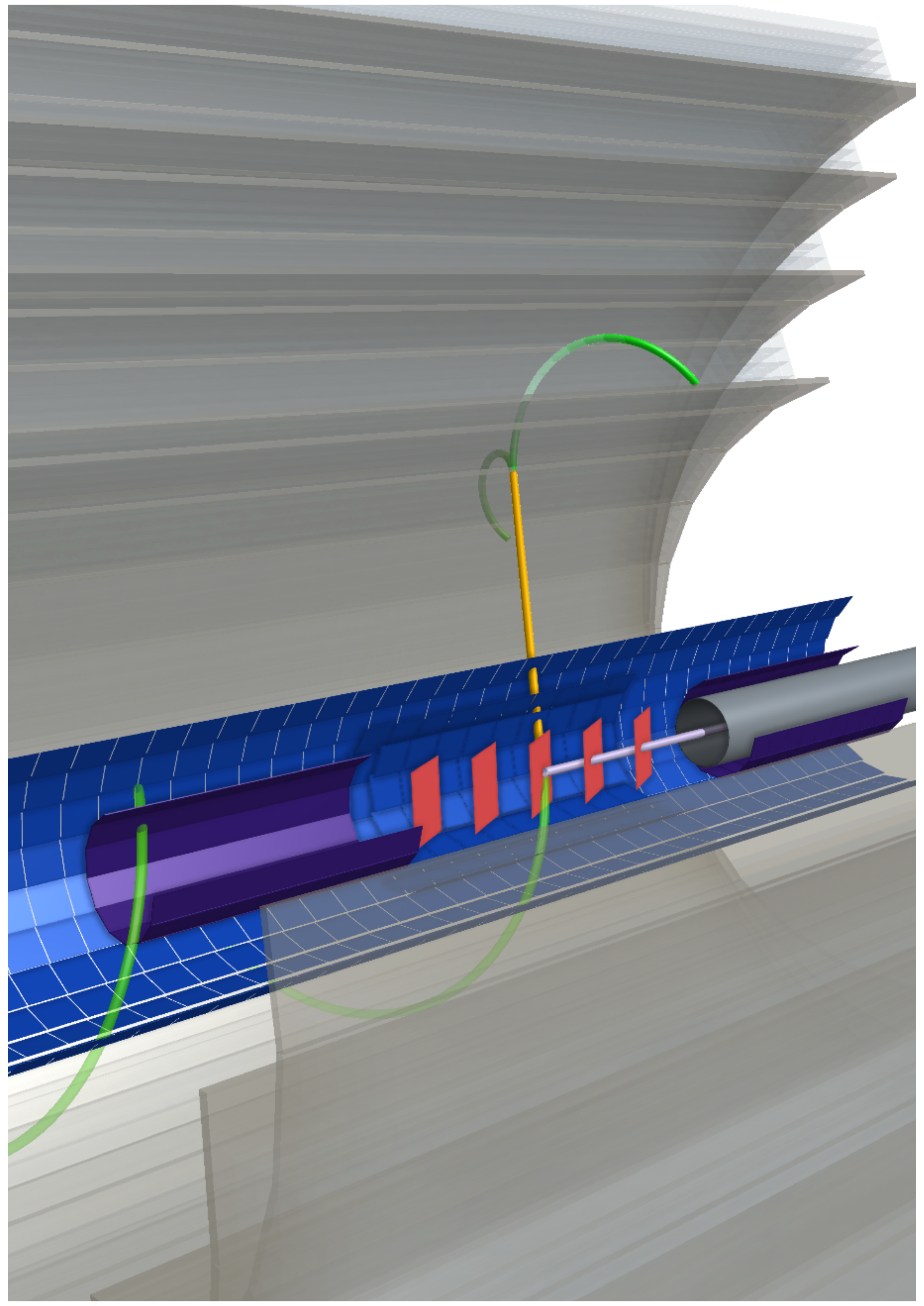
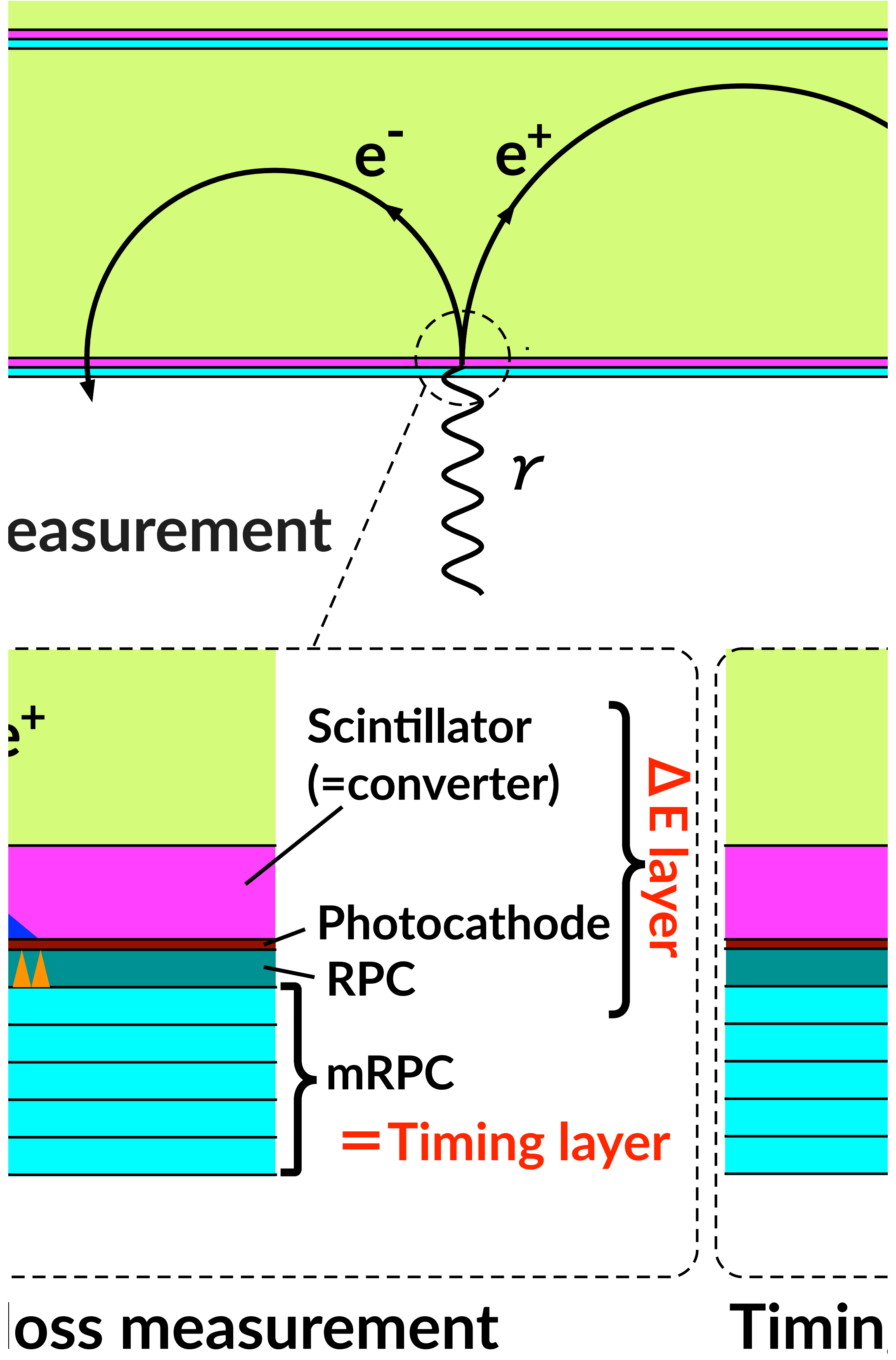
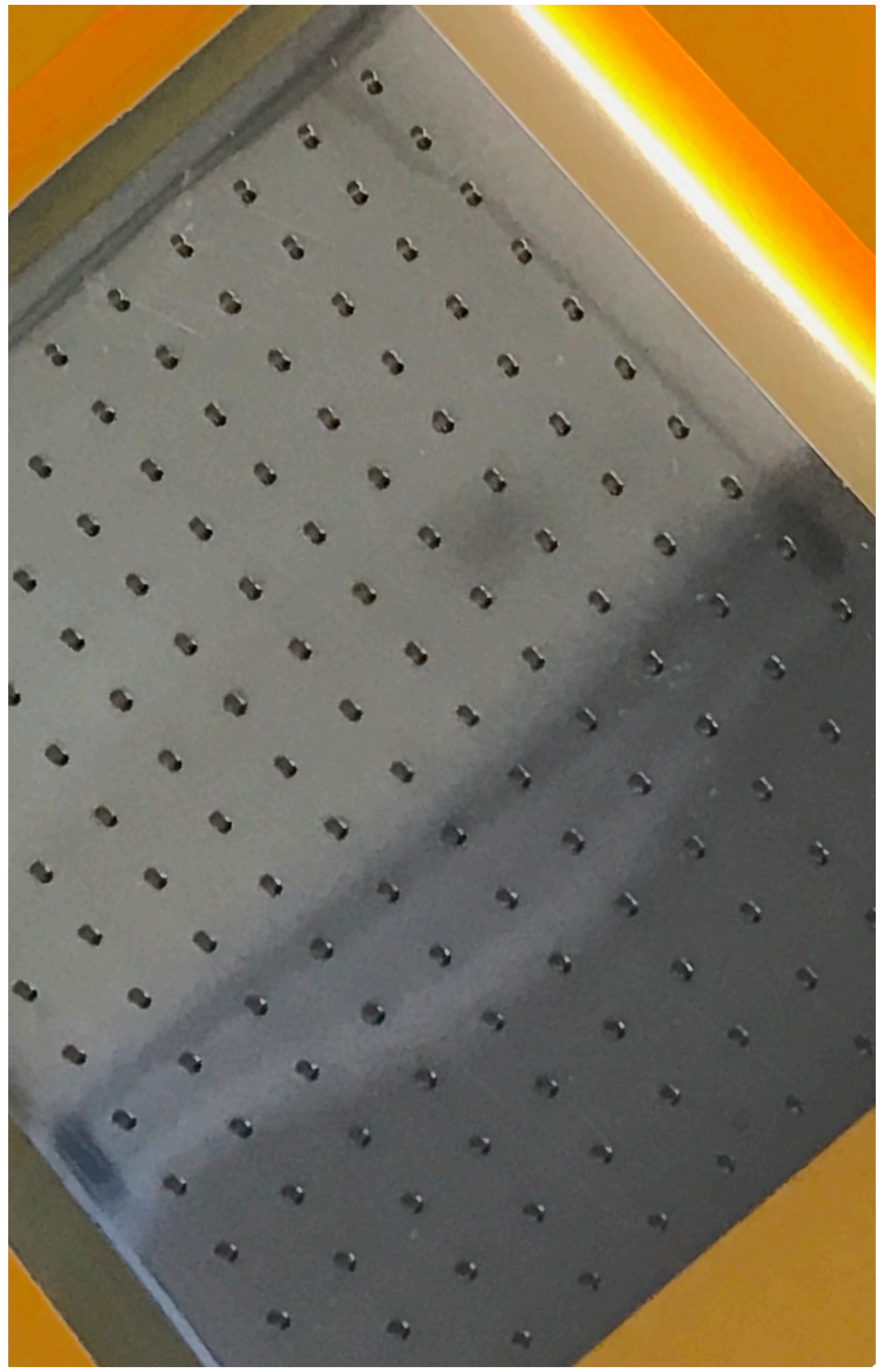
New $\mu \rightarrow e\gamma$ Experiment with Pair Conversion Spectrometer

K. Ieki, T. Iwamoto, K. Matsuoka, T. Mori, **W. Ootani**, H. Nishiguchi, A. Ochi, Y. Uchiyama

HIMB Physics Case Workshop, April 6th-9th, 2021





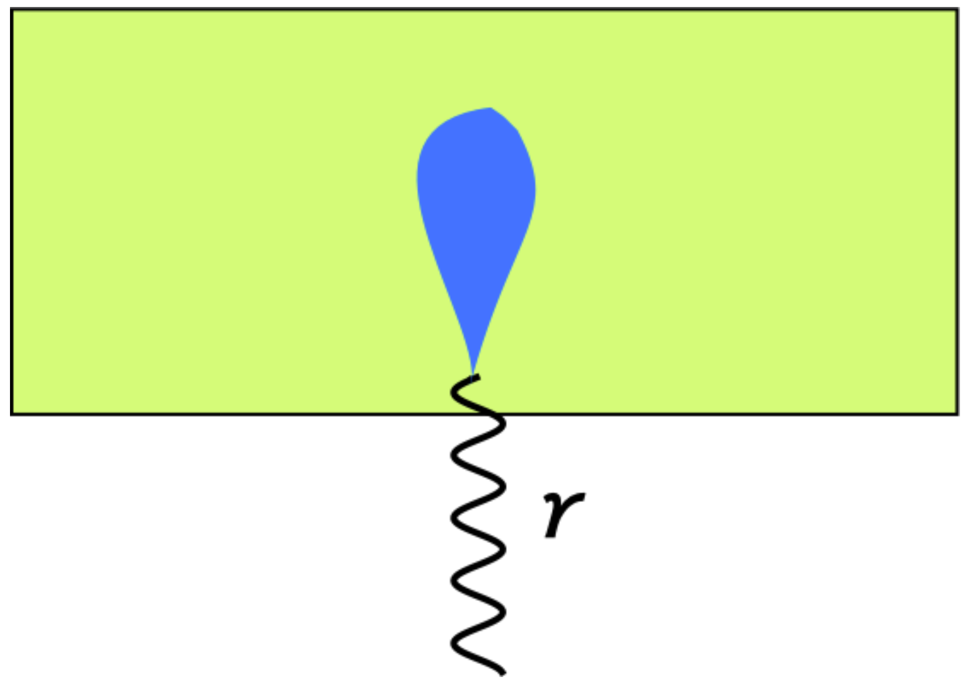


Caveats

- Consideration on design of new $\mu \to e\gamma$ experiment with an emphasis on conversion photon spectrometer
- Still feasibility study on experimental design and detector technologies

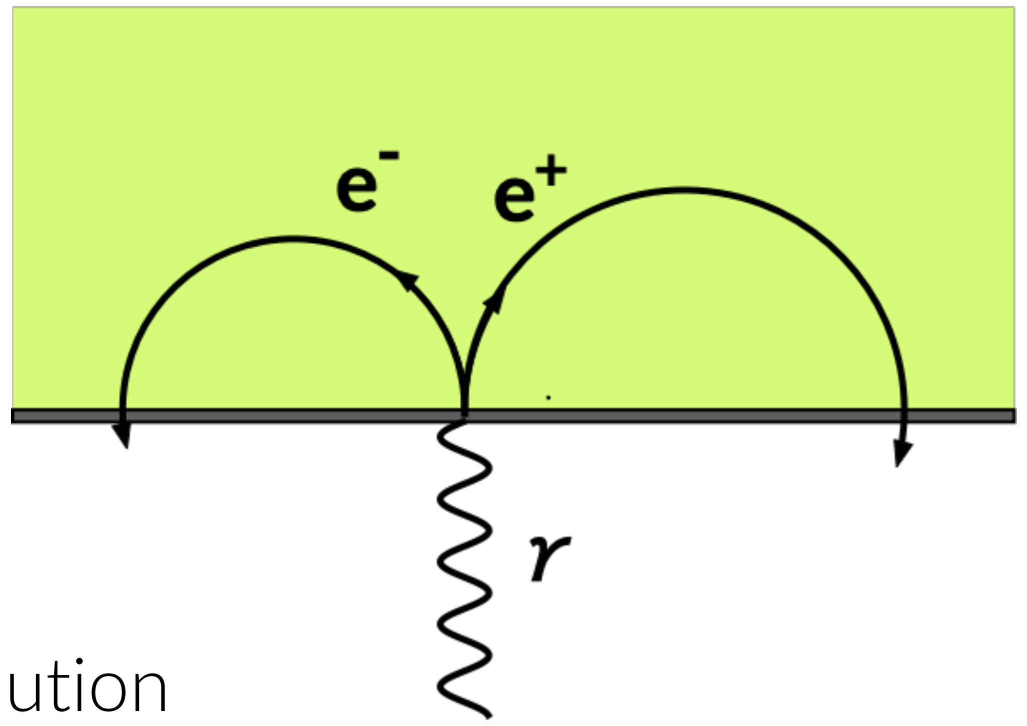
Calorimeter vs. Pair Spectrometer

Calorimeter



- Pros
  - High efficiency
- Cons
  - Moderate detector resolutions $(E, \vec{x}, t)$
  - Moderate rate capability

Pair spectrometer

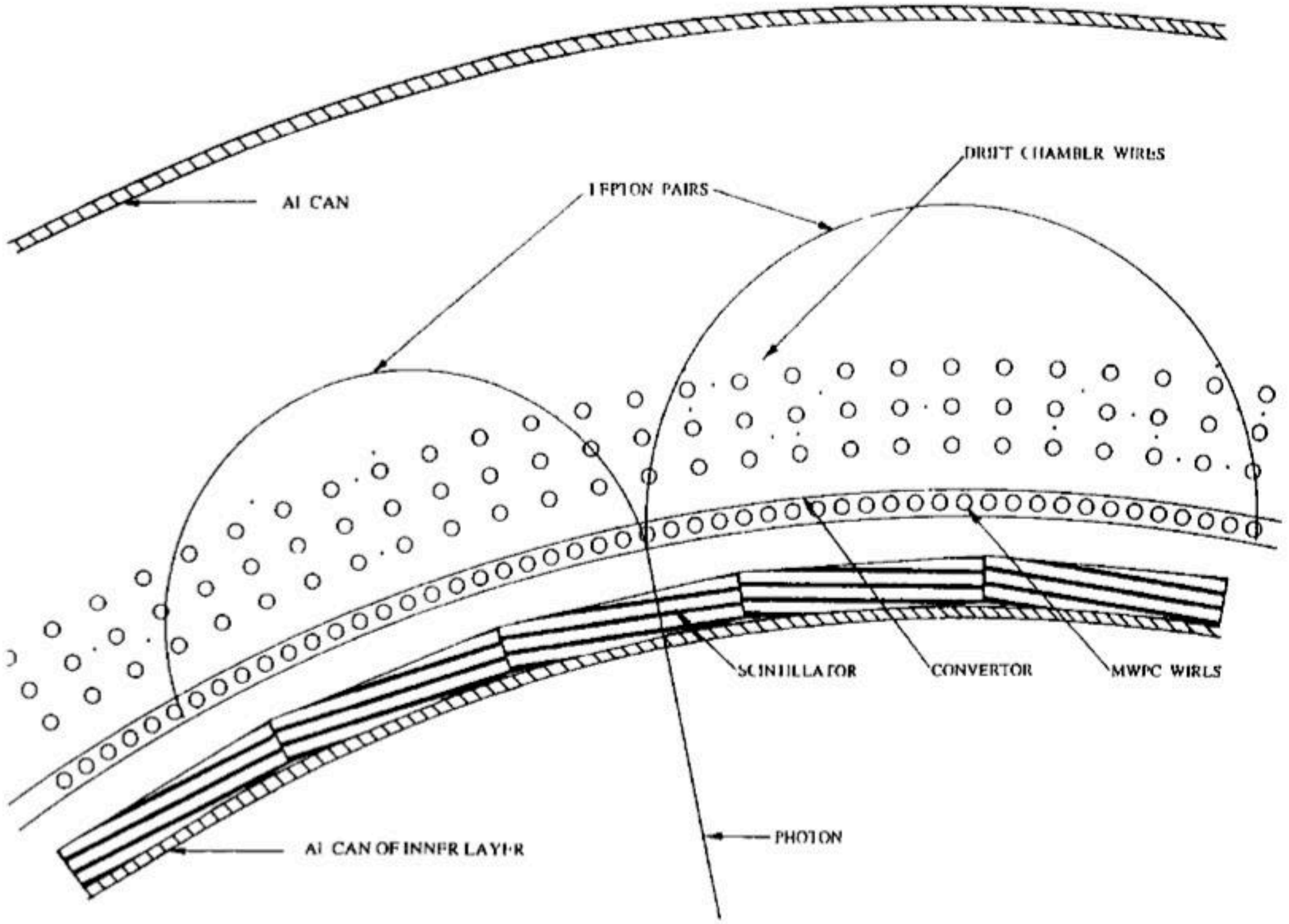


- Pros
  - High energy resolution
  - High position resolution
  - Photon direction can be measured
  - High rate capability
- Cons
  - Low efficiency
  - Energy loss in converter

Pair spectrometer would be a viable option for photon detector at future $\mu \to e\gamma$ experiment with higher beam rate

MEGA Pair Spectrometer

- Pair spectrometer at MEGA@LAMPF (1985-1999)
    - Three conversion layers
        - 250μm-thick Pb (4.5% X_0) × 2
        - Conversion pair tracked by CDCH
    - Detection efficiency ~5%
    - Energy resolution (FWHM): 5.7% (inner Pb), 3.3% (outer Pb)



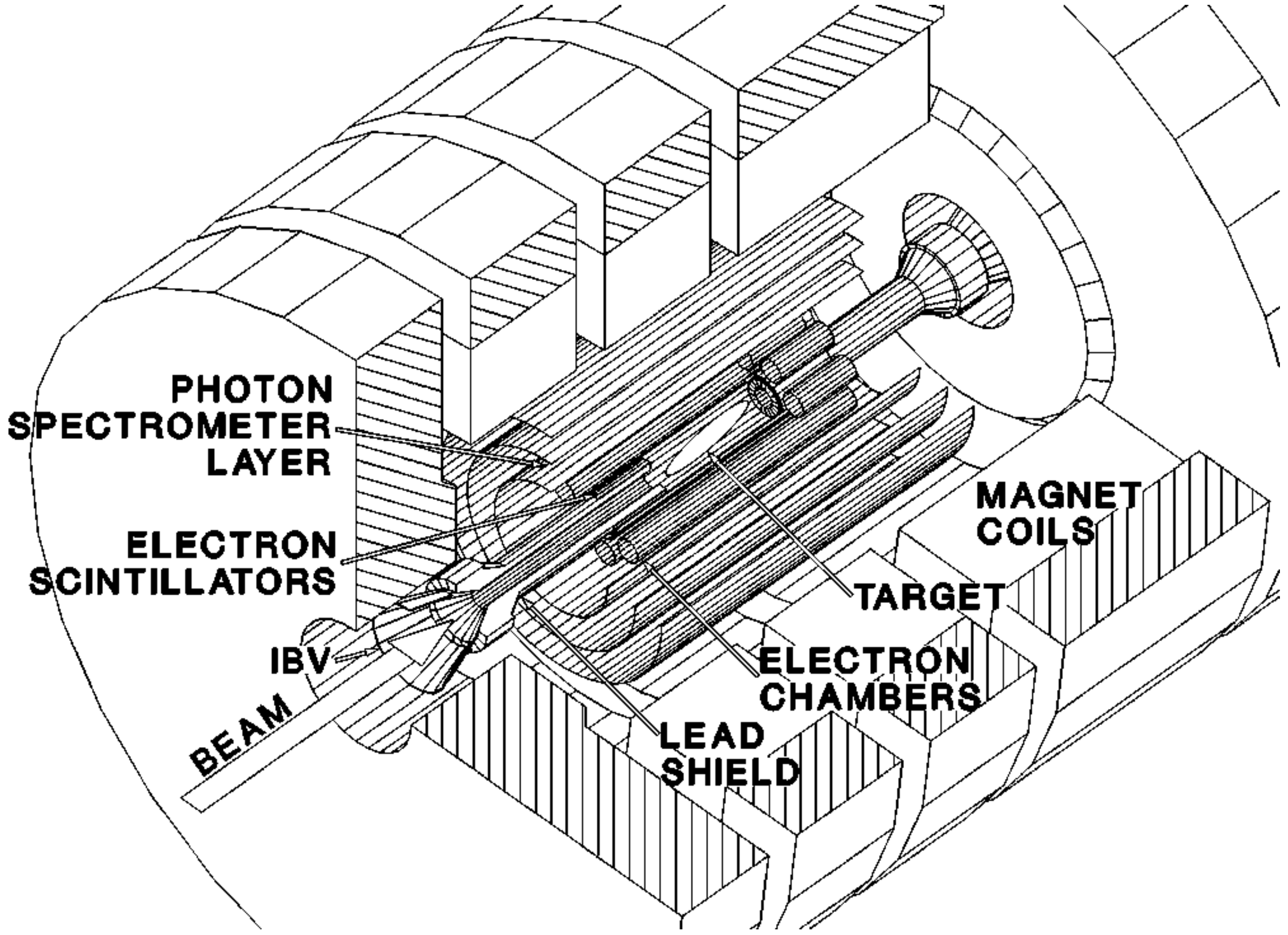
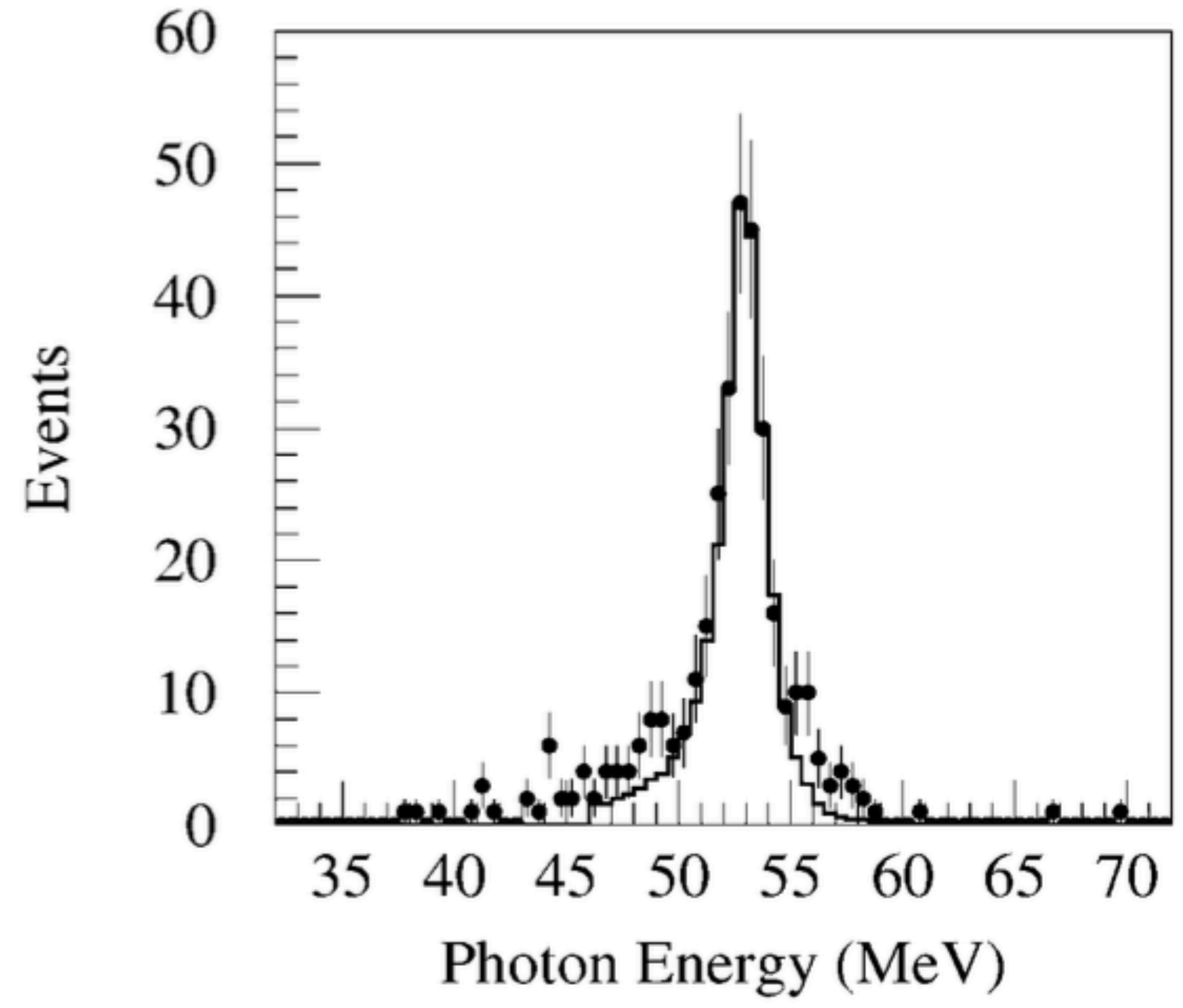


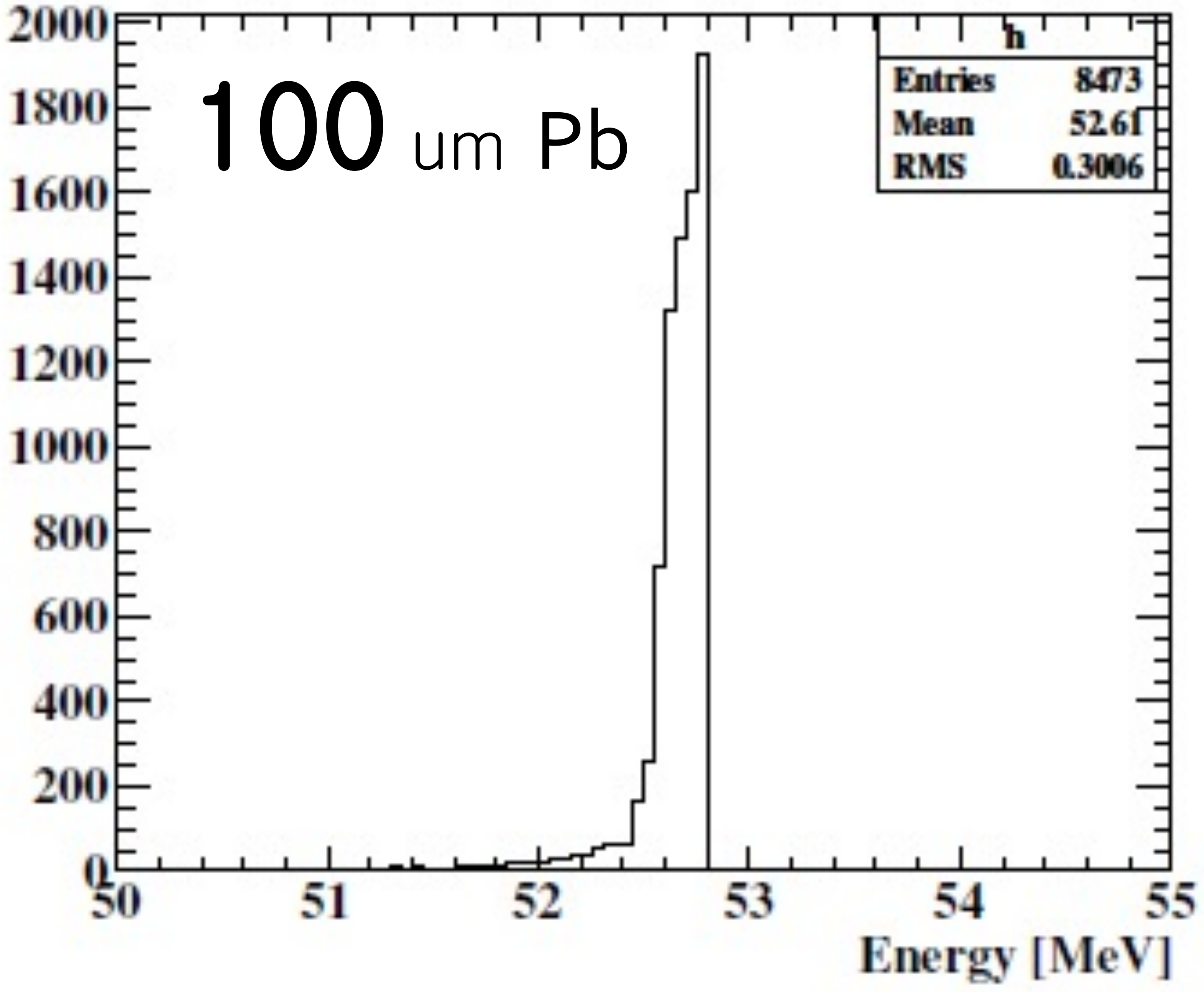
FIG. 1. A schematic view of the MEGA detector

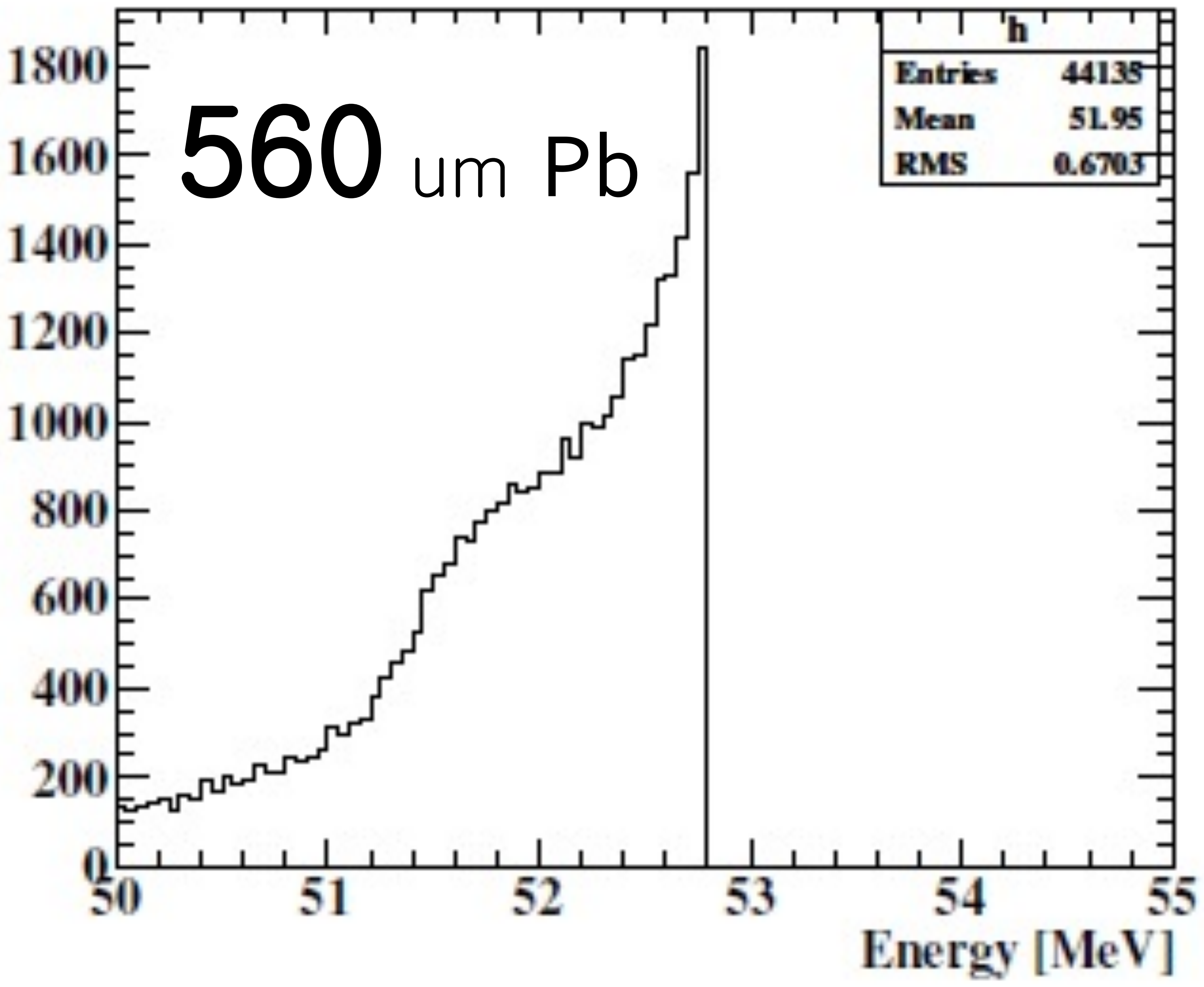


Energy Loss in Converter

- Crucial limiting factor = energy loss of conversion pair in converter
  - Energy resolution limited by energy loss

Energy of conversion pair after converter (MC)



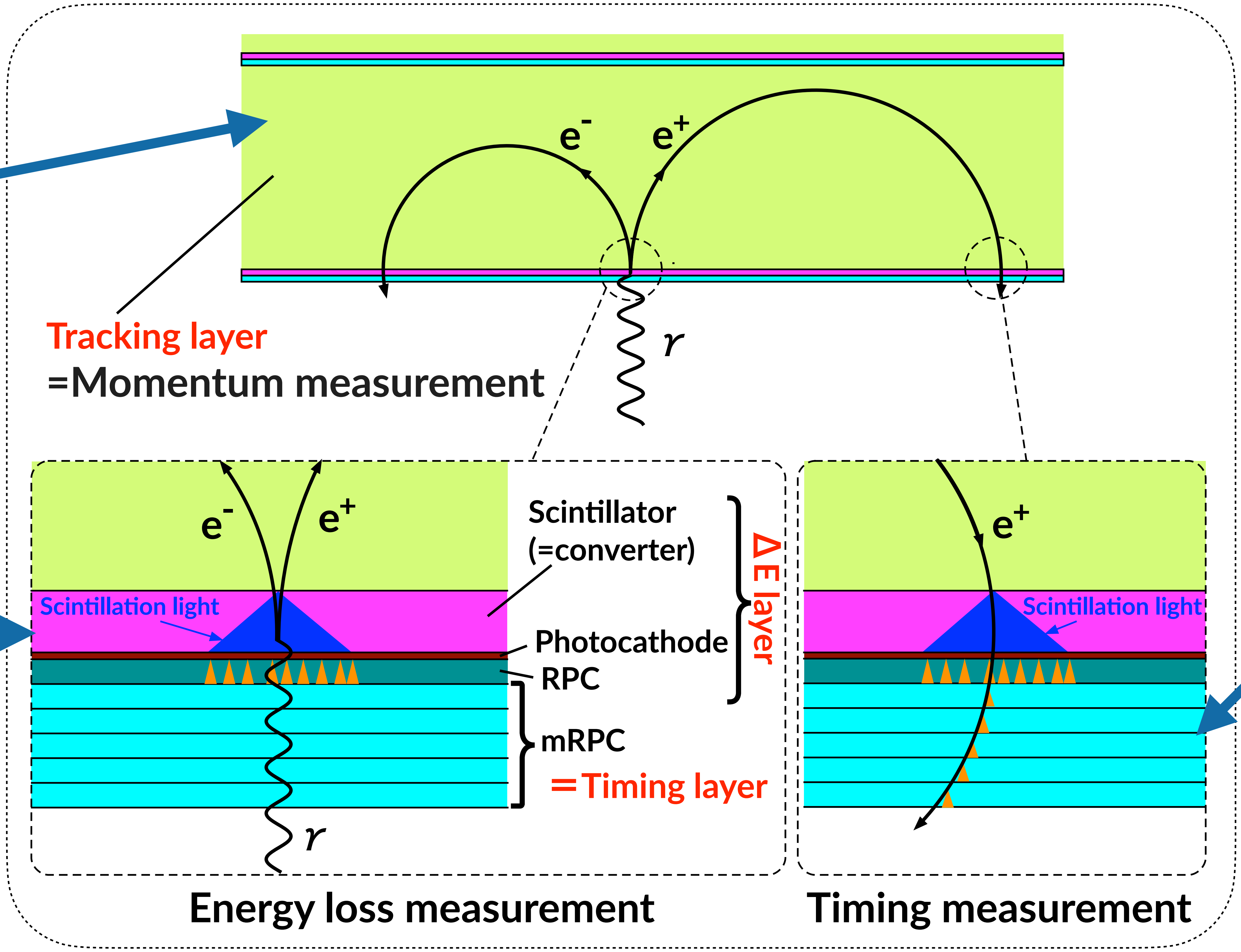


→New idea: **"active converter" to measure energy loss**

Pair Spectrometer with Active Converter

Tracking layer

- Measure momentum of conversion pair
- Possible technology: drift chamber (a la MEG II CDCH)



Active converter (ΔE layer)

- Thin active material to measure energy loss of conversion pair
- Possible technology: scintillator + photo-detector

Timing layer

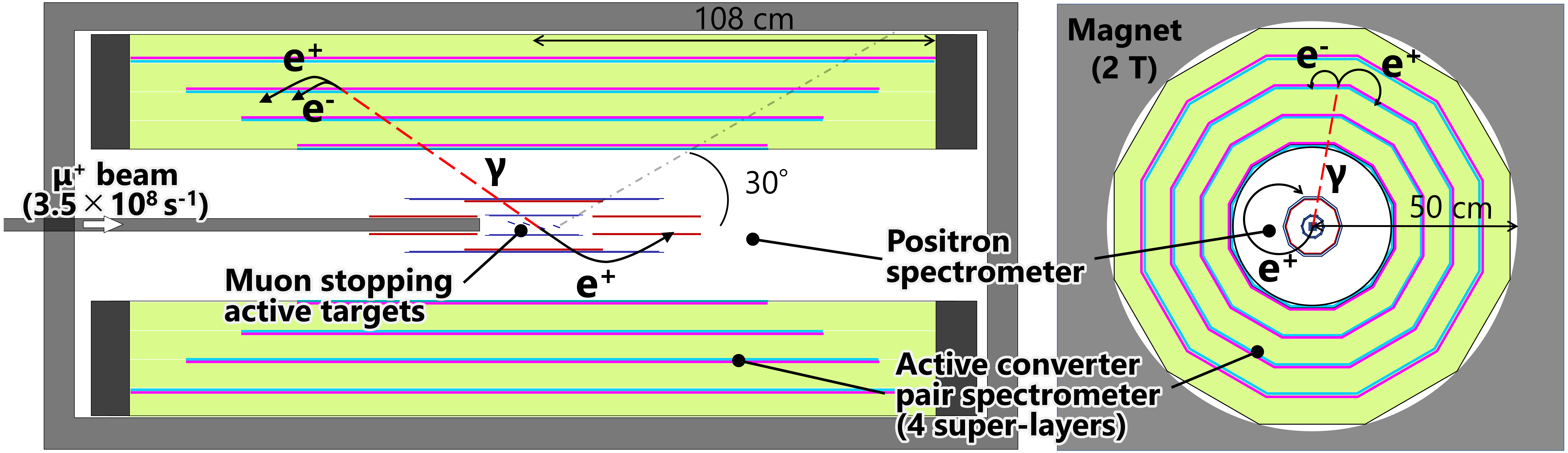
- Measure timing of returning conversion pair
- in front of active converter
- Possible technology: multi-layer RPC (mRPC)

Target performance

- Resolutions: energy 0.4%, timing 30ps, position 0.2mm, angle 50mrad
- Efficiency: 50% (several layers of active converter)

Possible Experimental Design with Pair Spectrometer

- Possible design with pair spectrometer
  - Photon spectrometer → higher resolutions (energy, timing, position), angle measurement
  - Positron spectrometer based on Si detector (a la Mu3e) → high rate capability, $\mu \to eee$ search
  - Separate active targets → higher vertex resolution, further BG suppression



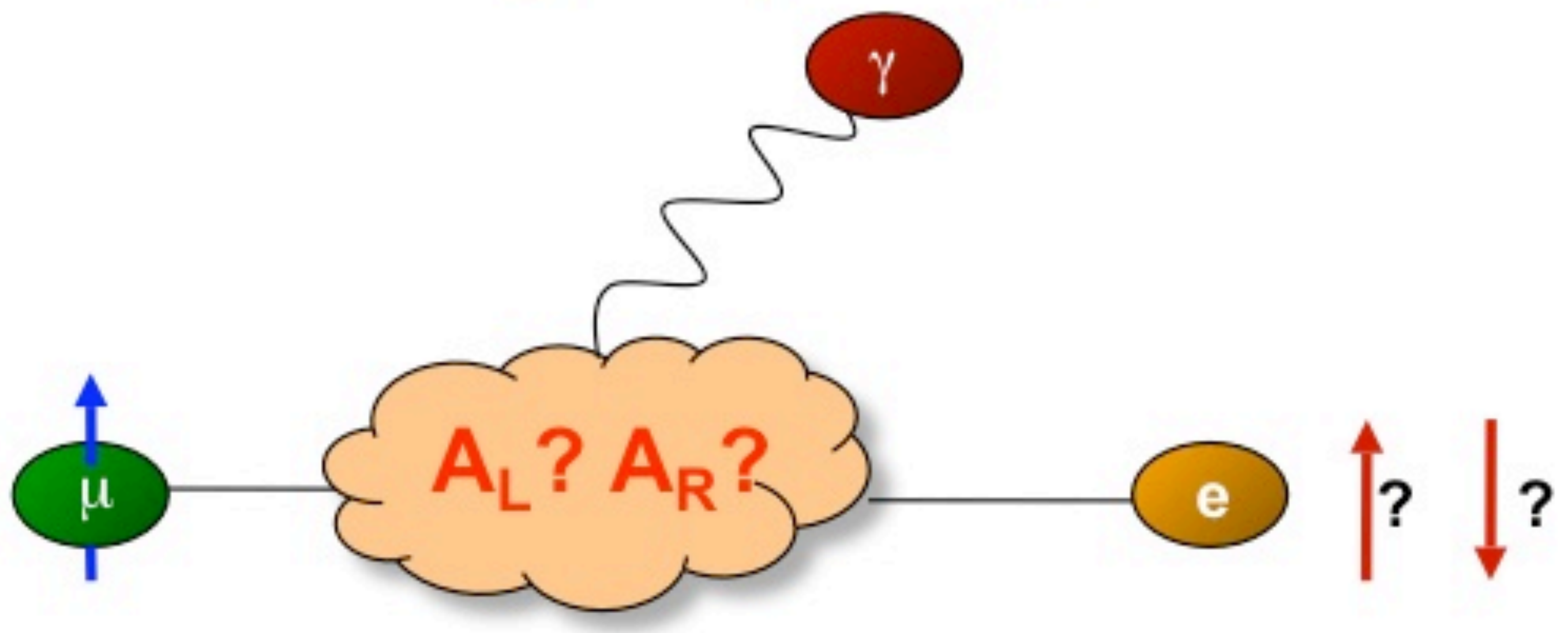
Enhanced Acceptance

Zenith-angle acceptance significantly improved w.r.t. MEG II

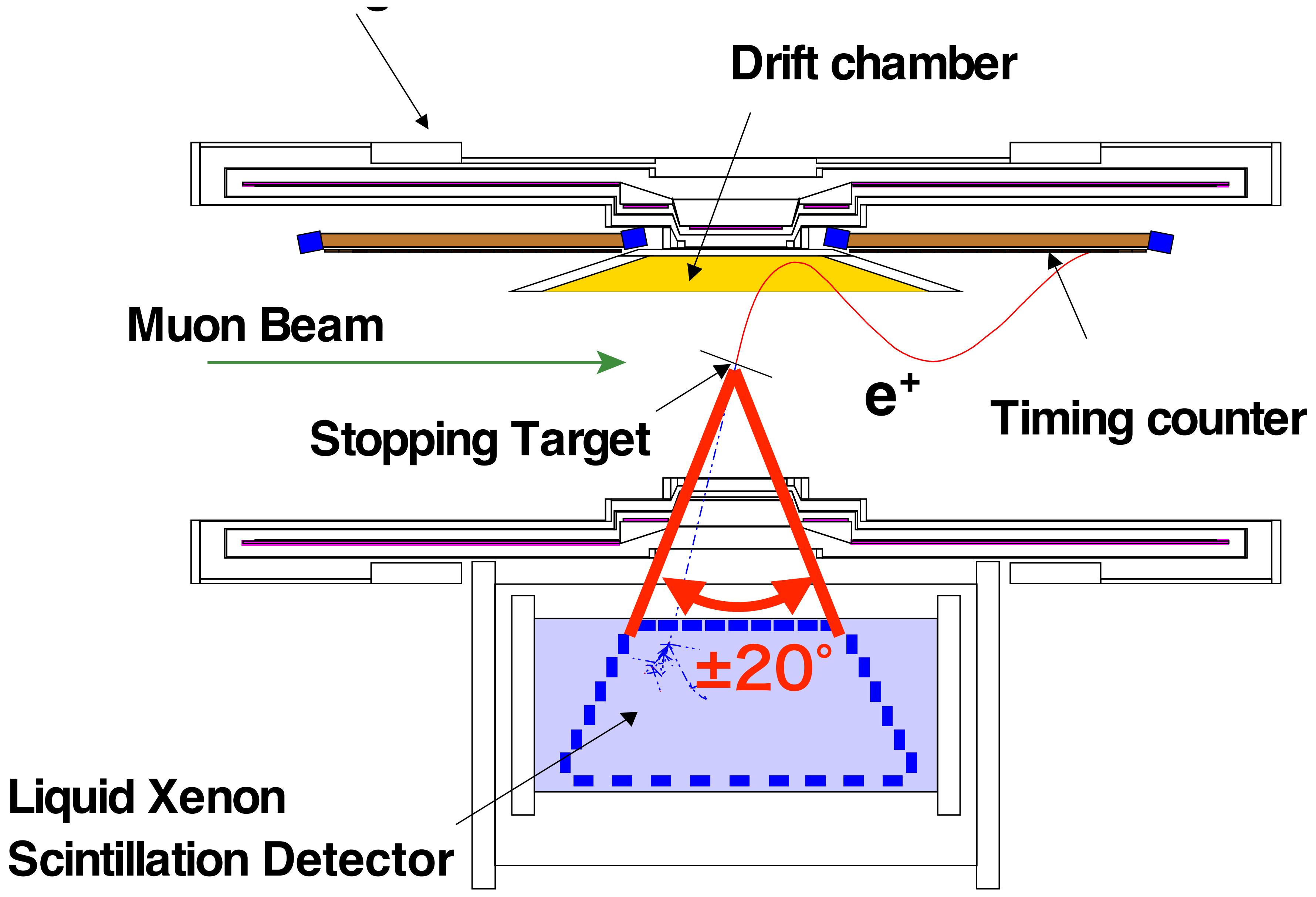
→ After $\mu \to e\gamma$ discovery, angular distribution can be measured with polarised muon beam ($P_\mu = -0.86$ @MEG)

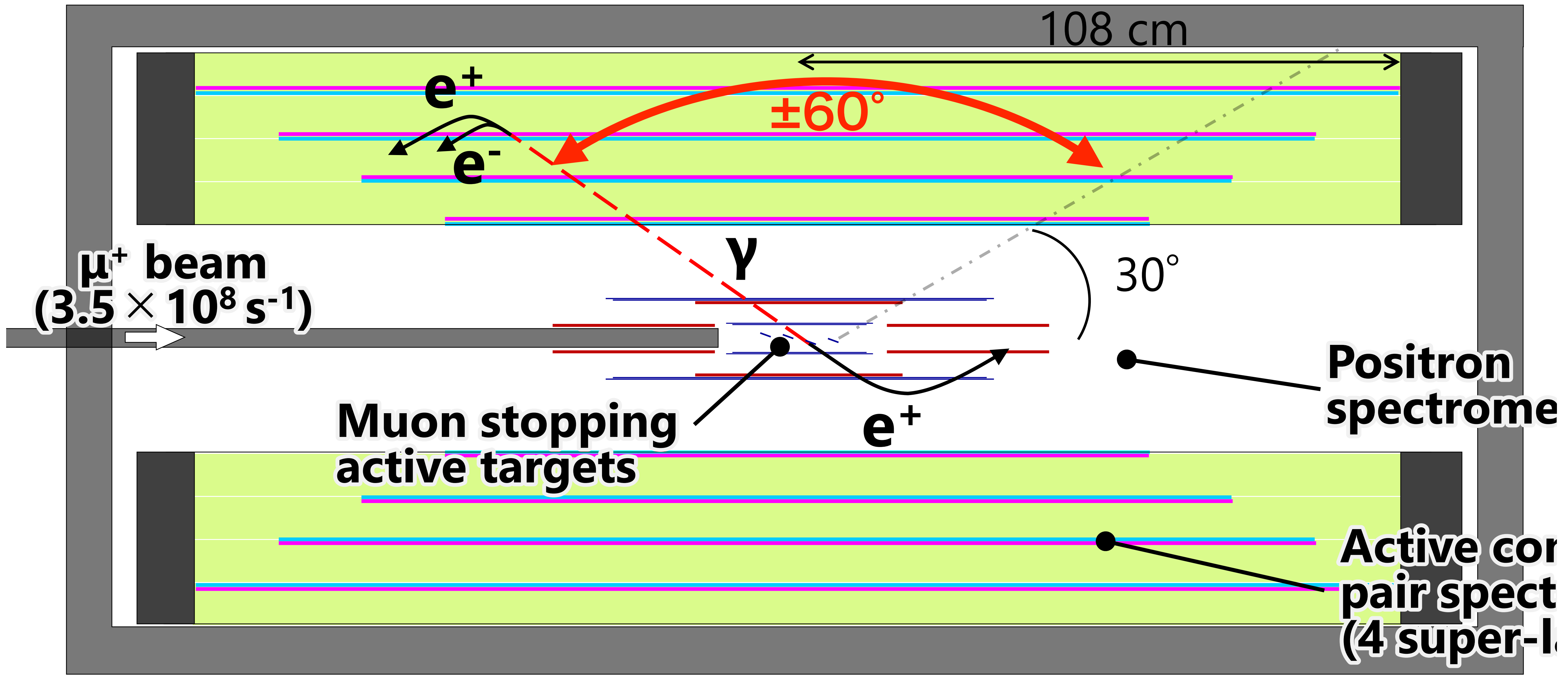
→ Pin-down underlying new physics

- e.g. SU(5) SUSY-GUT: $A_\mathrm{L} \neq 0, A_\mathrm{R} = 0$
- e.g. SO(10) SUSY-GUT: $A_\mathrm{L} \simeq A_\mathrm{R}$
- e.g. Non-unified SUSY with ν_R: $A_\mathrm{L} = 0, A_\mathrm{R} \neq 0$



$$\boxed{\frac{dB(\mu^+ \to e^+\gamma)}{d\cos\theta_e} \propto |A_R|^2(1 - P_\mu \cos\theta_e) + |A_L|^2(1 + P_\mu \cos\theta_e)}$$





Active Converter

Technology Options

- Scintillator
  - Crucial parameters
    - Light yield → energy resolution
    - Decay time → high rate capability
    - Radiation length → detection efficiency (6% for 4mm-thick YAP)
    - Critical energy → effect of bremsstrahlung (difficult to measure)
    - Cost
- Photo-detector for scintillation readout
  - Requirements: high light detection eff. + low mass
  - Photo-detector under consideration
    - Gas PM
    - SiPM

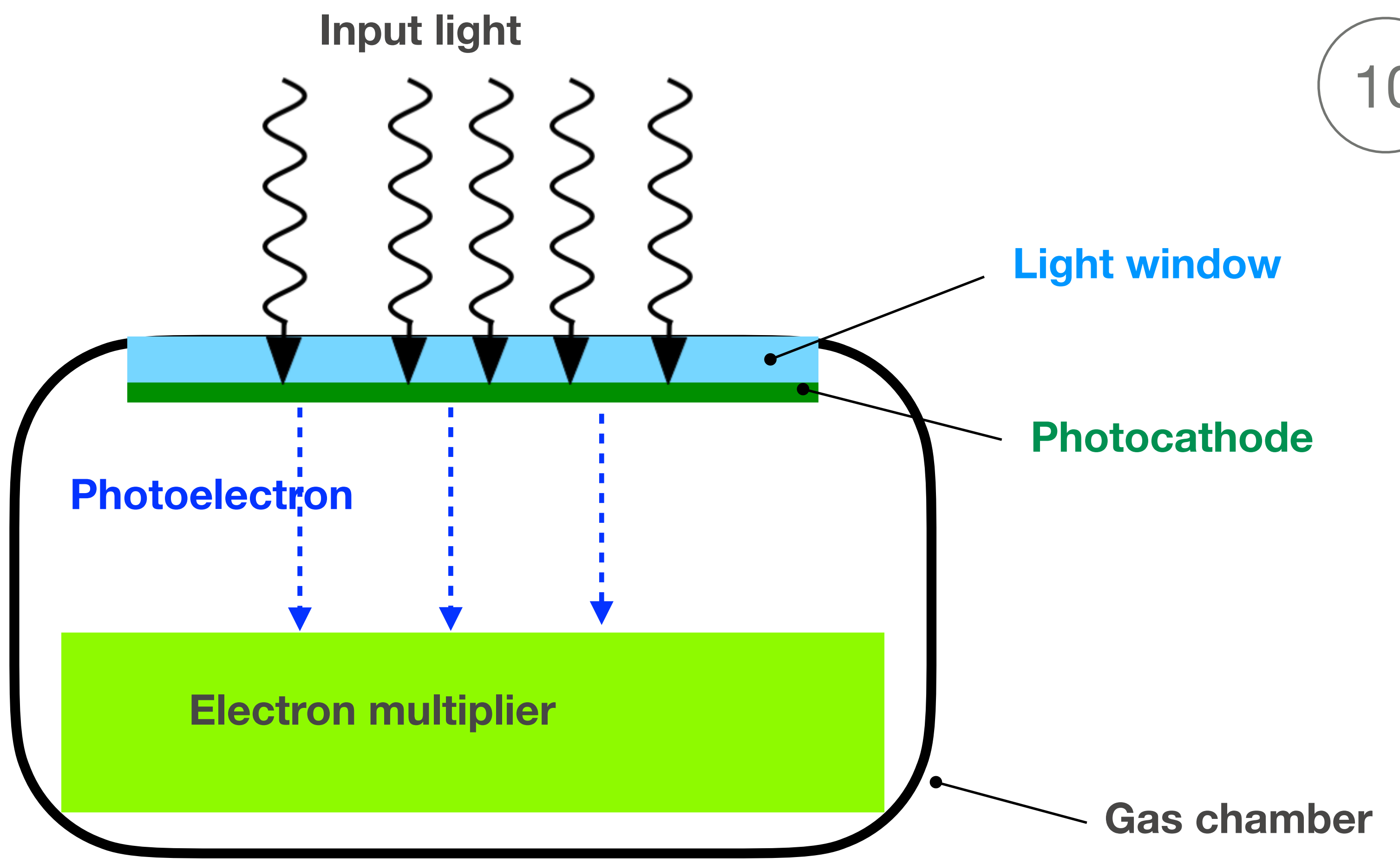
Crystal	NaI	LYSO(Ce)	$LaBr_3$(Ce)	YAP(Ce)
Density [g/cm^3]	3.7	7.4	5.1	5.4
Light yield (relative to NaI)	100%	75%	160%	70%
Peak Emission [nm]	415	420	380	370
Decay time [ns]	230	40	16	27
Radiation length [cm]	2.6	1.1	1.9	2.7
Critical energy* [MeV]	13	12	12	23
Hygroscopicity	Yes	No	Yes	No

* Critical Energy Ec: Ionisation $\lesssim$ Brems if E $\gtrsim$ Ec

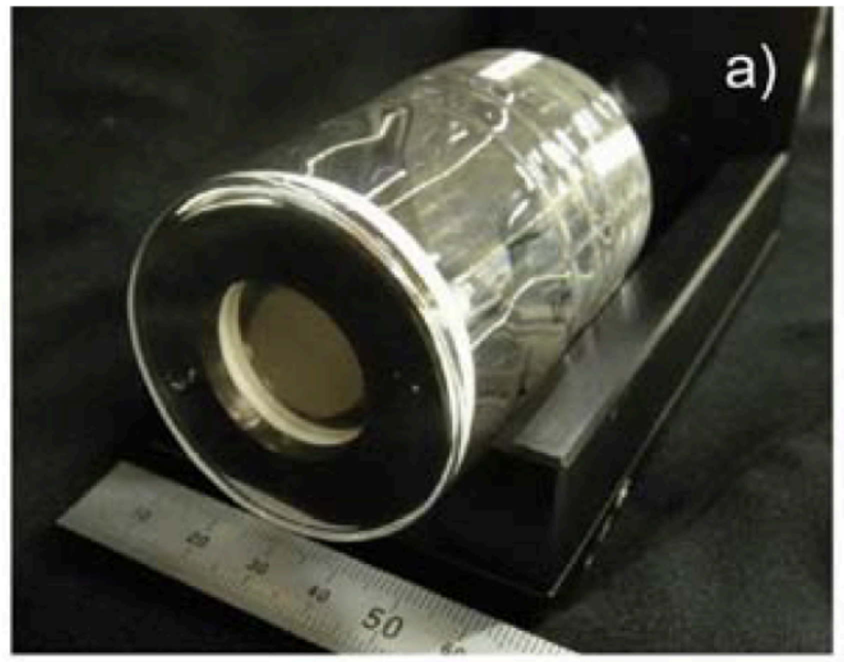
Gas PM

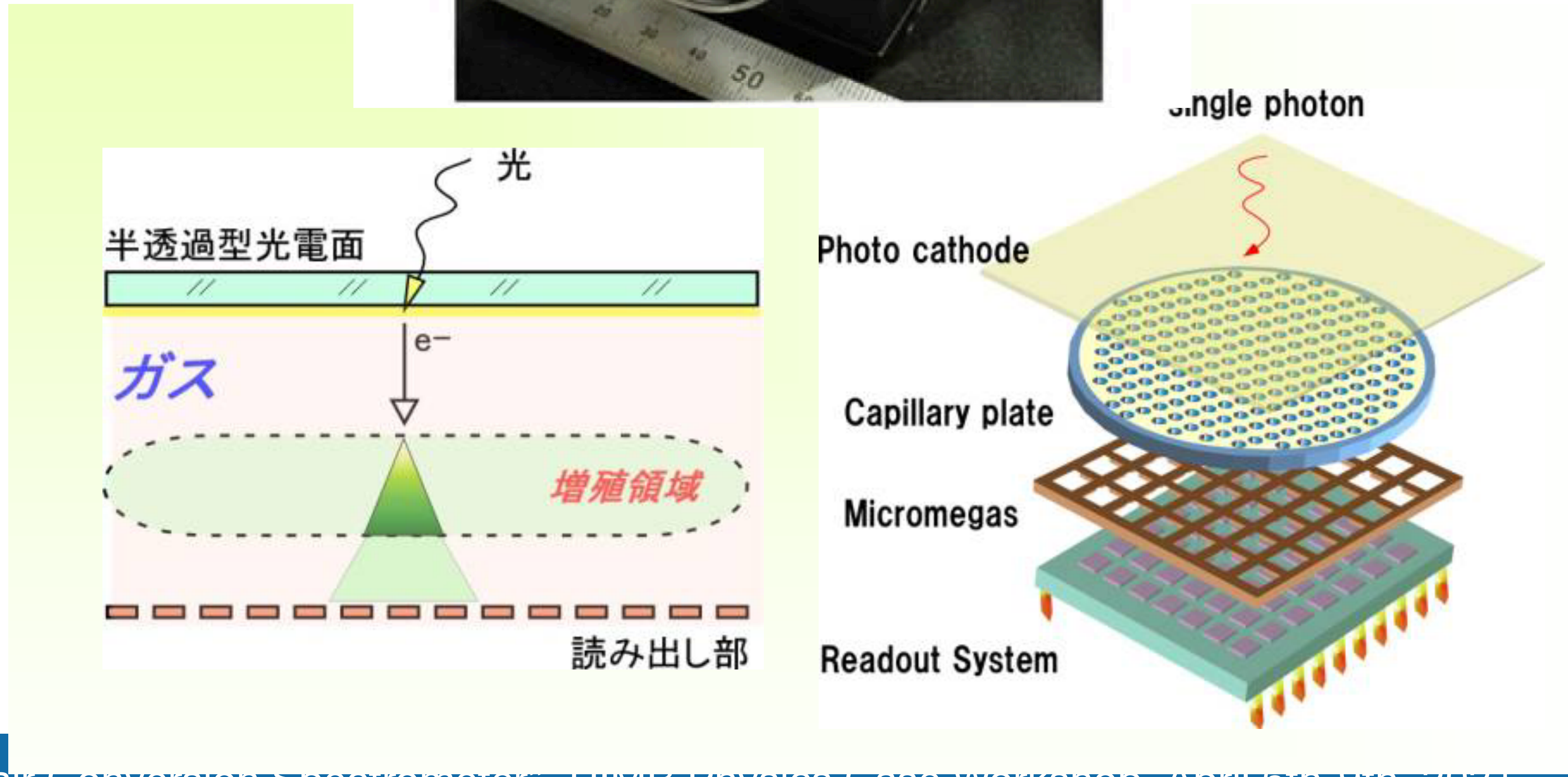
as Photo-detector

- Gas PM (a.k.a. Gaseous PMT)
  - Photocathode + electron multiplier in gas chamber
  - Pioneering work by F. Tokanai et. al → MPGD as electron multiplier
- Our idea: gas PM with RPC as electron multiplier
  - Ultra-low mass RPC with DLC developed for MEG II radiative decay counter (RDC)
  - In collaboration with Prof. K. Matsuoka who is developing gas PM with RPC
  - Need large area photocathode sensitive to scintillation light
    - Quite challenging (stability, cost,...)

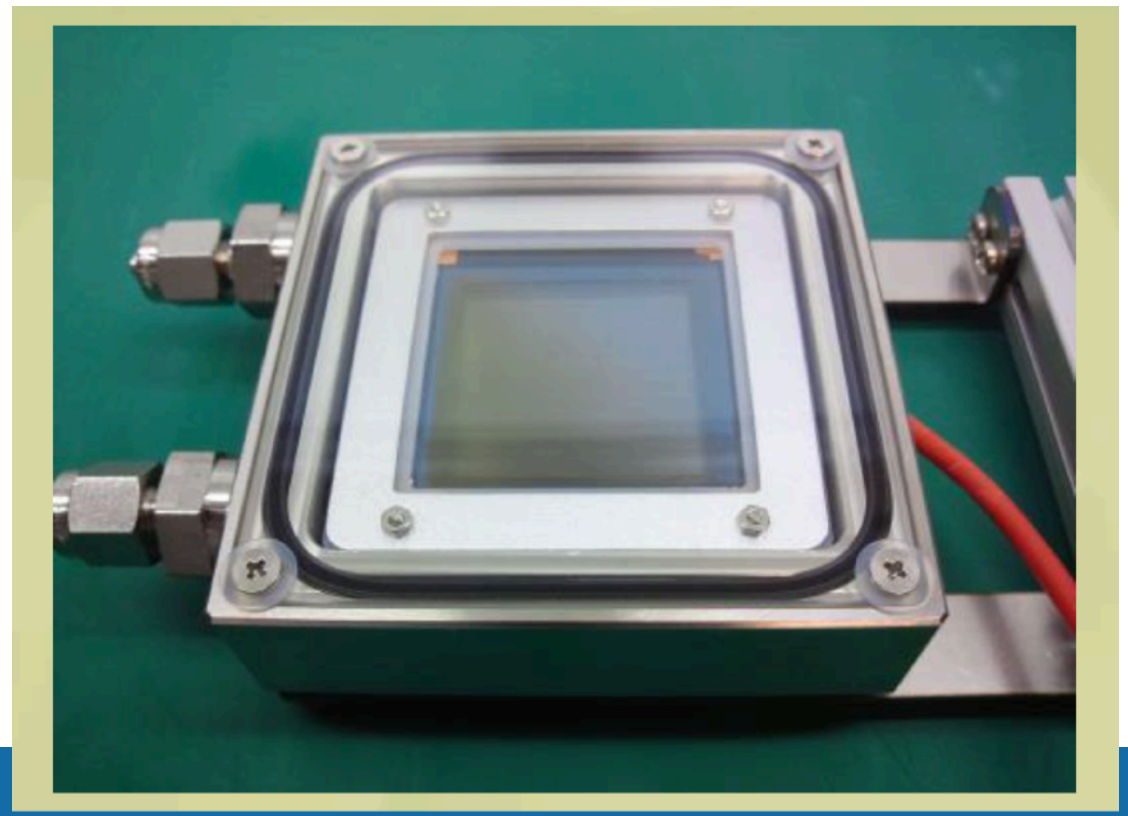


Gas PM with MPGD (Prof. F. Tokanai)





Prototype of Gas PM with RPC (Prof. K. Matsuoka)



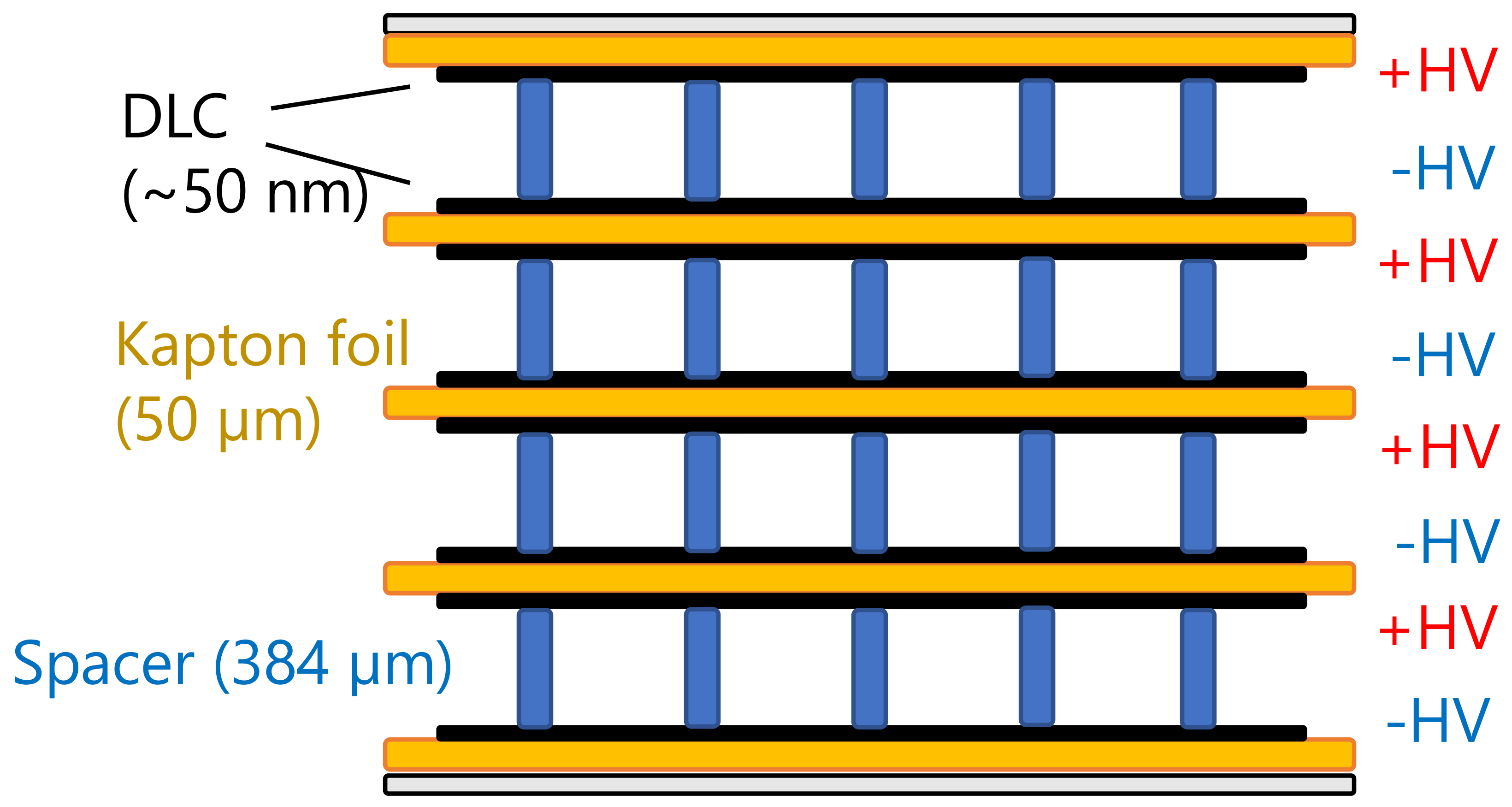
- Photocathode: LaB_6
  - Still low QE
  - Work function 2.6eV
- Intrinsic resolution: 31ps

RPC

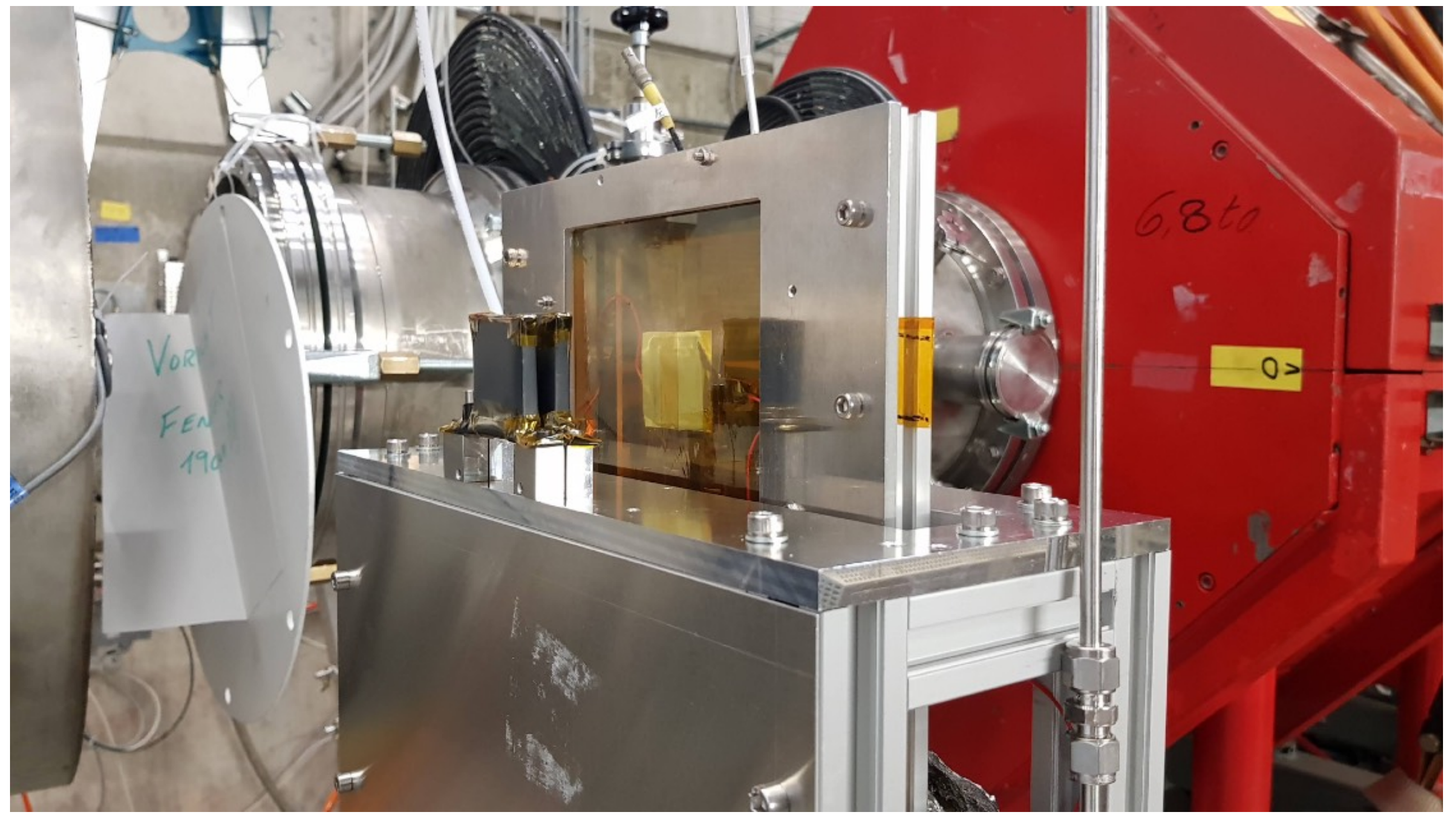
R&D for MEG II

- MEG II RPC
  - Diamond-Like Carbon (DLC) sputtered on Kapton foil as resistive electrode
  - Resistivity can easily be controlled
- Achievements
  - Ultra-low material: 0.1% X_0 with 4 layers
  - High efficiency: > 90% with 4 layers
  - Good time resolution: 250ps with single layer
- In-beam prototype test at πE5
  - Demonstrated the operation at $10^8\ \mu/\mathrm{s}$

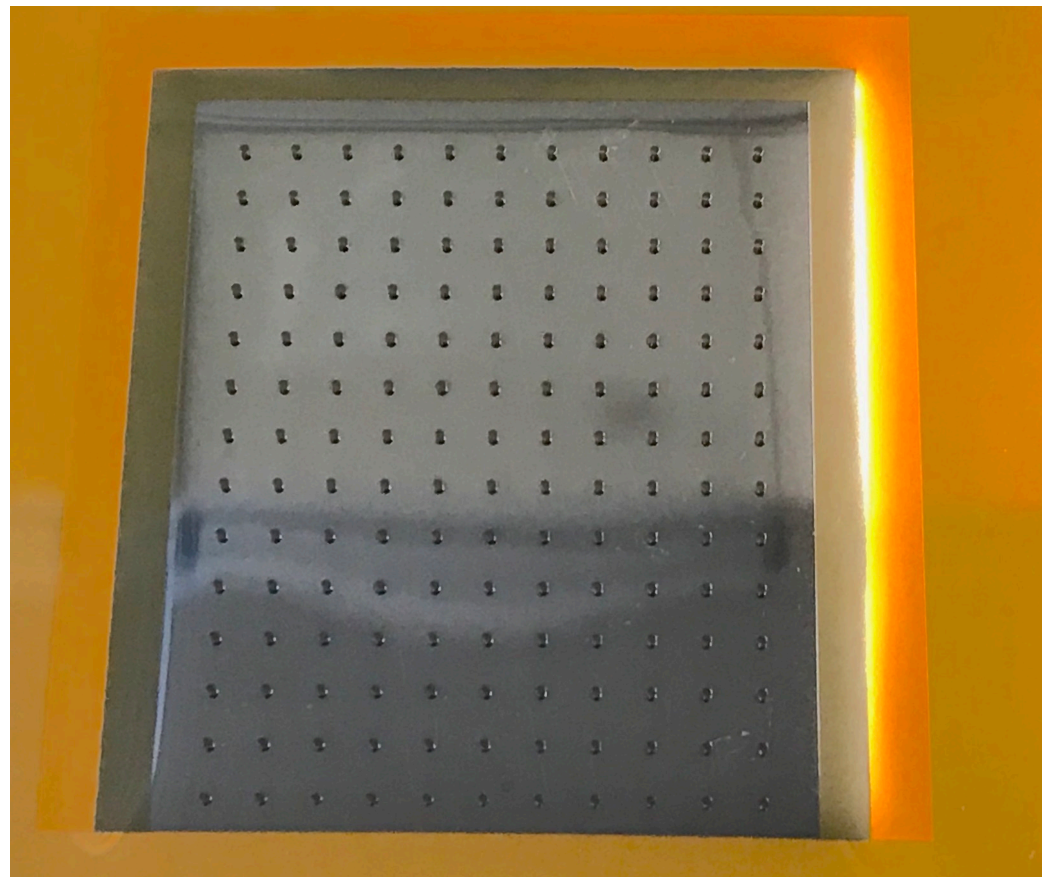
Multi-layer DLC-RPC (MEG II)



Prototype beam test at πE5



DLC on Kapton

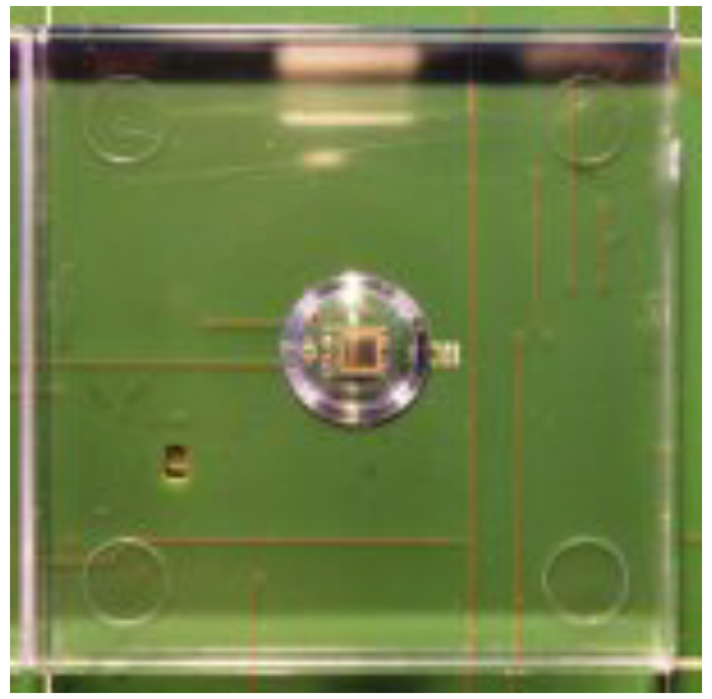


SiPM

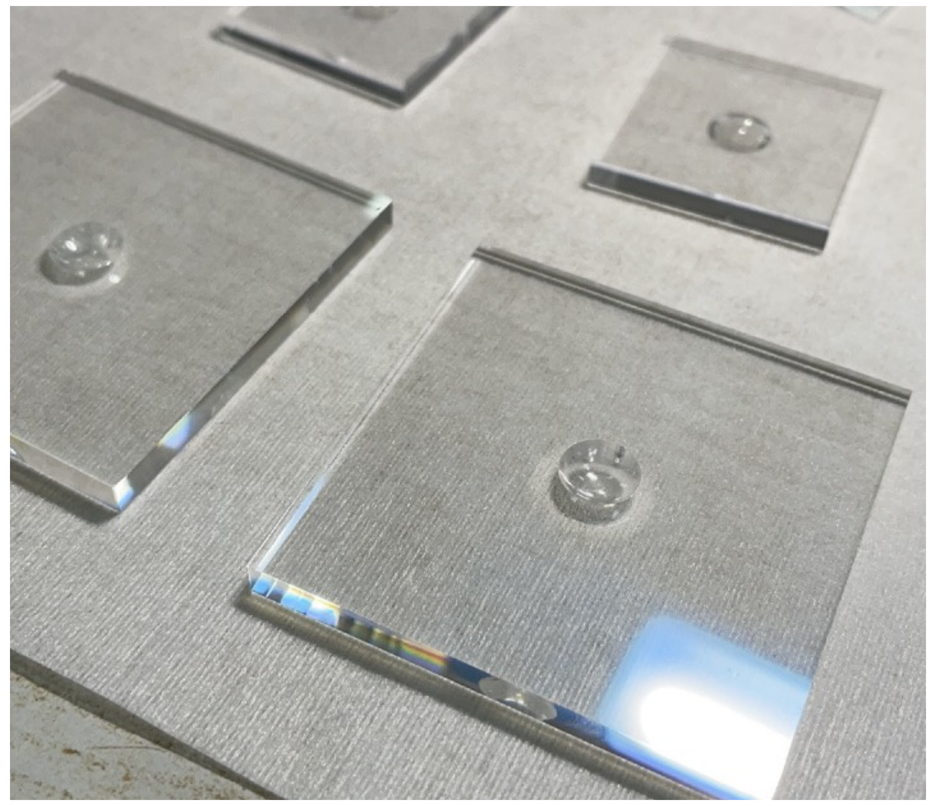
as Photo-detector

- Segmentation with scintillator cells readout by SiPM
  - Tile
  - Strip
- Good light correction eff. and uniformity demonstrated at
  - SiPM-on-tile technology for analogue hadron calorimeter for ILC (CALICE AHCAL)
  - Scintillator strip with SiPM readout for electromagnetic calorimeter for ILC (CALICE Sc-ECAL)
- LYSO cell prototype to be tested soon

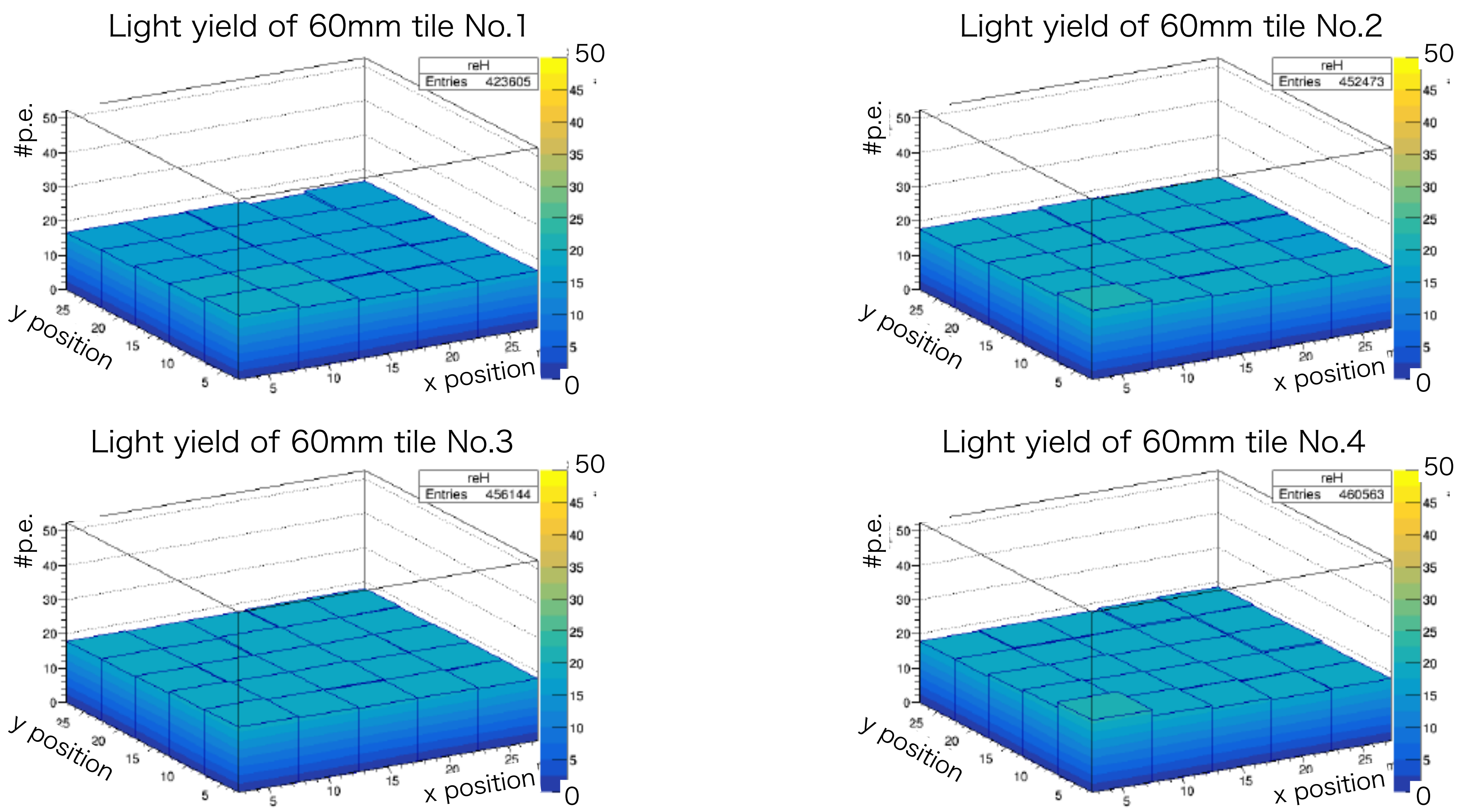
SiPM-on-tile
(AHCAL $30 \times 30 \times 3\ \mathrm{mm}^3$)



LYSO tile



Position dependence of light yield
($60 \times 60 \times 3\ \mathrm{mm}^3$)

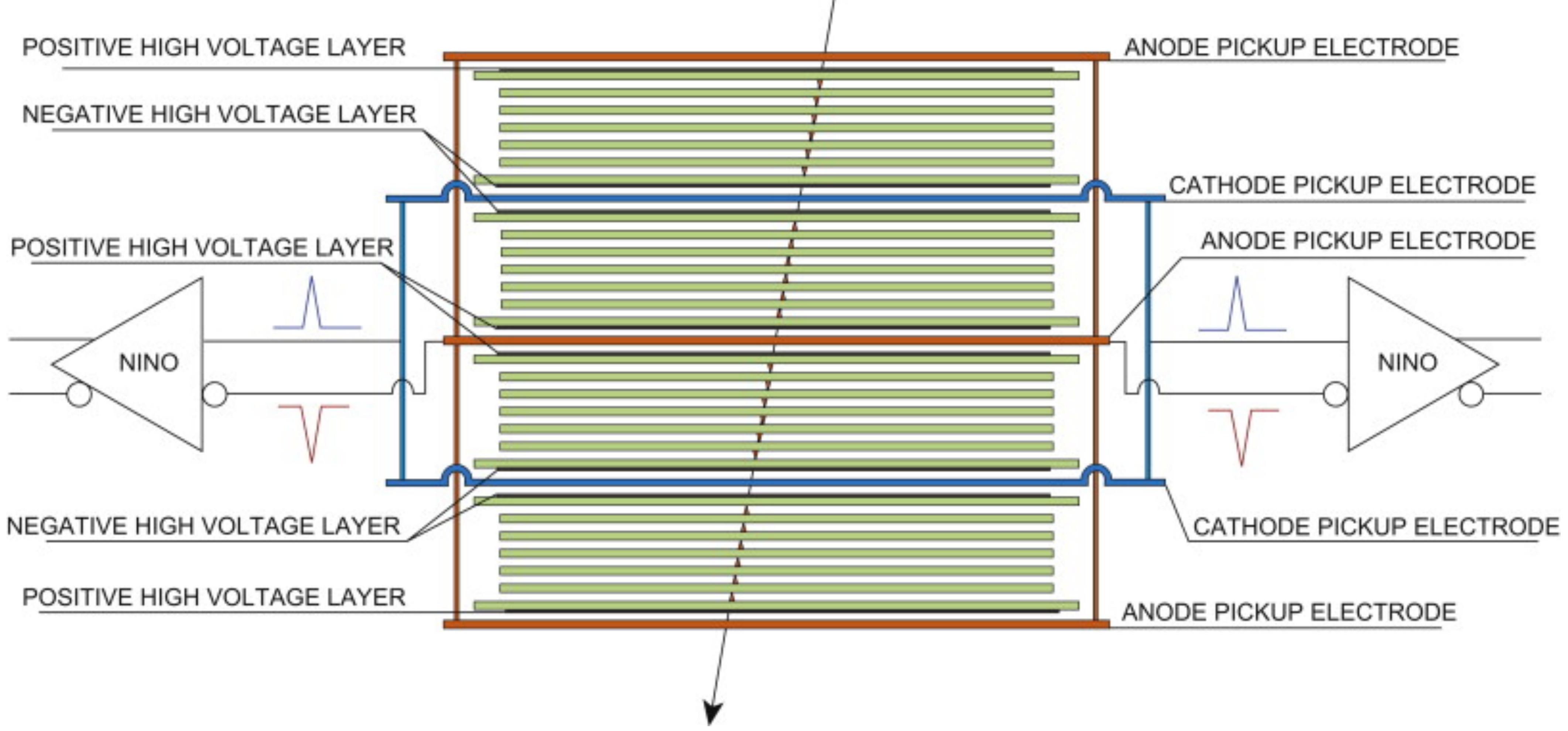


Multi-layer RPC (mRPC)

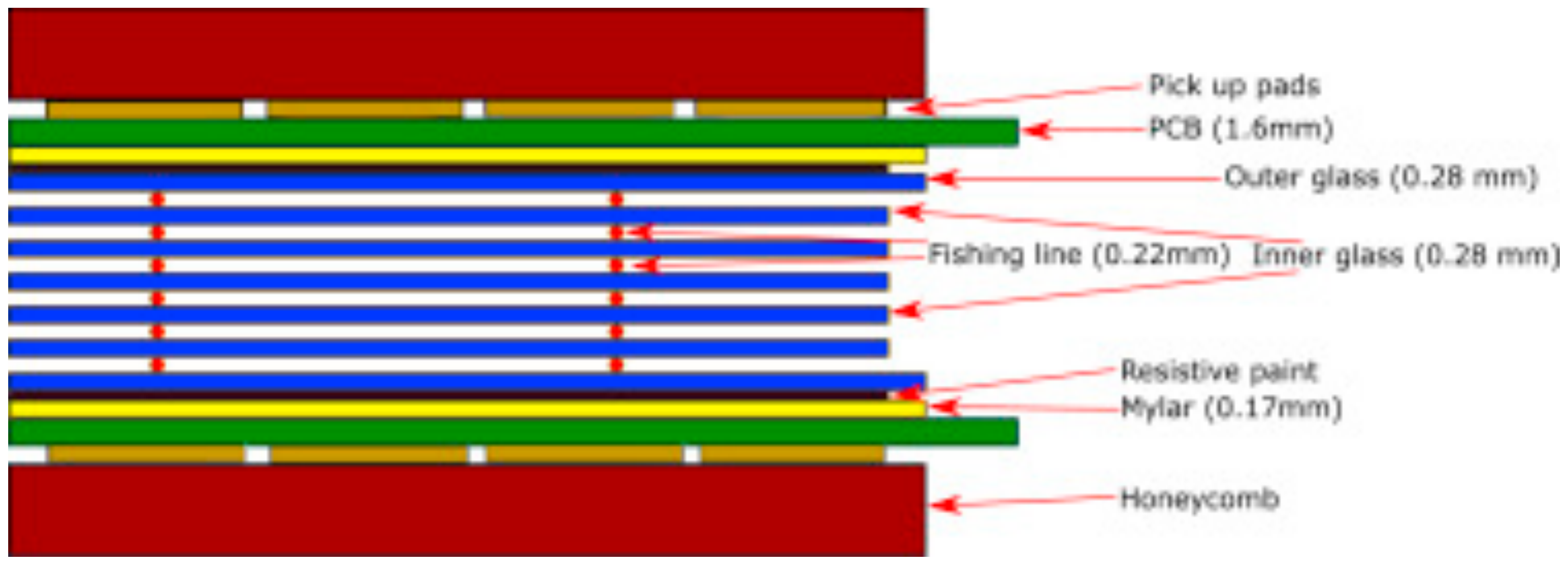
as Timing Layer

- mRPC for timing layer
- Requirements
    - Timing resolution 40ps (→ 30ps for combination of electron and positron)
    - Moderate requirement for material budget (it's in front of converter)
- Achievements in other projects
    - ALICE TOF
        - 20ps with 24 layers of 160µm gap
    - ILD SDHCAL
        - 30ps with 10 layers of 160µm gap
- MEG II DLC-RPC technology can be applied for mRPC
    - Can also be used for positron timing measurement

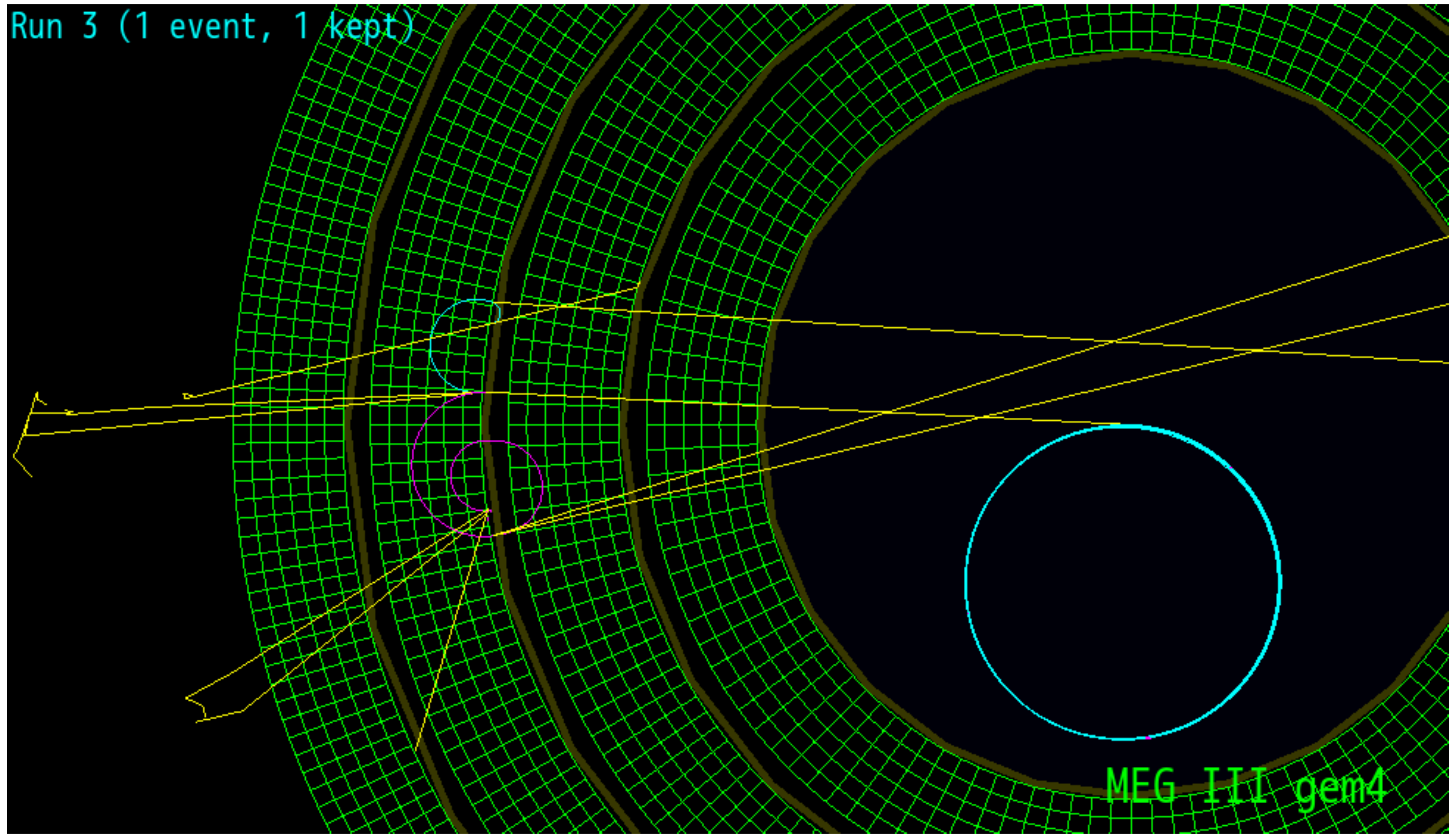
ALICE TOF

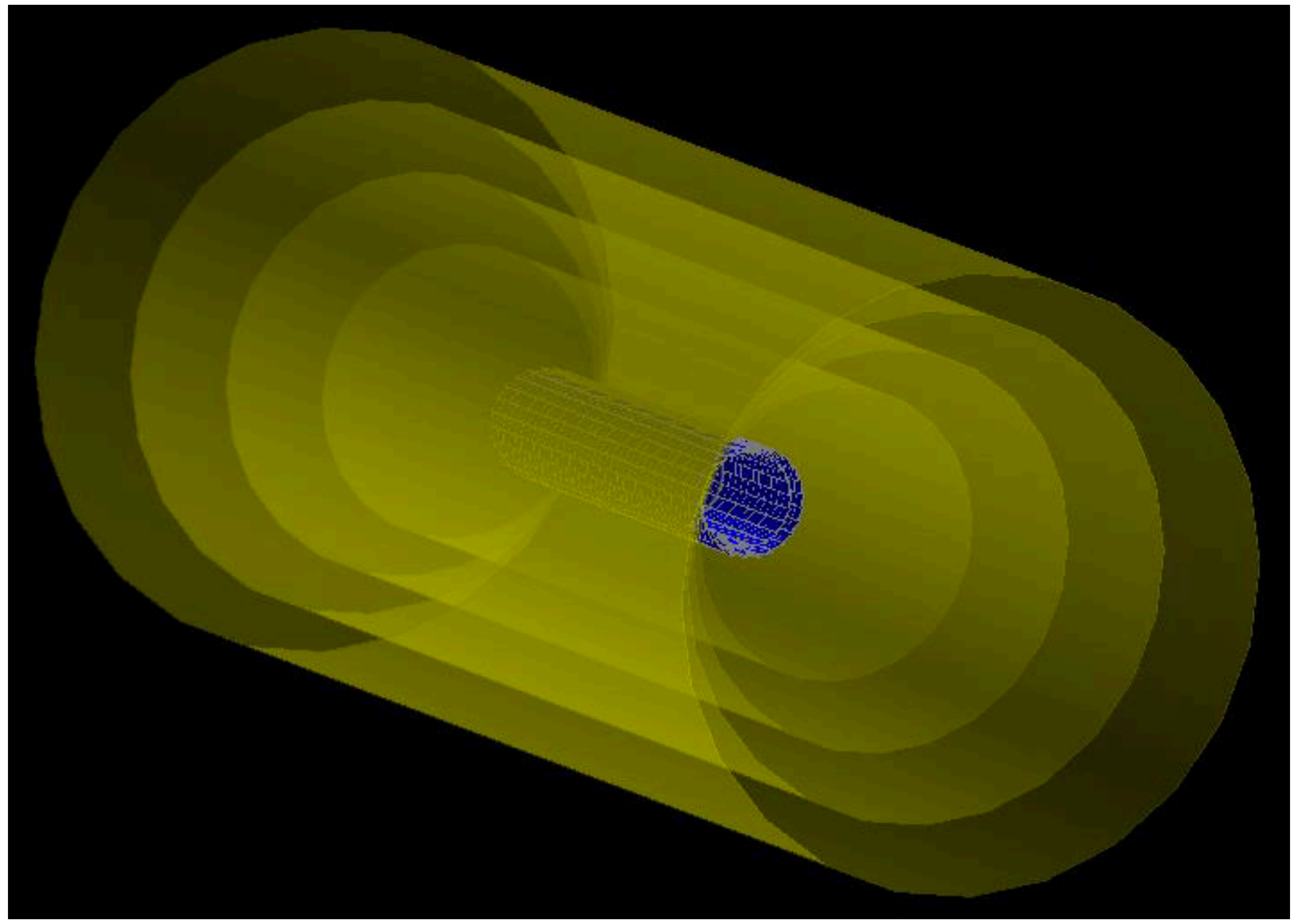


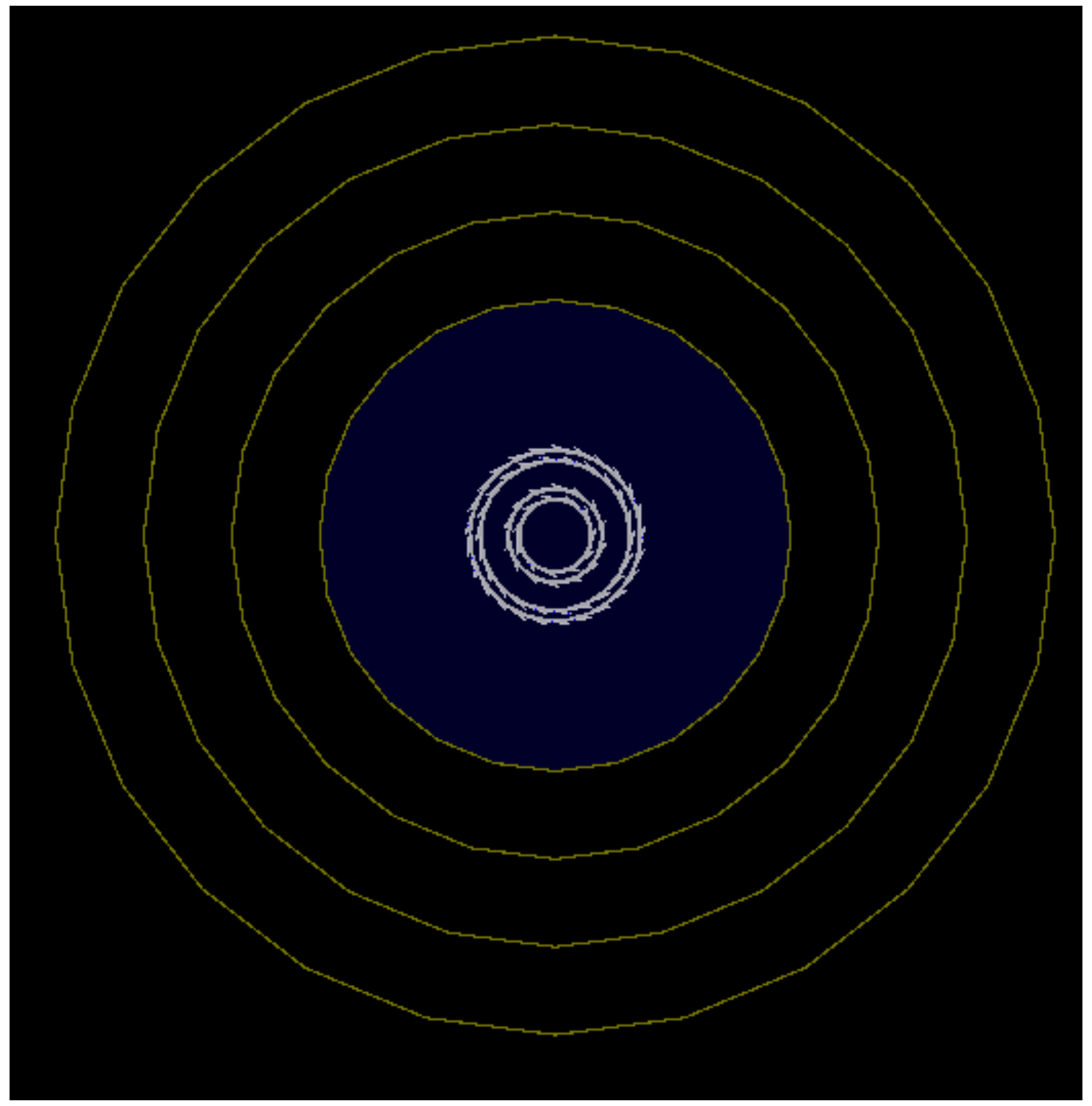
ILD SDHCAL



Simulation Tools in Preparation

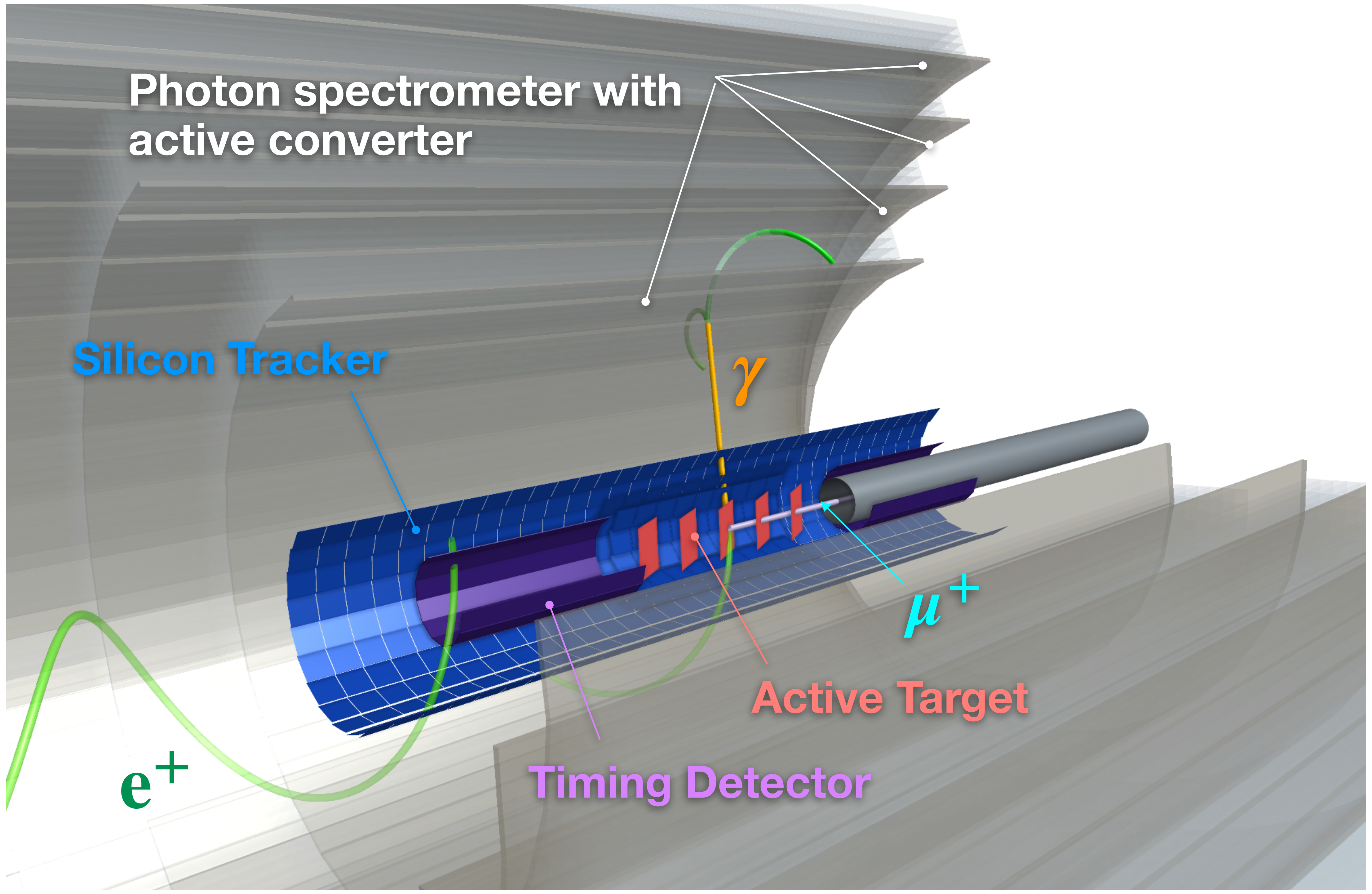






Summary

- Pair spectrometer as a viable option for photon detector at future $\mu \to e\gamma$ experiment
  - Active converter to overcome weak point of pair spectrometer
  - MEG II ultra low mass RPC technology can be applied to
    - Gas PM for active converter
    - Timing layer
- A lot of open questions
  - See the list in the attachment
- Further studies on detector performance in progress
  - Simulation studies
  - Prototype studies of detector technologies



Open Questions

- **Pair spectrometer**
  - Low efficiency
    - Thicker active converter
    - Compensate with higher beam intensity ↔ high rate capability of detectors, especially positron spectrometer
  - Pileup of low energy photons from RMD → Mitigated with radiation shielding in front of innermost conversion layer?
- Detector material for active converter
  - Any better material?
    - Effect of bremsstrahlung, light yield, stopping power, cost,…
    - Non-linear response of scintillator
  - Optimal thickness?
    - Efficiency (photon, conversion pair timing), angular resolution
- Photo-detector for active converter
  - Gas PM readout: large area and stability for photocathode → extremely challenging
  - SiPM readout: optimal segmentation of scintillator, SiPM coupling
- MEG II RPC technology for timing layer
  - Timing resolution of 40ps is possible? ← Multi-layer (>10 layers)
  - Can be used for timing layer of positron spectrometer → high rate capability

Open Questions

- Tracker for photon spectrometer
  - Gaseous or Si
    - Not so harsh environment at larger radius of photon spectrometer compared to positron detector $\rightarrow$ Gaseous tacker is better?
  - Gaseous tracker: drift chamber or TPC
    - Ion feedback at TPC
  - Si tracker
    - Pattern recognition with a limited number of hits
- **Target**
  - How does active target do better?
  - Separate or long target $\rightarrow$ suppress accidental BG
  - Muon polarisation preserved? $\rightarrow$ measurement of $\mu \rightarrow e\gamma$ angular distribution
- **Concurrent $\mu \rightarrow eee$ search?**
  - Tracker layout consistent with $\mu \rightarrow e\gamma$ search?
  - Can it be competitive with Mu3e Phase II sensitivity?
- **How far can we reach?**
  - Make sense only if 10^{-15} or better