Status of the Mu2e Experiment

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U.S. DEPARTMENT OF ENERGY

Fermilab

Charge

- You've been asked to specifically comment on the following:
  1) Changes made to the Project to meet cost envelope provided by OHEP
  2) Effect of changes on the experimental sensitivity
  3) Status and progress of simulation efforts

Charge

- My talk will follow this outline
  I. Mu2e Reminder and Recap
  II. Changes to the Project
  III. Effect of changes on Sensitivity
  IV. Status and Progress of Simulations
  V. Closing Remarks

Mu2e Reminder and Recap

Introduction

- Mu2e experiment is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^{-}N \rightarrow e^{-}N$
- In wide array of New Physics models CLFV processes occur at rates we can observe with next generation experiments
- The proposed experiment uses current proton source at Fermilab to achieve world's best sensitivity
- Target sensitivity has great discovery potential
  - Goal: <0.5 events background
  - Goal: Single-event-sensitivity of 2×10^{-17}
    (this yields Discovery Sensitivity for all rates > few 10^{-16})

Mu2e Physics Motivation

- Factor of 10^4 improvement over world's previous best results
  - W.Bertl et al. (Sindrum II), Eur Phys J C47 (2006) 337
  - C. Dohmen et al. (Sindrum II), Phys Lett B317 (1993) 631
- Discovery sensitivity over a very broad range of New Physics Models
  - SuperSymmetry, Little Higgs, Leptoquarks, Extended Technicolor, Extra Dimensions
- Complementary sensitivity to rest of the world HEP program
  - LHC, ν mixing, B-factory

Some CLFV Processes

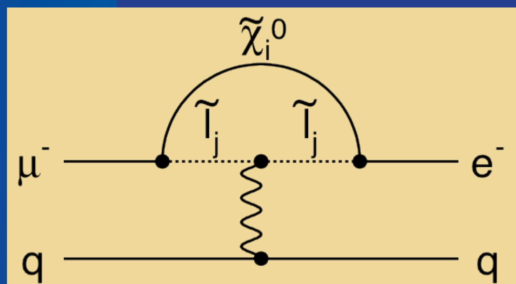
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (SuperB)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 2.4 E-12	10^{-13} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	
$\mu N \to eN$	$R_{\mu e}$ < 4.3 E-12	10^{-16} (Mu2e, COMET)

(current limits from the PDG)

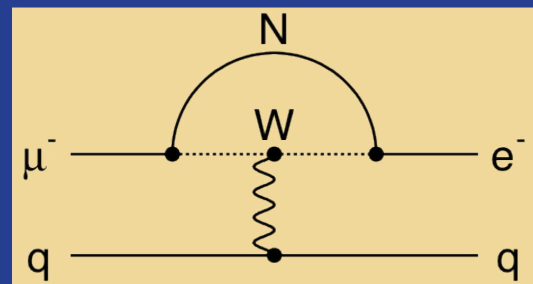
- Relative sensitivities model dependent
- Measure several to pin-down NP details

New Physics Contributions to Mu2e

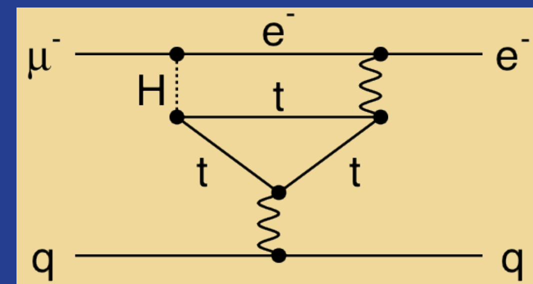
Loops



Supersymmetry

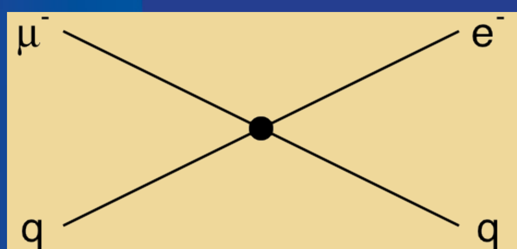


Heavy Neutrinos

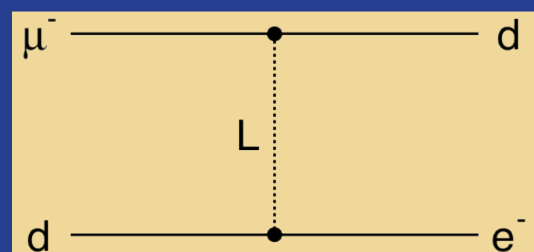


Two Higgs Doublets

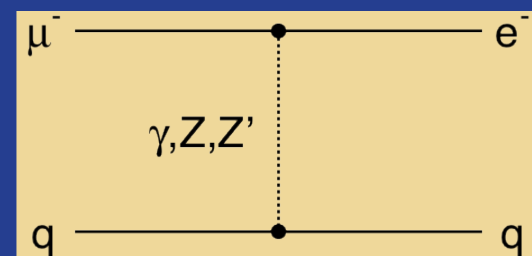
Contact Terms



Compositeness



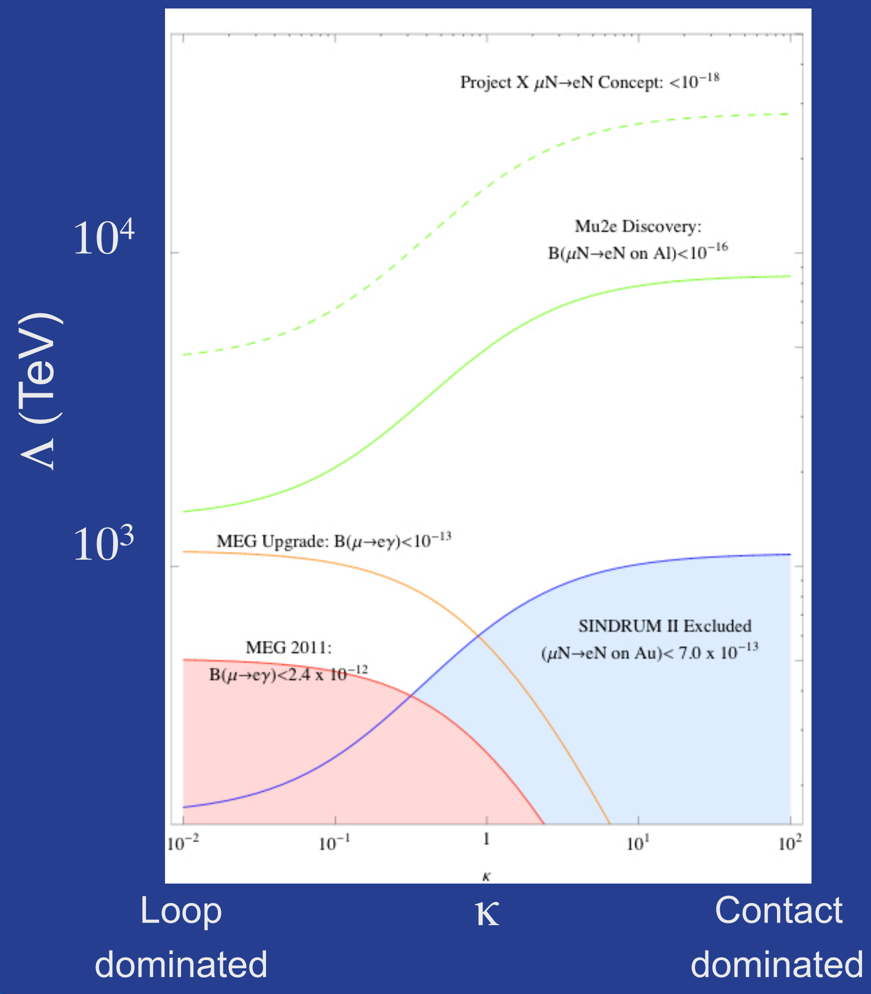
Leptoquarks



New Heavy Bosons /
Anomalous Couplings

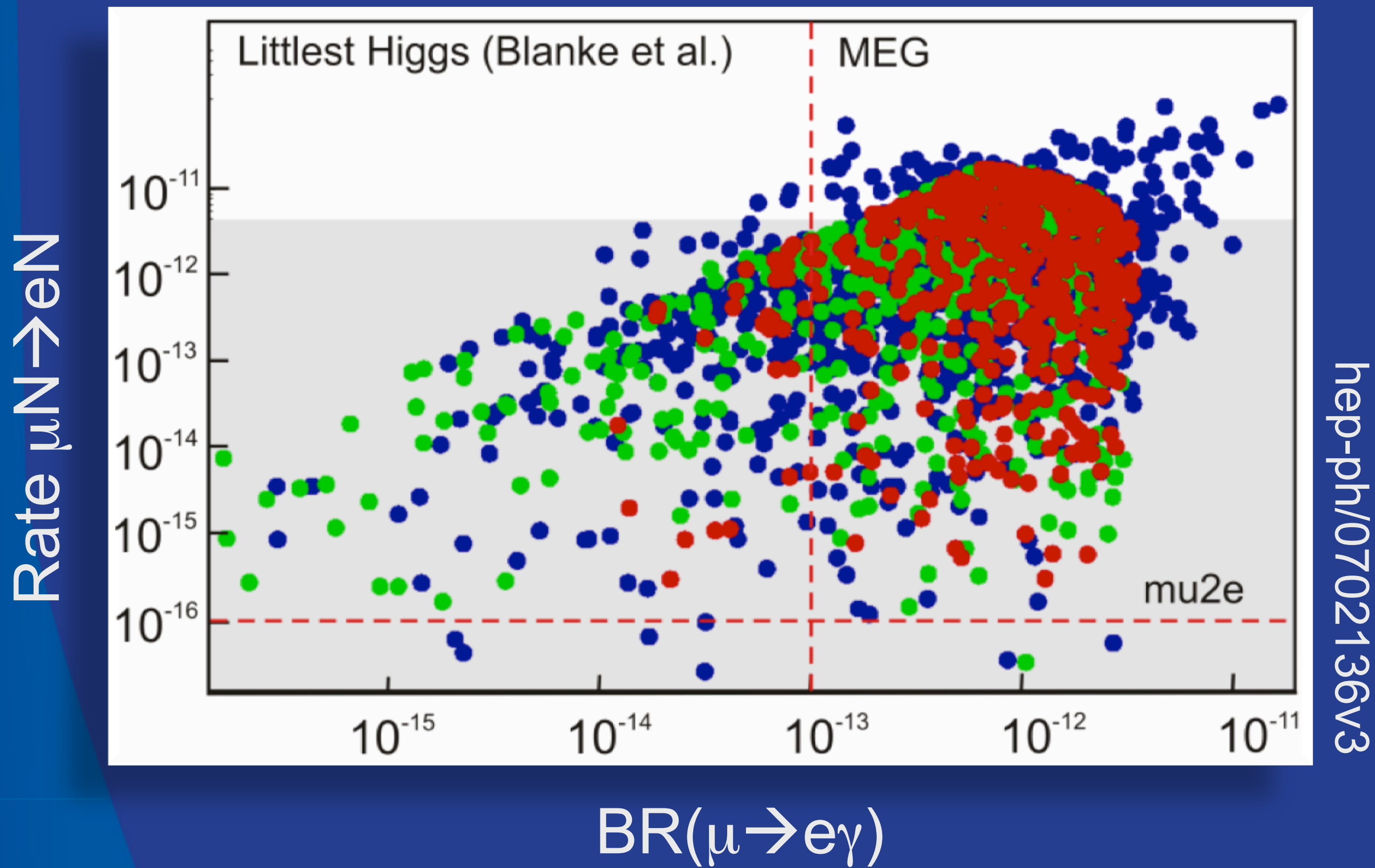
$\mu N \rightarrow eN$ sensitive to wide array of New Physics models

Mu2e Sensitivty



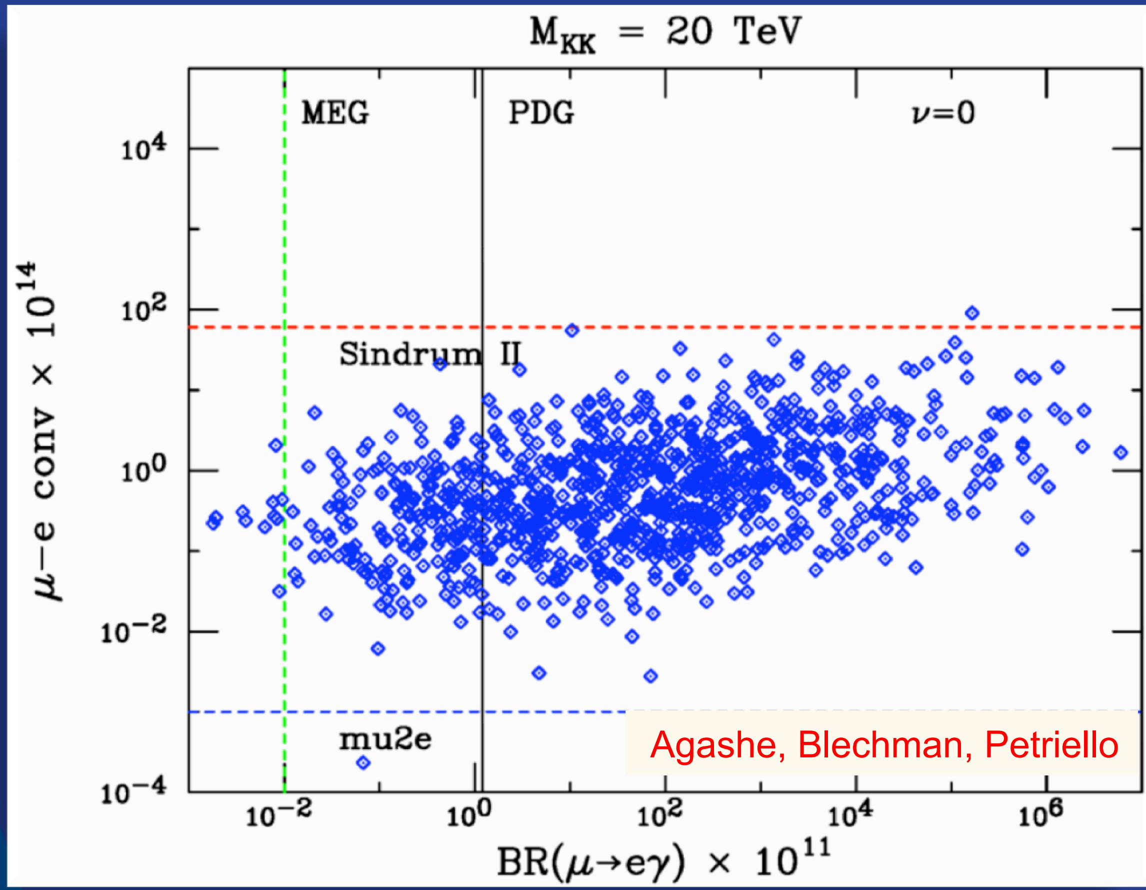
- Target Mu2e Sensitivity best in all scenarios

Mu2e Sensitivity



- Mu2e will cover the entire space

Mu2e Sensitivity

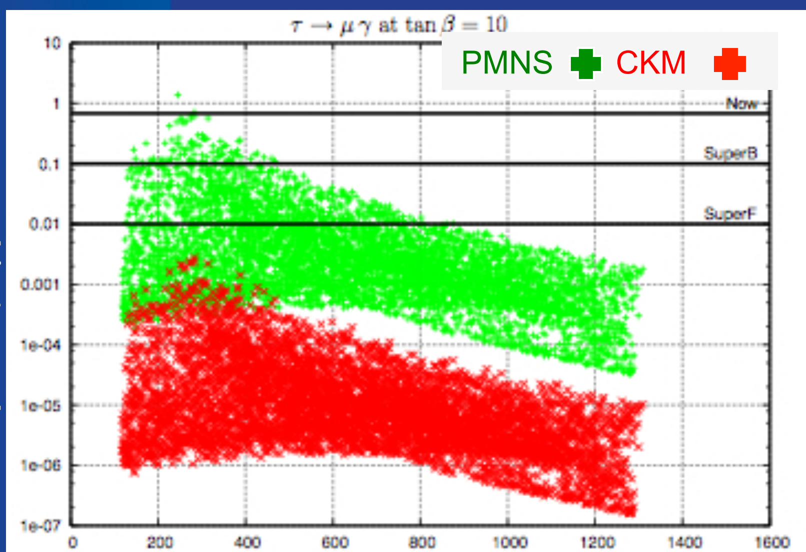


hep-ph/0606021v2

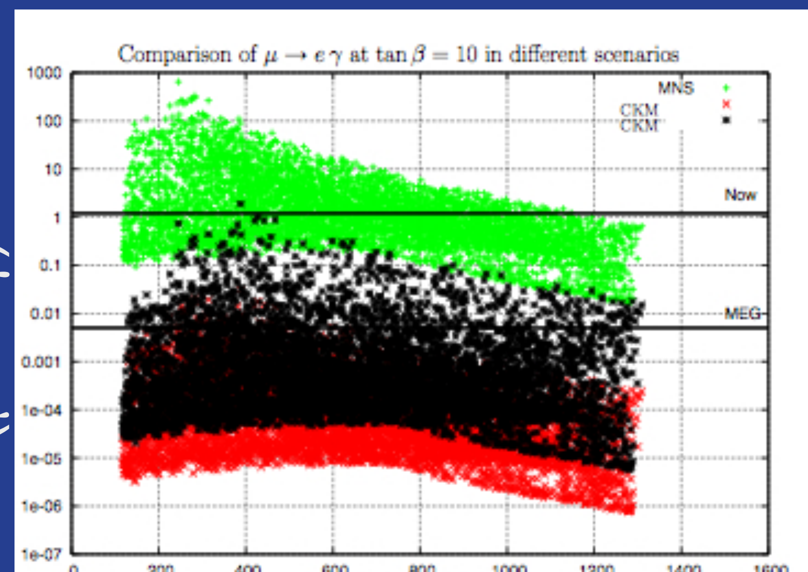
- Mu2e, MEG will each cover entire space

Mu2e Sensitivity

BR(τ→μγ) / 10-7



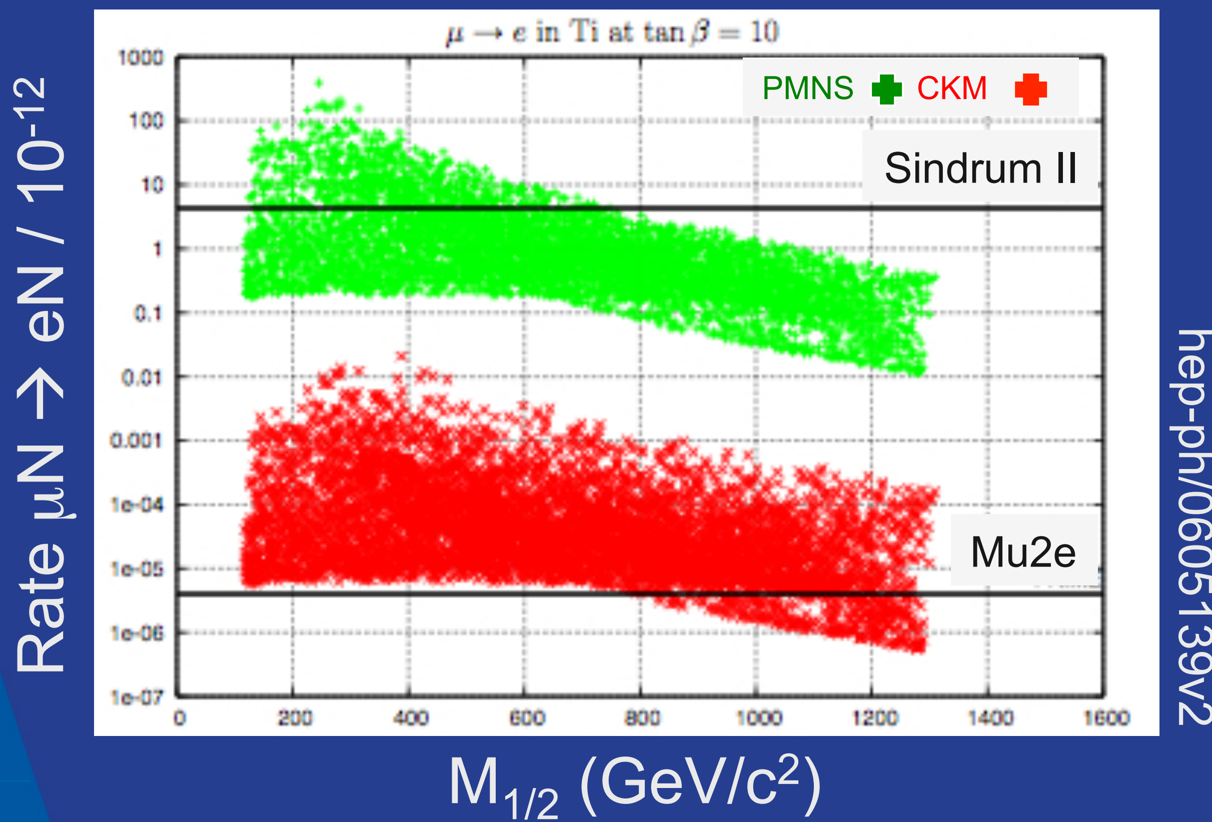
BR(μ→eγ) / 10-11



$M_{1/2}$ (GeV/c^2)

- μ→eγ, τ→μγ will begin to probe this space

Mu2e Sensitivity



- Mu2e will cover (almost) entire space

Mu2e Sensitivity

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

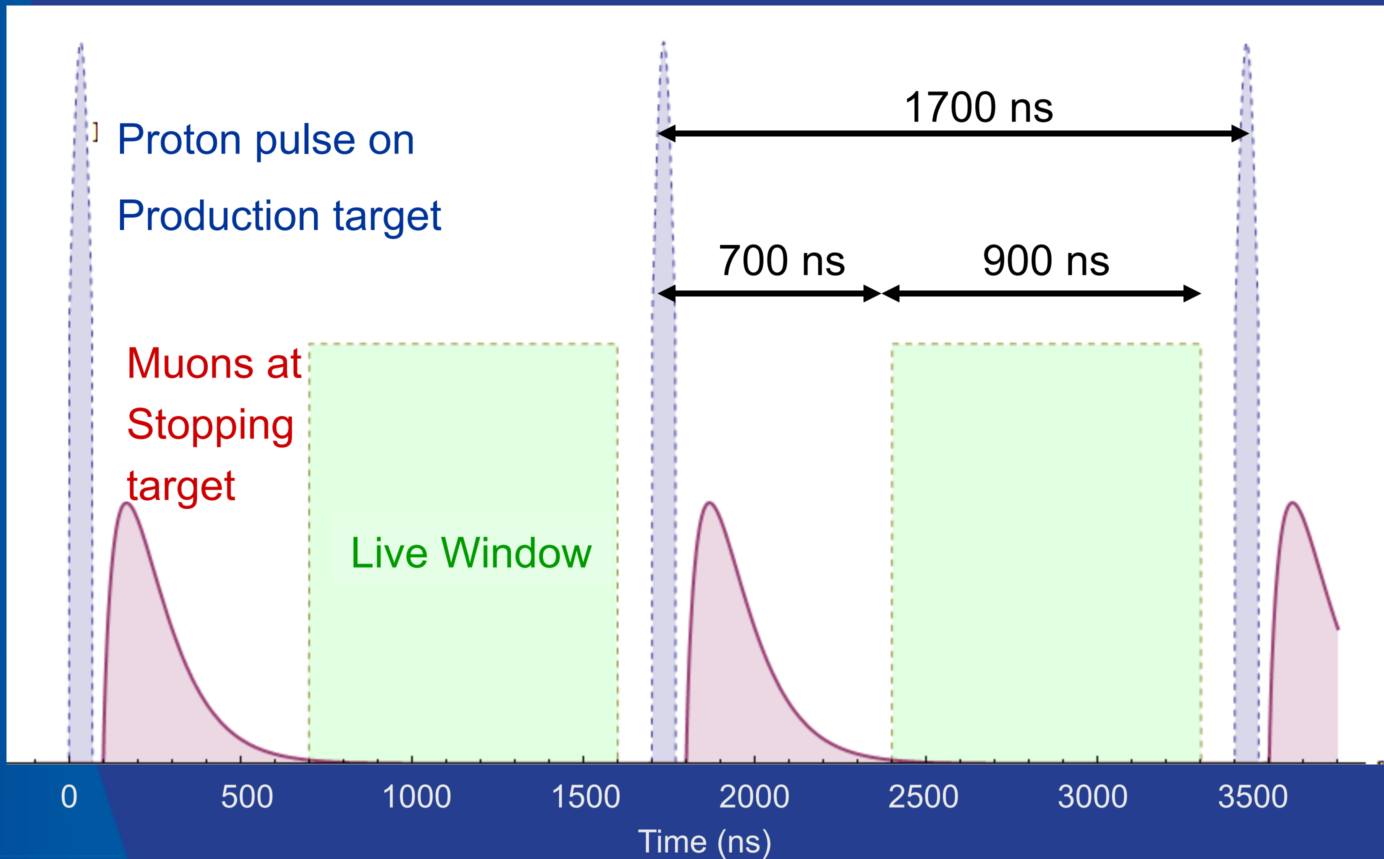
	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
$\mathrm{BR}(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	*$2.0 \cdot 10^{-15}$*	*$2.4 \cdot 10^{-14}$*	*$2.6 \cdot 10^{-15}$*	*$7.6 \cdot 10^{-14}$*	*$1.0 \cdot 10^{-16}$*	*$6.7 \cdot 10^{-16}$*	*$1.0 \cdot 10^{-16}$*	*$8.4 \cdot 10^{-16}$*	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	*$7.8 \cdot 10^{-10}$*	$2.7 \cdot 10^{-12}$	*$6.0 \cdot 10^{-10}$*	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/SuprB
- All of these will be observable by Mu2e

Mu2e Concept

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^N important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$

Mu2e Concept

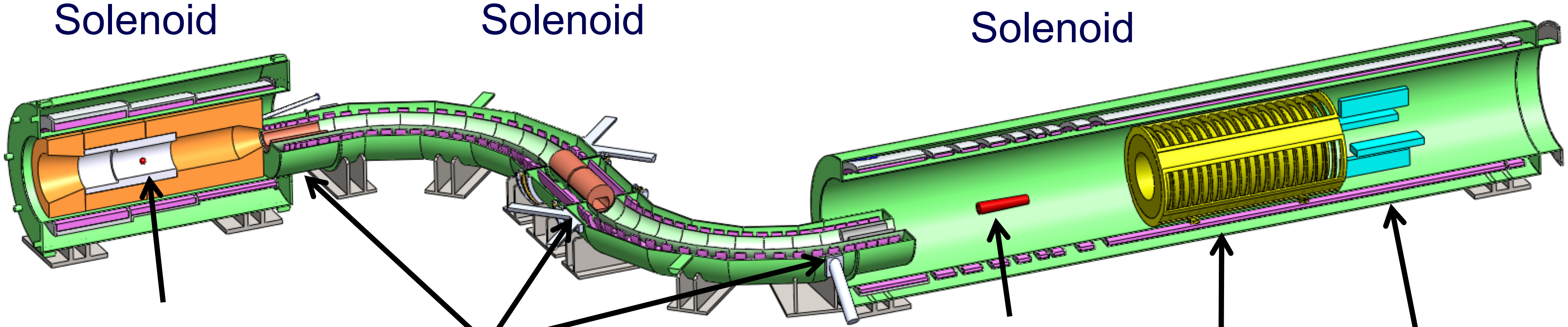


- Delayed live window suppresses prompt bgd
- Beam requirements well matched to Fermilab complex

Mu2e Signal

- The process is a coherent decay
  - The nucleus is kept intact
- Experimental signature is an electron and nothing else
  - Energy of electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
  - For aluminum: E_e=104.96 MeV
  - Important for discriminating background

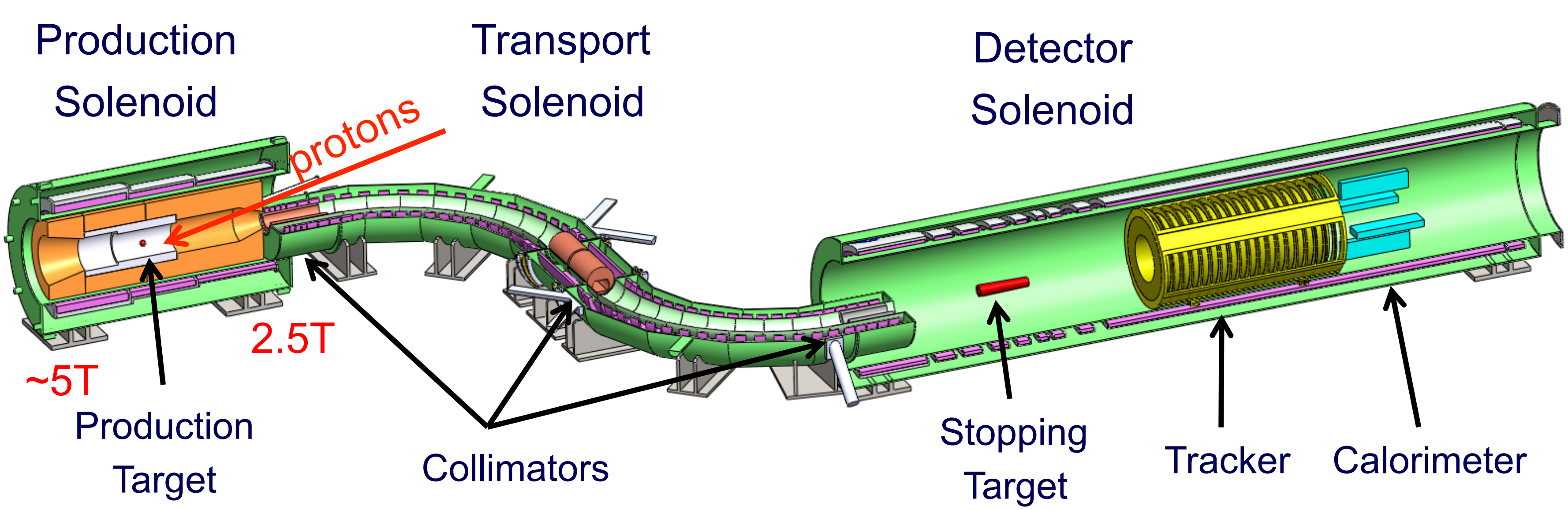
Mu2e Apparatus



(not shown: Cosmic Ray Veto, Proton Dump, Muon Dump, Proton/Neutron absorbers, Extinction Monitor, Stopping Monitor)

- Mu2e experiment consists of 3 solenoid systems

Mu2e Apparatus



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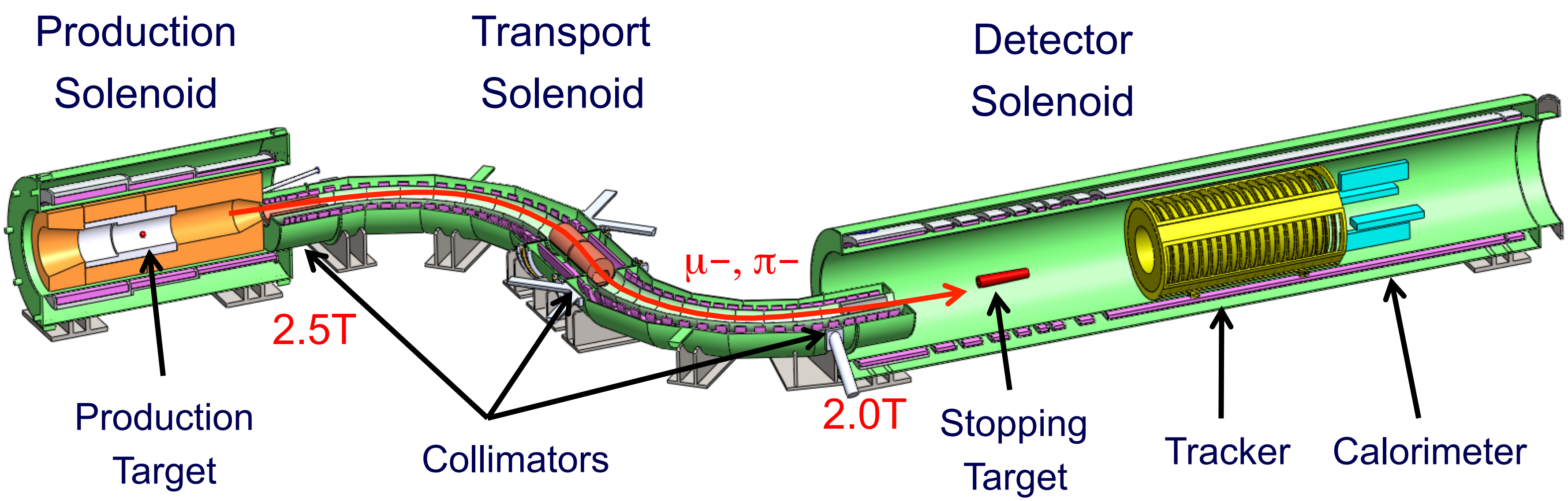

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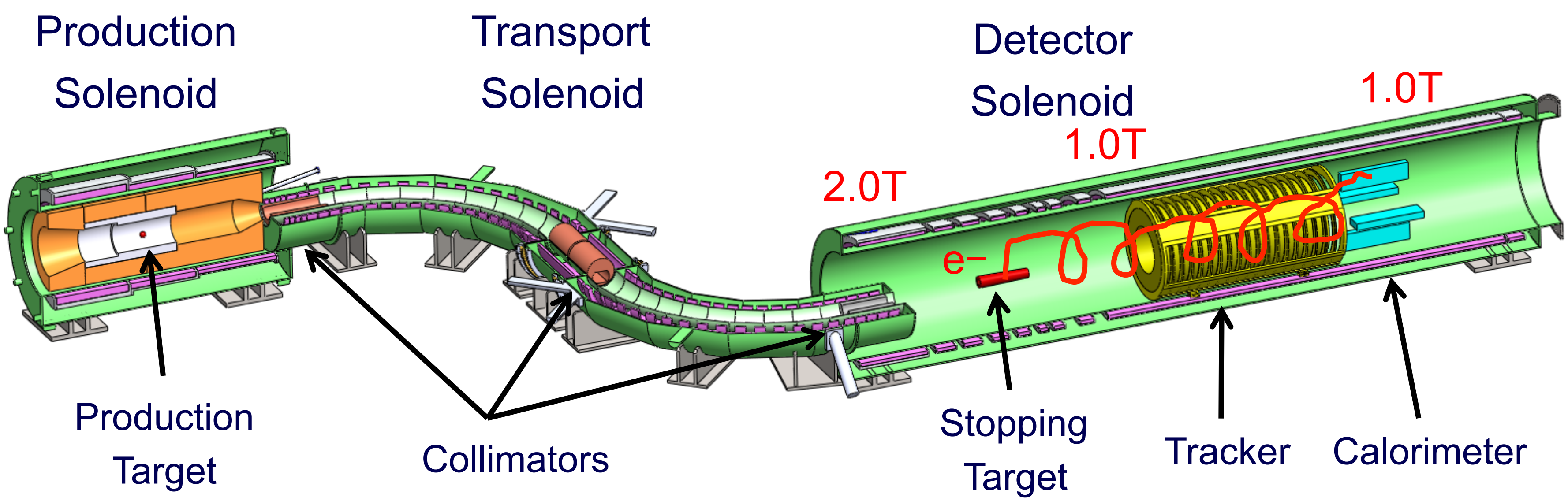

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- Mu2e experiment consists of 3 solenoid systems

Changes to the Project

Recall

- You last heard about the Project Status Jun-2011
  - Project Office fully staffed
  - All L2 and most all L3 managers identified
  - Additional engineering resources secured
  - Significant progress made in designs of Tracker, Solenoids, Accelerator, Cosmic Veto, etc.
  - An Independent Technical Review concluded Mu2e designs are “CD-1 Ready”
  - Development of CD-1 level cost estimate was in progress

Since June 2011

- From CD-0 we understood our cost drivers to be: Solenoids, Accelerator, and Civil Construction
  - Concentrated on first getting their cost estimates
- We found that the initial estimate of each was larger than expected
- Trend was clear… we were headed for a Total Project Cost that was unacceptable

Our Response

- We paused to Re-visit and Re-evaluate
  - Accelerator Task Force appointed to re-evaluate proton delivery scheme
  - Committee re-visited the Requirements Documents
  - Established Cost Review Committees
  - Pursued several value engineering possibilities

- In the end we've identified a Project design with a total cost < the DOE envelope
  - Will continue to evolve as estimates mature in preparation for CD-1 review next year

Summary of Changes

L2 System	New Base Cost + Contingency ($)	Changes Made
Project Management	16M	Leaner
Accelerator	38M	Accumulator eliminated, tungsten replaced, AIP
Civil Construction	24M	Footprint reduced, AP shielding eliminated, GPP
Solenoids	106M	Iron yoke eliminated, coil designs simplified, reduce PS field, GPP
Muon Channel	10M	Internal neutron shielding eliminated
Tracker	8M	No change
Calorimeter	0M	Supported off project (e.g. INFN)
Cosmic Veto	5M	No change
DAQ	6M	Use some physicist labor, reduce hardware
Total	**213M**	

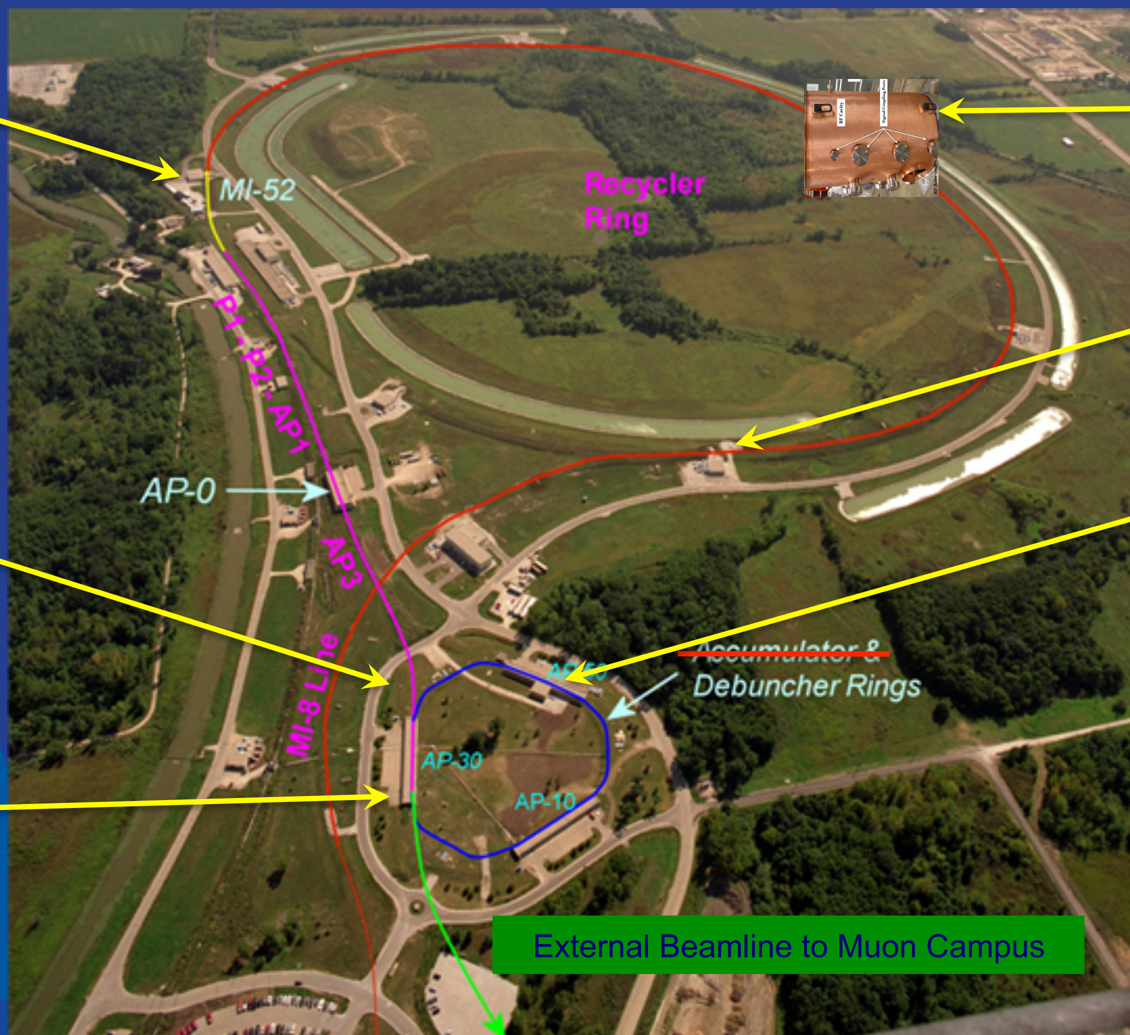
- Strategy: trade Rate for Run Time, Simplify

Mu2e and (g-2) Synthesis

Extraction kicker required by Mu2e and g-2.

New Debuncher Injection Kicker required by Mu2e and g-2.

Mu2e resonant extraction System/ g-2 Extraction Kicker



New 2.5 MHz RF system using recycled MI RF. Required by Mu2e and g-2.

Recycler Injection Kicker – Provided by NOvA

Abort Kicker – Required for Mu2e. Power supply shared with g-2 Extraction Kicker.

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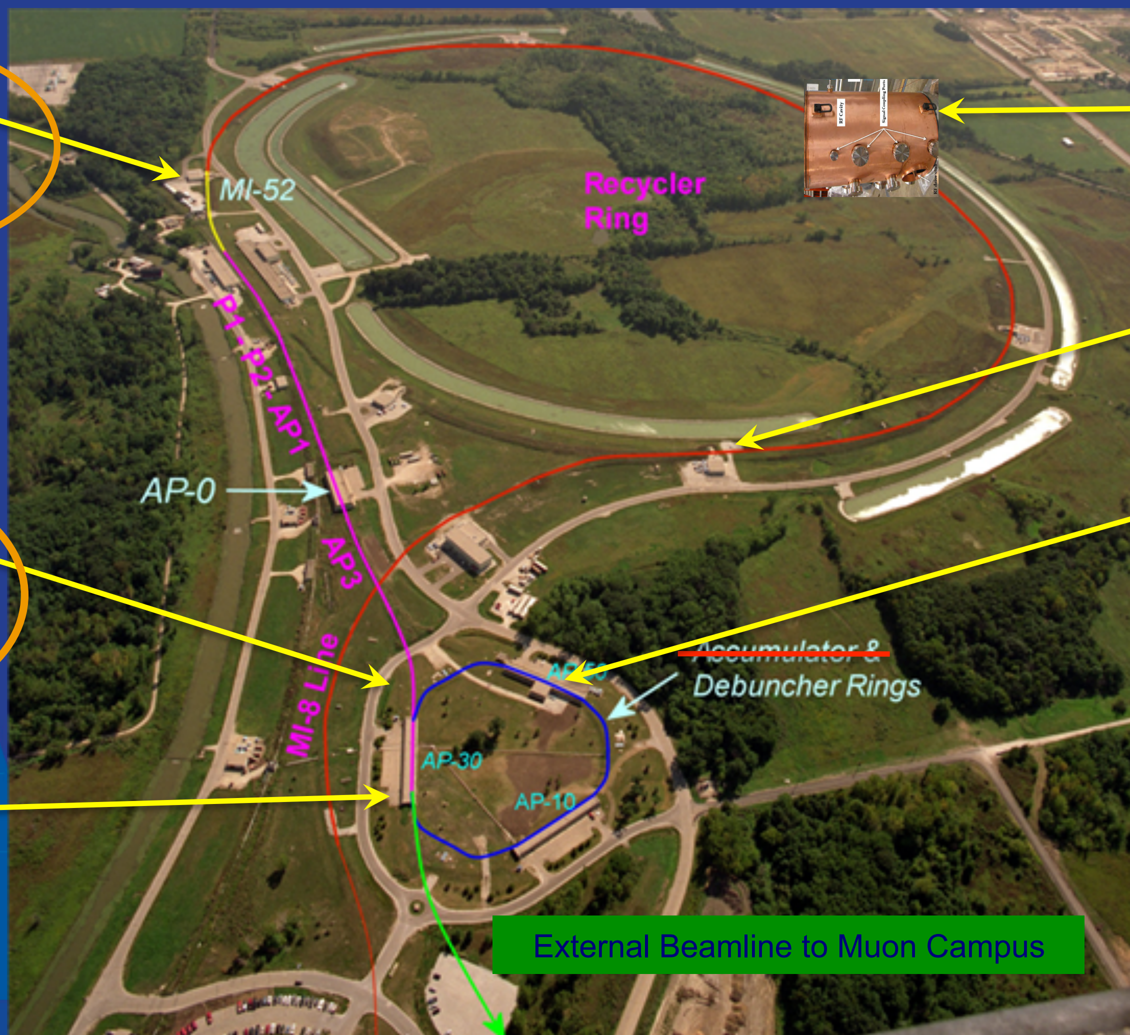

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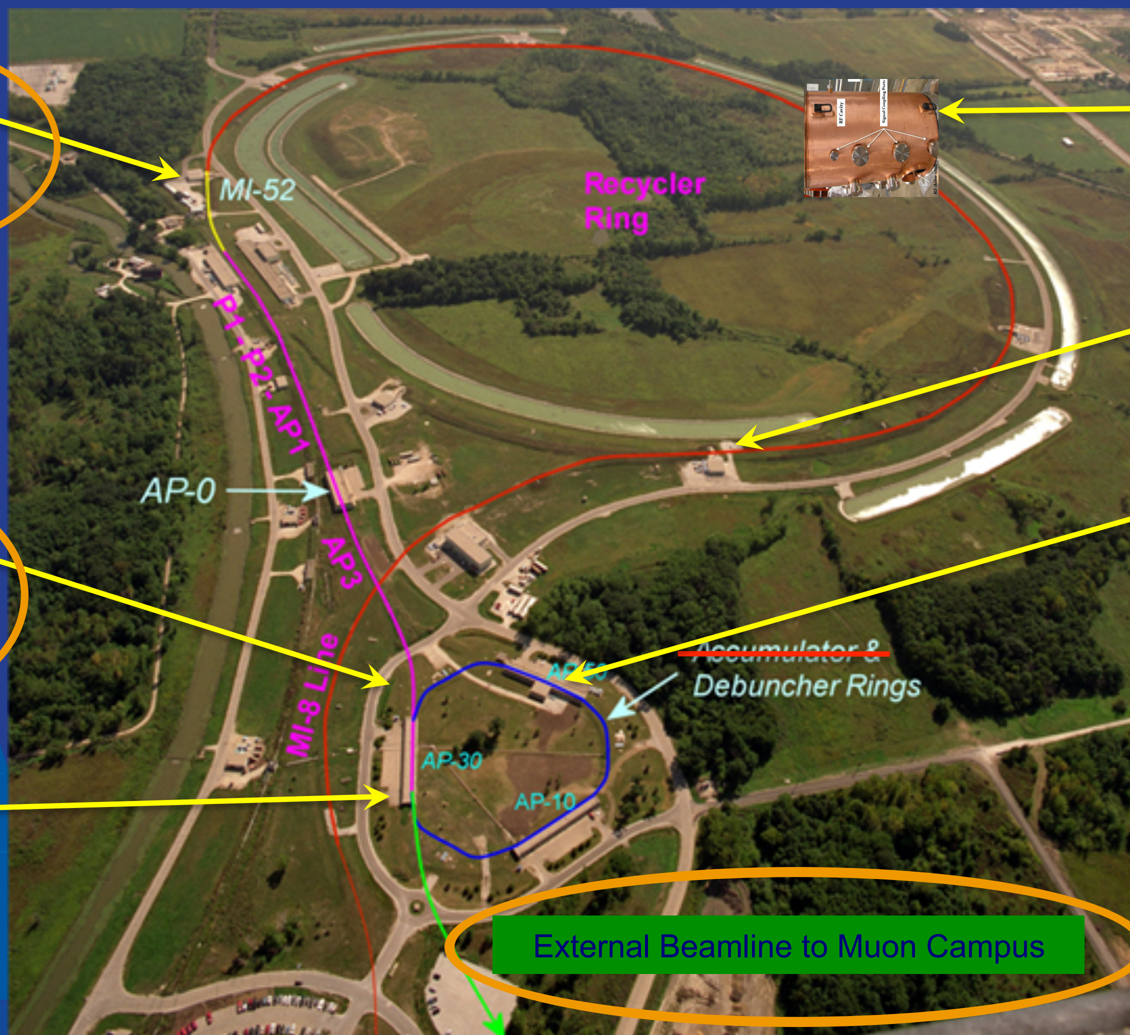

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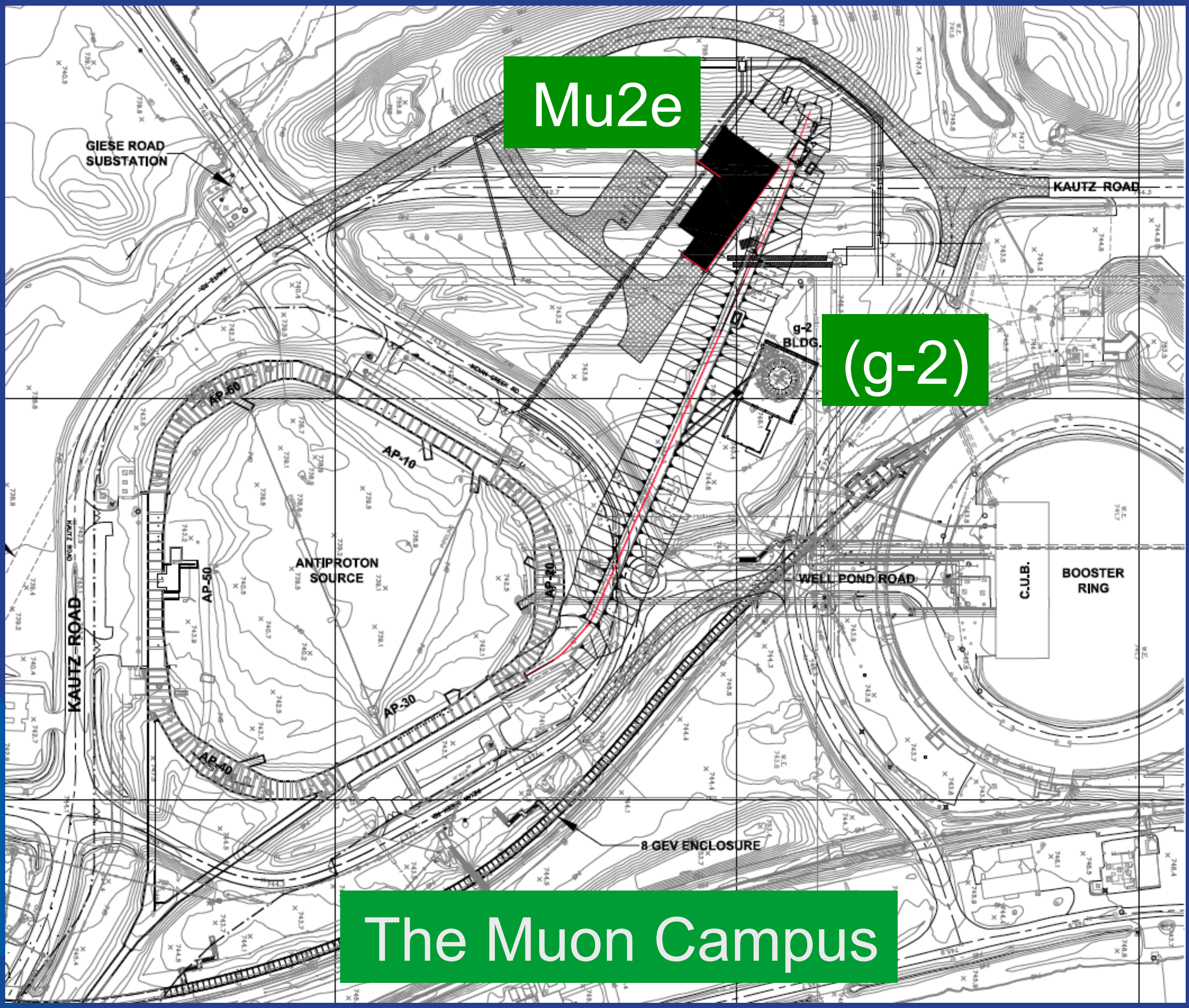

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Mu2e and (g-2) Synthesis

- By synthesizing the two projects Fermilab has a plan that allows for the completion of both experiments at a reduced cost
- Have identified the common elements and relabeled some of them as AIP/GPP packages
  - An easy way to track common elements
  - Affords some flexibility relative to CD timescales and funding profiles
  - Content and scheduling of these packages still a work in progress

Effect on Sensitivity

Bottom Line

- None of the changes are expected to significantly affect the sensitivity of the experiment
- With a (3+1)y run Mu2e should reach a single-event-sensitivity of 2 x 10^{-17} with a total background of < 0.5 event
  - Yields Discovery Sensitivity for all rates > few 10^{-16} (ie. unchanged)

Mu2e Background

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.009
	Radiative μ Capture	<0.001
Late Arriving	Radiative π Capture	0.040
	Beam electrons	<0.001
	μ Decay in Flight	0.034
	π Decay in Flight	0.003
Miscellaneous	Anti-Proton	0.060
	Cosmic Ray	0.025
Total Background		0.17

(assuming 1E18 stopped muons in 2E7 s of live time)

- Designed to be nearly background free

Mu2e Background

Category	Source	Contributing Experimental Effects
Intrinsic	μ Decay in Orbit	tracker resolution, instant. rate
	Radiative μ Capture	material
Late Arriving	Radiative π Capture	extinction, beam width, material
	Beam electrons	extinction, DS gradient, material, beam width
	μ Decay in Flight	extinction, TS transport
	π Decay in Flight	extinction, beam width
Miscellaneous	Anti-Proton	E(proton), Be window, material
	Cosmic Ray	shielding, overburden, live time

- Only a few of these contributors are affected by the changes made to the Project

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Comparison of Proton Beam Parameters

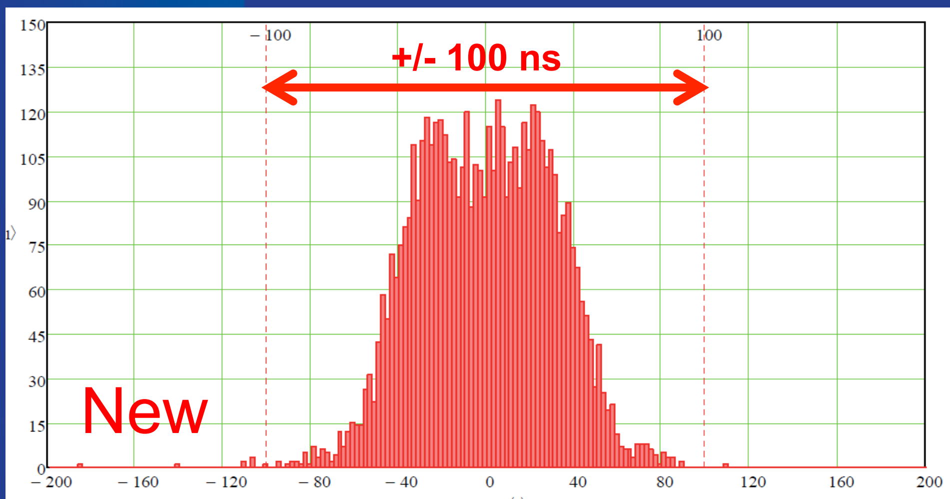
(assuming adequate shielding at the AP service buildings)

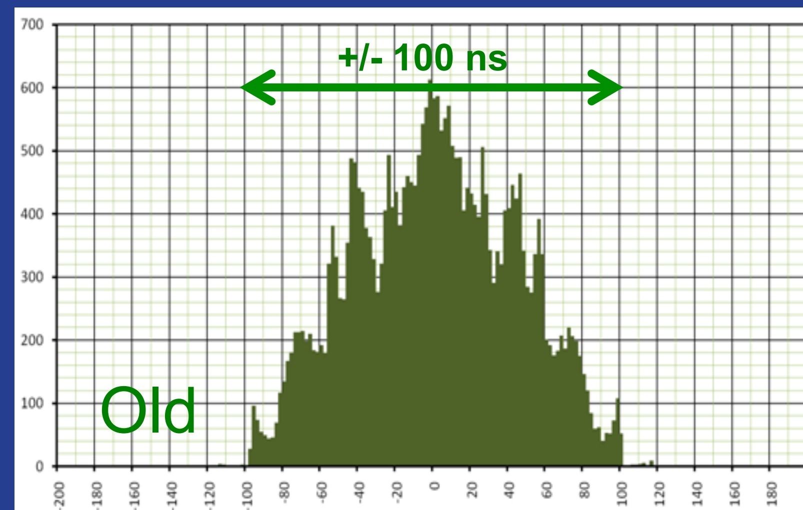
Scenario	#Booster Batches	Duty Factor	Instan. Rate	Average Rate
Old	6 / super-cycle	94%	100%	100%
New	2 / super-cycle	32%	97%	33%

- Booster Batch = 4 x 10^{12} protons
- Old Instantaneous rate = 19.1 x 10^{12} protons/s
- Old Average rate = 6.5 x 10^{16} protons/h

✓ New scheme is cheaper , offers less technical risk, and reduces instantaneous rates

Comparison of Beam Width





arrival time at production target (ns) arrival time at production target (ns)

(nb. extinction not modeled here)

- ✓ New schemes result in a *narrower* beam width… should reduce backgrounds

Other comparisons to note

- ✓ Removal of internal neutron absorber has no significant effect on rates in tracker
- ✓ Ratio of (out-of-time/in-time) protons: new and old schemes both achieve specification (10^{-10})
- Need to recalculate stopped-μ yield once new field maps available… expect 10% effect
- Need to replace the iron yoke with something … will effect the CR-induced background

Simulation Progress and Status

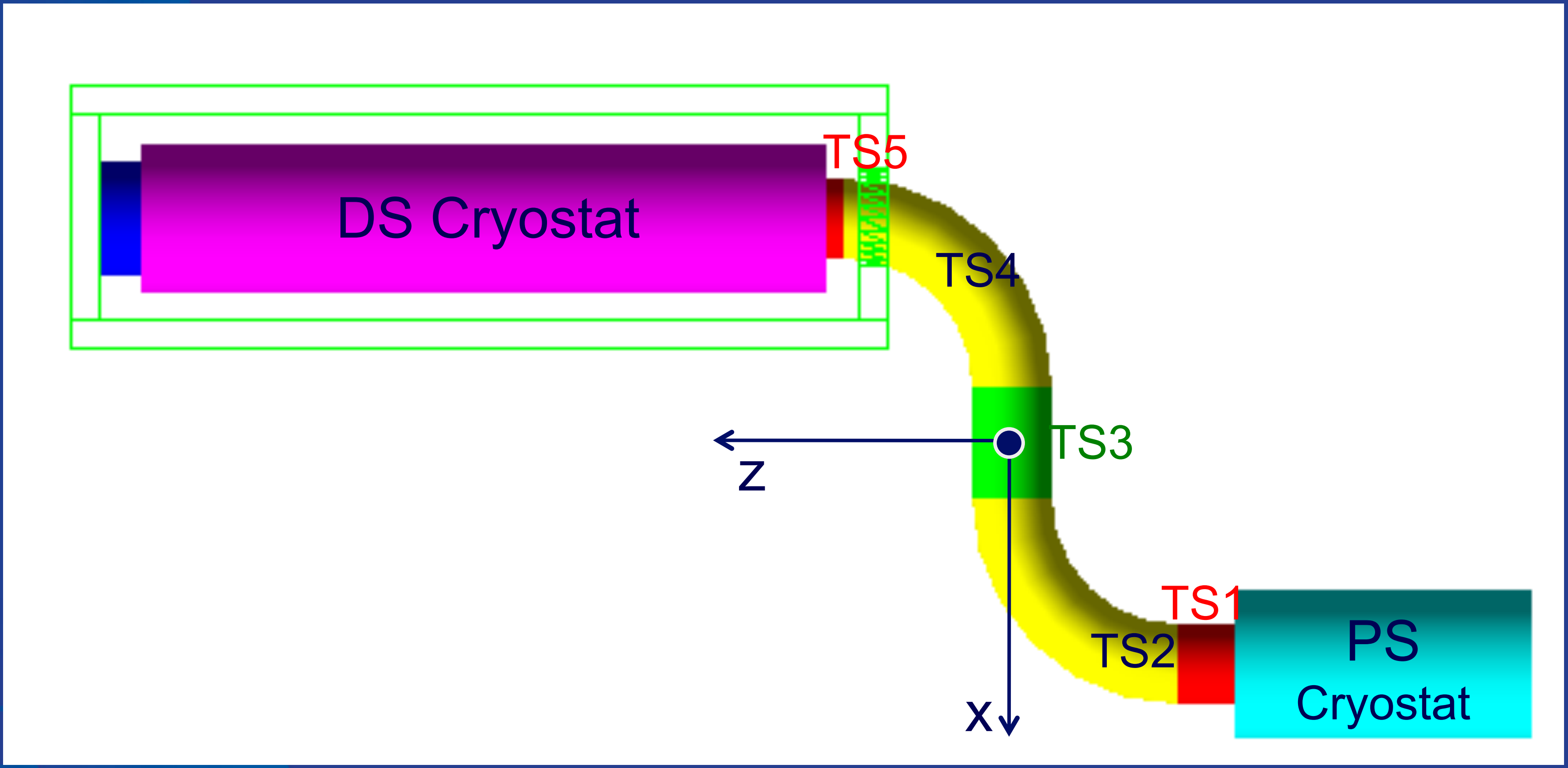
Recall

- You last heard about our simulation in Mar 2009
  - In process of resurrecting old FORTAN code
  - Most all background estimates taken from MECO with tweaks to account for differences between BNL and FNAL proton delivery schemes
  - Dedicated c++ code specific to Mu2e in nascent stage

Since March 2009

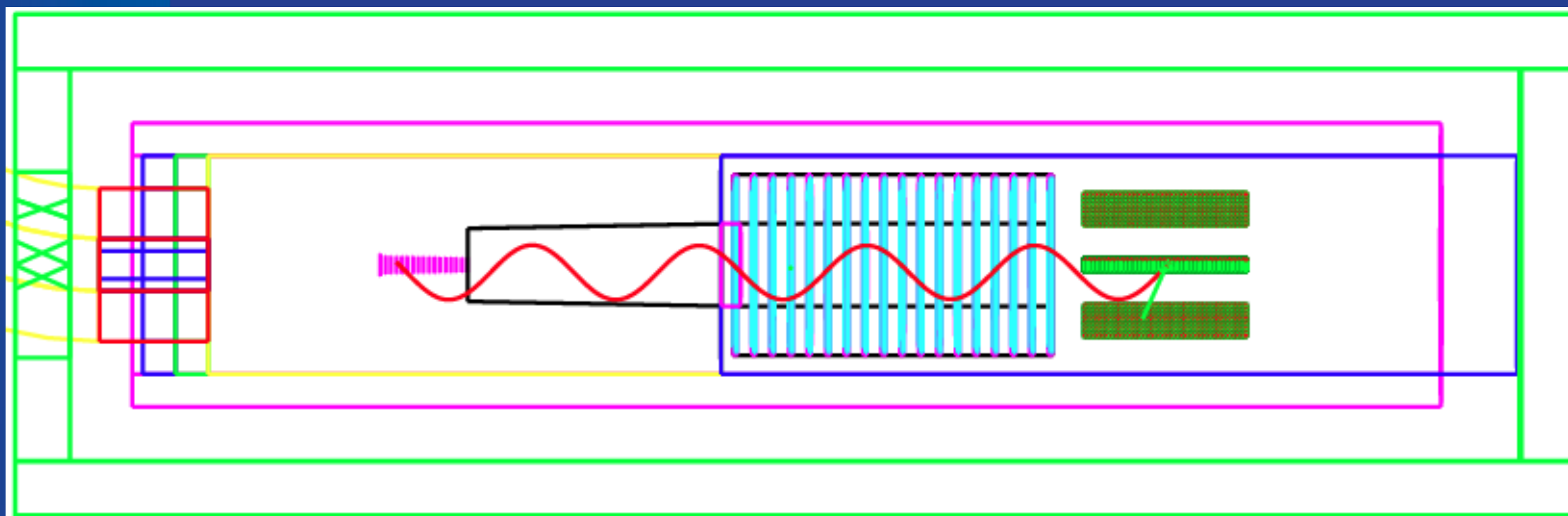
- Have established a mature framework
  - architecture inherited from CMS and shared among all Intensity Frontier experiments (“art”)
  - G4, hit level simulation that includes the full beam line and detector details
  - Includes all background processes
  - Includes capability to overlay events
  - Prototype event reconstruction for Tracker
  - Uses a Kalman filter track fitter
  - Has an event display
  - Includes MARS and MCNP neutron codes

Beam line in simulation



- Beam line, cryostats, collimators, pbar window, production target

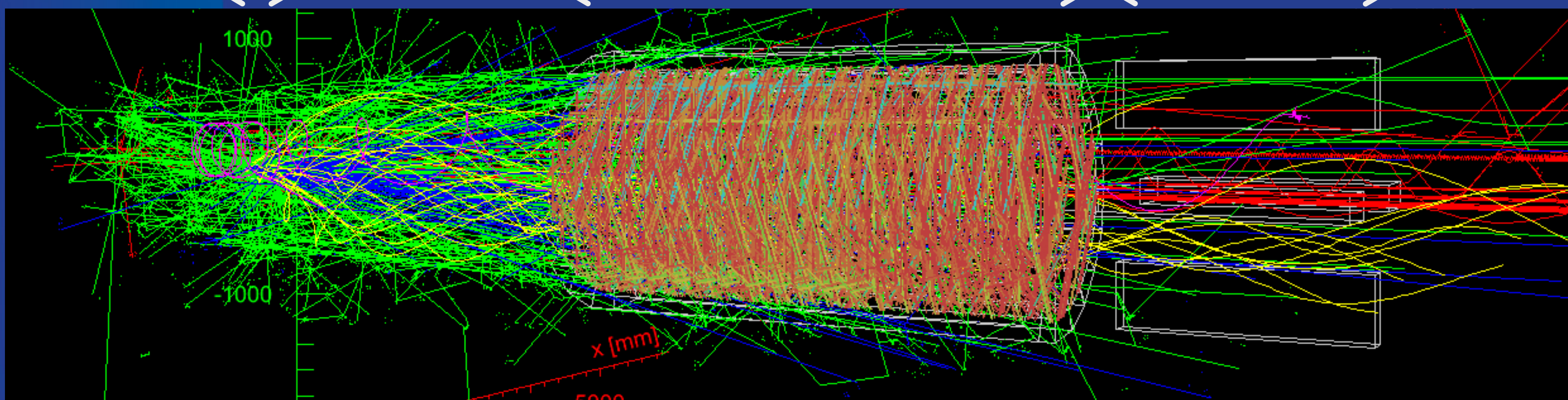
Detector in simulation



- Neutron absorbers, stopping target, iron yokes, cryostat walls, proton absorber, tracker, calorimeter, beam stops, supports, straw gas, straw walls, etc.
- Continually adding details and improving fidelity

Signal Event with Background Overlay

Stopping Target Straw Tracker Crystal Calorimeter



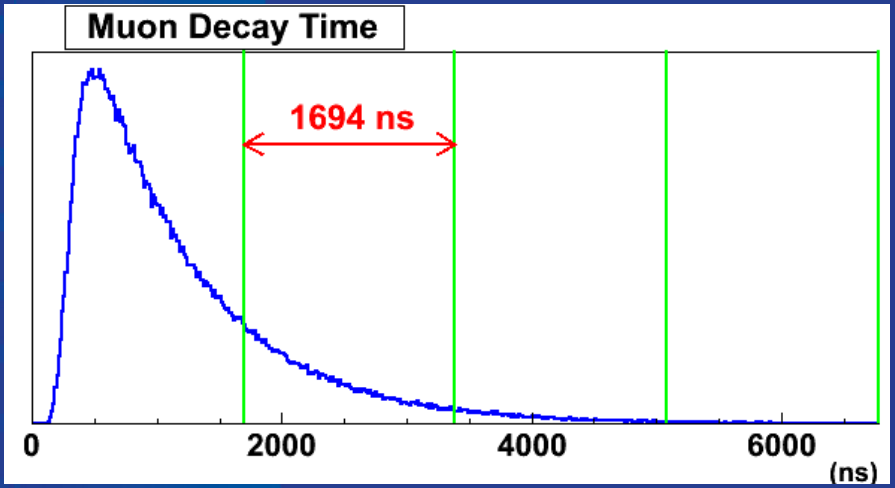
- A signal electron with background overlays (integrated within micro-bunch over 500-1695 ns)

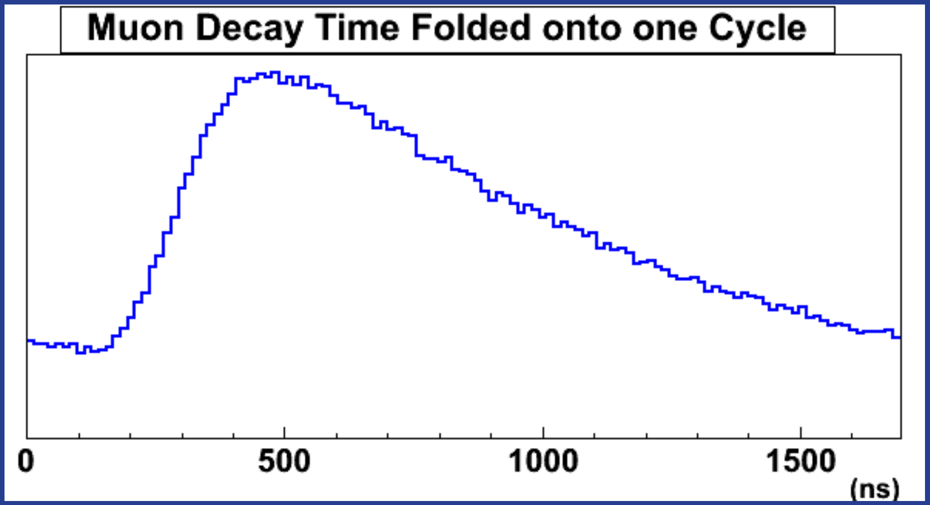
Background overlay cocktail

	DIO	protons	photons	neutrons
per proton pulse	36.0k	5.6k	112.5k	84.4k
with t>500 ns	22.5k	3.5k	70.2k	52.7k
Frac.(>0 tracker hits)	5.2E-4	4.2E-3	7.7E-4	1.2E-3
Yield / pulse	11.6	14.9	53.7	64.1

- Includes all dominant sources of occupancy
  - Muon DIO, protons/neutrons/γ from captured muons
- Need to include neutrons from Production Target, albedo from muon dump
  - Expect these to be ~1/10 the occupancy of above

Background overlay cocktail





- Occupancy from neighboring pulses is included
- Have dials to model pulse-to-pulse variations (spec: +/- 50% from Booster)

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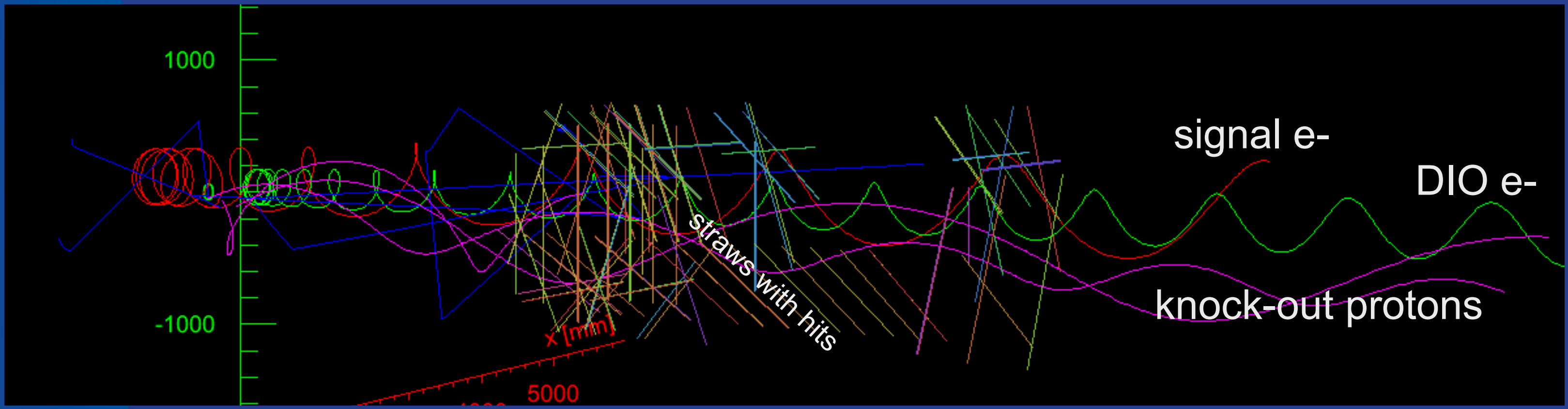
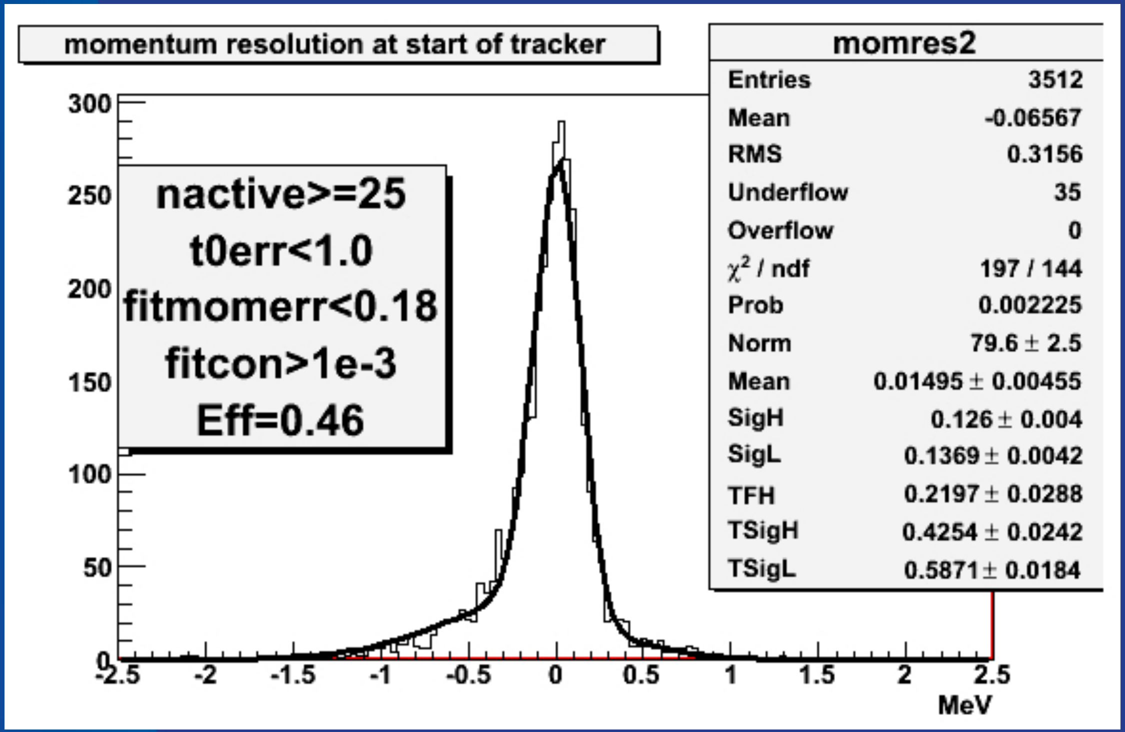
Pattern Recognition



(particles with hits within +/-50 ns of signal electron t_{mean})

- Previous picture an exaggeration re: Patt. Rec.
- Signal tracks deposit their hits over 100 ns
  - We use timing information to eliminate most hits and simplify pattern recognition

Effects of background overlaps on Resolution



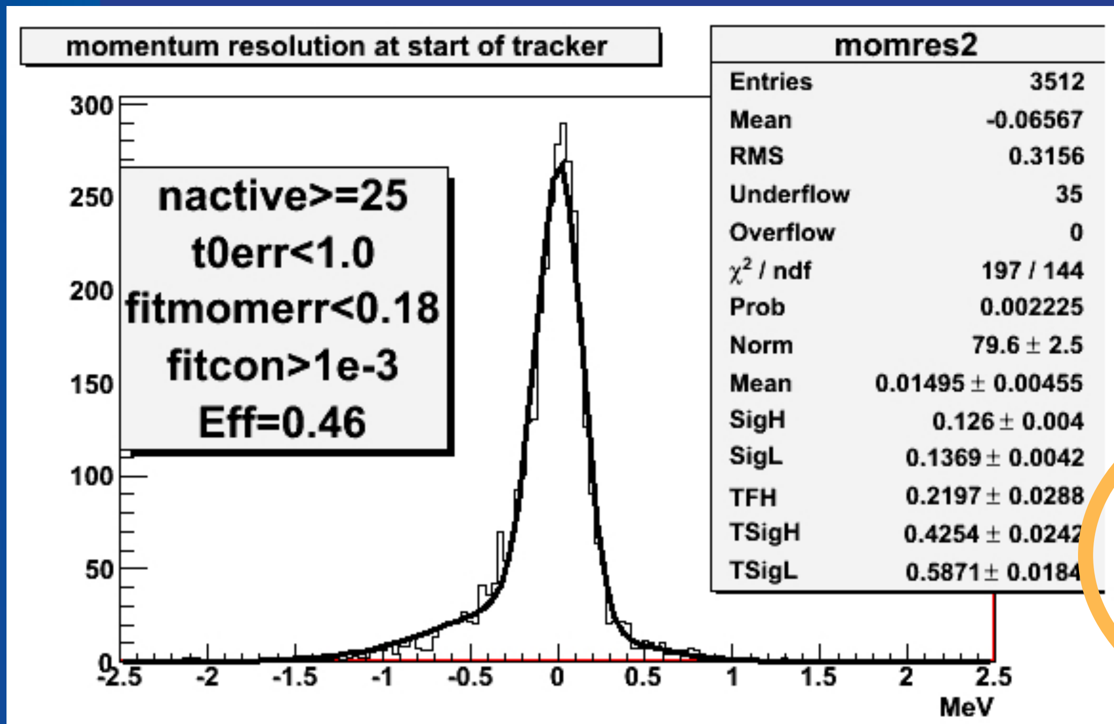
125 keV/c core

425 keV/c high tail

<1/1000 above 1 MeV/c

- Resolution unaffected, efficiency reduced
  - Known improvements exist and will be implemented
  - Variations of overlay (x2) affect efficiency at 5-10% level (ie. we're not sitting near a cliff edge)

Effects of background overlaps on Resolution



meet requirements

125 keV/c core

425 keV/c high tail

<1/1000 above 1 MeV/c

- Resolution unaffected, efficiency reduced
  - Known improvements exist and will be implemented
  - Variations of overlay (x2) affect efficiency at 5-10% level (ie. we’re not sitting near a cliff edge)

Using the Simulation

- Rate studies to determine background occupancies
- Tracker resolution studies
- Optimizations
  - Production Solenoid, Production target, Stopping target, neutron absorber, calorimeter geometry, etc.
- Studies of heat and radiation loads in solenoids
- Performed full background estimate as given in Table on page 34

Veracity of Simulation

- Have pinned production models to latest data
  (e.g. HARP π production data)
- Have discussed with G4 authors to understand best physics list for our purposes
  (QGSP_BERT, QGSP_BERT_HP)
- Have included latest DIO theory
  (Czarnecki, Tormo, Marciano arXiv:1106.4756 [hep-ph])
- Are all relevant processes accurately modeled?
  - Working with G4 collaboration to develop validation tests for the processes we most care about

Veracity of Simulation

Category	Source	Events	
	μ Decay in Orbit	0.009	67%
Intrinsic	Radiative μ Capture	<0.001	--
	Radiative π Capture	0.040	50%
	Beam electrons	<0.001	--
	μ Decay in Flight	0.034	50%
Late Arriving	π Decay in Flight	0.003	50%
	Anti-Proton	0.060	100%
Miscellaneous	Cosmic Ray	0.025	100%
Total Background		0.17	

(assuming 1E18 stopped muons in 2E7 s of live time)

- Have quantified our background uncertainties

(Some reductions possible as simulation and statistics mature)

Measuring Backgrounds

Category	Source	Methodology
Intrinsic	μ Decay in Orbit	Vary E_{min} requirement
	Radiative μ Capture	Use e+ spectrum
Late Arriving	Radiative π Capture	Use e+ spectrum, Spoil extinction, Vary t_{min} requirement
	Beam electrons	
	μ Decay in Flight	Spoil extinction
	π Decay in Flight	Spoil extinction, Go to early times
Miscellaneous	Anti-Proton	Remove pbar window, e+ spectrum
	Cosmic Ray	Beam off

- We will measure our backgrounds *in situ*

Closing Remarks

Mu2e Progress

- Have established a mature software framework
- Have developed a sophisticated simulation
  - Includes most of the dominant effects already
  - Will continue to evolve to include full detail
- Have developed an initial pattern recognition and track fitting algorithm
  - Demonstrates necessary resolutions are achievable with current detector design and rates

Mu2e Progress

- Have developed a Project Design with a total cost that fits within the DOE envelope
  - Includes proton delivery scheme, muon beam line, detector apparatus, and conventional construction
  - Includes overheads, escalation, and contingency
- We traded Rate for Run Time… ultimate sensitivity unchanged
- With a (3+1)y run the current design will achieve a factor of 10^4 improvement over current $\mu N \rightarrow eN$ experiments

Mu2e Plans

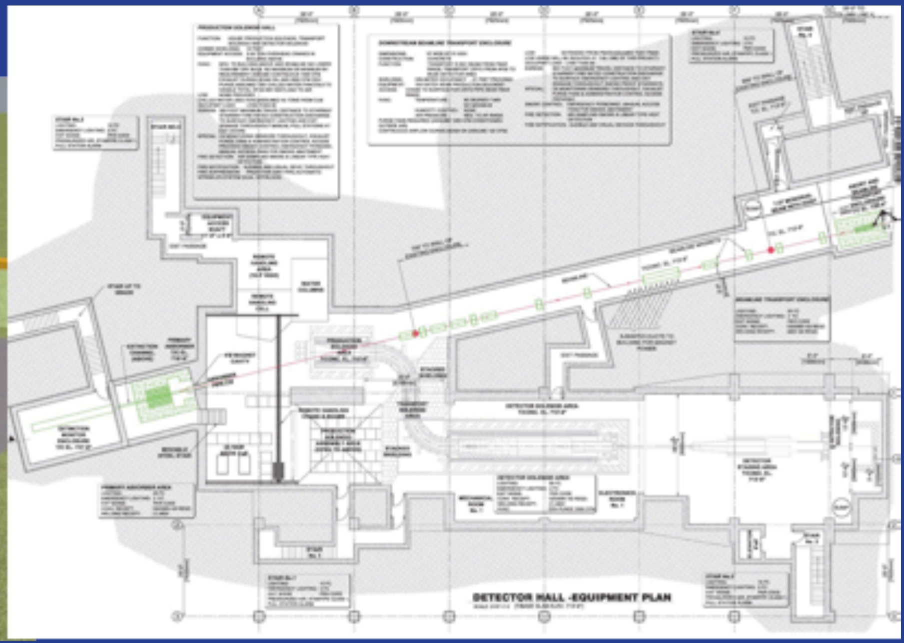
- Mu2e plans to be ready for CD-1 review in late Spring 2012
- Mu2e plans to discover charged lepton flavor violation later this decade

p.s. Other Progress

(there's lots of it)

Progress: Building

Mu2e on Muon Campus

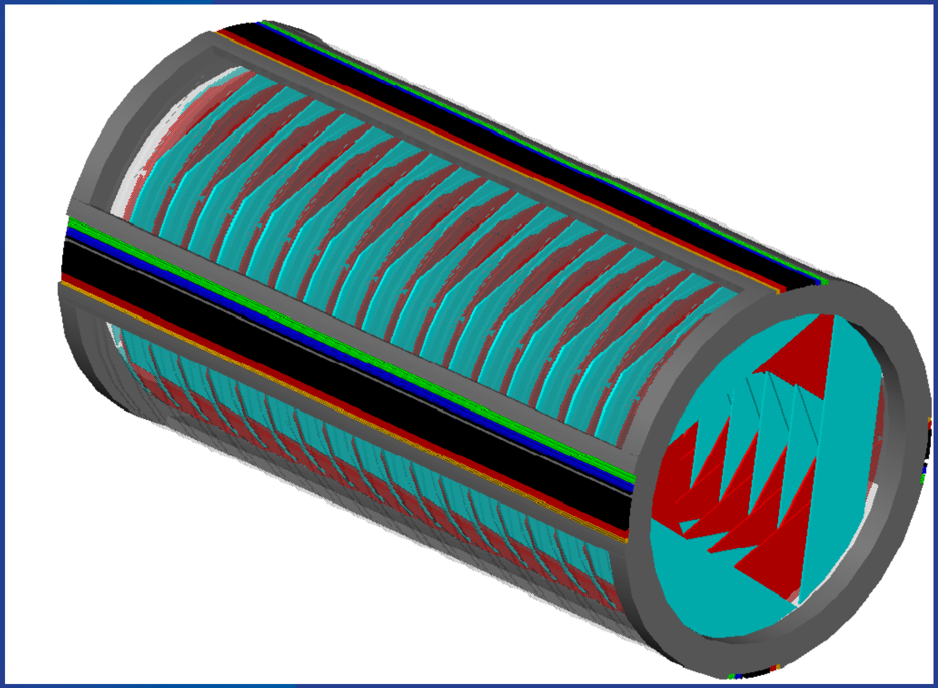


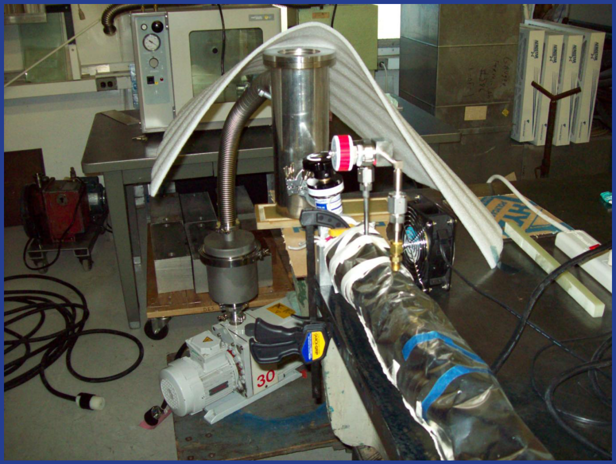
Design: Plan View

- Location determined, approvals obtained or in progress, design mature

Fermilab

Progress Tracker





- Mature design, proto-types in progress, tension tests, vacuum test, leak tests, etc.

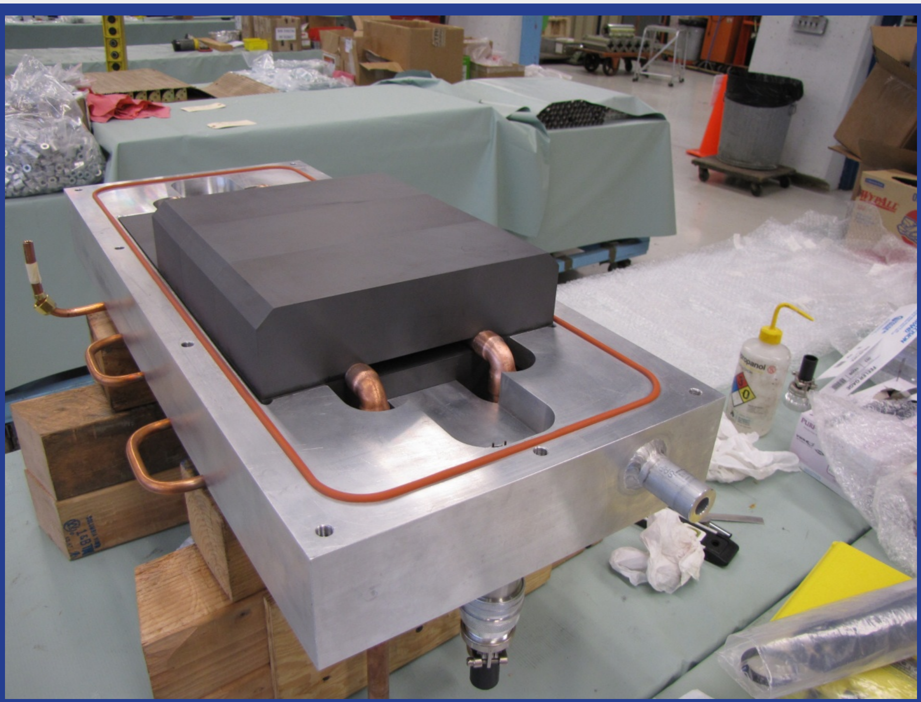
Progress: Extinction Systems

- Mature design, two prong attack:
  - "internal" : momentum scraping in rings
  - "external" : AC dipole in muon beamline
  - Our models tell us that in combination these will achieve an extinction of 10^{-12} << requirement (10^{-10})

- Extinction Monitors
  - Mature design
  - Two prong attack: "up" and "down" stream of AC dipole

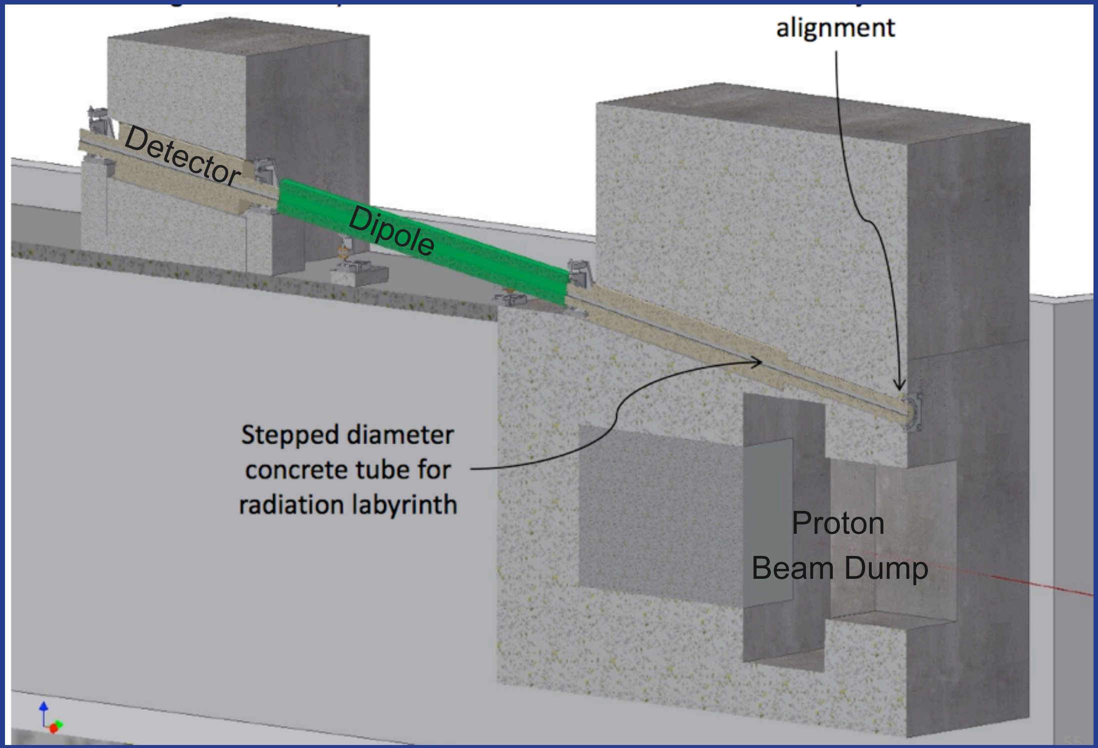
    (so that we can separately determine performance of internal and external extinction systems)

Progress: Extinction Dipole



- Proto-type extinction dipole is built
  - Part of US-Japan collaboration
  - Ferrites and power supplies identified
  - Performance will be measured

Progress: Extinction Monitors

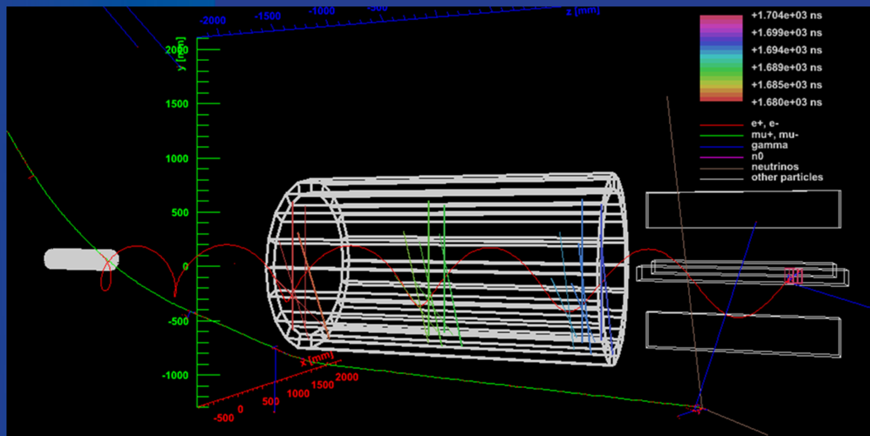


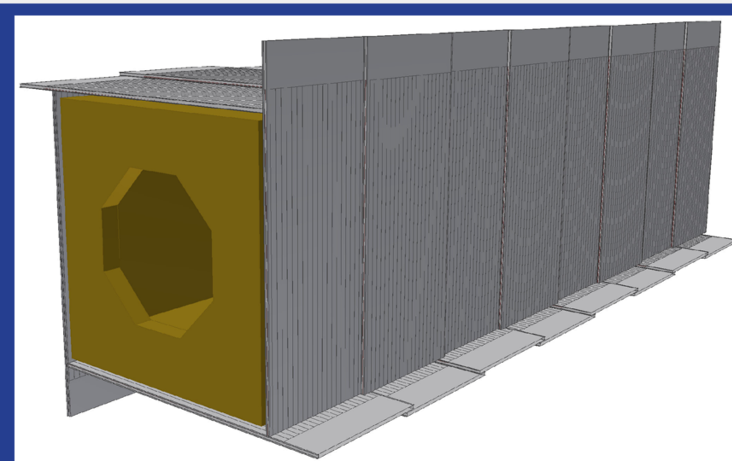
- Detailed studies underway, design well along, several detector technologies under discussion
- Will measure time integrated (~1h) extinction

Progress: Solenoids

- Conceptual designs completed
- Solicited a Request For Information concerning the final design and construction of the PS and DS solenoids - received numerous responses from companies around the world
- Also have designs for cryogenic, power, field mapping, installation, and commissioning infrastructure
- Partnered with Japan to fabricate aluminum stabilized SC cable for R&D tests

Progress: Cosmic Veto





- Using SiPMs have demonstrated required PE yield over full length of scintillator bars with test beam data
- Engineering designs for modules, FEE underway
- Extrusions tests to optimize scint. geometry, #fibers, etc. are underway
- Detailed simulation studies in progress

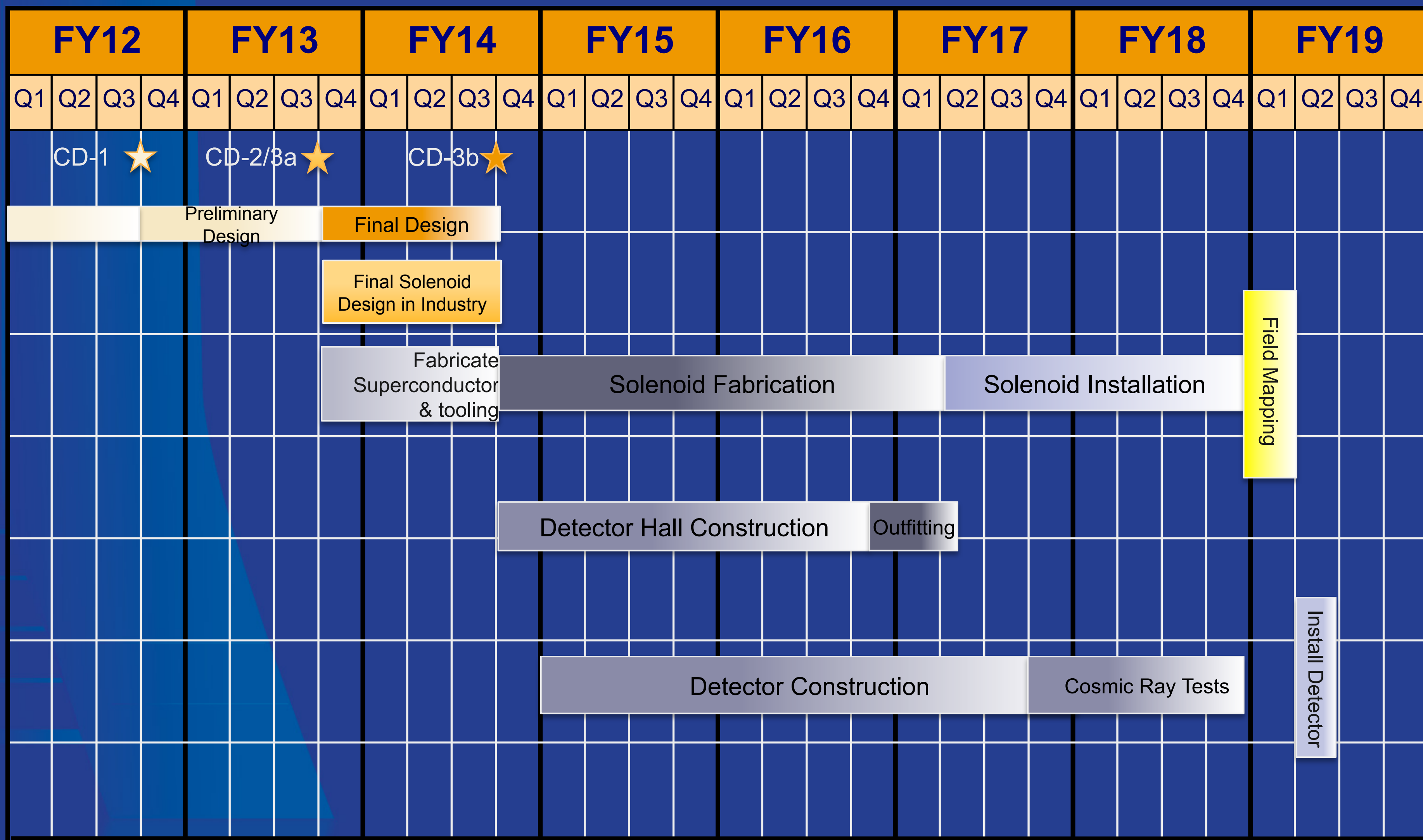
Fermilab

Progress: Calorimeter

- Mature design using LYSO+APD
- Prototype exists; achieved ~5% resolution at 100 MeV tagged photon beam
- Front-end electronics designed; achieved low noise (30 keV)
- Many simulation studies
  - Limit for resolution <2% at 100 MeV
  - Offers trigger, confirmation of (t,E,x,y) from tracker (ie. redundancy)
  - Geometry, volume, efficiency optimization underway

Backup Slides

Mu2e Schedule

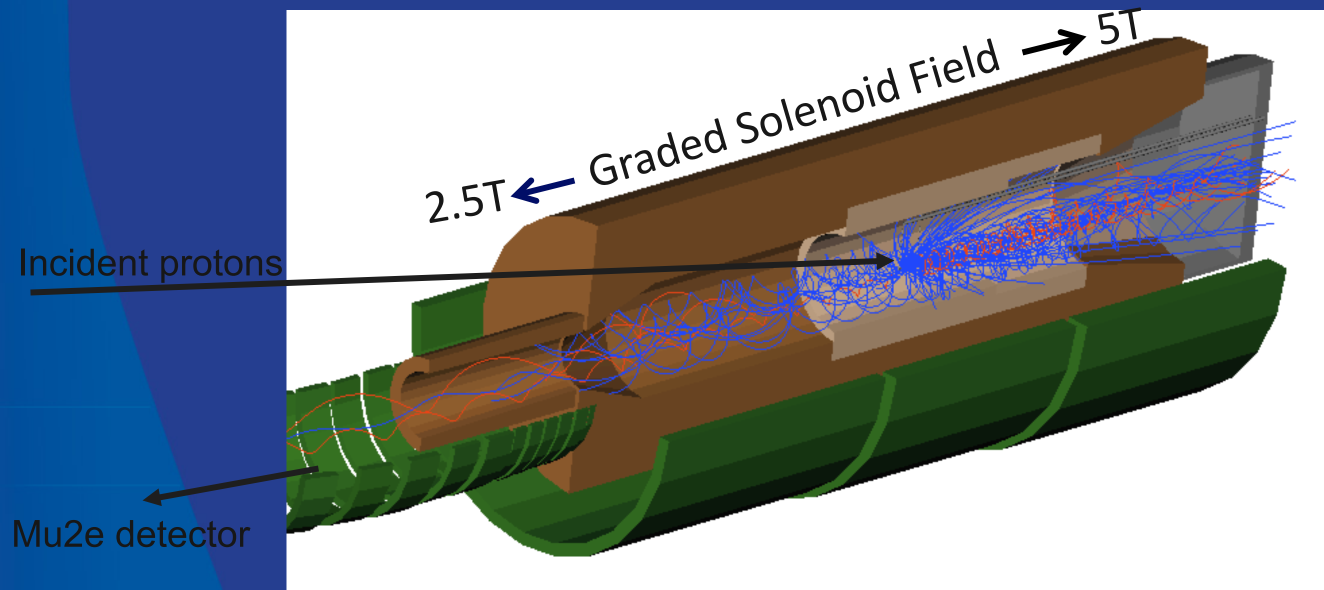


Mu2e Solenoids

- Production Solenoid
  - Slam lots of protons on to target to create lots of π^- (plus lots of other stuff)
- Transport Solenoid
  - Collect the π^- , momentum and sign select them
  - Transport the μ^- from $\pi^- \rightarrow \mu^-\nu$ decays to the detector
- Detector Solenoid
  - Stop the μ^- in a stopping target
  - Measure energy of outgoing electrons very precisely

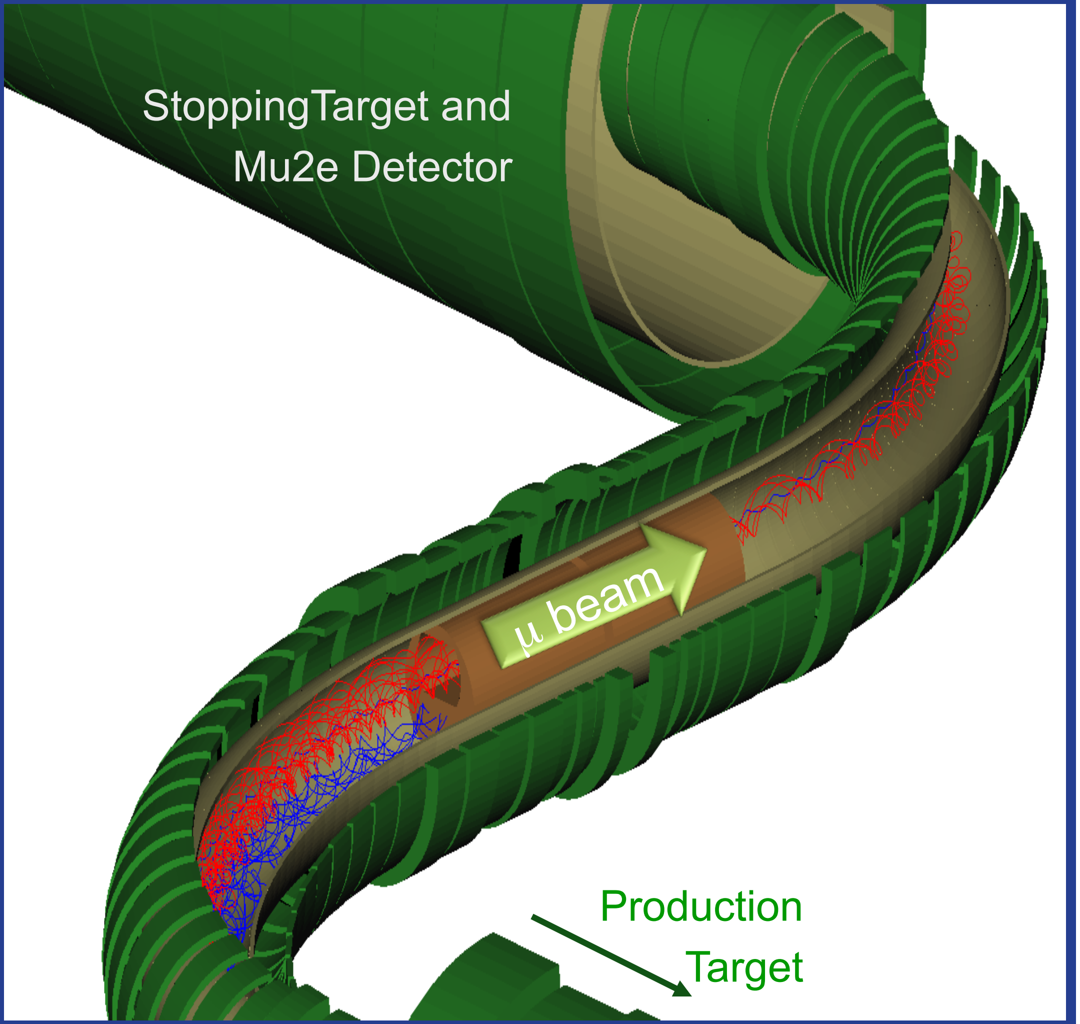
Mu2e Production Target

- Gold target (0.2m long, few mm diameter)
- Capture (mostly) backwards going pions
  - Eliminates backgrounds from the primary beam
  - Expect something like (1 stopped-μ / 500 POT)

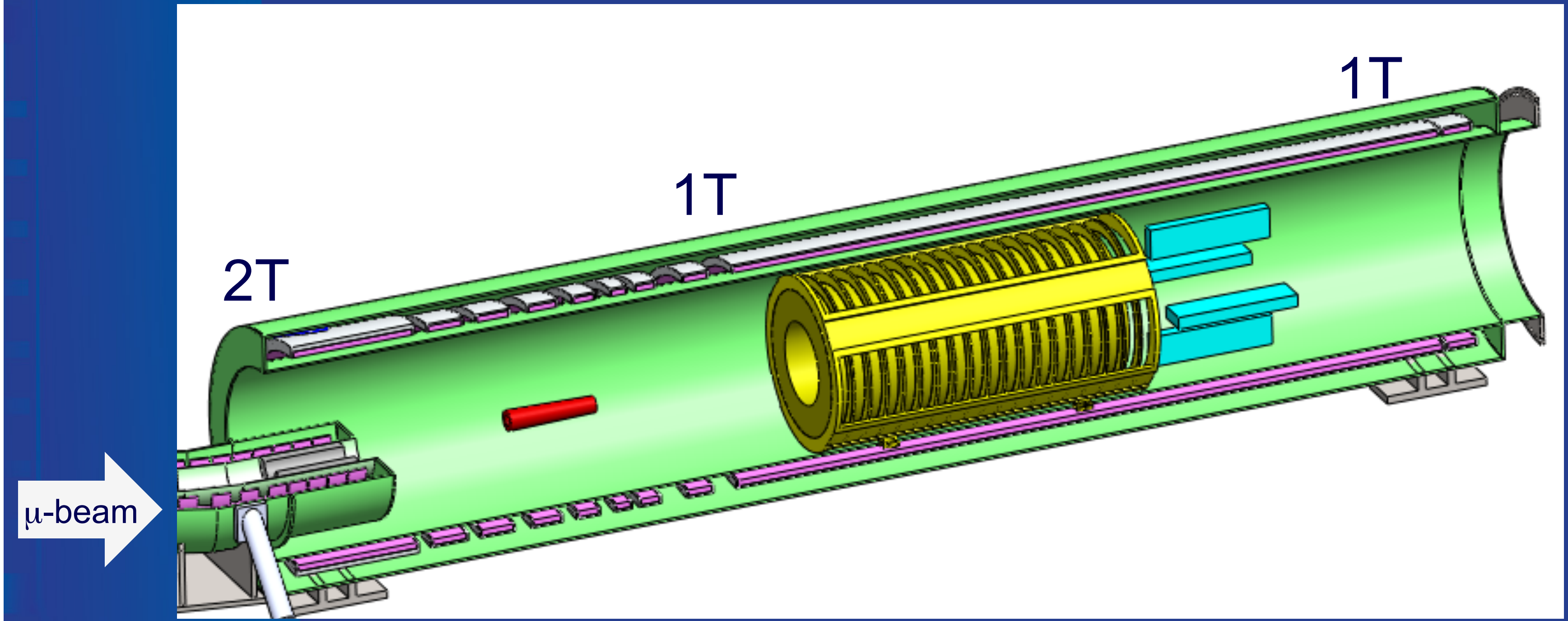


Mu2e Transport Solenoid

- Designed to sign select the muon beam
  - Collimator blocks positives after first bend
  - Negatives brought back on axis by the second bend
  - No line of sight between primary target and detector



Mu2e Detector Solenoid



Stopping Target
- 17 Al. foils each 200 μm thick
- spaced 5 cm apart
- radius tapers 10.0 to 6.5 cm
- <4% radiation length

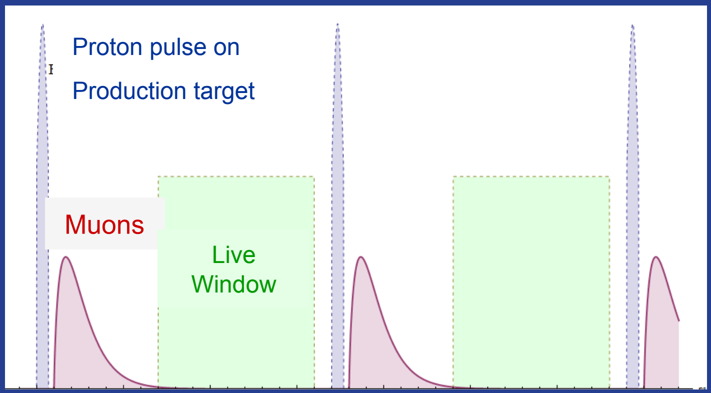
Straw Tracker
- 22k 0.3-1.0 long straws
- transverse to beamline
- intrinsic resolution at 105 MeV/c: 195 keV/c

EM Calorimeter
- 1.2k crystals (LYSO)
- σ_E / E = 5% at 100 MeV
- confirmation of track
- can provide a trigger

- **Designed to detect 105 MeV electrons, suppress BGD**

Mu2e Background

- Three basic categories
  - Intrinsic
    - These, like the signal, scale with the number of stopped μ
  - Late Arriving
    - These arise from out-of-time (ie. late) protons on the production target

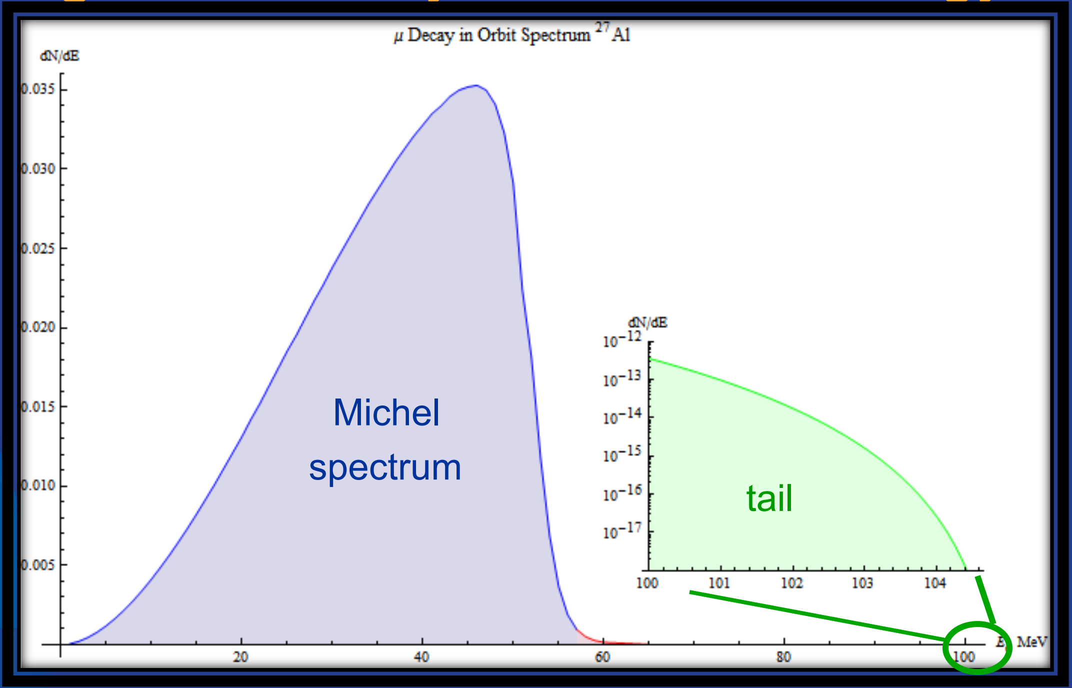


  - Miscellaneous
    - These include anti-proton and CR induced backgrounds

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \rightarrow e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 104.96 MeV
   - Strong function of your electron energy requirements



Electron energy in MeV

Fermilab

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

2) Capture on the nucleus:

- For Al. capture fraction is 61%
- Ordinary μ Capture
  - $\mu^- N_Z \rightarrow \nu N_{Z-1}$
  - Used for normalization
- Radiative μ capture
  - $\mu^- N_Z \rightarrow \nu N_{Z-1} + \gamma$
  - (# Radiative / # Ordinary) ~ 1 / 100,000
  - E_γ kinematic end-point ~102 MeV
  - Asymmetric $\gamma \rightarrow e^+e^-$ pair production can yield a background electron

Mu2e Late Arriving Backgrounds

- Backgrounds arising from all the other interactions which occur at the production target
  - Overwhelmingly produce a prompt background when compared to τ_{μ}^{Al} = 864 ns
  - Eliminated by defining a signal timing window starting 700 ns after the initial proton pulse
  - Must eliminate out-of-time (“late”) protons, which would otherwise generate these backgrounds in time with the signal window

out-of-time protons / in-time protons < 10^{-10}

Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z \dashrightarrow N^*_{Z-1} + \gamma$
    - For Al. RπC fraction: 2%
    - E_γ extends out to $\sim m_\pi$
    - Asymmetric γ --> e^+e^- pair production can yield background electron
    - Strong function of your timing requirements
  - Beam electrons
    - Originating from upstream π^- and π^0 decays
    - Electrons scatter in stopping target to get into detector acceptance
  - Muon and pion Decay-in-Flight
- Taken together these backgrounds account for ~45% of the total background and scale *linearly* with the number of out-of-time protons

Mu2e Miscellaneous Backgrounds

- Several additional miscellaneous sources can contribute background - most importantly
  - Anti-protons
    - Proton beam is just above pbar production threshold
    - These low momentum pbars wander until they annihilate
    - 300 μm mylar window in decay volume absorbs them all
    - Annihilations produce lots of stuff e.g. π^- can undergo RπC
    - 35% of total background
  - Cosmic rays
    - Suppressed by passive and active shielding
    - μ DIF or interactions in the detector material can give an e^- or γ that yield a background electron
    - Background listed assumes veto efficiency of 99.99%
    - 25% of total background

Effective Lagrangian: CLFV terms

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}$$

$$+ \quad \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

- Augment SM with some effective operators which enable CLFV
- Other (Dim-6) operators also possible, but these two alone do a good job of generically describing all CLFV predictions from concrete NP models

Project X $\mu N \rightarrow eN$ Possibilities

- If Mu2e observes a signal:
  - Change target to probe coupling (vector, scalar, etc)
  - Need to go to high Z
  - Hard because τ small for large Z (τ_{μ}^{Au} =72ns)
  - But signal rate increases
- This is a unique feature of the $\mu N \rightarrow eN$ measurements