The Mu2e Experiment: Search for Charged Lepton Flavor Violation

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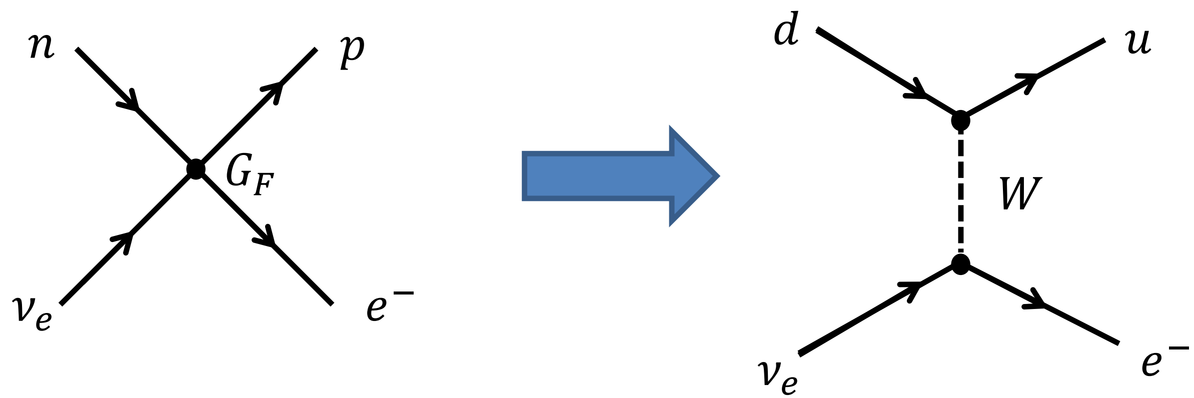
Why Search for Lepton Flavor Violation?

- Flavor changing weak interactions are ubiquitous in the quark sector:



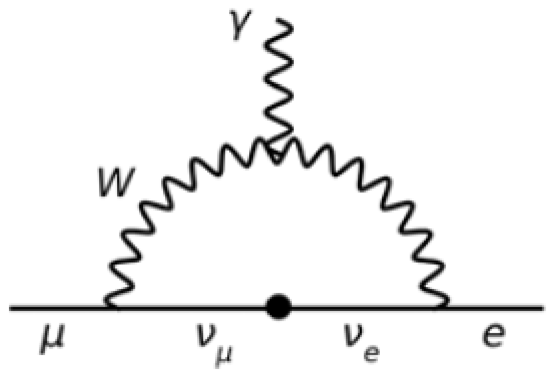
- Lepton flavor violation is observed in the neutrino sector:

$$\nu_e \leftrightarrow \nu_\mu \qquad\qquad \nu_\mu \leftrightarrow \nu_\tau$$

- Why shouldn't we also expect charged lepton flavor violation?

Charged Lepton Flavor Violation

- NOT forbidden by any symmetry principles
- It is an allowed process in the standard model:

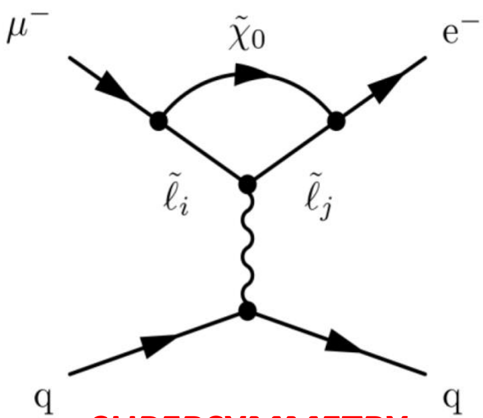


- Predicted branching fraction:

$$B_{SM}(\mu \to e\gamma) \sim 10^{-54}$$

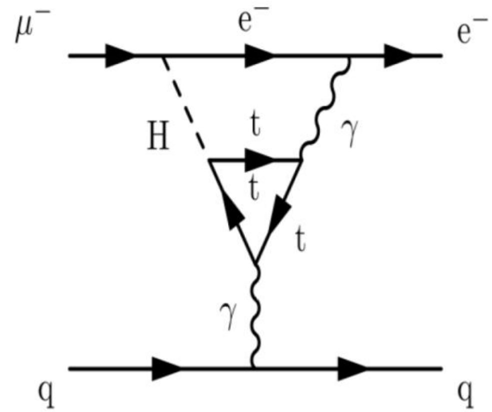
- This is unmeasurably small… any observed signal would have to be from something totally new!

Sensitivity to New Physics



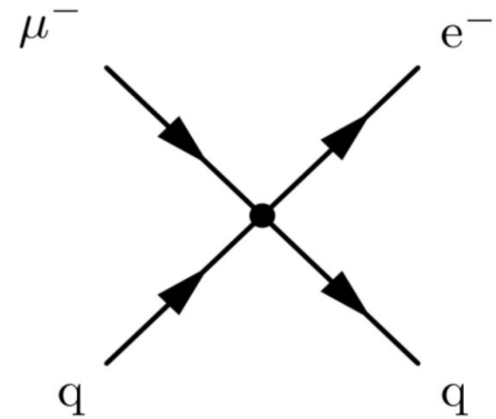
SUPERSYMMETRY

Rate $\sim 10^{-15}$



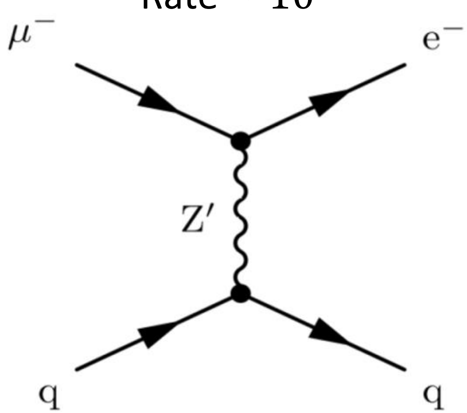
ADDITIONAL HIGGS

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



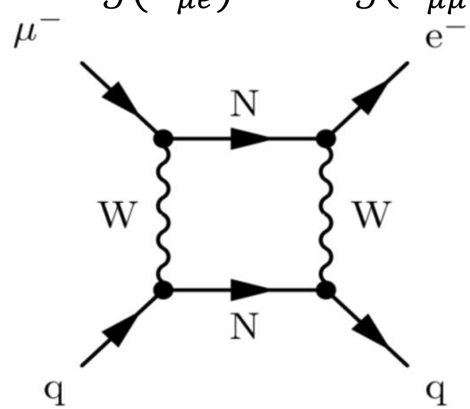
COMPOSITENESS

$\Lambda_c \sim 3000\ TeV$



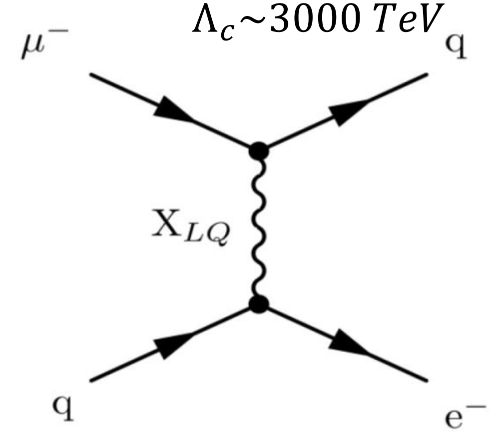
EXTRA DIMENSIONS

$M_{Z'} = 3000\ TeV/c^2$



HEAVY NEUTRINOS

$|U_{\mu N} U_{eN}|^2 \sim 8 \times 10^{-13}$



LEPTOQUARKS

$M_{LQ} = 3000(\lambda_{\mu d}\lambda_{ed})^2\ TeV/c^2$

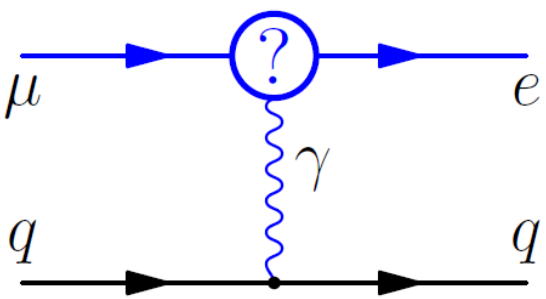
Effective Field Theories

Cirigliano, *et al.*
arXiv:hep-ph/0507001
(this includes only the dimension-6 operators)

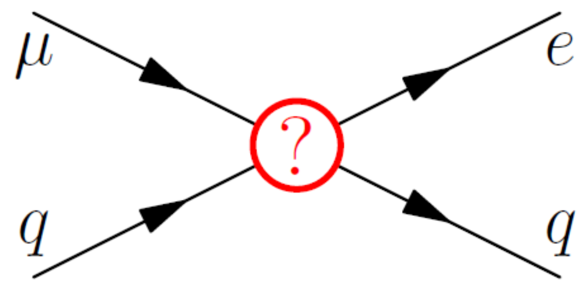
$$\mathcal{L}_{EFF} = \frac{m_\mu}{(1+\boldsymbol{\kappa})\boldsymbol{\Lambda}^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\boldsymbol{\kappa}}{(1+\boldsymbol{\kappa})\boldsymbol{\Lambda}^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

- Mass scale: $\boldsymbol{\Lambda}$, relative strength of contact term: $\boldsymbol{\kappa}$

Dipole coupling



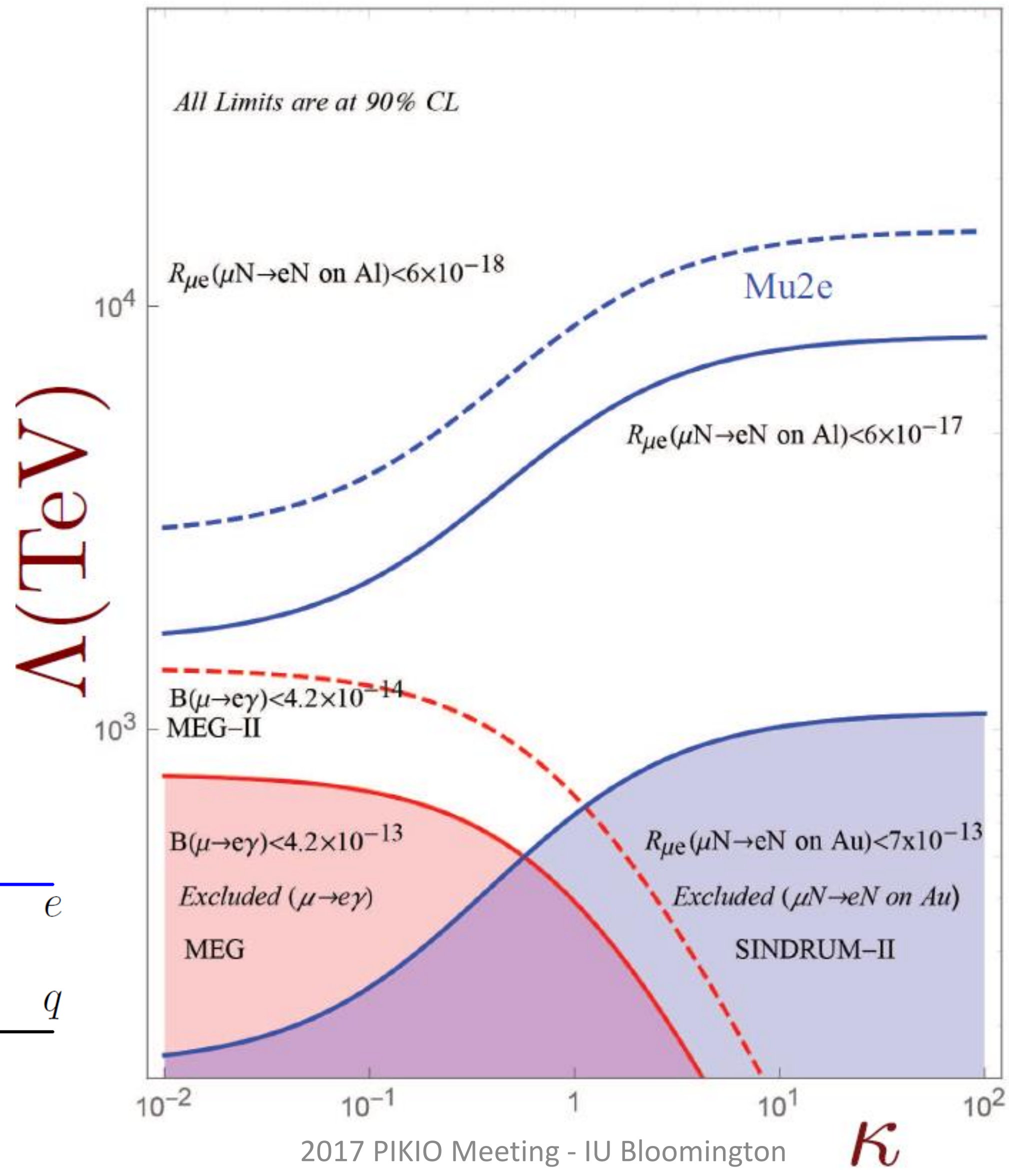
Contact coupling



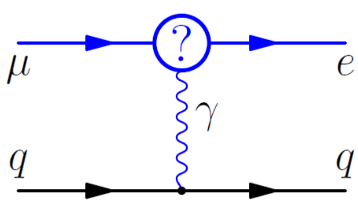
- Relative rates of $\mu \to e$ conversion and $\mu \to e\gamma$ are model dependent.

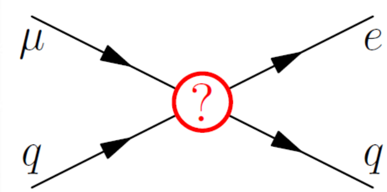
Sensitivity to New Physics

R. Bernstein, after de Gouvêa and Vogel, Prog. Part. Nucl. Phys. 71, 75 (2013)



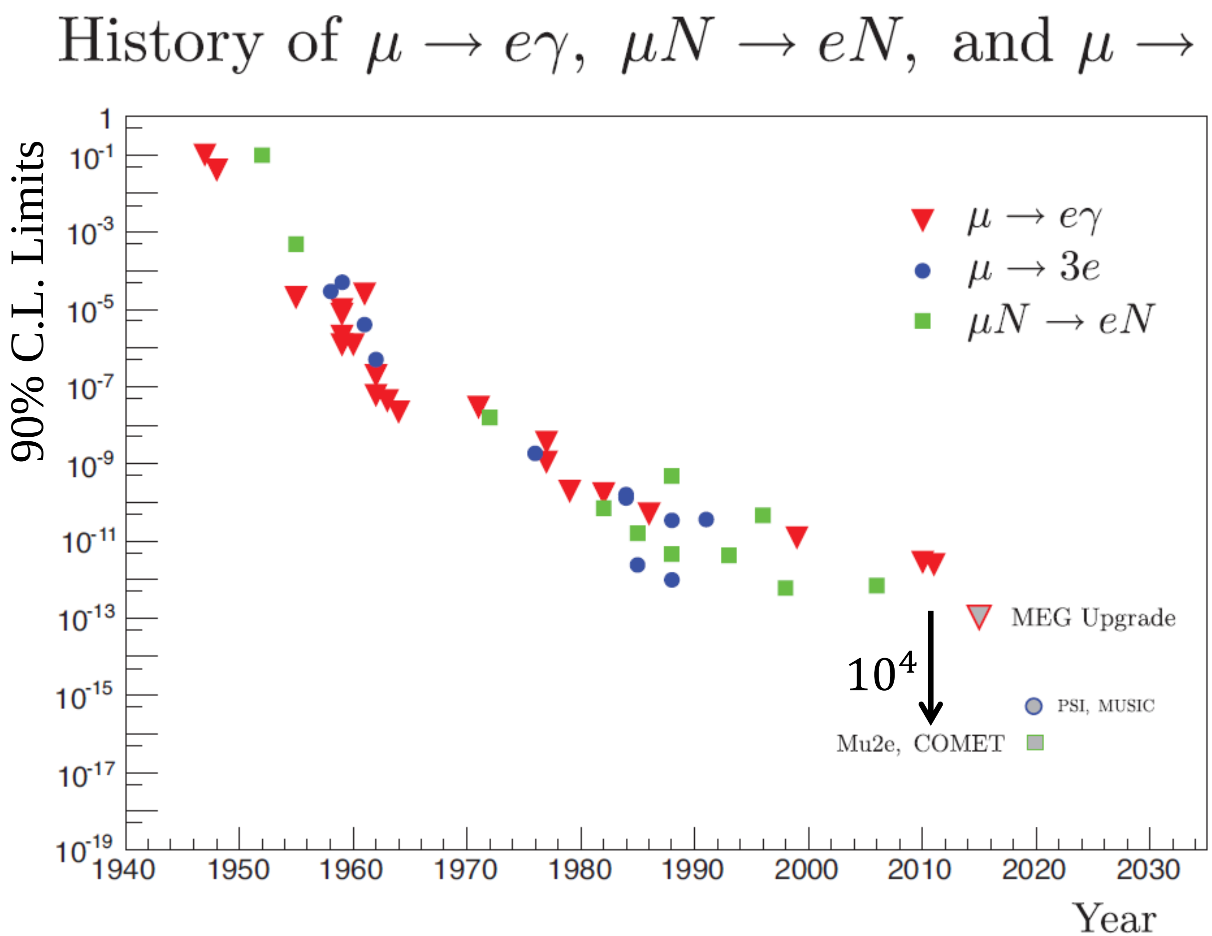
Mu2e Sensitivity



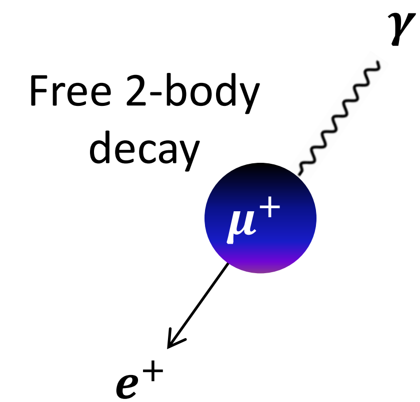


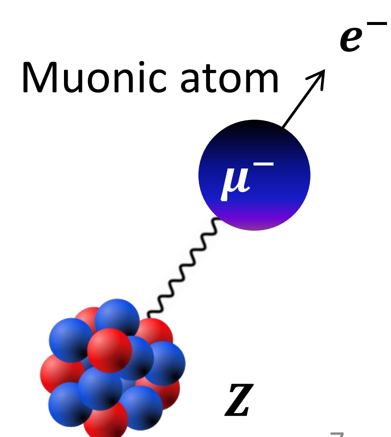
Searches for Charged Lepton Flavor Violation

- Searches for $\mu \rightarrow e\,\gamma$, $\mu\,N \rightarrow e\,N$, $\mu \rightarrow 3e$



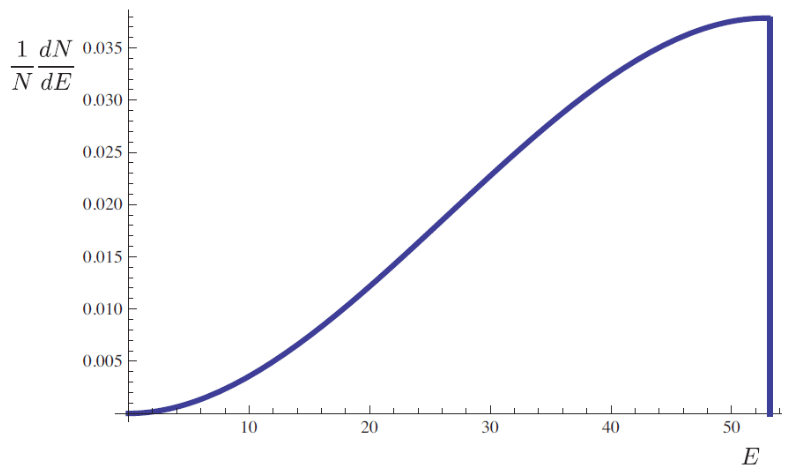
Bernstein and Cooper, Phys. Rep. 532: 27 (2013).





Muon to Electron Decays

- The electron from $\mu^+ \to e^+\gamma$ has $E_e = 52.8\ MeV$
- Electrons from $\mu^+ \to e^+\nu_\mu\bar{\nu}_e$ have a range of energies:



- But, if the electron recoiled against something very heavy (like a nucleus) then it could have almost all the energy.

First Experiment

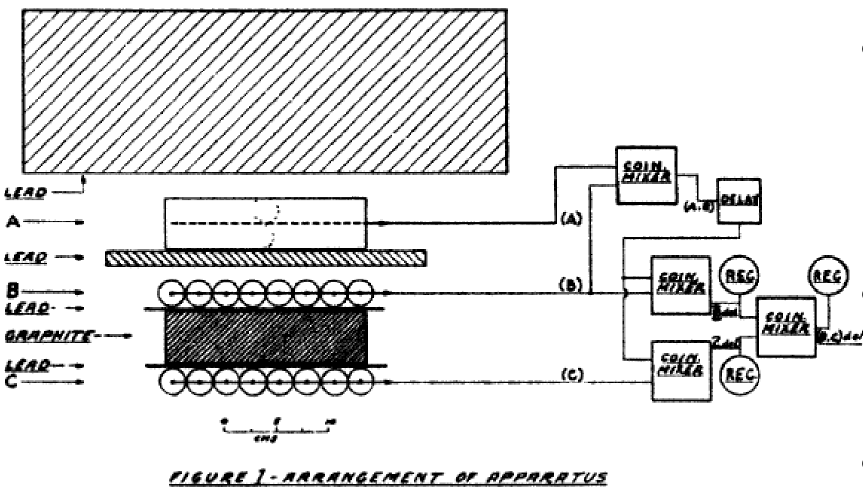


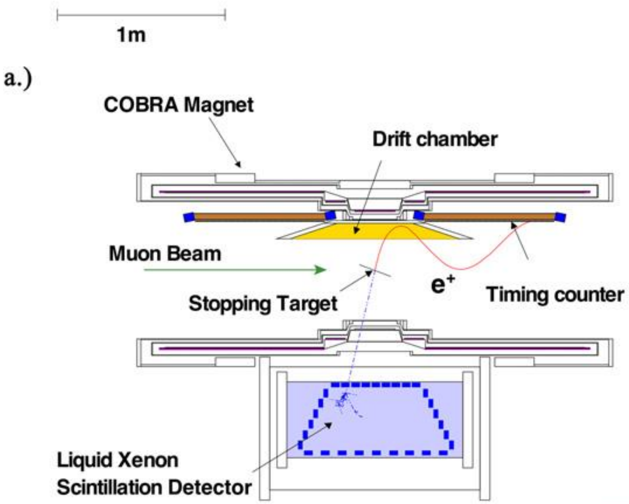
FIG. 1. Arrangement of apparatus.

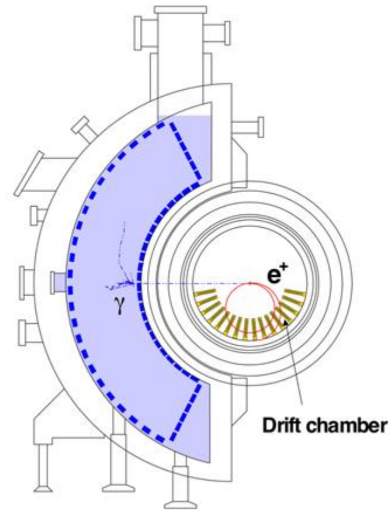
- Muons from cosmic rays are slowed down in the lead and stop in the graphite.
- An “event” is triggered by signals in A+B.
- A $\mu \rightarrow e\gamma$ event would cause a delayed coincidence in B+C.

Hincks and Pontecorvo, 1947 “This does not occur…”

- No difference in rate compared with A+B followed by A+B+C… $B(\mu \rightarrow e\gamma) < 0.1$

Most Recent Experiment



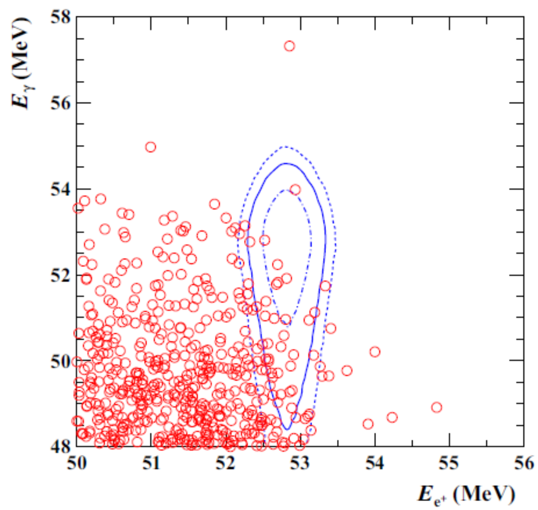


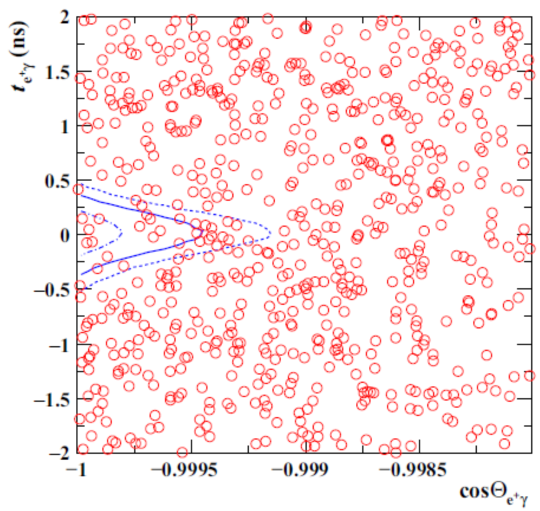
The MEG Experiment (2016)

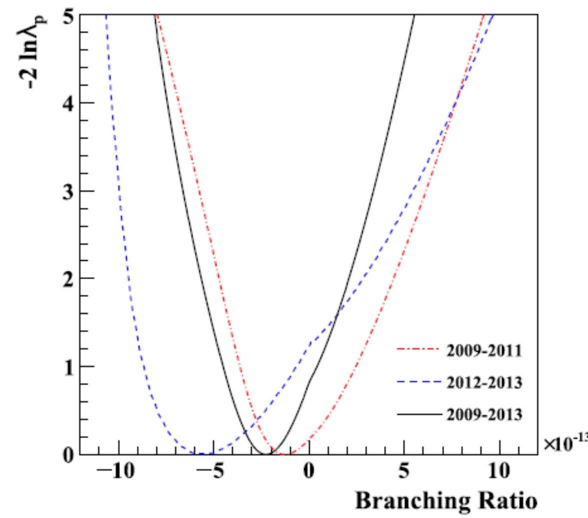
$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

Eur. Phys. J. C (2016) 76:434

PSI (Zurich)

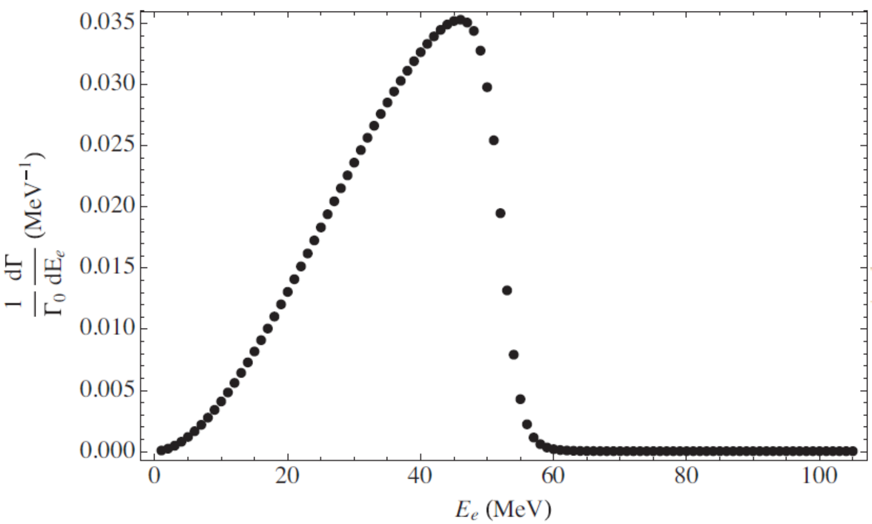


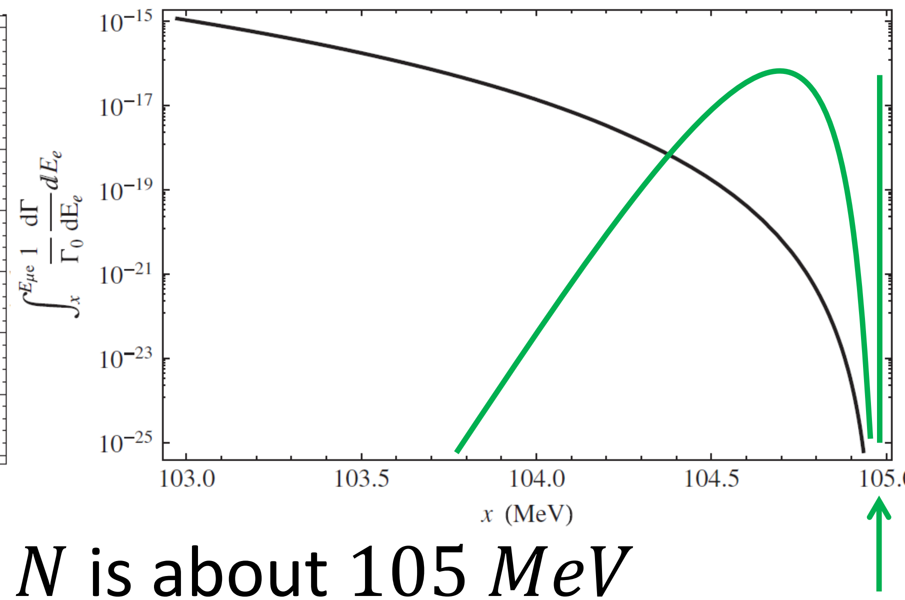




Muon Conversion Experiments

- Energy spectrum from muons captured by an atomic nucleus (Decay In Orbit – DIO): Czarnecki, Tormo, and Marciano, Phys. Rev. D **84**, 013006 (2011).

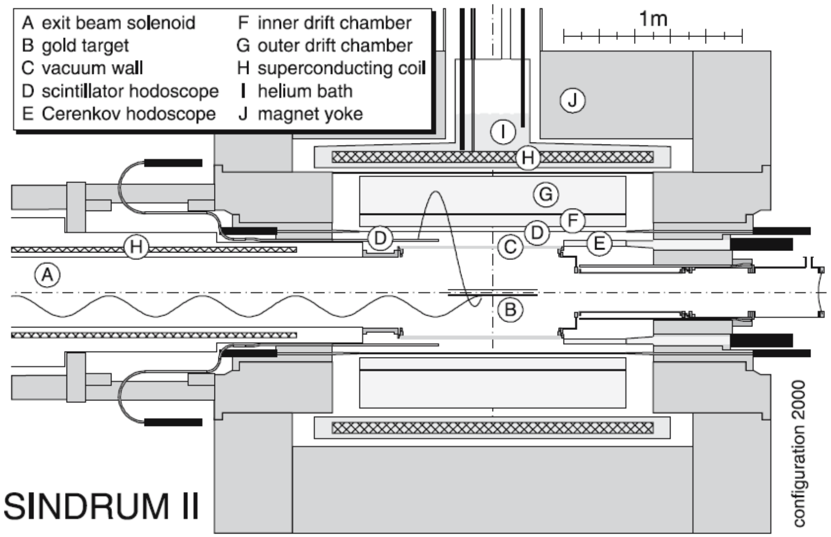




- E_e from $\mu^- + N \rightarrow e^- + N$ is about 105 MeV
- Almost no background from DIO… if the electron momentum can be measured precisely enough.

SINDRUM-II Result: $\mu^- N \rightarrow e^- N$

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

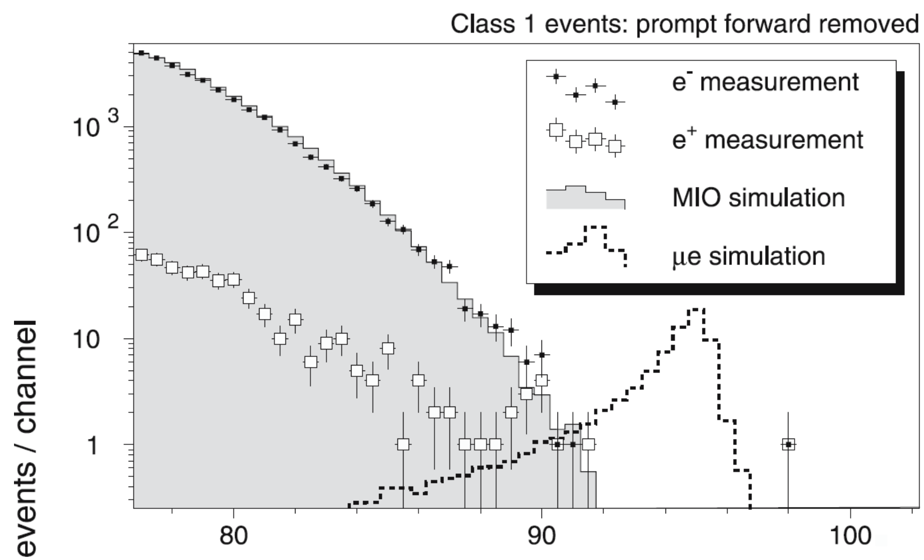


Muon production at PSI:
0.3 ns pulse every 20 ns

Muons stopped on a gold target.

One event observed! But it lies beyond the expected endpoint of the spectrum.

- Radiative pion capture?
- Cosmic ray?

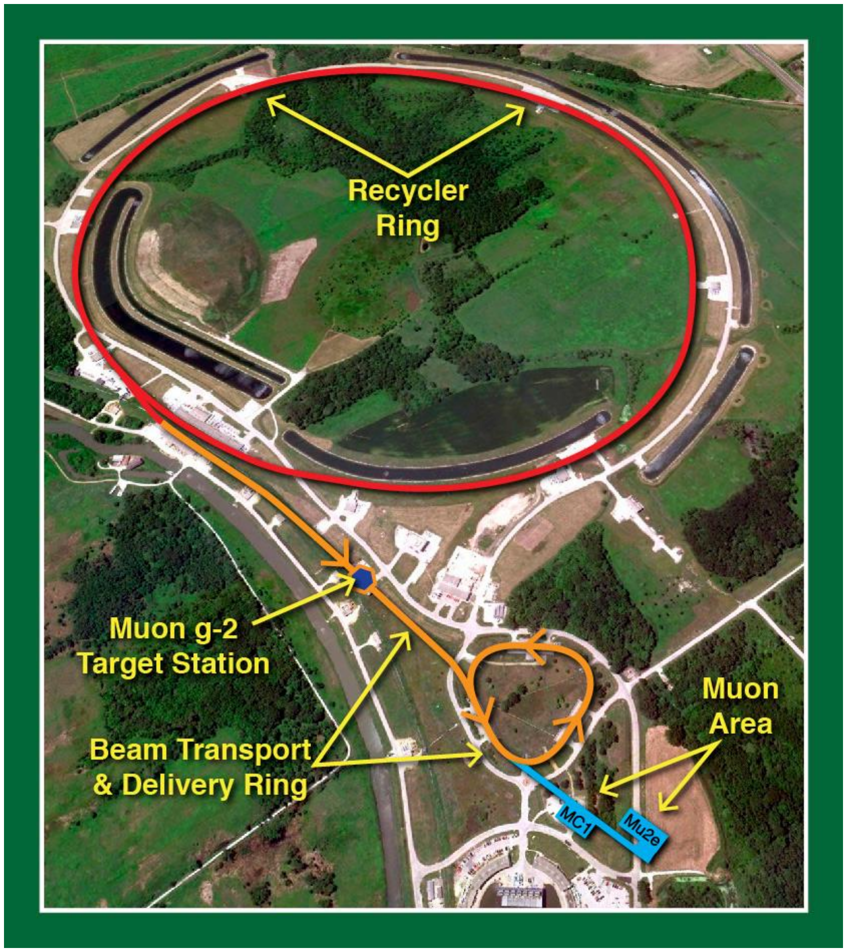


- *Mu2e will improve on this result by a factor of 10^4…*

The Mu2e Experiment

- Produce lots of muons: 1.2×10^{20} protons on target/year
  - Pulsed beam experiment: exploit time correlations in measurement
- Select negatively charged muons, stop them on an Al target
  - Captured muon lifetime on Al is $\boldsymbol{\tau_\mu = 864\ ns}$ ($\Gamma_{total} = \Gamma_{decay} + \Gamma_{capture}$)
- Wait for prompt backgrounds to die off
  - Primarily radiative pion capture, $\pi N \rightarrow \gamma N^*, \gamma \rightarrow e^+e^-$
  - Pion lifetime is $\boldsymbol{\tau_\pi \sim 26\ ns}$
- Measure electron energy spectrum
  - Look for an excess at the 105 MeV endpoint
- Normalize to the rate of muon capture:
  - Observe x-rays from $2P \rightarrow 1S$ transitions
- Run like this for 3 years: $\mathbf{6.7 \times 10^{17}}$ **stopped muons**

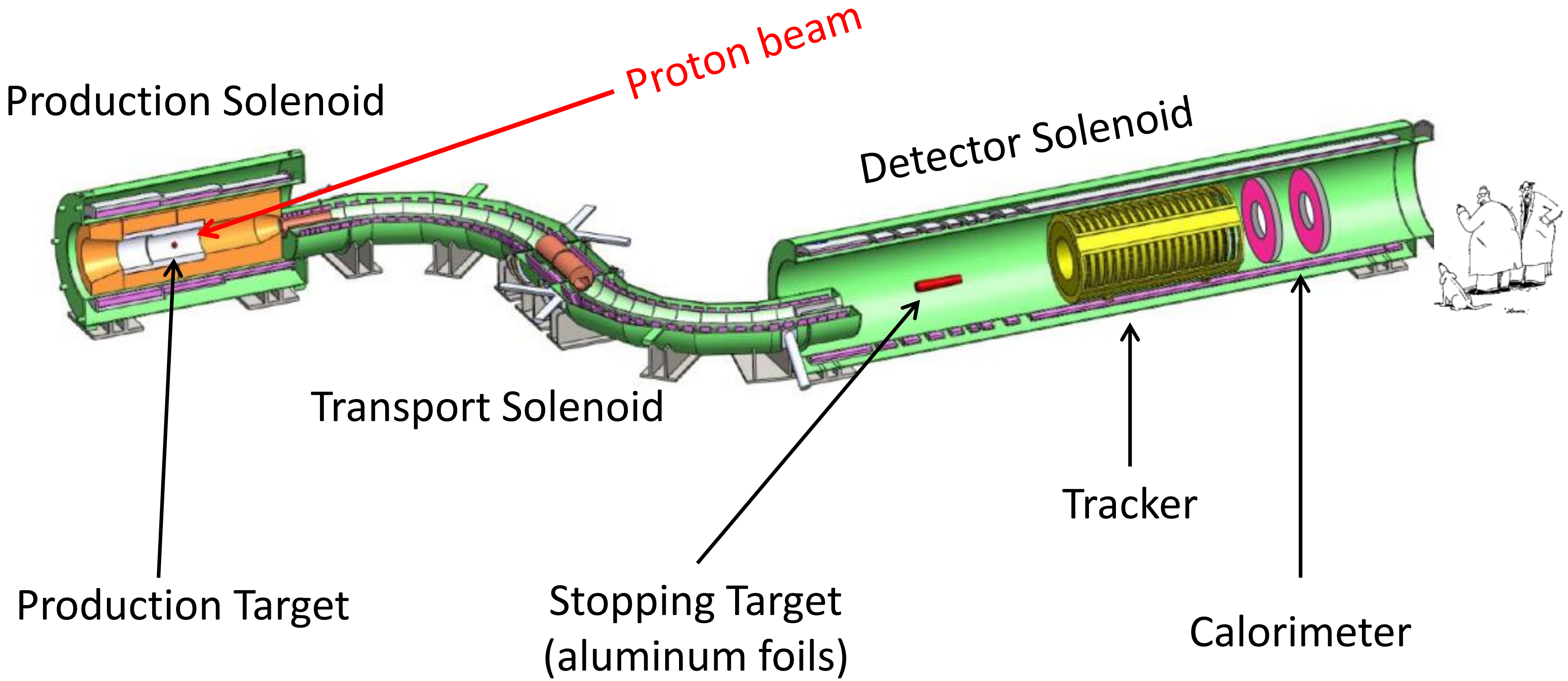
The Fermilab Muon Complex



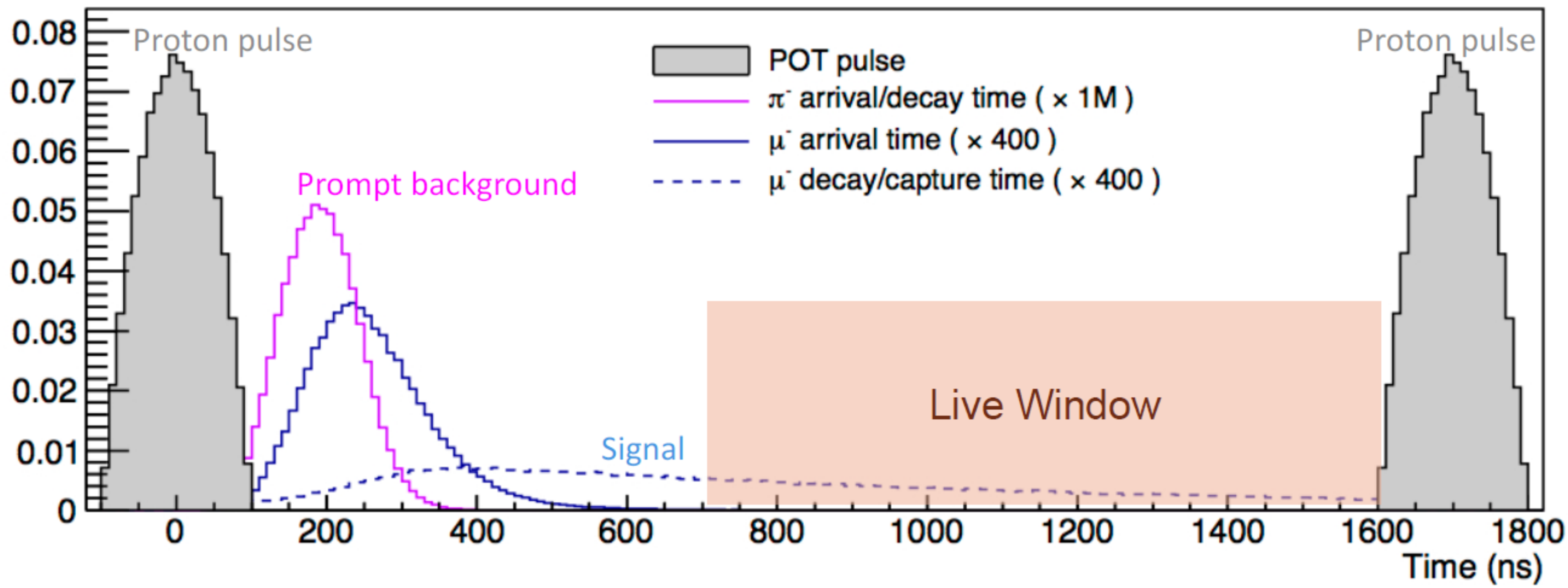
New Mu2e experimental hall

Muon g-2 experiment

The Mu2e Experiment

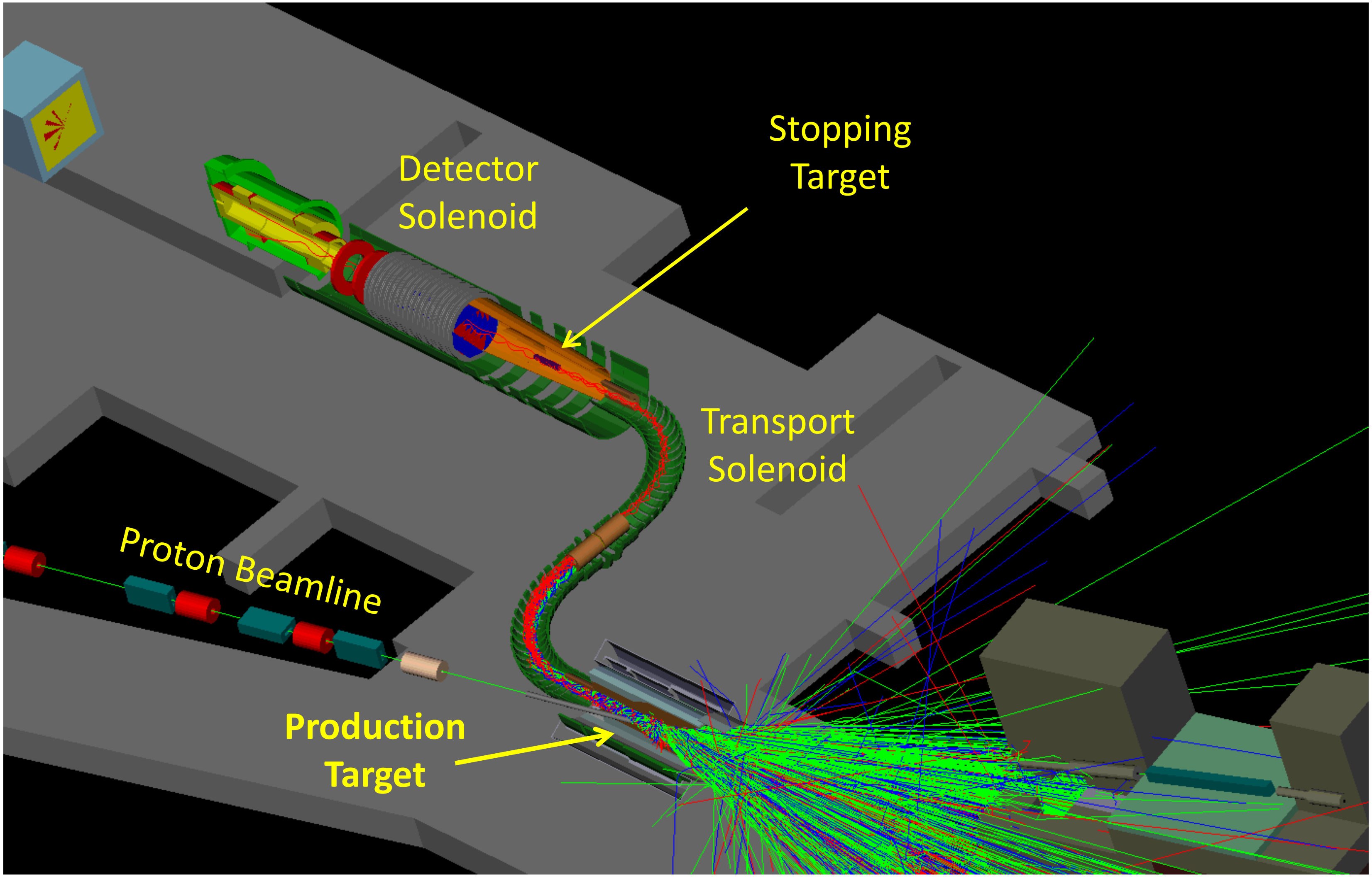


Pulsed Proton Beam

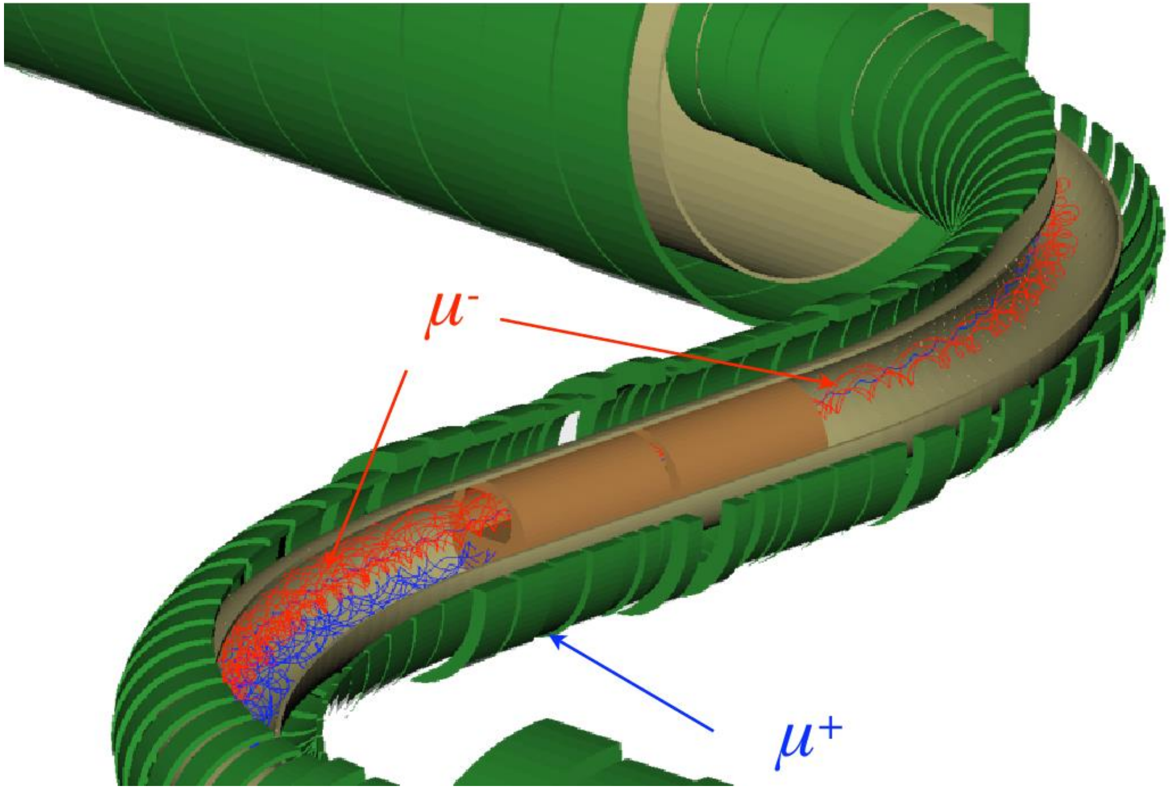


- Key parameter: beam extinction
  - Fraction of protons that arrive at the production target *outside* the proton pulse time window
  - Extinction is required to be < 10^{-10}

Muon Production Target

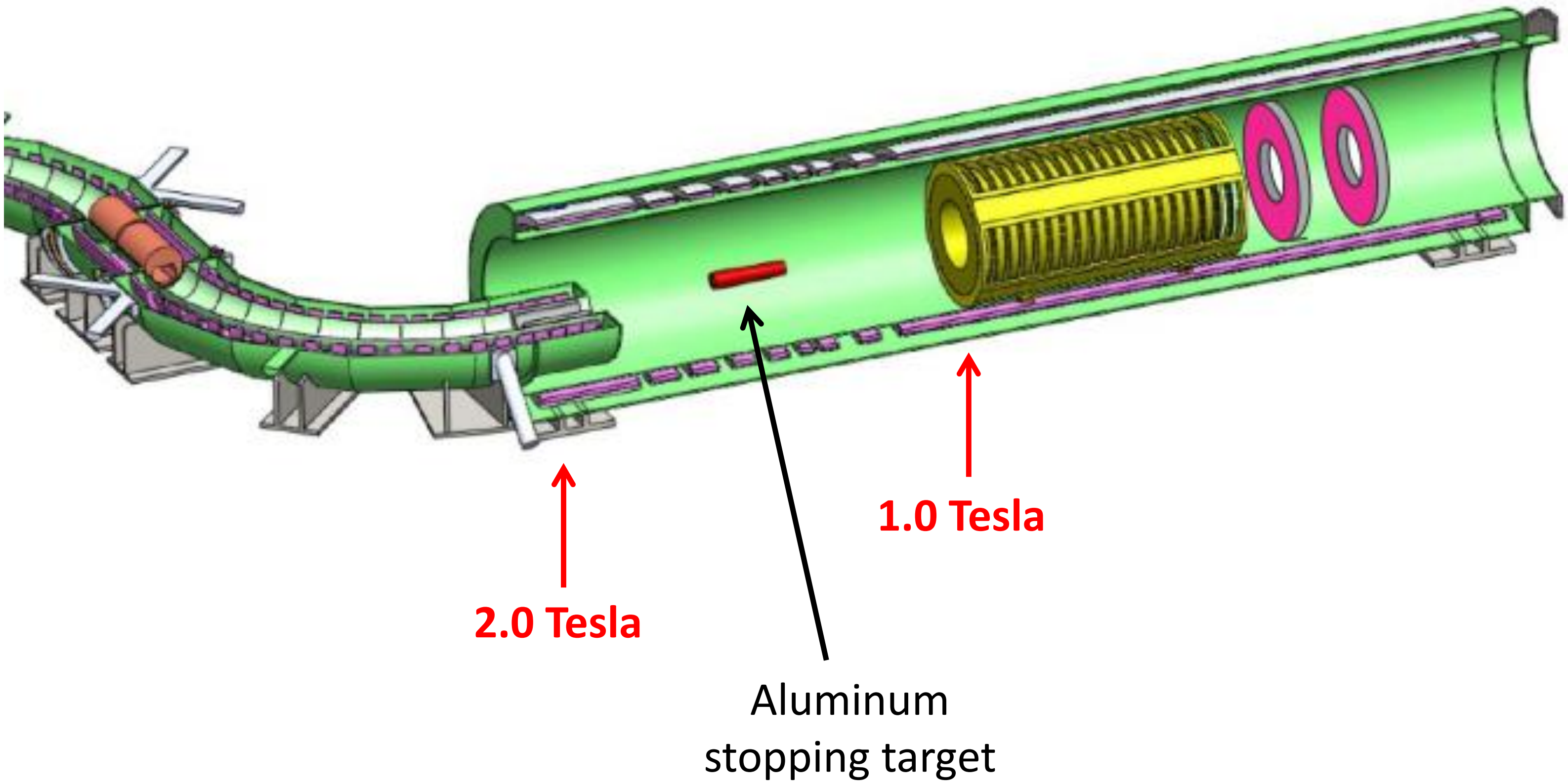


Transport Solenoid



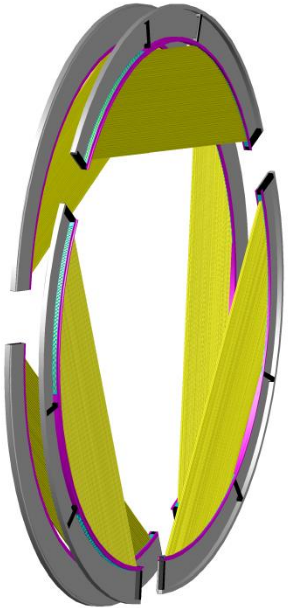
- Selects negative muons with limited range of momentum, optimized for stopping target (7.6 MeV kinetic energy).
- Puts the detector out of the direct line-of-sight for neutrons and gammas.

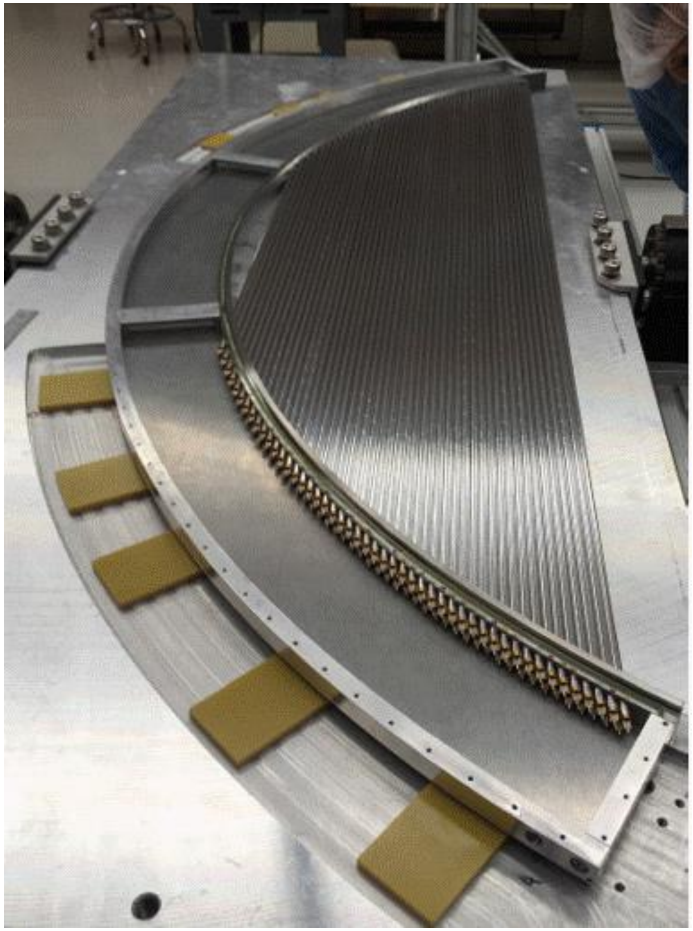
Detector Solenoid



A 105 MeV electron emerging from the stopping target will be focused back towards the tracker.

Straw Tube Tracker

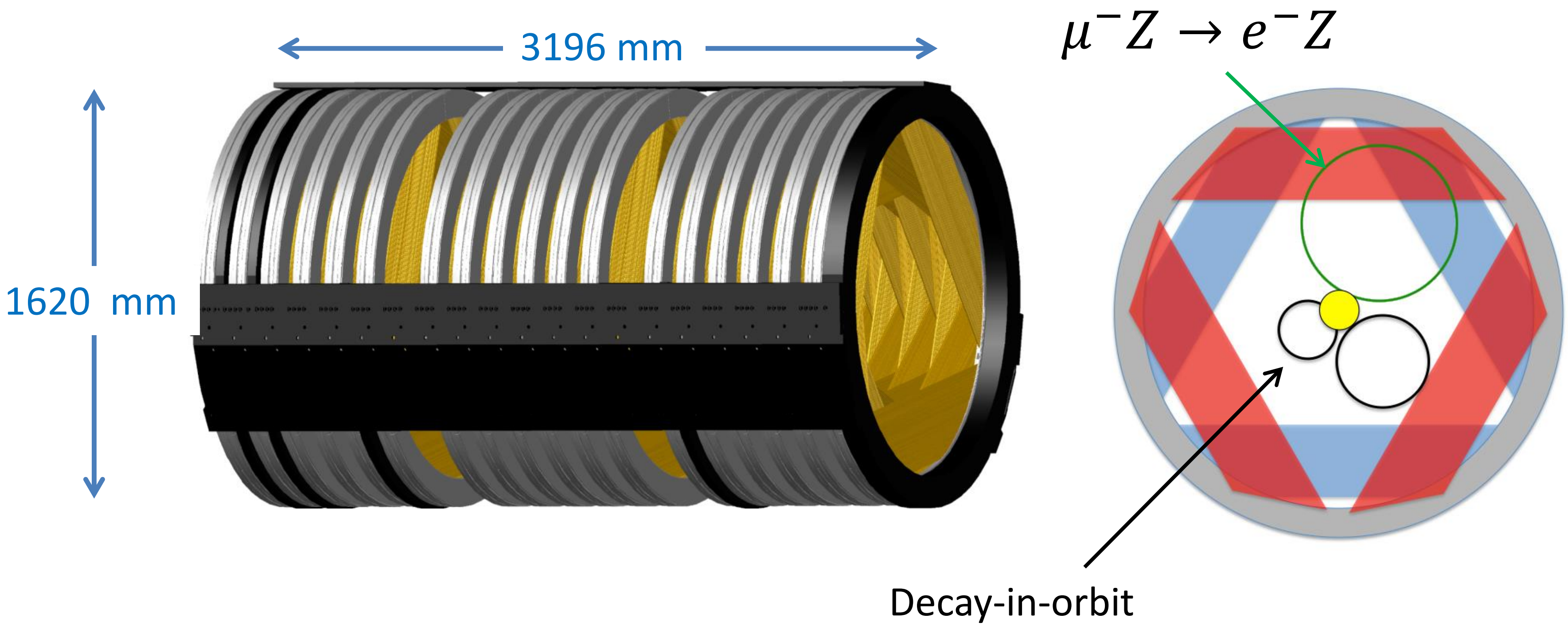




- 5 mm diameter
- Wall thickness: 15 μm
- Gas mixture: 1 Atm Ar/Co_2

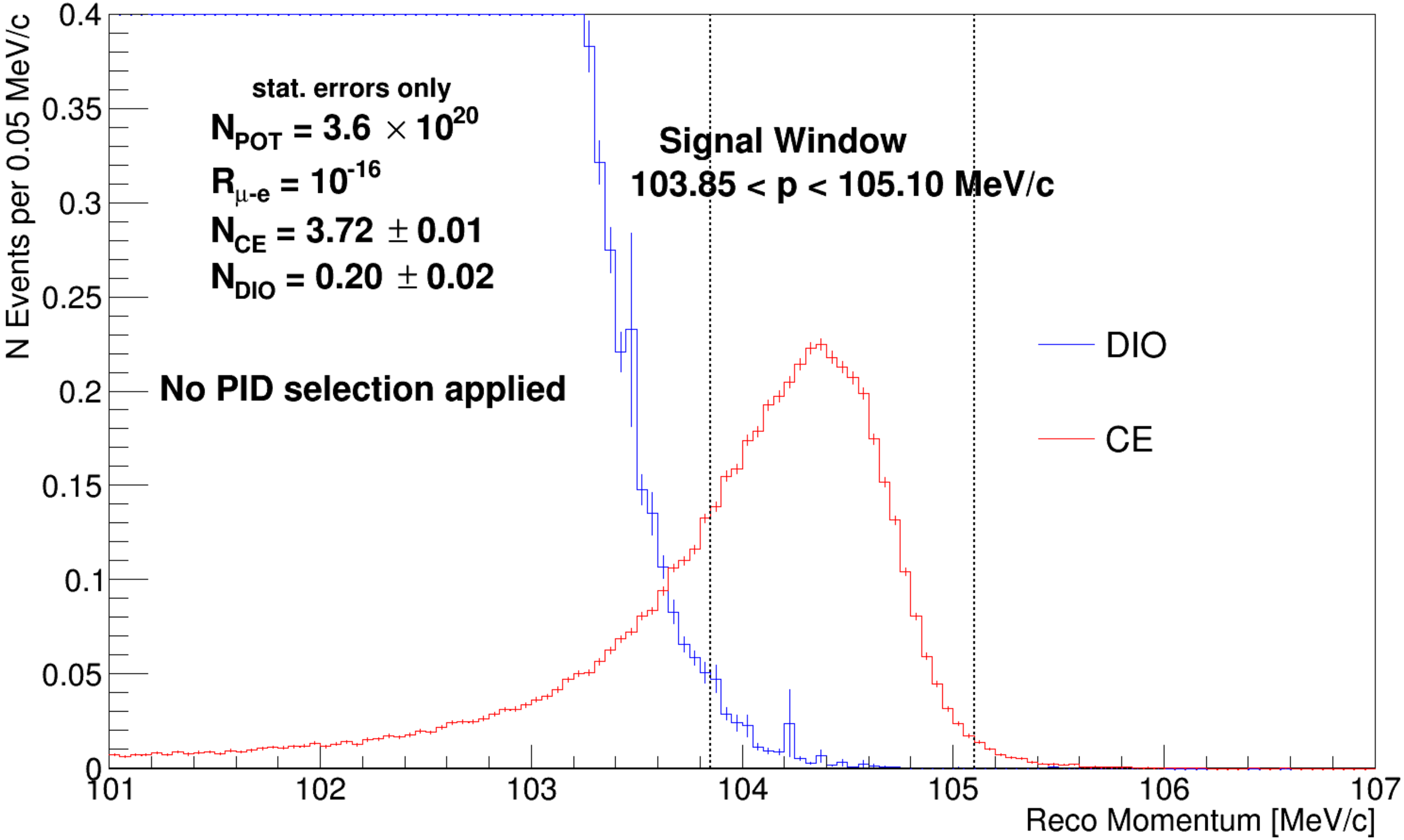
- 20736 straws, read out at both ends.
- Assembled into panels
- ***Placed in vacuum***

Straw Tube Tracker



- Graded magnetic field reflects electrons from the stopping target into the tracker.
- Only sensitive to electrons with energy near the 105 MeV end-point.

Tracking Resolution



Background Estimates

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

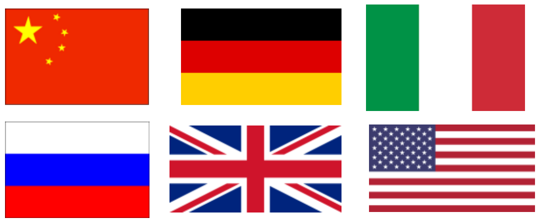
- Initial 3-year run is essentially background-free
- Single-event sensitivity expected to be $3x10^{-17}$

Summary

- The Mu2e experiment is an important part of the near-term US experimental HEP program.
- Construction is underway, commissioning in 2020
- Longer term upgrades:
  - Lower beam energy to below the $\bar{p}$ production threshold
  - Different target Z

- *Historically, the lepton sector has been full of surprises… Will this trend continue?*

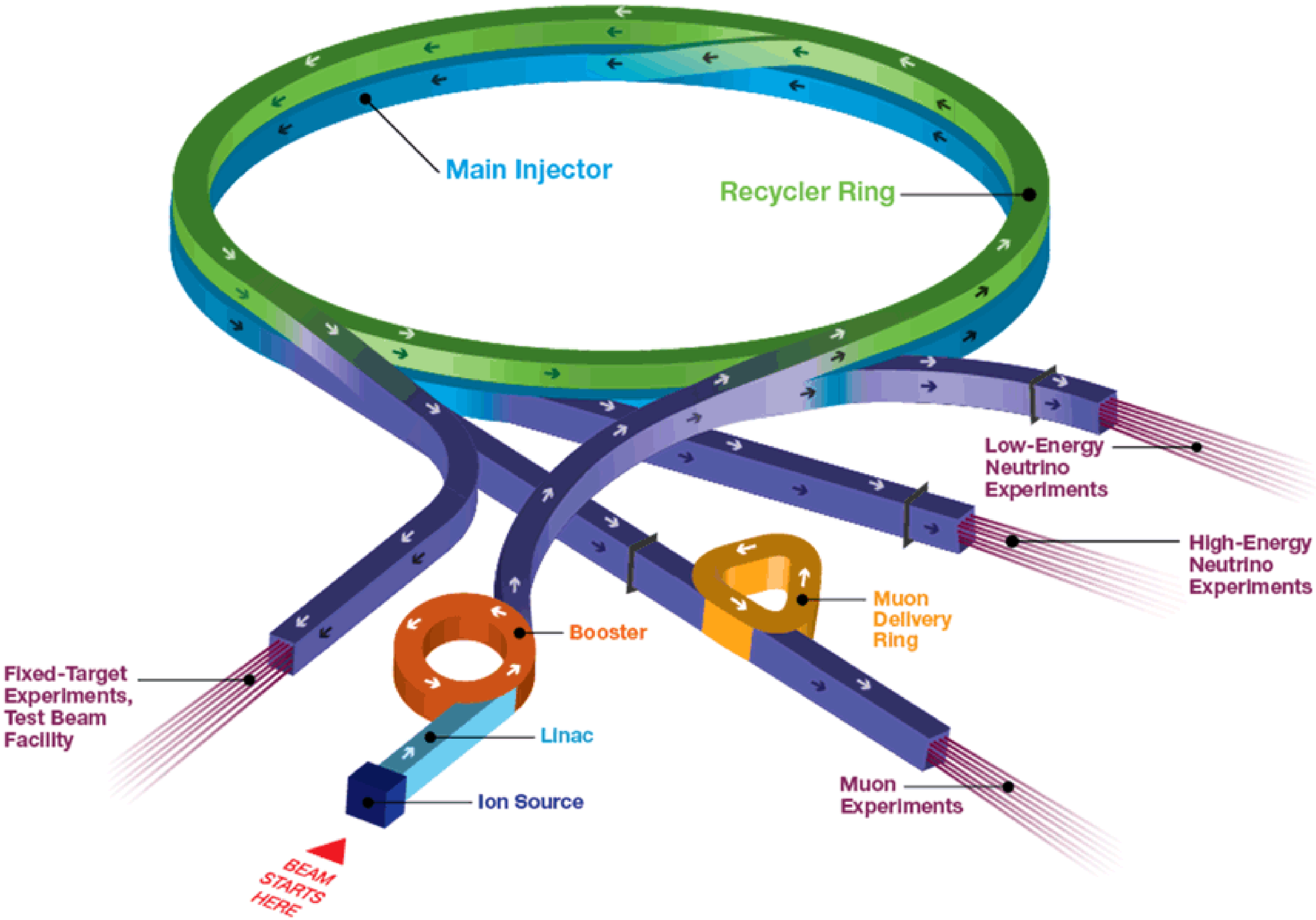
Mu2e Collaboration



Argonne National Laboratory ● Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory and University of California, Berkeley ● University of California, Irvine ● California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● Helmholtz-Zentrum Dresden-Rossendorf ● University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma ● University of Minnesota ● Institute for Nuclear Research, Moscow ● Muons Inc. ● Northern Illinois University ● Northwestern University ● Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● Rice University ● University of South Alabama ● Sun Yat Sen University ● University of Virginia ● University of Washington ● Yale University

Backup Slides

Fermilab Accelerator Complex



Older Experiments

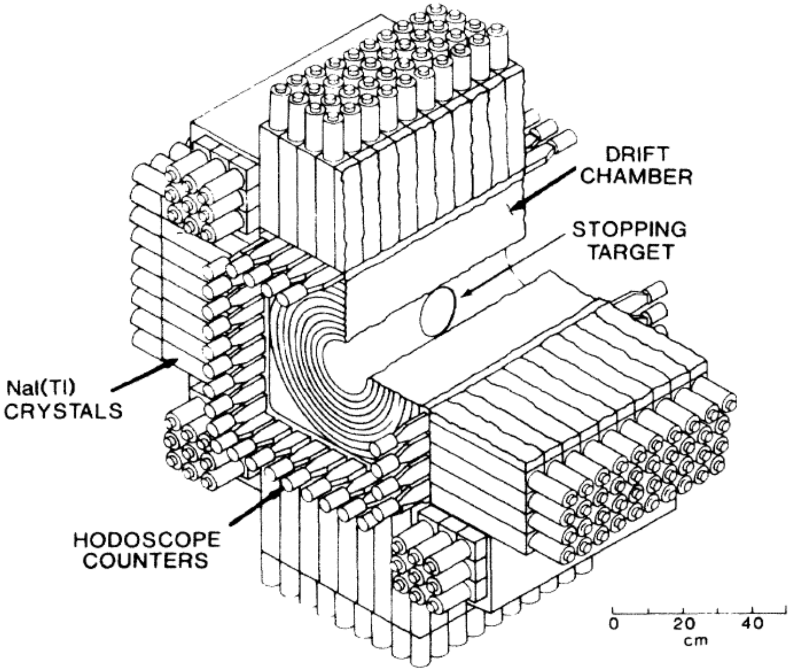


FIG. 1. A schematic diagram of the Crystal Box detector.

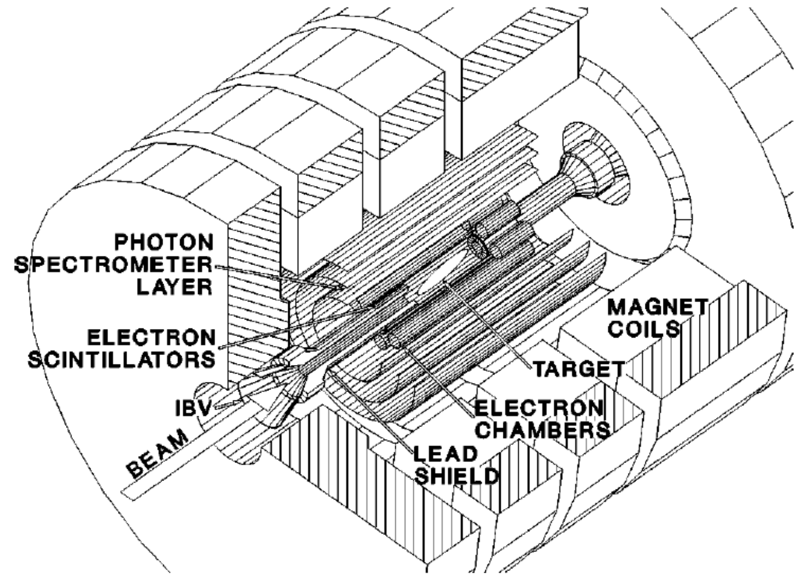


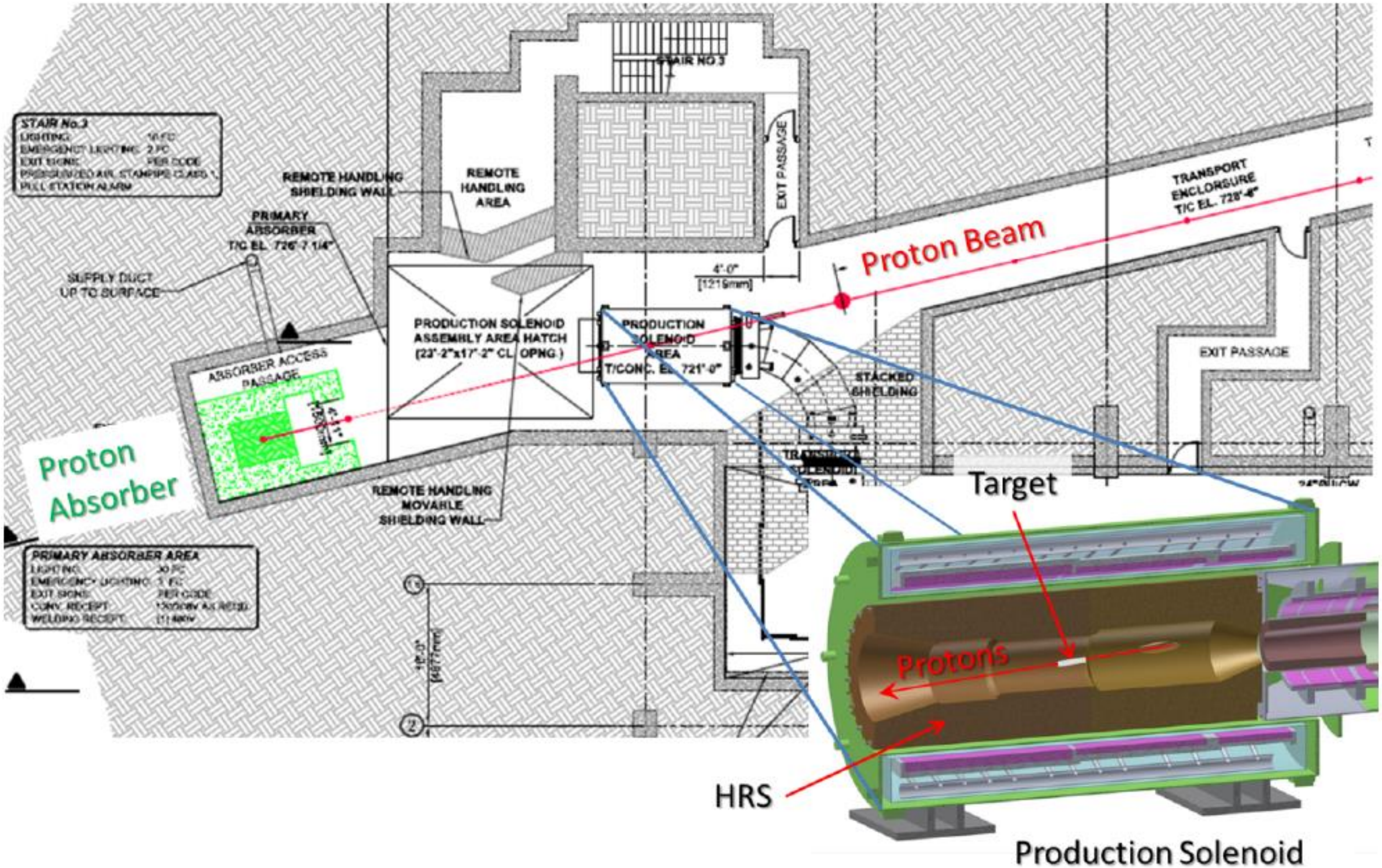
FIG. 1. A schematic view of the MEGA detector.

Crystal Box Detector
Bolton, *et al.* Phys. Rev. Lett. 56, 2461 (1988)
$B(\mu^+ \rightarrow e^+\gamma) < 4.9 \times 10^{-11}$

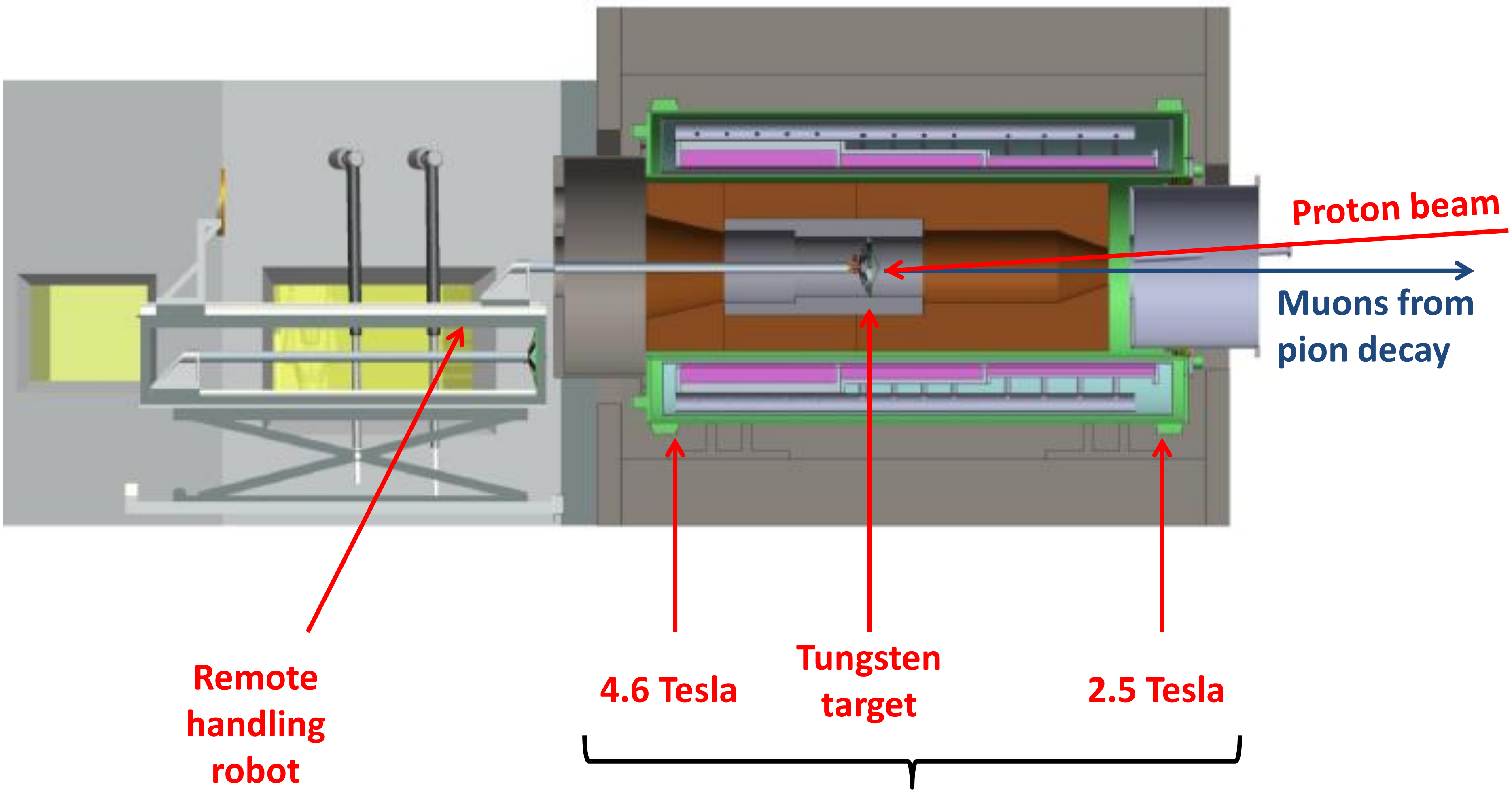
The MEGA Detector
Phys. Rev. D65, 112002 (2002)
$B(\mu^+ \rightarrow e^+\gamma) < 1.2 \times 10^{-11}$

Los Alamos Meson Physics Facility (LAMPF)

Muon Production Target



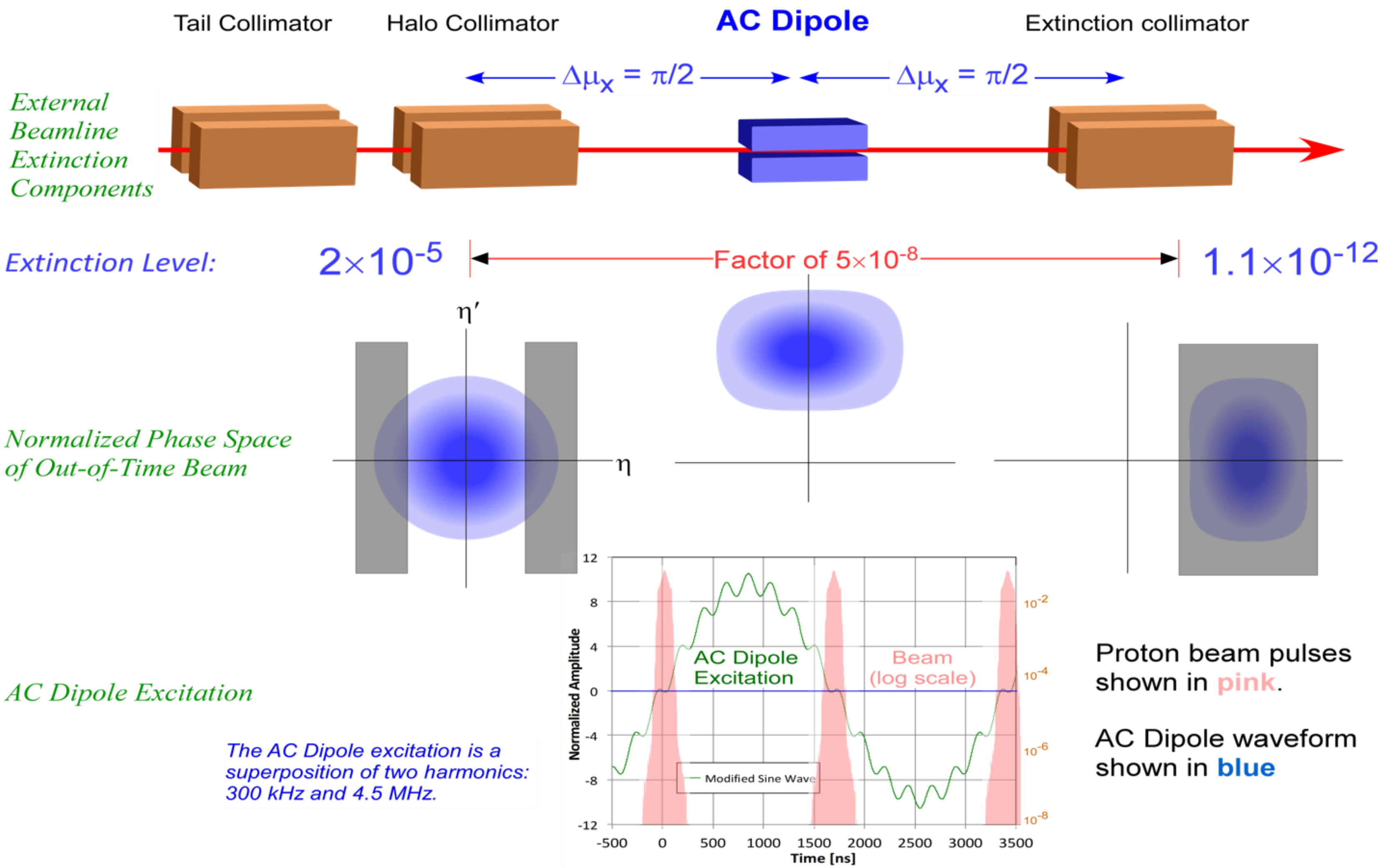
Muon Production Target



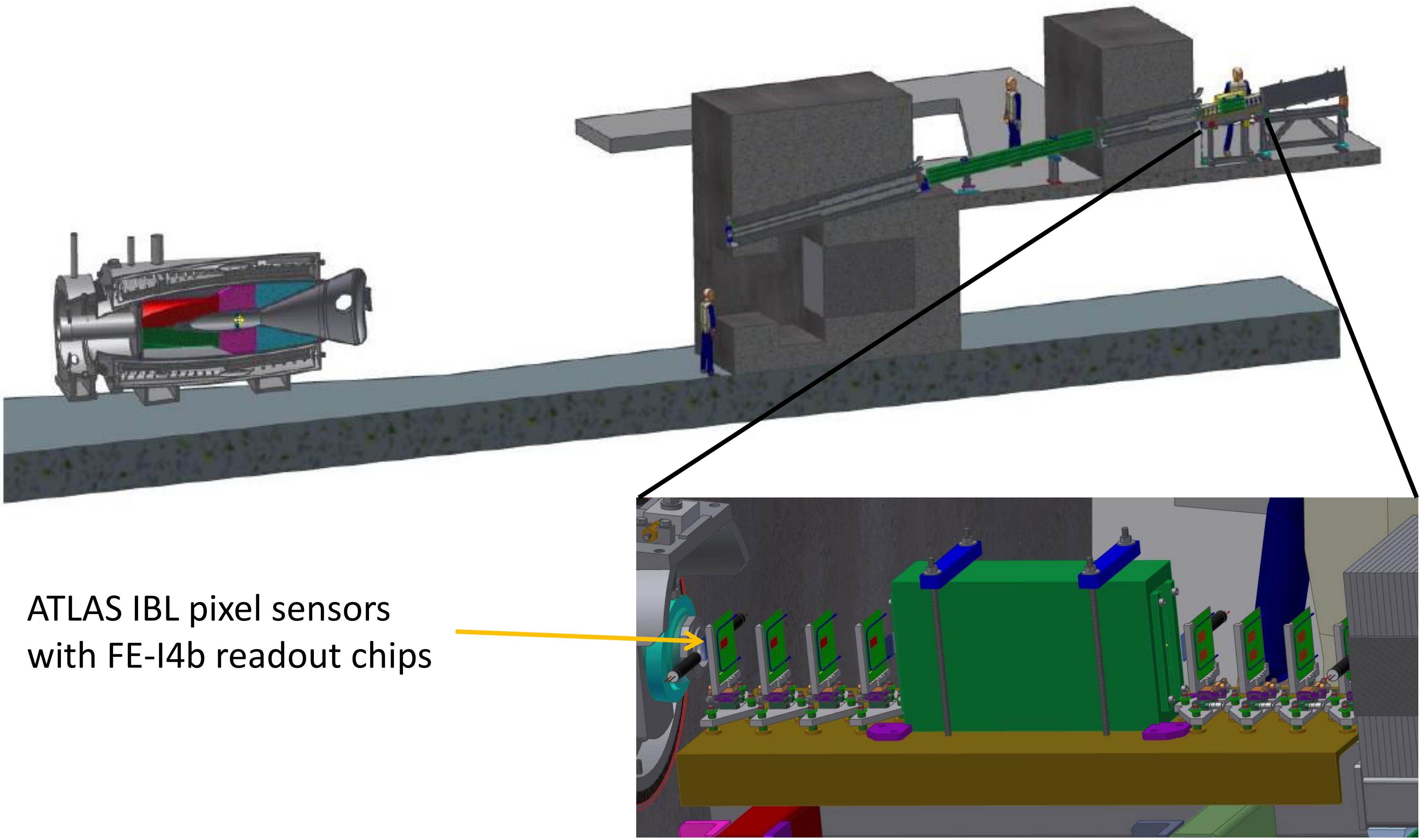
Protons on target per year: 10^{20}

Stopped muons per year: 2×10^{17}

Beam Extinction

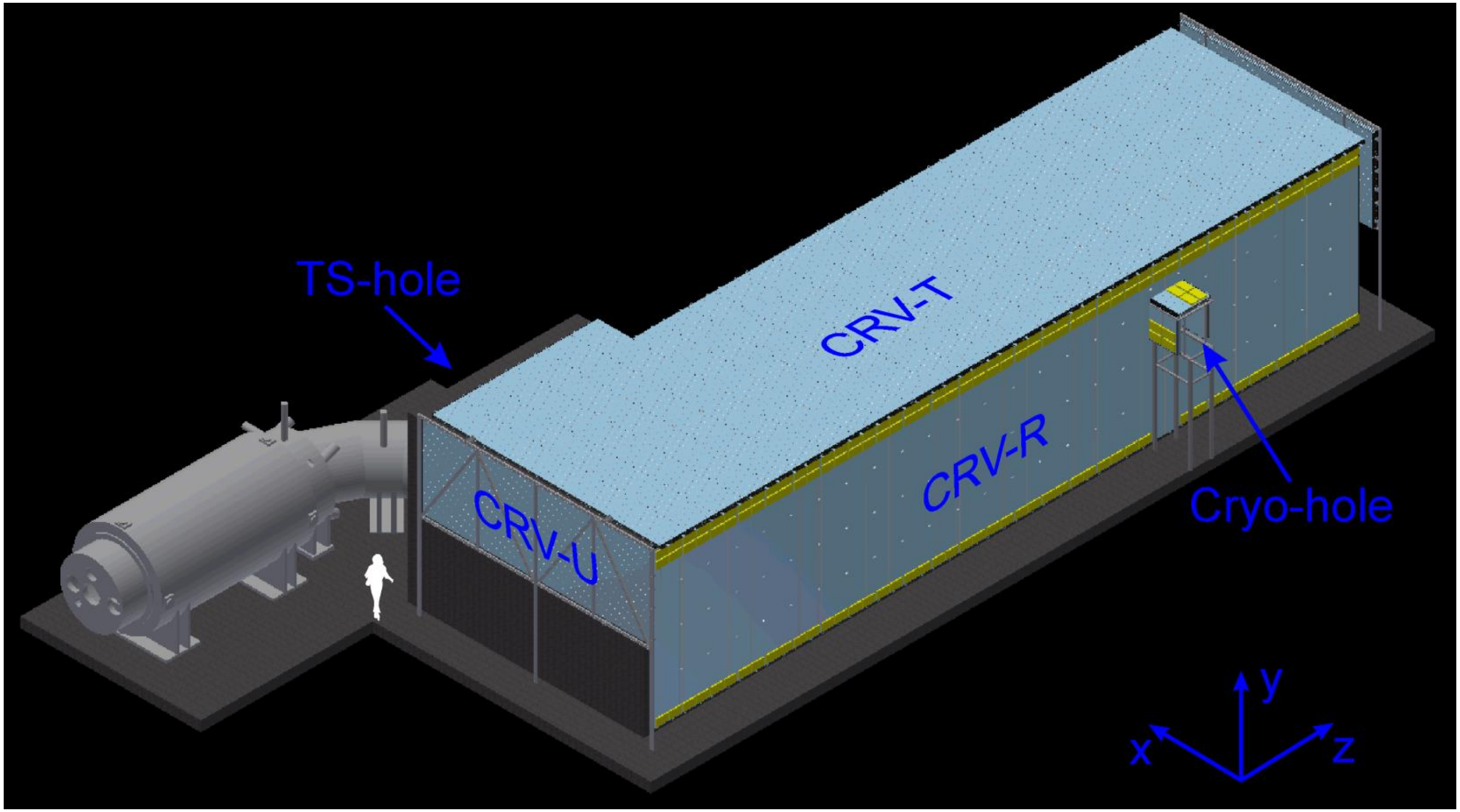


Target Extinction Monitor

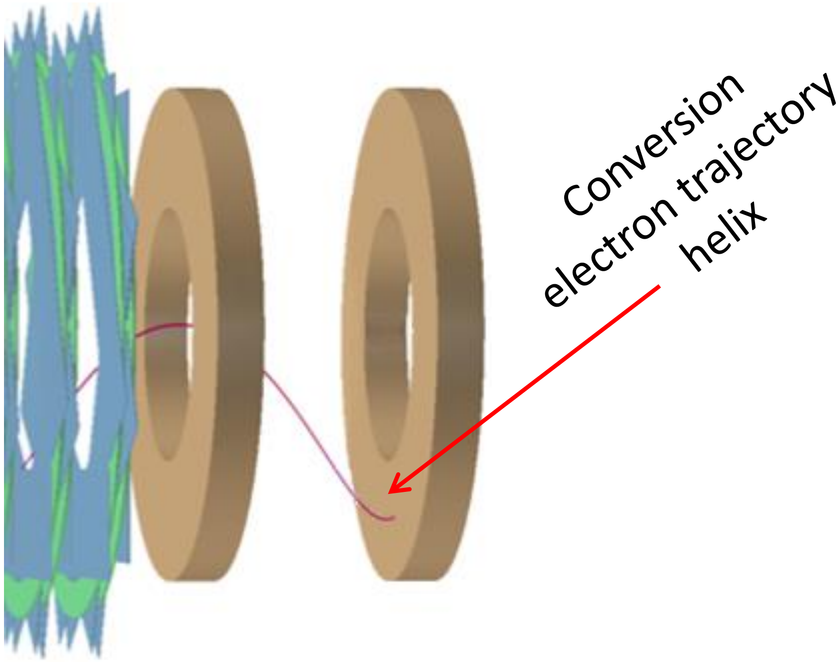


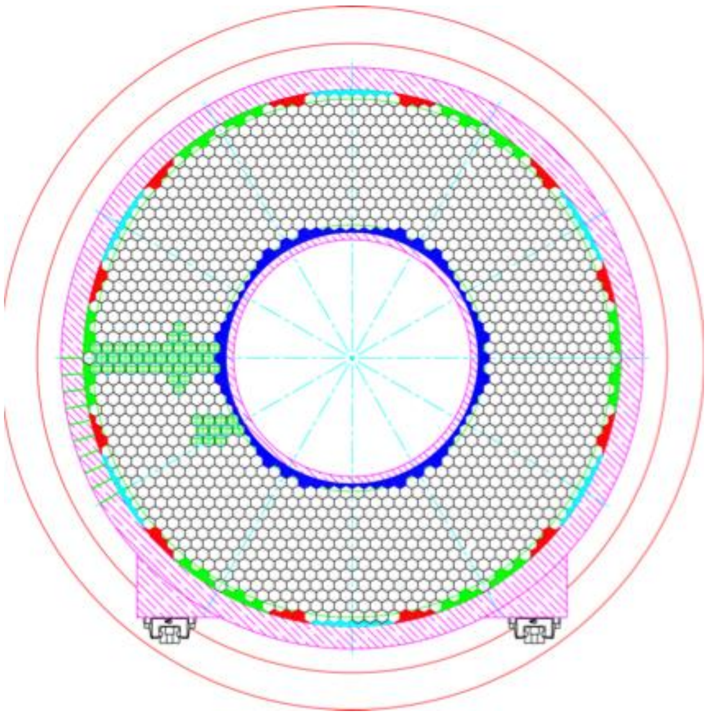
ATLAS IBL pixel sensors
with FE-I4b readout chips

Cosmic Ray Veto



Calorimeter

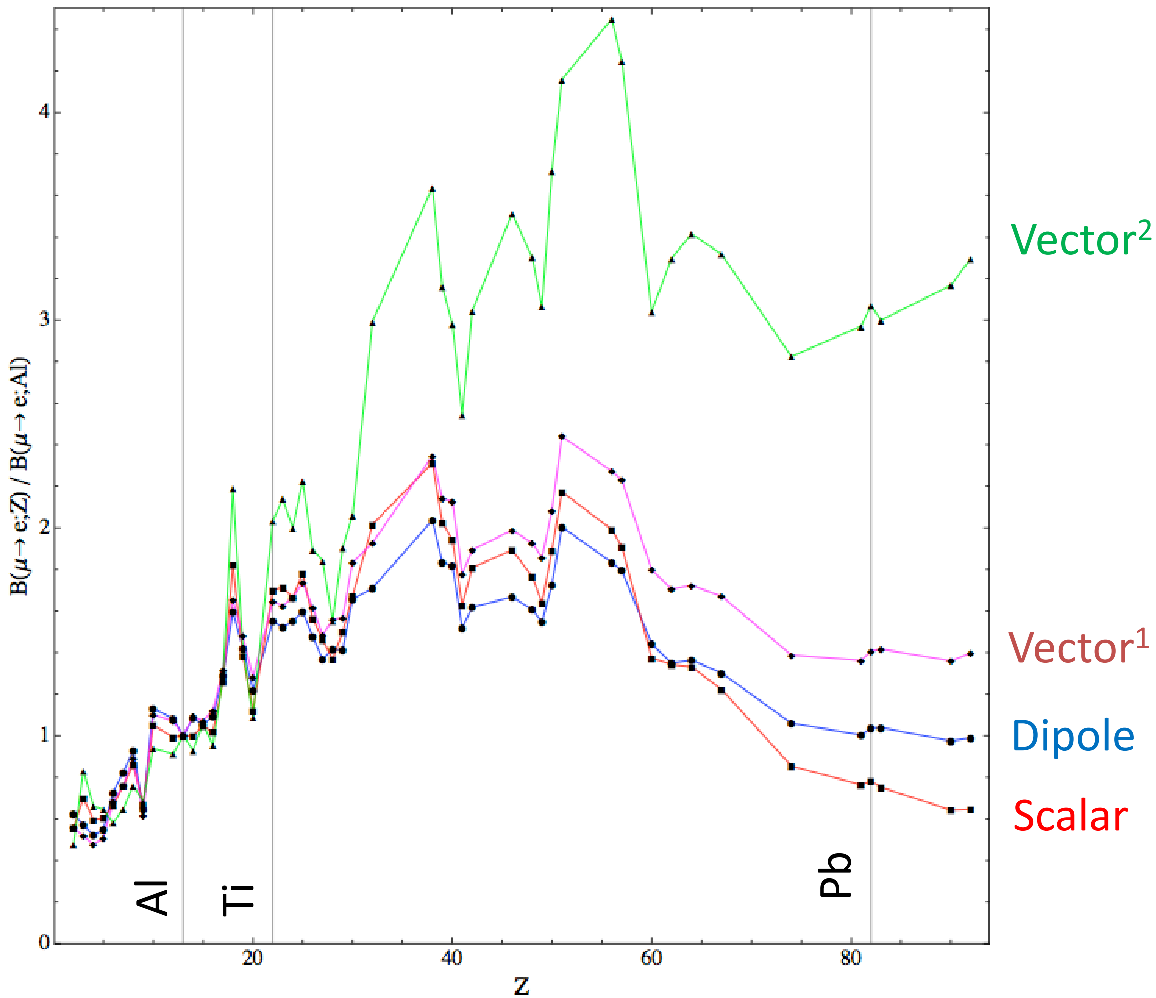




- Hexagonal BaF_2 or CsI crystals with SIPM or APD readout
- Discrimination between electrons, muons, pions, anti-protons

Nuclear Dependence

V. Cirigliano et al.,
Phys. Rev. **D80** 013002 (2009)



What about Tau Decays?

Process	B.R. Limit
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau \to \mu\eta$	$< 6.5 \times 10^{-8}$
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$
$\tau \to eee$	$< 2.7 \times 10^{-8}$

(2016 PDG)

- More sensitive to new physics on a per-decay basis
- Cannot compete with the muon production rate

$$\text{Mu2e } R(\mu N \to eN) \sim 10^{-17}$$