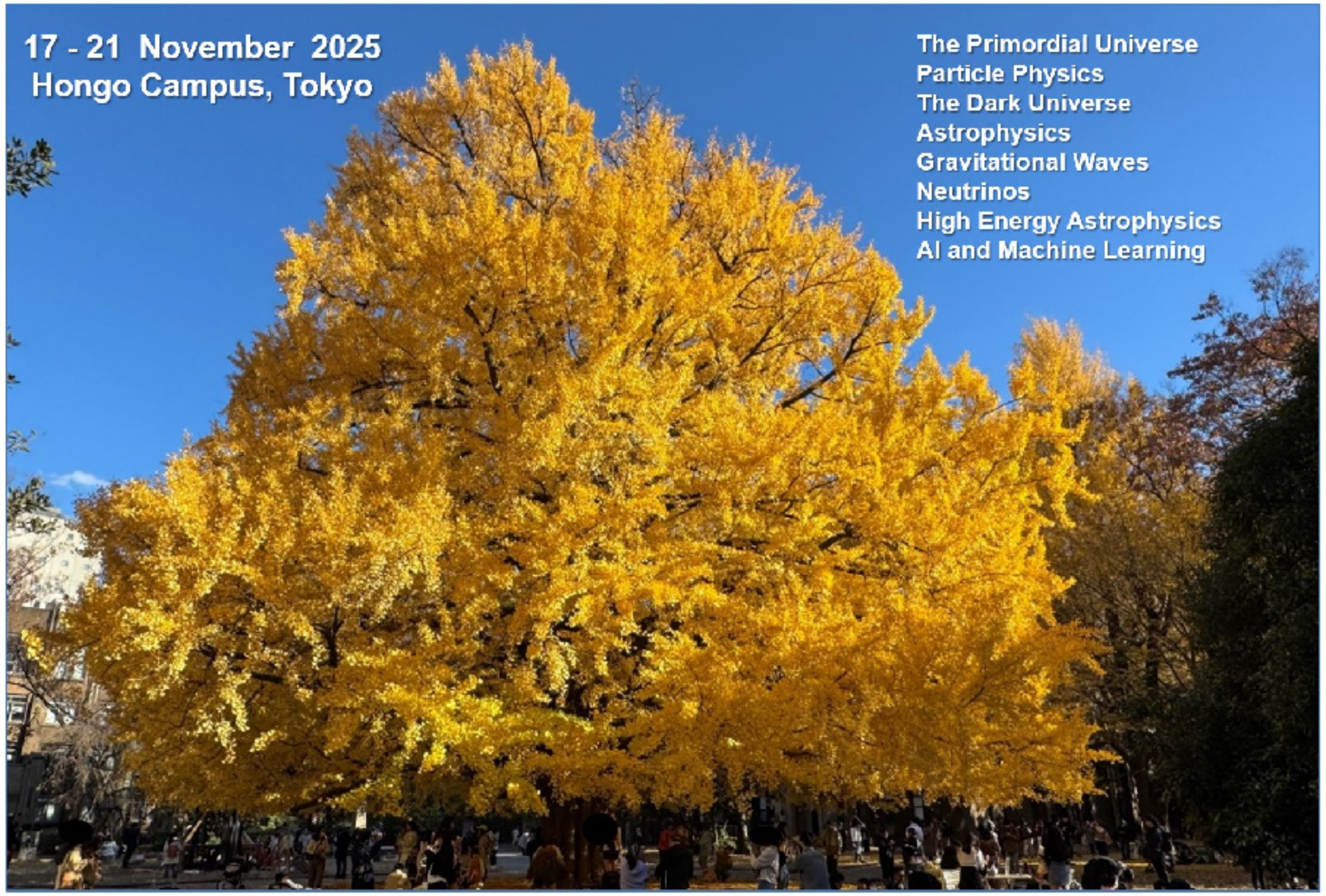
Low-Energy-beyond-the-Standard-Model Experiments



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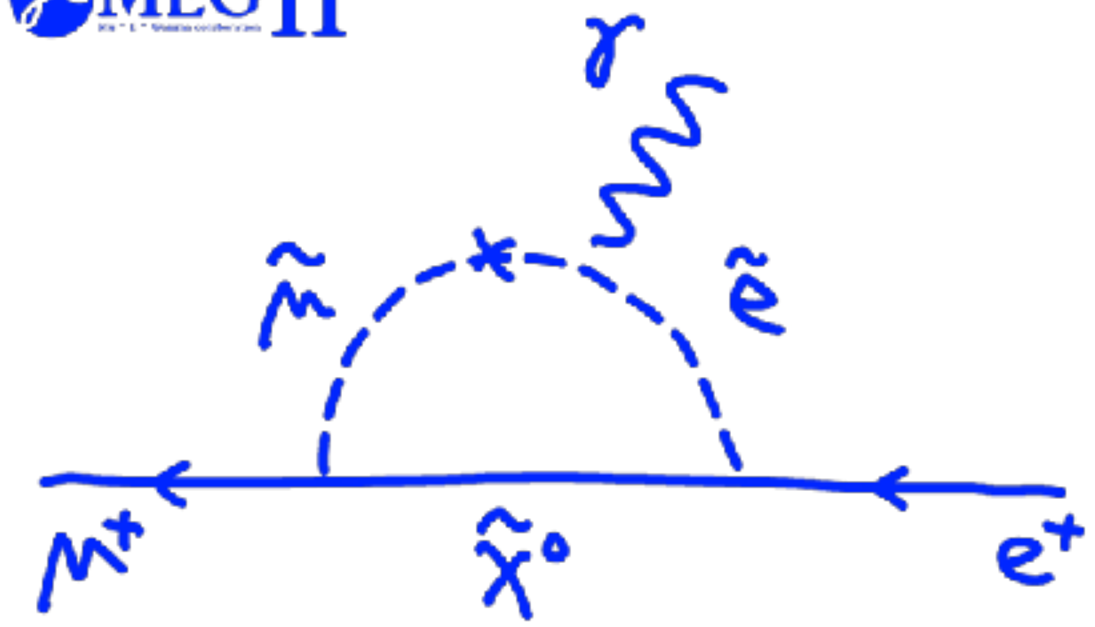
International Center for Elementary Particle Physics
The University of Tokyo

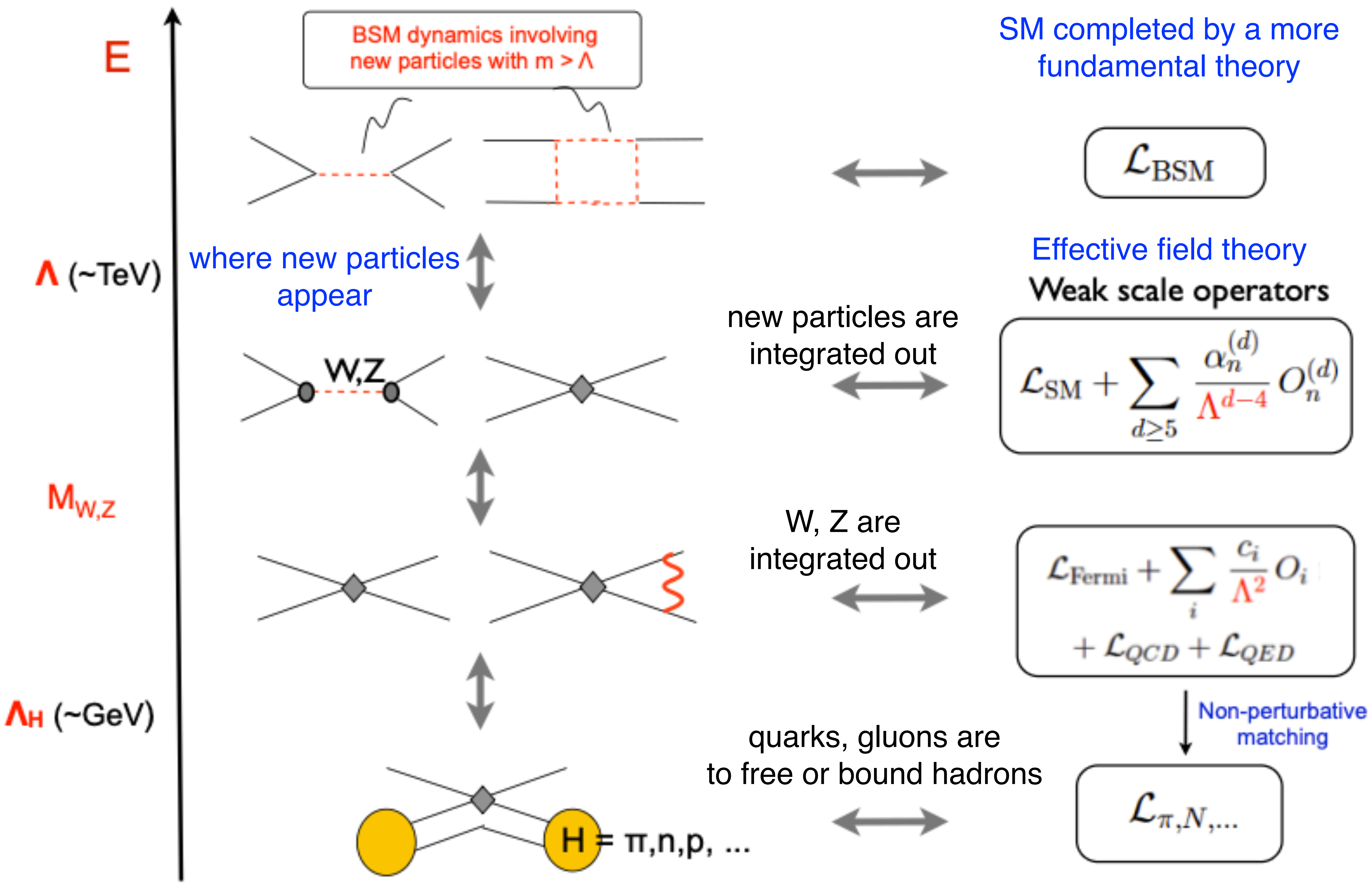
November 20th, 2025 @ Hongo, Tokyo
Second International Conference on the Physics of the Two Infinities

MEG II



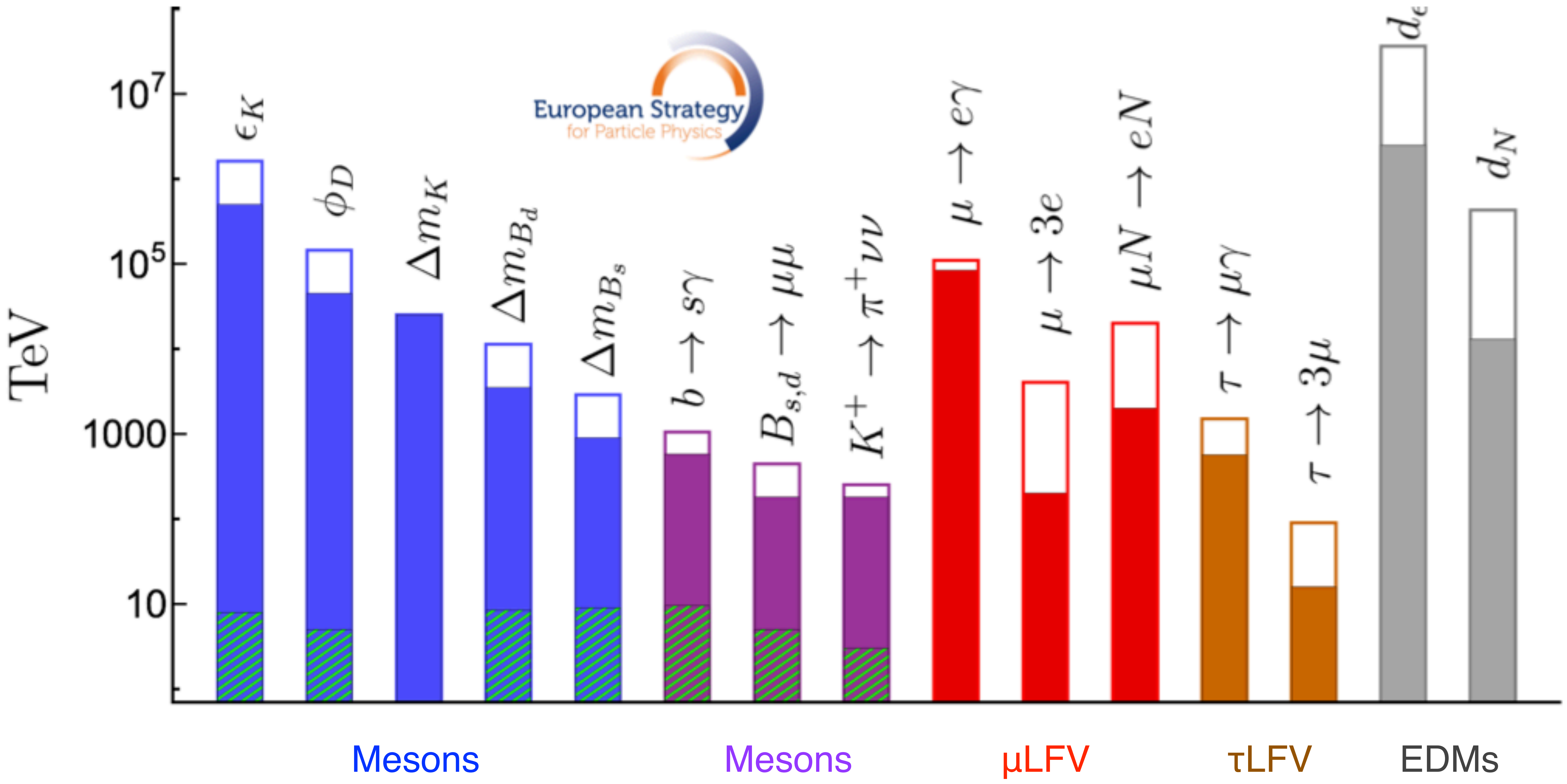
Introduction

- Elementary particle physics
  - Looking for new physics beyond the standard model to explain unsolved problems
    - Highest energy accelerator
      - Direct production of heavy new particles
      - No indication from LHC yet, HL-LHC, FCC-ee and -hh, ILC, CEPC, CLIC,
    - Low energy (high intensity) accelerator
      - Can play important roles
      - Indirect production (virtual state) of even heavier new particles
      - Intense sources and ultra-sensitive detectors are necessary



arXiv:1304.0017

Reach in new physics scale

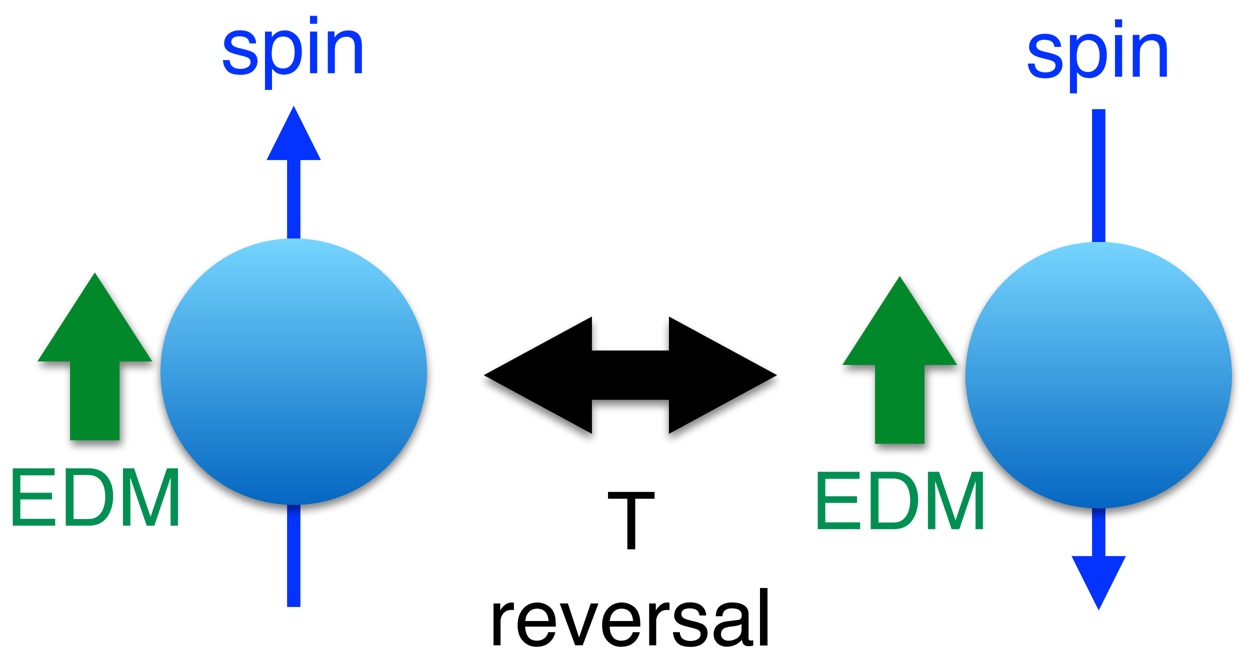


Bounds on Ci (=$1/\Lambda_i^2$)
of dimension-six operators

Physics Briefing Book,
arXiv: 2511.03883

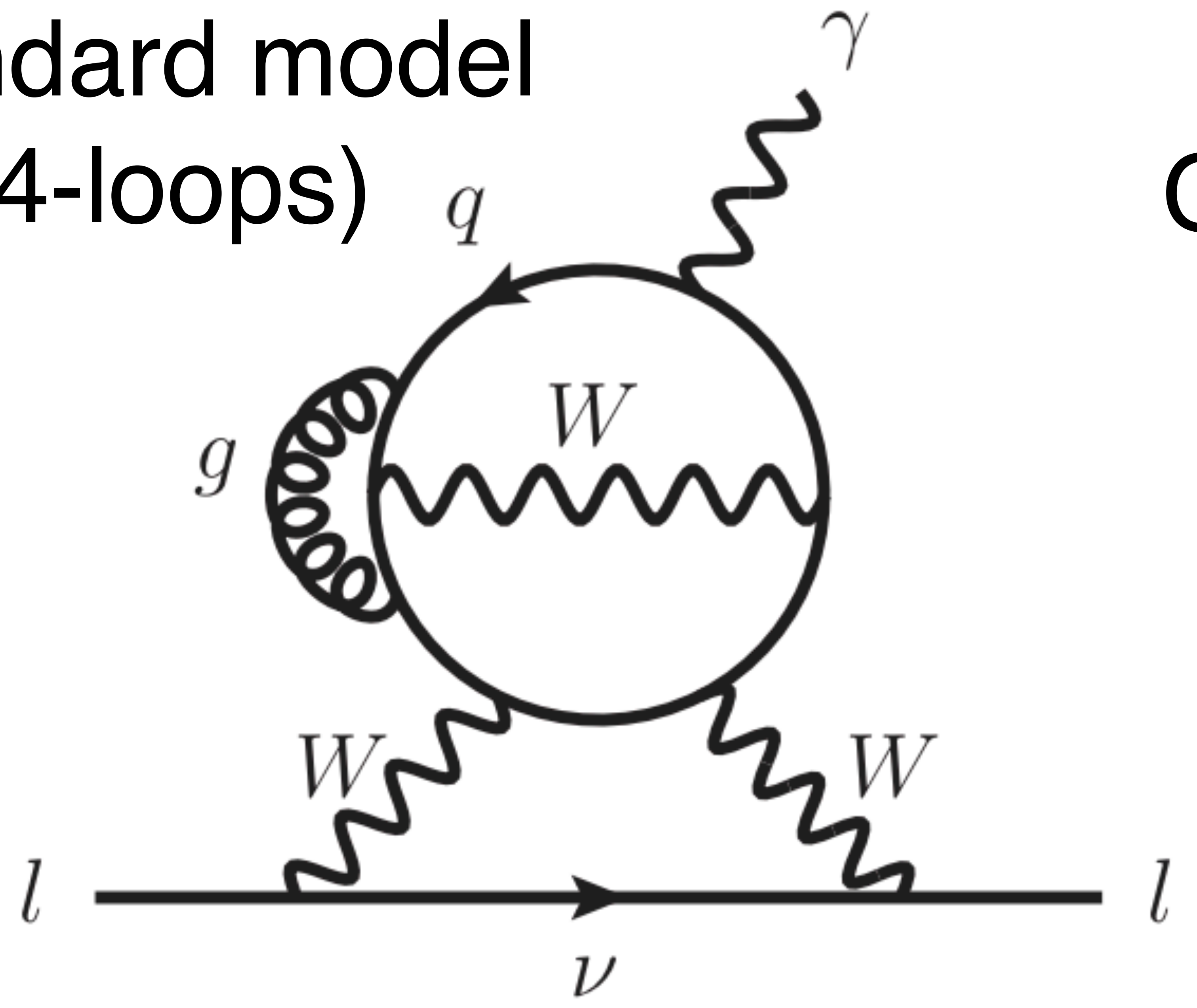
- Low energy (high intensity) experiments can reach even higher new physics scale than highest energy experiments
  - Small-scale experiments
    - Rare processes and precision measurements
    - EDMs, Muon LFV, rare pion decay
  - Mid-, Large-scale
    - K, B mesons, τ lepton
  - Anomalies
    - g_μ-2, LFU etc.

Electric Dipole Moments



- A finite EDM indicates an asymmetry of the charge distribution relative to the spin direction
  - If it exists, EDM violates T symmetry, and thus CP symmetry under the CPT

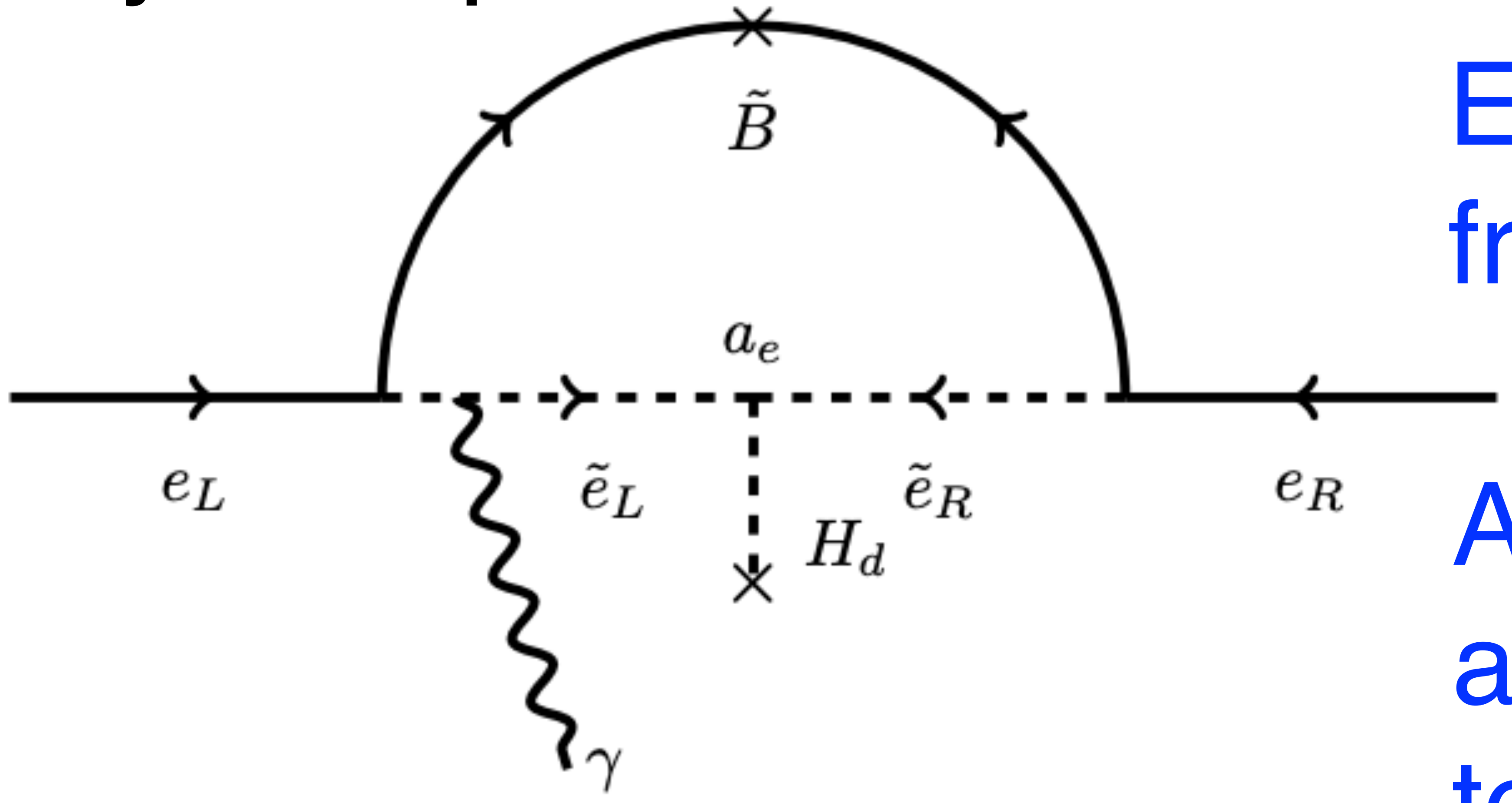
Standard model
(4-loops)



$d_e^{(SM)} \sim 5.8 \times 10^{-40}$ e cm

PRL 125, 241802(2020)

BSM
Only 1 loop



$d_e^{(BSM)} \sim 10^{-30}$ e cm ?

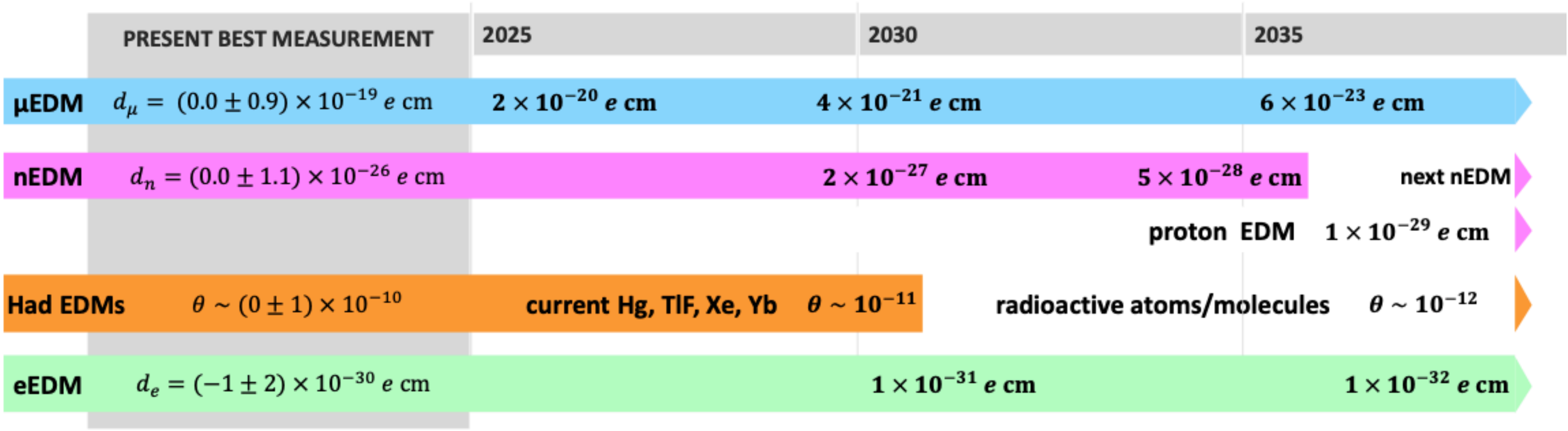
JHEP 05 (2019) 059

EDM is a background-free probe to the BSM

Any new CPV would be a significant discovery to explain for matter universe

EDM measurements

Physics Briefing Book, arXiv: 2511.03883



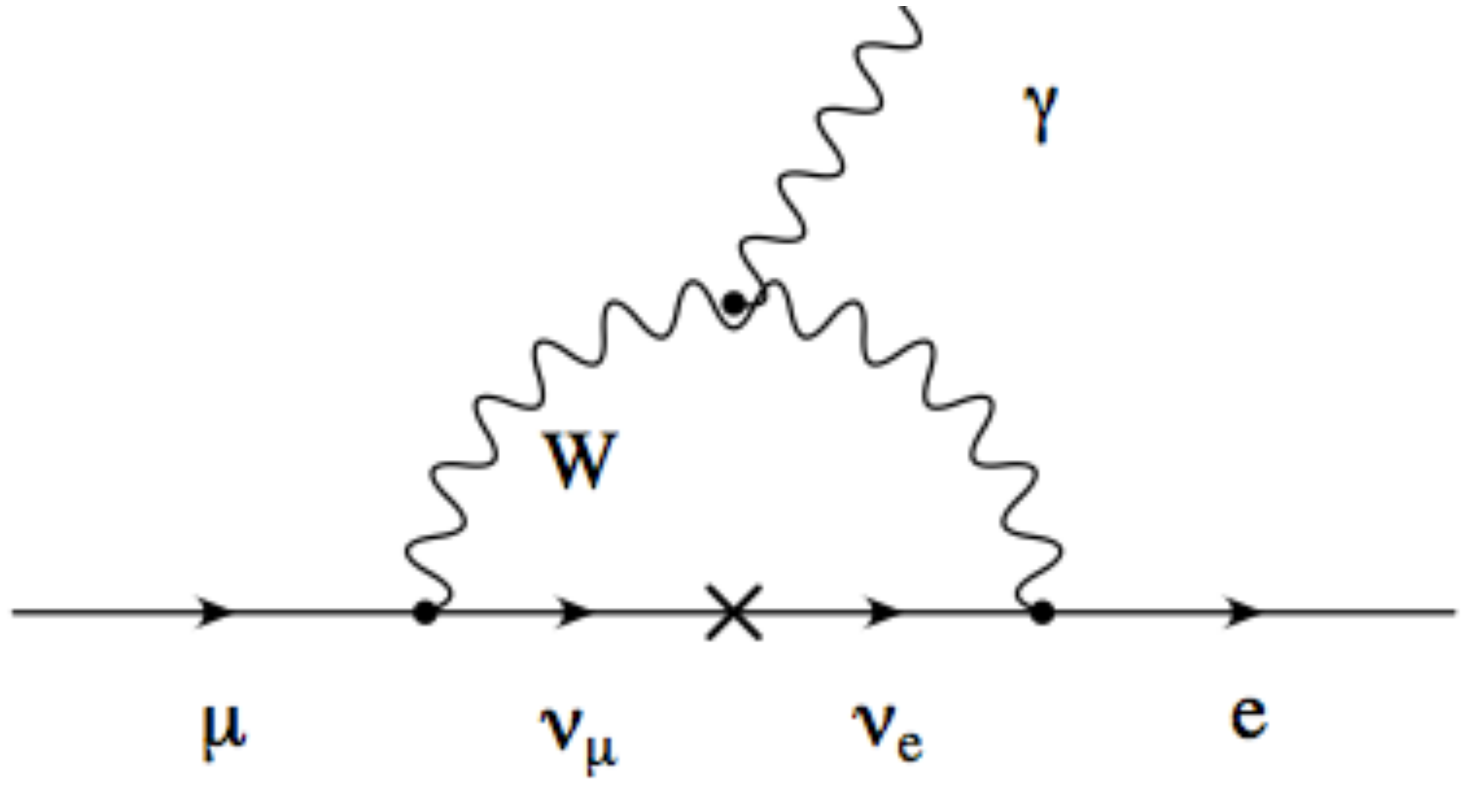
- Current experimental limit: $d_n = (0.0 \pm 1.1) \times 10^{-26}$ e cm, $d_e = (-1 \pm 2) \times 10^{-30}$ e cm
  - ➡ test NP at mass scales above 10TeV ~ 10^6 TeV
- Hadron EDM and lepton EDM searches are complementary
  - Different new physics can be tested
  - Hadron EDMs also provide direct information on the QCD CPV parameter θ

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

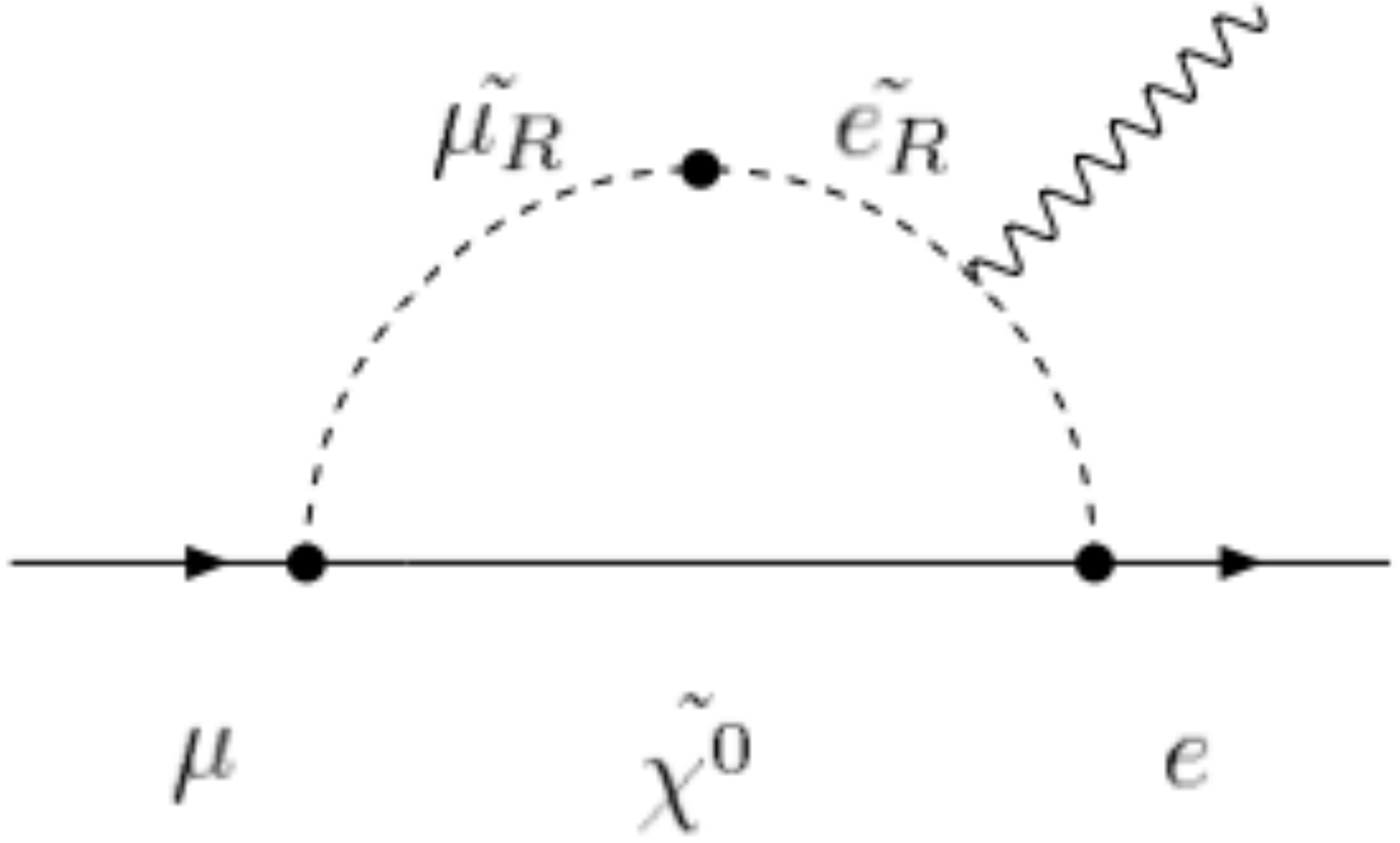
Charged lepton flavor transition has never been observed yet



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

$\sim 10^{-54}$

Neutrino is too light



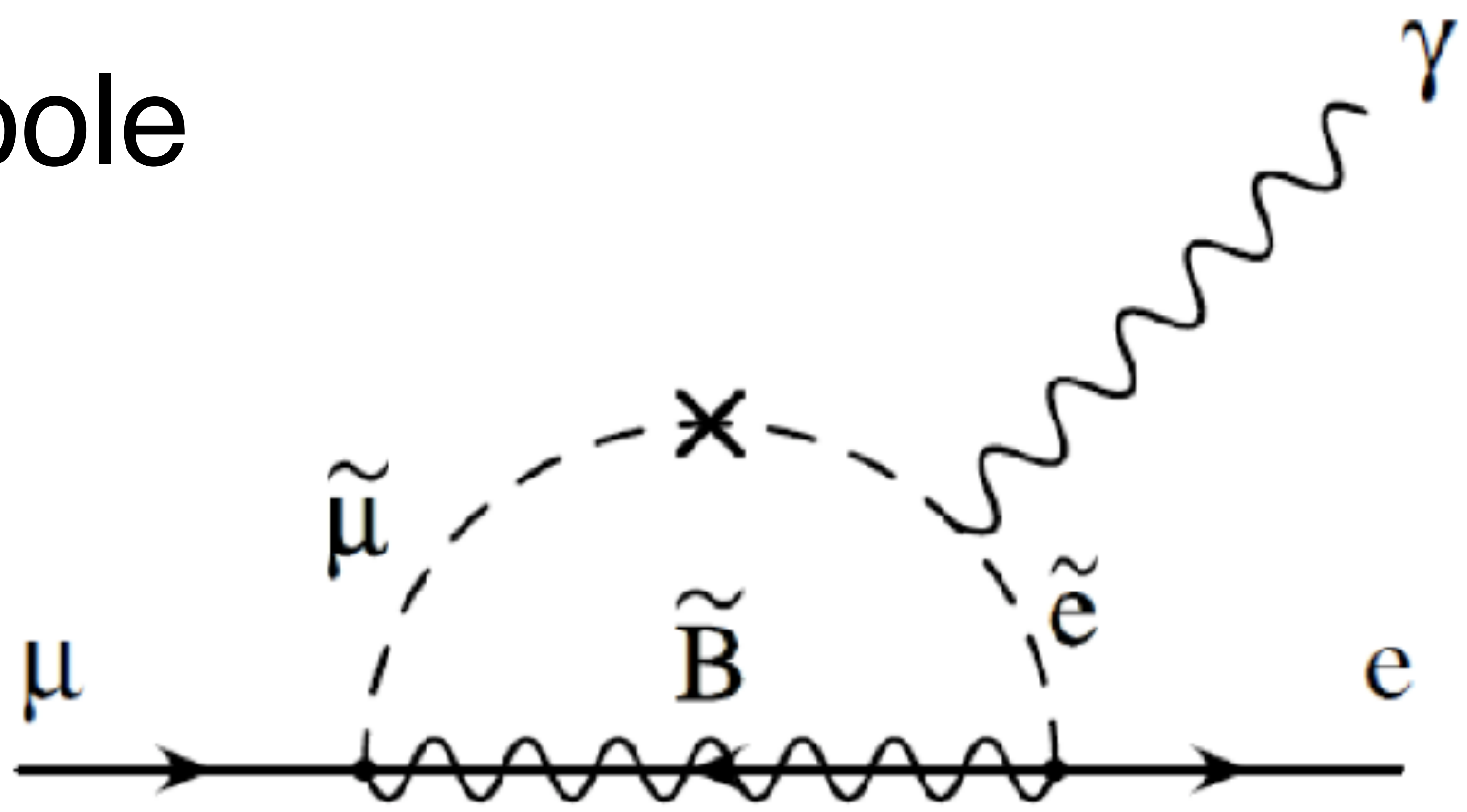
New particles from SUSY in the loop can enhance the branching ratio $10^{-12} – 10^{-14}$

SUSY-GUT / SUSY-seesaw

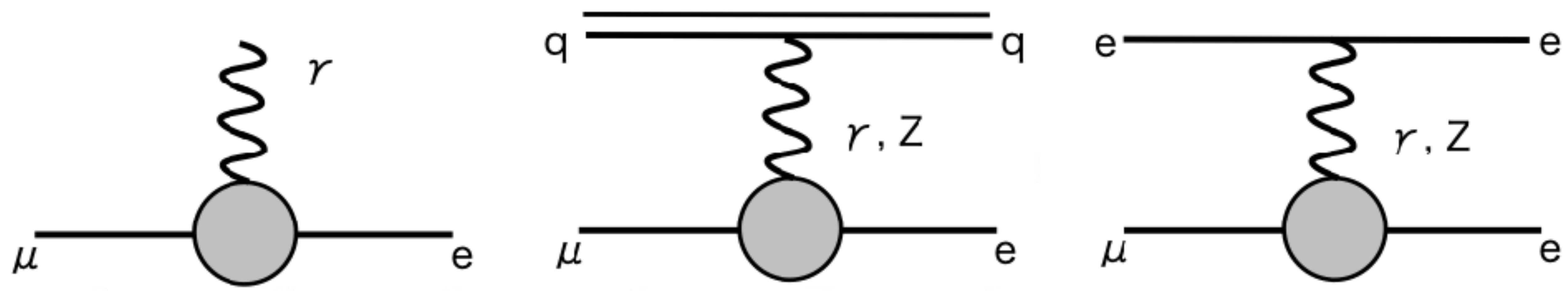
Evidence of $\mu^+ \to e^+\gamma$ = Evidence of new physics

New physics models

Dipole

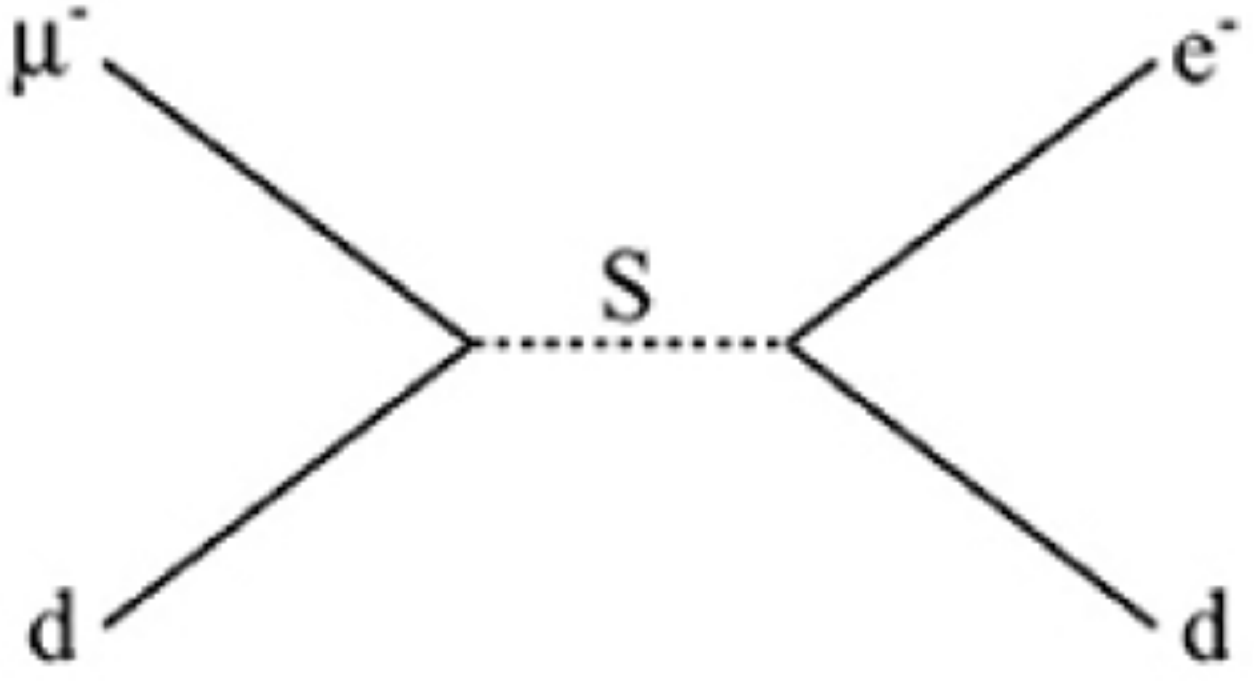


SUSY-GUT, SUSY-seesaw

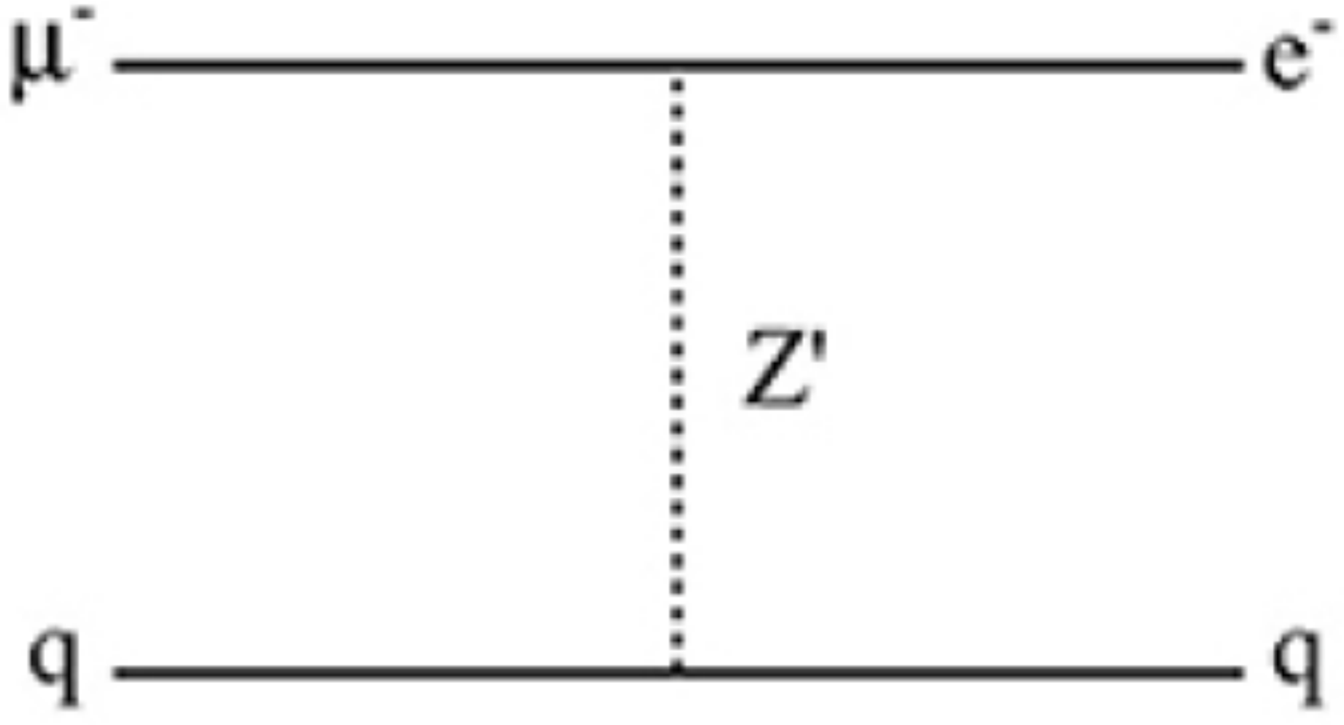


Br(μ→eγ) : R(μ-Al→e-Al) : Br(μ→3e)
= 1 : 1/170 : 1/390

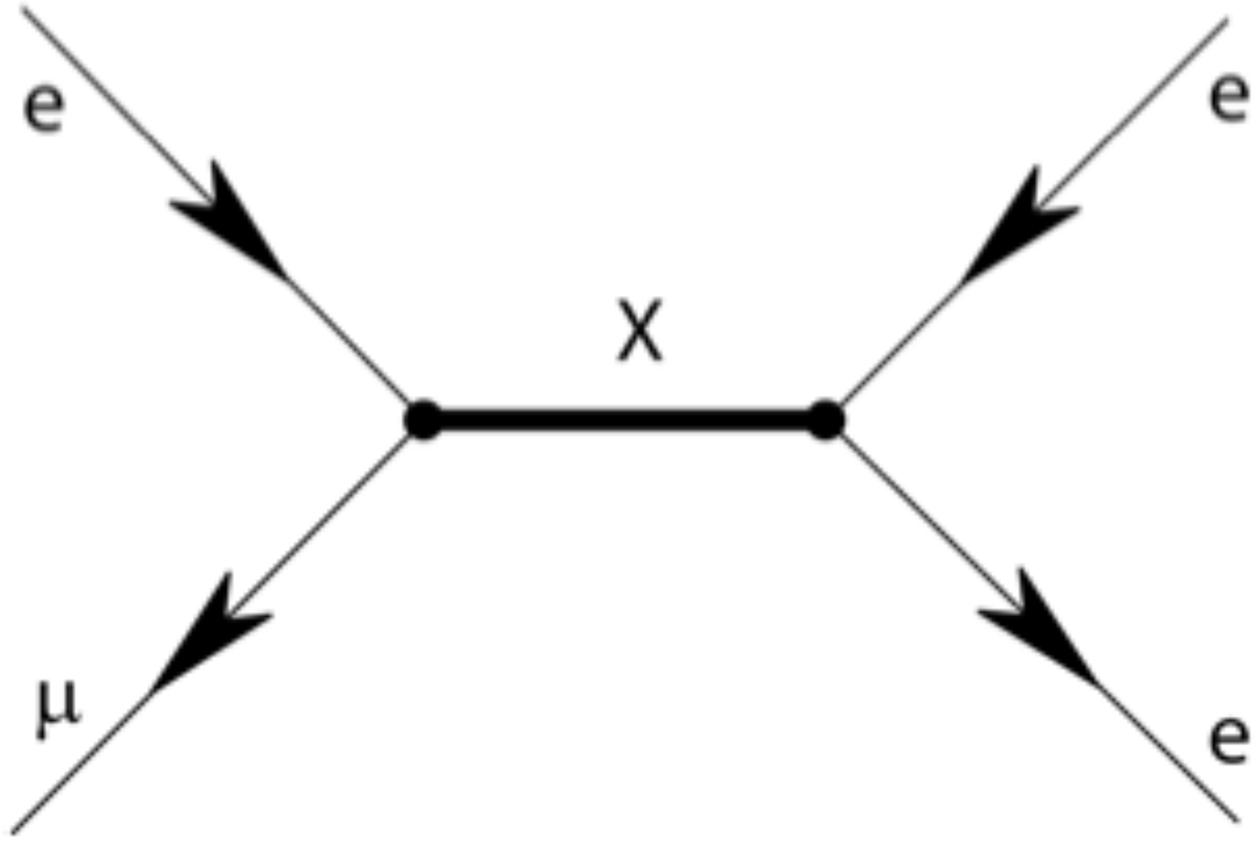
Tree



Scalar: RPV SUSY



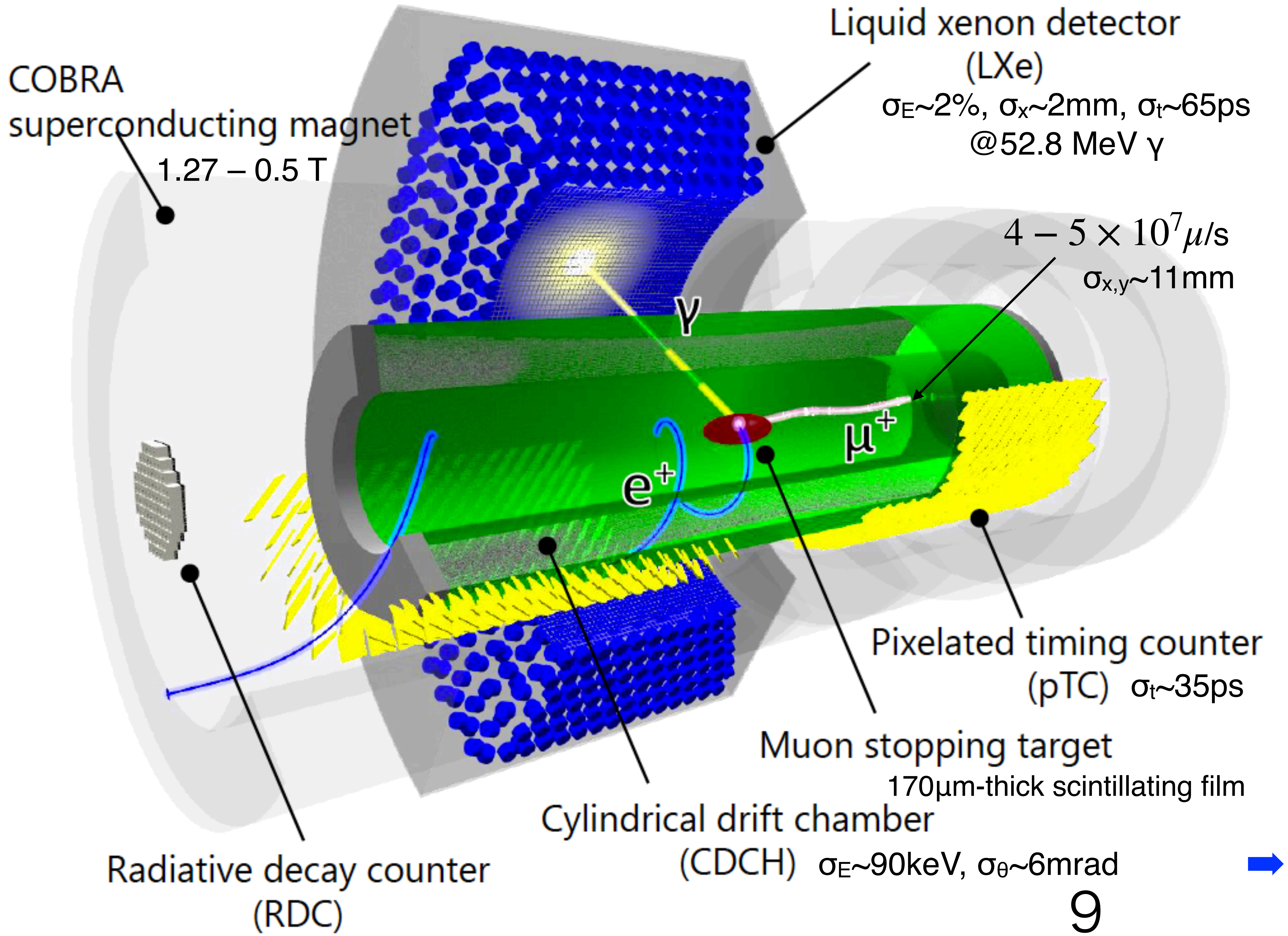
Vector: Leptoquarks, …



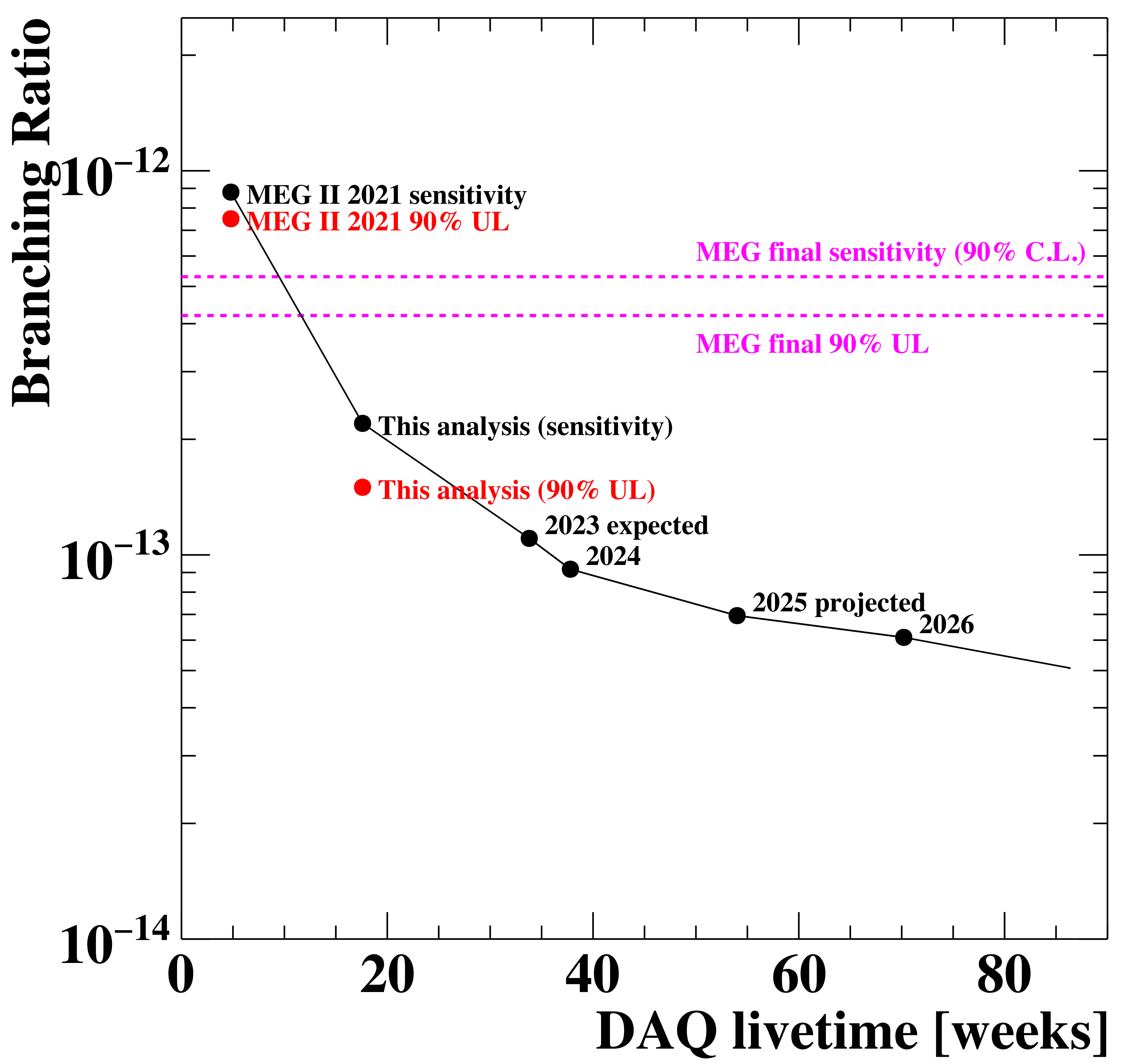
4-lepton:
Type II seesaw, RPV SUSY,
LRSM, …

Current running experiment

MEG II experiment @ PSI in Switzerland

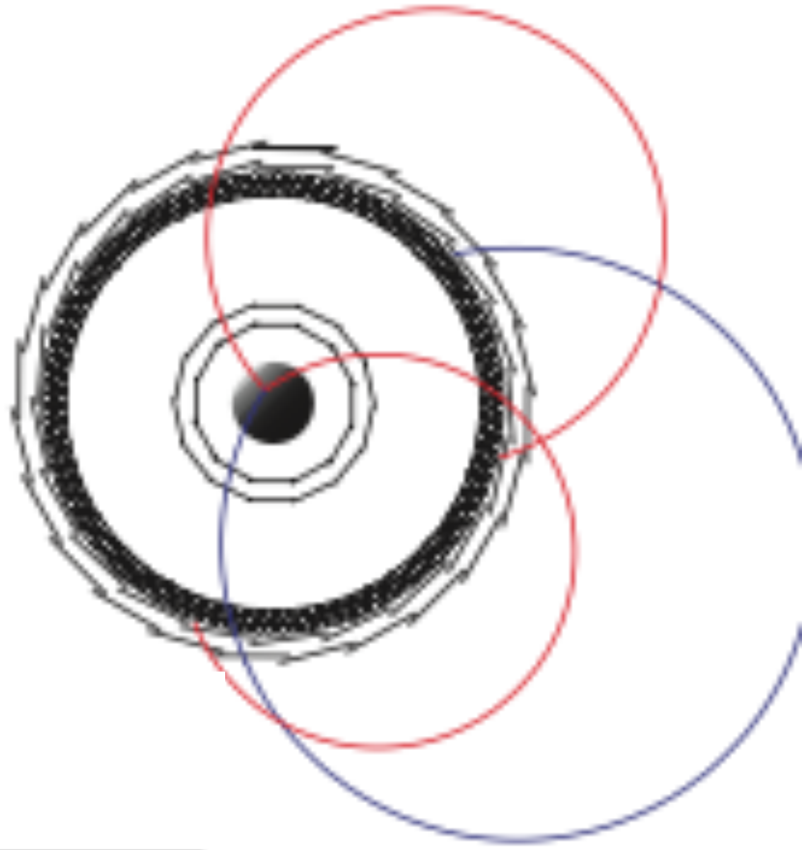


MEG II expected sensitivity



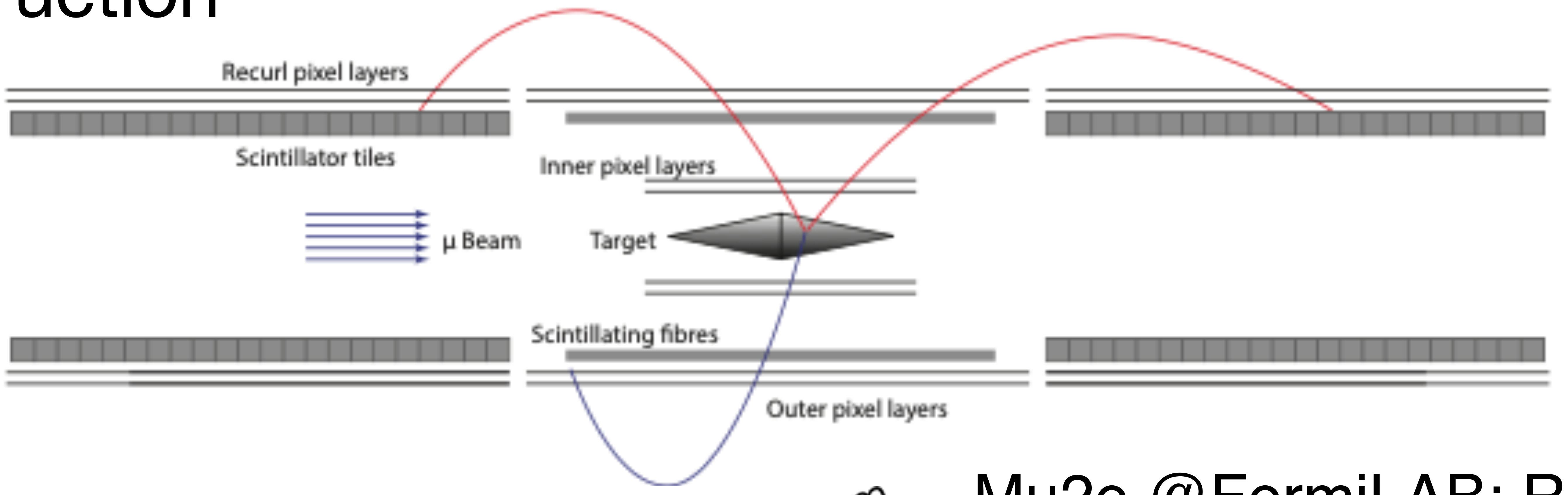
➡ test NP at mass scales above ~10^4 TeV

Experiments about to begin

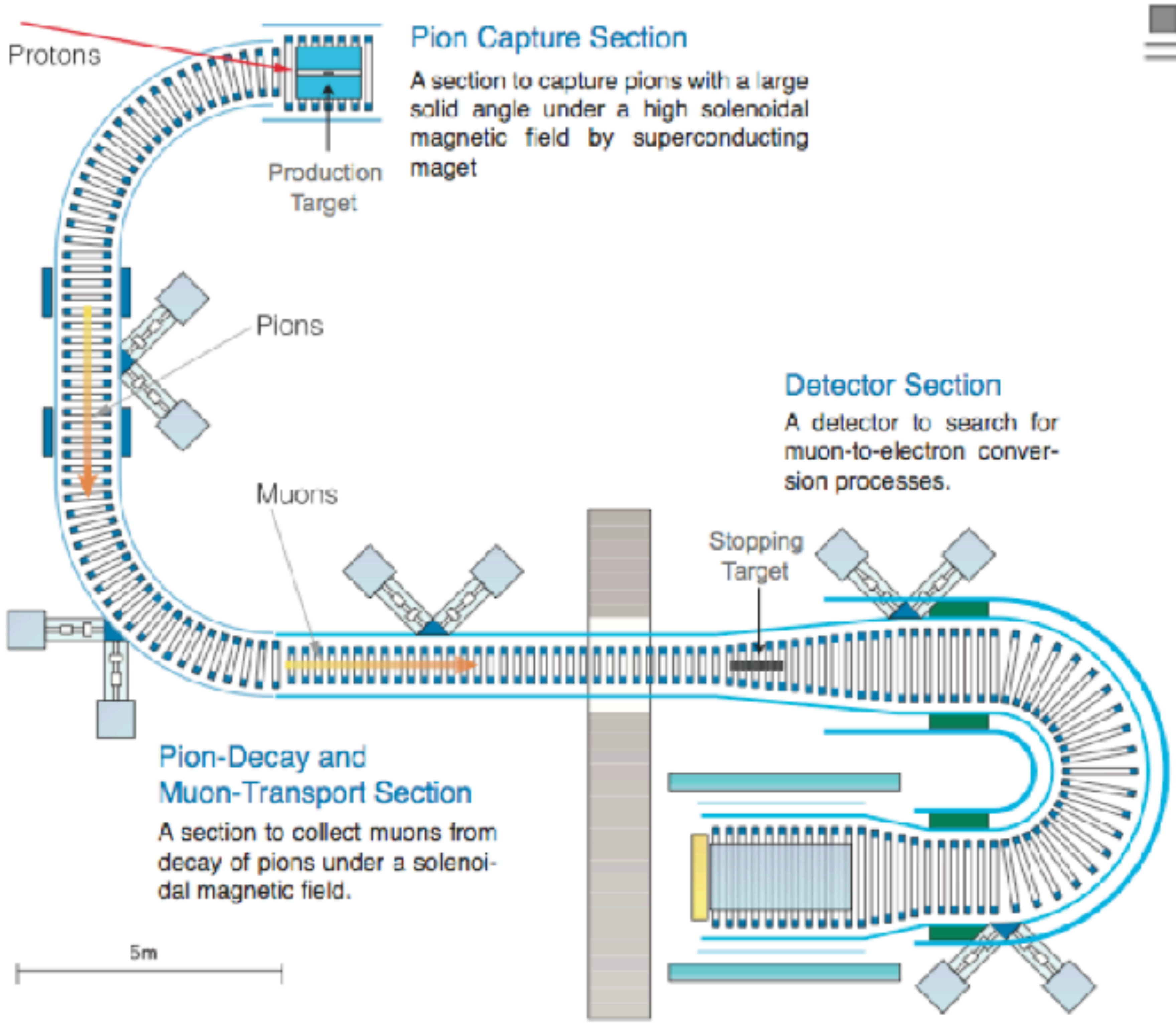


- Mu3e phase I, Mu2e-I, COMET: finalizing the detector construction

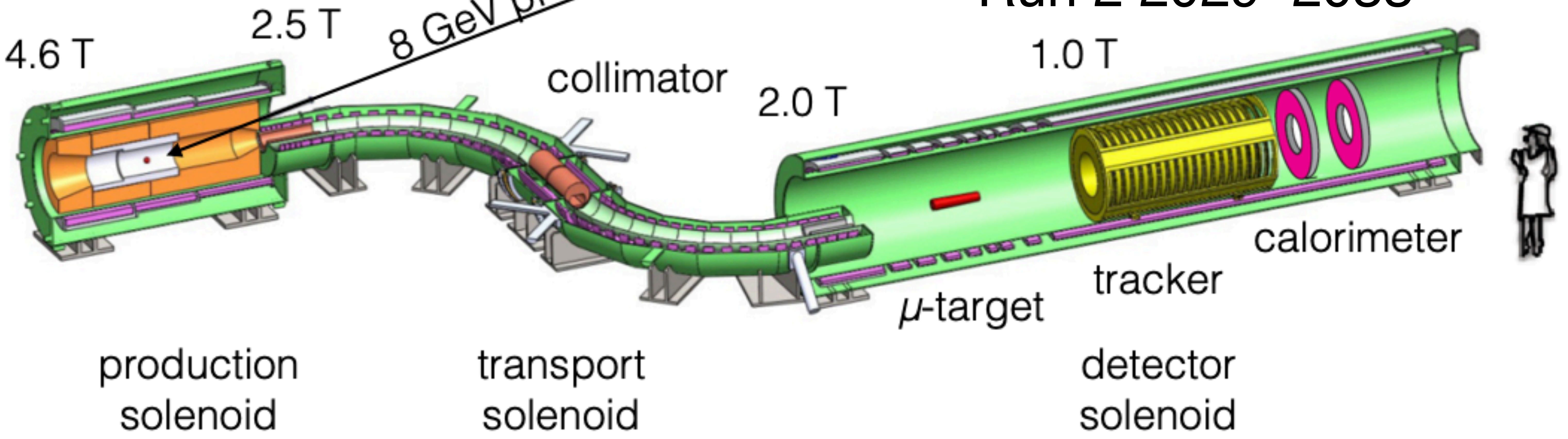
Mu3e-I @ PSI: 2026, 2029–



COMET Phase-I :
2026– @J-PARC



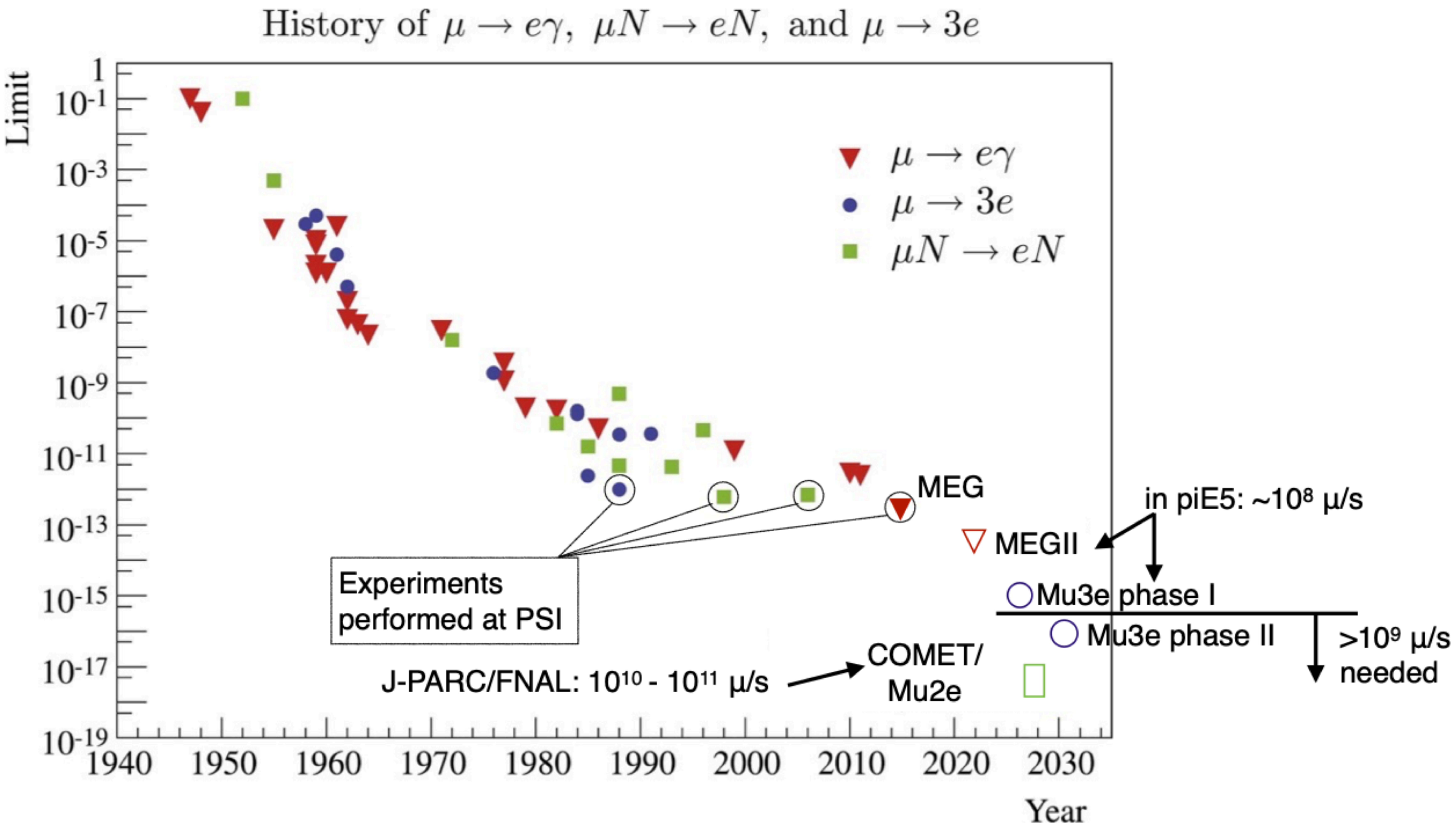
Mu2e @FermiLAB: Run 1 2026
Run 2 2029–2033



Exciting results will be available in 2030s

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

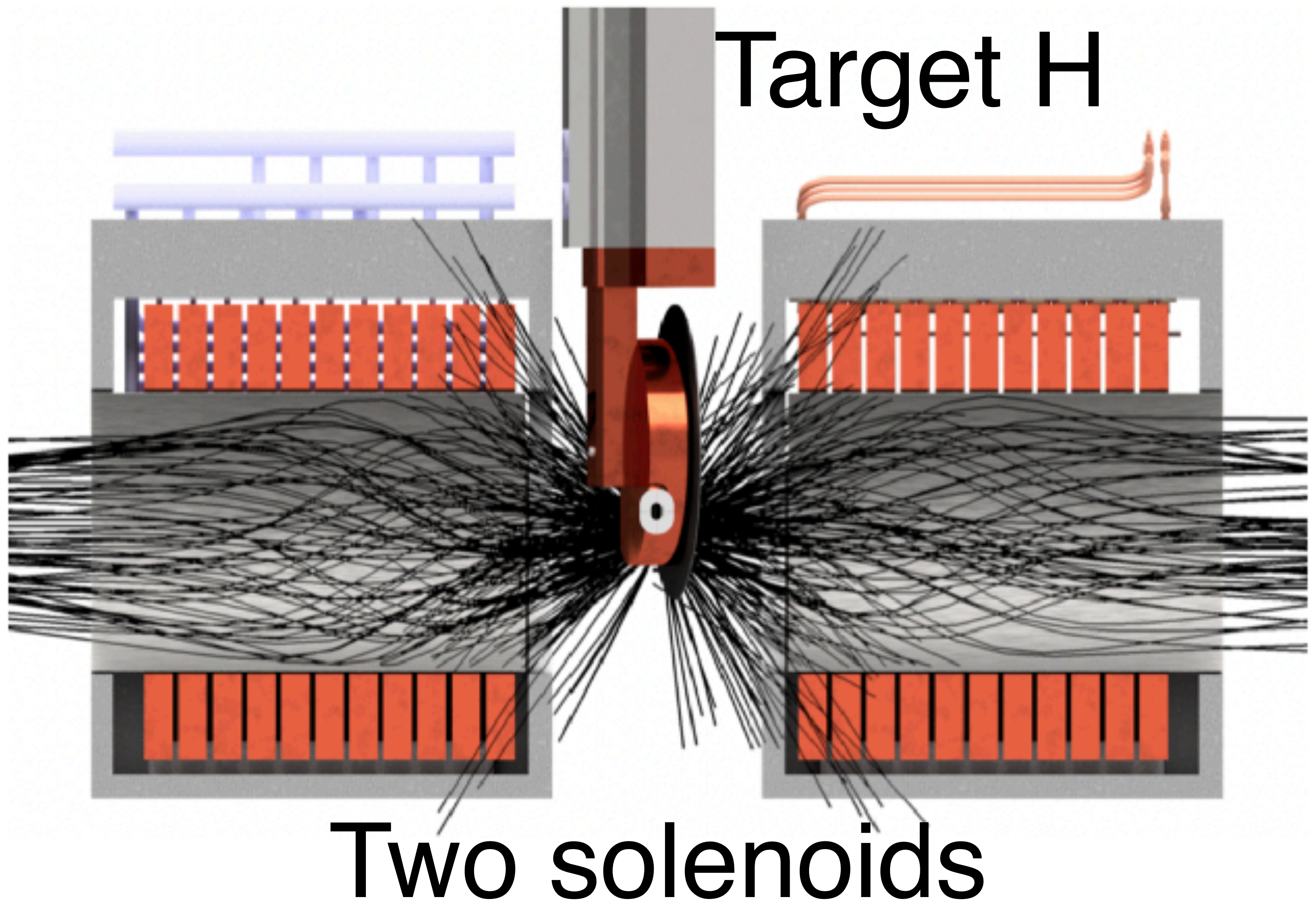
- Golden channels
  - High intensity muon beam
  - Clean signature
- Synergy to look for these decay modes at the same time
  - Maximize the discovery potential to different new physics model
  - Pin down the new physics model with independent branching ratio values after the discovery

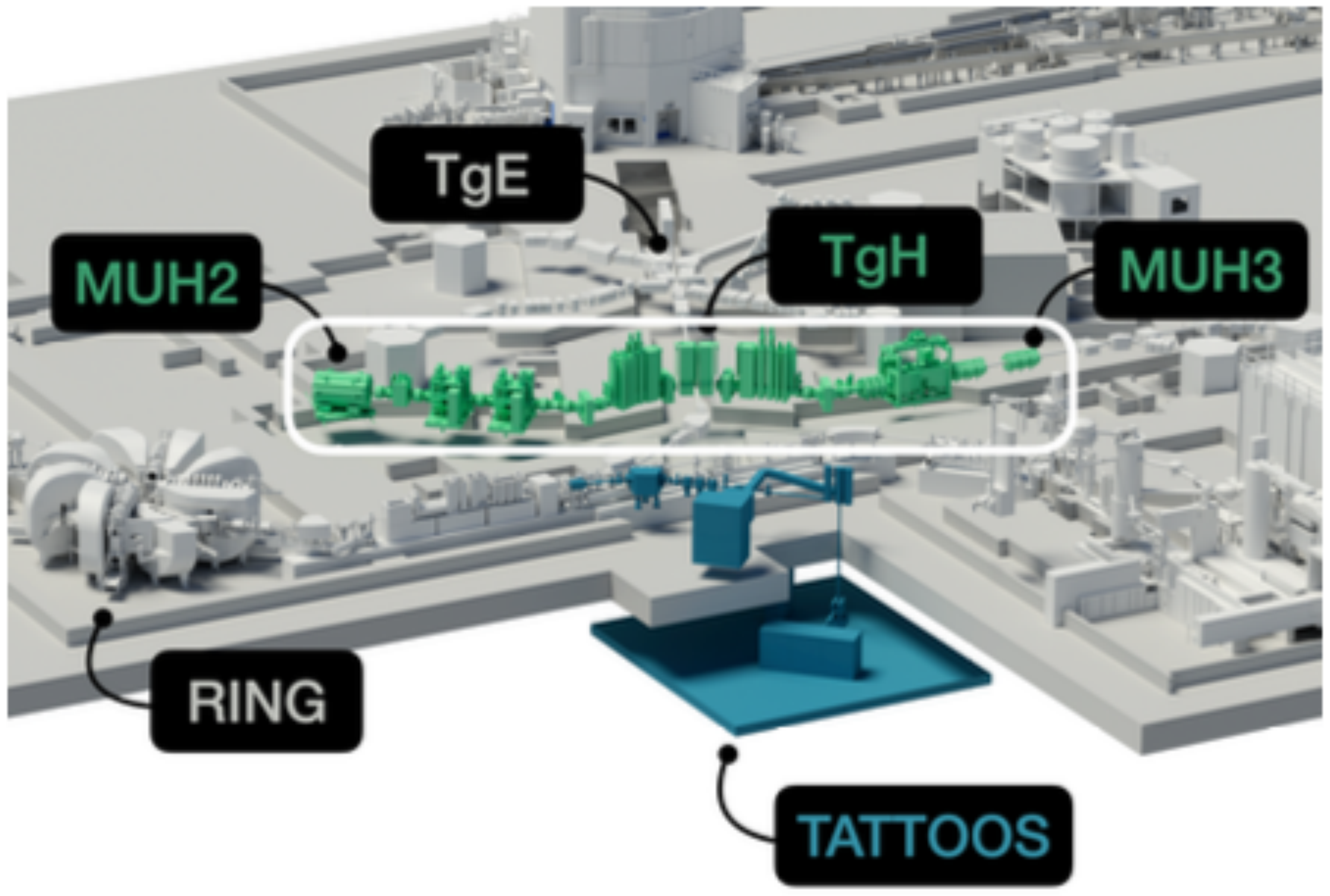


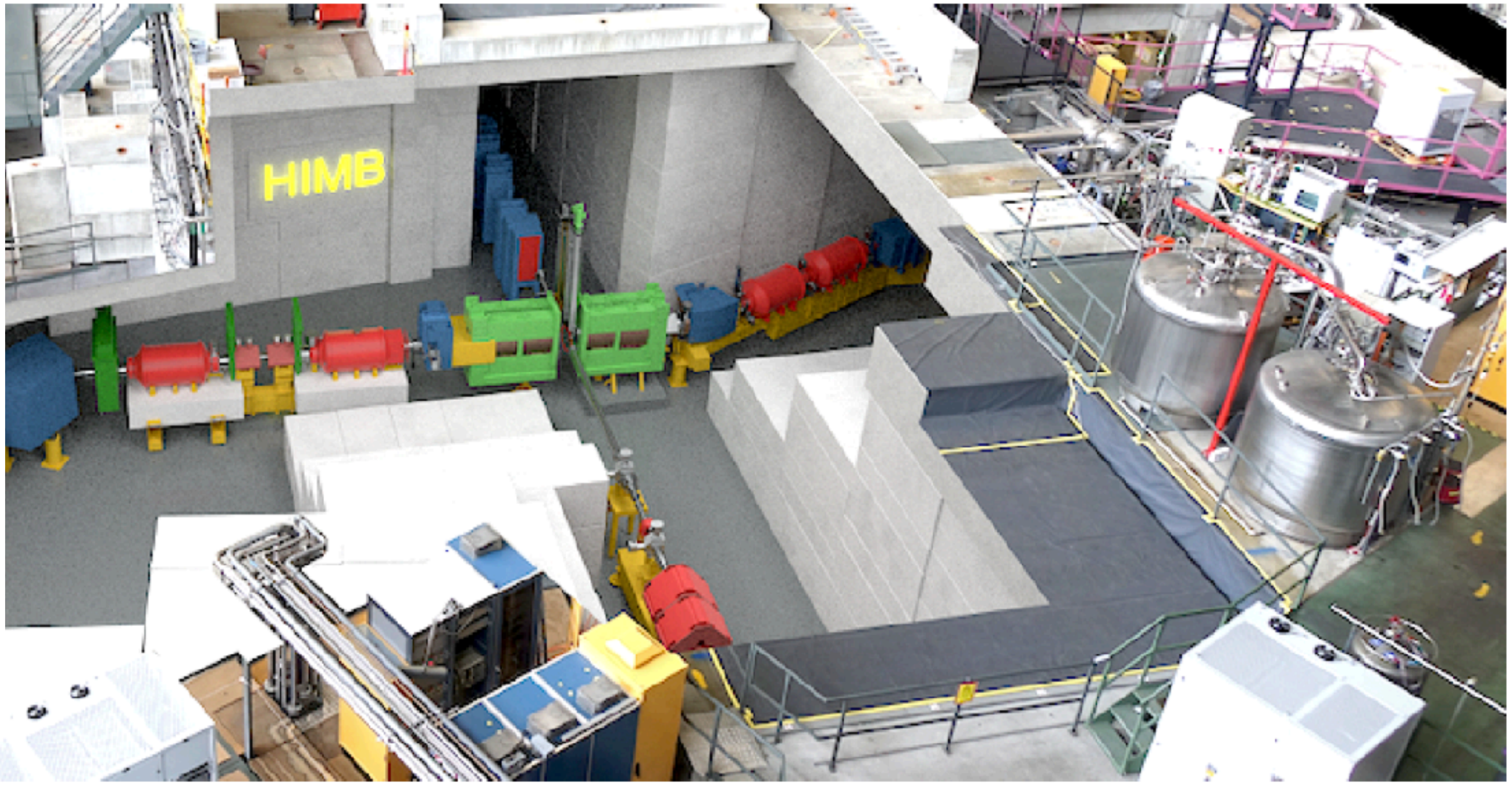
arXiv:2111.05788

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



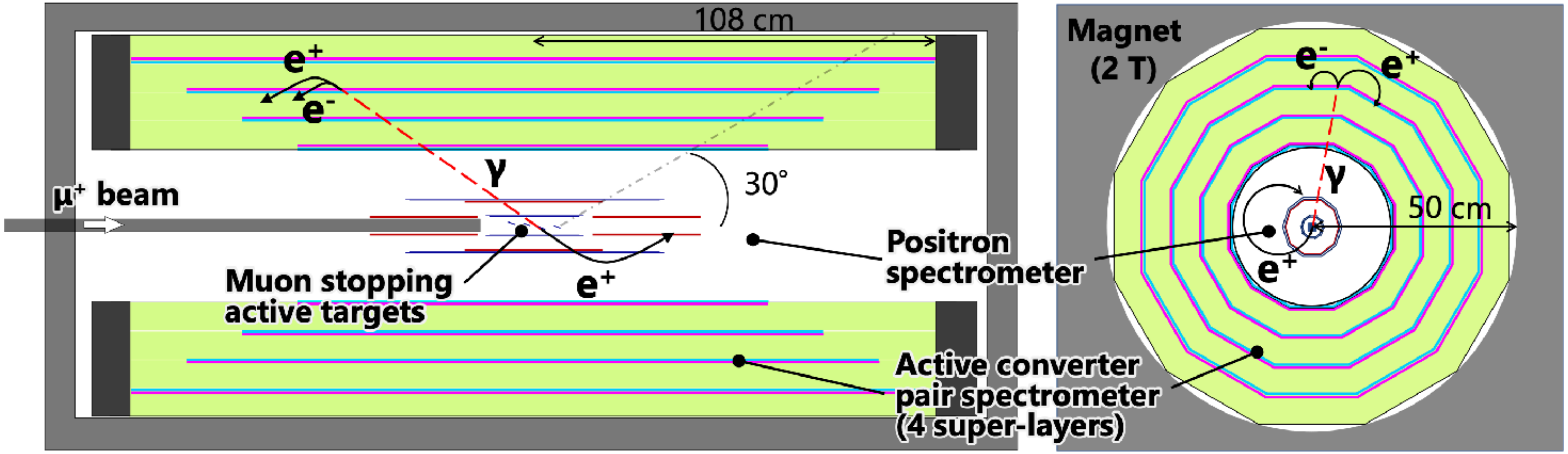




Future $\mu^+ \to e^+\gamma$

arXiv:2504.18831

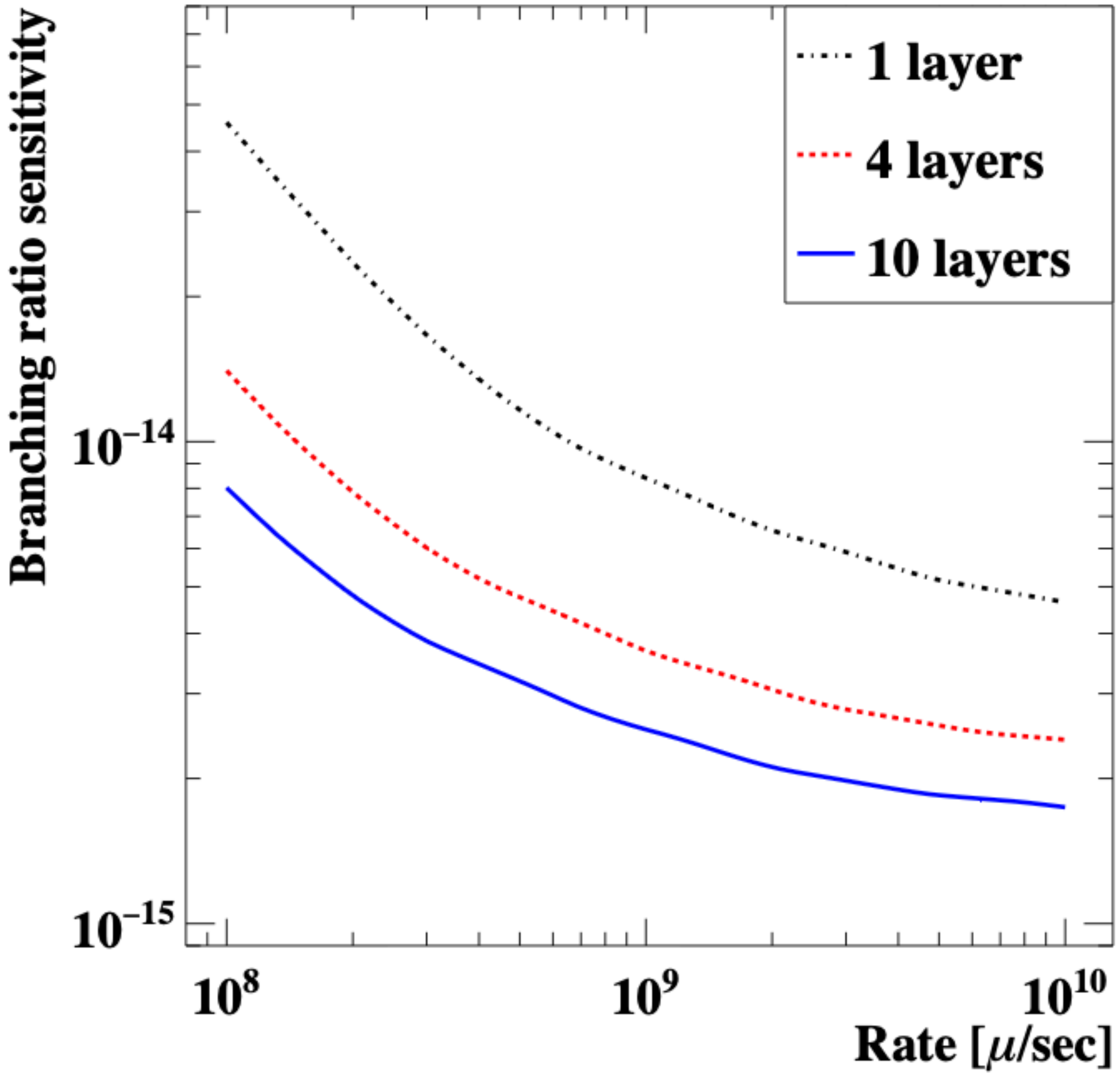
- Sensitivity of $\mu \to e\gamma$ searches is limited by the background from accidental coincidences
- Background scales with the square of the stopping muon rate, improvement in the detector resolutions inevitable to exploit beam rates up to 10^9-10^{10} μ/s
- Large acceptance to gain the statistics while beam intensity is kept as low as possible
- R&D of new detector concept (resolutions, efficiency, rate capability) is underway
  - Based on photon pair spectrometer with active converter, Silicon detector (like Mu3e) for positron, larger acceptance



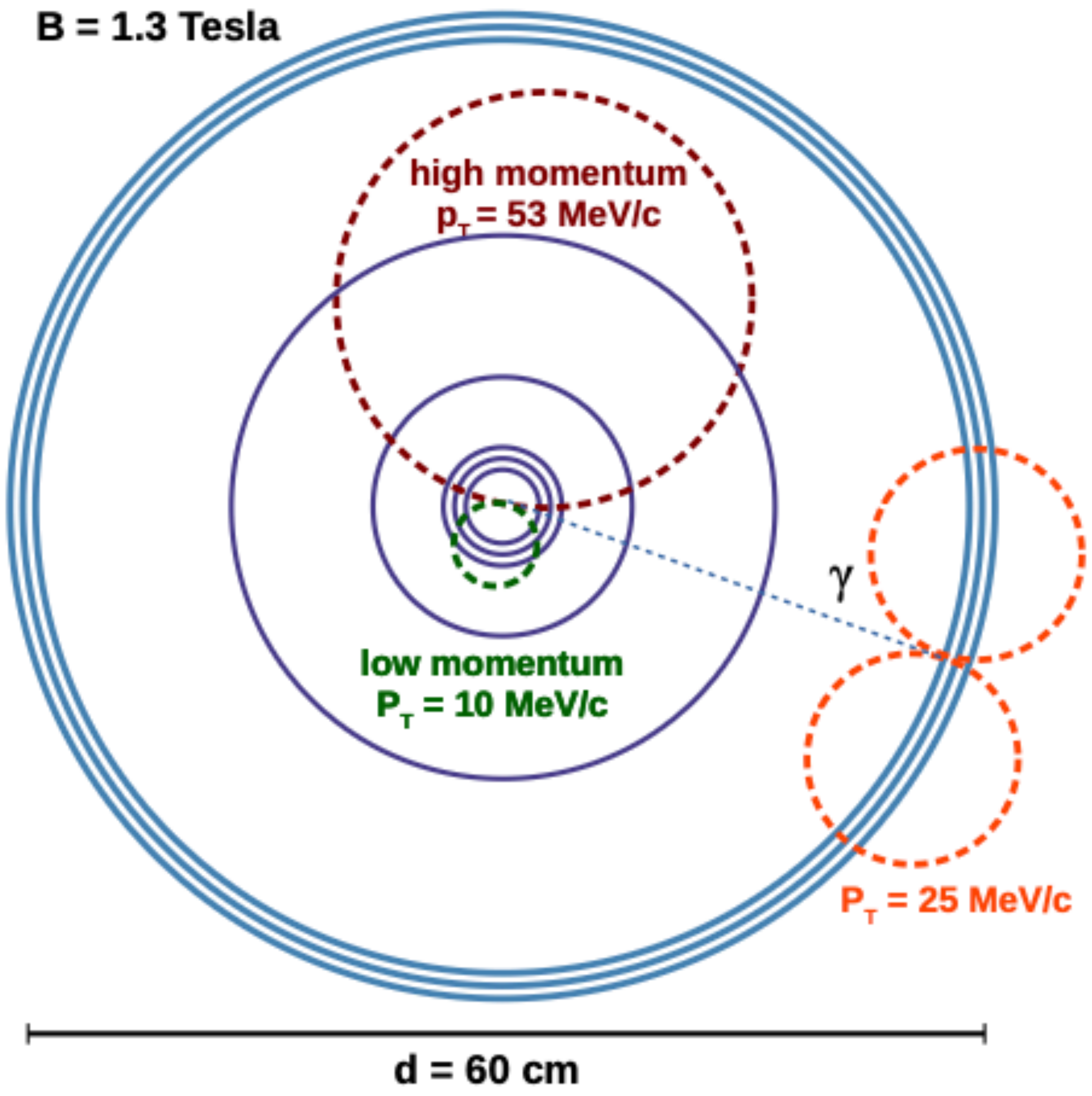
Sensitivity for future $\mu^+ \to e^+\gamma$

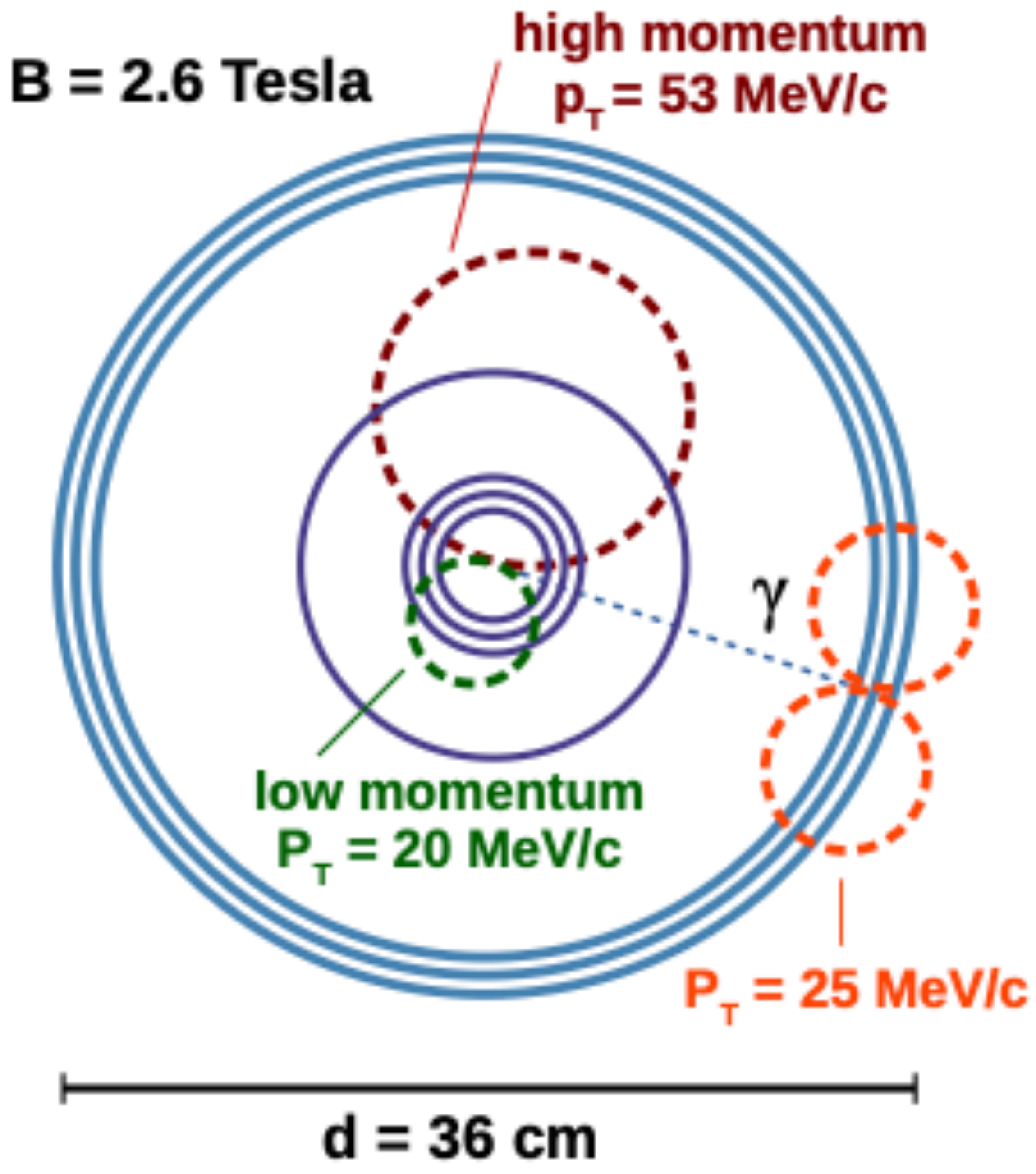
- Assumption
  - Five separate stopping targets
  - Detector performance in a table below
- (2–3) $\times 10^{-15}$ are reachable above $10^9 \mu^+$/s

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



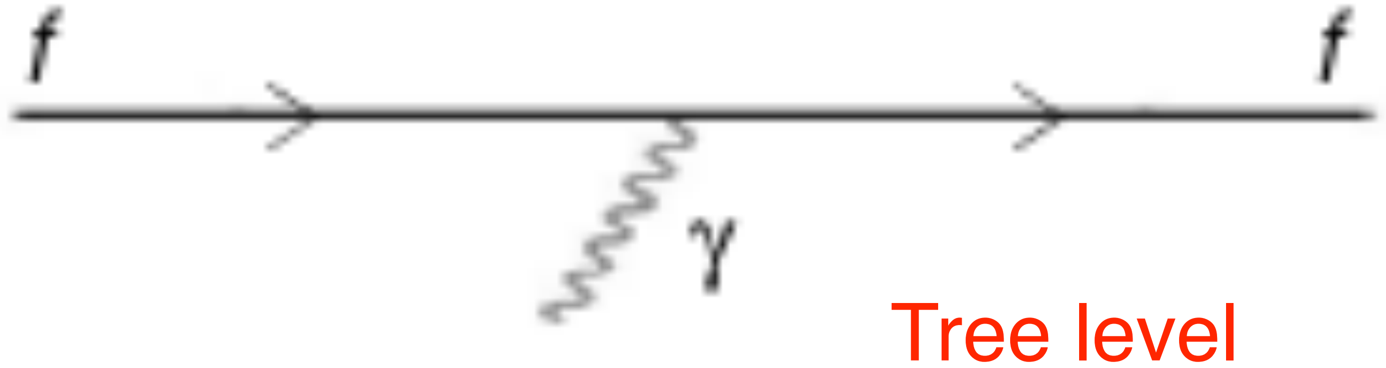


Open discussions on designs and technologies for future experiments. Currently the study group are mostly from MEG II and Mu3e, but always welcoming new participants

Muon g-2

- Dirac's equation for a point particle g-factor, $\vec{\mu} = g\frac{e}{2m}\vec{S}$, gives $g \equiv 2$

Leading (Dirac) term: g = 2

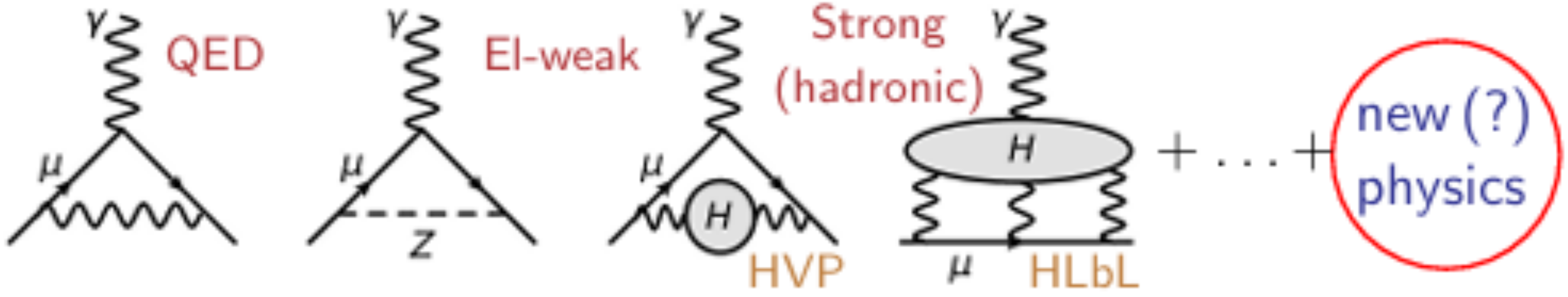


Tree level

$+$ higher (loop) terms $\Rightarrow$ magnetic anomaly: $a = \frac{g-2}{2} \neq 0$

Quantum fluctuations

Leading order processes contributing to a_μ:



- $\frac{\Delta a_\mu^{SM}}{a_\mu^{SM}} = 369 \times 10^{-9}$ (369 ppb in 2020)

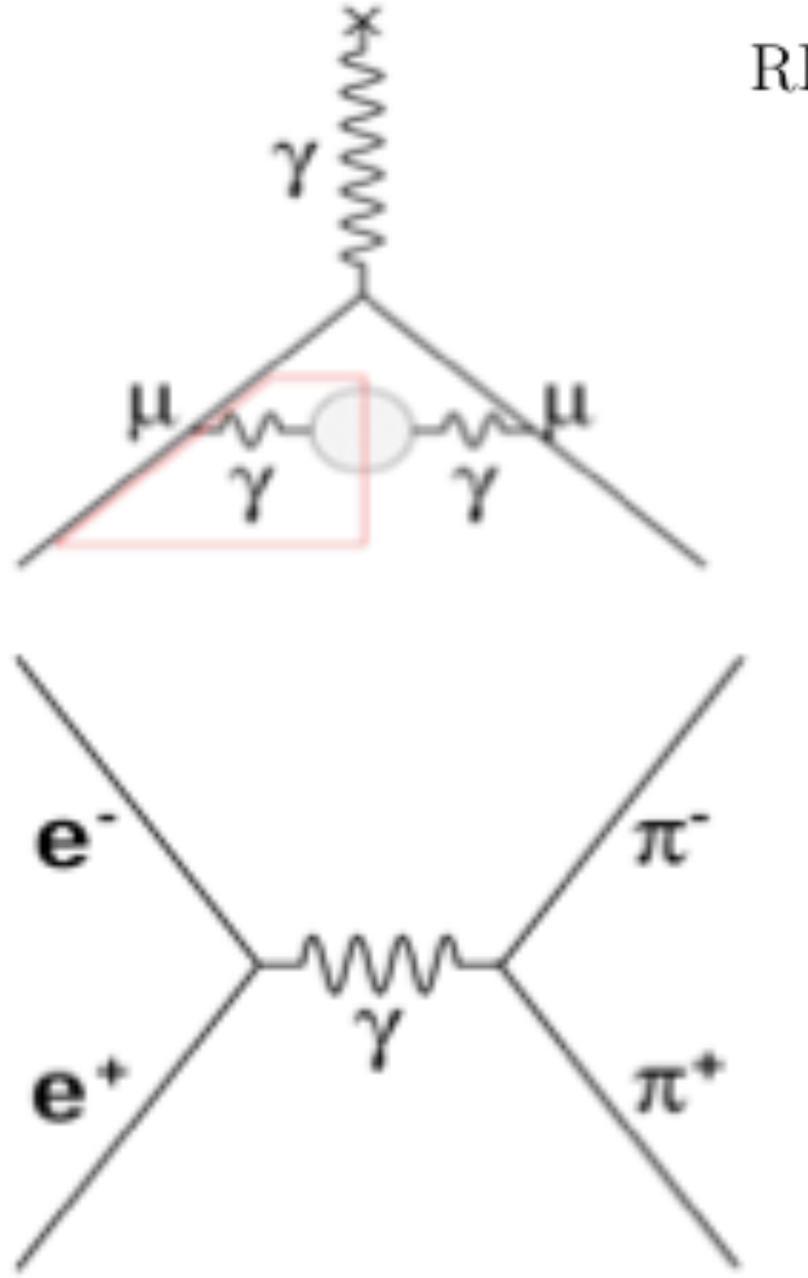
a_μ term	value ($\times 10^{-11}$)	uncert.	
QED	116,584,718.931	0.104	
El-weak	153.6	1.0	
HVP	6 845	40	0.6%
HLbL	92	18	
Total SM	116,591,810	43	

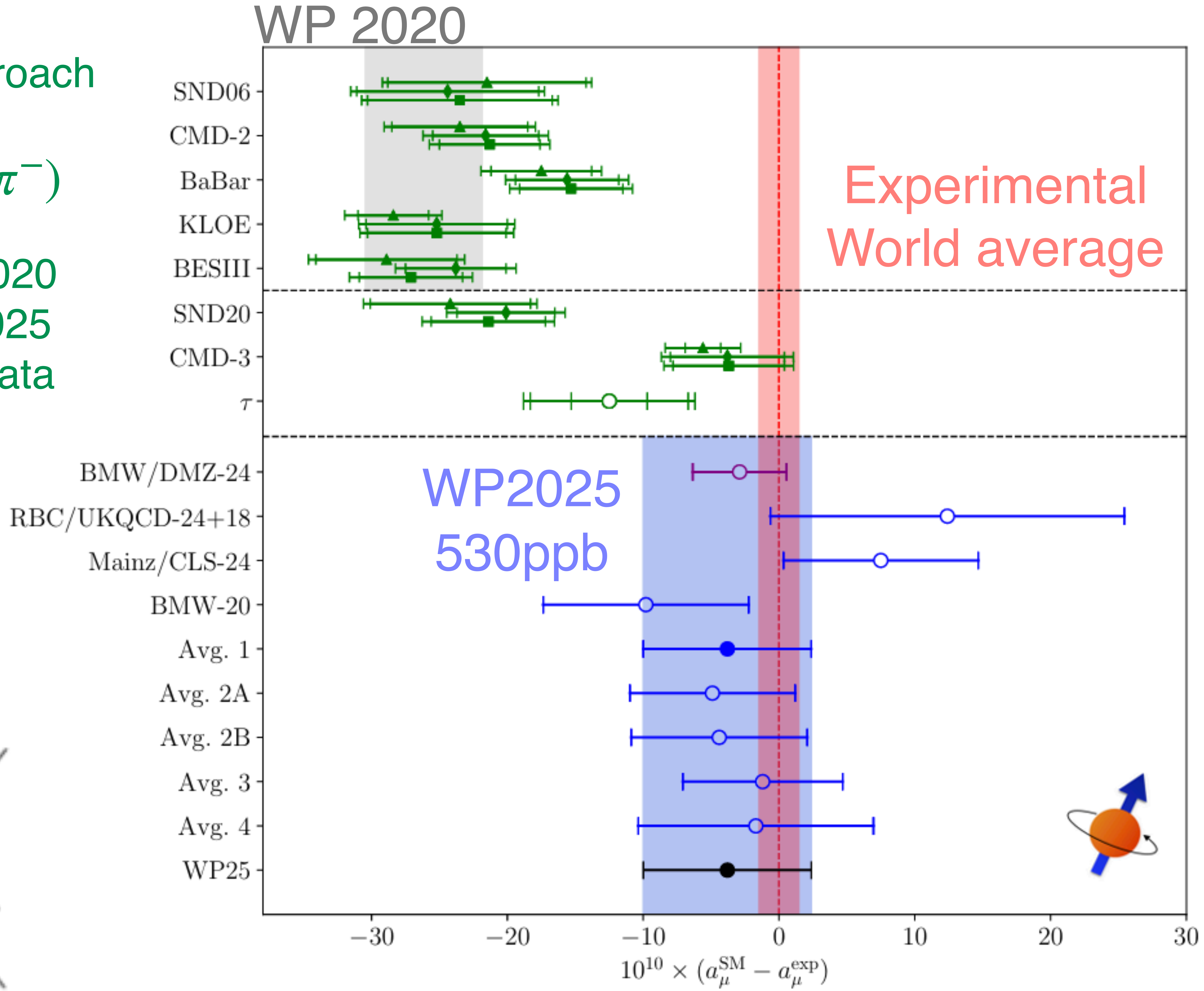
Muon g-2 summary

Dispersive approach for HVP

$\sigma(e^+e^- \to \pi^+\pi^-)$

Adopted in 2020
Tension in 2025
Need more data





Final precision
E989
127ppb

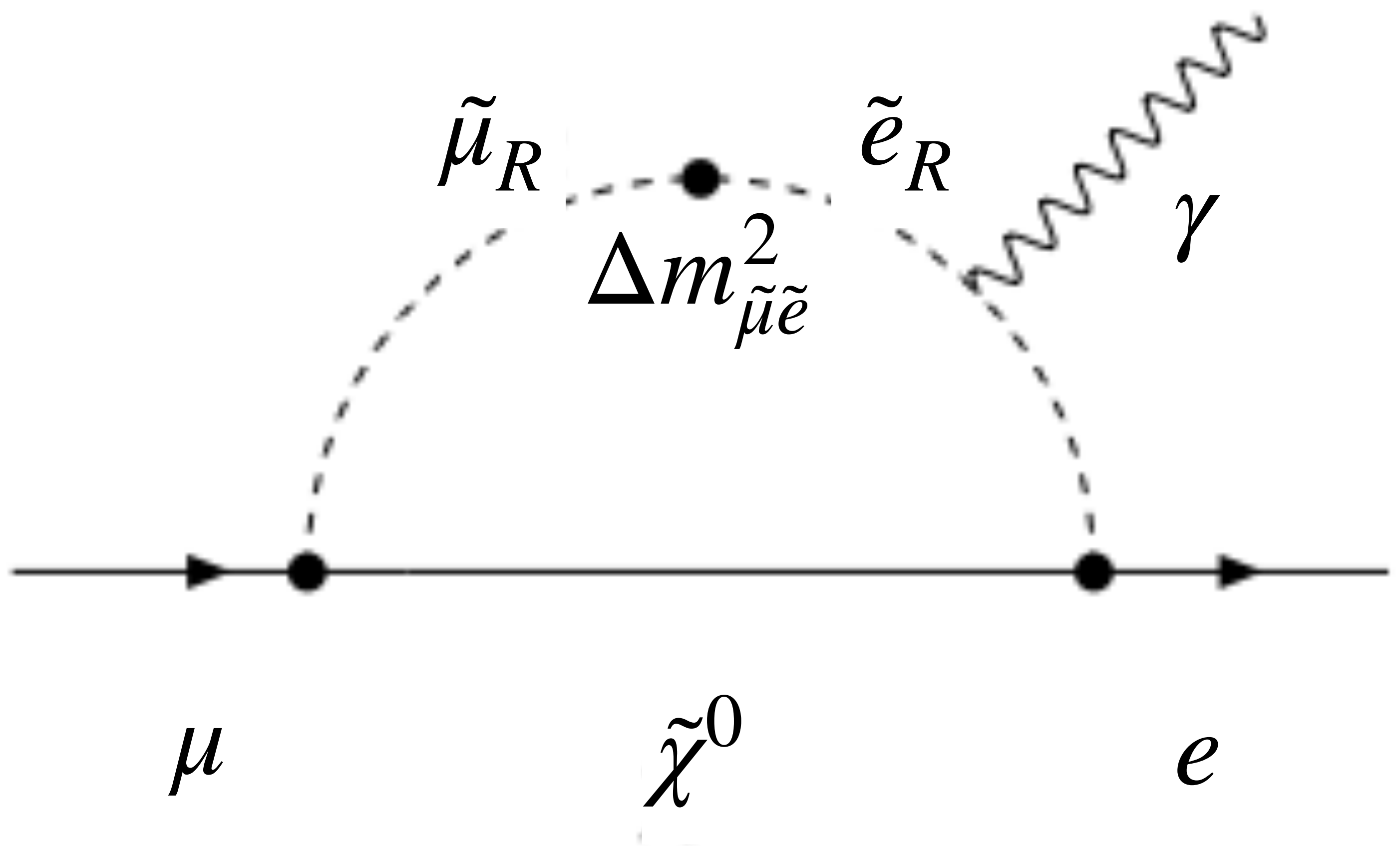
Lattice-QCD for HVP
not mature in 2020
Adopted in 2025

Further investigations are planned both from the theory and experimental sides

Relation between LFV, EDM, g-2

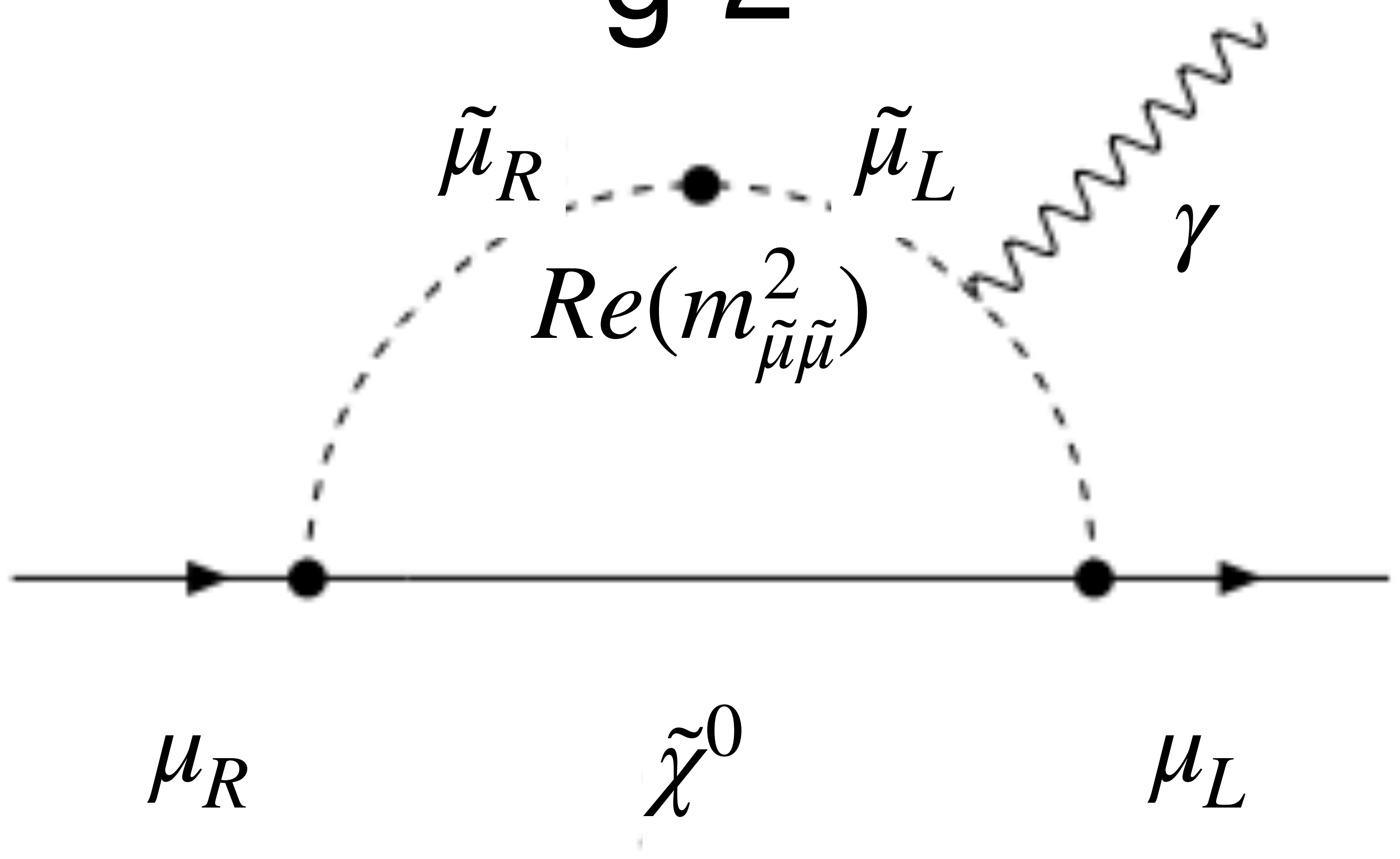
- In SUSY models, LFV processes are induced by the off-diagonal terms in the slepton mass matrices
  - EDM $\propto Im(m^2_{\tilde{e}\tilde{e}})$ or $Im(m^2_{\tilde{\mu}\tilde{\mu}})$
  - cLFV $\propto \Delta m^2_{\tilde{e}\tilde{\mu}} + \Delta m^2_{\tilde{\mu}\tilde{e}}$
  - g-2 $\propto Re(m^2_{\tilde{\mu}\tilde{\mu}})$

$\mu \to e\gamma$

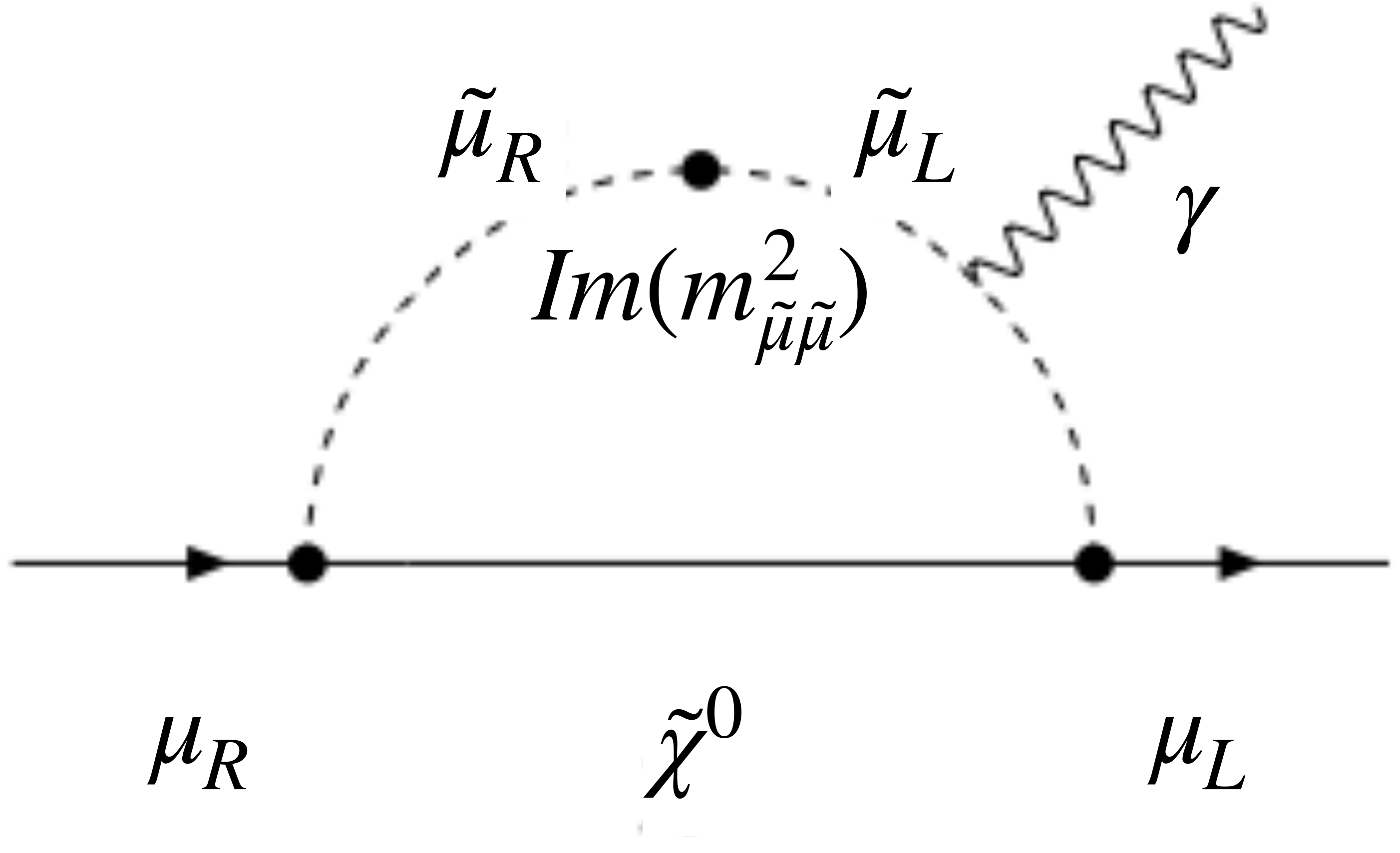


$$M^2_{\tilde{l}\tilde{l}} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

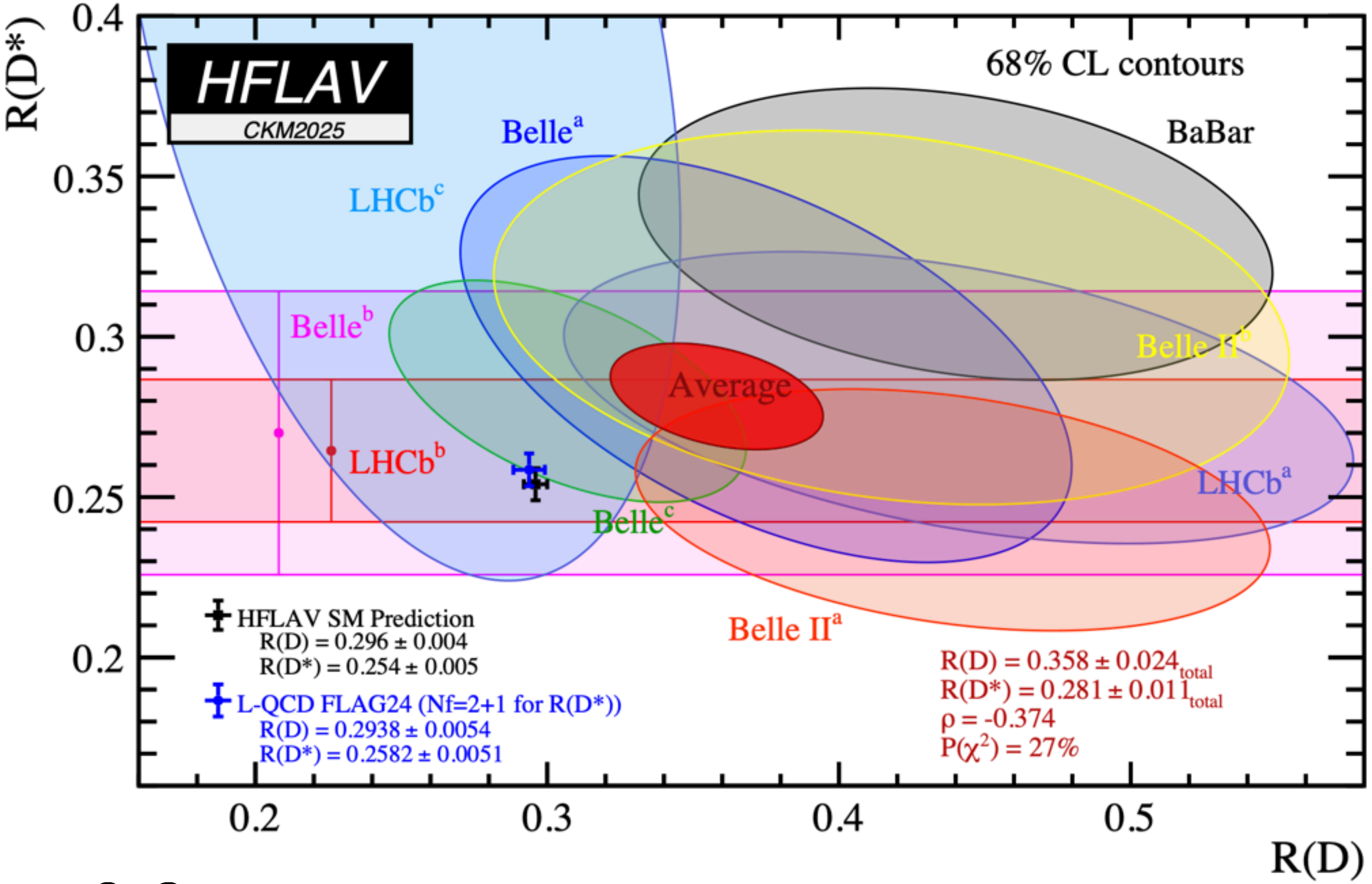
g-2



EDM

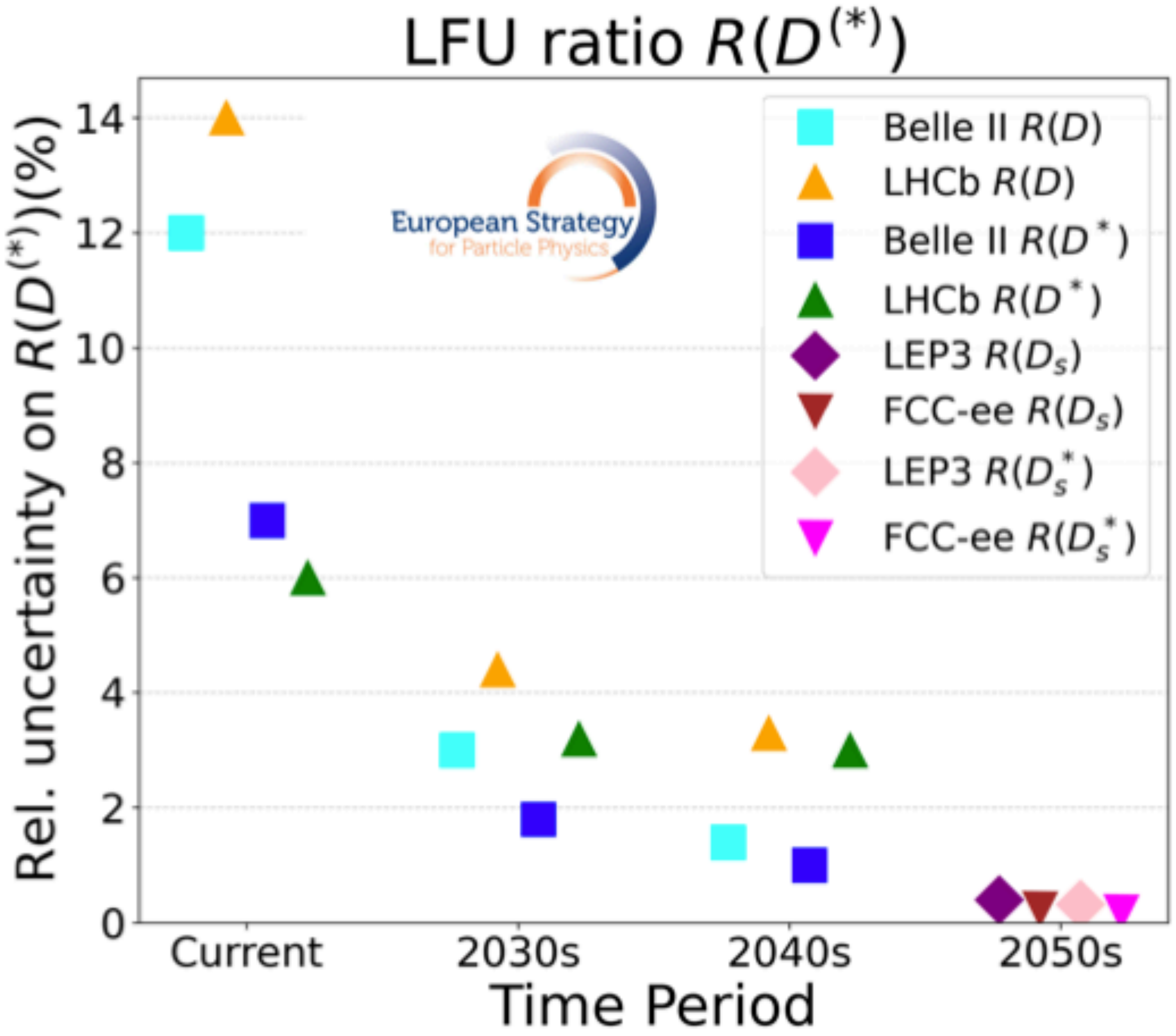


R(D) and R(D*) measurements



Belle II[a] = Had-tag
Belle II[b] = SL-tag

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$



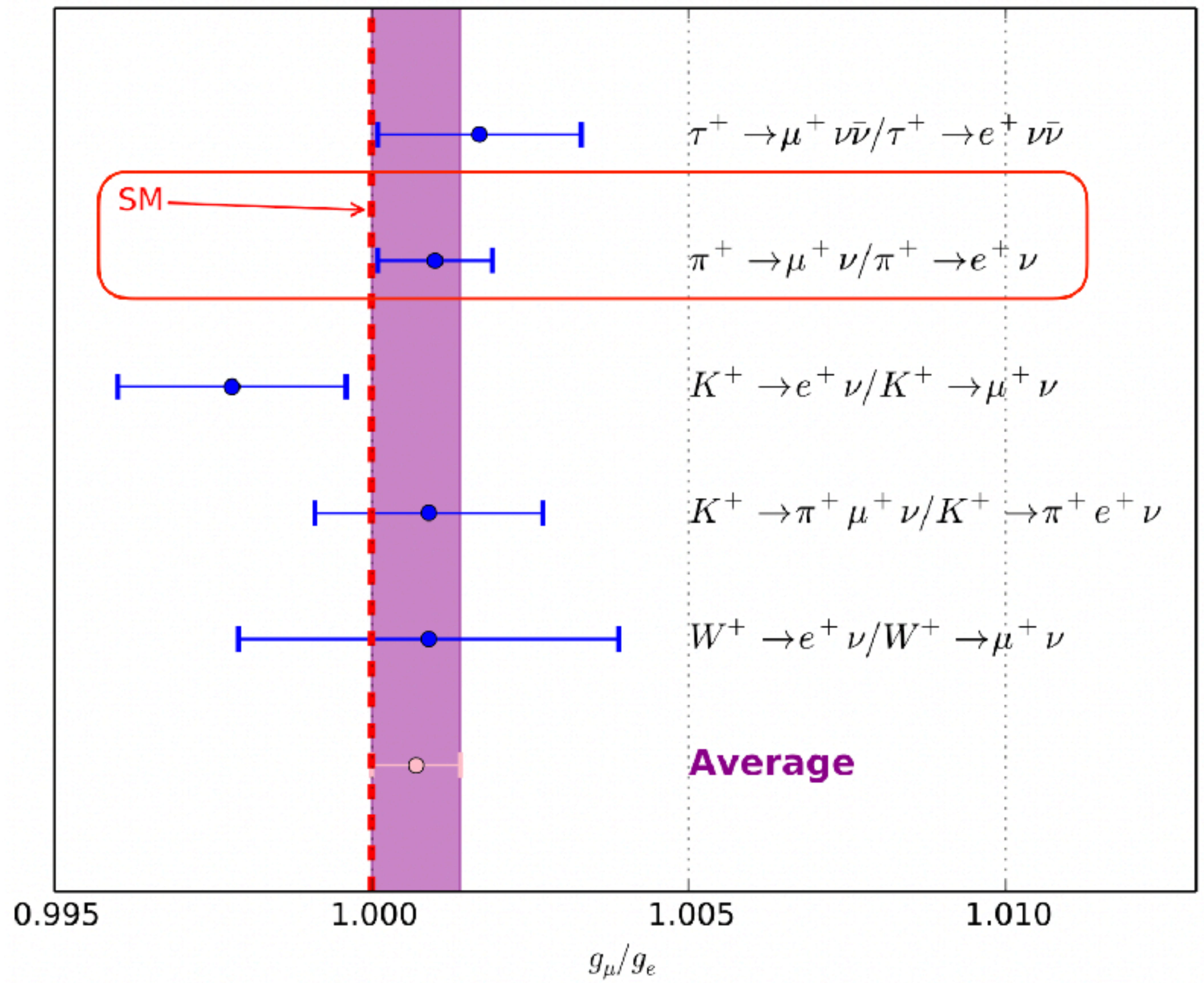
$\sim 3.8\sigma$ deviation

- Can be a hint of LFUV between τ and μ

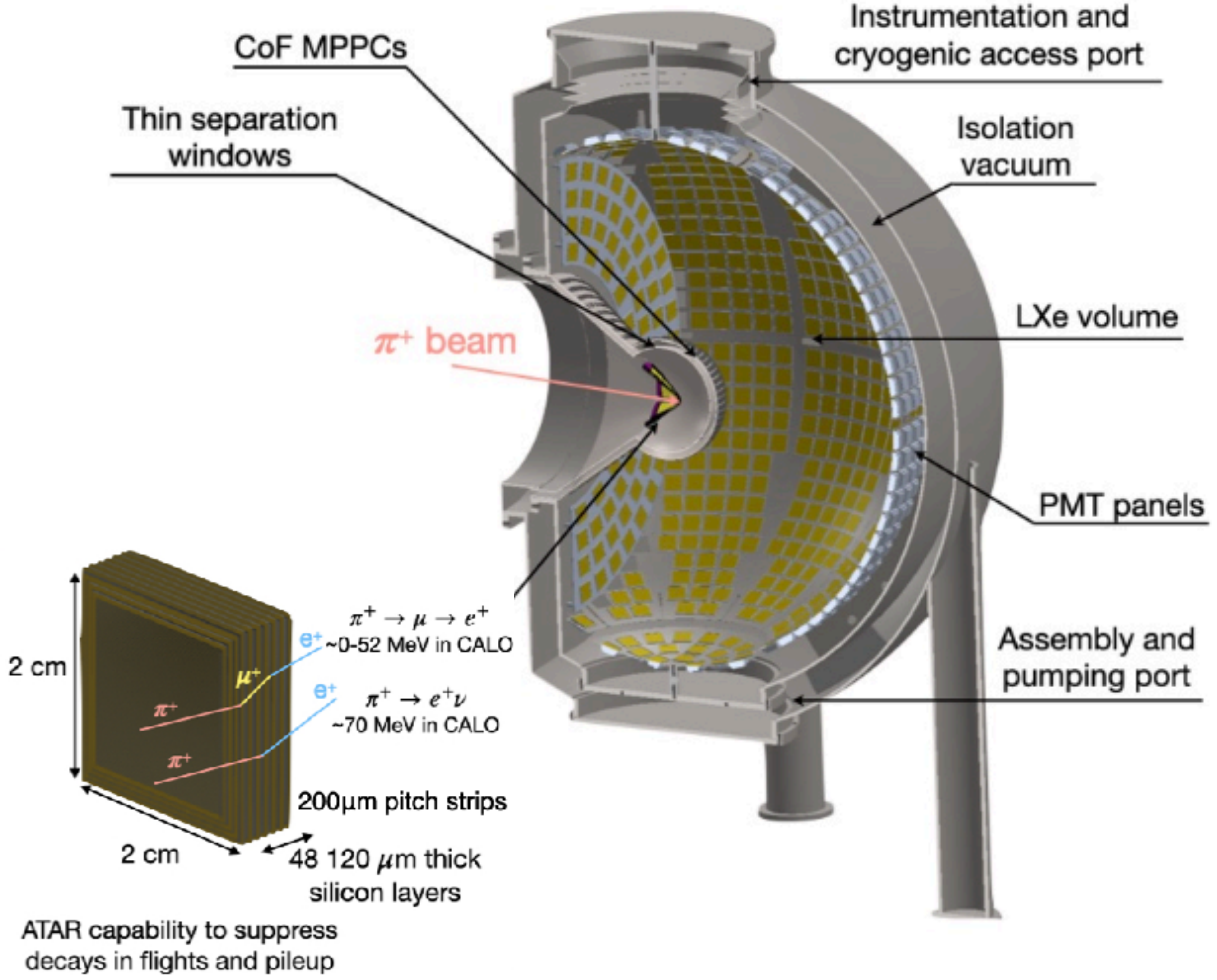
by Michele Veronesi
P2I Tuesday

arXiv: 2511.03883

Lepton universality check with pion



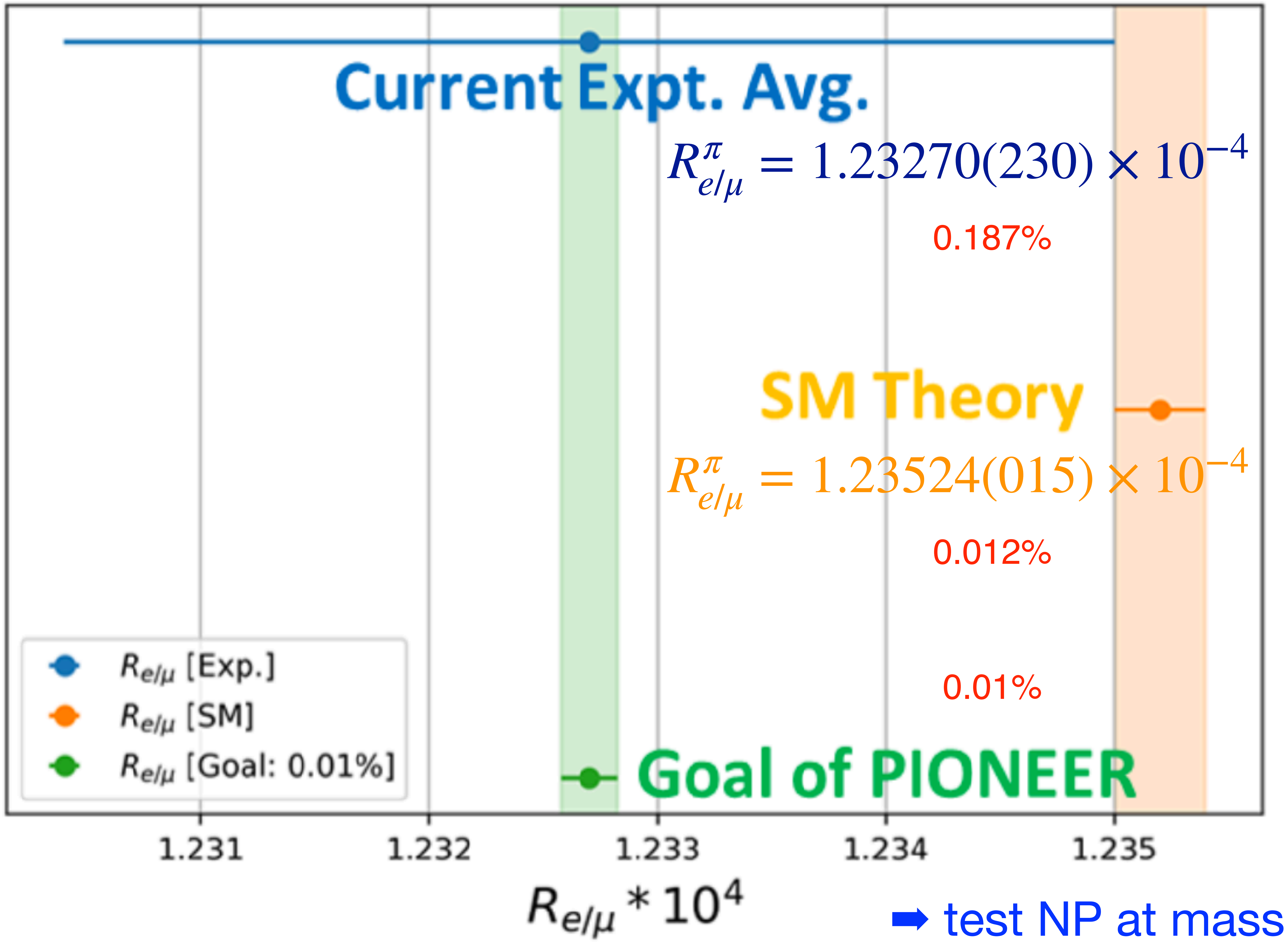
PIONEER experiment @ PSI



$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}_e(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))}$$ measurement

provides the best result so far to test LFU

PIONEER phase I goal

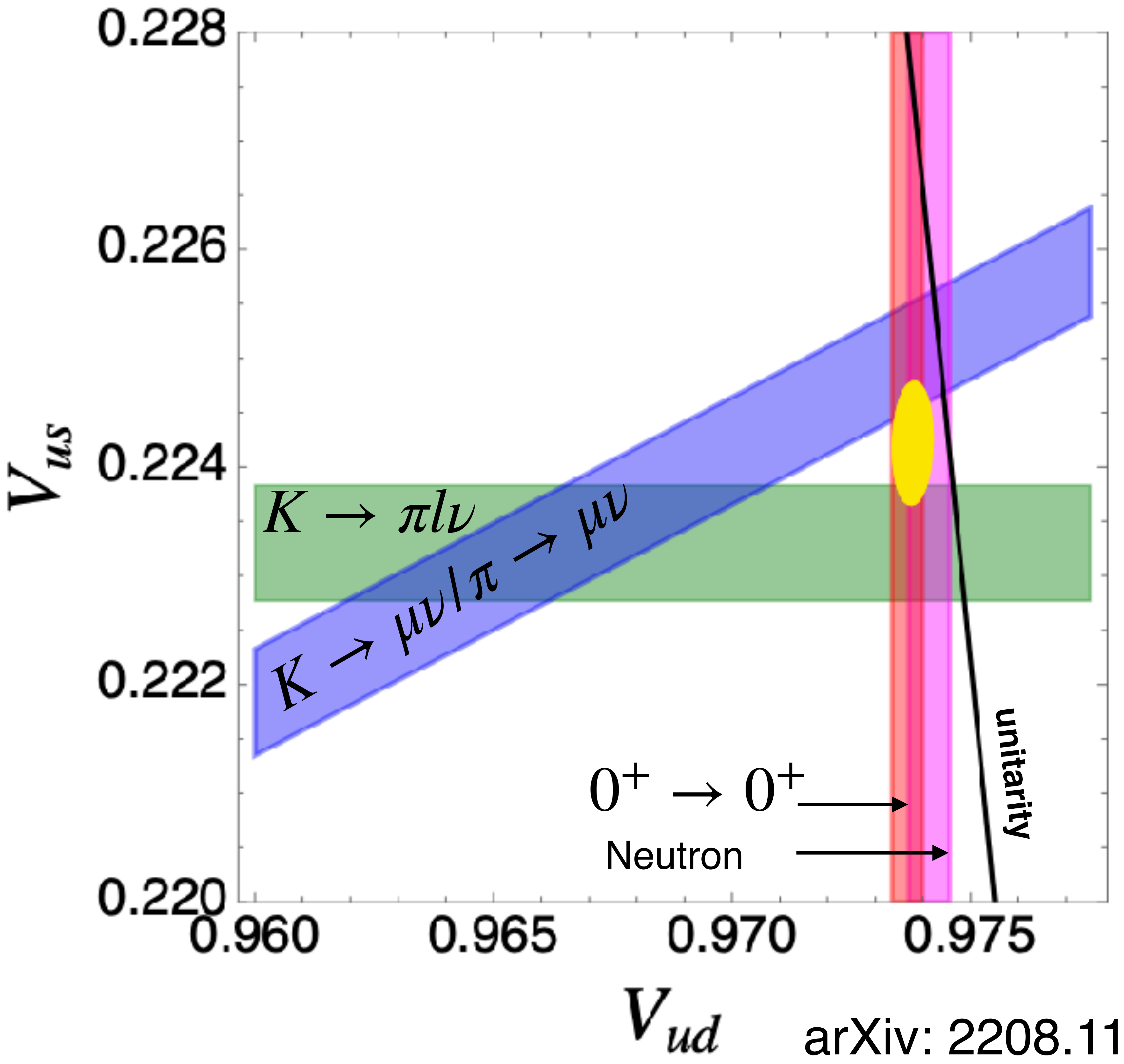


➡ test NP at mass scales ~10^3 TeV

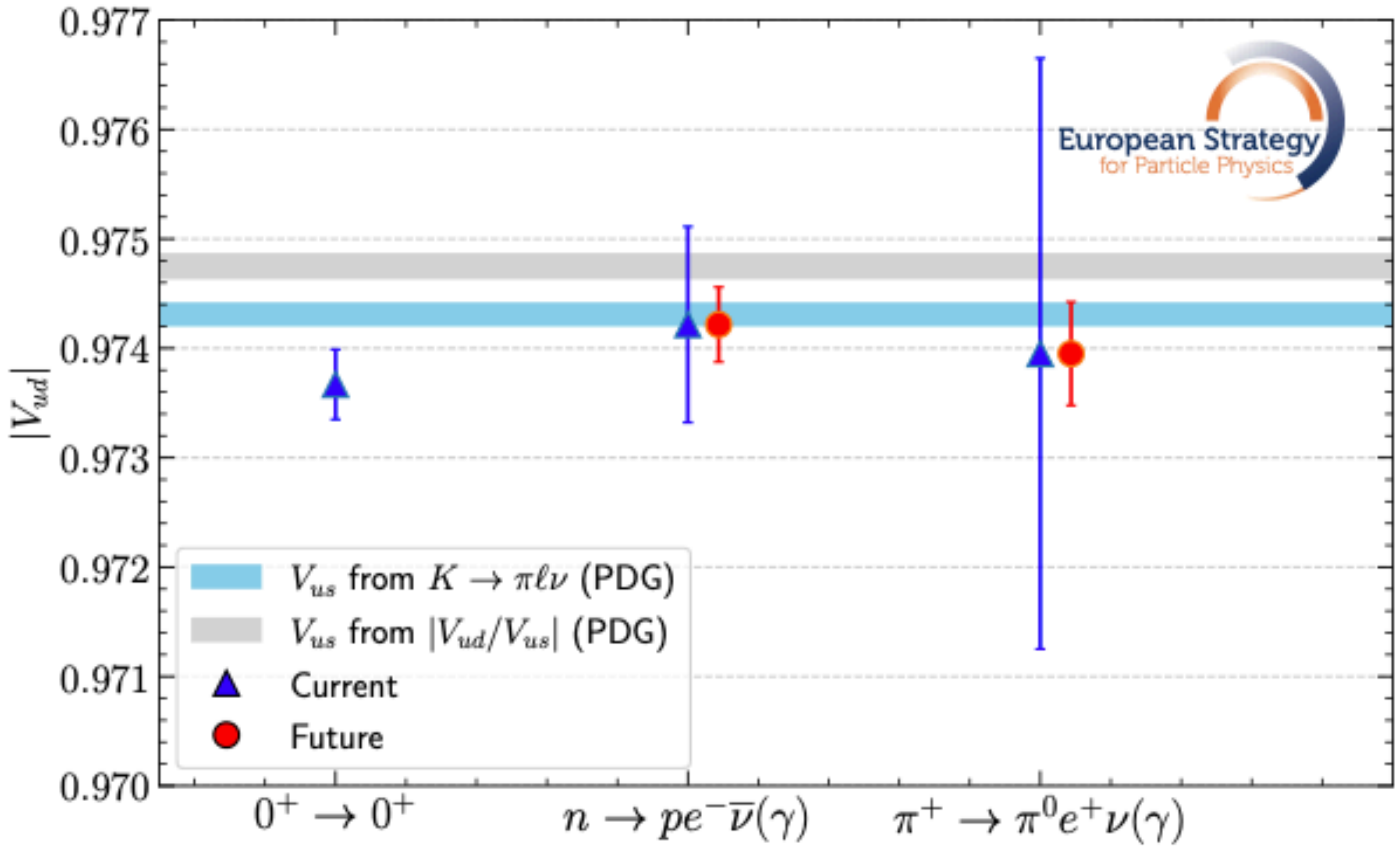
PIONEER phase II goal

Unitarity of the CKM matrix

$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$



arXiv: 2208.11707



arXiv: 2511.03883

~3σ deviation (Cabibbo Angle Anomaly)

This can also be interpreted as a LFUV

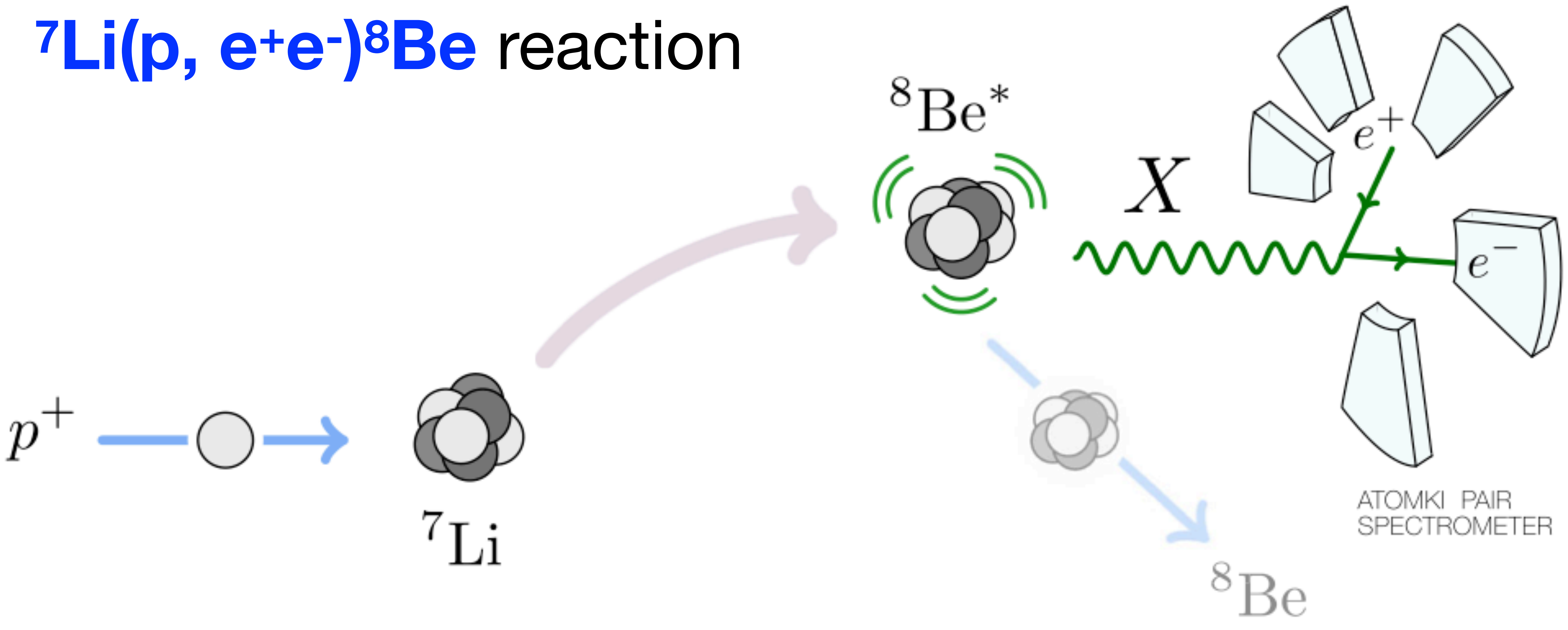
- V_{ud} from e, V_{us} from μ meas.

Summary

- Experiments using low energy (high intensity) accelerators can reach even higher energy new physics scale than highest energy accelerator.
- A wide variety of complementary experiments can play a role that is synergistic with high-energy frontier experiment. Since the energy scale of new physics remains unknown, this is a particularly important research area.
- Small-scale experiments including EDMs, LFV, g-2, LFUV are discussed here. These including mid- and large-scale experiments are an indispensable part of the future strategy for particle physics.

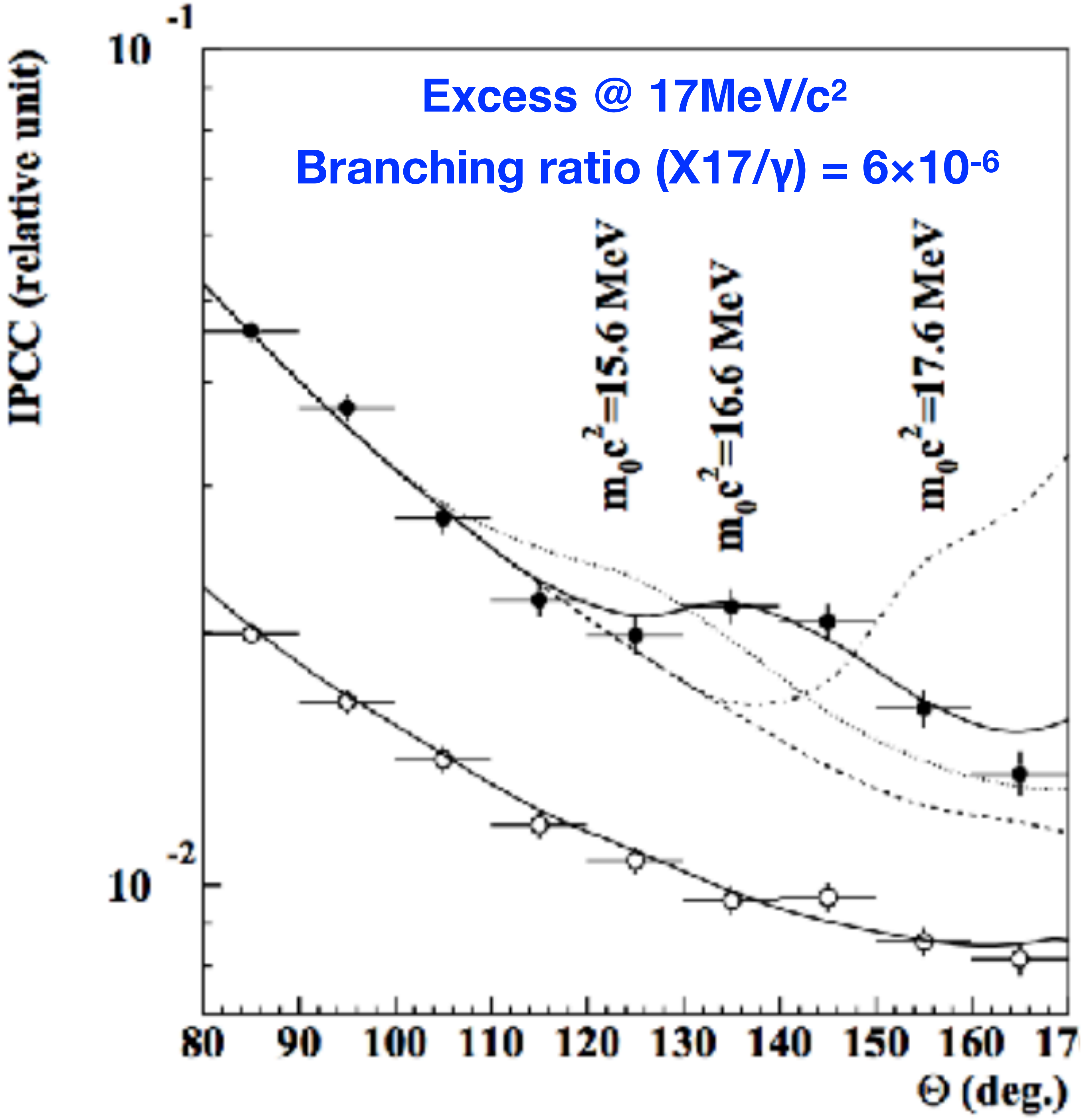
X17 boson search at MEG II

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

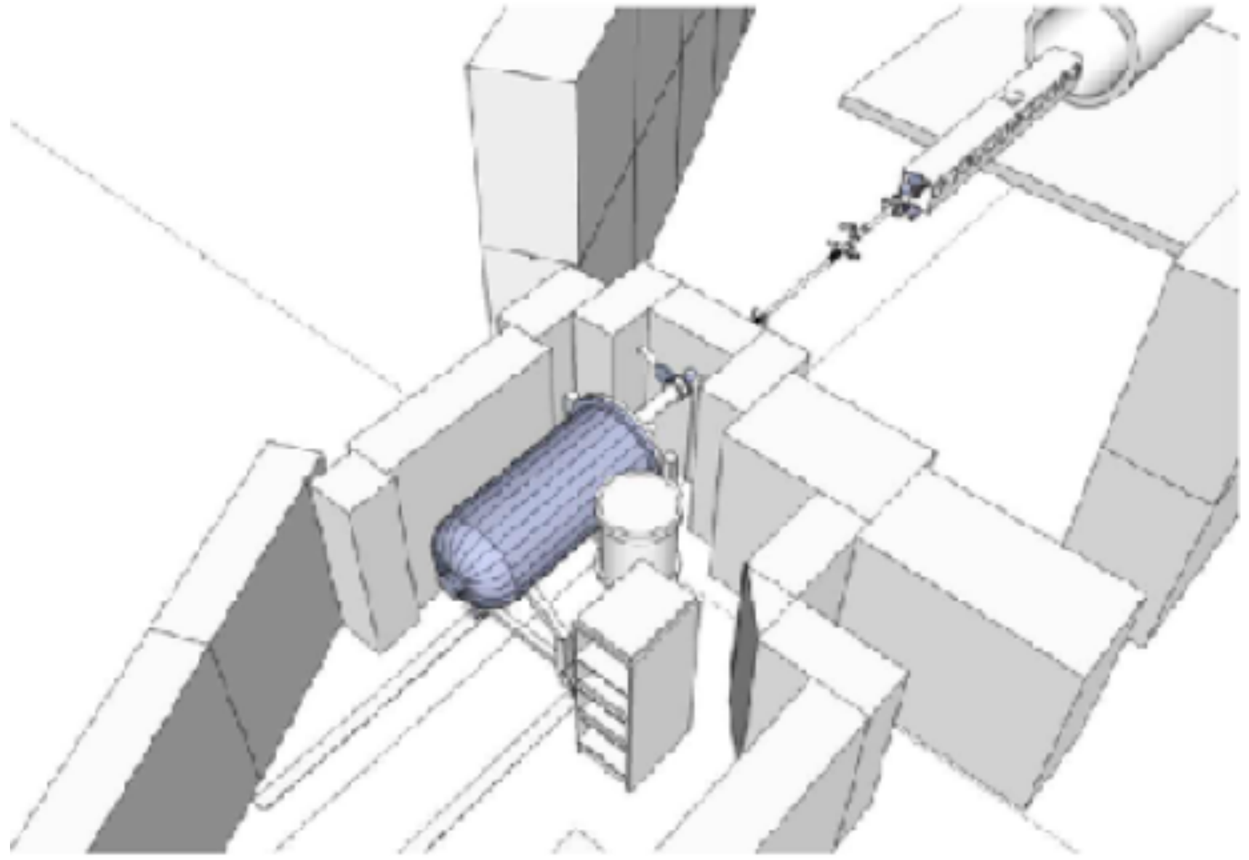
Hint for a neutral, 17MeV boson: X17 (Atomki collaboration)



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

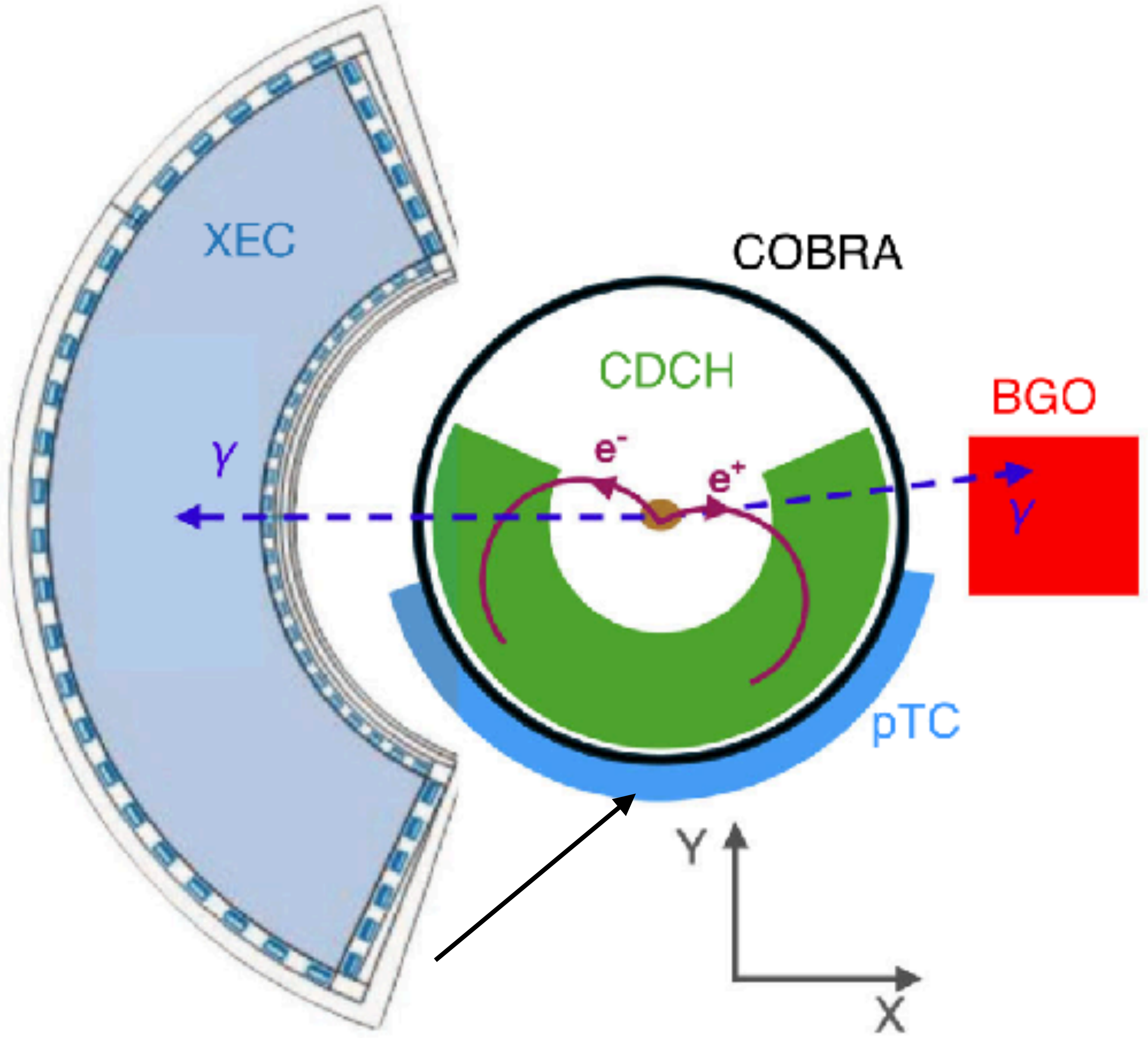
X17 boson search at MEG II

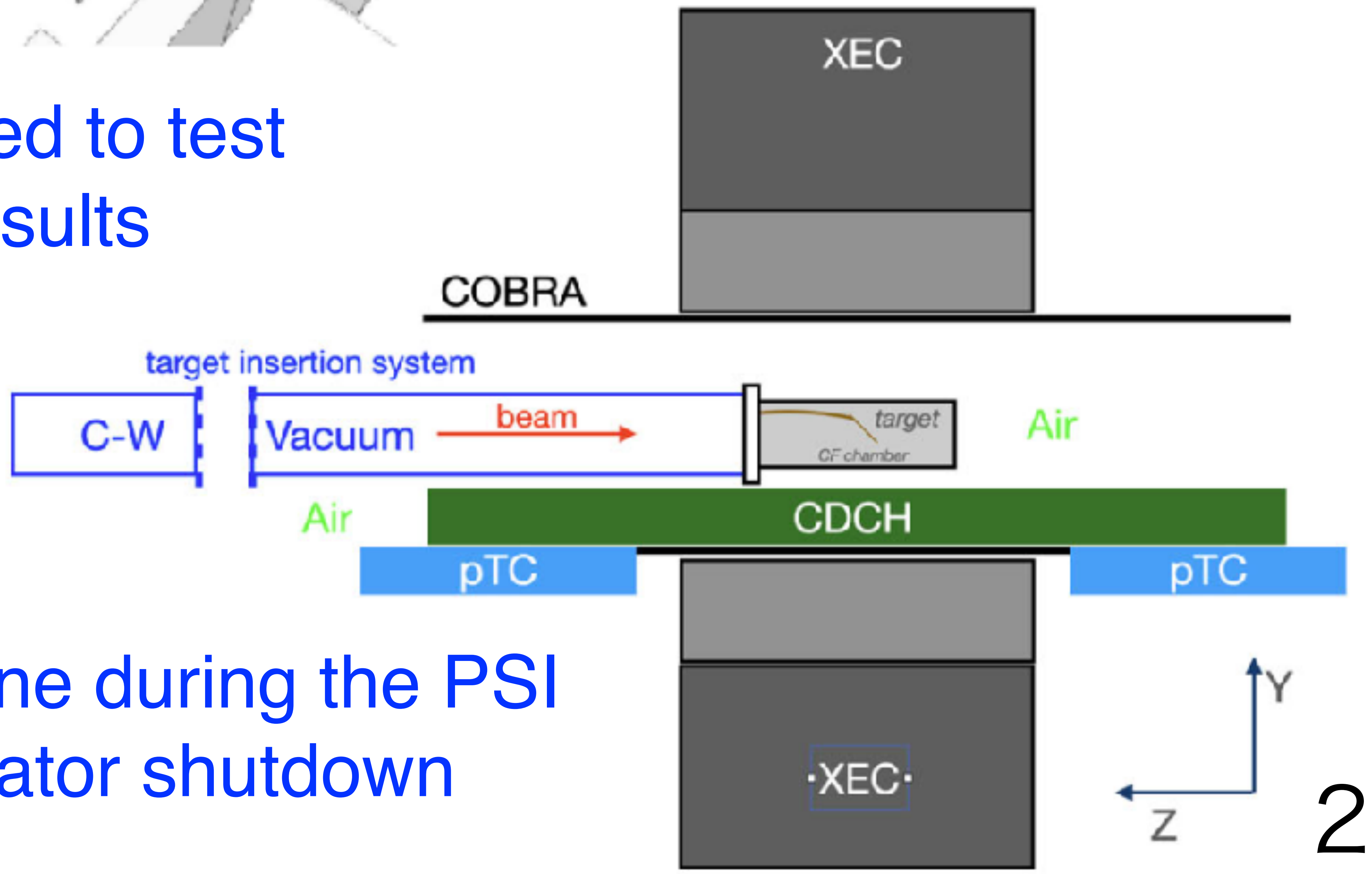
^{7}Li(p, γ)^{8}Be 17.6 MeV γ used for MEG II LXe Calibration



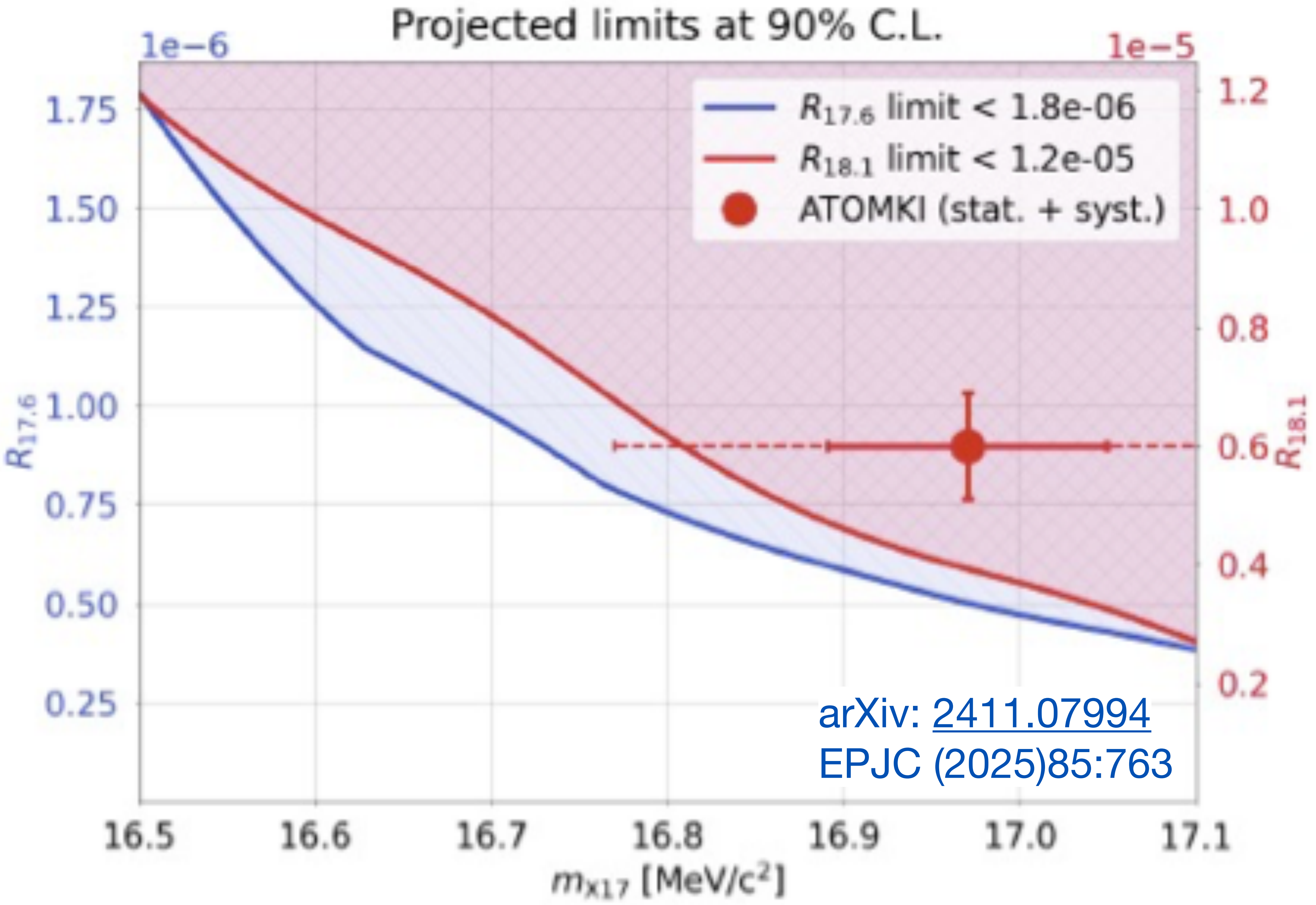
Can be used to test X17 results

Can be done during the PSI accelerator shutdown





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



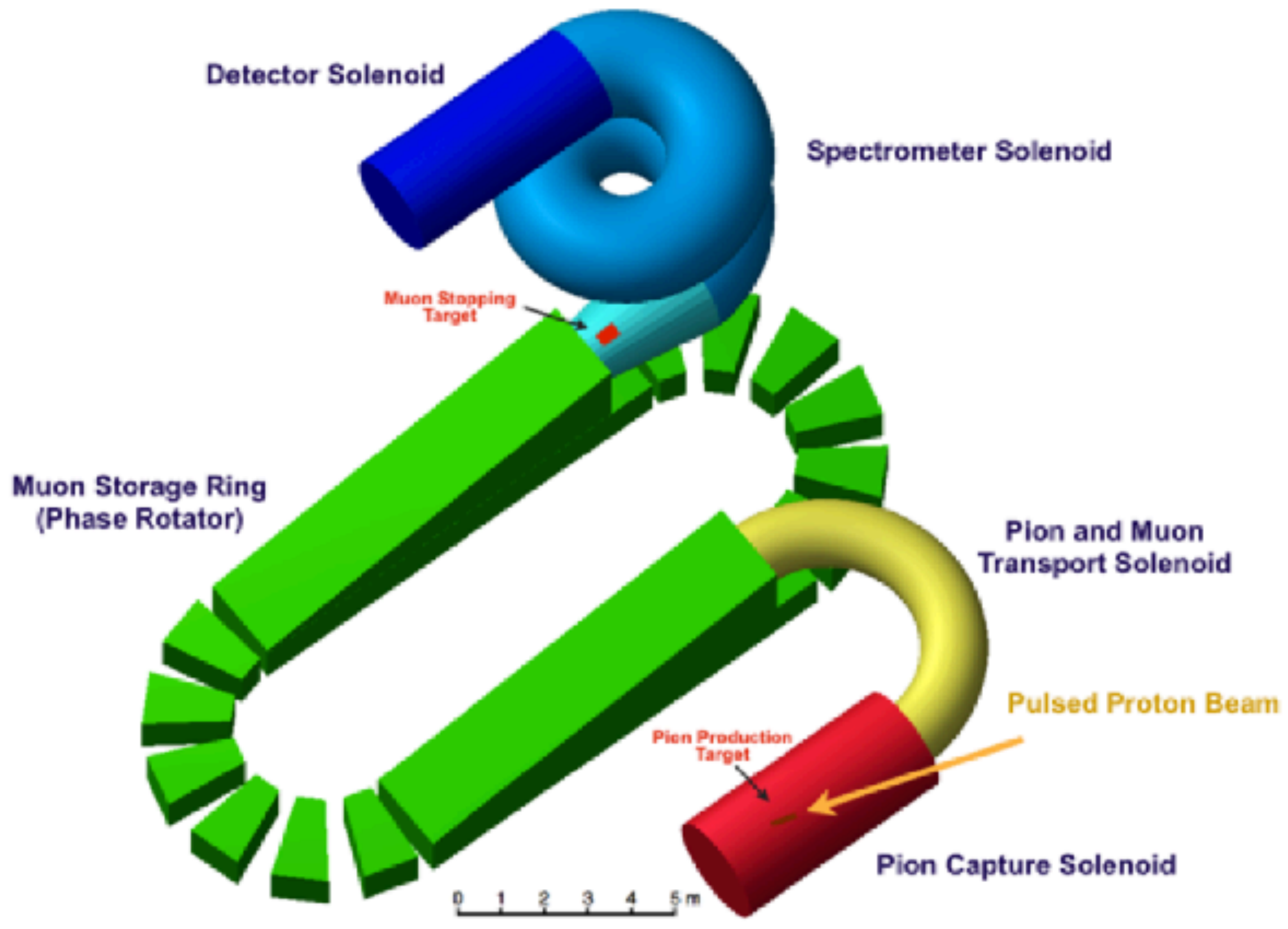
arXiv: 2411.07994
EPJC (2025)85:763

No significant signal observed

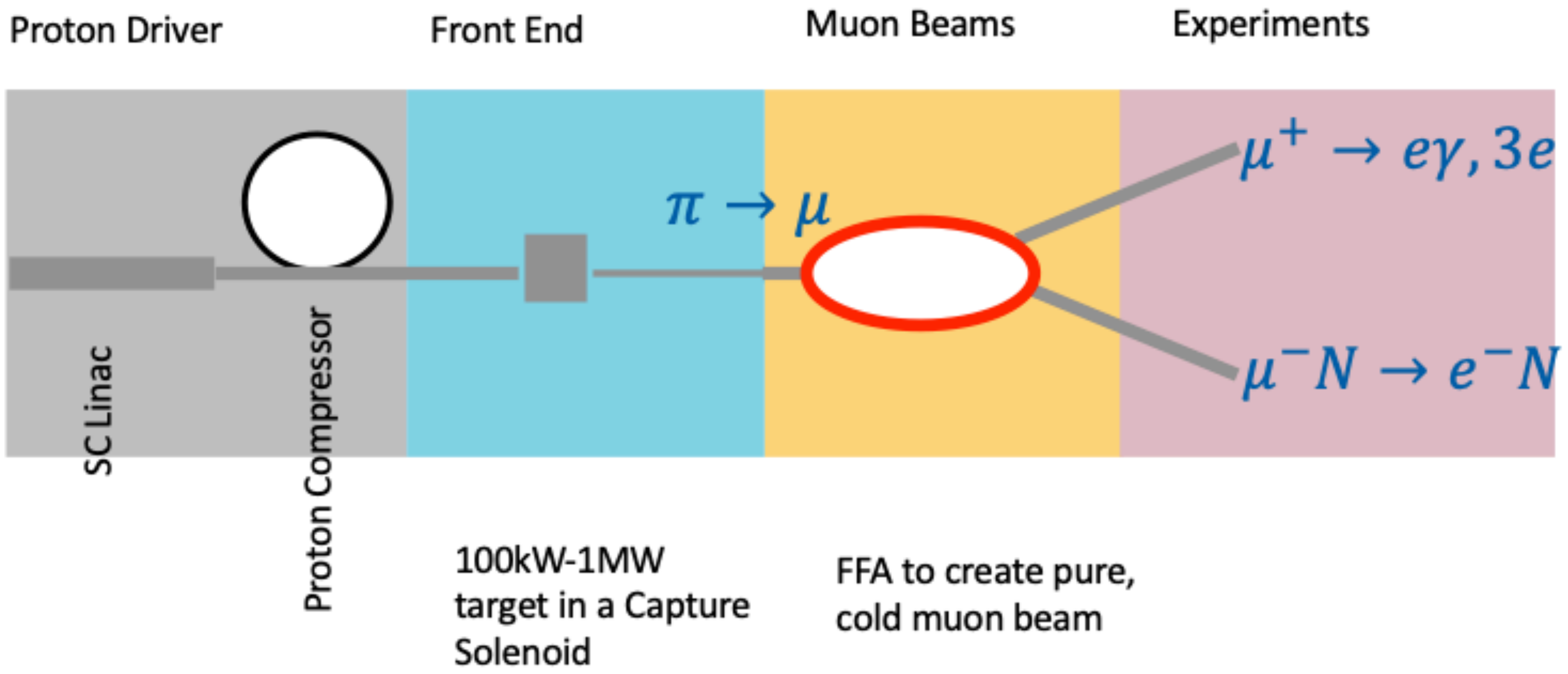
ATOMKI result was excluded at 94%

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

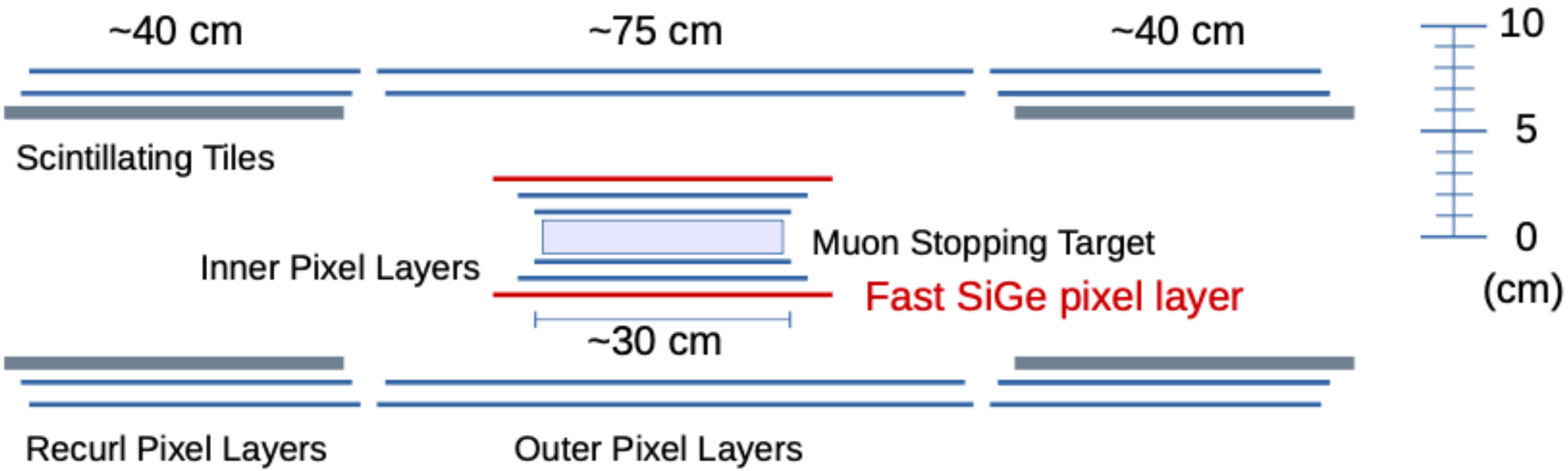


FFA example arXiv: 1310.0804



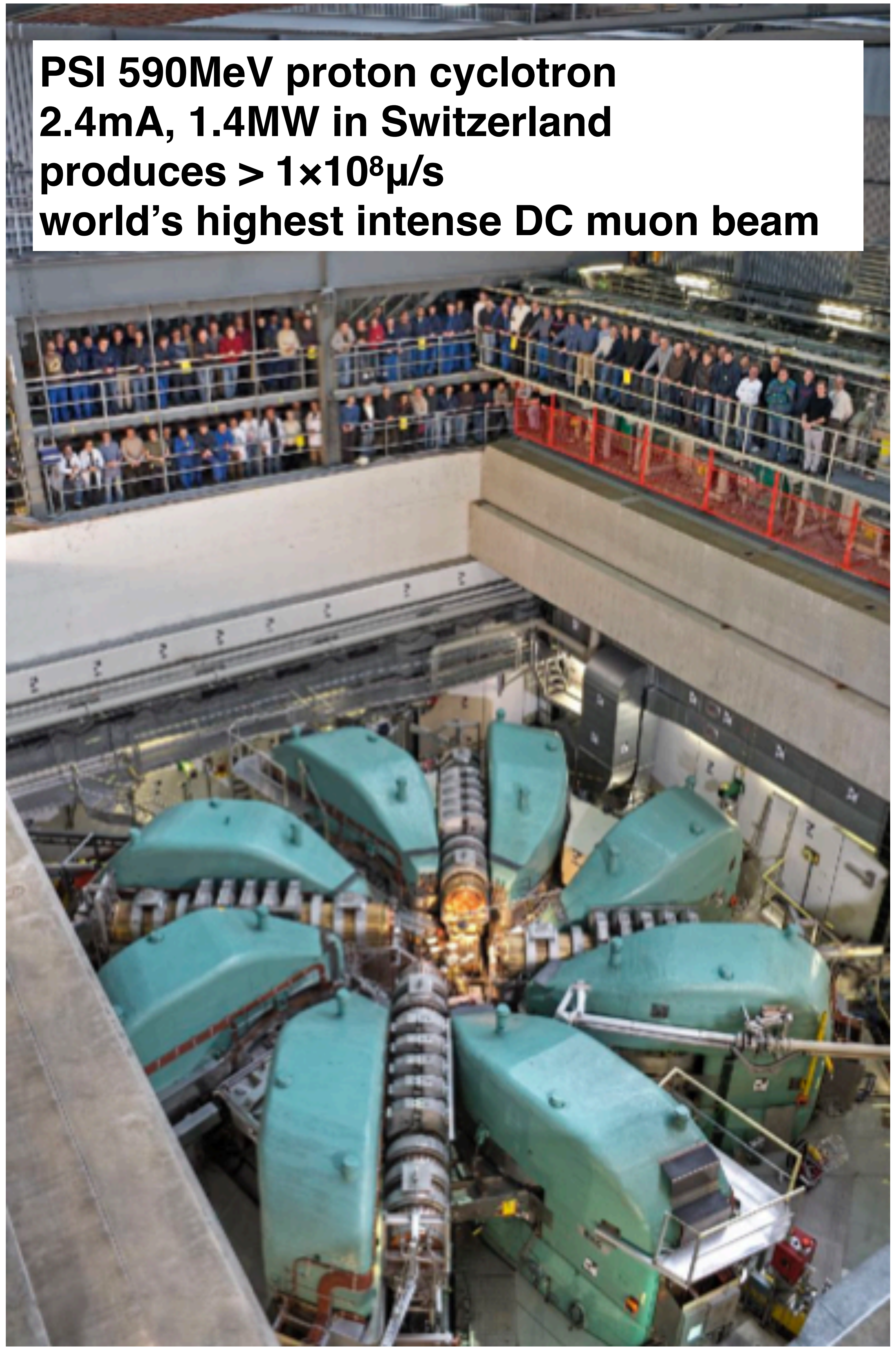
Mu3e phase II

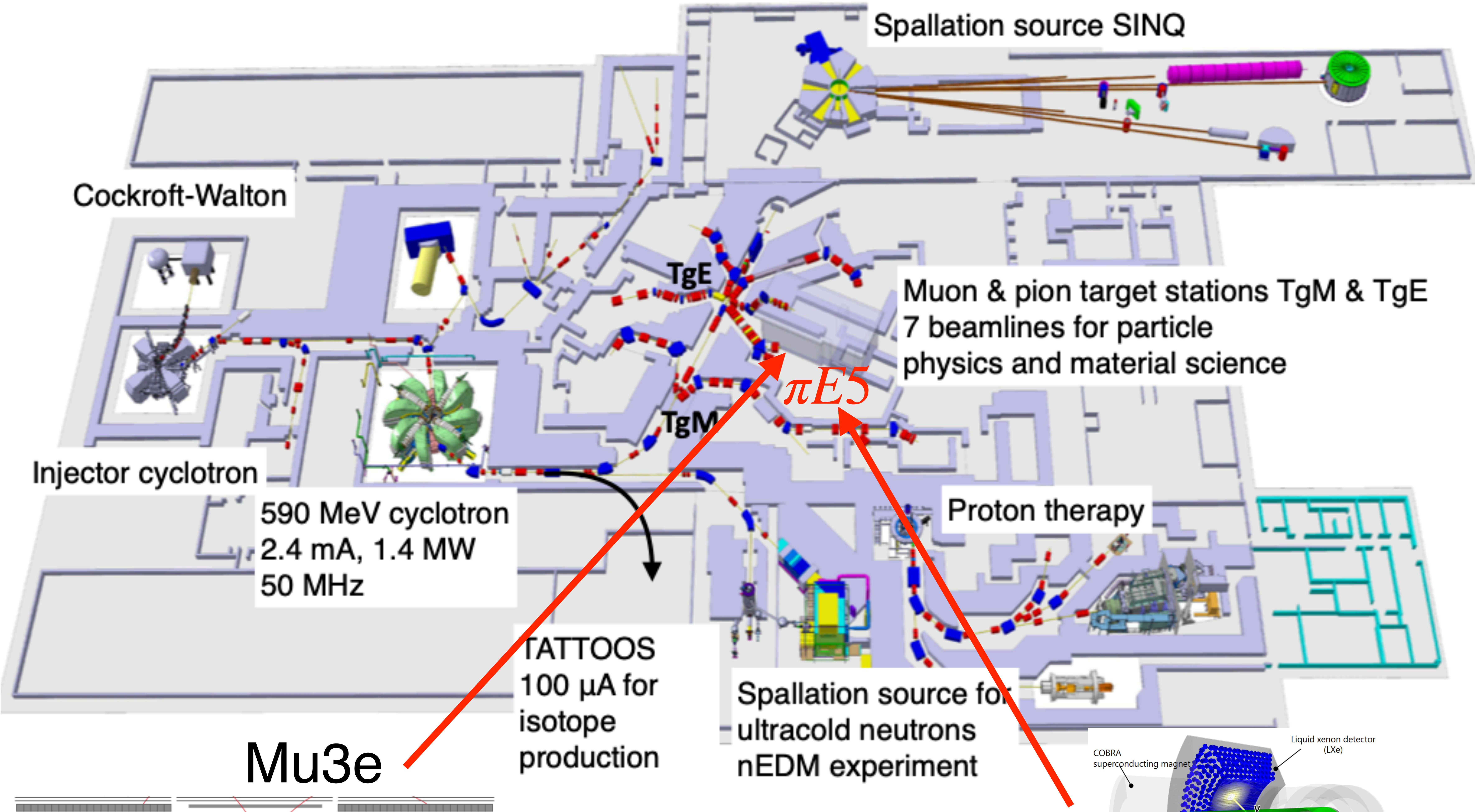
- Extension of the muon-stopping target, reduction of the material in the stopping target region and the first tracking layer, further improving the time and vertex resolution of HVMAPS
- HVMAPS with even smaller thickness and smaller pixel sizes, with 100 ps time resolution
- Muon stopping rates of ~ 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

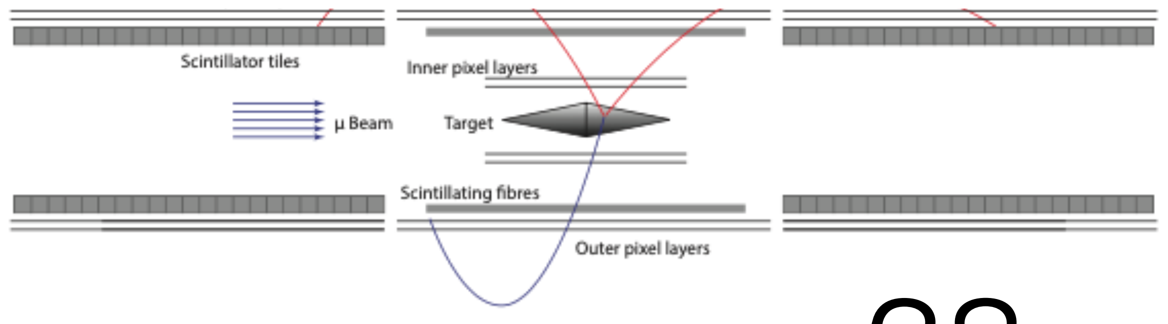


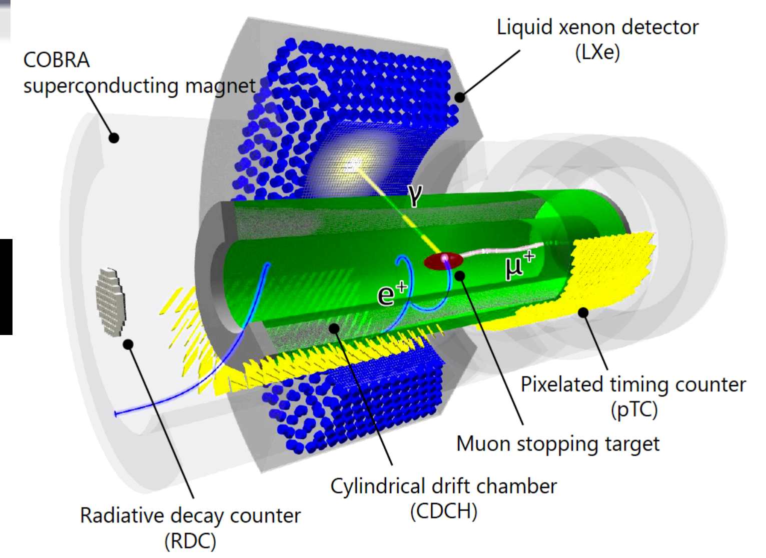
Paul Scherrer Institute (PSI) in Switzerland

PSI 590MeV proton cyclotron
2.4mA, 1.4MW in Switzerland
produces > $1\times10^{8}\mu/s$
world's highest intense DC muon beam



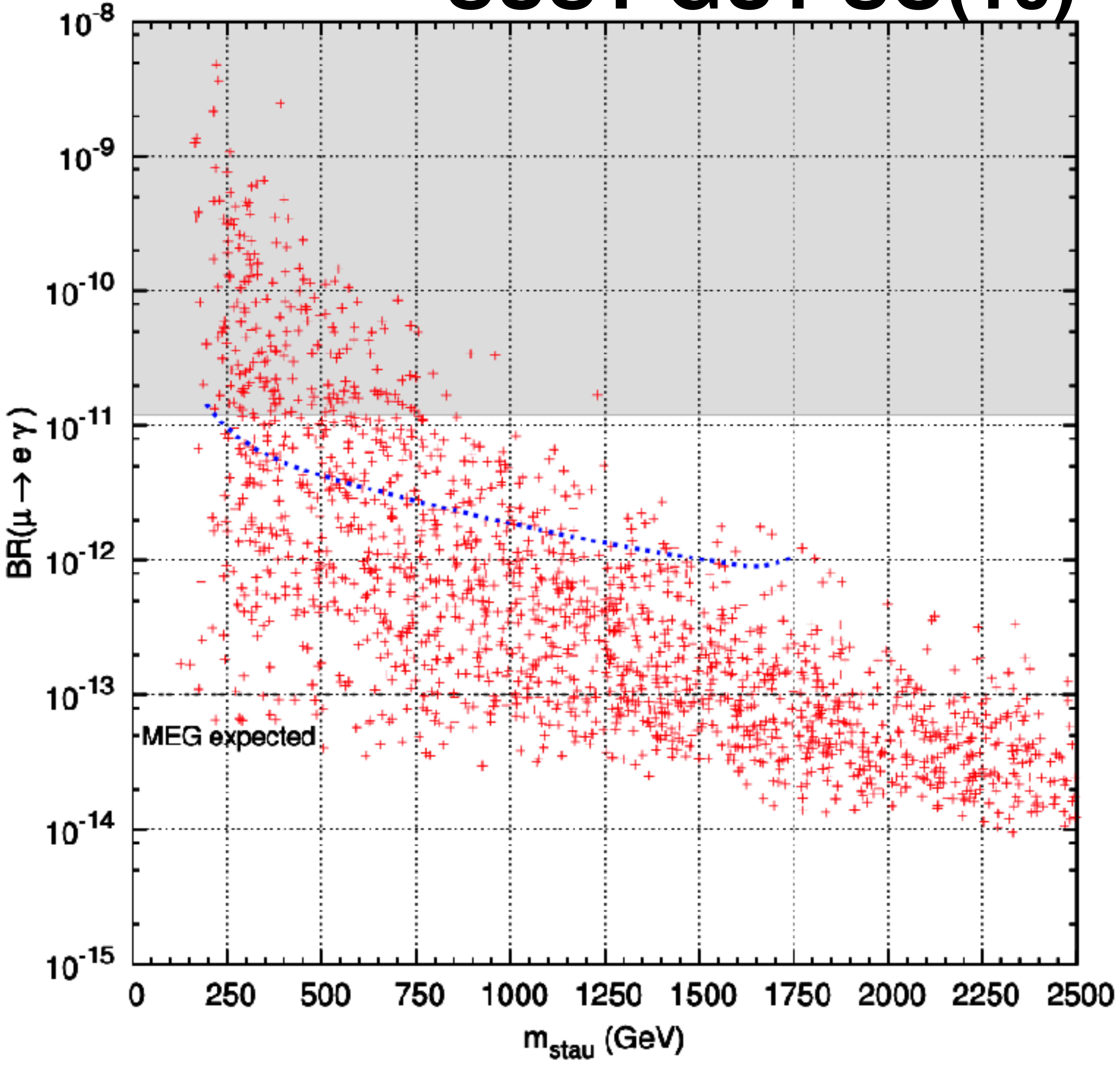






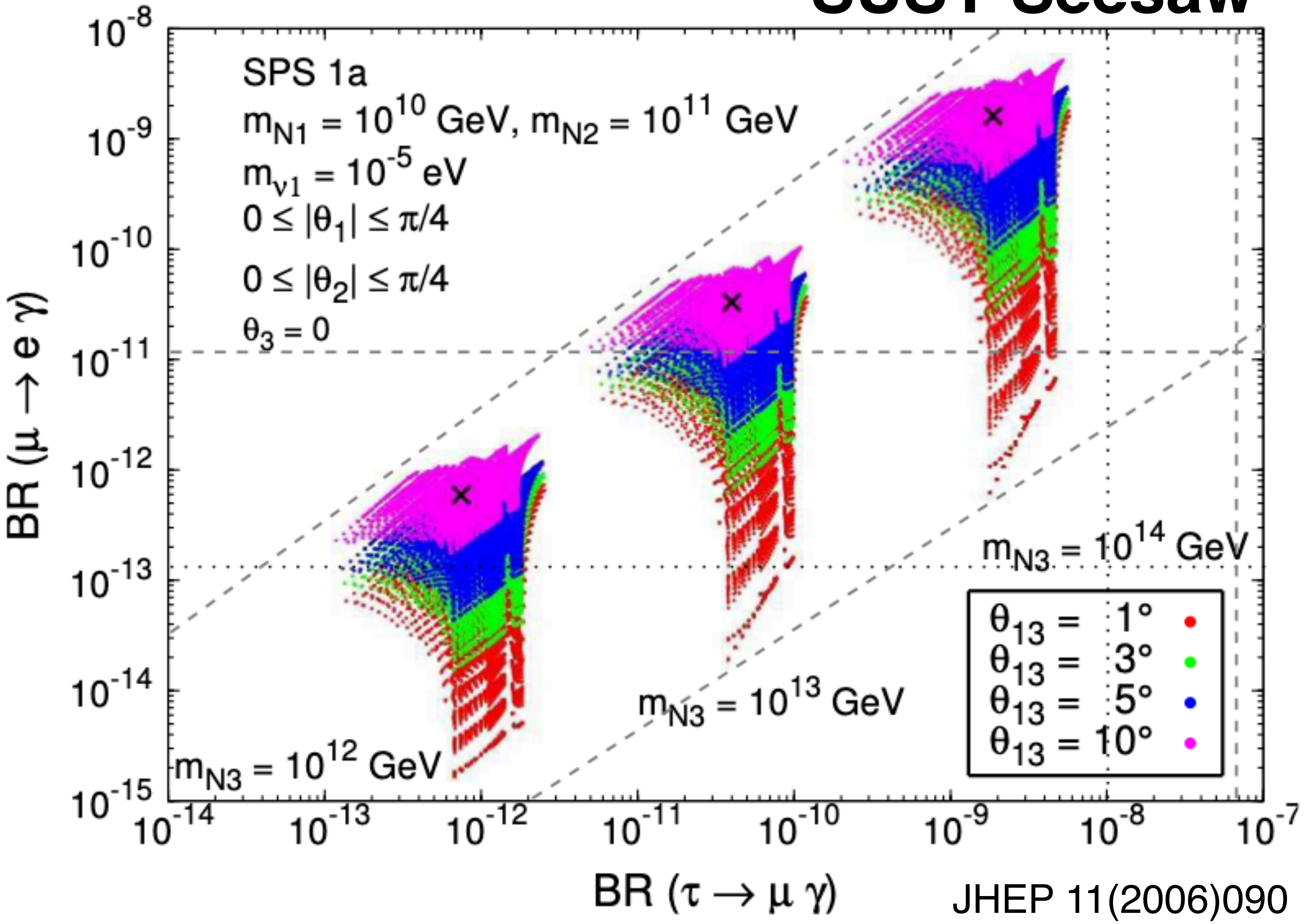
Examples of new physics

SUSY-GUT SO(10)



JHEP 0912(2009)057

SUSY-Seesaw



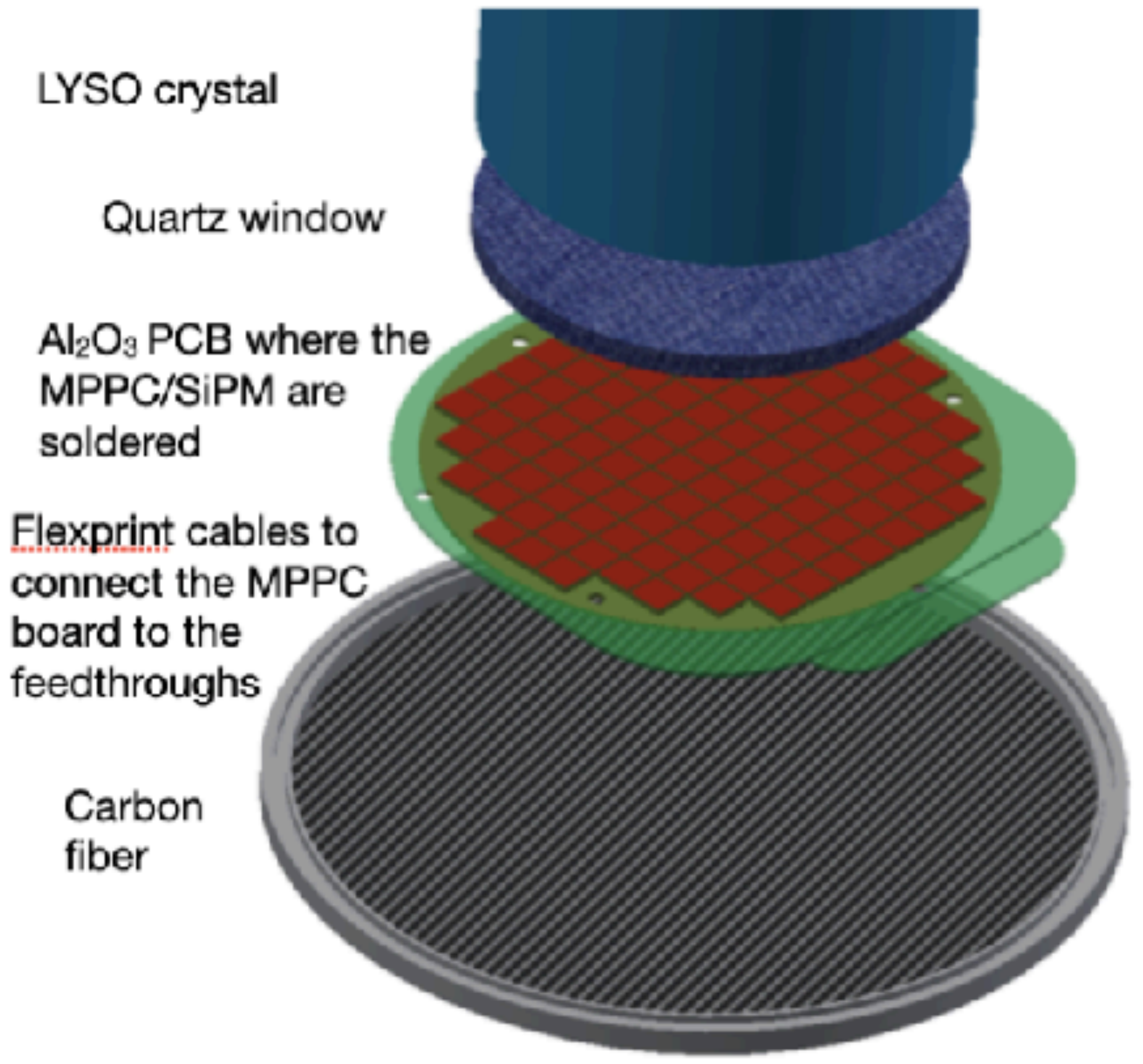
JHEP 11(2006)090

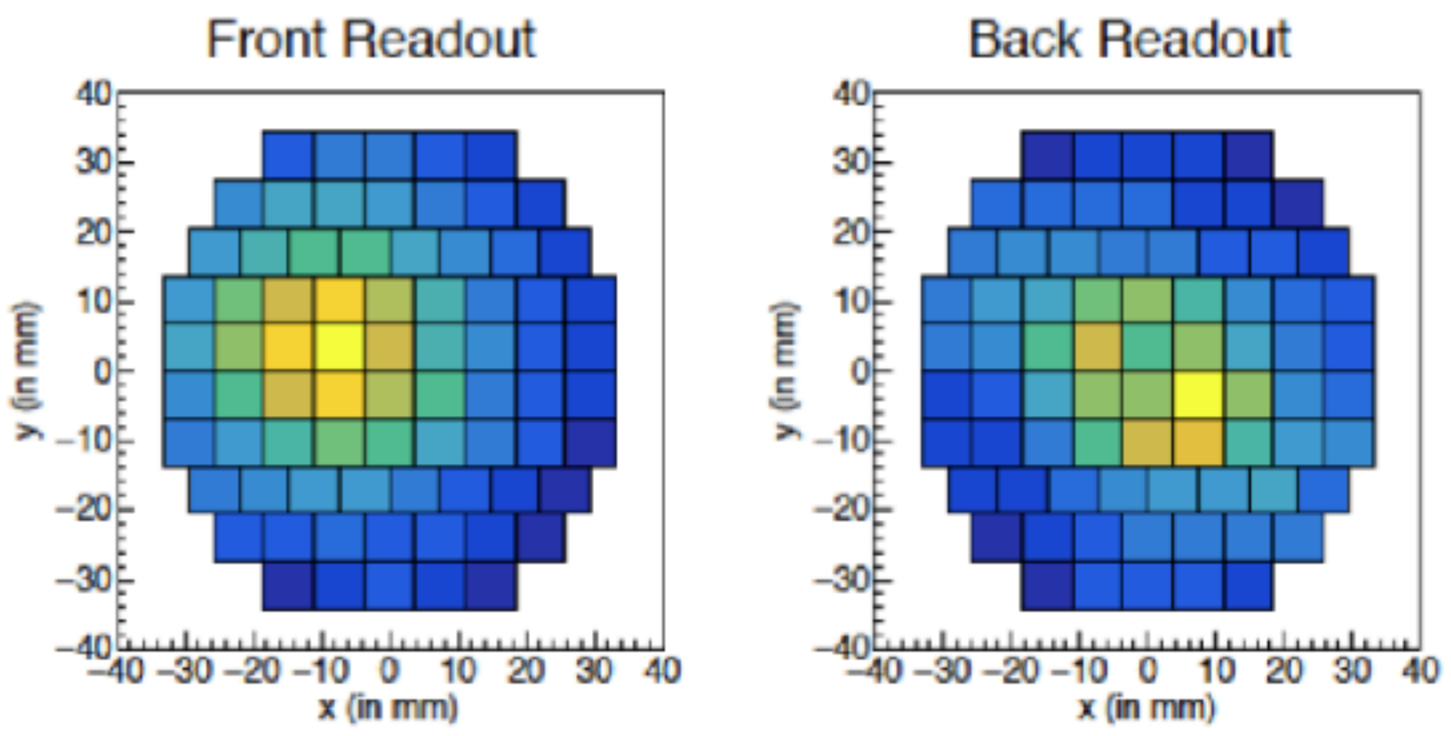
Real chance for discovery

Already some regions from theoretical expectation excluded

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

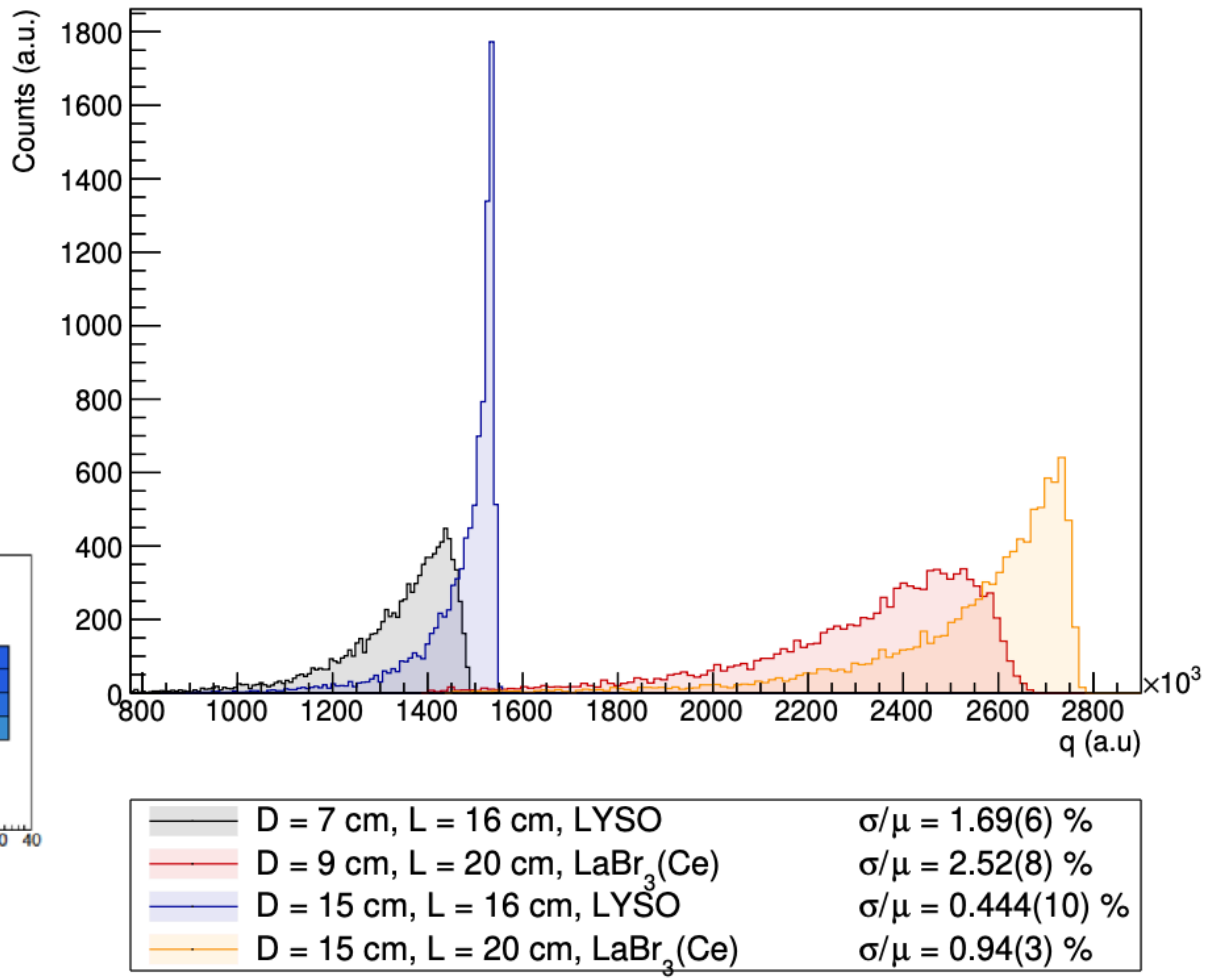




(a) Hit in Central Region: $(x, y) = (-10\,\text{mm}, 3\,\text{mm})$

Expected performances:

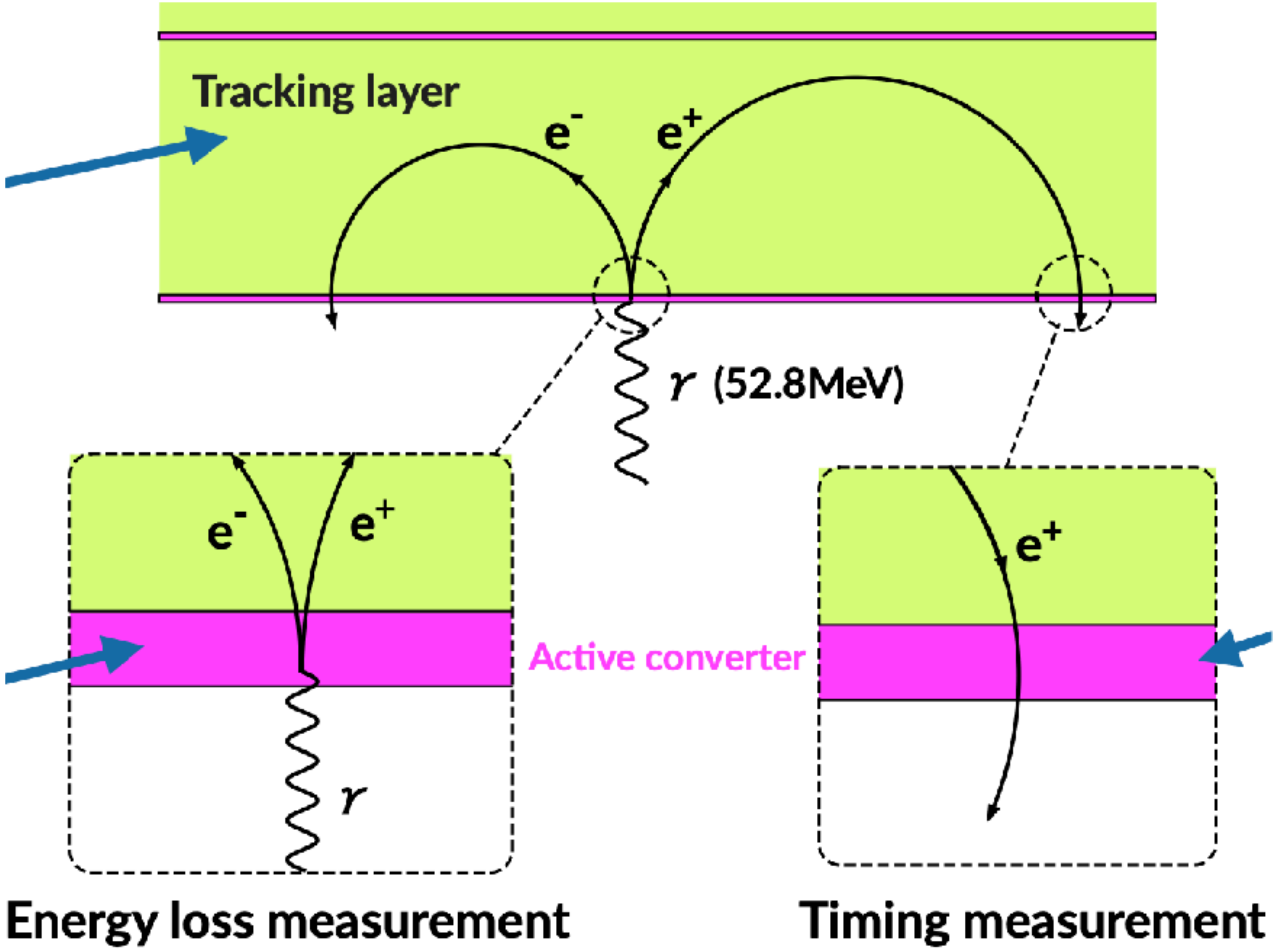
- σ_e/E [%] = 1.7(1)
- σ_t [ps] = 35(1)
- $\sigma_{x,y,z}$ [mm] = 3-5



Photon measurement: Pair Spectrometer with Active Converter

Baseline option for photon measurement

- Tracking in a magnetic spectrometer
  - Drift chamber
  - Radial-TPC
  - Silicon detector
- Active converter
  - A layer of dense material to convert photons into e^+e^- pairs
  - Scintillator+SiPM
  - Silicon detector



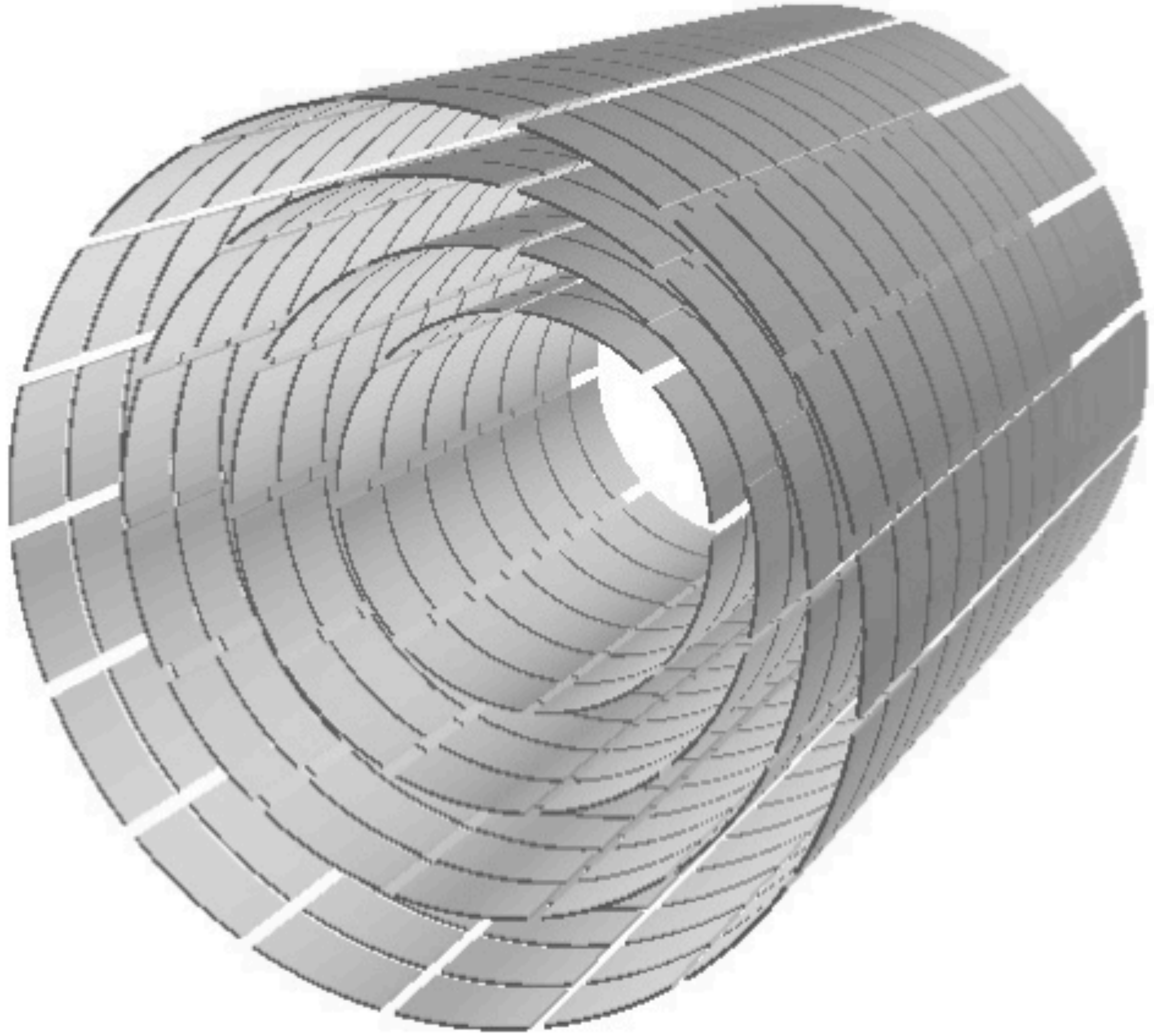
- Timing measurement
  - Measure timing of returning conversion pair
  - in front of active converter
  - Multi-layer RPC
  - Active converter = timing detector

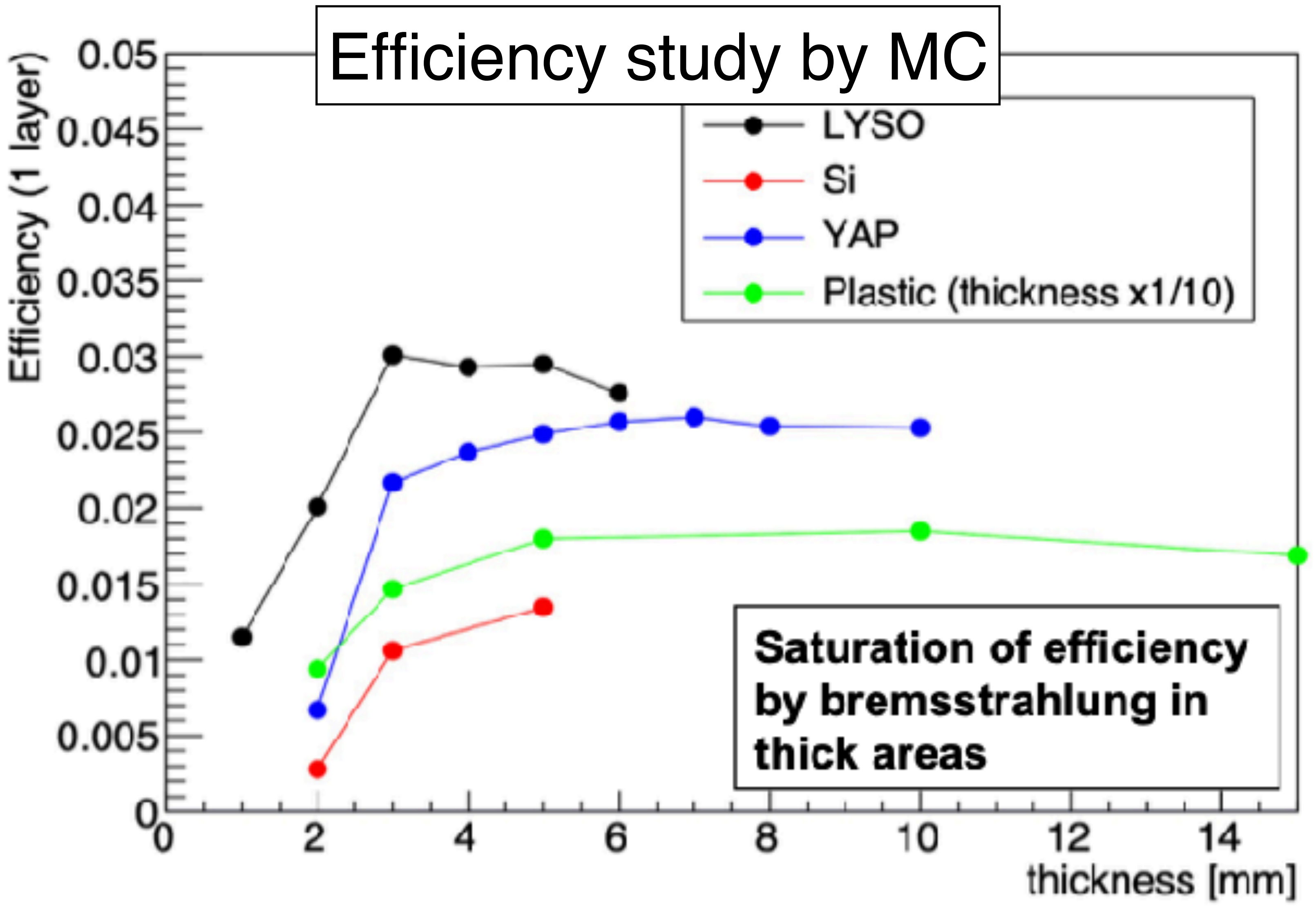
Target performance: $\sigma_E/E = 0.4\,\%$, $\sigma_t = 30ps, \sigma_x = 0.2mm$

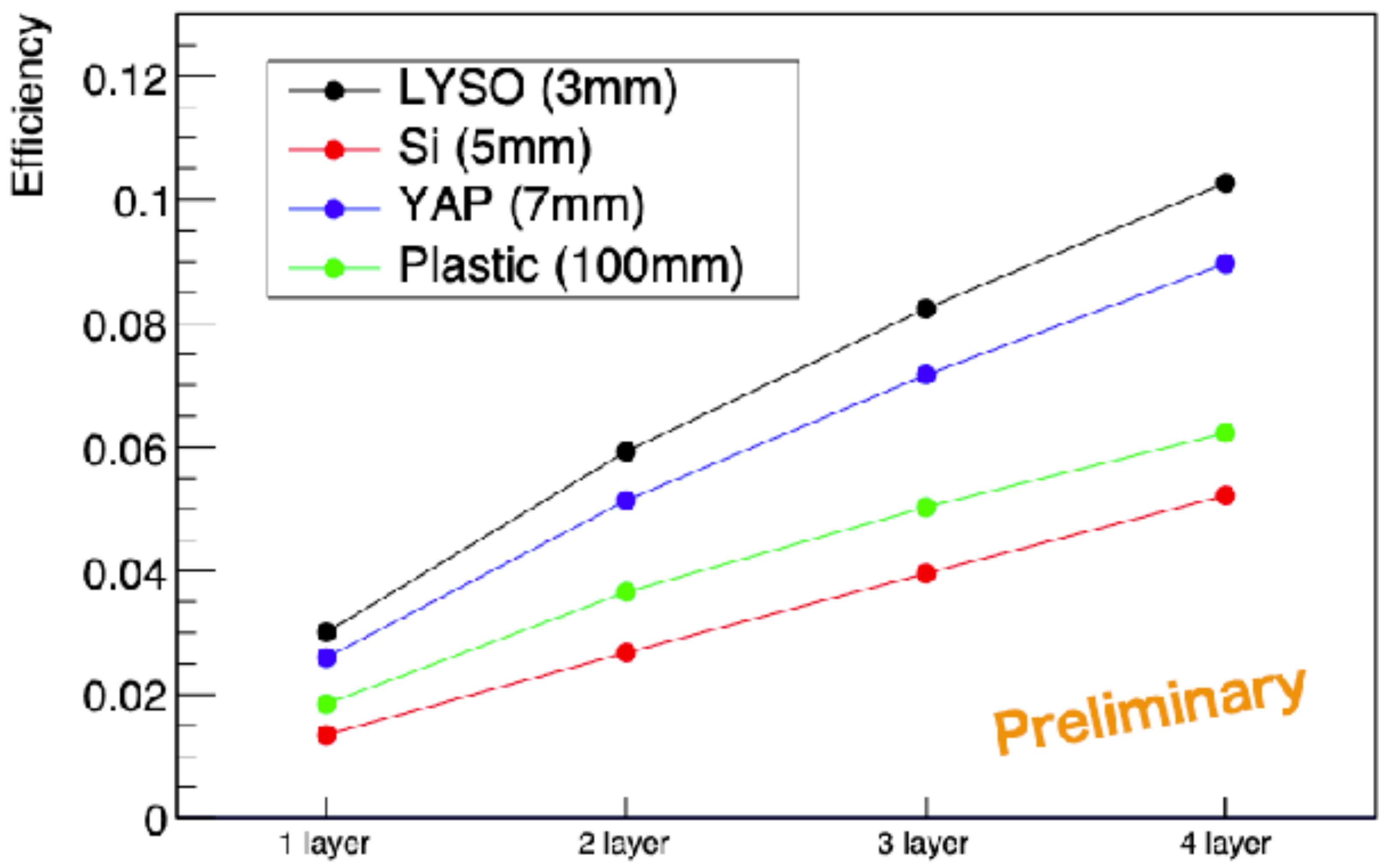
(MEG II : $\sigma_E/E = 1.8\,\%$, $\sigma_t = 65ps, \sigma_x = 2.5mm$)

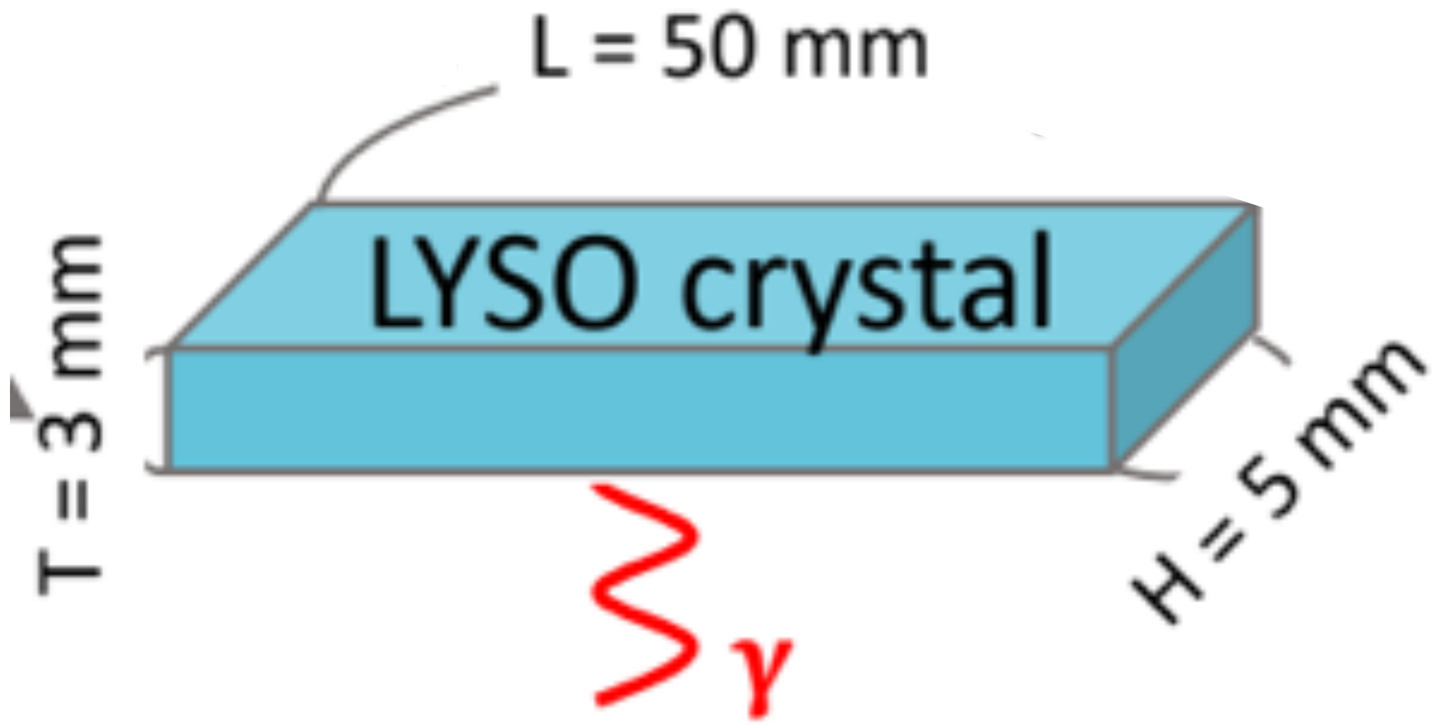
Current R&D

- Active converter material and size are evaluated by Simulation study

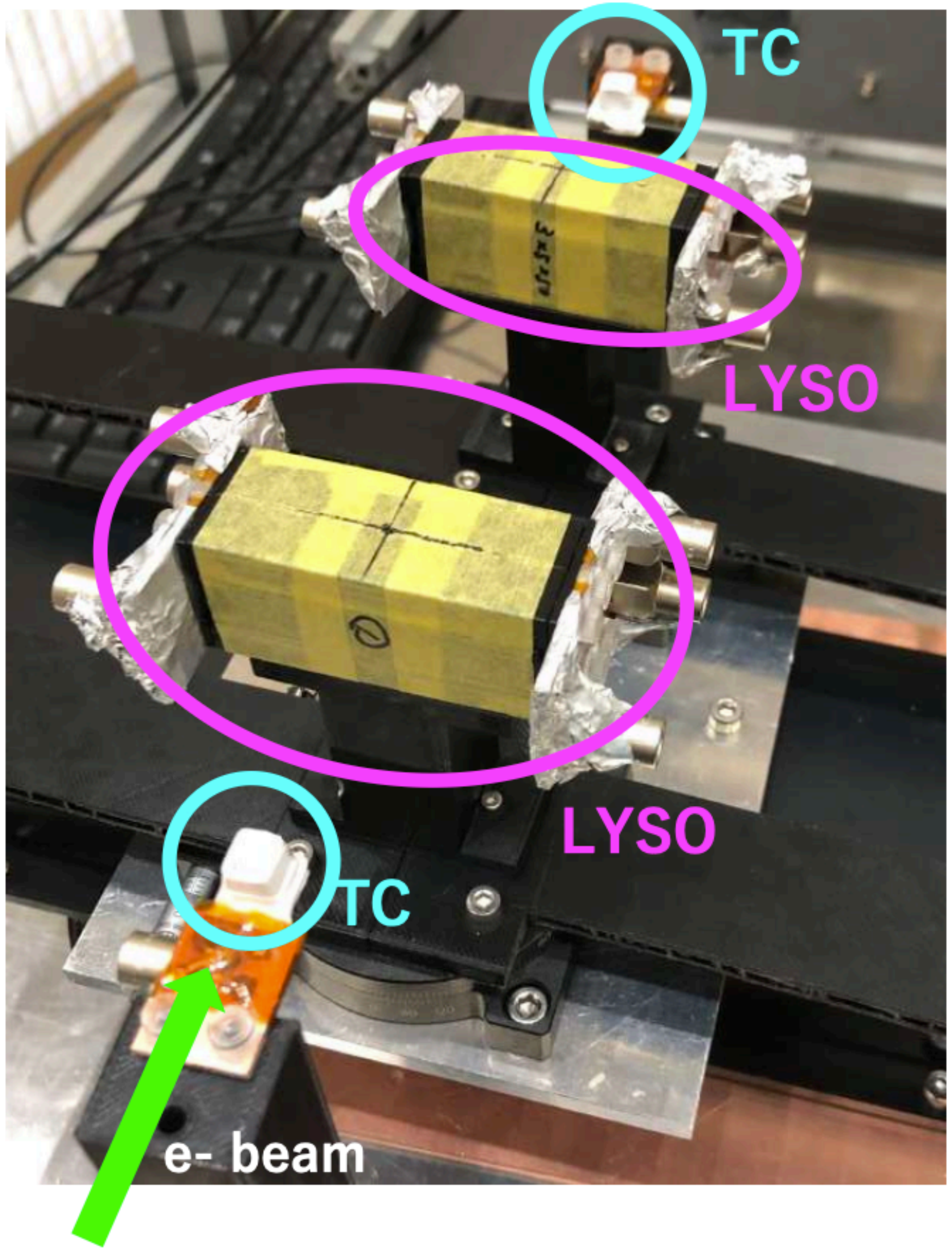


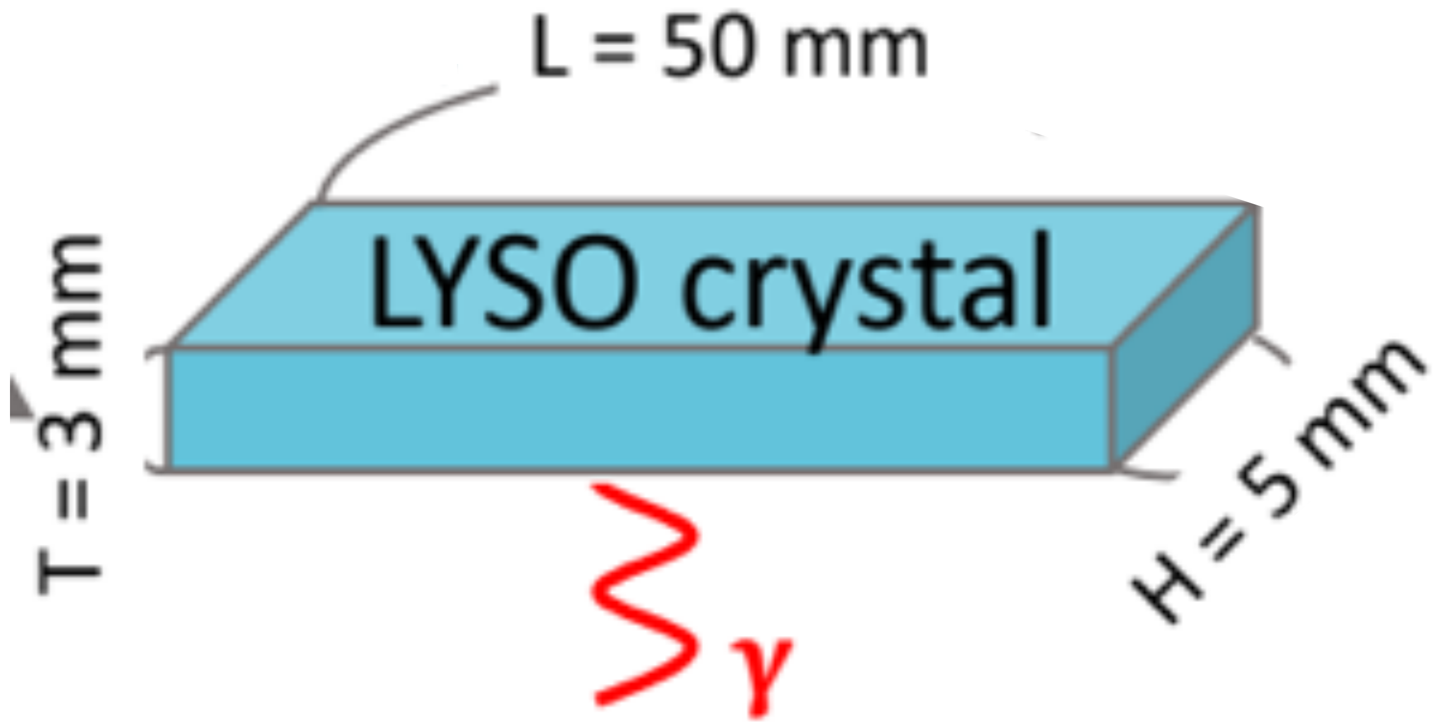


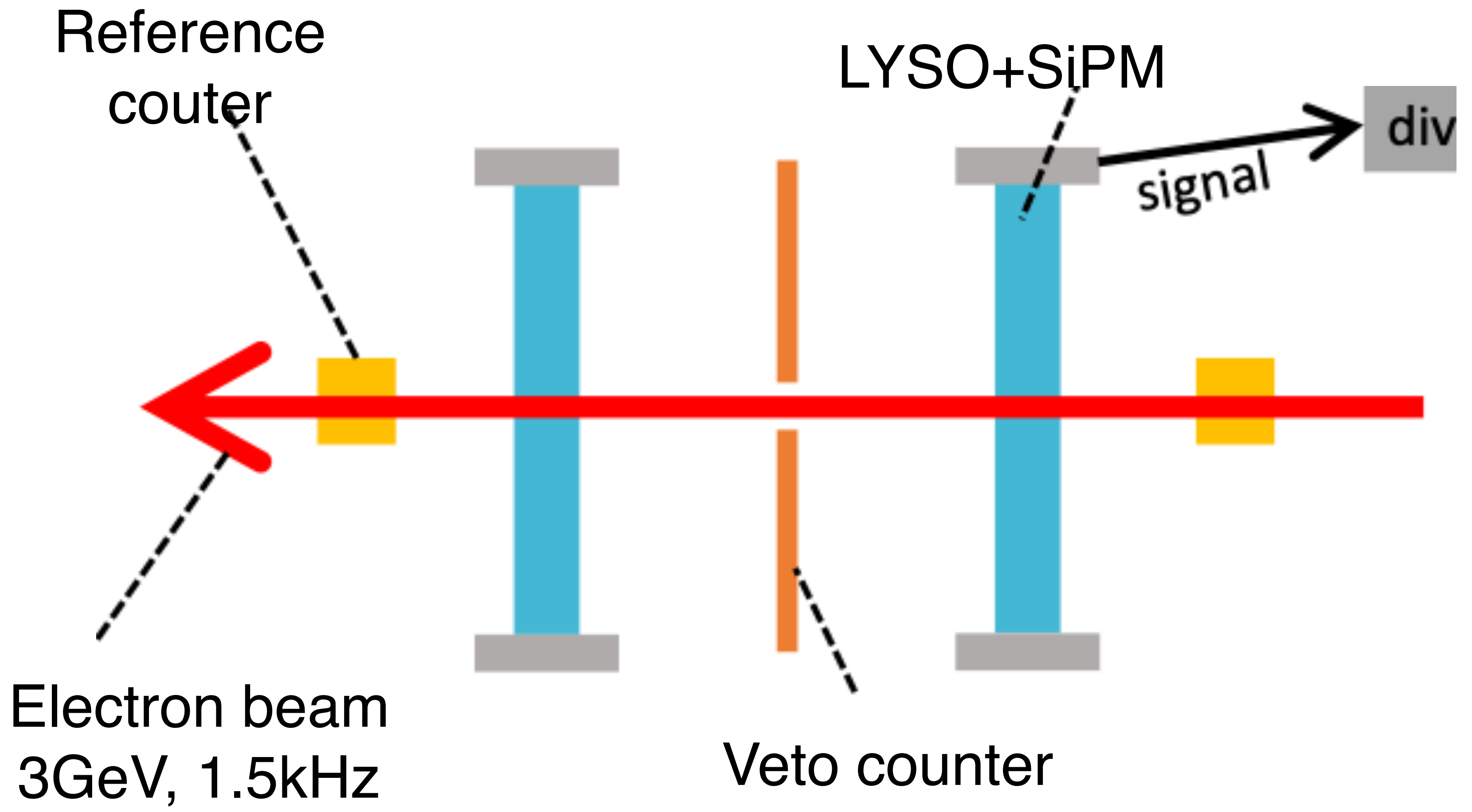


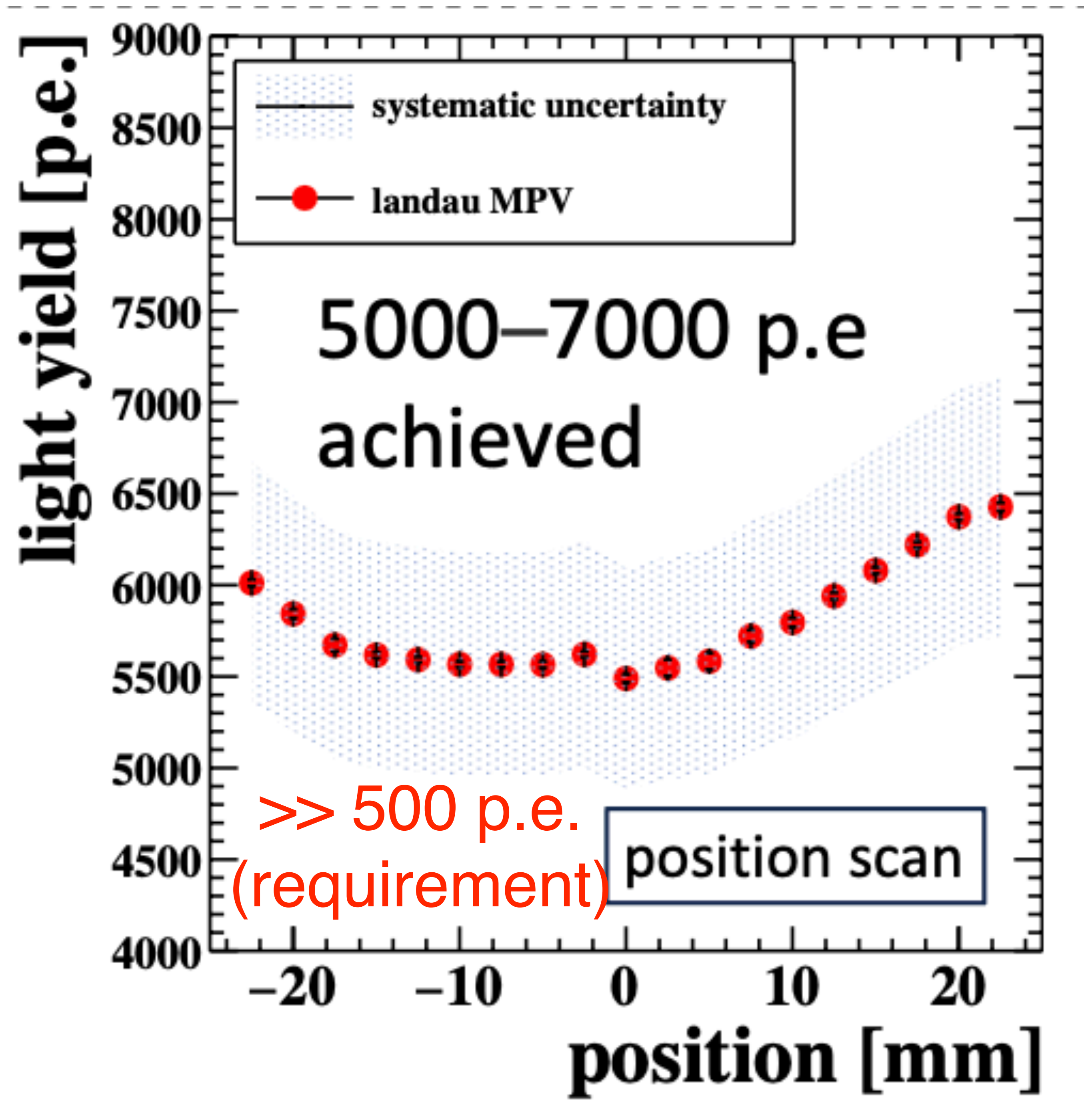


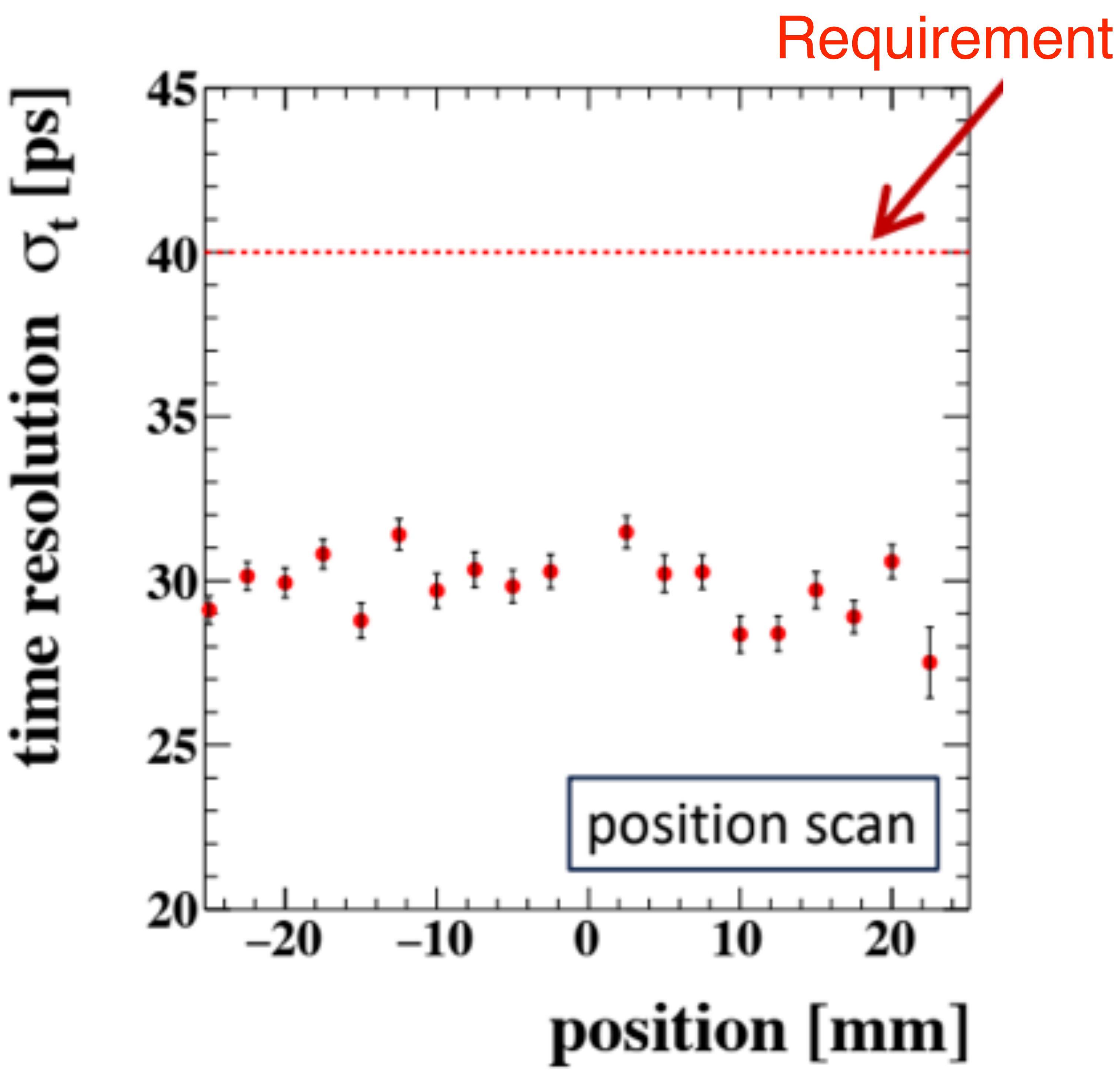
Active converter prototype beam test





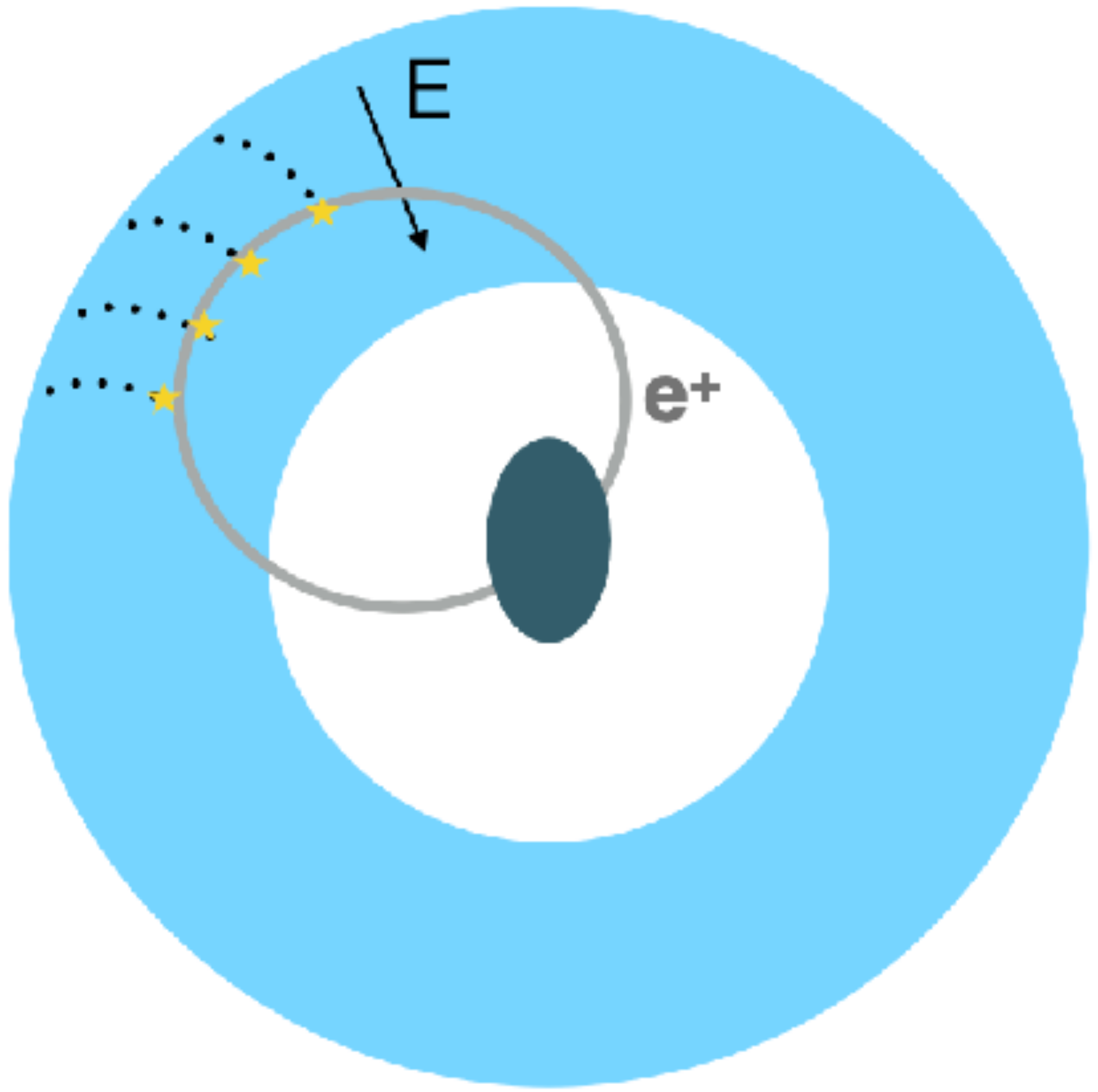


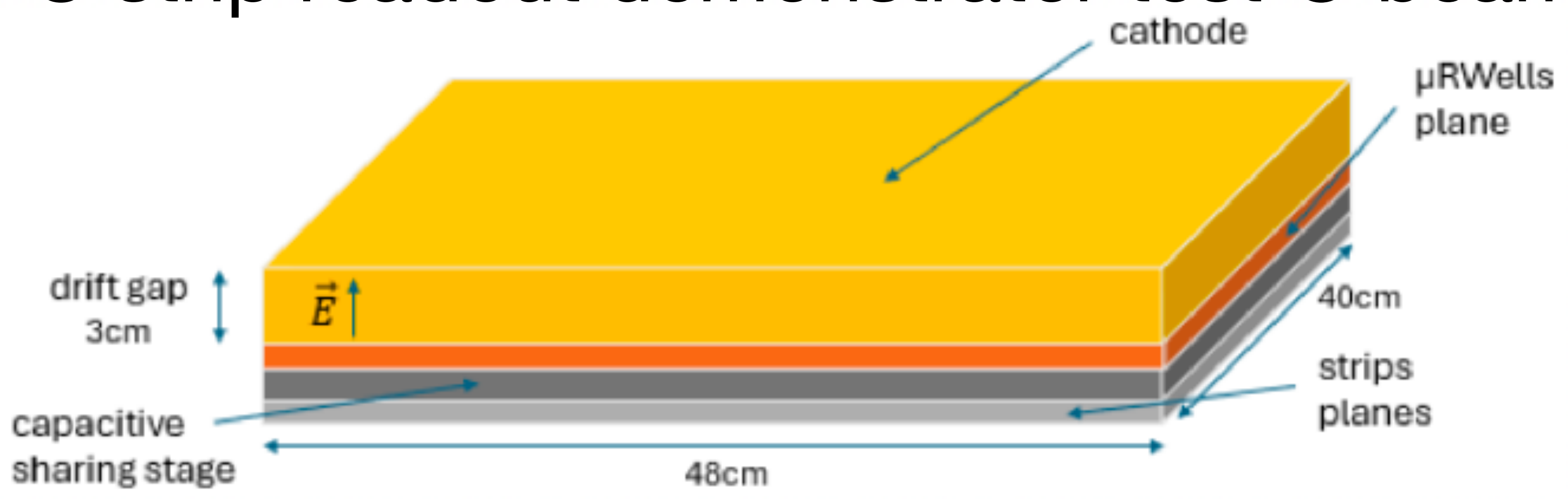


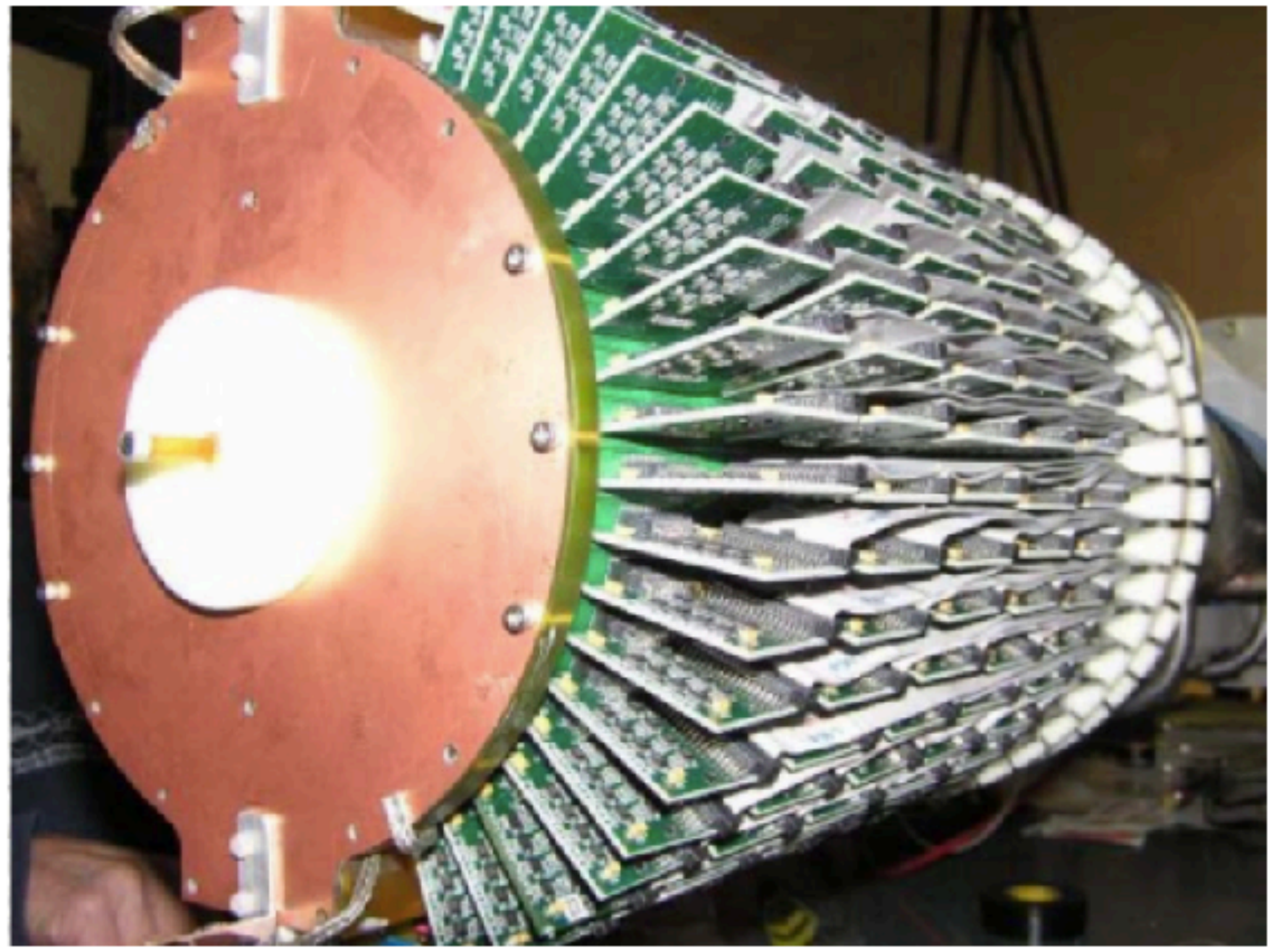


e^+e^- tracker for reconstruction of converted photons

- 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



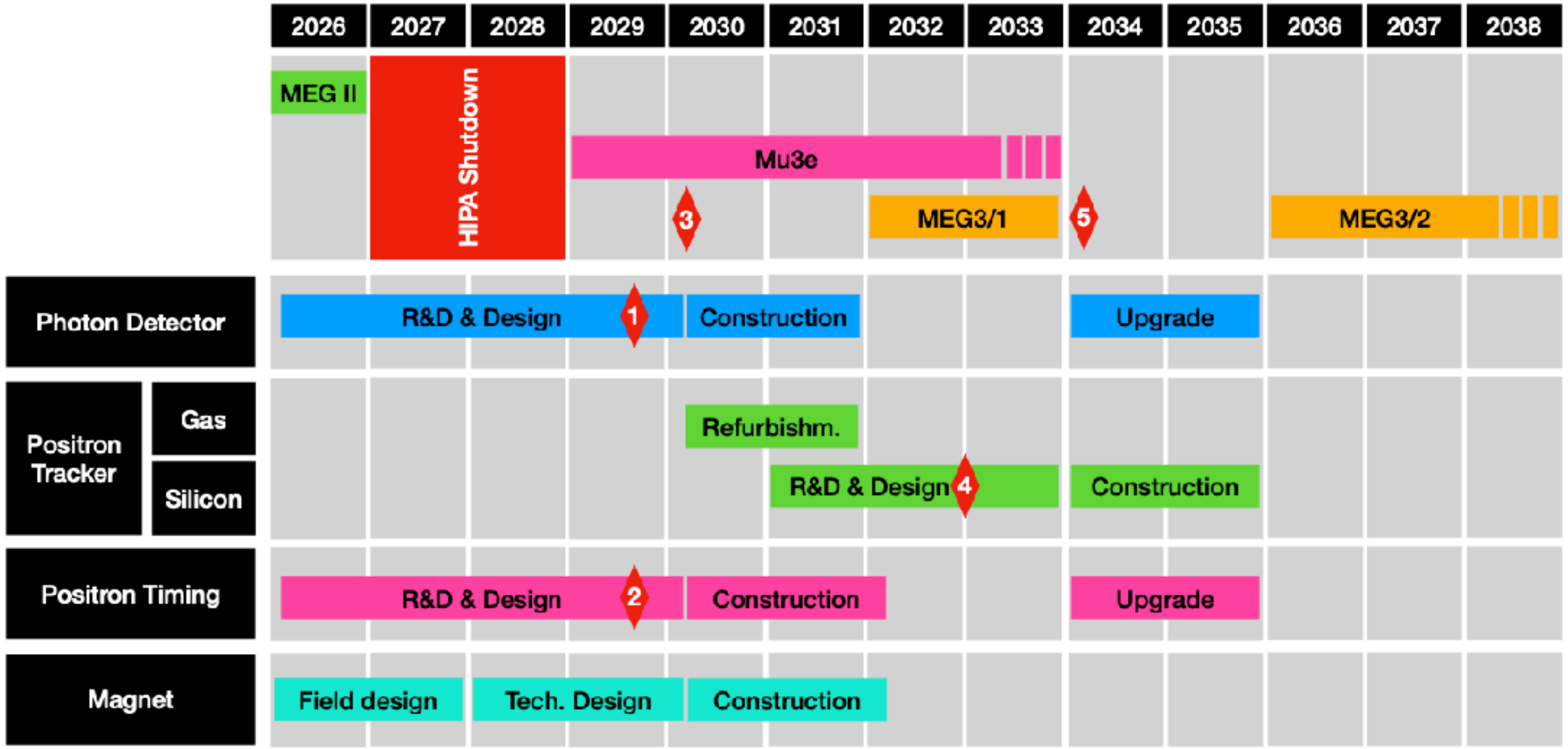




BONuS radial TPC @ J-LAB

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

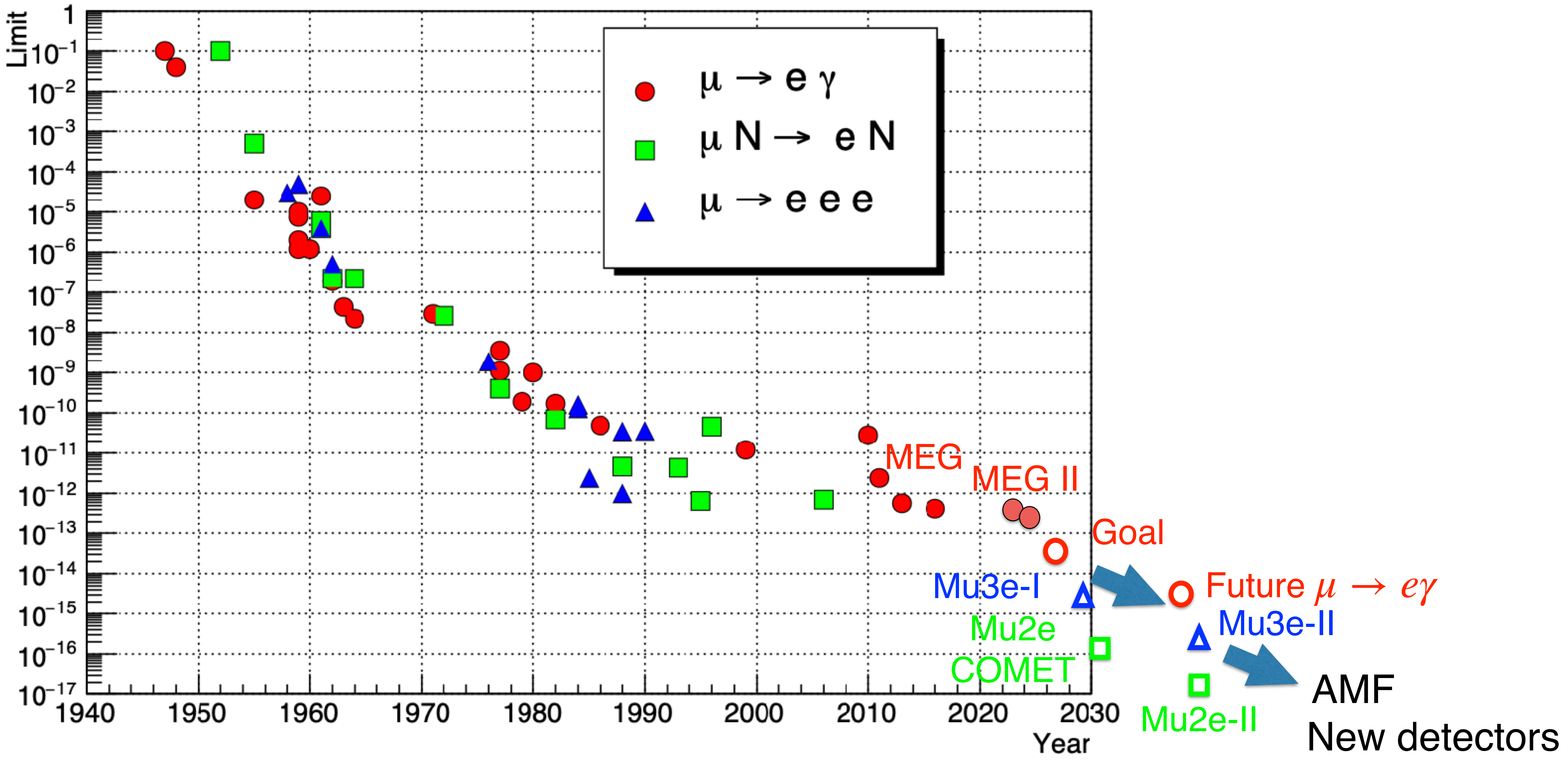


◆1: Photon converter proof of principle (CEX with converter + tracker in the MEG COBRA magnet)
◆2: Decision about positron timing technology
◆3: phase-I approval by PSI and funding agencies
◆4: Decision about positron tracker technology for phase-II
◆5: phase-II approval by PSI and funding agencies

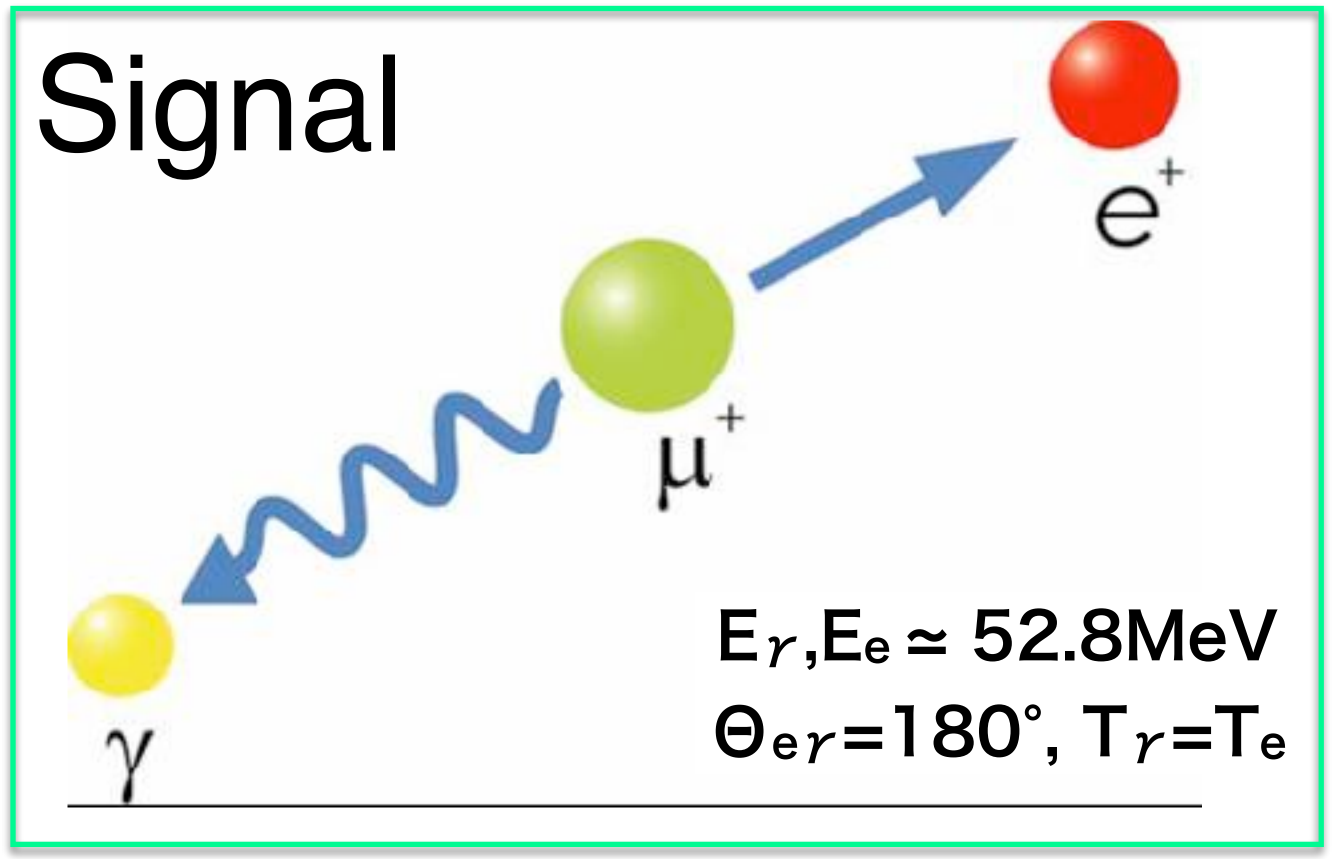
Mu2e-II

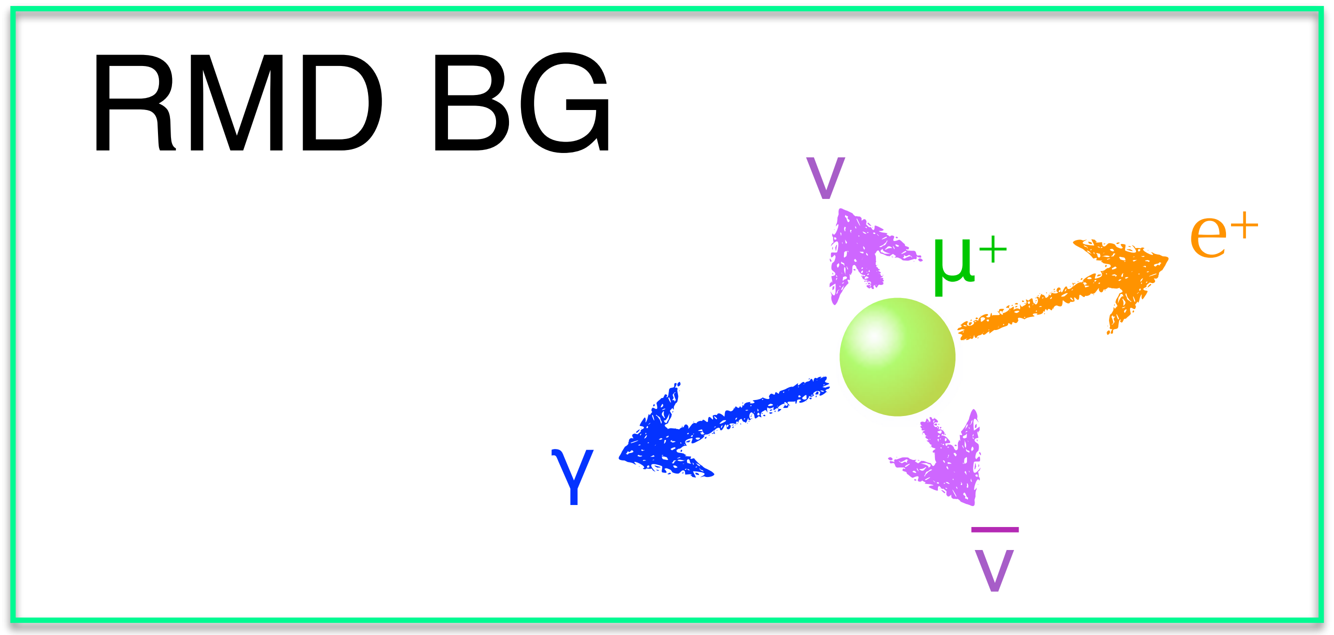
- Upgrade of the Mu2e experiment
  - If Mu2e discovers CLFV in aluminum, Mu2e-II can measure with different target materials to pin down NP parameters
  - If Mu2e does not find a signal, repeat the measurement to push limits even further
  - An order of magnitude improvement in sensitivity over Mu2e 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

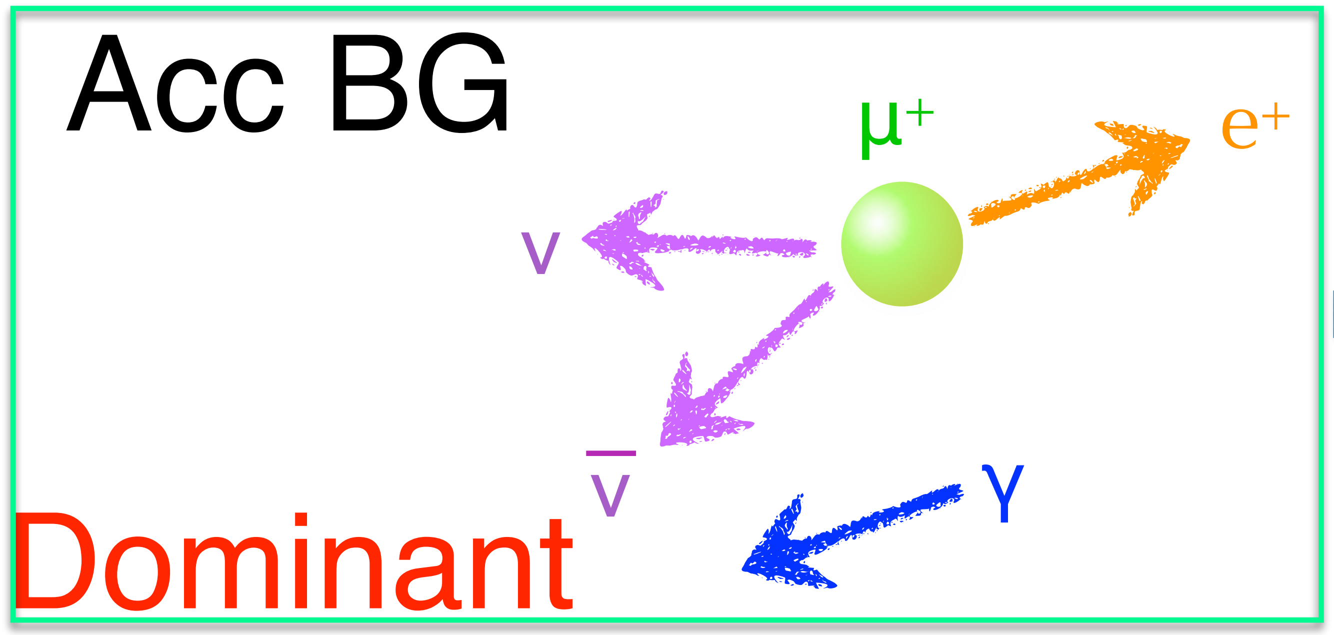
cLFV search prospects

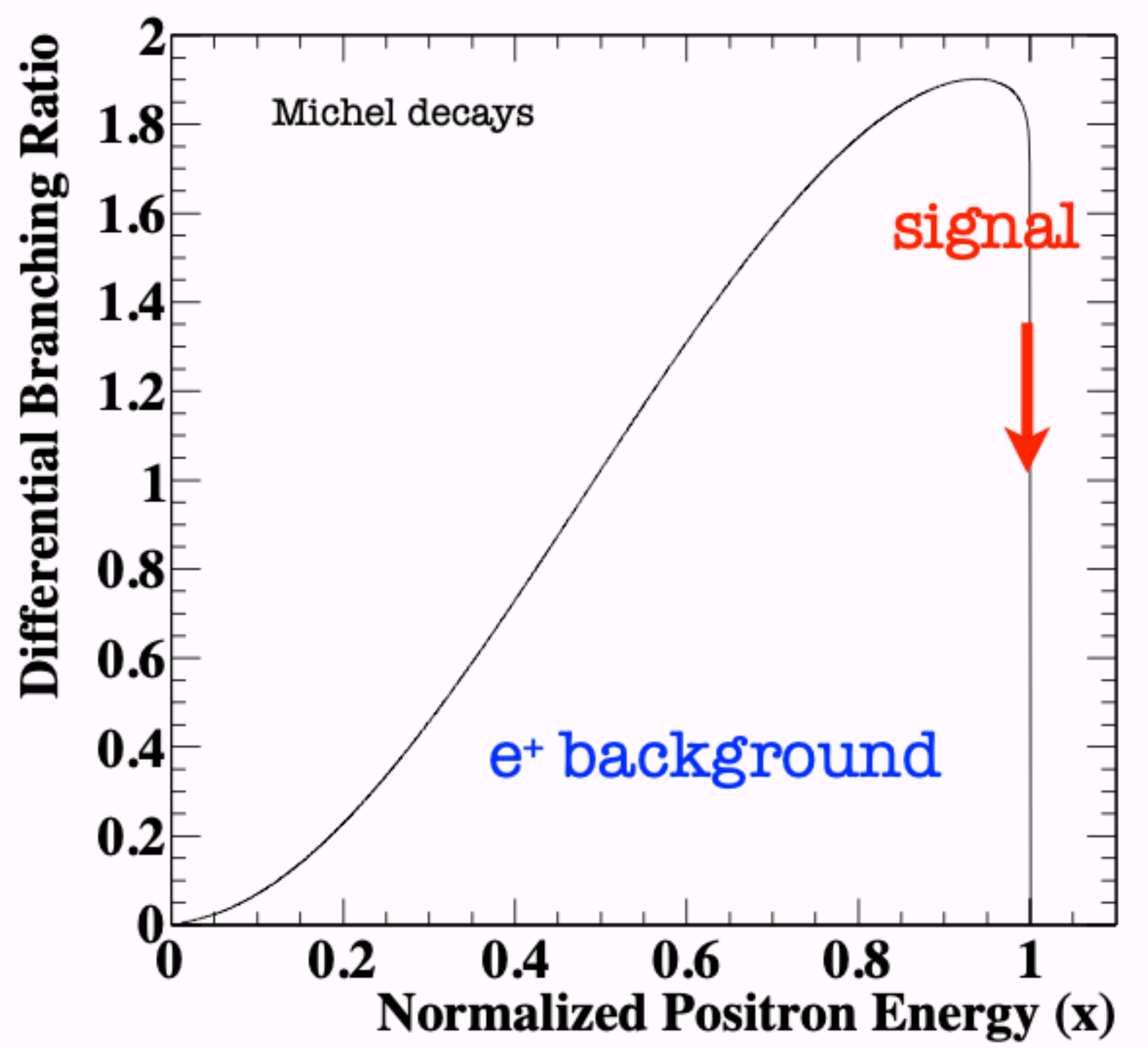


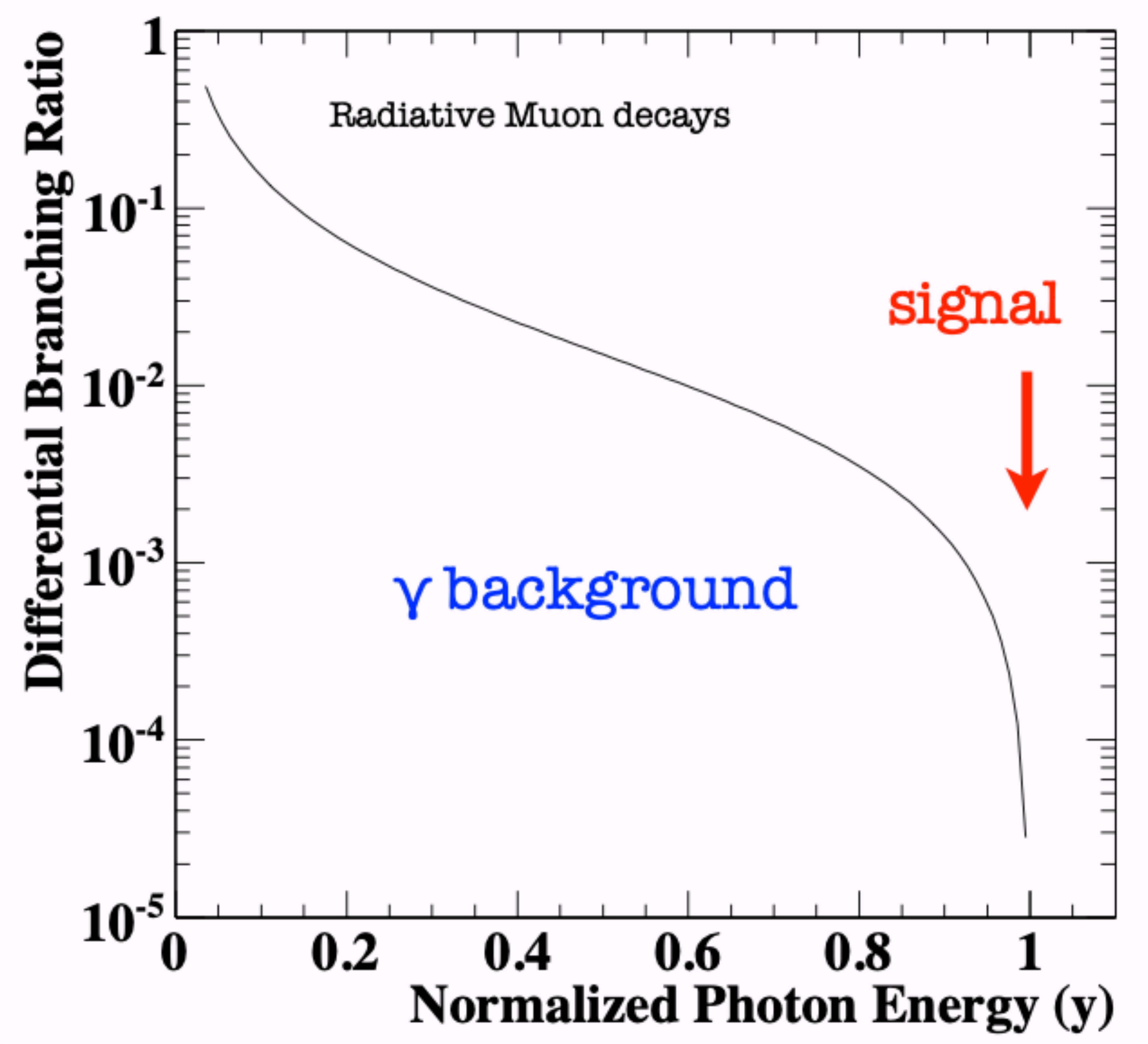
$\mu^+ \to e^+\gamma$ signal and backgrounds











$N_{Sig} \propto R_\mu \times T \times Br(\mu \to e\gamma) \times \varepsilon$ — 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 (R_μ); Resolutions (ΔE_γ, ΔE_e, $\Delta\Theta_{e\gamma}$, $\Delta t_{e\gamma}$); Elapsed time (T)

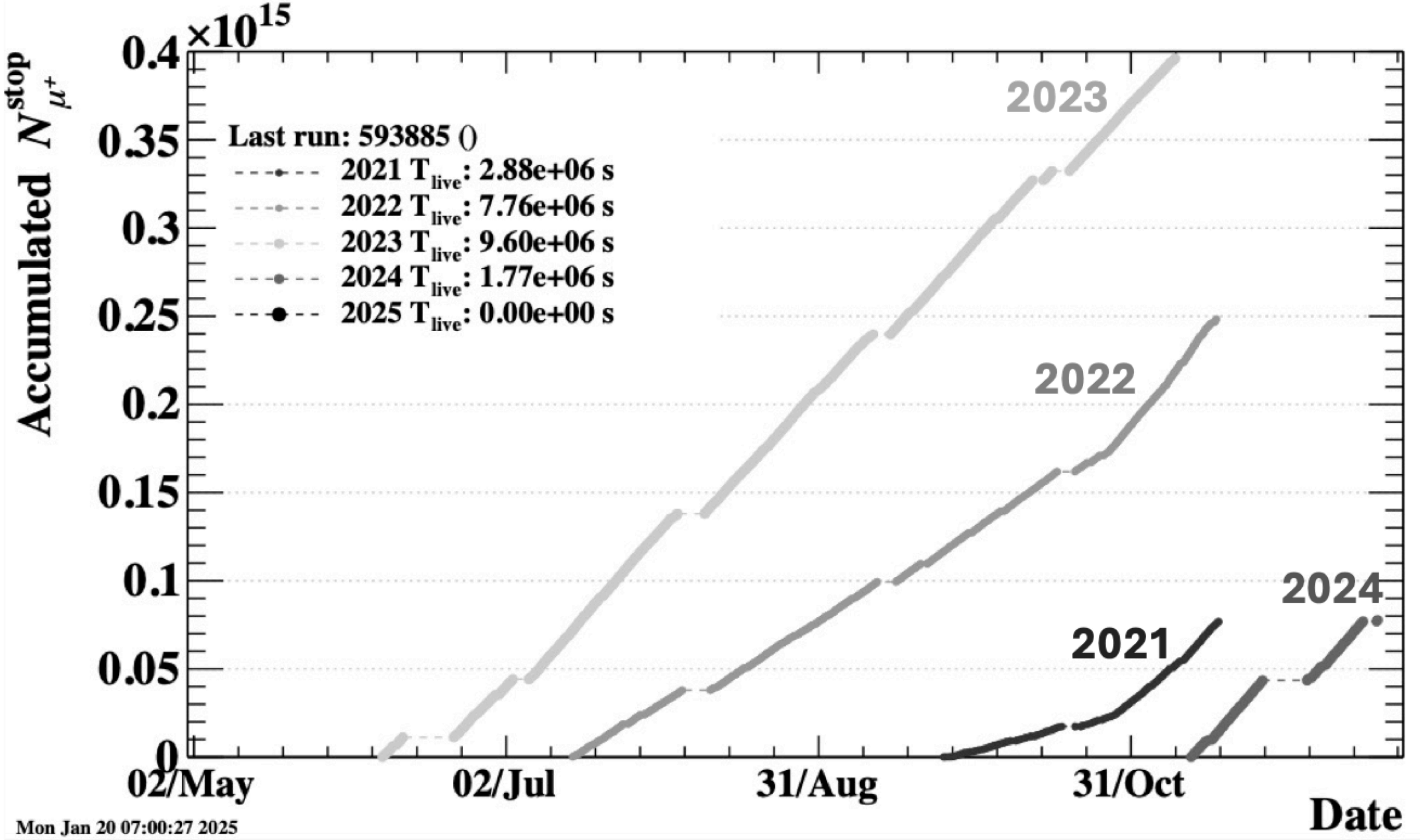
Detector performance summary

Table 6 Resolutions (Gaussian σ) and efficiencies measured at $R_\mu = 4 \times 10^7\ s^{-1}$, 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
ε_{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

nuisance parameters

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

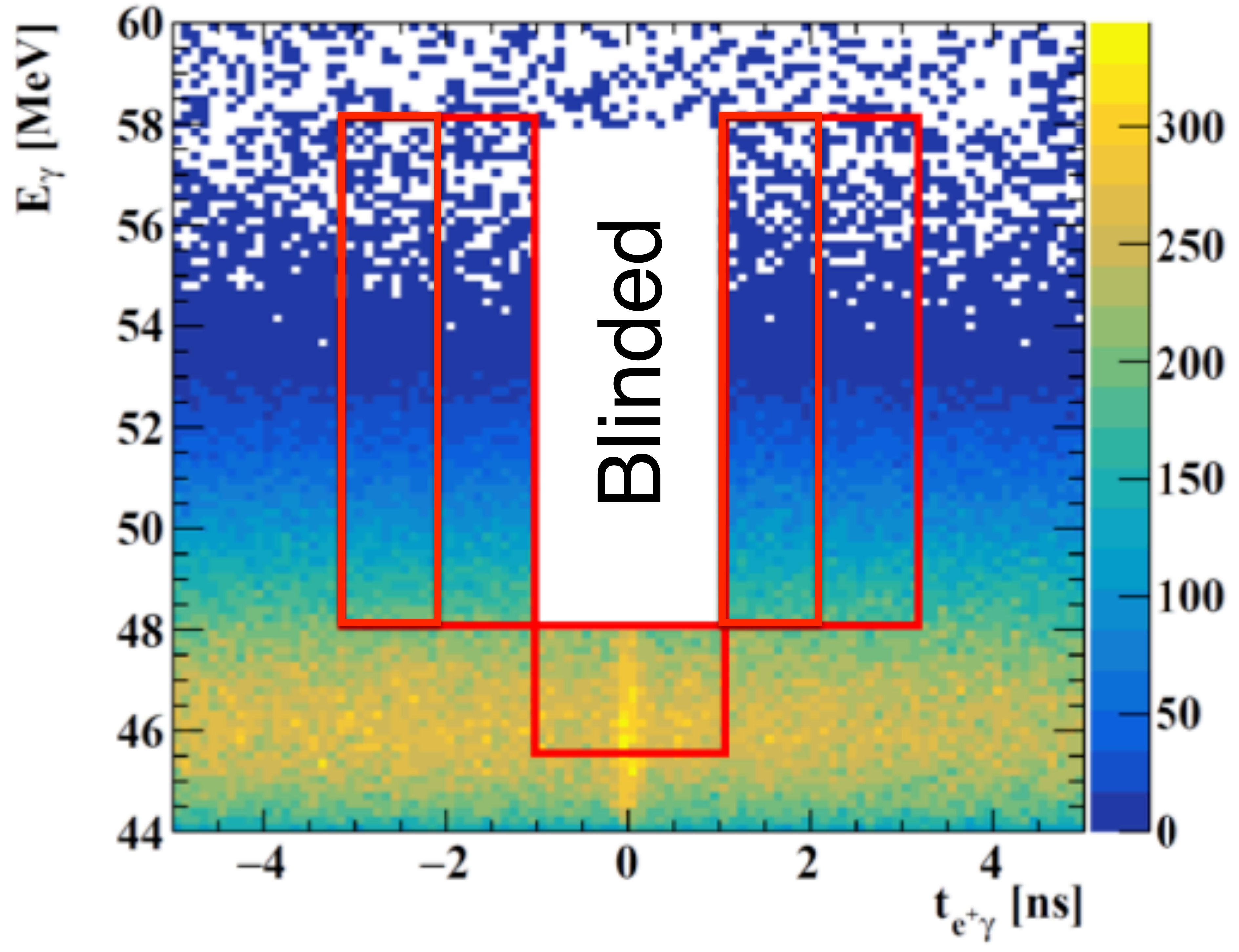
constrained

constrained by sideband

per-event PDFs

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

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

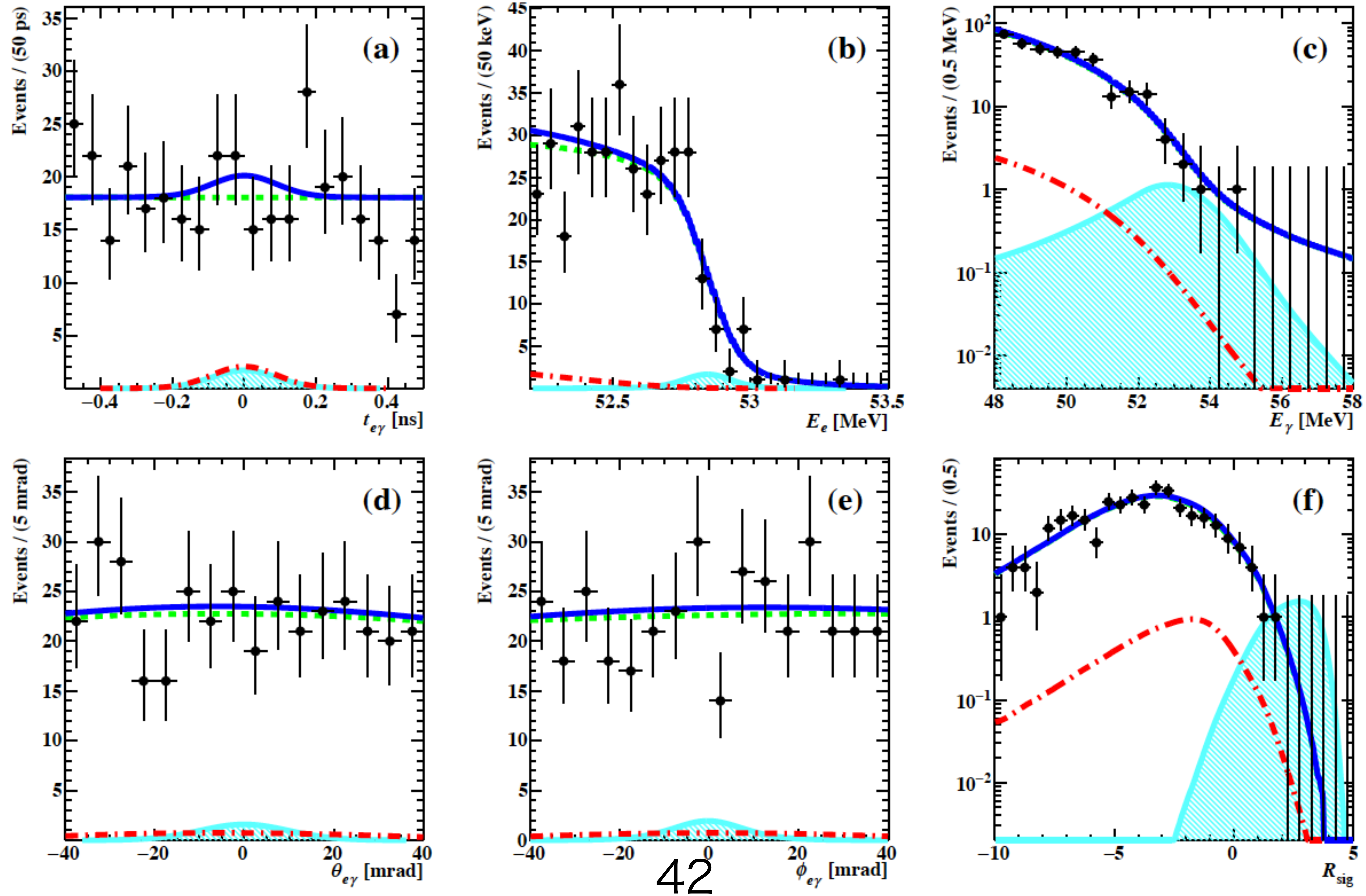


Analysis Region

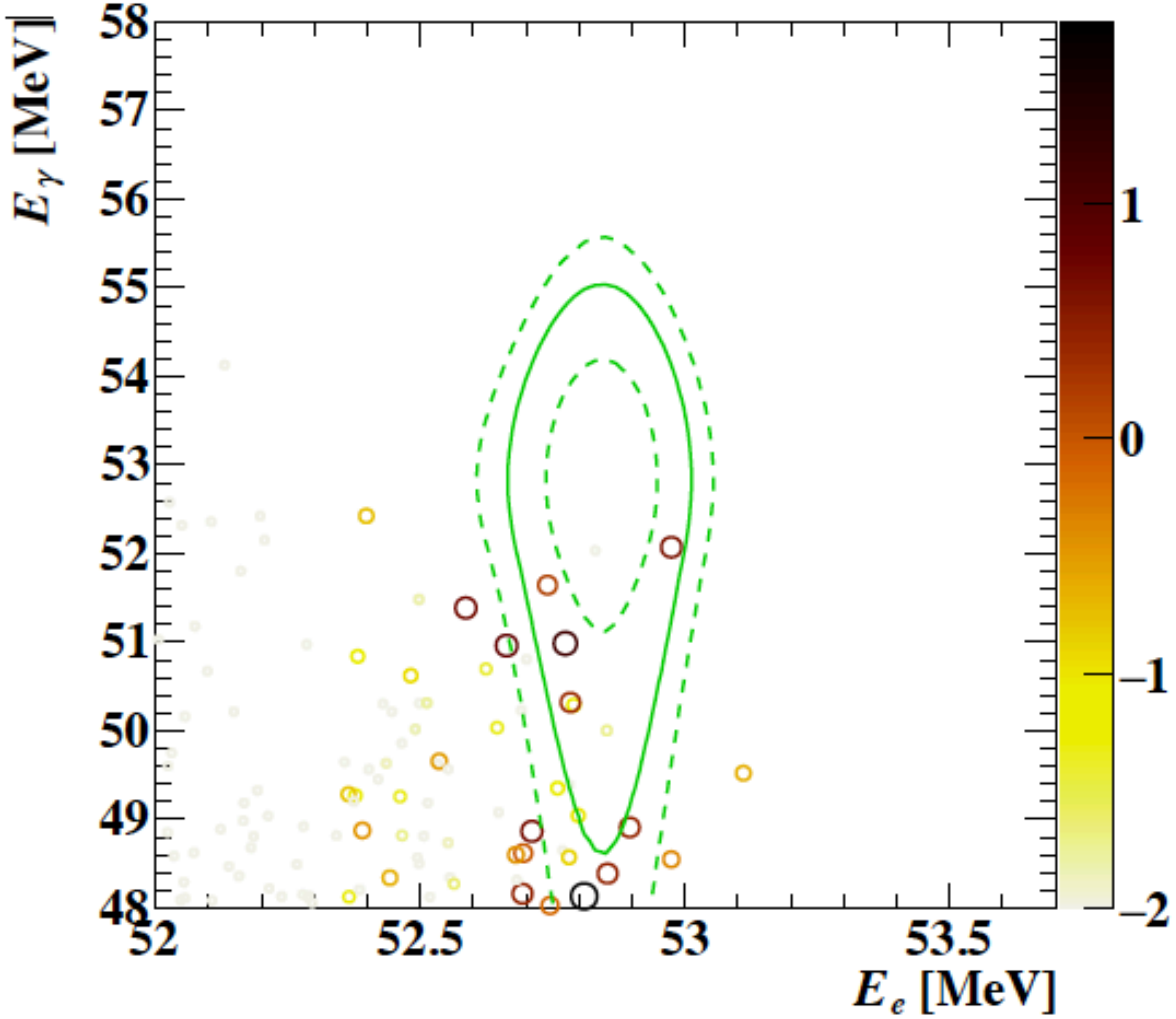
$48 < E_\gamma < 58\text{MeV}$ $\quad 52.2 < E_{e^+} < 53.5\text{MeV}$

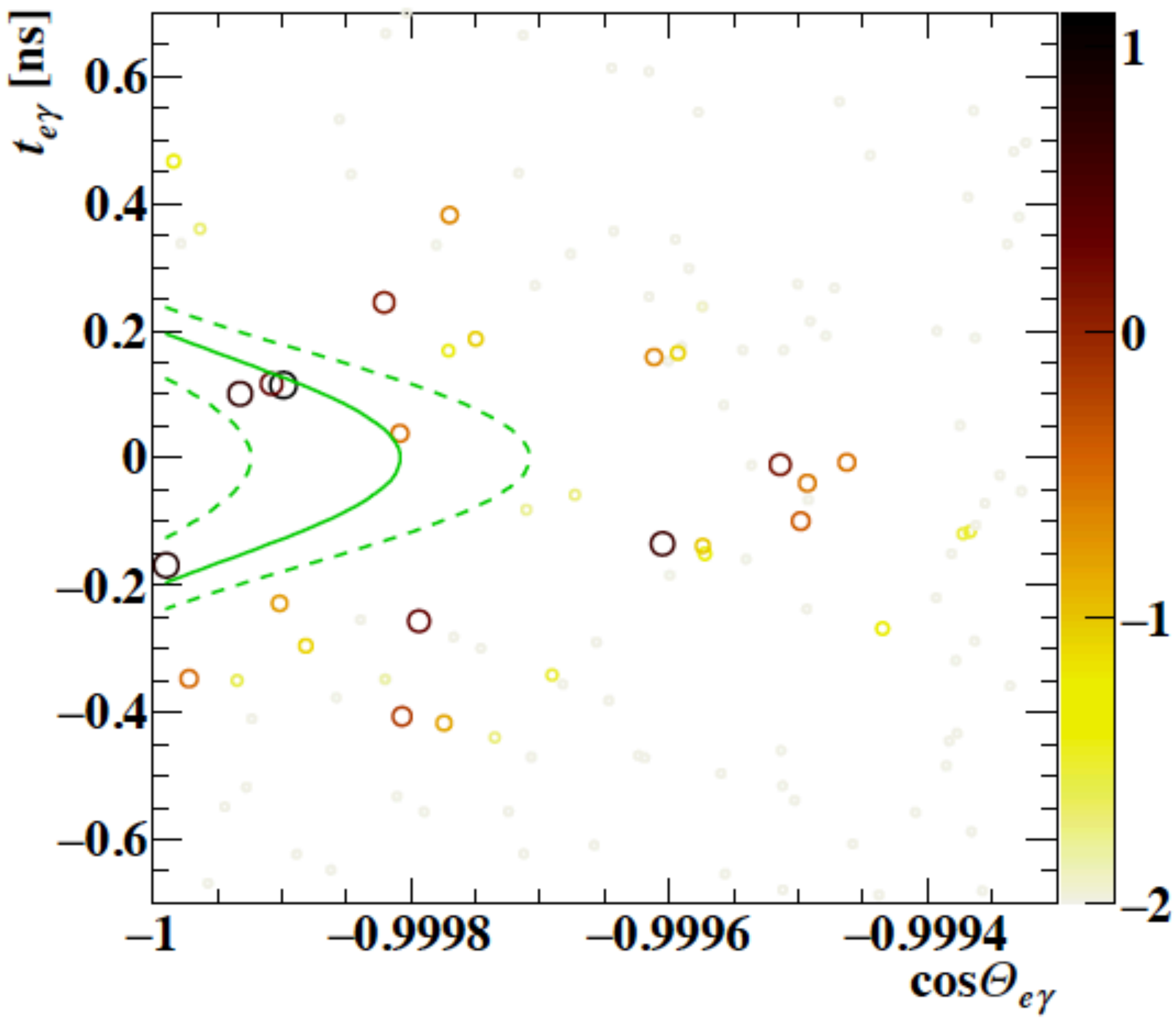
$|t_{e^+\gamma}| < 0.5\text{ns}$ $\quad |\theta_{e^+\gamma}| < 40\text{mrad}$ $\quad |\phi_{e^+\gamma}| < 40\text{mrad}$

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

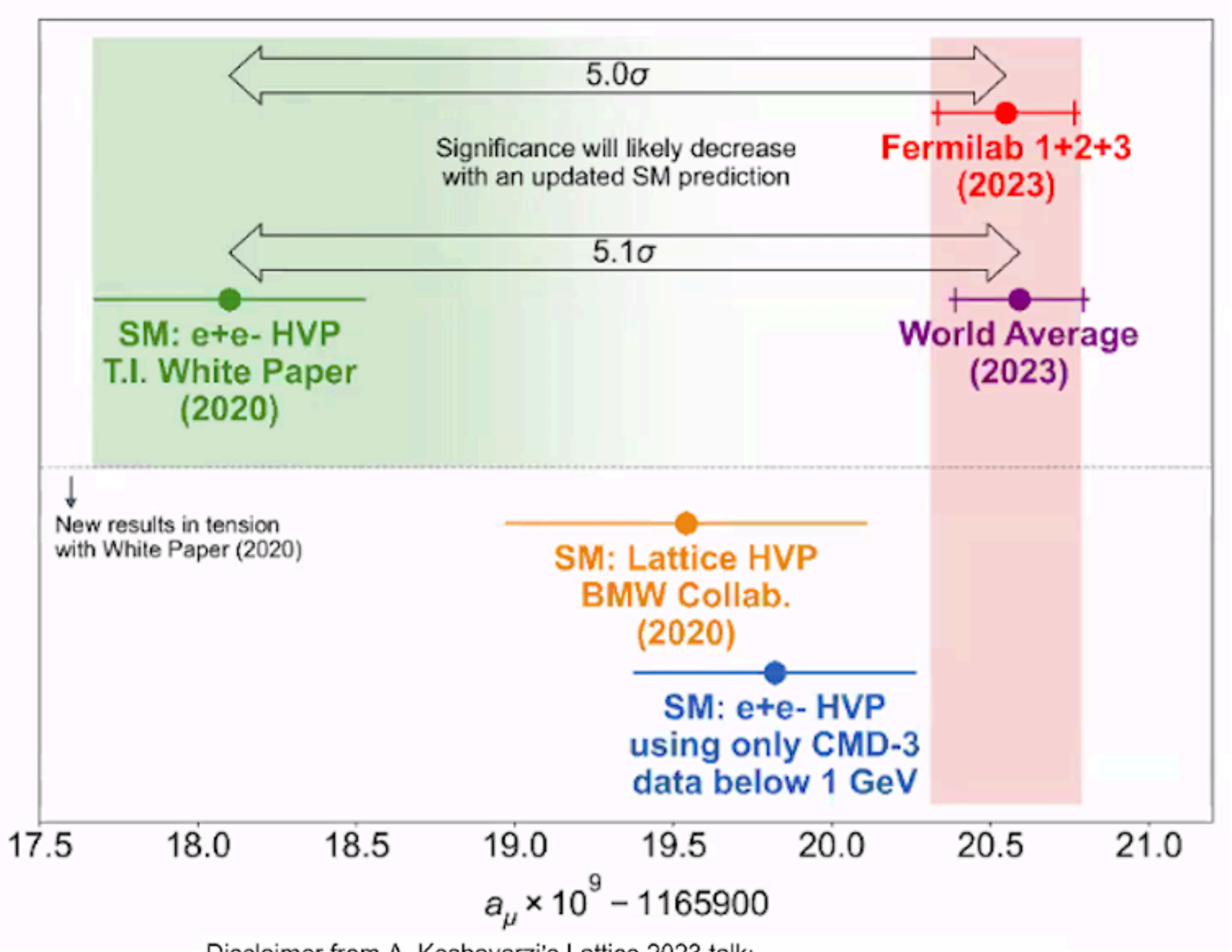


2-D event distributions



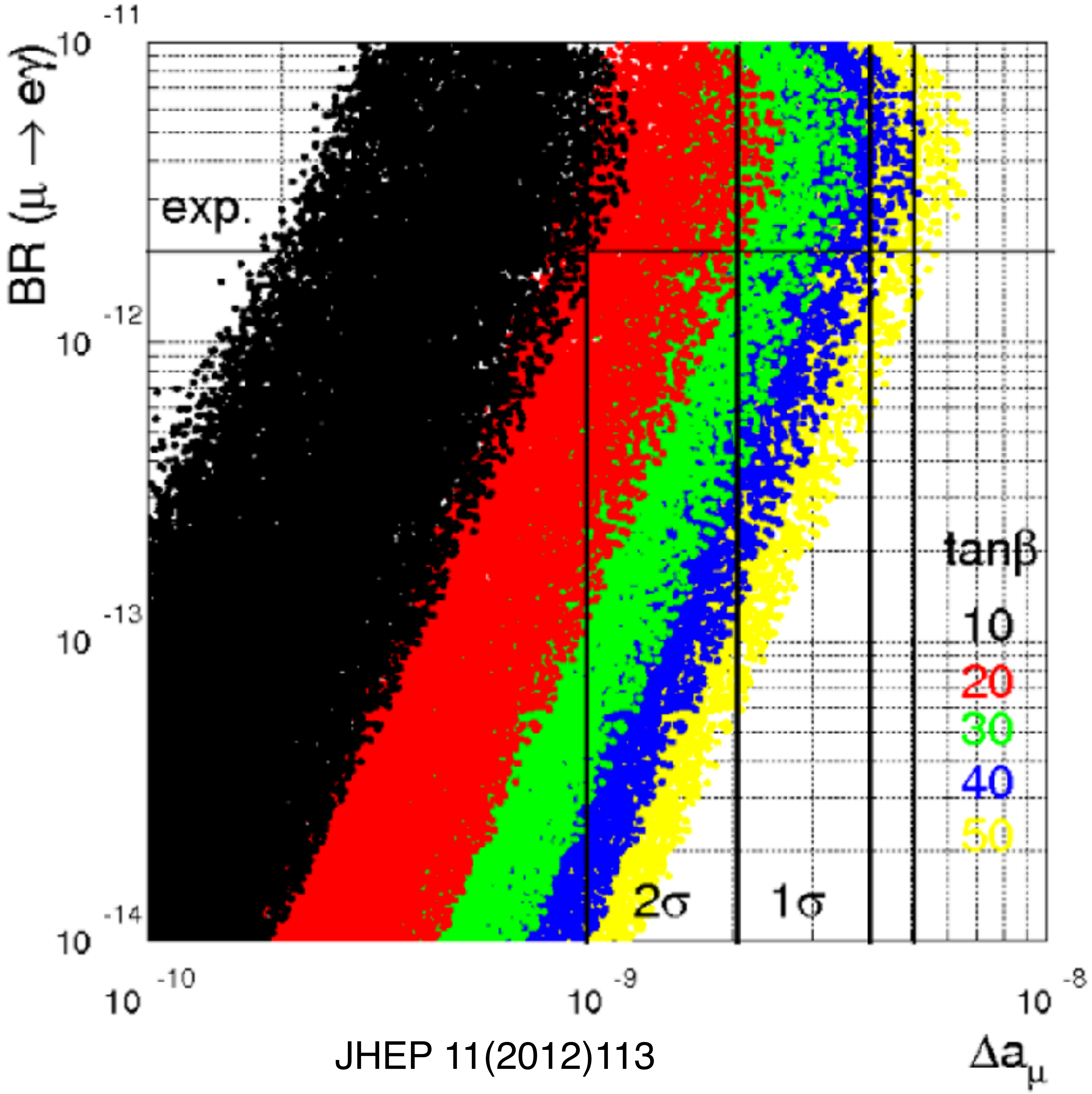


CLFV with other indications



Disclaimer from A. Keshavarzi's Lattice 2023 talk:

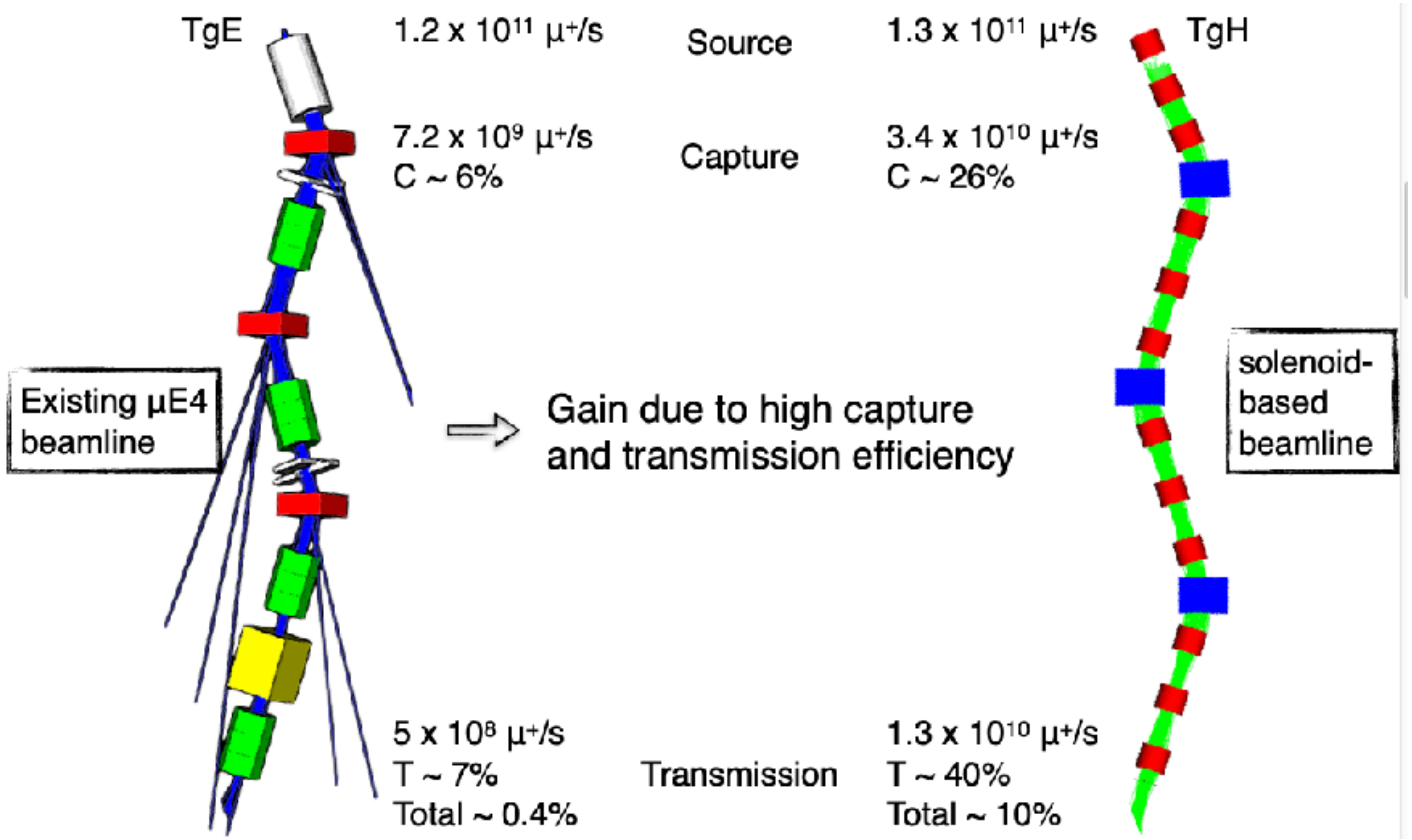
IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → <u>should not be taken as final!</u>

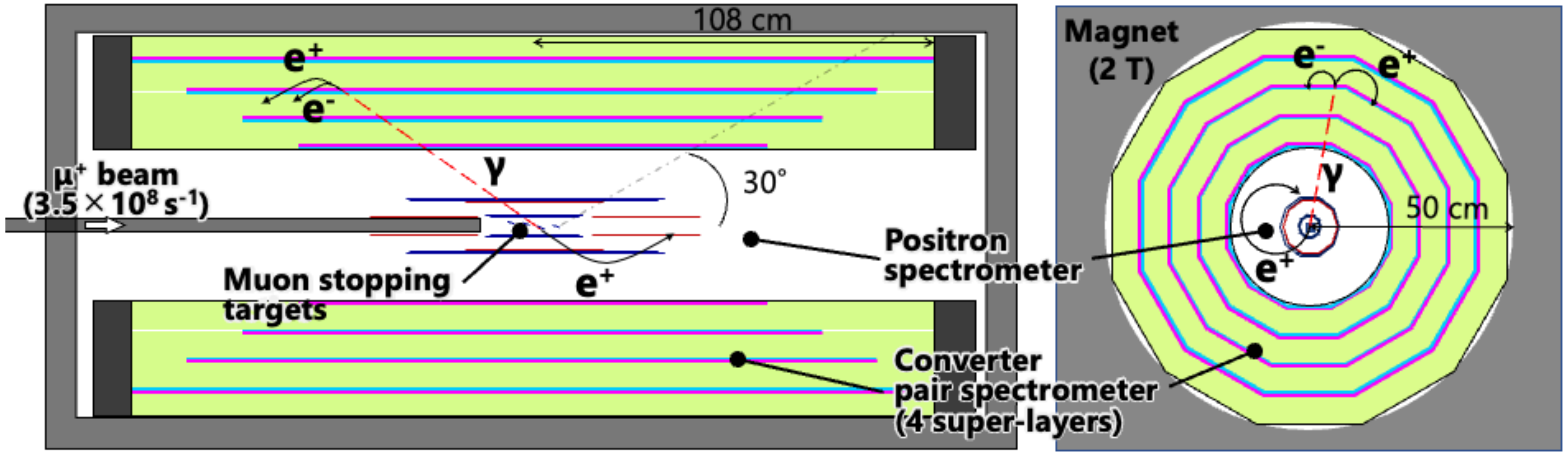


JHEP 11(2012)113

After MEG II

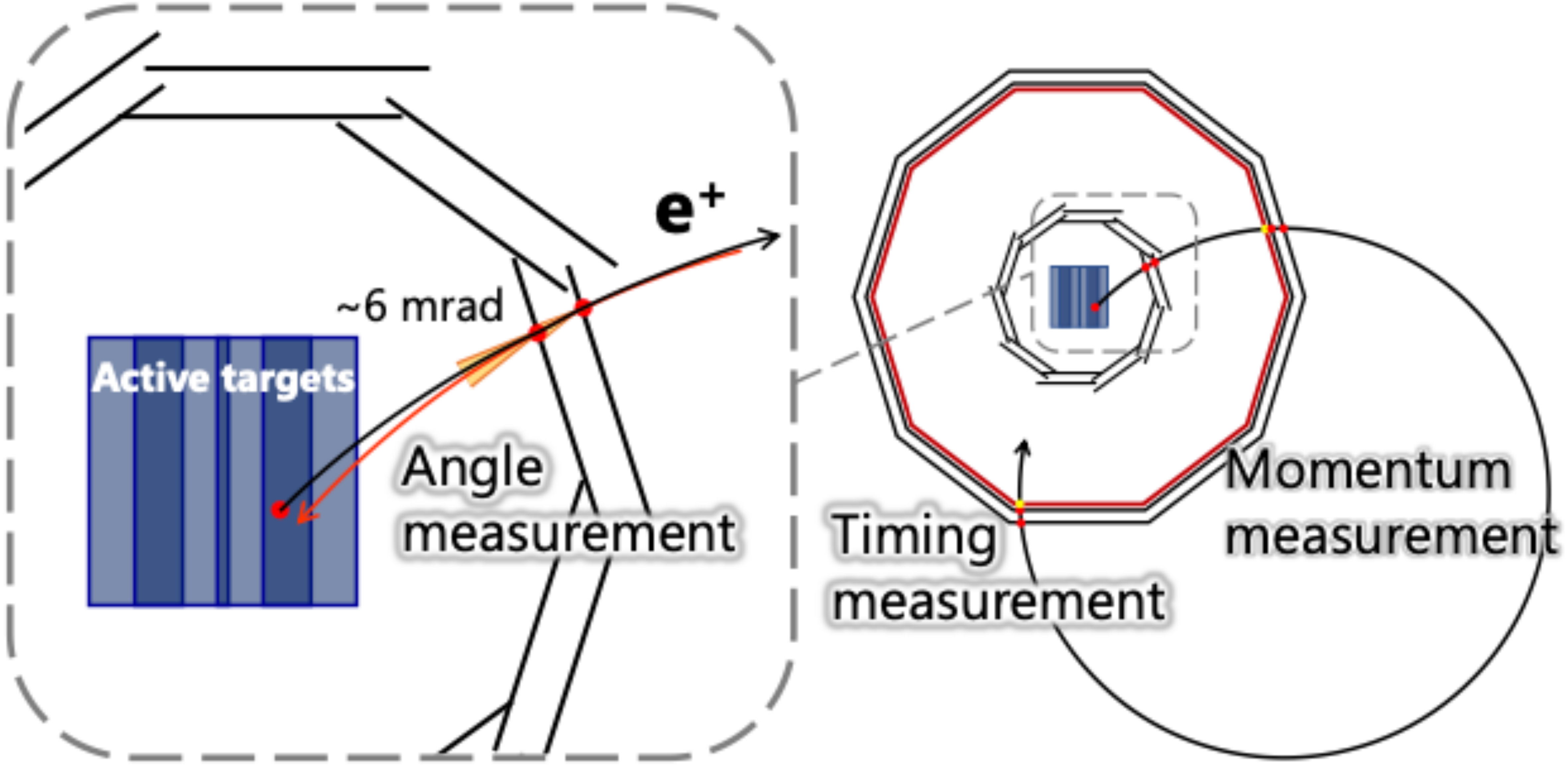
- High Intensity Muon Beam project (HiMB) at PSI
  - 10^{10} μ^+/s (100× improvement)
  - CDR by end of 2021
  - Implementation during 2027/2028
  - Science Case workshop 6-9 April 2021
- Future μ→eγ experiment for CLFV
  - Goal: Br(μ→eγ) ~10^{-15}
  - Discover new physics and precision measurements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

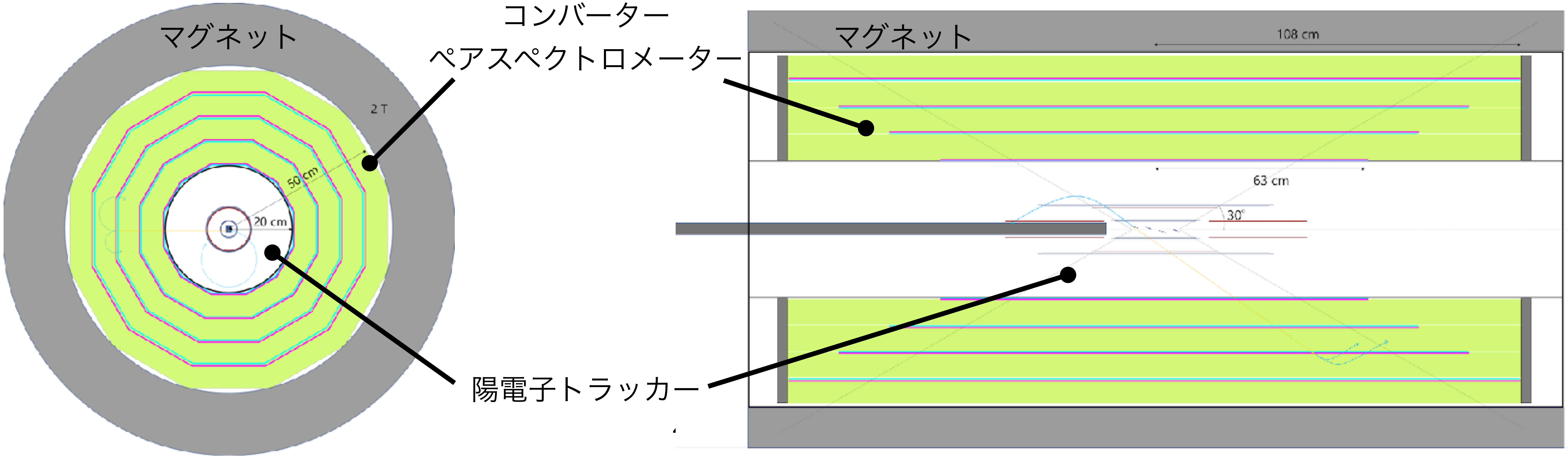




Future μ→eγ

- 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*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

ArXiv: 1709.00294

Complementarity in target materials