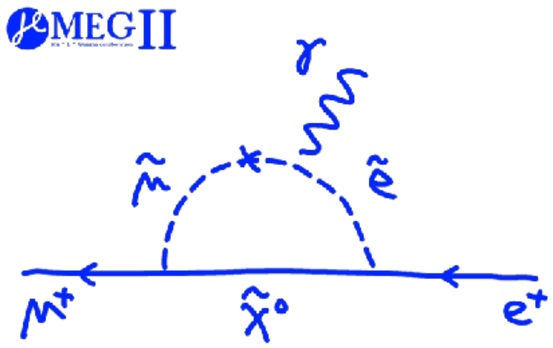
MEG II
- The Latest Results from the CLFV Search Experiment -

Toshiyuki Iwamoto
ICEPP, the University of Tokyo
On behalf of the MEG II collaboration

June 10th, 2025 @ Madison Wisconsin
15th Conference on the Intersections of Particle and Nuclear Physics

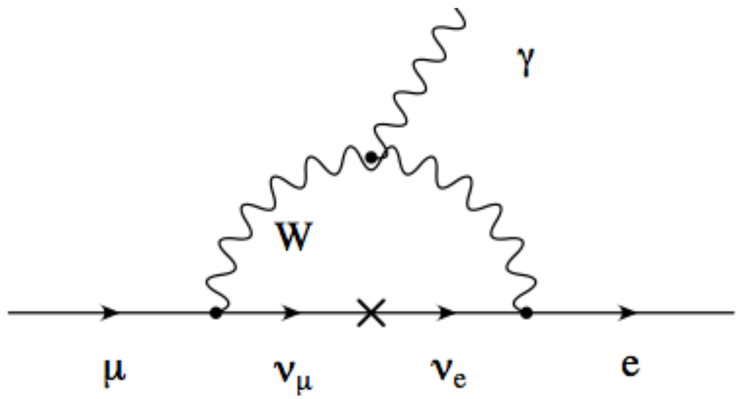


Charged lepton flavor violation (cLFV)

- One of the most powerful probes to search for New Physics (NP)
- The conservation of the lepton flavor is an accidental symmetry in SM
  - arising from the absence of right-handed neutrinos
- This symmetry is typically lost in NP models
  - lepton flavor violation is commonly predicted at the level of the current experimental sensitivities
- Discovery of neutrino oscillations demonstrated this symmetry is not exact
  - it is not sufficient to give observable cLFV effects
  - Their existence further stimulates the search for cLFV

Charged lepton flavor violation in Standard model (with ν mass) vs New physics

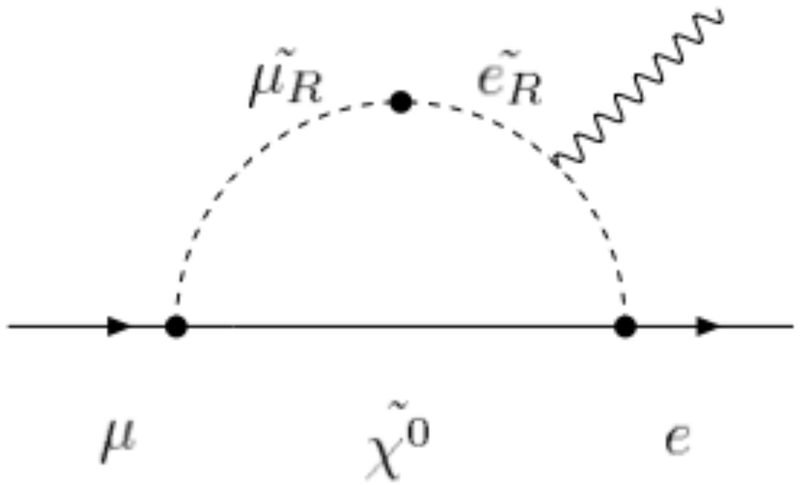
Charged lepton flavor transition has never been observed yet



$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U_{ek}^* m_{\nu_k}^2}{M_W^2} \right|^2$$

$\sim 10^{-54}$

Neutrino is too light



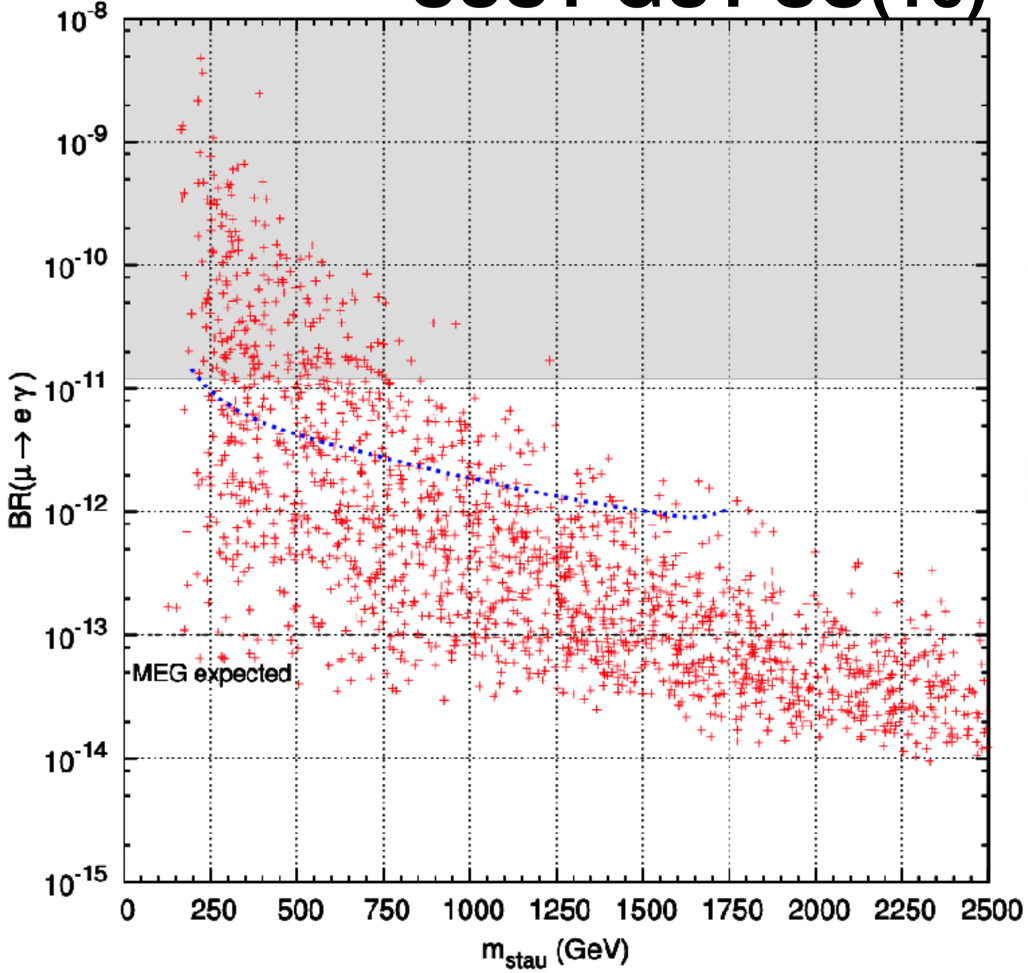
New particles from SUSY in the loop can enhance the branching ratio 10^{-12} – 10^{-14}

SUSY-GUT / SUSY-seesaw

Evidence of $\mu^+ \to e^+\gamma$ = Evidence of new physics

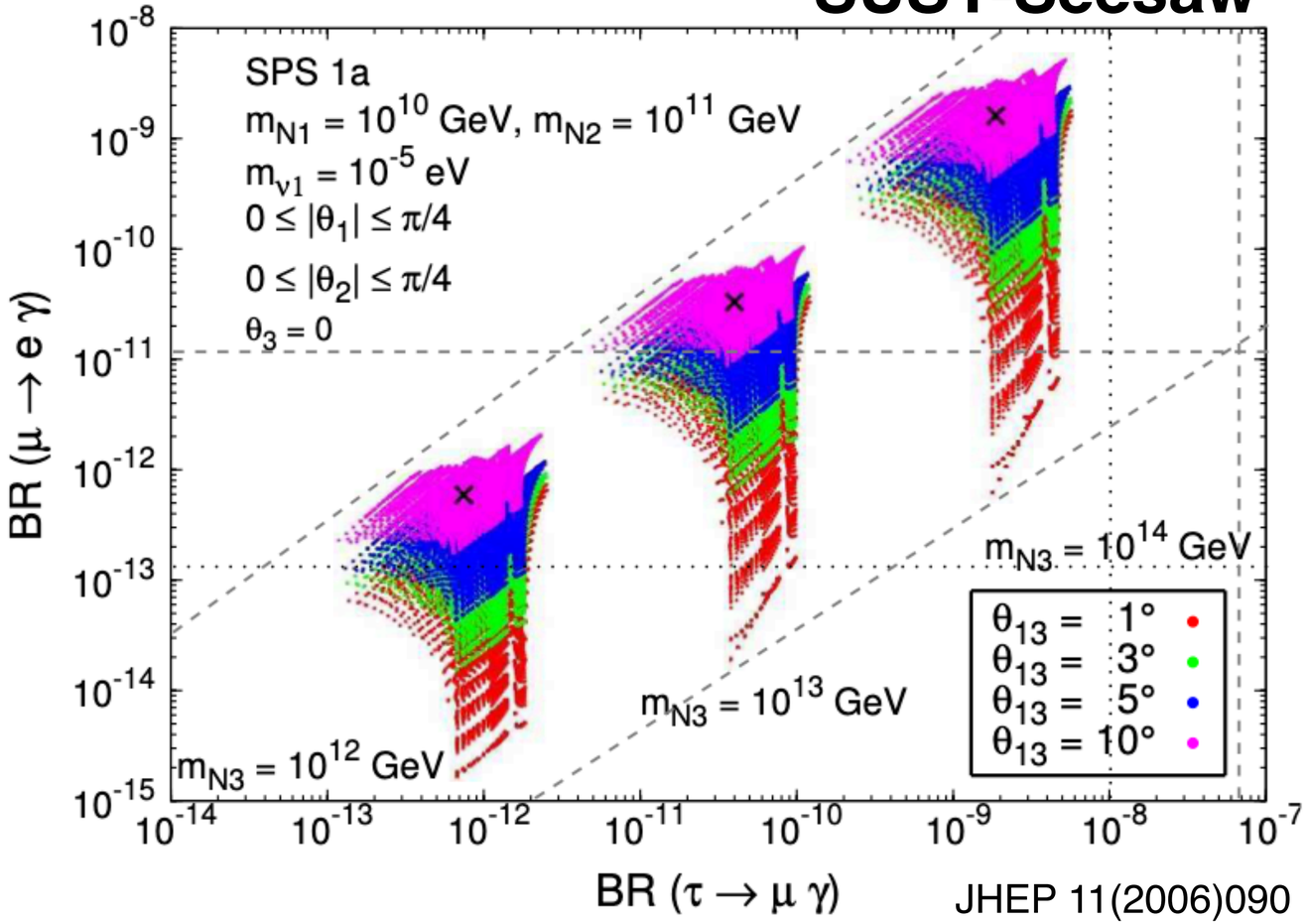
Examples of new physics

SUSY-GUT SO(10)



JHEP 0912(2009)057

SUSY-Seesaw



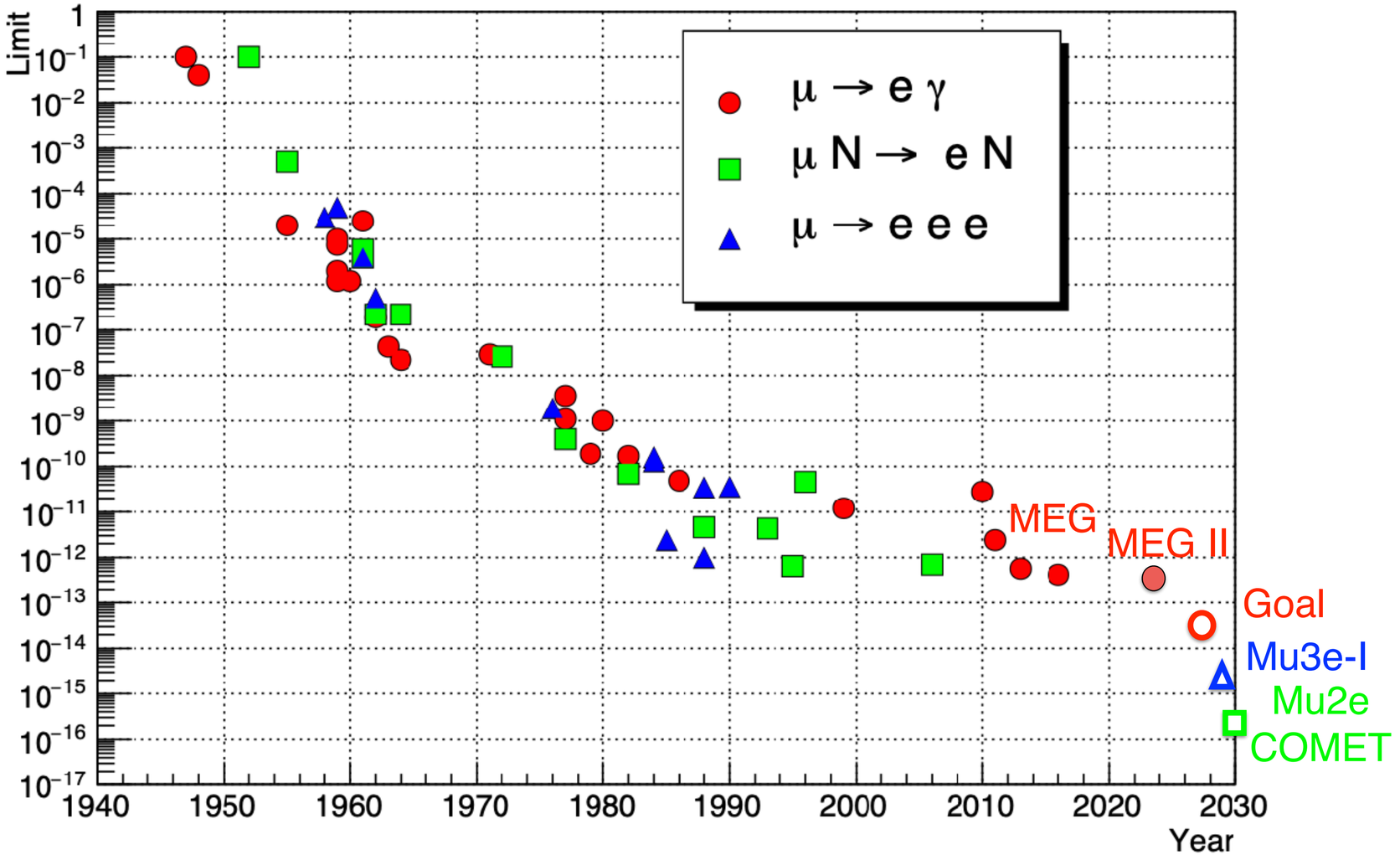
JHEP 11(2006)090

Real chance for discovery

Already some regions from theoretical expectation excluded

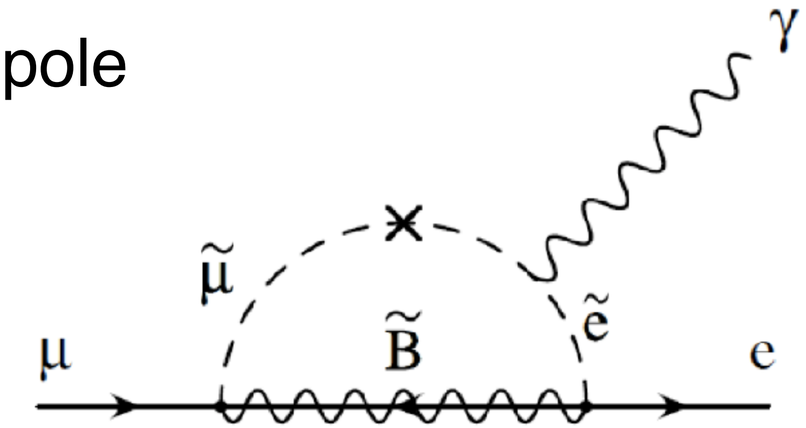
$\mu^+ \to e^+\gamma, \mu^+ \to e^+e^-e^+, \& \mu^- \to e^-$

- Golden channels
  - High intensity muon beam
  - Clean signature
- Synergy to look for these decay modes at the same time
  - Maximize the discovery potential to different new physics model
  - Pin down the new physics model with independent branching ratio values after the discovery

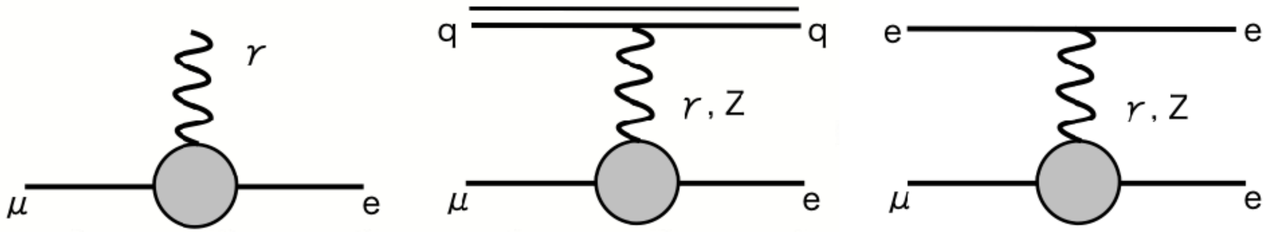


New physics models

Dipole



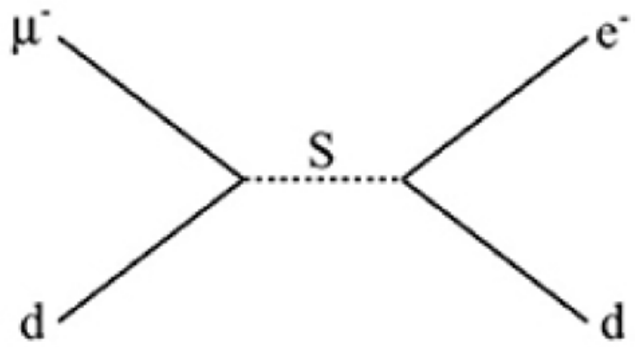
SUSY-GUT, SUSY-seesaw



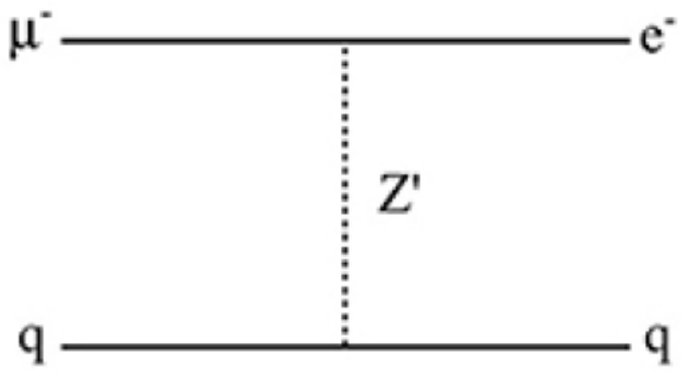
Br(μ→eγ) : R(μ-Al→e-Al) : Br(μ→3e)

= 1 : 1/390 : 1/170

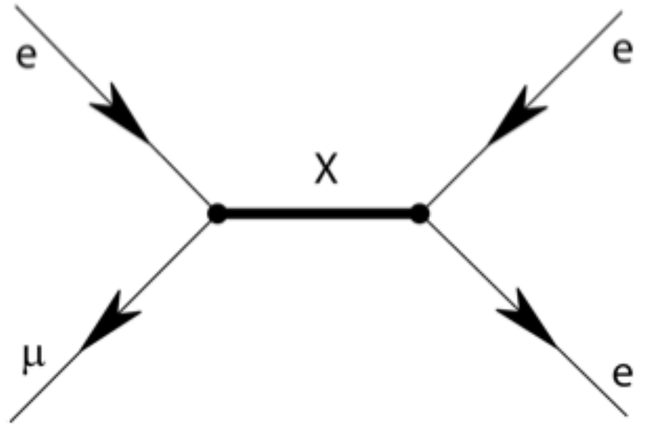
Tree



Scalar: RPV SUSY

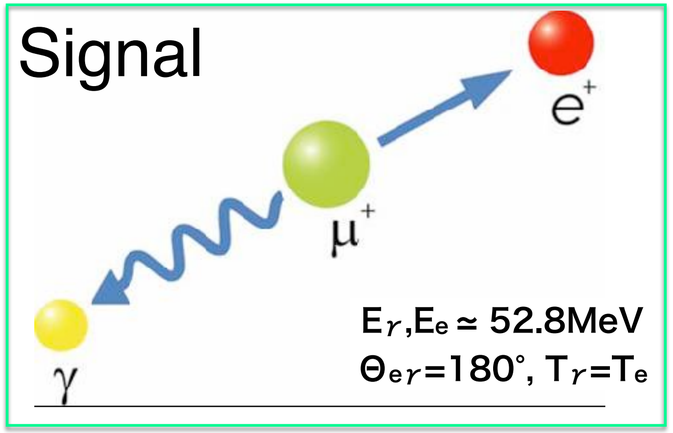


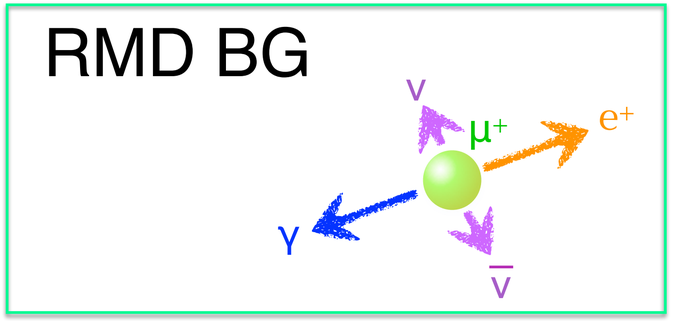
Vector: Leptoquarks, Z',…

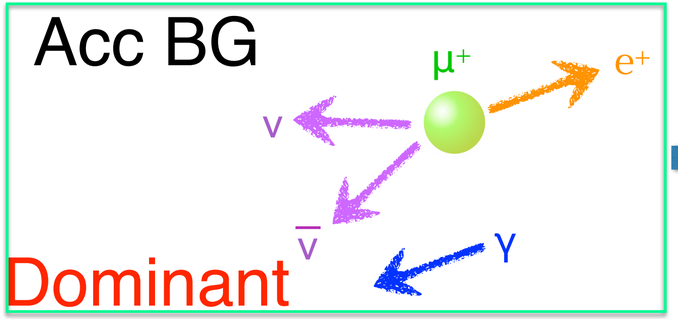


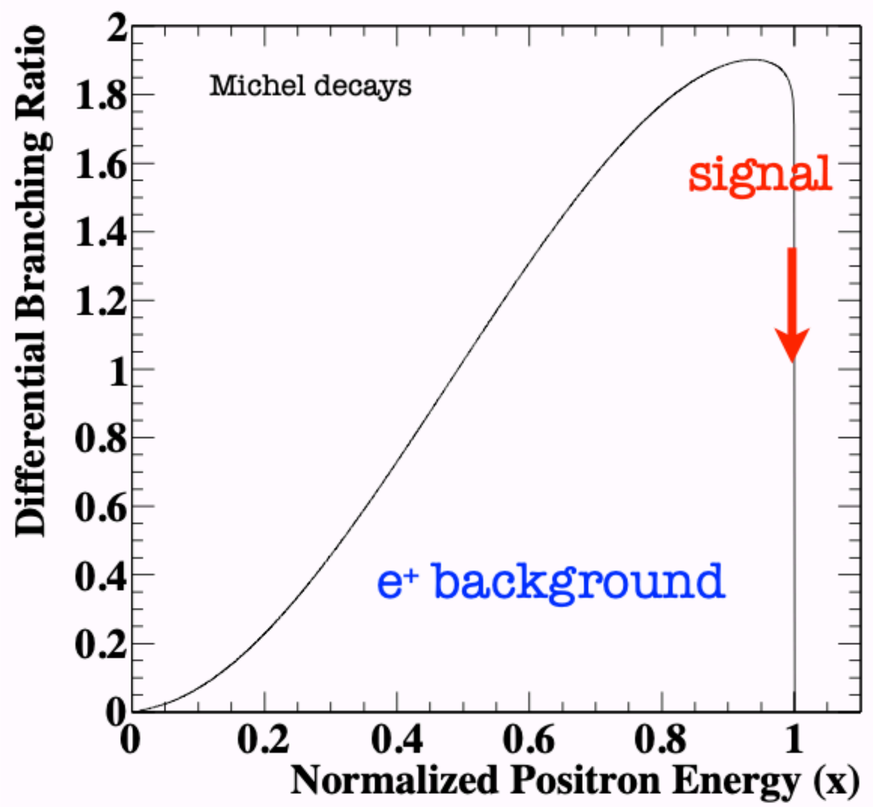
4-lepton:
Type II seesaw, RPV SUSY, LRSM, …

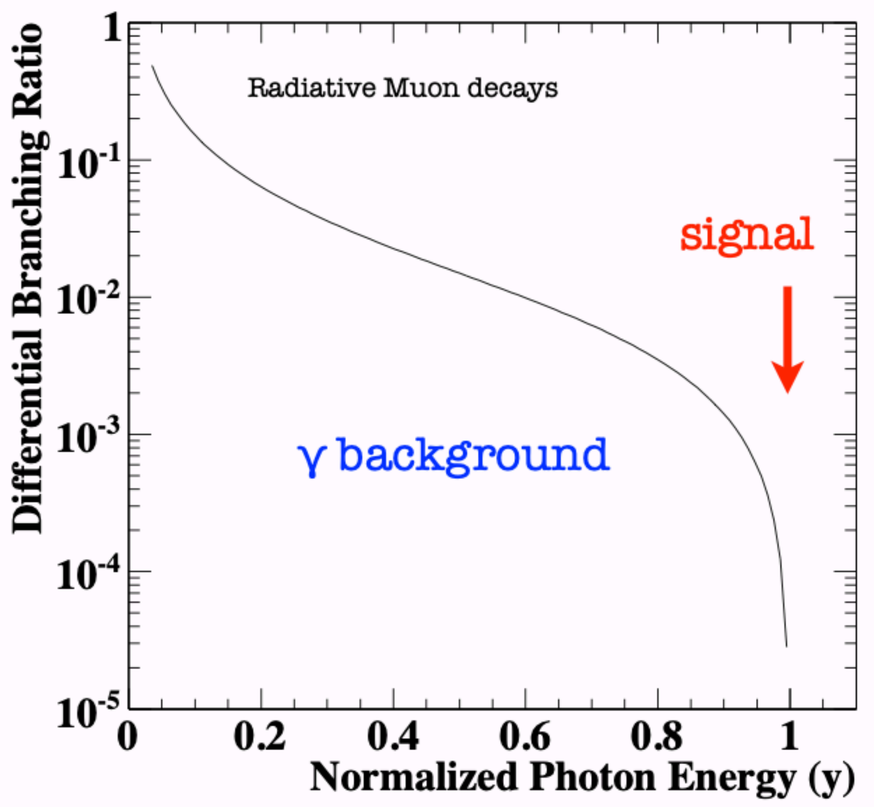
$\mu^+ \to e^+\gamma$ signal and backgrounds











$N_{Sig} \propto R_\mu \times T \times Br(\mu \to e\gamma) \times \varepsilon$

Efficiency crucial for statistics

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

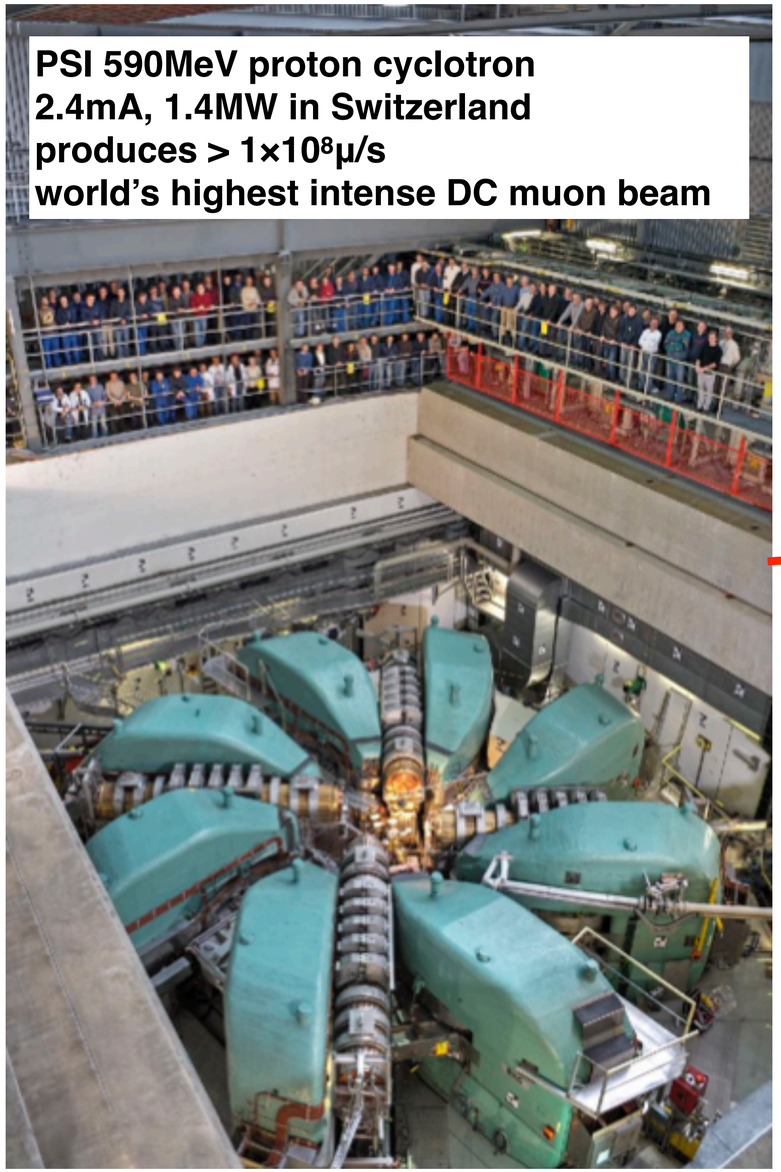
Good resolution crucial to lower the accidental background (N_{BG})

Beam rate

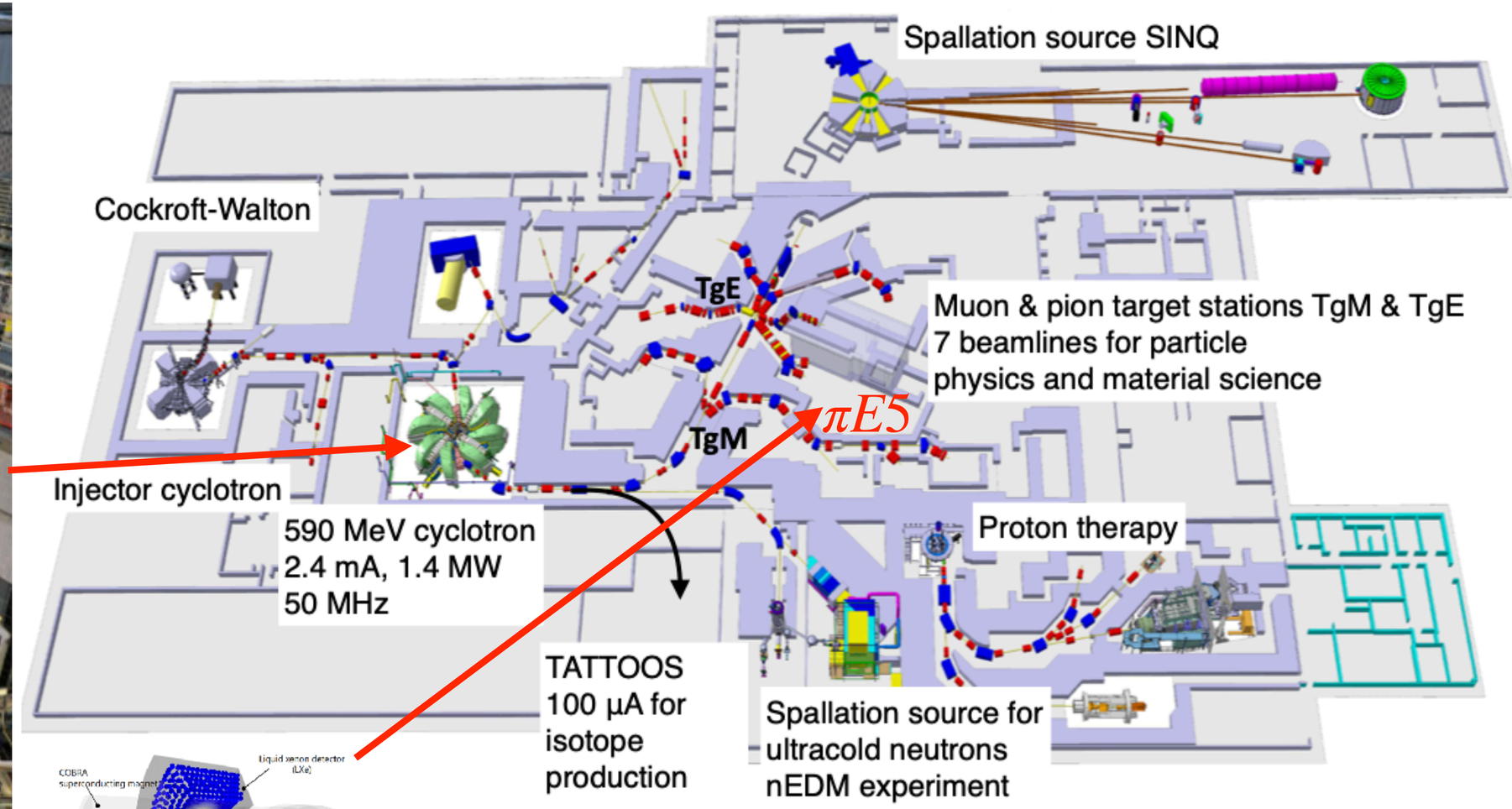
Resolutions

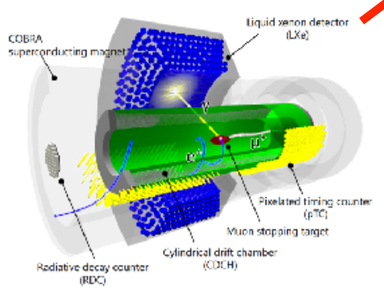
Elapsed time

Paul Scherrer Institute (PSI) in Switzerland



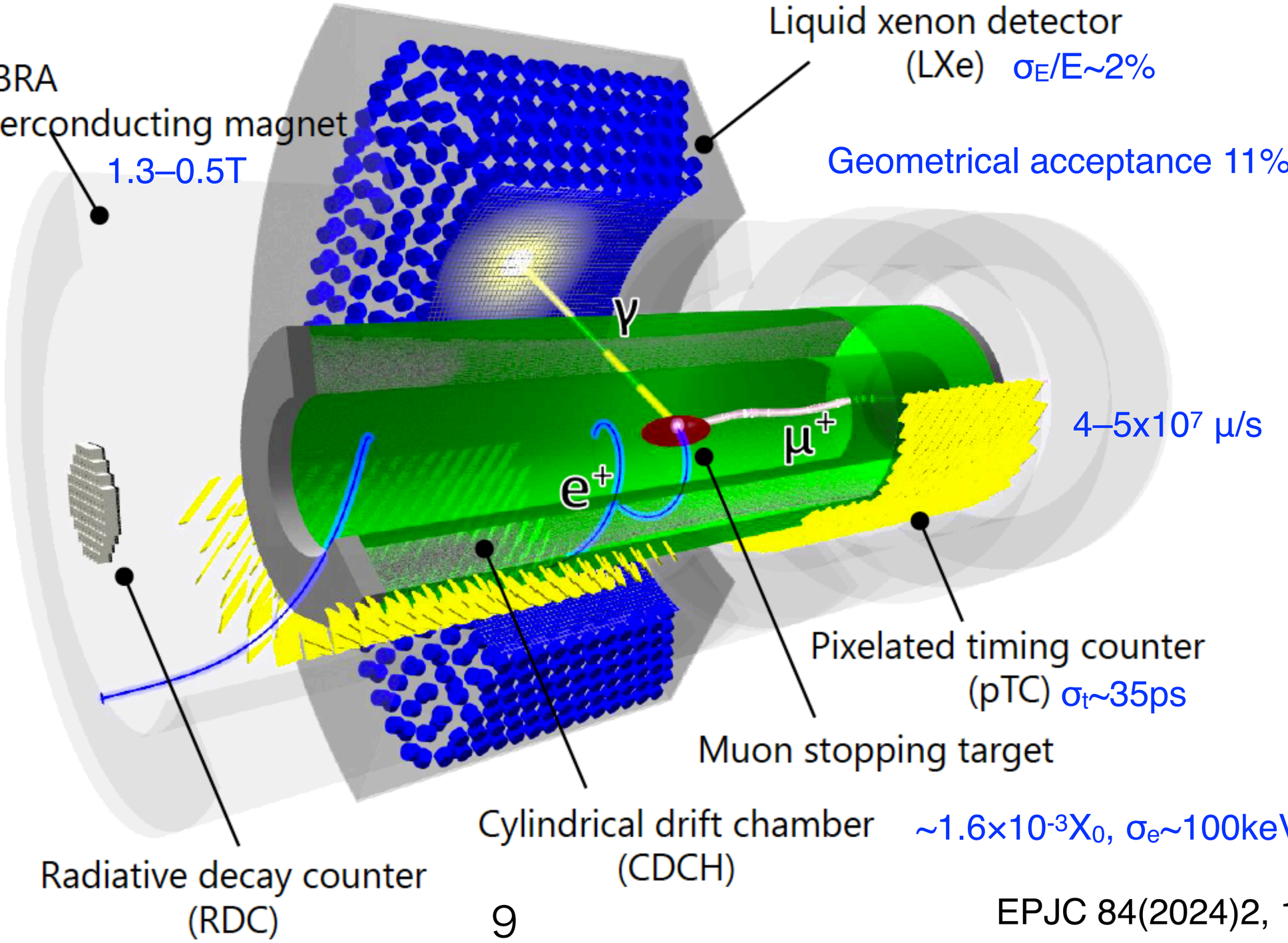
PSI 590MeV proton cyclotron
2.4mA, 1.4MW in Switzerland
produces > 1×10^{8}μ/s
world's highest intense DC muon beam





MEG II → Needs high intensity muon beam

MEG II



Target sensitivity :
6×10^{-14} (90%C.L.)

MEG final result:
4.2×10^{-13}(90%CL)

MEG sensitivity:
5.3×10^{-13}(90%CL)

Eur. Phys. J.C76(8),434(2016)

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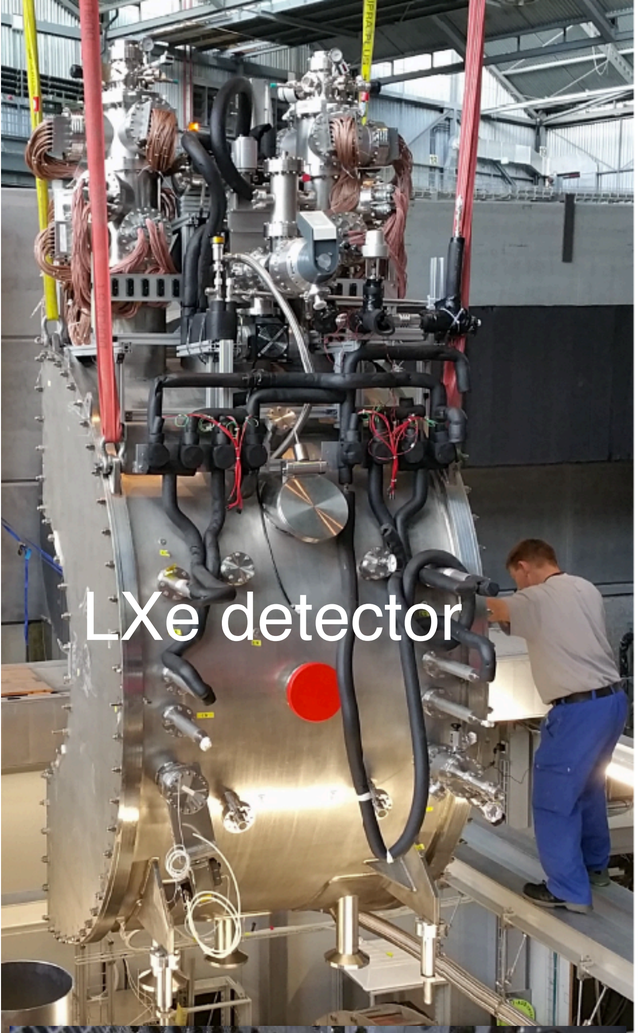
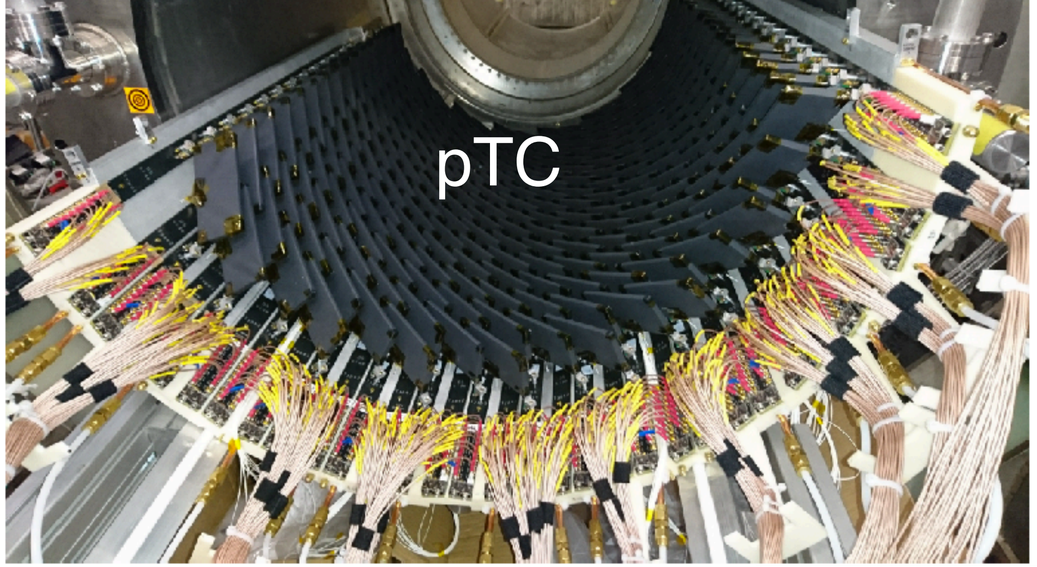
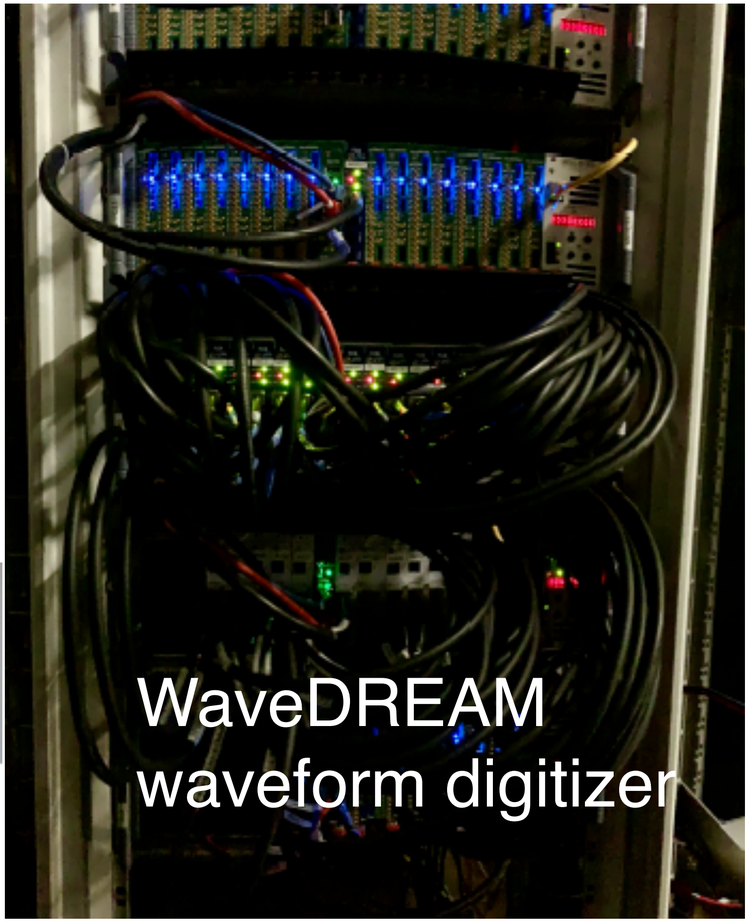
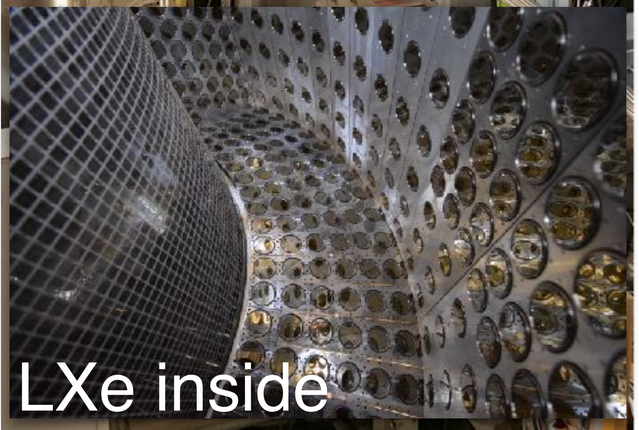
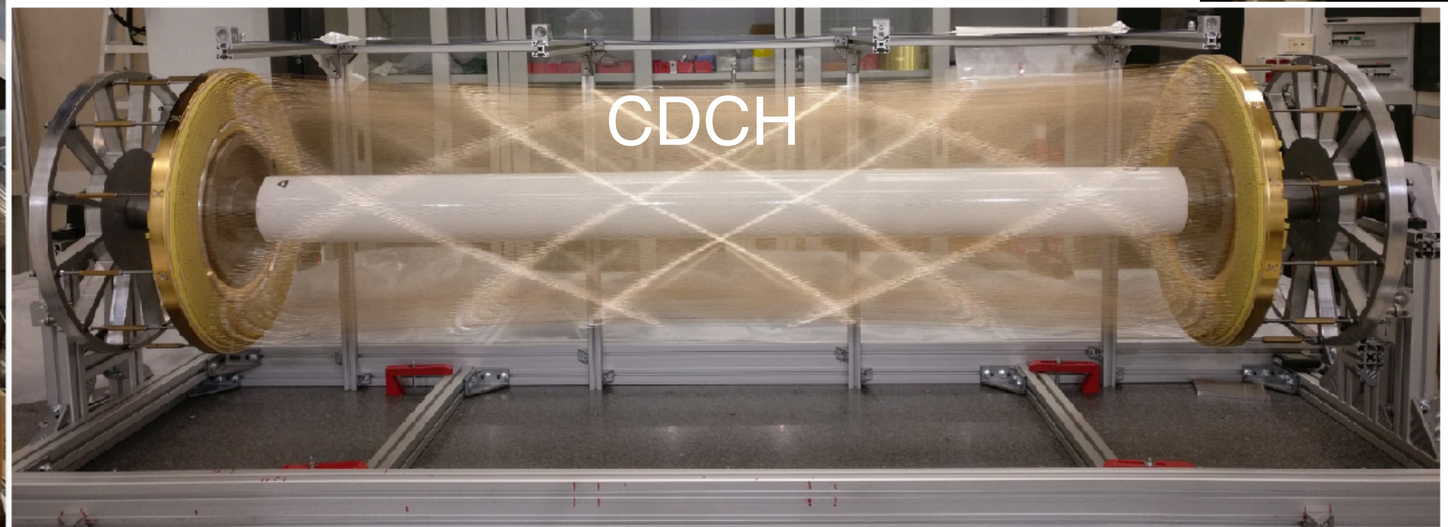


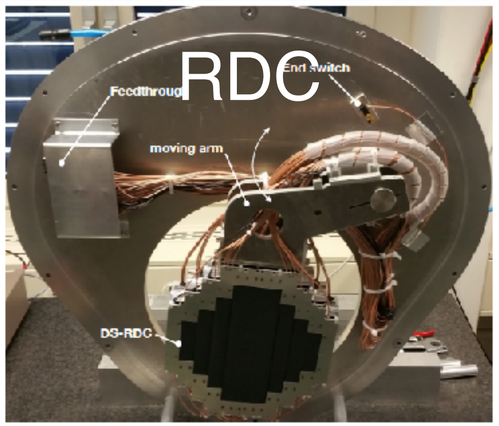


MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-

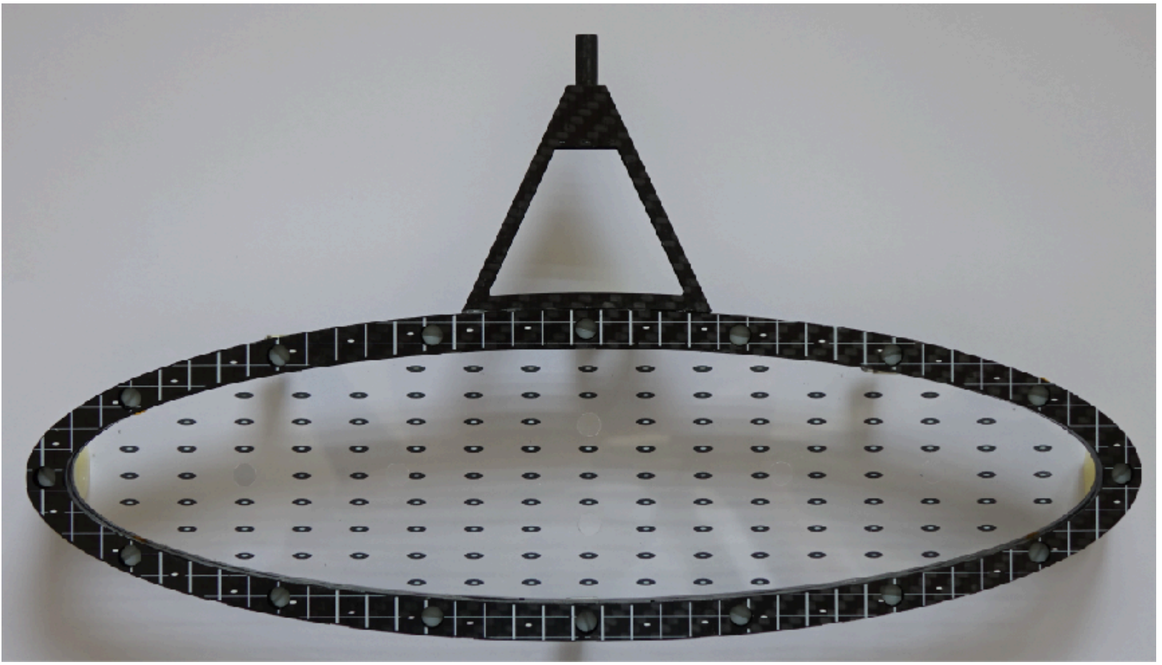


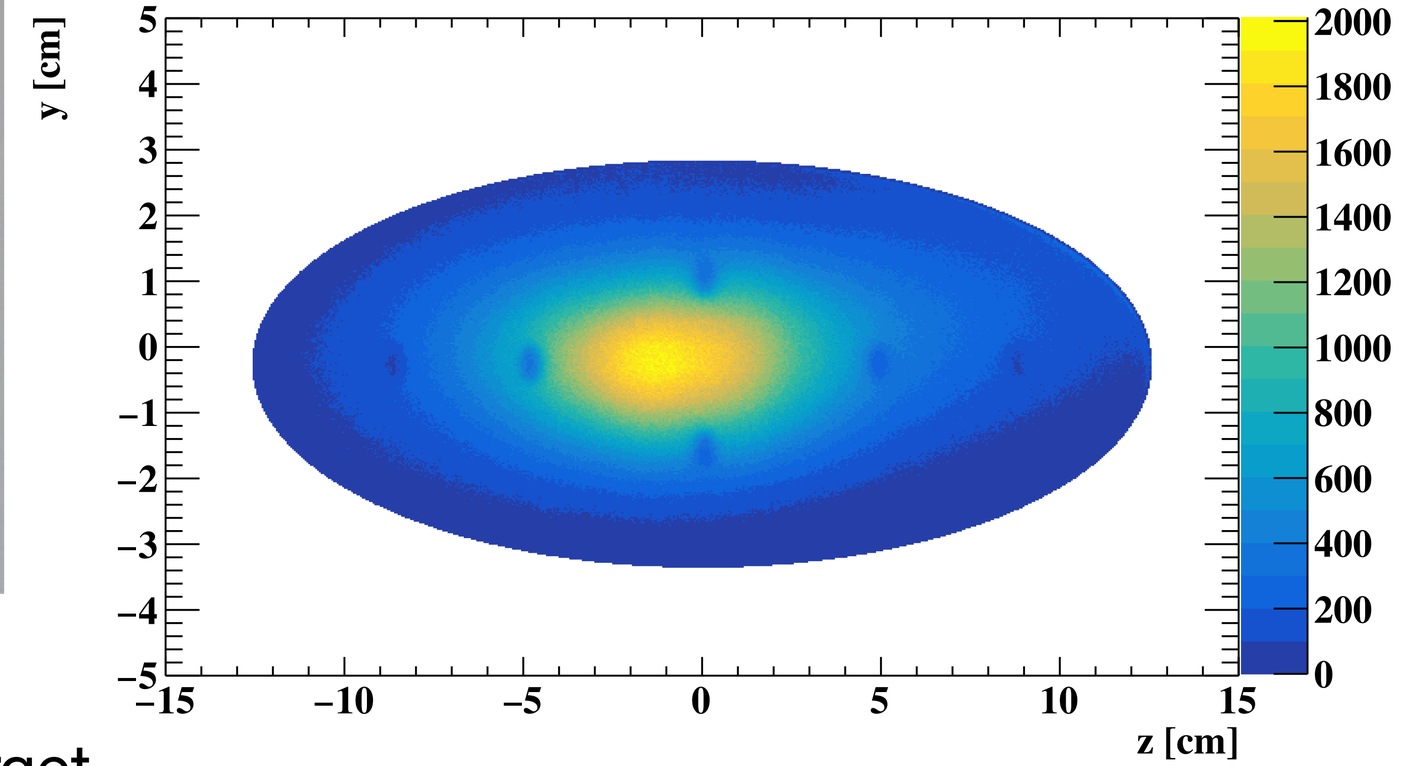




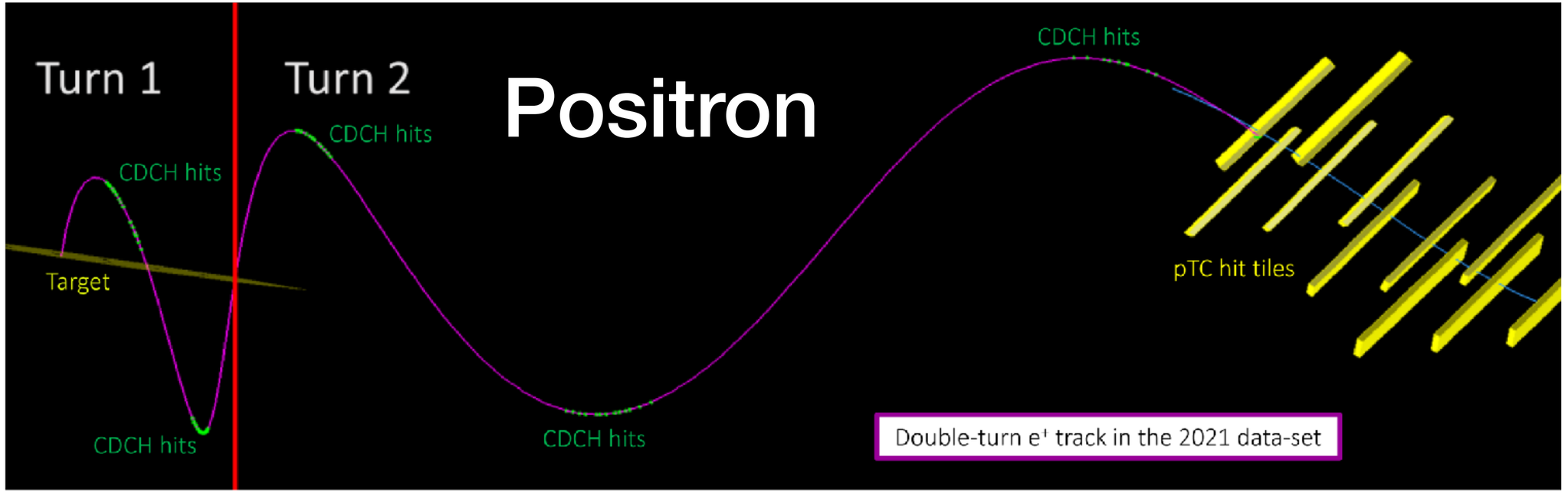


Target

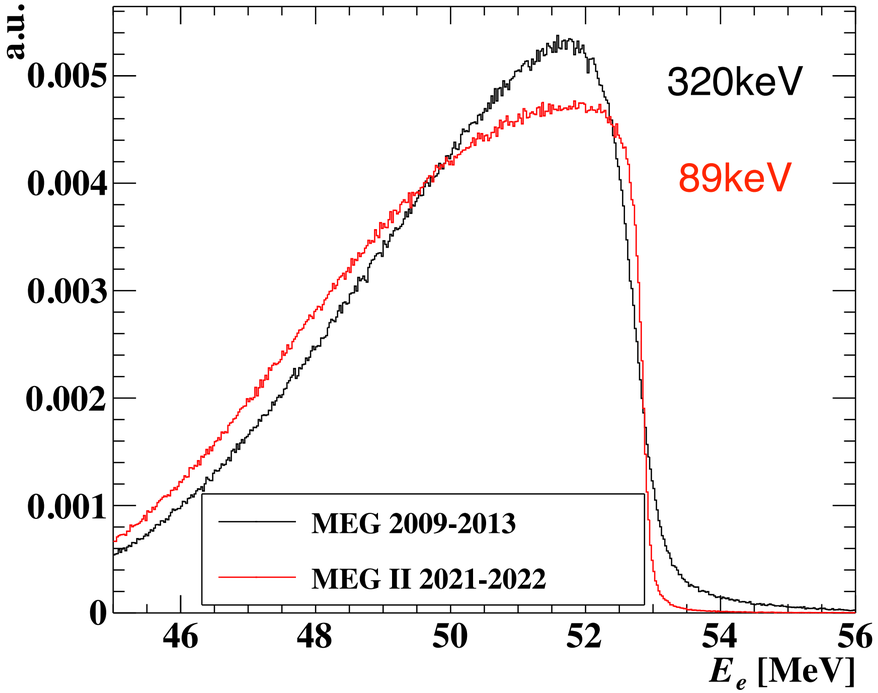


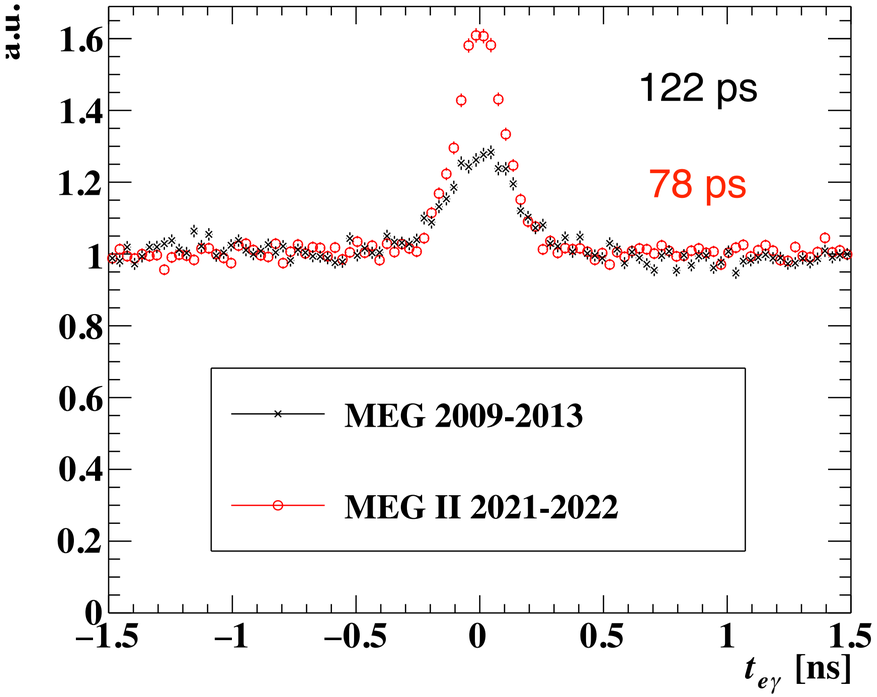


- Slanted 174μm thick BC400 target
  - 6 holes (reconstructed positron distribution) and a pattern of dots (photographed by a camera) to continuously monitor the shape and position of the foil



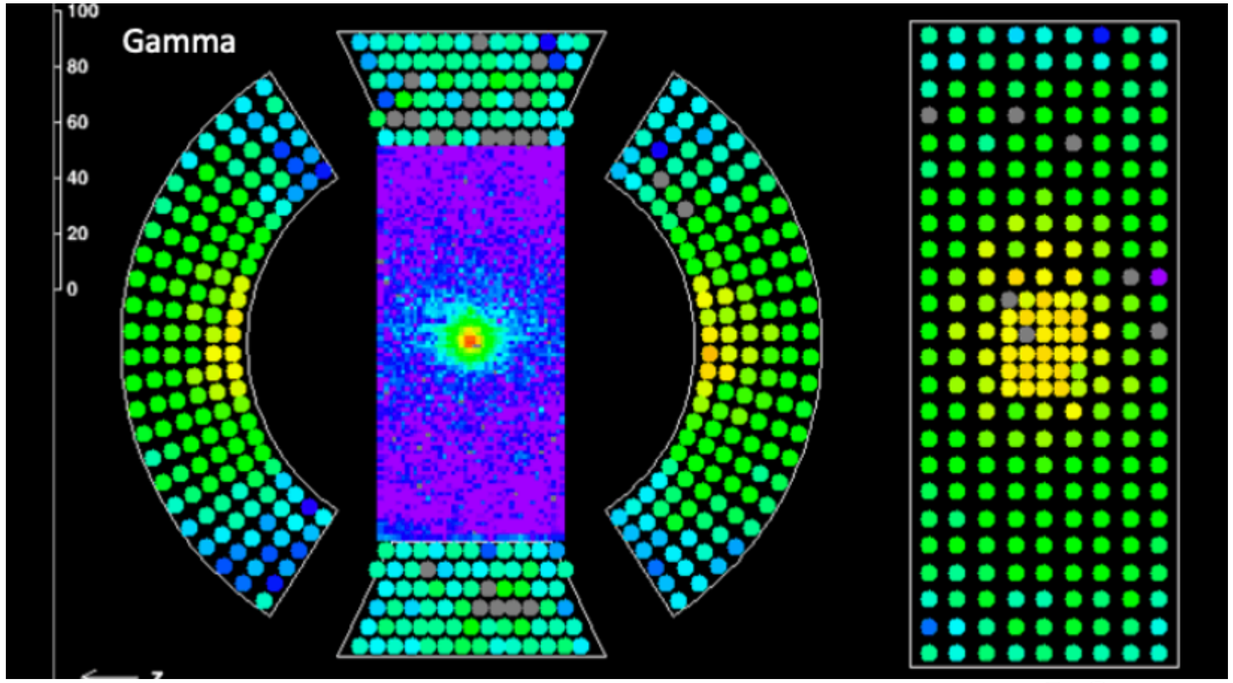
- Drift chamber
  - 0.16% X_0 (low mass)
  - Stereo wire geometry
  - Square cells with 6mm, 9 layers
- Pixelated timing counter
  - 256 x 2 BC422 scint. + SiPMs
  - 9 hits on average

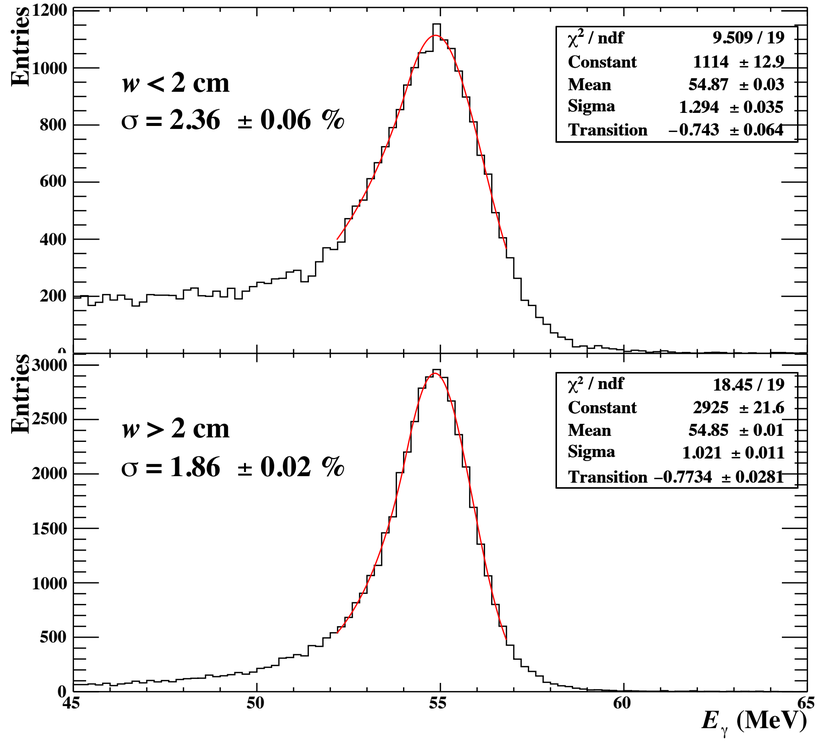


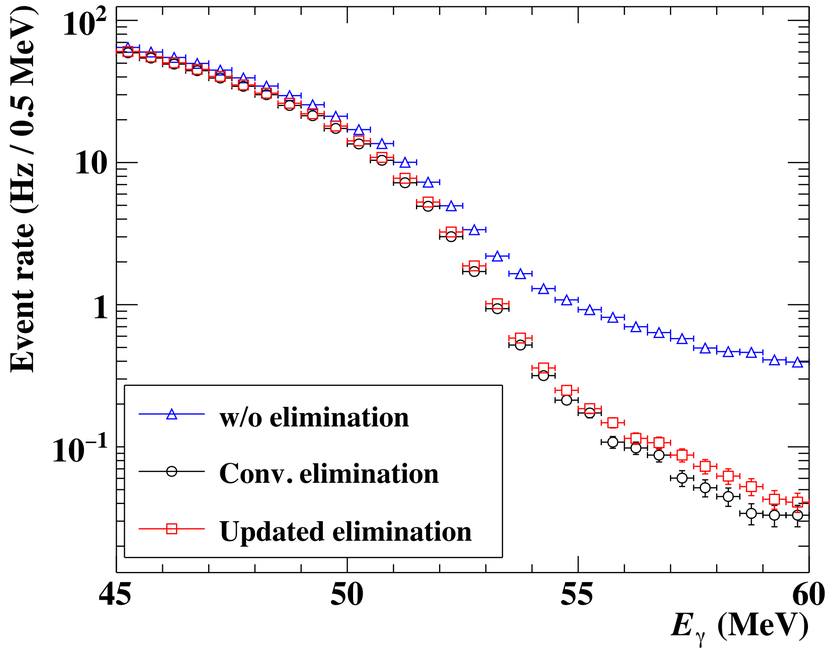


Photon

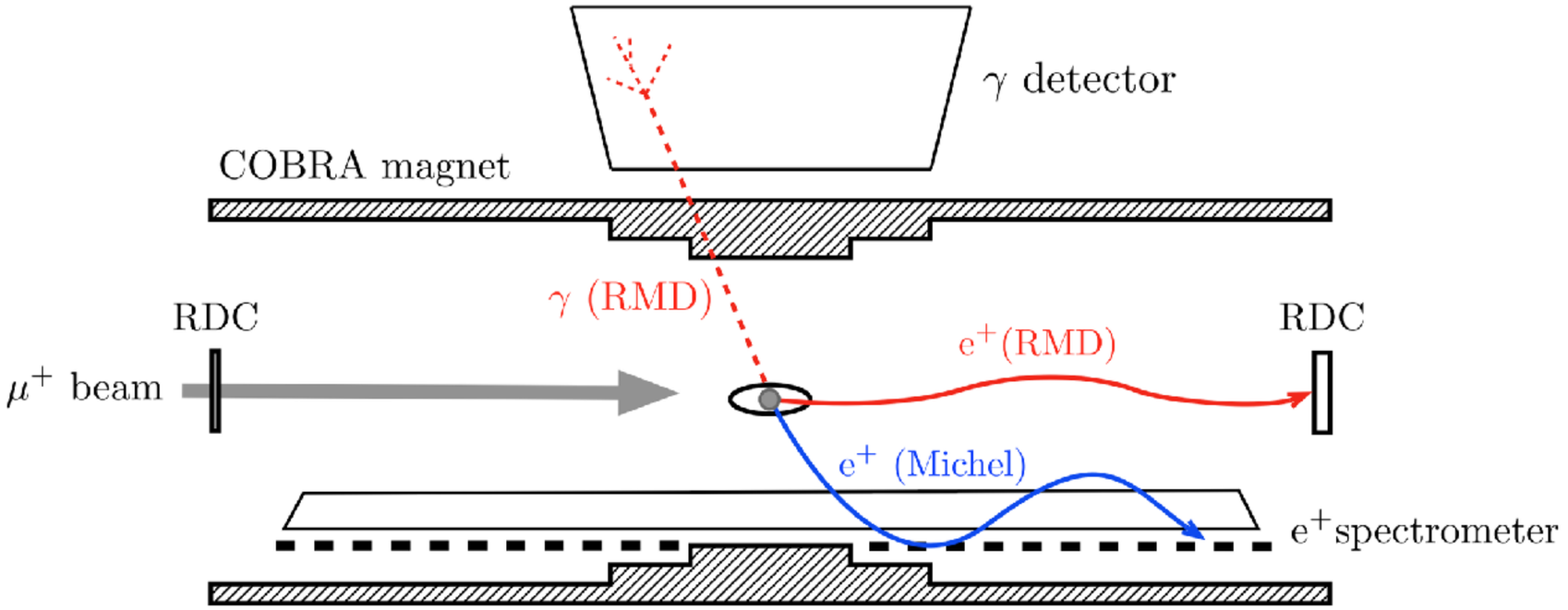
- 900 L liquid xenon at 165K
- VUV-sensitive 4092 MPPCs + 668 PMTs at 175nm
- Performance check
  - 55 MeV γ from $\pi^- p \rightarrow \pi^0 n (\pi^0 \rightarrow \gamma\gamma)$
- Pileup removal by light distribution and waveform timing



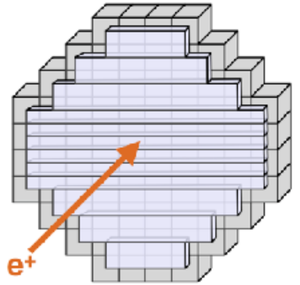




Radiative Decay Counter

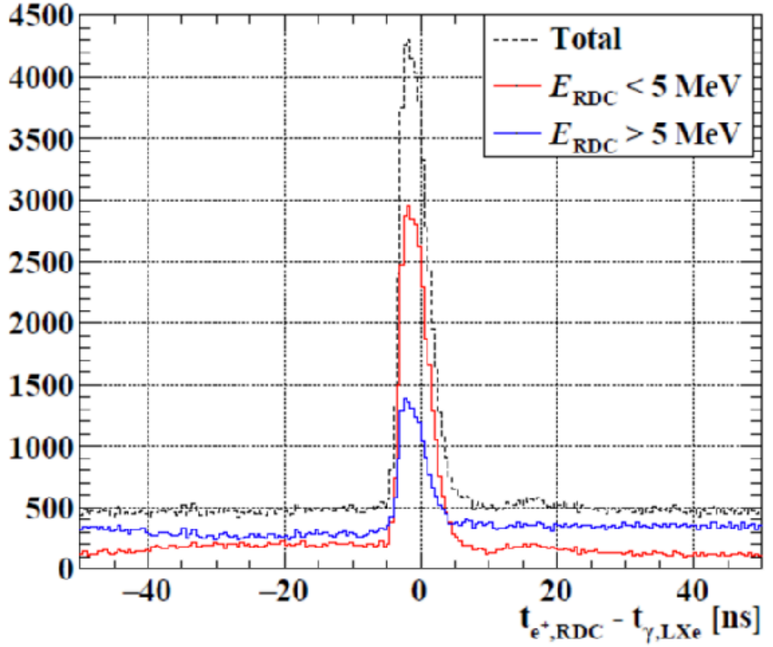


LYSO 2×2×2 cm³+SiPM for e⁺ energy



Plastic Scinti.+SiPM for e⁺ timing

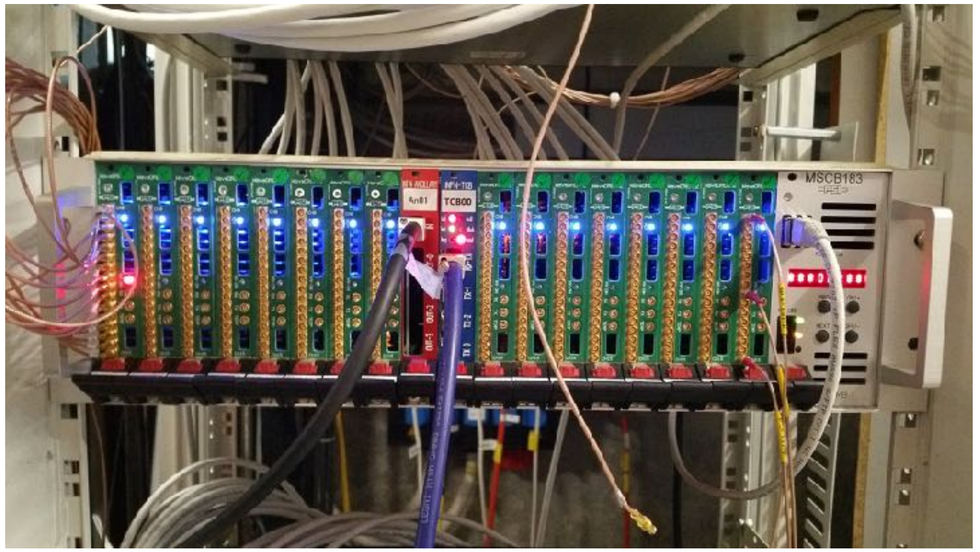
RDC e⁺ and LXe γ time difference

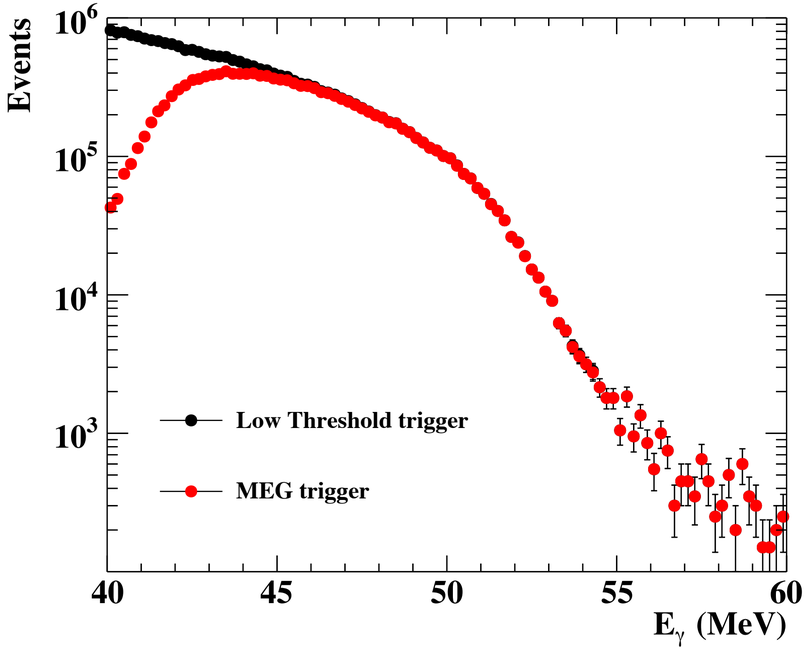


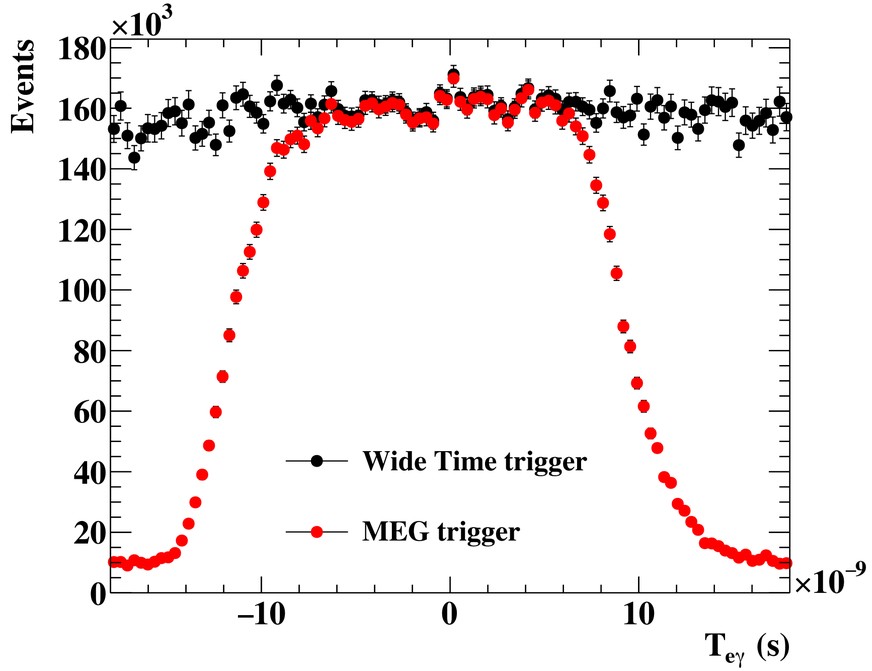
- New device for MEG II
  - Tagging high energy γ background from RMD ($\mu^+ \to e^+\nu\nu\gamma$) by identifying low momentum e^+

Electronics

- WaveDAQ system
  - Waveform of all the detectors (~9000 ch.) are readout
  - developed by PSI and INFN
  - Waveform digitizer (DRS4)+amplifier+SiPM voltage supply (~240V) with 1.4 GSPS (in our application, possible up to 5 GSPS) readout speed
- Online trigger
  - FPGA based trigger system
  - Trigger rate:
    10-30Hz for $\mu \rightarrow e\gamma$







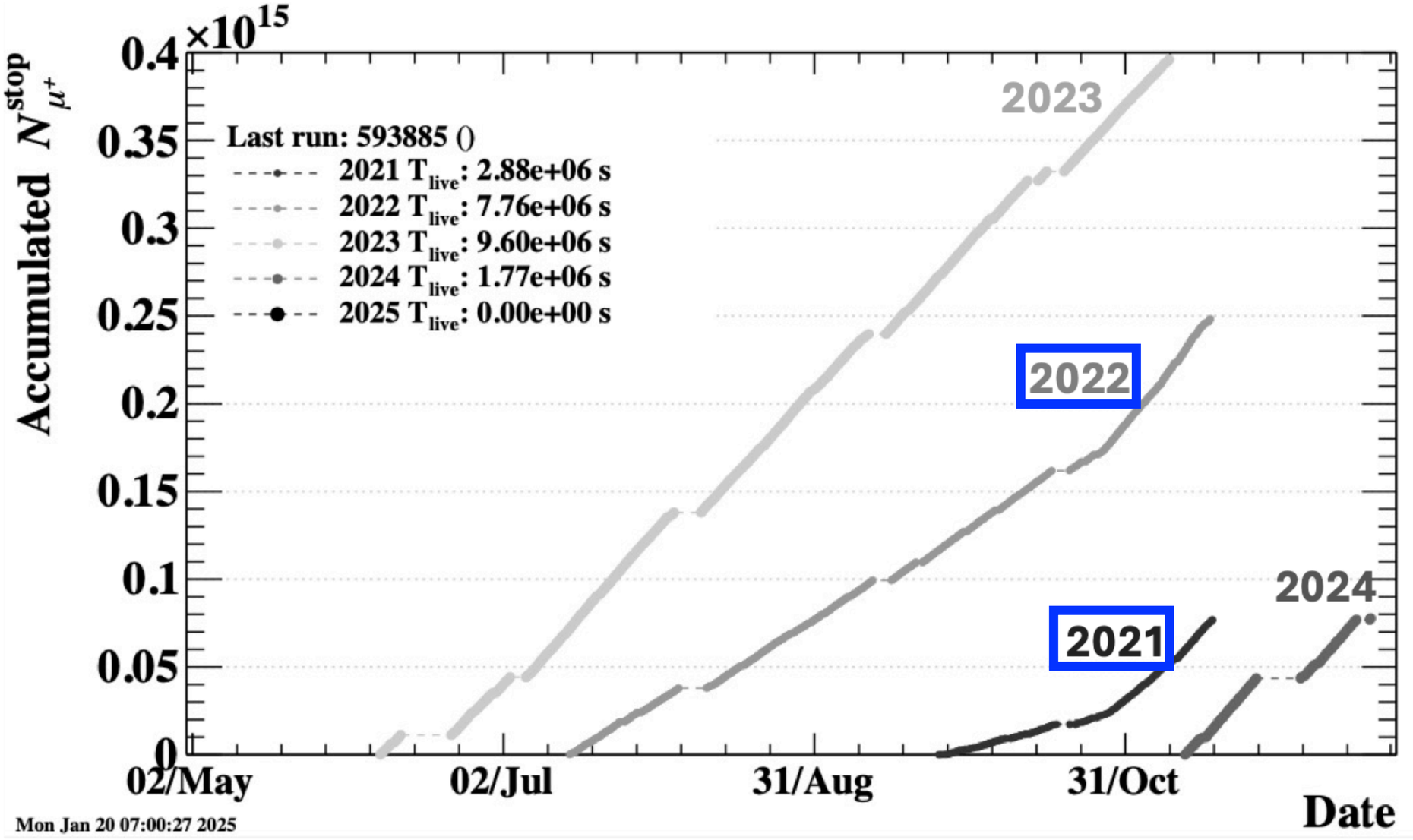
Detector performance summary

Table 6 Resolutions (Gaussian σ) and efficiencies measured at $R_\mu = 4 \times 10^7\ \mathrm{s}^{-1}$, compared with the predictions from [3,57].

Resolutions	Foreseen	Achieved	MEG
E_{e^+} (keV)	100	89	320
ϕ_{e^+} [a], θ_{e^+} (mrad)	3.7/6.7	5.2/6.2	9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.61/1.76	
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.4/1.9 (2.1/1.8)	2.4 / 1.7
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5 / 5 / 6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
ε_{e^+}	65	67	30
ε_{TRG}	≈99	91 (88)	96
		2022 (2021)	

updated from EPJC 84(2024)2, 190

MEG II data taking so far



MEG II statistics so far (-2024)

8.1 x 10^{14} μ stops

This time (2021-2022)

3.5 x 10^{14} μ stops

Sensitivity(2021-2022)

2.2 x 10^{-13}

Method of $\mu \to e\gamma$ search

- Blind analysis
  - Time coincidence $t_{e^+\gamma}$ within 1ns, 48MeV<E_γ<58MeV
- Sideband to extract PDFs, analysis check
  - Four time sidebands for N_{ACC} study
  - low energy sideband for N_{RMD} study
- Maximum likelihood analysis to estimate N_{sig}
  - Confidence interval from Feldman-Cousins method

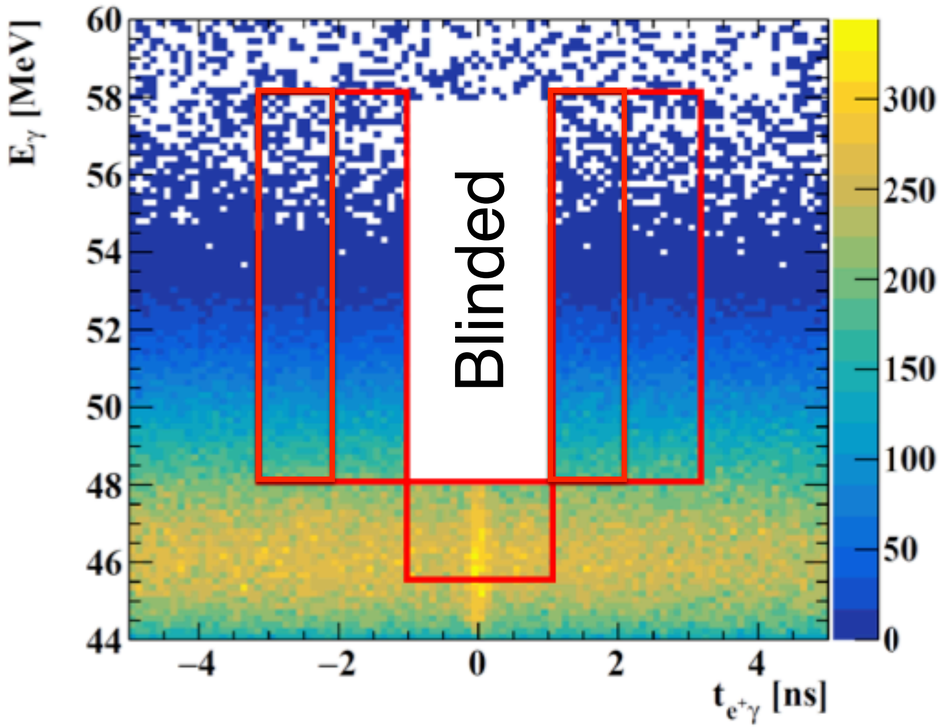
nuisance parameters

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) = \frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm ACC})}}{N_{\rm obs}!} \underbrace{C(N_{\rm RMD}, N_{\rm ACC}, x_{\rm T})}_{\text{constrained}} \times \underbrace{\prod_{i=1}^{N_{\rm obs}} (N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm ACC} A(\vec{x}_i))}_{\text{constrained by sideband}}$$

per-event PDFs

$\vec{x}_i = (E_e, E_\gamma, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}, \Delta t_{\rm RDC}, E_{\rm RDC}, n_{\rm pTC})$

$x_{\rm T}$ represents the target misalignment uncertainty



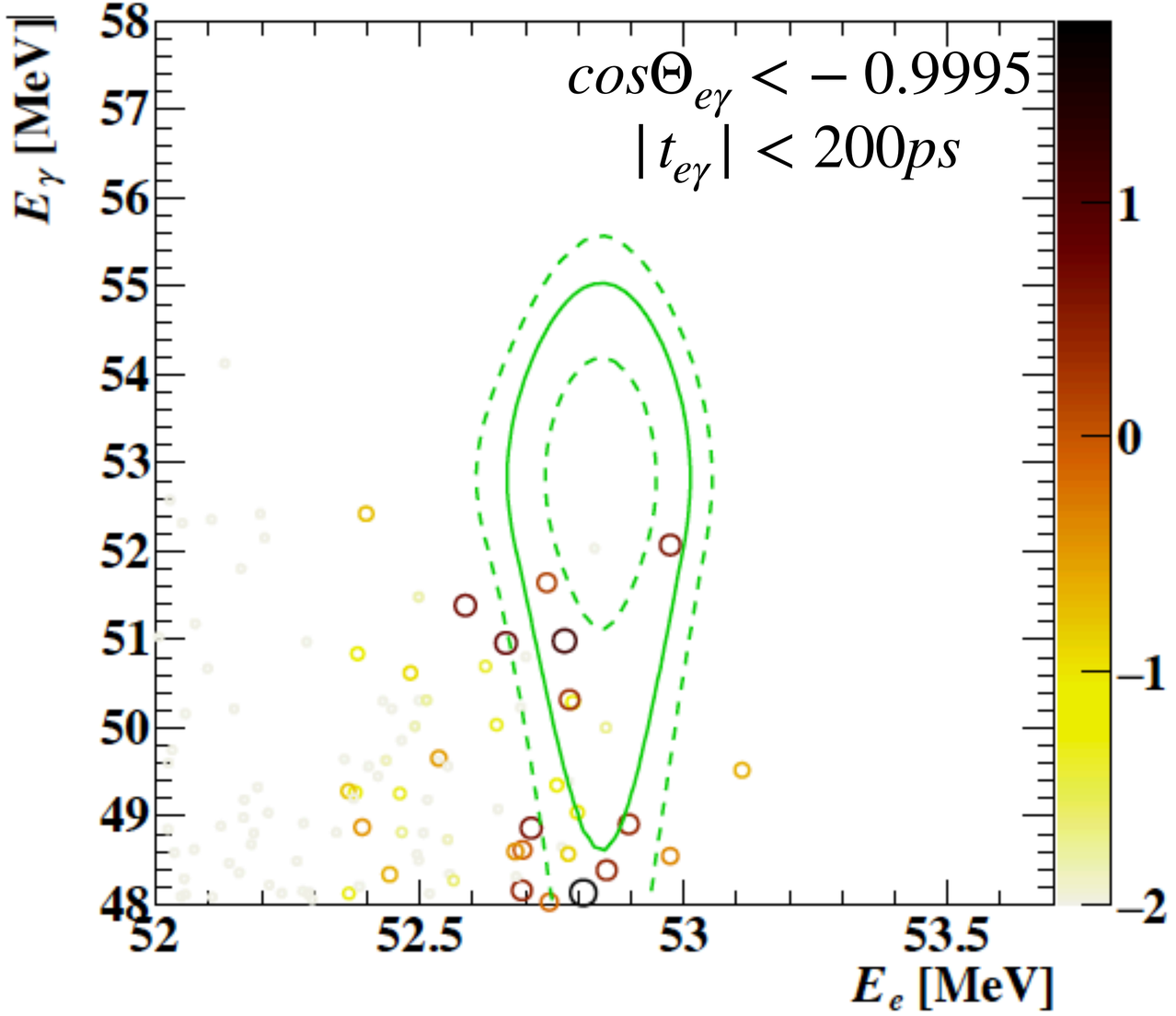
Analysis Region

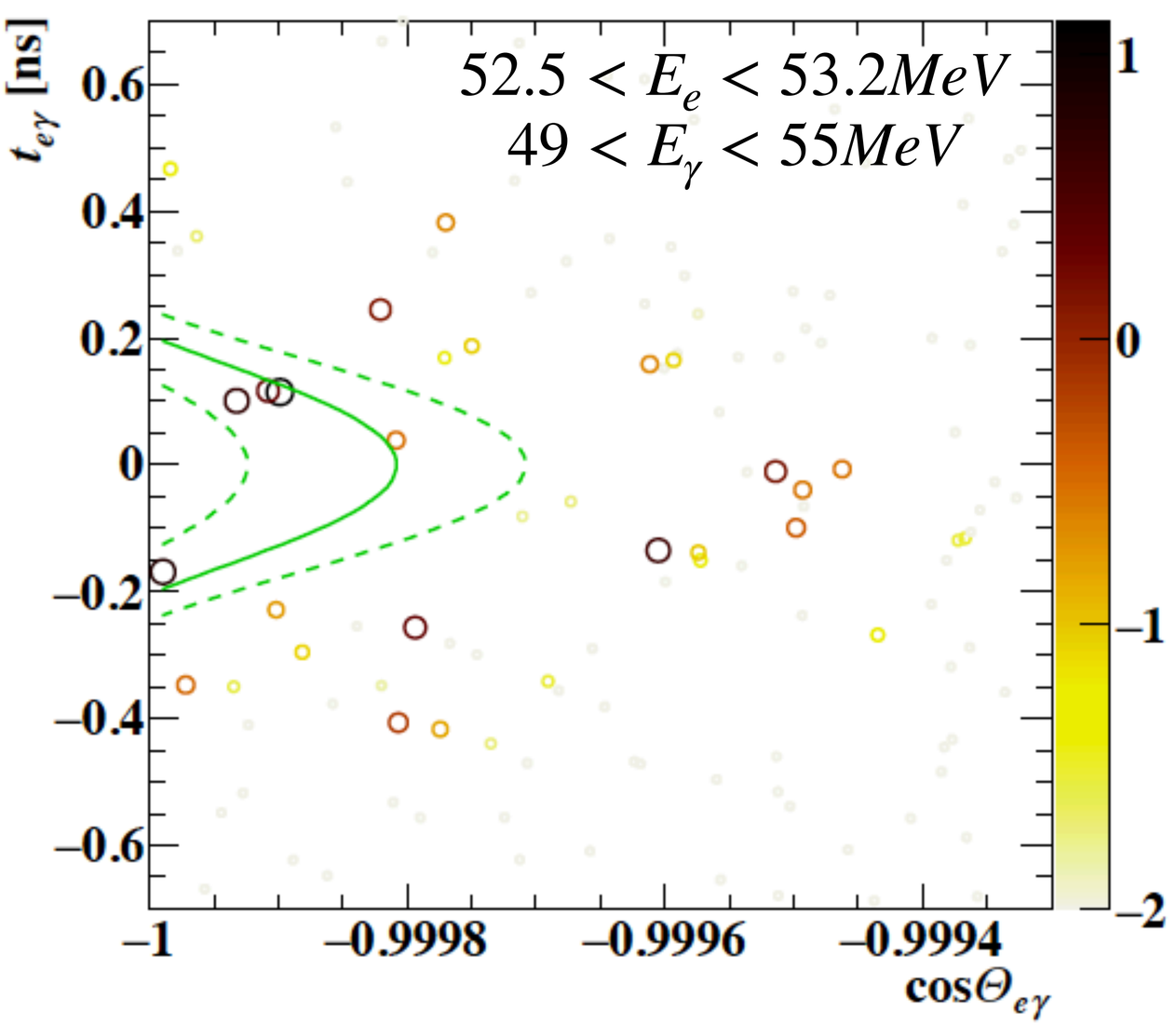
$48 < E_\gamma < 58\text{MeV} \quad 52.2 < E_{e^+} < 53.5\text{MeV}$

$|t_{e^+\gamma}| < 0.5\text{ns} \quad |\theta_{e^+\gamma}| < 40\text{mrad} \quad |\phi_{e^+\gamma}| < 40\text{mrad}$

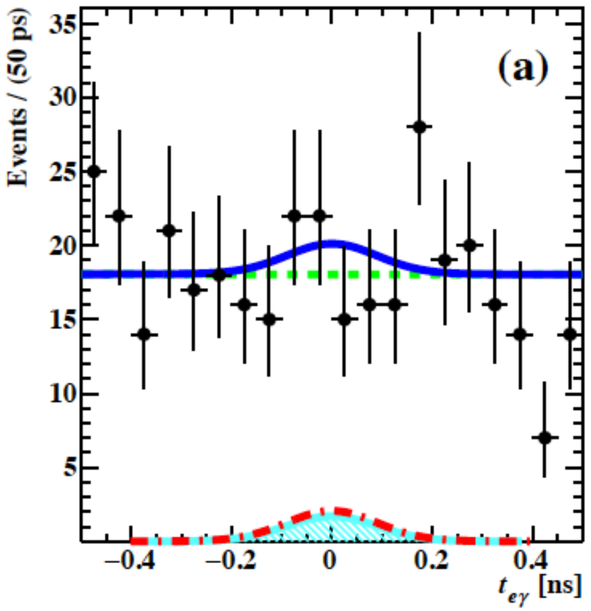
2-D event distributions

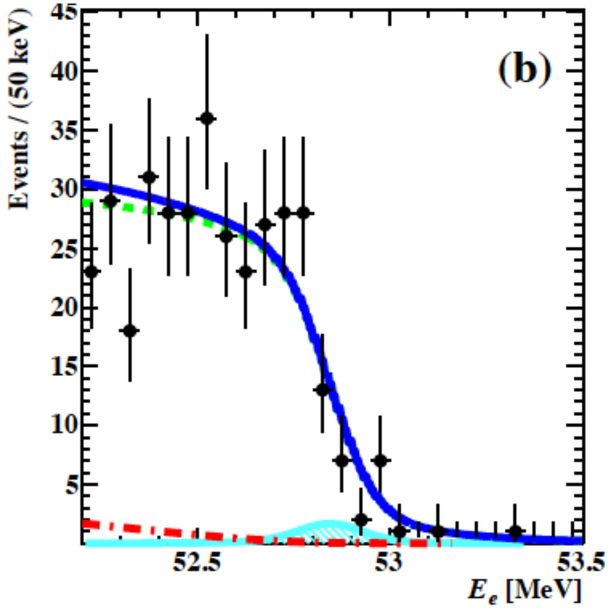
$$R_{sig} = log_{10}(\frac{S(x)}{B(x)})$$

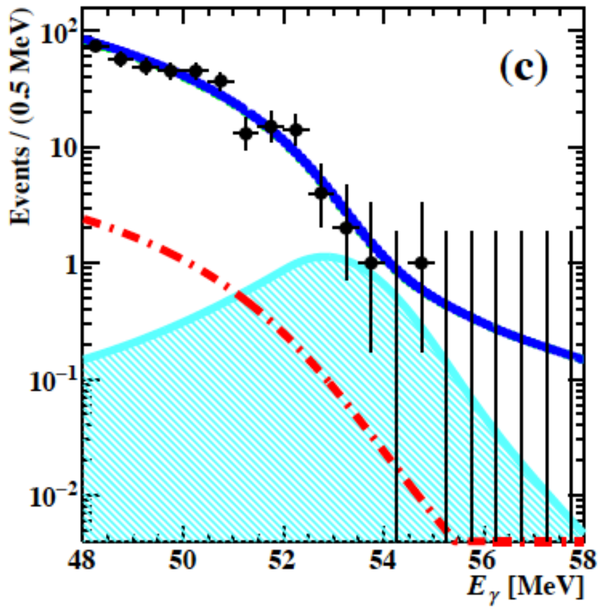


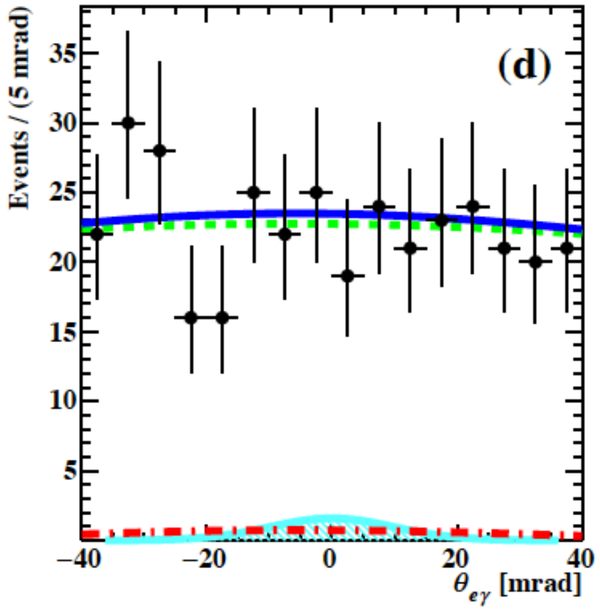


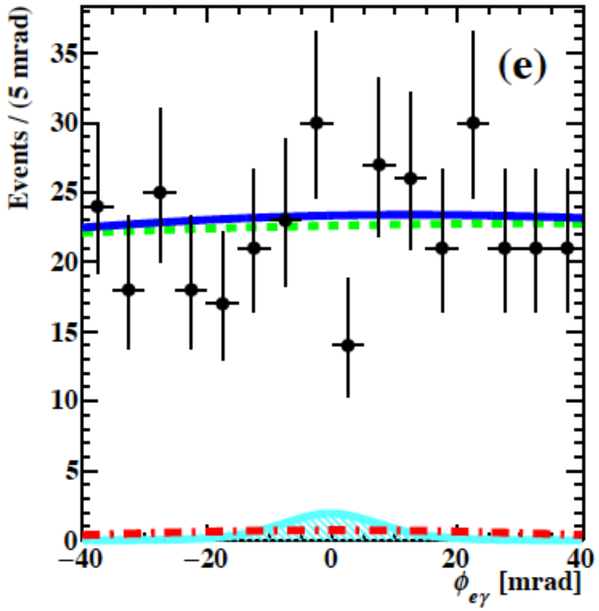
Projections of PDFs to observables (2021+2022 data set)

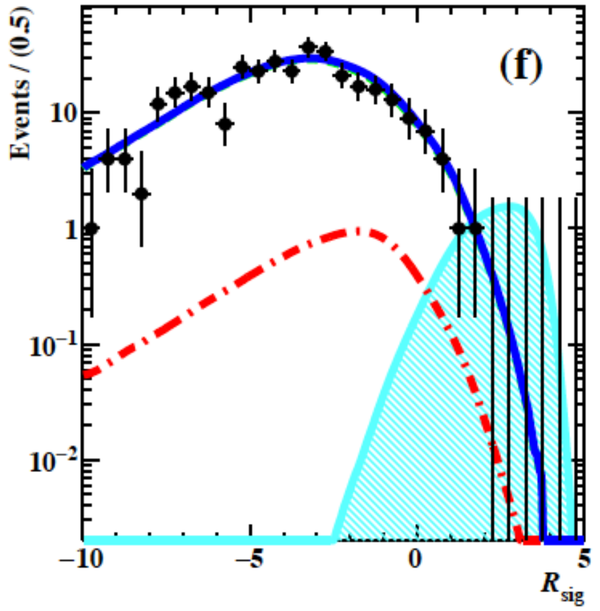












Data
Best fit
UL on N_{sig} x 4
Accidental
RMD

No signal Observed

Upper limit:
1.5×10^{-13}
(90%C.L.)

arXiv:2504.15711
(Submitted to PRL)

$$R_{sig} = log_{10}(\frac{S(x)}{B(x)})$$

Beam intensity

- Optimal beam intensity should be chosen to maximize the sensitivity
  - Statistics ($\propto R_\mu$)
  - Background ($\propto R_\mu^2$)
  - Reconstruction efficiency with pileup
  - Trigger rate & data size
  - Detector tolerance

- The current optimum intensity is 4×10^7/s
- Future improvements (expecting O(10%) efficiency improvement from the ML-tracking) may allow higher intensity (5×10^7/s)

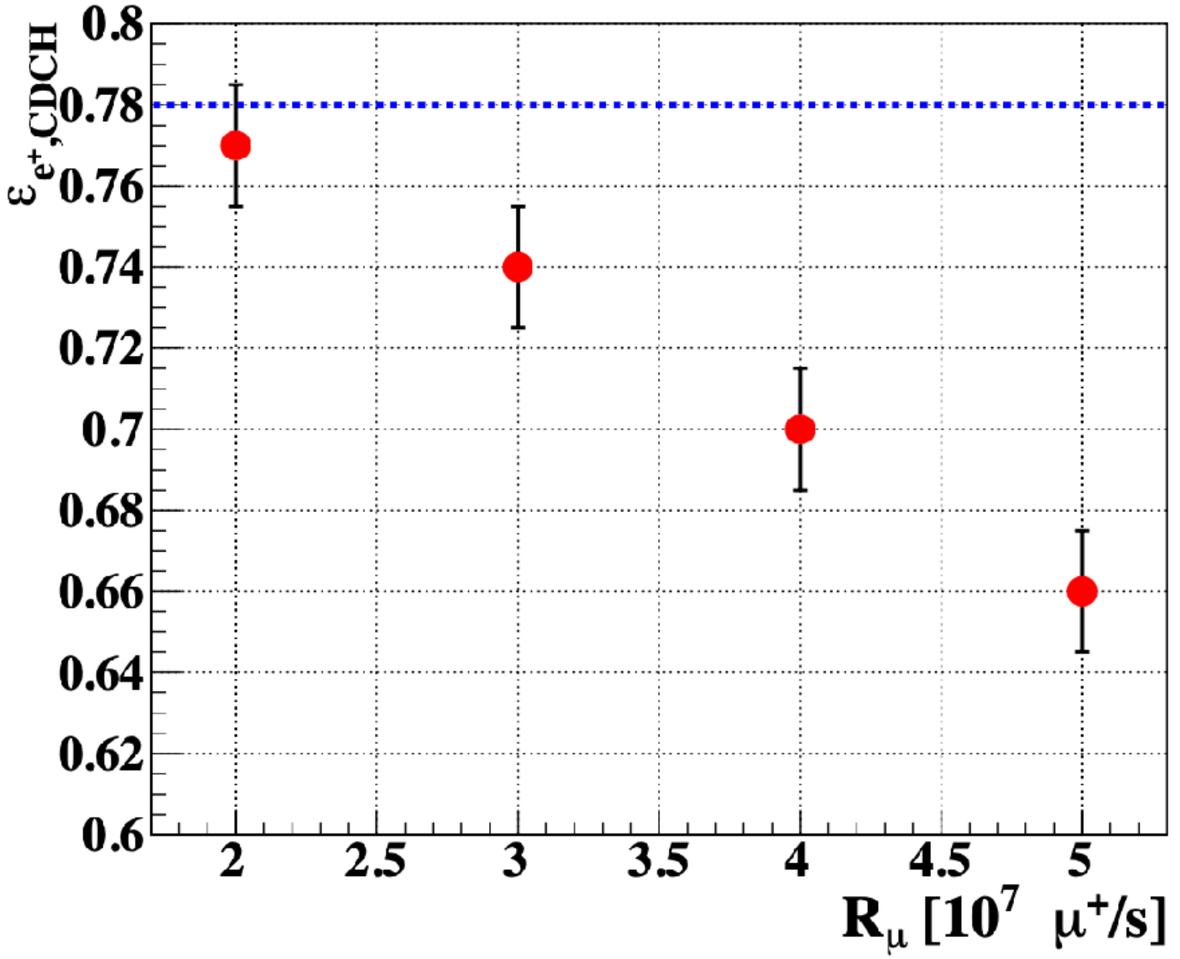
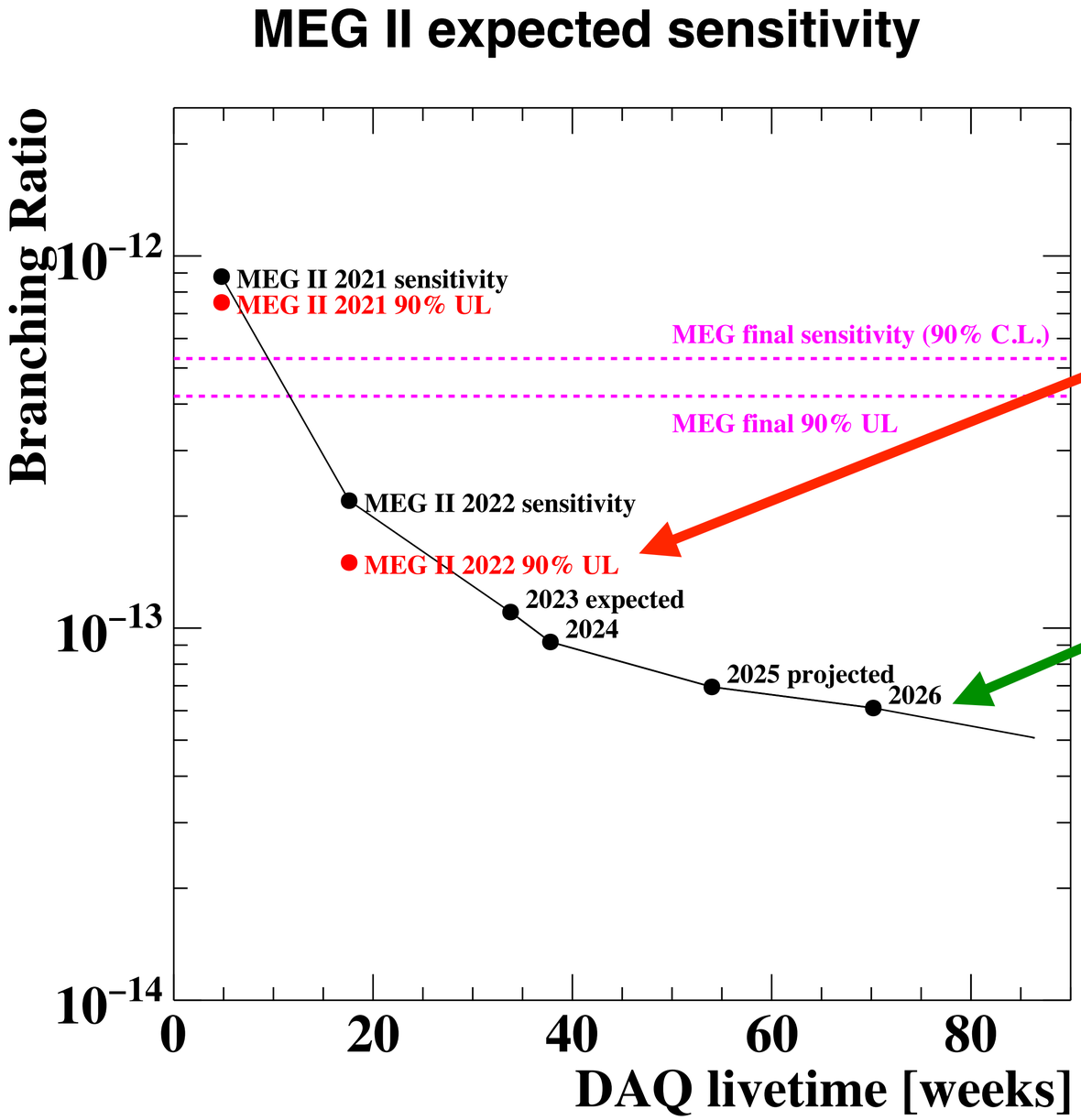


Figure 20 CDCH tracking efficiency as a function of R_μ for signal positrons. The blue dotted line is the design value.

MEG II prospects



New best UL (MEG II 2021+2022)
$Br=1.5\times10^{-13}$

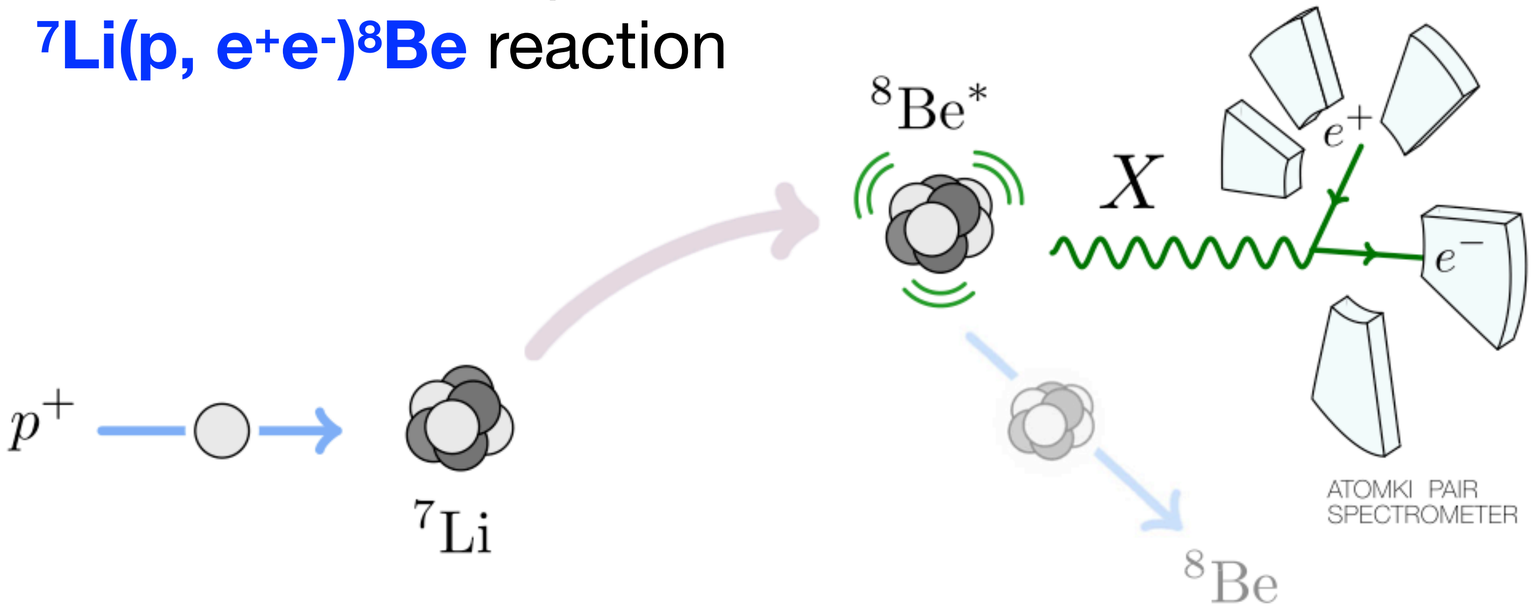
MEG II proposal goal
$S=6\times10^{-14}$

20 weeks of DAQ in 2025-2026
Current performance assumed

Analysis improvement may lead
to better sensitivity further

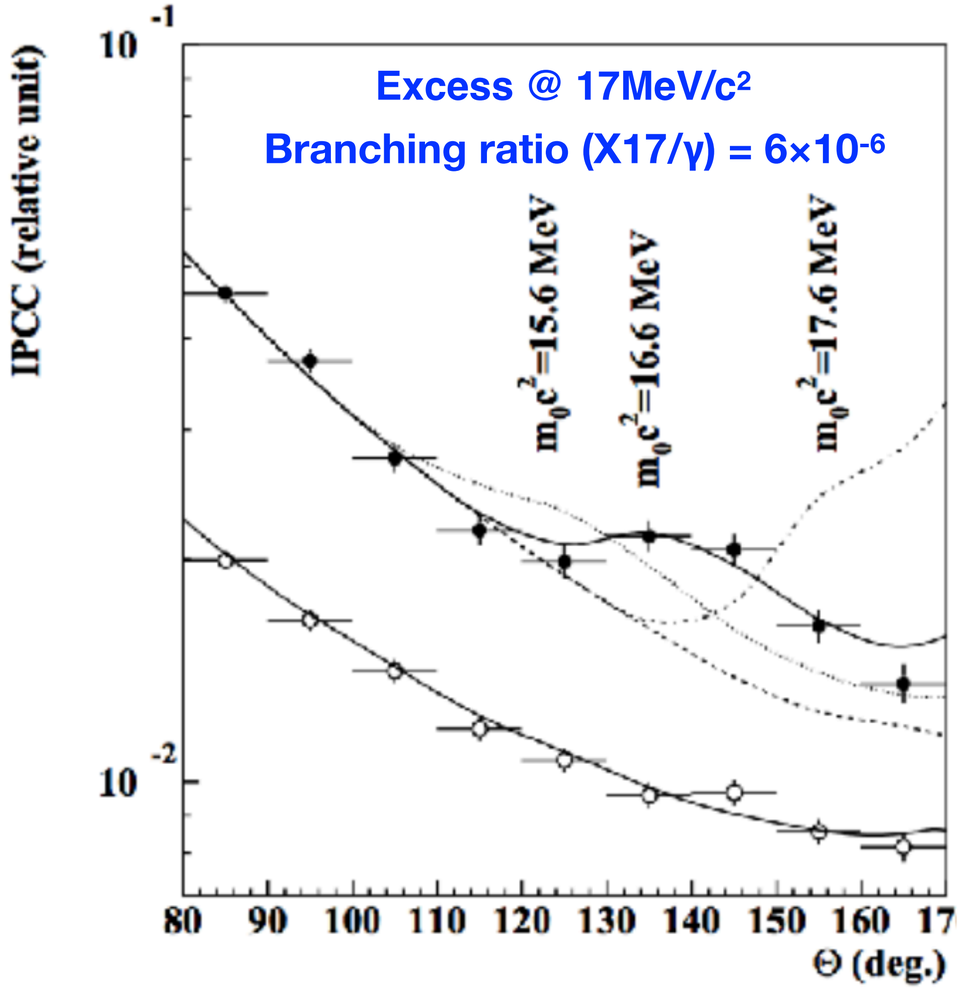
X17 boson search at MEG II

An experiment at **Atomki** reported an **anomaly** in the angular distribution of the internal e+e- pairs conversion of **^{7}Li(p, e^{+}e^{-})^{8}Be** reaction



If confirmed, this would be evidence of a new particle beyond the SM

Hint for a neutral, 17MeV boson: X17 (Atomki collaboration)



Phys. Rev. Lett. 116, 042501 (2016)

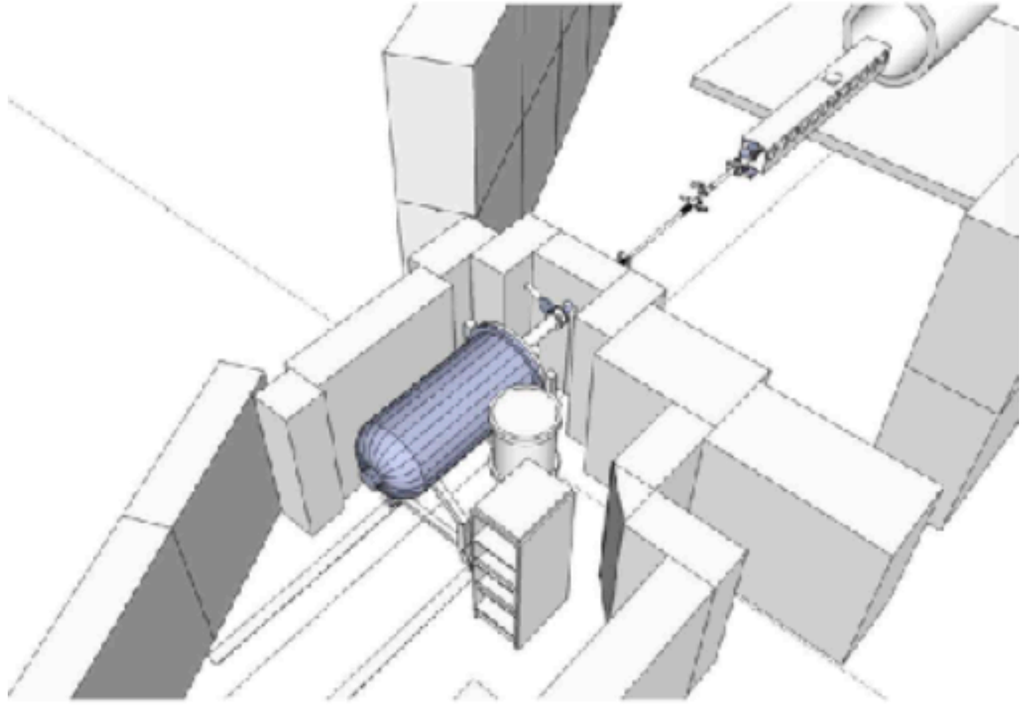
X17 boson search at MEG II

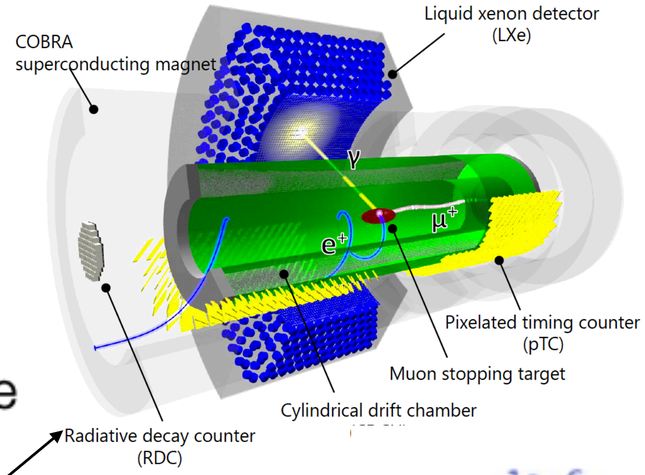
$^{7}Li(p, \gamma)^{8}Be$ 17.6 MeV γ used for MEG II LXe Calibration

Can be used to test X17 results

The MEG II CW accelerator and its beamline

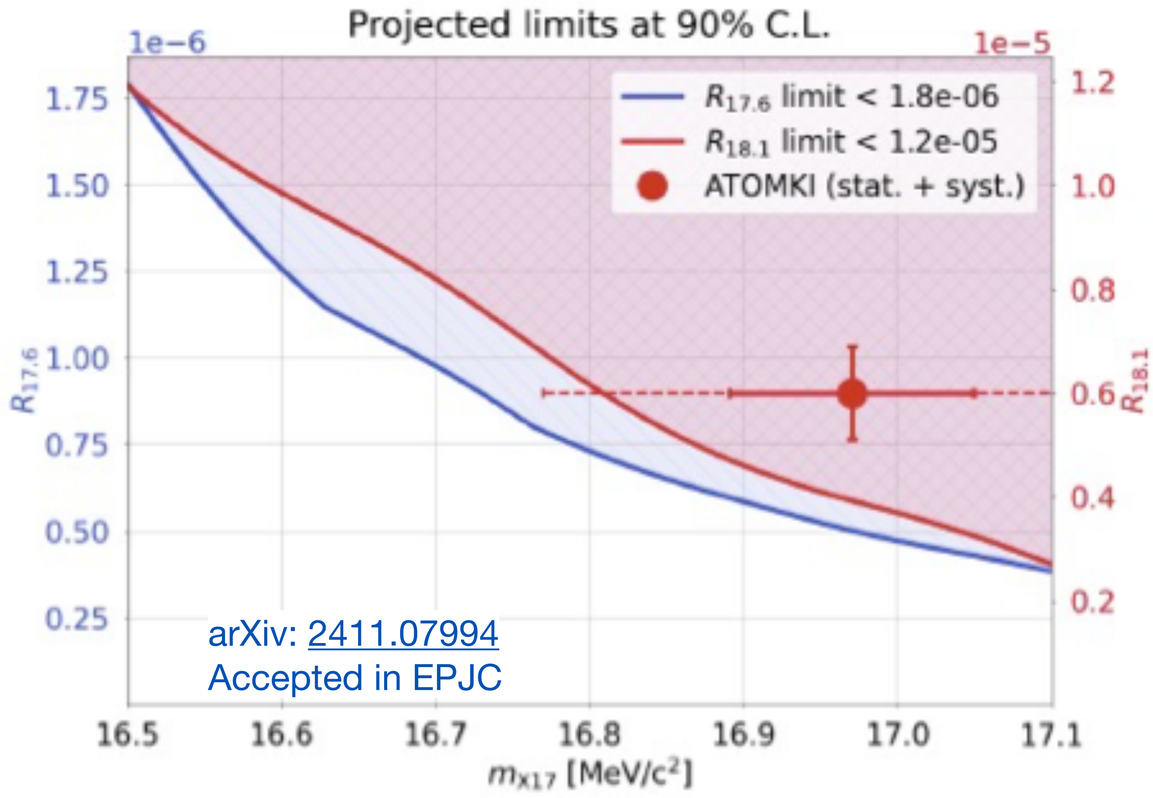
Can be done the PSI accelerator shutdown





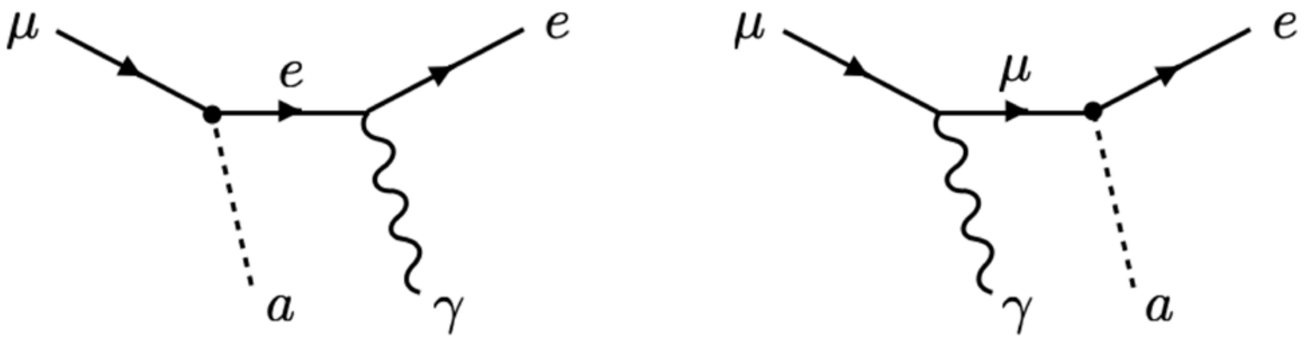
No significant signal observed

ATOMKI result was excluded at 94%

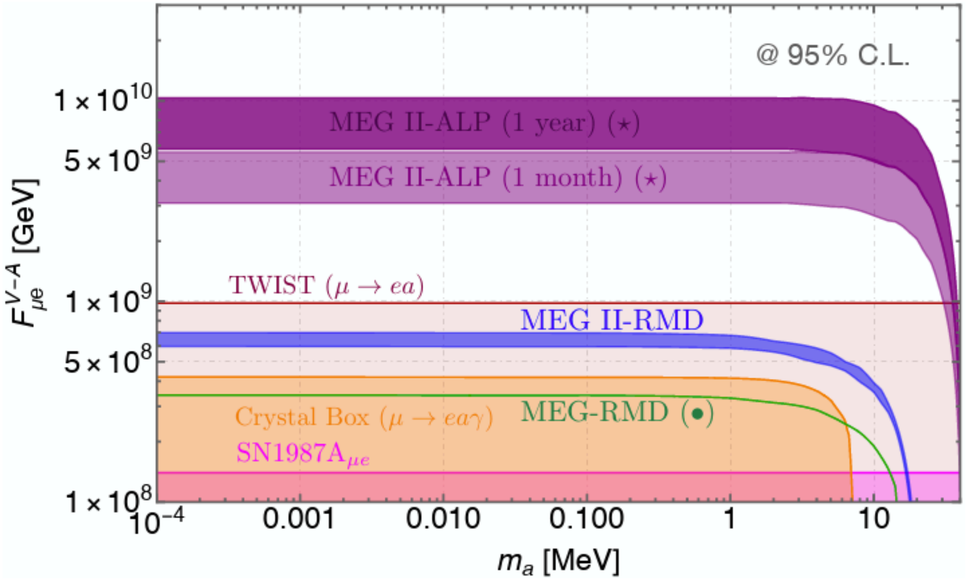


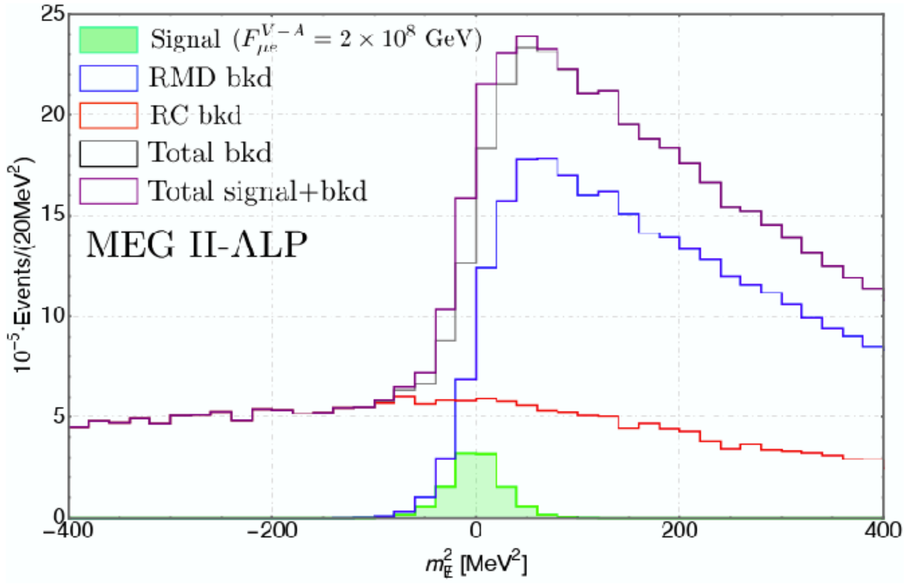
ALP search at MEG II

arXiv:2203.11222



- The muon decay to ALP, $\mu \to ea\gamma$ can be searched for at MEG II
  - Dedicated run with relaxed trigger conditions
    - lower photon energy (>~10MeV)
    - lower beam rate (~10^6/s)
- Preliminary analysis indicates that we can possibly exceed the TWIST limit with the data taken for ~ 10 days in 2021-2023





Future prospects

New experiment for $\mu \rightarrow e\gamma$ search

- HiMB project at PSI (~$10^{10}\mu/s$) (2027 – 2028)
- High resolution, high rate capability for the detectors

Photon pair spectrometer with active converter

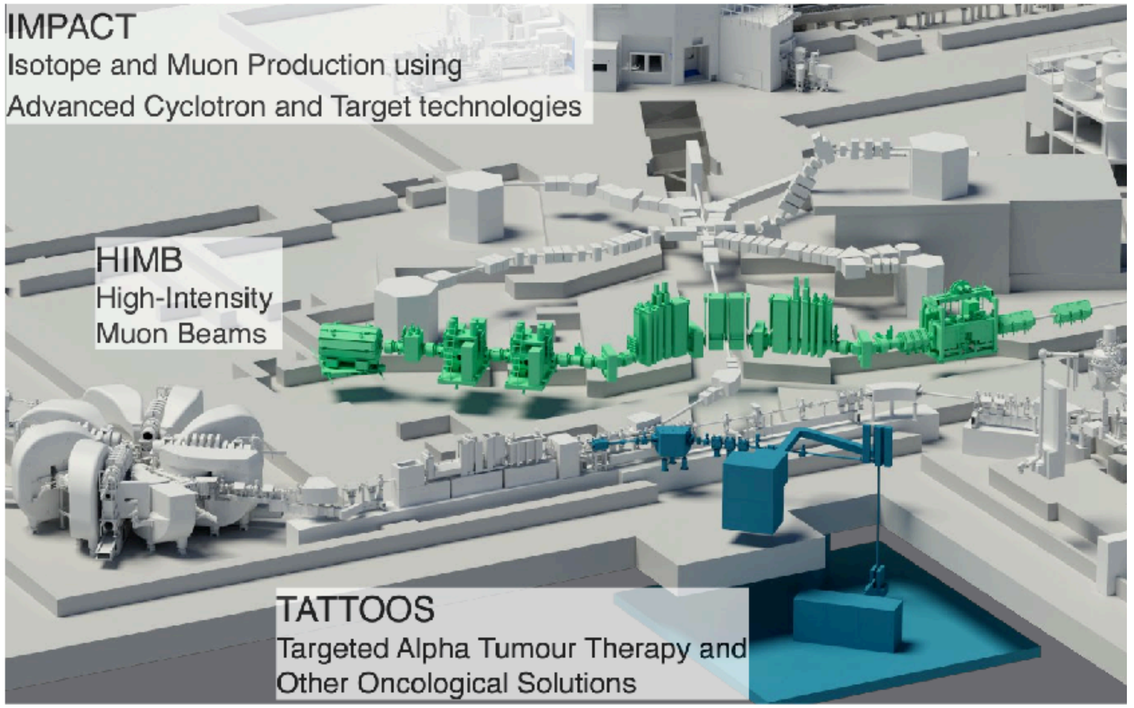
- Better resolutions, angle measurements

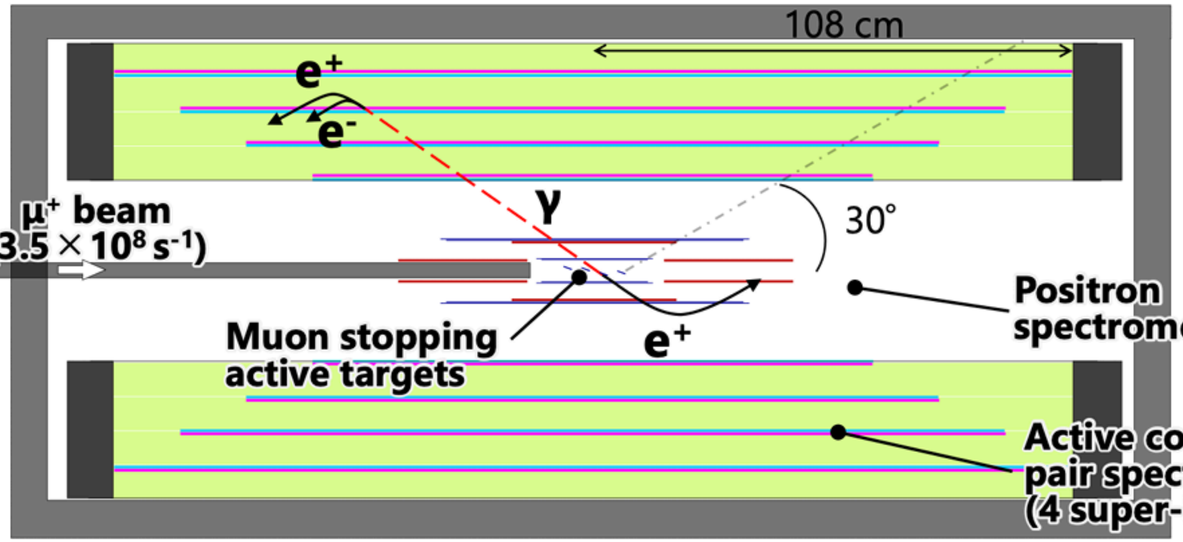
Silicon positron spectrometer similar with Mu3e

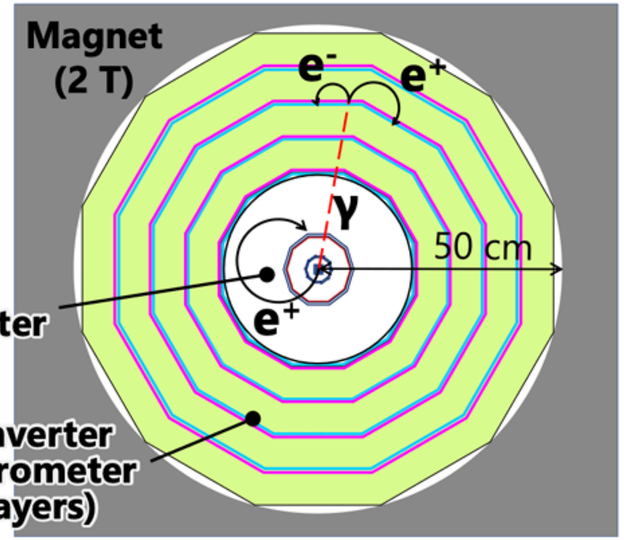
Separate active targets

Target sensitivity

Br($\mu \rightarrow e\gamma$) ~ $\mathcal{O}(10^{-15})$



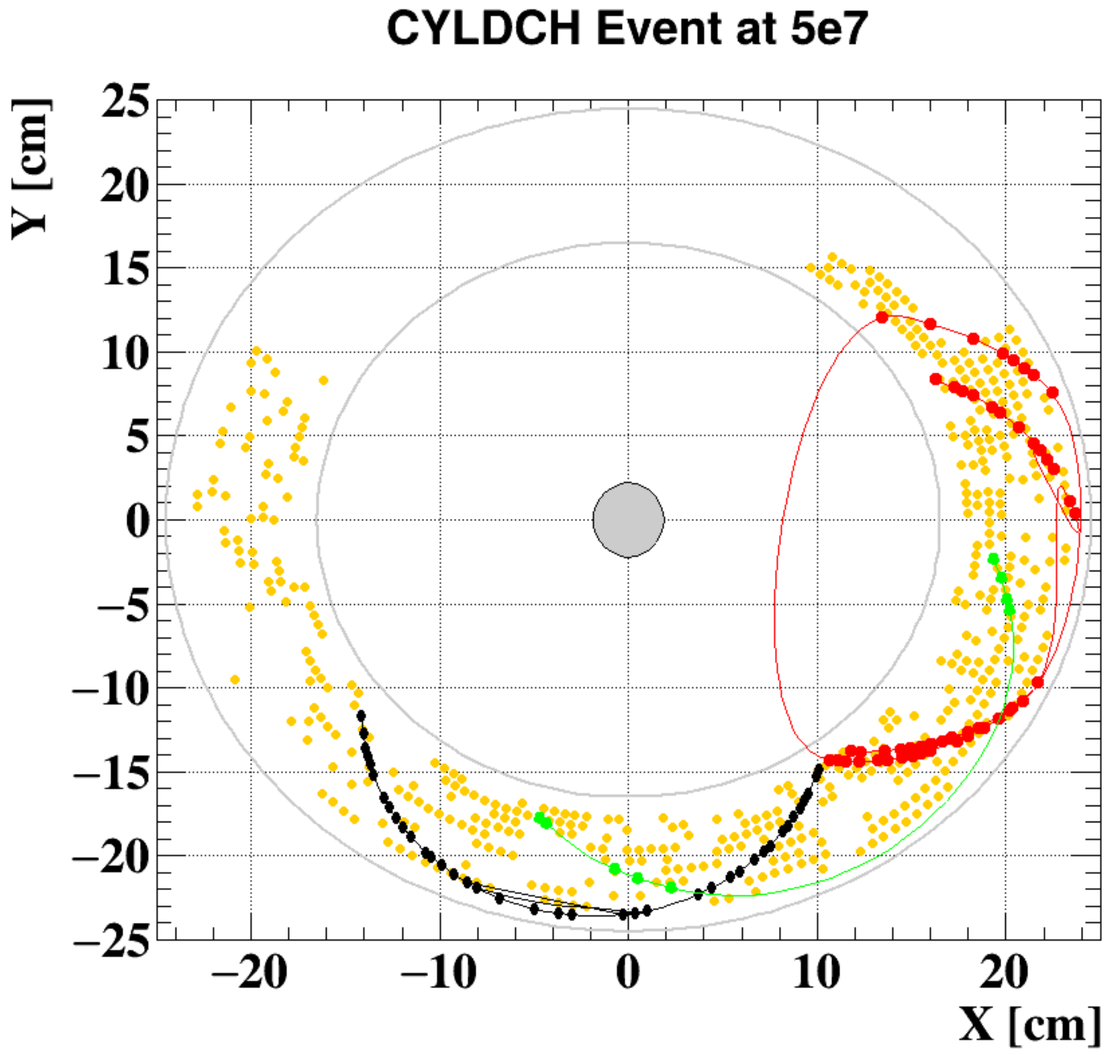


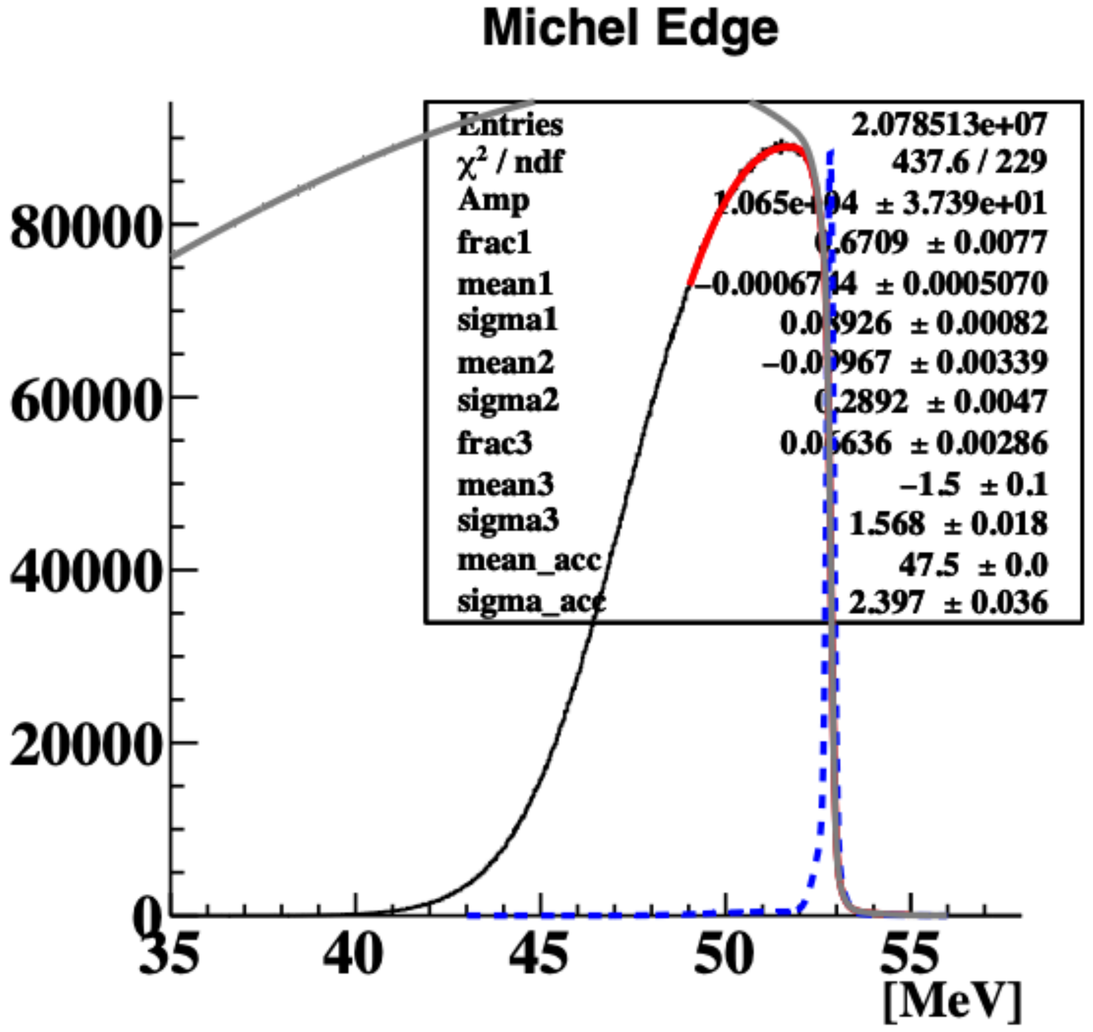


Conclusion

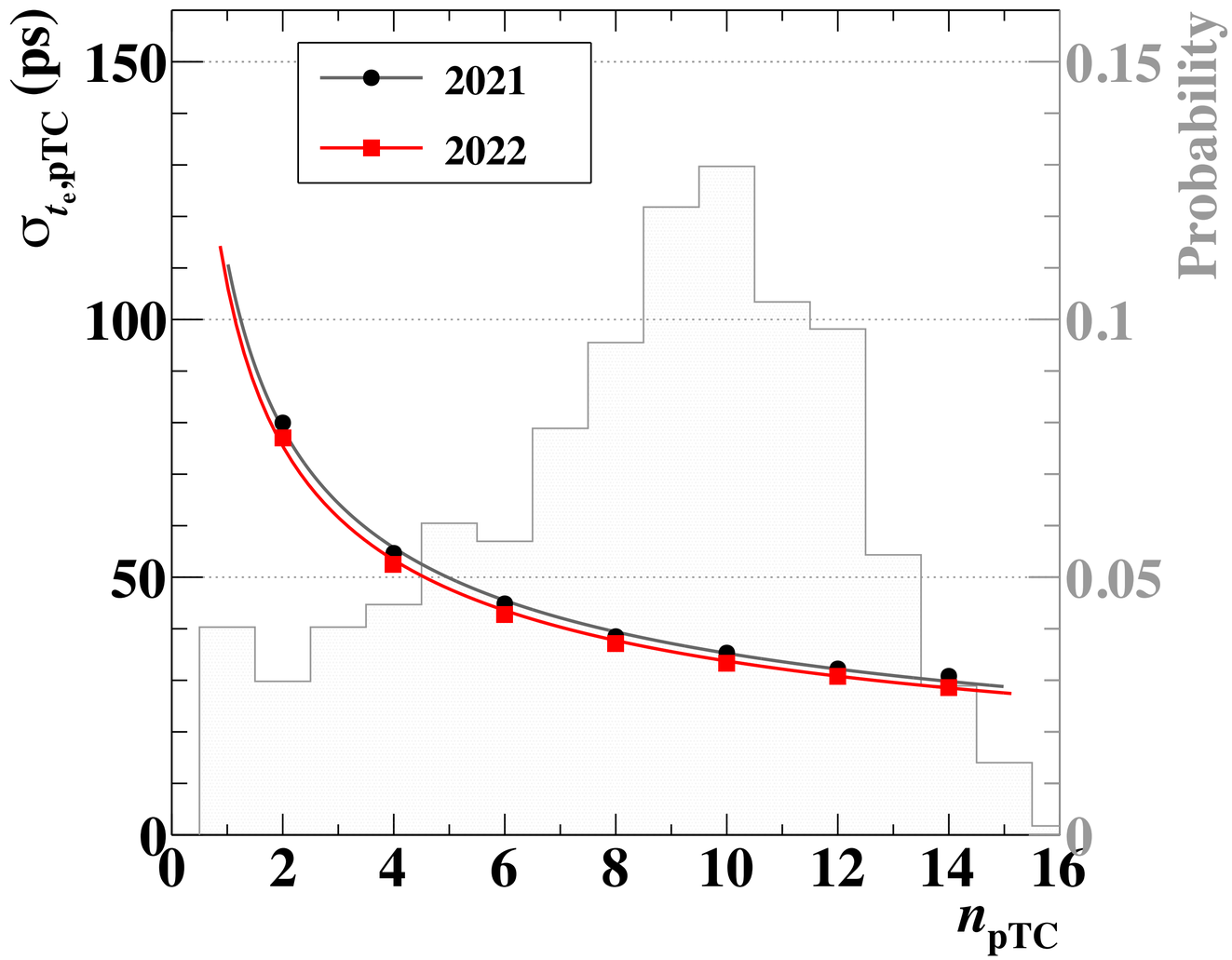
- The MEG II experiment has started physics run in 2021, and the results based on MEG II 2021+2022 data were published in May 2025, a new limit of $Br(\mu \to e\gamma) < 1.5 \times 10^{-13}$ (90% CL).
- Our target sensitivity (6×10^{-14}) will be reachable with two more years DAQ until 2026.

CDCH


CYLDCH Event at 5e7
Y [cm]
X [cm]
25
20
15
10
5
0
−5
−10
−15
−20
−25
−20
−10
0
10
20

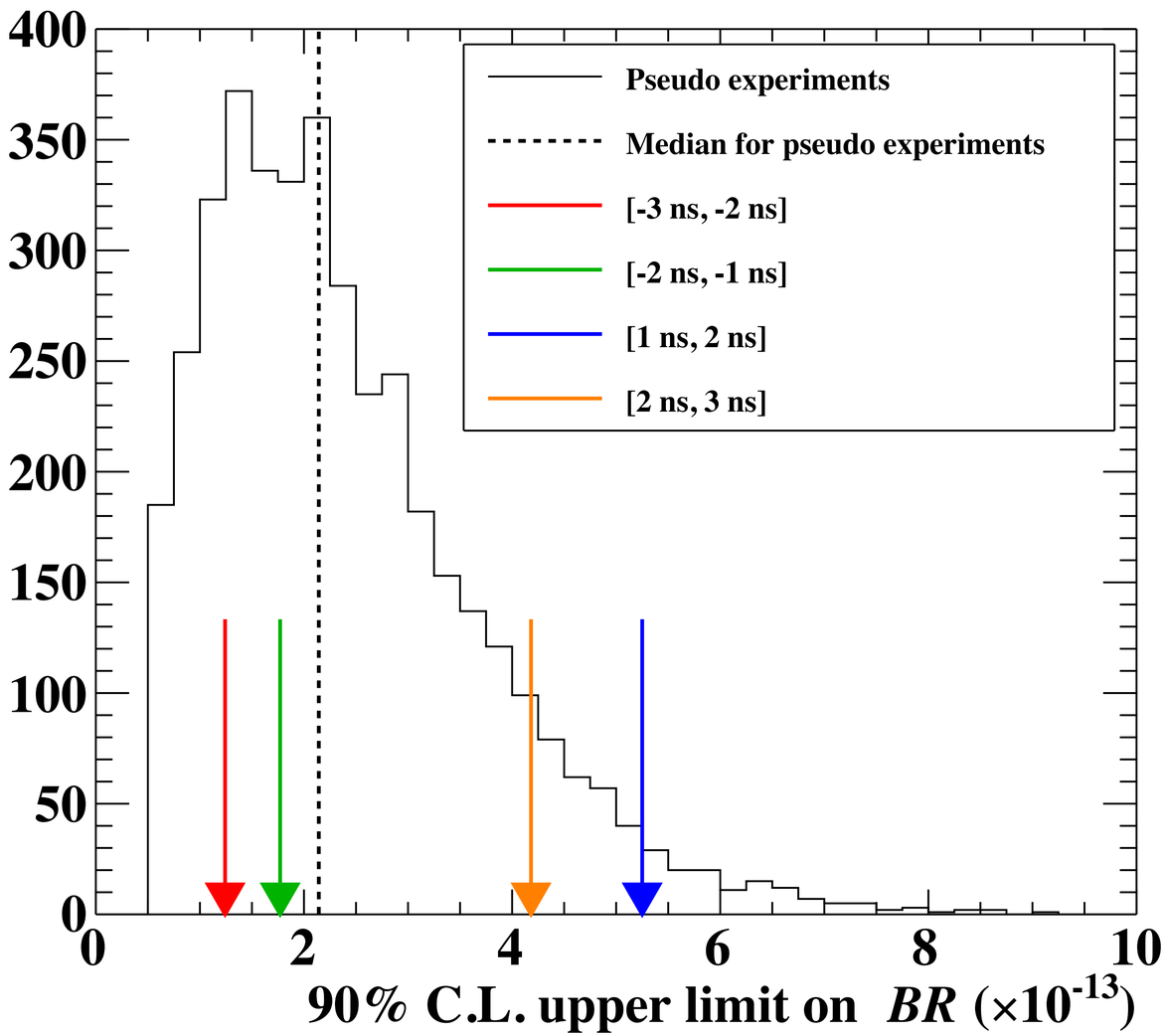

Michel Edge
Entries 2.078513e+07
χ² / ndf 437.6 / 229
Amp 1.065e+04 ± 3.739e+01
frac1 0.6709 ± 0.0077
mean1 −0.0006744 ± 0.0005070
sigma1 0.03926 ± 0.00082
mean2 −0.0967 ± 0.00339
sigma2 0.2892 ± 0.0047
frac3 0.06636 ± 0.00286
mean3 −1.5 ± 0.1
sigma3 1.568 ± 0.018
mean_acc 47.5 ± 0.0
sigma_acc 2.397 ± 0.036
80000
60000
40000
20000
0
35
40
45
50
55
[MeV]

pTC

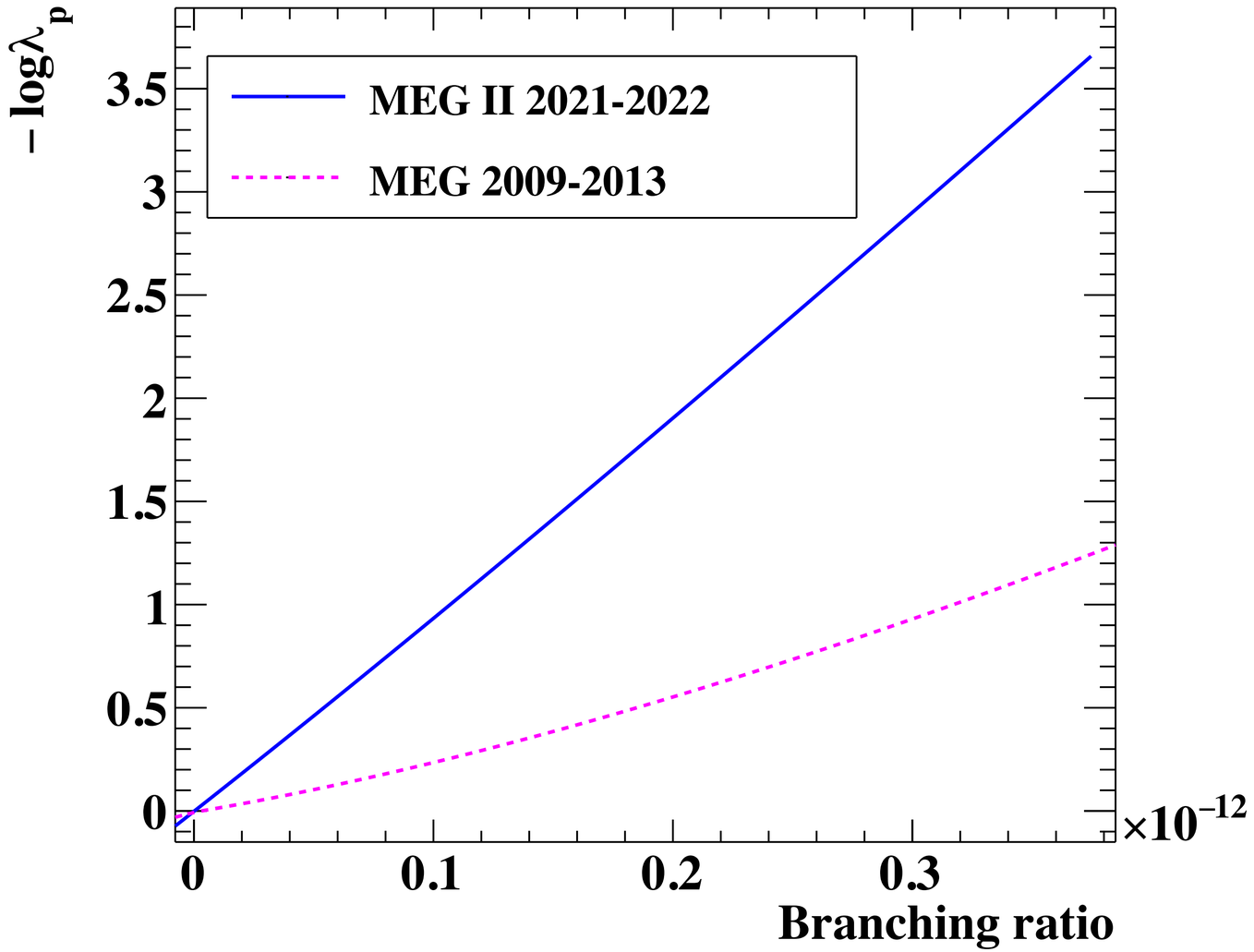

2021
2022
$\sigma_{t_e,\mathrm{pTC}}$ (ps)
Probability
150
100
50
0
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
16
n_{pTC}

Sensitivity

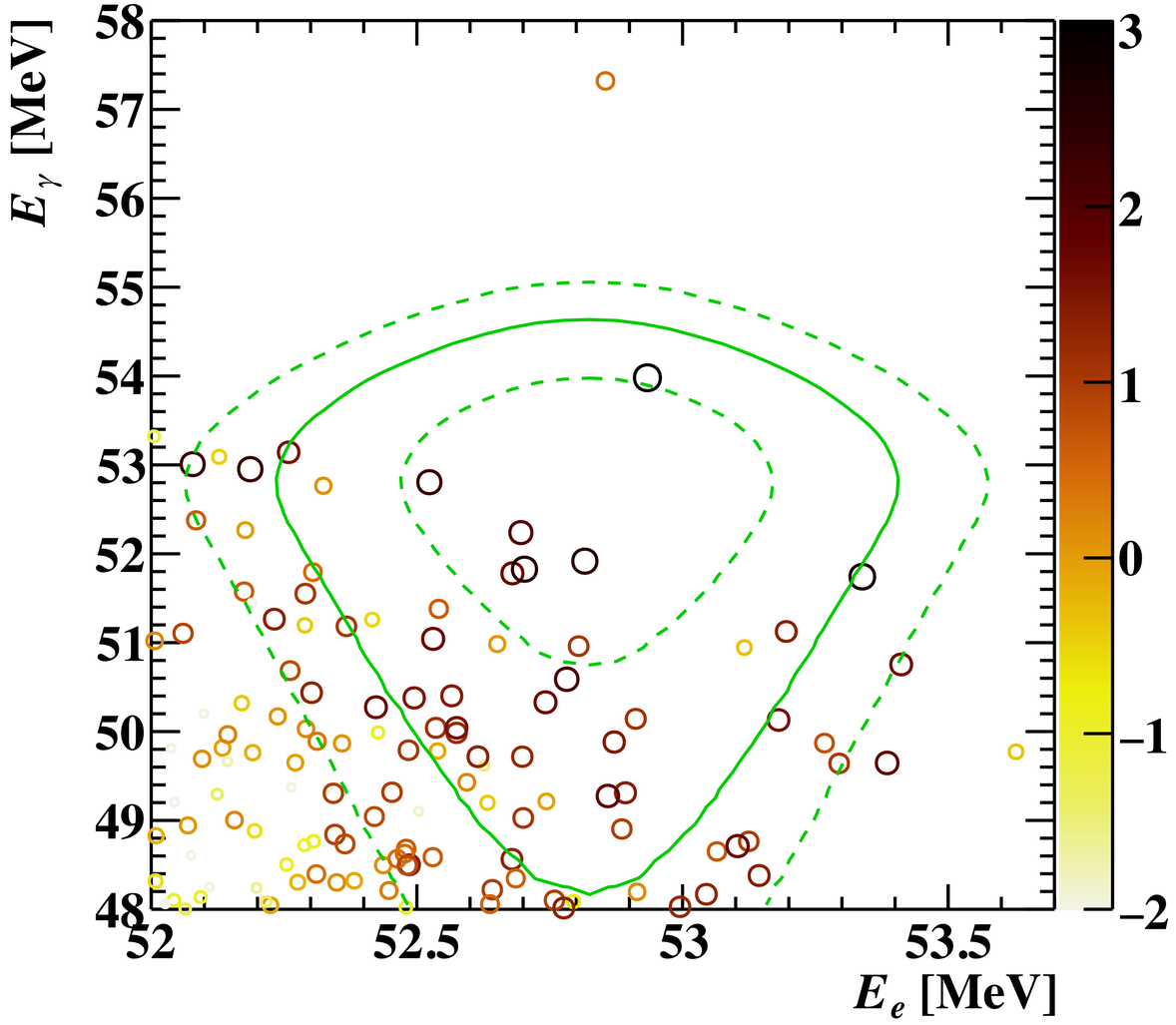
- Distribution of 90% C.L. upper limits on branching ratio
- 2.2×10^{-13} with systematics
- 2.1×10^{-13} w/o systematics

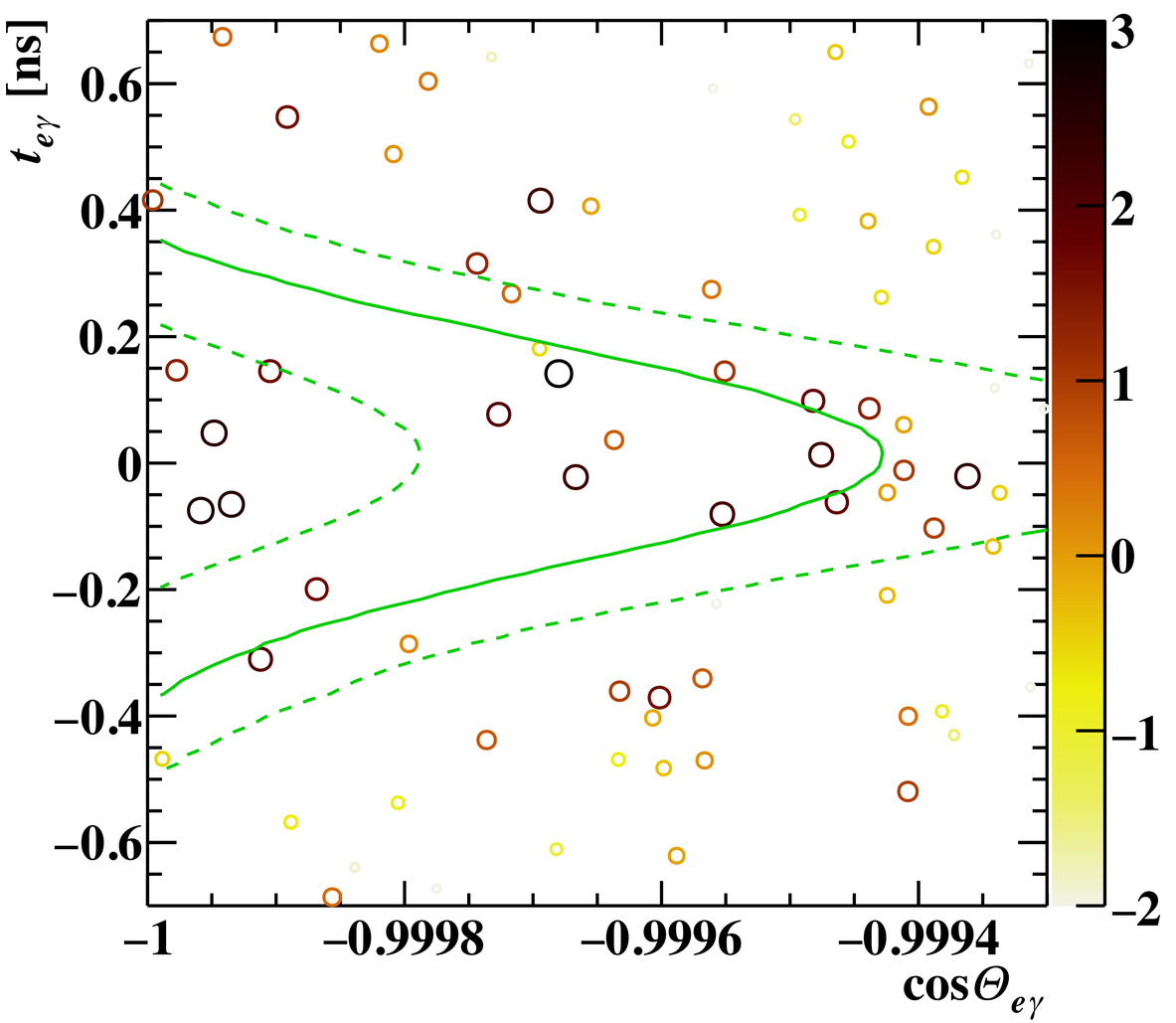


Negative log likelihood-ratio vs branching ratio



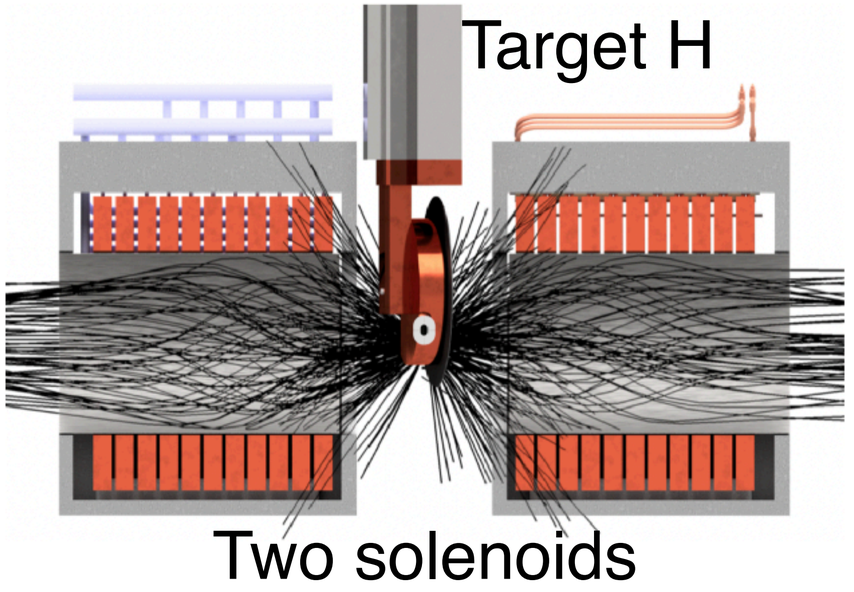
2-D event distribution (MEG)

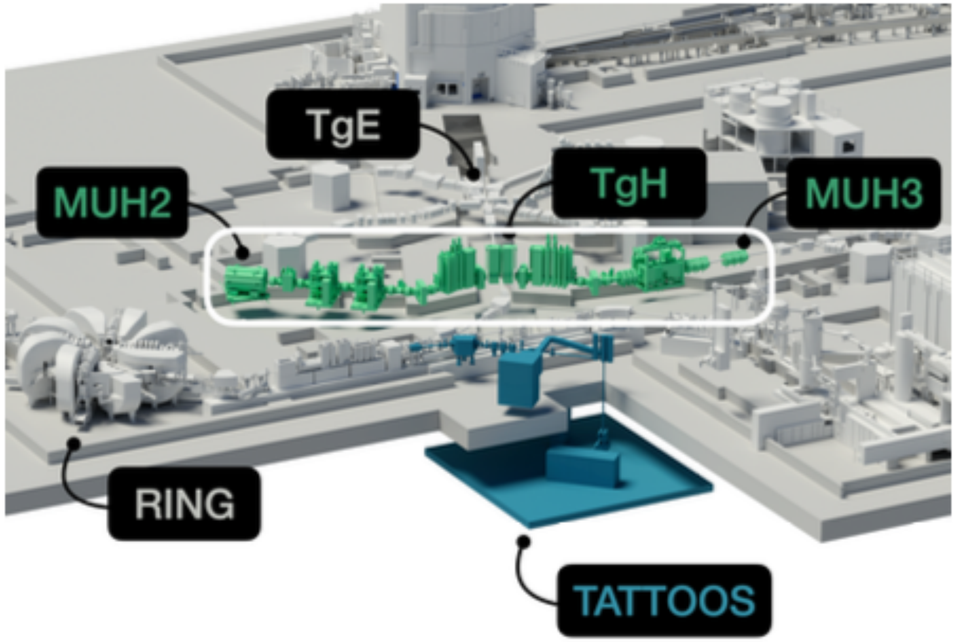


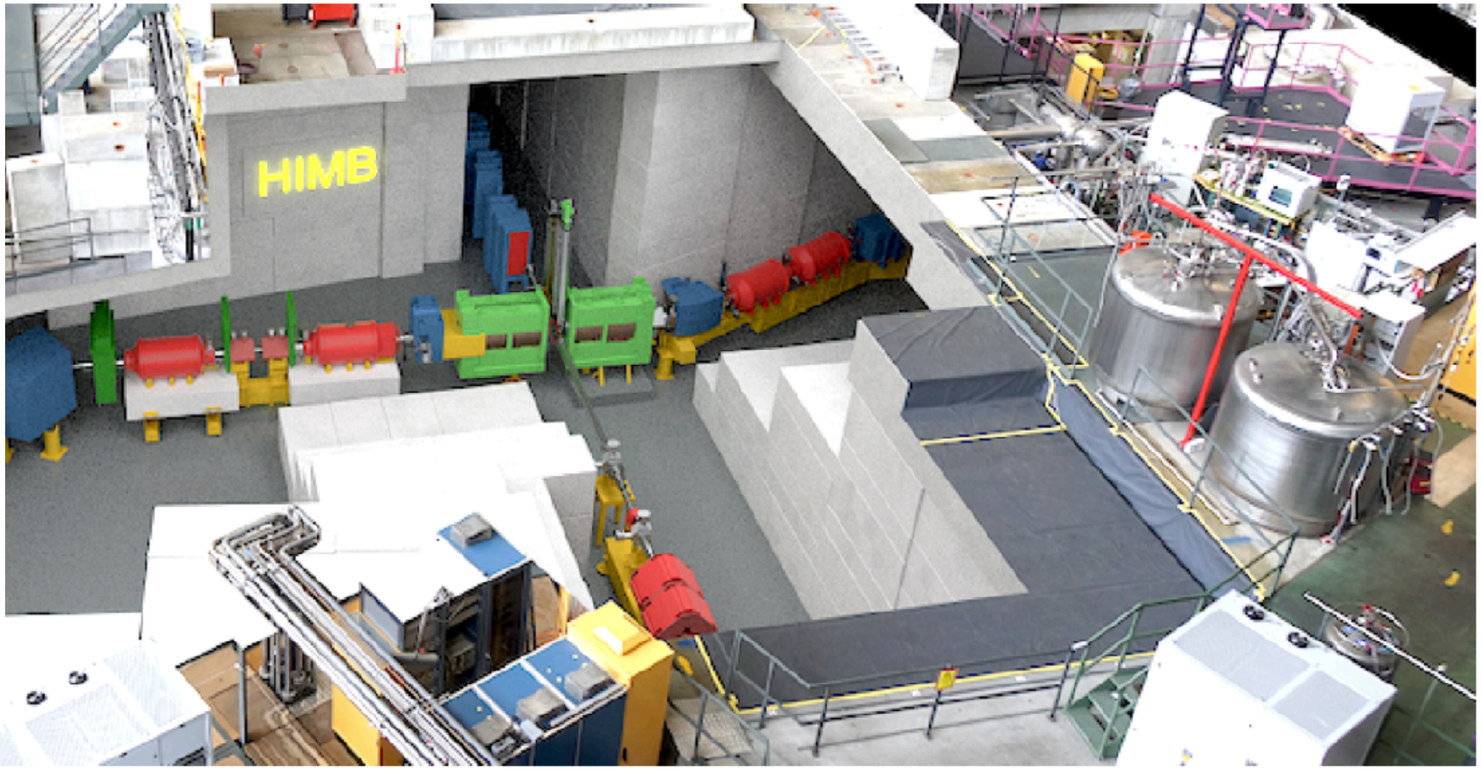


High intensity muon beam line @ PSI

- Shutdown of about two years from 2027
- New target geometry, 4 times capture efficiency, 6 times transport efficiency, resulting in > 10^{10}μ/s ($5x10^{8}$μ/s now) available from late 2028
- Beam spot σ~40mm



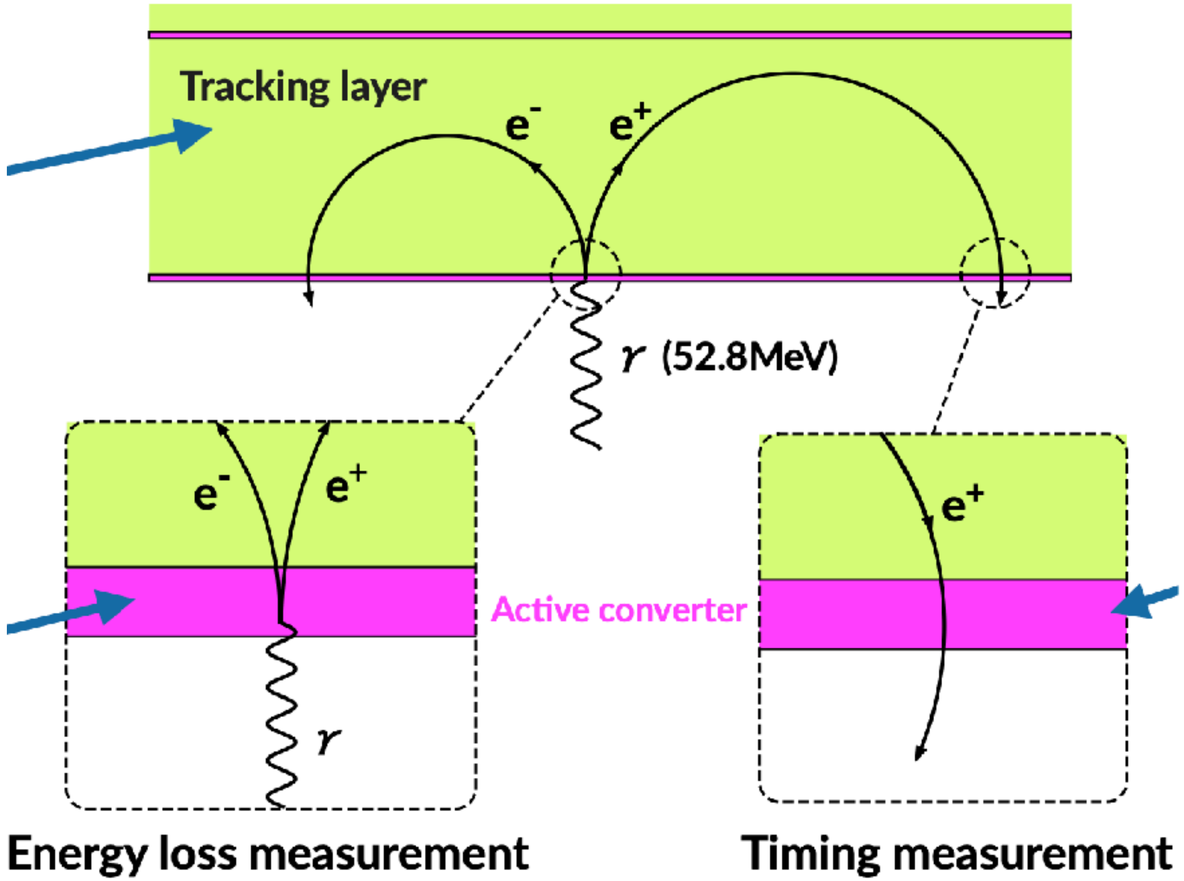




Photon measurement: Pair Spectrometer with Active Converter

Baseline option for photon measurement

- Tracking in a magnetic spectrometer
  - Drift chamber
  - Radial-TPC
  - Silicon detector



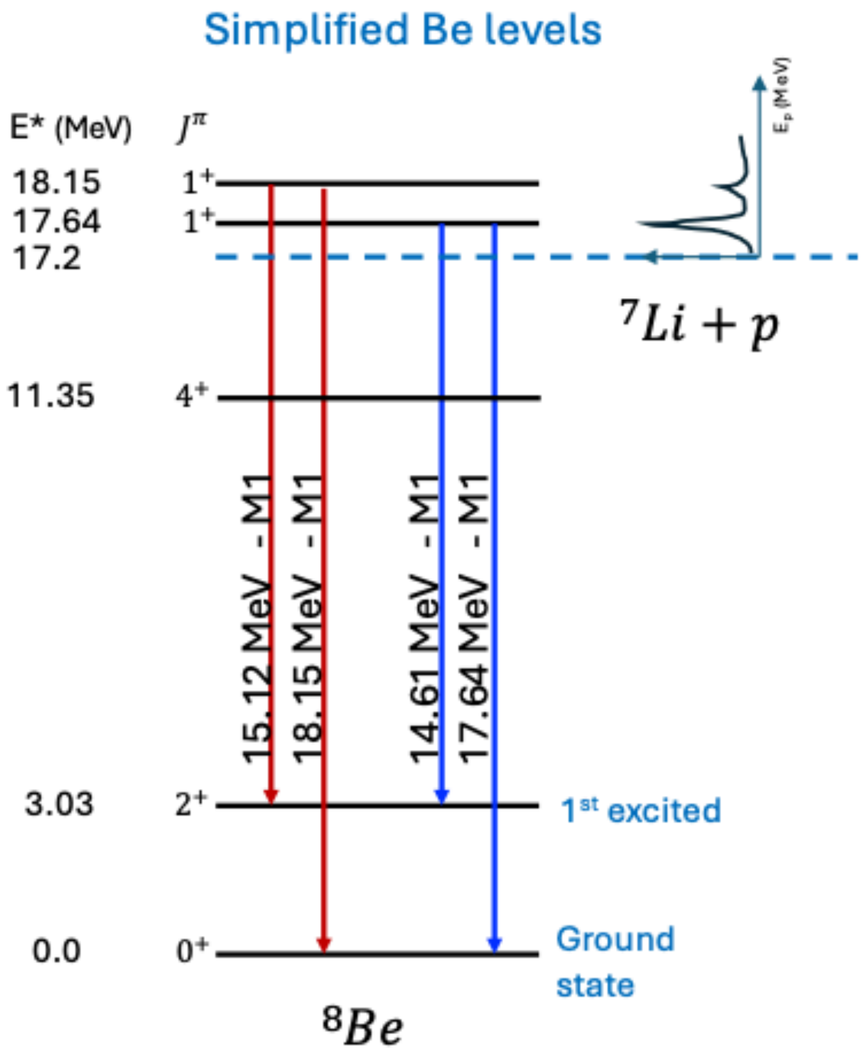
- Active converter
  - A layer of dense material to convert photons into e^+e^- pairs
  - Scintillator+SiPM
  - Silicon detector

- Timing measurement
  - Measure timing of returning conversion pair
  - in front of active converter
  - Multi-layer RPC
  - Active converter = timing detector

Target performance: $\sigma_E/E = 0.4\,\%$, $\sigma_t = 30ps$, $\sigma_x = 0.2mm$

(MEG II : $\sigma_E/E = 1.8\,\%$, $\sigma_t = 65ps$, $\sigma_x = 2.5mm$)

The X17 production



- The state $^7Li + p$ yields 17.2 MeV above the ^8Be ground state
  → many ^8Be excited states are easily accessible
- Cross section to the resonant excited states are very different

$E_p = 0.440$ MeV $Q = 17.6$ MeV

$E_p = 1.030$ MeV $Q = 18.1$ MeV

A further non-resonant state is present at 17.9 MeV

- Two γ transitions for each excited state