AMF: Physics Goals and General Description

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Future Muon Program at Fermilab Workshop

Caltech

2203.08278

(I feel silly giving this talk since all of you know this already)

What is AMF?

- Advanced Muon Facility
  - goal is to build a one-stop muon program for all three muon CLFV experiments and muonium-antimuonium oscillations
  - using PIP-II and Booster Replacement program
  - at orders-of-magnitude beyond planned experiments
- I am not going to talk much about detectors
  - not significantly past Mu2e/COMET for $\mu^- N \to e^- N$
  - will need new concepts for $\mu \to e\gamma,\ 3e$

AMF Problems

- How do we supply beam to *both* stopped muon and conversion experiments?
  - do we build two facilities, one with a stopped beam à la PSI and another for conversion?
  - can we make one beamline that does both?
- How can we target > 100 kW in a superconducting solenoid?
  - closely related to muon collider R&D
  - discussions underway (Porter, STFC)

How Well Do we Need to Do?

S. Davidson and B. Echenard, 2010.00317 [hep-ph]

- Write EFT Lagrangian:

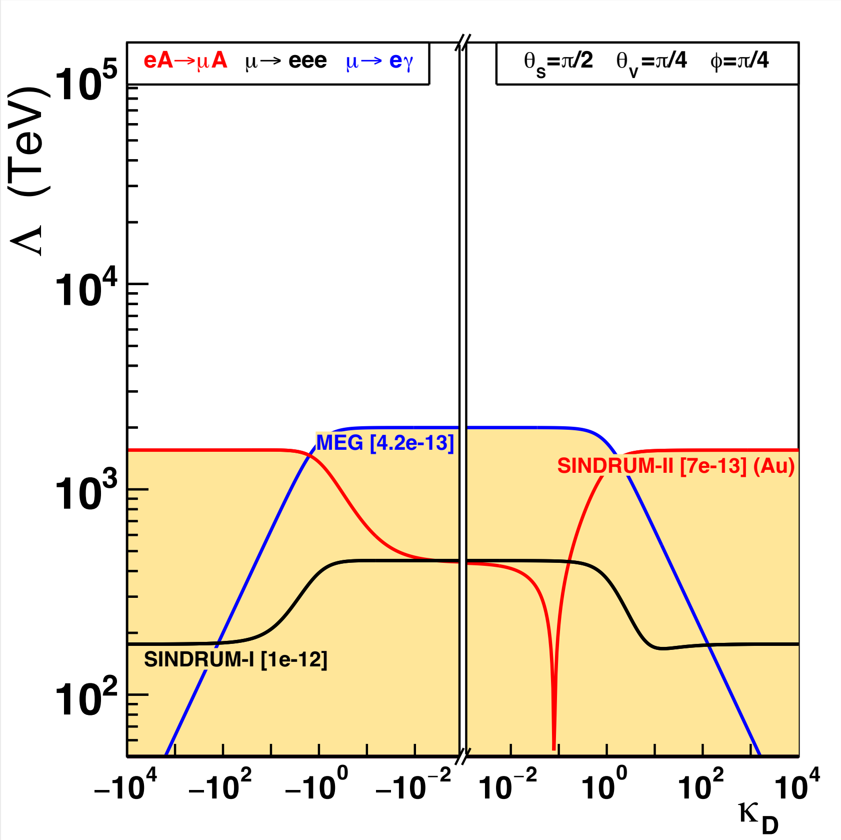
  - Dipole ($\mu \to e\gamma$) +
    Contact Scalar ($\mu \to 3e$)$_L$ +
    Contact Vector ($\mu \to 3e$)$_R$ +
    Contact $\mu N \to eN$ (light nuclei) +
    Contact $\mu N \to eN$ (heavy nuclei)

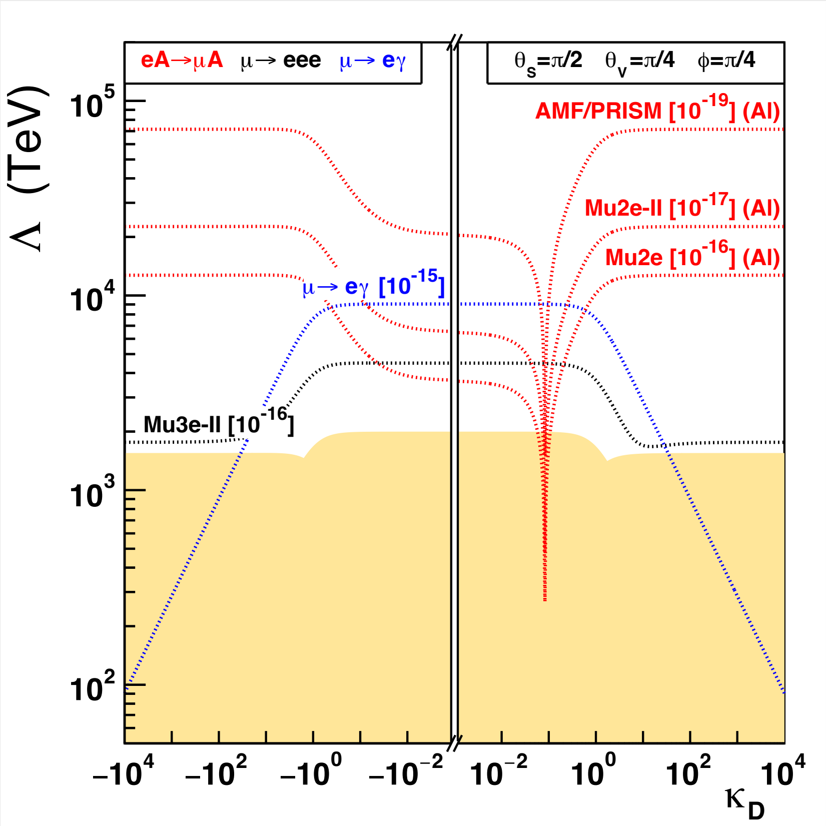
- Parameterize coefficient space with spherical coordinates: *lets you express constraints on all three processes simultaneously*

- Will show you “slices” in the multi-dimensional space

Physics Goals

- If you're going something new, push a couple of orders of magnitude





S. Davidson and B. Echenard, 2010.00317 [hep-ph]

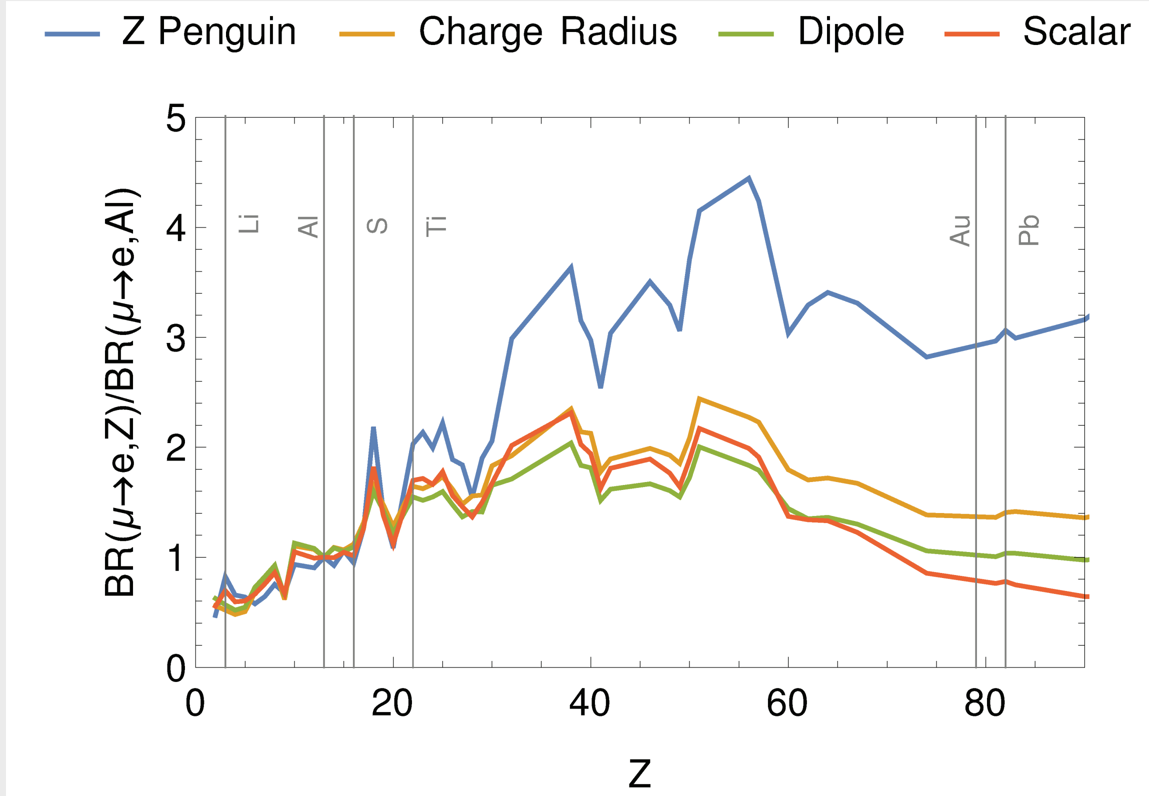
Physics Goals

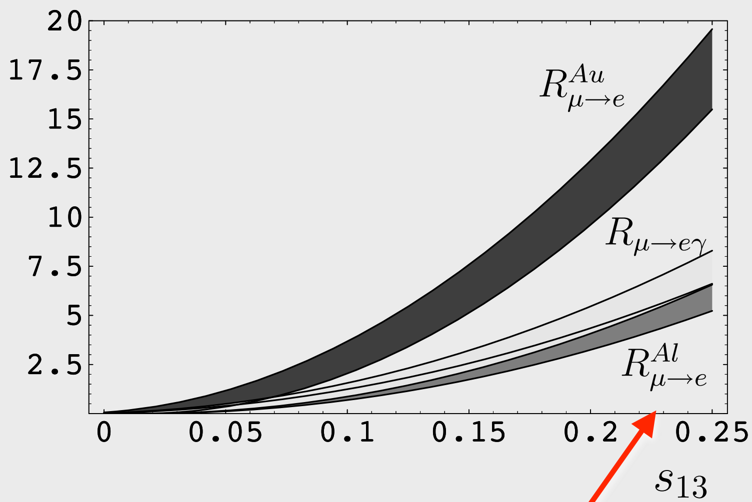
- one can obviously tweak the values of θ and ϕ but as a general goal:
  - $\mu \rightarrow e\gamma$: $\mathcal{O}(10^{-15})$
  - $\mu \rightarrow 3e$: $\mathcal{O}(10^{-16})$
  - $\mu^- N \rightarrow e^- N$: $\mathcal{O}(10^{-18-19})$ on high Z
- $\mu^- e^+ \leftrightarrow \mu^+ e^-$ x100 existing to about $10^{-5} G_F$

Conversion Experiments

Why High Z?

- Model Discrimination
- Linkage to other experiments





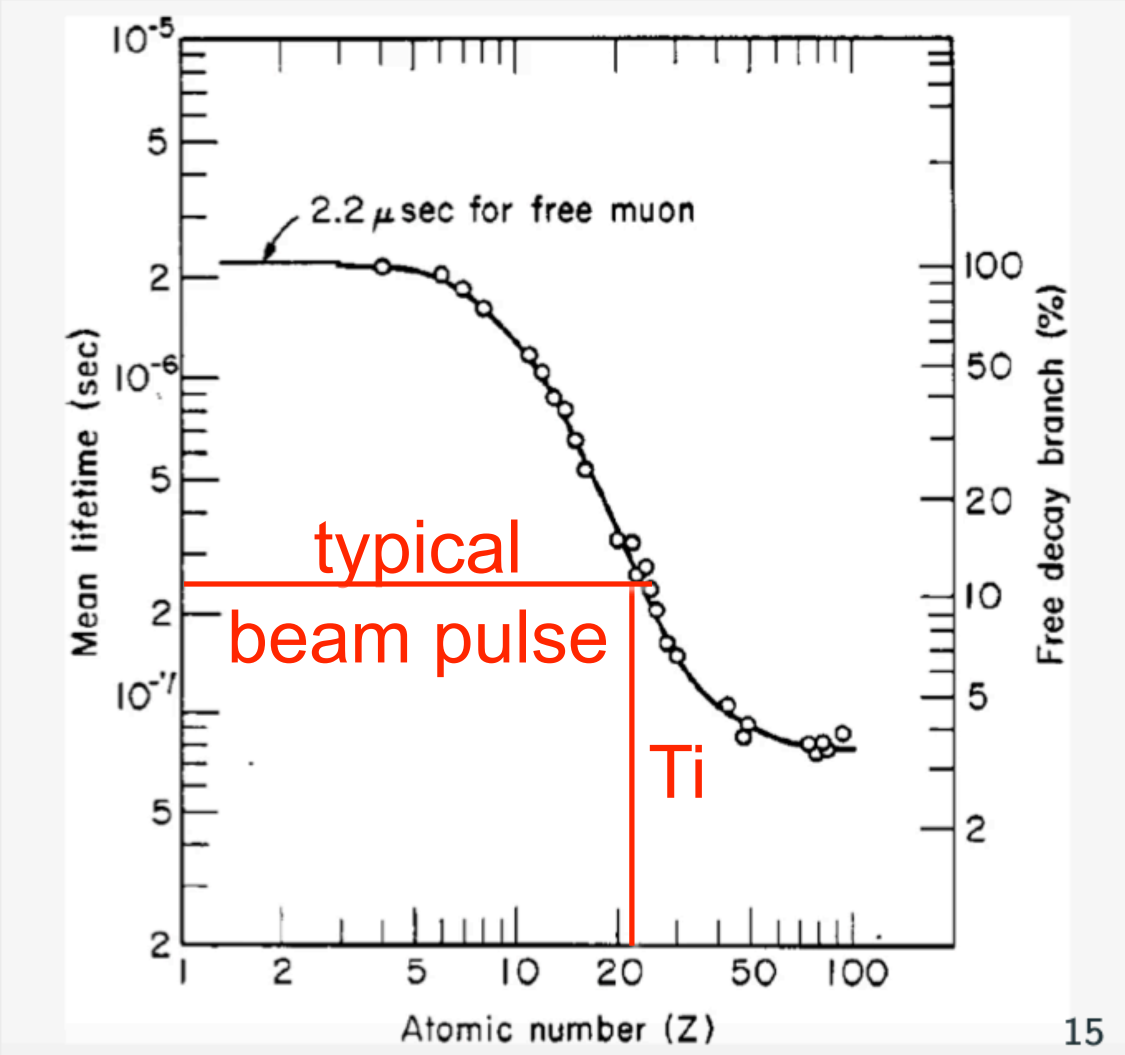
about x7 in this model

PDG: $(0.22 \pm 0.007) \times 10^{-3}$

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005

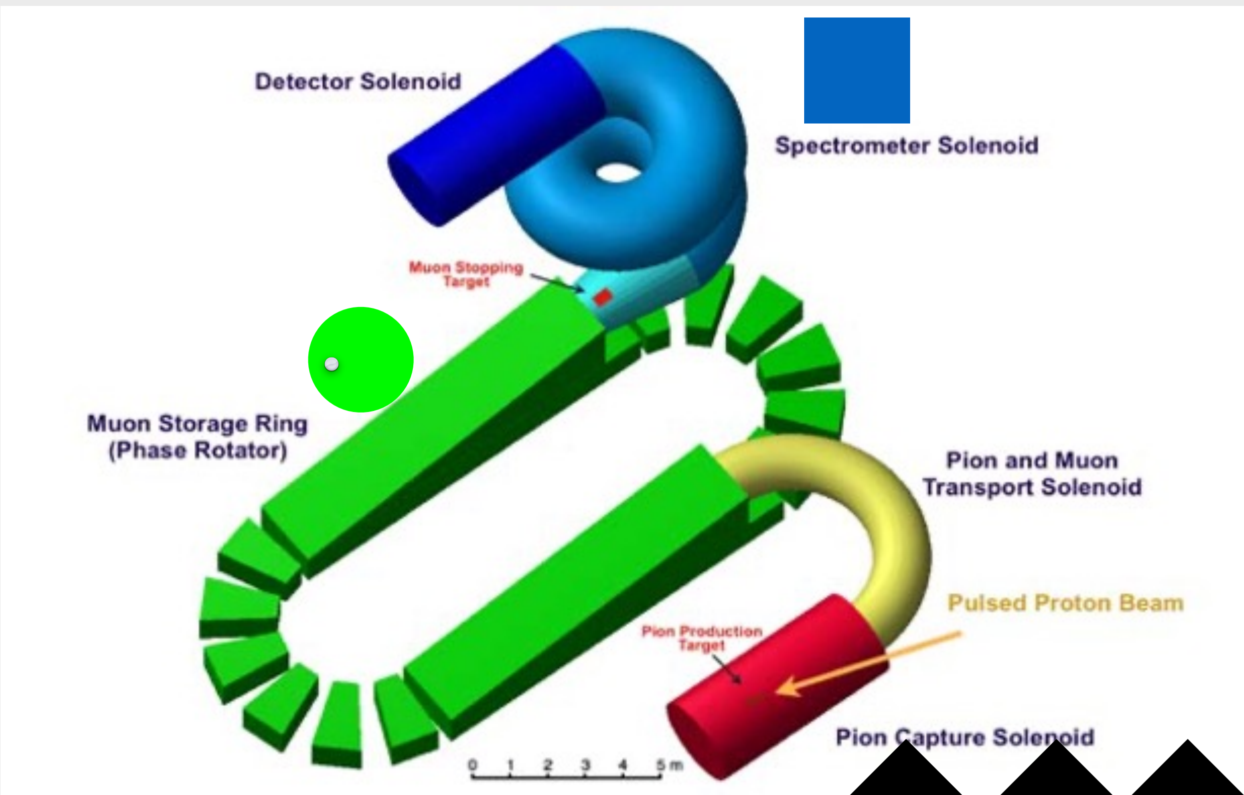
What's so hard about high-Z?

- A beam pulse is ~250 ns FWHM
- You can't do an experiment inside the debris from the beam pulse
- And therefore you can't go to high *Z:* Ti about limit



One Concept for $\mu^- N \rightarrow e^- N$

- FFA (PRISM) is essentially a muon storage ring
- Wait out π decays in the beam, produce a pure, cold muon beam



skier's guide

hard but not new

really hard but not new

really hard AND new

Advantages of PRISM

- We no longer have a “beam flash” as in Mu2e or COMET
- can spill out muons slowly and no longer sit in the beam pulse
- go for Gold!

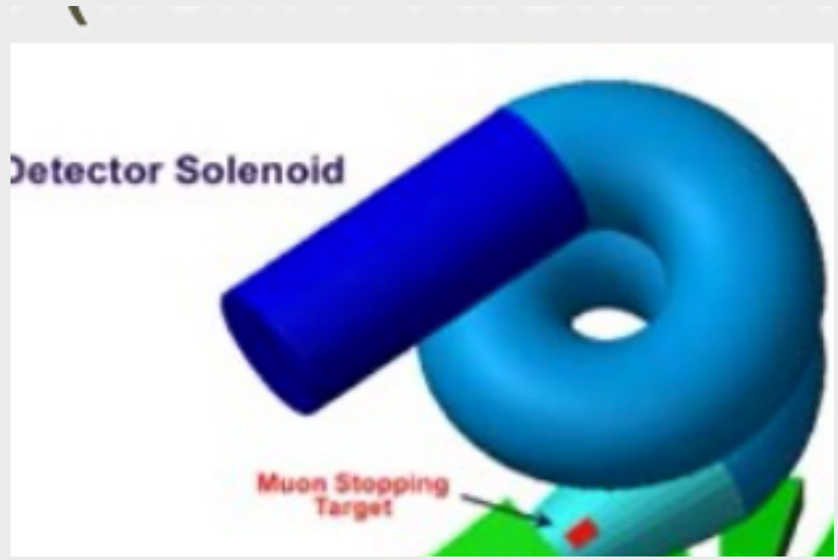
Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

Detector Technical Challenges

- $\mu^- N \rightarrow e^- N$
  - halving momentum resolution on signal e^-
    - not just making Mu2e straws thinner
    - rethink detector design
  - dominant background (we think) will be cosmic ray production of electrons in signal region
    - a CRV x100-x1000 better than Mu2e
    - multiple systems?

Detector/Solenoid "Interference"

- Still have activity from muon capture
  - if x100 or so in rate, how does detector survive?
- May need a curved detector solenoid like PRIME (the "Guggenheim" design)
  - but then we lose simultaneous $\mu^- N \rightarrow e^+ N'$



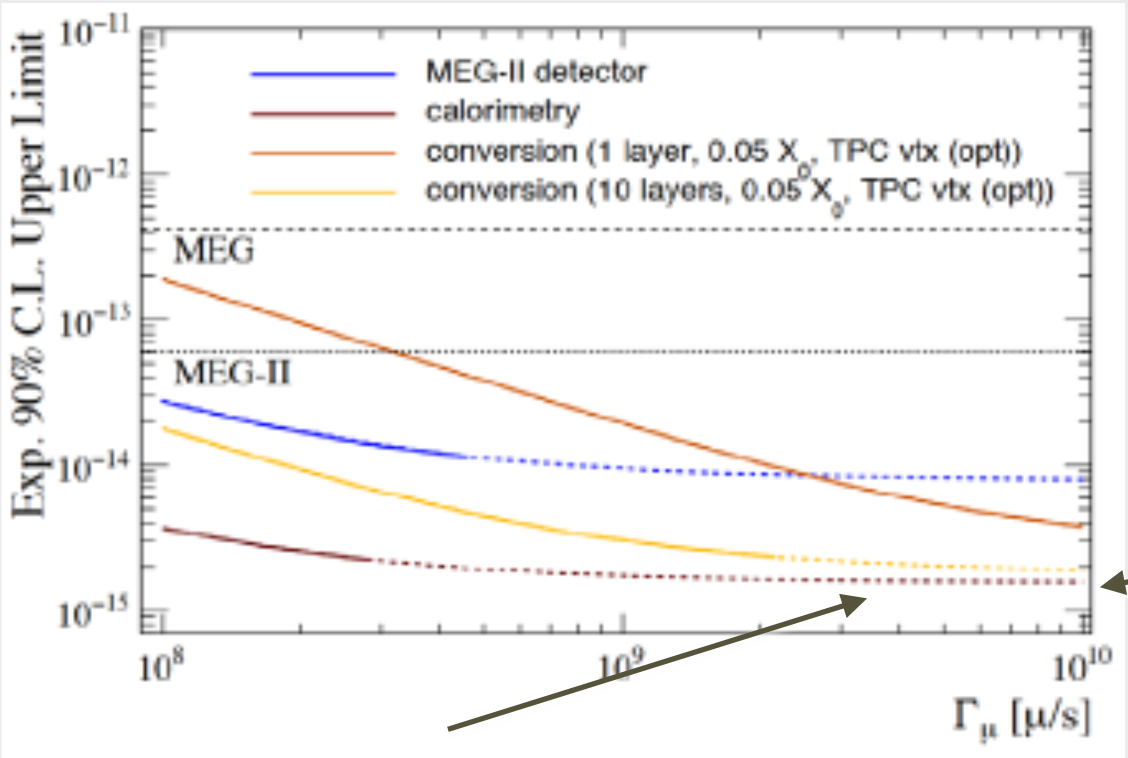
Decay Experiments

Decay Experiments

- $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$
  - these bring low energy (~ 30 MeV) μ^+ to rest in material and observe the decay (surface muon)
  - in $\mu^+ \to e^+\gamma$, accidentals scaling as I^2 are the limit; accidentals come from multiple muon decays and resolution limits
    - since accidentals drive the background, we want as continuous a beam as possible
  - in $\mu^+ \to e^+e^+e^-$, additional bkg from radiative muon decay, $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ with small E_ν

$\mu \rightarrow e\gamma$ Limits

- $\mu^+ \rightarrow e^+\gamma$ as in MEG, but convert the photon for improved resolution (have a vertex from tracks)
  - lowers statistics by ~x100 but improves background rejection



levels out at 10^{10} μ/sec, about HiMB PSI upgrade

Renga et al.,1811.12324[hep-ex]

this is why a new detector concept is needed

Decay Experiments:

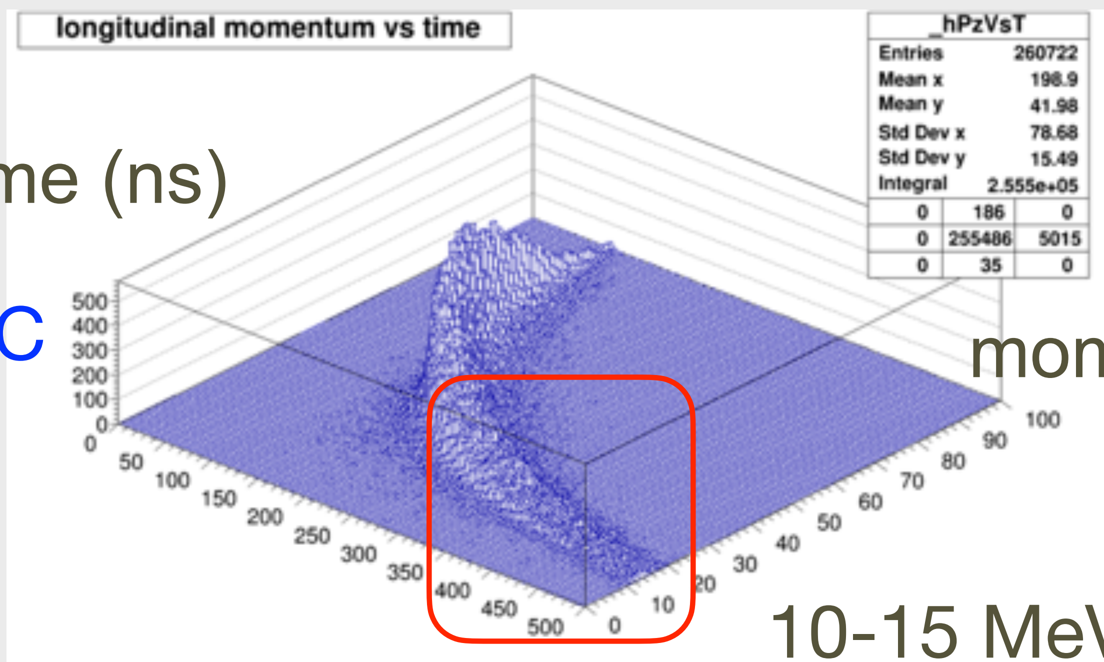
- Italy and Japan MEG groups are thinking about how to go beyond MEG-II design
- Can Mu2e people help?
- We might also want to think about a detector that does both $\mu \to e\gamma$ and $\mu \to 3e$
  - Two-body and three-body decay modes have very different kinematics — MEG uses back-to-back at the core of the design
  - not clear to me at least this has a solution

Single Beam to Both Experiments

- Arrival time for a delta-function beam like PIP-II
  - this uses Mu2e geometry but idea is the same: lower momentum muons take longer to arrive
- Slow down beam to constant momentum with time-varying deceleration

time (ns)

serious MC needed



momentum (MeV/c)

10-15 MeV instead of 29.6

Why Would we want lower momentum?

- $\mu \to e\gamma$ (MEG) is a two-body process: $\theta_{e\gamma} = 180$

RHB and PS Cooper, https://arxiv.org/abs/1307.5787

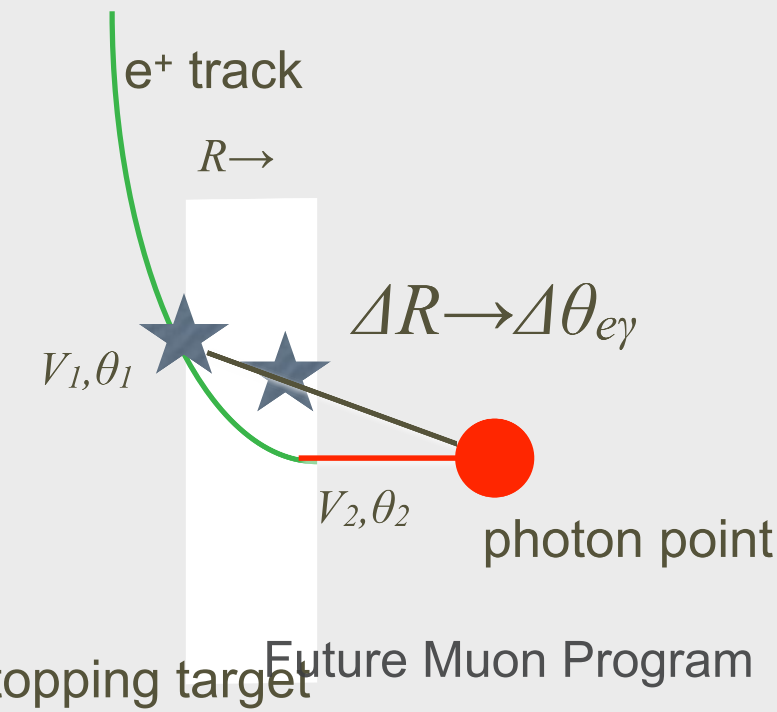
- Dependence of background on resolutions:

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

- If you don't convert the photon, and use *B*-field to measure p_e

- Range straggling grows as $\Delta R \sim T^{1.75}$ at these momenta

- if enough stopped muons, then can trade γ-conversion ($\sim 1\% \, X_o$) rate for three-track vertex ⇒this facility



Or Two Facilities

- PSI has a stopped muon beam at 1MW
- Steal their work
- Muon Physics only gets a small amount of this 1MW at PSI; we could have all of it
- But then we need to duplicate an expensive facility
  - on the other hand it might be more flexible

PIP-II

- For same reasons as Mu2e-II, AMF would like 2 GeV
- but bunched beam has to go into a compressor ring to rebunch

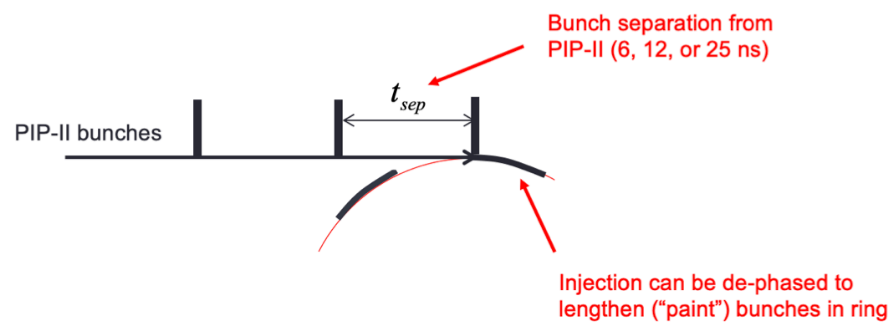


FIG. 4. Schematic illustration of injection into the compressor ring. Beam is distributed both transversely and longitudinally.

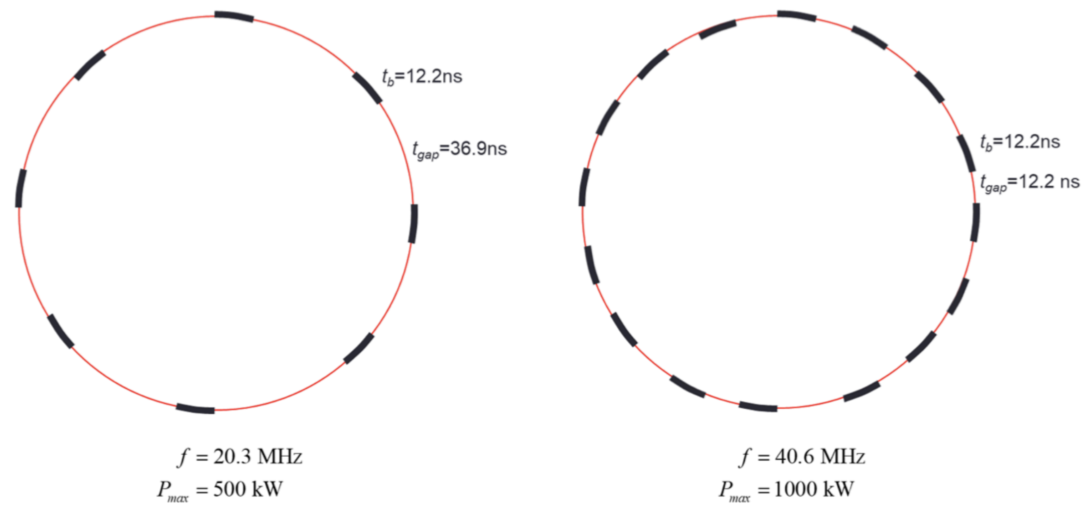


FIG. 5. Two possibilities for a 100 m compressor ring. The ring on the left shows 20 MHz bunches, each 12 ns long, separated by 37 ns. This ring would reach a total power of ~ 500 kW. To achieve 1 MW, a bunch frequency of 41 MHz would be needed (right ring), but this would represent a challenge for the extraction kicker.

Production Solenoid

- Mu2e at 8 kW requires a complicated heat and radiation shield to keep superconductor from quenching; COMET proposes 56 kW
- Conceptual designs exist for 100 kW
  - “moving mass” target and thicker shield: Vitaly’s LDRD
- AMF would provide world-class physics at high-*Z* *;* 100 kW is just the first step
- Various ideas for 1MW have been promoted
  - ν targets for NOvA get to nearly 1MW…why so hard?
  - *not inside a superconductor*

1 MW targeting

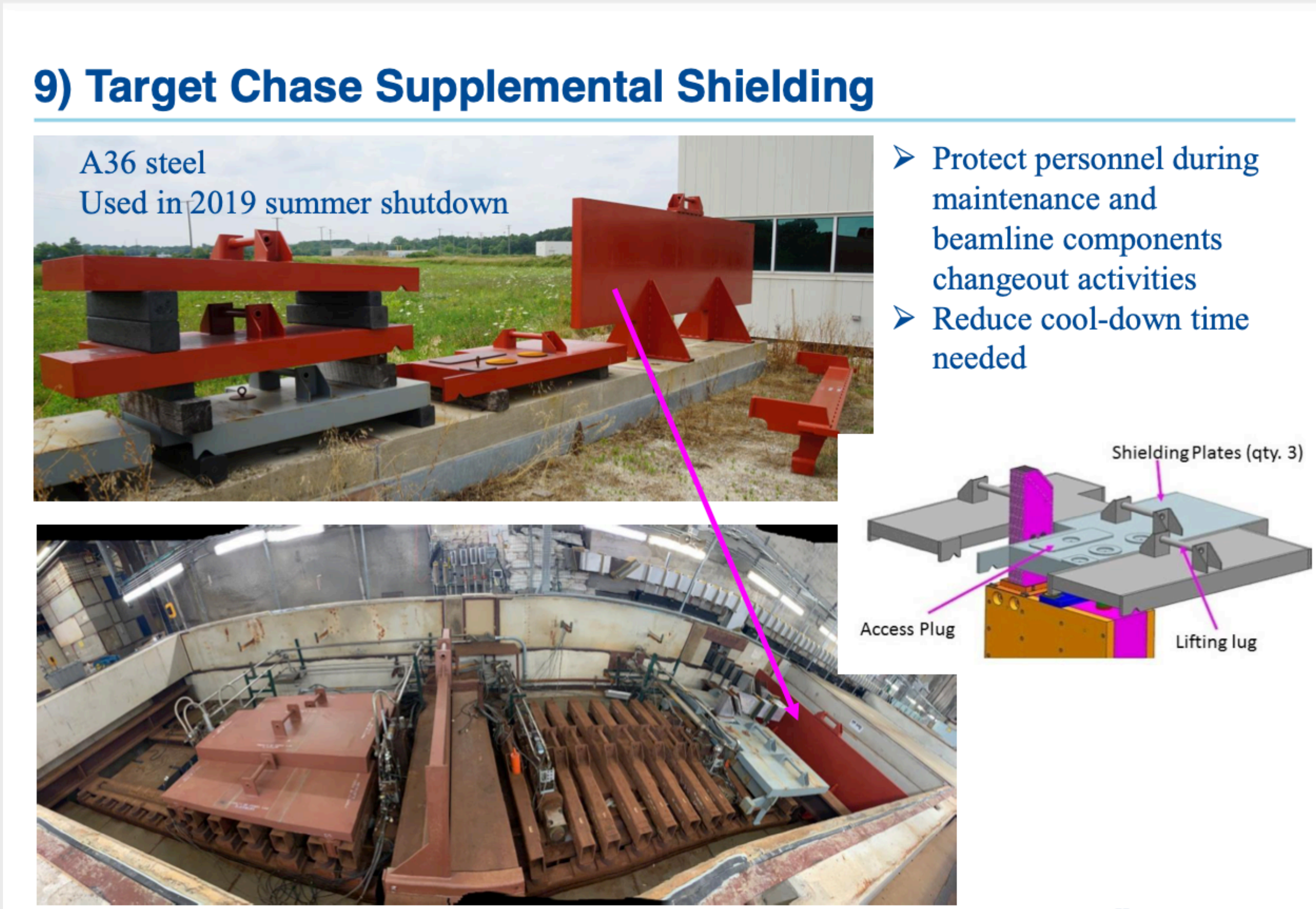
- MERIT experiment

  https://aip.scitation.org/doi/pdf/10.1063/1.3399332

  - Liquid mercury — this is an environmental problem (Minamata Convention)
  - Rep rates only about 70 Hz, limited by disruption of the jet. We need x10 faster
  - MERIT is not a proof as is sometimes claimed
- SNS moved to rotating tungsten
- Discussion of muon collider targetry: https://indico.cern.ch/event/1016248/contributions/4282384/attachments/2215324/3752155/MCa__MUC_Targetry__25Mar2021_v1.pdf

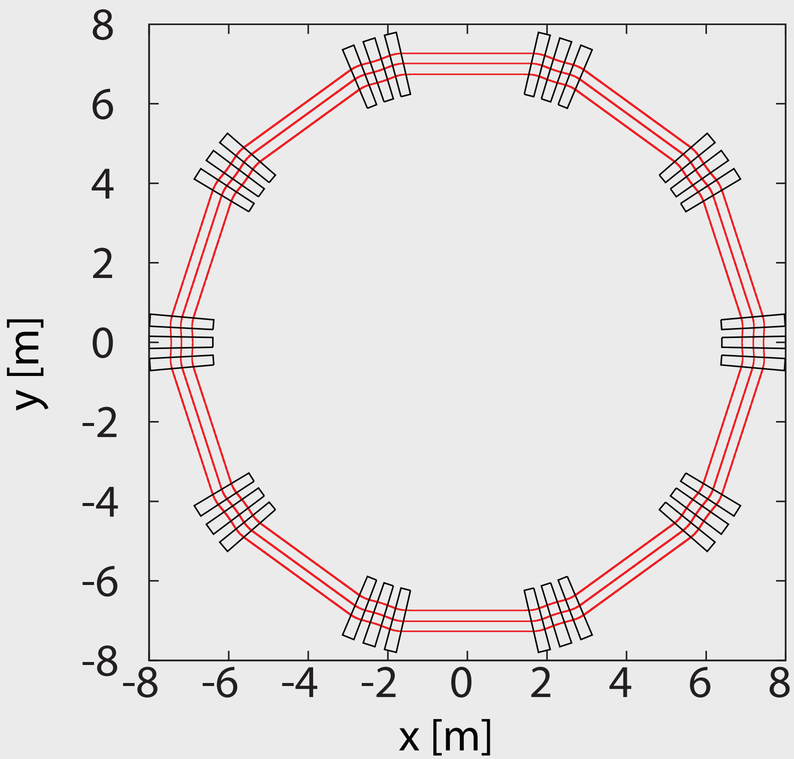
If you're not scared by now

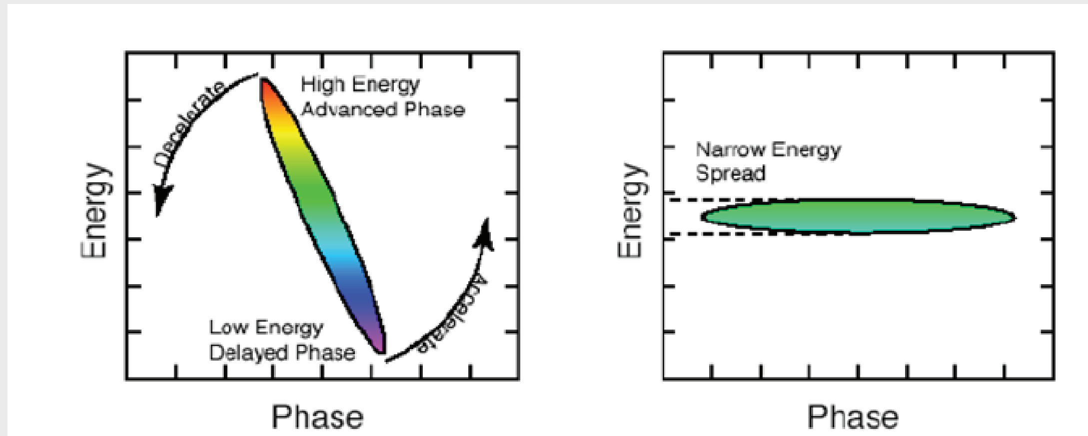
- you're not paying attention. Put your superconducting solenoid in the NuMI target chase

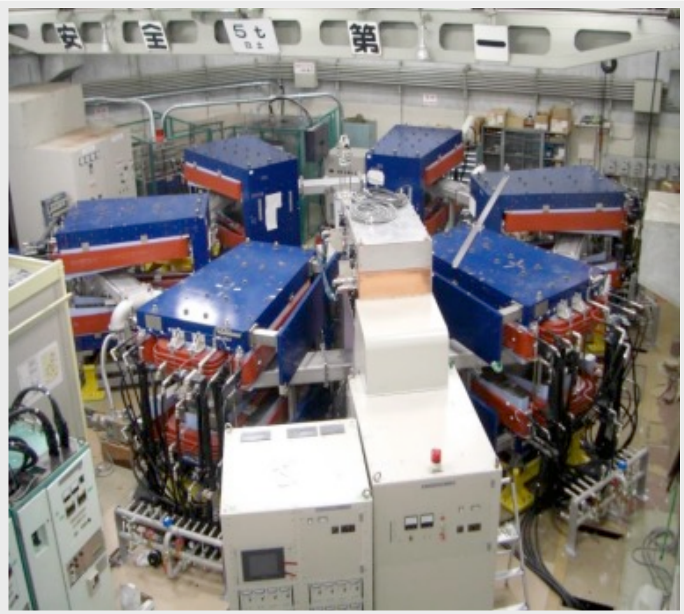


FFA

- PRISM (Phase Rotated Intense Source of Muons) (arXiv:1310.0804 [physics.acc-ph])







6 cell demonstrator at Osaka

Fermilab's ACE

- ACE = Accelerator Complex Enhancement
- Replaces Booster (50 years old and something bad will break)
- Coupled to PIP-II linac
- Really designed around DUNE but might be great for us; just not clear now

ACE

- We want 2 GeV pulsed

S. Valishev, https://indico.fnal.gov/event/58272/

Booster replacement scenarios

Considered 6 Configurations: 3 SRF Linac, 3 Rapid-Cycling Synchrotron (RCS)

In addition to 2.4MW to LBNF, the options enable new science 'spigots':

- 2 GeV Continuous wave (CW)
- 2 GeV Pulsed Beam (~ 1MW)
- 8 GeV Pulsed (~ 1MW)

RCS Configurations:

C1a) 10 Hz: metallic vac. chamber

C1b) 20 Hz: ceramic vac. chamber

C1c) 20 Hz: ceramic vac. chamber, high current linac

The specific upgrade scenario to be selected and developed with community input and informed by P5 and DOE decisions

SRF Linac Configurations:

C2a) Basic: small increase in PIP-II current, demonstrated XFEL RF

C2b) High duty factor RF source: small increase in PIP-II current

C2c) Higher Current PIP-II: significant current upgrade (5mA)

Fermilab

22 3/21/23 Valishev I Fermilab Accelerator Complex Evolution

One ACE Configuration

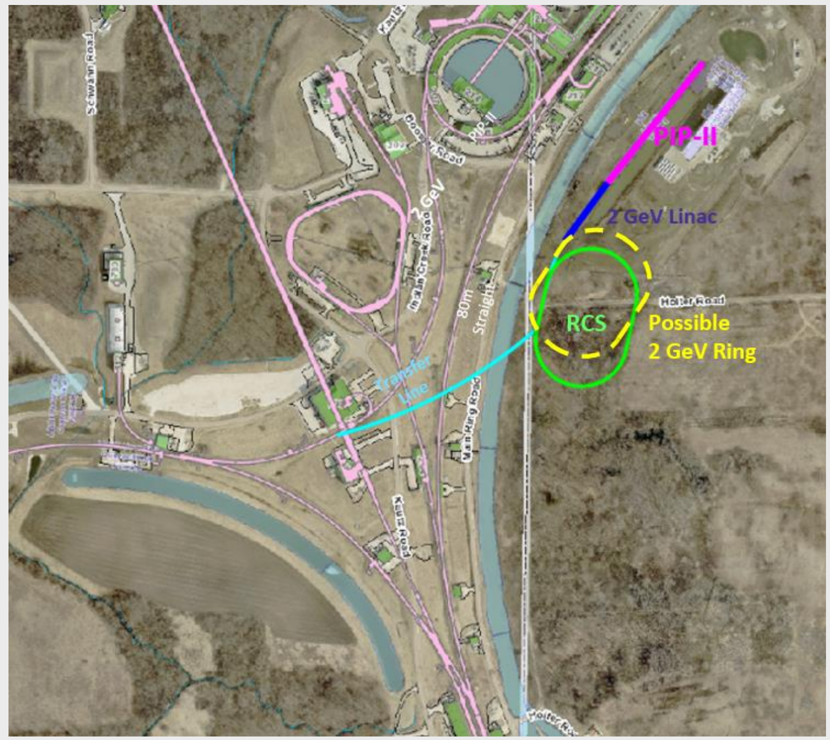
- I don’t have numbers, but this might be our compressor ring feeding FFA.

- Will have to talk to the Lab

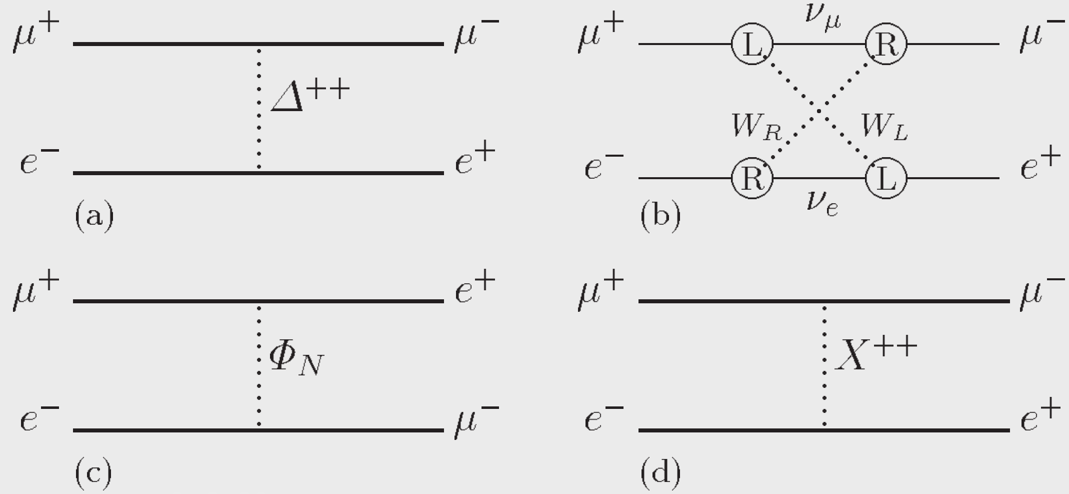
Example 1

Configuration C1b:

- 20Hz RCS + 2 GeV AR
- Main elements
  - 1-2GeV Linac
  - 20Hz 8GeV RCS
  - 2 GeV Accumulator Ring
  - MI Upgrades
  - Transfer Lines

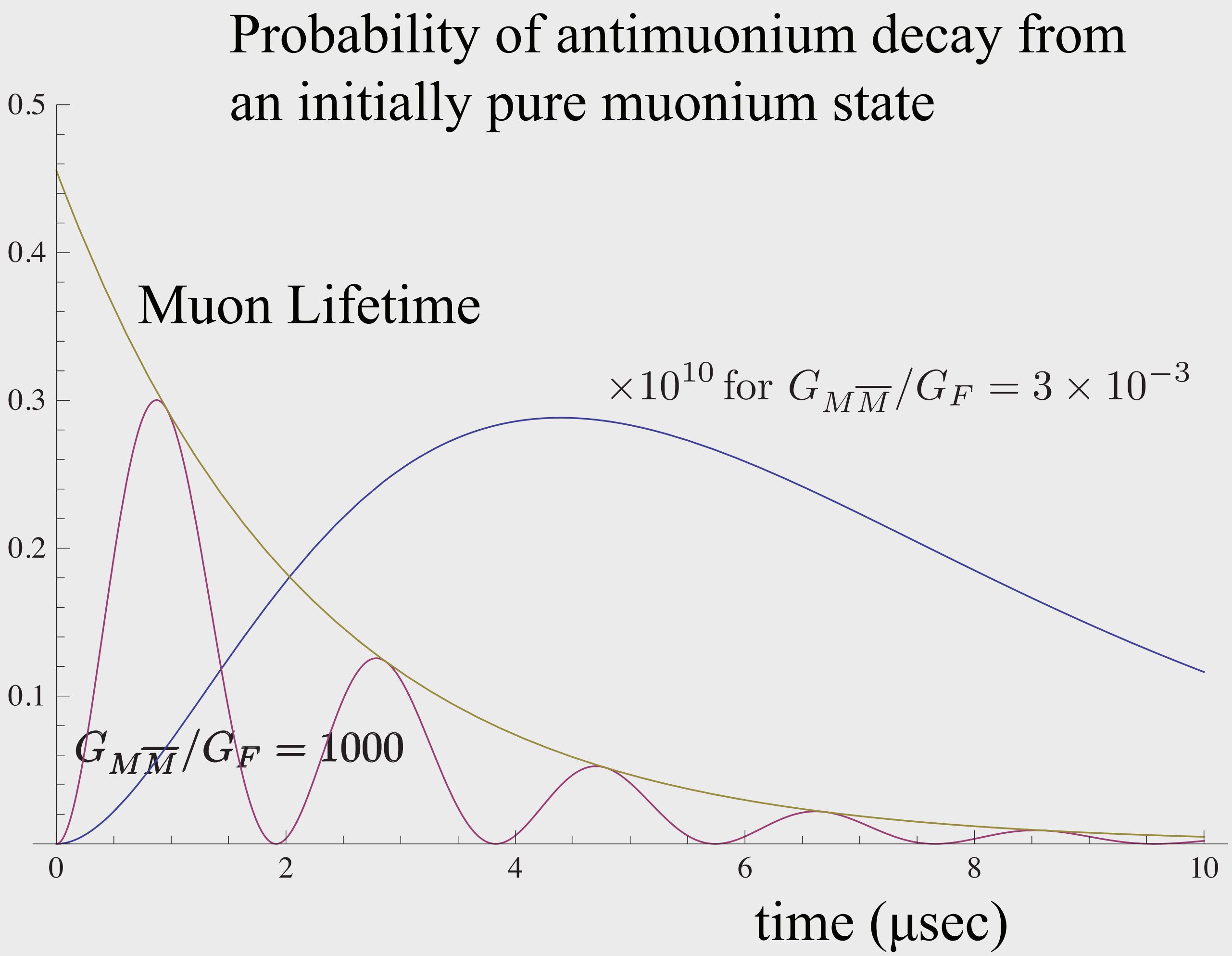


Muonium-Antimuonium



- $\mu^+ e^- \leftrightarrow \mu^- e^+$
  - Leptoquarks, doubly charged Higgs, Heavy Majorana neutrinos,...
  - New interactions break degeneracy
  - Not unlike $K^o \bar{K}^o$system
  - Usually parameterize interaction strength as G/G$_F$

Math



best paper on muonium-antimuonium theory:

G. Feinberg and S. Weinberg, Phys.Rev. 123, 1439 (1961).

Relevant Equations

$$\frac{\delta}{2} = \frac{8\,G_F}{\sqrt{2}n^2\pi a_o^3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

where n is the principal quantum number and a_o is the Bohr radius of the muonium atom. For $n = 1$,

$$\delta = 2.16 \times 10^{-12}\,\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\ \mathrm{eV}$$

Assuming an initially pure μ^+e^- state, the probability of transition is given by:

$$\mathcal{P}(t) = \sin^2\left(\frac{\delta t}{2\hbar}\right)\ \lambda_\mu e^{-\lambda_\mu t}$$

where λ_μ is the muon lifetime. Modulating the oscillation probability against the muon lifetime tells us the maximum probability of decay as anti-muonium occurs at $t_{\mathrm{max}} = 2\tau_\mu$. The overall probability of transition is

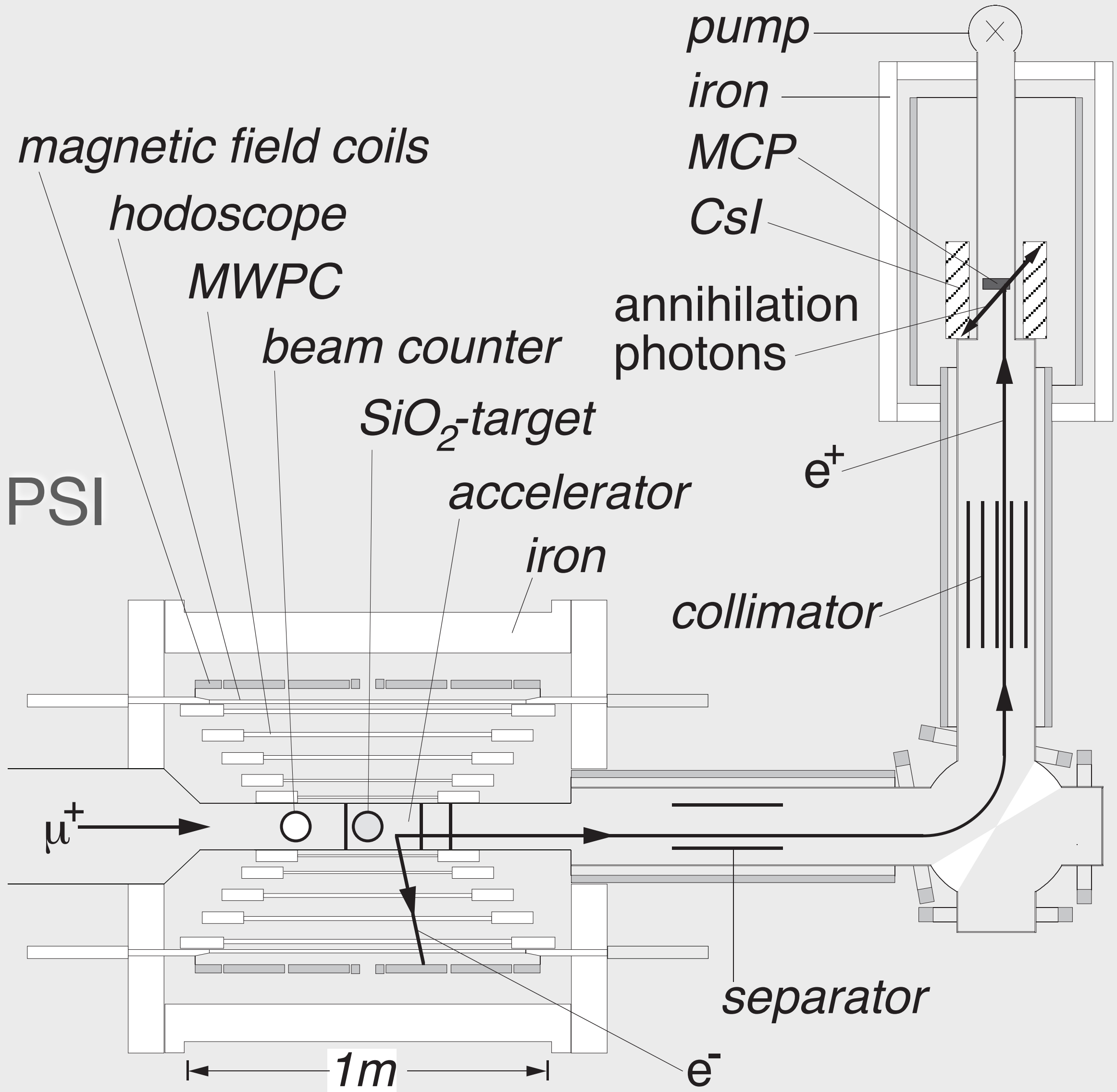
$$P_{\mathrm{total}} = 2.5 \times 10^{-3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

Beautiful Experimental Methods

- How do you make muonium?
  - make a sub-surface beam
    - sub-surface beams stop inside, not on surface, and have a lower momentum distribution than surface beams
    - this yields a smaller straggling by $\Delta R \sim p^{3.5}$ and a tighter spatial stopping distribution
    - let the positive muons stop in SiO_2 powder, a technique invented at TRIUMF
  - The powder structure stops the positive muon and the voids permit the muonium to escape

Experiment

- MACS at PSI



Signal and Background

$$G/G_F < 3. \times 10^{-3} @ 90\,\%\,\mathrm{CL}$$

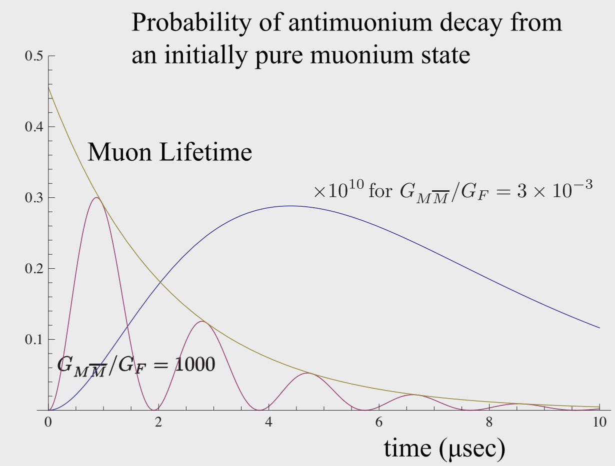
Willmann, L., et al. (1999), Phys. Rev. Lett. 82, 49.

- Signal:
  - μ^- decay (e^-near Michel peak) in coincidence with e^+
  - Backgrounds:

1. The rare decay mode $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ with a branching ratio of 3.4×10^{-5}. If one of the positrons has low kinetic energy and the electron is detected, this channel can fake a signal.
2. The system starts as muonium, hence $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ yields a positron. If the e^+ undergoes Bhabha scattering, an energetic electron can be produced. Background results from the coincidence of that scattering with a scattered e^+. The positron's time-of-flight is is used to reject background.

$e^+e^- \to e^+e^-$, annihilation or scattering

How to do better?



- Both backgrounds can be suppressed with a pulsed beam and by waiting for the muon lifetime to suppress the muon decay
  - can make up the muon flux at a hotter beam, which did not exist at the time of MACS
- Modern detectors have much better resolution
- discussions with experts: x100 should be achievable