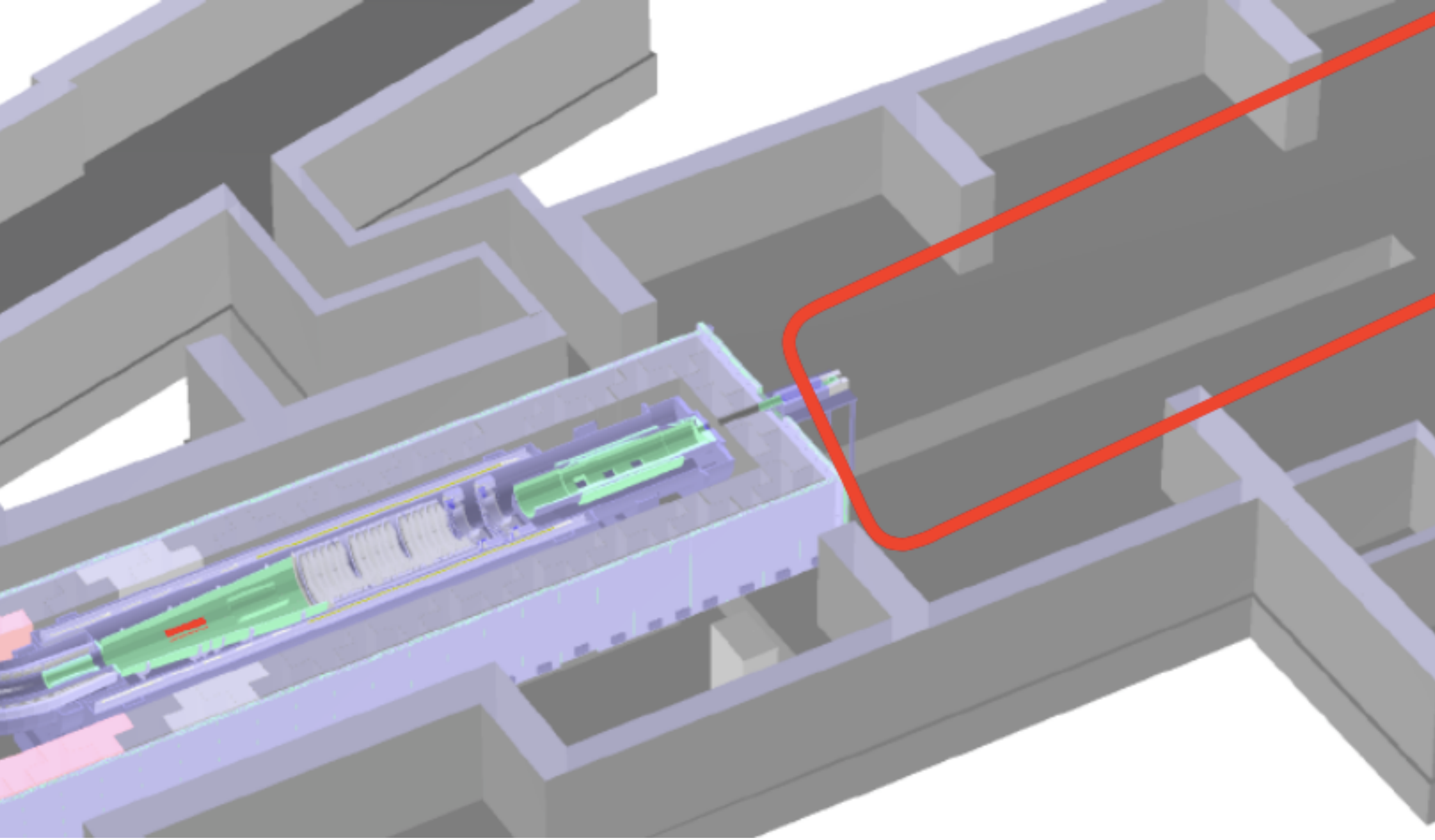


Prospects for a new cLFV program at FNAL

Francesco Renga - *INFN Roma*
Robert Bernstein - *FNAL*
David Neuffer - *FNAL*

Outline

- Generalities of rare muon decay searches
- **$\mu \to e\ \gamma$** and **$\mu \to 3e$** — search strategy, current status and future perspectives
- Future high-intensity muon beam lines
- **Prospects for a new cLFV program at FNAL**

Generalities of rare muon decay searches

- Key ingredients:
  - *high intensity muon beams*
  - *precise reconstruction of low-energy electrons, positrons and photons*

Continuous, low-momentum, positive muon beams are preferred:

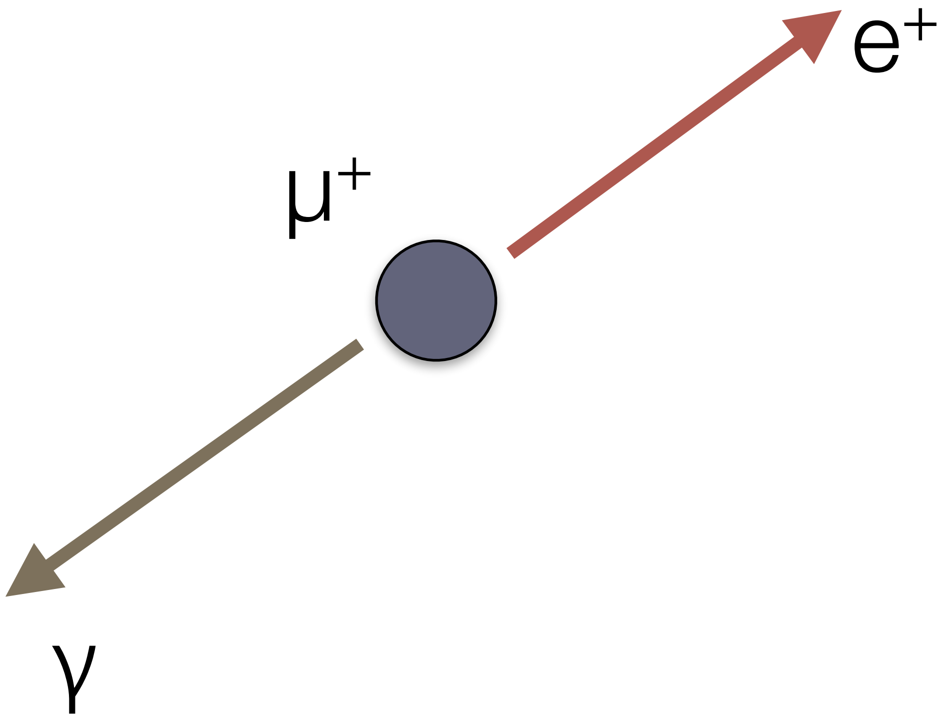
- continuous time structure to suppress accidental coincidences
- positive muons are not captured by nuclei (decay spectra not distorted)
- low-momentum to stop muons in thin targets (low material budget)

Tracking detectors with very low material budget

- gaseous detectors are preferred
- silicon detectors, if used, need to be pushed at the technological limits in terms of material budget

Photon detectors tailored for low energies

μ -> e γ searches

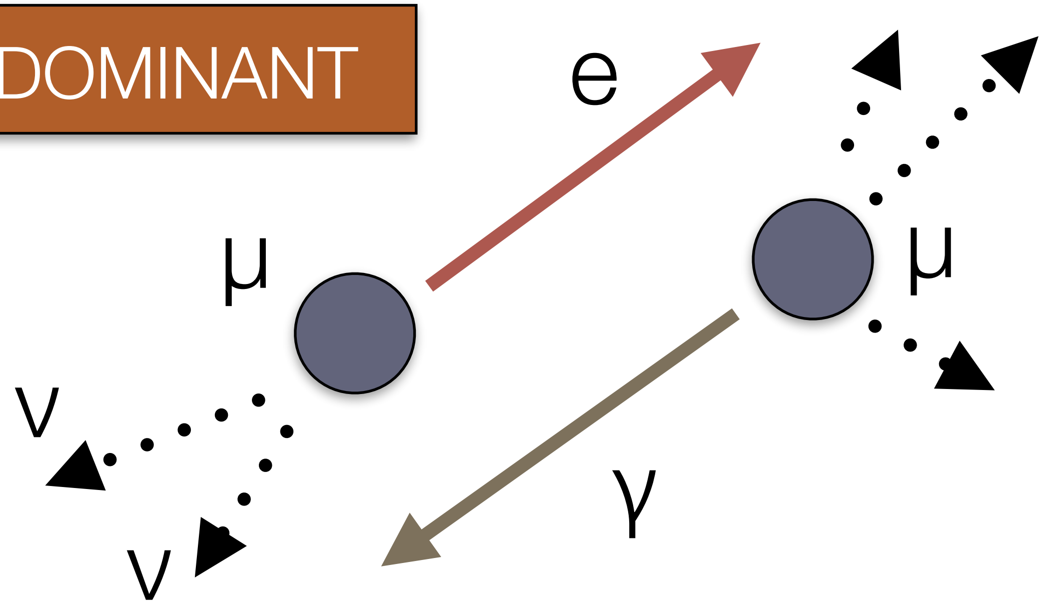


28 MeV/c muons are stopped on a thin target

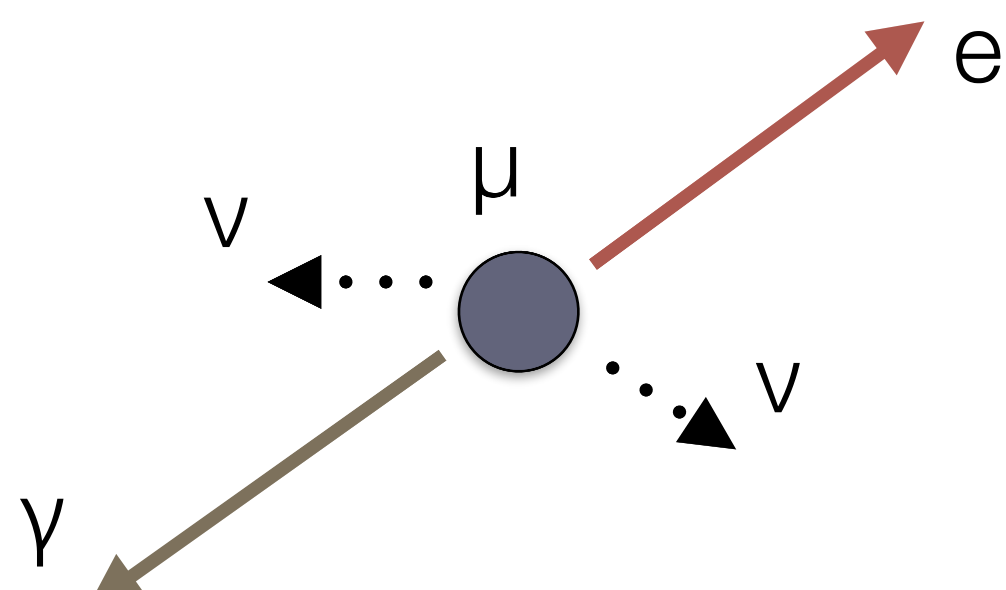
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the **same time**;

Accidental Background

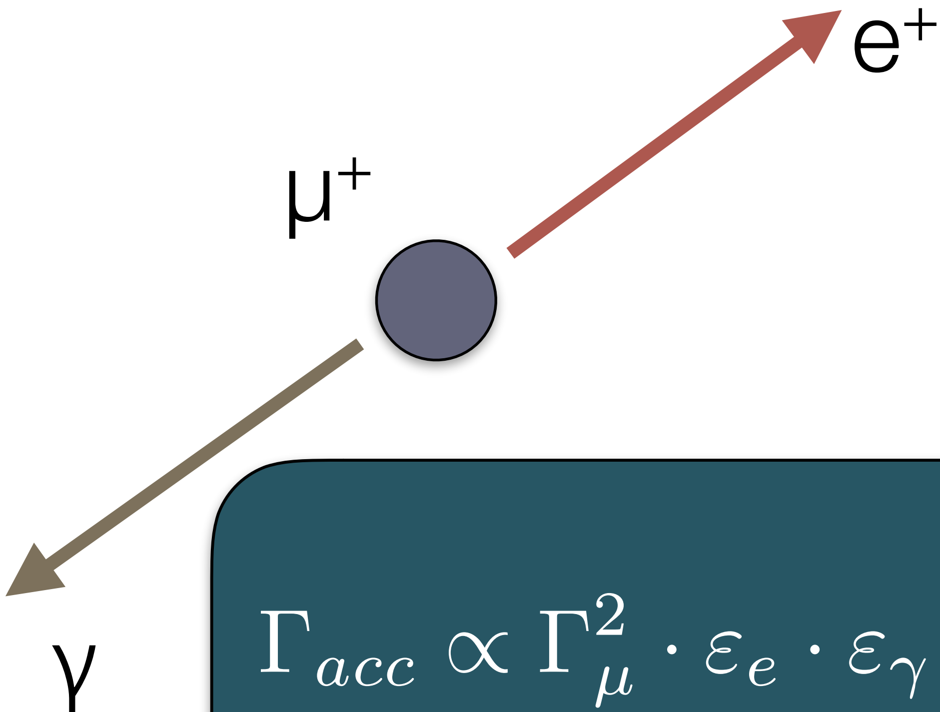
DOMINANT



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**;

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

Accic... ... **...ay (RMD)**

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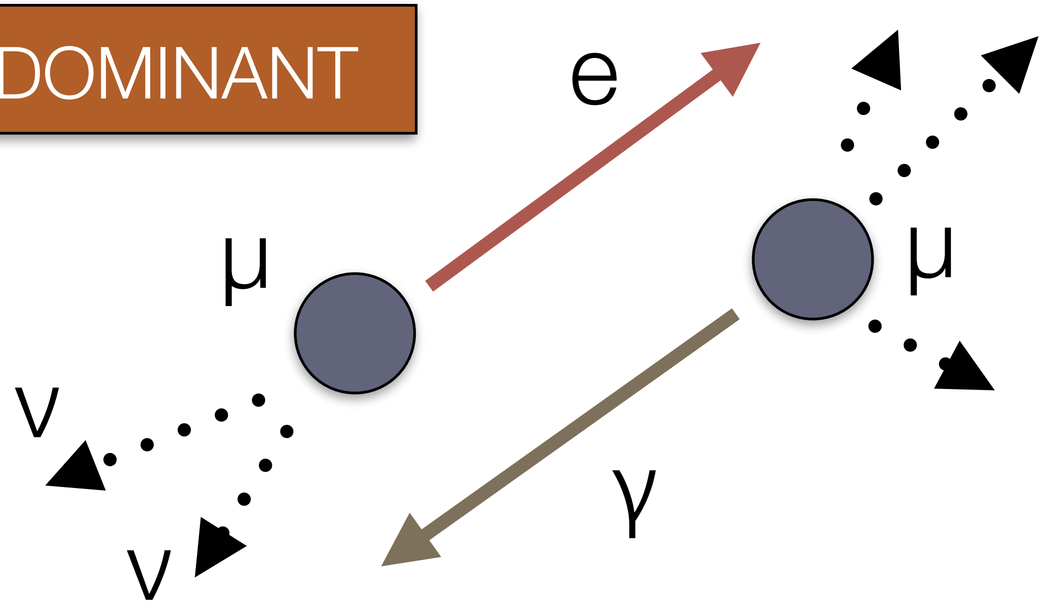
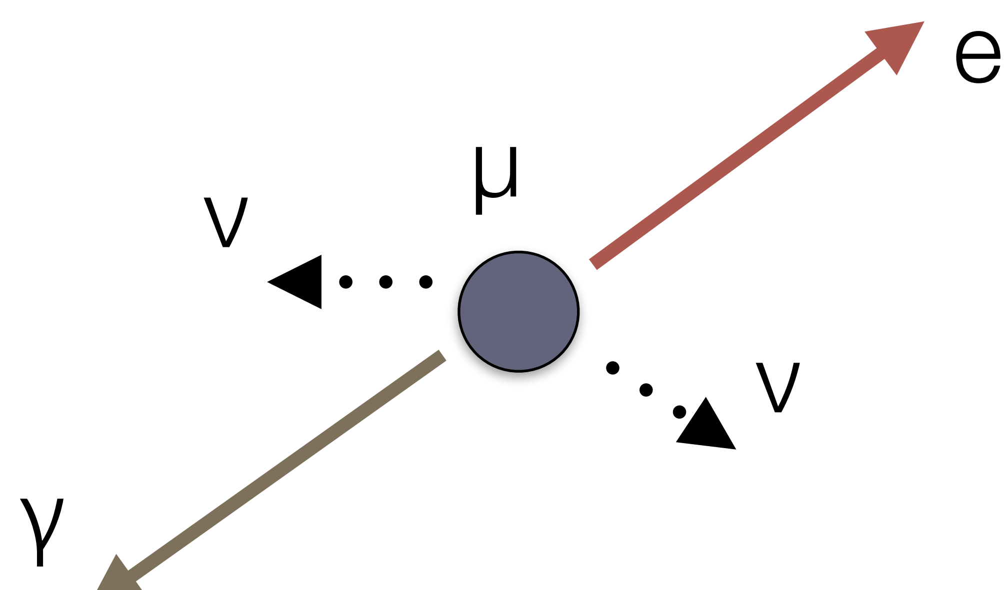




μ -> e γ searches — Some critical aspects

- Extremely good positron resolutions require very **low multiple scattering**, not only in the detector but also **in the target**

In MEG-II, the target thickness necessary to stop most of the muons is almost enough to make MS in the target one of the dominant contributions to the angular resolution

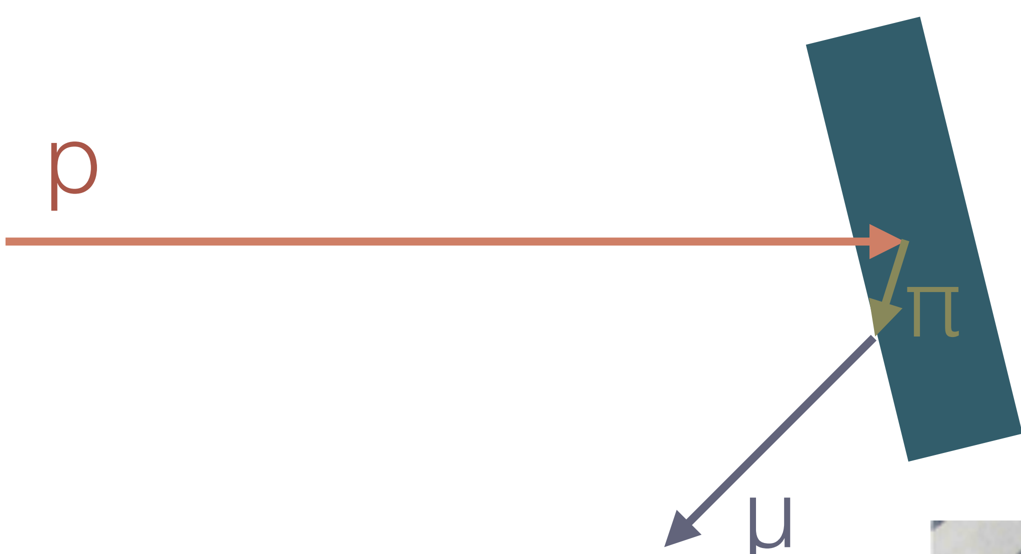
—> a beam with *low energy* and *low momentum bite* is necessary in order to stop muons in a very thin target

- **Time resolution** is critical both on the positron and photon side

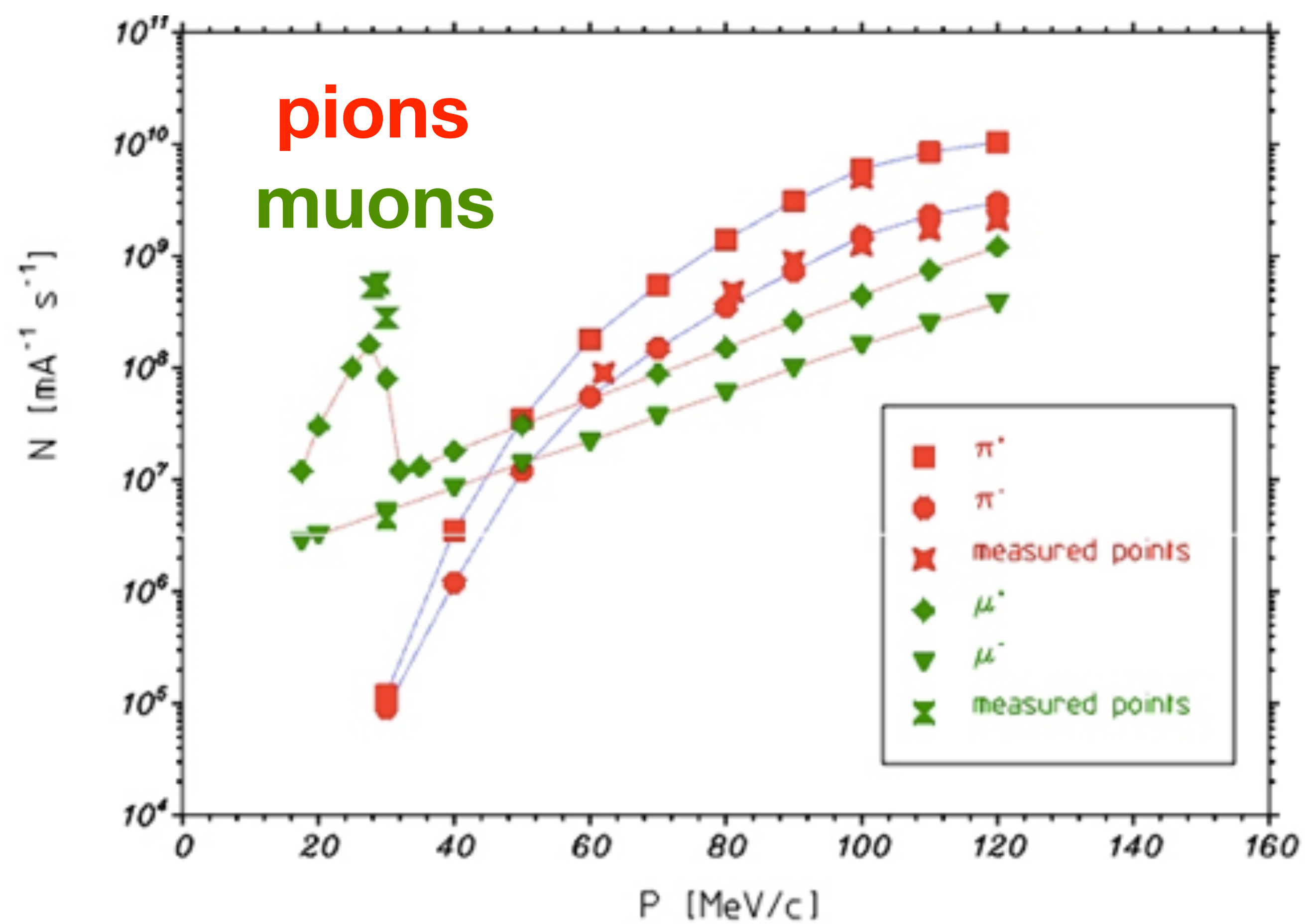
- **Aging** of detectors to be carefully considered

Surface muons

- Surface muons:
  - from pions decaying at rest near the surface of a proton target
  - p ~ 30 MeV/c, E_{KIN} ~ 4 MeV



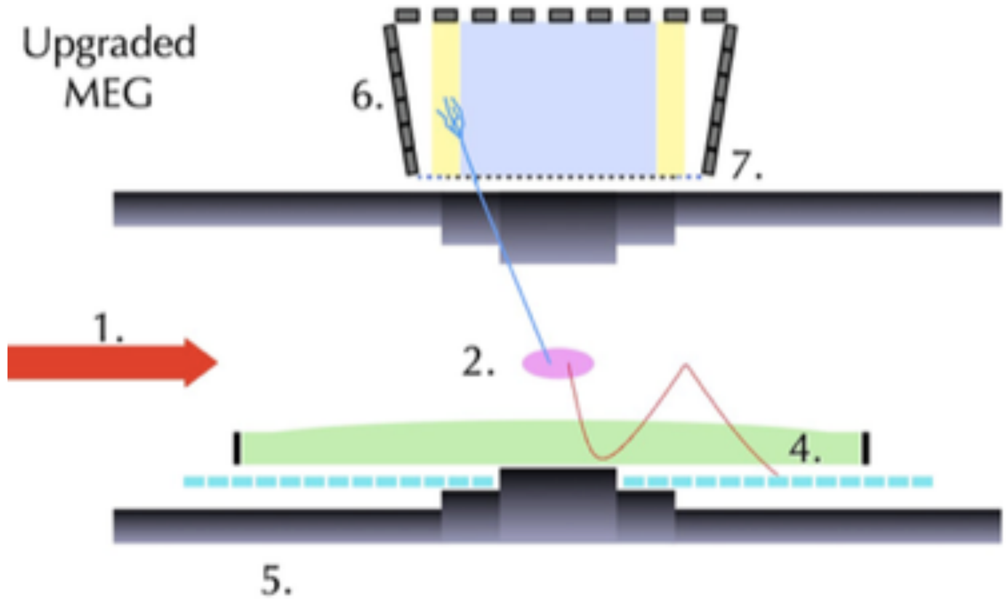
PSI “target E”

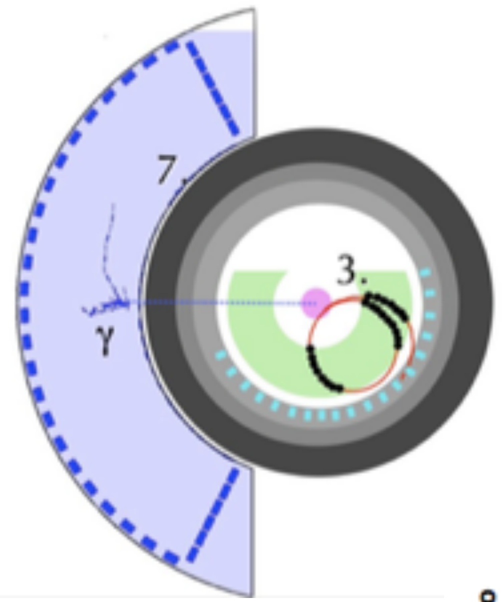


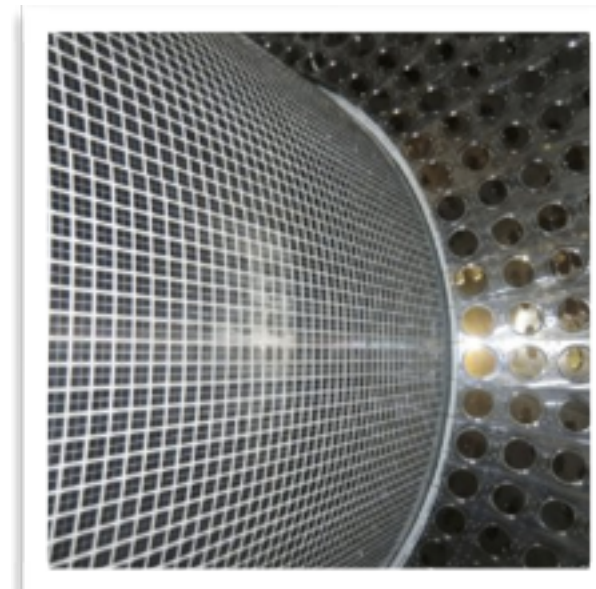
Surface muons

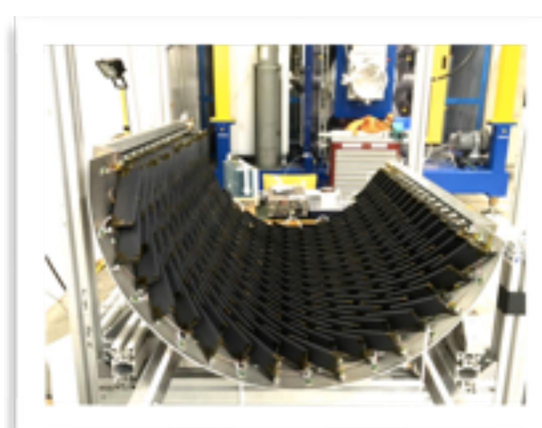
- Surface muons:
  - from pions decaying at rest near the surface of a proton target
  - p ~ 30 MeV/c, E_{KIN} ~ 4 MeV
- A convenient choice for rare muon decay searches:
  - high intensity
  - high purity
  - low energy
  - low momentum bite

MEG-II status



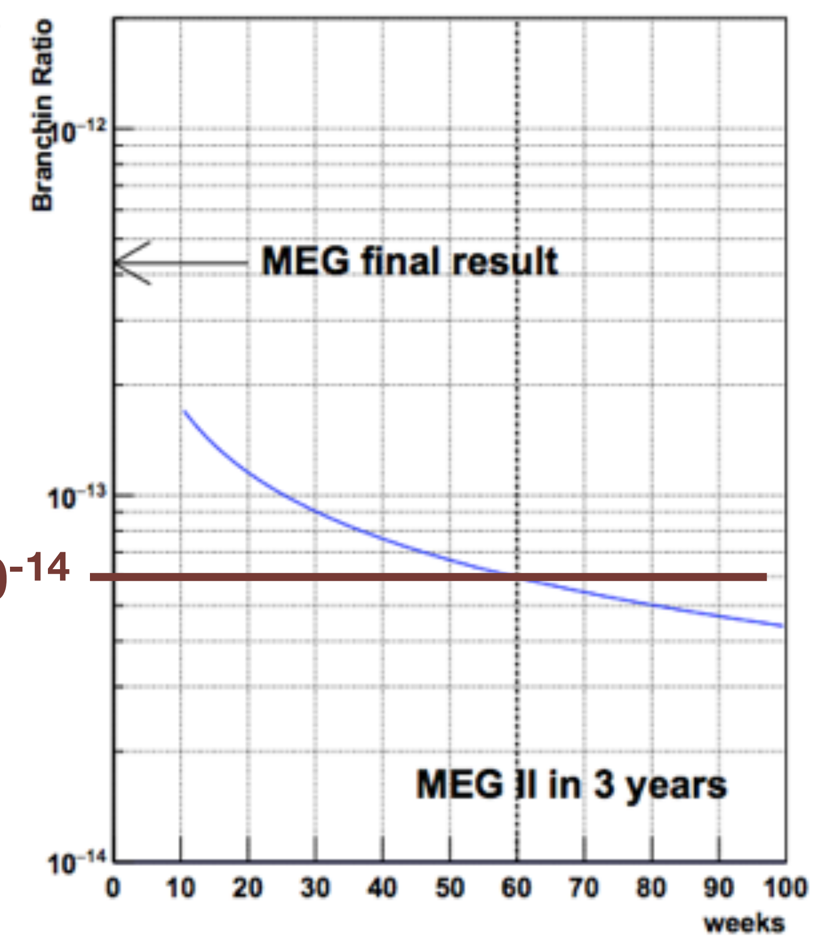






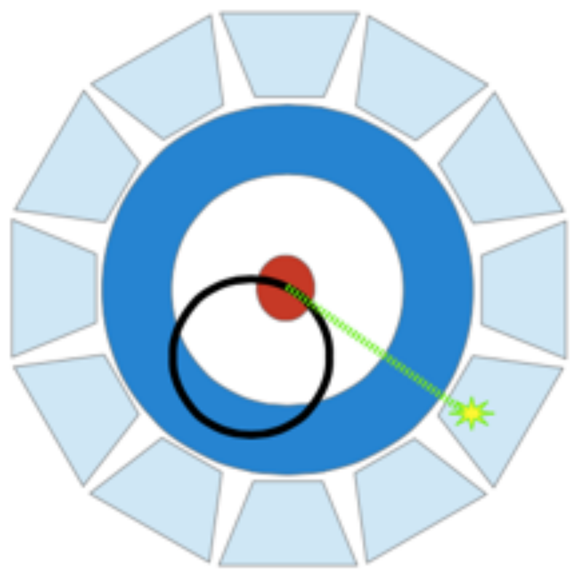
Final detector integration in fall 2020
First physics run in 2021

~ 6 x 10^{-14}



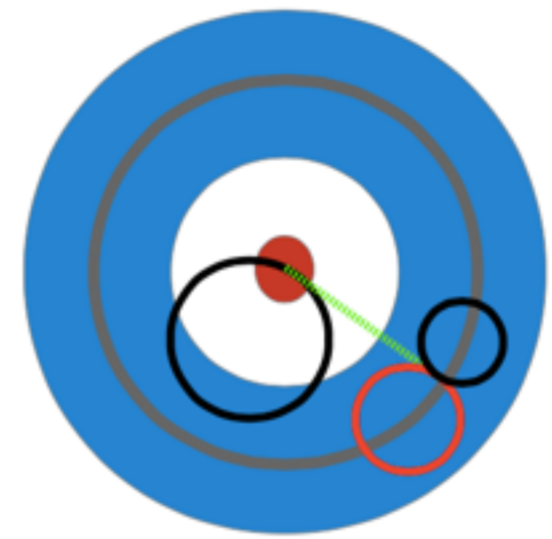
G. Cavoto, A. Papa, FR, E. Ripiccini and C. Voena
Eur. Phys. J. C (2018) 78: 37

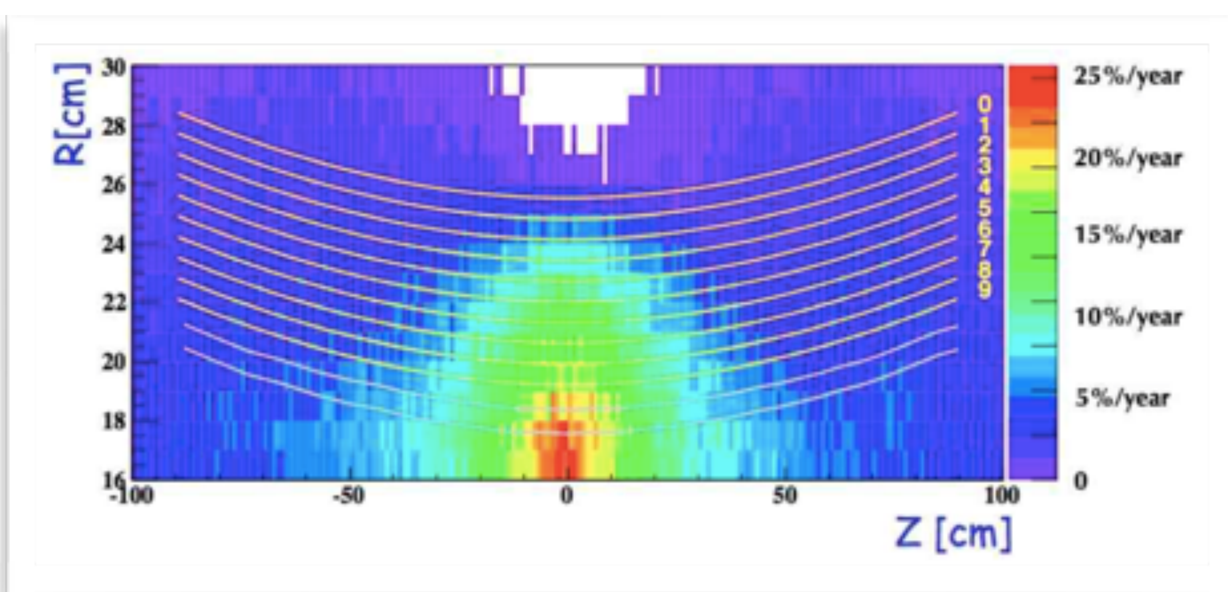
μ -> e γ searches — Future perspectives



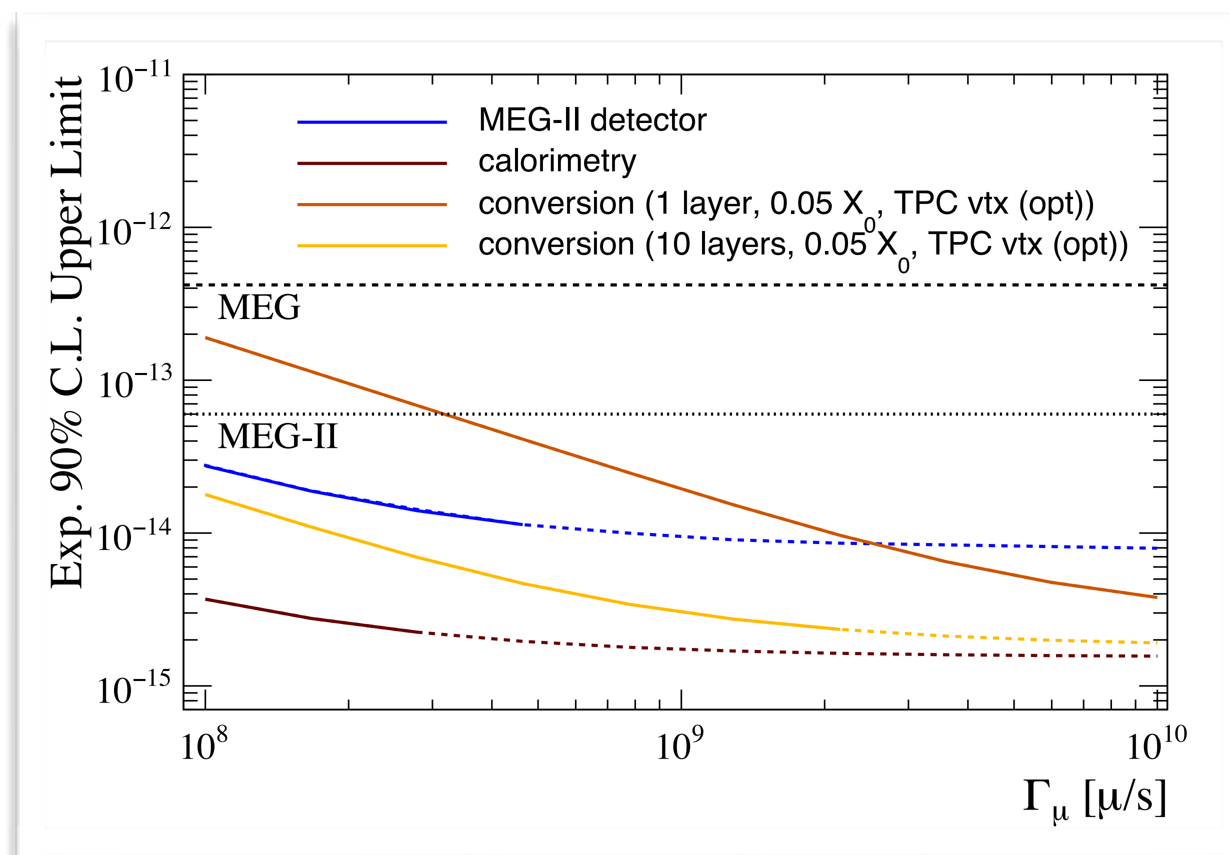
Calorimetry vs. Photon conversion

High efficiency vs. extremely good resolutions & low cost



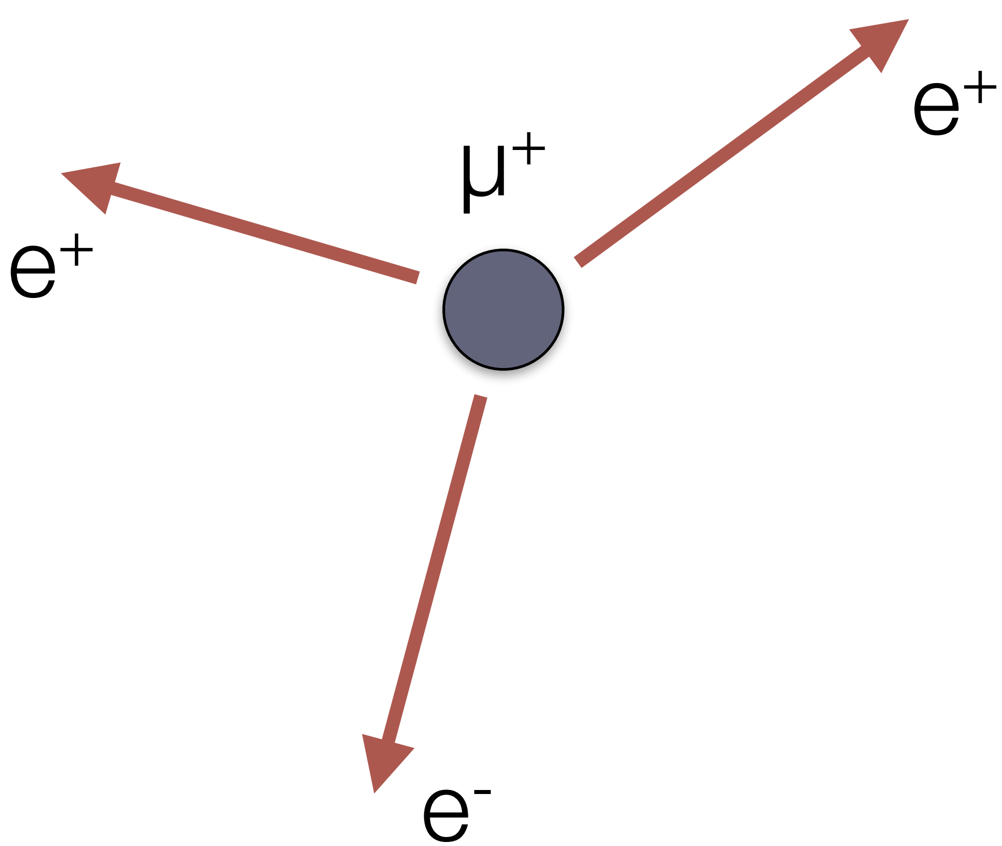


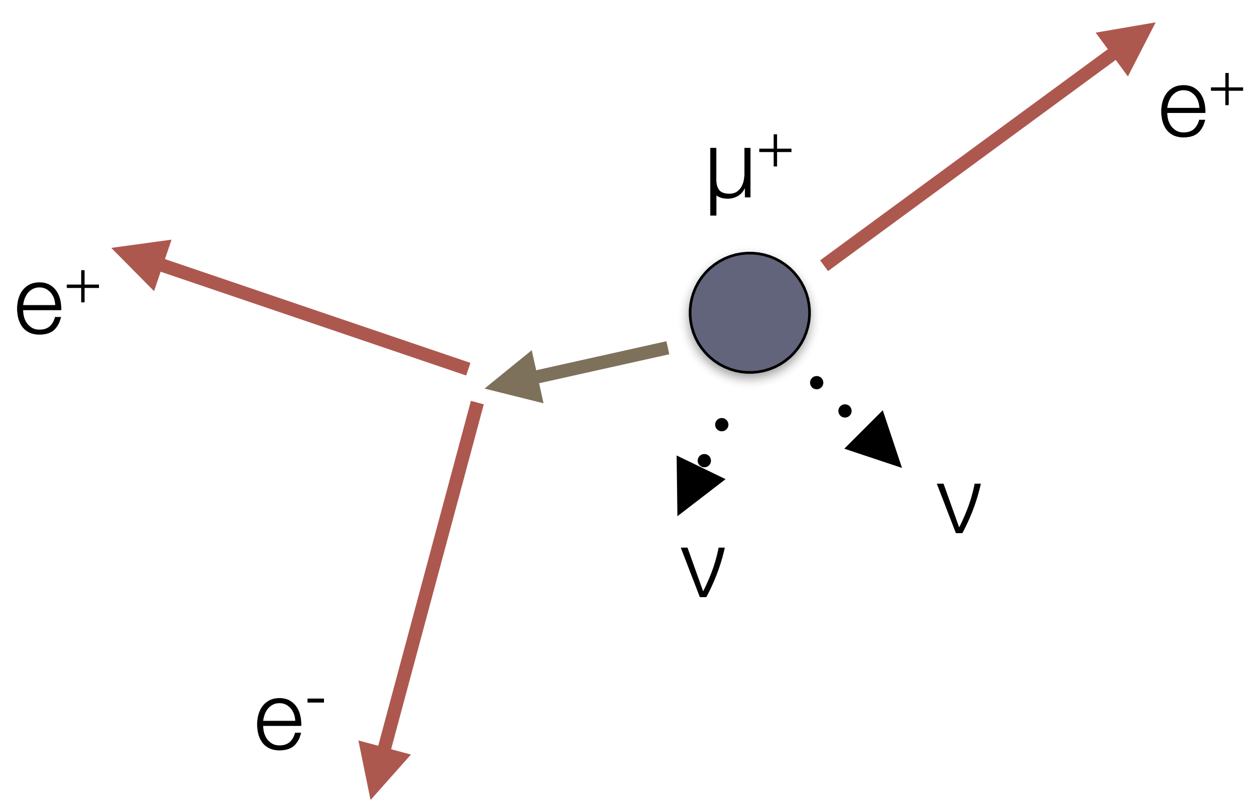
Gaseous detector aging will be an issue



μ -> 3e searches

- 3 charged tracks allow for vertexing:
  - strong suppression of accidental background —> higher beam rates can be exploited
  - excellent 3-momentum resolution to reject SM background —> low material budget

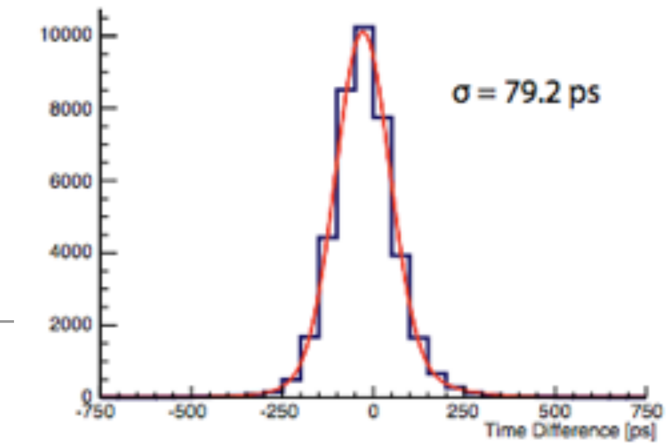


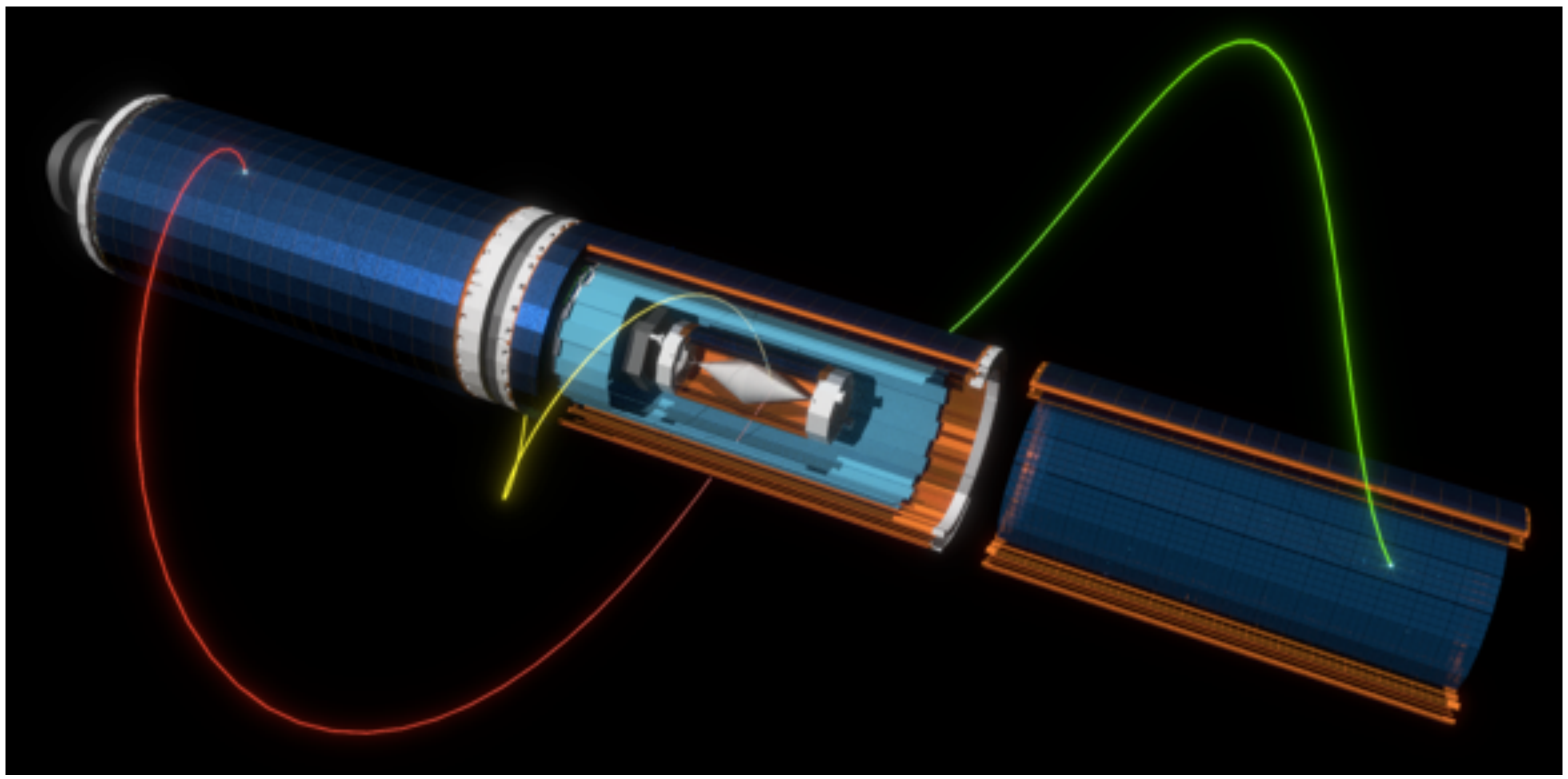


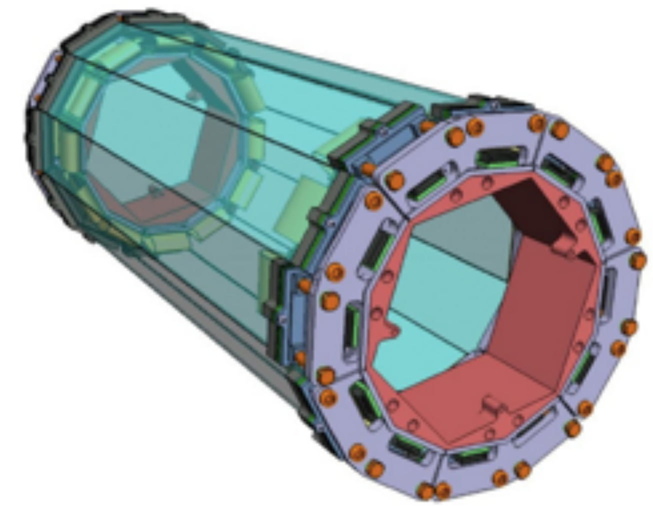
RMD + Internal pair conversion

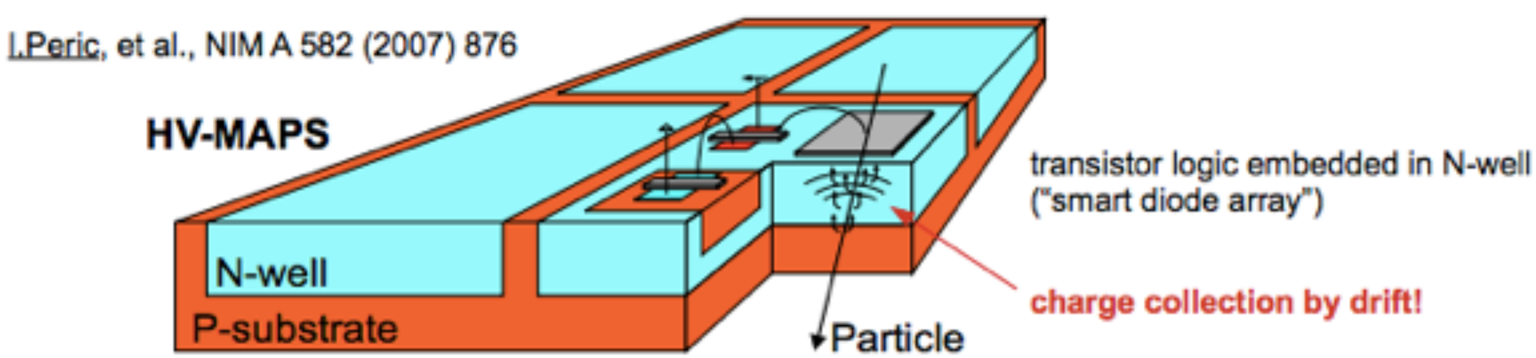
Mu3e status

Successful test beam of timing detectors in 2019







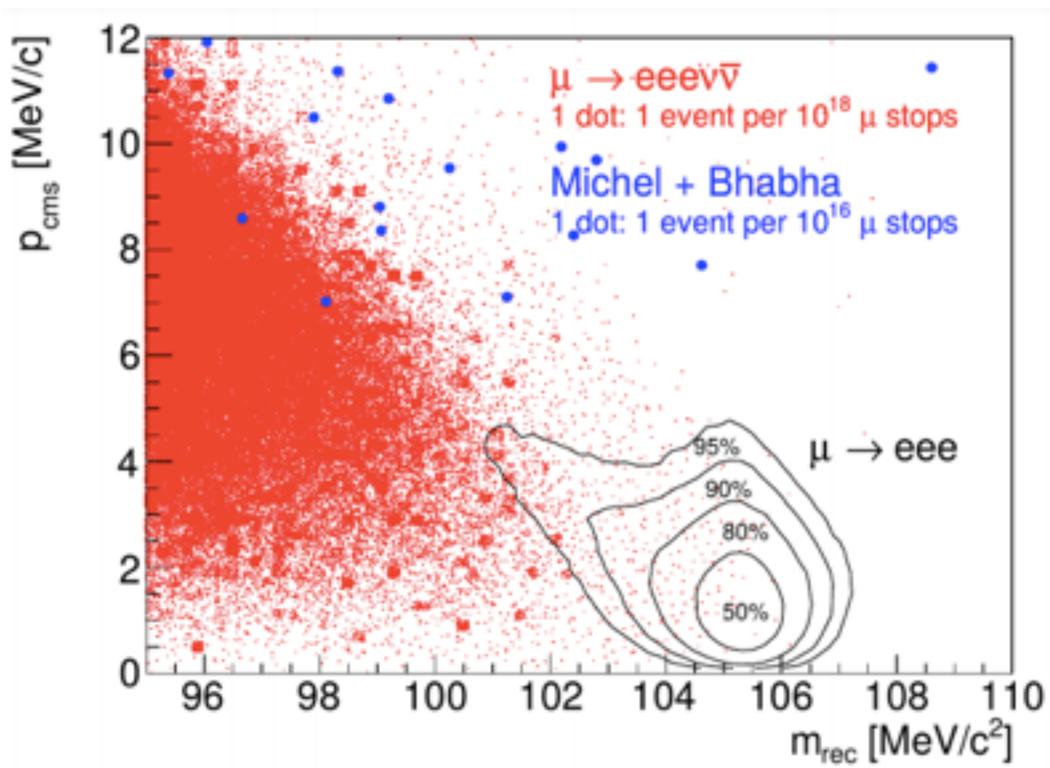


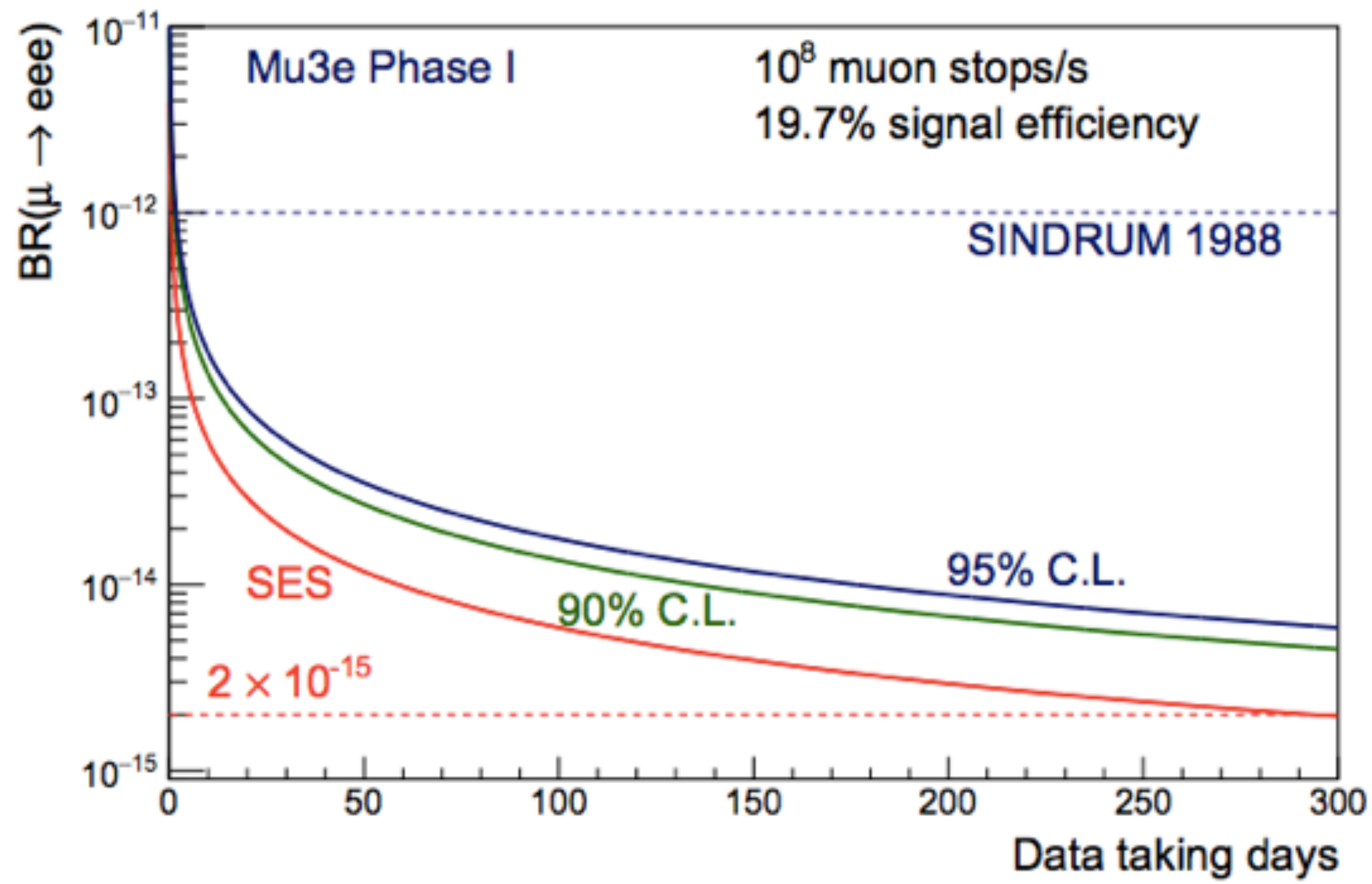
Final design of pixel sensors completed

Magnet delivered to PSI ***this morning***

Mu3e — Sensitivity and perspectives

Data taking expected after 2022





- **~ 5 x 10^{-15}** UL sensitivity in phase I (current PSI beam)
- Down to **10^{-16}** with present technology and increased beam intensity
- Thinner silicon detector, with better time resolution, is critical to go below 10^{-16}

Future 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

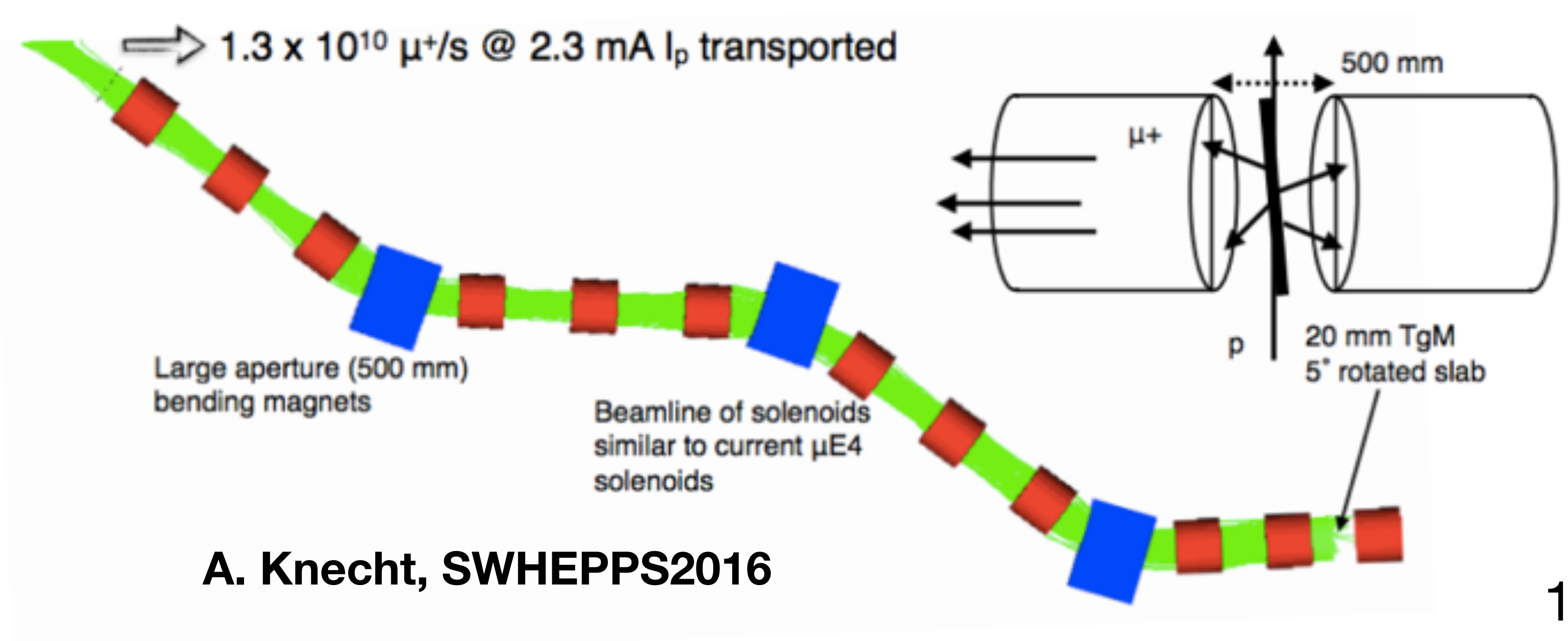
- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x100 the MEG-II beam)
- Optimization of the beam optics:
  - improved muon capture efficiency at the production target
  - improved transport efficiency to the experimental area

x4 μ capture eff.

x6 μ transport eff.

1.3×10^{10} μ/s

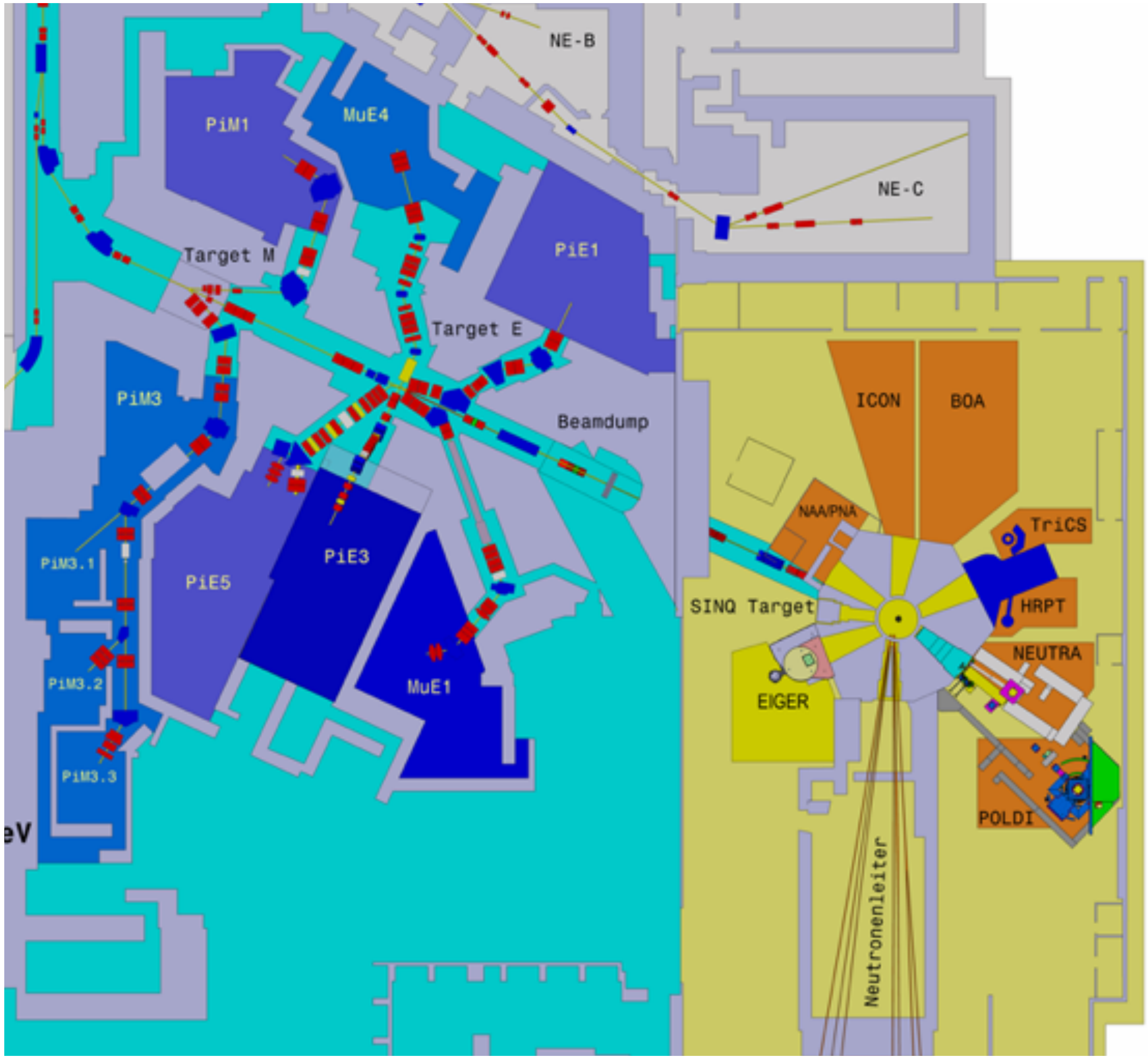
in the experimental area with 1400 kW beam power



A. Knecht, SWHEPPS2016

Production target

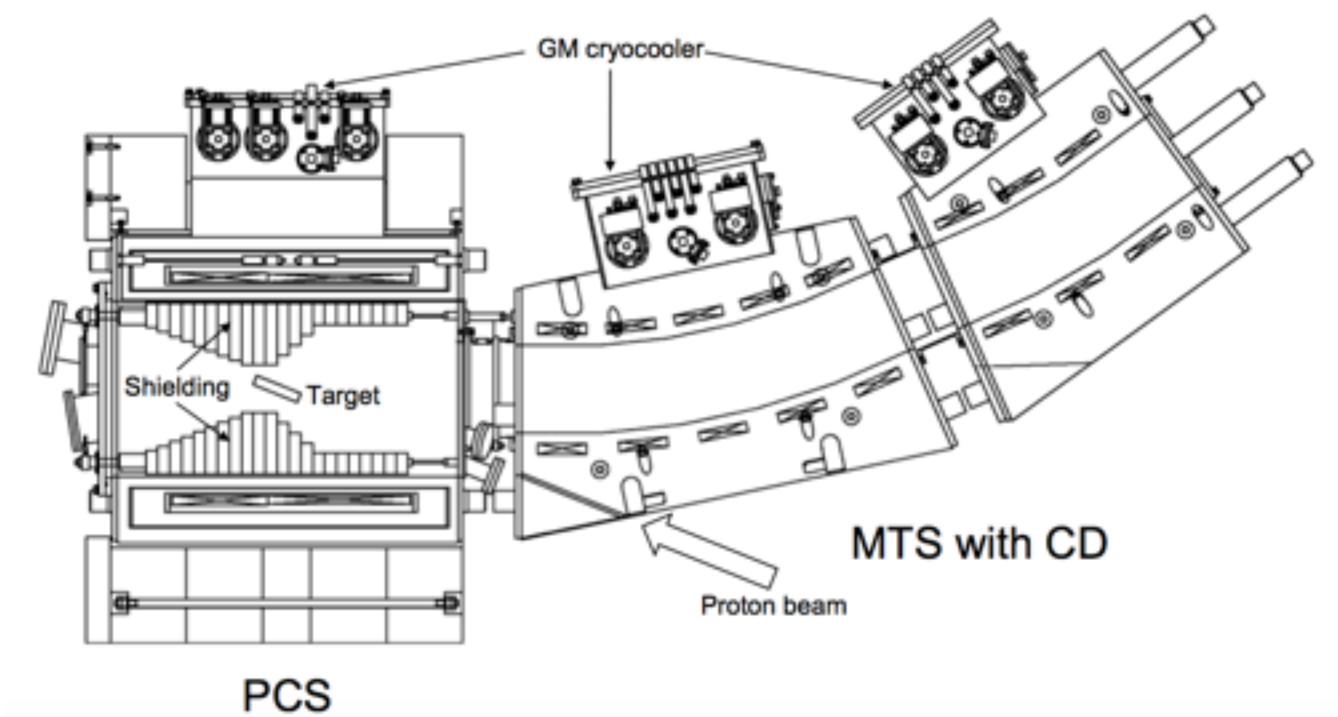
- The ring cyclotron at PSI also serves a **neutron spallation source** (SINQ) downstream of the π/μ production target
    - the proton beam need to be mostly preserved -> **thin production target**



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

muon capture solenoid

4×10^8 μ/s

at the production target

with 400 W beam power

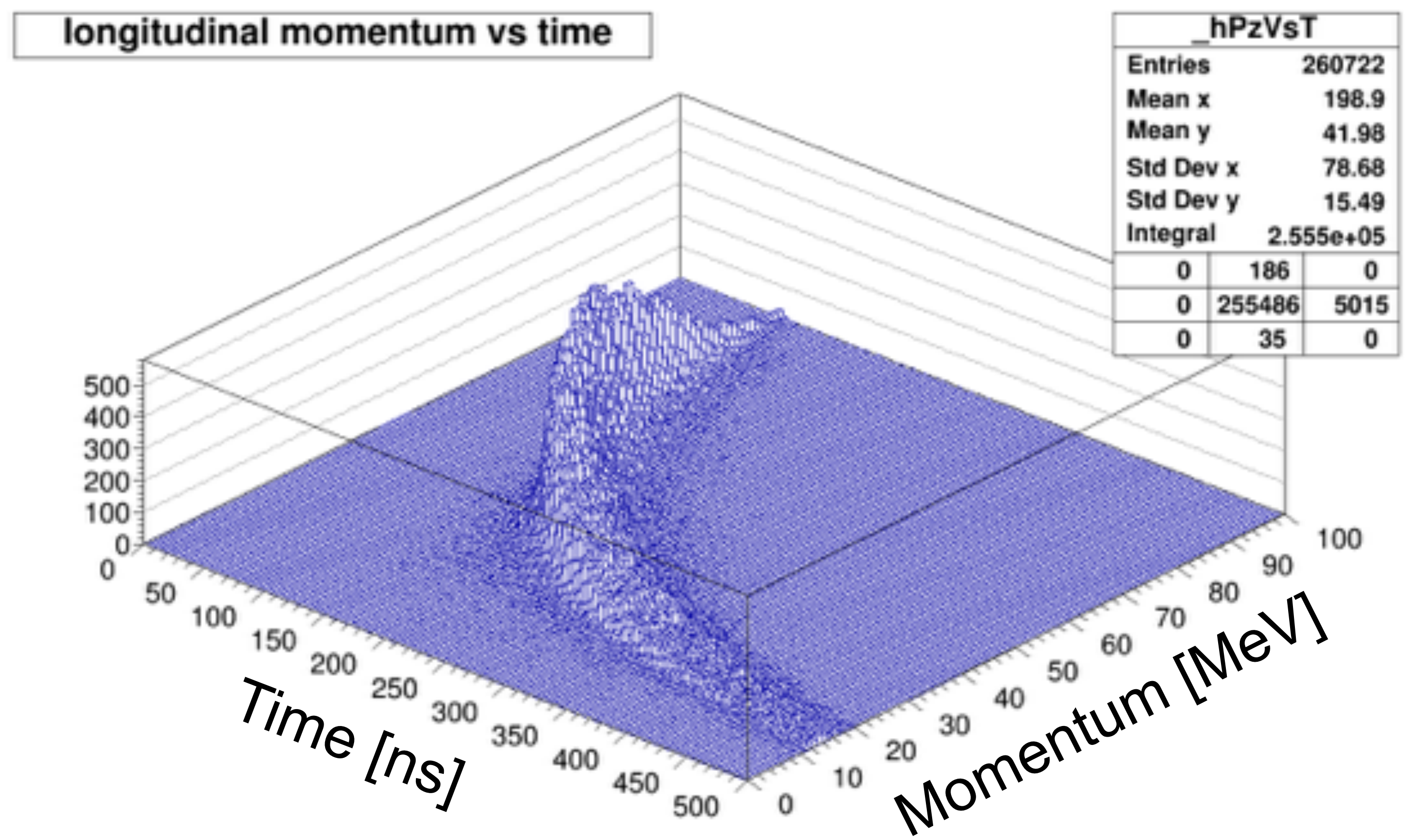
S. Cook *et al.*, Phys. Rev. Accel. Beams 20 (2017)

A beam line for muon decay searches at PIP-II

- PIP-II can provide plenty of muons — can be used for rare decay searches?

- One option is to take the Mu2e beam and make it
  - **positive** (*easy*)
  - **continuous** (*easy - propagation in the beam line spread the muon arrival times, muon lifetime makes the rest*)
  - **low momentum** (*difficult*)
  - **monochromatic** (*very difficult*)

Time-varying deceleration

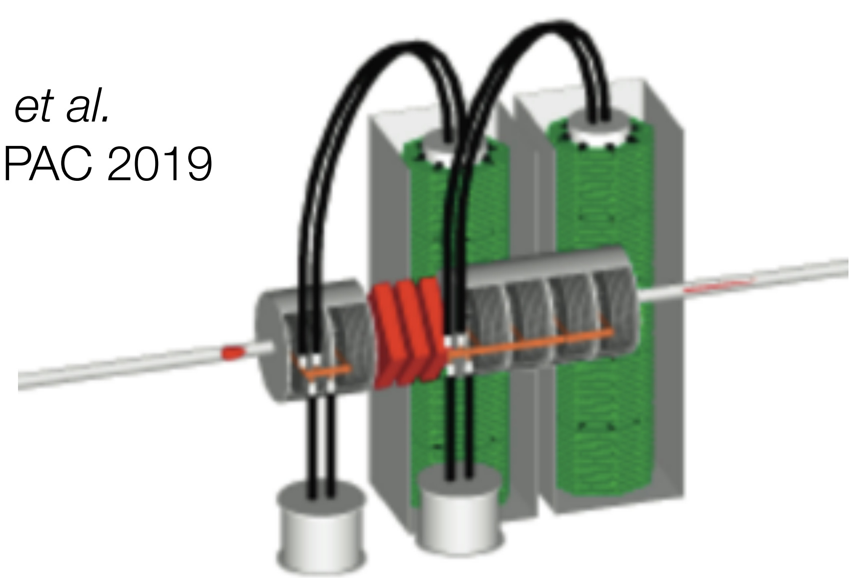


- Exploit the time structure of the Mu2e beam (faster muons arrive sooner):
  - time-varying deceleration can be applied with an **induction linac** technique

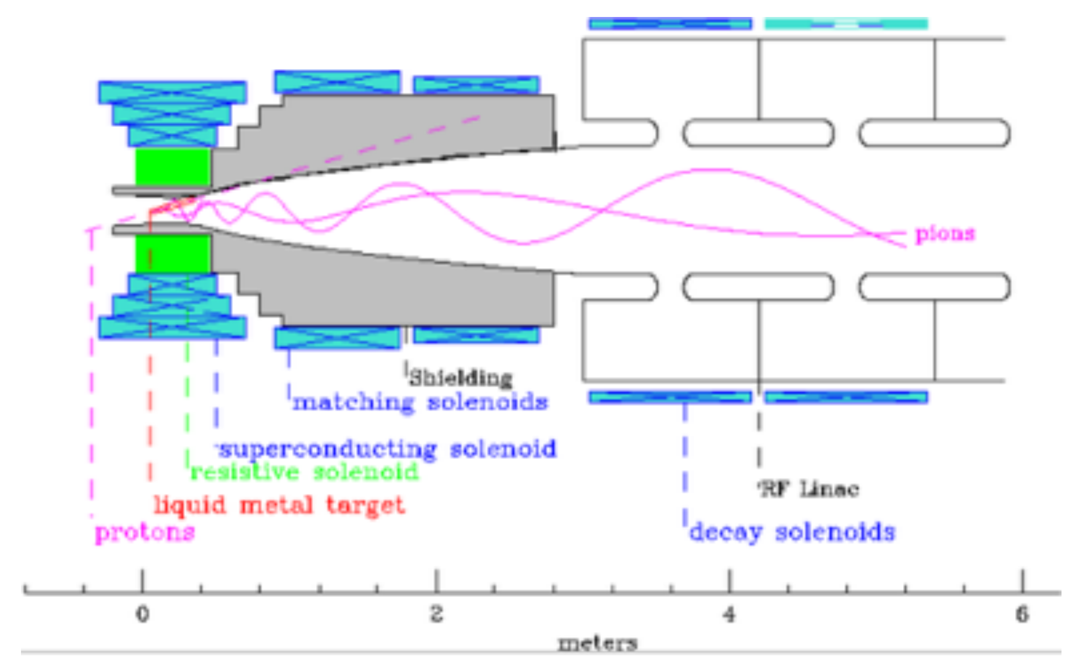
Induction linac approach

- Keep beam captured with a solenoid
  - Mu2e muons are traveling in helices, requiring a solenoid to keep them trapped
  - Then use a combination of induction linac and dE/dx to decelerate (match to time distribution)

C. Ohmori *et al.*
in the Proc. of IPAC 2019



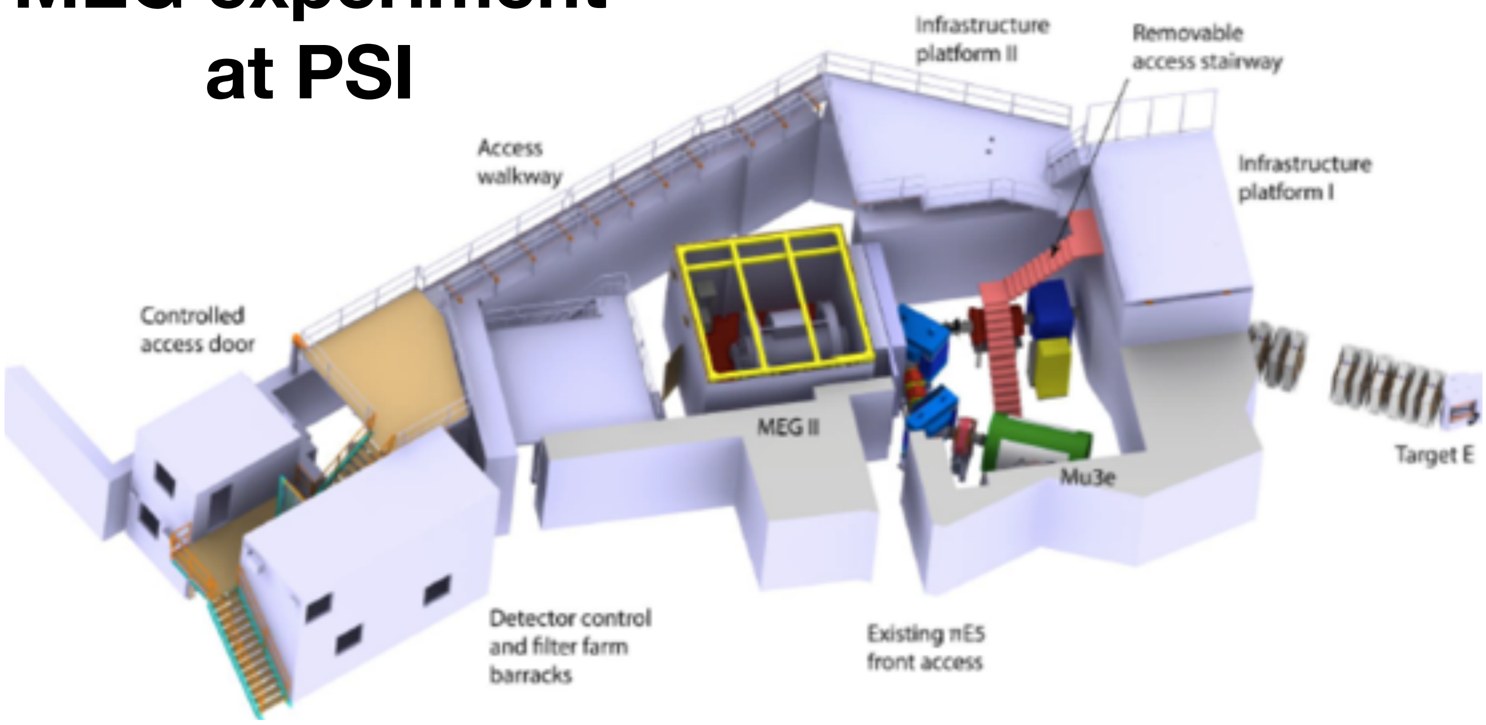
J-Parc MLS μSR induction linac acceleration



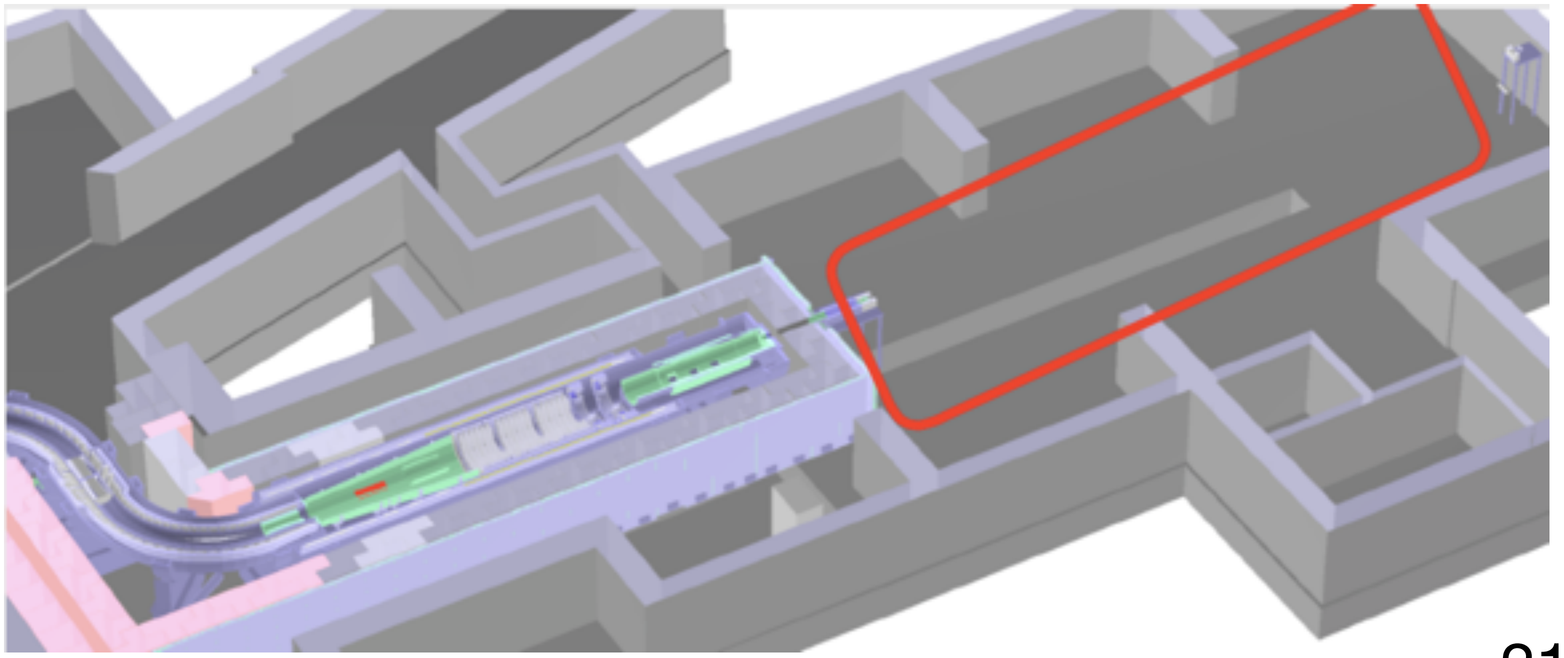
Goal: E_{KIN} ~ 2 MeV

Civil engineering aspects

MEG experiment at PSI



Possibly available space downstream of Mu2e



Goals

- Such a facility could exploit the huge amount of muons that are expected at PIP-II

Facility	pos. muons/sec
Current Mu2e	10^{11}
PIP-II	10^{12}
PSI	$2 \times 10^{8*}$
HiMB PSI	10^{10}

Technical aspects

- The induction linac technology is mature and successfully applied to muon acceleration at J-PARC
- Capture solenoid techniques already studied for neutrino factories
- Most of the beamline technologies and conditions are the same of Mu2e
    - different arrangement and handling of different energy and time structure are the hardest part of this idea
- Alternate run of Mu2e and muon decay experiments

Alternative option - Surface muon beam

- The possibility of having a **surface muon beam** at PIP-II is also under investigation
- Conventional technology
- Could we explore a MuSIC-like concept?
  - thick production target — ***ok***
  - muon capture solenoid — ***very hard at high beam power***
- Deceleration could be still applied to reduce energy and momentum bite w.r.t. conventional surface muon beams

Surface muons — what can we get from PIP-II?

PIP-II parameters

Parameter	Pulsed sequential multi-user up to CW-single user	CW concurrent multi-user 3-way separator, 2 users	Comment
Energy [MeV]	800	800	Upgradable
Pulse length [us]	Programmable, sequentially shared between users, up to CW in single-user mode, repetitive (e.g. 20 Hz)	CW	
H-/bunch	Up to 1.9E8	1.5E+08	Pulse beam current limited to 2 mA
Max bunch freq. [MHz], bunch pattern	Up to 162.5 Programmable	40.625	Defined by RFQ and RF Separator frequency
Pulse beam current to user [mA], averaged over 1 us	2	1	Limited by selected amplifiers
Min. Bunch Spacing [ns]	6.2	24.6	
Bunch length [ps]	4	4	Defined by beam dynamics
Pulse beam power averaged over 1 us [kW]	1600	N/A	
Average power [kW]	Up to 1600, Proportional to user share	800	

Figures similar to PSI ring cyclotron, but the full beam power can be exploited —> 1 to 2 orders of magnitude gain is reasonable

Strong points of a muon decay facility at PIP-II

- All cLFV experiments could be carried on in the same place:
  - global leadership
  - strong community
  - easier exchange of knowledge and experience would make the experimental efforts **stronger and faster**
- An opportunity to leverage the Mu2e and Mu2e-II investments

Conclusions

- We are investigating the possibility of having a facility for the search of rare muon decays at FNAL
- The beam intensity of the possible PSI upgrade (HiMB) could be exceeded by a factor 10÷100
- Opportunity to build a large community and strengthen the experimental efforts toward the discovery of cLFV
- A Letter of Interest will be submitted to Snowmass2021