The search for CLFV with the Mu2e and COMET Experiments

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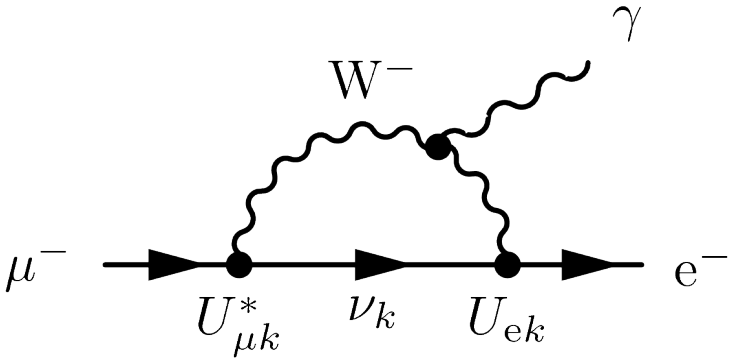
What we'll cover…

- CLFV in general
- Neutrinoless conversion
  - Mu2e
  - COMET
- Summary and future

Mu2e and COMET are searches for charged lepton flavor violation with discovery potential

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

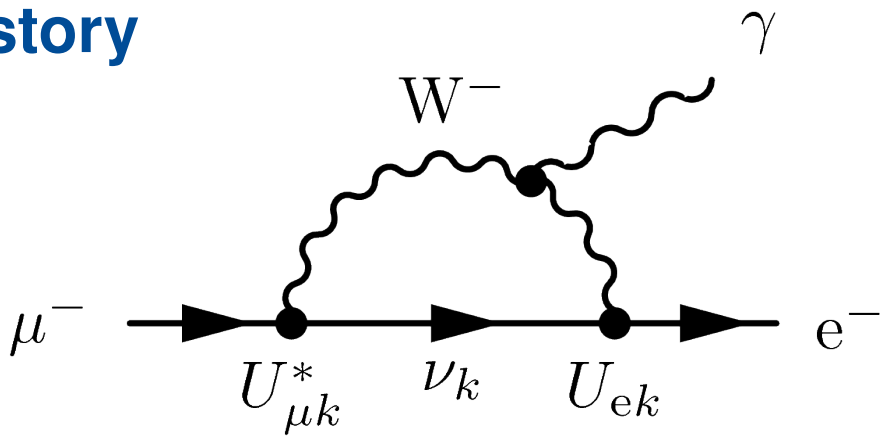


However, the predicted SM rates are unobservably small:

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

This is a good news/bad news story

First, the bad news: we'll never observe this!



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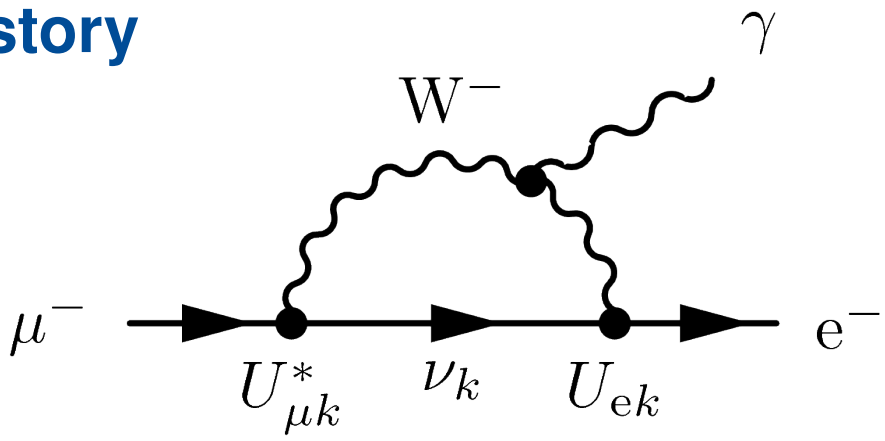
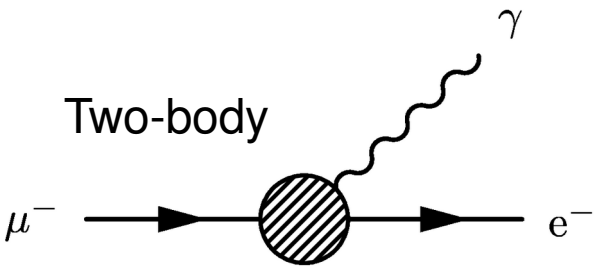


Now, the good news: we'll never observe this!

Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!

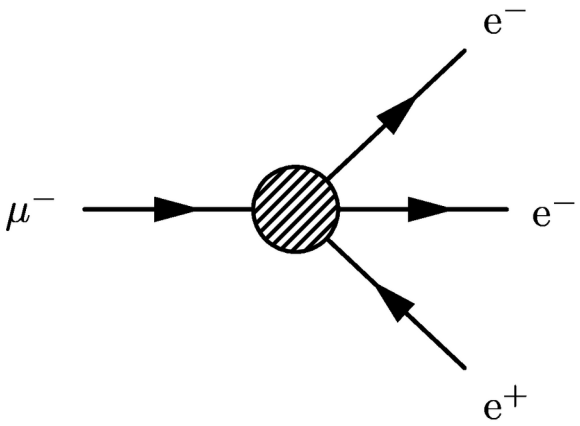
There are three powerful signatures of CLFV in the muon sector

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



MEG/MEG-II at PSI

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



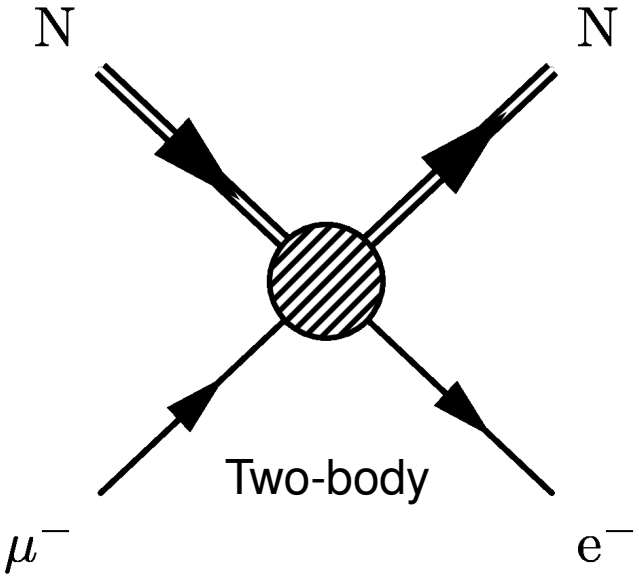
Mu3e at PSI

There are three powerful signatures of CLFV in the muon sector

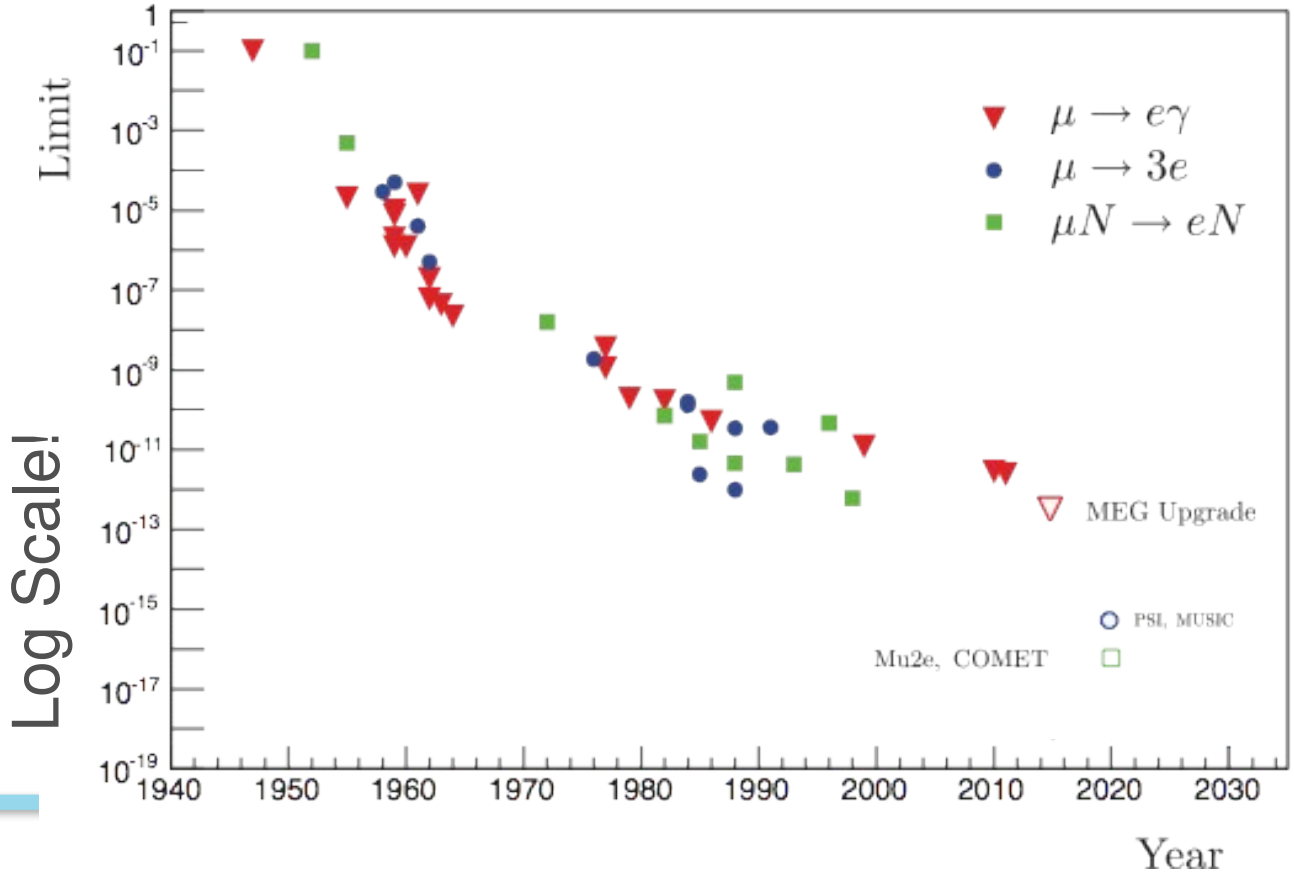
Mu2e and COMET will search for Coherent Conversion

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

$$R_{\mu e} = \frac{\Gamma\left(\mu^- A \to e^- A\right)}{\Gamma\left(\mu^- A \to \nu_\mu A'\right)}$$

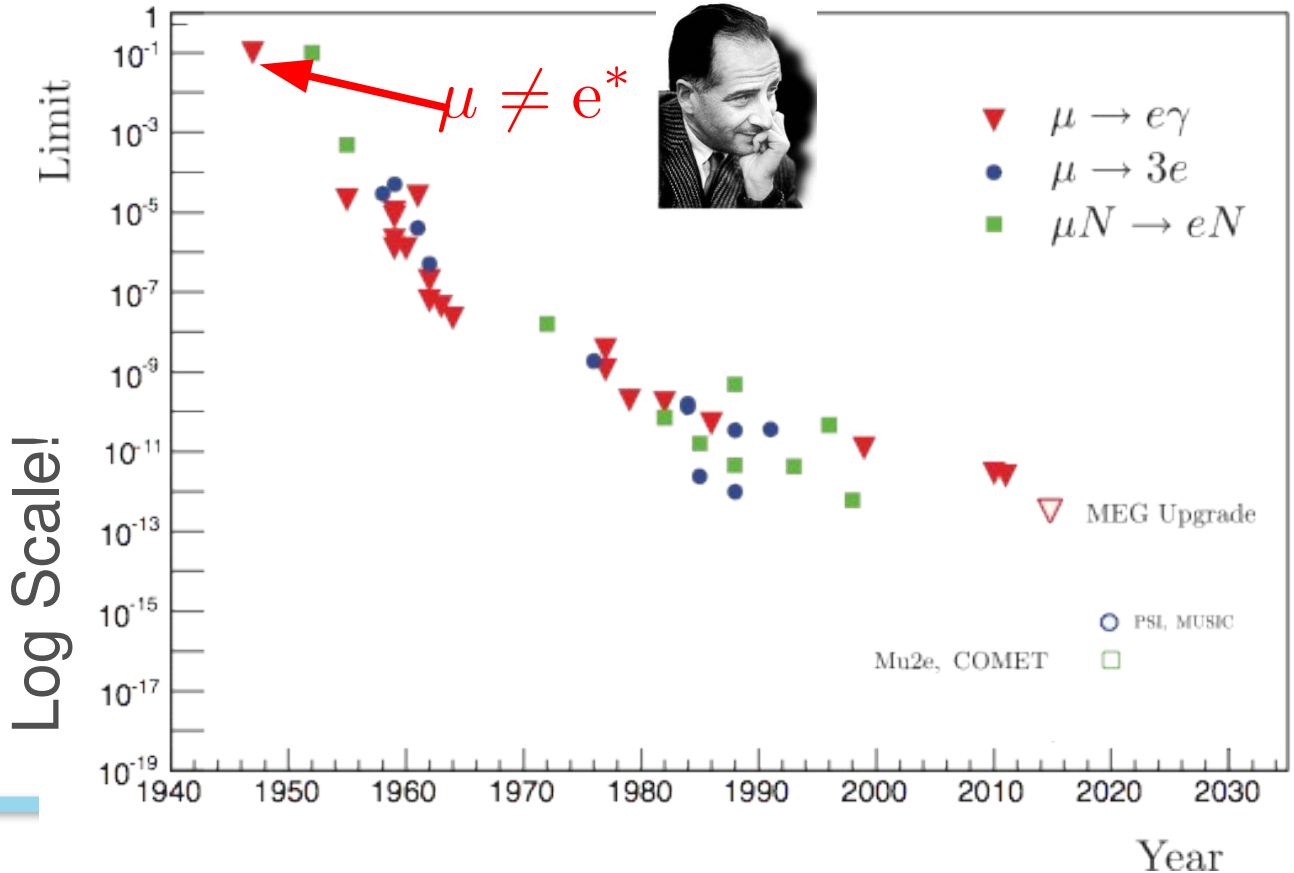


We're extending a long line of experiments designed to understand the mystery of muon flavor



Fermilab

We're extending a long line of experiments designed to understand the mystery of muon flavor



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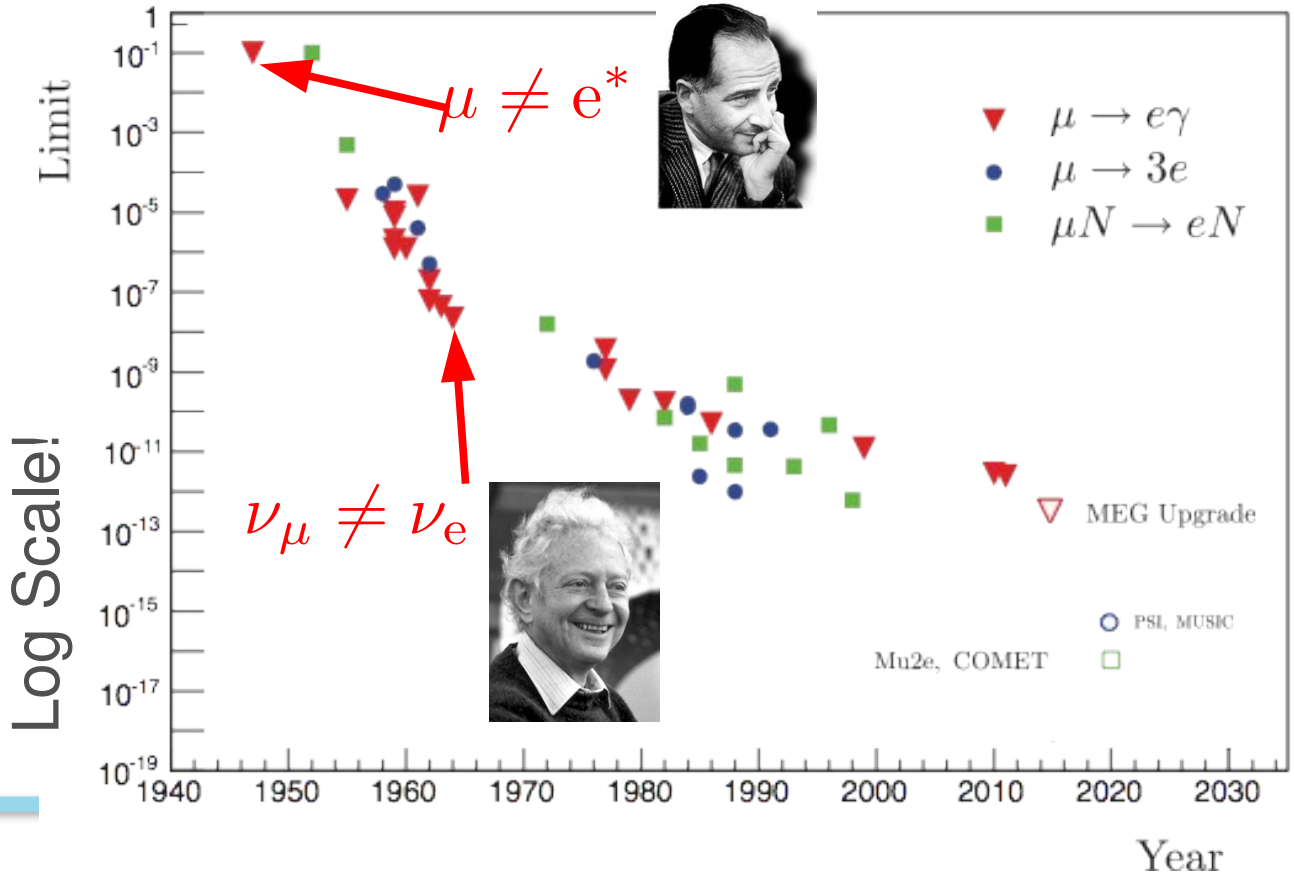

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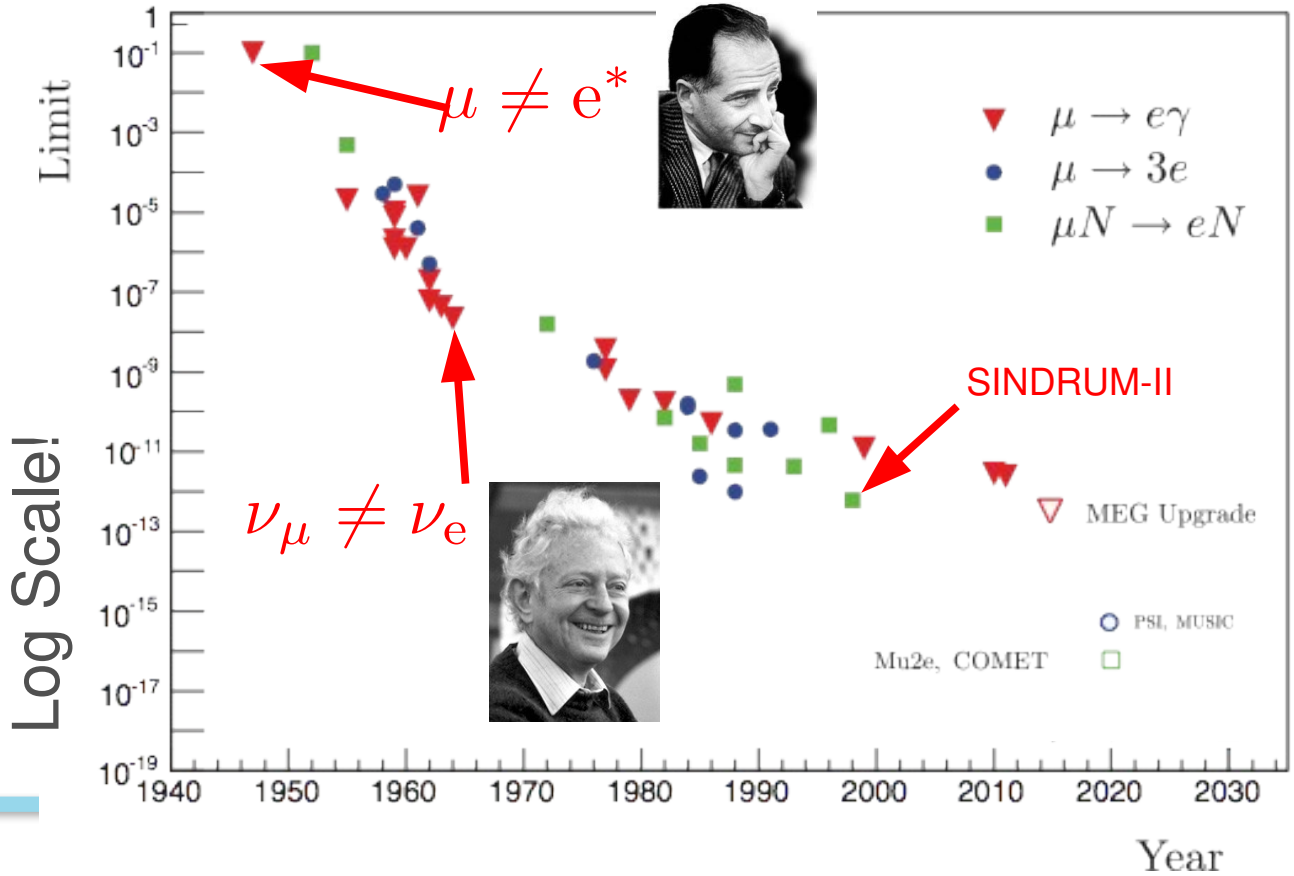

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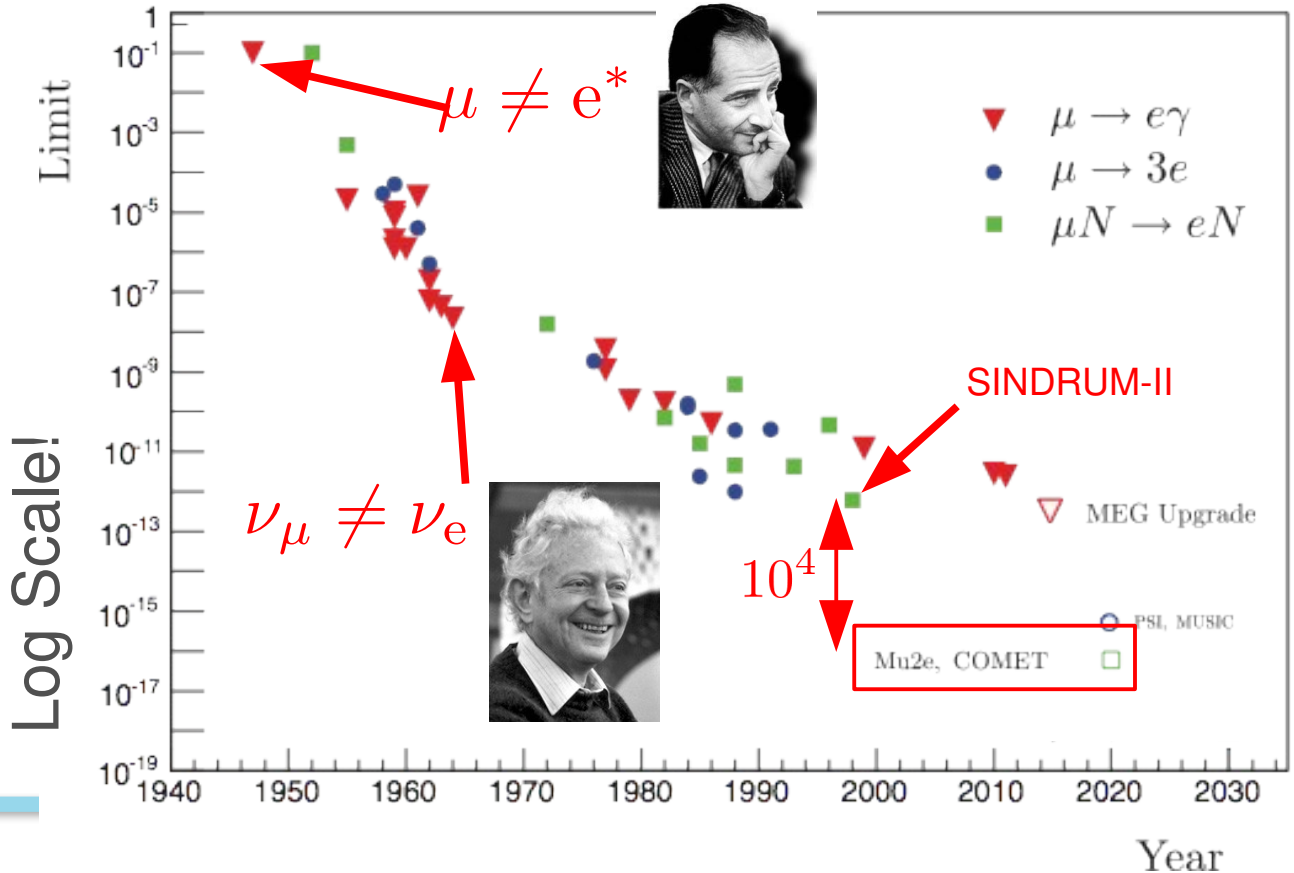

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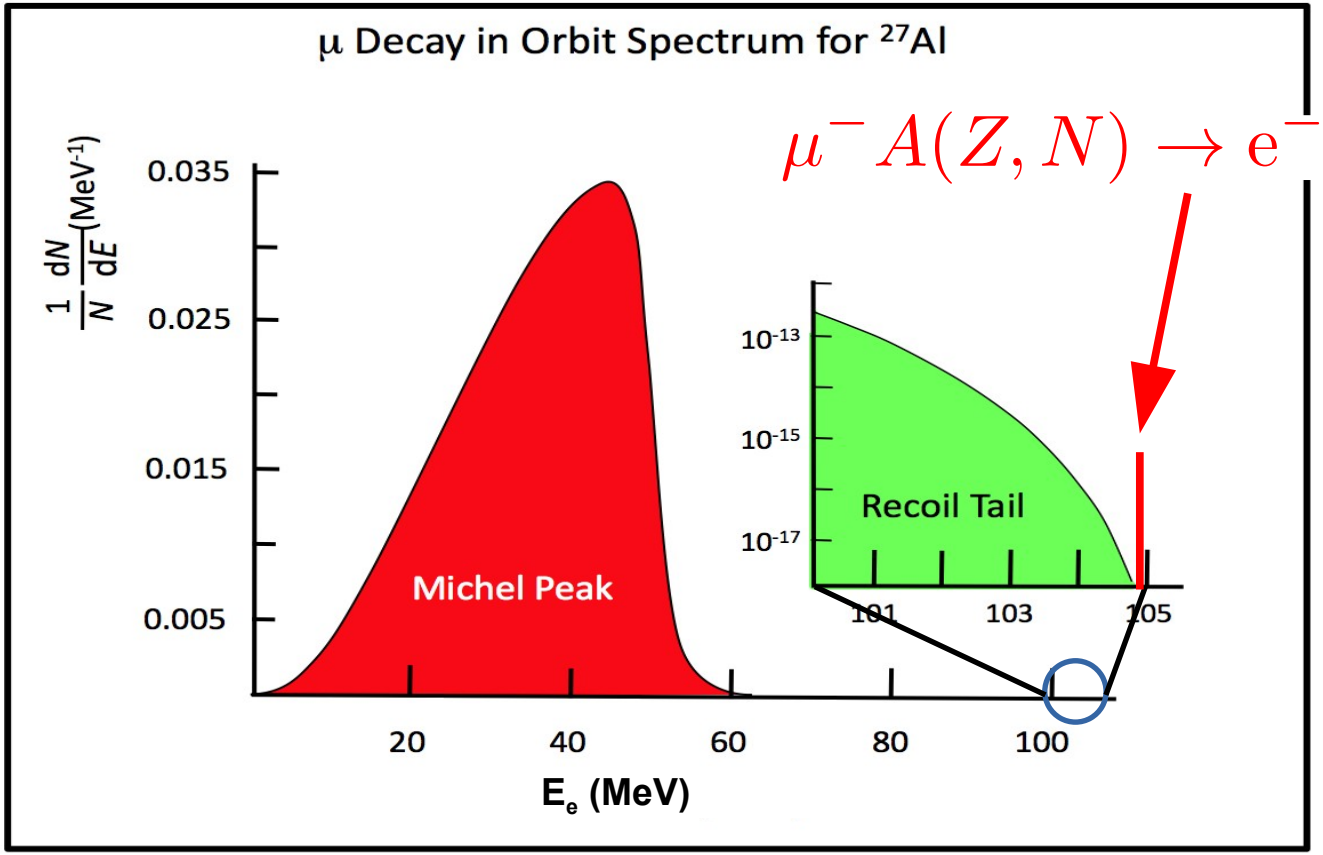
Our key advantage: conversion is kinematically distinct from the background muon decay spectrum



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

Our signal is a mono-energetic electron at 105 MeV, above the background tail!

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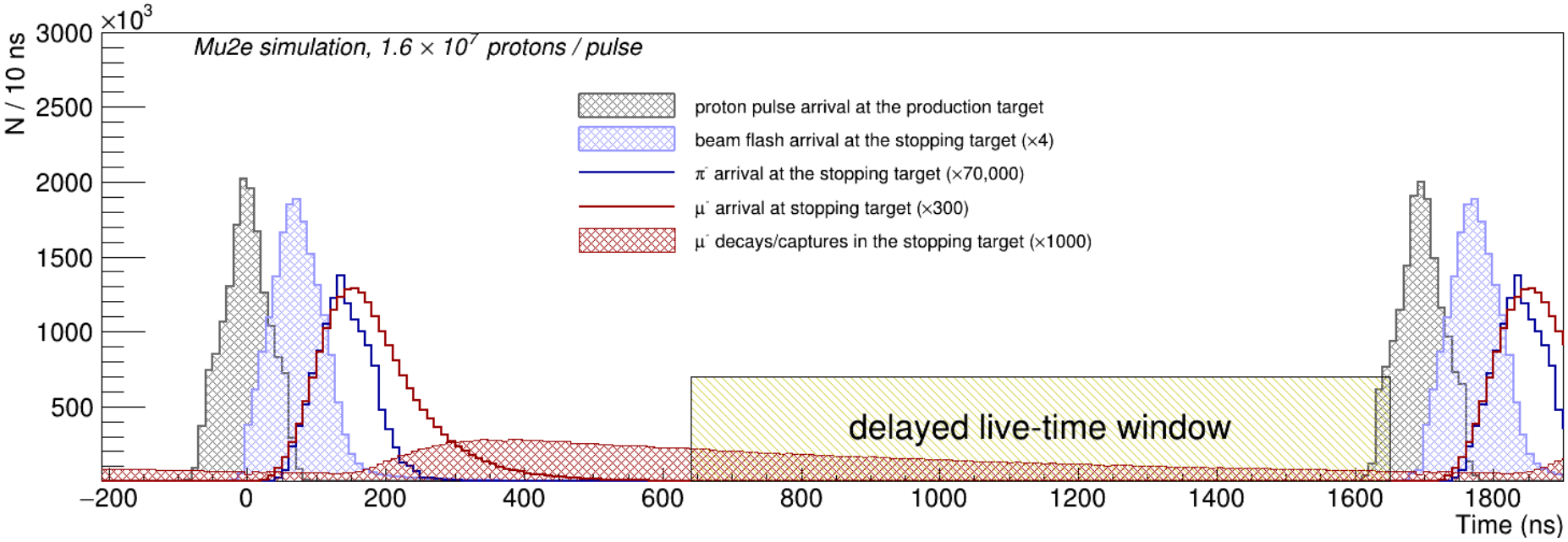
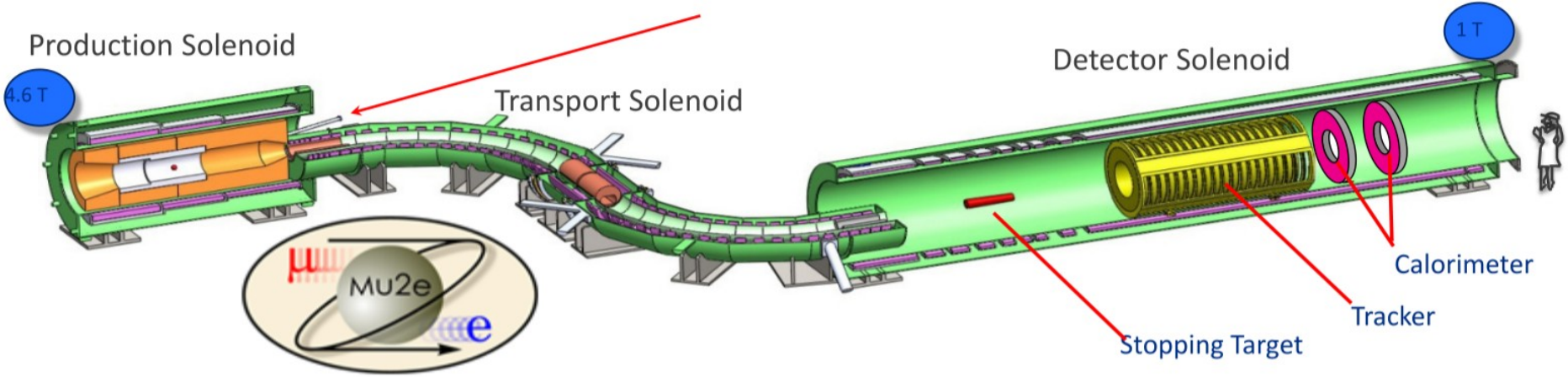
Beam induced backgrounds can be reduced by using a pulsed beam source

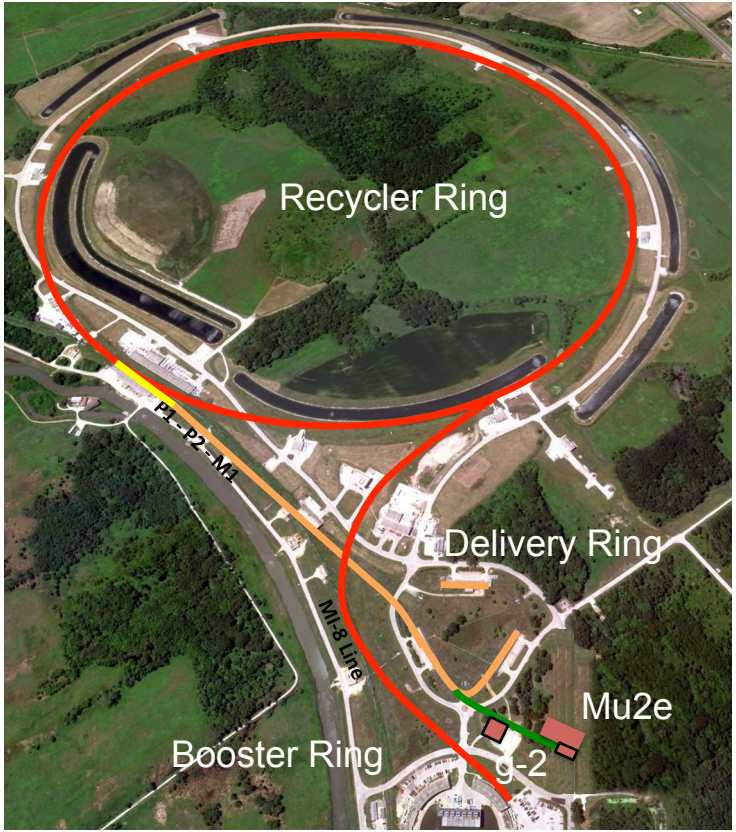


Let’s first explore how Mu2e will tackle this challenge

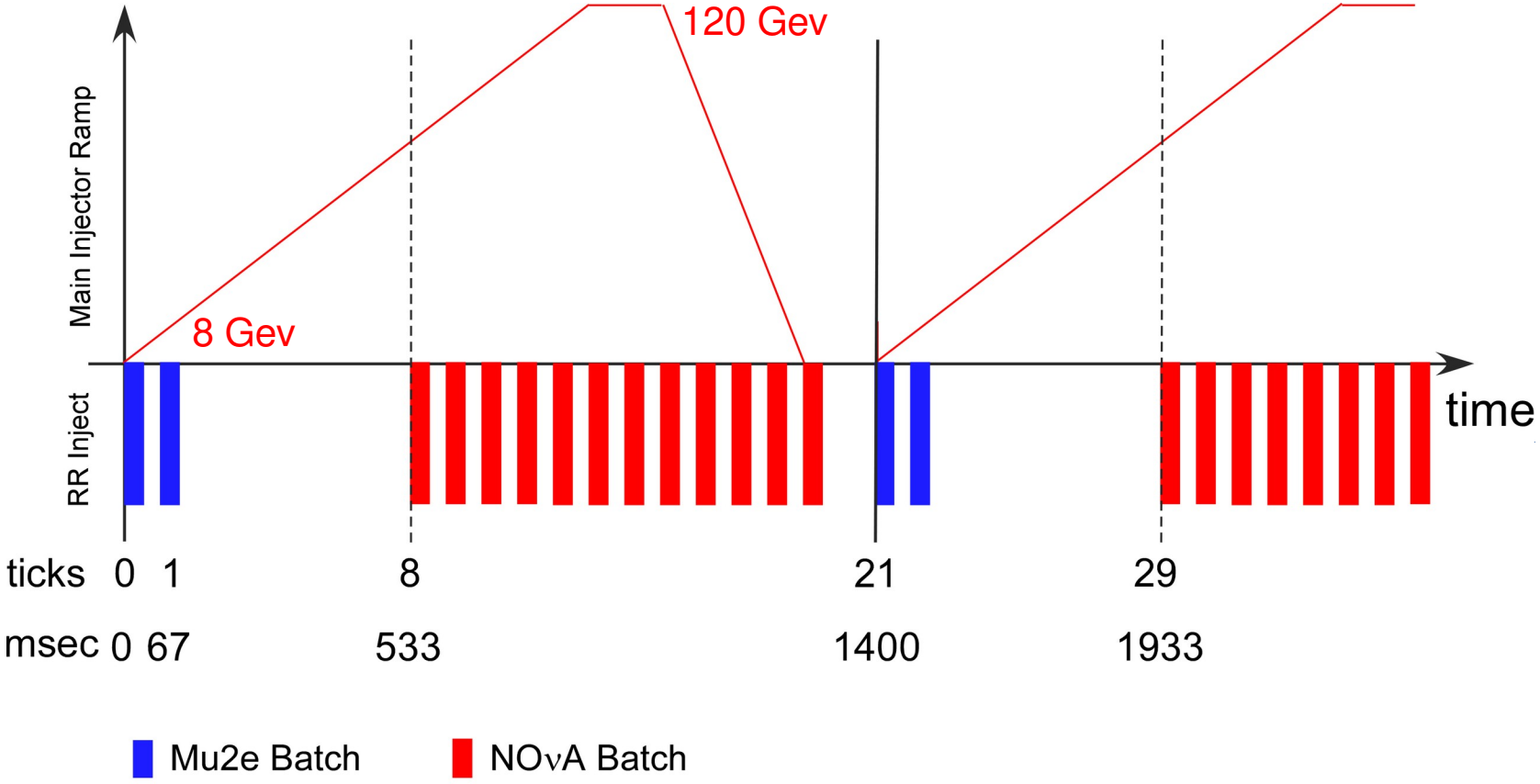


The Fermilab Muon Campus runs on 8 GeV protons

- Linac: 0 → 400 MeV
- Booster: 400 MeV → 8 GeV
- Recycler rebunches protons
- Delivery Ring slow extracts protons
- Mu2e production target produces pions

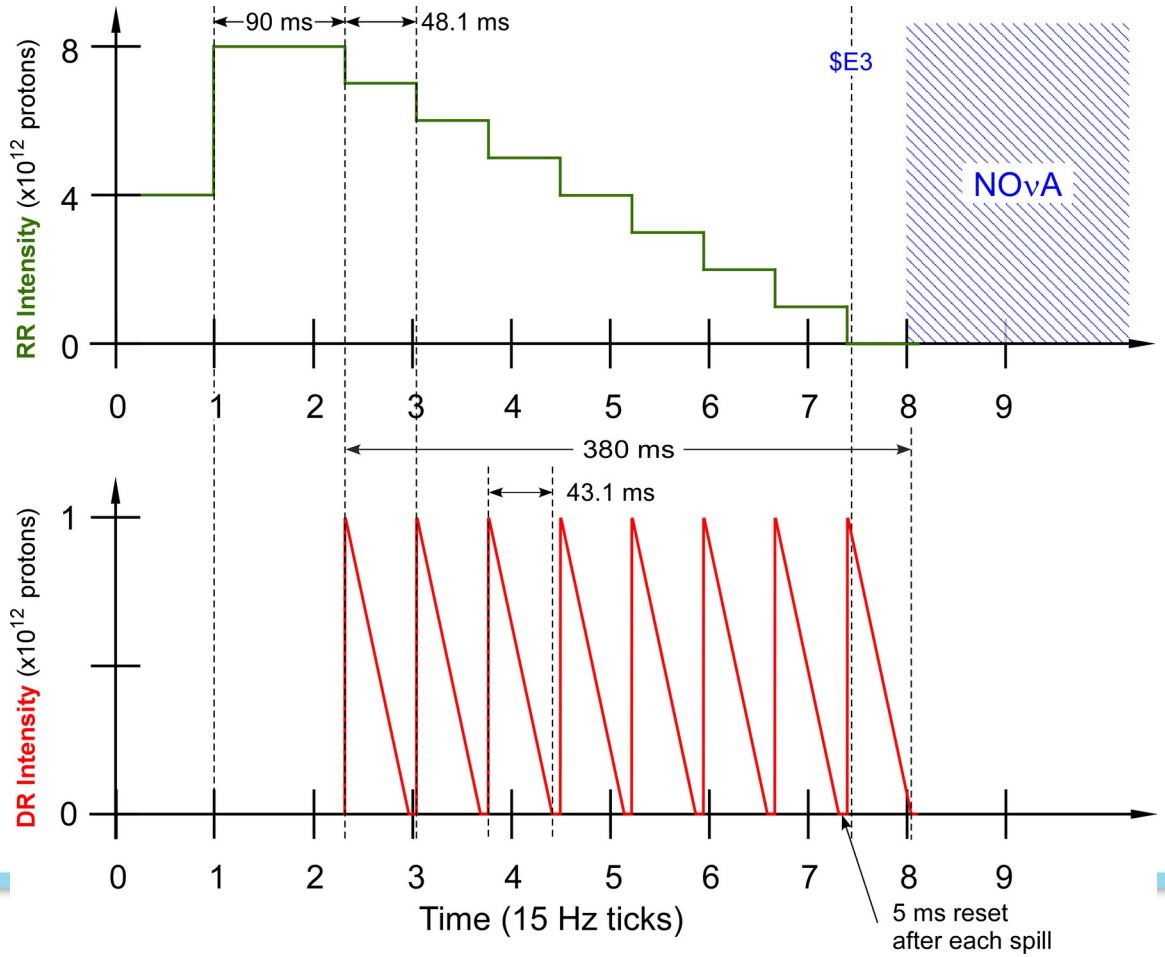


The neutrino program drives 8 GeV proton economics



1 tick = 1/15 sec

Protons are slow extracted from the DR to Mu2e



Deliver average proton beam power of 7.3 kW at 8 GeV KE

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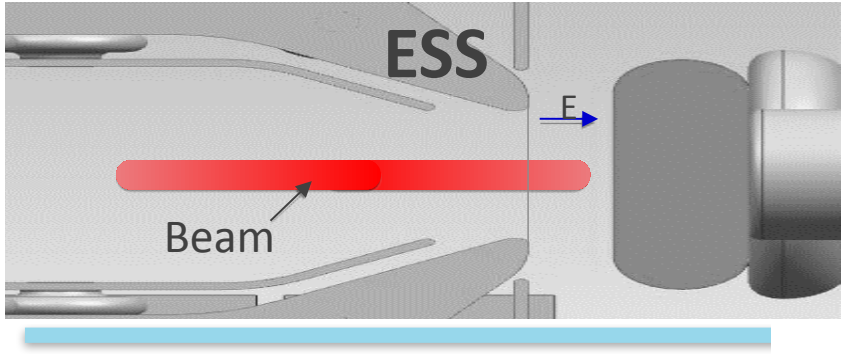
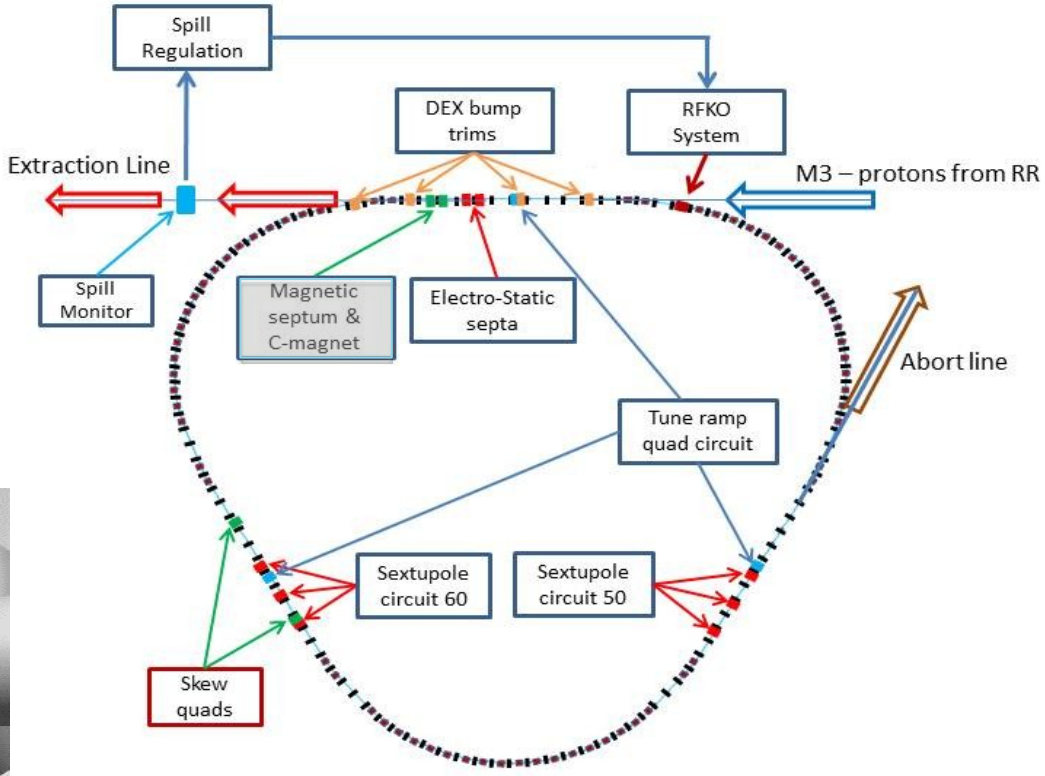
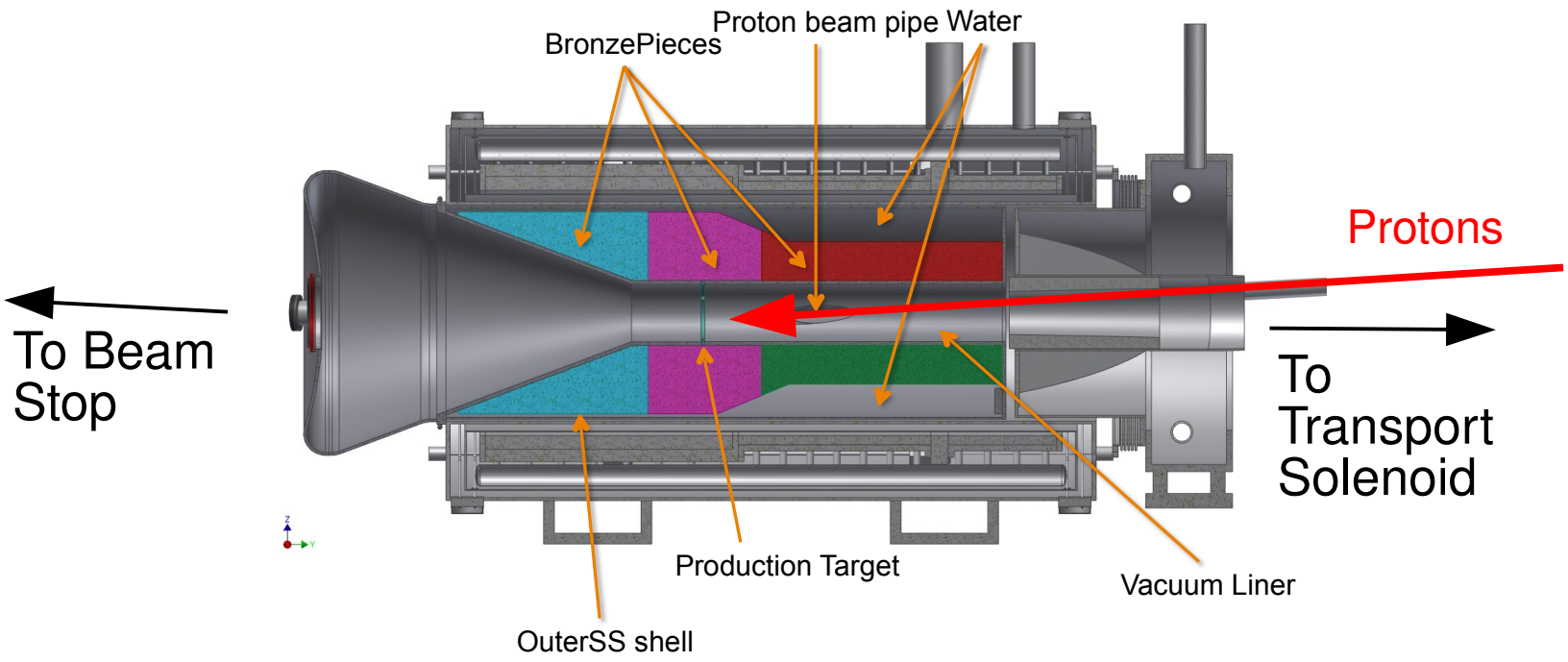
Deliver Ring manipulations

- Quadrupoles drive a 1/3 integer resonance (29/3) in the horizontal tune
- Sextupoles induce a controlled beam instability
- Septum peels off a microbunch on each turn
- Dynamic spill regulation control via an RFKO system
- Full extraction over ~32,000 turns



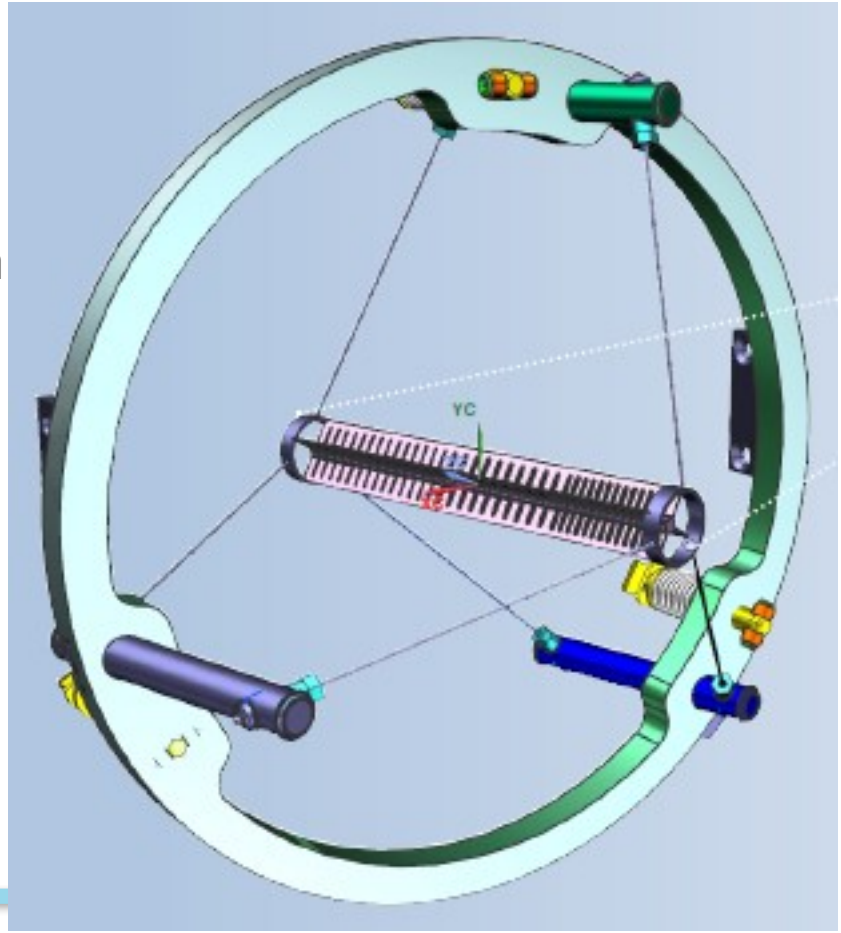


The production target is mounted inside a high field Production Solenoid, and we capture and transport backward muons

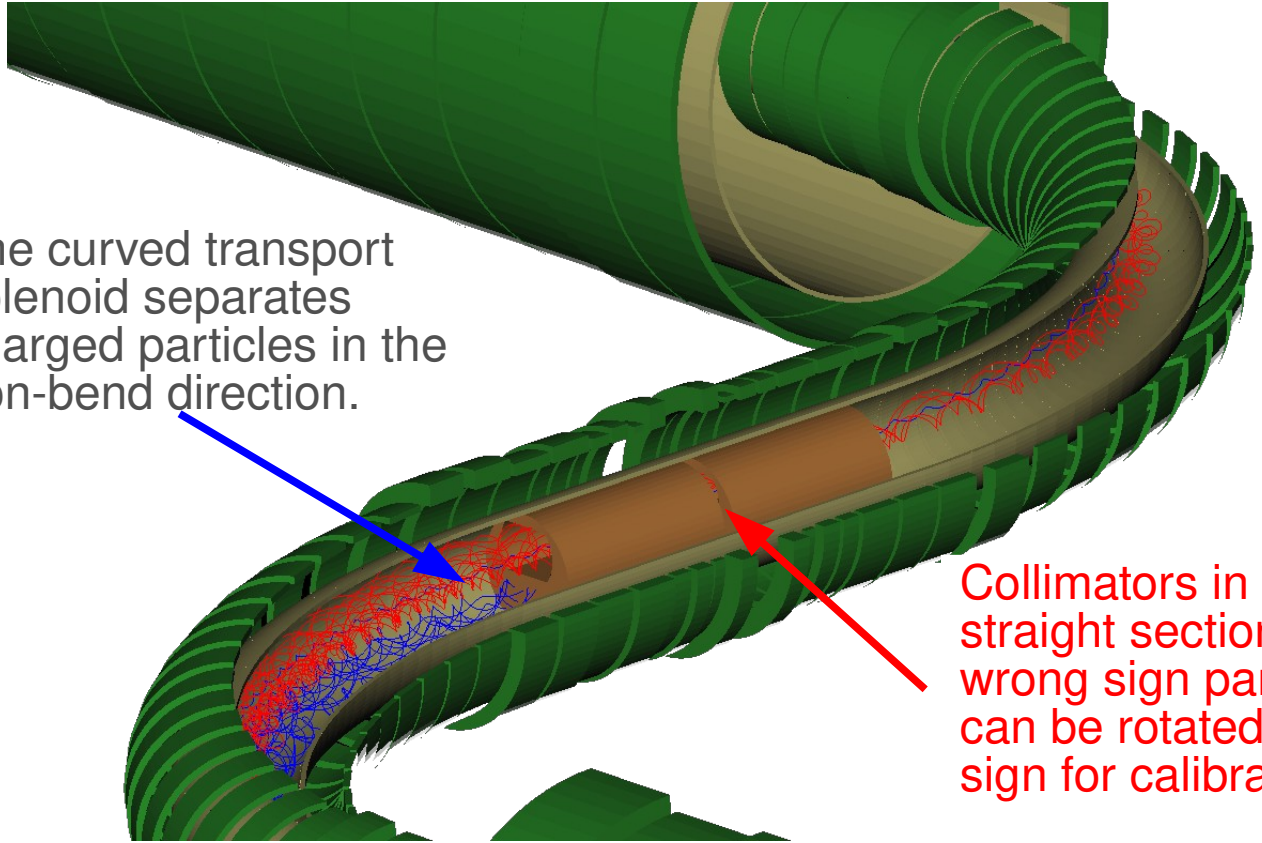


The production target is a radiatively cooled tungsten structure

- Bicycle wheel support
- LaO_2-doped Tungsten, core is EDMed from single rod
- Longitudinally segmented cylinder (stress management):
  - 3.15 mm radius, 160+60 mm length
- Longitudinal fins (structure and thermal management)
- 1mm tungsten spokes
- ~ 700 W power absorption
- ~ 1500 K temperature



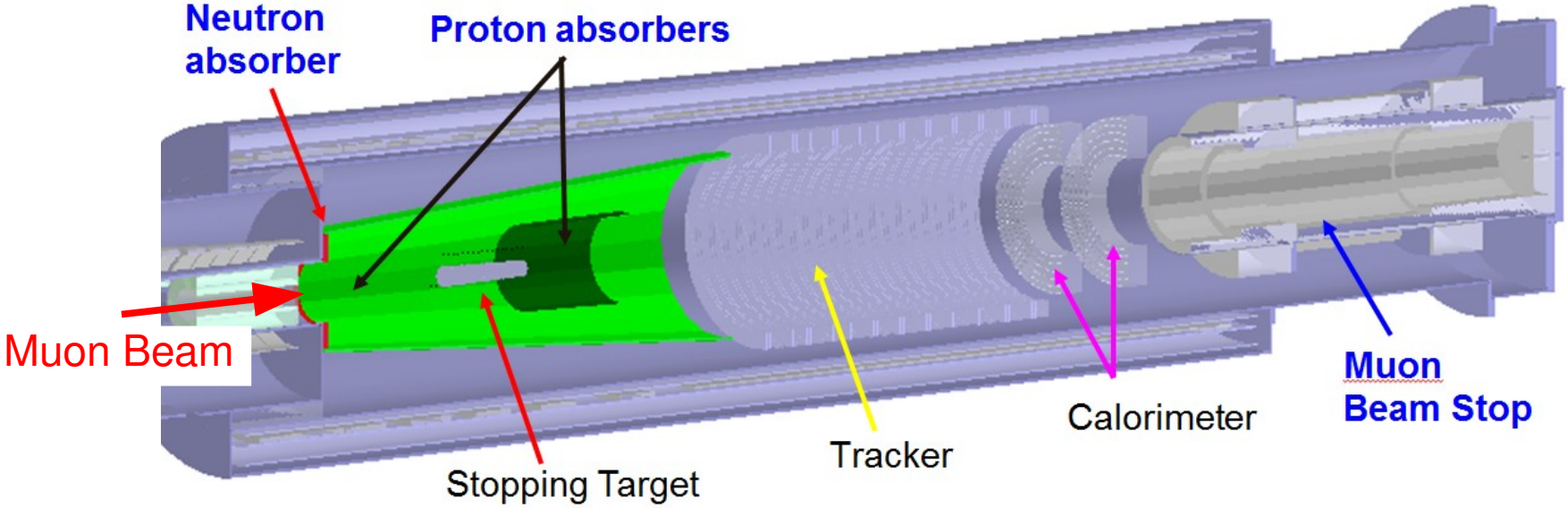
The Transport Solenoid sign selects with a collimator



The curved transport solenoid separates charged particles in the non-bend direction.

Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

The Detector Solenoid is the heart of the experiment



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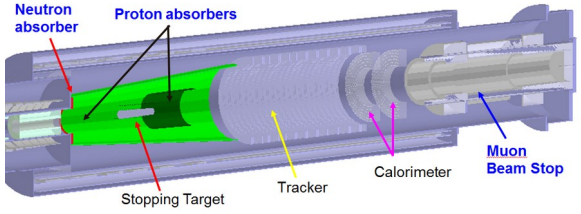
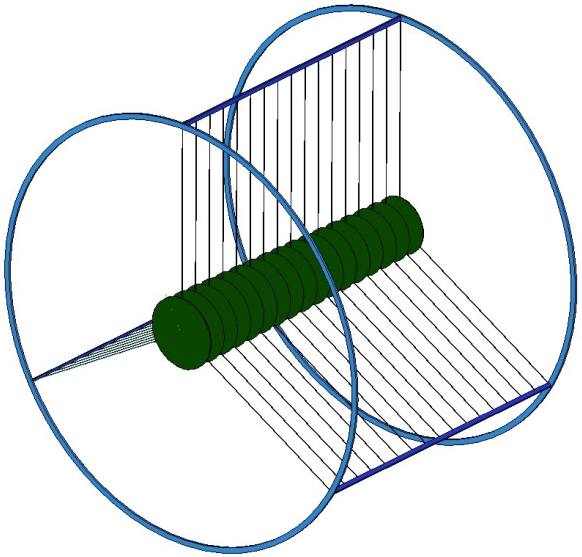
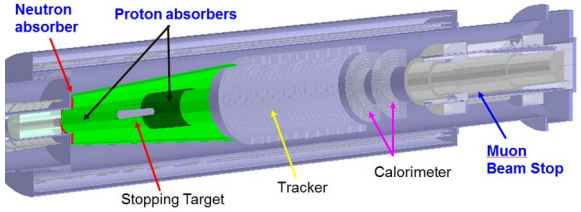
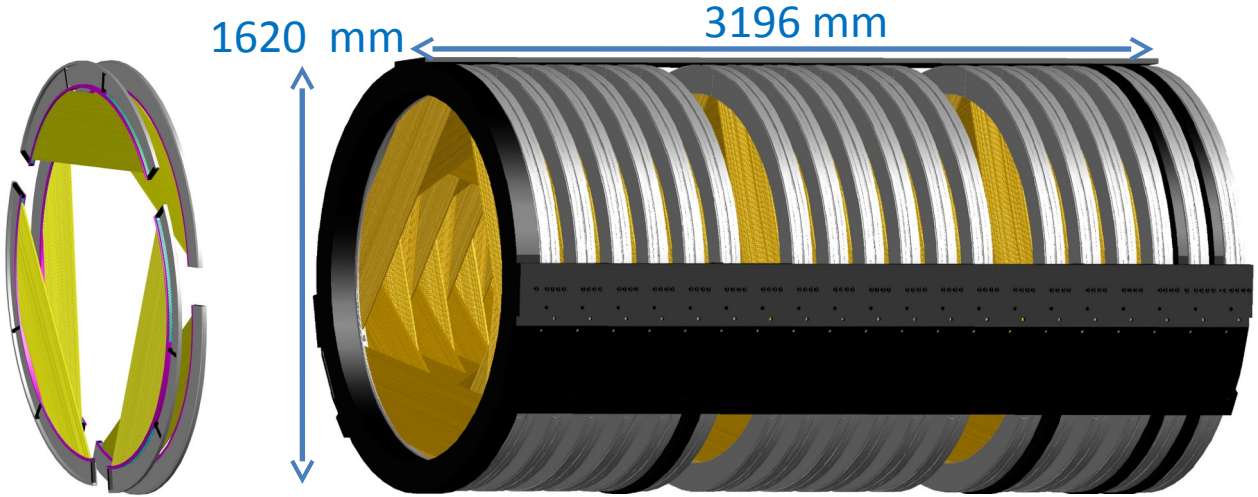




The stopping target is 17 Al foils to intercept and stop the secondary beam

The Detector Solenoid is the heart of the experiment

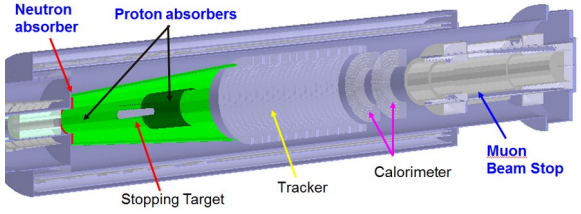


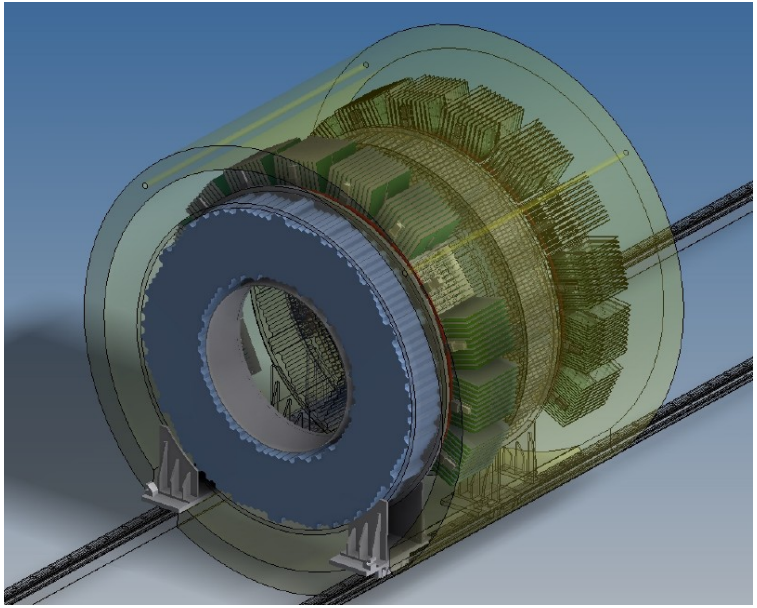


The electron tracker is a low mass straw tube design with 18 stations of tubes transverse to the secondary beam, with 21,000 straws in total.

It provides precision momentum measurement.

The Detector Solenoid is the heart of the experiment



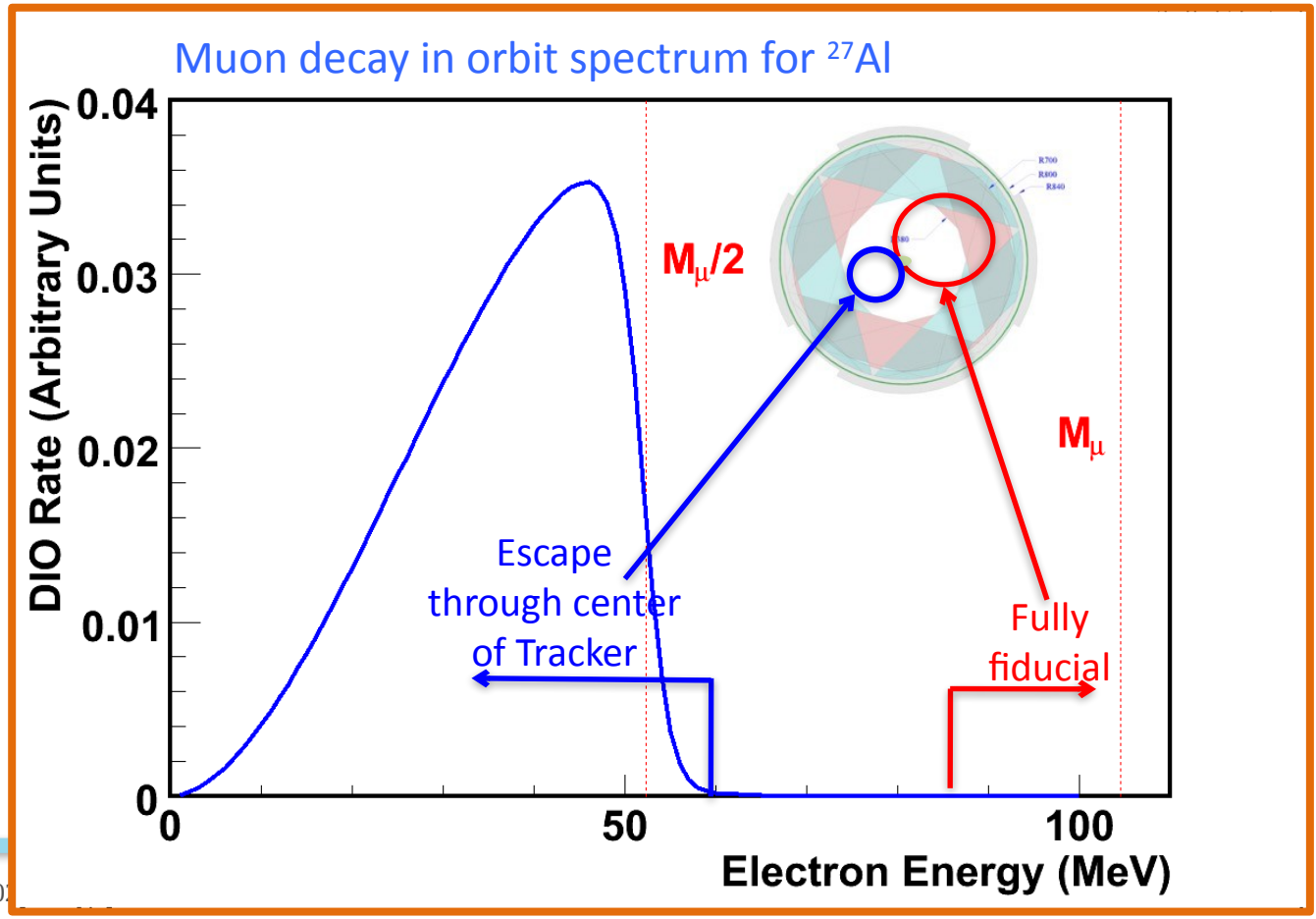


The calorimeter is a two layer, annular, undoped CsI crystal calorimeter.

It provides precision timing and particle ID

Detectors are uninstrumented along the axis of the solenoid

The vast majority of remnant beam, brehmstrahlung, and muon decay products escape down this central hole and are captured in a muon beam stop designed to prevent “back splash”



Mu2e running will be split by the LBNF shutdown

Construction should complete in 2025, with commissioning and Run 1 physics data in 2026-2027.

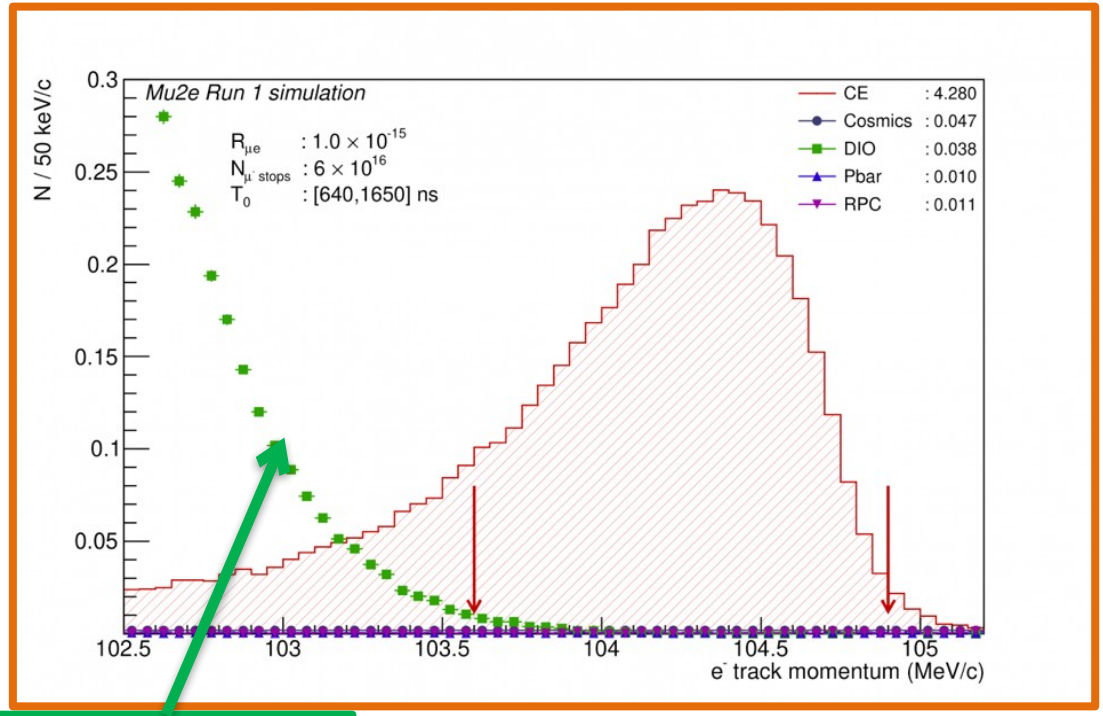
Recently completed a sensitivity estimate for Run 1:

- 5σ discovery R = 1.1 x 10^{-15}
- 90% CL R < 5.9 x 10^{-16}
- 1000x better than SINDRUM-II
- Paper to be submitted to Universe

Run 2 will commence in 2029 with a goal to improve the measurement to 10000x better than SINDRUM-II.

For the full dataset, our expected sensitivity

- 90% CL R < few x 10^{-17}



Long DIO tail due to nuclear recoil

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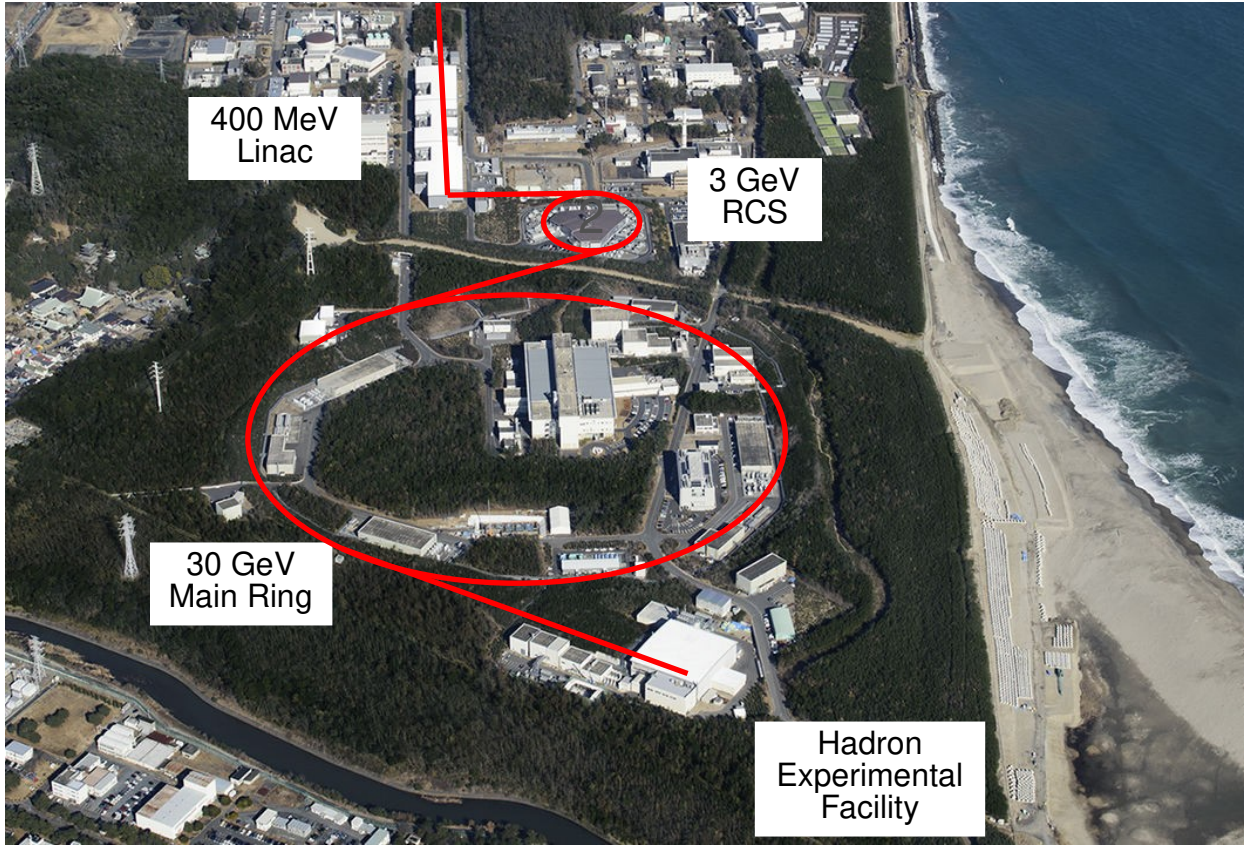
COMET will run at JPARC, and shares significant DNA with Mu2e

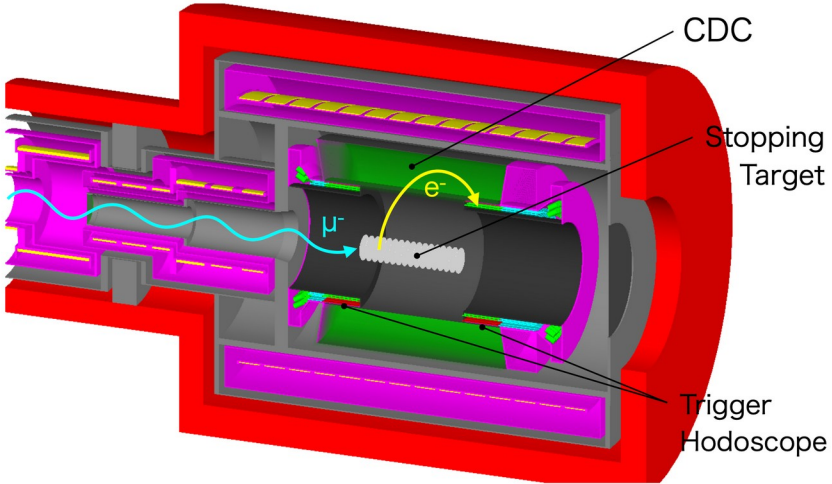
COMET will also use a slow extracted, pulsed proton beam at 8 GeV, although with a different time structure from Mu2e

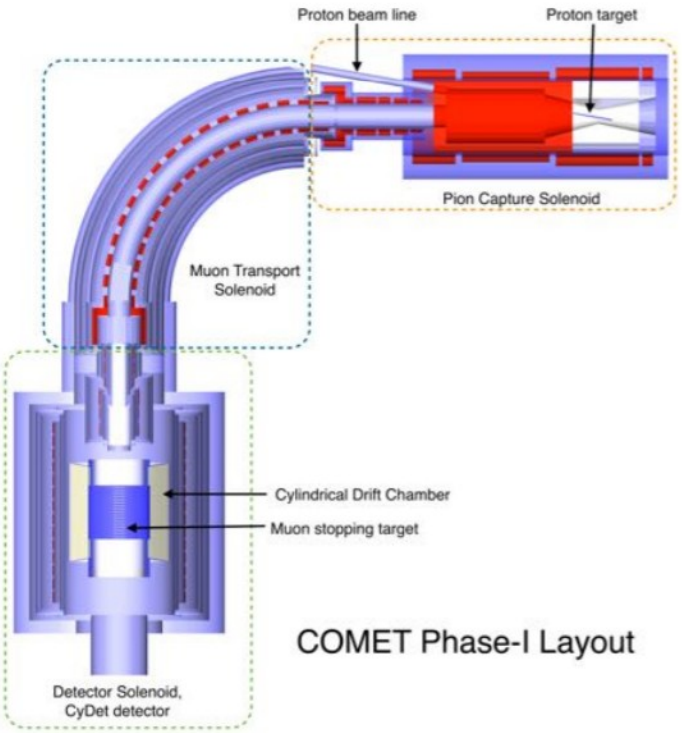


COMET will split their running into two phases, with different apparatus

In Phase 1, COMET will improve on SINDRUM-II by a factor of 100 starting 2024

- Use a graphite production target with 3.2kW of beam power,
- Transport backward muons though a 90 degree bend,
- To an Al foil stopping target surrounded by a cylindrical detector, CyDet

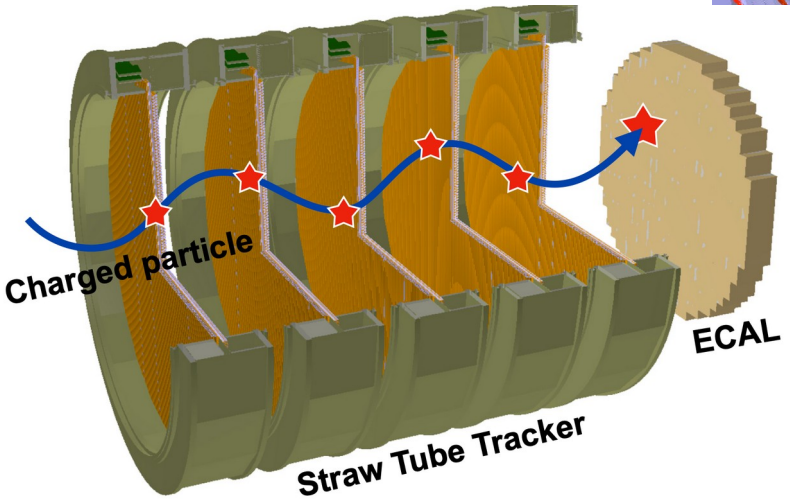


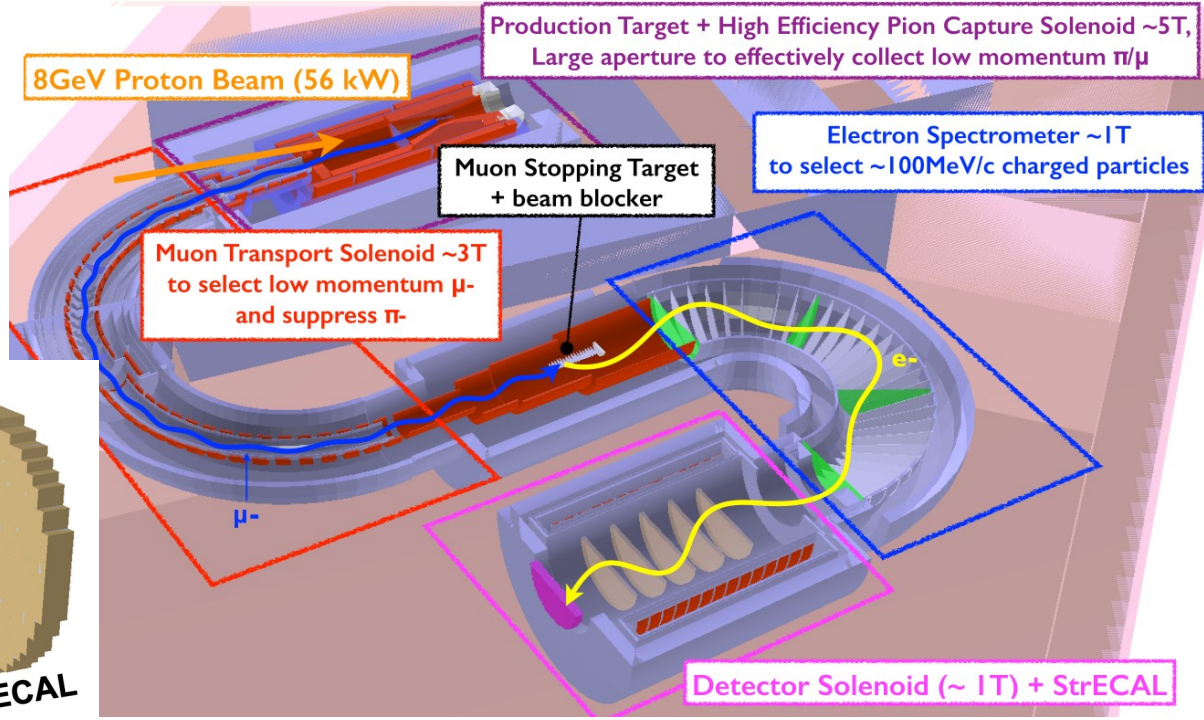


COMET Phase 2 will enable 10000x improvement after Phase 1 completes

Significant modifications

- 56 kW beam on tungsten target
- Multiple C-shaped solenoids for background rejection
- Significantly improved detector systems





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To summarize…

- Fundamental muon physics today is focused on CLFV searches
  - $\mu \rightarrow e\,\gamma$
  - $\mu \rightarrow eee$
  - $\mu^- N \rightarrow e^- N$
- Mu2e and COMET are friendly competition in the conversion search with much shared DNA
  - Both aim for a 10,000x improvement over SINDRUM-II
- Although I couldn't talk about them (see the backup slides!), there are ideas to gain an additional 2-3 orders of magnitude with future searches in these and other channels

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

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

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

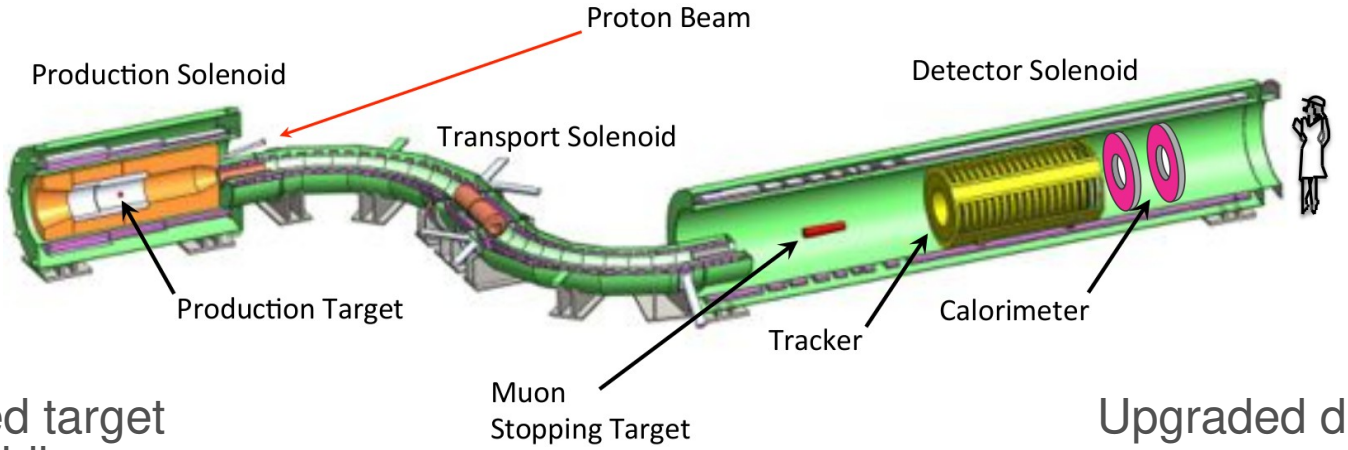
CLFV and LNV!

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



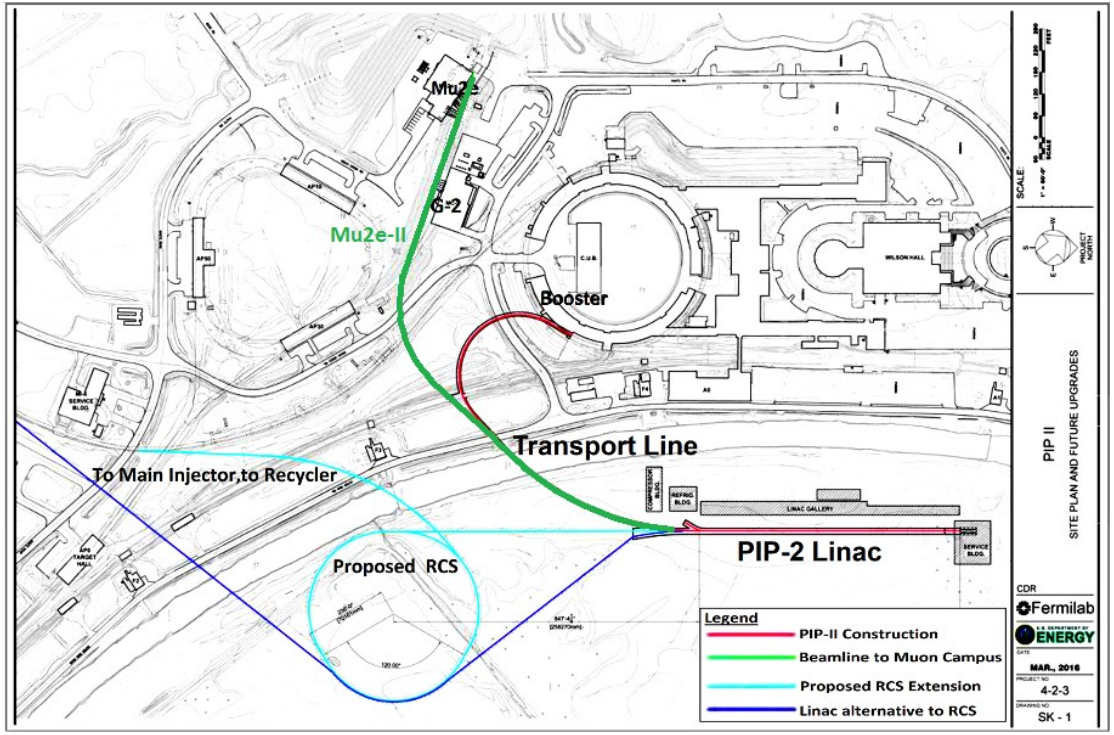
Upgraded target and shielding

Upgraded detectors

Different stopping materials

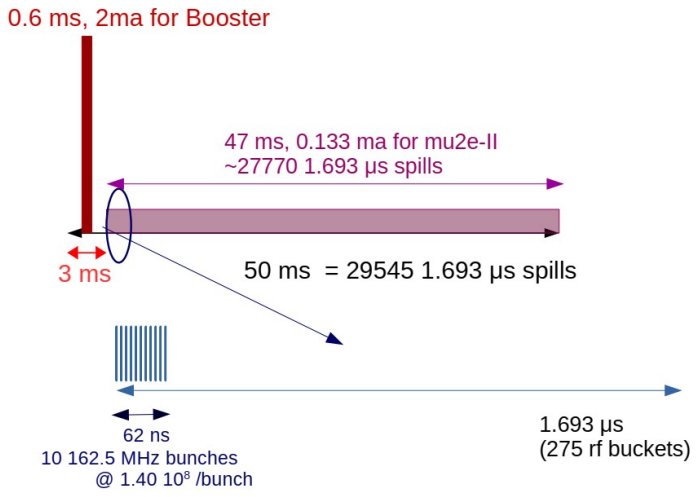
Mu2e-II in the 2030s

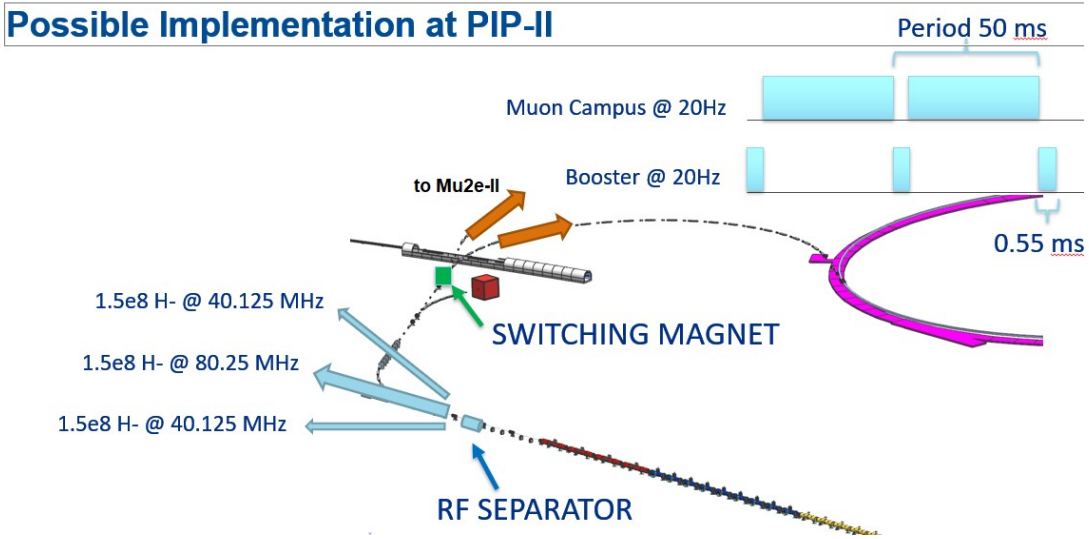
- The key enabling technology is PIP-II



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!



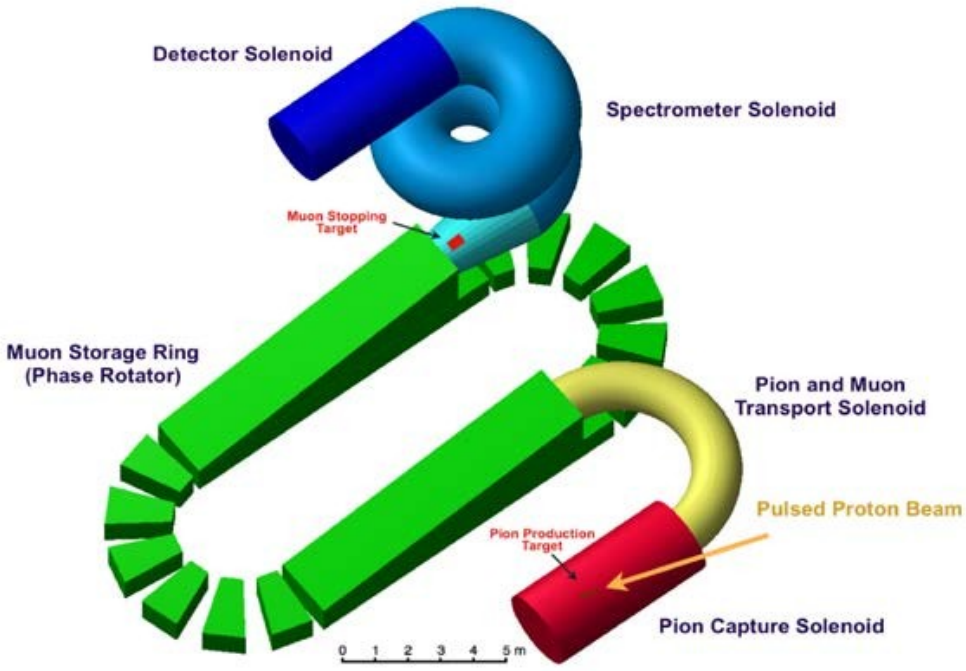


AMF: an advanced muon facility for Fermilab beyond Mu2e-II

- 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

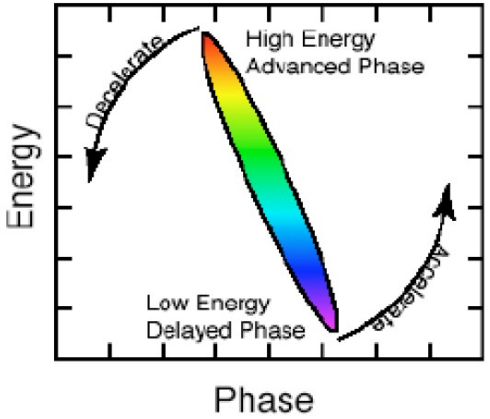
AMF enabling technologies

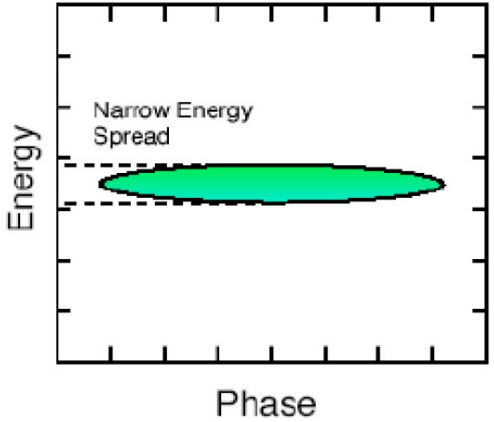
- PIP-II
  - Proton source
- Proton compressor ring
  - Convert CW beam to intense proton pulses
- Production solenoid and target systems
  - House production target
- Muon transport
  - Eliminate LOS from target to experiments
  - Match beam dynamics solenoid ↔ FFA
- FFA ring
  - Phase rotation → monochromator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



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



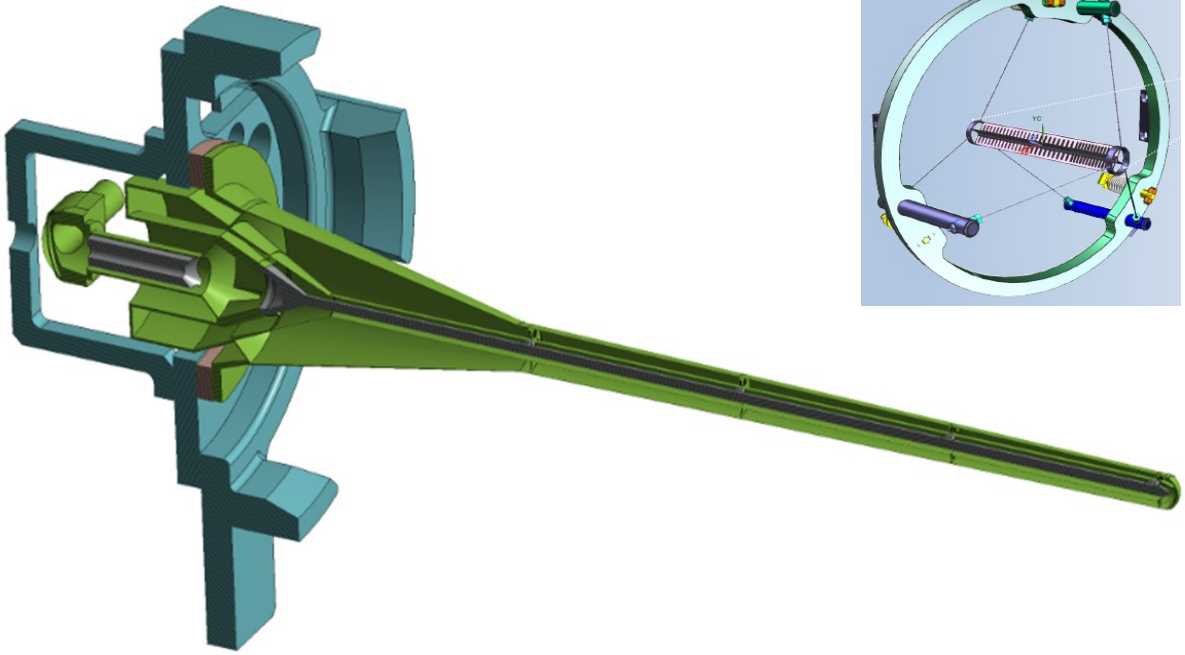


Chief AMF technical challenges

- 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

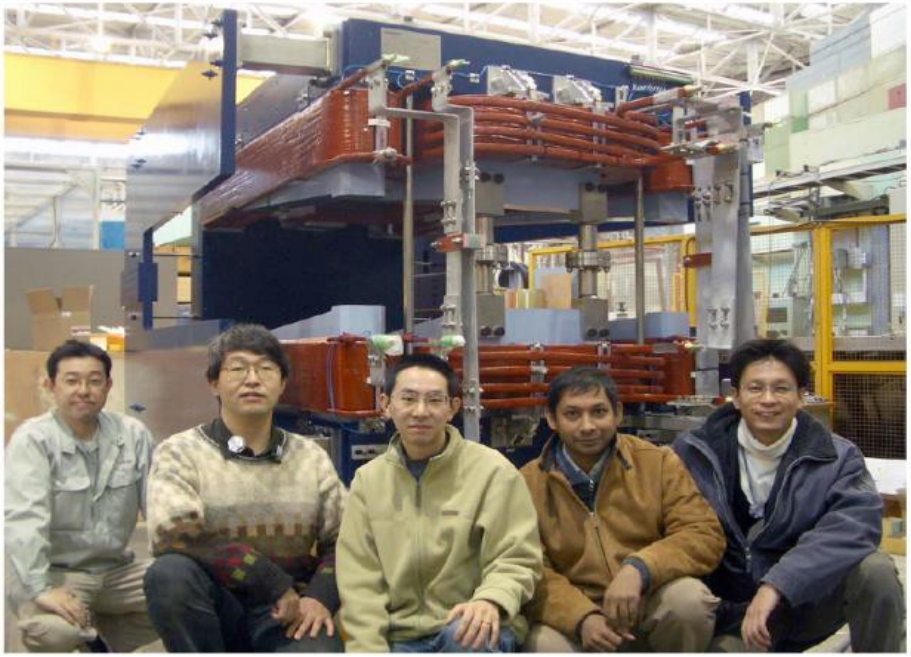


Mu2e Target Core
6.3mm x 220mm x 250kW

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!