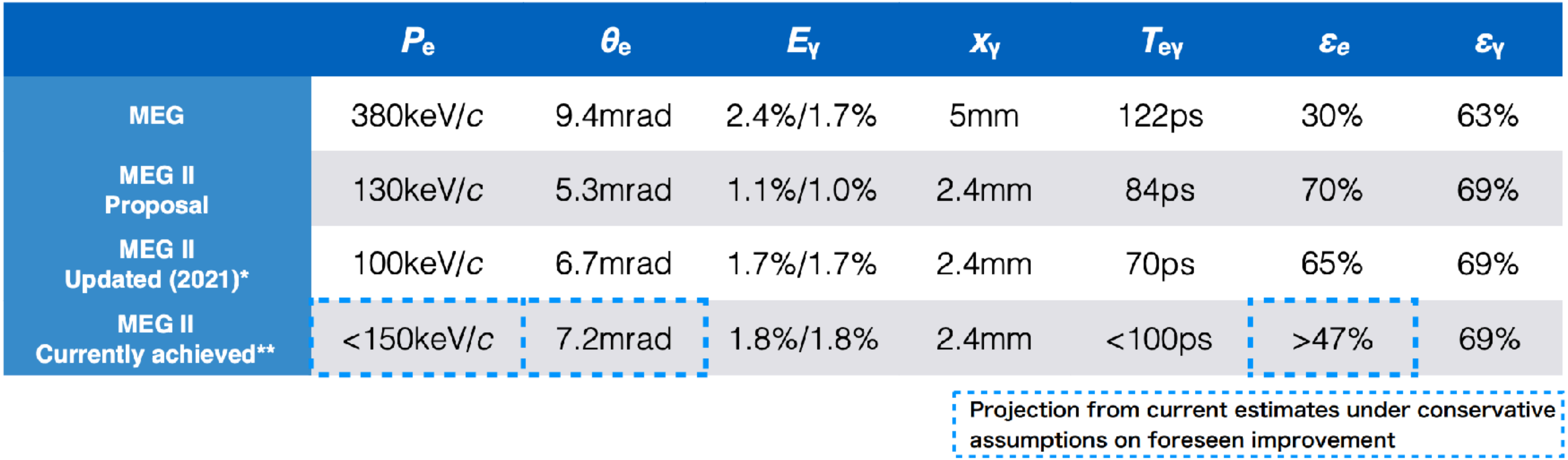
RMD event detection

- Dataset
  - Physics run: Oct. 28 — Nov. 17, 2021
  - Beam intensity: (3—5)×10^7μ/s
  - μ→eγ trigger
- Analysis
  - Event selection
    - Invariant mass, positron track quality, positron propagation, etc.
- Observed clear RMD peak
  - $T_{e\gamma}$ resolution : ~100 ps (preliminary)
  - Still to be improved (LXe photosensor calibration, other systematics, etc.)
  - Already better than MEG (122 ps)

μ→eννγ event



Detector performance summary



	P_e	θ_e	E_γ	x_γ	$T_{e\gamma}$	ε_e	ε_γ
MEG	380keV/*c*	9.4mrad	2.4%/1.7%	5mm	122ps	30%	63%
MEG II Proposal	130keV/*c*	5.3mrad	1.1%/1.0%	2.4mm	84ps	70%	69%
MEG II Updated (2021)*	100keV/*c*	6.7mrad	1.7%/1.7%	2.4mm	70ps	65%	69%
MEG II Currently achieved**	<150keV/*c*	7.2mrad	1.8%/1.8%	2.4mm	<100ps	>47%	69%

Projection from current estimates under conservative assumptions on foreseen improvement

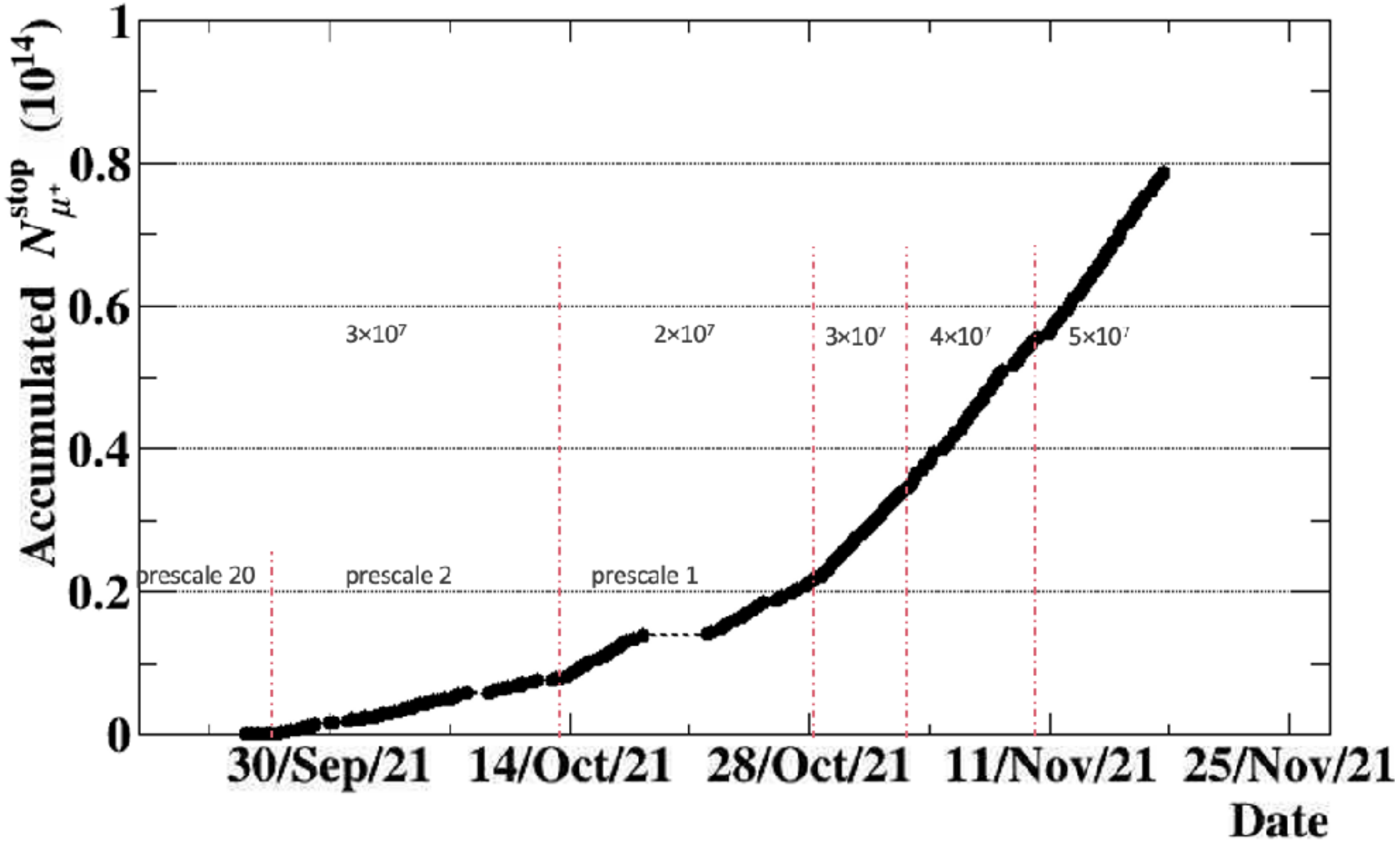
* : Symmetry 2021, 13(9), 1591

** : Beam rate = 5×10^7 μ/s

- The numbers are still preliminary, and more improvements are foreseen.

Physics run in 2021

- Physics run
    - Sep. 25 — Nov. 17, 2021 (53.6 days)
    - DAQ live time : 33.8 days
- Sensitivity estimate
    - N_{μ} estimated from delivered proton current converted to normalization factor
        - N_{sig} / BR ~ 1/SES
    - Assuming efficiencies with uncertainties
    - Normalization factor will be estimated later with Michel positron counting
- Expected sensitivity with data 2021
    - $(5.3—6.1)\times10^{-13}$
    - Already comparable with MEG sensitivity



Physics run in 2022

- Beam time allocation
  - 24 weeks from June 6
  - The last 3 weeks are suspended (MEGII/Mu3e)
- Schedule
  - One month detector preparation & beam tuning
  - Physics run from Mid. July until October
  - CEX run in November
  - One week for Upstream RDC (RPC) beam test

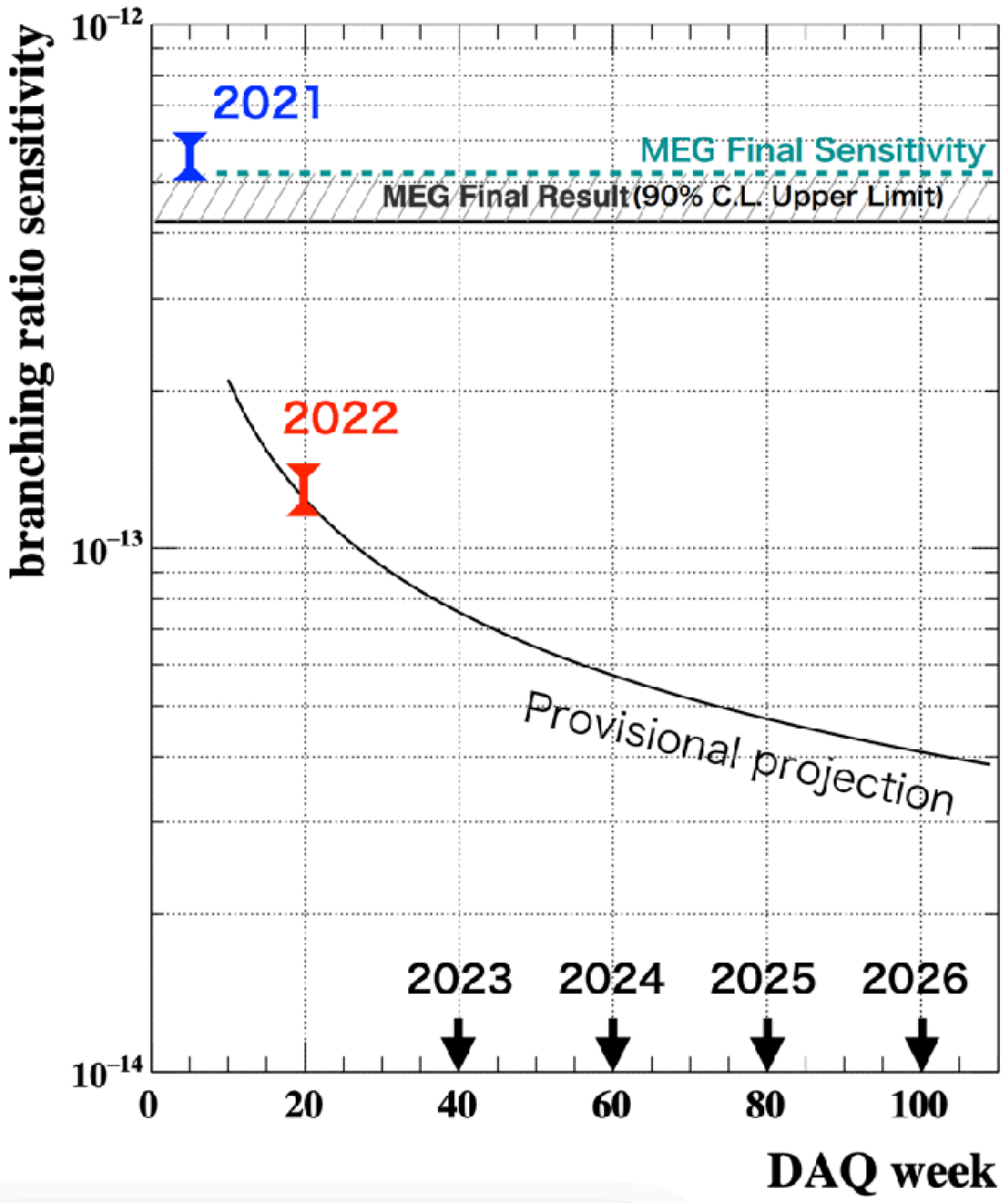
- Stable & long physics data taking to go beyond MEG
  - Still expected to be statistics-dominant
  - Successful LXe MPPC annealing extremely crucial
- Assumption
  - DAQ time for physics run : 100 days
  - Beam rate: 5×10^7 μ/s (still to be decided)
    → $N_\mu = 4.9\times10^{14}$

Beam Schedule 2022

https://www.psi.ch/de/sbl/schedules		<stefan.ritt@psi.ch>	Month	April				May				June				July					August				September					October				November				December			
Last update:	1/28/2022 9:16:54		Week number	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
			Availability	🟥	🟥	🟥	🟥	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩🟥	🟥🟩	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩🟥
			Days	0	0	0	0	7	7	3	7	6	7	3	7	6	7	3	7	6	4	4	7	7	6	7	3	7	7	6	7	3	7	7	6	7	3	7	7	6	4
			Start (Monday)	Apr/4/22	Apr/11/22	Apr/18/22	Apr/25/22	May/2/22	May/9/22	May/16/22	May/23/22	May/30/22	Jun/6/22	Jun/13/22	Jun/20/22	Jun/27/22	Jul/4/22	Jul/11/22	Jul/18/22	Jul/25/22	Aug/1/22	Aug/8/22	Aug/15/22	Aug/22/22	Aug/29/22	Sep/5/22	Sep/12/22	Sep/19/22	Sep/26/22	Oct/3/22	Oct/10/22	Oct/17/22	Oct/24/22	Oct/31/22	Nov/7/22	Nov/14/22	Nov/21/22	Nov/28/22	Dec/5/22	Dec/12/22	Dec/19/22
Area	Experiment	PSI Contact	End (Sunday)	Apr/10/22	Apr/17/22	Apr/24/22	May/1/22	May/8/22	May/15/22	May/22/22	May/29/22	Jun/5/22	Jun/12/22	Jun/19/22	Jun/26/22	Jul/3/22	Jul/10/22	Jul/17/22	Jul/24/22	Jul/31/22	Aug/7/22	Aug/14/22	Aug/21/22	Aug/28/22	Sep/4/22	Sep/11/22	Sep/18/22	Sep/25/22	Oct/2/22	Oct/9/22	Oct/16/22	Oct/23/22	Oct/30/22	Nov/6/22	Nov/13/22	Nov/20/22	Nov/27/22	Dec/4/22	Dec/11/22	Dec/18/22	Dec/25/22
PiE5	R-99-05.2 MEG	Papa	Mori										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨		
	R-12-03.1 Mu3E	Meier	Schoening					🟩	🟩	🟩																											▨	▨	▨	▨	
	R-16-02.1 HyperMu	Antognini	Antognini																																						
	R-22-01.1 PIONEER	Knecht	Kammel								🟩	🟩																													
	muSR Pixel	Meier	Meier																																						▨

Expected sensitivity

- Sensitivity estimate
  - Branching ratio sensitivity calculated with likelihood analysis
  - Large uncertainty in detector performance evaluation
- Expected sensitivities
  - Data 2021: (5.3–6.1)×10^{-13}
    - Already approaching MEG sensitivity (5.3×10^{-13})
  - Data 2021+2022: (1.2—1.4)×10^{-13}
    - Well beyond MEG sensitivity (5.3×10^{-13})
- Prospects
  - Further evaluation of the detector performance with data 2021/2022
    - More reliable sensitivity estimate
  - Observed detector performance is already not far from what we expected, but a lot of improvements are foreseen.



Conclusion

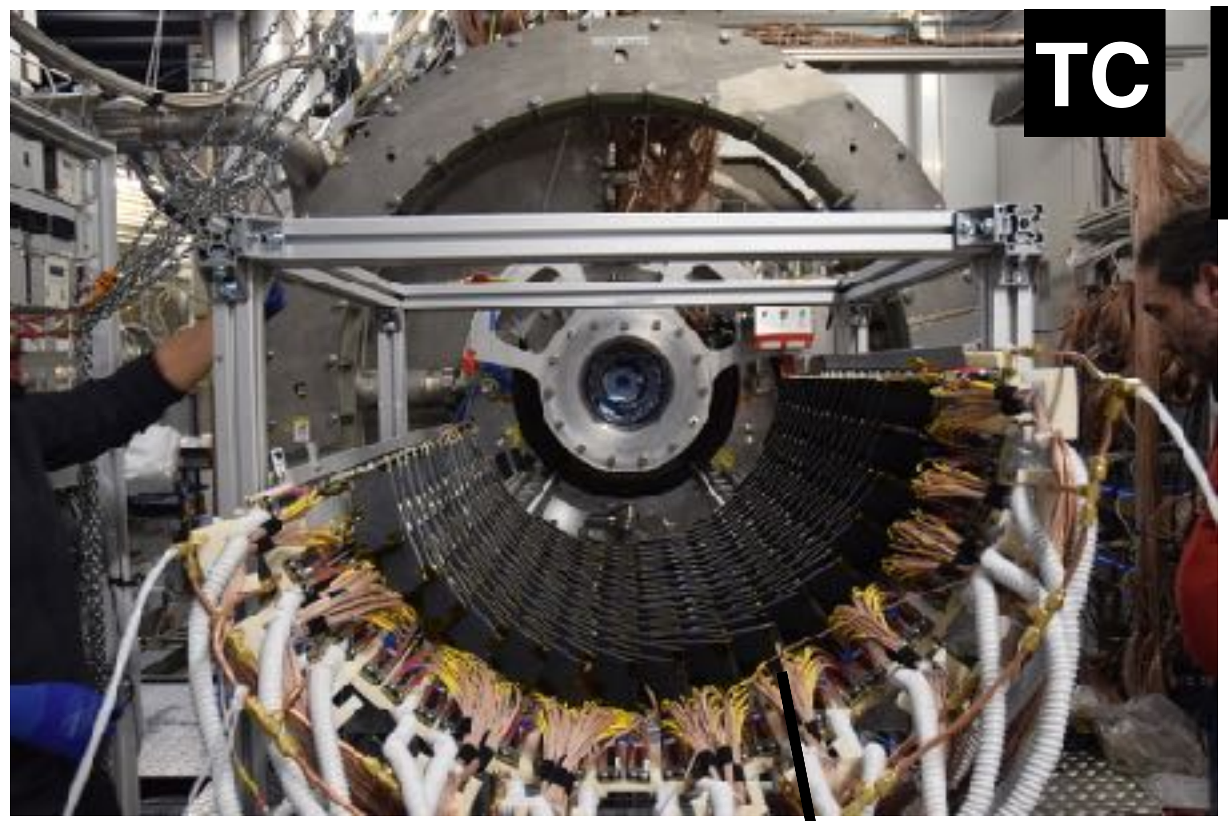
- The MEG II experiment has started physics run in 2021, and continue it in 2022.
- In order to extract the maximum sensitivity, the optimization of detector calibration methods, beam intensity, and further improvements will be expected.
- This year's sensitivity will reach well beyond the MEG experiment, and we will aim at reaching our target sensitivity (6×10^{-14}) within 3 years.

MEG II Status before 2020 run

- All detectors are constructed
- 20% of electronics readout channels are produced and tested

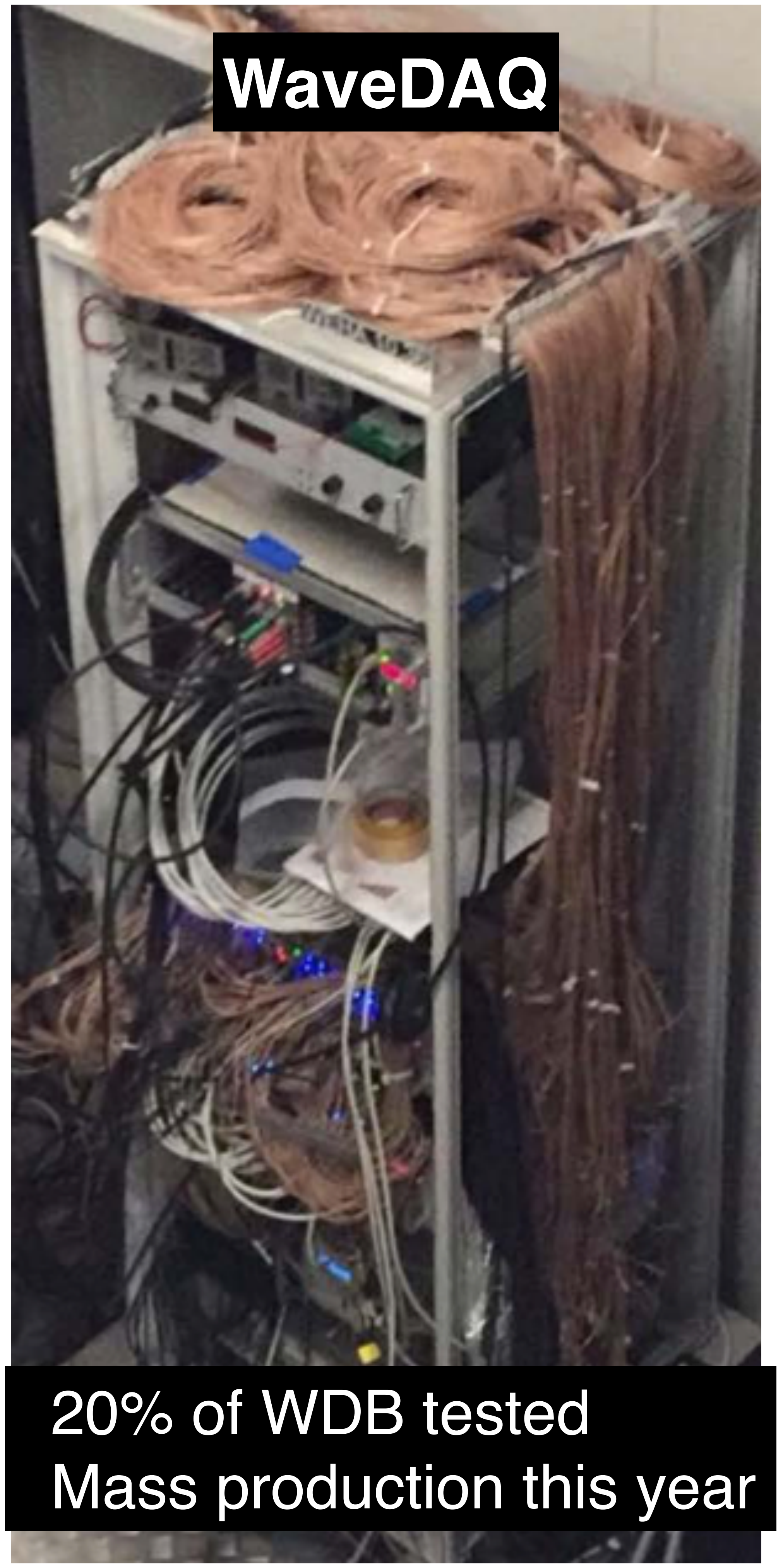
LXe

Construction finished in 2017.
Performance check ongoing.



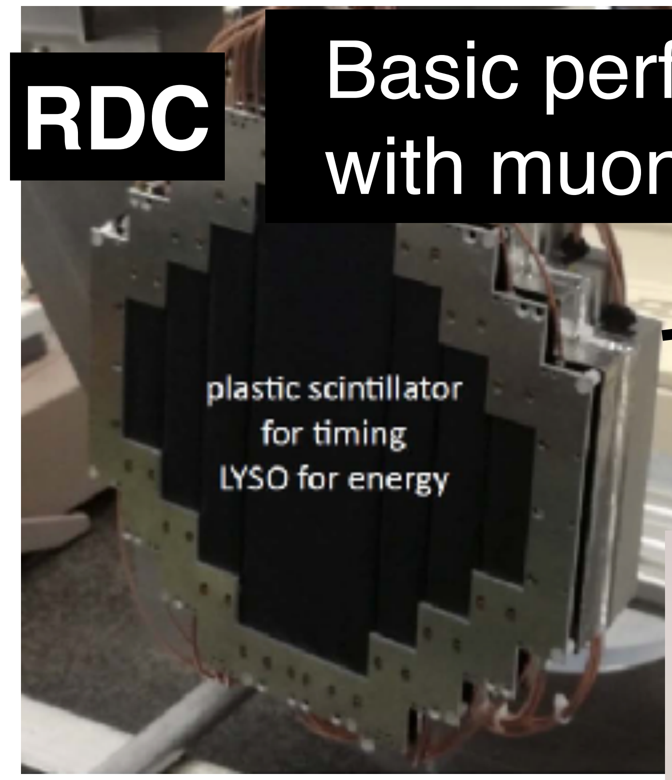
TC

Basic performance test with muon beam finished



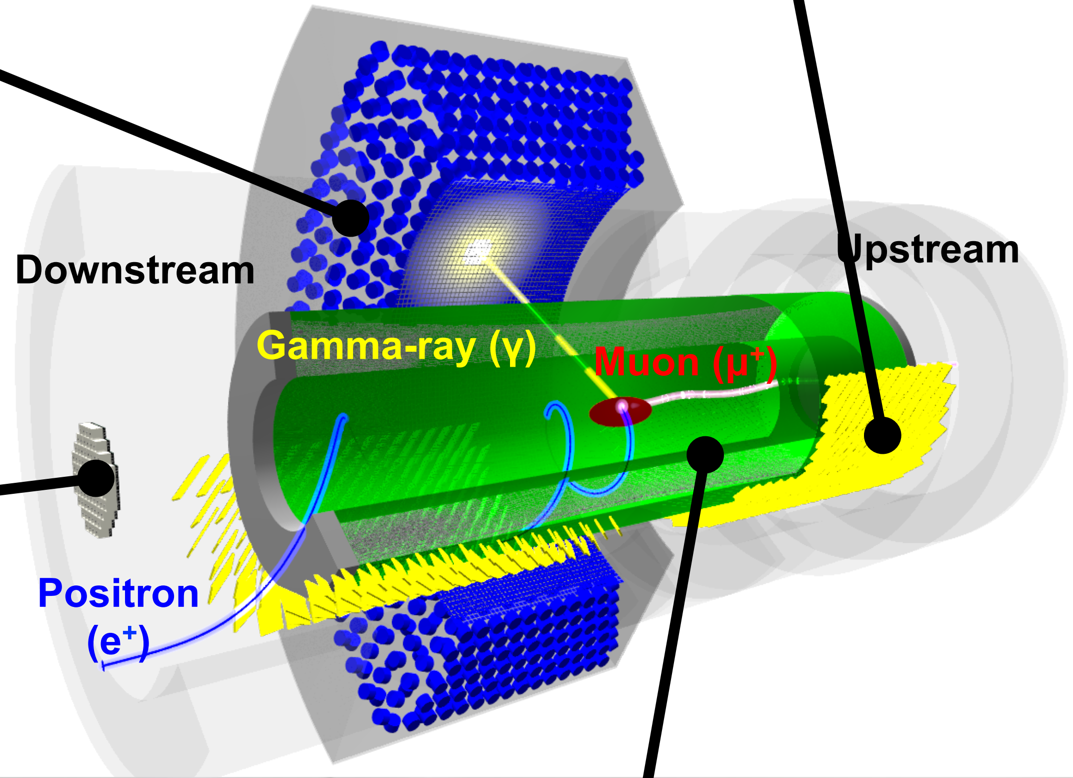
WaveDAQ

20% of WDB tested
Mass production this year



RDC

Basic performance test with muon beam finished

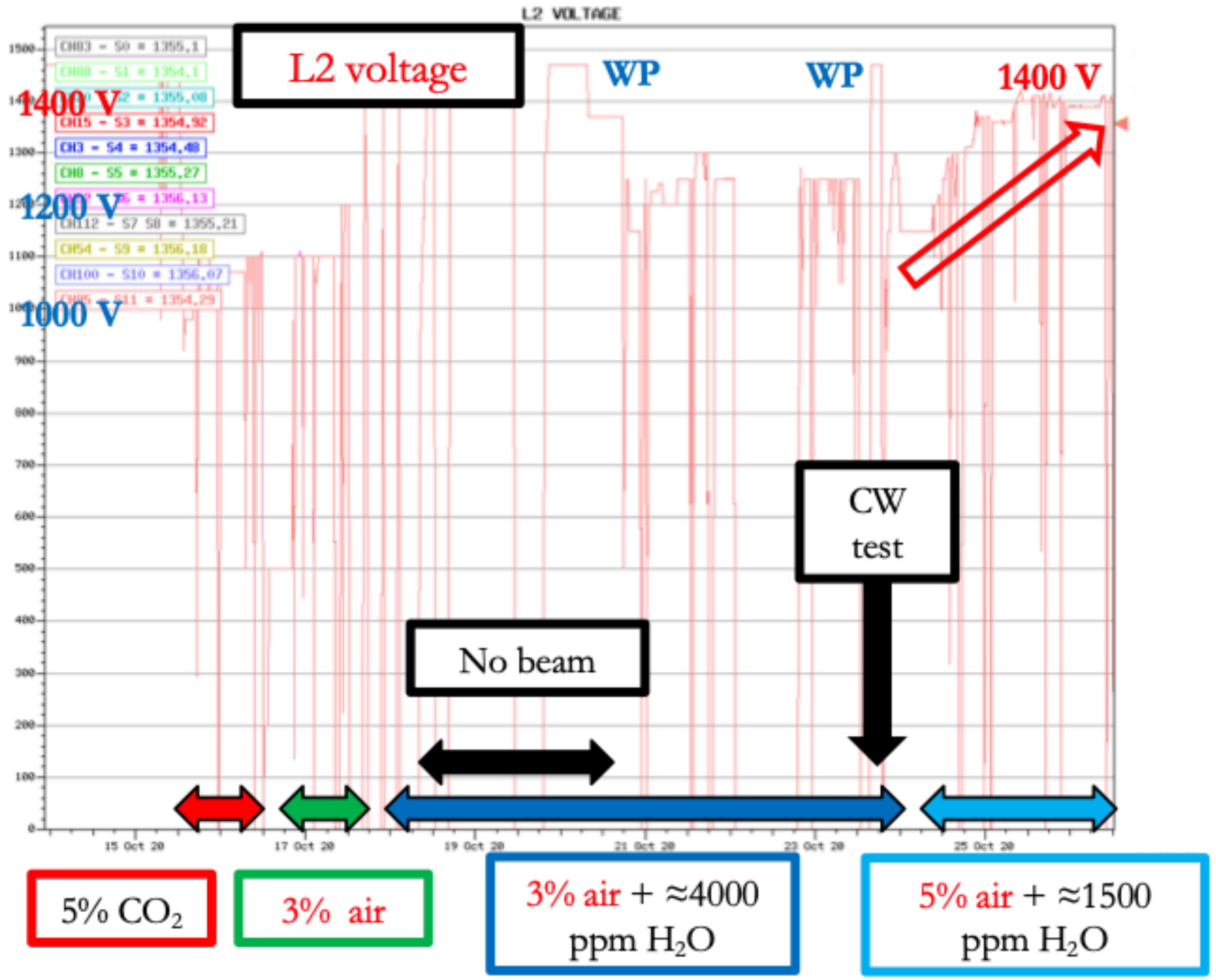


CDCH

Construction finished in 2018.
Stability check under muon beam ongoing

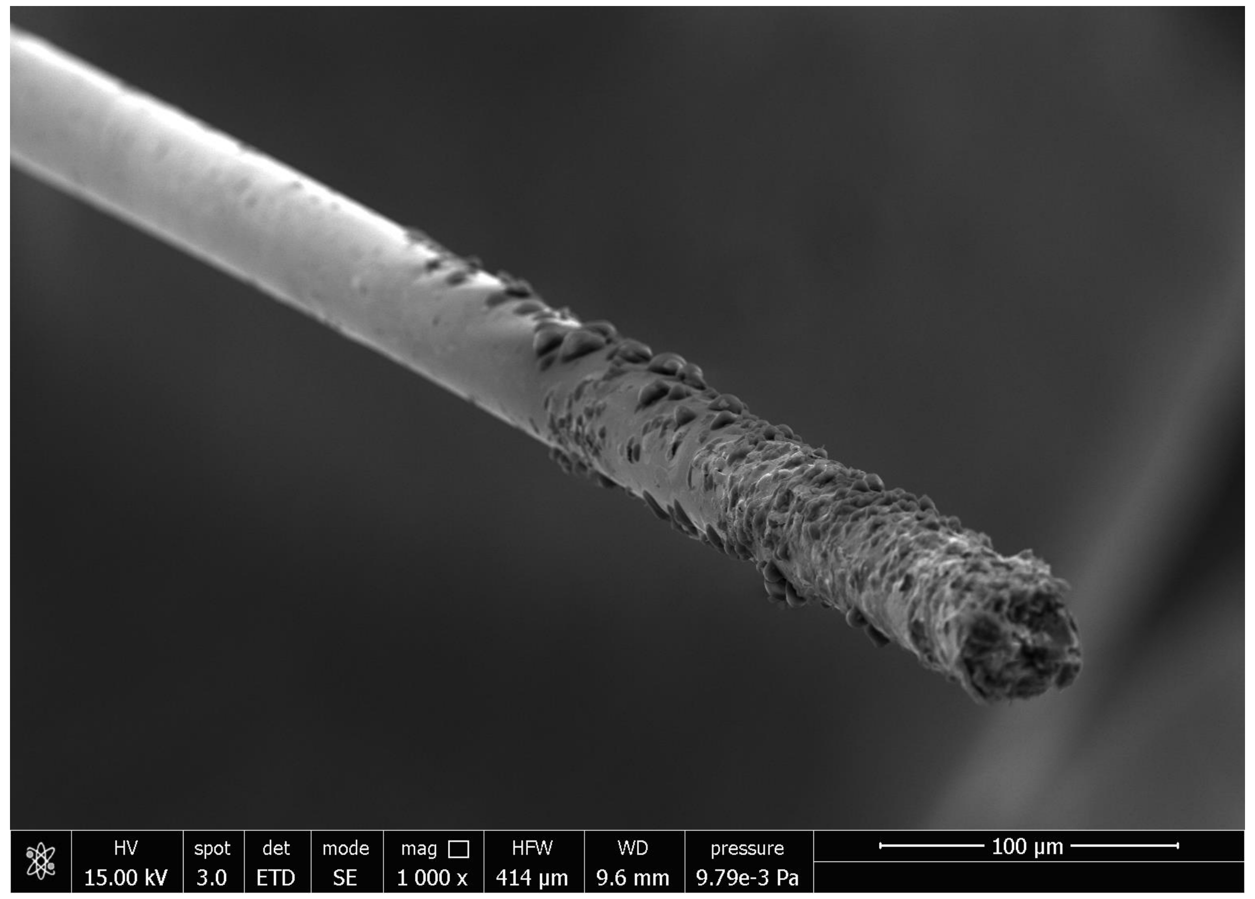
Solution for drift chamber discharge

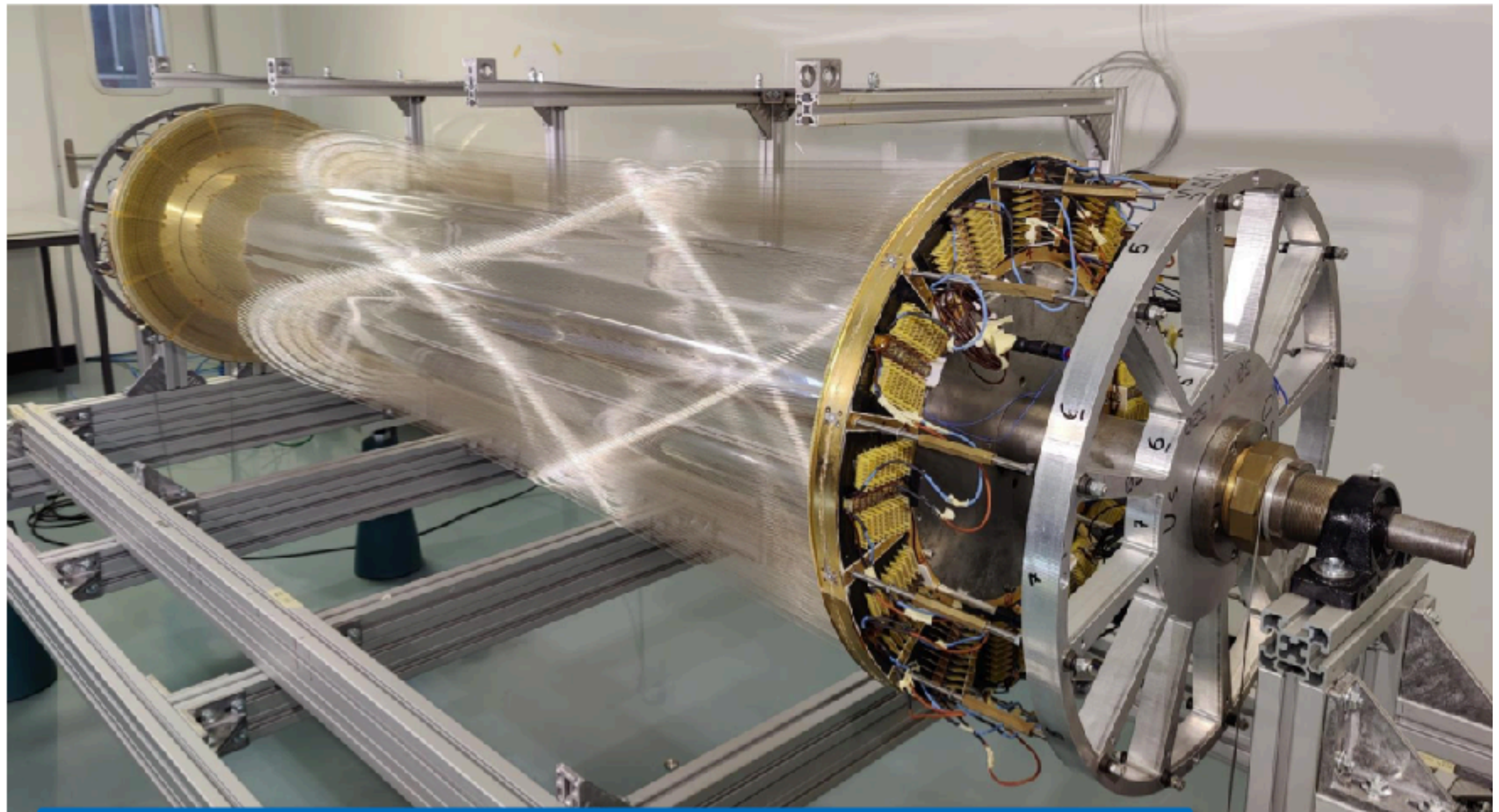
- Different gas mixtures were tested under muon beam run in 2020
    - Only water, CO_2, or O_2 was not effective
- Adequate gas mixture was finally found
    - He:iso-butane= 90:10 +H_2O 3500ppm+pure O_2 2%
    - Nominal HV at MEG II intensity ($7 \times 10^7 \mu/s$) was achieved.
- One wire might be broken during this test
    - Due to corrosion by water?
    - Water was replaced with 1% Isopropyl alcohol, and it worked!
- O_2 concentration reduced down to 0.5%
    - Attachment of electrons loses electron in the drift (lower gain)
- Final gas mixture
    - He:iso-butane = 90:10 + Isopropanol 1% + O_2 0.5%



Drift chamber broken wire problem

- Wire breaking was induced by humidity
    - Corrosion evolved with water & wire tension
- Drift chamber had been operated in closed condition with dry environment
    - Small amount of water vapor (13% relative humidity) induced a wire breaking in 2020?
    - No wire breaking in 2021 with isopropyl alcohol?
    - Wire removal work is necessary in this spring
- Discussion for drift chamber 2
    - With thicker cathode wires (Ag/Al 40→50~60μm)
    - Backup and better solution
    - Two years necessary for production,
      the current chamber will be anyway used until CDCH2 ready



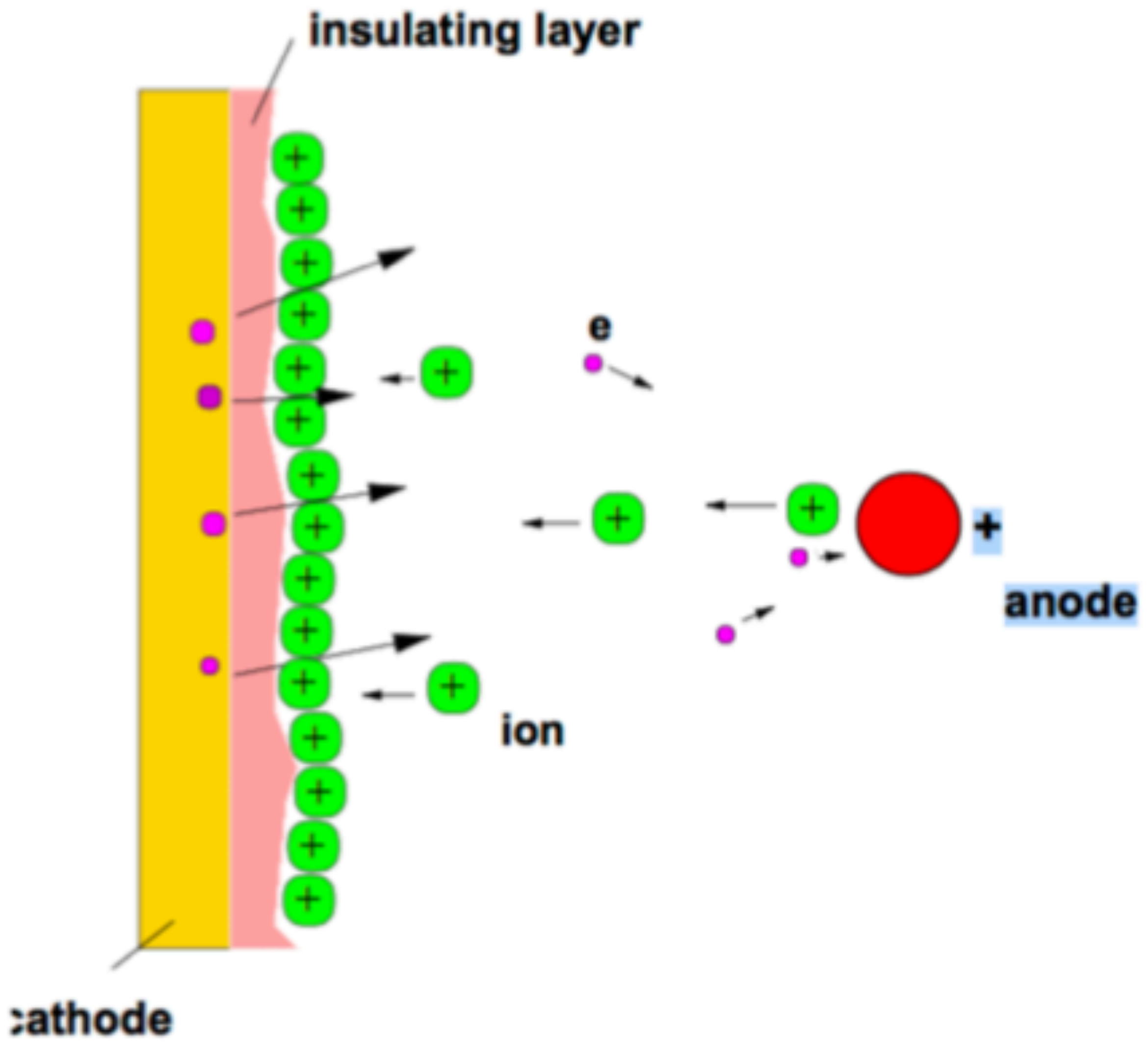


- ➢ CDCH re-opened on 16/02
- ➢ During the short period with the chamber exposed to the cleanroom atmosphere T was 22-23°C and RH did not exceed 35%

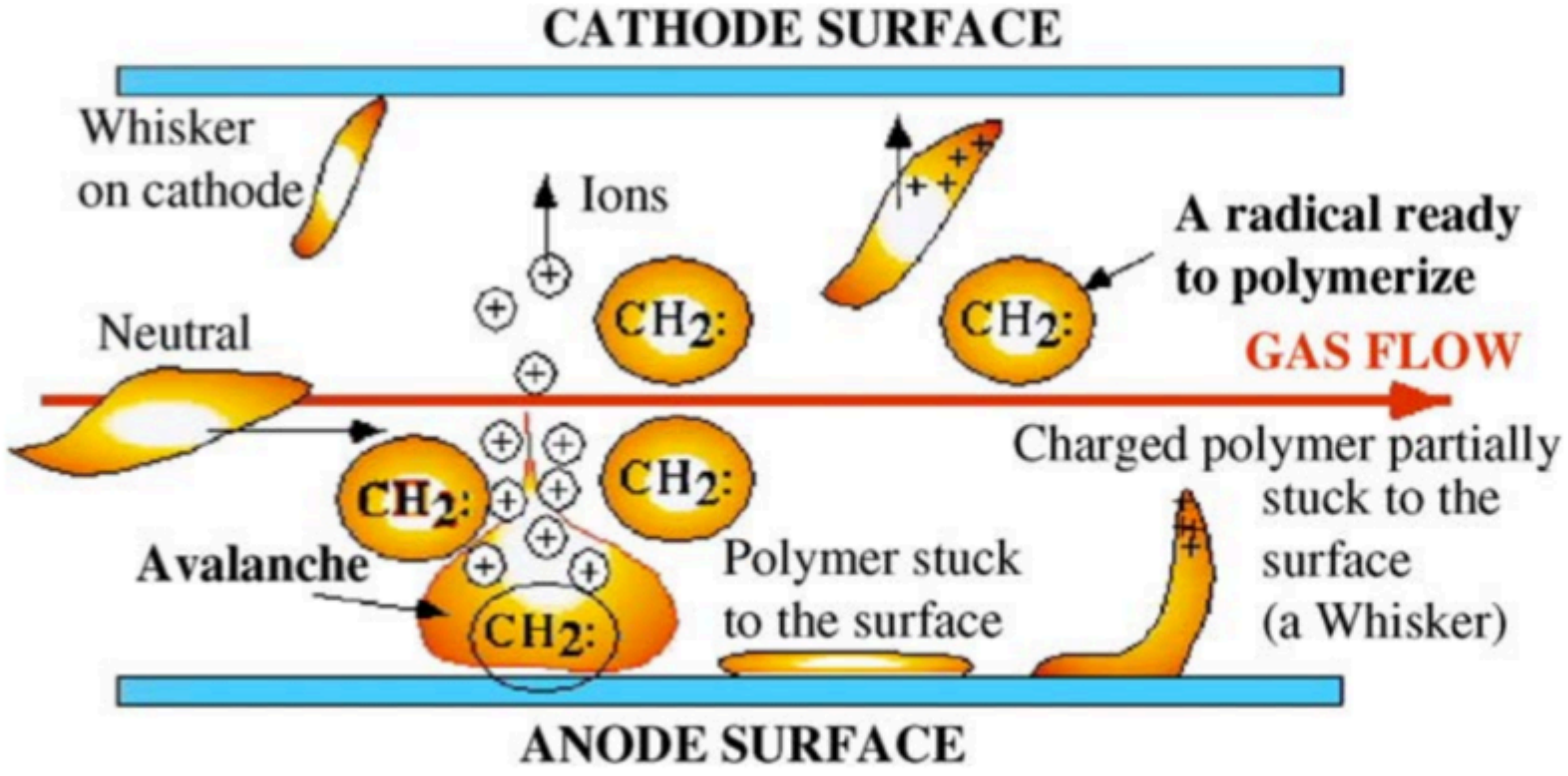
Sensitivity estimate from e+ 13aT2-1 宇佐見

e+ reconstruction14aT3-7 内山

Malter effect and free radical formation



Malter effect

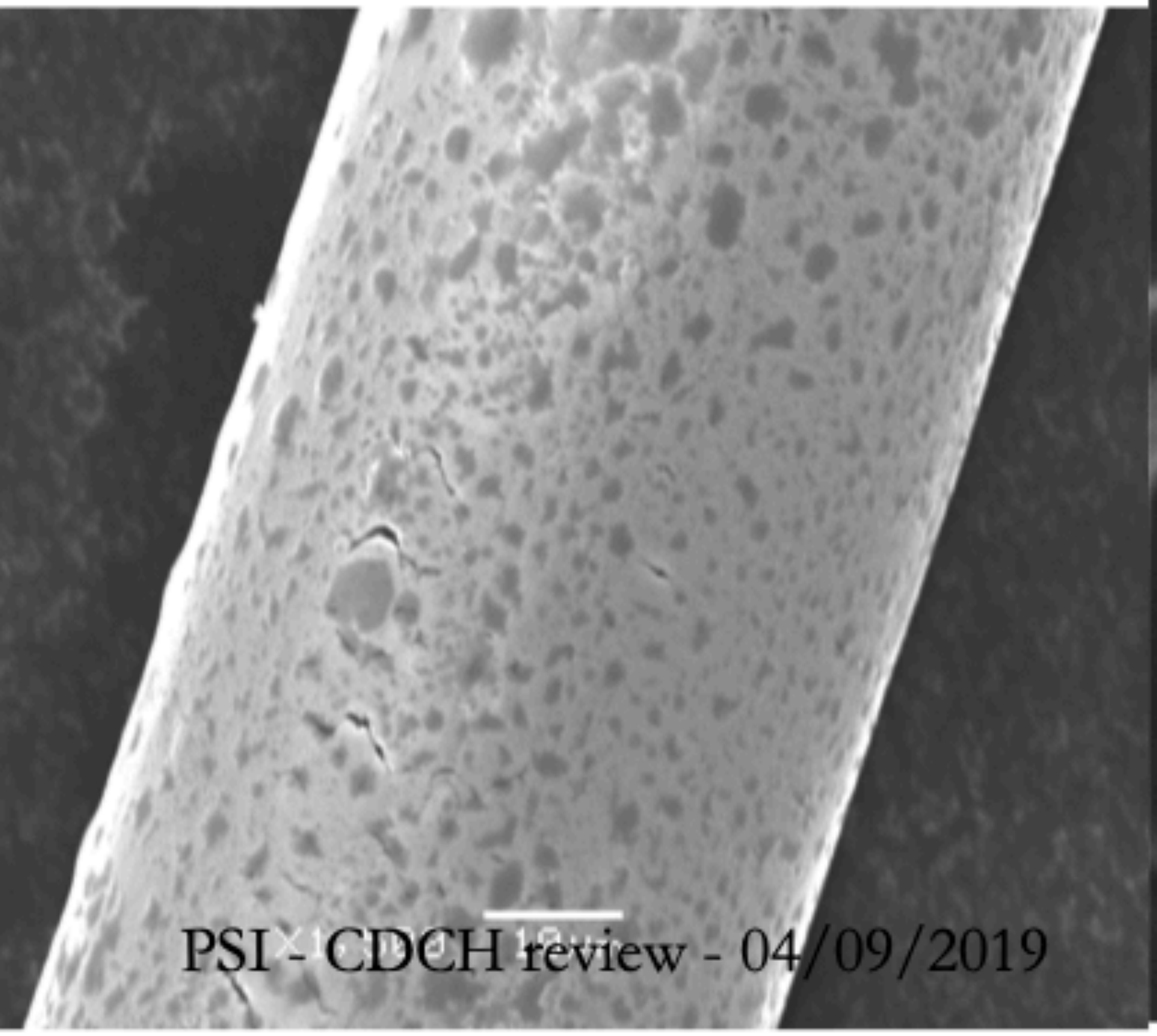


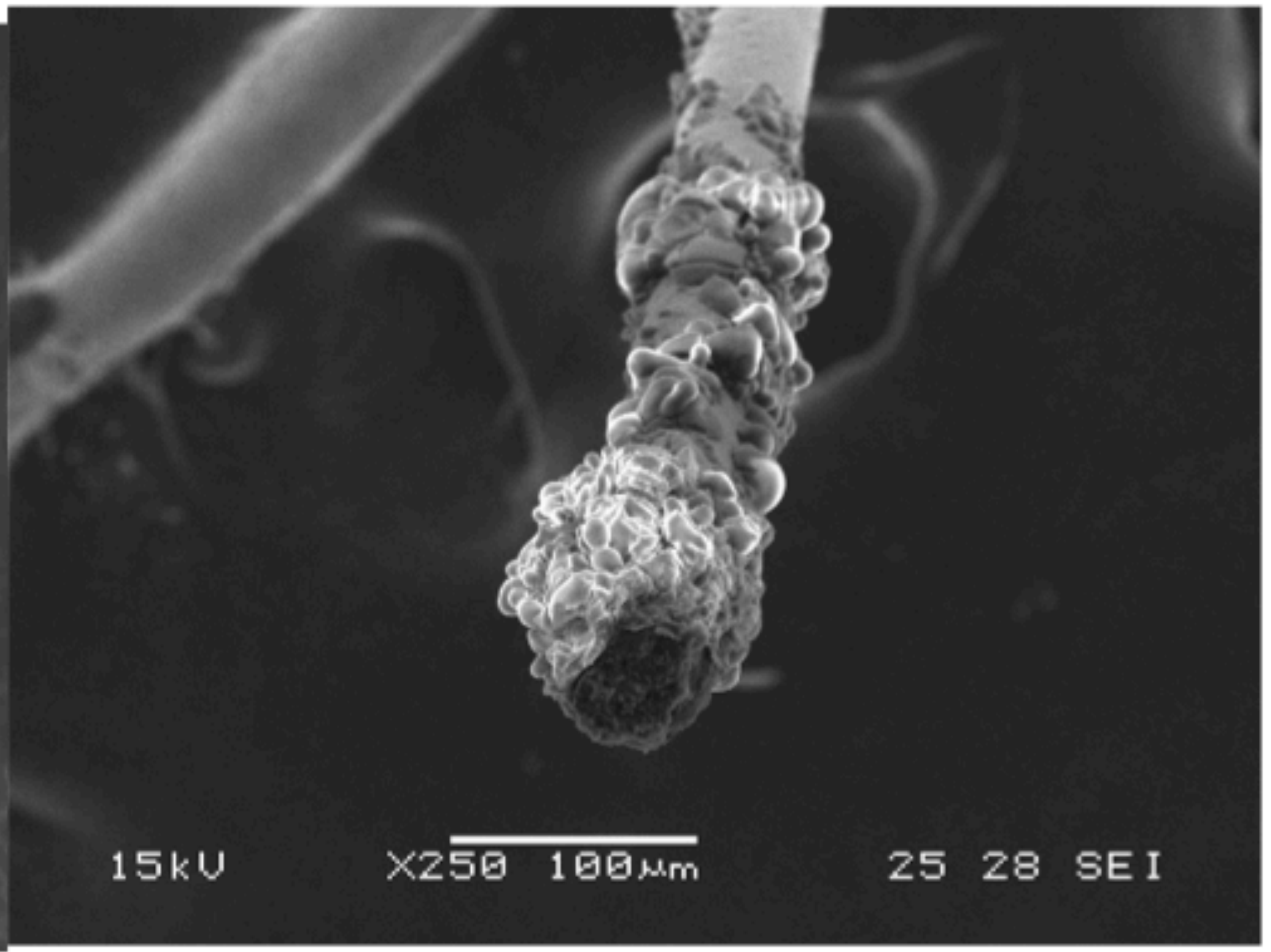
Free radical formation

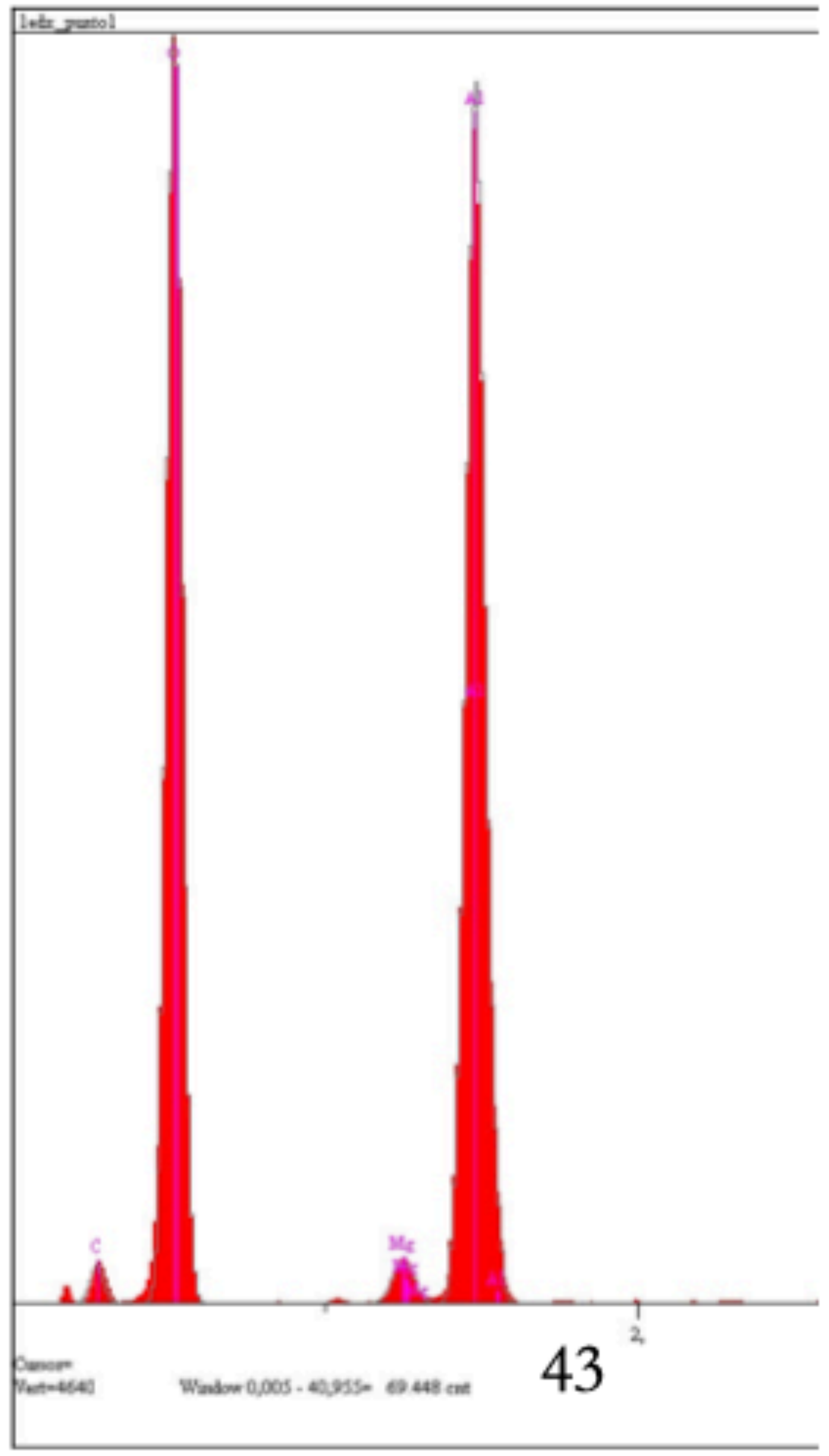
- Polymerization
  - fragmentation of chamber gas molecules can form free radical which deposits on wire surfaces
  - Charged polymer can be stuck to the surface (like Malte effect) → induce current
- Oxygen
  - can be radical in plasma under muon beam, and can attack the polymer (plasma cleaning)
- Isopropanol (Water)
  - can mitigate the surface charge deposit, but can not remove the polymer

Humidity effect

- Test were performed in Lecce and in Pisa
  - Aluminium wires were immersed or sprayed with demineralized water and with 3% water solution of NaCl
  - In all cases induced wire breaking were identical to the ones observed on the chamber
  - The salt near the wire edge contains Al and O: it could be aluminium oxide or aluminium hydroxide







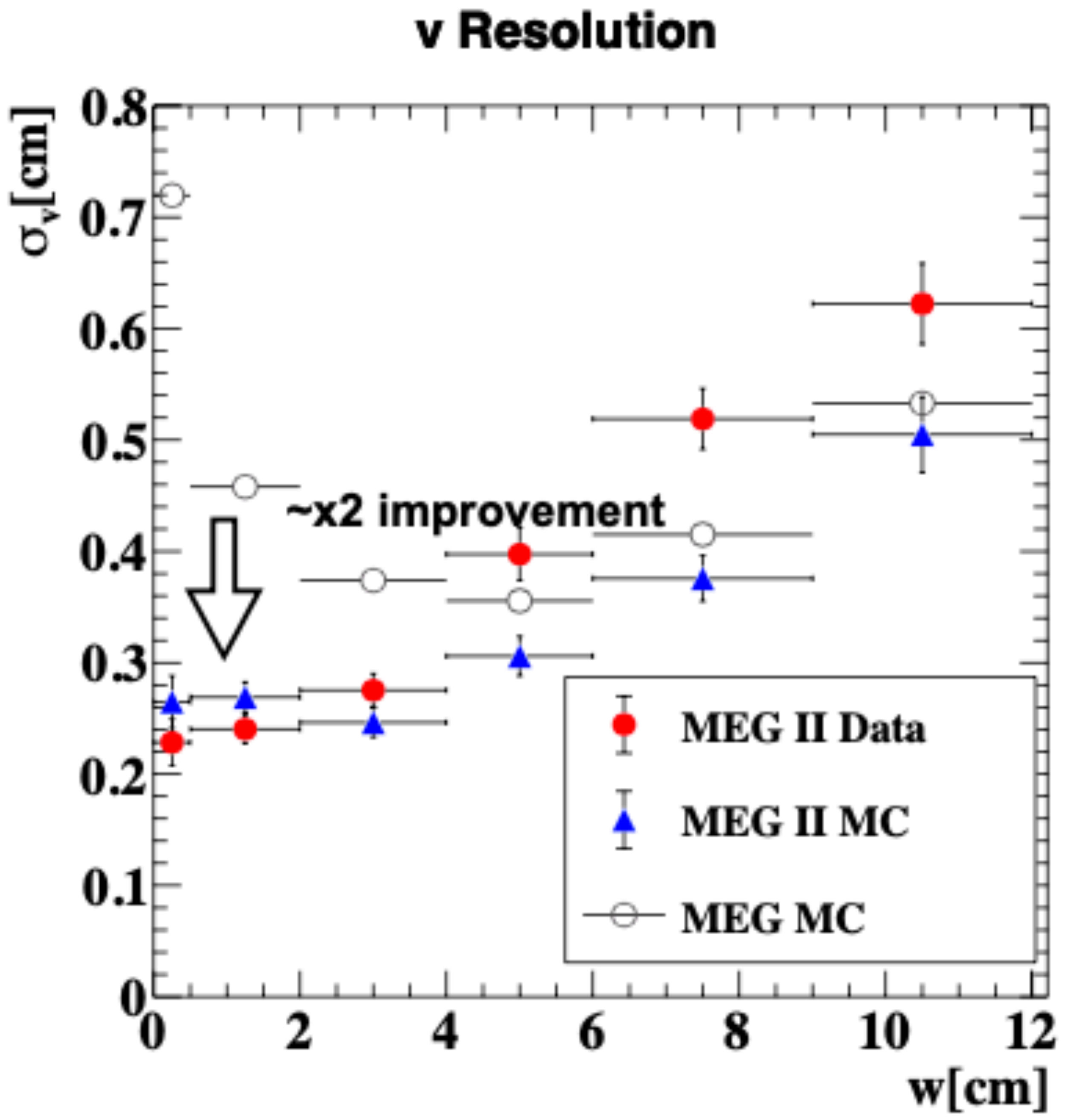
$$Al + 3Cl^- \longleftrightarrow AlCl_3 + 3e^-$$

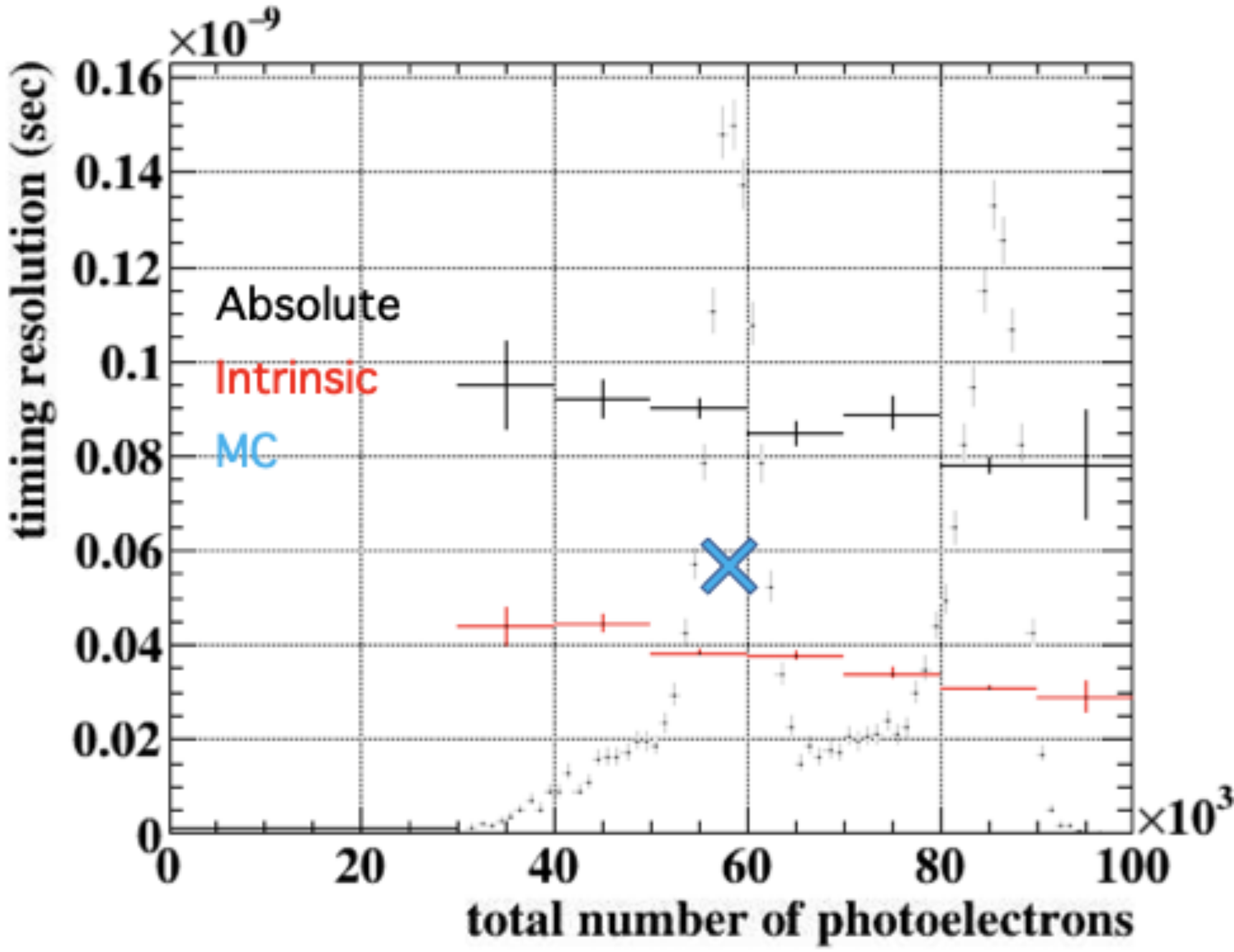
$$AlCl_3 + 3H_2O \longleftrightarrow Al(OH)_3 + 3H^+ + 3Cl^-$$

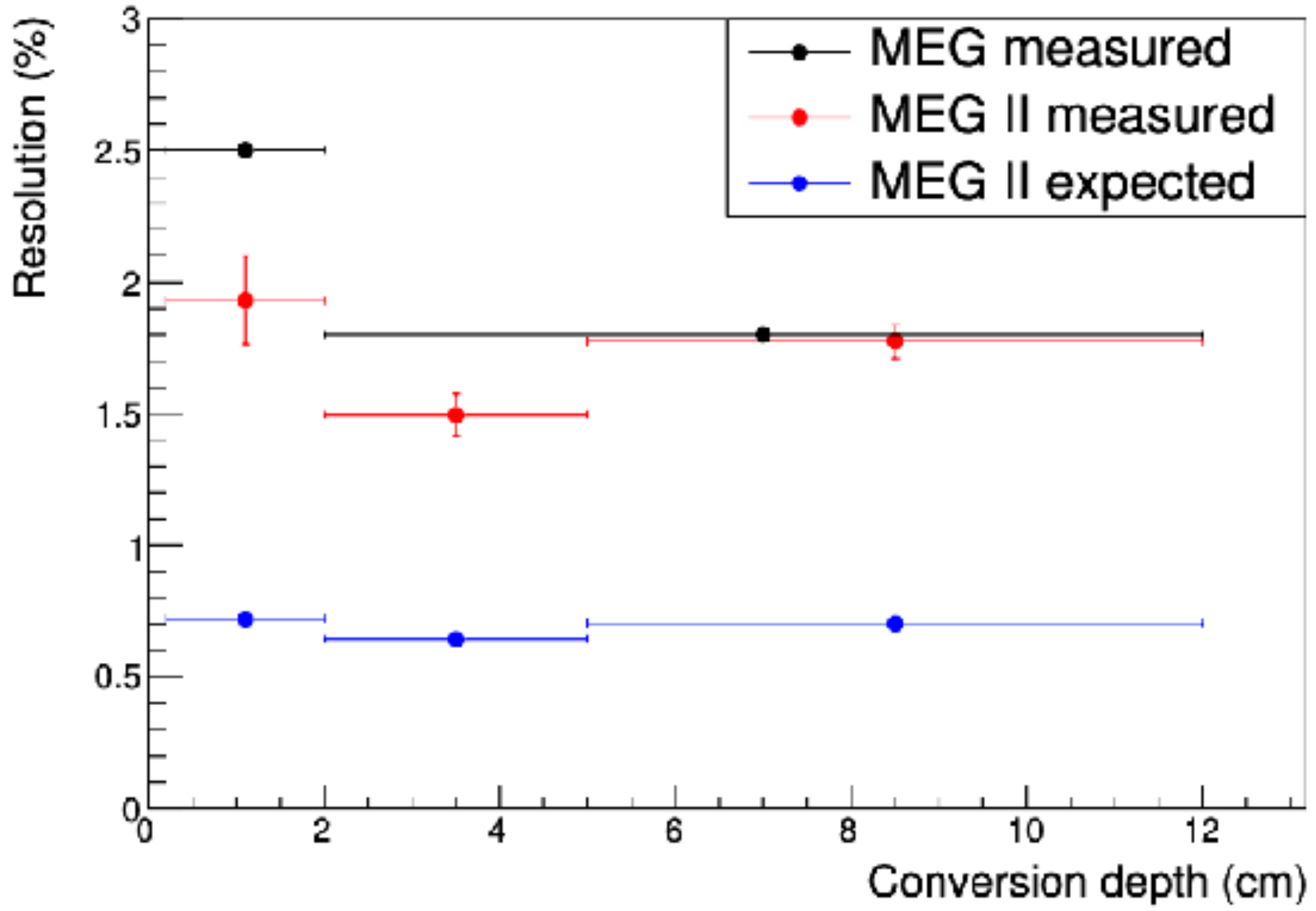
LXe performance

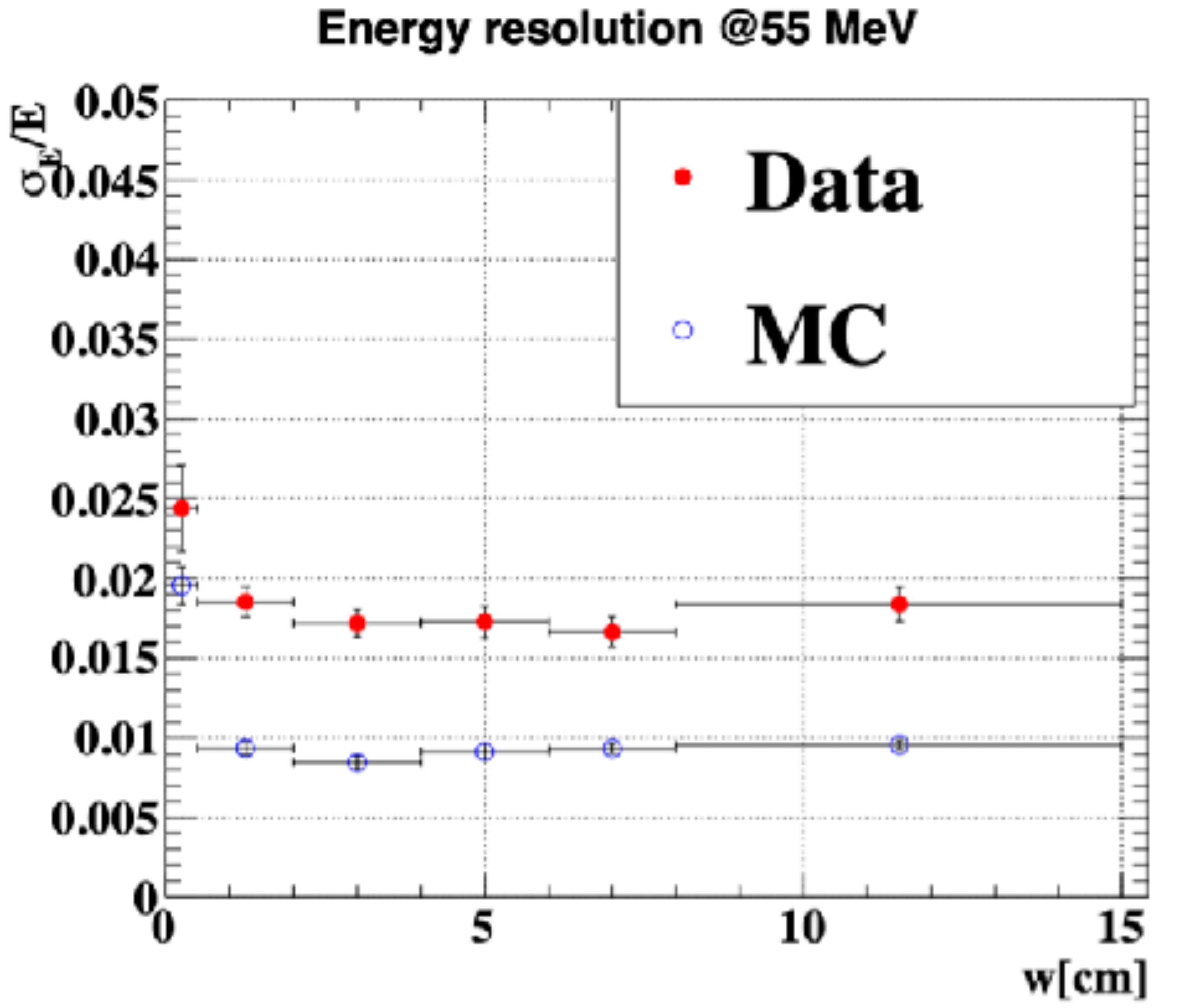
- Position resolution
    - almost consistent with MC expectation
- Time resolution 14aT2-3 恩田
    - 82 ps is still worse than MC expectation (57 ps)
- Energy resolution 14aT2-2 小林
    - worse than MC expectation
    - better than MEG at depth<2cm
- Prospects
    - Measurements done with a limited number of channels, and will be updated with full electronics
    - Calibration&algorithm still to be improved

14aT2-1 家城



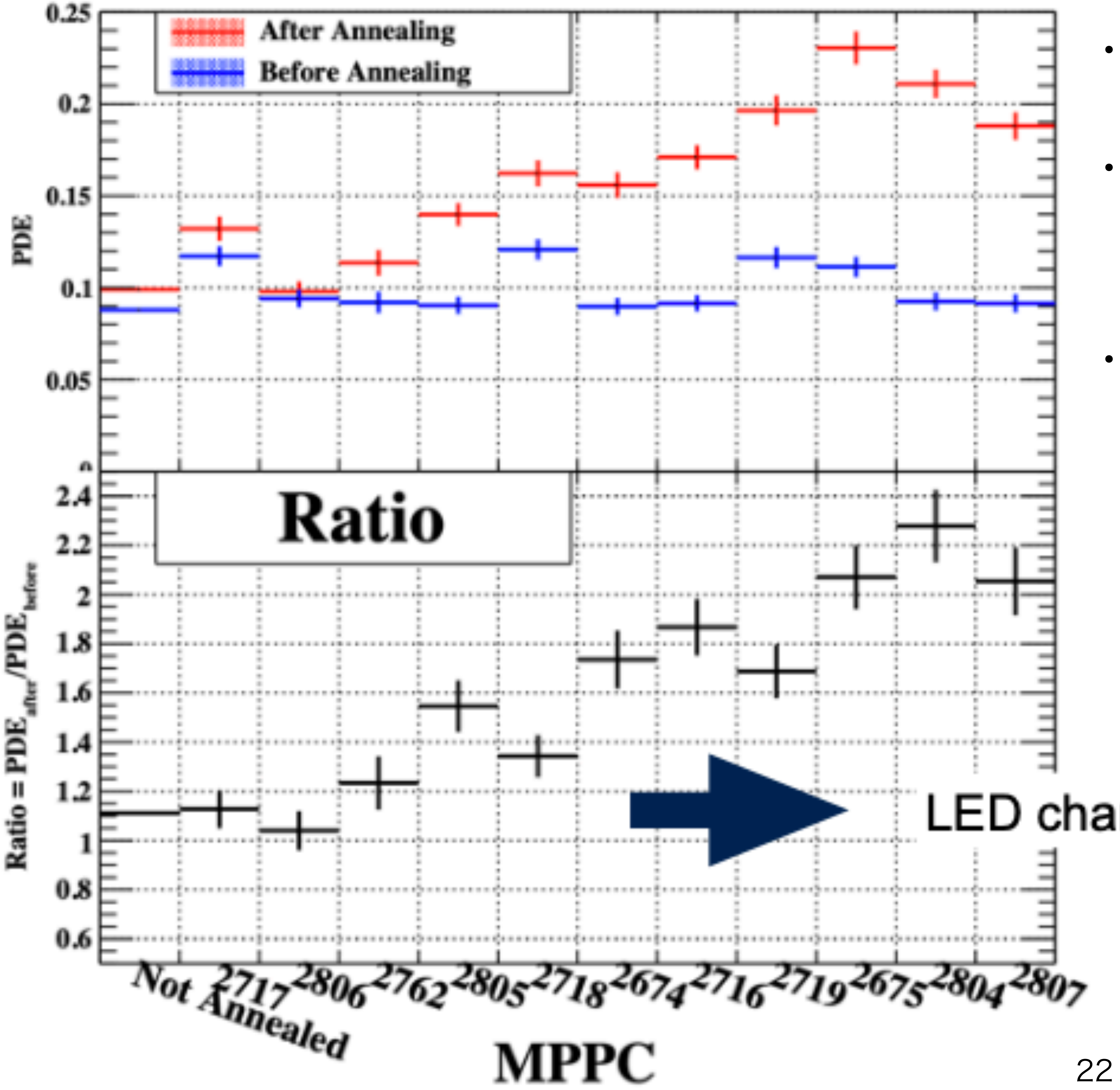




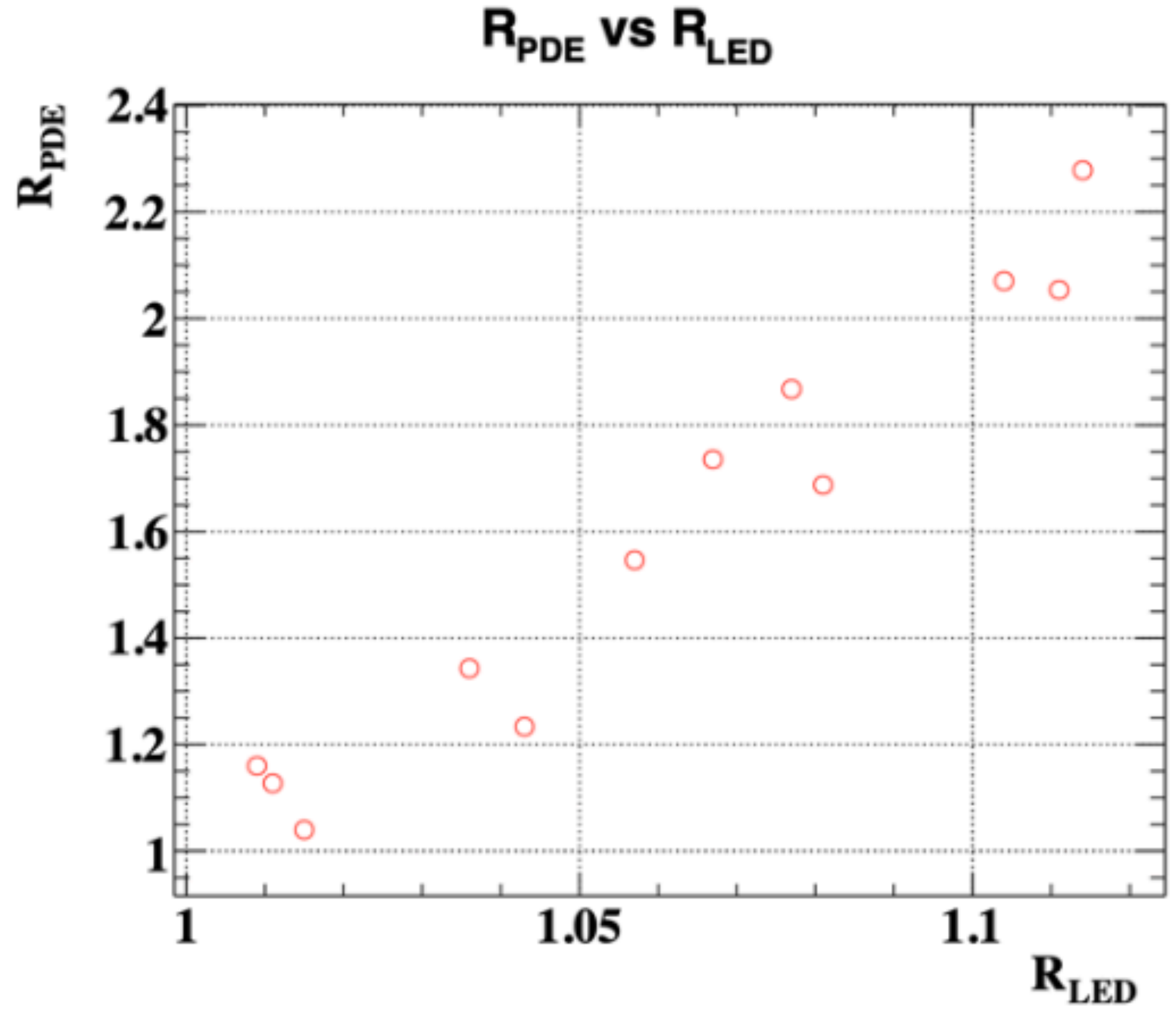


Annealing effect measured by VUV light

- PDE is measured by α sources after the detector is filled with liquid xenon
- PDE recovery after annealing is confirmed
  - PDE value up to ~20% for several MPPCs (full recovery by annealing)
  - Consistent with PDE measured in lab.
- $\mathrm{PDE}_{\mathrm{VUV}}$ (α) vs $\mathrm{PDE}_{\mathrm{VIS}}$ (LED)
  - Clear correlation is observed
    - $\mathrm{PDE}_{\mathrm{VIS}} \sim 0.1 \times \mathrm{PDE}_{\mathrm{VUV}}$
  - We can monitor PDE recovery by blue LED during annealing



LED charge recovery



Possible Cause

- **Surface damage by VUV-light**

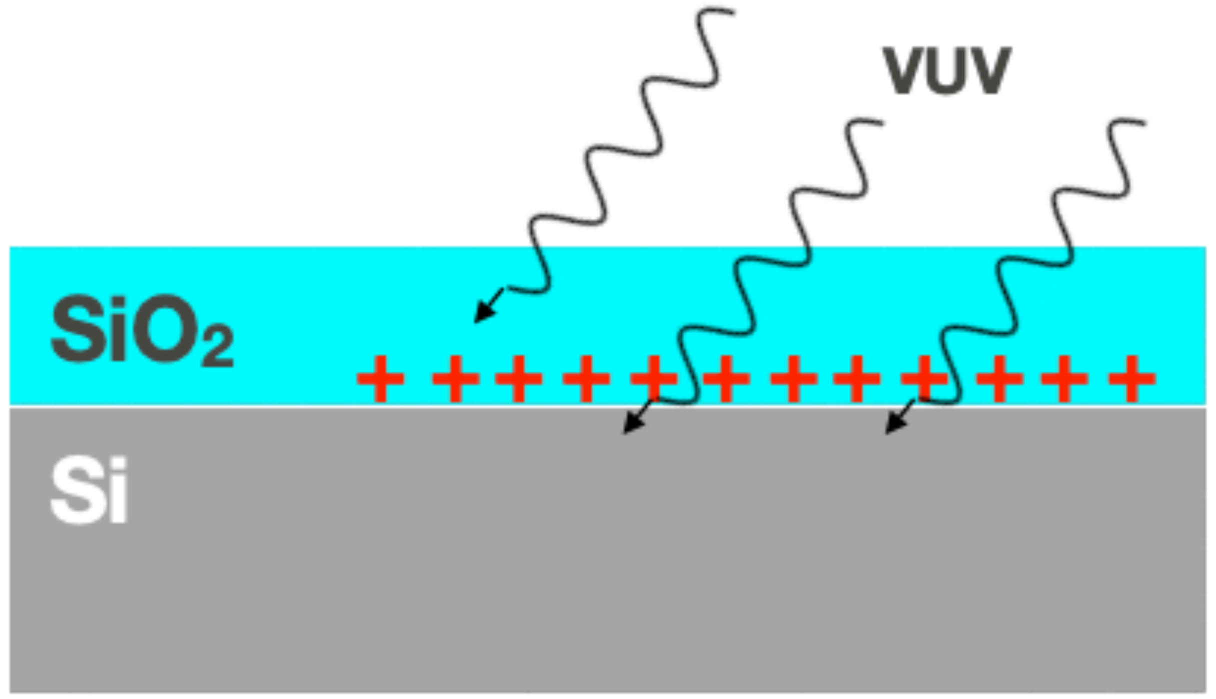
  Electron-hole pair generated in SiO_2 by VUV light

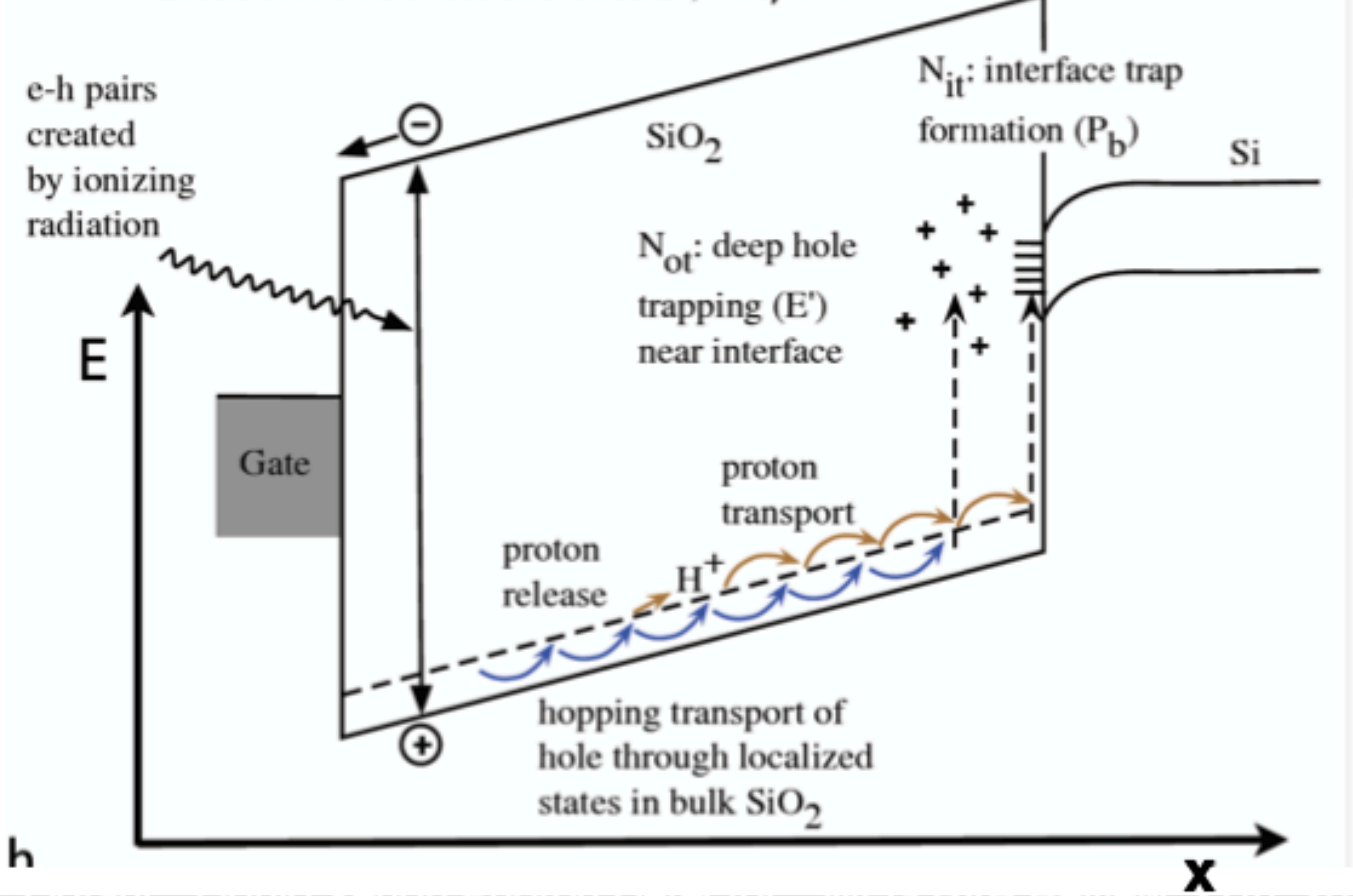
  →Holes are trapped at interface SiO_2 - Si

  →Accumulated positive charge will reduce electric field near Si surface, reducing collection efficiency of charge carrier

  - N.B. charge carrier generated within 5nm at Si surface for VUV

- **Similar phenomena are known for UV photo diode**
  - Degradation happens only with much larger amount of light at room temp.
  - Degradation seems accelerated at low temp.

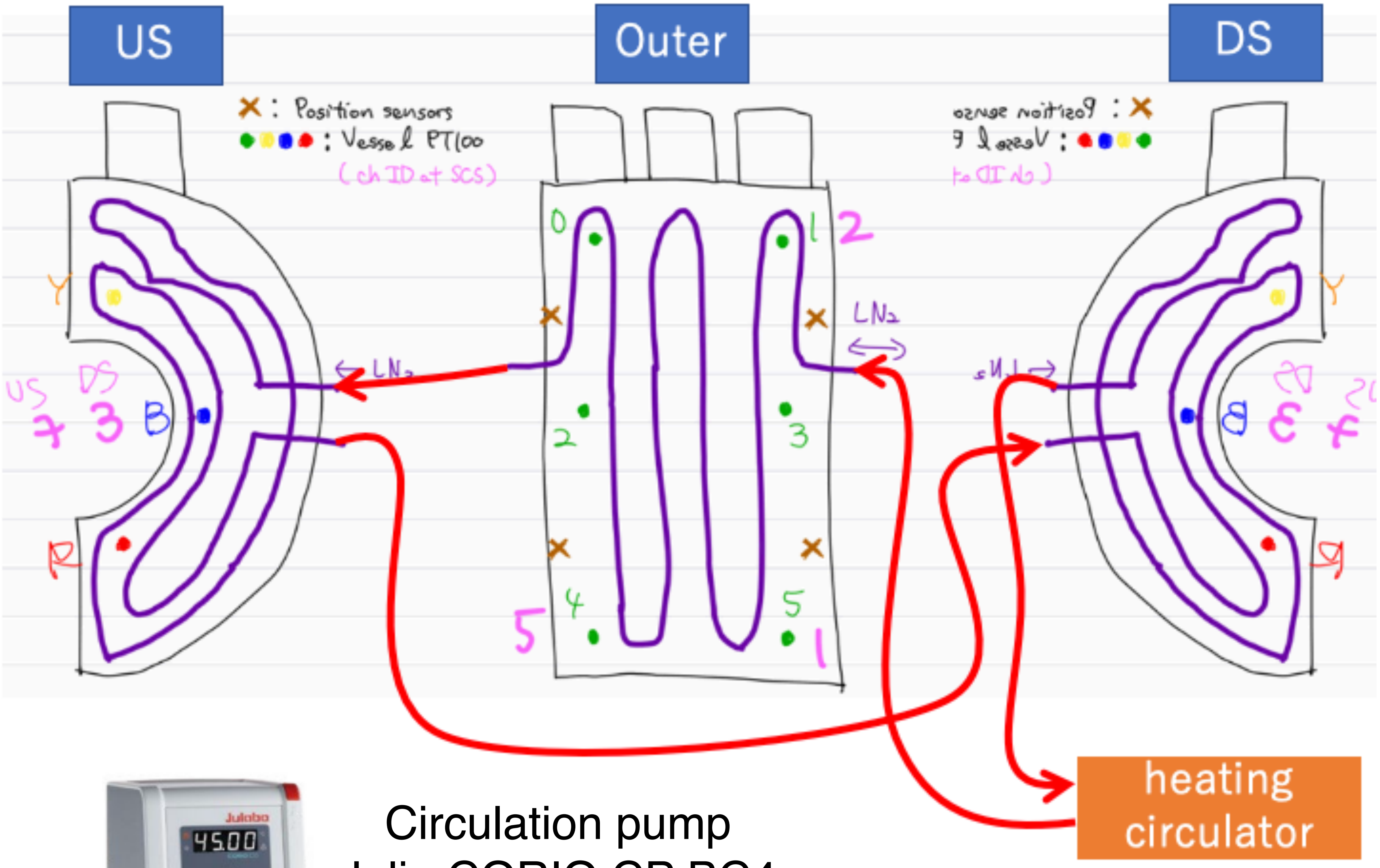



from T.P. Ma and Paul V. Dressendorfer, „Ionizing Radiation Effects in MOS Devices and Circuits“, Wiley 1989

W. Ootani, "Liquid Xenon Photon Detector", MEG BVR Review: 27th, 2020, PSI 16

Towards annealing for all MPPCs

- Two methods are currently considered
- Hot water circulation in LN_2 pipe
  - Heater(+pump) used for the hot water circulation
    - to heat the detector to 40°C, 4 hours at minimum
  - All channels can be annealed at once
  - No need for cabling : easy
  - Temperature can be measured at PMT holders
  - Remaining issues
    - How fast can we warm the detector?
    - Annealing is successful at 40°C?
    - Can we drain water from LN_2 pipe completely?
- Joule heat with HV module
  - The basic principle for annealing is confirmed
  - Cabling work is required
  - Temperature increase must be carefully checked to anneal more channels at the same time
- Hot water method is better, but basic tests for both will be done this year, and annealing for all MPPCs will be done in 2022.

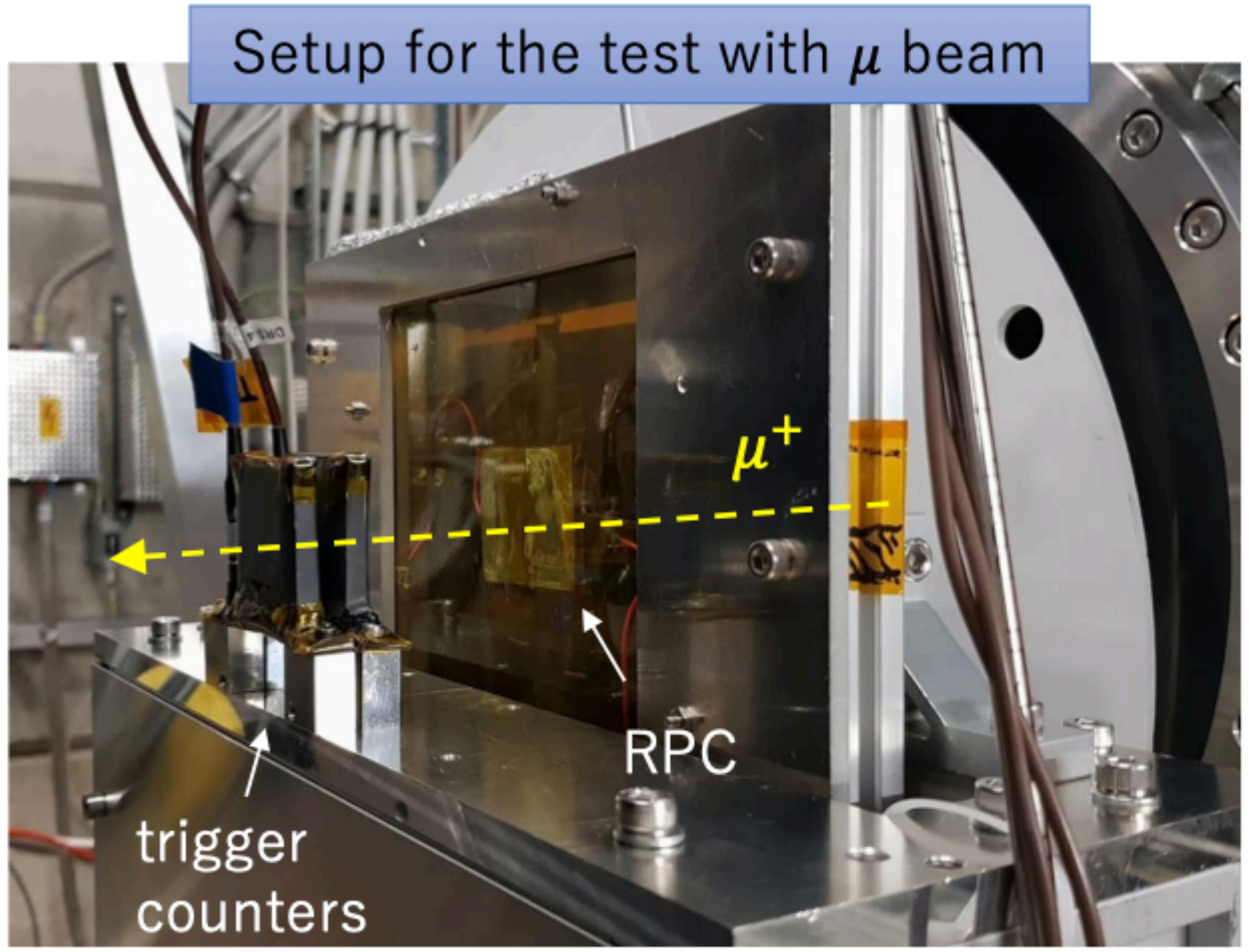


Circulation pump
Julio CORIO CP BC4

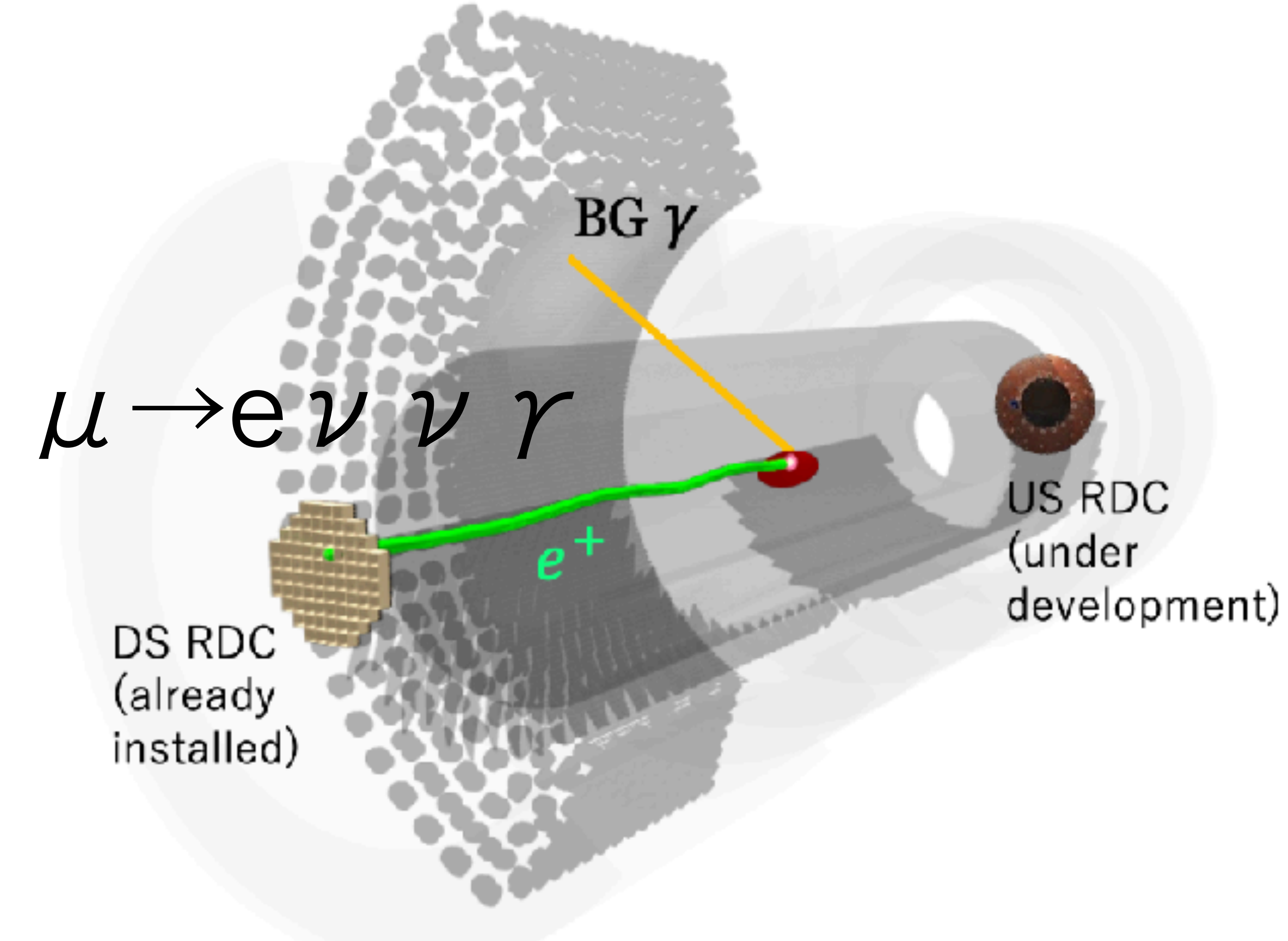
Test HV module
(30ch, high current)

US RDC (RPC) beam test

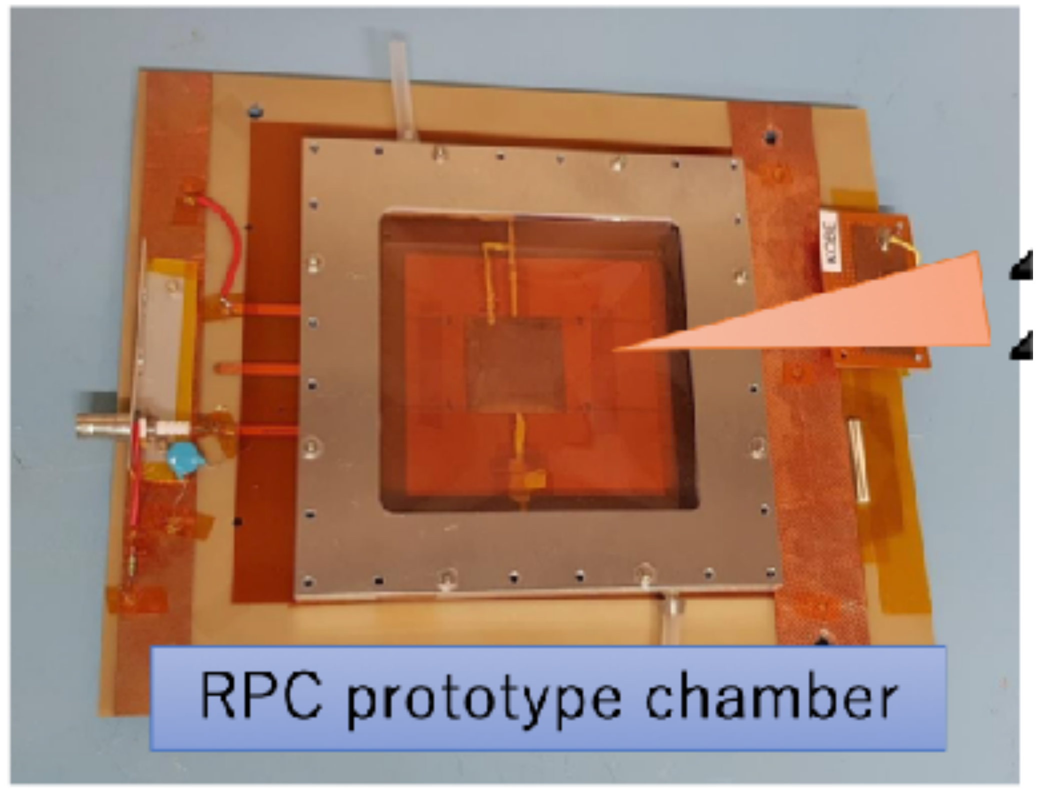
- RDC to identifies RMD backgrounds
- DS RDC : ready for the physics run
- US RDC : under development
  - Extremely low mass (<$0.001X_0$) because muon beam must penetrate it
  - Resistive Plate Chamber (RPC) with Diamond-Like Carbon (DLC) resistive electrodes is under development
  - Efficiency > 90%, σ_t<250 ps fulfilled

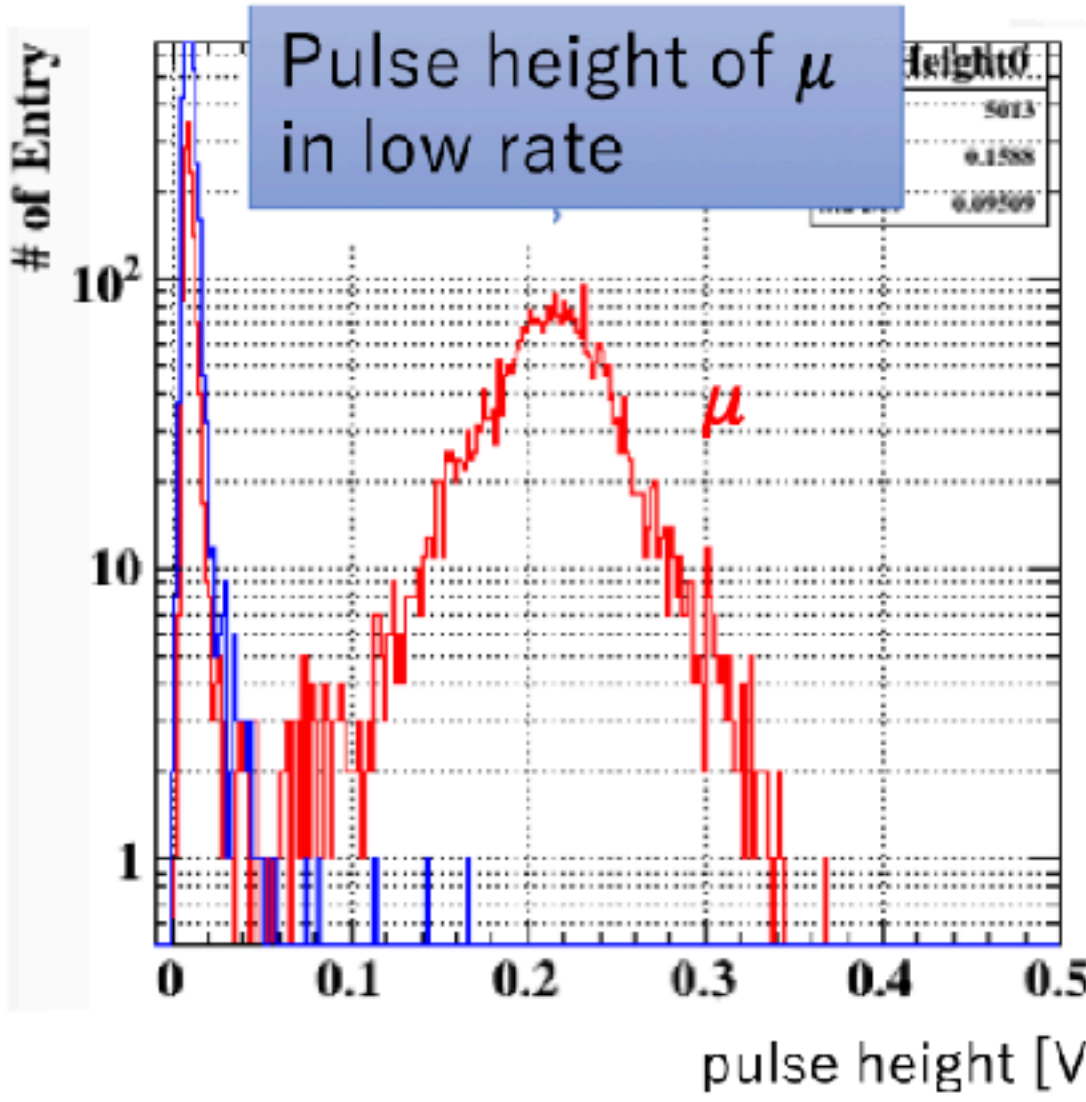

Setup for the test with μ beam

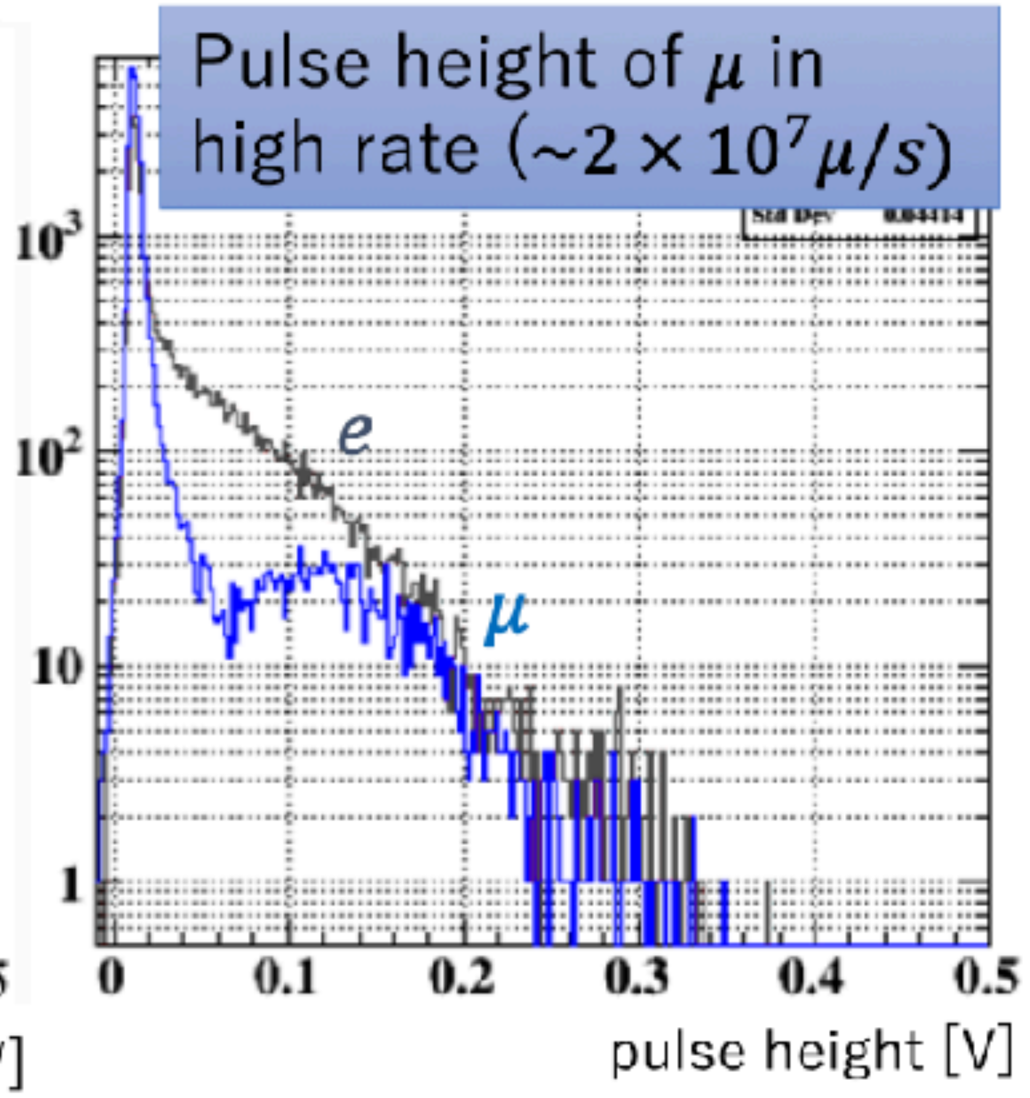
- Remaining concern
  - does it work under high rate μ beam?
- RPC beam test was performed
  - muon signal was successfully obtained, and voltage drop is also observed as expected.
- The design will be finalized based on these results



RPC beam test
13aT2-2,3 山本、大矢

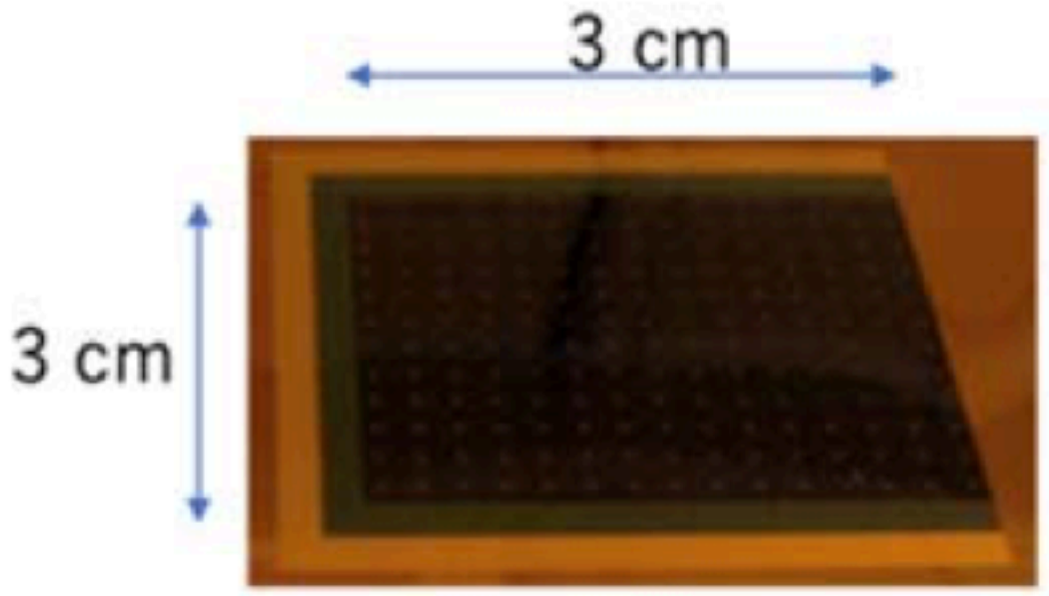

RPC prototype chamber

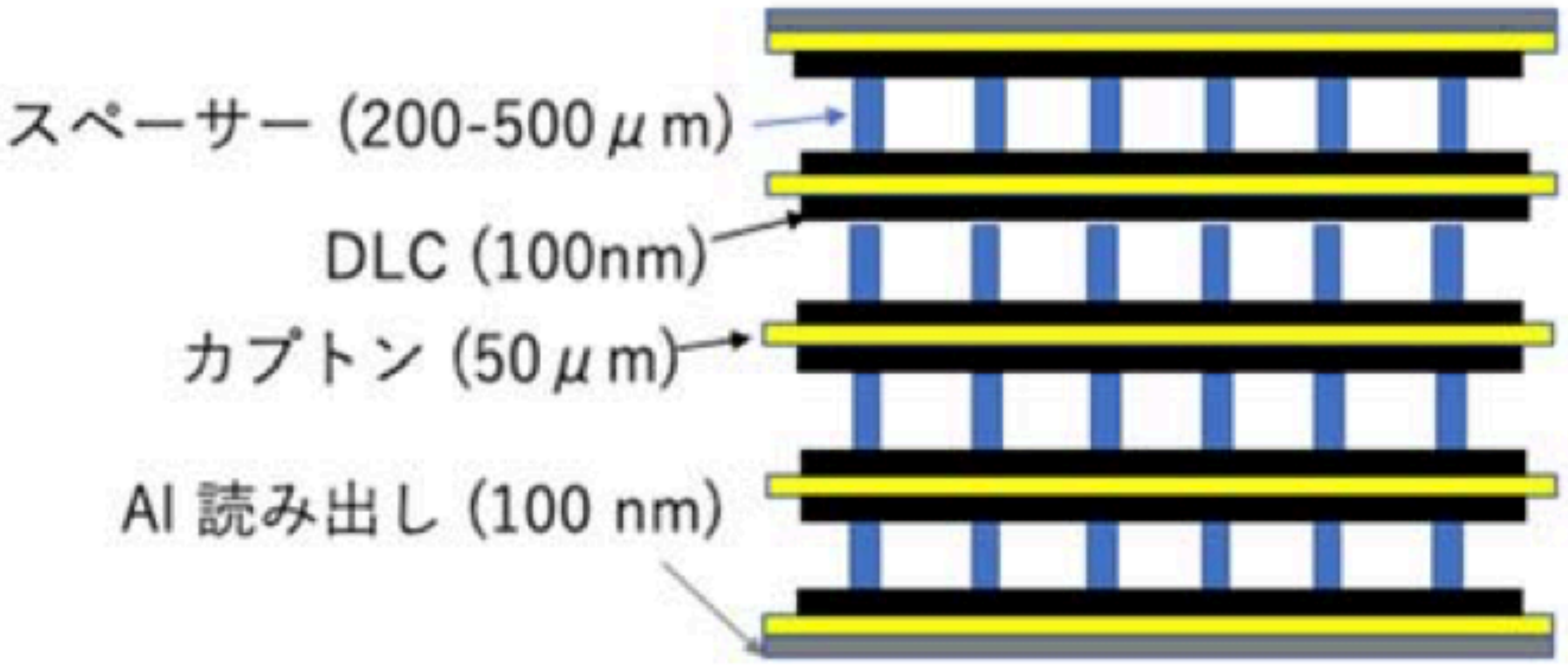

Pulse height of μ in low rate

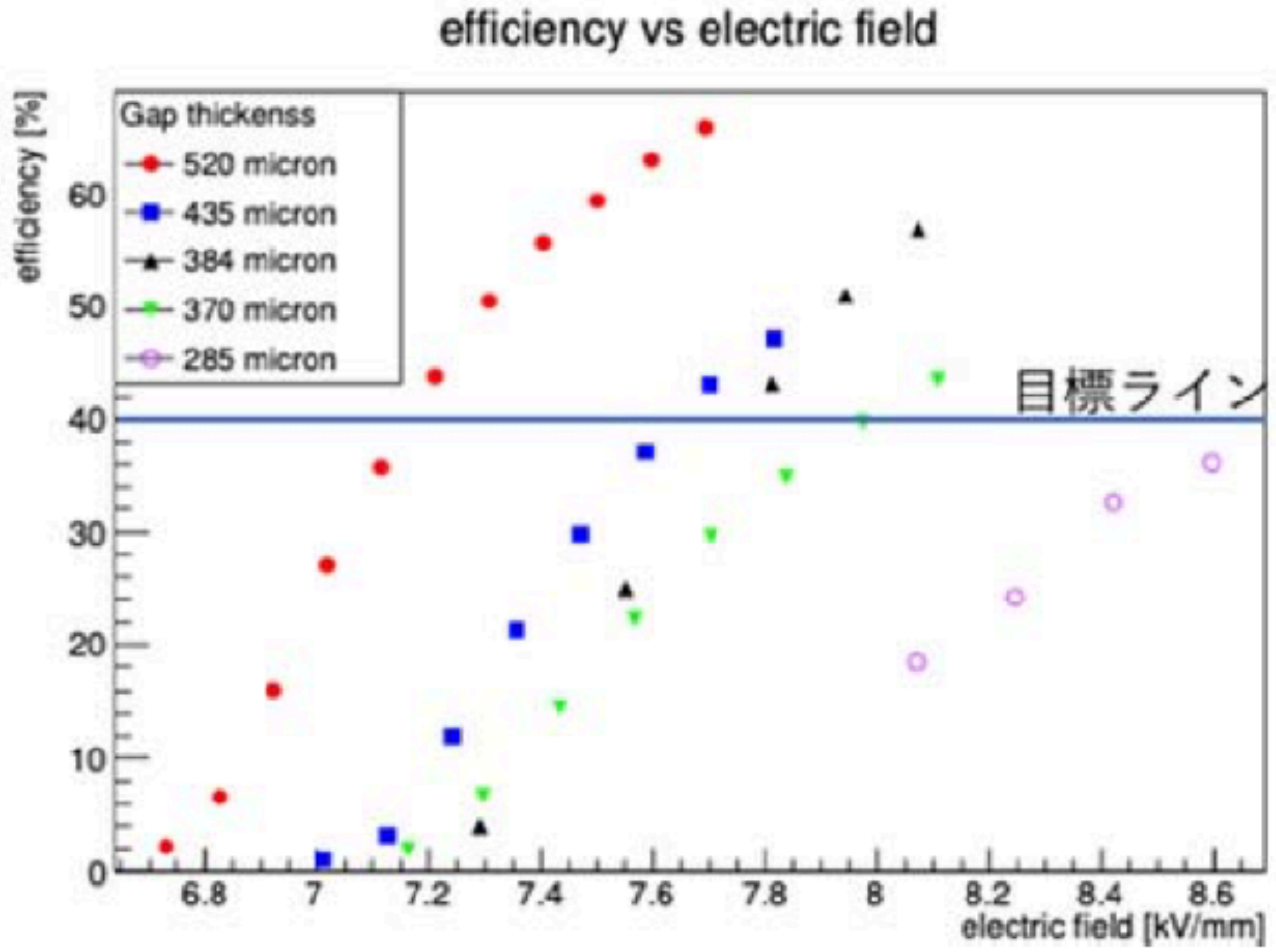

Pulse height of μ in high rate ($\sim 2 \times 10^7 \mu/s$)

US RDC (RPC)

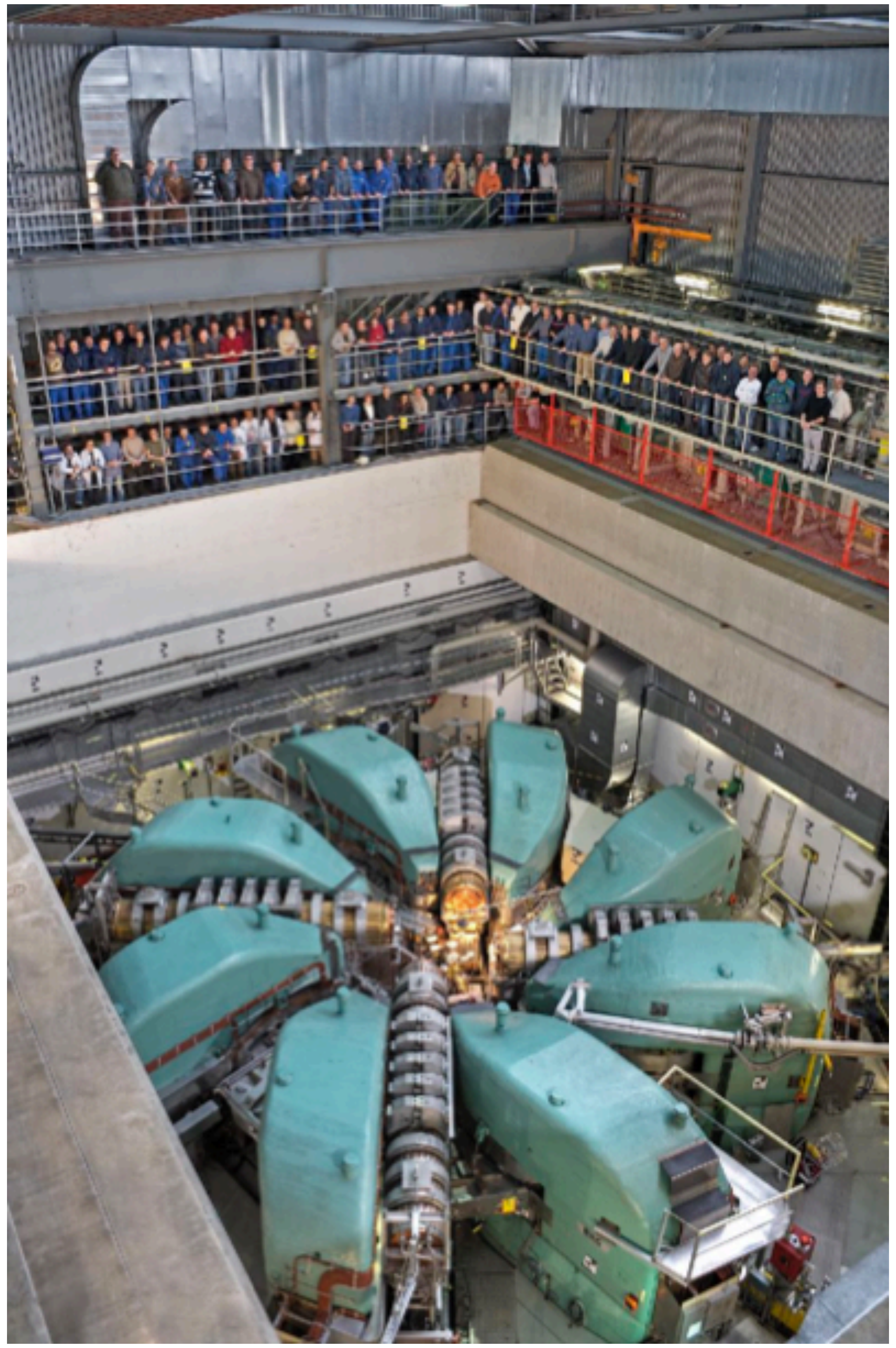
- US RDC
  - High intensity muon beam will pass through
  - High detection efficiency (90% for 1-5 MeV e^+)
  - Ultra low material budget (<0.1% X_0)
  - High rate tolerant (10^8 μ/s)
  - Diameter 20cm
- Ultra thin gaseous detector (RPC) with diamond-Like-Carbon (DLC) resistive electrode
  - R134a (Freon) based gas
  - Gap thickness : 200μm - 2mm
  - DLC: high resistive material w/ mixed structure of sp^2 bond and sp^3 bond
  - DLC sputtering on 50 μm Kapton
  - Resistivity adjustable
  - High efficiency can be achieved by multilayer design

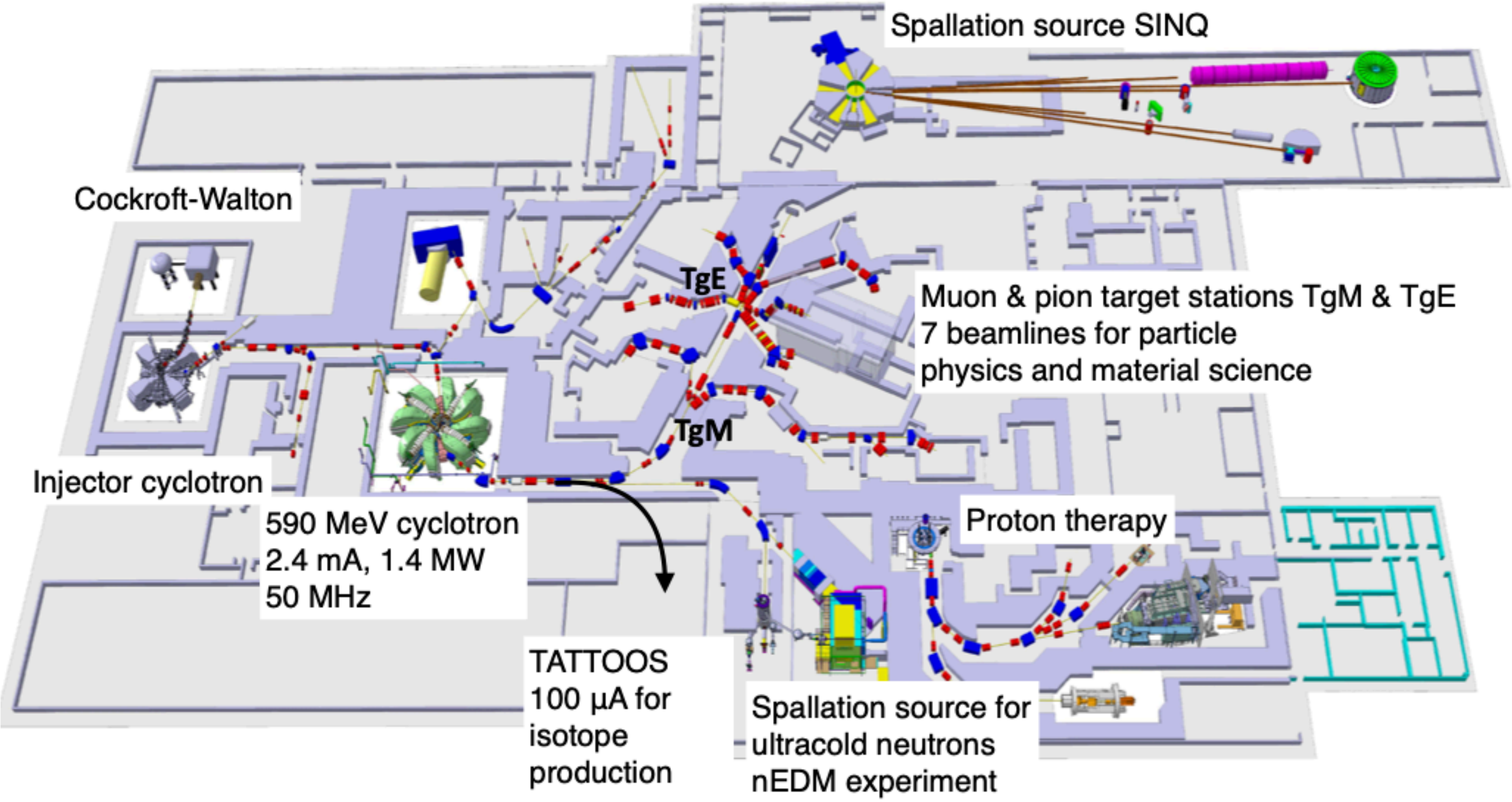






PSI accelerator

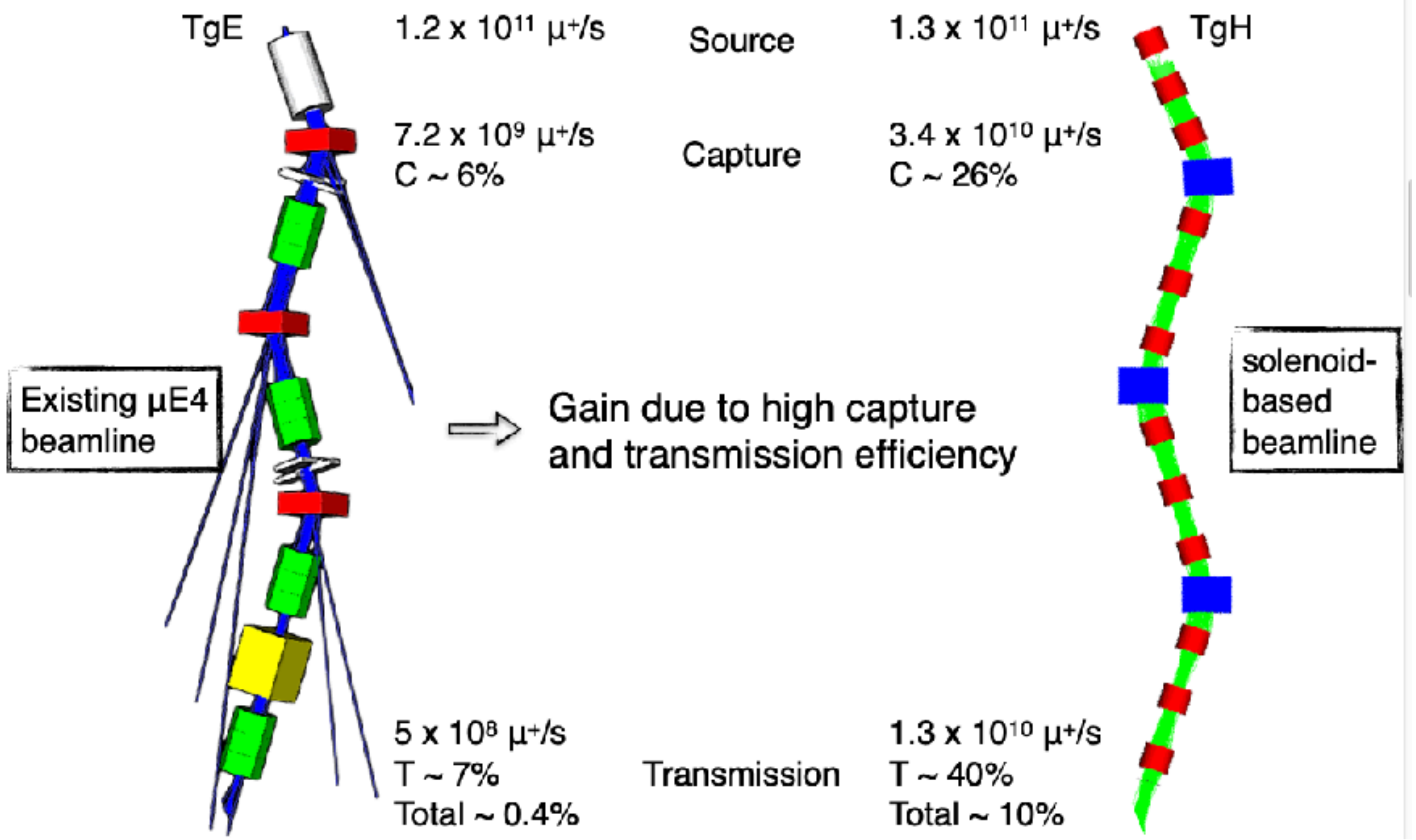


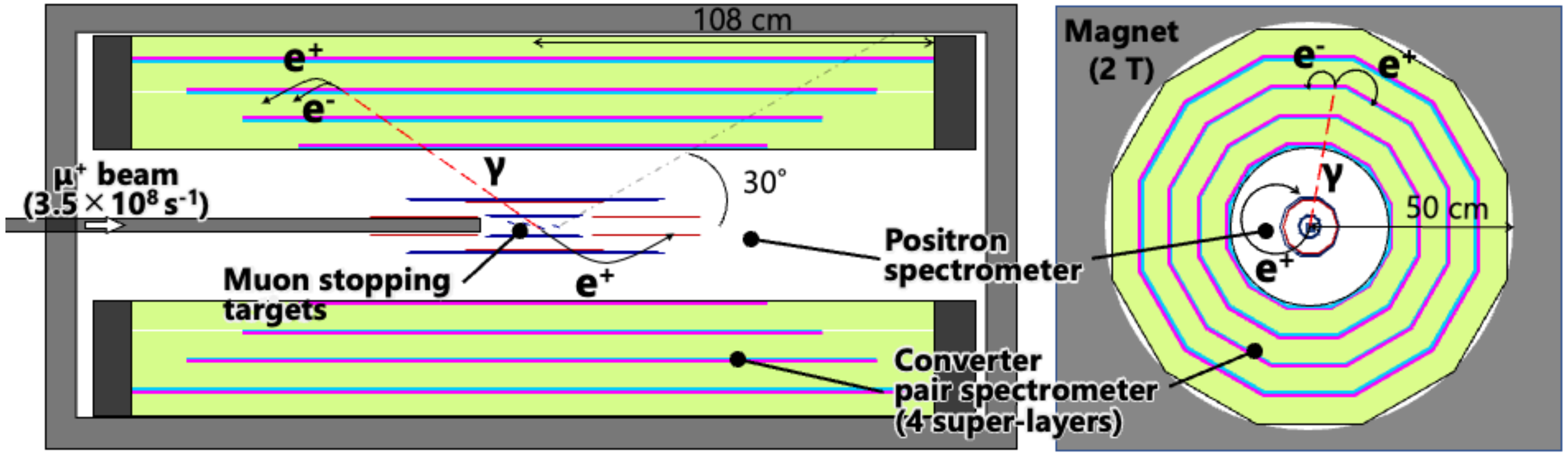


- CHRISP - Swiss Research InfraStructure for Particle physics at Paul Scherrer Institute in Switzerland
- World most intense DC muon beam available : > $10^8 \mu^+/s$
- High precision particle physics experiments complementary to the experiments at the highest energies at CERN’s LHC
- There is an upgrade project, HIMB (High Intensity Muon Beam) project, 10^{10} µ/s
  - Science case workshop 6-9 April 2021
  - Conceptual Design Report by end 2021
  - Implementation during 2027/2028 during 16-months HIPA shutdown

After MEG II

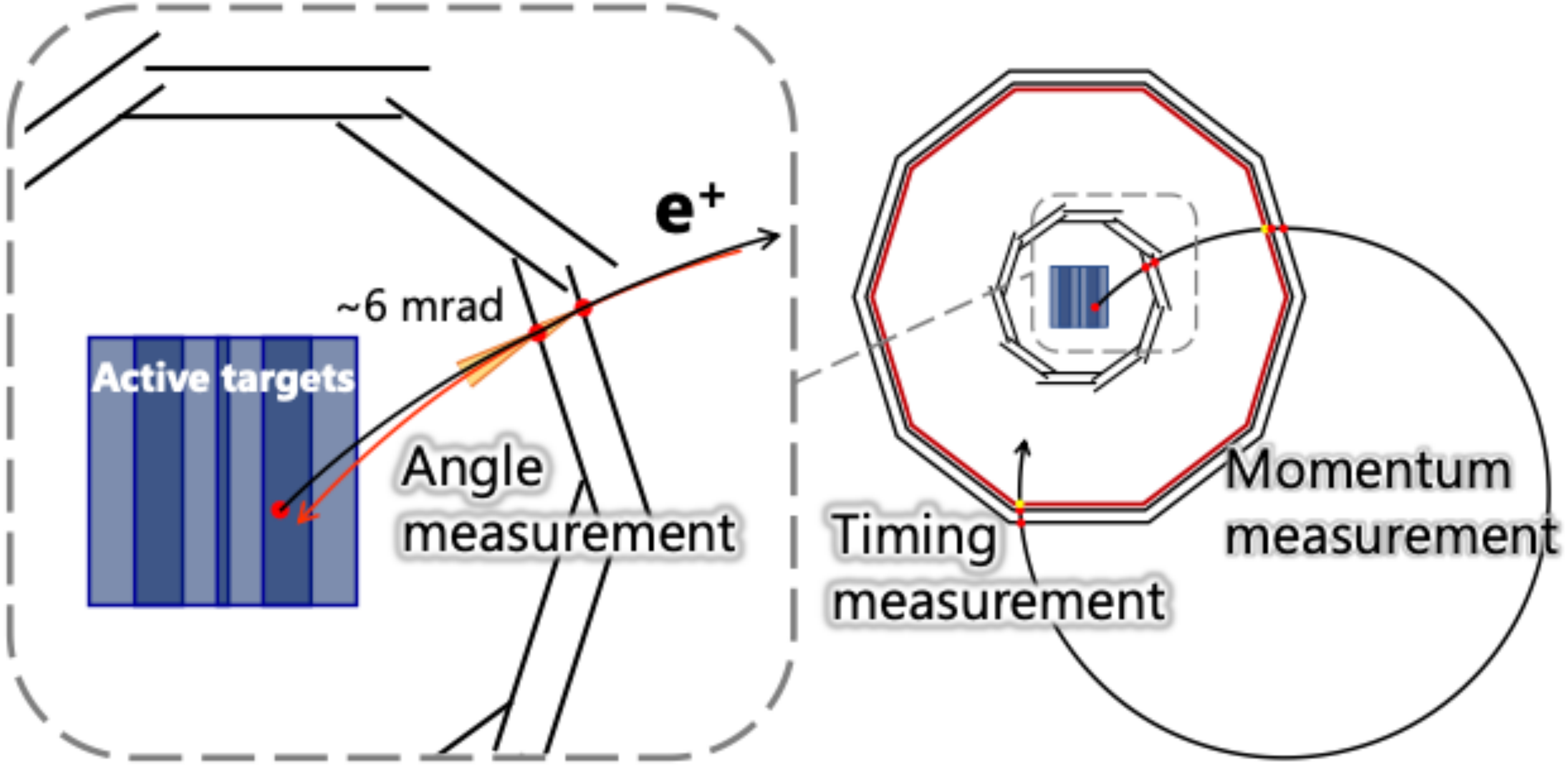
- High Intensity Muon Beam project (HiMB) at PSI
  - 10^{10} μ+/s (100× improvement)
  - CDR by end of 2021
  - Implementation during 2027/2028
  - Science Case workshop 6-9 April 2021
- Future μ→eγ experiment for CLFV
  - Goal: Br(μ→eγ) ~10^{-15}
  - Discover new physics and precision measurements
  - Detector R&D to make maximum use of HiMB
  - Resolution improvements
    - Calorimeter → converter + pair spectrometer
  - High rate tolerance
    - Drift chamber → Silicon detector
- Possible to measure μ→eee at the same time

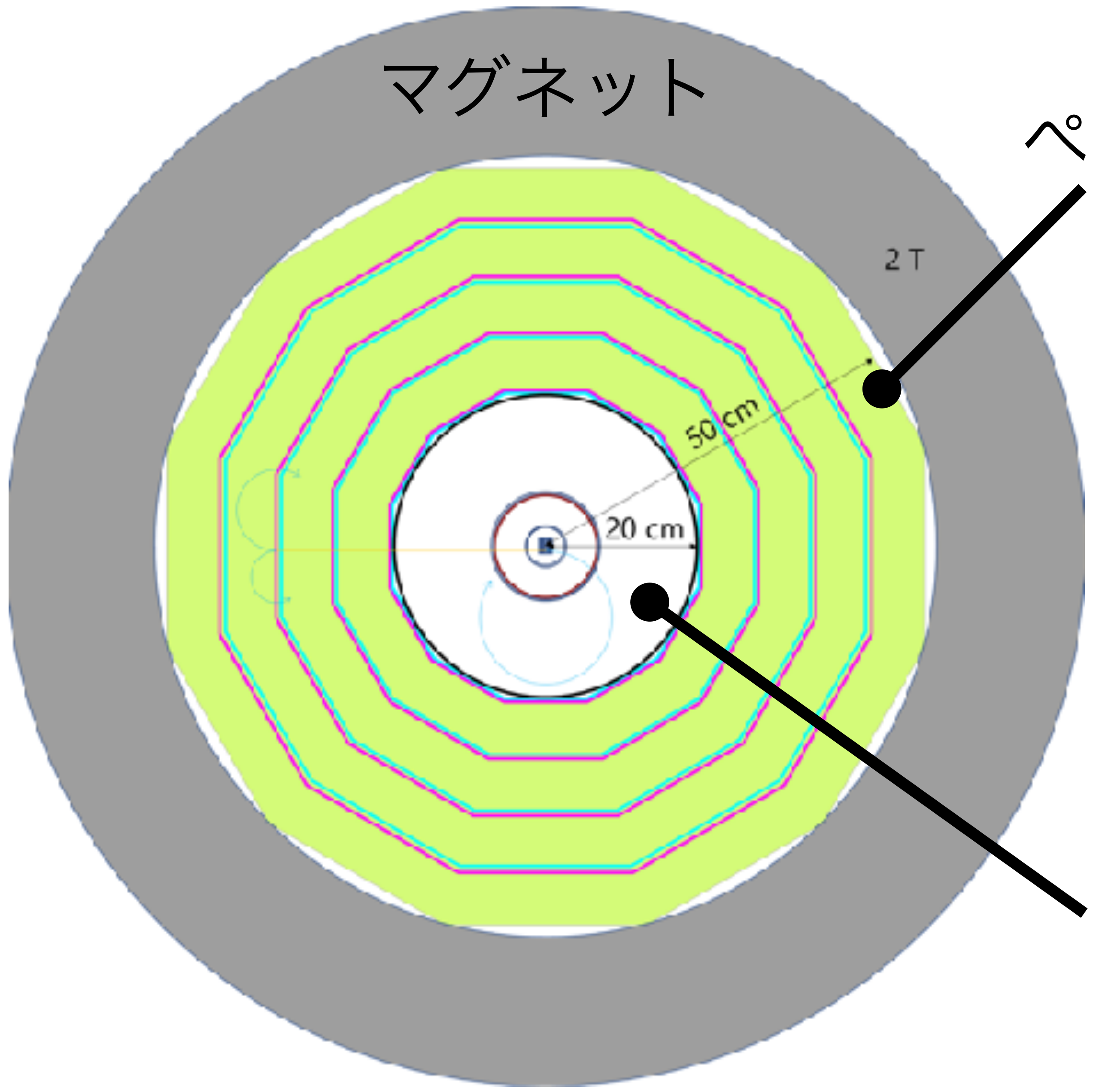




Future μ→eγ

- Positron spectrometer
  - HV-MAPS + scintillator or mRPC
  - Resolutions
    - energy 0.3%(150keV)・time 30ps・angle 6mrad・detection efficiency 70%
- Gamma converter + pair spectrometer
  - Resolutions
    - energy 0.4% (200keV)・time 30ps・position 0.2mm・angle 50mrad・detection eff. 60%





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