Future μ→eγ Experiments

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on behalf of the
Study Group for Future $\mu\to e\gamma$ Search Experiment

Muon4Future
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Introduction

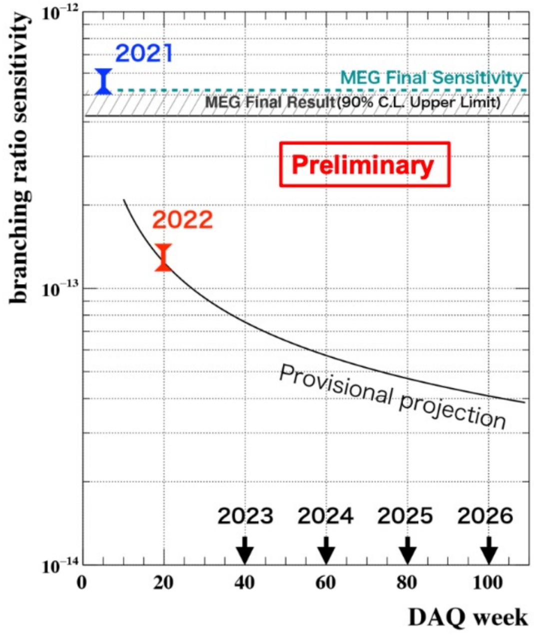
- MEG experiment at PSI: best world limit on $\mu \to e\gamma$ (I_μ = 3x10^7 μ^+/s)

BR ($\mu \to e\gamma$) < 4.2x 10^{-13} at 90% C.L.

Eur.Phys.J.C76 (2016)

- MEG II is taking data (I_μ = 5x10^7 μ^+/s)

MEG II sensitivity (provisional)



- Future facilities (HiMB, AMF,J-Park) will provide up to 10^9 -10^{10} μ^+/s

- **It's time to design a new $\mu \to e\gamma$ experiment** to exploit this opportunity:

  - *new detector concept is required*
  - *R&D already on going*
  - *possibility of synergies with other experimental activities*

Beam Requirements

- As for other searches of rare muon decays ($\mu \rightarrow eee$) the beam must be

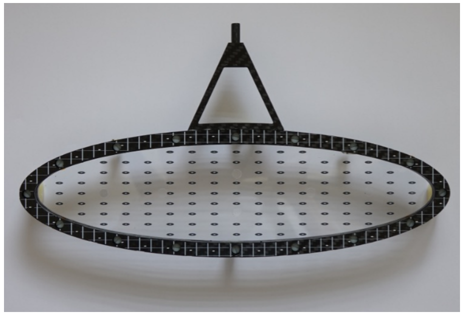
  - **intense**
  - **positive** muons (avoid capture)
  - **continous time structure** (minimize accidental background)
  - **low momentum** (about 30 MeV/c)

- Low momentum is critical to have a small straggling of the total range => thin target => minimization of interactions of decay products

- Possibility to have only a fraction of the beam stopped in the target
  - requires vacuum to reduce background

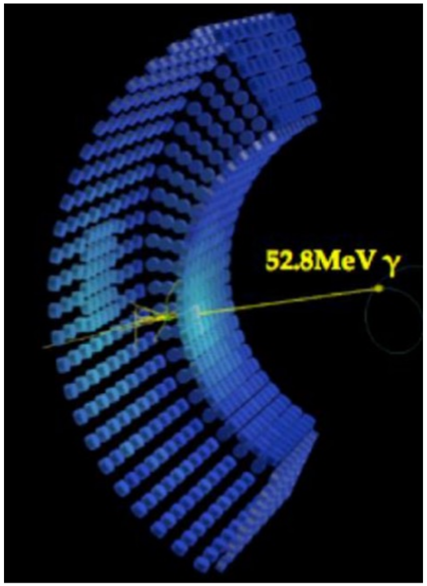
MEG II target:
- 174μm average thickness
- scintillating material

We have the possibility to design the new $\mu \rightarrow e\gamma$ detector in close contact with the development of the new beams to optimize the experiment

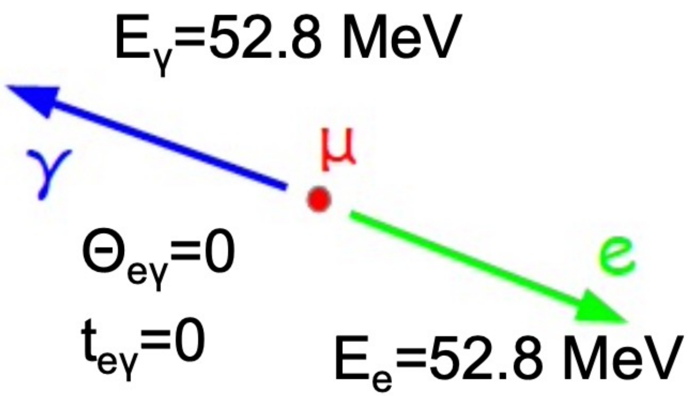


Current Experimental Principle (MEG II)

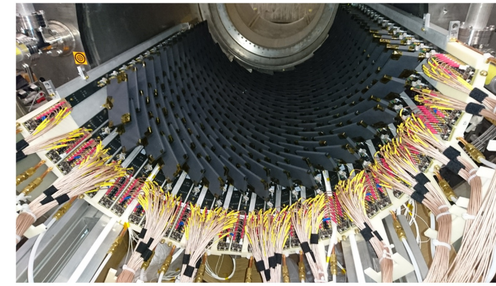
liquid xenon calorimeter



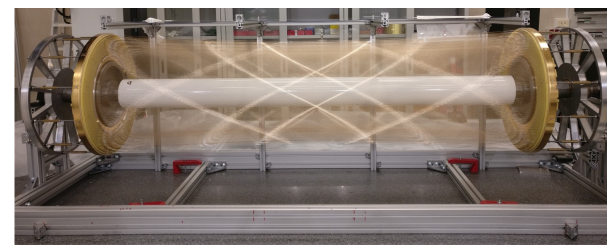
Observables: $E_{e+}, E_{\gamma}, \theta_{e\gamma}, \varphi_{e\gamma}, t_{e\gamma}$



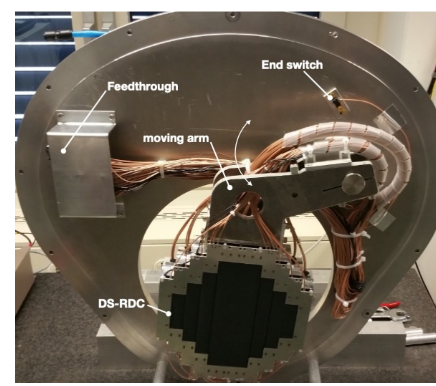
fast scintillating TC



light drift chamber in
a magnetic field



radiative decay counter

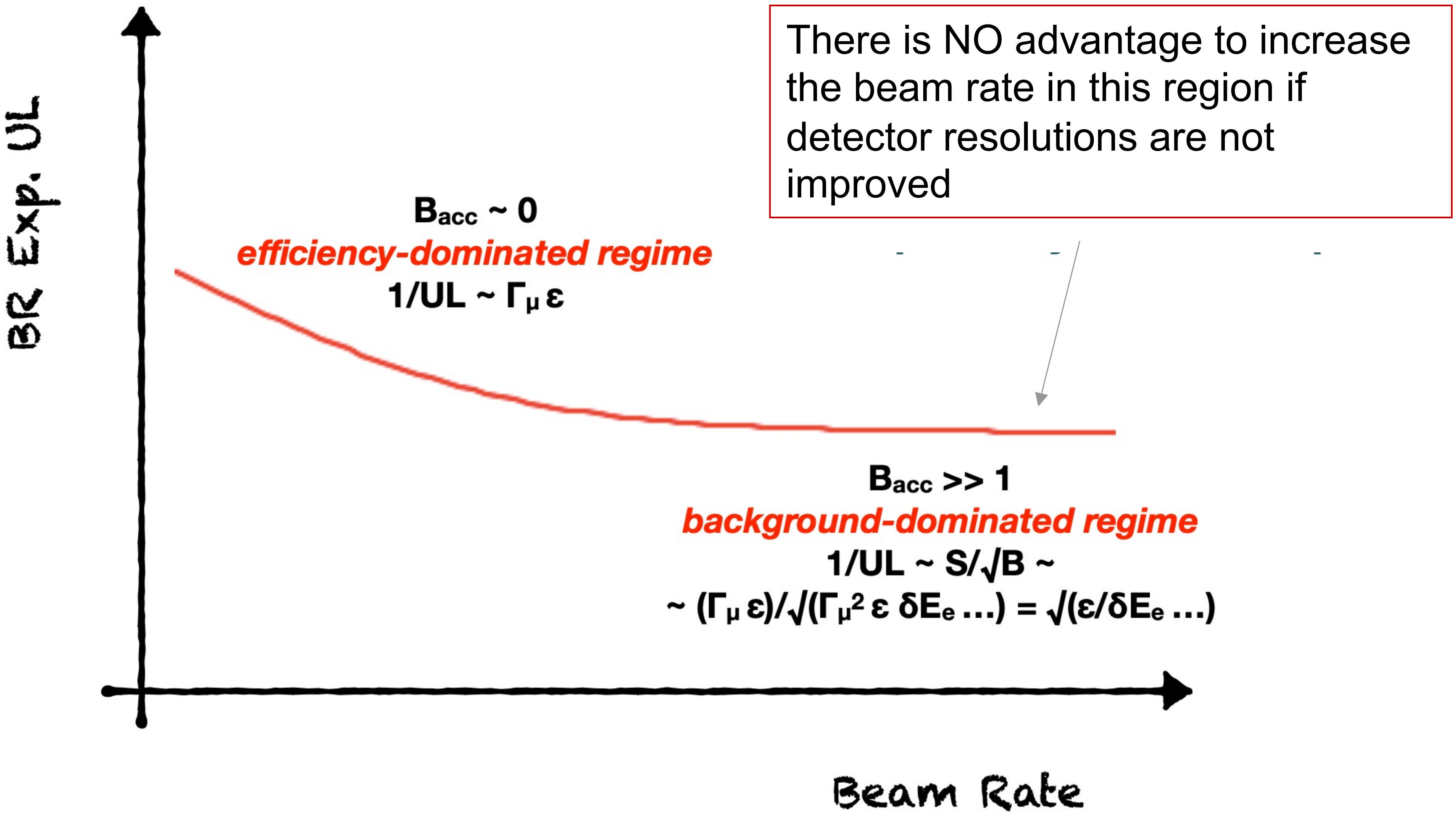


- The core of the design is the kinematic of the 2-body decay (muon decays at rest) to suppress dominant accidental background

Next Generation of μ→eγ Searches

accidental background $B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^2$ resolutions

beam rate



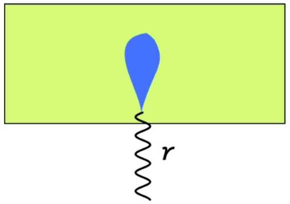
Toward a New Concept of a $\mu \rightarrow e\gamma$ Detector

- If beam rate increases → detector performances must improve accordingly
- Two requirements
  - Detector performances: resolutions, efficiency
  - Rate capability

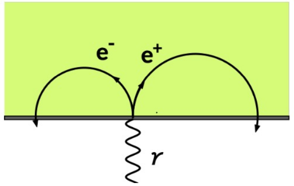
Positron — magnetic spectrometers with tracking detectors
- gaseous:
  - **drift chamber**
  - **TPC**
- **silicon**

+ faster time detector needed in both cases

Photon
- **calorimeter**



- **photon conversion spectrometer**



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

- Informal group set up to follow up the discussion in HiMB Physics Case Workshop (April 2021, PSI)
- ~30 people mainly from MEG and Mu3e
- Aim: discuss and create synergies about R&D, create common tools
- Some ideas already under R&D

Photon

Conversion spectrometer

- scintillator+gaseous tracker (W. Ootani, F. Renga)
- silicon (A. Schöning)

Calorimeter (A. Papa)

Positron

- gaseous detector (F. Renga)
- silicon (A. Schöning)

Next Generation of μ→eγ Searches: Positron Reconstruction

- Low (~50 MeV/c) positron momentum: very light trackers have to be used

- Large volumes gaseous detectors:

  - best compromise of single hit resolution and material budget
  - poor granularity and significant ageing at high beam rate

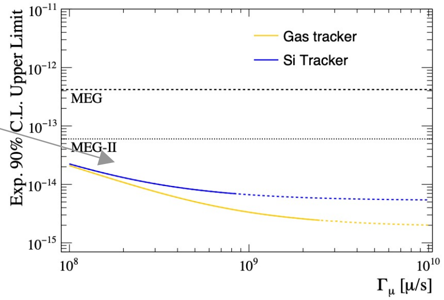
- Options for future $\mu \to e\gamma$ experiments:

à la Mu3e

Improve rate capabilities of gaseous detectors
- *transverse drift chambers*
- *radial TPC*
- *transverse drift tubes à la Mu2e*
- *new wire materials*
- *hydrocarbon-free gas mixture*

Silicon trackers *are becoming competitive*
- next generation HV-MAPS thinned down to 25μm
- optimization of geometry and magnetic field

with the present 50 μm thickness silicon could be the only viable solution at high rate



modified from G. Cavoto et al., Eur.Phys.J.C 78 (2018)

Positron Tracker: Drift Chambers

- Main issue: rate capability

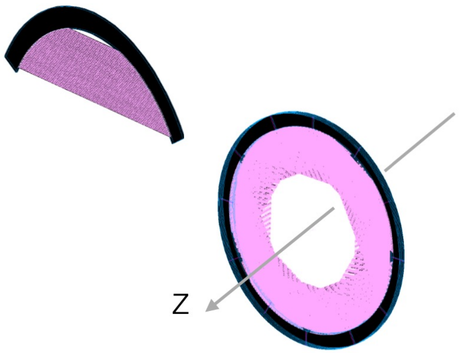
- The rate per wire can be reduced with an alternative arrangement of the wires

Transverse wires (xy plane)

- shorter => lower rate per wire

- support material for wires to be kept low

- no electronic in the tracking volume (long trasmission lines for HV and signals)



Positron Tracker: Radial TPC

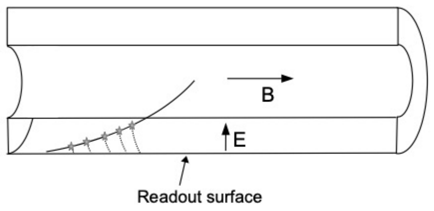
- Unconventional geometry can mitigate the issue related to long drifts (diffusion, space charge)

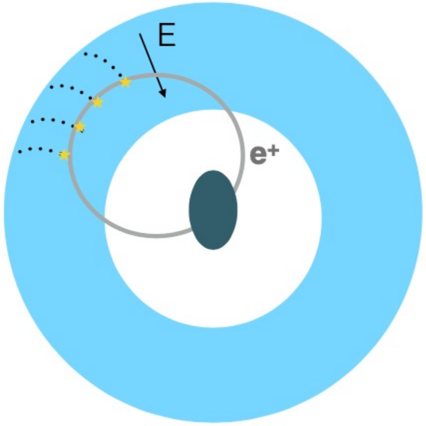
F. Renga

- Cylindrical MPGD readout

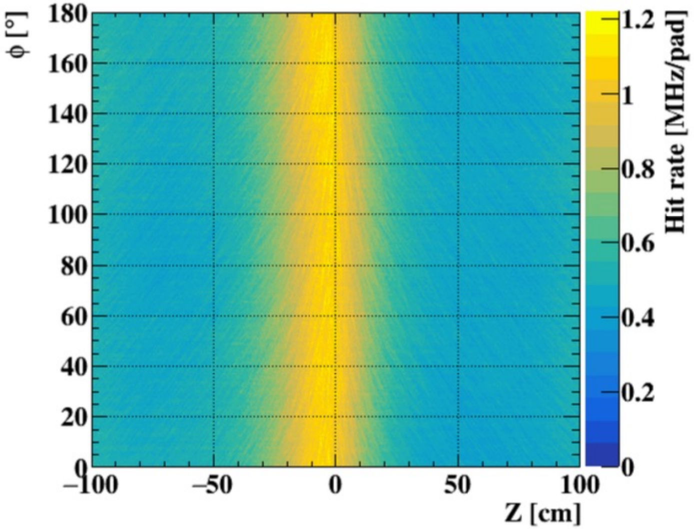
  - 2 m long, 30 cm radius (10 cm radial extension)
  - light mixture with low diffusion
  - correction of field deformation is needed

Feasibility studies on going





Simulation at 10^9 μ/s



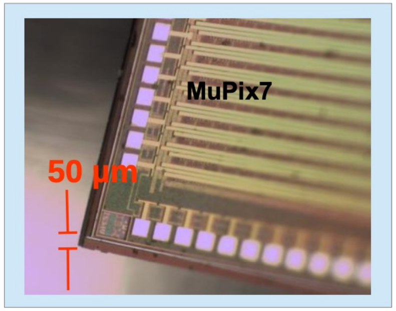
Assuming 5 x 3 mm^2 pads
B field as in MEG II

Positron Tracker: Silicon

A. Schöning

- Detector à la **Mu3e** (silicon HV-MAPS)
  - high rate capability
  - expected improvement: 25 μm thickness

MuPix (HV-MAPS)



Monolithic pixel sensor in 180 nm HV-CMOS

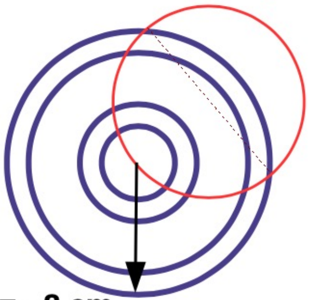
- Limitations
  - vertexing: finite sensor thickness determines positron angular resolution
  - momentum resolution is limited by multiple scattering in the Helium environment

Example (p_e=53 MeV/c):

- 50 µm Si → $\sigma(\Theta_e) = 6.0$ mrad
- 30 µm Si → $\sigma(\Theta_e) = 4.6$ mrad

- In strong magnetic fields a momentum resolution of <80 keV/c can be reached

B = 2.6 Tesla

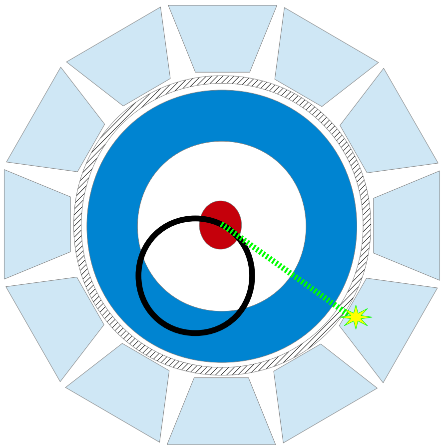


Next Generation of μ→eγ Searches: Photon Reconstruction

- To reconstruct the photon two possible approaches:

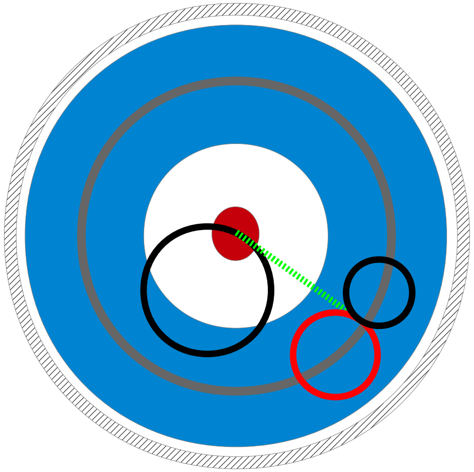
Calorimetric

- high efficiency, good resolution
- moderate rate capability
- requirements:
  * high light yield
  * fast response



Photon conversion spectrometer

- low efficiency (%), extreme resolution
- photon direction (eγ vertex)
- energy loss in the converter is an issue



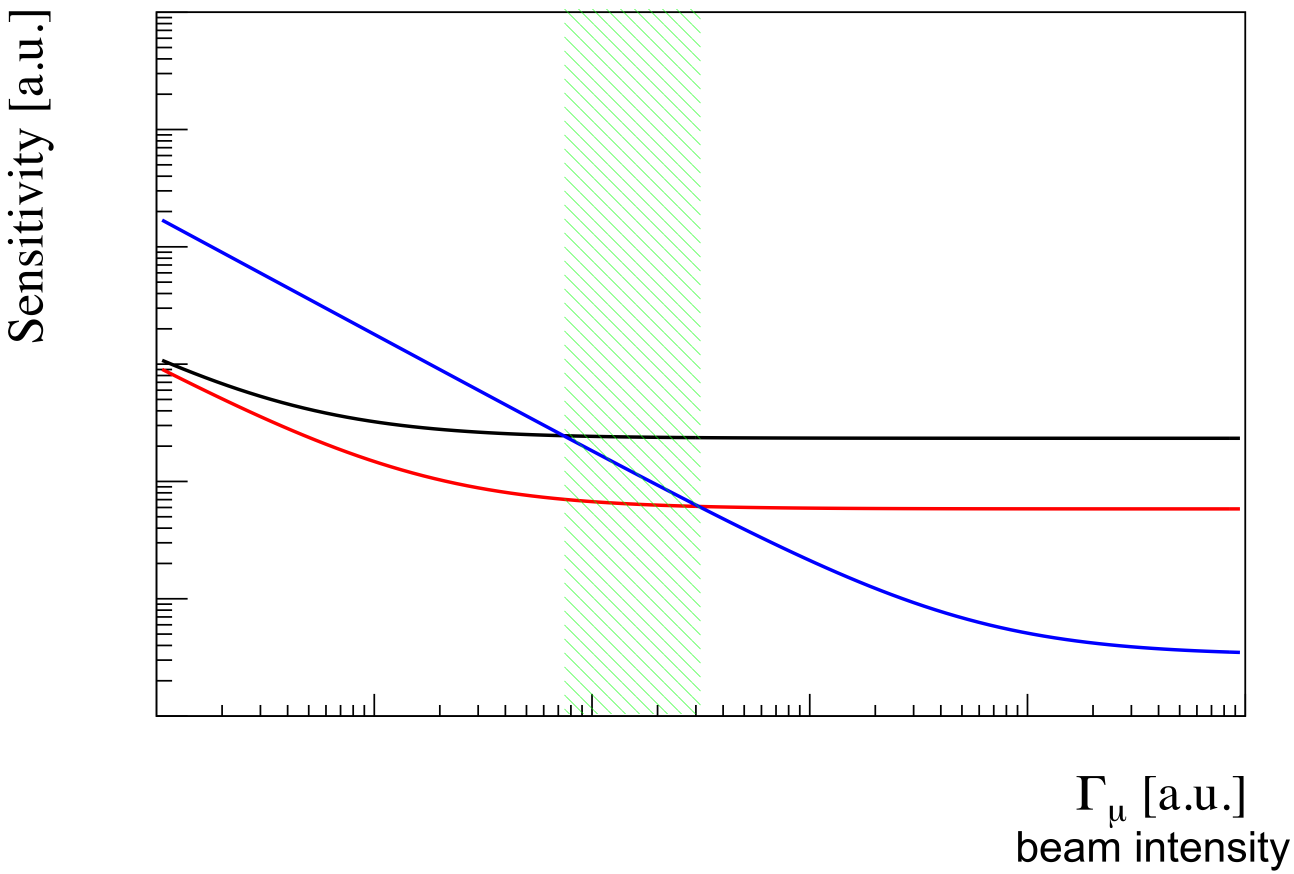
Calorimeter vs Photon Conversion

Sensitivity on $\mu \to e\gamma$ trend vs beam intensity

blue = photon conversion design

black = calorimeter design

red = calorimeter design with x2 resolution



Photon Reconstruction - Calorimeter

- MEG (MEG II) LXe calorimeter

  - limited acceptance (10%) due to costs and complexity
  - presently cannot push resolution much better than 1 MeV
  - pile-up issue at increased beam intensity

- **Innovative crystals look promising** (cost can be an issue)

- E.g. brillance: LaBr3(Ce):
  G. Cavoto et al., Eur.Phys.J.C **78 (2018)**

  - 800 keV resolution within reach
  - time and position resolution looks adequate (30 ps possible)

- MC studies & prototyping on going

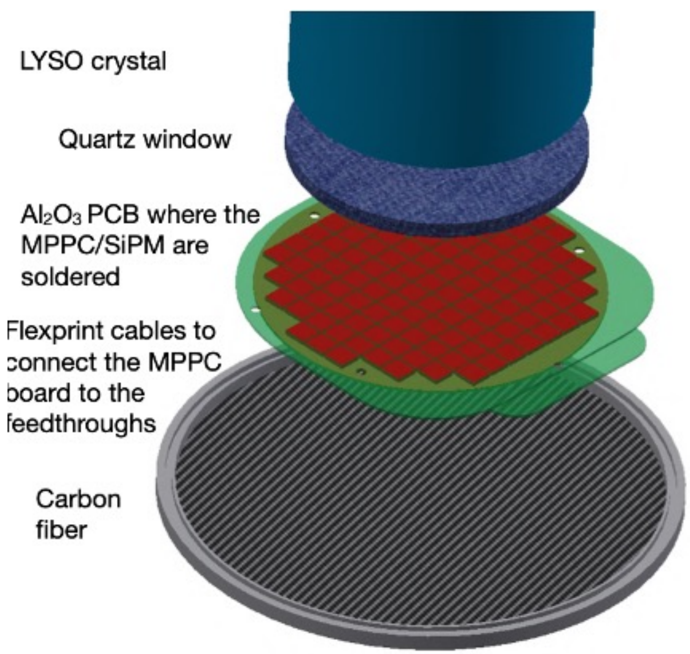
$$\text{F.o.M.} = \sqrt{\left(\frac{\rho \cdot LY}{\tau}\right)}$$

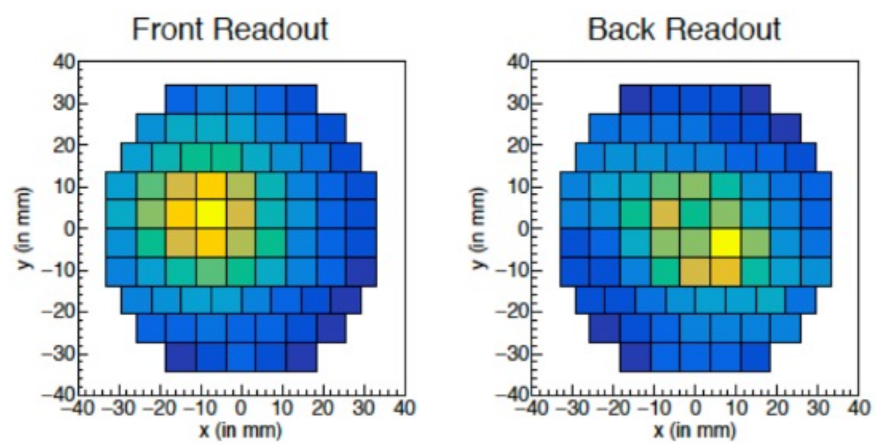
Scintillator	Density ρ [g/cm³]	Light Yield LY [ph/keV]	Decay time τ [ns]	F.o.M. $\sqrt{(\rho \times LY / \tau)}$
LaBr3(:Ce)	5.08	63	16	4.55
LYSO	7.1	27	41	2.17
YAP	5.35	22	26	2.13
LXe	2.89	40	45	1.61
NaI(Tl)	3.67	38	250	0.75
BGO	7.13	9	300	0.46

Photon Reconstruction - Calorimeter

A. Papa

- LYSO or LaBr3(Ce) big crystals with front and back readout (MPPC/SiPM)
- MC simulations based on GEANT4 (including photosensors and electronic) look very promising
- First large prototype under construction (D=7cm and L=16 cm) (LYSO crystals and photo-sensors delivered at PSI)





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

Expected performances:

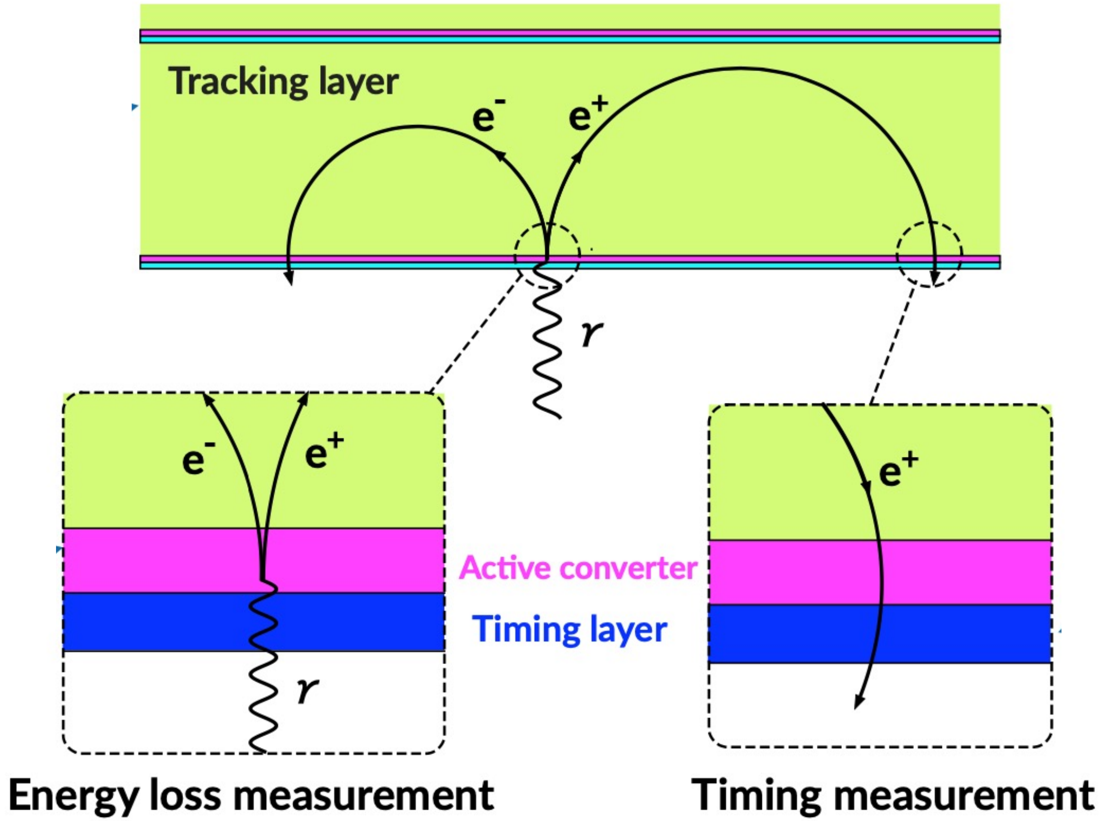
- σ_e/E [%] = 1.7(1)
- σ_t [ps] = 35(1)
- $\sigma_{tx,y,z}$ [mm] = 3-5

Photon Conversion with Active Converter

Tracking layer
- necessity to stack multiple conversion layers
- drift chamber (difficult to fit this design)
- radial TPC
- silicon detector

Active conversion layer
- scintillator + photo-detector
- silicon detector

Timing layer
- multi gap TPC (mRPC)
- use active layer to measure time = no timing layer



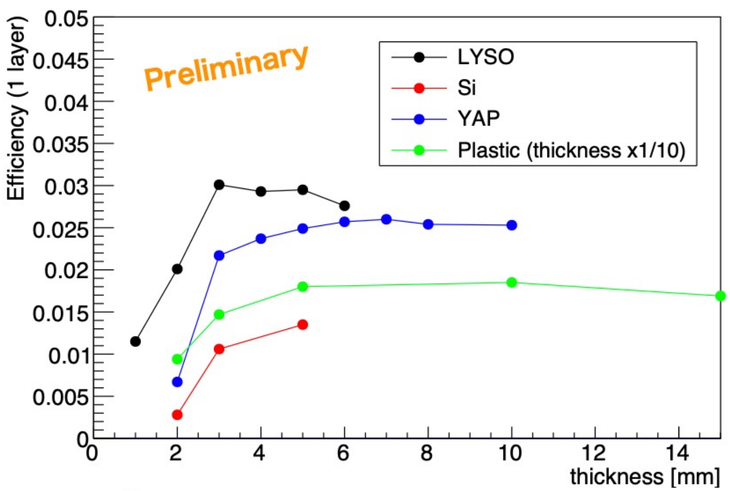
Scintillator Active Converter

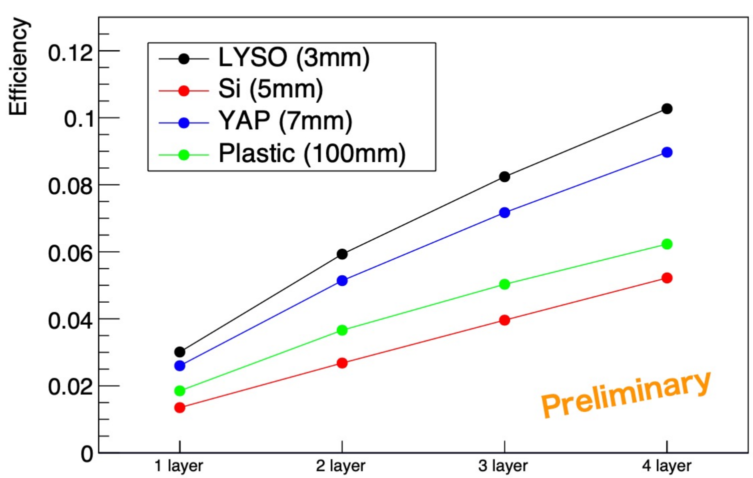
Scintillator:
- light yield
- fast decay time
- high X0,
- low cost, high critical energy

Photon detector:
- high light detection efficiency
- low mass

W. Ootani

- Simulation studies and tests beams are on going
- Preliminary results with four layers of 3-mm thick LYSO crystals: 10% efficiency
- Expected energy resolution: 140 keV (p.e. statistics)
- Optimization to mitigate pile-up in progress





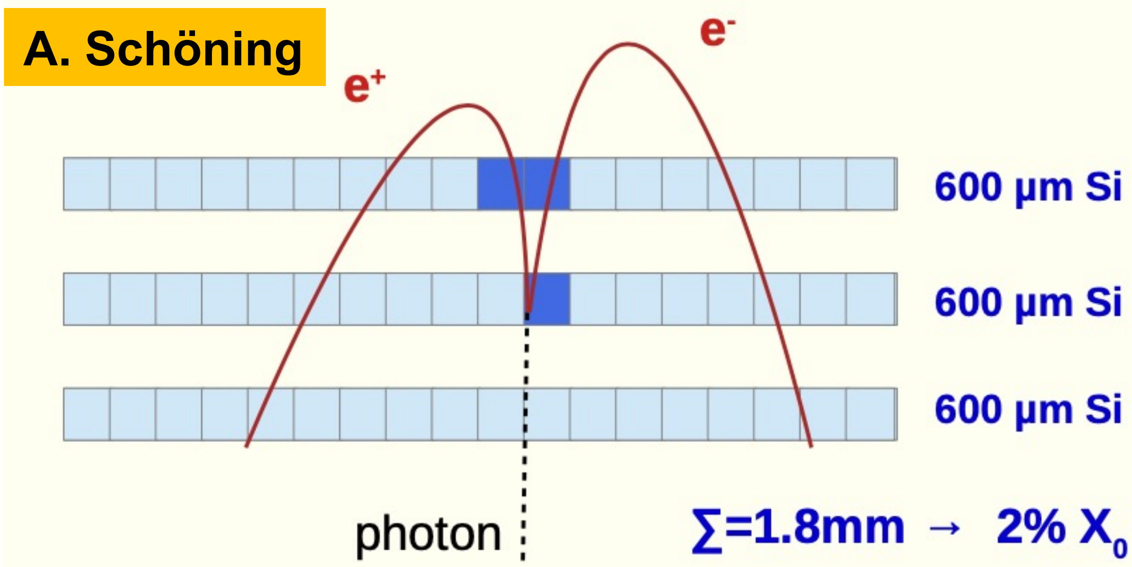
(N.B. Effect of pileup hit of returning conversion pair is not taken into account)

Silicon Active Converter and Tracking Layer

Example:

1 pixel layer as converter (critical energy in Si is 35 MeV)

2 pixel layers for tracking



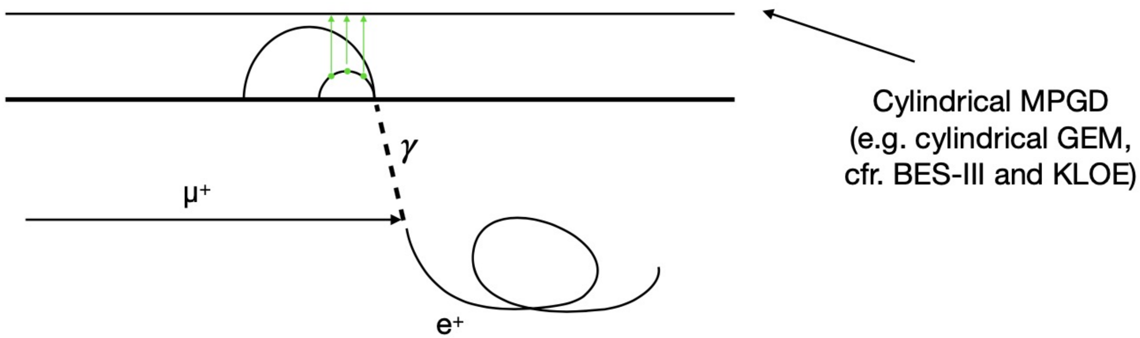
- Measure energy loss and conversion point in **Si**
- Could also be used for precise timing → **<100ps?**
- Caveat: only small radiation length possible
  → to be simulated

Gaseous Pair Tracking Layer

F. Renga

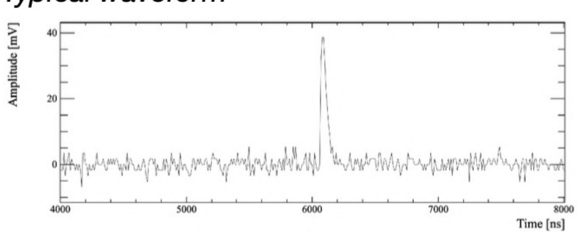
- Low rate: less demanding vs positron tracker
- Studies on going with a **radial TPC with strip readout**

Radial TPC

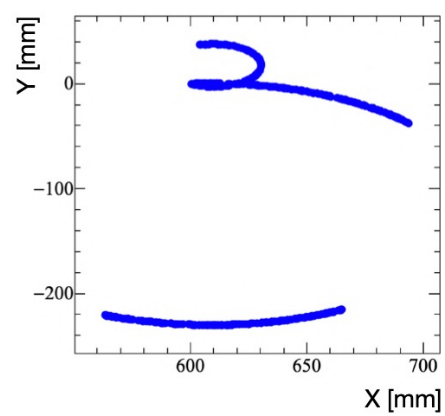


- **Work in progress**

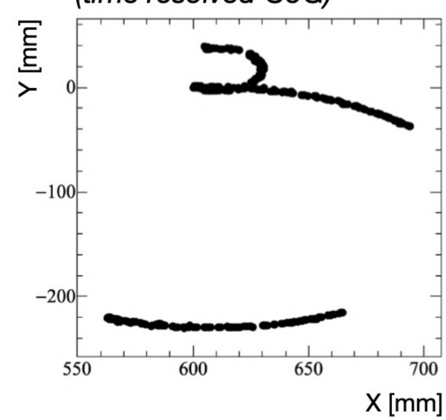
Typical waveform



True tracks



Reco track
(time resolved CoG)



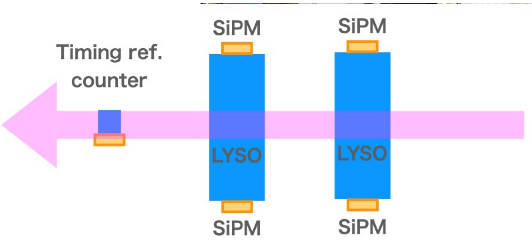
Timing Layer

- Target resolution: 40 ps for MIP (=> 30 ps for conversion pair)
- **Active converter (e.g. LYSO) can measure timing**

W. Ootani

- Beam test @KEK PF-AR beam line, Nov. 2022
  - Standard LYSO, Fast LYSO (FTRL) 3 × 5 × 50 mm^3 wrapped with ESR
  - SiPM: S14160-3015PS (3 × 3 mm^2, 15 μm), S14160-3050HS (3 × 3 mm^2, 50 μm)
  - Waveform digitizer: DRS4 (1.6 GSPS)

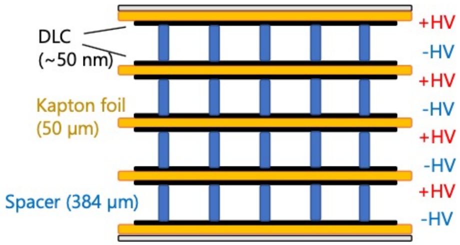
Good timing resolution of 40 − 50 ps **for fast LYSO**



- **Other option: mRPC**

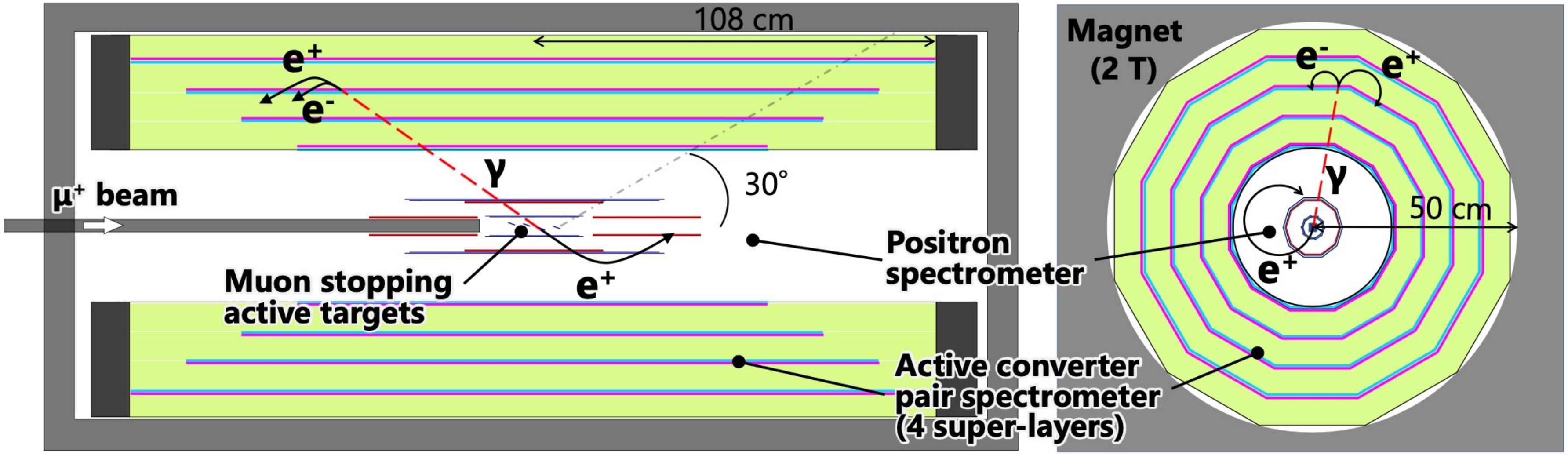
- DLC-RPC technology developed for MEG II US-RDC
- single p.e. time resolution of 110 ps achieved for single layer RPC
- Optimisation for timing under study:
  * thinner gap
  * higher efficiency and timing resolution with many layers

Multi-layer DLC-RPC (MEG II)



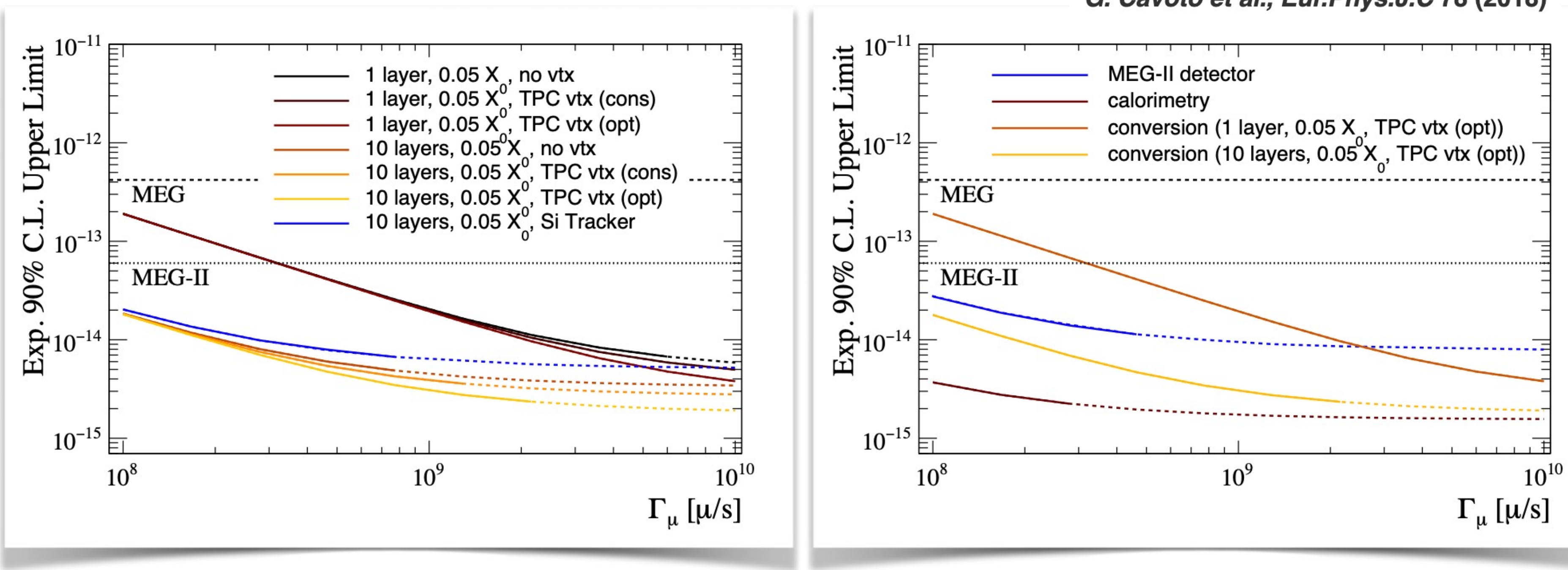
A Possible Design for a Future μ→eγ Experiment

- Photon spectrometer with active converter
- Positron spectrometer based on Si detector (à la Mu3e)
- Separate active targets => further backgrounds suppression
- Significantly improved acceptance vs MEG II => possible angular distribution measurement in case of discovery



Expected Sensitivity (3 Years Data Taking)

G. Cavoto et al., Eur.Phys.J.C 78 (2018)



A few 10^{-15} level seems to be within reach for 3 years running at 10^9 μ/s

(further improvements possible with R&D)

Conclusion

- Future facilities will make available **intense muon beams**
- A window of opportunity for **new $\mu \to e\gamma$ experiments** is opening
- New experimental concept is needed to do deal with high rate and accidental background
  - we have the possibility to optimize the experiment together with the future beams
- A **study group** has been constituted

Present main R&D directions ➡ LYSO crystals, radial TPC, HV-MAPS

- Synergy with $\mu \to eee$ search possible
  - Mu3e experience with HV-MAPS can be exploited
  - both searches can take advantage of improvements in this technology (thickness, timing)
  - can a single future experiment perform both searches ?
- 10^{-15} sensitivity seems within reach

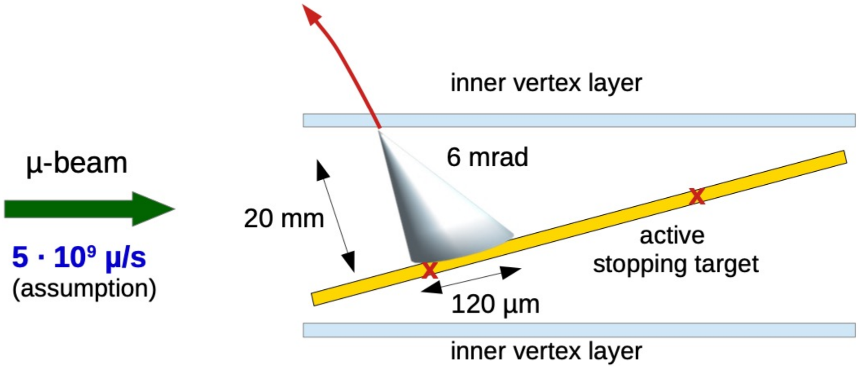
Backup

Random ideas for futuristic μ -> e γ searches

- Active targetry
  - μ/e separation
  - very thin
- Target + detector in vacuum
  - containing the Bragg peak would not be needed anymore (—> thinner target and compensate with more intensity)
  - multiple target option
  - could next-generation straw tubes be a good option for tracking also in μ -> e γ? Too much supporting material? What about silicon detectors (cooling)?
- What about spreading muon stops over a very large surface?
- Stored vs. stopped muons?
- μ -> e γ + μ -> 3e
  - possible in a detector with 2π acceptance in φ
  - give up the low-energy cut of the MEG spectrometer —> higher rate tolerance needed, should be not a problem in a Mu3e-like design

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!

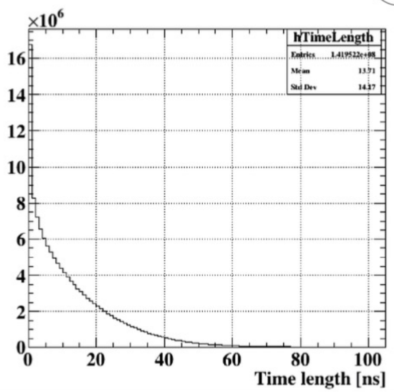
F. Renga

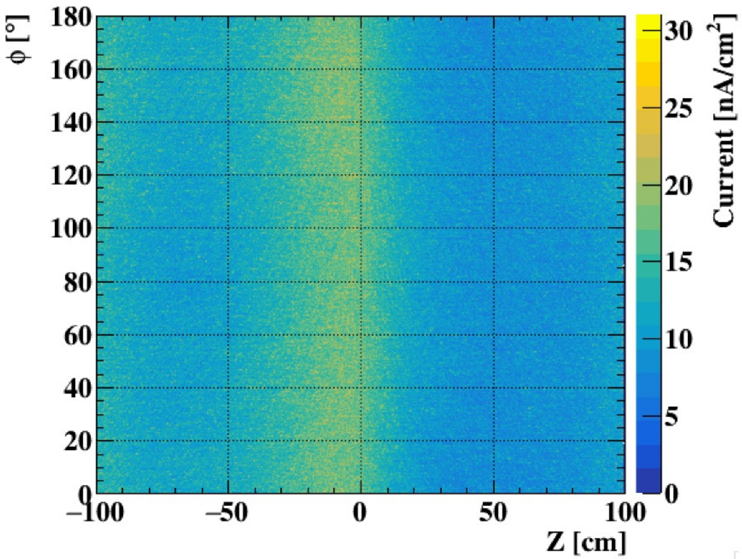
Radial Time Projection Chamber

Feasibility Study

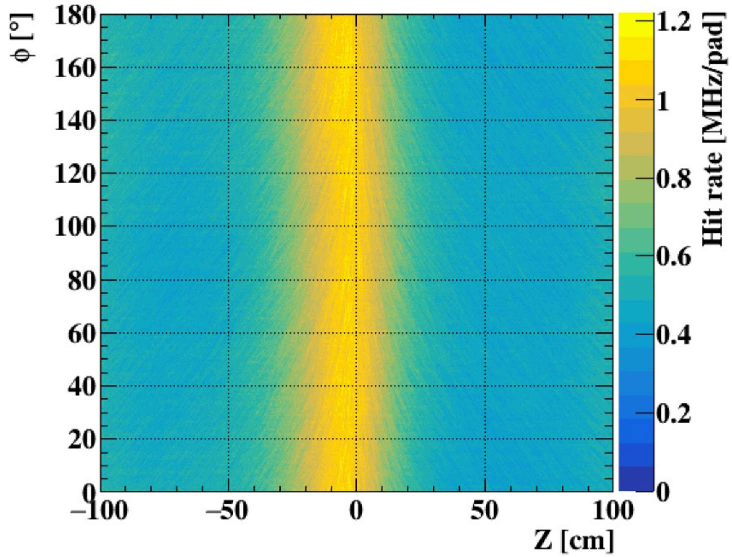
- Simulation at 10^9 μ/s
- One should consider ~ 250k readout channels
  - challenging **FE integration** and **cooling** in the outer surface of the cylinder with a reasonable material budget (~ few % X_0)

Time spread of electrons arriving to the same pad





cfr. ALICE GEM-TPC ~ 10 nA/cm²

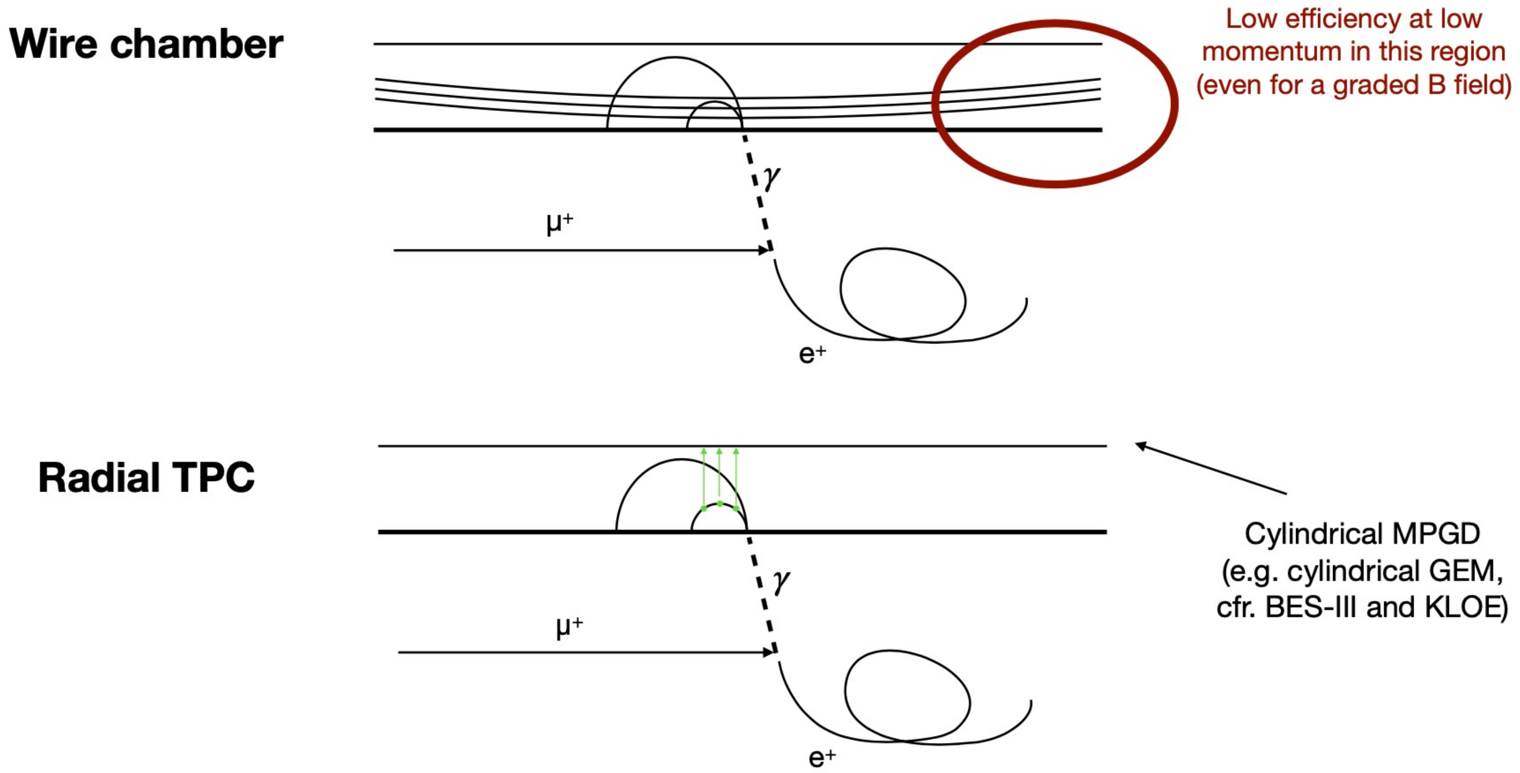


Assuming 5 x 3 mm² pads

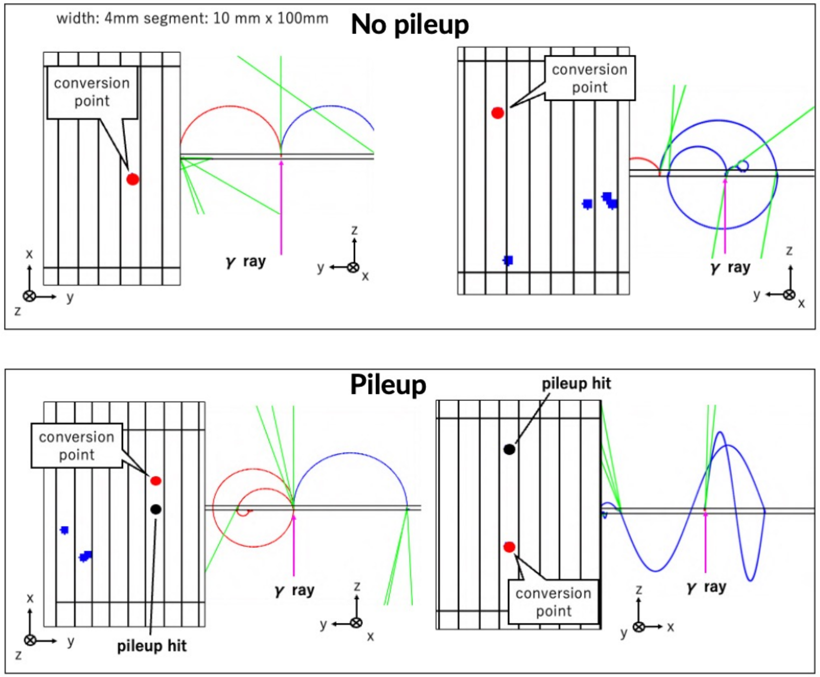
Gaseous Pair Tracking Layer

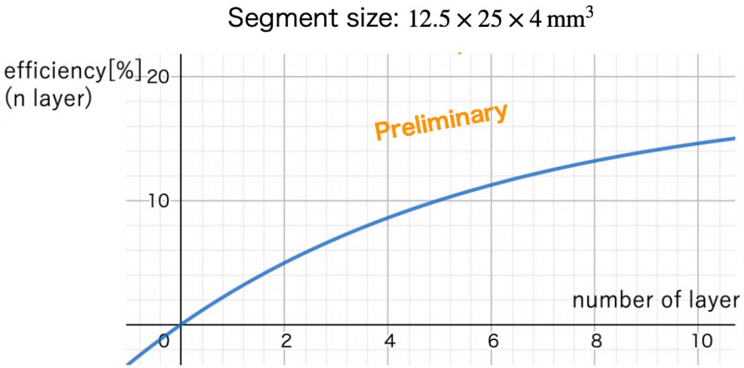
- Low rate: less demanding vs positron tracker
- Studies on going with a radial TPC with strip readout

F. Renga

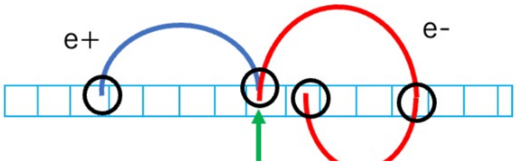


Active Target





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



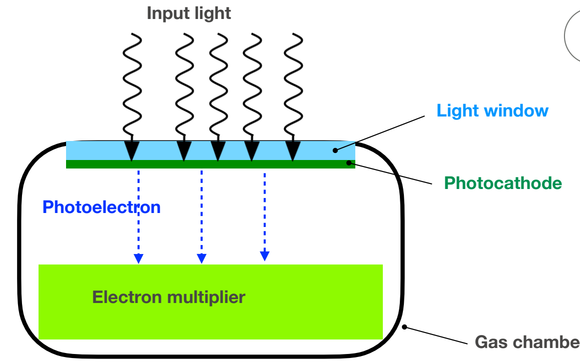
Energy Resolution

- 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: $4 \times 10^4\,\mathrm{photons/MeV}$
  - 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

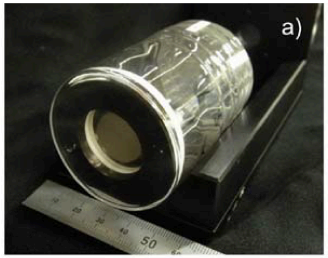
Gas PM

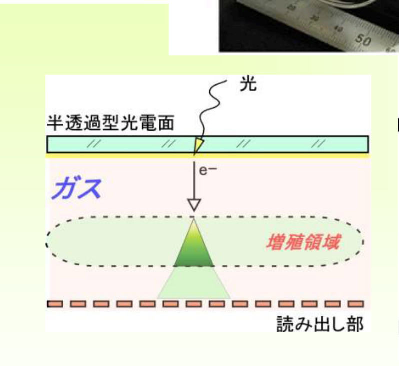
as Photo-detector

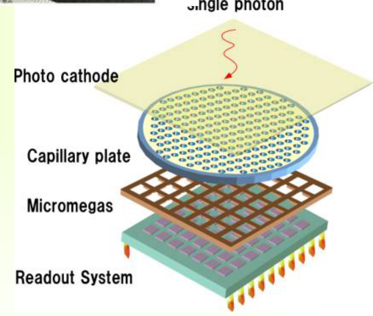


- Gas PM (a.k.a. Gaseous PMT)
  - Photocathode + electron multiplier in gas chamber
  - Pioneering work by F. Tokanai et. al → MPGD as electron multiplier
- Our idea: gas PM with RPC as electron multiplier
  - Ultra-low mass RPC with DLC developed for MEG II radiative decay counter (RDC)
  - In collaboration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

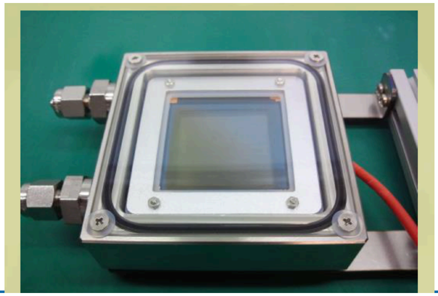
Gas PM with MPGD (Prof. F. Tokanai)







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



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