$\mu \to e\gamma$ 将来実験

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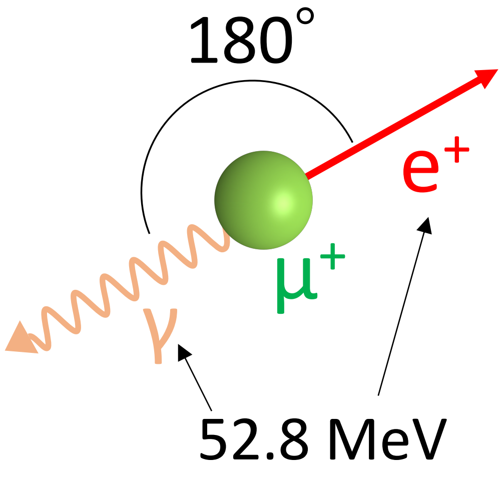
Introduction to concept

How to detect $\mu \to e\gamma$?

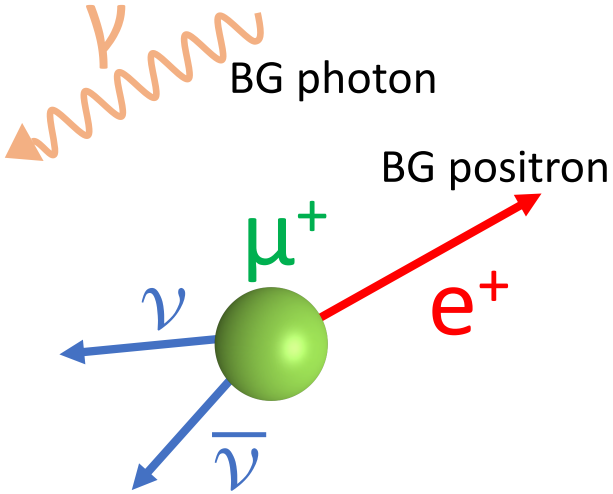
Signal

2-body kinematics



Main background

Accidental coincidence



RMD background

Radiative muon decay ($\mu \to e\nu\nu\gamma$)

→ **Minor** (effectively 10^{-16})

E_e	52.8 MeV	< 52.8 MeV
E_γ	52.8 MeV	< 52.8 MeV
$t_{e\gamma}$	0	Flat distribution
$\Theta_{e\gamma}$	180°	No correlation

What determines sensitivity?

$$N_{sig} \propto R_\mu \times \mathrm{Br}(\mu \to e\gamma) \times \text{efficiency}$$

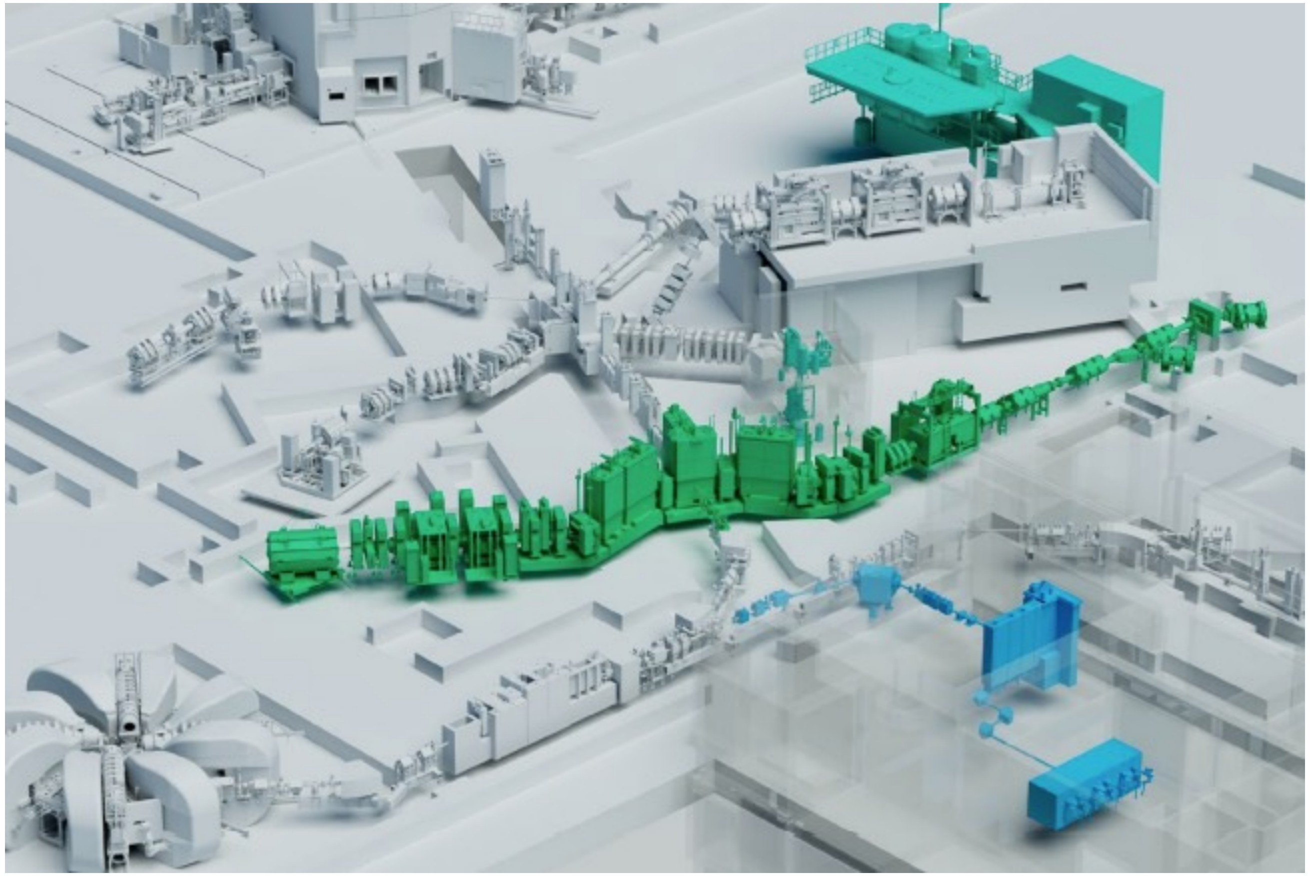
$$N_{BG} \propto R_\mu^2 \underbrace{\sigma_t\, \sigma_\Theta^2\, \sigma_{E_e}\, \sigma_{E_\gamma}^2}_{\text{Resolution}}$$

- **High efficiency & high rate**
- **Continuous muon beam**
- **High resolution**

HiMB project @PSI

- MEG II runs on $\pi E5$ beamline
  - Operate @5×10^7 μ/sec (continuous)
  - Plan to complete DAQ in 2026

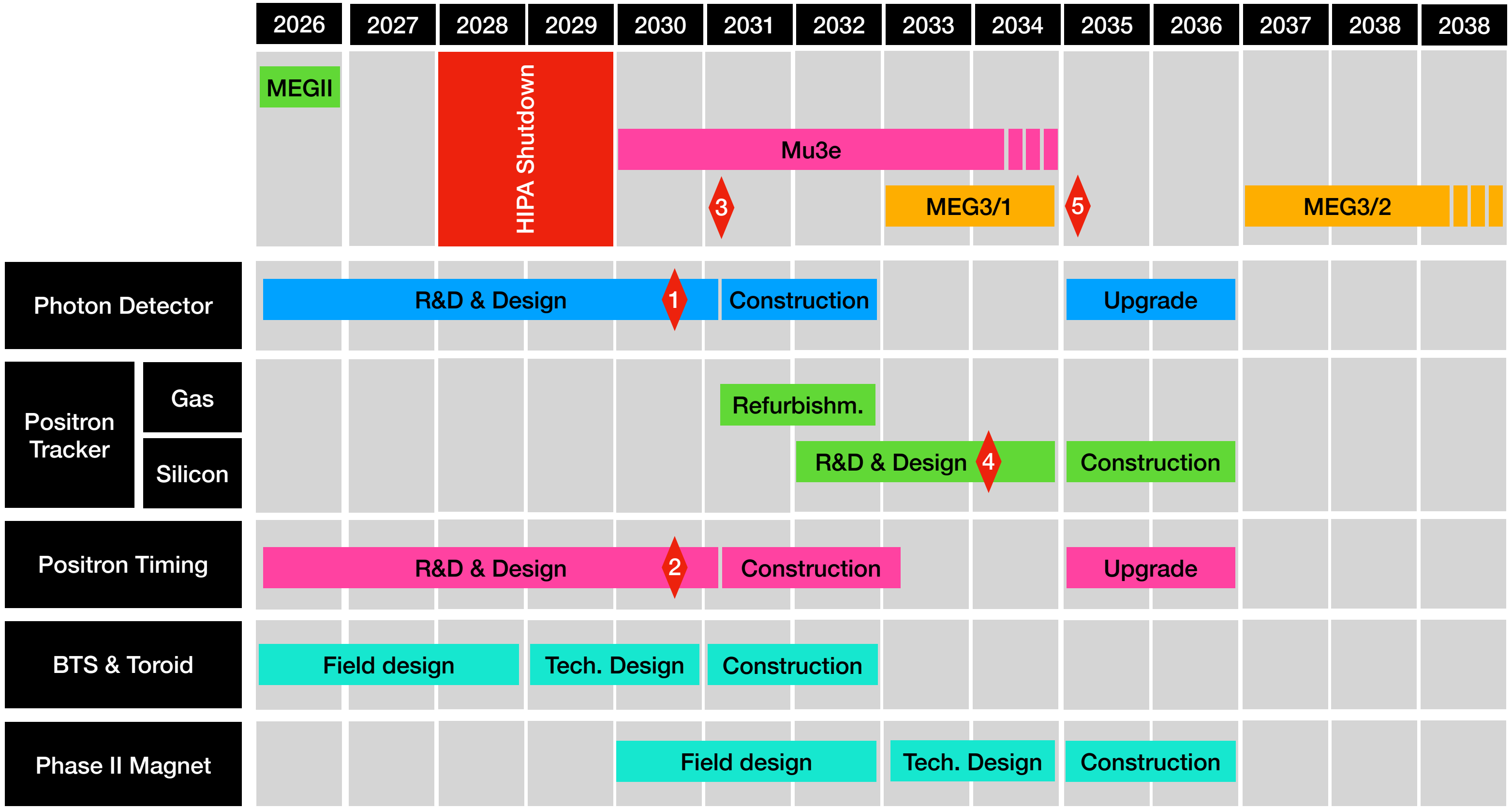
- High Intensity Muon Beam @PSI
  - $\times100$ intense beam: 10^{10} μ/sec
  - Planned to be built in 2028 – 2029 (long shutdown scheduled)



Future experiment plans to exploit 10^{10} μ/sec beam

Future experiment: Proposal

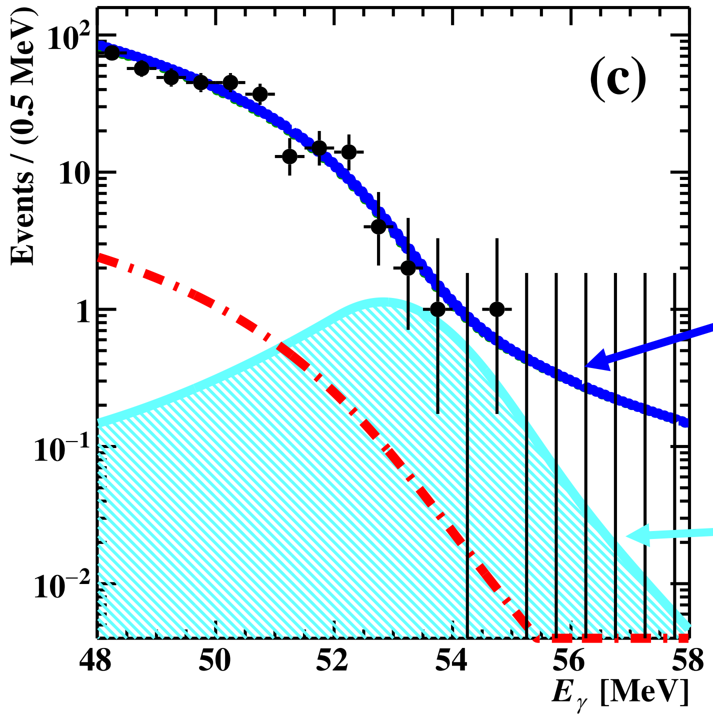
- Proposing new $\mu \to e\gamma$ experiment at HiMB
  - Letter of intent submitted to PSI
  - $O(10^{-15})$ sensitivity to branching ratio
  - Aiming to start in 2030s with possible phased approach



Ideas to maximize opportunity

- Suppression of background events
  - $N_{BG} \propto R_\mu^2\, \sigma_t\, \sigma_\Theta^2\, \sigma_{E_e}\, \sigma_{E_\gamma}^2$
  - Much higher resolution required than MEG II
  - In particular, **photon energy resolution** is important

MEG II latest analysis plot



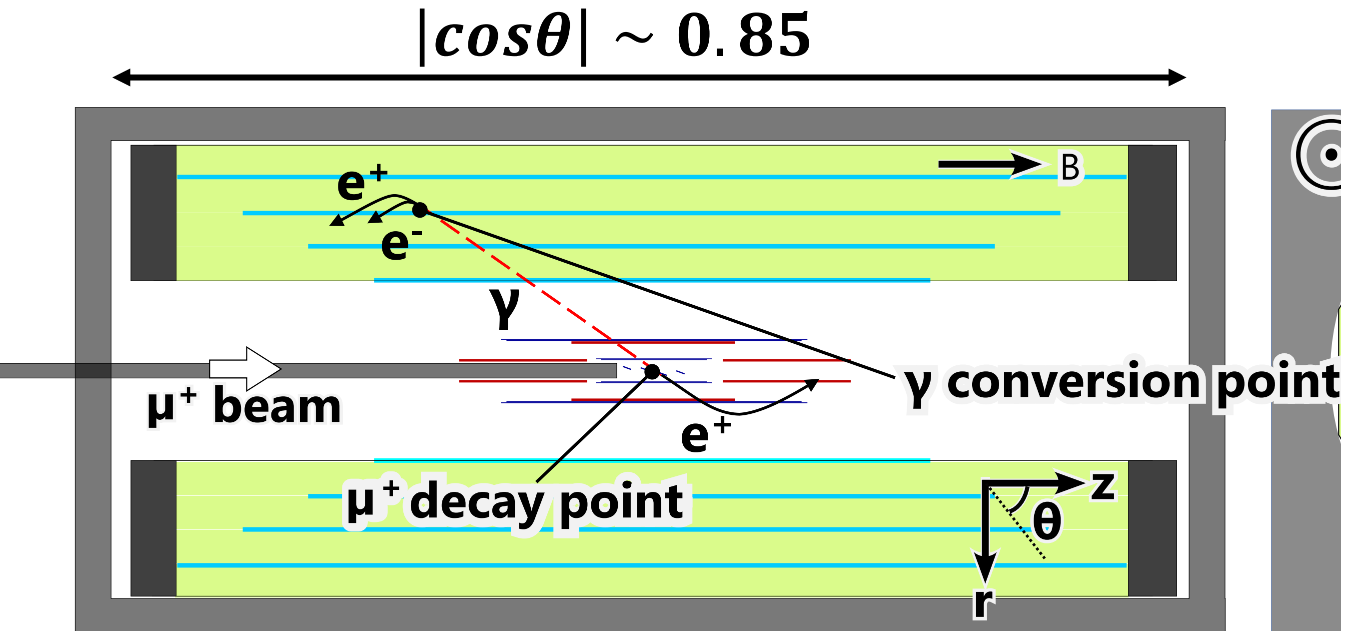
Pileup contributes to long high energy tail of BG events in MEG II
→ Need higher rate capability with photon detector

MEG II is running with ~ 2% resolution
→ Aiming to achieve 0.4% in future experiment

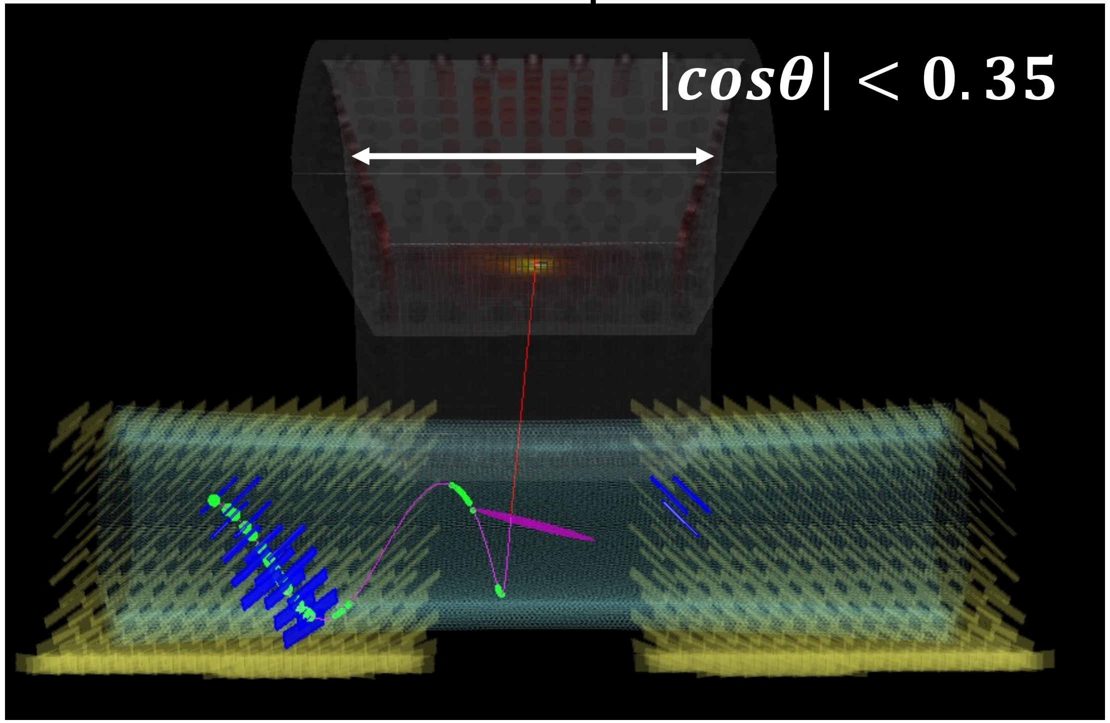
Ideas to maximize opportunity

- Wider angle coverage of detector
  - Geometrical acceptance of 85% (c.f. 11% in the MEG II)
  - Polarization dependence becomes more accessible with larger θ coverage
    → Can study $\mu \to e_L\gamma$ vs $\mu \to e_R\gamma$ with polarized μ
  - P_μ at HiMB to be studied, but use μ from $\pi \to \mu\nu$

Future experiment

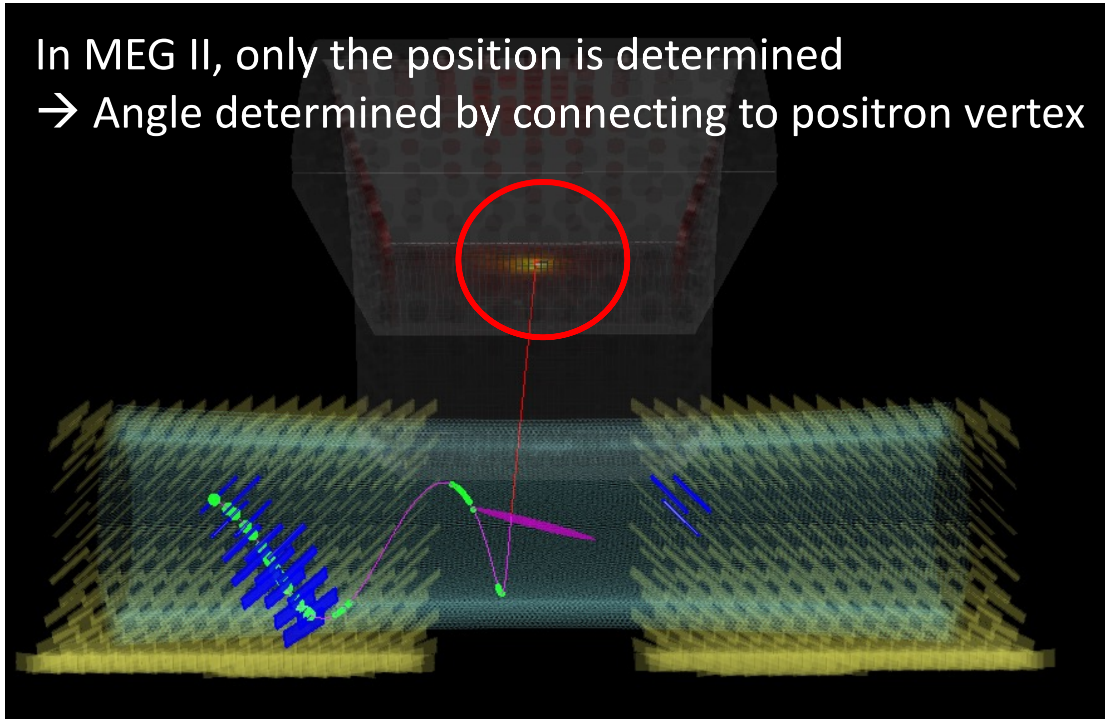


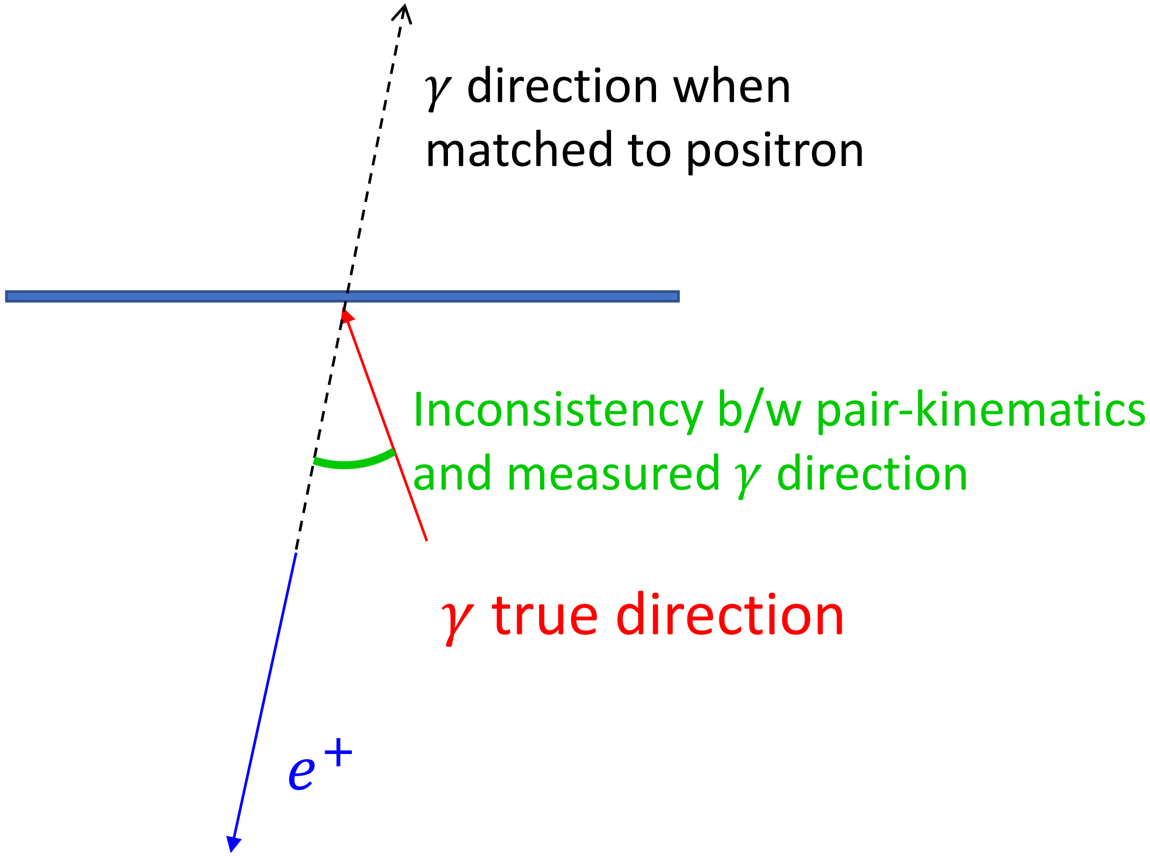
MEG II experiment



Ideas to maximize opportunity

- Suppression of BG events
  - Direct measurement of photon direction constrains $e\gamma$ combinatorials (Combinations with inconsistent photon angle and position can be discarded)

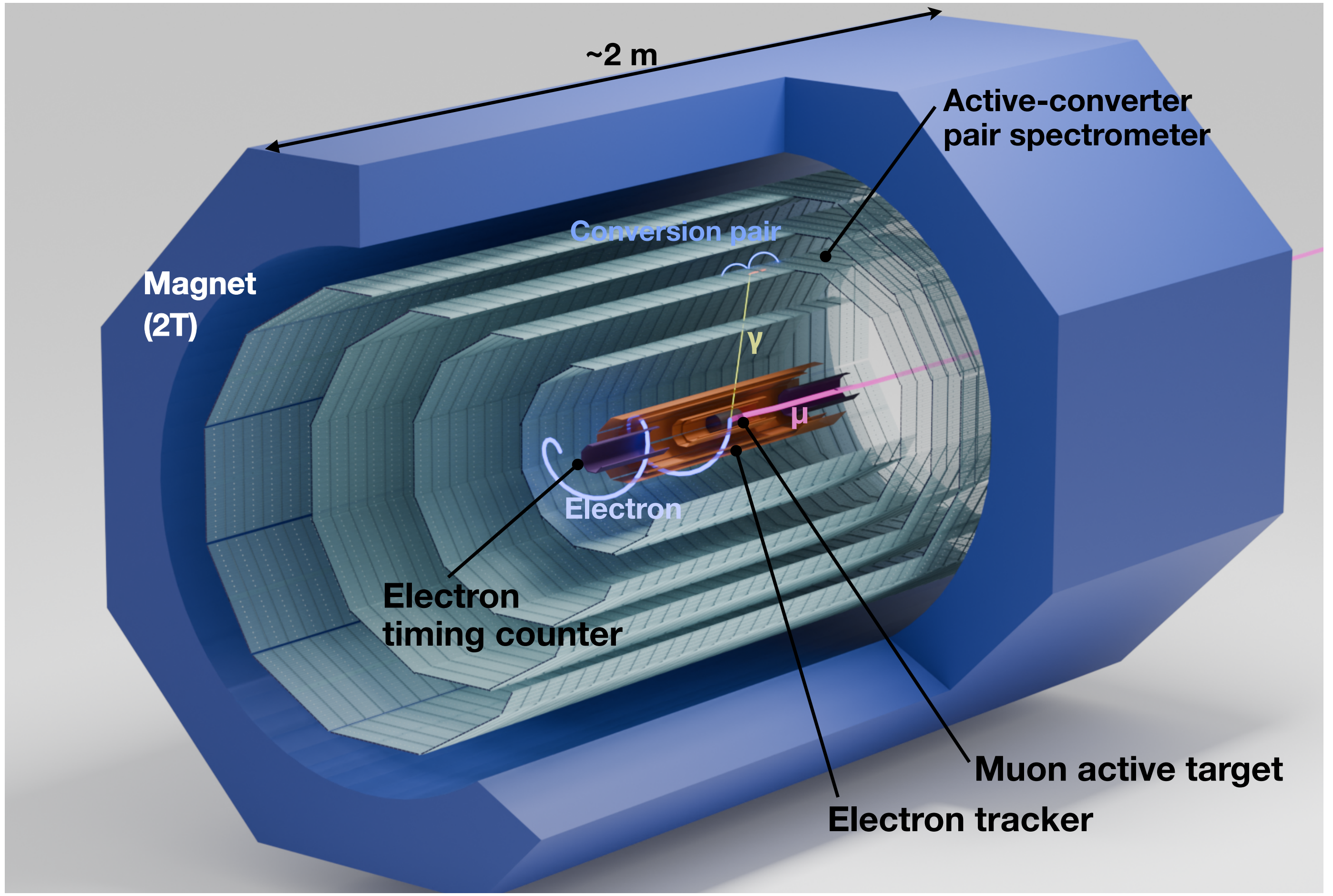




Baseline detector concepts

- Positron detectors
  - Tracking: Si detector possibly with active muon stopping target
  - Timing: scintillation detector or fast silicon detector (e.g. LGAD)

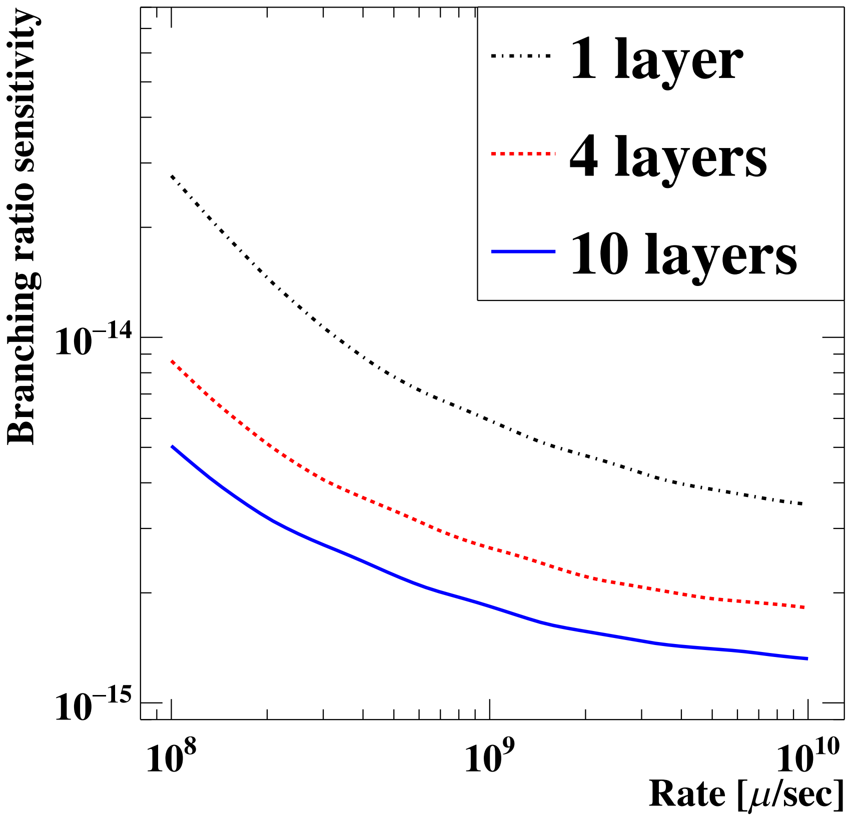
- Photon detectors
  - Conversion pair-spectrometer with active converter
  - Stacking to maximize efficiency: 4-layers as baseline



Baseline scenario of experiment

- Baseline scenario
  - Sensitivity estimate: $2-3\times10^{-15}$ sensitivity in reach w/ $> 10^9$ μ/s rate
  - Relies on many assumptions on detector performance

	Resolutions/efficiencies
Photon energy	200 keV
Photon position	200 μm
Photon timing	30 ps
Photon angle	150 mrad
Photon detection efficiency (4 layers)	10 %
Positron energy	100 keV
Positron angle	6 mrad
Positron timing	30 ps
Positron detection efficiency	70 %
Geometrical acceptance	85 % (36 %)



Possible use for other search?

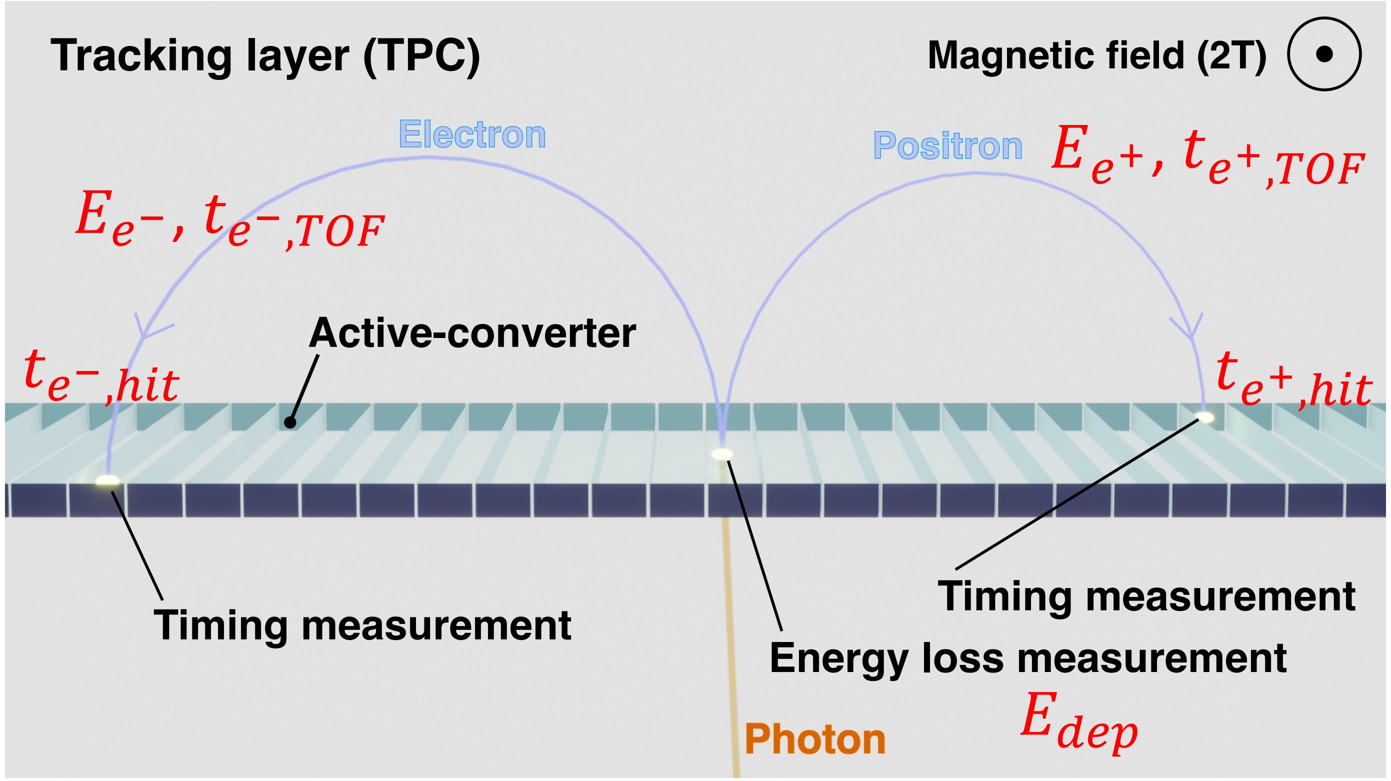
- Simultaneous measurement of $\mu \rightarrow eee$
  - Not just splitting beamline resource with dedicated Mu3e experiment
  - Technical challenges: Momentum acceptance for positrons
    (Mu3e experiment optimized for 20 – 30, $\mu \rightarrow e\gamma$ wants to measure 52.8 MeV)

- Any other options?
  - Michel spectrum studies?
  - Etc.

R&D of detector technology

Conversion pair-spectrometer

- Working principle
    - Photon conversion + Pair-tracking
    - Energy: $E_\gamma = E_{e^+} + E_{e^-} + E_{dep}$
      → 200 keV target resolution
    - Time: $t_{e^\pm,hit} - t_{e^\pm,TOF}$
      → 30 ps target resolution

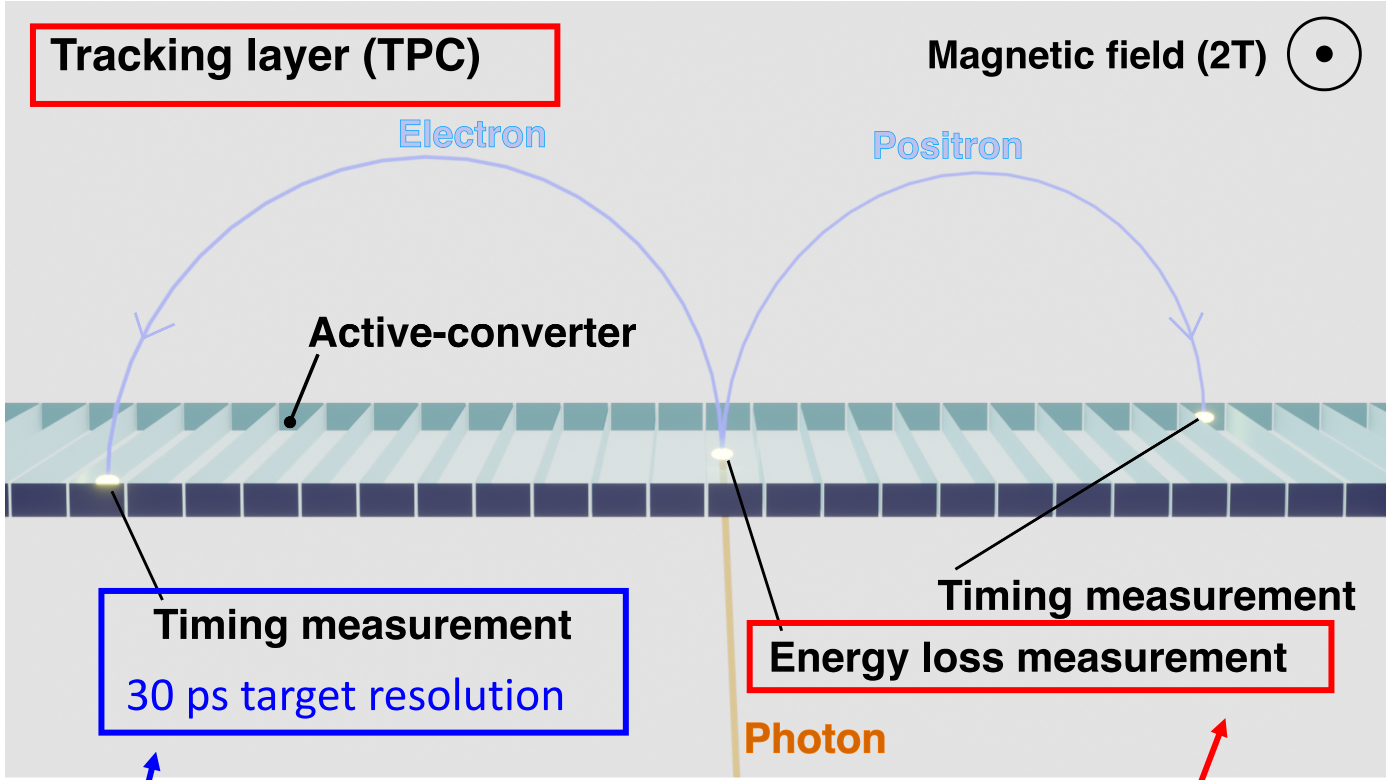


- Properties
    - Excellent σ_{E_γ} w/ tracking detector
    - Photon direction estimated by $\vec{p}_{e^+} + \vec{p}_{e^-}$
    - Pileup: Easy to disentangle pileup photons
    - But, low efficiency with thin converter → Compensated by stacking approach

Conversion pair-spectrometer

- Target performance
  - 200 keV energy resolution
  - 30 ps time resolution
  - 150 mrad direction measurement
  - 0.2 mm position resolution

200 keV target resolution



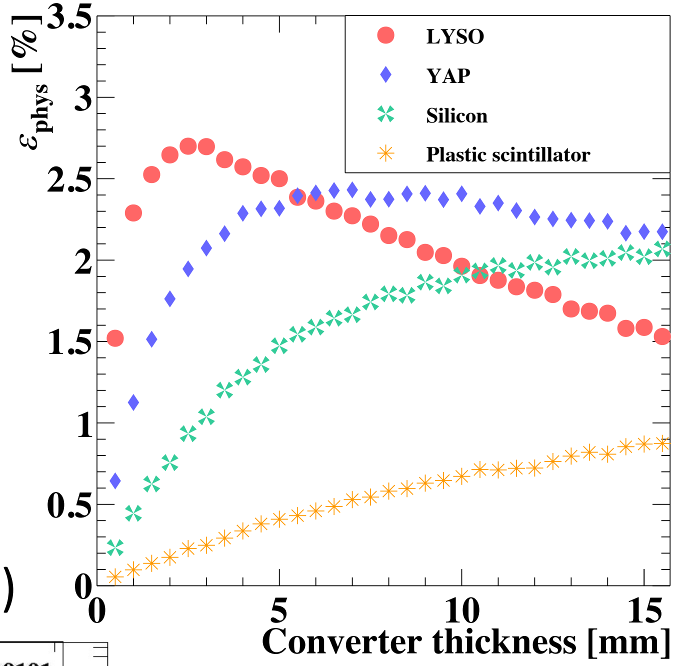
150 mrad, 0.2 mm

With two counters, 40 ps resolution for each hit

With 3 mm-thick LYSO (discussed later) for active converter, need 400 p.e/MeV light yield

Active converter simulation

- Simulated energy spectrum
  - Sharp peak + low-energy tail for signal
  - 3 mm LYSO maximizes N of events in the peak region
  - Suppression of background spectrum at 52.8 MeV



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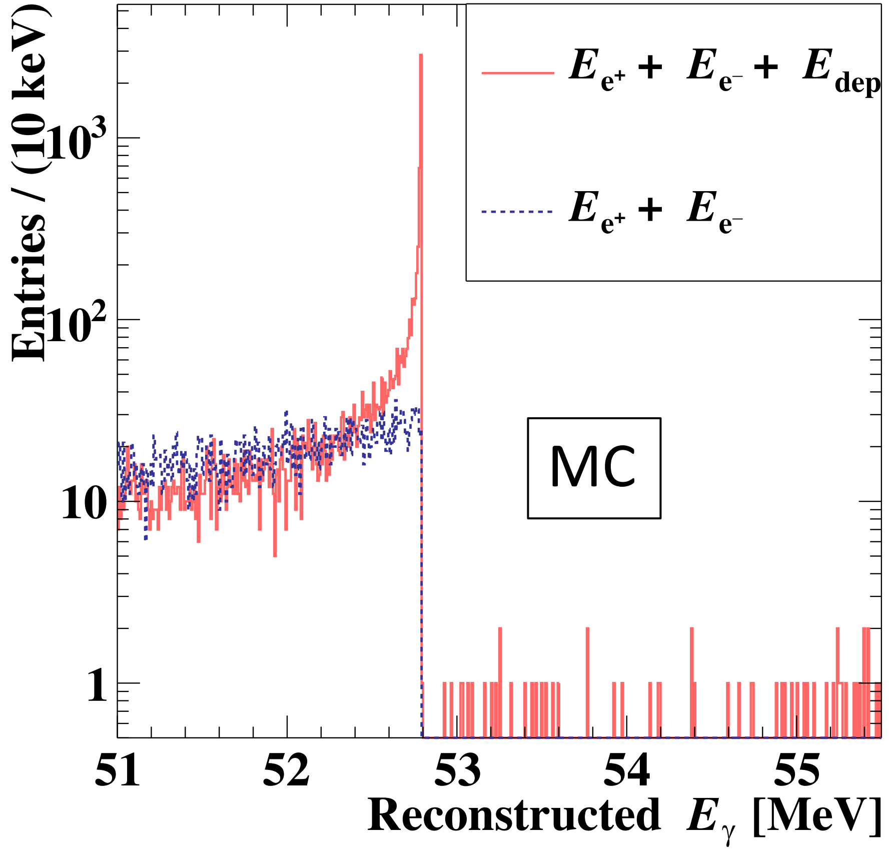
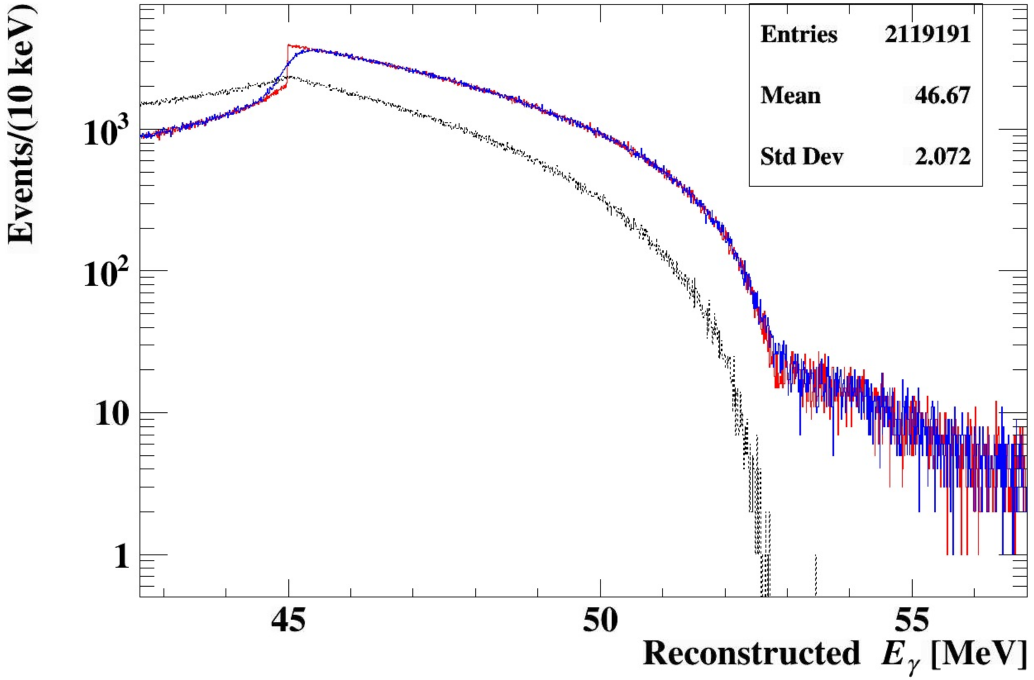
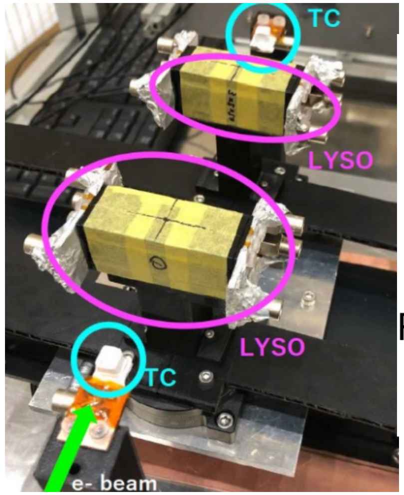


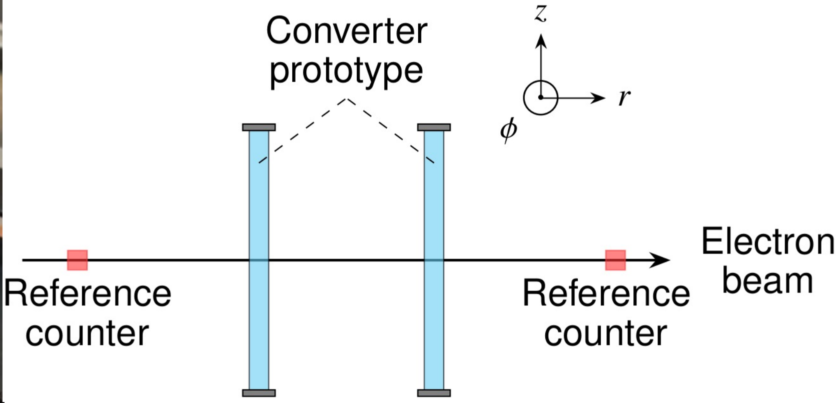
Background spectrum (radiative decay)



Active converter performance test

- LYSO performance study so far
  - Performance studied with 3 GeV e^-
  - 25 ps single counter resolution (40 ps required)
  - 10000 p.e. observed for 2.7 MeV E_{dep} (400 p.e. /MeV required)
- Importance of quality control
  - Position dependence
  - Counter to counter difference





PF-AR test beamline @KEK

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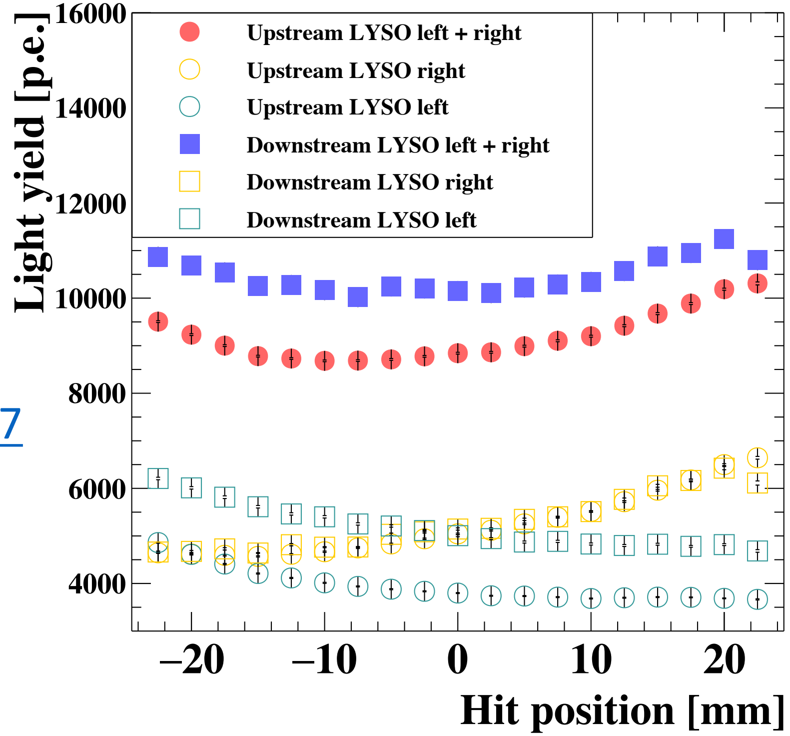
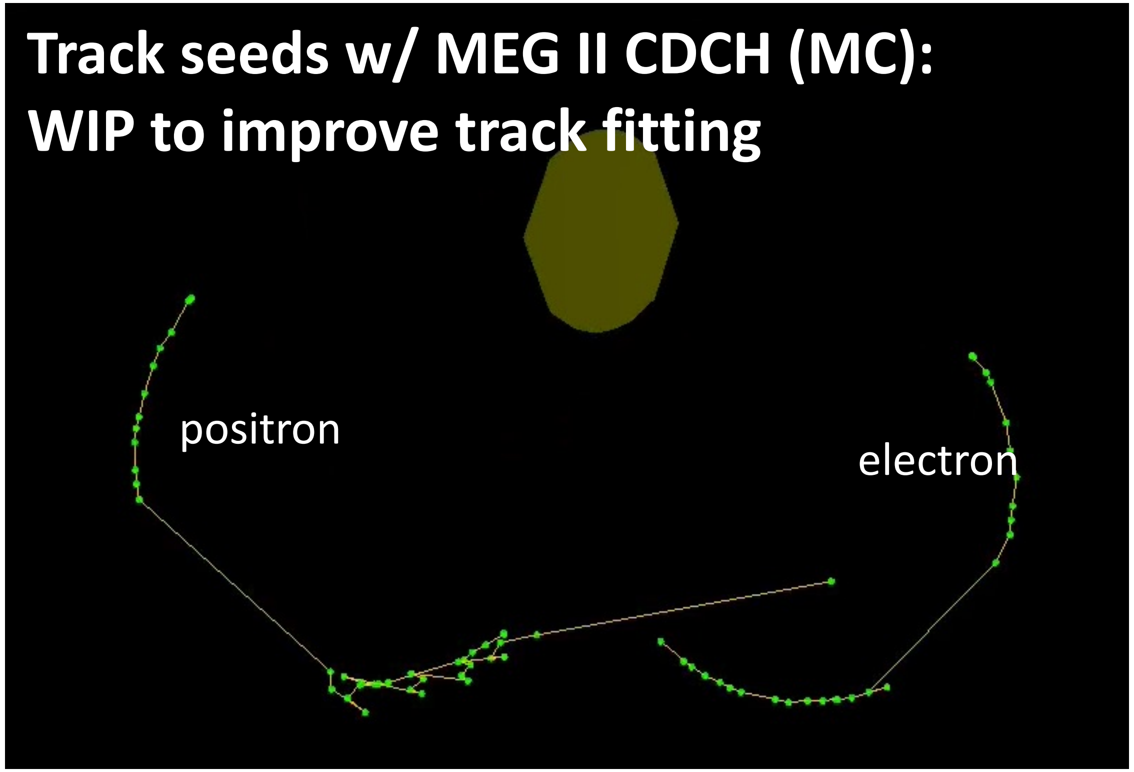
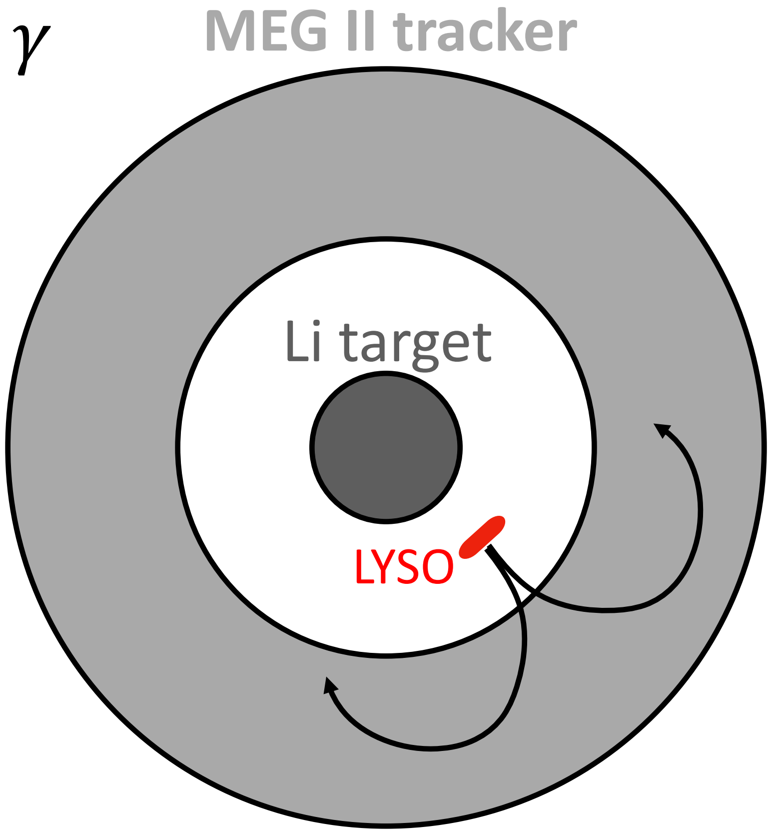


Proof of concept test for active converter

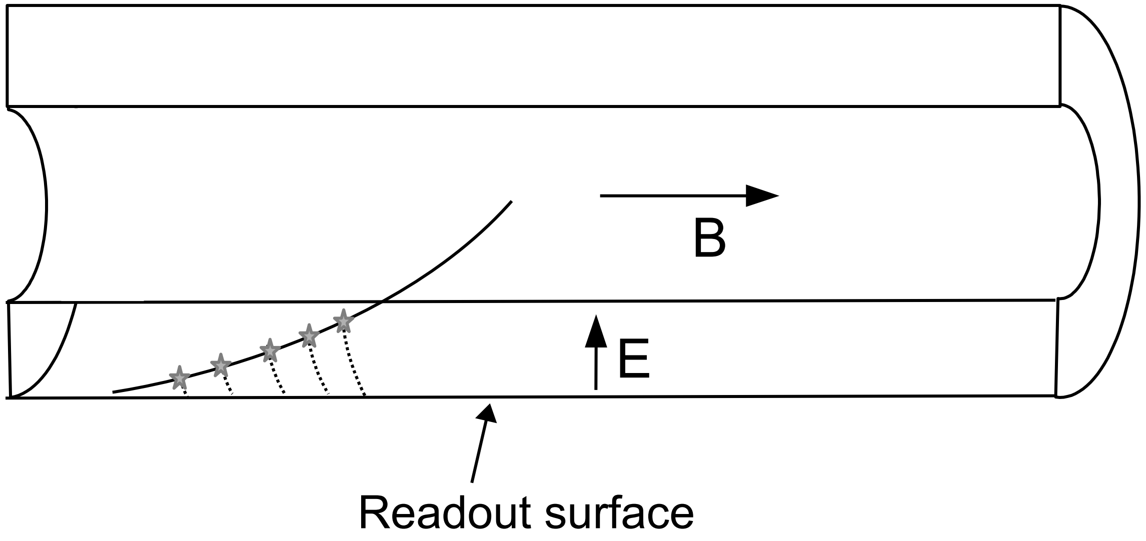
- Next plan: Demonstration of energy measurement for γ
  - Proof of concept reusing MEG II apparatus
  - Use of 17.6 MeV γ from $^{7}\mathrm{Li}(\mathrm{p},\gamma)^{8}\mathrm{Be}$ reaction
  - Use of MEG II CDCH for pair tracking
  - Planning beam test in **this winter**



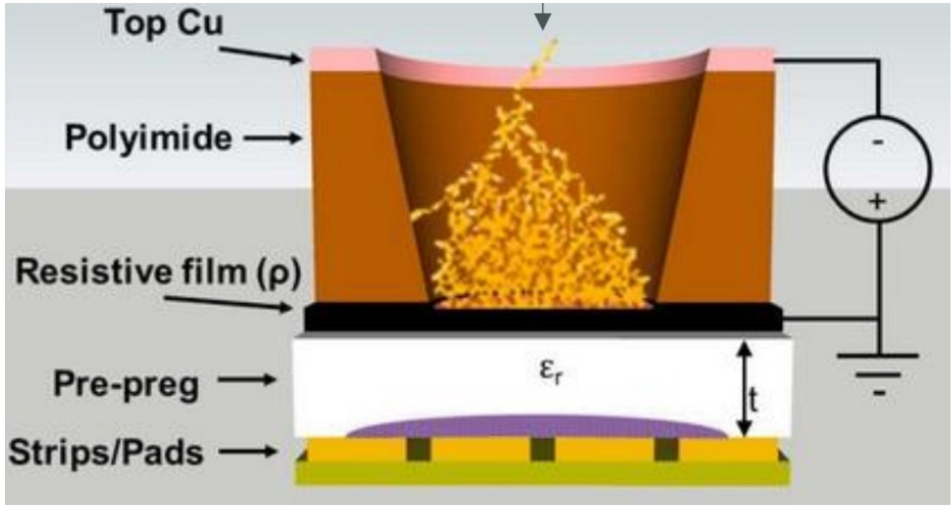


Conversion pair-tracker

- Candidate technology: Radial TPC
  - High hit density inside gas
  - Ionization clusters drift in the radial direction
    → Drift distance can be kept short
  - Cylindrical gas amplification (i.e. by MPGD)
  - Important study: Operation with light gas
    (Ideally, He-based gas, unusual for MPGD)

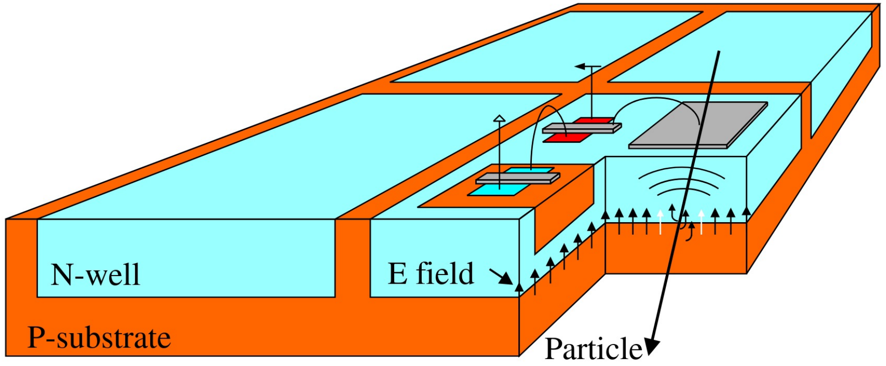


- R&D for gas multiplier
  - µRWELL (May, 2024) & GEM (planned this autumn)
  - Measurement of hit resolution
    (500 µm target resolution)



Positron tracking detector

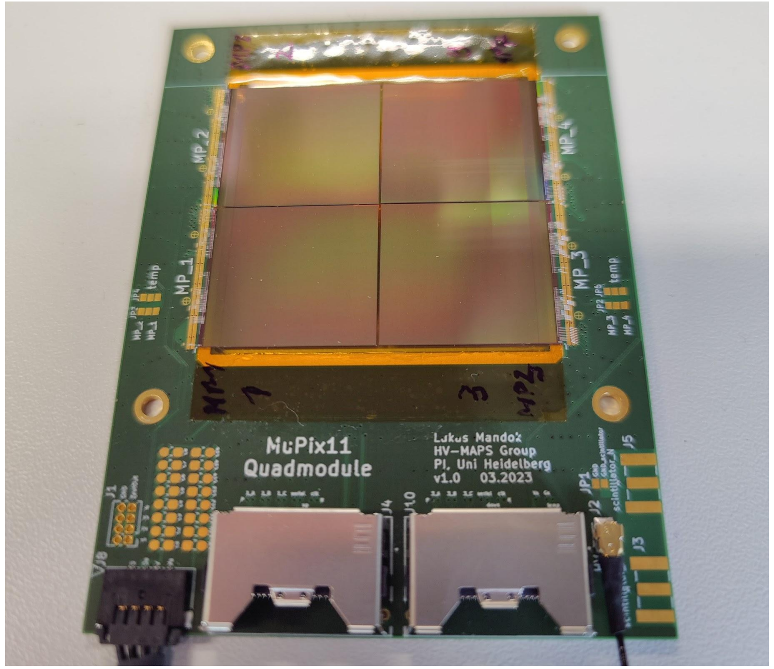
- Primary candidate: HV-MAPS
  - Based on technology developed for Mu3e
  - Excellent hit resolution with $80 \times 80\ \mu m^2$ pixel size
  - Only candidate that can operate at $O(10^9)$ μ/s



I. Peric et al., NIMA 582 (2007) 876

- Target performance at 52.8 MeV
  - 100 keV momentum resolution
  - 70% overall tracking efficiency

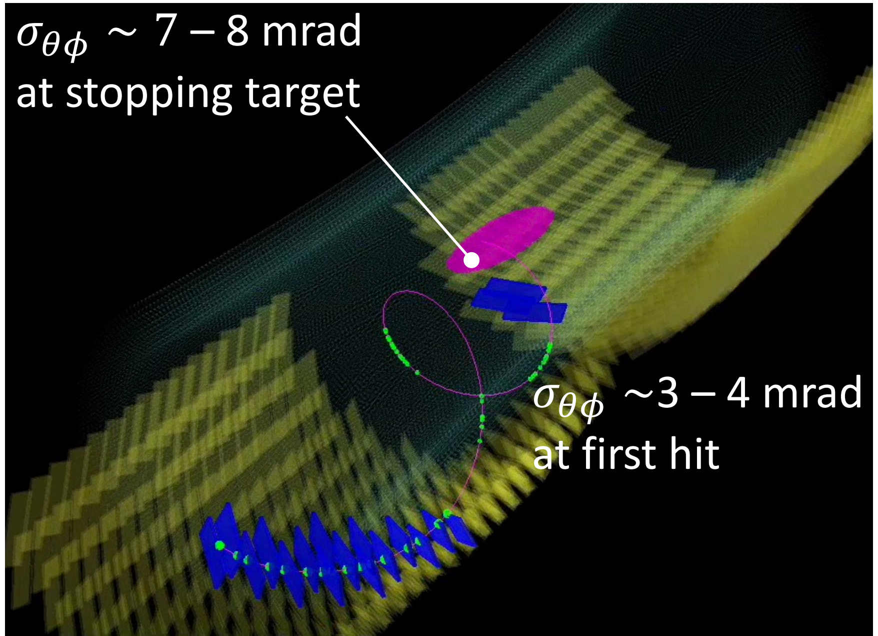
MuPix11 prototype for Mu3e



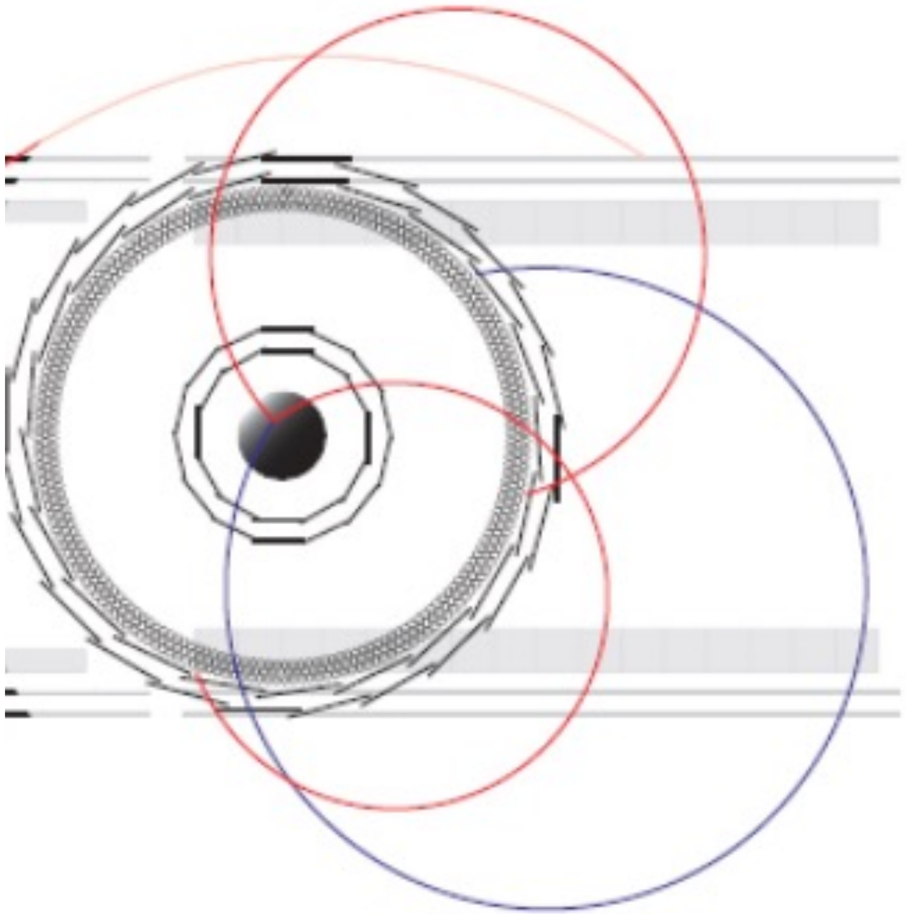
- Technological challenges with HV-MAPS
  - Scattering will limit tracking performance
  - Planning R&D for MAPS technology to reduce material

Positron tracking detector

- Tracking layer layout
  - Layout optimization depends on momentum range
  - Mu3e layout is optimized for 20 – 30 MeV e^+e^-
  - Open question: Can we have enough acceptance to wide momentum range?
  - Possibility of active target
    (Further improve angle resolution)



Inner & outer pixel layer layout for Mu3e

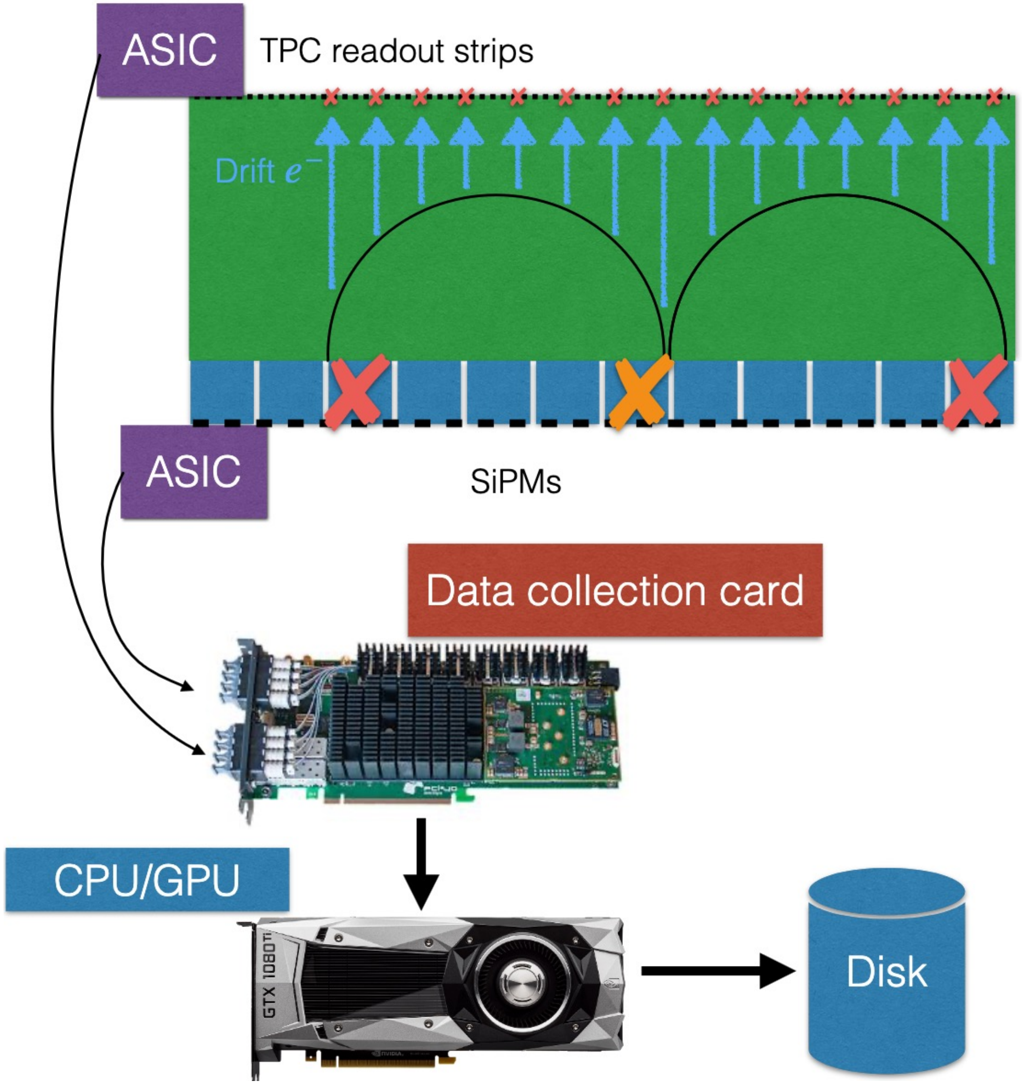


https://doi.org/10.21468/SciPostPhysProc.1.037

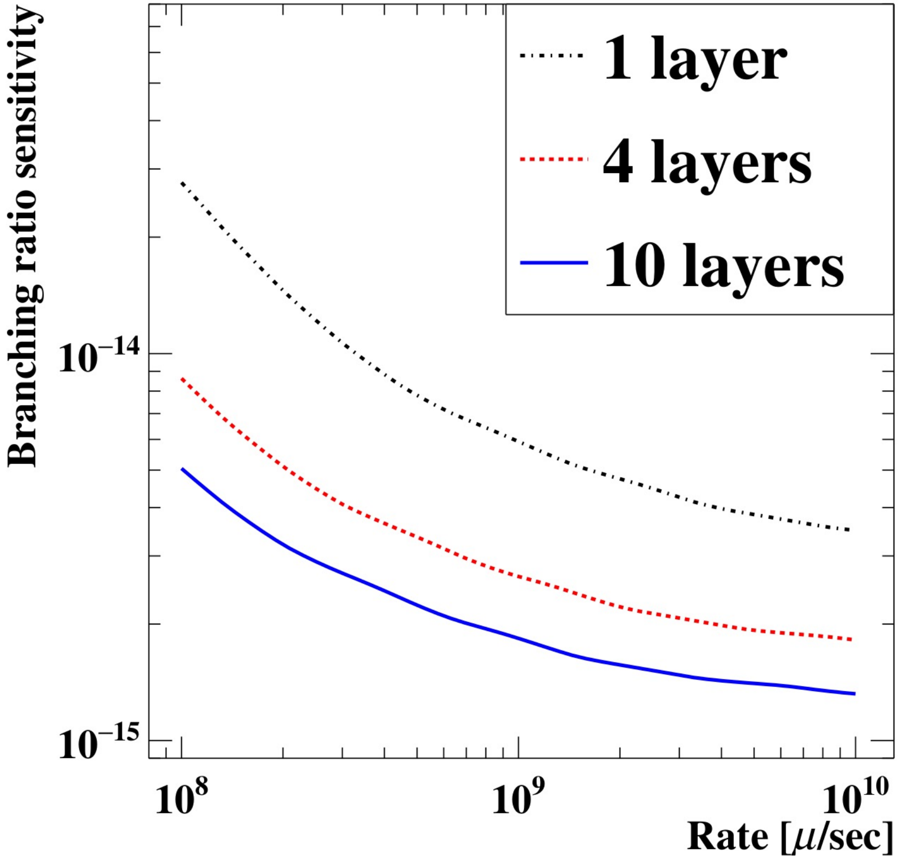
Electronics

- Considering triggerless DAQ
  - Full data streaming (e.g. LHCb, Mu3e)
    → Reconstruction for all hits
  - Concern1: Calibration quality (needed in real time)
  - Concern2: Digitization only at high level
    (full waveform not available)

- New opportunity?
  - In MEG II, Michel positrons dropped by trigger
    → Only 50 Hz trigger rate. Far below 10^7 /s
  - Streaming method better suited to accumulate Michel positron events
  - Opportunity with Michel spectrum study?
  - Note: Feasibility at $> 10^9$/s rate?



Summary



- Proposal for future $\mu \to e\gamma$ experiment
  - Exploiting HiMB beam line, constructed in 2028 – 2029
  - Target Br upper limit sensitivity of $O(10^{-15})$
  - Letter of intent (arxiv: 2504.18831) submitted to PSI
  - 2030s (likely in phased approach)

- Planning drastic renewal of detector technologies
  - Conversion pair-spectrometer for γ detection: Excellent energy resolution to be achieved
  - Wider geometrical acceptance to be more sensitive to polarization
  - New DAQ system: Possibly opening new opportunities to other search channels

Summary

- Key differences to consider new physics opportunities
  - E.g. Small γ efficiency is not optimal for multi-photon channels

	Future experiment	**MEG II experiment**
N_μ in $\mu \to e\gamma$ search	$\sim 10^{16}$ (10^9 μ/s)	$\sim 7\times10^{13}$ (expected)
Sensitivity to polarization	$\lvert\cos\theta\rvert < 0.85$, P_μ to be studied	$\lvert\cos\theta\rvert < 0.35$, $P_\mu \sim 0.8$
γ efficiency	10%	65%
γ resolution	Target: 200 keV	$\sim$ 1 MeV
Low momentum positron	To be studied	$E_e >$ 45 MeV

- Ideas on other physics opportunities are welcome!
  - New technologies may open other opportunities in addition to $\mu \to e\gamma$