The search for $\mu^- \to e^+$ conversion at Mu2e

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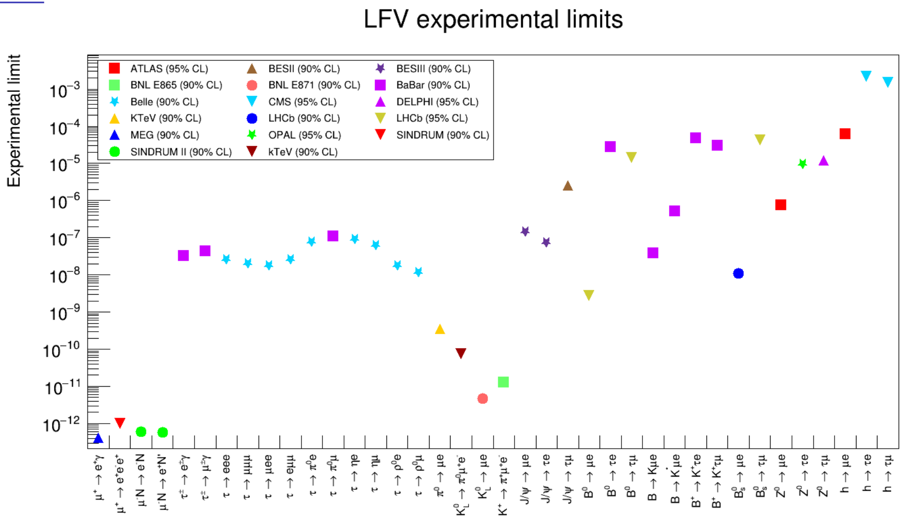
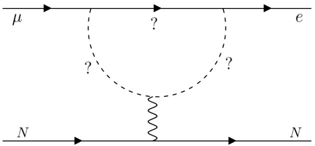
CLFV limits

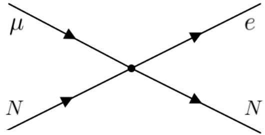


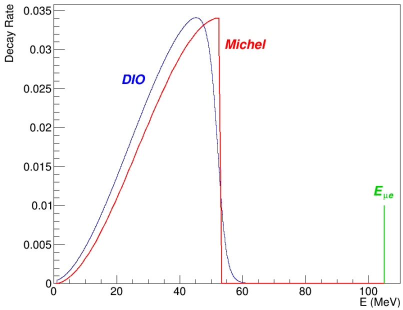
- The figure shows the experimental limits on CLFV as of 2022 summarized by Ref. [1]
- The most stringent limits on CLFV come from muon experiments

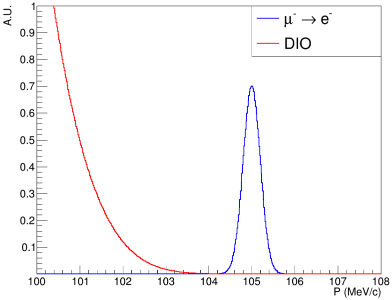
$\mu^- \to e^-$ conversion

- Muon channels provide the most stringent tests of CLFV to date
- One such channel is the coherent conversion of a muon into an electron in the field of a nucleus ($\mu^- \to e^-$), which produces a monoenergetic signal electron near the muon mass
- An intrinsic background to this search is from muon decay in orbit electrons (DIO), where interactions with the nucleus extends the spectrum past the Michel edge up to the conversion electron energy



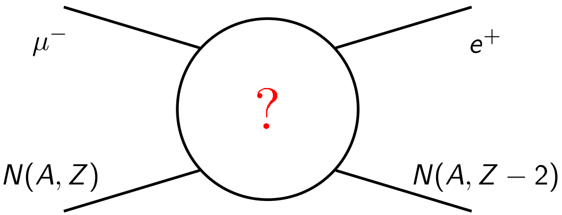


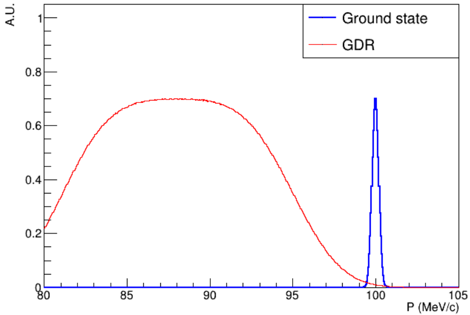




$\mu^- \to e^+$ search at Mu2e

- Muon conversion experiments are typically able to also search for the both CLFV and lepton number violating process of muon to positron conversion ($\mu^- \to e^+$) with $\Delta L = 2$
- $\mu^- \to e^+$ is deeply connected to $0\nu\beta\beta$ decay processes and the search for $\mu^- \to e^+$ conversion is complementary to those searches
- Two final states are considered for the outgoing nucleus: a ground state and a giant dipole resonance (GDR)
- The ground state transition leads to a monochromatic positron similar to the $\mu^- \to e^-$ search



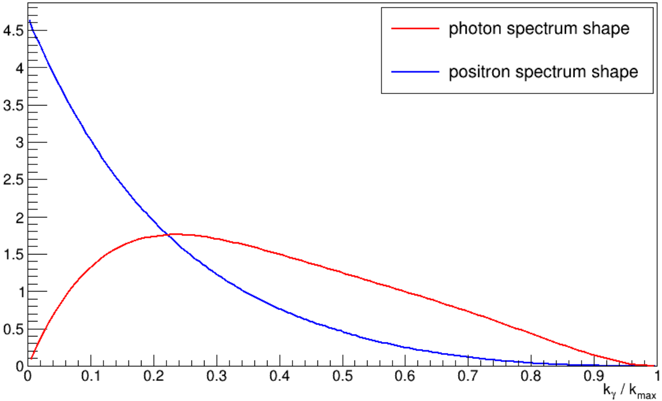


Main background: Radiative Muon Capture (RMC)

- In the $\mu^- \to e^+$ search the positron spectrum is dominated by RMC, where either real photons convert in the detector ("external" conversion) or virtual photons convert internally ("internal" conversion)
- The common parameterization of the RMC photon spectrum is the closure approximation, which replaces the sum over final nuclear states with a single transition with the mean nuclear excitation:

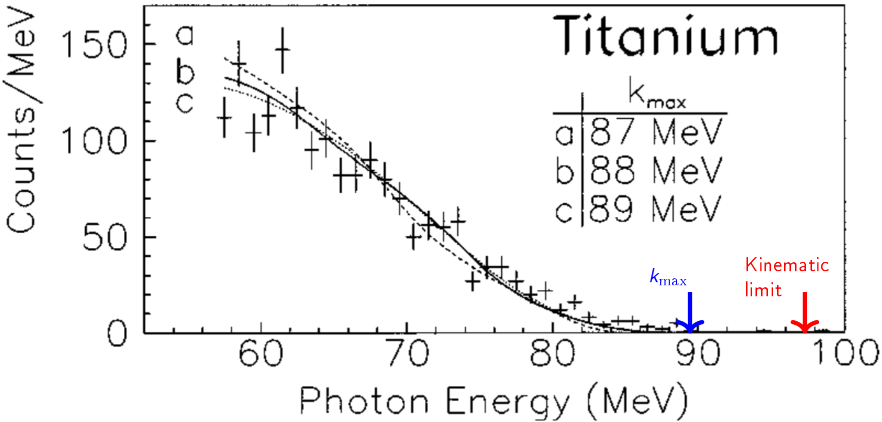
$$dN/dx \sim (1 - 2x + 2x^2) \cdot x \cdot (1 - x)^2, \quad x = k/k_{\rm max}$$

- This has one free shape parameter – the endpoint of the spectrum



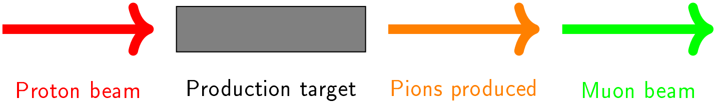
Main background: Radiative Muon Capture (RMC)

- Fits of the experimental RMC data find $k_{\max}$ values $\sim$ 10 MeV below the kinematic endpoint

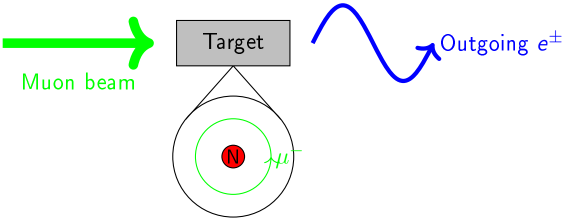


- TRIUMF RMC spectrometer Ti measurement (1999) [2]:
  - $\mathrm{R}(\mathrm{k}_\gamma > 57\ \mathrm{MeV/c}) = (1.3 \pm 0.12) \cdot 10^{-5}$
  - Fit $k_{\max} = 89.2 \pm 2\ \mathrm{MeV}$
  - Kinematic limit $= 99.2\ \mathrm{MeV}$

Experimental approach

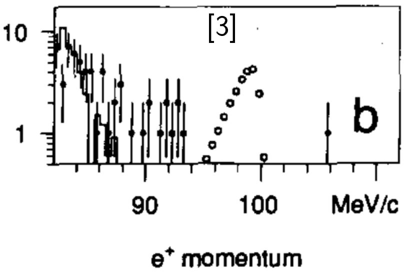


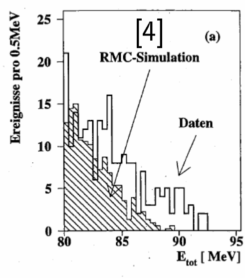
- The typical experimental approach is to first use a proton beam to produce pions that decay into the muon beam

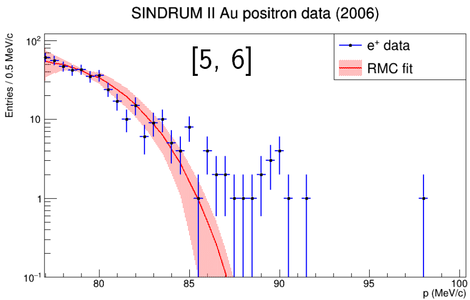


- The muon beam is guided to the nuclear target where the muons stop and form muonic atoms
- Outgoing electrons/positrons are then reconstructed to search for the conversion signals

Past muon conversion experiments' positron data

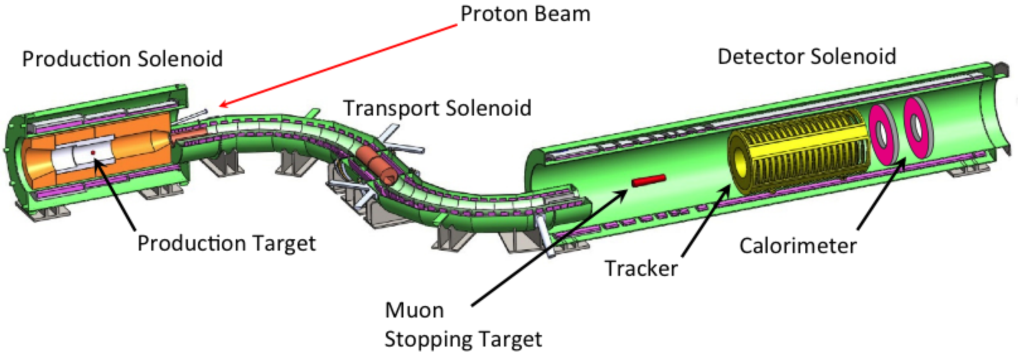






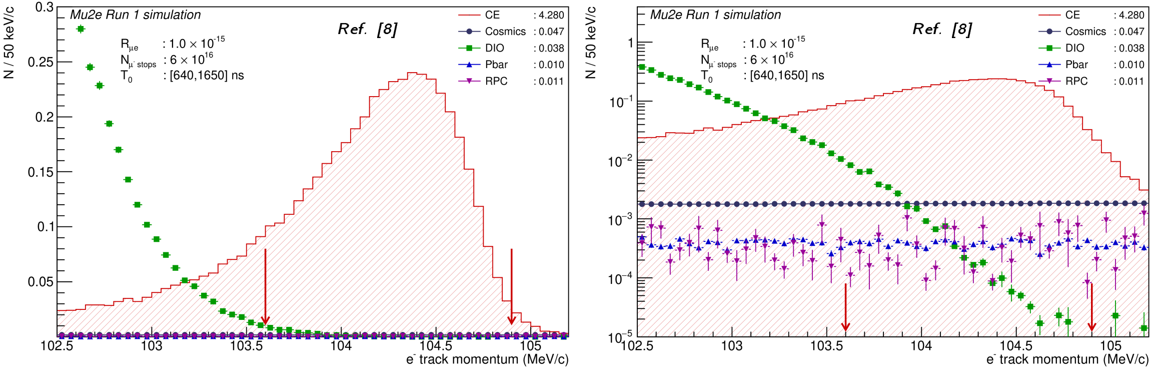
- All previous high statistics muon experiments failed to describe their positron data using the RMC closure approximation
- This shows that the closure approximation is breaking down near the endpoint for previous experiments

Mu2e experiment



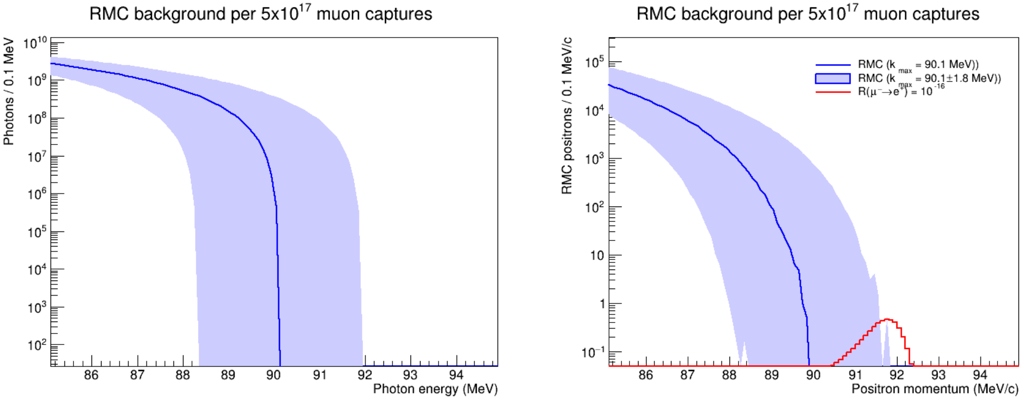
- Mu2e is a next generation muon conversion experiment at FNAL, starting data collection in 2026
- Mu2e will have around 10^4 more muons (and therefore muon captures) than the previous muon conversion experiments [7]

$\mu^- \to e^-$ at Mu2e



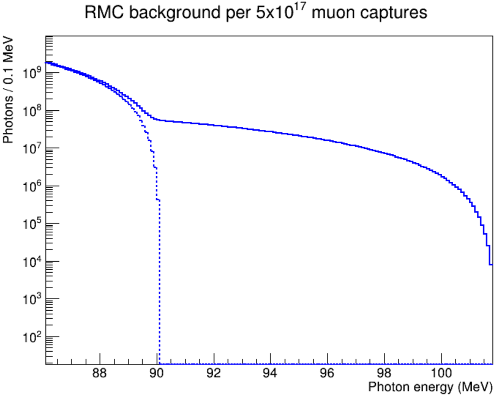
- Mu2e will be 10,000 times more sensitive to $\mu^- \to e^-$ conversion than previous experiments, with an expected discovery sensitivity of $\mu^- \to e^-$ at conversion rates as low as $\mathcal{O}(10^{-16})$
- Mu2e is not sensitive to RMC in the search for $\mu^- \to e^-$ conversion due to the higher signal electron energy signature
- The expected sensitivity to $\mu^- \to e^+$ conversion much more strongly depends on the RMC spectrum

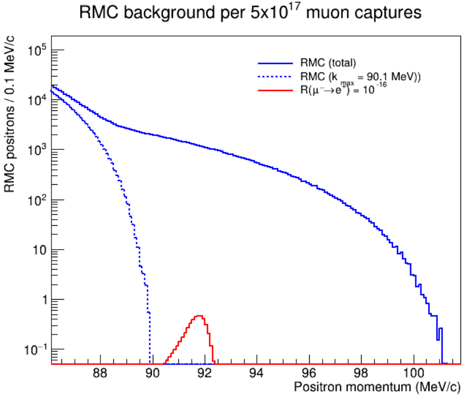
RMC and $\mu^- \to e^+$ at Mu2e



- The TRIUMF RMC Spectrometer group fit $k_{\max} = 90.1 \pm 1.8$ MeV on aluminum
- From the measured closure approximation spectrum, the total RMC background at Mu2e would be $0.2^{+4.7}_{-0.2}$ events
- Assuming this model of RMC, Mu2e would expect to improve the $\mu^- \to e^+$ sensitivity by four orders of magnitude

RMC and $\mu^- \to e^+$ at Mu2e





- The TRIUMF RMC measurement was only sensitive to rates of $\mathcal{O}(10^{-8})$, whereas Mu2e expects $\mathcal{O}(5 \times 10^{17})$ muon captures over the lifetime of the experiment
- We can consider a model with a second closure approximation using the kinematic endpoint with a rate $R(E_\gamma > 90) = 10^{-8}$
- As shown in the above toy model, the background would rise to $\mathcal{O}(10^4)$ events in the $\mu^- \to e^+$ signal region

$\mu^- \to e^+$ and RMC outlook at Mu2e

- $\mu^- \to e^+$ conversion is a both LFV and LNV process that Mu2e will be sensitive to
- In order to search for $\mu^- \to e^+$ conversion at Mu2e and utilize the unprecedented number of stopped muons, Mu2e needs to be able to model the RMC background
- There are several strategies to model or measure the RMC background being investigated at Mu2e:
  - Measuring the real RMC photon spectrum using the calorimeter disks
  - Measuring the real RMC photon spectrum using pair conversions in the tracker
  - Using data-driven sideband fits to model the positron data
- Depending on the RMC spectrum, Mu2e will be sensitive to up to 10,000$\times$ smaller rates of $\mu^- \to e^+$ conversion than previous muon conversion experiments
- The RMC spectrum high energy tail is a good candidate for a Mu2e Run 1 measurement and necessary for a $\mu^- \to e^+$ conversion search

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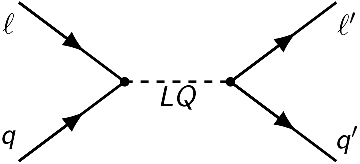
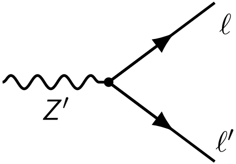
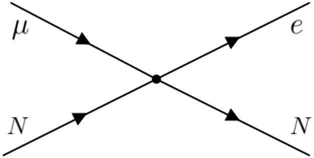
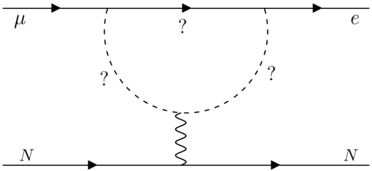
Backup slides

CLFV beyond the standard model





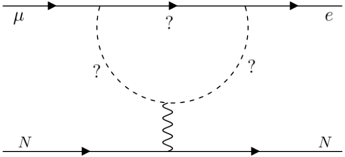


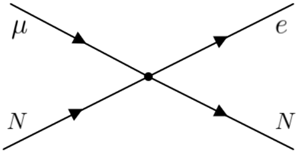


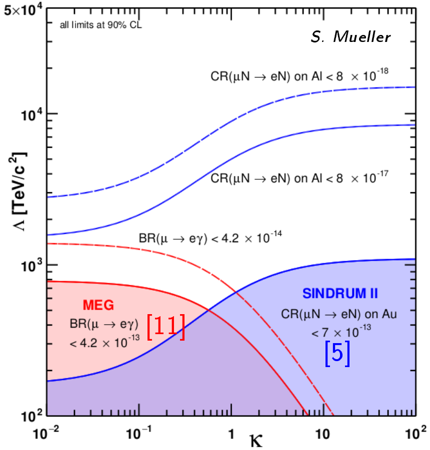
- In the standard model, charged lepton flavor violation (CLFV) is only allowed through neutrino oscillation in loops with W bosons
- This is highly suppressed by $\frac{(\Delta m_\nu^2)^2}{M_W^4}$, where $\mathrm{BR}(\mu \to e\gamma) \simeq 10^{-54}$ [9]
- Many new physics models predict observable rates of CLFV [10]

$\mu^- \to e^-$ as a new physics probe

- Muon channels provide the most stringent tests of CLFV to date
- One such channel is the coherent conversion of a muon into an electron in the field of a nucleus ($\mu^- \to e^-$), which produces a monoenergetic signal electron
- In the effective lagrangian parameterization on the right Λ is the effective mass scale and κ controls the relative contribution of the magnetic moment term and the four fermion term





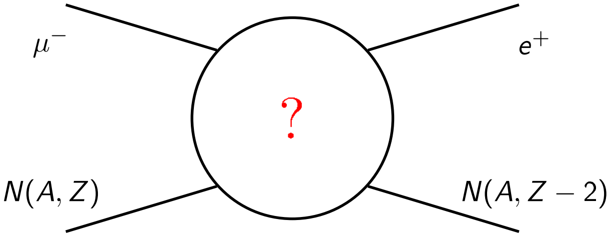


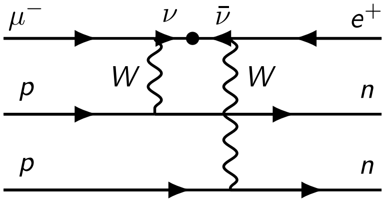
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right) \text{ [12]}$$

$\mu^- \to e^-$ searches probe a wide range of new physics parameter space

$\mu^- \to e^+$ search at Mu2e

- Mu2e will also be able to search for the both CLFV and lepton number violating process of muon to positron conversion ($\mu^- \to e^+$) with $\Delta L = 2$
- This process is forbidden even in the standard model extended to include neutrino masses
- $\mu^- \to e^+$ is deeply connected to $0\nu\beta\beta$ decay processes and the search for $\mu^- \to e^+$ conversion is complementary to those searches
- From Berryman et al. [13], the discovery of $\mu^- \to e^+$ but not $0\nu\beta\beta$ would likely imply complex flavor effects and non-tree level generation of the neutrino masses



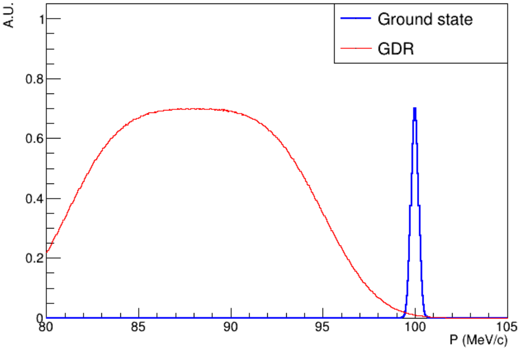


$\mu^- \to e^+$ experimental signal

- $\mu^- \to e^+$ conversion differs by having a different outgoing nucleus
- Two final states are considered for the outgoing nucleus: a ground state and a giant dipole resonance (GDR)
- In the former case, the signal is a monochromatic positron, similar to the $E(e^-)$ equation but with a term for the change in nuclear mass:

$$E(e^+) = m_\mu - E^{1s}_{\text{bind}} - E_{\text{recoil}} - (M(A, Z-2) - M(A, Z)) \quad (1)$$

- In the latter case, the positron energy spectrum is lowered and spread out and is therefore more difficult to measure, as shown in the cartoon below



TRIUMF search for $\mu^- \to e^+$ on Ti, 1988 [3]

- The TRIUMF TPC experiment used the TRIUMF stopped π/μ beamline
- A 500 MeV proton beam hit a beryllium target to produce pions which were used to create a 73 MeV/c μ^- beam
- The experiment collected 1.1×10^{13} stopped muons in a titanium target

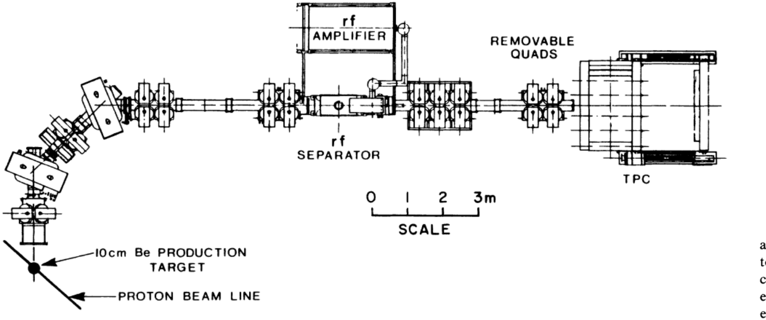


FIG. 3. The M9 stopped π/μ channel at TRIUMF.

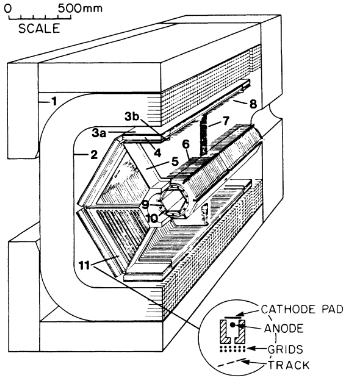
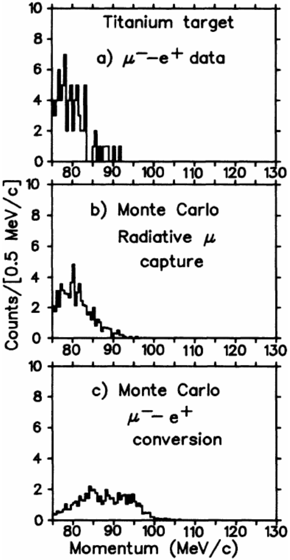


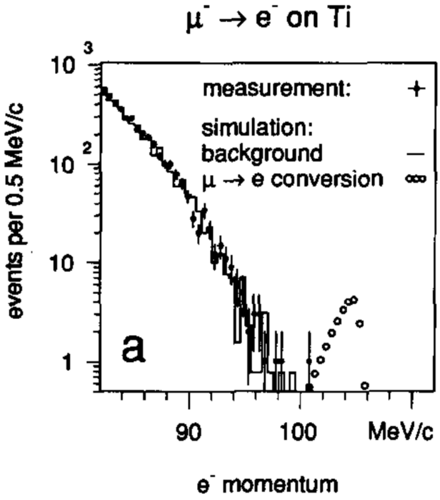
FIG. 1. A perspective view of TPC. The numbered elements are 1, magnet iron; 2, magnet coil; 3, exterior trigger scintillators, a, *W* counters, b, *E* counters; 4, exterior trigger wire chambers EWC; 5, TPC end-cap support frame; 6, central electric-field cage wires; 7, central high-voltage plane; 8, outer electric-field cage wires; 9, interior (*I*) trigger scintillators; 10, interior cylindrical wire chamber IWC; 11, TPC end-cap proportional wire modules for track detection. The detail shows the arrangement of the grid and anode wires and cathode pads.

TRIUMF search for $\mu^- \to e^+$ on Ti, 1988 [3]

- The TRIUMF group only searched for the GDR in this analysis: $R(\mu^- \to e^+) < 1.7 \times 10^{-10}$ (90% CL), where muon conversion rates are normalized with respect to muon captures
- They were not able to describe their positron background by using the closure approximation alone
- The RMC MC plot in the middle:
  - 90% : closure approximation, $k_{\text{max}} = 91$ MeV (consistent with the future measurement of 89.2 ± 2 MeV)
  - 10% : closure approximation, $k_{\text{max}} = 99.3$ MeV, the kinematic RMC endpoint
- Without the additional 10% kinematic endpoint component there is an excess in the high momentum tail, though this is with low statistics

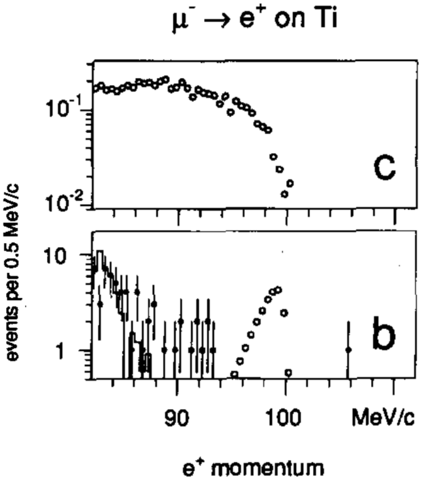


SINDRUM II, Ti target (1993) [14]



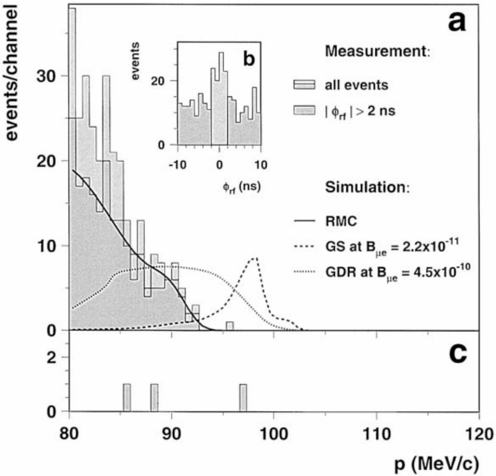
- N(μ^- stops) $= 4.9 \times 10^{12}$, $R(\mu^- \to e^-) < 4.3 \cdot 10^{-12}$ (90% CL)
- Good description of the e^- spectrum: the momentum scale is well calibrated

SINDRUM II, Ti target (1993) [14]



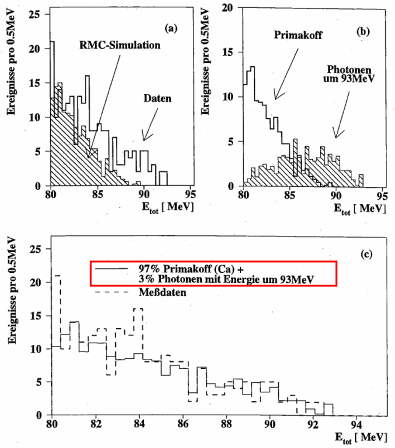
- $R(\mu^- \to e^+) < 4.3 \cdot 10^{-12}$(GS), $8.9 \cdot 10^{-11}$(GDR) (90% CL)
- Significant excess of e^+ events above 90 MeV/c
- Their analysis ignored the excess – the expected signal is in a higher momentum window

SINDRUM II 1998, Ti target (1998) [15]



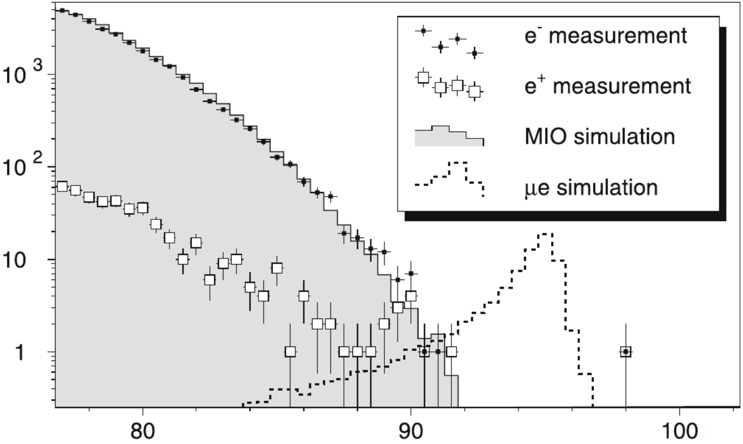
- N(μ^- stops) $= 2.95 \times 10^{13}$, $R(\mu^- \to e^+) < 1.7 \times 10^{-12}$ @90% CL (GS)
- Appears that the positron data is well described here

SINDRUM II: Thesis of Jorg Kaulard (1997)



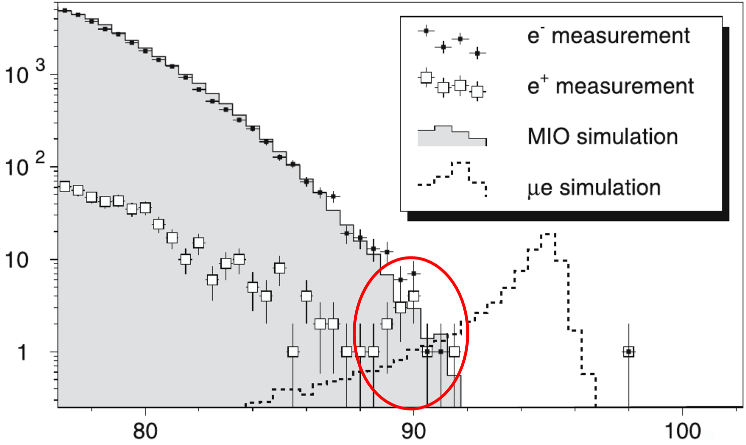
- PhD thesis underlying the 1998 SINDRUM II paper
  - A $E_\gamma = 93$ MeV delta-line added to describe the e^+ spectrum
  - Without this addition, there is a significant excess of events around the RMC endpoint, shown in figure (a)
  - This delta-line is not physically motivated here

SINDRUM II 2006, Au target (2006) [5]



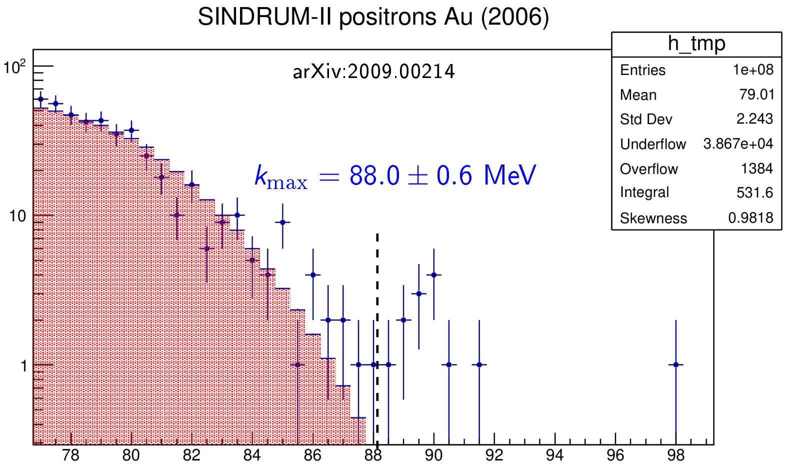
- N(μ^- stops) = 4.37×10^{13}, R($\mu^- \to e^-$) $< 7 \times 10^{-13}$
- This was the highest statistics muon conversion experiment, where the current limit on $\mu^- \to e^-$ is from
- They did not publish a search for $\mu^- \to e^+$ using this dataset

SINDRUM II 2006, Au target (2006) [5]



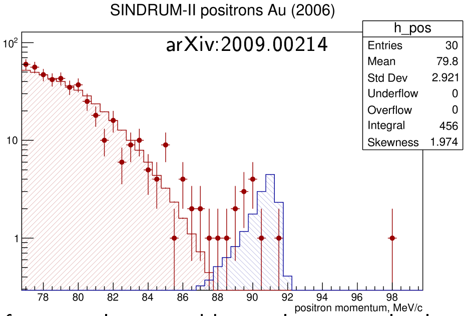
- There is a statistically significant bump in the e^+ spectrum, near the RMC endpoint
- The shape is consistent with the detector response to monochromatic e^+
  - Possible $\mu^- \to e^+$ signal?

SINDRUM II 2006, Au target: looking at the e^+ spectrum alone



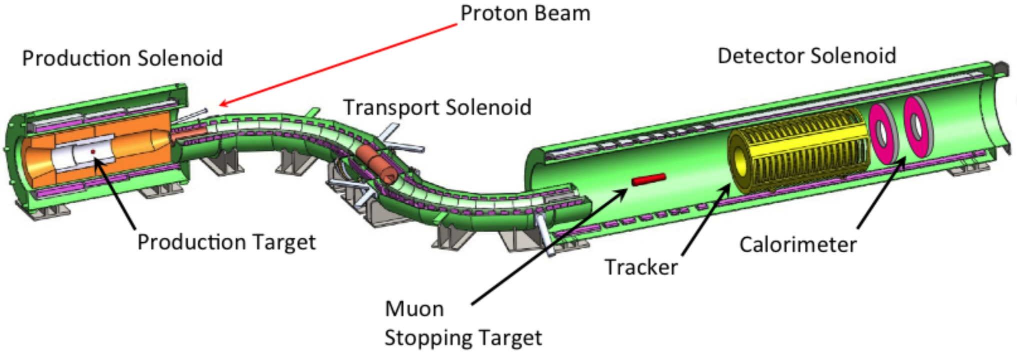
- The bump is in $88 < p < 92$ MeV/c, 13 data events
- We tune a simplistic detector model to the electron data to model the positron response
- We fit the closure approximation to the data below 88 MeV/c
  - N(RMC) < 1 under the bump

SINDRUM II 2006, Au target: looking at the e^+ spectrum alone



- We also consider the background from cosmic rays and beam pion contamination
  - N(other bkg.) < 1 under the bump
- The total background in this window is then less than 2 events
  - $P(n \geq 13 \mid \mu = 2) = 2.1 \cdot 10^{-7}$
- The closure approximation again fails to describe the high momentum positron background
- The bump is 1 MeV/c ($\sim 4\sigma$) lower than the expected $\mu^- \to e^+$ signal on gold
  - With the energy losses well understood, it is a large discrepancy

Mu2e detector



Production solenoid

8 GeV pulsed proton beam impinges on tungsten target

Pions and muons guided into transport solenoid

Transport solenoid

Selects low momentum muons

Rotating collimator selects μ^- or μ^+ beam

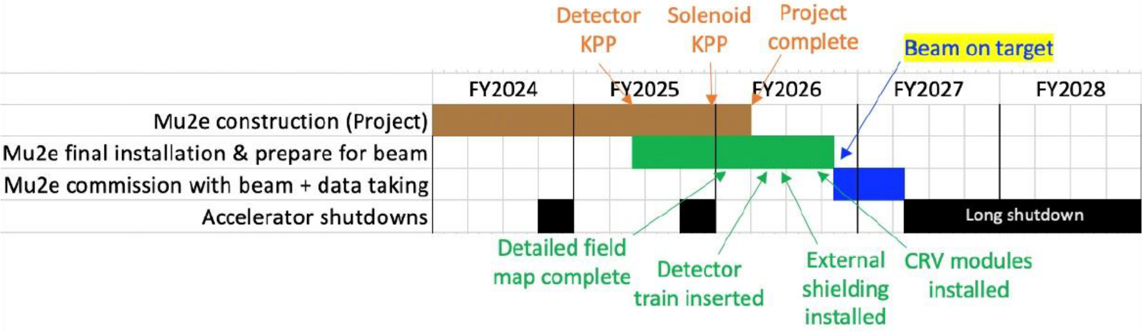
Absorbers along beamline reduce antiproton background

Detector solenoid

Aluminum target collects muons

Annular tracker and calorimeter detect potential signal electrons

Mu2e timeline



- Mu2e will begin taking data in 2026, collecting data until until the long shutdown at FNAL
- Mu2e will then run for two more years after the FNAL accelerator long shutdown
- Mu2e will collect $\mathcal{O}(5 \times 10^{17})$ muons over its lifetime, and will start with 10% of the statistics during Run 1 before the long shutdown

Mu2e backgrounds

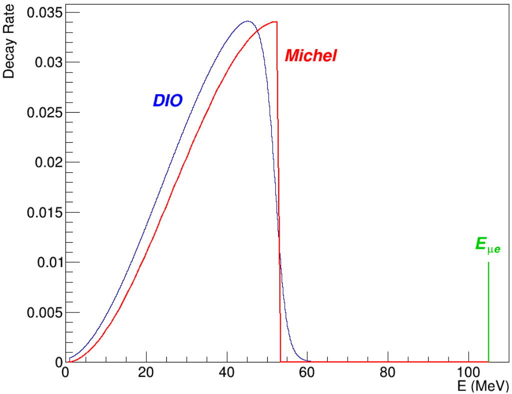
- Mu2e is a precision experiment with an expected background less than one event over the course of the experiment
- The main background sources are:
  - Muon decay in orbit (DIO):
    - Mitigated by reducing material and improving tracking resolution to minimize the spectra overlap
  - Cosmic ray events:
    - Cosmic rays can interact with detector material, producing ~1 signal-like event per day!
    - These are mitigated by surrounding the detector with a scintillating detector to veto charged cosmic ray events
  - Radiative pion capture:
    - Pions can travel from our production target to our detector where photons from radiative captures can produce signal-like events
    - We use a pulsed primary proton beam and can suppress these backgrounds by waiting for the pions to decay/capture

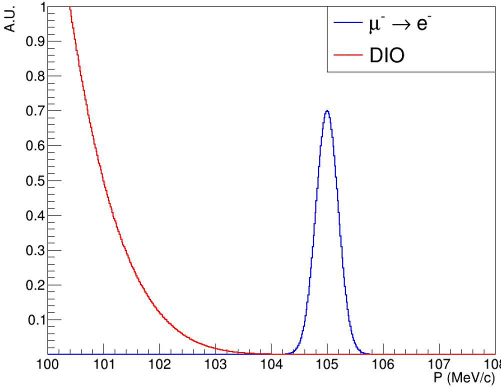
$\mu^- \to e^-$ experimental signal

- $\mu^- \to e^-$ conversion results in a monoenergetic electron near the muon mass:

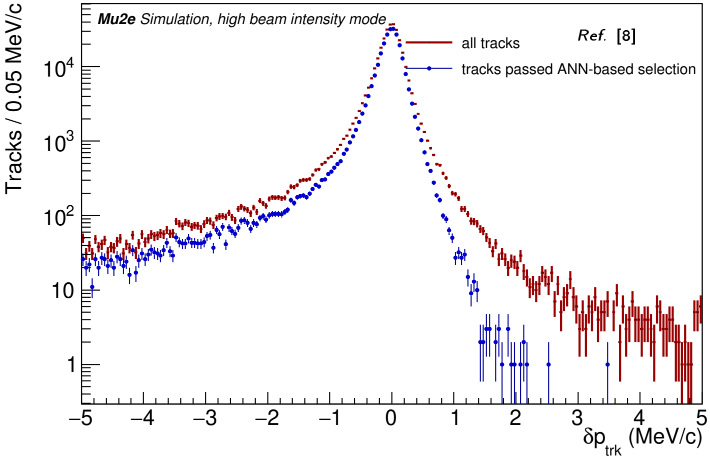
$$E(e^-) = m_\mu - E^{1s}_{\mathrm{bind}} - E_{\mathrm{recoil}} \quad (2)$$

- An intrinsic background to this search is from muon decay in orbit electrons (DIO), where interactions with the nucleus extends the spectrum past the Michel edge up to the conversion electron energy





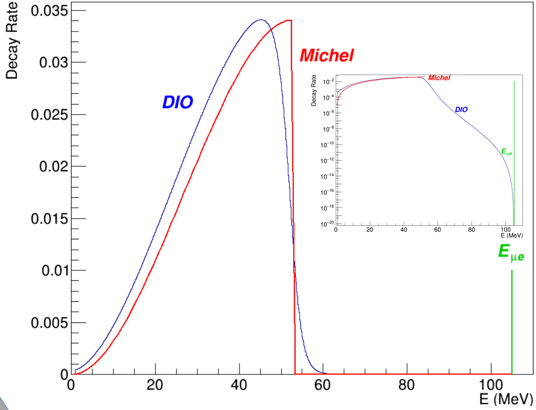
DIO

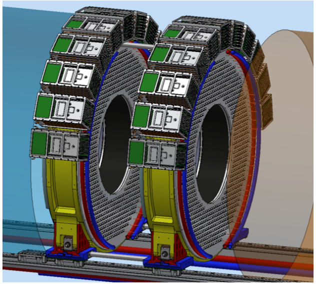


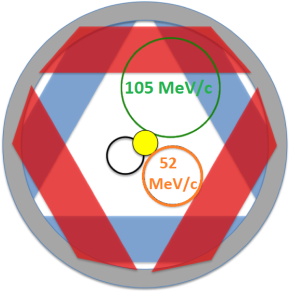
- It is crucial that the track momentum is well reconstructed in order to suppress the DIO background
- To improve the momentum resolution, an artificial neural network (ANN) is trained to select well reconstructed events by separating events with a momentum error above 700 keV/c from events within 250 keV/c of the true track momentum [16]

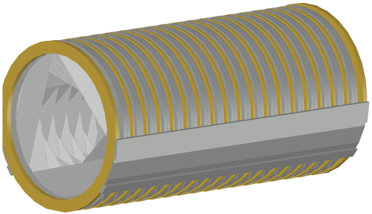
DIO

- Unlike free muon decays, decay in orbit (DIO) electrons' interaction with the nucleus smears the electron energy spectrum up to the $\mu^- \to e^-$ conversion energy
- Resolution and material effects lead to the two spectra overlapping
- Mu2e uses a low mass straw tube tracker to improve resolution and annular detectors to blind the low momentum backgrounds

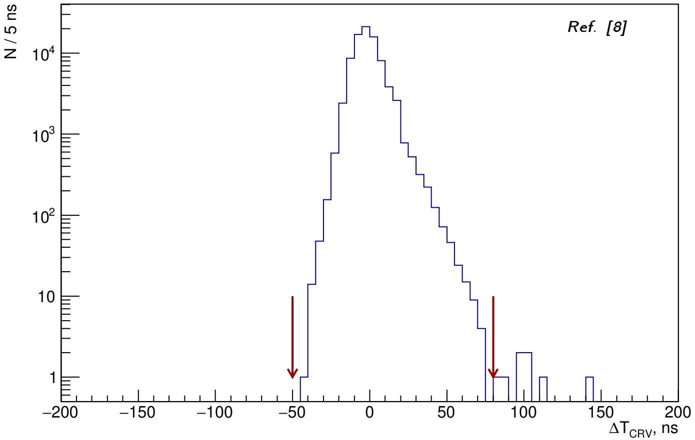








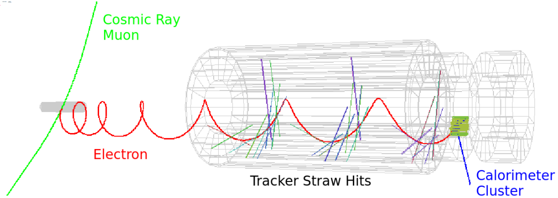
Cosmic rays

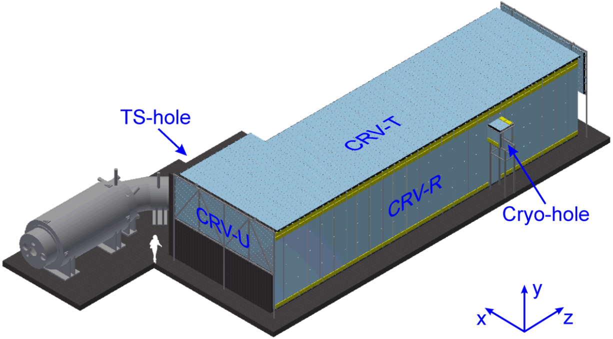


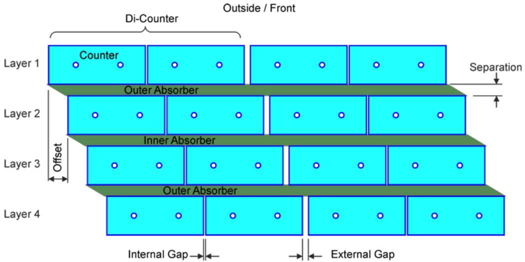
- Cosmic ray events are identified by having a coincidence cluster in the CRV with hits in 3/4 layers
- The time of the track matched to the cluster is required to be within $-50 < t_{crv} < 80$ ns of the cluster time after accounting for the cosmic ray propagation
- This timing cut is necessary to avoid a high rate of "dead-time" where beam pileup produces spurious CRV clusters

Cosmic rays

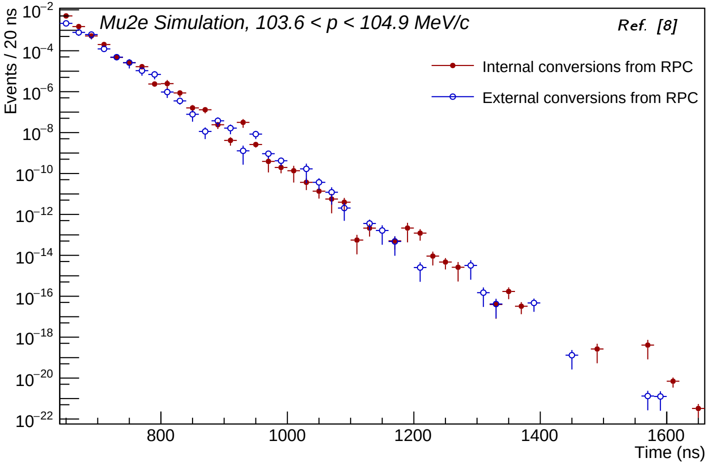
- Cosmic rays interacting with the detector material can produce signal-like electrons/positrons
- We expect ~1 signal-like event per day!
- The cosmic ray veto (CRV) is a scintillating detector surrounding the detector, to identify cosmic rays entering the detector
- The CRV is required to be 99.99% efficient





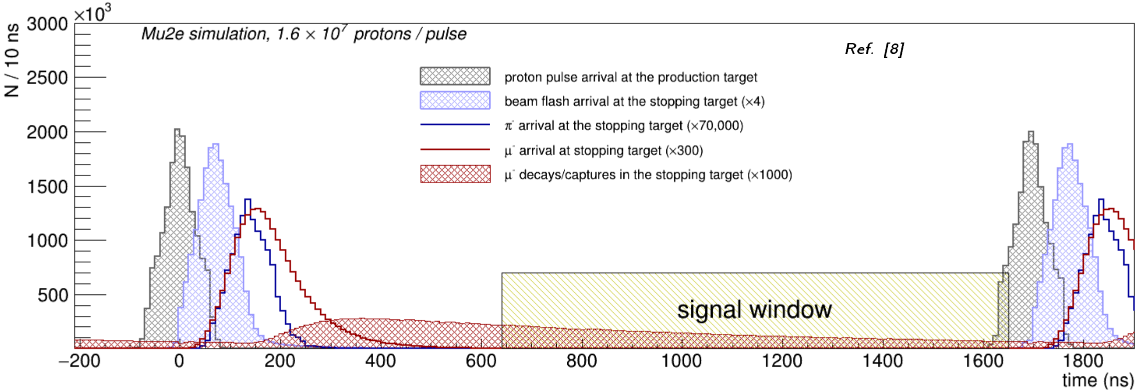


Beam-related



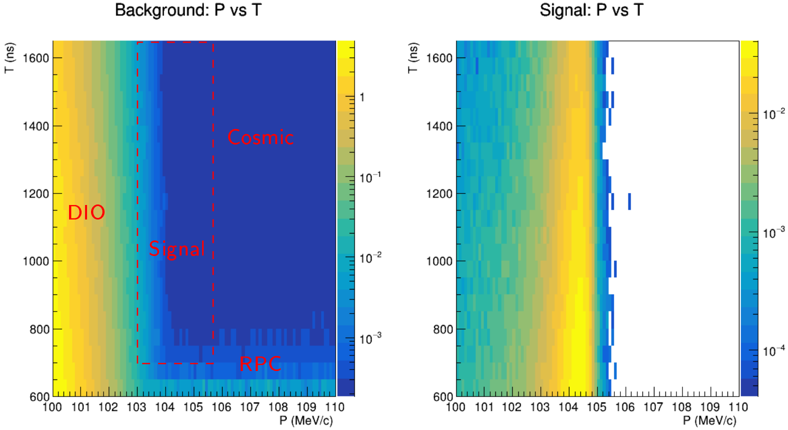
- The contribution from on- and off-shell RPC events drops rapidly in time, where each component contributes roughly equally to the total background

Beam-related



- Pions contaminating the beam can survive to the stopping target, where radiative pion captures (RPC) can produce signal-like electrons/positrons
- Due to the short lifetime of pions, these can be suppressed by using pulsed proton beam along with a delayed live-time window
- Mu2e requires the rate of out-of-time primary protons over in-time ones to be $< 10^{-10}$ to suppress out-of-time beam backgrounds

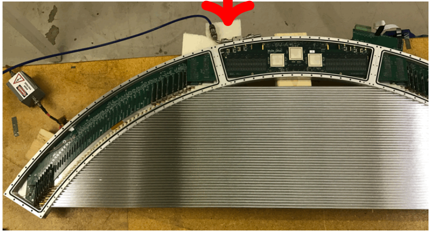
Sensitivity optimization

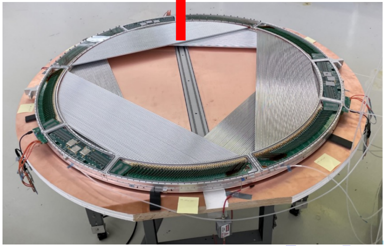


- Mu2e will collect around 10% of our expected muon stops in a Run 1 before the long accelerator shutdown at FNAL
- Using a cut-and-count analysis, the expected median 90% CL upper limit in the absence of a signal is $6.2 \cdot 10^{-16}$
- Mu2e recently published our expected sensitivity to $\mu^- \rightarrow e^-$ conversion using the Run 1 dataset [8]
- Recent work has shown we can improve the sensitivity by 10-20% by using shape-based fits

Tracker status

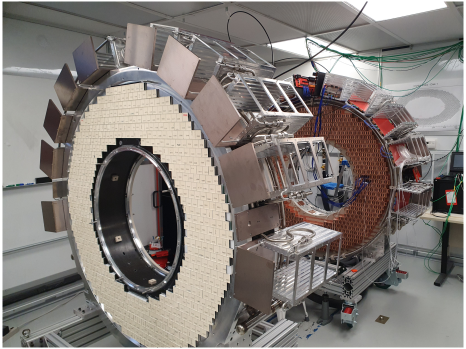
- All 20,736 straws have been produced
- All 216 panels have been constructed
- 30/36 planes have been assembled so far

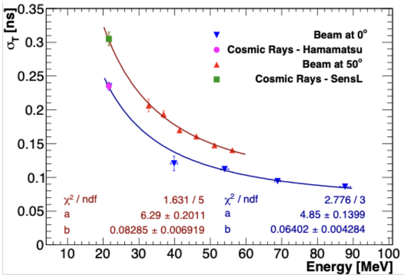


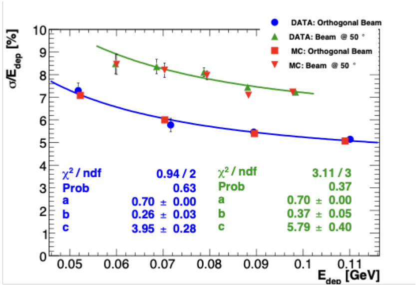


Calorimeter status

- All 1348 crystals and SiPMs have been produced
- The first disk has been assembled, with the second disk underway
- Test beam timing and energy resolution distributions are shown below, well within the 500 ps and 10% requirements, respectively

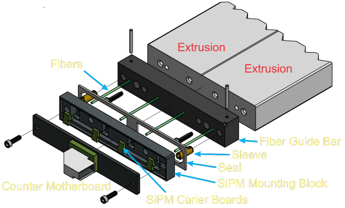


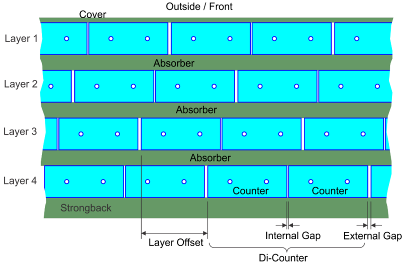


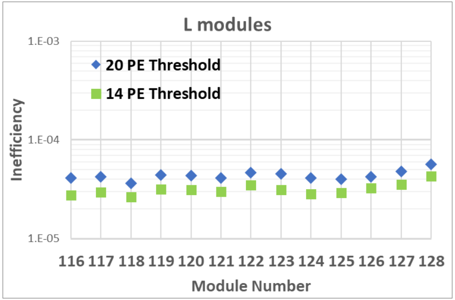


CRV status

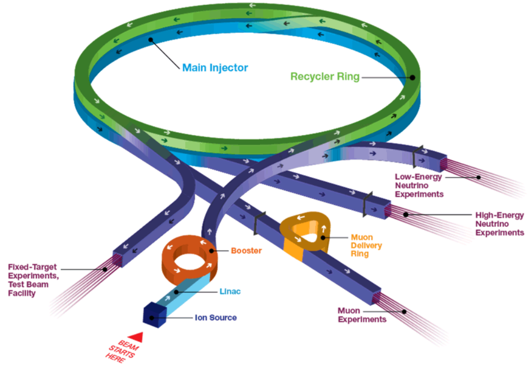
- All 5344 counters have been produced
- All 83 modules constructed
- Achieving 99.99% efficiency necessary

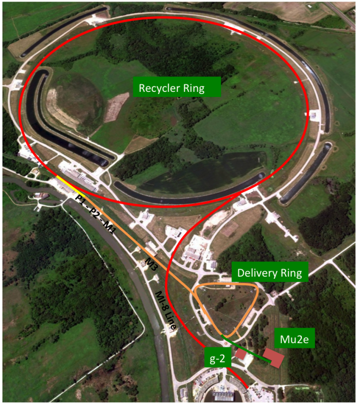






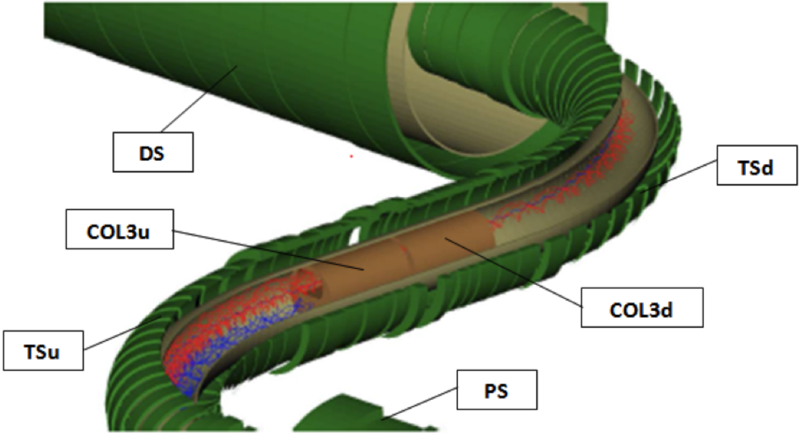
FNAL accelerator





- The 8 GeV protons that are used to produce pions in the production solenoid are from the FNAL booster, which receives 400 MeV protons from the Linac
- These are transported from the delivery ring along the M4 beamline to Mu2e in 1695 ns separated pulses with on average 31 million protons
- Mu2e requires the fraction of out-of-time beam to in-time beam to be less than 10^{-10}

Muon beam charge splitting



- The asymmetric collimator in the transport solenoid allows one to select the charge of the beam by utilizing the charge dependent drift direction