Mu2e Muon Beam Optimization

NuFACT 2019
Daegu, Republic of Korea

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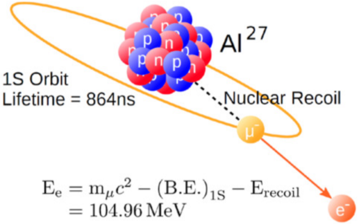
For the Mu2e Collaboration

29 August 2019

What is Mu2e

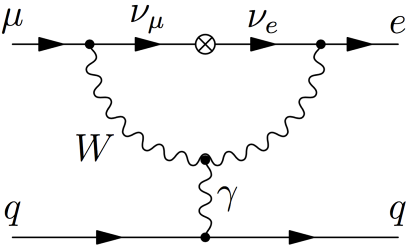
New experiment under construction at Fermilab.
We are looking for new physics – **charged lepton flavor violation** (CLFV).
Rare interaction: muon converting to electron, without neutrinos, in the presence of an atomic nucleus.



Flavor violation among the charged leptons is linked to flavor violation among the neutrinos

What is Mu2e

An example of the link between CLFV and neutrino flavor mixing: Although it has never been observed, we know that CLFV must occur, even in the Standard Model, through neutrino loop effects.



What is Mu2e

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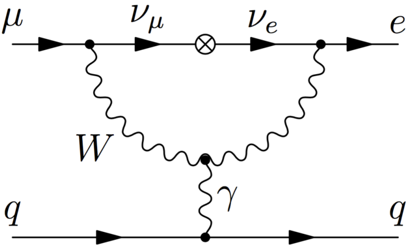
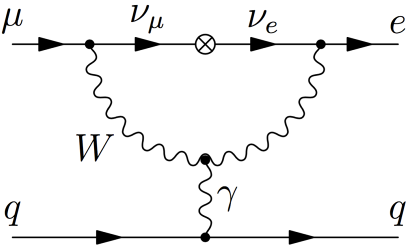


However, the predicted Standard Model rates are unobservably small:

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

What is Mu2e

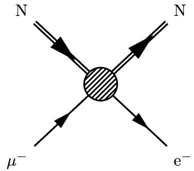
An example of the link between CLFV and neutrino flavor mixing: Although it has never been observed, we know that CLFV must occur, even in the Standard Model, through neutrino loop effects.



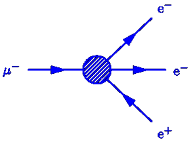
Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!

Muon Experiments Looking for CLFV

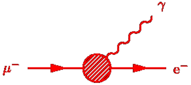
This is an exciting field, with lots of excellent experiments looking for CLFV in $\mu N \to eN$, $\mu \to eee$, and $\mu \to e\gamma$ interactions:



Mu2e @ FNAL, COMET @ J-PARC, DeeMe @ J-PARC



Mu3e @ PSI



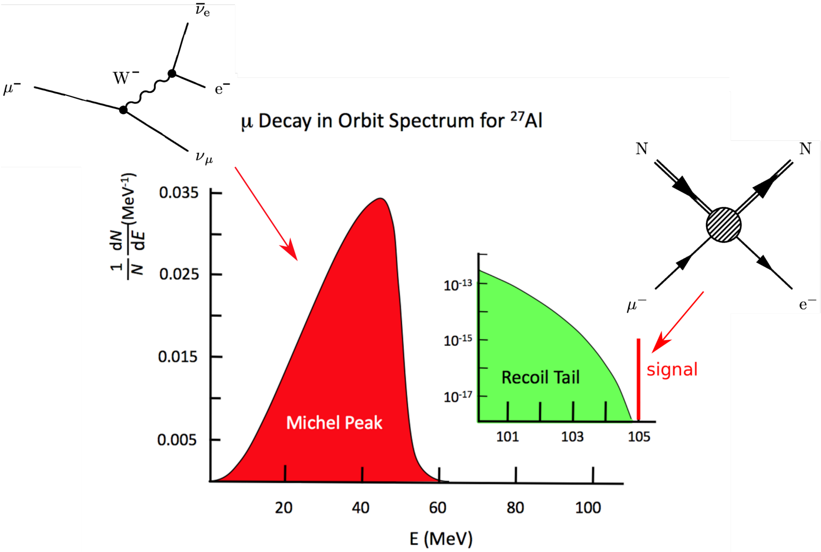
MEG @ PSI, MEG II @ PSI

Plus exciting developments in muon beams at PSI and RCNP!

Mu2e Backgrounds

Decay in orbit

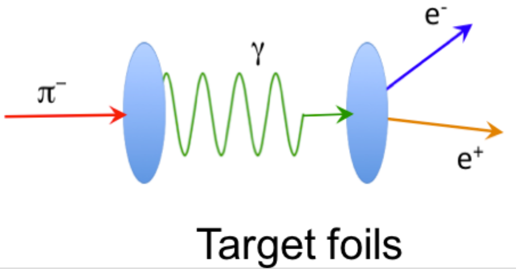
Muon undergoes SM decay while in orbit around the nucleus:



Mu2e Backgrounds

Radiative pion capture

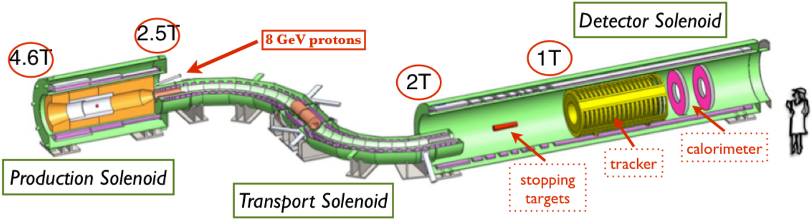
Pion captured by nucleus, resulting in an excited nucleus which quickly emits a photon:
$\pi^- + (A, Z) \to (A, Z-1) + \gamma$.
That photon can then undergo pair production:



If the resulting electron has kinetic energy $\sim$105 MeV, this becomes a fake event!
π^+/π^- lifetime is 26 ns.
Major consequences for beam time structure

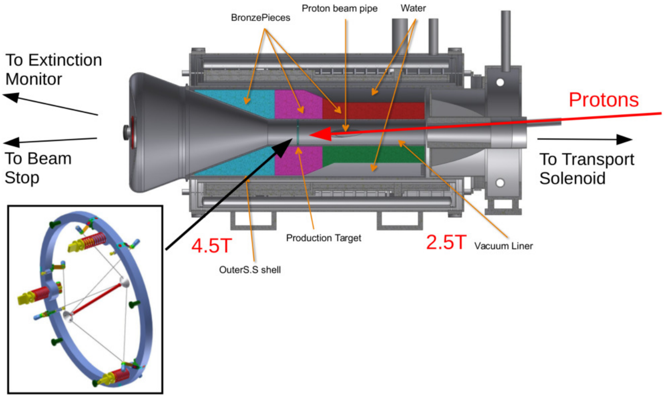
What is Mu2e

The Mu2e apparatus separates the production of muons and our observations of their decays.



Production Solenoid

The production solenoid produces a backward beam to further reduce prompt backgrounds

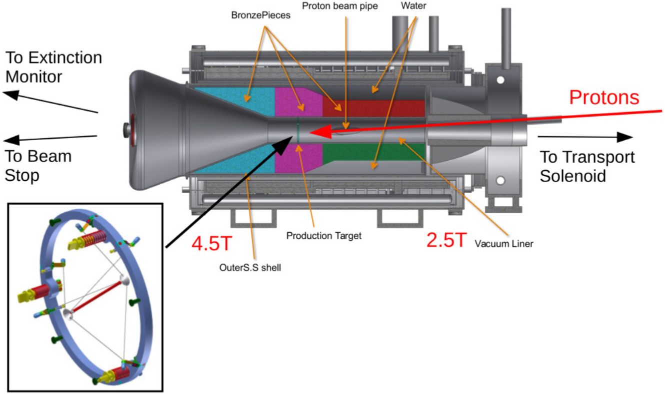


The tungsten production target is about the size of a pencil

The graded field acts as a "mirror" for charged particles, increasing the flux of muons into the TS

Production Solenoid

The production solenoid produces a backward beam to further reduce prompt backgrounds

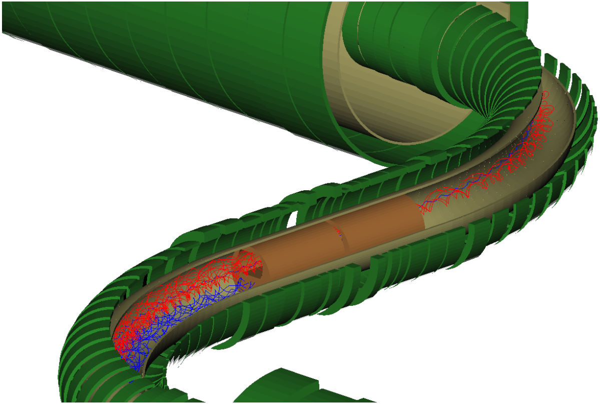


The tungsten production target is about the size of a pencil

Total muon yield in the stopping target: 0.0018 μ^-/POT.
Muon beam intensity: 10^{10} μ/sec.

Transport Solenoid

The transport solenoid sign selects charged particles



(μ^- in red, μ^+ in blue)

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

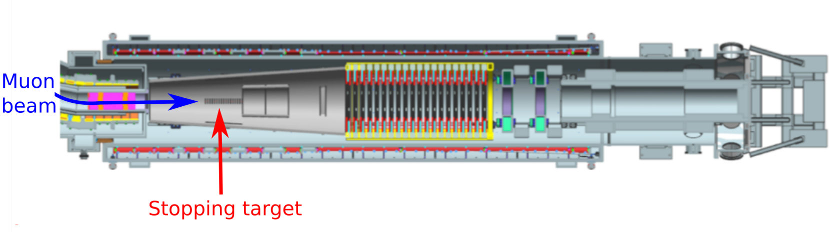
Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

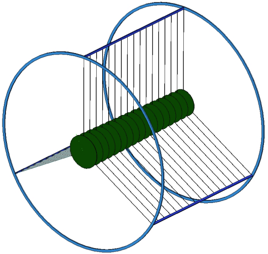
Detector Solenoid

Graded magnetic field between entrance from TS and tracker to direct electrons toward the tracker.

Nearly uniform magnetic field in tracker to simplify tracking.

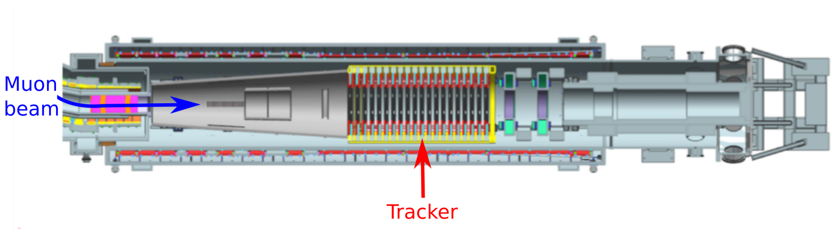
Detector Solenoid

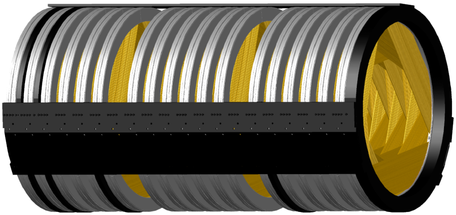




Stopping target is a series of Al foils to intercept and stop the muon beam.

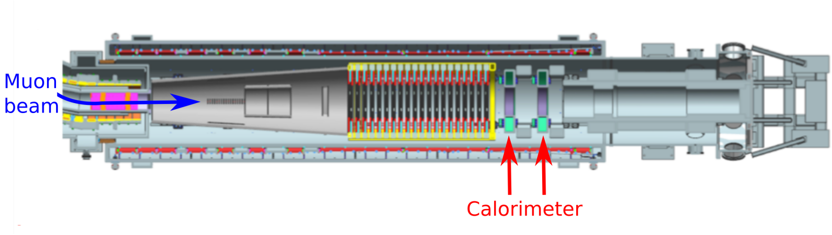
Detector Solenoid



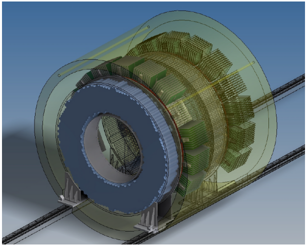


The electron tracker is made of over 20,000 low mass straw drift tubes, arranged in planes transverse to the muon beam. Momentum resolution $\sigma_p < 180$ keV/c.

Detector Solenoid



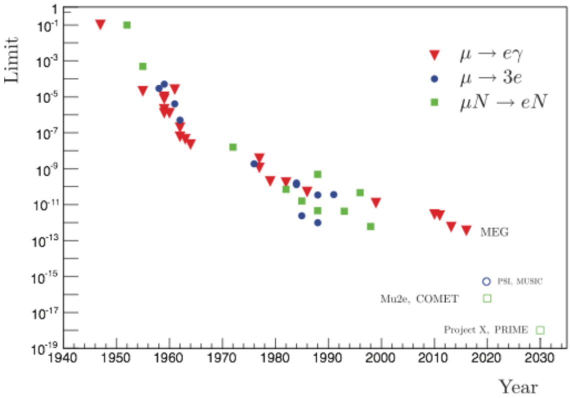
The calorimeter is made of two annular disks, totalling 1400 CsI crystals and 2800 SiPMs. Provides independent time, energy, and position measurements, trigger info, and particle ID.



Our Goal

Search for $\mu \to e$ conversion with a 90% CL limit at 8×10^{-17}

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



Plot from R.H. Bernstein, P.S. Cooper (2013), with MEG results added

If there is new weak scale physics, Mu2e is in an excellent position to observe CLFV.

Our Goal

In a three-year run, we expect a nearly background-free signal:

Process	Expected event yield
Cosmic rays	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

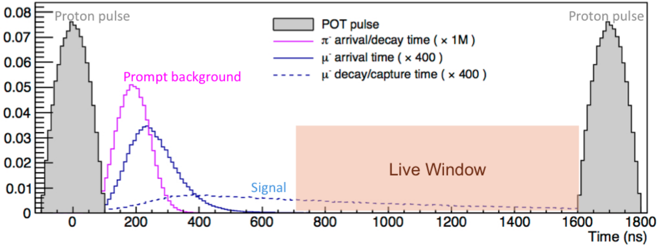
Every part of the experiment is optimized for background reduction, but for this talk, I will focus on the muon beam.

In particular, this talk will focus on:

- time structure
- selection of low-momentum, negative muons

Beam Time Structure

The muon beam time structure is ultimately driven by requirements for the proton beam pulse structure.
Pulse separation and duration driven by separating signal from prompt background in time.



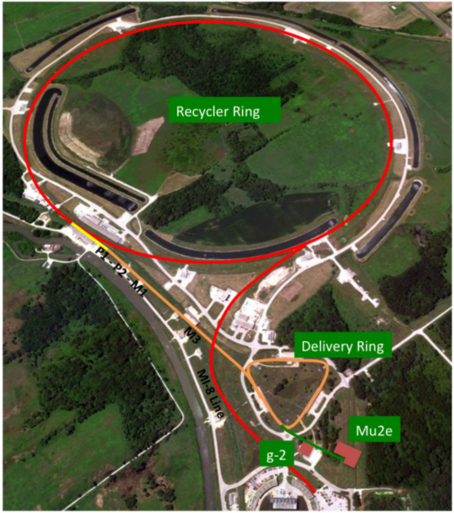
Require:

- pulse duration $\ll$ muonic Al lifetime
- pulse separation $>$ muonic Al lifetime
- extinction between pulses $< 10^{-10}$

This will suppress pion backgrounds by 11 orders of magnitude

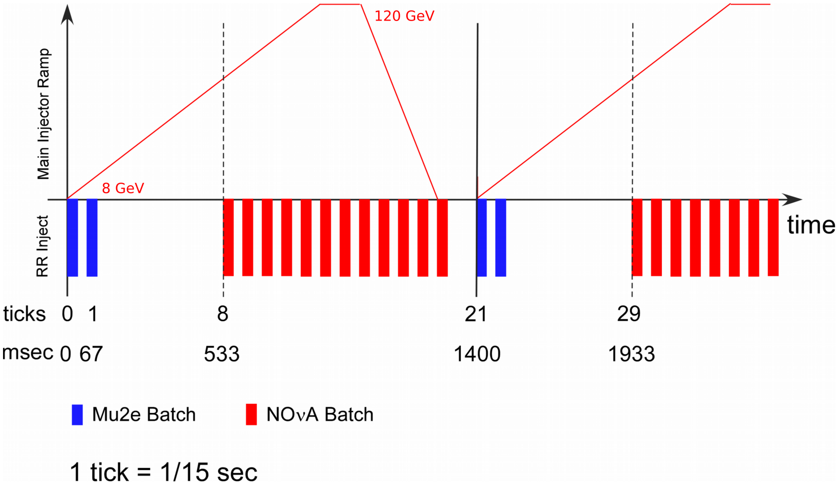
Proton Beam

The Muon Campus program is run with 8 GeV protons

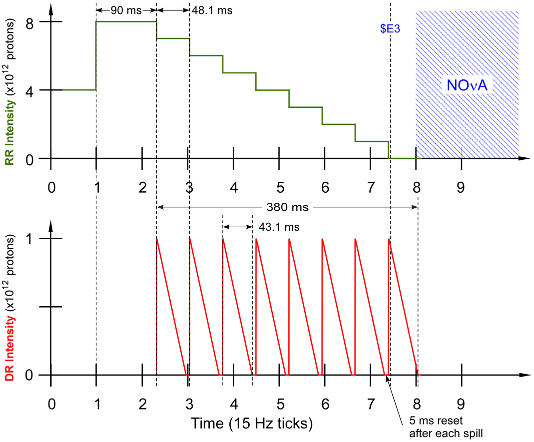


Proton Beam Batches

Protons for Mu2e are injected into the Recycler Ring while the Main Injector ramps up to 120 GeV for Noνa



Proton Beam Manipulations



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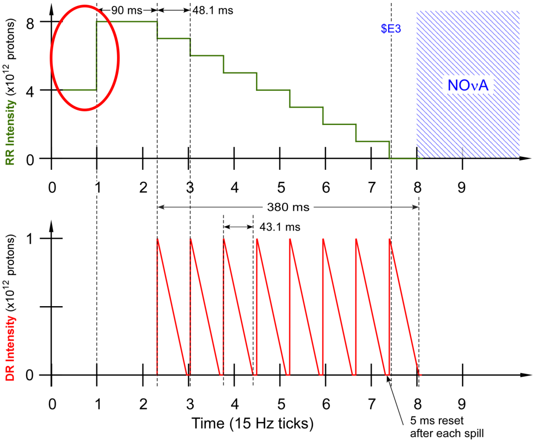
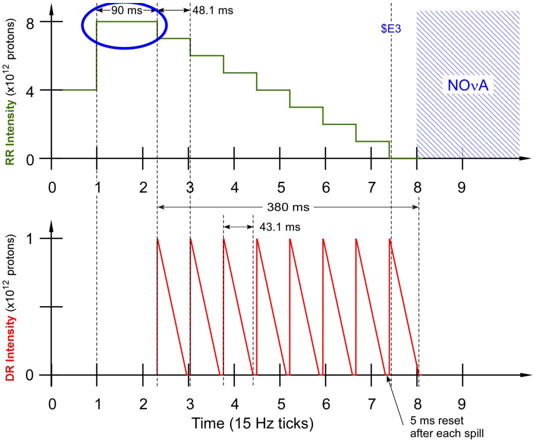


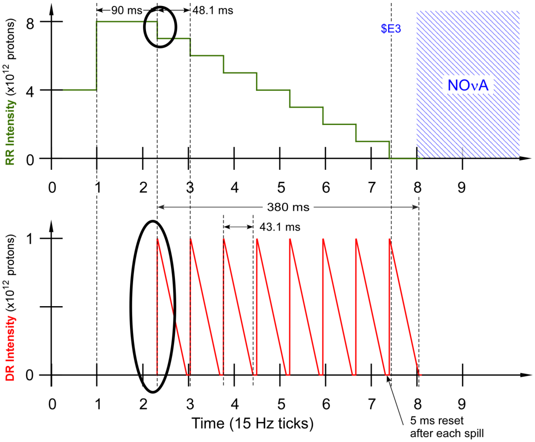
Two booster batches loaded into Recycler for Mu2e.

Proton Beam Manipulations



Two booster batches loaded into Recycler for Mu2e. The 2.5 MHz Mu2e Recycler RF system ramps up to rebatch from 2 to 8 bunches.

Proton Beam Manipulations

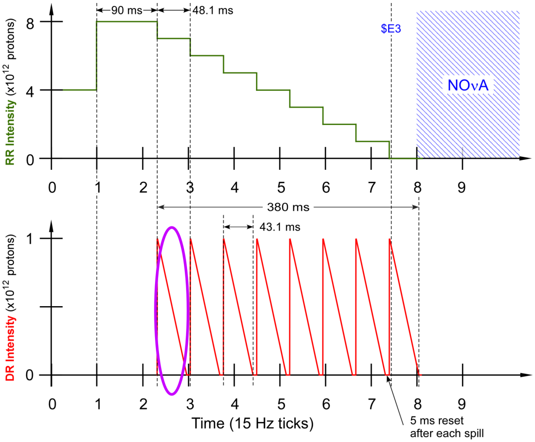


Two booster batches loaded into Recycler for Mu2e.

The 2.5 MHz Mu2e Recycler RF system ramps up to rebatch from 2 to 8 bunches.

Each of these bunches is individually transferred to the Delivery Ring.

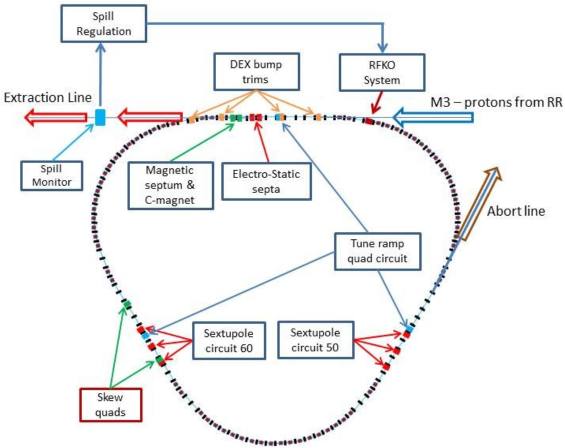
Proton Beam Manipulations



Two booster batches loaded into Recycler for Mu2e. The 2.5 MHz Mu2e Recycler RF system ramps up to rebatch from 2 to 8 bunches. Each of these bunches is individually transferred to the Delivery Ring. Resonant extraction slow spills protons from the DR and sends them to Mu2e.

Delivery Ring

Delivery ring orbital period = 1695 ns;
about twice the muonic aluminum lifetime



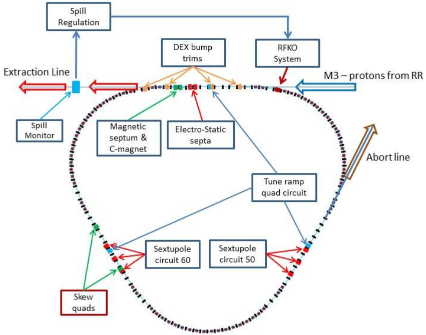
Delivery Ring

Quadrupoles drive a 1/3 integer resonance (29/3) in the horizontal tune.

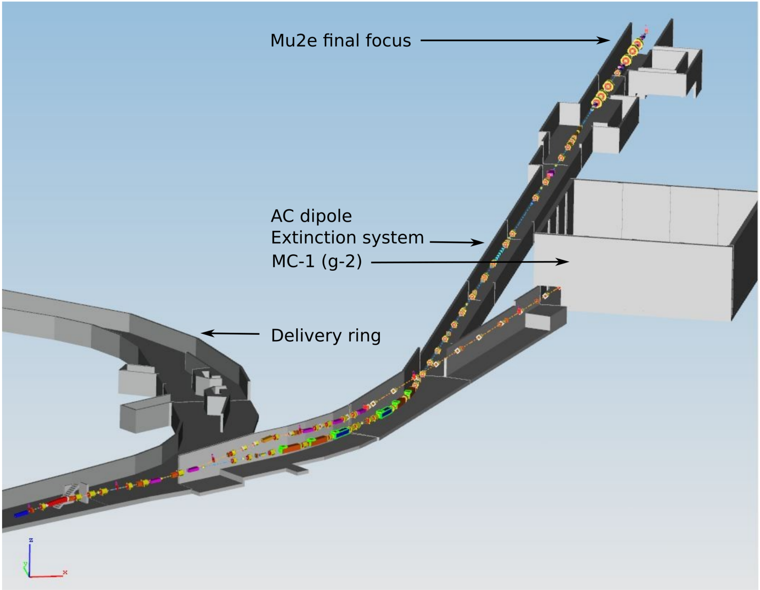
Sextupoles induce a controlled beam instability.

Septum peels off a microbunch on each turn.

Full extraction over $\sim$32,000 turns



Extinction System



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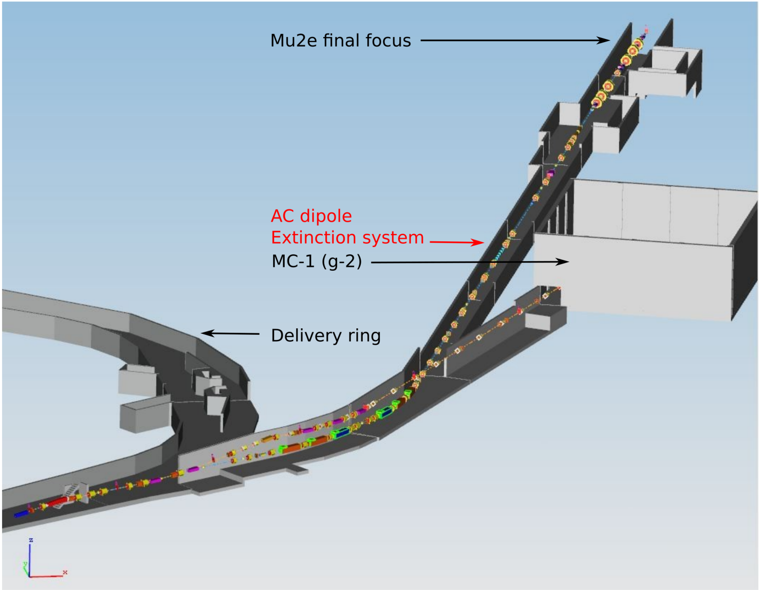
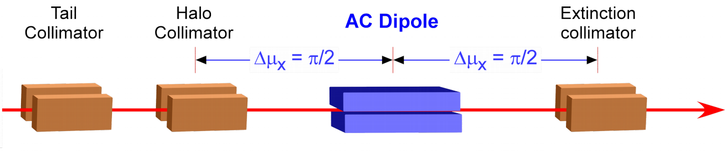


Extinction System

AC Dipole – significantly reduces out-of-time beam

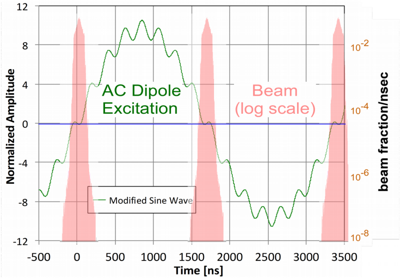
External Beamline Extinction Components



Extinction Level: Extracted from DR 2×10^{-5} — Factor of 5×10^{-8} — At Proton Target 1.1×10^{-12}

AC Dipole Excitation

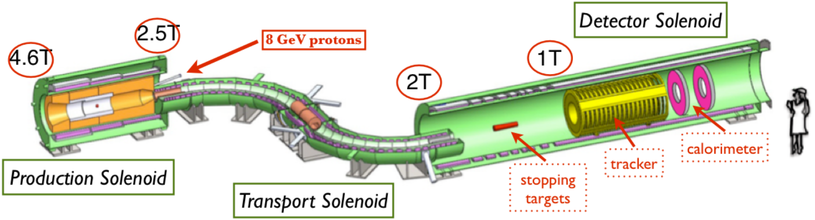
The AC Dipole excitation is a superposition of two harmonics: 300 kHz and 4.5 MHz.



Proton beam pulses shown in pink.

AC Dipole waveform shown in **blue**

Selection of low-momentum negative muons



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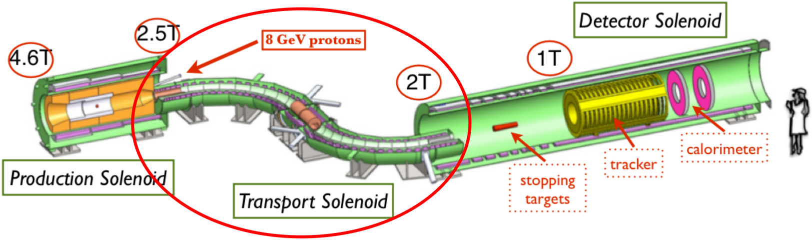
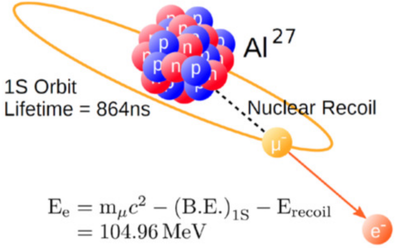


Selection of low-momentum negative muons

We are looking for a monoenergetic signal at 105 MeV.
Average momentum of muons in our beam is ∼40 MeV.



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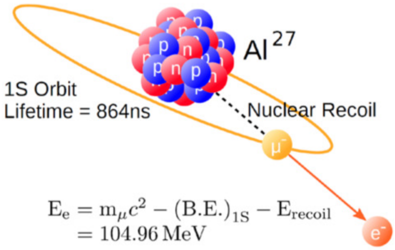
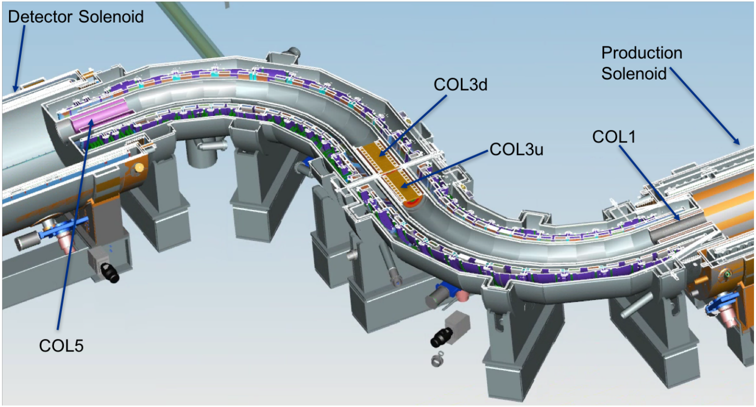


$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\mathrm{MeV}$$

Requirements:

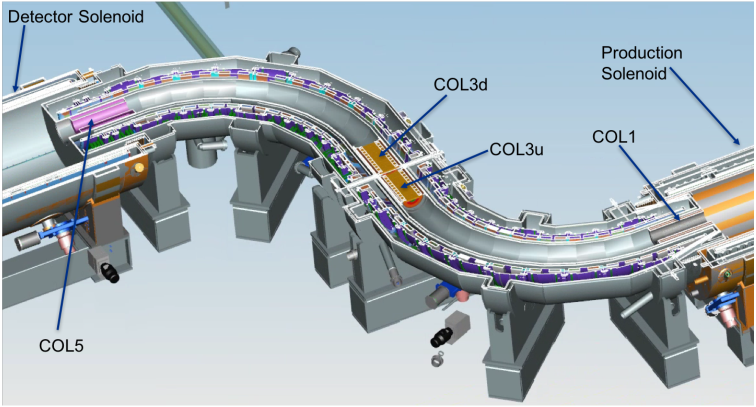
- Prevent charged particles at ∼ 105 MeV from entering the Detector Solenoid
- Allow only low-momentum negative muons to stop in the stopping target
- Prevent non-muon particles from entering the Detector Solenoid

Transport Solenoid



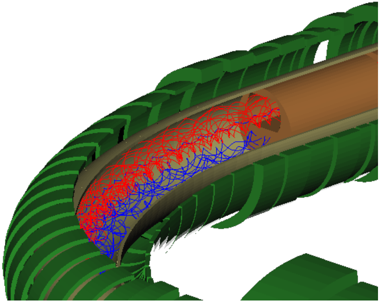
- S-shaped solenoid (two partial toroids, 90° turn each)
- Three sets of collimators – one at either end and two in the middle
- Antiproton window at entrance to transport solenoid from production solenoid, and between center collimators

Transport Solenoid



- Field strength varies between 2 - 2.5 T
- Field lines follow the curved shape of the solenoid

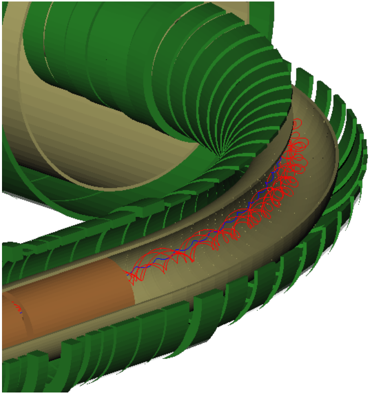
Charge Separation



Upstream toroidal section of TS – negative charges drift upwards, positive downwards.
Charged particles spiral in the magnetic field – if $p >\sim 80$ MeV, they will not make it around the bend.

Vertical displacement at the center collimator: $D = \frac{Q}{e}\frac{\pi}{0.6B}\frac{p_L^2+0.5p_T^2}{p_L}$
(D in m, magnetic field B in T, longitudinal and transverse momentum p_L and p_T in GeV/c).
Center collimator can rotate to select positive or negative muons.

Charge Separation

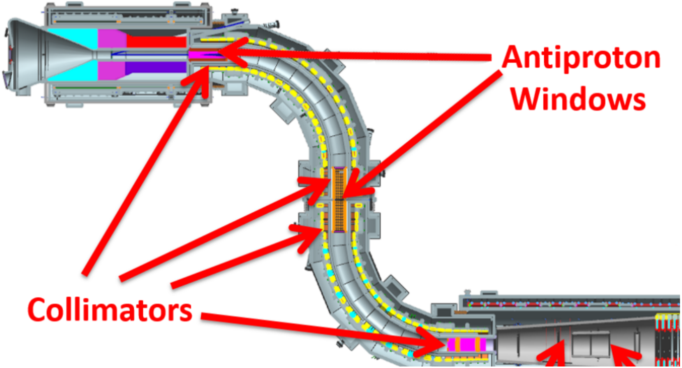


Downstream toroidal section of TS – negative charges drift back to center

Vertical displacement at the center collimator: $D = \frac{Q}{e}\frac{\pi}{0.6B}\frac{p_L^2+0.5p_T^2}{p_L}$ (D in m, magnetic field B in T, longitudinal and transverse momentum p_L and p_T in GeV/c).

Center collimator can rotate to select positive or negative muons.

Antiproton Windows



Thin windows at entrance to transport solenoid and between center collimators

- stop antiprotons from reaching detector solenoid
- separate upstream transport solenoid vacuum from detector solenoid vacuum (blocks radioactive ions, etc from production target)

Summary

- Mu2e is looking for new physics in neutrinoless muon-to-electron conversion
- For our goal sensitivity, we will require a pulsed muon beam with strict requirements
- Beam optimizations for the proton beam include the time structure and extinction
- Beam optimizations for the muon beam include momentum selection and removal of unwanted particles
- Data in 2023!

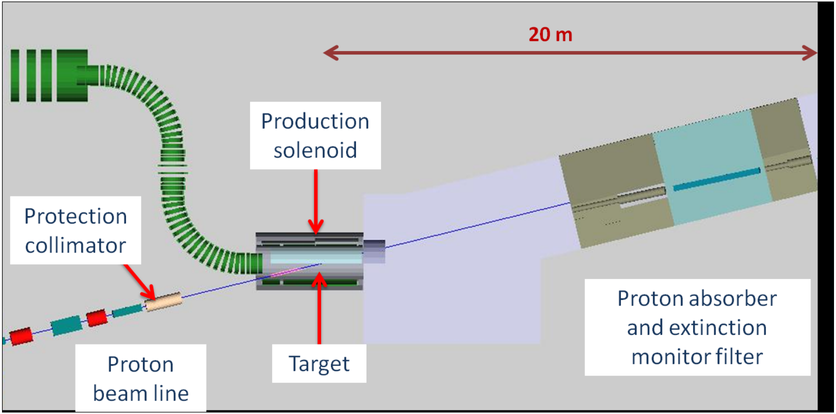
Backup slides

Proton Beam Requirements

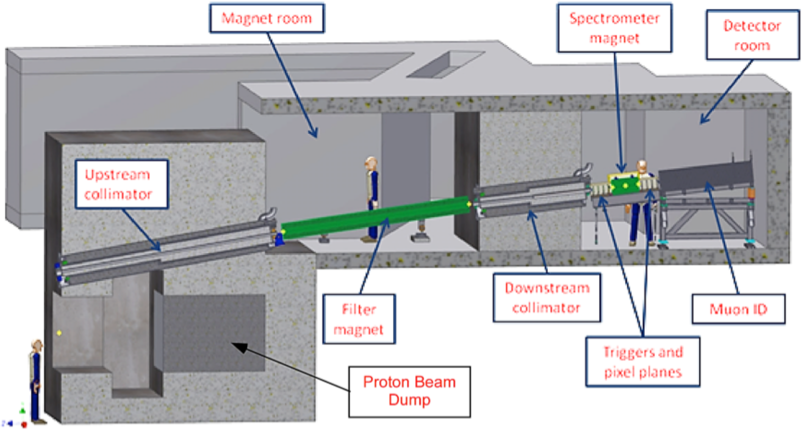
	Parameter	Design Value	Requirement	Unit
	Total protons on target	4.7×10^{20}	$\geq 4.7\times10^{20}$	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
	Maximum variation in pulse separation	< 1	10	nsec
	Spill duration	43.1	> 20	msec
	Beamline Transmission Window	230	< 250	nsec
	Transmission Window Jitter (rms)	< 5	<10	nsec
	Out-of-time extinction factor	1.6×10^{-12}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.9×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
	Target rms beam divergence	0.5	< 4.0	mrad

Extinction Monitor

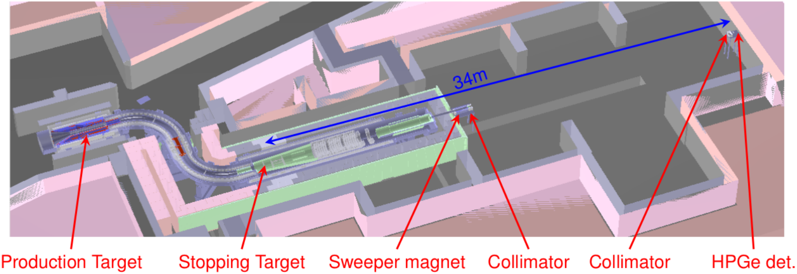
Position (overhead)



Extinction Monitor



Stopping Target Monitor



Measures X-rays and gamma rays from muonic Al

- 347 keV 2p $\rightarrow$ 1s X-ray (80% of muon stops)
- 844 keV delayed gamma ray(5% of muon stops)
- 1809 keV gamma ray (30% of muon stops)

Acknowledgments

The work presented here was supported by the United States Department of Energy; my travel to Nufact 2019 was supported under grant number DE-SC0019027