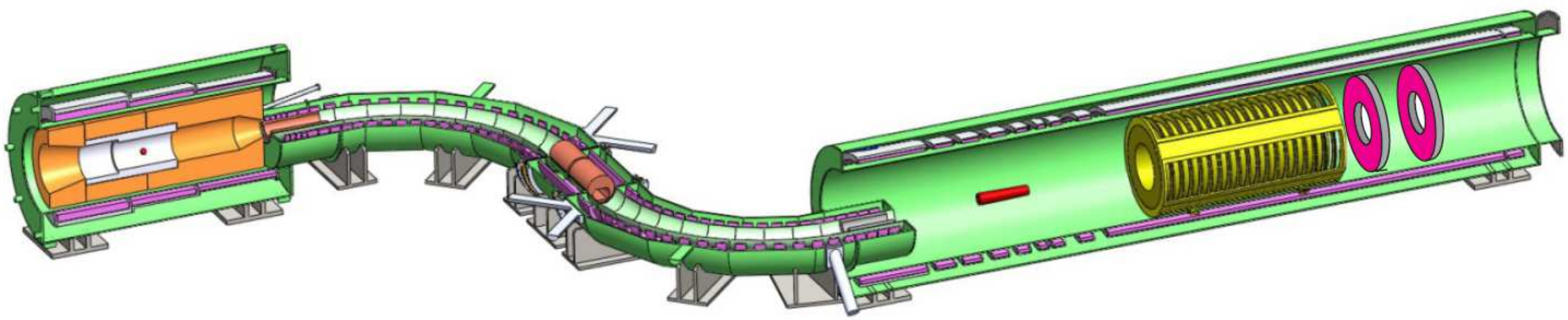
The Mu2e experiment



Zhengyun You

University of California, Irvine

(for the Mu2e Collaboration)

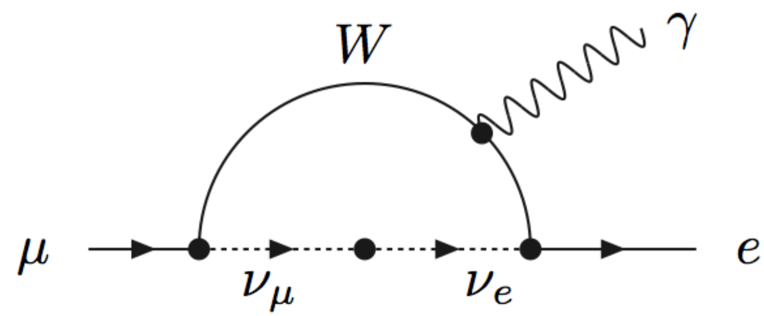
08/21/2013

Outline

- Physics
  - CLFV
  - Muon-to-electron conversion
- The Mu2e experiment at Fermilab
  - Detector setup
  - Signal & background
  - Sensitivity
- Schedule and Future
- Summary

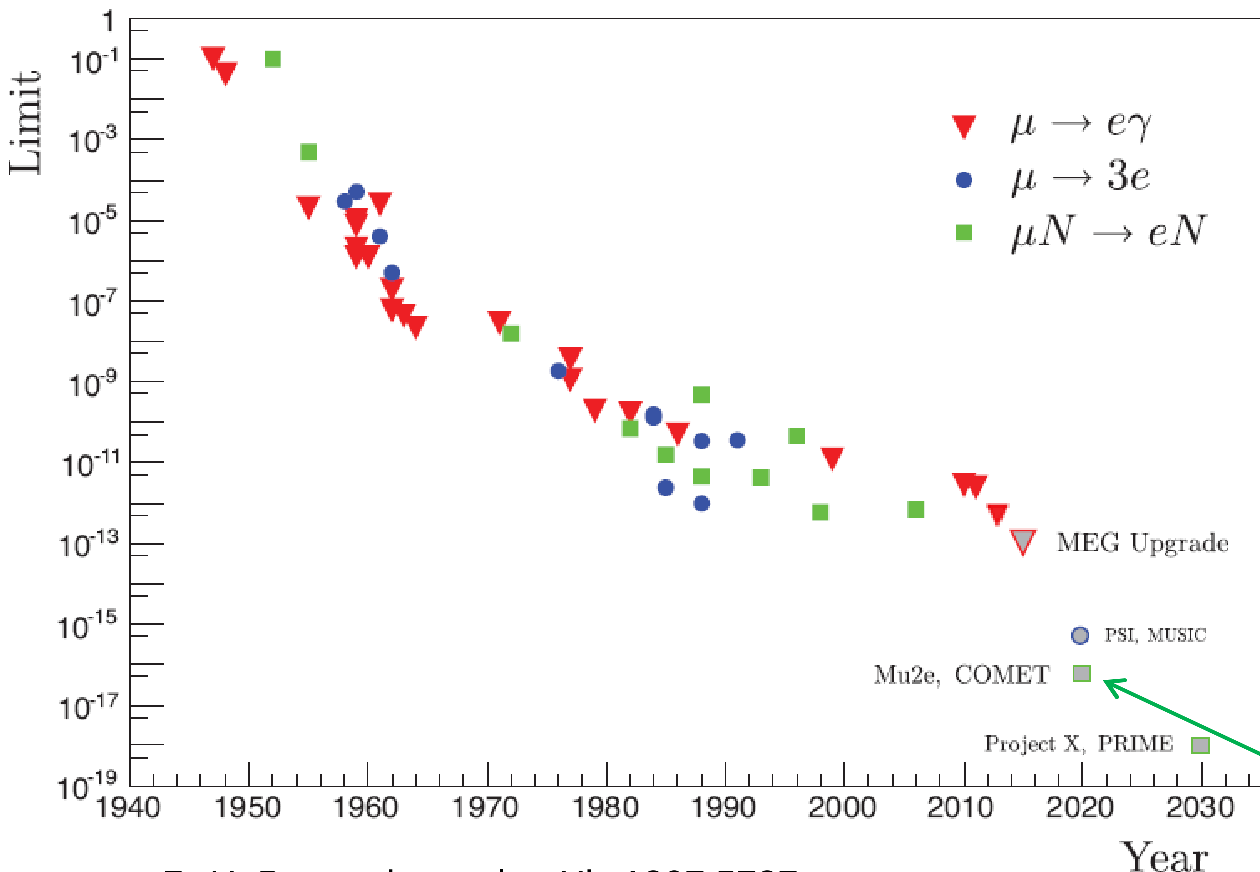
Charge Lepton Flavor Violation (CLFV)

- Lepton flavor is violated in neutrino mixings
- Charged lepton mixing is strongly suppressed in the Standard Model, un-observably small
- Any observation of CLFV would be new physics Beyond Standard Model (BSM)



$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{*}_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2$$
$$< 10^{-54}$$

CLFV history in muon to electron



R. H. Bernstein et. al. arXiv:1307.5787

Current best limits

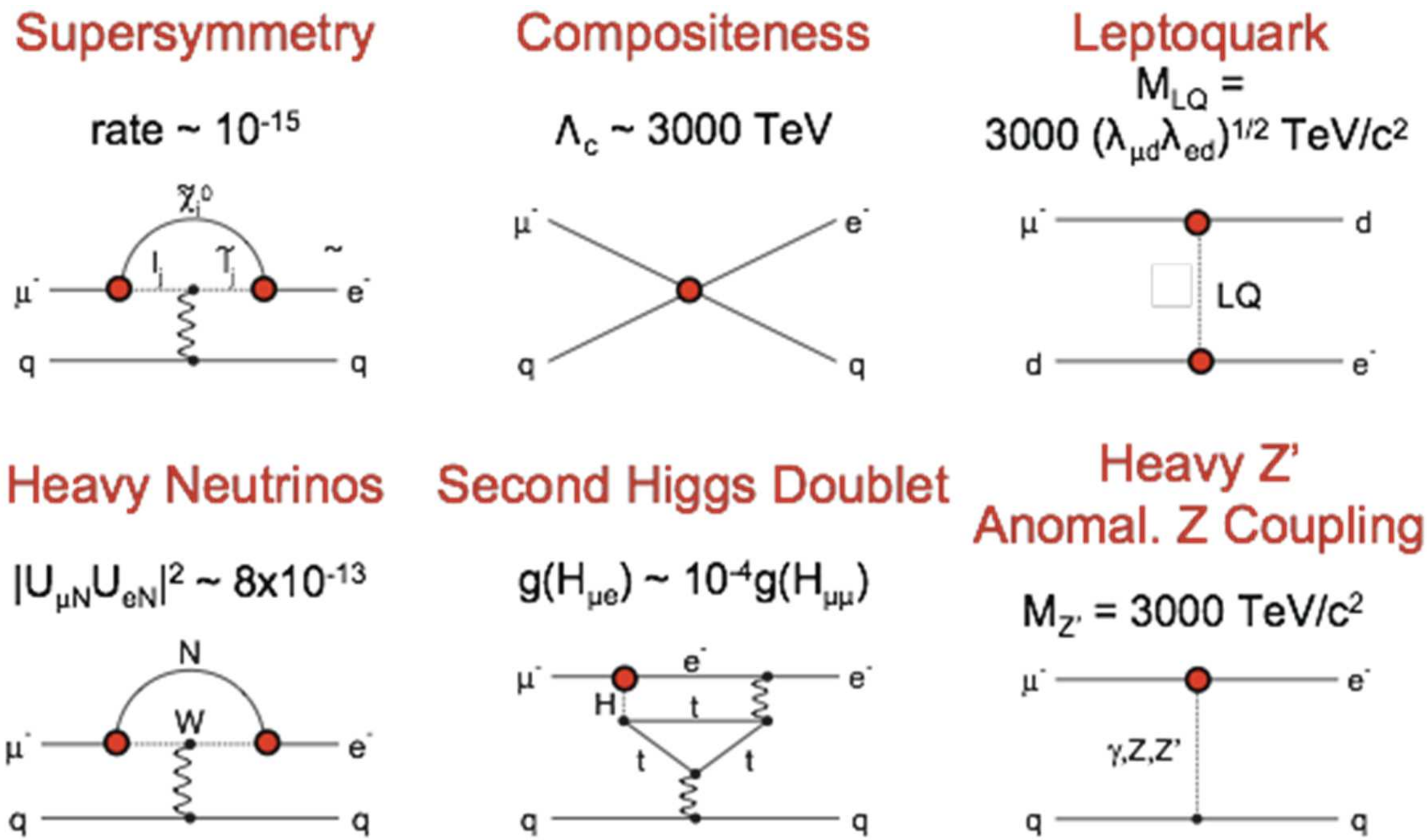
BR($\mu \rightarrow e\gamma$) < 5.7 x 10^{-13}
MEG 2013

BR($\mu \rightarrow 3e$) < 1 x 10^{-12}
SINDRUM-I 1988

$R_{\mu e}$ < 7 x 10^{-13}
SINDRUM-II 2006

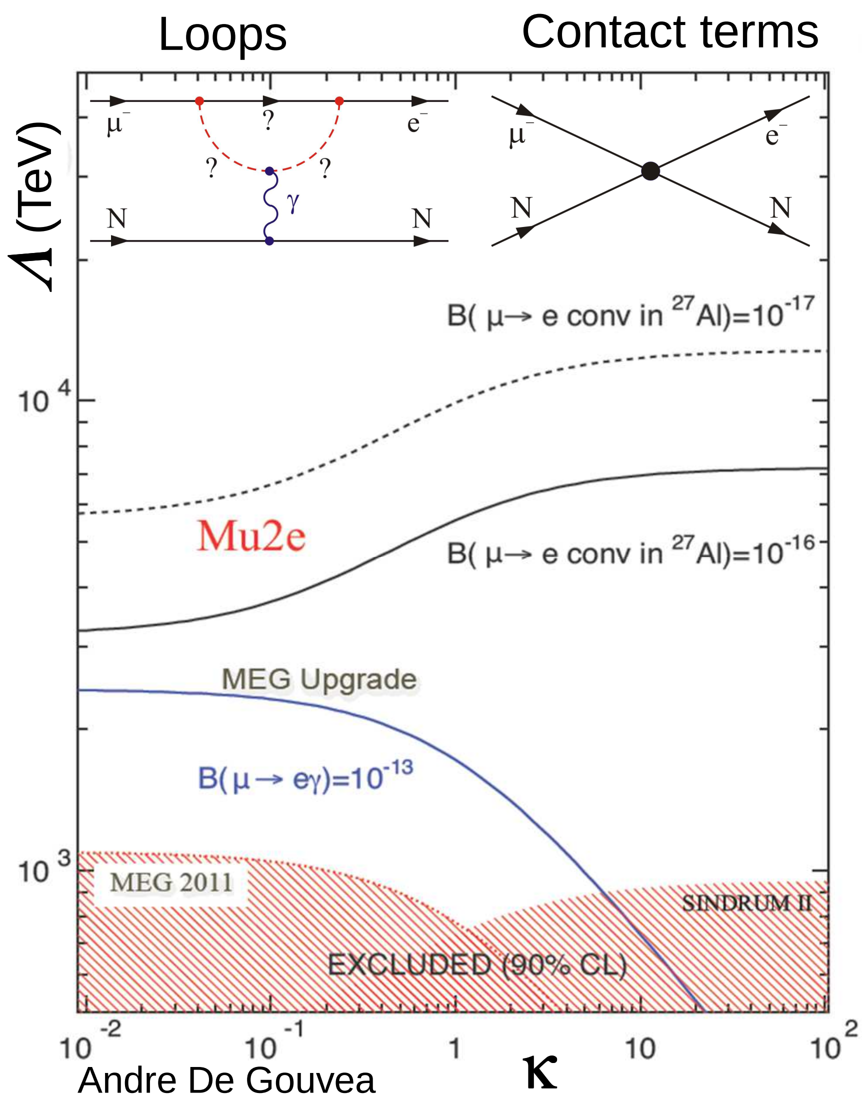
$R_{\mu e}$ = few x 10^{-17}
Mu2e goal

New Physics in $\mu \rightarrow e$ Conversion



Flavor physics of leptons and dipole moments, [arXiv:0801.1826]

Probing new physics with CLFV



Andre De Gouvea

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

Effective Lagrangian

- Contact κ, mass scale Λ
- 'Loops', charged Higgs model, κ<<1, can be probed by $\mu\rightarrow e\gamma$
- 'Contact terms', direct coupling between quarks and leptons, κ>>1, only accessible by $\mu N\rightarrow eN$
- Probe mass scales Λ 2000~10000 TeV, significantly above the direct reach of LHC

$\mu N \rightarrow eN$ Conversion

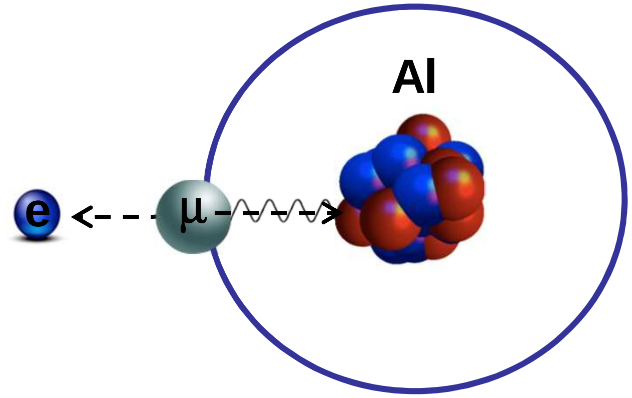
What we measure

- The ratio of muon to electron conversions to conventional muon captures

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Signal: Neutrinoless conversion of a muon to electron in the field of a nucleus

- Experimental signature
  - Mono-energetic electron
  - $E_e = m_\mu - E_{bind} - E_{recoil}$
  - For Al, E_e = 104.97 MeV



Measurement : Electron energy spectra

- Signal

  Conversion electrons with energy at Decay in Orbit (DIO) endpoint

  104.97 MeV

- Background
  - Muon decay in orbit

    $$\mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al$$

  - Radiative muon capture

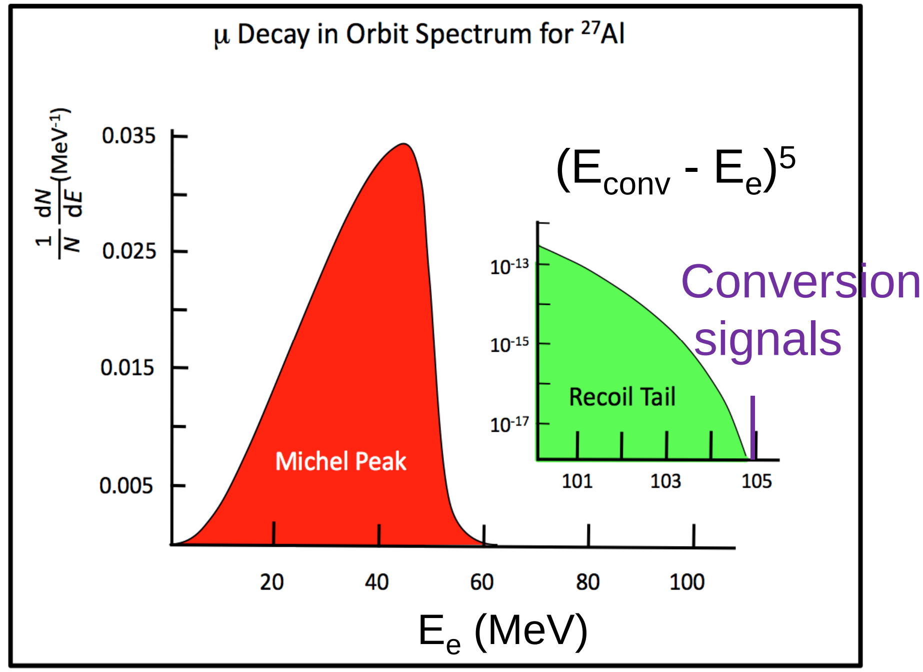
    $$\mu^- + Al \rightarrow \nu_\mu + \gamma + Mg$$

  - Radiative pion capture

    $$\pi^- N \rightarrow \gamma N^*, \gamma \rightarrow e^+ e^-$$

    $$\pi^- N \rightarrow e^+ e^- N^*$$

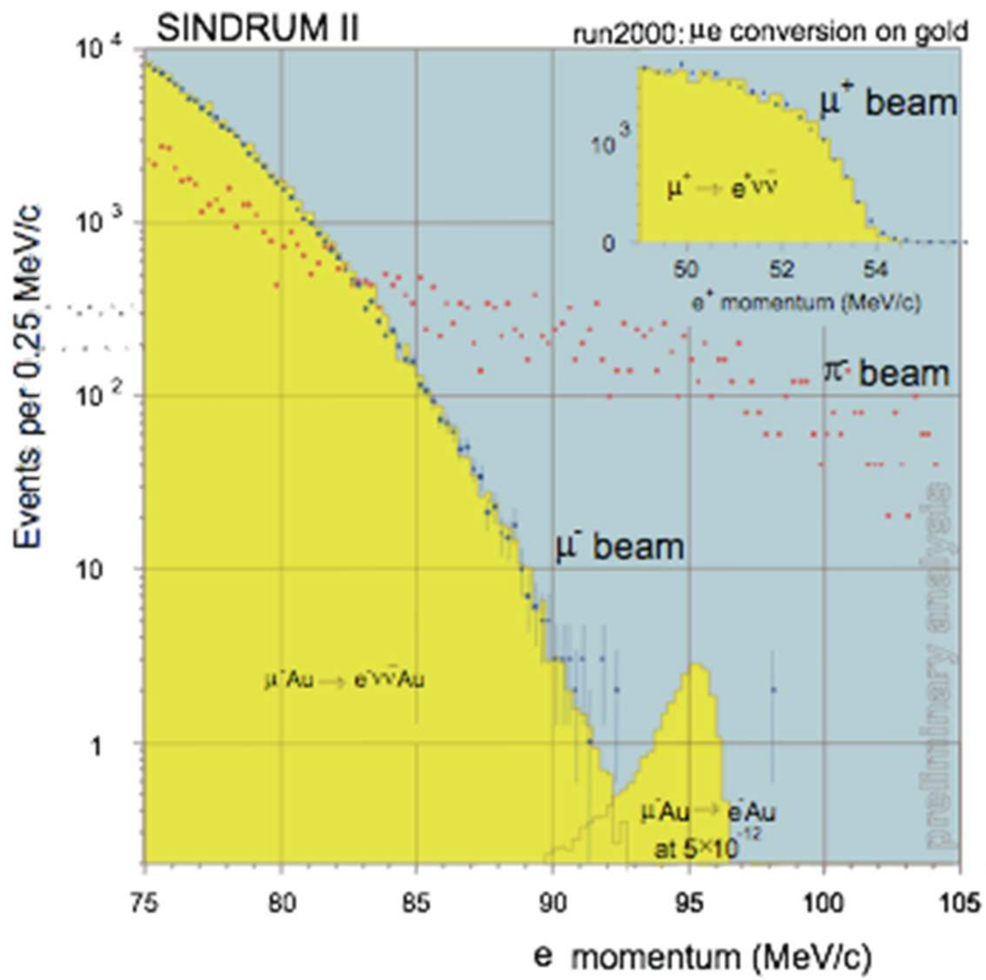
  - Antiprotons annihilation gamma
  - Pion/muon decay in flight
  - Electrons from beam
  - Electrons from Cosmic rays



Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2

Current Best Measurement in $\mu N \rightarrow eN$

- Current best limits
  - $R_{\mu e}$ (Ti) $< 4.3 \times 10^{-12}$
  - $R_{\mu e}$ (Au) $< 7 \times 10^{-13}$
- Simulated signal at DIO tails
- Au target: different electron energy endpoint than Al



W. Bertl et al, Eur. Phys. J. C 47, 337-346 (2006)

Process and Beam Selection

$\mu \to e\gamma$

- Signal particles ≤ 53 MeV
  - high background region
- Signal: combination of particles
  - Bkg rejection: cuts on combination
  - Accidental coincidences limit usable muon rate
- Continuous beam
- $\mu+$
  - Capture rates: $\Gamma_{\mu+} = 0$

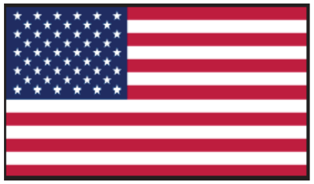
$\mu N \to eN$

- Signal particle at 105 MeV
  - Away from Michel peak
- Signal: single track
  - Fewer handles to reject background
  - Coincidences not a problem
- Use pulsed beam
  - suppress background between pulses
- Need cosmic ray veto
- $\mu-$
  - Capture rates: $\Gamma_{\mu-} \sim Z^4$
  - Potential background

The Mu2e Experiment

- Goal: To search for the conversion of $\mu N \rightarrow eN$ in the field of Aluminum nucleus
- Sensitivity of Branching Fraction
  - Single event sensitivity: $R_{\mu e} = 2.5 \times 10^{-17}$ (6×10^{-17} @ 90% C.L.)
- Statistics
  - Requires $\sim 10^{18}$ stopped muons
  - Requires $\sim 3.6 \times 10^{20}$ protons on target
  - 3 years data taking
- Requires background events to be negligible (<1)
- Location: Fermi National Acceleratory Laboratory (FNAL)
- Schedule: expect to start commissioning & data taking in 2020

The Mu2e Collaboration



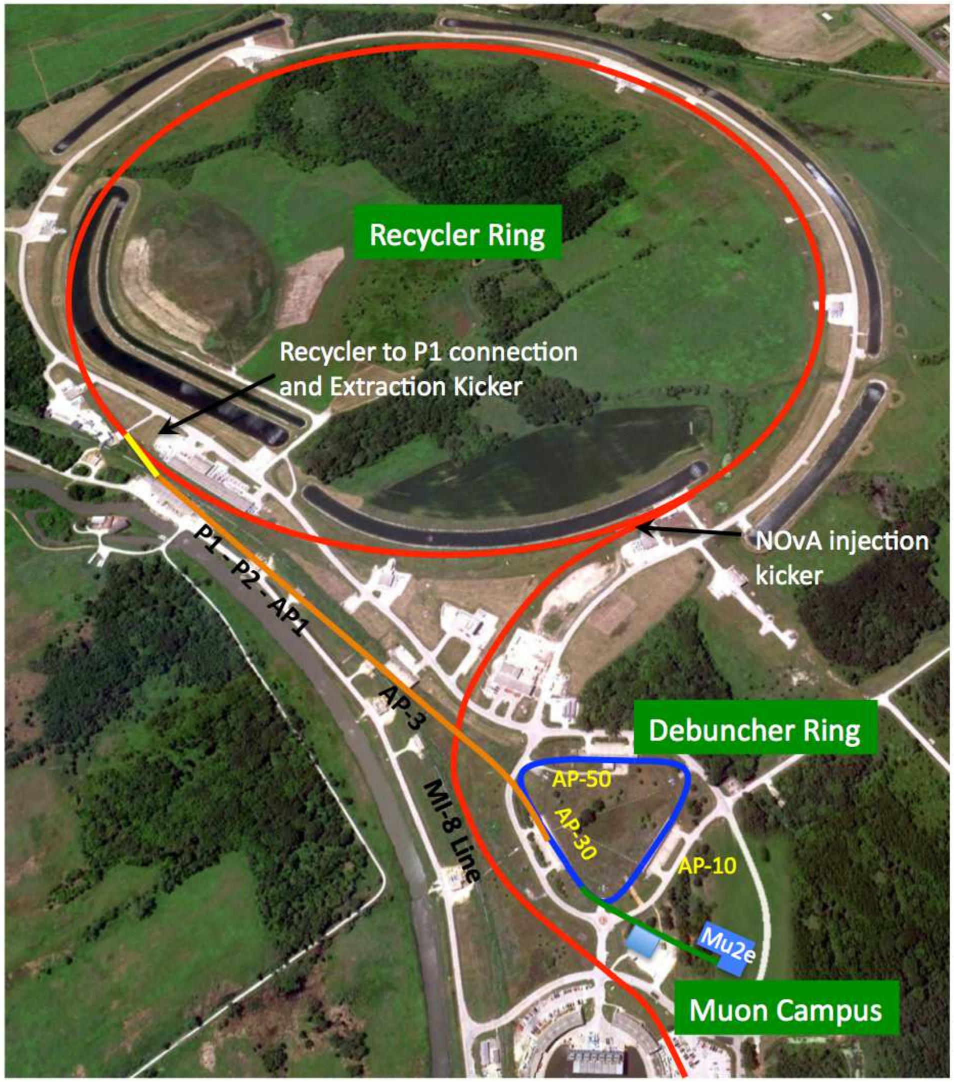
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory &
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois, Urbana-Champaign
Lewis University
University of Massachusetts, Amherst
Muons, Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington

INFN Lecce/Università del Salento
INFN Lecce/Università Marconi
INFN Pisa
Universita di Udine, Udine
Laboratori Nazionali di Frascati

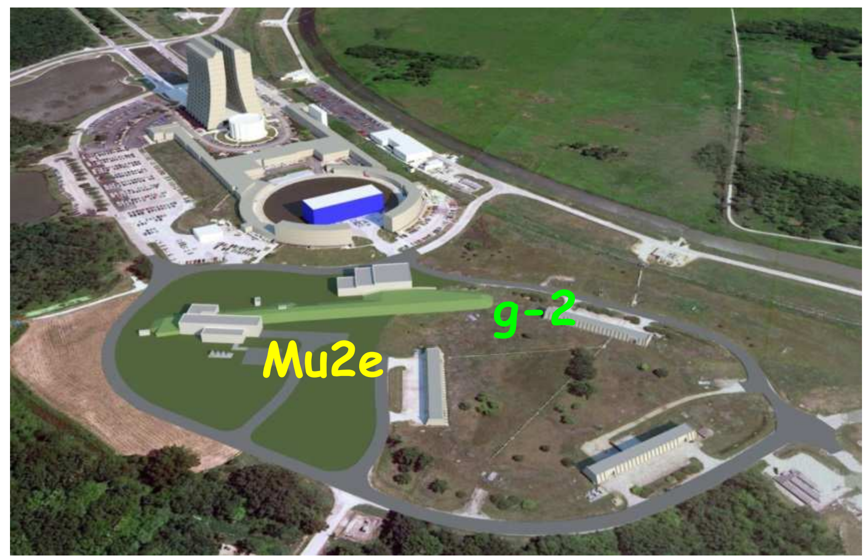
Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

26 institutions
~140 collaborators

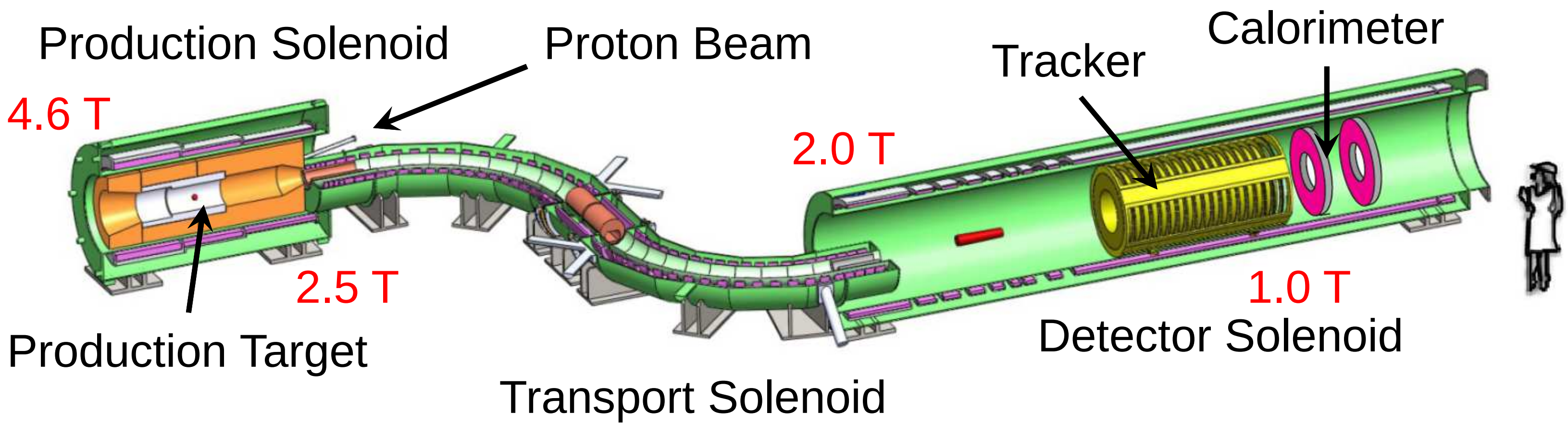
Proton Delivery & Muon Campus



- 8 GeV proton beams
- $3\text{x}10^7$ protons per bunch
- Bunch spacing 1.7 μs
- 30% duty factor
- Run after g-2
- Shared with NOVA

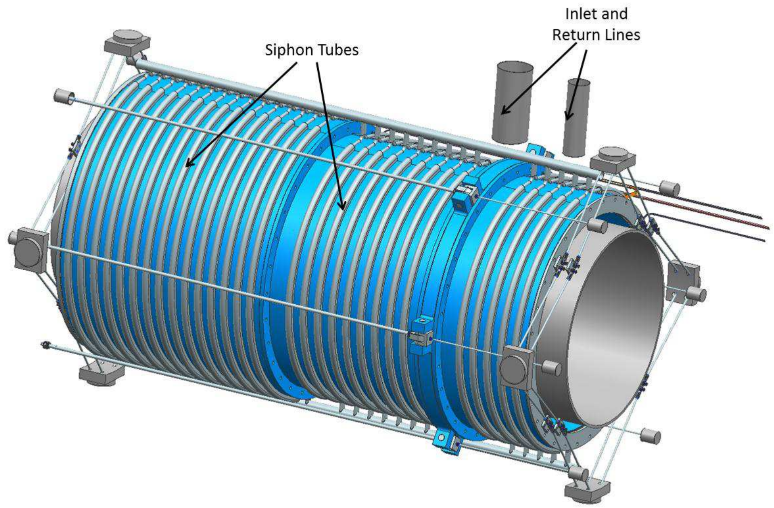


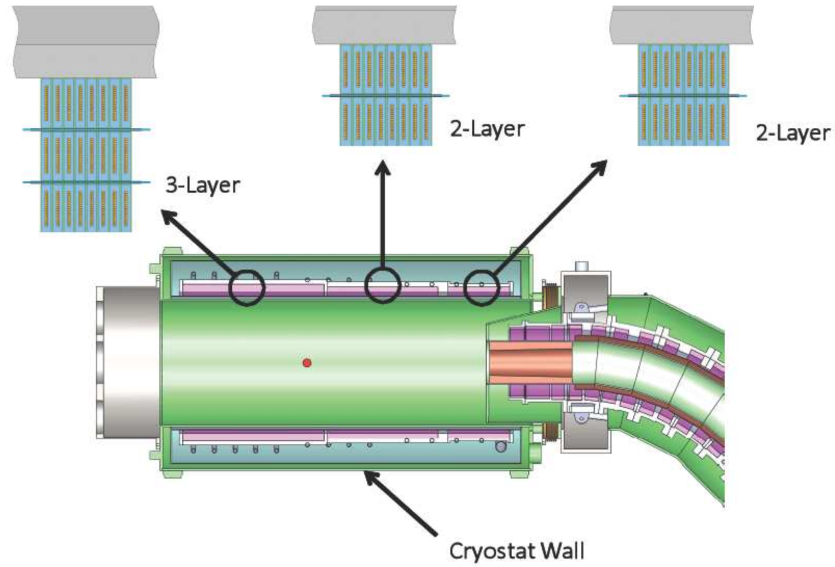
Overview of Mu2e Design



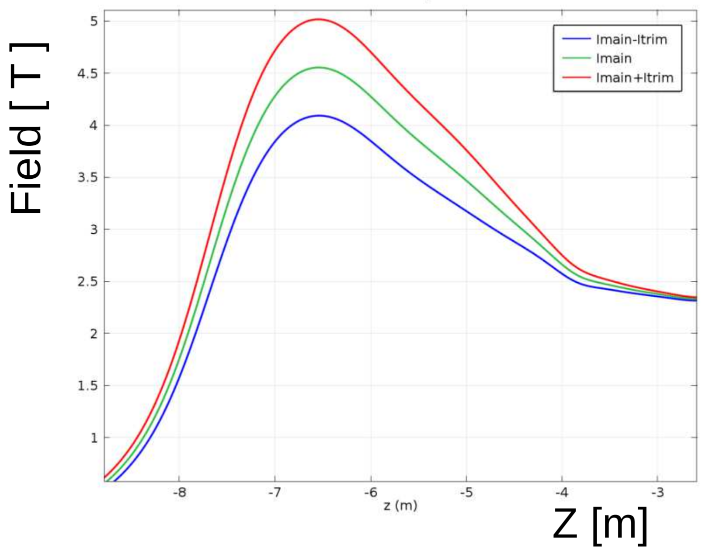
- Production Solenoid / Target
  - Protons hitting target and produce pions
  - Solenoid reflect slow forward μ/π and contains backward μ/π
- Transport Solenoid
  - Filter low momentum μ^-
- Stopping Target, Detector Solenoid and Detectors
  - Stop μ^- on Al foils and wait for them to decay
  - Events reconstructed by tracker and calorimeter, optimized for 105MeV.

Production Solenoid

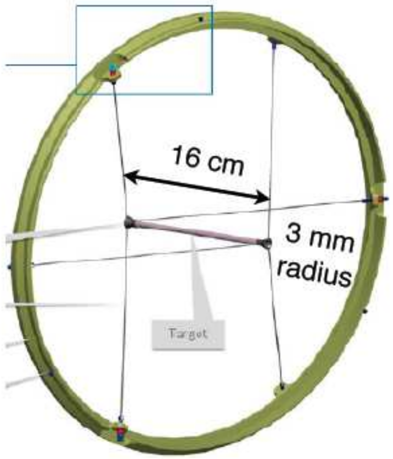


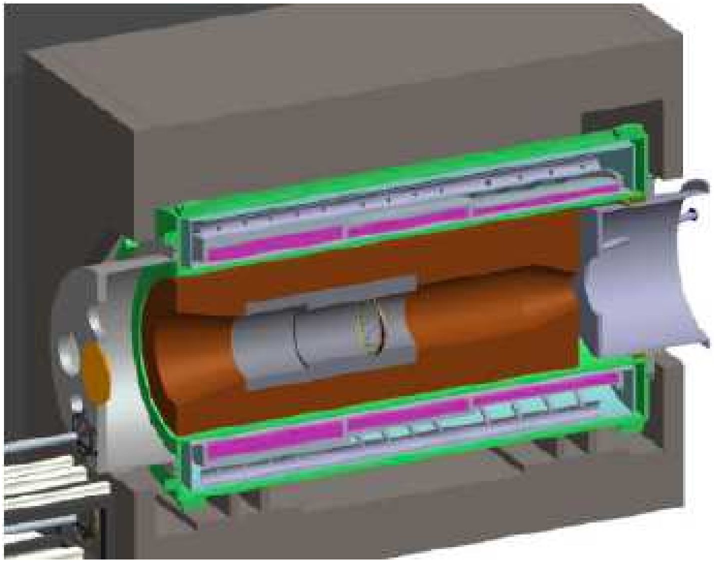


- To maximize muon yield
- The axially graded magnetic field reflects slow pions/muons towards the TS direction
- 3 coils with 2 or 3 layers



Target and Heat Radiation Shield

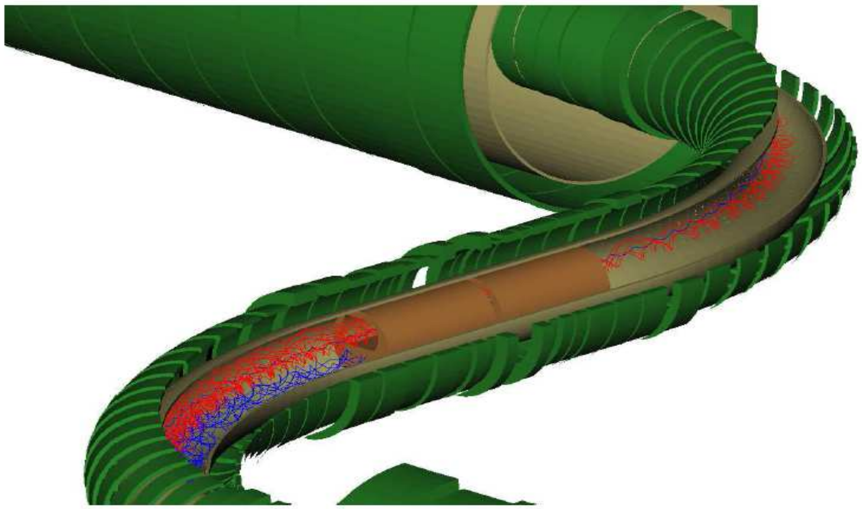


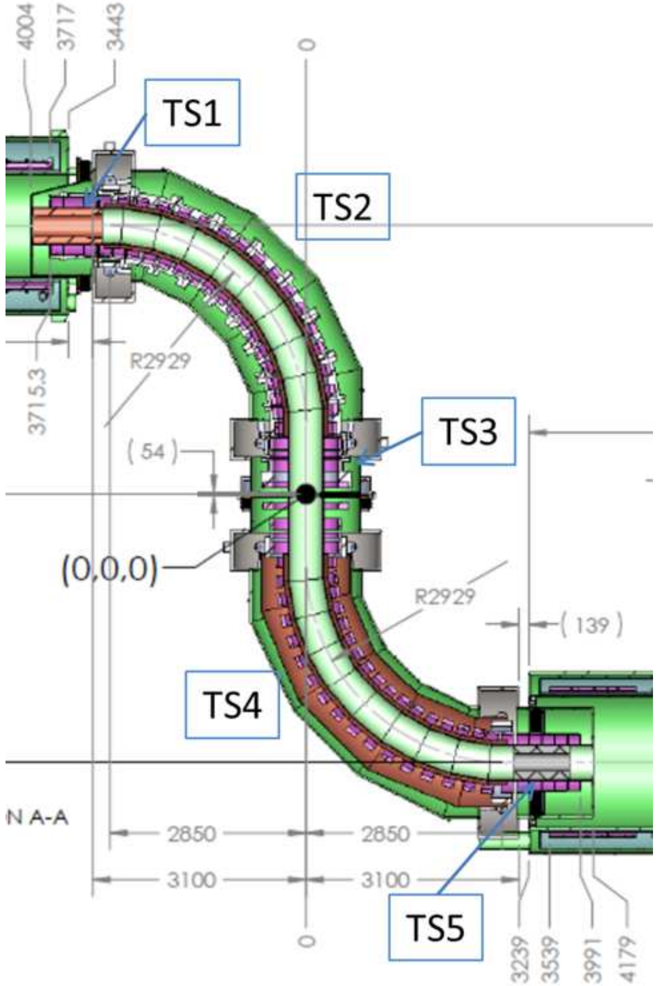


- Production Target
  - Protons striking target produce pions, which decay into muons
  - High A and high density material Tungsten to maximize muons production
  - High melting temp, radiative cooling (~1600ºC), with 8kW beam (700w in target)
- Heat Radiation Shield
  - To protect superconductor of PS and upstream TS
  - To limit heat load and radiation damage
  - ~25 tons of Bronze

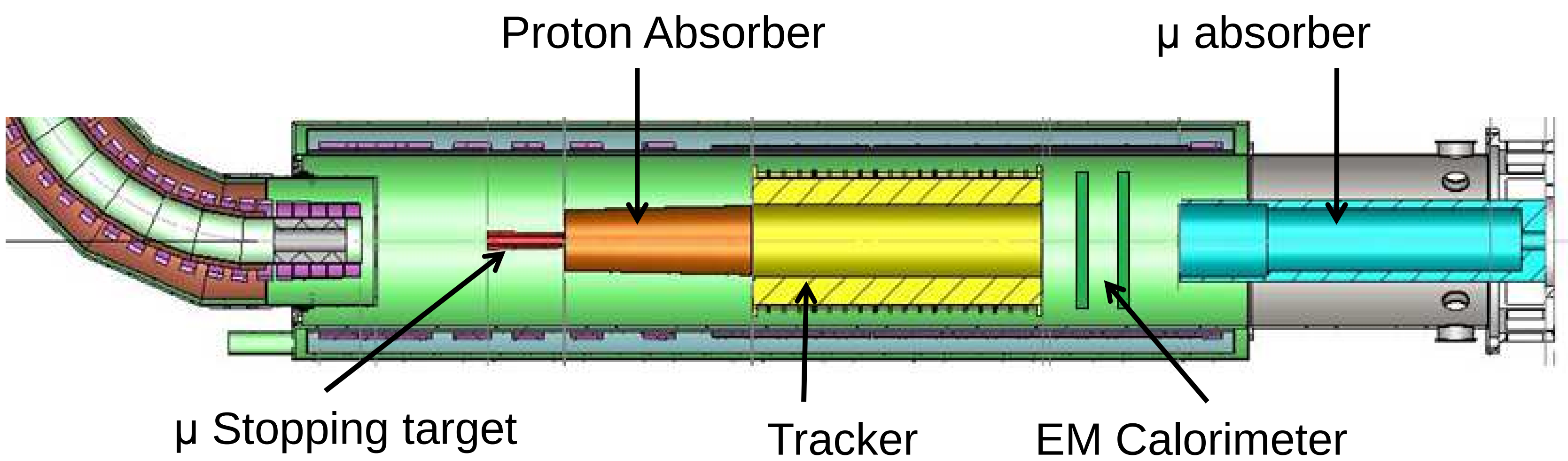
Transport Solenoid

- Gradient magnetic field from 2.5 T to 2.0 T
- S-shaped magnetic channel to transmit low-momentum negatively charged particles in helical trajectories
- D-shaped collimators to remove positively charged and high-momentum particles



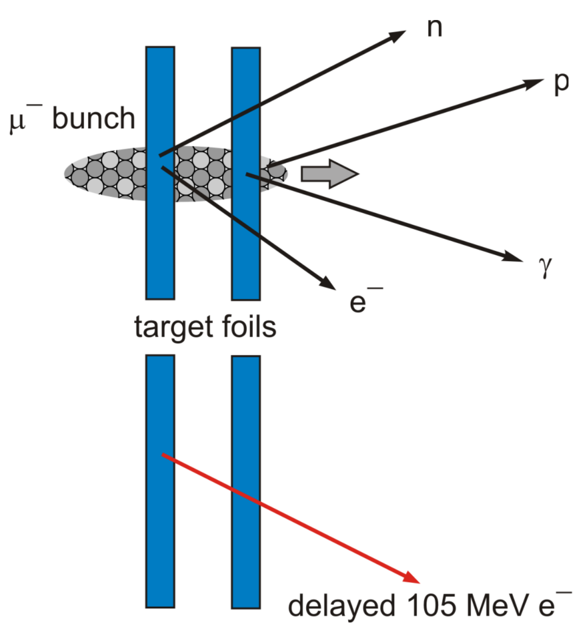


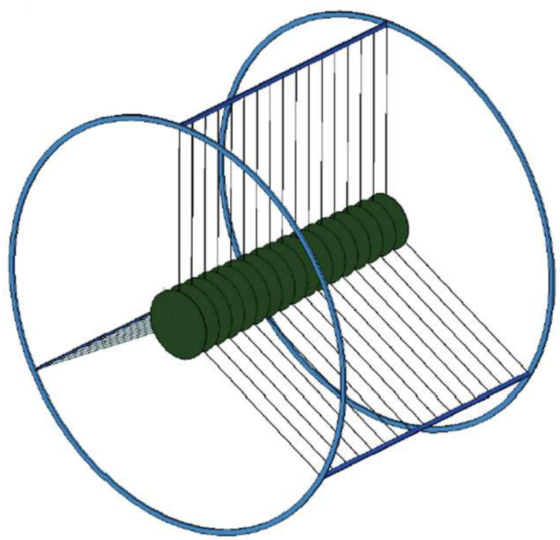
Detector Solenoid

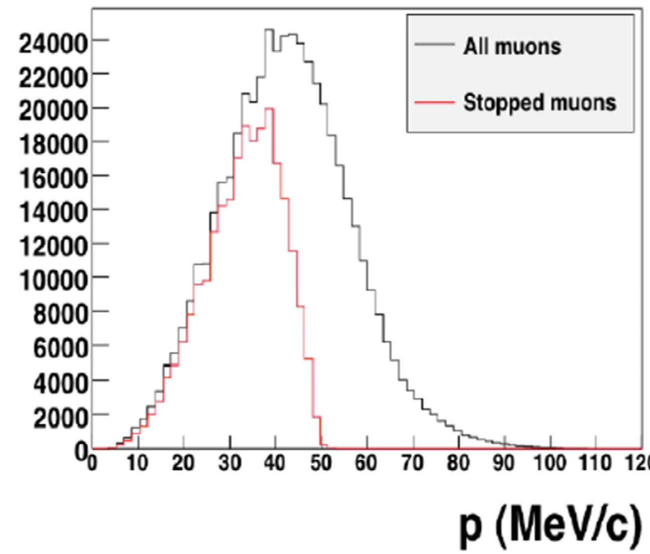


- Stopping target to stop muons
- Graded magnetic field from 2 T to 1 T, captures conversion electrons with bigger acceptance, shifts the pitch of beam particles to reduce background
- Tracker and Calorimeter in a uniform field to reconstruct and identify electrons
- Vacuum in DS to limit background from muons stopped on gas atoms

Stopping Target

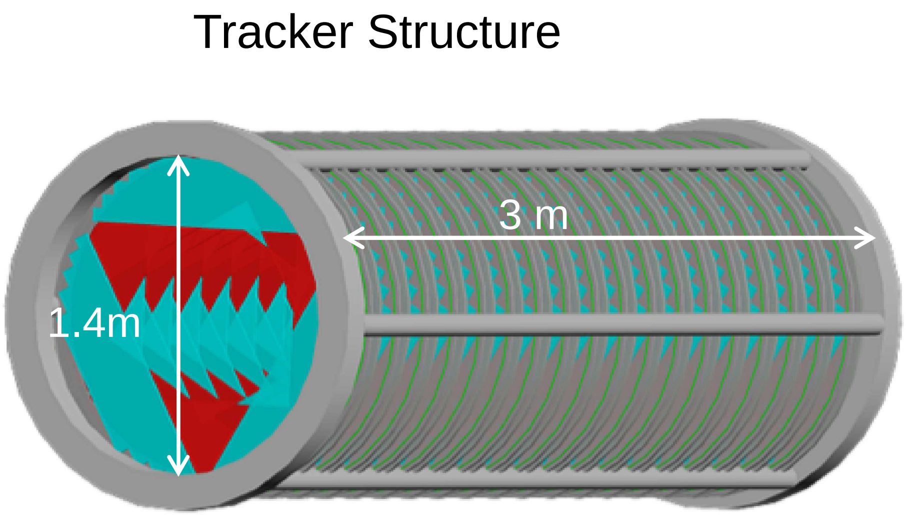


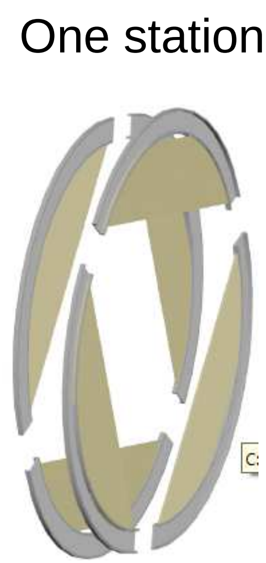


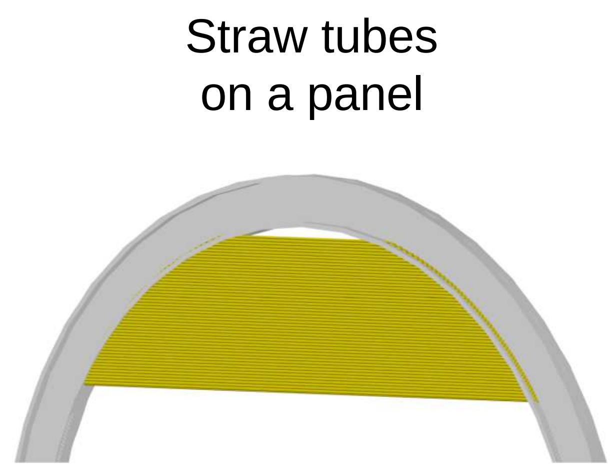


- μ^- stopped in thin foils and form muonic atoms
- μ^- in Al, life time = 864 ns
- Conversion electrons signal energy ~105 MeV
- 17 circular aluminum foils
- 200 μm thick, spaced 50 mm
- Currently stop ~49% muons
- Geometry under optimization

Tracker



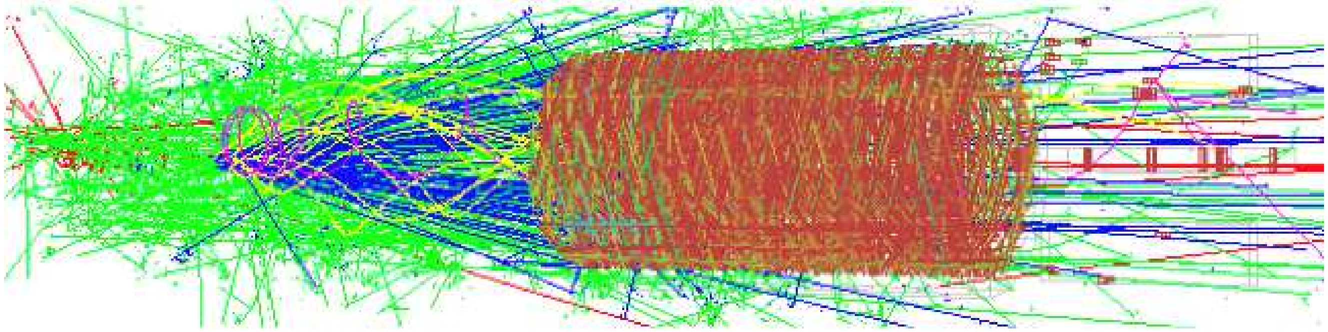




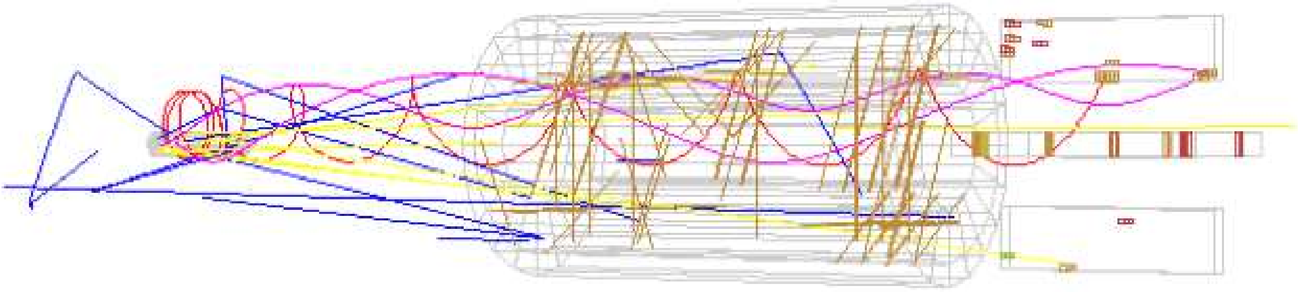
- From two designs: T tracker / I tracker, T tracker is selected
- 3 m long, 1.4 m diameter, in a uniform 1 T magnetic field
- Made of 21,600 straw drift tubes, 18 stations, 2 planes/station
- Each straw 5 mm diameter, 25 μm sense wire, 15 μm mylar walls
- Custom ASIC for Time Division Readout, Δt resolution < 50 ps
- ADC for dE/dx capability to separate highly ionizing protons.

Tracks in one pulse

all tracks in search window of a proton pulse

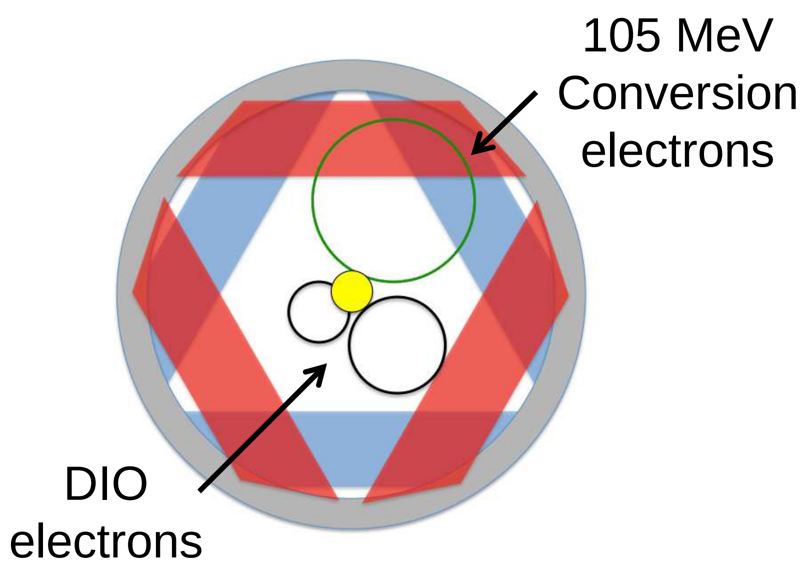


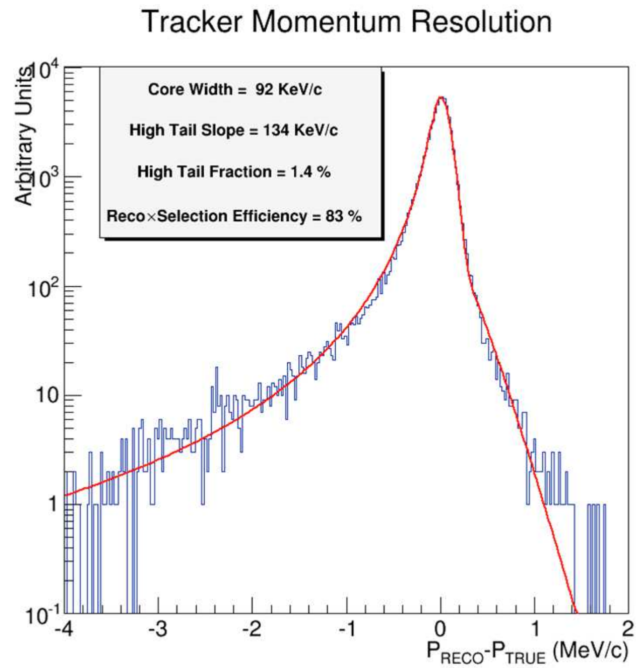
±50 ns around conversion electron



- Quite challenging to find the conversion electron
- Good tracker performance and pattern recognition algorithm critical

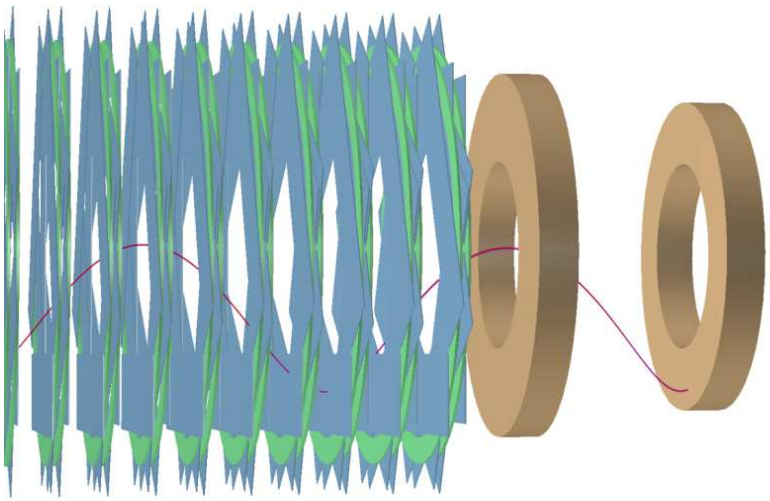
Track Reconstruction

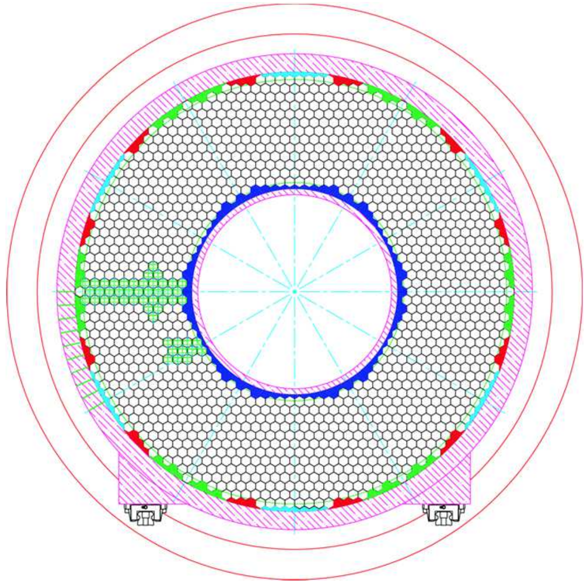




- Measure trajectories of conversion electrons, most low-momentum DIO electrons curl in the field and pass through the hole in DS
- Find tracks using time clustering plus pattern recognition algorithm
- Fit Track using Kalman filter

Calorimeter

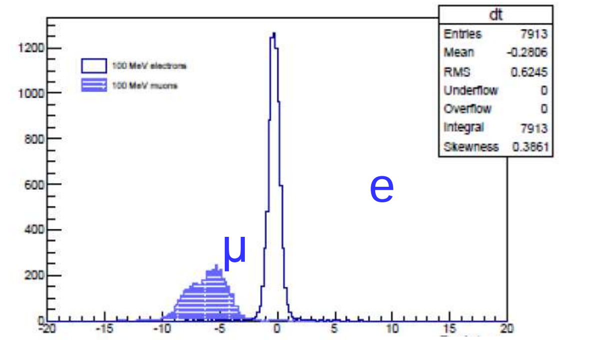




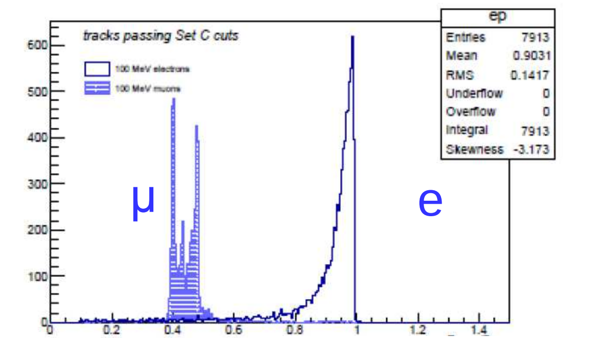
- Provides independent energy, time and position measurements
- Helps to eliminate backgrounds and provides a cross check to verify the validity of signal events.
- Disk structure is selected from two designs: Vane / Disk
- Two disks composed of hexagonal LYSO crystals
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N'$

Calorimeter

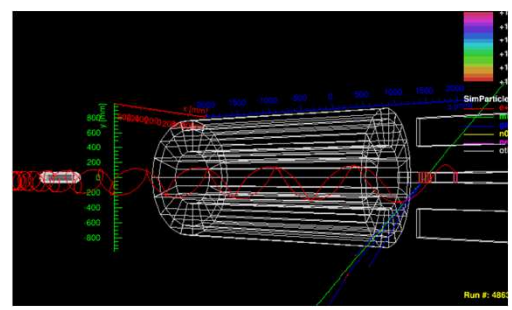
- Particle Identification
  - Geometrical acceptance for events passing tracker cuts >95%
  - Combine distribution in ΔT and E/P to build a particle ID likelihood
  - Calorimeter + Tracker PID
    - Electron efficiency >99%
    - Muon rejection in the range $10^2 – 10^3$
- To reject cosmic background
- Provides alternative seed for track finding algorithm
- Provide independent trigger, reducing requirements on DAQ



Track Δt [ns]

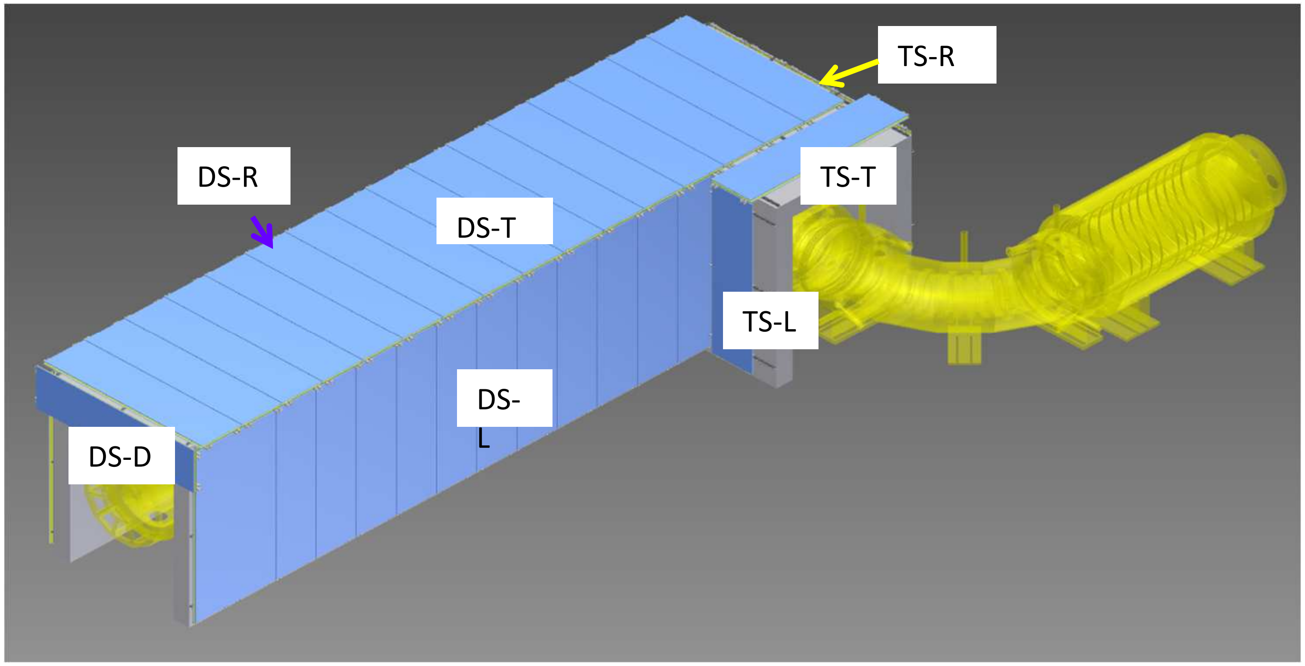


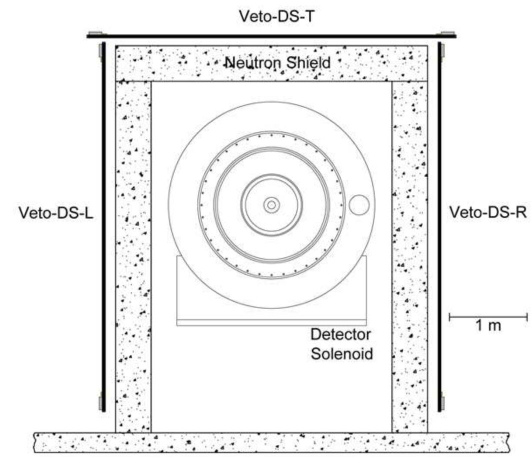
$E_{cluster} / P_{track}$



A cosmic event

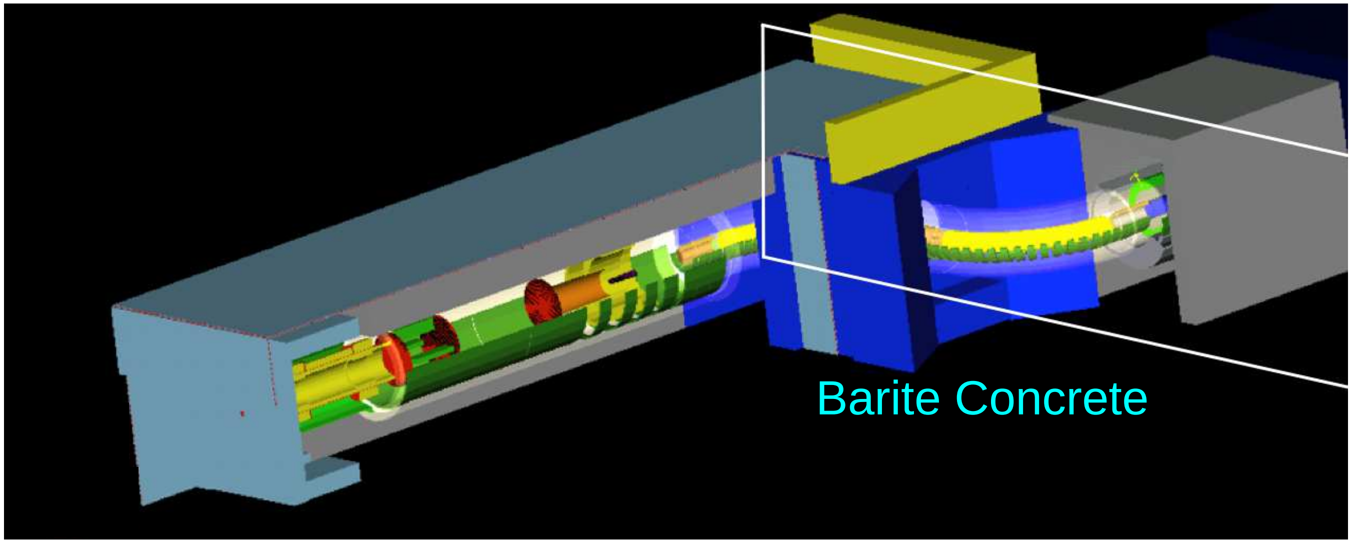
Cosmic Ray Veto





- Cosmic rays is a major sources of background
  - Muons hitting stopping target or DS materials, generating delta rays
  - Muons decay into electrons
- CRV are composed of 3 layers overlapping scintillators, placed around DS and part of TS area
- Requires 0.9999 efficiency to achieve proposed background rejection

Neutron and Photon Background



- Neutrons can be produced in production target, HRS, collimators…
- Neutrons have radiation damages to SIPMs and make fake hits on detectors
- Neutrons get thermalized, captured and produce gammas
- Shielding with Barite loaded concrete, polyethylene in TS and DS area
- Geometry under optimization

Calibration

Calibration tools provide cross check and corrections for detector description (magnetic field, material, geometry, alignment, …)

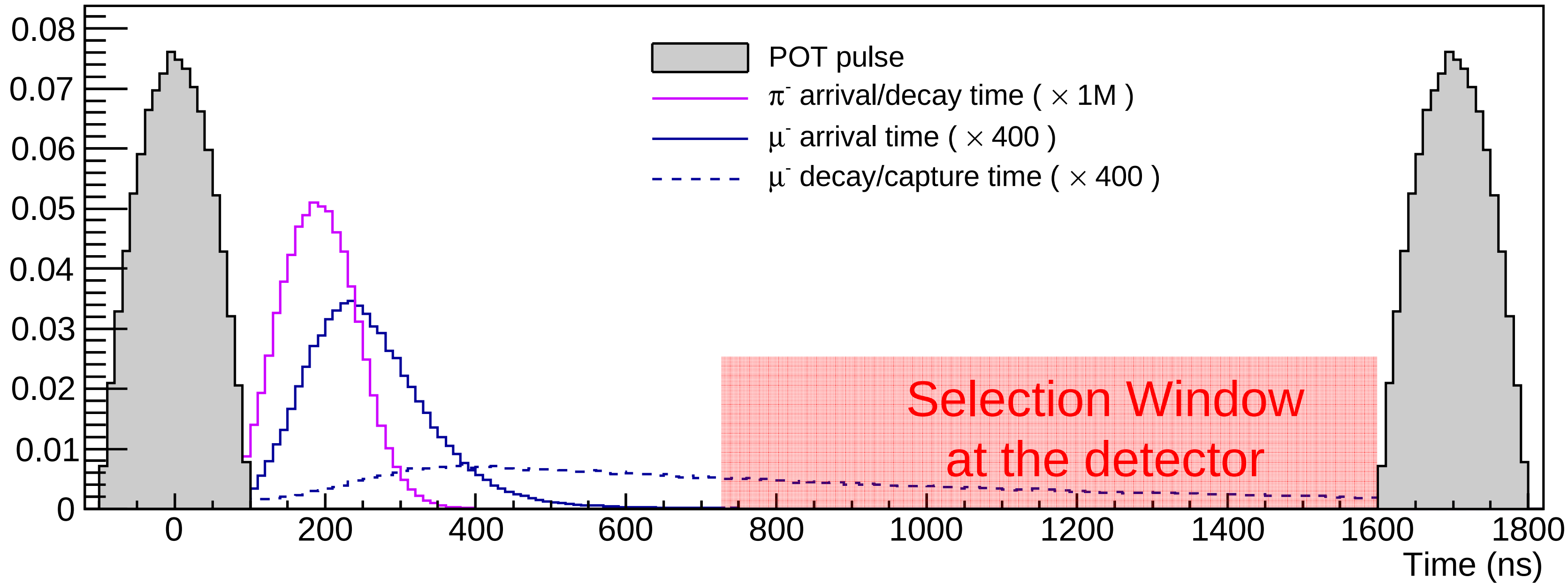
Tracker Calibration

- Requires absolute momentum (Δ<100KeV/c) to separate DIO background from conversion electrons
- Calibrate with $\pi^+ \rightarrow e^+ \nu_e$ events at ~70 MeV/c
- Calibrate by fitting the Michel edge with $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ events at ~53 MeV/c
- Both requires special beam, detector and magnetic field configuration
- Calibrate by fitting DIO spectrum and cosmic electron resolution study

Calorimeter Calibration

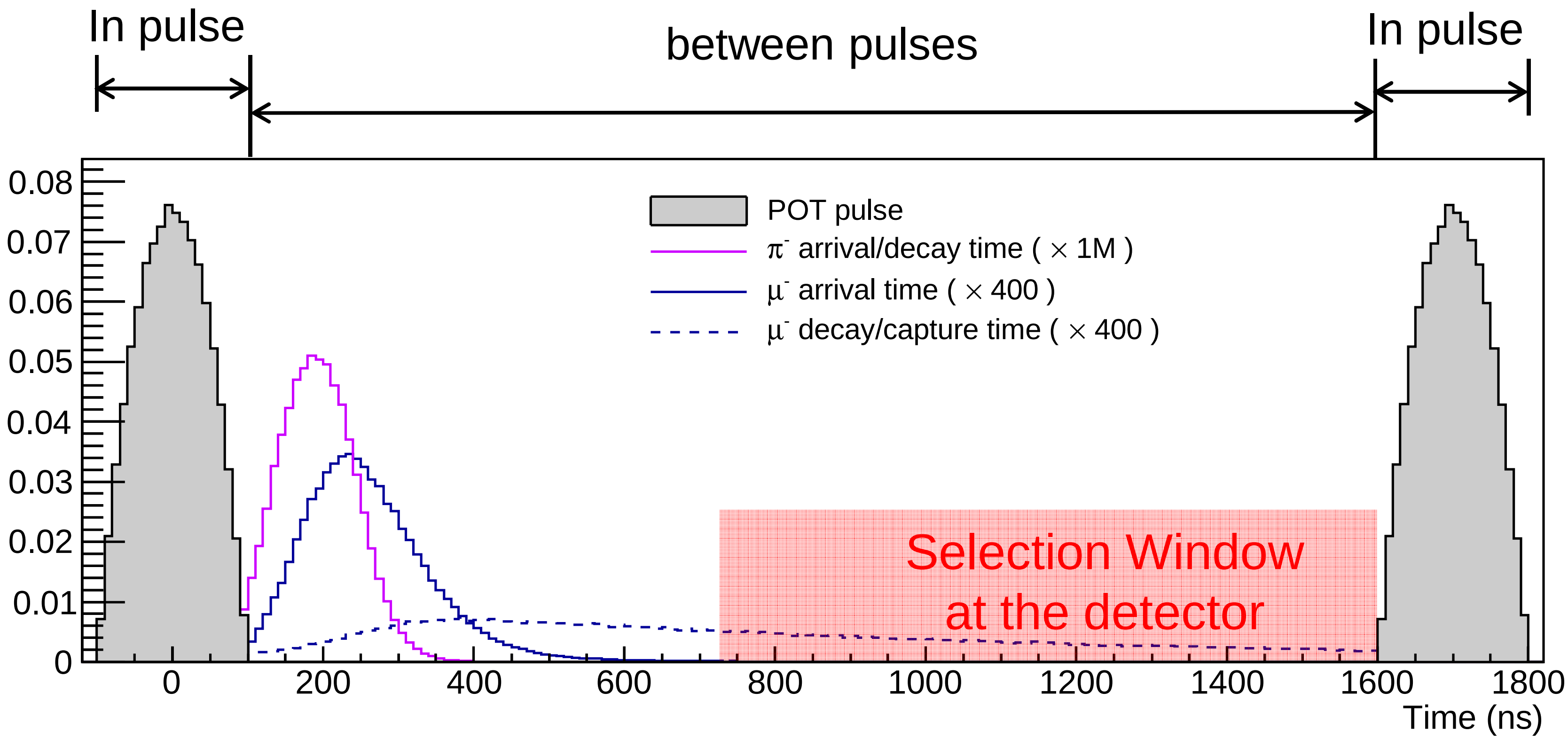
- Requires energy precision δ_E<2% at 100 MeV
- Source calibration system with 6.13 MeV photons
- Calibration with cosmic ray muons
- DIO events give a very precise calibration and can be compared with tracker, if enough data has been taken.

Timing in Mu2e measurement



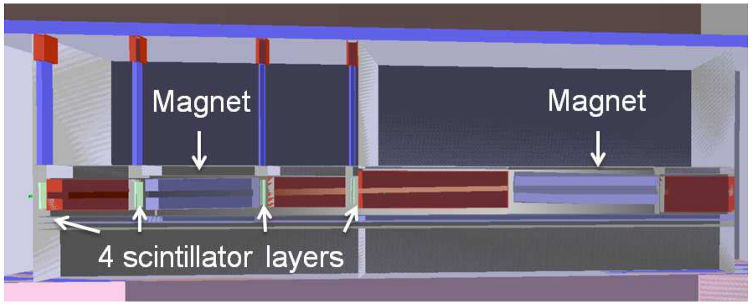
- A proton beam bunch hits on production target
- Generate pulsed beam of low momentum μ^-
- μ^- captured on stopping target to form muonic atoms
- Wait for prompt backgrounds to decay
- Select tracks in search window, when π^- disappear

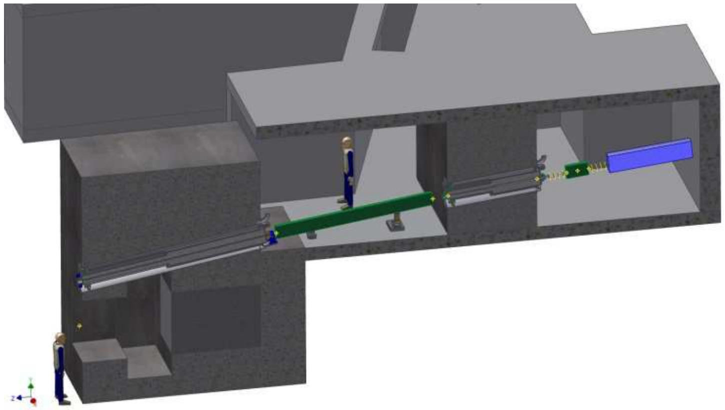
Proton beam extinction



- Beam extinction = (# protons between pulses) / (# protons in pulses)
- Protons produced between two pulses generate additional background
- Important for beam related background rejection

Extinction Monitor Design





Scintillator based

- 4 layers scintillator counters
- Detect particles ~ 1GeV/c
- Measure time of flight for different particles
- Track reconstruction from time of flight between layers

Silicon pixel detector based

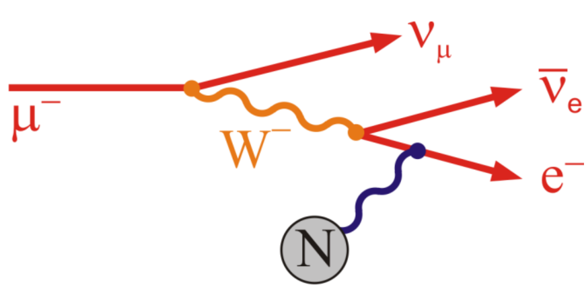
- 8 planes pixel detectors
- Detect particles 3~4 GeV/c
- Measure track hits position and reconstruct
- Selected for Mu2e
- More details in next talk

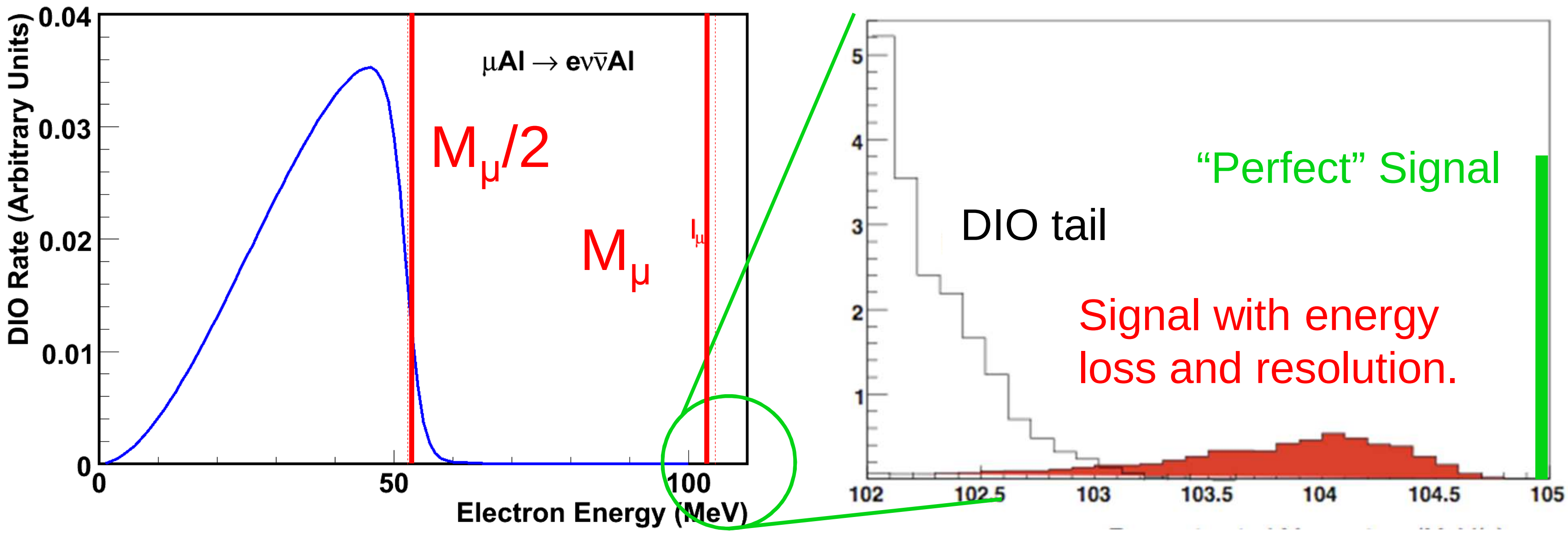
Dominant Background

1. Muon Decay-in-orbit (DIO)
   - Electron energy $E_{\mu e} = m_\mu - E_b - E_{rec}$

     Binding energy $E_b \sim Z^2\alpha^2 m_\mu/2$

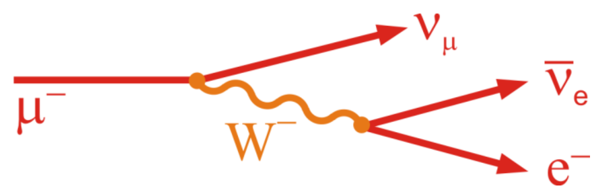
     Nuclear Recoil energy $E_{rec} \sim m^2_\mu/(2m_N)$
   - DIO Rate ~ $(E_{MAX} - E_e)^5$, E_{MAX} ~105 MeV
   - Requires good energy resolution

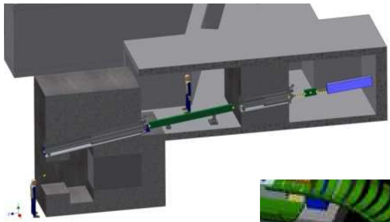




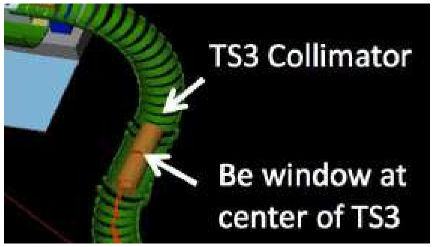
Other Backgrounds

2. Beam Related Background
   - μ/π free decay in flight
   - Radiative π- capture
   - Beam electrons
   - Beam extinction monitor to suppress protons between pulses < 10^{-10}

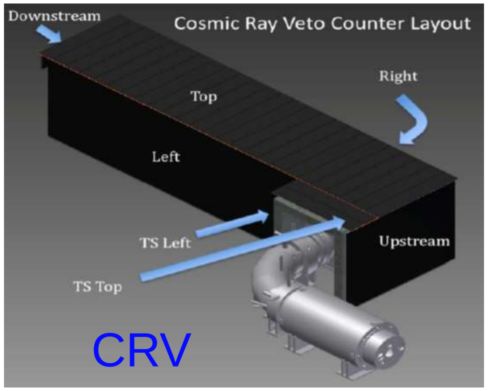




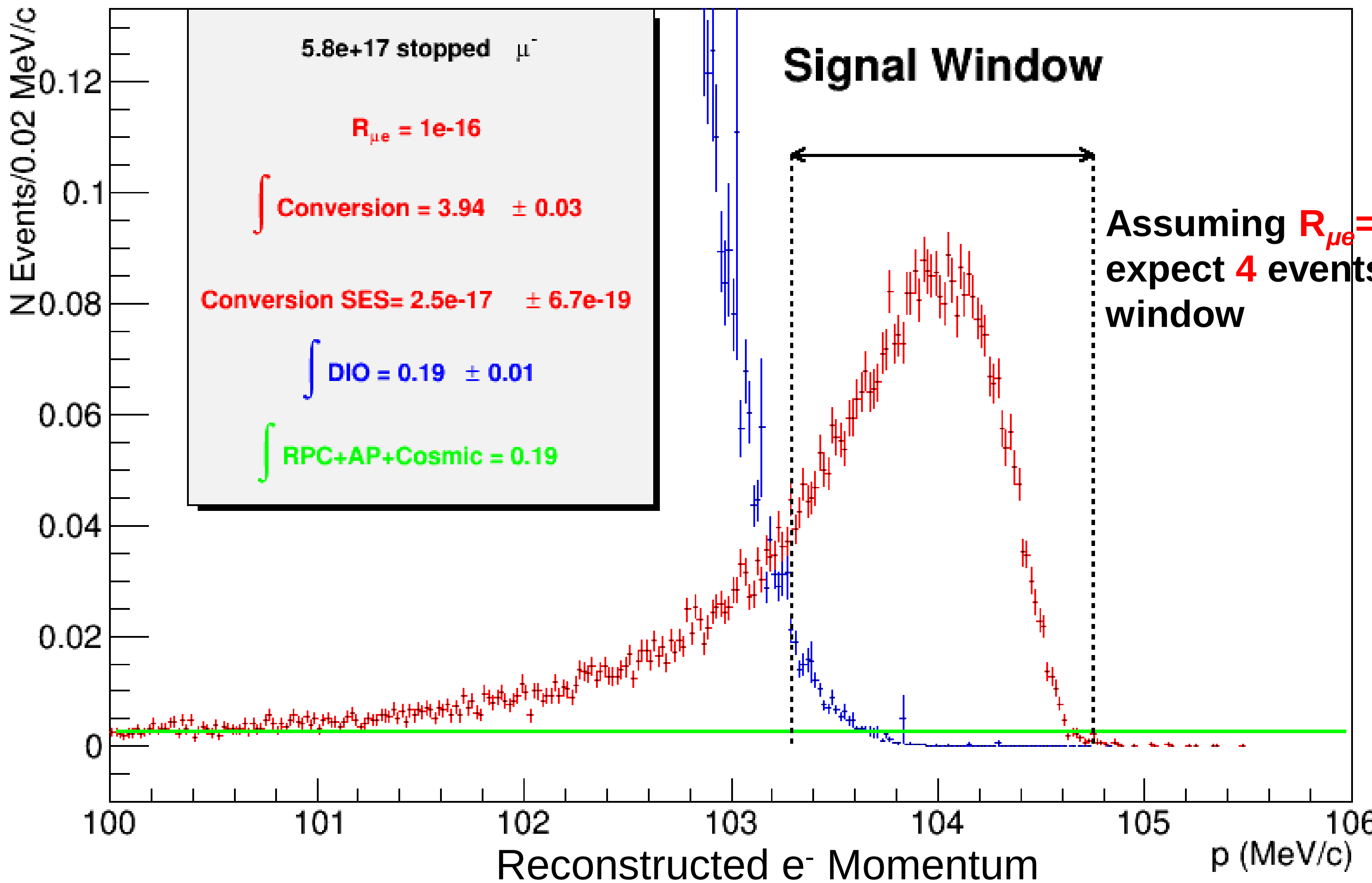
3. Anti-protons annihilation
   - Thin Be-window placed at TS center to stop anti-protons



4. Background from cosmic rays
   - Electrons generated by cosmic μ interaction
   - Time window and shielding from overburden & side
   - Cosmic ray veto with inefficiency < 10^{-4}



Reconstructed Signal and Background



Assuming $R_{\mu e}$=1 x 10^{-16} expect 4 events in signal window

Full Geant4 simulation, background overlay and reconstruction

Background & Sensitivity

Category	Source	Events	Error
Muon-Induced	μ decay in orbit	0.20	±0.06
	radiative π capture	0.04	±0.02
Prompt	Beam electrons	0.001	±0.001
	μ decay in flight	0.01	±0.005
Miscellaneous	Anti-proton induced	0.10	±0.05
	Cosmic ray induced	0.05	±0.013
Total		**0.4**	**0.1**

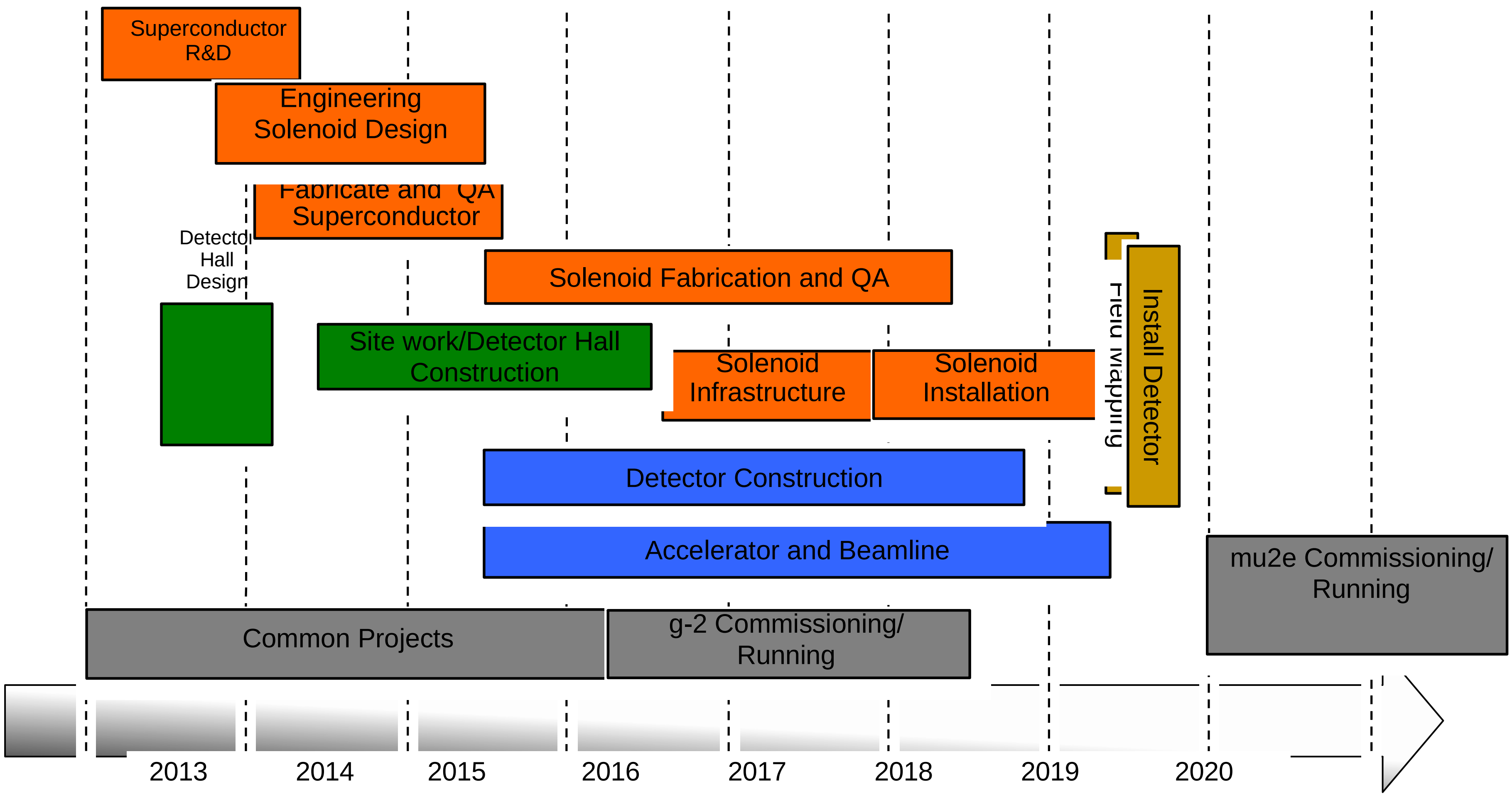
Preliminary Values

Backgrounds for 3 years run

Single event sensitivity $R_{\mu e} = 2.5 \times 10^{-17}$

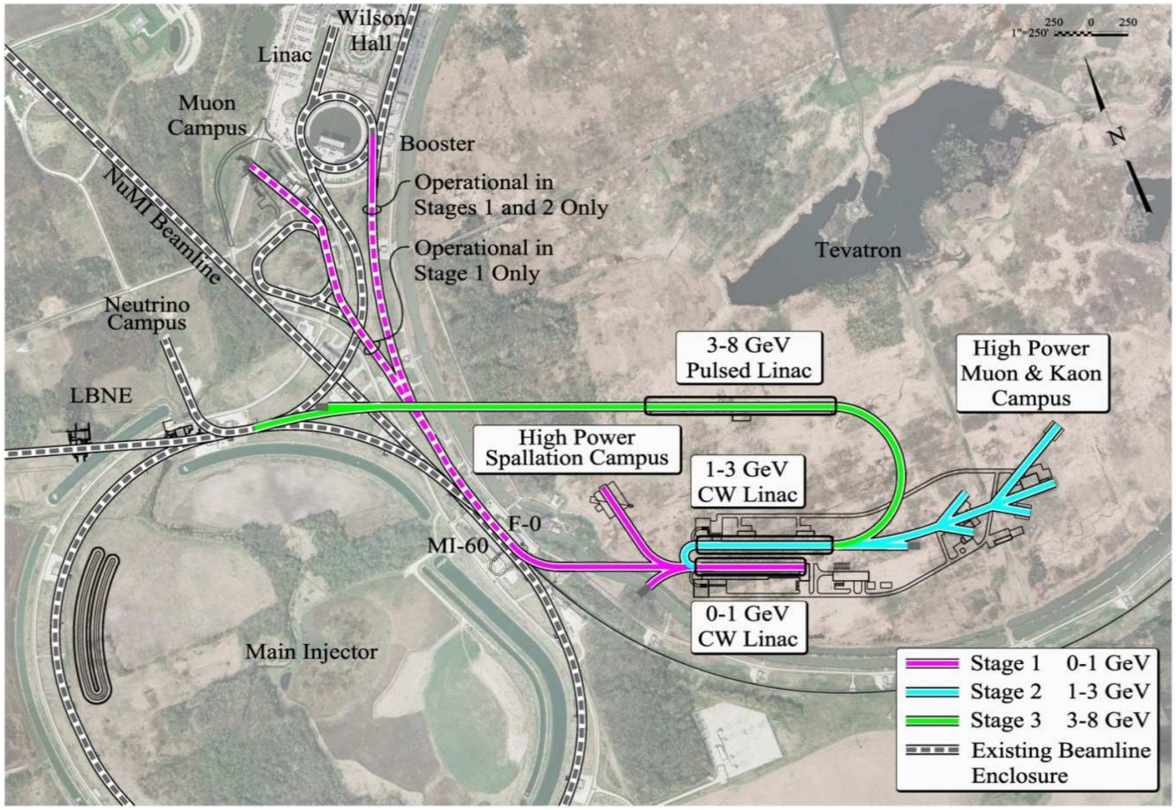
90% C.L. (if no signal) $R_{\mu e} < 6 \times 10^{-17}$

Mu2e Schedule



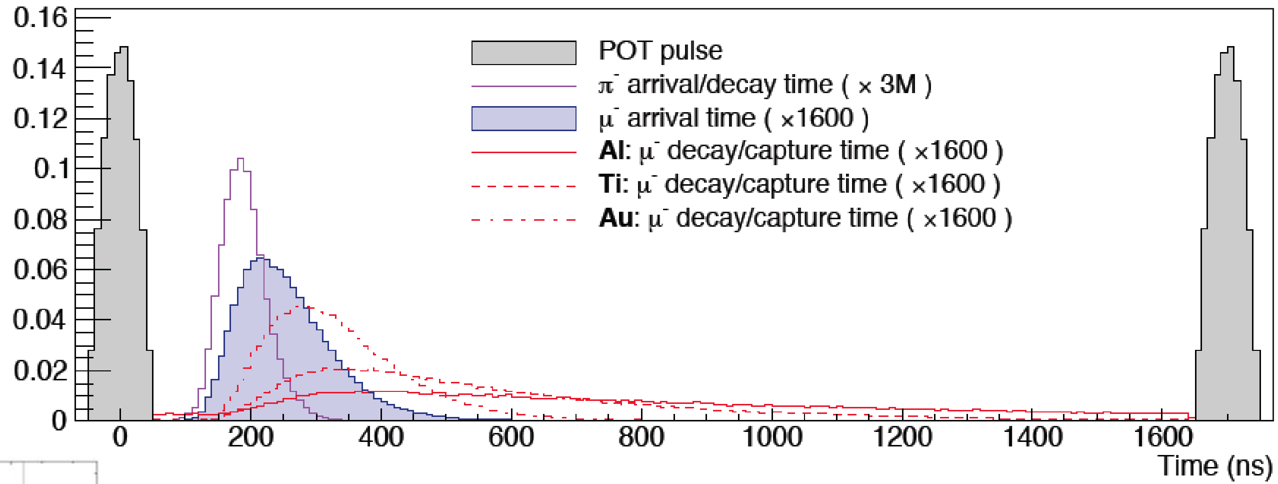
- Start construction in 2015
- Start running in 2020

Project X



- A proposed new high intensity proton linac at Fermilab
- 3 phases, compelling physics opportunities at each stage:
  - Neutrinos, Kaons, Muons, nucleons, and atomic probes
- Programmable pulse structure for many experiments

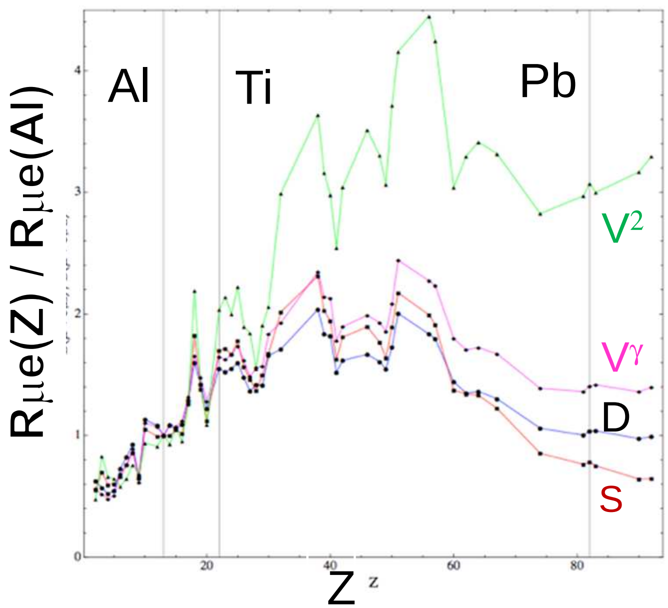
Mu2e at Project X



K. Konepfel et. al. arXiv:1307.1168

If signal:

Change target to study Z dependence of nucleus



V. Cirigliano et al., PRD 80 (2009) 013002

Project X beams will provide 10x muons ($10^{11}\mu/s$)

- Higher intensity, narrower pulse…

If no signal:

- Increase sensitivity by another 100x to $R_{\mu e} < 10^{-18}$
- Reuse most of Mu2e apparatus to achieve the first factor of 10

Summary

- CLFV is a good window to probe new physics beyond Standard Model with energy scale up to thousands of TeV
- Mu2e will search for CLFV in the process of $\mu N \rightarrow eN$
  - The goal is to achieve SES $R_{\mu e} = 2.5 \times 10^{-17}$
  - 4 orders of magnitude improvement to current limit
- The Mu2e project is well on-going
  - Conceptual design completed (DOE CD-1 in 7/2012)
  - Technical design to be completed in 2014
  - Start construction in 2015
  - Expect to start running in 2020
  - Project X could further improve the study in CLFV.

For Further Information

- Home page: http://mu2e.fnal.gov
- CDR: http://arxiv.org/abs/1211.7019
- Document Database:
  - http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase
  - Conference presentations
- Project X:
  - Accelerator Reference Design: physics.acc-ph:1306.5022
  - Physics Opportunities: hep-ex:1306.5009
  - Broader Impacts: physics.acc-ph:1306.5024

Thank you !