Current Status and Future Proposals for CLFV Muon Searches

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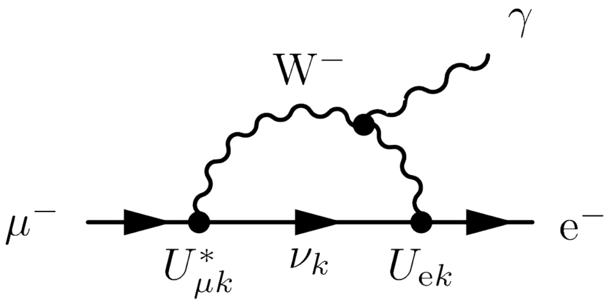
Muon Collider Synergies Workshop, Orsay, France

23 June 2023

Charged Lepton Flavor Violation

Although it has never been observed, we know that cLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.



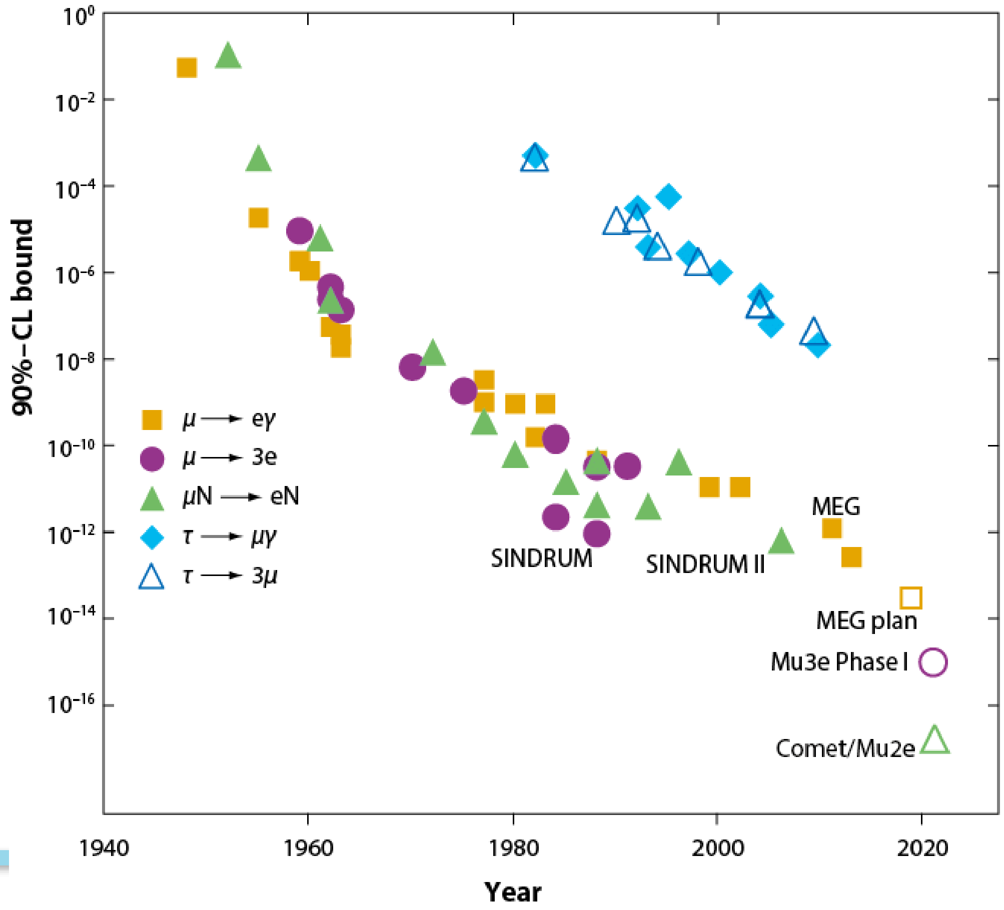
However, the predicted SM rates are unobservably small:

$$\mathrm{Br}(\mu \to \mathrm{e}\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{\mathrm{e}k} \frac{\Delta m^2_{1k}}{M^2_{\mathrm{W}}} \right|^2 < 10^{-54}$$

Any CLFV (or LNV) observation must be new physics!

Muons could have a lot to tell us about CLFV

This insight is certainly not new…



Muons could have a lot to tell us about CLFV

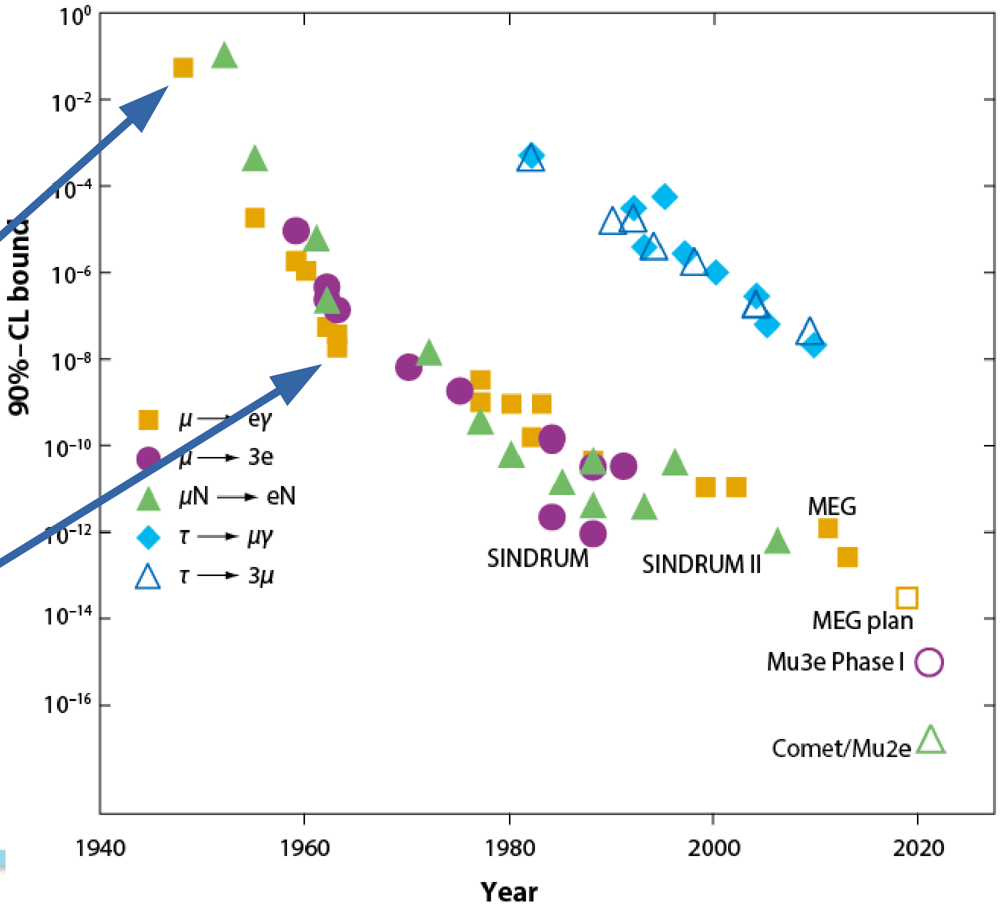
This insight is certainly not new…

1947:
Pontecorvo
and Hincks

$$\mu \neq e^*$$

1962:
Lederman,
Schwartz,
and
Steinberger
1988 Nobel

$$\nu_\mu \neq \nu_e$$



In many channels, we know how to do better in the future (in some cases much better) than we can today

Surface muon beams

$$\mu^+ \to e^+\gamma$$

$$\mu^+ \to e^+e^+e^-$$

$$\mu^+ e^- \leftrightarrow \mu^- e^+$$

Double CLFV!

"High" energy beams

$$\mu^- A(Z,N) \to e^- A(Z,N)$$

$$\mu^- A(Z,N) \to e^+ A(Z-2,N)$$

CLFV and LNV!

There are a large number of experiments proposed to further address these channels; I apologize for only mentioning those I'm involved with.

Overview of the current generation of experiments

- There is a globally distributed program to pursue muon sector CLFV
  - MEG, Mu3e at PSI
  - Mu2e at Fermilab
  - COMET at J-PARC
- The details of the new physics may be revealed in the pattern of CLFV rates across processes and (for conversion) target nucleii.

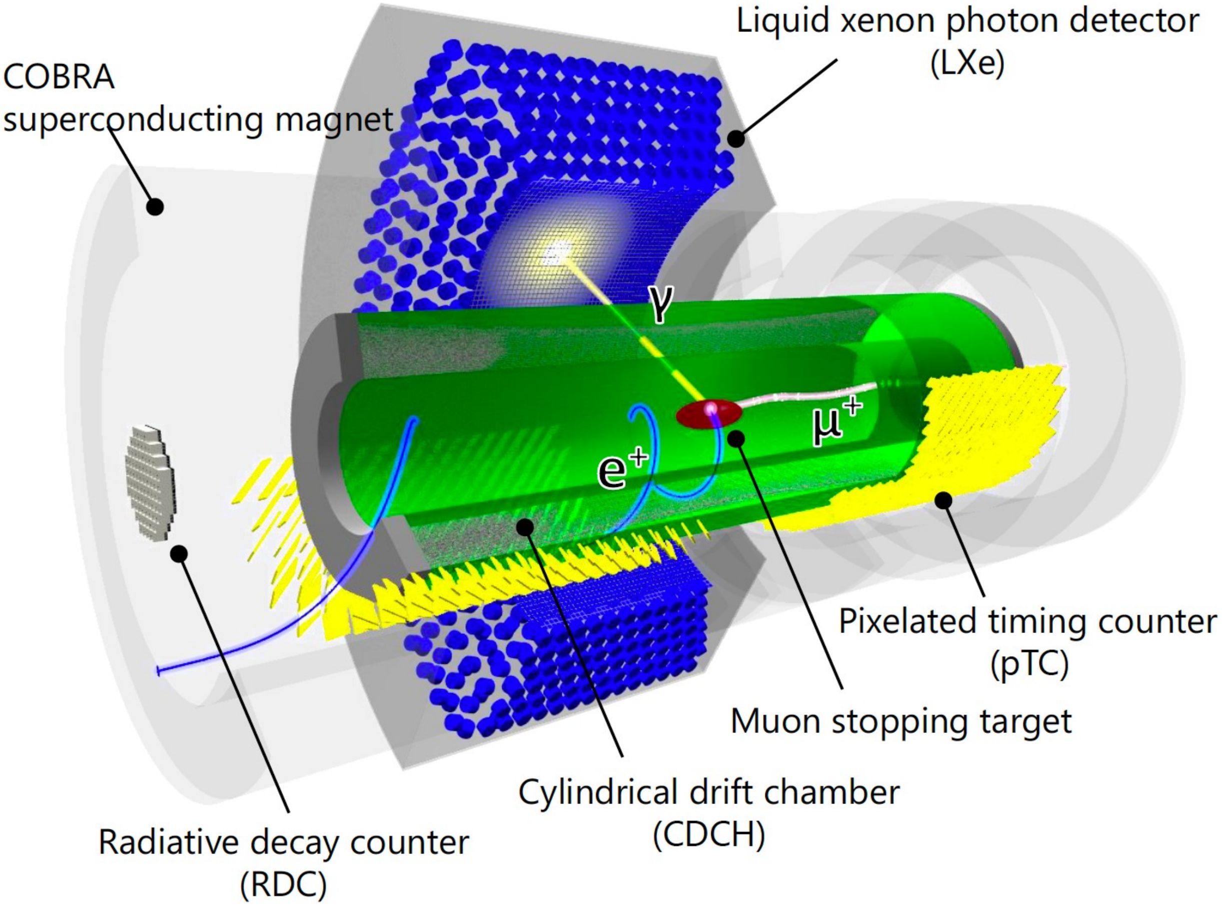
Mode	Current Upper Limit (at 90% CL)		Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	4.2×10^{-13}	MEG	4×10^{-14}	MEG II
$\mu^+ \rightarrow e^+e^+e^-$	$\sim 10^{-12}$	SINDRUM	$10^{-15} \sim 10^{-16}$	Mu3e
$\mu^- N \rightarrow e^- N$	7×10^{-13}	SINDRUM II	10^{-15} 10^{-17}	COMET Phase-I Mu2e/COMET Phase-II

Table borrowed from S. Middleton

MEG/MEG-II

$$\mu^+ \to e^+\gamma$$

- Data collection should be complete in 2026.
- Improving resolution in this channel beyond MEG-II will require some new experimental concept; see talk by F. Renga at CLFV 2023.



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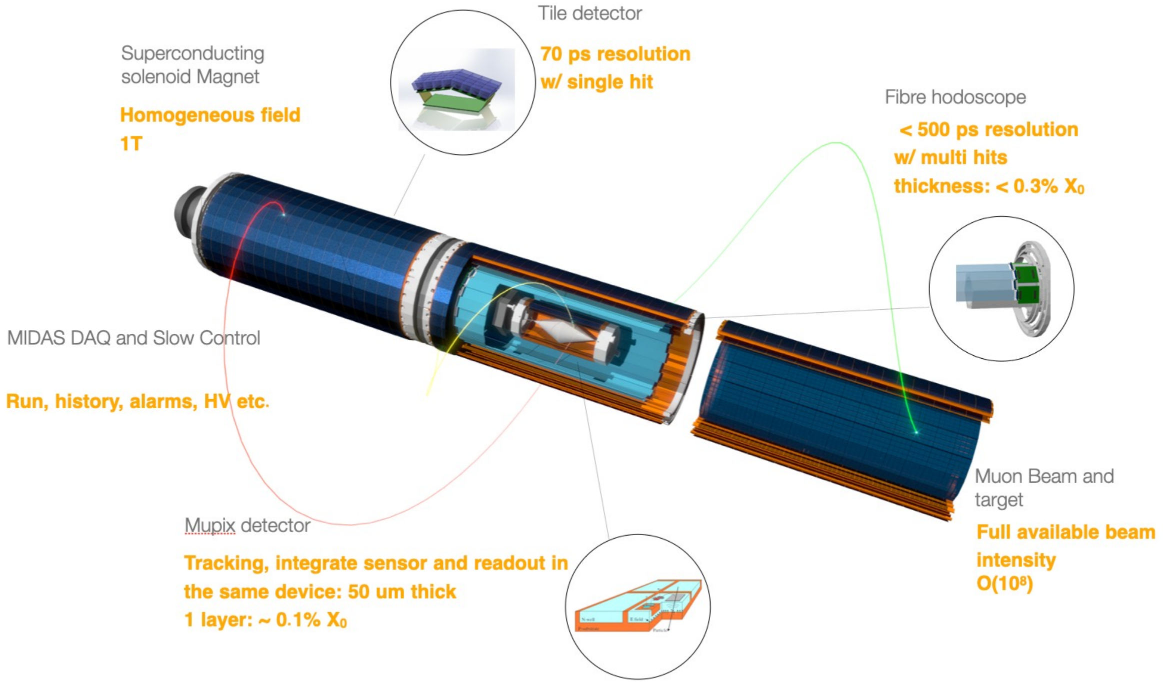
See L. Galli's talk at CLFV 2023

Mu3e

$$\mu^+ \rightarrow e^+e^+e^-$$

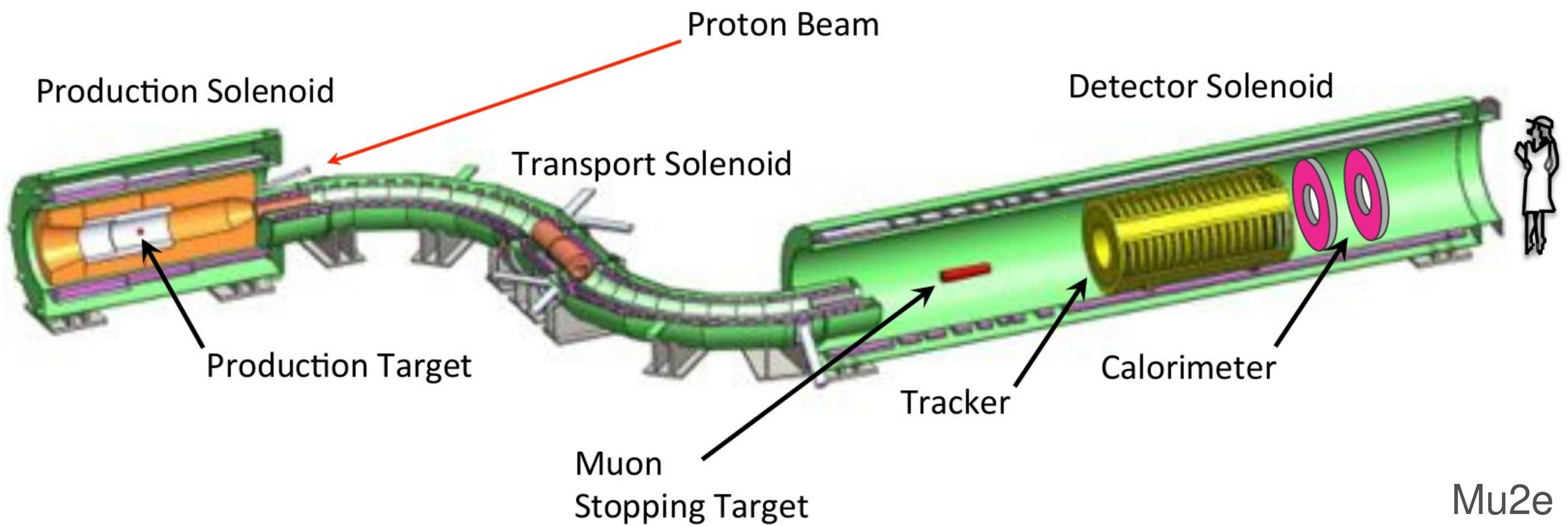
- Phase I: 2025-2026
- Phase II: HiMB



See F. Wauters talk from CLFV 2023

Mu2e and COMET

$$\mu^- A(Z,N) \to e^- A(Z,N) \qquad \mu^- A(Z,N) \to e^+ A(Z-2,N)$$

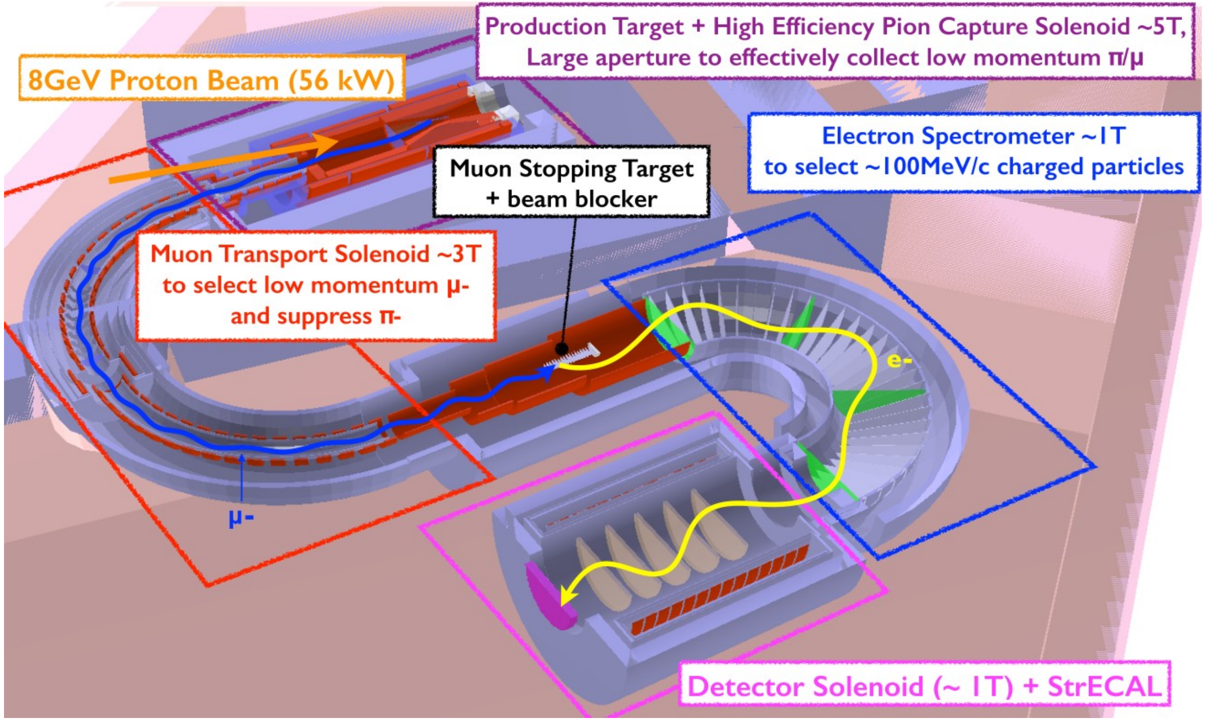


Mu2e

See A. Edmonds talk at CLFV 2023

Mu2e and COMET

$$\mu^- A(Z,N) \to e^- A(Z,N)$$



COMET

See J. Tang’s talk at CFLV 2023

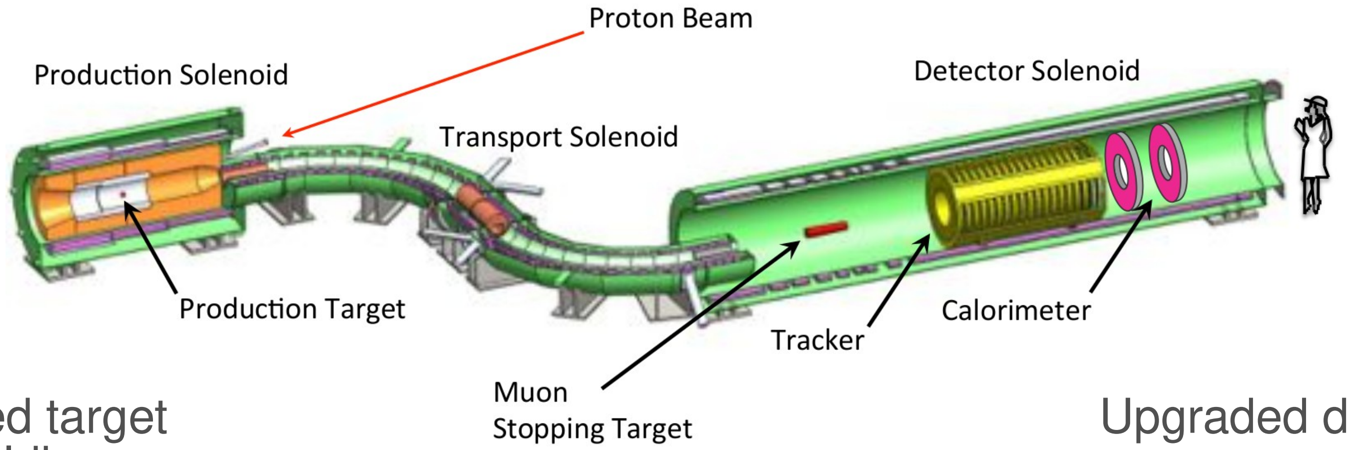
More generations of these searches are under development

- Mu2e-II at Fermilab
- PRISM/PRIME at J-PARC
- AMF at Fermilab (all channels!)
- MACE at CSNS

Mu2e-II in the 2030s

- Mu2e-II would be a “minimal” evolution of Mu2e with targeted upgrades to achieve an additional factor of 10 improvement in sensitivity

100kW PIP-II beam power



Upgraded target and shielding

Upgraded detectors

Different stopping materials

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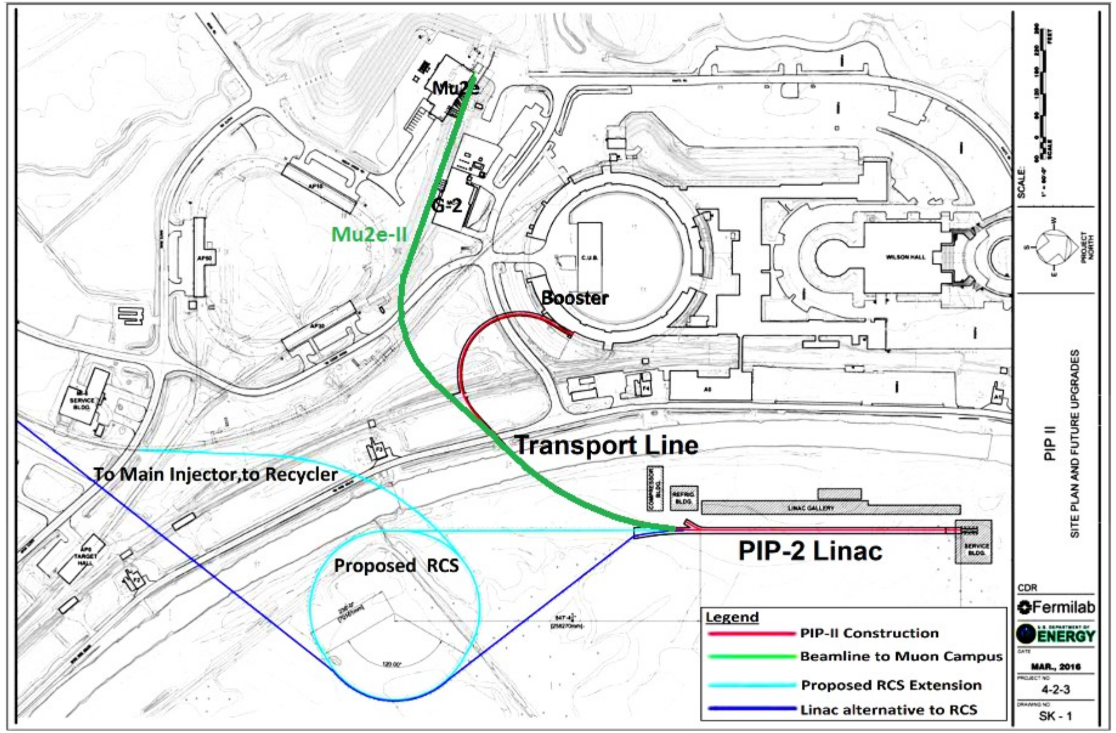
See S. Müller’s talk at CLFV 2023

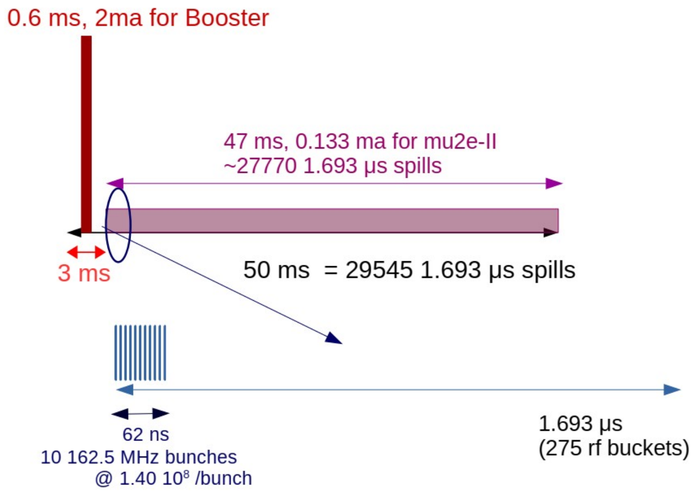
Mu2e-II in the 2030s

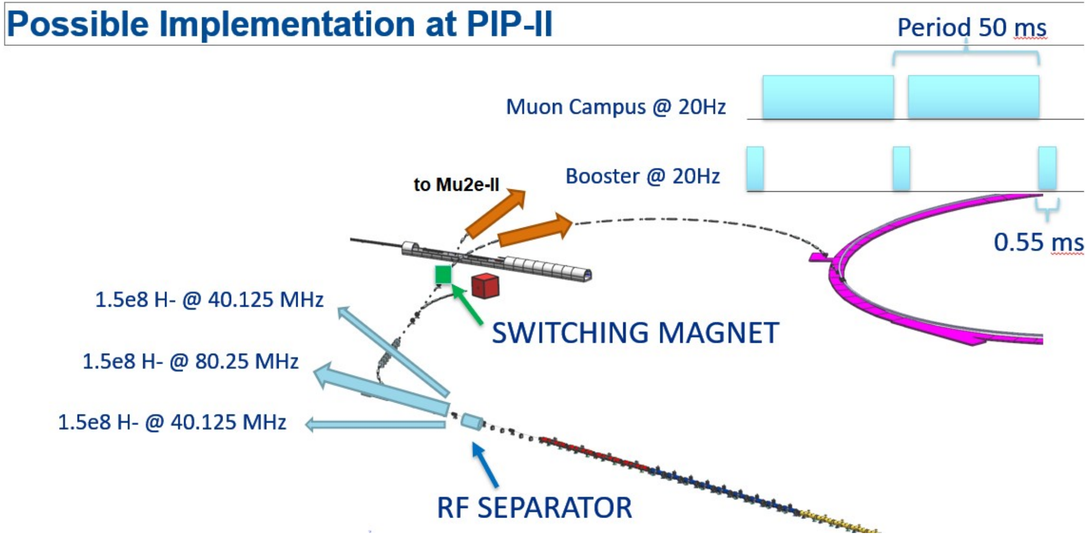
- The key enabling technology is PIP-II



Mu2e-II in the 2030s

- The key enabling technology is PIP-II
  - It's being built for LBNF/DUNE, but 99% of its capacity will be un-utilized!





AMF in the 2040s: an advanced muon facility for Fermilab beyond Mu2e-II

- Utilize the available proton beam enabled by PIP-II that will be unused by LBNF/DUNE – up to 1MW
- Provide a flexible facility for future experiments after the current muon program has run its course
- Build on synergies with the dark matter and muon collider communities
  - Workshop on a Future Muon Program at Fermilab May 2023, Caltech

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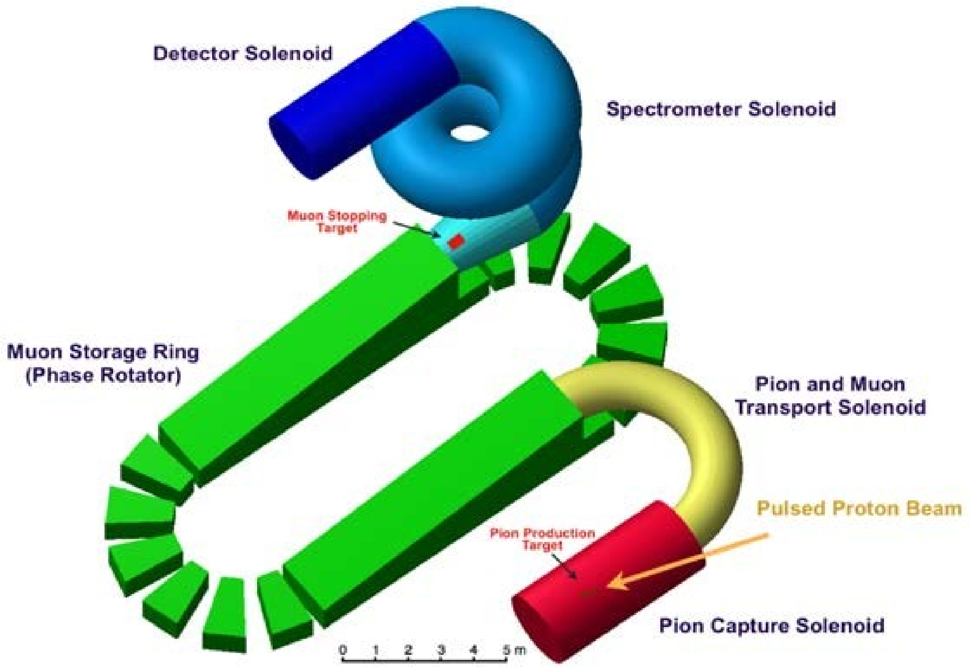
See D. Hitlin's talk at CLFV 2023

AMF enabling technologies

- PIP-II
  - Proton source
- Proton compressor ring
  - Convert CW beam to intense proton pulses
- Production solenoid and target systems
  - House production target
- Muon transport
  - Eliminate LOS from target to experiments
  - Match beam dynamics solenoid ↔ FFA
- FFA ring
  - Phase rotation → monochromator
- Induction linac
  - Reduce bunch energy to minimize target thickness



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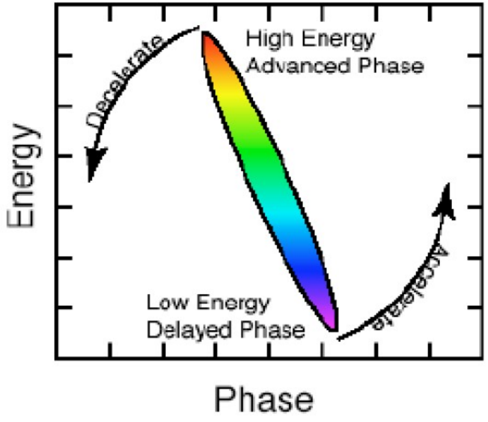
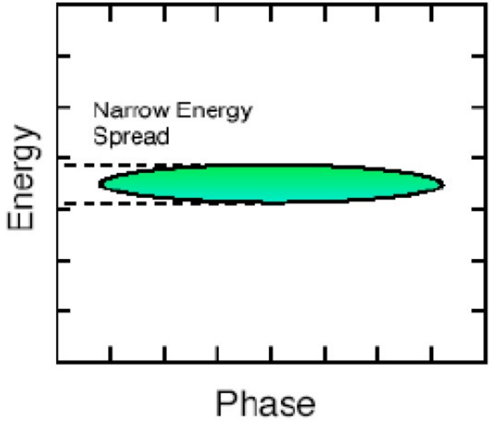
The key enabling technology for AMF is the PRISM FFA

- **P**hase **R**otated **I**ntense **S**ource of **M**uons
  - High intensity, short duration proton pulses produce muons with short time duration, but large momentum spread
  - Inject muons into FFA
  - Phase rotation reduces momentum spread
  - Monochromatic muon bunches
  - Eliminate pion contamination
  - Extract beam to experiments



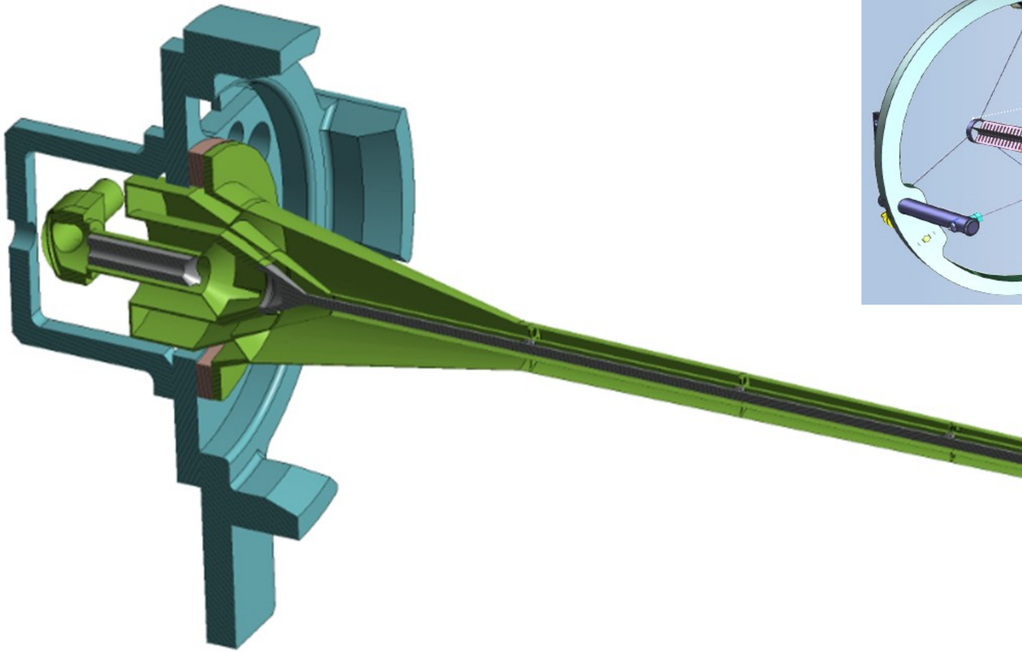


Chief AMF technical challenges – with Muon Collider synergies!

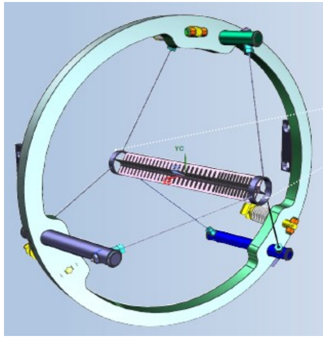
- Compressor ring
  - Kicker rates and rise/fall times limit beam power
  - 100Hz → 1kHz?
- Target and PS
  - Concepts for 100kW targets exist
    - Mu2e-II
  - Compact MW scale targets are a true R&D effort!
- High field, radiation resistant solenoids

Chief AMF technical challenges

LBNF Target core
16mm x 1.5m x 25kW



Mu2e Target Core
6.3mm x 220mm x 250kW



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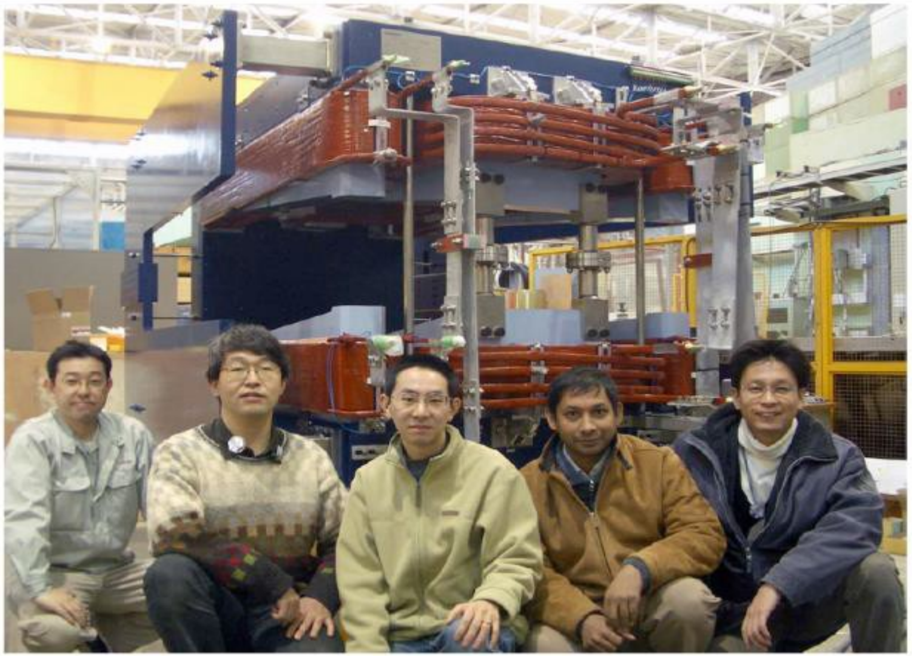
Chief AMF technical challenges

- A 6-cell large-acceptance FFA ring has been demonstrated at Osaka

The First PRISM-FFAG Magnet



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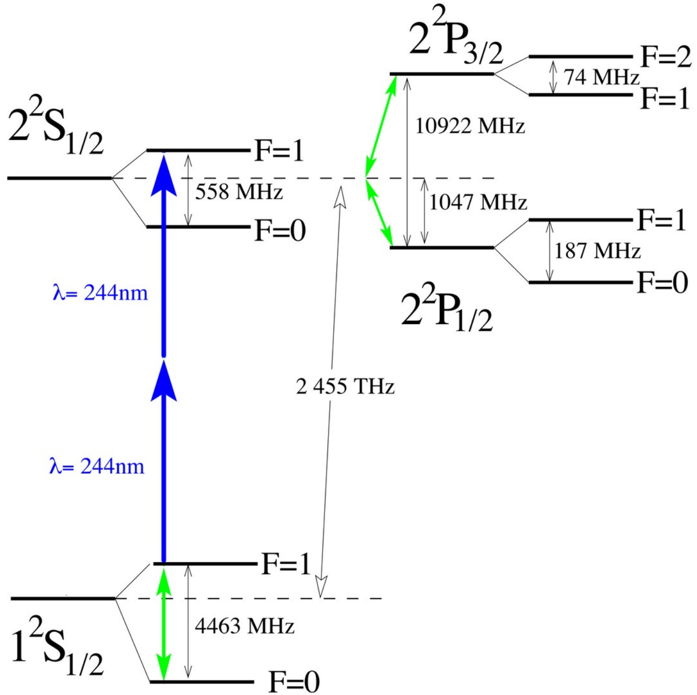
AMF enables a suite of experiments

- The primary motivation for AMF is CLFV physics:
  - Muon decay experiments
    - mu→3e, mu→e gamma
    - Factor 100 improvement over MEG-II
  - Muon conversion experiments
    - Factor 100-1000 improvement over Mu2e
    - High-Z targets (very short bunches)
- But there are other possibilities with an intense source!
  - Muonium physics
  - Muon MDM/EDM source
  - MuSR (industrial users?)
  - Pions/Kaons
- AMF could potentially feed multiple experiments simultaneously!

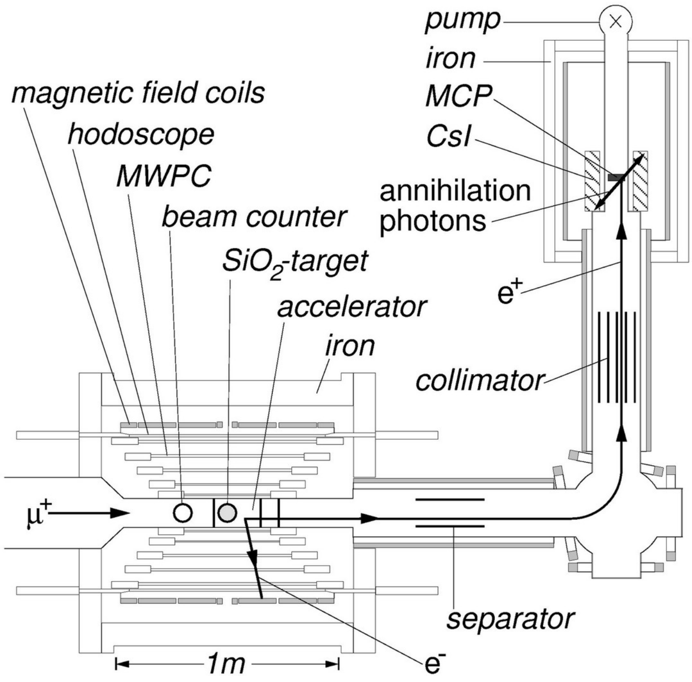
Muonium physics

- Mu is the simplest atomic species: μ +e- atom
  - Purely leptonic hydrogen species!
- Rich structure and phenomenology
  - Readily formed
  - Spectrum understood
  - Forms molecules!
  - Decays with free muon lifetime



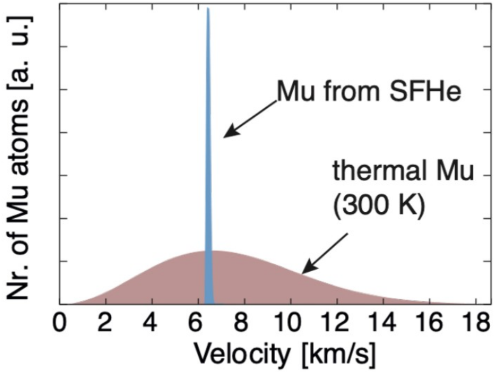
Muonium – antimuonium oscillation

- A double CLFV process!   μ +e- ↔ μ -e+
- Current limits from MACS at PSI is 8.3 x10^{-11} (90%)
- The key insight: muon daughters have Michel spectrum (fast!) while the atomic electron has spectrum given by binding energy (slow!)
- There is the MACE proposal for CSNS, a proposal connected to the Muon g-2 project at J-PARC, and there are people interested in bringing this measurement to Fermilab.



Muonium production needs a new approach

- Stop (nearly!) a positive muon beam in a target in vacuum; some of the muonium will be ejected into the vacuum space
- J-PARC g-2 plans to utilize laser ablated silica aerogel
  - This yields of order 1% muonium in vacuum, with thermal momentum distribution
  - Thermal Mu requires cooling for beam formation
- PSI and Fermilab muonium experiments plan to use layers of superfluid helium on target surfaces
  - "Hydrogen" is immiscible in superfluid helium → stopped Mu ejected from the surface with a very narrow momentum spread (chemical potential)
  - Naturally cooled and emitted at 6,300 m/s normal to surface
  - A superfluid layer can also be used as a slow Mu mirror



In summary...

- There is a very bright future for CLFV physics, with lots of experiments in operation, under construction, or in development, across the globe.
- The observation of CLFV signals will be an unambiguous proof of new physics, and measurements in all of these channels will be required to elucidate the underlying physical theory.
- There are numerous synergies between these developing experiments, dark matter searches, and muon collider R&D that should be encouraged and exploited for all our benefit.