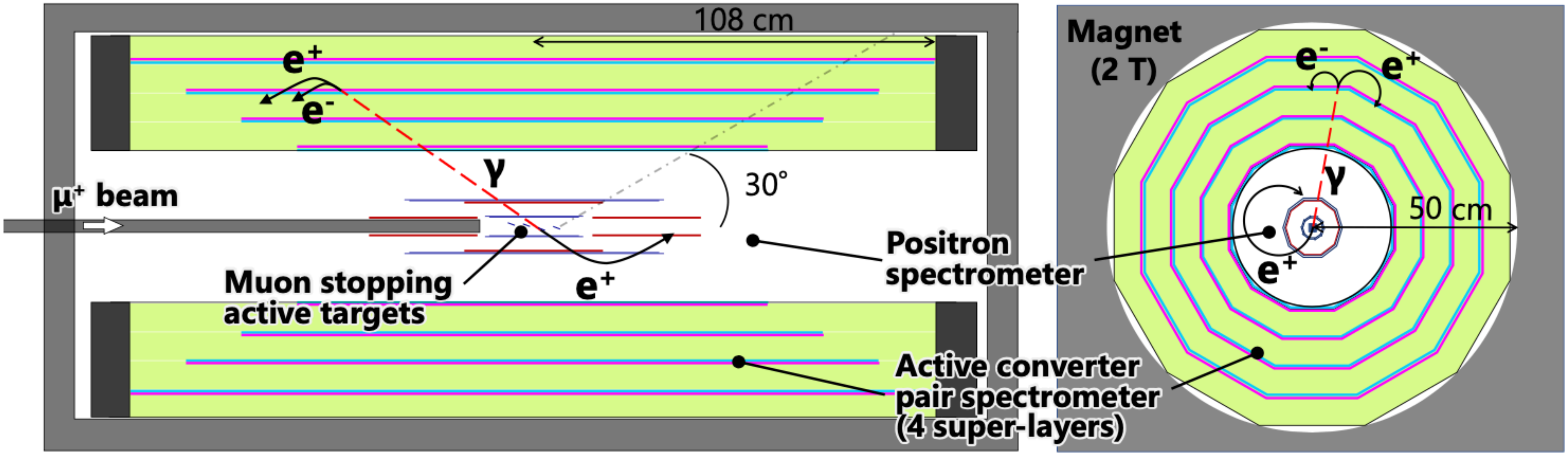
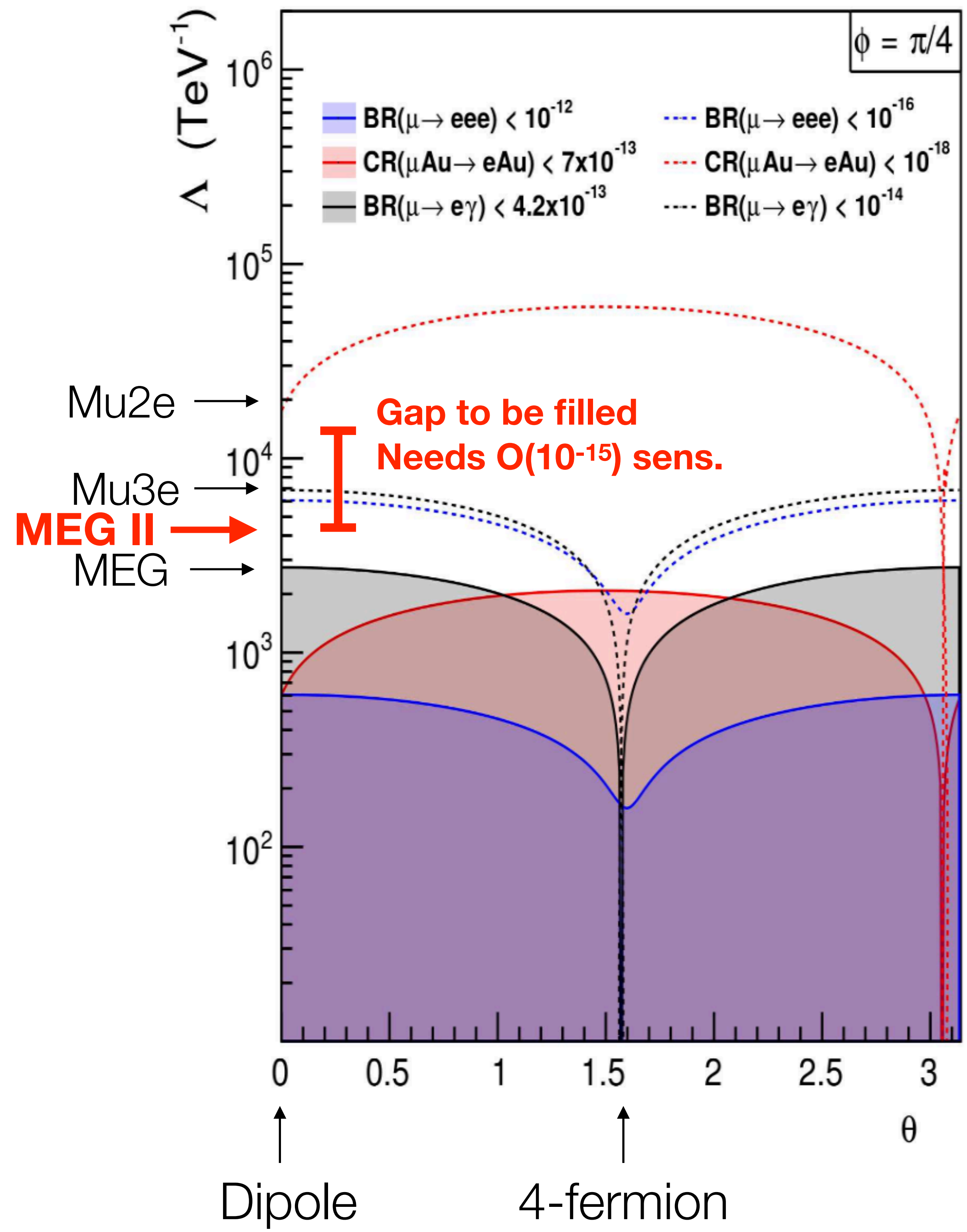


μ -> e γ Photon Detection Techniques

Francesco Renga
INFN Roma

Physics motivation

- In EFT, muon cLFV takes contributions from several different operators
- Each operator affects differently the three golden channels (μ -> e γ, μ -> 3e, and μ -> e conversion)
    - if an observation is done in one channel, we learn nothing about the underlying physics unless we have searches of the others with comparable sensitivity
- It is critical to maintain comparable sensitivities in all channels
- *We have a unique know-how to effectively initiate an effort toward the next μ -> e γ search*



HiMB @ PSI and the future of $\mu \rightarrow e\gamma$

- An upgrade of the PSI muon beamlines is foreseen during a 2027-2028 long shutdown
    - up to 10^{10} μ/s in the new experimental areas —> can we exploit it?

The study Group for Future μ -> e γ experiment

Future perspectives for $\mu^+ \to e^+\gamma$ searches

Contact Persons: Waratu Ootani[1] and Francesco Renga[2]

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Abstract

Searches for charged lepton flavor violation in the muon sector stand out among the most sensitive and clean probes for physics beyond the Standard Model. Currently, $\mu^+ \to e^+\gamma$ experiments provide the best constraints in this field and, in the coming years, new experiments investigating the processes of $\mu^+ \to e^+e^+e^-$ and $\mu \to e$ conversion in the nuclear field are anticipated to surpass them. However, it is essential to maintain comparable sensitivities across all these processes to fully leverage their potential and differentiate between various new physics models if a discovery occurs. In this document, we present ongoing efforts to develop a future experimental program aimed at improving the sensitivity of $\mu^+ \to e^+\gamma$ searches by one order of magnitude within the next decade.

Input submitted to the ESPPU, arXiv:2504.18831

THE STUDY GROUP FOR FUTURE $\mu^+ \to e^+\gamma$ EXPERIMENTS

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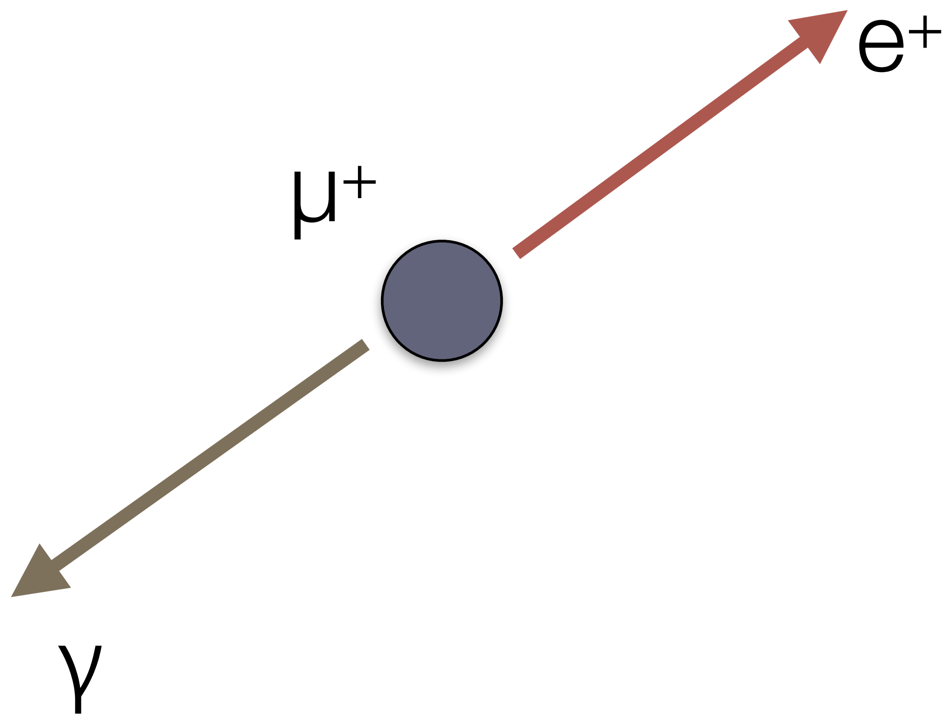
Not an effort within the MEG II and/or the Mu3e collaborations, but a cooperation among individuals from MEG II and Mu3e, and open to external contributions

μ -> e γ searches

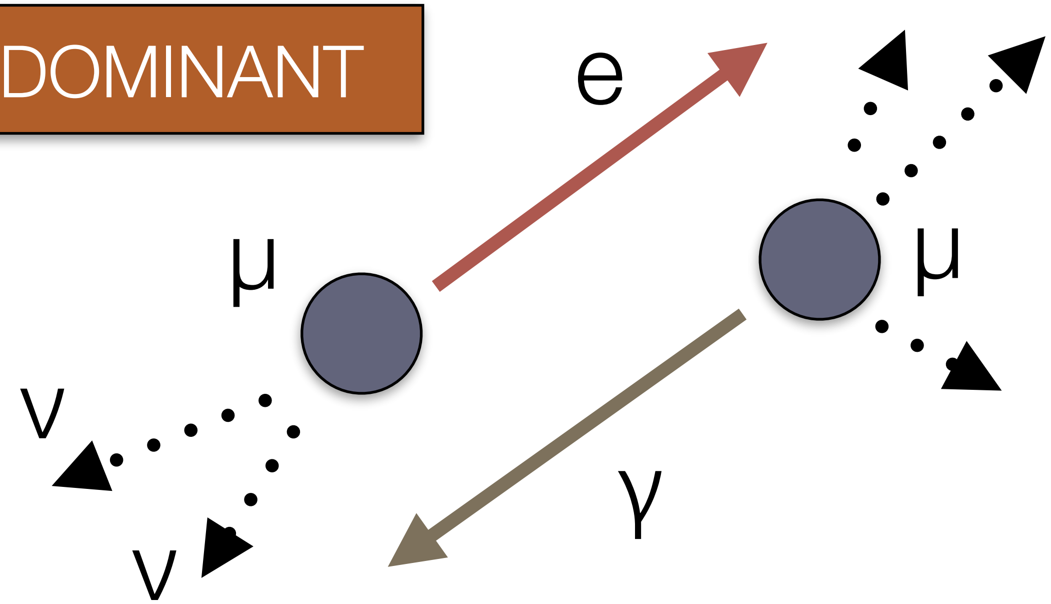


28 MeV/c muons are stopped on a thin target

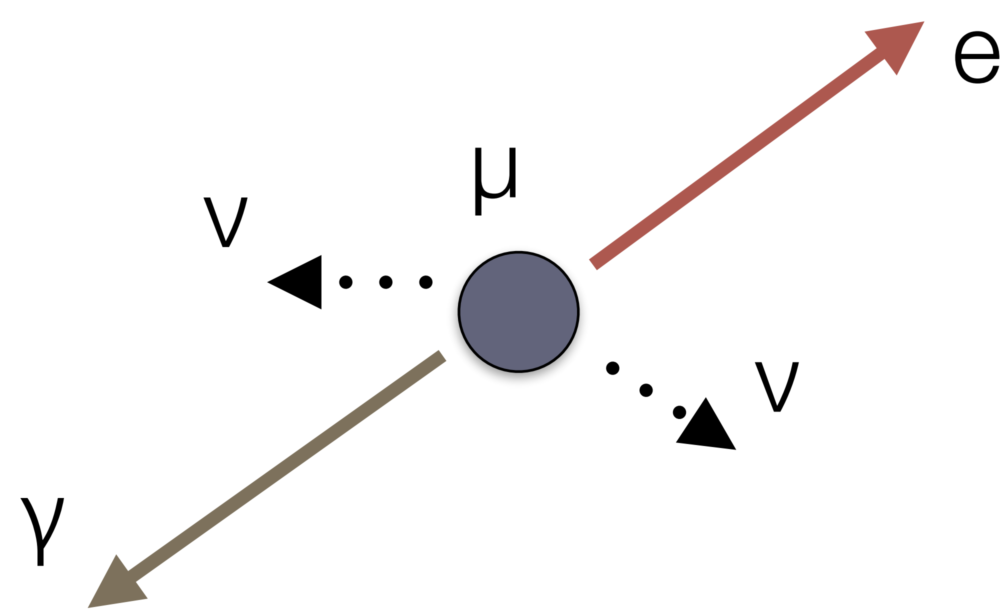
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the same time;

Accidental Background

DOMINANT

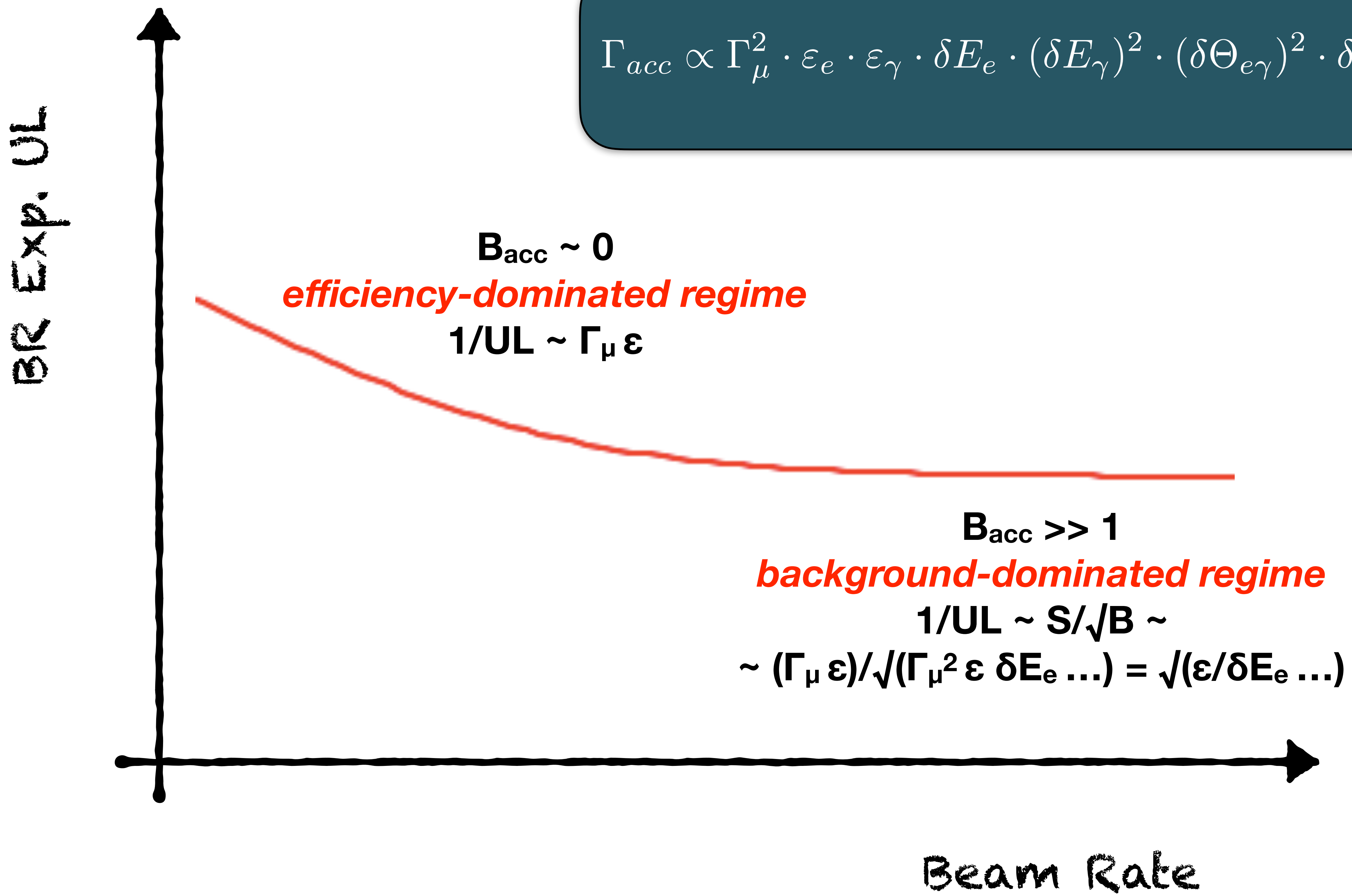


Radiative Muon Decay (RMD)



Sensitivity of μ -> e γ searches

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

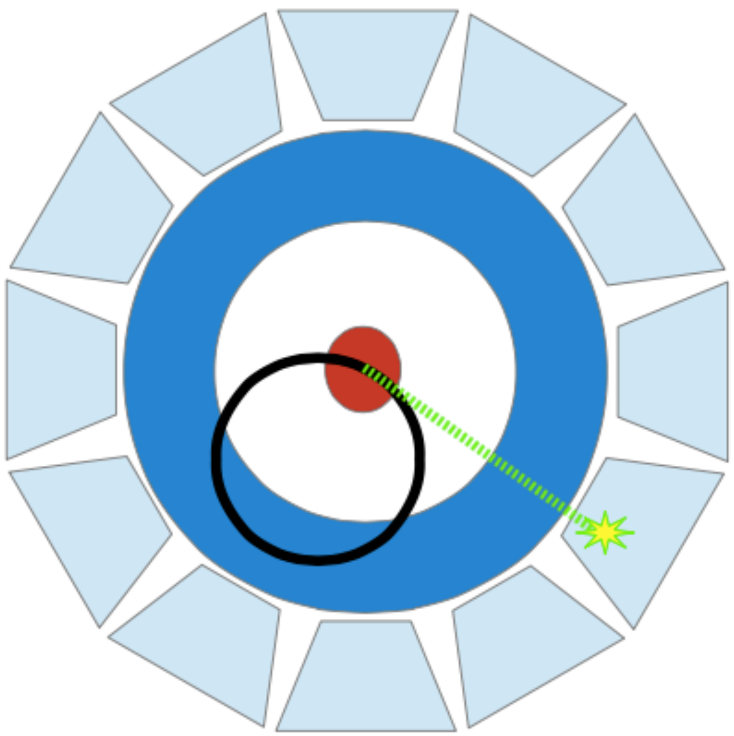


HiMB @ PSI and the future of μ -> e γ

- An upgrade of the PSI muon beamlines is foreseen during a 2027-2028 long shutdown
  - up to 10^{10} μ/s in the new experimental areas
- MEG II optimal beam rate is ~ 4-5 x 10^7
  - how to exploit higher beam rates for a future experiment?
  - it looks unlikely to improve positron resolutions (dominated by MS in detector and target materials) by a large factor
  - what about photon reconstruction?

G. Cavoto et al., EPJ C 78 (2018) 1, 37

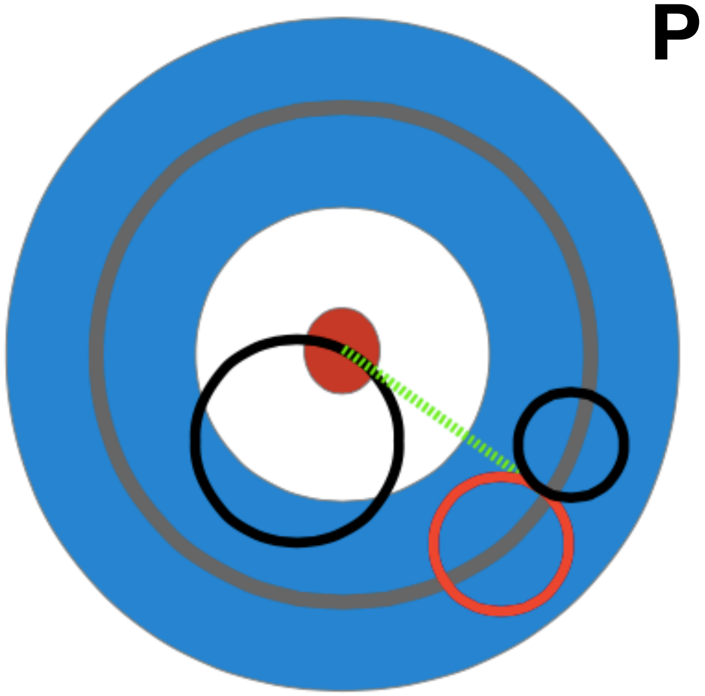
Toward the next generation of μ -> e γ searches: Photon Reconstruction



Calorimetry

High efficiency
Good resolutions

MEG:
LXe calorimeter
10% acceptance

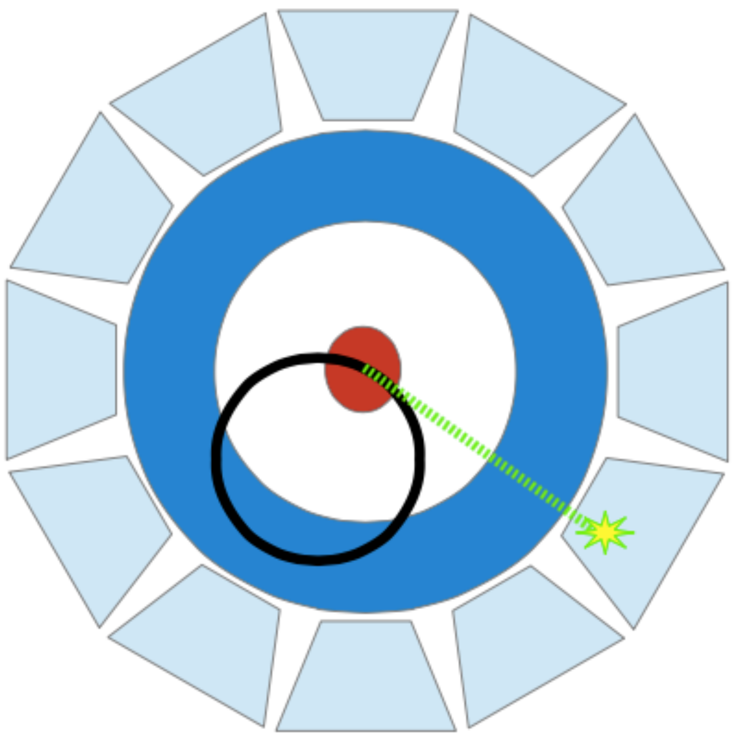


Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

G. Cavoto et al., EPJ C 78 (2018) 1, 37

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



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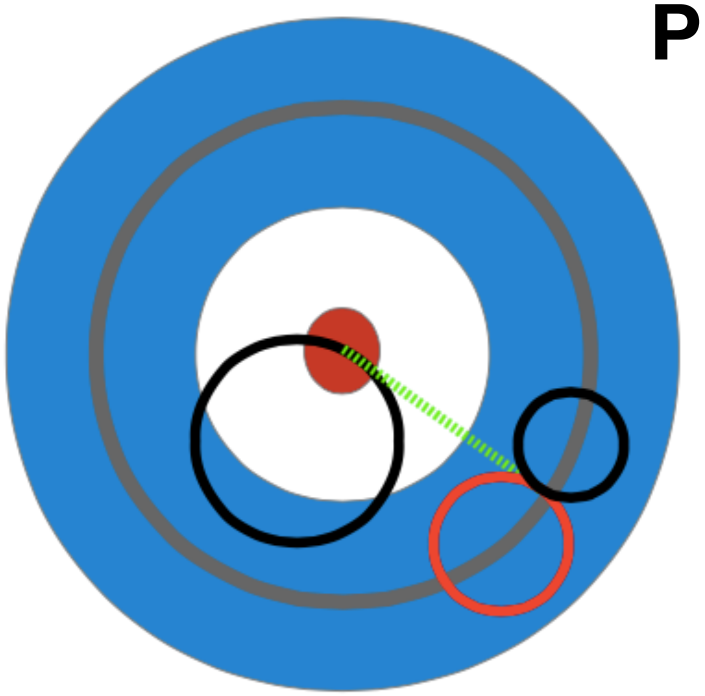

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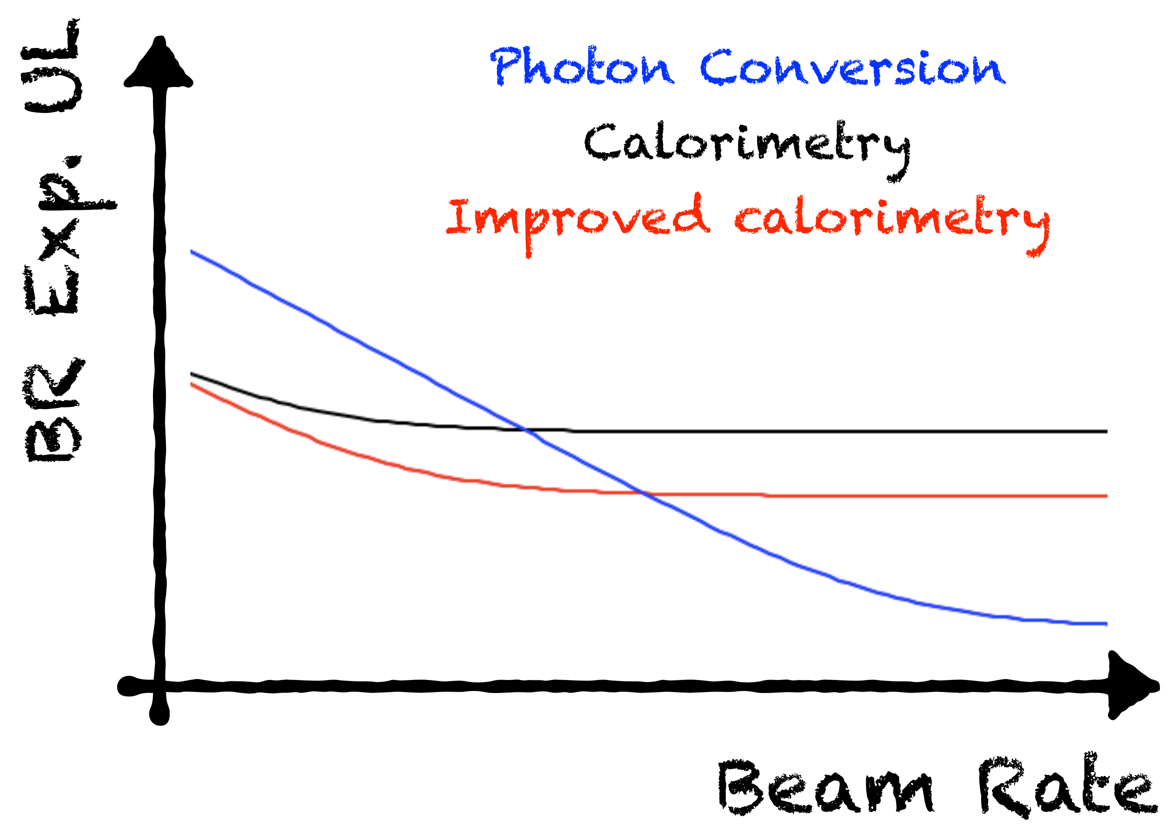

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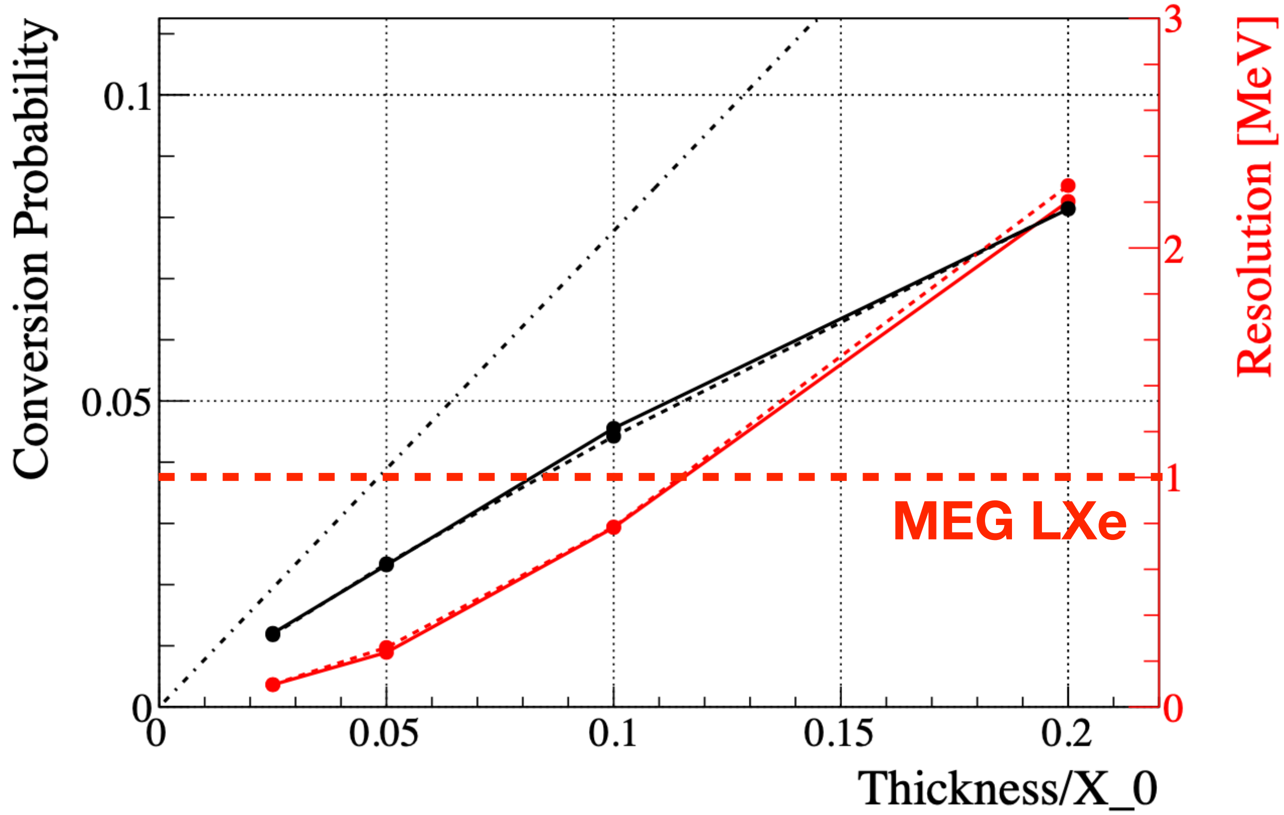
Resolutions with photon conversion (I)

- With passive converter + e^+e^- tracker, the resolution is dominated by the *energy loss fluctuations in the converter*

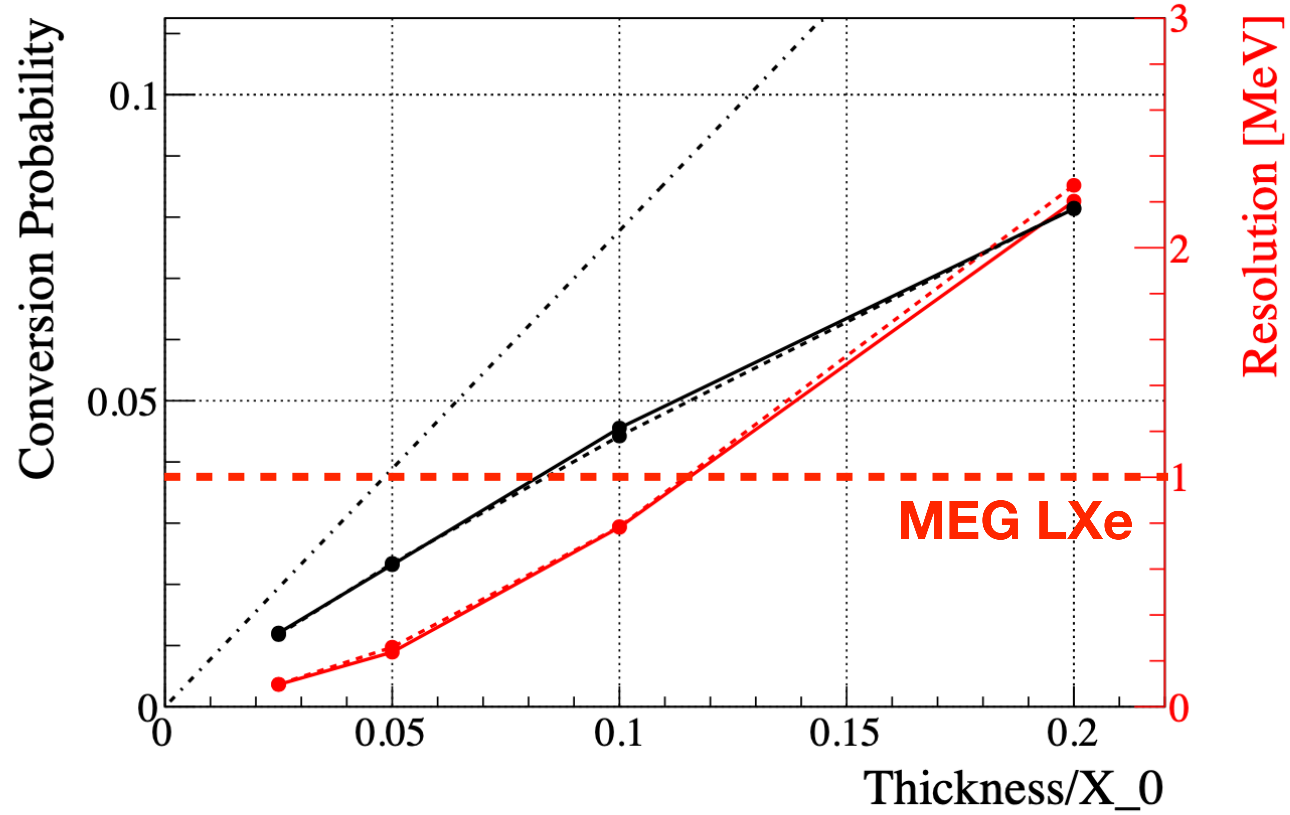


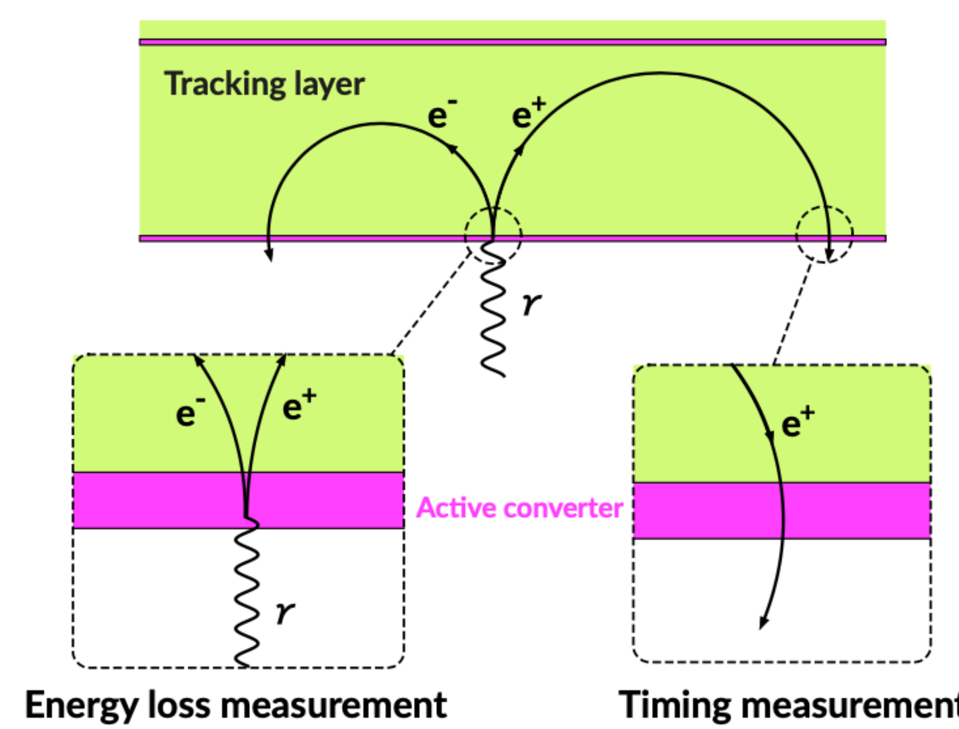
Resolutions with photon conversion (I)

- With passive converter + e^+e^- tracker, the resolution is dominated by the *energy loss fluctuations in the converter*

- Need to recover this energy loss

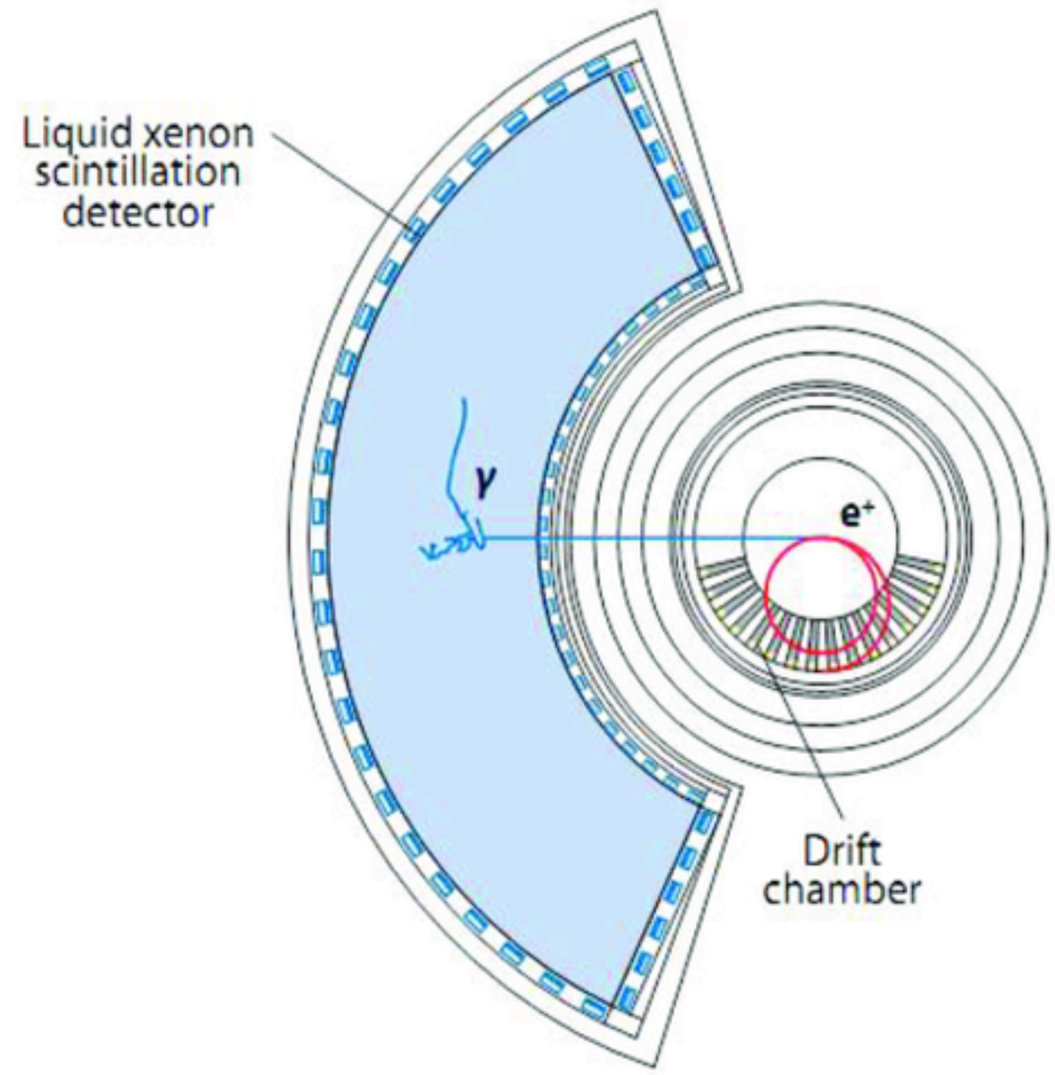
  - **active converter**





Resolutions with photon conversion (II)

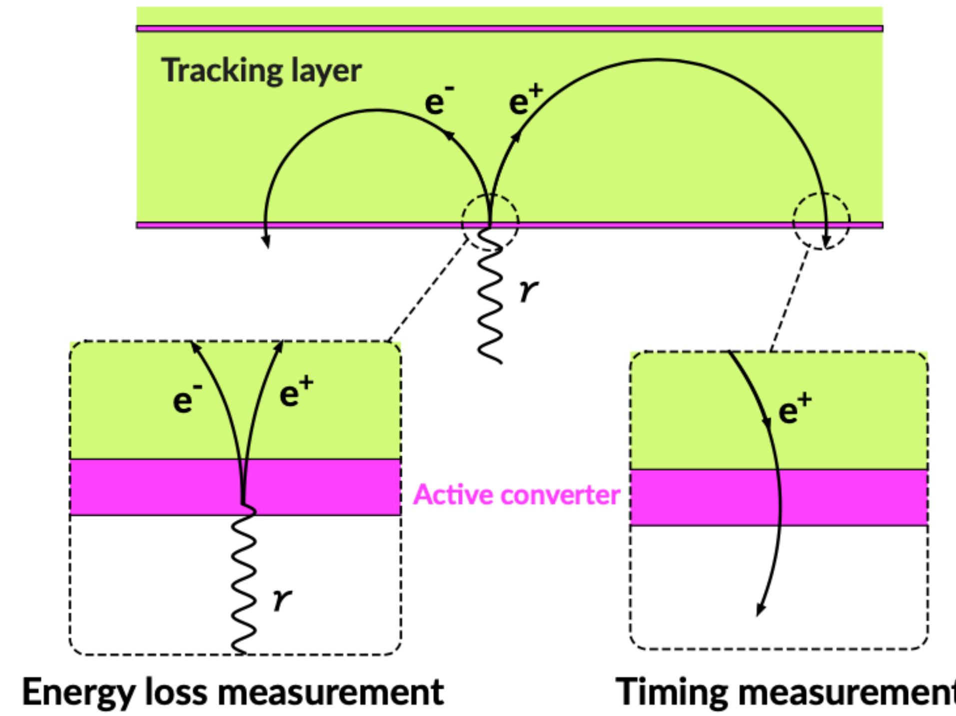
- Calorimetry does not provide a usable measurement of the photon direction
    - photon direction only determined assuming the same vertex of the positron

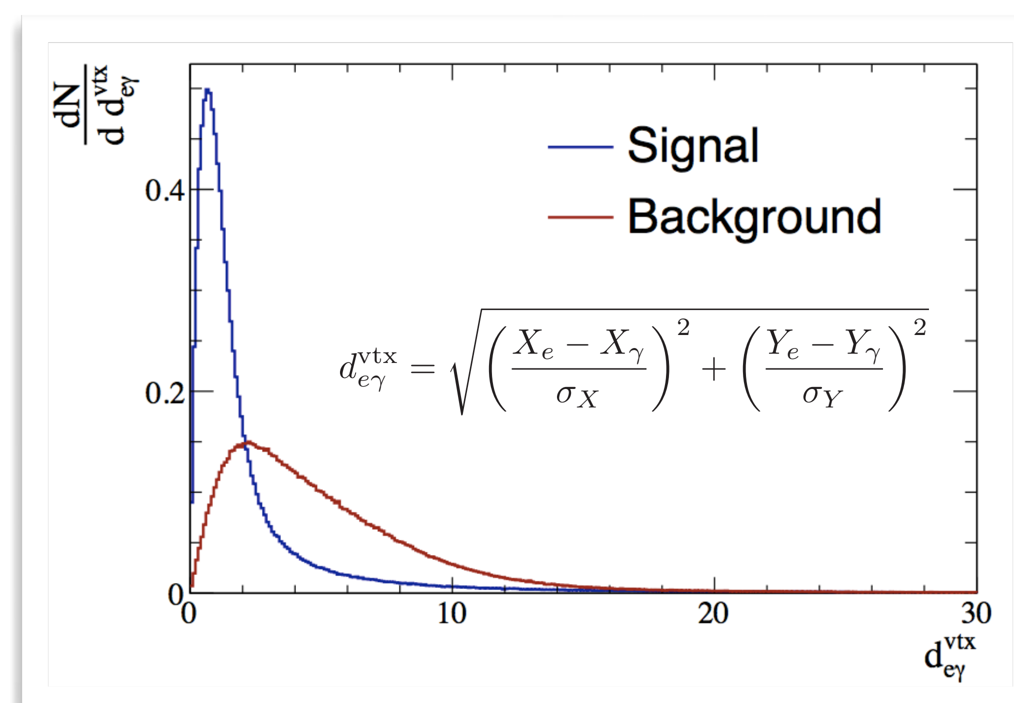


Resolutions with photon conversion (II)

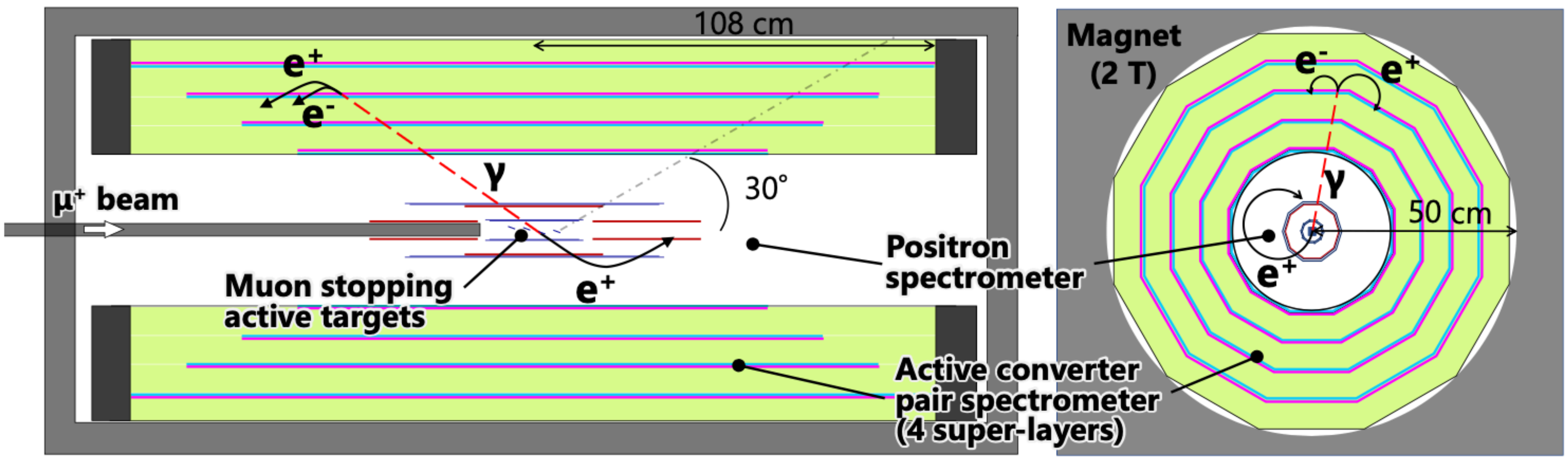
- Calorimetry does not provide a usable measurement of the photon direction
    - photon direction only determined assuming the same vertex of the positron

- Photon conversion makes **vertexing** possible, helping reducing the accidental background





A baseline design for a future μ -> e γ experiment

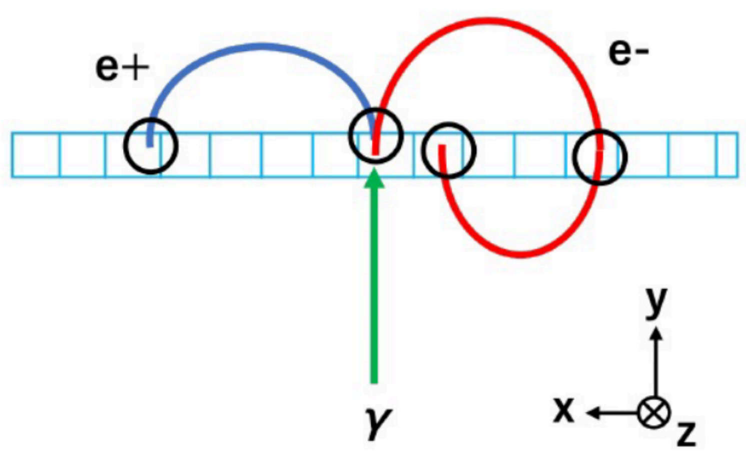


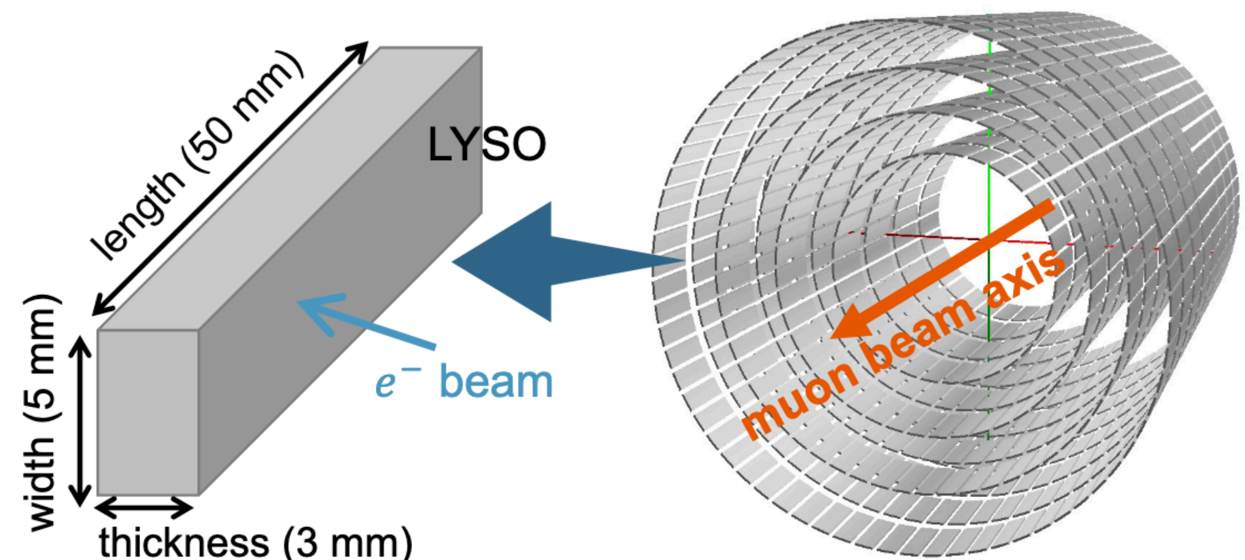
- Inner tracker + timing for positrons
- A few layers of active converter + radial TPC

Challenges

- Active converter:
  - careful optimization of granularity to limit pileup while avoiding an explosion of the number of channels
- e^+e^- Tracker:
  - pairs can be highly asymmetric in momentum
  - ➡ tracking momenta down to a few MeV with high efficiency and resolution
  - ➡ extremely light detector (avoid MS) with extreme granularity and resolution (reconstruct very low bending radii)
  - ➡ gaseous Time Projection Chamber (TPC) with radial drift

Active converter

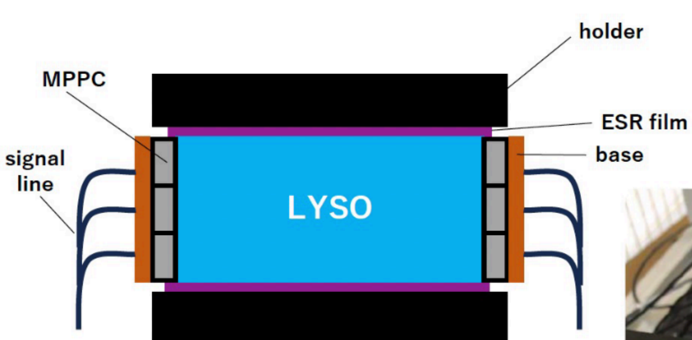


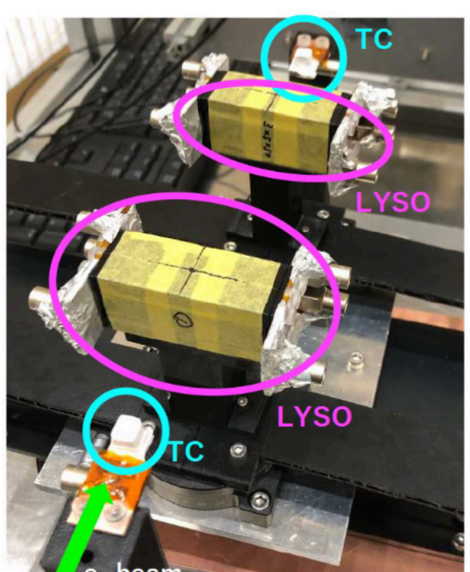


one segment
(standard size)

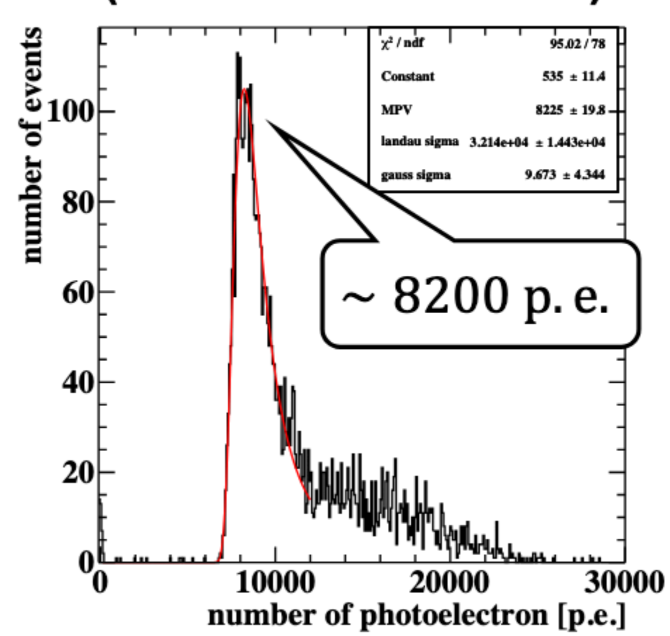
segmentation of converter
in the future experiment

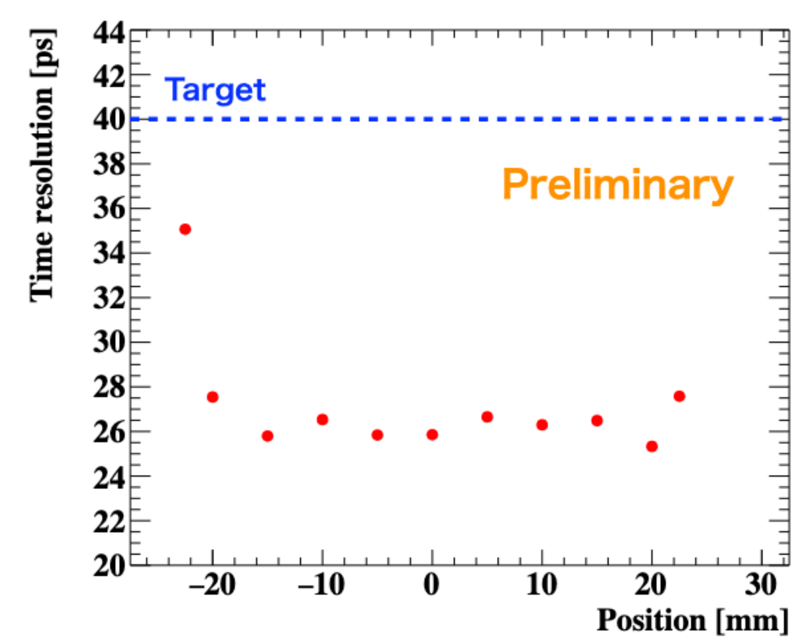
CONVERTER PROTOTYPE



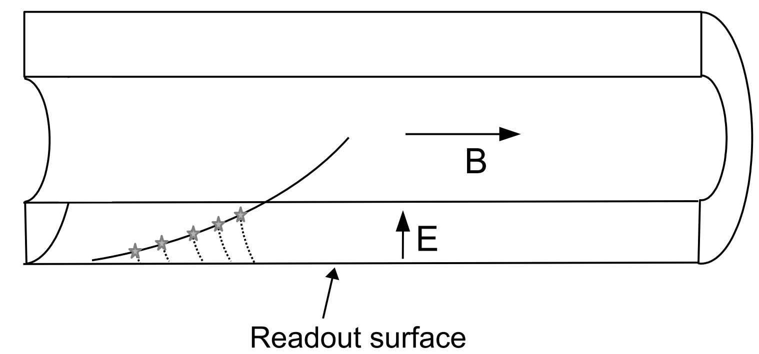


standard size
(3 mm×5 mm×50 mm)

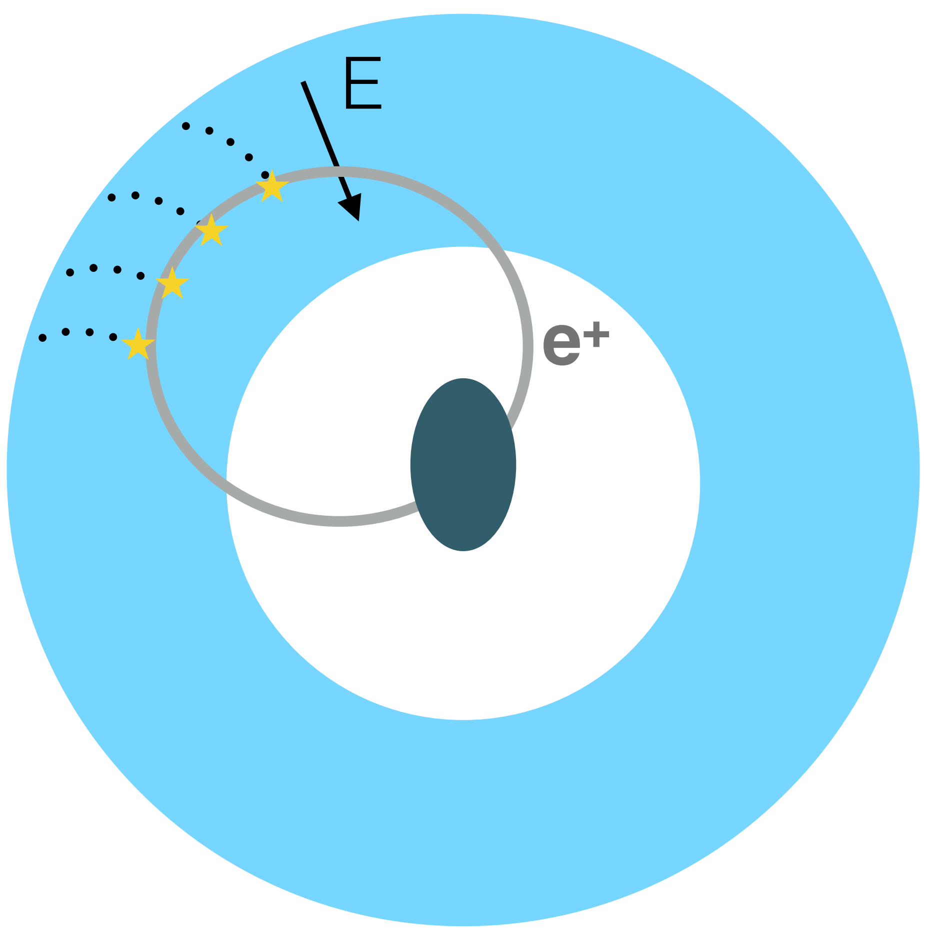




Radial Time Projection Chamber



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



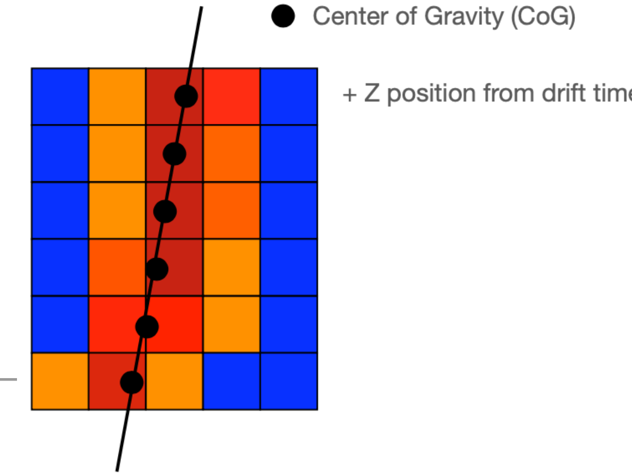
Need to develop a radial TPC with cylindrical MPGD readout, ~ 2 m long and ~ 30 cm radius

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

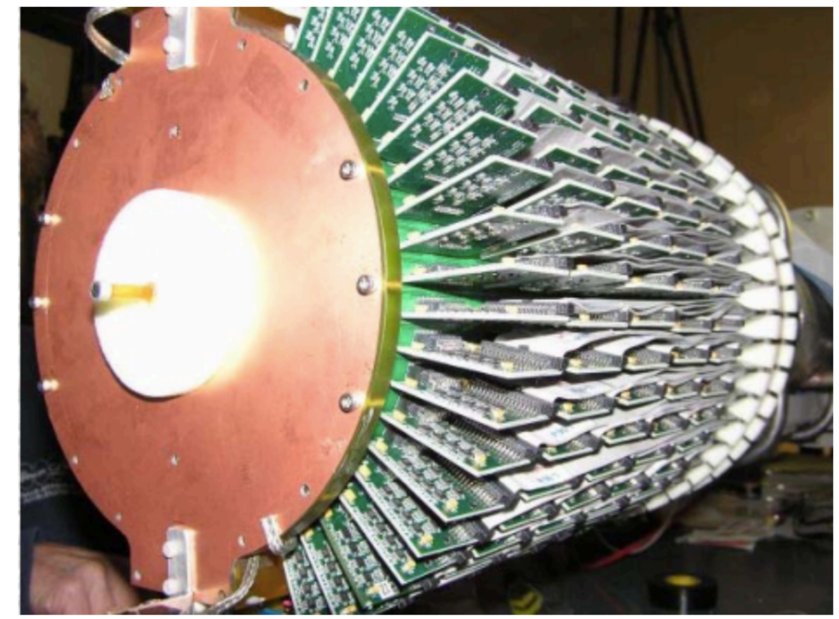
Need to develop advanced algorithms for correcting field deformations

Need to develop an electronic readout approach compatible with the geometrical constraints of the experiment

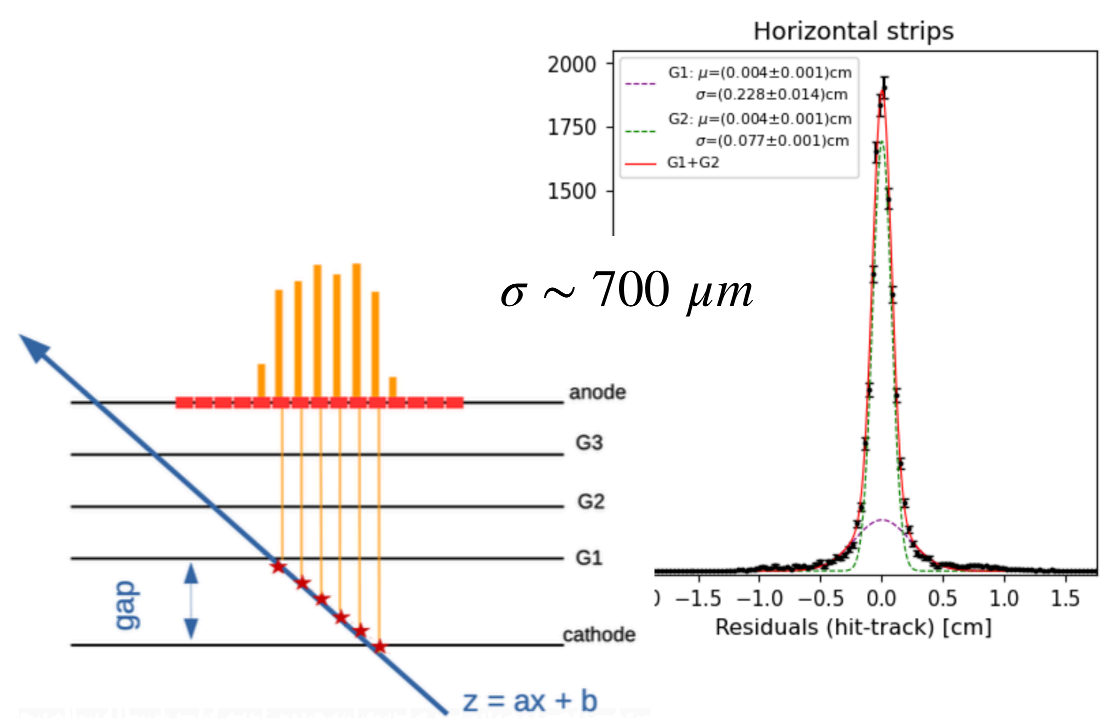
Radial TPC readout



- TPCs are usually read out by pad structures, requiring electronics crowding the outer side on the readout surface
  - incompatible with stacking multiple conversion layers
- Strip readout at the end-caps is necessary
  - possible systematics from charge sharing among contiguous strips
  - rarely used used with O(10 mm) drift
  - R&D started to assess the achievable resolutions



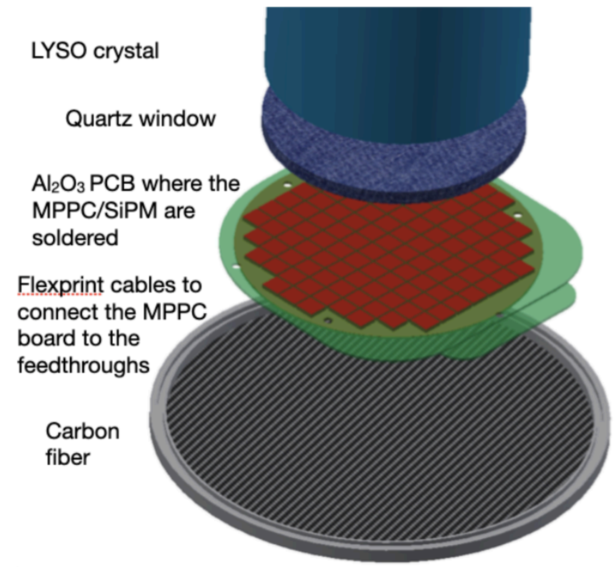
BONuS radial TPC @ J-LAB

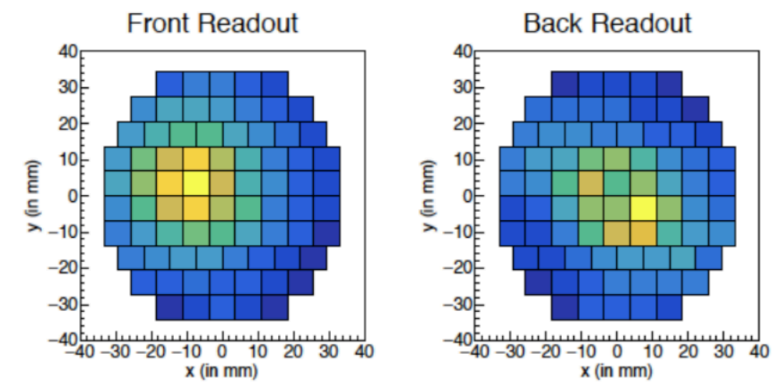


$\sigma \sim 700\ \mu m$

Alternative designs

- Calorimetry with crystals (LYSO) can still be interesting for an intermediate step with a moderate increase of the beam intensity (~ 10^8 μ/s)

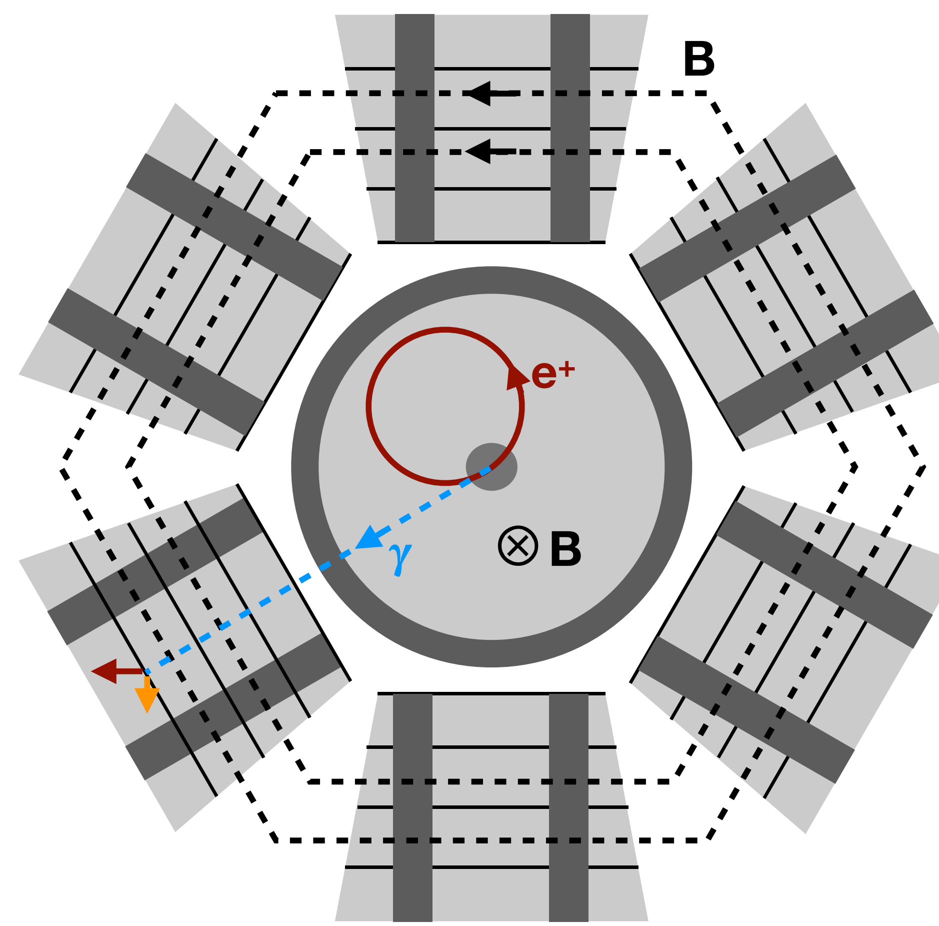




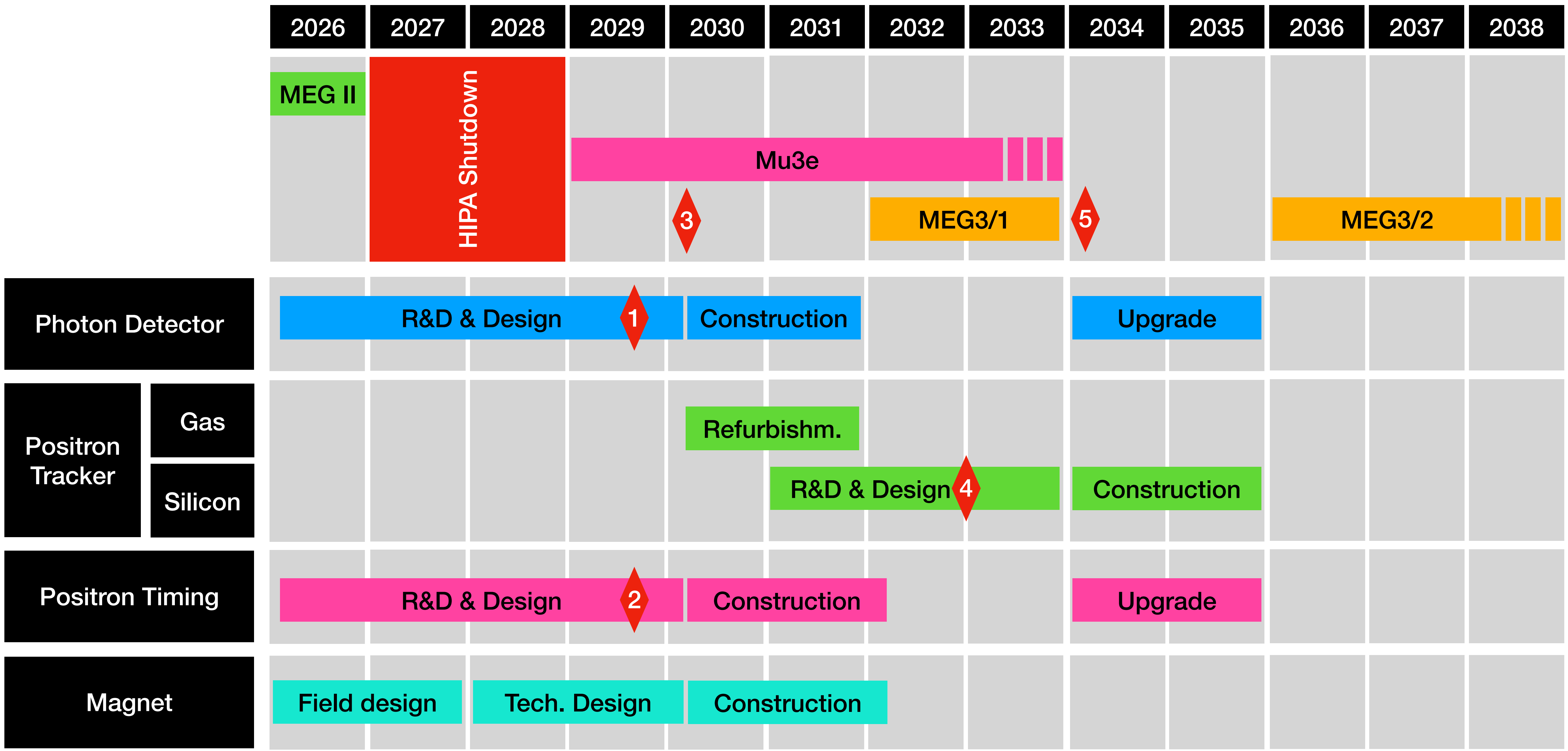
(a) Hit in Central Region: $(x, y) = (-10\,\mathrm{mm}, 3\,\mathrm{mm})$

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

- An alternative design of the magnetic field, with inner solenoid (e^+) + external toroid (γ)
  - can relax geometrical constraints, add handles to optimize the fields and simplify the technical design of detectors and magnets



Schedule



♦1: Photon converter proof of principle (CEX with converter + tracker in the MEG COBRA magnet)

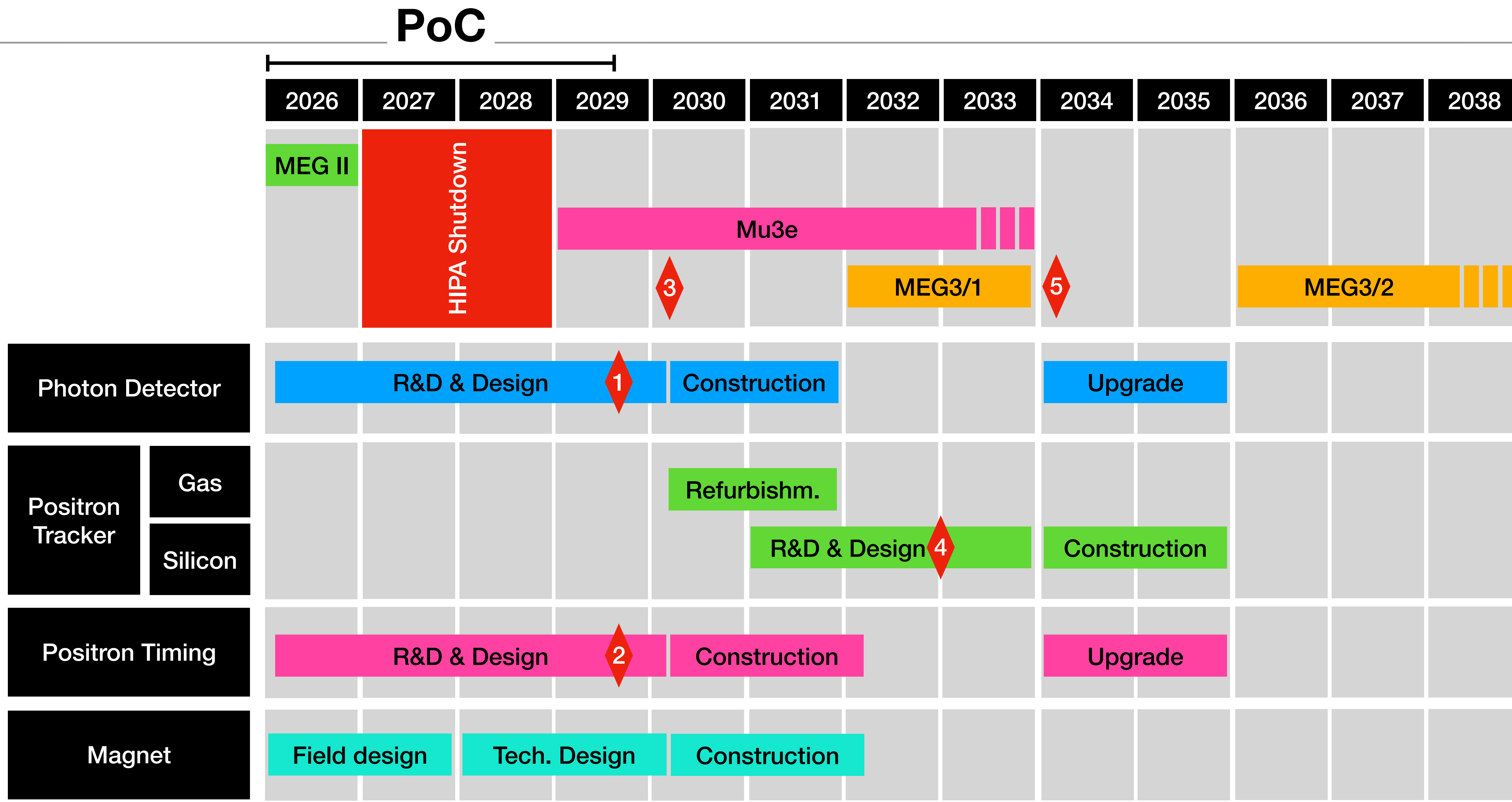
♦2: Decision about positron timing technology

♦3: phase-I approval by PSI and funding agencies

♦4: Decision about positron tracker technology for phase-II

♦5: phase-II approval by PSI and funding agencies

Schedule



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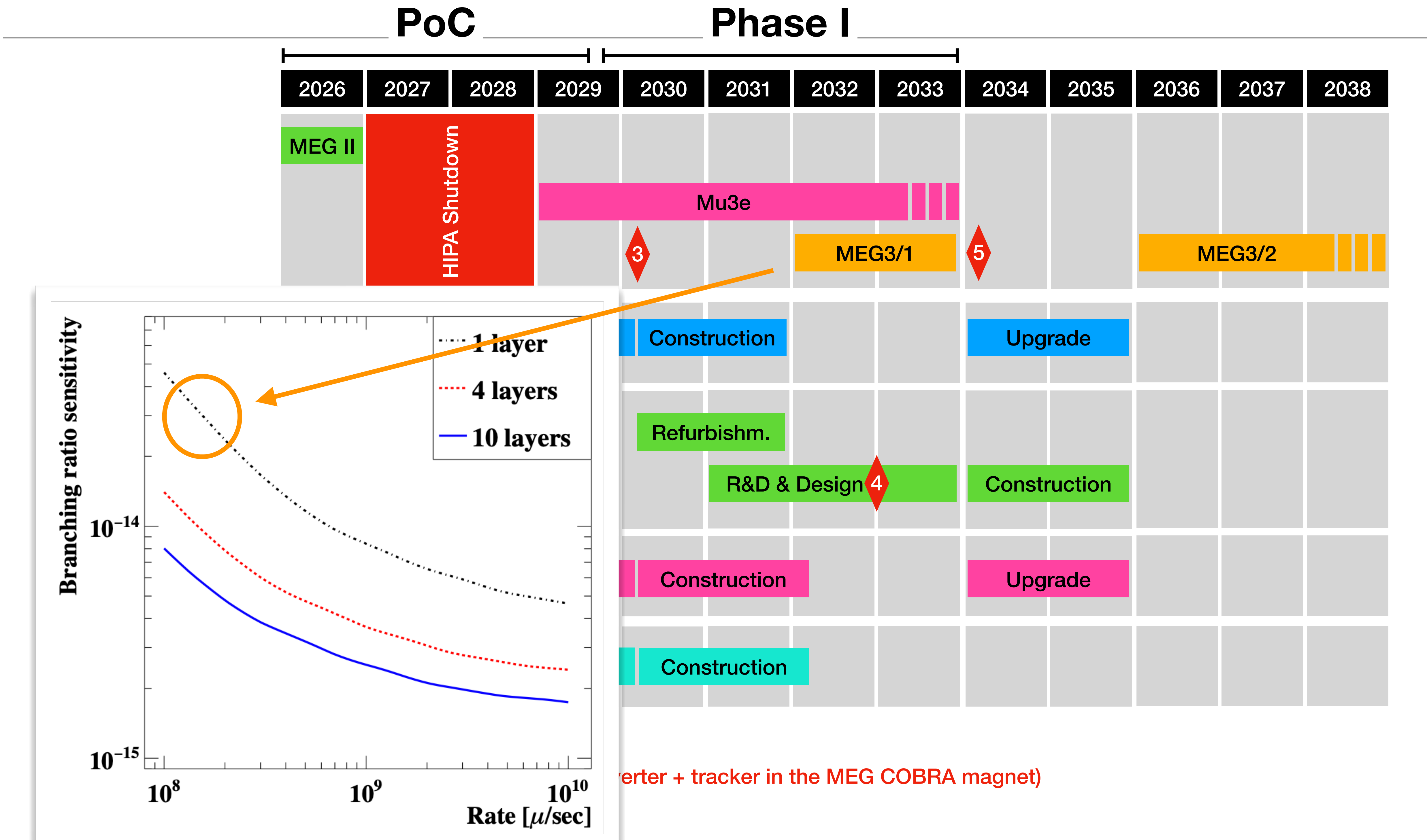

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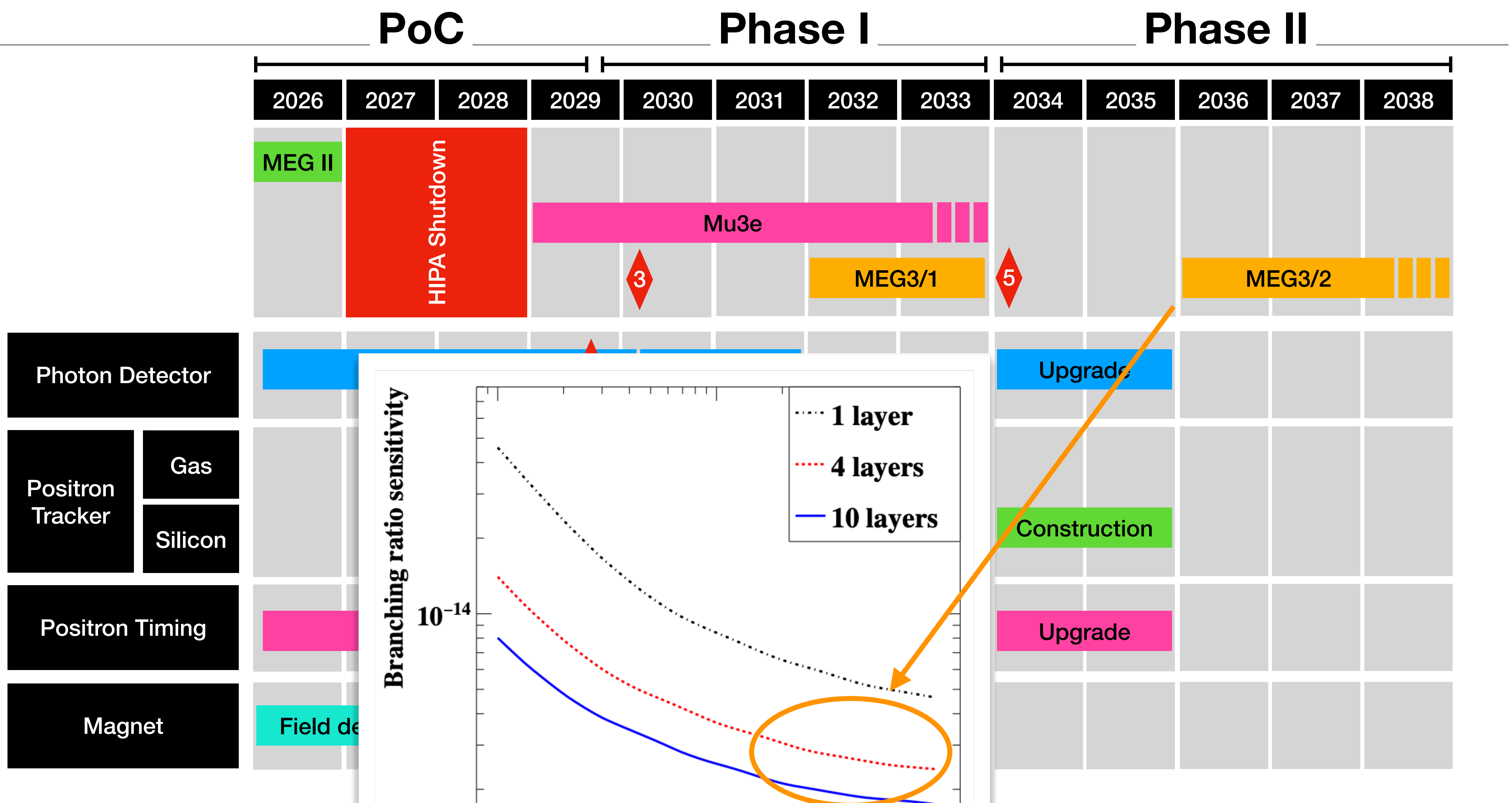

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Conclusions

- The upgrade of the PSI beam lines opens new perspectives for cLFV searches in muon decays

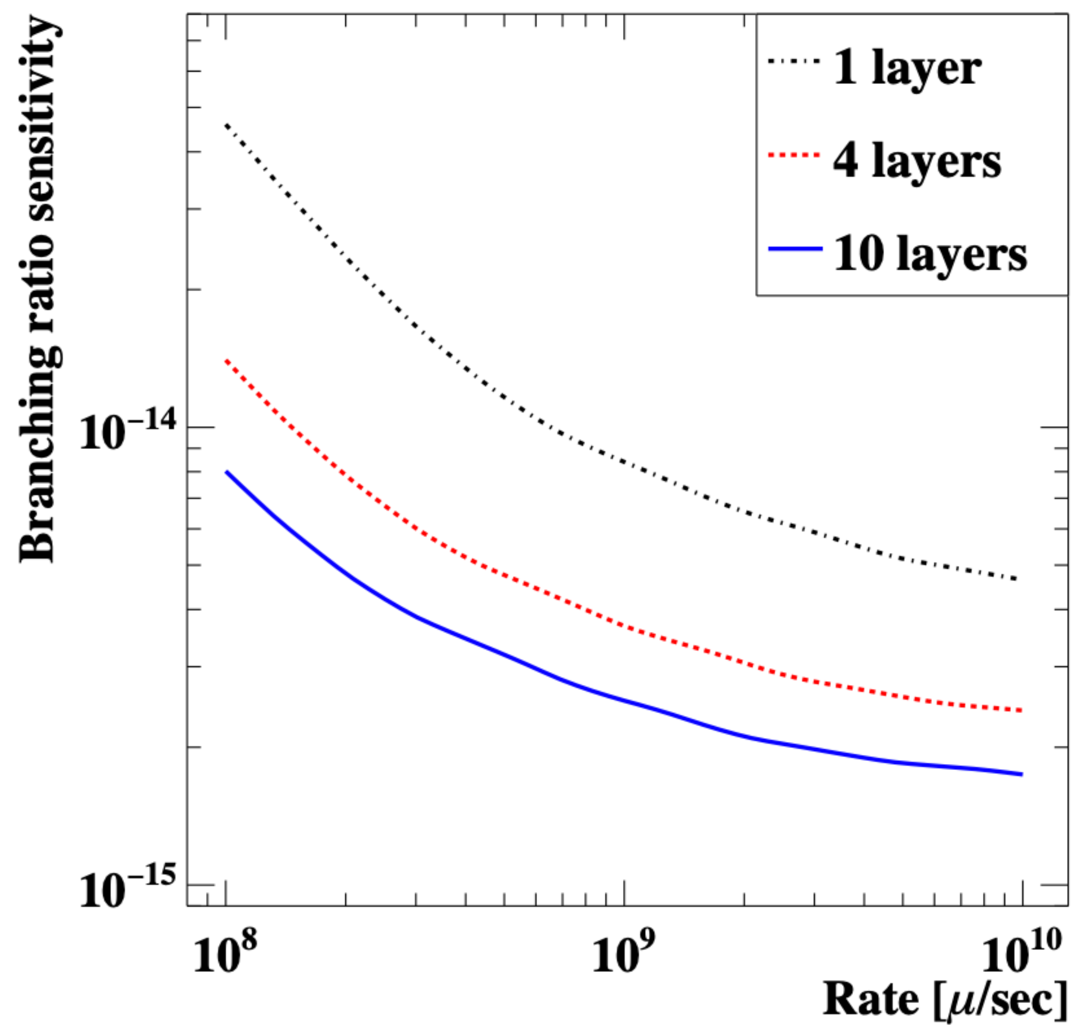
- Photon detection with pair conversion could allow to fully exploit the highest available intensities for $\mu \to e \gamma$ searches

- Exploring BR($\mu \to e \gamma$) ~ O(10^{-15}) could be reasonably possible within the next 15 years

Backup

Sensitivity reach

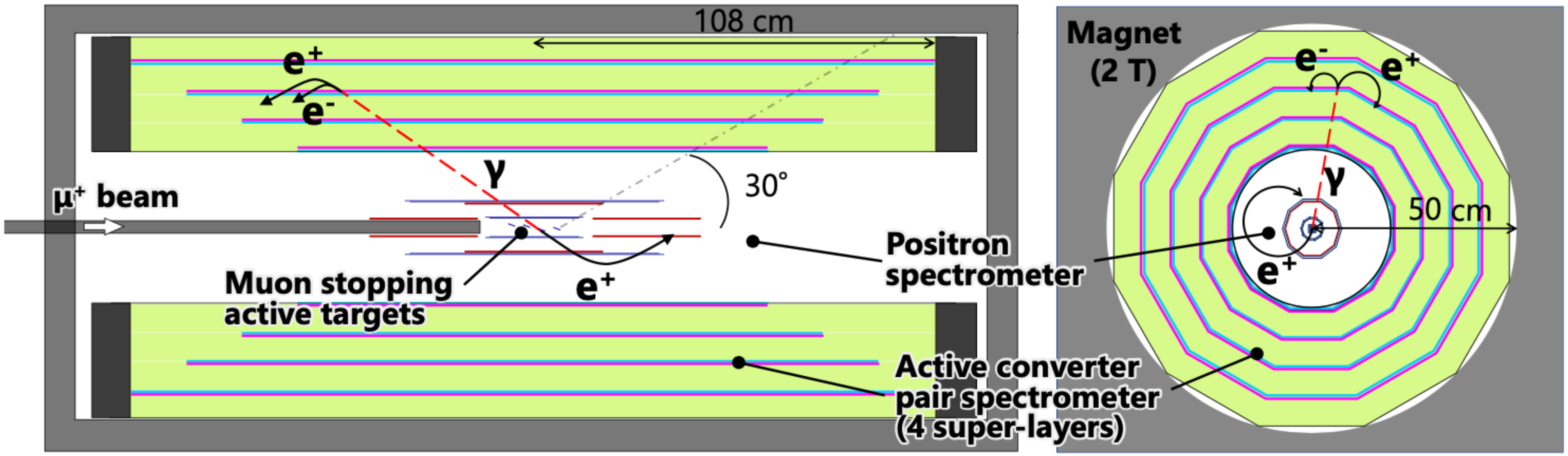
	Resolutions/efficiencies
Photon energy	200 keV
Photon position	200 μm
Photon timing	30 ps
Photon angle	150 mrad
Photon detection efficiency (4 layers)	6 %
Positron energy	100 keV
Positron angle	6 mrad
Positron timing	30 ps
Positron detection efficiency	70 %
Geometrical acceptance	85 %

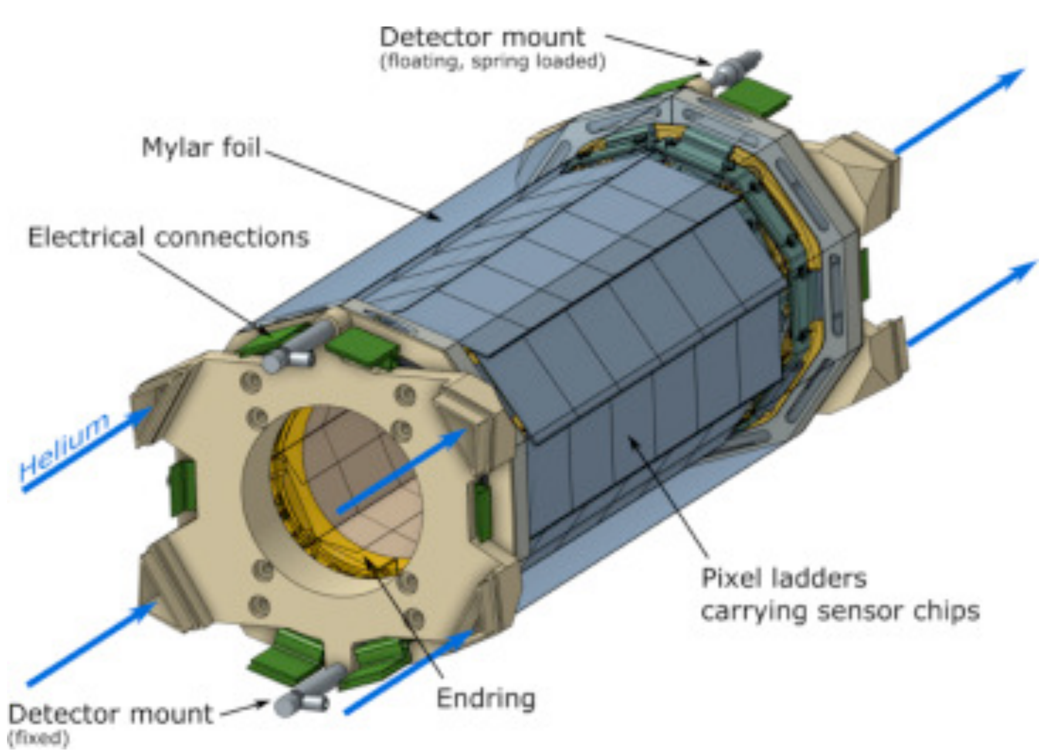


MEG II

Resolutions	
E_{e^+} (keV)	89
ϕ_{e^+}, θ_{e^+} (mrad)	5.2/6.2
y_{e^+}, z_{e^+} (mm)	0.61/1.76
E_γ(%) (w_γ<2 cm)/(w_γ>2 cm)	2.4(2.1)/1.9(1.8) → ~ 1 MeV
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.5/2.5/5.0
$t_{e^+\gamma}$ (ps)	78
Efficiencies (%)	
ε_γ	63
ε_{e^+}	67
$\varepsilon_{\mathrm{TRG}}$	91(88)

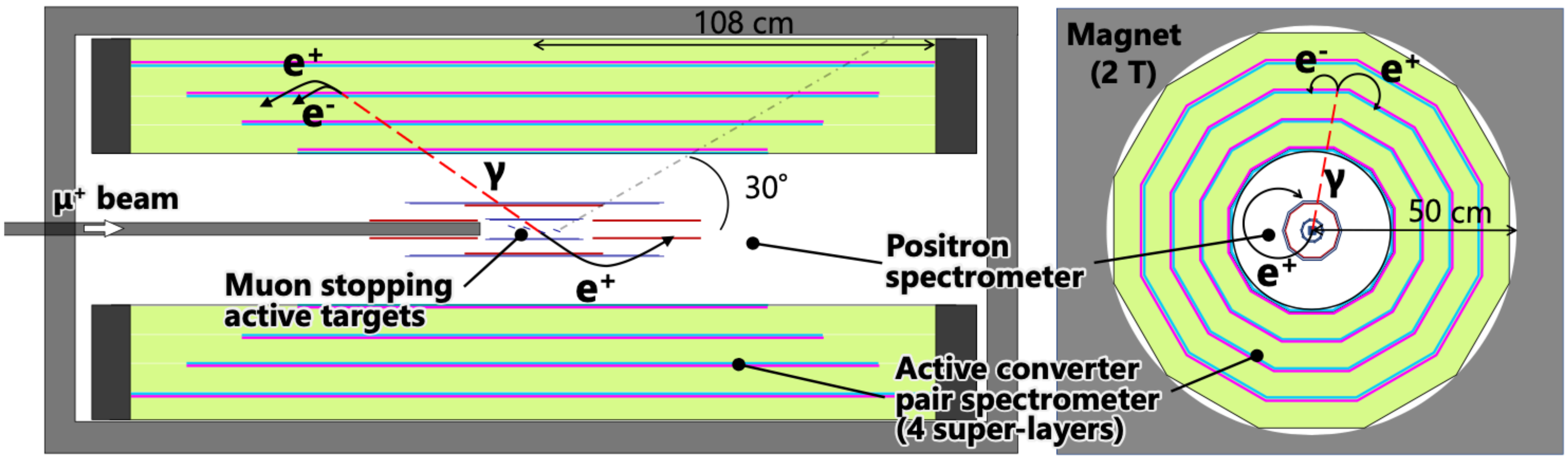
A baseline design for a future μ -> e γ experiment

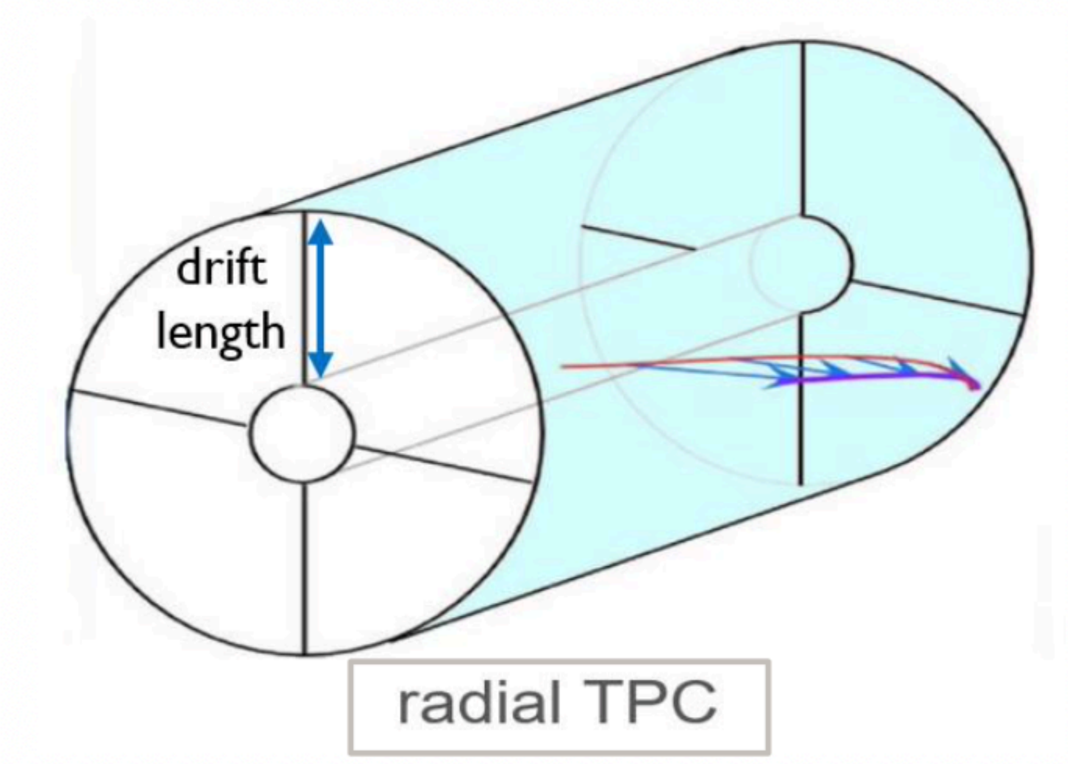




- Silicon tracker à la Mu3e for positron tracking
  - unique solution to tolerate the extremely high positron fluxes at 10^9 - 10^{10} μ/s
  - performance only slightly worse than (or possibly equivalent to) gaseous detectors
  - **would allow μ -> e γ and μ -> e e e in the same experiment**
- Scintillating pixels for positron timing (other options also under consideration)

A baseline design for a future μ -> e γ experiment





- Radial GEM-TPCs for e^+e^- tracking:
  - Low material budget
  - optimal geometrical configuration (compared to drift chambers)
  - optimal single-hit resolution (short drift —> low diffusion)
  - low cost (compared to silicon trackers)

Limiting factors — Photon calorimetry

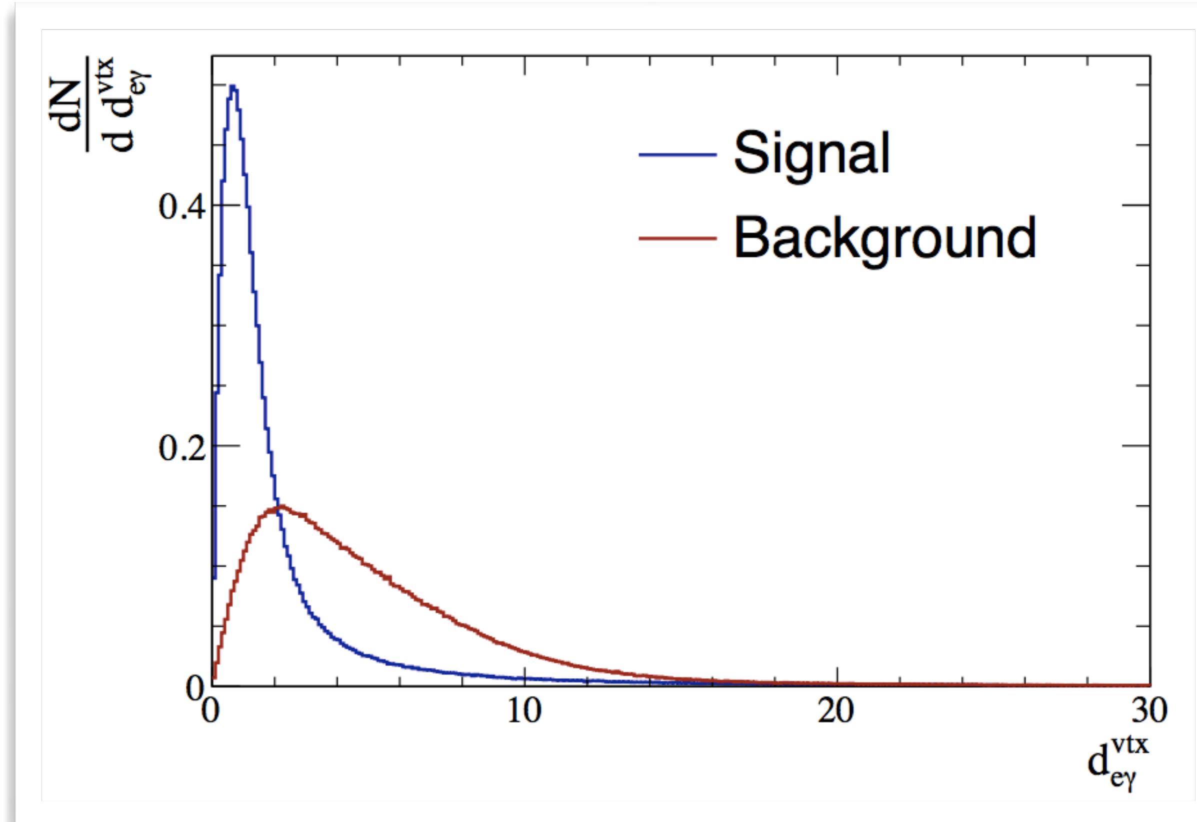
- MEG (LXe) could not get yet a photon energy resolution much better than 1 MeV:
  - not completely understood
  - limited acceptance due to large cost and complex infrastructure
- Innovative crystals like $LaBr_3(Ce)$ — a.k.a. *Brillance* look a very good candidate for future experiments
  - 800 keV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

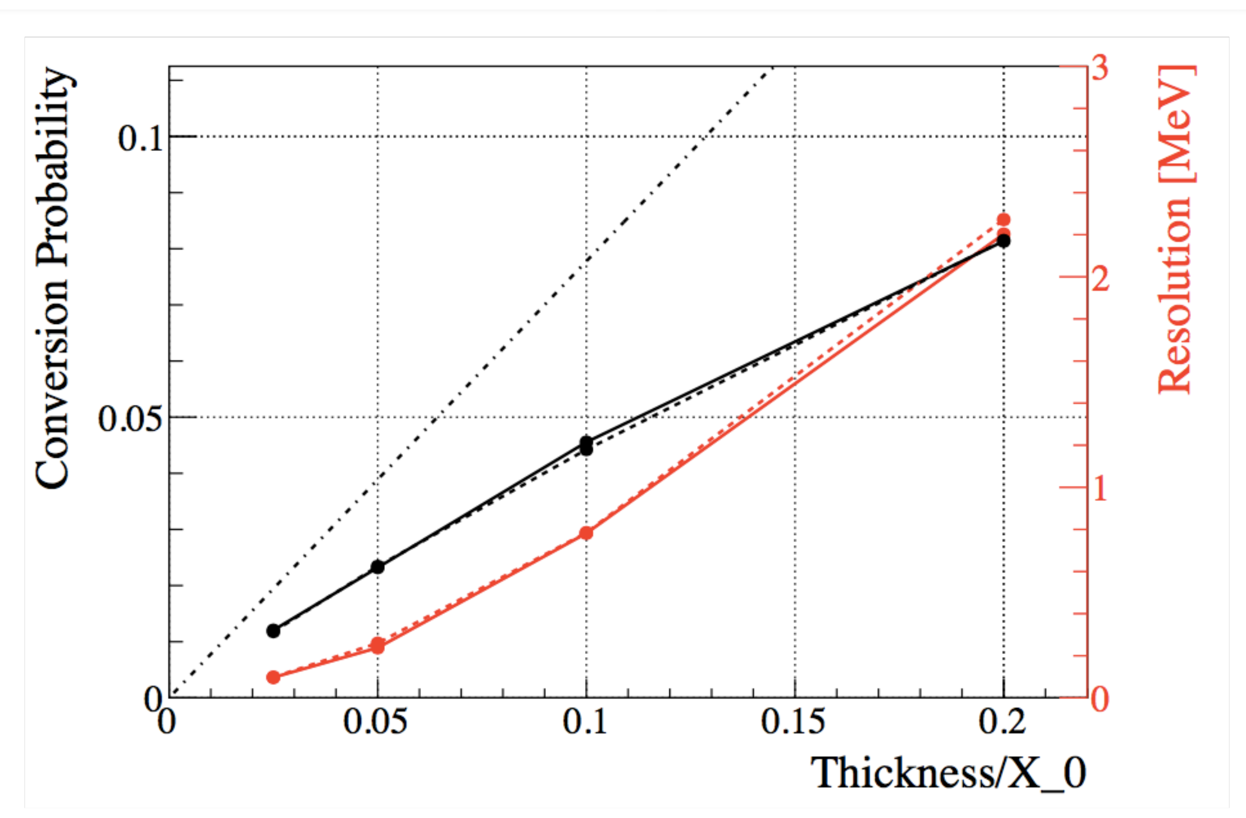
Scintillator	Density] [g/cm^3]	Light Yield [ph/keV]	Decay Time [ns]
$LaBr_3(Ce)$	5.08	63	16
LYSO	7.1	27	41
YAP	5.35	22	26
LXe	2.89	40	45
NaI(Tl)	3.67	38	250
BGO	7.13	9	300

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

Limiting factors — Photon conversion

- Interactions in the converter (conversion probability, e+e- energy loss and MS)
- Possible improvement with active converter (see W. Ootani's talk)



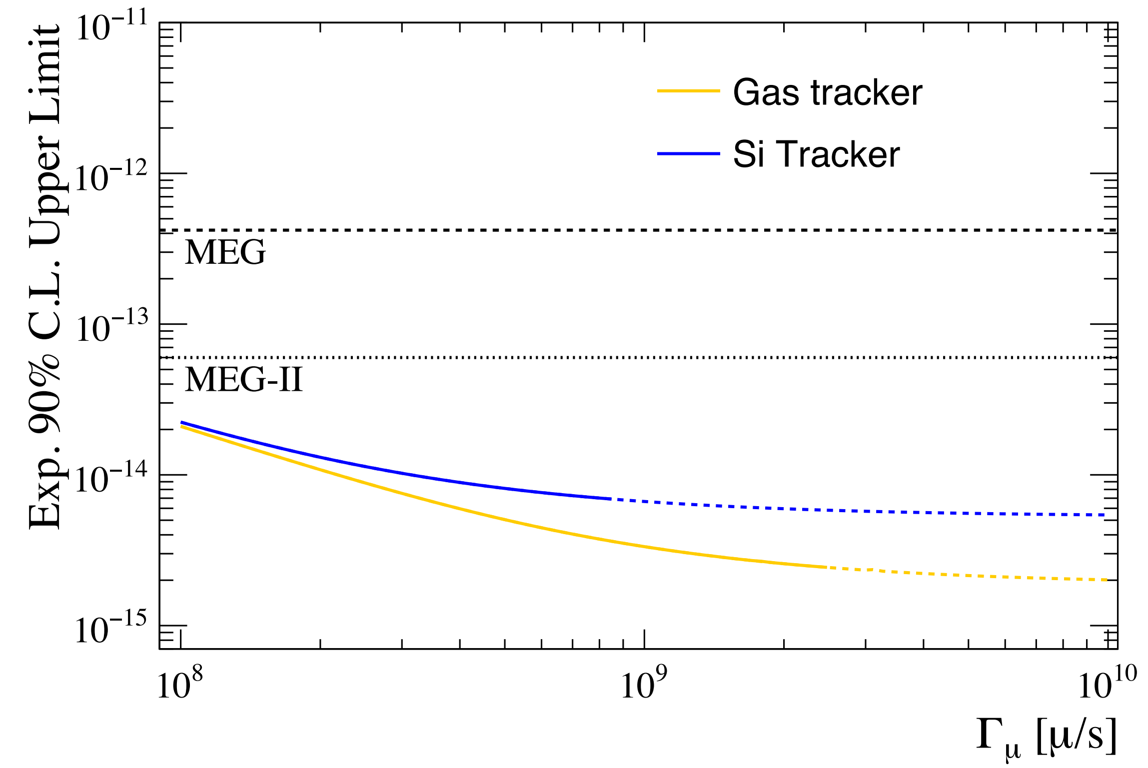


- Can take advantage of the photon direction determination form the e+e- reconstruction

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

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)**

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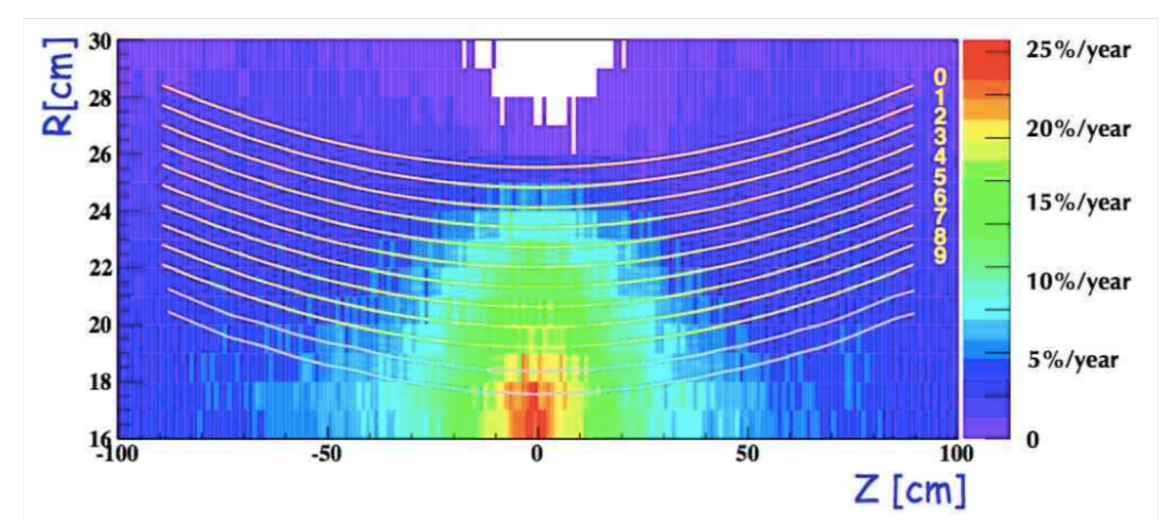
    - going toward 25 µm HV-MAPS

Expected aging (gain loss) in MEG II

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



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  - 100 keV energy resolution in MEG II
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- 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

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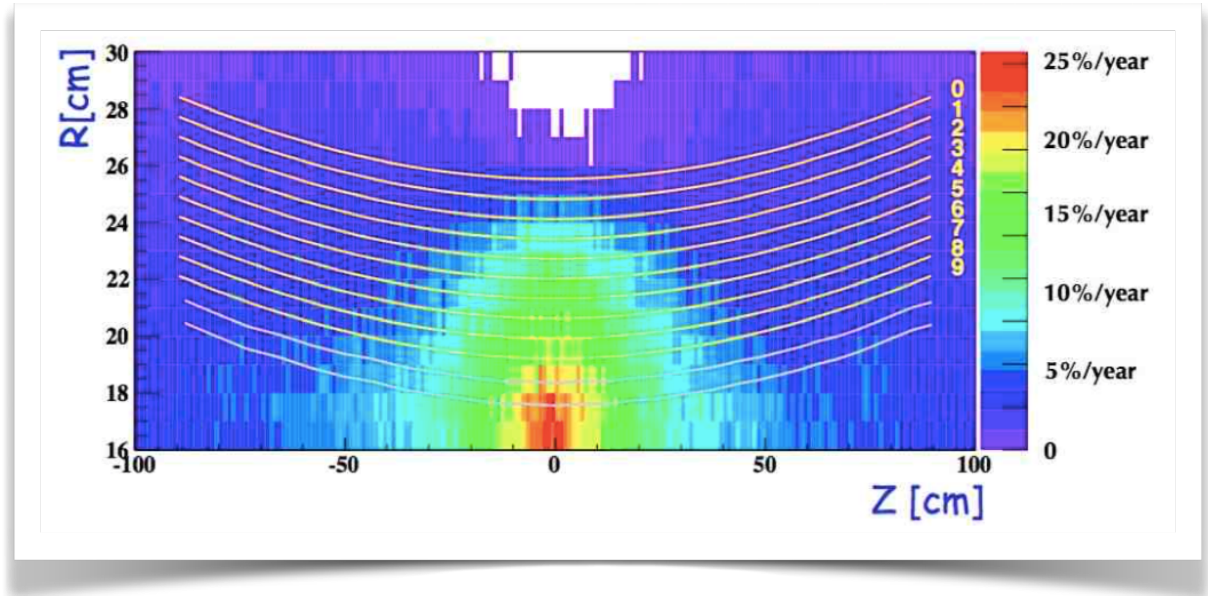
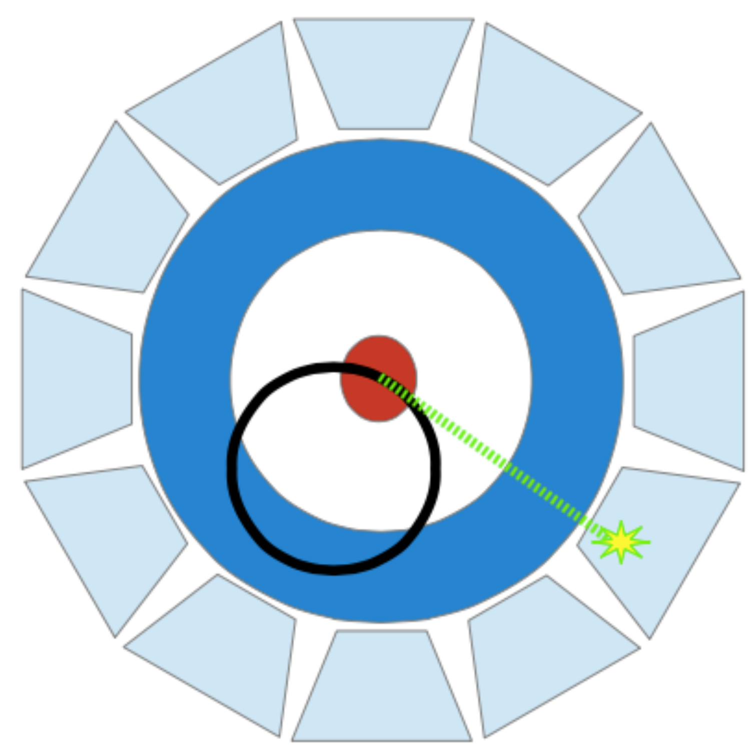


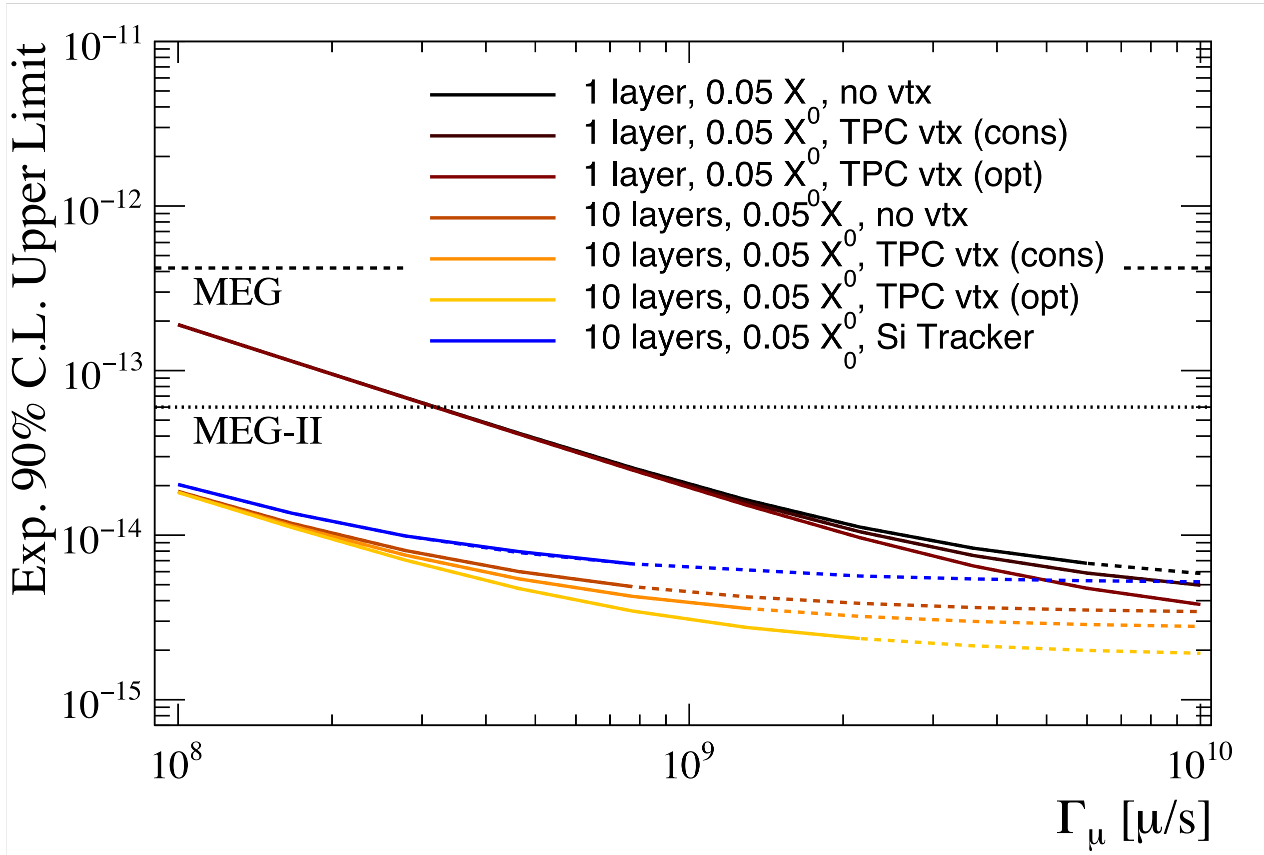


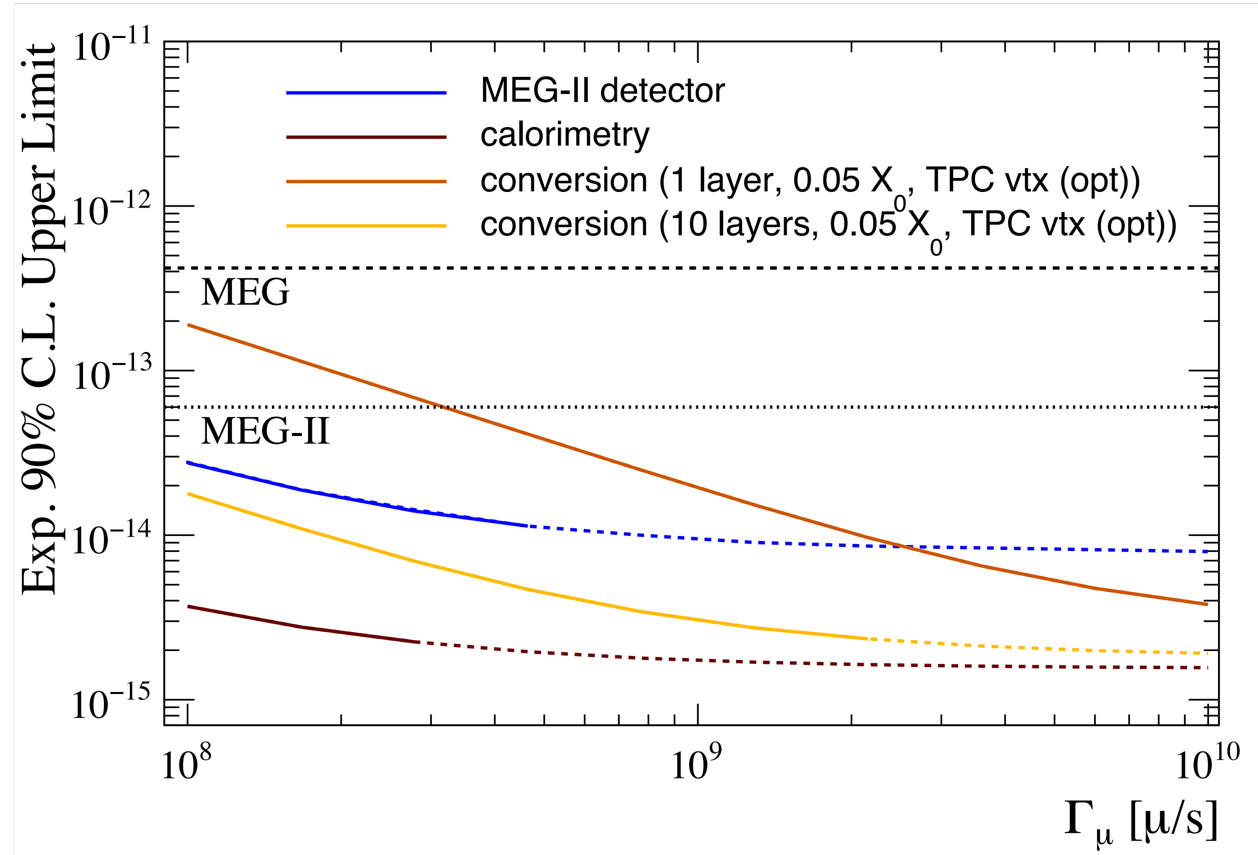
MS in target and beam requirements

- 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

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***

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

Miscellanea

- We already had regular meetings (every three months on average) where we discussed ideas and R&D progresses:
  - an informal setting, with lively discussions
  - ~ 30 people from MEG and Mu3e joined the last meeting at PSI on January
  - to be protracted, trying to involve even more people
- Common tools (simulation frameworks, track fit tools, document repositories) would be extremely useful for the next steps
- Ongoing activities should be efficiently advertised at the upcoming cLFV and muon physics workshops
  - also an occasion to produce some written document

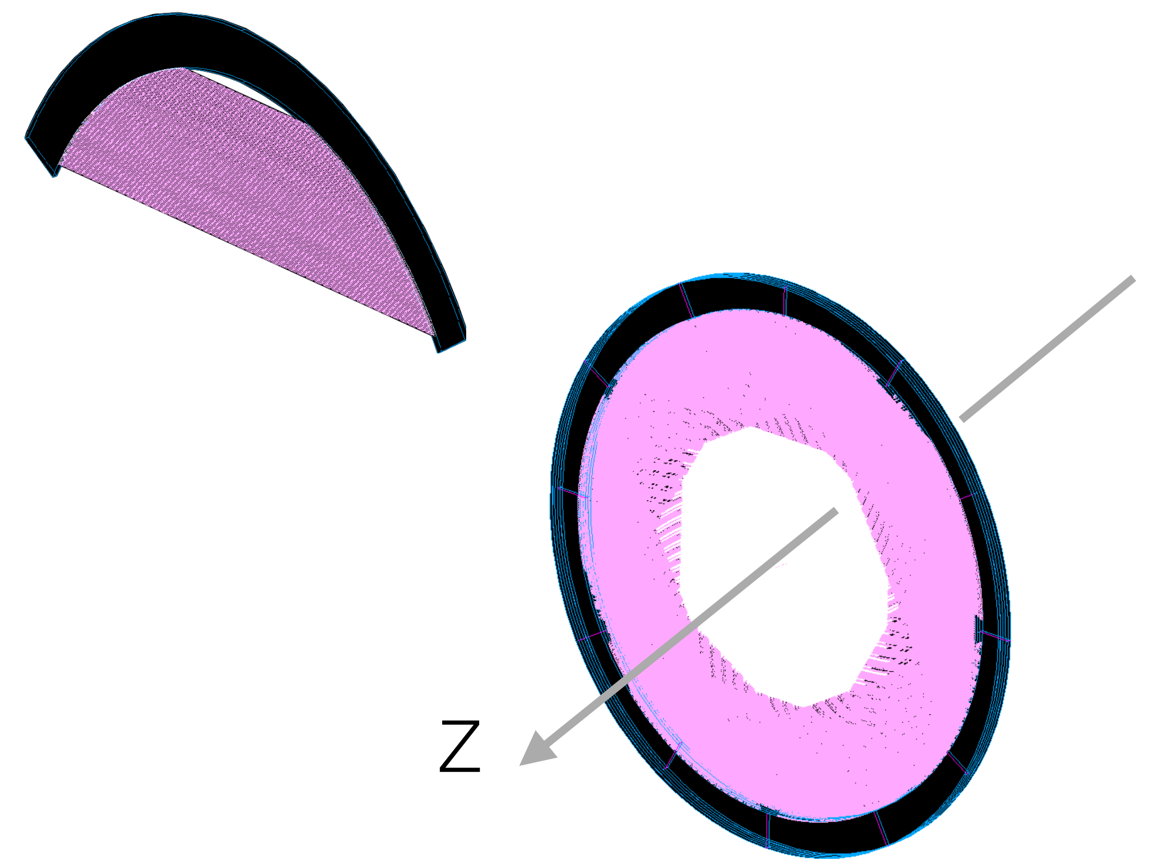
Gaseous positron trackers toward 10^9 - 10^{10} μ/s

- 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**

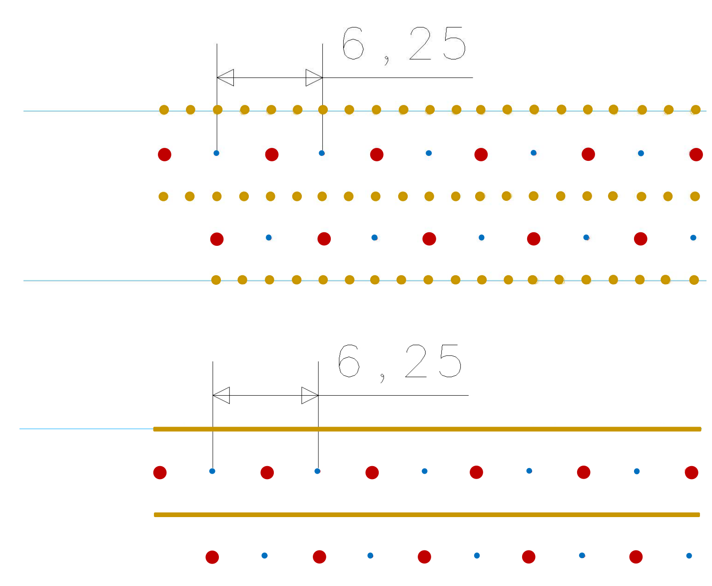
Drift chamber

- 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

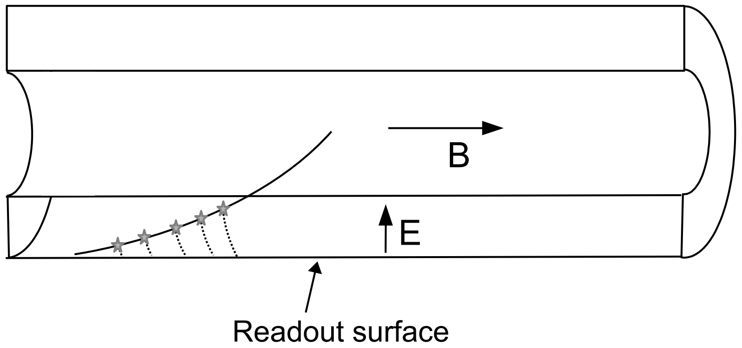


The main challenge is the material budget

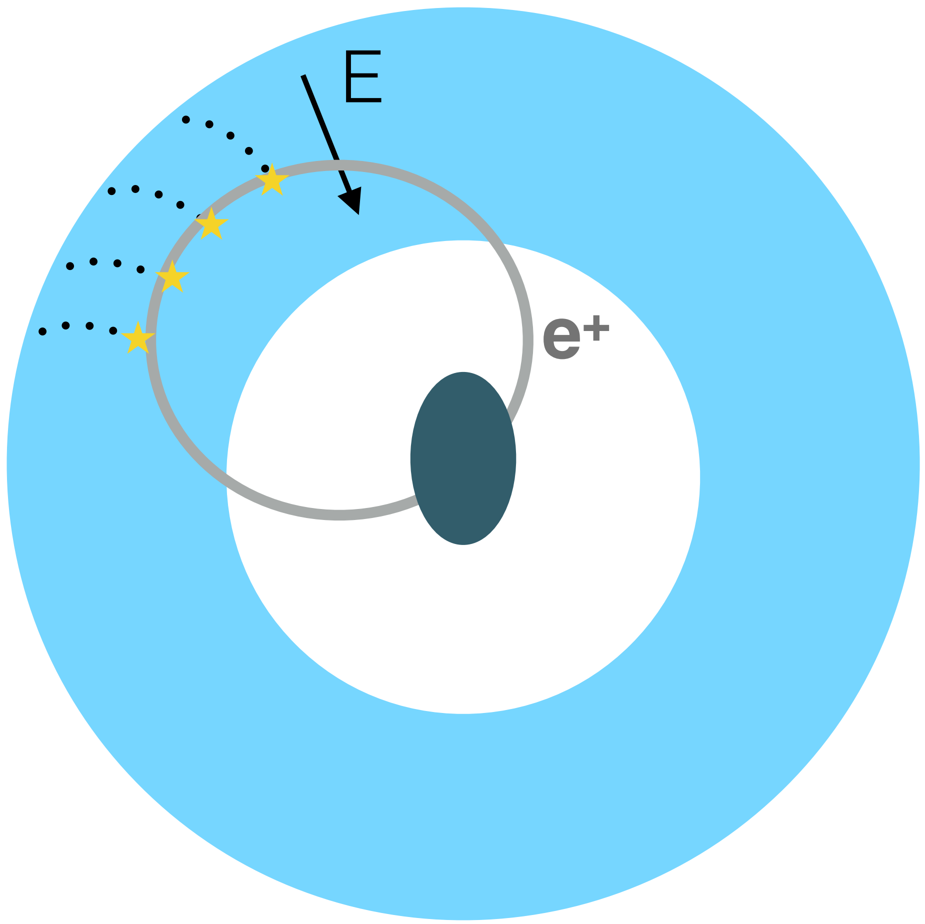
- very light wire supports
- no electronics in the tracking volume —> long transmission lines



Radial Time Projection Chamber



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



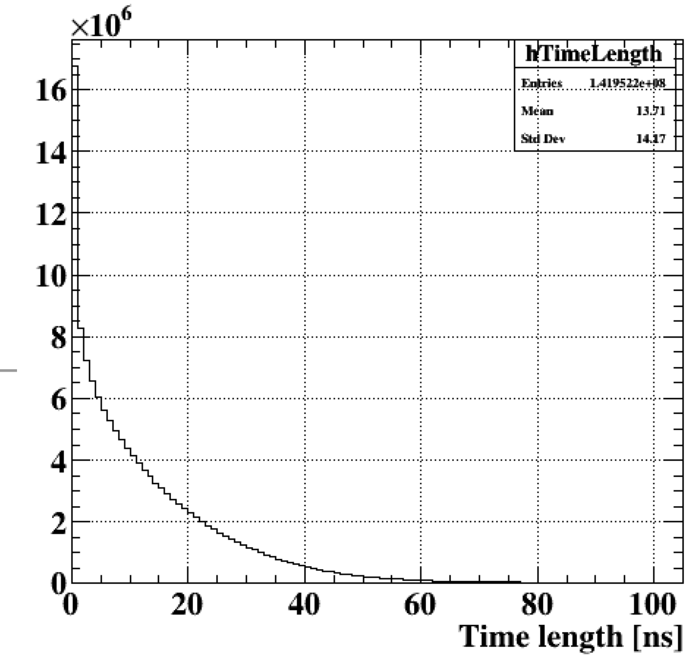
Need to develop a radial TPC with cylindrical MPGD readout, ~ 2 m long and ~ 30 cm radius

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

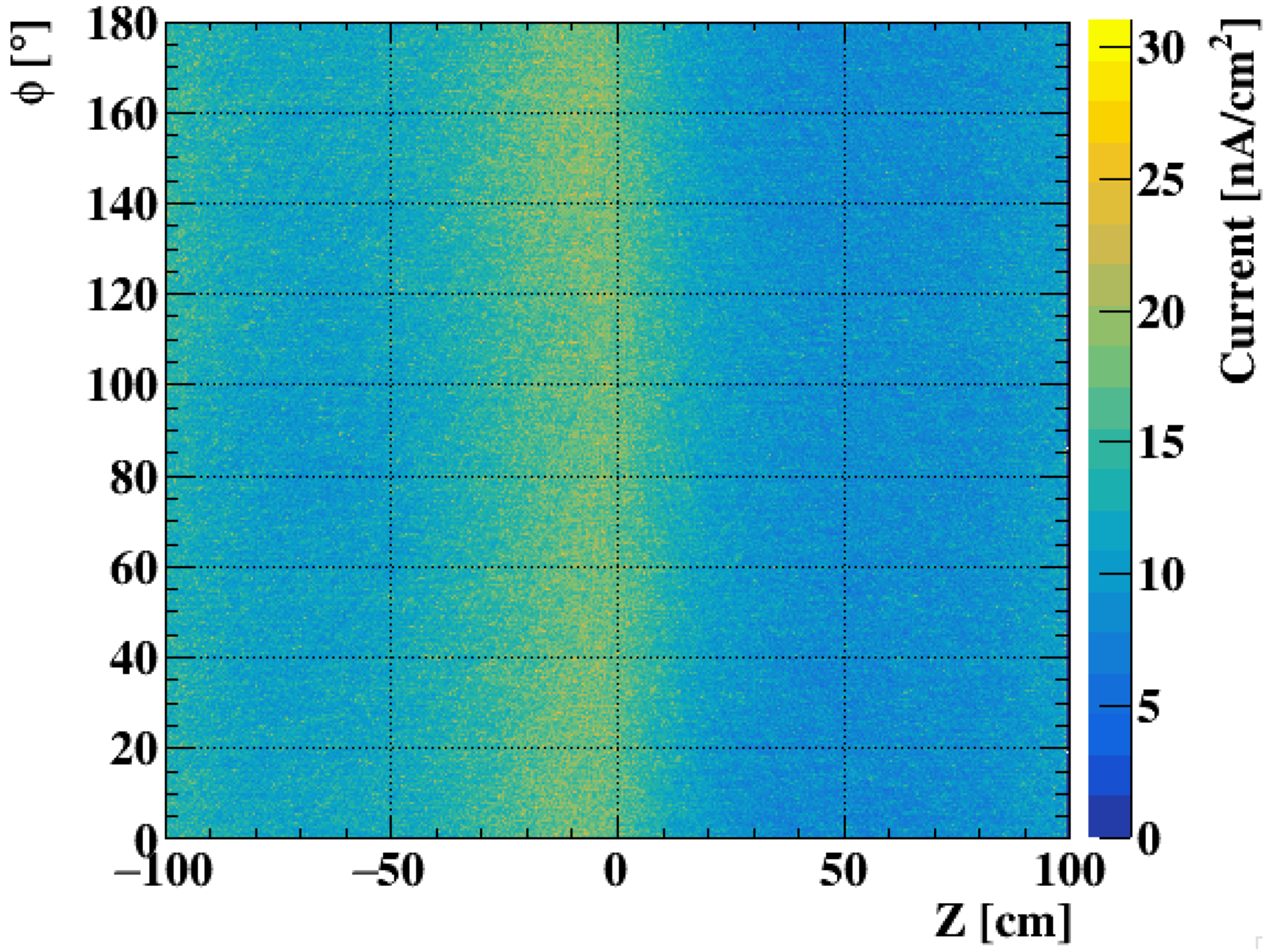
Need to develop advanced algorithms for correcting field deformations

Feasibility studies

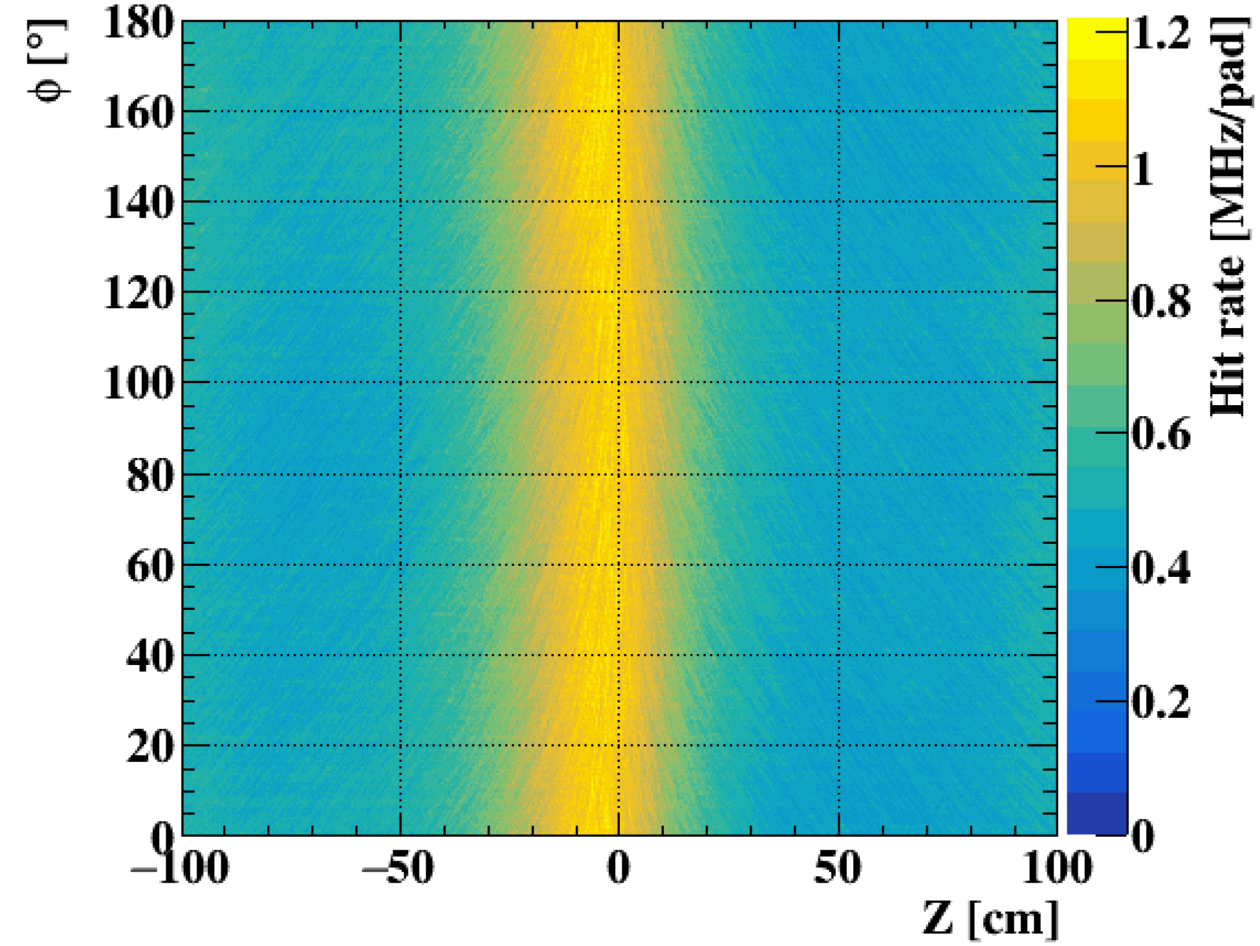
Time spread of electrons arriving to the same pad



- 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

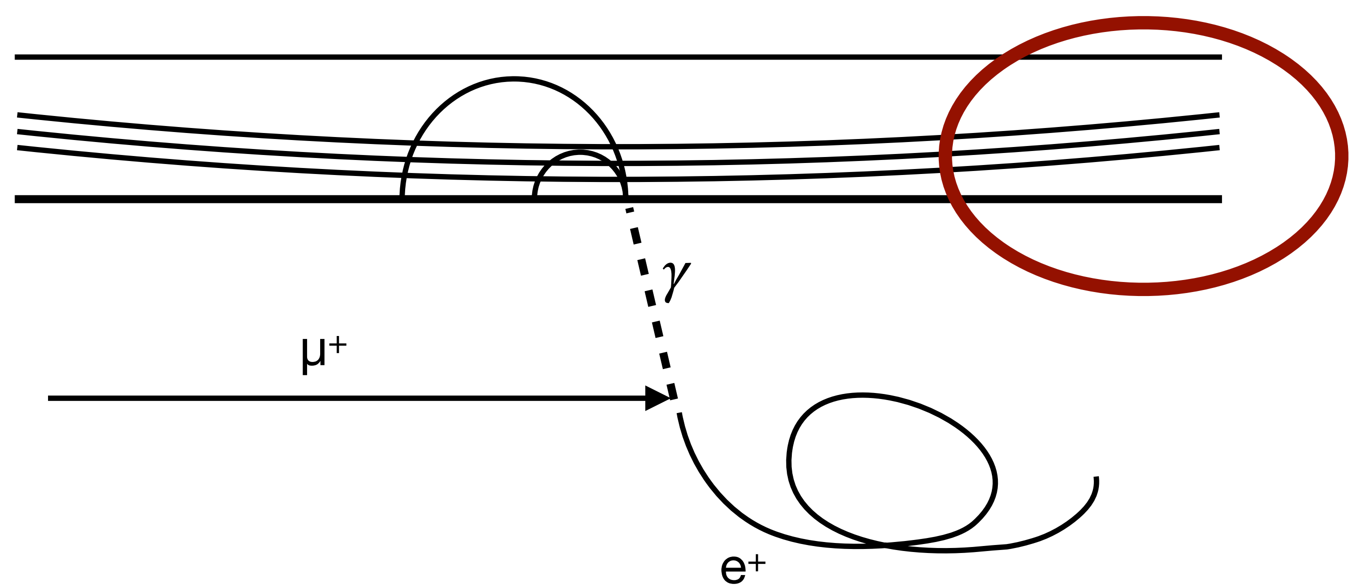


Assuming 5 x 3 mm² pads

Gaseous tracker for photon reconstruction

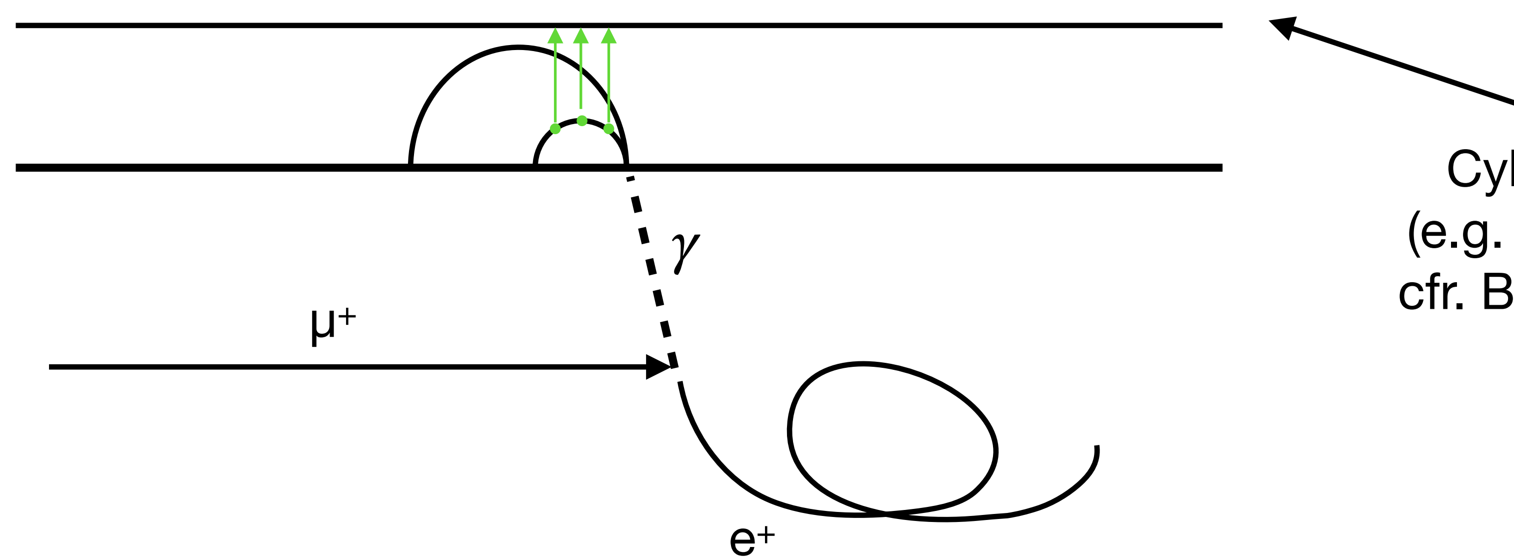
- Low rate —> much less demanding w.r.t. positron trackers

Wire chamber



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

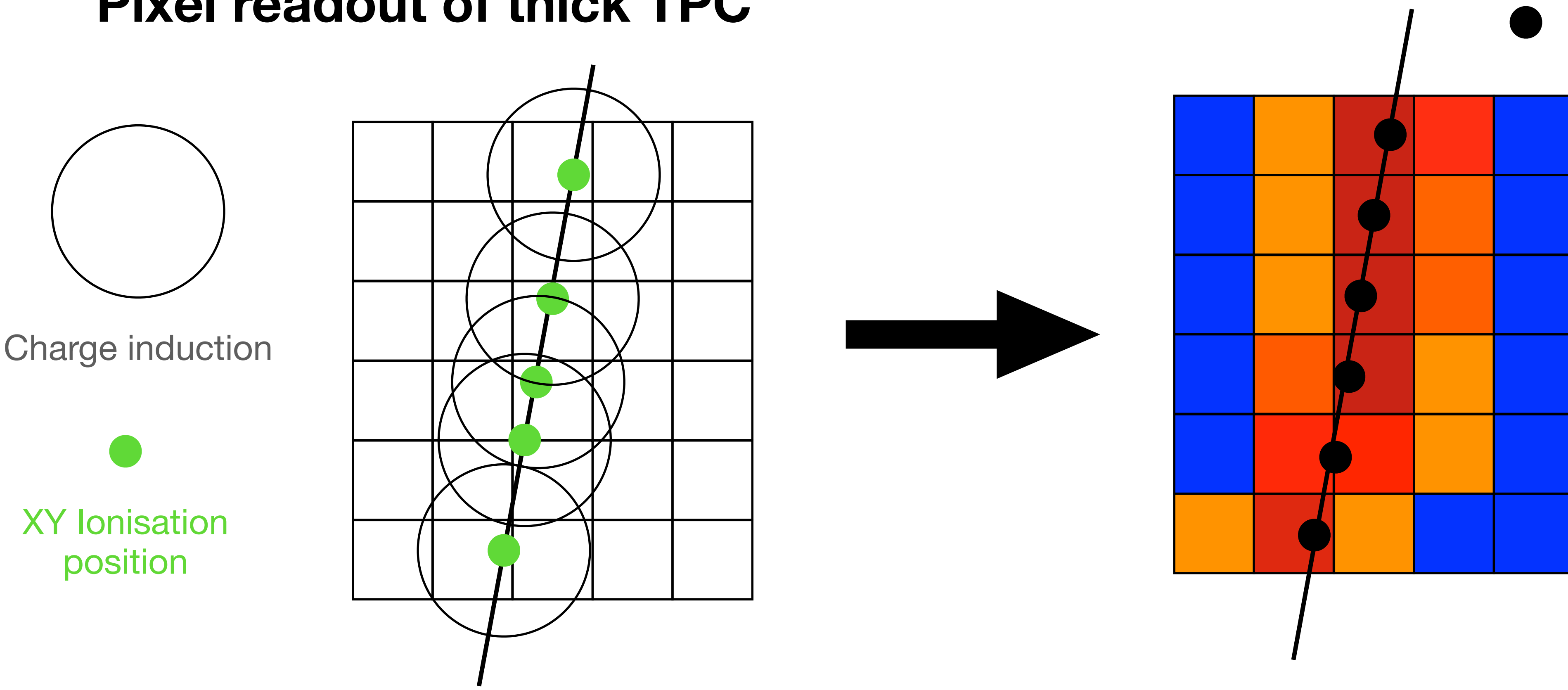
Radial TPC



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

Strip vs. Pixel Readout

Pixel readout of thick TPC



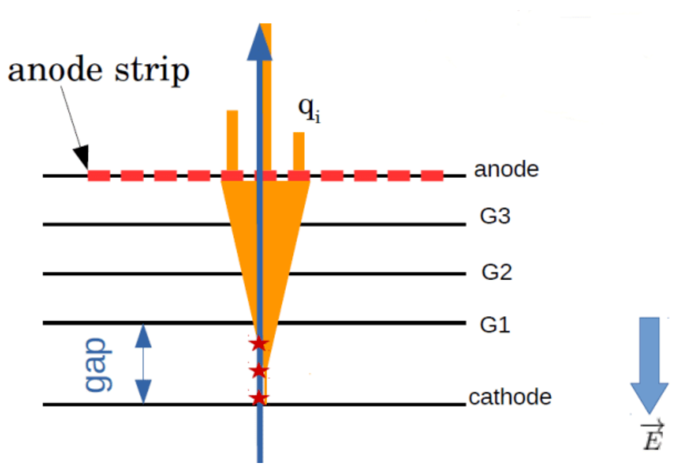
Center of Gravity (CoG)

+ Z position from drift time

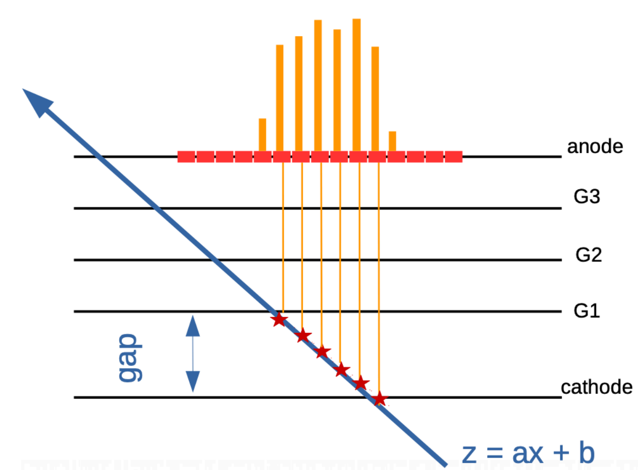
Very challenging in a radial TPC, unless a lot of space for the electronics is reserved in the outer cylindrical surface

Stereo strip readout of thin-gap chambers

CoG



µTPC

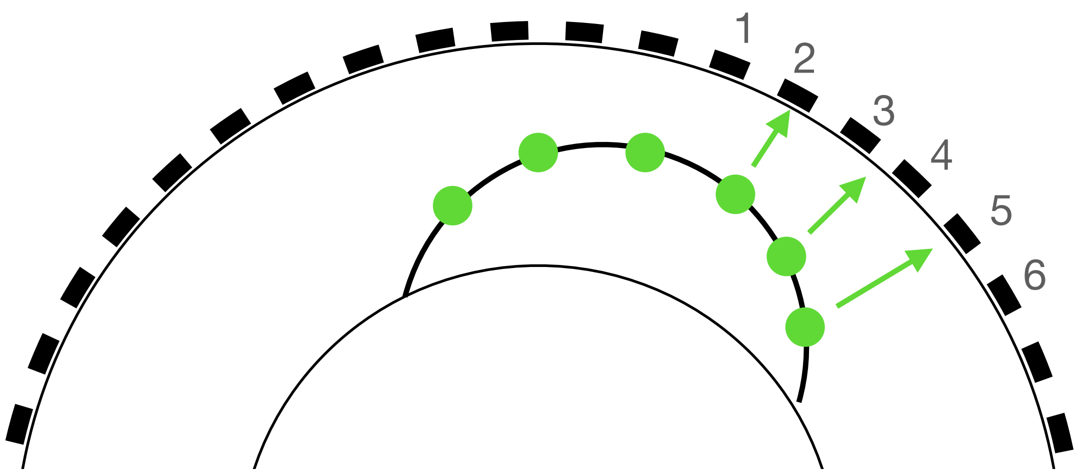


Doesn't work in a TPC due to track angle (several strips are on within the typical charge integration time of the electronics)

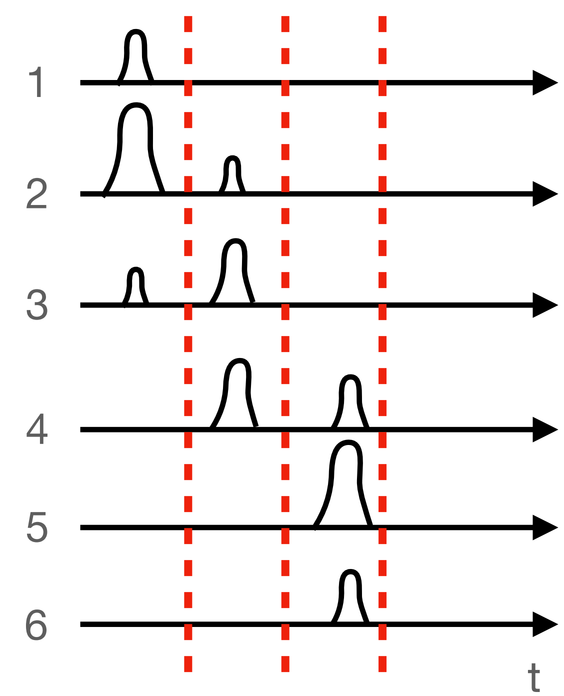
Suboptimal resolution with O(10cm) drift
(R: diffusion up to O(1 mm)
phi: strip granularity O(1/sqrt(12) mm))

Readout of a radial TPC

Stereo strip readout with time-resolved CoG measurement



Good resolutions can be achieved
(R: diffusion —> O(0.5 mm)
phi: CoG —> O(0.1 mm)
Z: CoG / sin(stereo) -> O(… mm))



CoG in bins of time
(ideal binning depends on
ionization density, ~ 50 ns,
diffusion effect, ~ 25 ns, and
electronics shaping time)
+
radial coordinate from precise
time measurements

Requires electronics with:

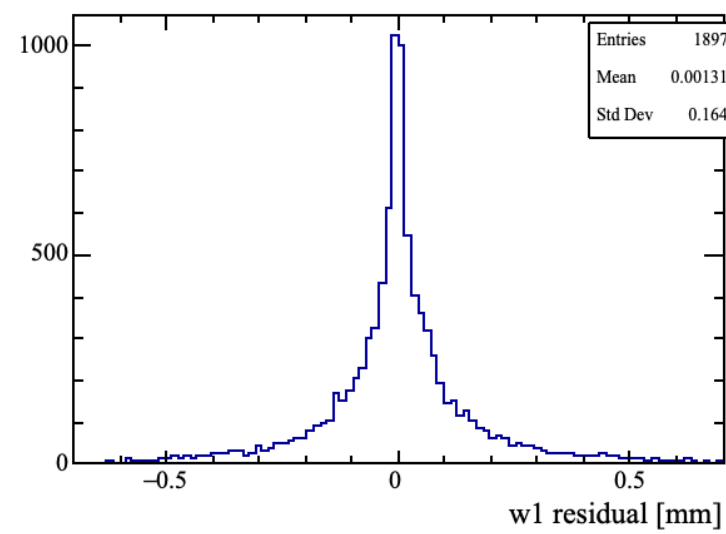
- large digitization speed (>> 10 MSPS)
- short peaking time (<< 100 ns)
- ~ 10 us digitization depth

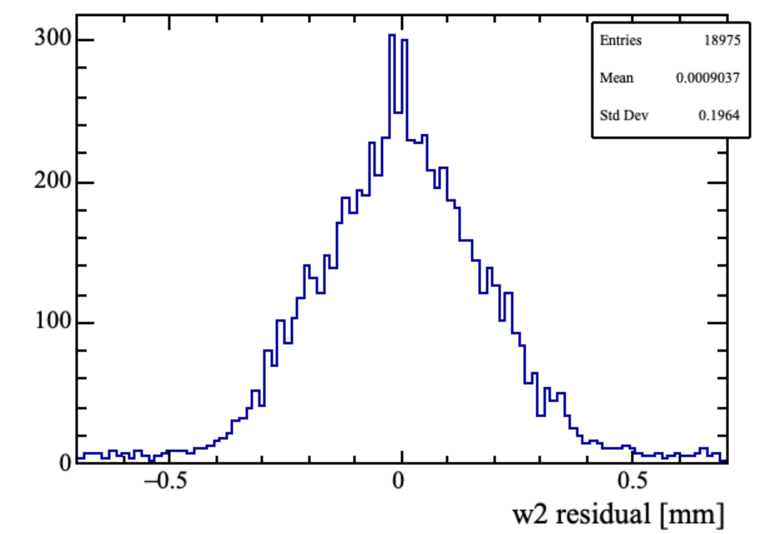
	PASA/ALTRO	AGET	Super-ALTRO	SAMPA
TPC	ALICE	T2K	ILC	ALICE upgrade
Pad size	4x7.5 mm^2	6.9x9.7 mm^2	1x6 mm^2	4x7.5 mm^2
Pad channels	5.7 x 10^5	1.25 x 10^5	1-2 x 10^6	5.7 x 10^5
Readout Chamber	MWPC	MicroMegas	GEM/MicroMegas	GEM
Gain	12 mV/fC	0.2-17 mV/fC	12-27 mV/fC	20/30 mV/fC
Shaper	CR-$(RC)^4$	CR-$(RC)^2$	CR-$(RC)^4$	CR-$(RC)^4$
Peaking time	200 ns	50 ns-1us	30-120 ns	80/160 ns
ENC	385 e	850 e @ 200ns	520 e	482 e @ 180ns
Waveform Sampler	ADC	SCA	ADC	ADC
Sampling frequency	10 MSPS	1-100 MSPS	40 MSPS	20 MSPS
Dynamic range	10 bit	12 bit(external)	10 bit	10 bit
Power consumption	32 mW/ch	<10 mW/ch	47.3 mW/ch	17 mW/ch
CMOS Process	250 nm	350 nm	130 nm	130 nm

Feasibility studies

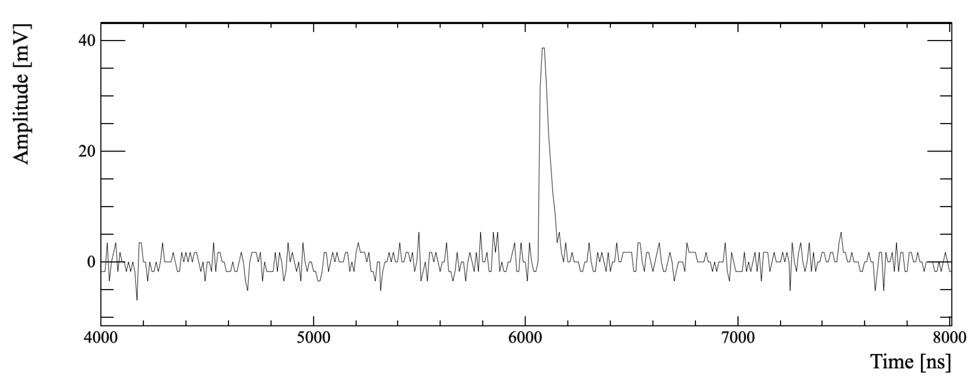
e+e- reconstruction in a radial TPC with strip readout

WORK IN PROGRESS

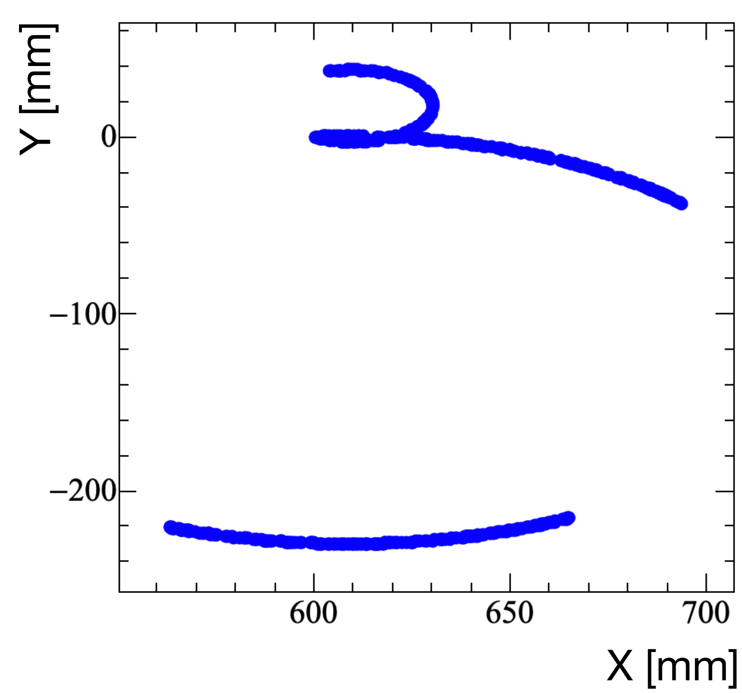




Typical waveform



True tracks



Reco track
(time resolved CoG)