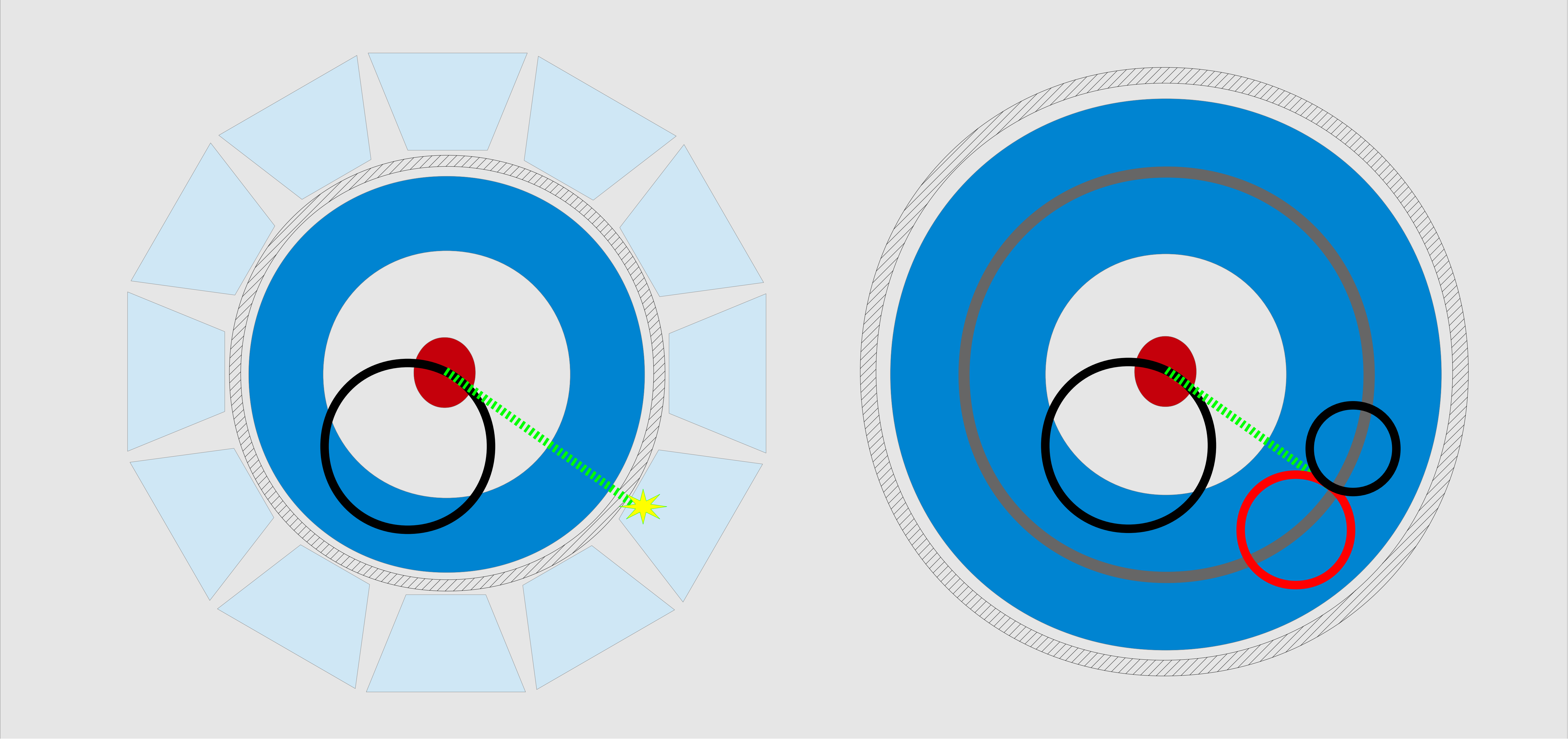


Muon decay experiments and cLFV at high intensity muon beam facilities

Francesco Renga
INFN Roma

Latest muon decay experiments

Measurement of decay parameters

$$\frac{d^2\Gamma(\mu^\pm \to e^\pm \bar{\nu}\nu)}{dx\, d\cos\theta_e} = \frac{m_\mu G_F^2}{4\pi^3} W_{e\mu}^4 \sqrt{x^2 - x_0^2}\left[F_{IS}(x) \pm P_\mu \cos\theta_e F_{AS}(x)\right]$$

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)\,,$$

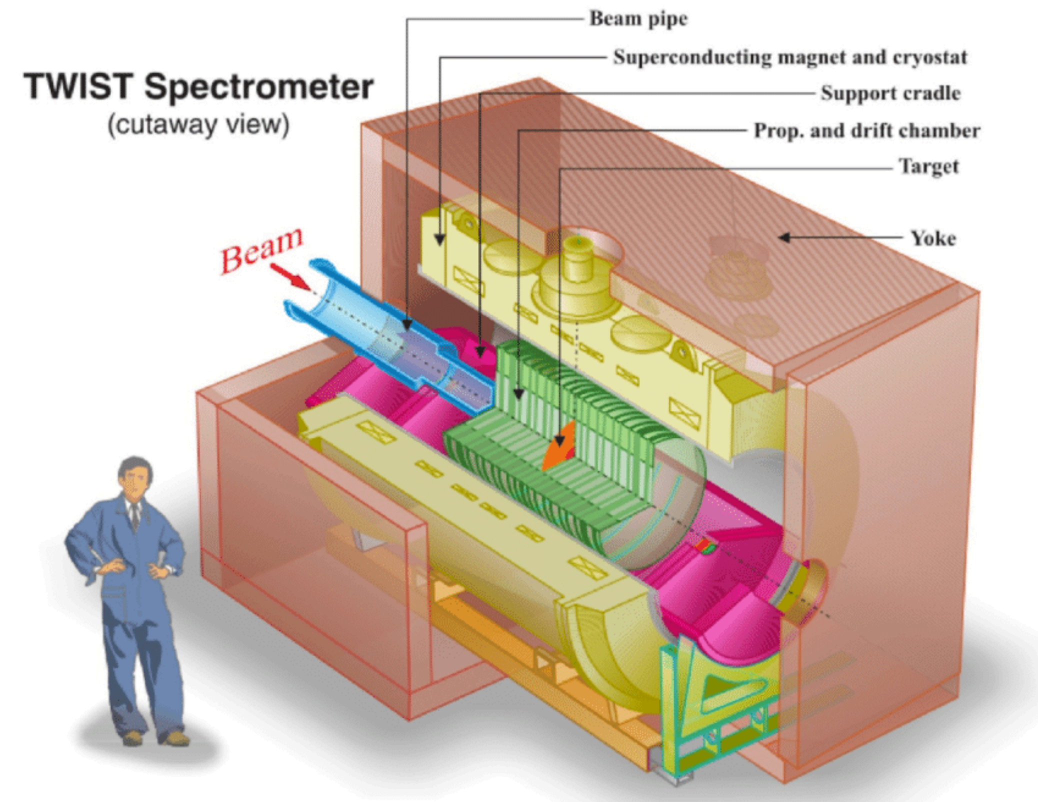
$$F_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left\{1 - x + \frac{2}{3}\delta\left[4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right]\right\}$$

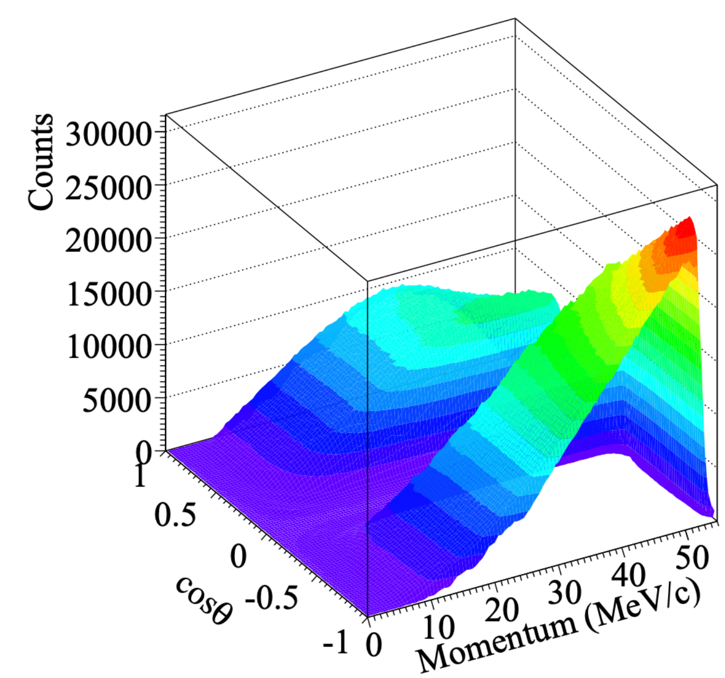
$$x = 2E_e/m_\mu \quad W_{e\mu} = (m_\mu^2 + m_e^2)/(2m_\mu) \quad x_0 = m_e/W_{e\mu}$$

In the Standard Model

$$\rho = 3/4 \quad \eta = 0 \quad \xi = 1 \quad \delta = 3/4$$

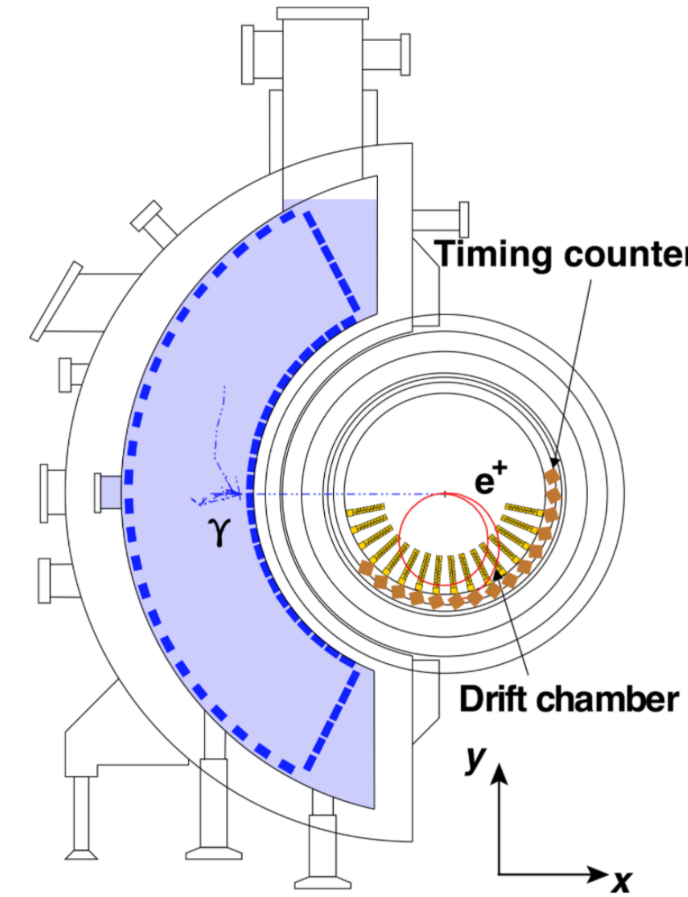
$$\rho = 0.74977 \pm 0.00012\,(\text{stat}) \pm 0.00023\,(\text{syst})$$
$$\delta = 0.75049 \pm 0.00021\,(\text{stat}) \pm 0.00027\,(\text{syst})$$





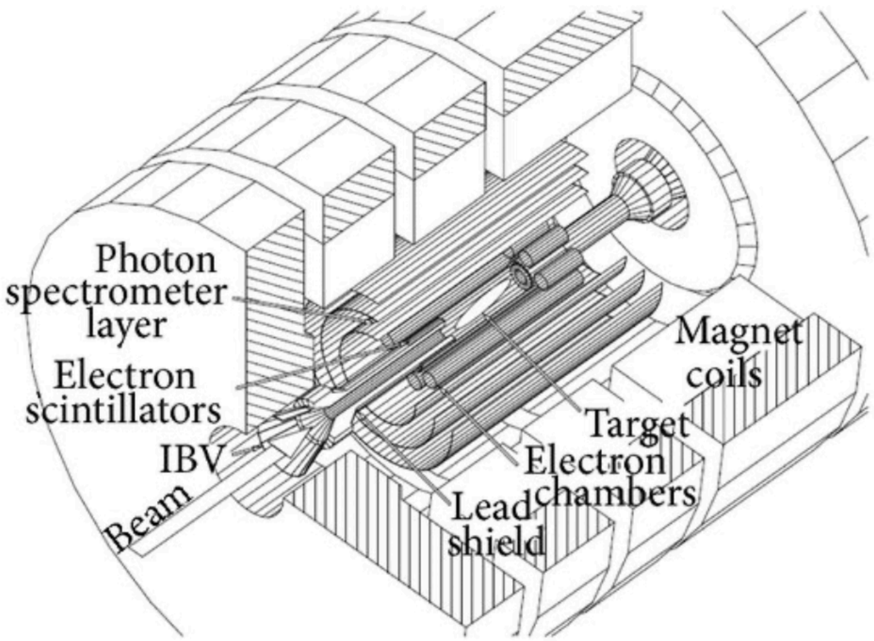
Latest muon decay experiments

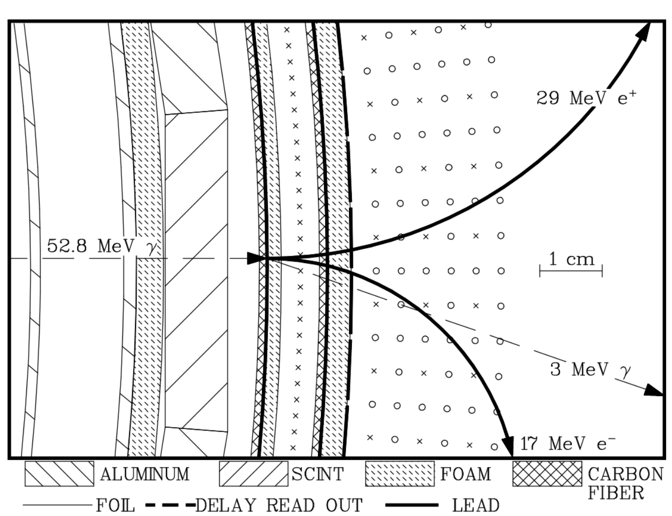
$\mu^+ \rightarrow e^+\gamma$



MEGA (LANL) - 2002

$$BR(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$$

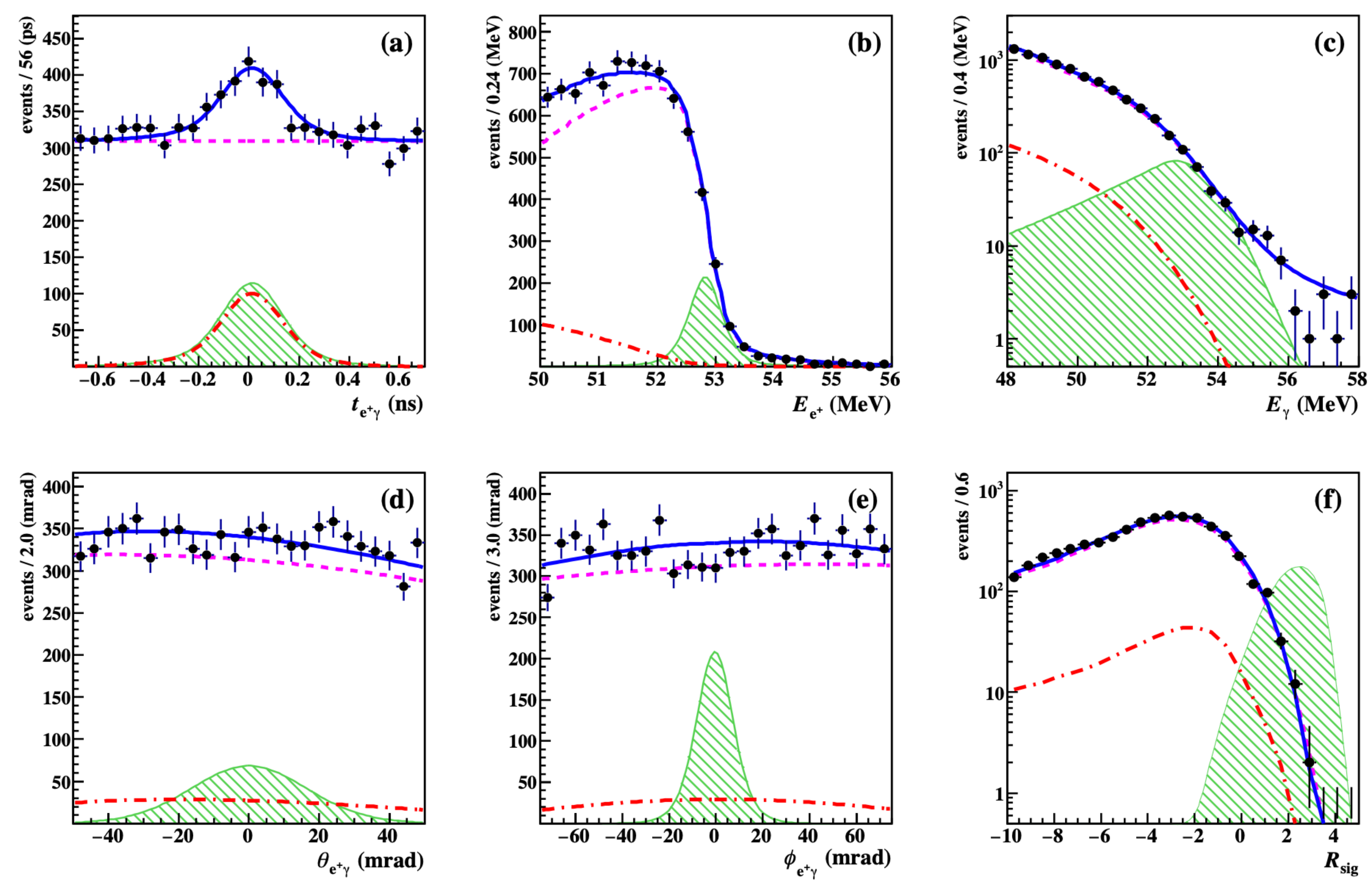




MEG (PSI) - 2016

$$BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$$

An upgrade (MEG II) is on going - 10x better sensitivity

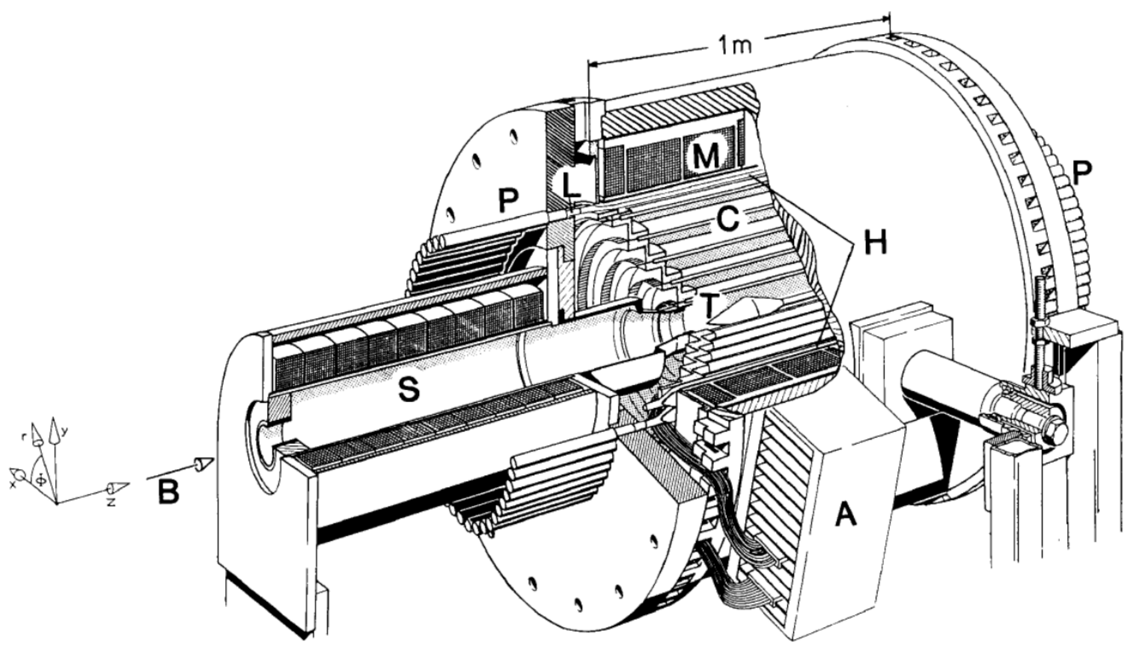


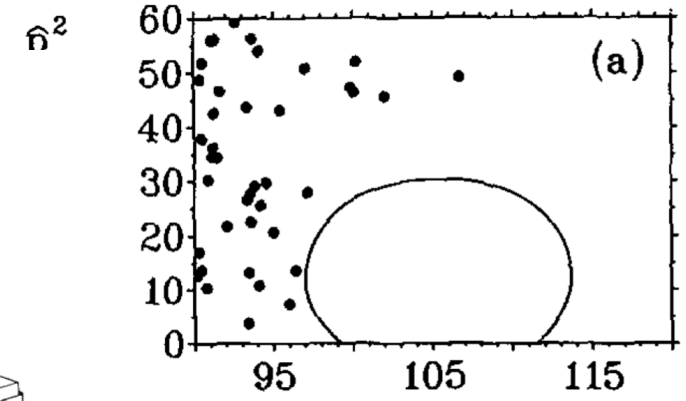
Latest muon decay experiments

$\mu^+ \to e^+e^+e^-$

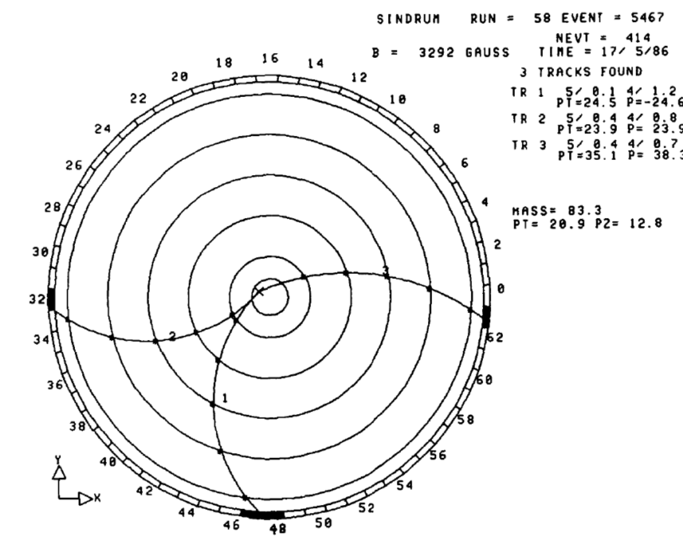
SINDRUM (PSI) - 1988

$BR(\mu \to eee) < 1 \times 10^{-12}$





(a)

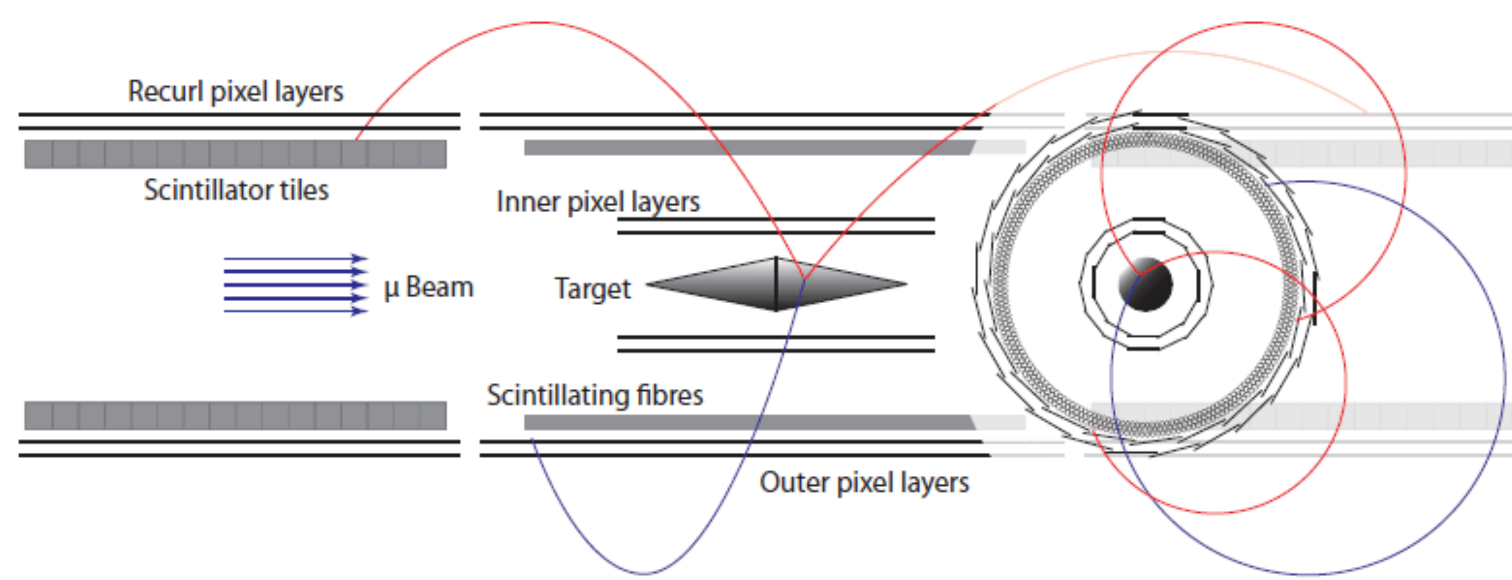


Mu3e (PSI)

under commissioning

5 x 10^{-15} UL sens. (phase I)

~ 10^{-16} UL sens. (phase II)



Experimental techniques for muon decay studies

Beam and target

- Muon decay experiments suffer of backgrounds from accidental coincidences of particles from multiple muon decays:
  - **continuous or quasi-continuous beams** are preferable over pulsed beams
  - very high beam intensity can be useless, if the resolutions are not sufficient to suppress the accidental background down to a negligible level

$$S \propto \Gamma_\mu \,, \;\; B \propto \Gamma_\mu^2 \,, \;\; S/\sqrt{B} = \text{const} \,.$$

- Decay at rest of free muons to maximally exploit the kinematical constraints
  - **positive muons** are preferable over negative muons, to avoid muon capture by nuclei
  - low-energy electrons/positrons and photons, challenging the **material budget** of the experimental apparatus
  - a **well monochromatic, low momentum beam** on a **very thin target**, to get high stopping efficiency with reduced material budget

Experimental techniques for muon decay studies

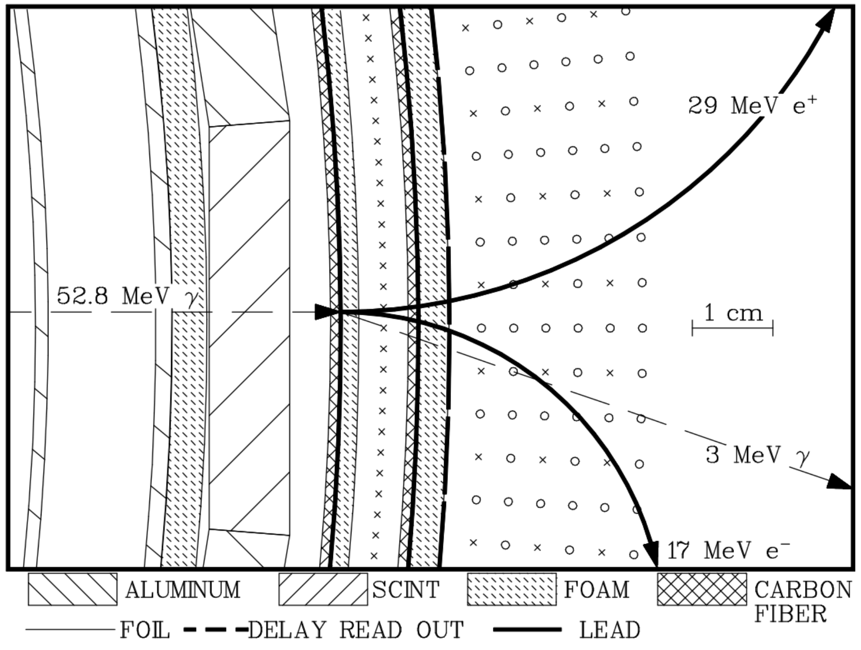
Charged particle tracking

- Tracking in a magnetic field provides the best performances for the reconstruction of low-momentum electrons and positrons, but a very low material budget is required
  - gaseous detectors as a standard choice over the last decades
  - very thin monolithic silicon pixels just started becoming competitive

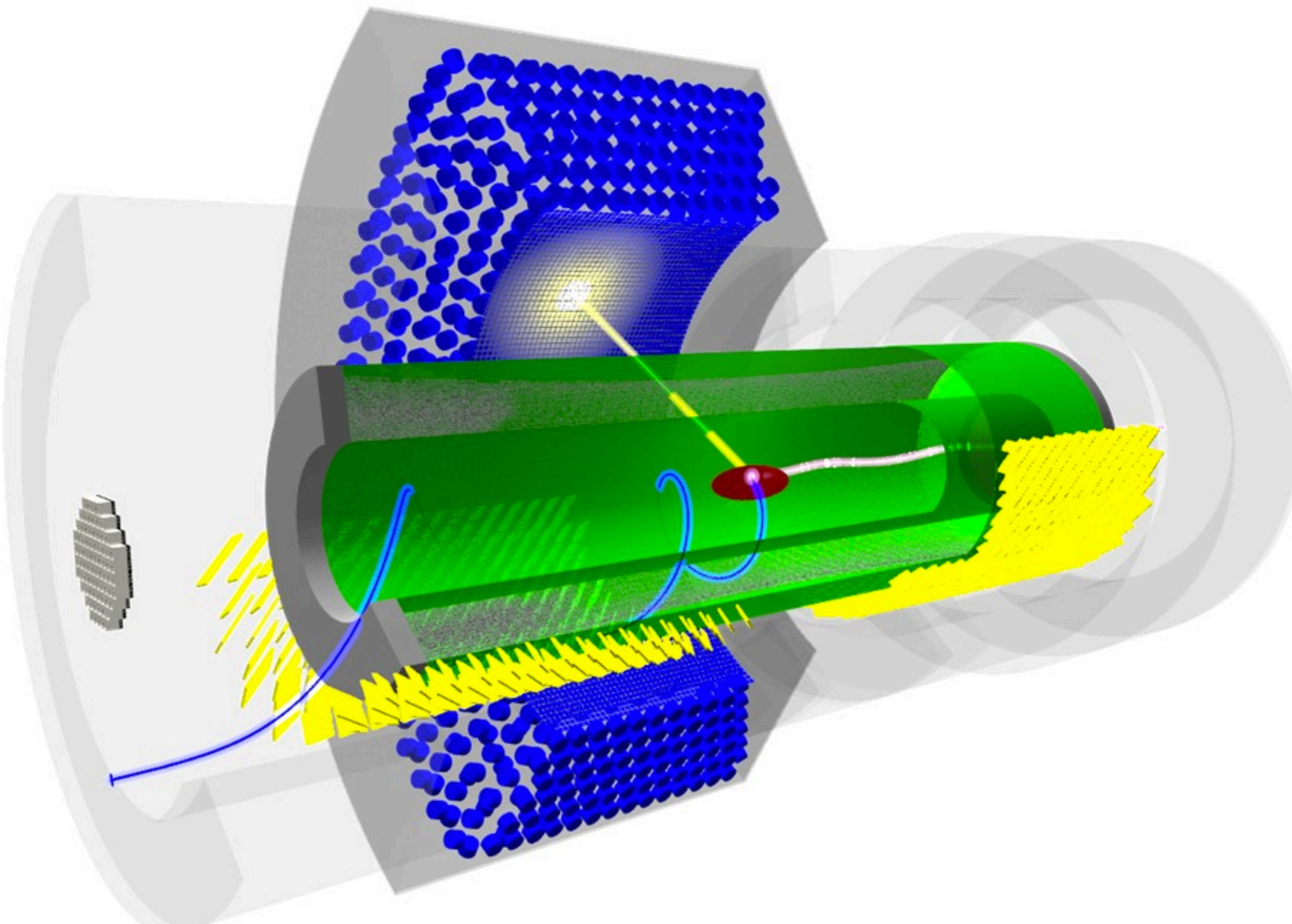
Experimental techniques for muon decay studies

Photon reconstruction

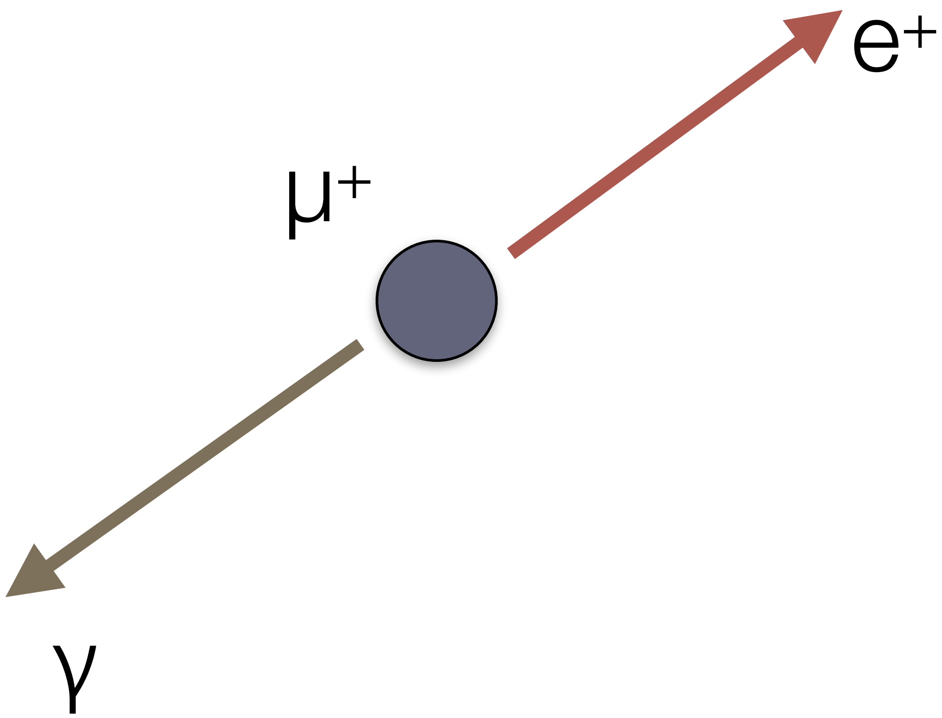
- Challenging and expensive low-energy calorimetry is required for a highly efficient photon reconstruction
- If very high muon beam intensities are available, it can become advantageous to improve the energy resolution with a photon pair conversion spectrometer, at the cost of a very small reconstruction efficiency



The quest for $\mu^+ \to e^+\gamma$



μ -> e γ searches

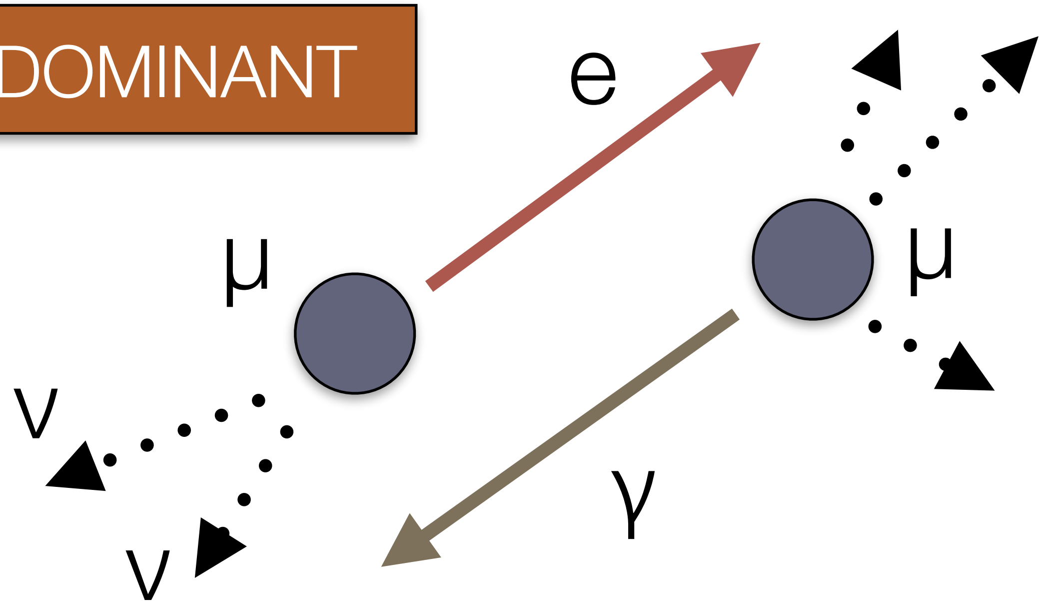


28 MeV/c muons are stopped on a thin target

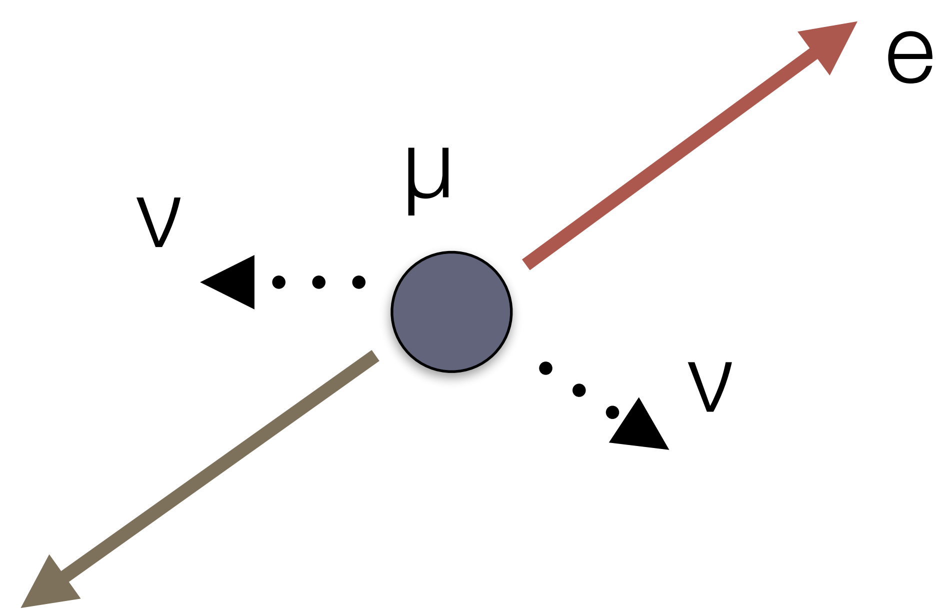
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the **same time**;

Accidental Background

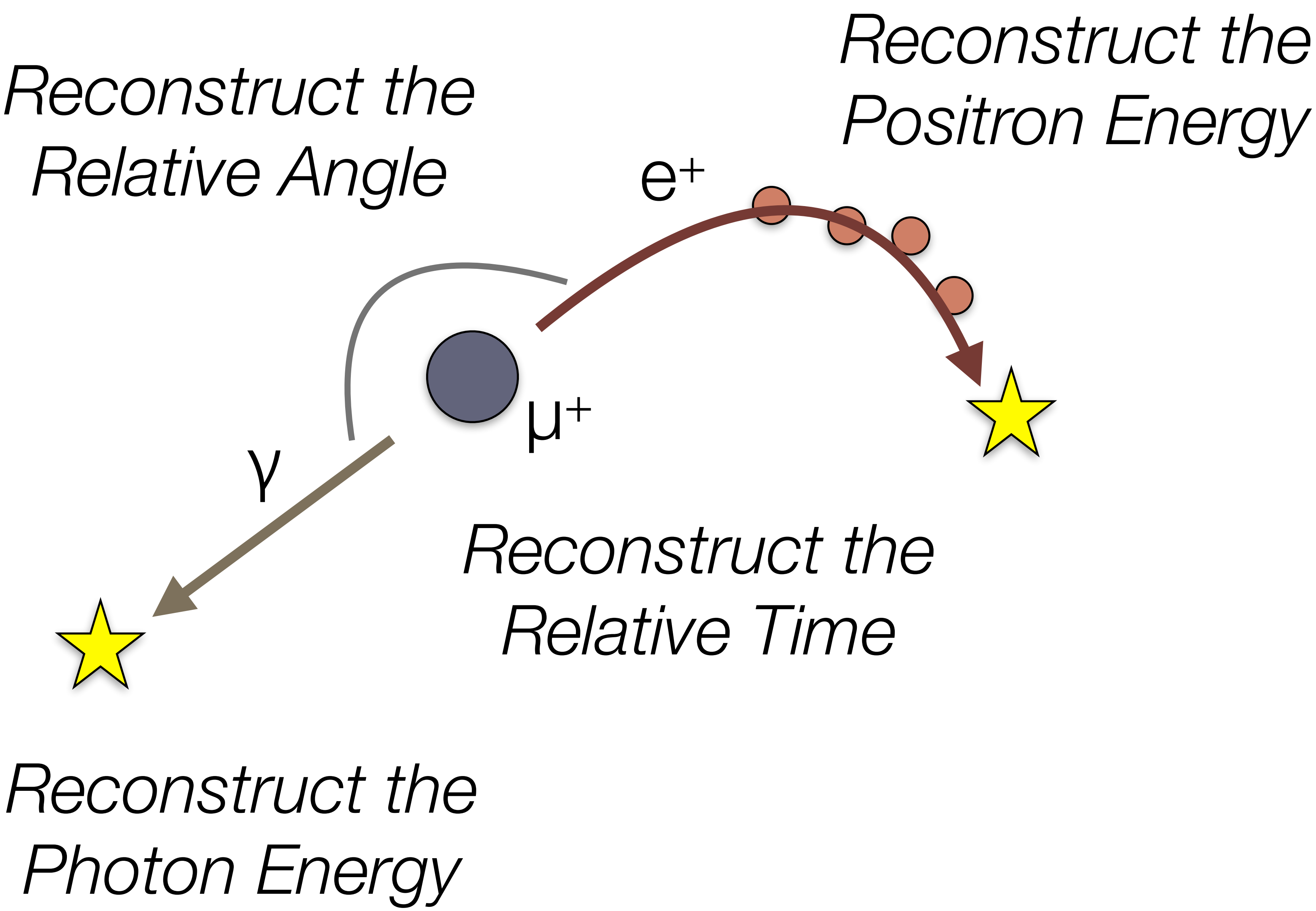
DOMINANT



Radiative Muon Decay (RMD)



Ingredients for a search of μ -> e γ



The MEG Experiment

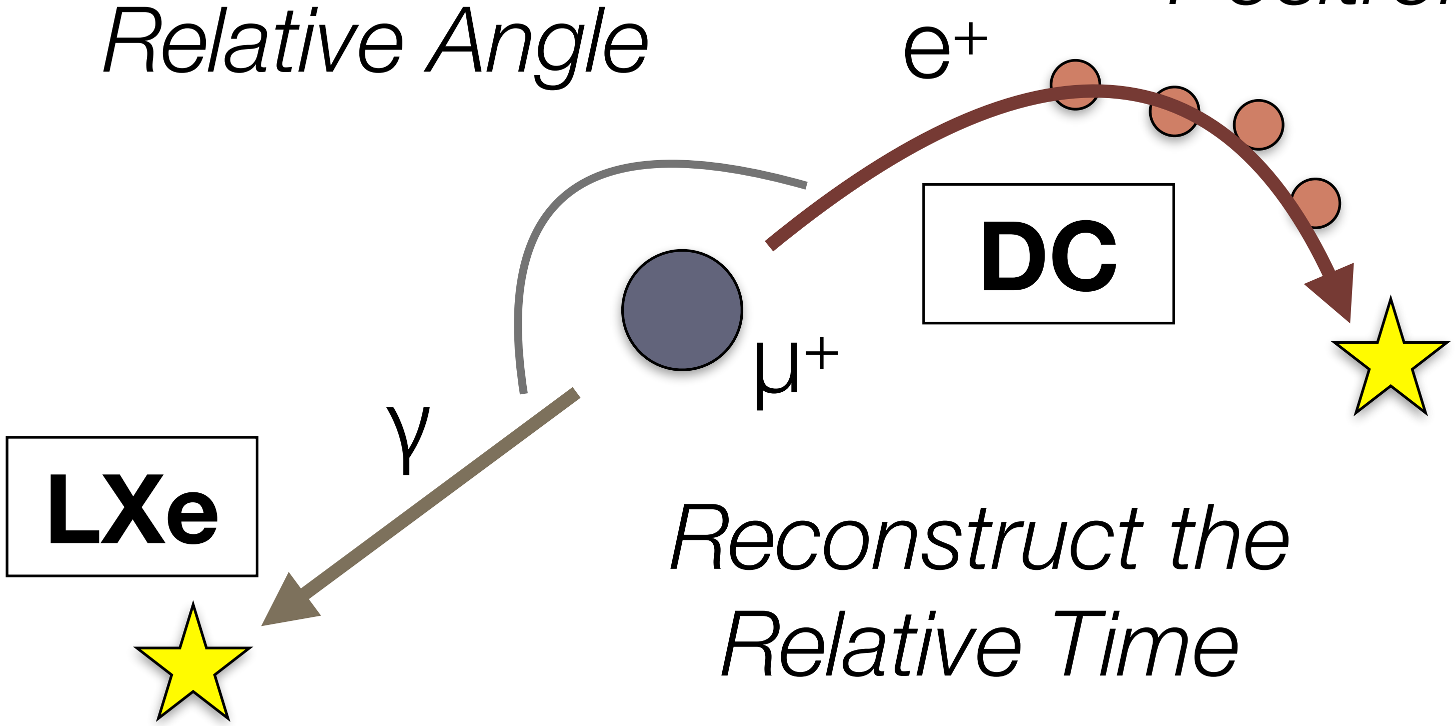
Reconstruct the Relative Angle

Reconstruct the Positron Energy

LXe calorimeter (XEC)

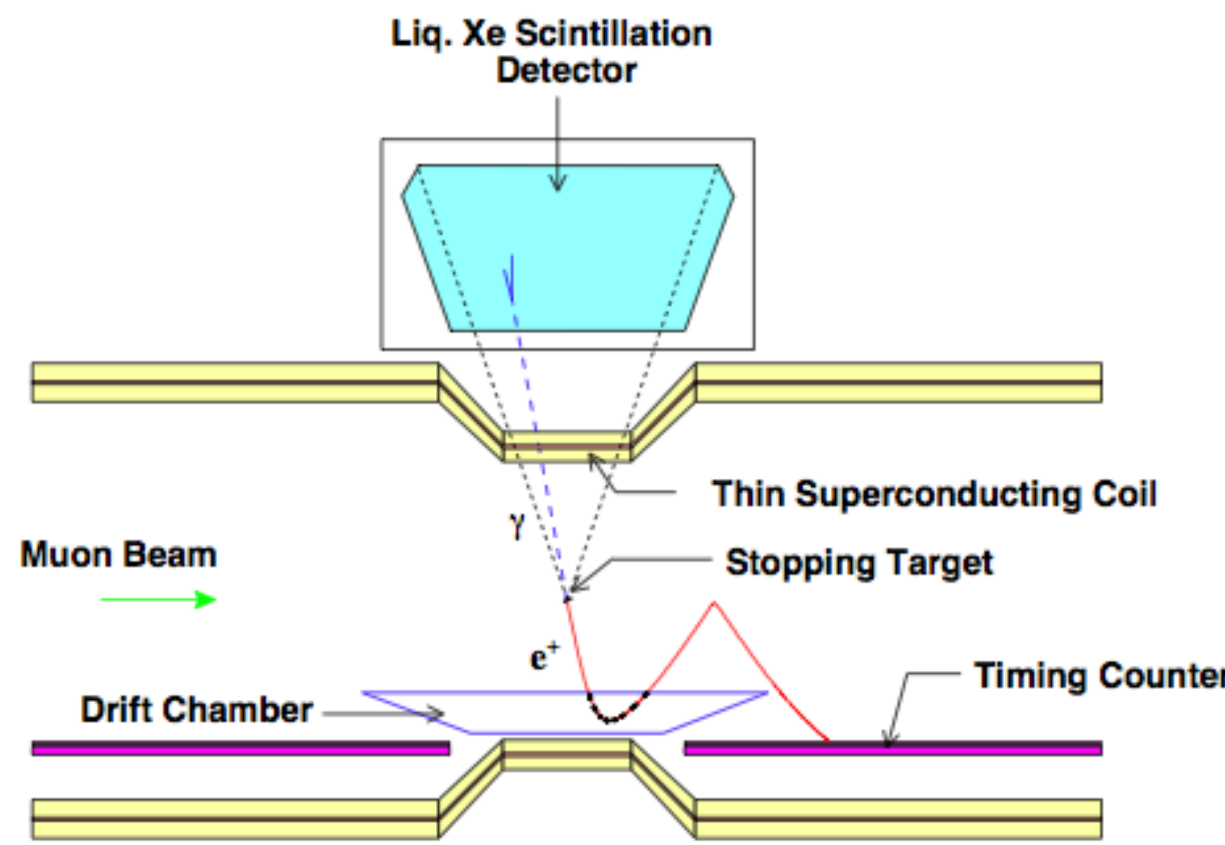
16 Drift Chambers (DC) in a magnetic field

30 scintillating bars for timing & trigger (TC)



Reconstruct the Relative Time

Reconstruct the Photon Energy

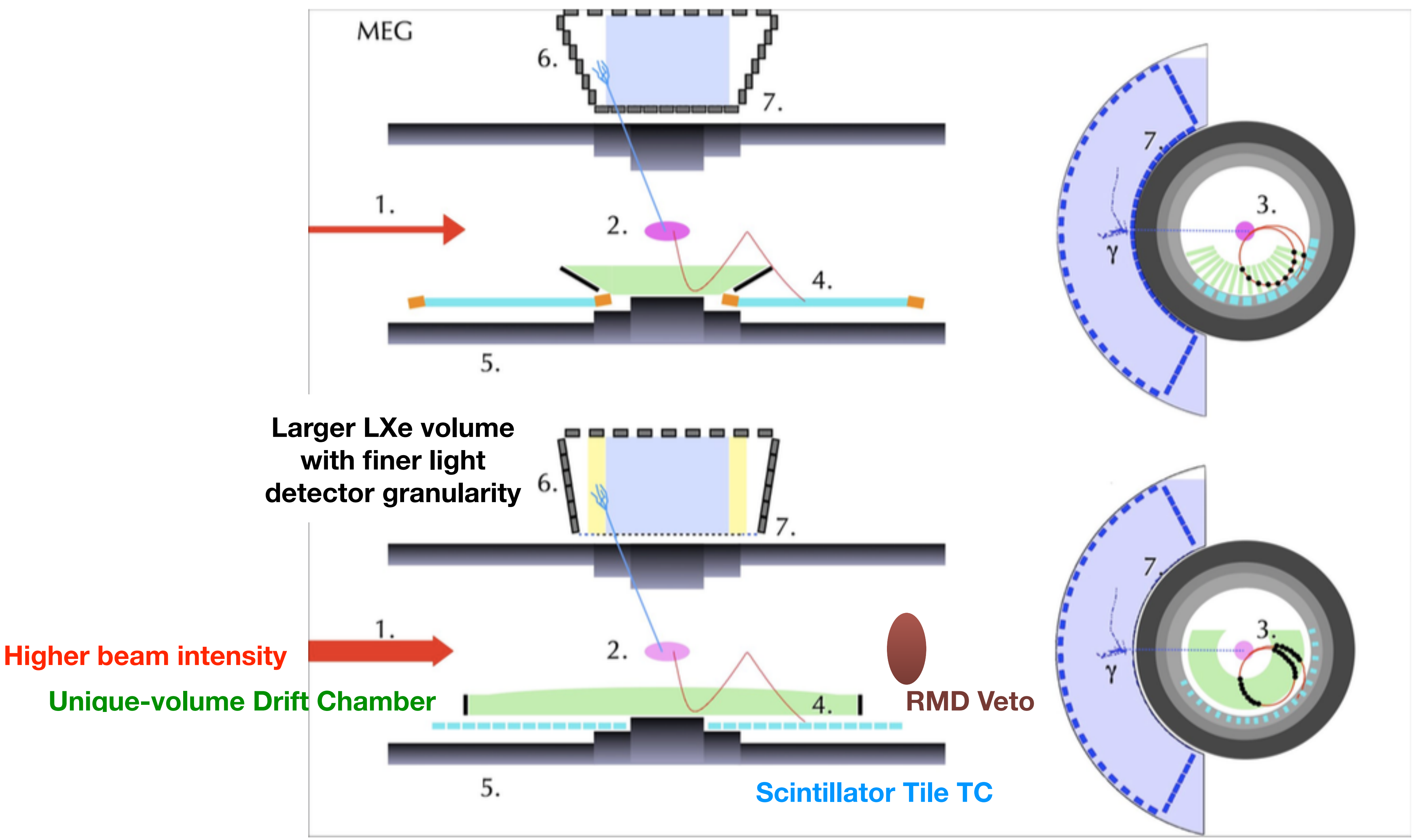


7.5×10^{14} μ on target

BR(μ -> e γ) < 4.2×10^{-13} @ 90% C.L.

MEG-II

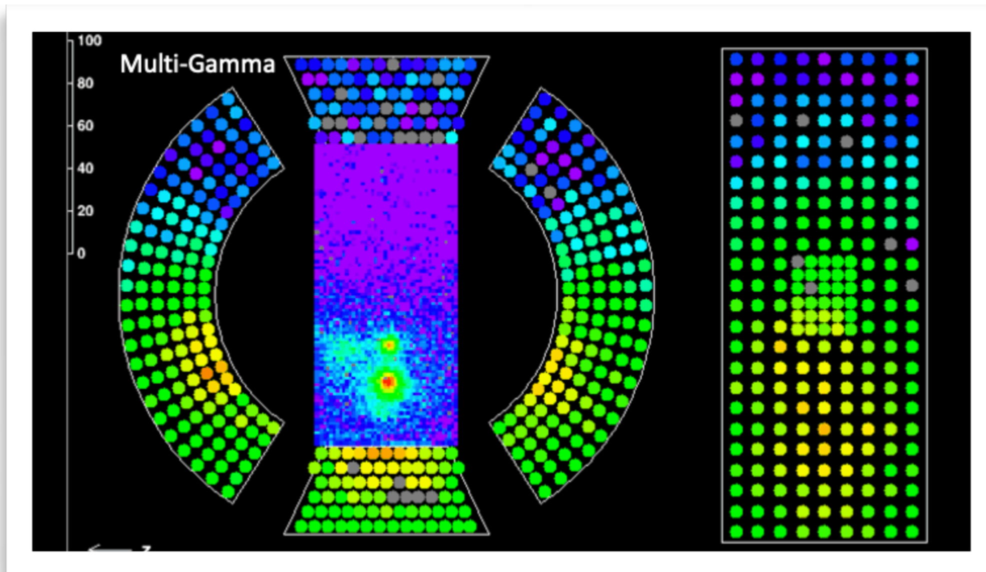
- The MEG experiment has been upgraded in all sub-detectors



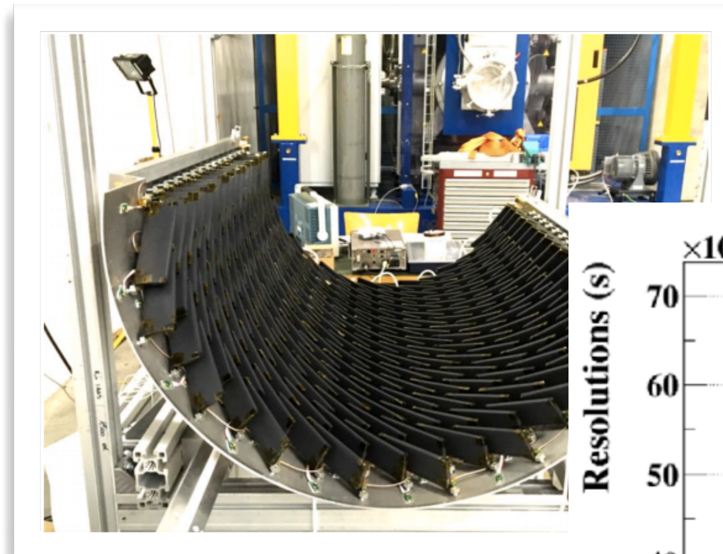
MEG-II status

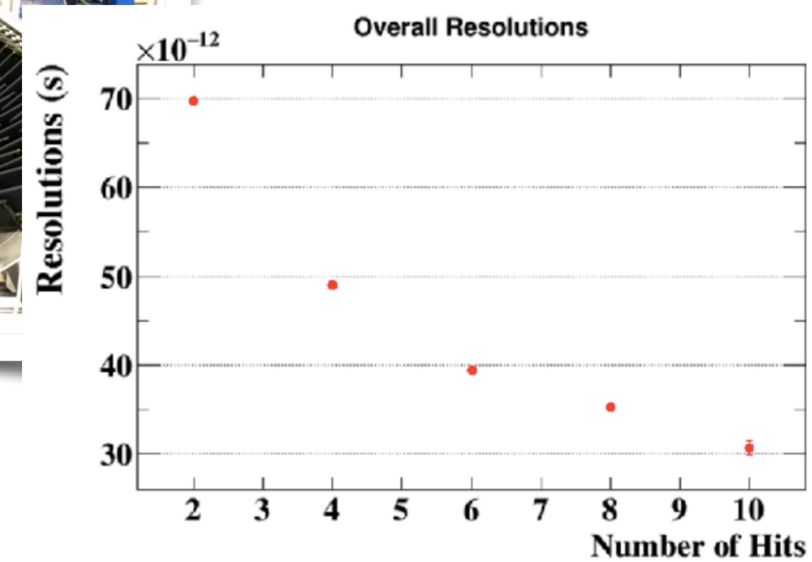
In 2021, first physics data collected with full readout

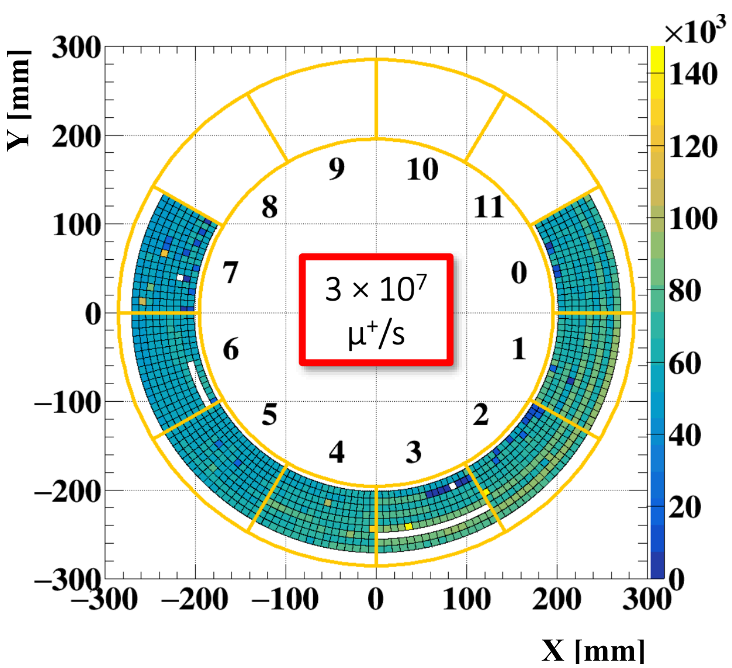
Example of XEC multi-photon event

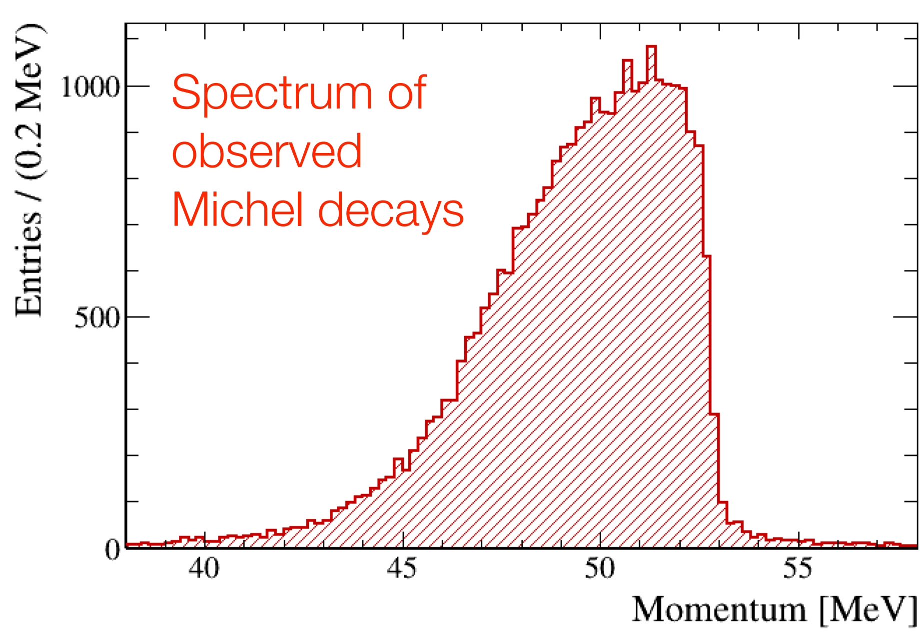


TC already reached the design resolution









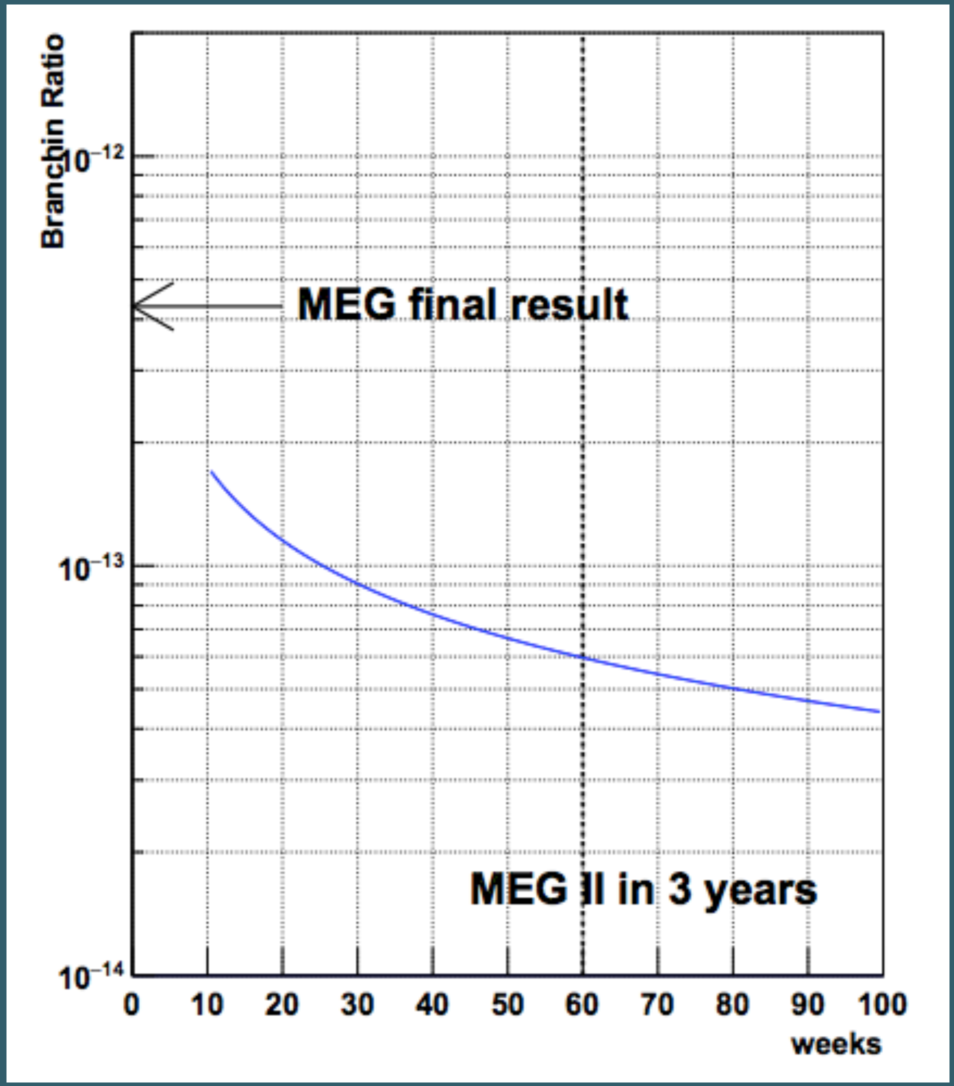
The drift chamber could be operated stably under beam

First positron tracks observed

MEG-II status

First physics run in 2021

Expected UL $\sim 6 \times 10^{-14}$ in a 3-year run at 5×10^{7} μ/s



What next?

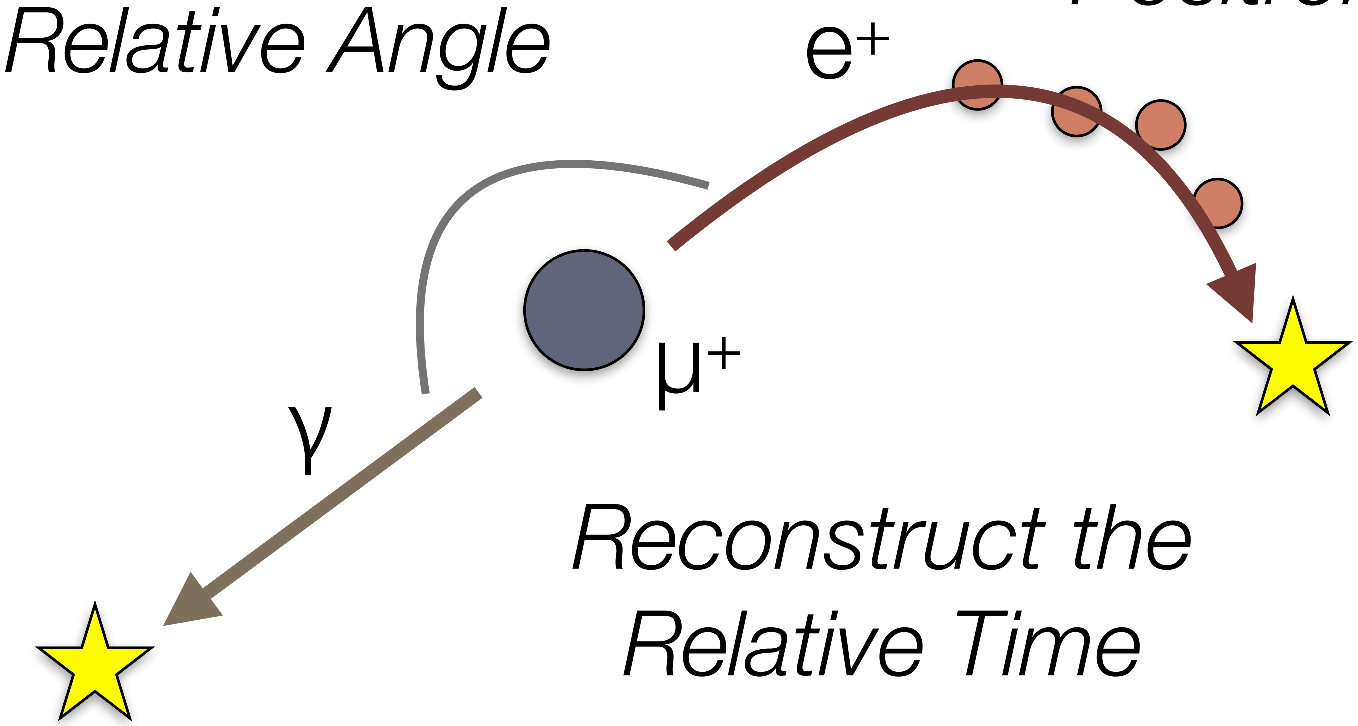
G. Cavoto, A. Papa, FR, E. Ripiccini and C. Voena

Eur. Phys. J. C (2018) 78: 37

Ingredients for a search of μ -> e γ

Reconstruct the Relative Angle

Reconstruct the Positron Energy



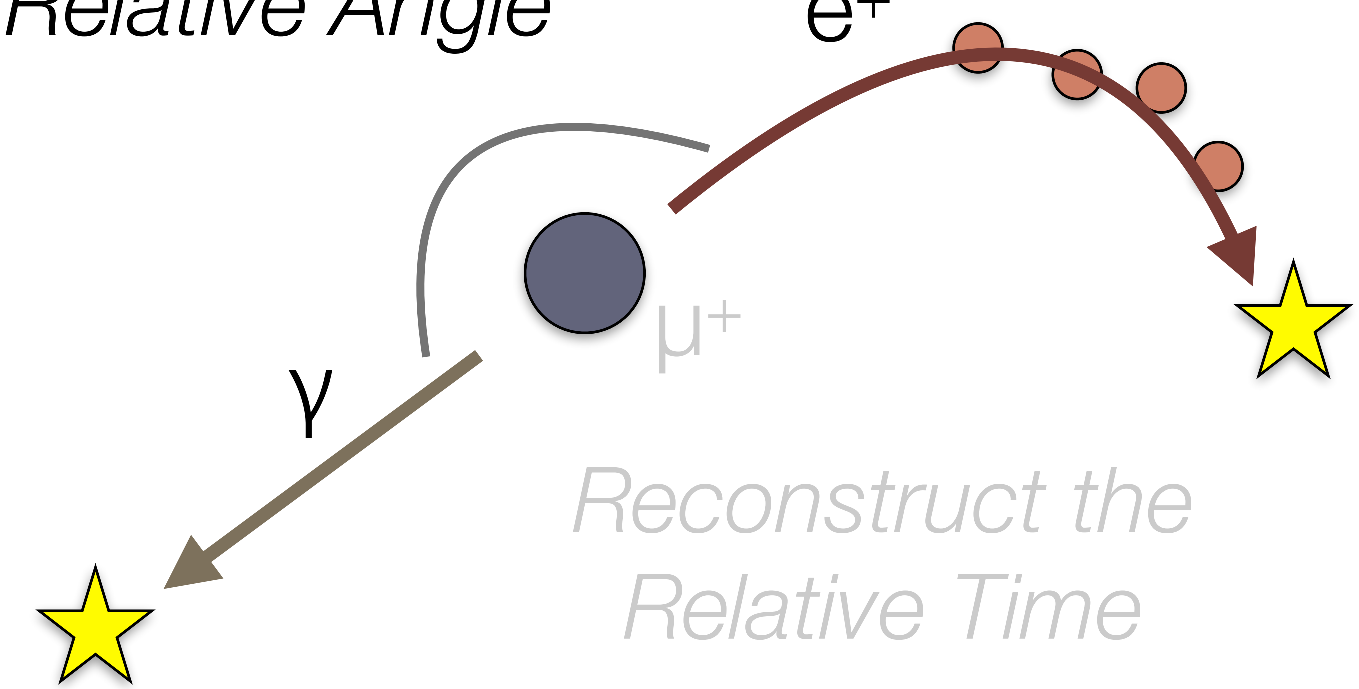
Reconstruct the Relative Time

Reconstruct the Photon Energy

Ingredients for a search of μ -> e γ

Reconstruct the Relative Angle

Reconstruct the Positron Energy



Reconstruct the Photon Energy

The target itself contribute significantly to the angular resolution (target as thin as possible —> ***low momentum beam, as monochromatic as possible***)

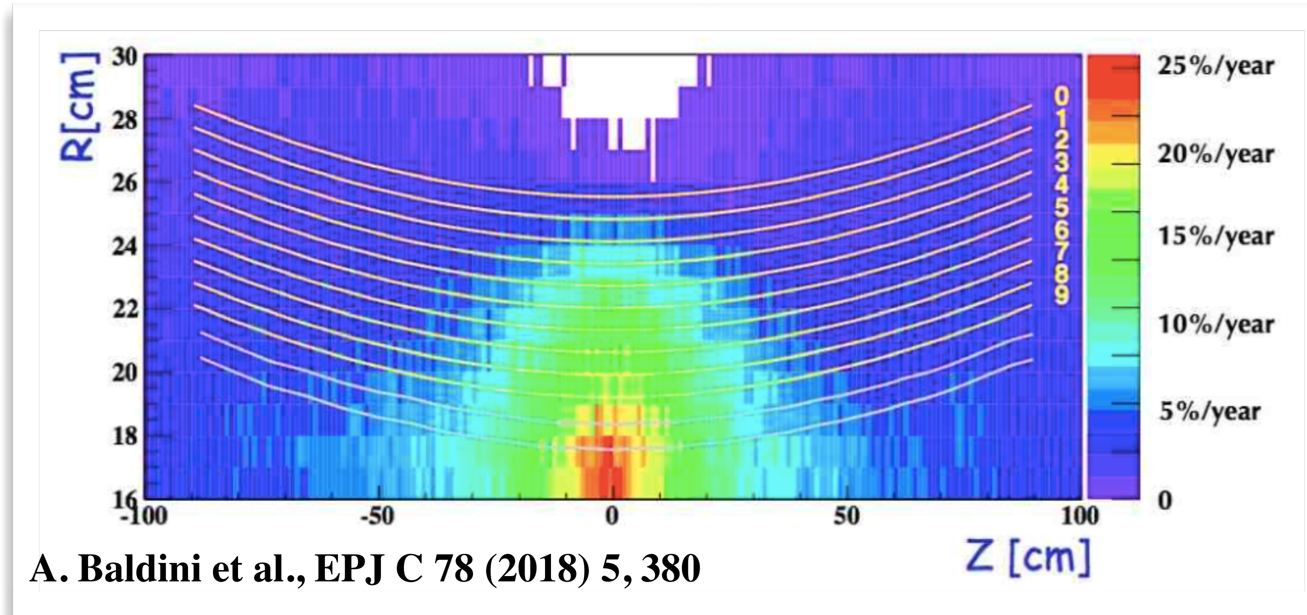
Magnetic spectrometer to get the best resolutions

52.8 MeV/c —> large multiple scattering —> very low material budget (ideally a gaseous detector)

Positron Reconstruction at High Beam Rate

- MS makes useless an extreme position resolution (e.g. silicon detectors) and plays in favour of light gaseous detectors, but…

…would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?



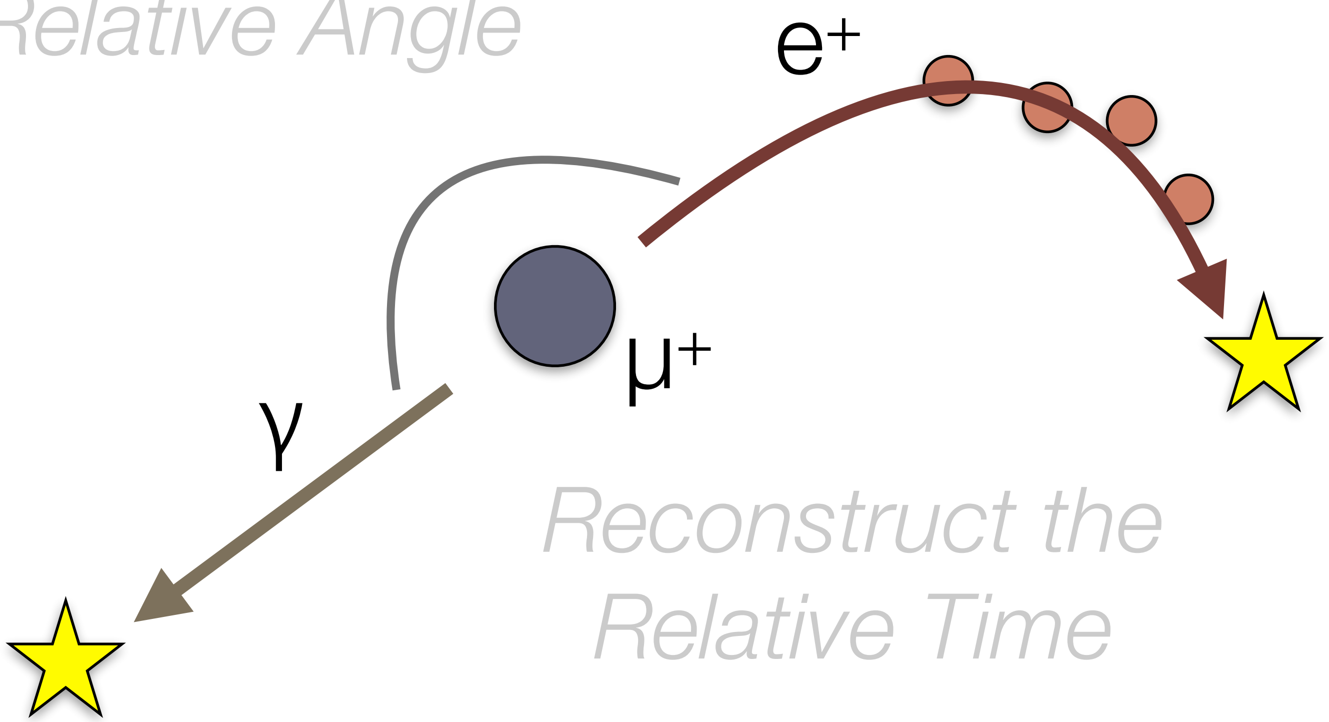
Expected ageing (gain loss) in the MEG-II Drift Chamber

- Silicon detectors could be a practical solution
  - Competitive performances with the next generation of 25 μm monolithics
  - **Experience from Mu3e** will be critical
- Solutions for a gaseous detector with high rate capabilities are also under study (new geometries, optical readout,…), in **synergy with Mu2e**

Ingredients for a search of μ -> e γ

Reconstruct the Relative Angle

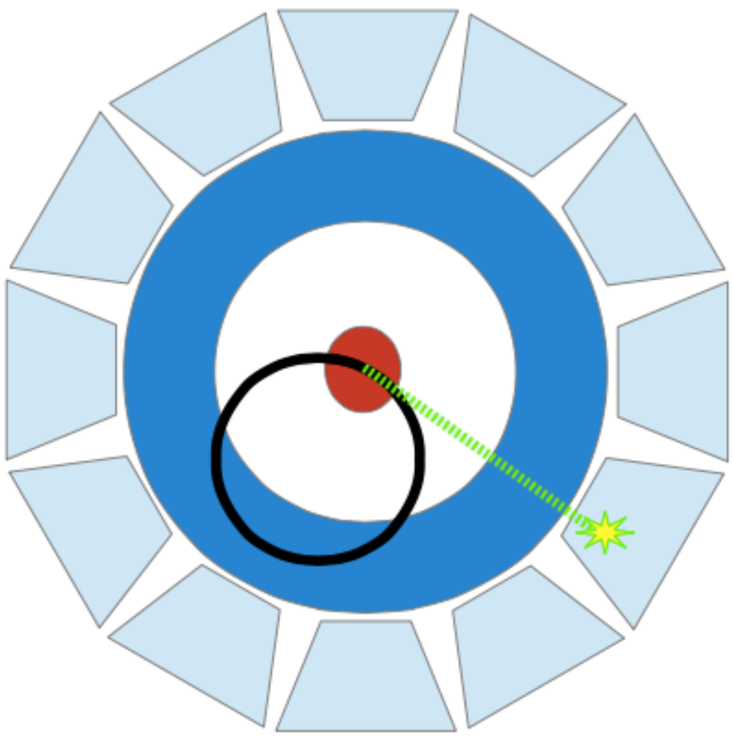
Reconstruct the Positron Energy



Reconstruct the Relative Time

Reconstruct the Photon Energy

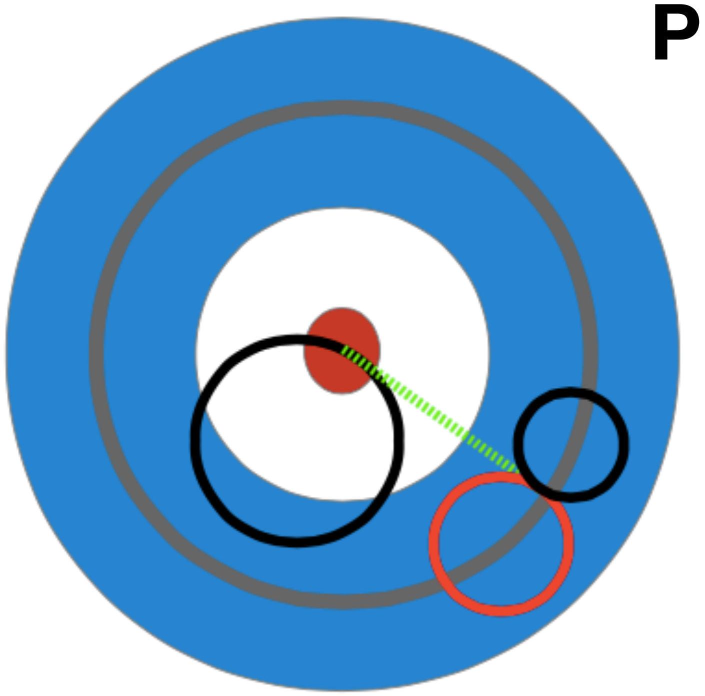
Calorimetry vs. Photon Conversion

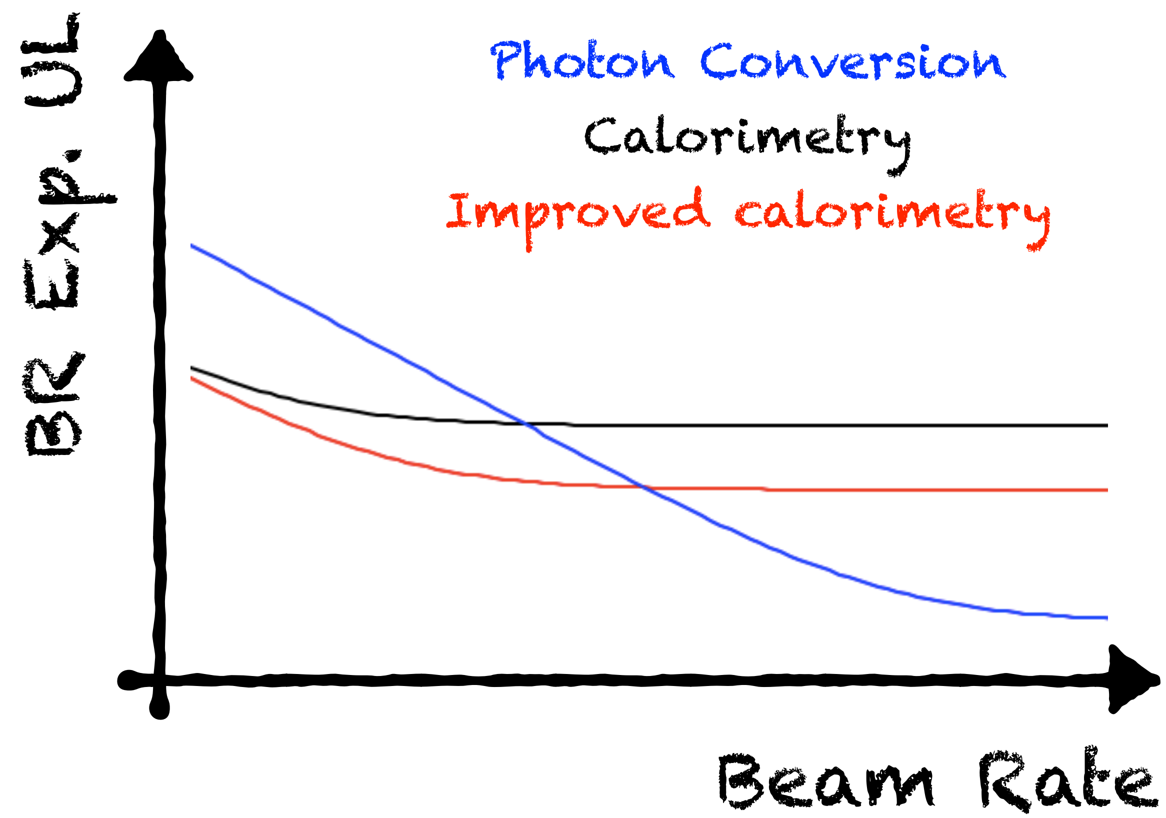


Calorimetry

High efficiency
Good resolutions

MEG:
LXe calorimeter
10% acceptance

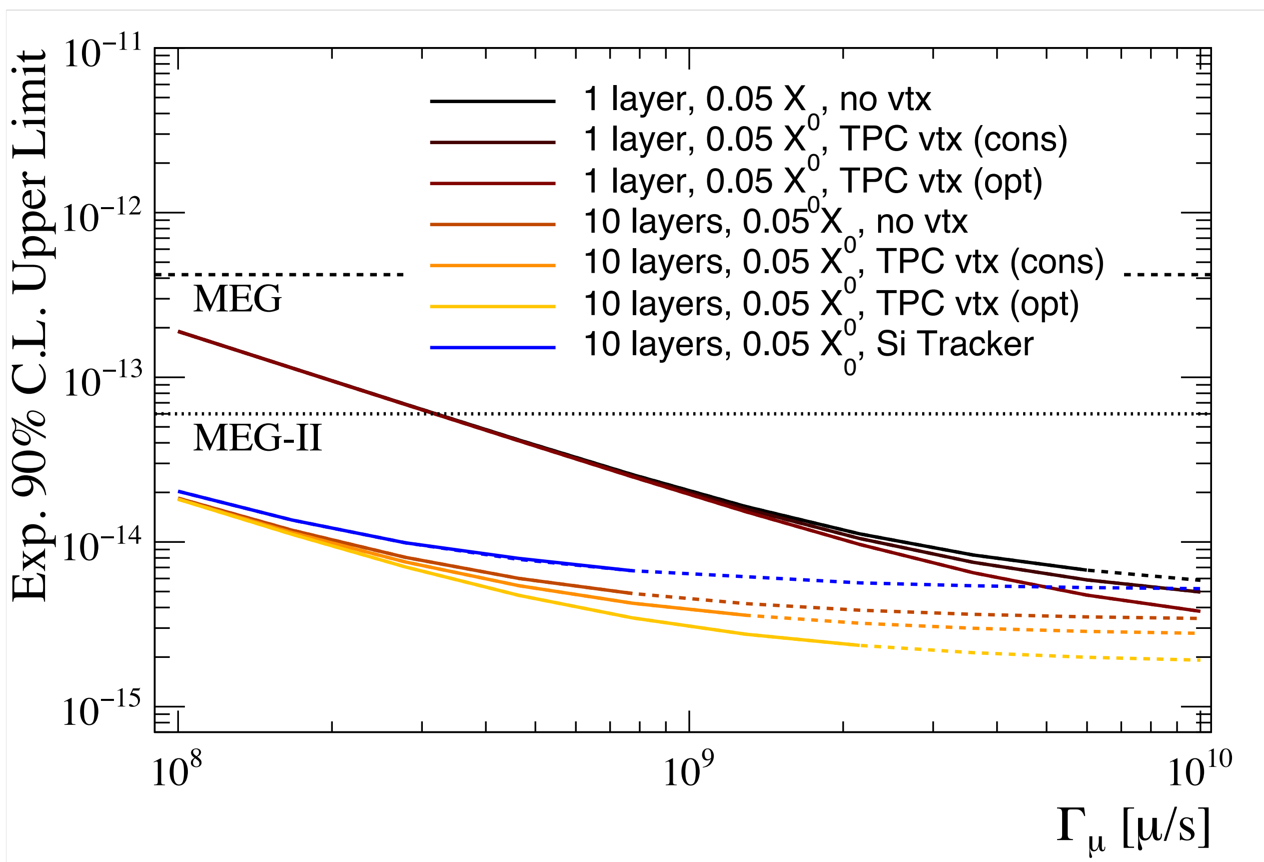


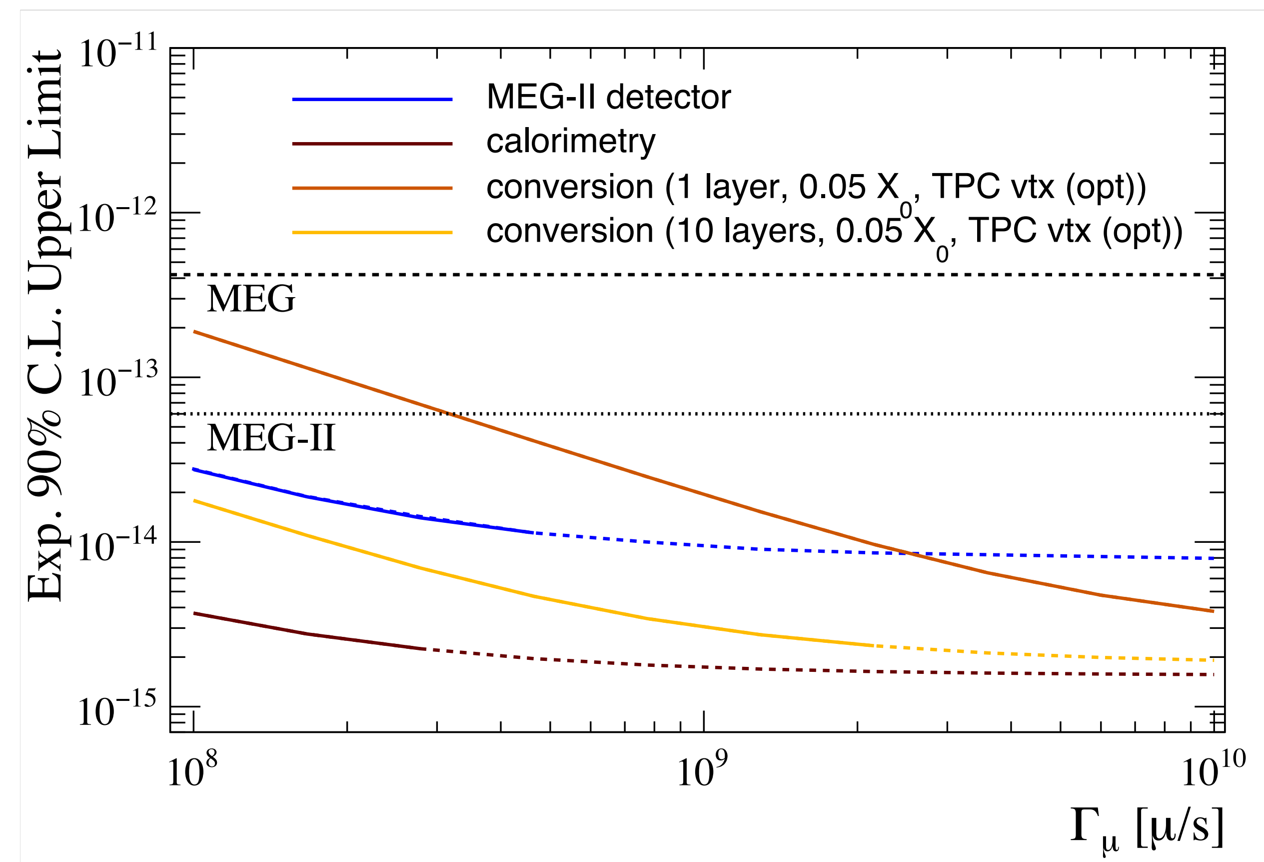


Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

Expected Sensitivity

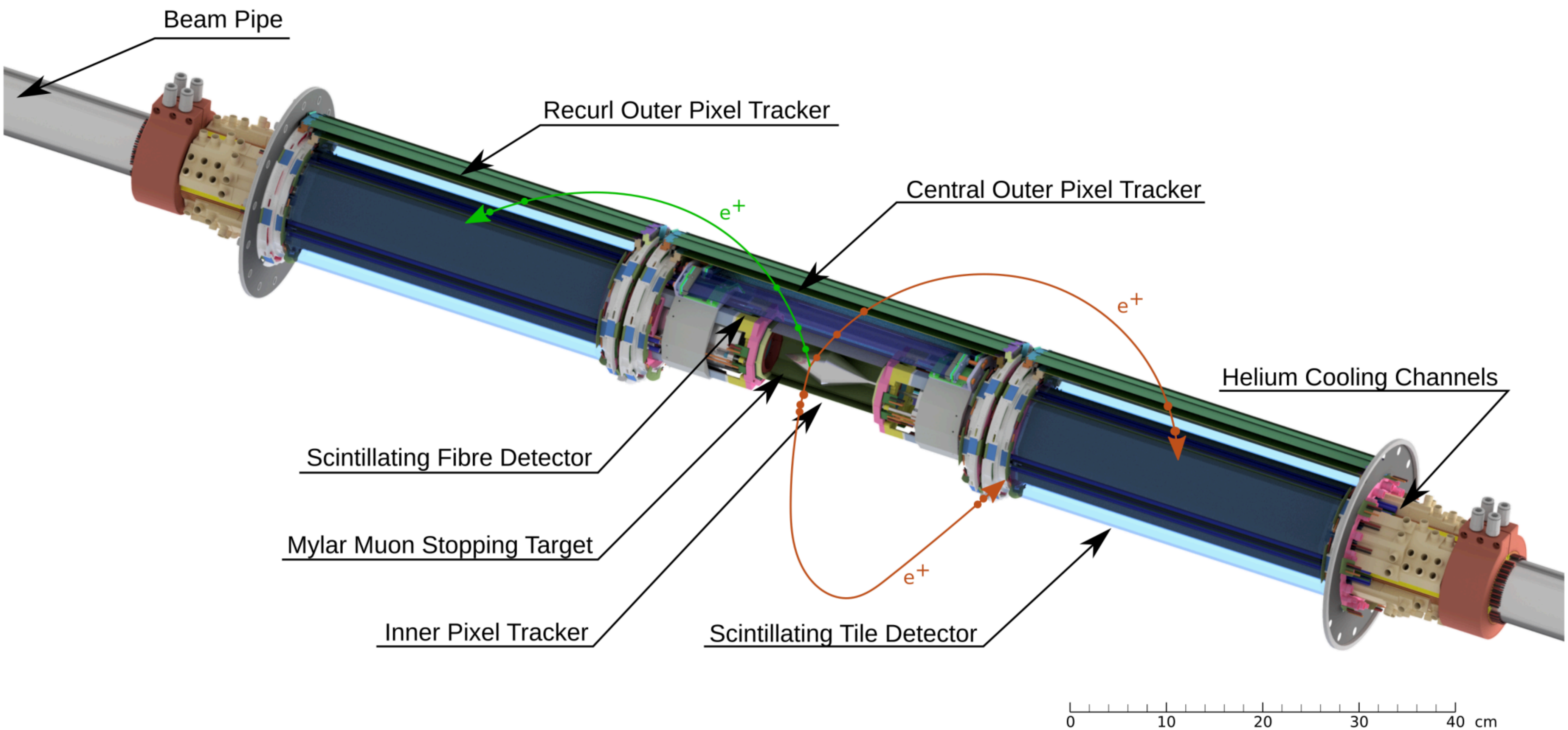




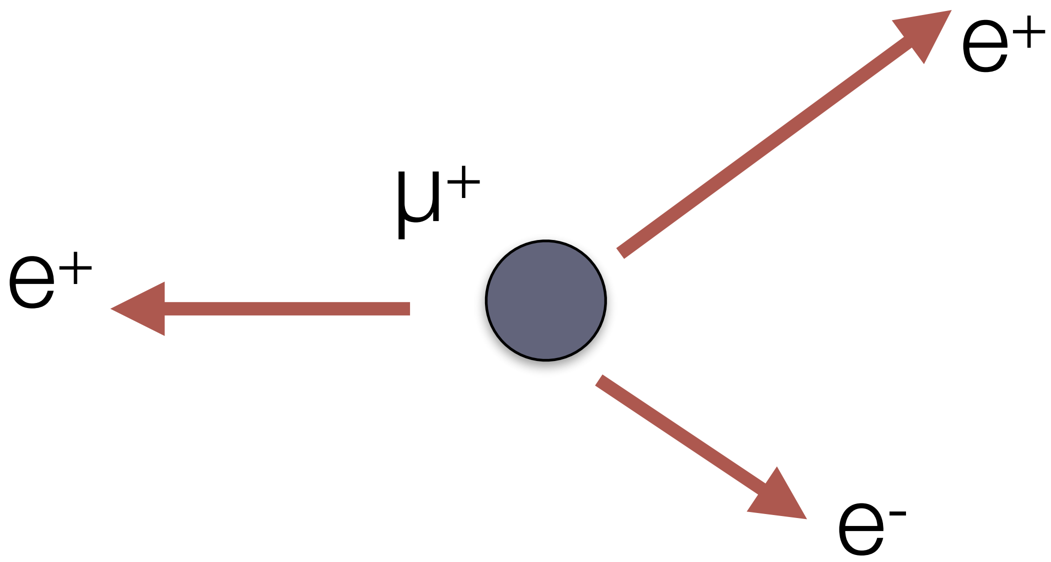
A few 10^{-15} seems to be within reach for a 3-year run at ~ 10^8 μ/s with calorimetry (*expensive*) or ~ 10^9 μ/s with multiple conversion layers (*cheap*)

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

The mu3e experiment at PSI

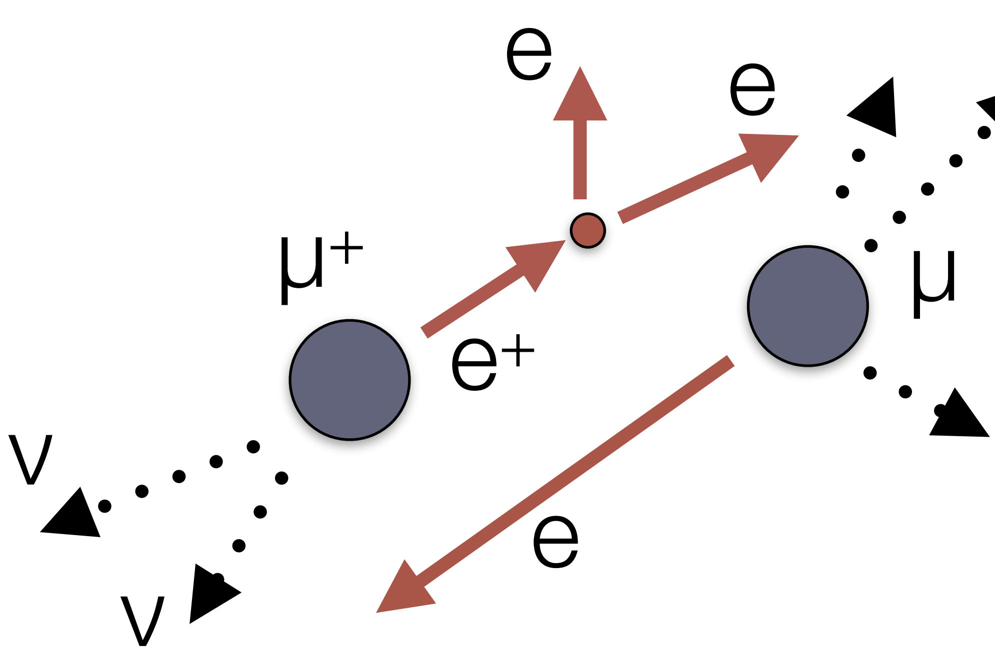


Signal and background



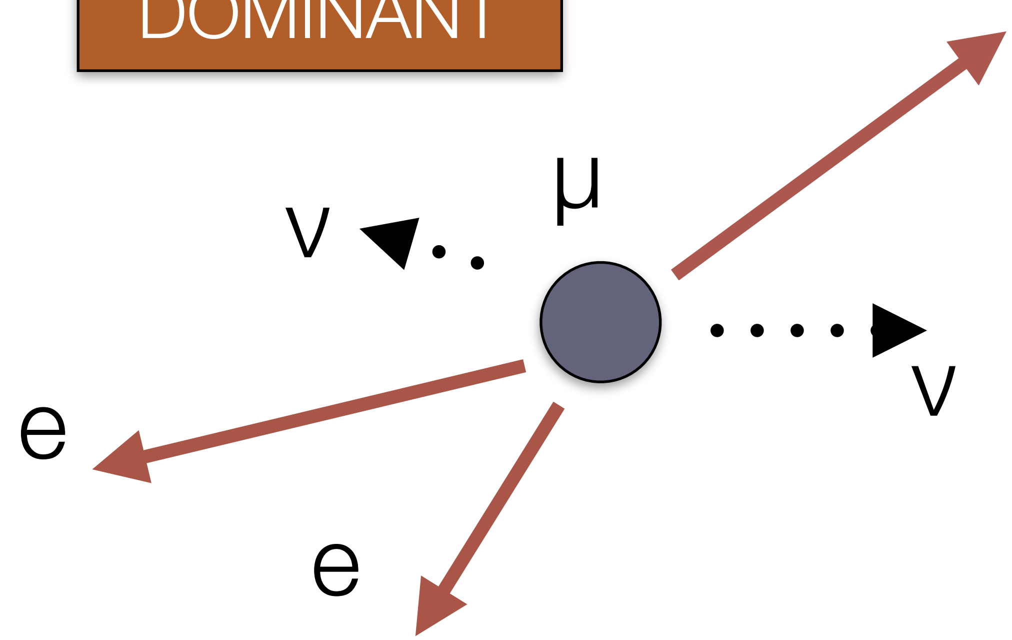
2 positrons and 1 electron
produced at the **same time**,
in the **same place**, with $\mathbf{M_{inv} = M_{\mu}}$

Accidental Background
(e.g. 2 μ decays + Bhabha)



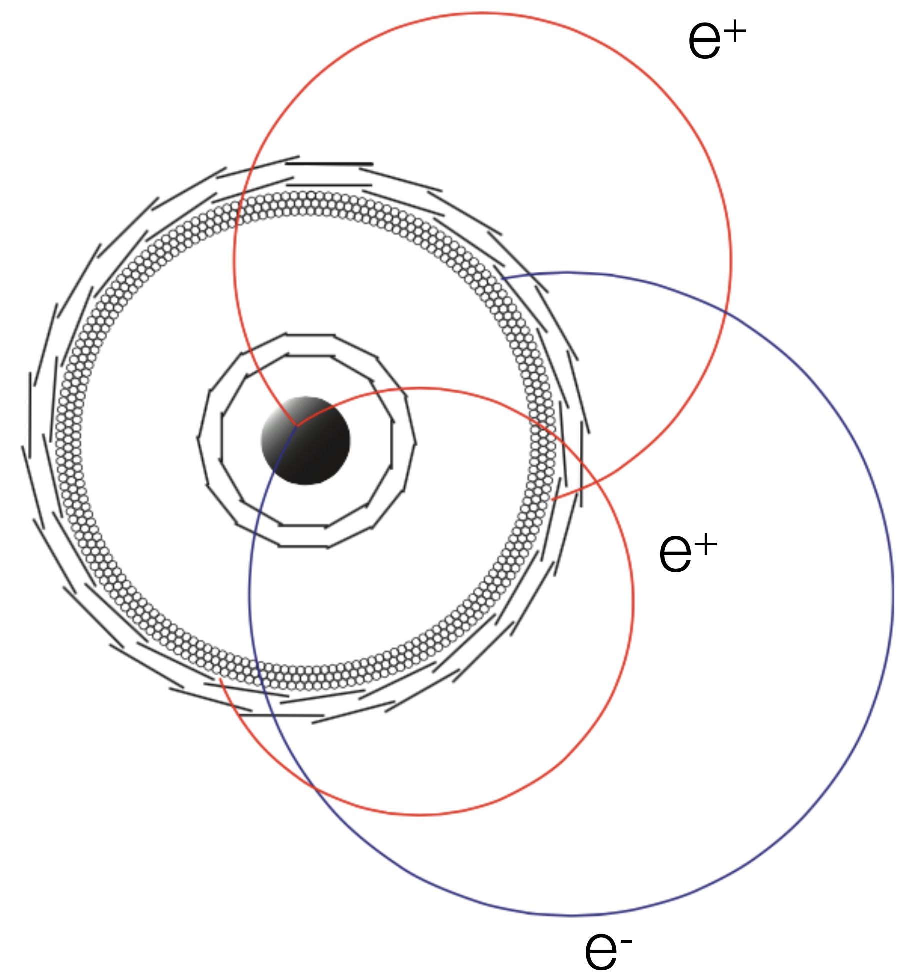
eeevv Muon Decay (RMD + IPC)

DOMINANT



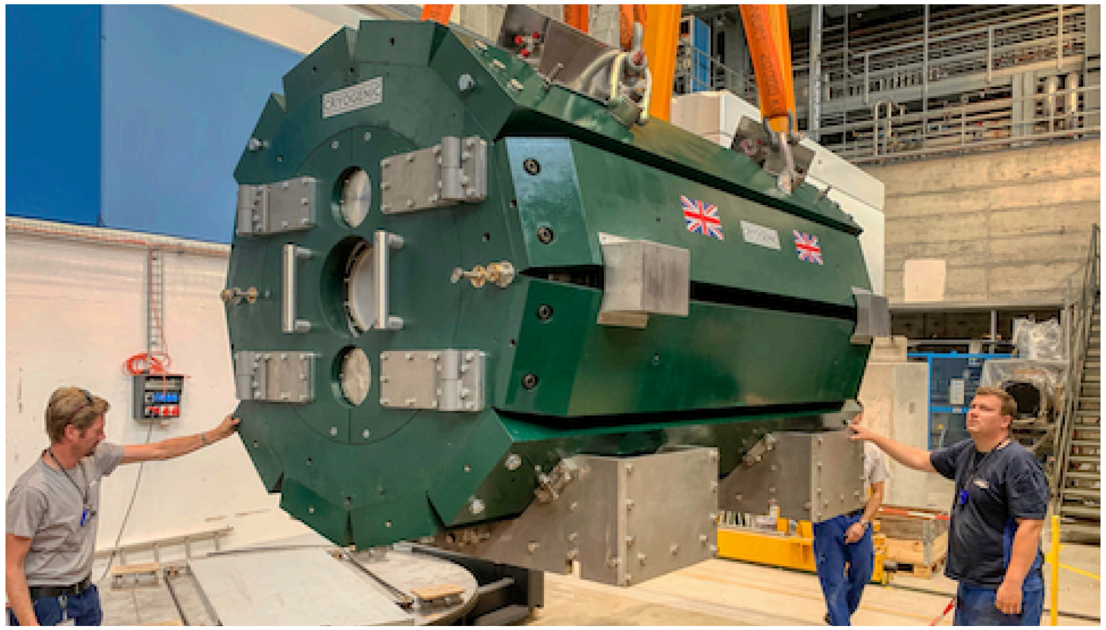
The Mu3e concept @ PSI

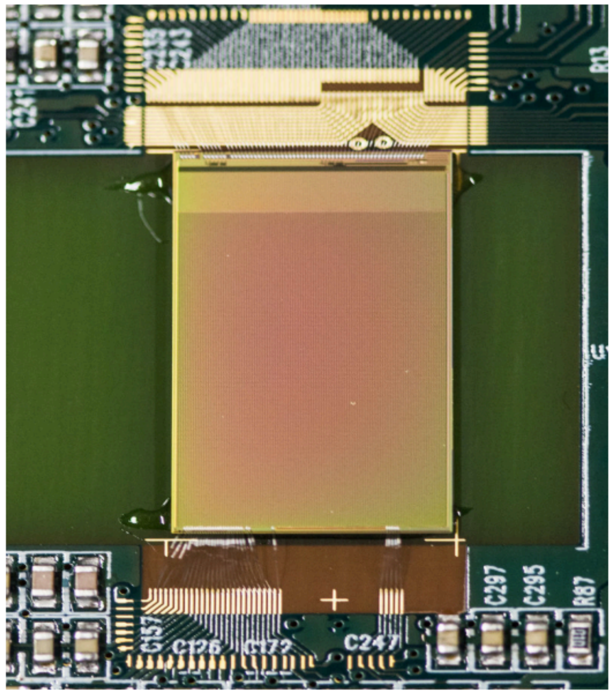
- Silicon tracker in a solenoid + scintillators for timing
  - 50 μm HV-maps
  - 250 μm fibers + 1x1 mm^2 SiPM
  - 5 mm thick tiles + 3x3 mm^2 SiPM
- Phase-I:
  - New compact beam line for a quick switch between MEG & Mu3e
- Phase-II:
  - New high intensity muon beam line (HiMB) with a few 10^9 μ/s muons
- Possibility of including a single conversion layer to search for $\mu \to e\gamma$

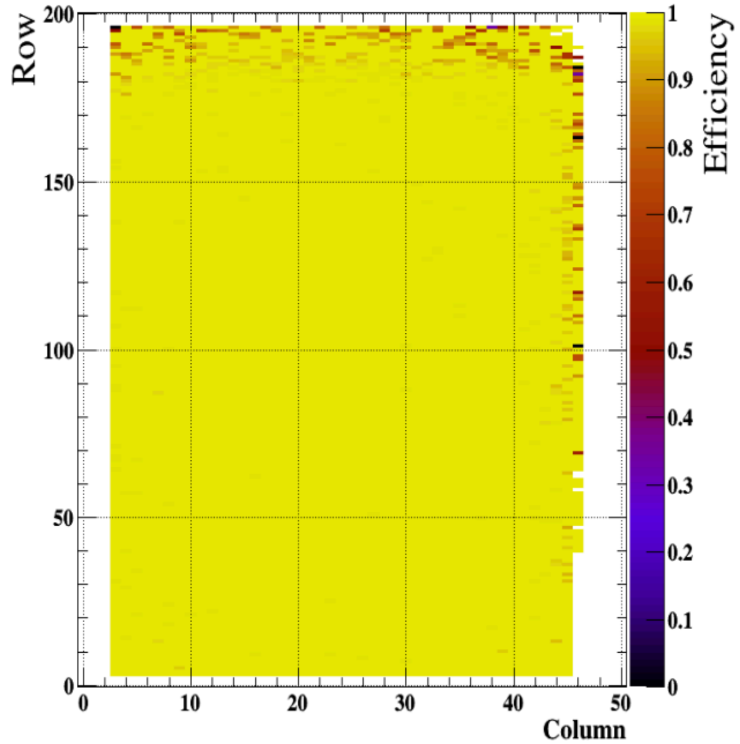


Current status

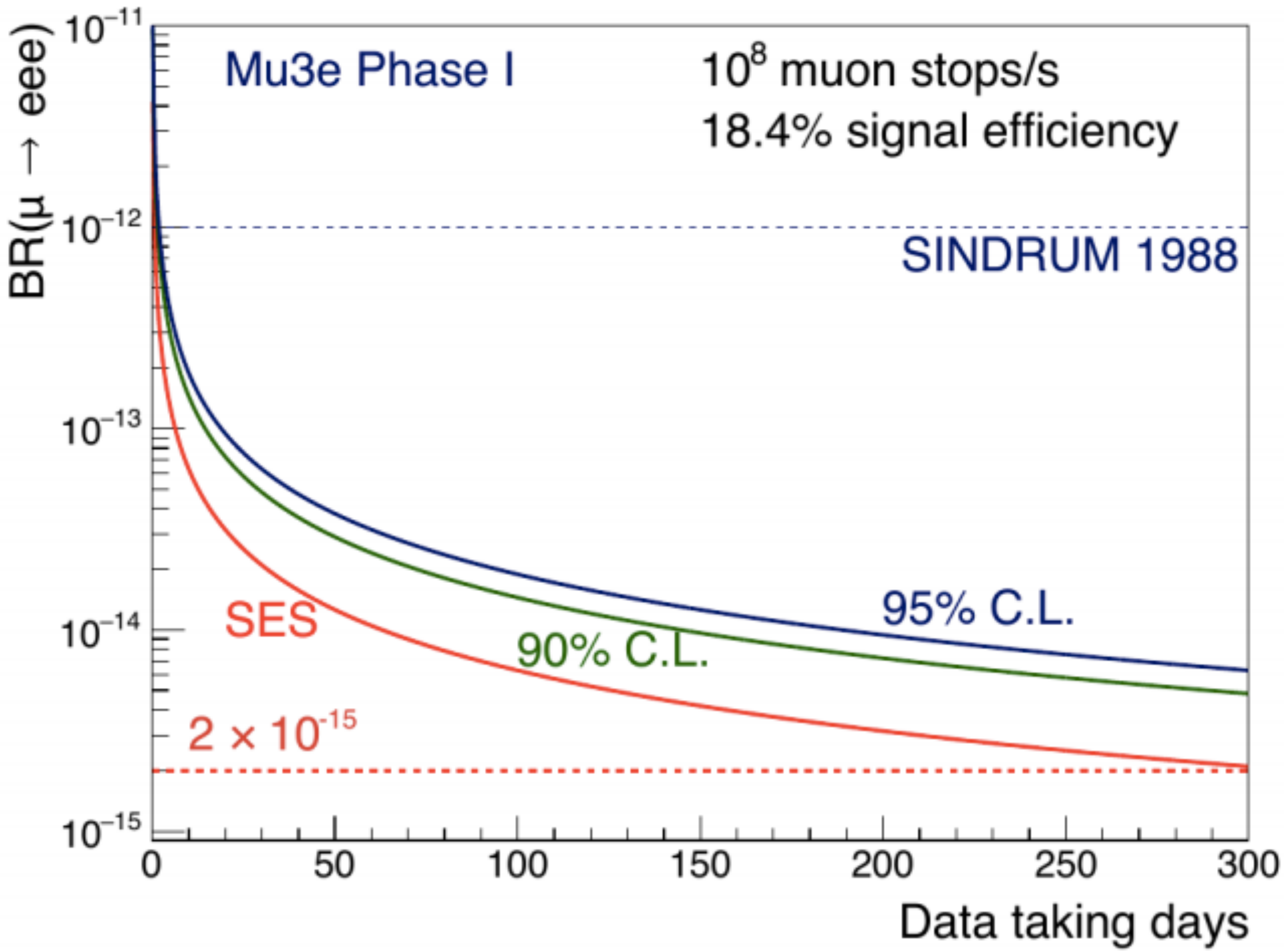
- The magnet was installed and tested with beam in 2021
- MuPix8 chip beam tests show promising performances







Expected sensitivity



Searches for exotic particles

Inclusive searches

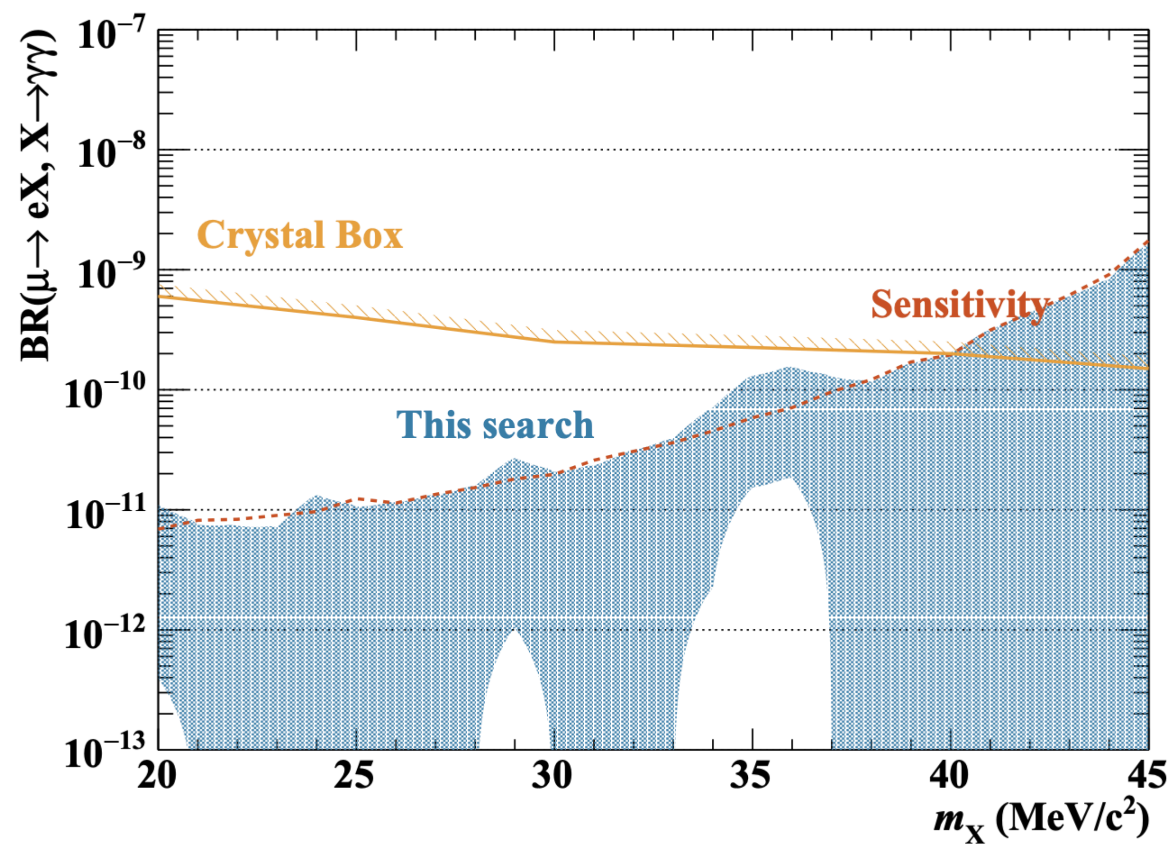
- Exotic particles with mass < m_μ can be searched for in the $\mu \to e\,X$ and $\mu \to e\,X\,\gamma$ channels, looking only at the positron and photon
  - either at the kinematical end point ($m_X = 0$) or not
  - some of the best measurements date back to the 80s
  - recent update on $\mu \to e\,X$ from TWIST
    Phys.Rev.D91(2015)052020
- Control of systematic uncertainties and model dependence are critical

Exclusive searches

- If the exotic particles decays to standard particles, it can be searched for exclusively in given decay channel:

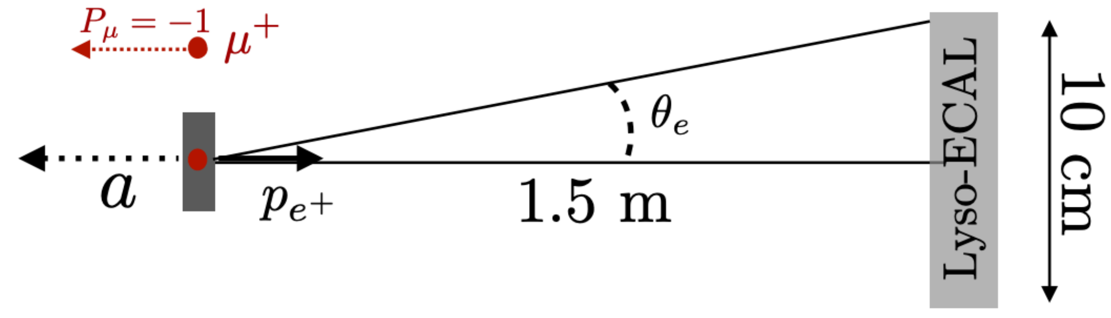
- MEG recently published a search for $\mu \to e\,X$ with $X \to \gamma\gamma$
  ***Eur.Phys.J.C* 80 (2020) 9, 858**

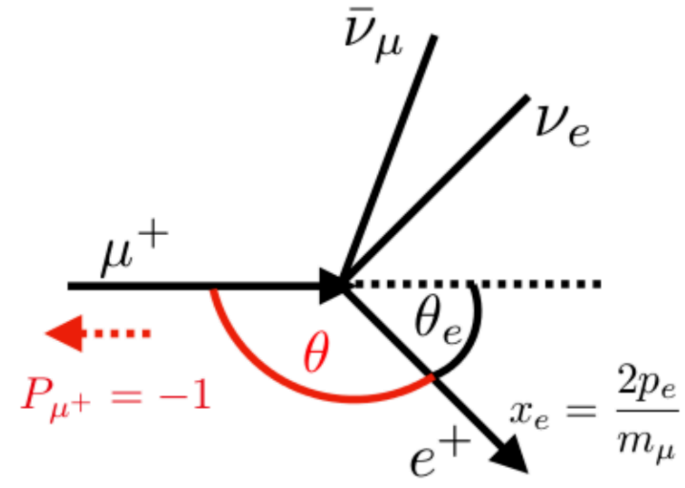
- Mu3e can search for $X \to e^+e^-$ looking for invariant-mass peaks in $\mu^+ \to e^+e^+e^-$

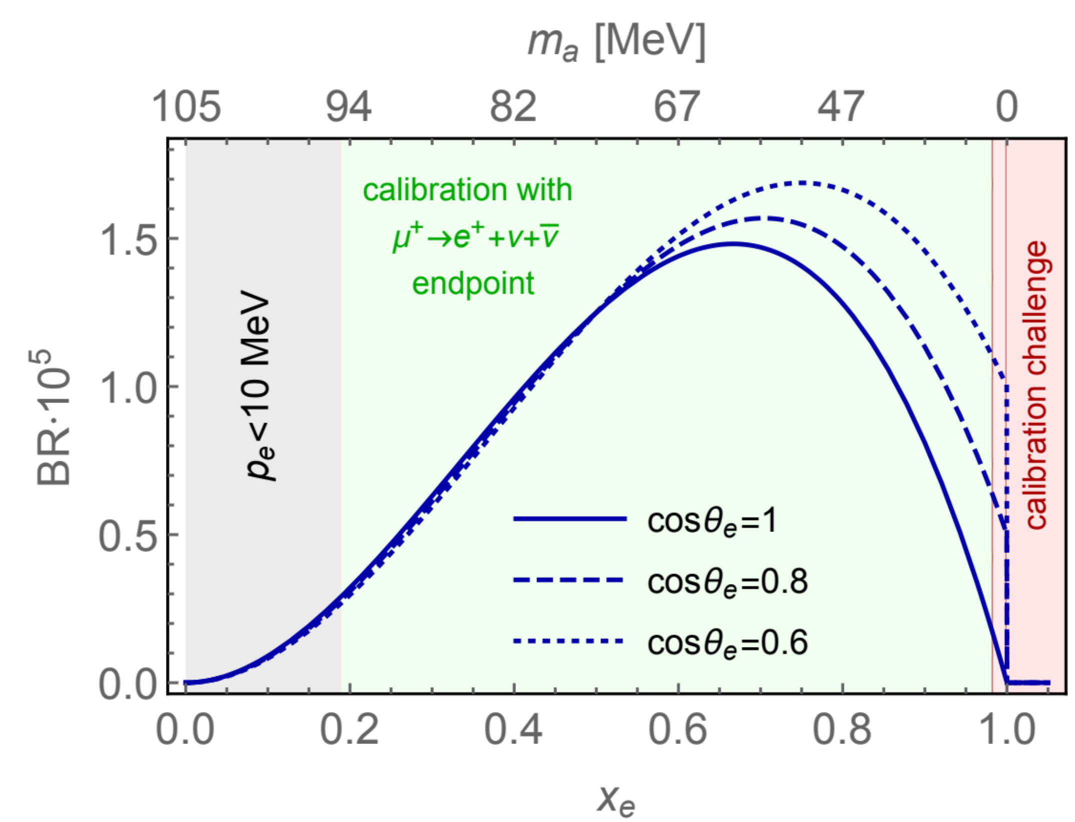


A case study: the MEGII-fwd concept

- In 2020 Calibbi et al. proposed the installation of a forward detector in MEG II to search for $\mu \to e\,X$ in a scenario where the V-A coupling suppresses the Michel spectrum with respect to the detection of an ALP with V, A or V+A coupling







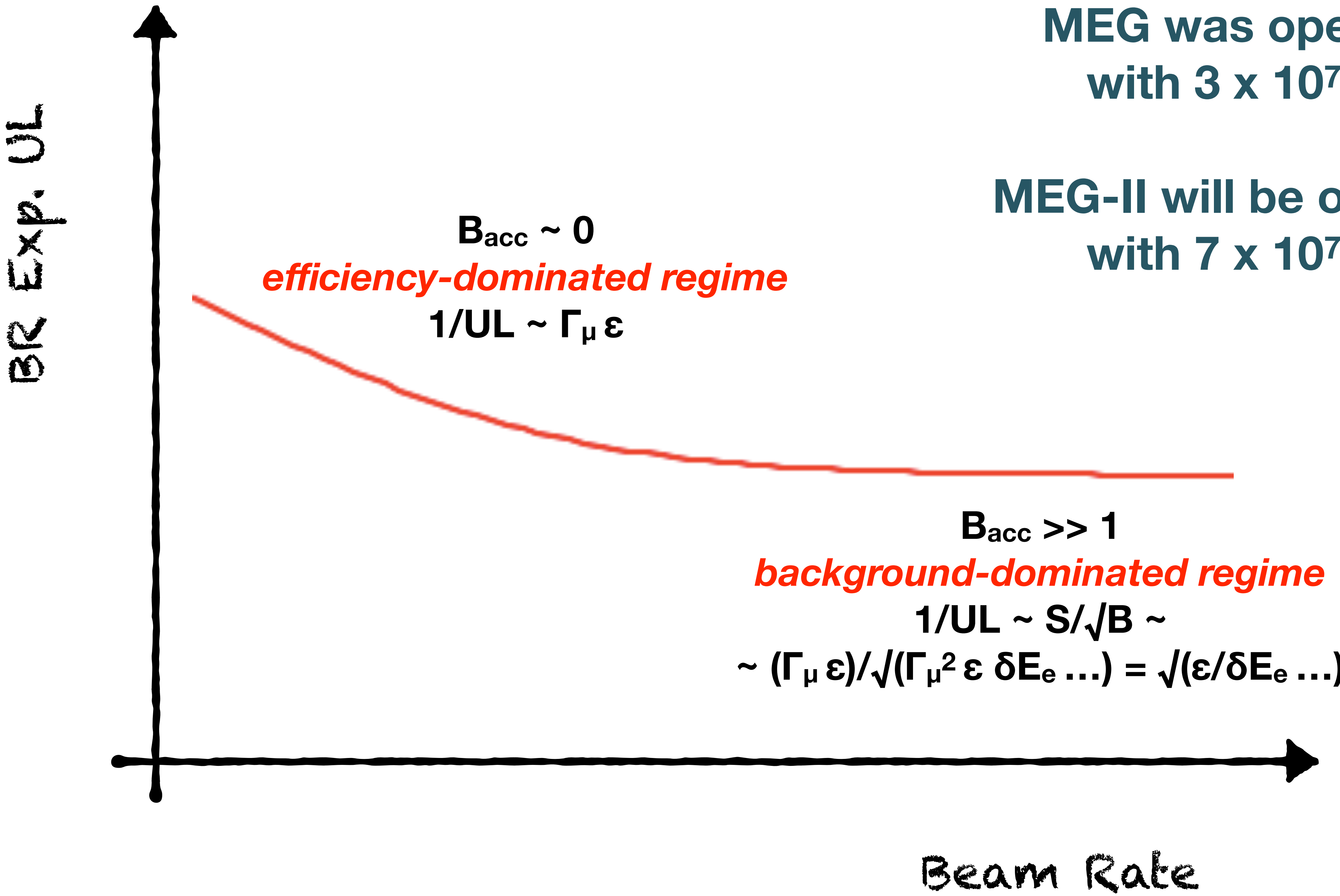
L. Calibbi et al., JHEP 09 (2021) 173

Conclusions

- A new era for cLFV searches in muon decays is just starting with MEG II and Mu3e phase I
- A new generation of muon beam facilities with 10x or 100x larger beam rate would give a great opportunity to reach the ultimate limits allowed by the current experimental approaches:
    - Mu3e phase II already designed for this
    - a MEG-like experiment would require a significative R&D effort
    - new ways for the search of light exotic particles
- **From the beam perspective, not just a matter of accumulating muons:**
    - beam features critically affect the experimental sensitivity — the possibility of designing a dedicated facility could give more optimization margin
- All these efforts would largely take advantage of a new muon campus, which also means a **single community working in close synergy** on different projects, exchanging information and expertise

Backup

μ -> e γ searches



MEG was operated with 3×10^7 μ/s

MEG-II will be operated with 7×10^7 μ/s

γ Reconstruction: Limiting factors — Calorimetry

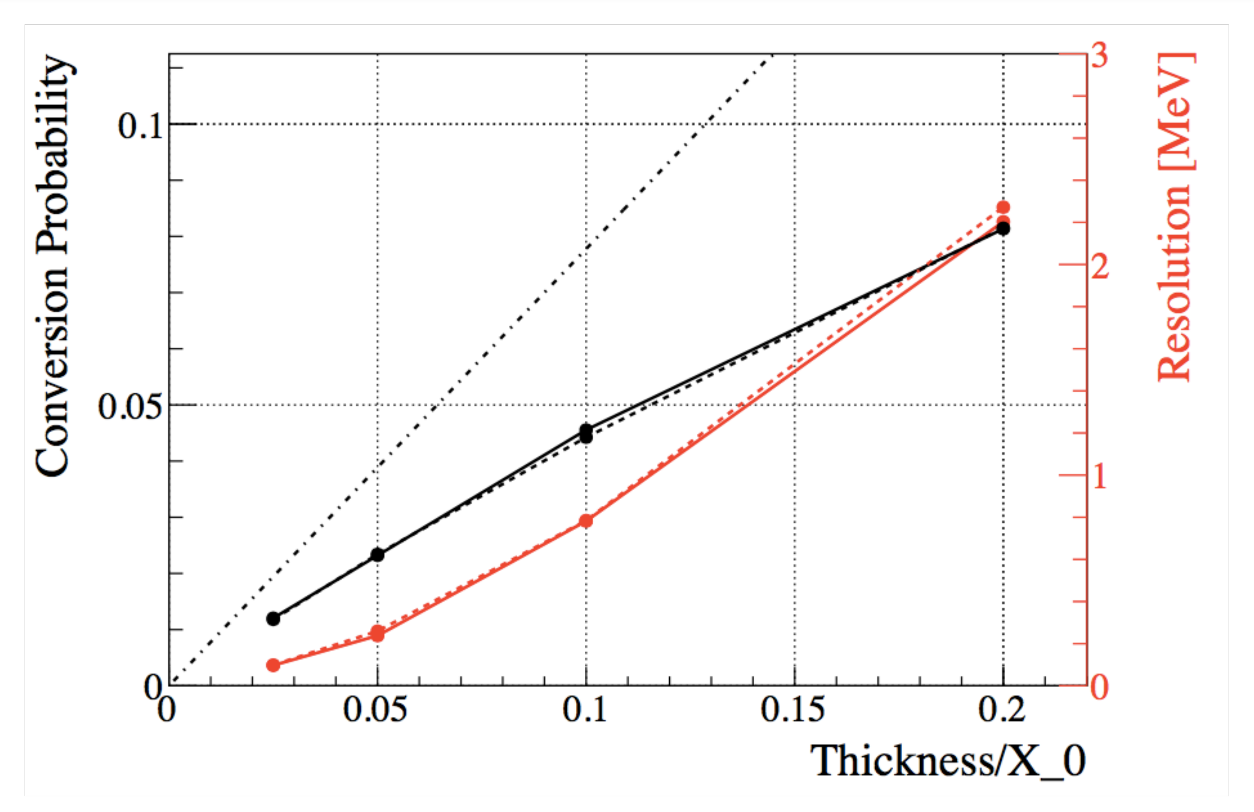
- Photon Statistics
- Scintillator time constant
- Detector segmentation

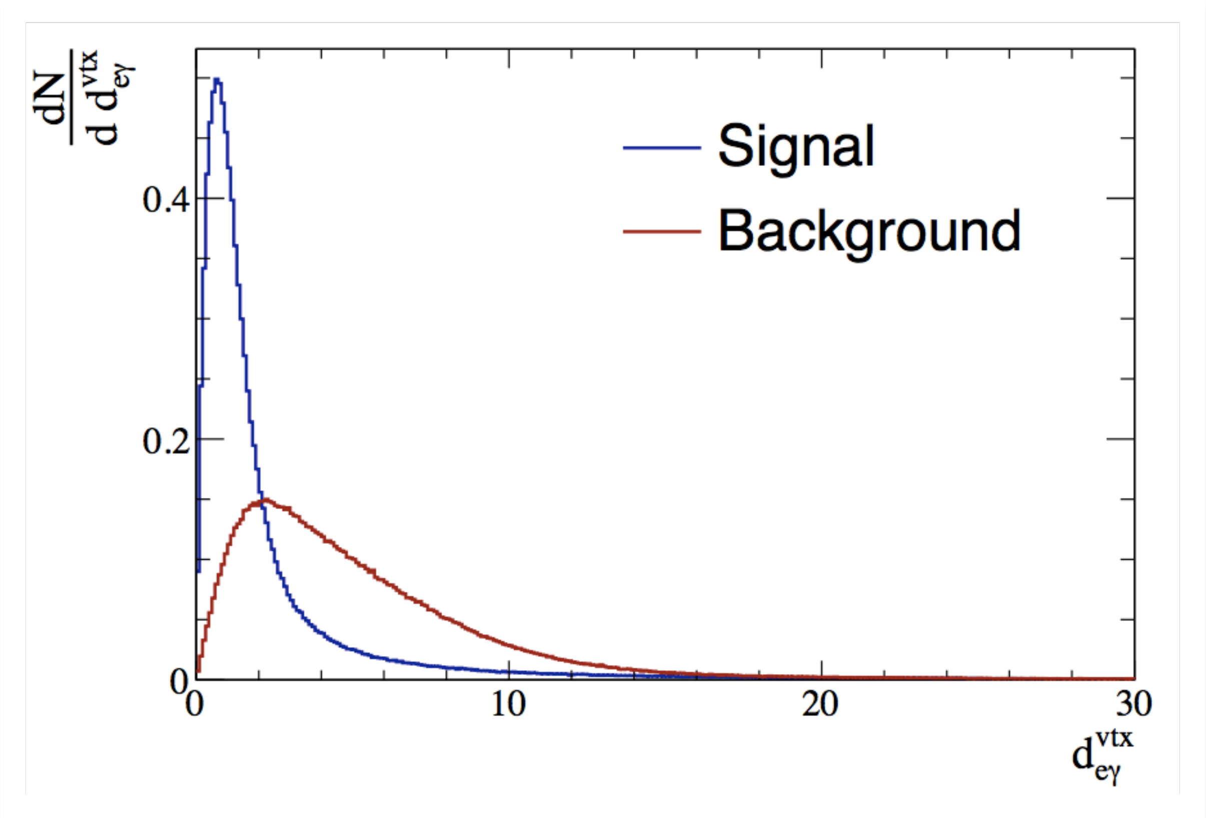
Scintillator	Density] [g/cm^3]	Light Yield [ph/keV]	Decay Time [ns]
$LaBr_3$(Ce)	5.08	63	16
LYSO	7.1	27	41
YAP	5.35	22	26
LXe	2.89	40	45
NaI(Tl)	3.67	38	250
BGO	7.13	9	300

- $LaBr_3$(Ce) — a.k.a. *Brillance* looks a very good candidate:
  - our simulations & tests indicate that ~ 800 keV resolution can be reached
  - extreme time resolution (~ 30 ps)
  - large acceptance
  - very expensive

γ Reconstruction: Limiting factors — Conversion

- Interactions in the converter (conversion probability, e+e- energy loss and MS)
- Large Z materials (Pb, W) give the best compromise of efficiency vs. resolution





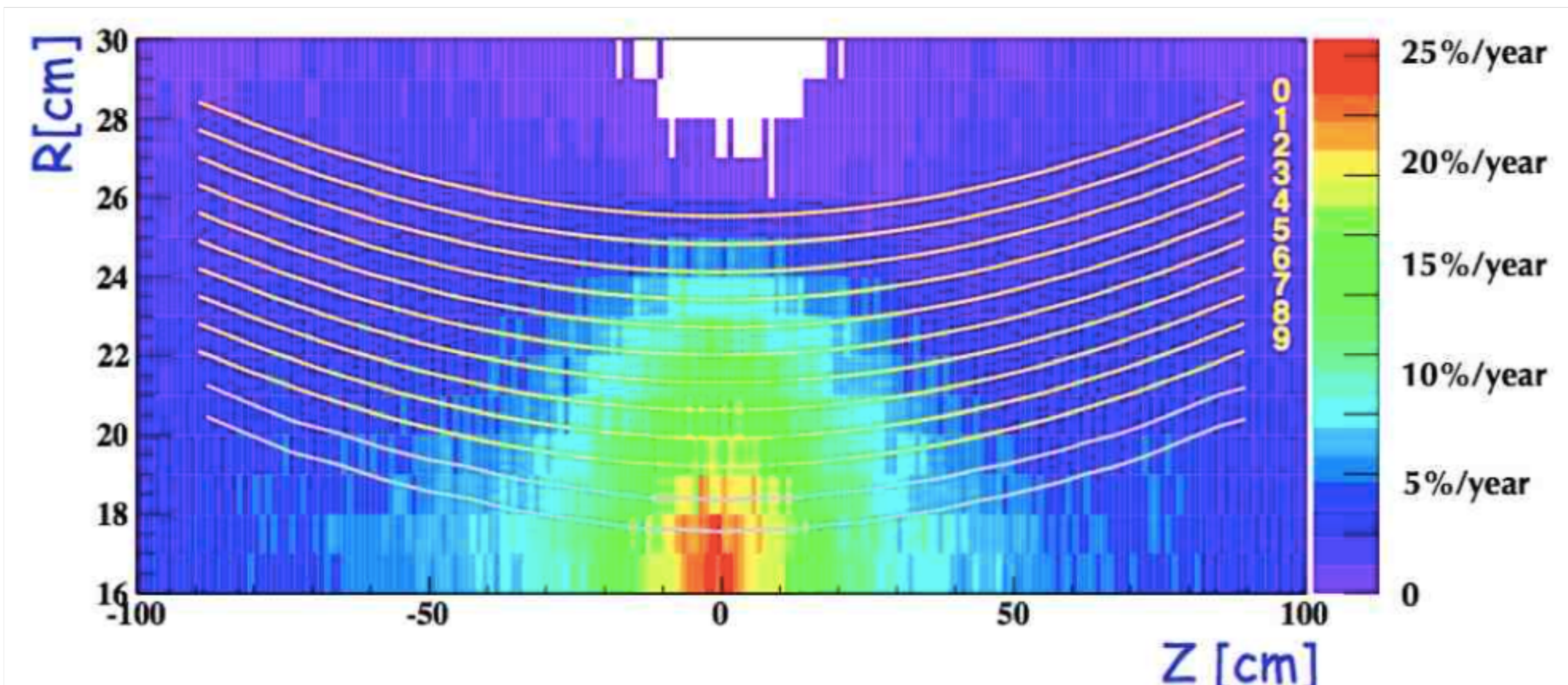
- Can take advantage of the photon direction determination form the e+e- reconstruction

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

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

- Tracking detectors in a magnetic field are the golden candidates:
    - high efficiency
    - better resolutions w.r.t. calorimetry ($\sigma(E_e)$ down to 0.2% vs. > 1%)
- Performances are limited by Multiple Scattering of 52.8 MeV positrons in target and tracker materials
    - Need a very light detector (the MEG drift chambers gave ~ 2 x 10^{-3} X_0 over the whole positron trajectory, 200 μm silicon equivalent)
    - Silicon trackers are likely to be not competitive with gaseous detectors in terms of resolutions **(C-H. Cheng et al. arXiv: 1309.7679)**

Positron Reconstruction at High Beam Rate



A. Baldini et al., MEG Upgrade Proposal, arXiv:1301:7225

Expected aging (gain loss) in the MEG-II Drift Chamber

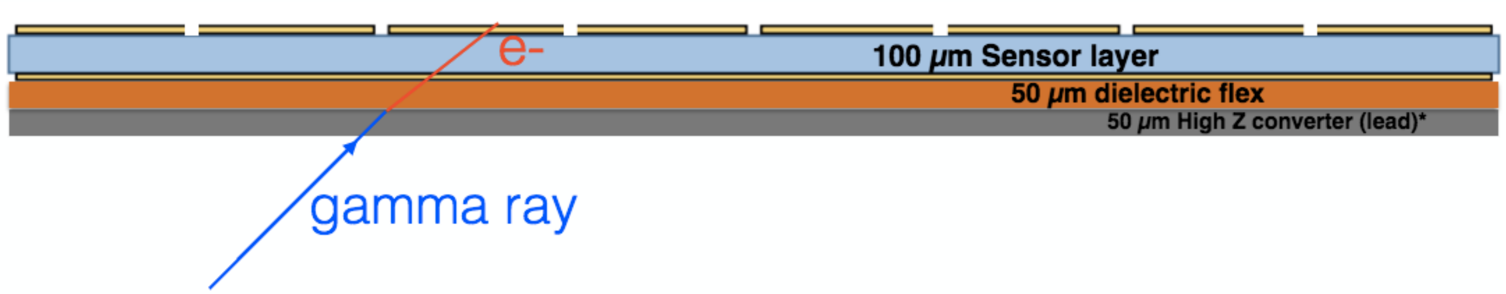
Would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?

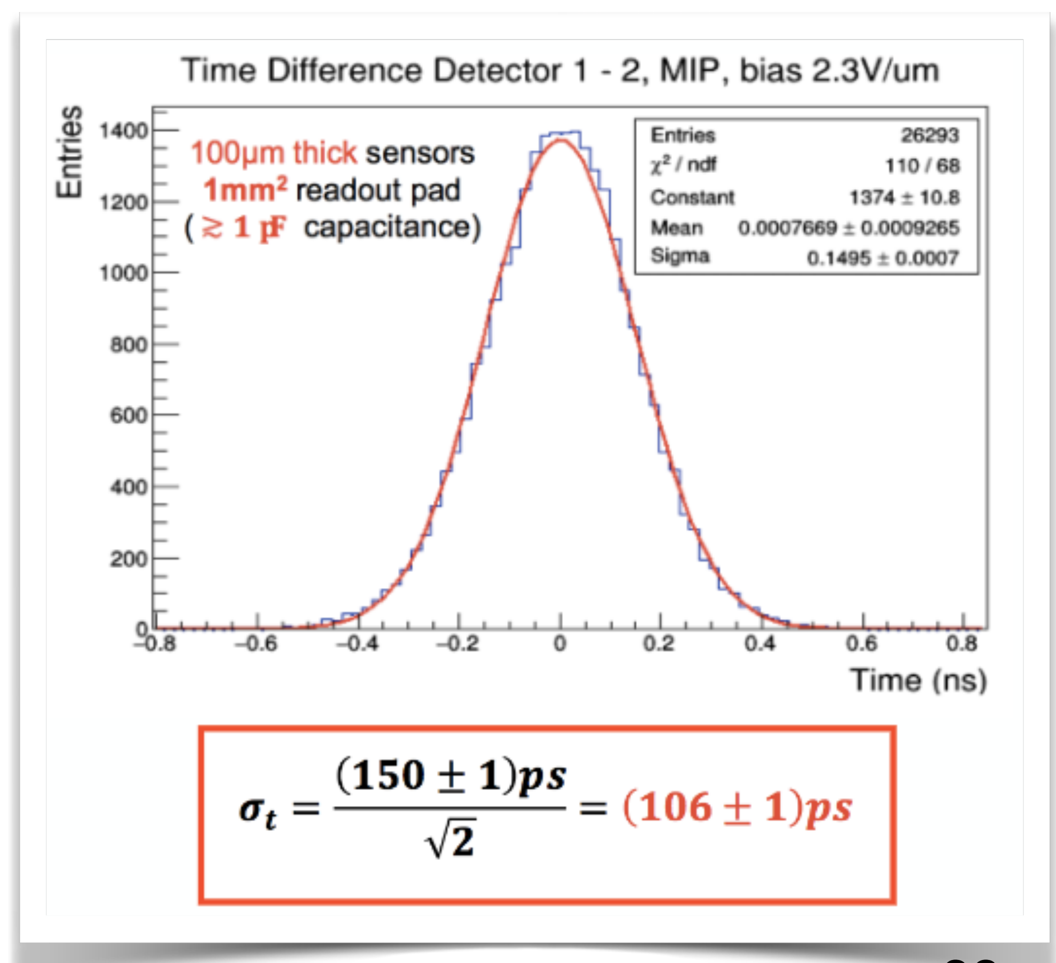
An active conversion layer

- Low Z active material for timing deteriorates the best efficiency/resolution configuration
  - the active layer must be as thin as possible
- Scintillators have poor “timing to thickness” figures (~ 1 ns for 250 μm fibers)

FAST SILICON DETECTORS

- R&D on going for PET application (**TT-PET**)





M. Benoit et al., JINST 11 (2016) no. 03, P03011

Possible Scenarios

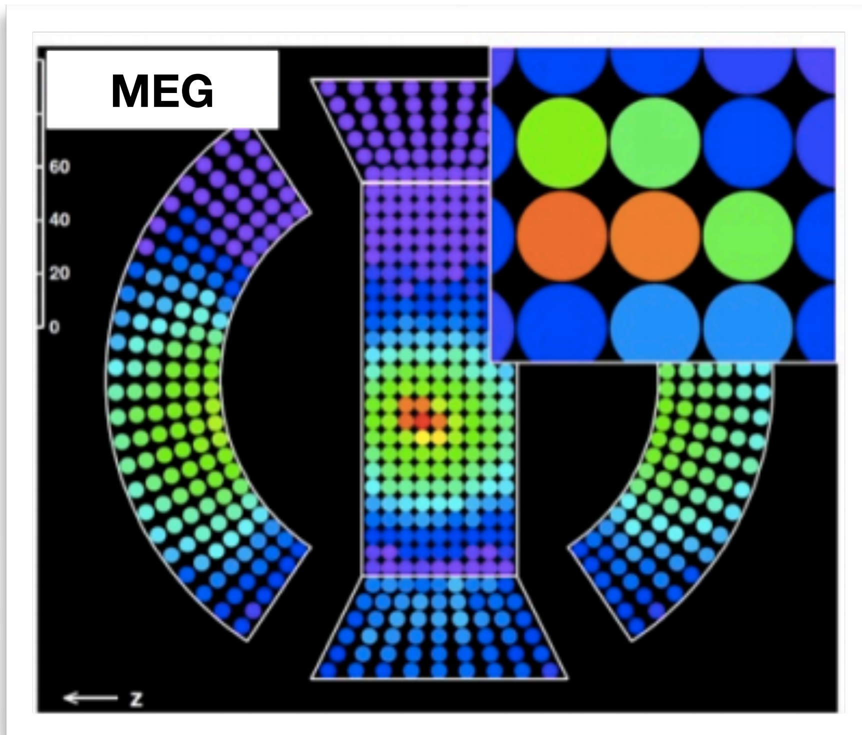
CALORIMETRY

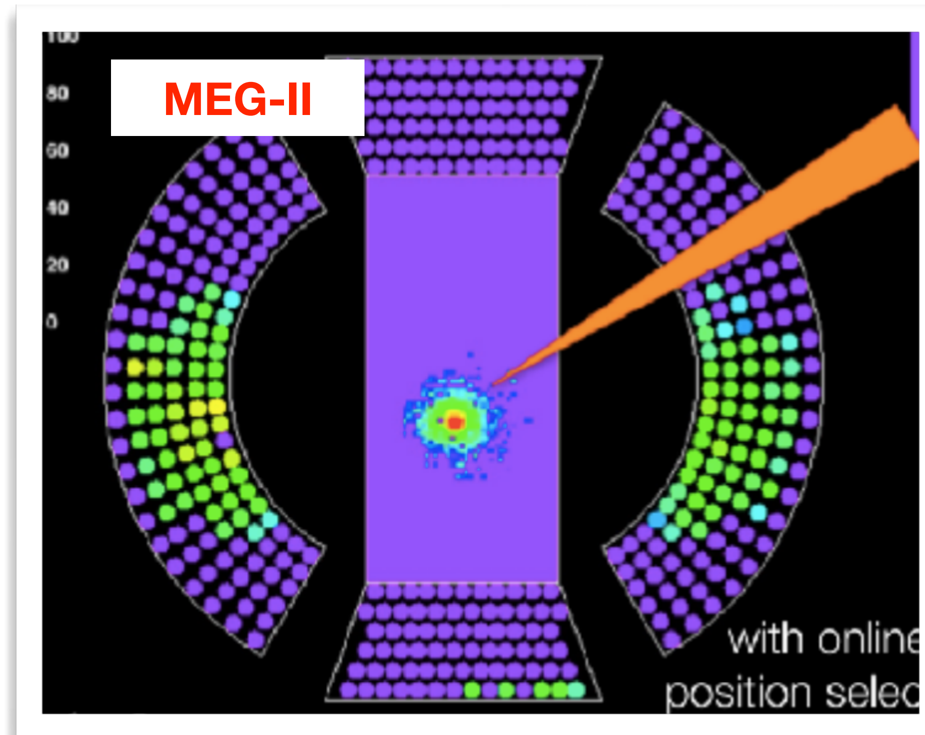
Variable	Resolution w/o vtx detector	w/ TPC vtx detector conservative	w/ TPC vtx detector optimistic	w/ silicon vtx detector conservative	w/ silicon vtx detector optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			30		
E_e [keV]			100		
E_γ [keV]			850		
Efficiency [%]			42% **(70% γ acceptance)**		

PHOTON CONVERSION

Variable	Resolution w/o vtx detector	w/ TPC vtx detector conservative	w/ TPC vtx detector optimistic	w/ silicon vtx detector conservative	w/ silicon vtx detector optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			50		
E_e [keV]			100		
E_γ [keV]			320		
Efficiency [%]			1.2 **(1 LAYER, 0.05 X_0)**		

MEG-II Highlights - The LXe Calorimeter

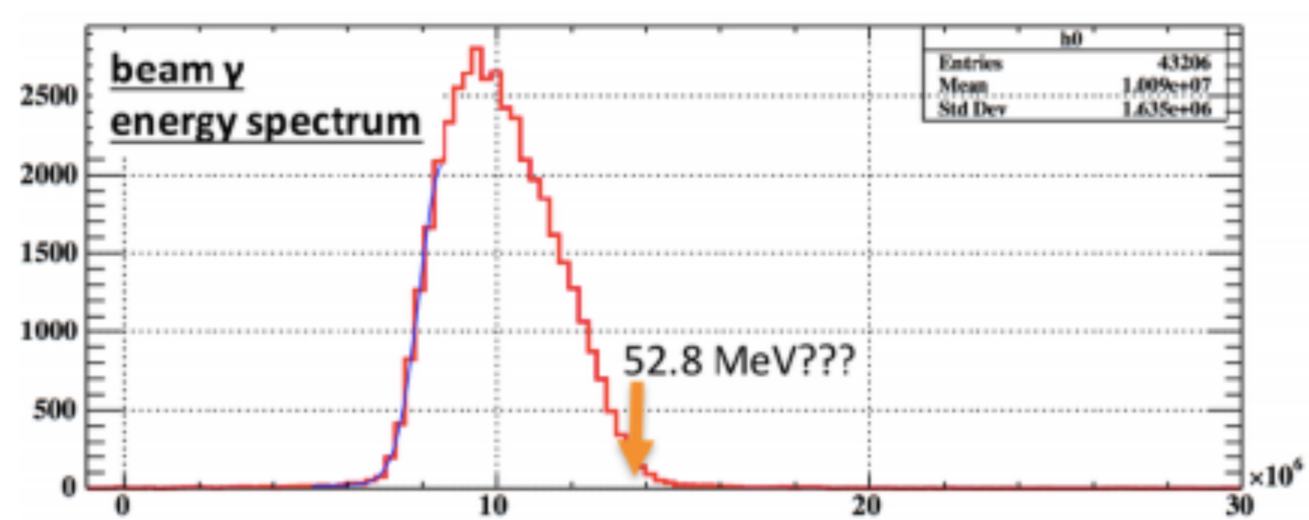




First events/spectra from 2017 data

We developed large-area (12x12 mm^2), UV-sensitive MPPCs to cover the inner face of the LXe calorimeter

Better Resolution, better pile-up rejection

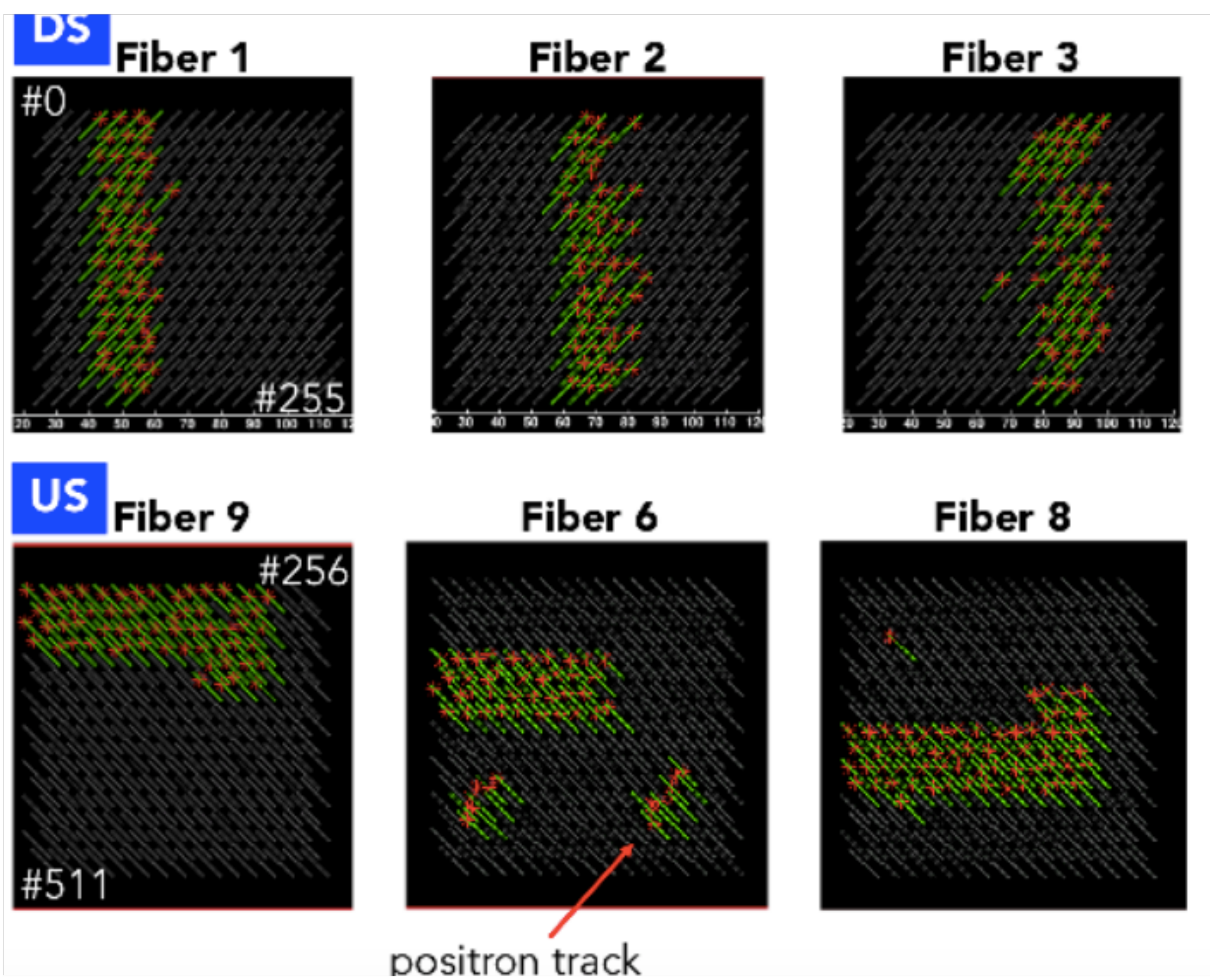


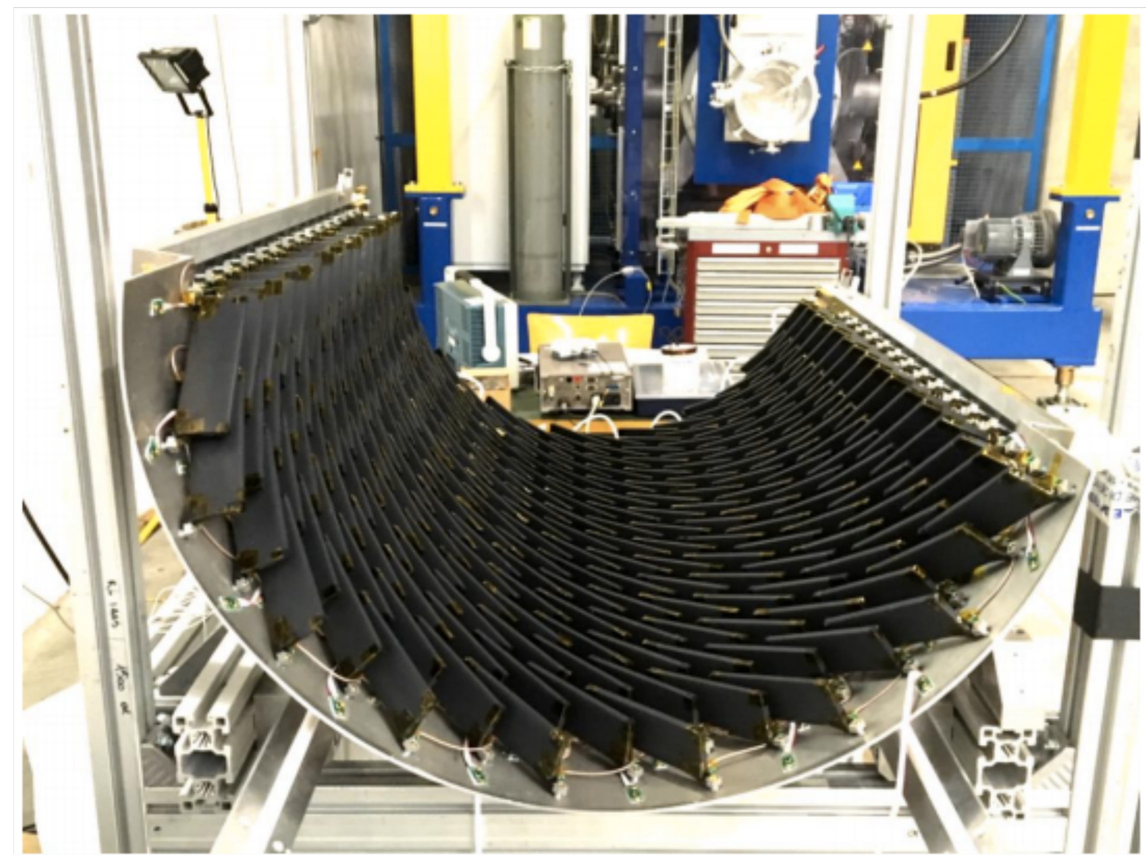
σ_E ~ 1%, $\sigma_{position}$ ~ 2/5 mm (x,y/z)

MEG-II Highlights - The Timing Counters

5mm-thick Scintillator Tiles read out by 3x3 mm^2 SiPM

Complete detector took data in 2017



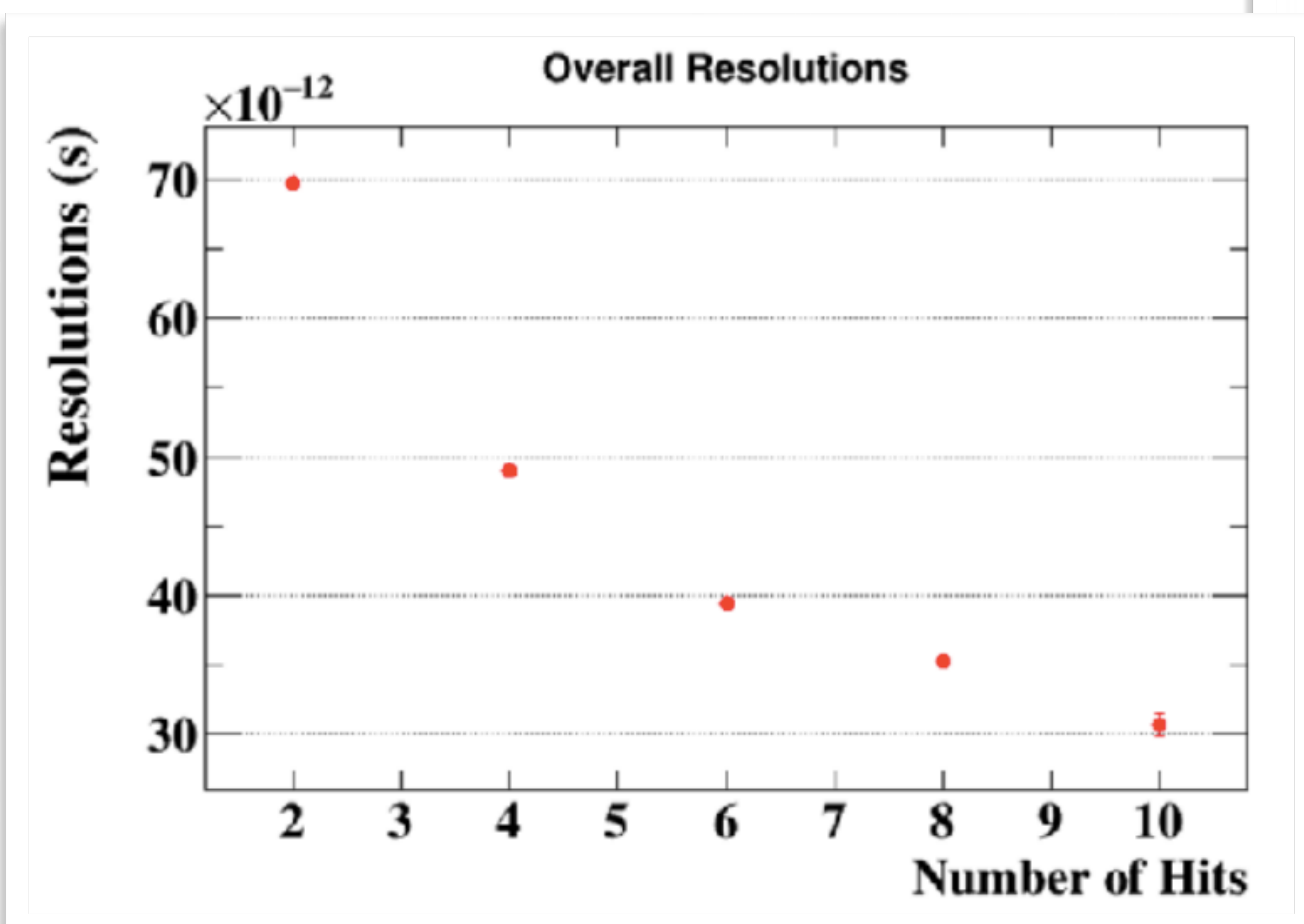


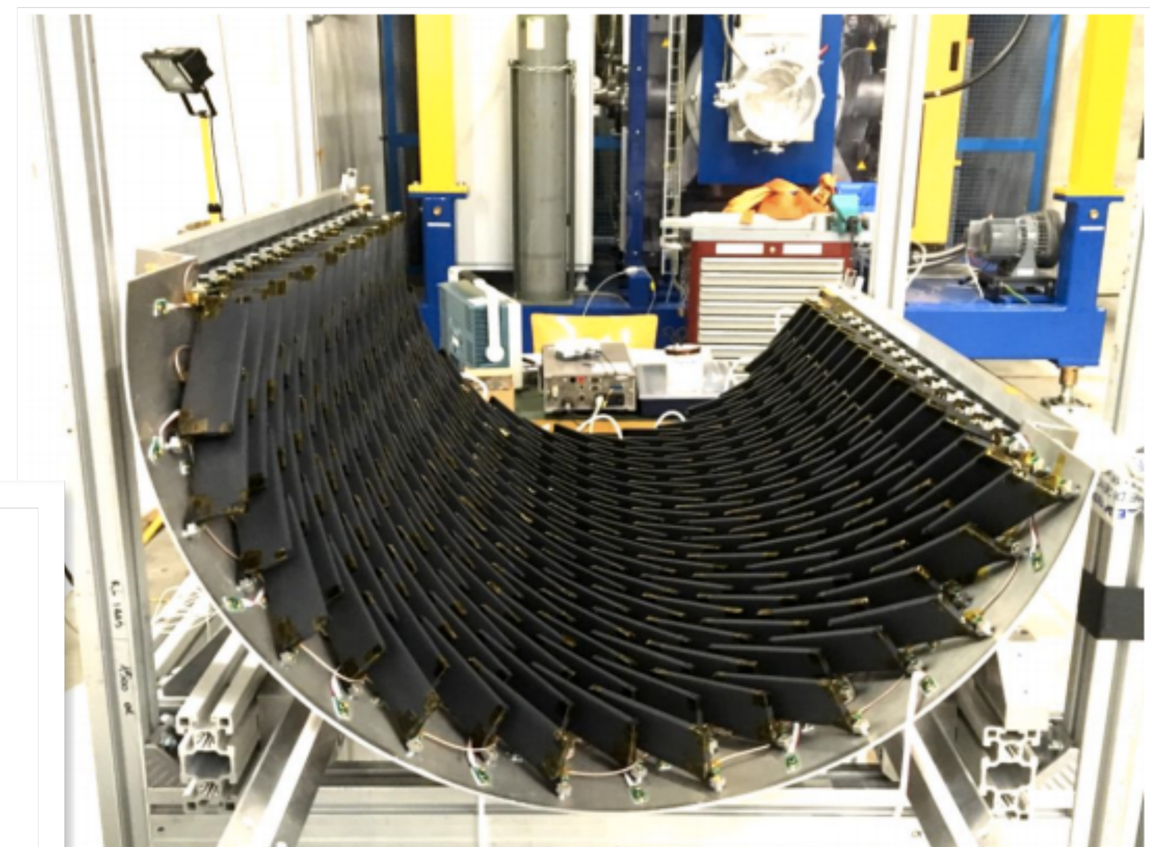
Calibration with dedicated laser

MEG-II Highlights - The Timing Counters

5mm-thick Scintillator Tiles read out by 3x3 mm^2 SiPM

Complete detector took data in 2017

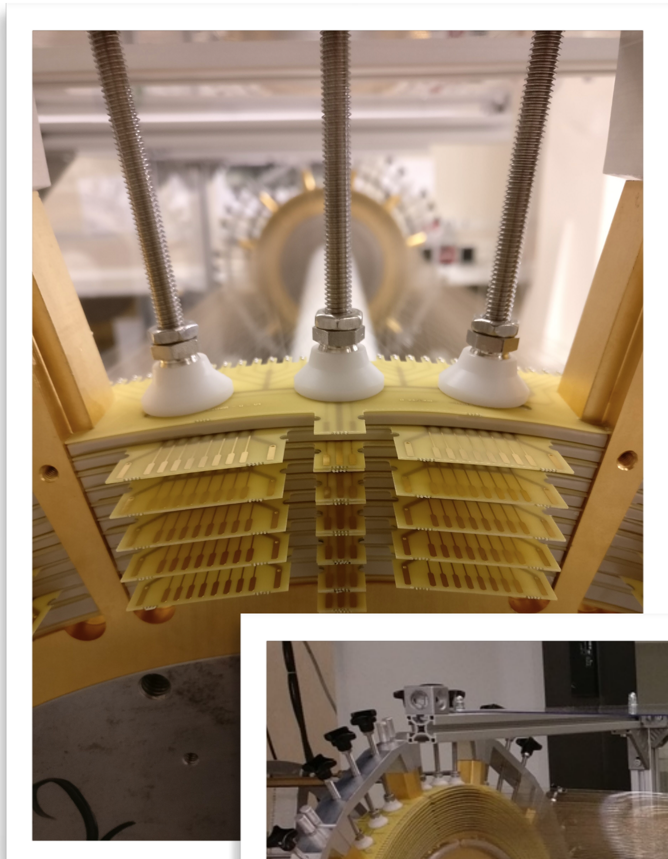




$\sigma_T \sim 35$ ps

Already reached the design resolution

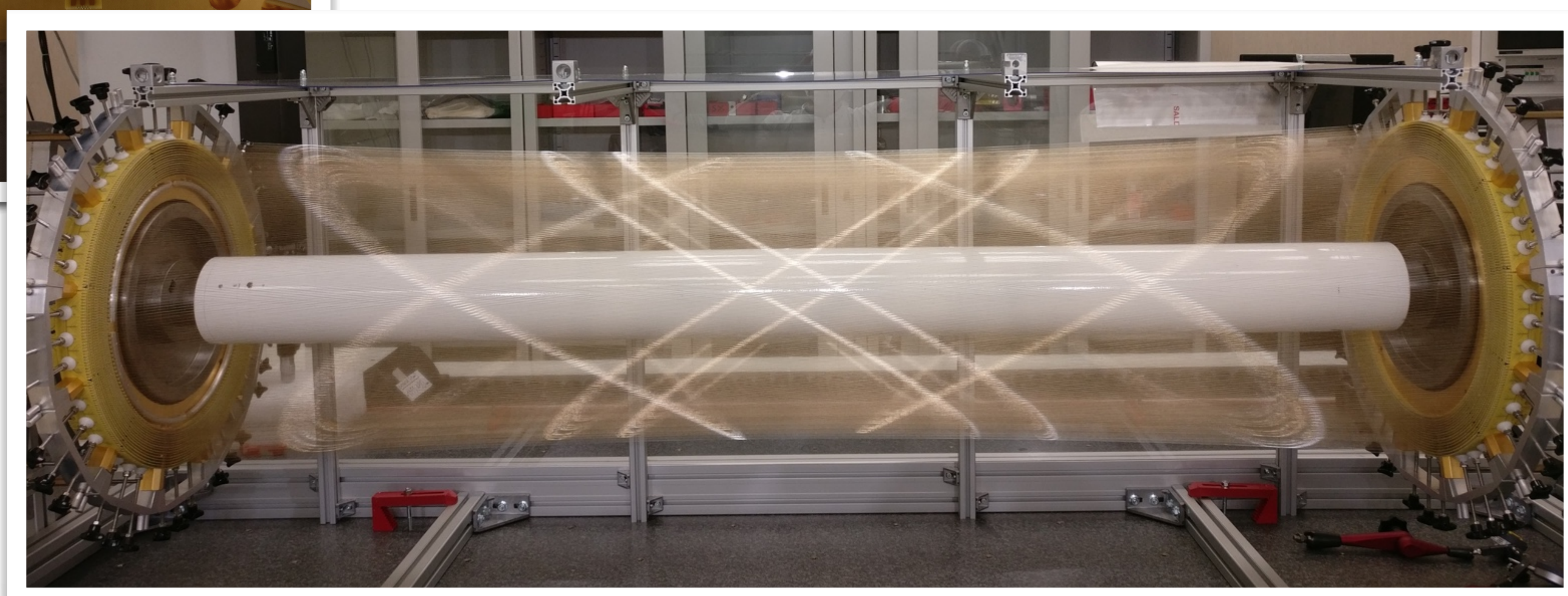
MEG-II Highlights - The Drift Chamber



Wiring, assembly and sealing have been completed

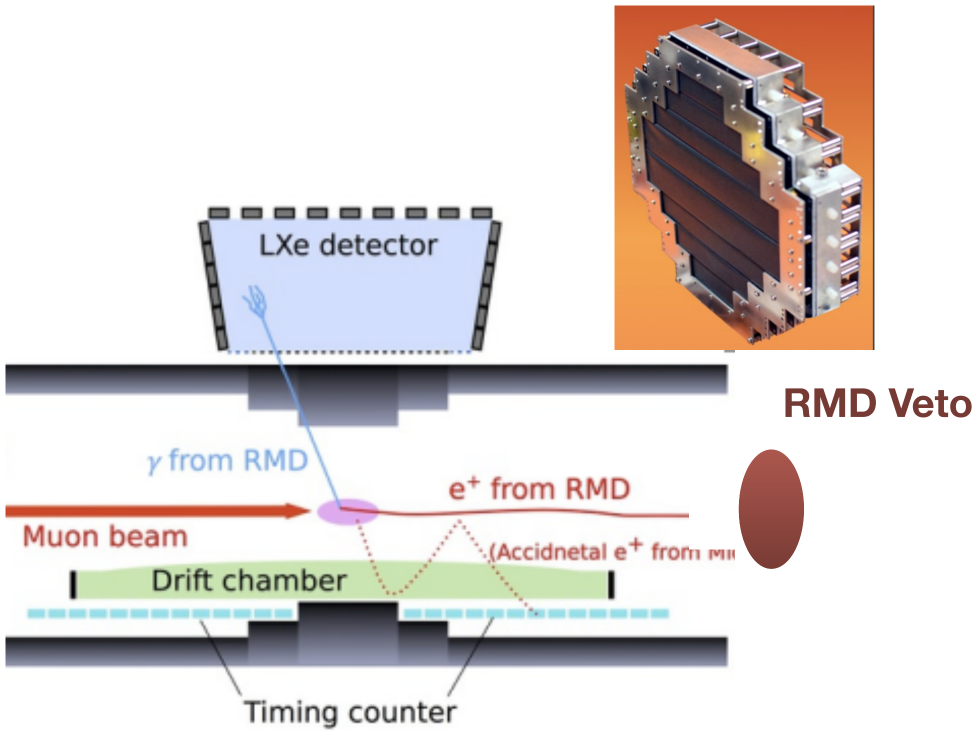
Had to face severe problems of wire fragility in presence of contaminants + humidity

On beam in Fall 2018



σ_E ~ 130 keV, σ_{angles} ~ 5 mrad, 2x larger positron efficiency

MEG-II Highlights - RDC, DAQ, Trigger



50% of acc. background photons come from RMD w/ positron along the beam line

Can be vetoed by detecting the positron in coincidence with the photon

A new detector (LYSO + plastic scint.) built and tested in 2017 -> 16% better sensitivity

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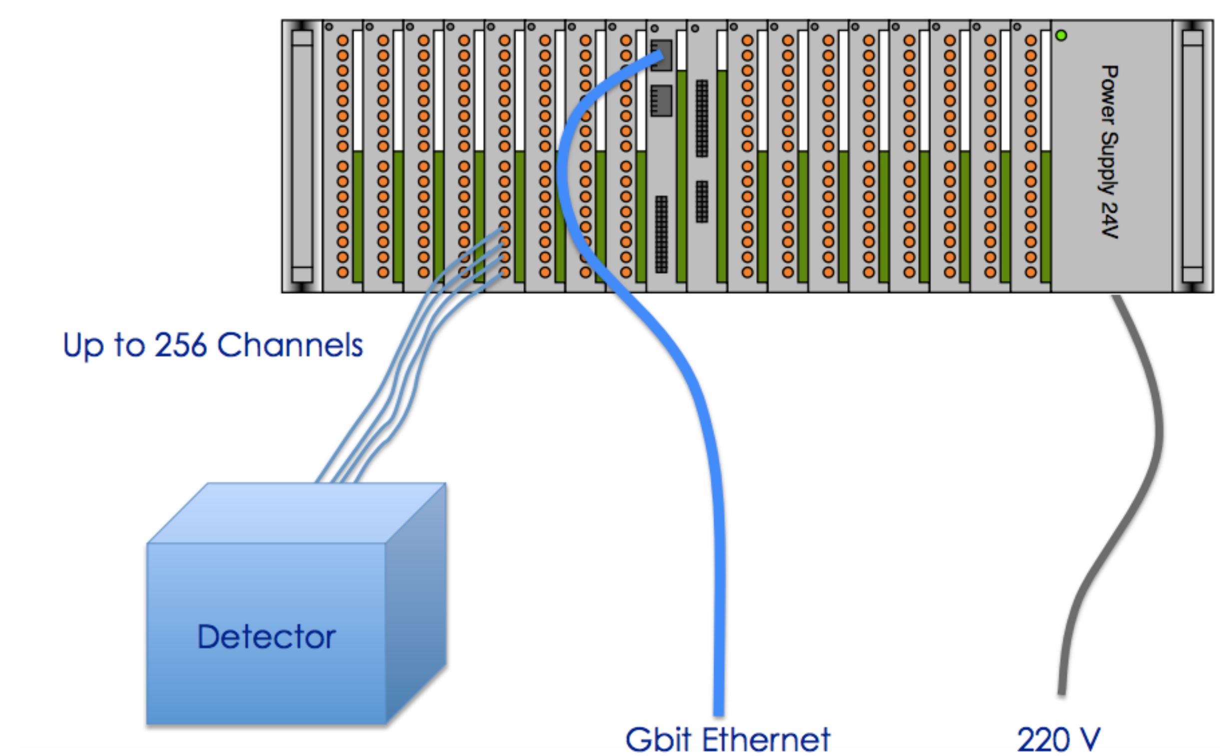
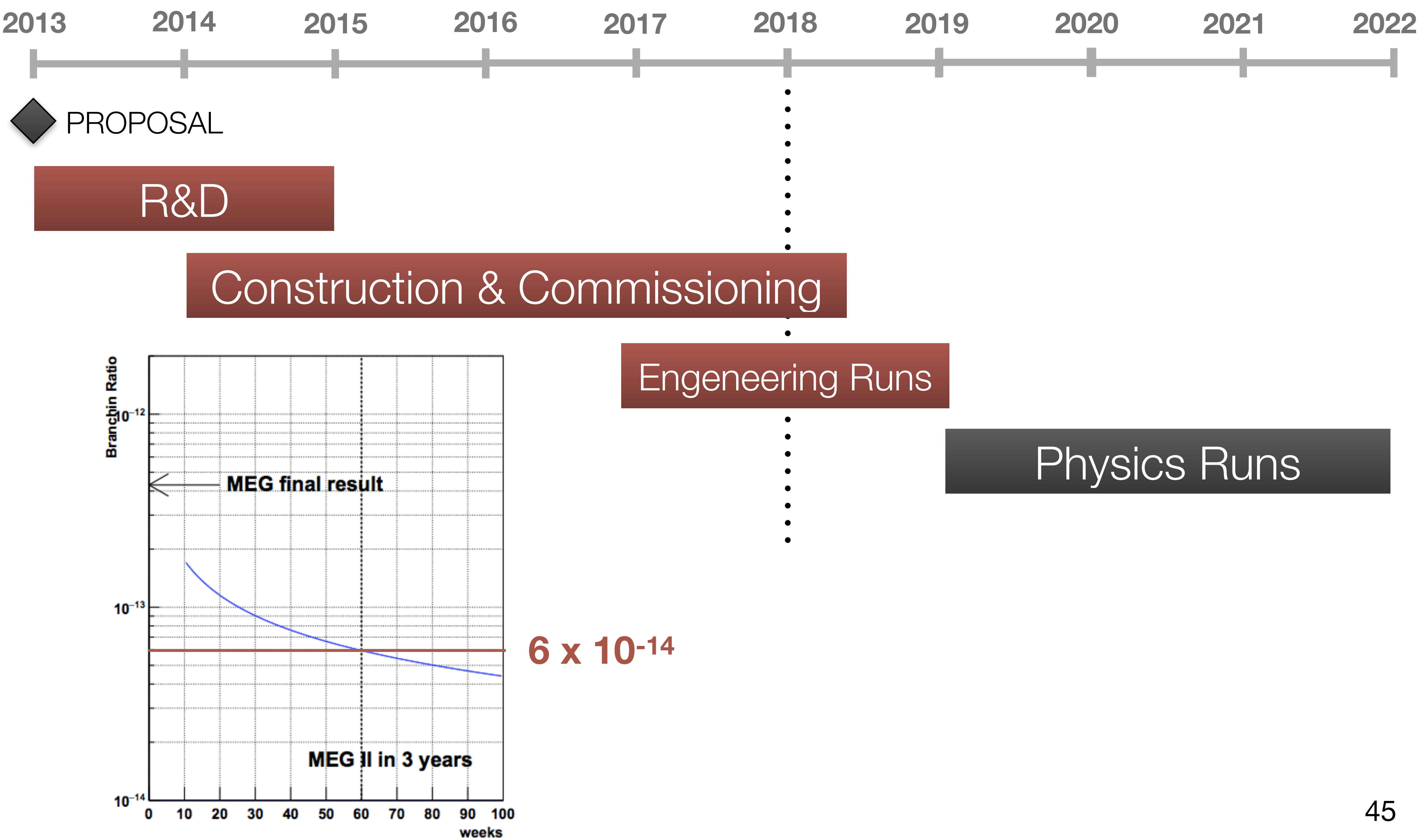
Trigger and DAQ will be integrated in a single, compact system (WaveDAQ)

Also provides power and amplification for SiPM/MPPC

Successfully tested in 2017 with XEC, TC and RDC



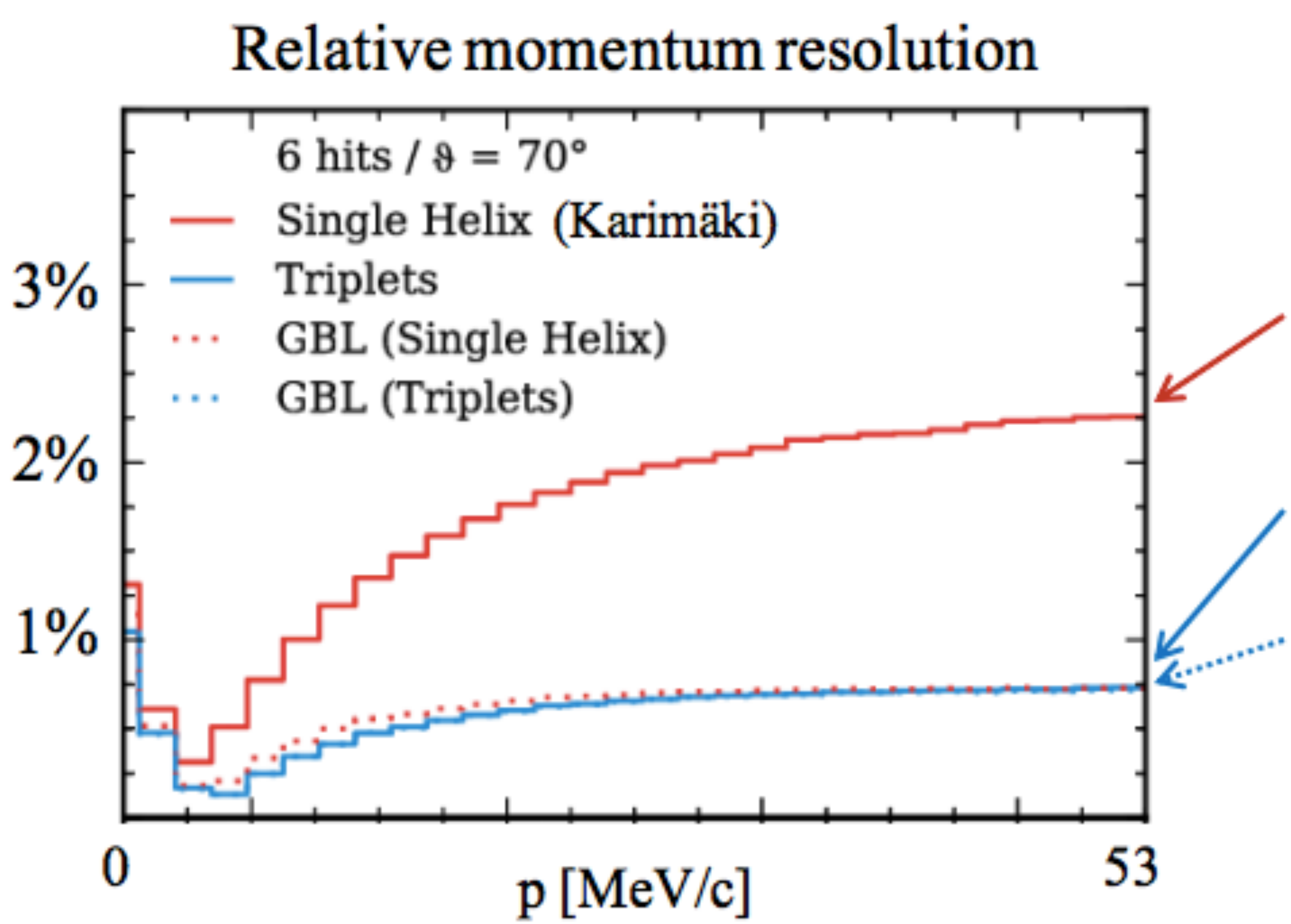
MEG-II schedule & sensitivity



Silicon detector momentum resolution

Mu3e momentum resolution (B = 1T)

4x worse than MEG-II



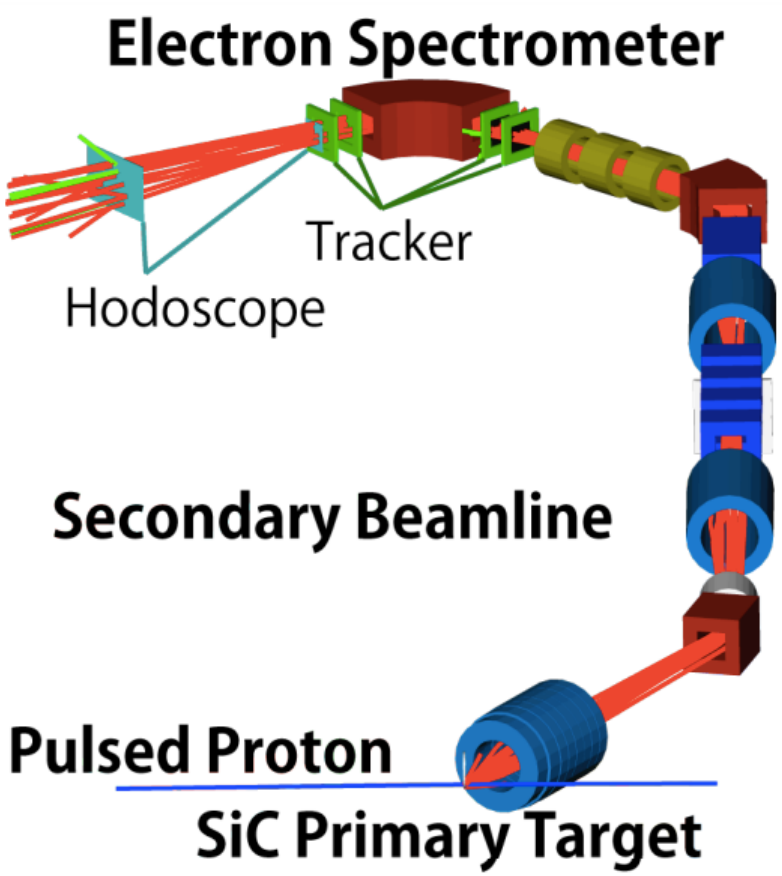
Single Helix (Karimäki)
- Neglect MS

Triplets
- MS fit

GBL (**G**eneral **B**roken **L**ines)
- Fast global track **refit** with full covariance matrix
- Equivalent to Kalman filter

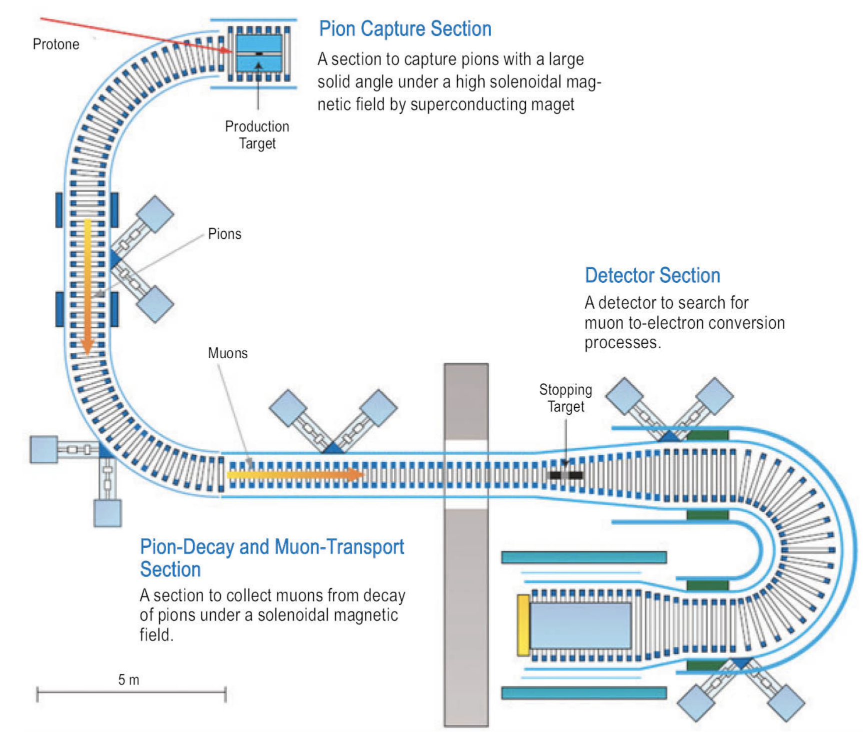
A. Kozlinskiy, Mu3e Collaboration, CTD/WIT 2017

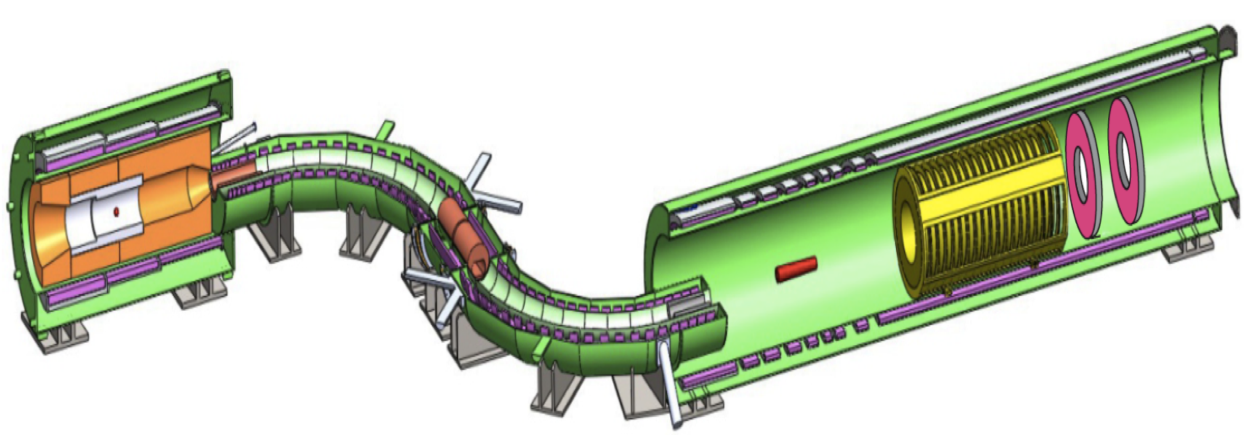
DeeMee / COMET / Mu2e



DeeMee: will start data taking soon SES ~ 10^{-14}

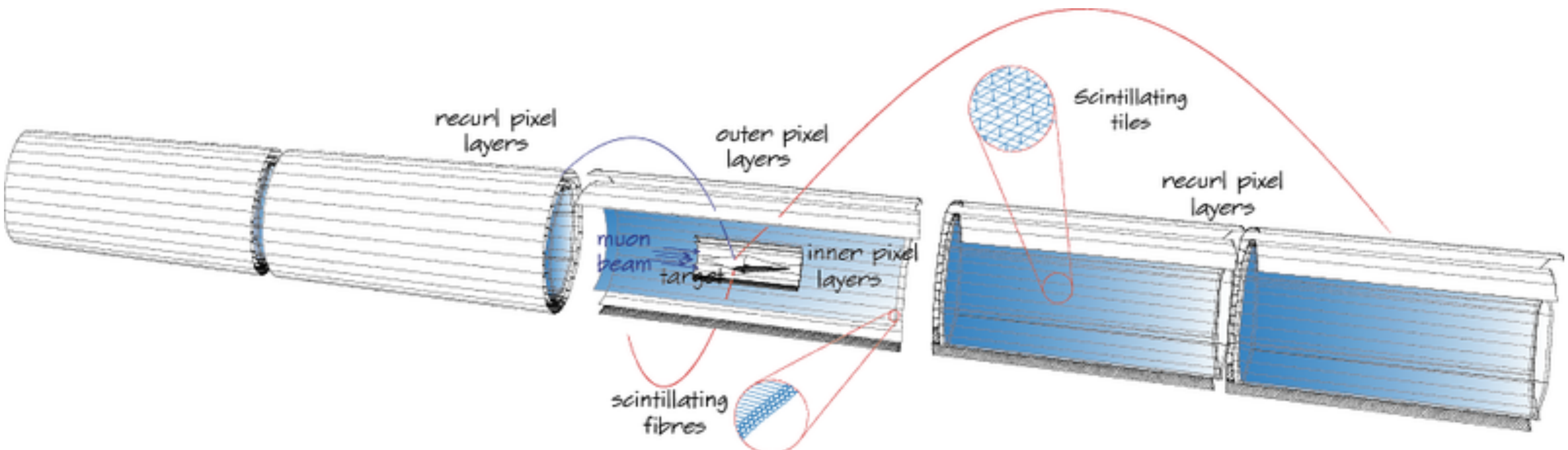
COMET: Will start phase-I commissioning ~ 2019 phase-II SES ~ 10^{-17}





Mu2e: Data taking expected ~ 2022 SES < 10^{-16}

Mu3e



R&D almost completed

Commissioning will start soon

Data taking expected > 2020

Expected BR UL ~ 10^{-16}