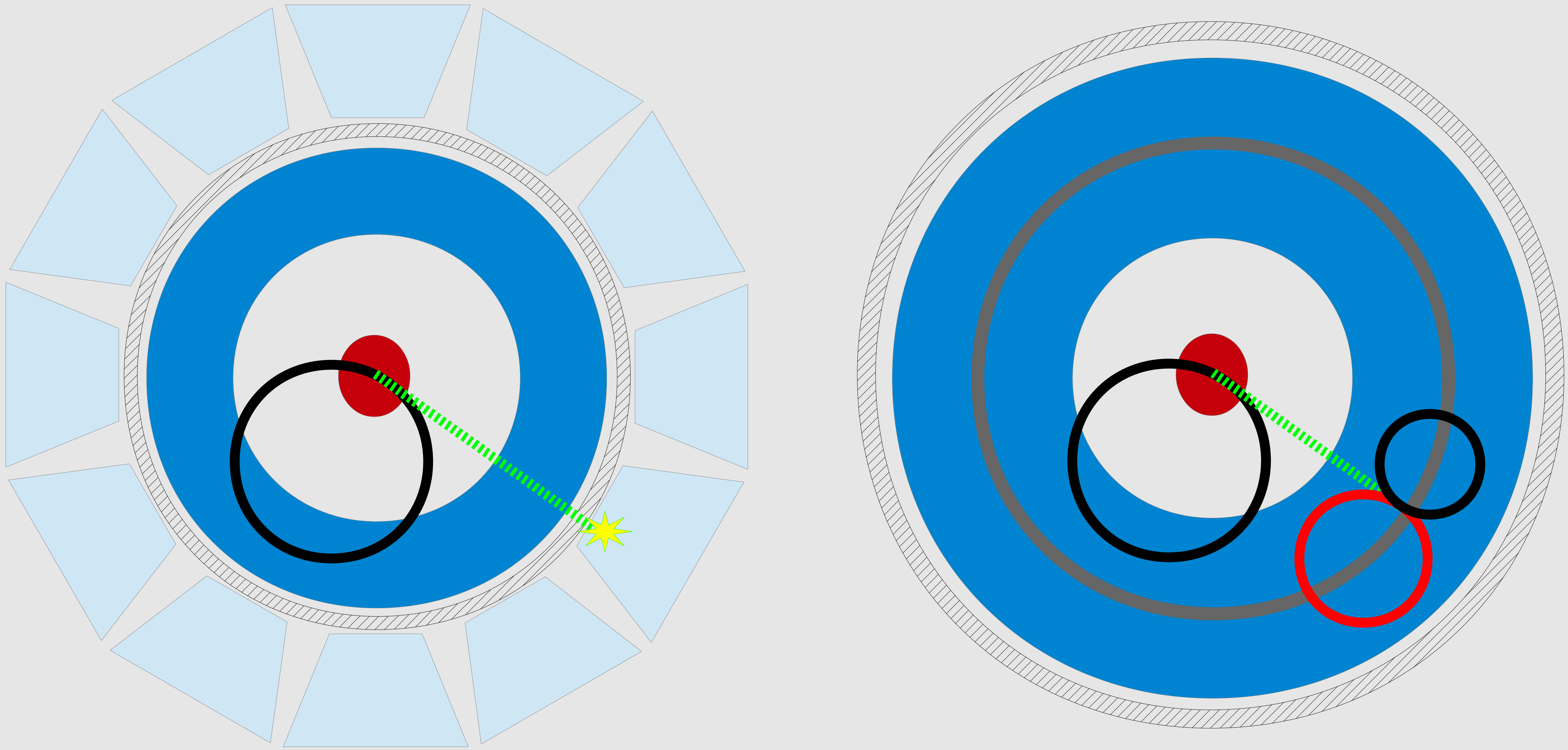
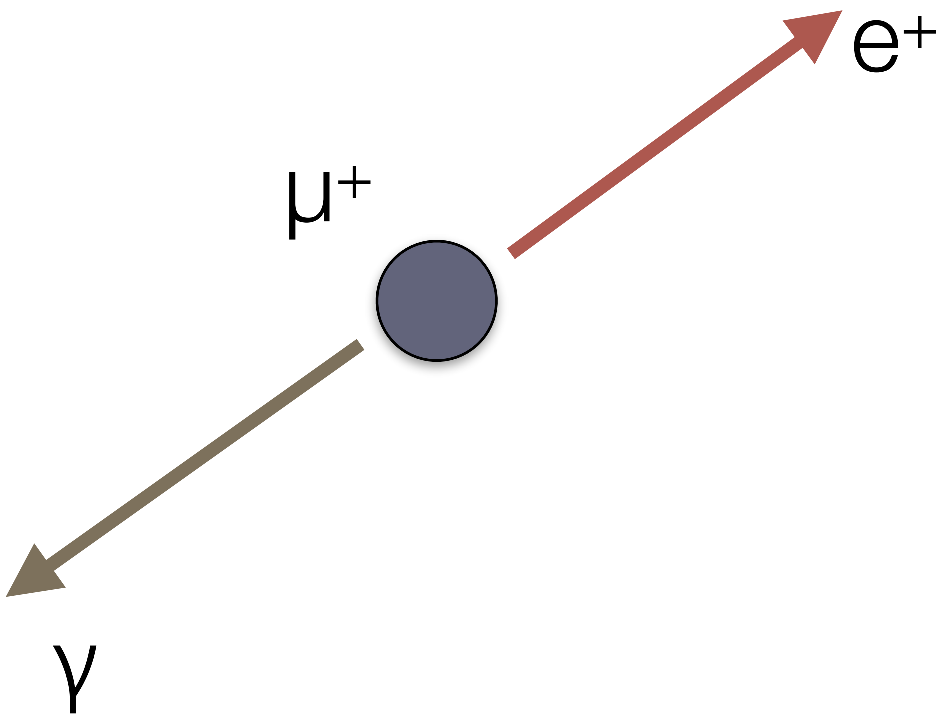


The Quest for μ -> e γ and its Experimental Limiting Factors at Future High Intensity Muon Beams

Francesco Renga
INFN Roma

μ -> e γ searches

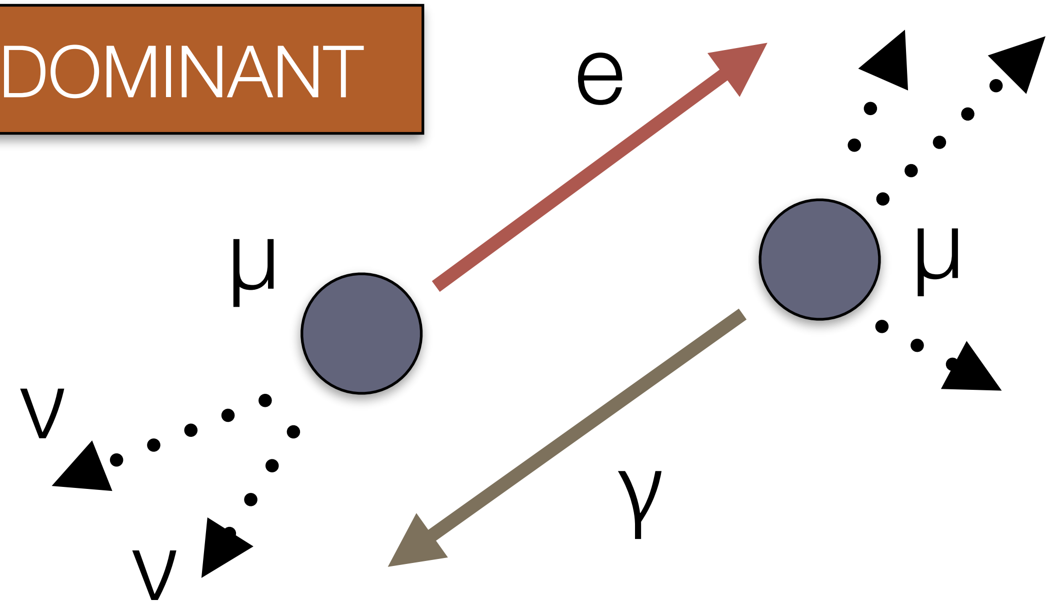


28 MeV/c muons are stopped on a thin target

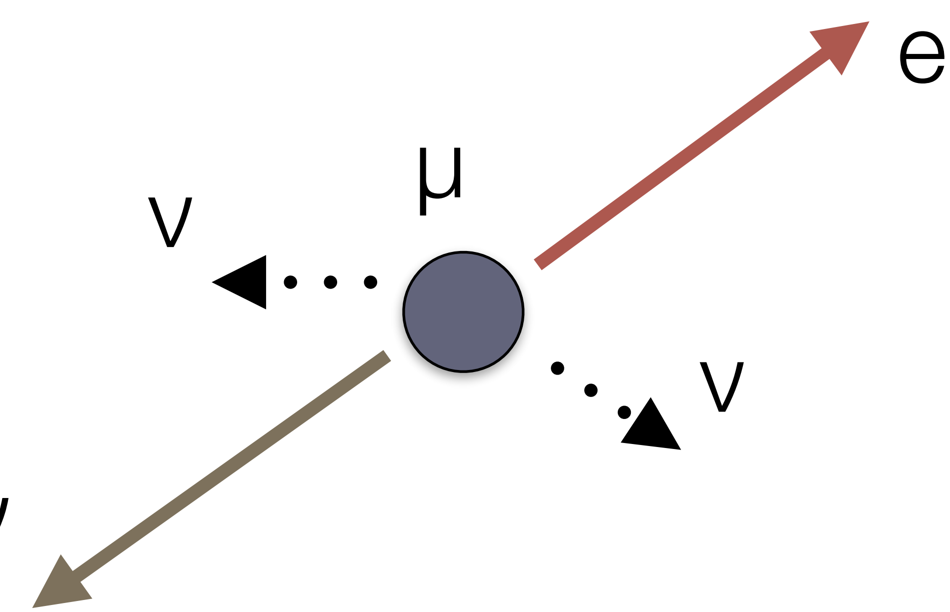
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the same time;

Accidental Background

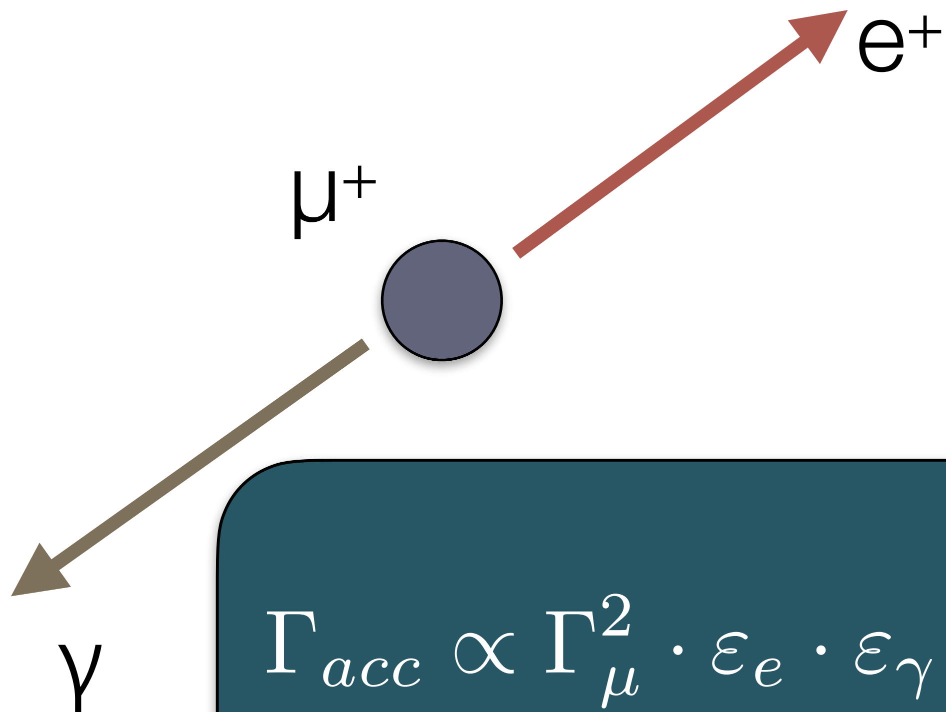
DOMINANT



Radiative Muon Decay (RMD)



μ -> e γ searches



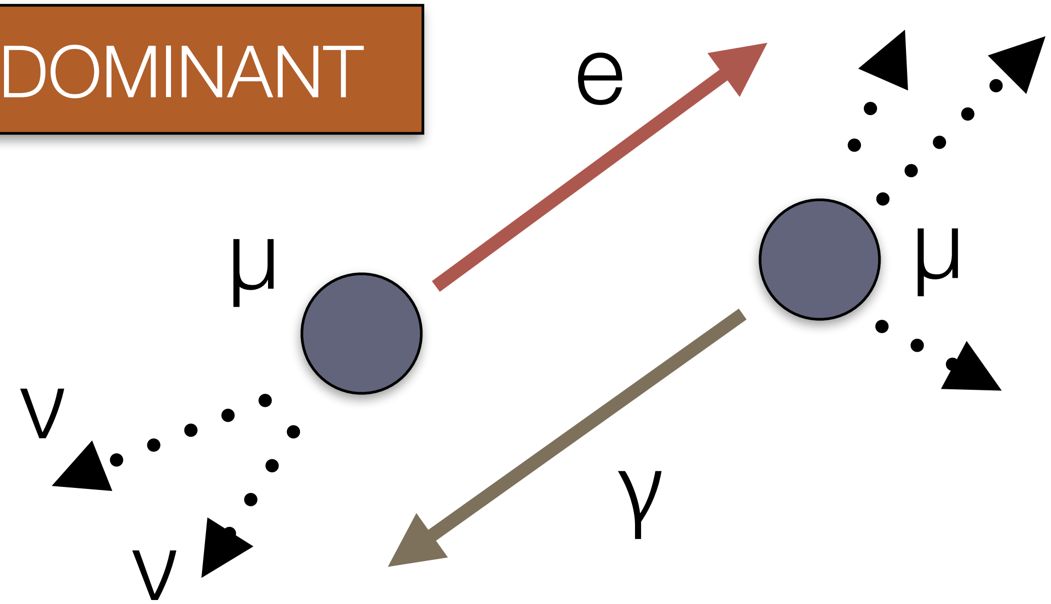
28 MeV/c muons are stopped on a thin target

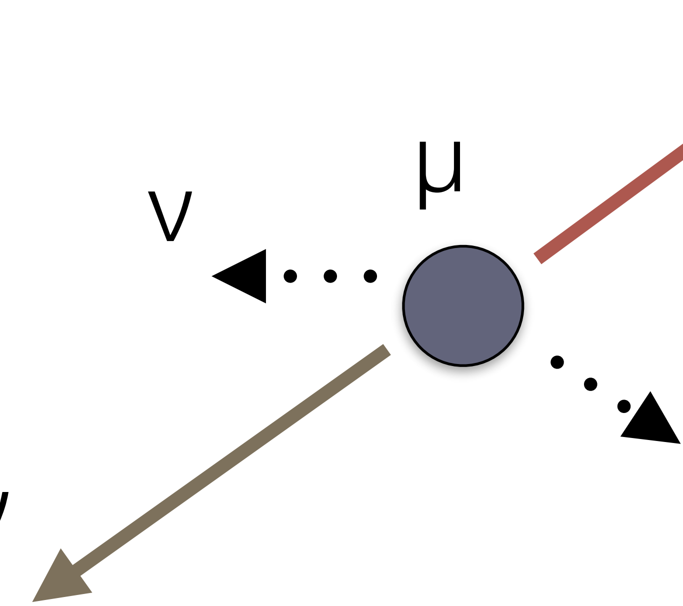
Positron and photon are **monochromatic** (52.8 MeV), … d … **time**;

$$\Gamma_{acc} \propto \Gamma_\mu^2 \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2 \cdot \delta T_{e\gamma}$$

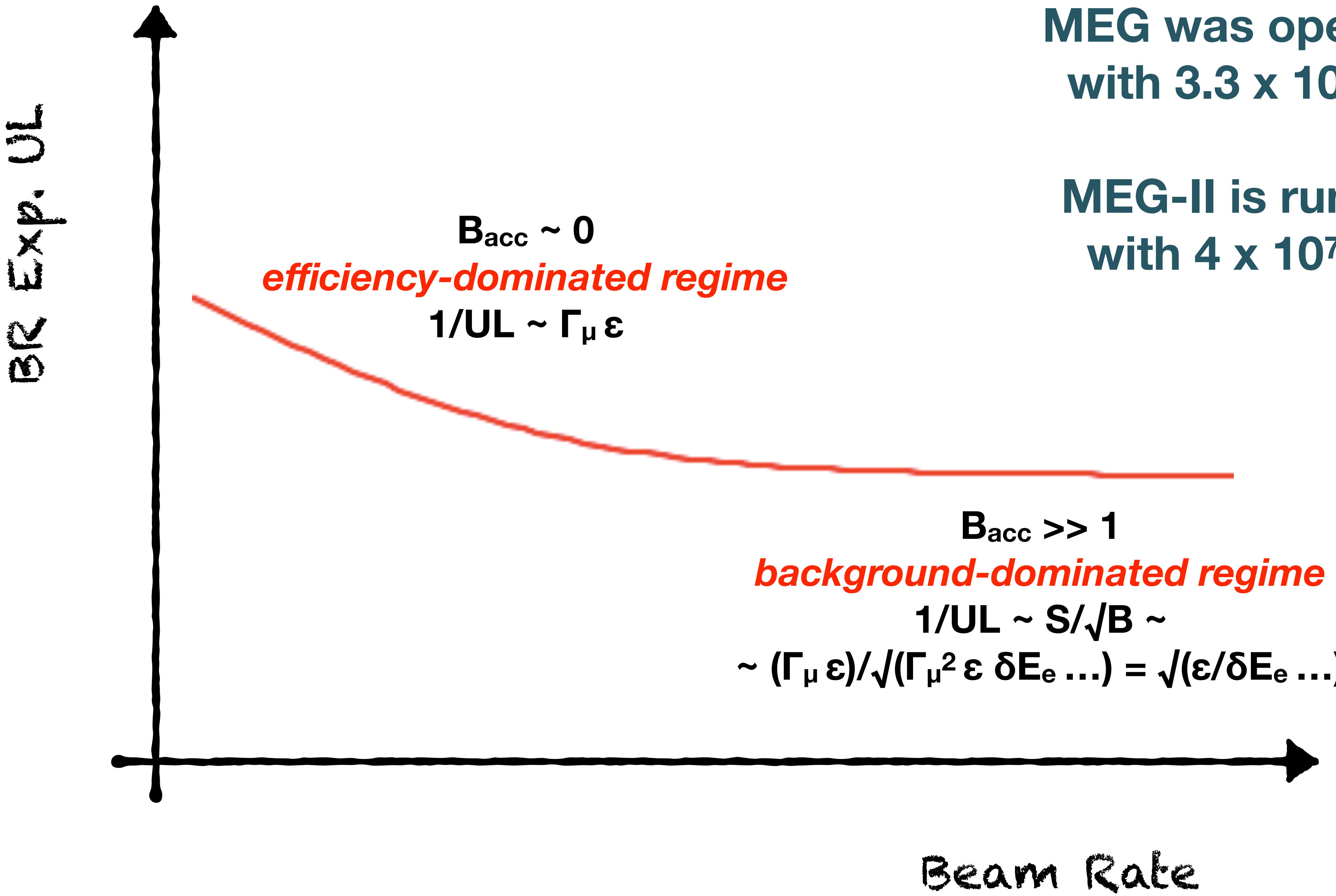
Acci … **ay (RMD)**

DOMINANT





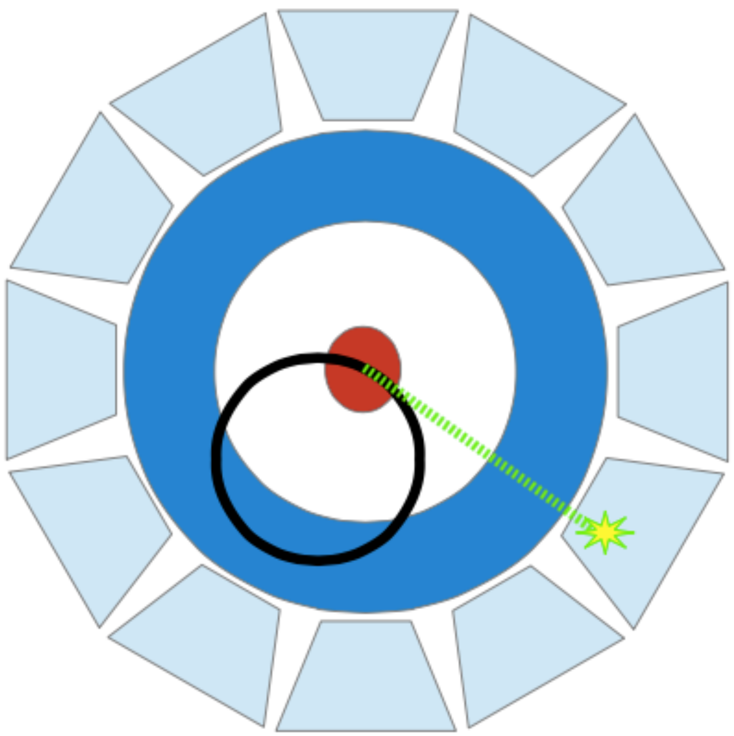
μ -> e γ searches



MEG was operated with 3.3×10^7 μ/s

MEG-II is running with 4×10^7 μ/s

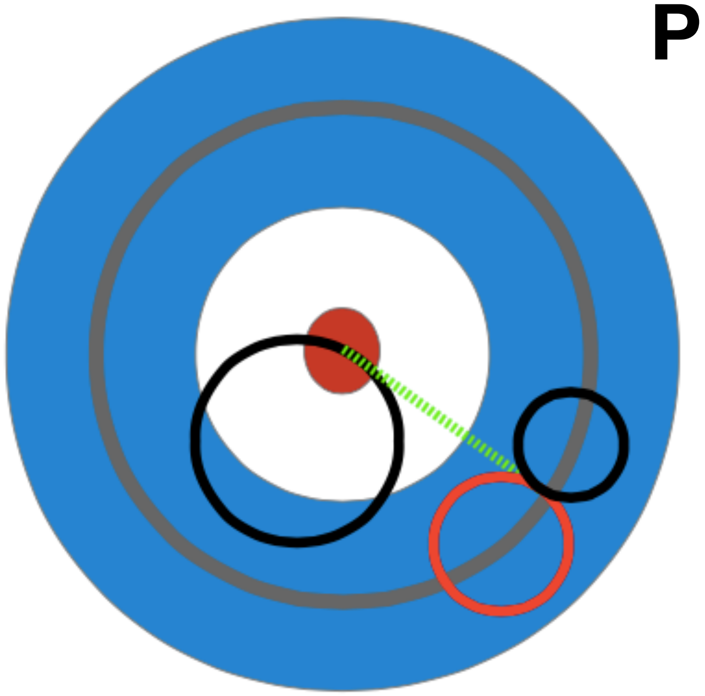
Toward the next generation of μ -> e γ searches: Photon Reconstruction



Calorimetry

High efficiency
Good resolutions

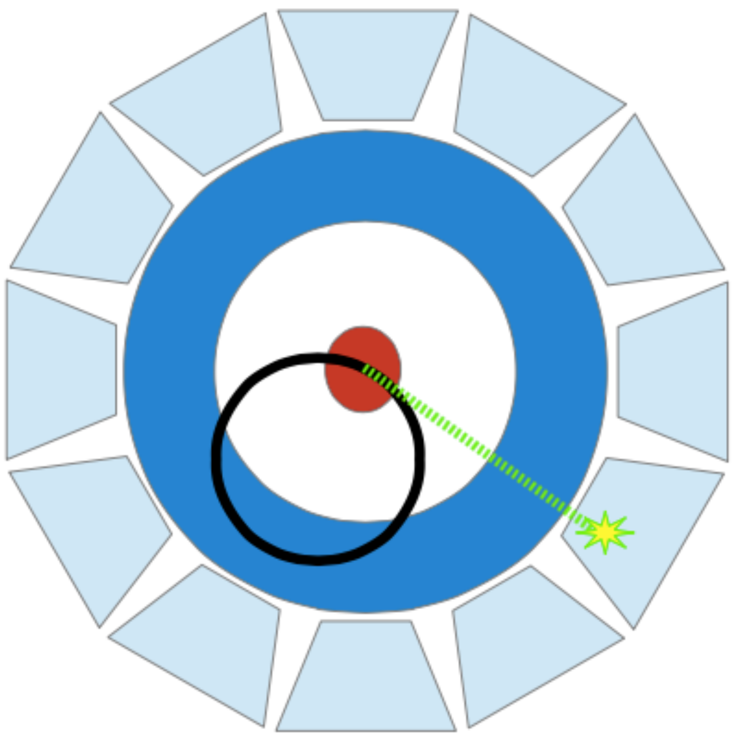
MEG:
LXe calorimeter
10% acceptance



Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

Toward the next generation of μ -> e γ searches: Photon Reconstruction



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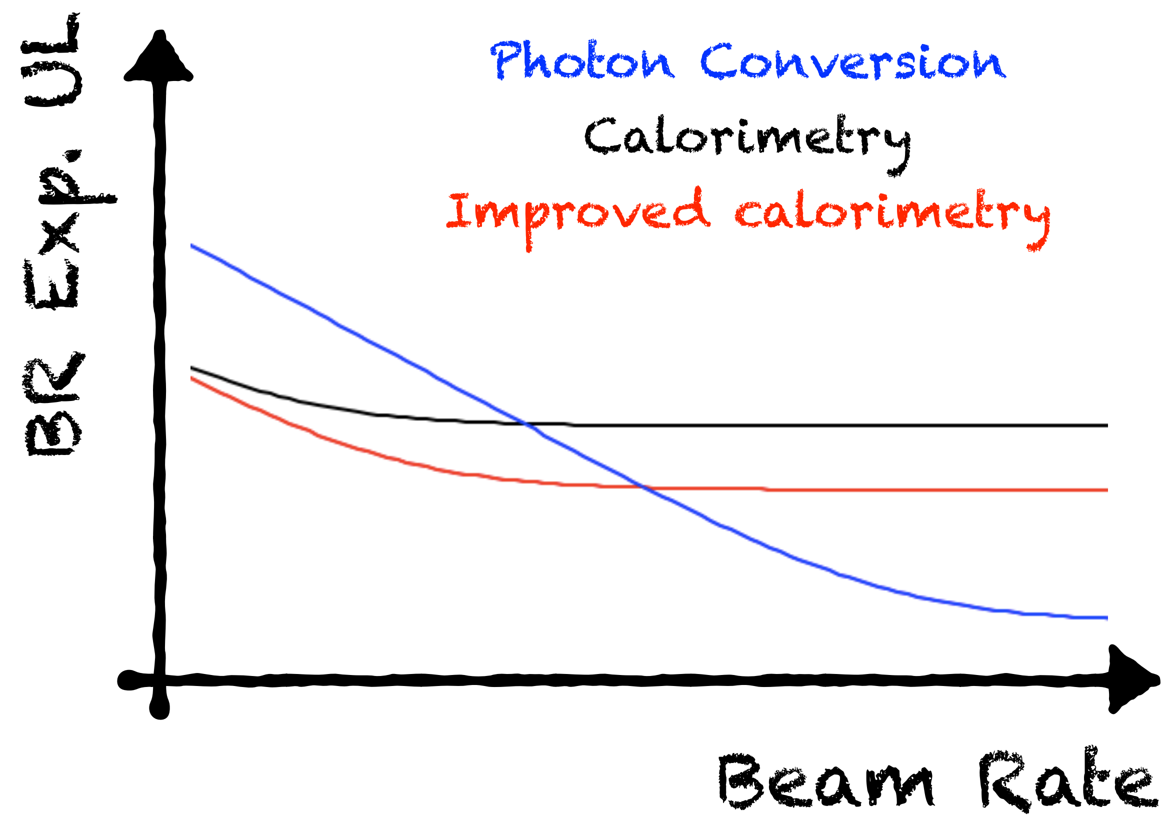
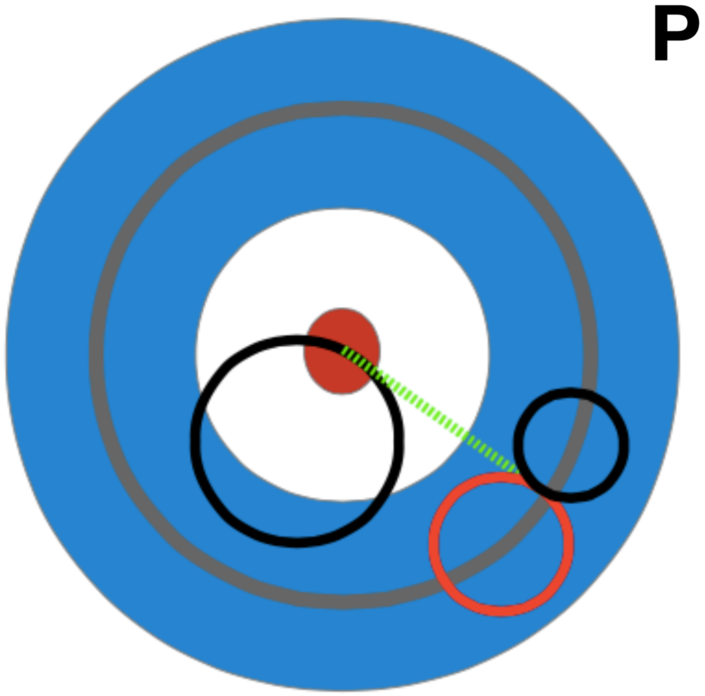




Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

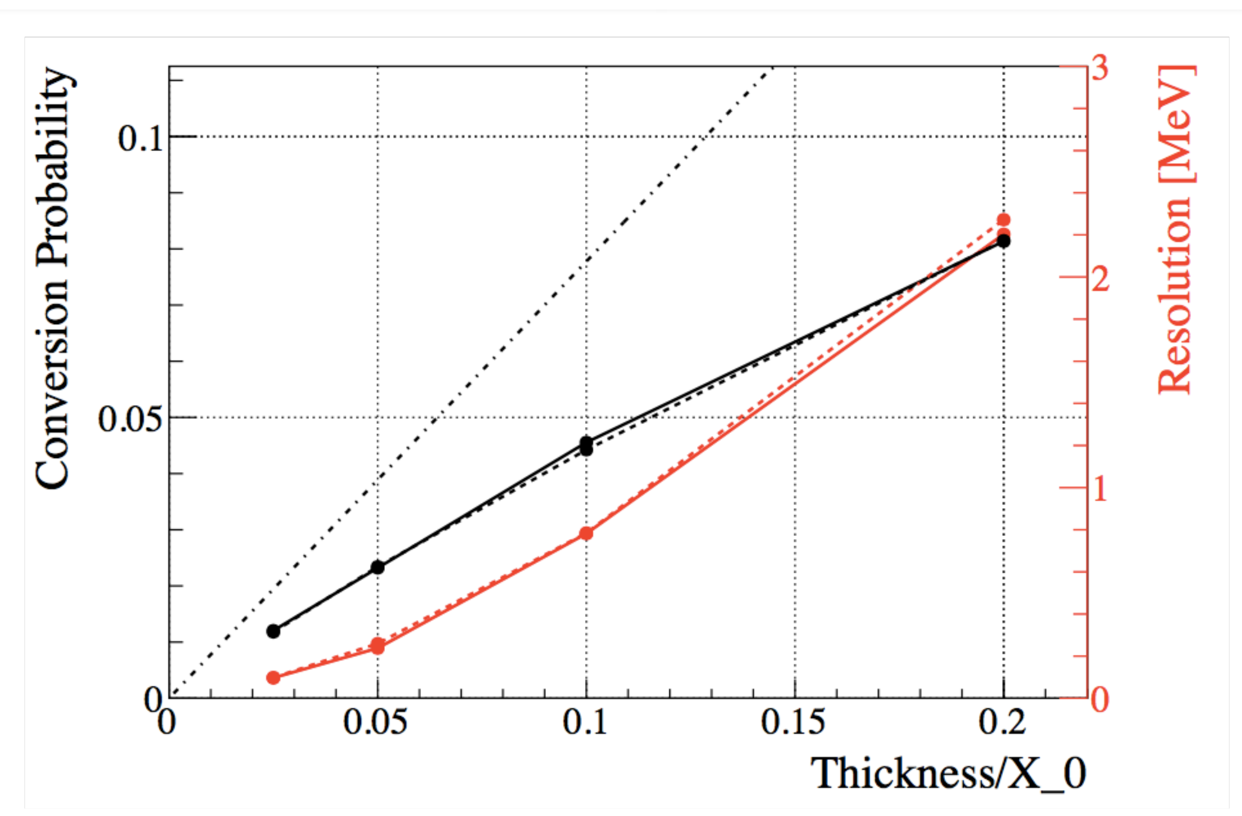
Limiting factors — Photon calorimetry

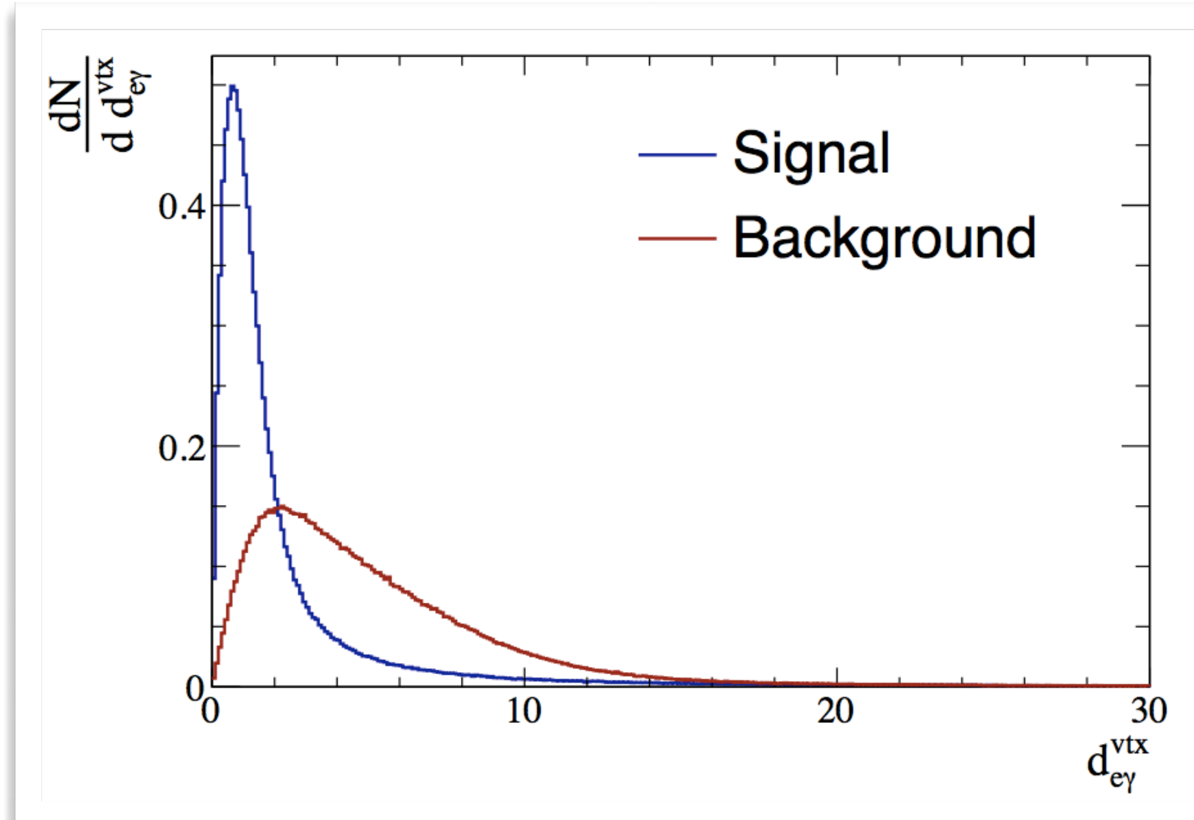
- MEG LXe calorimeter was a breakthrough, but could not get yet a photon energy resolution much better than 1 MeV:
  - not completely understood
  - limited acceptance due to large cost and complex infrastructure
- Innovative crystals like $LaBr_3$(Ce) — a.k.a. *Brillance* look a very good candidate for future experiments
  - 800 keV resolution could be within the reach
  - cost can be again an issue
- Time and position resolution looks less problematic
  - 30 ps is possible

Scintillator	**Density]** [g/cm^3]	**Light Yield** [ph/keV]	**Decay Time** [ns]
$LaBr_3$(Ce)	5.08	63	16
LYSO	7.1	27	41
YAP	5.35	22	26
LXe	2.89	40	45
NaI(Tl)	3.67	38	250
BGO	7.13	9	300

Limiting factors — Photon conversion

- Interactions in the converter (conversion probability, e+e- energy loss and MS)
- Possible improvement with active converter (see later)



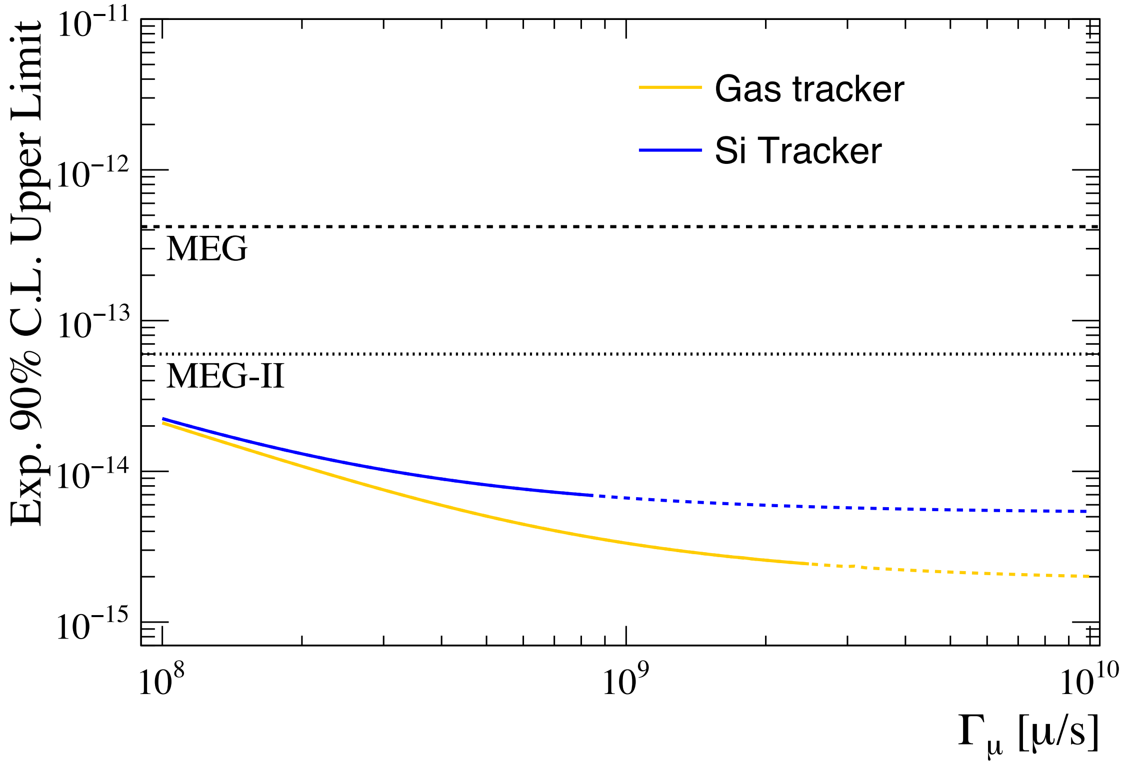


- Can take advantage of the photon direction determination form the e+e- reconstruction

$$d_{e\gamma}^{\mathrm{vtx}} = \sqrt{\left(\frac{X_e - X_\gamma}{\sigma_X}\right)^2 + \left(\frac{Y_e - Y_\gamma}{\sigma_Y}\right)^2}$$

Limiting factors — Positron

- Gaseous tracking detectors currently provide the best resolutions
  - very light gas mixtures
  - 100 keV energy resolution in MEG II



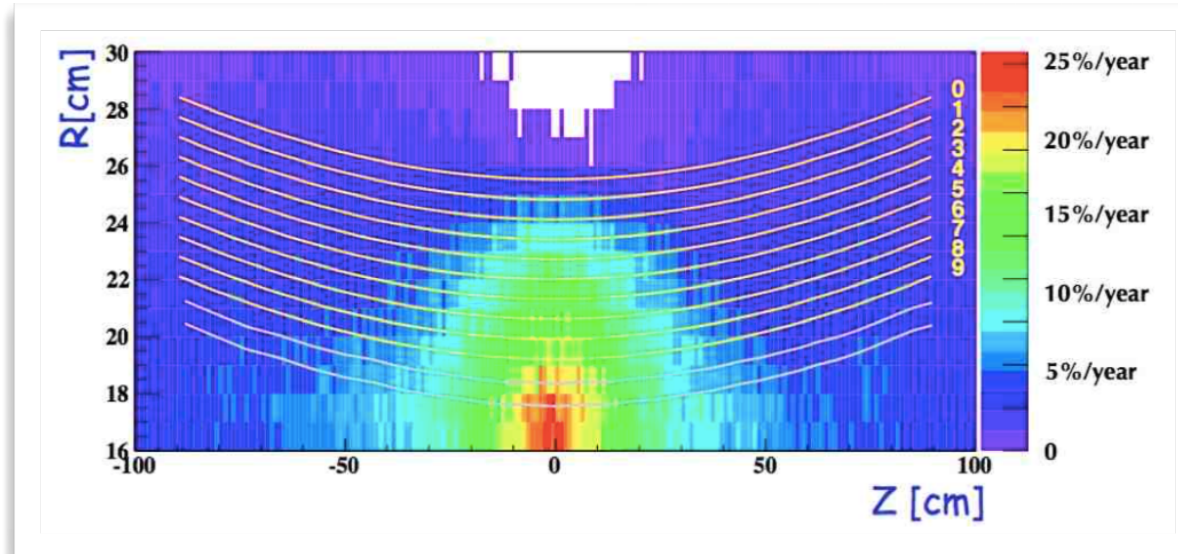
***modified from G. Cavoto et al., Eur.Phys.J.C* 78 (2018)**

Limiting factors — Positron

- Gaseous tracking detectors currently provide the best resolutions
  - very light gas mixtures
  - 100 keV energy resolution in MEG II
  - aging and pattern recognition are a severe issue at large rates
- Silicon detectors are becoming competitive with expected developments
  - going toward 25 μm HV-MAPS

Expected aging (gain loss) in MEG II

A. Baldini et al., arXiv:1301:7225



Limiting factors — Positron

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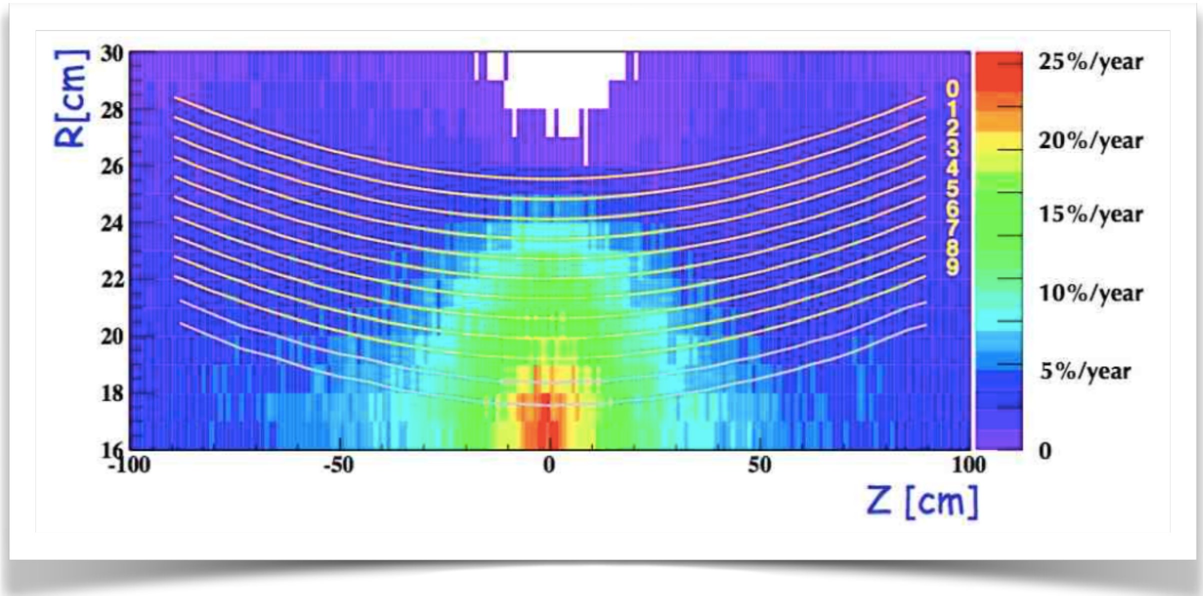
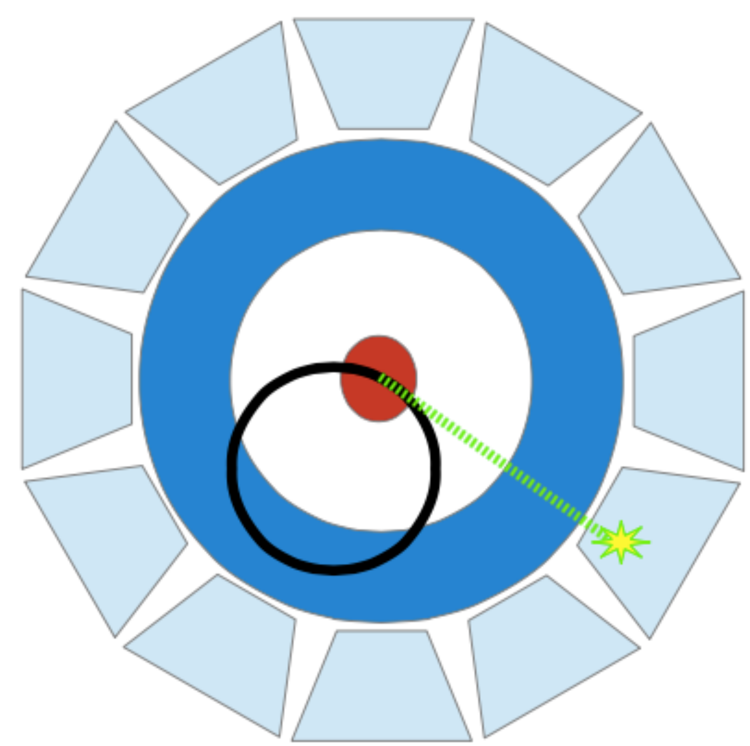
  - 100 keV energy resolution in MEG II
  - aging and pattern recognition are a severe issue at large rates
- Silicon detectors are becoming competitive with expected developments
  - going toward 25 μm HV-MAPS
- Multiple scattering before the detector (target + gas + detector walls)
  - ~ 4 mrad contribution to the angular resolutions

Expected aging (gain loss) in MEG II

A. Baldini et al., arXiv:1301:7225





MS in target and beam requirements

- In MEG and MEG II muons are stopped by a combination of a degrader and the target

- The degrader slows down the muons (—> thinner target to stop the average muon) but increases the momentum bite (—> thicker target to contain the Bragg peak)

    - optimization of degrader thickness to minimize the target thickness

- Starting from a lower beam momentum with comparable momentum bite can result in a thinner target

Study Group

- Informal group set up to follow up the discussion we had in the 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

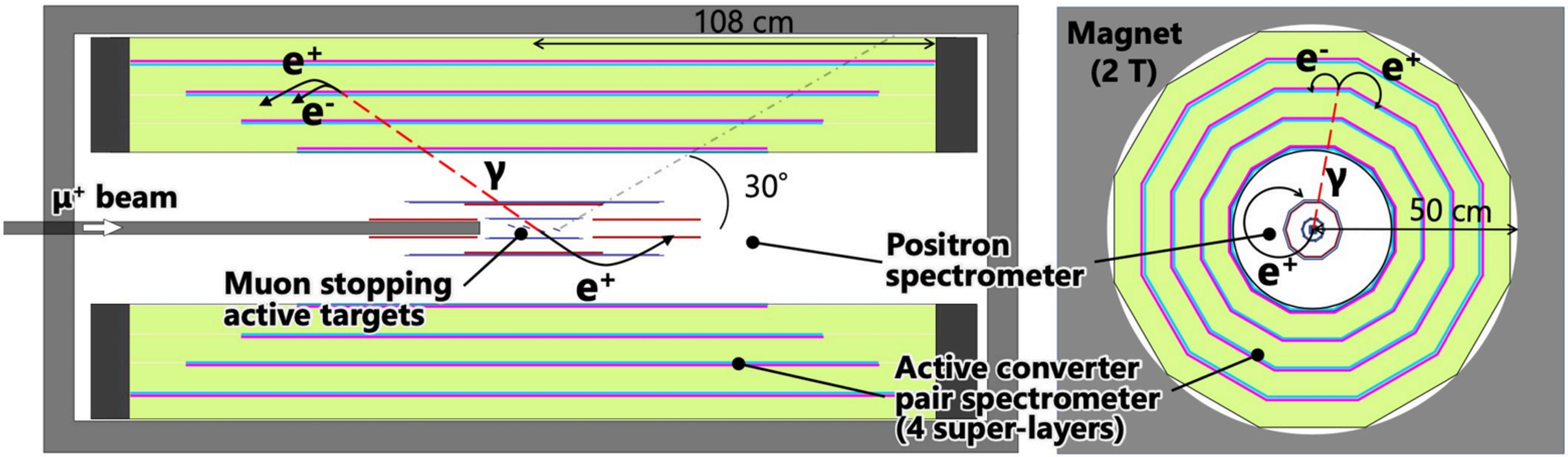
Photon

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

Positron

- Gaseous detector (F. Renga)
- Silicon (A. Schöning)

Conceptual design — Silicon tracker + Conversion



Positron Tracker — Silicon detectors

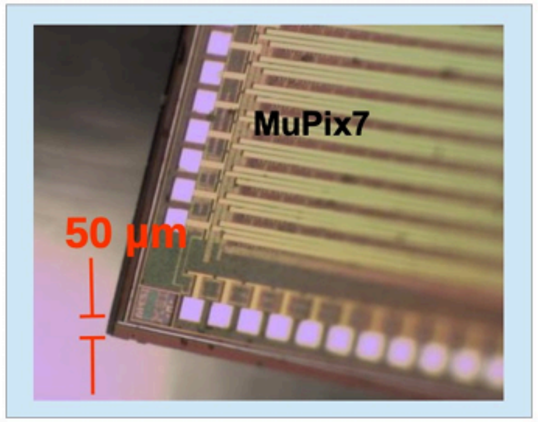
A. Schöning

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

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

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

MuPix (HV-MAPS)

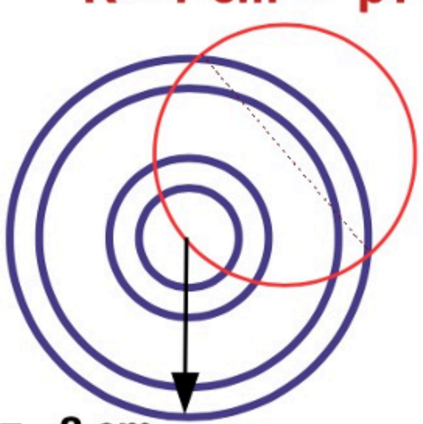


Monolithic pixel sensor in 180 nm HV-CMOS

Example (p_e=53 MeV/c):

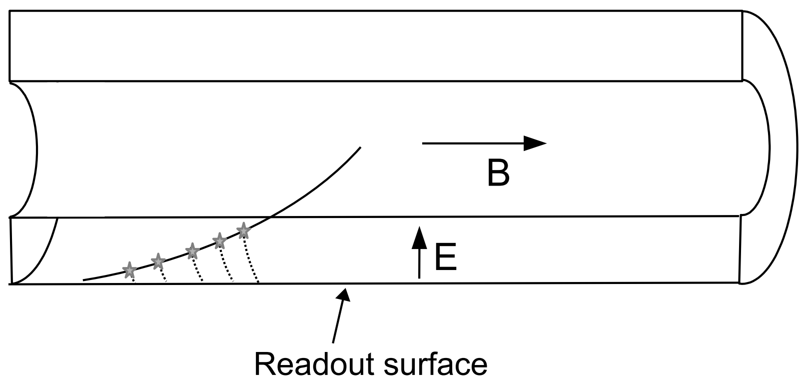
- 50 µm Si → $\sigma(\Theta_e) = 6.0$ mrad
- 30 µm Si → $\sigma(\Theta_e) = 4.6$ mrad

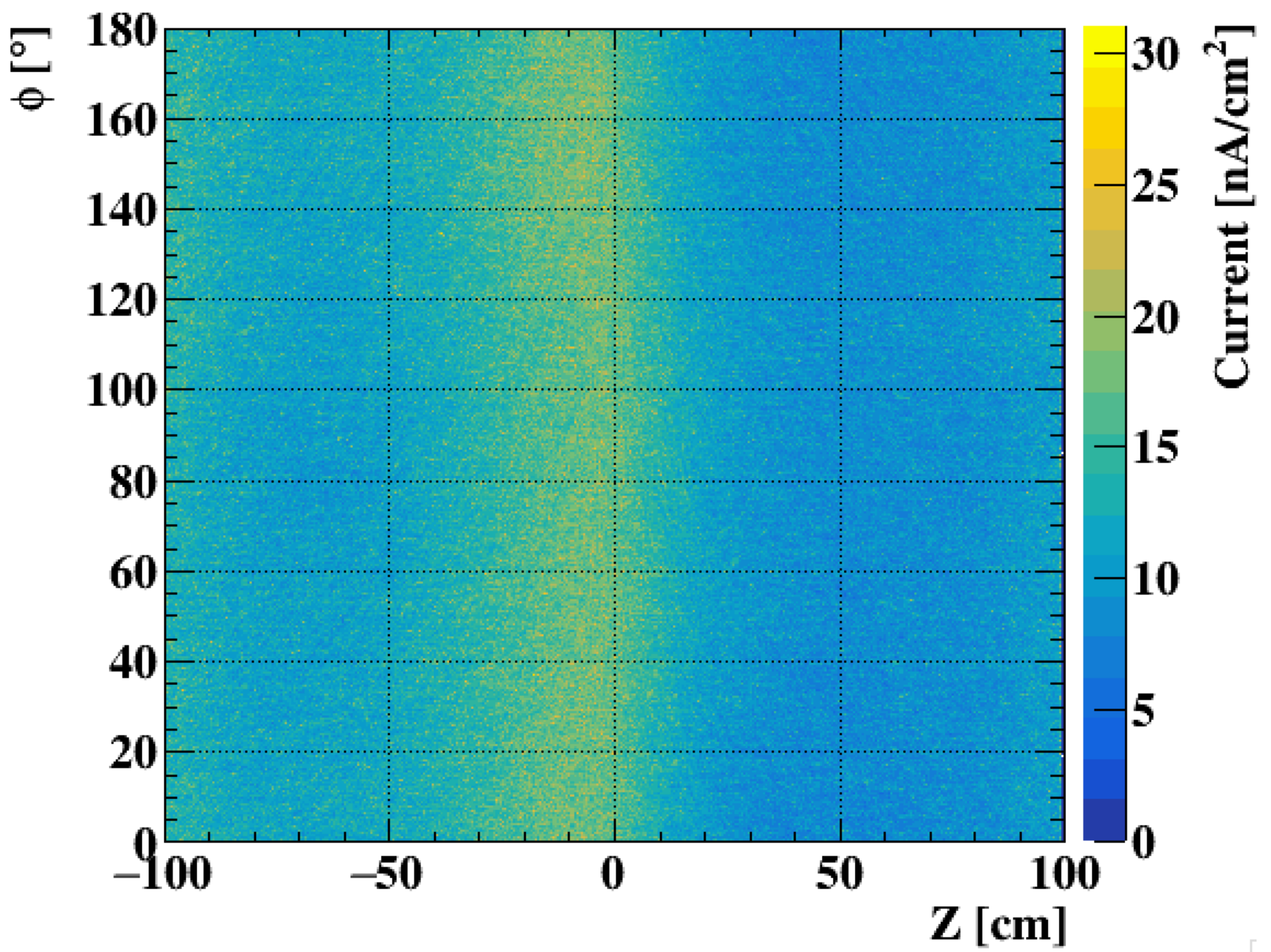
B = 2.6 Tesla



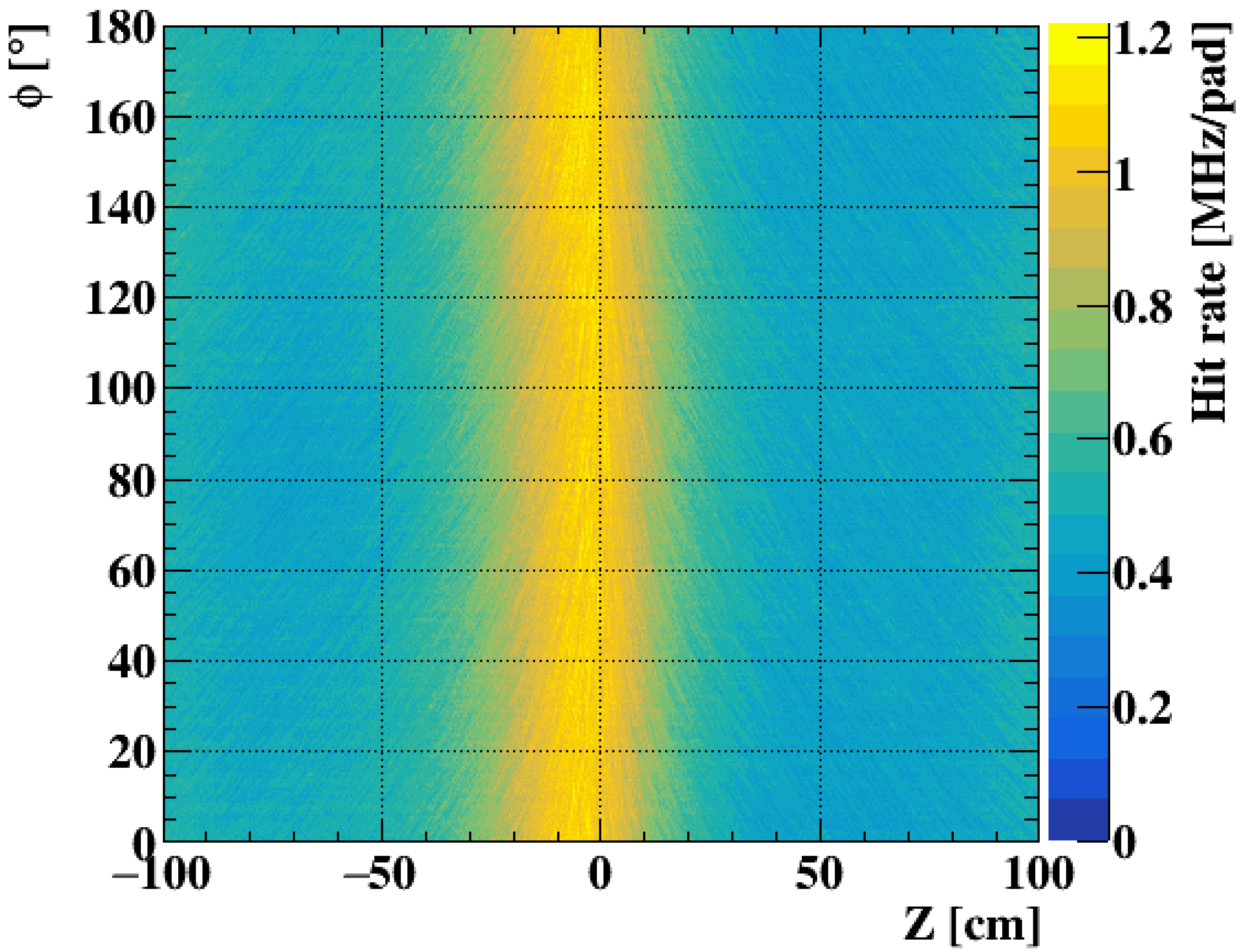
Positron Tracker — Gaseous detectors

- 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)





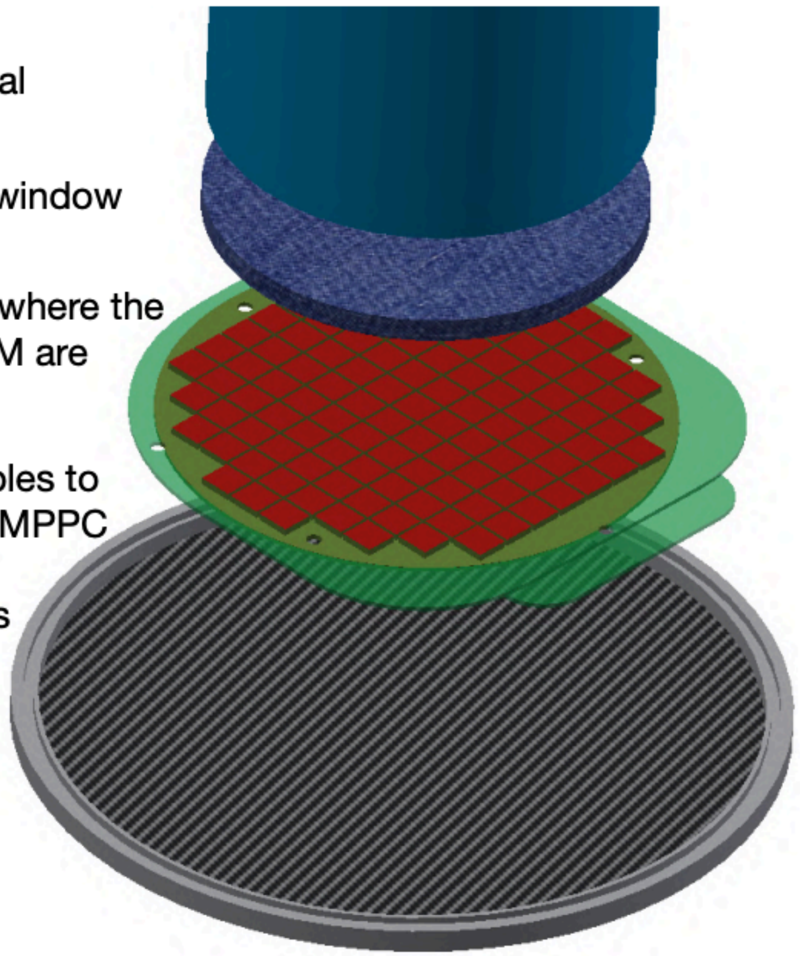
cfr. ALICE GEM-TPC ~ 10 nA/cm²

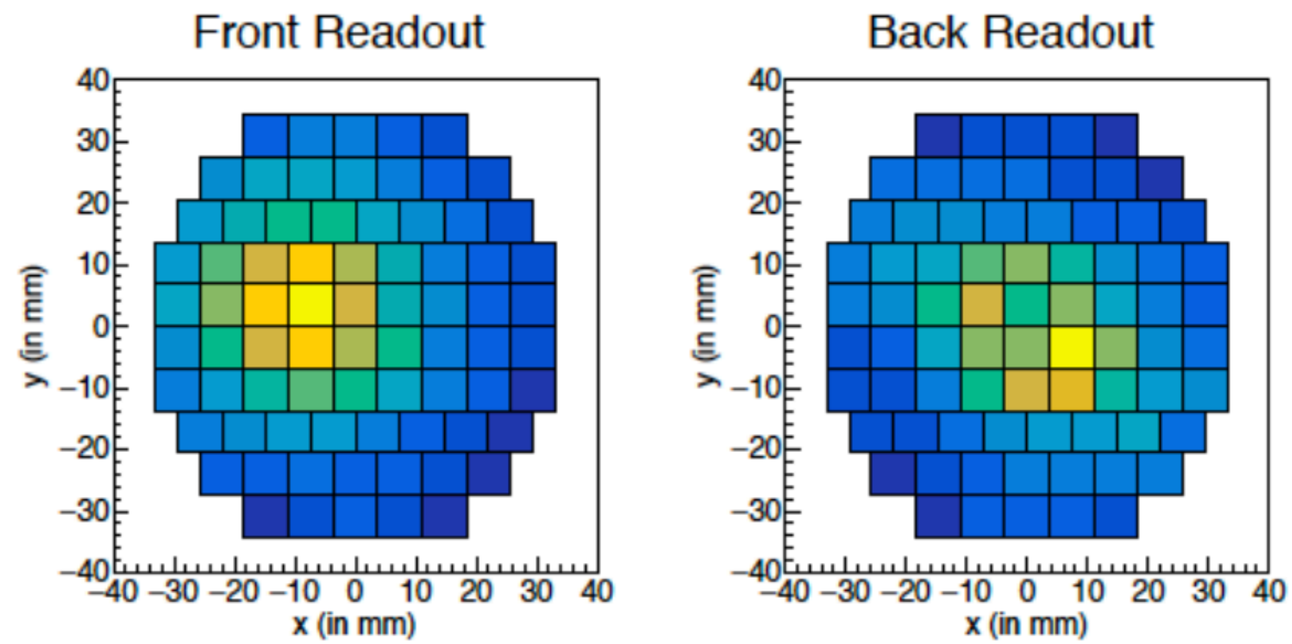


Assuming 5 x 3 mm² pads

Photon detector — Calorimetery

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





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

Expected performances:

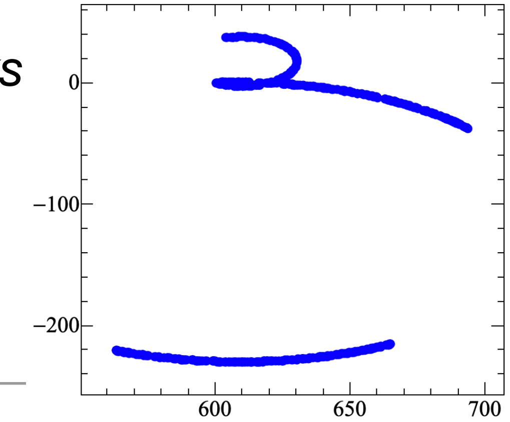
- σ_e/E [%] = 1.7(1)
- σ_t [ps] = 35(1)
- $\sigma_{tx,y,z}$ [mm] = 3-5

A. Papa

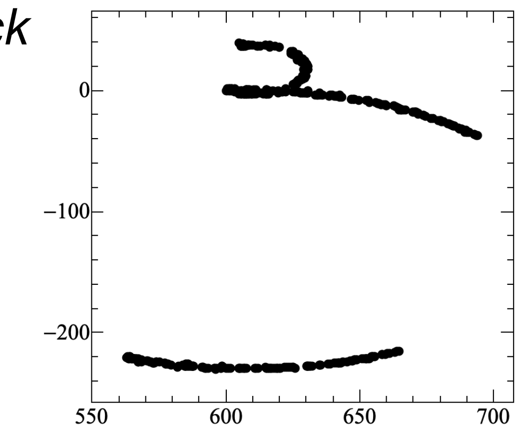
Photon detector — Conversion

W. Ootani

True tracks

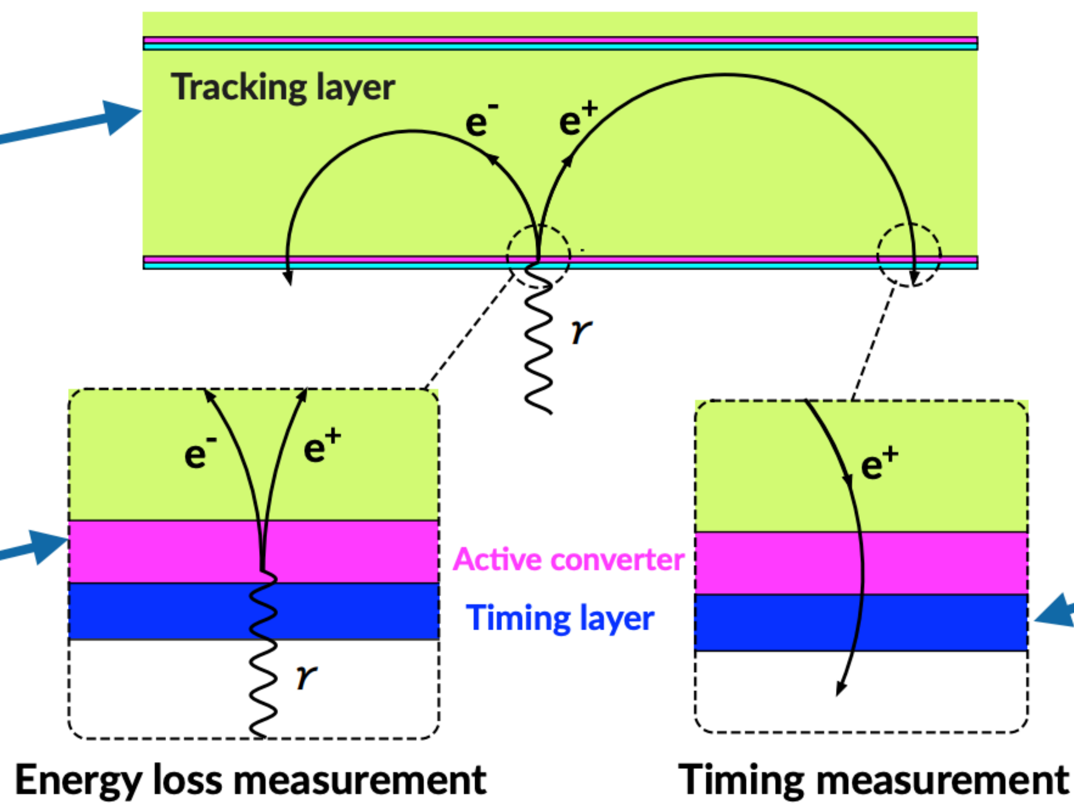


Reco track



Tracking layer

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

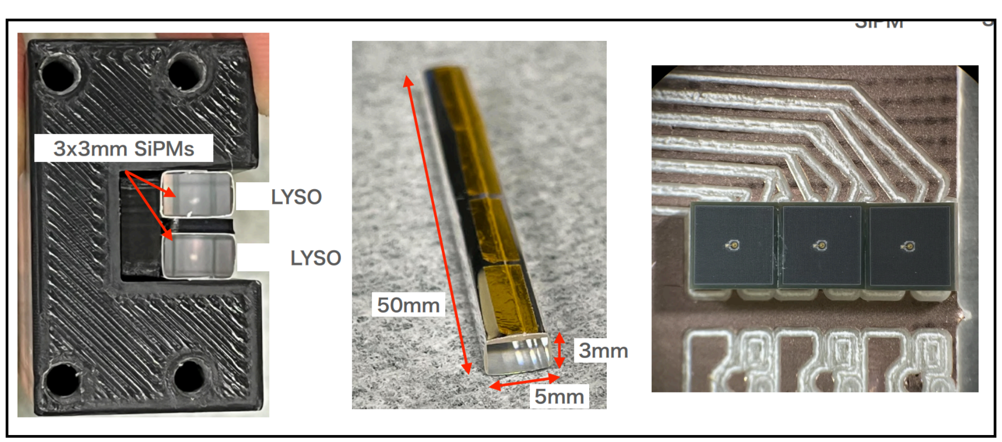


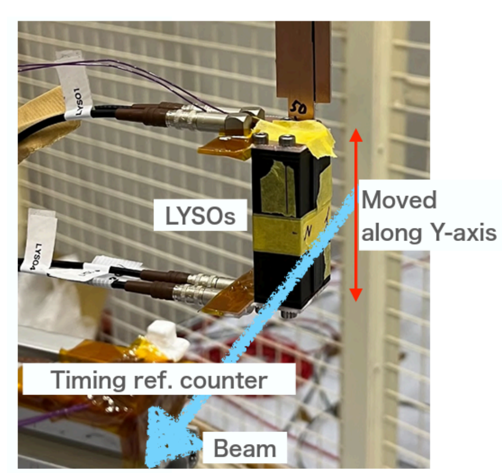
Active conversion layer

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

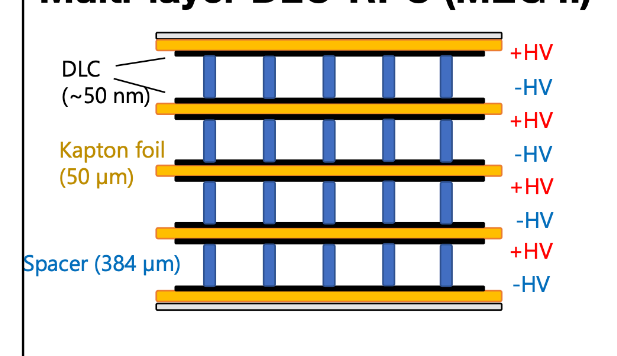
Timing layer

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



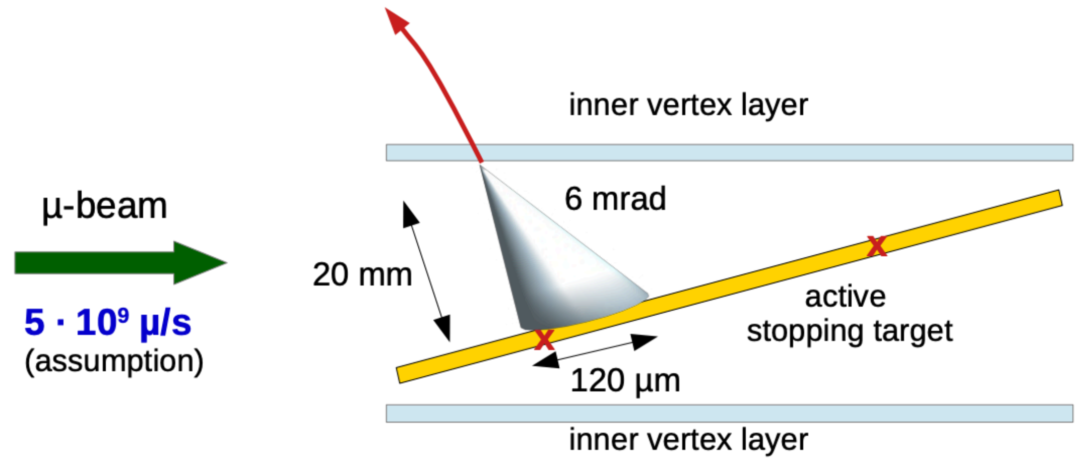


Multi-layer DLC-RPC (MEG II)



Random ideas for futuristic μ -> e γ searches

- Active targetry
  - μ/e separation
  - very thin

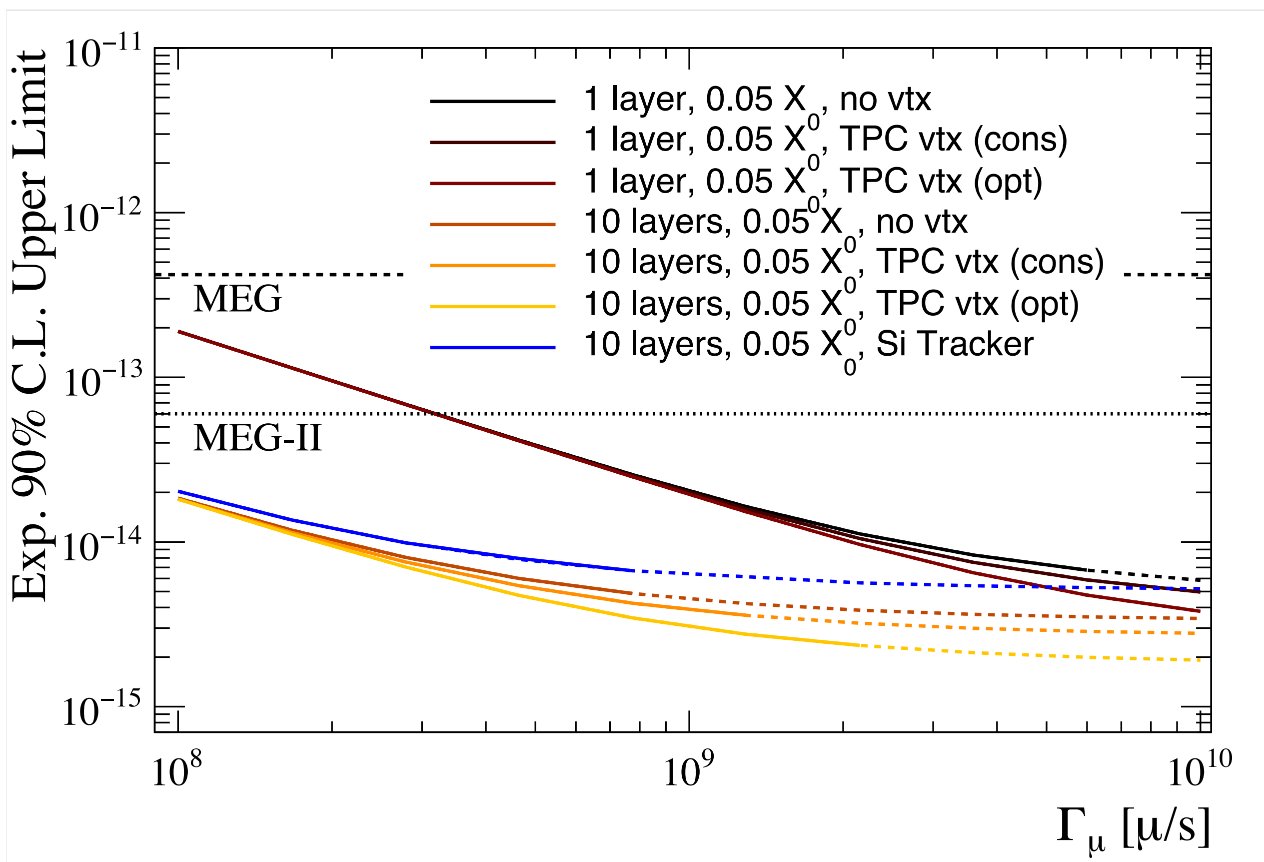


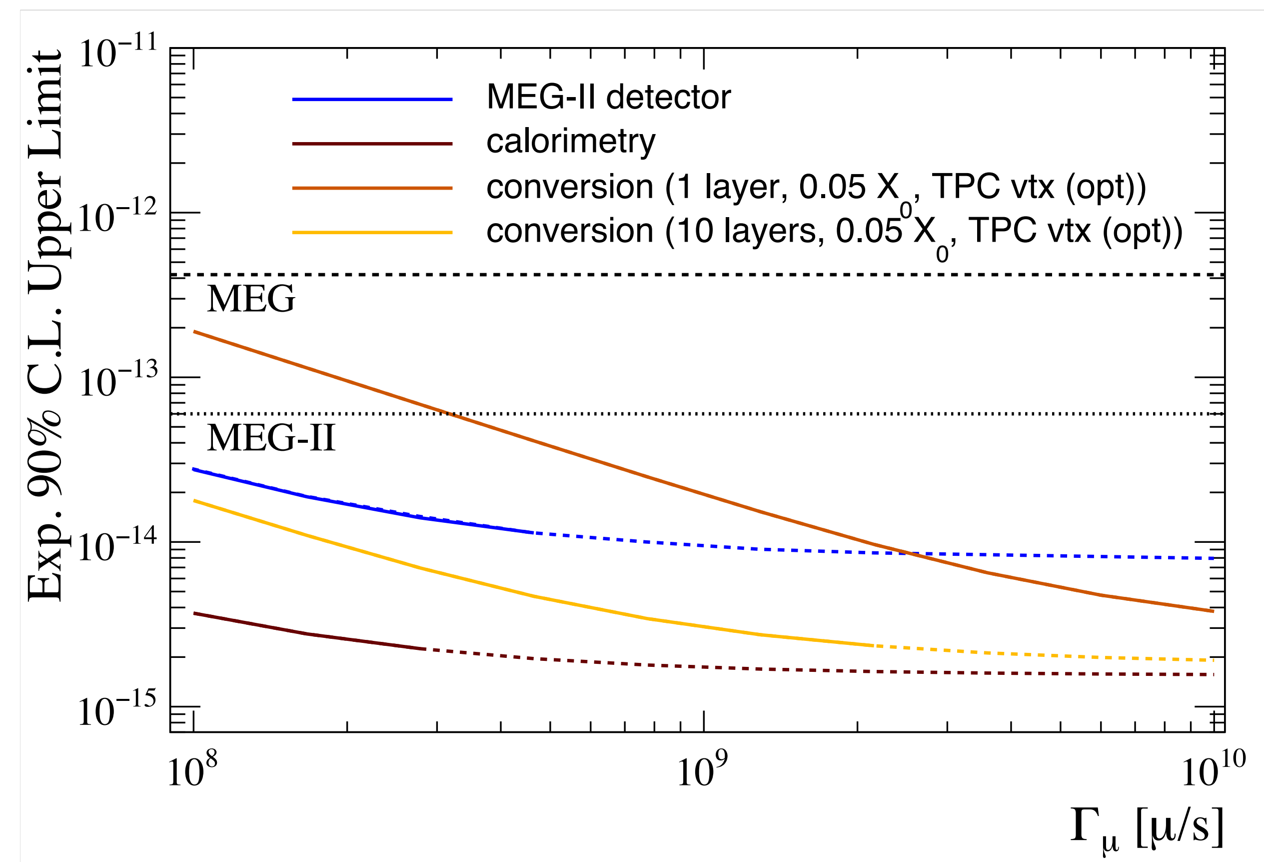
- Target + detector in vacuum
  - containing the Bragg peak would not be needed anymore (—> thinner target and compensate with more intensity)
  - multiple target option
  - could next-generation straw tubes be a good option for tracking also in μ -> e γ? Too much supporting material? What about silicon detectors (cooling)?

- What about spreading muon stops over a very large surface?
- 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

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

Expected Sensitivity





A few 10^{-15} seems to be within reach for a 3-year run at ~ 10^8 μ/s with calorimetry (*expensive*) or ~ 10^9 μ/s with conversion (*cheap*)

Fully exploiting 10^{10} μ/s and breaking the 10^{-15} wall seem to require a ***novel experimental concept***

Backup

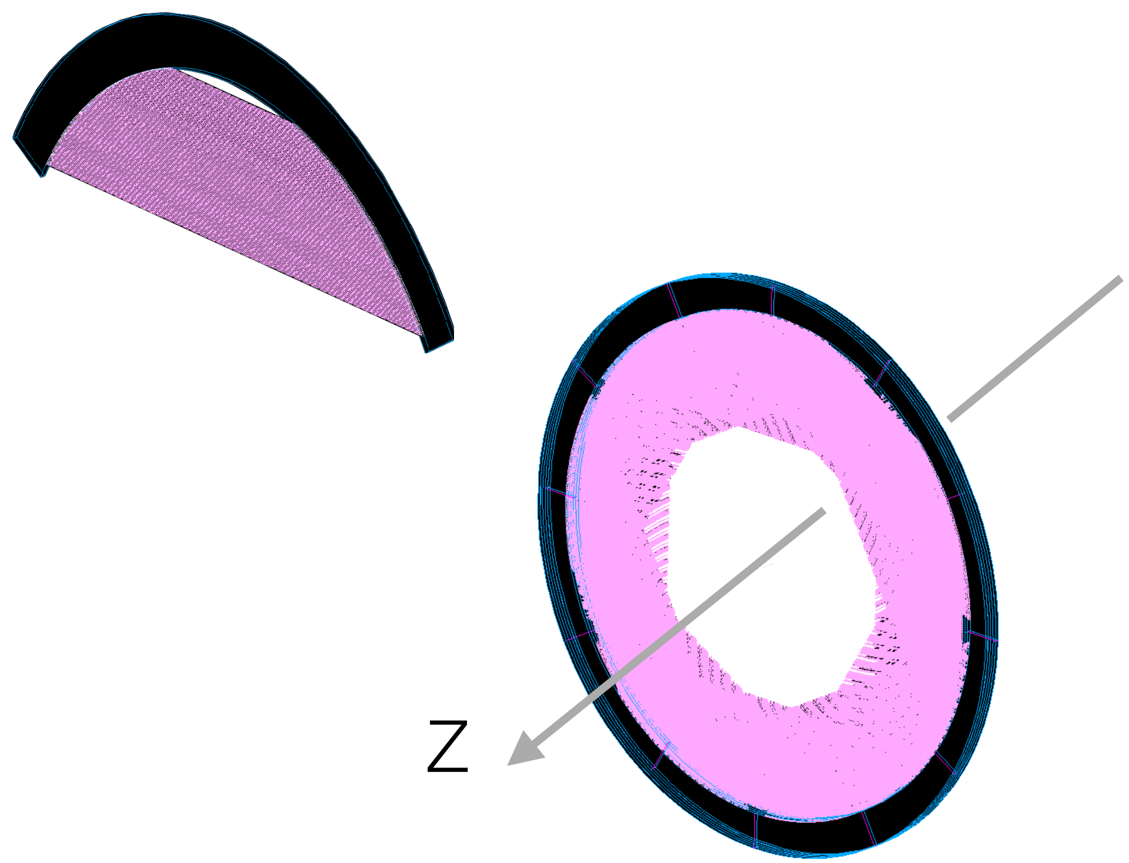
Gaseous positron trackers toward 10^9 - 10^{10} μ/s

- 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**

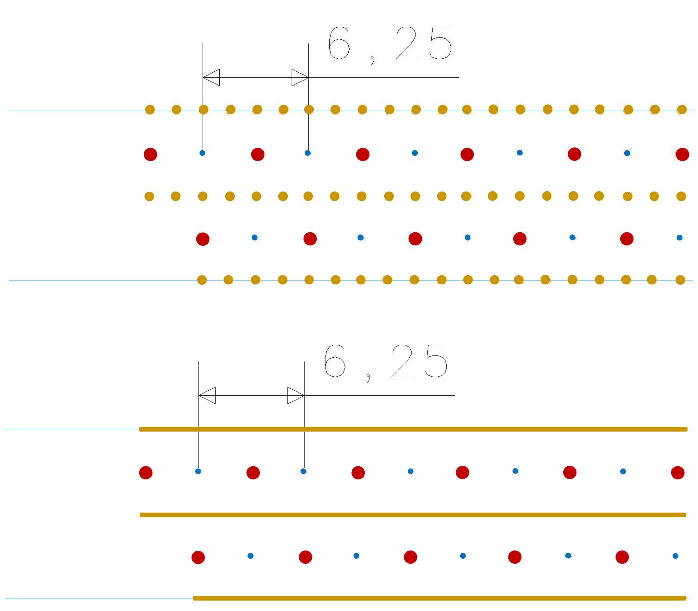
Drift chamber

- 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

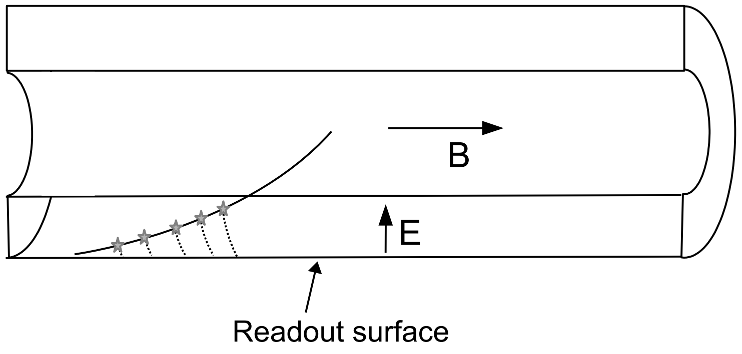


The main challenge is the material budget

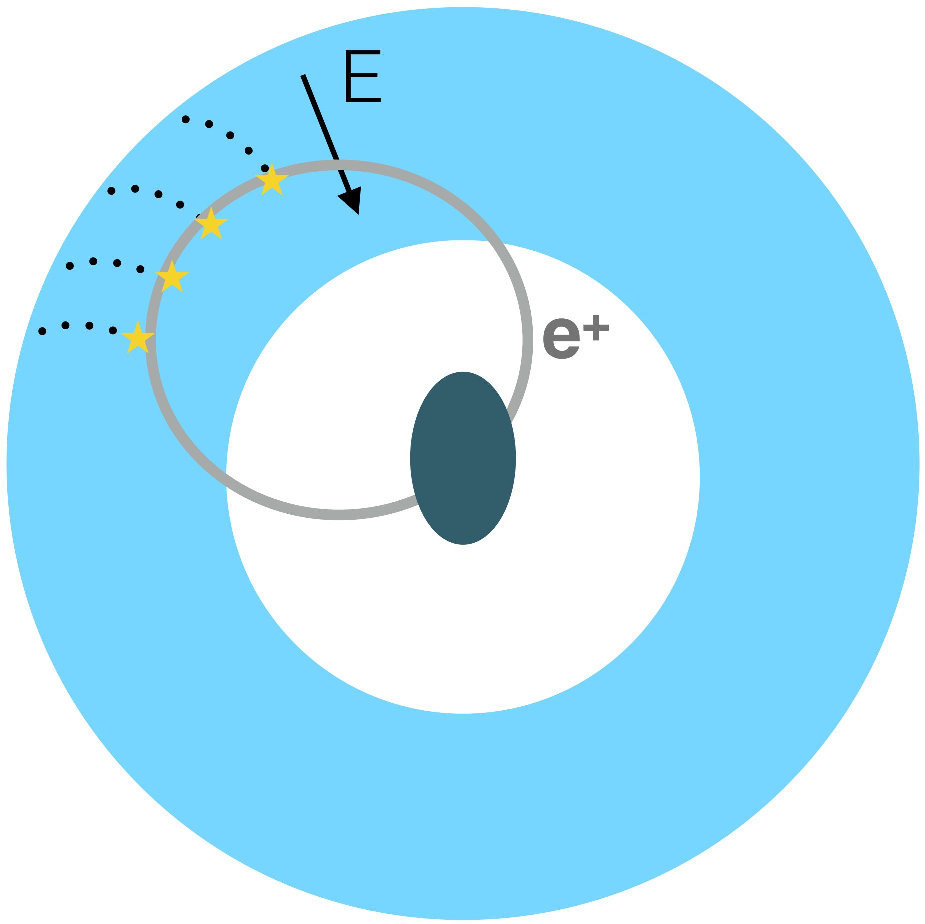
- very light wire supports
- no electronics in the tracking volume —> long transmission lines



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

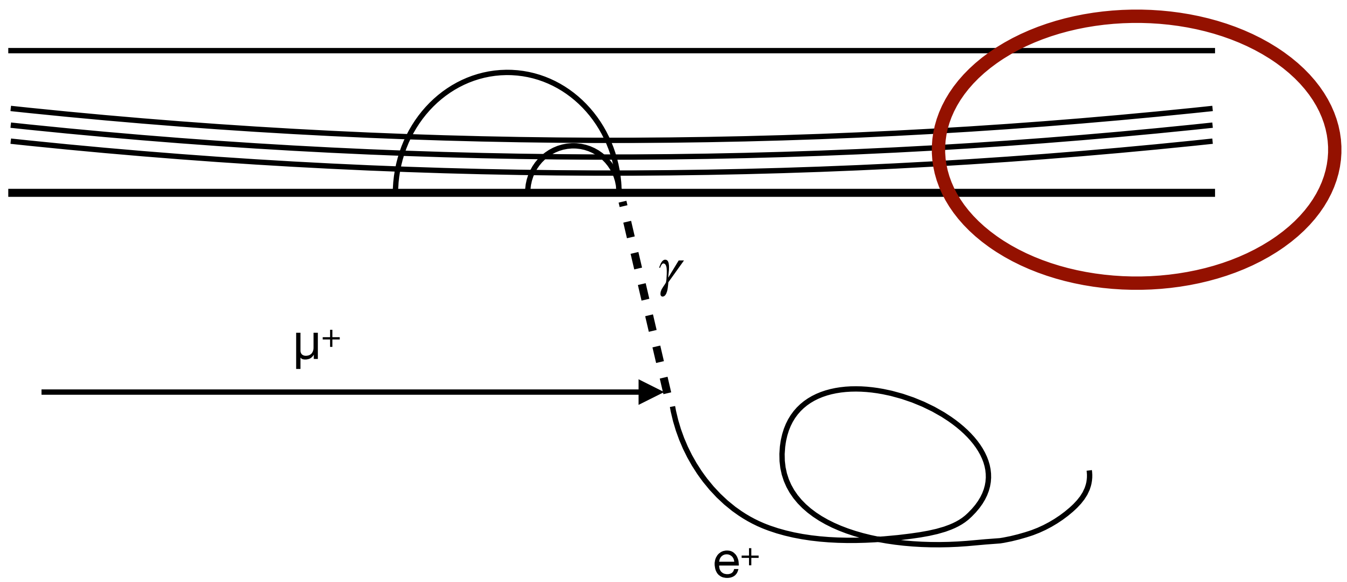
Need to find a very light gas mixture to operate it with reasonably low diffusion

Need to develop advanced algorithms for correcting field deformations

Gaseous tracker for photon reconstruction

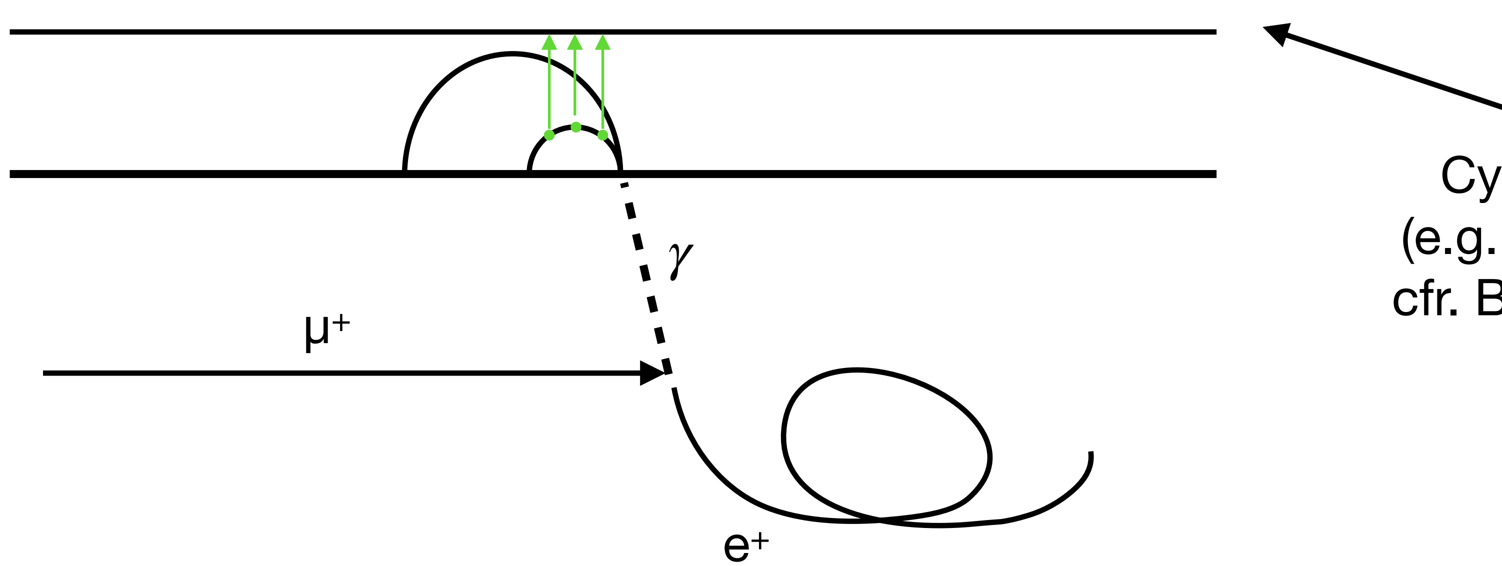
- Low rate —> much less demanding w.r.t. positron trackers

Wire chamber



Low efficiency at low momentum in this region (even for a graded B field)

Radial TPC

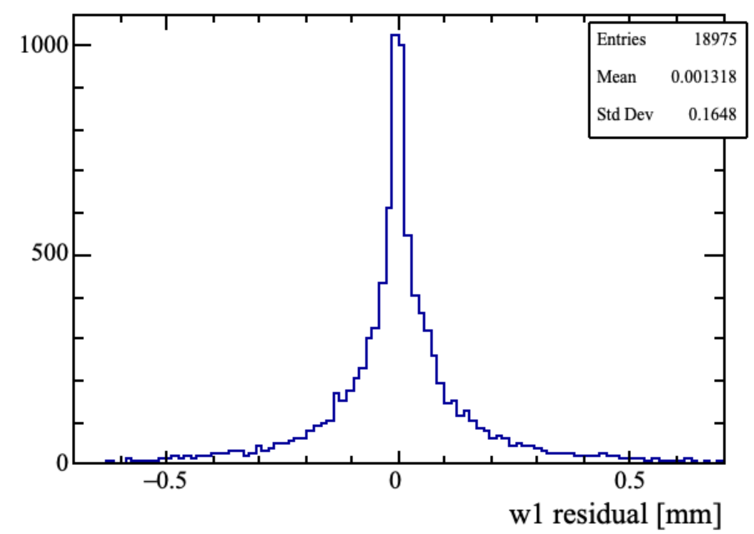


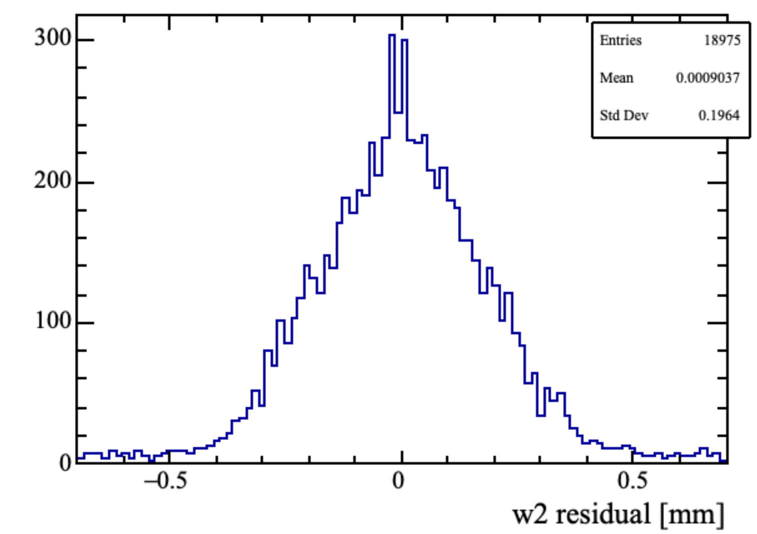
Cylindrical MPGD
(e.g. cylindrical GEM,
cfr. BES-III and KLOE)

Feasibility studies

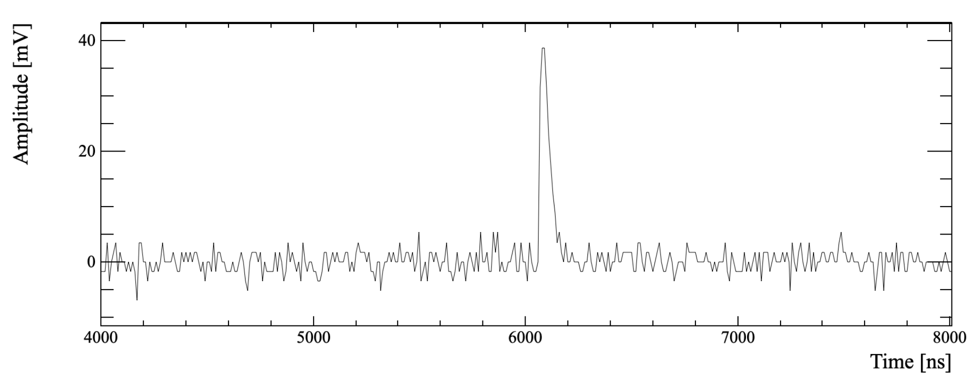
e+e- reconstruction in a radial TPC with strip readout

WORK IN PROGRESS

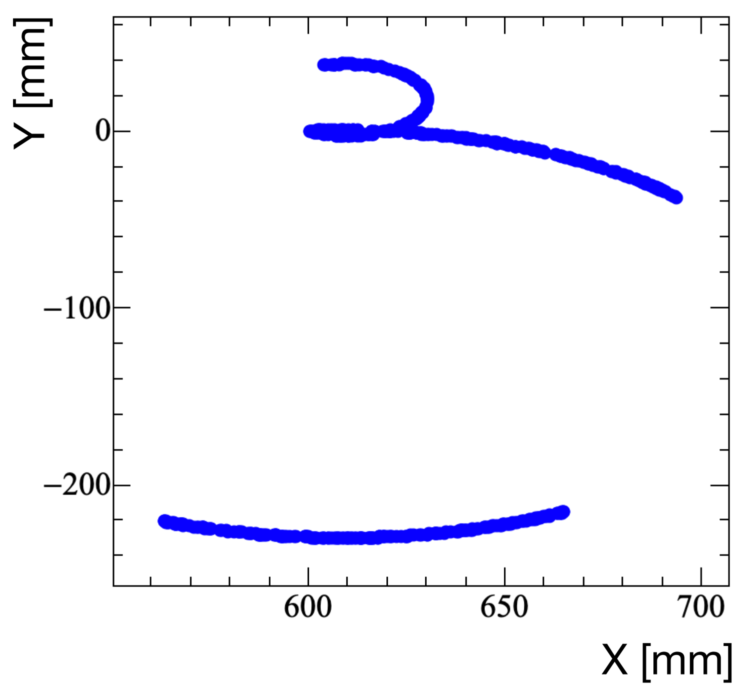




Typical waveform



True tracks



Reco track
(time resolved CoG)