The Future of Experimental Muon Physics

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3 August 2022

The future of experimental muon physics is bright!

- There is so much going on and proposed, I will only have time to hit a few of the highlights:
  - Flavor
    - CLFV
    - LNV
  - Precision measurements
    - Spectroscopy
    - Antimatter gravity
    - Dipole moments
  - Practical applications
    - Energy applications
    - Remote sensing and tomography
- This talk is heavily influenced by my personal interests, and is not endorsed by anyone, including my family, my pets, and perhaps not even future self … I have inevitably left out your favorite experiment.

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Prediction is very difficult, especially if it’s about the future!
Neils Bohr

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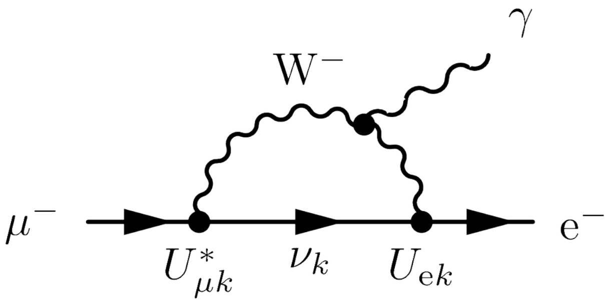
Physics of flavor

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.



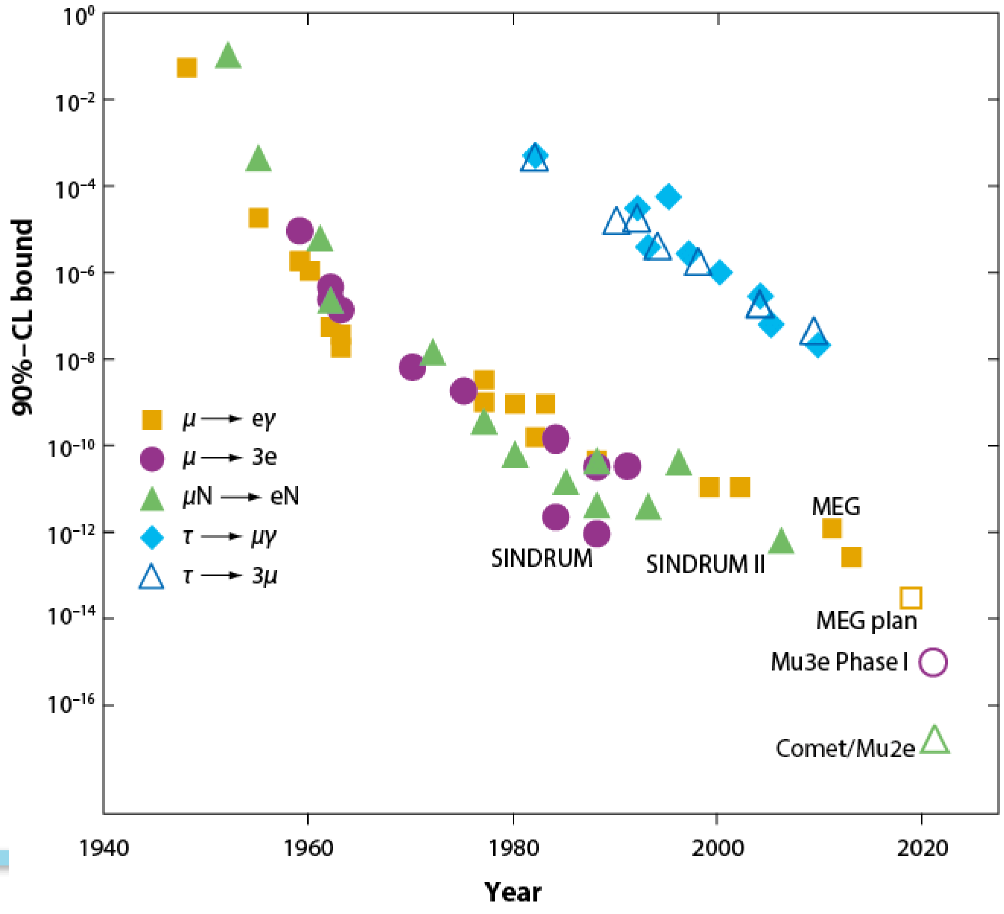
However, the predicted SM rates are unobservably small:

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

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

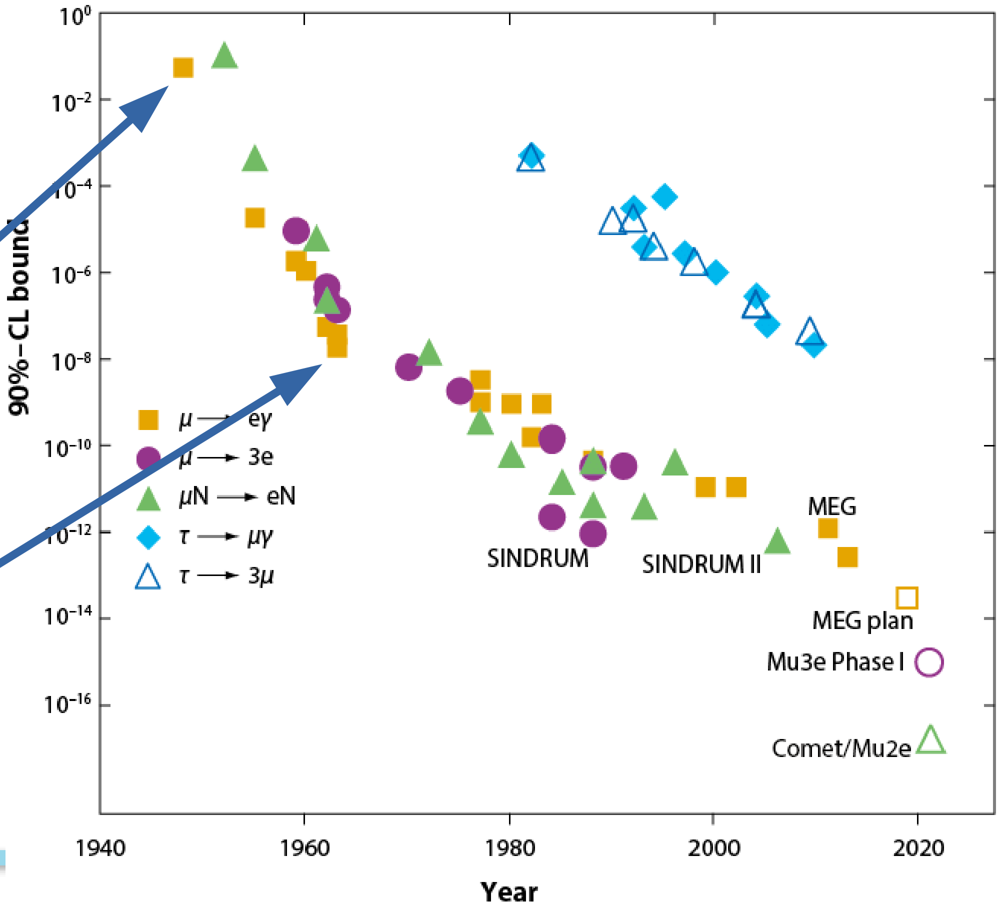
This insight is certainly not new…

1947:
Pontecorvo
and Hincks

$\mu \neq e^*$

1962:
Lederman,
Schwartz,
and
Steinberger
1988 Nobel

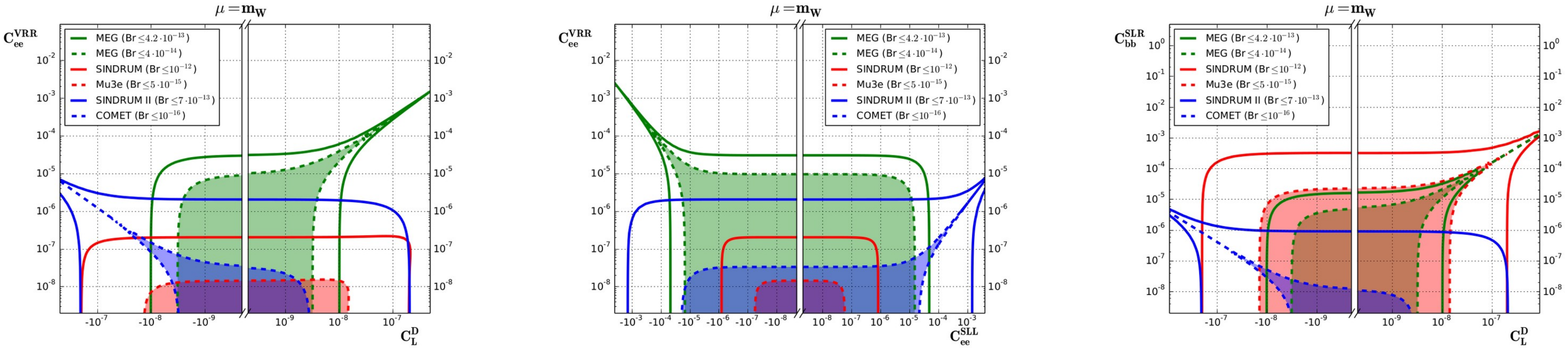
$\nu_\mu \neq \nu_e$



Muons could have a lot to tell us about CLFV

We know the Standard Model is incomplete, and attempts to fix it generically introduce flavor violation, particularly in the muon sector.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum \mathcal{O}_5 + \frac{1}{\Lambda^2}\sum \mathcal{O}_6$$



Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

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

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

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

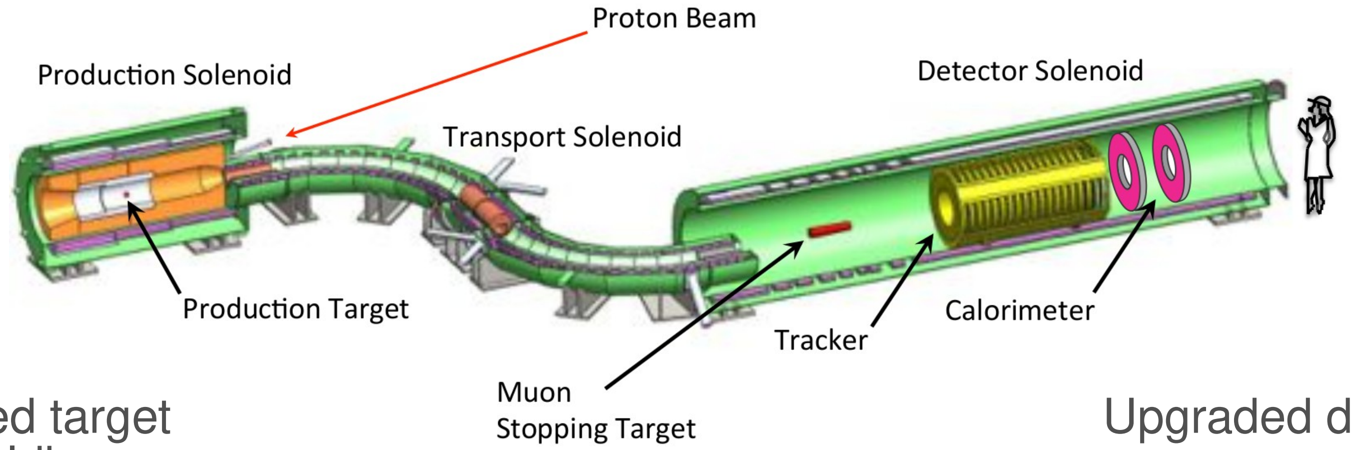
CLFV and LNV!

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

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



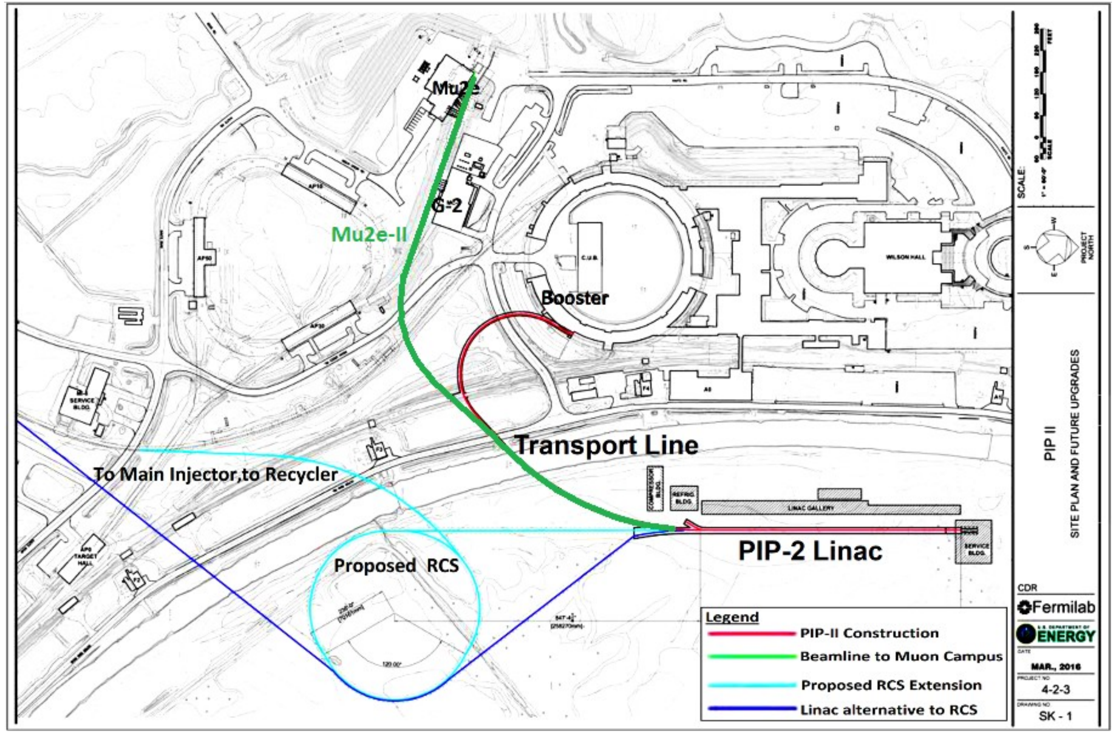
Upgraded target and shielding

Upgraded detectors

Different stopping materials

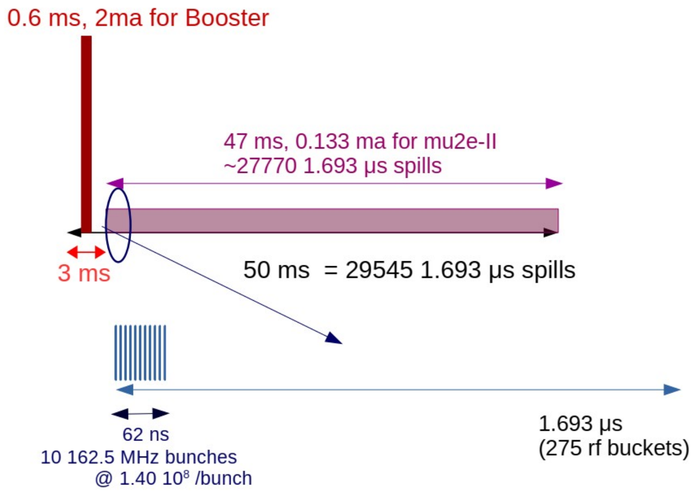
Mu2e-II in the 2030s

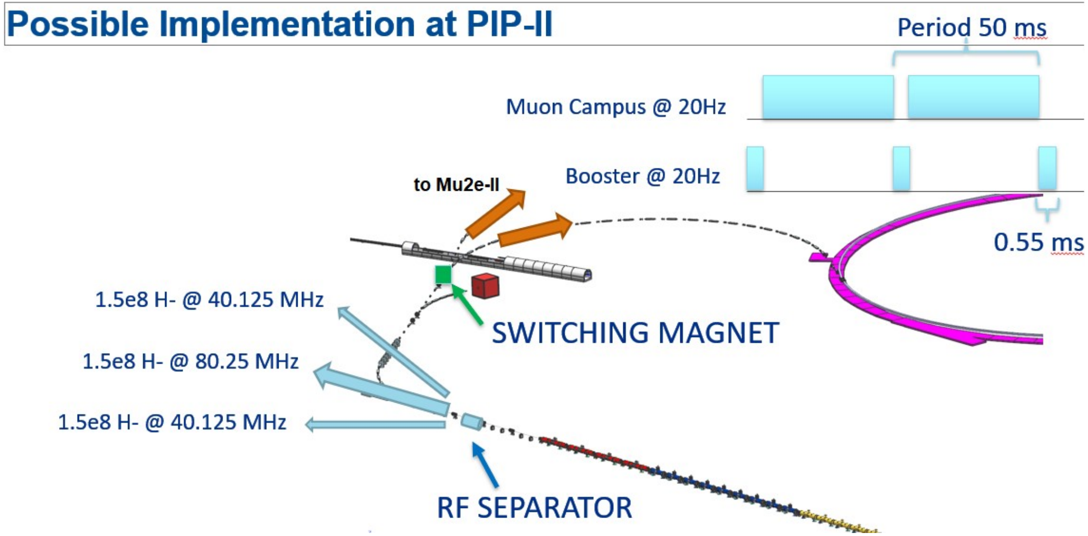
- The key enabling technology is PIP-II



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!



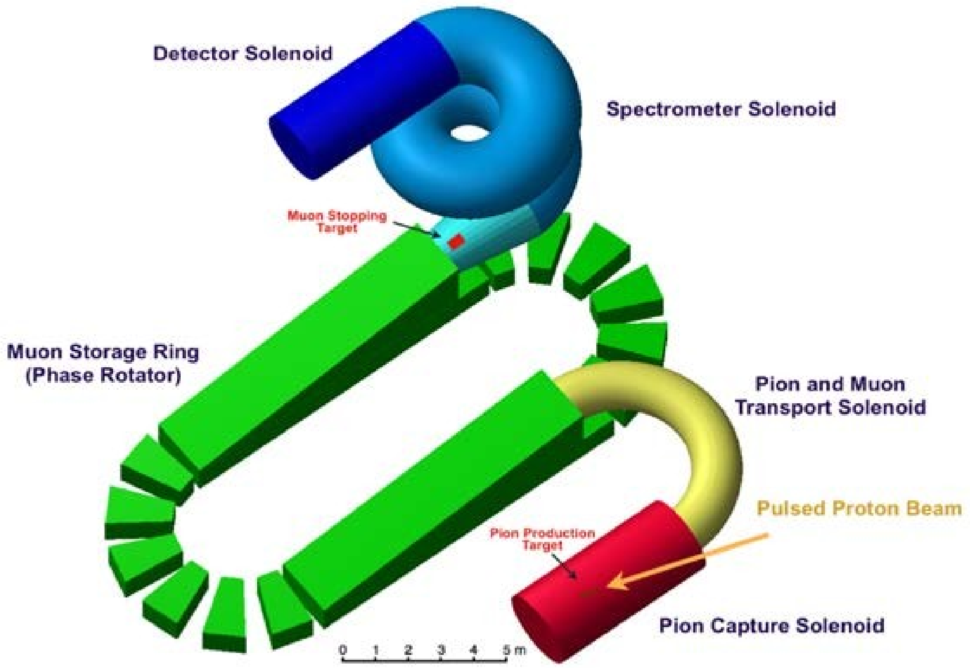


AMF: an advanced muon facility for Fermilab beyond Mu2e-II

- 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

AMF enabling technologies

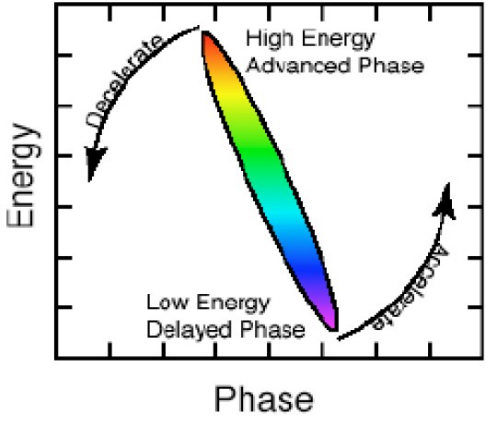
- PIP-II
  - Proton source
- Proton compressor ring
  - Convert CW beam to intense proton pulses
- Production solenoid and target systems
  - House production target
- Muon transport
  - Eliminate LOS from target to experiments
  - Match beam dynamics solenoid ↔ FFA
- FFA ring
  - Phase rotation → monochromator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

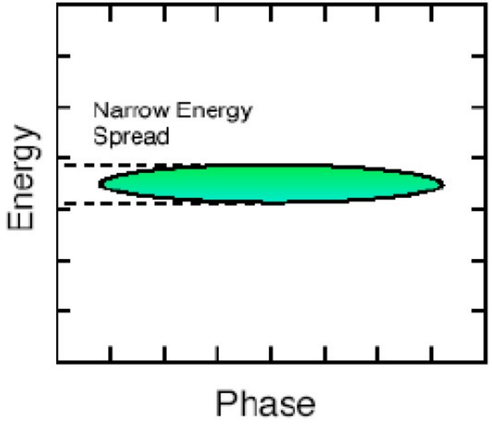


Fermilab

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



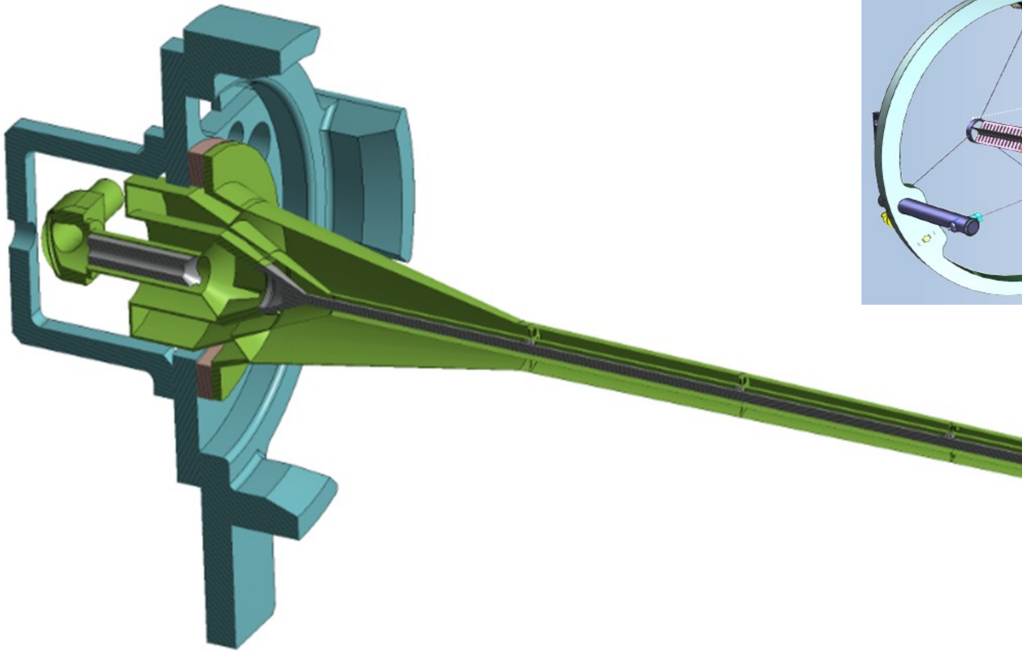


Chief AMF technical challenges

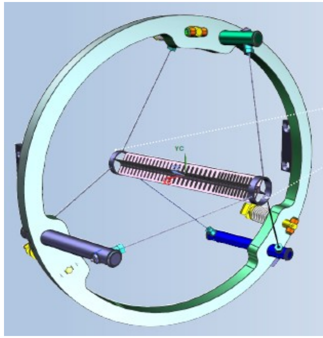
- Compressor ring
  - Kicker rates and rise/fall times limit beam power
  - 100Hz → 1kHz?
- Target and PS
  - Concepts for 100kW targets exist
    - Mu2e-II
  - Compact MW scale targets are a true R&D effort!   Synergies with muon collider!

Chief AMF technical challenges

LBNF Target core
16mm x 1.5m x 25kW



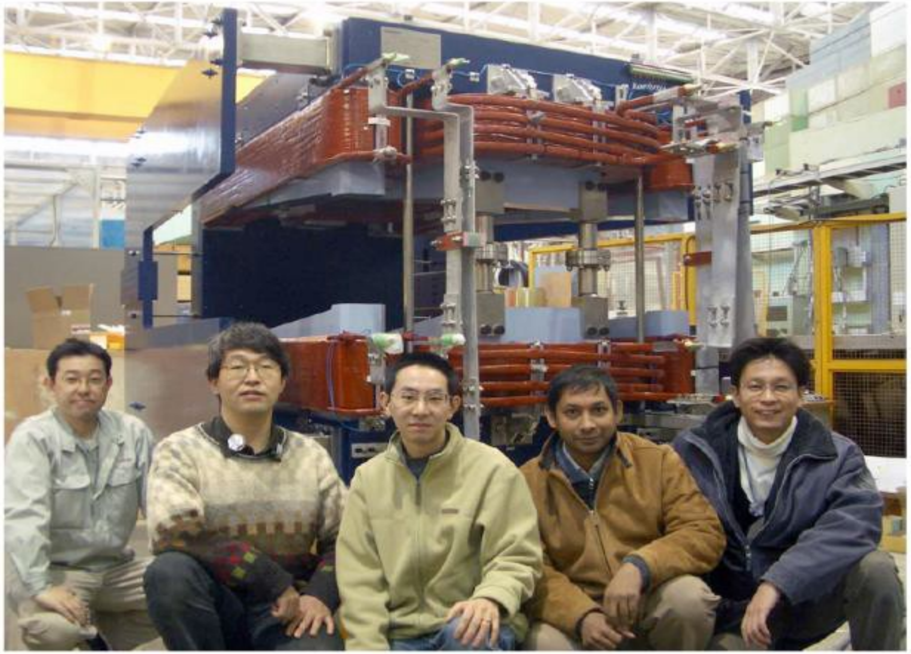
Mu2e Target Core
6.3mm x 220mm x 250kW



Chief AMF technical challenges

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

The First PRISM-FFAG Magnet



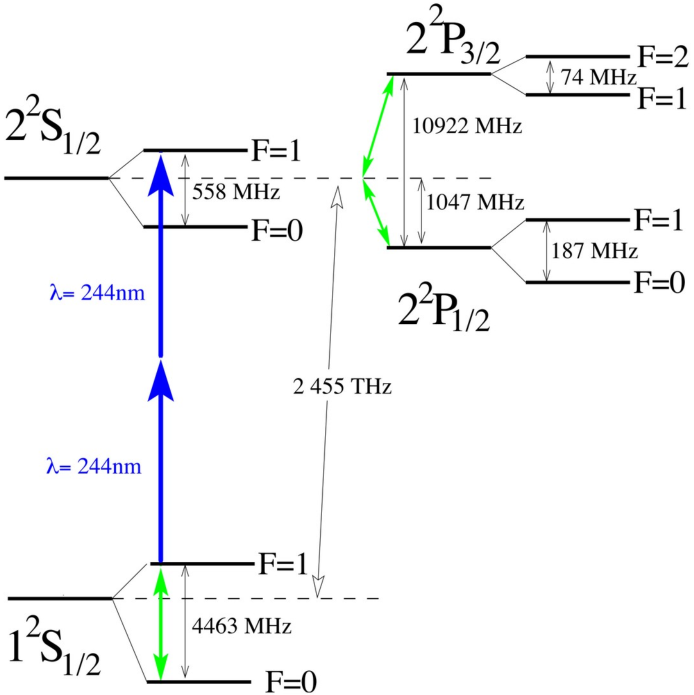
AMF enables a suite of experiments

- 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!

Precision Measurements

Muonium physics

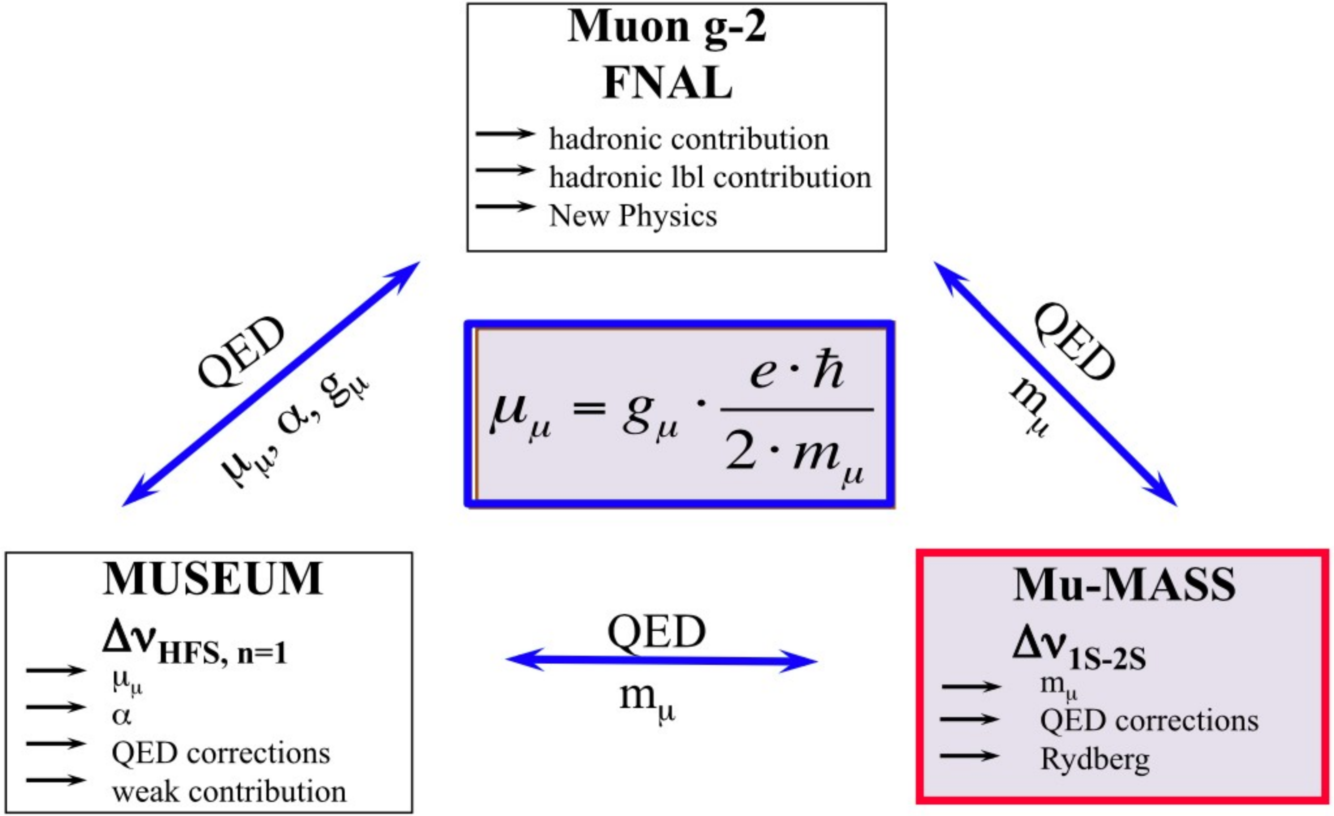
- Mu is the simplest atomic species: μ +e- atom
  - Purely leptonic hydrogen species!
- Rich structure and phenomenology
  - Readily formed
  - Spectrum understood
  - Forms molecules!
  - Decays with free muon lifetime



Precision muonium physics

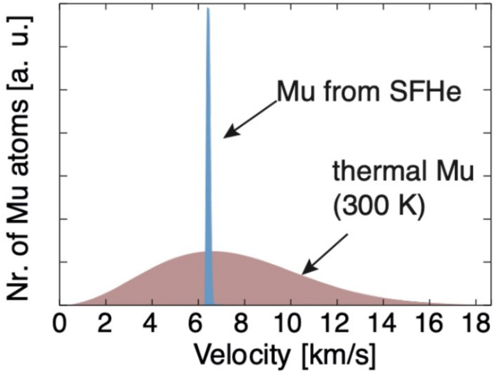
- 1s-2s transition frequency predicted in QED to 0.6 ppb
  - Minimal hadronic contributions!
- Similar story for 1s hyperfine splitting
- Mu-MASS at PSI
  - Improve 1S-2S measurement three orders of magnitude
  - Improves muon mass determination to 1ppb
- MuSEUM at J-PARC
  - Improve hyperfine measurement one order of magnitude – 1ppb
- The combination will determine the Rydberg constant to 4ppt!

Precision muonium physics



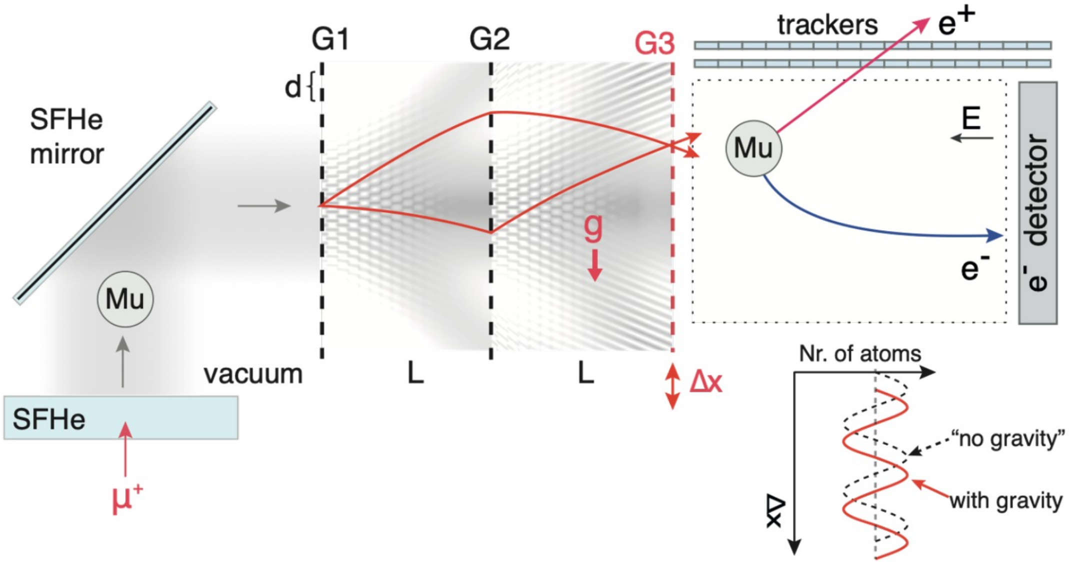
Muonium production

- 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



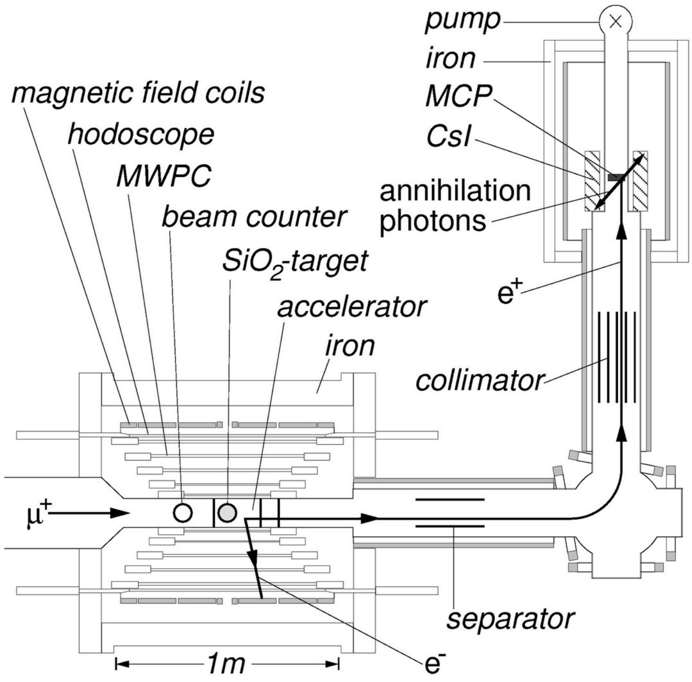
Muonium gravity

- The effect of gravity on antimatter has never been measured!
  - We don't even know the sign of g for antimatter!
- Leming at PSI and MAGE at Fermilab aim to address that
  - Muonium source and mirror
  - Mach-Zehnder interferometer
    - 100nm!
  - Muonium decay trigger detectors
  - Sign of g in 1 day at 100kHz
  - ~month to precision comparison



Muonium – antimuonium oscillation

- A double CLFV process! μ +e- ↔ μ -e+
- Current limits from MACS at PSI is 8.3 $\times 10^{-11}$ (90%)
- The key insight: muon daughters have Michel spectrum (fast!) while the atomic electron has spectrum given by binding energy (slow!)
- I don't know of an current active effort, but there are people interested in bringing this to Fermilab



Muon dipole moments

- The g-2 experiment at Fermilab currently leads the dipole moment space
- J-PARC is developing a new approach to measure MDM and EDM with vastly different systematics

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} - \frac{\vec{E}}{c}\right)\right]$$

MDM EDM

Muon dipole moments

- The key difference is how they handle this term:

$$\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}$$

Fermilab

$$\gamma \approx 29.3 \rightarrow p_\mu \approx 3.1\,\mathrm{GeV}$$

Can use electric fields to focus within the storage ring → large ring!

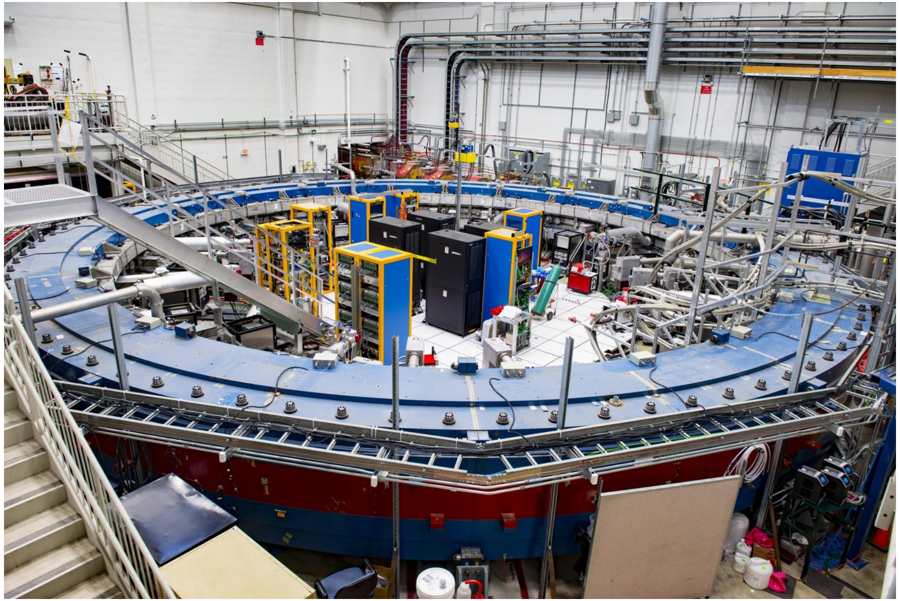
J-PARC

$$\vec{E} = 0$$

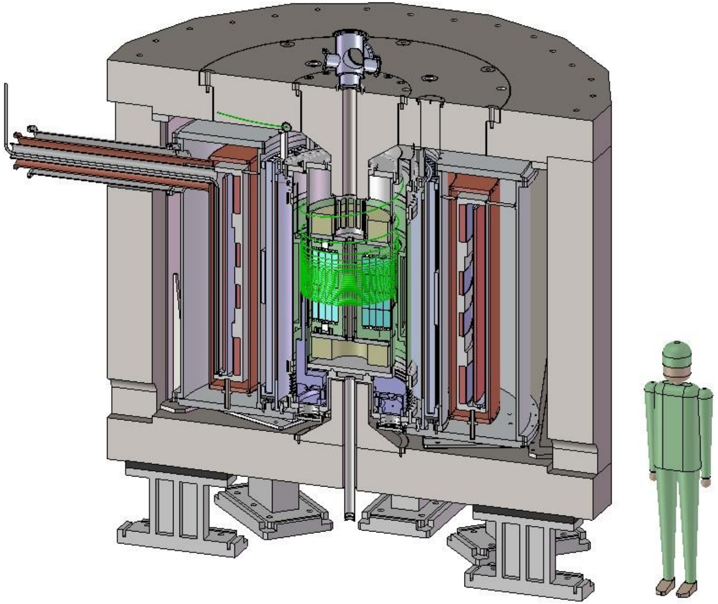
Purely magnetic focusing, low momentum possible → small ring!

Muon dipole moments

Fermilab

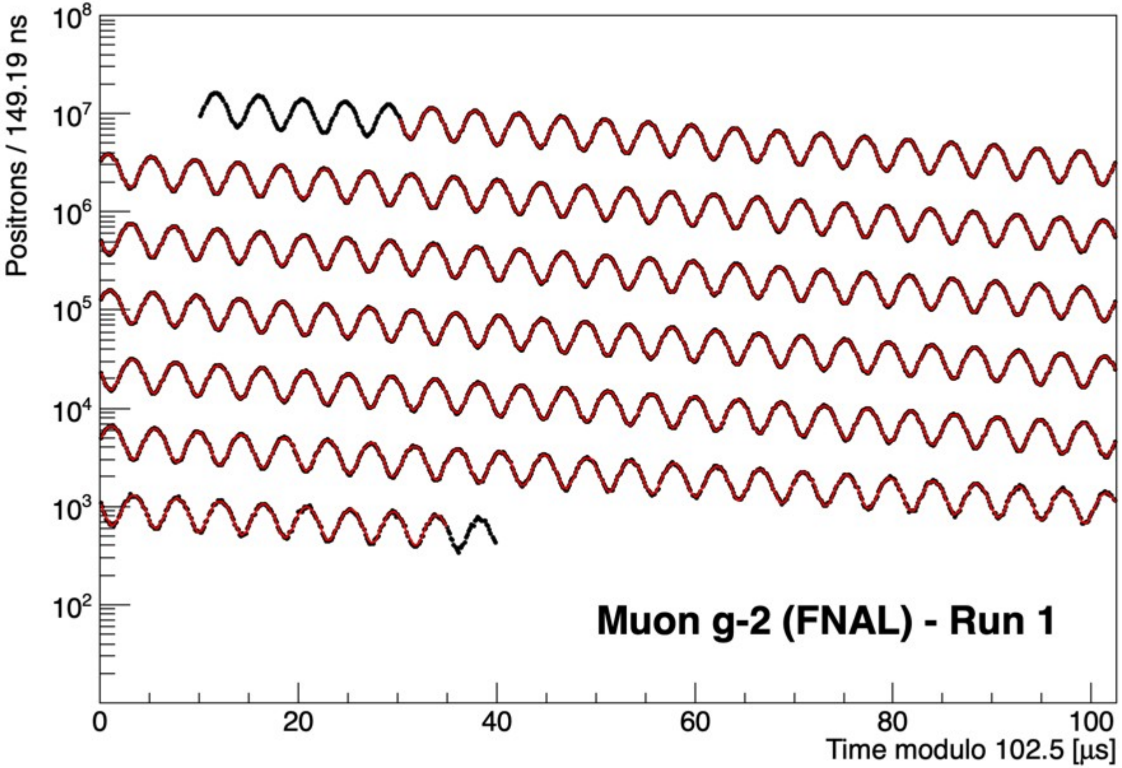


J-PARC



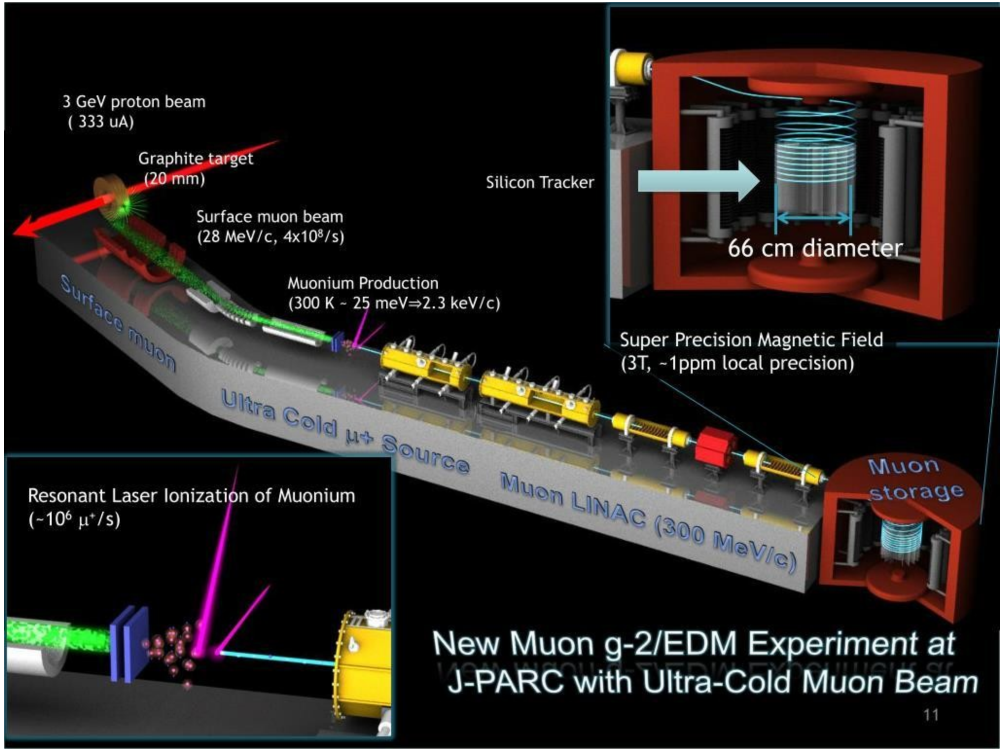
Dipole moments

- Both MDM and EDM can be extracted from the decay positron data
  - Weak interaction is chiral!
- In plane oscillation: MDM
- Out-of-plane oscillation:EDM



Muon dipole moments at J-PARC

- The J-PARC effort also utilizes a novel, low momentum dispersion muon source

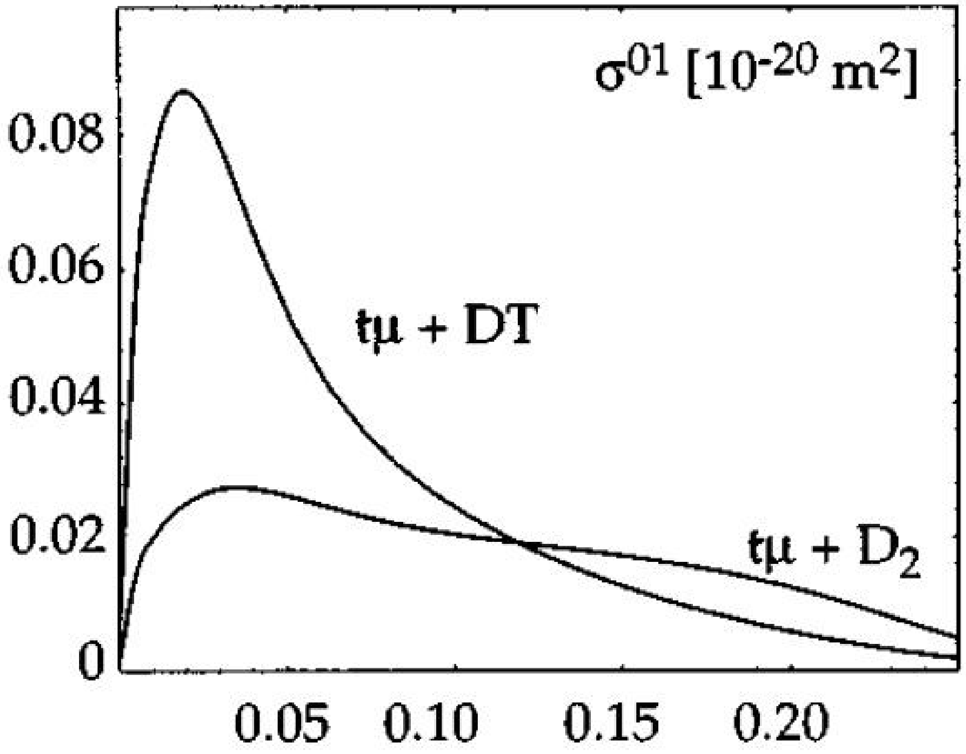


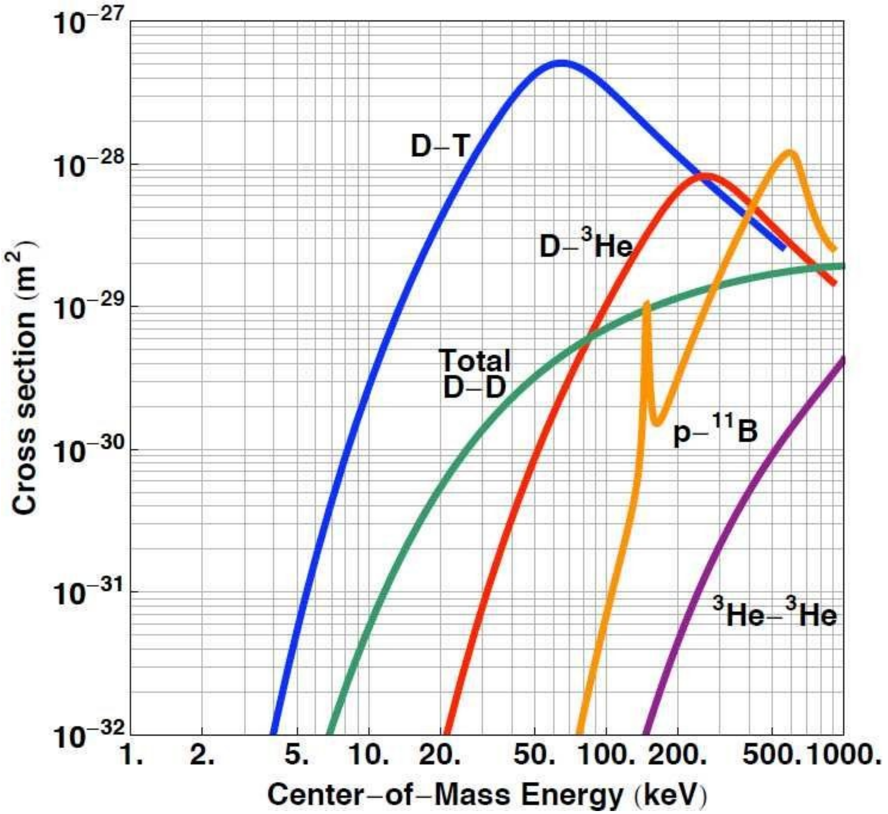
Muon dipole moments at J-PARC

- J-PARC data taking: mid-decade
- MDM Precision goal is BNL scale: 450ppb
  - Completely different systematics!!!
- EDM Precision goal is 100 improvement on BNL

“Practical” applications

Muon catalyzed fusion

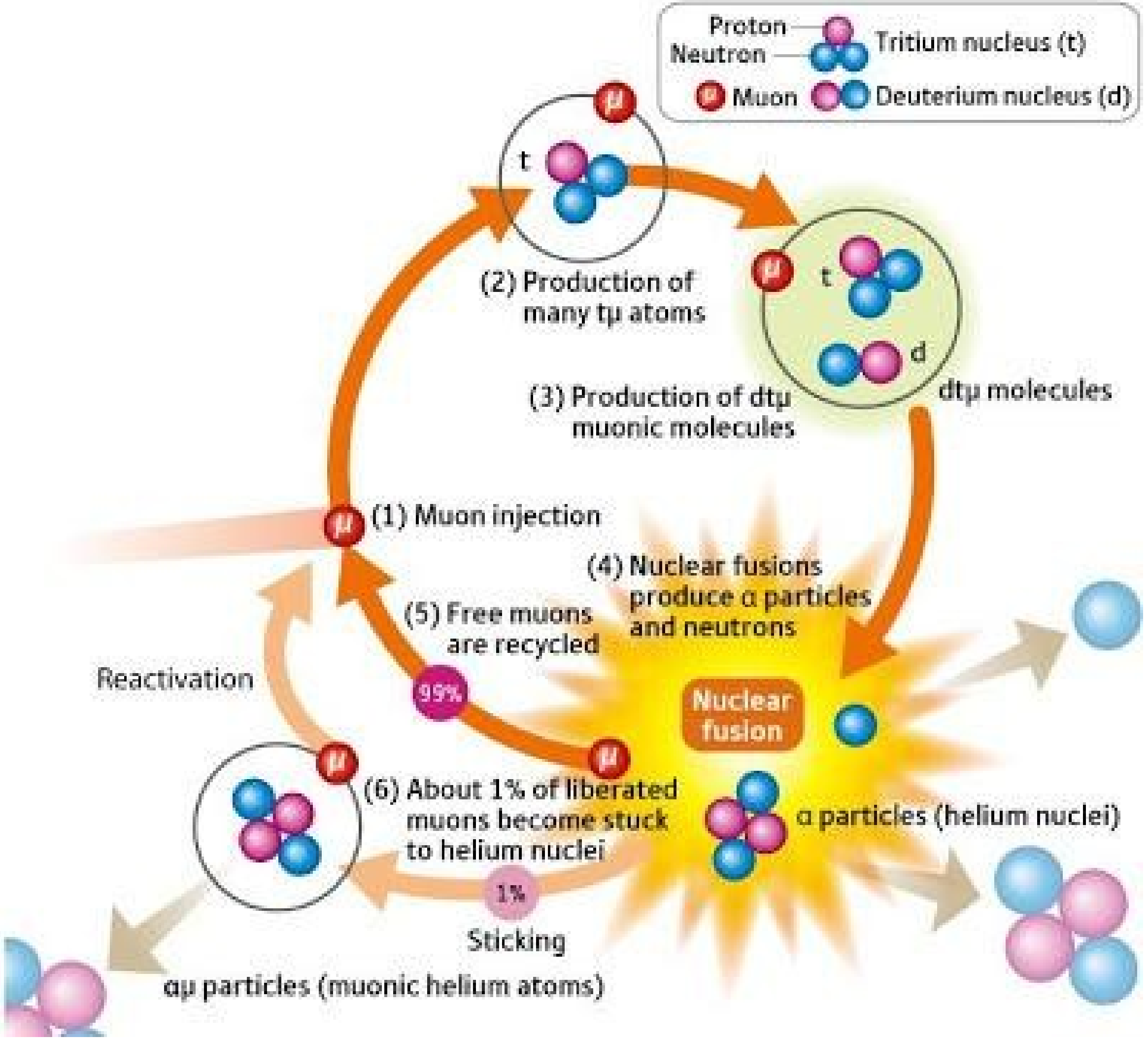




Muon catalyzed fusion

Key parameters that control breakeven:

- Muon production energy budget
- Cycling rate
- Sticking fraction



Muon catalyzed fusion – cycling rate

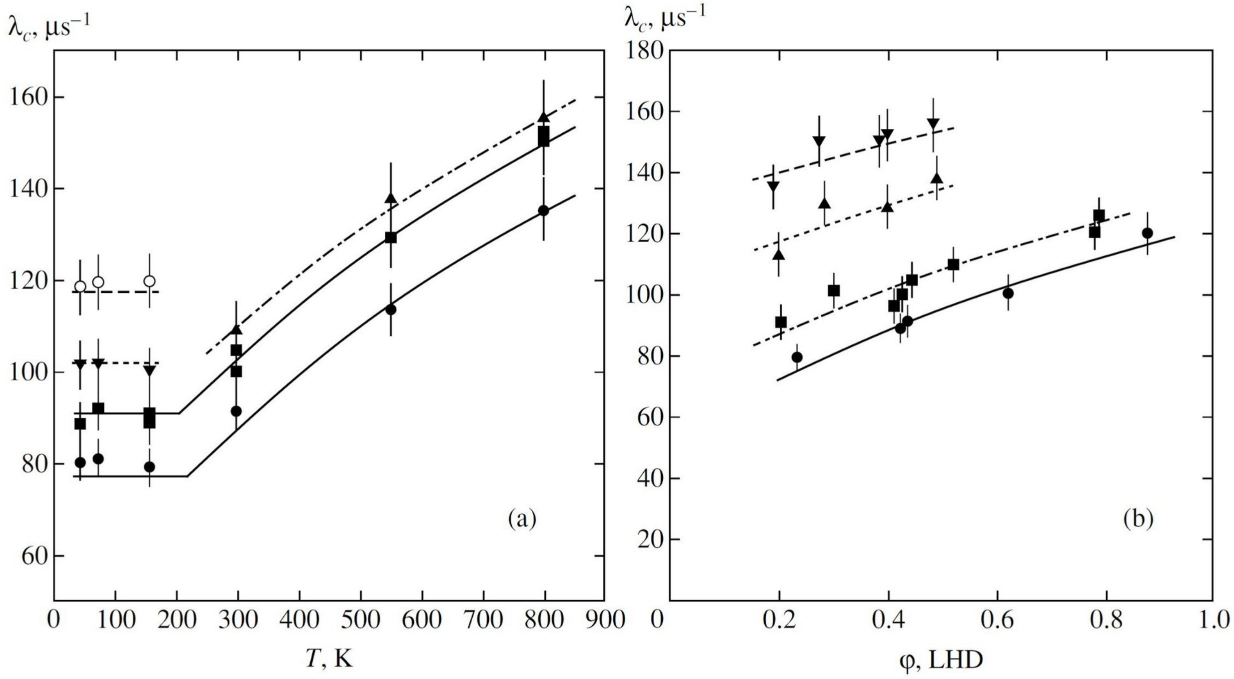
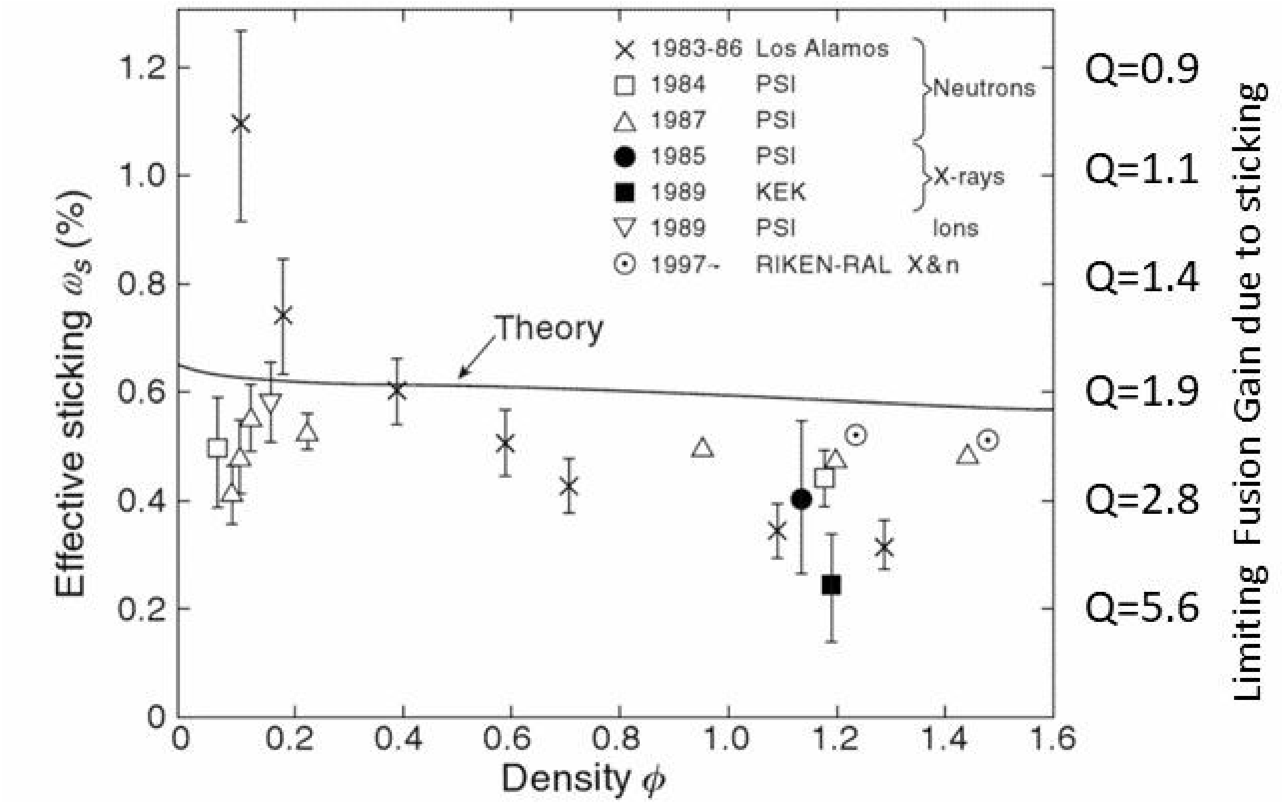


Fig. 12. (a) Normalized cycling rates as a function of temperature for the gaseous D/T mixture at $C_t \approx 33\%$ and different densities φ = 0.88–0.91 (○), 0.62–0.64 (▼), 0.49–0.52 (▲), 0.39–0.45 (■), 0.19–0.24 (●) LHD. (b) Normalized cycling rates as a function of density for the gaseous D/T mixture at $C_t \approx 33\%$ and different temperatures T = 800 K, C_t = 0.34–0.36 (▼); T = 550 K, C_t = 0.33–0.36 (▲); T = 300 K, C_t = 0.31–0.36 (■); T = 158 K, C_t = 0.31 (●). The curves are obtained with optimum parameters.

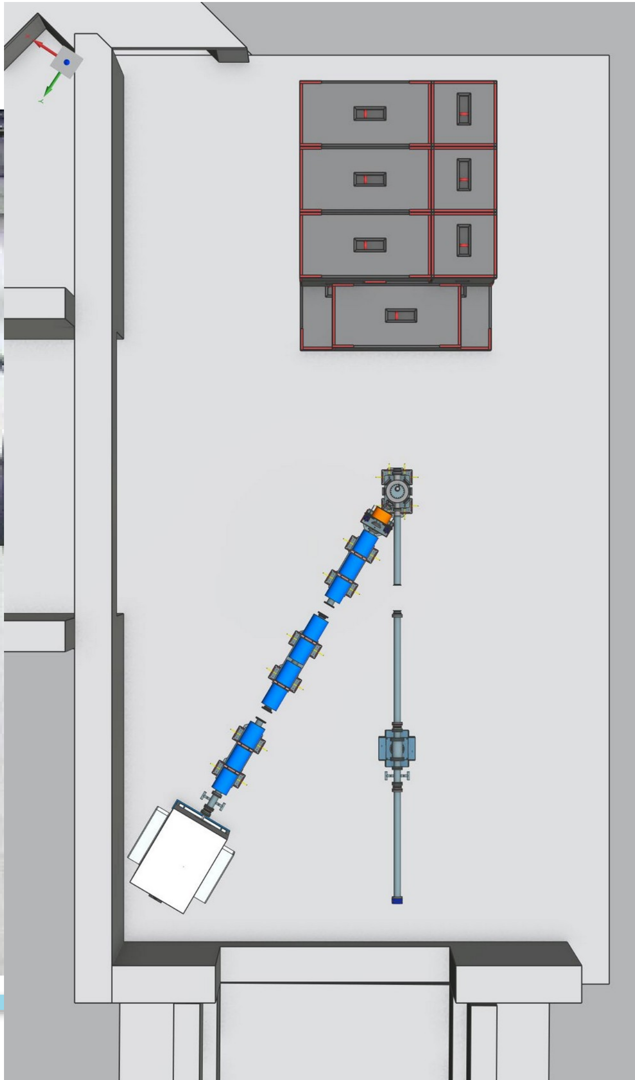
Muon catalyzed fusion – sticking fraction



Muon catalyzed fusion – renewed interest?

- Recent (2022!) theoretical and experimental work from Japan
- New measurements of sticking and cycling rates funded by ARPA-E
  - Measurement campaign on DD at PSI
  - LDRD funded LEM beamline at Fermilab MTA for DT campaign
    - Will be available for other work … muonium? μSR?

Muon catalyzed fusion - MTA



Remote sensing and tomography

DARPA is interested in funding development for a compact, 10-100GeV muon source of "useful intensity" utilizing Laser Plasma Acceleration.

https://www.darpa.mil/news-events/2022-07-22

What a time to be a muon physicist!

Fermilab