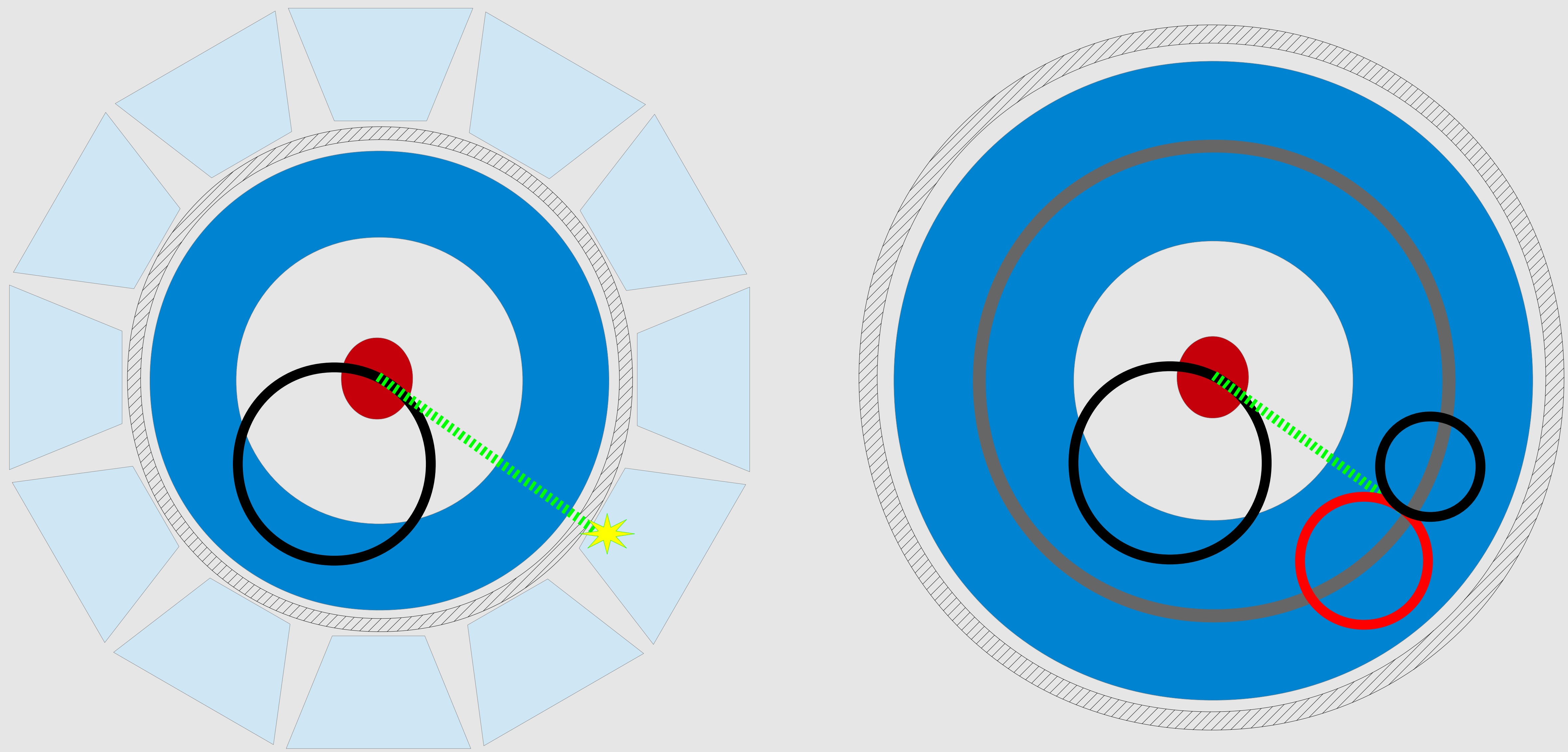


The Quest for μ -> e γ and its Experimental Limiting Factors at Future High Intensity Muon Beams

G. Cavoto, A. Papa, FR, E. Ripiccini and C. Voena
Eur. Phys. J. C (2018) 78: 37

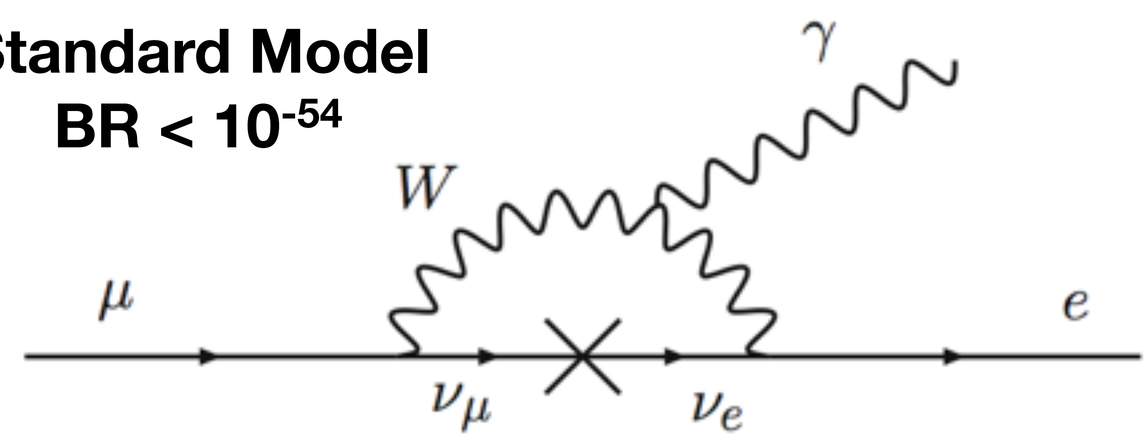
Francesco Renga
INFN Roma

Lepton Flavor Conservation in the Standard Model

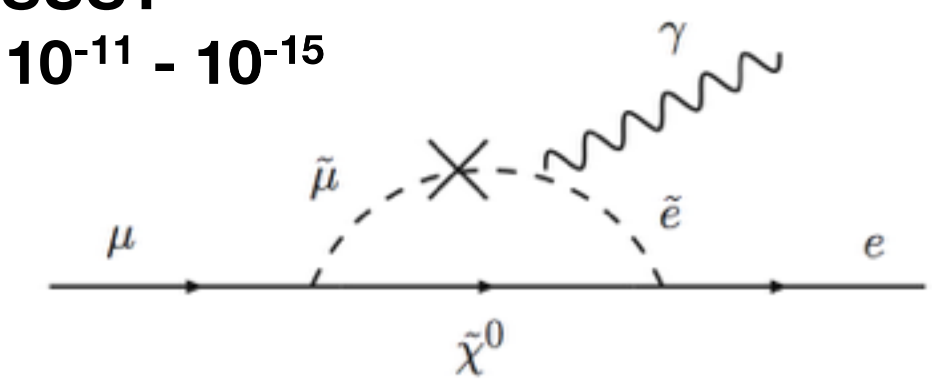
- Lepton Flavor conservation in the Standard Model (SM) is an *accidental symmetry*, arising from the particle content of the model

- Generally violated in most of New Physics (NP) models

Standard Model
BR < 10^{-54}



SUSY
BR ~ 10^{-11} - 10^{-15}

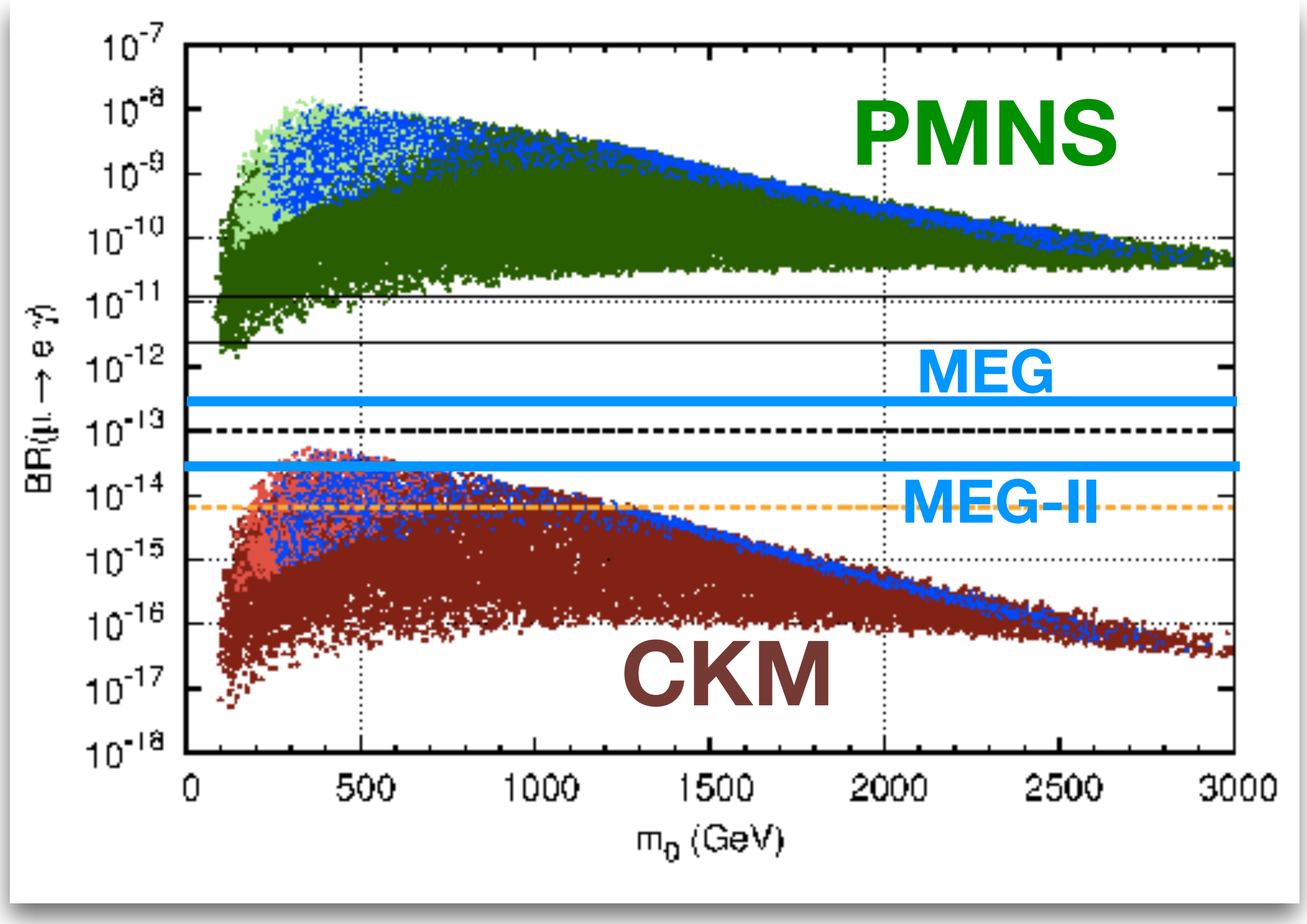


"Charged LFV (cLFV) is THE signature for New Physics"
— A. Schöning

cLFV and direct NP searches at the LHC

- cLFV rates strongly depend on the details of the flavor structure of new physics:
    - even within the same model, sLFV constraints can be much stronger or much weaker than LHC constraints
    - LHC searches still leave a lot of place for cLFV

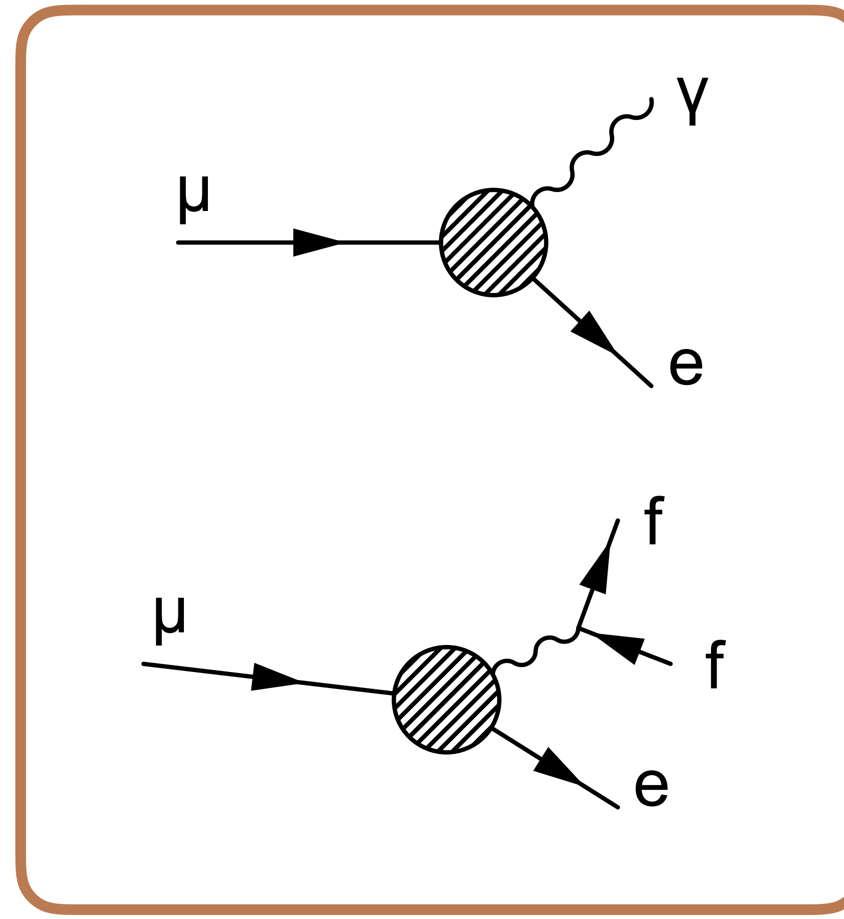
STRONG COMPLEMENTARITY

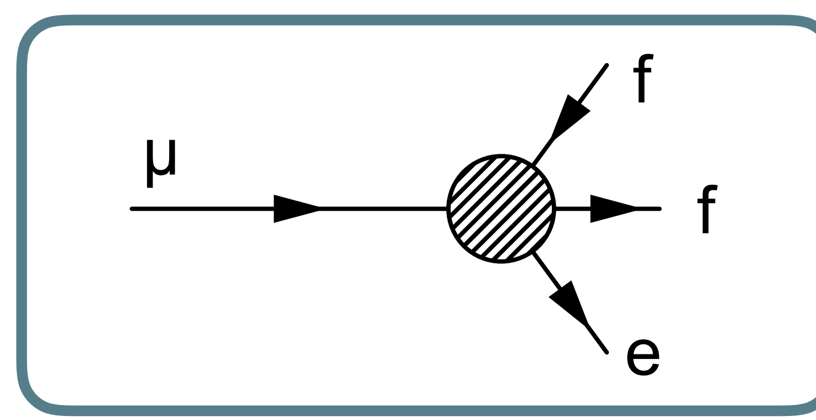


L. Calibbi et al., Eur. Phys. J. C72 (2012) 1863

cLFV searches in the muon sector - the naive view

- cLFV searched for in muon decays (**μ -> e γ**, **μ -> e e e**) and **μ -> e conversion** in nuclei
- Effective Field Theory (EFT) approach (tree level):
  - **μ -> e γ** sensitive to dipole operator
  - **μ -> e e e** and **μ N -> e N** sensitive to both dipole and 4-fermion operators

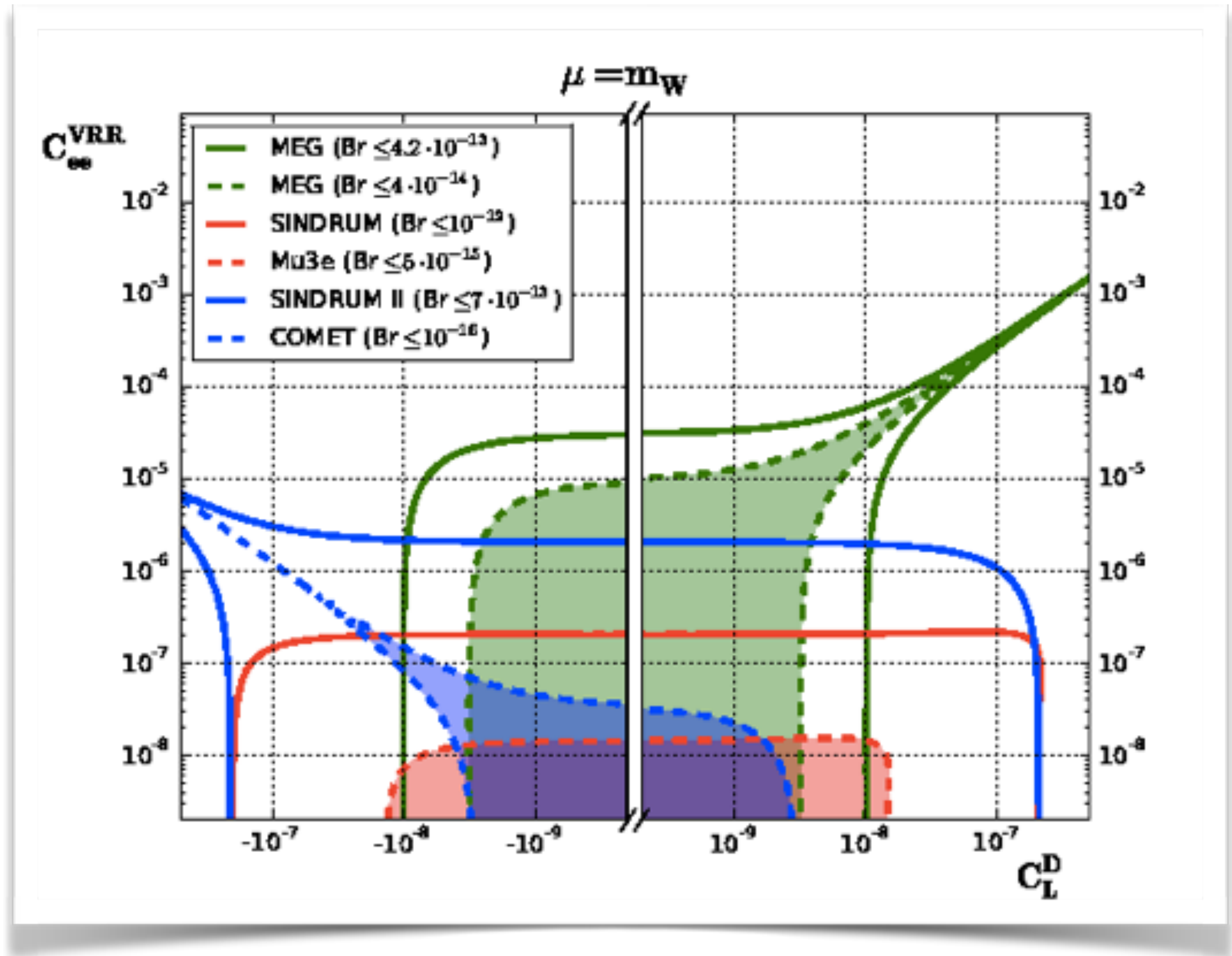




Naive conclusion: the upcoming μ -> e conversion experiments will overcome the muon decay experiments

cLFV searches in the muon sector - the full view

- Operators mix at the loop level:
  - **μ -> e γ** also sensitive to 4-fermion operators
  - **μ -> e γ** gives the strongest bound to dipole operators in some scenarios



STRONG COMPLEMENTARITY

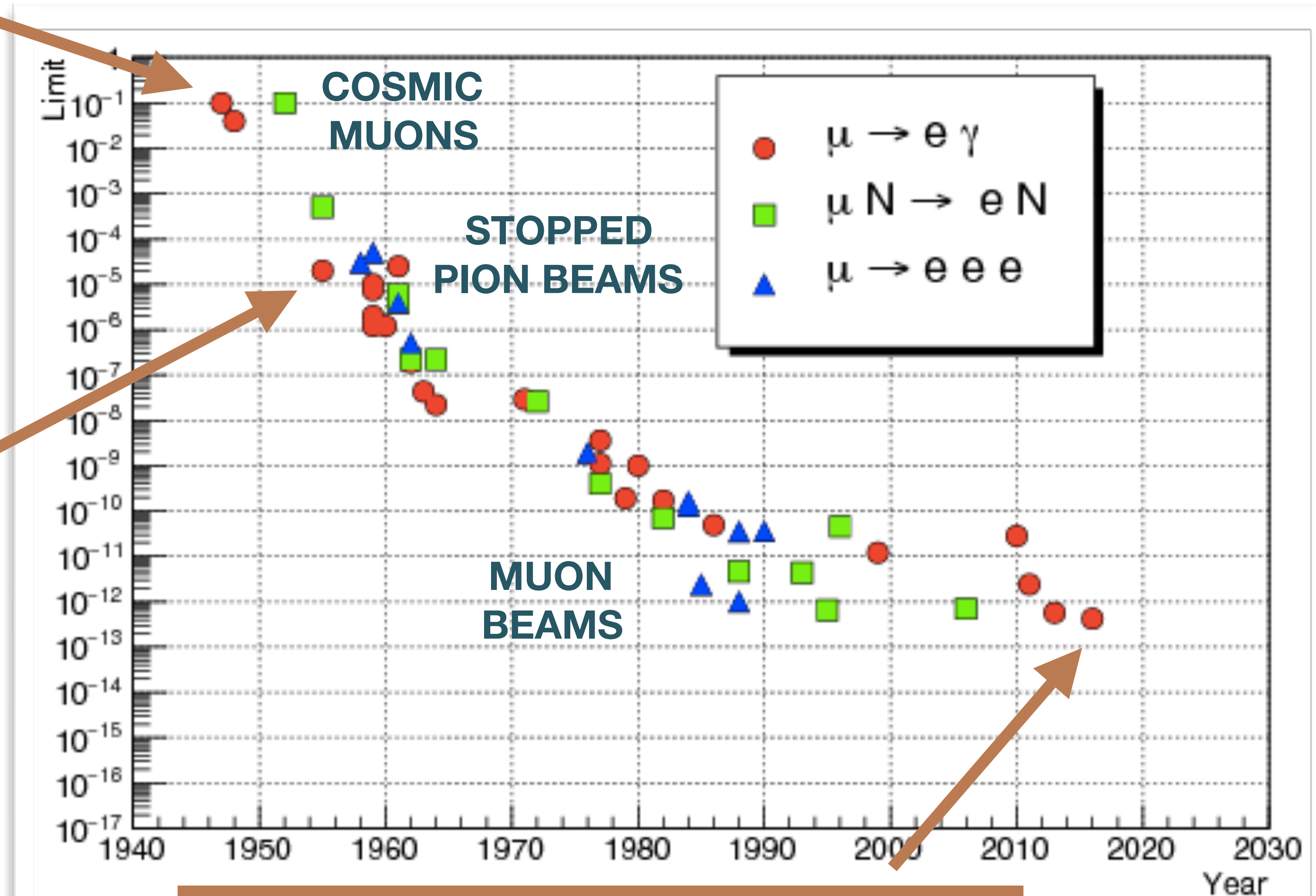
A. Crivellin et al., JHEP 1705 (2017) 117

Even in the era of the upcoming μ -> e conversion experiments, μ -> e γ (and μ -> e e e) will continue to play a crucial role

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

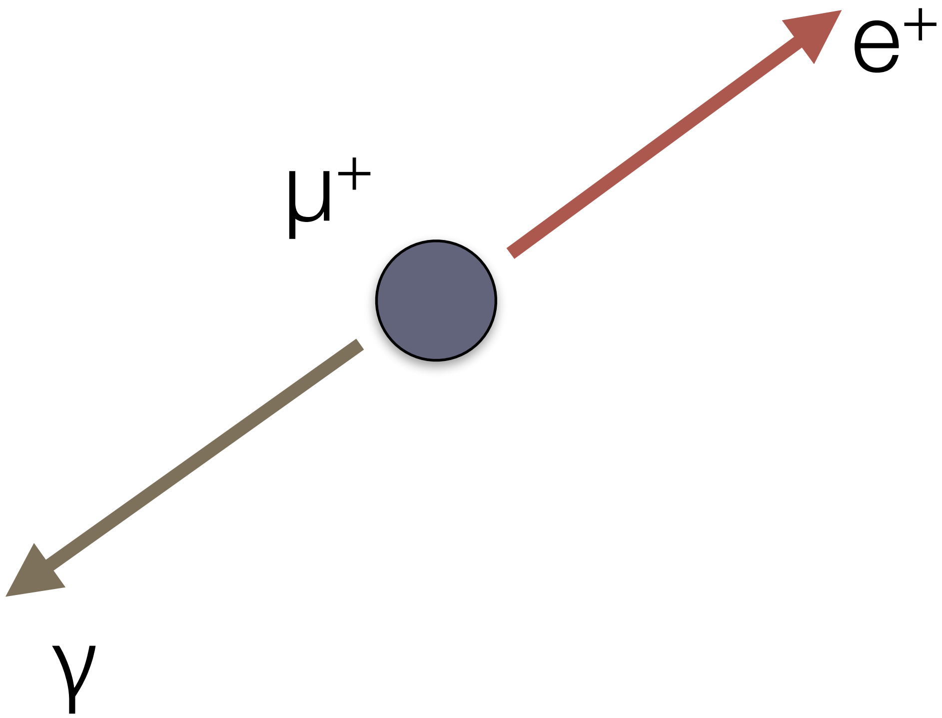


MEG Experiment
[Eur.Phys.J. C76 (2016) 8, 434]
BR(μ -> e γ) < 4.2 x 10^{-13}

Muon beams for μ -> e γ

- Muon beams are obtained from proton beams stopped on a target, through the decay of pions
  - clean and intense 28 MeV/c muon beams from pions decaying at rest at the target surface (*surface muons*)
- **Continuous** (*to avoid pileup*) **positive** (*to avoid capture by nuclei in the stopping target*) muon beams are used for cLFV in muon decays at rest
- The Paul Scherrer Institut (PSI, Villigen, CH) currently delivers the most intense DC muon beams (up to 10^8 μ/s)

μ -> e γ searches

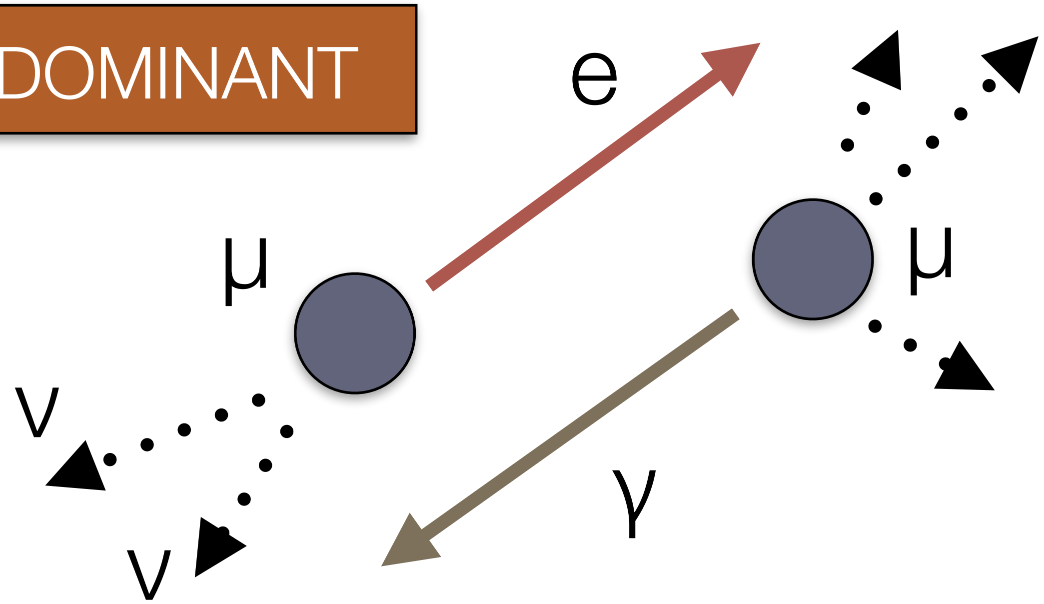


28 MeV/c muons are stopped on a thin target

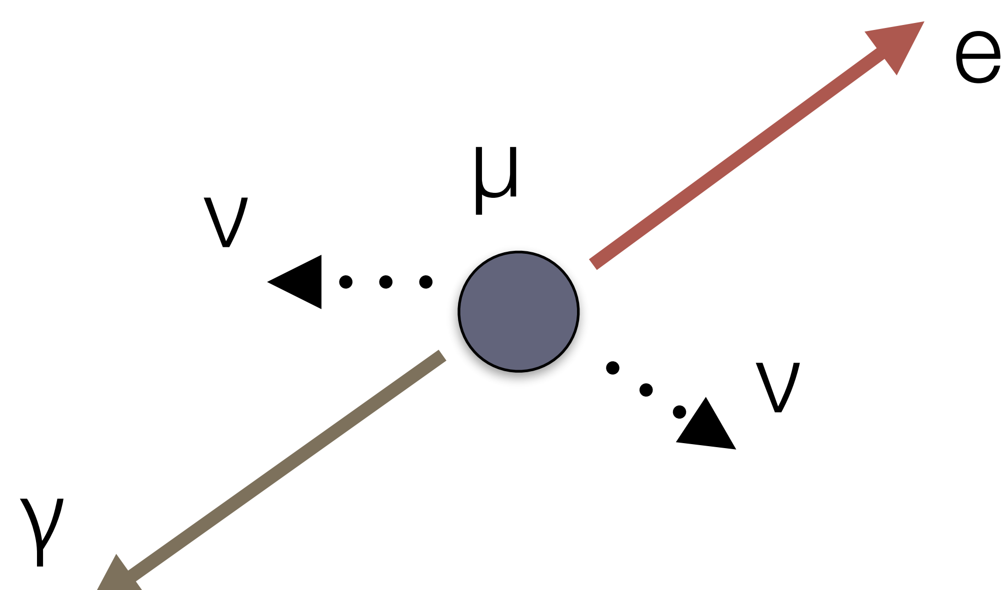
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the same **same time**;

Accidental Background

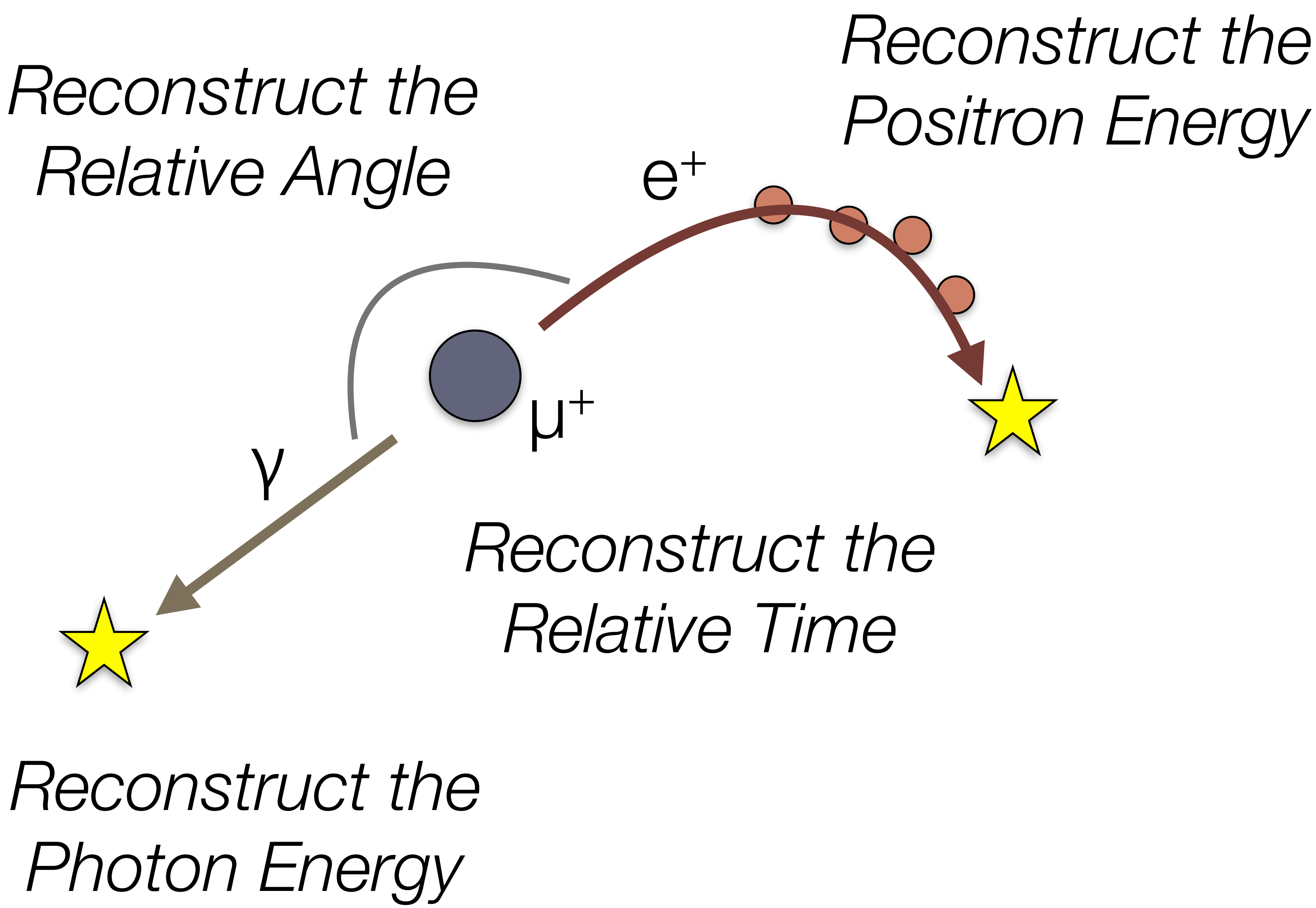
DOMINANT



Radiative Muon Decay (RMD)



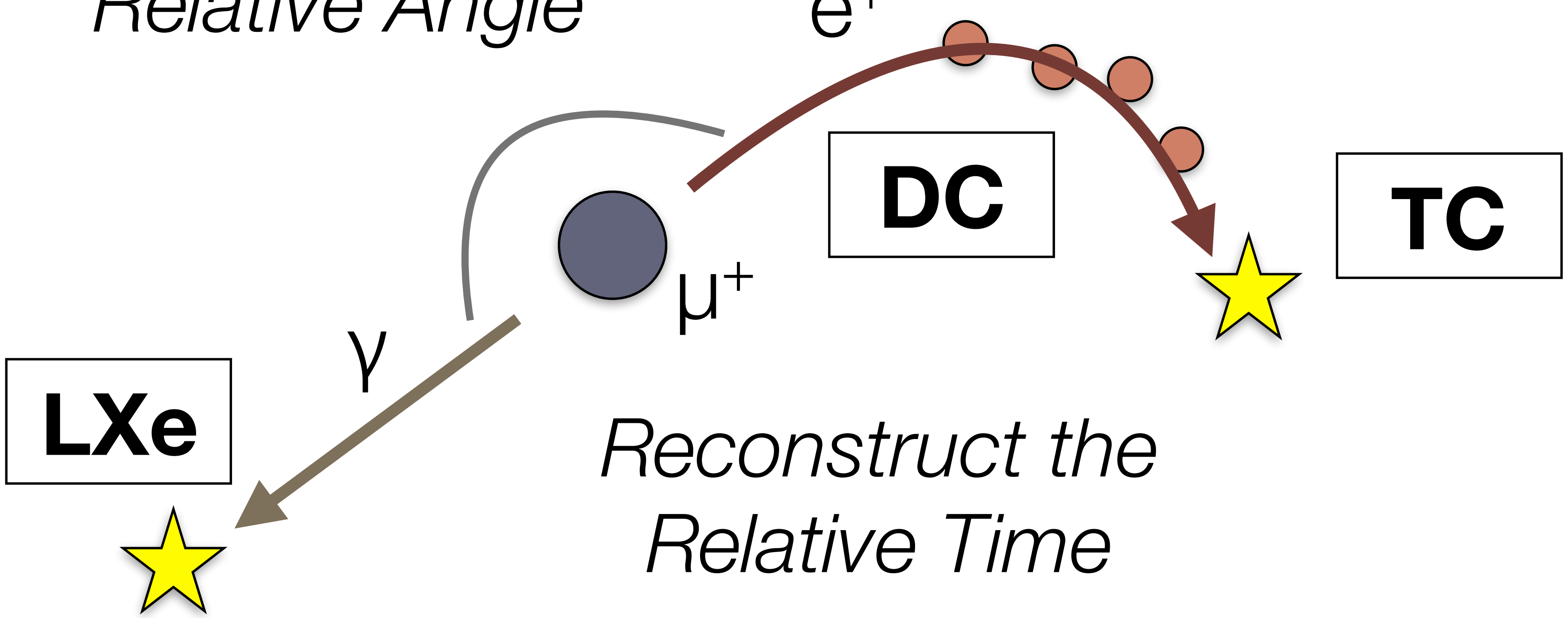
Ingredients for a search of μ -> e γ



The MEG Experiment

Reconstruct the Relative Angle

Reconstruct the Positron Energy



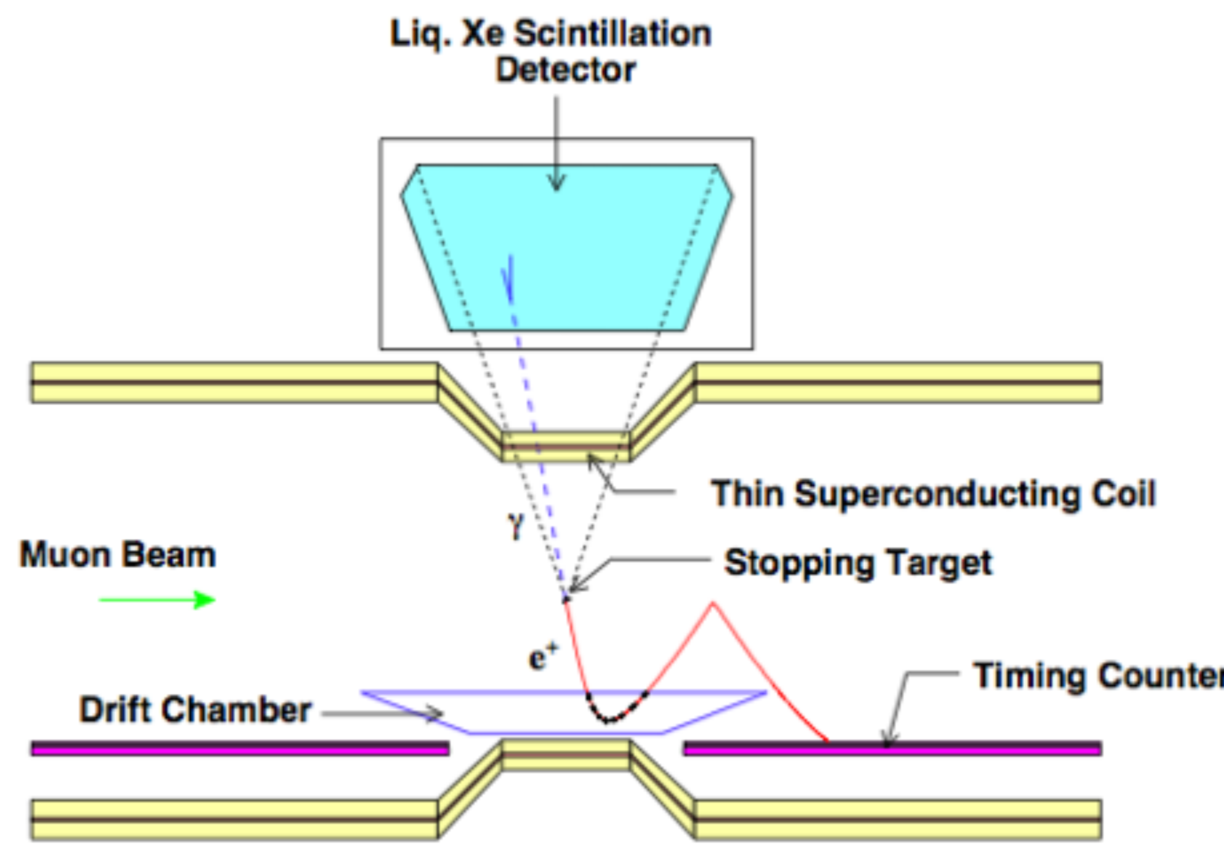
Reconstruct the Relative Time

Reconstruct the Photon Energy

LXe calorimeter (XEC)

16 Drift Chambers (DC) in a magnetic field

30 scintillating bars for timing & trigger (TC)

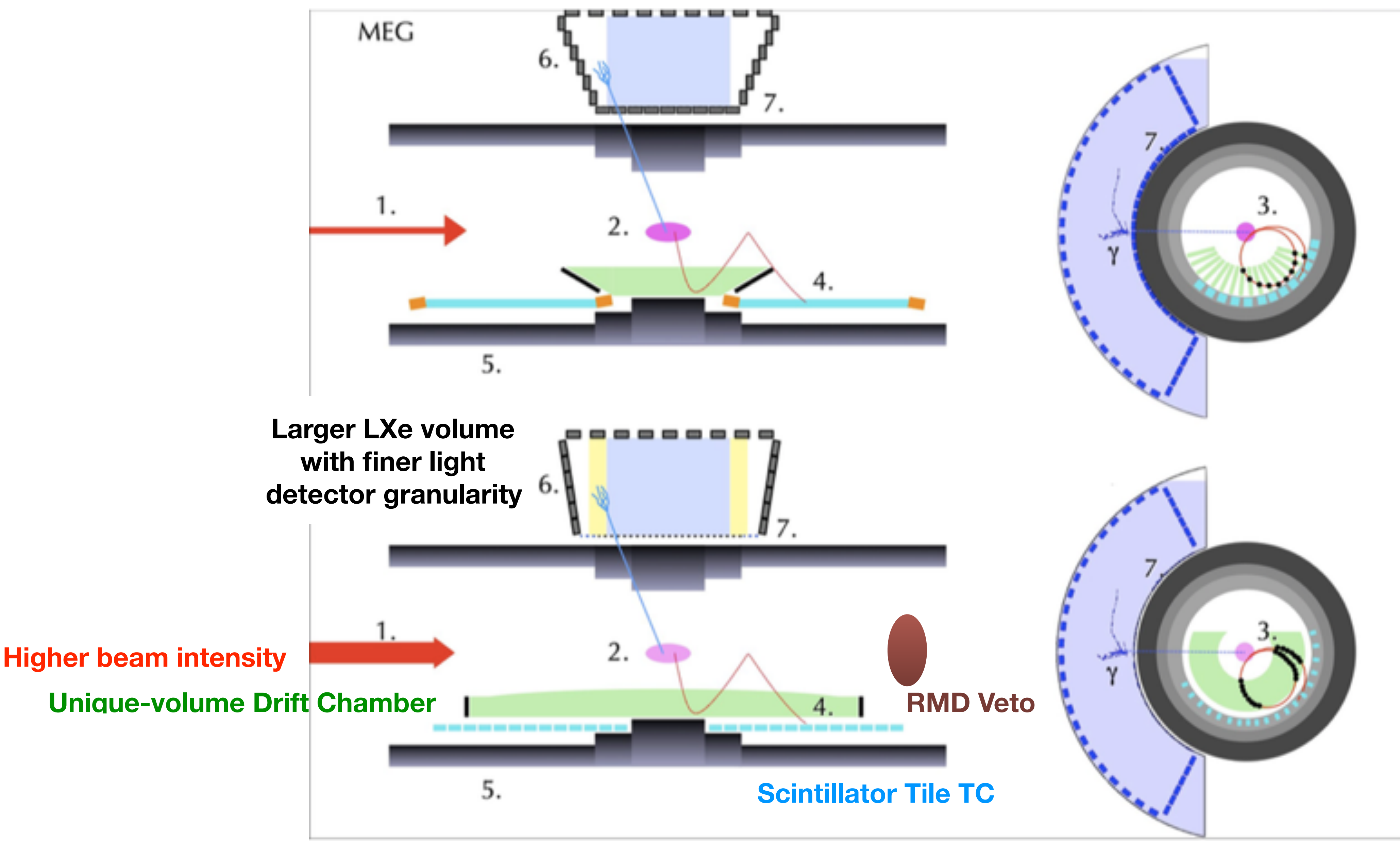


7.5 x 10^{14} μ on target

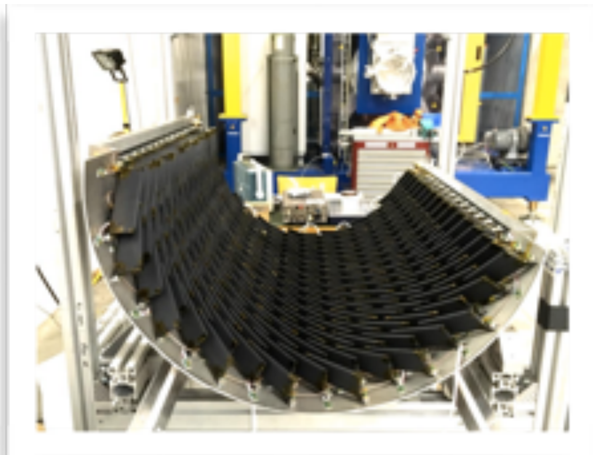
BR(μ -> e γ) < 4.2 x 10^{-13} @ 90% C.L.

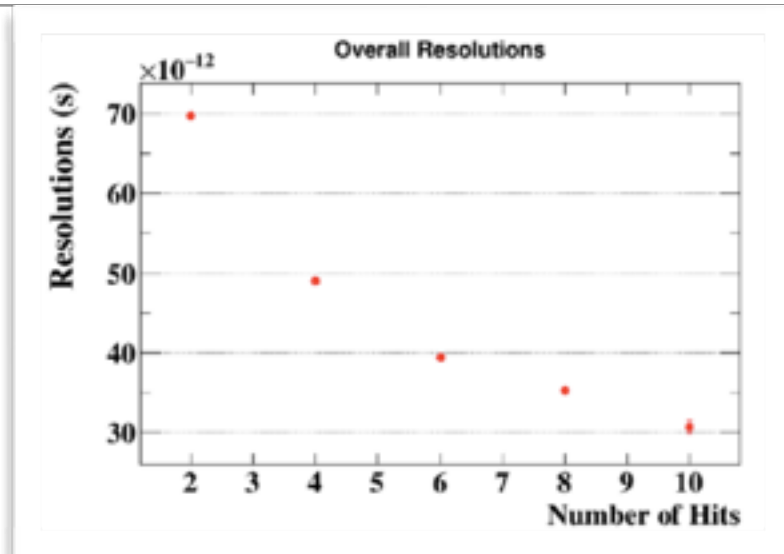
MEG-II

- The MEG experiment is undergoing an upgrade which involves all sub-detectors



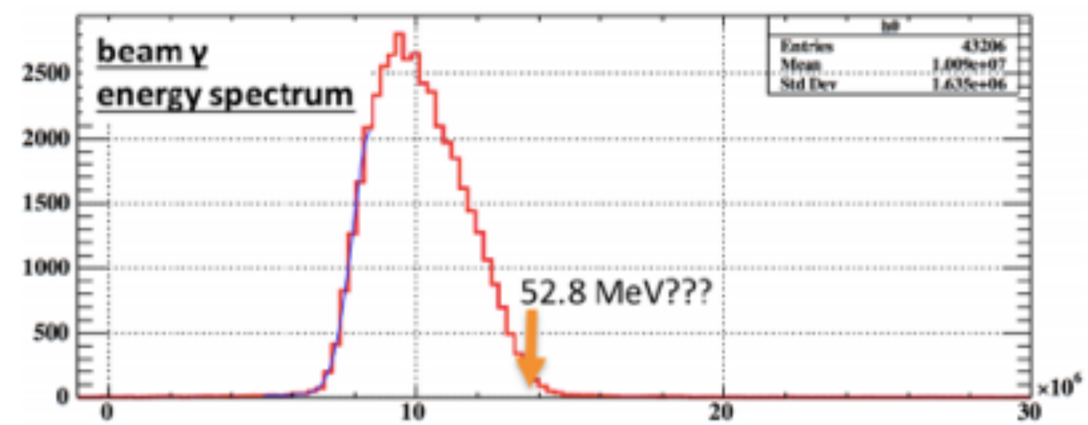
MEG-II status





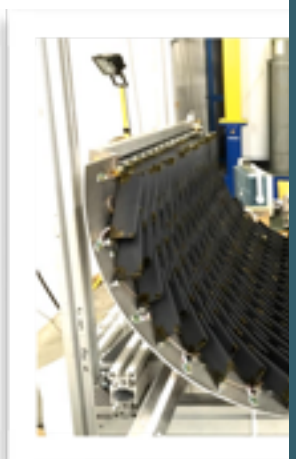
TC built and commissioned
in 2016-2017
σ_T ~ 35 ps

First photons in the upgraded XEC in 2017
σ_E ~ 1% @ 52.8 MeV



New DC fully assembled
and installed
in 2018
σ_E ~ 130 keV

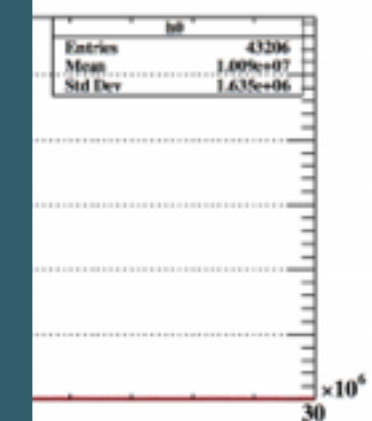
MEG-II status



TC

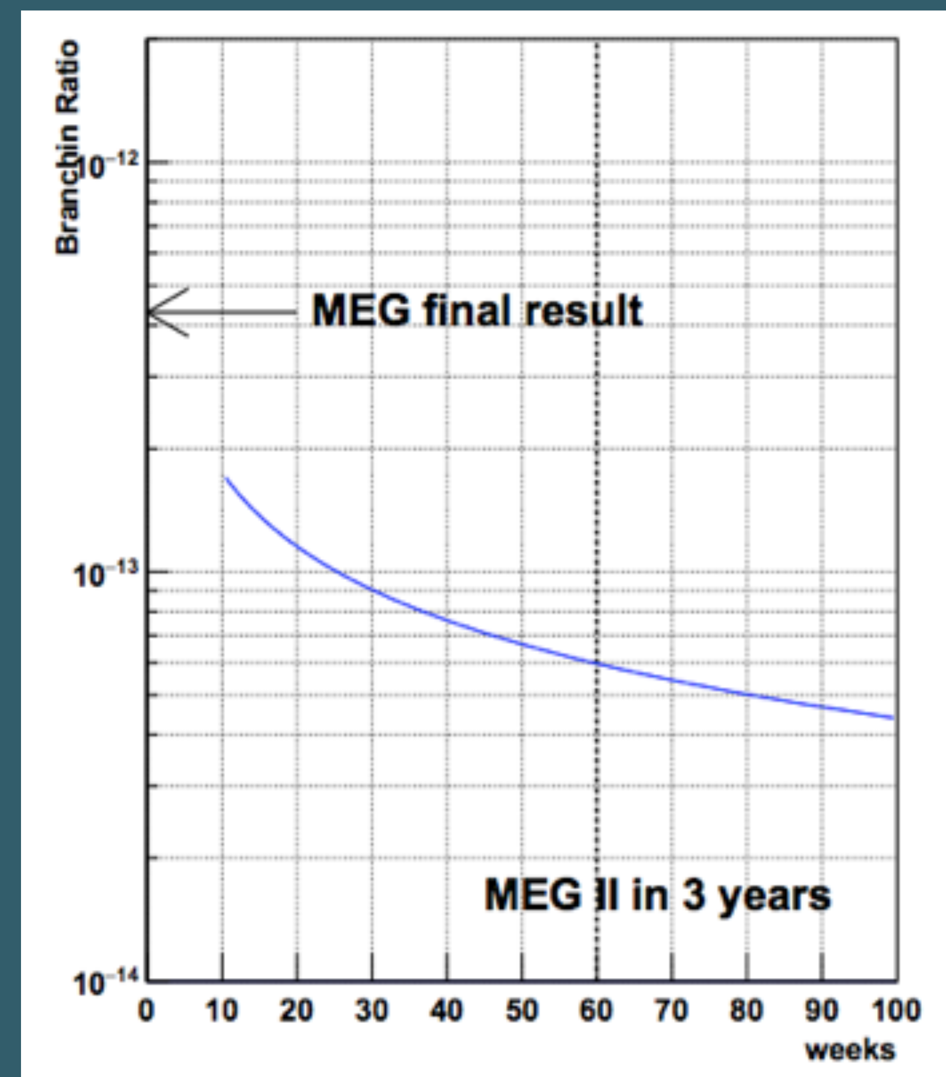
pgraded

MeV



First physics run in 2019

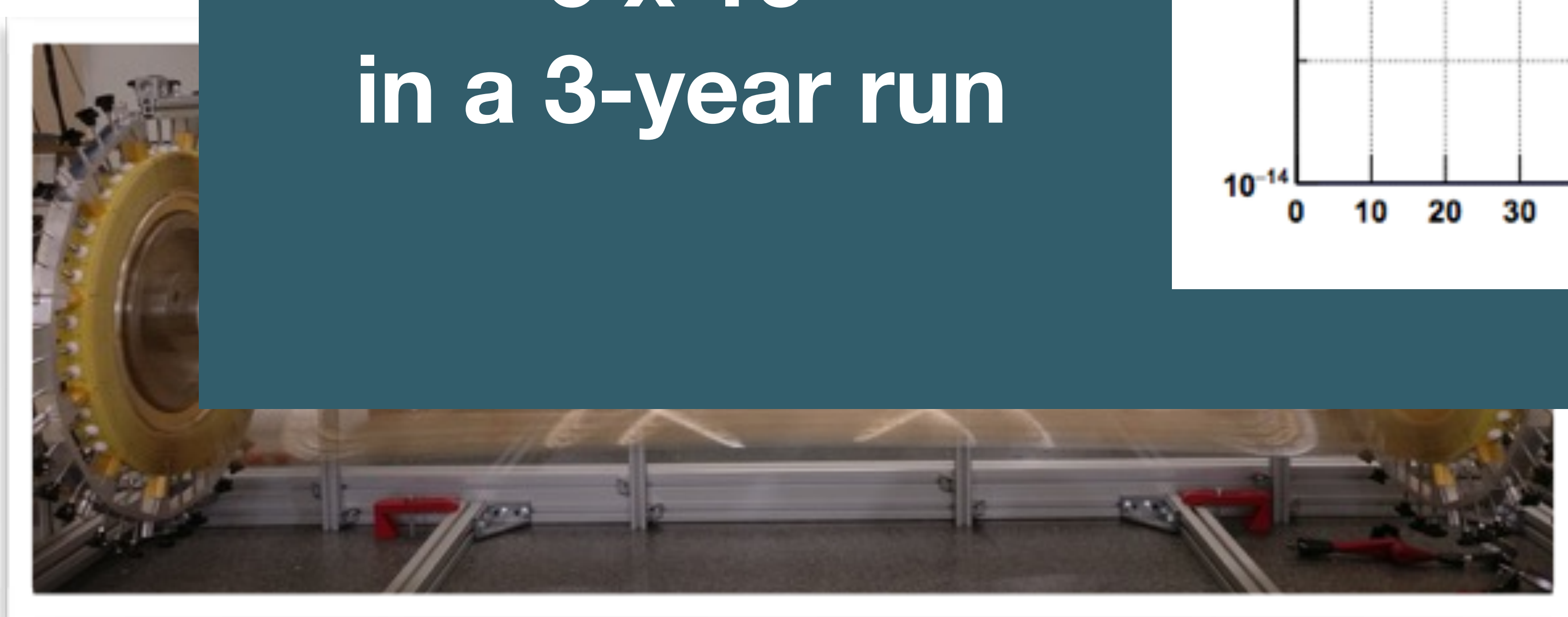
Expected UL ~ 6 x 10^{-14} in a 3-year run



ssembled

alled

σ_E ~ 130 keV



What next?

G. Cavoto, A. Papa, FR, E. Ripiccini and C. Voena
Eur. Phys. J. C (2018) 78: 37

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

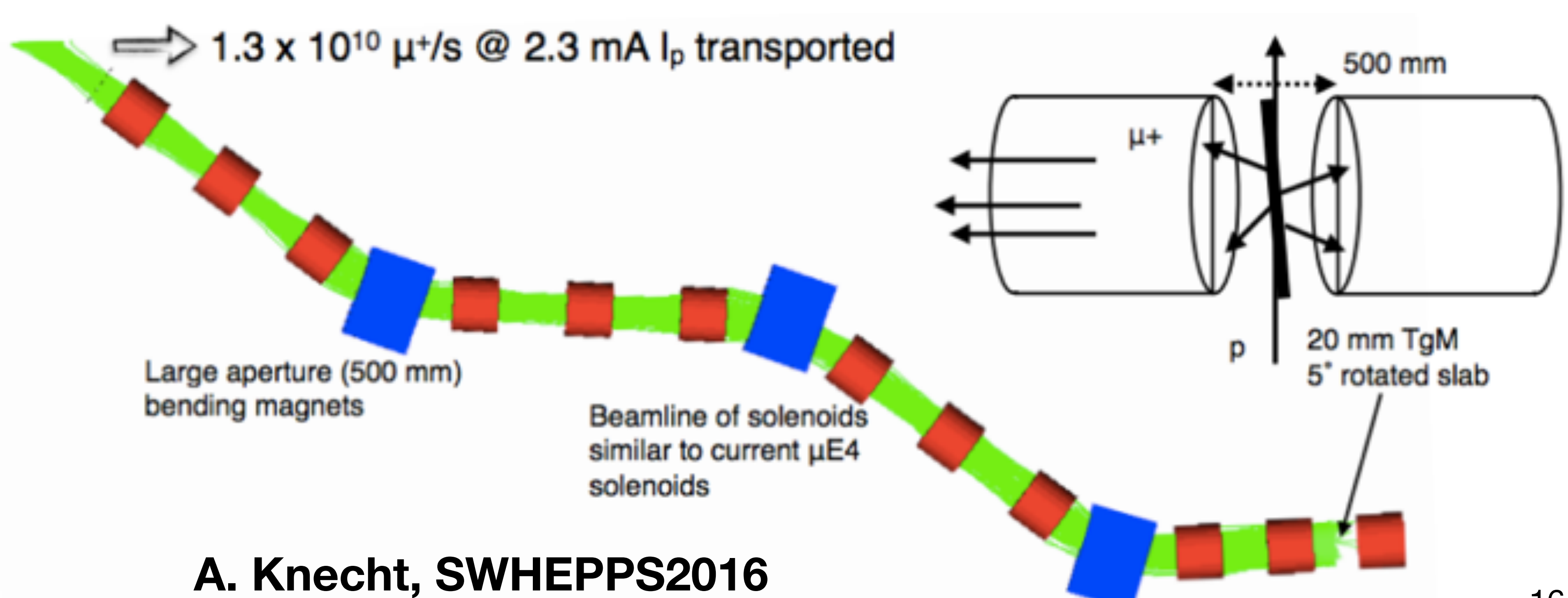
- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x100 the MEG-II beam)
- Optimization of the beam optics:
  - improved muon capture efficiency at the production target
  - improved transport efficiency to the experimental area

x4 μ capture eff.

x6 μ transport eff.

1.3 x 10^{10} μ/s

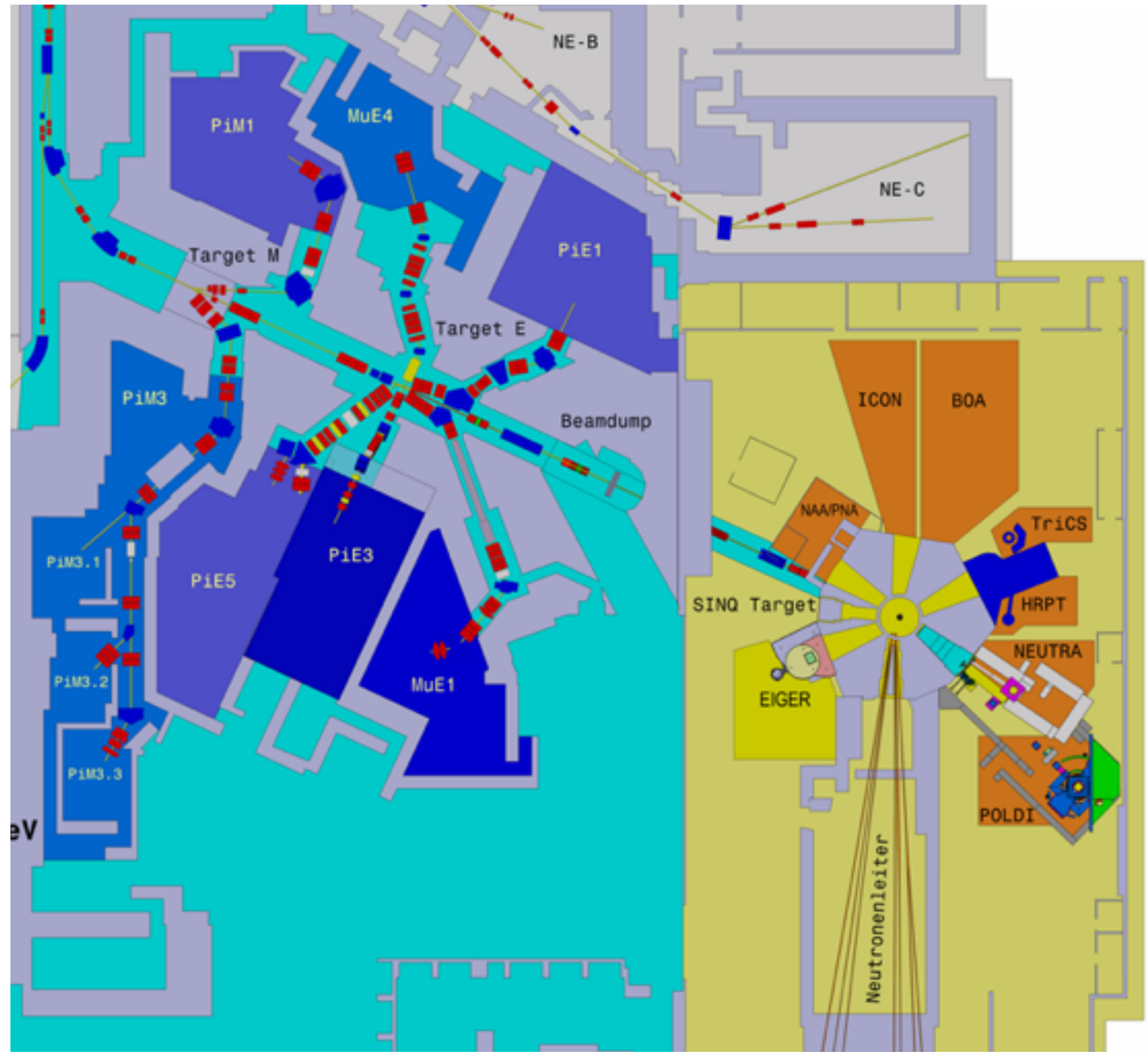
in the experimental area with 1400 kW beam power



A. Knecht, SWHEPPS2016

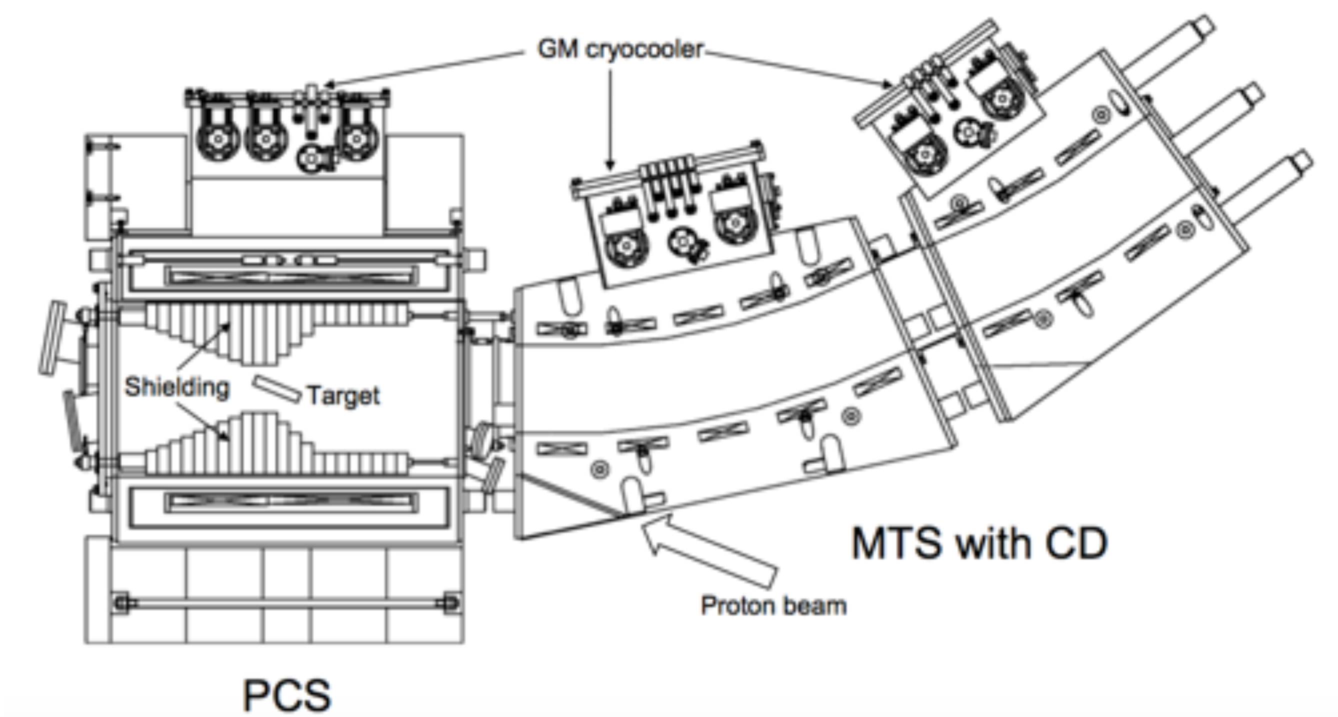
Production target

- 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)



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

Thick production target

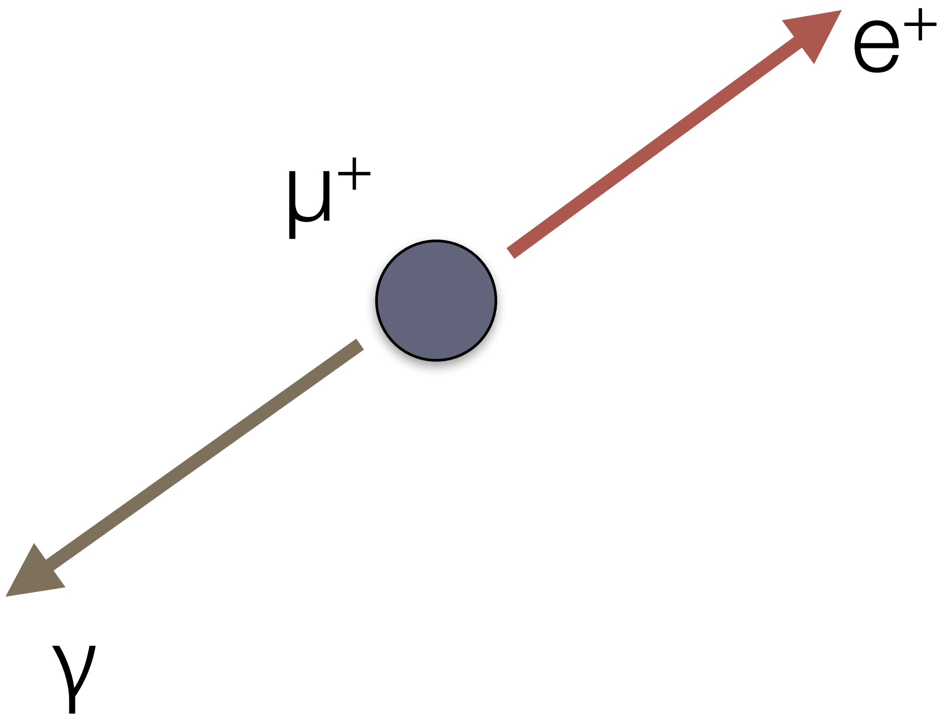
π capture solenoid

4×10^8 μ/s

at the production target

with 400 W beam power

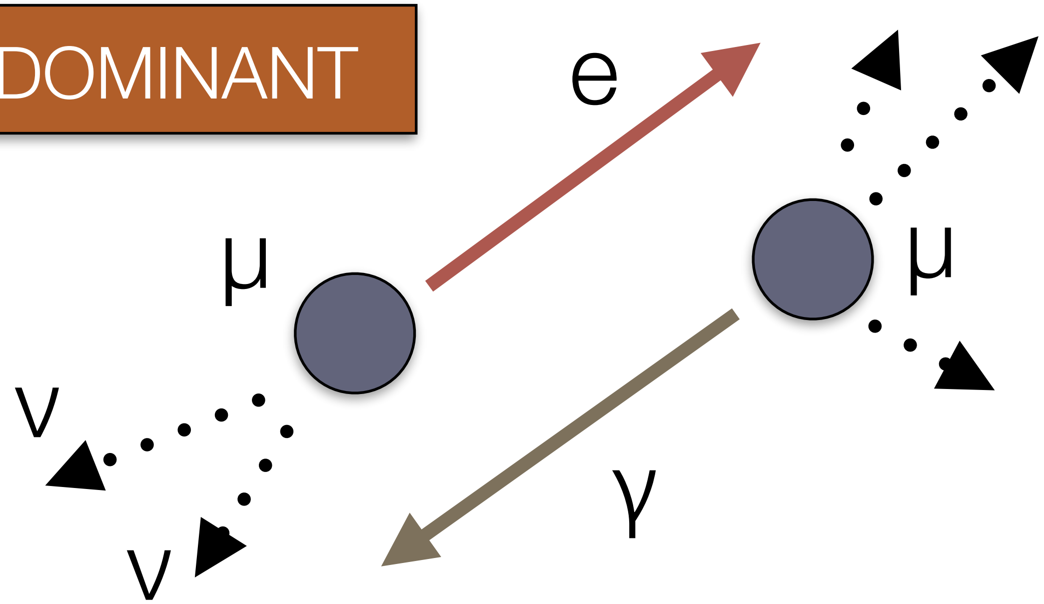
μ -> e γ searches



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

Accidental Background

DOMINANT



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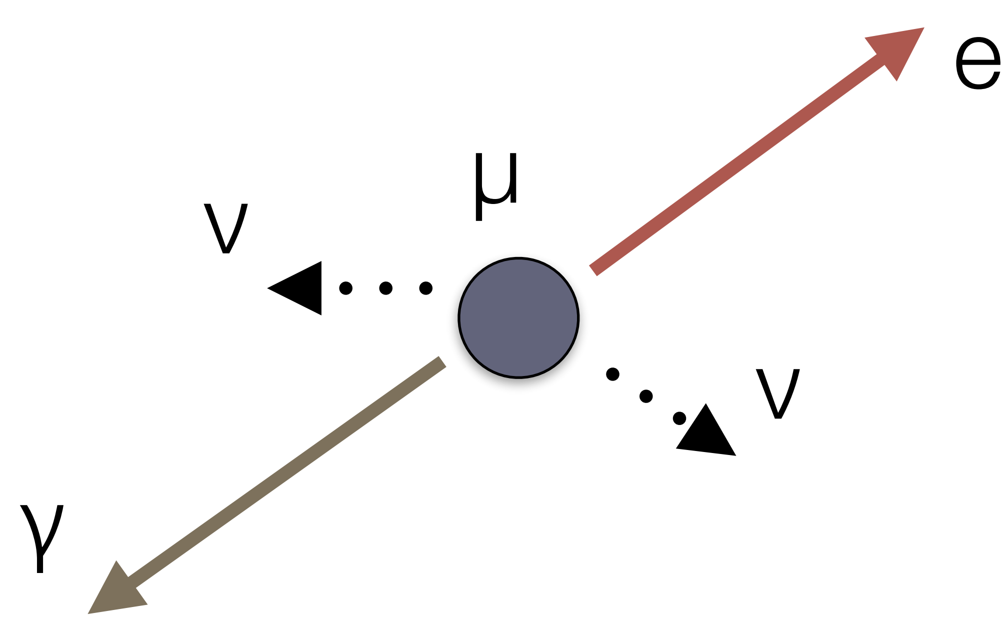
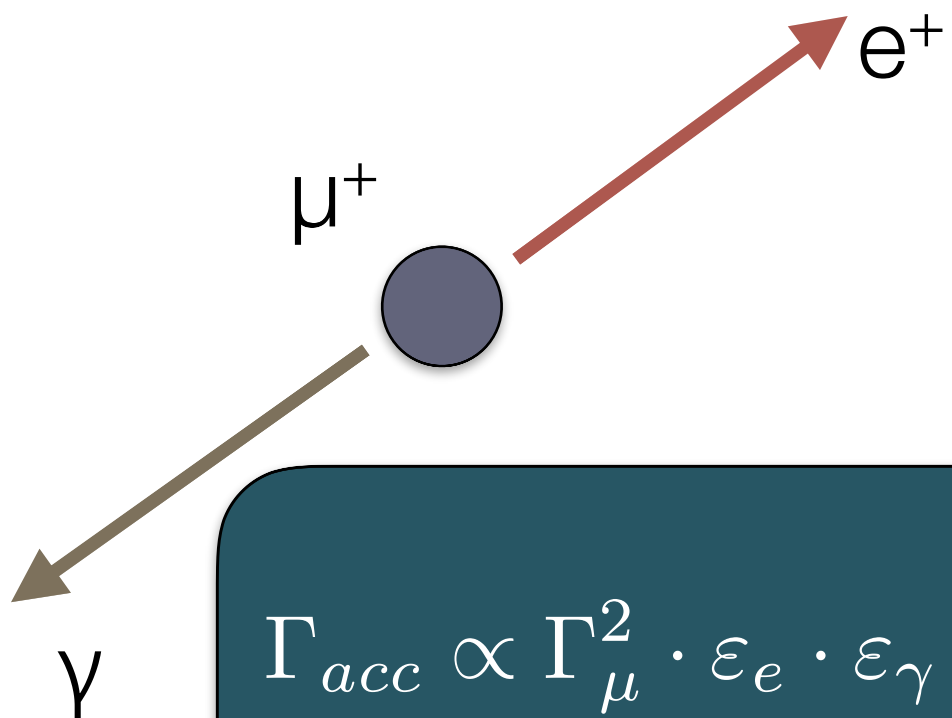


μ -> e γ searches

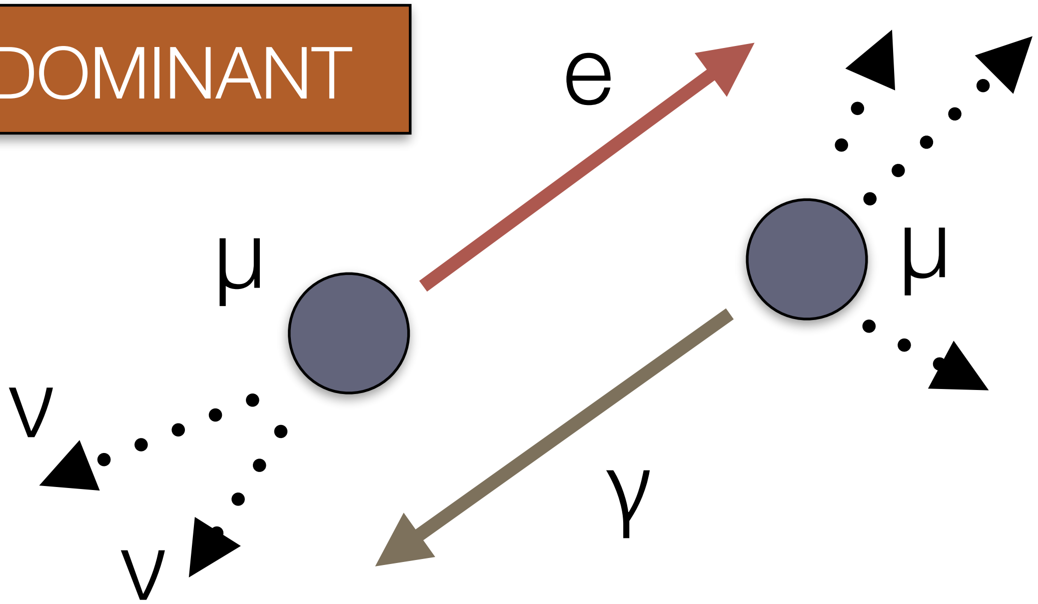


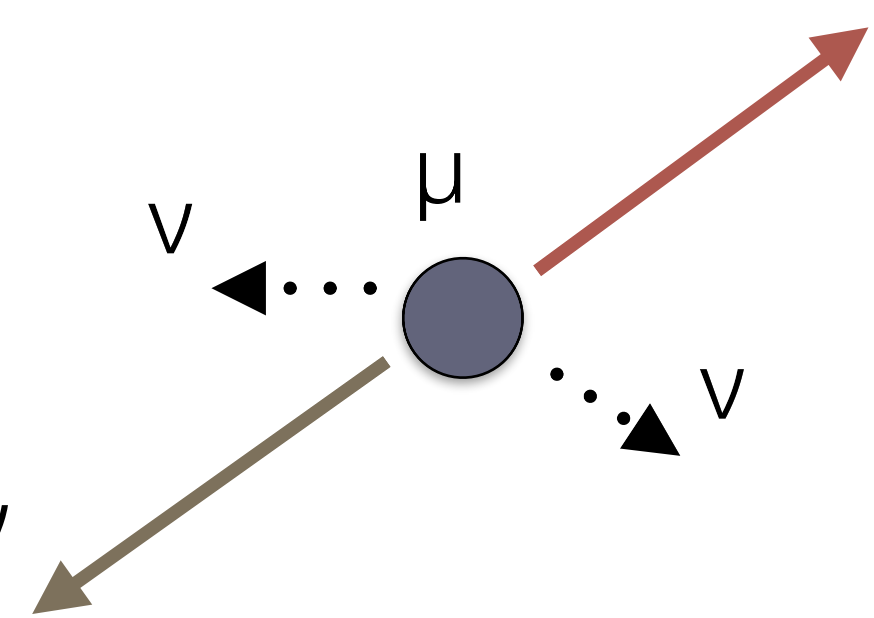
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the **same time**;

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

Acci **ay (RMD)**

DOMINANT

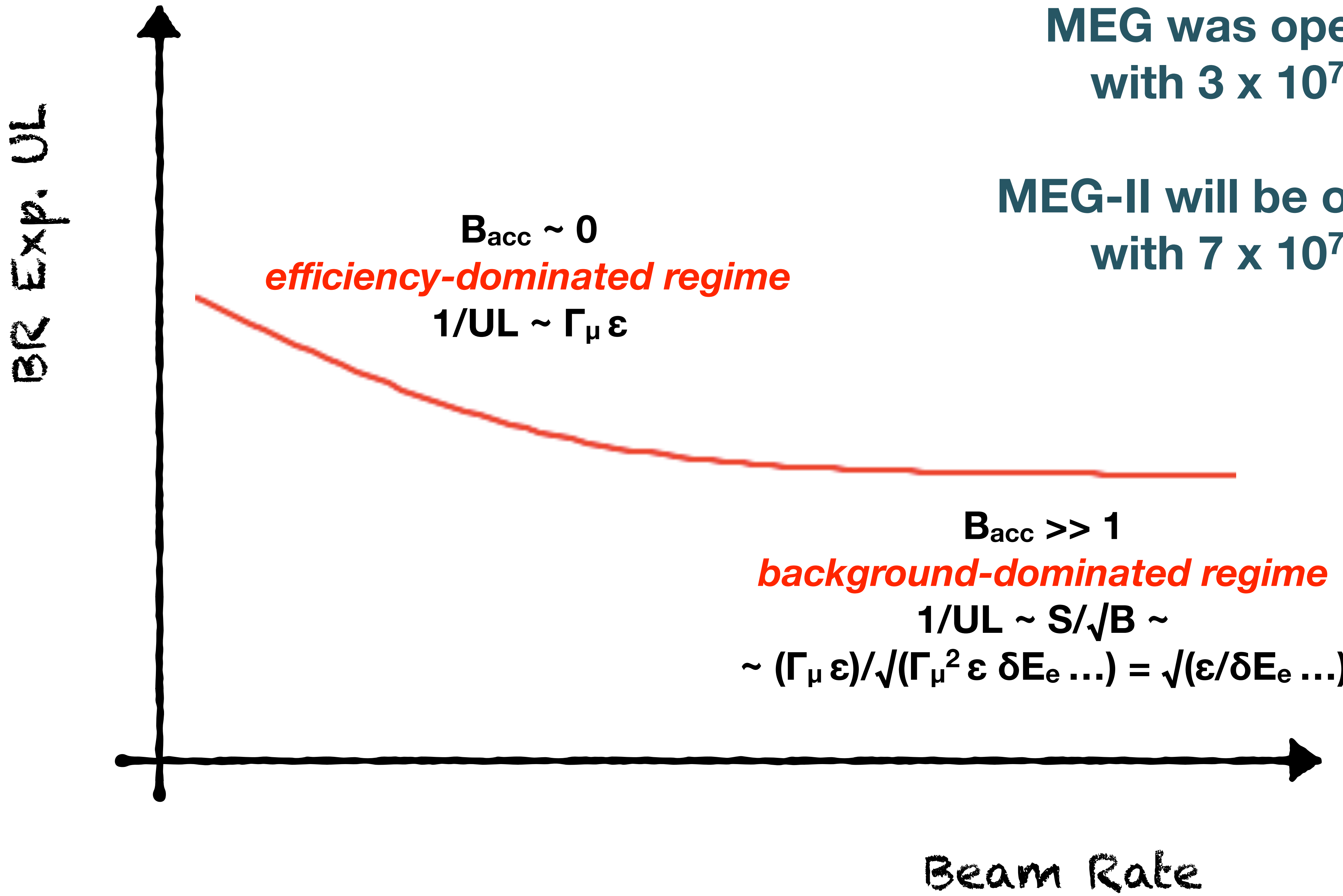




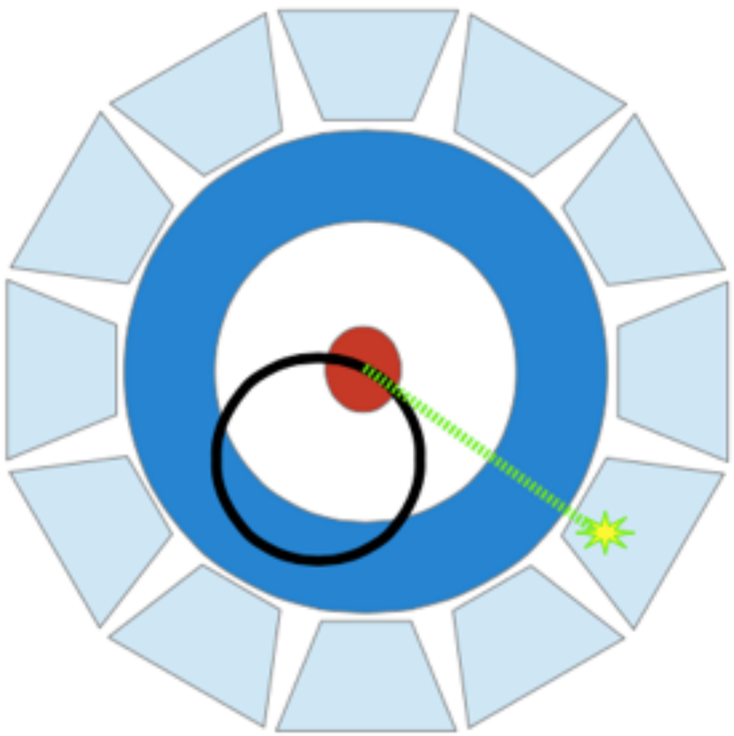
μ -> e γ searches

MEG was operated with 3 x 10^7 μ/s

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



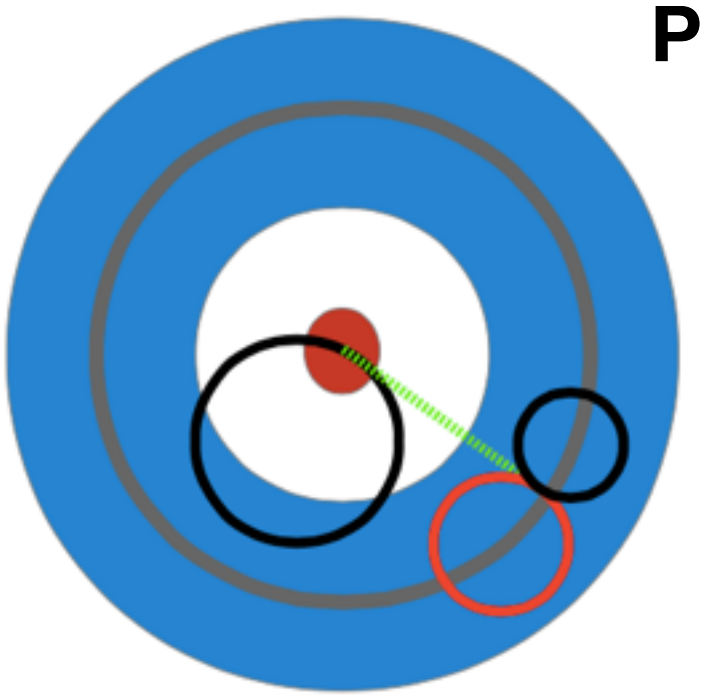
Toward the next generation of μ -> e γ searches: Photon Reconstruction



Calorimetry

High efficiency
Good resolutions

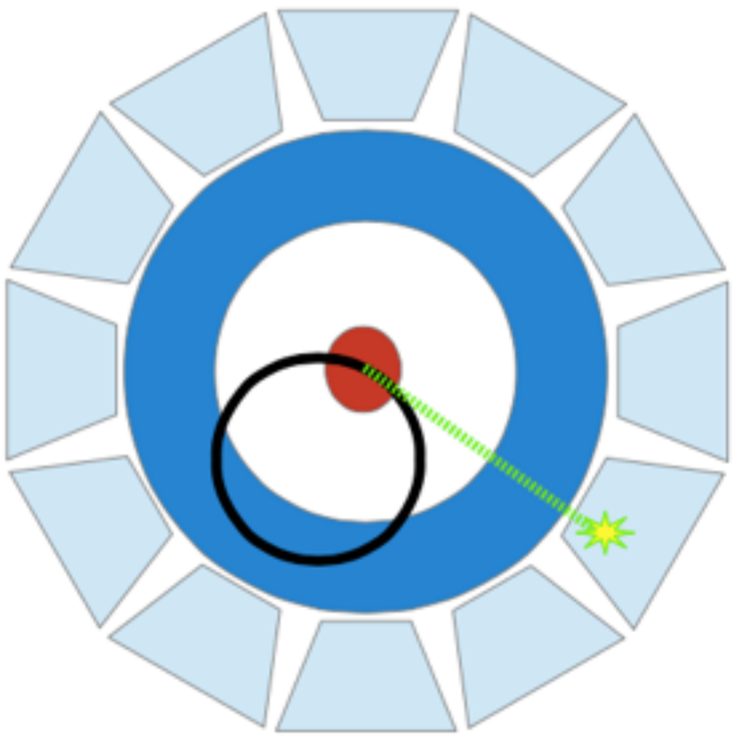
MEG:
LXe calorimeter
10% acceptance



Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

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



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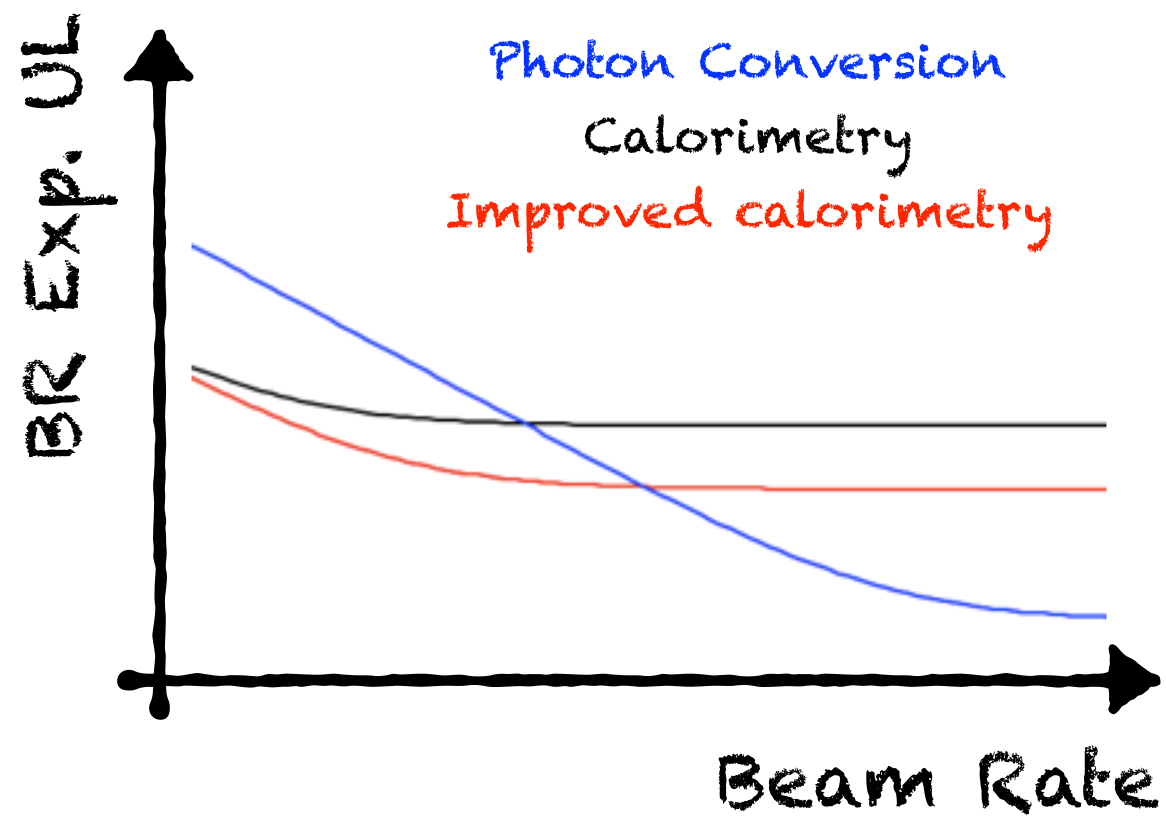
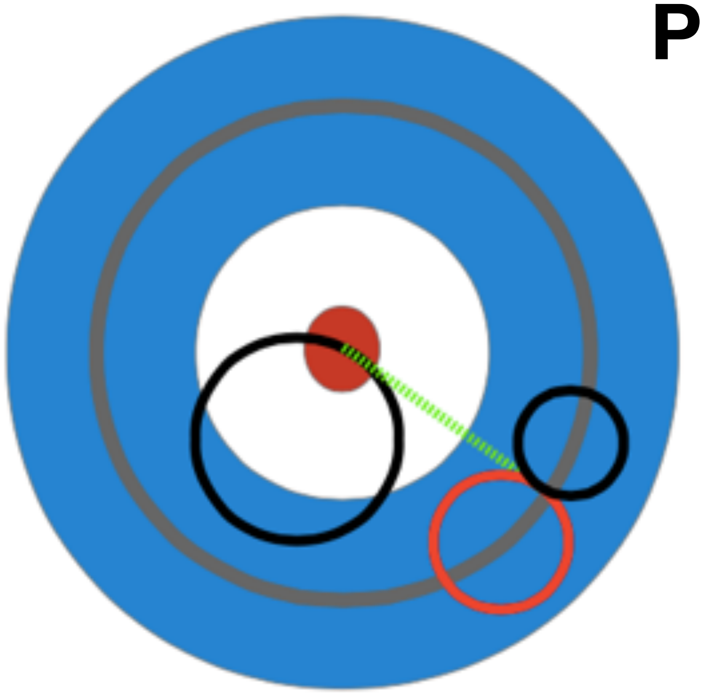




Photon Conversion

Low efficiency (~ %)
Extreme resolutions
+ eγ Vertex

γ Reconstruction: Limiting factors — Calorimetry

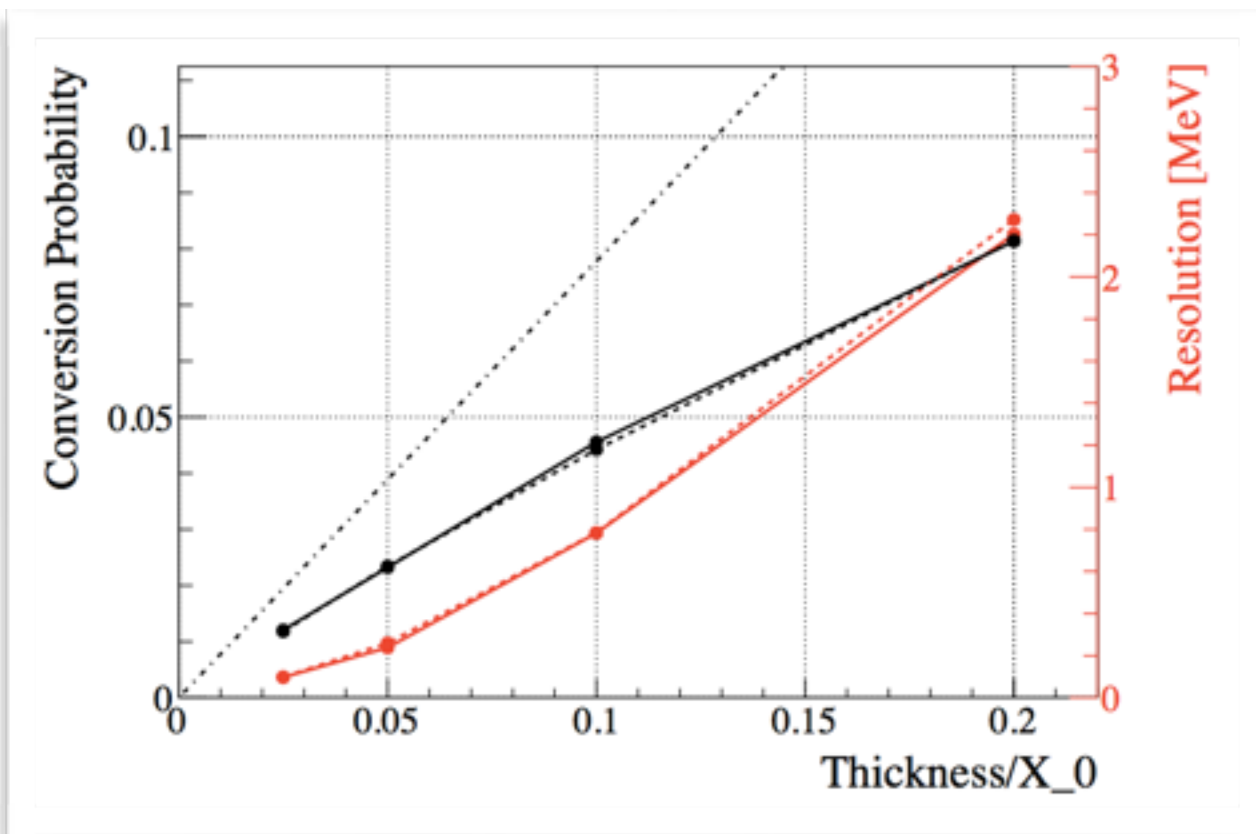
- Photon Statistics
- Scintillator time constant
- Detector segmentation

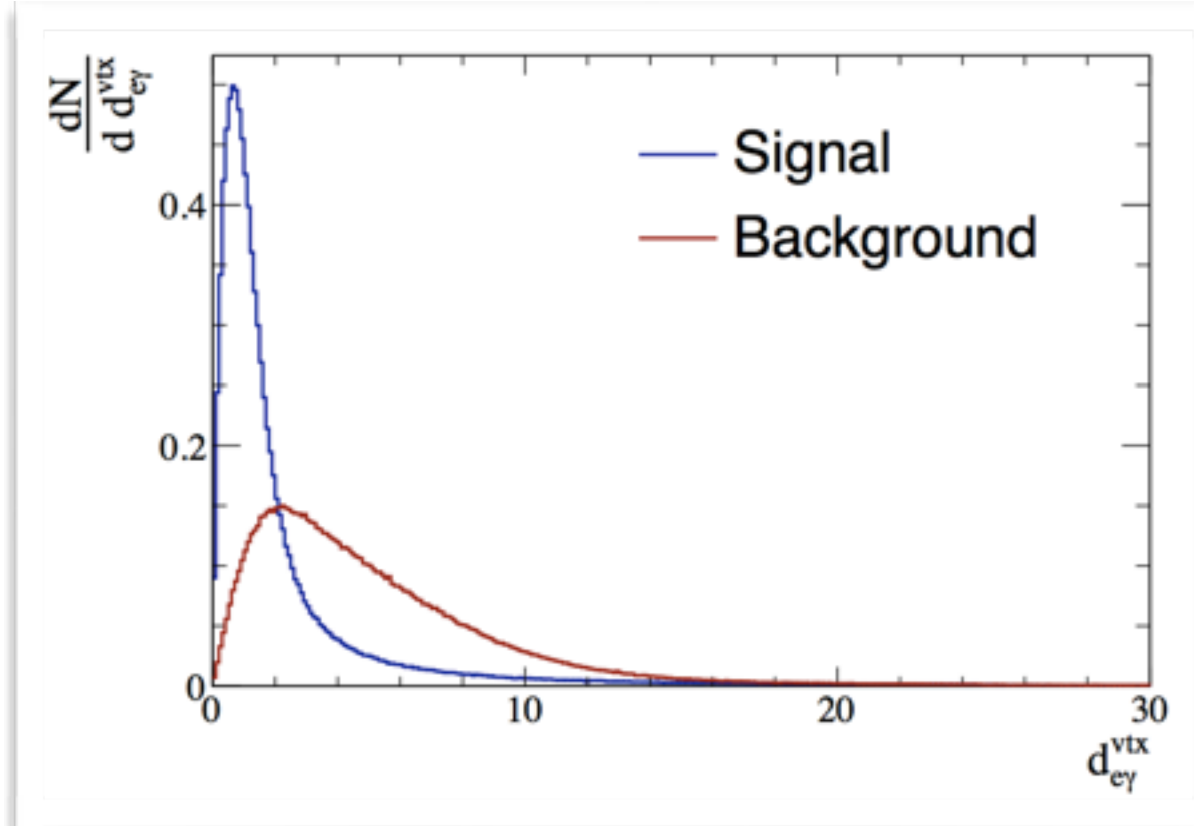
Scintillator	Density] [g/cm^3]	Light Yield [ph/keV]	Decay Time [ns]
$LaBr_3$(Ce)	5.08	63	16
LYSO	7.1	27	41
YAP	5.35	22	26
LXe	2.89	40	45
NaI(Tl)	3.67	38	250
BGO	7.13	9	300

- $LaBr_3$(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





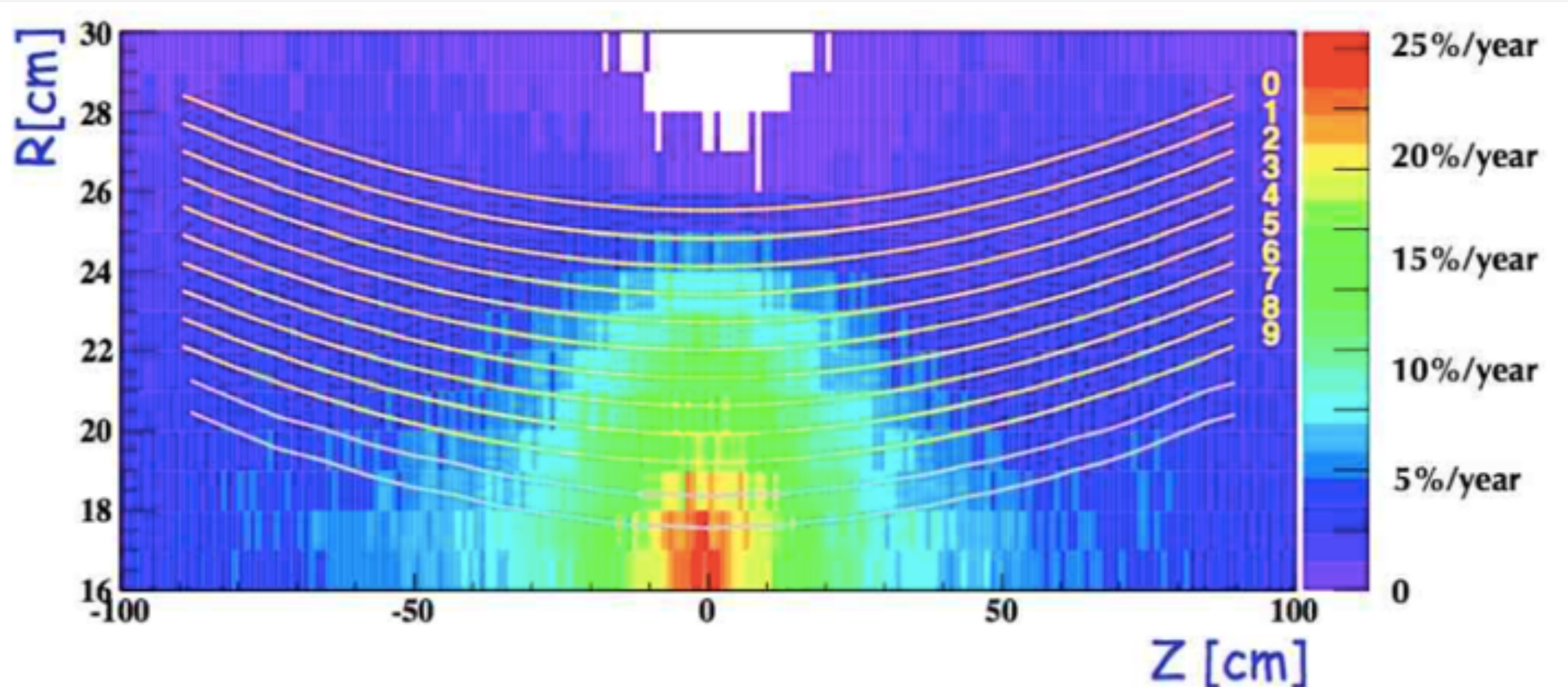
- Can take advantage of the photon direction determination form the e+e- reconstruction

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

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



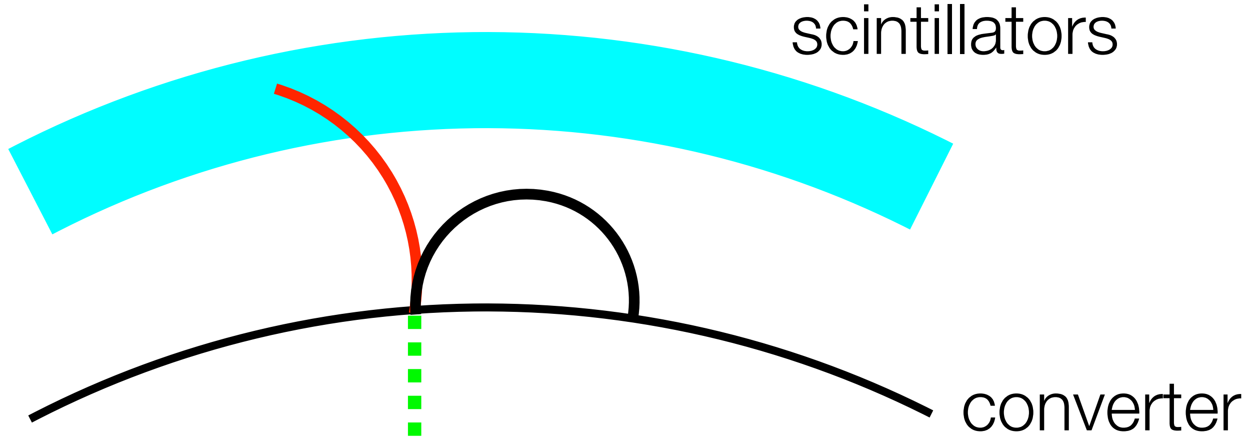
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301:7225

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?

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**



What about stacking multiple layers?

Photon and Positron timing

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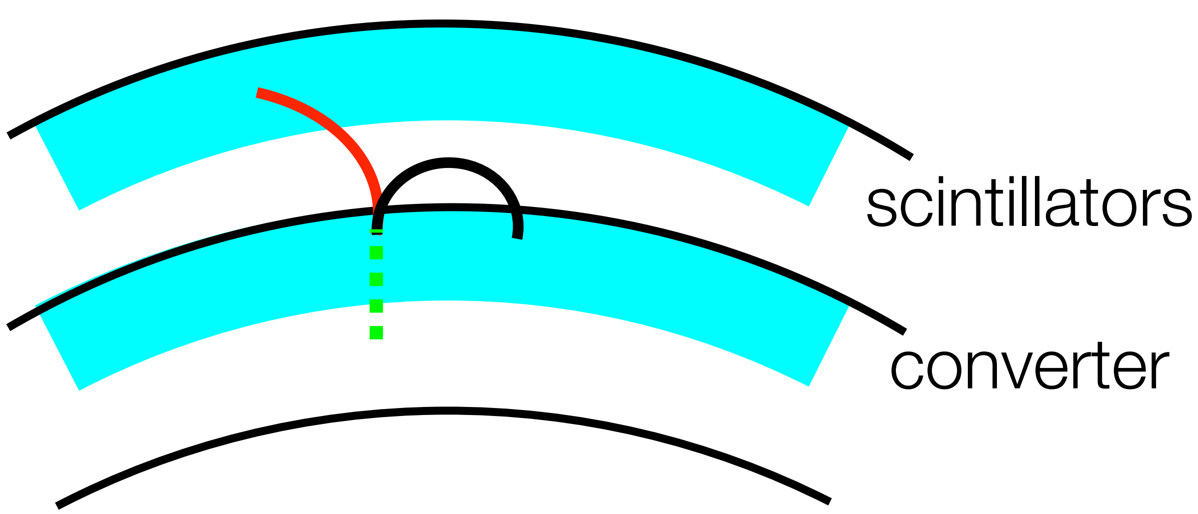


Effective converter material with lower Z

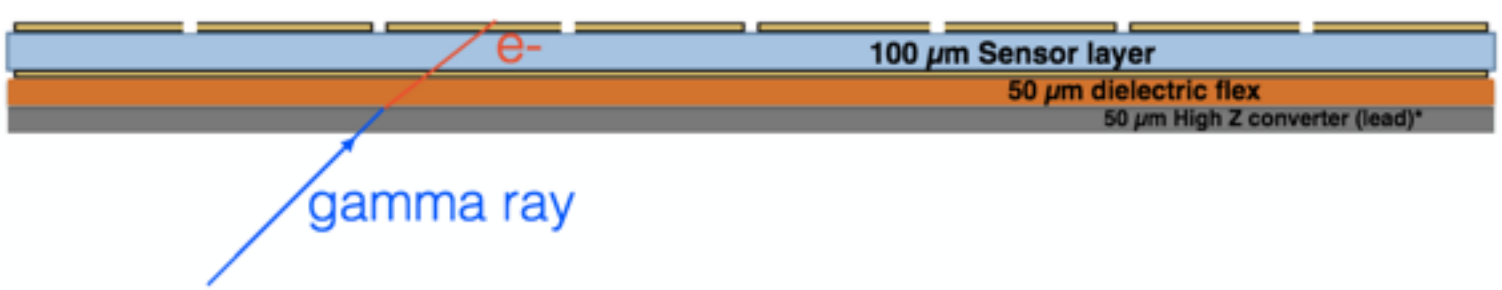
Worse compromise of efficiency vs. resolution

An active conversion layer

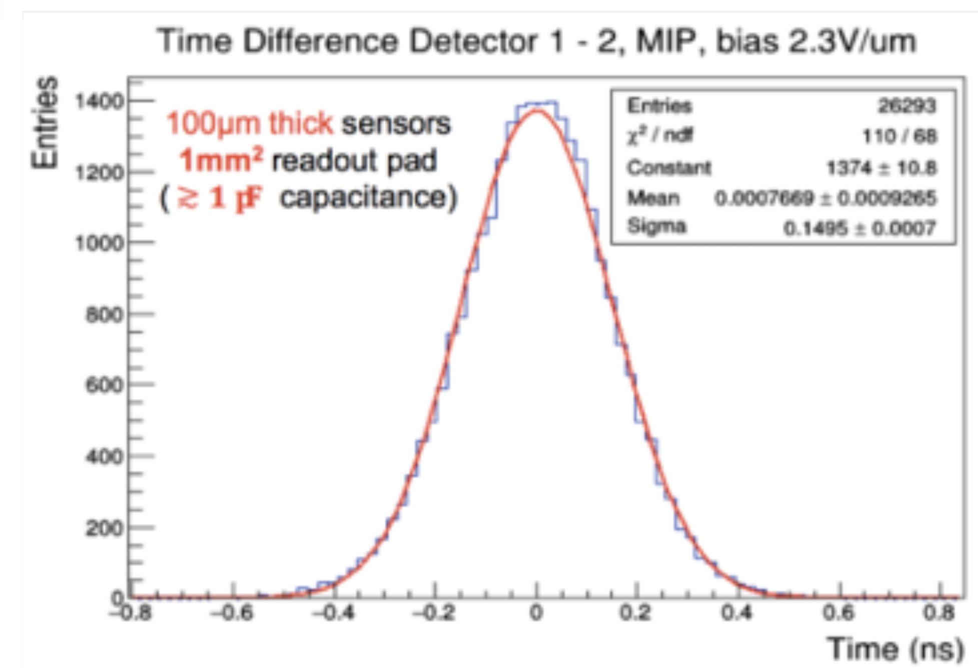
- Low Z active material for timing deteriorates the best efficiency/ resolution configuration
  - the active layer must be as thin as possible
- Scintillators have poor “timing to thickness” figures (~ 1 ns for 250 μm fibers)

FAST SILICON DETECTORS

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



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



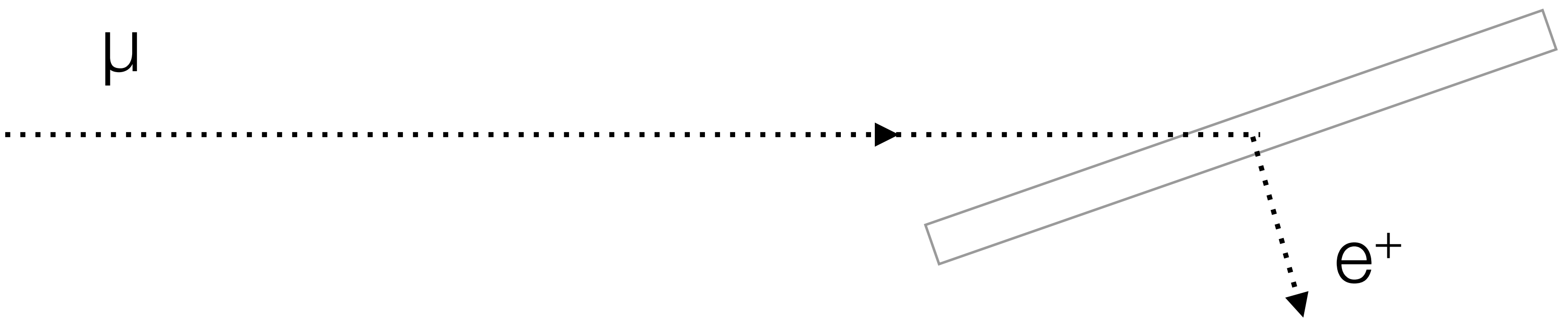
$$\sigma_t = \frac{(150 \pm 1)ps}{\sqrt{2}} = (106 \pm 1)ps$$

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

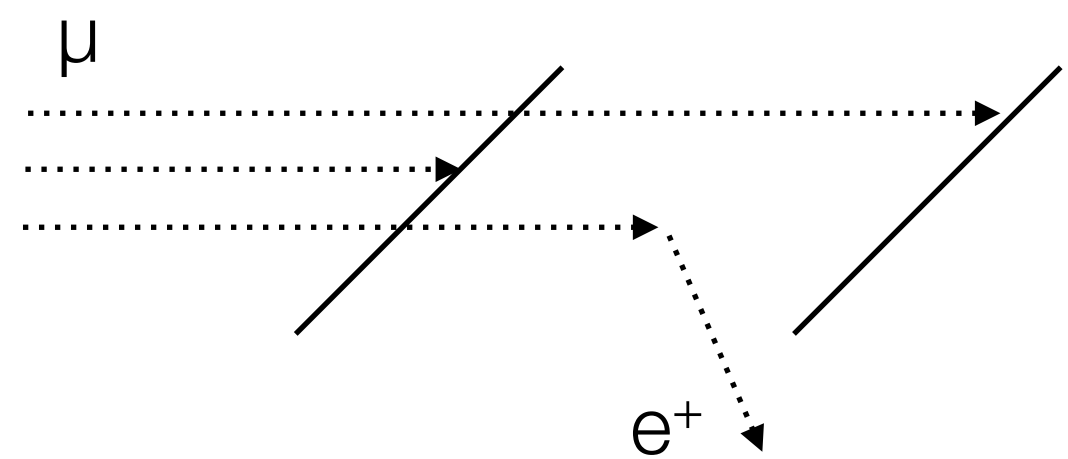
Optimal target
Be, 90 µm



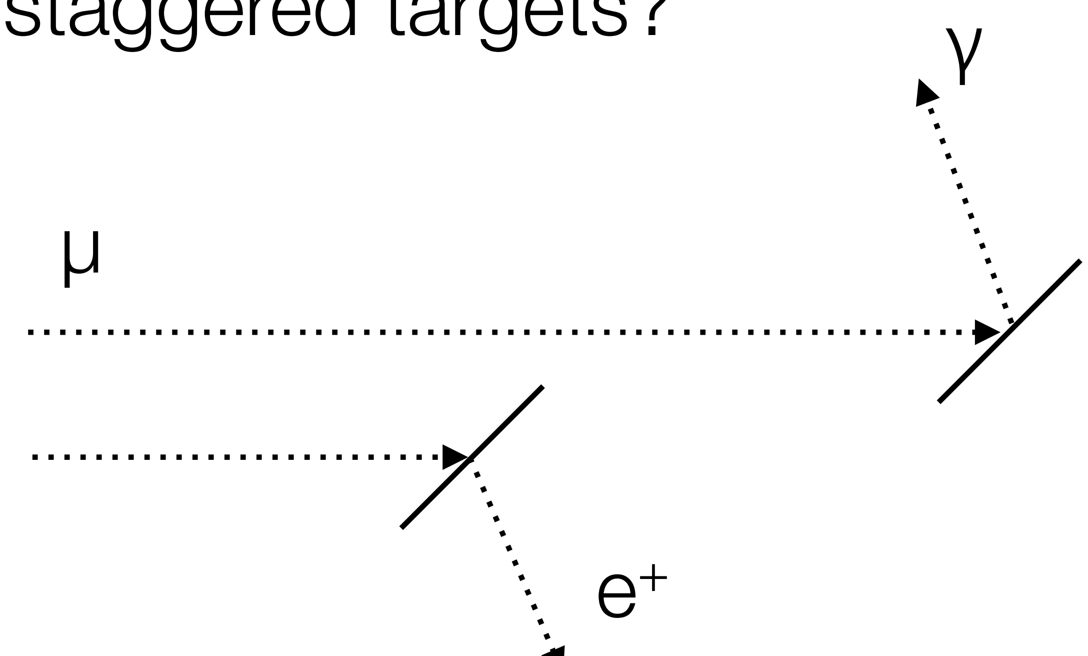
$\theta_{MS}(e^+)$ ~ 2.5 - 3 mrad

Multiple Targets?

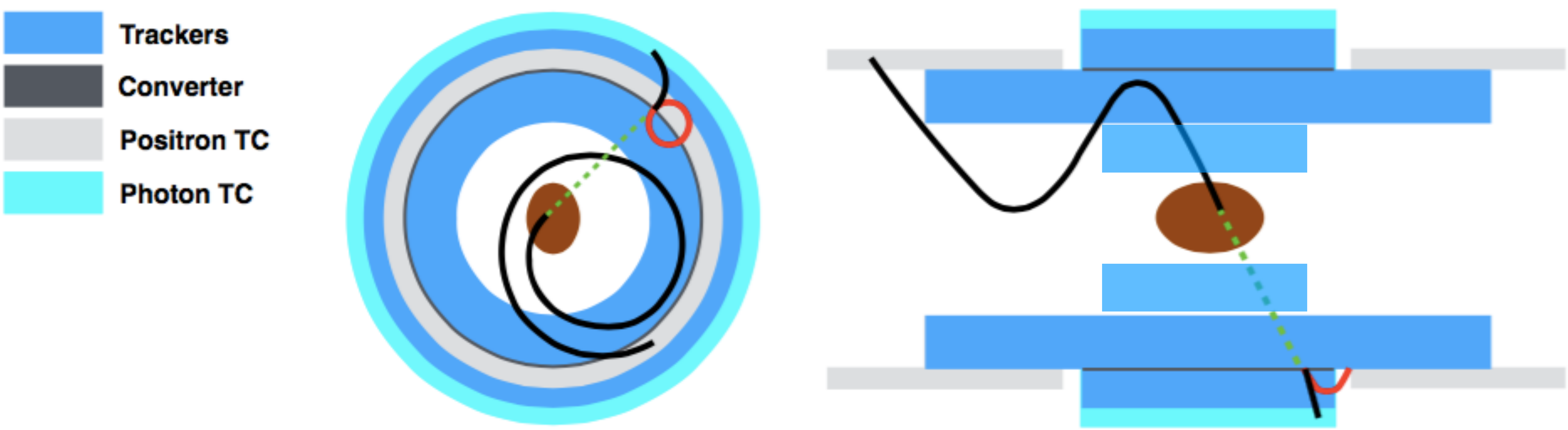
- Does it make sense to use multiple thinner targets in sequence?
  - probably not: many muons would decay in the gas between the two targets (background, efficiency loss,…)



- Does it make sense to use multiple staggered targets?
  - probably yes: with photon direction from conversion, it could reduce the acc. bkg. by a factor of 2



A Tentative Design



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)**	

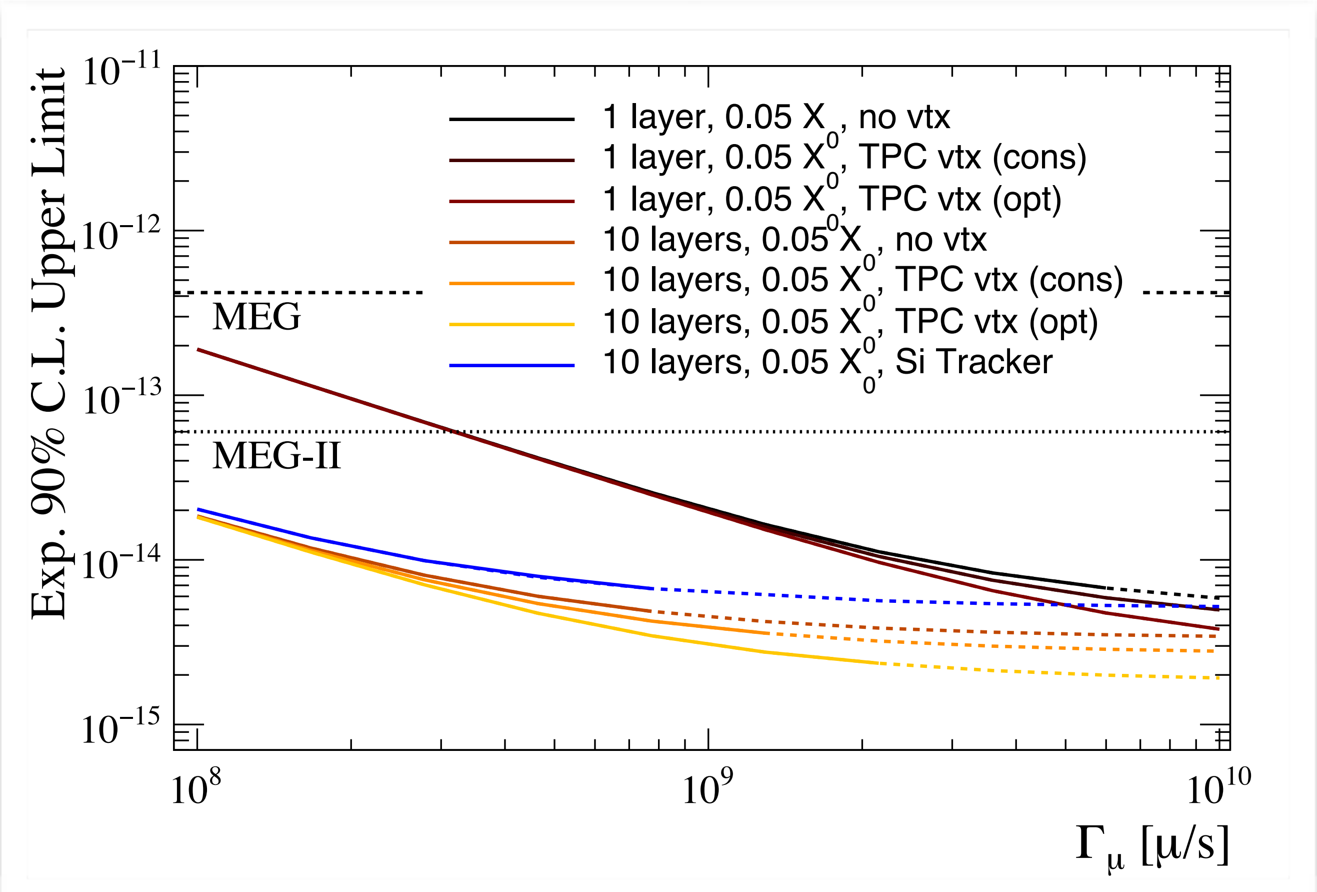
PHOTON CONVERSION

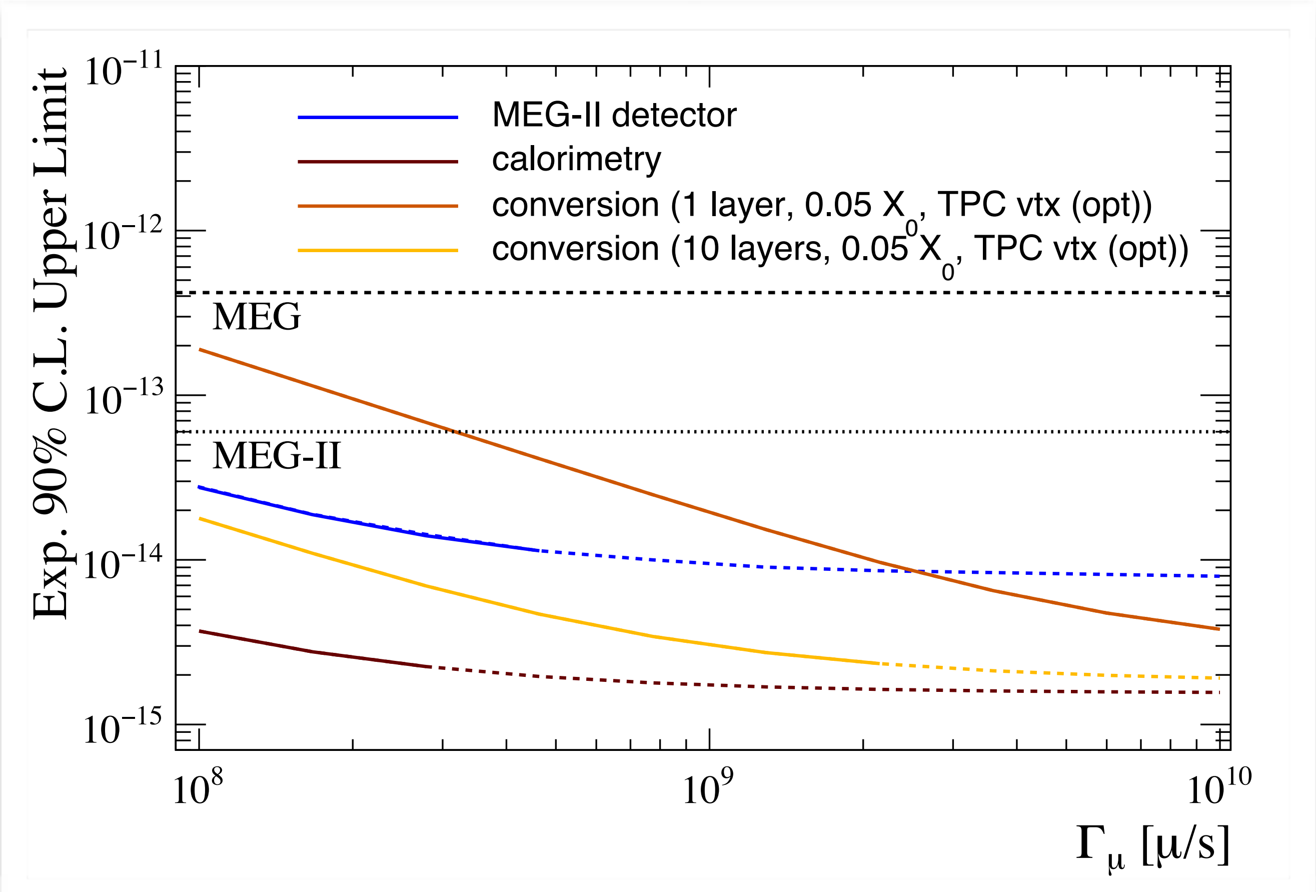
Variable	Resolution: w/o vtx detector	w/ TPC vtx detector: conservative	w/ TPC vtx detector: optimistic	w/ silicon vtx detector: conservative	w/ silicon vtx detector: optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			50		
E_e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

Discussion

- Projecting the $\mu \to e \gamma$ sensitivity to future experiments requires to take into account many subtle experimental effects
- Most of the experimental **limiting factors** will come from the **physics of the particle interaction** with the detector materials (MS, dE/dx, etc.):
  - *almost no room to break these limits by incremental improvements of the detector technologies!*
- **Significative technological efforts** still needed to sustain high intensity muon beams and to reach these limits (detector aging, pileup rejection, etc.)

Expected Sensitivity



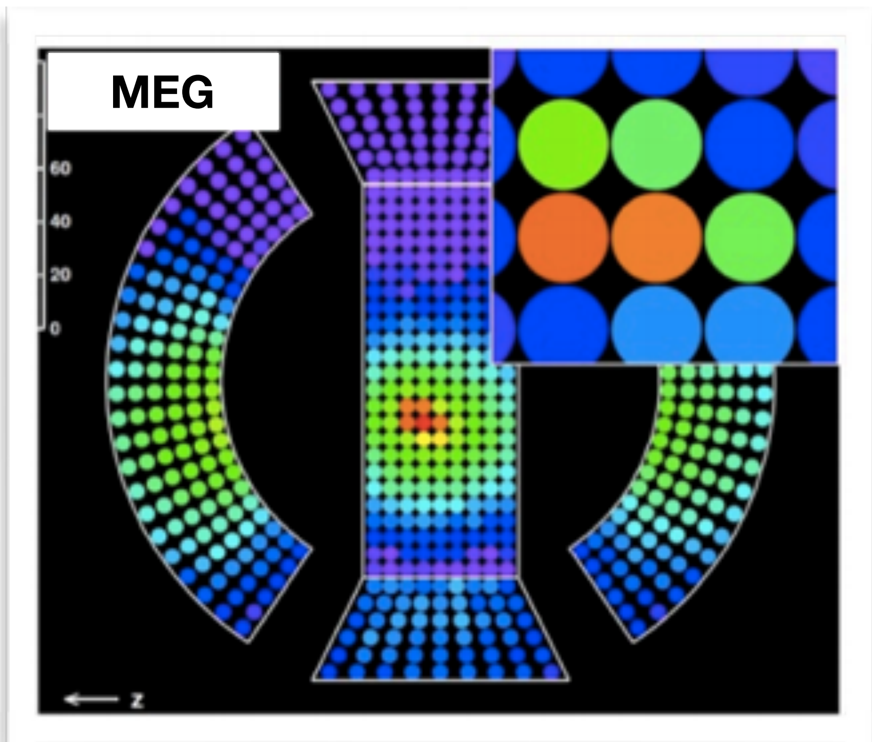


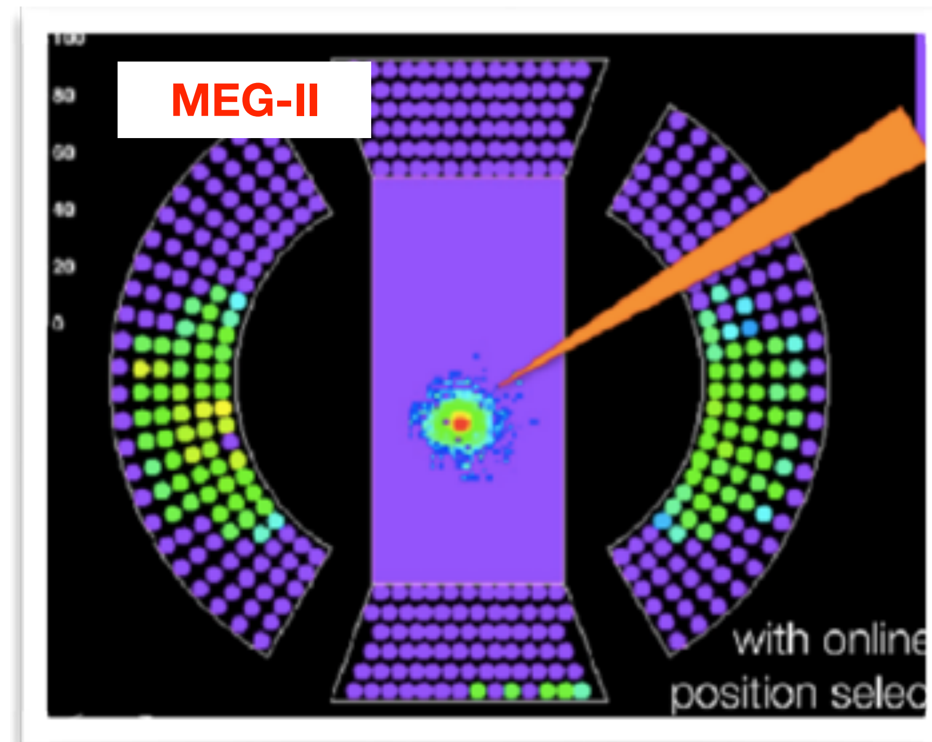
A few 10^{-15} seems to be within reach for a 3-year run at ~ 10^8 μ/s with calorimetry (*expensive*) or ~ 10^9 μ/s with conversion (*cheap*)

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

Backup

MEG-II Highlights - The LXe Calorimeter

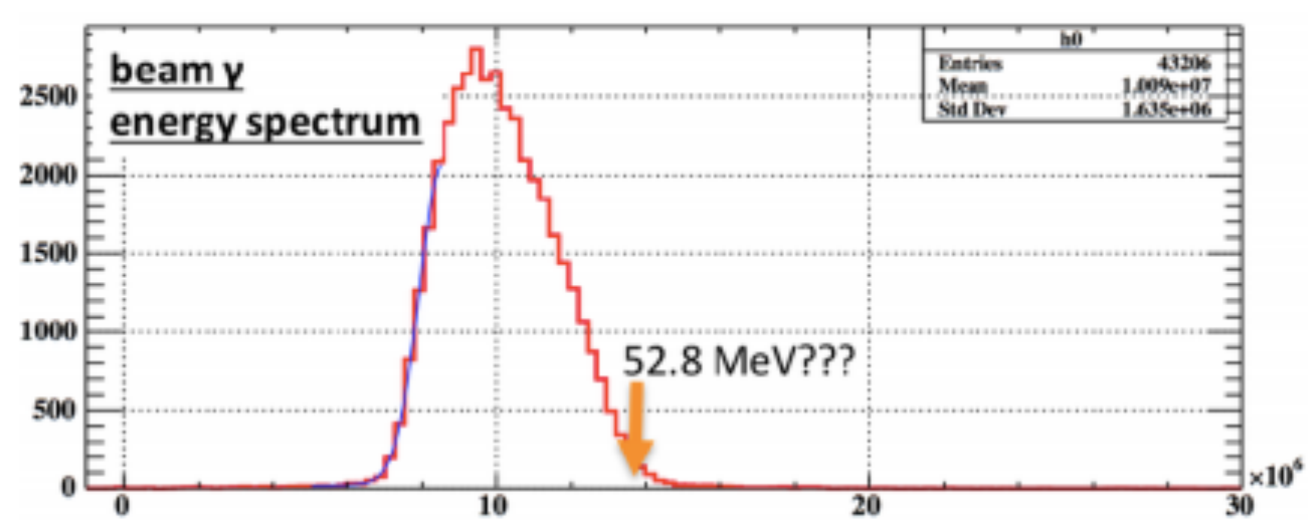




First events/spectra from 2017 data

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

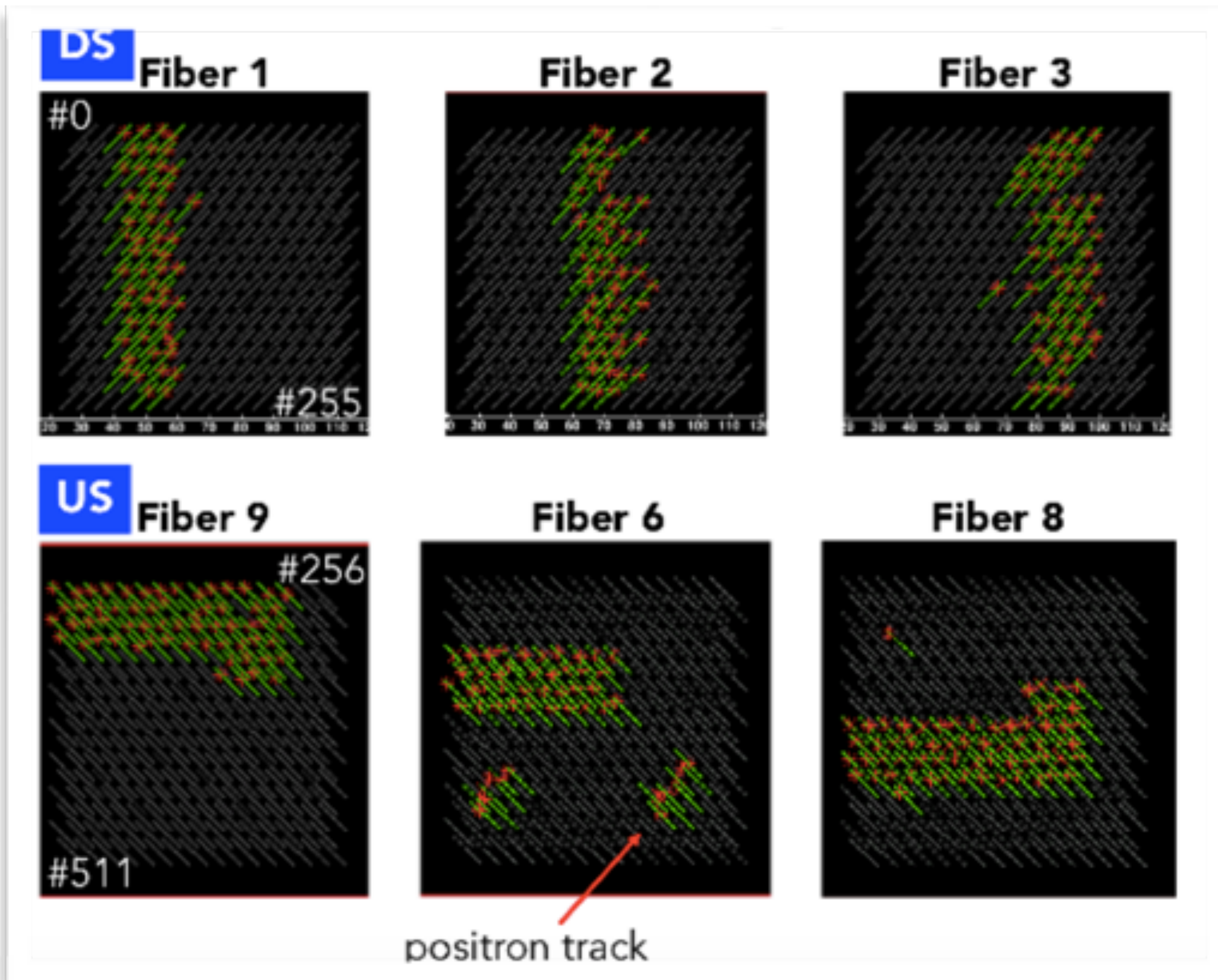


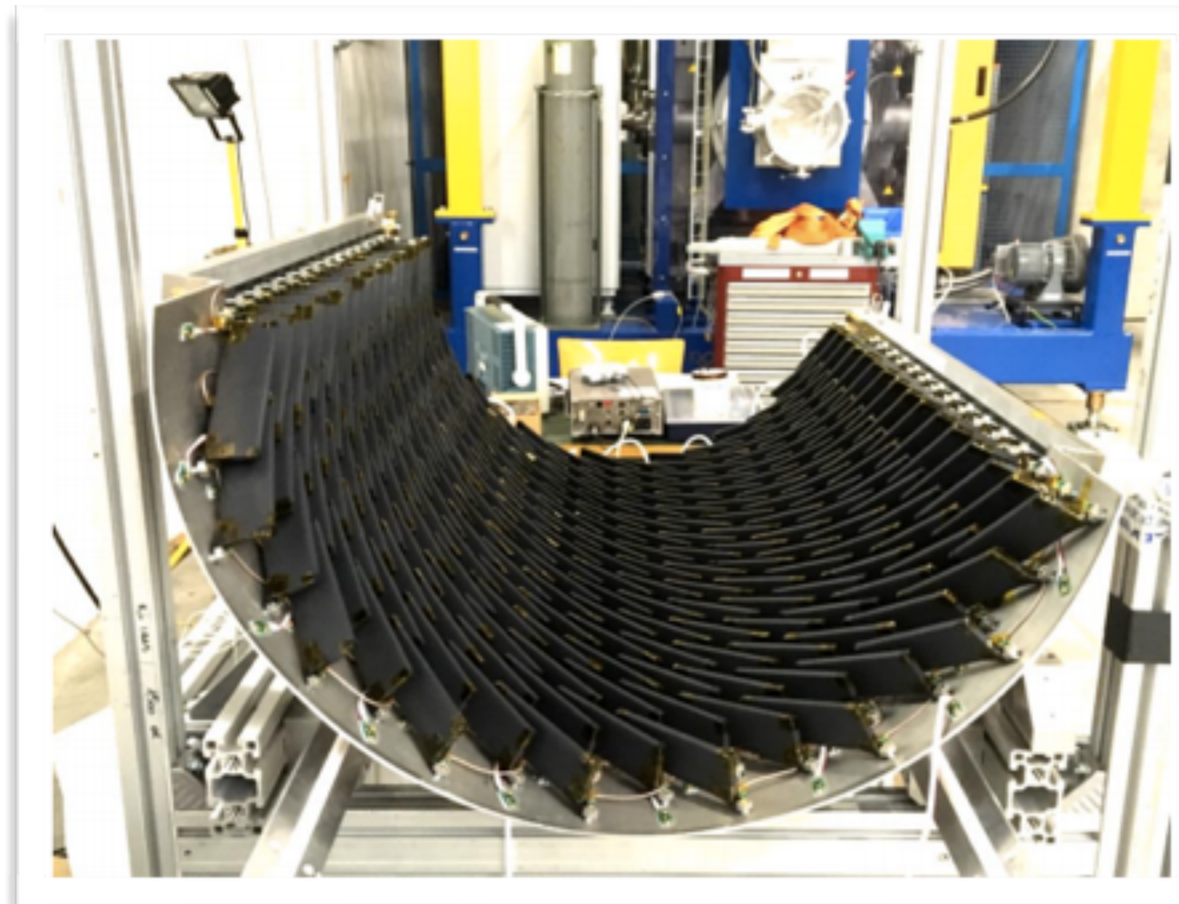
$\sigma_E \sim 1\%$, $\sigma_{position} \sim 2/5$ mm (x,y/z)

MEG-II Highlights - The Timing Counters

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

Complete detector took data in 2017



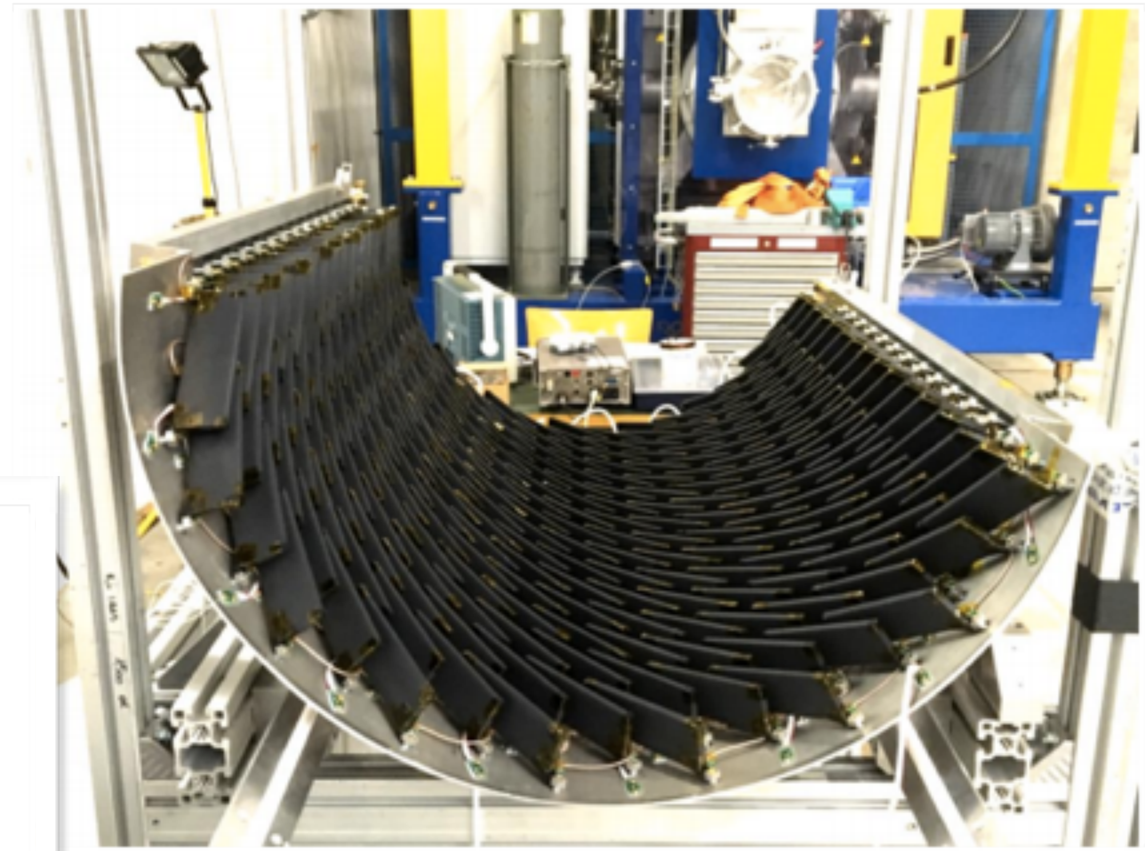


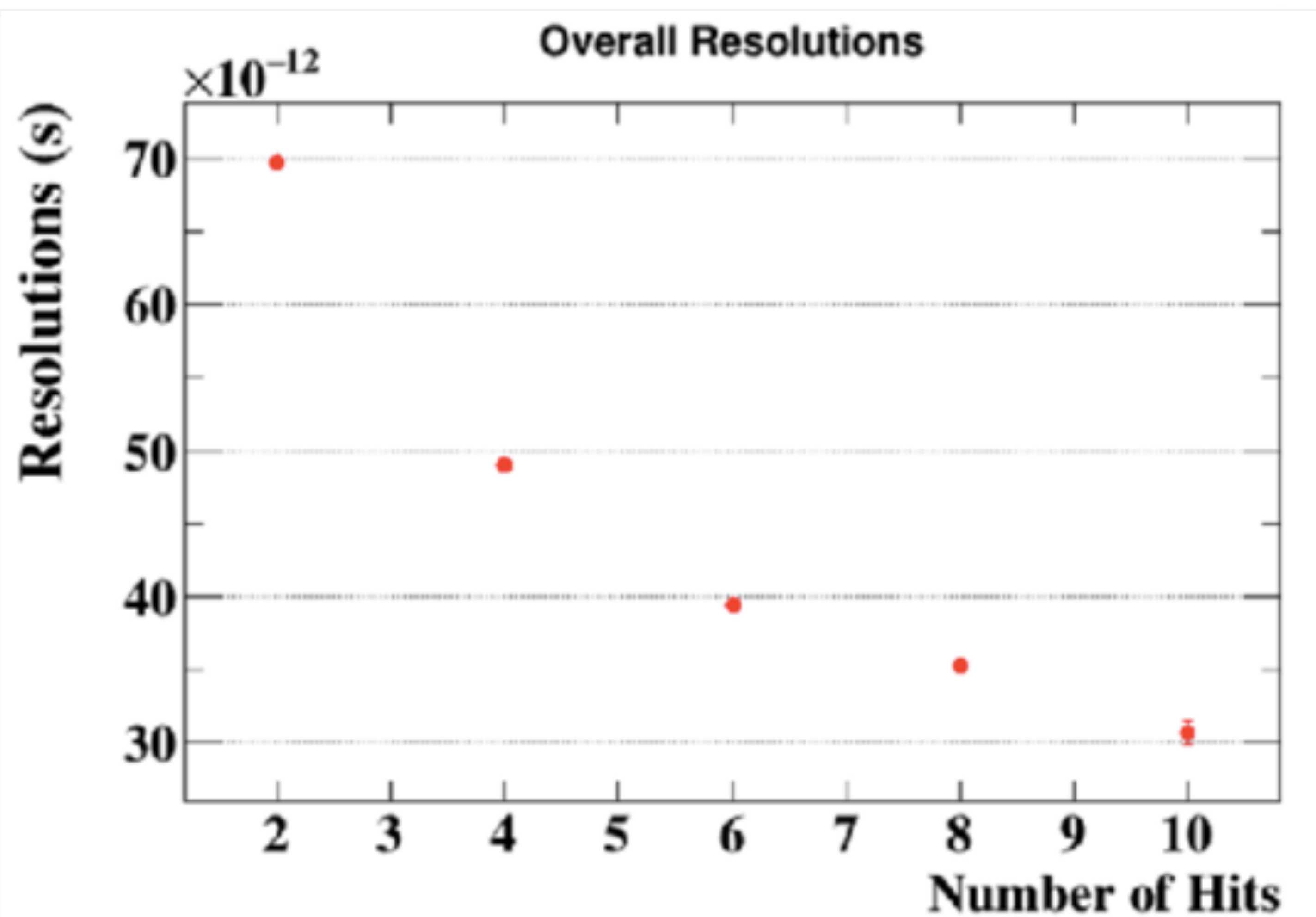
Calibration with dedicated laser

MEG-II Highlights - The Timing Counters

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

Complete detector took data in 2017

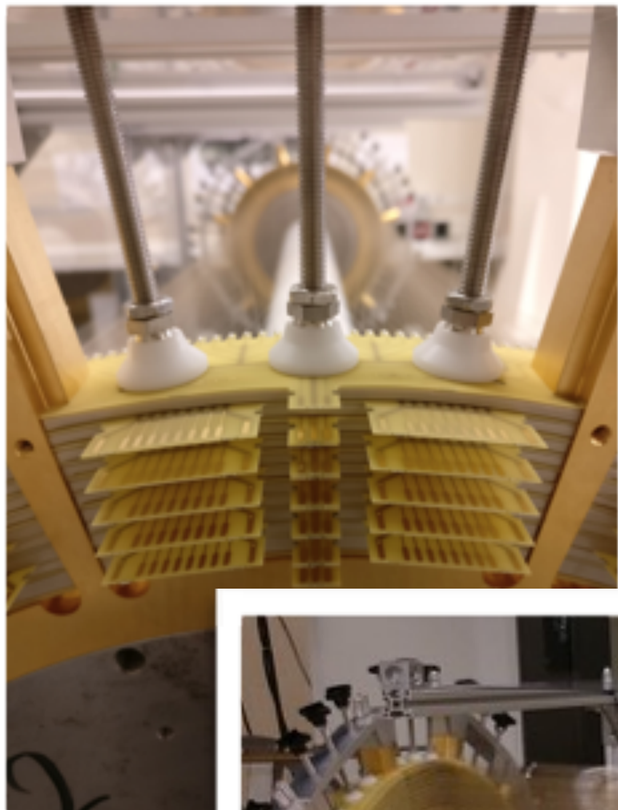




$\sigma_T \sim 35$ ps

Already reached the design resolution

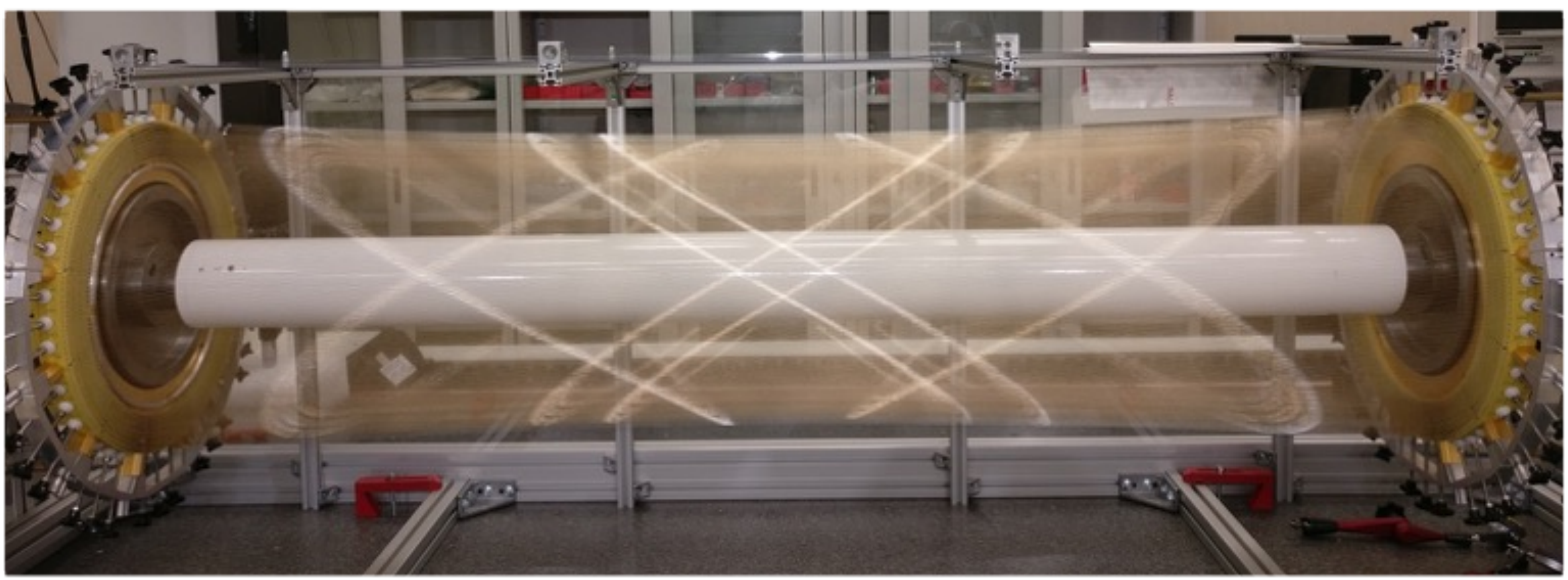
MEG-II Highlights - The Drift Chamber



Wiring, assembly and sealing have been completed

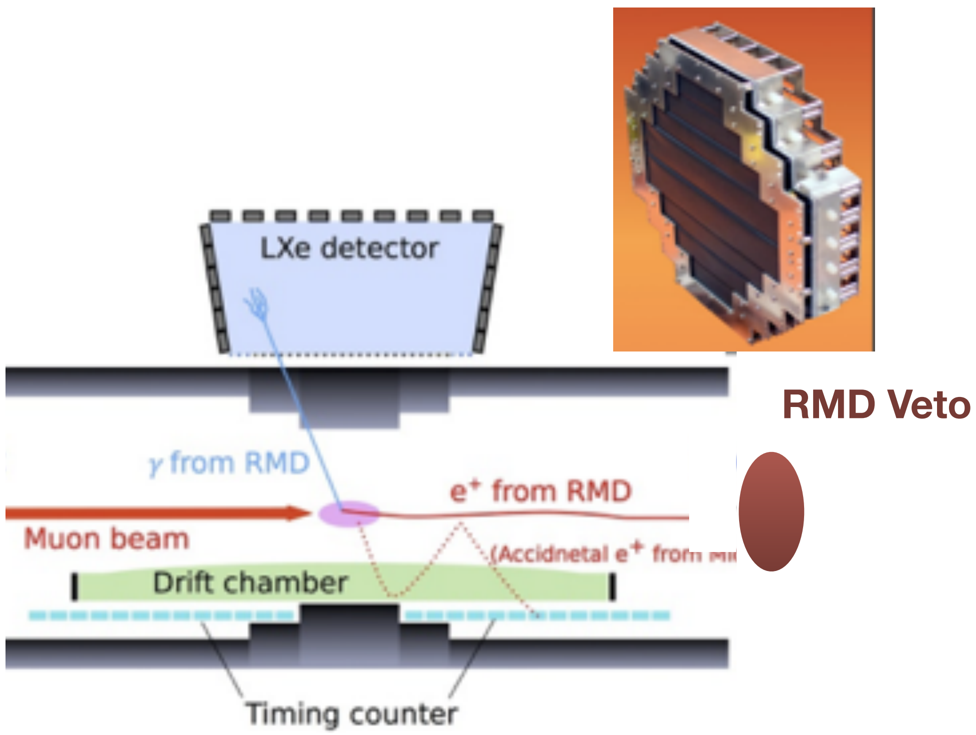
Had to face severe problems of wire fragility in presence of contaminants + humidity

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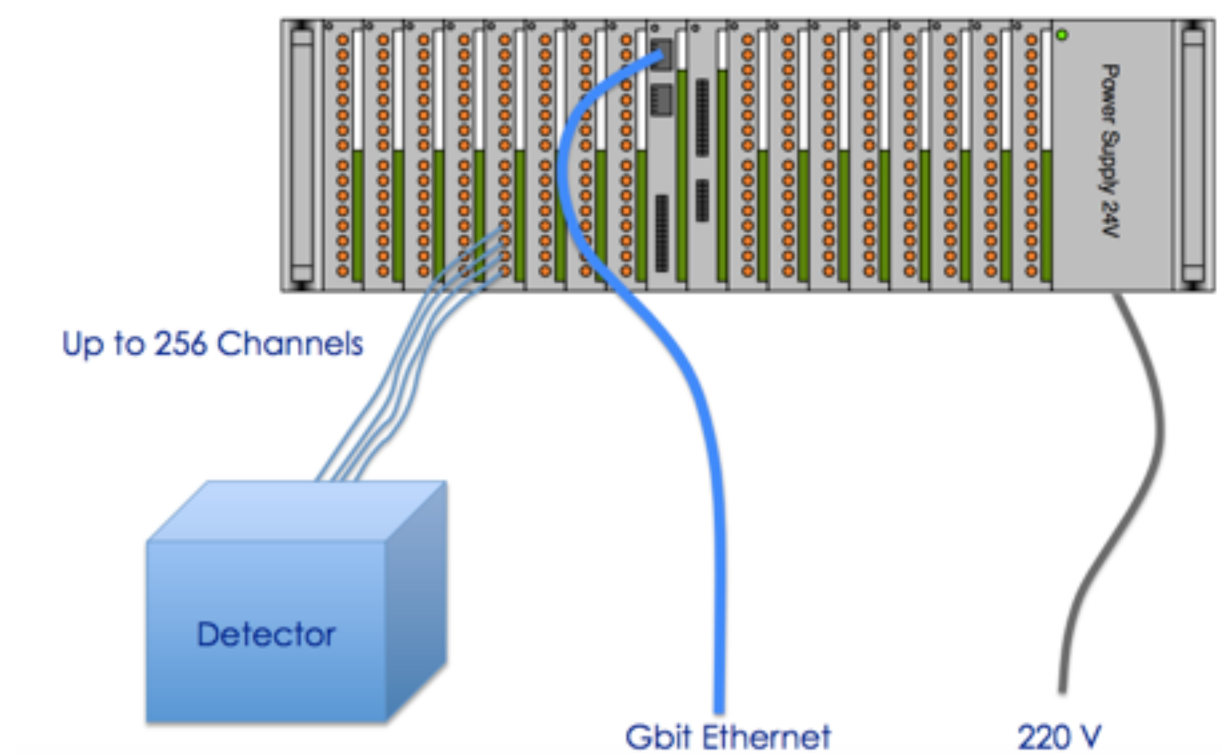
Trigger and DAQ will be integrated in a single, compact system (WaveDAQ)

Also provides power and amplification for SiPM/MPPC

Successfully tested in 2017 with XEC, TC and RDC



MEG-II schedule & sensitivity

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

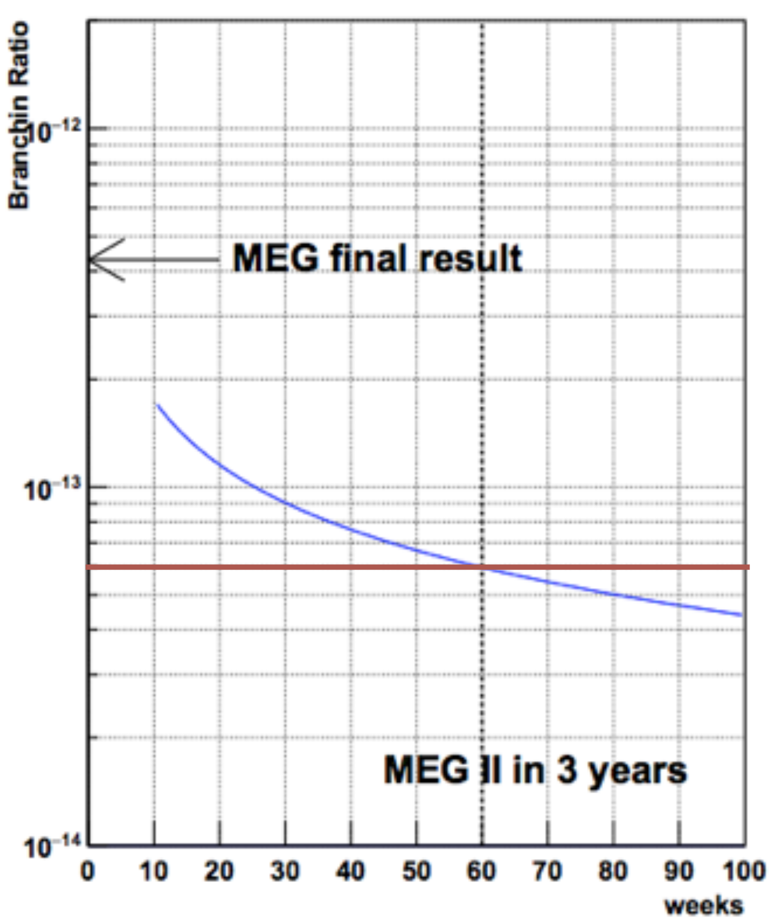
PROPOSAL

R&D

Construction & Commissioning

Engeneering Runs

Physics Runs

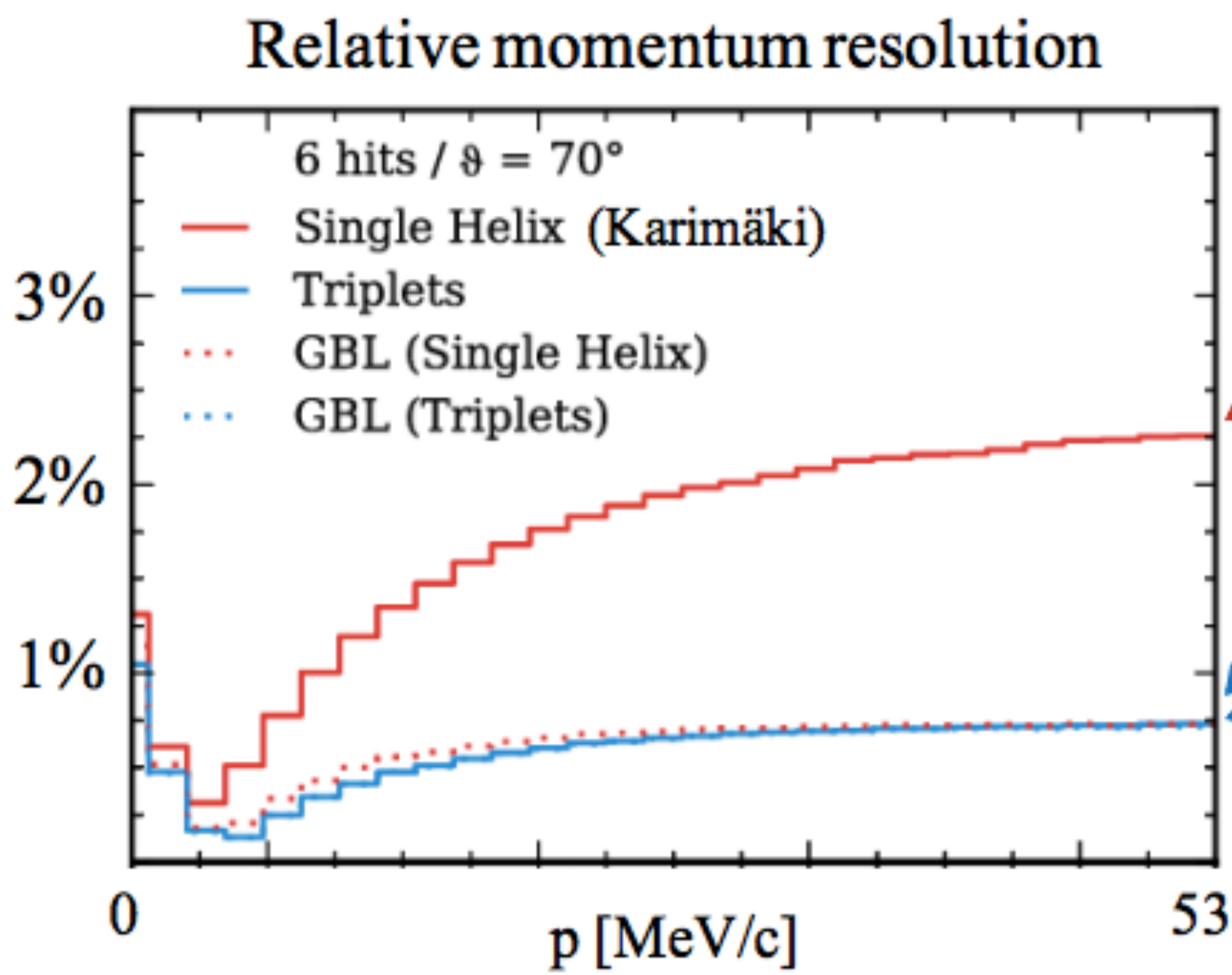


6×10^{-14}

Silicon detector momentum resolution

Mu3e momentum resolution (B = 1T)

4x worse than MEG-II



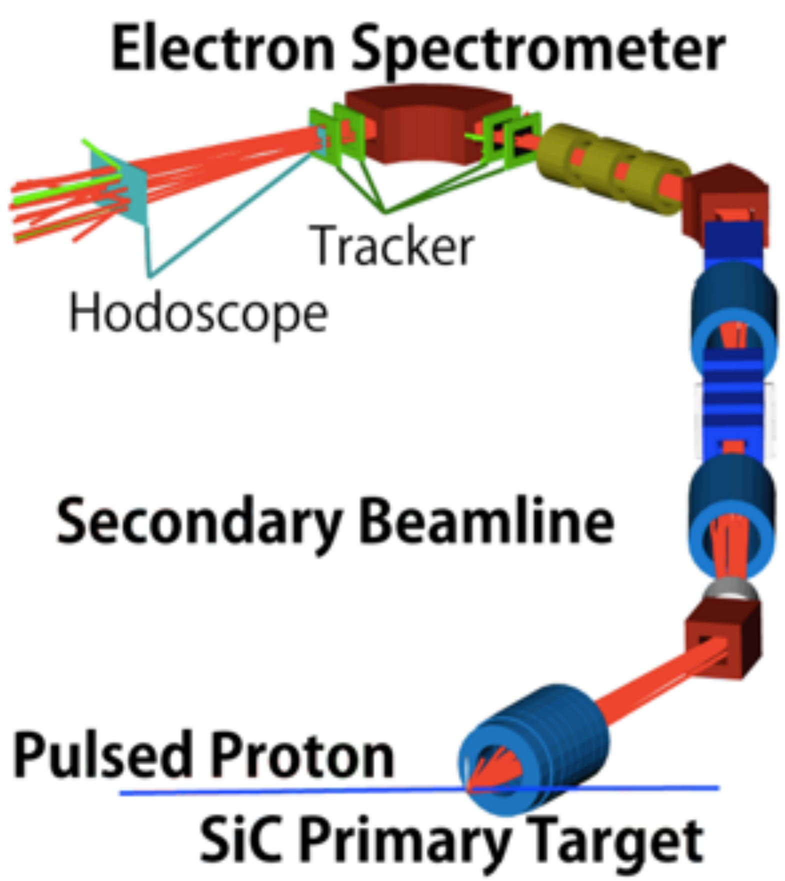
Single Helix (Karimäki)
- Neglect MS

Triplets
- MS fit

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

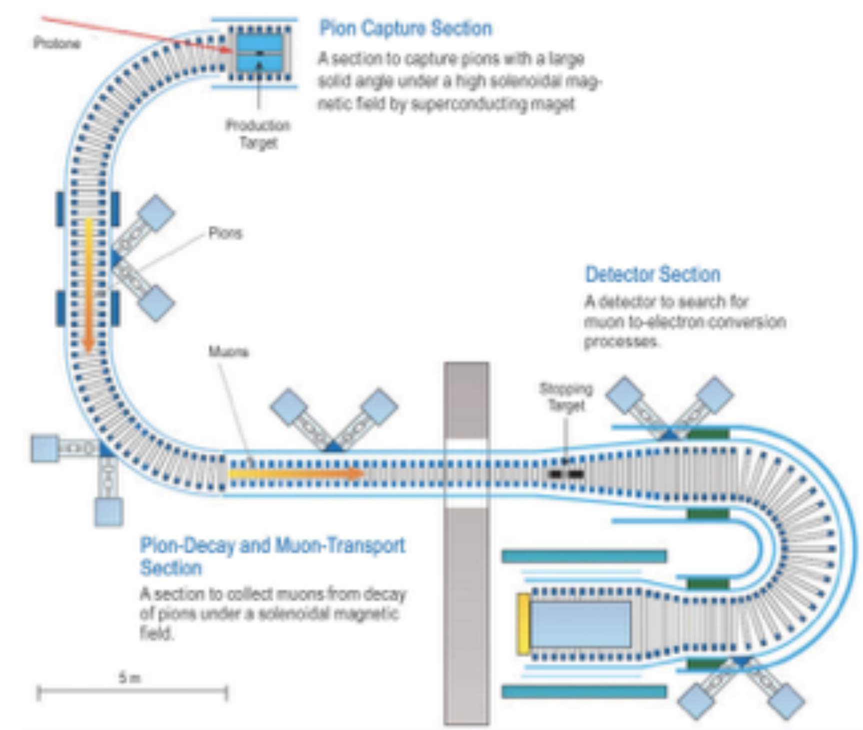
A. Kozlinskiy, Mu3e Collaboration, CTD/WIT 2017

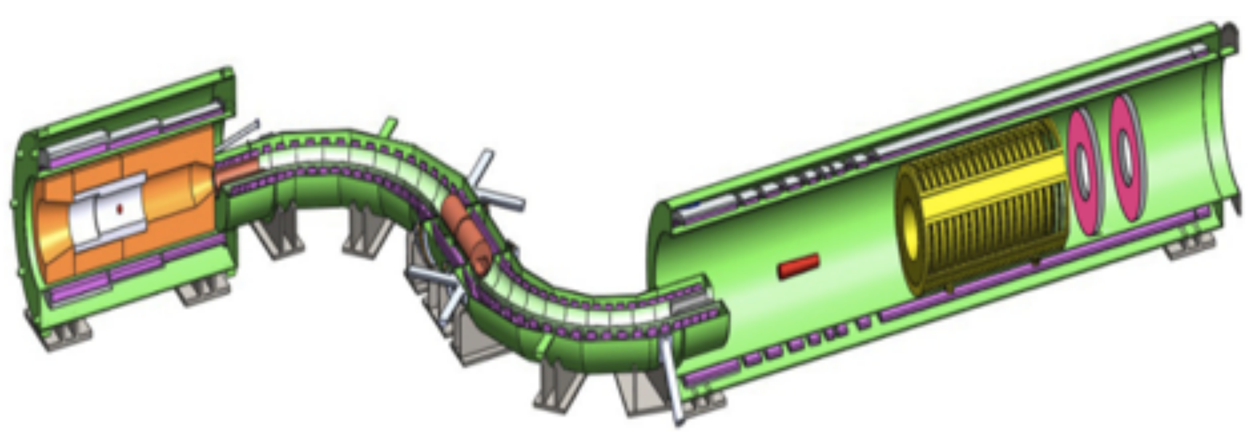
DeeMee / COMET / Mu2e



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

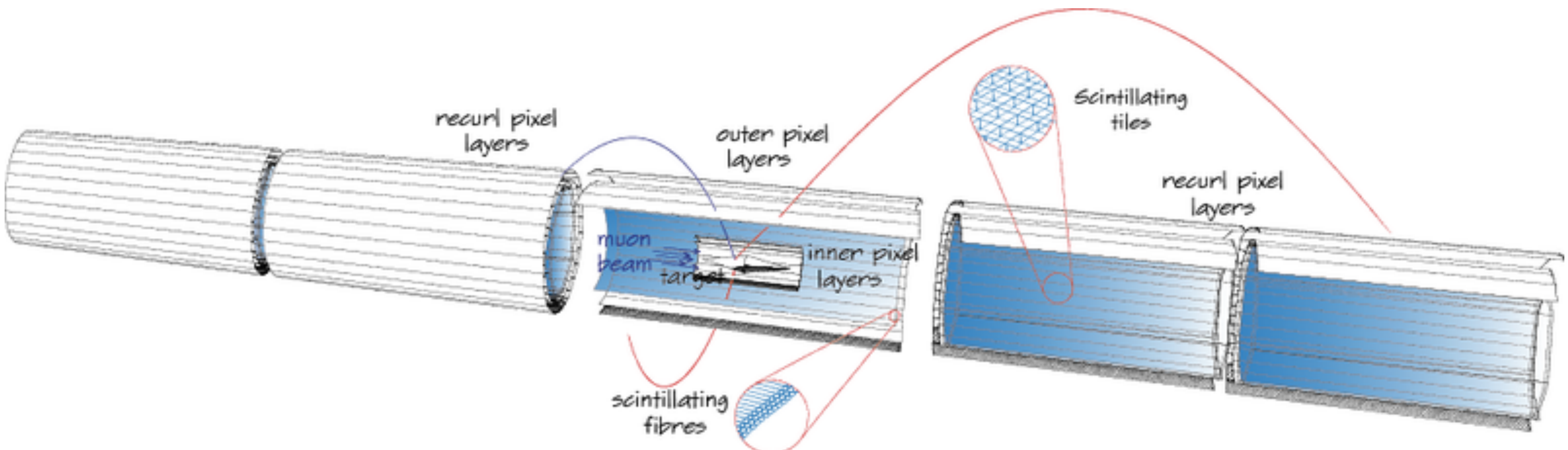
COMET: Will start phase-I commissioning ~ 2019 phase-II SES ~ 10^{-17}





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}