The Mu2e Experiment at Fermilab

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on behalf of the Mu2e Collaboration

Lake Louise Winter Institute
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The Mu2e Collaboration (∼200 scientists)

Photo: October 2015

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Kansas State University
Lewis University
University of Louisville
University of Minnesota
Muons Inc.
Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

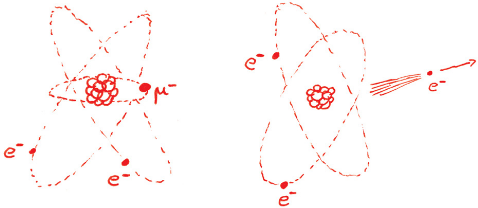
Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce
INFN Pisa
Università del Salento
Università Marconi, Roma

Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics
Institute for Nuclear Research, Moscow

Helmholtz-Zentrum Dresden-Rossendorf

Mu2e overview

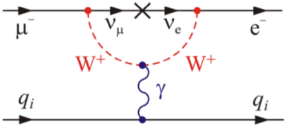
$$\mu N \rightarrow eN$$



The Mu2e Experiment is a highly-sensitive search for Charged Lepton Flavor Violation (CLFV).

Specifically, Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \rightarrow eN$)

Since the discovery of neutrino masses, this process is allowed, albeit at an extremely suppressed rate (10^{-52}).



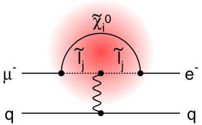
No SM background!
Any observation would be unambiguous evidence of new physics!

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal et al, Eur.Phys.J.C57:13-182,2008
A. de Gouva, P. Vogel, arXiv:1303.4097

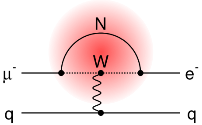
Possible “new physics” contributions to CLFV

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

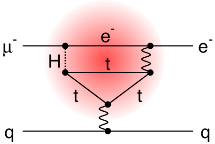
Supersymmetry

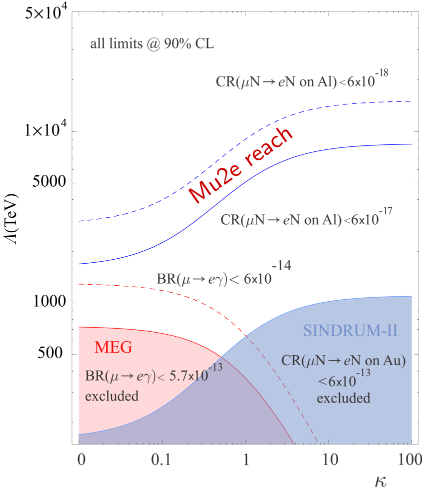


Heavy neutrinos



Two Higgs doublet

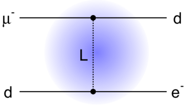




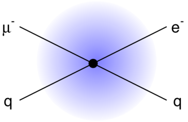
Loop dominated

Contact Interaction dominated

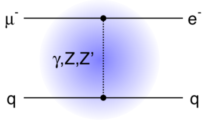
Leptoquarks



Compositeness



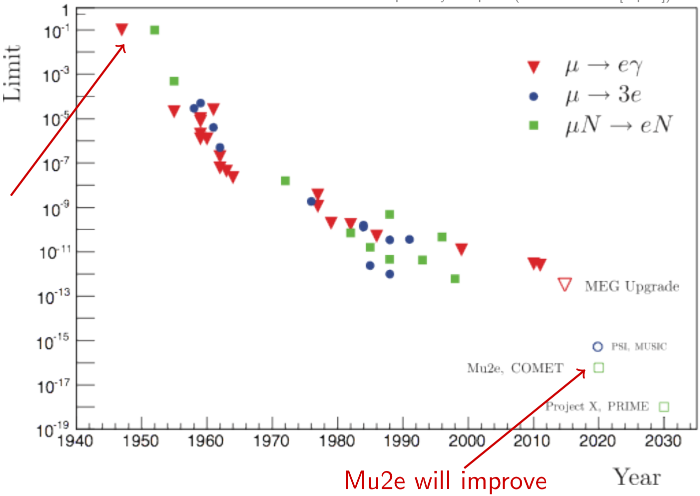
New heavy bosons
Anamolous coupling



History of CLFV searches

R.H. Bernstein and P.S. Cooper. Phys. Rept. C (arXiv:1307.5787 [hep-ex])

$\mu \neq e$
Pontecorvo, 1948

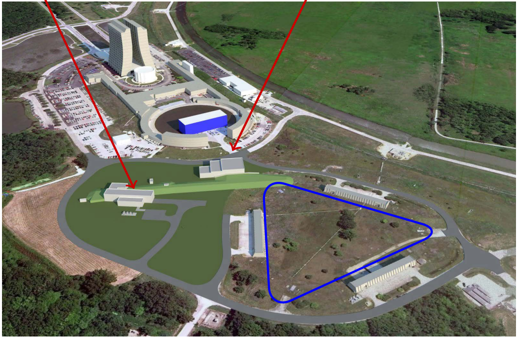


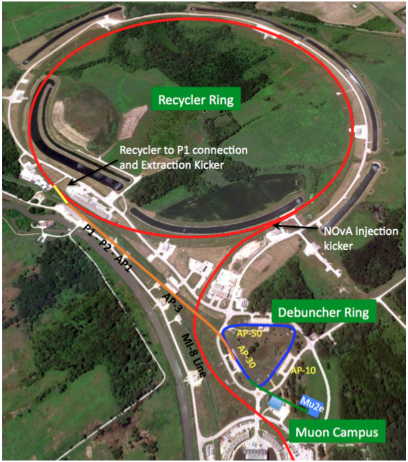
Mu2e will improve the sensitivity of the world's best limit by $\sim$10,000$\times$

Fermilab - Proton delivery

- Booster: Plan is for Mu2e to take 2 out of 21 batches in the 1.4 second main injector cycle. (we'll share with NOνA)
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 bunches. These are extracted one at a time to the Delivery Ring

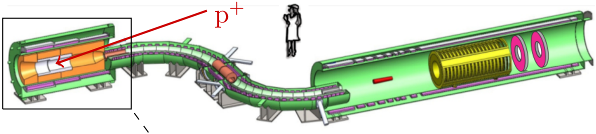
Mu2e $g-2$

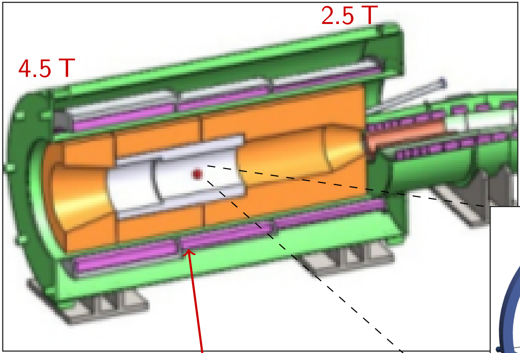


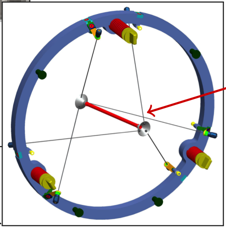


- Protons are extracted into pulses of $\sim 3 \times 10^7$ protons each, separated by 1.7 ms (delivery ring period)
- These proton pulses are sent to Mu2e

Production Solenoid

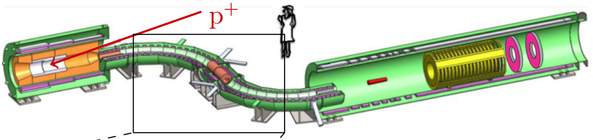


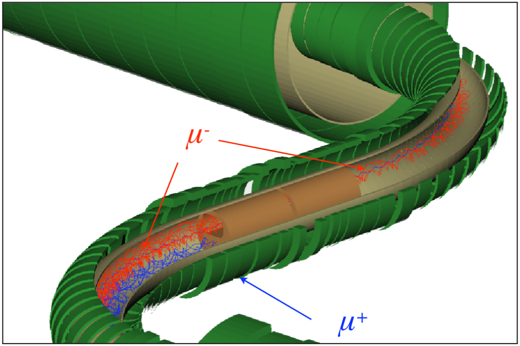




- 8 GeV proton beam enters Production Solenoid and hits Production Target.
- Gradient field captures/reflects pions towards Transport Solenoid.
- Pions decay to muons.

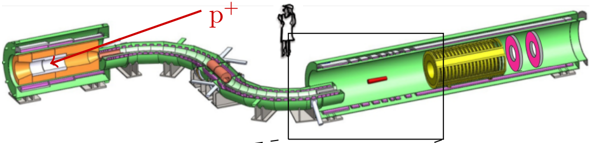
Transport Solenoid

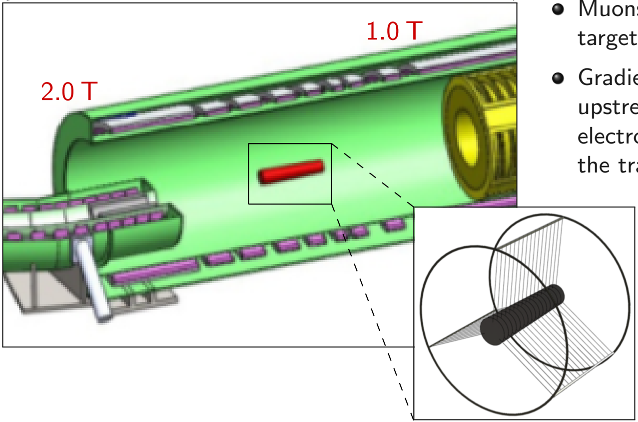




- S-shape eliminates photons and neutrons
- Antiproton absorber removes $\bar{p}$
- Toroidal magnetic fields separate oppositely charged particles vertically
- Collimators select low-momentum negatively-charged muons.

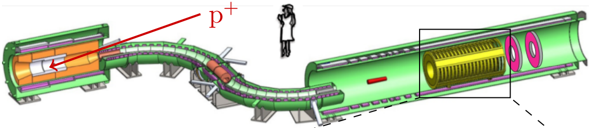
Detector Solenoid (Stopping Target)



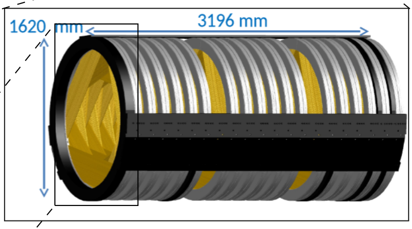


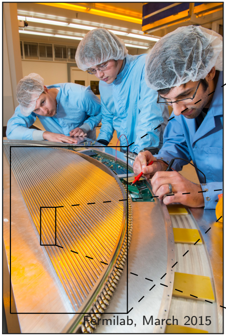
- Muons capture on Aluminum target foils
- Gradient field reflects upstream-going conversion electrons back downstream into the tracker & calorimeter

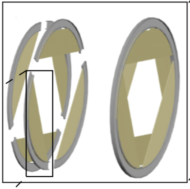
Detector Solenoid (Straw Tracker)



- Straw drift tubes
- Low mass, operates in vacuum
- 5 mm diameter straws
- Walls: 12 µm Mylar, 3 µm epoxy

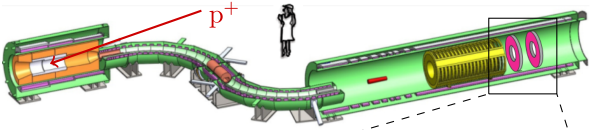



Fermilab, March 2015

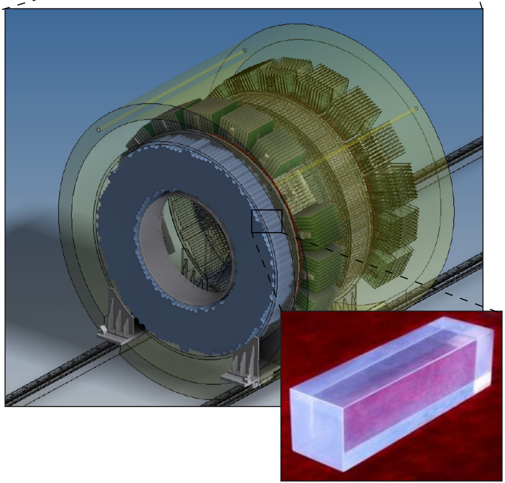


- Self-supporting panel (∼100 straws)
- 6 panels make a "plane"
- 80%/20% Ar/CO_2
- >20k straws
- near live-window expect 20 kHz/cm^2 inner straws, avg. 10 kHz/cm^2 all straws

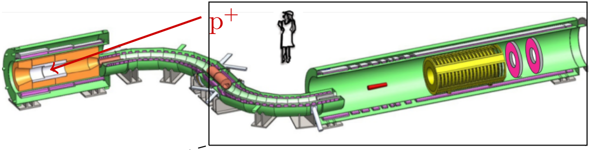
Detector Solenoid (Calorimeter)



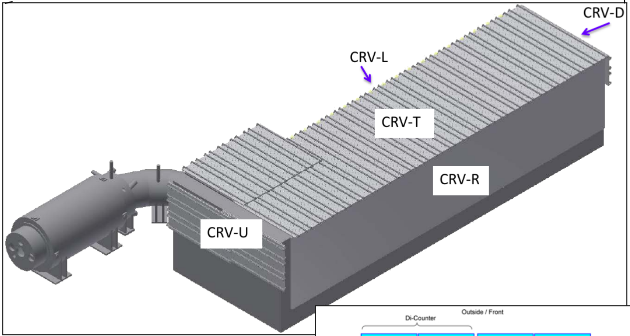
- Crystal calorimeter composed of two annuli separated by half a wavelength
- Each annulus is made of ∼700 pure CsI crystals read-out by SiPM
- CsI:
  - Fast scintillating visible light ($\tau = 30$ ns at 310 nm)
  - Radiation hard up to ∼100 kRad (expected 30 kRad)
- Provides independent measurement of
  - Energy $\mathcal{O}(5\%)$
  - Time $\mathcal{O}(0.5$ ns$)$
  - Position $\mathcal{O}(1$ cm$)$
- Particle ID
- Seed for track finding algorithm
- Triggers independently from tracker



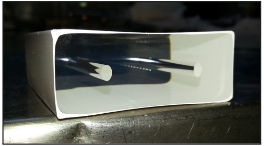
Cosmic Ray Veto (CRV)

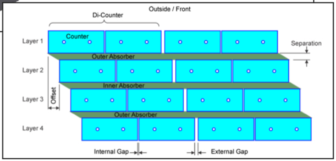


- Cosmic rays can mimick conversion electrons, $\sim$once per day!

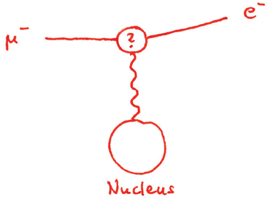


- 4 overlapping layers of scintillator
- Two wavelength shifting fibers per bar
- read out both ends of each fiber with SiPM
- Test Beam achieved $\epsilon > 99.4\%$ per layer



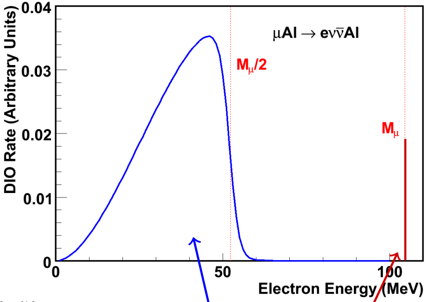


Mu2e signal

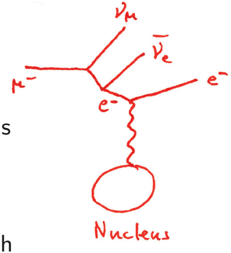


- Single mono-energetic electron
  $E_{\mathrm{e}} = m_{\mu} c^2 - E_{\mathrm{b,1s}} - E_{\mathrm{recoil}} = 104.973$ MeV (for Al)
- Nucleus coherently recoils off outgoing electron, no break-up.

Mu2e background: decay-in-orbit (DIO)

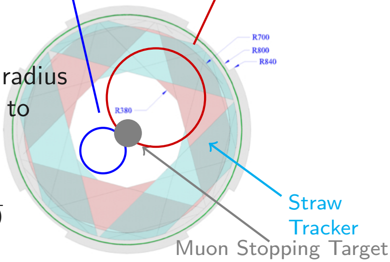


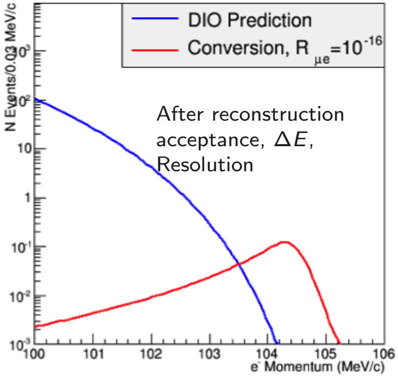
- Decay-in-orbit (∼40%)
- Inner 38 cm of tracker is un-instrumented → blind to >99% of decays-in-orbit (also blind to beam flash background)



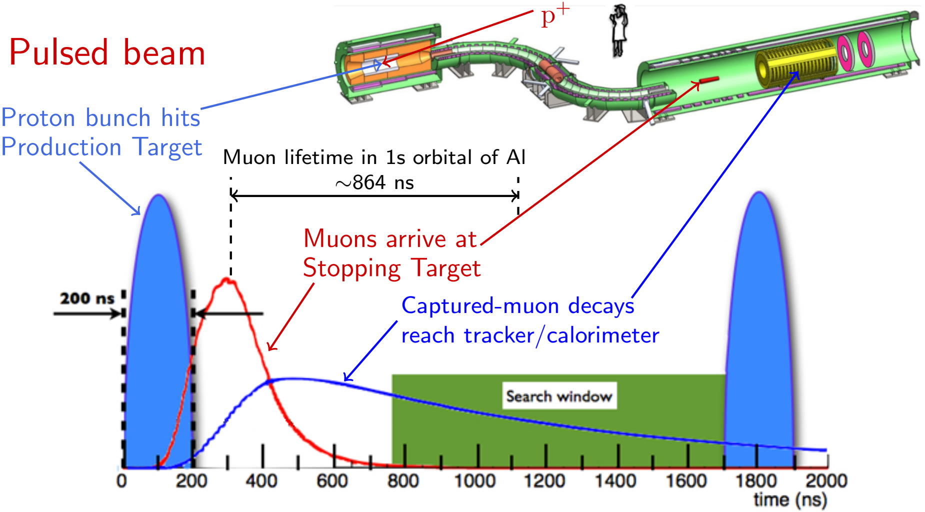
Spiral track radius proportional to transverse momentum:

$$r = \frac{p}{qB\cos(\alpha)}$$



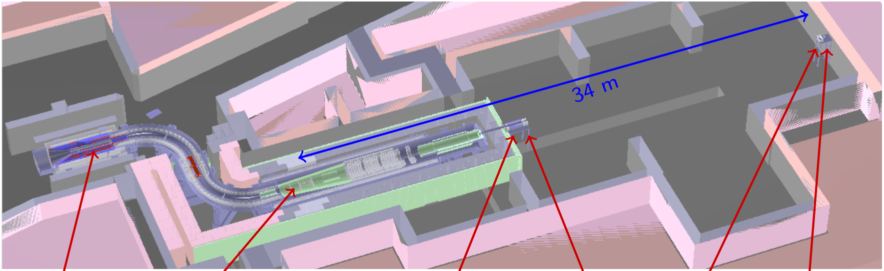


Pulsed beam



- Fermilab accelerator complex provides ideal pulse spacing for Mu2e.
- Pulsed beam suppresses prompt background during proton-pulses
- Must achieve extinction: (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$ to avoid prompt background

Normalization, $R_{\mu e} = \frac{\Gamma(\mu Al \to eAl)}{\Gamma_{capture}(\mu Al)}$



Preliminary design of Stopping-Target Monitor

- High-purity Germanium (HPGe) detector
  - determines overall muon-capture rate on Al to about the 10% level
  - measures X- and γ-rays from muonic Aluminum
    347 keV $2p$-$1s$ X-ray (80% of μ stops)
    844 keV γ-ray (4% of μ stops)
    1809 keV γ-ray (30% of μ stops)
- Downstream of Detector Solenoid
- Line-of-sight view of Muon Stopping Target
- Sweeper magnet
  - reduce charged particle background
  - reduce radiation damage to detector

Estimated sensitivity after 3 years of running

- 1.2×10^{20} protons-on-target per year
- $\sim 10^{18}$ stopped muons
  (There are $\sim 10^{18}$ grains of sand on the entire earth)
- estimated <0.5 background events
- If $R_{\mu e} = 10^{-16}$ we'd expect 3.5 signal events
- Single event sensitivity:
  $R_{\mu e} = 2.9 \times 10^{-17}$ (goal 2.5×10^{-17})

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

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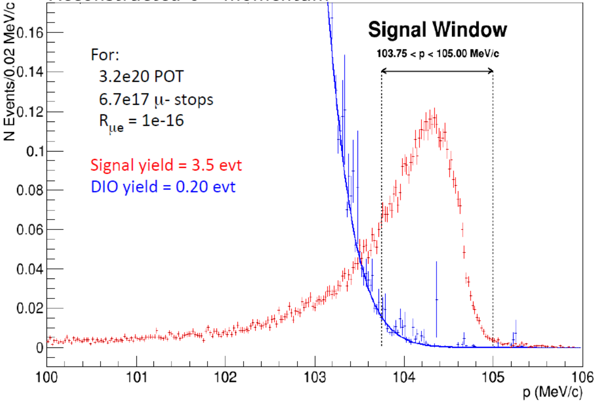
Reconstructed e^- momentum



Conclusion

- Within the next 10 years, Mu2e will either unambiguously discover CLFV or push the limit on muon$\rightarrow$electron conversion by four orders of magnitude.
- Single Event Sensitivity goal of 2.5×10^{-17}
- Already under construction $\rightarrow$ begin commissioning $\sim$2020
- For more information:
  - Mu2e Homepage: http://mu2e.fnal.gov
  - Technical Design Report: http://arxiv.org/abs/1501.05241
  - Spokespersons:
    - Doug Glenzinski: douglasg@fnal.gov
    - Jim Miller: miller@bu.edu

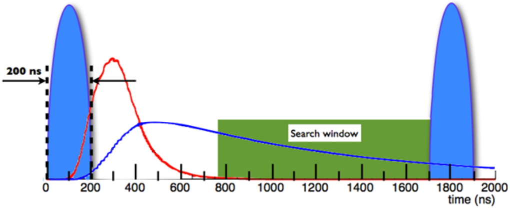
Extra slides:

Prompt background suppression - Proton Extinction

Must achieve extinction:

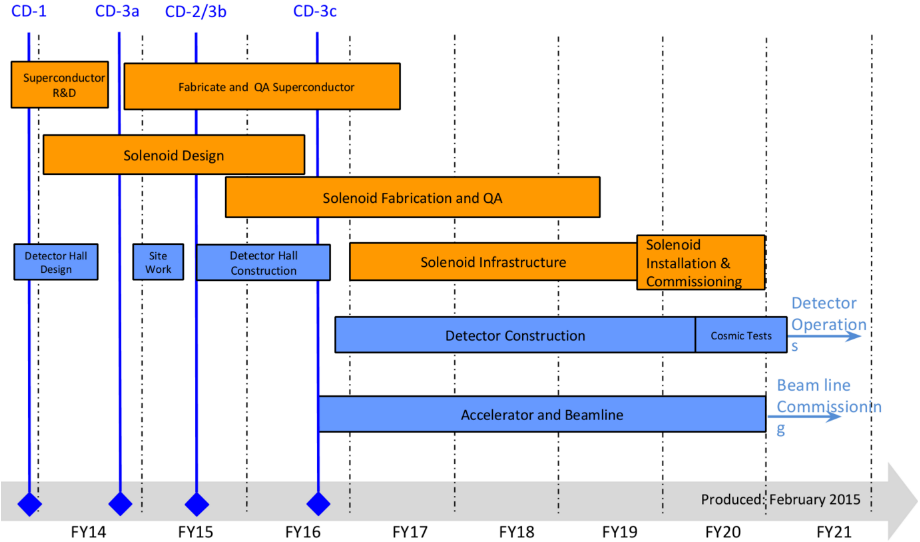
$$\frac{N_{\mathrm{p}+}\text{ out of pulse}}{N_{\mathrm{p}+}\text{ in pulse}} \leq 10^{-10}$$

to avoid prompt background



- RF structure of Fermilab recycler ring provides intrinsic extinction
  Extinction (intrinsic): $\sim 10^{-5}$
- AC dipole (custom made) located just upstream of the production target provides additional external extinction
  Extinction (AC dipole): 10^{-6}–10^{-7}
- Total extinction:
  Extinction (total): $\sim 10^{-11}$–10^{-12}

Mu2e Timeline



Mu2e building under construction

Nov 02 2015