Prospects of charged lepton flavor violation

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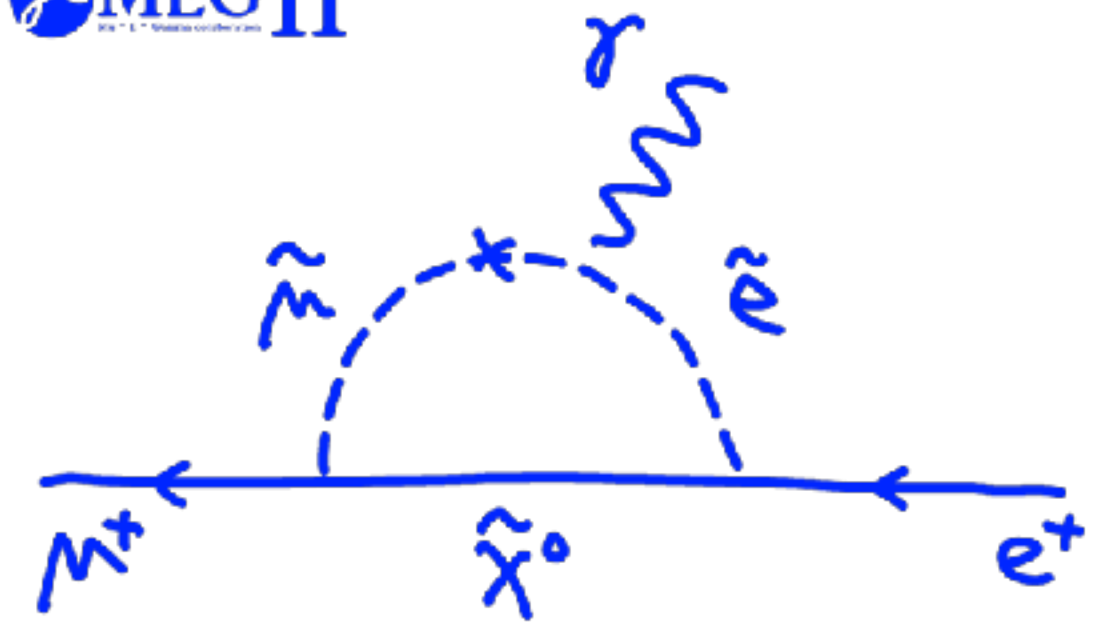
MEG II

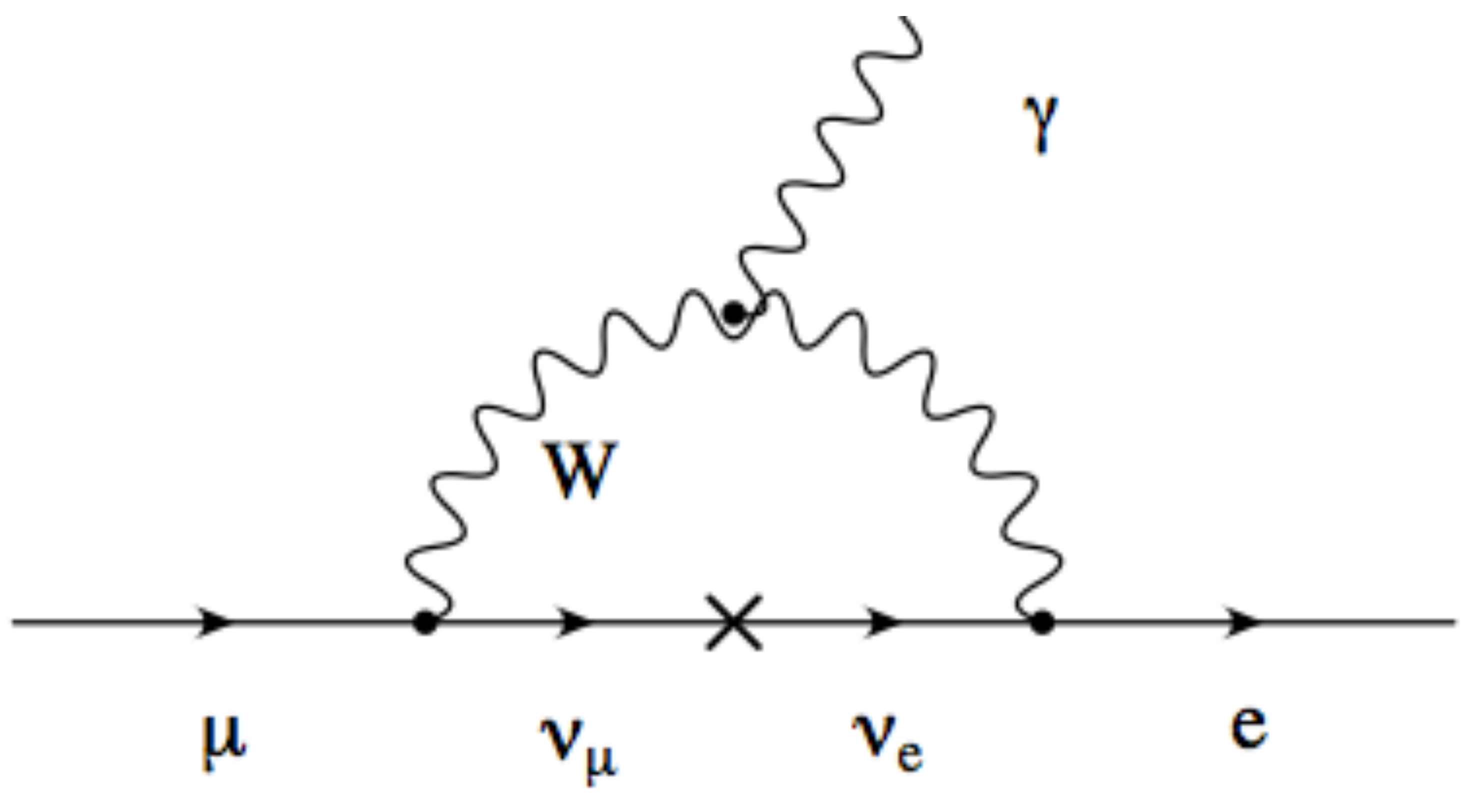


Charged lepton flavor violation (cLFV)

- 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

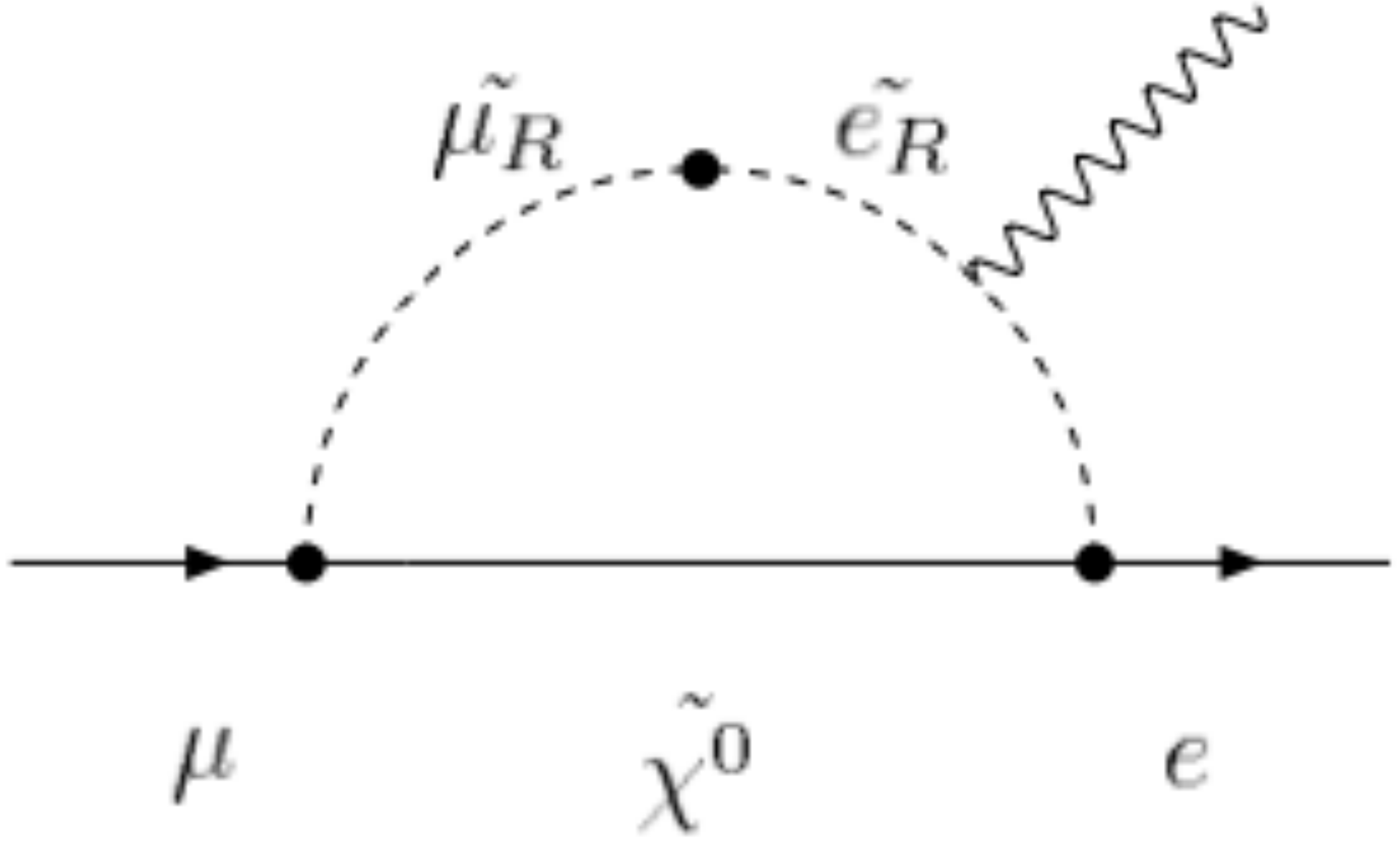
Charged lepton flavor transition has never been observed yet



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

$$\sim 10^{-54}$$

Neutrino is too light



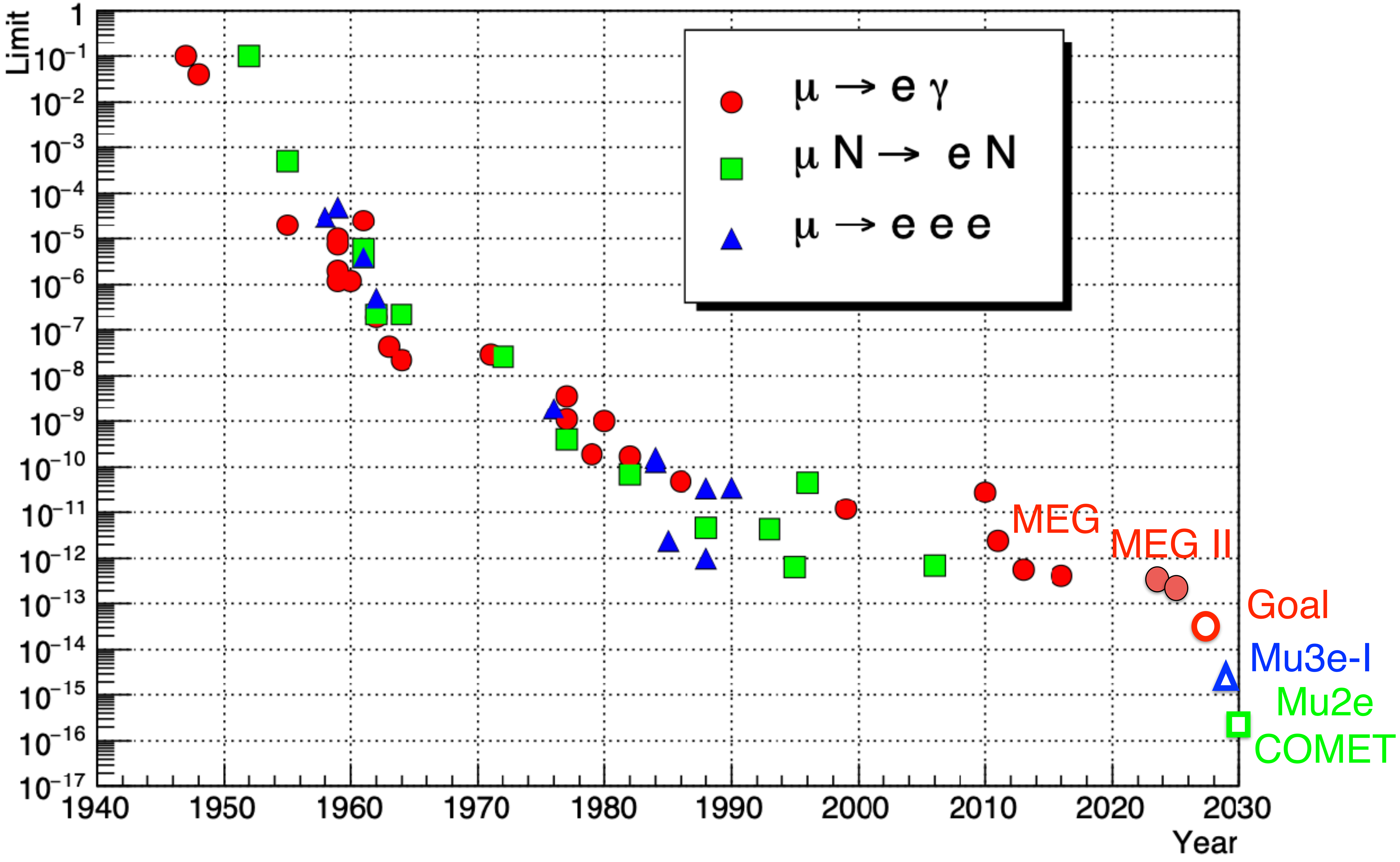
New particles from SUSY in the loop can enhance the branching ratio 10^{-12} – 10^{-14}

SUSY-GUT / SUSY-seesaw

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

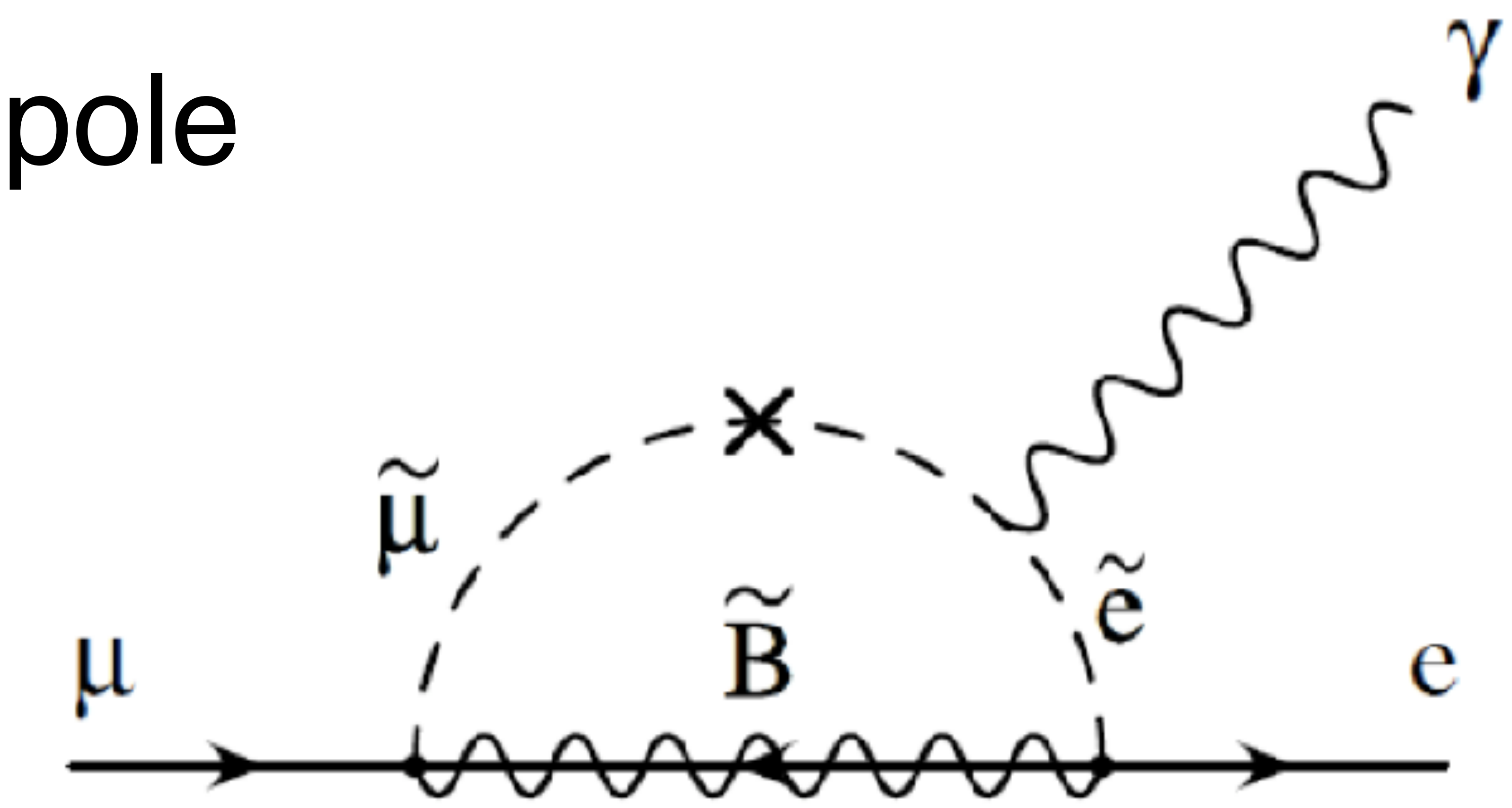
$\mu^+ \to e^+\gamma, \mu^+ \to e^+e^-e^+, \& \ \mu^- \to e^-$

- 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

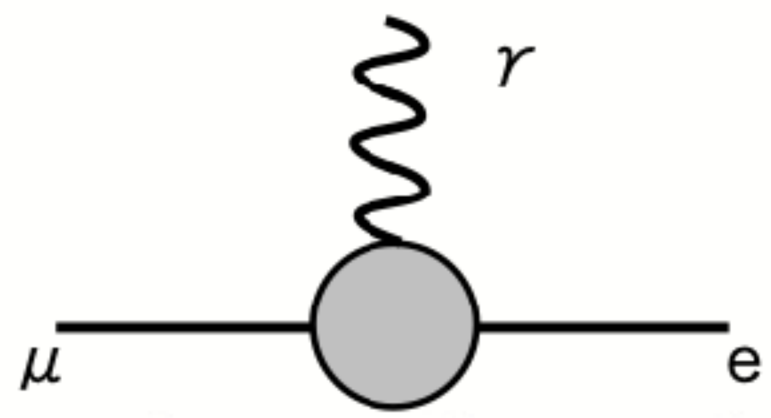


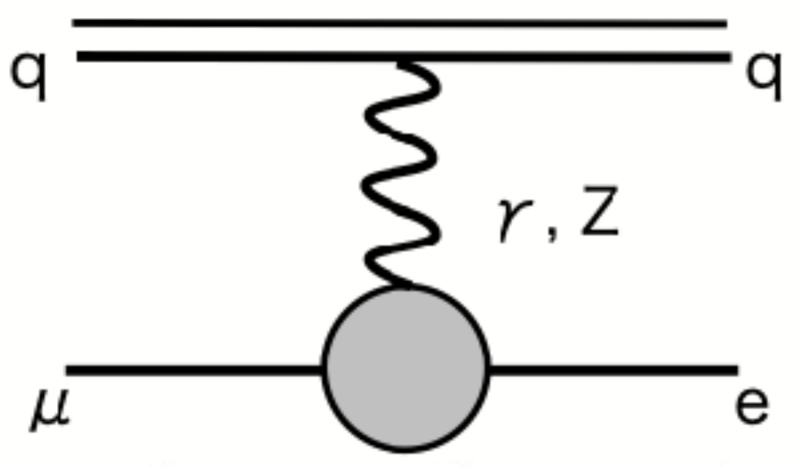
New physics models

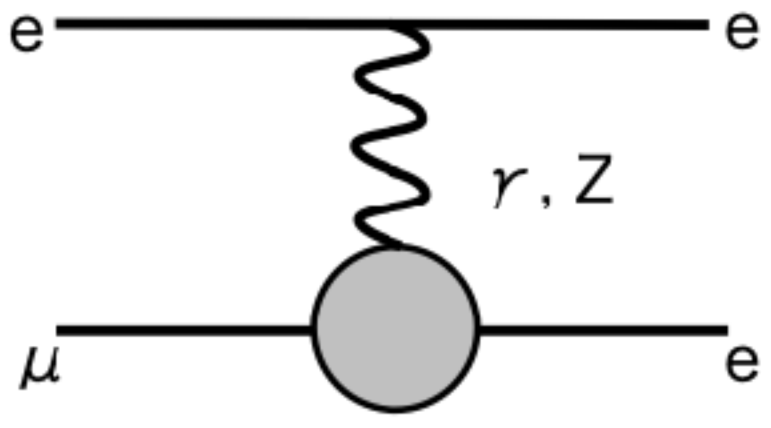
Dipole



SUSY-GUT, SUSY-seesaw

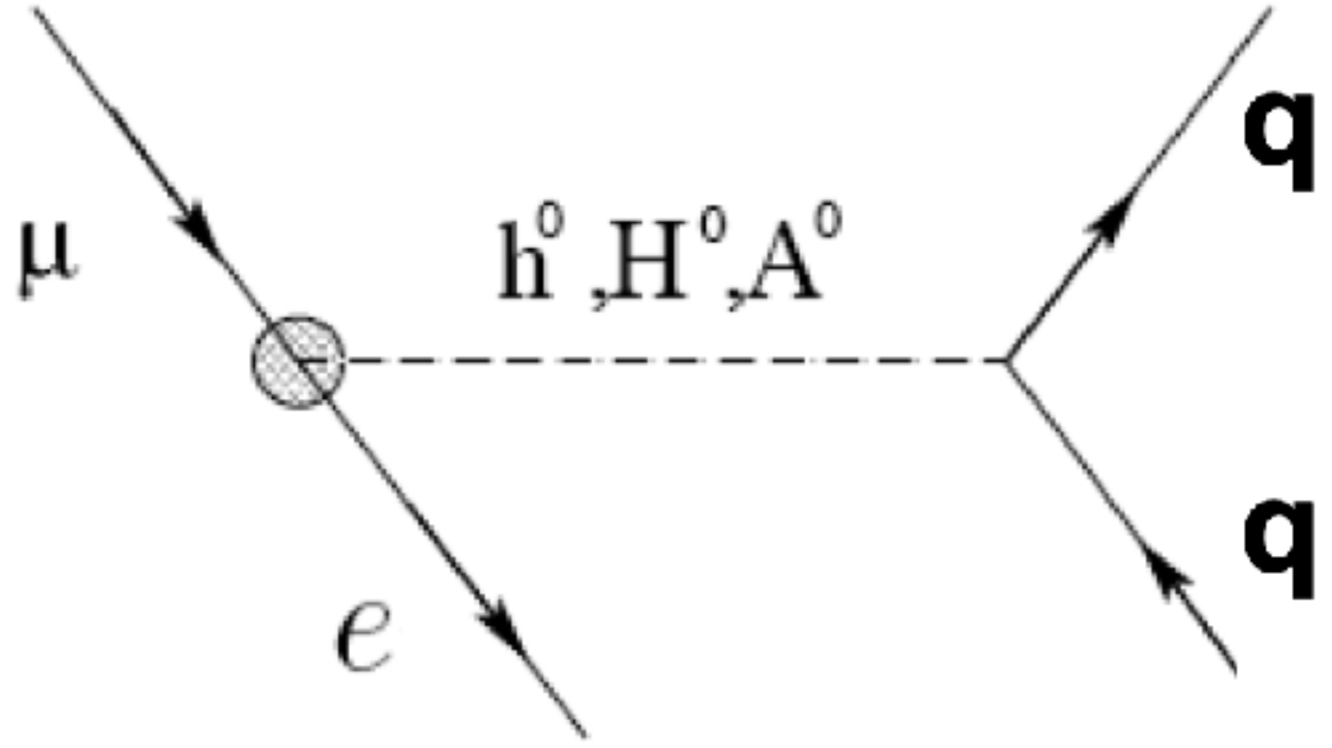




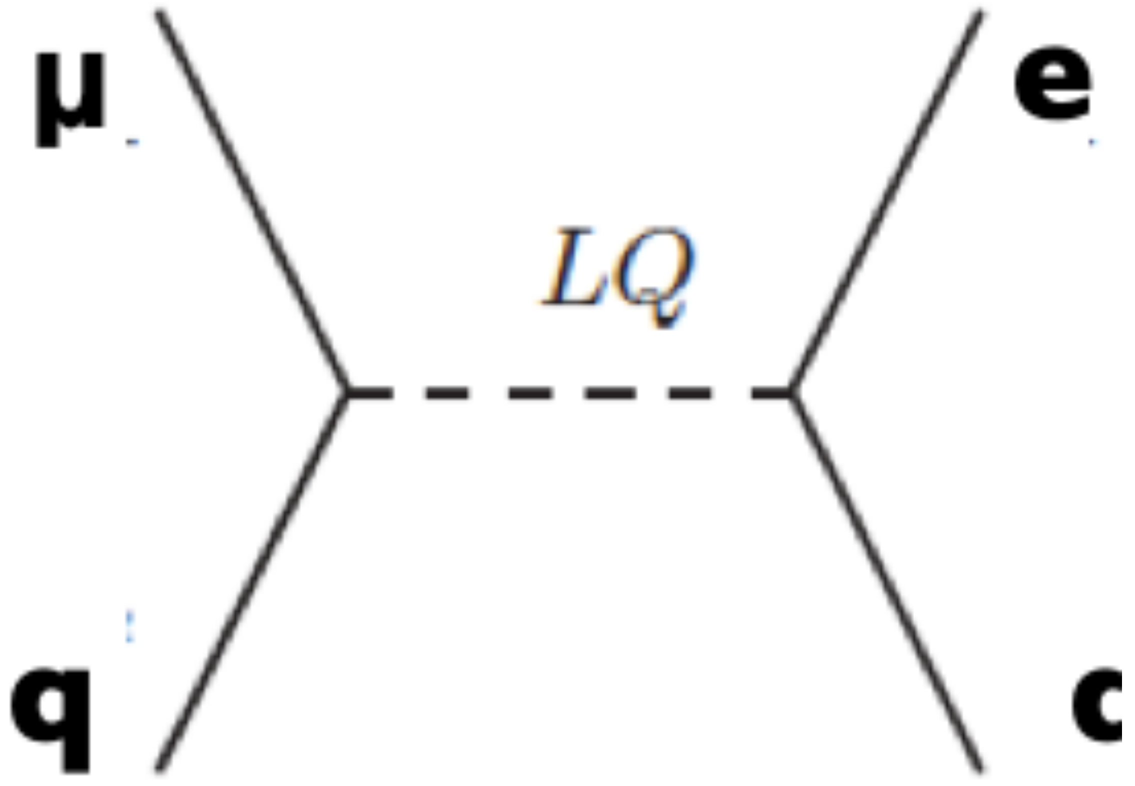


$Br(\mu \to e\gamma)$: $R(\mu\text{-Al} \to e\text{-Al})$: $Br(\mu \to 3e)$
= 1 : 1/170 : 1/390

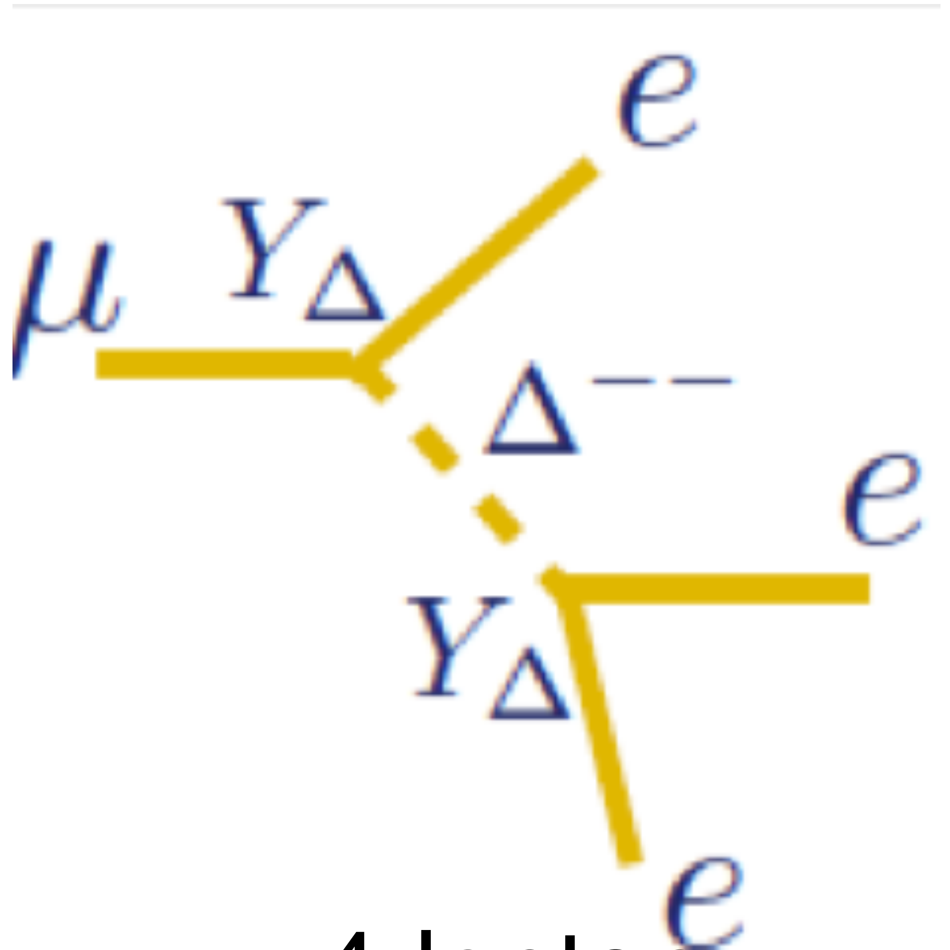
Tree



Scalar: RPV SUSY



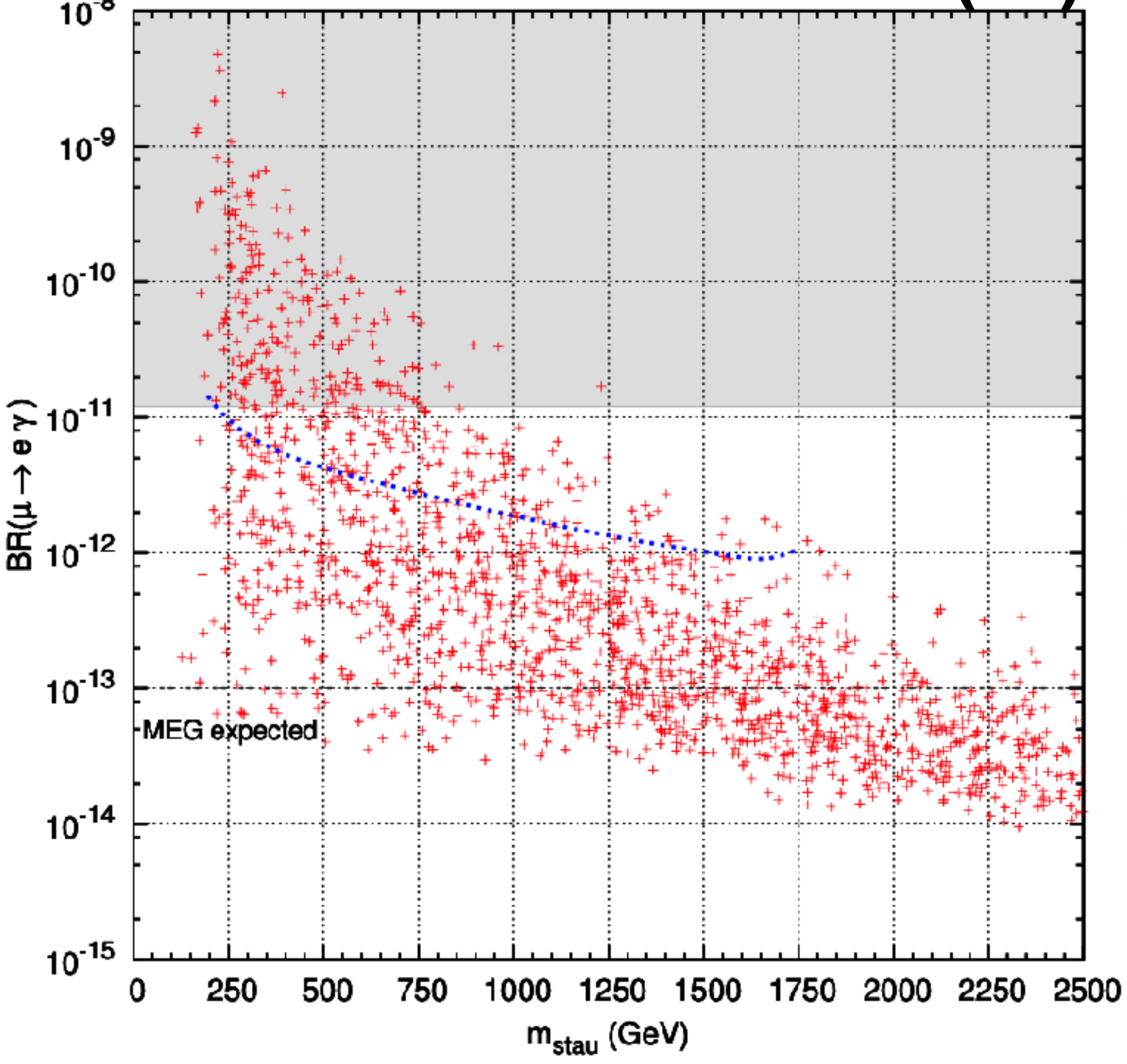
Vector: Leptoquarks, …



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

Examples of new physics

SUSY-GUT SO(10)



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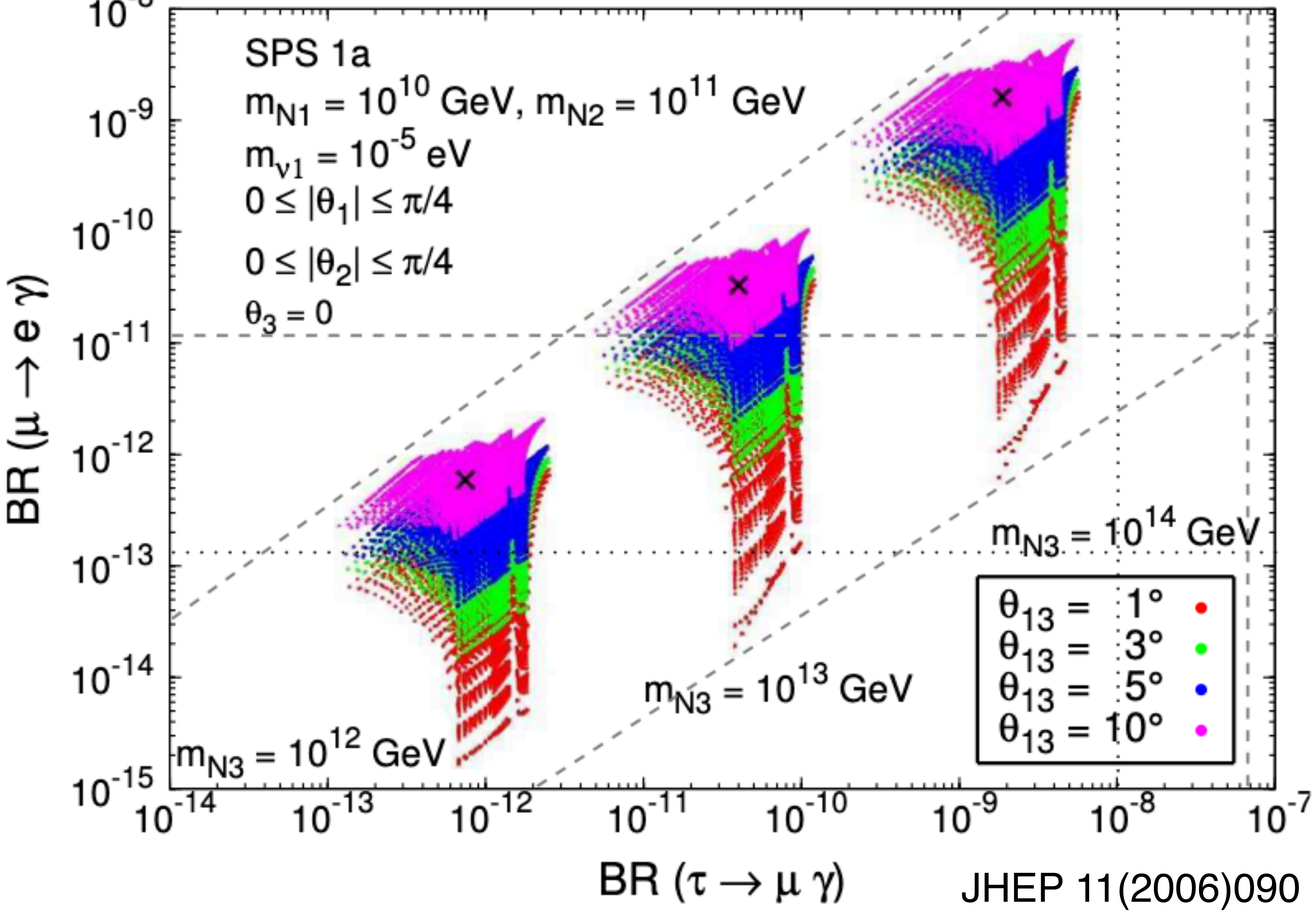
SUSY-Seesaw

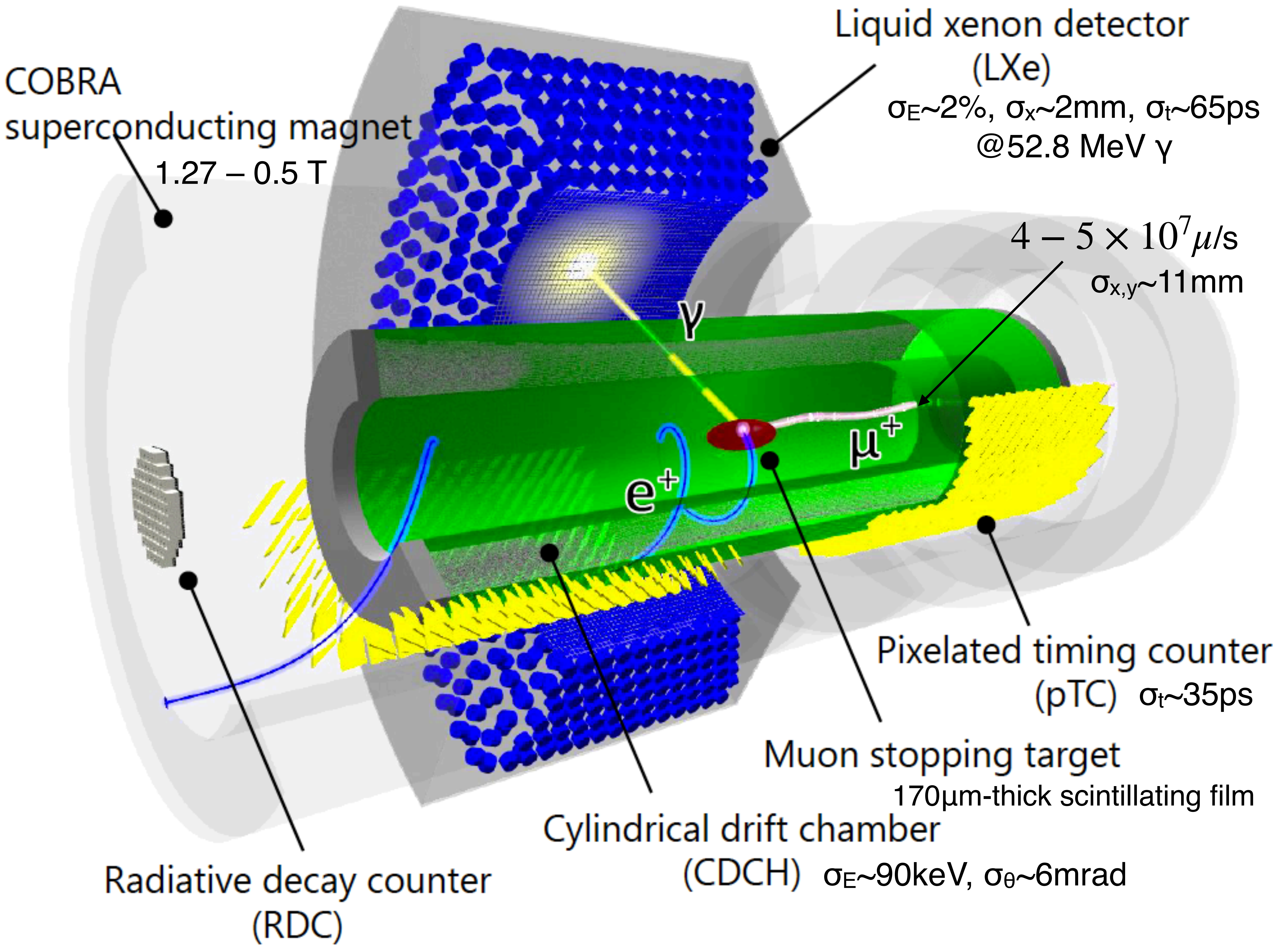


JHEP 11(2006)090

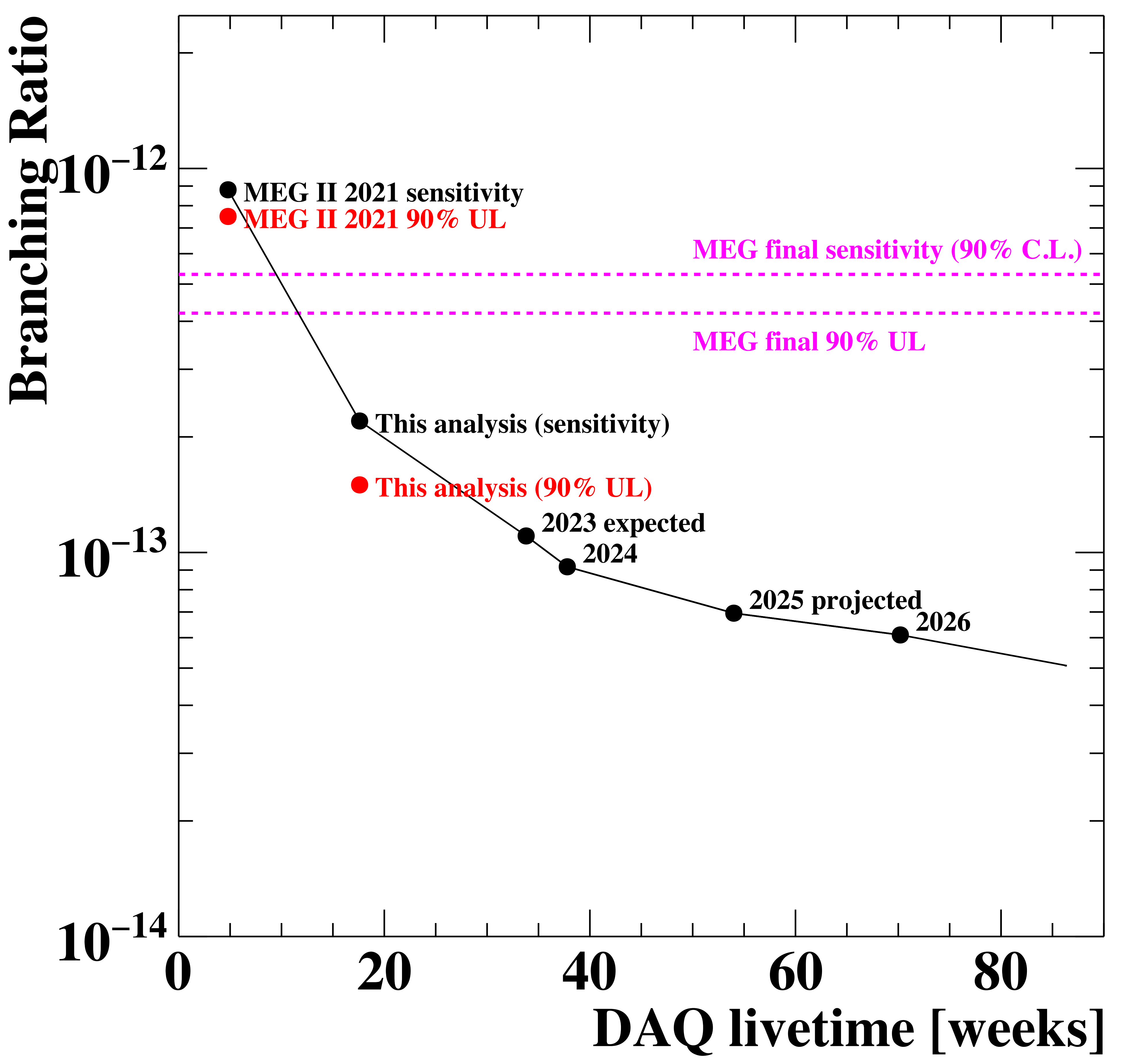
Real chance for discovery

Already some regions from theoretical expectation excluded

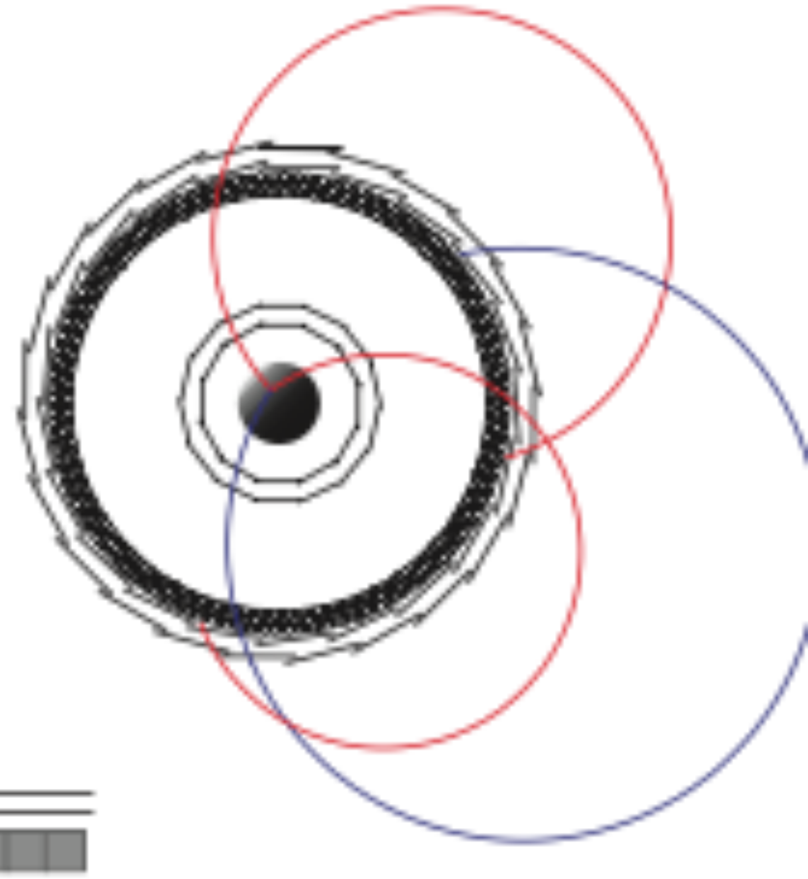
Current running experiment



MEG II expected sensitivity

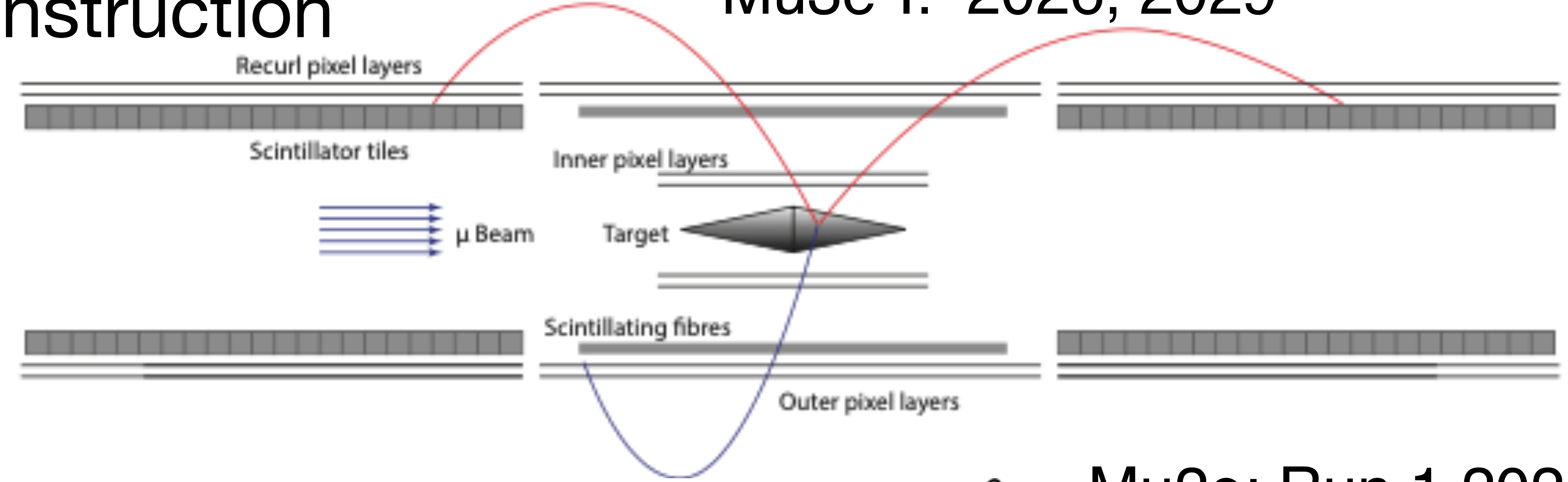


Experiments about to begin

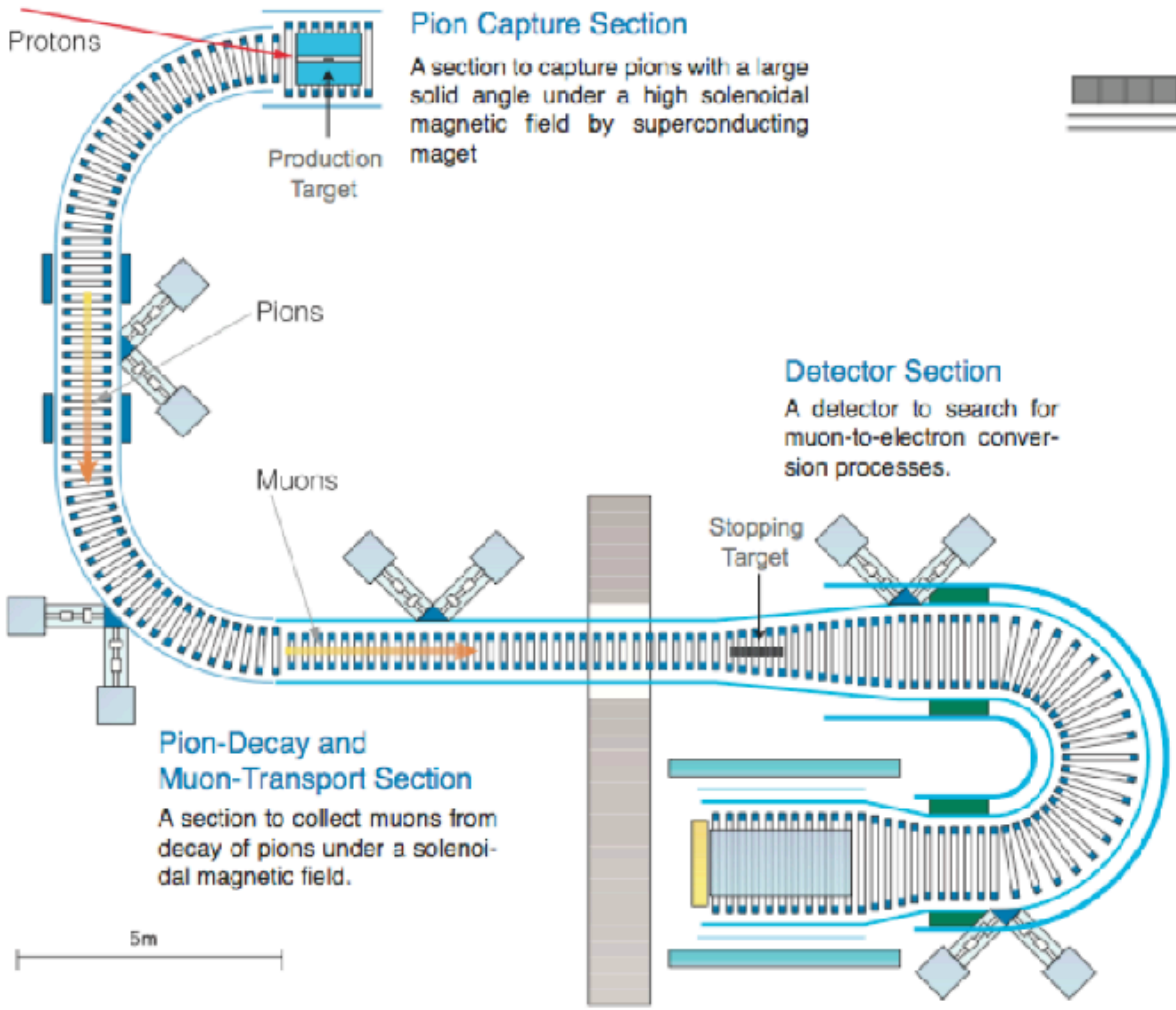


- Mu3e phase I, Mu2e-I, COMET: finalizing the detector construction

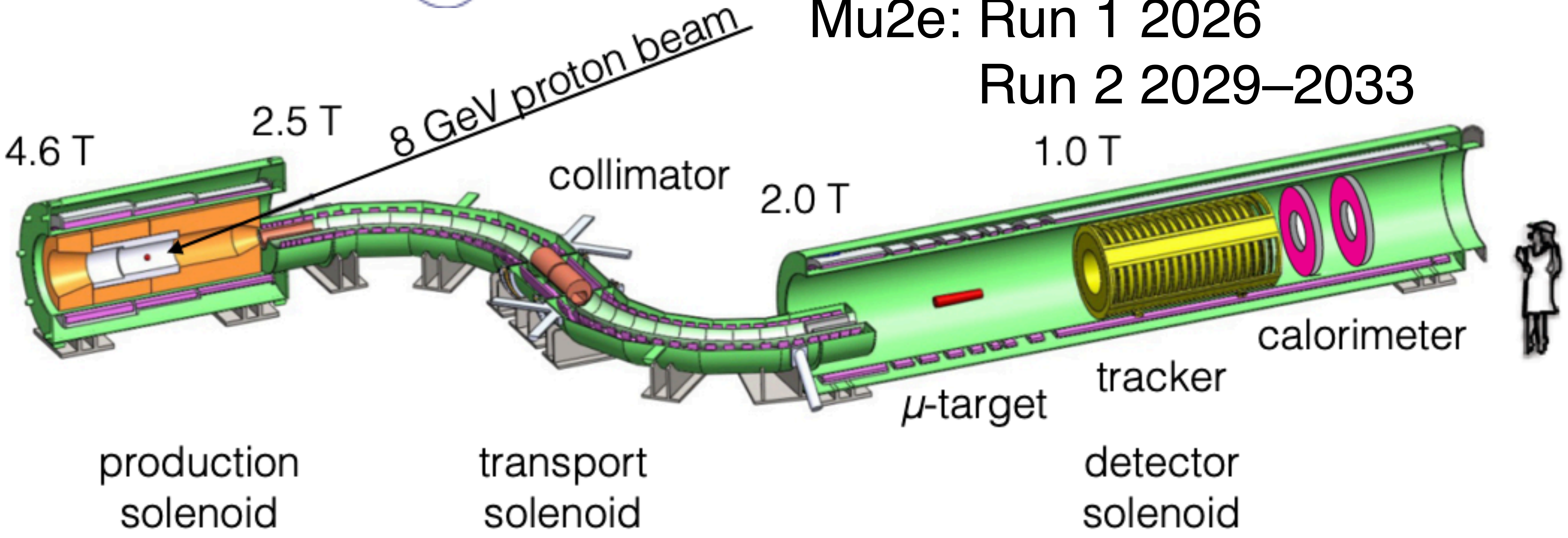
Mu3e-I: 2026, 2029–



COMET Phase-I : 2026–



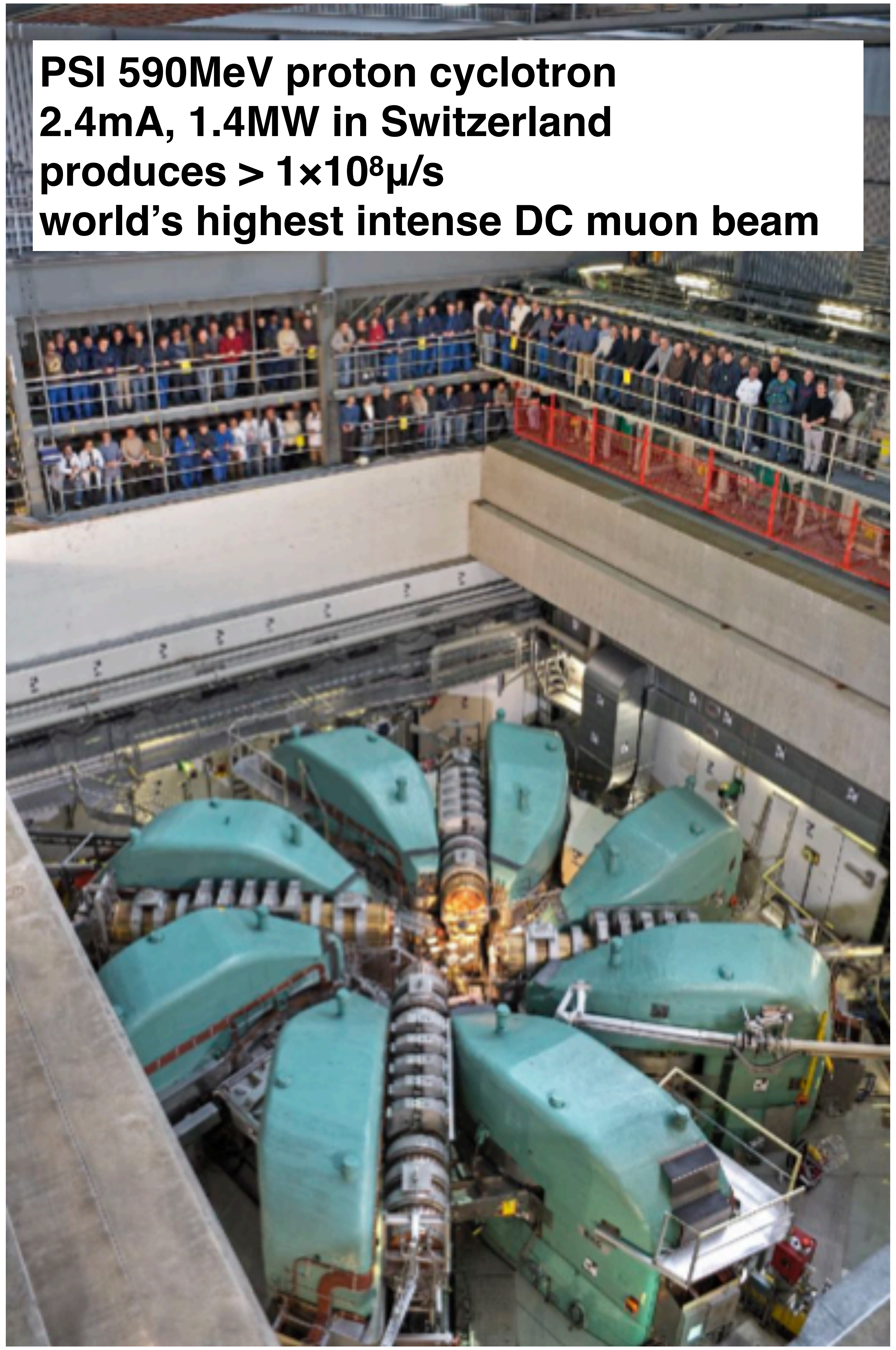
Mu2e: Run 1 2026
Run 2 2029–2033

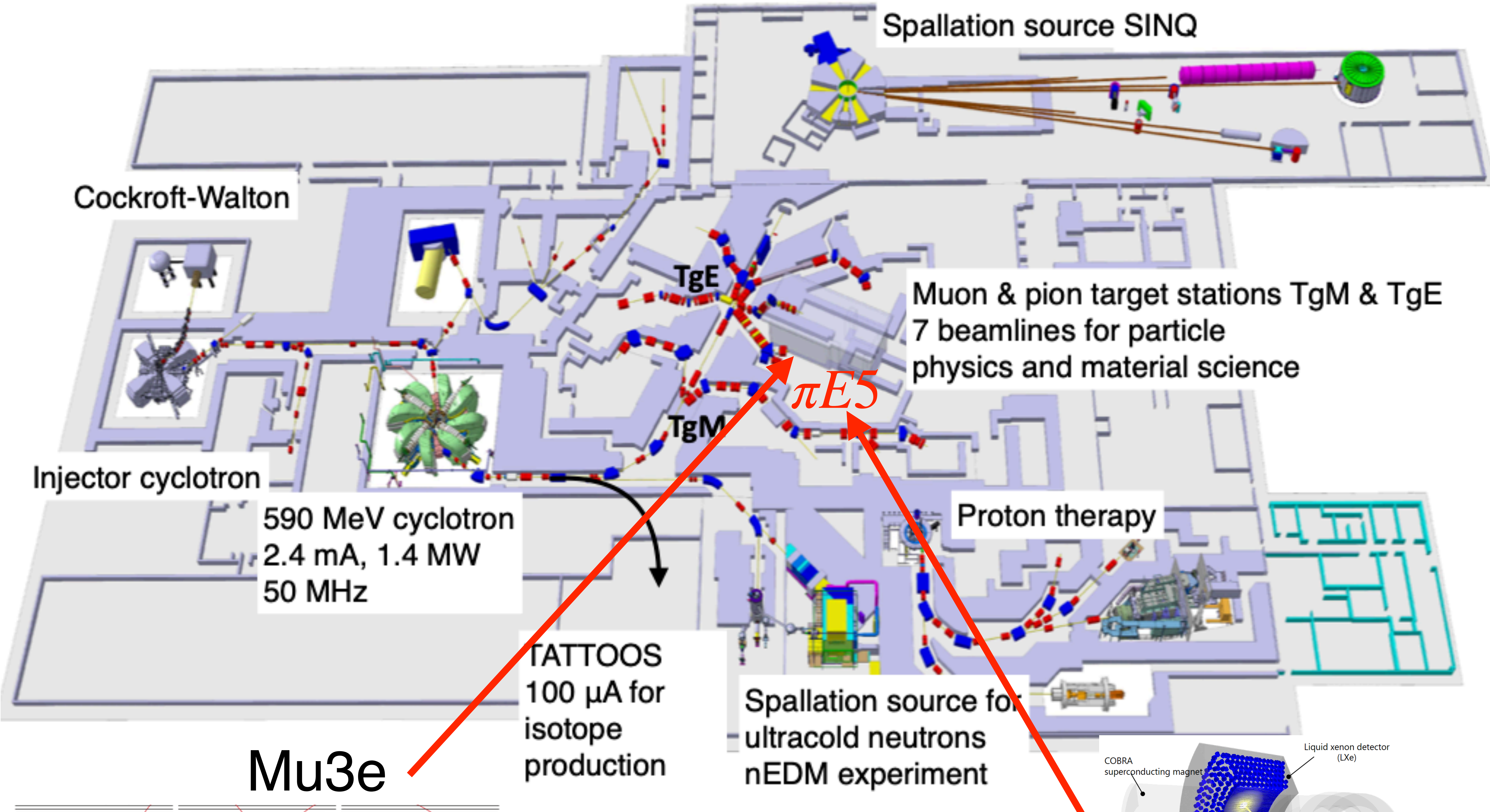


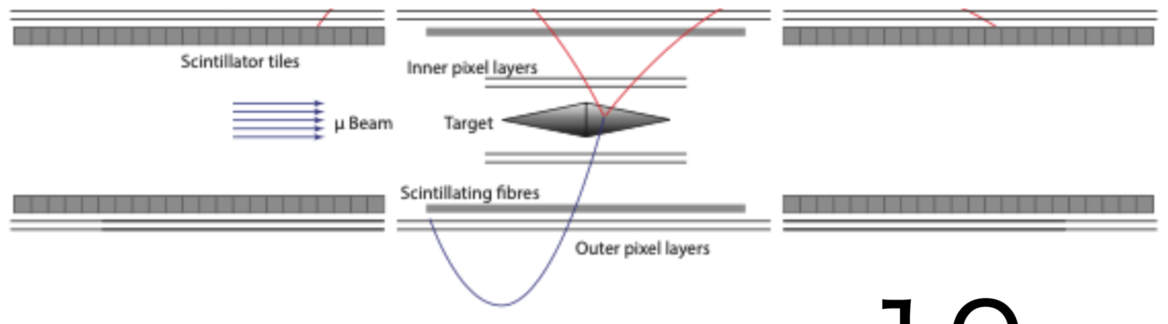
Exciting results will be available in 2030s

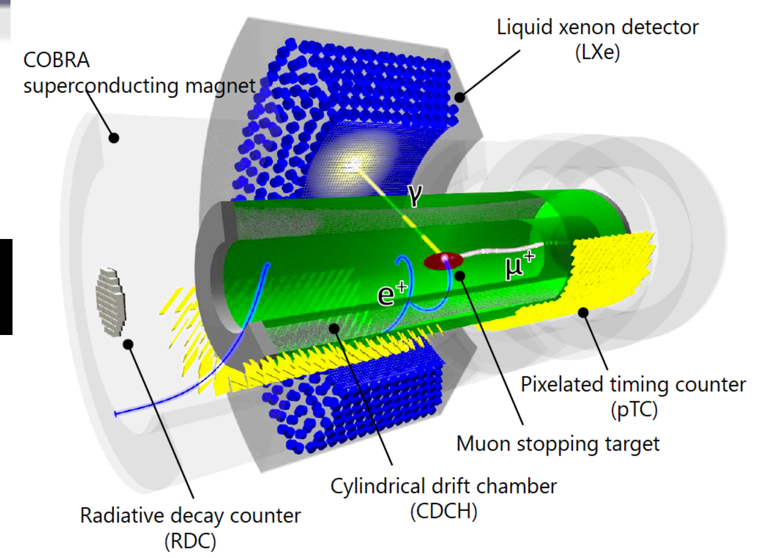
What’s next?

Paul Scherrer Institute (PSI) in Switzerland



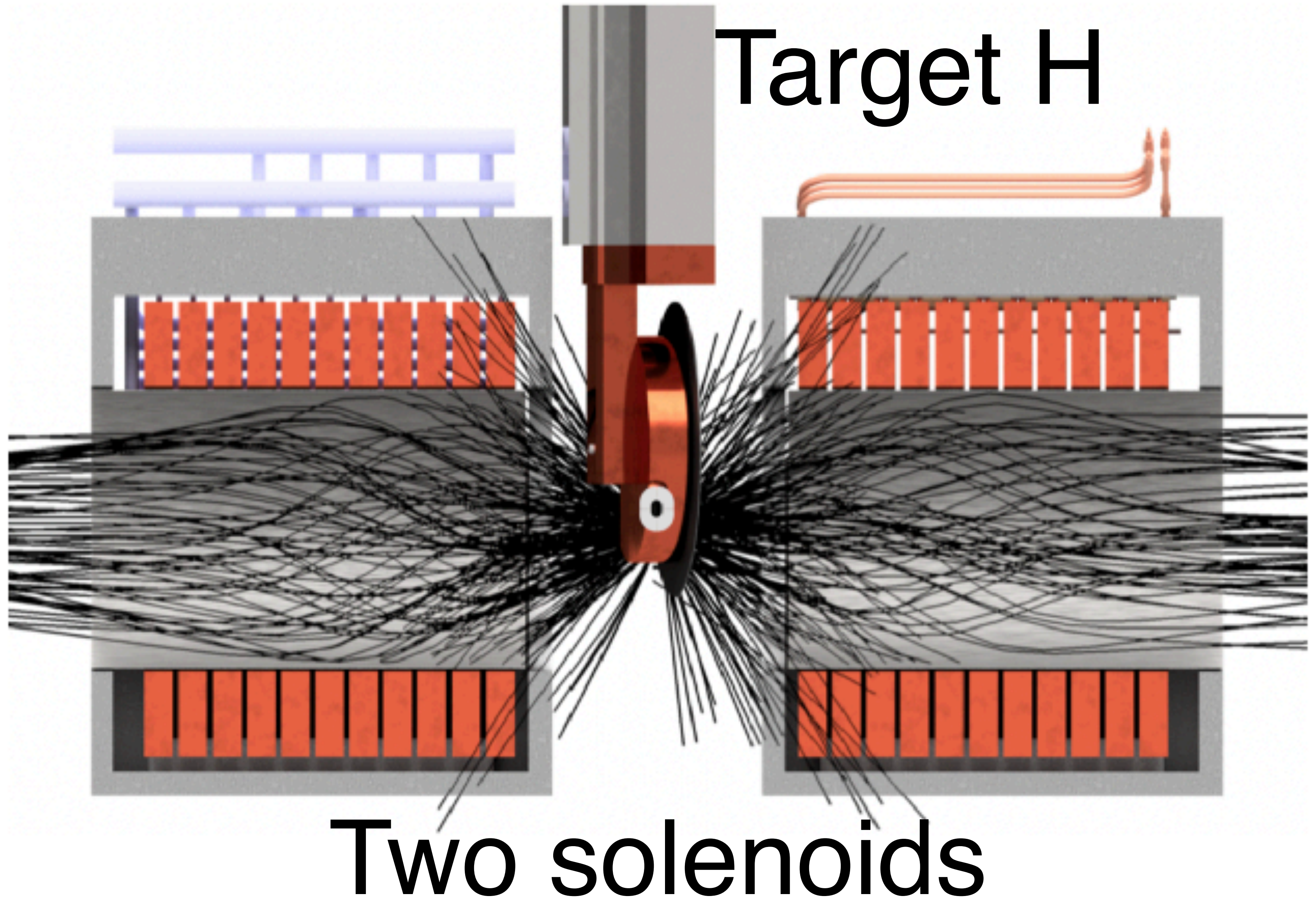


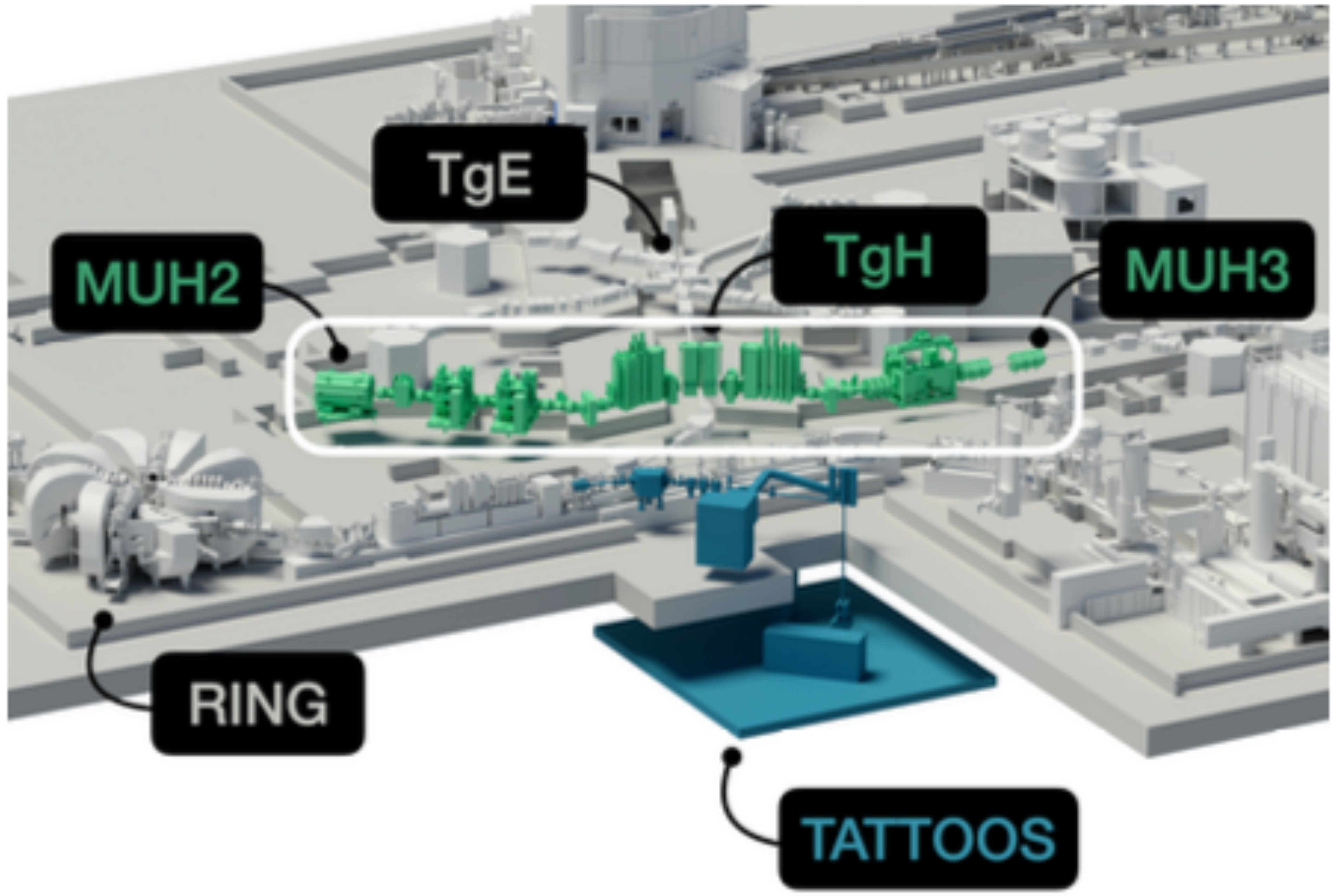


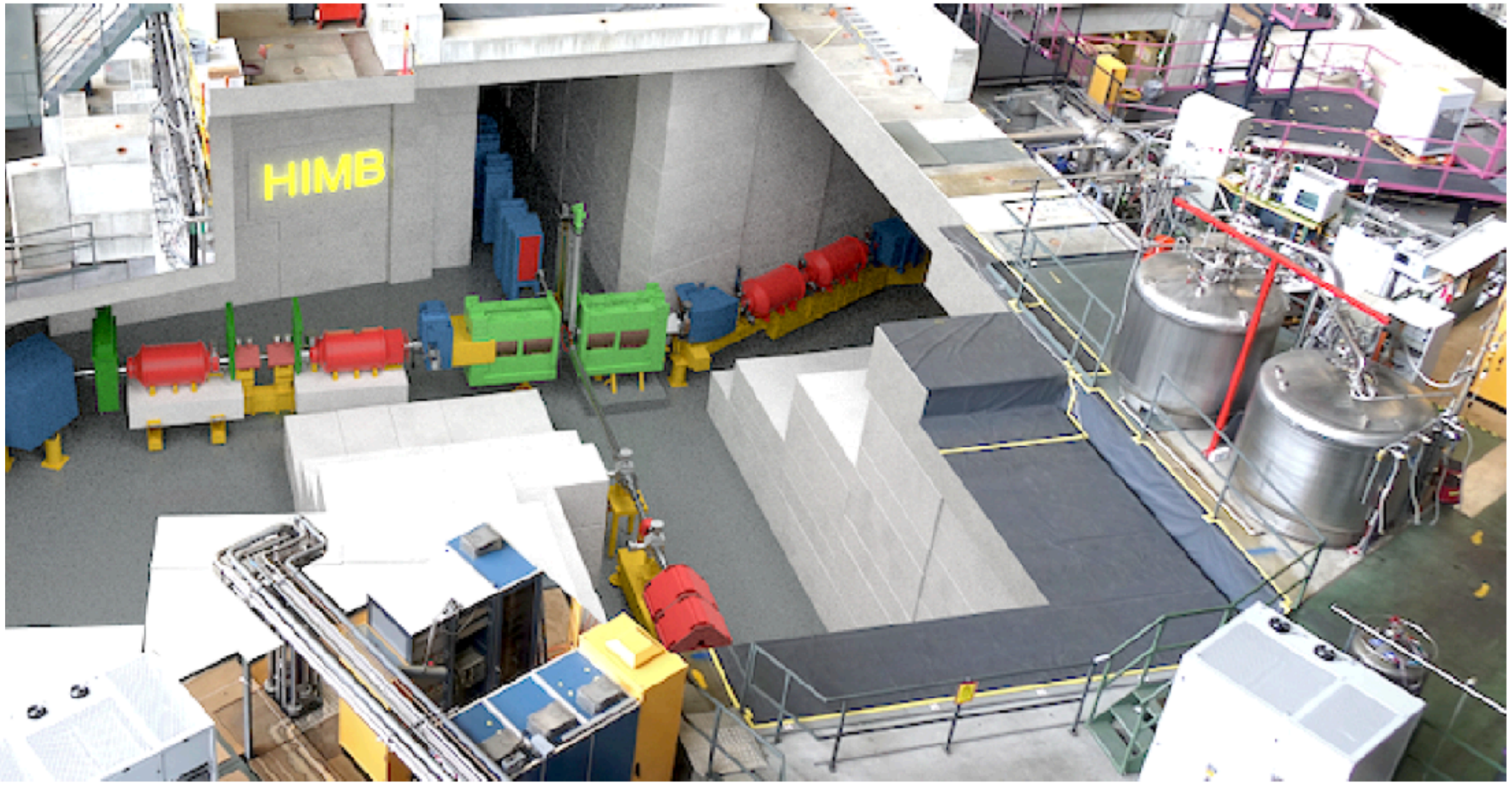


High intensity muon beam line @ PSI

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

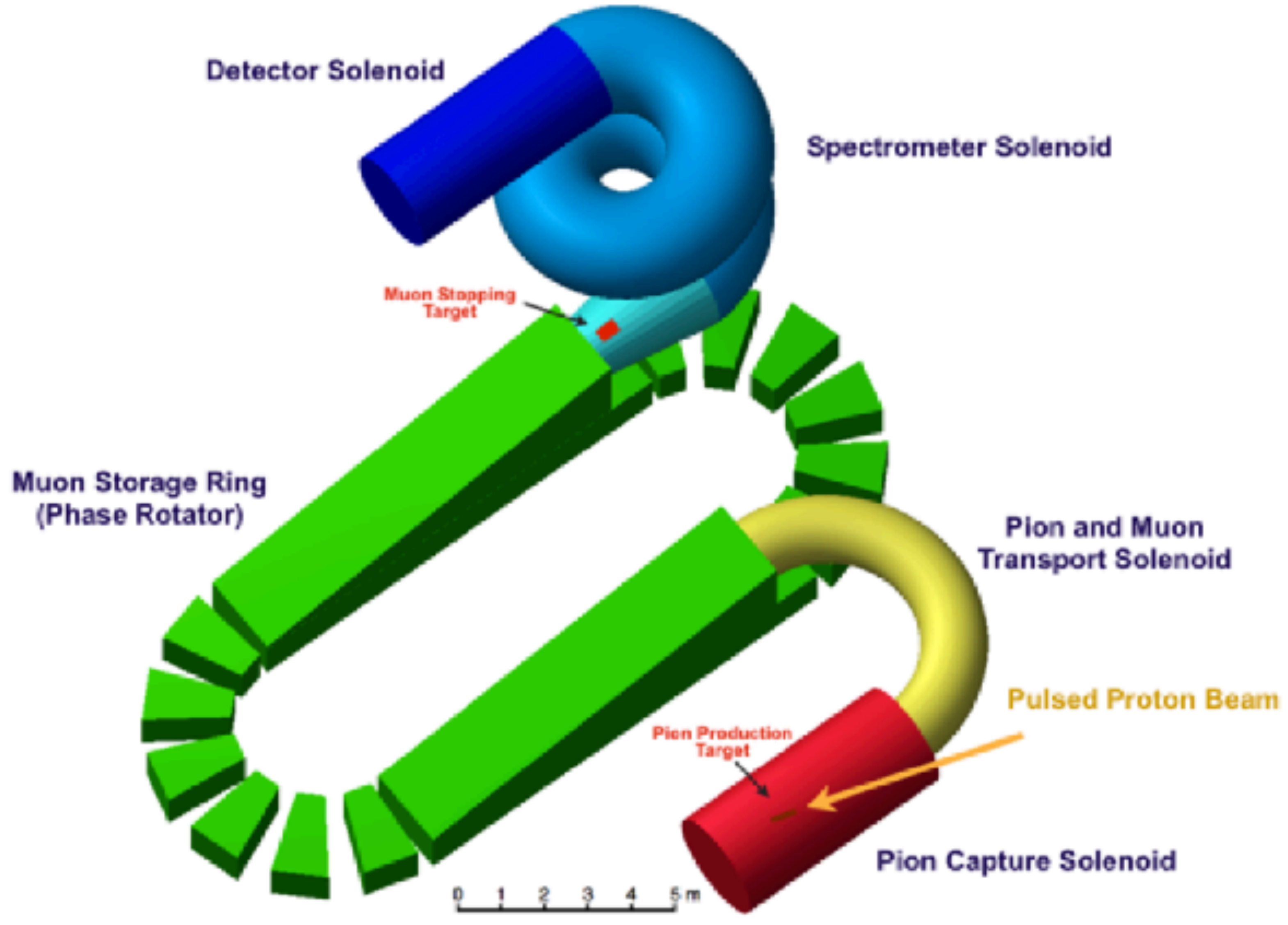




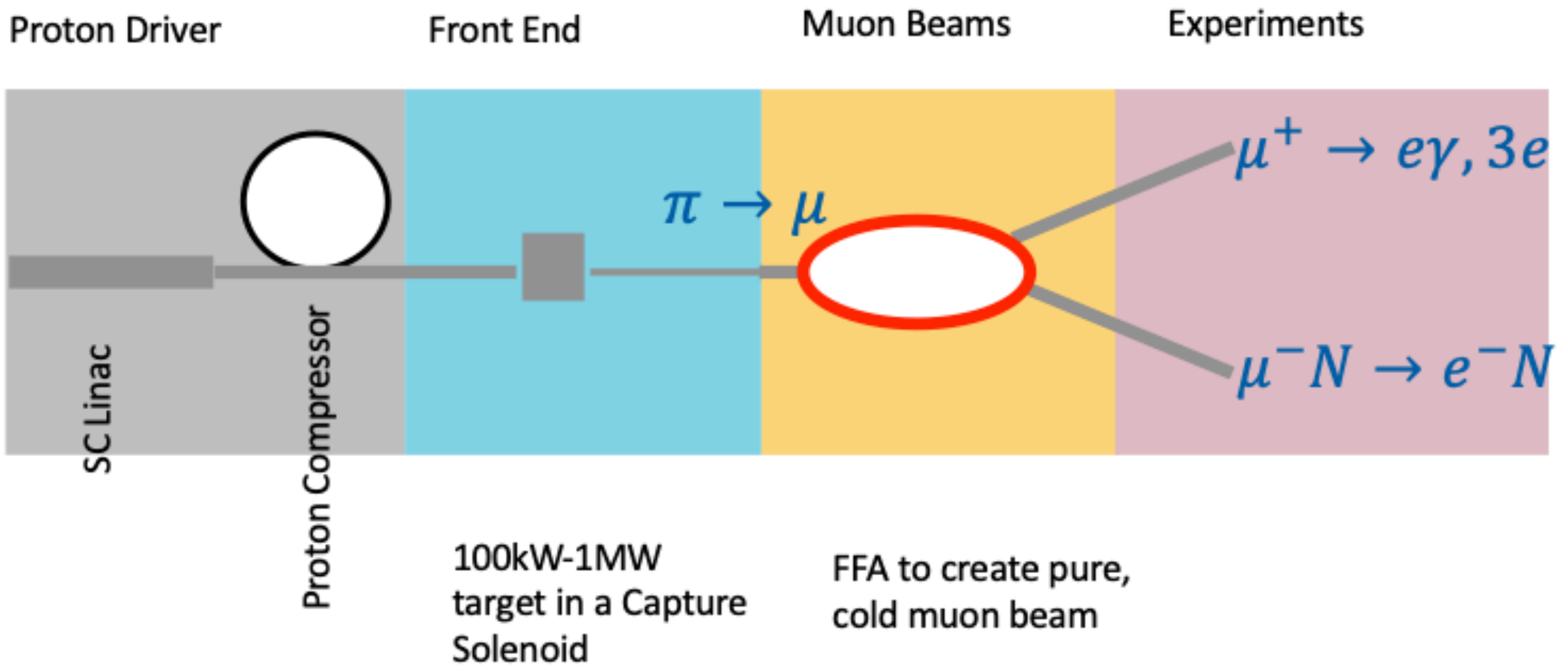


Advanced Muon Facility (AMF) at Fermilab

- Proton improvement plan (PIP-II) @ FNAL from 2029
  - Primary goal is a neutrino experiment (DUNE)
- Exploiting the full potential of the PIP-II accelerator
  - Use 800MeV p from PIP-II linac for Mu2e-II from ~2035
- AMF complex would use a fixed-field alternating gradient synchrotron (FFA)
  - Cold, intense muon beam with low momentum dispersion
- World's most intense μ^+ and μ^- beams for CLFV experiments
- AMF could also be an R&D step toward a muon collider
- Aim in the 2040s



FFA example arXiv: 1310.0804



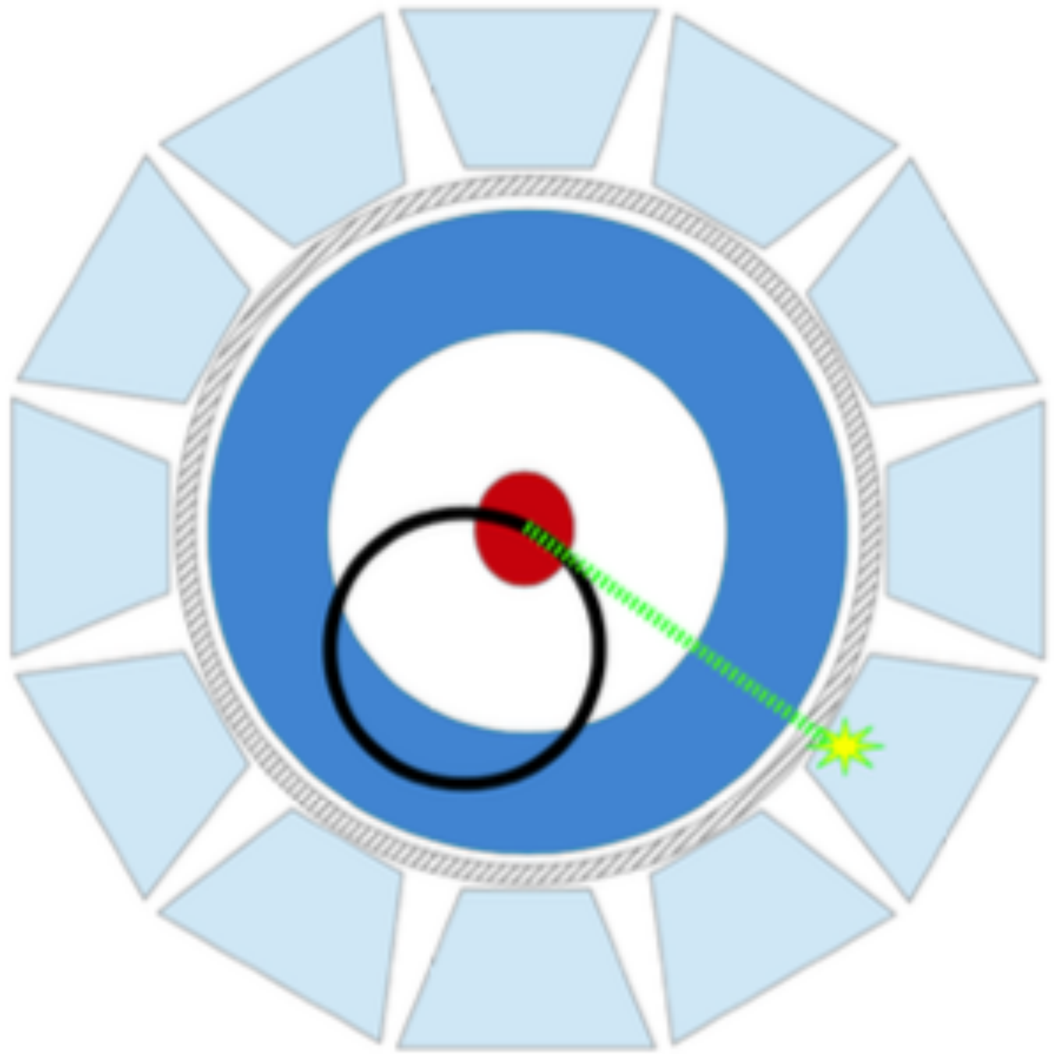
Future $\mu^+ \to e^+\gamma$

arXiv:2504.18831

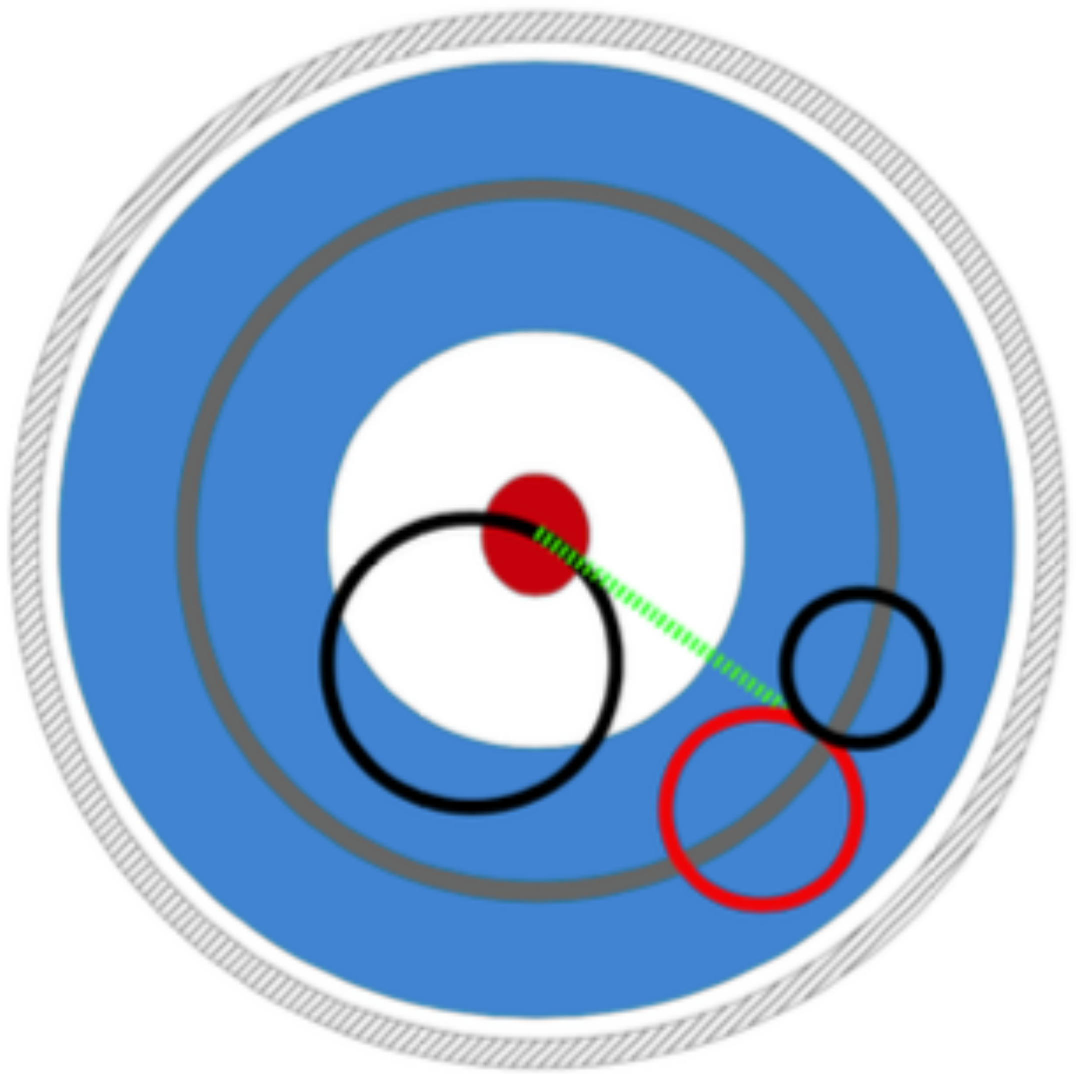
- Sensitivity of $\mu \to e\gamma$ searches is limited by the background from accidental coincidences
- Background scales with the square of the stopping muon rate, improvement in the detector resolutions inevitable to exploit beam rates up to 10^9-10^{10} μ/s
- Large acceptance to gain the statistics while beam intensity is kept as low as possible

- R&D of new detector concept (resolutions, efficiency, rate capability) is underway

Calorimeter



Photon conversion

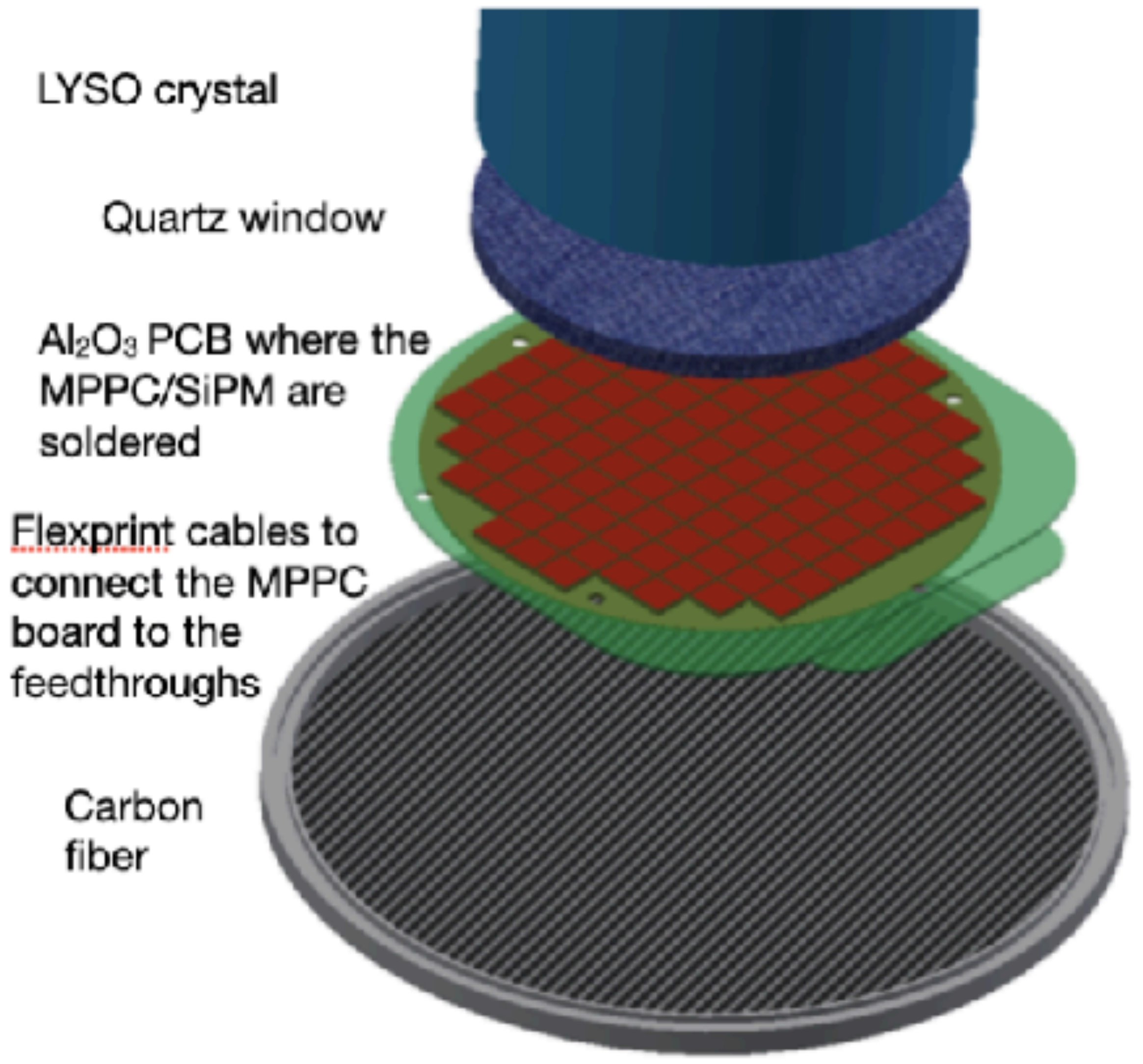


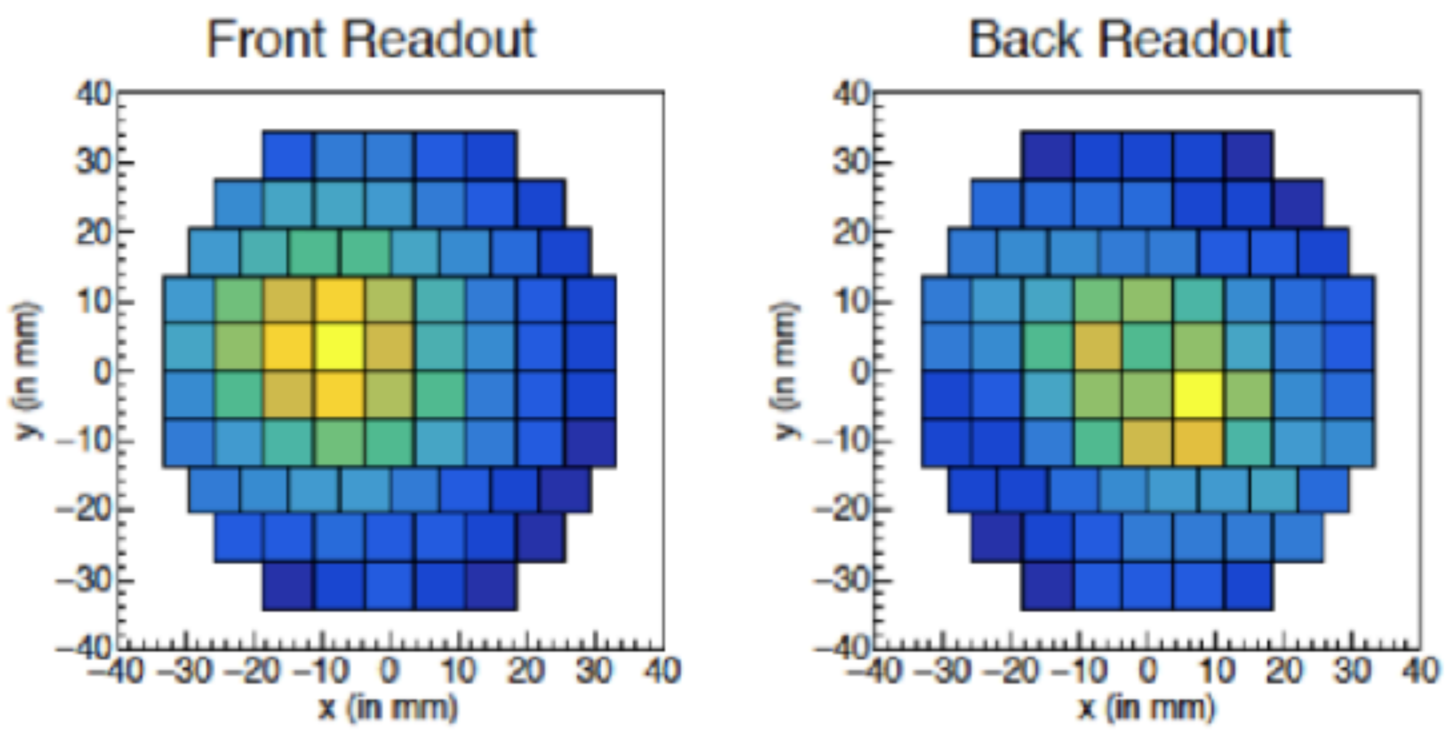
Future $\mu^+ \to e^+\gamma$

- Design: Based on photon pair spectrometer
  - Photon spectrometer with active converter: higher resolutions (energy, timing, position), angle
  - Positron spectrometer based on Si detector (like Mu3e): high rate capability
  - Separate active targets: higher vertex resolution, further BG suppression
  - Significantly improved acceptance: angular distribution measurement after discovery

Photon measurement : Calorimeter

- Two promising materials
  - LaBr3(Ce) and LYSO with SiPM readout
- Limiting factor could be capability of growing large crystals and their cost
  - Interesting option for an intermediate phase in a staged approach

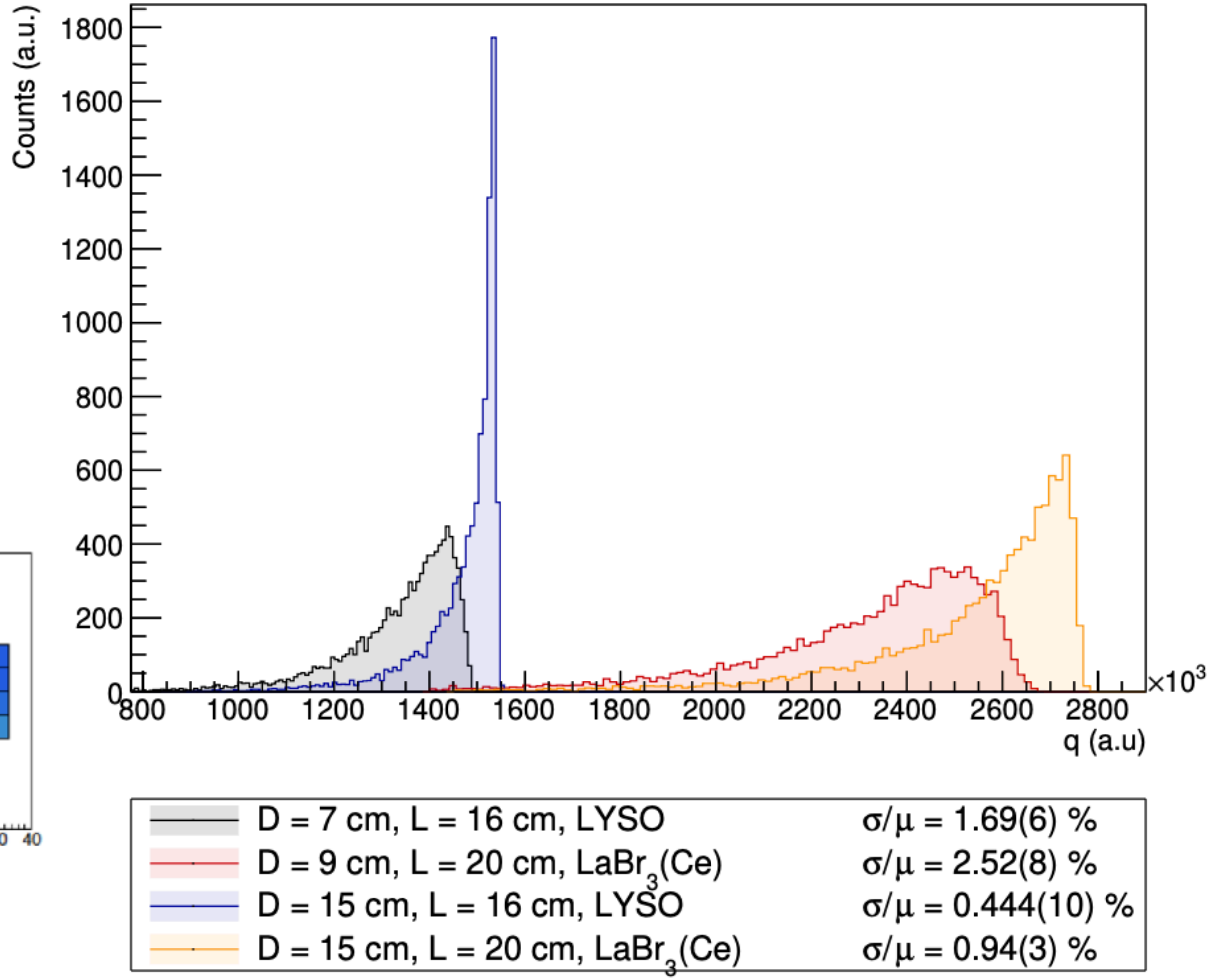




(a) Hit in Central Region: $(x, y) = (-10\,\mathrm{mm}, 3\,\mathrm{mm})$

Expected performances:

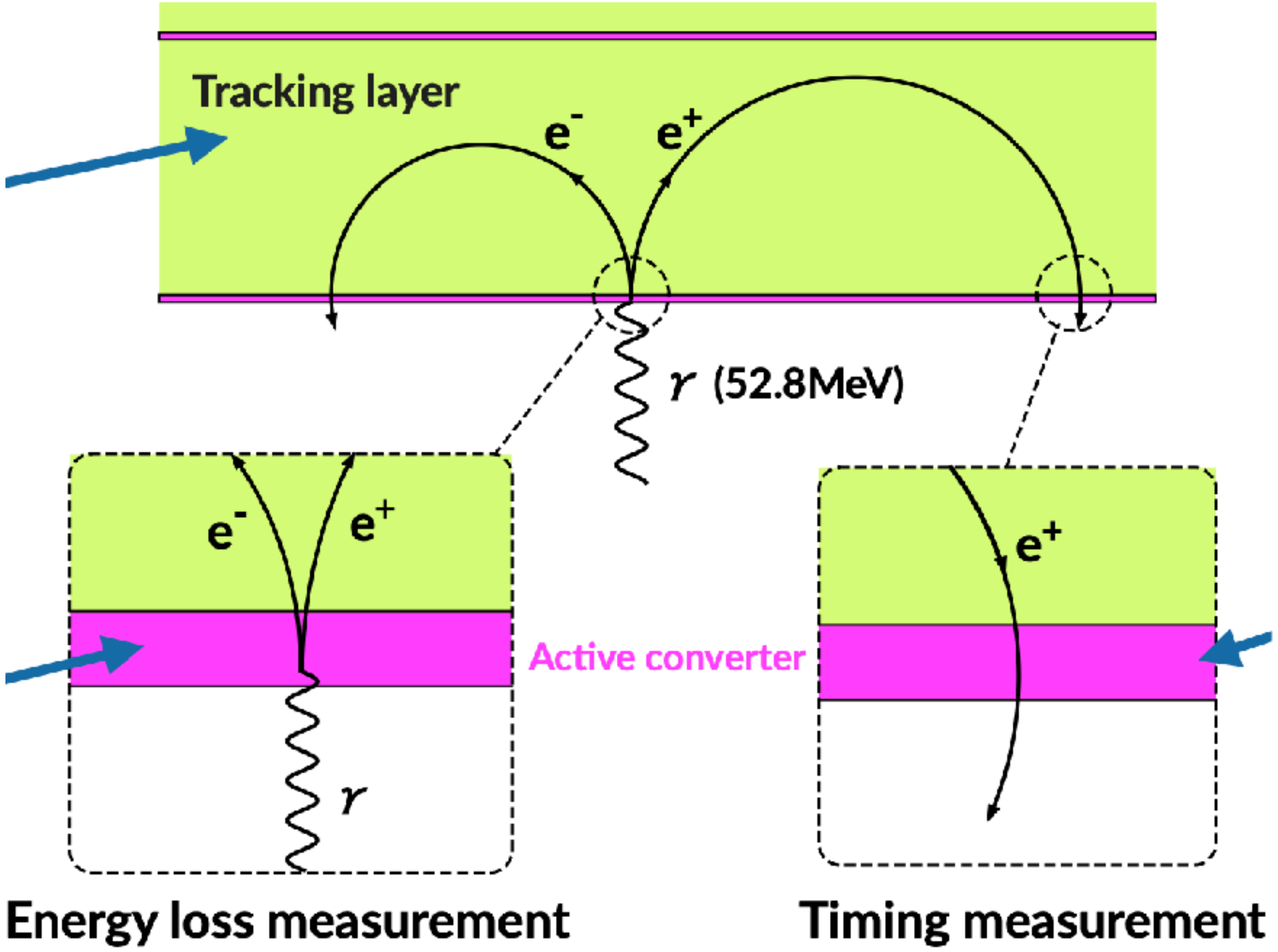
- σ_e/E [%] = 1.7(1)
- σ_t [ps] = 35(1)
- $\sigma_{tx,y,z}$ [mm] = 3-5



Photon measurement: Pair Spectrometer with Active Converter

Baseline option for photon measurement

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



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

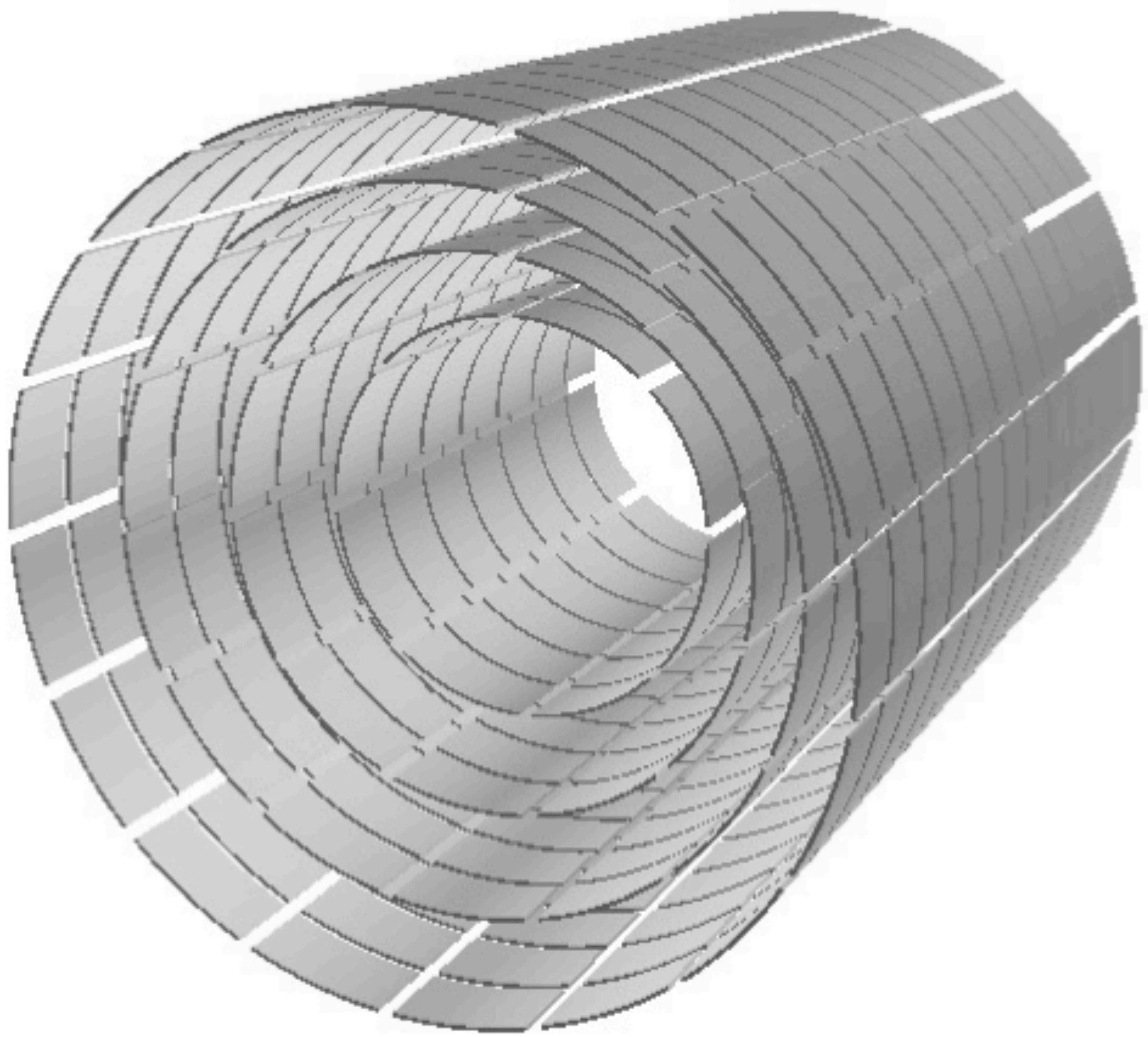
- Active converter
  - A layer of dense material to convert photons into e^+e^- pairs
  - Scintillator+SiPM
  - Silicon detector

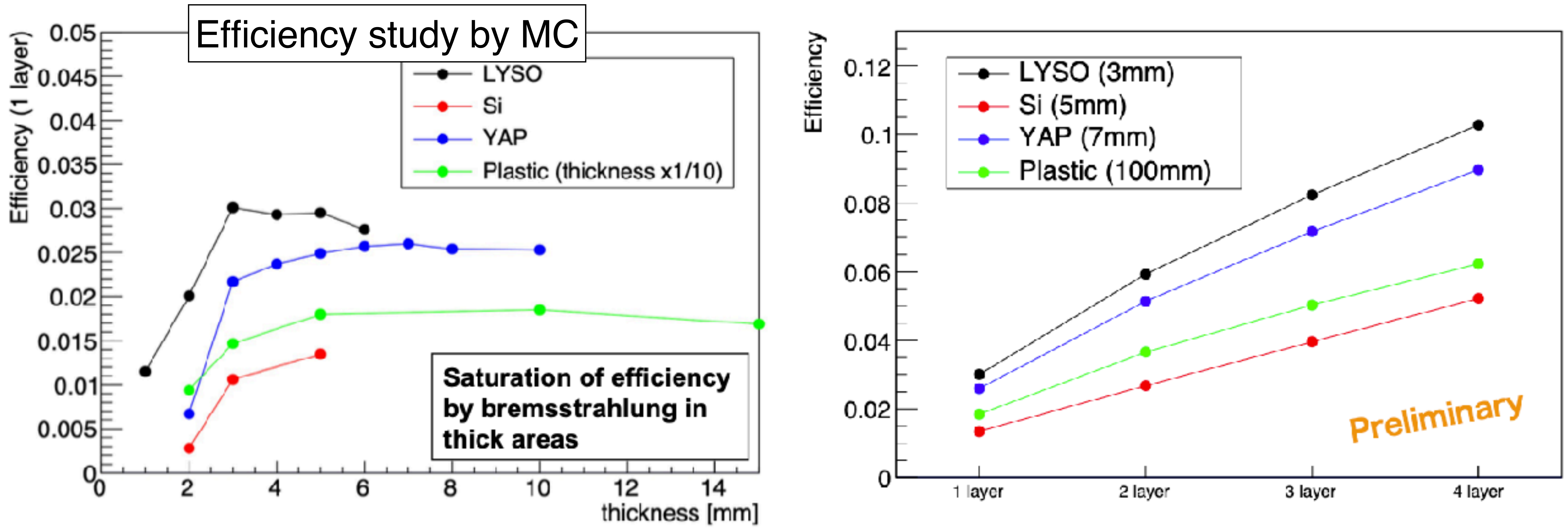
Target performance: $\sigma_E/E = 0.4\,\%\,, \sigma_t = 30ps, \sigma_x = 0.2mm$

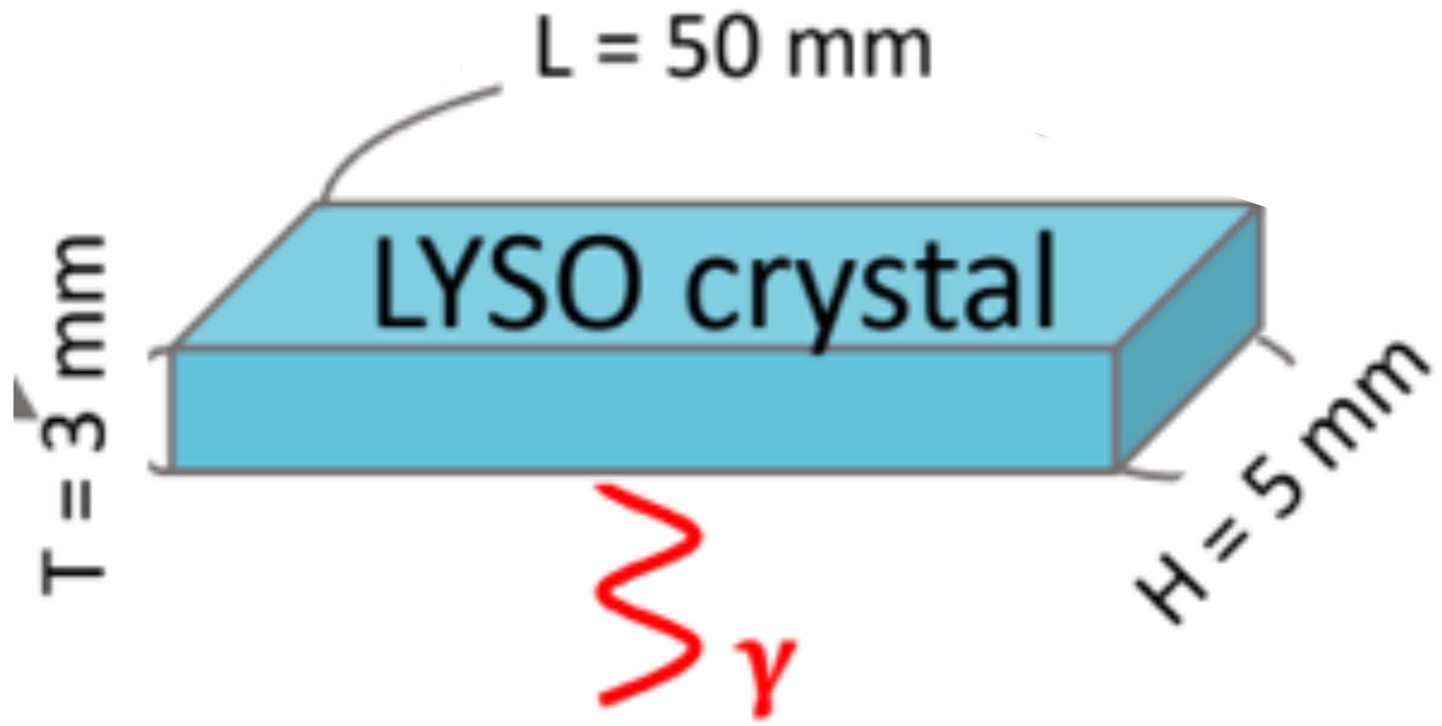
(MEG II : $\sigma_E/E = 1.8\,\%\,, \sigma_t = 65ps, \sigma_x = 2.5mm$)

Current R&D

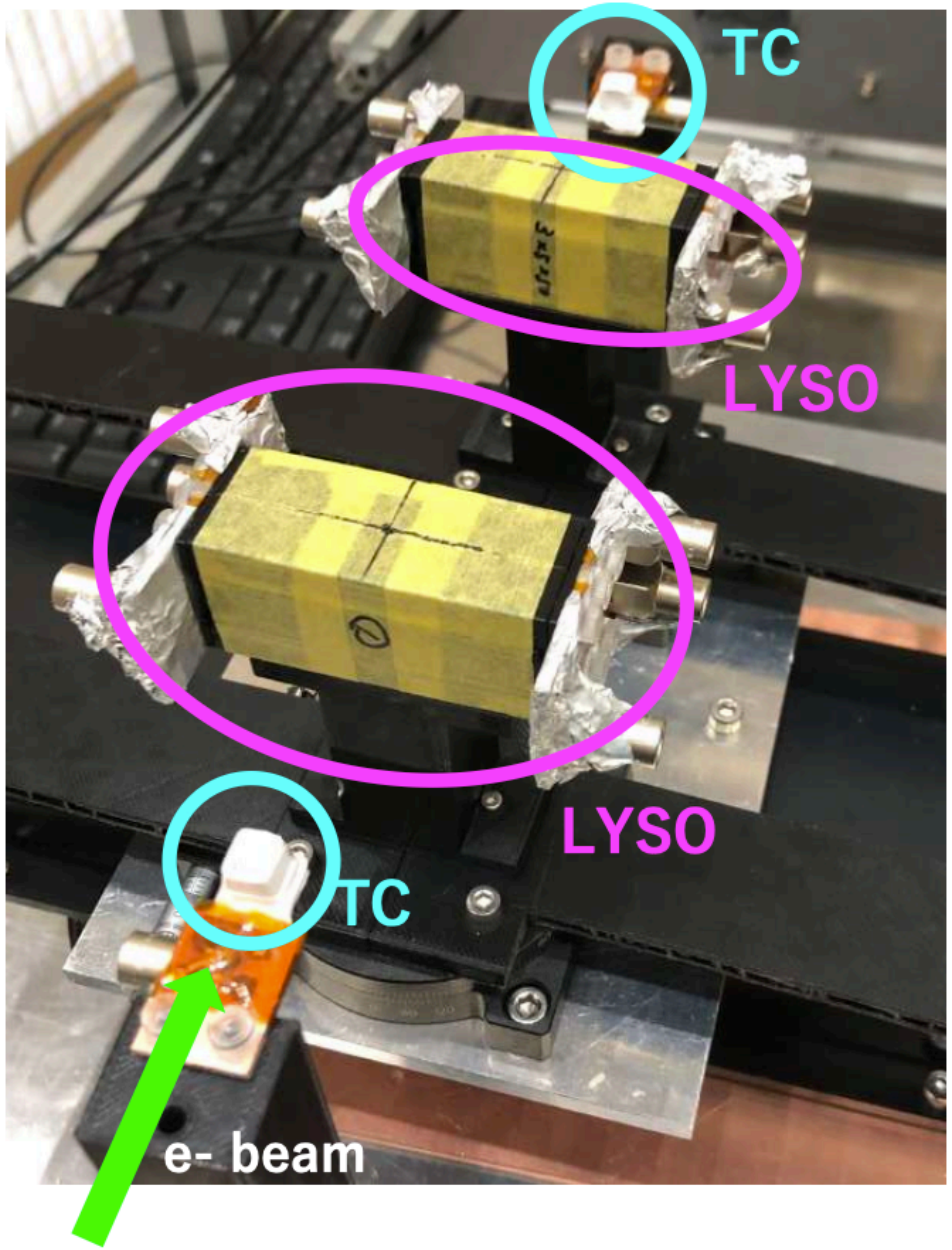
- Active converter material and size are evaluated by Simulation study

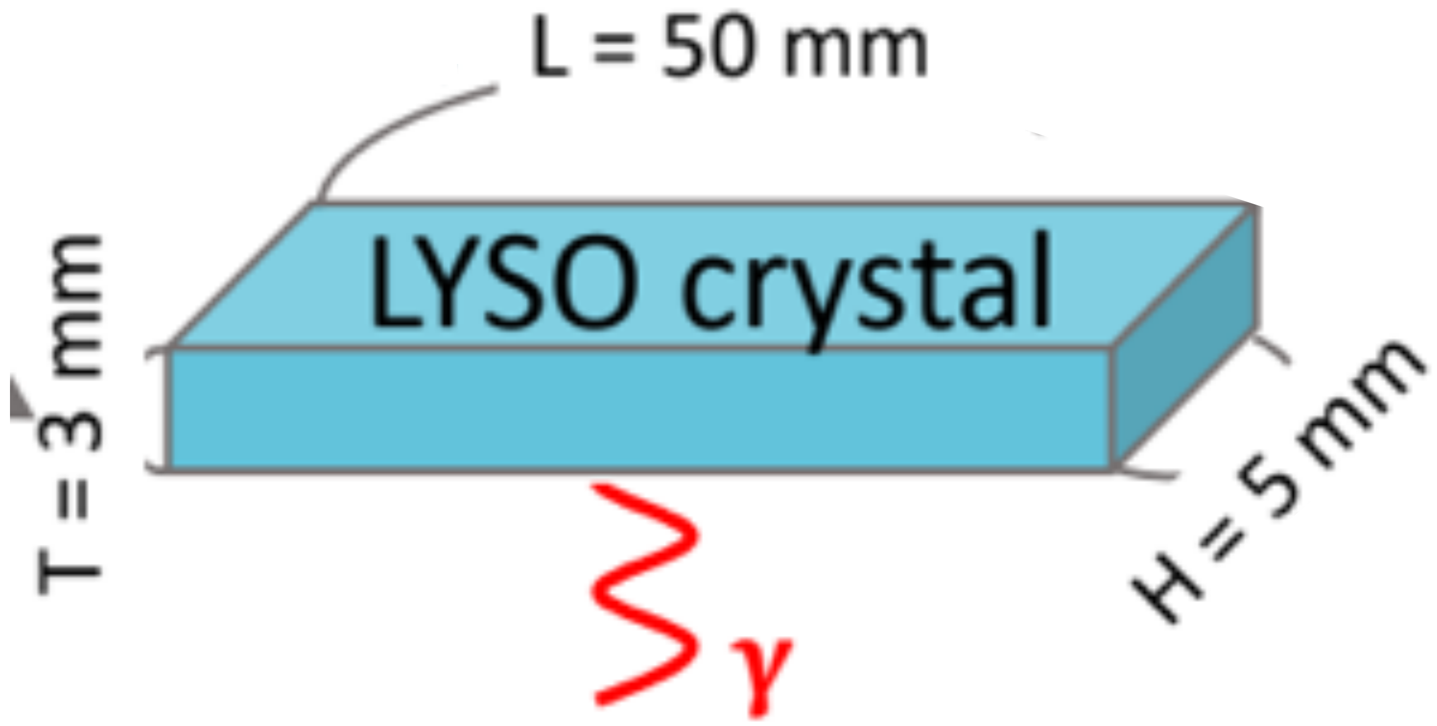


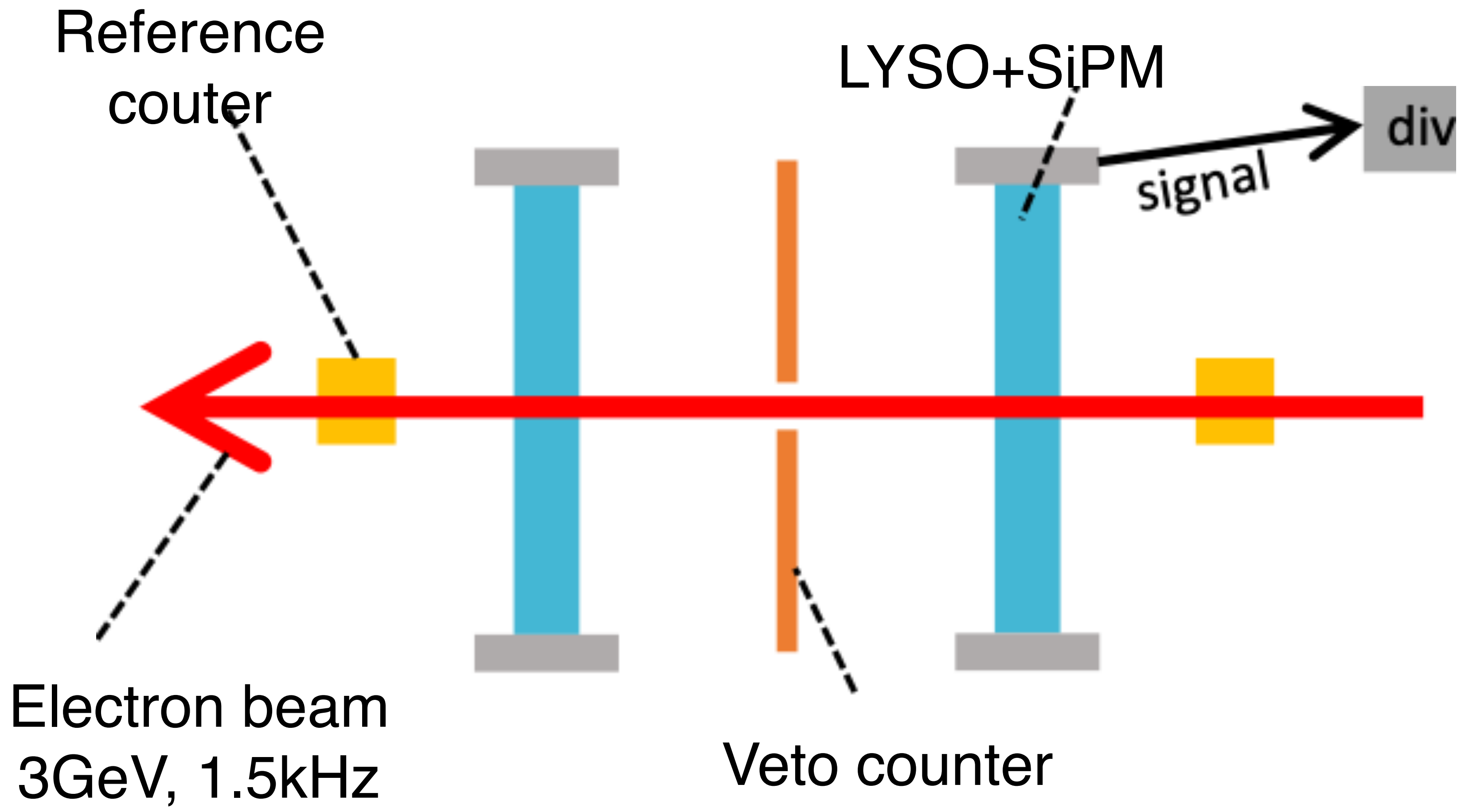


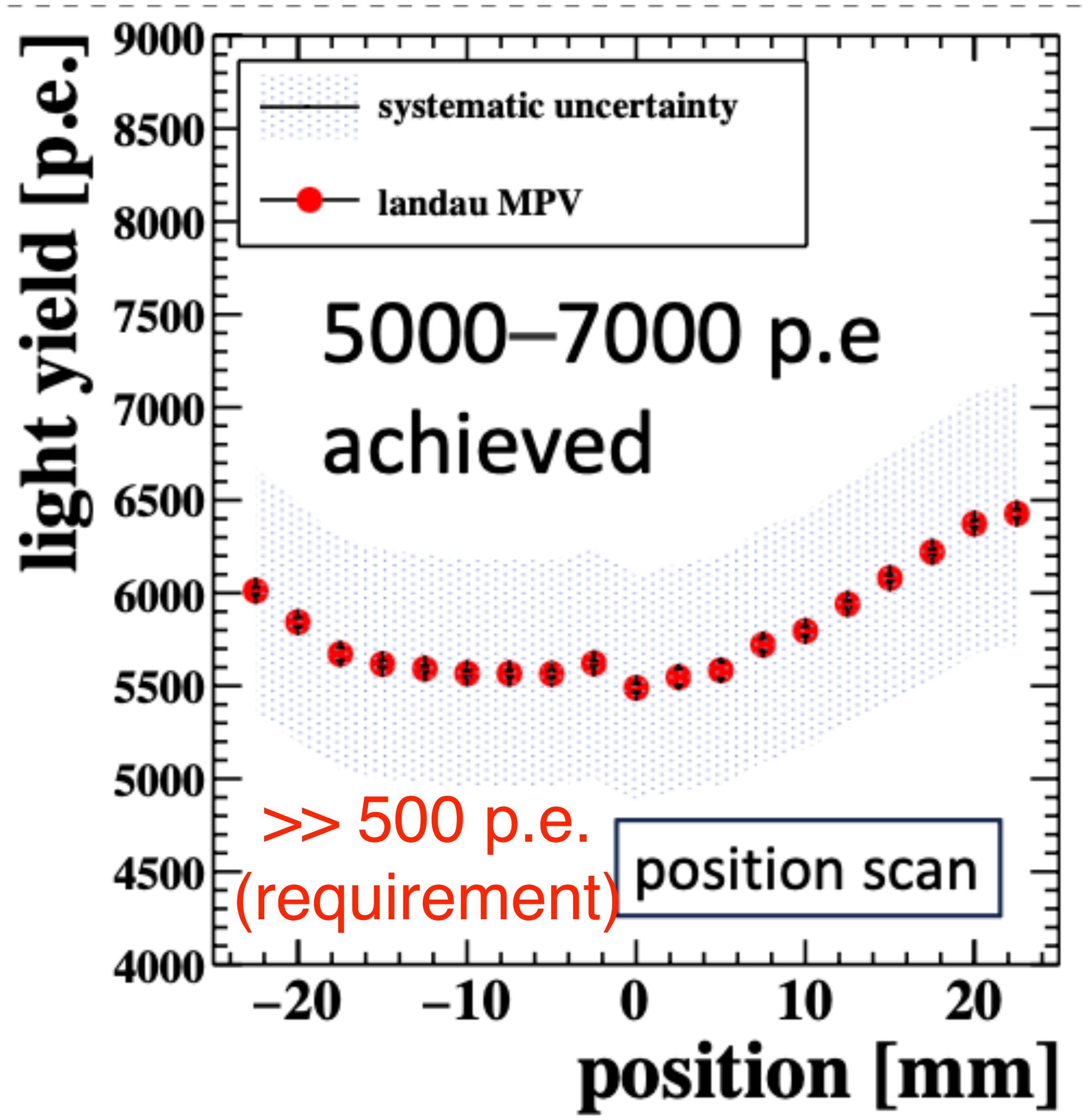


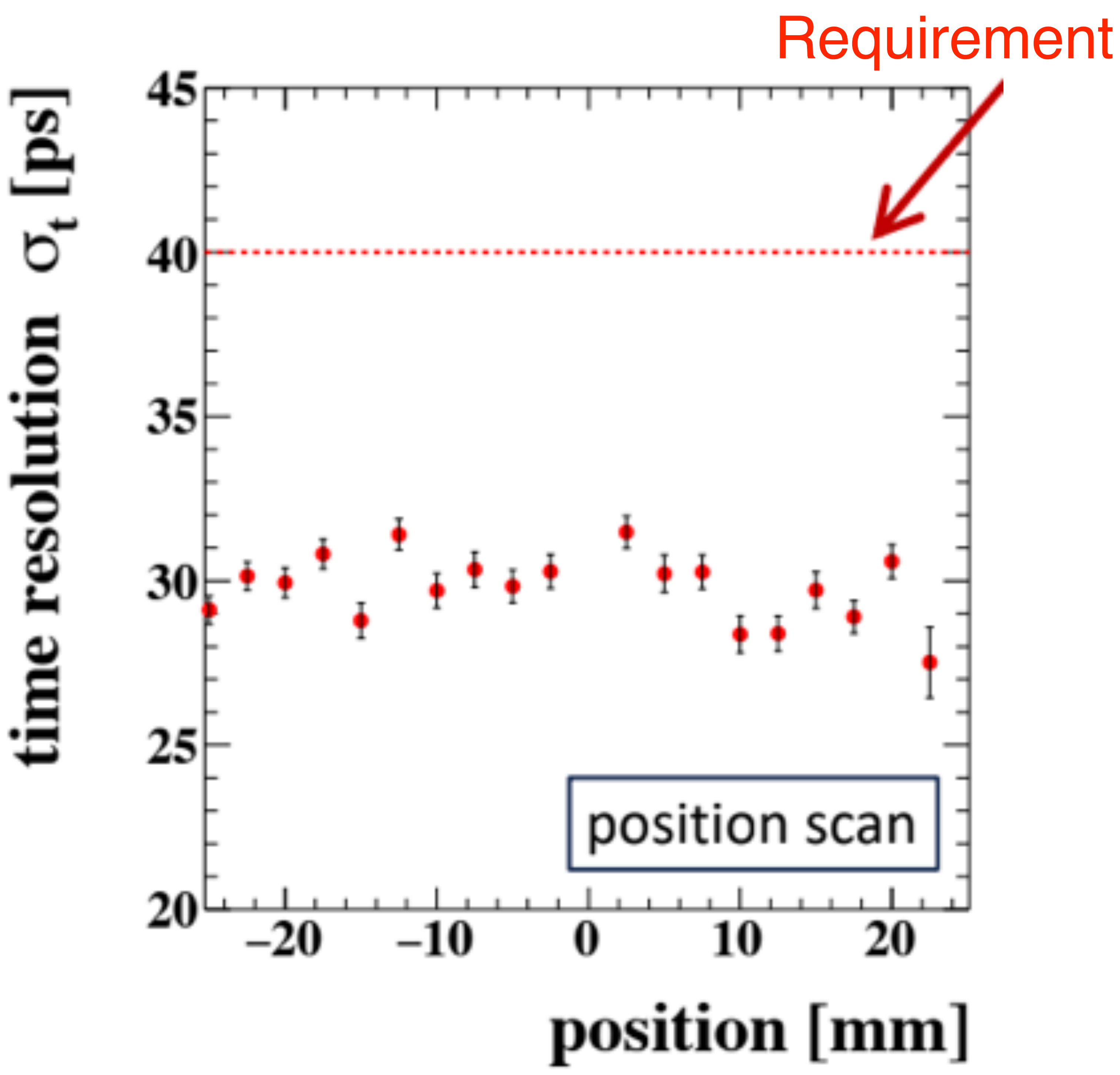
Active converter prototype beam test





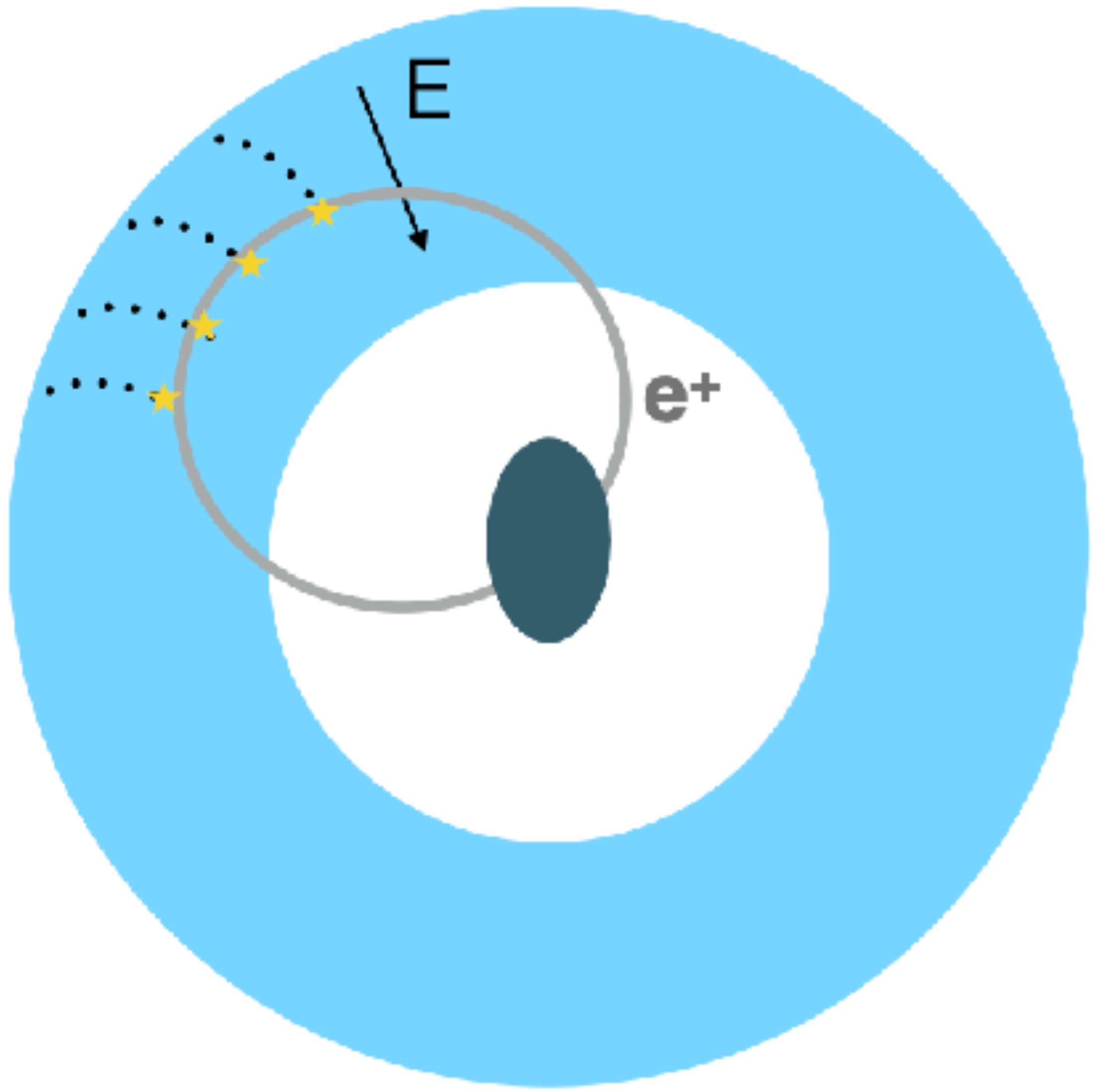


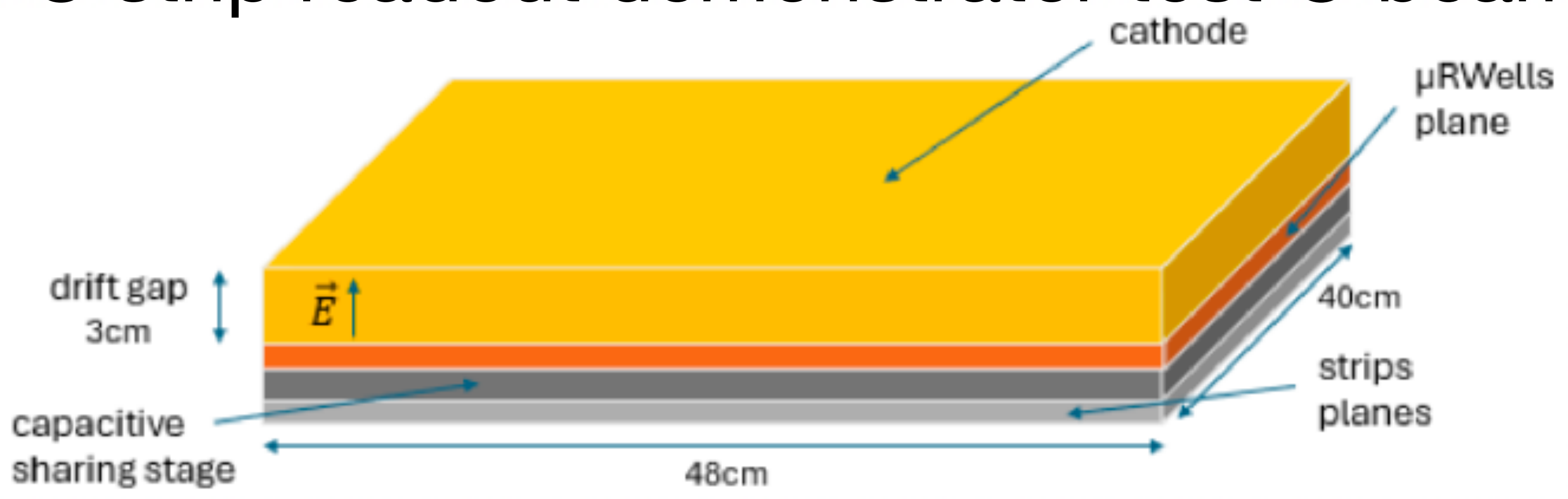


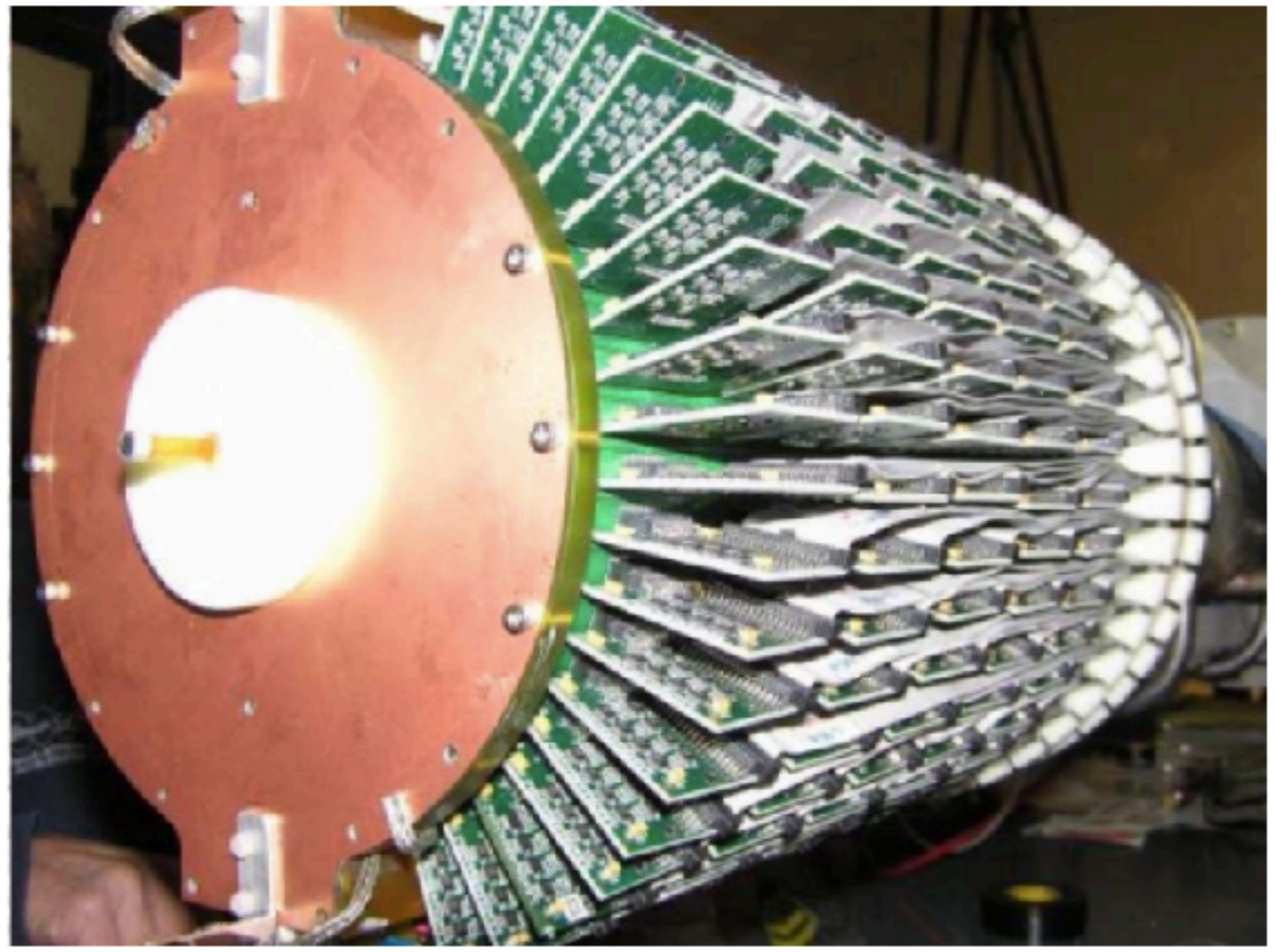


e^+e^- tracker for reconstruction of converted photons

- Silicon tracker
  - surely satisfies the performance requirements
  - O(10m2/conv. layer) → can be expensive
- Drift chamber
  - stereo geometry needed → acceptance limited
  - granularity limited by cell size → difficult for low p
- Time projection chamber
  - overcomes limitations of a drift chamber
  - requires a light gas mixture
  - Drift cannot be along beam → radial TPC
  - Limited space for readout electronics
  - TPC strip readout demonstrator test @ beam





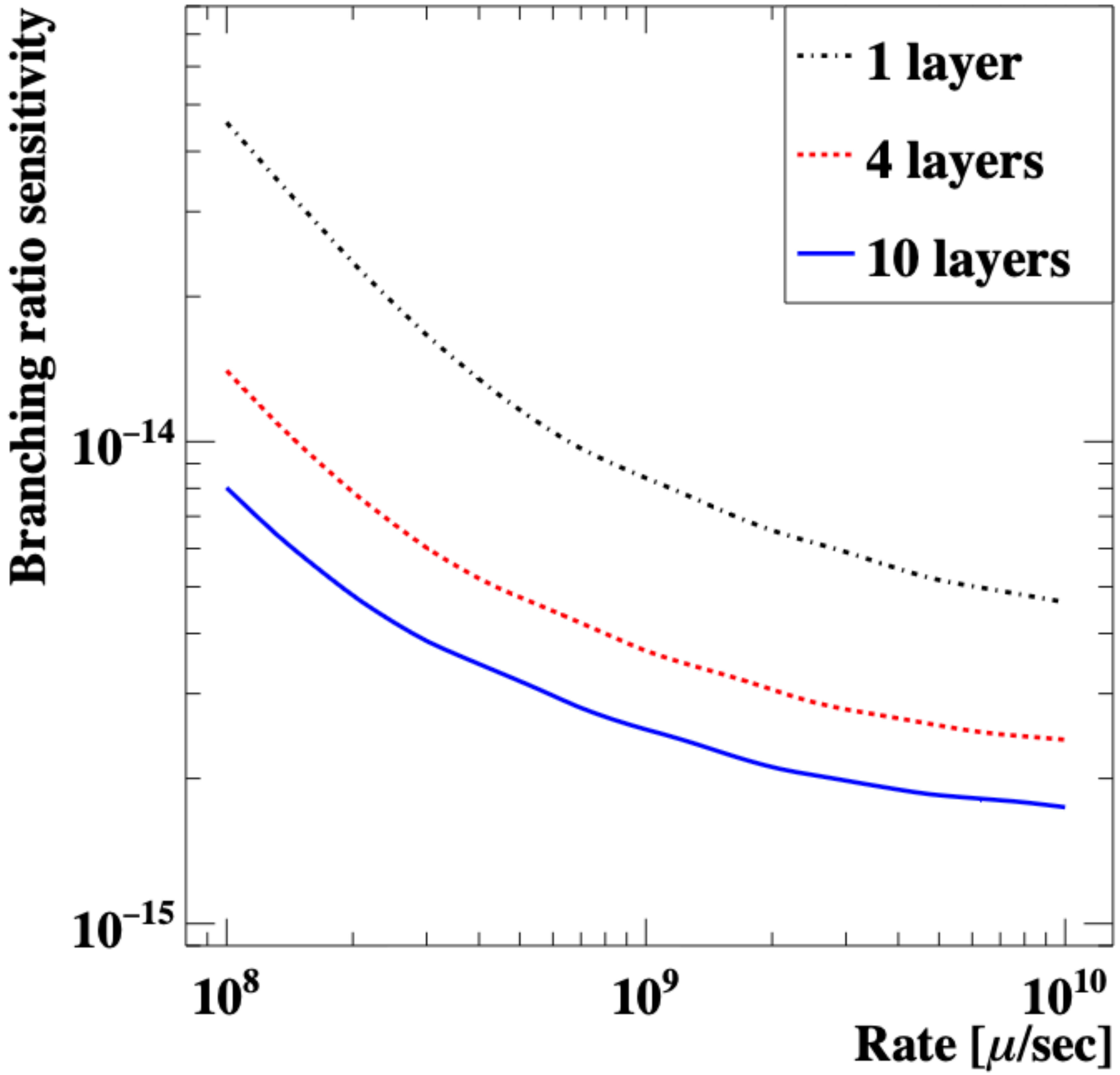


BONuS radial TPC @ J-LAB

Sensitivity for future $\mu^+ \to e^+\gamma$

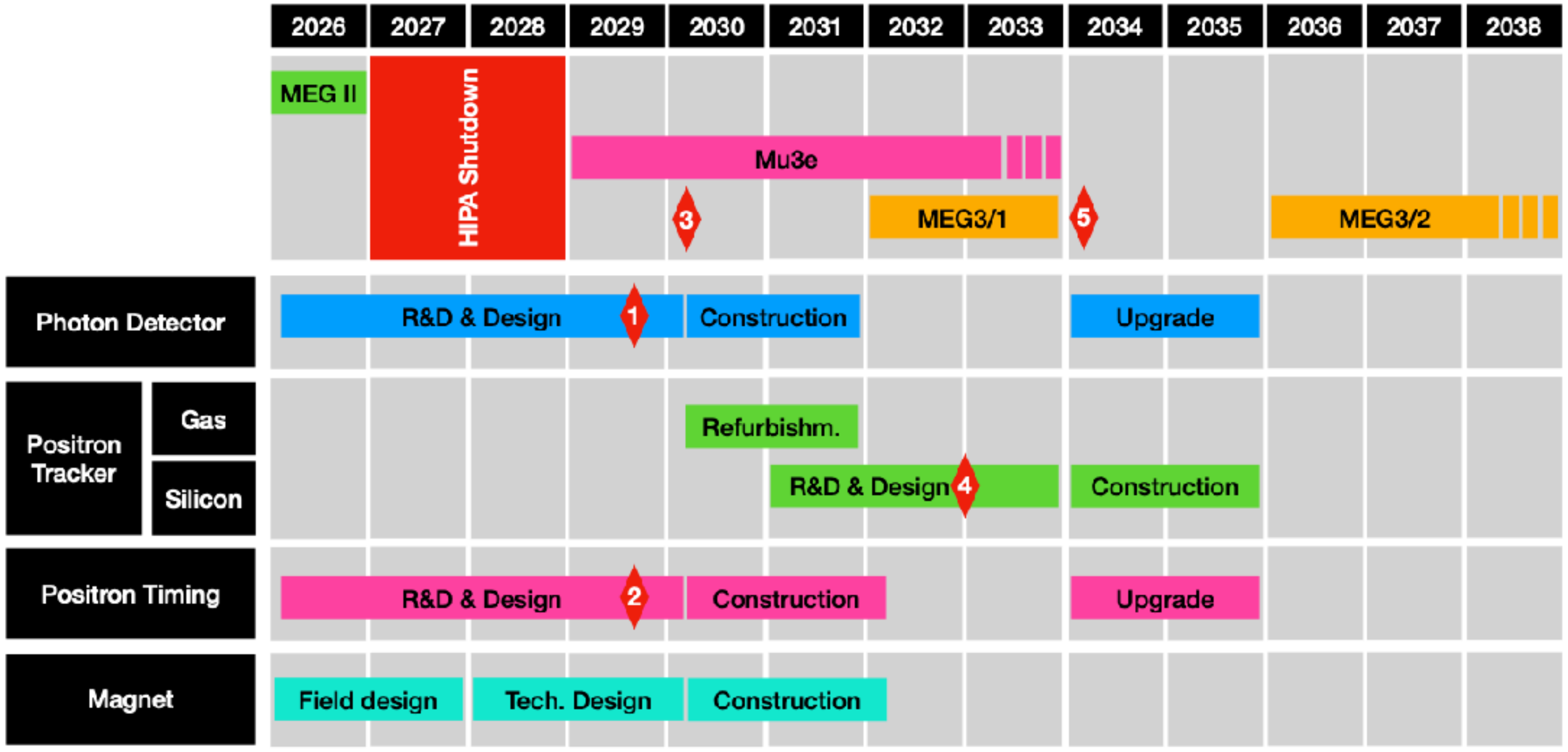
- Assumption
  - Five separate stopping targets
  - Detector performance in a table below
- (2–3) $\times 10^{-15}$ are reachable above $10^9 \mu^+$/s

	Resolutions/efficiencies		MEG II
Photon energy	200 keV	0.4%	2%
Photon position	200 µm		2.5mm
Photon timing	30 ps		65ps
Photon angle	150 mrad		— —
Photon detection efficiency (4 layers)	6 %		62%
Positron energy	100 keV		100 keV
Positron angle	6 mrad		6 mrad
Positron timing	30 ps		30 ps
Positron detection efficiency	70 %		67%
Geometrical acceptance	85 %		11%



Future $\mu^+ \to e^+\gamma$ Schedule

- Staged approach
- Phase-I
  - Proof of principle of the conversion technique
    - CEX 55MeV γ with converter+tracker in COBRA
  - Running at 10^8 μ^+/s, sensitivity of a few 10^{-14} (possible in PiE5)
- Phase-II
  - New silicon positron tracker
  - Construction after the completion of Mu3e at HIMB
  - Experiment in the second half of the next decade



◆1: Photon converter proof of principle (CEX with converter + tracker in the MEG COBRA magnet)

◆2: Decision about positron timing technology

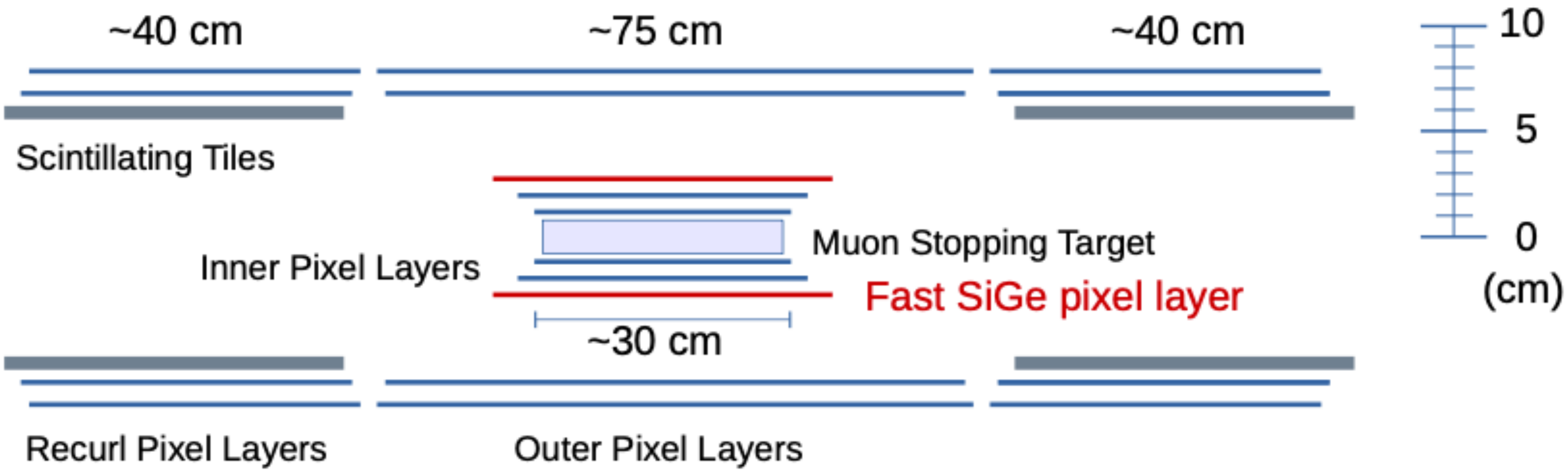
◆3: phase-I approval by PSI and funding agencies

◆4: Decision about positron tracker technology for phase-II

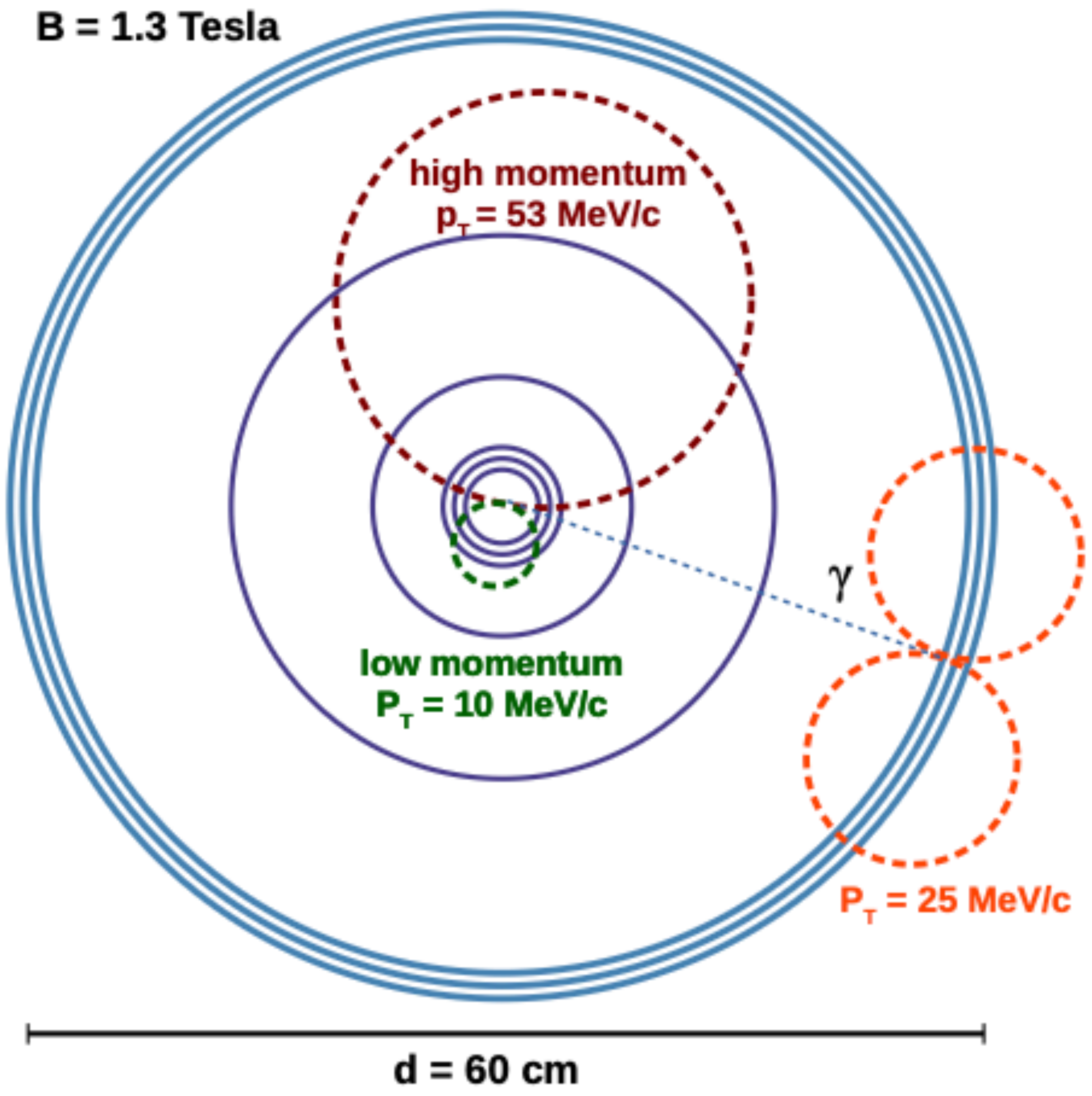
◆5: phase-II approval by PSI and funding agencies

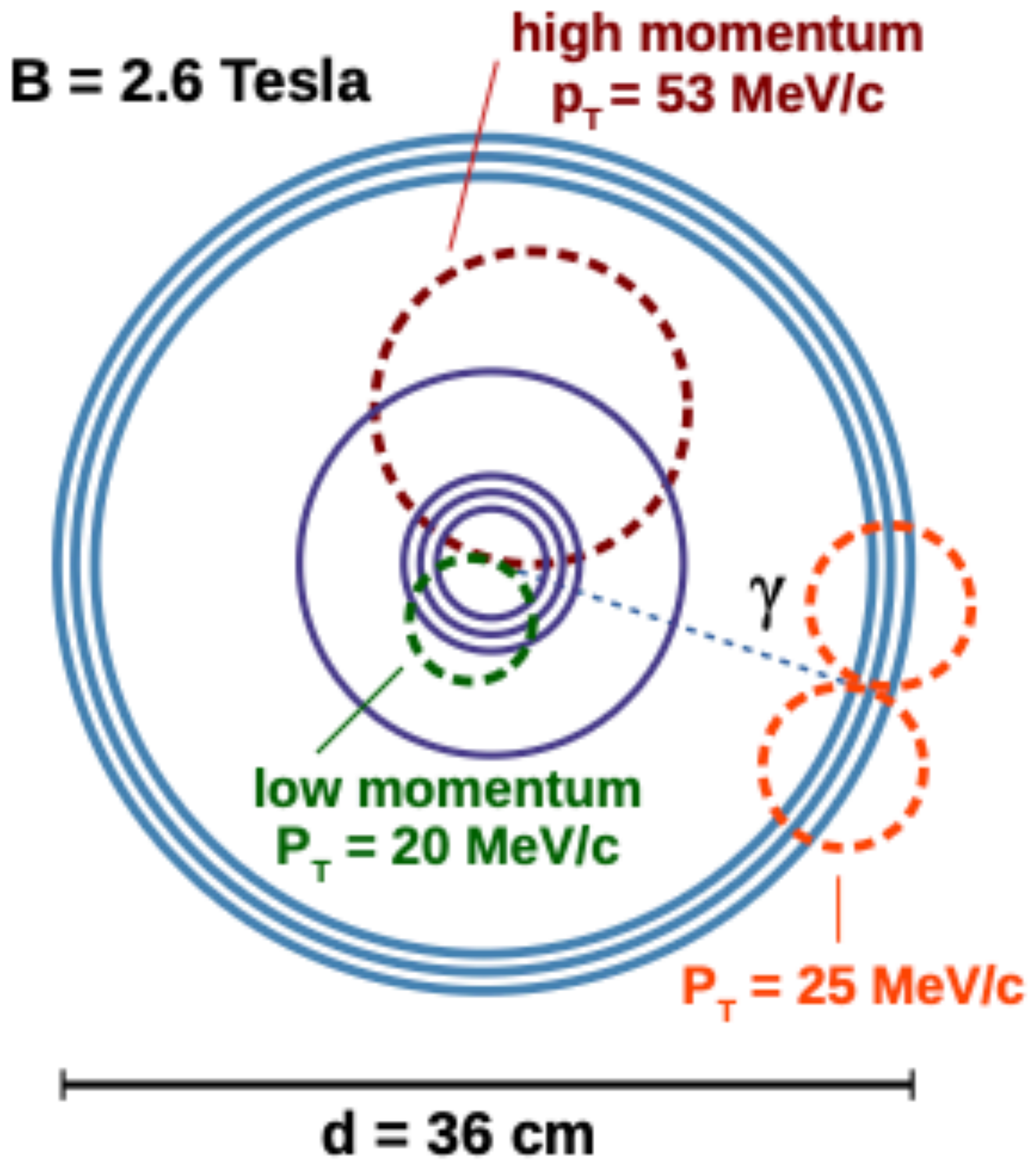
Mu3e phase II

- Extension of the muon-stopping target, reduction of the material in the stopping target region and the first tracking layer, further improving the time and vertex resolution of HVMAPS
- HVMAPS with even smaller thickness and smaller pixel sizes, with 100 ps time resolution
- Muon stopping rates of ~ 2×10^9/s in HiMB, Magnetic field to 2 T
- Start in the early 2030s, ultimate sensitivity of B(mu->3e) ~ 10^{-16} after three years of operation



Future $\mu \to e\gamma$ + Mu3e ?



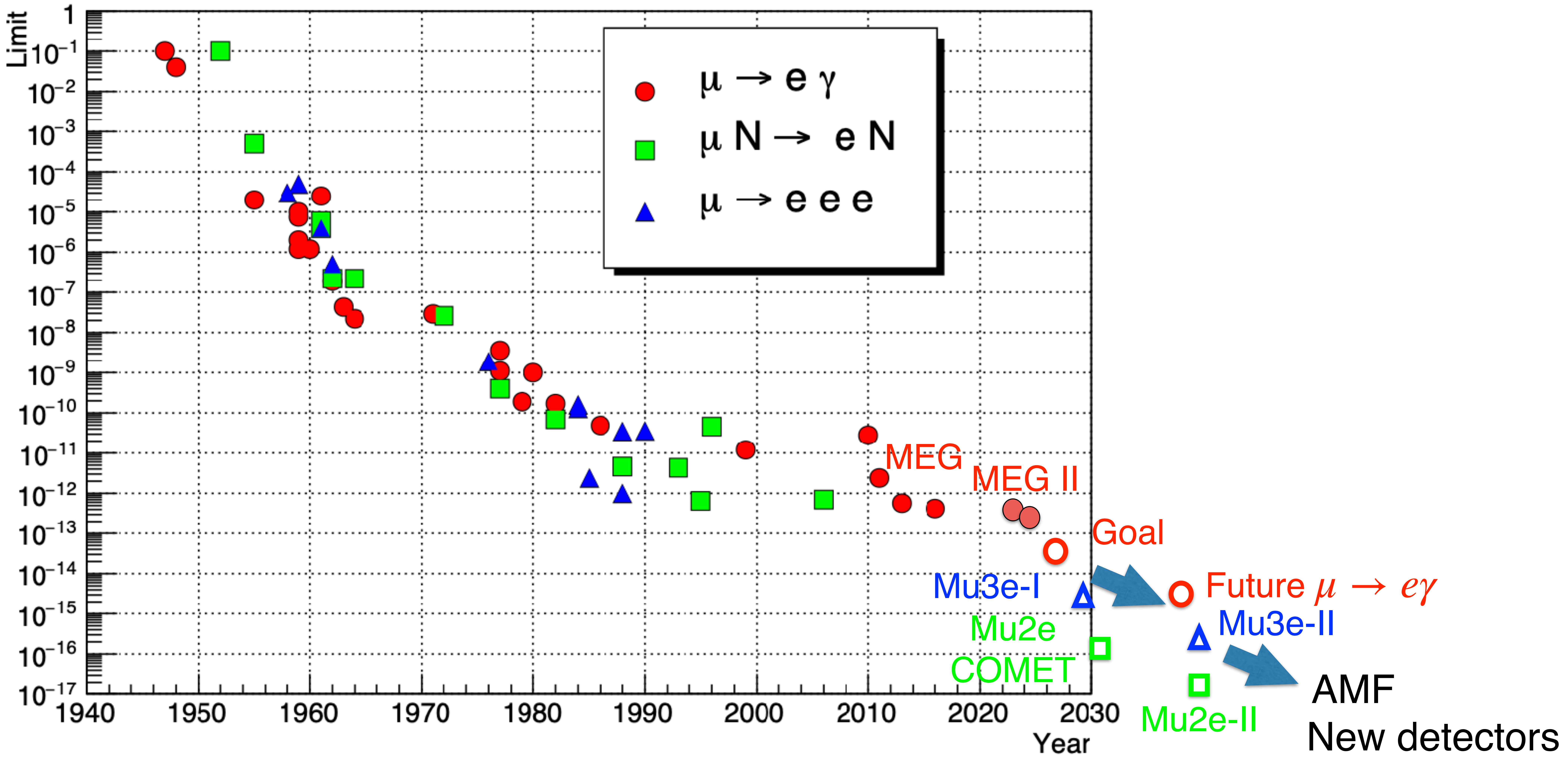


Open discussions on designs and technologies for future experiments. Currently the study group are mostly from MEG II and Mu3e, but always welcoming new participants

Mu2e-II

- Upgrade of the Mu2e experiment
  - If Mu2e discovers CLFV in aluminum, Mu2e-II can measure with different target materials to pin down NP parameters
  - If Mu2e does not find a signal, repeat the measurement to push limits even further
  - An order of magnitude improvement in sensitivity over Mu2e with 5y of data taking
- Reuse as many components of Mu2e as possible
- PIP-II baseline to provide ~100kW protons (8kW for Mu2e)
- Challenges (rates, radiation, resolution)
  - Design a target for very high heat and rad loads
  - Replace bronze heat and radiation shield with tungsten shield
  - R&D for tracker, calorimeter, cosmic ray veto
- Can act as a bridge to Advanced Muon Facility

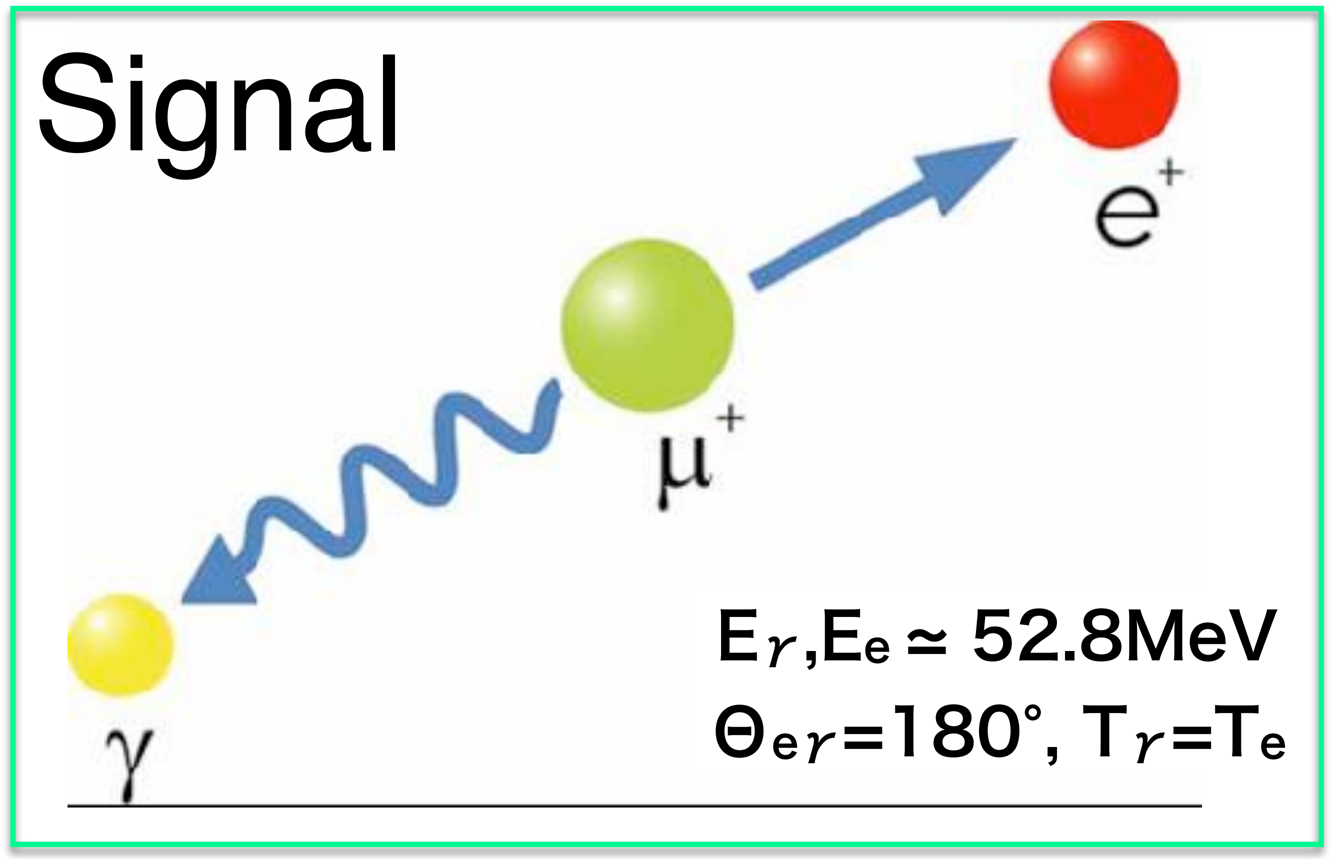
cLFV search prospects

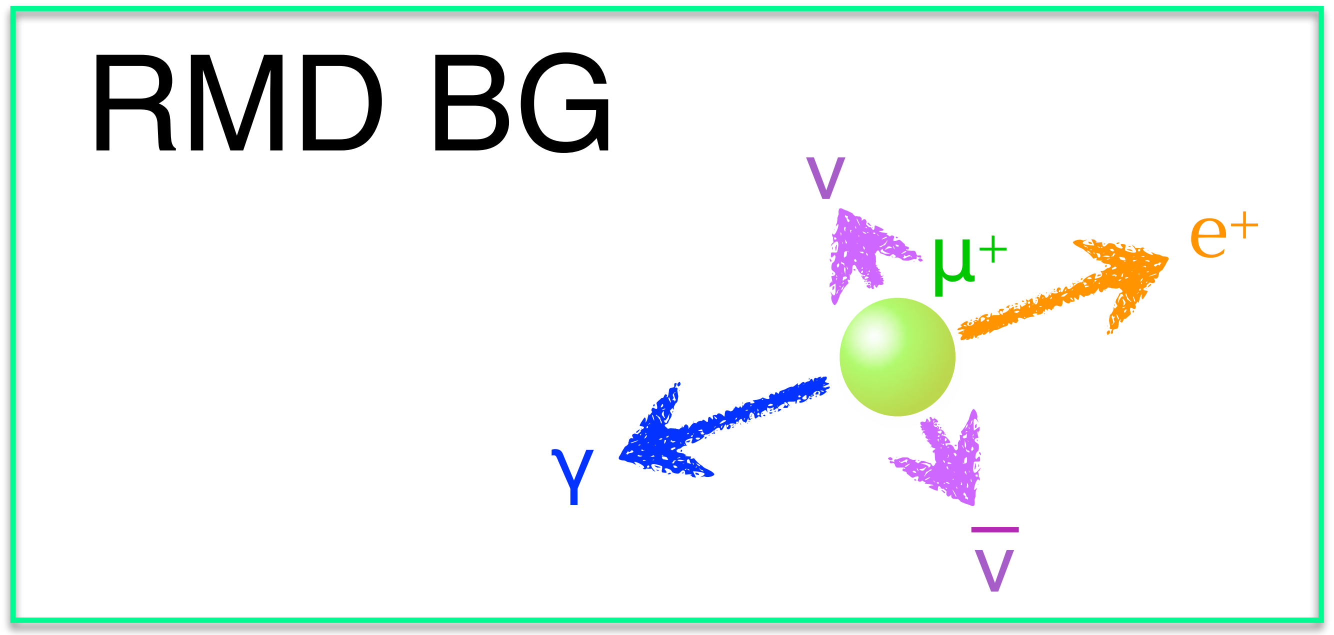


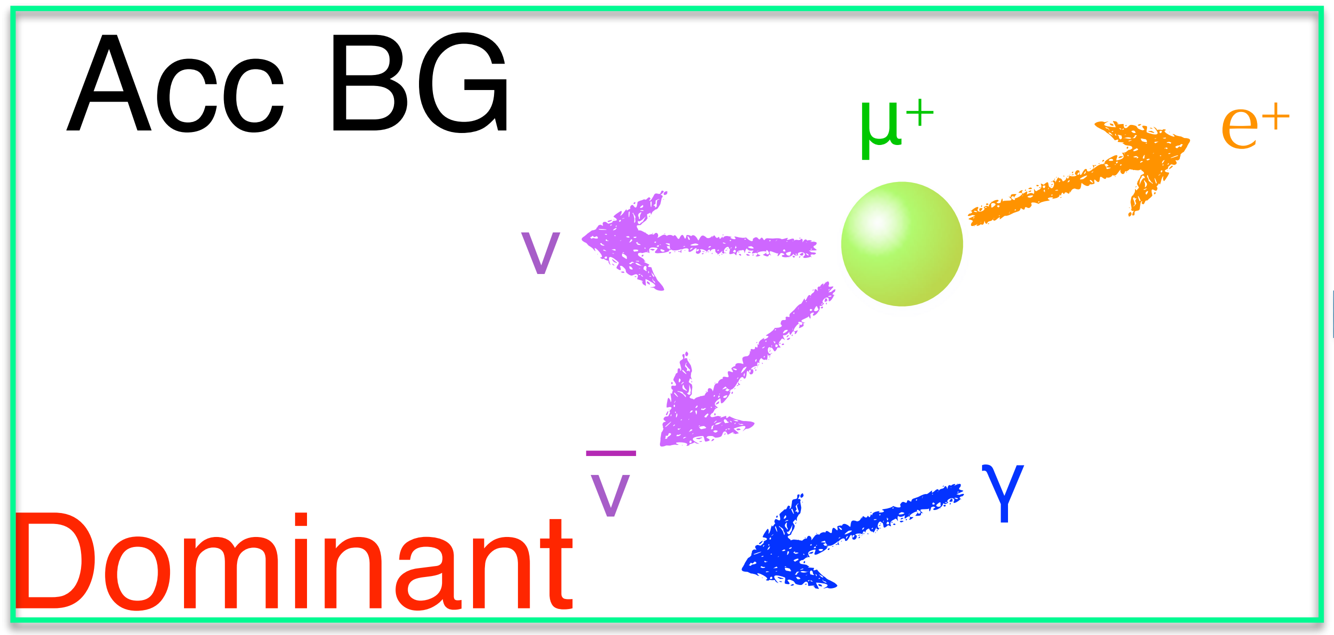
Summary

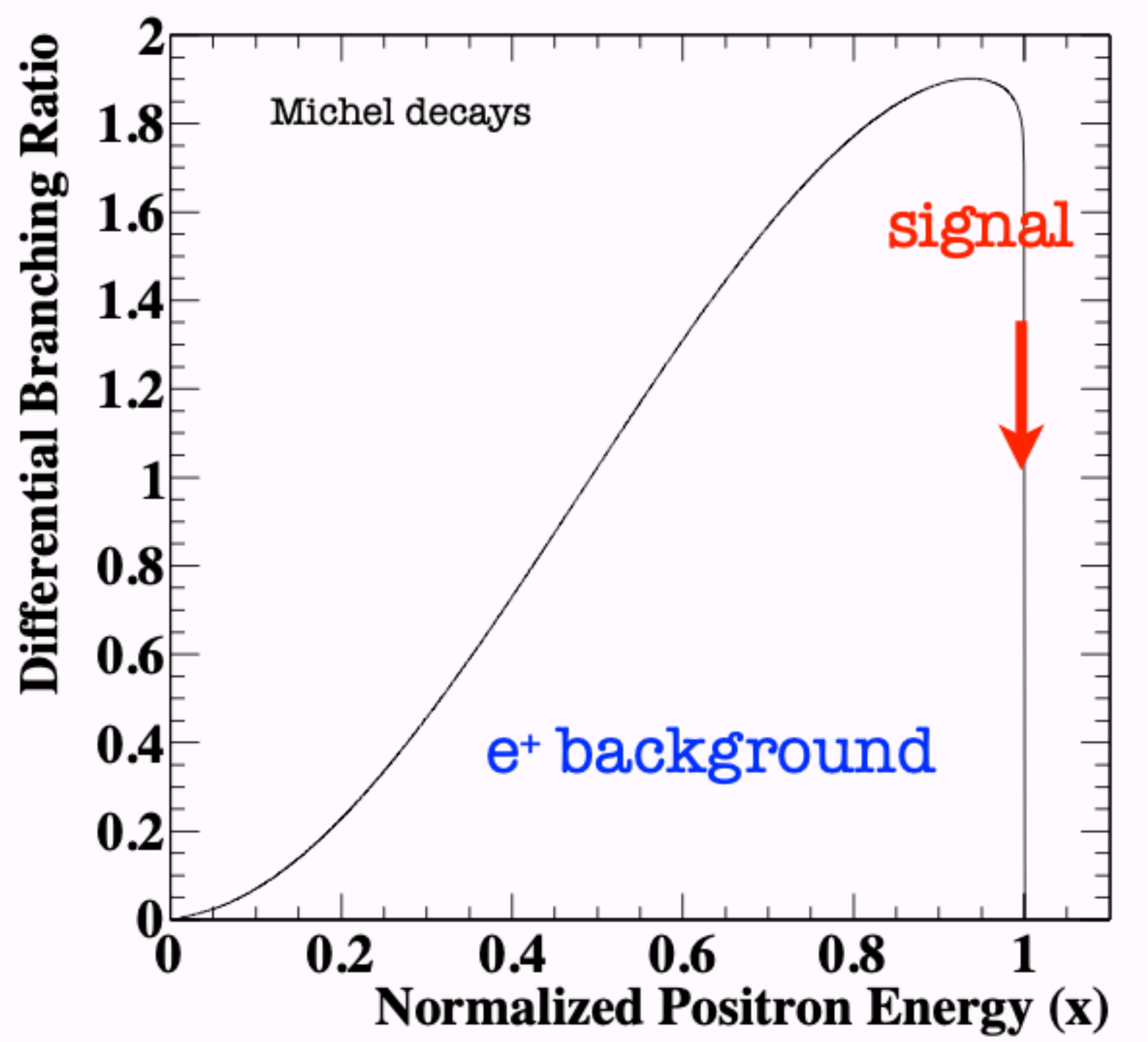
- CLFV experiment is one of the most powerful probe to search for new physics, and the golden channels ($\mu^+ \to e^+\gamma$, $\mu \to e^+e^-e^+$, $\mu^- \to e^-$) can be complementary in searching for and pinning down the new physics
- MEG II experiment is the running experiment. Mu3e, COMET phase-I, and Mu2e Run1 will start soon, and new outputs will emerge in a decade.
- The muon beam intensity improvement plan is underway to accommodate these developments, especially at PSI (HiMB) and at Fermilab (AMF). It is important that the development of experimental apparatus also be promoted in line with this trend.

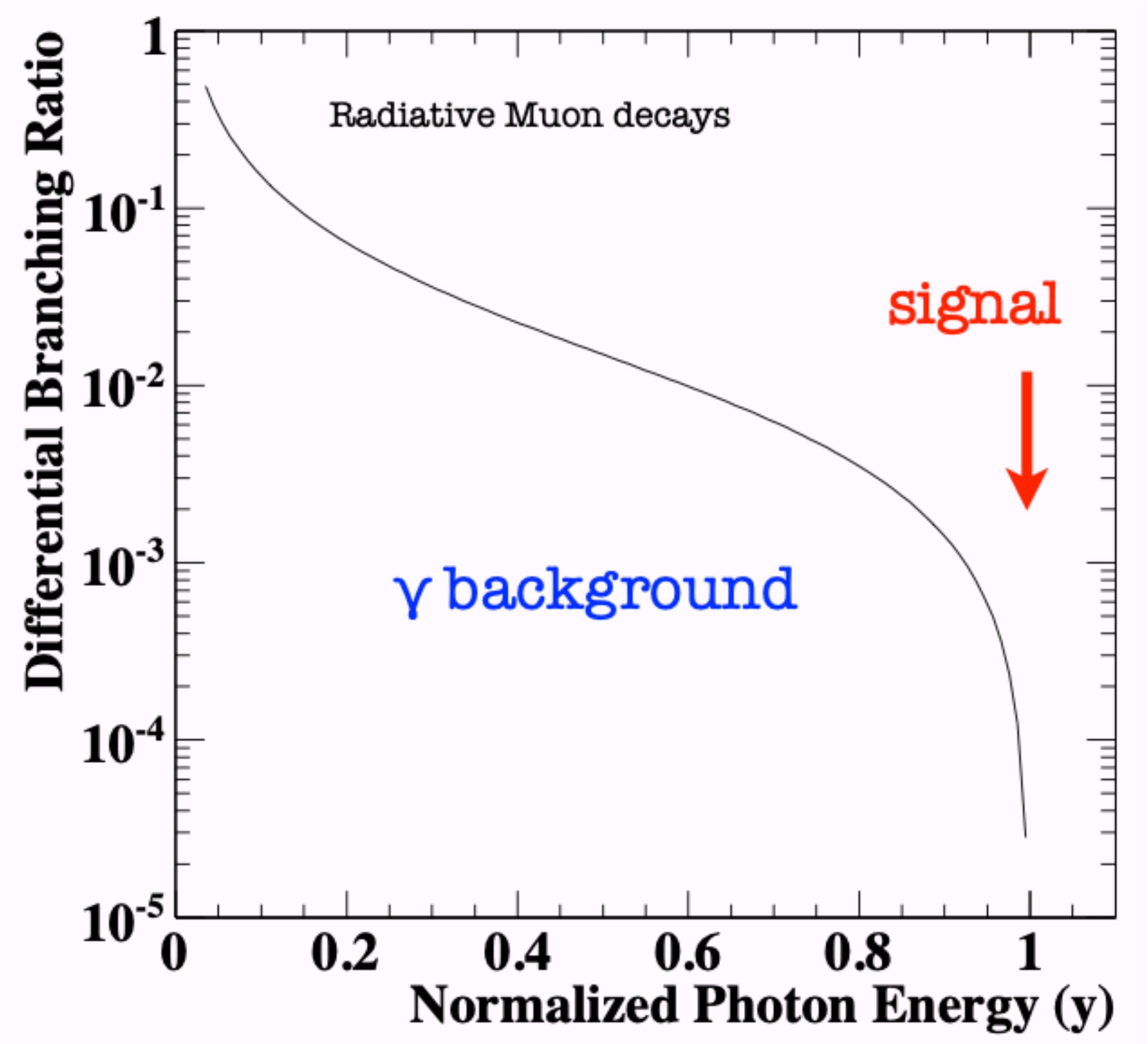
$\mu^+ \to e^+\gamma$ signal and backgrounds











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

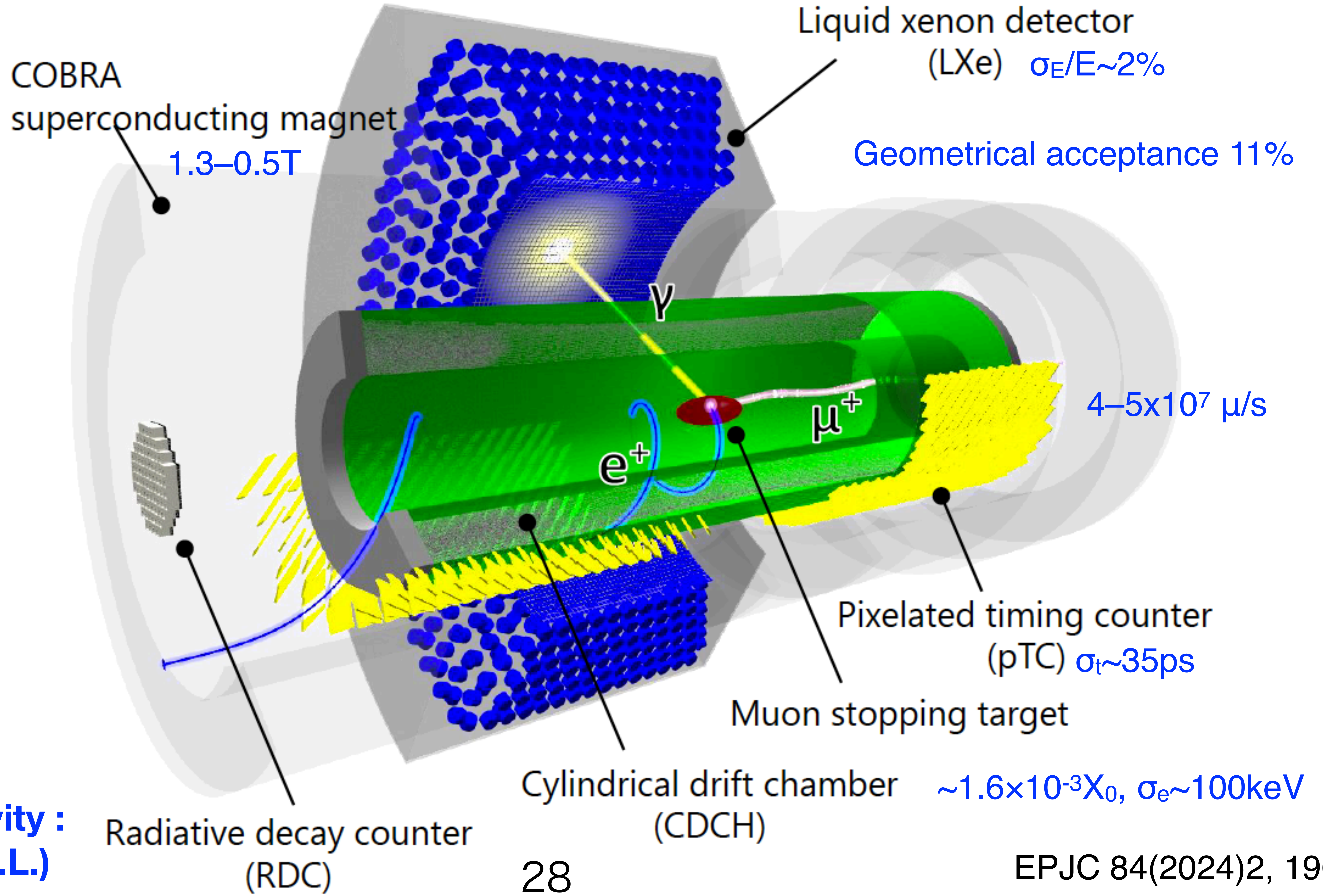
$N_{BG} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$ Good resolution crucial to lower the accidental background (N_{BG})

Beam rate

Resolutions

Elapsed time

MEG II



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

EPJC 84(2024)2, 190

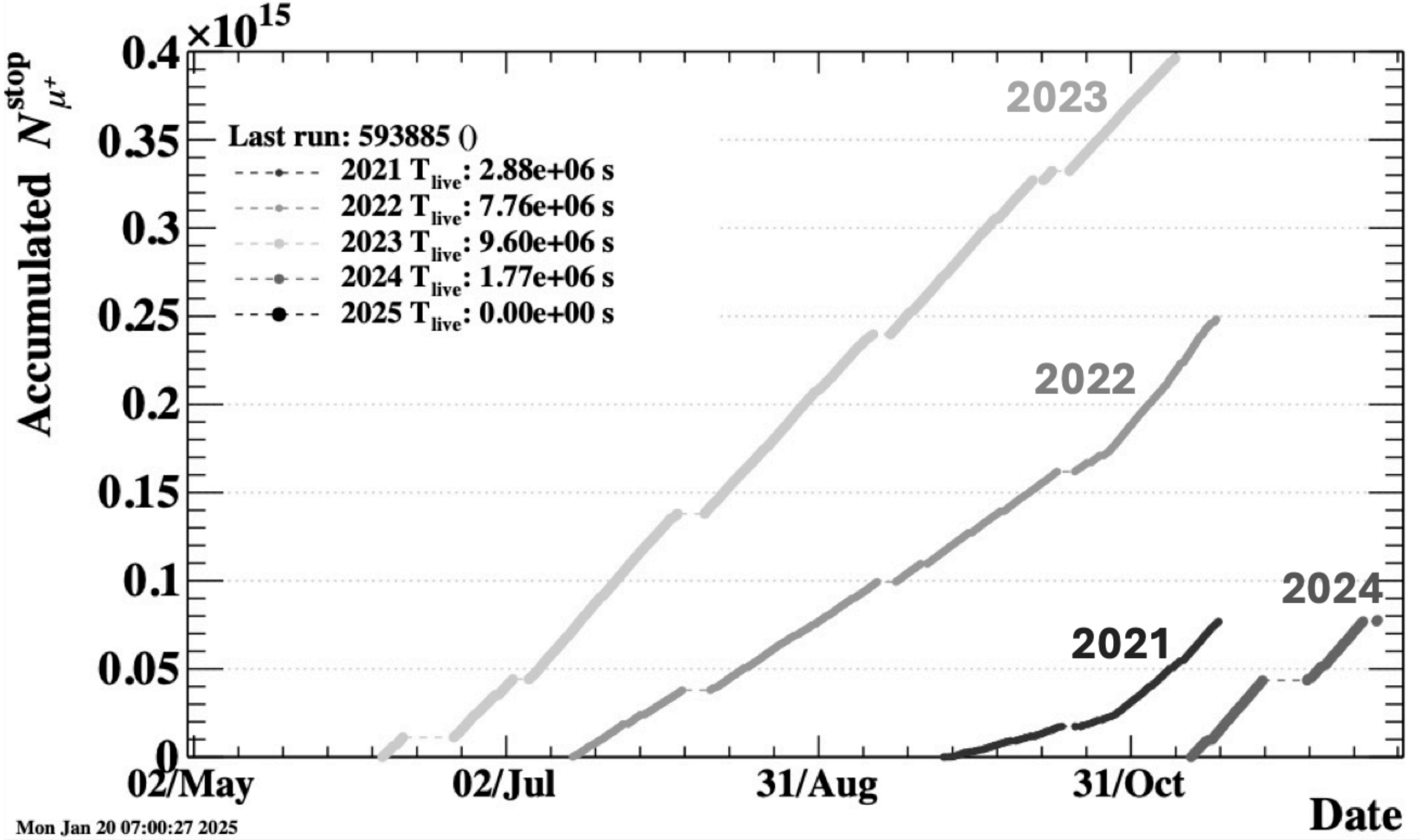
Detector performance summary

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	4.1/7.2	9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.74/2.0	
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	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	62	63
ε_{e^+}	65	67	30
$\varepsilon_{\mathrm{TRG}}$	≈99	80	99

EPJC 84(2024)2, 190

MEG II data taking so far



MEG II total statistics
8.1 x 10^{14} μ stops

~ x10 the 2021 published statistics

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

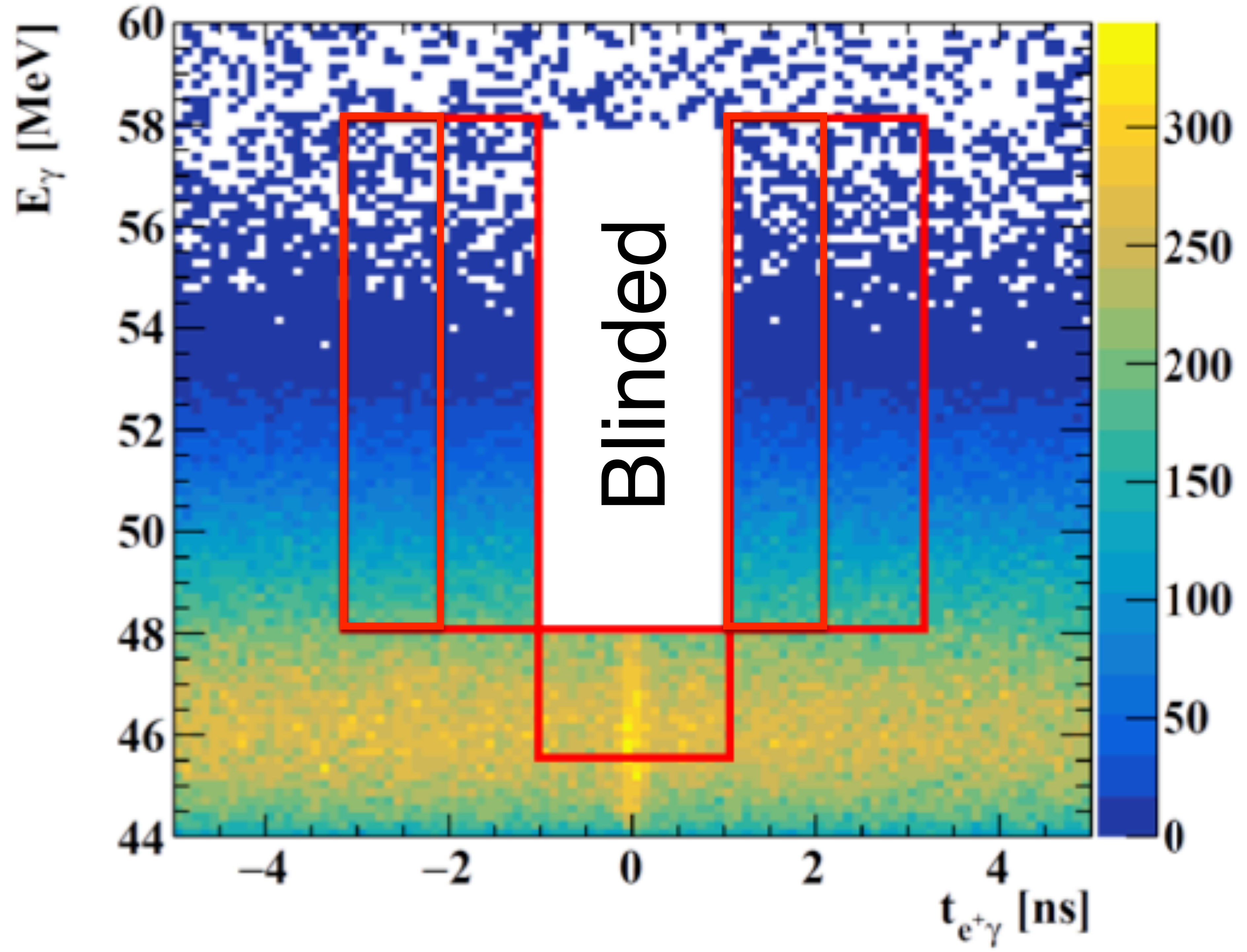
$$\mathcal{L}(N_{\mathrm{sig}}, \overbrace{N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}}^{\text{nuisance parameters}}) =$$

$$\frac{e^{-(N_{\mathrm{sig}}+N_{\mathrm{RMD}}+N_{\mathrm{ACC}})}}{N_{\mathrm{obs}}!} C(\underbrace{N_{\mathrm{RMD}}, N_{\mathrm{ACC}}}_{\text{constrained by sideband}}, \overbrace{x_{\mathrm{T}}}^{\text{constrained}}) \times$$

$$\prod_{i=1}^{N_{\mathrm{obs}}} (N_{\mathrm{sig}} \underbrace{S(\vec{x}_i)} + N_{\mathrm{RMD}} \underbrace{R(\vec{x}_i)} + N_{\mathrm{ACC}} \underbrace{A(\vec{x}_i)}_{\text{per-event PDFs}})$$

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

x_{T} represents the target misalignment uncertainty

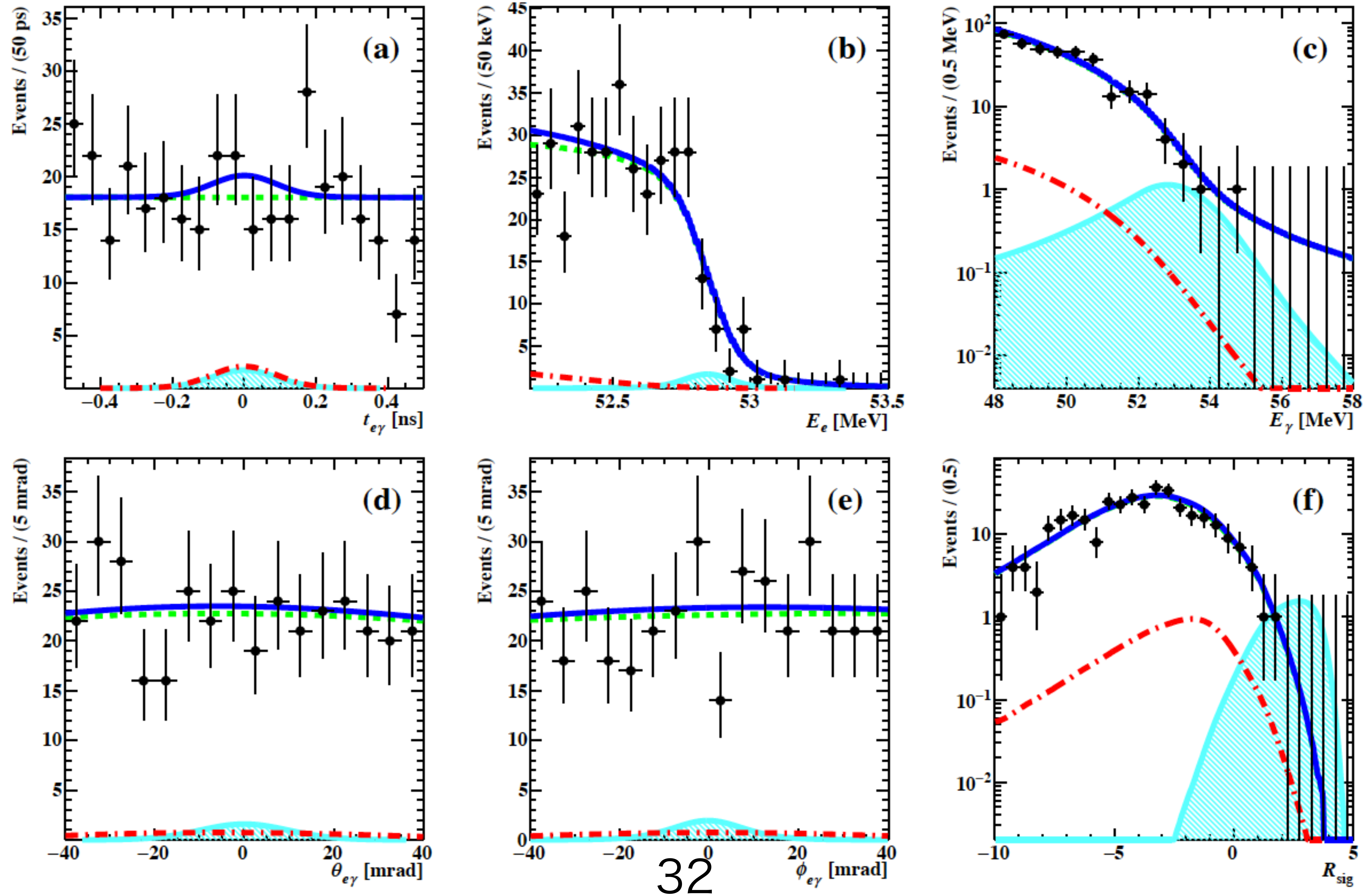


Analysis Region

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

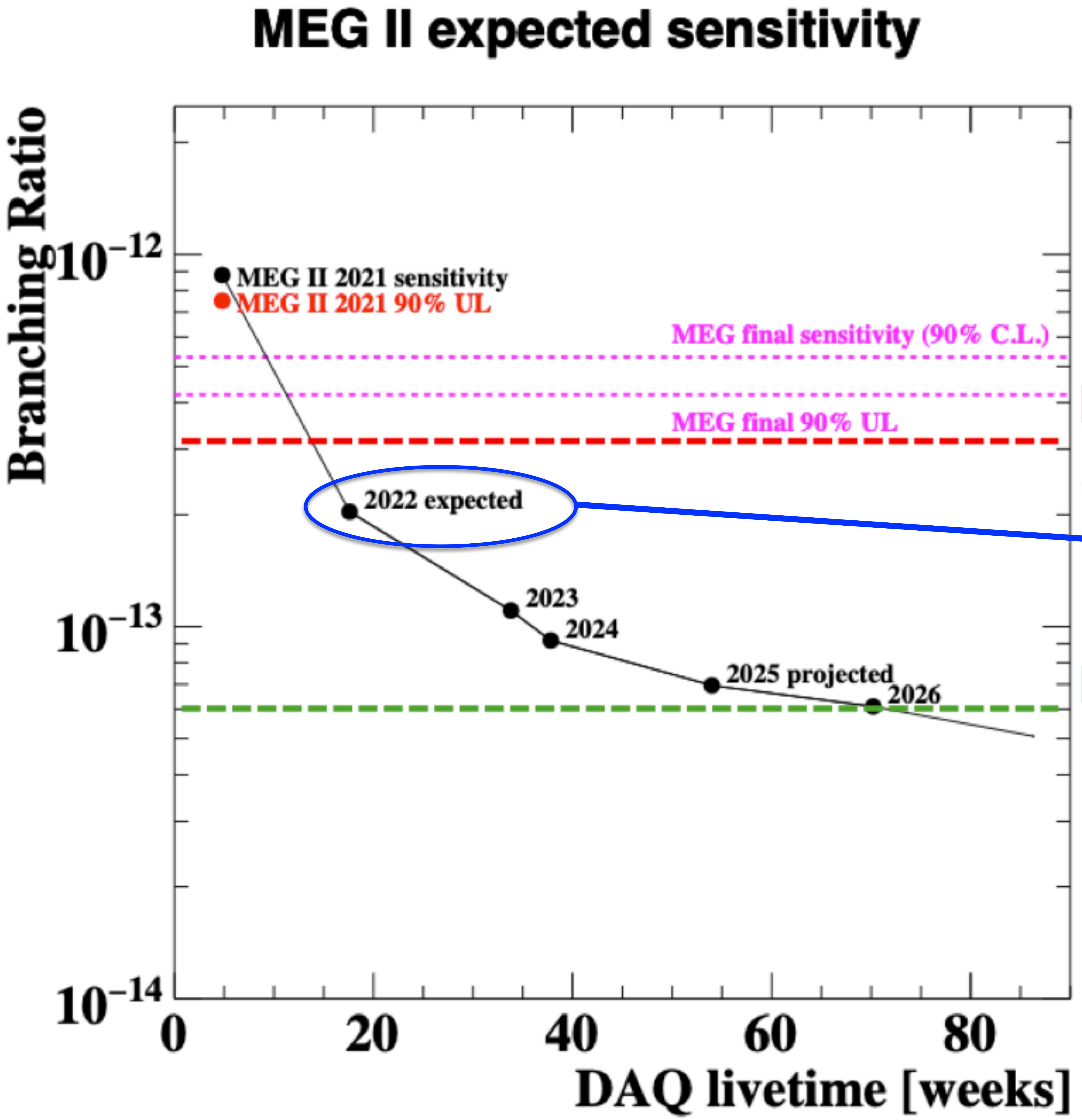
$|t_{\mathrm{e}^+\gamma}| < 0.5\mathrm{ns}$ $\quad |\theta_{\mathrm{e}^+\gamma}| < 40\mathrm{mrad}$ $\quad |\phi_{\mathrm{e}^+\gamma}| < 40\mathrm{mrad}$

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



2-D event distributions

MEG II prospects



New best UL (MEG+MEG II):
$\mathcal{B}_{90}$=3.1x10^{-13}

Analysis been finalized
Results published soon

MEG II proposal goal:
$\mathcal{S}_{90} = 6{\times}10^{-14}$

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 may allow higher intensity (5×10^7/s)

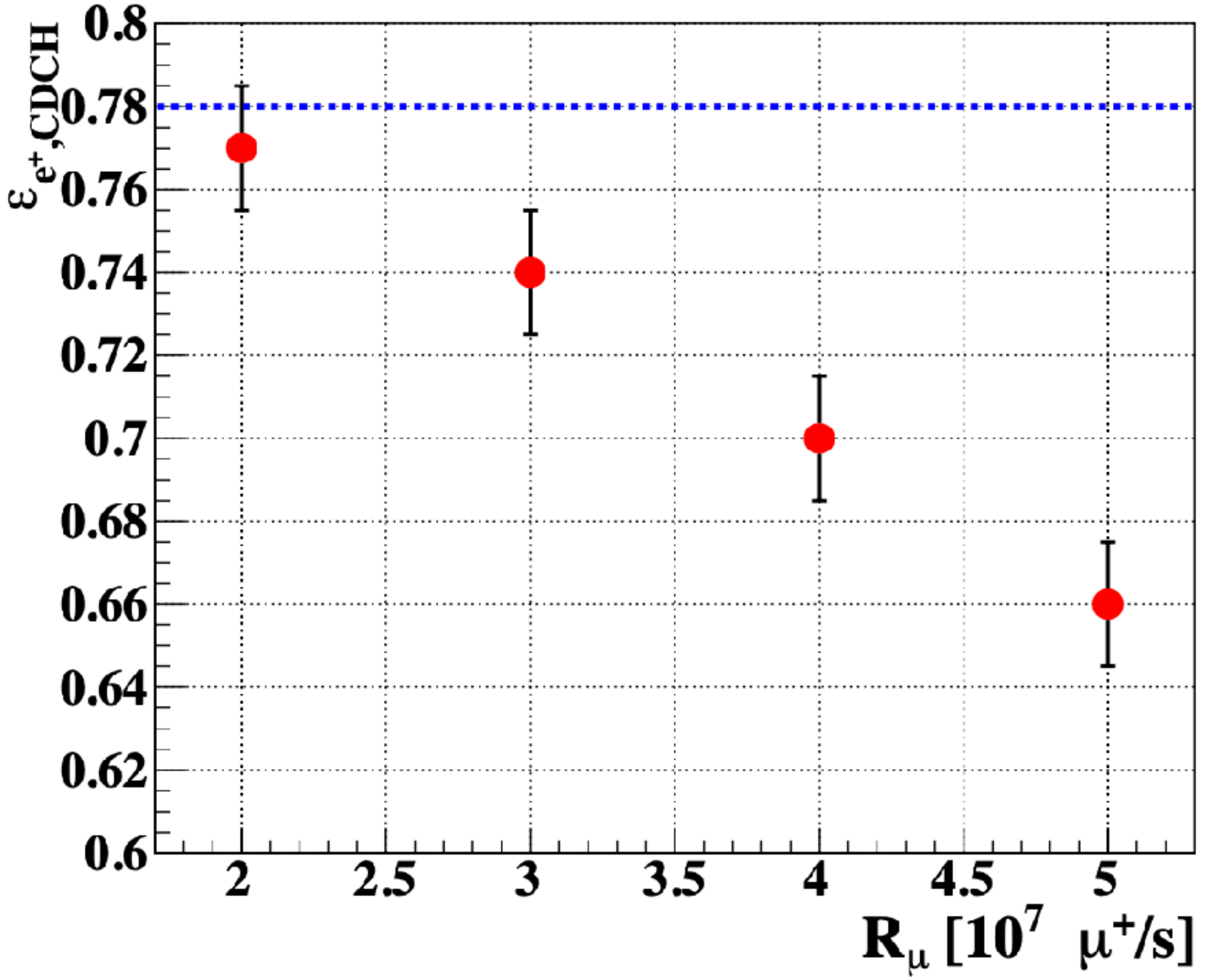


Figure 20 CDCH tracking efficiency as a function of R_μ for signal positrons. The blue dotted line is the design value.

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

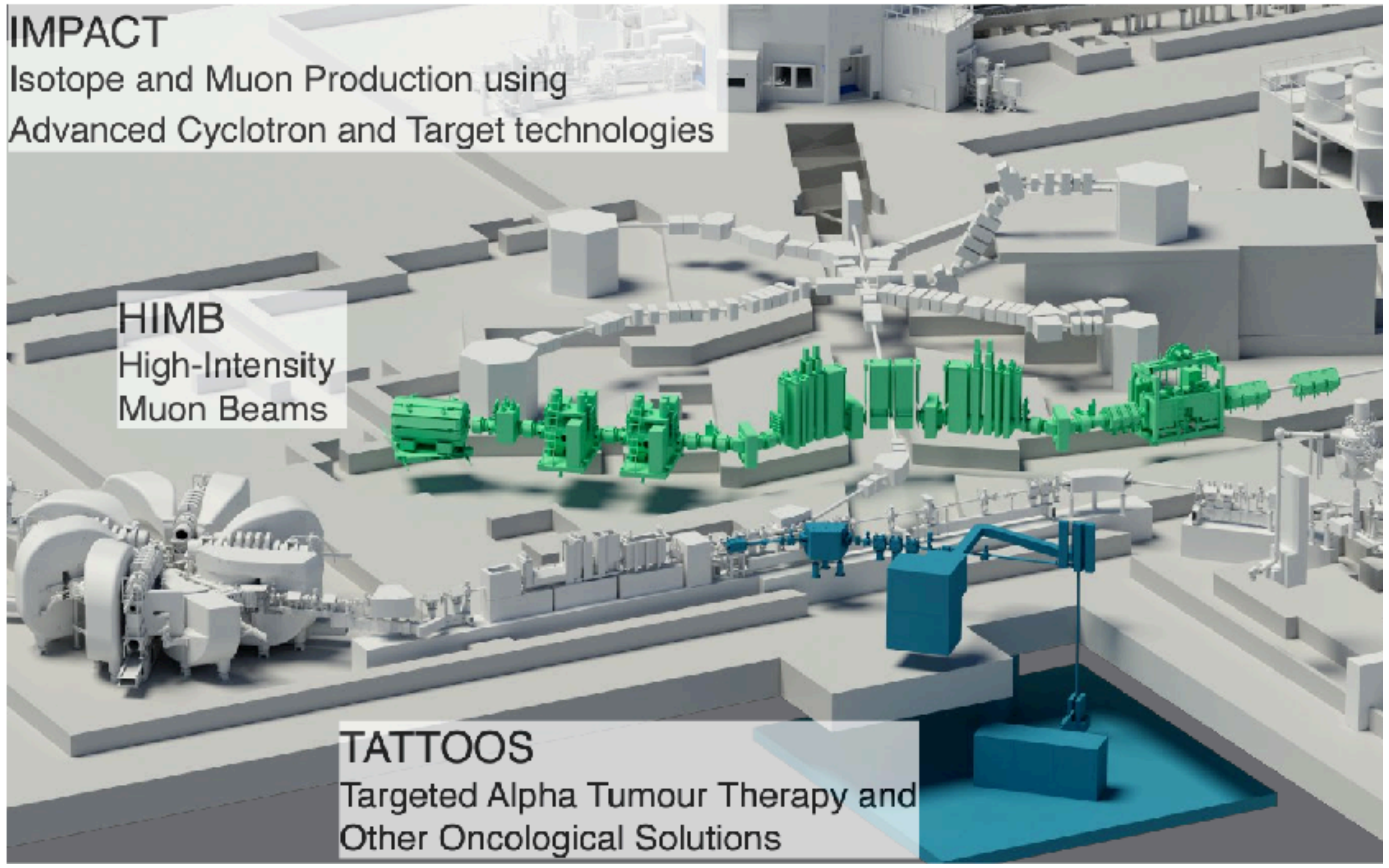
- Better resolutions, angle measurements

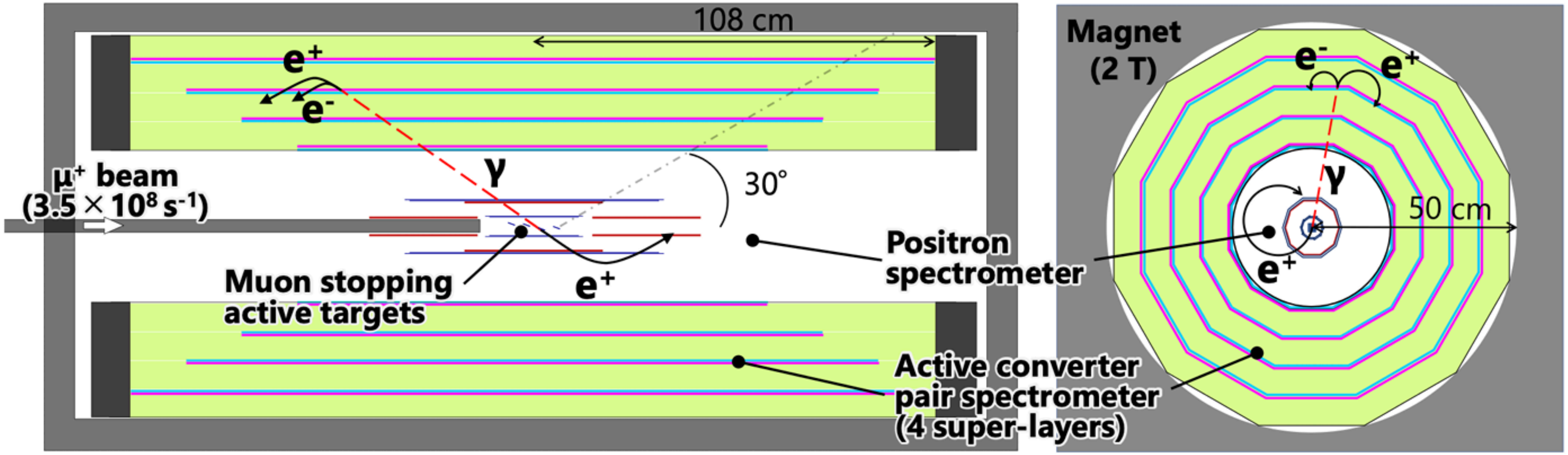
Silicon positron spectrometer similar with Mu3e

Separate active targets

Target sensitivity

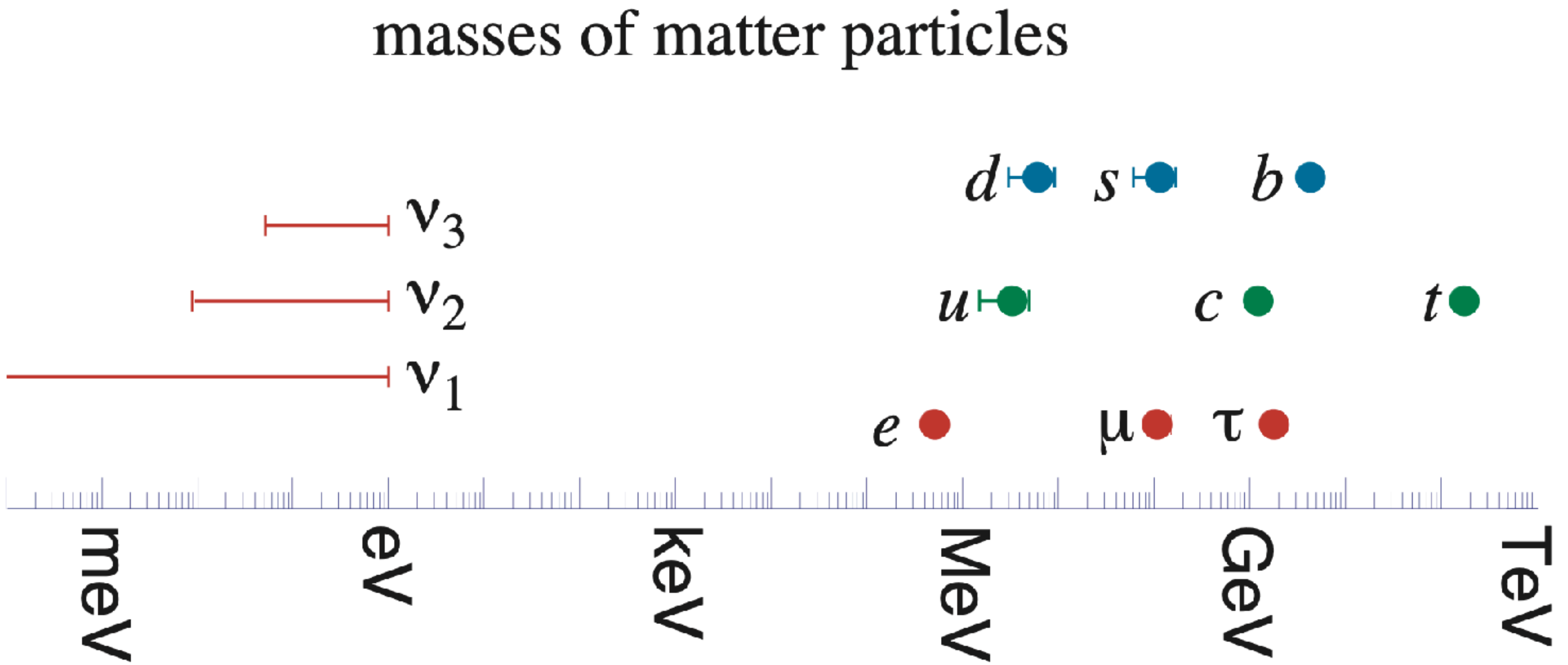
Br($\mu \to e\gamma$) ~ $\mathcal{O}(10^{-15})$





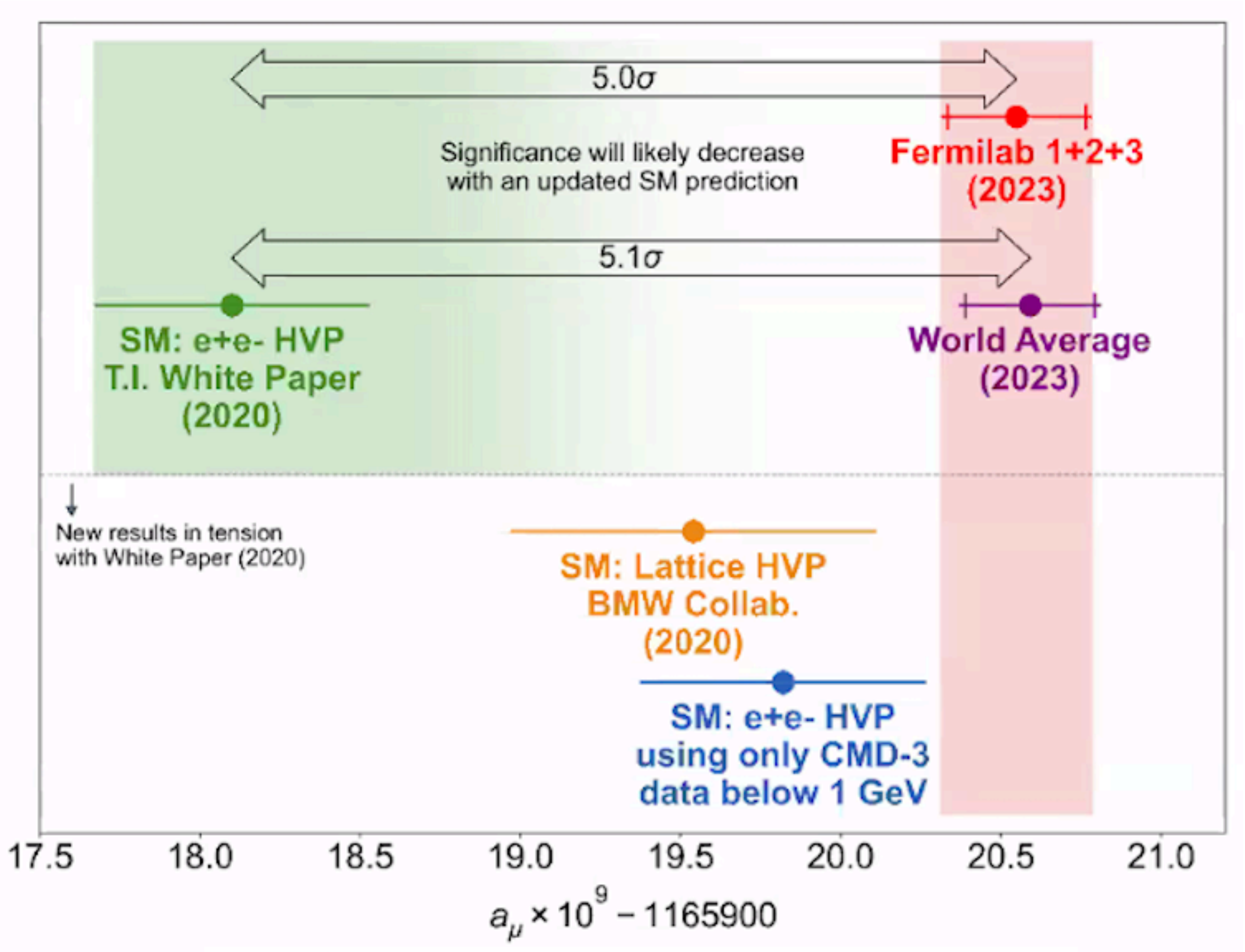
Charged lepton flavor violation

- There are three generations (flavors), but the reason remains a mystery
- Flavor transition in Quark and in neutrino has played a decisive role in the development of particle physics
- No observation yet for the charged lepton flavor transition



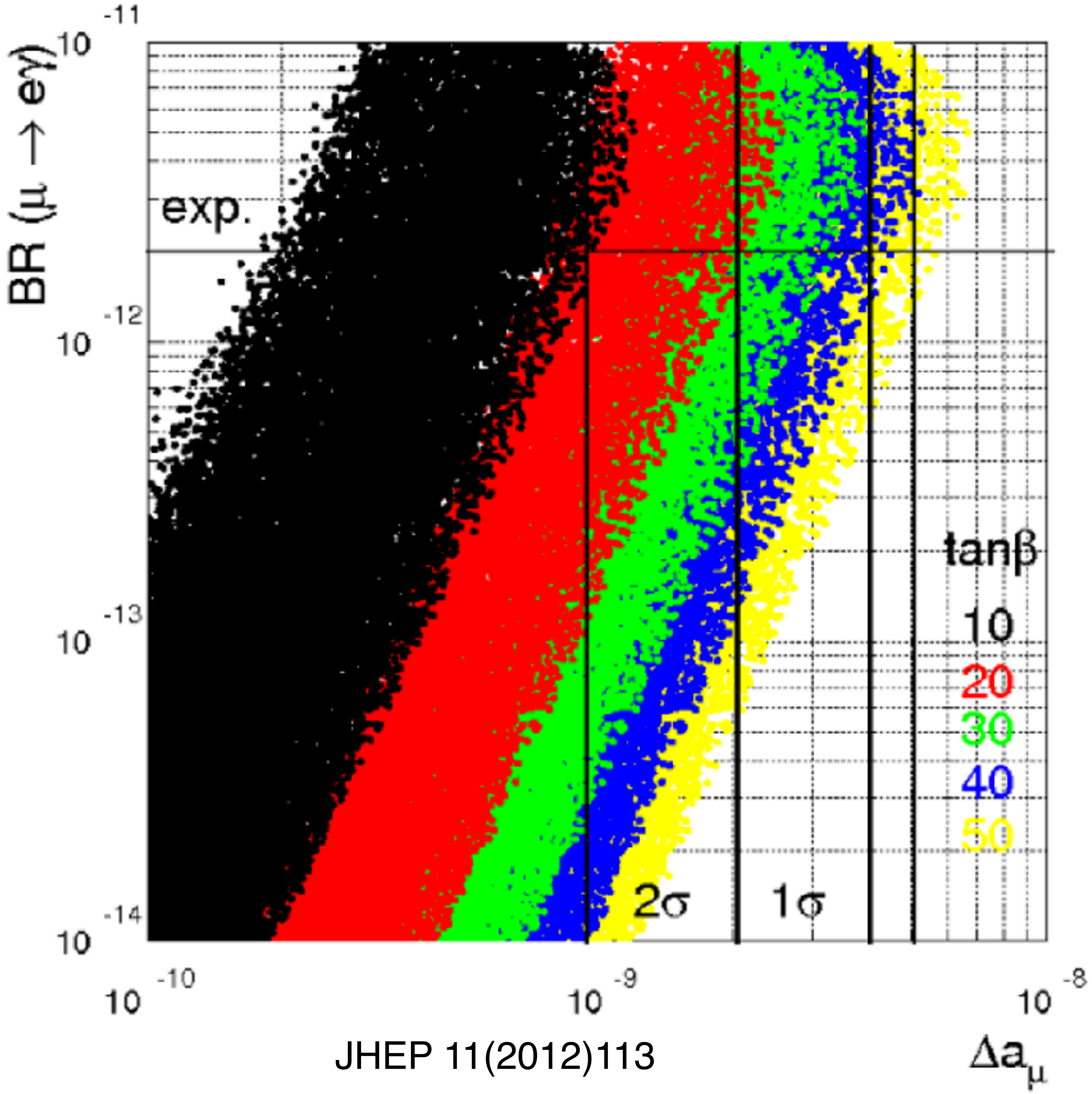
arXiv:1205.2671

CLFV with other indications



Disclaimer from A. Keshavarzi's Lattice 2023 talk:

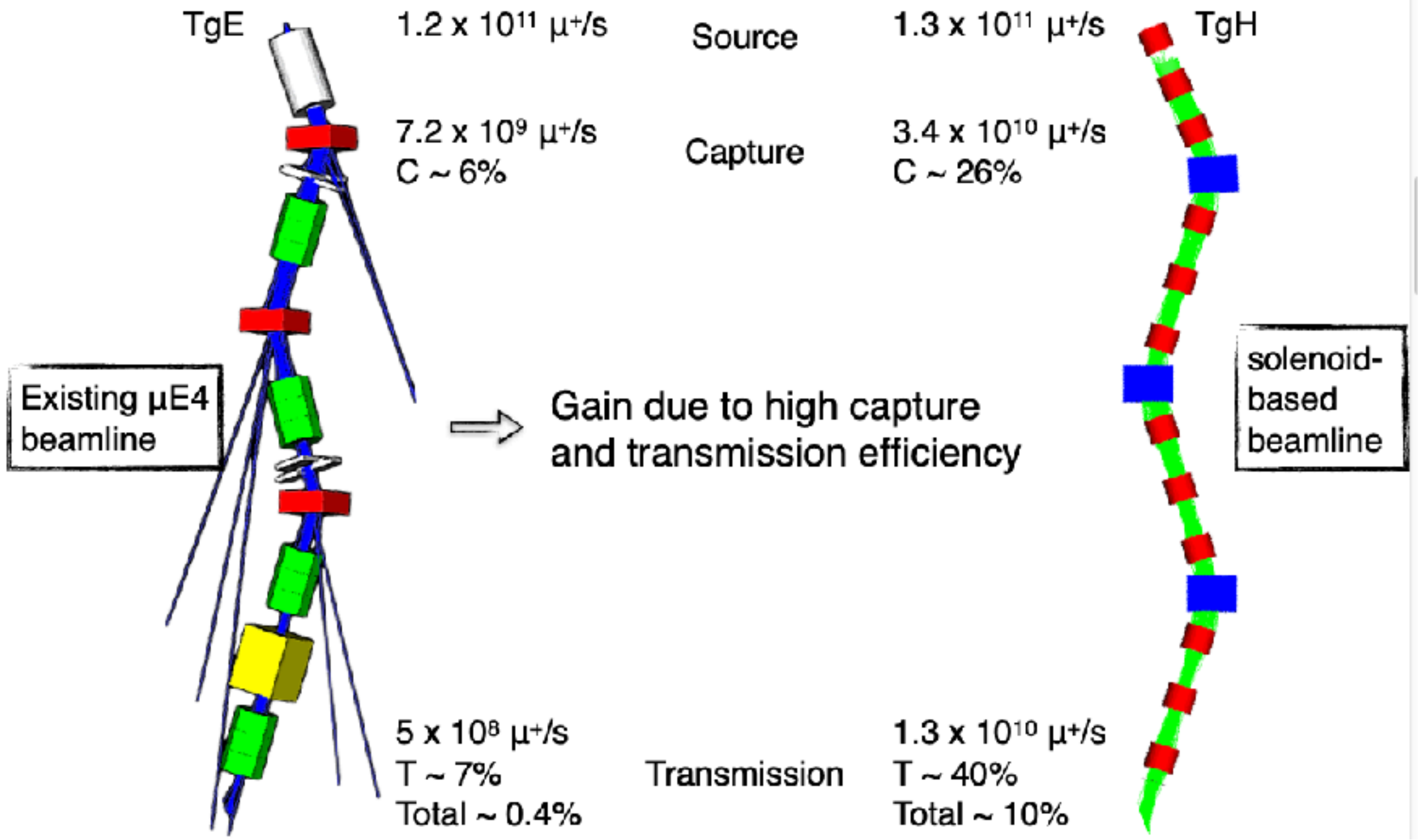
IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → <u>should not be taken as final!</u>

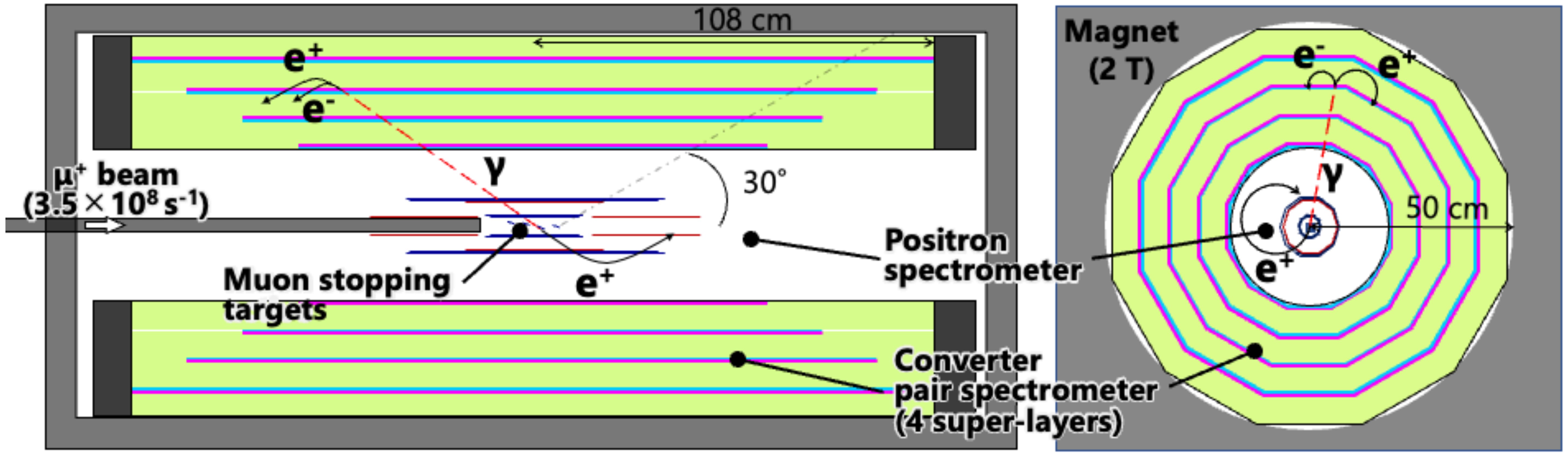


JHEP 11(2012)113

After MEG II

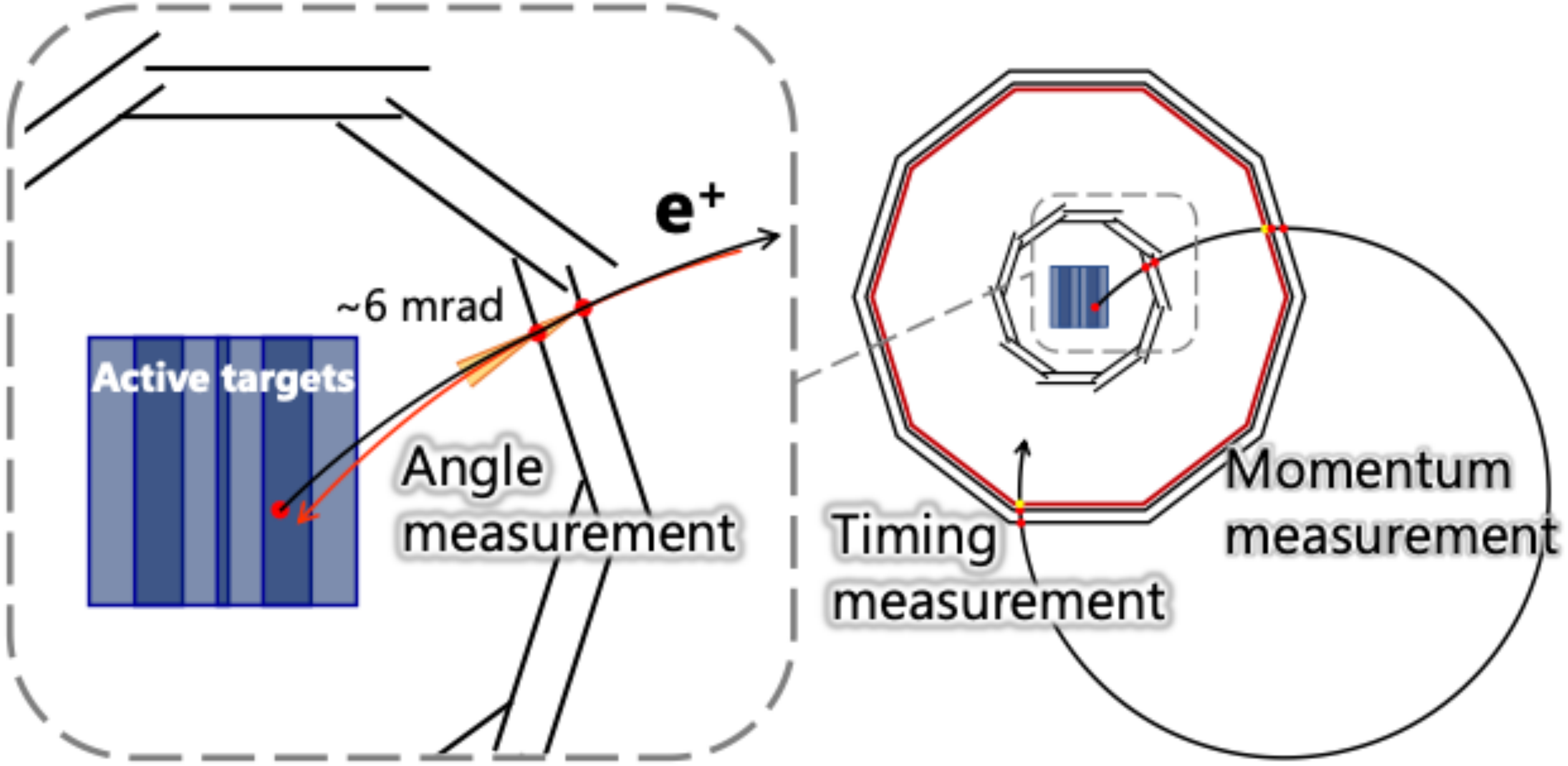
- High Intensity Muon Beam project (HiMB) at PSI
  - 10^{10} μ^+/s (100× improvement)
  - CDR by end of 2021
  - Implementation during 2027/2028
  - Science Case workshop 6-9 April 2021
- Future μ→eγ experiment for CLFV
  - Goal: Br(μ→eγ) ~10^{-15}
  - Discover new physics and precision measurements
  - 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

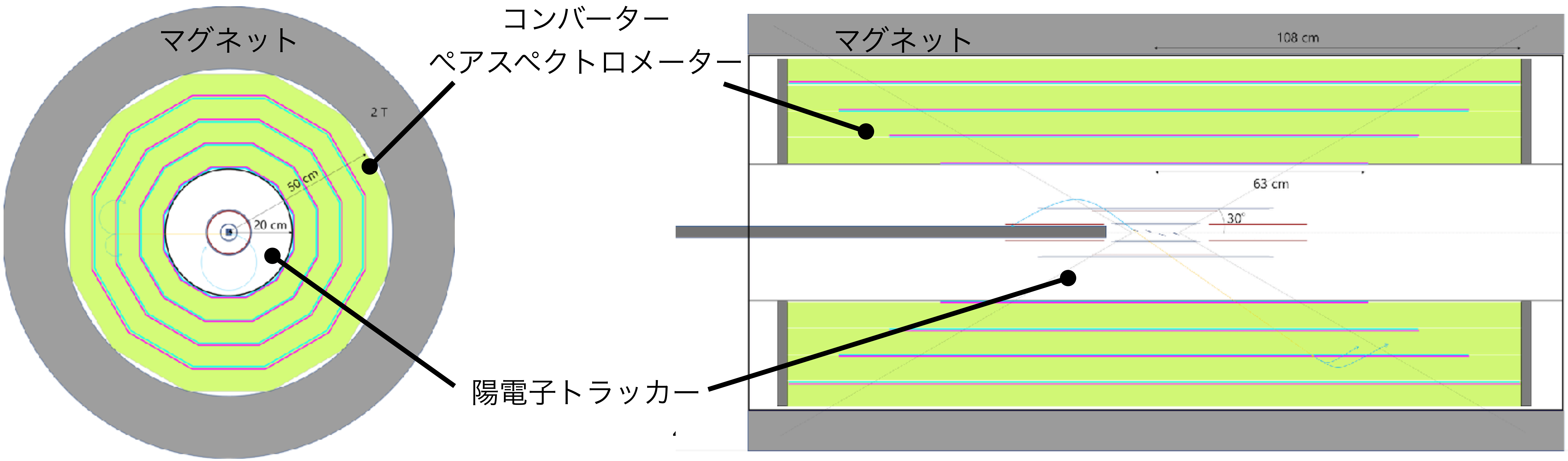




Future μ→eγ

- 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%





Pattern of the relative predictions in several models

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)}$	$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^3$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^3$	$\mathcal{O}(10^3)$
LFV Higgs	Loop†	Loop$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

ArXiv: 1709.00294

Complementarity in target materials