Conceptual Design and R&D Activities for a Future $\mu \to e\gamma$ Search

W. Ootani, ICEPP, Univ. of Tokyo

Workshop on a Future Muon Program at Fermilab, Mar. 29th, 2023

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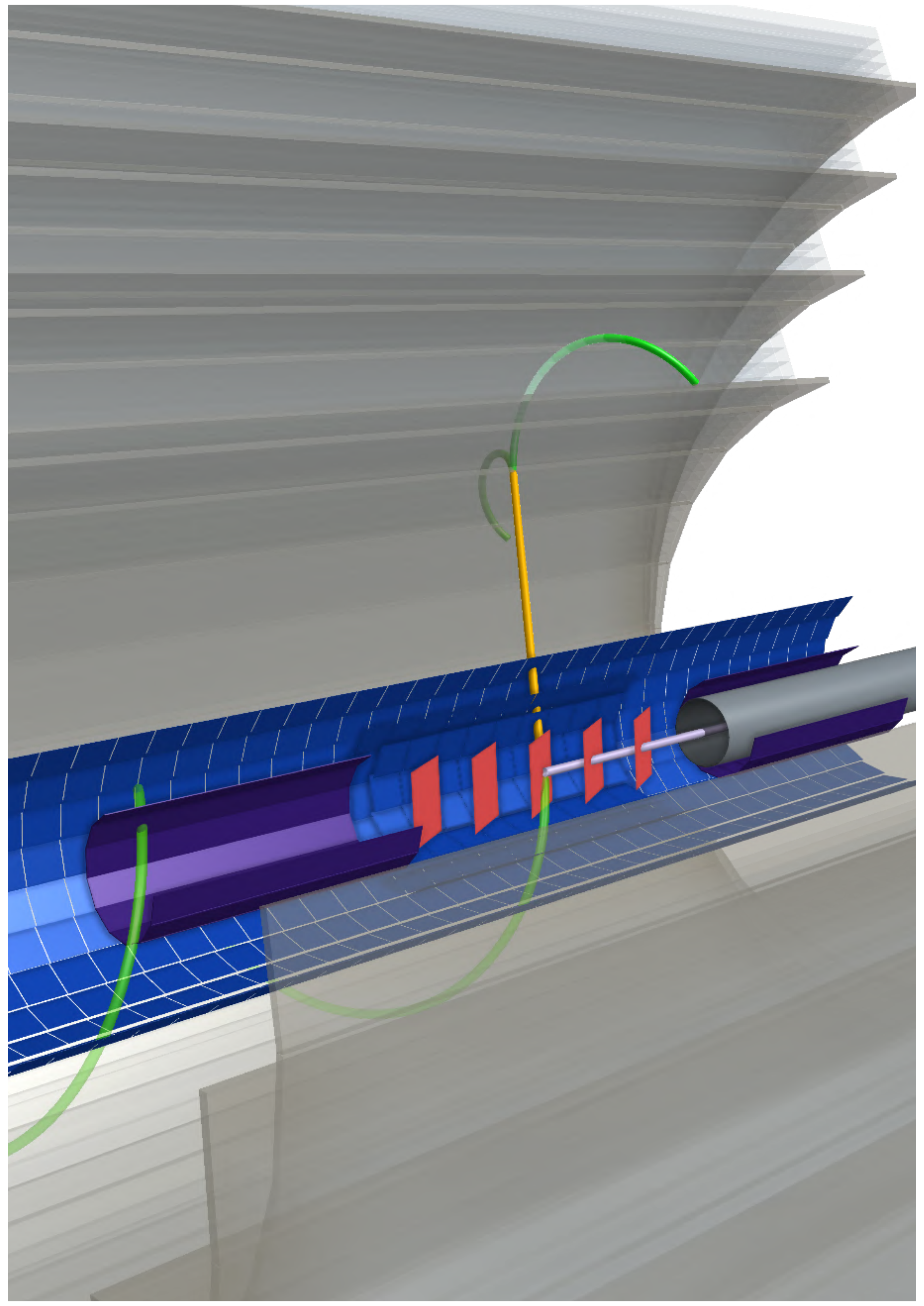
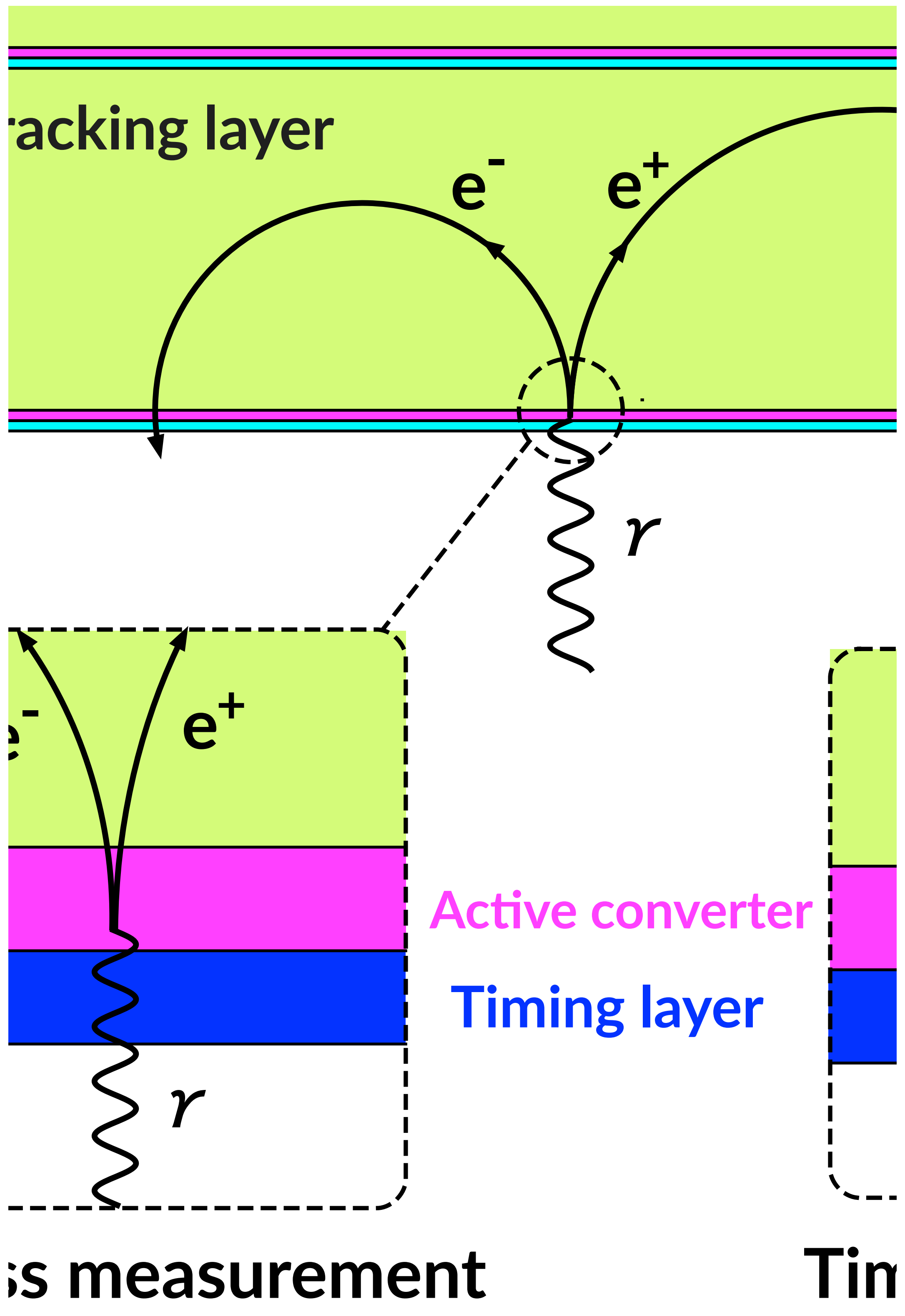
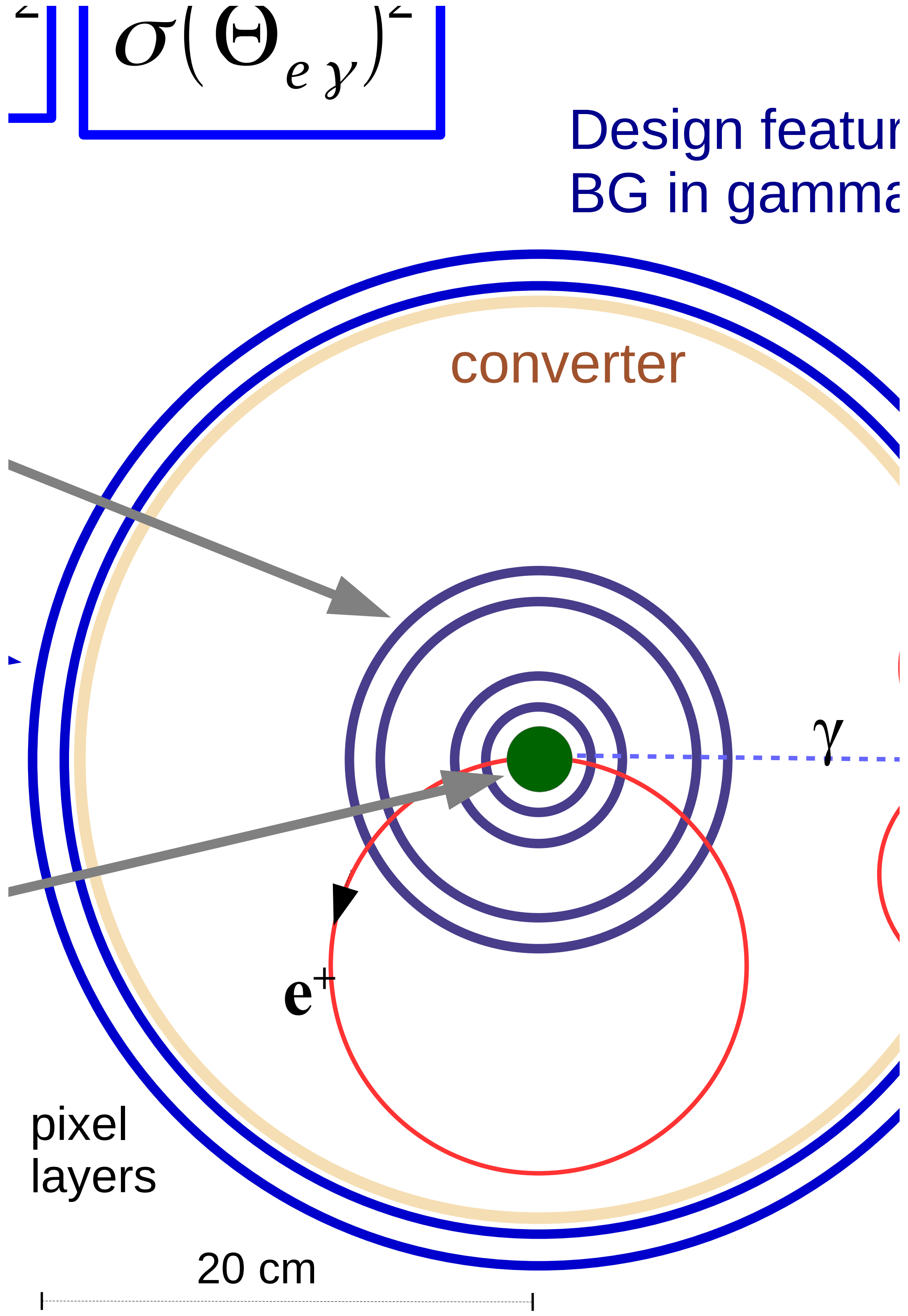




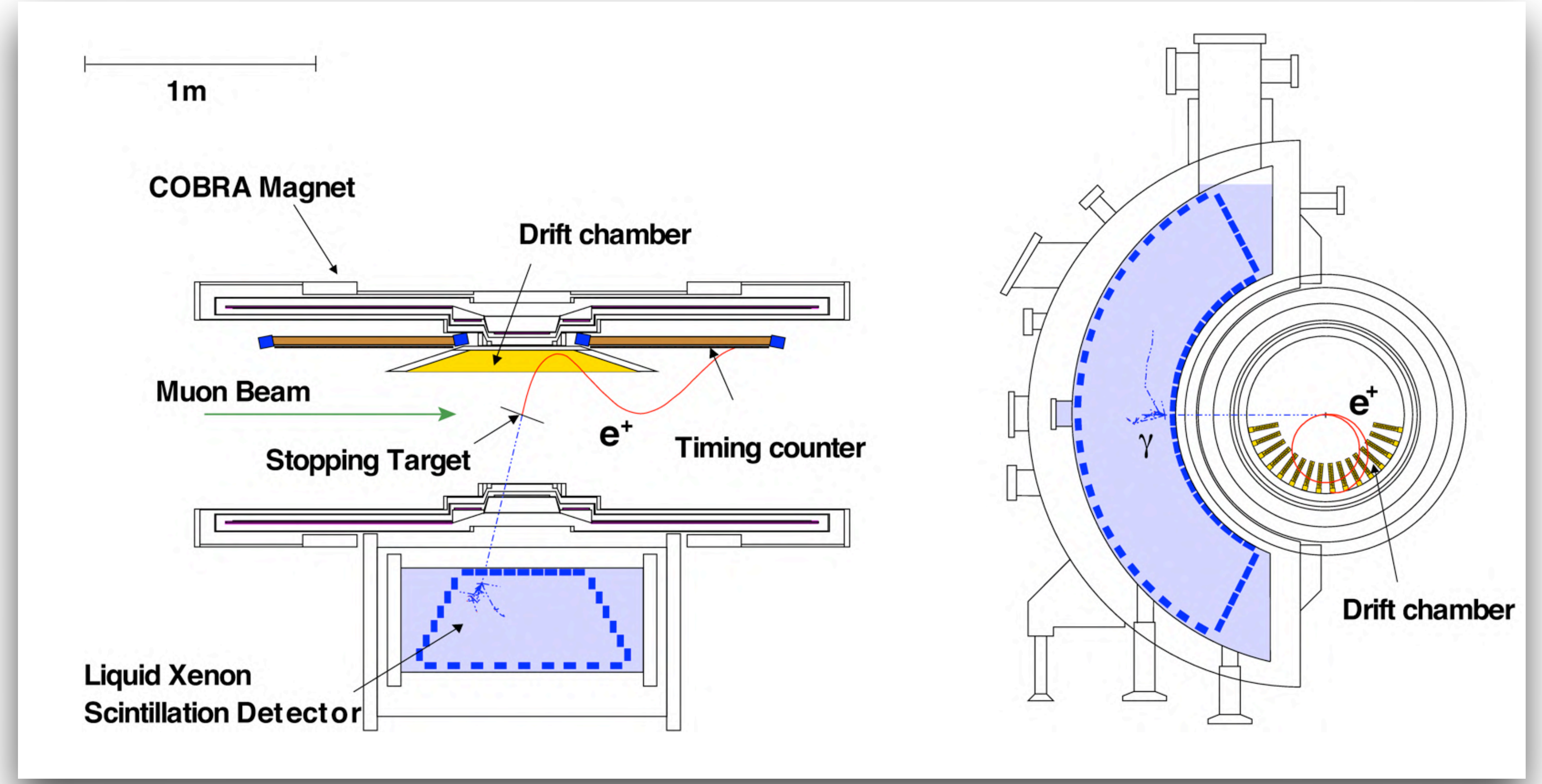


Contents

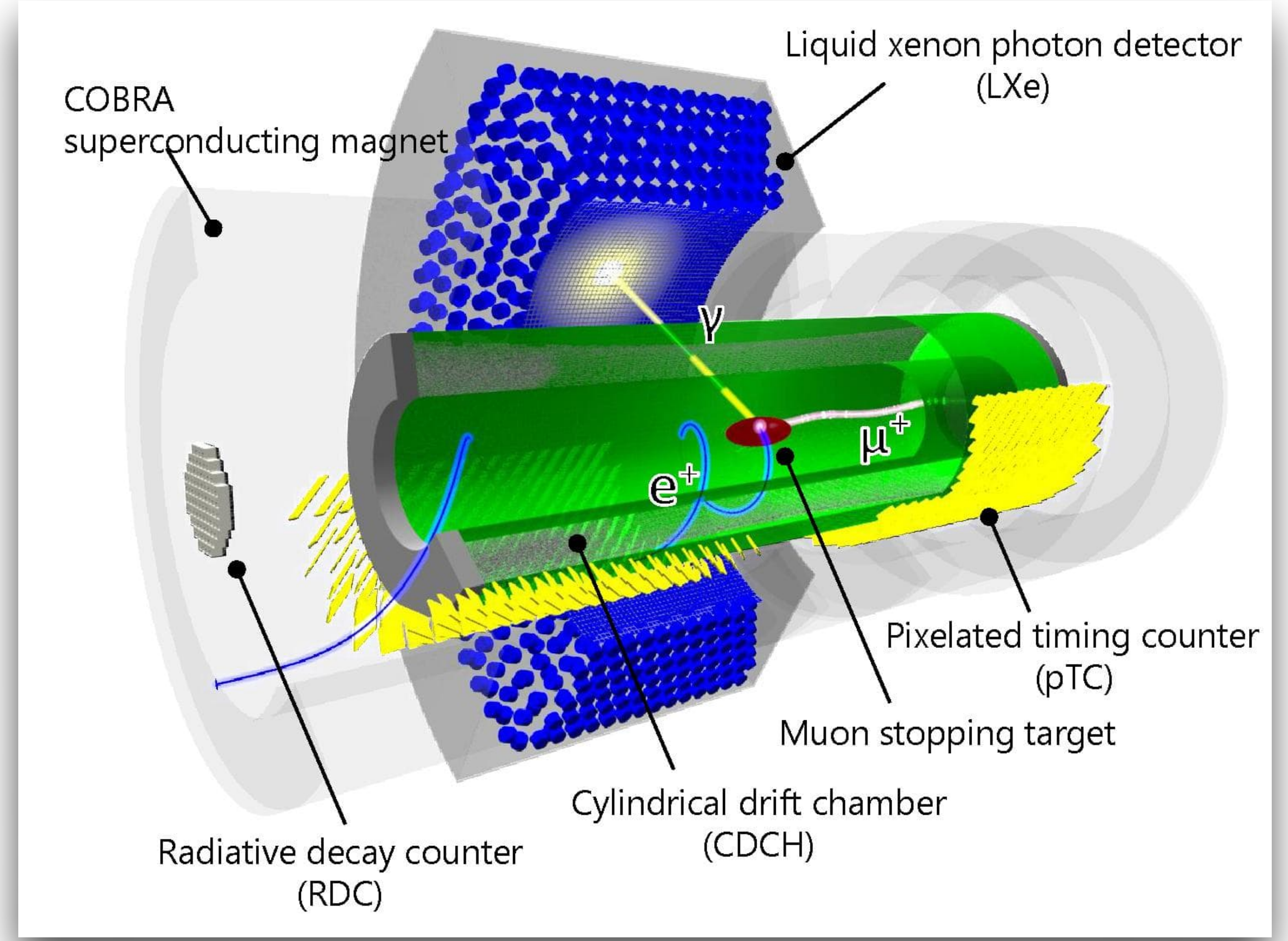
How to Reach $\mathcal{O}(10^{-15})$ Sensitivity?

- Quite difficult based on MEG concept
- Need a totally different approach

MEG



MEG II



?

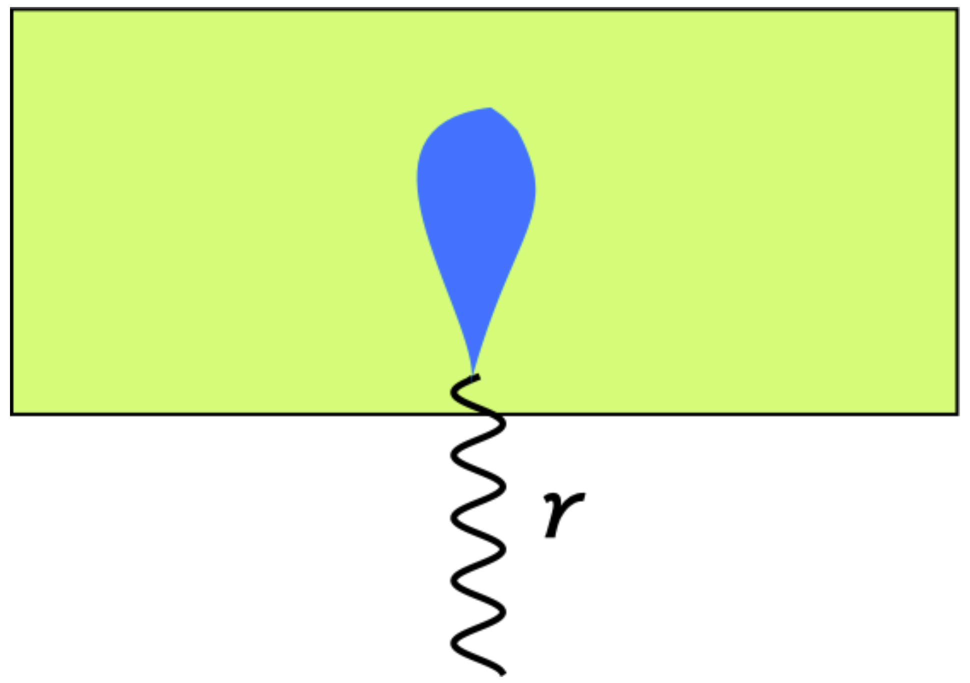
Study Group for Future $\mu \rightarrow e\gamma$ Search Experiment

- Set up to follow-up the discussions in HIMB Physics Case Workshop (April 2021) and the write-up (https://doi.org/10.48550/arXiv.2111.05788) and to devise solider experimental concepts for future $\mu \rightarrow e\gamma$ search
- Open discussions on designs and technologies for future experiment. Not limited to a specific design
- **Photon**
    - **Conversion spectrometer**
        - Scintillator + gaseous tracker (W. Ootani, F. Renga)
        - Silicon (A. Schöning)
    - **Calorimeter** (A. Papa)
- **Positron**
    - **Gaseous detector** (F. Renga)
    - **Silicon** (A. Schöning)

Contents

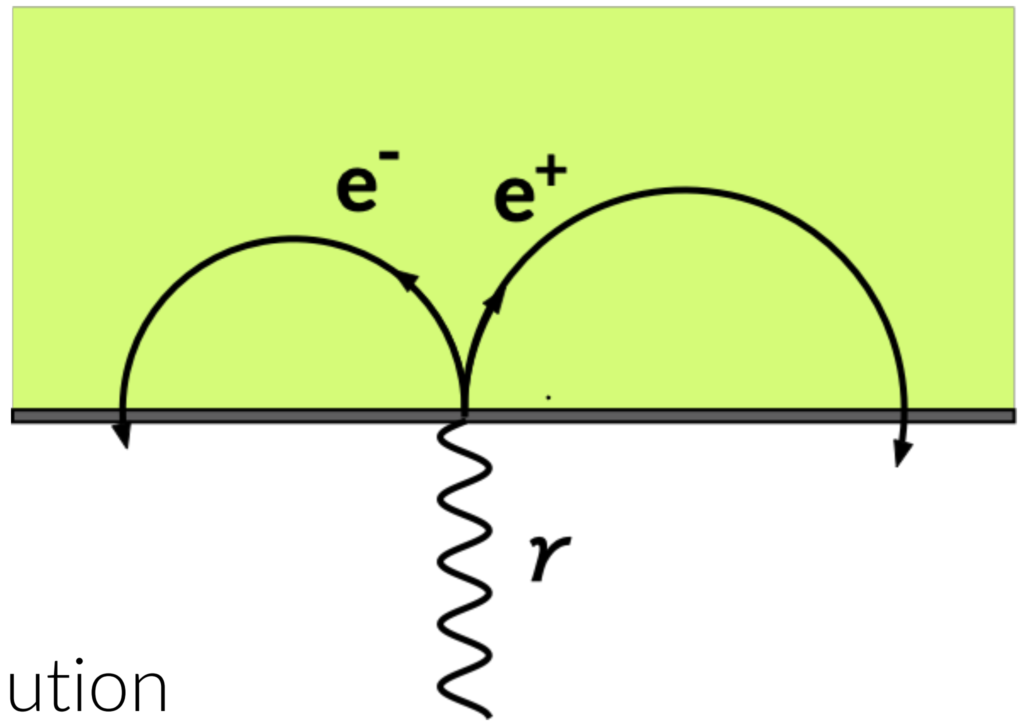
Calorimeter vs. Pair Spectrometer

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

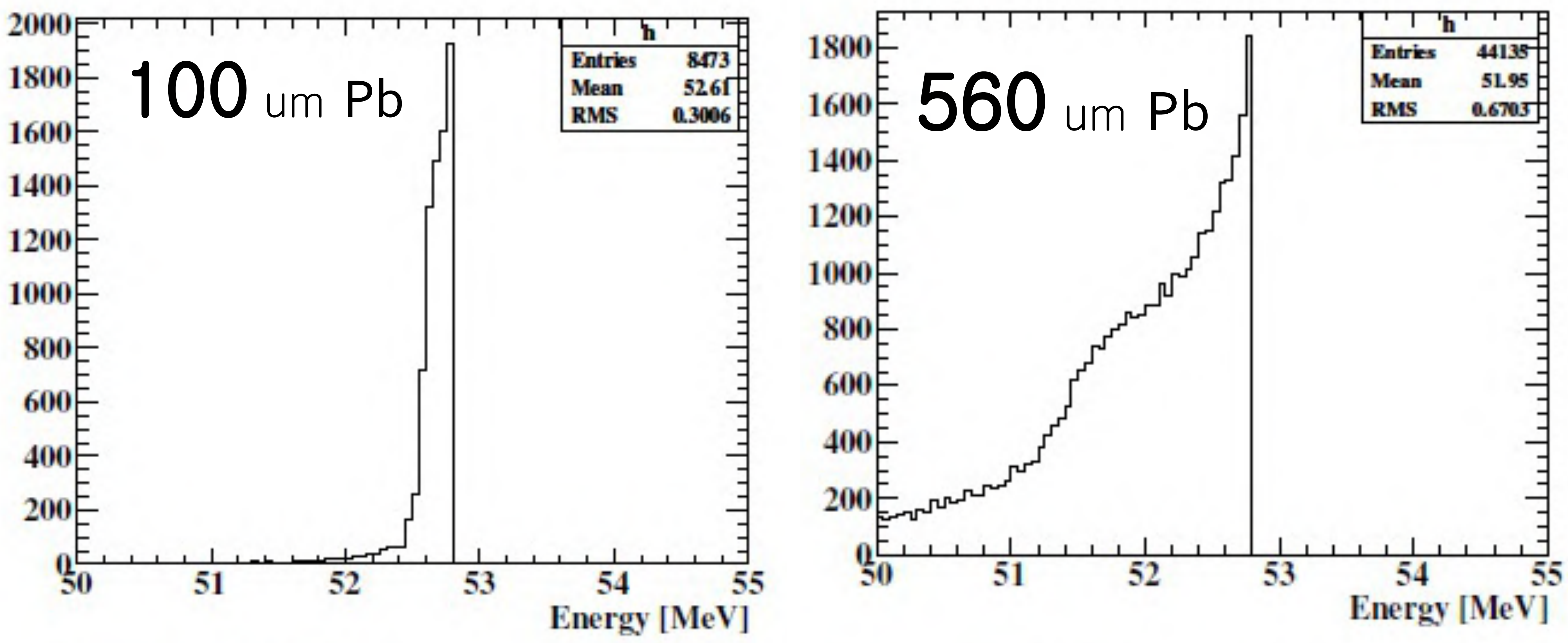
Pair spectrometer would be a viable option for photon detector at future $\mu \to e\gamma$ experiment with higher beam rate

Active Converter

- Energy loss of conversion pair in converter

  ⇒ **Active converter** to measure energy loss

Energy of conversion pair after converter (MC)



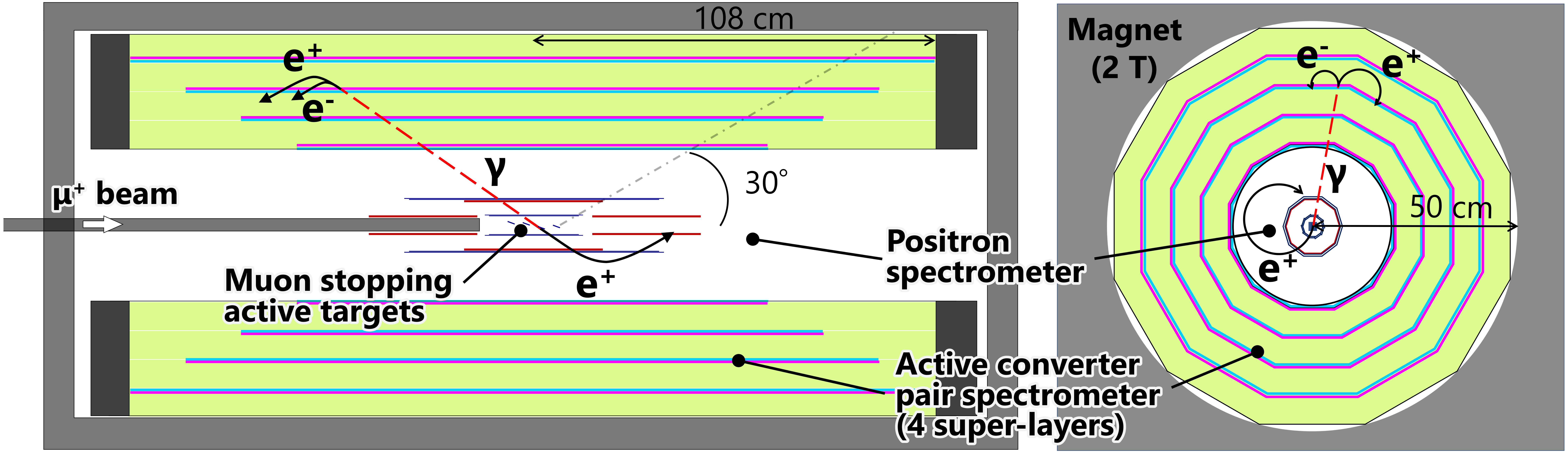
- Low efficiency

  ⇒ **Multi-layer**

  ⇒ **Heavy active material**

Experimental Design under Consideration

- Experimental design based on pair spectrometer
  - **Photon spectrometer with active converter** → higher resolutions (energy, timing, position), angle measurement
  - **Positron spectrometer based on Si detector** (a la Mu3e) → high rate capability, concurrent search for $\mu \to eee$
  - **Separate active targets** → higher vertex resolution, further BG suppression
  - **Significantly improved acceptance** especially for zenith-angle → angular distribution measurement after discovery



Enhanced Acceptance

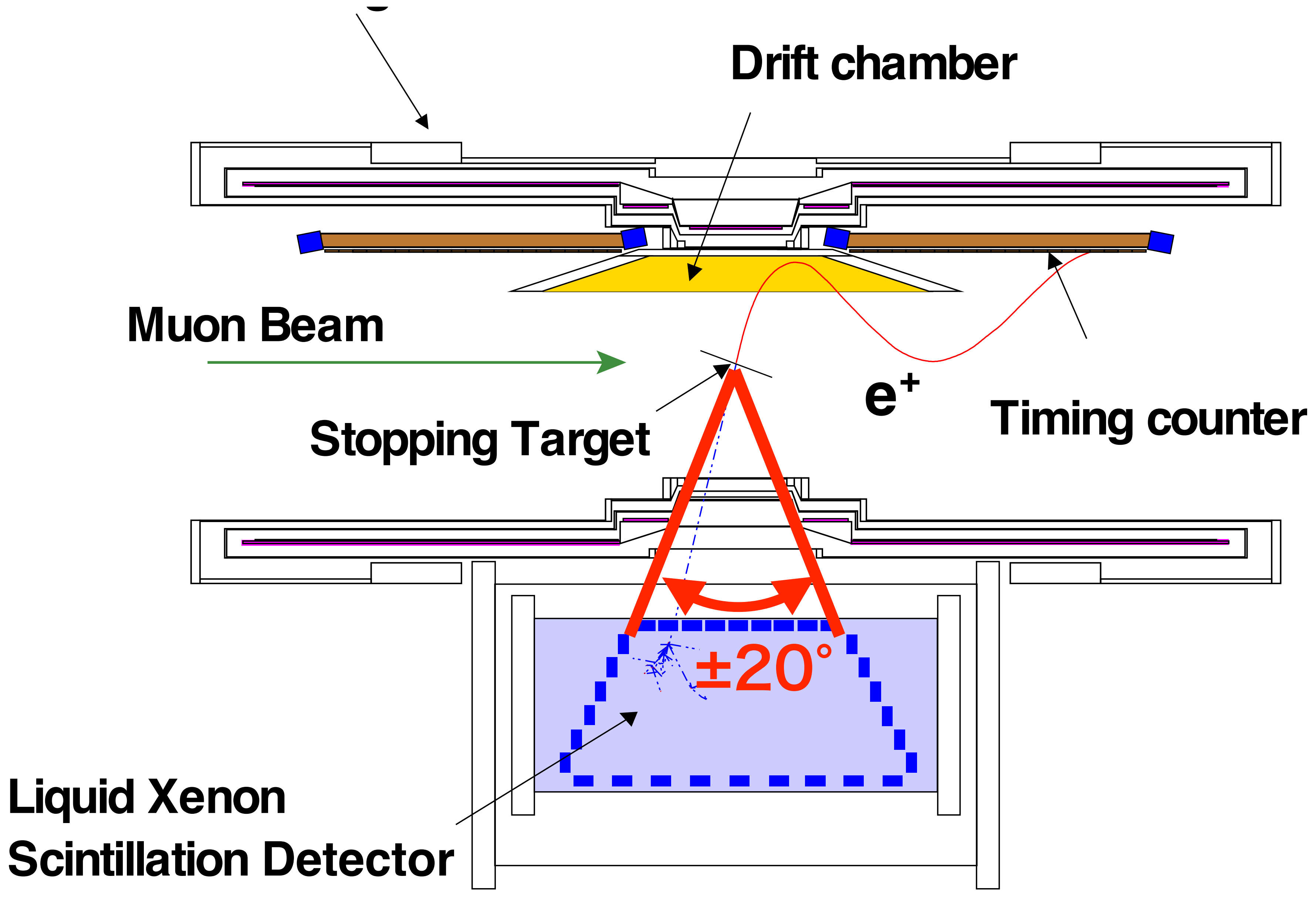
Zenith-angle acceptance significantly improved w.r.t. MEG II

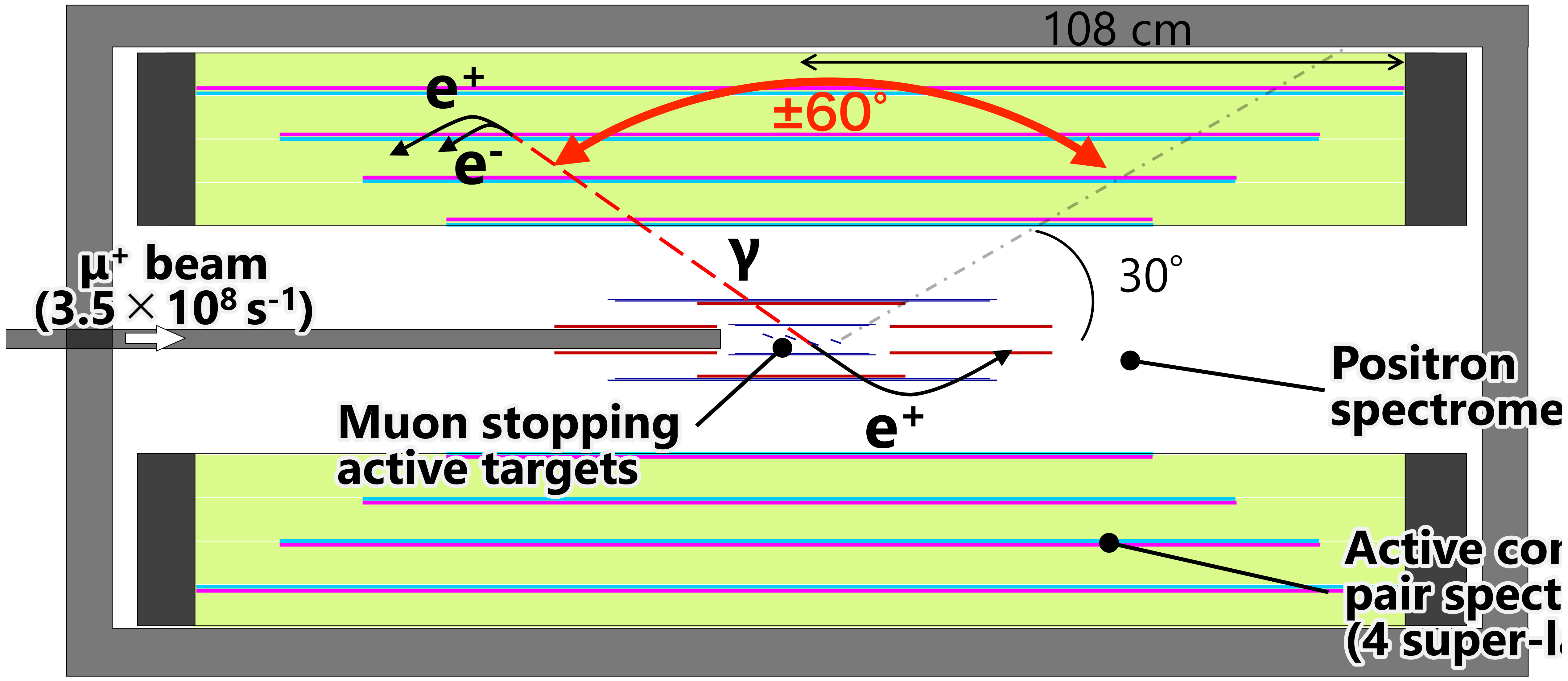
→ After $\mu \to e\gamma$ discovery, angular distribution can be measured with polarised muon beam ($P_\mu = -0.86$ @MEG)

→ Pin-down underlying new physics

- e.g. SU(5) SUSY-GUT: $A_L \neq 0, A_R = 0$
- e.g. SO(10) SUSY-GUT: $A_L \simeq A_R$
- e.g. Non-unified SUSY with ν_R: $A_L = 0, A_R \neq 0$

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



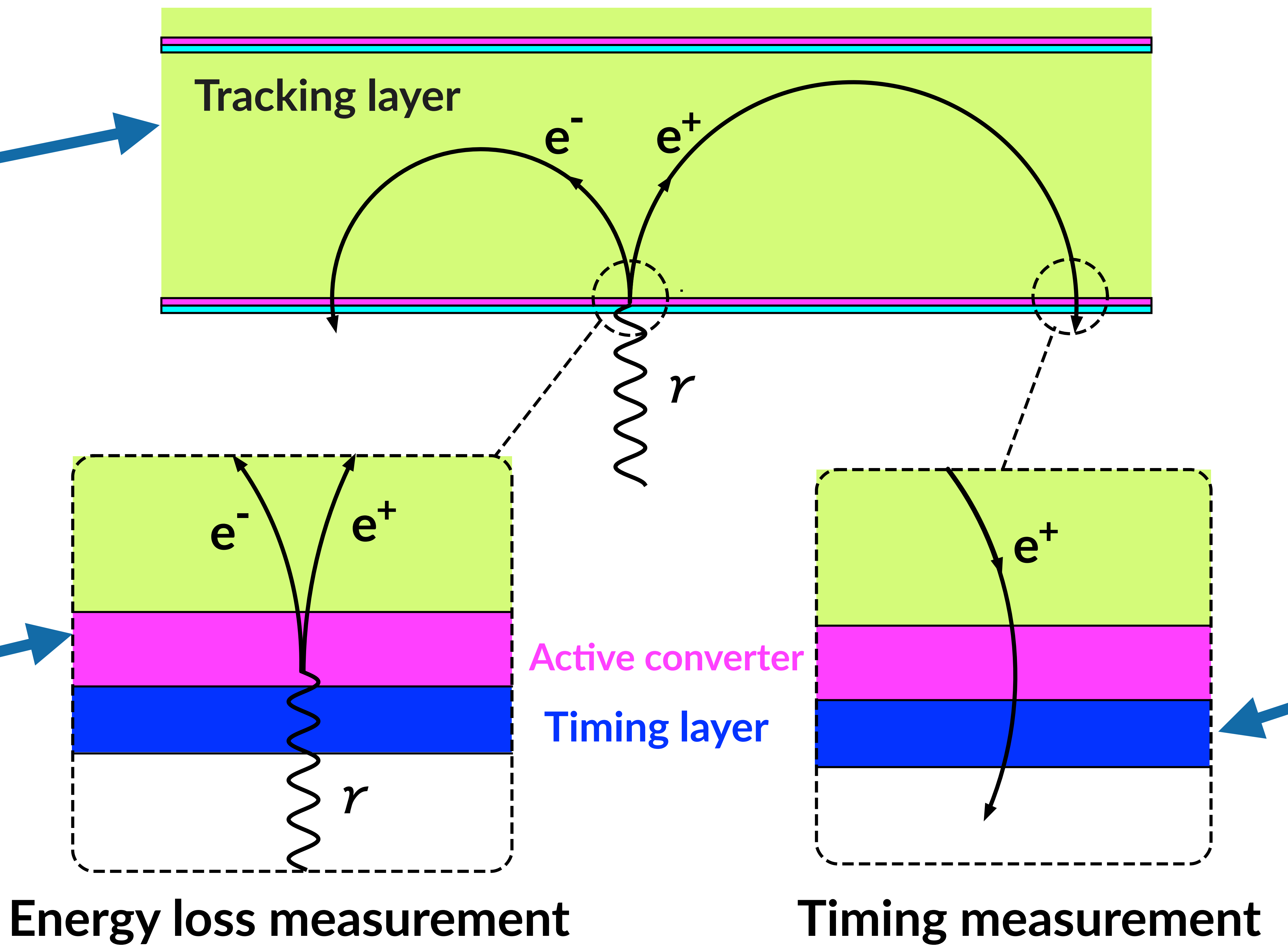


Pair Spectrometer with Active Converter

Reminder

Tracking layer

- Measure momentum of conversion pair
- Possible technologies
  - Drift chamber (a la MEG II CDCH)
  - Radial-TPC
  - Silicon detector



Active conversion layer

- Thin active material to measure energy loss of conversion pair
- Possible technologies
  - Scintillator + photo-detector
  - Silicon detector

Timing layer

- Measure timing of returning conversion pair
- in front of active converter
- Possible technologies
  - Multi-layer RPC (mRPC)
  - Active converter = timing detector

Active Converter

Scintillator

- Scintillator as active converter material
  - Light yield → energy resolution
  - Decay time → high rate capability
  - Radiation length → detection efficiency
  - Critical energy → effect of bremsstrahlung (difficult to measure)
  - Cost
- Photo-sensor for scintillation readout
  - Requirements: high light detection eff. + low mass
  - Photo-detector under consideration
    - GasPM
    - SiPM

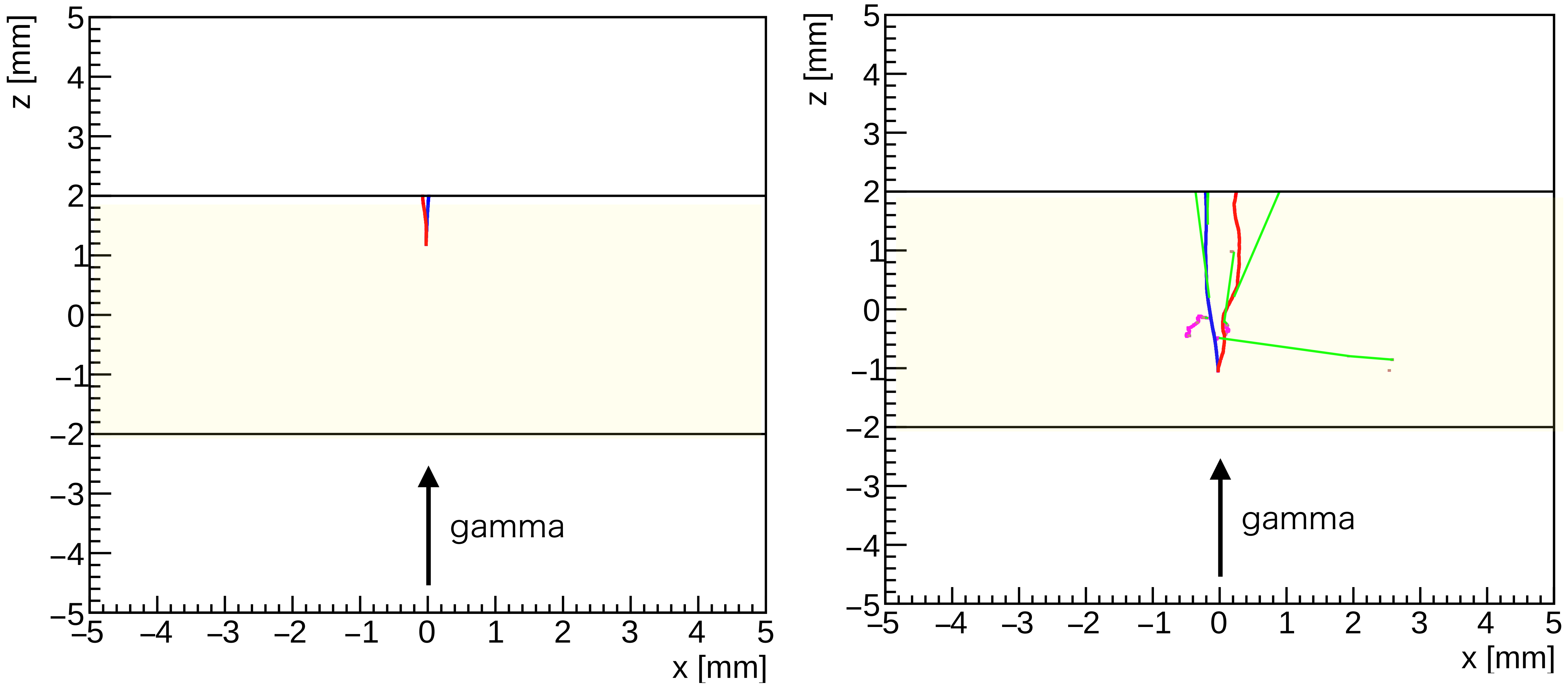
Crystal	NaI	LYSO(Ce)	$LaBr_3$(Ce)	YAP(Ce)	Plastic scintillator	Silicon
Density [g/cm^3]	3.7	7.4	5.1	5.4	1.0	2.3
Light yield (relative to NaI)	100%	75%	160%	70%	30%	-
Peak Emission [nm]	415	420	380	370	400	-
Decay time [ns]	230	40	16	27	2-4	-
Radiation length [cm]	2.6	1.1	1.9	2.7	43	9.4
Critical energy* [MeV]	13	12	12	23	93	39
Hygroscopicity	Yes	No	Yes	No	No	-

* Critical Energy Ec: Ionisation ≶ Brems if E ≷ Ec

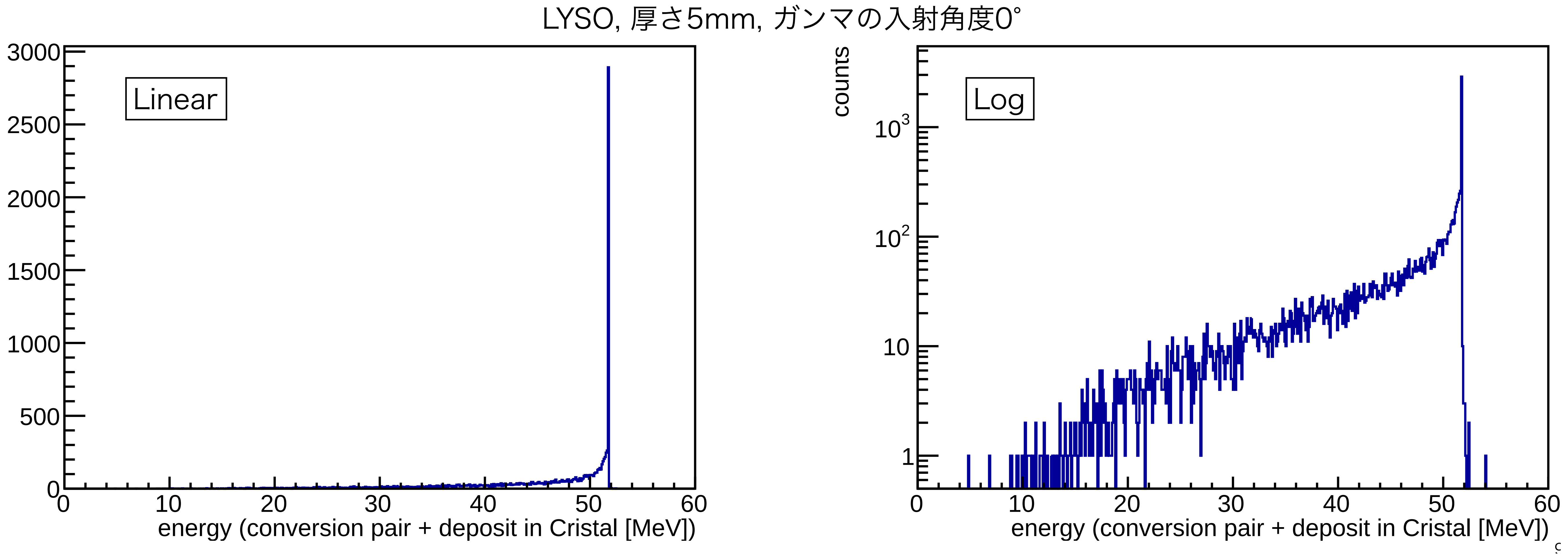
Active Converter

Simulation Study

- Started simulation study with simple setup
- Estimate total energy which can be measured with converter + tracker
  - Efficiency is estimated with event fraction for
    $E > (52.8\,\mathrm{MeV} - 2 \times m_e) - \delta E$
    (Target energy resolution: $2\delta E = 0.2\,\mathrm{MeV}$)
  - Resolution for conversion pair tracker is not taken into account



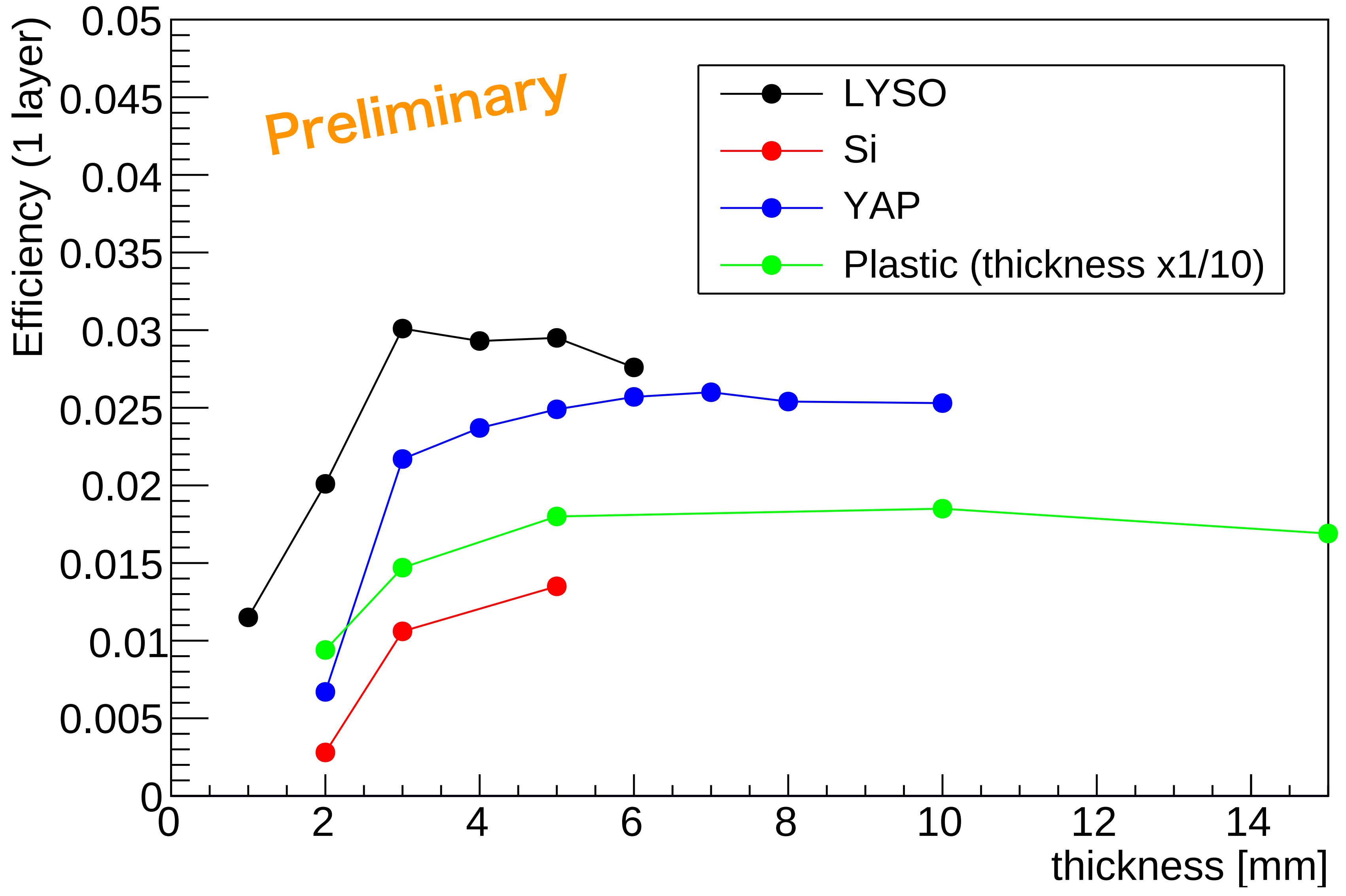
blue : electron (conversion)
red : positron (conversion)
magenta : electron (ionization)
brown : electron (photo-absorption)
green : photon

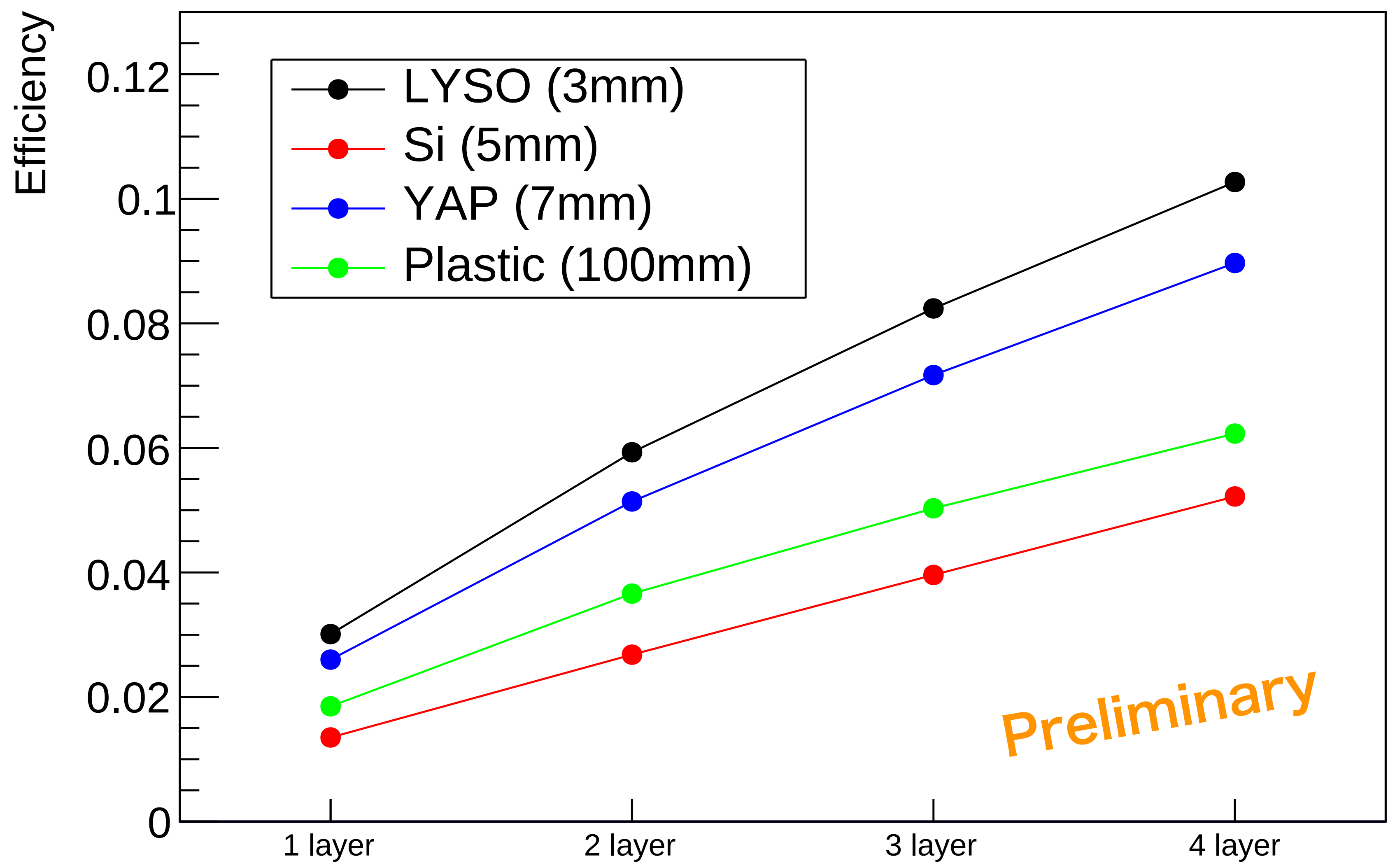


Active Converter

Simulation Study

- Efficiency
  - Efficiency saturates with increasing thickness due to energy escape by increasing bremsstrahlung and loss of conversion pair
  - Heavy scintillator has a higher detection efficiency despite lower critical energy ← Some of bremsstrahlung can be absorbed in converter
  - 10% with 4 layers of LYSO(3mm-thick)
- Issues
  - Multiple scattering ⇒ worsening position/direction resolution
  - Segmentation required to mitigate pileup



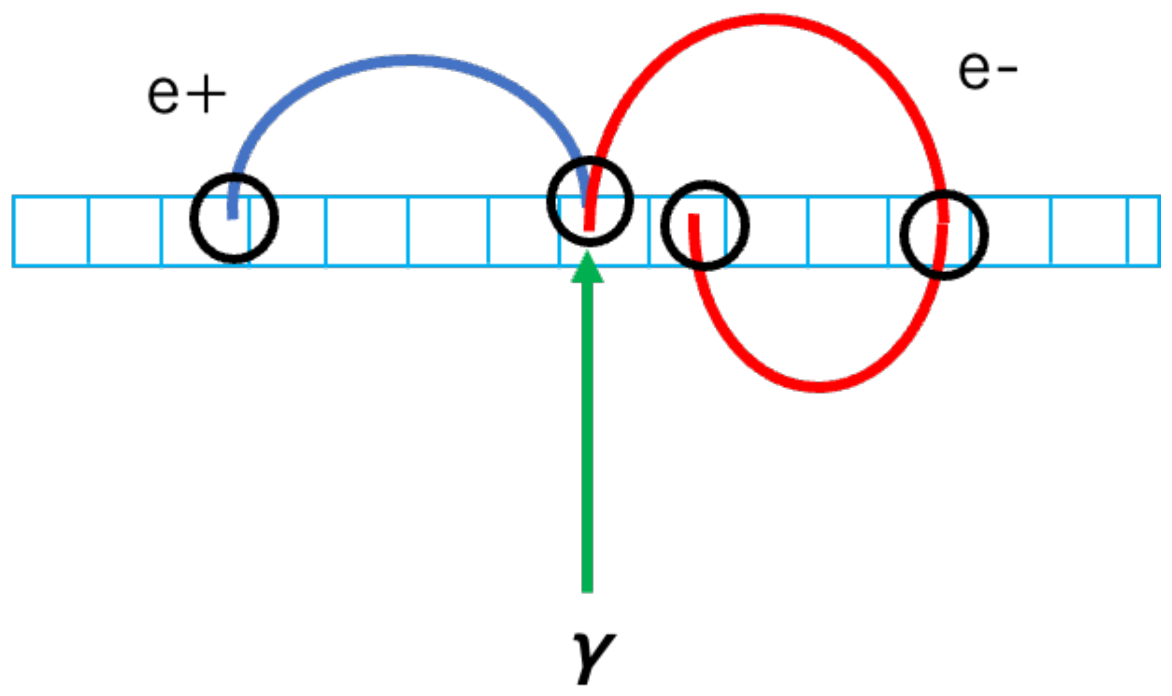


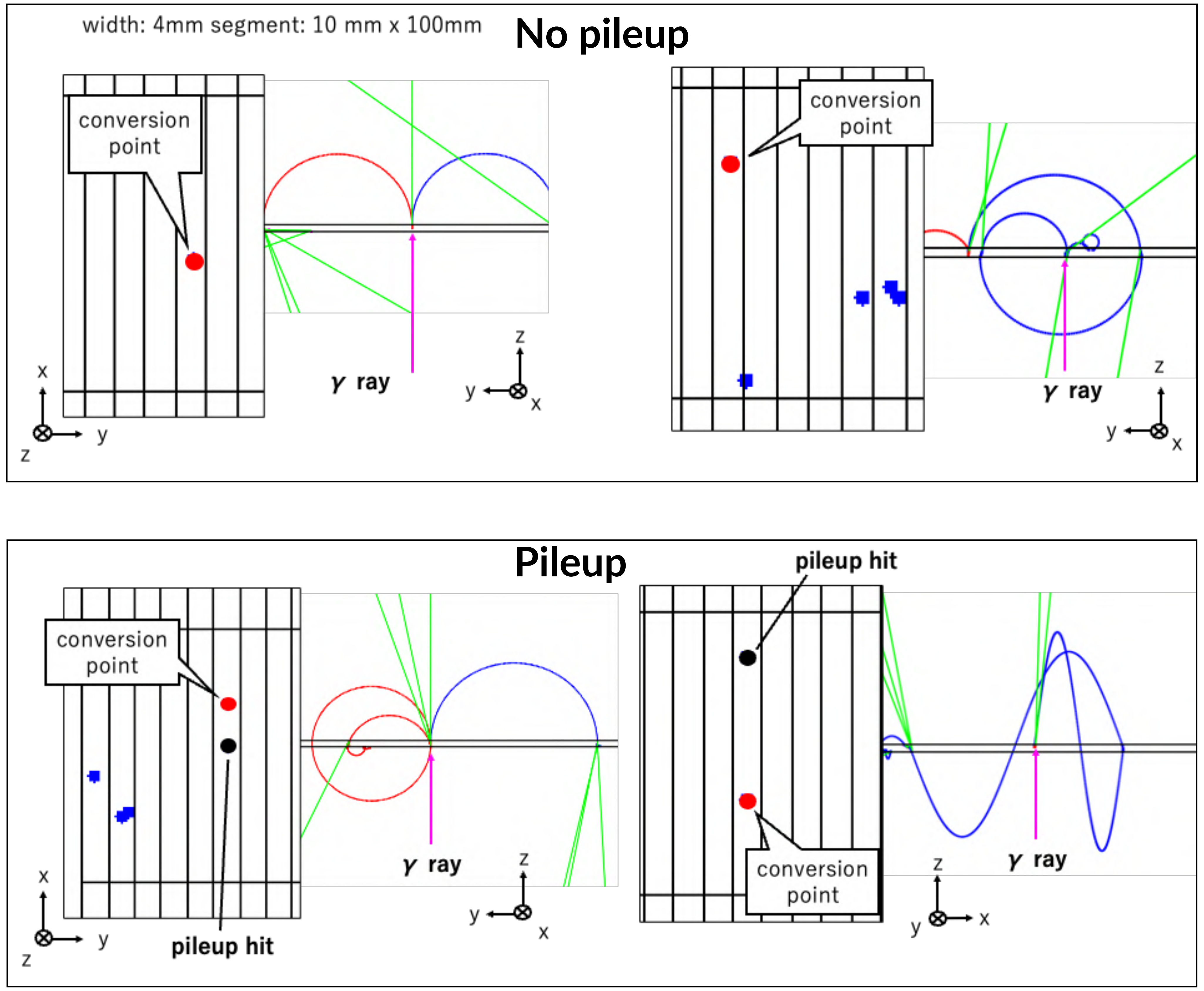
(N.B. Effect of pileup hit of returning conversion pair is not taken into account)

Active Converter

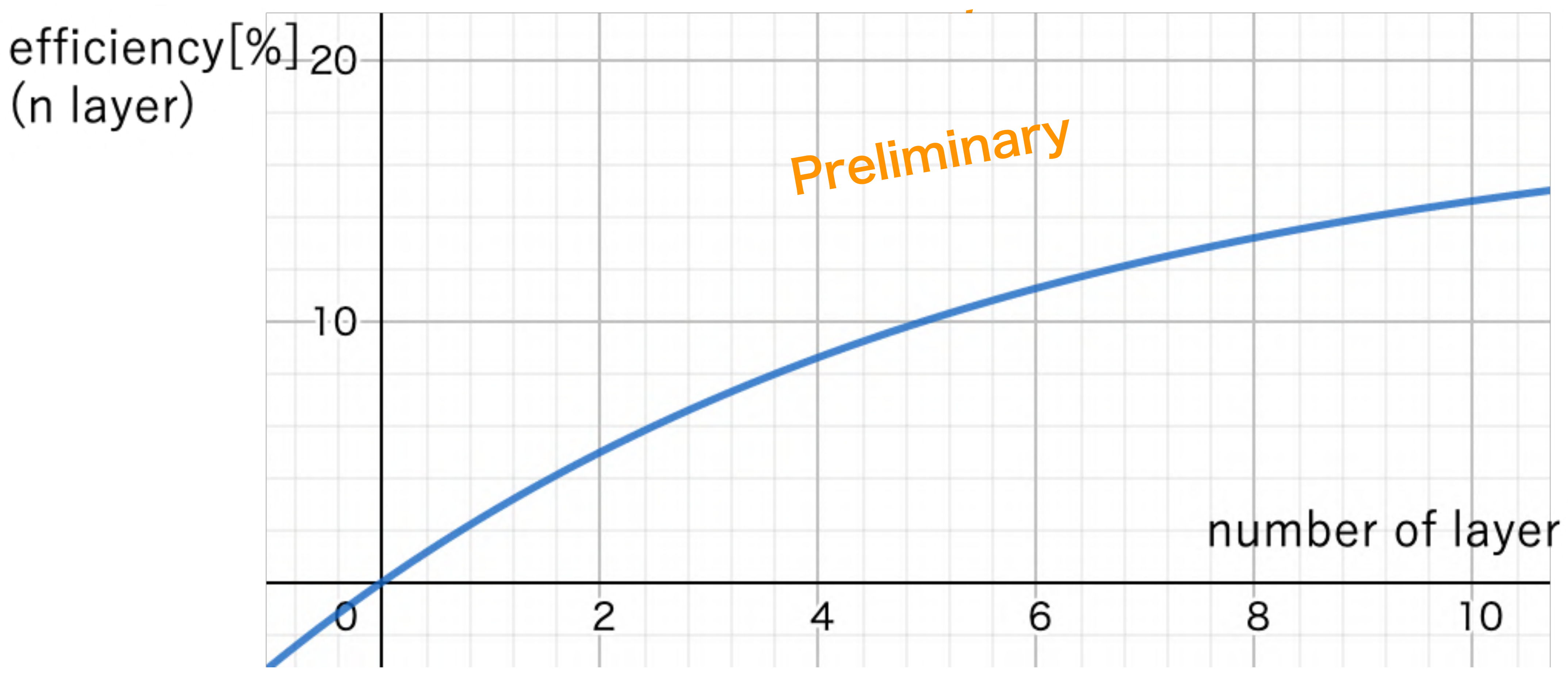
Simulation Study

- Segmentation
  - Segmentation to mitigate pileup by returning conversion pair
  - Optimisation of segmentation is in progress. Observed slight worsening of efficiency.





Segment size: $12.5 \times 25 \times 4\,\mathrm{mm}^3$



1 layer: efficiency = 2.7%
5 layer: efficiency = 10%
10 layer: efficiency = 15%

Active Converter

Energy Resolution

- Expected photoelectron statistics for LYSO + SiPM
  - Mean energy deposit for MIP (3mm-thick LYSO): 3.36MeV → 6.72MeV for conversion immediately after incidence
  - Light yield: 4×10^4 photons/MeV
  - 2200 p.e. measured with $30 \times 30 \times 4\,\mathrm{mm}^3$ and 2×SiPM (S13360-2050VE, $2 \times 2\,\mathrm{mm}^2$, $50\,\mu\mathrm{m}$)

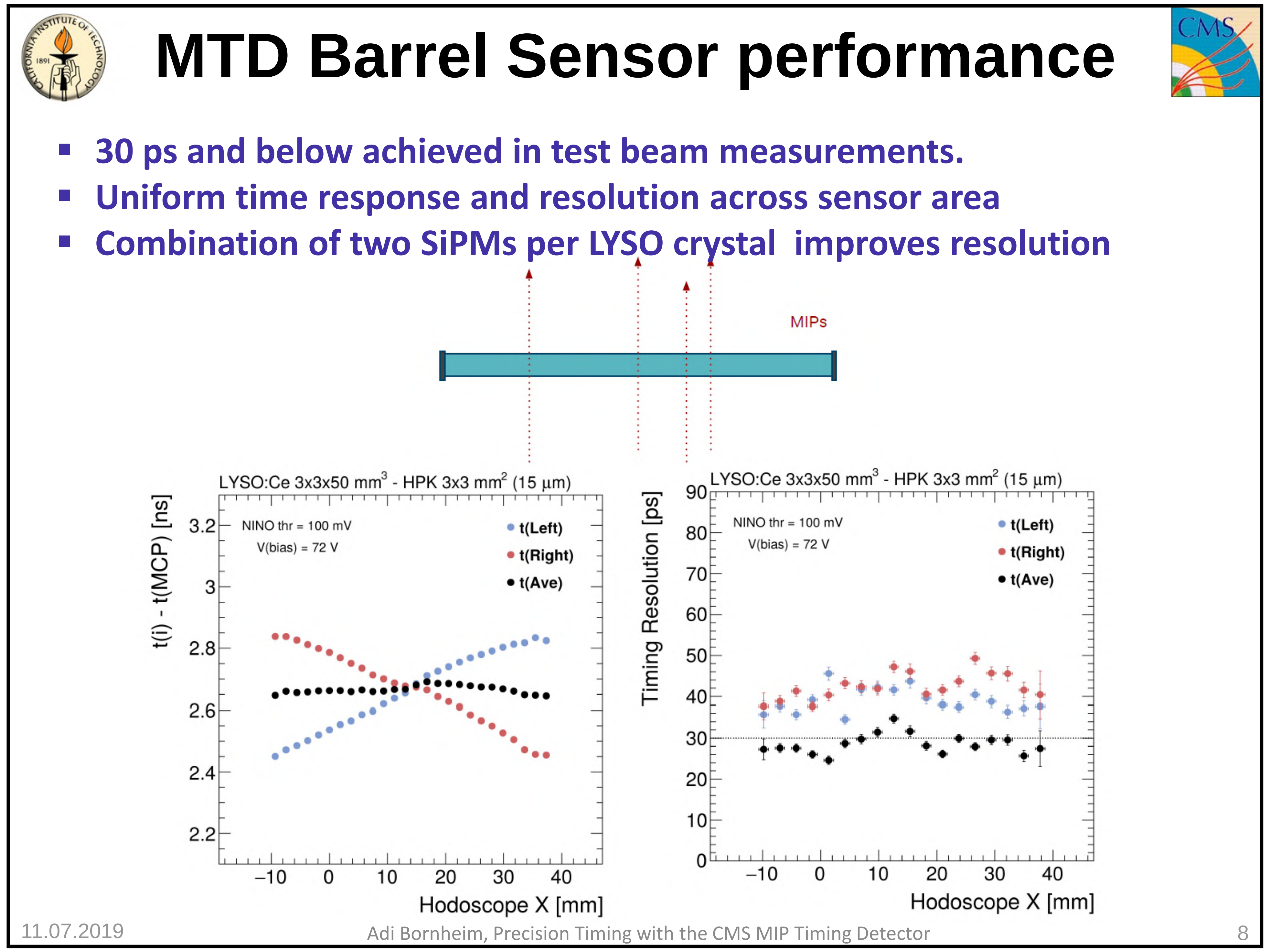
    $\Rightarrow \sigma_E \sim 140\,\mathrm{keV}$ (p.e. statistics)
  - Photoelectron statistics should be enough

- Other potential contributions to energy resolution
  - Position dependence of photoelectron yield → not very large (a few %). In any case, can be corrected with measured conversion position
  - dE/dx dependence of scintillation light yield → not very large

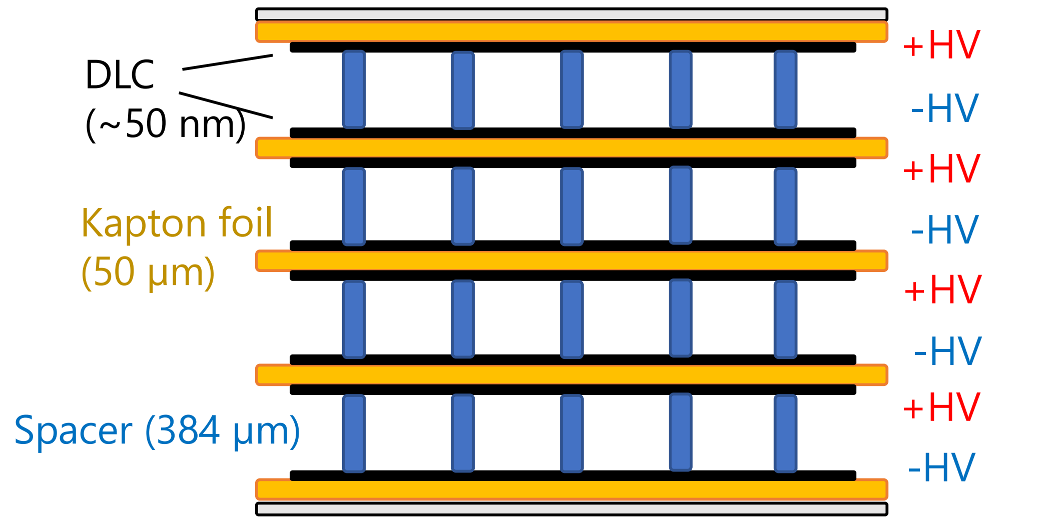
Timing Layer

Technology Options

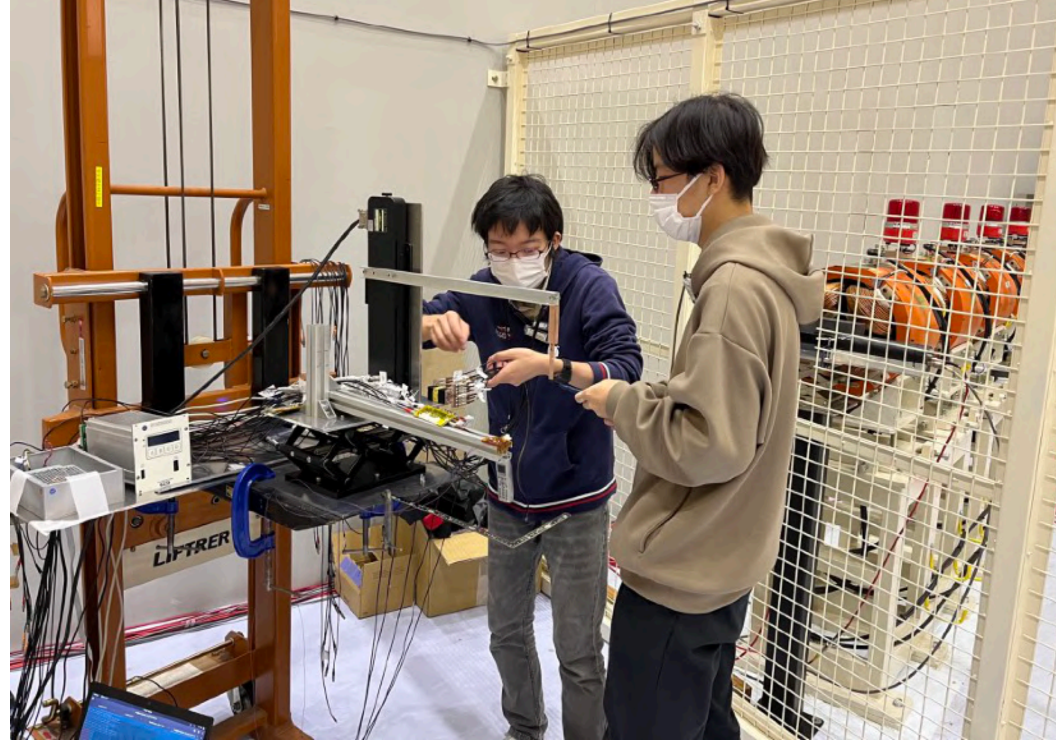
- Target resolution: 40ps for MIP (→ 30ps for conversion pair)
- Technology options
  - Converter = Timing layer
  - mRPC as timing layer
- LYSO converter as timing layer
  - CMS MIP Timing Detector HL-LHC: 30ps with LYSO bar ($3 \times 3 \times 50\,\mathrm{mm}^3$)
- multi-layer RPC (mRPC)
  - DLC-RPC technology developed for MEG II US-RDC
  - Single p.e time resolution of 110ps achieved for single layer RPC 194μm (not optimised for timing)
  - Optimisation for timing under study
    - Thinner gap
    - Higher efficiency and timing resolution with multi-layer



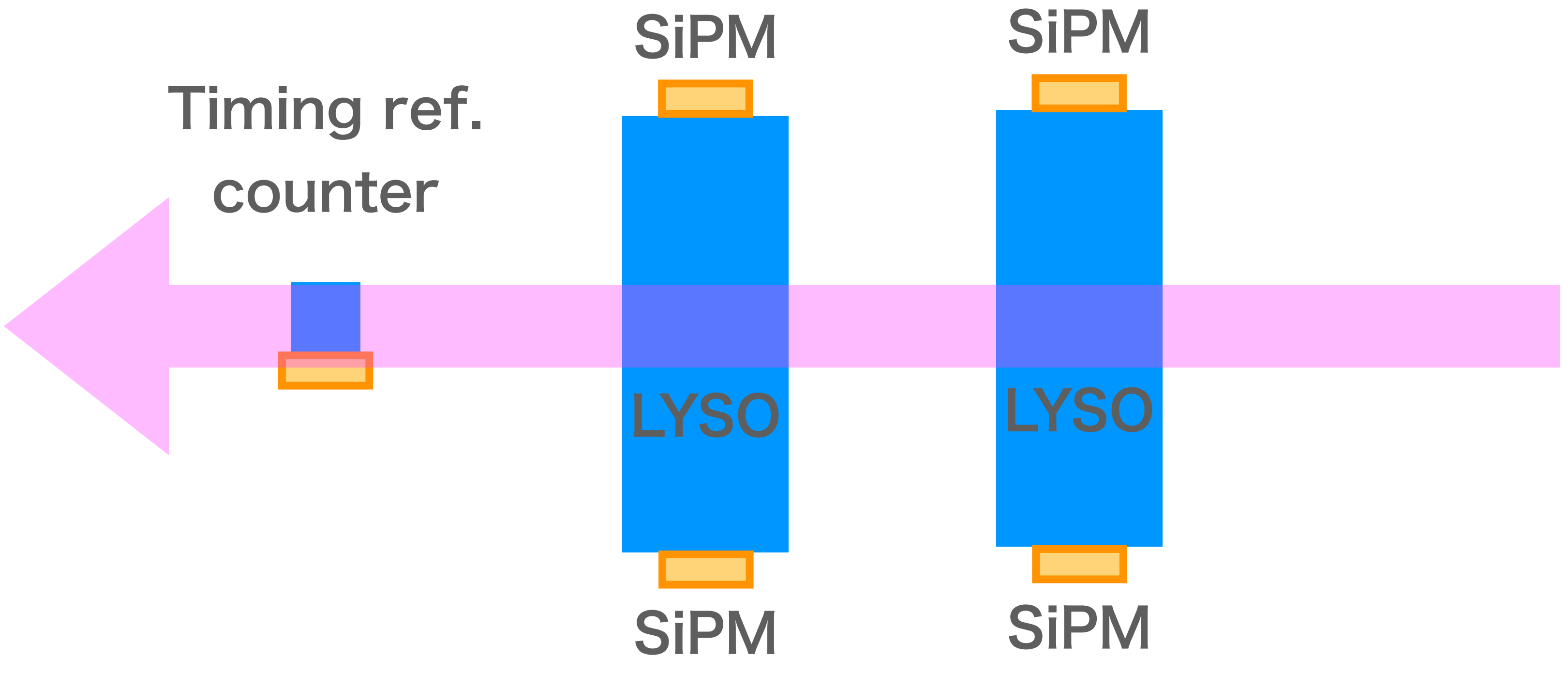
Multi-layer DLC-RPC (MEG II)

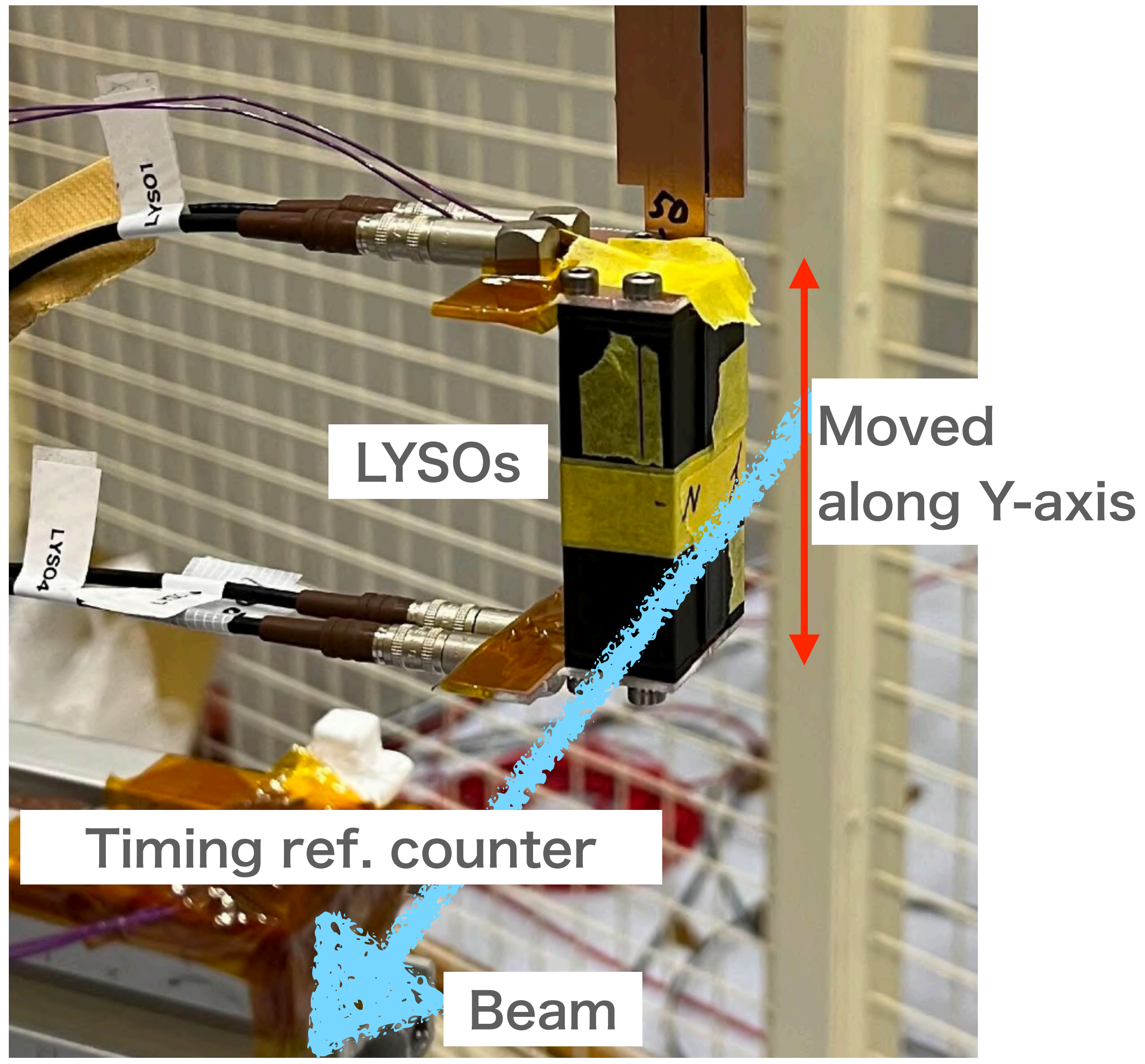


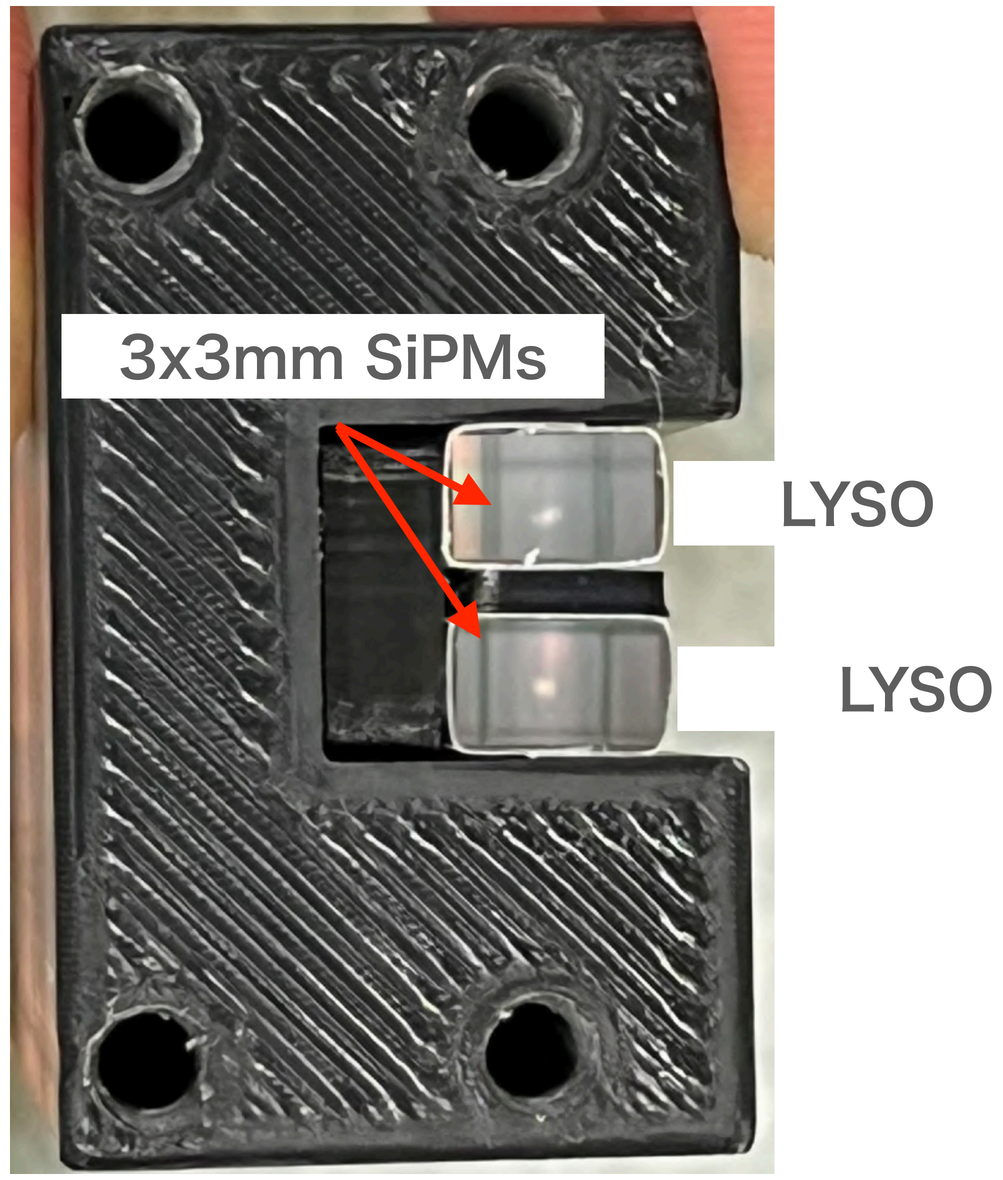
LYSO Beam Test

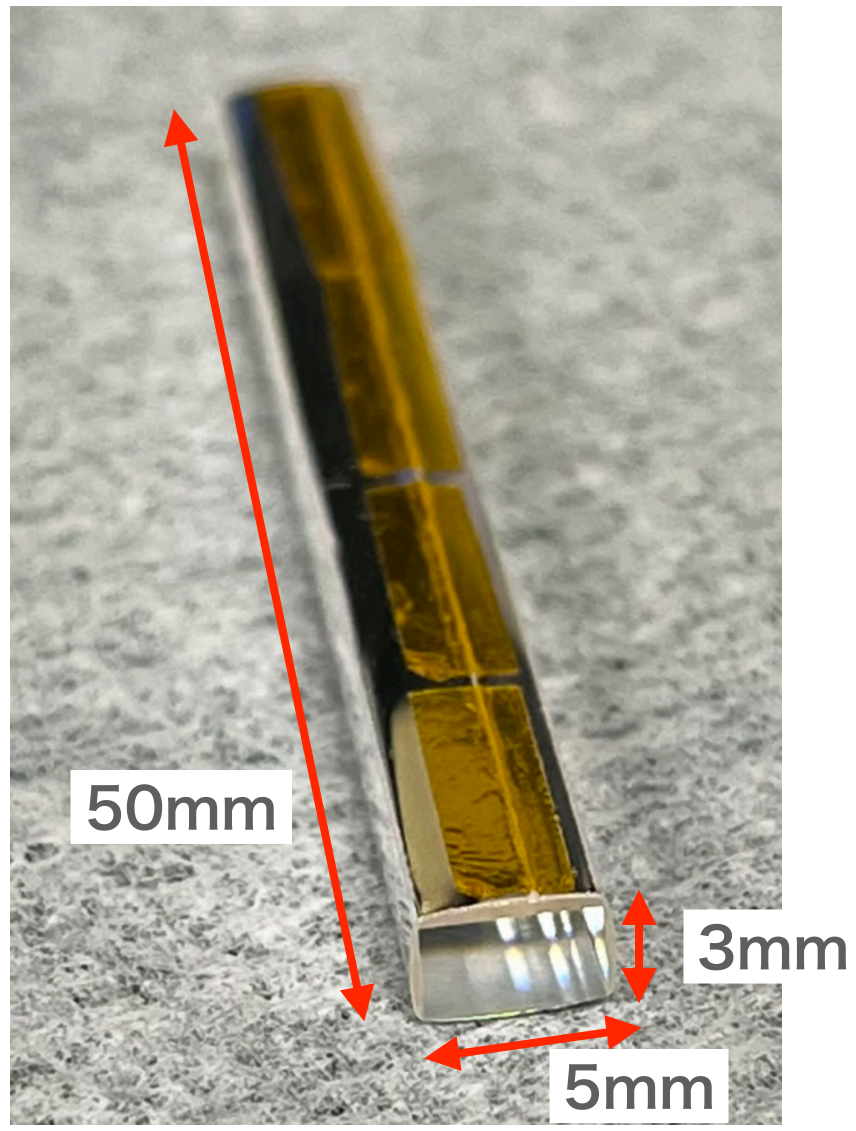


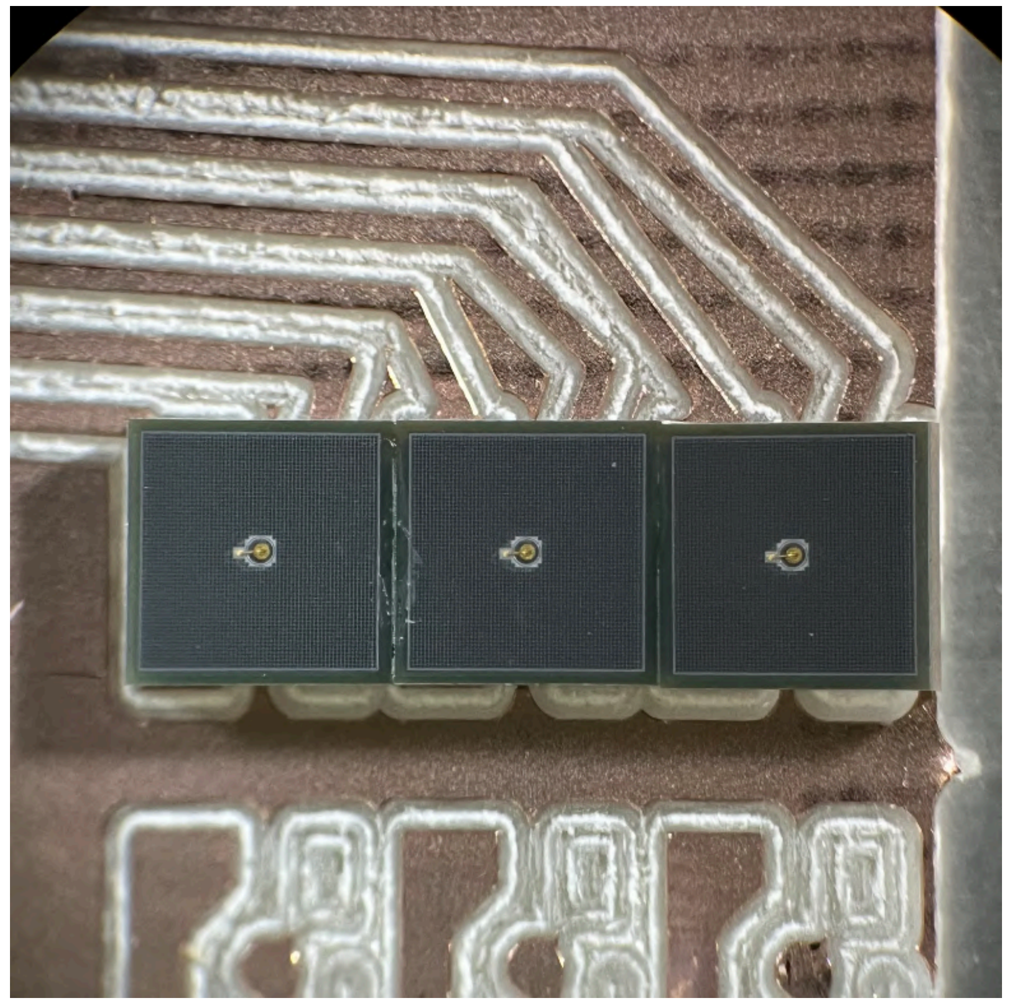
- Beam test @KEK PF-AR beam line, Nov. 16-21, 2022
  - Electron beam 0.5-5GeV
- Two types of LYSO
  - Standard LYSO, Fast LYSO (FTRL)
  - $3 \times 5 \times 50\,\mathrm{mm}^3$ wrapped with ESR
  - SiPM: S14160-3015PS ($3 \times 3\,\mathrm{mm}^2$, $15\,\mu\mathrm{m}$), S14160-3050HS ($3 \times 3\,\mathrm{mm}^2$, $50\,\mu\mathrm{m}$)
  - Waveform digitizer: DRS4 (1.6 GSPS)



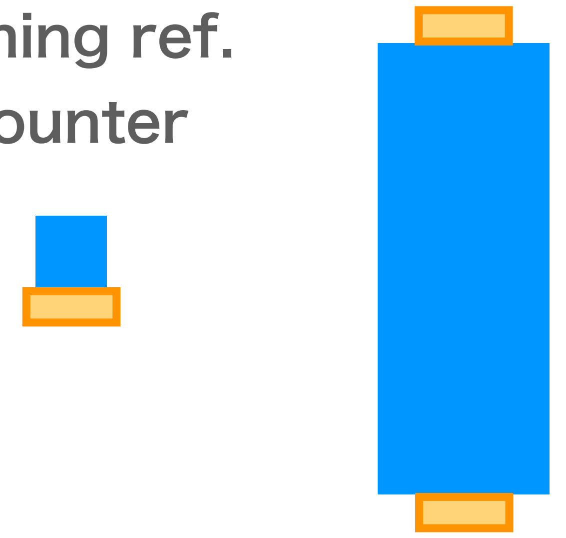




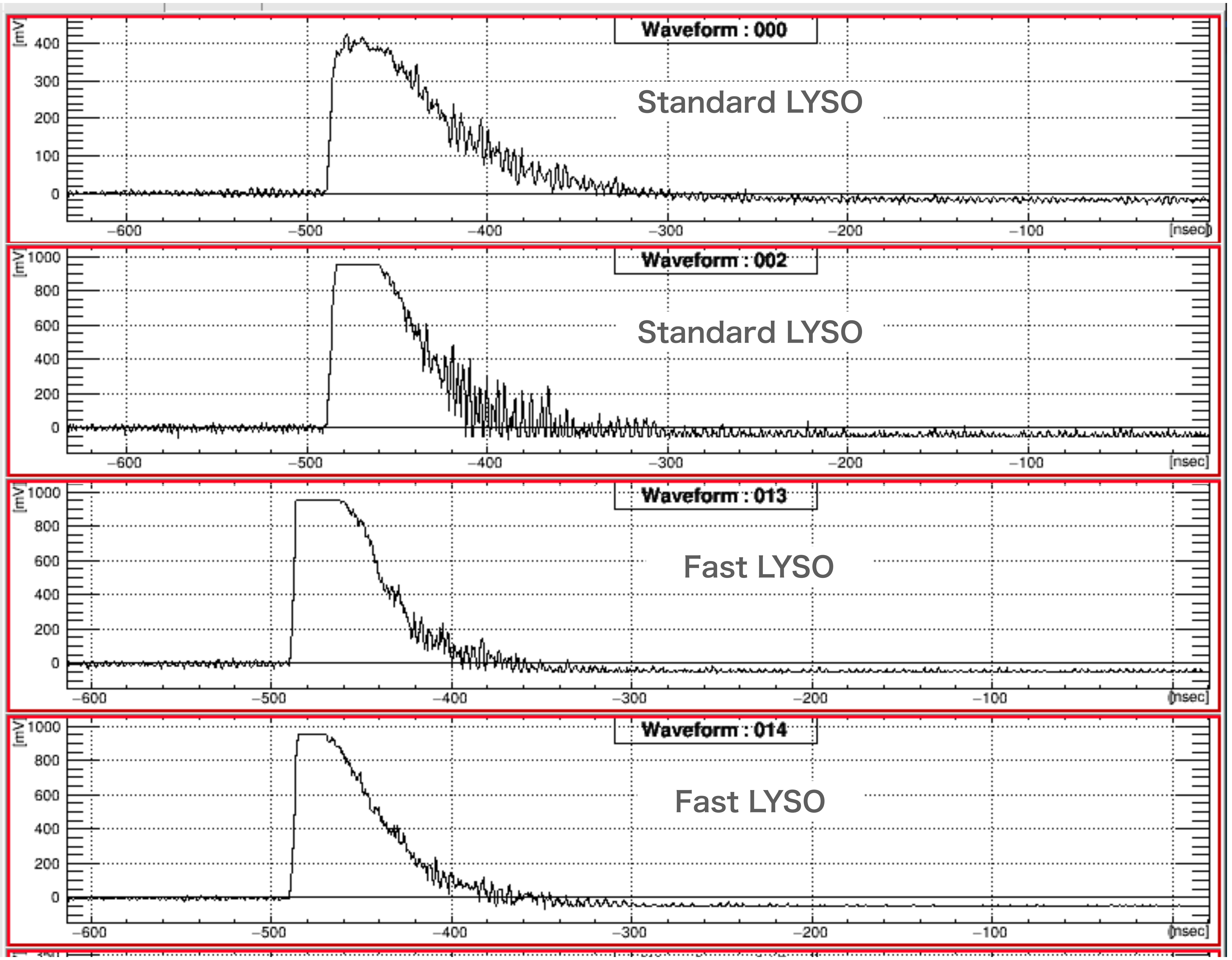




LYSO Beam Test



- Analysis
  - Time pickup @ leading edge
  - Time-walk correction by TOT
  - Time resolution is estimated in two methods
    - $\sigma(t_{\text{side a}} - t_{\text{side b}})/2$
    - $\sigma((t_{\text{side b}} + t_{\text{side b}})/2 - t_{\text{timing ref. counter}})$
  - **Good timing resolution of** $40 - 50\,\text{ps}$ **for fast LYSO**



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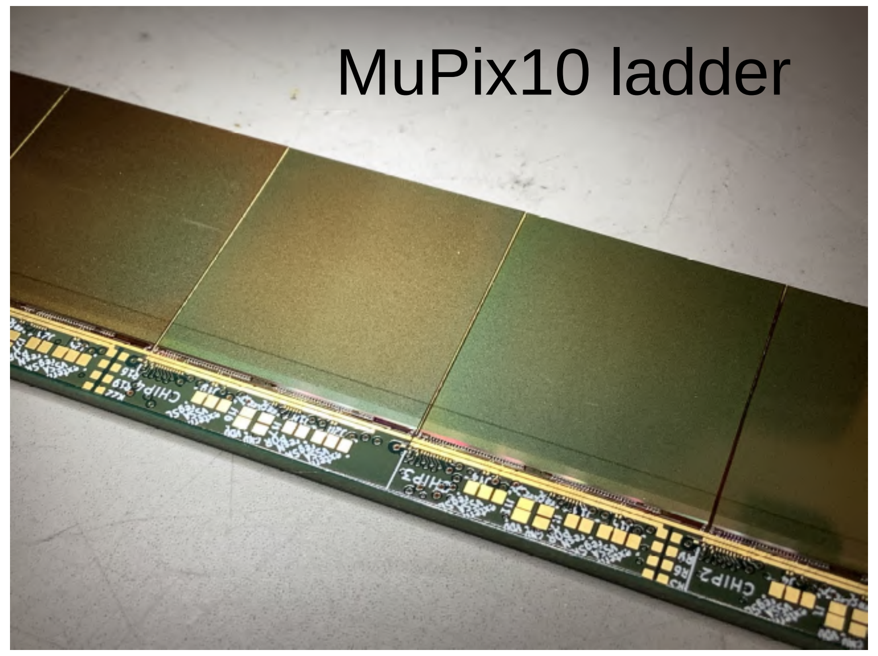
HV-MAPS for Mu3e

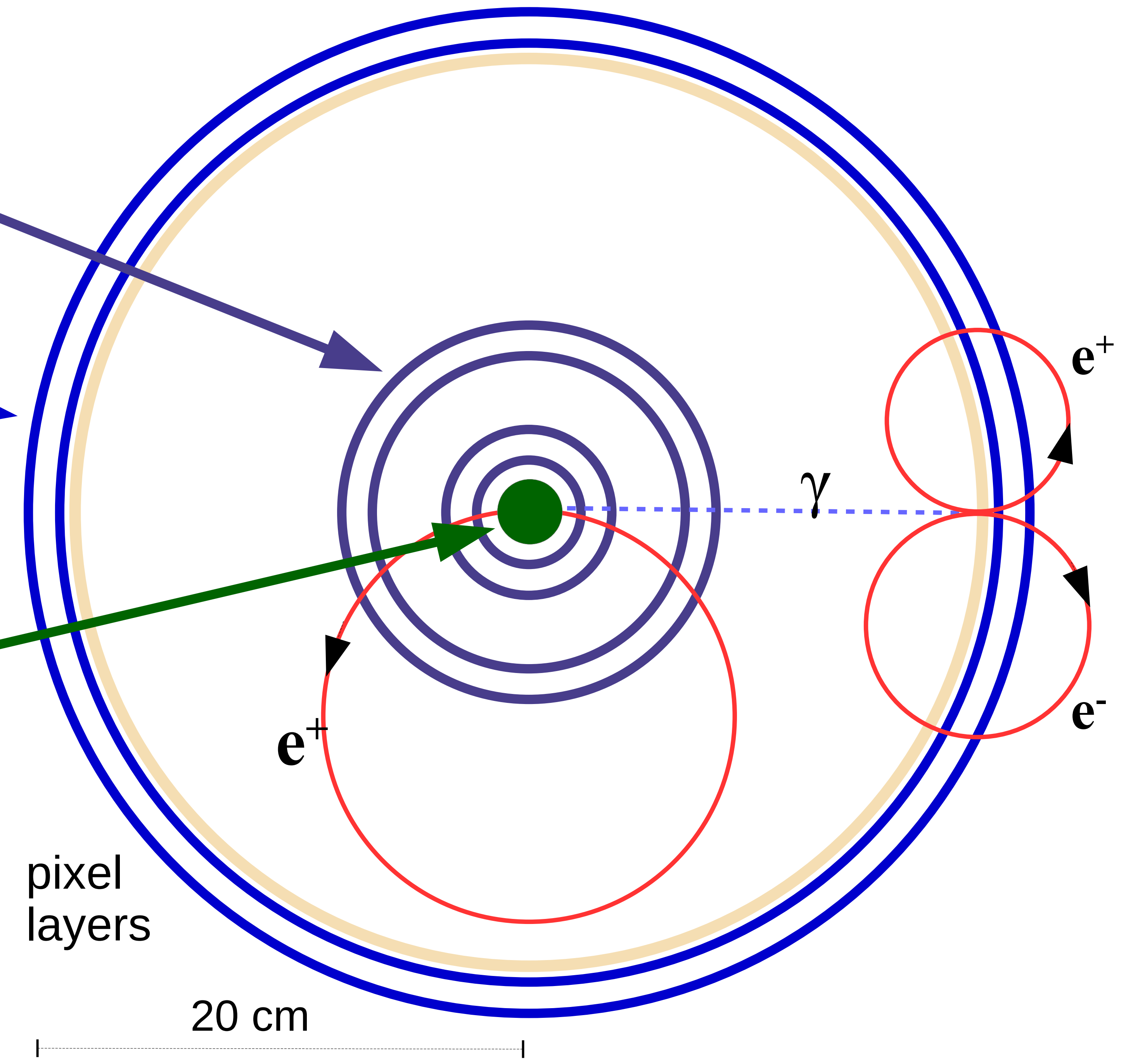


All Silicon $\mu \to e\gamma$ Detector

$$\frac{N_{acc}}{N_{sig}} \stackrel{\text{def}}{=} B_{acc} \propto R_\mu \, \sigma(p_e) \, \sigma(E_\gamma)^2 \, \sigma(\Theta_{e\gamma})^2$$

TIME RESOLUTION
IS HERE IGNORED

- **Positron Tracker (incl. Vertex Detector)**
  - **high rate tolerance (+++)**
  - **good vertex resolution (+++)**
- **Converted Photon Tracker**
  - **high spatial resolution (+++)**
  - **good directional resolution (+++)**
  - **low efficiency (---)**
- **Active Muon Stopping Target**
  - **precise decay vertex (+++)**
  - **technologically challenging (---)**



→ high resolution allows for high muon-stopping rates (R_μ) → high single event sensitivity (SES)

A. Schöning, Heidelberg 4 HiMB Workshop, 7.April 2021

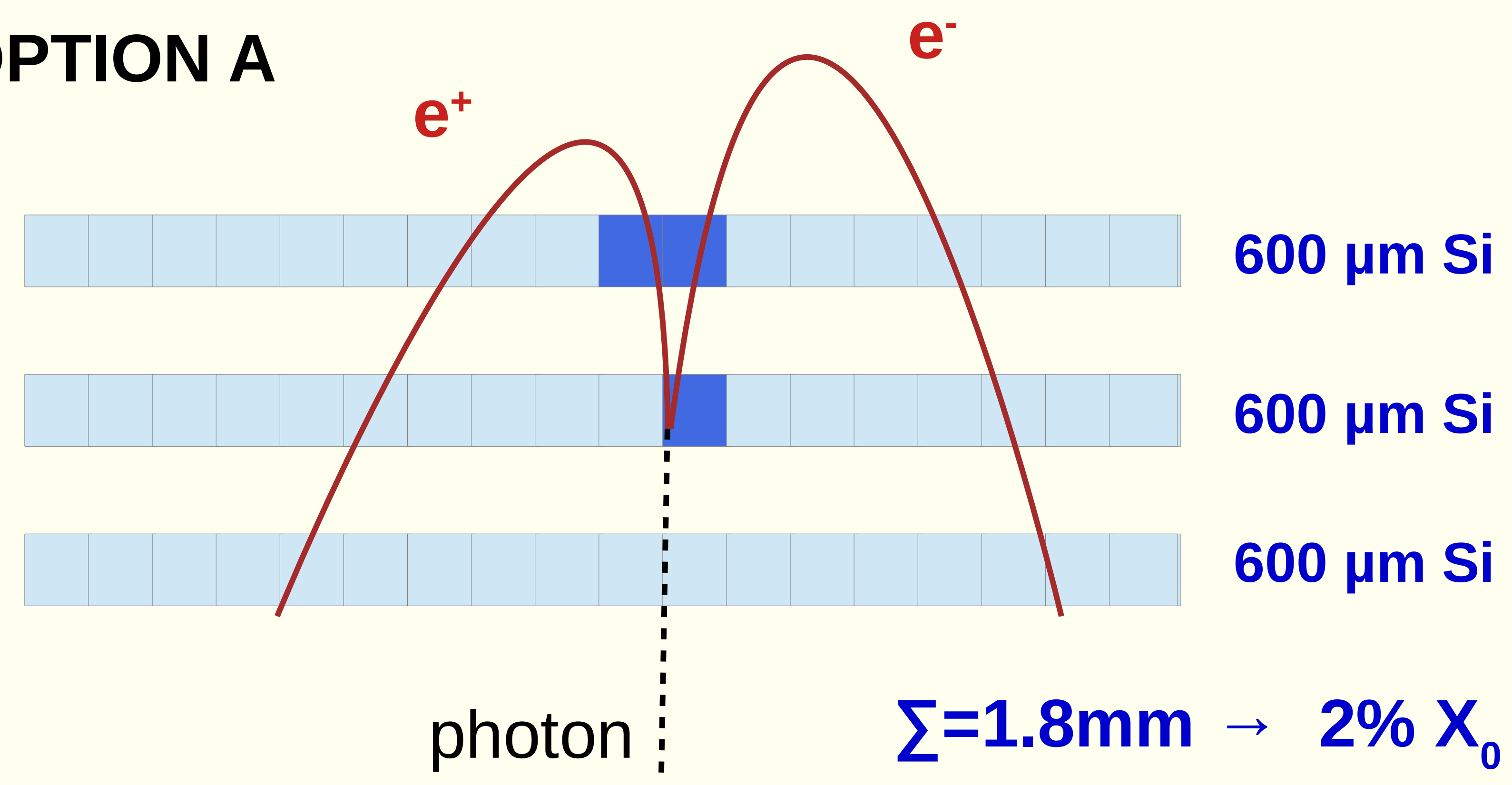
All Silicon $\mu \rightarrow e\gamma$ Detector

Active Converter

Idea: Active Converter

- critical energy is E_{crit} ~ 35 MeV in silicon
- average e^+/e^- energy is 25 MeV
- ionisation loss dominates → can be measured

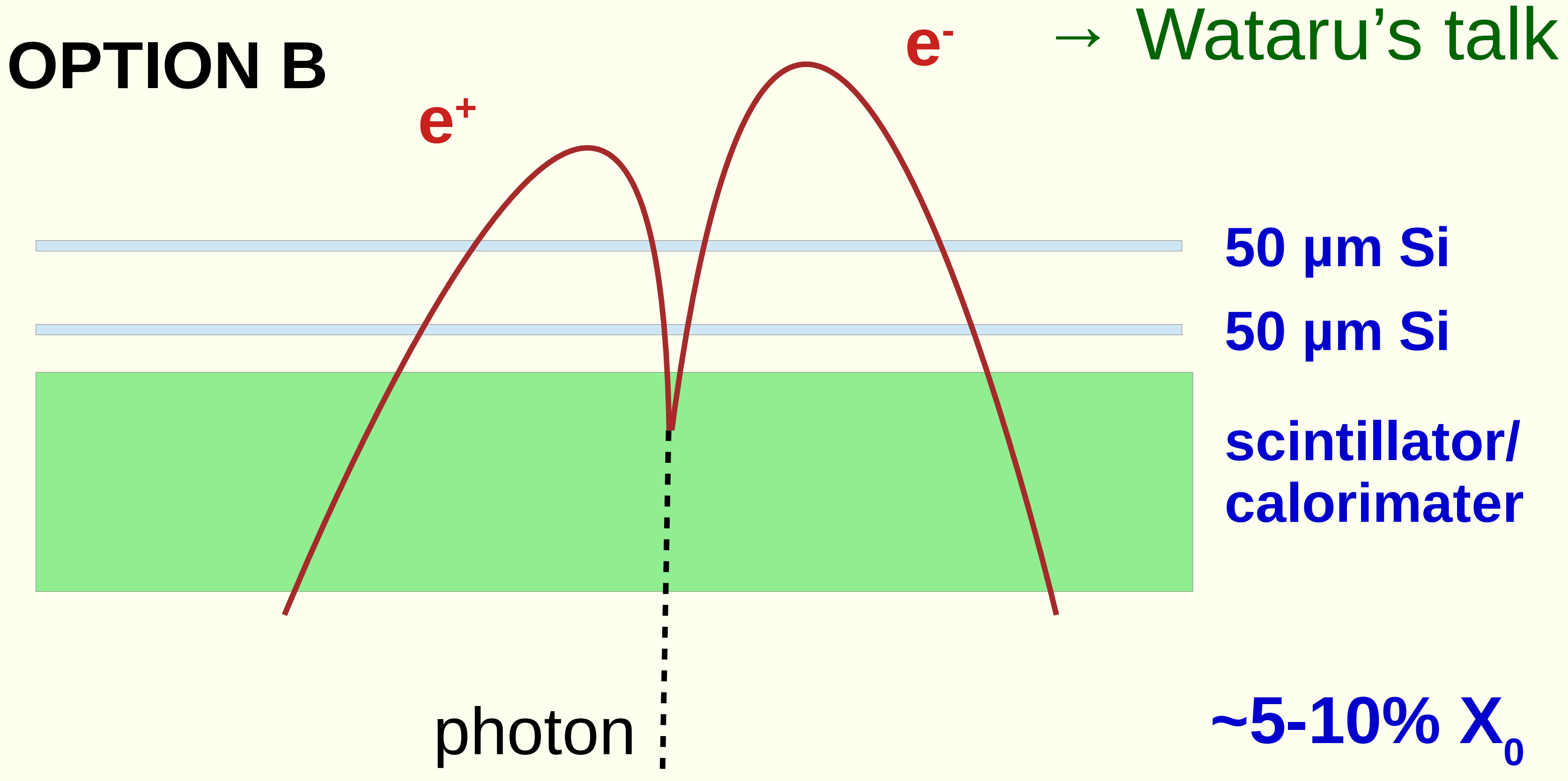
OPTION A



- Measure energy loss and conversion point in **Si**
- Could also be used for precise timing → **<100ps?**
- Caveat: only small radiation length possible
  → to be simulated

OPTION B

→ Wataru's talk

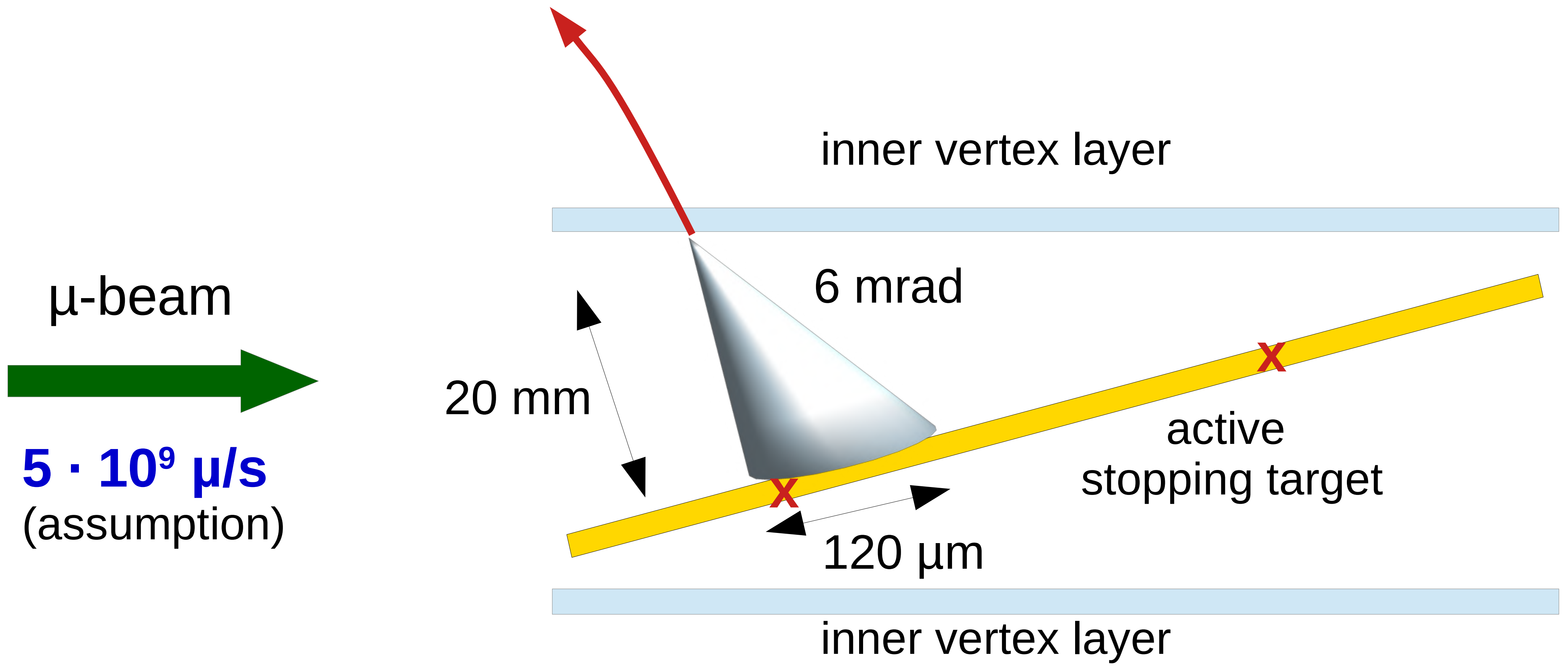


- Measure energy loss in thick **scintillator**
- good timing possible **<100ps**
- Caveat: need to be segmented (curling tracks)
- possible at all?

A. Schöning, Heidelberg 18 HiMB Workshop, 7.April 2021

All Silicon $\mu \to e\gamma$ Detector

Active Target



for 50 µm Si-layer → **Θ_{MS} = 6 mrad**

Idea:
measure vertex position more precisely

- vertex position uncertainty from extrapolation: **~120 µm** (6 mrad x 20 mm)
- best achievable spatial resolution in stopping target: **~12 µm**
  - resulting photon direction resolution: → **Θ(γ) ~0 mrad**
  - electron direction resolution given by multiple scattering in stopping target: → **Θ(e) ~3 mrad** (for 30 µm silicon thickness)

Conclusion: only 30 µm thin stopping target makes sense, since gain would be marginal otherwise!

Contents

Gaseous Positron Trackers toward 10^9 - 10^{10} μ/s

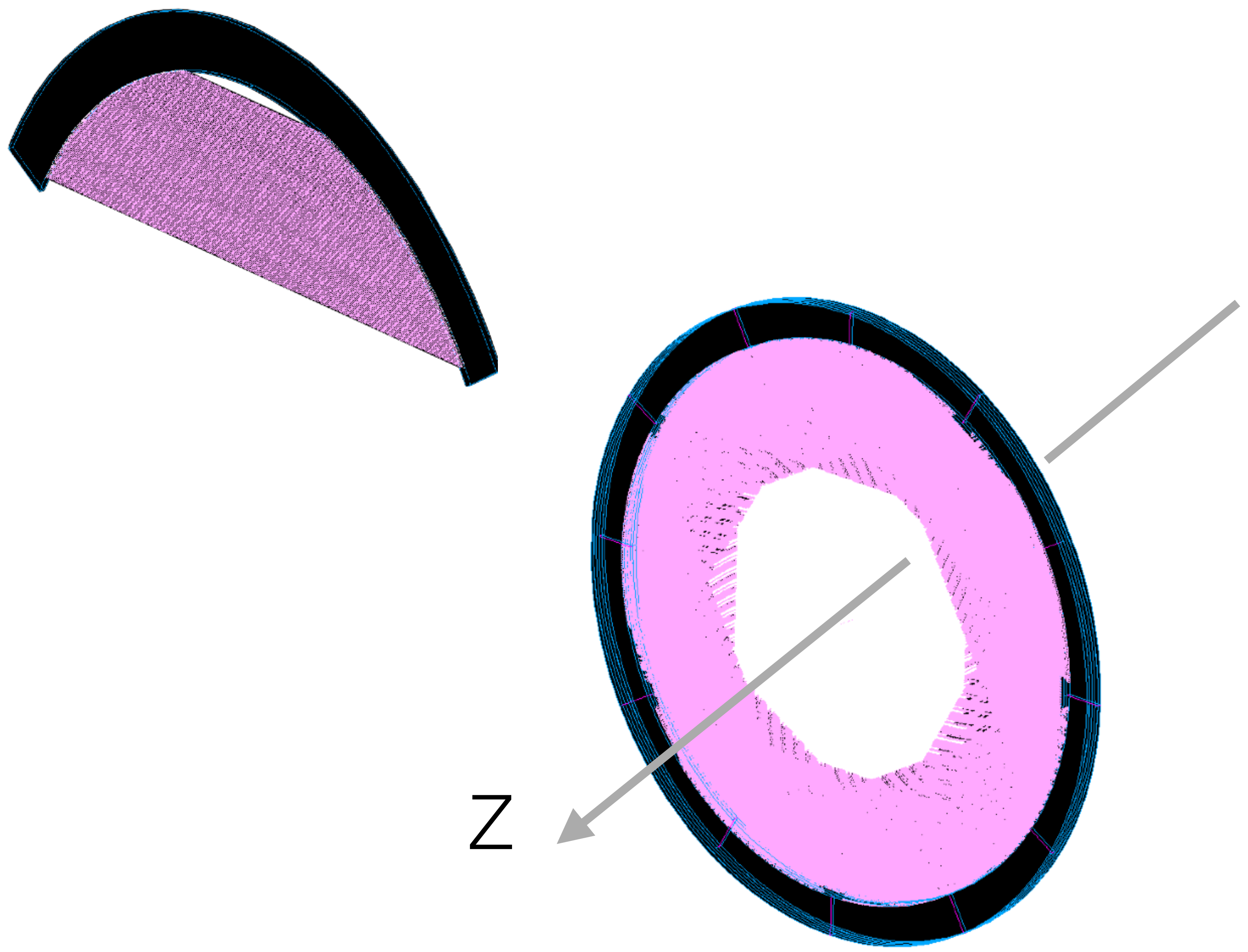
- Some improvement in the resolution could come from the cluster counting technique (not a huge factor), then we are at the ultimate performances for drift chambers

- Future R&D should aim to:

  - preserve such good resolutions
  - keep the same (or reduce the) material budget
  - **operate at extremely high rates**

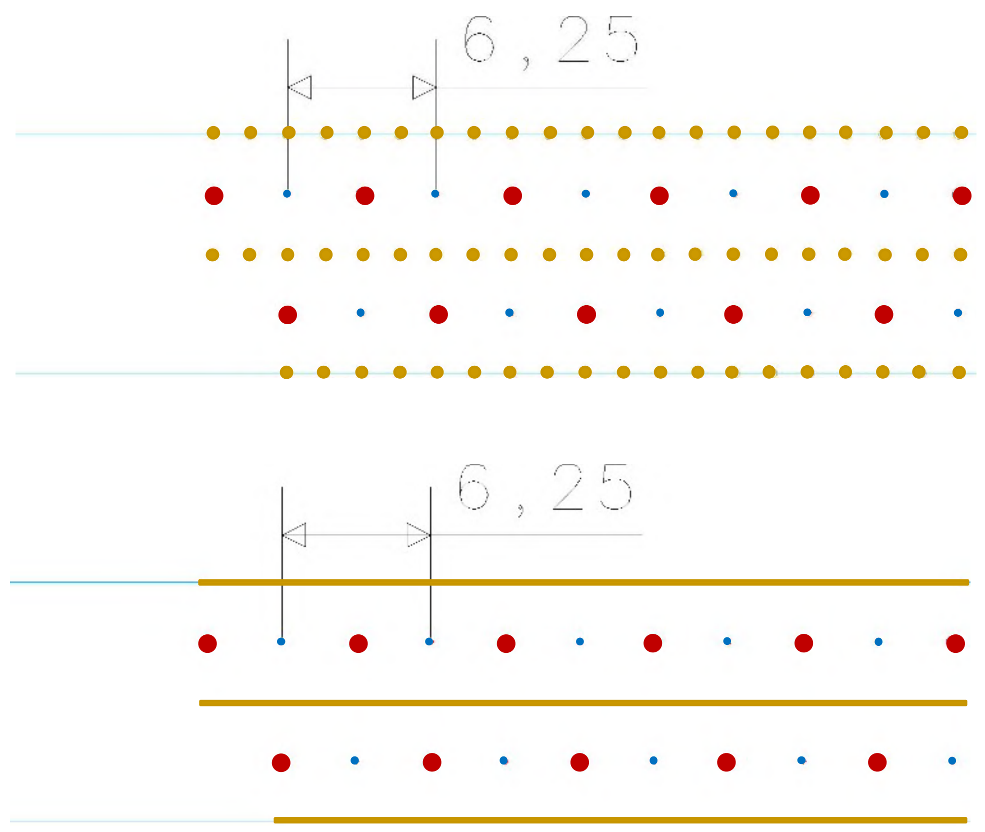
Drift Chamber

- The rate per wire can be reduced with an alternative arrangement of the wires
- Transverse wires (in the xy plane):
  - inspired to the geometry of the Mu2e tracker
  - more, shorter wires -> lower rate per wire
- Same rate per wire as MEG II with ≳ 10 times larger muon rate



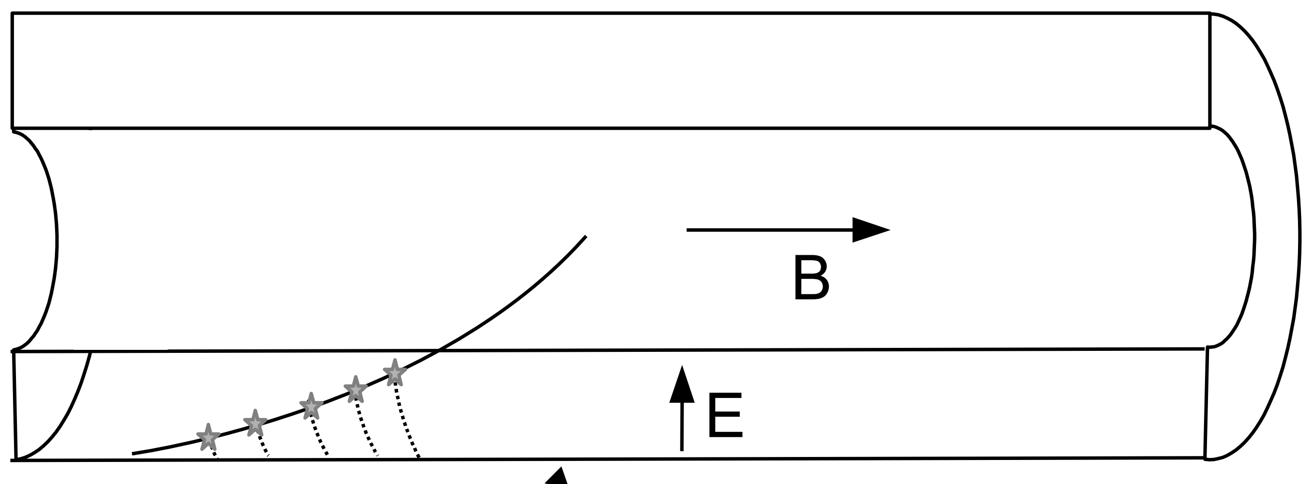
The main challenge is the material budget

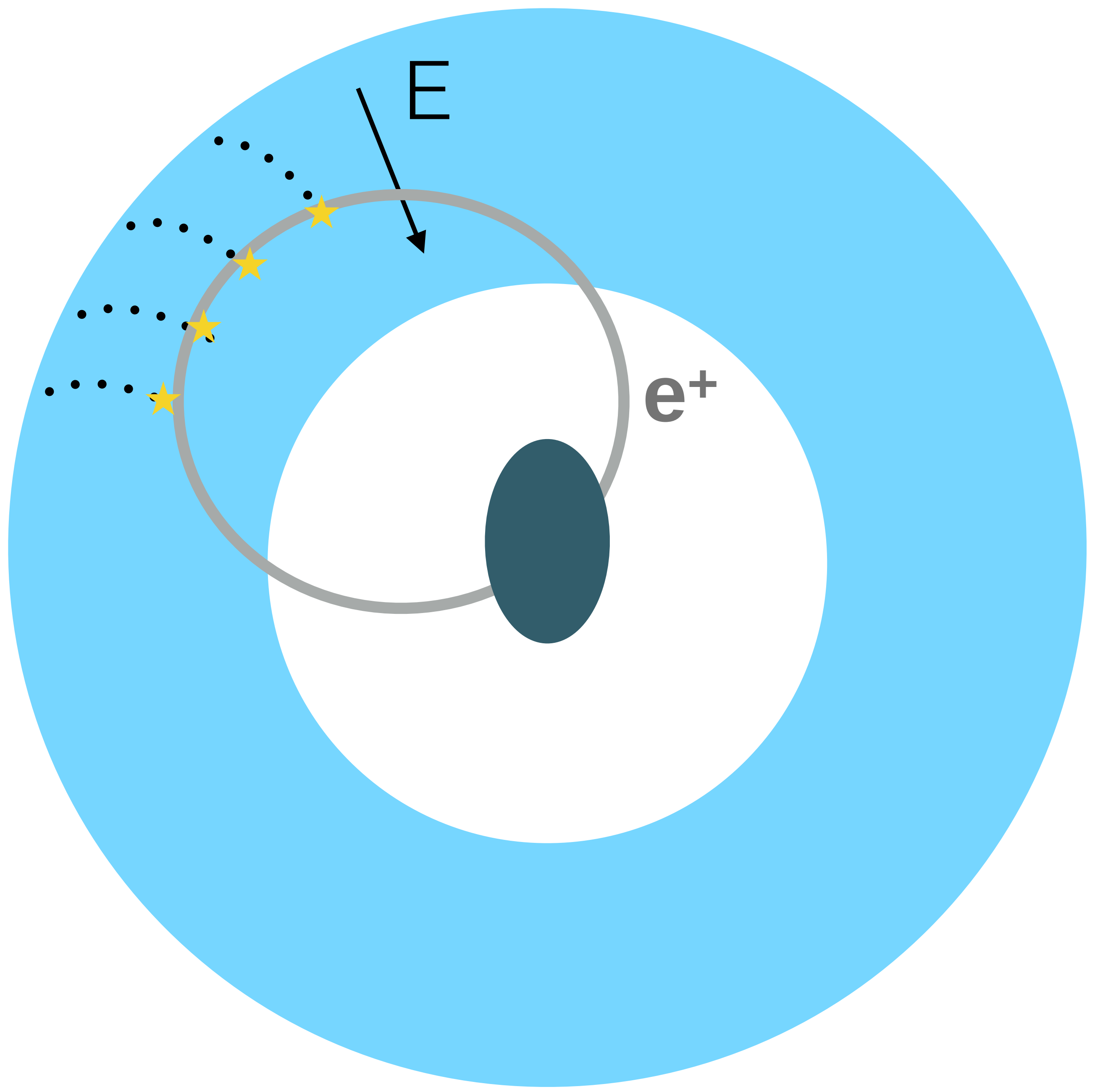
- very light wire supports
- no electronics in the tracking volume —> long transmission lines



Radial Time Projection Chamber

- Unconventional radial geometry to mitigate effects related to long drifts (diffusion, space charge)
  - radial extension O(10 cm):





Need to develop a radial TPC with cylindrical MPGD readout, ~ 2 m long and ~ 30 cm radius

Need to find a very light gas mixture to operate it with reasonably low diffusion

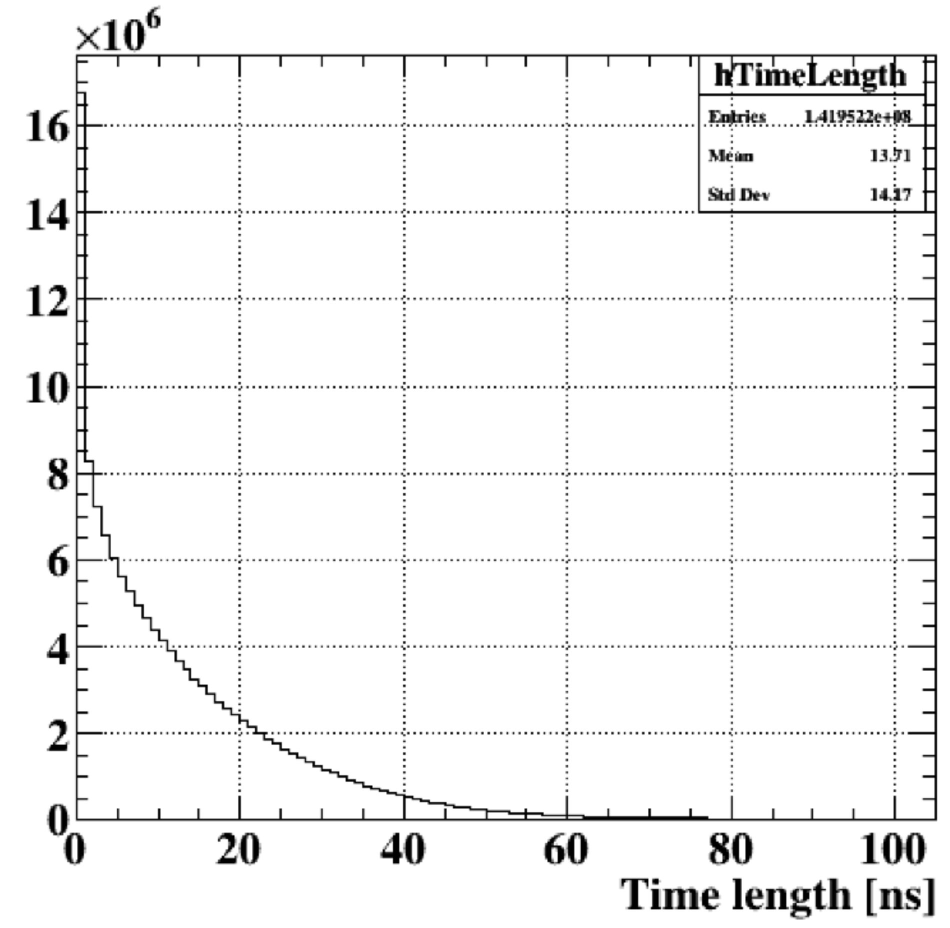
Need to develop advanced algorithms for correcting field deformations

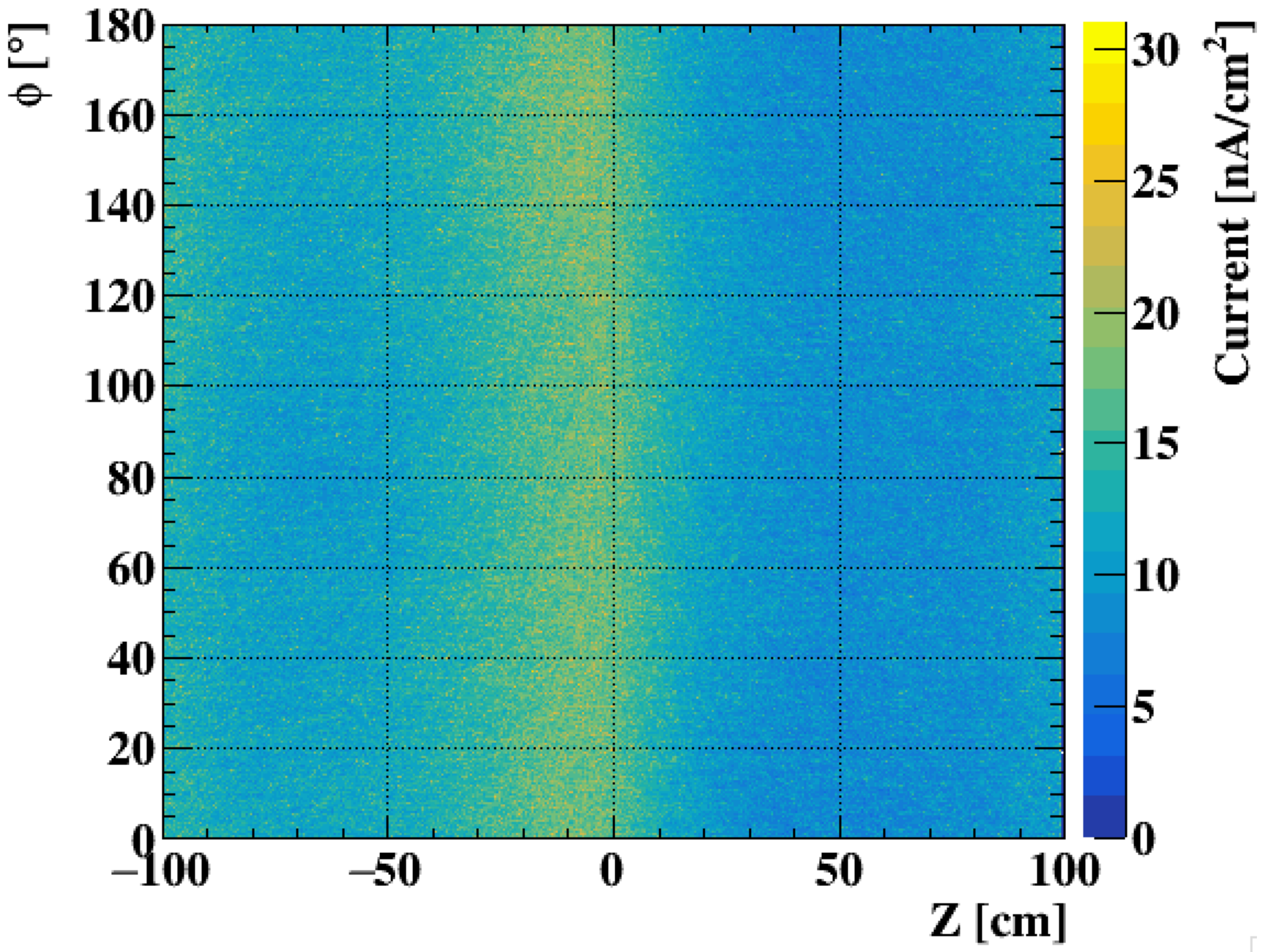
Radial Time Projection Chamber

Feasibility Study

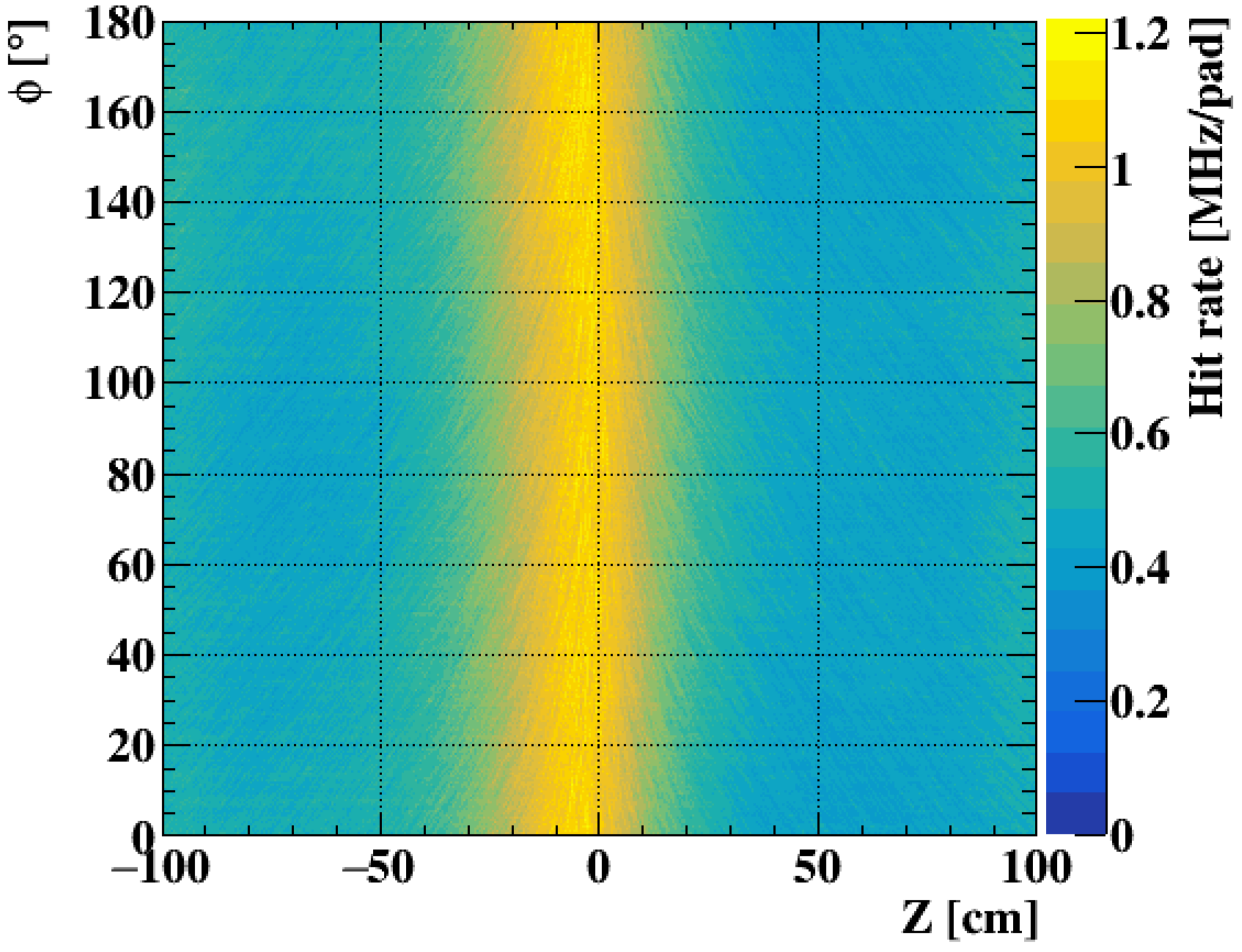
- Simulation at 10^9 μ/s
- One should consider ~ 250k readout channels
  - challenging **FE integration** and **cooling** in the outer surface of the cylinder with a reasonable material budget (~ few % X_0)

Time spread of electrons arriving to the same pad





cfr. ALICE GEM-TPC ~ 10 nA/cm²

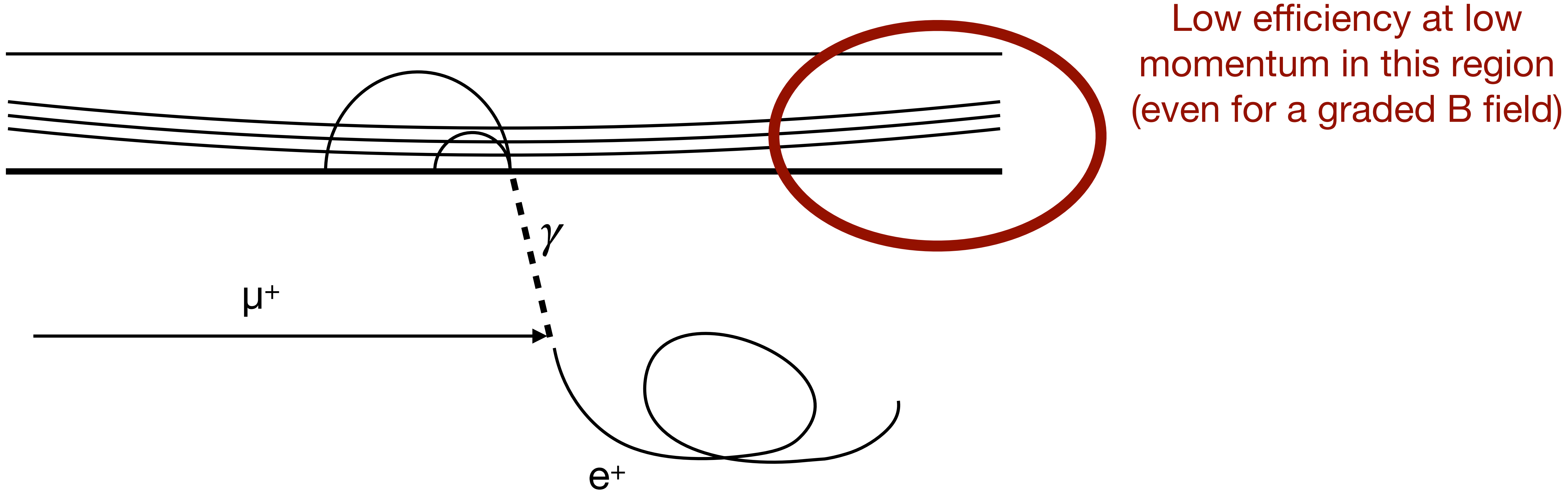


Assuming 5 x 3 mm² pads

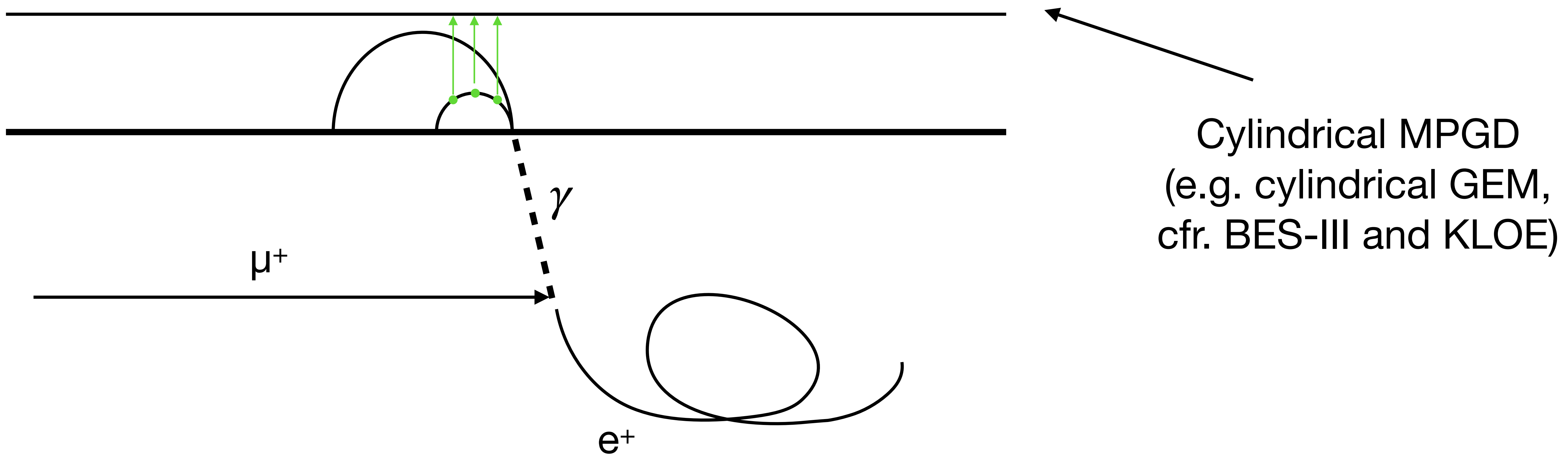
Gaseous Conversion Pair Tracker

- Low rate —> much less demanding w.r.t. positron trackers

Wire chamber



Radial TPC



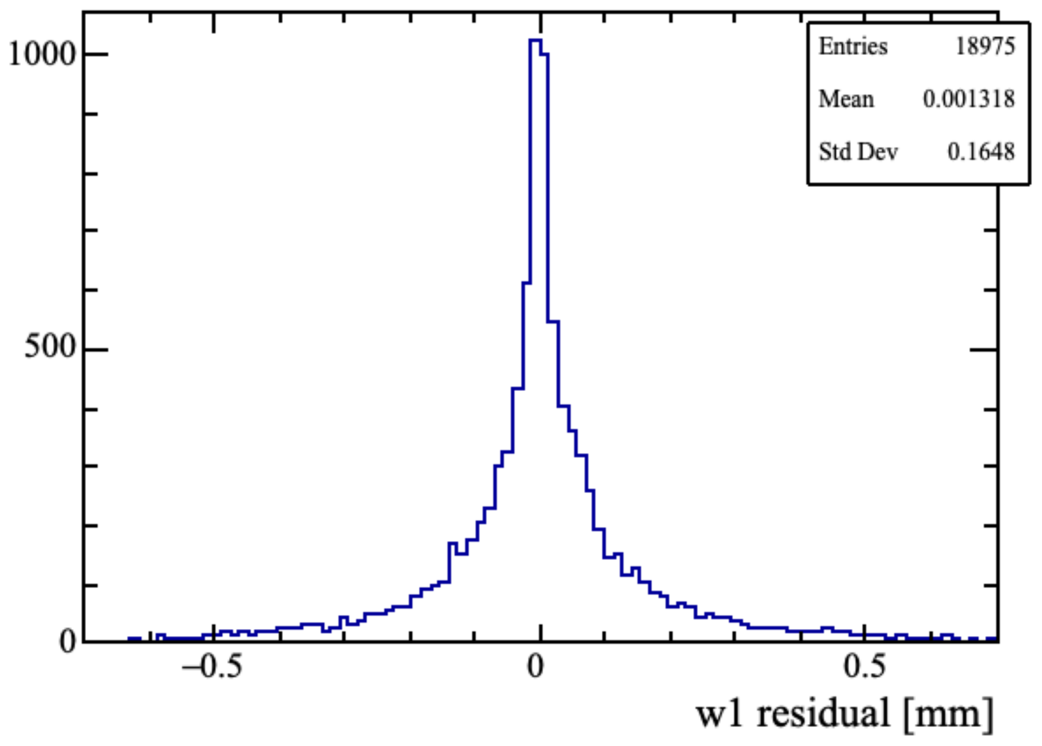
Gaseous Conversion Pair Tracker

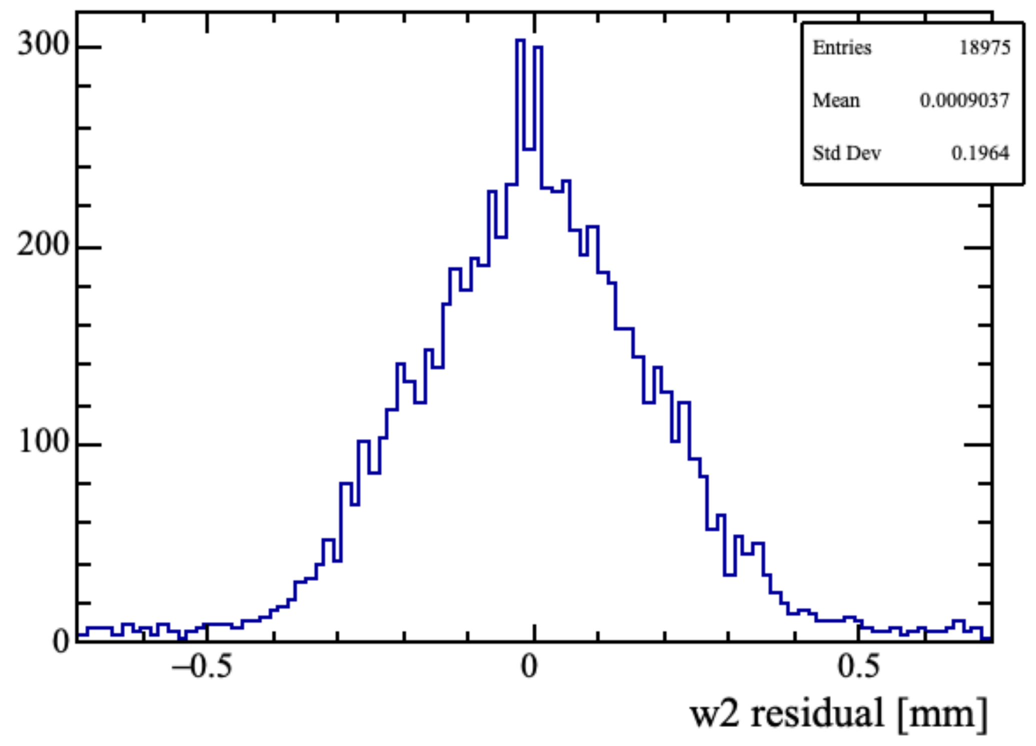
Feasibility Study

Resolutions are evaluated in two coordinates (w1, w2)
in a virtual plane orthogonal to the track,
with w2 almost parallel to z

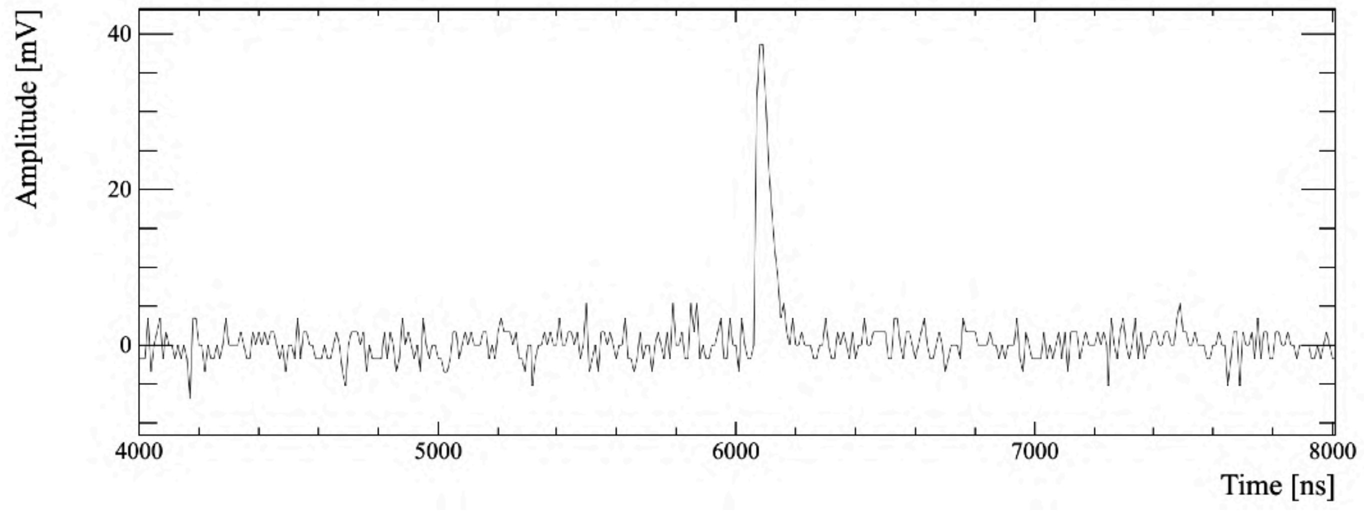
e+e- reconstruction in a radial TPC with strip readout

WORK IN PROGRESS

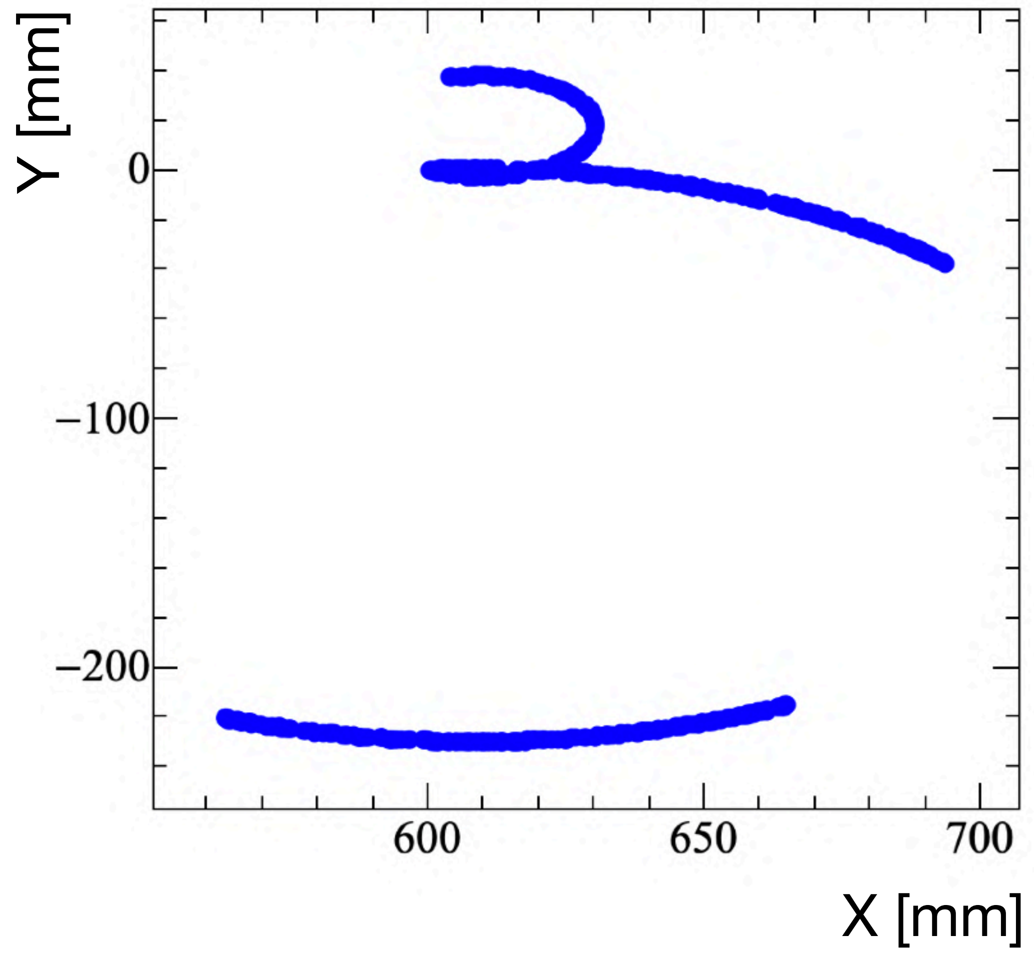




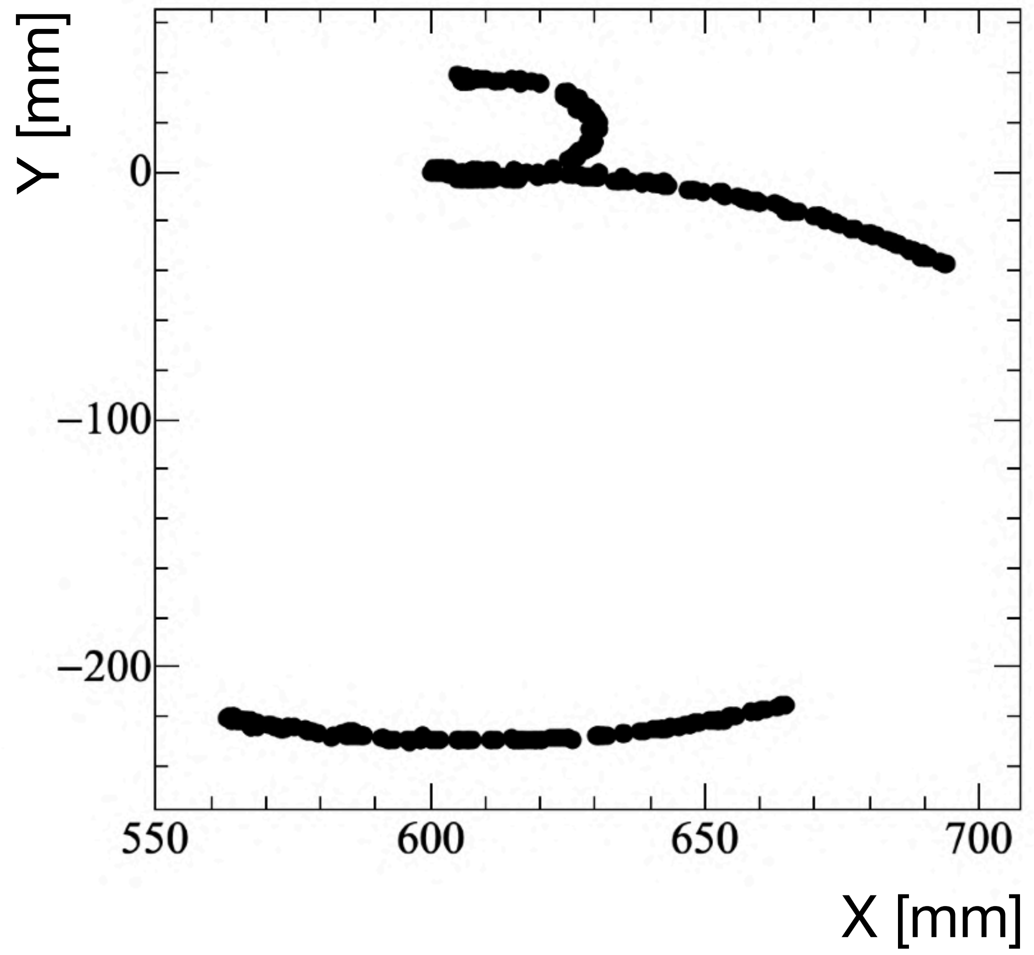
Typical waveform



True tracks



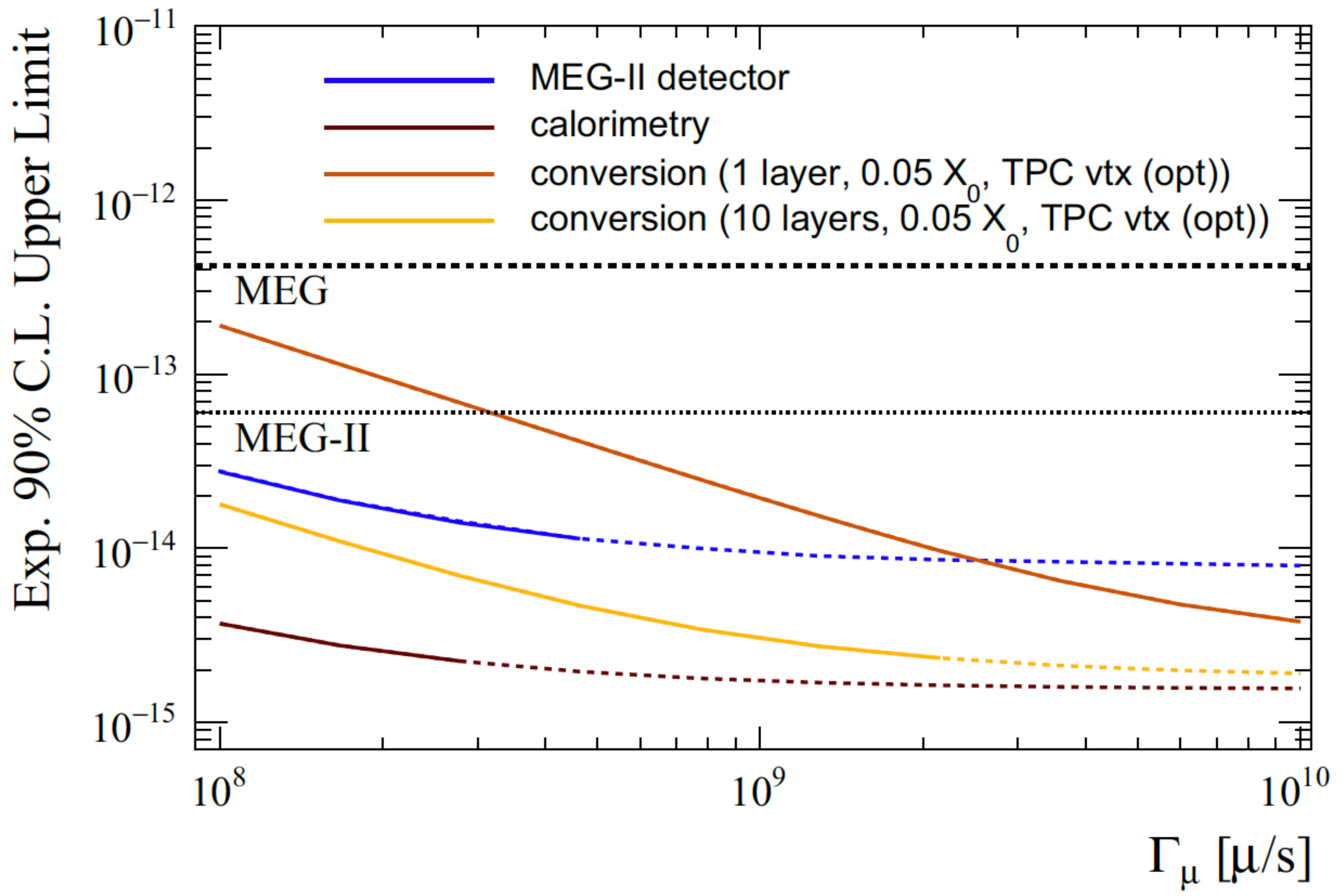
Reco track
(time resolved CoG)



Contents

Calorimeter for Photon Detector

- Based on the current technology development the calorimetry is still an option for beam rate not higher than 5 10^8 mu/s



Calorimetry("MEG" approach):

E_γ : 0.8%

t_γ = 30 ps

X_γ ~ O(3-5) mm

ε_{det} : 60%

Acceptance : 70%

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- Comparison with other scintillators via the figure of merite F.o.M. = $\sqrt{\left(\frac{\rho \cdot LY}{\tau}\right)}$

Scintillator	Density ρ [g/cm³]	Light Yield LY [ph/keV]	Decay time τ [ns]	F.o.M. $\sqrt{(\rho \times LY / \tau)}$
LaBr3(:Ce)	5.08	63	16	4.55
LYSO	7.1	27	41	2.17
YAP	5.35	22	26	2.13
LXe	2.89	40	45	1.61
NaI(Tl)	3.67	38	250	0.75
BGO	7.13	9	300	0.46

Calorimeter for Photon Detector

- **Goal: Detect photons with energy O(50) MeV with ultra-precise time resolution and supreme energy resolution at the Intensity Frontiers**
- LYSO or LaBr(Ce) big crystals
- Photosensor: MPPC/SiPM for a front and back readout
- Use granularity for geometrical reconstruction
- MC simulations based on GEANT4 and including the photosensors and the electronics. Reconstruction algorithm based on waveform analysis

The first large prototype is under construction (D = 7 cm and L = 16 cm)

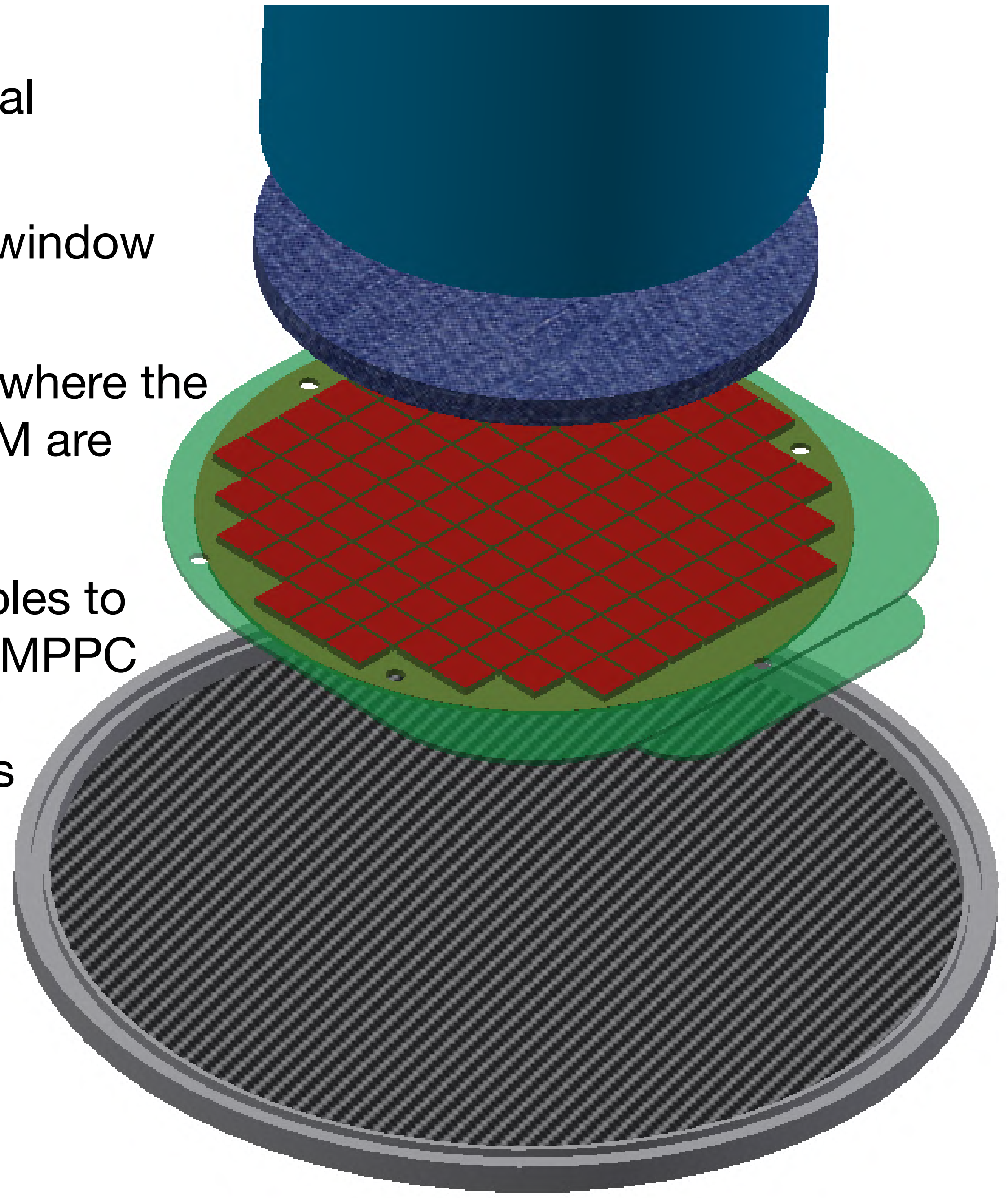
LYSO crystal

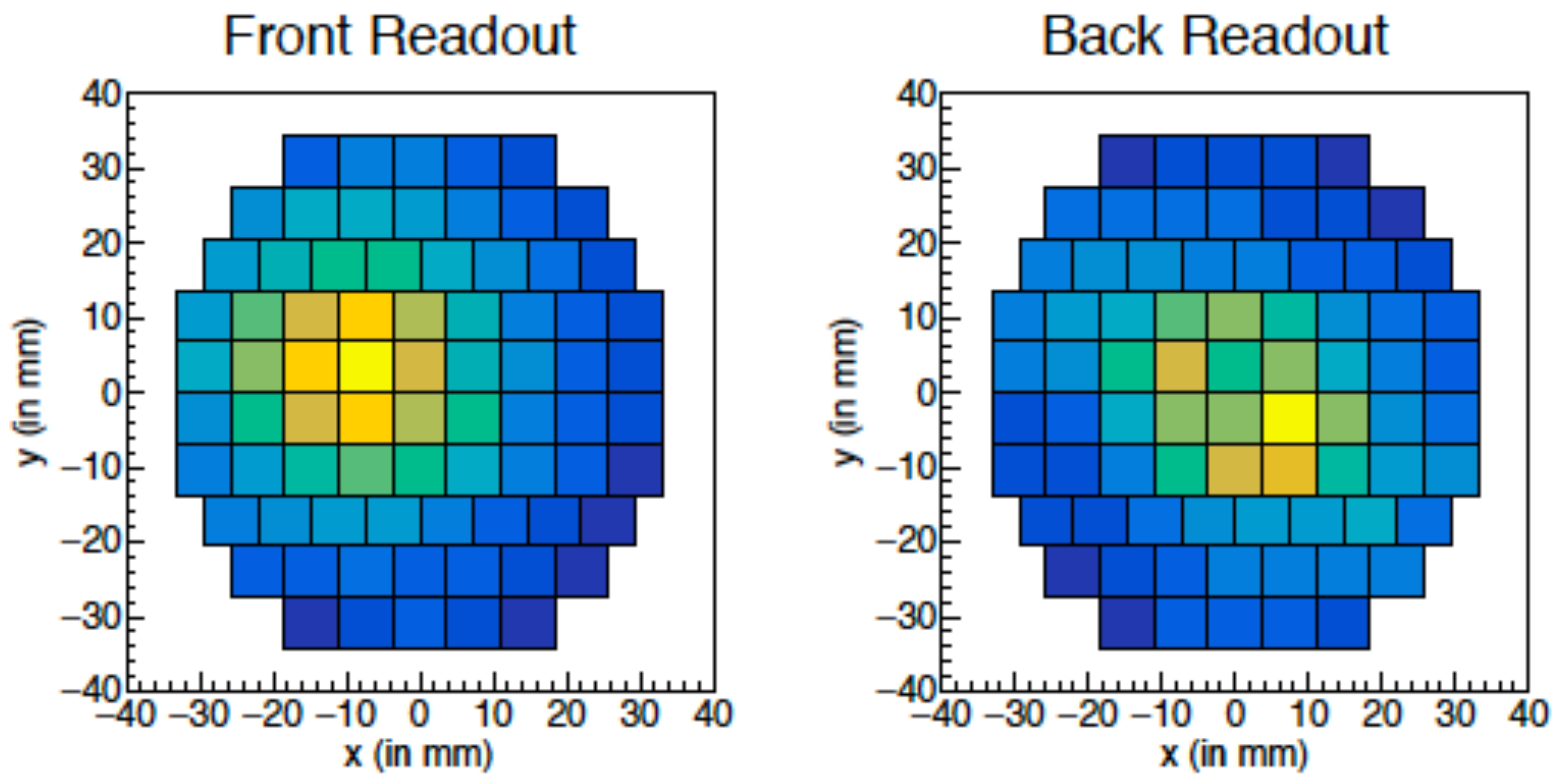
Quartz window

Al_2O_3 PCB where the MPPC/SiPM are soldered

Flexprint cables to connect the MPPC board to the feedthroughs

Carbon fiber



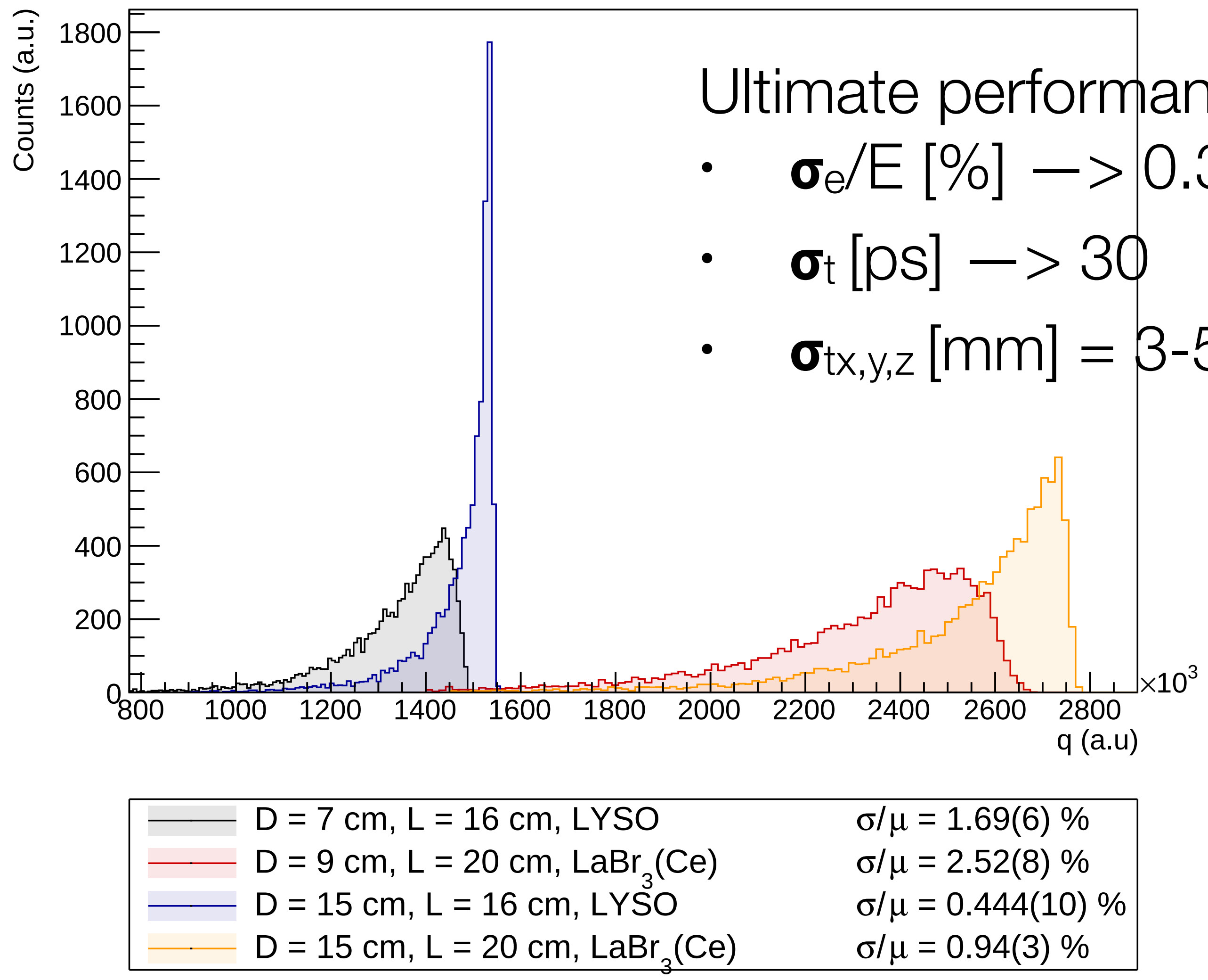


(a) Hit in Central Region: $(x, y) = (-10\,\text{mm}, 3\,\text{mm})$

Expected performances:

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

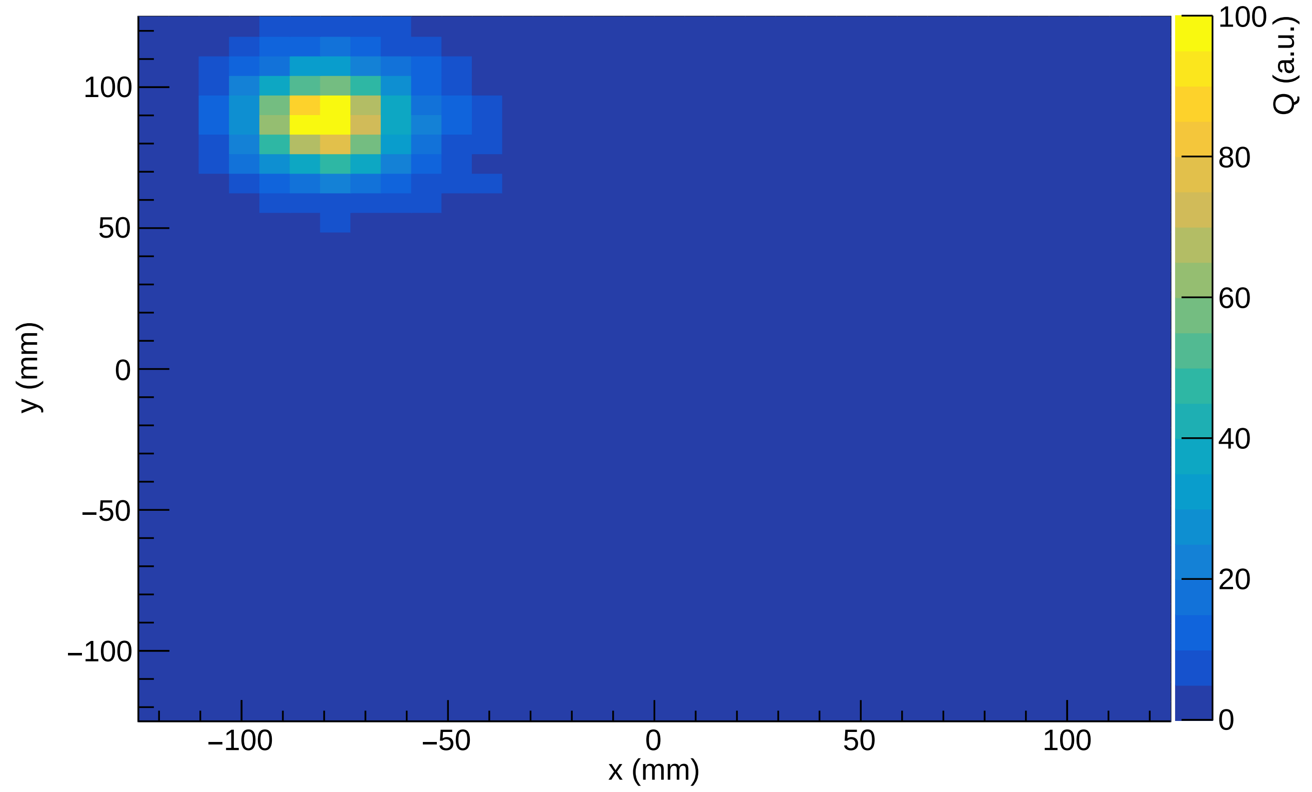
Energy Resolution at O (50 MeV)



Ultimate performances

- σ_e/E [%] —> 0.3-0.4
- σ_t [ps] —> 30
- $\sigma_{tx,y,z}$ [mm] = 3-5

Photons detected per SiPM on the inner surface of an ultimate big crystal



Summary

- R&D efforts for future $\boldsymbol{\mu} \rightarrow \mathbf{e}\boldsymbol{\gamma}$ search with $\mathcal{O}(10^{-15})$ sensitivity with higher intensity muon beam
    - Open discussions on designs and technology options for future experiment
- Different R&D activities ongoing
    - Pair spectrometer with active converter
    - All silicon $\mu \rightarrow \mathrm{e}\gamma$ detector
    - Gaseous detector
    - Calorimeter with high performance scintillator
- Further studies with more detailed simulations and prototypes will come.
- We would greatly appreciate your participation in our effort!