The Mu2e Experiment

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Overview

- Motivation and Theory
- Experiment Overview
- Experiment Design
    - Proton Beam
    - Production and Stopping Targets
    - Tracker
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    - CRV
    - DAQ/Trigger
- Mu2e Schedule
- Mu2e II
- Summary

Motivation

- Mu2e is searching for Charged Lepton Flavor Violation (CLFV)
  - Specifically, the conversion of a μ^- to an e^- in the field of a nucleus:

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$

- Using the current Fermilab accelerator complex, we intend to achieve a sensitivity 4 orders of magnitude better than current limits:

Target Sensitivity:

$$R_{\mu e} = \frac{\Gamma\left[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)\right]}{\Gamma\left[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)\right]} < 6.7 \times 10^{-17} (90\%\mathrm{CL})$$

4 orders of magnitude better than current limits: **SINDRUM II [W. Bertl et al., Eur. Phys. J. C 47, 337-346 (2006)]**

- We will have discovery sensitivity over a broad range of New Physics parameter space

Flavor Violation

- We have known for a long time that quarks mix $\Longrightarrow$ (Quark) Flavor Violation
  - Mixing strengths parameterized by the CKM matrix

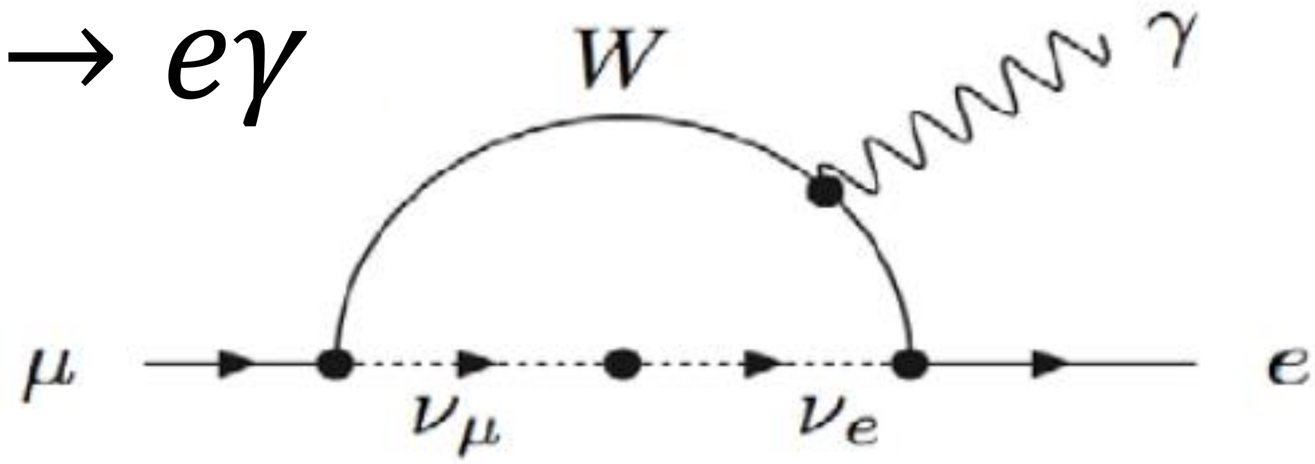
- We have known since 2001 that neutrinos can also mix $\Longrightarrow$ (Neutral) Lepton Flavor Violation
  - Mixing strengths parameterized by the PMNS matrix

- Why not charged leptons as well?
  - Charged Lepton Flavor Violation (CLFV)

CLFV in the Standard Model

- CLFV is not technically allowed in the SM because since charged lepton number is accidentally conserved when neutrinos are massless
- However, if we include massive neutrinos in our model then CLFV becomes possible at the loop level due to neutrino oscillations:

$$\mu \to e\gamma$$



- This process is extremely suppressed ($\mathcal{B}(\mu^- \to e^-\gamma) < 10^{-54}$)
- Therefore, any signal at our sensitivity would be a sign of new physics

Example CLFV Processes

- Potential channels for CLFV searches:

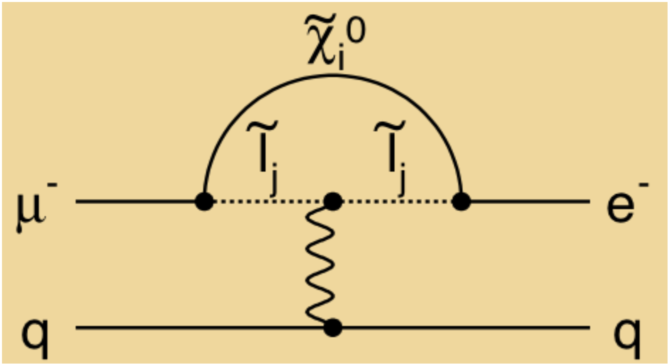
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \times 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 6.8 \times 10^{-8}$	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 3.2 \times 10^{-8}$	
$\tau \to eee$	$\mathrm{BR} < 3.6 \times 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \times 10^{-12}$	
$K^+ \to \pi^+ e^- \mu^+$	$\mathrm{BR} < 1.3 \times 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \times 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \times 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2\ \mathrm{x} \times 10^{-13}$	10^{-14} (MEG Upgrade)
$\mu^+ \to e^+ e^+ e^-$	$\mathrm{BR} < 1.0 \times 10^{-12}$	10^{-16} (Mu3e)
$\mu N \to eN$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17} (Mu2e, COMET)

- Although CLFV τ processes could have larger branching ratios than μ processes, dedicated muon experiments can produces $O(10^{10})$ μ/s whereas colliders produce $O(10^{10})$ τ/year

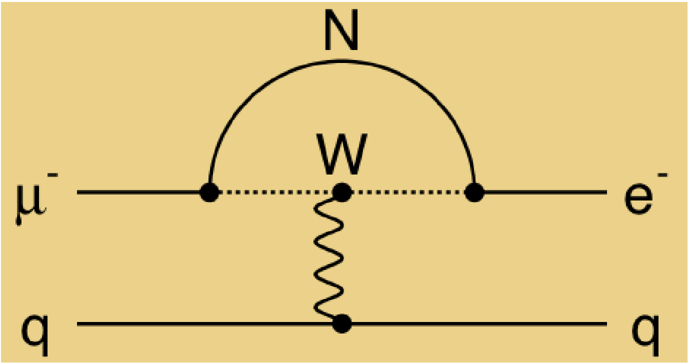
New Physics Reach

- There are many possible new physics contributions to $\mu N \rightarrow e N$, either through loops or the exchange of heavy intermediate particles
  - Many NP models predict rates observable at next gen CLFV experiments

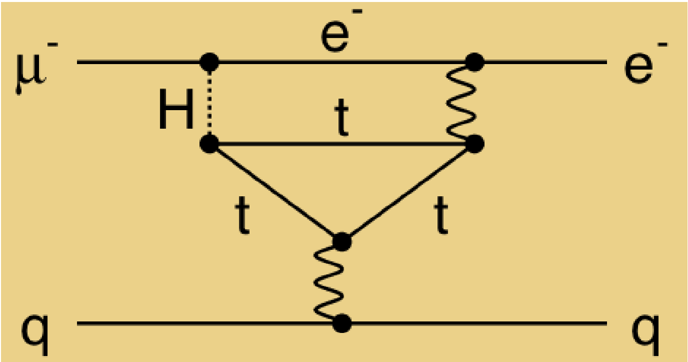
Loops



Supersymmetry

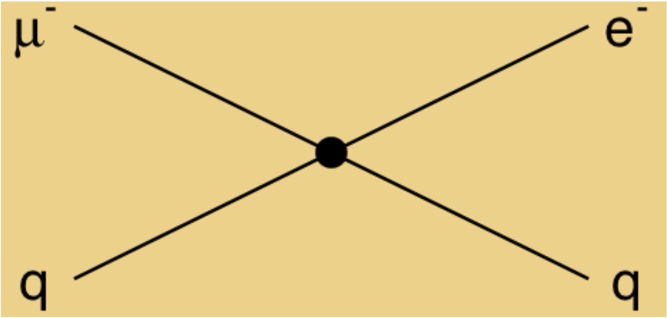


Heavy Neutrinos

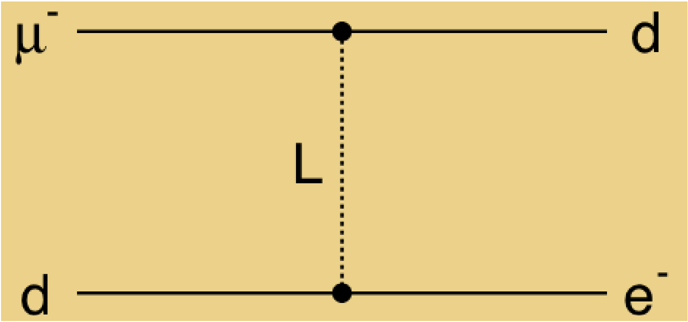


Two Higgs Doublets

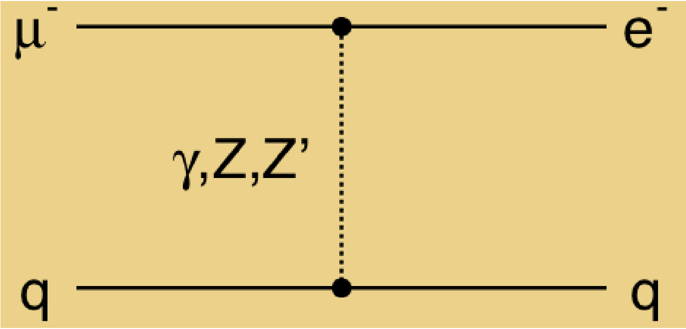
Contact Terms



Compositeness



Leptoquarks



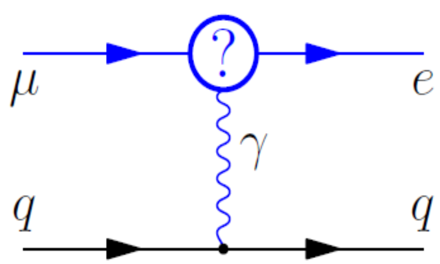
New Heavy Bosons / Anomalous Couplings

Model-Independent Effective Lagrangian

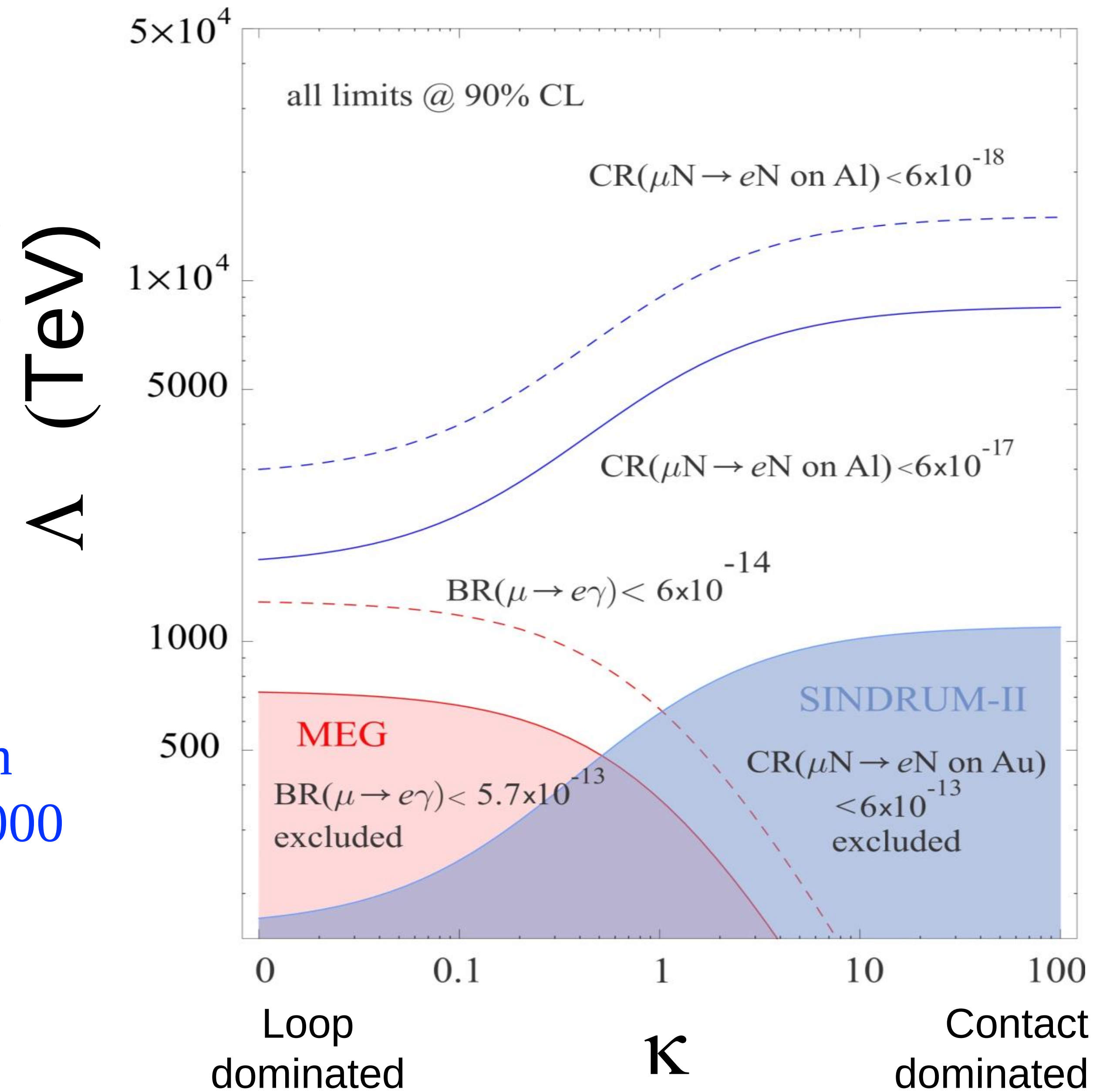
$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} \quad + \quad \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) \quad + h.c.$$

Λ: effective mass scale of New Physics κ: relative contribution of the contact term

"Dipole term"

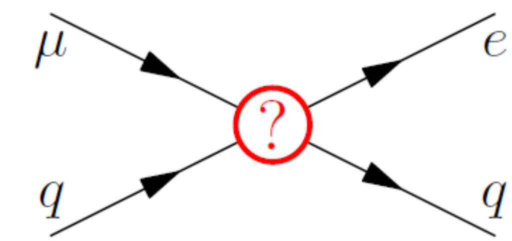


Contributes to $\mu \rightarrow e\gamma$



Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

"Contact term"



No contribution to $\mu \rightarrow e\gamma$

- CLFV can probe very high mass scales O(1000 – 10,000 TeV)

Motivation II

- Mu2e has discovery sensitivity across a wide range of models:

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

arXiv:0909.1333[hep-ph]

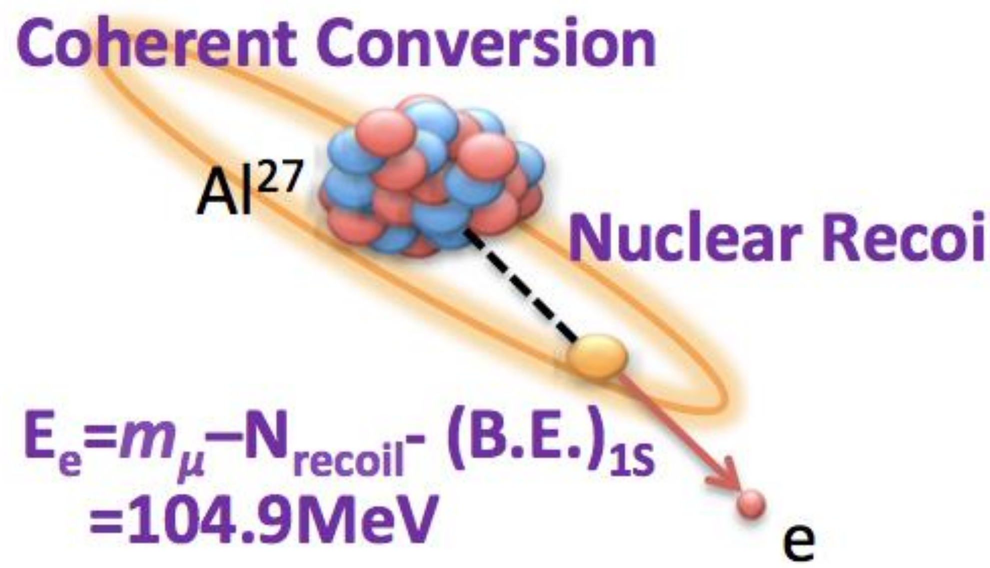
★★★= Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s \gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^* \mu^+ \mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)} \nu \bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+ \mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+ \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0 \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e \gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu \gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

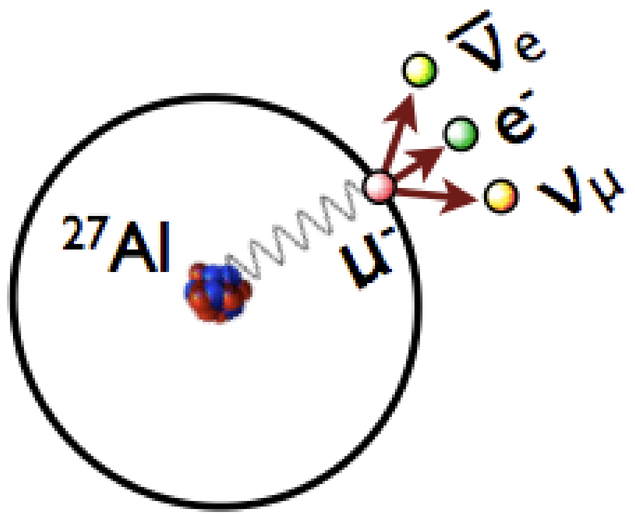
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Experimental Concept

- Generate a beam of low momentum muons
  - Muons are stopped in an aluminum target
  - When stopped muons convert to electrons, the nucleus recoils and the electron is emitted at a specific energy



- Signal is mono-energetic electron at 104.9 MeV
  - Main background is Decay In Orbit (DIO) events

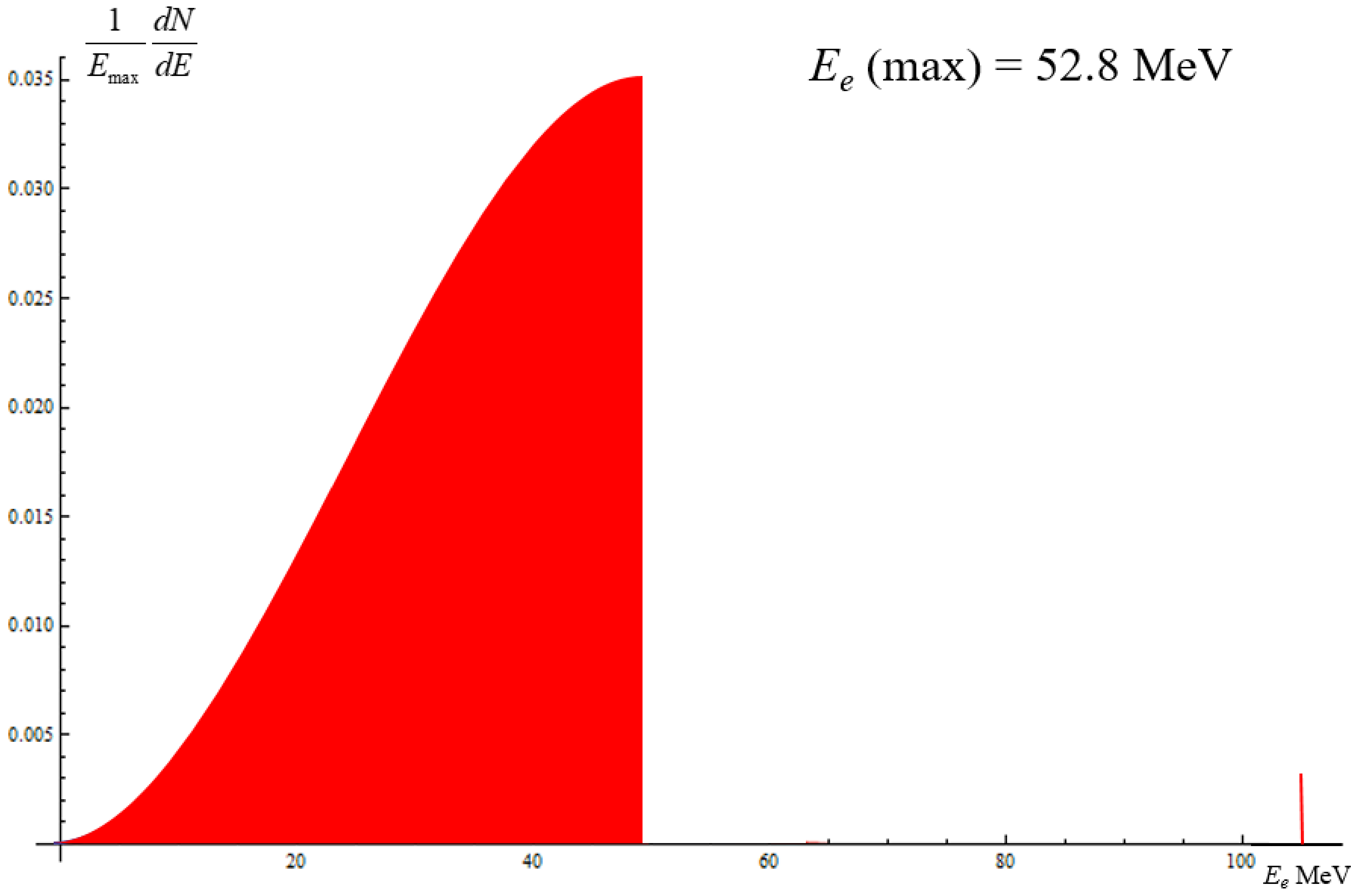


Decay In Orbit

- To achieve our target sensitivity, we need ~10^{18} stopped muons over 3 year run
  - => ~10^{10} stopped muons per second

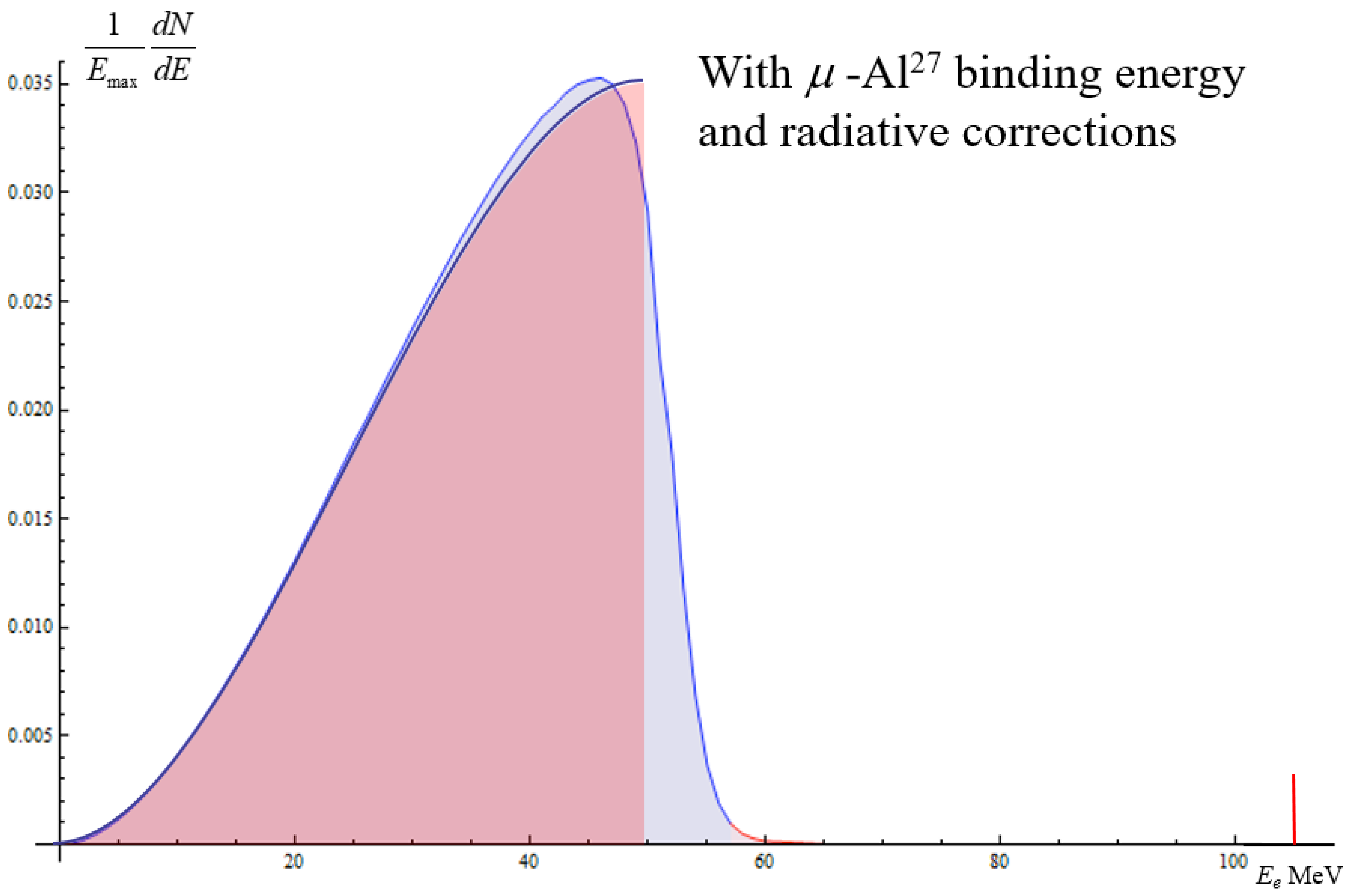
Decay In Orbit Energy Distribution

- Although naively, the maximum electron energy from muon decay should be far below our signal energy (104.9 MeV)…



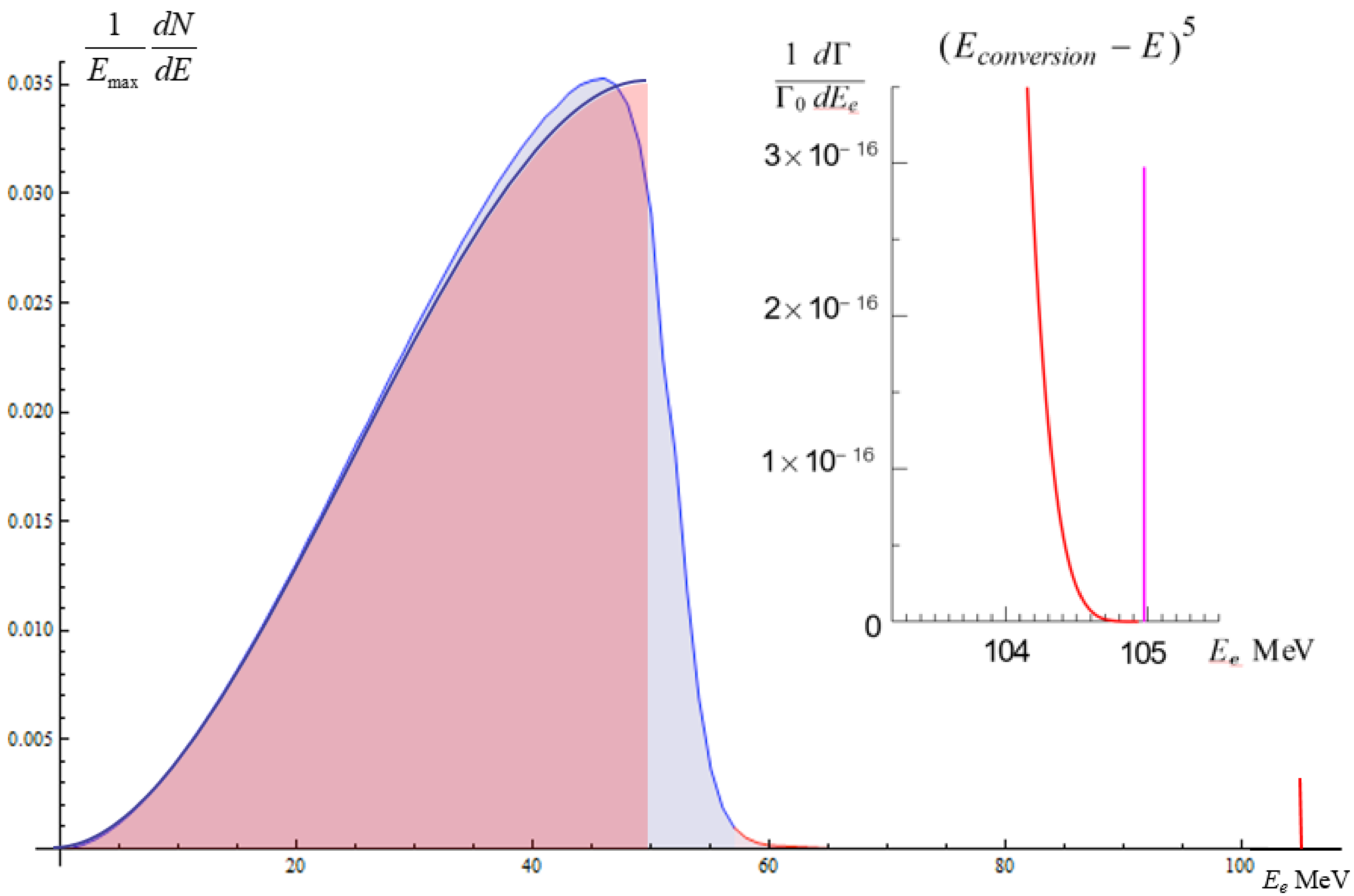
Decay In Orbit Energy Distribution

- Once you include the effect of the μ-Al^{27} binding energy and radiative corrections…



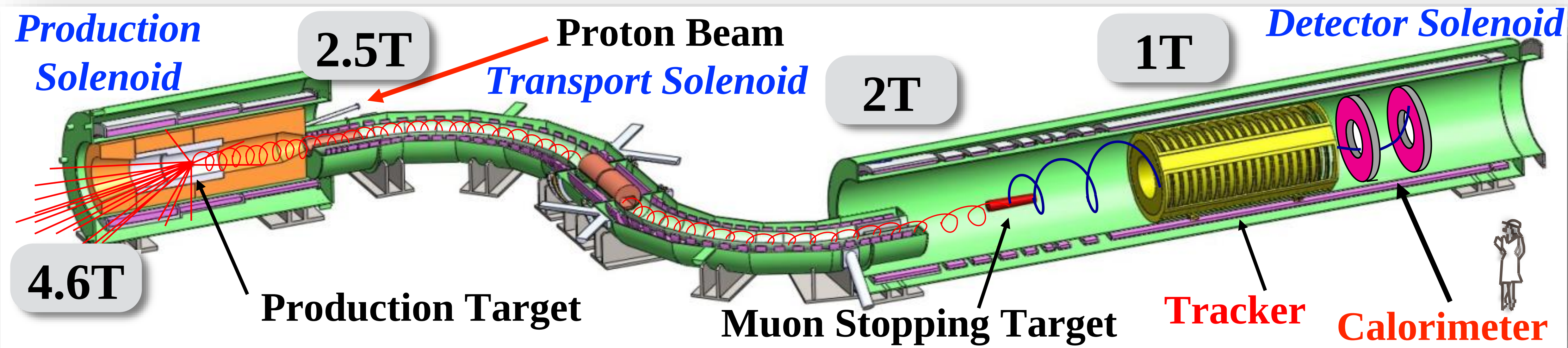
Decay In Orbit Energy Distribution

- The maximum energy for the DIO electrons comes very close to the signal energy:

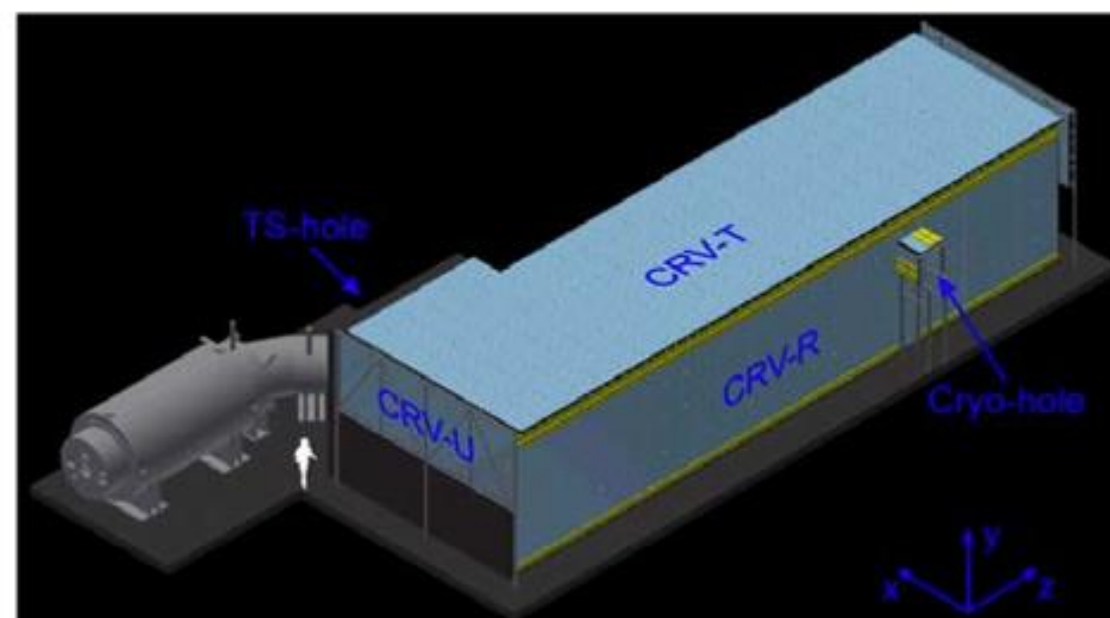


- Therefore, it is important that we have good energy resolution

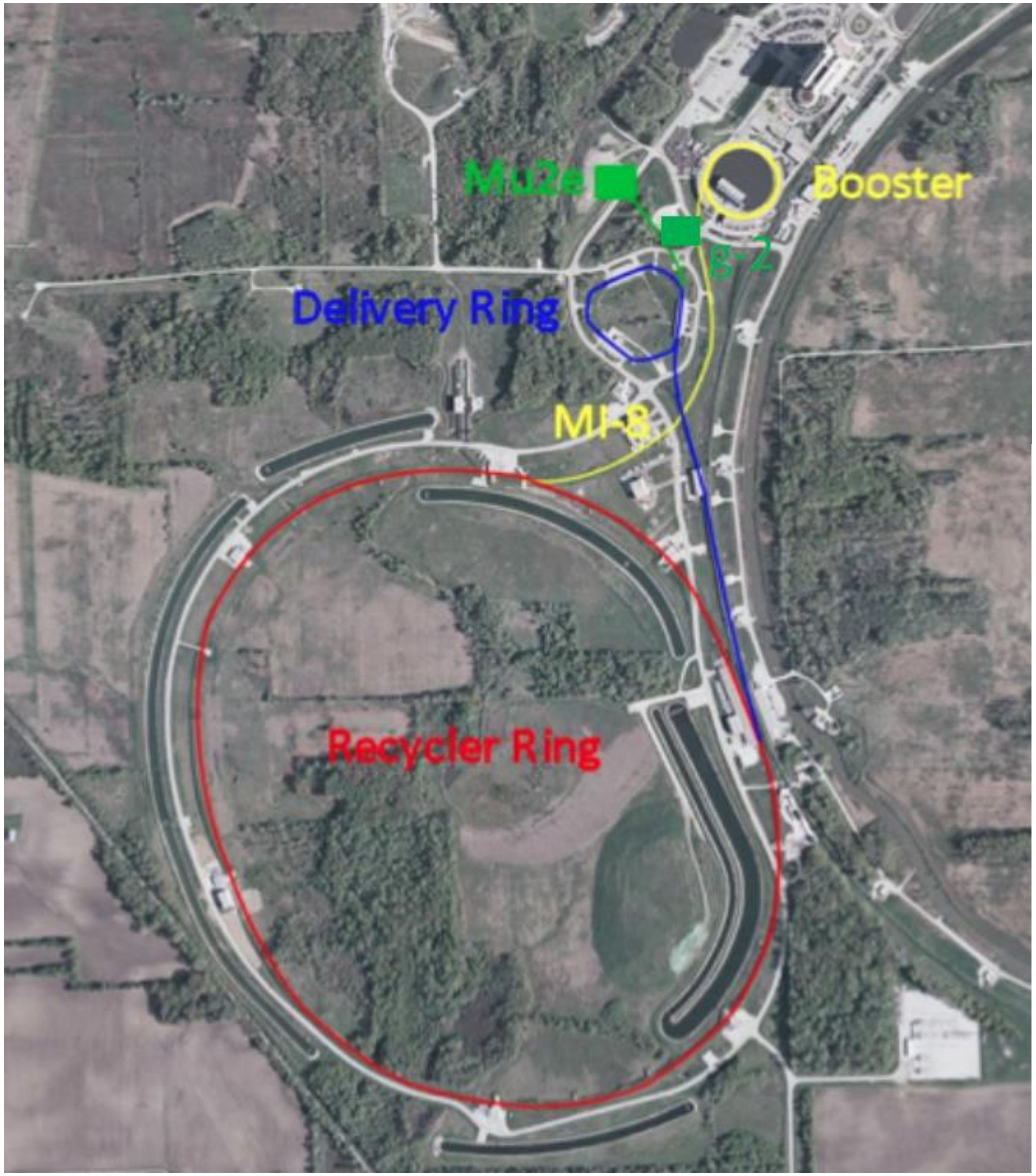
Design Overview



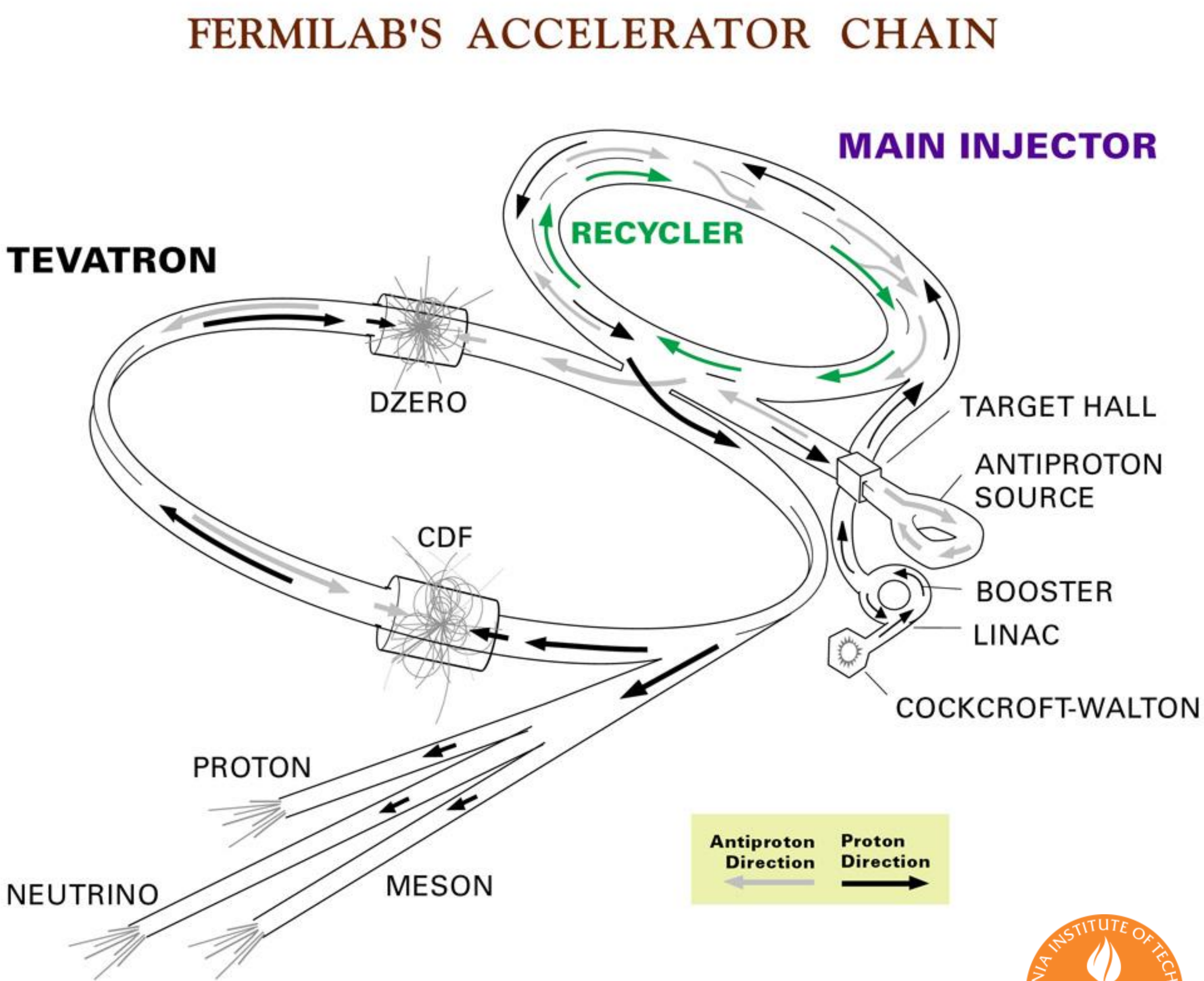
- Production Target + Production Solenoid
  - High intensity, pulsed, 8 GeV proton beam strikes tungsten production target producing pions
  - Pions are captured by the graded magnetic field and decay to muons
- Transport Solenoid
  - Selects low momentum, negative muons
  - Absorbers and Collimators eliminate high energy negative particles, positive particles, and line-of-sight neutrals
- Stopping Target, Detector, and Detector Solenoid
  - Muons are stopped on an aluminum target
  - Tracker measures momentum and trajectories of from muonic atoms
  - Calorimeter measures energy/time
- Cosmic Ray Veto detector surrounds detector solenoid



The Mu2e Proton Beam

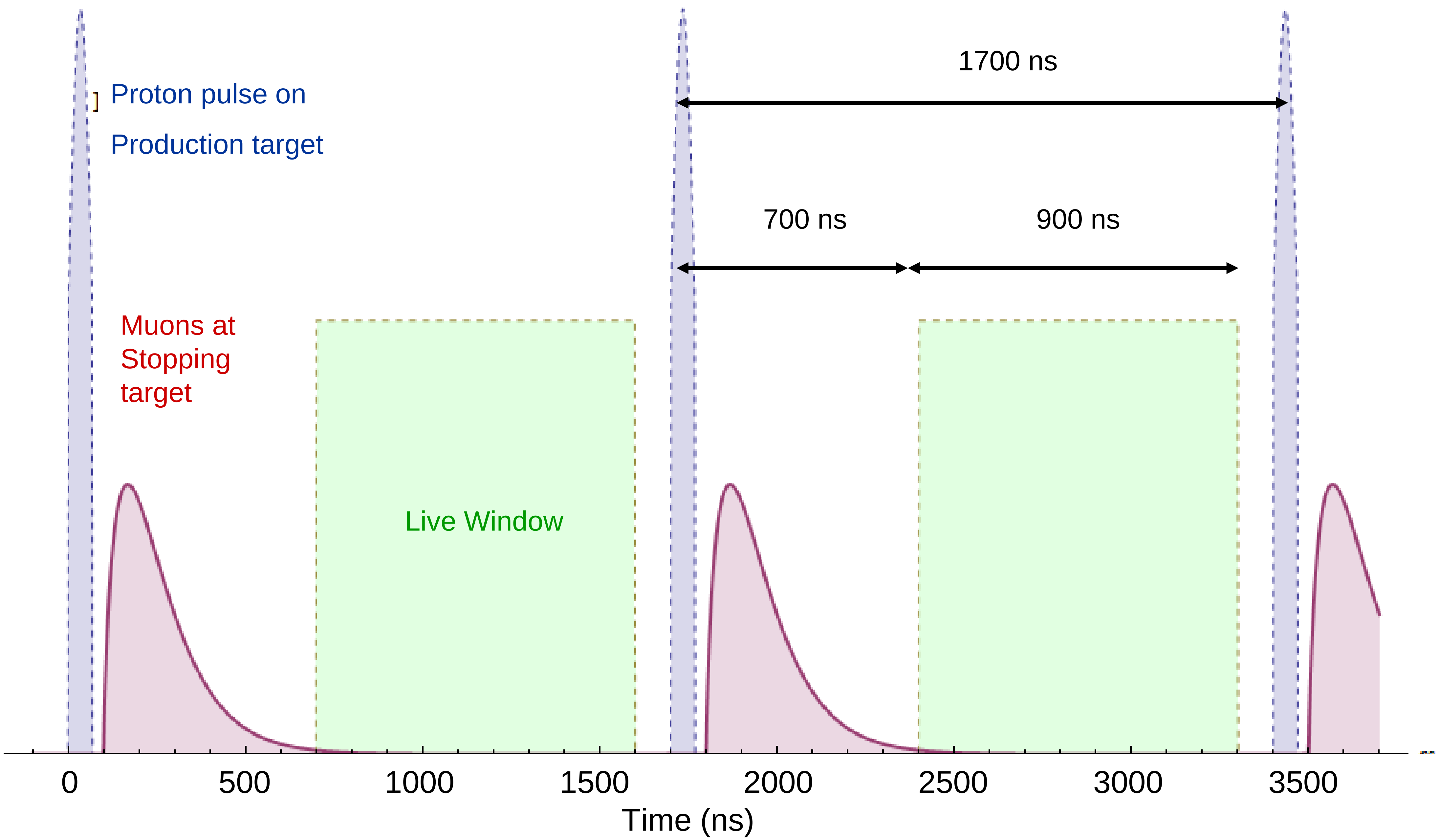


- Mu2e will take advantage of the existing Booster, Recycler, Accumulator, and Antiproton Source Debuncher rings at Fermilab
- Mu2e will run in parallel with NOvA



Proton Pulse Structure

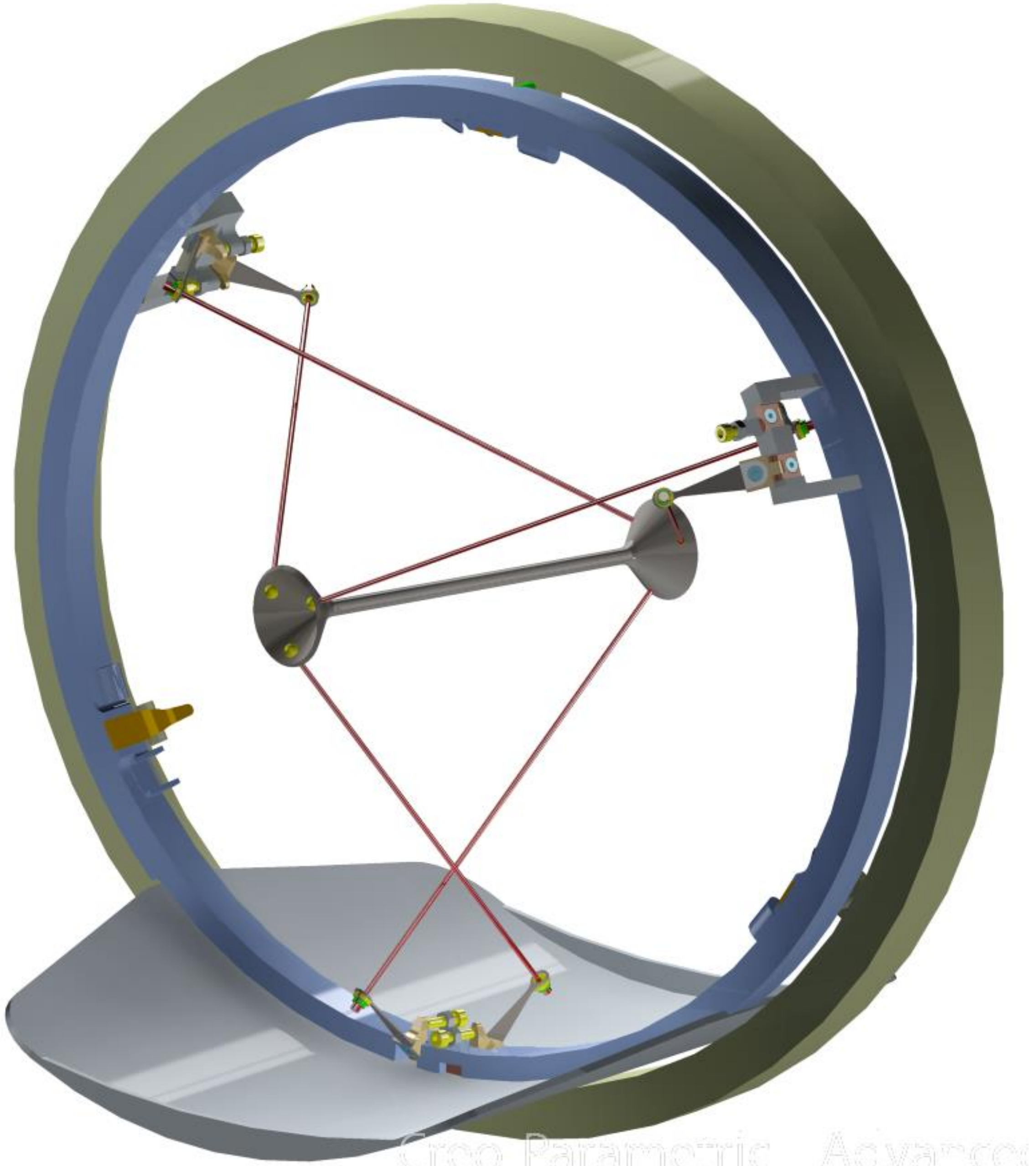
- Proton Pulse Structure:



- We use a pulsed proton beam with a delayed data-taking window to suppress short-lived (prompt) backgrounds
- A 700 ns delay reduces pion background by $> 10^{-9}$

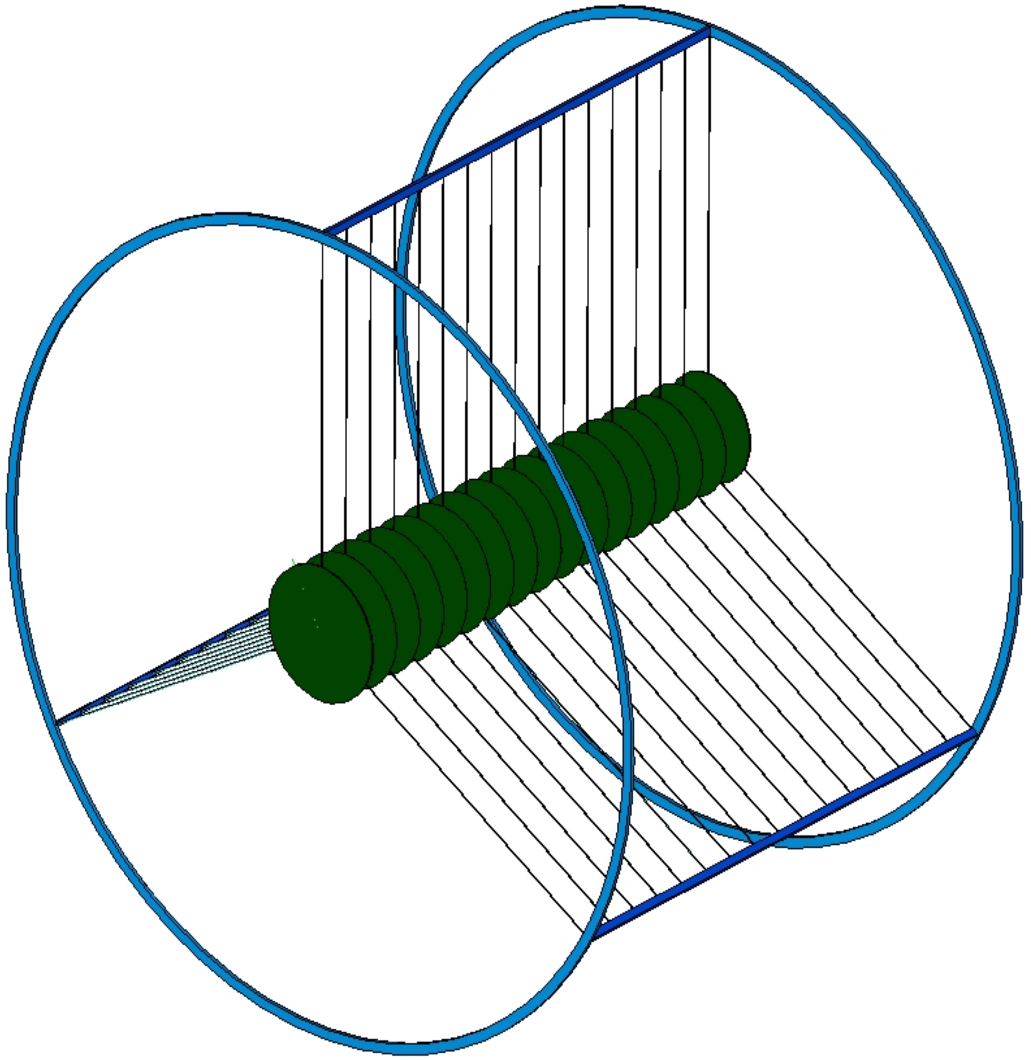
Production Target

- Production Target
  - Radiatively cooled tungsten target suspended by wires
  - Produces pions when struck by the proton beam
  - Pions are guided to the stopping target by the production and transport solenoids



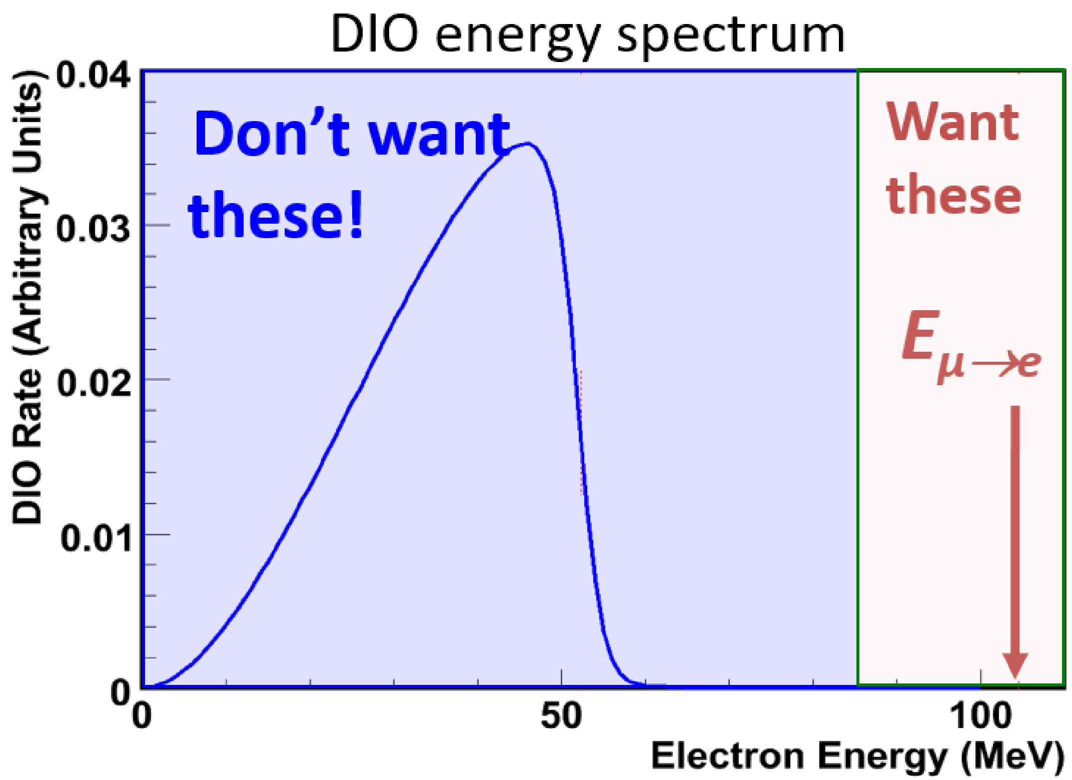
Stopping Target

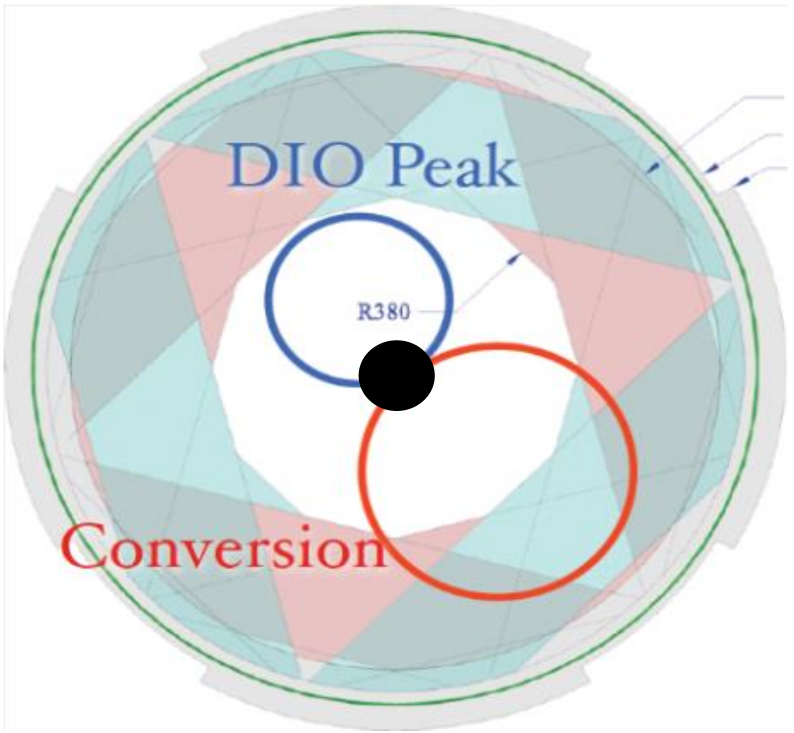
- Stopping Target
  - Aluminum stopping target composed of foils suspended by wires
  - If a signal is seen, other stopping target materials may be used to narrow down what kind of physics is responsible
  - Design is still being optimized, but it will probably consist of something like aluminum foil annuli suspended at intervals in a cylindrical volume



Tracker I

- A low-mass annular tracker provides us with high-precision measurements of charged particle momenta
  - Designed to function in a high background environment
  - Within the detector solenoid, track radius is proportional to energy so we use an annular design that only detects particles with large enough radii





  - Expect < 180 keV/c p_T resolution at 105 MeV/c (< 0.18%)

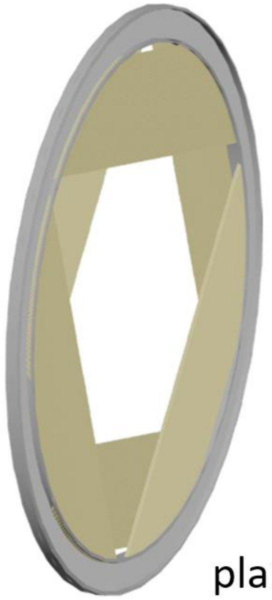
Tracker II

- Tracker Construction:
  - Tracker is constructed from self-supporting panels of low mass straws tubes detectors:

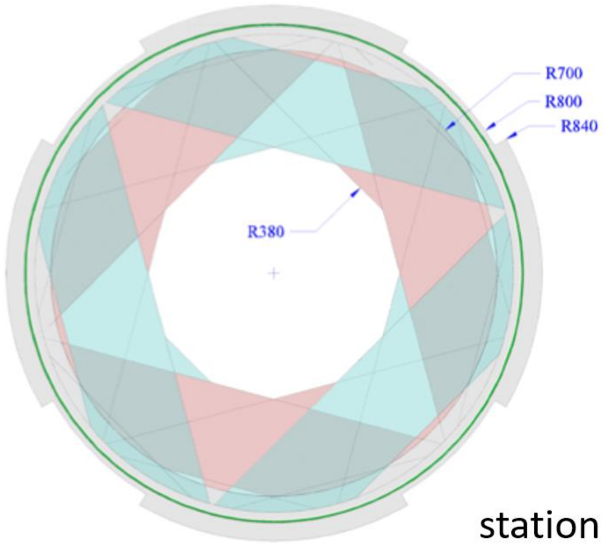
- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 mm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO2 with HV < 1500 V

96 straws/panel

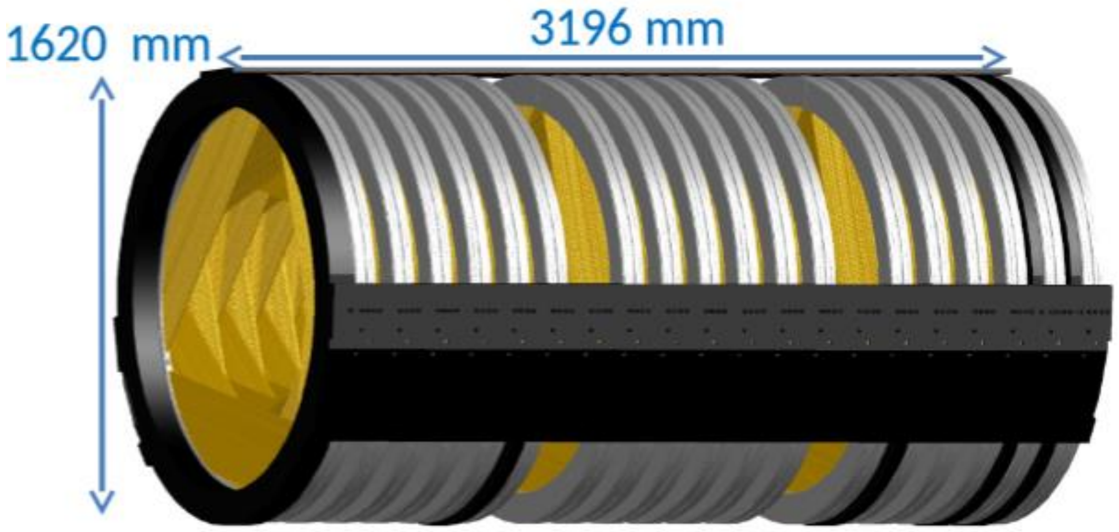
- Sets of 6 panels are attached to form a plane, 2 planes are combined to form a station, and 18 stations are arranged in a cylindrical volume to form the tracker:



6 panels/plane



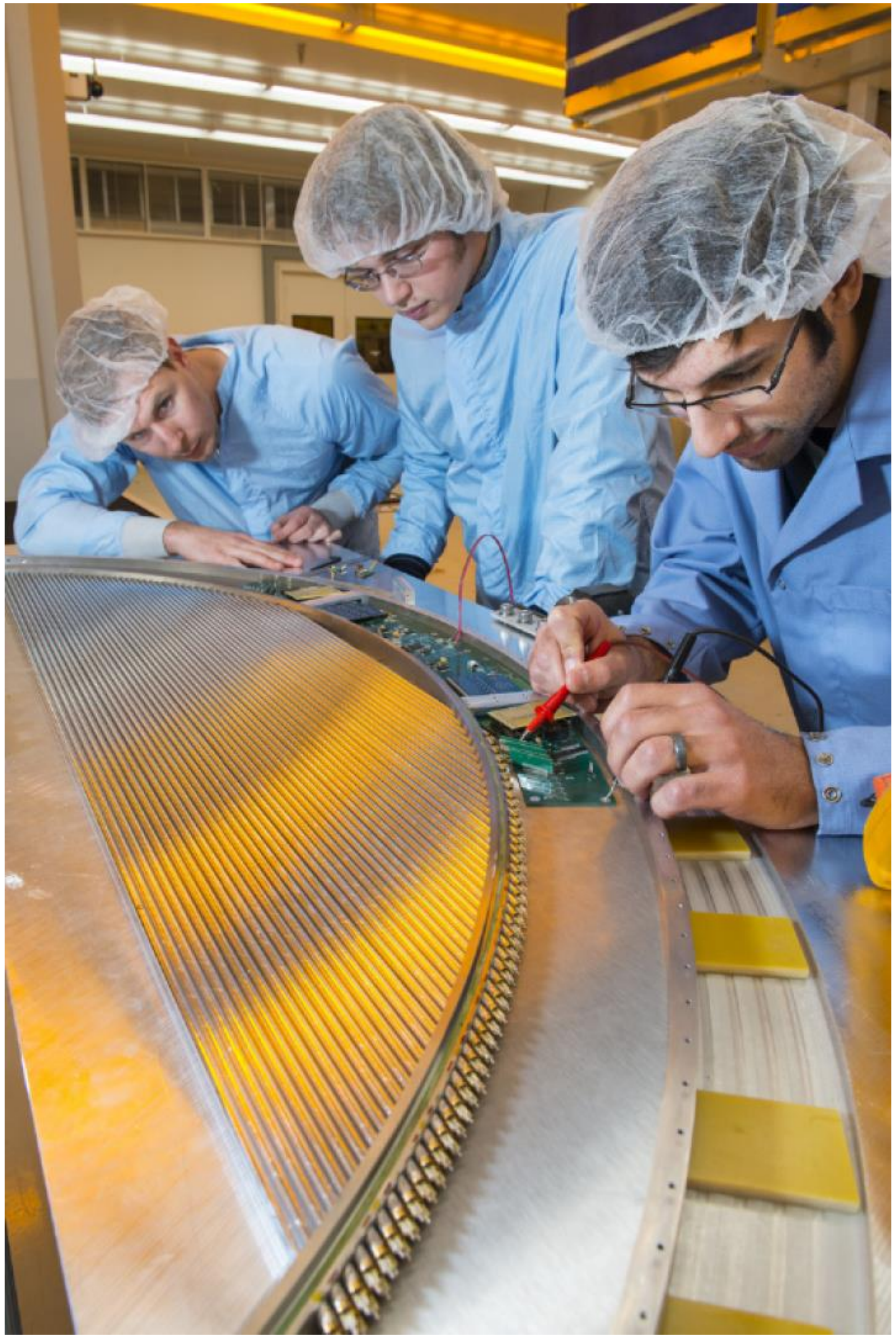
2 panels/station



18 station tracker

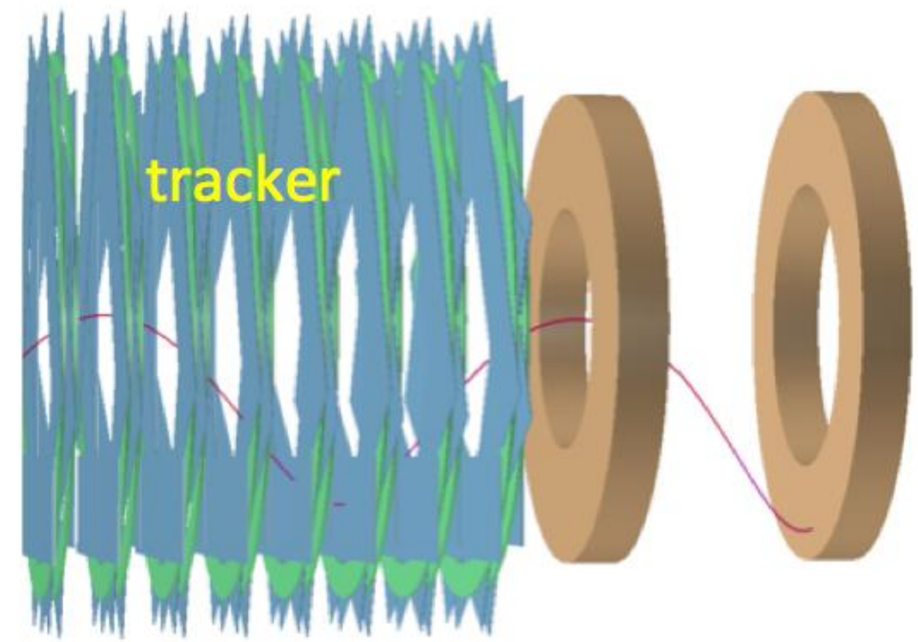
Tracker III

- Tracker Construction:

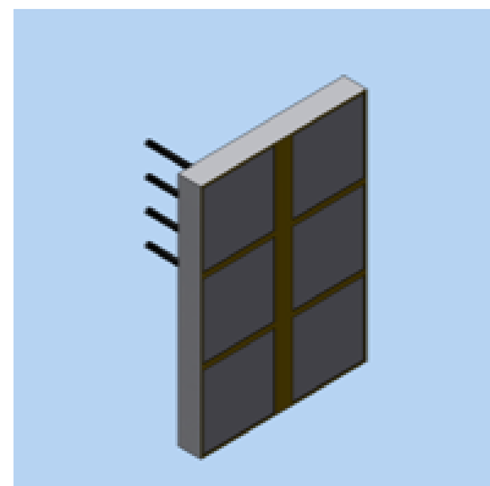


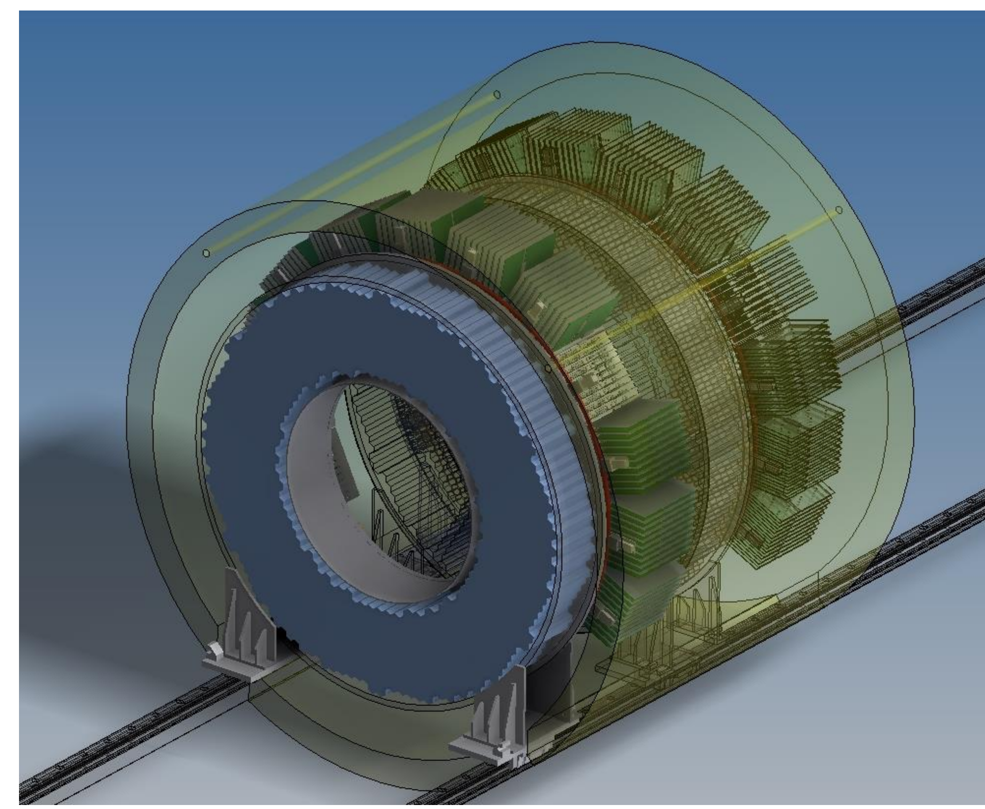
Calorimeter I

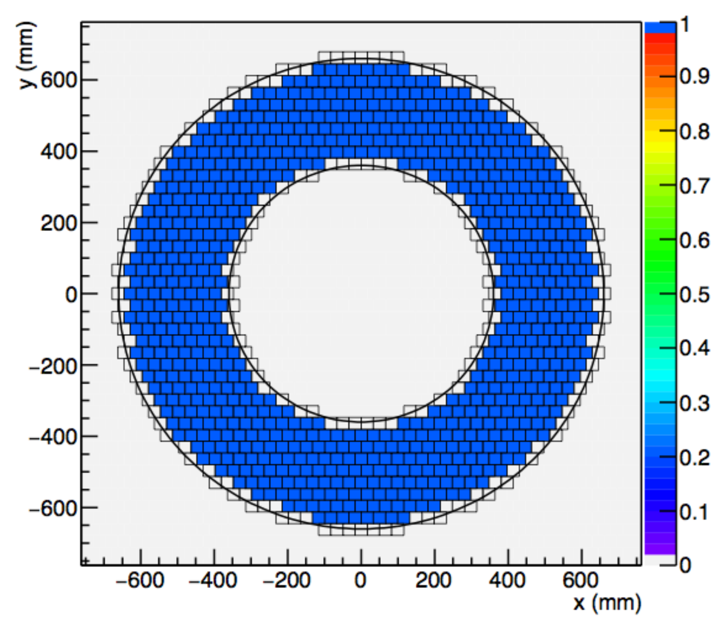
- Calorimeter Serves to
  - Distinguish muons from electrons
  - Aid in track pattern recognition
  - Provide tracker-independent trigger
  - Provide accurate timing information for bkg rejection



- Calorimeter Design:
  - Two annuli with radius 37-66 cm
  - Disks separated by 70 cm (1/2 λ)
  - ~674 CsI crystals per disk
  - Two 14x20 mm^2 six-element SiPMs / crystal
  - Square crystals (34x34x200 mm^3)

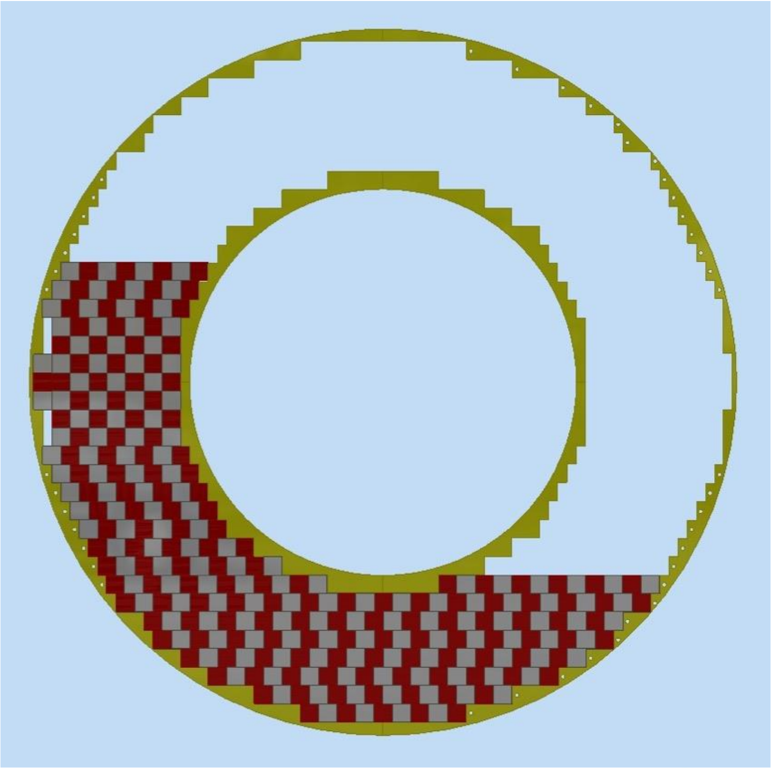




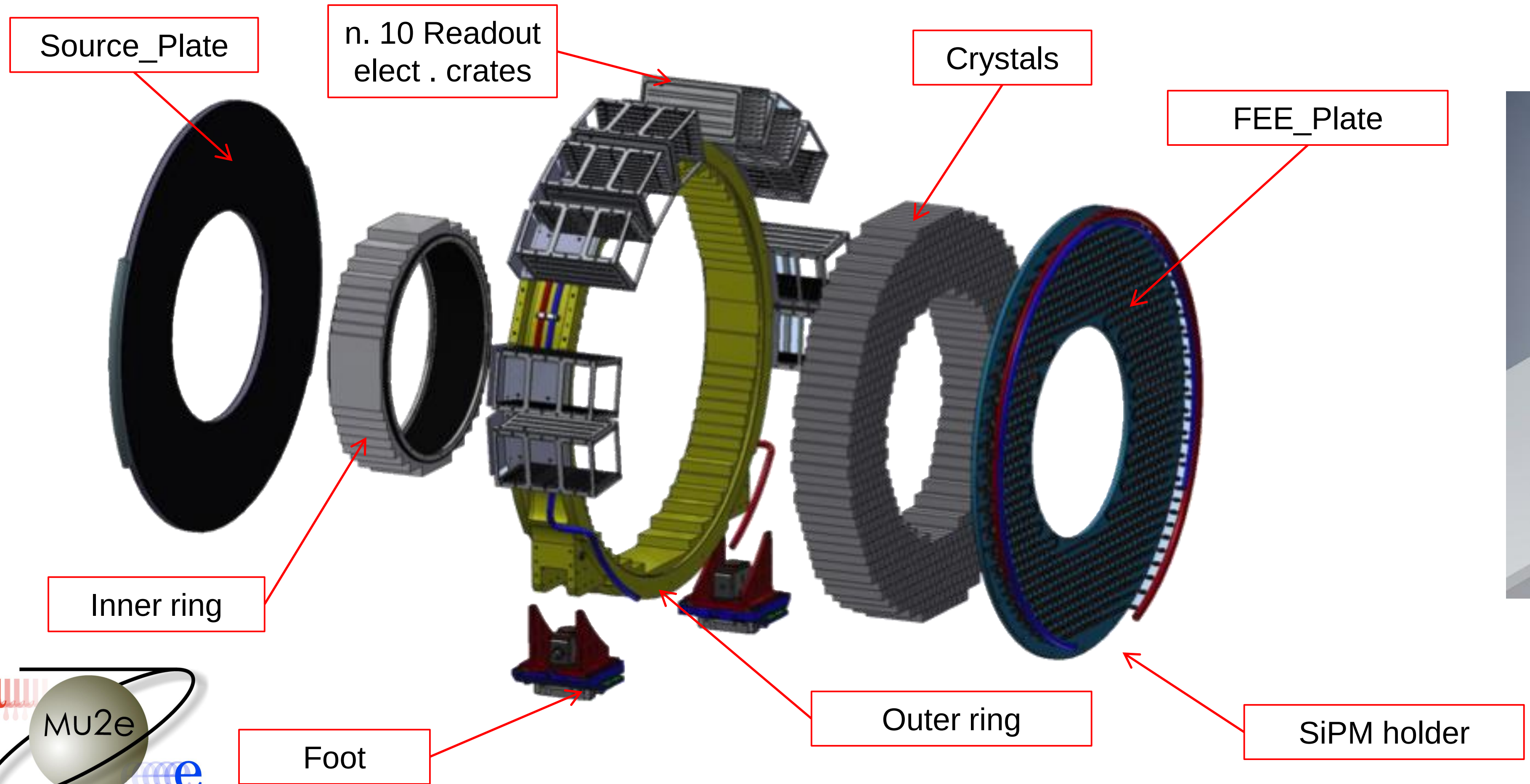


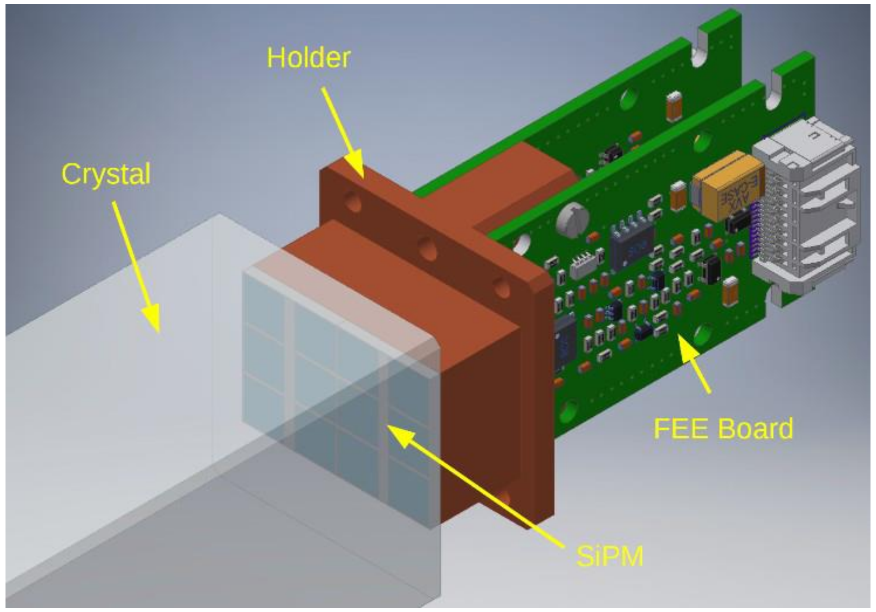
Calorimeter II

- Wrap crystals in Tyvek and stack in annulus
- A backplane assembly provides cooling and slots mounting crystal readout electronics
  - Insert SiPM holders with front end electronics (FEE) into the backplane (air-gap coupling)
  - FEE are read out by readout controllers housed in crates



Crystal Stacking

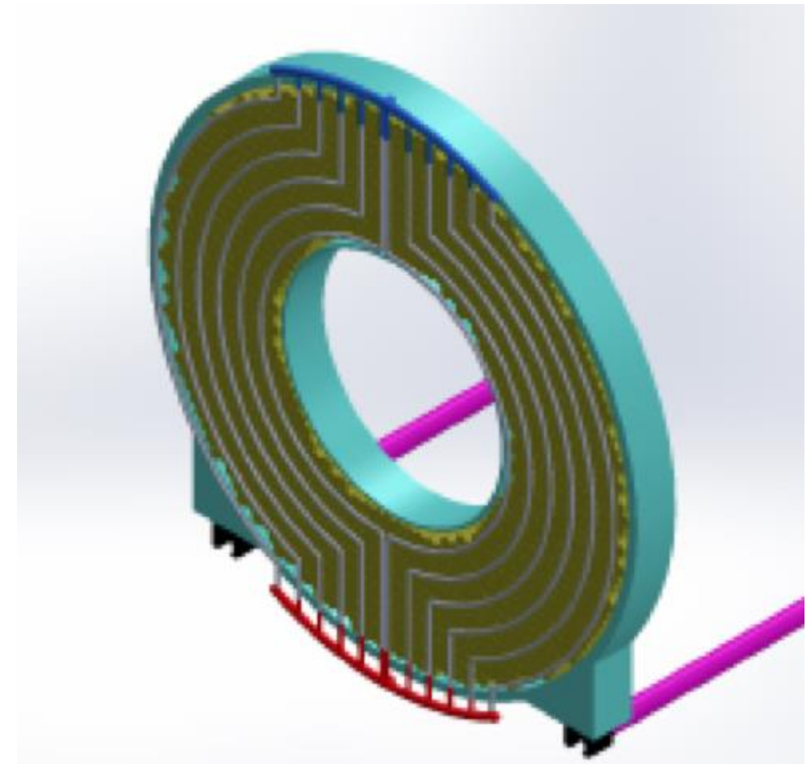


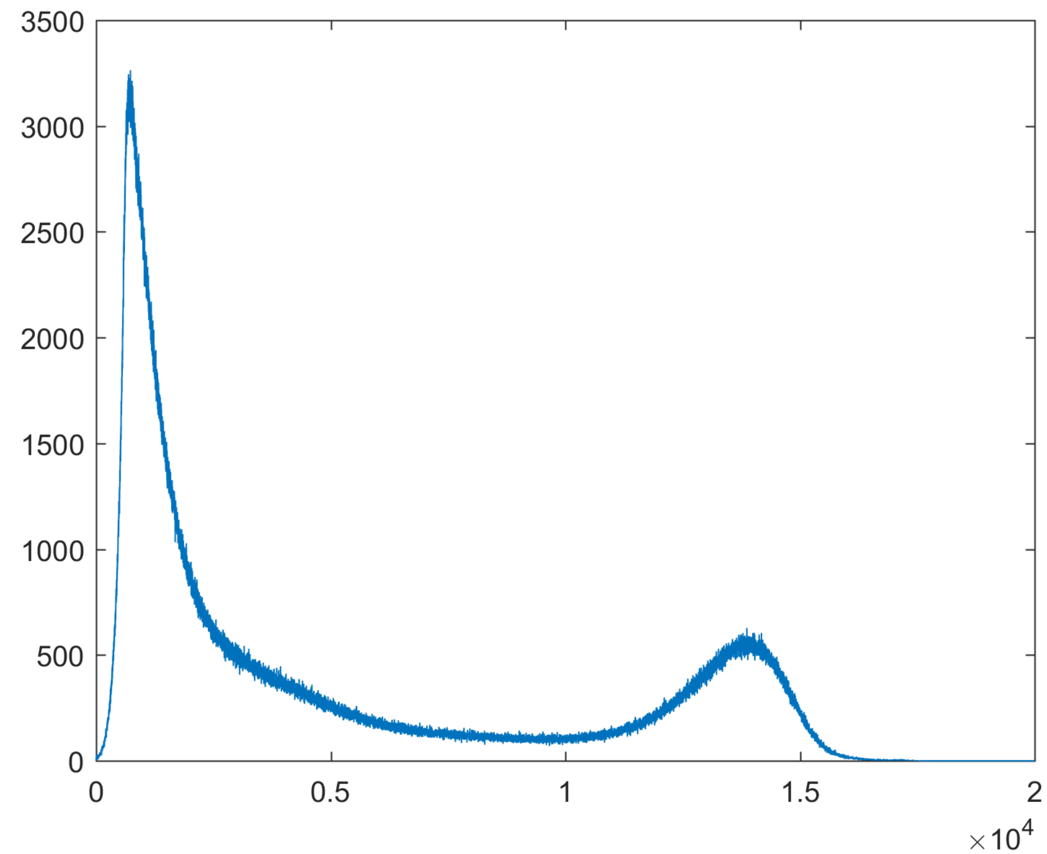


SiPM Holder

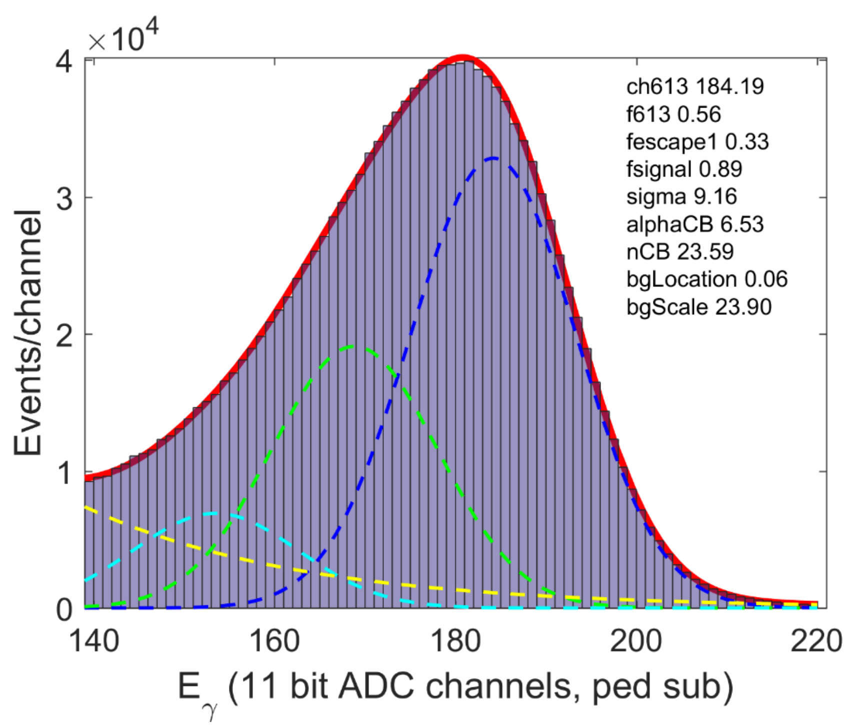
Calorimeter III

- The calorimeter will be calibrated using activated Fluorine-rich fluid
  - Fluorinert is activated using neutrons from a DT generator
  - Fluid is pumped through pipes in front of the disks
  - Calibrate energy scale to < 0.5% in a few minutes
- A UV laser system will continuously monitor SiPM gains
  - Distribute light using silica optical fibers

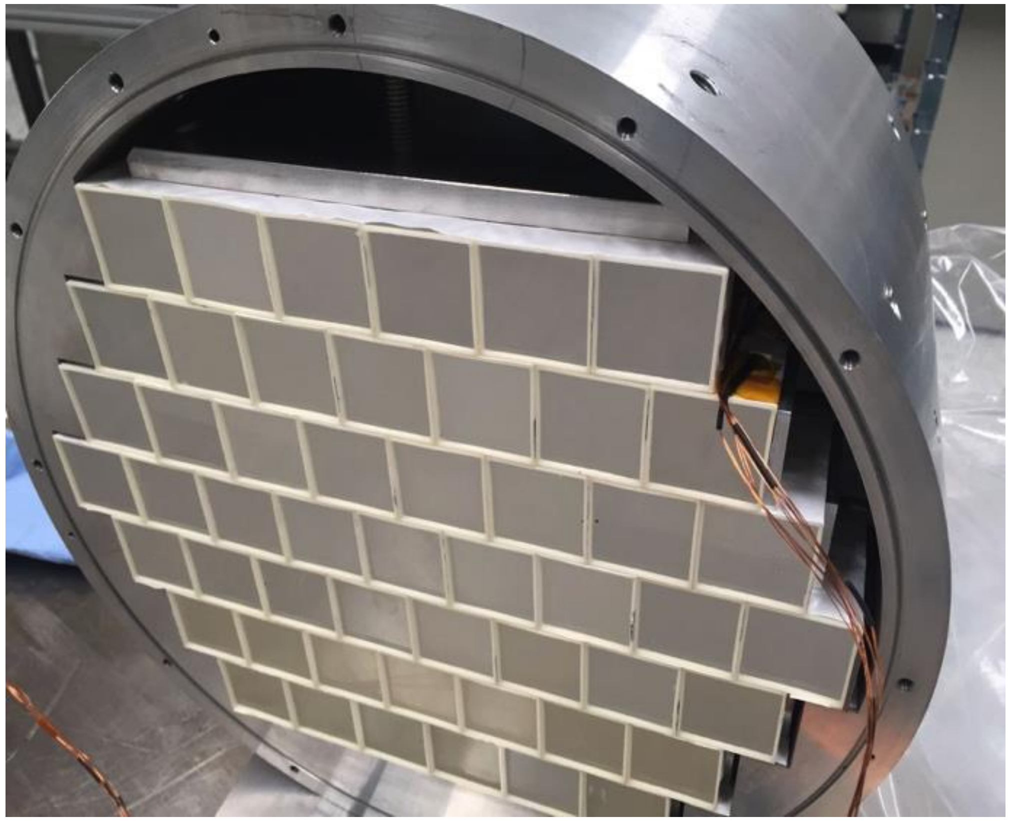


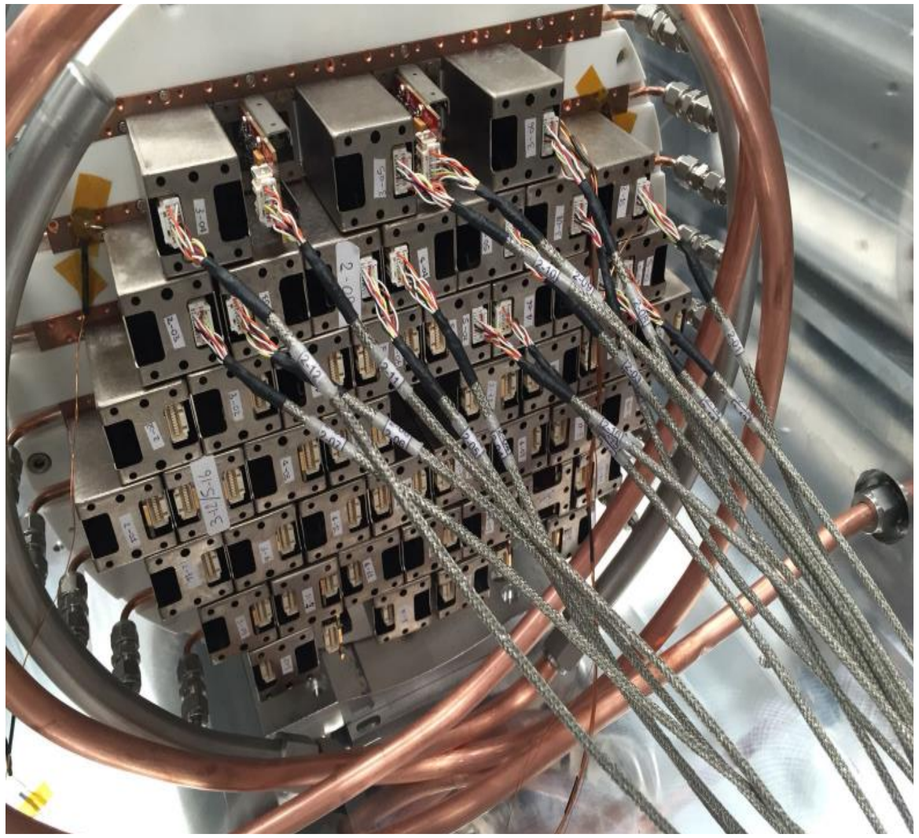


Prototype Spectrum



Calorimeter Prototype

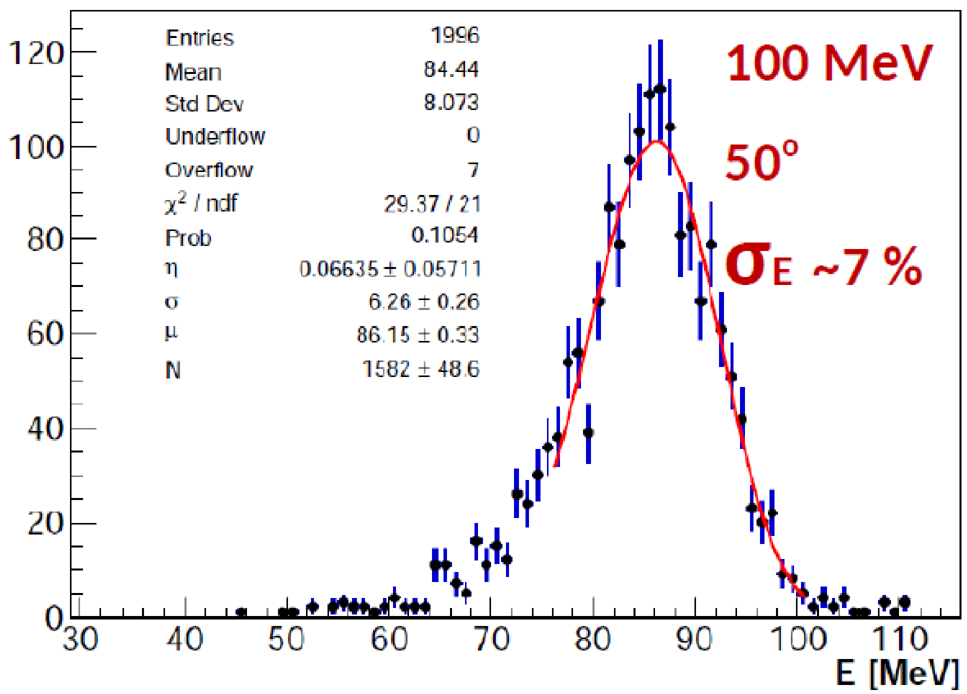




Calorimeter Prototype Test Beam

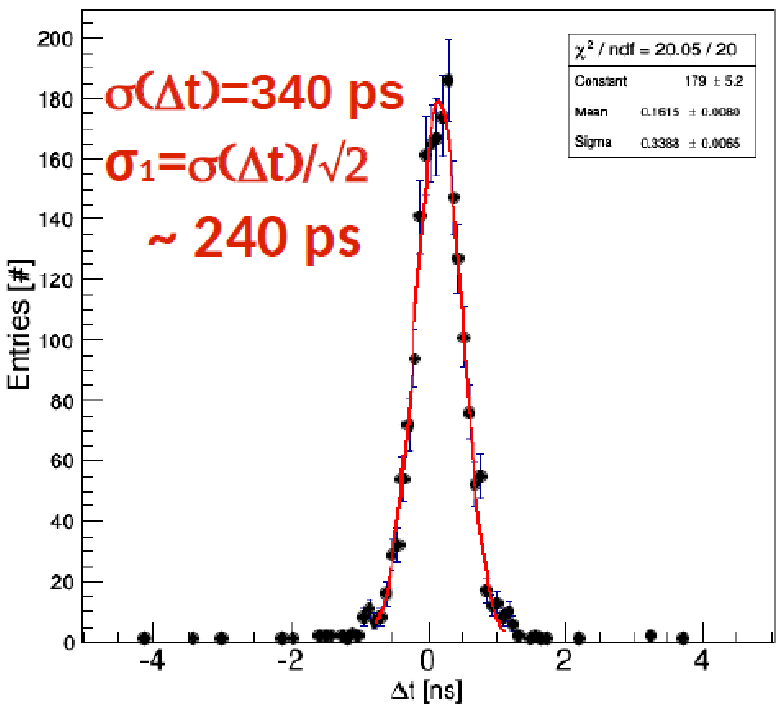
- May 2017 test beam with 70-115 MeV electrons at INFN Frascati
  - 51 30x30x200 mm^3 CsI crystals
  - Readout: Hamamatsu, SNESL, and Advansid MPPCs
- Results:

ENERGY RESOLUTION



Calibration with e^- at 0°
For 100 MeV e^- at 50°:
Energy resolution ~7%

TIME RESOLUTION



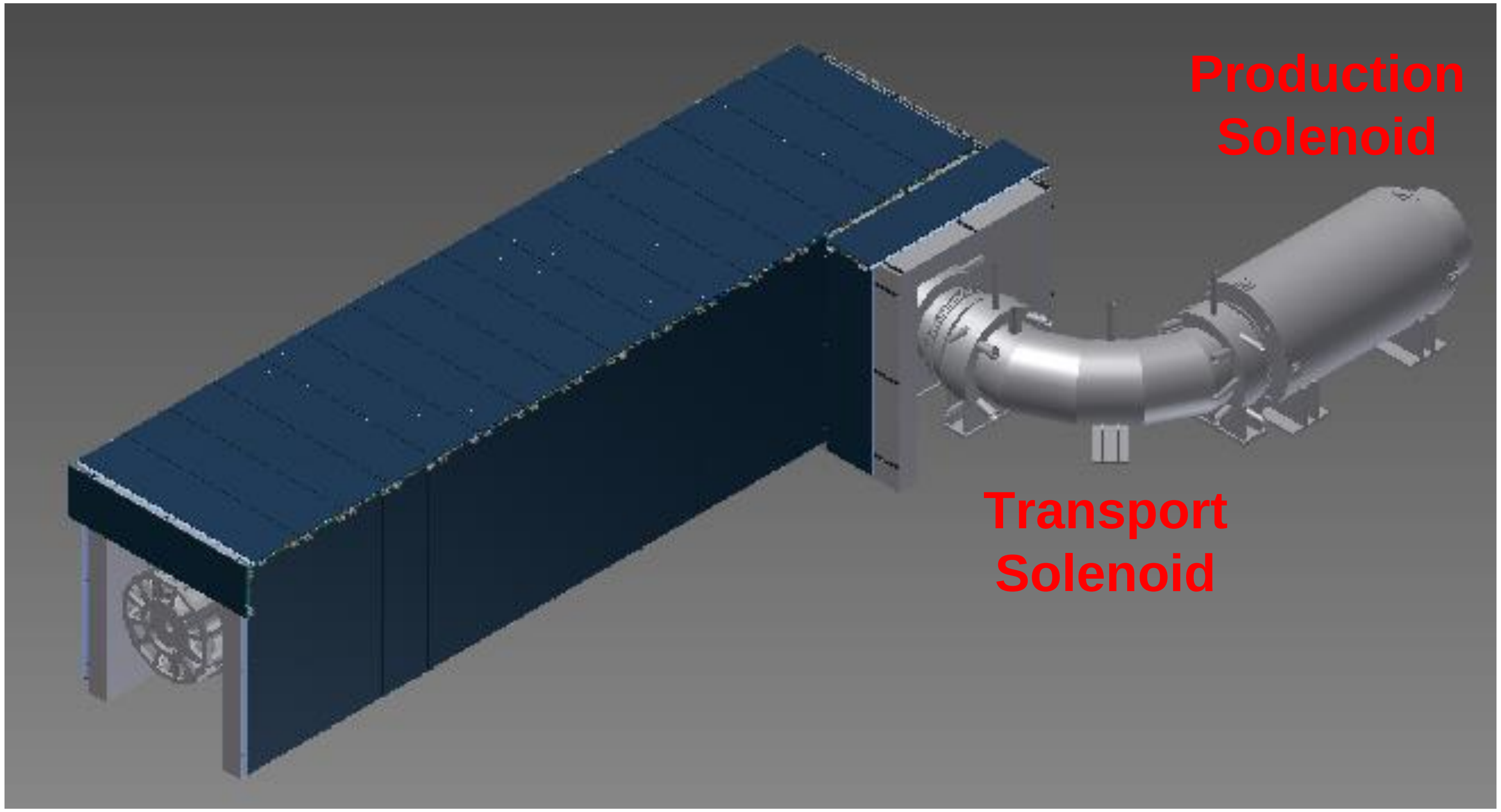
Δt: Time difference between two sensors reading the same crystal.

For 100 MeV e^- at 50°:
Δt resolution ~340 ps
Single sensor resolution ~240 ps

- Energy and time resolutions are well within the requirements

Cosmic Ray Veto I

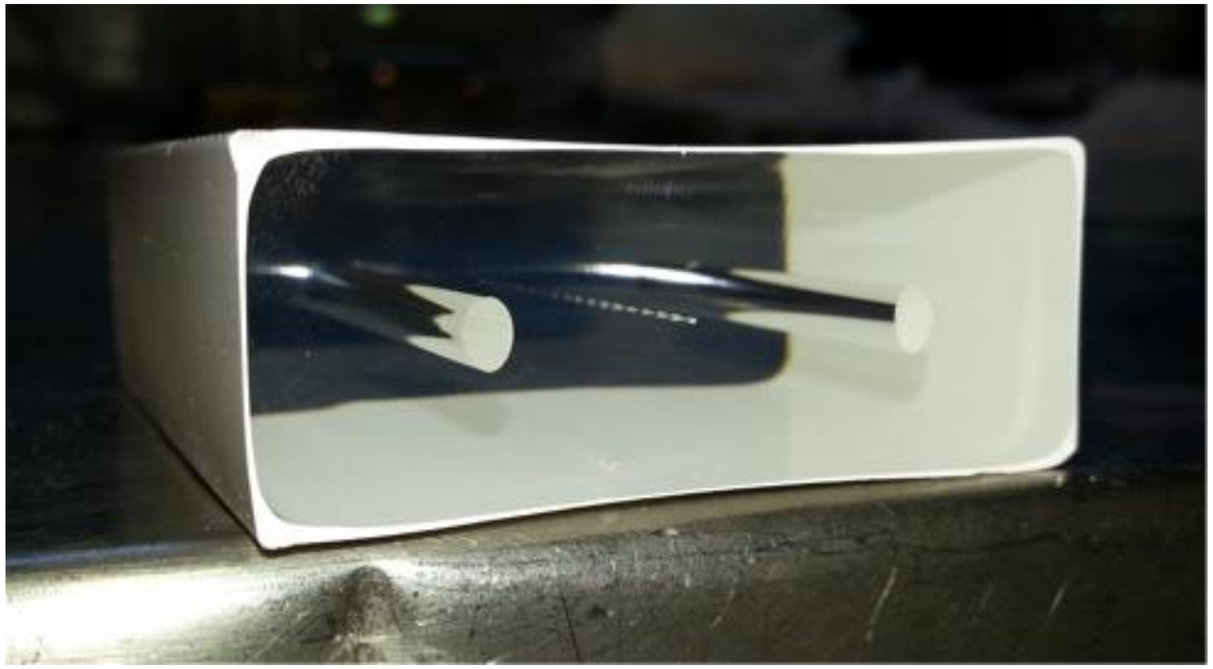
- The Cosmic Ray Veto (CRV) system surrounds the detector solenoid and half the transport solenoid
  - CRV identifies cosmic ray muons

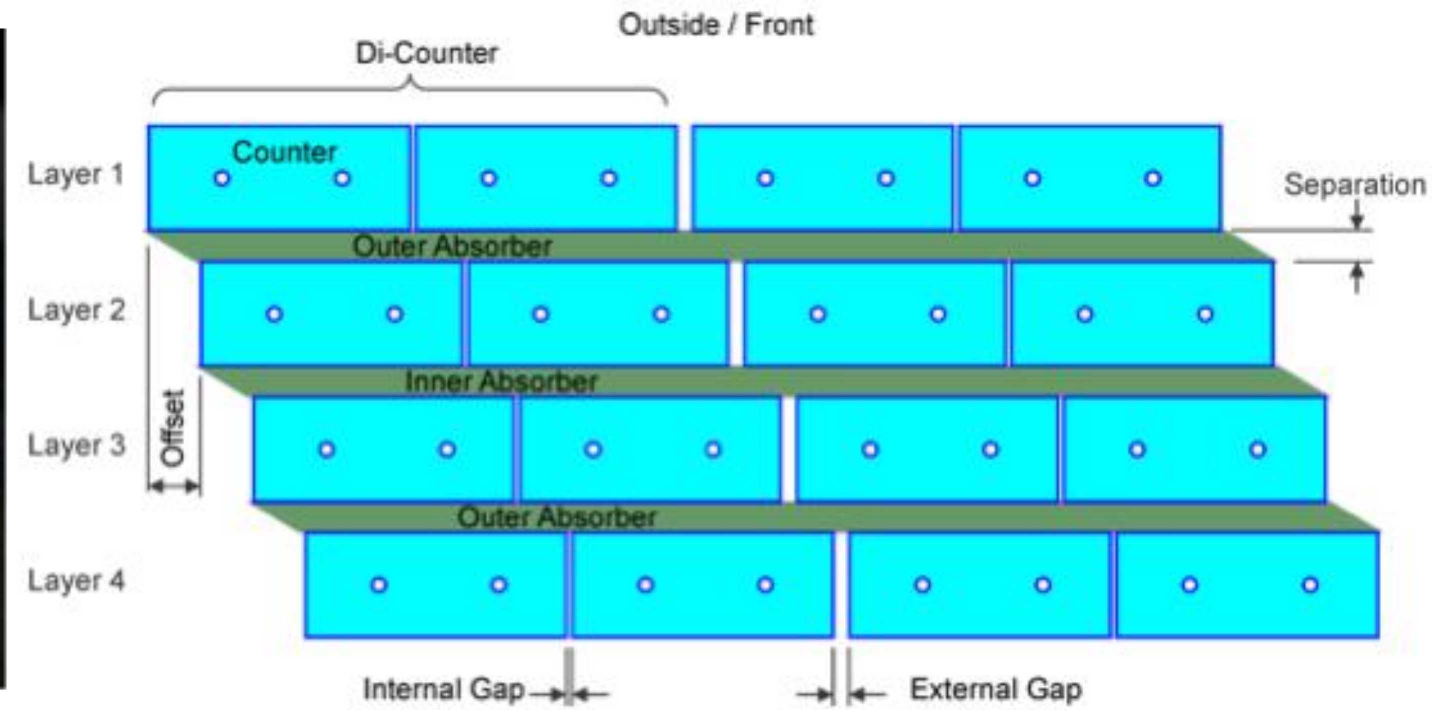


- Each day, ~1 conversion-like electron is produced by cosmic rays
  - Need the CRV to suppress this background

Cosmic Ray Veto II

- The CRV is composed of 4 layers of overlapping panels of extruded polystyrene scintillator

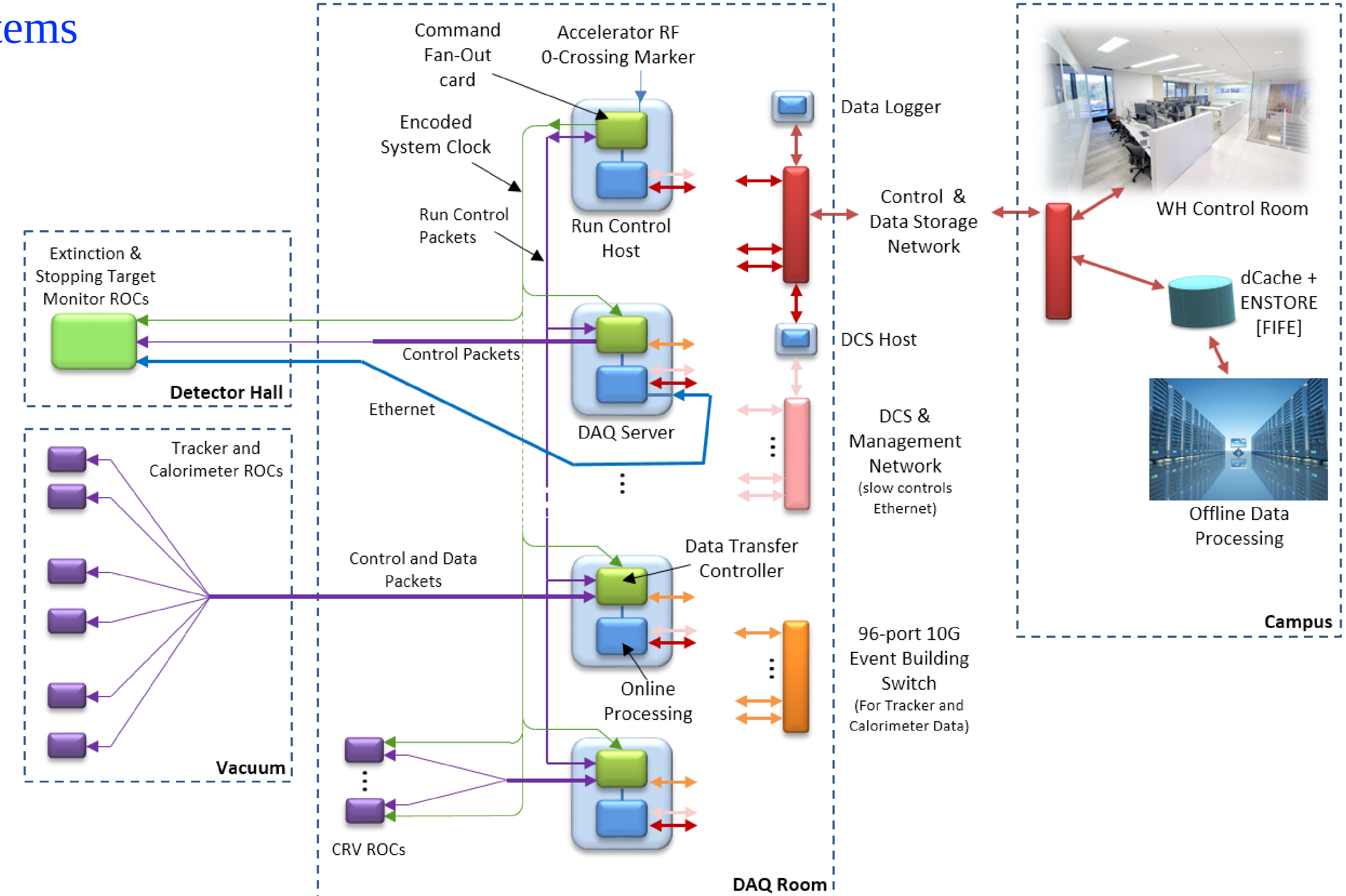




- Each panel is composed of 5 x 2 x ~450 cm^3 scintillator bars
  - 2 embedded wavelength-shifting fibers per bar
  - Both ends of the bars are readout by SiPMs
  - In testing, the veto achieves $\varepsilon > 99.4\%$ per layer

DAQ/Trigger

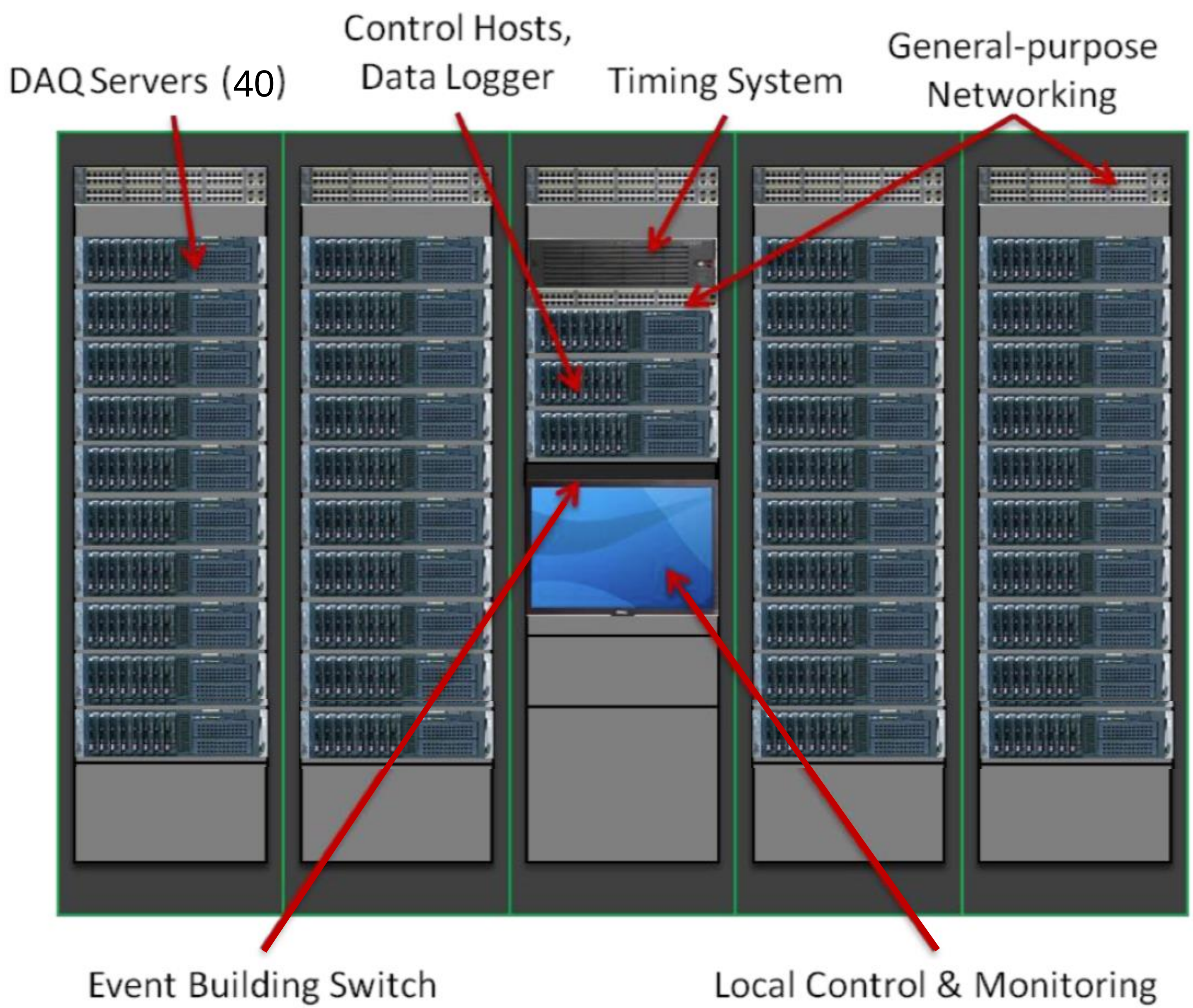
- Data Acquisition (DAQ) system provides readout and control for all the detector subsystems



- Trigger processing is handled almost entirely in software (with some FPGA-based pre-processing)
  - Allows us to take advantage of commercial computing hardware
  - Filters designed and tested in the offline environment can be run in the online trigger environment

DAQ Server Setup

- Online processing provided by 40 commercial 3U rack-mount servers
- Each server houses 2 PCIe cards with onboard FPGA and custom firmware that provide detector readout/control as well as data pre-processing



Mu2e Building

Mu2e

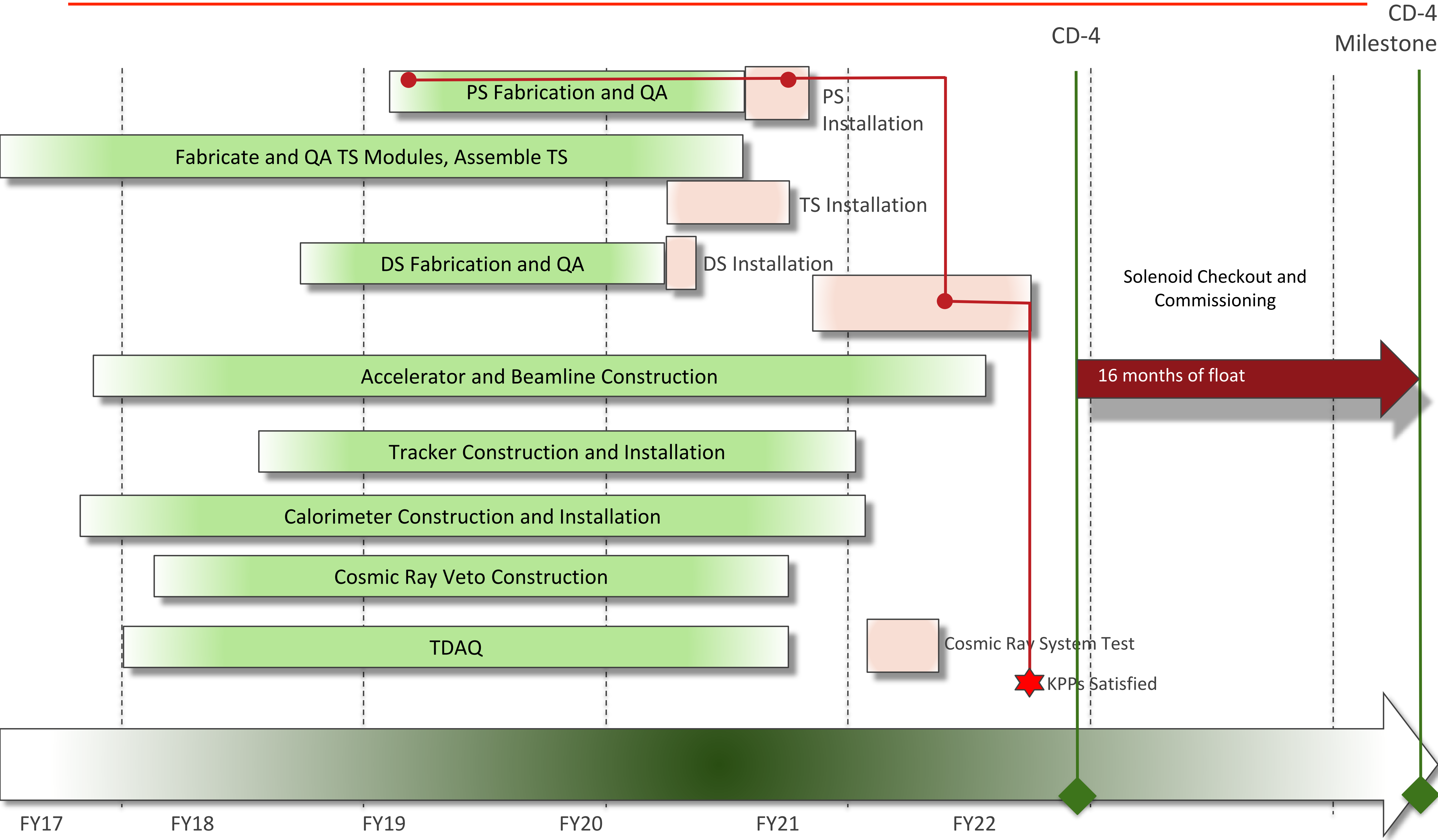
The Mu2e Collaboration

Over 200 Scientists from 37 Institutions

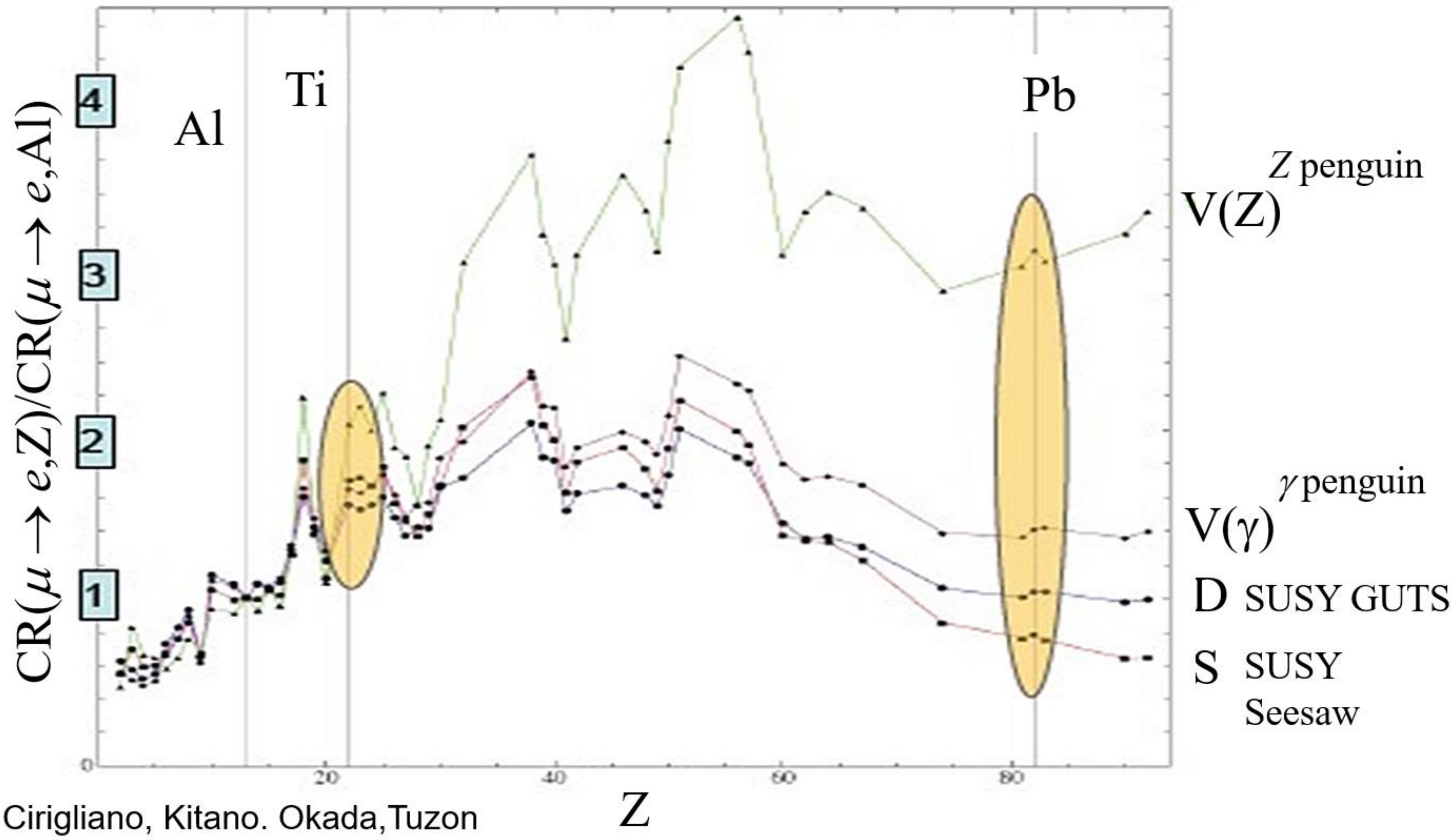
Argonne National Laboratory ● Boston University Brookhaven National Laboratory Lawrence Berkeley National Laboratory and University of California, Berkeley ● University of California, Davis ● University of California, Irvine ● California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● HelmholtzZentrum Dresden-Rossendorf ● University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma ● University of Minnesota ● Institute for Nuclear Research, Moscow ● Muons Inc. ● Northern Illinois University ● Northwestern University ● Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● University of Virginia ● University of Washington ● Yale University

Detector Hall (Lower Level)

Mu2e Schedule



Z-Dependence of $\mu \rightarrow e$ Conversion



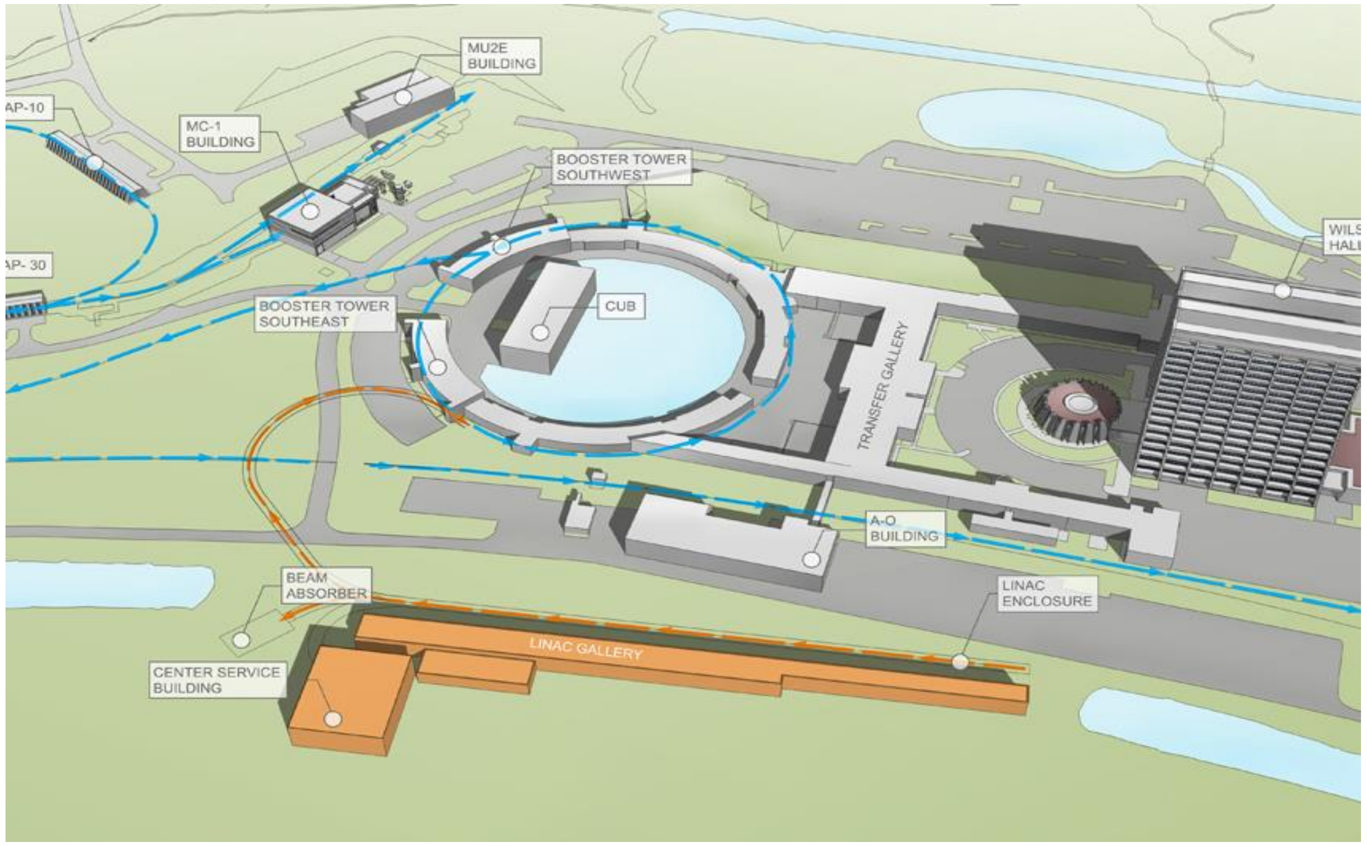
Cirigliano, Kitano. Okada,Tuzon

Mu2e II Introduction

- As Mu2e approaches commissioning, we are also looking toward future upgrades
- The proposed Mu2e II experiment aims to achieve an order of magnitude improvement in sensitivity over Mu2e
  - If there is no signal at Mu2e: We could extend our sensitivity to find a signal or set new limits
  - If Mu2e does see something: We can improve our statistical significance and use different target materials to narrow down the NP processes involved
- To achieve a 10X improvement, we need:
  - An upgraded proton source (already approved)
  - Other upgrades to parts of the detector
- We aim to reduce costs by reusing parts of mu2e wherever feasible

Mu2e II Plans

- So far, various studies of Mu2e II backgrounds, sensitivity, and radiation damage have been performed
- A series of Mu2e II workshops has been held and the collaboration is involved in the Fermilab PIP-II planning process (a superconducting linac for LBNF and the muon campus)
    - PIP-II will have an energy of 800 MeV (Mu2e's proton source is 8 GeV) which is below the anti-nucleon production threshold and will result in less background
- An expression of interest was recently submitted to the Fermilab PAC
- Timecale:
    - Mu2e is expected to run for 4 years of data-taking at full intensity
    - Assuming 2-3 years from the end of Mu2e to the start of Mu2e II, Mu2e II could begin taking data around 2030



Summary

- The Mu2e experiment will improve current $\mu^- N \rightarrow e^- N$ CLFV sensitivity limits by 4 orders of magnitude (and thereby constrain many NP models at mass scales up to ~10,000 TeV)

- Mu2e will be sensitive to a broad range of NP models
  - If we see a signal, switching to another stopping target material will provide further information about the Lorentz structure of the NP

- Progress is on schedule and we plan to begin commissioning in 2020

Backup Slides

Purely Leptonic Conversion Processes

$$L_{\text{CLFV}} = \frac{m_m}{(1+k)\Lambda^2}\bar{m}_R s_{mn} e_L F^{mn} + \frac{k}{(1+k)\Lambda^2}\bar{m}_L g_m e_L (\bar{e}_L g_m e_L) + h.c.$$

Λ: effective mass scale of New Physics k: relative contribution of the contact term