Mu2e

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Fermilab

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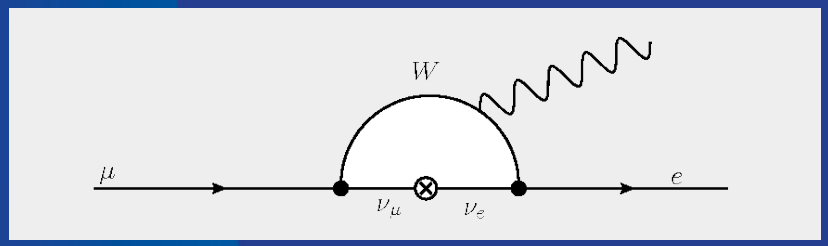
U.S. DEPARTMENT OF ENERGY

Fermilab

Mu2e

- Mu2e is an experiment to search for *charged lepton flavor violation* via coherent conversion of a μ^- to an e^- in field of a nucleus.
  - No emission of neutrinos, nucleus remains intact.
- We have observed neutrino oscillations, so lepton flavor is not conserved.
- Charged leptons *must* mix through neutrino loops.



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W}\right|^2 \leq 10^{-54}$$

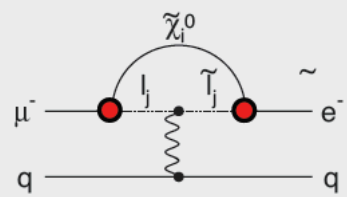
- No standard model pollution! An observation is unambiguous evidence for new physics.
- Wide array of new physics models predict muon to electron conversion at rates that can be observed by Mu2e.

Discovery Sensitivity

- Sensitivity over a broad range of new physics models

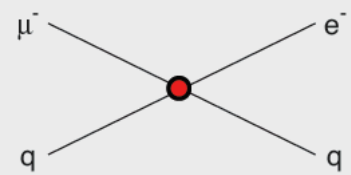
Supersymmetry

rate ~ 10^{-15}



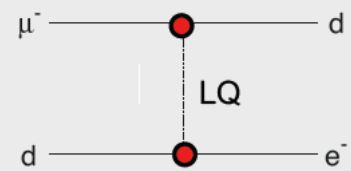
Compositeness

Λ_c ~ 3000 TeV



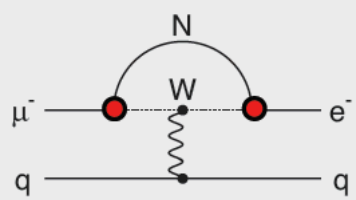
Leptoquark

M_{LQ} = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



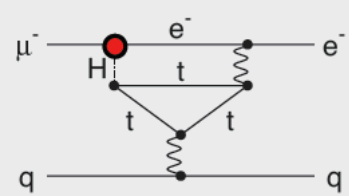
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



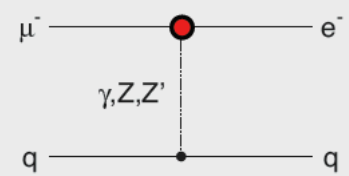
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



Mu2e Sensitivity

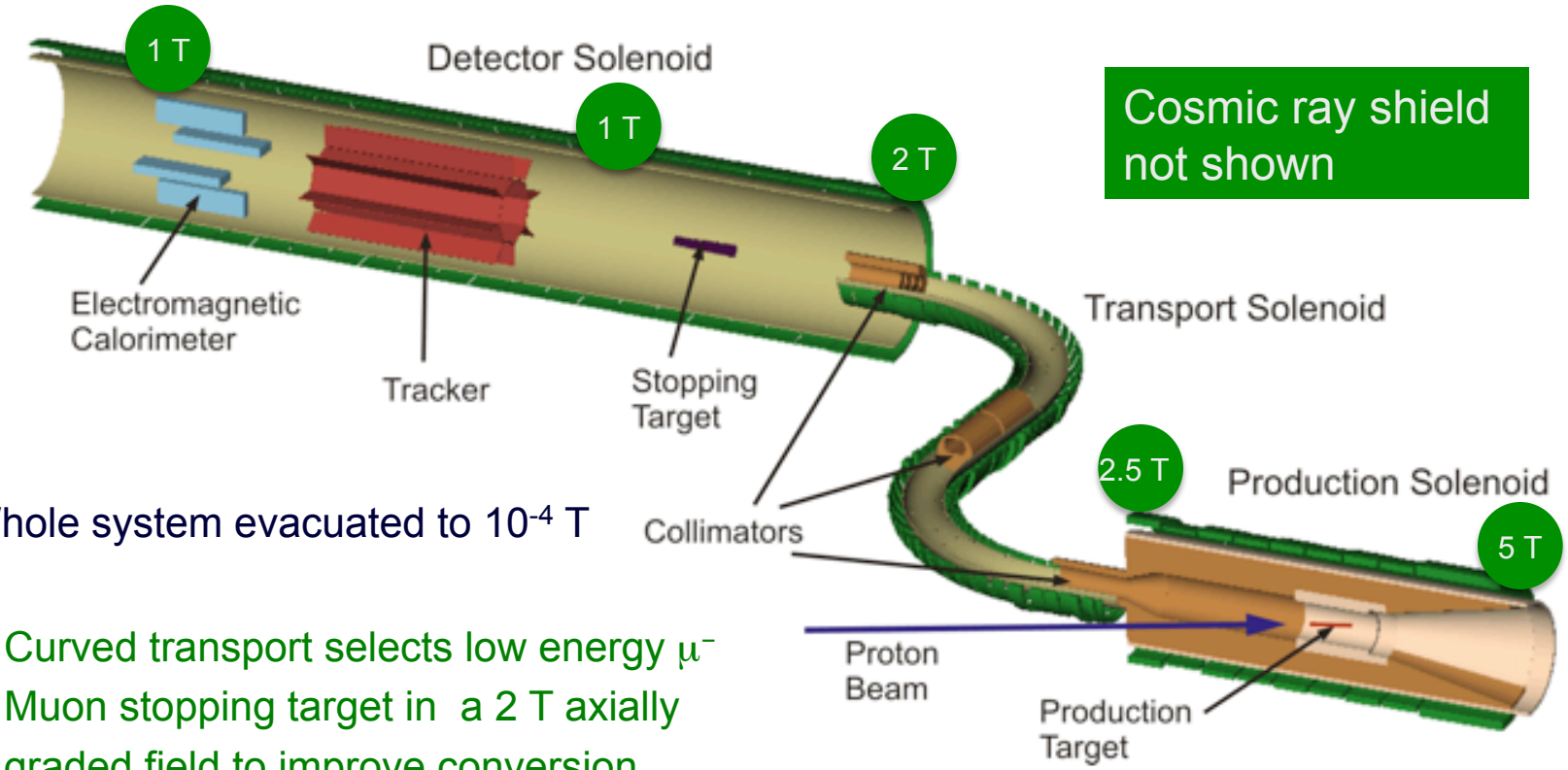
- Single event sensitivity = 2×10^{-17}

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)},$$

- For 10^{18} stopped muons
  - If $R_{\mu e} = 10^{-15}$ we will observe ~ 50 events
  - If $R_{\mu e} = 10^{-16}$ we will observe ~ 5 events
- Expected background < 0.5 event
  - Assumes 2×10^{7} s of running.
- Expected limit = 6×10^{-17} (90% C.L.)
  - Best existing limit is 6×10^{-13} (90% C.L.) from SINDRUM II
- > 5σ sensitivity for all rates > few 10^{-16}
  - 10^{-15} is near the middle of the range for LHC accessible SUSY.

Mu2e Detector

- High Z target to maximize pion production
- Axially-graded field to maximize pion capture



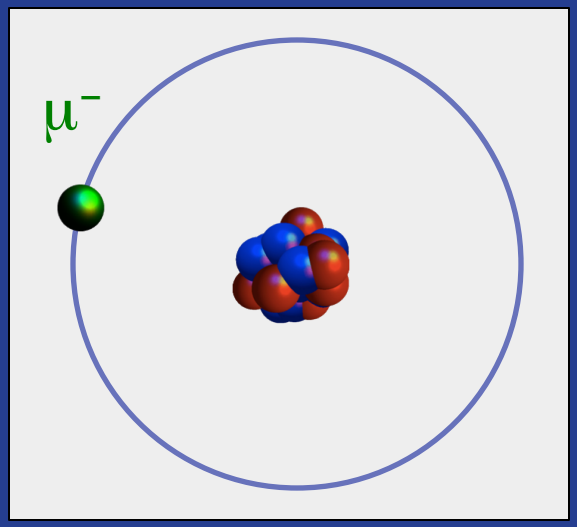
Cosmic ray shield not shown

Whole system evacuated to 10^{-4} T

- Curved transport selects low energy μ^-
- Muon stopping target in a 2 T axially graded field to improve conversion acceptance
- High rate e^- detectors in constant 1 T field.

Experimental Technique

- Divide Booster batches of 4×10^{12} protons into micro-bunches of 3×10^{7} protons separated by 1 – 2 muon lifetimes.
- Make lots of pions which decay to muons. Collect the muons.
- Stop ~ 5×10^{10} μ^- per Booster batch in an aluminum target. Make muonic Al.
  - Bohr radius ~ 20 fm
  - Al nuclear radius ~ 4 fm
  - Lifetime: 864 ns
- Wait 700 ns for prompt backgrounds to clear.

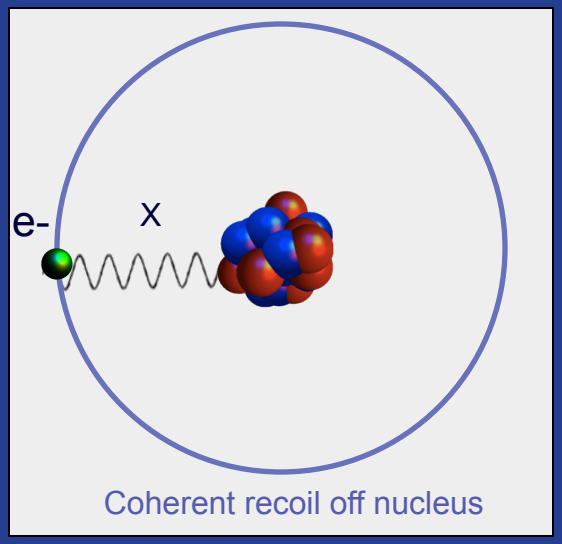


Experimental Technique

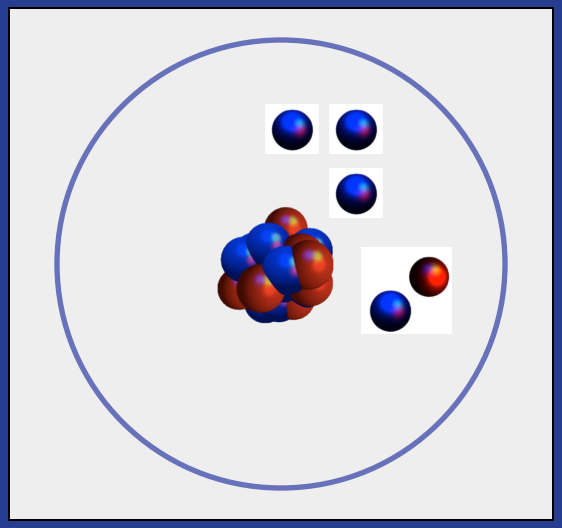
One of three things can happen to the stopped muons

1. Coherent, neutrinoless μ to e conversion

   Monoenergetic 105 MeV electron

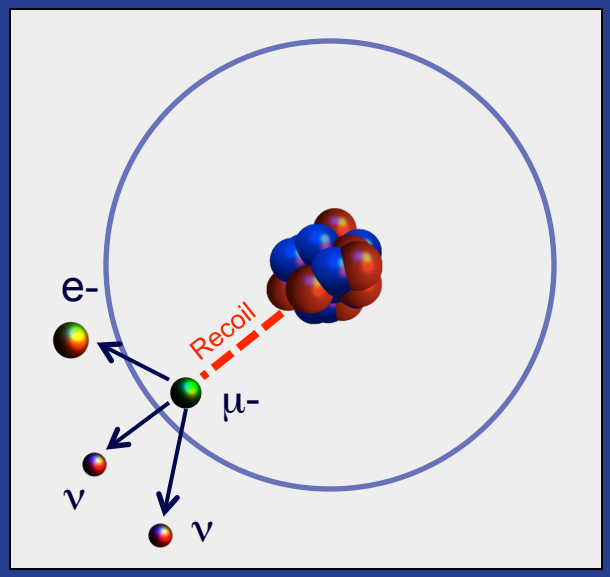


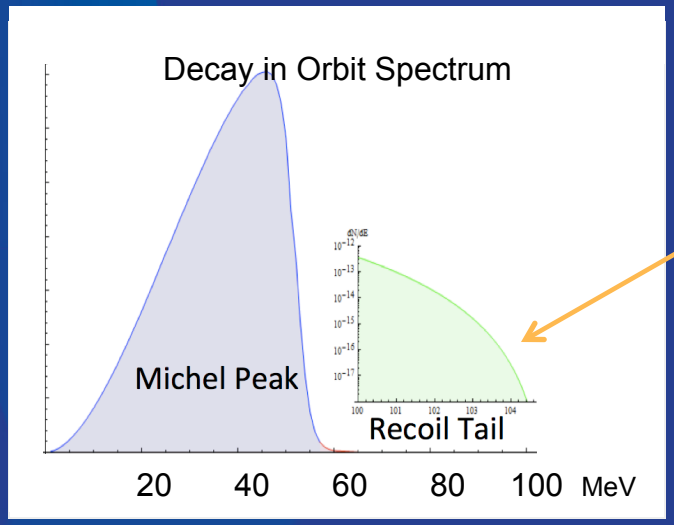
2. Muon capture on nucleus - 60%
   - Nuclear breakup
     - Emission of p, n, γ
       - Protons are the largest source of rate in the tracker.
       - Neutrons can fire cosmic ray veto
     - Energy spectrum of particles not well known.
       - Test beam at PSI to measure proton spectrum



Experimental Technique

3. Muon decay in orbit (DIO) - 40%
   - Recoil of nucleus distorts the Michel spectrum (slightly) and adds a recoil tail with an endpoint at the conversion energy.
     - Virtually all of the decays from the Michel peak pass through a hole in the center of the tracker and calorimeter and do not interact, contribute rate or background.

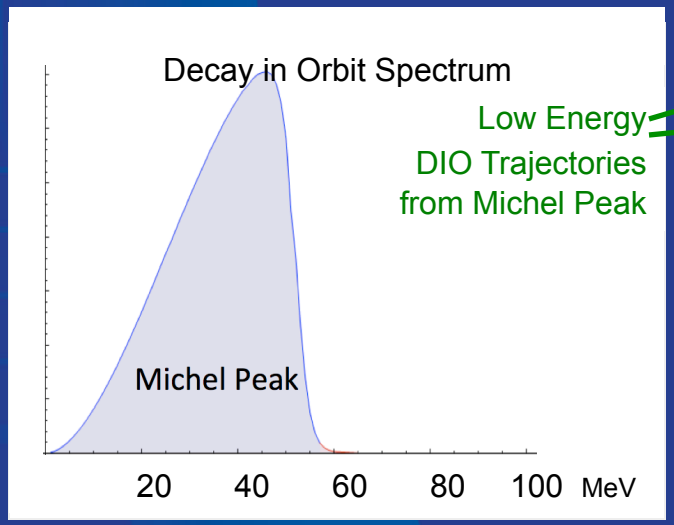


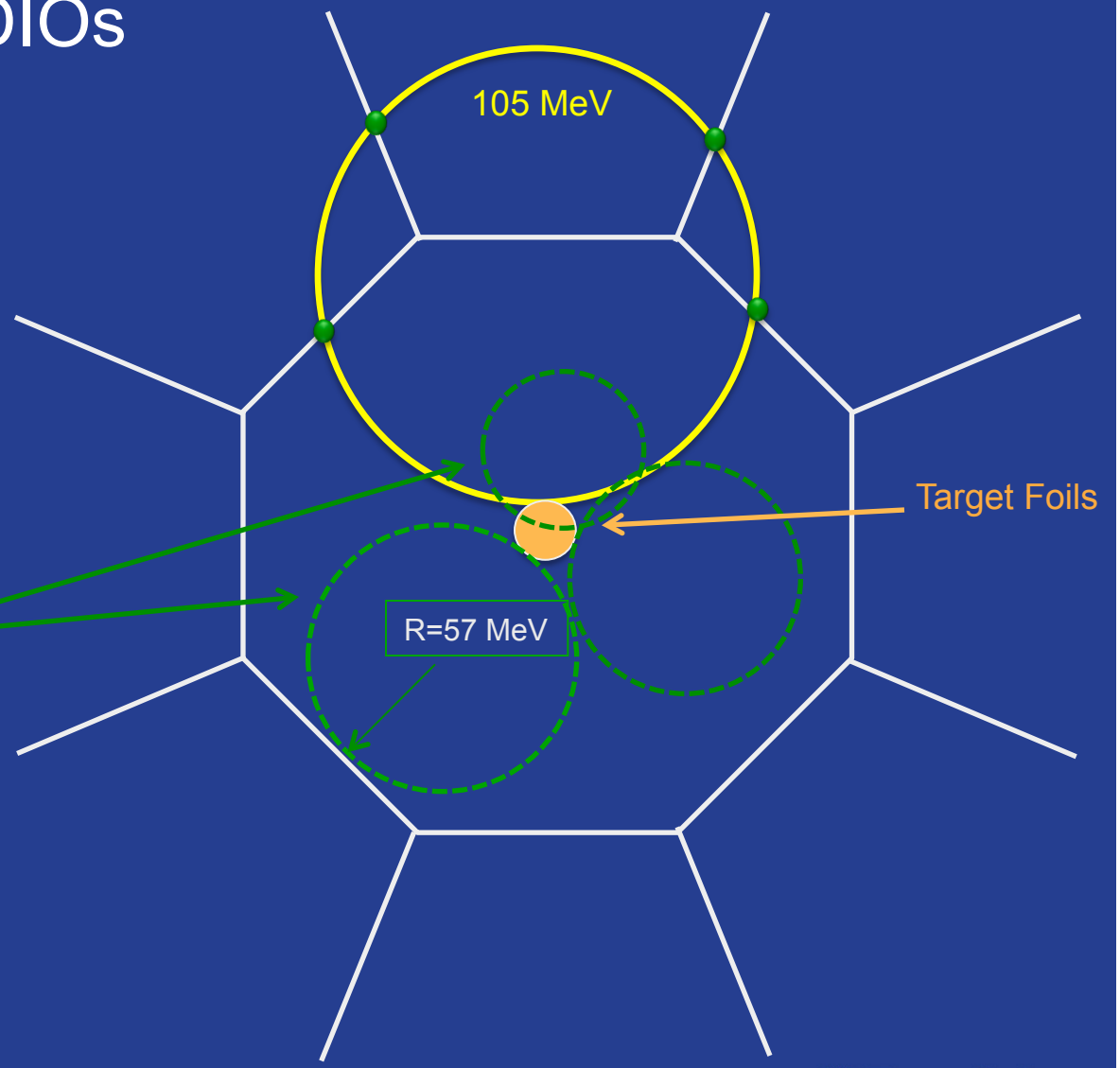


Events near the endpoint of the recoil tail can cause background if their momentum is not measured accurately.

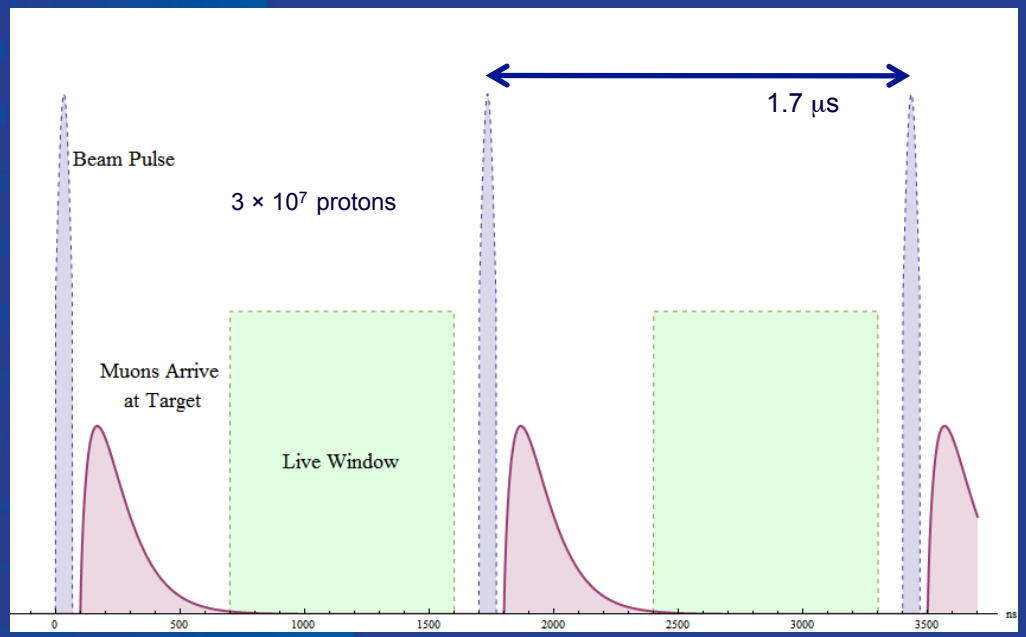
Rate from DIOs

Virtually all of the DIOs pass through the hole in the detector without interacting.





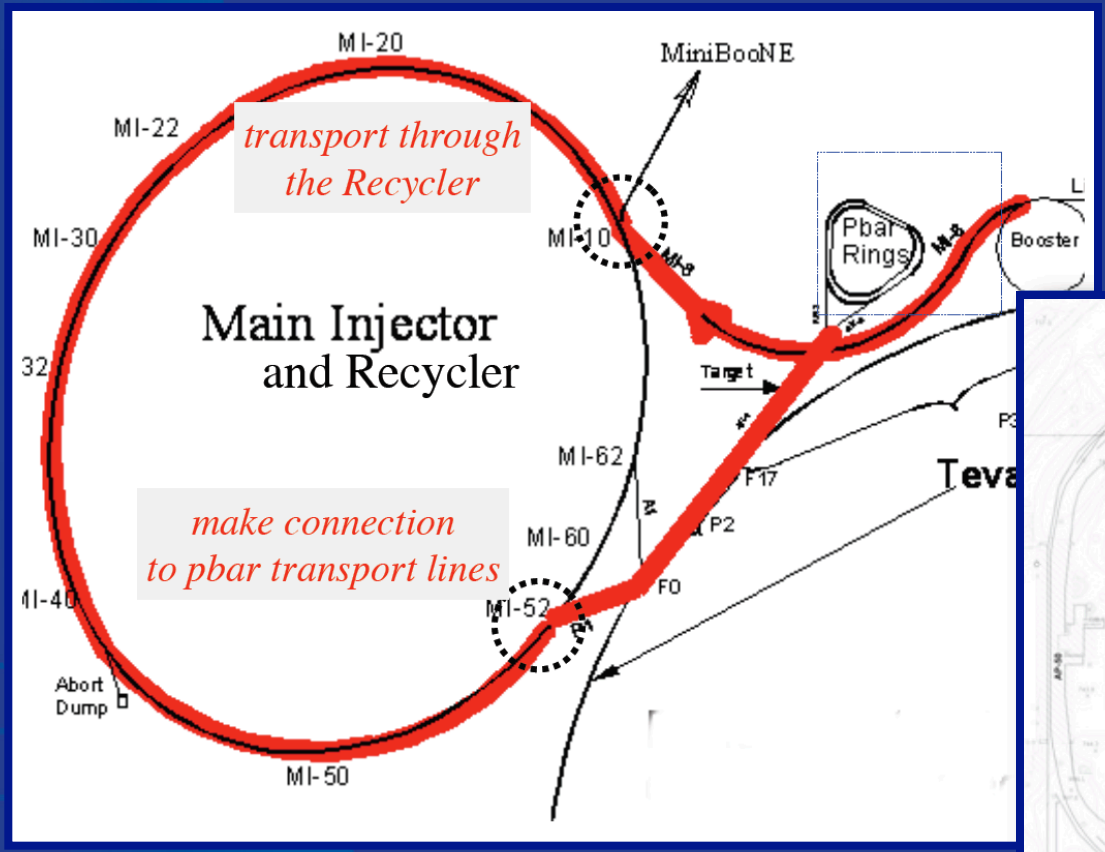
Maximizing the productivity of the existing facility. The Mu2e accelerator scheme.



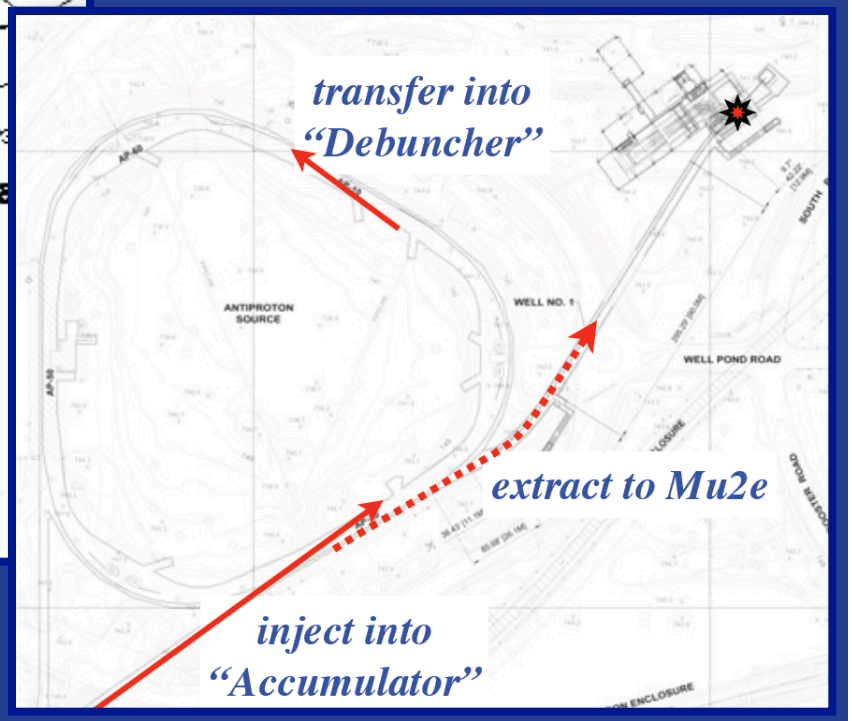
Don't want proton beam between pulses

- Mu2e requires a very specific beam structure
- We can accomplish this with some modest changes and upgrades to the existing Fermilab accelerator plant.
- In particular, the pbar source is ideally suited to our needs
- We require proton pulses separated by 1-2 muon lifetimes
  - Revolution time in Fermilab pbar source is 1.7 μs. Perfect!

Accelerator Concept



- Use Booster batches that are available when Main Injector is ramping.
  - No impact on NOvA

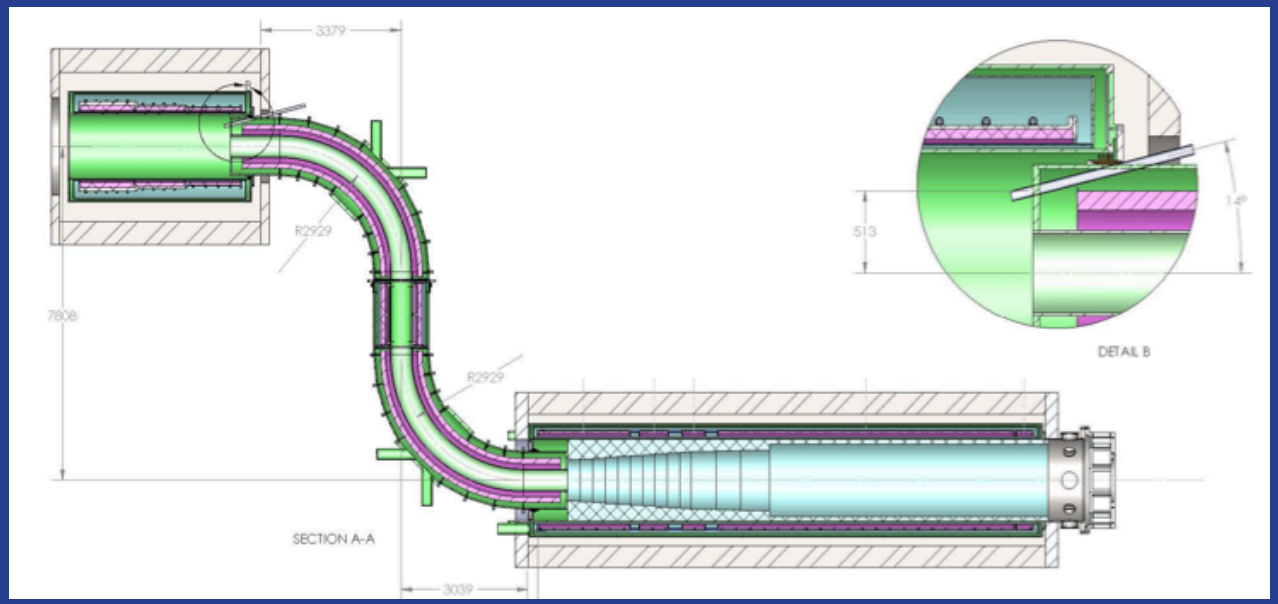


Future Facility Upgrades: The Booster

- In order to use remaining Booster cycles all Booster components must operate at 15 Hz.
- In NOvA era, 15 Hz operation is necessary to run MicroBooNe and Mu2e.
  - Improves reliability for NOvA as well.
- 15 Hz operation is not part of any project is part of continuing accelerator facility upgrade plans.
  - Task force formed by AD Division Head

Solenoids

- The solenoids are the cost and schedule driver for Mu2e. They are the most complex and challenging part of the project.
- The Fermilab Technical Division has taken the lead on the Solenoid system providing management, engineering and technical expertise.

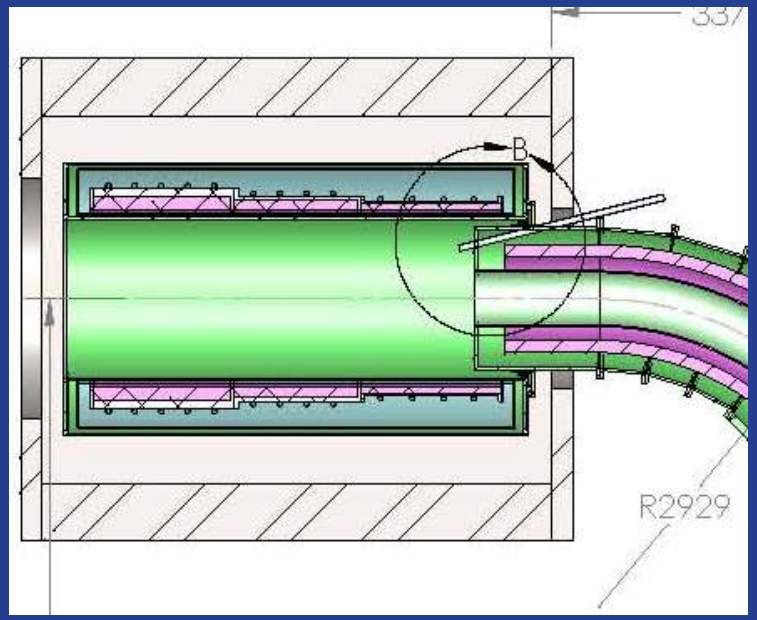


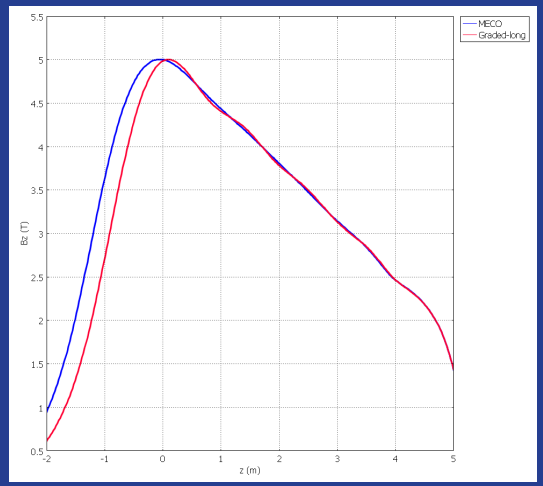
Solenoids

- Starting point for the Mu2e solenoids was the MECO design.
  - We inherited a nearly complete set of field specifications from MECO that drive the overall design.
  - MECO design nearly 10 years old
  - Heavily constrained because of free SSC superconductor
- Technical Division Magnet Design Group has developed modern designs for the solenoids that are simpler, less risky, less expensive to operate and (hopefully) less expensive than the original designs.

Production Solenoid

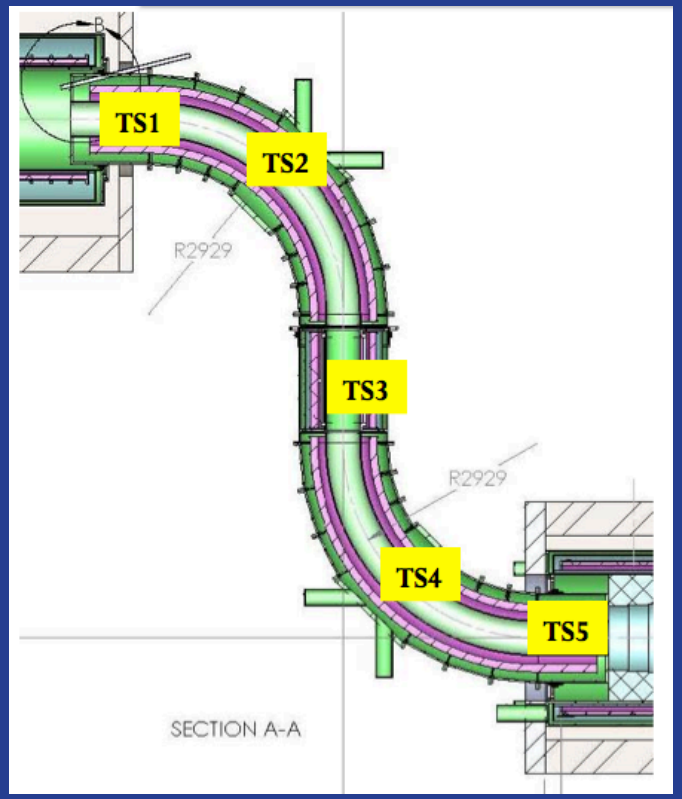
- Simple 3-coil design meets field specs. Gradient made by 3 axial coils with same turn density but increased # of layers.
  - MECO PS – 11 individual coils
    - Driven by SSC cable lengths
- Aluminum stabilized NbTi
  - Reduce weight and nuclear heating
- Higher Current/lower inductance
  - Efficient energy extraction
  - Fewer layers simplifies winding, minimizes thermal barriers from conductor to cooling channels. Allows for simpler cooling scheme.



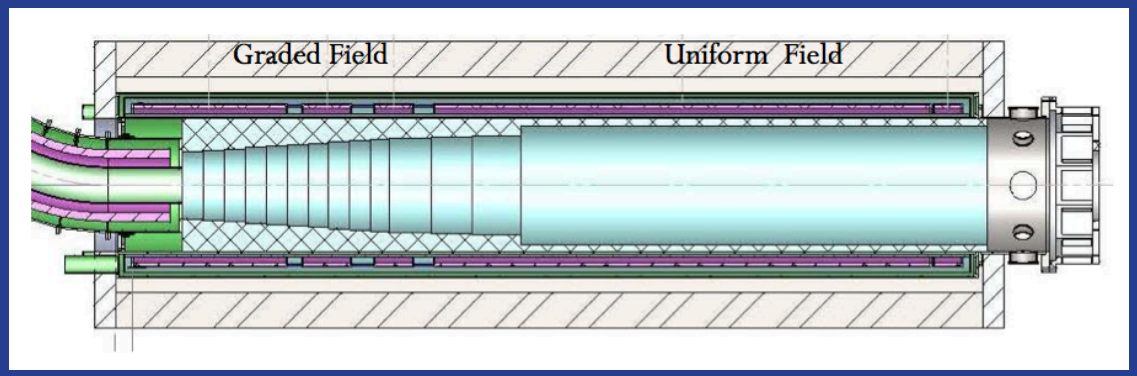


Transport Solenoid

- MECO design is very complex.
  - 62 individual coils, almost all of them different. Many with half windings, one with reverse current.
- Working on a simpler design with fewer unique components.
  - 5 magnetic elements TS1- TS5 placed in 3 separate cryostats
  - TS1, TS3, TS5 wound on single straight mandrel,
  - TS2,TS4: solenoid rings wound on wedge mandrels units
  - “Wire in channel” conductor may be a good approach here because of small stored energy.



Detector Solenoid



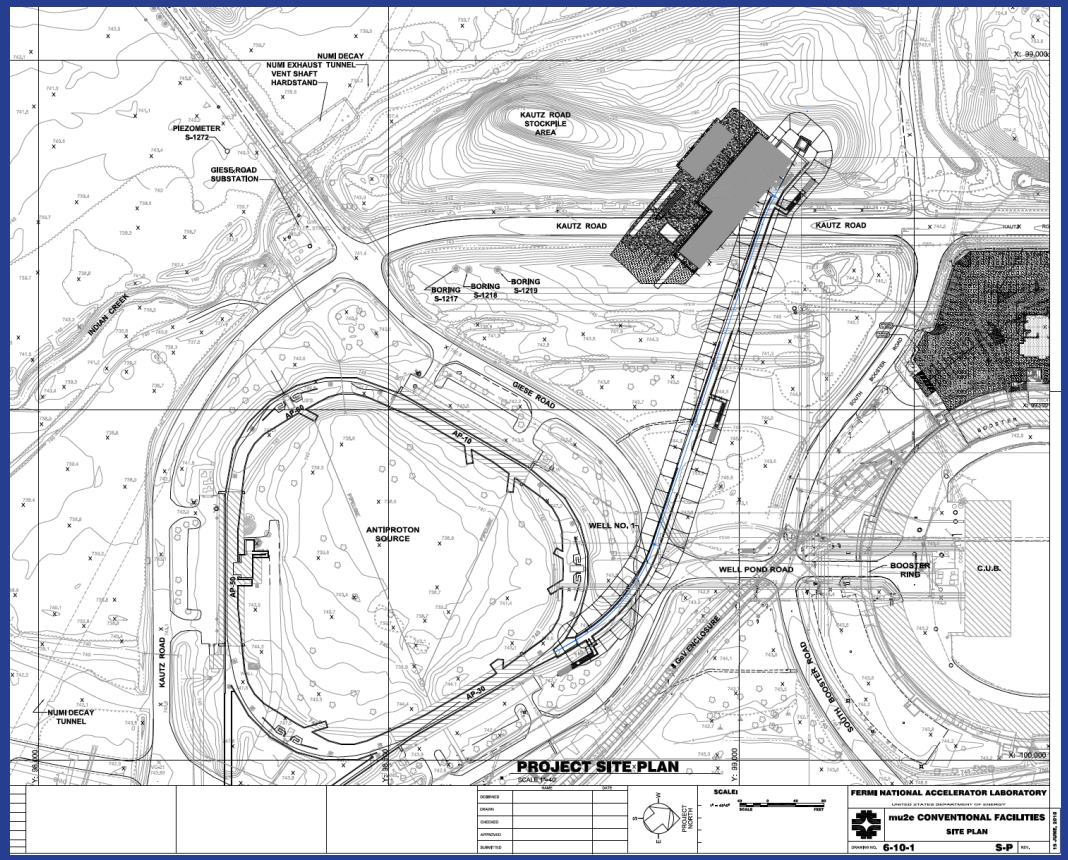
- Graded and Uniform coils wound on separate mandrels
- Place in “single cryostat”
- Use Al stabilized NbTi conductor
  - More experience with detector solenoid vendors
  - Considerably less weight
- Two layer coils throughout
  - Achieve axial gradient by effectively changing winding density and by introducing spacers.

Solenoid Procurement Plan

- Plan is to do design and build for the Production and Detector Solenoids.
  - This will be a complex, time consuming, expensive and high-profile procurement.
  - Fermilab Procurement experts are critical to this process.
  - Mike Yeoward from Business Services Section assigned to solenoid project.
- Plan to design and build the Transport Solenoid at Fermilab
  - Procure many of the parts from Industry.
- Fermilab acts as the general contractor for the solenoid project.

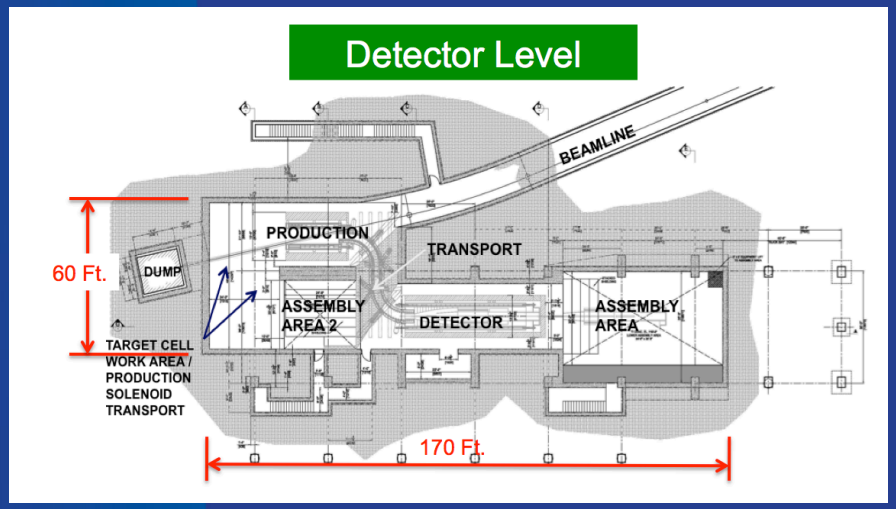
Civil Construction

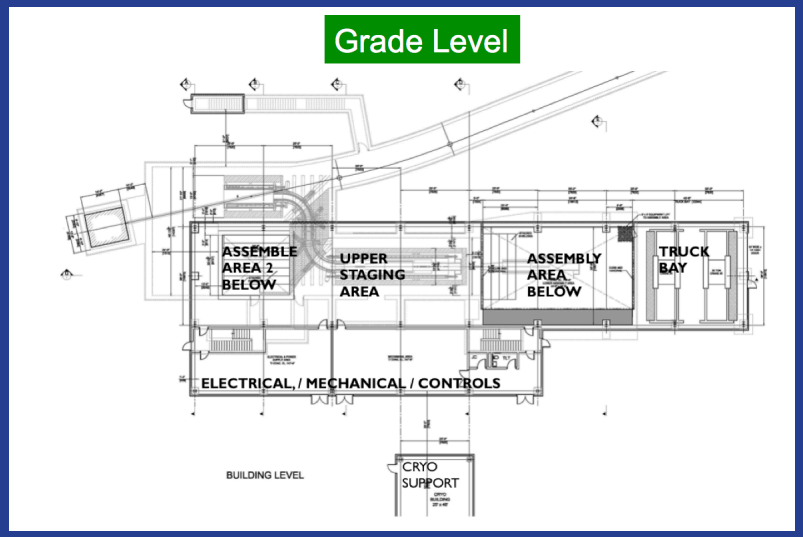
- Design and construction of detector hall led by FESS engineers and designers
- Design is the result of extensive discussions with various stakeholders

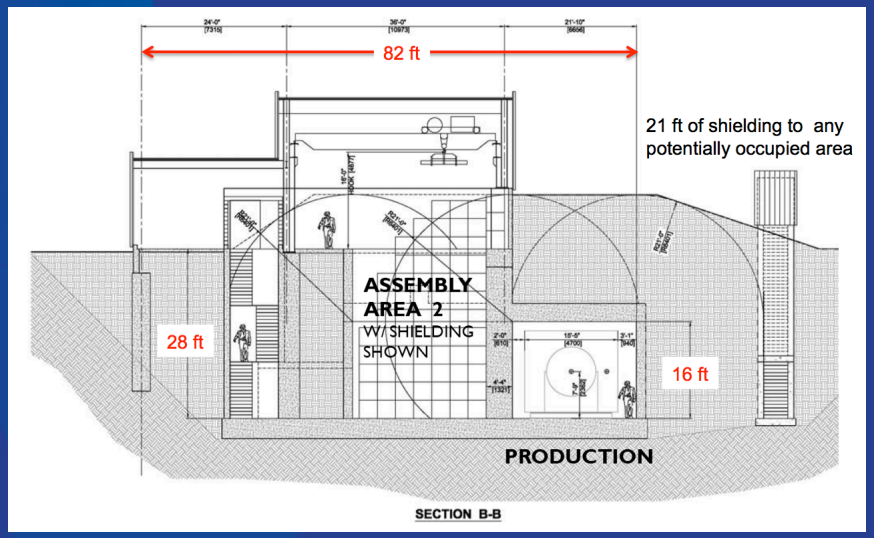


Bird's Eye View

New location is here

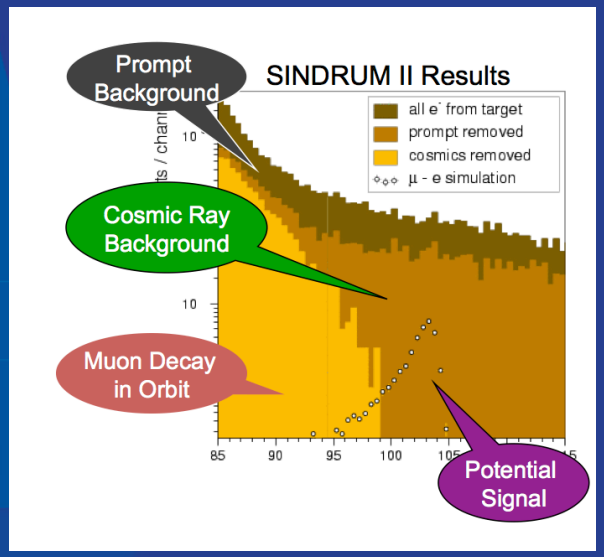

Detector Level
BEAMLINE
PRODUCTION
TRANSPORT
60 Ft.
DUMP
ASSEMBLY AREA 2
DETECTOR
ASSEMBLY AREA
TARGET CELL
WORK AREA /
PRODUCTION
SOLENOID
TRANSPORT
170 Ft.

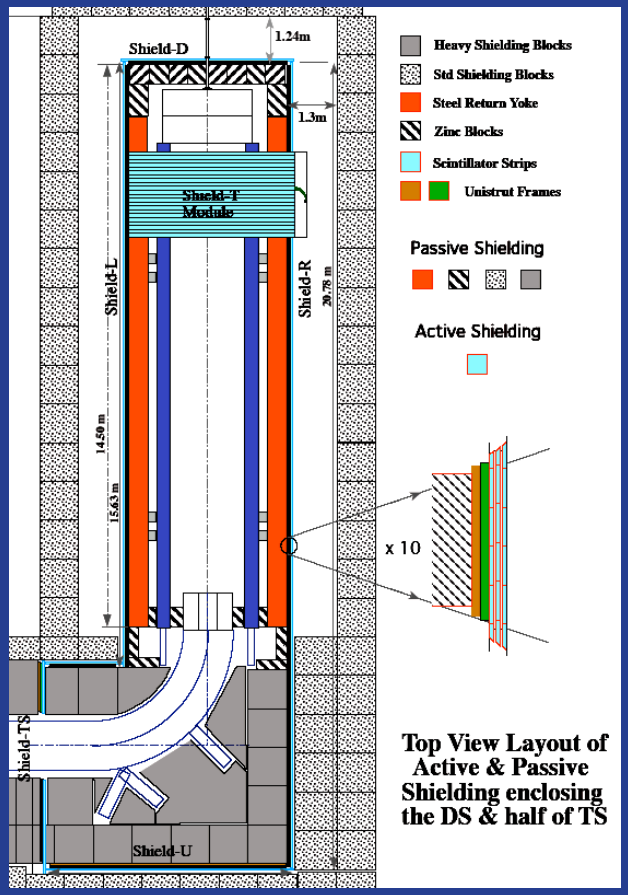

Grade Level
ASSEMBLE AREA 2 BELOW
UPPER STAGING AREA
ASSEMBLY AREA BELOW
TRUCK BAY
ELECTRICAL, / MECHANICAL / CONTROLS
BUILDING LEVEL
CRYO SUPPORT


82 ft
21 ft of shielding to any potentially occupied area
ASSEMBLY AREA 2
W/ SHIELDING SHOWN
28 ft
16 ft
PRODUCTION
SECTION B-B

Scintillator for Cosmic Ray Veto

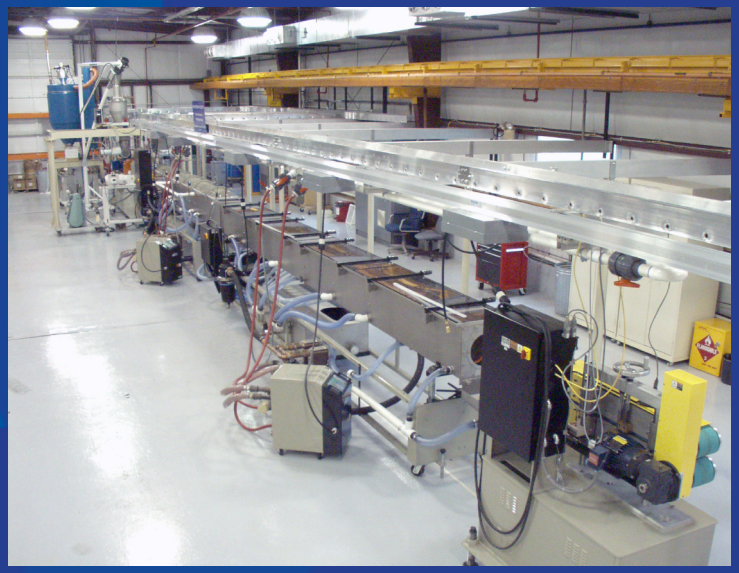
- Cosmic rays have generated background events in previous experiments.
  - Mu2e needs a high efficiency (> 99%), nearly hermetic, veto around the Detector Solenoid.
  - Insensitive to neutrons

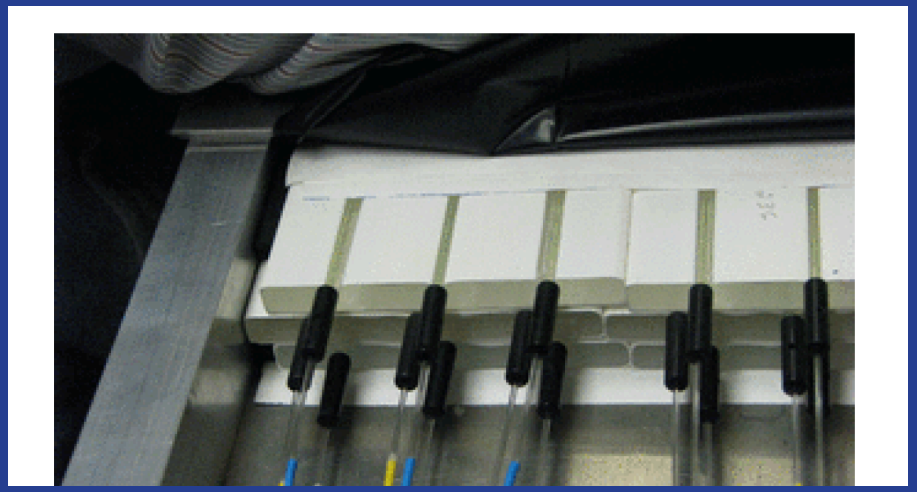




Cosmic Ray Veto

- Baseline veto design is extruded scintillator from the FNAL - NICADD scintillator extrusion facility.
  - Internationally recognized facility
    - MINERvA, K2K → SciBooNe, JLaB, Sandia
- Ongoing R&D effort for Mu2e to optimize light output and neutron ID and to minimize cracks.



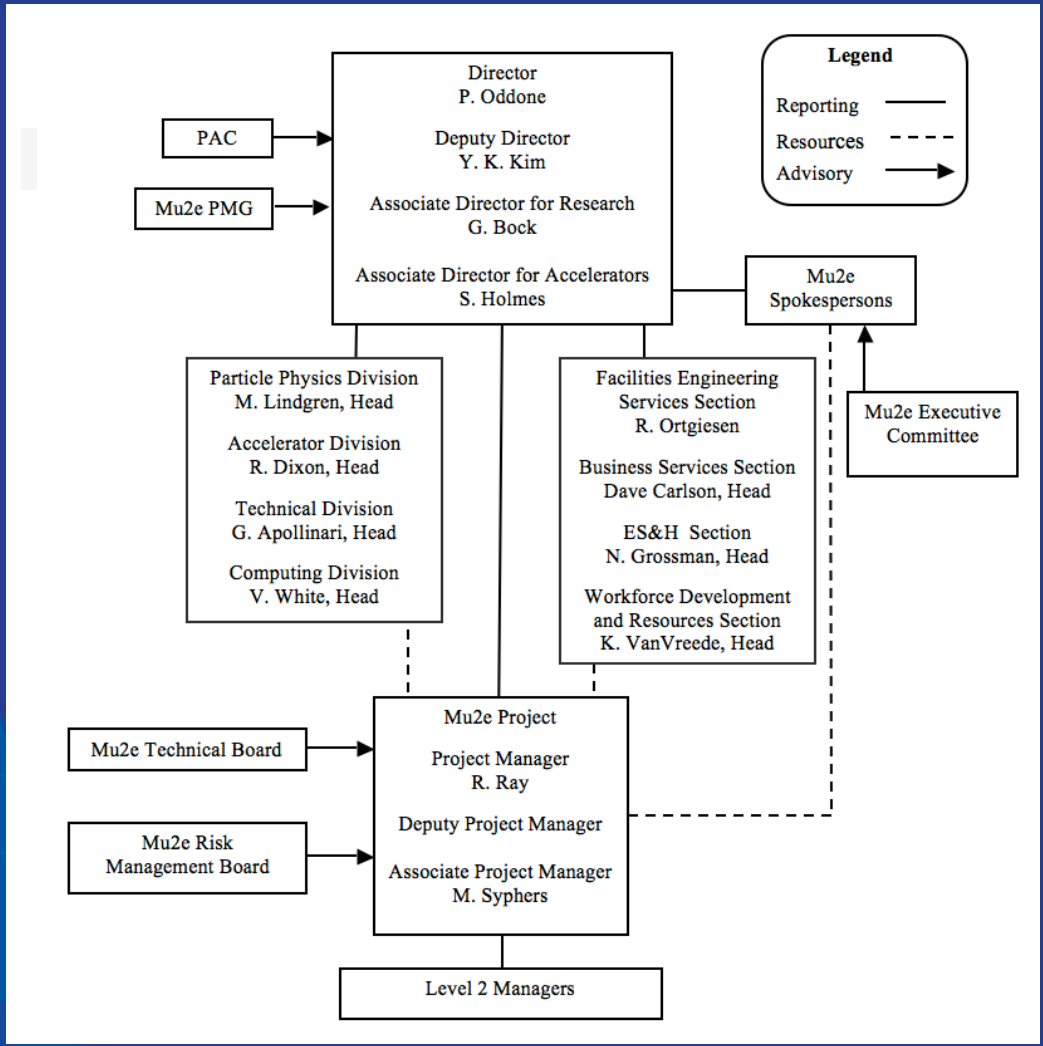


Computing

High statistics simulation runs are important for many aspects of the Mu2e design.

- Swimming large samples of particles through the solenoids to identify potential traps for low energy particles that could arrive late and create background.
- Large statistics samples of tracks in the straw tubes to look for misreconstructed events that might appear as background.
  - Study how to identify these events with the calorimeter.
- The Fermilab grid provides us with this capability.

Project Management

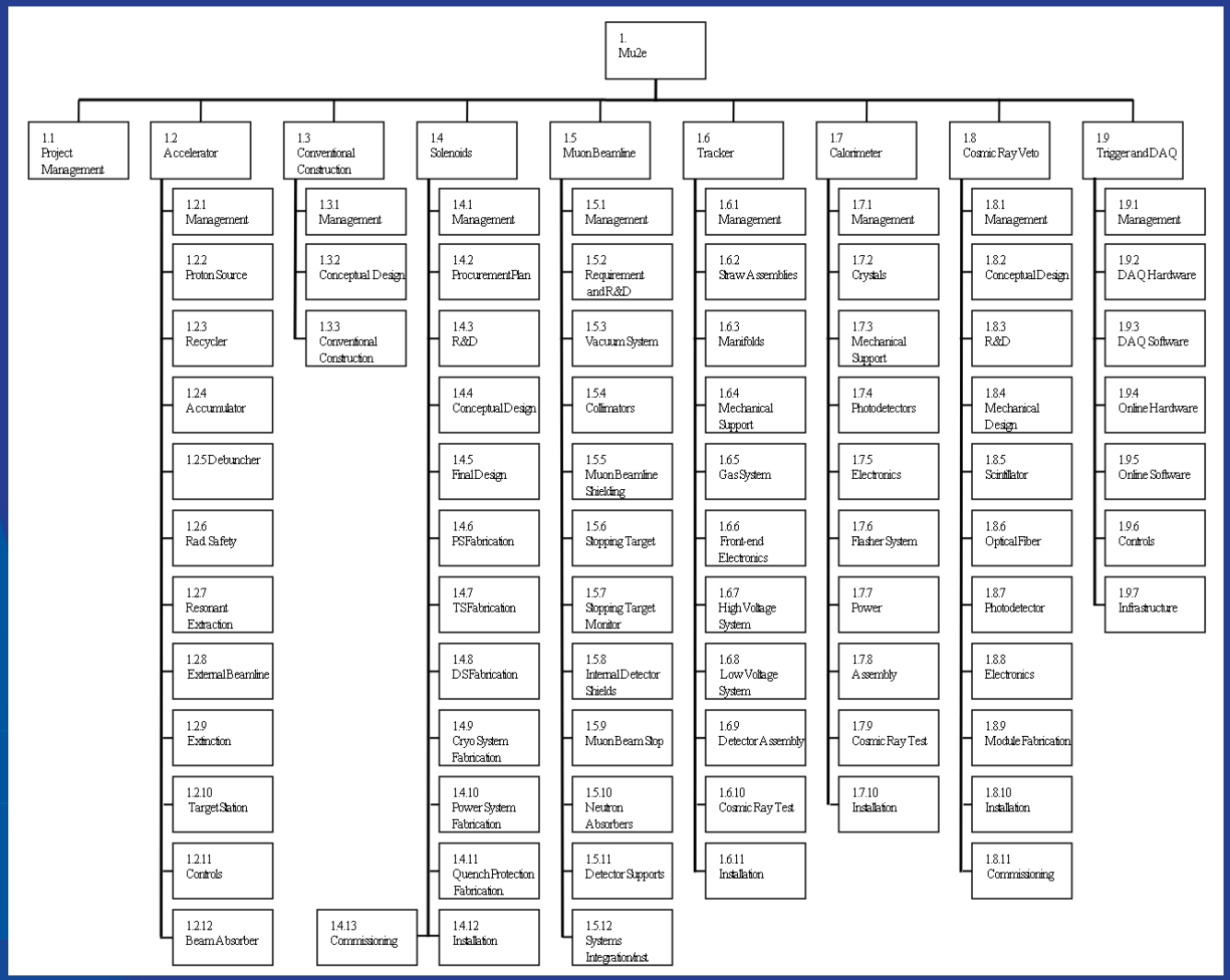


Project Management

1.1 Project Management R. Ray FNAL	**1.2 Accelerator** M. Syphers FNAL	**1.3 Conventional Construction** T. Lackowski FNAL	**1.4 Solenoids** M. Lamm FNAL	**1.5 Muon Channel** S. Feher FNAL
1.6 Tracker A. Mukherjee FNAL	**1.7 Calorimeter** INFN	**1.8 Cosmic Ray Veto** C. Dukes UVa.	**1.9 Trigger and DAQ** M. Bowden FNAL	

7 of 9 L2 Managers from Fermilab

WBS – L3


1. Mu2e
1.1 Project Management
1.2 Accelerator
1.2.1 Management
1.2.2 Proton Source
1.2.3 Recycler
1.2.4 Accumulator
1.2.5 Debuncher
1.2.6 Rad. Safety
1.2.7 Resonant Extraction
1.2.8 External Beamline
1.2.9 Extinction
1.2.10 Target Station
1.2.11 Controls
1.2.12 Beam Absorber
1.3 Conventional Construction
1.3.1 Management
1.3.2 Conceptual Design
1.3.3 Conventional Construction
1.4 Solenoids
1.4.1 Management
1.4.2 Procurement Plan
1.4.3 R&D
1.4.4 Conceptual Design
1.4.5 Final Design
1.4.6 PS Fabrication
1.4.7 TS Fabrication
1.4.8 DS Fabrication
1.4.9 Cryo System Fabrication
1.4.10 Power System Fabrication
1.4.11 Quench Protection Fabrication
1.4.12 Installation
1.4.13 Commissioning
1.5 Muon Beamline
1.5.1 Management
1.5.2 Requirement and R&D
1.5.3 Vacuum System
1.5.4 Collimators
1.5.5 Muon Beamline Shielding
1.5.6 Stopping Target
1.5.7 Stopping Target Monitor
1.5.8 Internal Detector Shields
1.5.9 Muon Beam Stop
1.5.10 Neutron Absorbers
1.5.11 Detector Supports
1.5.12 Systems Integration/Inst.
1.6 Tracker
1.6.1 Management
1.6.2 Straw Assemblies
1.6.3 Manifolds
1.6.4 Mechanical Support
1.6.5 Gas System
1.6.6 Front-end Electronics
1.6.7 High Voltage System
1.6.8 Low Voltage System
1.6.9 Detector Assembly
1.6.10 Cosmic Ray Test
1.6.11 Installation
1.7 Calorimeter
1.7.1 Management
1.7.2 Crystals
1.7.3 Mechanical Support
1.7.4 Photodetectors
1.7.5 Electronics
1.7.6 Flasher System
1.7.7 Power
1.7.8 Assembly
1.7.9 Cosmic Ray Test
1.7.10 Installation
1.8 Cosmic Ray Veto
1.8.1 Management
1.8.2 Conceptual Design
1.8.3 R&D
1.8.4 Mechanical Design
1.8.5 Scintillator
1.8.6 Optical Fiber
1.8.7 Photodetector
1.8.8 Electronics
1.8.9 Module Fabrication
1.8.10 Installation
1.8.11 Commissioning
1.9 Trigger and DAQ
1.9.1 Management
1.9.2 DAQ Hardware
1.9.3 DAQ Software
1.9.4 Online Hardware
1.9.5 Online Software
1.9.6 Controls
1.9.7 Infrastructure

Project Office

Currently on board
Needed by CD-1
Needed by CD-2

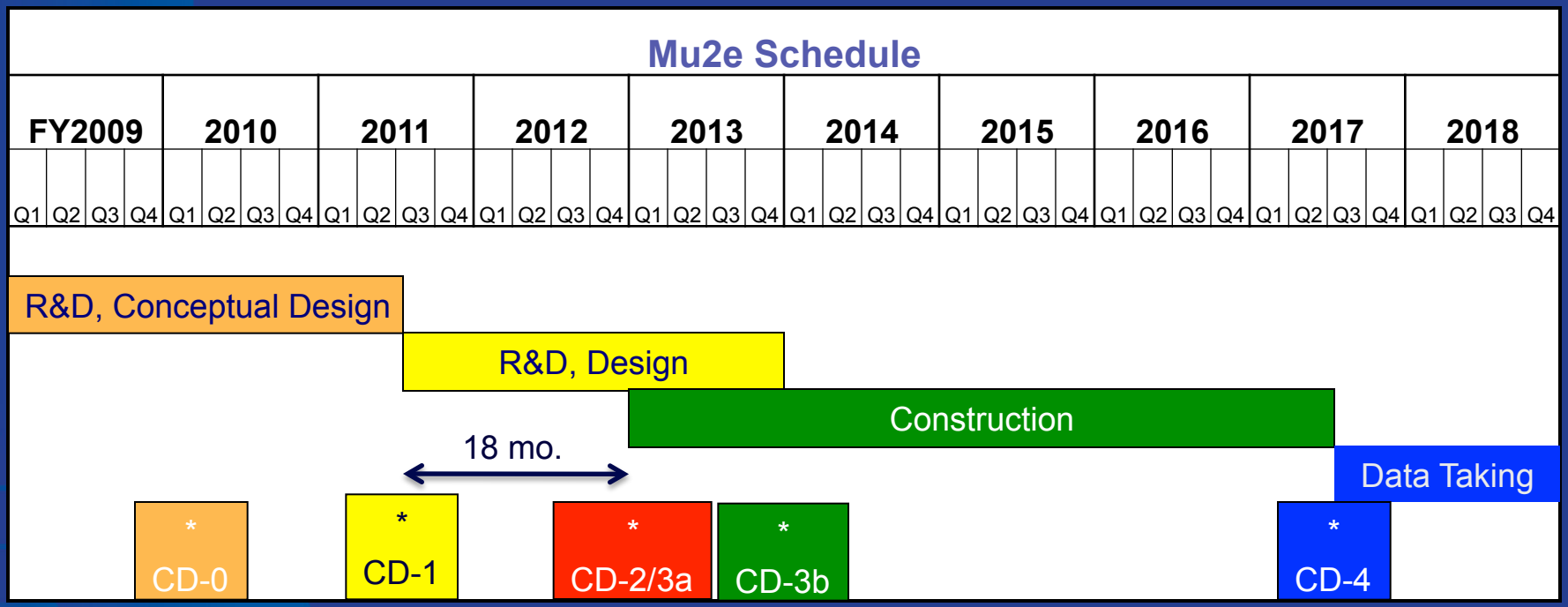
- Project Manager (1 FTE)
- Deputy Project Manager
- Associate Project Manager (0.75 FTE)
- L2 Managers (7 of 8)
- Project Controls (1.5 FTE*)
- Project Budget Manager (0.25 FTE)
- Project Mechanical Engineer (0.25 FTE)
- Project Electrical Engineer
- Project Procurement Administrator
- Project Risk Manager
- Project Configuration Manager
- Project Quality Manager
- Project ES&H (0.1 FTE)
- Project Webmaster
- Project Administration (0.1 FTE**)

* Since June

** Department admin helping out

Schedule

Schedule is technically driven but consistent with finding profile



Obtained CD-0 in Nov. 2009

TPC Estimate

- $200M Total Project Cost that includes a 51% overall contingency.
  - This is the profile that we submitted for CD-0 in April, 2009.
    - Did not include the cost of scientists. New rules implemented in December, 2009.
  - Top down estimate based on MECO cost & input from AD and FESS.
  - For CD-1 we will have a new estimate based on our WBS.
    - Will match the funding profile
    - Shooting for 40 – 45% contingency. (35% at CD-2).

	2009	2010	2011	2012	2013	2014	2015	2016	Total
R&D	$600	$4,200							**$4,800**
Conceptual Design	$1,800	$4,200							**$6,000**
PED			$14,700	$17,300					**$32,000**
Construction					$62,500	$47,500	$33,000	$14,200	**$157,200**
Total AY k$	$2,400	$8,400	$14,700	$17,300	$62,500	$47,500	$33,000	$14,200	**$200,000**

Support of Collaborators

- Bought 2 Professors out of teaching to reside for a year at the Lab.
  - One continuing for a second (and last) year.
- 3 International Fellows from INFN will be in residence for 2 years beginning this summer.
- Support for CERN scientist to spend a year at Fermilab working on the solenoids
- Support for Russian and Italian colleagues to spend time at the lab over the summer.

From upcoming Symmetry Magazine article on Mu2e

From the Last Review

- Comments:
  - The collaboration urgently requires additional strength, with more substantial commitments from the collaborators.
- Response
  - A Continuing concern.
  - In the past year Los Alamos and the University of Houston have joined.
  - New RAs at Rice and Virginia have made a big difference
    - Funds for a second RA at Rice are being provided. Trying to get an RA at Berkeley/LBNL.
  - New junior faculty at Virginia, jointly funded by Fermilab, expected to make significant contribution.
  - Groups funded by nuclear physics having a hard time getting funding for Mu2e.

From the Last Review

Comments:

- A substantial effort to attract international collaborators would also be appropriate. This may require consideration of and coordination with, a similar project being proposed in Japan.
- Response:
  - INFN is engaged but needs to be more coherent.
  - Ranko Ostojic from CERN will spend a year at Fermilab working on the solenoids.
  - We are in regular contact with the Japanese, share information on numerous fronts, are doing some joint R&D and working together on plans for a conversion experiment at Project X.
    - Open invitation to Japanese to join Mu2e

From the Last Review

Comment:

- The Mu2e project may is very challenging and its schedule is aggressive. The lab should conduct a systematic review of the performance required of each of the critical components and what is required in terms of R&D and demonstrations to show that this performance is achievable. The actual experiment may need several tries to reach its full potential. The lab should ascertain the needs for long-term commitment of lab resources and personnel to see this through.

From the Last Review

Response:

- Monthly working group meetings with lab management began in the spring.
- Regular meetings with Steve Holmes and Greg Bock
- Internal solenoid review conducted last week in June.
- Series of internal design reviews scheduled for the Fall.
- Formal Director's Design Review of entire project to take place in the fall.
- Mu2e fully engaged in OHAP long range planning exercise.

From the Last Review

Recommendations:

- Laboratory management and the collaboration should develop a plan that details the resources needed by both the project and the collaboration to successfully mount and execute the experiment.

Response

- This is a work in progress. We have a good understanding of the resources needed to get to CD-1. Working on the longer term needs.
- Fully engaged in the OHAP process.

Summary

- Mu2e was strongly recommended by P5 based on its physics reach and potential impact. The science is first-rate.
- Mu2e is a technically challenging experiment that requires a complex, state-of-the art detector.
- We are taking advantage of Fermilab's unique capabilities and facilities to provide beam to the experiment, to design, build and procure the solenoids, to produce inexpensive scintillator, to do high statistics computing and to manage the project.
- Still struggling to get collaborators more engaged. Some modest support for RAs goes a long way.