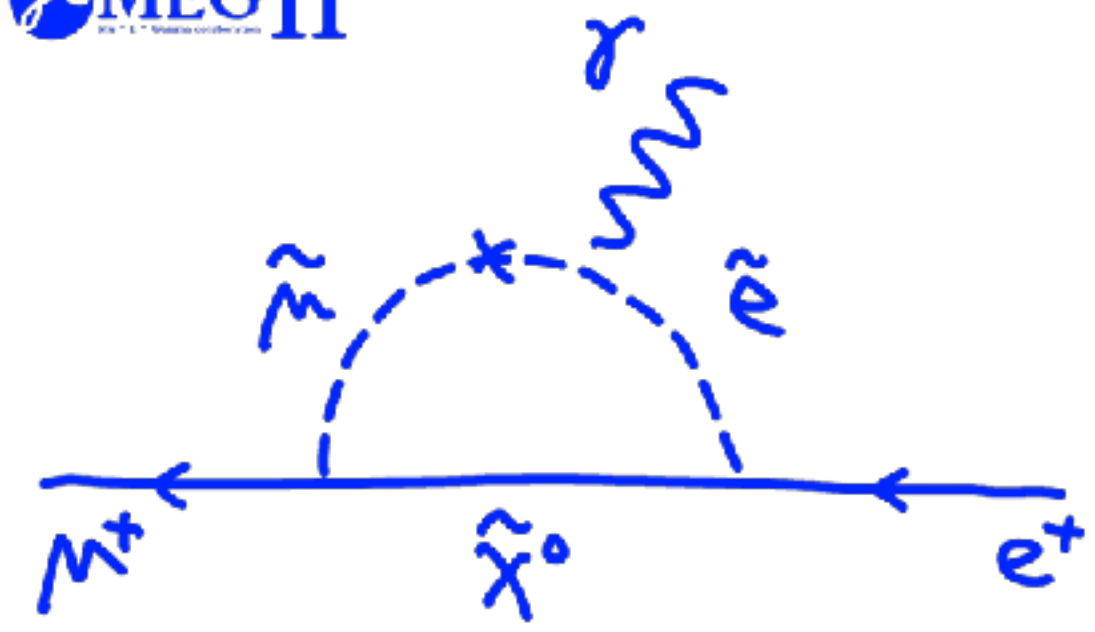
The Results of Charged Lepton Flavor Violation Search with MEG II Experiment



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

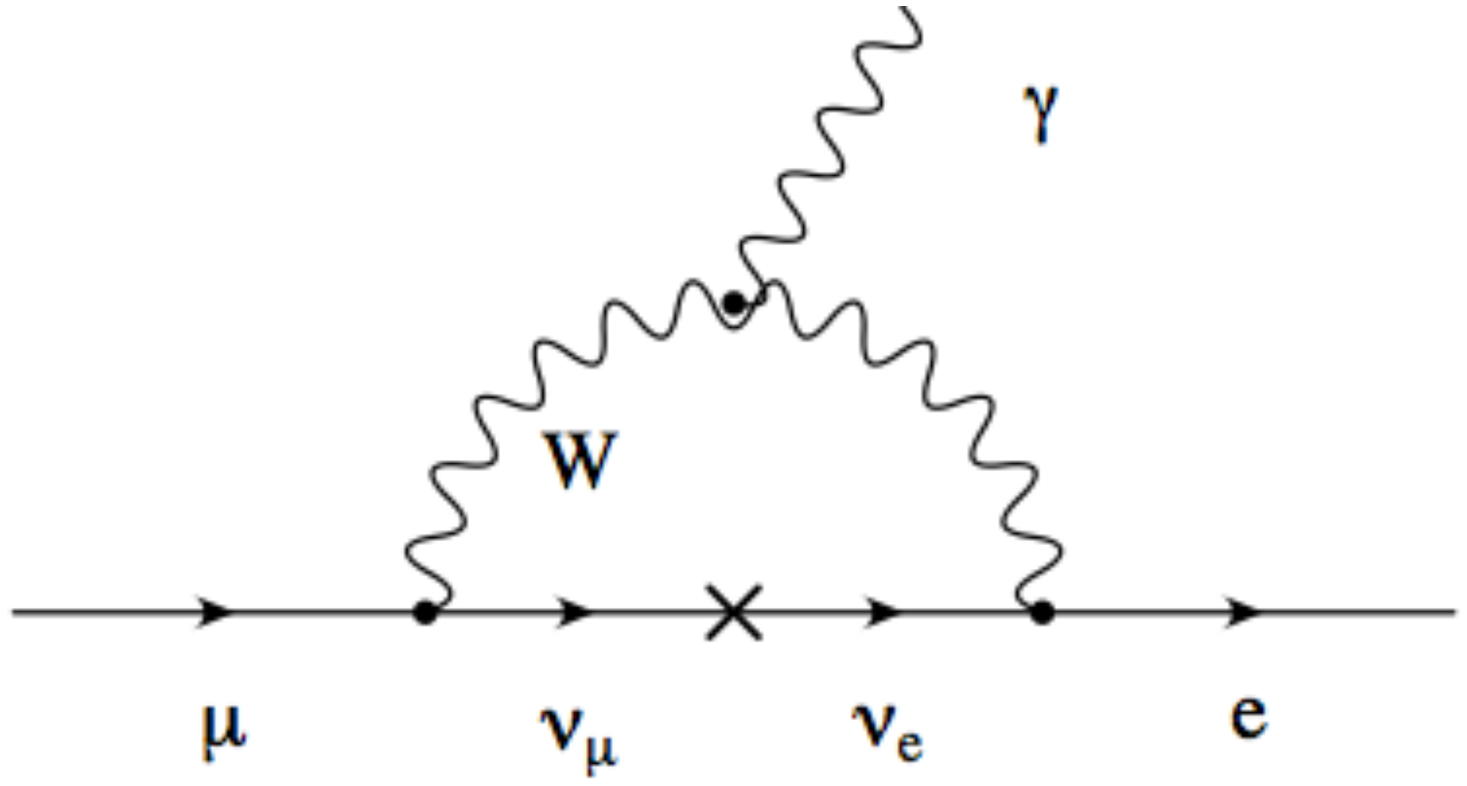
August 17-23, 2025 @ Quy Nhon, Vietnam
Vietnam Flavour Physics Conference 2025

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

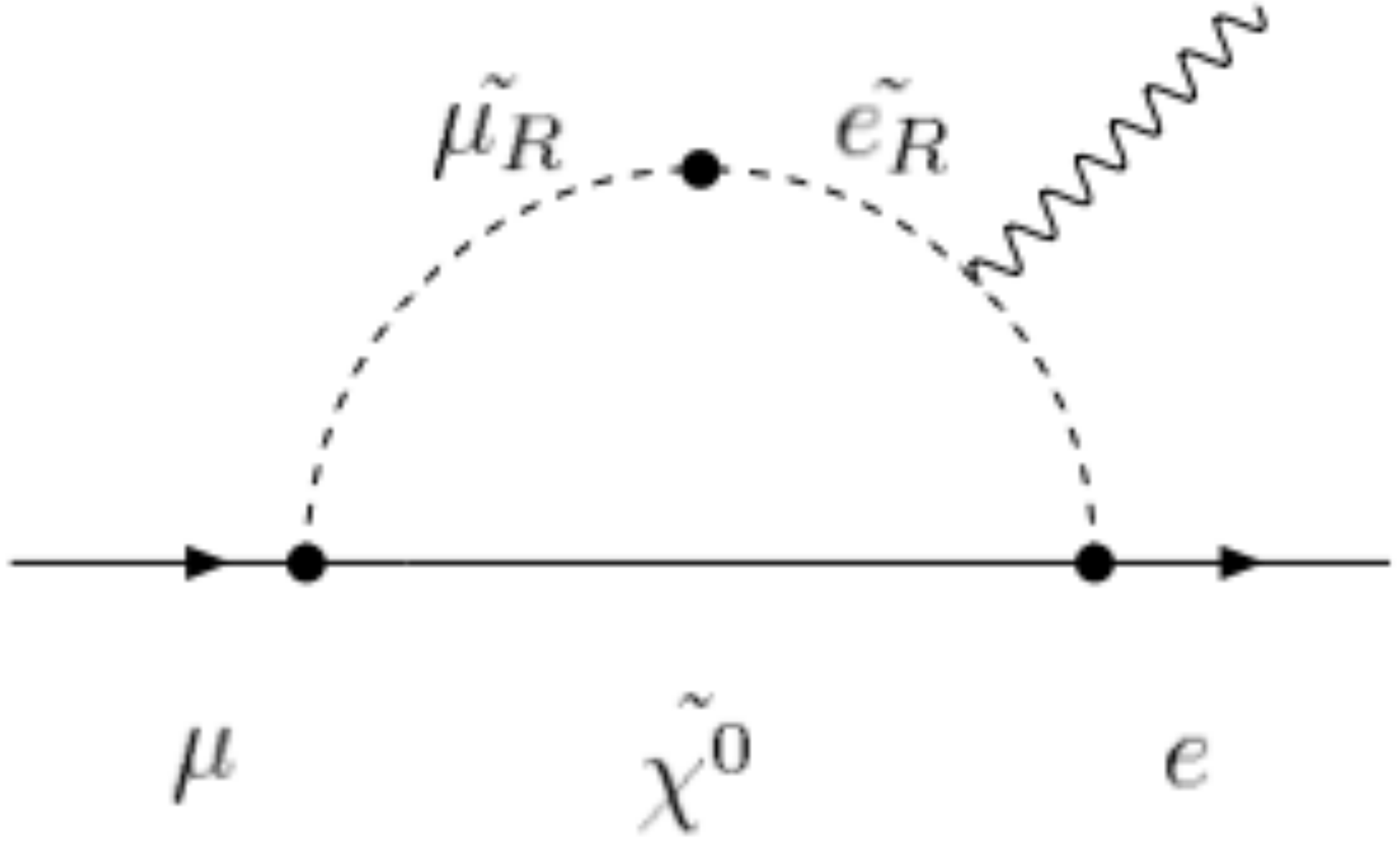
Charged lepton flavor transition has never been observed yet



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

$\sim 10^{-54}$

Neutrino is too light



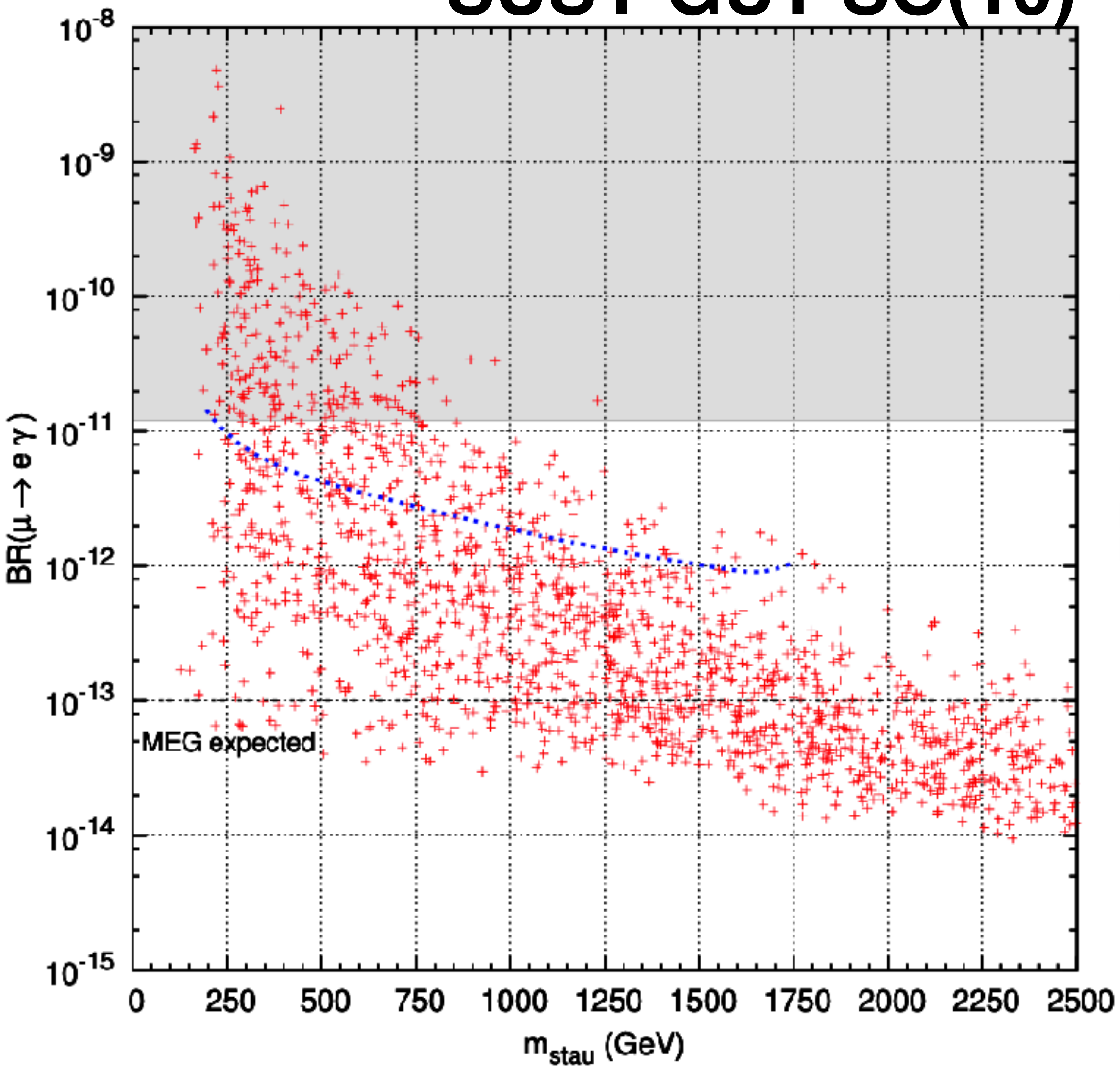
New particles from SUSY in the loop can enhance the branching ratio $10^{-12} - 10^{-14}$

SUSY-GUT / SUSY-seesaw

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

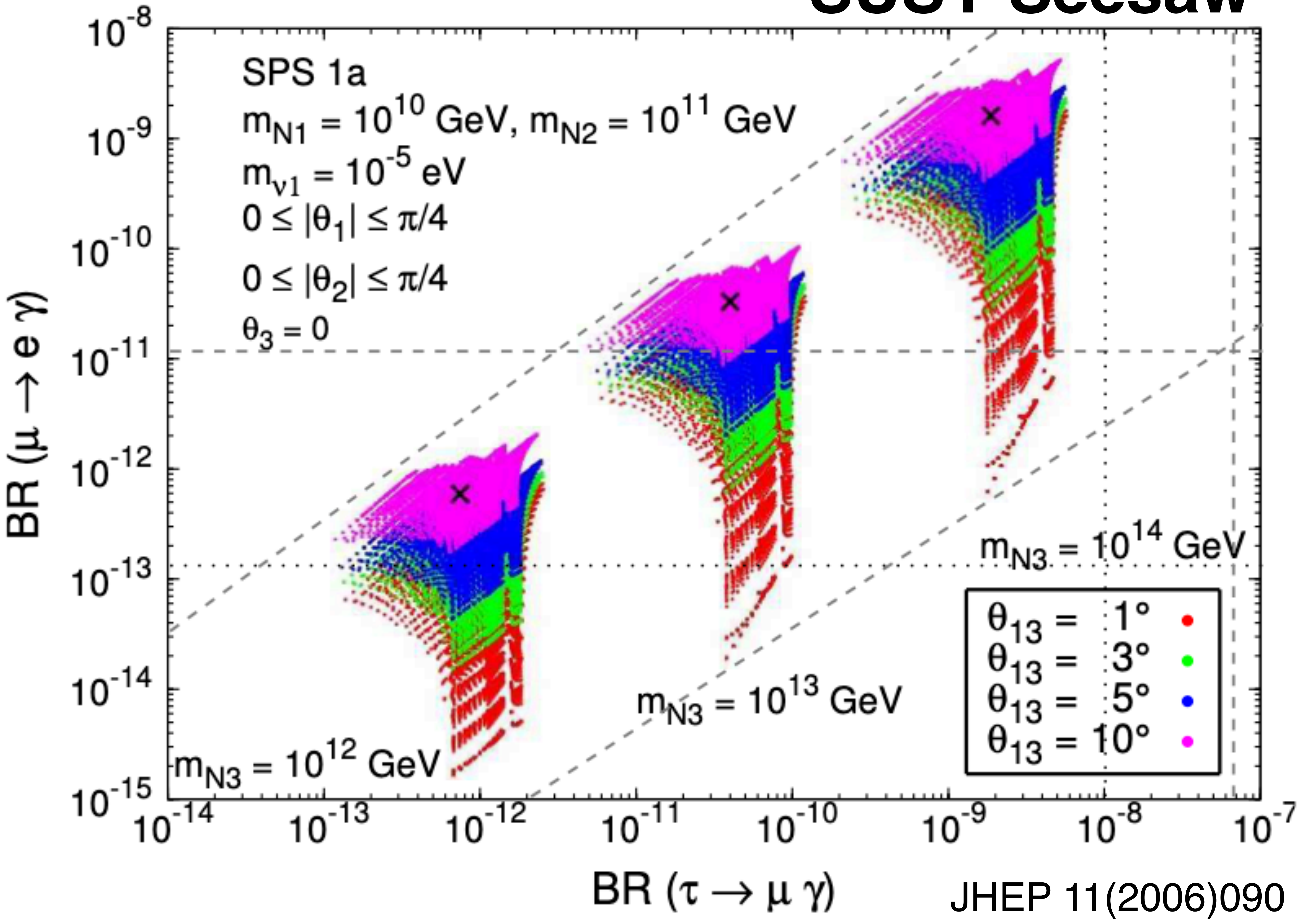
Examples of new physics

SUSY-GUT SO(10)



JHEP 0912(2009)057

SUSY-Seesaw



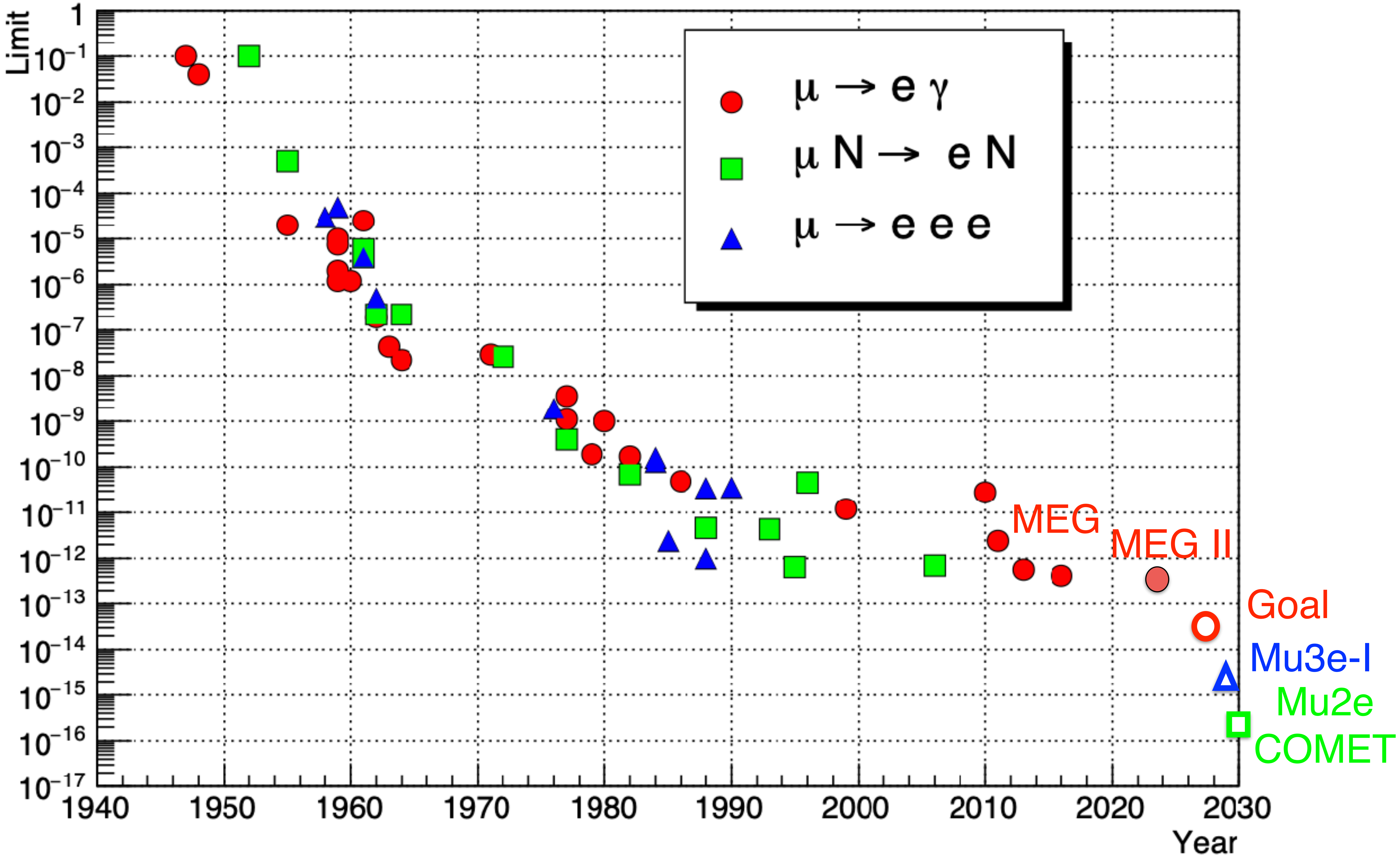
JHEP 11(2006)090

Real chance for discovery

Already some regions from theoretical expectation excluded

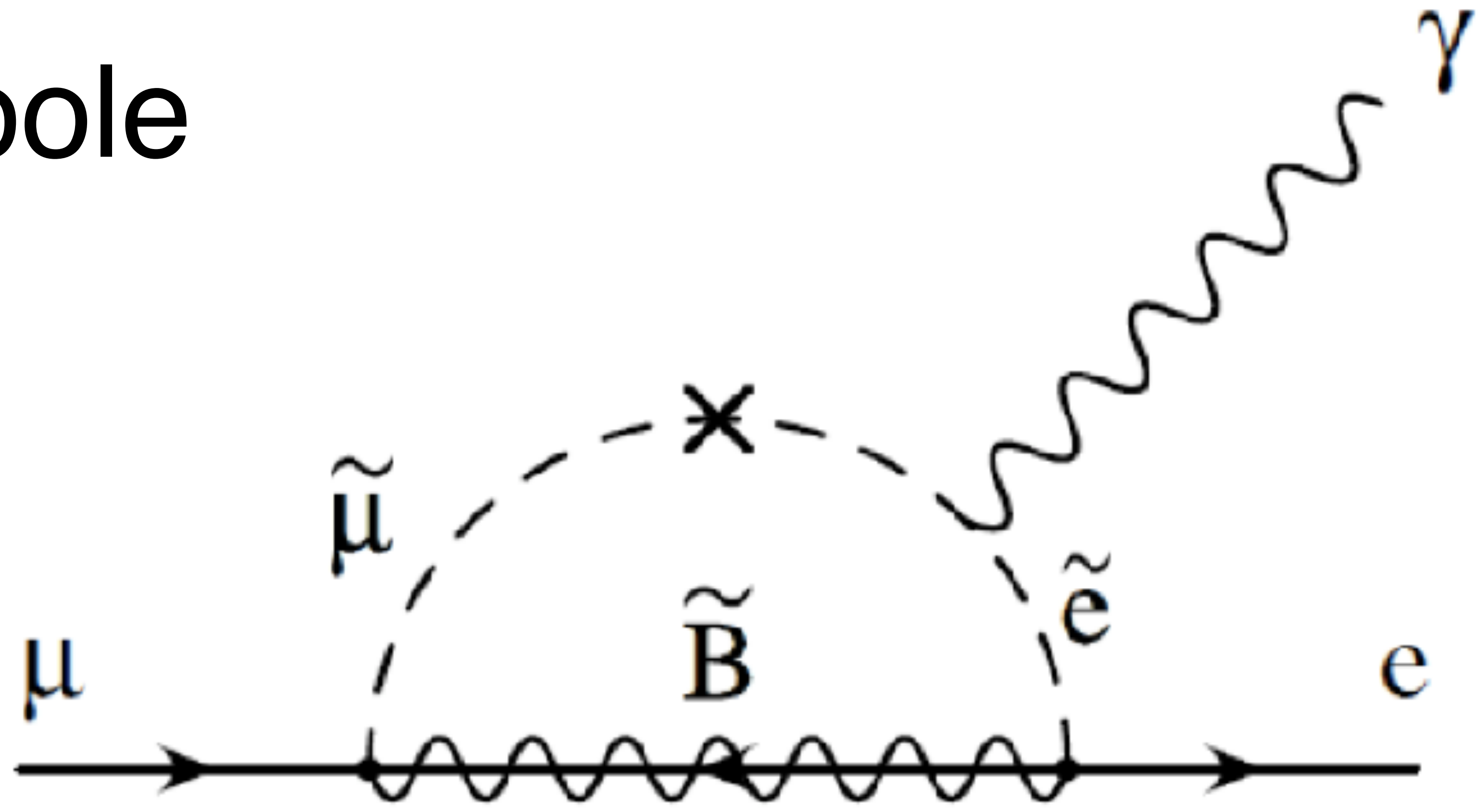
$\mu^+ \to e^+\gamma, \mu^+ \to e^+e^-e^+$, & $\mu^- \to e^-$

- 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

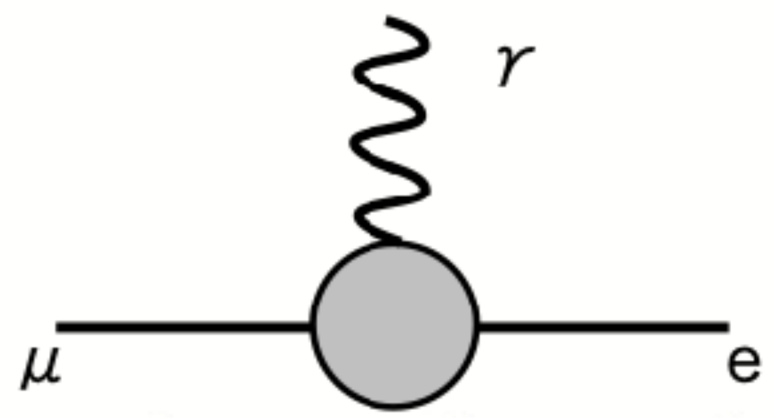


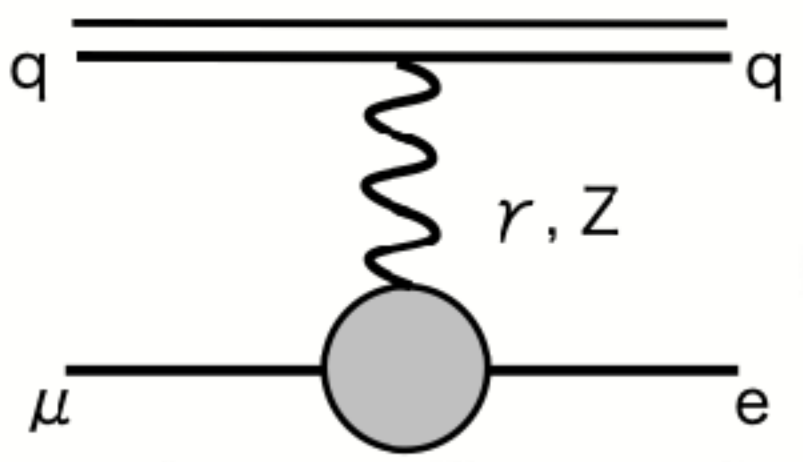
New physics models

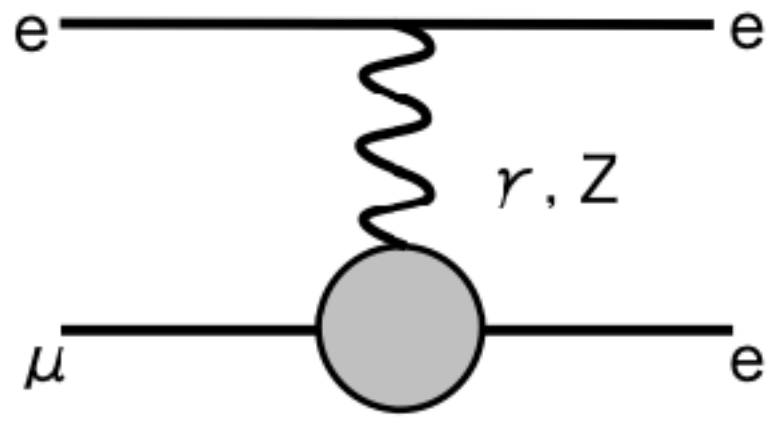
Dipole



SUSY-GUT, SUSY-seesaw

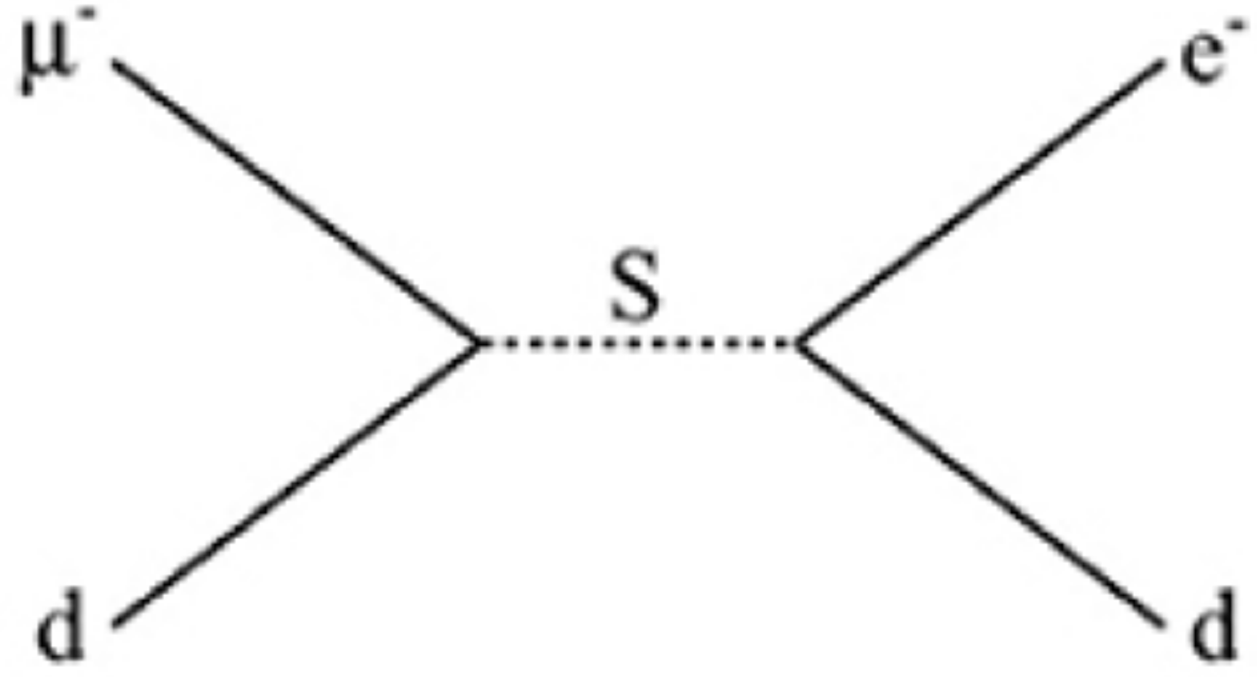




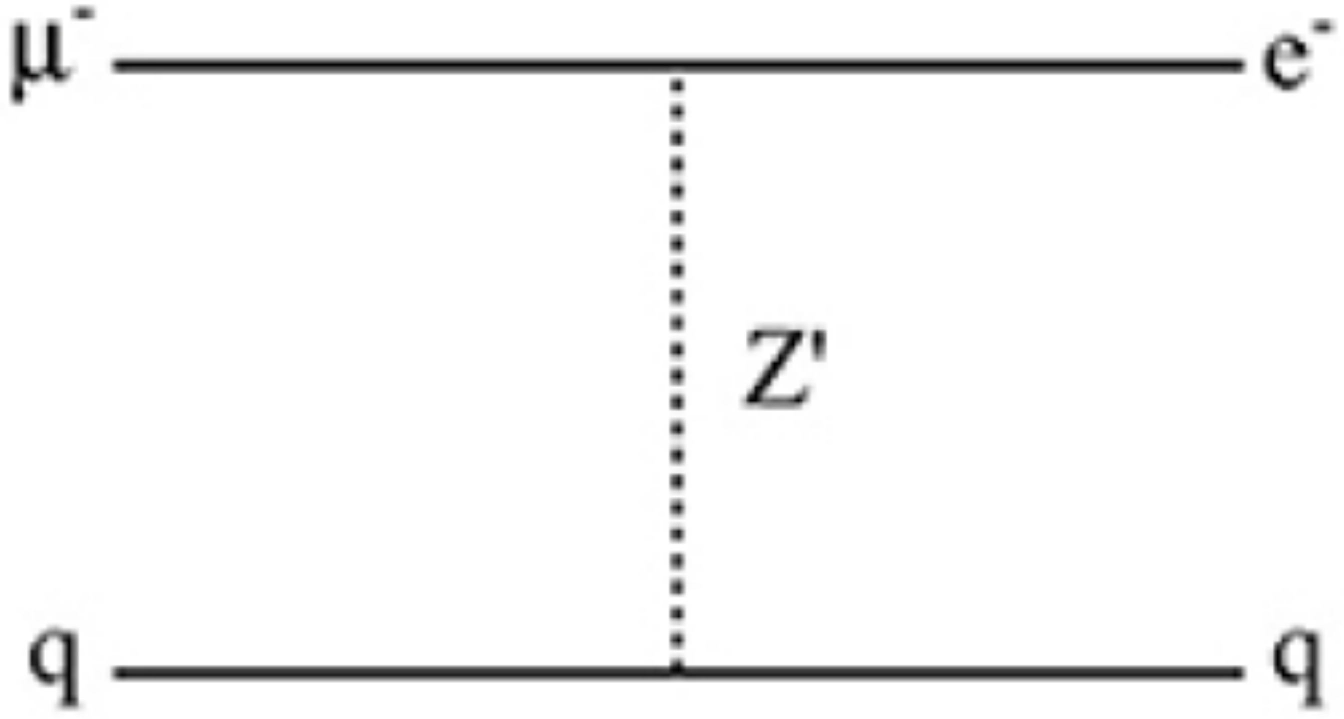


$$\mathrm{Br}(\mu \to e\gamma) : R(\mu\text{-Al} \to e\text{-Al}) : \mathrm{Br}(\mu \to 3e)$$
$$= 1 : 1/390 : 1/170$$

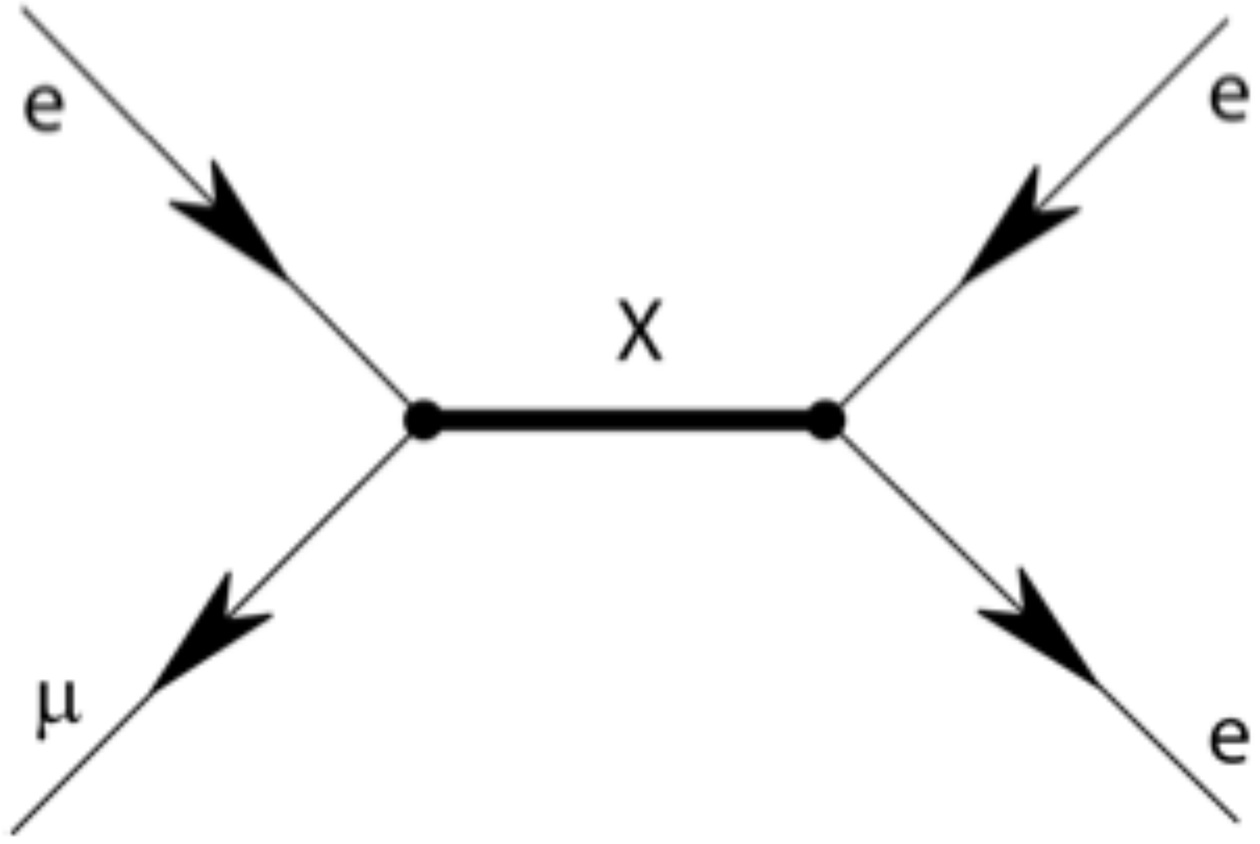
Tree



Scalar: RPV SUSY



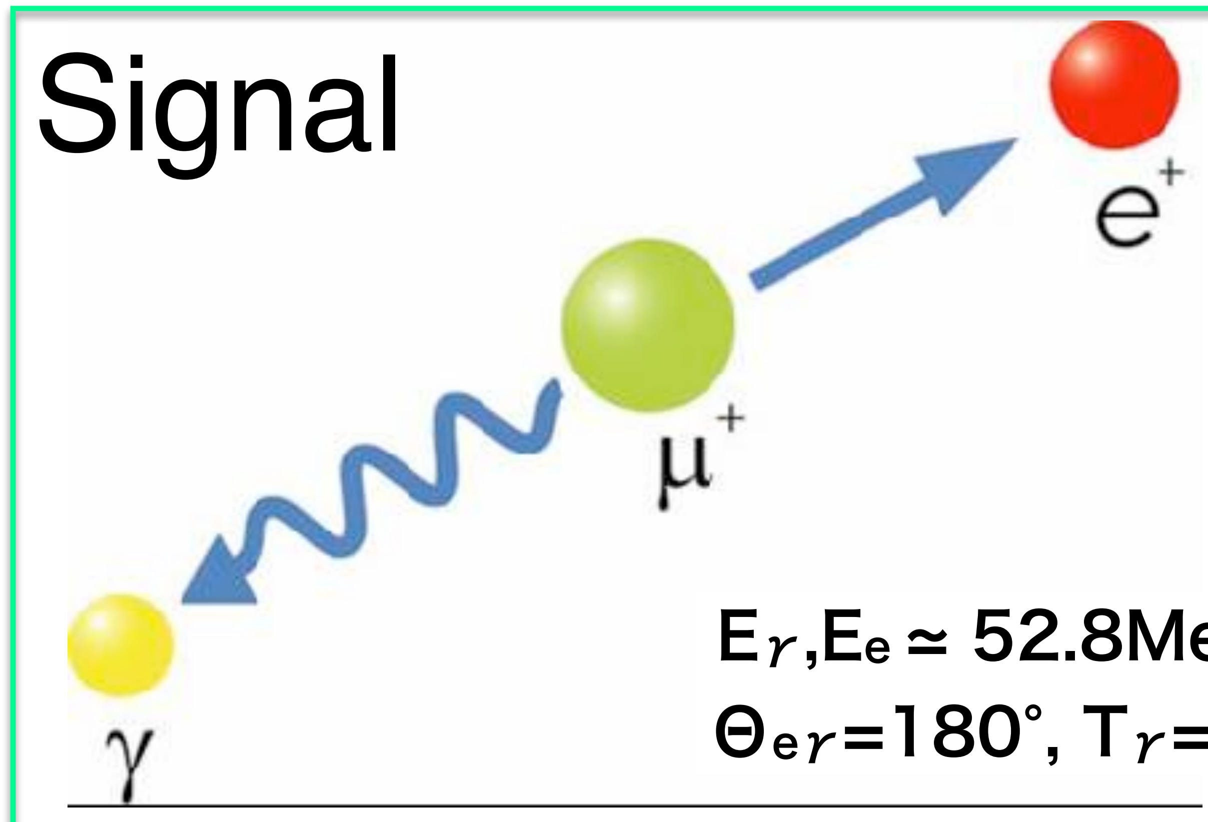
Vector: Leptoquarks, Z',…



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

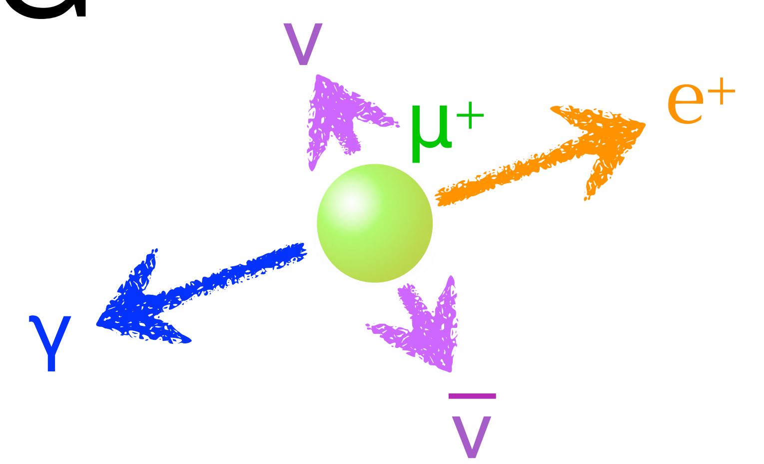
$\mu^+ \rightarrow e^+\gamma$ signal and backgrounds

Signal

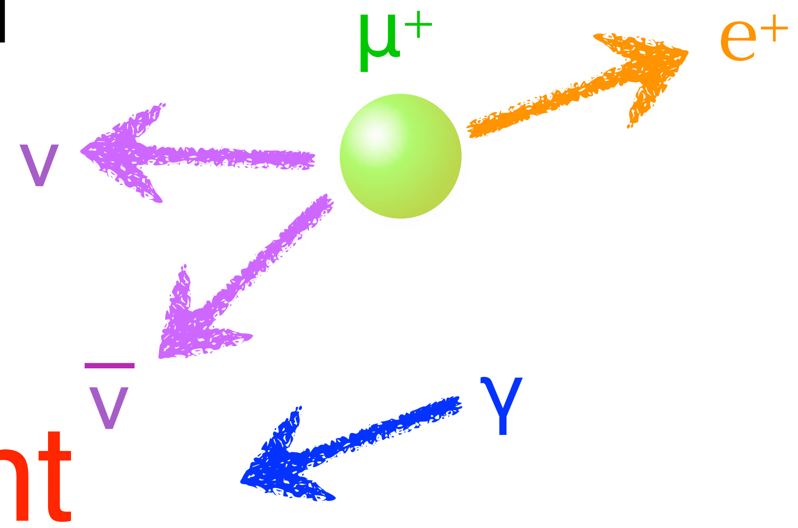


$E_\gamma, E_e \simeq 52.8\,\mathrm{MeV}$
$\Theta_{e\gamma} = 180^\circ,\ T_\gamma = T_e$

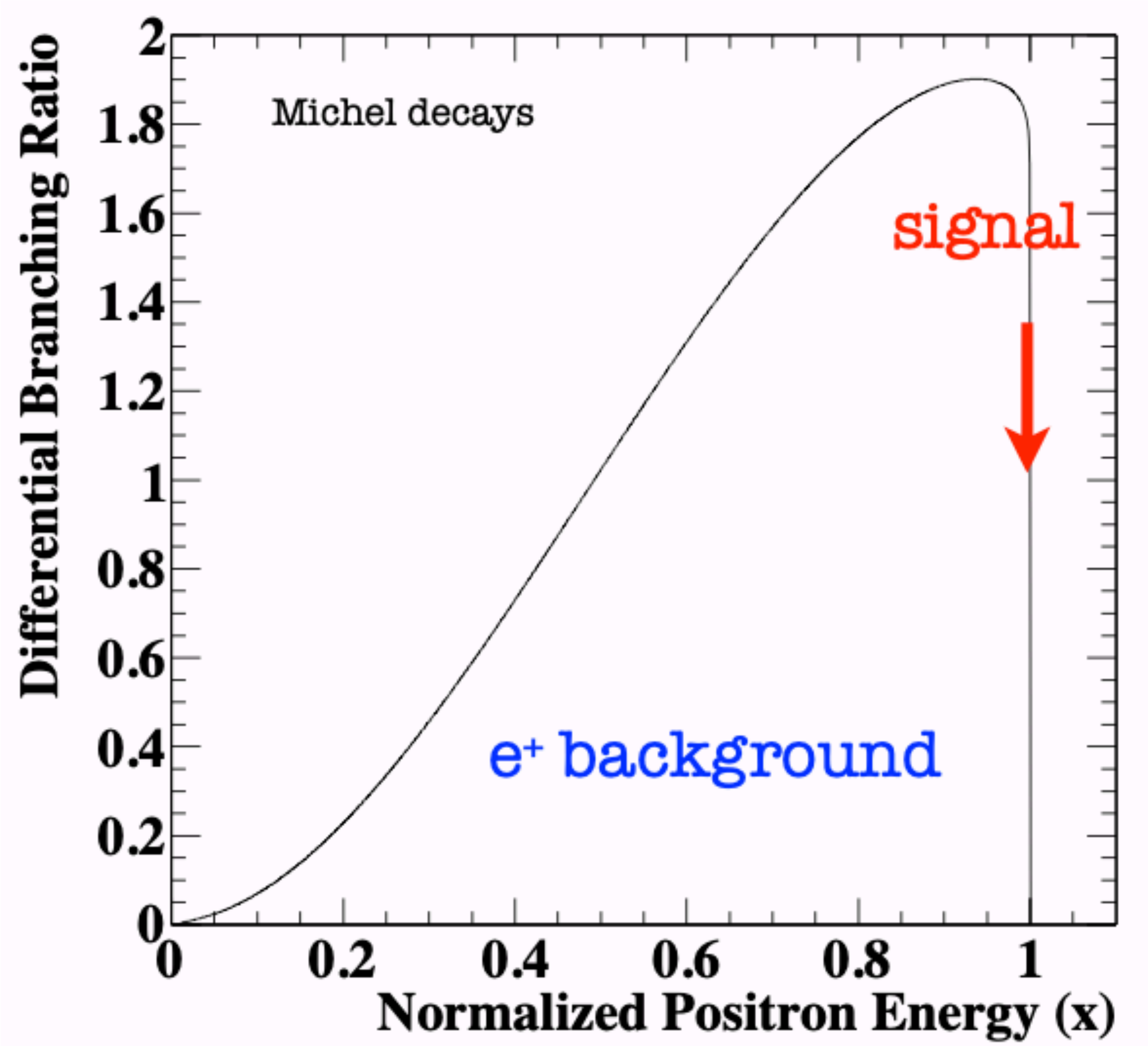
RMD BG

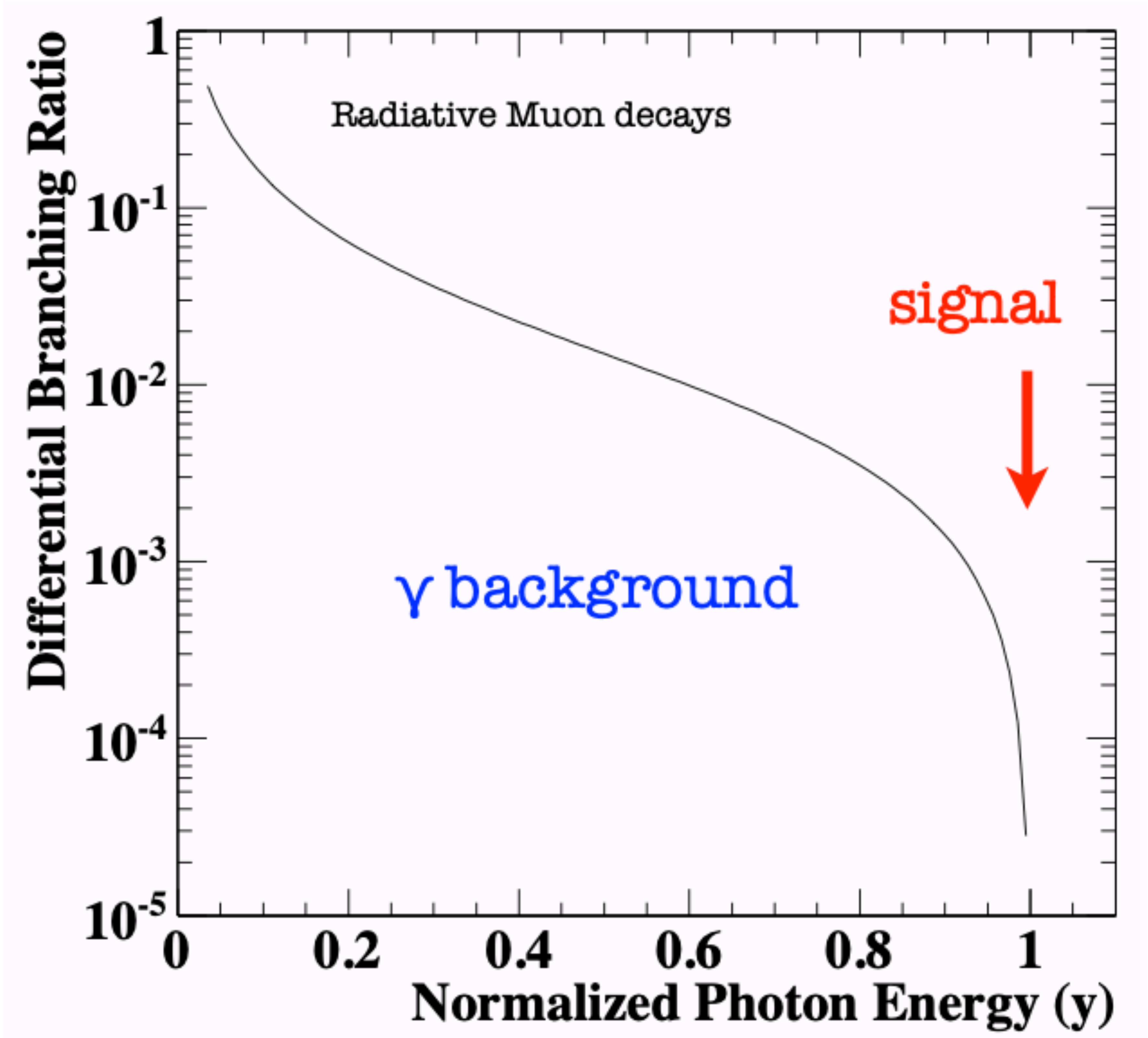


Acc BG



Dominant





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

Efficiency crucial for statistics

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

Beam rate

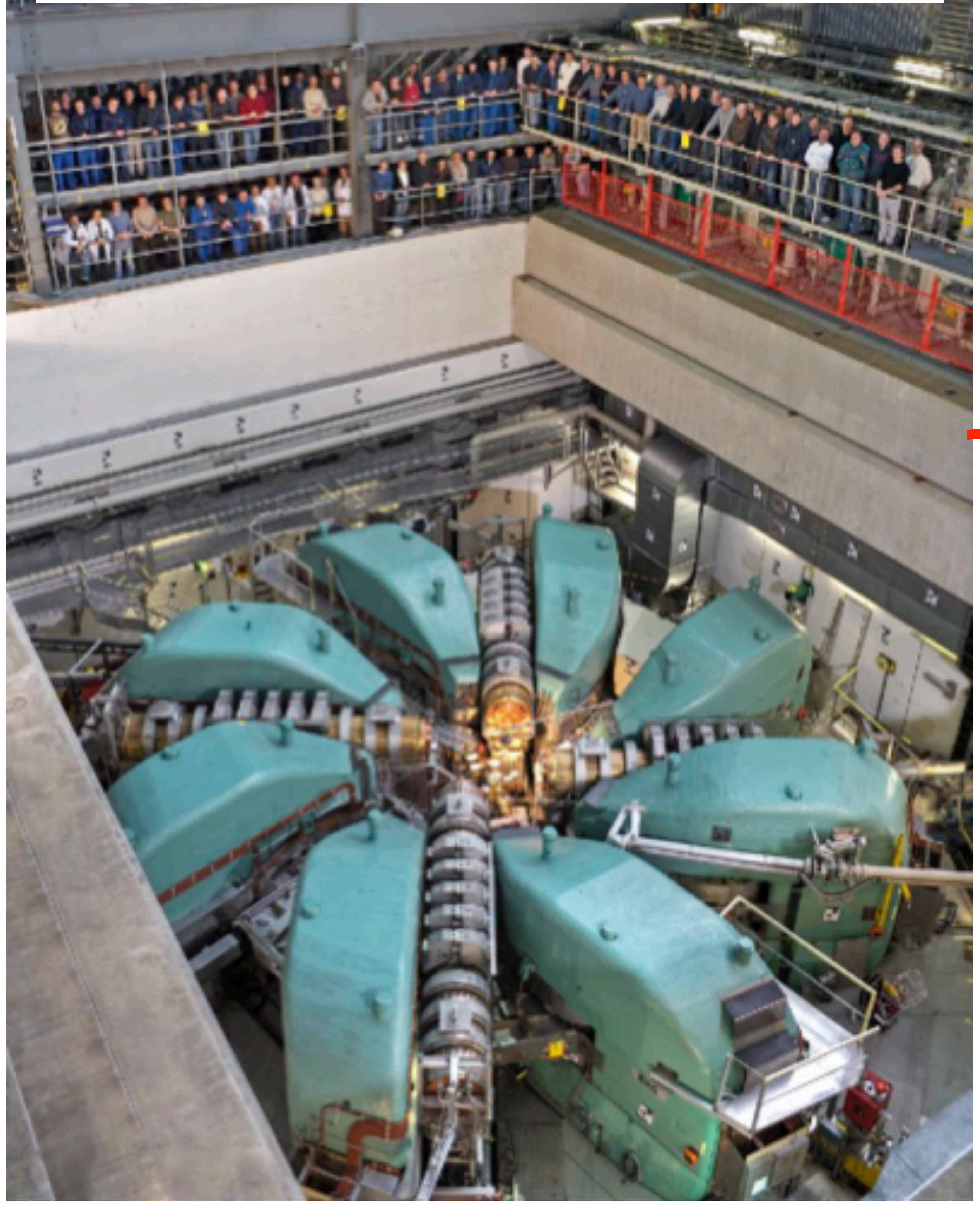
Resolutions

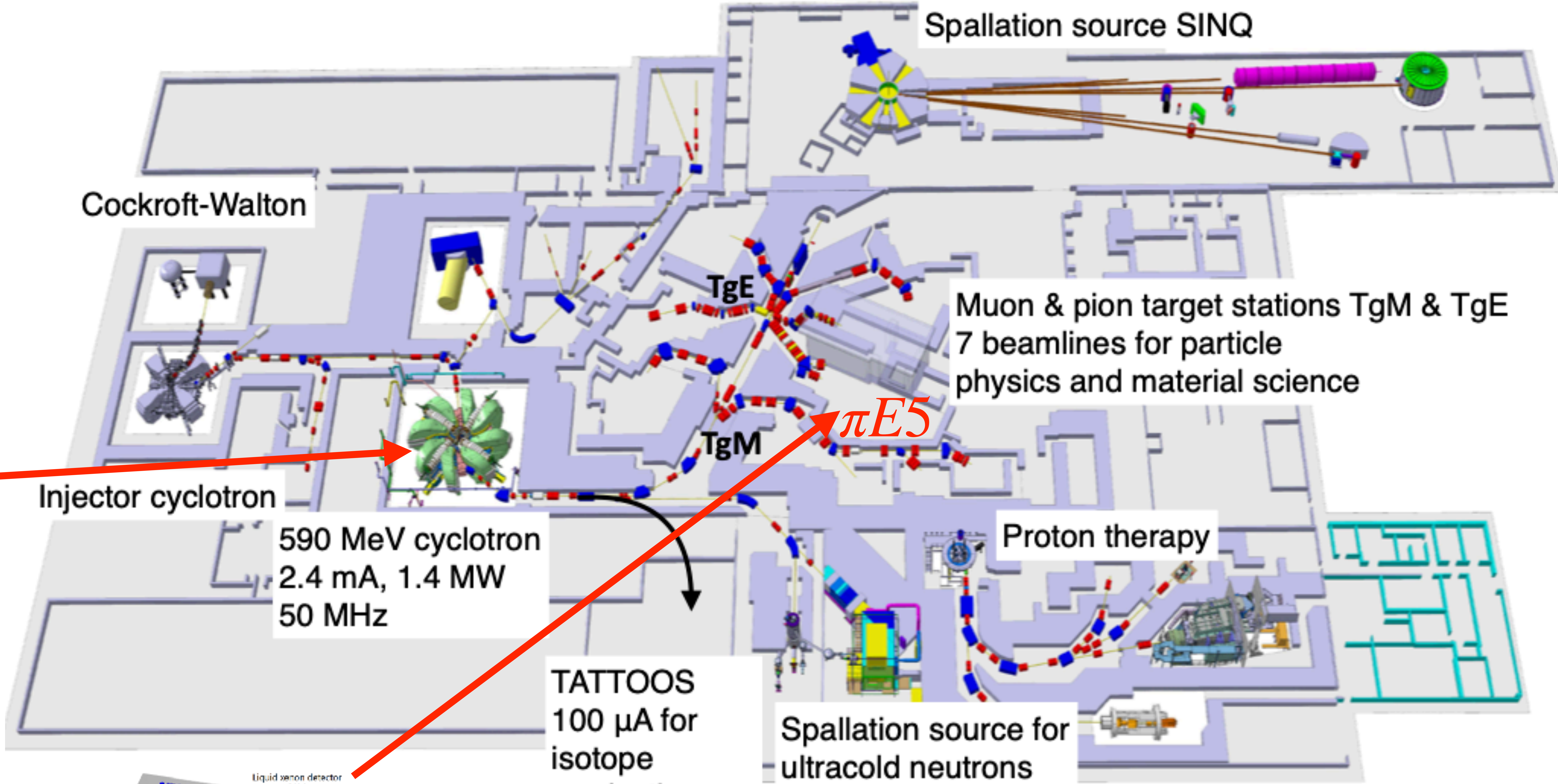
Elapsed time

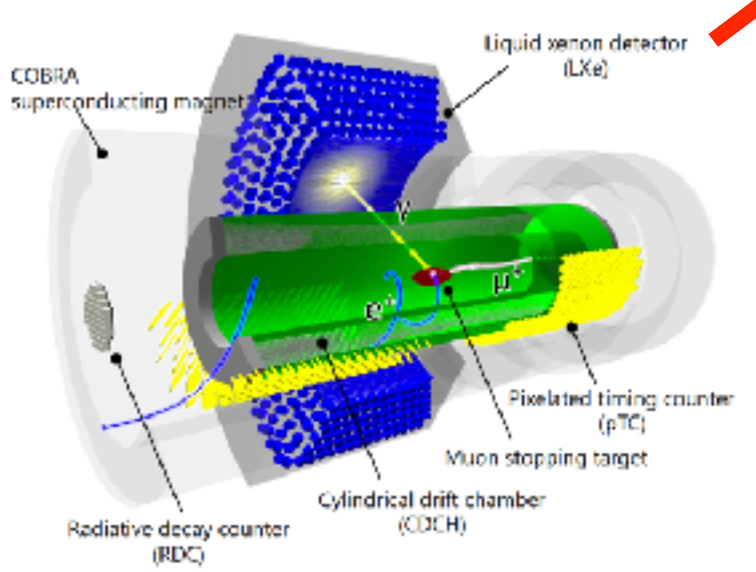
Good resolution crucial to lower the accidental background (N_{BG})

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

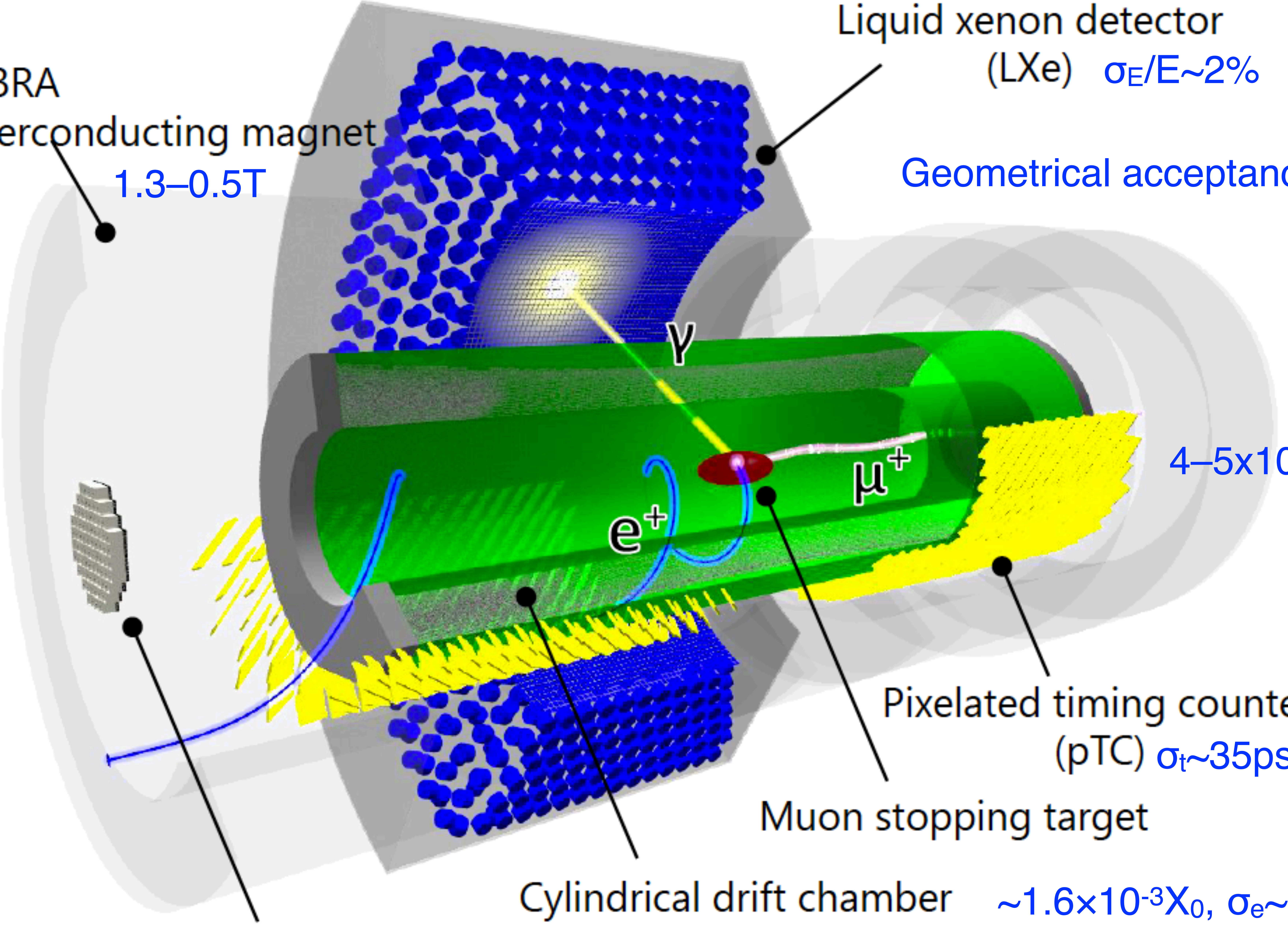






MEG II → Needs high intensity muon beam

MEG II



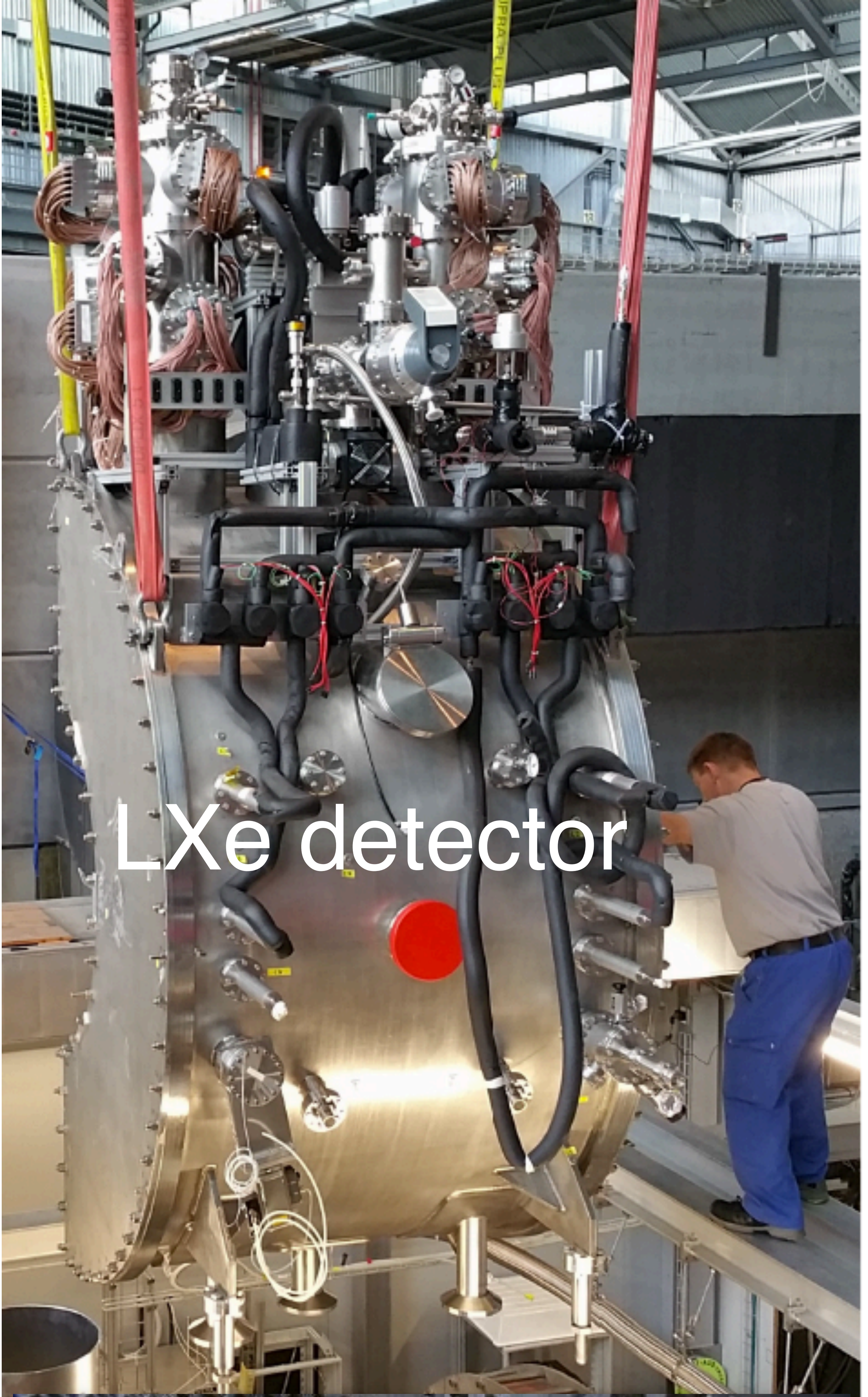
Target sensitivity :
6×10^{-14} (90%C.L.)

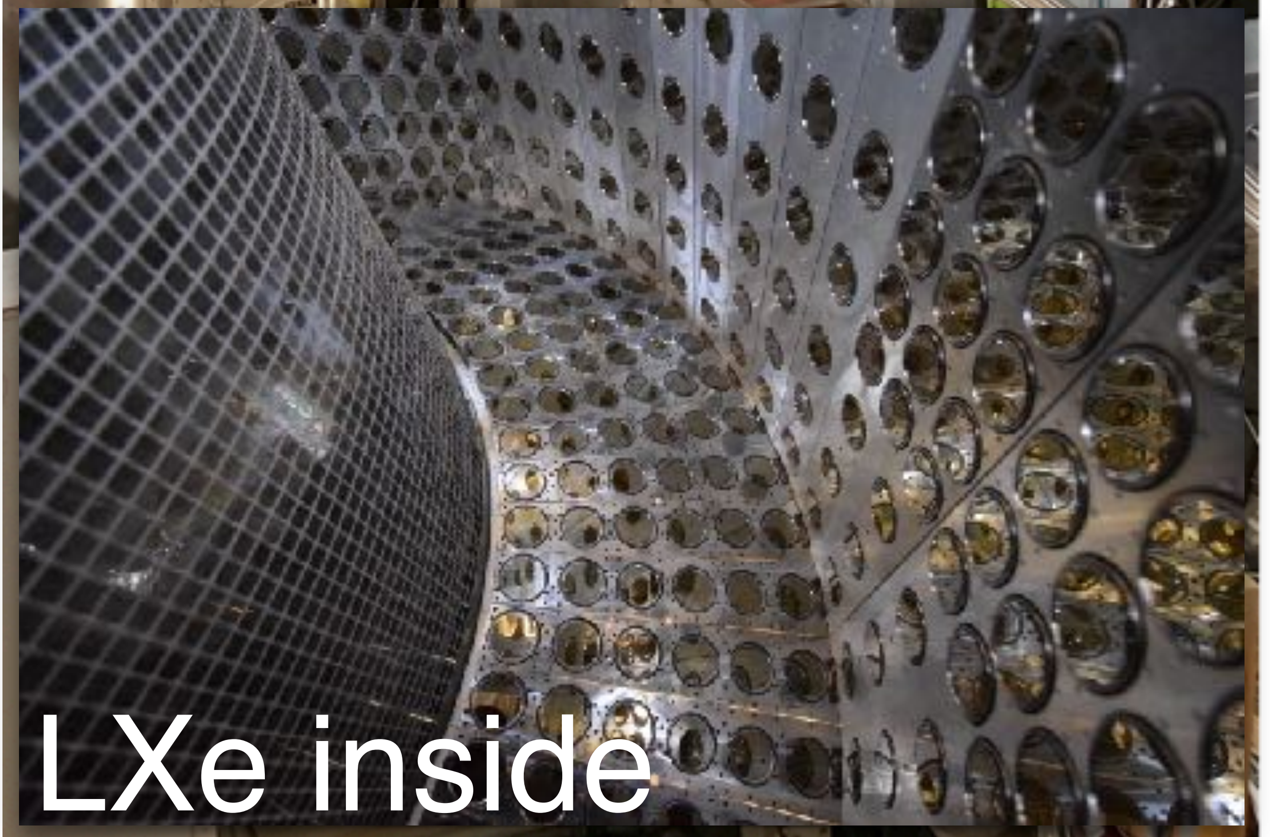
MEG final result:
4.2×10^{-13}(90%CL)

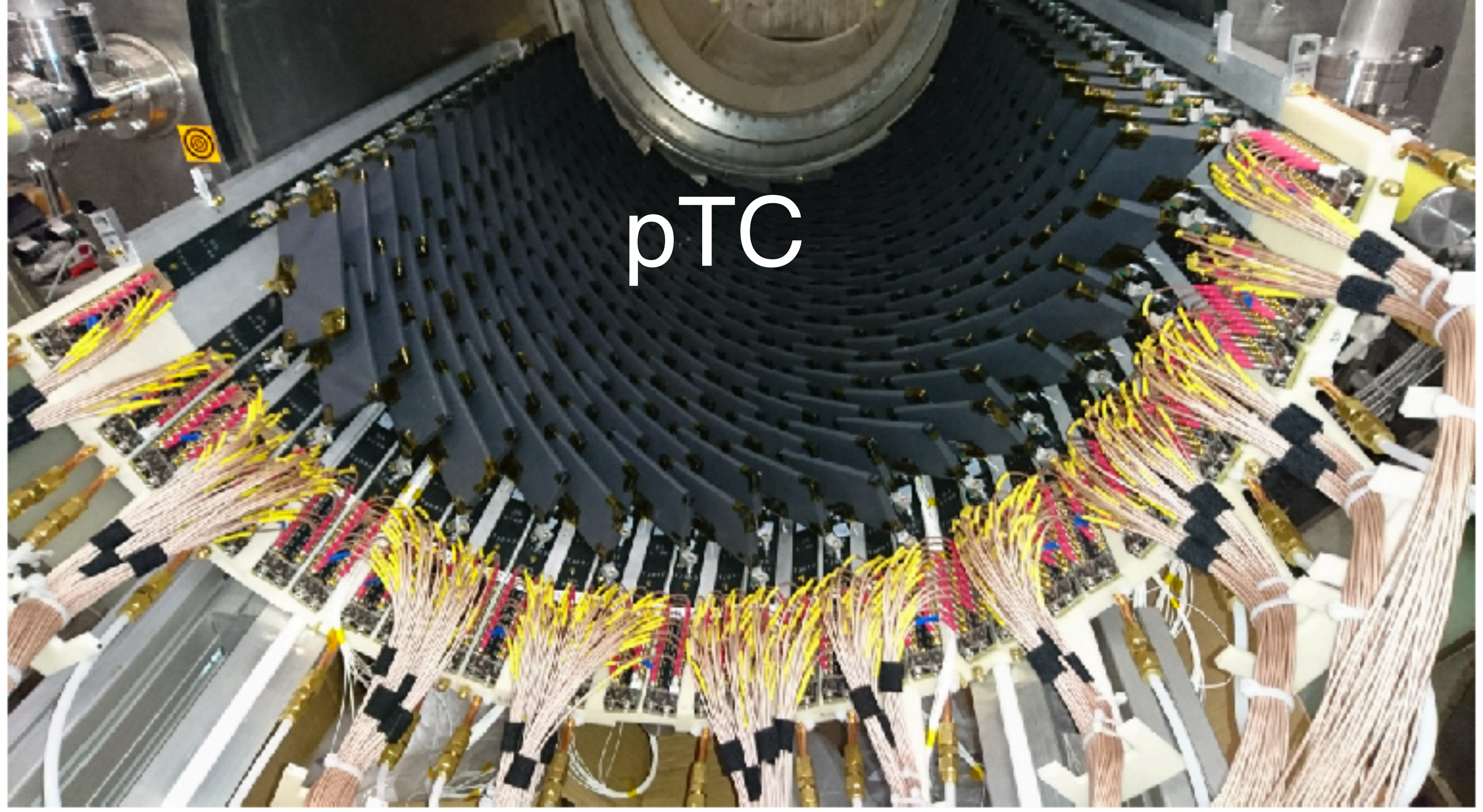
MEG sensitivity:
5.3×10^{-13}(90%CL)

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

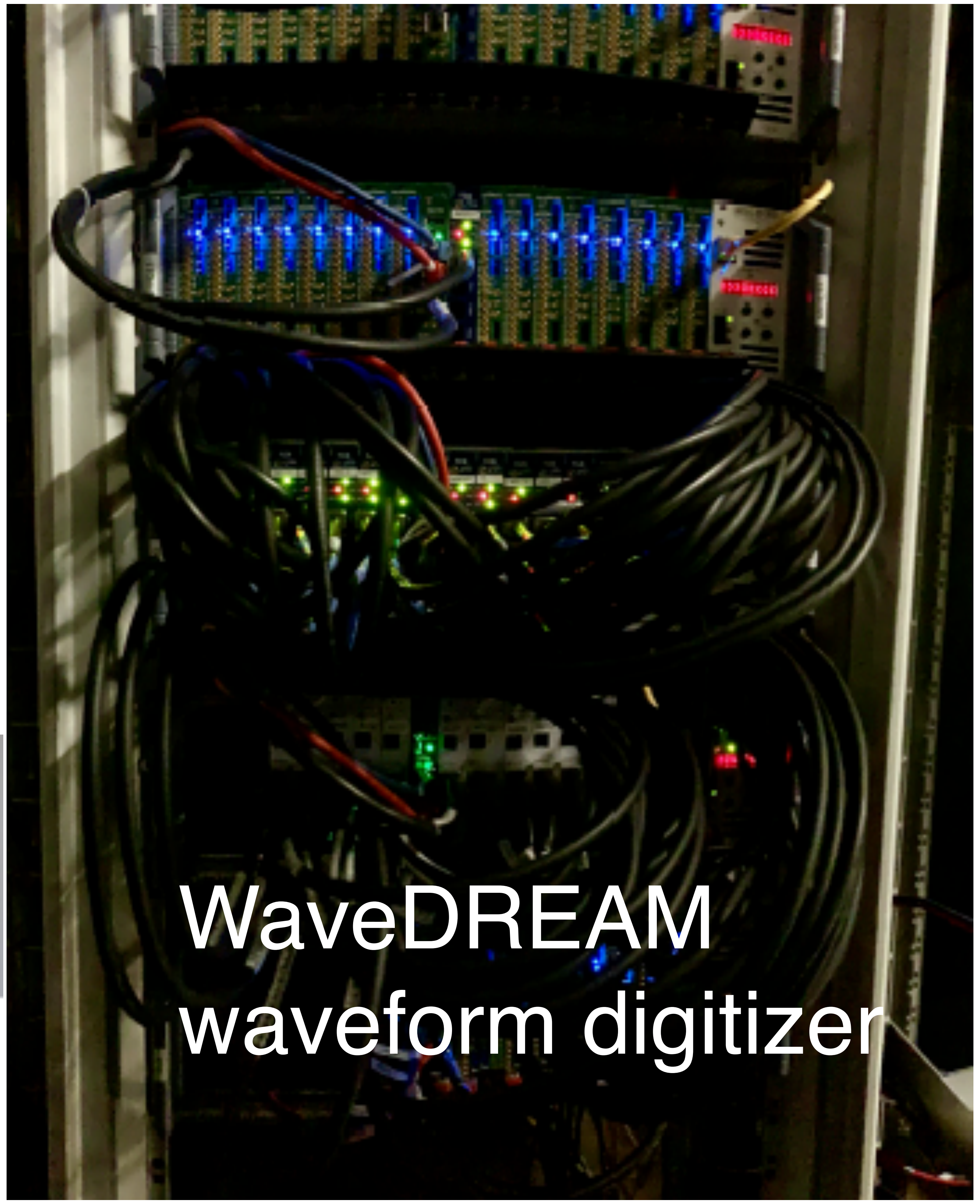
EPJC 84(2024)2, 190

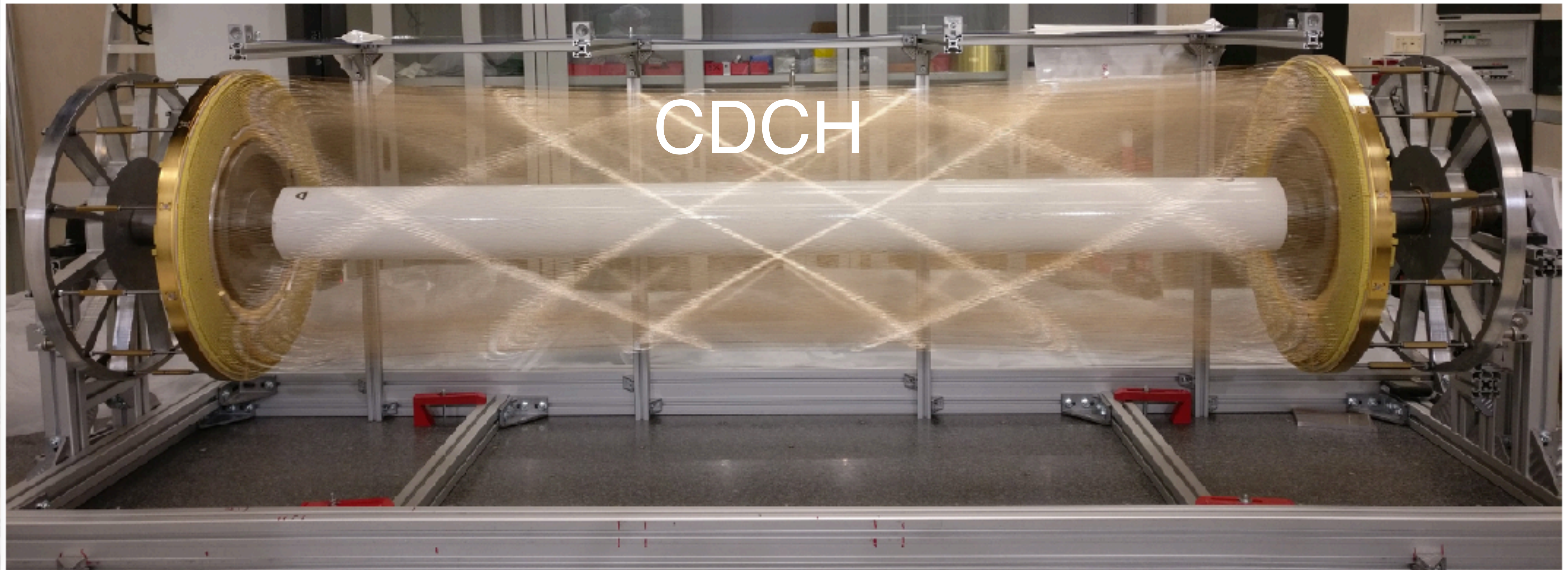


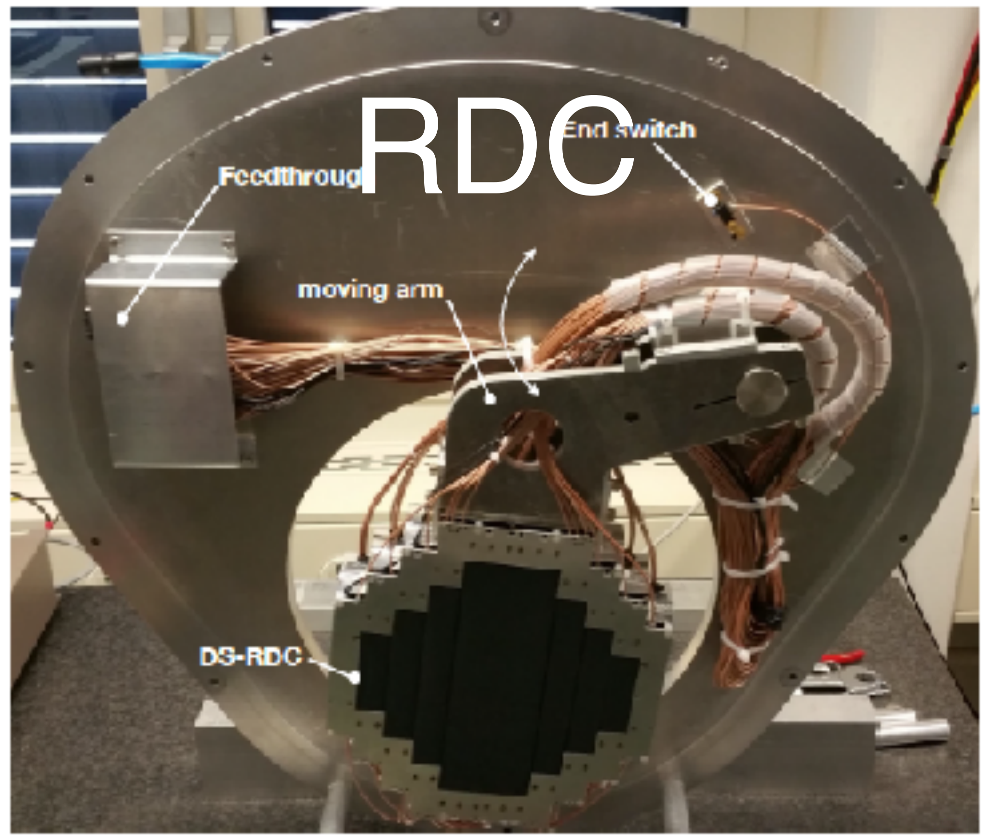




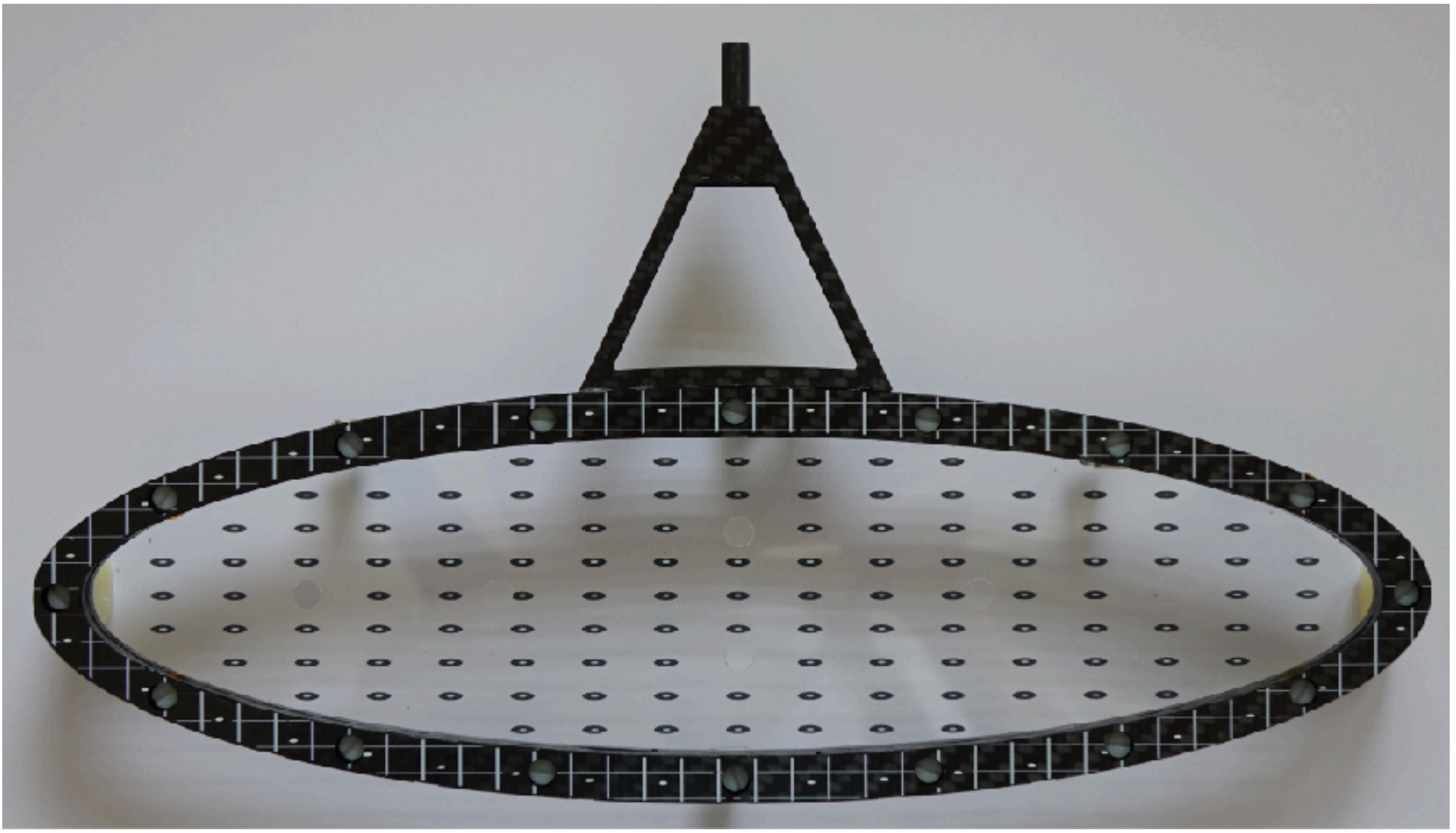
MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-

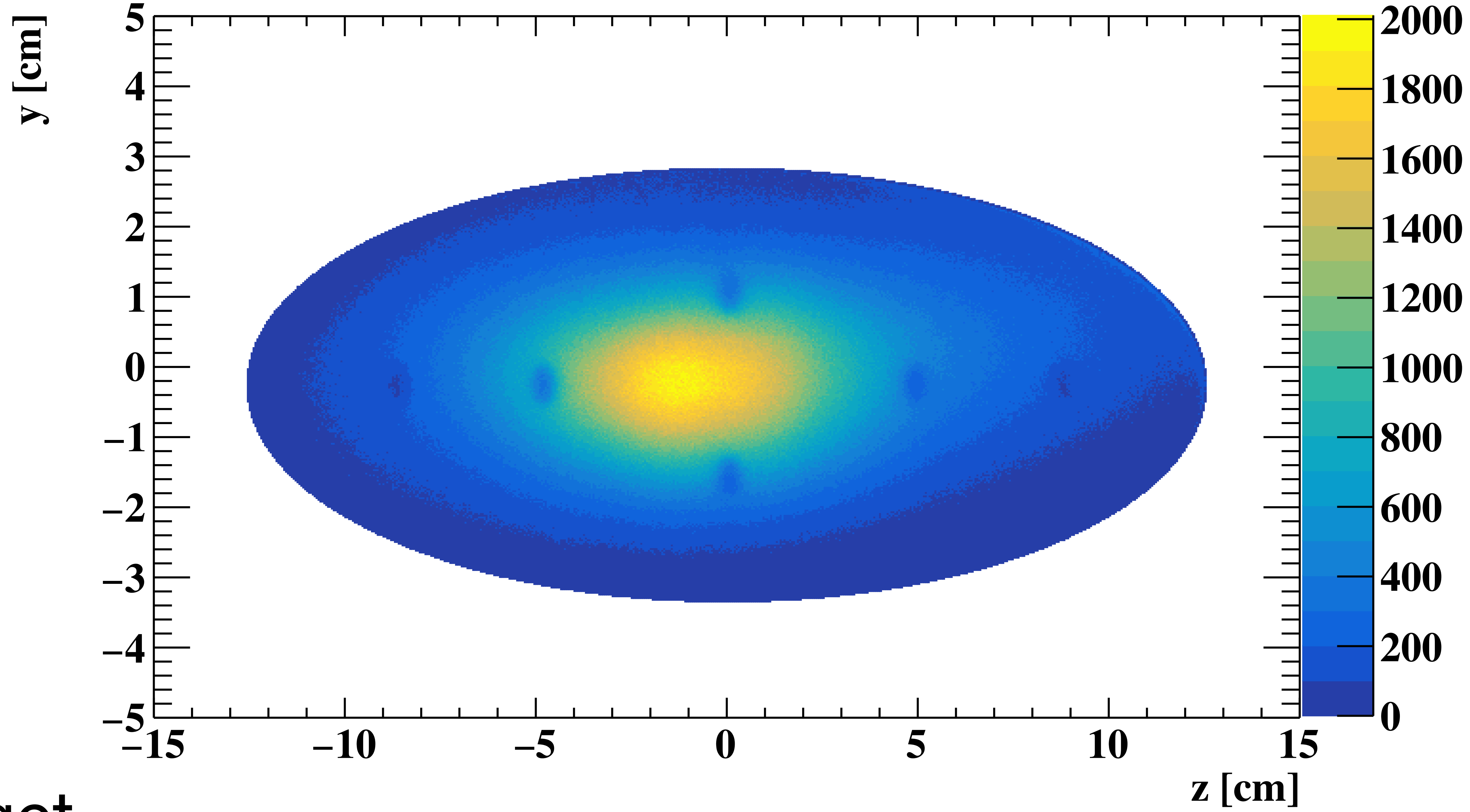




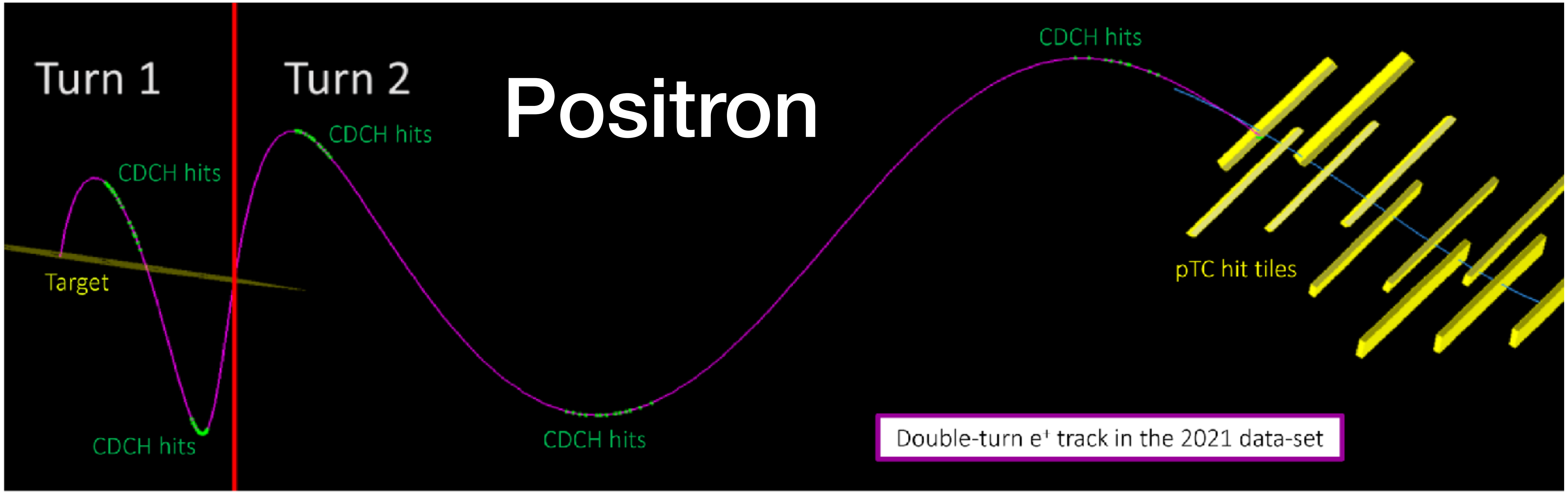


Target

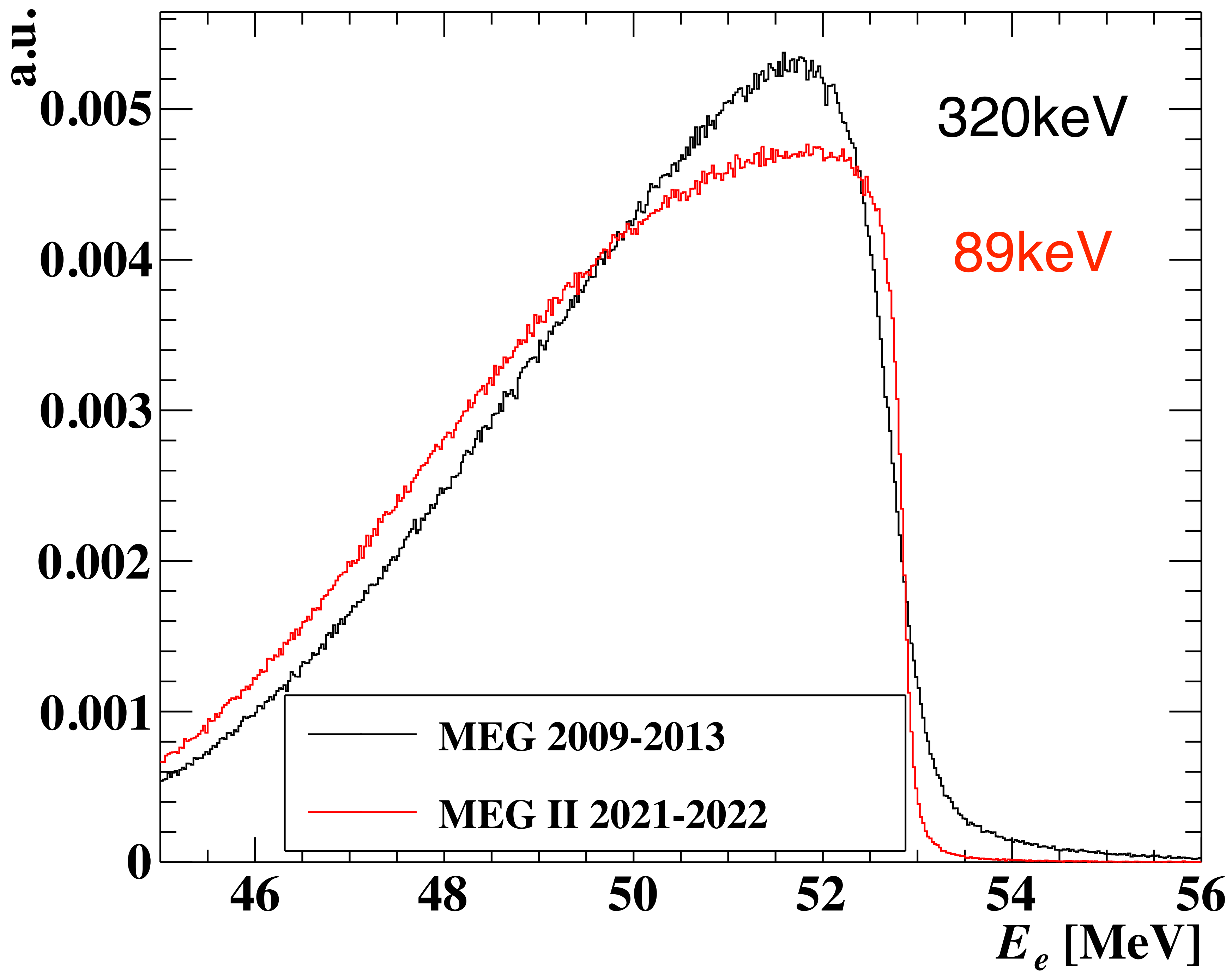


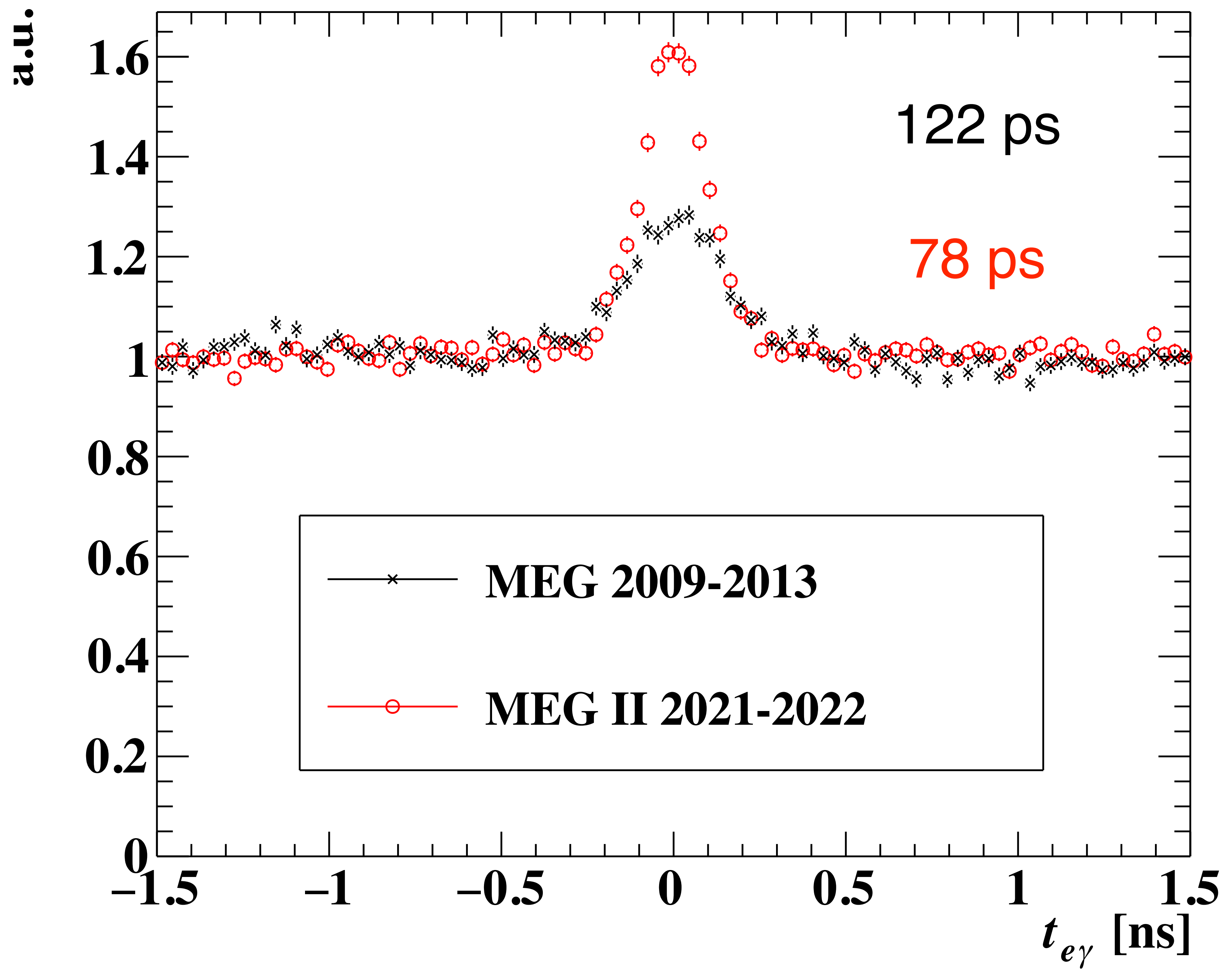


- Slanted 174µm thick BC400 target
  - 6 holes (reconstructed positron distribution) and a pattern of dots (photographed by a camera) to continuously monitor the shape and position of the foil



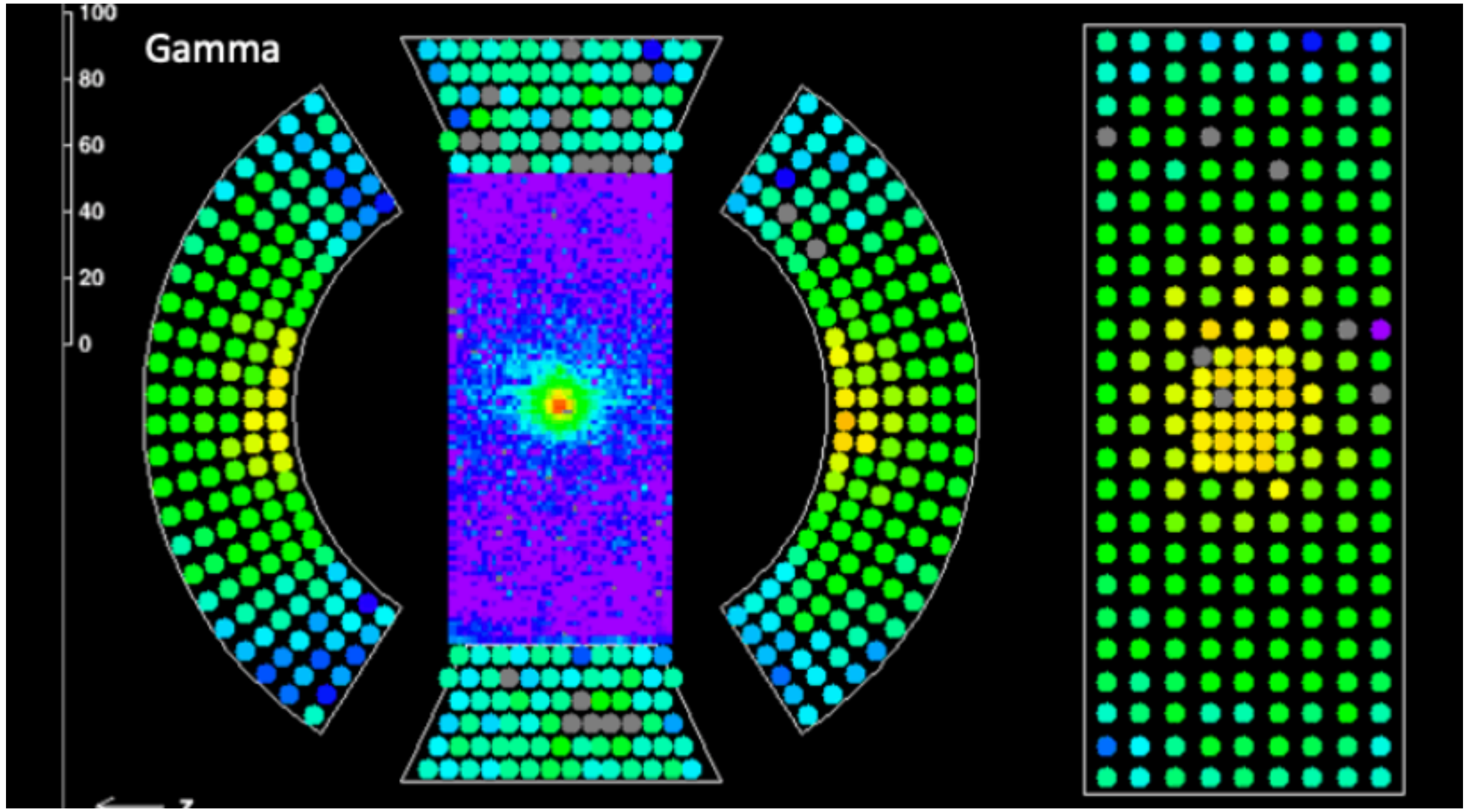
- Drift chamber
  - 0.16% X_0 (low mass)
  - Stereo wire geometry
  - Square cells with 6mm, 9 layers
- Pixelated timing counter
  - 256 x 2 BC422 scint. + SiPMs
  - 9 hits on average

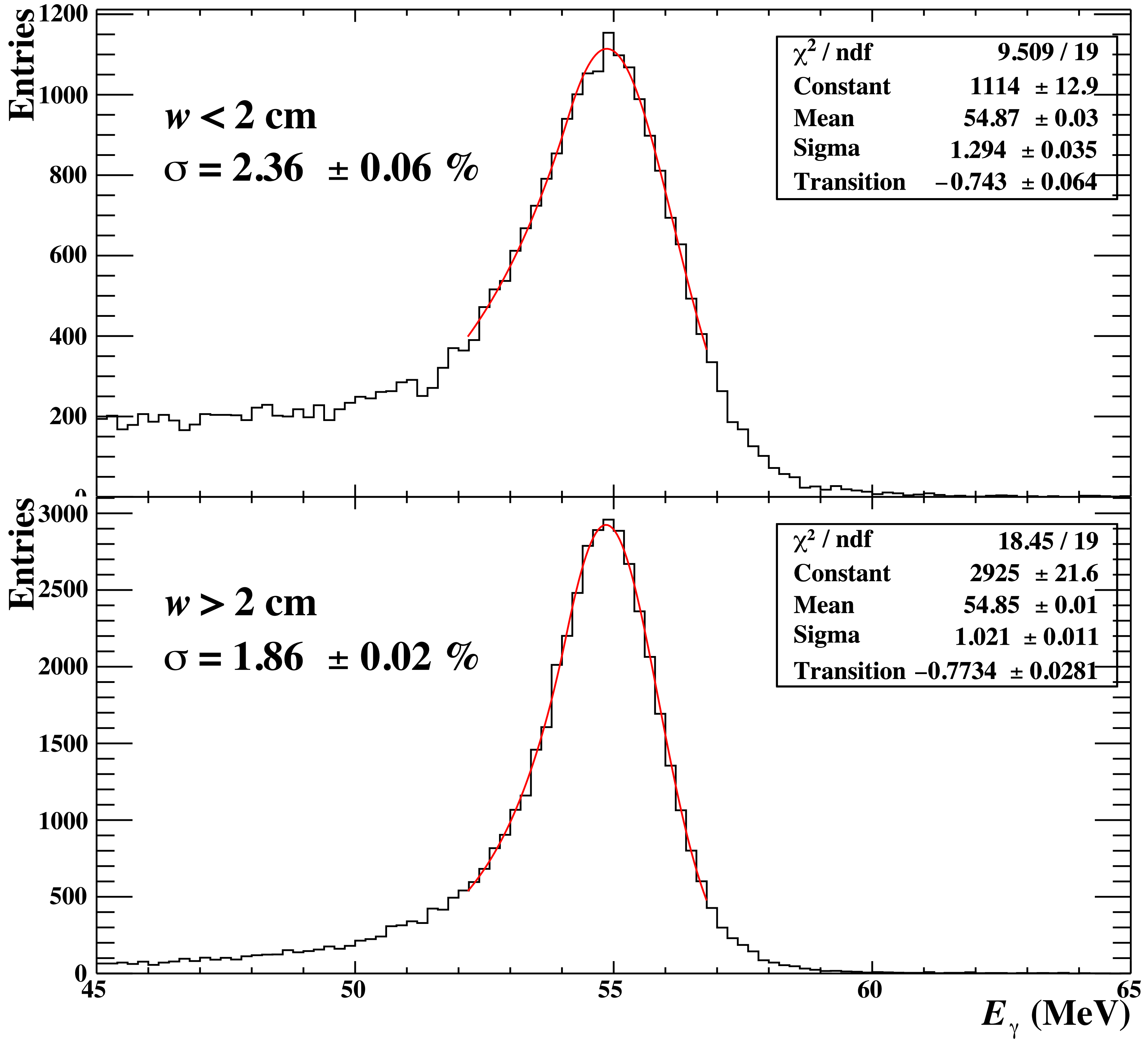


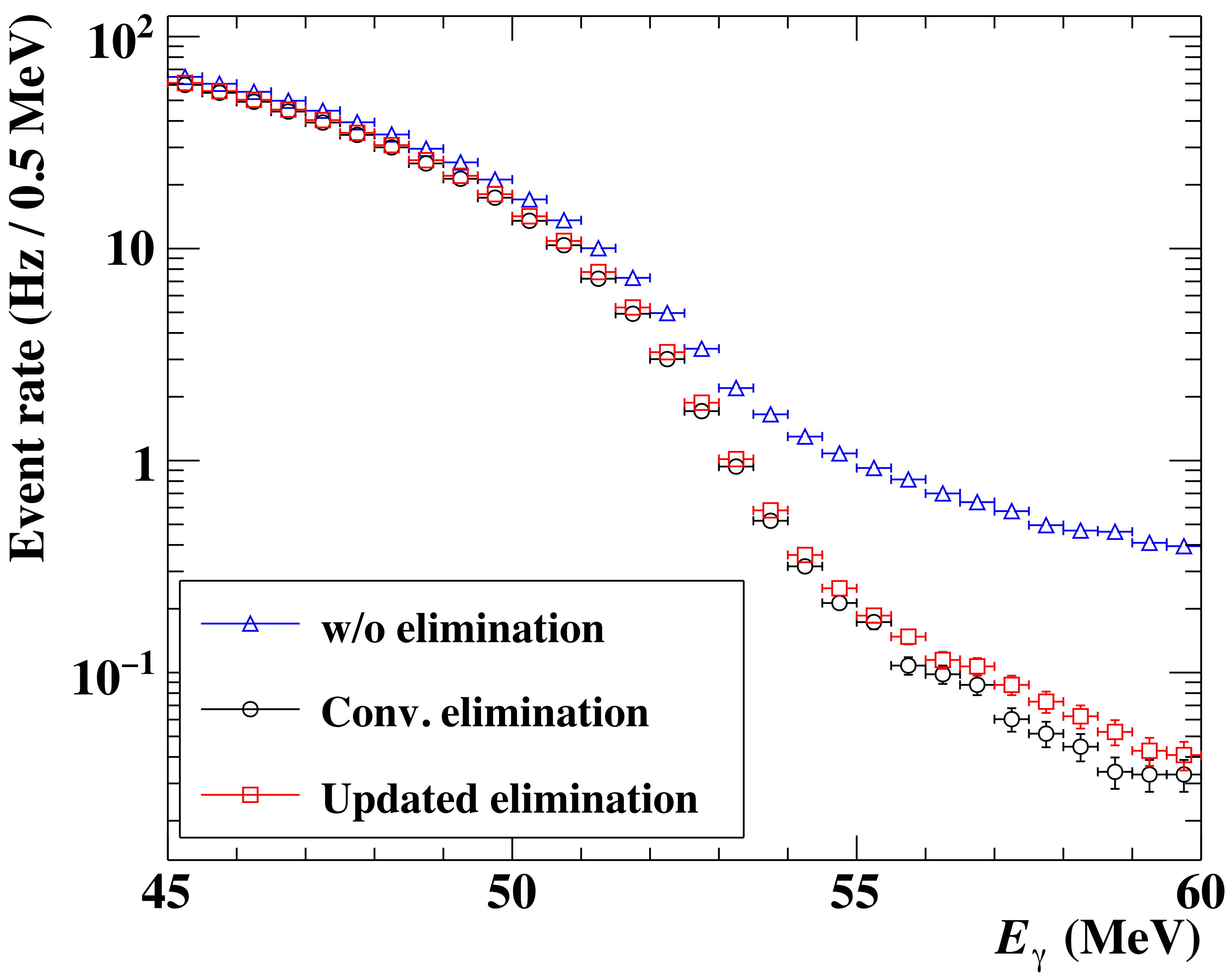


Photon

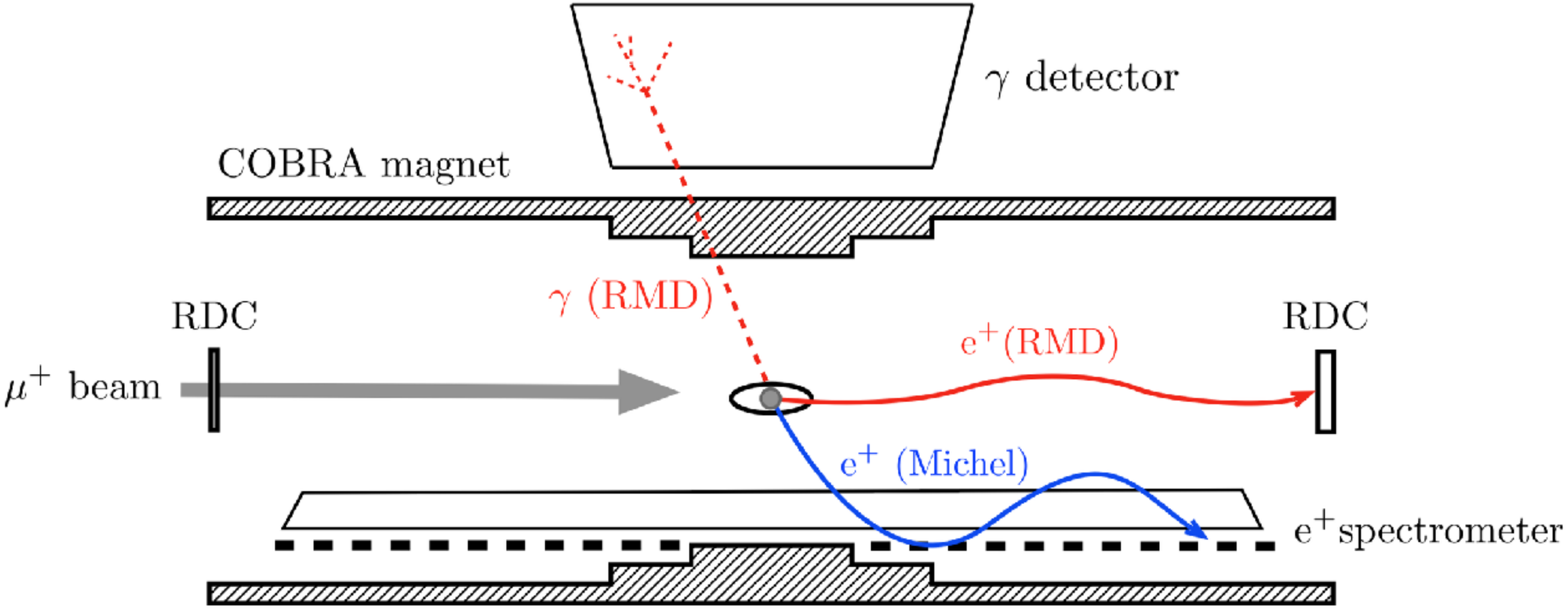
- 900 L liquid xenon at 165K
- VUV-sensitive 4092 MPPCs + 668 PMTs at 175nm
- Performance check
  - 55 MeV γ from $\pi^- p \rightarrow \pi^0 n (\pi^0 \rightarrow \gamma\gamma)$
- Pileup removal by light distribution and waveform timing



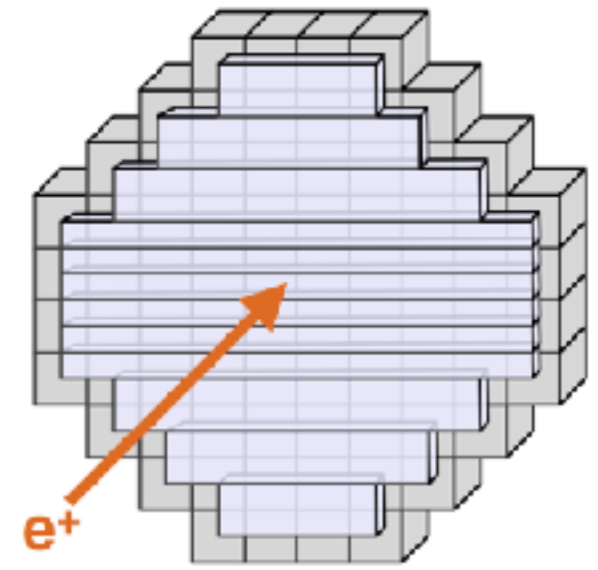




Radiative Decay Counter

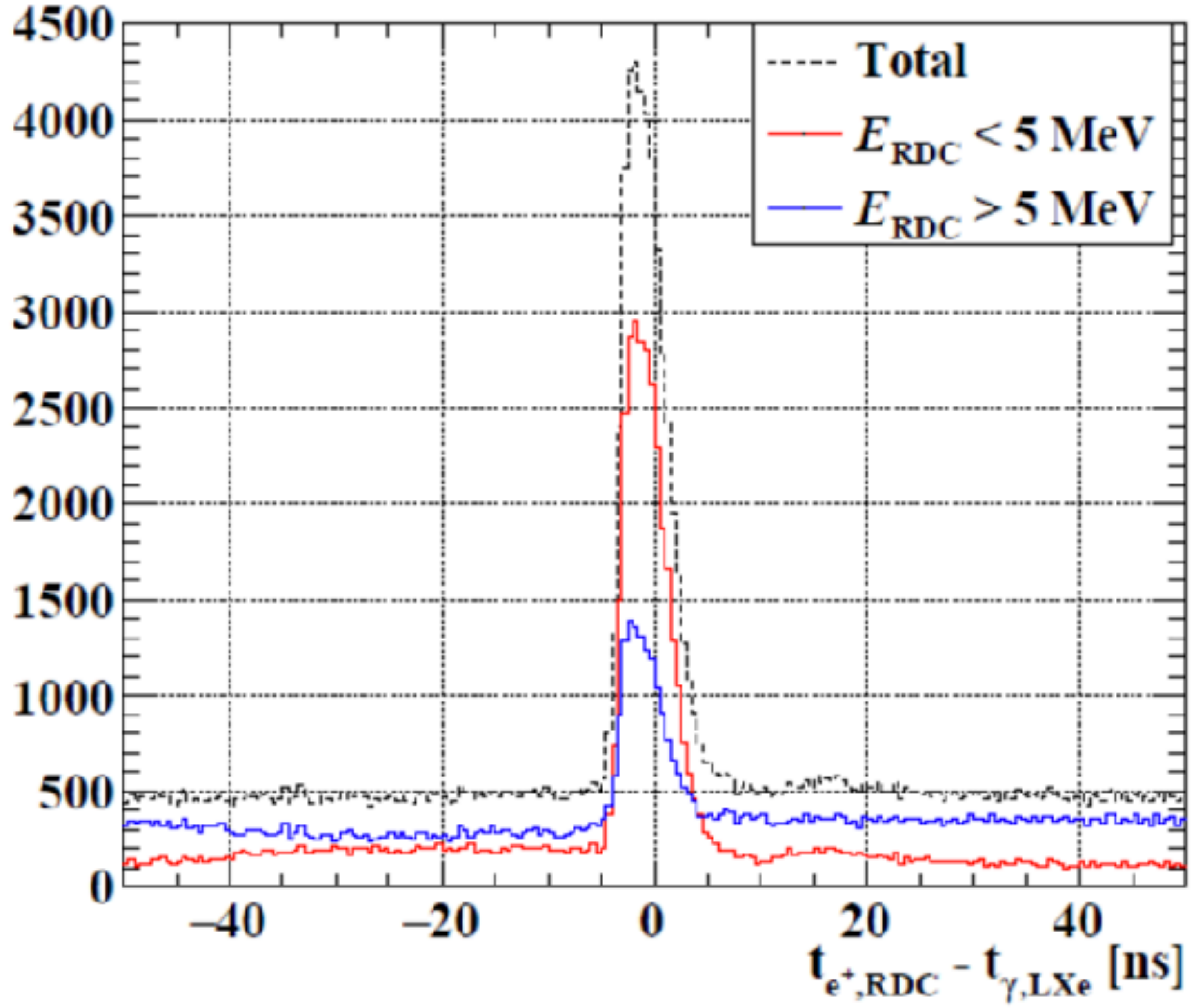


LYSO 2×2×2 cm³+SiPM for e+ energy



Plastic Scinti.+SiPM for e+ timing

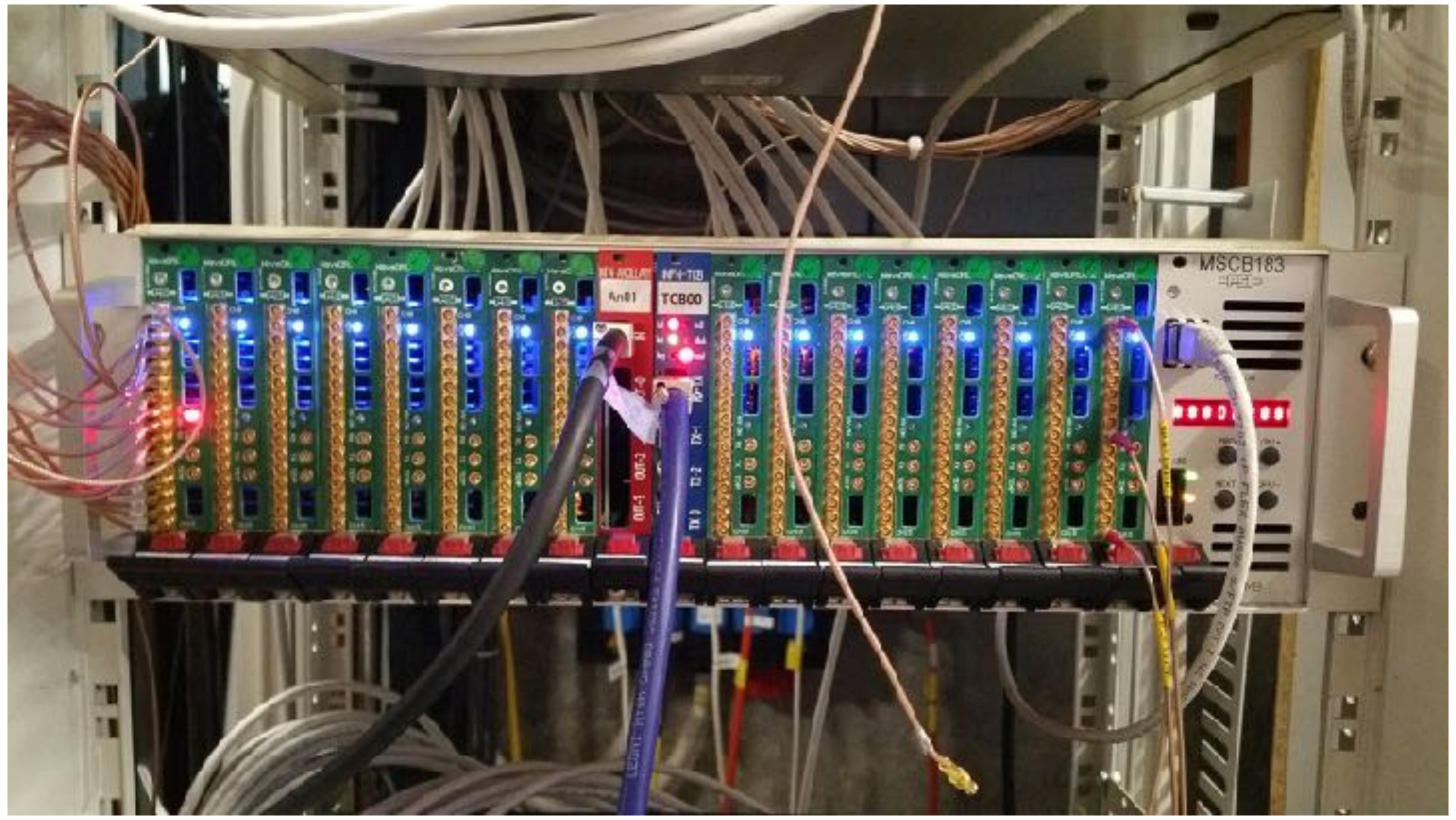
RDC e+ and LXe γ time difference



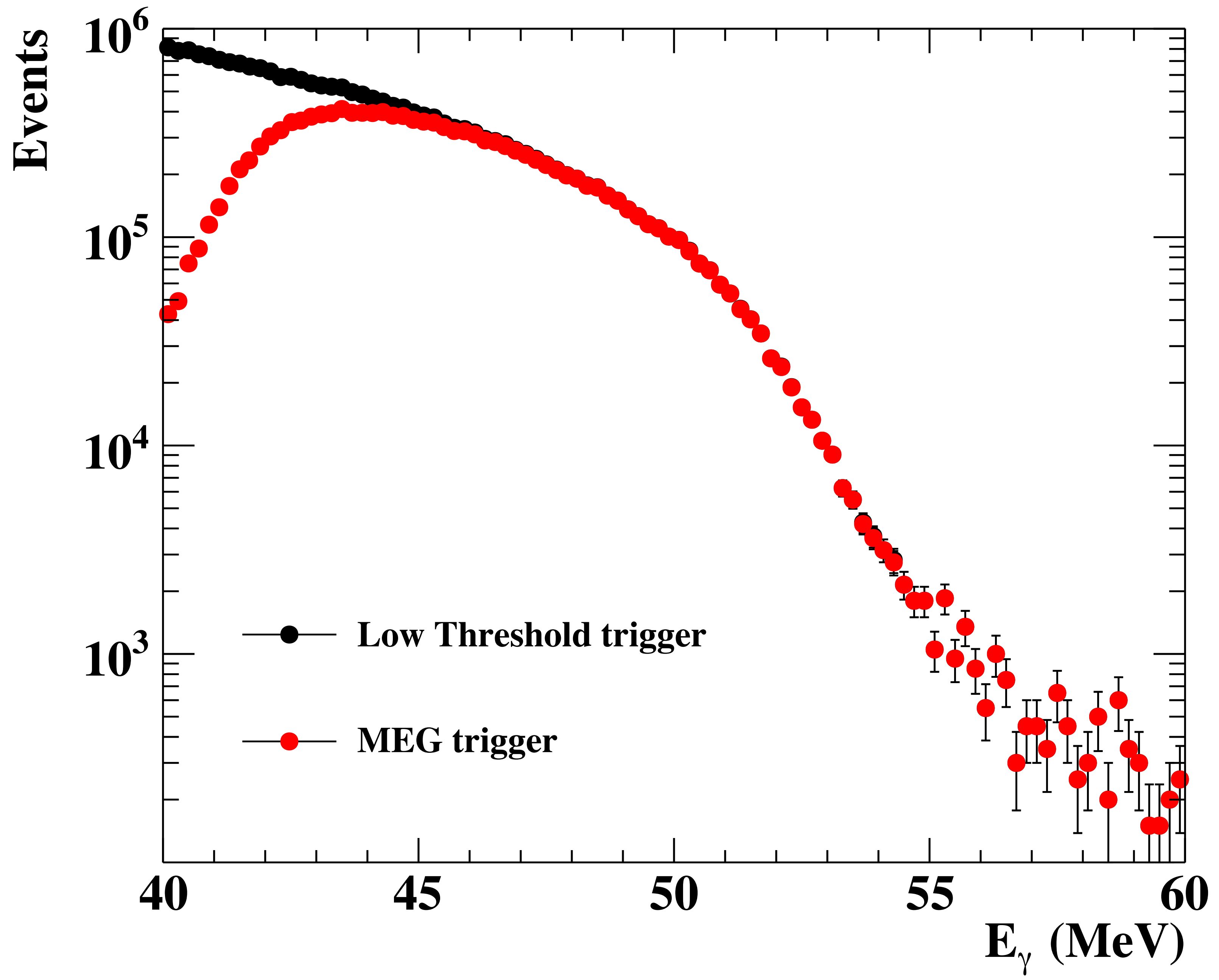
- New device for MEG II
  - Tagging high energy γ background from RMD ($\mu^+ \to e^+ \nu\nu\gamma$) by identifying low momentum e^+

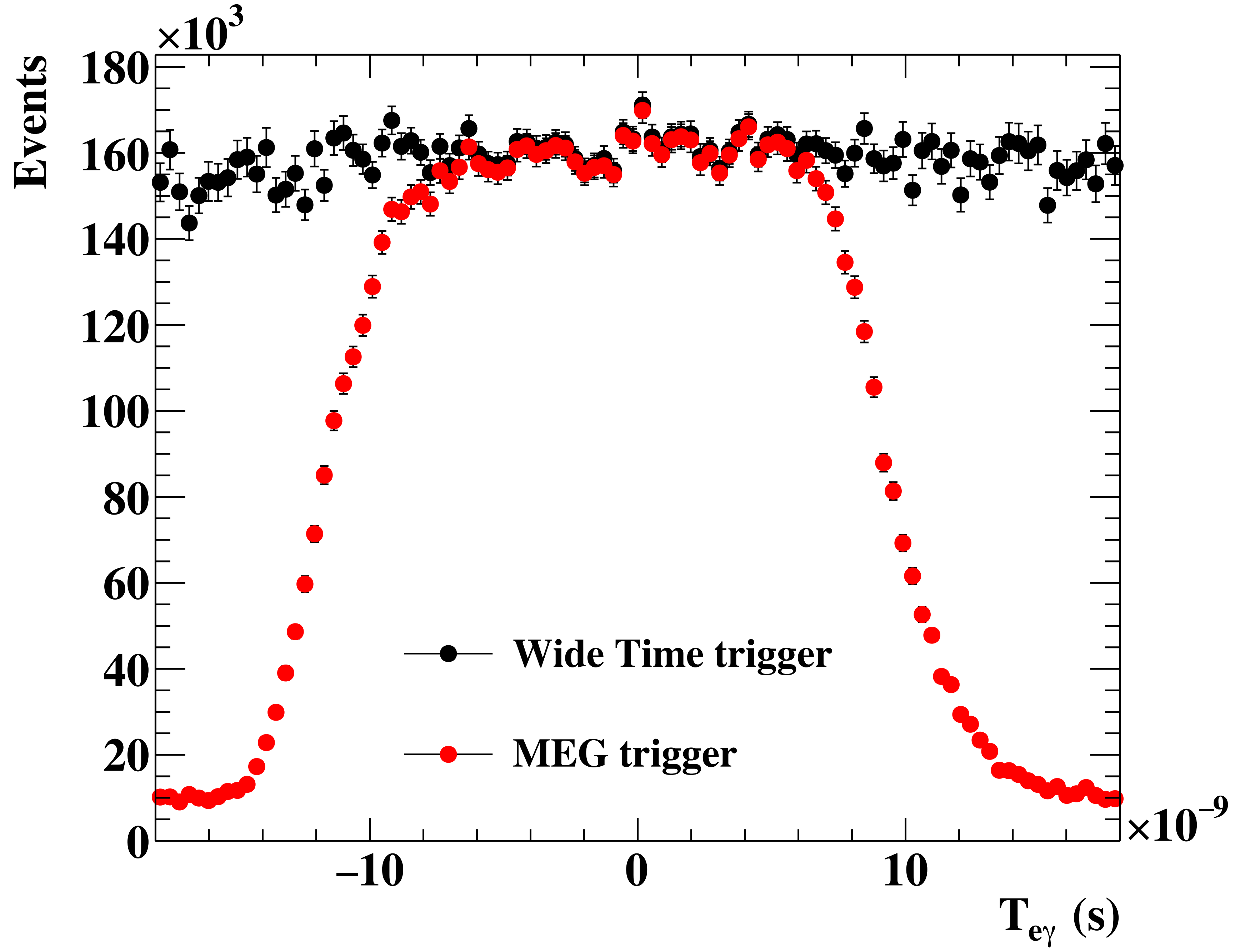
Electronics

- 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 $\mu \to e\gamma$





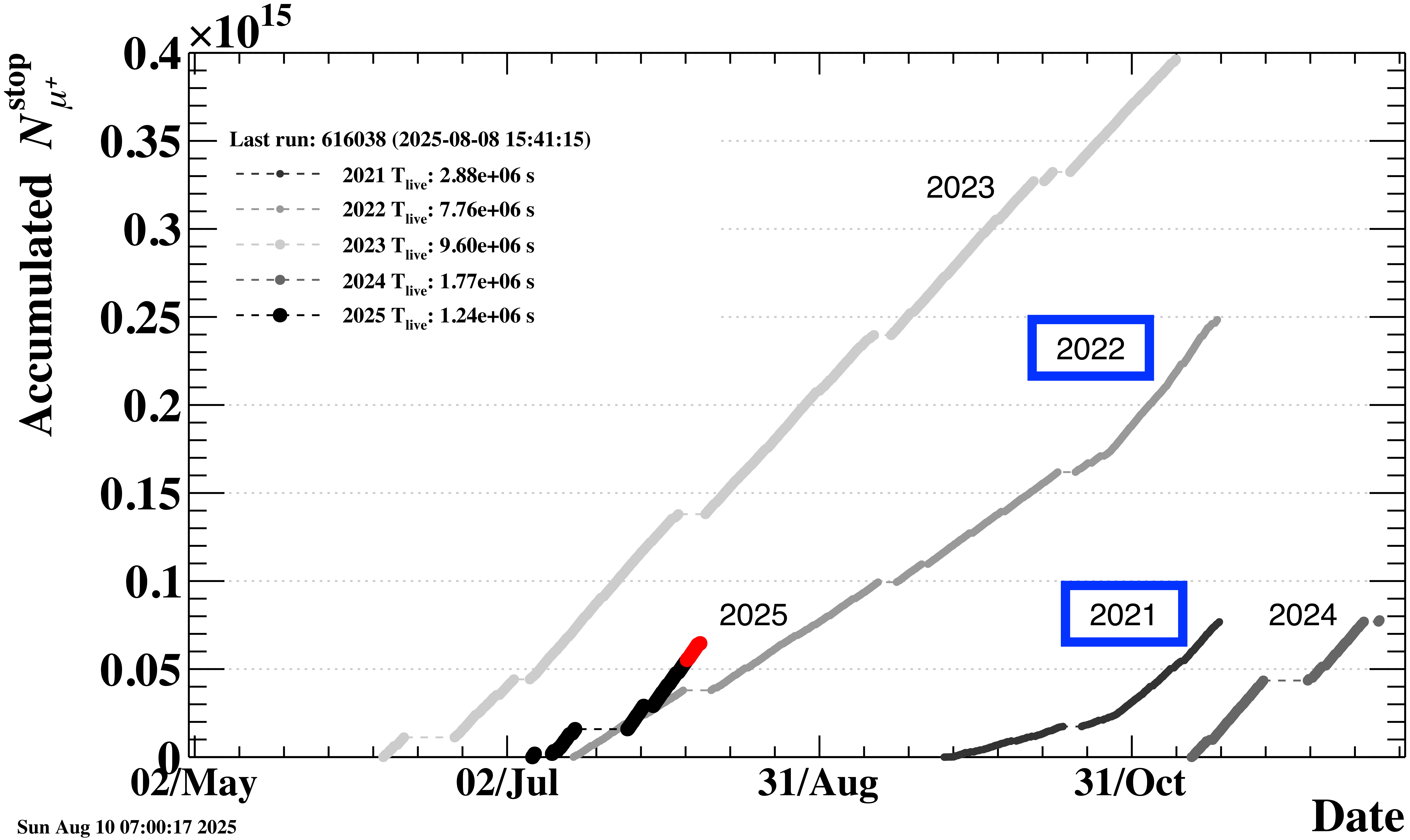
Detector performance summary

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
$y_{\mathrm{e}^+}, z_{\mathrm{e}^+}$ (mm)	0.7/1.6	0.61/1.76	
$E_\gamma(\%)$ (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
$t_{\mathrm{e}^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
$\varepsilon_{\mathrm{e}^+}$	65	67	30
$\varepsilon_{\mathrm{TRG}}$	≈99	91 (88)	96
		2022 (2021)	

updated from EPJC 84(2024)2, 190

MEG II data taking so far



MEG II statistics so far (-2025 now)

8.7 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

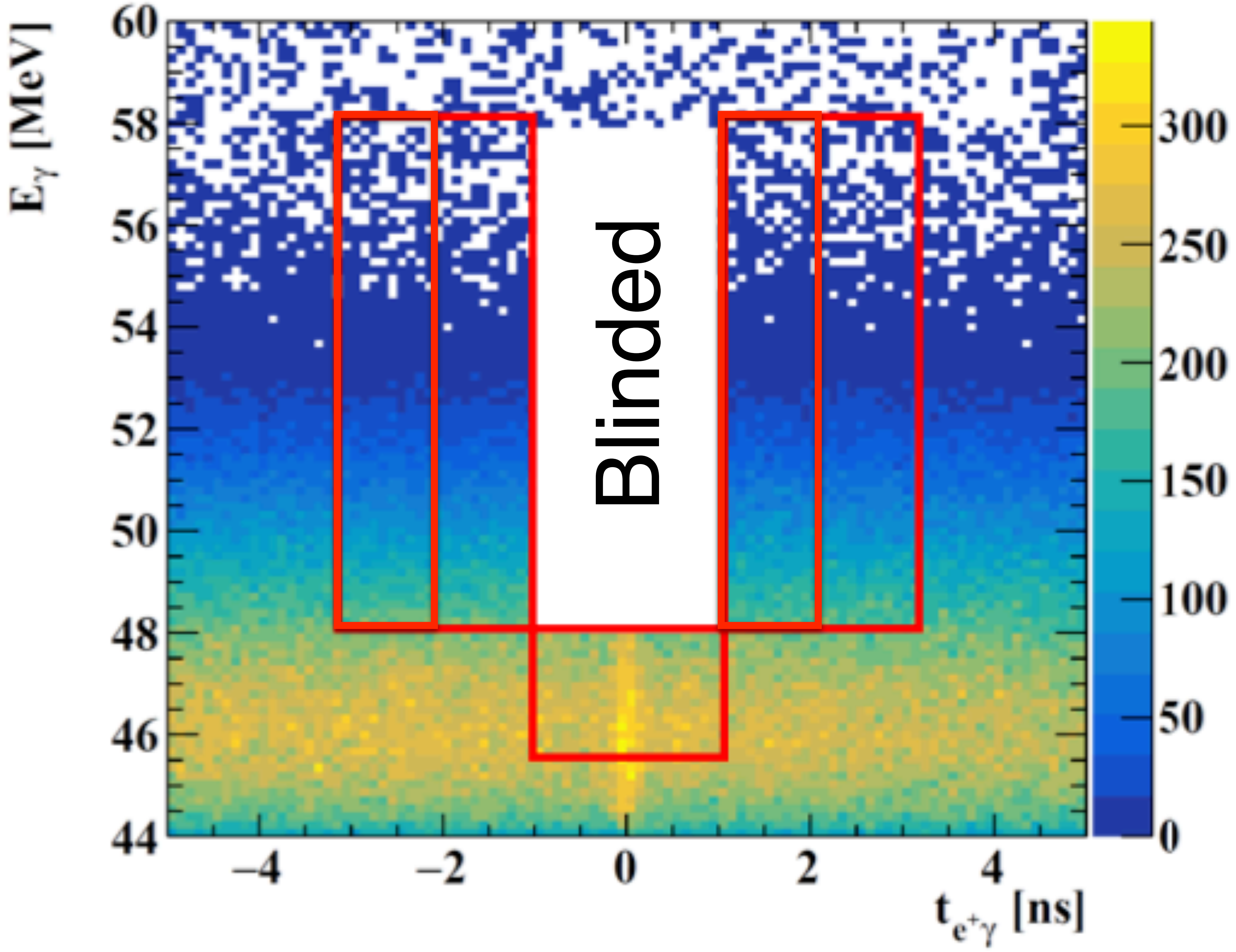
- Blind analysis
  - Time coincidence $t_{e^+\gamma}$ within 1ns, 48MeV<E_γ<58MeV
- Sideband to extract PDFs, analysis check
  - Four time sidebands for N_{ACC} study
  - low energy sideband for N_{RMD} study
- Maximum likelihood analysis to estimate N_{sig}
  - Confidence interval from Feldman-Cousins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

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

per-event PDFs

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

x_{T} represents the target misalignment uncertainty



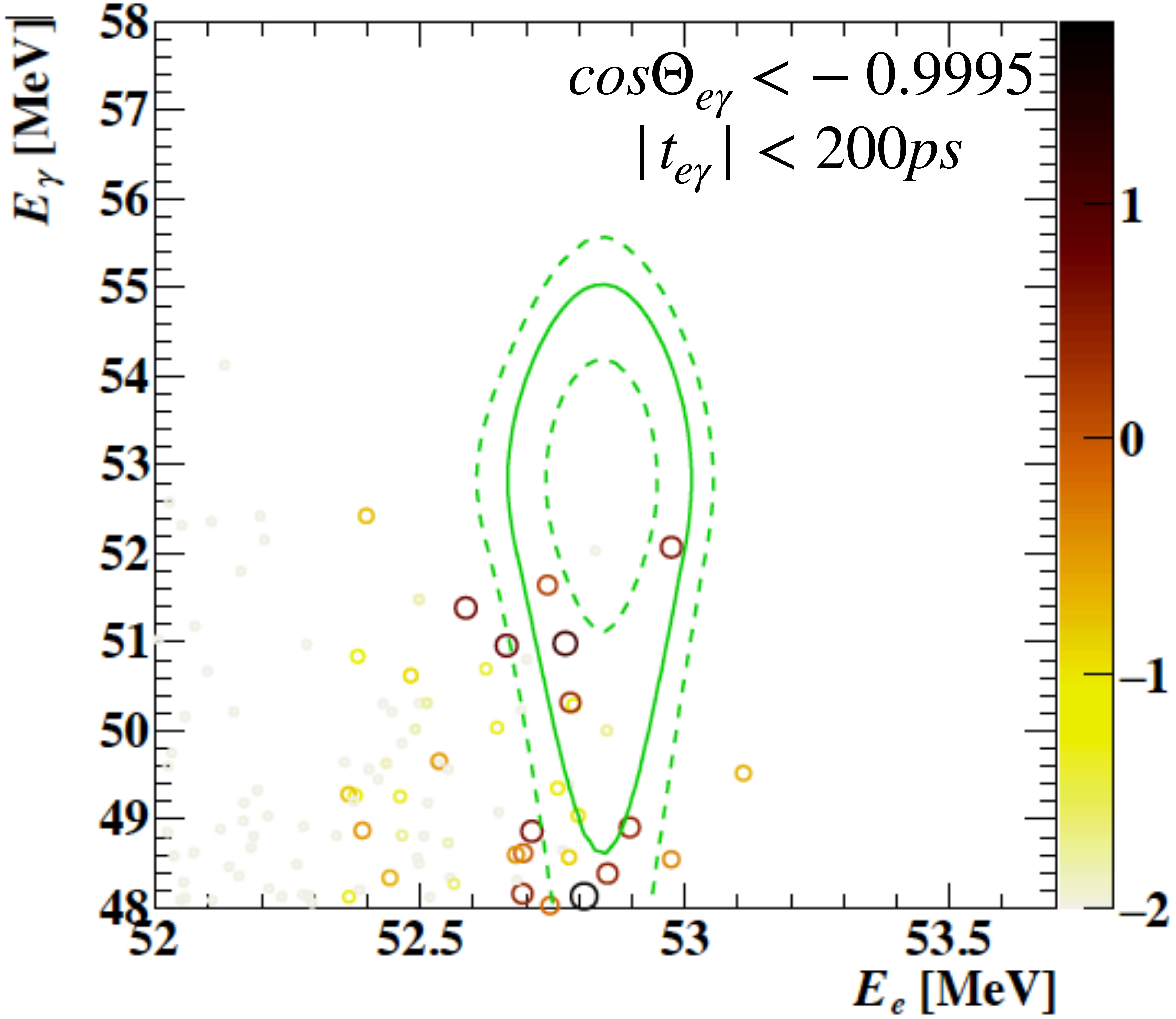
Analysis Region

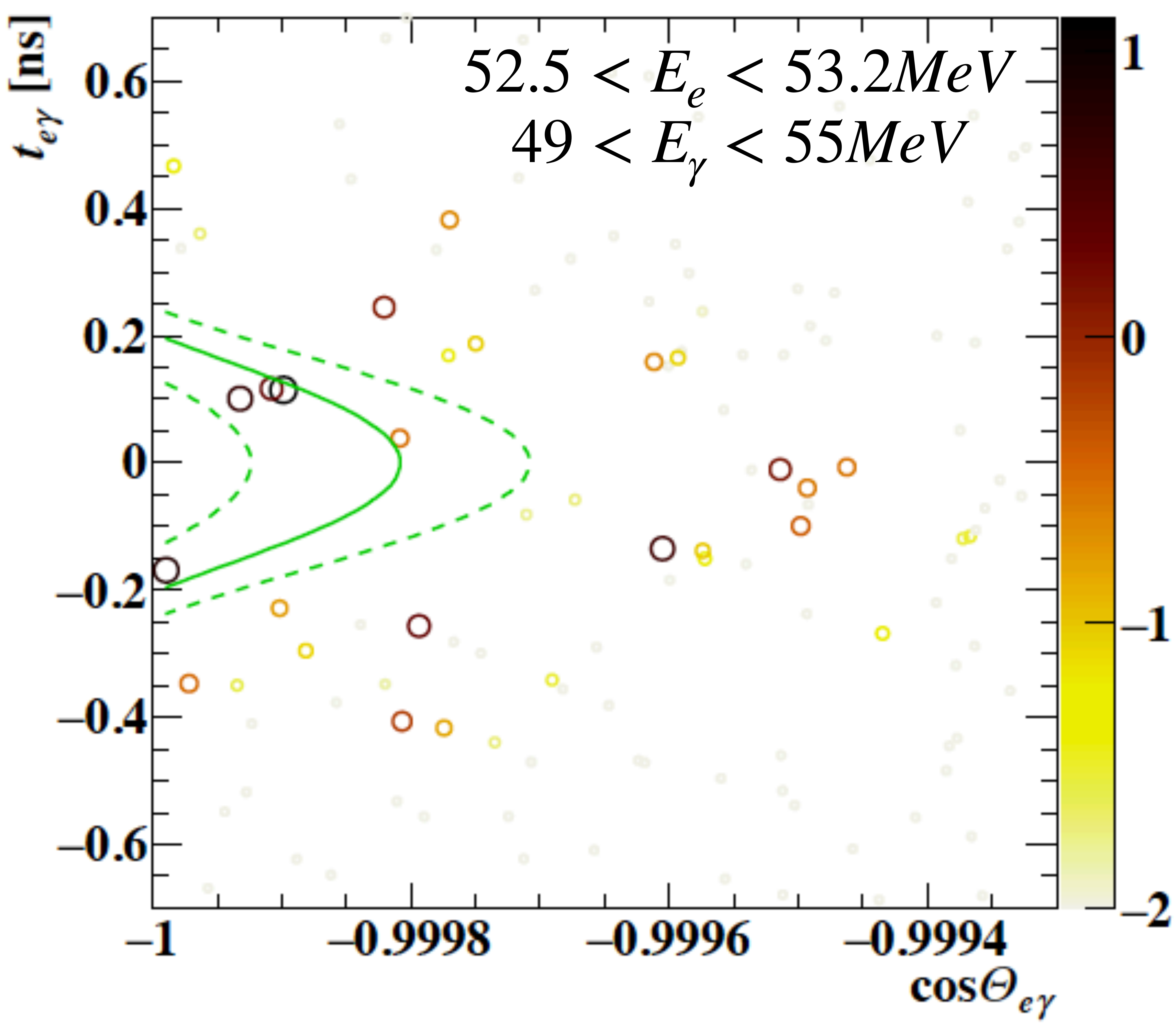
$48 < E_\gamma < 58\mathrm{MeV}$ $\quad 52.2 < E_{e^+} < 53.5\mathrm{MeV}$

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

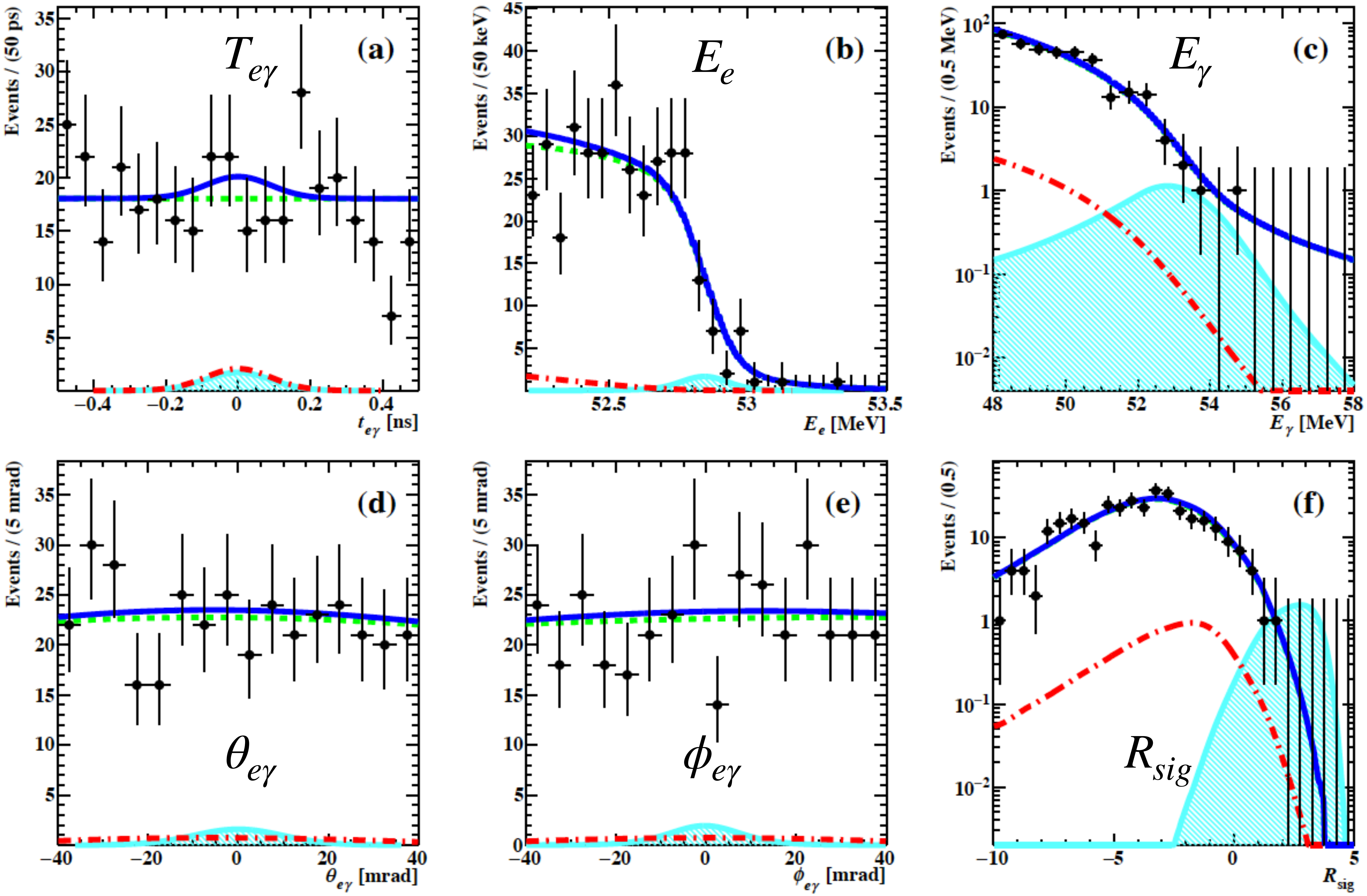
2-D event distributions

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





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



Data ($N_{obs} = 357$)

Best fit

(UL on $N_{sig} < 2$) x 4

$N^{exp}_{Acc} = 364 \pm 9.5$

$N^{exp}_{RMD} = 10.1 \pm 1.7$

No signal Observed

Upper limit: 1.5×10^{-13} (90%C.L.)

arXiv:2504.15711 (Submitted to EPJC)

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

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 optimum intensity was 4×10^7/s until 2024
- Future improvements (expecting O(10%) efficiency improvement from the ML-tracking) were observed. Higher intensity (5×10^7/s) is used in 2025

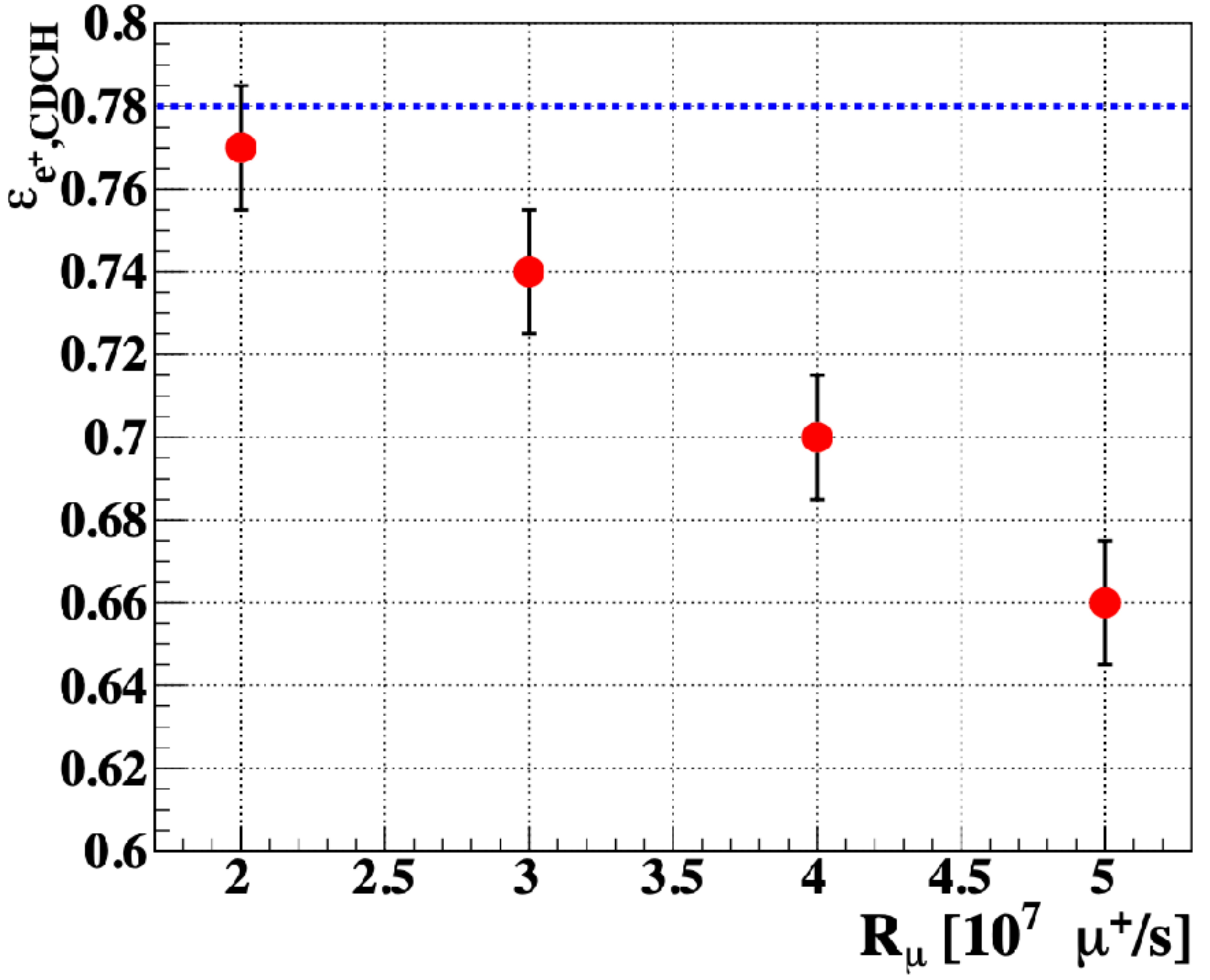
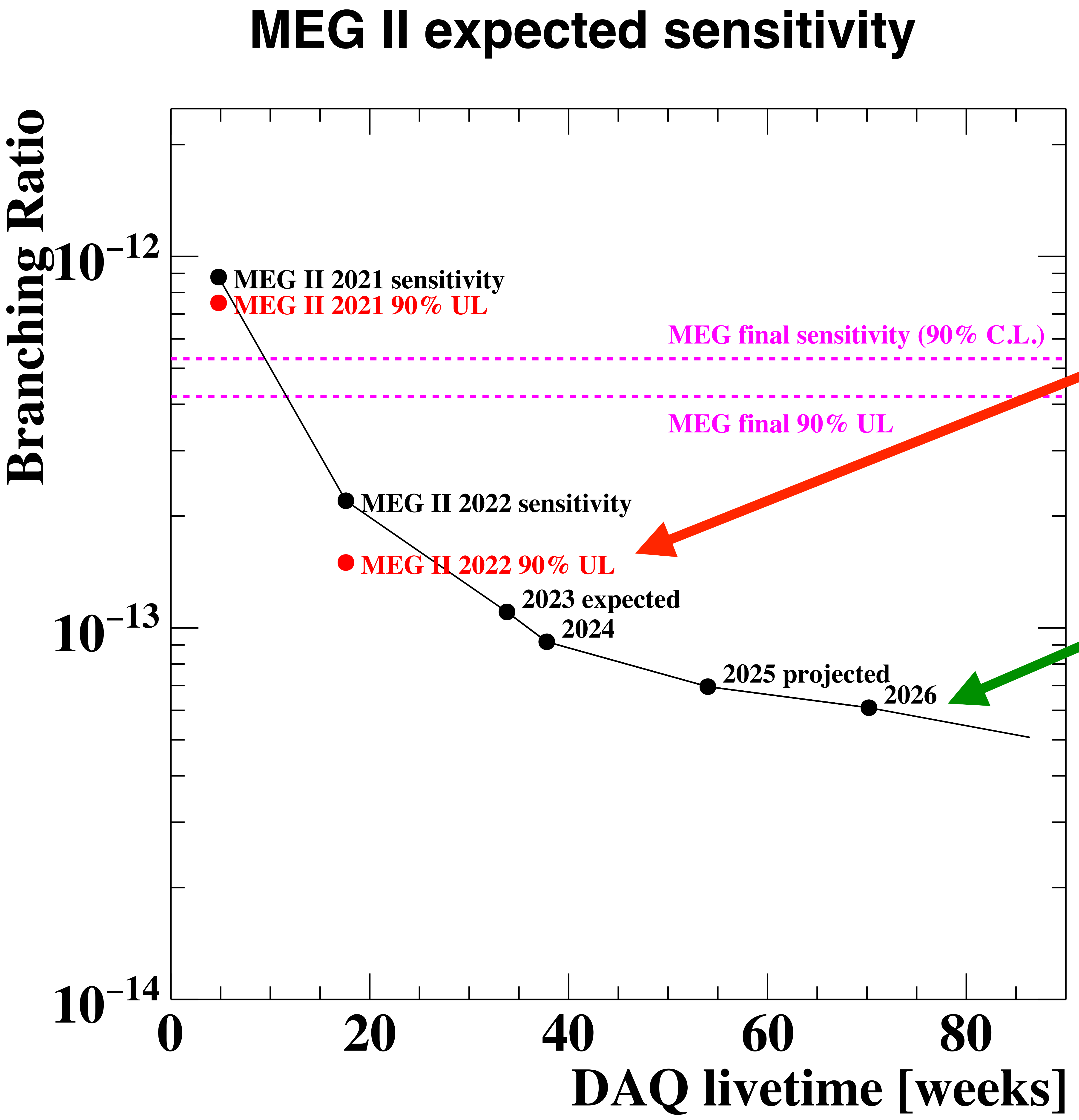


Figure 20 CDCH tracking efficiency as a function of R_μ for signal positrons. The blue dotted line is the design value.

MEG II prospects



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

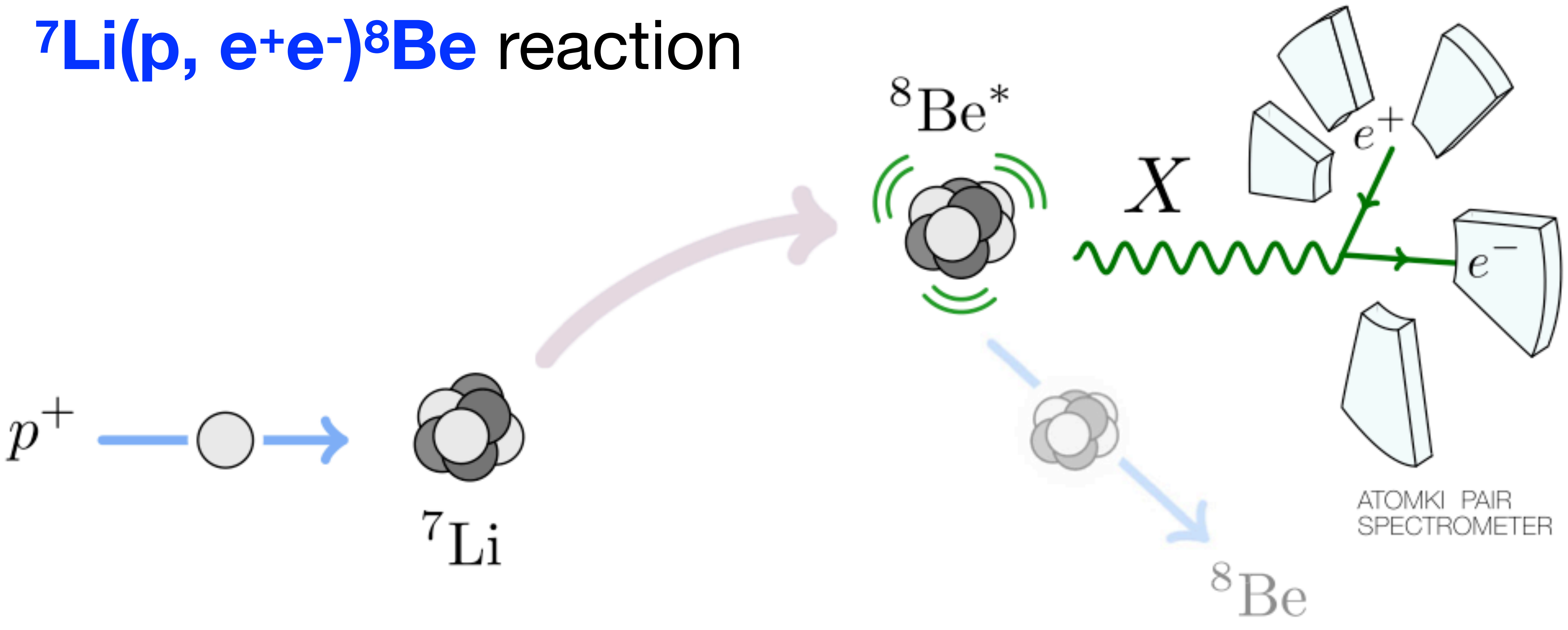
MEG II proposal goal
$S=6\times10^{-14}$

20 weeks of DAQ in 2025-2026
Current performance assumed

Analysis improvement may lead to better sensitivity further ($4 \rightarrow 5 \times 10^7$ from 2025 not included in this figure yet)

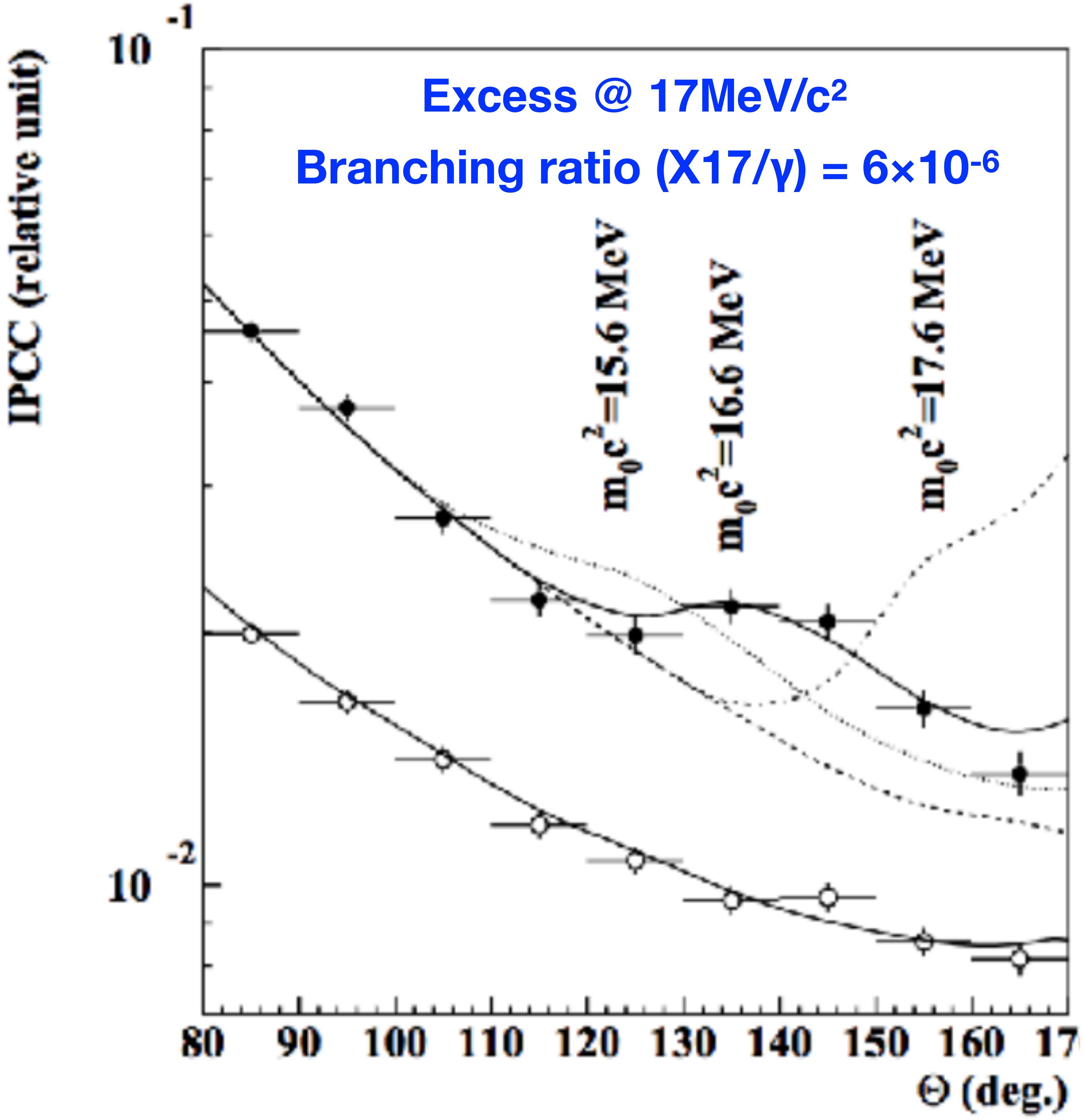
X17 boson search at MEG II

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

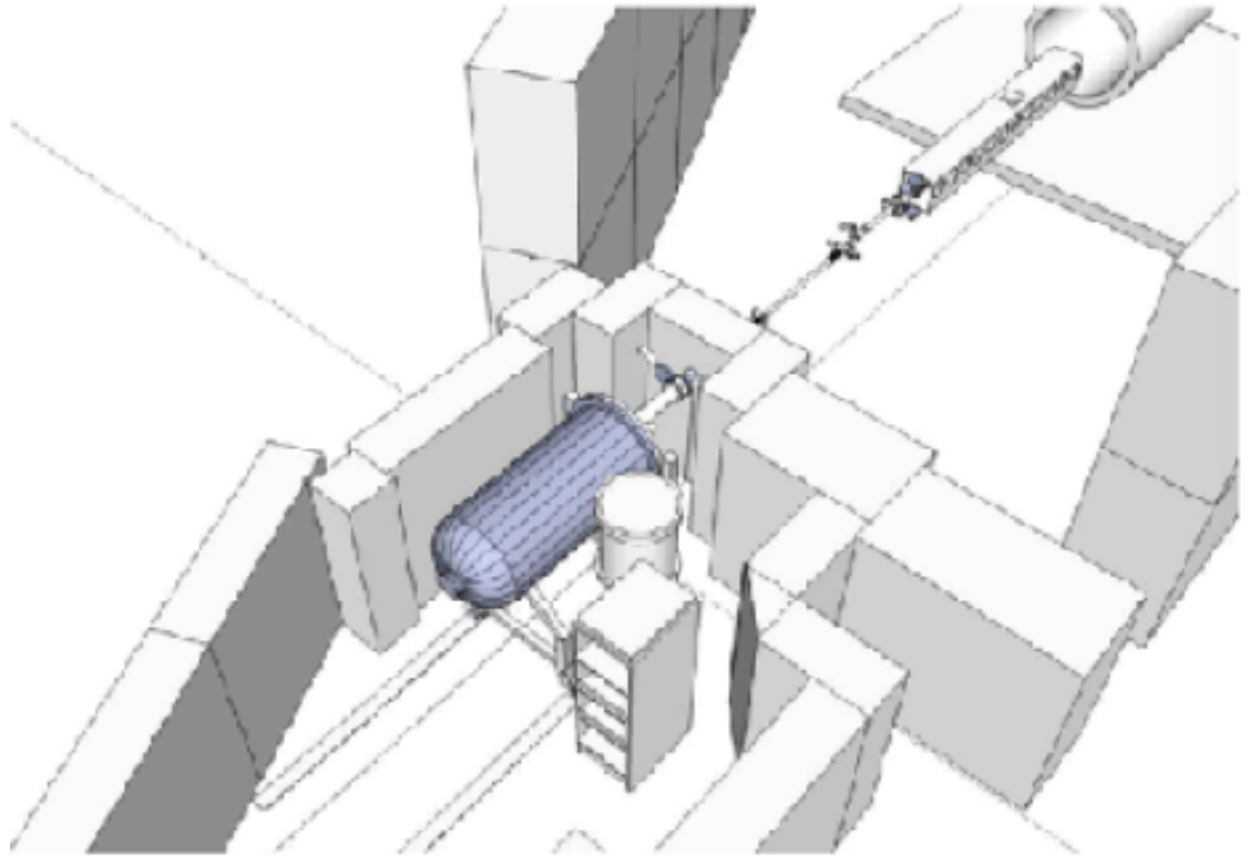
Hint for a neutral, 17MeV boson: X17 (Atomki collaboration)

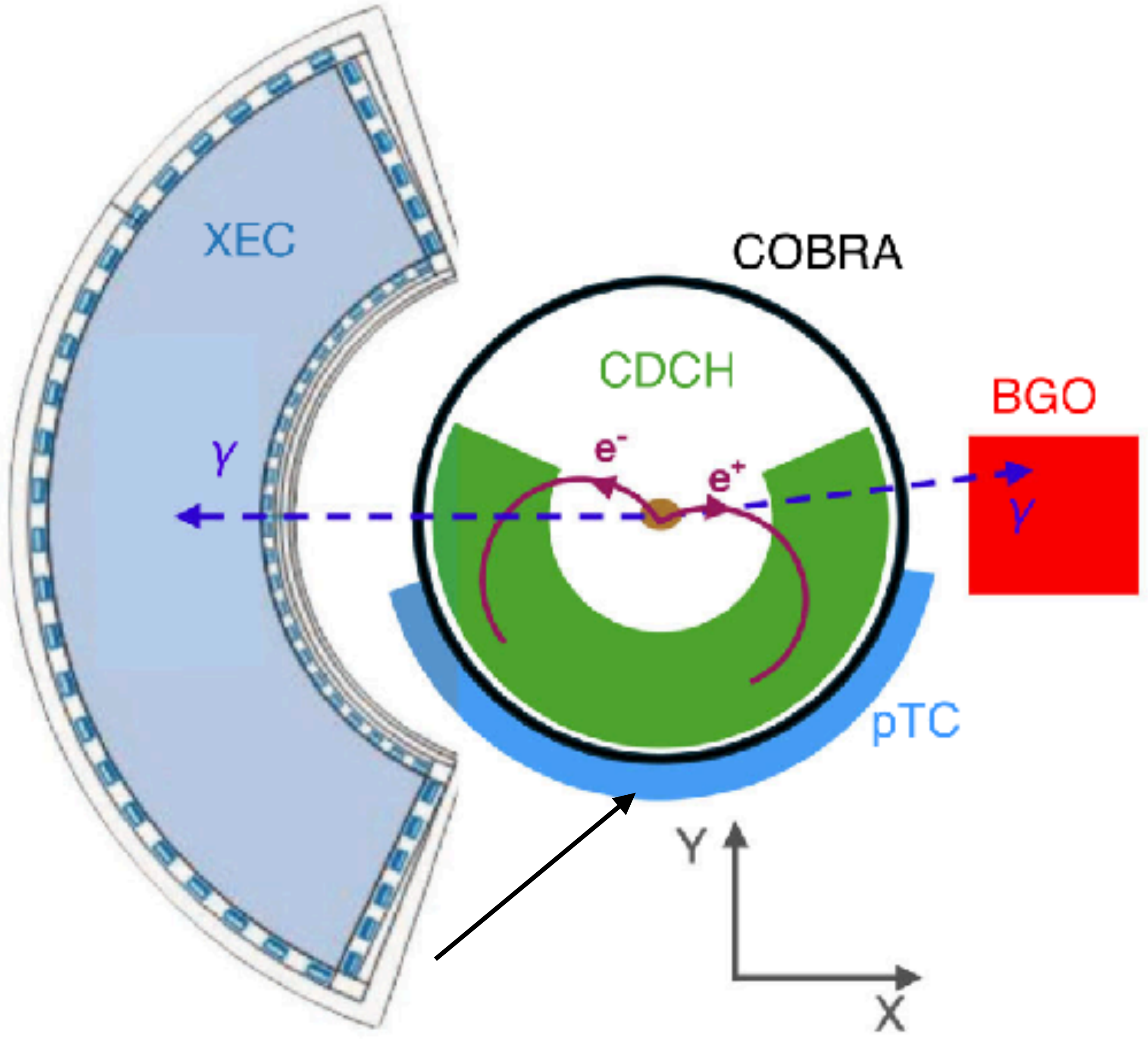


Phys. Rev. Lett. 116, 042501 (2016)

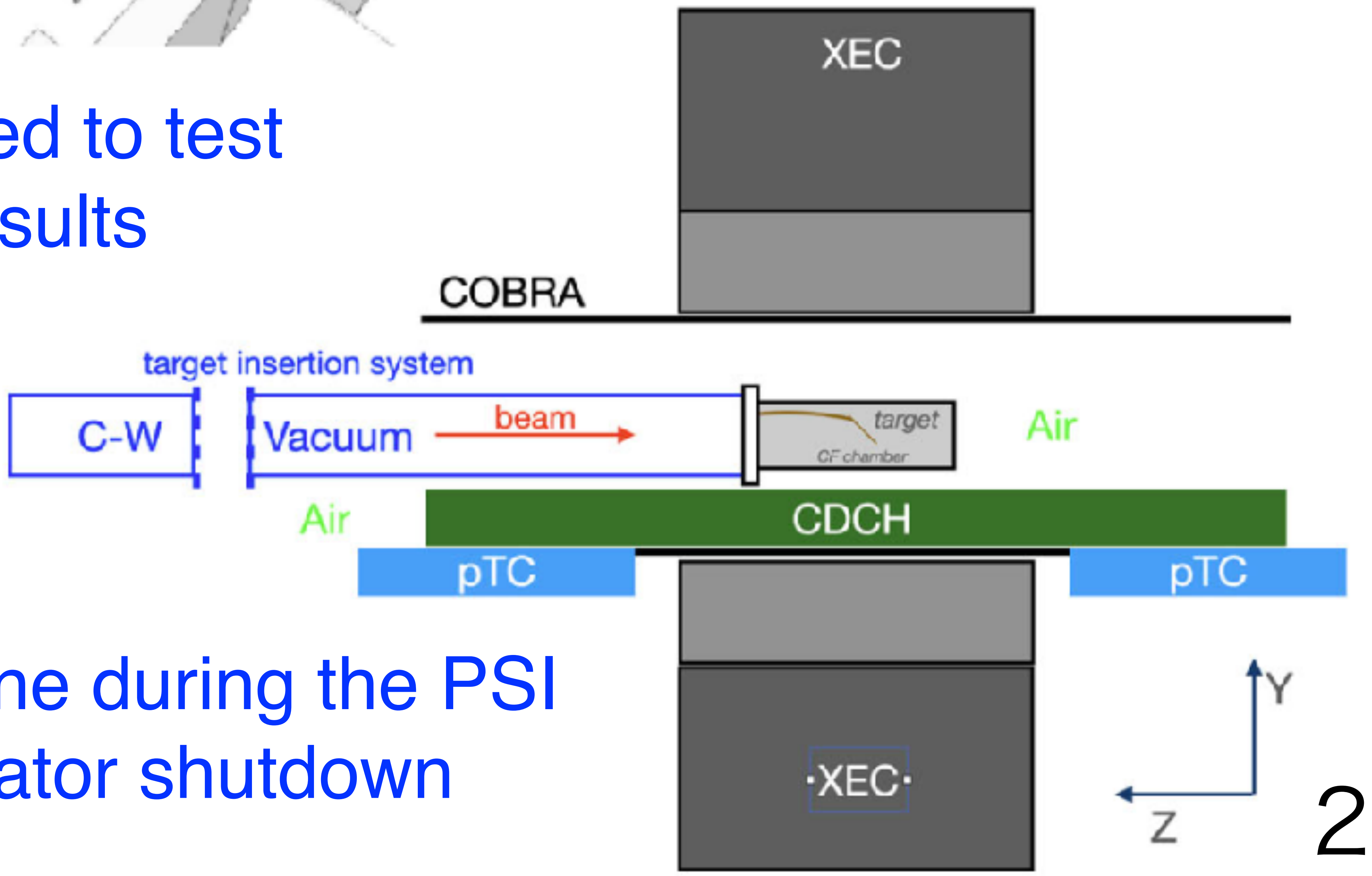
X17 boson search at MEG II

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



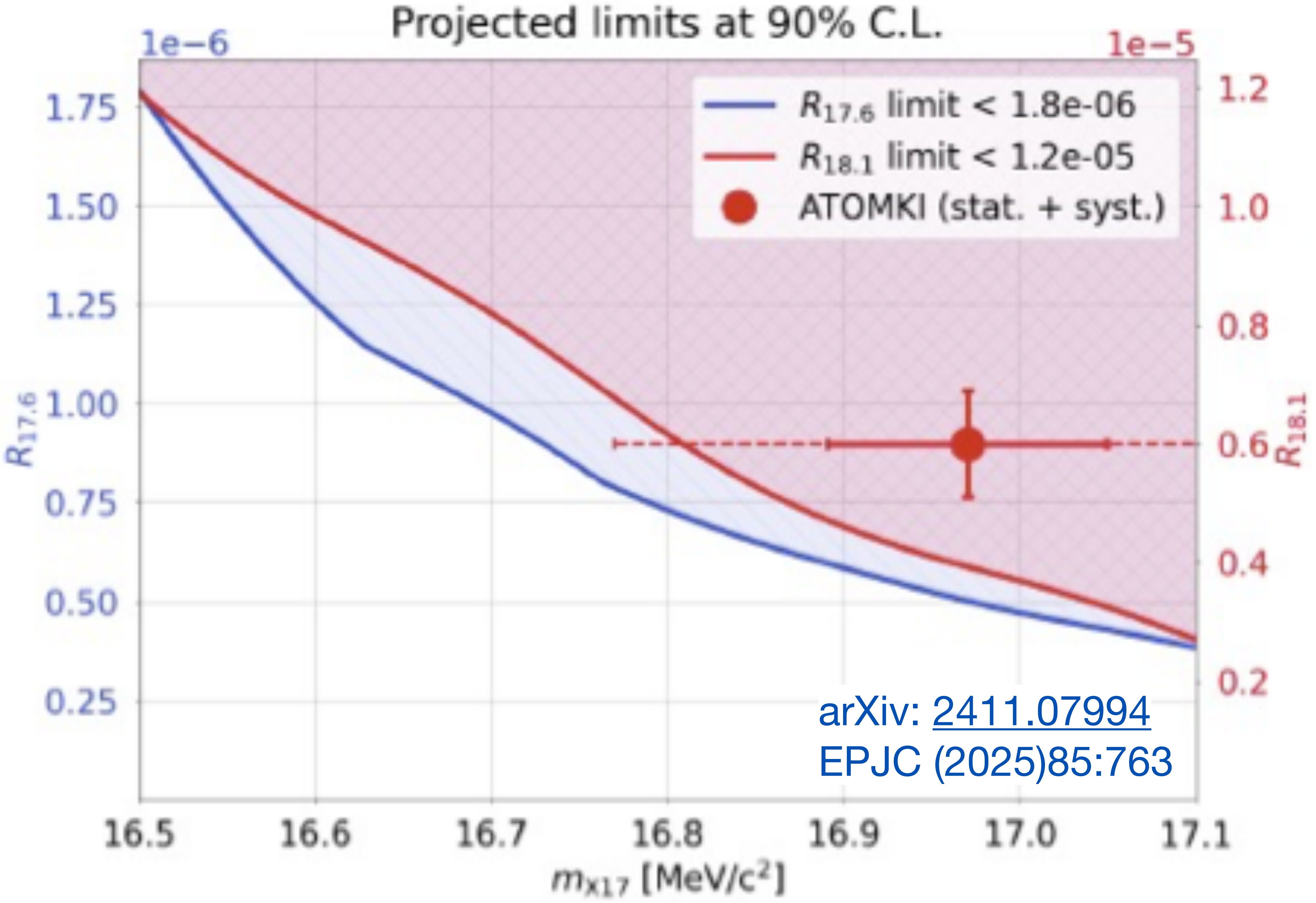


Can be used to test X17 results



Can be done during the PSI accelerator shutdown

^{7}Li(p, $X \to e^{+}e^{-}$)^{8}Be search

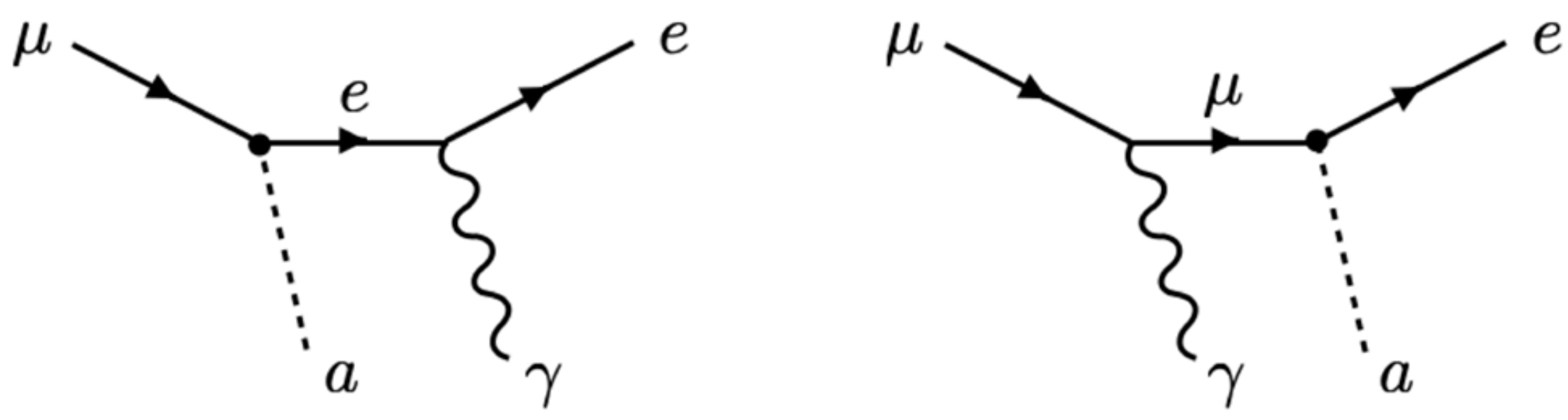


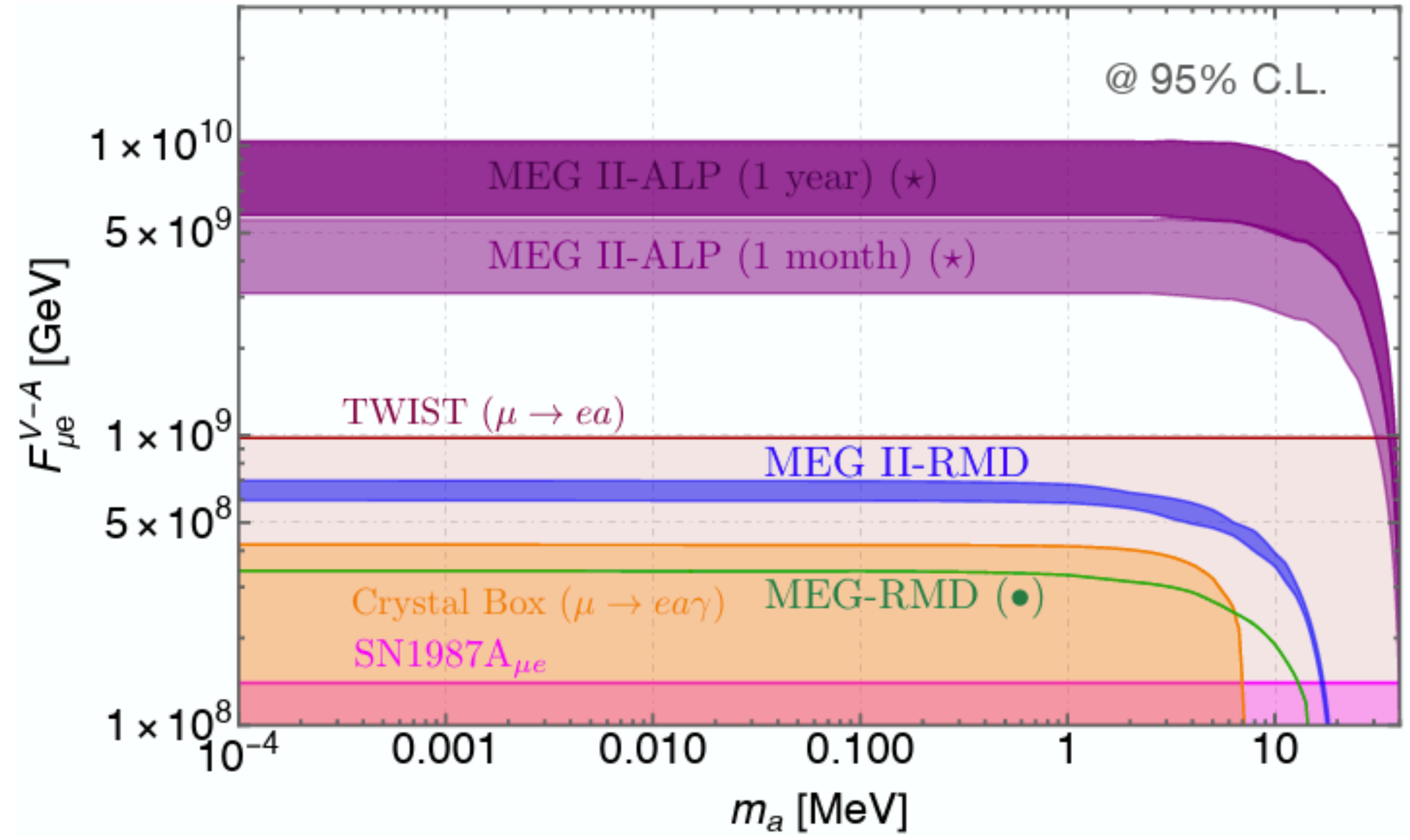
No significant signal observed

ATOMKI result was excluded at 94%

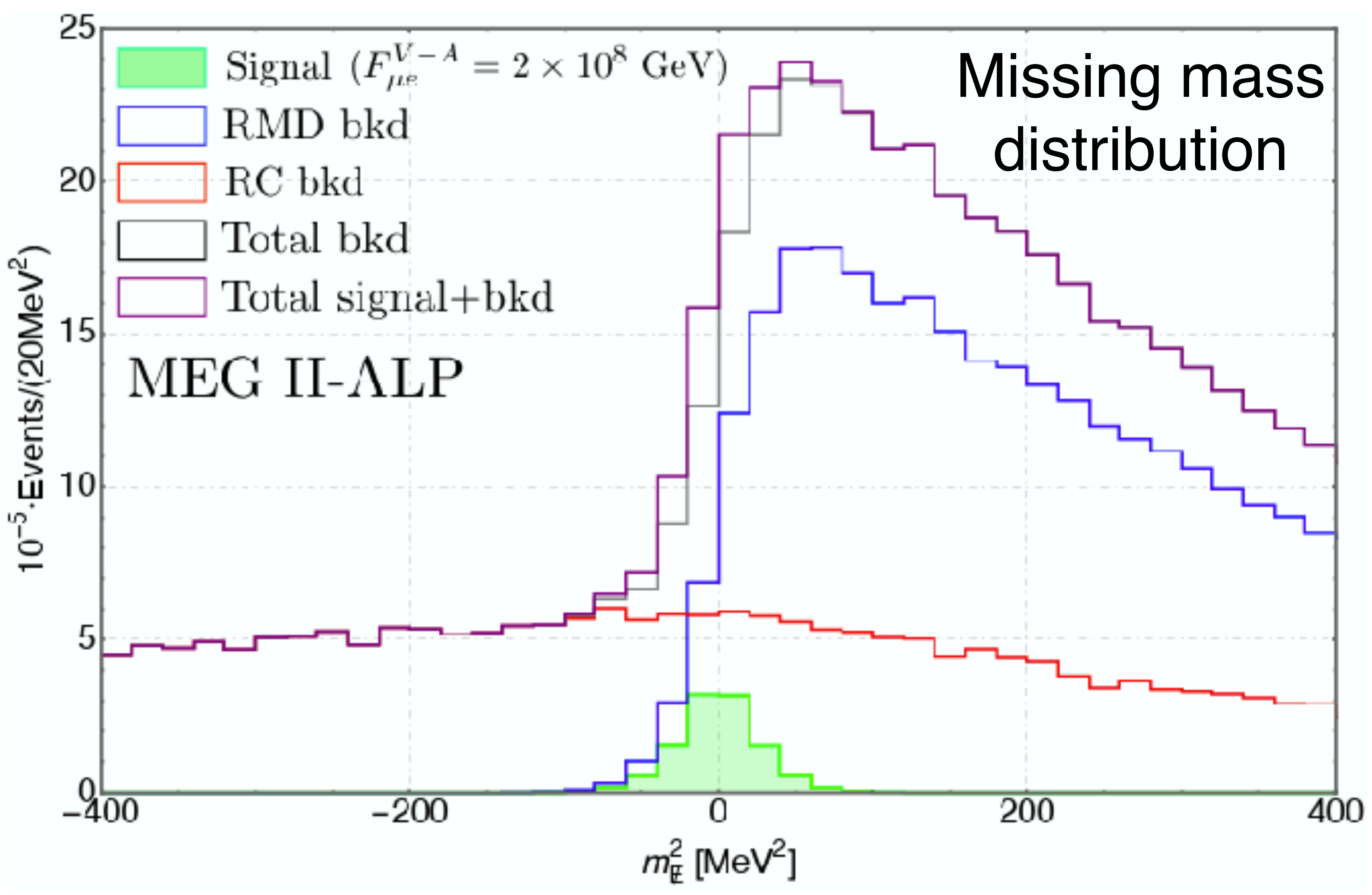
ALP search at MEG II

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 $\mu \to e\gamma$ 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

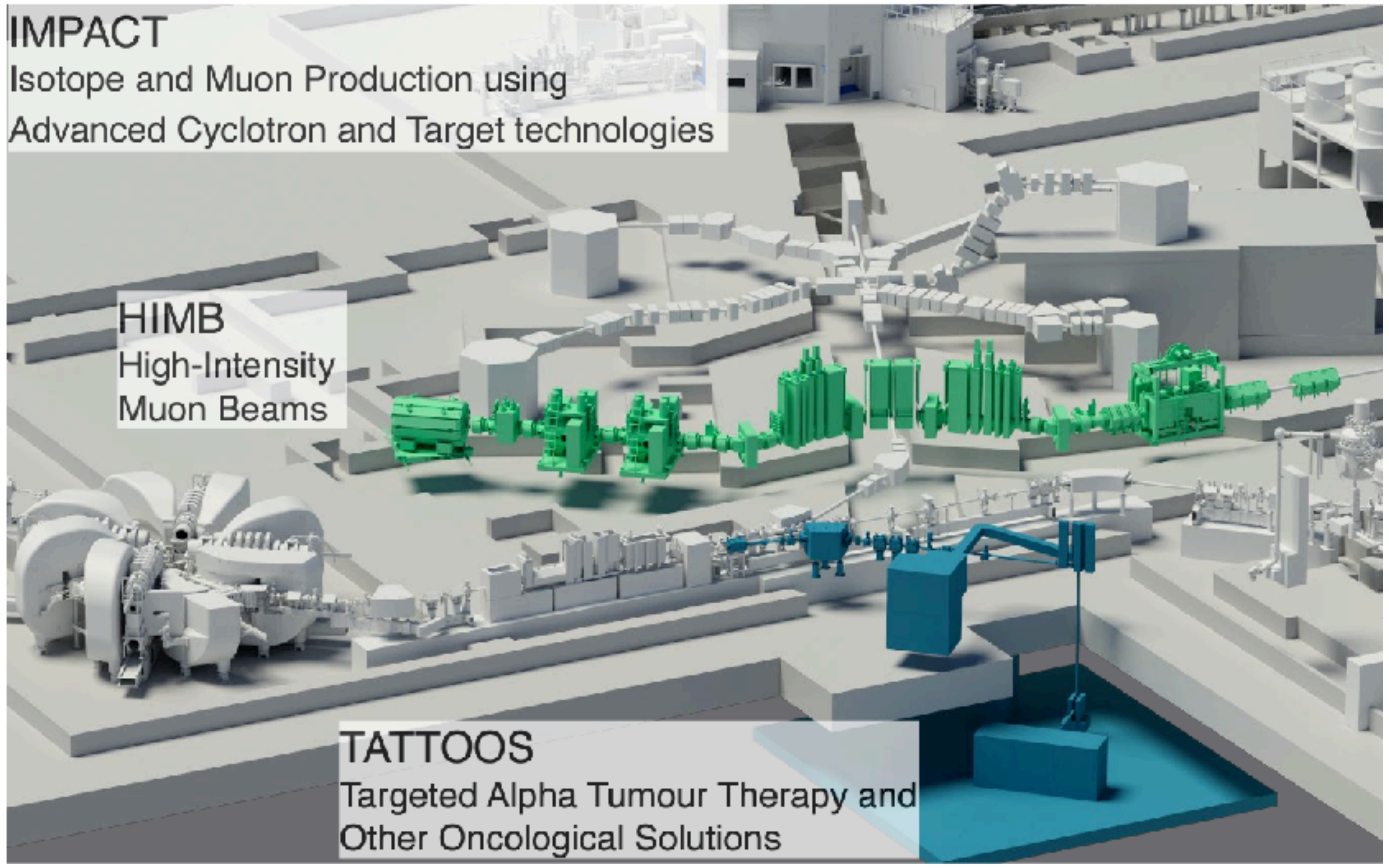
- Better resolutions, angle measurements

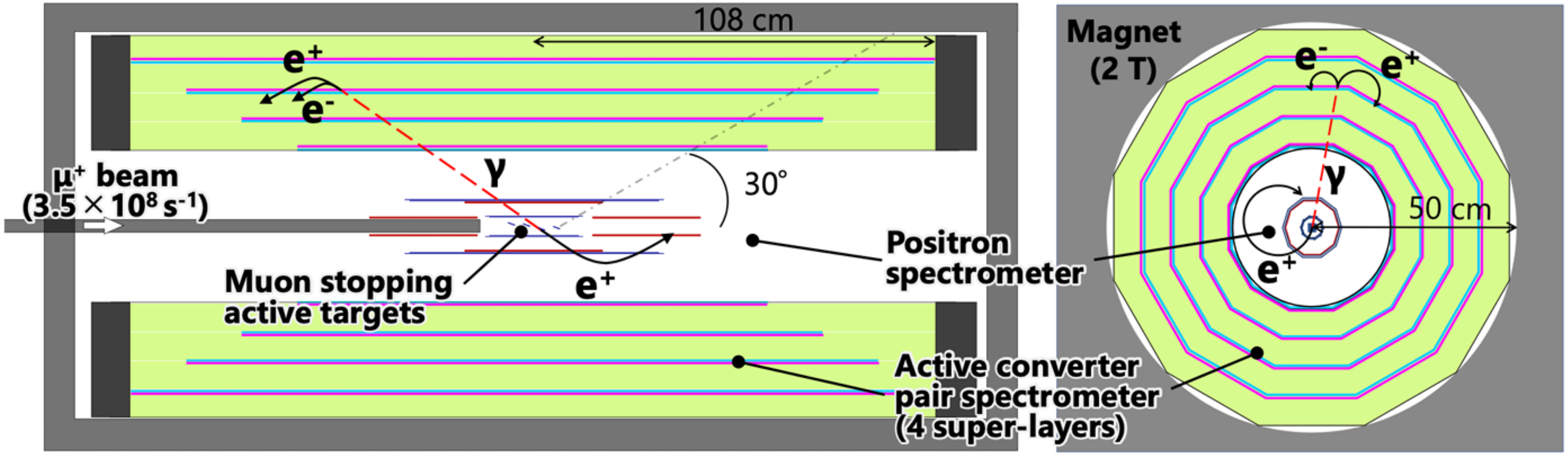
Silicon positron spectrometer similar with Mu3e

Separate active targets

Target sensitivity

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

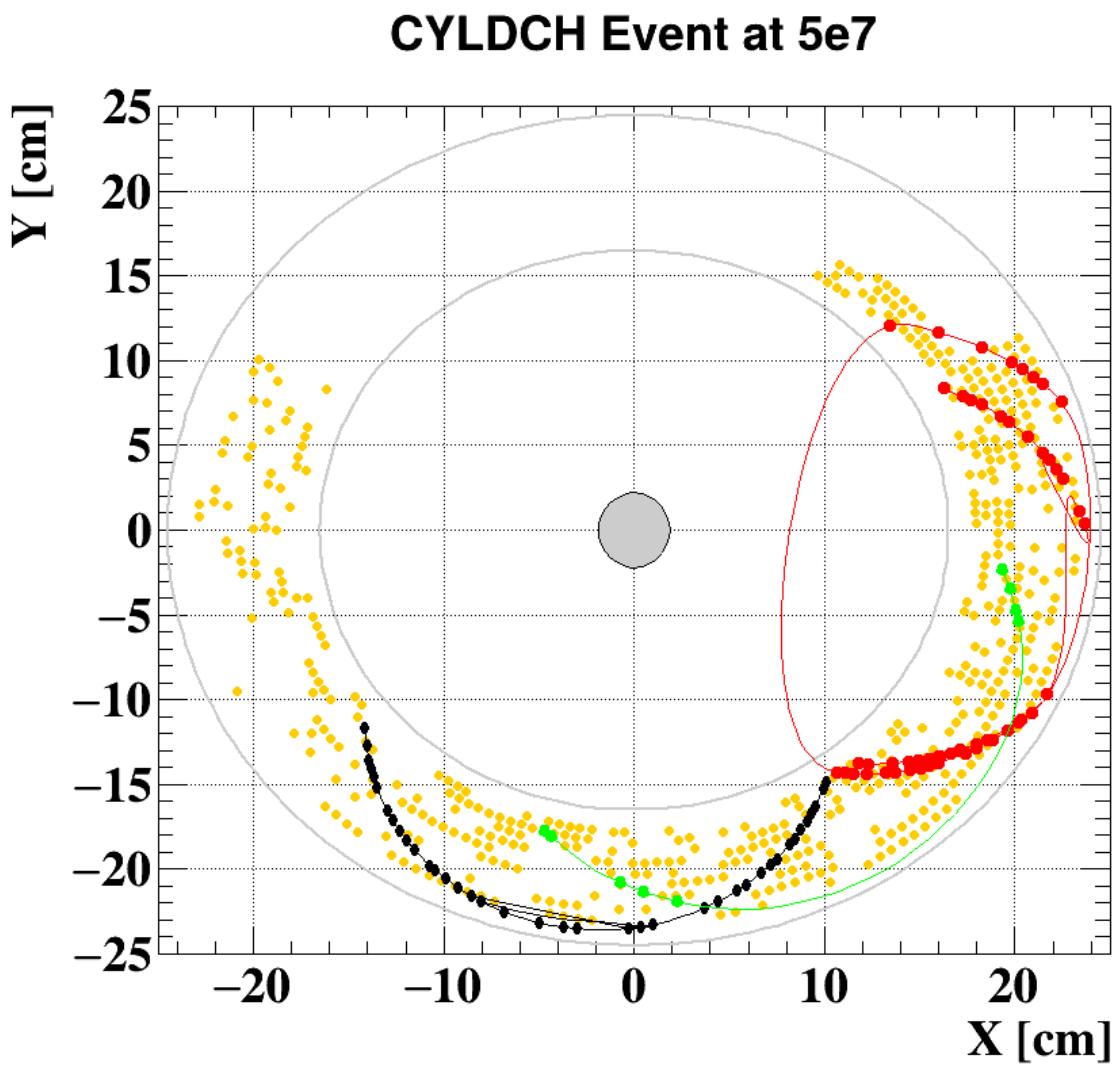


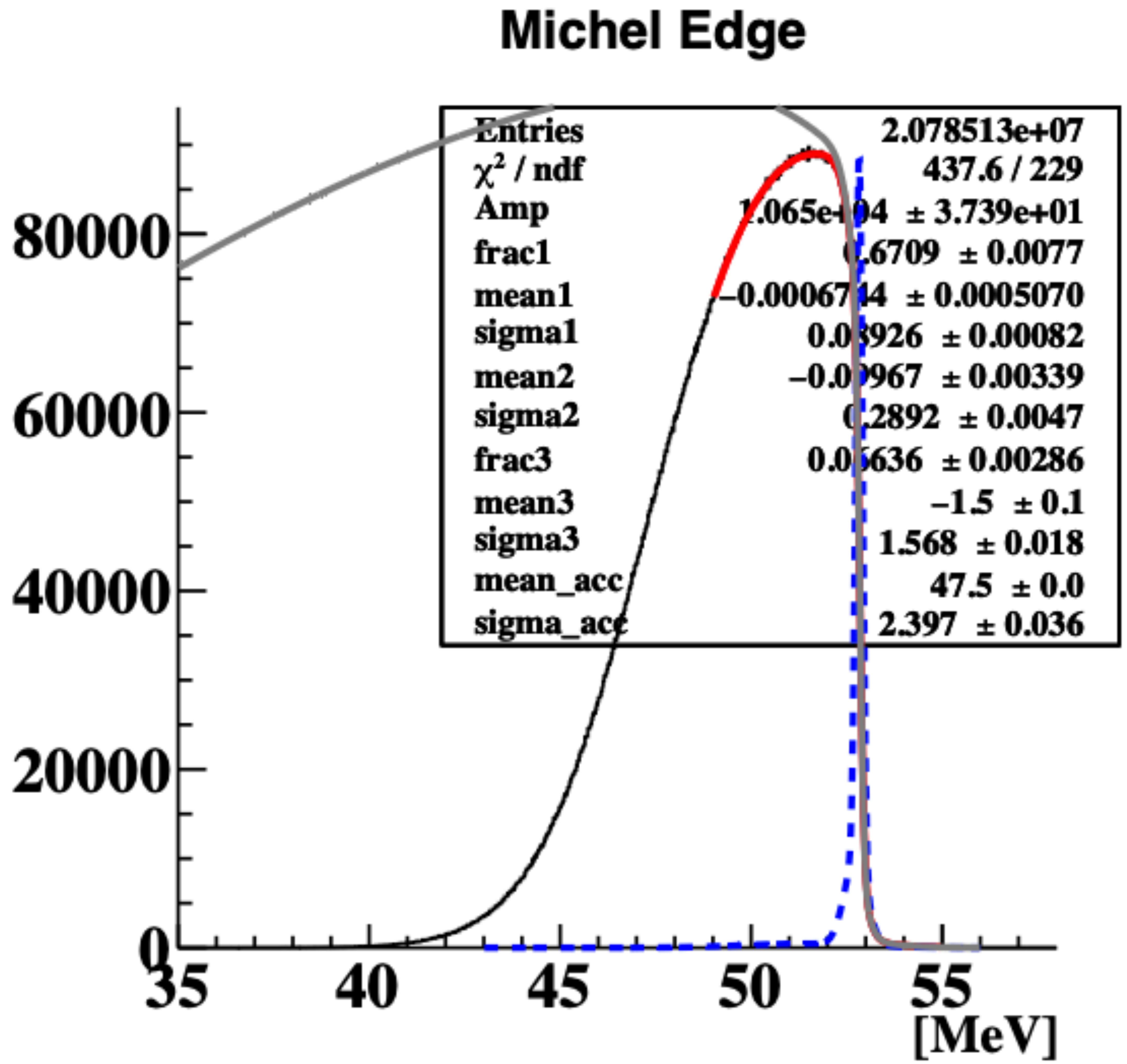


Conclusion

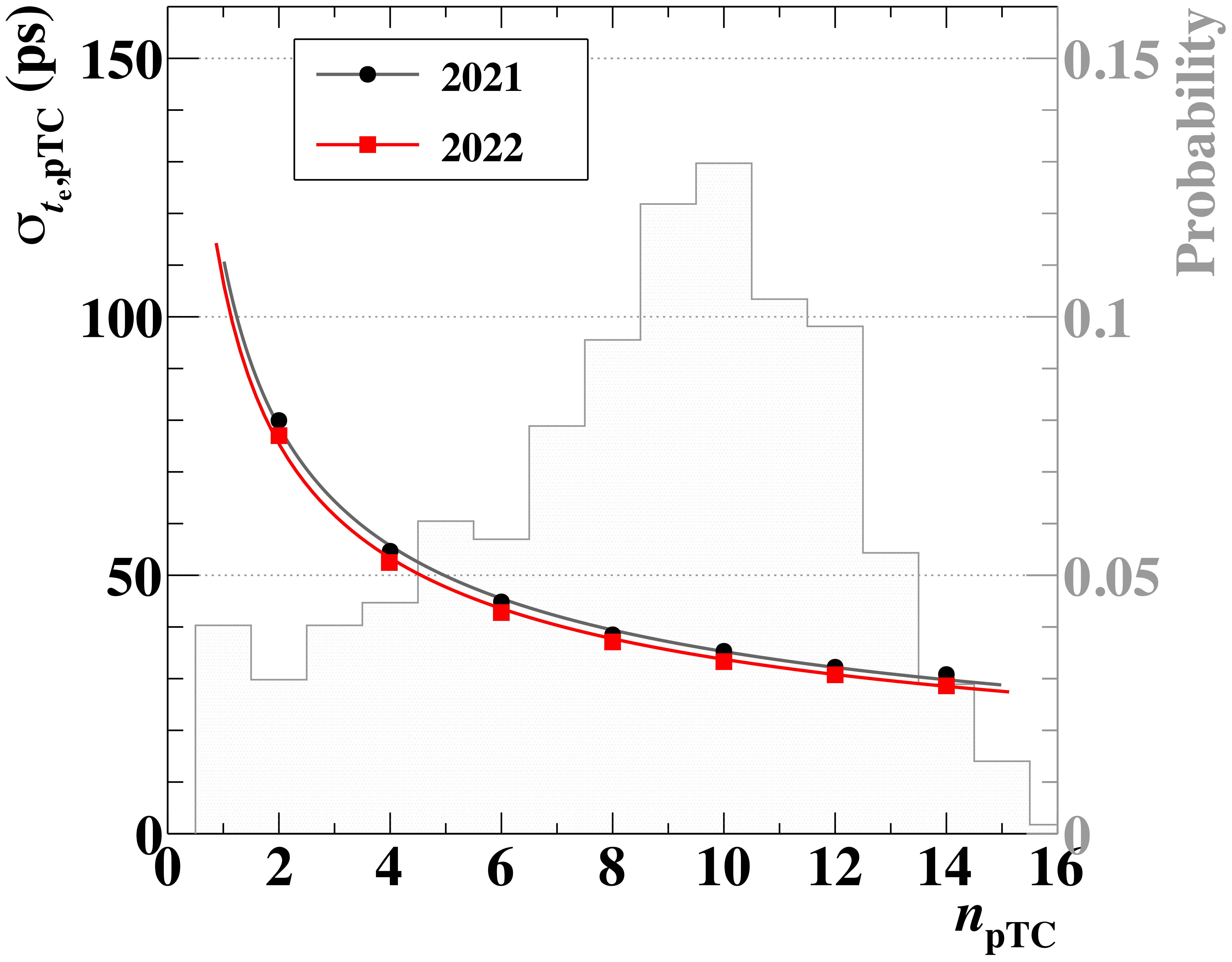
- The MEG II experiment has started physics run in 2021, and the results based on MEG II 2021+2022 data were published in May 2025, a new limit of $Br(\mu \rightarrow e\gamma) < 1.5 \times 10^{-13}$ (90% CL).
- Our target sensitivity (6×10^{-14}) will be reachable with two more years DAQ until 2026.

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
χ^2 / ndf 437.6 / 229
Amp 1.065e+04 ± 3.739e+01
frac1 0.6709 ± 0.0077
mean1 −0.0006714 ± 0.0005070
sigma1 0.08926 ± 0.00082
mean2 −0.09967 ± 0.00339
sigma2 0.2892 ± 0.0047
frac3 0.05636 ± 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]

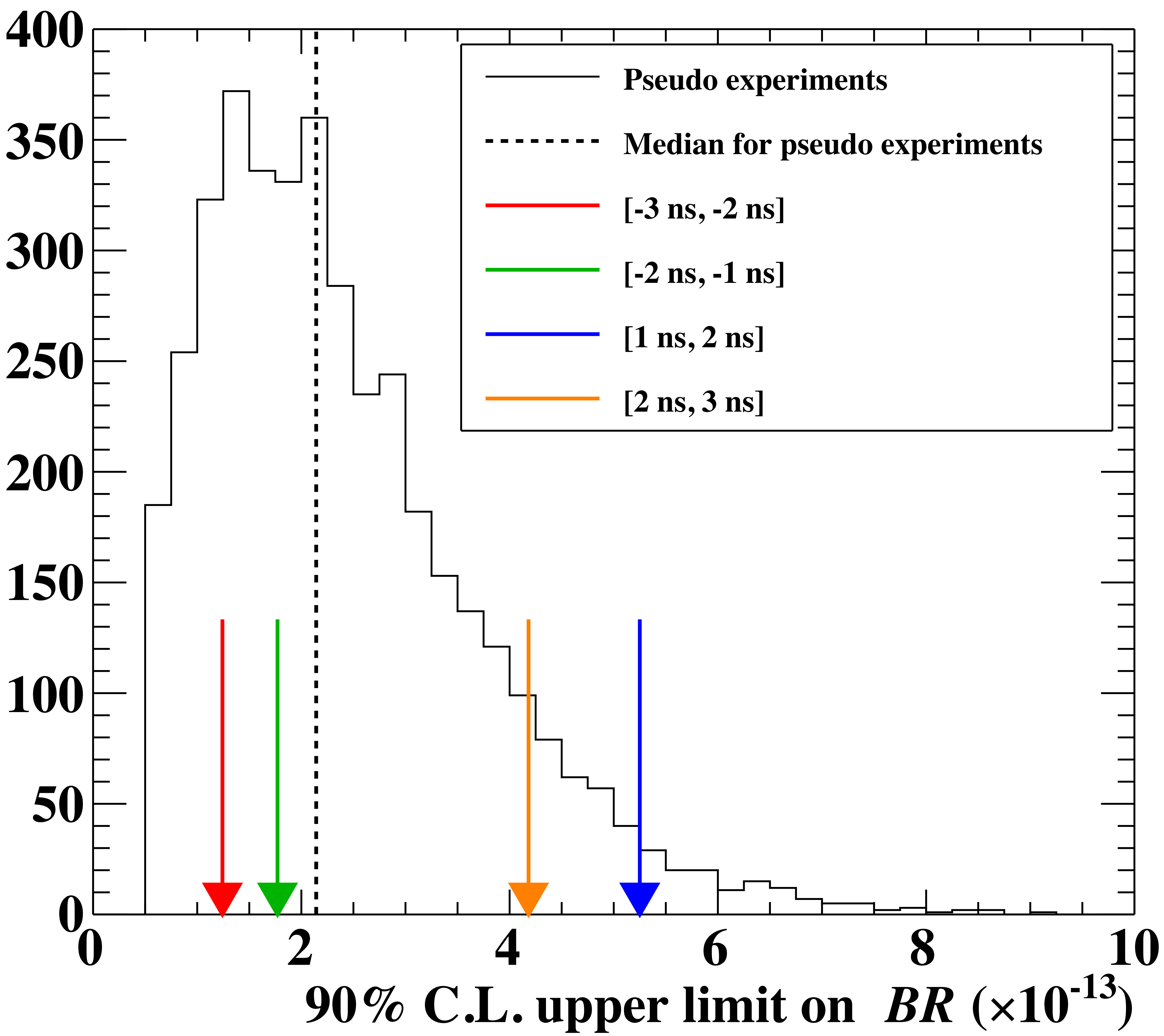
pTC



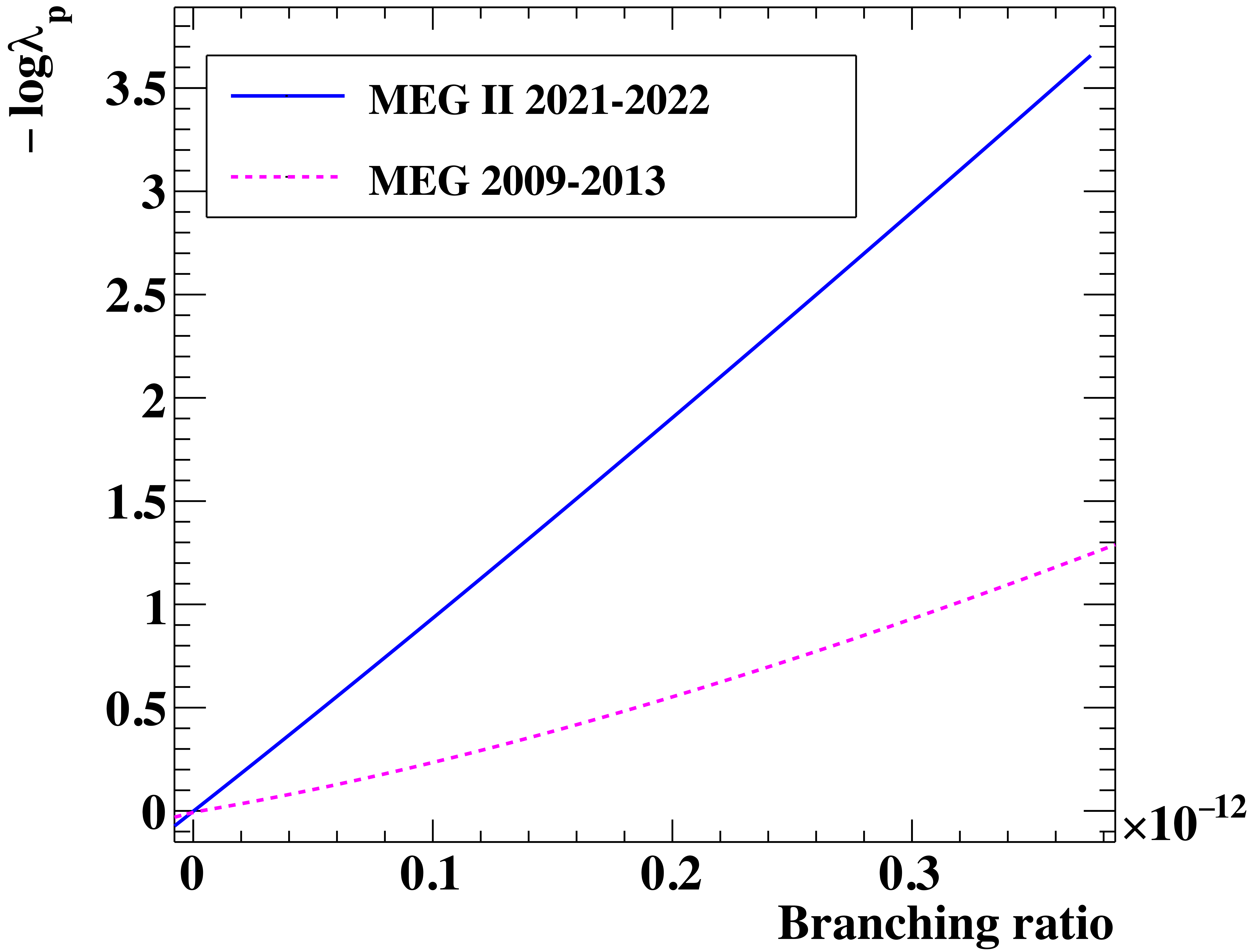
$\sigma_{t_e,\mathrm{pTC}}$ (ps)
150
100
50
0
0
2
4
6
8
10
12
14
16
n_{pTC}
Probability
0.15
0.1
0.05
0
2021
2022

Sensitivity

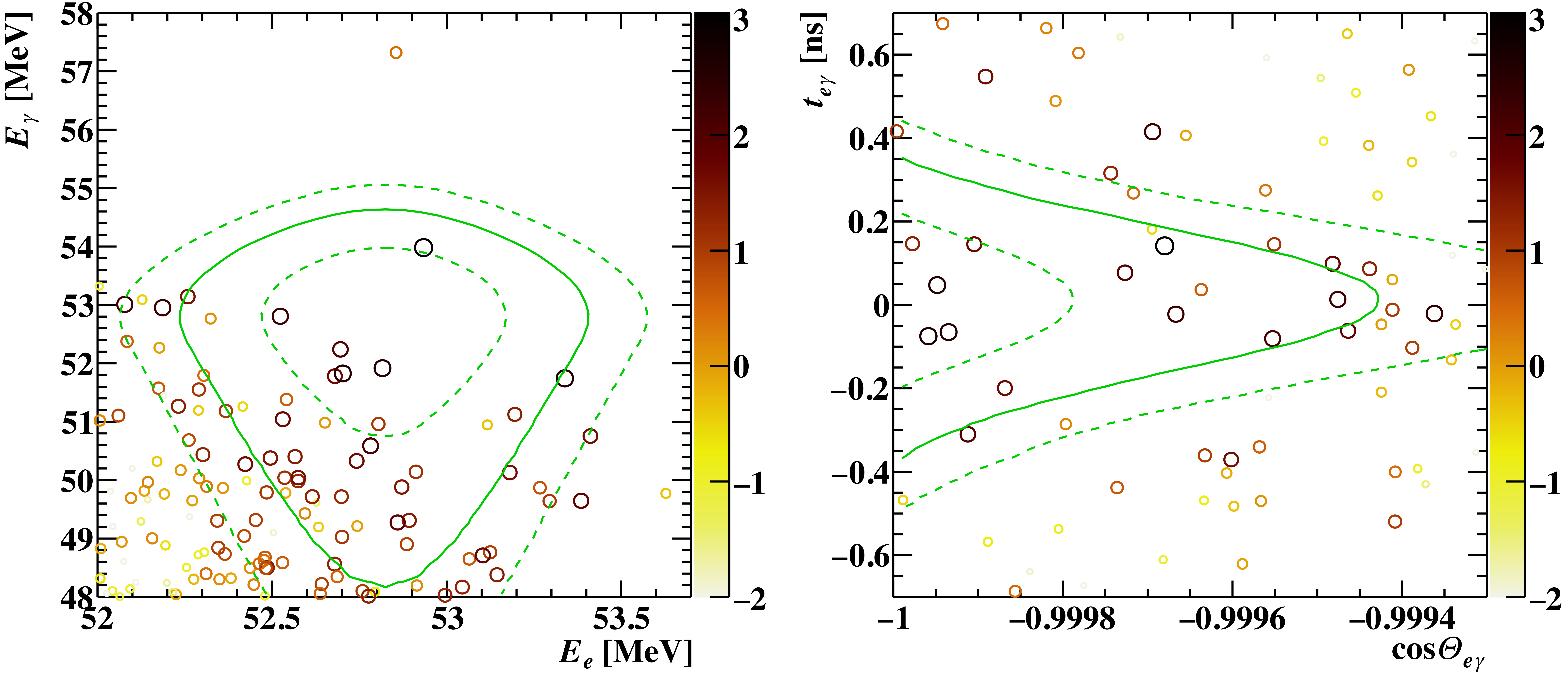
- Distribution of 90% C.L. upper limits on branching ratio
- 2.2×10^{-13} with systematics
- 2.1×10^{-13} w/o systematics



Negative log likelihood-ratio vs branching ratio

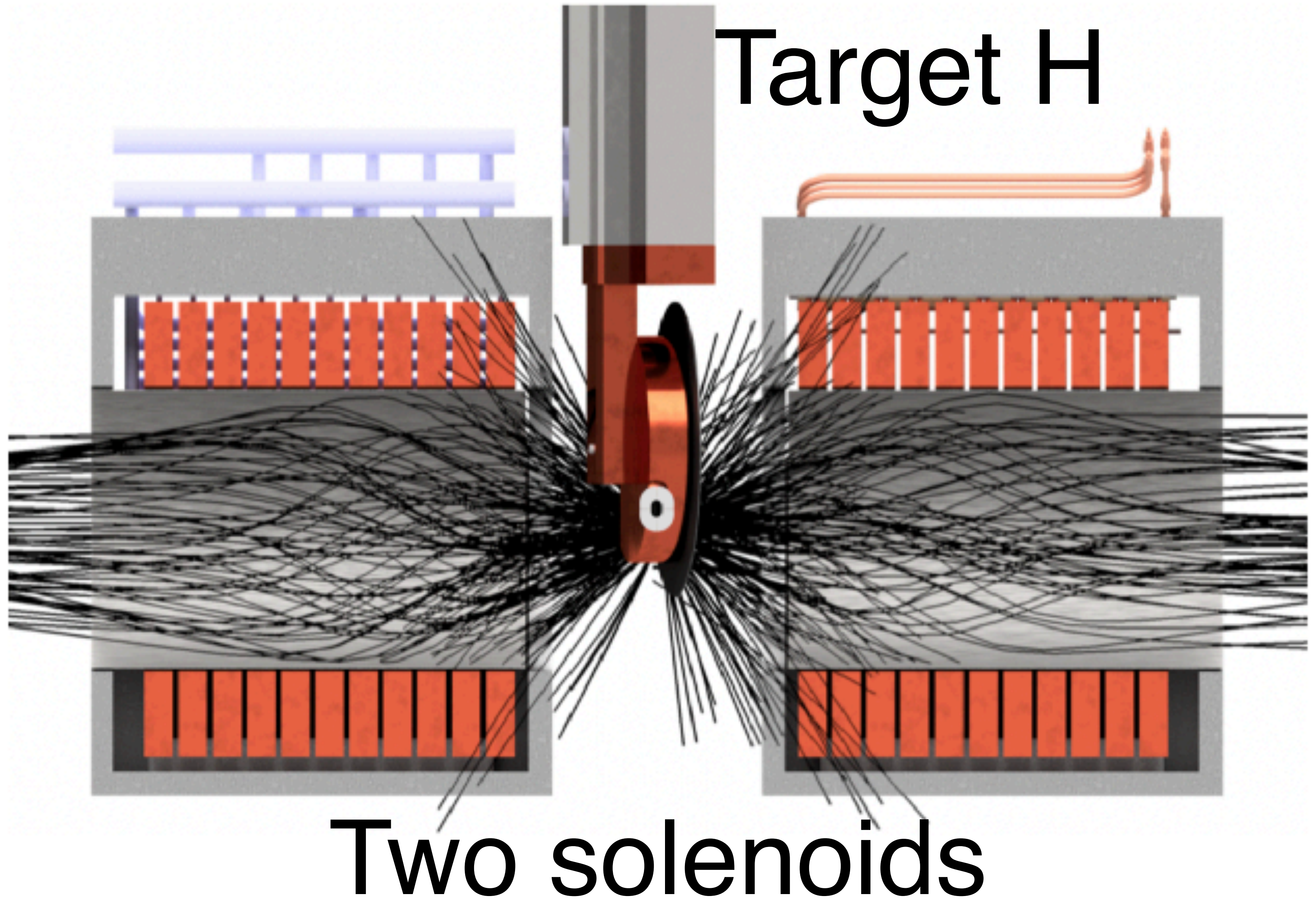


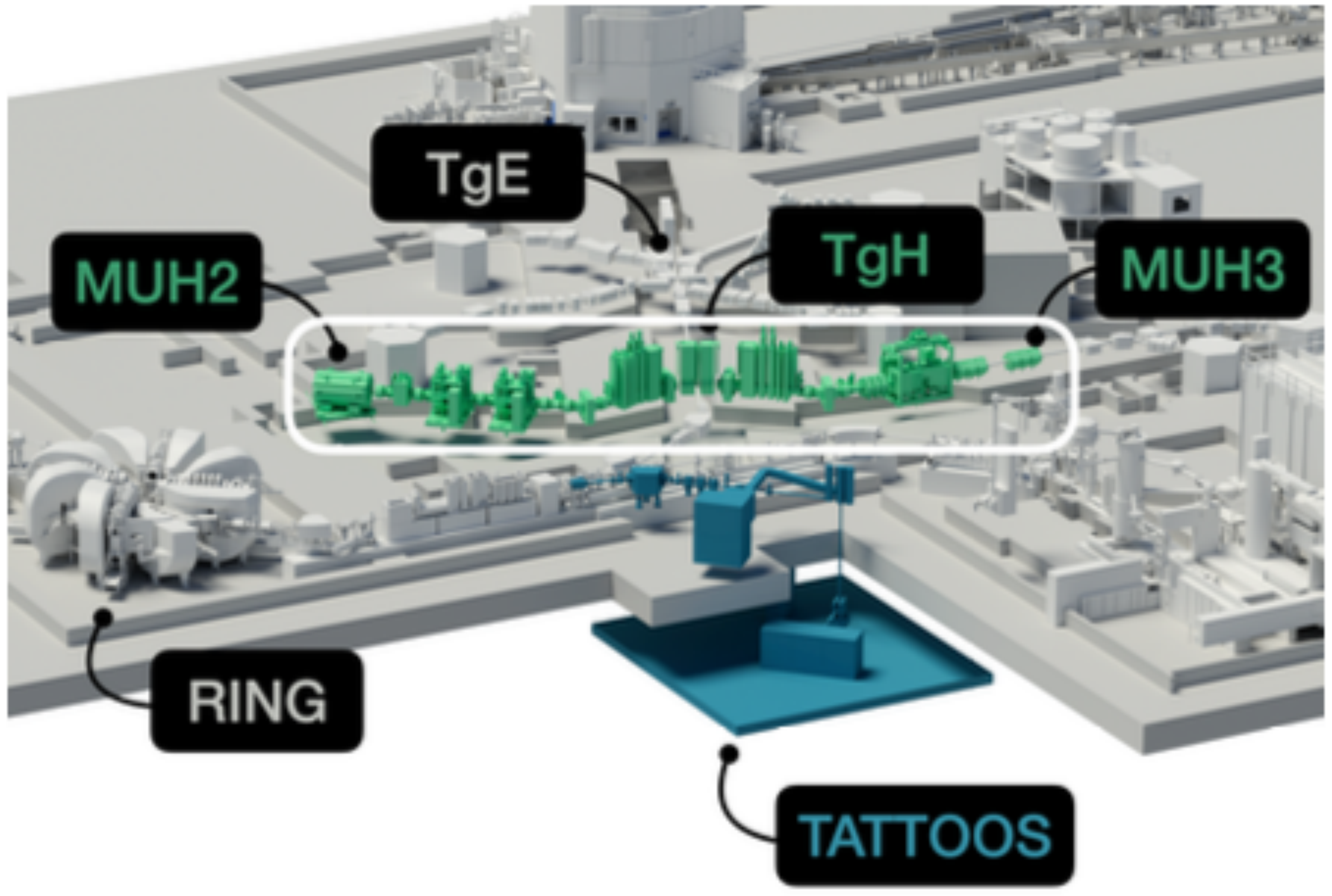
2-D event distribution (MEG)

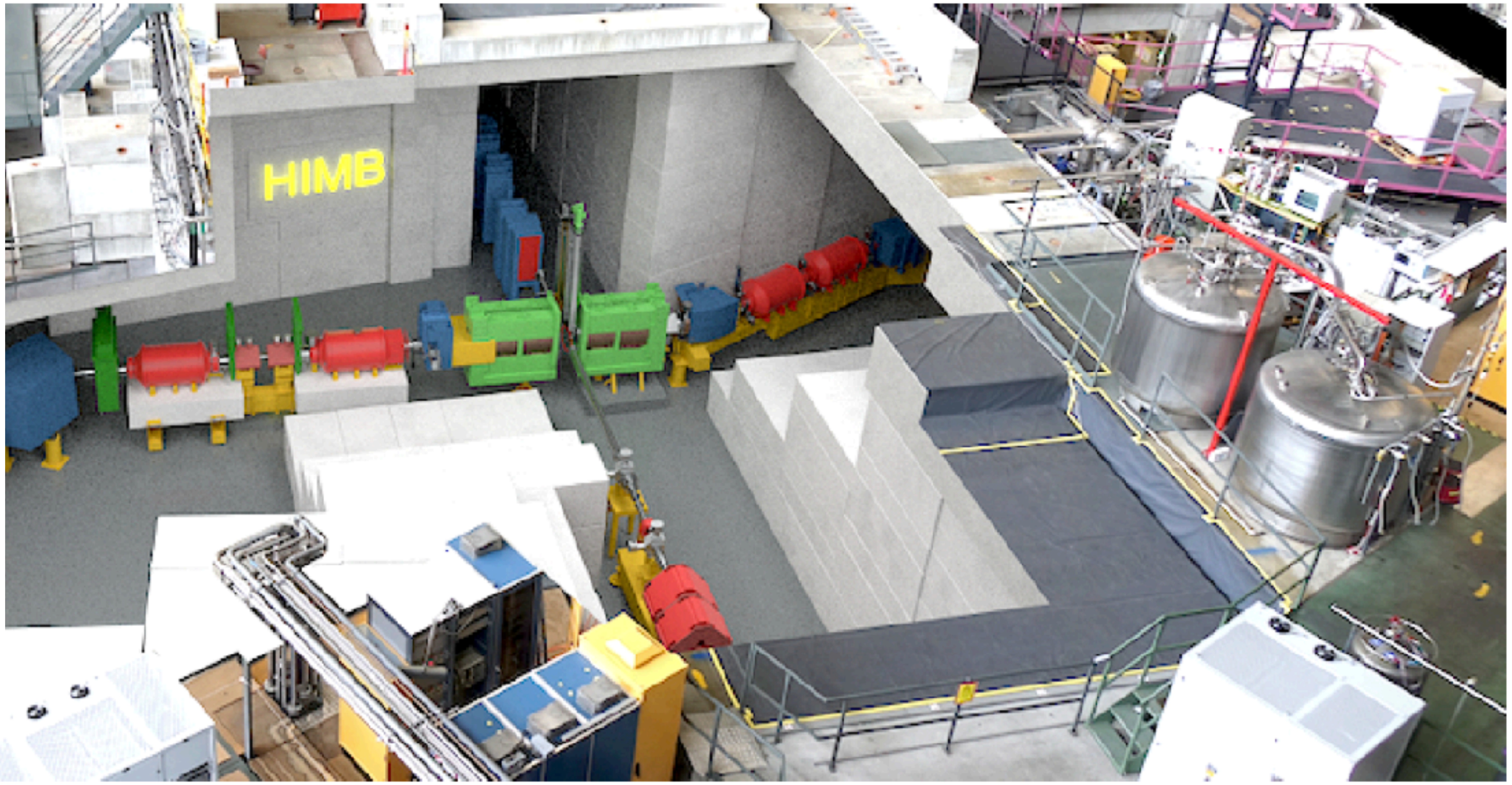


High intensity muon beam line @ PSI

- Shutdown of about two years from 2027
- New target geometry, 4 times capture efficiency, 6 times transport efficiency, resulting in > $10^{10}\mu/s$ ($5\times10^{8}\mu/s$ now) available from late 2028
- Beam spot σ~40mm



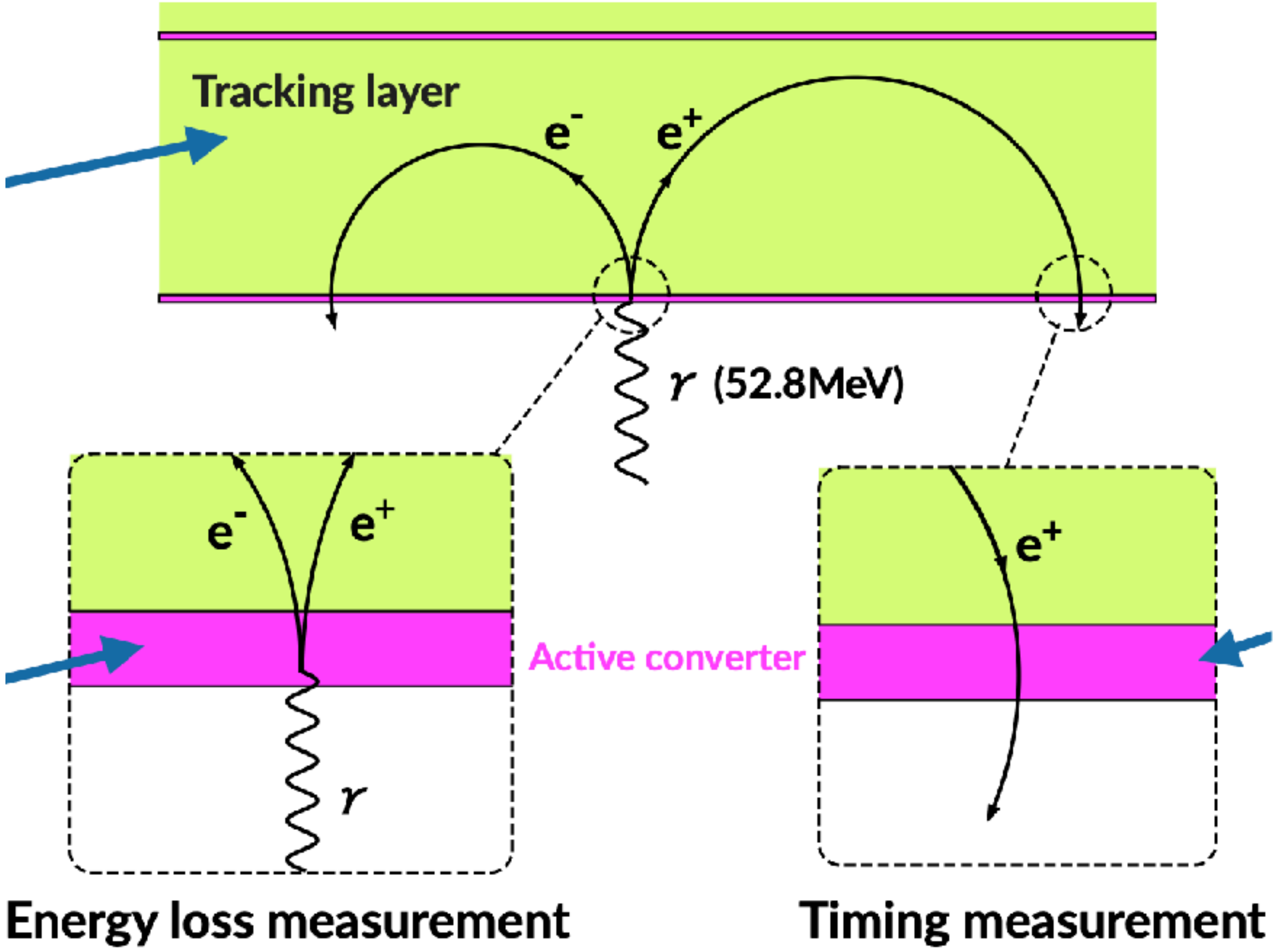




Photon measurement: Pair Spectrometer with Active Converter

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

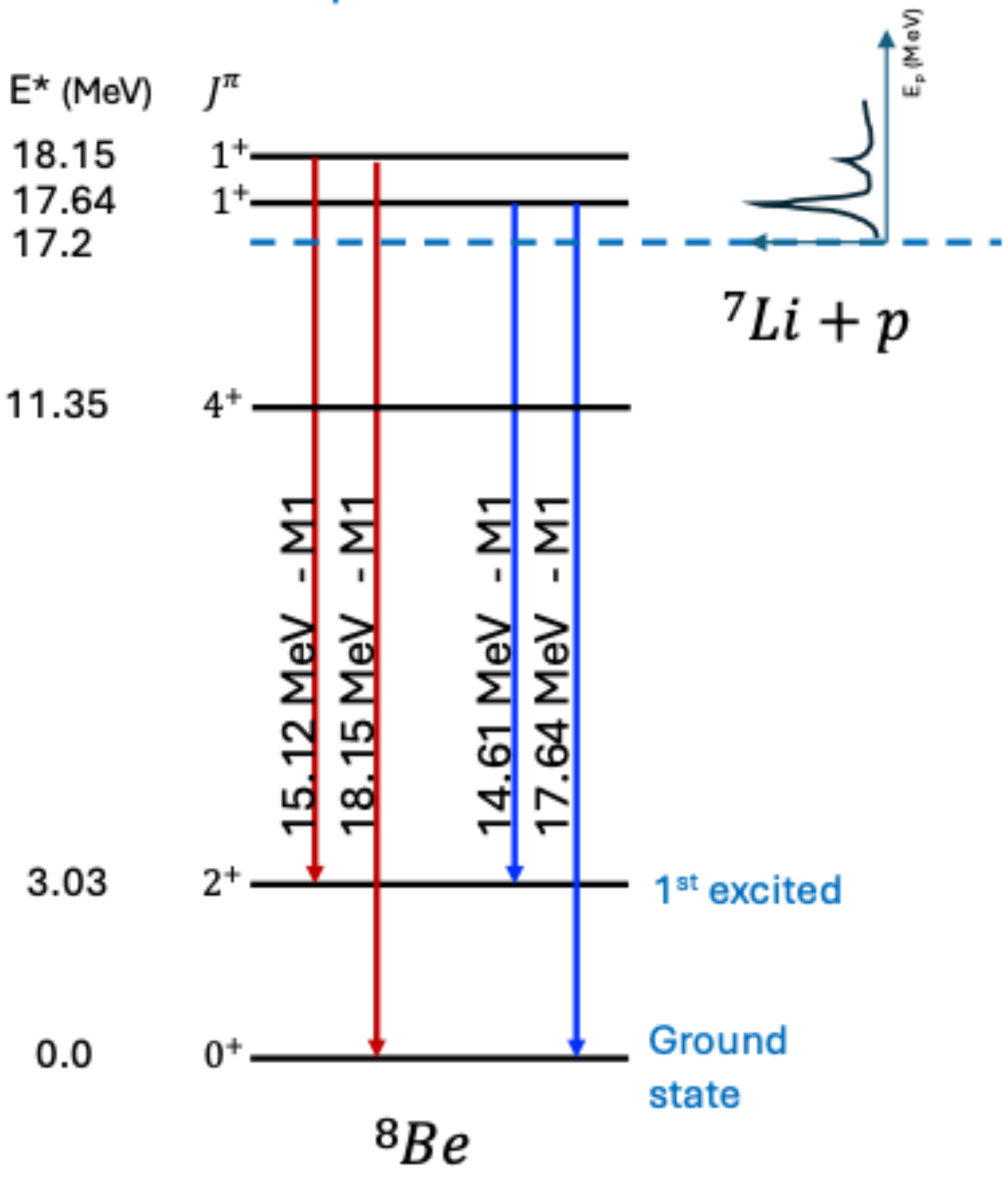
- Timing measurement
  - Measure timing of returning conversion pair
  - in front of active converter
  - Multi-layer RPC
  - Active converter = timing detector

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

Simplified Be levels



- 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

$$E_p = 0.440 \text{ MeV} \quad Q = 17.6 \text{ MeV}$$

$$E_p = 1.030 \text{ MeV} \quad Q = 18.1 \text{ MeV}$$

A further non-resonant state is present at 17.9 MeV

- Two γ transitions for each excited state