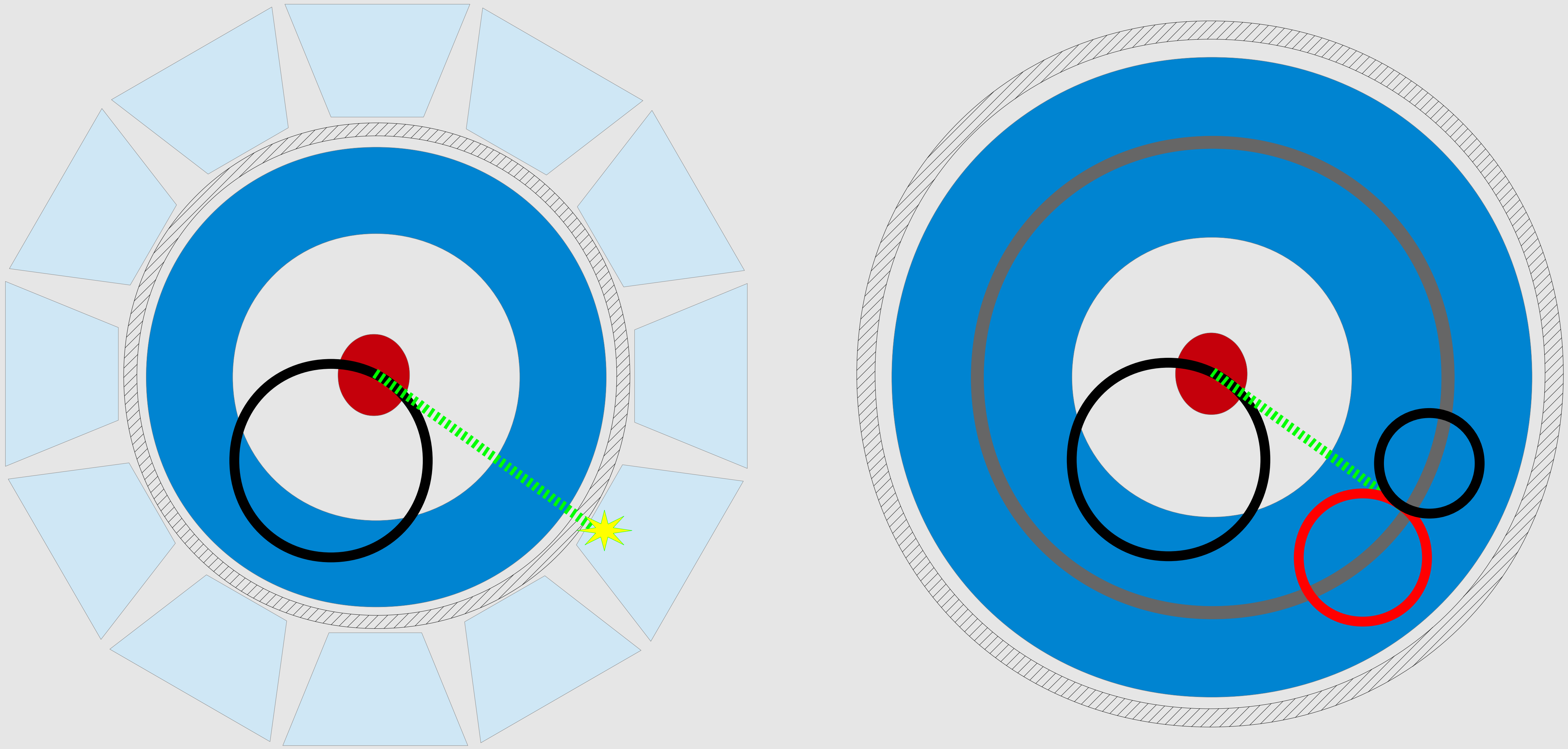


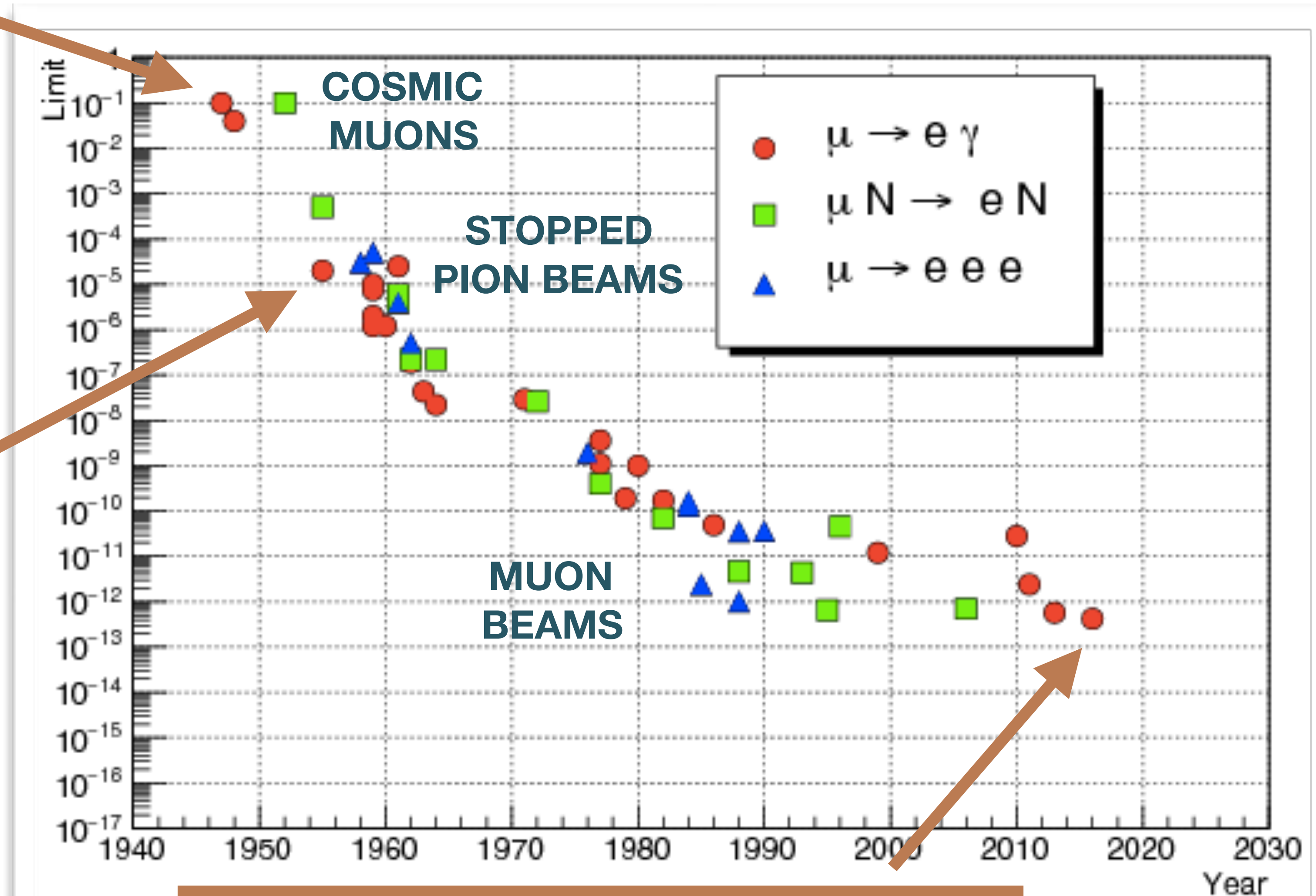
μ -> e γ
Experimental Aspects

RF05: CLFV - Muon Decays and Transitions
July 2nd, 2020

Francesco Renga
INFN Roma

History of cLFV searches

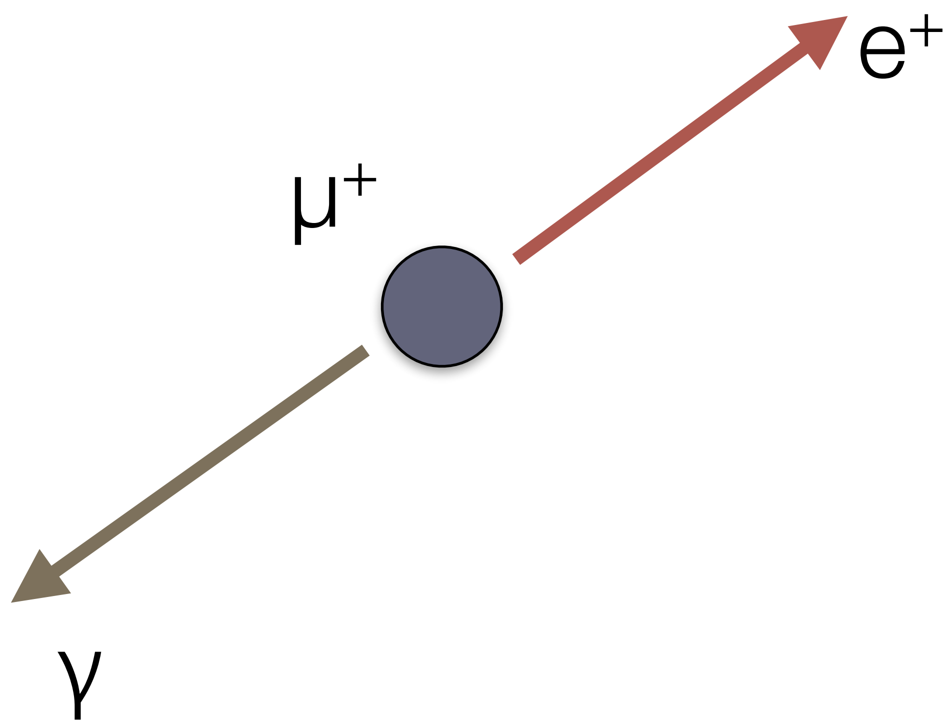
Hincks & Pontecorvo
[Phys. Rev. 73 (1948) 257]
muon is not an "excited electron"



Lokanathan & Steinberger
[Phys. Rev. A 98 (1955) 240]
lepton flavors

MEG Experiment
[Eur.Phys.J. C76 (2016) 8, 434]
BR(μ -> e γ) < 4.2 x 10⁻¹³

μ -> e γ searches

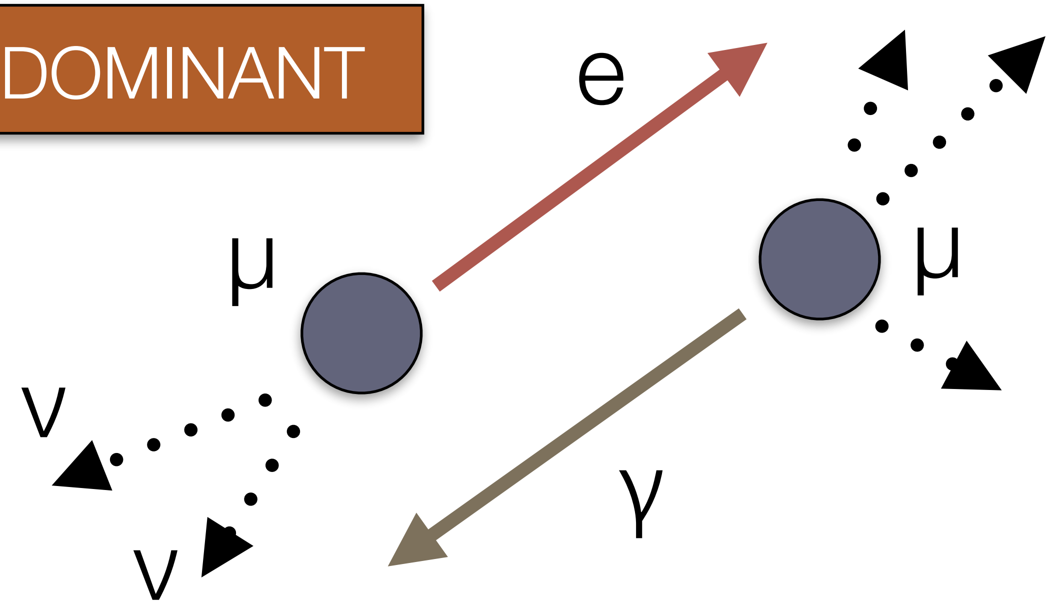


28 MeV/c muons are stopped on a thin target

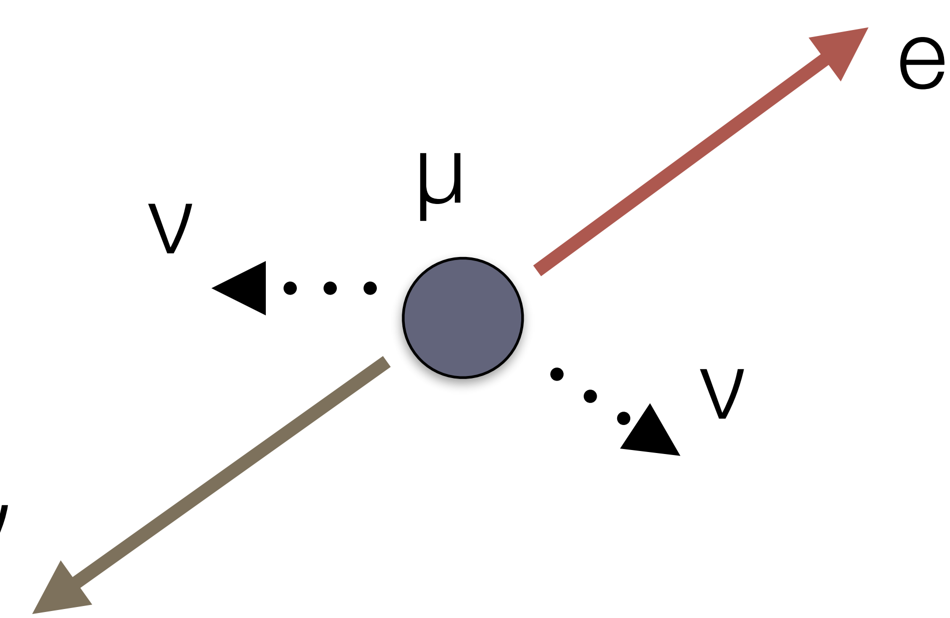
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the **same time**;

Accidental Background

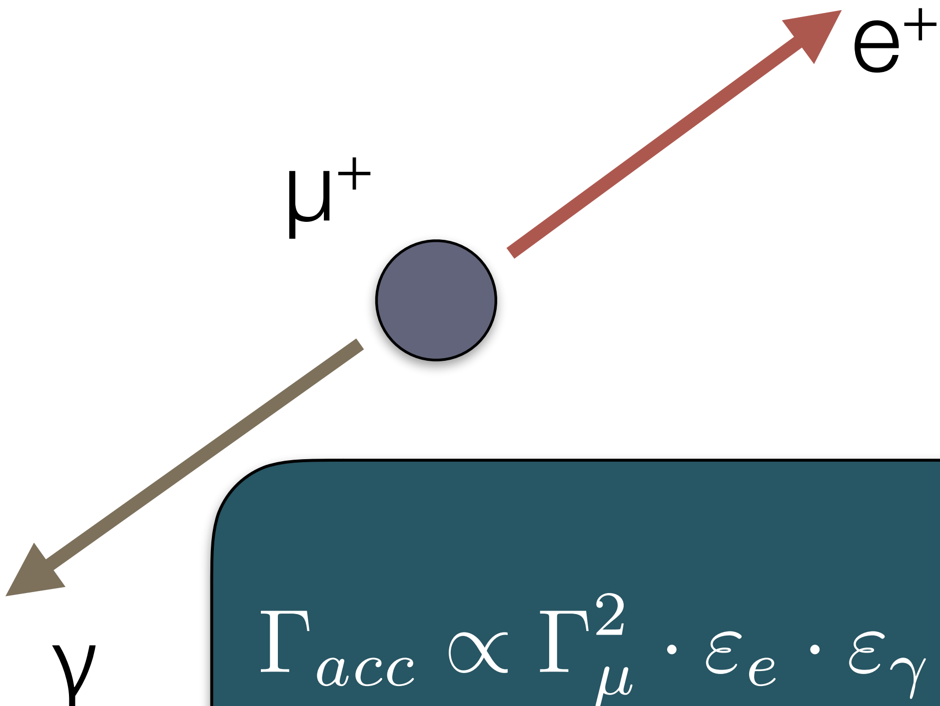
DOMINANT



Radiative Muon Decay (RMD)



μ -> e γ searches



28 MeV/c muons are stopped on a thin target

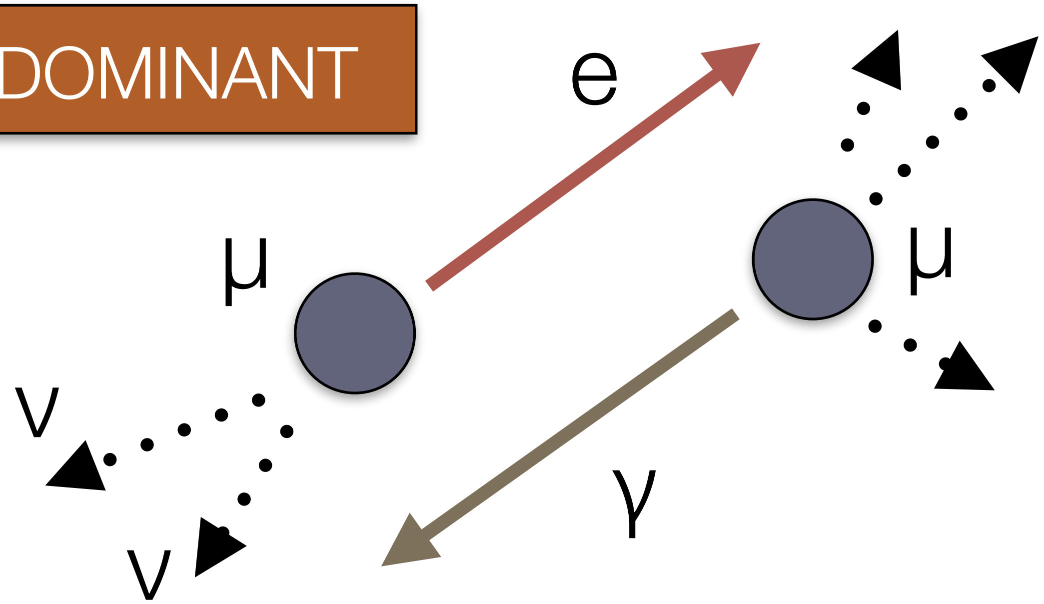
Positron and photon are **monochromatic** (52.8 MeV),
d
time;

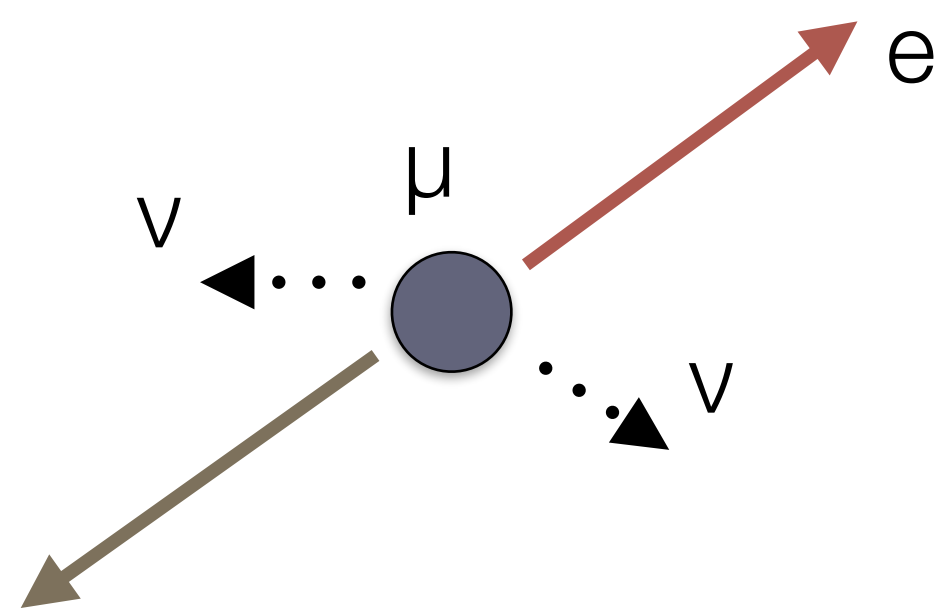
$$\Gamma_{acc} \propto \Gamma_\mu^2 \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2 \cdot \delta T_{e\gamma}$$

Accid

ay (RMD)

DOMINANT

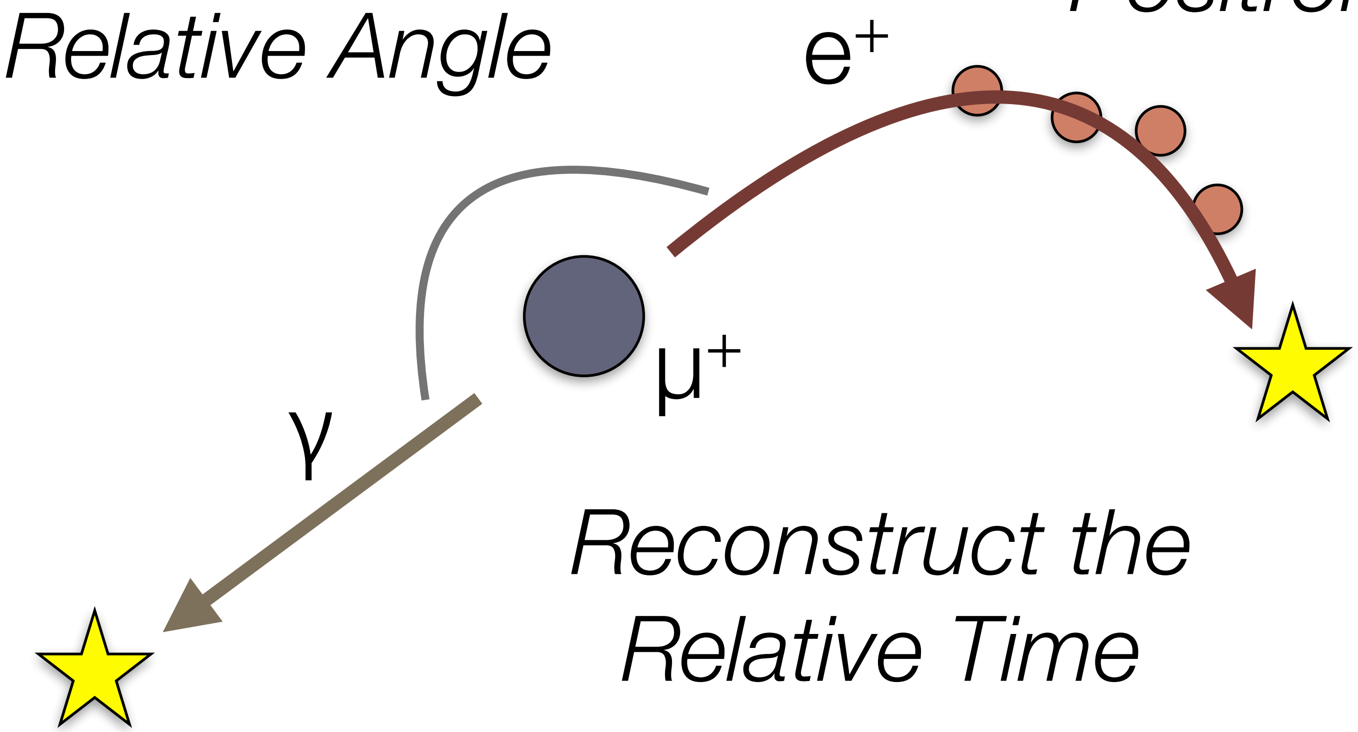




Ingredients for a search of μ -> e γ

Reconstruct the Relative Angle

Reconstruct the Positron Energy



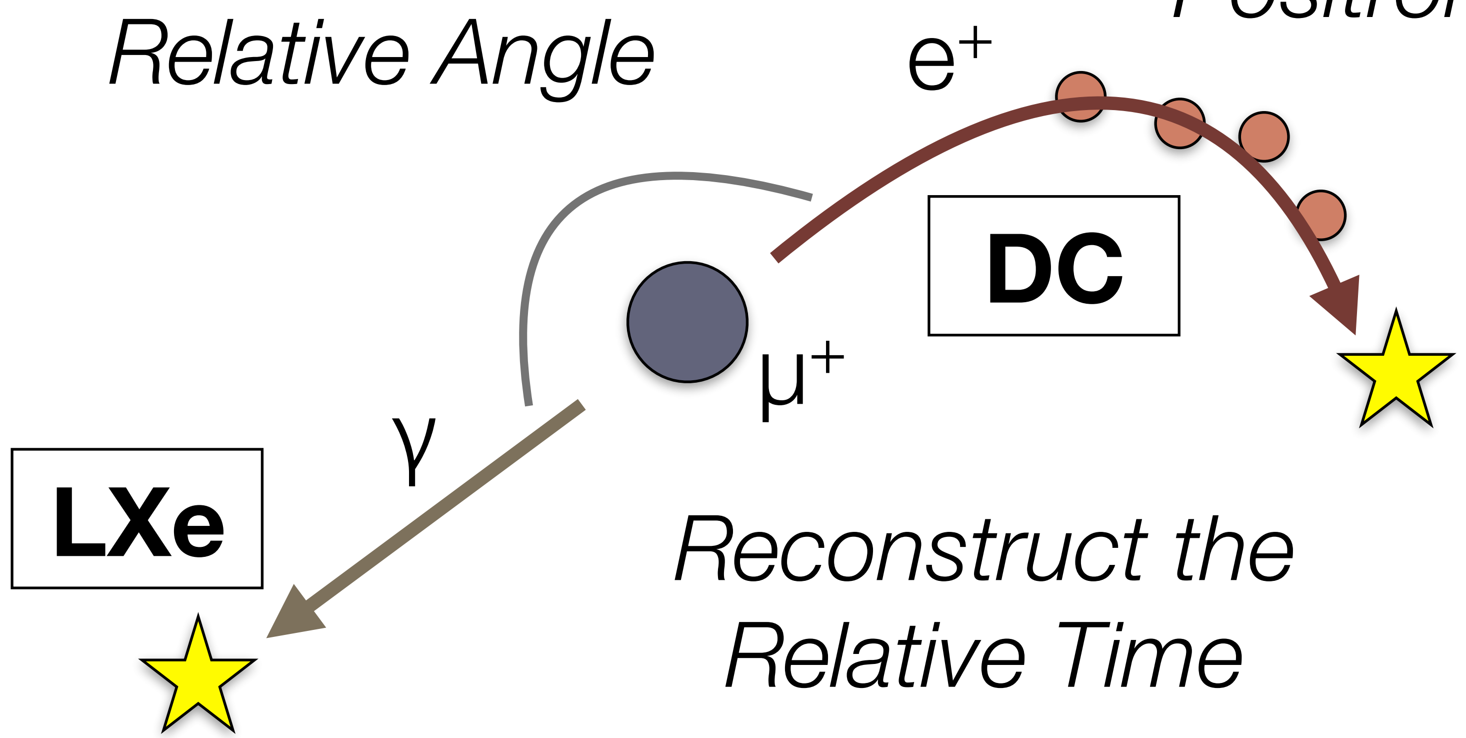
Reconstruct the Relative Time

Reconstruct the Photon Energy

The MEG Experiment

Reconstruct the Relative Angle

Reconstruct the Positron Energy



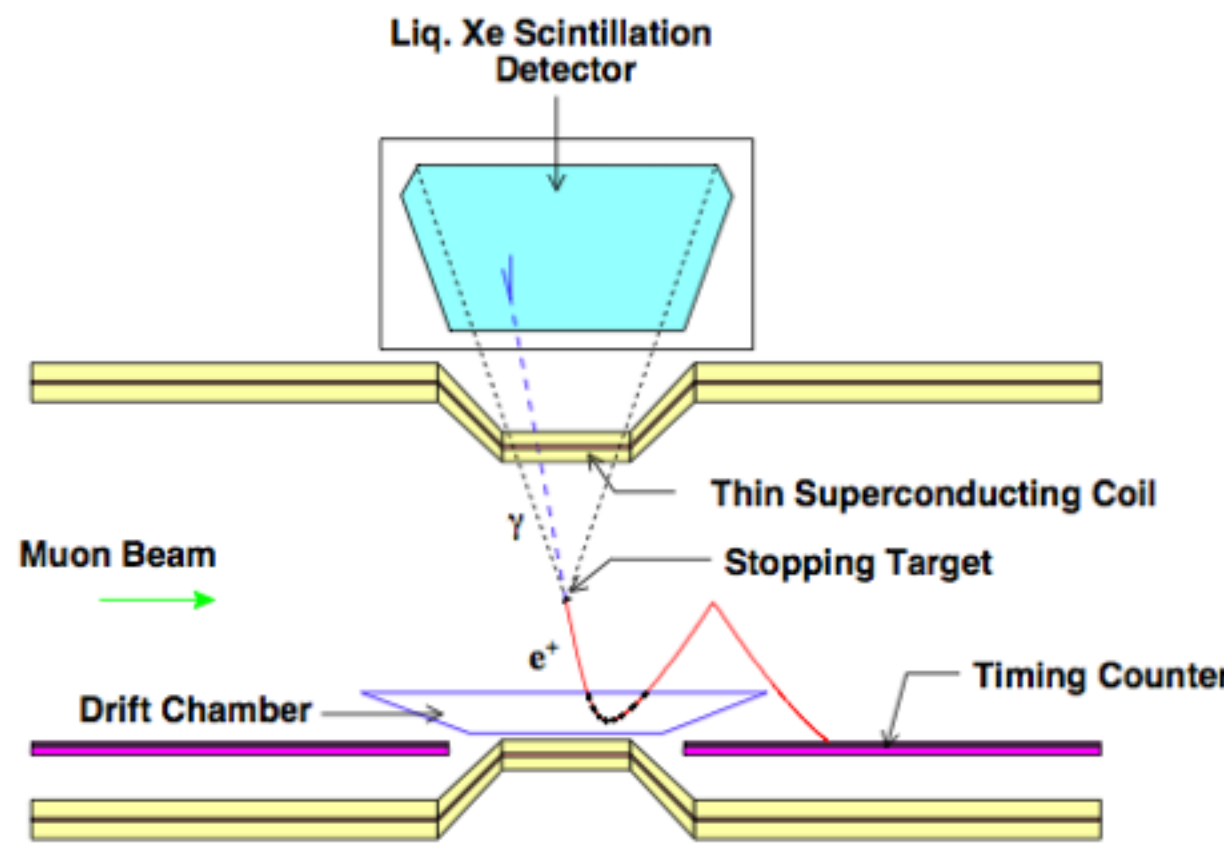
Reconstruct the Relative Time

Reconstruct the Photon Energy

LXe calorimeter (XEC)

16 Drift Chambers (DC) in a magnetic field

30 scintillating bars for timing & trigger (TC)

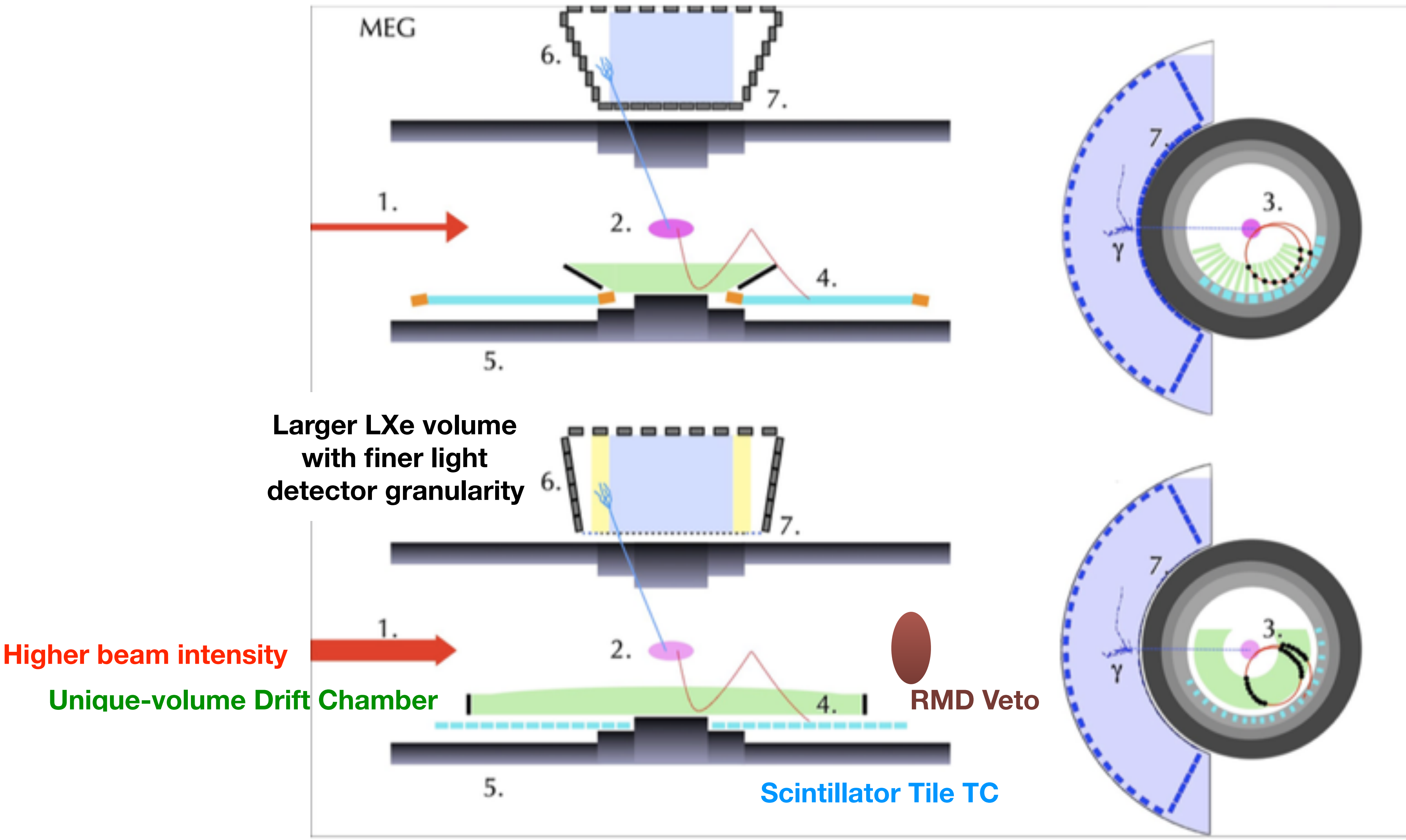


7.5 x 10^{14} μ on target

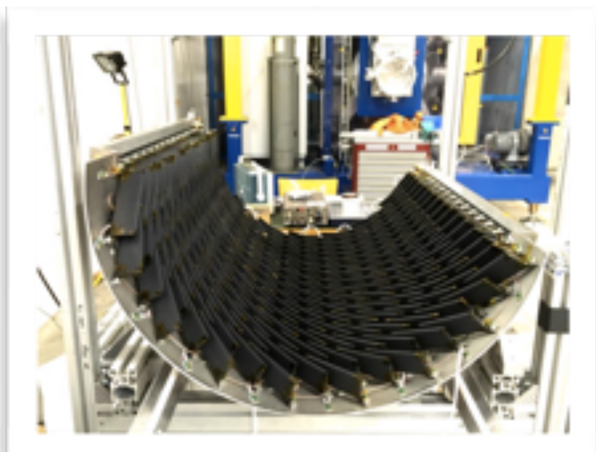
BR(μ -> e γ) < 4.2 x 10^{-13} @ 90% C.L.

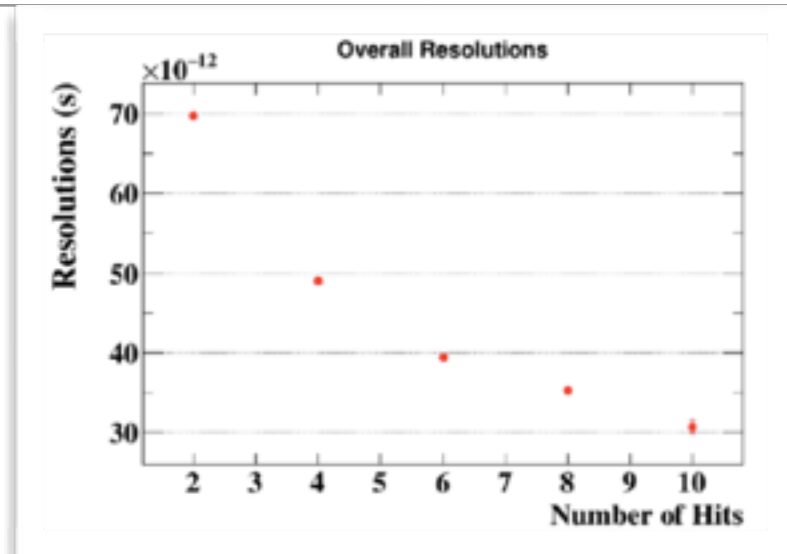
MEG-II

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



MEG-II status



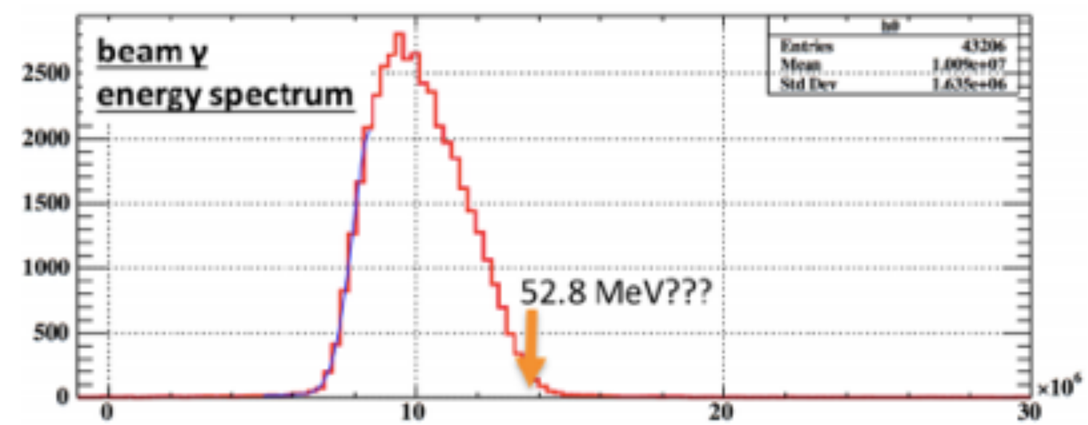


TC built and commissioned in 2016-2017

σ_T ~ 35 ps

First photons in the upgraded XEC in 2017

σ_E ~ 1% @ 52.8 MeV



New DC under commissioning

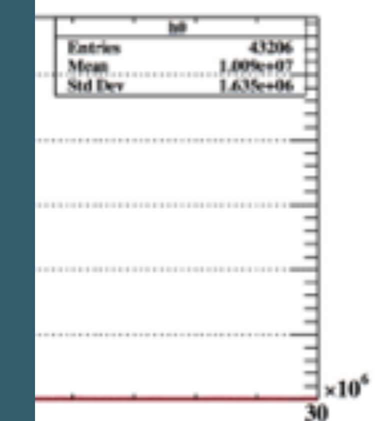
Expected to be fully operational in 2021

σ_E ~ 130 keV

MEG-II status

pgraded

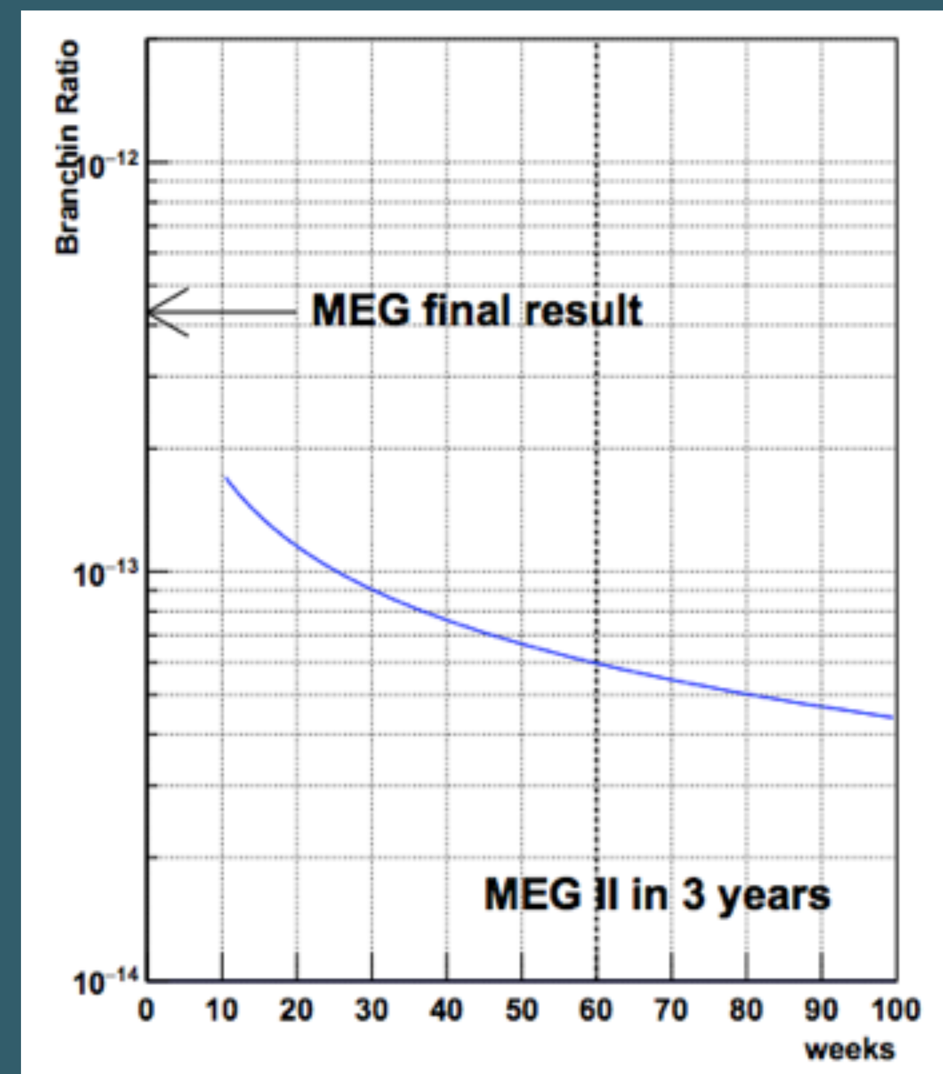
MeV



TC

First physics run in 2021

Expected UL ~ 6 x 10^{-14} in a 3-year run

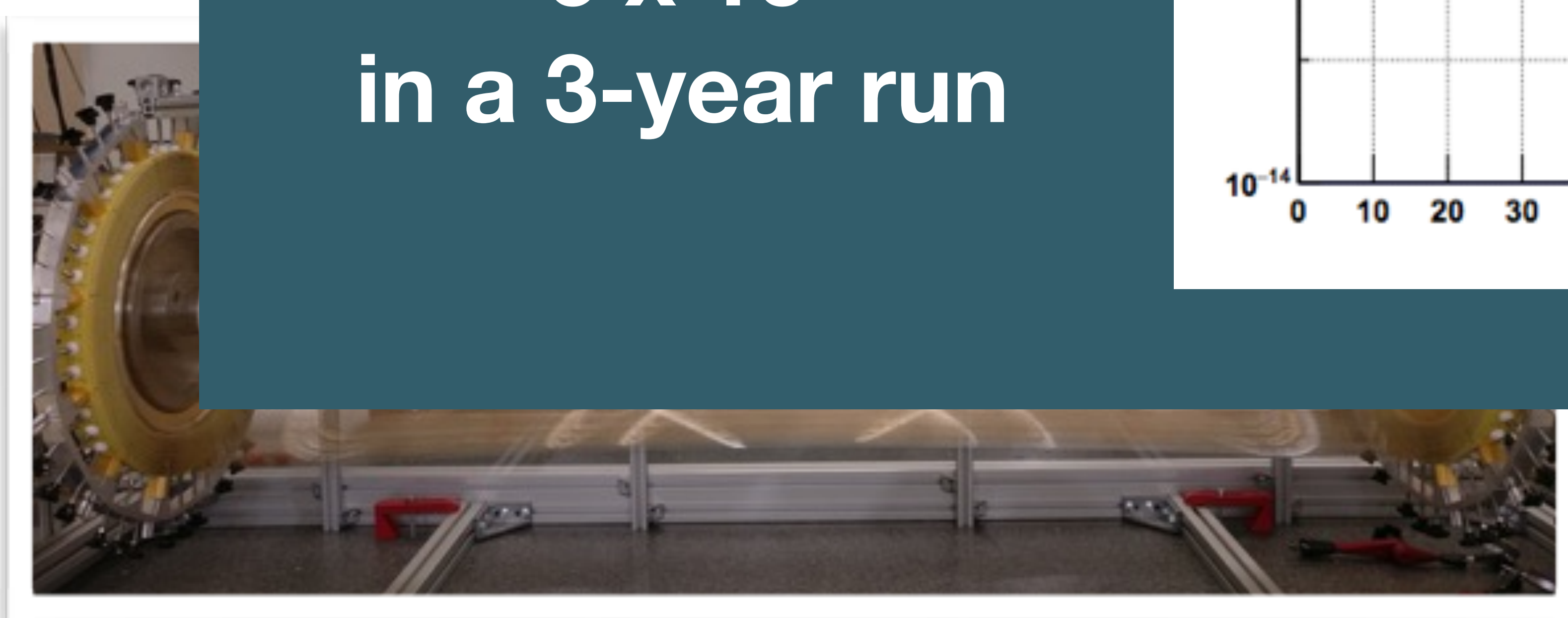


nder

oning

be fully operational in 2021

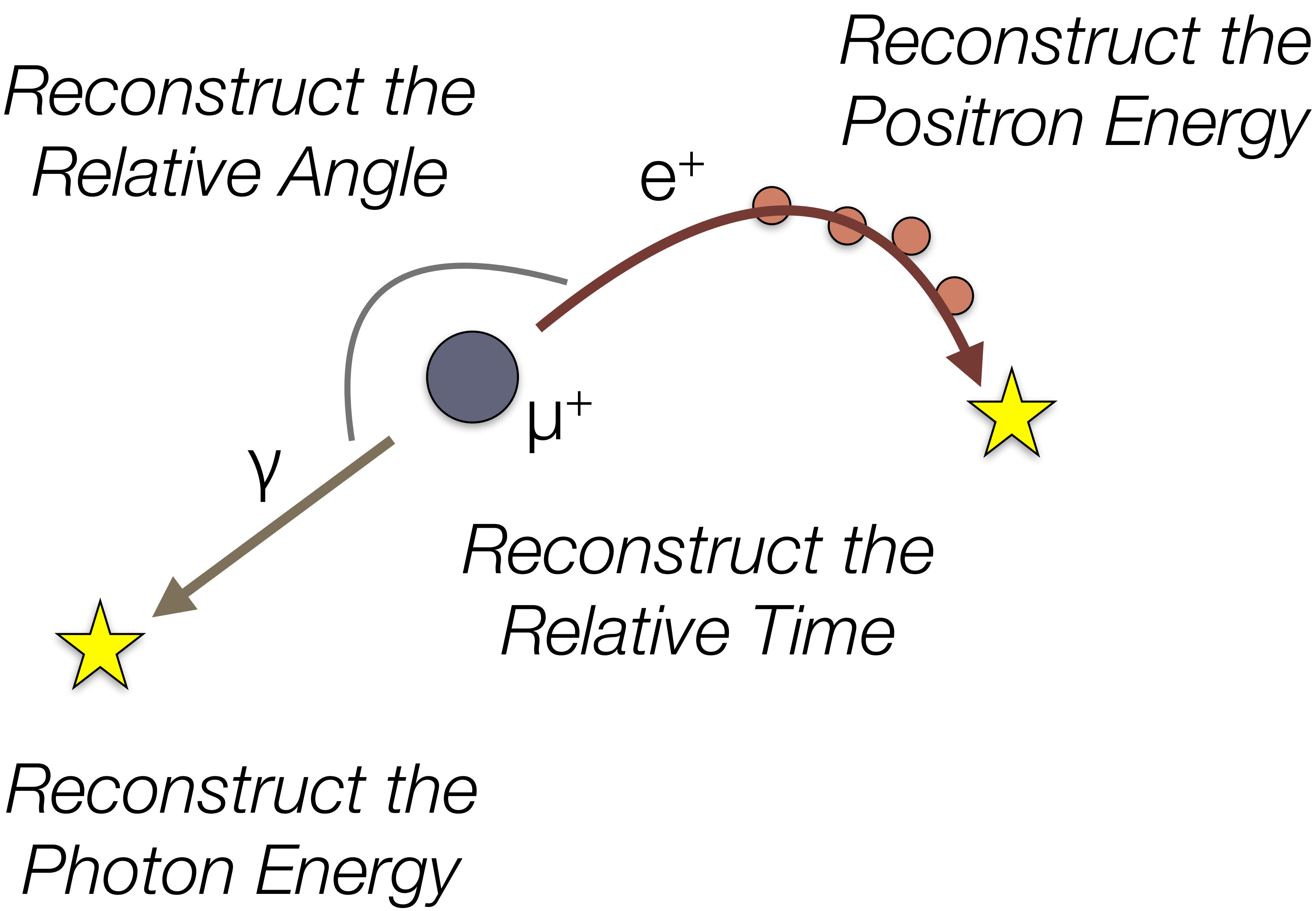
σ_E ~ 130 keV



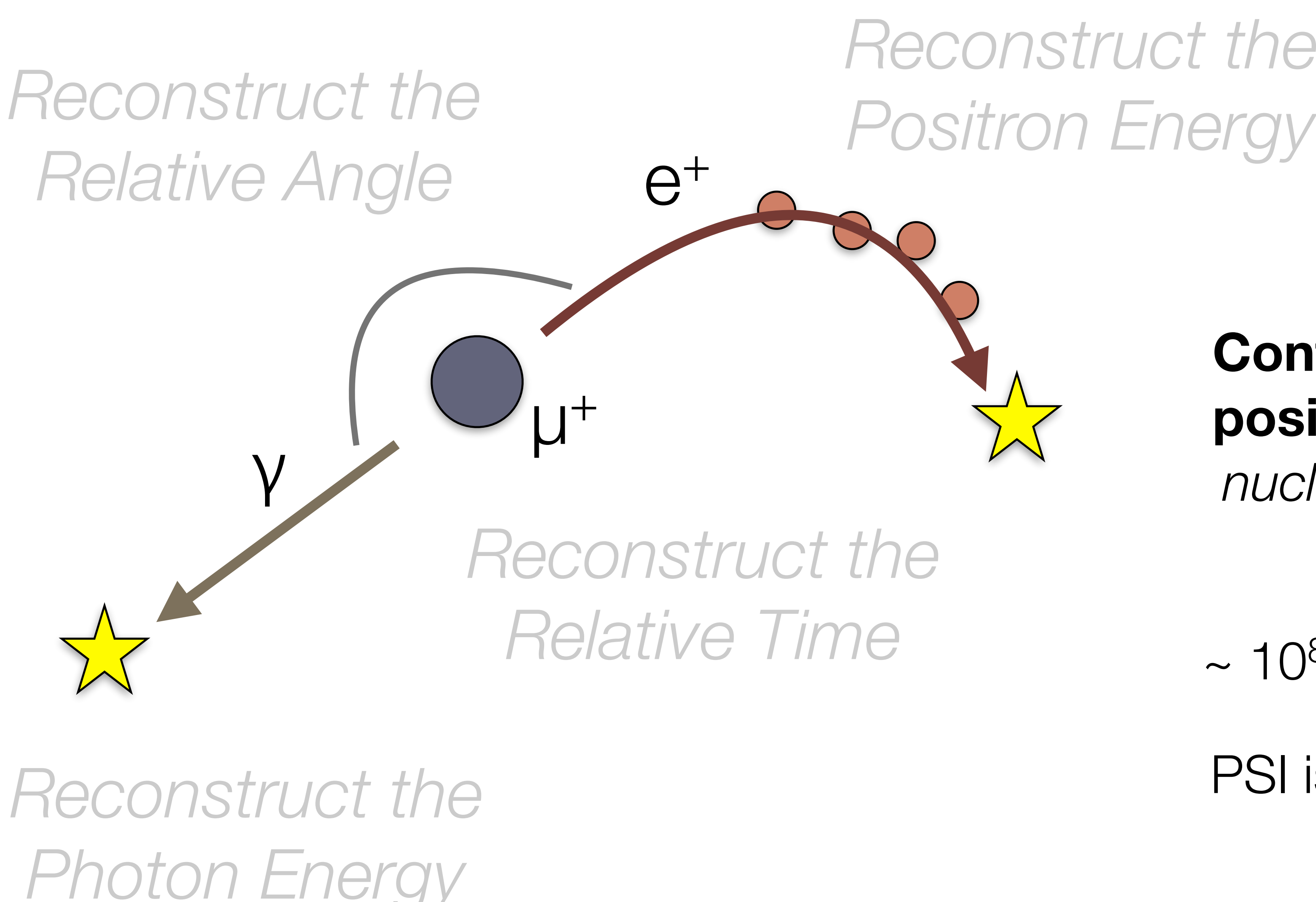
What next?

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



Ingredients for a search of μ -> e γ



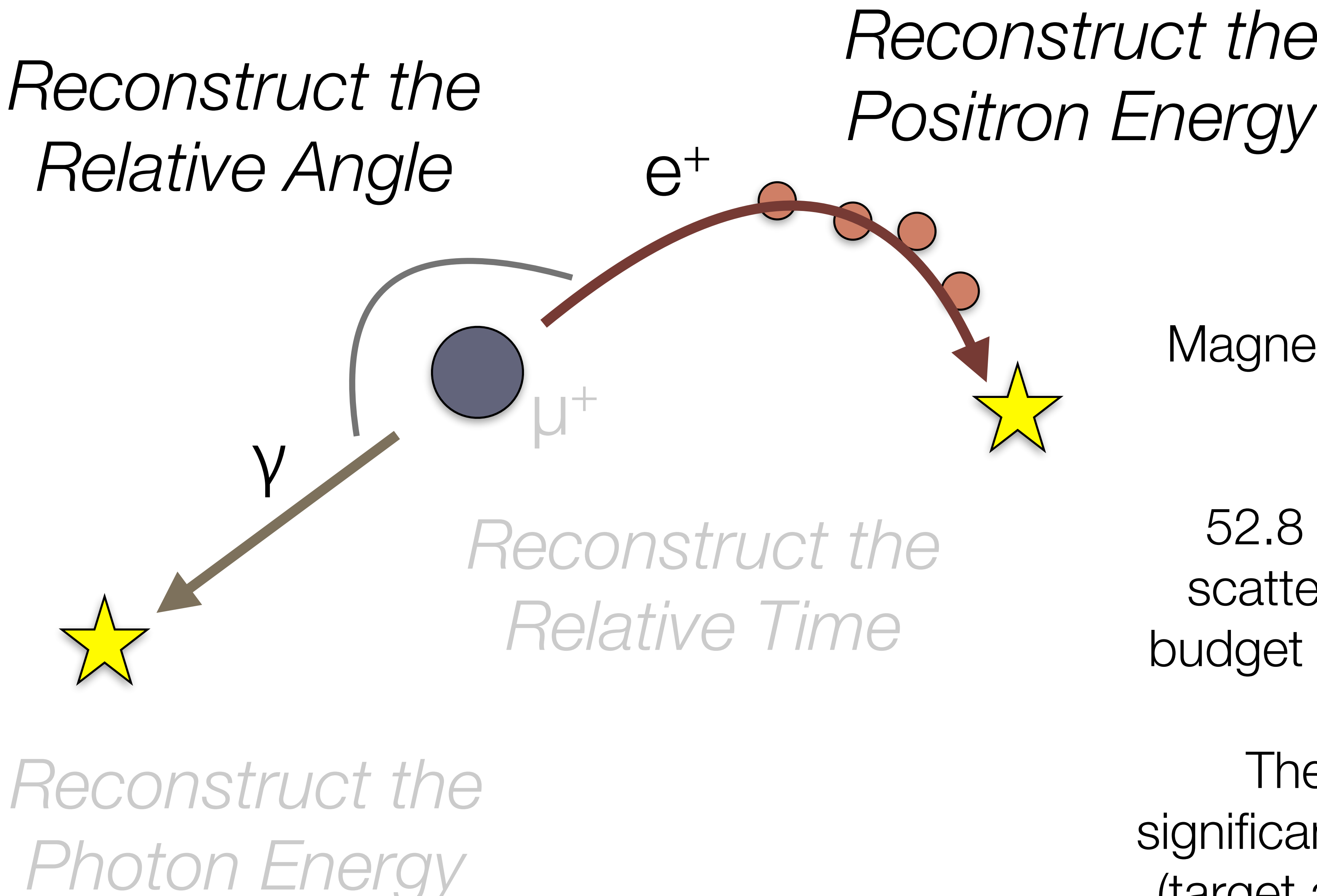
Continuous (*to avoid pileup*)
positive (*to avoid capture by nuclei in the stopping target*)
muon beams

~ 10^8 μ/s available at PSI now

PSI is considering a beamline with > 10^9 μ/s

Prospects for DC muon beams at PIP-II (Fermilab) are under study

Ingredients for a search of μ -> e γ



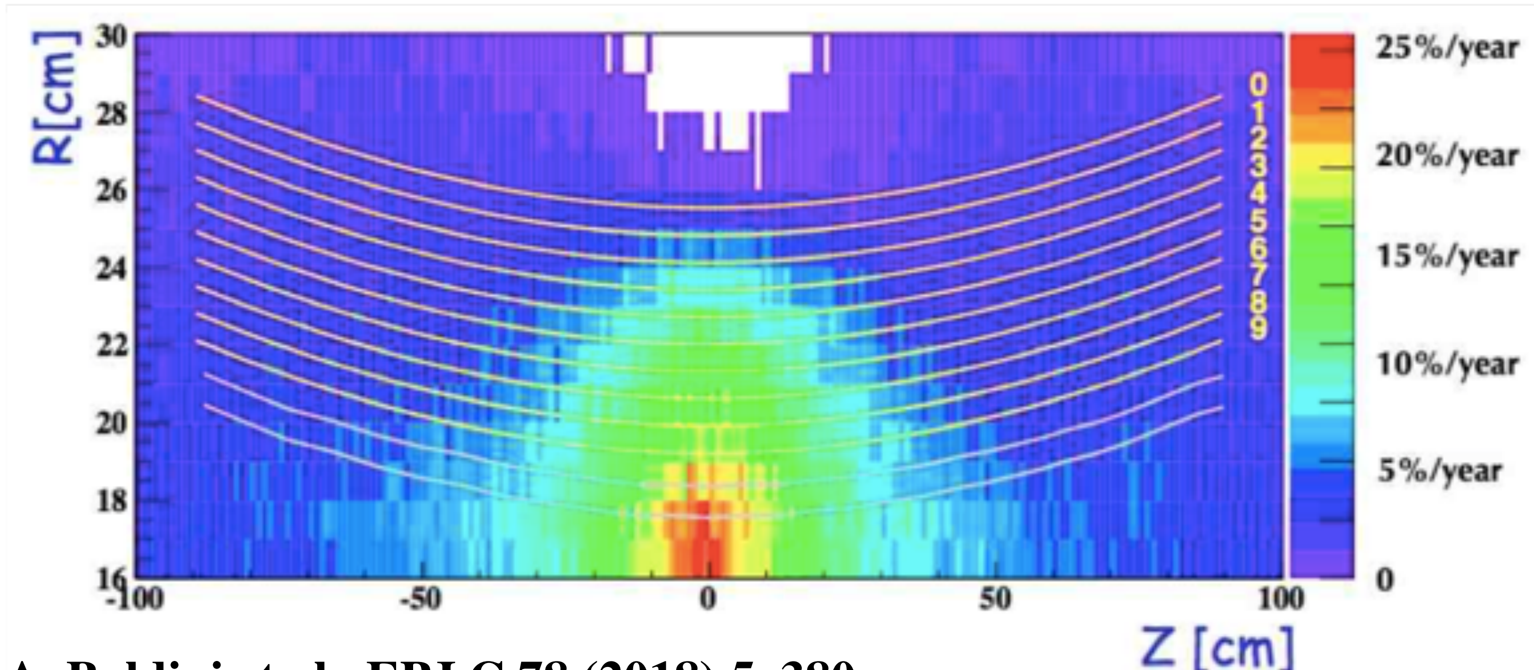
Magnetic spectrometer to get the best resolutions

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

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

Positron Reconstruction at High Beam Rate

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



A. Baldini et al., EPJ C 78 (2018) 5, 380

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

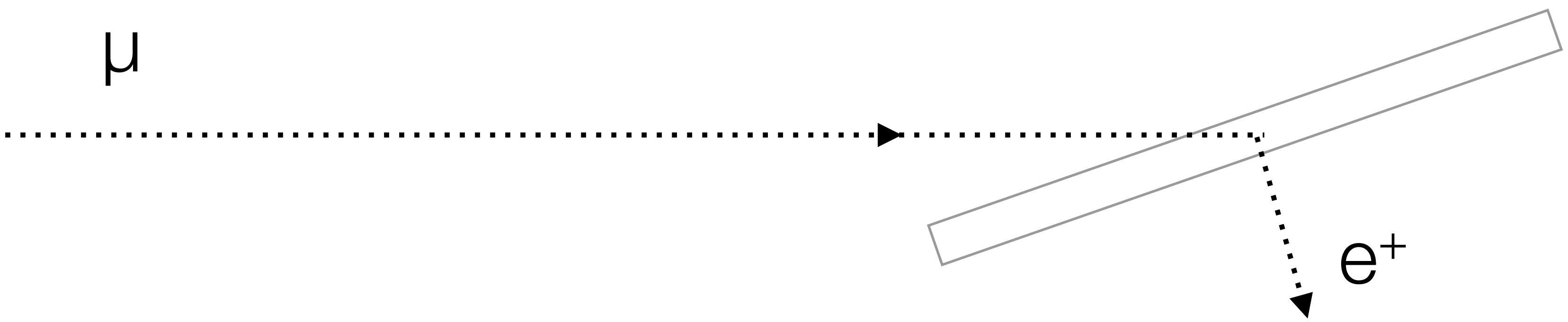
…would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?

- Solutions for a gaseous detector with high rate capabilities are also under study (new geometries, optical readout,…)

Muon Stopping Target

- The target plays a crucial role in determining the positron angular resolution, due to the Multiple Coulomb Scattering:
  - target must be as thin as possible
- In order to stop a significative fraction of muons, it must be at the Bragg peak:
  - muons not stopped by the target are stopped in the gas right after, giving background without contributing to the signal

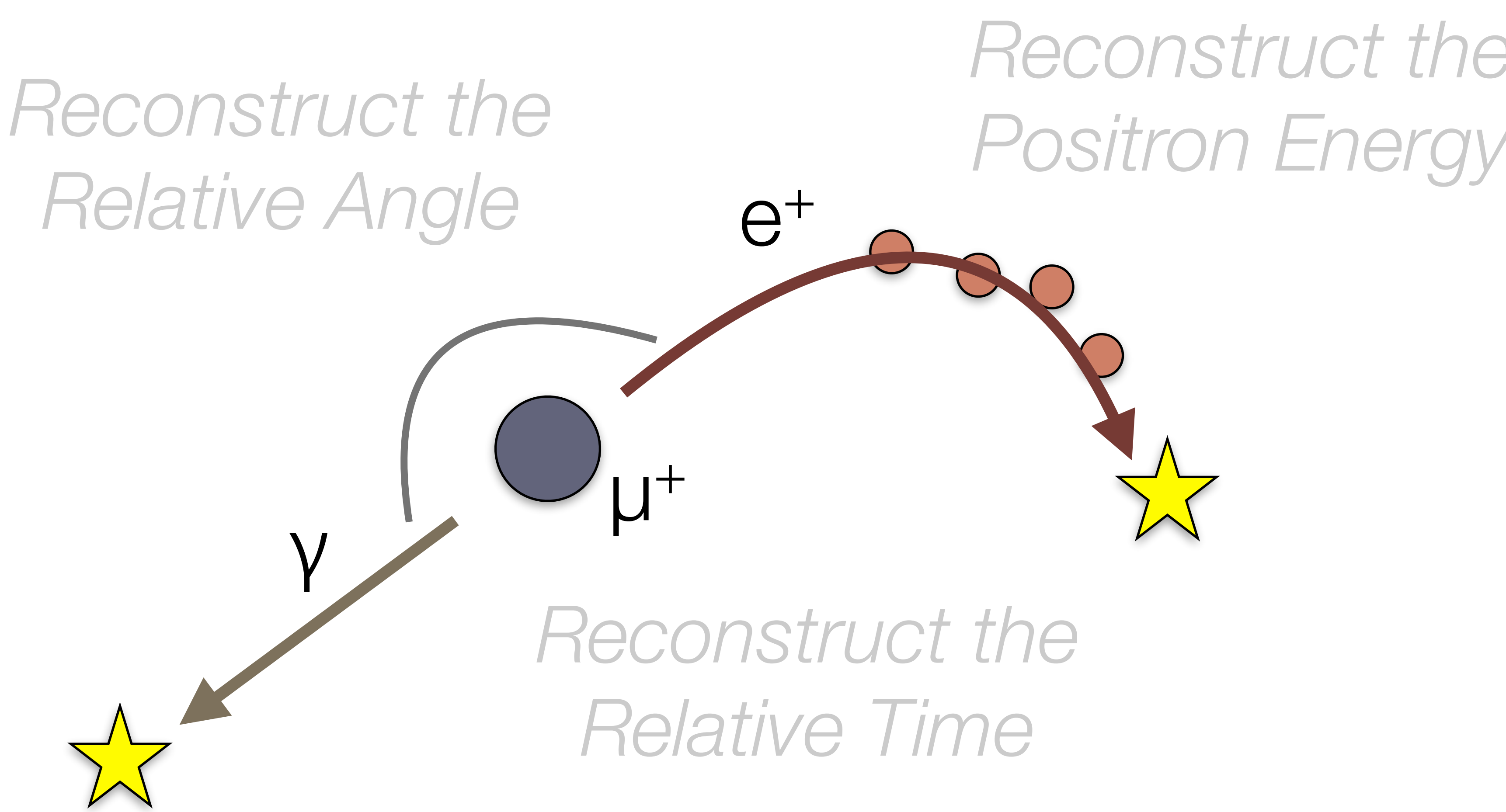
➡ enough thickness to stop ~ all muons



Optimal target
Be, 90 μm

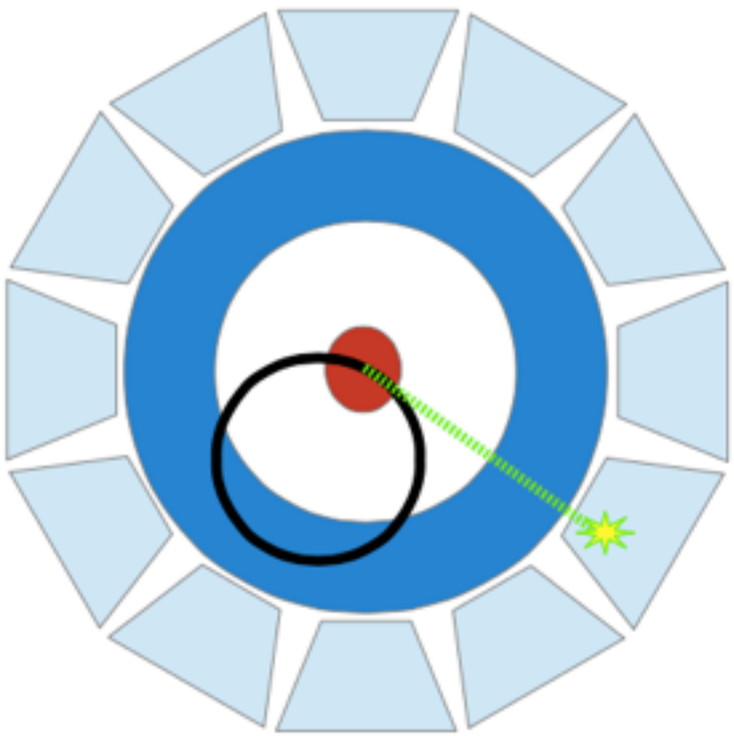
$\theta_{MS}(e^+) \sim 2.5 - 3$ mrad

Ingredients for a search of μ -> e γ



Reconstruct the Photon Energy

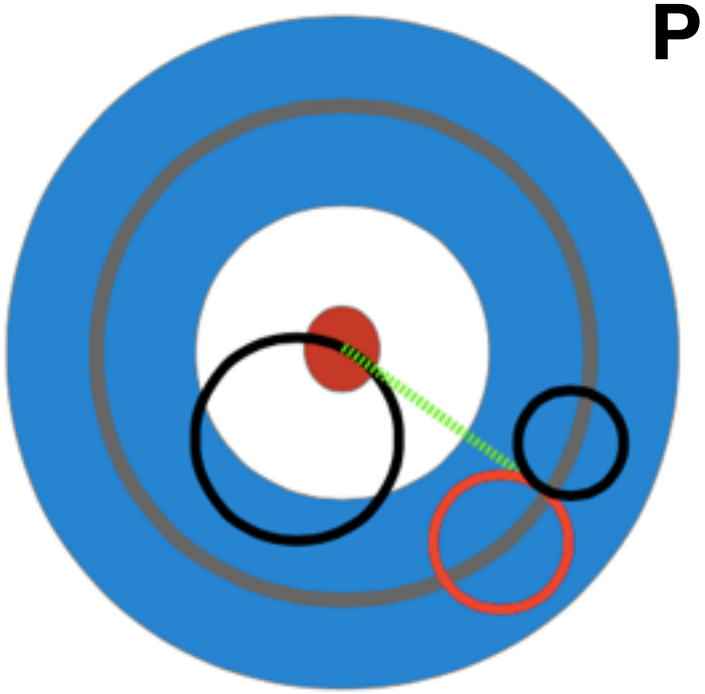
Calorimetry vs. Photon Conversion



Calorimetry

High efficiency
Good resolutions

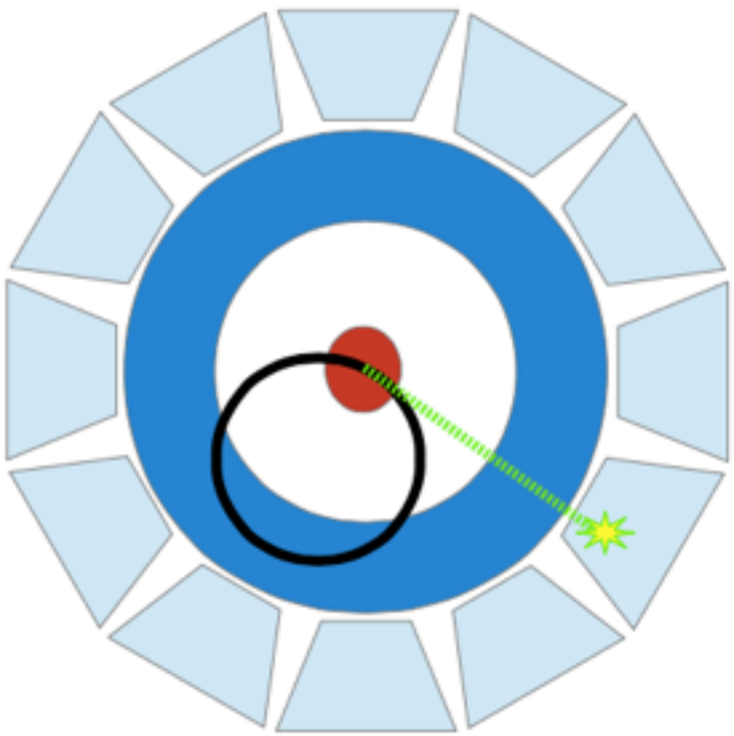
MEG:
LXe calorimeter
10% acceptance



Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

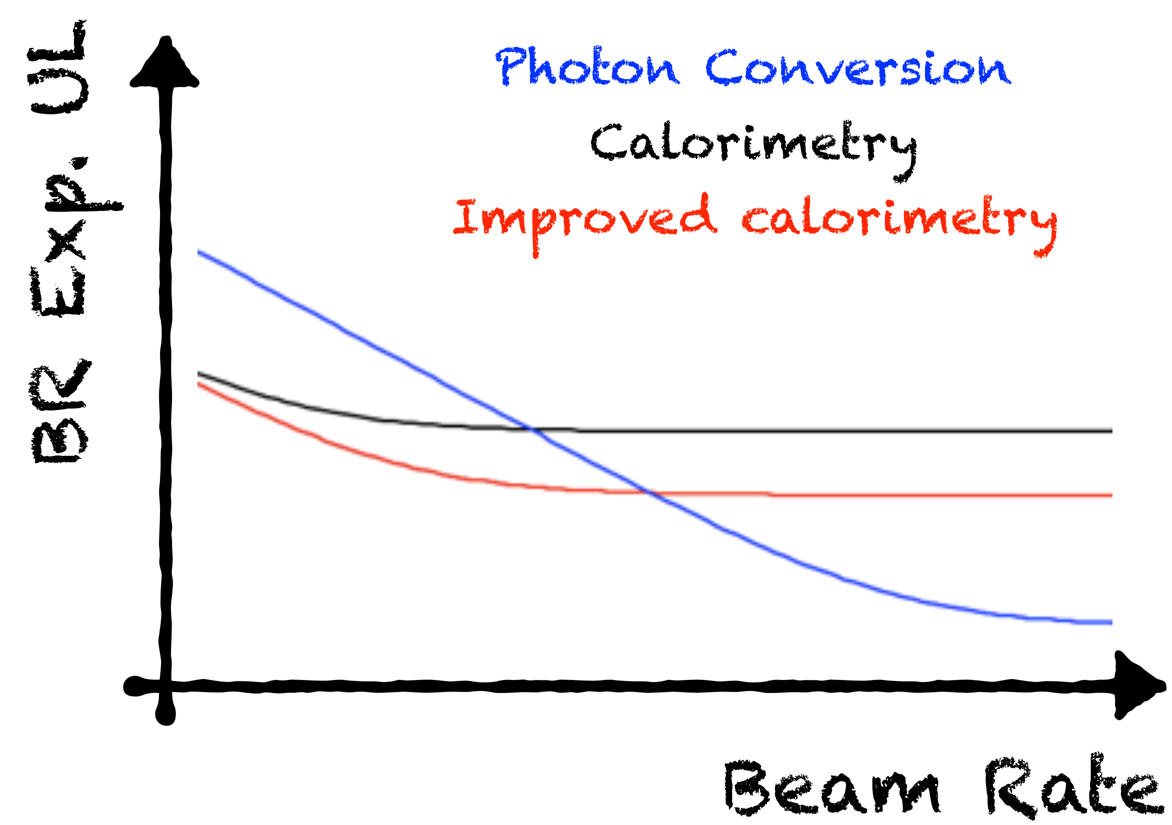
Calorimetry vs. Photon Conversion

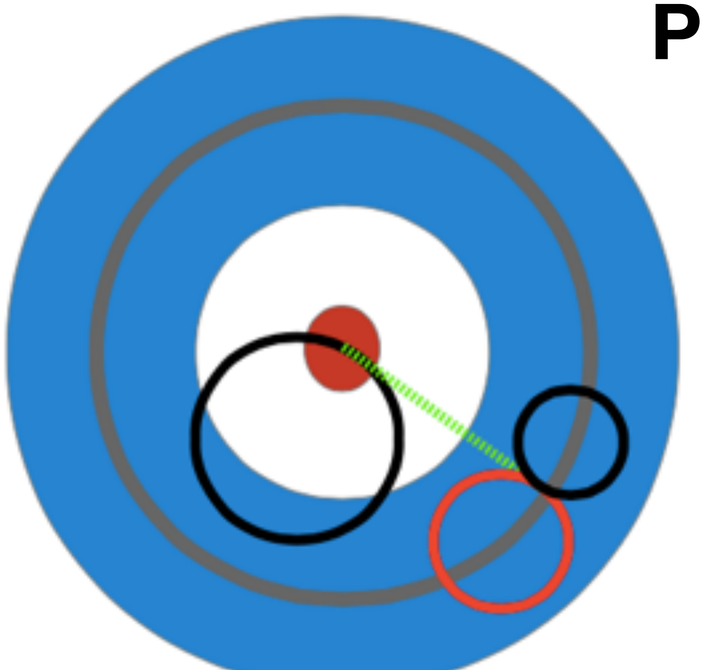


Calorimetry

High efficiency
Good resolutions

MEG:
LXe calorimeter
10% acceptance

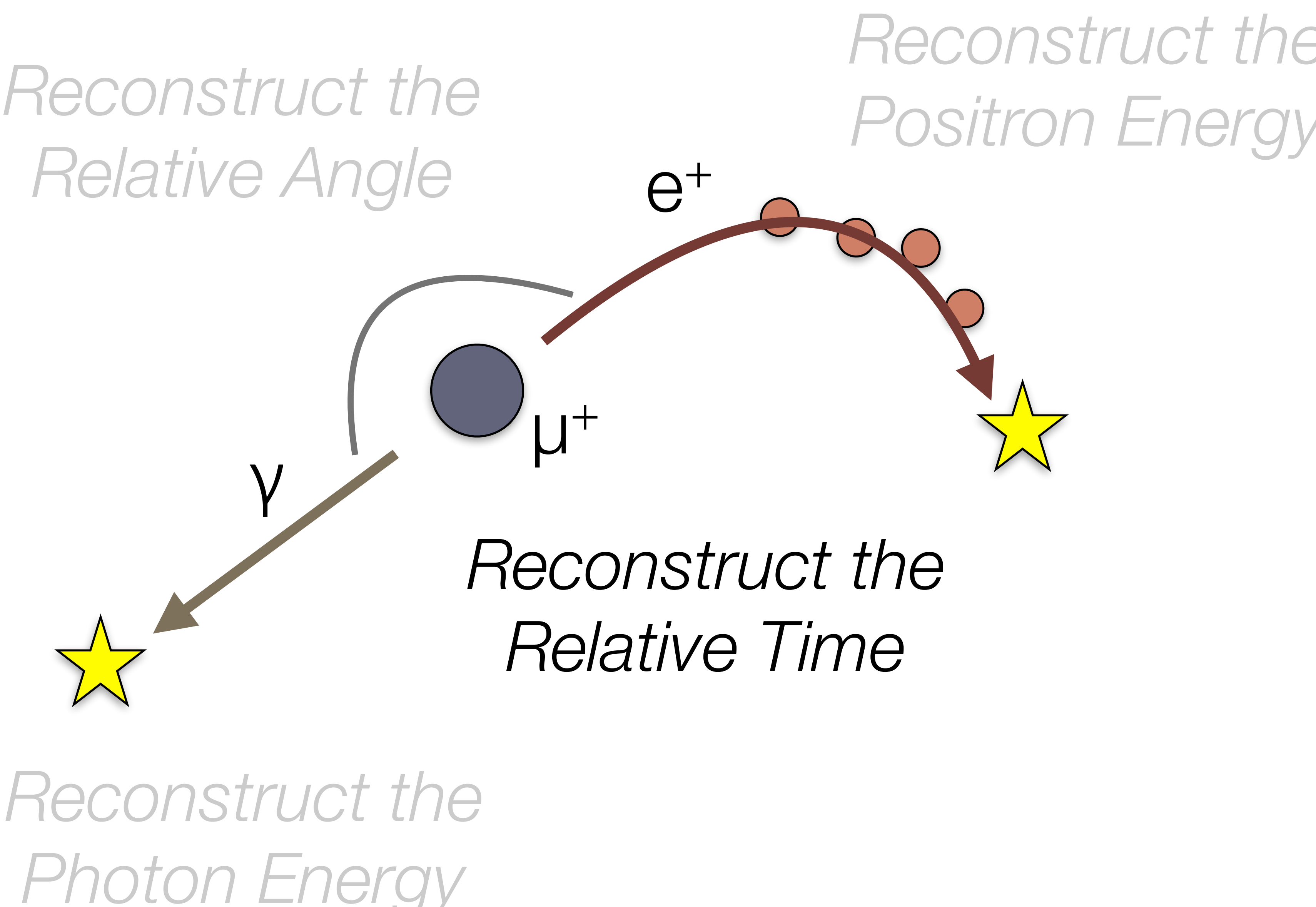




Photon Conversion

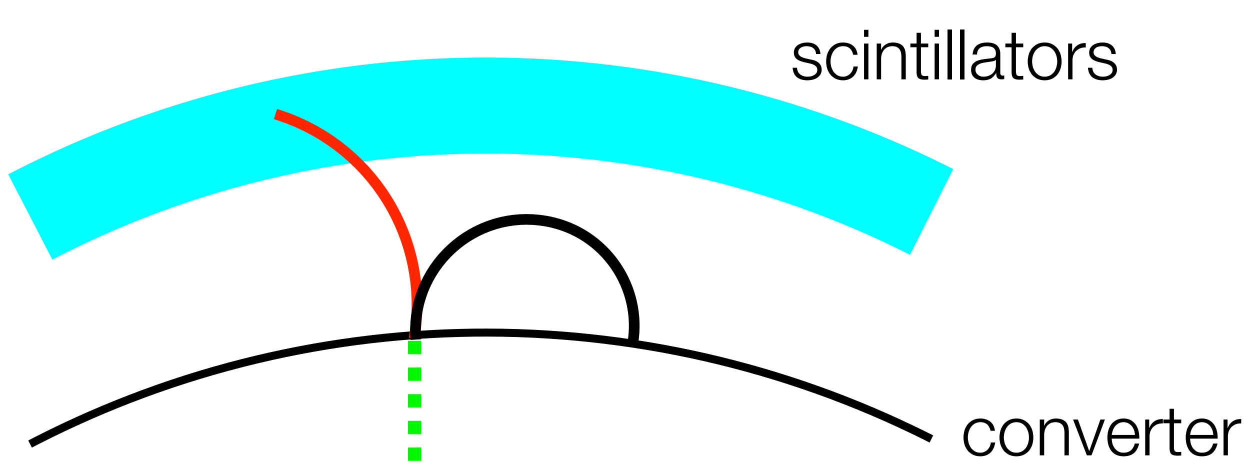
Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

Ingredients for a search of μ -> e γ



Photon and Positron timing

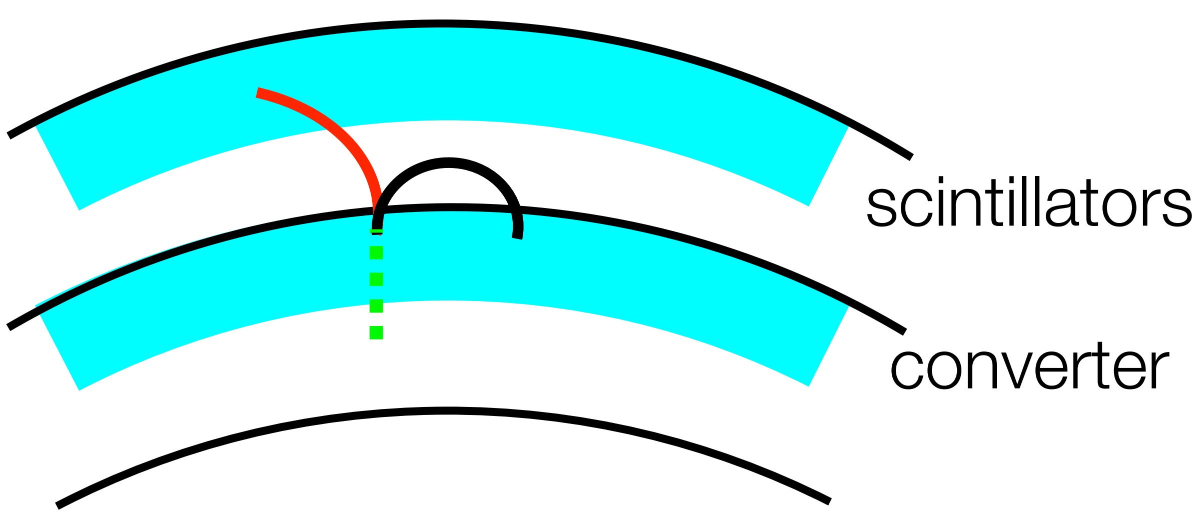
- Timing plays a crucial role in $\mu \to e\gamma$ searches (accidental coincidences!!!):
  - need a very good positron and photon timing
  - $\sigma(T_{e\gamma}) \sim 80$ ps in MEG-II
- $LiBr_3(Ce)$ calorimeters + positron scintillating counters like in MEG can give the required performances
- For photon conversion, need to detect e^+ or e^- in a **fast detector**



What about stacking multiple layers?

Photon and Positron timing

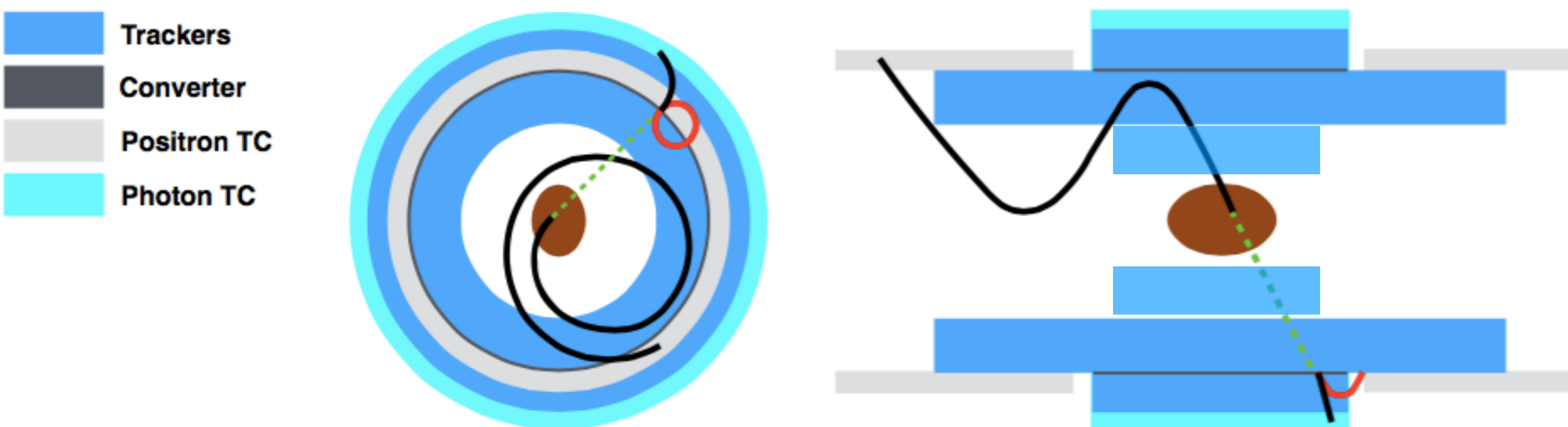
- Timing plays a crucial role in μ -> e γ searches (accidental coincidences!!!):
  - need a very good positron and photon timing
  - σ(Teγ) ~ 80 ps in MEG-II
- $LiBr_3(Ce)$ calorimeters + positron scintillating counters like in MEG can give the required performances
- For photon conversion, need to detect e^+ or e^- in a **fast detector**



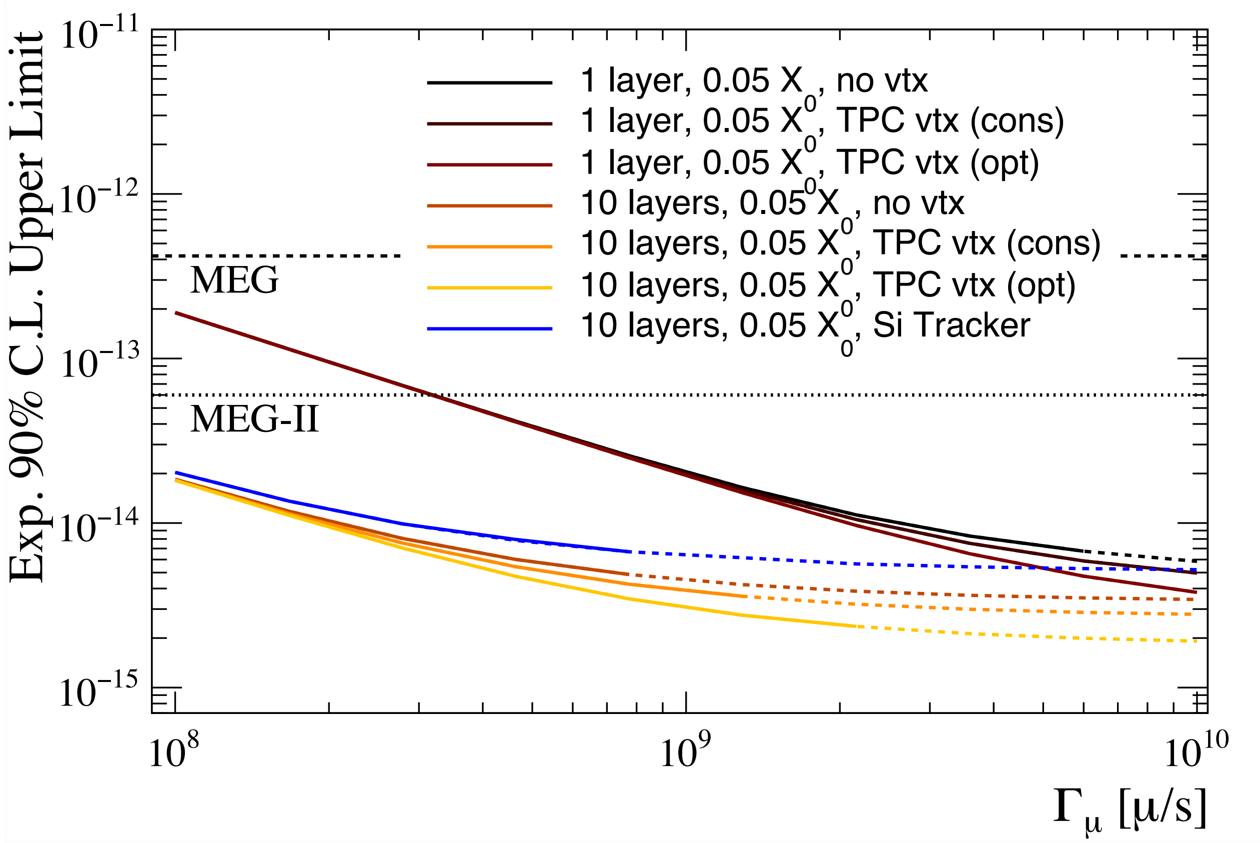
Effective converter material with lower Z

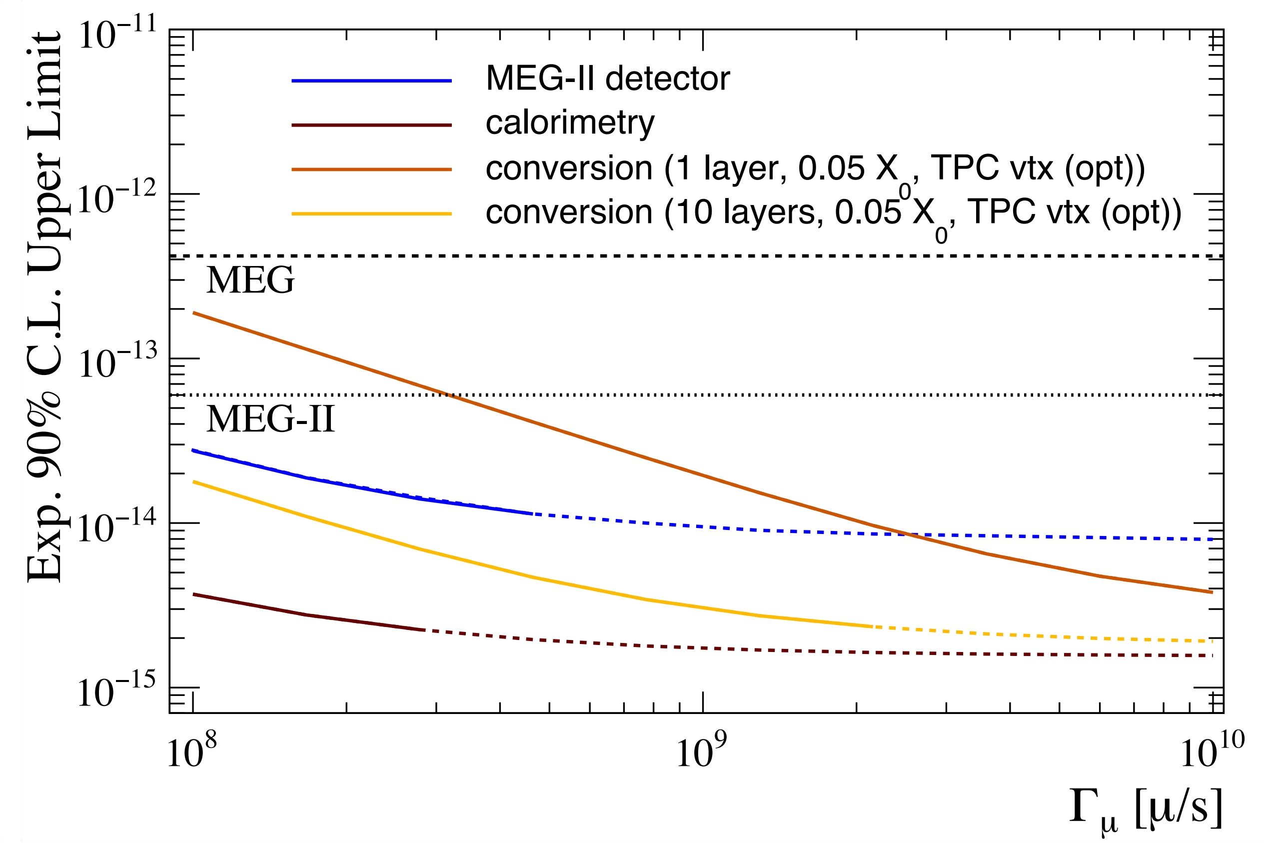
Worse compromise of efficiency vs. resolution

A conceptual design



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***

A beam for μ -> e γ and μ -> 3e at FNAL

Credit: R. Bernstein

Muon beam for muon LFV decays at FNAL

- PIP-II can provide a huge amount of muons - is it reasonable to think about a μ -> e γ / μ -> 3e program at FNAL?

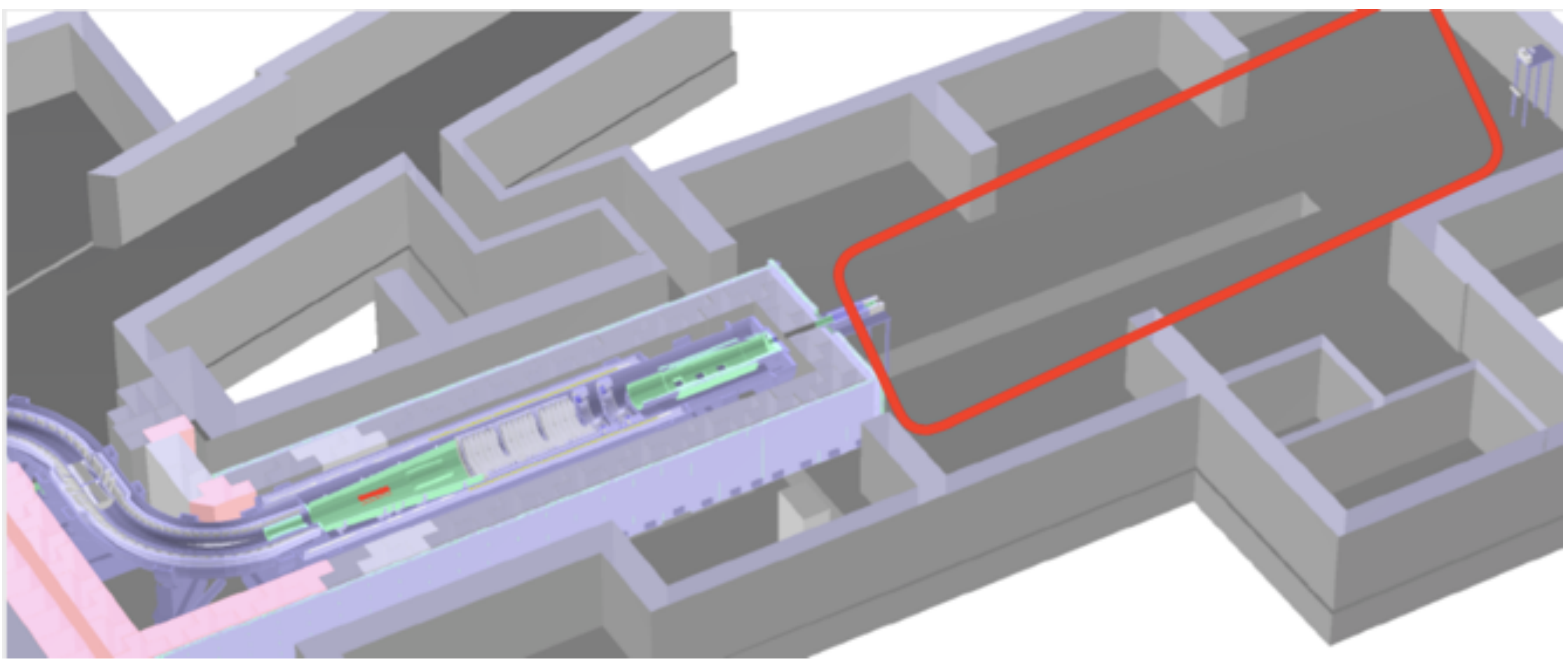
    1. Start from the Mu2e beam line

    2. make the beam **positive** (*easy*), **continuous** (*easy - propagation in the beam line spread the muon arrival times, muon lifetime makes the rest*), **low momentum** (*difficult*) and **monochromatic** (*very difficult*)

- Some ideas came out recently to get the necessary low-momentum, monochromatic beam (*time-varying deceleration*) — can get > 10^{10} μ/s

Muon beam for muon LFV decays at FNAL

- Alternate running of μ -> e conversion, μ -> e γ and μ -> 3e experiments would be possible in the same place, with great advantages in terms of community building and return on investment



- An application for a staff exchange project (aMUSE), including activities related to this opportunity, has been submitted to the European Community (ERC RISE program)

Backup

High Intensity Muon Beams

- High intensity muon beams are crucial in the search for cLFV
- A few projects to get muon beams 1 or 2 orders of magnitude more intense than now are under study around the world:
  - HiMB @ PSI
  - MuSIC @ RCNP (Osaka, Japan)
  - prospects for DC muon beams at PIP-II (Fermilab, USA) are under studies

The HiMB Project @ PSI

- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x100 the MEG-II beam)

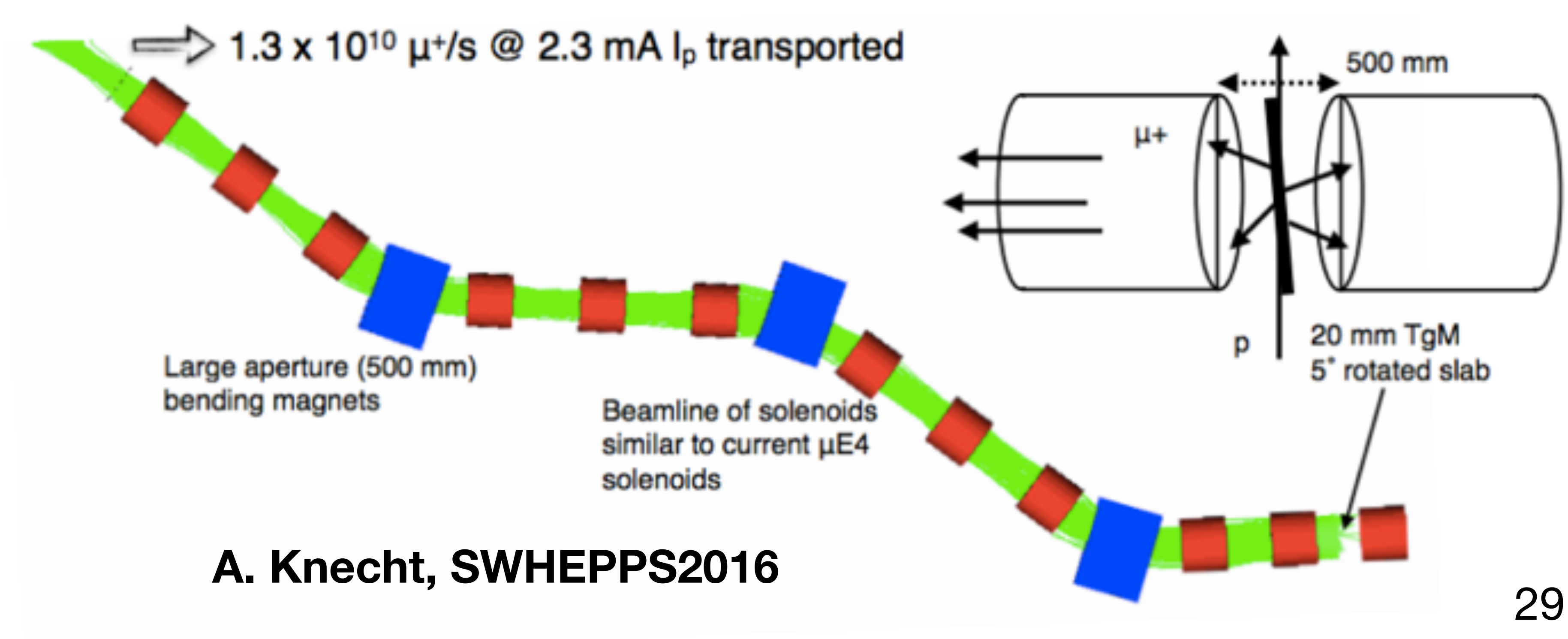
- Optimization of the beam optics:
  - improved muon capture efficiency at the production target
  - improved transport efficiency to the experimental area

x4 μ capture eff.

x6 μ transport eff.

1.3×10^{10} μ/s

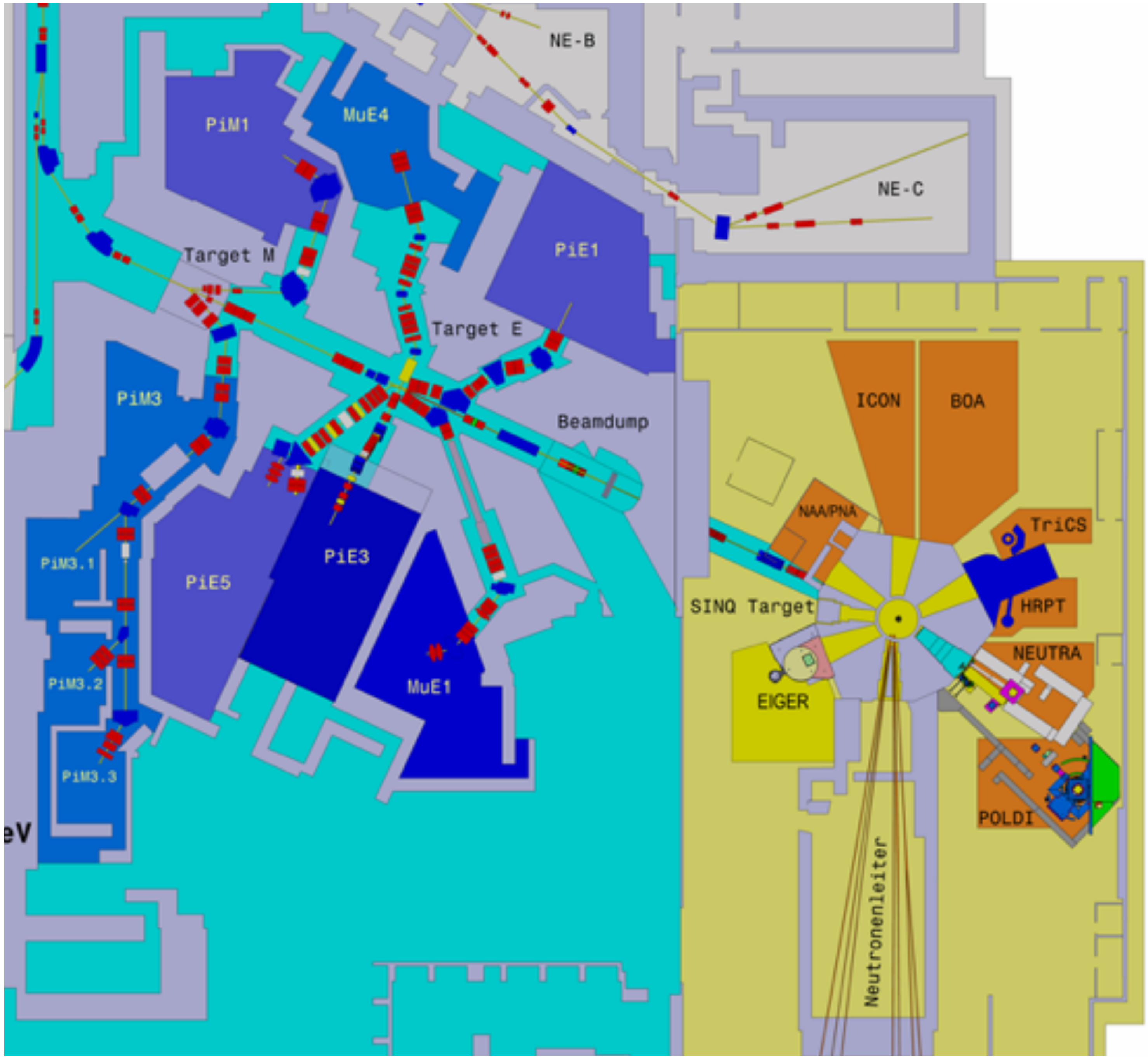
in the experimental area with 1400 kW beam power



A. Knecht, SWHEPPS2016

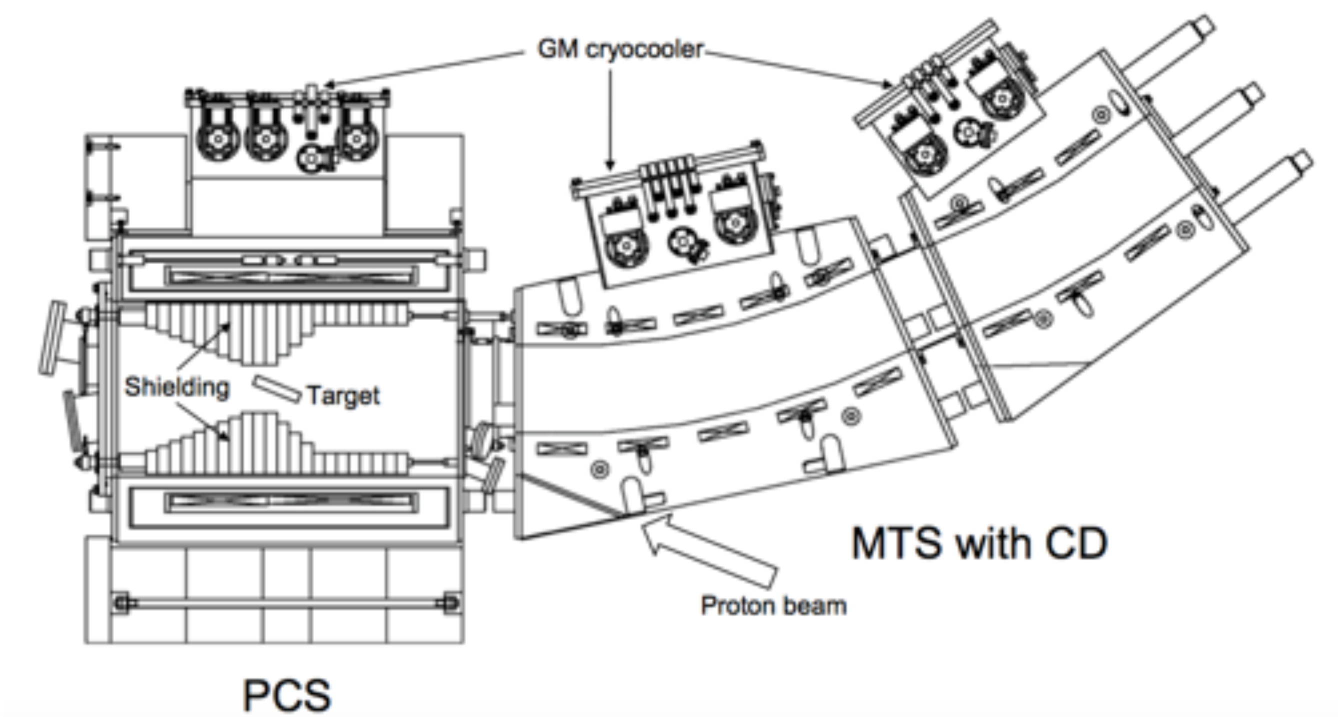
Production target

- The ring cyclotron at PSI also serves a **neutron spallation source** (SINQ) downstream of the π/μ production target
    - the proton beam need to be mostly preserved -> **thin production target**



The MuSIC Project @ RCNP

- At RCNP in Osaka (Japan) the goal is to fully exploit the proton beam power with a thick production target:
  - 10^6 μ per Watt of beam power (vs. 10^4 μ/W at HiMB)



Thick production target

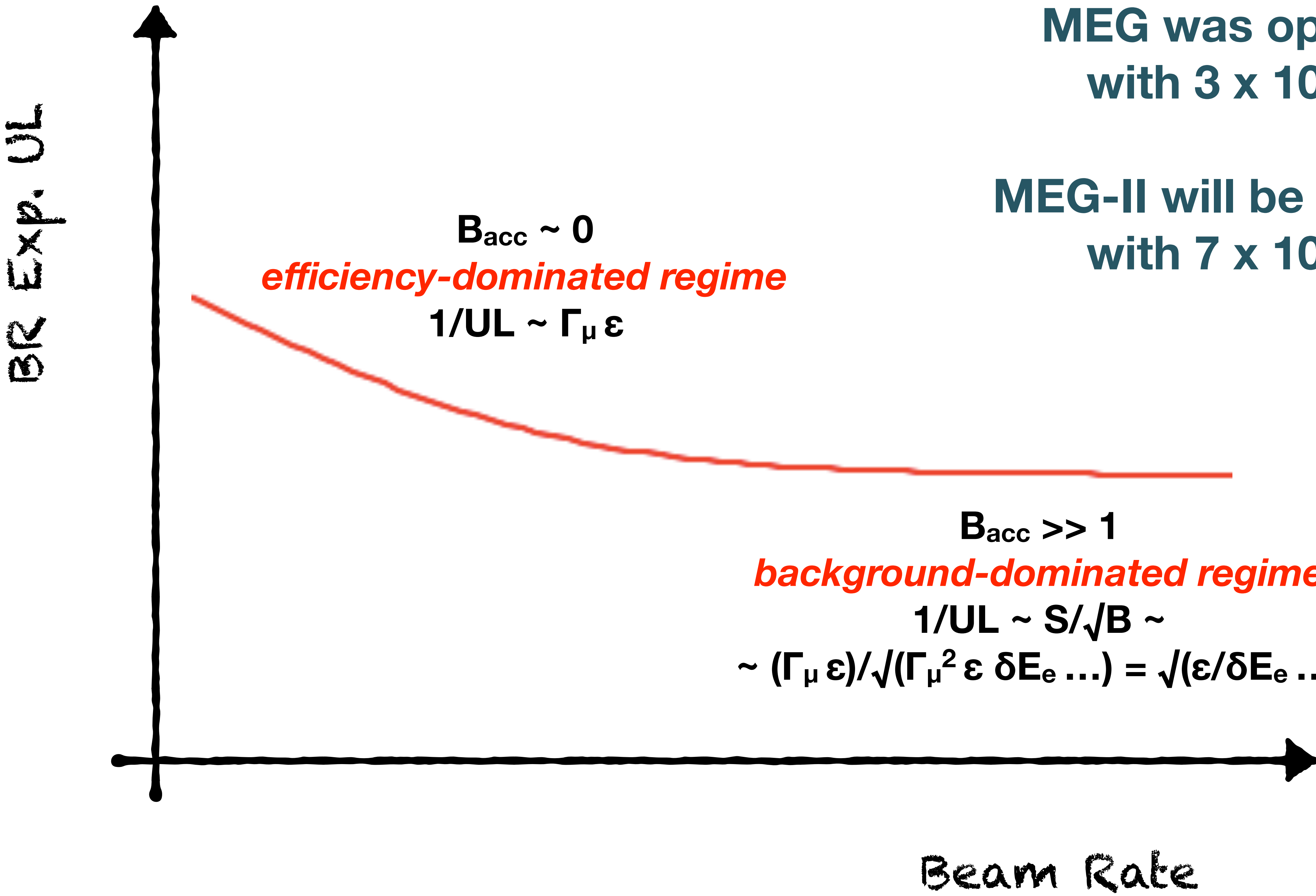
π capture solenoid

4 x 10^8 μ/s

at the production target with 400 W beam power

S. Cook *et al.*, Phys. Rev. Accel. Beams 20 (2017)

μ -> e γ searches



MEG was operated with 3 x 10^7 μ/s

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

γ Reconstruction: Limiting factors — Calorimetry

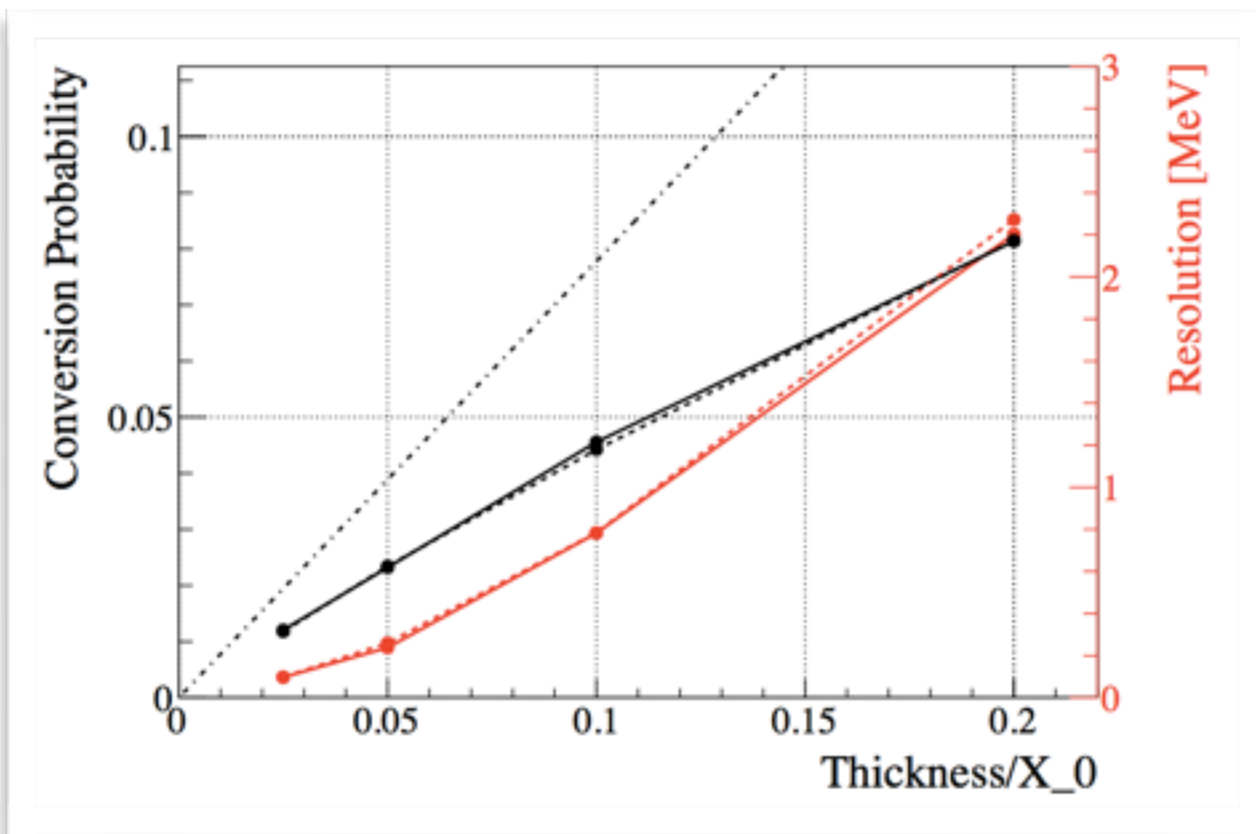
- Photon Statistics
- Scintillator time constant
- Detector segmentation

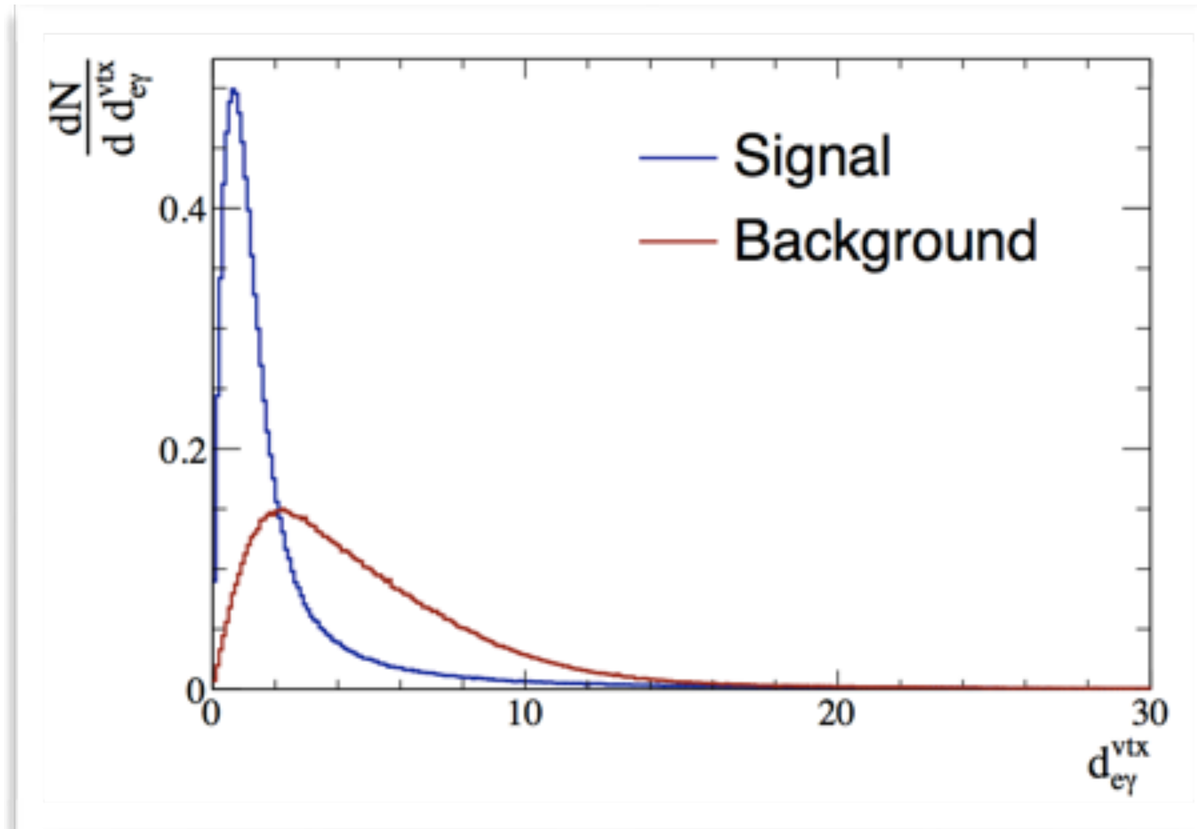
Scintillator	Density] [g/cm^3]	Light Yield [ph/keV]	Decay Time [ns]
$LaBr_3$(Ce)	5.08	63	16
LYSO	7.1	27	41
YAP	5.35	22	26
LXe	2.89	40	45
NaI(Tl)	3.67	38	250
BGO	7.13	9	300

- $LaBr_3$(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





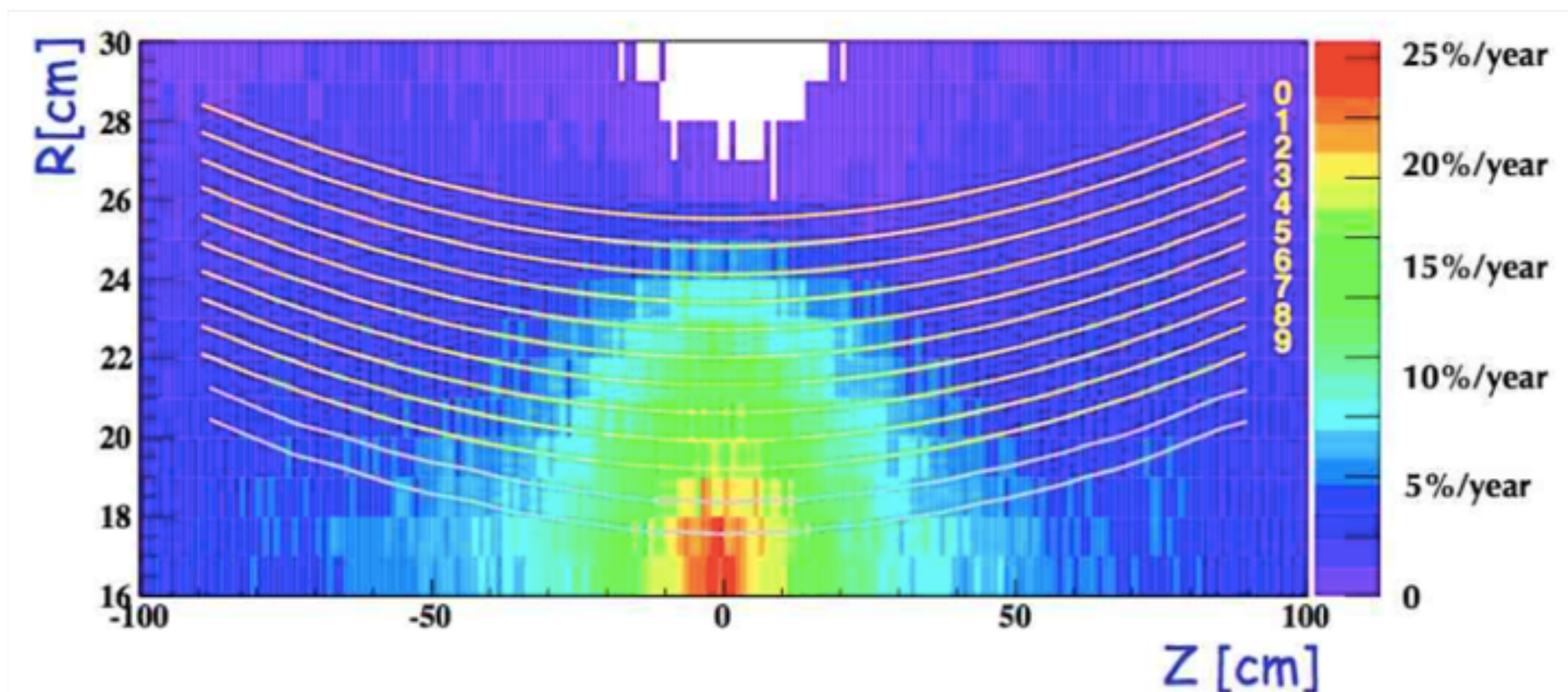
- Can take advantage of the photon direction determination form the e^+e^- reconstruction

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

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

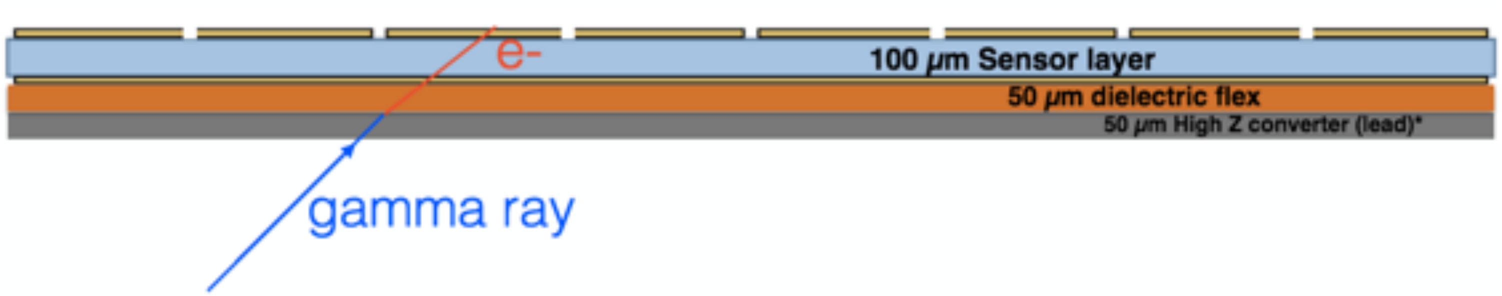
Would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?

An active conversion layer

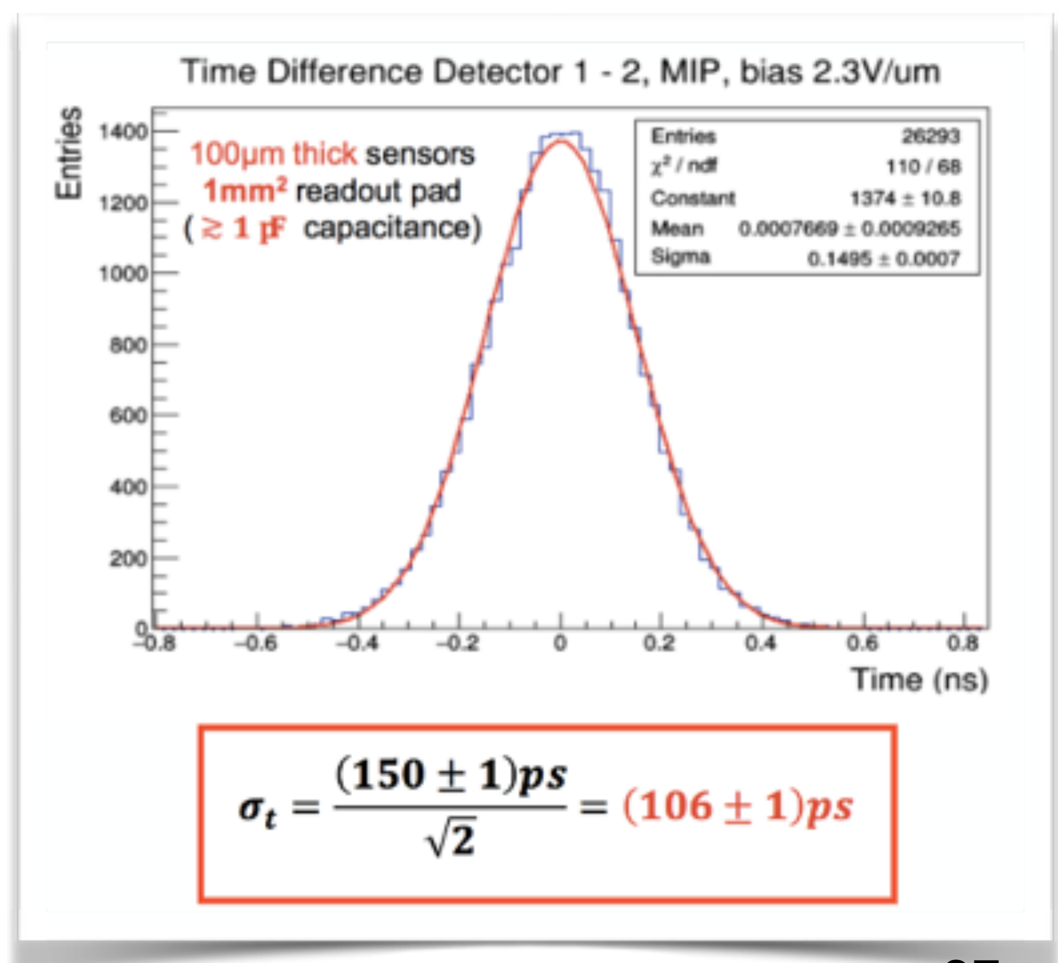
- Low Z active material for timing deteriorates the best efficiency/resolution configuration
  - the active layer must be as thin as possible
- Scintillators have poor “timing to thickness” figures (~ 1 ns for 250 μm fibers)

FAST SILICON DETECTORS

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



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



Possible Scenarios

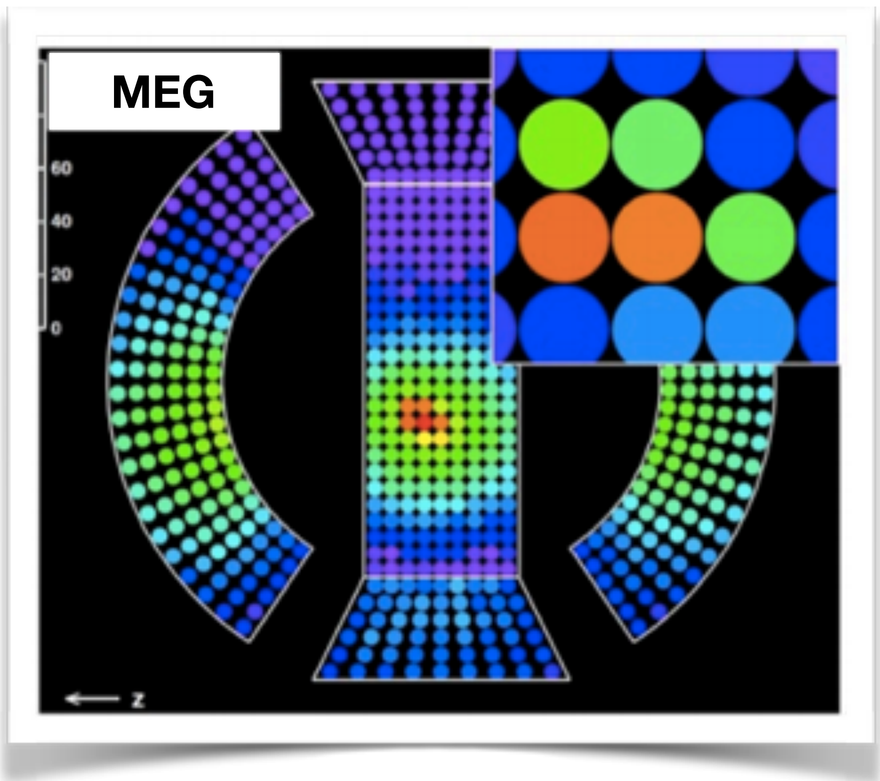
CALORIMETRY

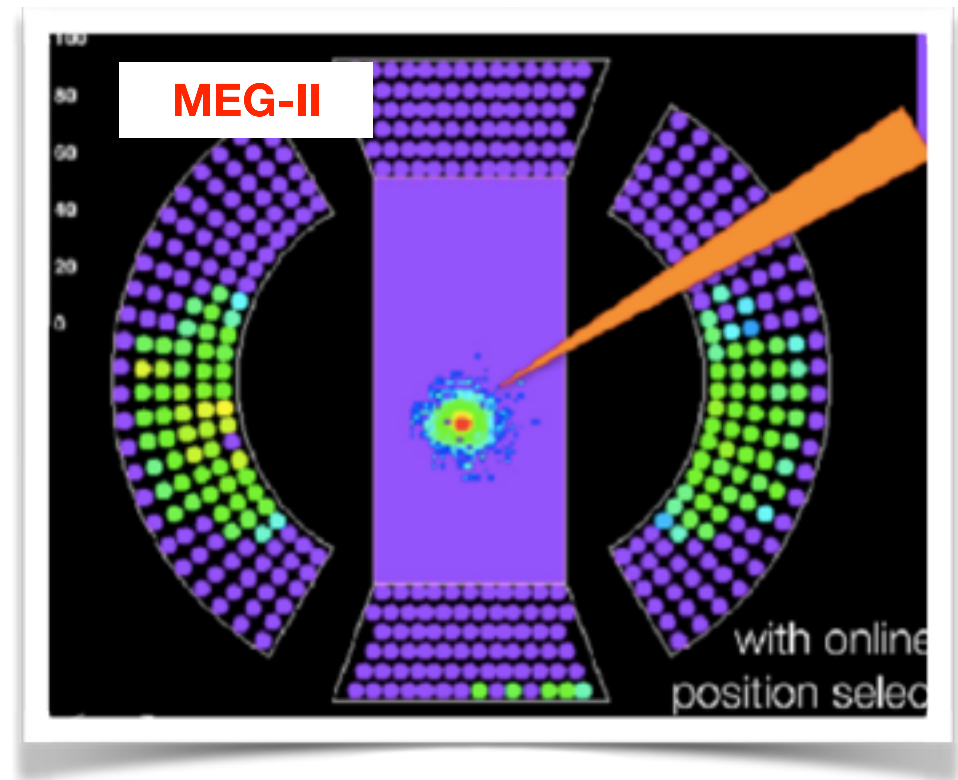
Variable	Resolution				
	w/o vtx detector	*w/ TPC vtx detector*		*w/ silicon vtx detector*	
		conservative	optimistic	conservative	optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			30		
E_e [keV]			100		
E_γ [keV]			850		
Efficiency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

PHOTON CONVERSION

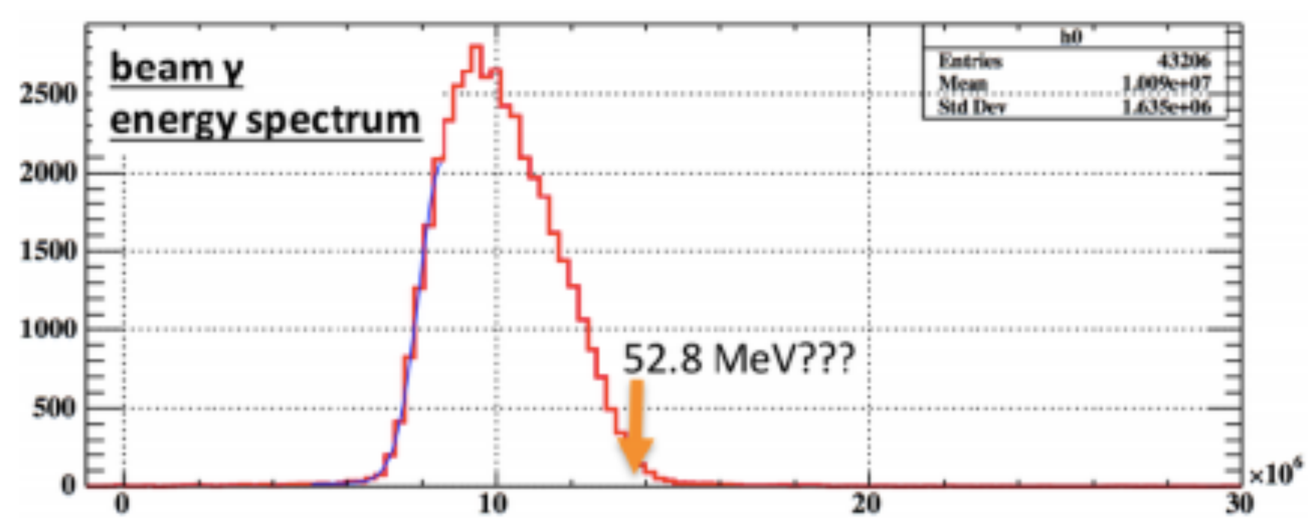
Variable	Resolution				
	w/o vtx detector	*w/ TPC vtx detector*		*w/ silicon vtx detector*	
		conservative	optimistic	conservative	optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			50		
E_e [keV]			100		
E_γ [keV]			320		
Efficiency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

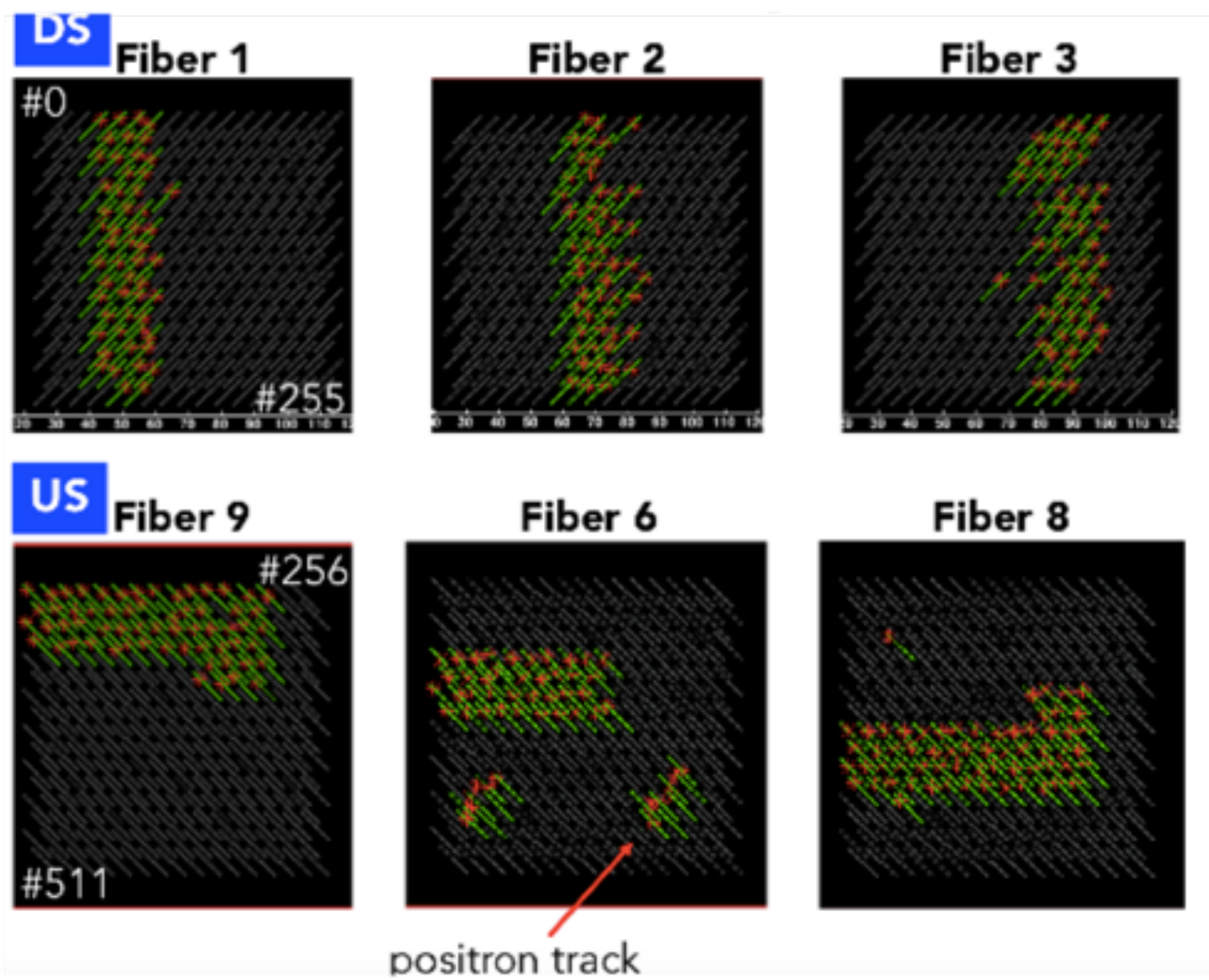
Better Resolution, better pile-up rejection

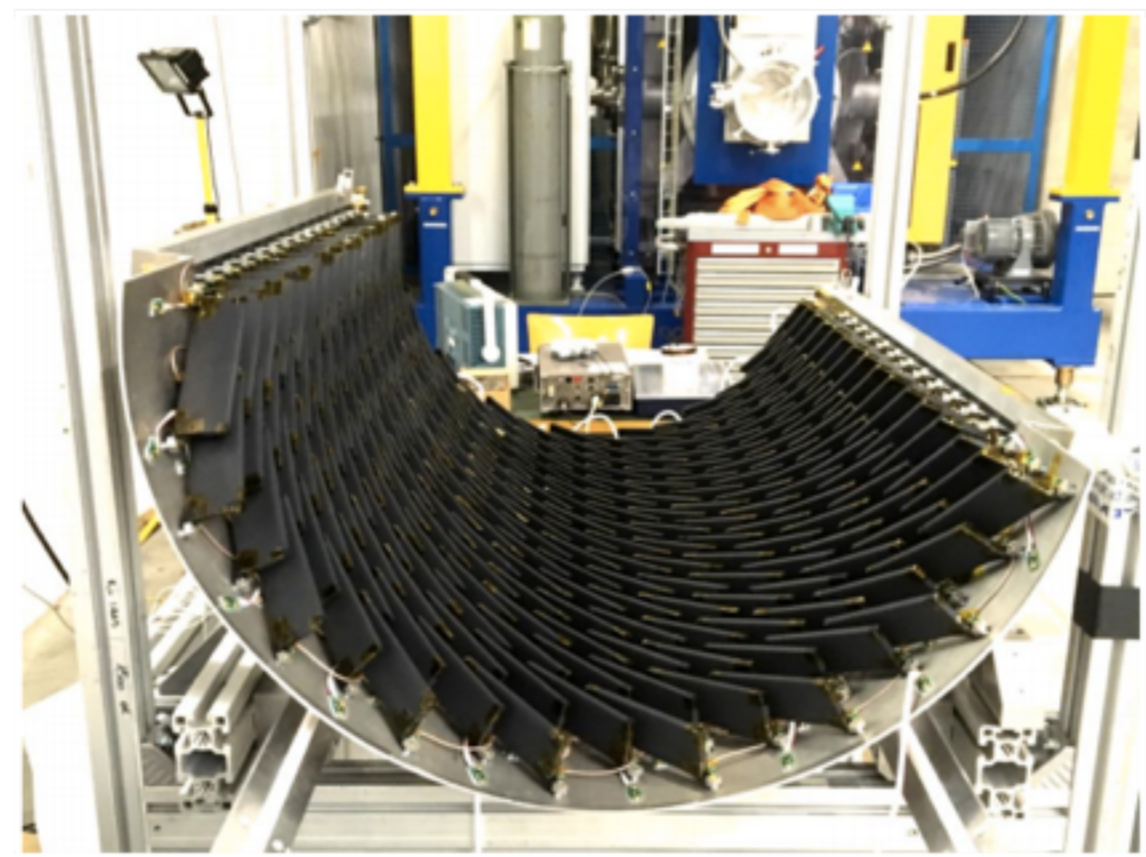
$\sigma_E \sim 1\%$, $\sigma_{position} \sim 2/5$ mm (x,y/z)

MEG-II Highlights - The Timing Counters

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

Complete detector took data in 2017



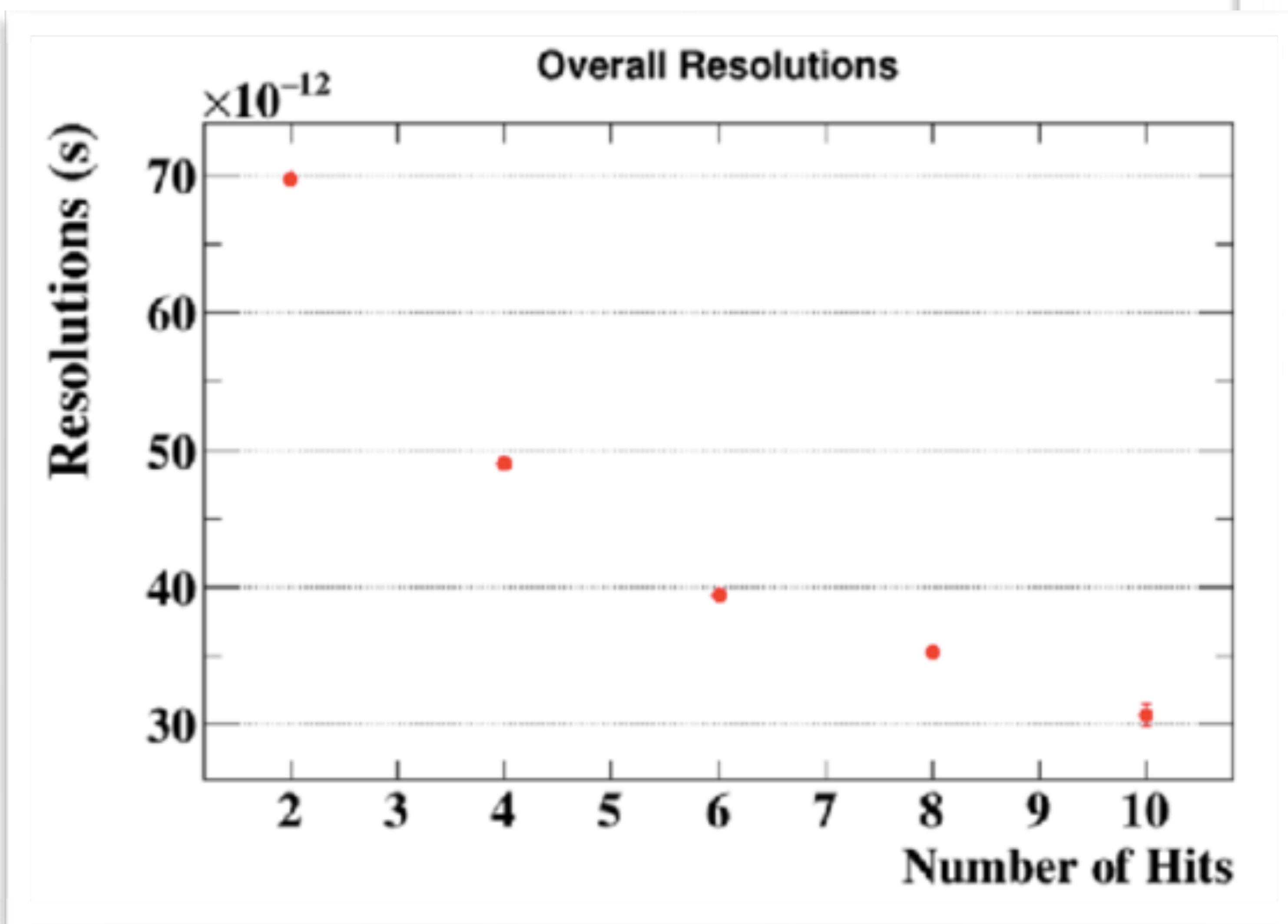


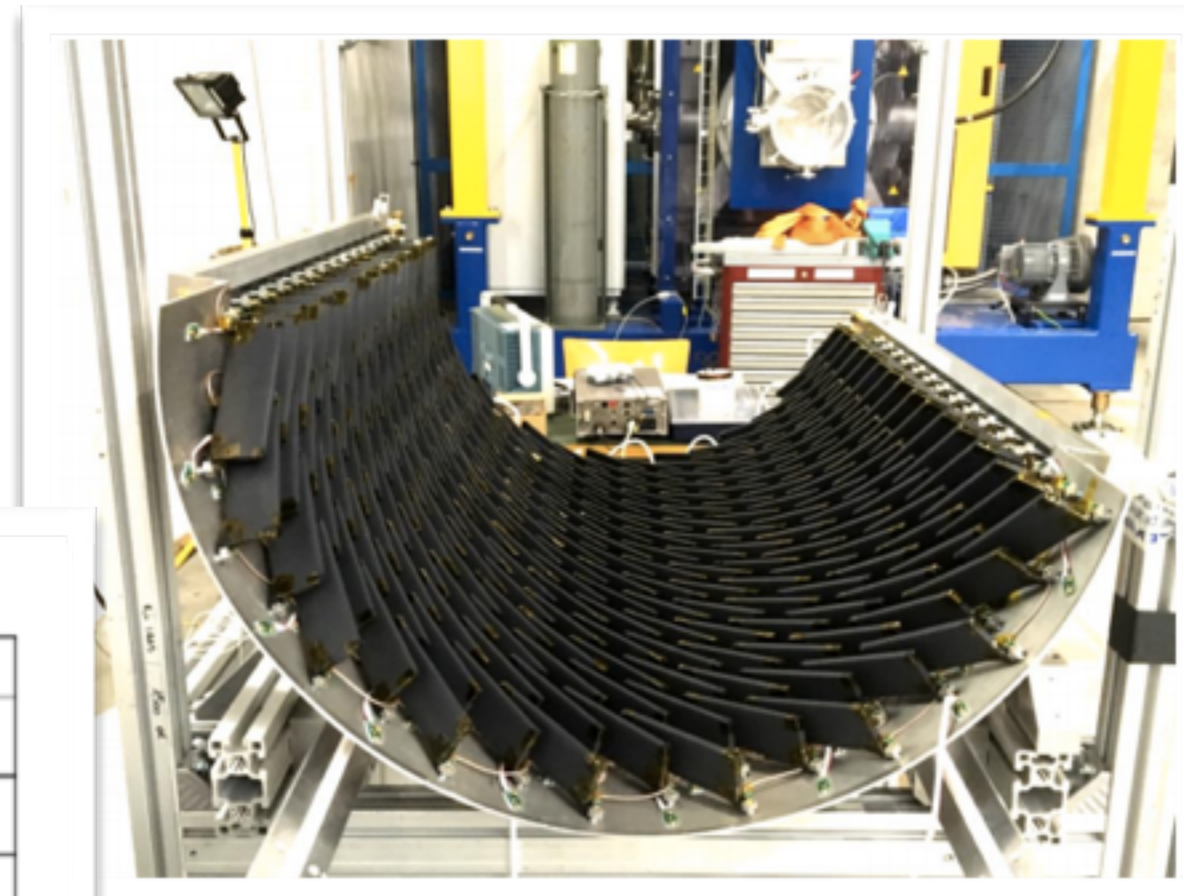
Calibration with dedicated laser

MEG-II Highlights - The Timing Counters

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

Complete detector took data in 2017

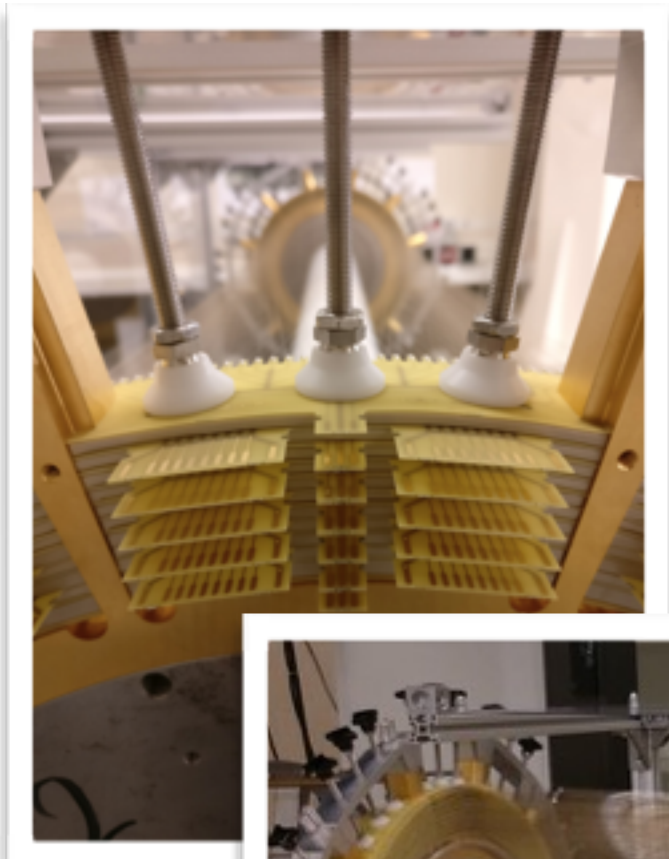




σ_T ~ 35 ps

Already reached the design resolution

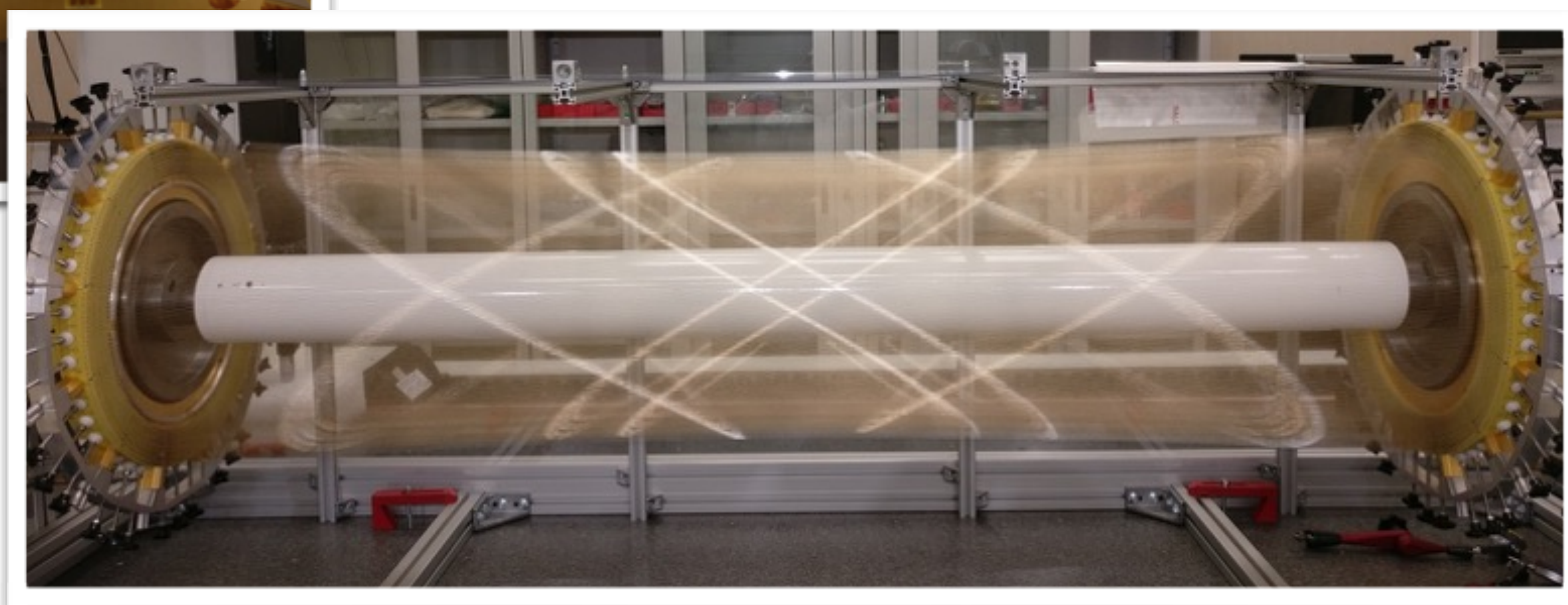
MEG-II Highlights - The Drift Chamber



Wiring, assembly and sealing have been completed

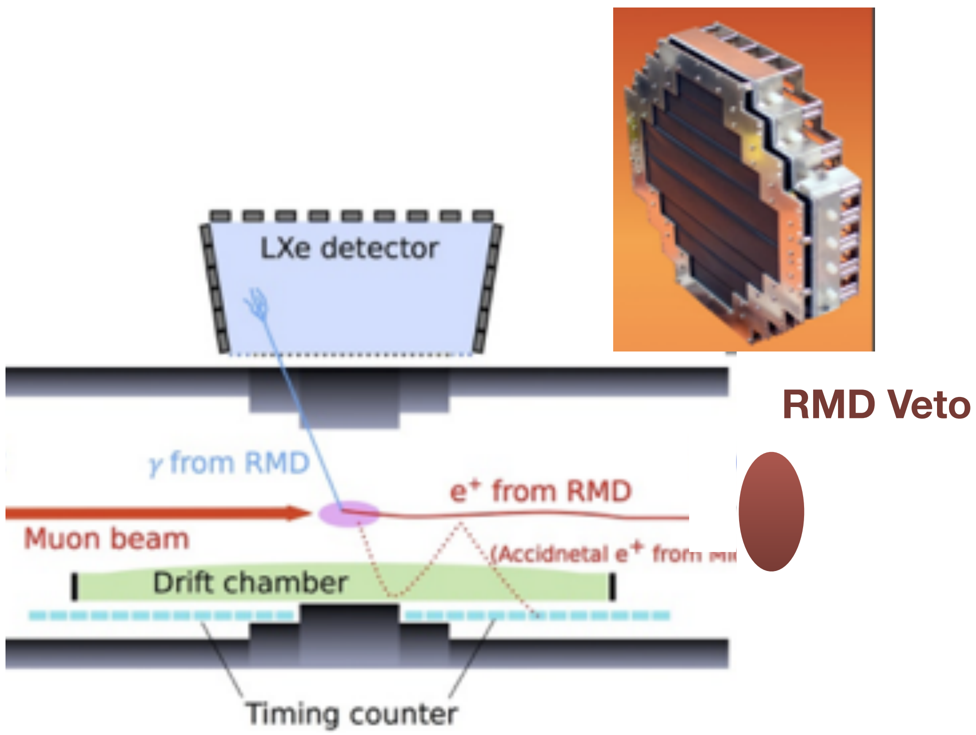
Had to face severe problems of wire fragility in presence of contaminants + humidity

On beam in Fall 2018



$\sigma_E \sim 130$ keV, $\sigma_{angles} \sim 5$ 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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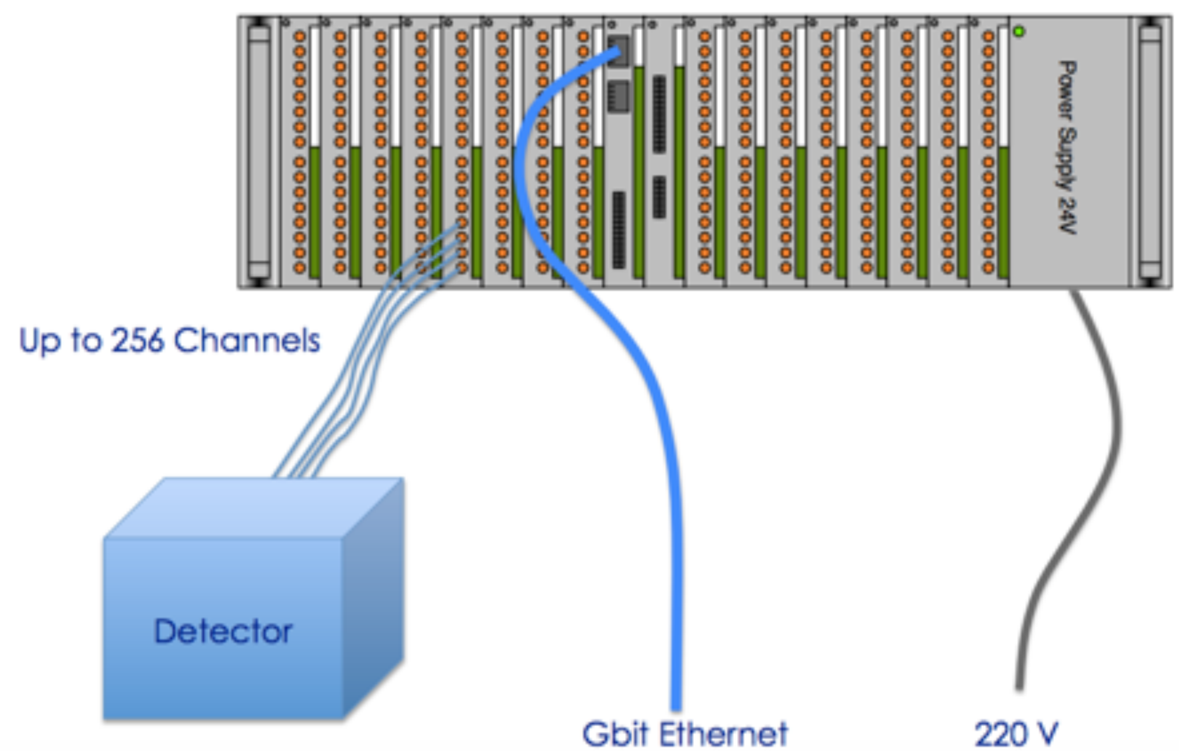
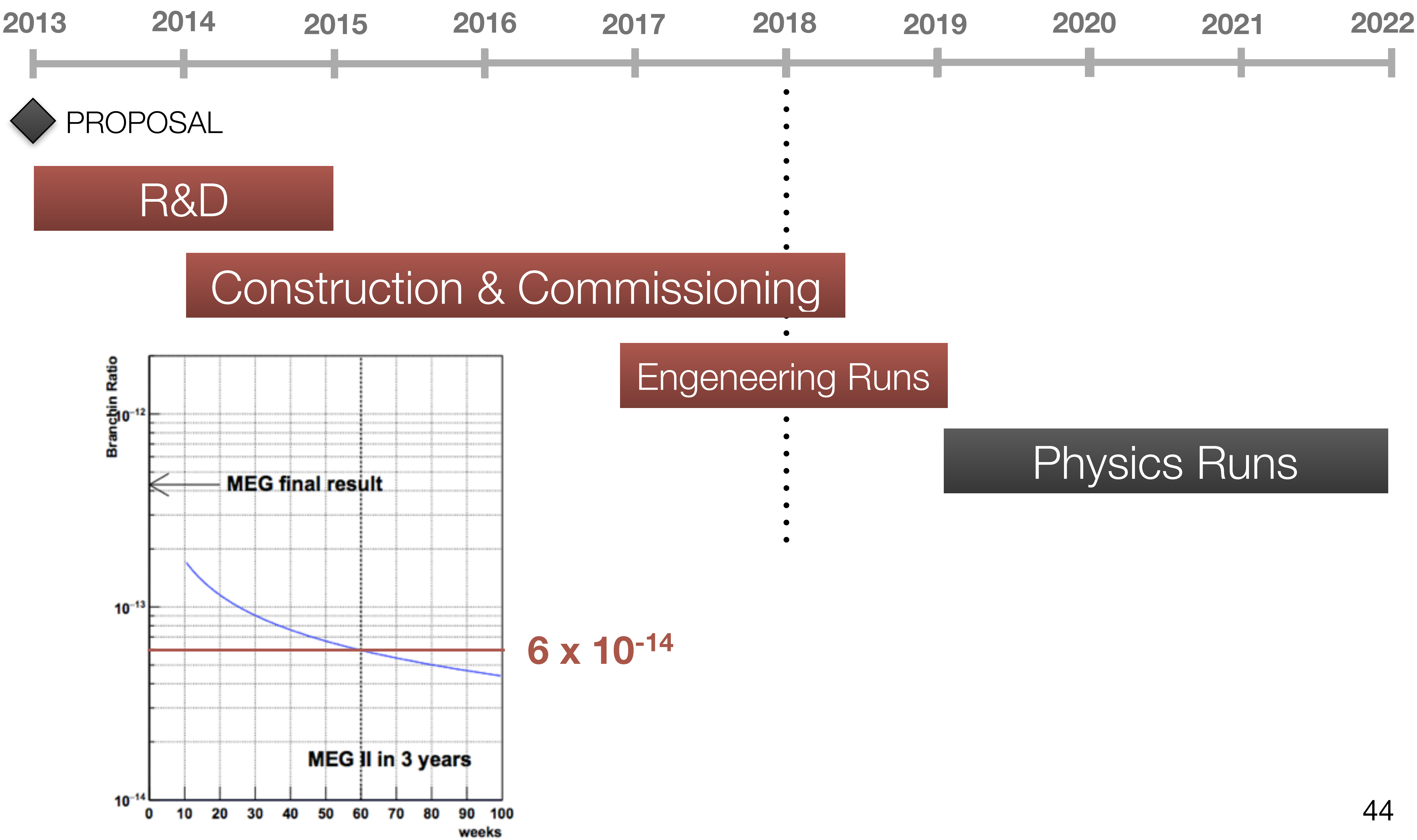
Trigger and DAQ will be integrated in a single, compact system (WaveDAQ)

Also provides power and amplification for SiPM/MPPC

Successfully tested in 2017 with XEC, TC and RDC



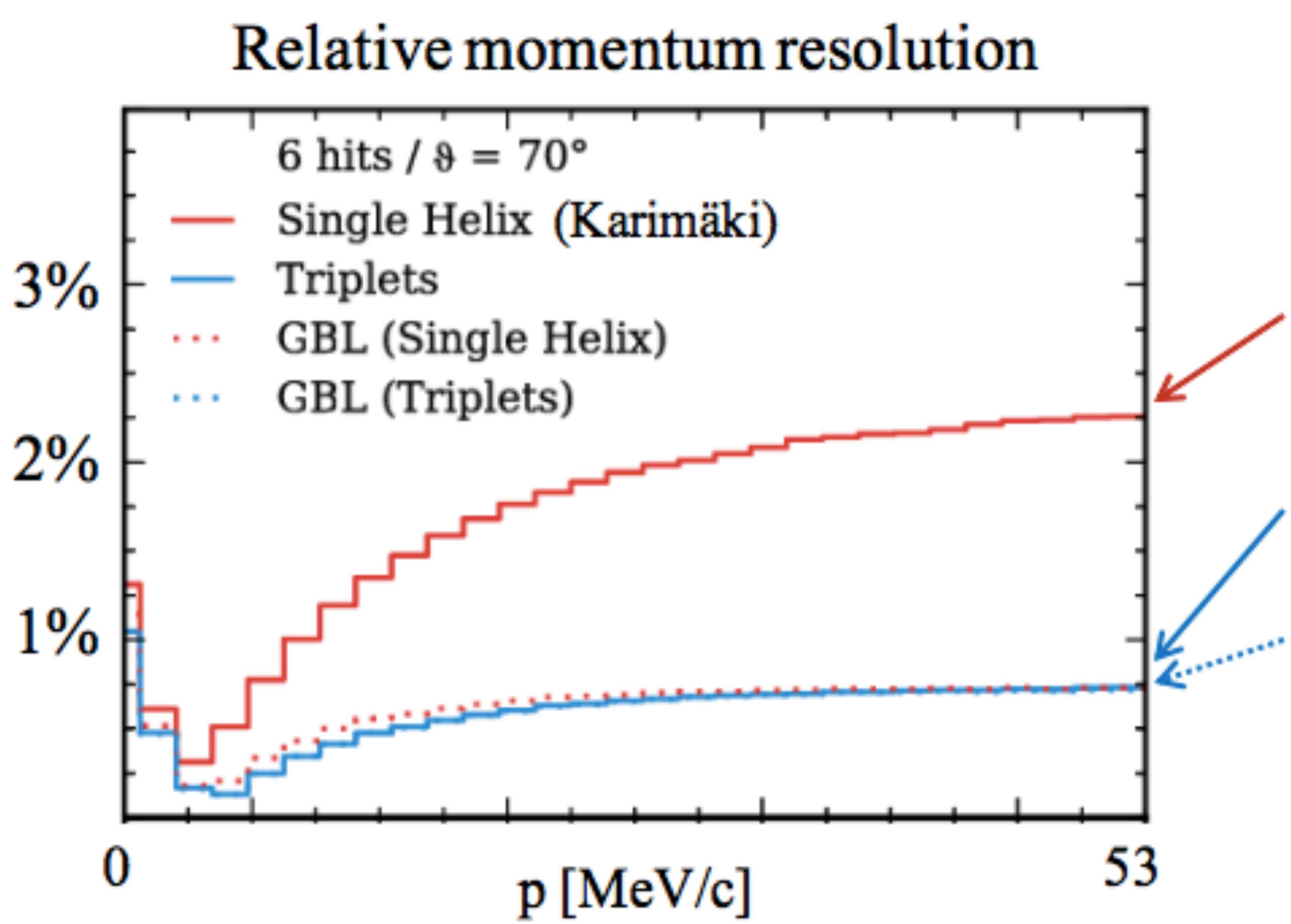
MEG-II schedule & sensitivity



Silicon detector momentum resolution

Mu3e momentum resolution (B = 1T)

4x worse than MEG-II



Single Helix (Karimäki)

- Neglect MS

Triplets

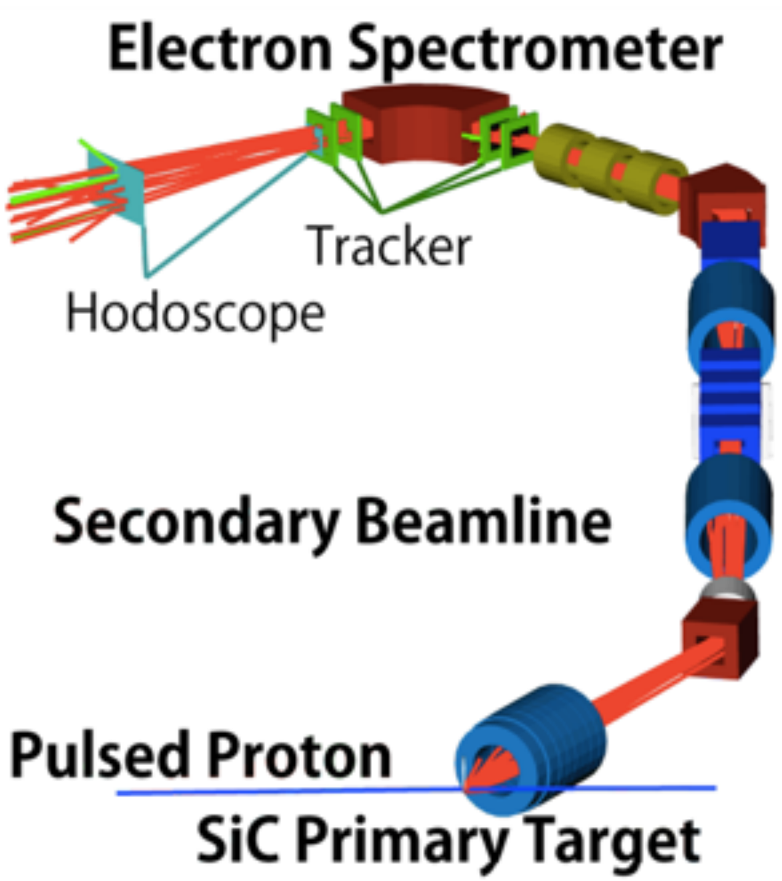
- MS fit

GBL (**G**eneral **B**roken **L**ines)

- Fast global track **refit** with full covariance matrix
- Equivalent to Kalman filter

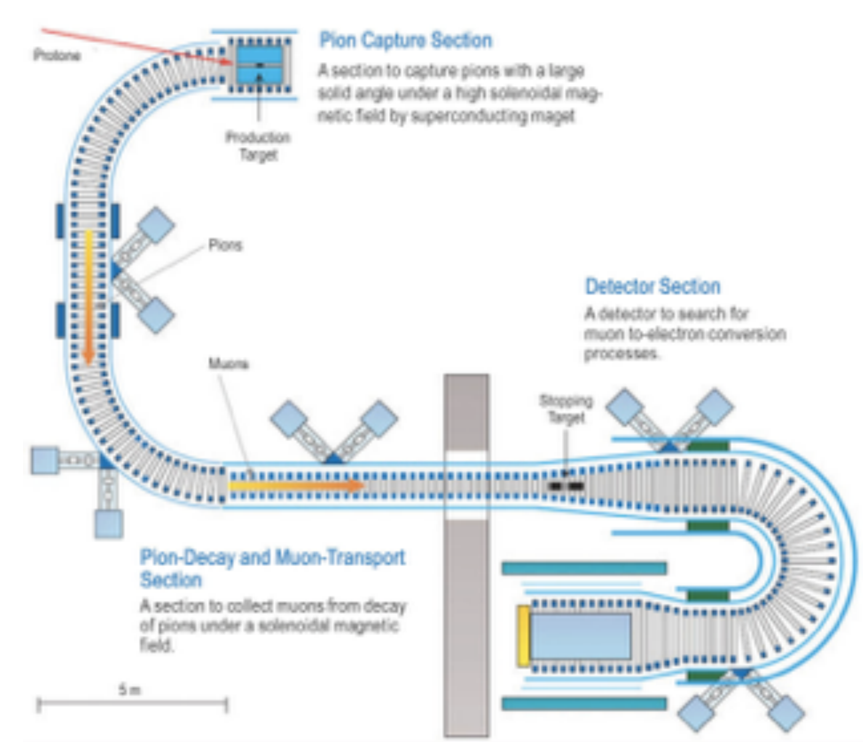
A. Kozlinskiy, Mu3e Collaboration, CTD/WIT 2017

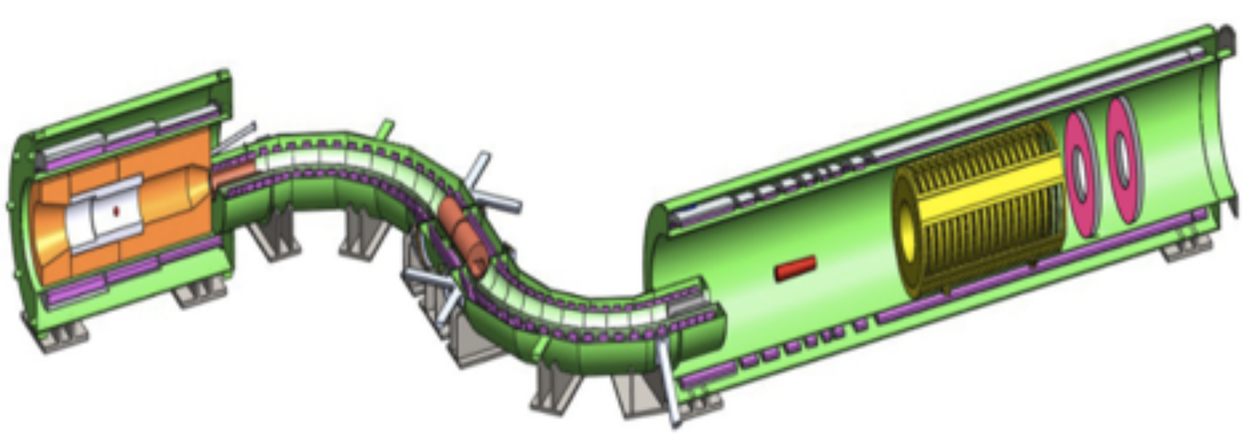
DeeMee / COMET / Mu2e



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

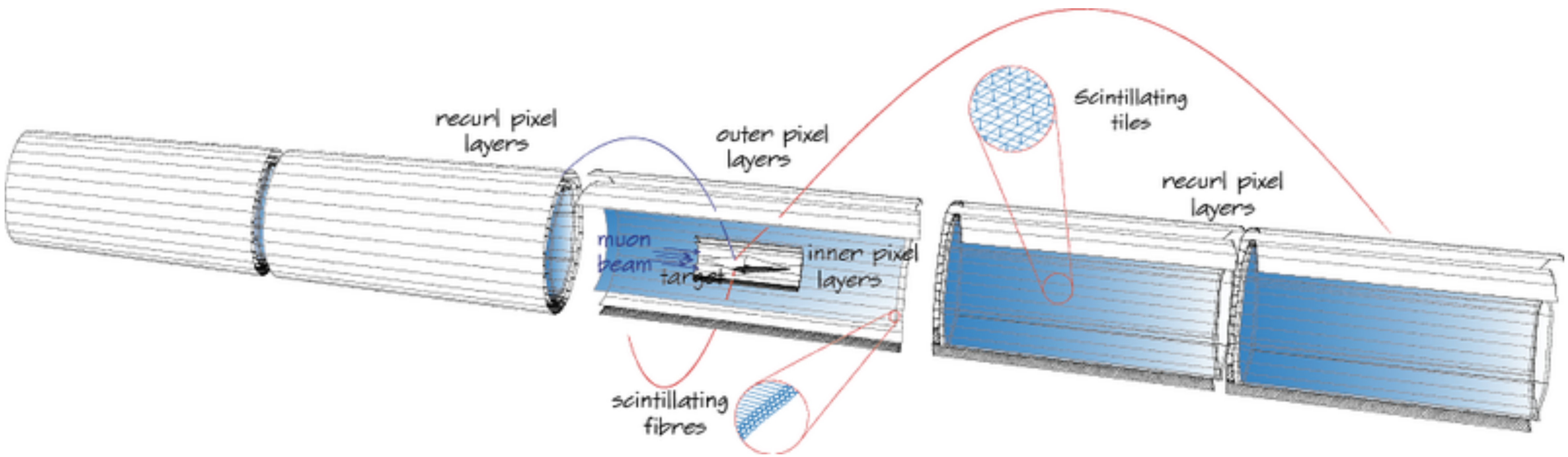
COMET: Will start phase-I commissioning ~ 2019
phase-II SES ~ 10^{-17}





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}