Mu2e: Search for Muon to Electron Conversion at Fermilab

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For the Mu2e Collaboration

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Mu2e Collaboration

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

currently 155 collaborators
28 institutions

Istituto G. Marconi Roma
Laboratori Nazionale di Frascati
INFN Genoa
Università di Pisa, Pisa
INFN Lecce and Università del Salento
Gruppo Collegato di Udine

Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia

Outline

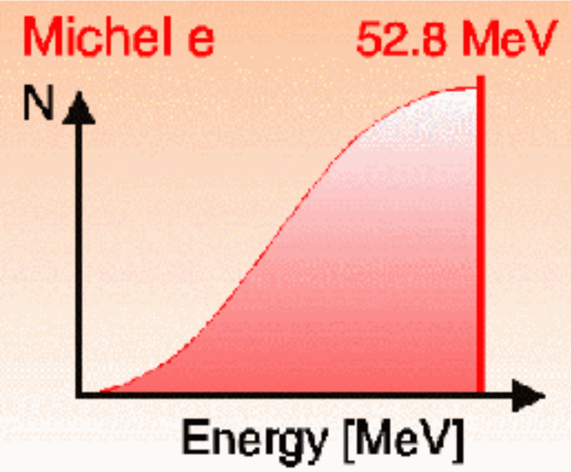
- Theoretical Motivation
- Experimental Technique
- Making Mu2e work at Fermilab ← Will spend quite a bit of time on this
- Sensitivities
- Future Upgrades
- Conclusion

Provocative Comments

- Once upon a time, high energy physics moved forward by going to higher energies and “seeing what came out”.
  - The last time this happened was the discovery of the tau lepton and b quark in the 70s!
- For the last 40 years, all other discoveries have been preceded by strong indirect evidence
  - $K \rightarrow \mu^+\mu^-$ suppression ➔ charm quark
  - CP Violation ➔ third generation
  - Weak decays ➔ W and Z particles and their masses
  - Precision tests at LEP and elsewhere ➔ top and Higgs masses
- With the discovery of the Higgs, we now find ourselves without guidance for the first time in half a century
  - The LHC was “guaranteed” to discover the Higgs (or it would have been even more interesting)
  - No one knows the next “sure bet” energy!
- If the past is any indicator, such guidance will likely come from indirect evidence.

Ancient History

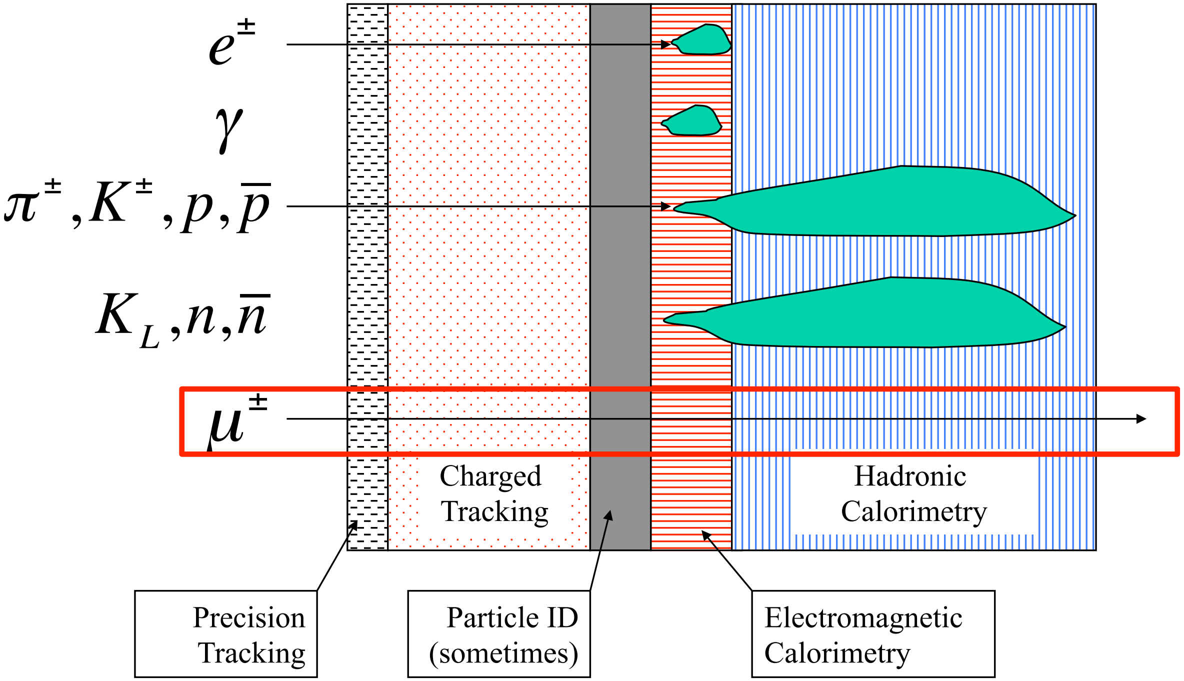
- The muon was originally discovered in 1936 Anderson and Neddermeyer while studying cosmic ray data
- Hypothesized to be Yukawa's proposed mediator of the nuclear binding force, but did not interact strongly
  - Yukawa's particle was the pion
- Excited electron?
  - If so, expect $\mu \rightarrow e + \gamma$
  - Not seen!
- The muon was observed to decay to electron+"something invisible" with a spectrum consistent with a three body decay



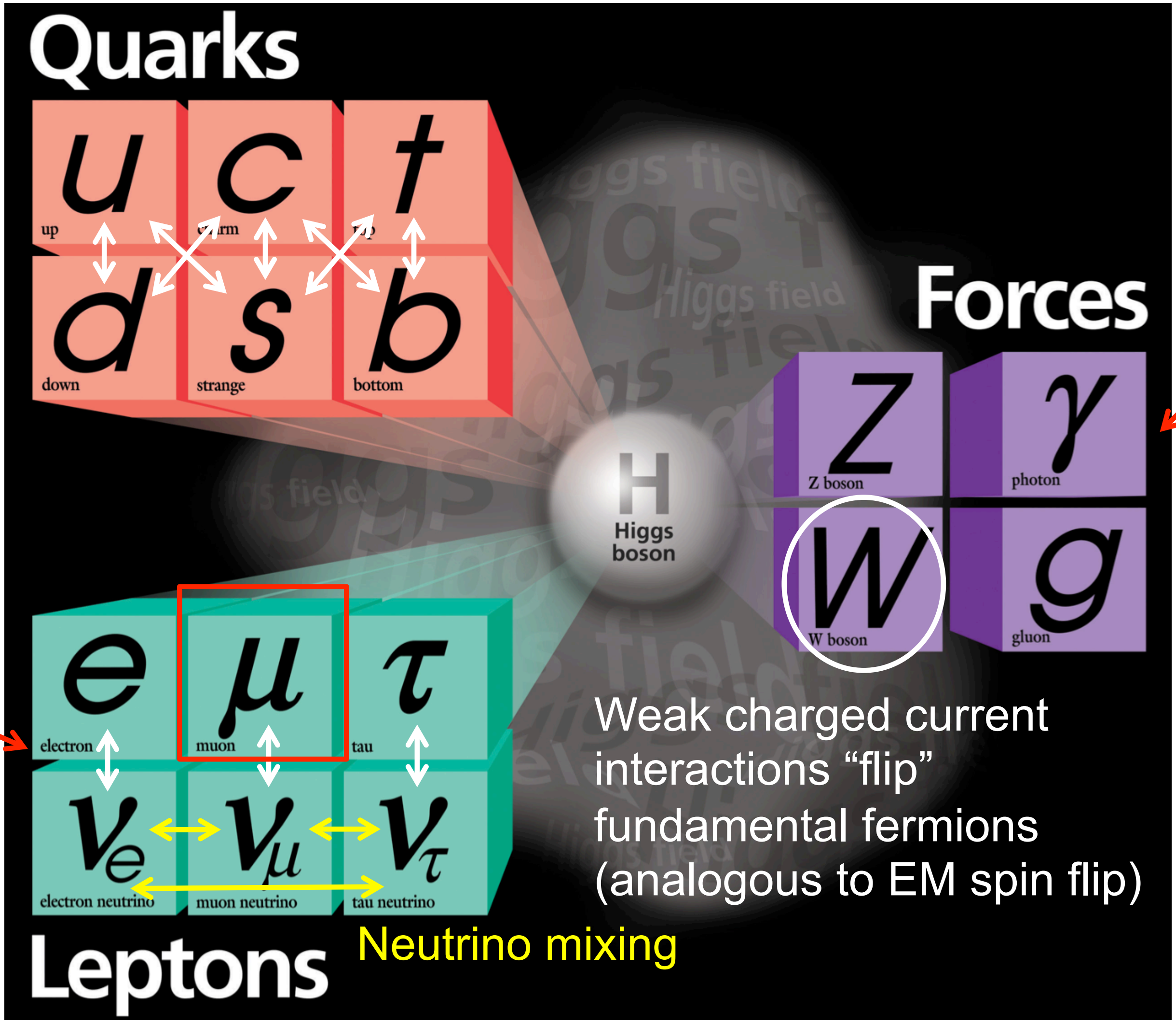
Fast forwarding (and skipping a whole bunch of stuff)…

Introducing: the Muon

- Mass: 105.66 MeV/c² (~200m_e ~0.1m_p)
- Charge: ±e
- Spin: ½ħ (fermion)
- Lifetime: 2.2 μsec (cτ=660m)
- Interactions: Electromagnetic and Weak, but NOT strong
- Because muons are so much heavier than electrons, they are very penetrating



The Standard Model



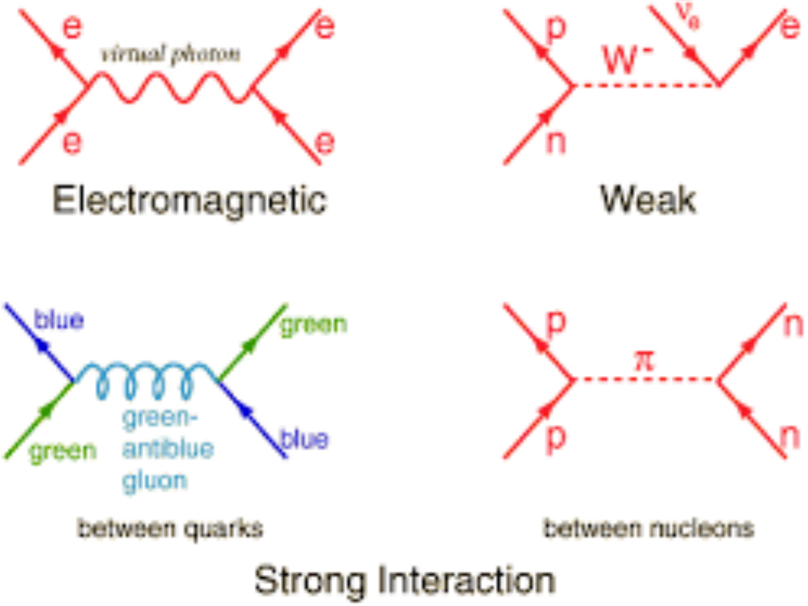
Combine to form hadrons

Mediate interactions

Free

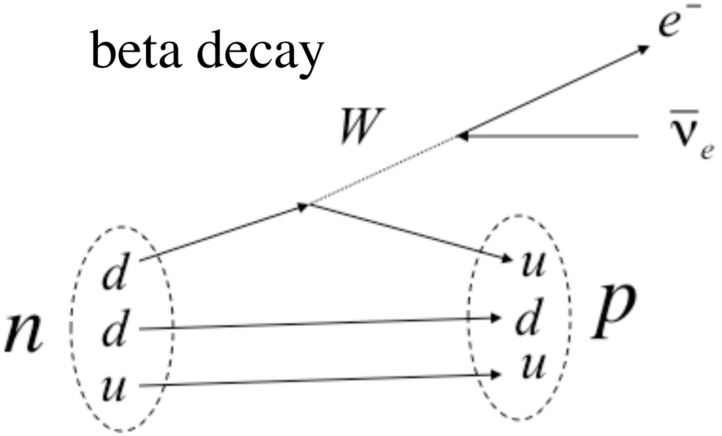
Weak charged current interactions "flip" fundamental fermions (analogous to EM spin flip)

Interactions in the Standard Model

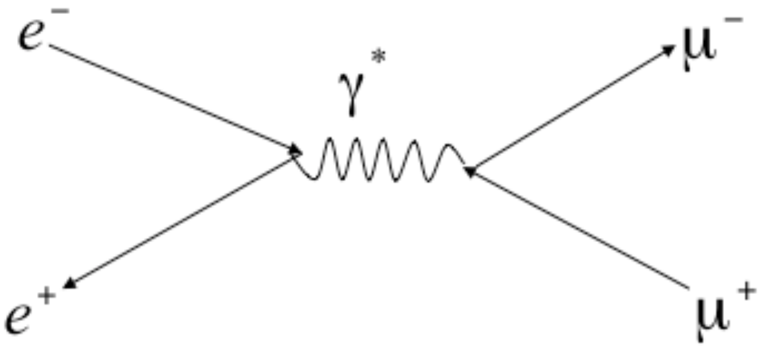


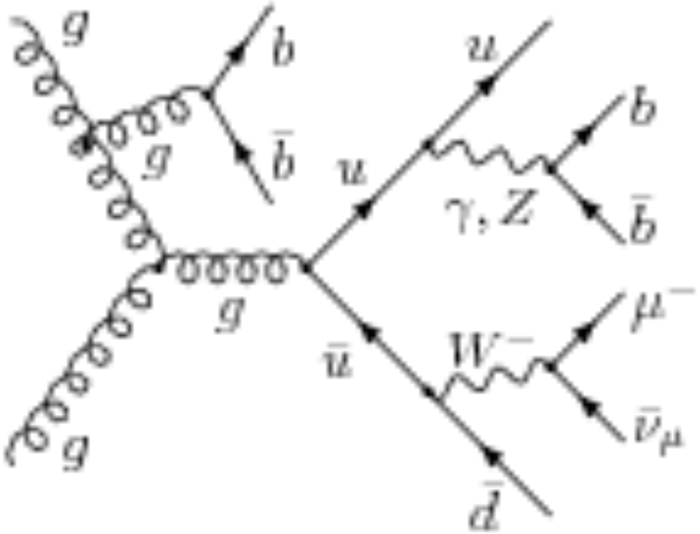
$$n \rightarrow p + e^- + \bar{\nu}_e$$

beta decay



$$e^+e^- \rightarrow \mu^+\mu^-$$





Generation (Flavor) Transitions

- In both the quark and lepton sector, the weak eigenstates are related to the mass eigenstates by a unitary matrix

$$\begin{bmatrix} d' & s' & b' \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

"almost" diagonal

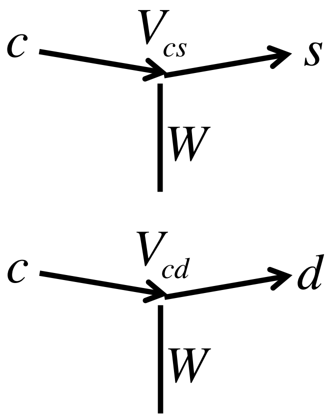
$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

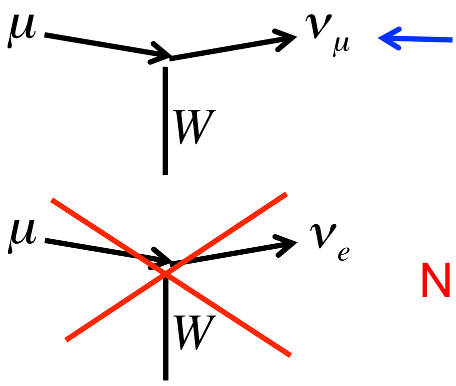
~maximum mixing

- However, because the neutrino mass differences are so small, the phenomenology is *very* different

Quarks: generational transitions observed

Leptons: weak transitions and mixing proceed separately





Pure weak state. Propagates as a superposition of mass eigenstates → "neutrino mixing"

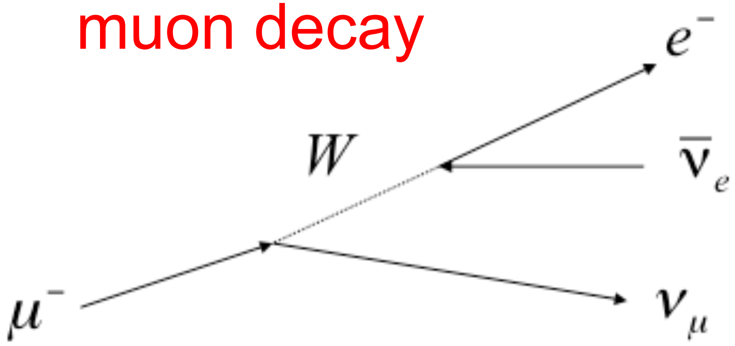
NOT observed!

Lepton Number and Lepton Flavor Number

Both lepton number and lepton “flavor” (generation) number are individually conserved*

	l	l_e	l_μ
μ^-	1	0	1
total	1	0	1

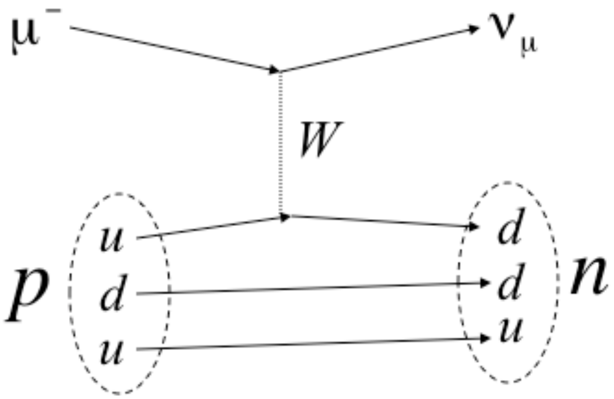
muon decay



	l	l_e	l_μ
e^-	1	1	0
$\bar{\nu}_e$	−1	−1	0
ν_μ	1	0	1
total	1	0	1

	l	l_e	l_μ
μ^-	1	0	1
p	0	0	0
total	1	0	1

$\mu+p \rightarrow \nu+n$

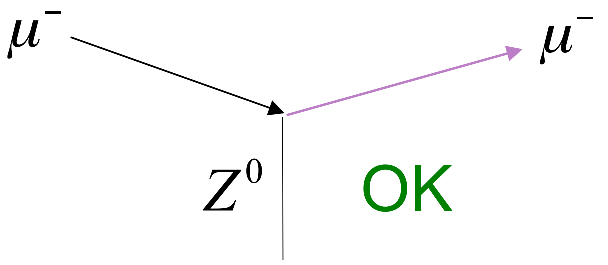


	l	l_e	l_μ
ν_μ	1	0	1
n	0	0	0
total	1	0	1

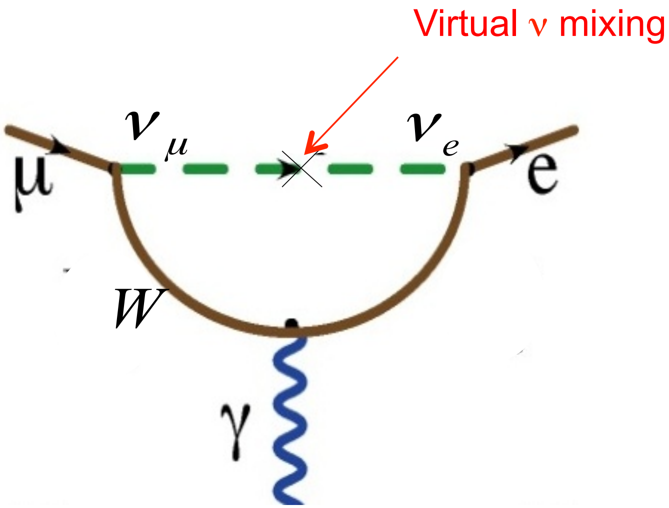
*except in neutrino mixing

Charged Lepton Flavor Violation

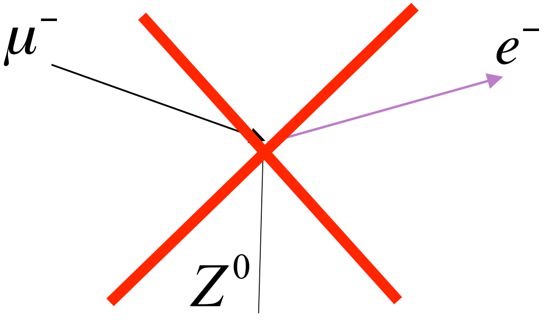
Neutral Current Scattering



Higher order dipole “penguin”:



Flavor Changing Neutral Current (FCNC):



- Forbidden in Standard Model

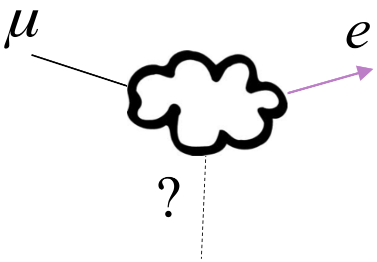
- Observation of neutrino mixing shows this can occur at a *very small* rate
- Photon can be real (μ->eγ) or virtual (μN->eN)
- Standard model branching ratio ~$\mathcal{O}(10^{-52})$ (effectively zero)

Beyond the Standard Model

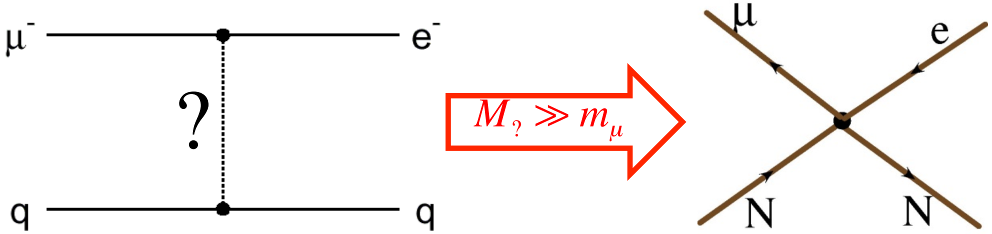
- Because extensions to the Standard Model couple the lepton and quark sectors, Charged Lepton Flavor Violation (CLFV) is a nearly universal feature of such models.
- The fact that it has not yet been observed already places strong constraints on these models.
- CLFV is a powerful probe of multi-TeV scale dynamics
  - complementary to direct collider searches
- Among various possible CLFV modes, rare muon processes offer the best combination of new physics reach and experimental sensitivity

Generic Beyond Standard Model CLFV

Flavor Changing Neutral Current

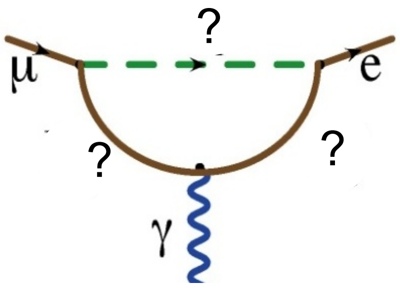


- Mediated by *virtual*(!) massive neutral Boson, e.g.
    - Leptoquark
    - Z'
    - Composite
- Approximated by "four fermi interaction"

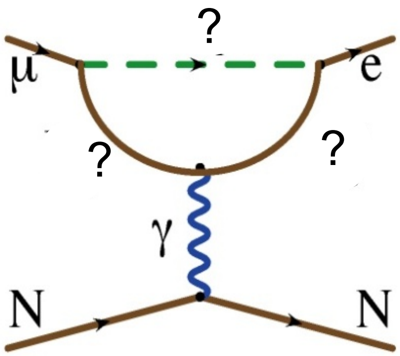


Dipole (penguin)

- Can involve a real photon

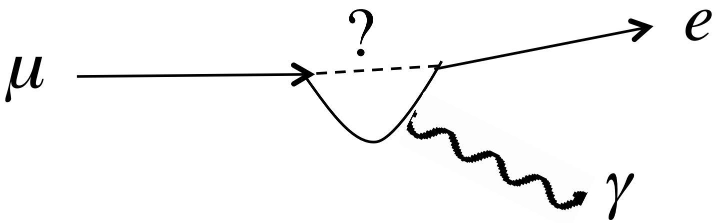


- Or a virtual photon



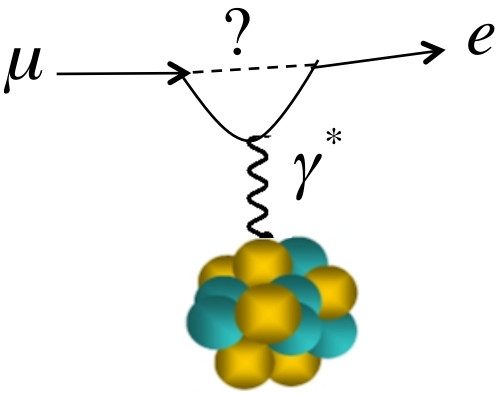
Decay vs. Conversion

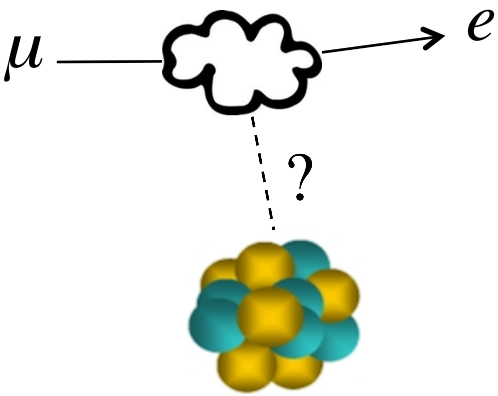
- Only the “dipole”-like reactions can lead to a decay



$$\mu \rightarrow e + \gamma$$

- However, if we capture a muon on a nucleus, it could exchange either a virtual photon or other (as yet unknown) neutral boson with the nucleus

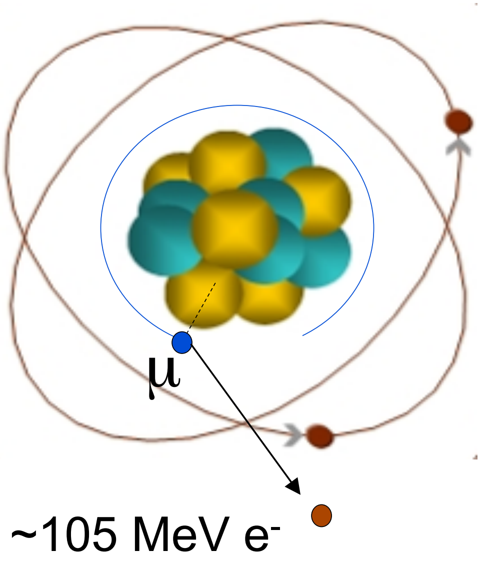




Experimental Signature of μ+N → e+N

- When captured by a nucleus, a muon will have an enhanced probability of exchanging a virtual particle with the nucleus.
- This reaction recoils against the entire nucleus, producing a *mono-energetic* electron carrying most of the muon rest energy

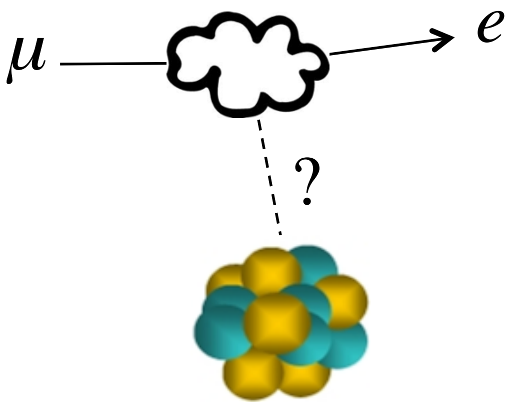
$$E_e = m_\mu c^2 - \frac{\left(m_e c^2\right)^2}{2 m_N c^2}$$



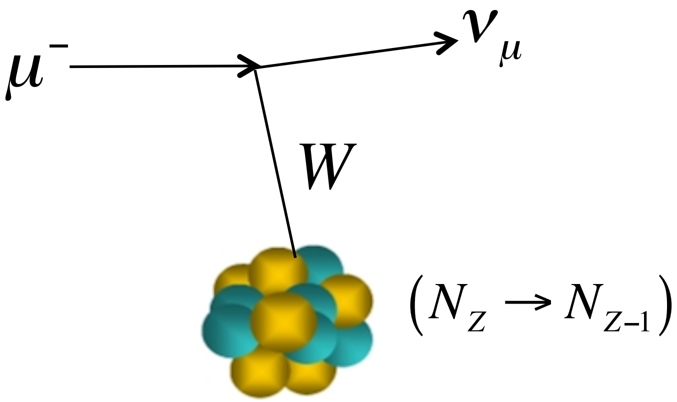
- Similar to μ→eγ, with important advantages:
  - No combinatorial background.
  - Because the virtual particle can be a photon *or* heavy neutral boson, this reaction is sensitive to a broader range of new physics.
- Relative rate of μ→eγ and μN→eN is the most important clue regarding the details of the physics

What We (Plan to) Measure

- We will measure the rate of μ to *e* conversion…



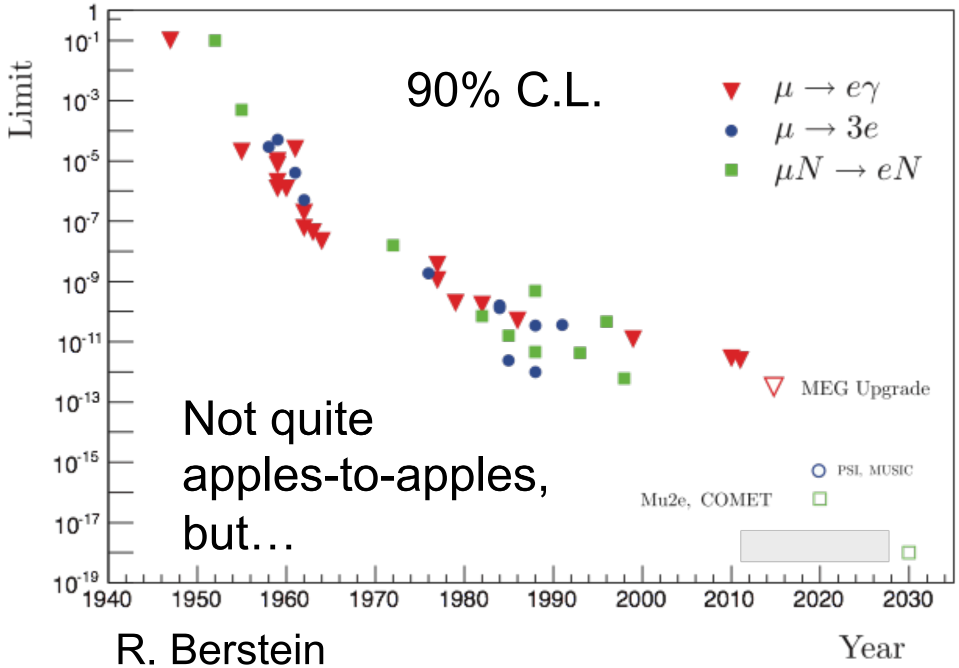
…relative to ordinary μ capture



- This is defined as

$$\boxed{R_{\mu e}} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \rightarrow e^- + \mathrm{N(A,Z)}\right)}{\Gamma\left(\mu^- \mathrm{N(A,Z)} \rightarrow \nu_\mu + \mathrm{N'(A,Z\text{-}1)}\right)}$$

History of Lepton Flavor Violation Searches



90% C.L.

Not quite apples-to-apples, but…

R. Berstein

- Best Limits
  - $R_{\mu e} < 7\times10^{-13}$ (Sindrum-II 2006)
  - $Br(\mu \rightarrow e\gamma) < 6\times10^{-13}$ (MEG 2013)
  - $Br(\mu \rightarrow 3e) < 1\times10^{-12}$ (Sindrum-I 1988)

Mu2e will measure:

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \rightarrow e^- + \mathrm{N(A,Z)}\right)}{\Gamma\left(\mu^- \mathrm{N(A,Z)} \rightarrow \nu_\mu + \mathrm{N'(A,Z\text{-}1)}\right)}$$

Goal: single event sensitivity of $R_{\mu e} = 3\times10^{-17}$

Just to be clear…

- We are not planning to make a measurement and compare it to a calculation.
- We are looking for something that (effectively) doesn’t exist in the Standard Model.
- Our goal is to build a experiment with negligible backgrounds, such that any observed signal would be *unambiguous evidence of new physics.*
- We planning for a improvement of roughly four orders of magnitude in sensitivity over the best previous measurement.

Just How Rare is that?

Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

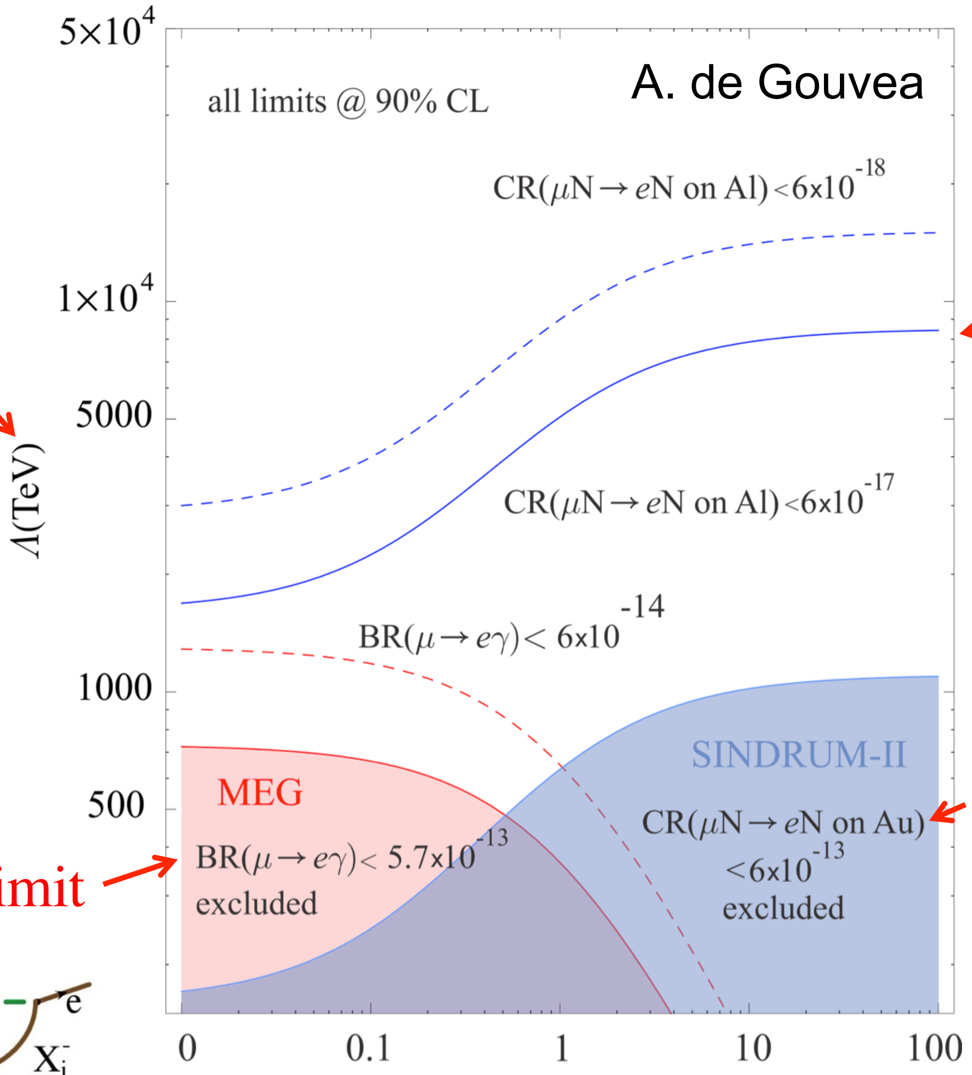
~90% C.L. goal

Single event sensitivity of Mu2e

Dipole vs. Contact Reaction

Mass Scale

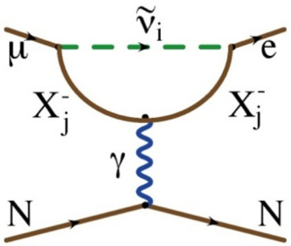
$$\left(\text{Rate} \propto \frac{1}{\Lambda^4}\right)$$

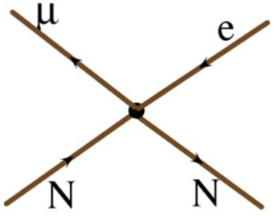


Our goal:
10^4 in rate
10 in mass

Best $\mu N \to eN'$ limit

Best $\mu \to e\gamma$ limit





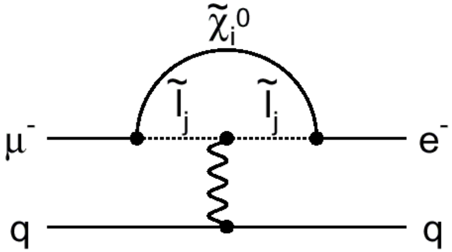
κ

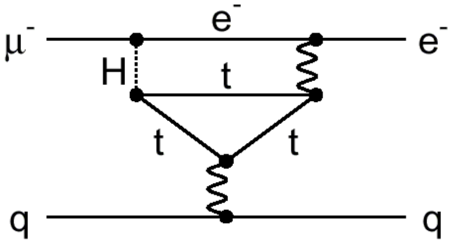
(different for different models)

Example Sensitivities*

Supersymmetry

Predictions at 10^{-15}



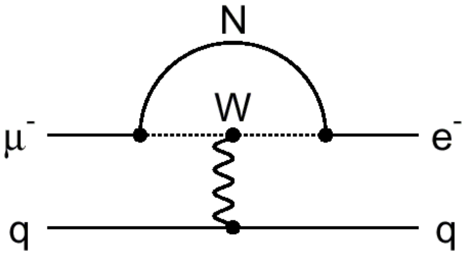


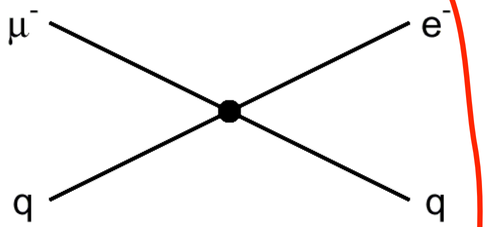
Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$





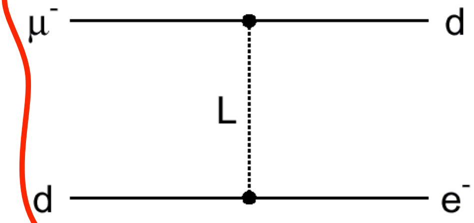
Compositeness

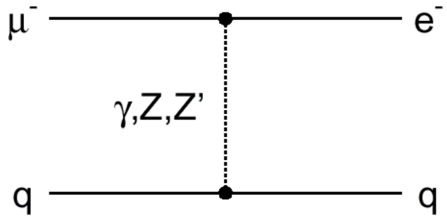
$\Lambda_C = 3000$ TeV

Leptoquarks

$M_L =$

$3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





Heavy Z',
Anomalous Z
coupling

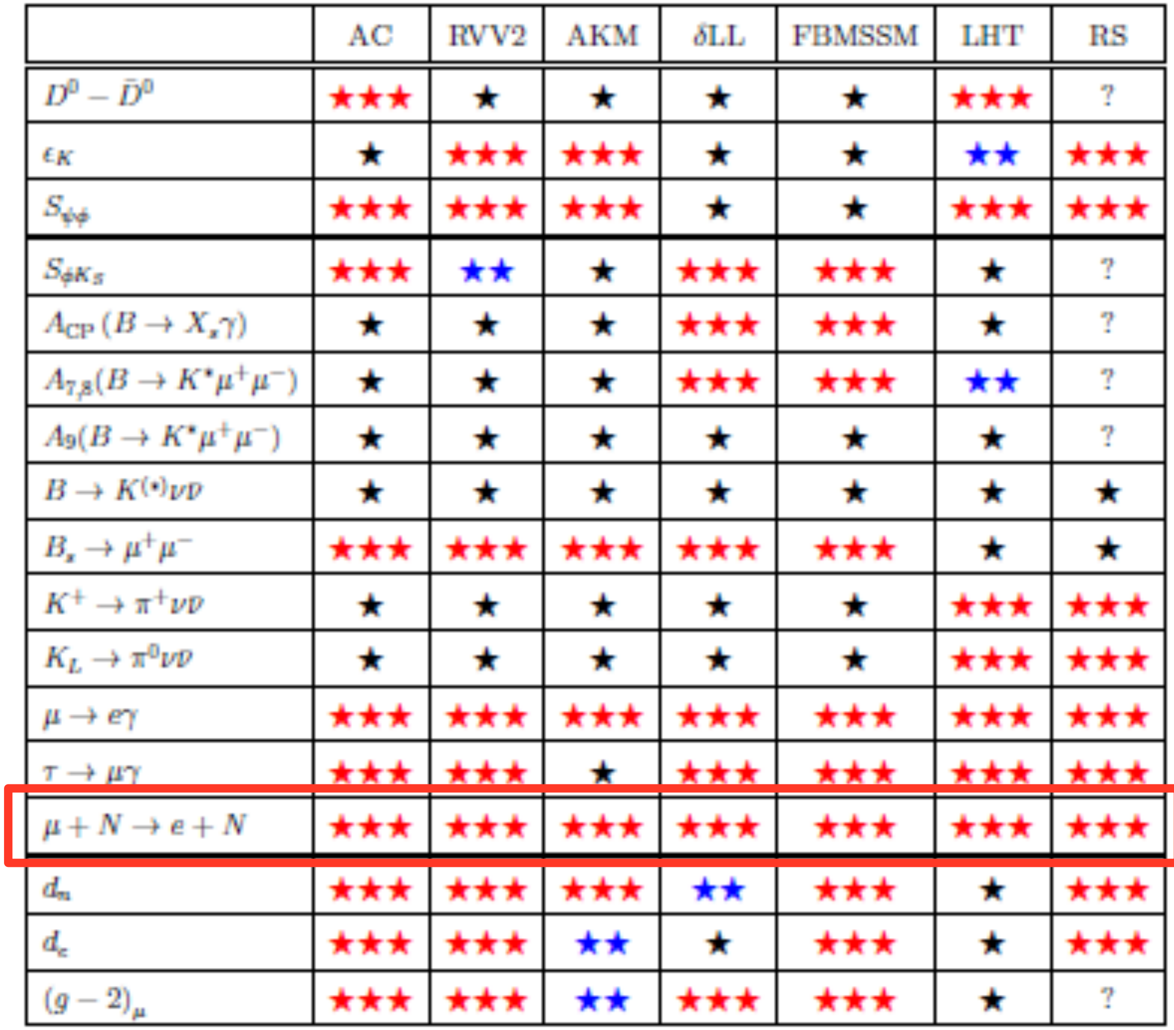
$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

*After W. Marciano

No μ➔eγ signal

Example: μ→e in Supersymmetry*



	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

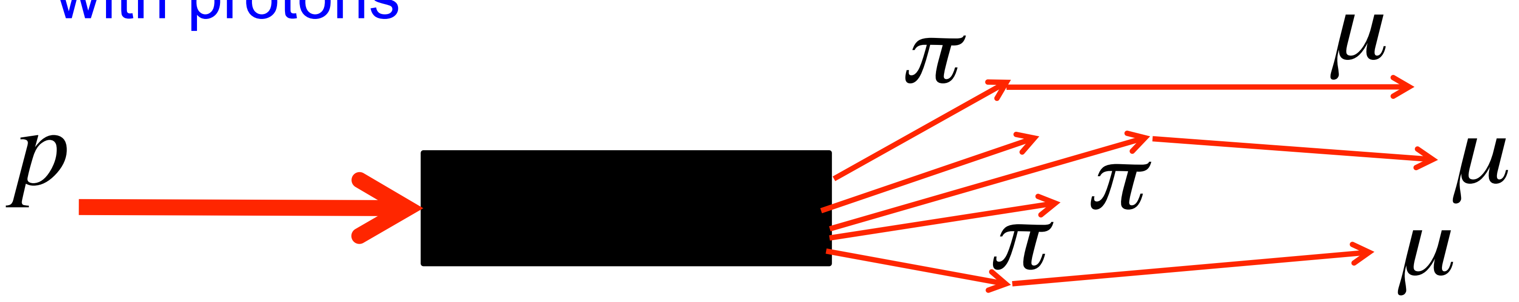
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

SUSY Models

All SUSY models predict both μ→eγ and μN→eN

*from Altmannshofer, Buras, *et al*, **Nucl.Phys.B830:17-94, 2010**

How do we make muons?



Hit a target
with protons

This produces
mostly pions

These quickly
decay to muons

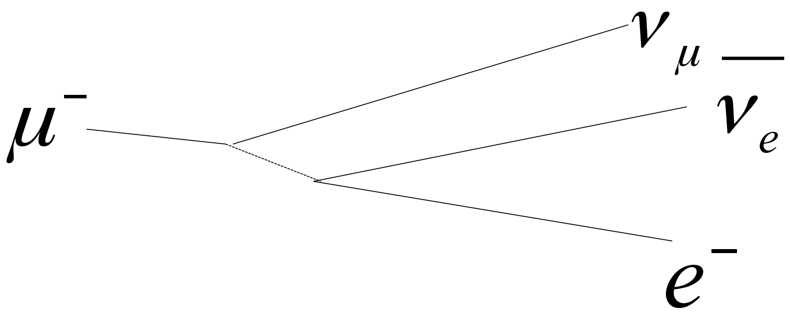
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad \tau_{\pi^\pm} = 26 \text{ ns}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau_{\mu^\pm} = 2200 \text{ ns}$$

Muons go much further

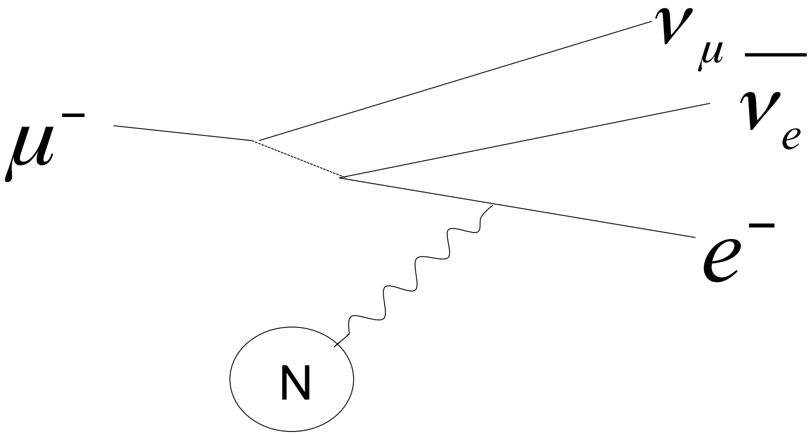
Our Biggest Issue: Decay in Orbit (DIO)

In-flight Decay:



- Very high rate
- Peak energy ~53 MeV
- Must design detector to be very *insensitive* to these.

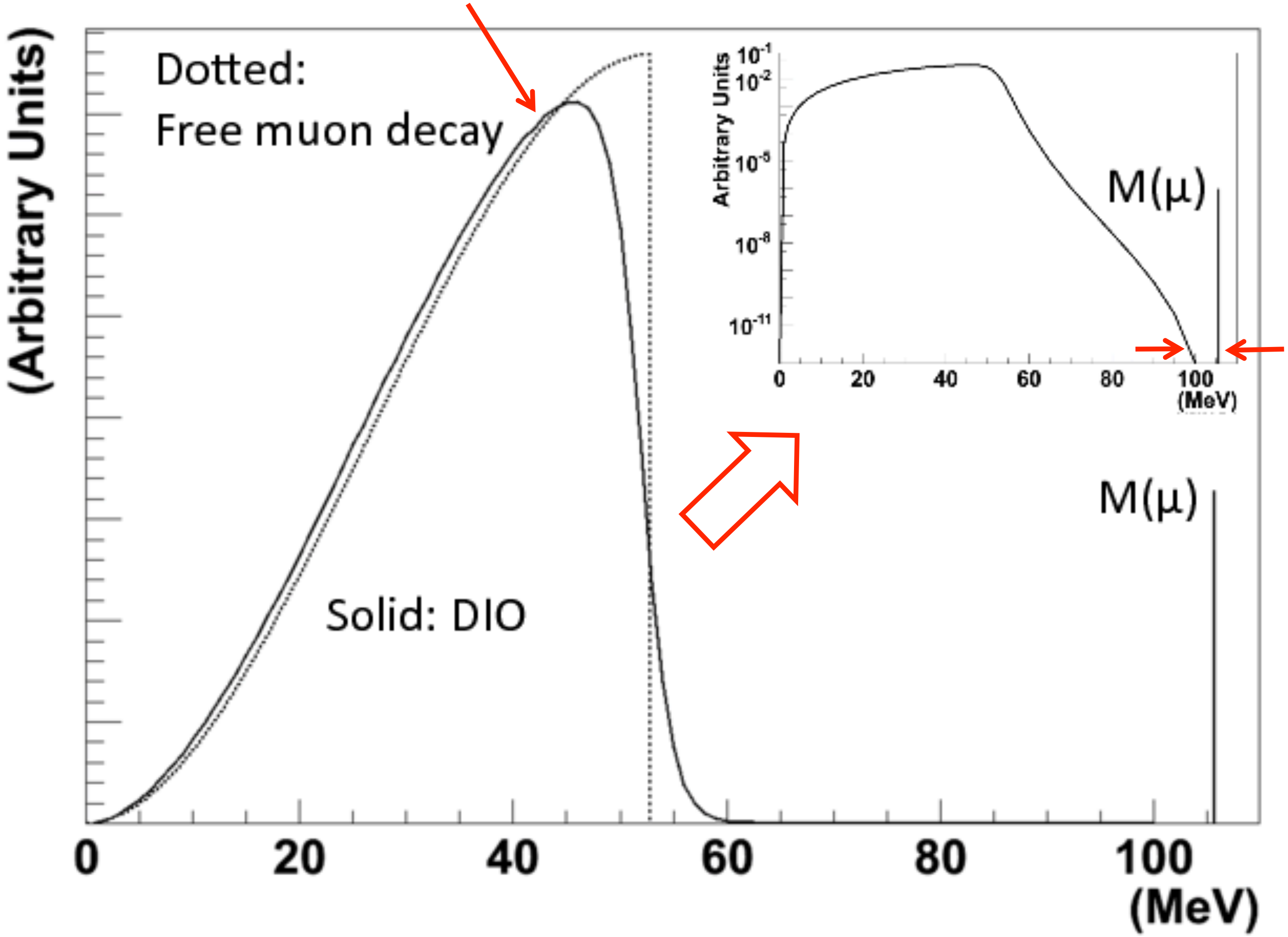
Coherent DIO:



- Nucleus coherently balances momentum
- Rate approaches conversion (endpoint) energy as ~$(E_{\text{conversion}}-E)^5$
- Drives resolution requirement.

DIO Spectrum

We want to be blind to this (acceptance)



We must resolve this

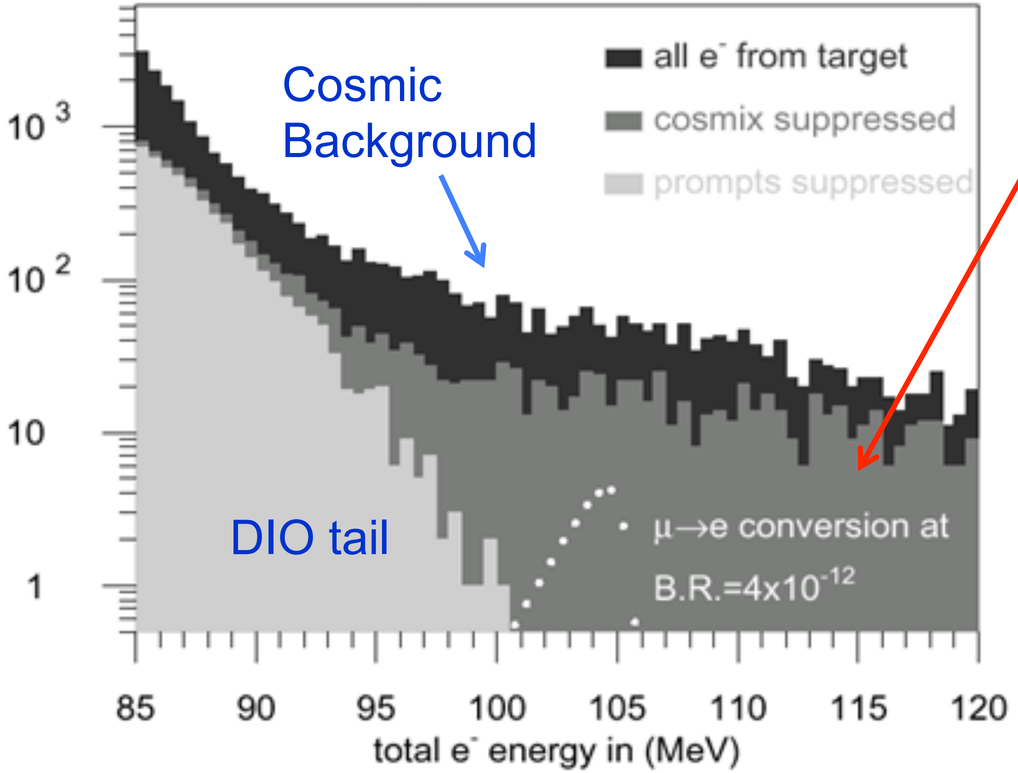
Prompt Backgrounds

- There are significant backgrounds related to the production and transport of the muons.
  - Radiative π- capture
    $\pi^- N \rightarrow N^* \gamma$, $\gamma Z \rightarrow e^+e^-$

    Biggest problem
  - Muon decay in flight
    $\mu^- \rightarrow e^- \nu\nu$
  - Pion decay in flight
    $\pi^- \rightarrow e^- \nu_e$
  - Prompt electrons
- General approach
  - Produce muons
  - Transport muons to target where some are captured.
  - Wait(!) for prompt backgrounds to go away
  - Open detection window to look for conversion of captured muons.

The Problem

μ->e Conversion: Sindrum II

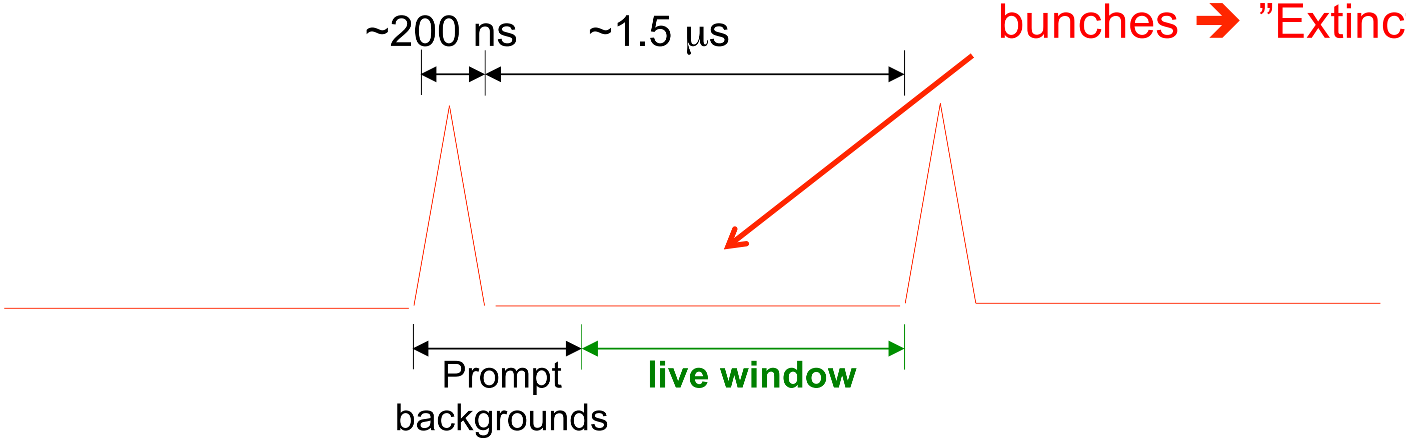


$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- Au \to e^- Au\right)}{\Gamma\left(\mu^- Au \to \text{capture}\right)} < 7 \times 10^{-13}$$

- Most backgrounds are prompt with respect to the beam
  - Mostly radiative pion capture
- Previous experiments suppressed these backgrounds *by vetoing all observed electrons* for a period of time after the arrival of *each proton*.
  - This leads to a fundamental to a rate limitation.

Pulsed Beams (first proposed for MELC)

- Eliminate prompt beam backgrounds by using a primary beam consisting of short proton pulses with separation on the order of a muon life time



“Nothing” between bunches ➔ ”Extinction”

~200 ns

~1.5 μs

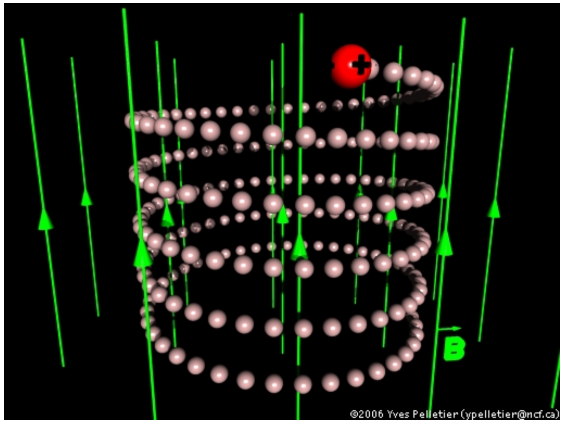
Prompt backgrounds

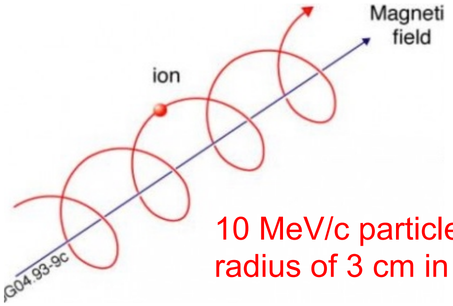
live window

- Design a transport channel to optimize the transport of right-sign, low momentum muons from the production target to the muon capture target.
- Design a detector which is very insensitive to electrons from ordinary muon decays, and has excellent tracking resolution.

Refresher: Fun with Solenoids

- Particles in a solenoidal field will generally move in a helical path
- Low momentum particles are effectively “trapped” along the field lines
  - We use this to transport muons
- A particle trapped along a *curved* solenoidal field will drift out of the plane of curvature
  - This is how we will resolve muon charge and momentum in the transport line

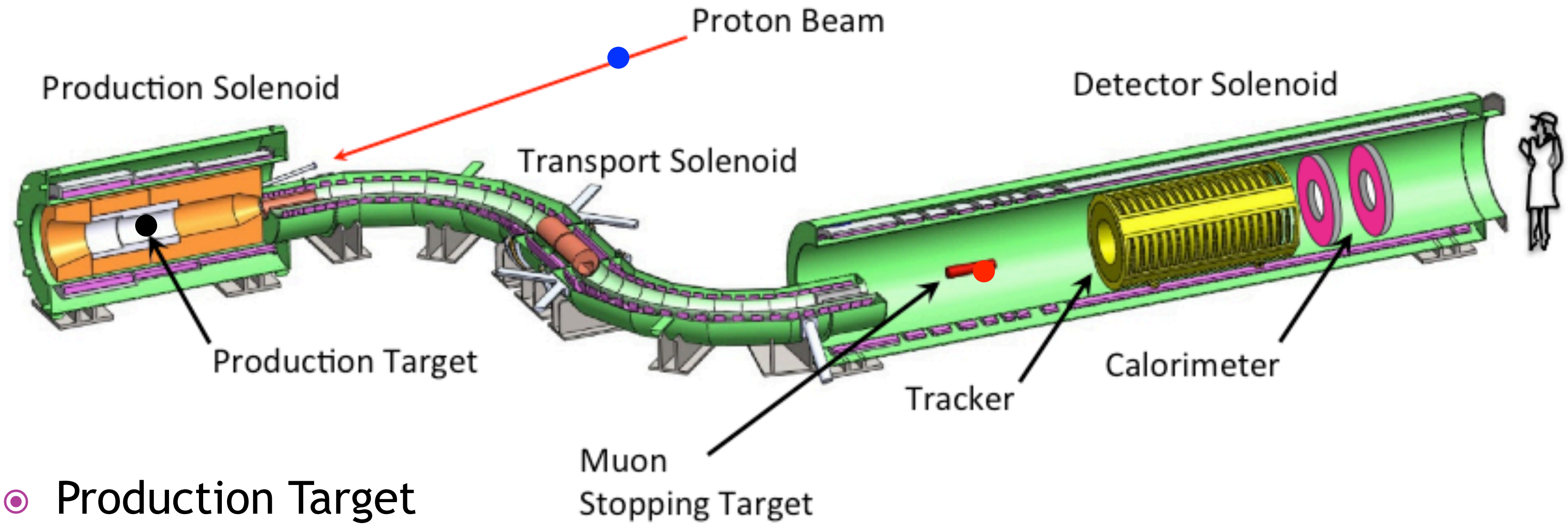




10 MeV/c particle will have a radius of 3 cm in a 1 T field

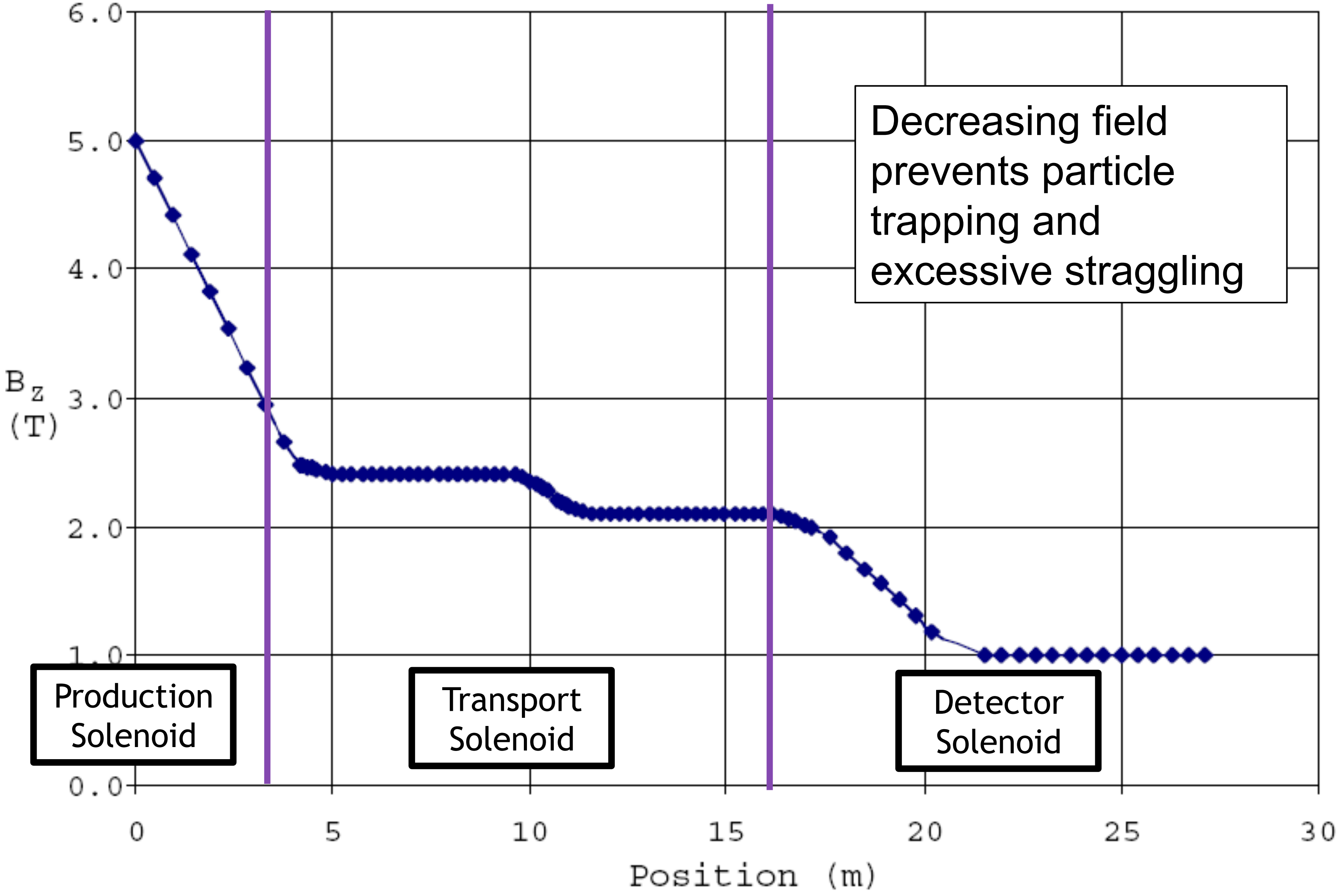
- For higher momentum particles, the curvature can be used to measure momentum
  - This is how we will measure the momentum of electrons from the capture target

Mu2e: The Big Picture



- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on target and wait for them to decay
  - Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2}m_\mu c^2$
  - Optimized for $E \sim m_\mu c^2$

Magnetic Field Gradient



Decreasing field prevents particle trapping and excessive straggling

Production Solenoid

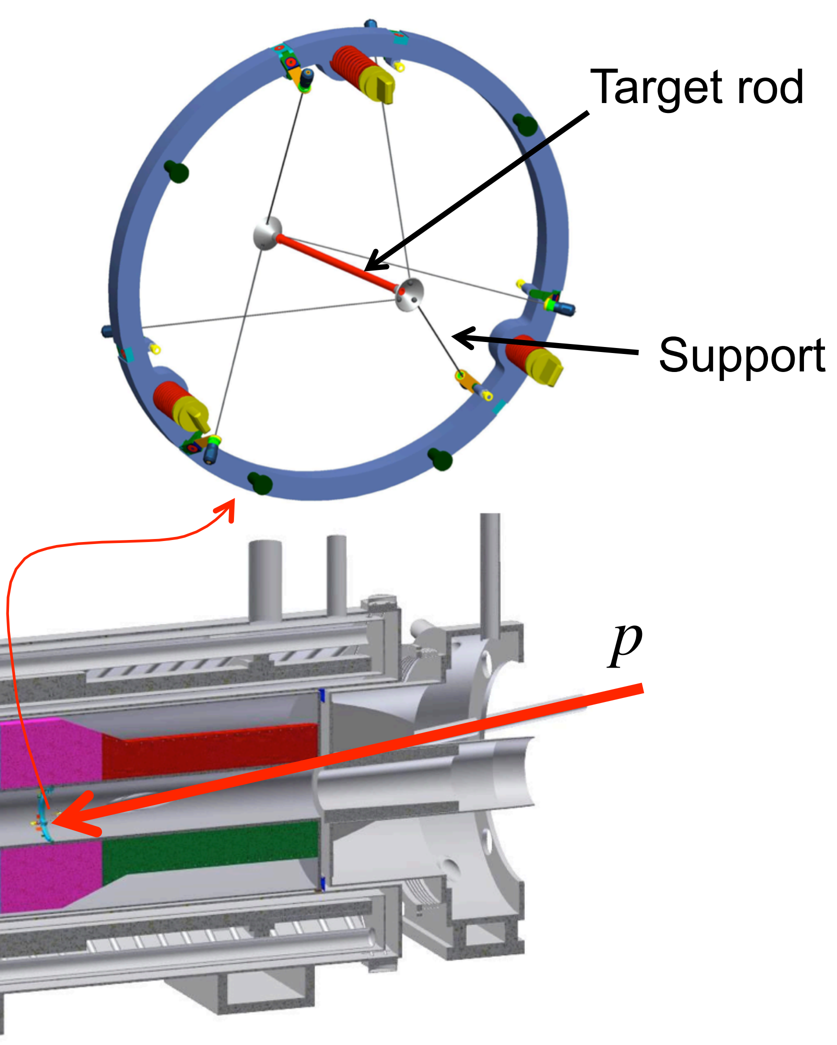
Transport Solenoid

Detector Solenoid

Target and Heat Shield

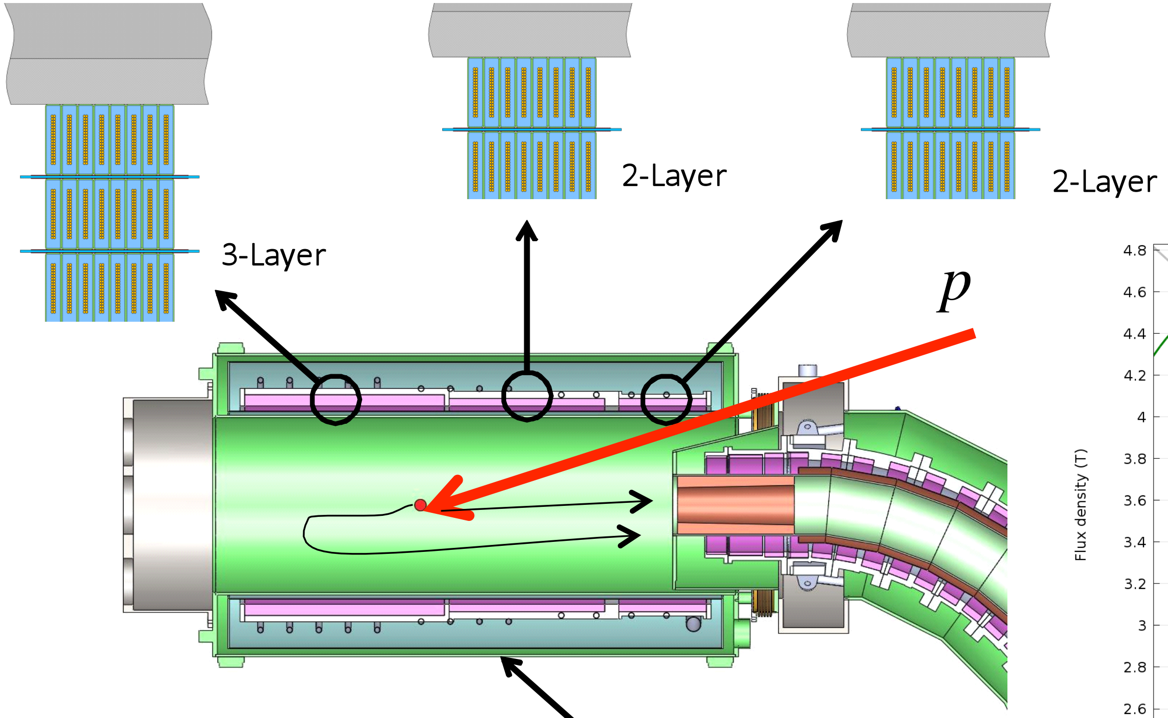
- Produces pions which decay into muons
- Tungsten Target
    - 8 kW beam
    - 700 W in target
    - Radiatively cooled
- Heat Shield
    - Bronze insert
    - 3.3 kW average heat load

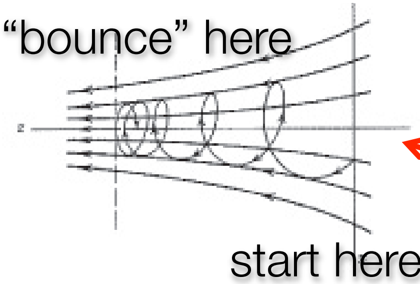
Remember, this is inside a superconducting magnet



Production Solenoid

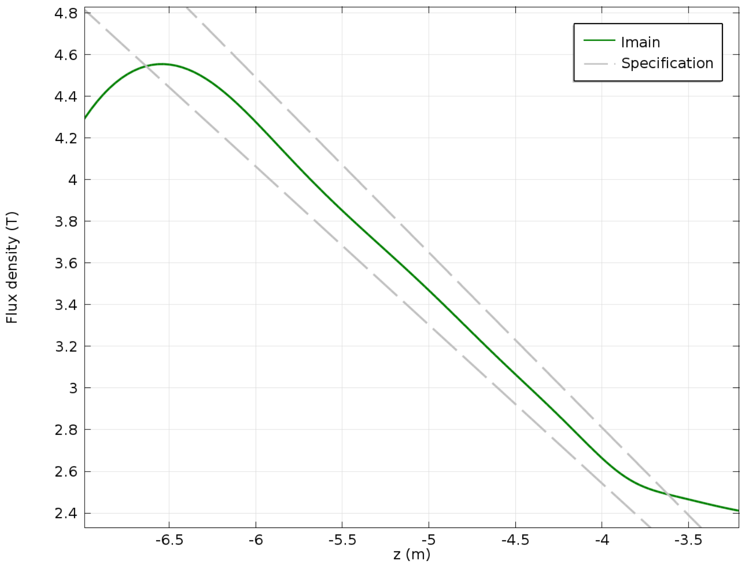
- Axially graded (~5T➔2.5T) solenoid captures low energy backward and *reflected* pions, directing to the Transport Solenoid



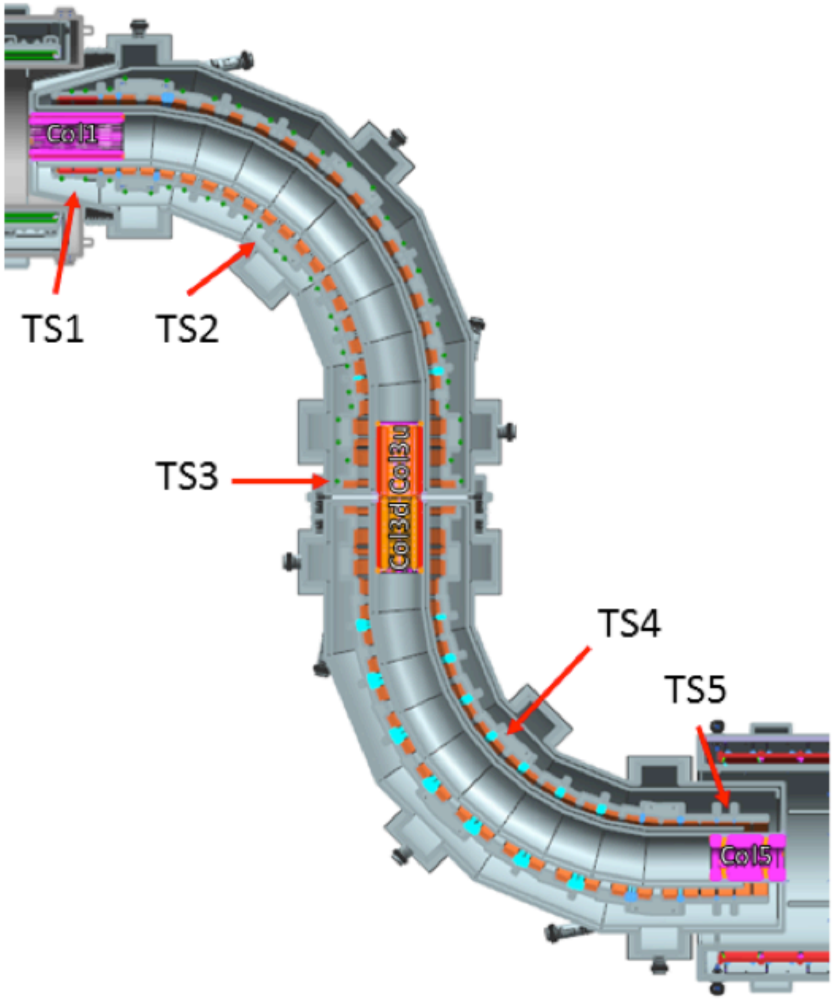


Magnetic reflection (pinch confinement)

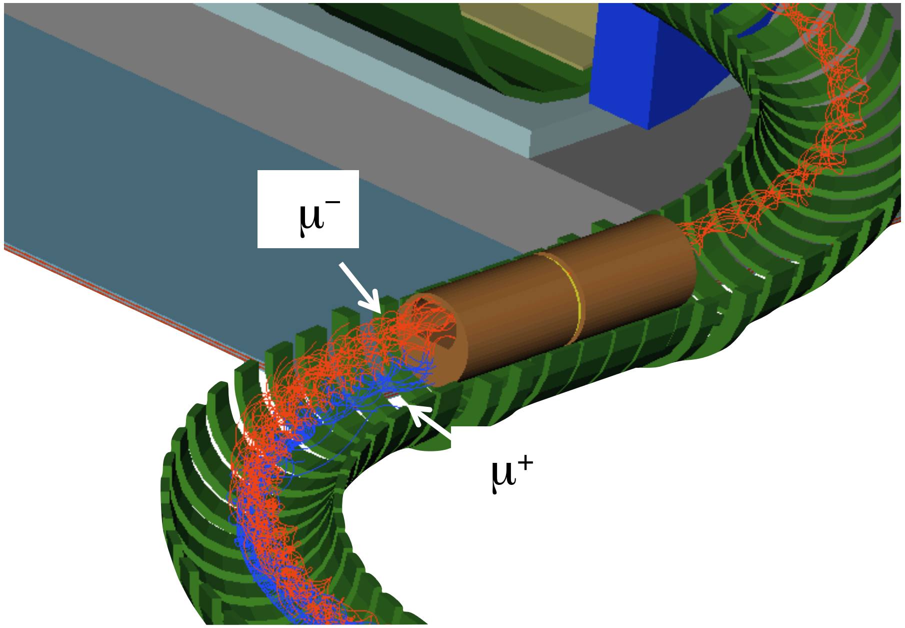
Magnetic Gradient



Transport Solenoid



- Transports muons from production target to capture target
- Curved solenoid eliminates line-of-sight backgrounds
- Collimator in center selects low momentum negative muons
  - *RxB* drift causes sign/momentum dependent *vertical* displacement



Choosing the Capture Target

- The probability of of exchanging a virtual particle with the nucleus goes up with Z, *however*
- Lifetime is *shorter* for high-Z
  - Decreases useful live window
- Also, need to avoid background from radiative muon capture limits choices

$$\begin{aligned}&\mu N \to \nu_\mu N'\gamma\\ &\qquad\qquad\quad \hookrightarrow e^+ \enclose{circle}{e^-}\end{aligned}$$

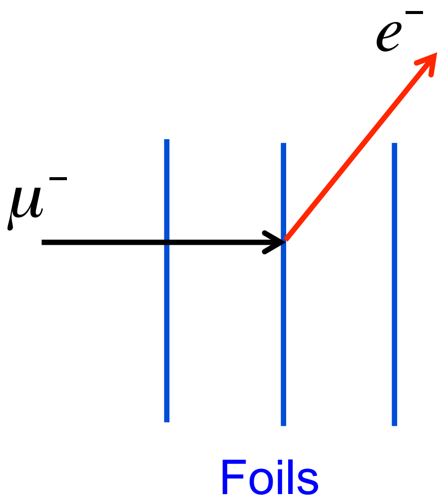
$\Rightarrow$Want M(Z)-M(Z-1) < signal energy

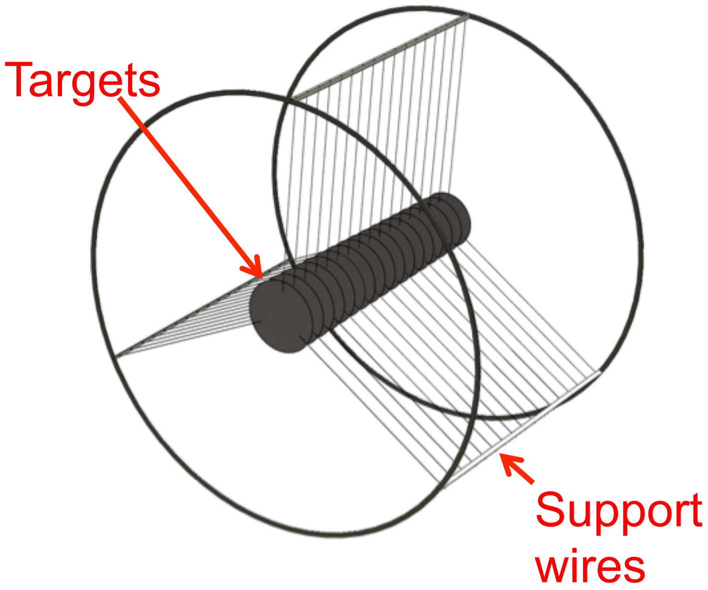
$\boxed{\Rightarrow\text{Aluminum is initial choice for Mu2e}}$

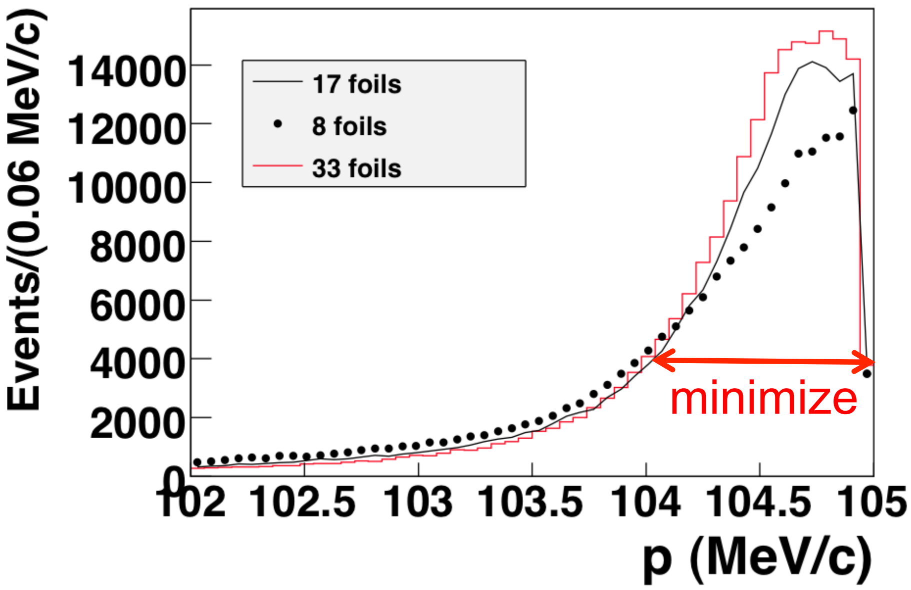
Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

Stopping (capture) Target

- Multiple thin layers to allow decay or conversion electrons to exit with minimal scattering
  - 17 Aluminum foils
  - 200 μm thick
- Stops 49% of arriving muons

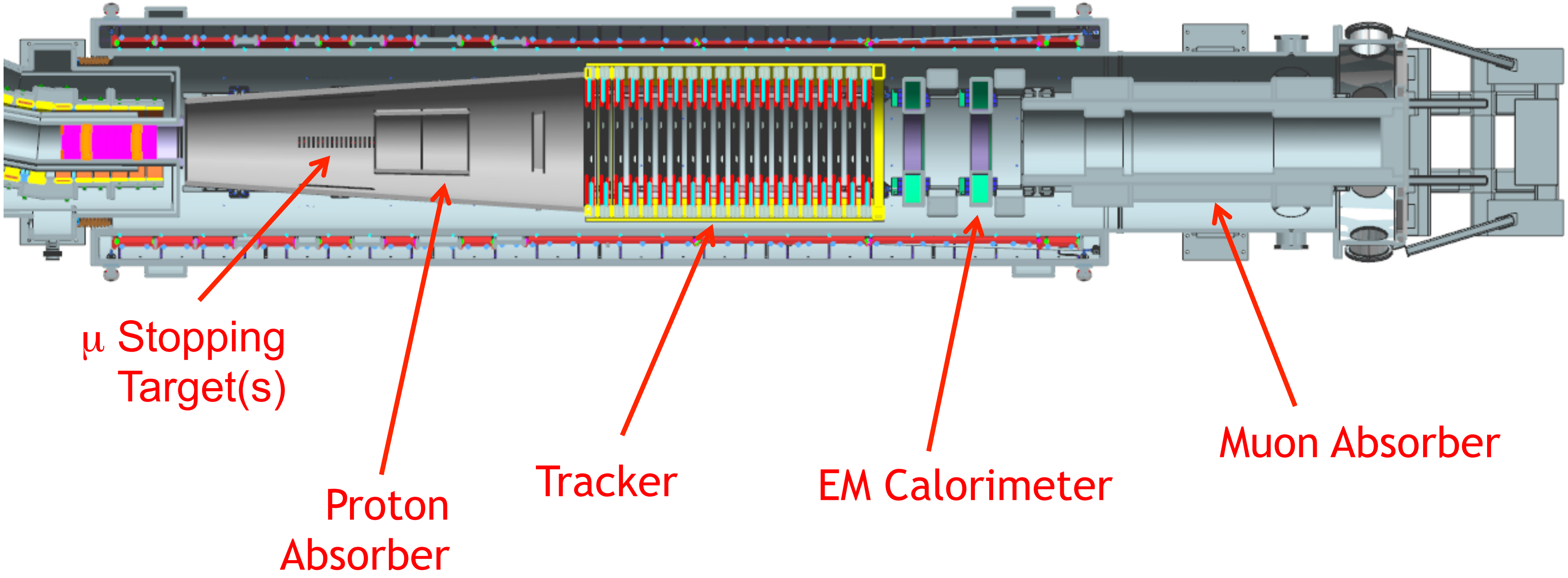




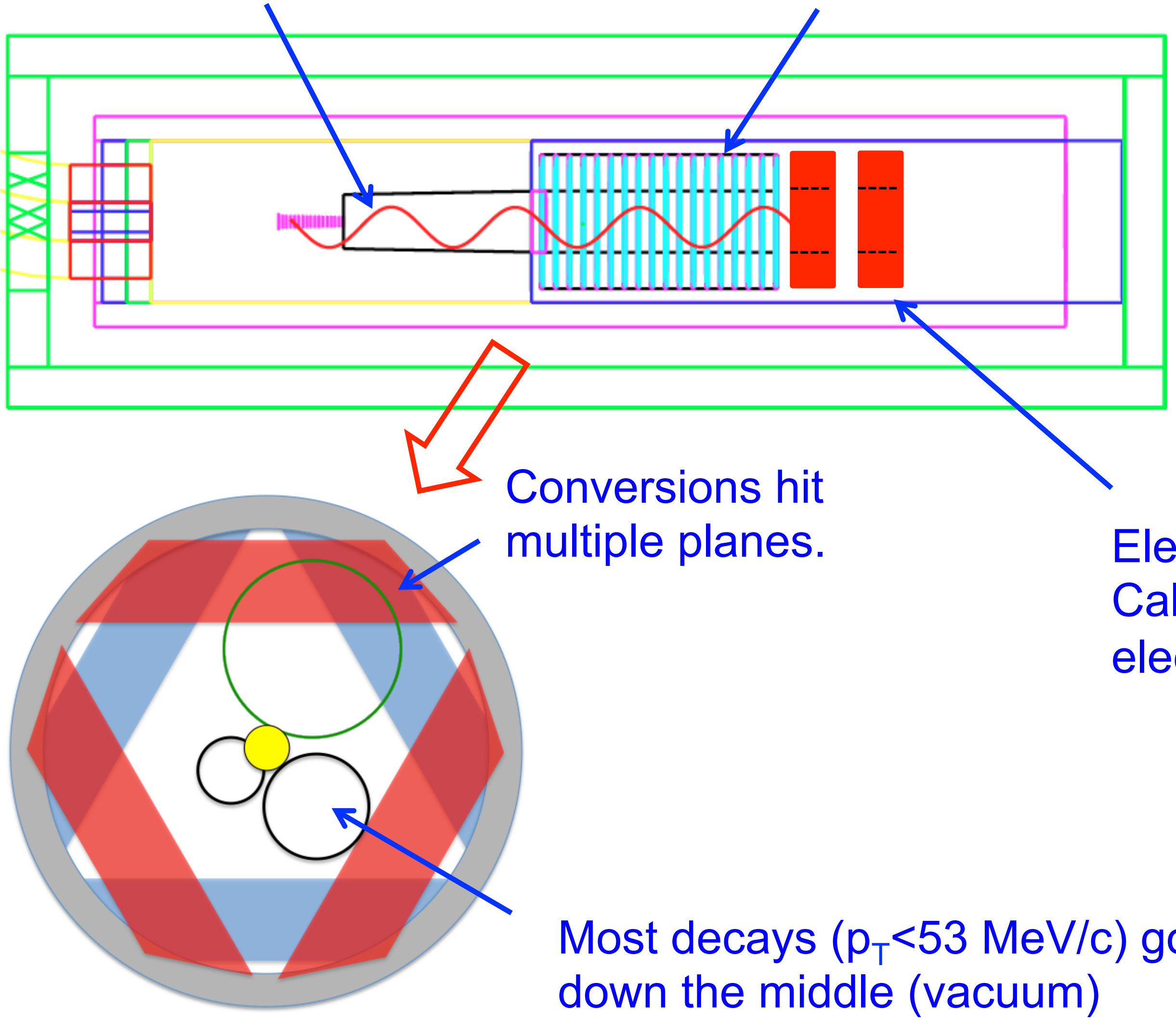

Conversion electron spectrum:

Detector and Detector Solenoid

- Graded field around stopping target to increase acceptance
  - Magnetic reflection again
- Uniform field in tracking volume
- Electromagnetic calorimeter to tag electrons.



Particle Detector



Helical trajectory

Charged tracking

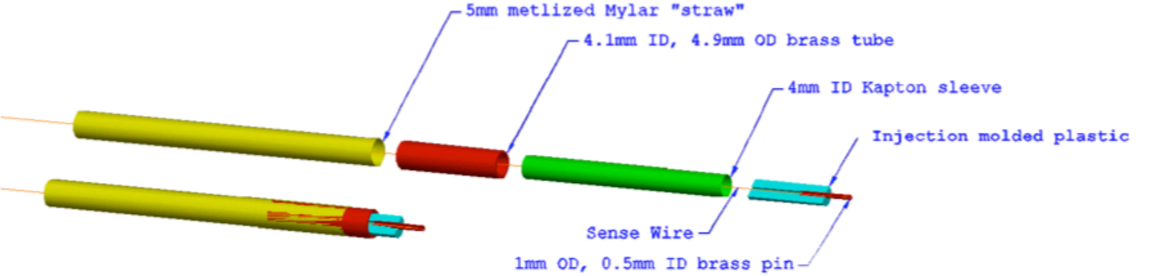
Conversions hit multiple planes.

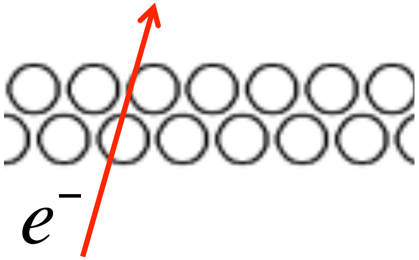
Electromagnetic Calorimeter to tag electrons

Most decays (p_T<53 MeV/c) go down the middle (vacuum)

Particle Tracking Technology

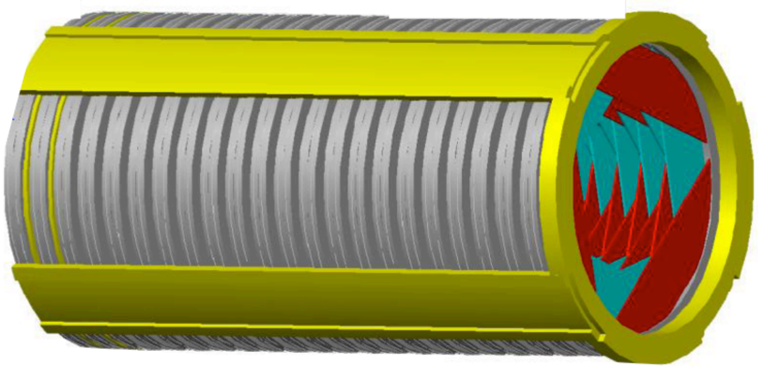
- To achieve the required resolution, must keep mass as low as possible to minimize scattering
- We've chosen transverse planes of "straw chambers" (~23,000 straws)





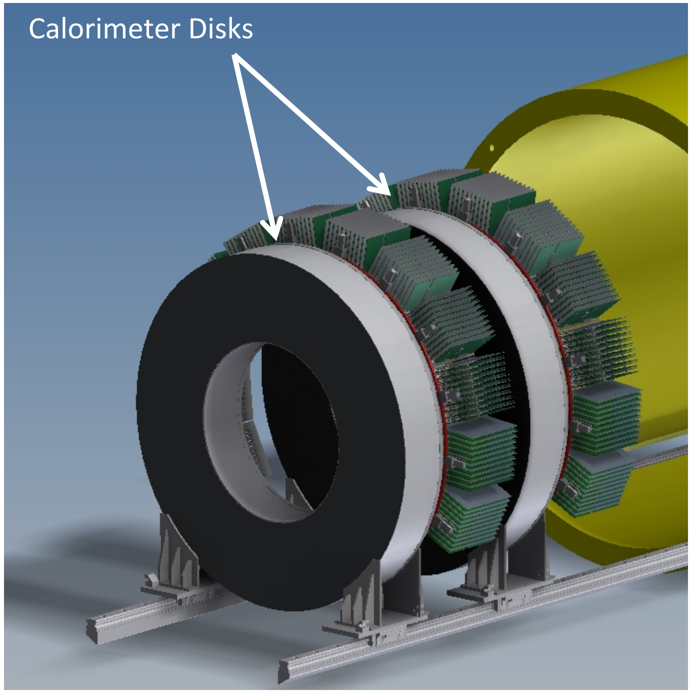
- Track ionizes gas in tube
- Charge drifts to sense wire at center
- Drift time gives precision position

- Advantages
  - Established technology
  - Modular: support, gas, and electronic connections at the ends, outside of tracking volume
  - Broken wires isolated
- Challenges
  - Our specified wall thickness (15 μm) has never been done
  - Operating in a vacuum may be problematic

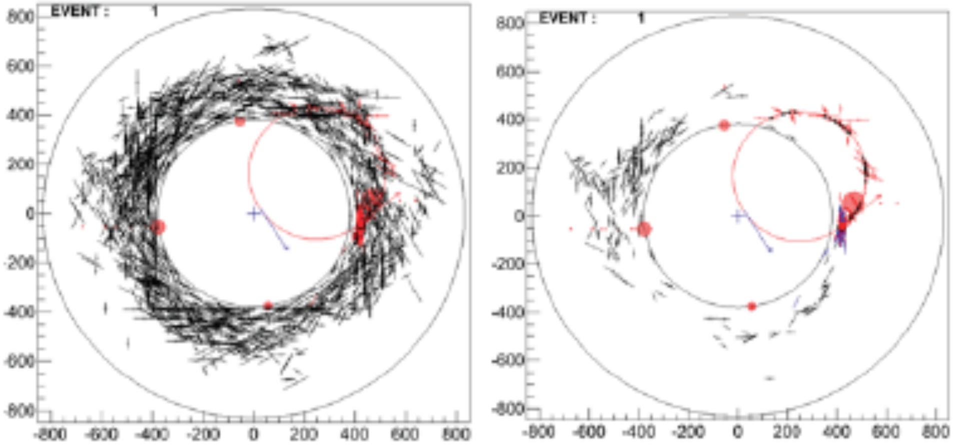


Calorimeter

- The Calorimeter will be used to tag electrons
  - Electrons will deposit all of their energy
  - Muons will deposit a small amount of ionization energy
- Two layers of 200 mm long BaF_2 crystals
  - 1860 total



- Very useful for timing

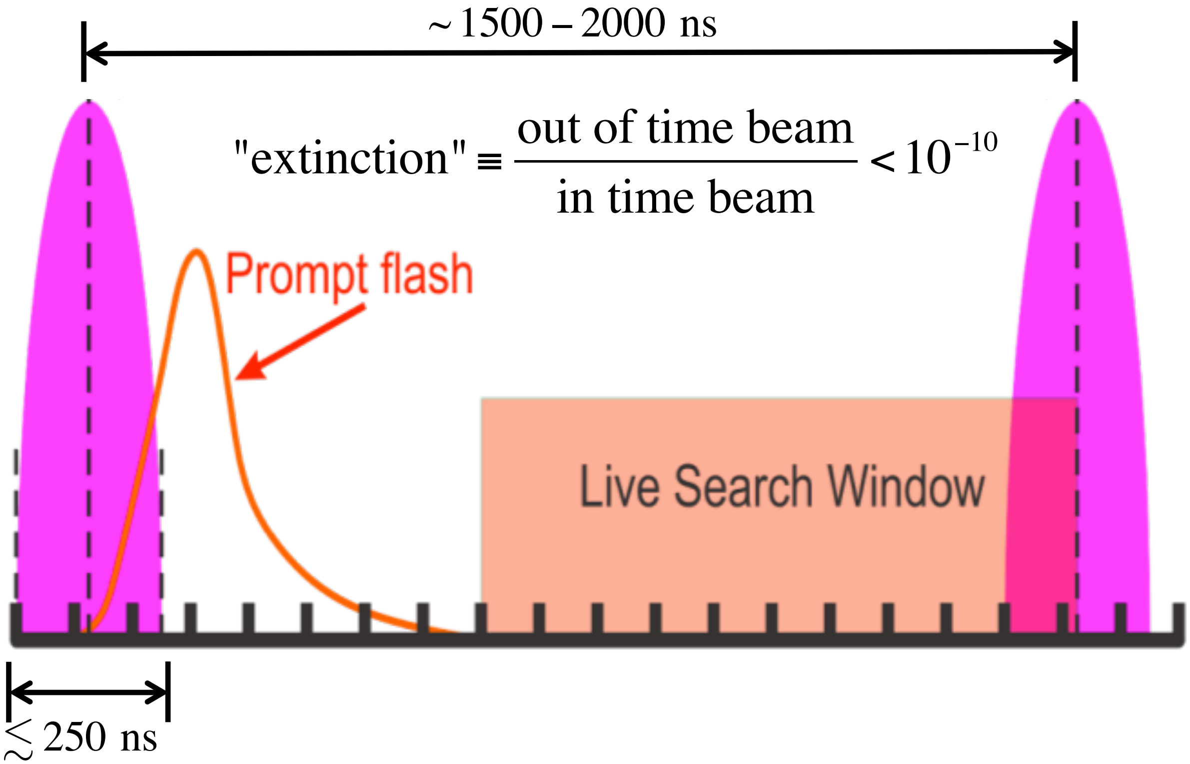

Tracker Hits

Before timing cut

After timing cut

Beam Needs

- We've talked about the experiment. Now where do we put it?
- We need a beam that looks kind of like this



$$\text{"extinction"} \equiv \frac{\text{out of time beam}}{\text{in time beam}} < 10^{-10}$$

- This is where Fermilab comes in…

A Brief History of Fermilab (evolving slide)

- 1968: construction begins
- 1972: first beams
  - 200→400 GeV proton beams
  - Highest energy lab ~~ever since~~ until recently
- ~1985:
  - "Tevatron": first superconducting synchrotron.
  - 900GeV x 900 GeV p-pBar collisions
- Upgraded in 1997
  - Main Injector-> more intensity
  - For awhile 980 GeV x 980 GeV p-pBar collisions
  - Intense neutrino program
- ~~Soon the second most powerful collider~~

- Fermilab is now the only remaining US High Energy Physics Lab
- With the LHC now the highest energy collider, the lab must focus on different types of physics.

Guidance: The P5 Report

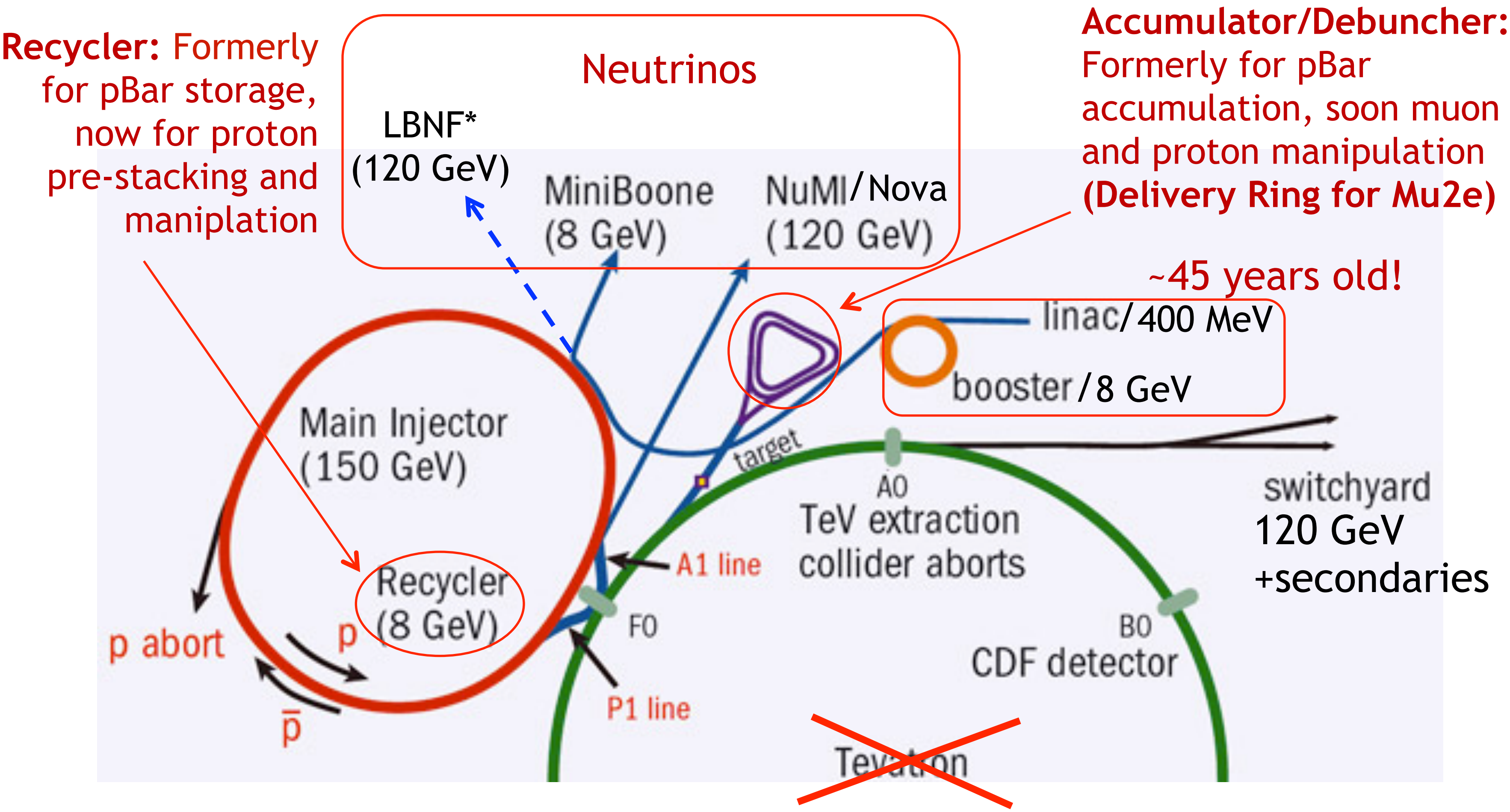
- The Particle Physics Project Prioritization Panel (P5) advises the DOE Office of High Energy Physics.
- In 2013, the P5 was charged to determine priorities in US particle physics (primarily priorities for Fermilab) under various funding scenarios
- In 2014, the panel report recommended proceeding with Mu2e under all scenarios.

Project/Activity	Scenario A	Scenario B	Scenario C
Large Projects			
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y
HL-LHC	Y	Y	Y
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y
NuSTORM	N	N	N
RADAR	N	N	N

- So… full speed ahead!

Fermilab Accelerator Complex Today

- As LHC takes over the Energy Frontier, Fermilab focuses on intensity-based physics



Recycler: Formerly for pBar storage, now for proton pre-stacking and maniplation

Neutrinos

LBNF*
(120 GeV)

Accumulator/Debuncher: Formerly for pBar accumulation, soon muon and proton manipulation **(Delivery Ring for Mu2e)**

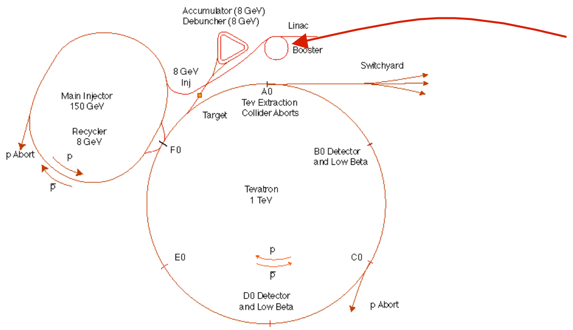
~45 years old!

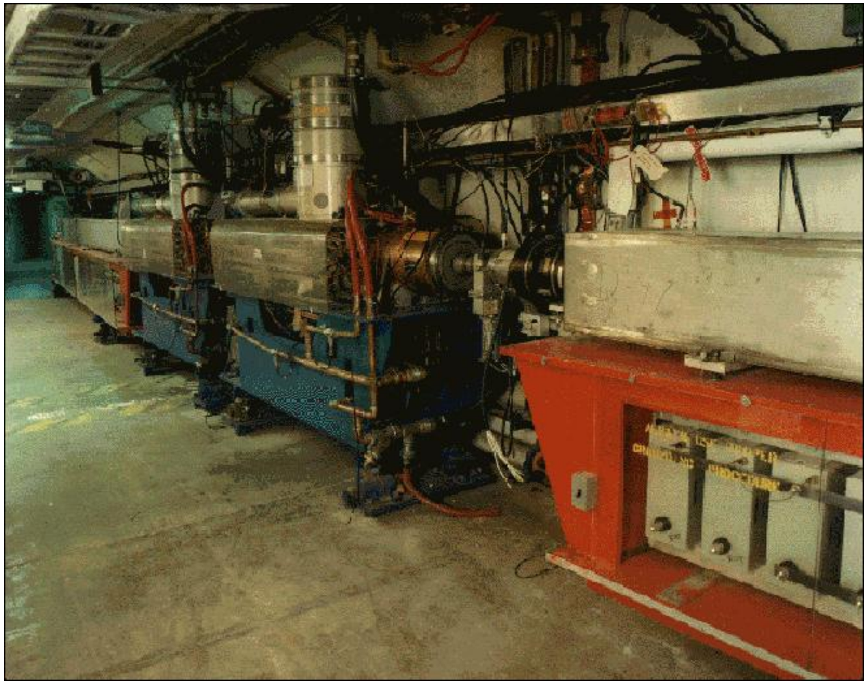
linac/ 400 MeV
booster/ 8 GeV

switchyard
120 GeV
+secondaries

*proposed

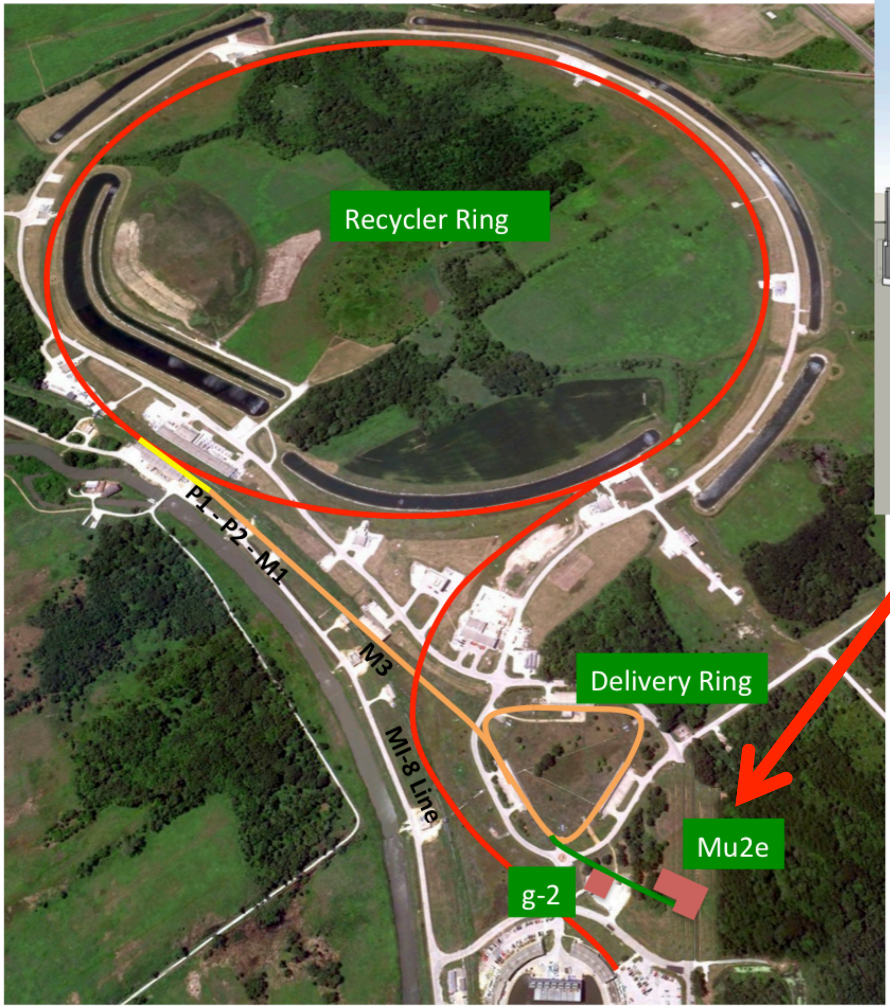
Fermilab Booster

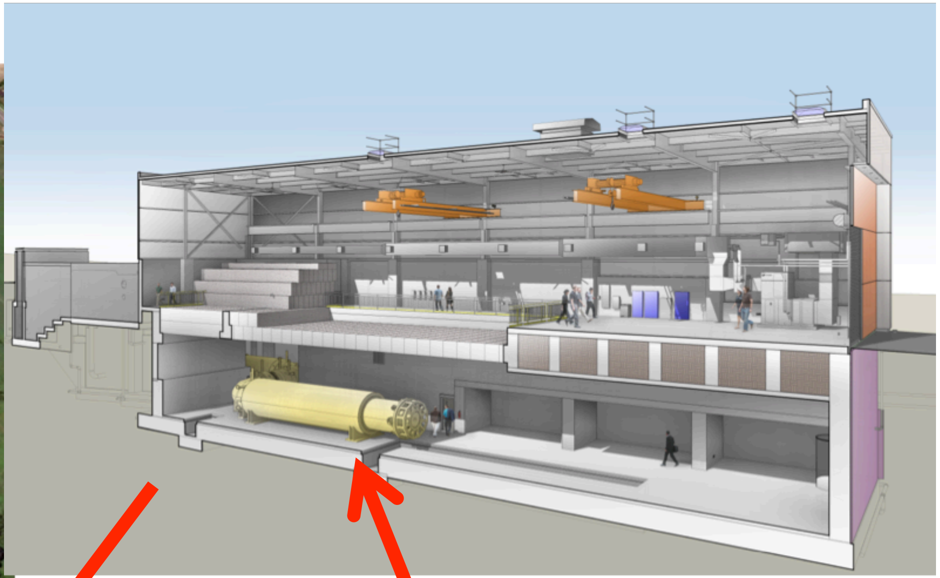


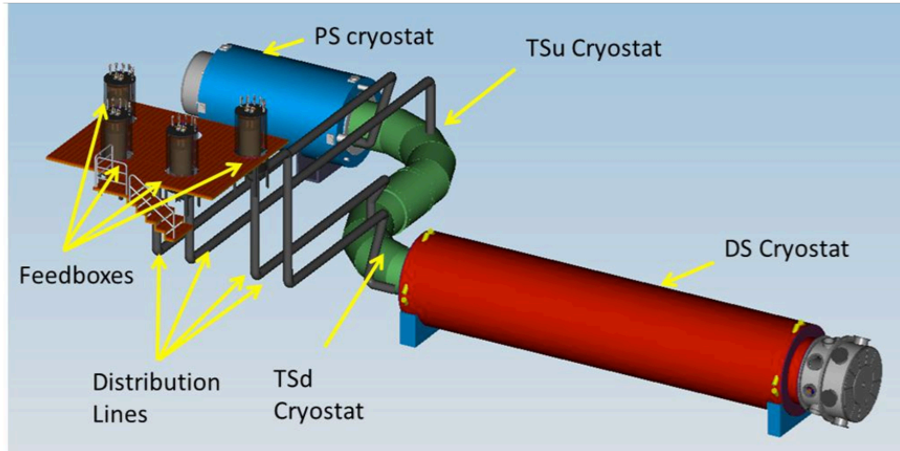


- Accelerates protons from 400 MeV to 8 GeV
- Operates in a 15 Hz resonant circuit
  - No time for beam manipulation
  - Can’t make required beam structure
- Sets a fundamental clock for the complex
  - 15 Hz “tick”
- Sets a fundamental unit of protons
  - 1 “batch” = up to ~4x10^{12} protons
- Since the can’t make the beam we need, how do we do it?
  - By using almost everything else!

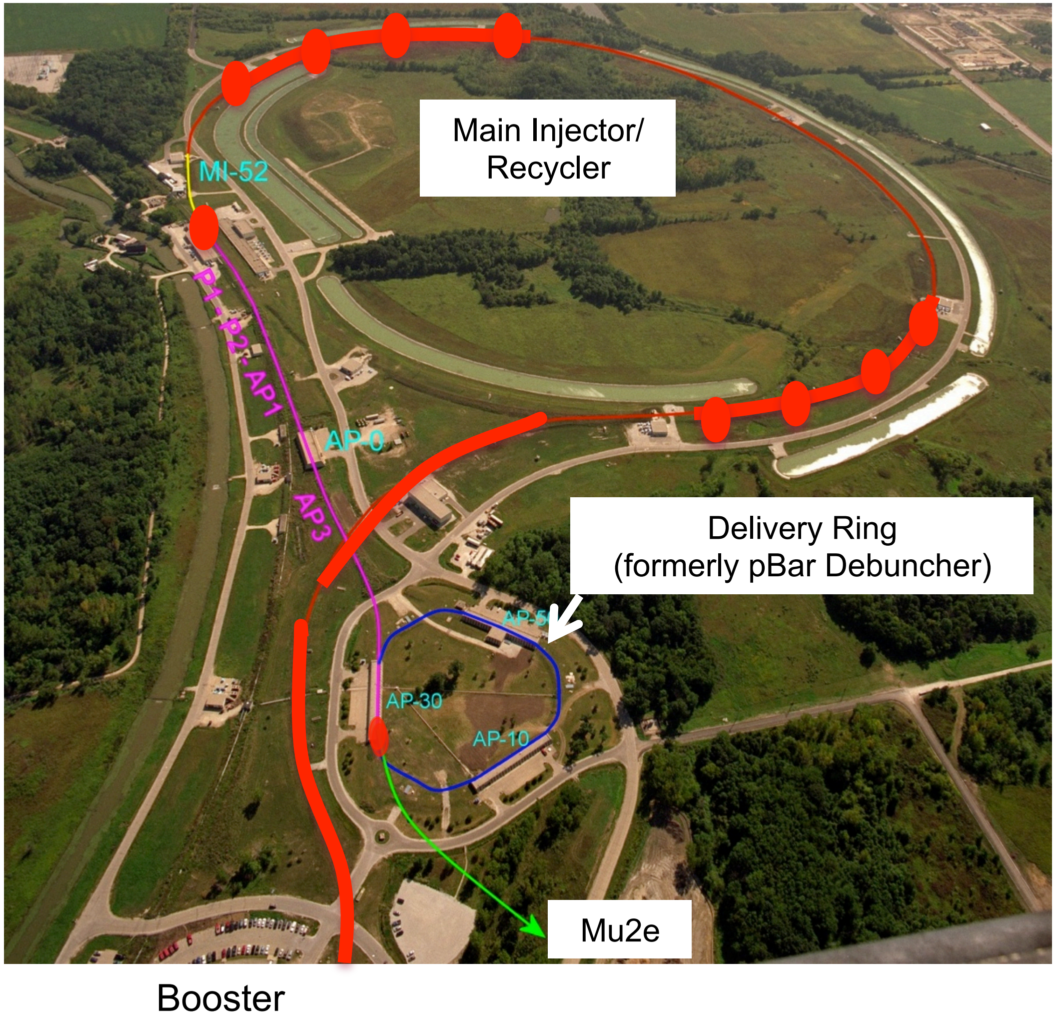
Orientation





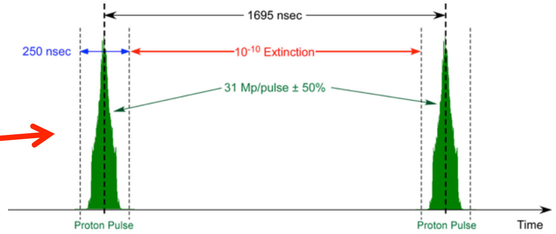


Mu2e Proton Delivery



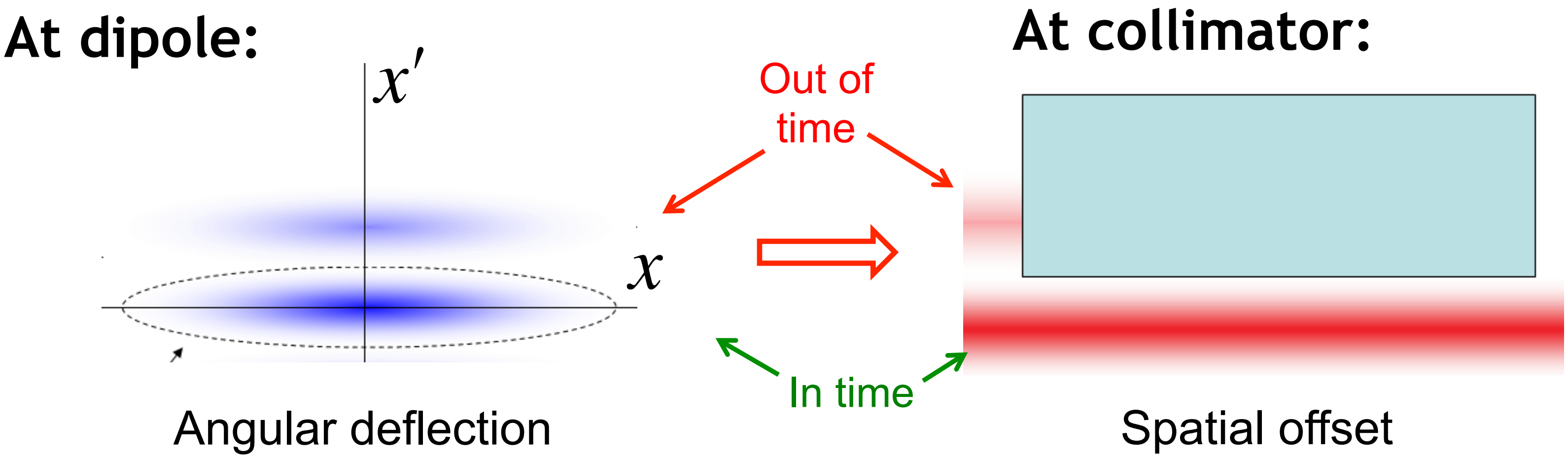
- One Booster "batch" is injected into the Recycler (8 GeV storage ring).
  - 4×10^{12} protons
  - 1.7 μsec long
- It is divided into 4 bunches of 10^{12} each
- These are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As a bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Bunches of ~3×10^7 protons each
  - Separated by 1.7 μsec

Exactly what we need →



Eliminating out of Time Beam (Extinction)

- A set of resonant dipoles in the beam deflects beam such that only in-time beam is transmitted through a system or collimators:

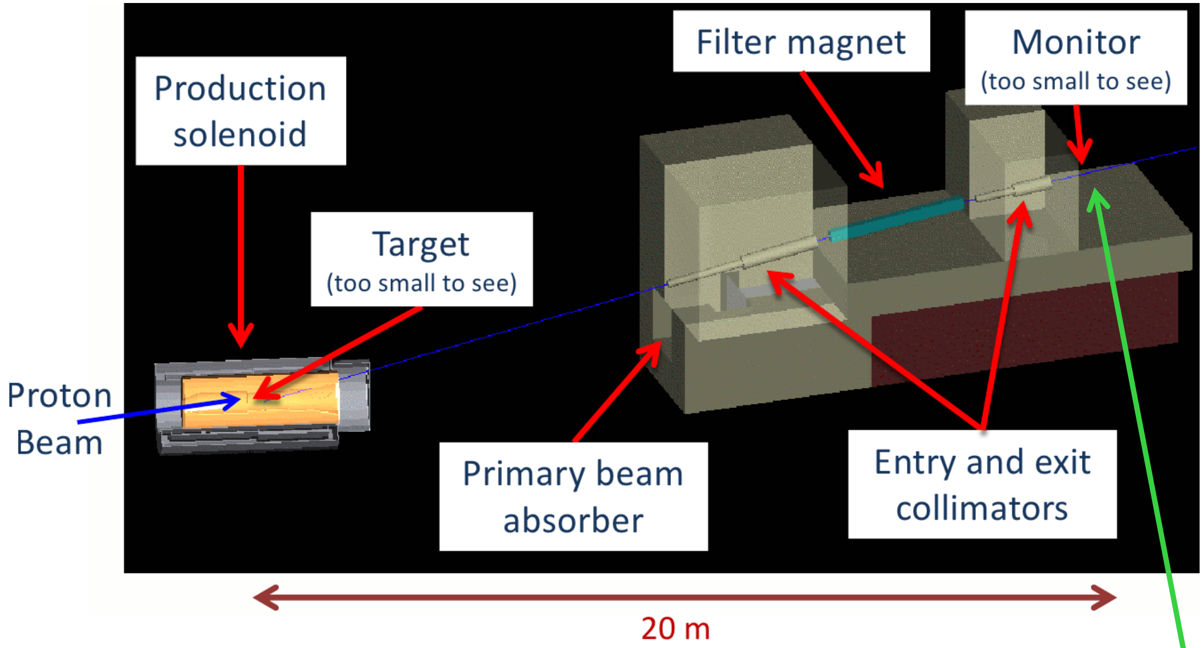


- Think miniature golf

Extinction Monitor

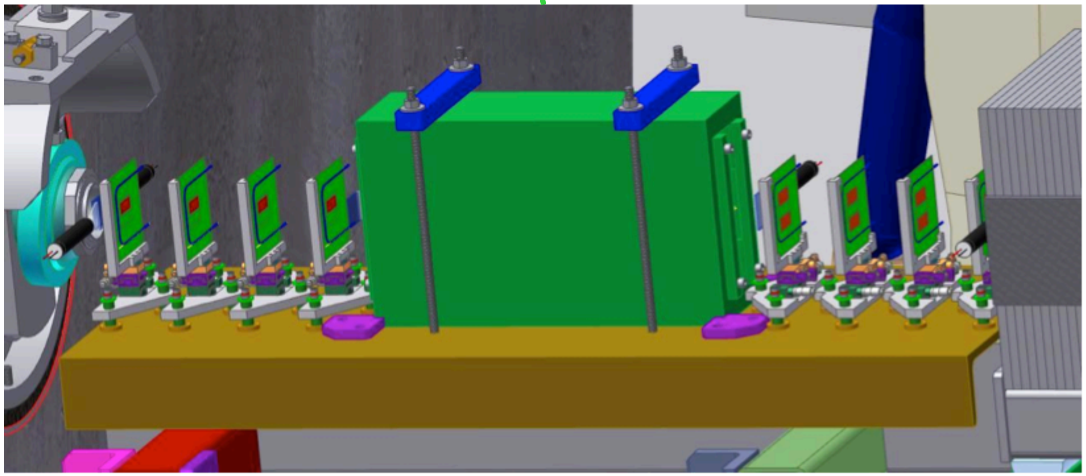
- Achieving 10^{-10} extinction is hard, but it’s not useful unless we can verify it.
- Must measure extinction to 10^{-10} precision
  - Roughly 1 proton every 300 bunches!
- Monitor sensitive to single particles not feasible
  - Would have to be blind to the 3×10^{7} particles in the bunch.
- Focus on statistical technique
  - Design a monitor to detect a small fraction of scattered particles from target
    - 10-50 per in-time bunch
  - Good timing resolution
  - Statistically build up precision profile for in time and out of time beam.
- Goal
  - Measure extinction to 10^{-10} precision in a few hours

Extinction Monitor Design



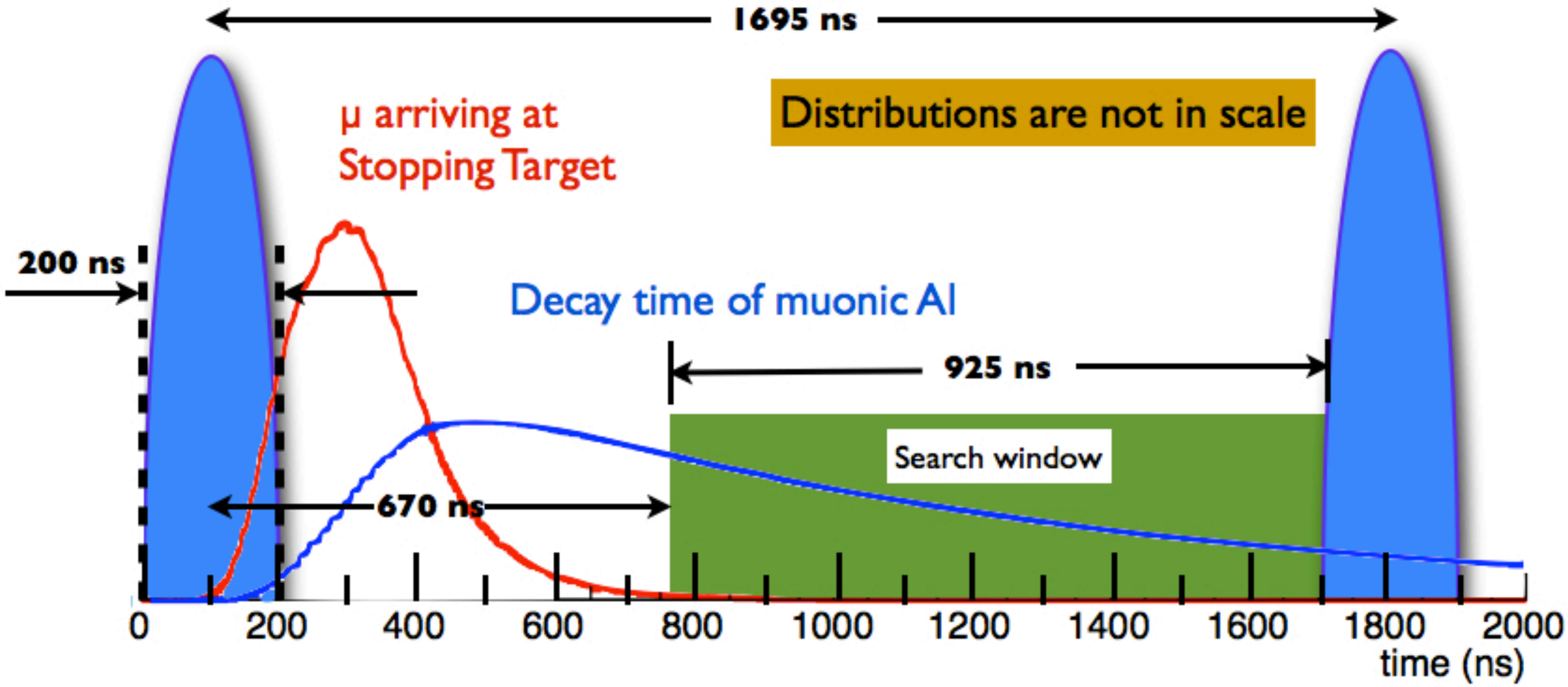
Peter Kasper, NUFACT-2012

Selection channel built into target dump channel



- Spectrometer based on 8 planes of ATLAS pixels
- Optimized for few GeV/c particles

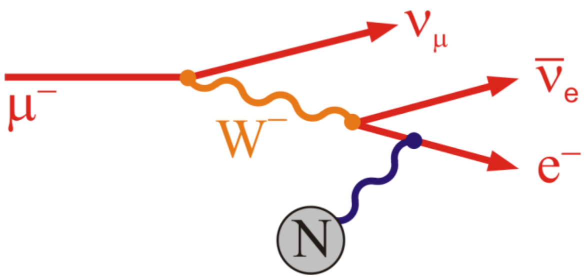
End Product



Target data set: ~3.6×10^{20} protons in ~3 years

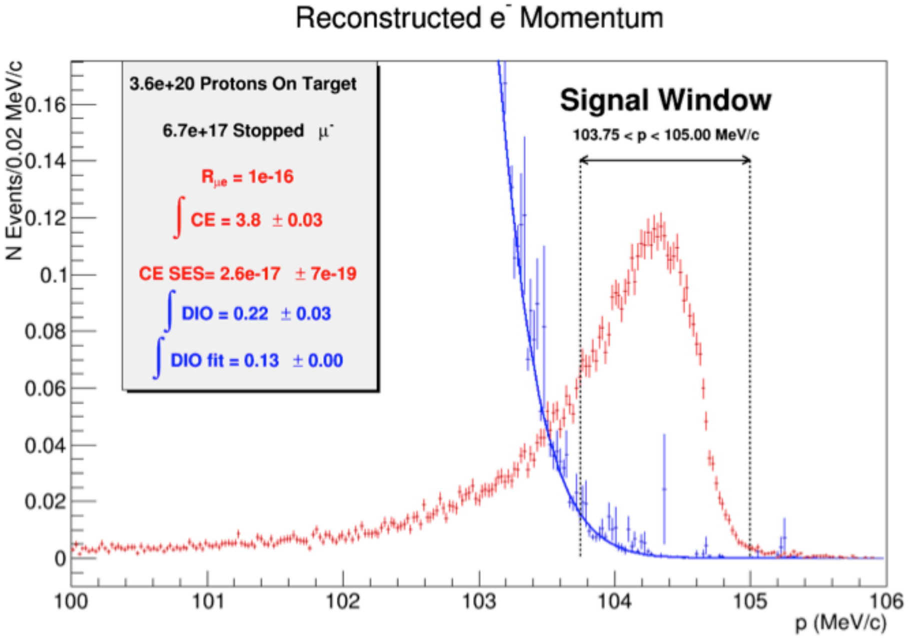
Major Backgrounds Revisisted

1. Muon decay in orbit (DIO)



$\mu^- \rightarrow e^- \nu\nu$

- $E_e < m_\mu c^2 - E_{NR} - E_B$
- $N \sim (E_{conversion} - E_e)^5$
- Fraction within 3 MeV of endpoint ~ $5\text{x}10^{-15}$
- Defeated by good energy resolution

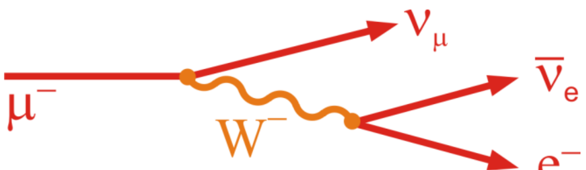


Major Backgrounds (cont'd)

2. Beam Related Backgrounds

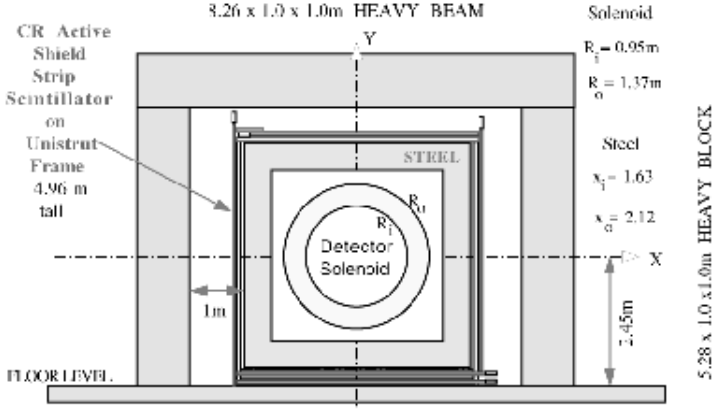
Goal: Prompt background ~equal to all other backgrounds

- Radiative π^- capture:
  $\pi^- N \rightarrow N^*\gamma$, $\gamma Z \rightarrow e^+e^-$
- Muon decay in flight:
  $\mu^- \rightarrow e^-\nu\nu$
  - Since $E_e < m_\mu c^2/2$, $p_\mu > 77$ GeV/c
- Beam electrons
- Pion decay in flight:
  $\pi^- \rightarrow e^-\nu_e$
- Suppressed by minimizing beam between bunches and waiting
  - Need ≲ 10^{-10} extinction (see previous discussion)



3. Asynchronous Backgrounds

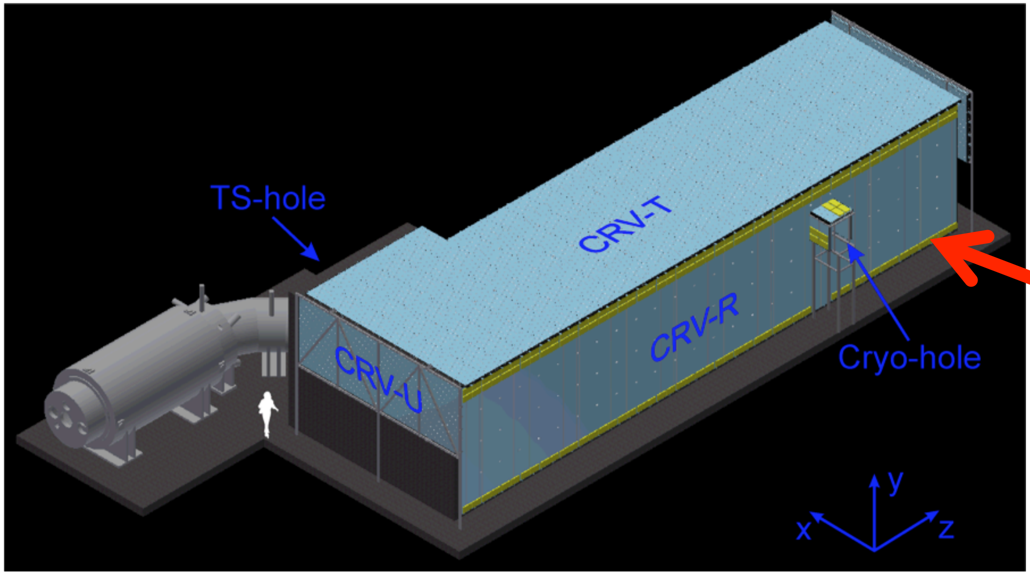
- Cosmic rays
  - suppressed by active and passive shielding

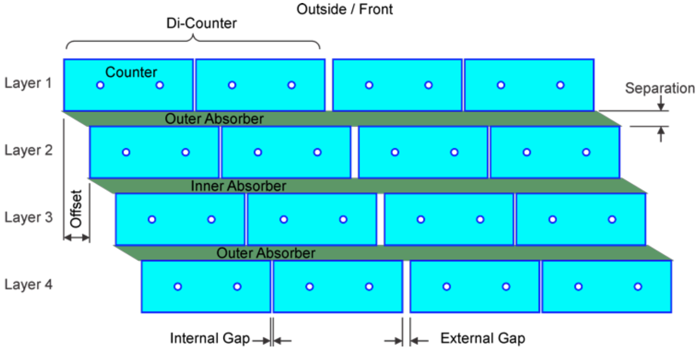


MECO DETECTOR SOLENOID
END VIEW

Cosmic Ray Veto (CRV)

- Multiple layers of scintillator panels surround detector to veto cosmic rays

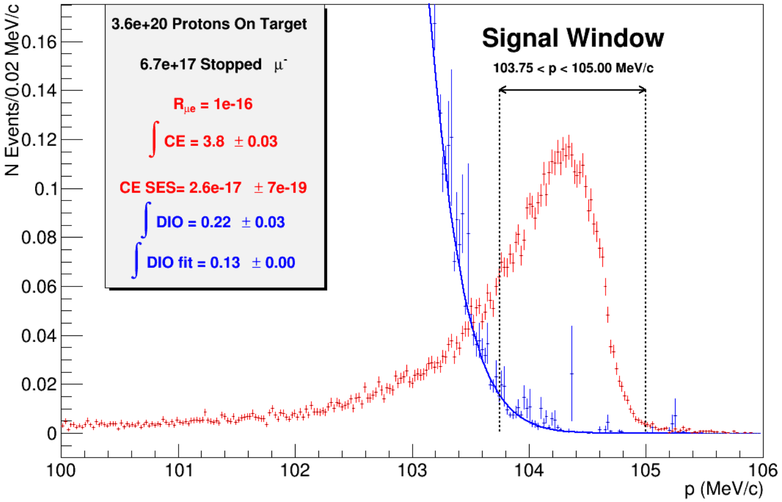




- Efficiency specification: >99.99%

Sensitivity

- Cuts chosen to maximize signficance
- 3.6×10^{20} protons on target
  - 3 years nominal running



Parameter	Value
Physics run time @ 2×10^7 s/yr.	3 years
Protons on target per year	1.2×10^{20}
μ^- stops in stopping target per proton on target	0.0019
μ^- capture probability	0.609
Total acceptance x efficiency for the selection criteria of Section 3.5.3	$\left(8.5 \pm^{1.1}_{0.9}\right)\%$
Single-event sensitivity with Current Algorithms	$\left(2.87 \pm^{0.32}_{0.27}\right) \times 10^{-17}$

Single Event Sensitivity: $R_{\mu e} = 2.9 \times 10^{-17}$

Significance

- Backgrounds

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

- Bottom line:
  - Single event sensitivity: $R_{\mu e}=3\text{x}10^{-17}$
  - 90% C.L. (if no signal) : $R_{\mu e}<7\text{x}10^{-17}$
  - Typical SUSY Signal: ~40 events or more

4 order of magnitude improvement!

A long time coming

1992	Proposed as “MELC” at Moscow Meson Factory
1997	Proposed as “MECO” at Brookhaven (at this time, experiment incompatible with Fermilab)
1998-2005	Intensive work on MECO technical design
July 2005	Entire rare-decay program canceled at Brookhaven
2006	MECO subgroup + Fermilab physicists work out means to mount experiment at Fermilab
Fall 2008	Mu2e Proposal submitted to Fermilab
November 2008	Stage 1 approval. Formal Project Planning begins
November 2009	DOE Grants CD-0
July 2012	CD-1
March 2015	CD-2/3b

In DOE project-speak, this is the first “Critical Decision”: Statement of mission need = official existence

Approval of baseline and money for long lead elements

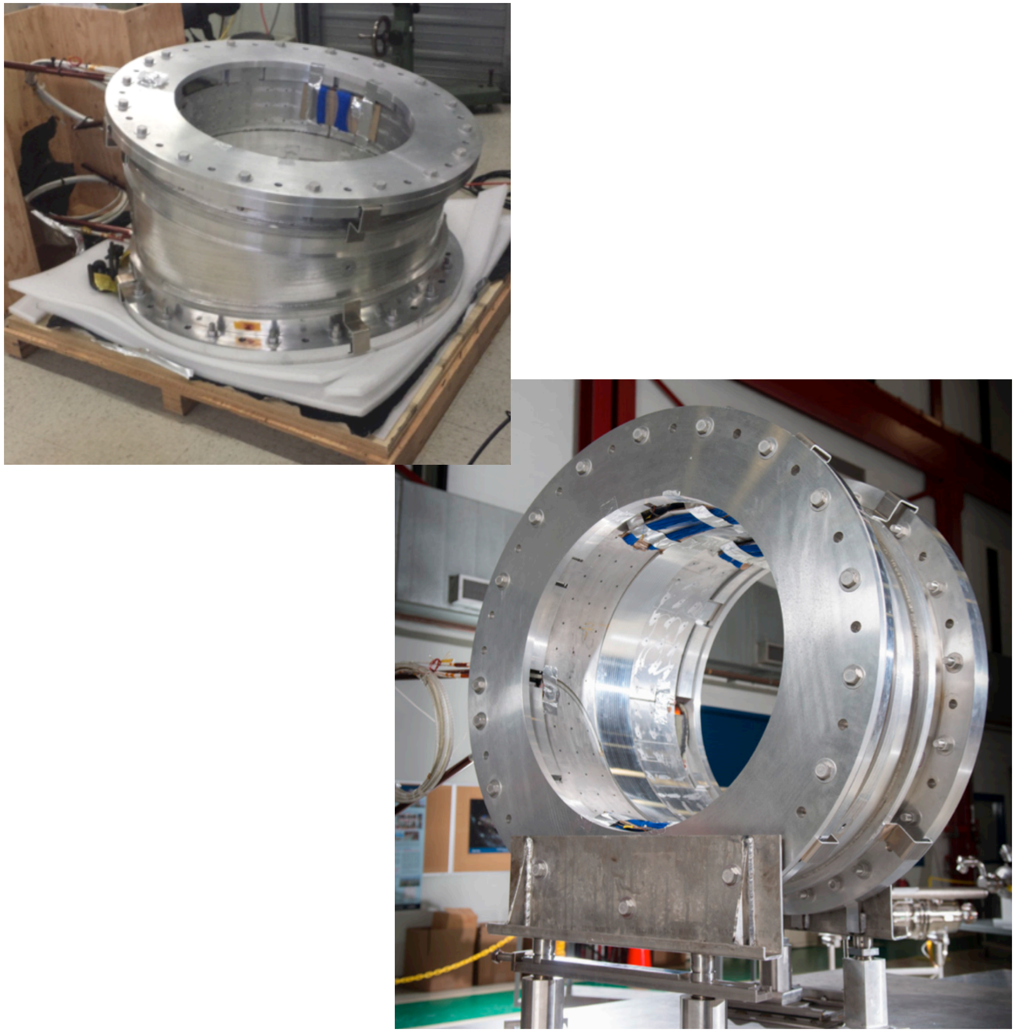
Things are really happening

Civil Construction

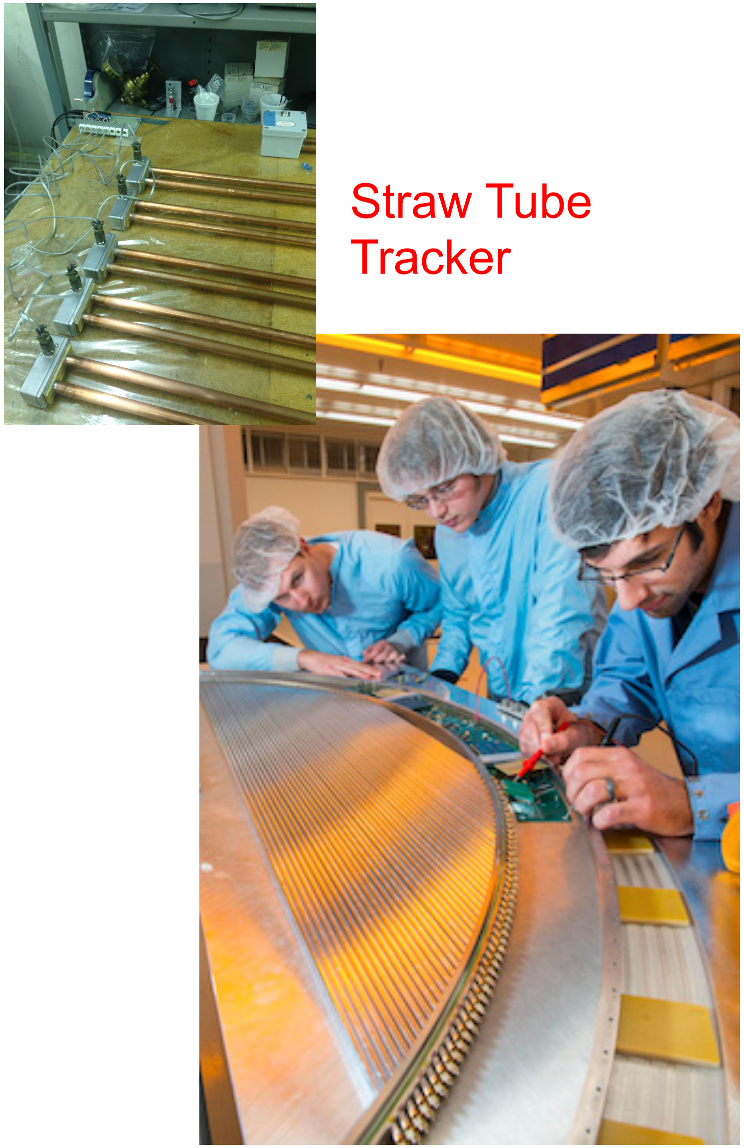
Magnet Procurement and Testing

Cable acceptance

Successful test of Transport Solenoid segment

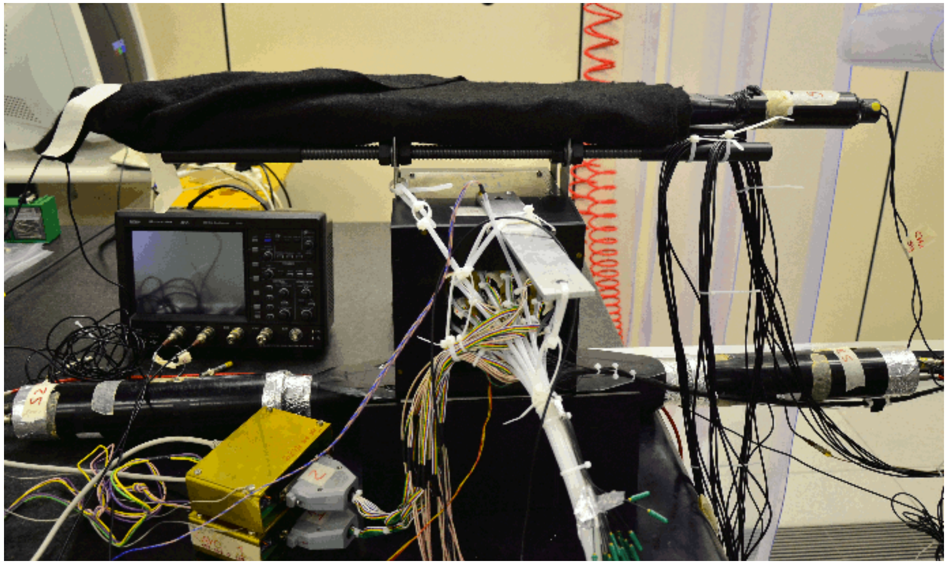


Detectors



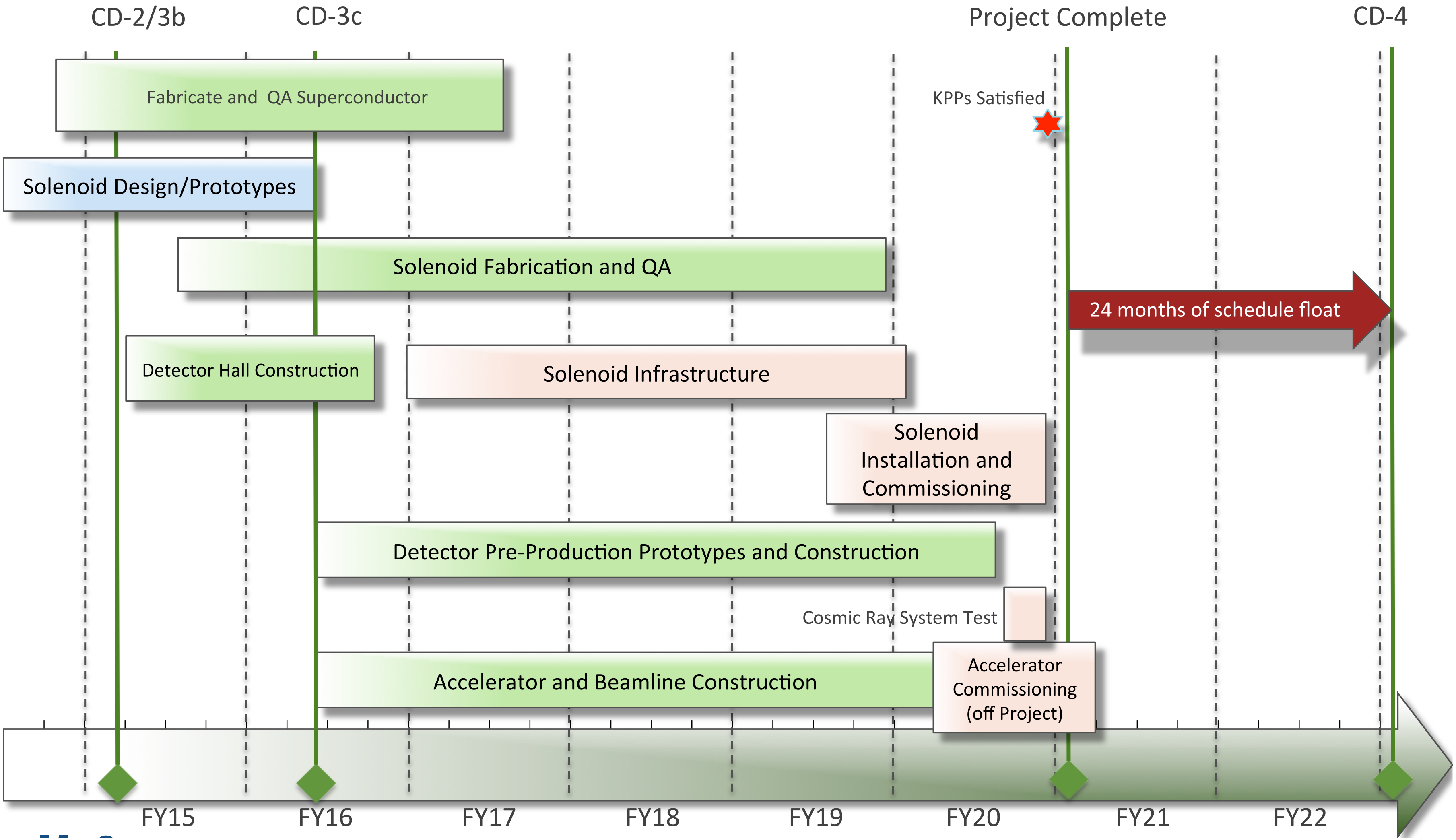
Straw Tube Tracker

Calorimeter Crystal Test



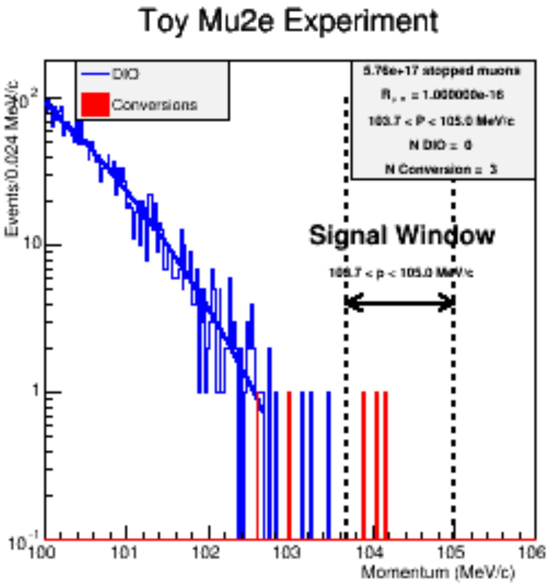
Cosmic Ray Veto

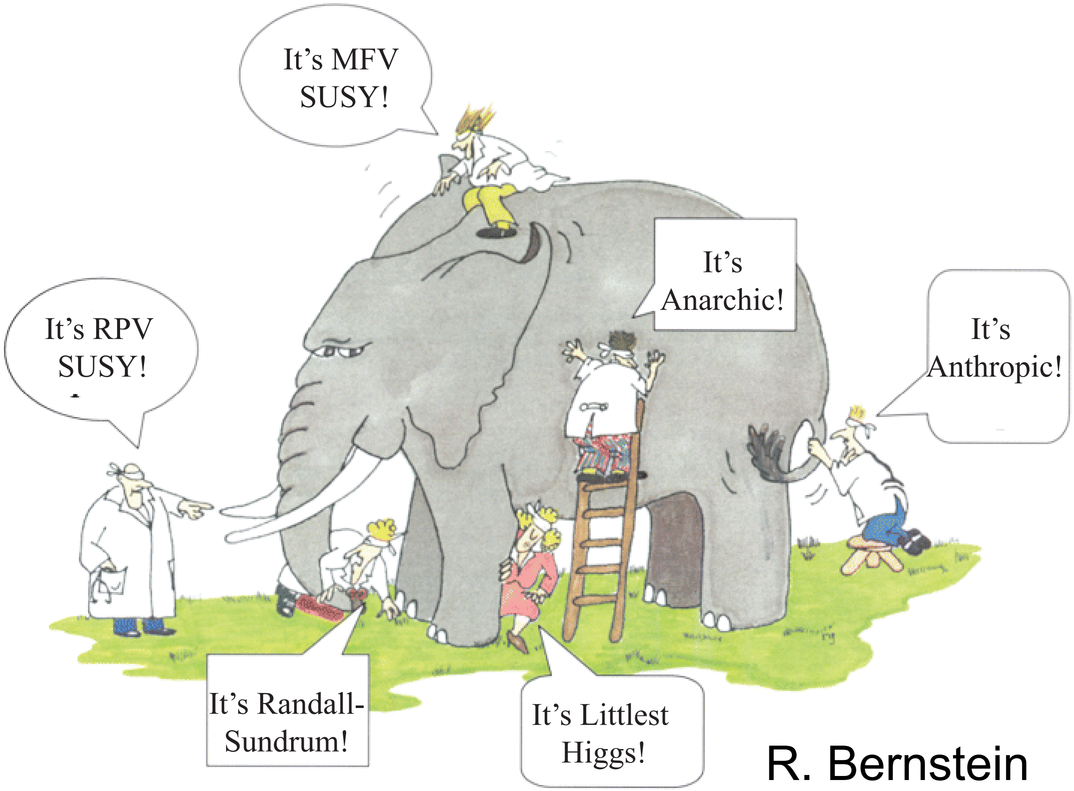
Schedule


CD-2/3b
CD-3c
Project Complete
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design/Prototypes
Solenoid Fabrication and QA
24 months of schedule float
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Pre-Production Prototypes and Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22

What if we see something?

$$R_{\mu e} = 10^{-16}$$

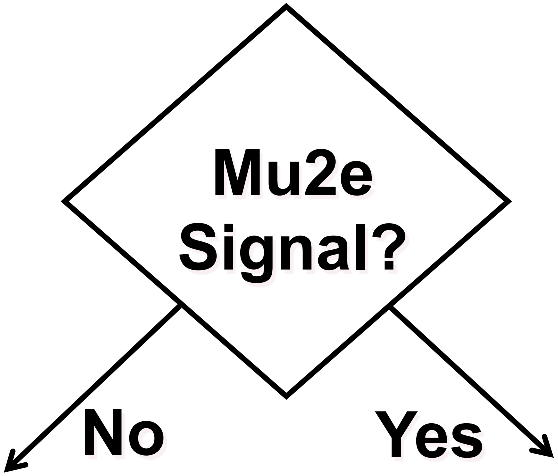




R. Bernstein

- Next questions:
  - What's the μ➔eγ signal (if any)
  - What's the target dependence?

Upgrade scenarios



Mu2e Signal?

No

Yes

- Both prompt and DIO backgrounds must be lowered to measure

  $R_{\mu e} \sim 10^{-18}$

- Must upgrade all aspects of production, transport and detection.

- Must compare different targets.
- Optimize muon transport and detector for short bound muon lifetimes.
- Backgrounds might not be as important.

Target Dependence

- Different models predict different target dependence and different relative rates for μN➔eN and μ➔eγ

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

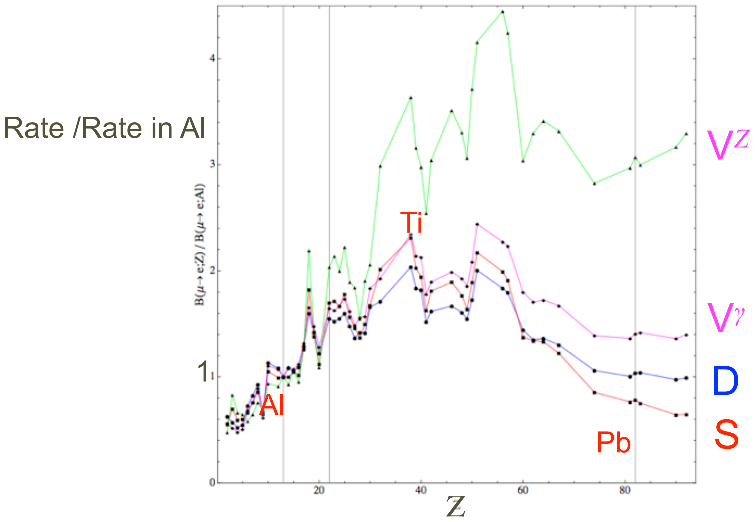
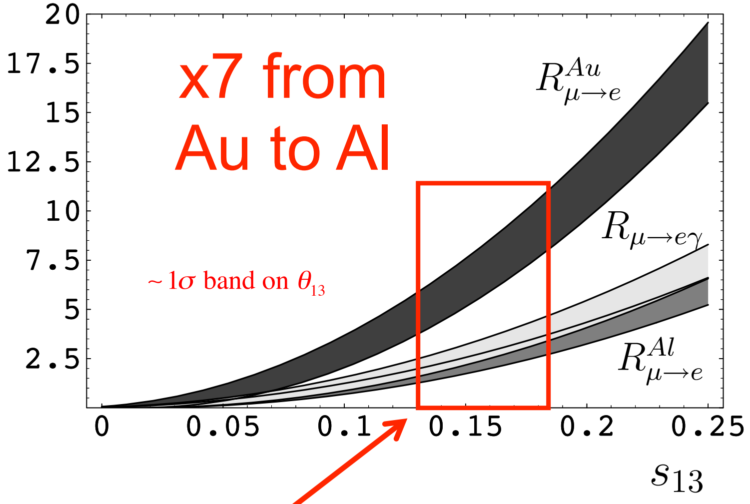


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

θ_{13}: G. Fogli et al., arXiv:1205.5254



x7 from Au to Al

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005

Now we know this!

Conclusions

- We have proposed a realistic experiment to measure

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- \mathrm{Al} \to e^- + \mathrm{Al}\right)}{\Gamma\left(\mu^- \mathrm{Al} \to \ (\mathrm{All\ Captures})\right)}$$

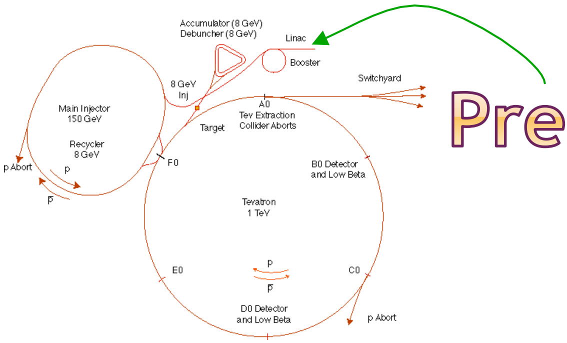
  - Single event sensitivity of $R_{\mu e} = 3\mathrm{x}10^{-17}$
  - This represents an improvement of *four orders of magnitude* compared to the existing limit, or over a *factor of ten* in effective mass reach. For comparison
    - TeV -> LHC = factor of 7 (difference in luminosity makes in comparable)
    - LEP 200 -> ILC = factor of 2.5
- ANY signal would be unambiguous proof of physics beyond the Standard Model
- The absence of a signal would be a very important constraint on proposed new models.

BACKUP SLIDES

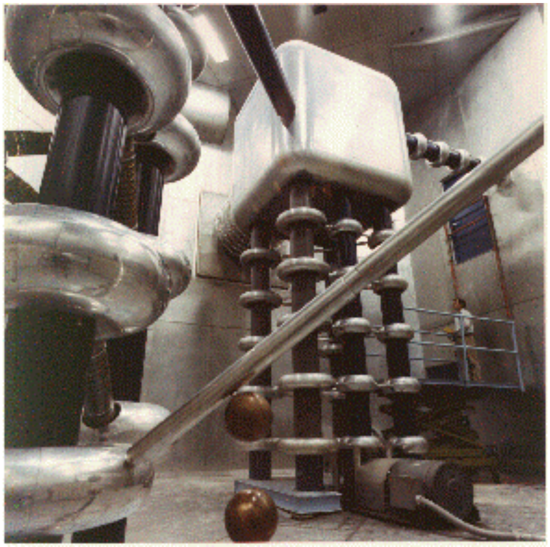
Experimental Challenges for Increased Flux

- At our level of sensitivity, we hit fundamental limits with this technique
  - Simply increasing the proton flux will not improve the limit dramatically
- Improve momentum resolution for the ~100 MeV electrons to reject high energy tails from ordinary DIO electrons.
  - Limited by multiple scattering in target and detector plane

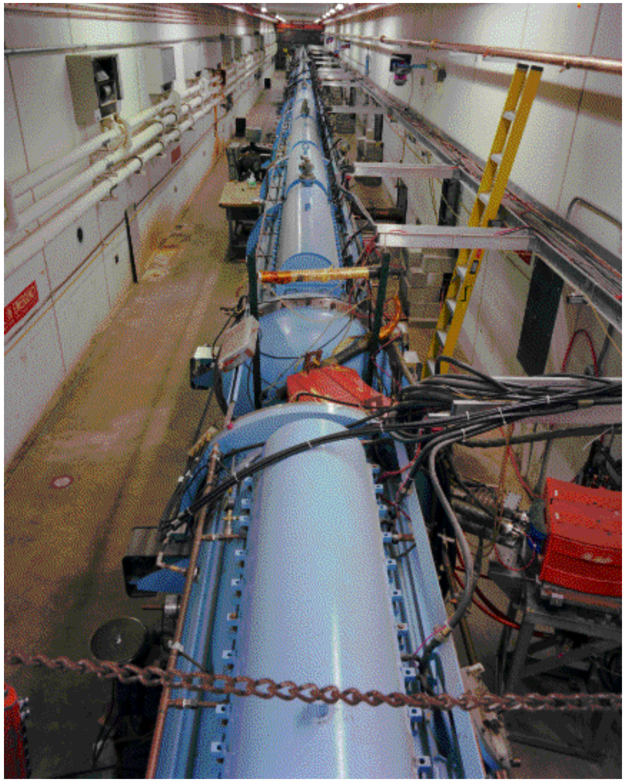
    ➔ go to bunched, mono-energetic muon beam, allowing for thinner target
- Allow longer decay time for pions to decay
- Both of these lead to a decay/compressor ring
- Other issues with increased flux
  - Upgrade target and capture solenoid to handle higher proton rate
    - Target heating
    - Quenching or radiation damage to production solenoid
  - High rate detector
- All of these efforts will benefit immensely from the knowledge and experience gained during the initial phase of the experiment.
- If we see a signal a lower flux, can use increased flux to study in detail
  - Precise measurement of $R_{\mu e}$
  - Target dependence
  - Comparison with $\mu \rightarrow e\gamma$ rate



Preac(cellerator) and Linac

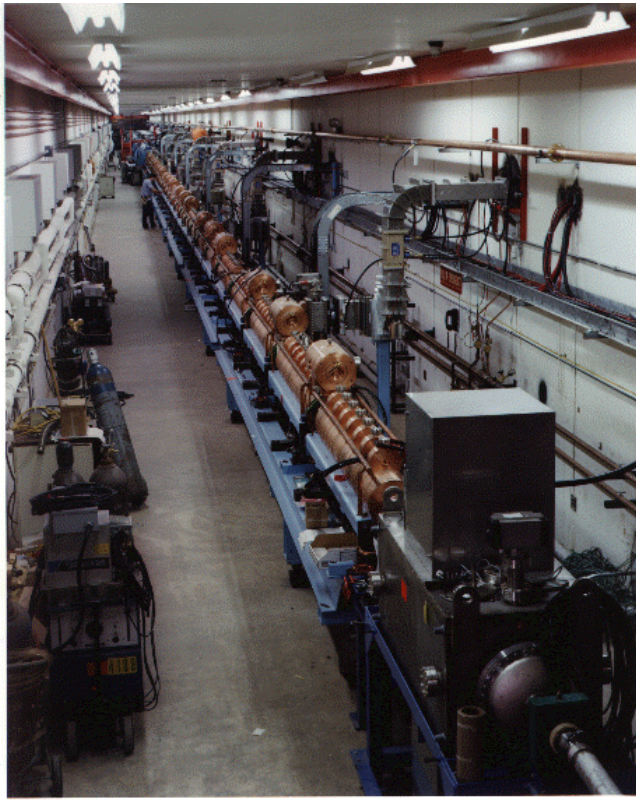


“Preac” - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.

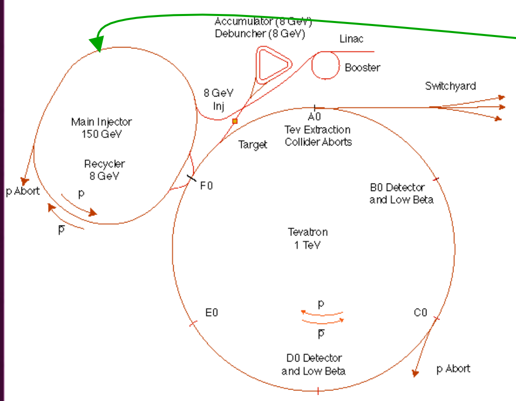


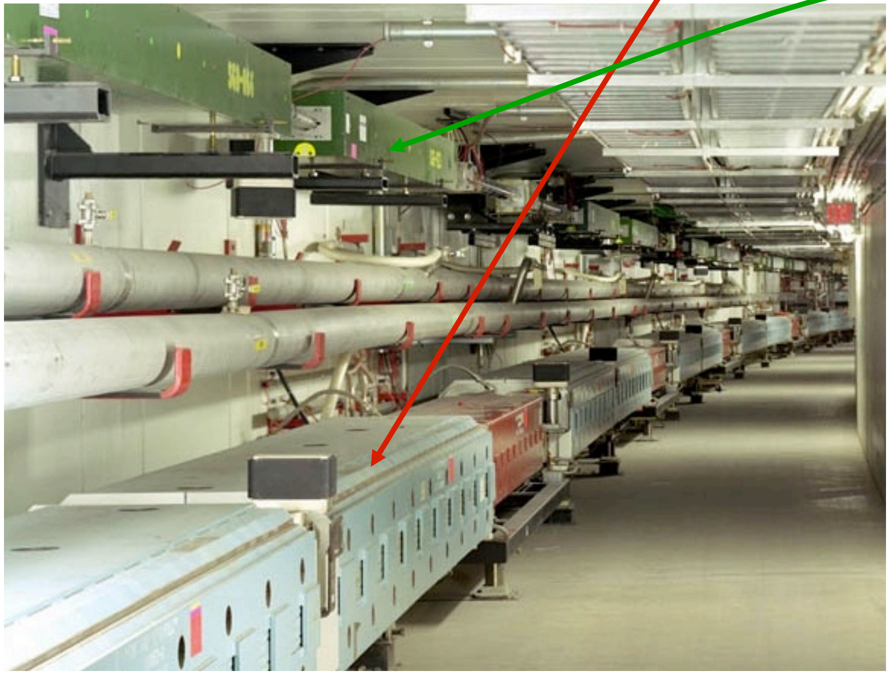
“Old linac”(LEL)- accelerate H- ions from 750 keV to 116 MeV

“New linac” (HEL)-
Accelerate H- ions from 116 MeV to 400 MeV



Main Injector/Recycler

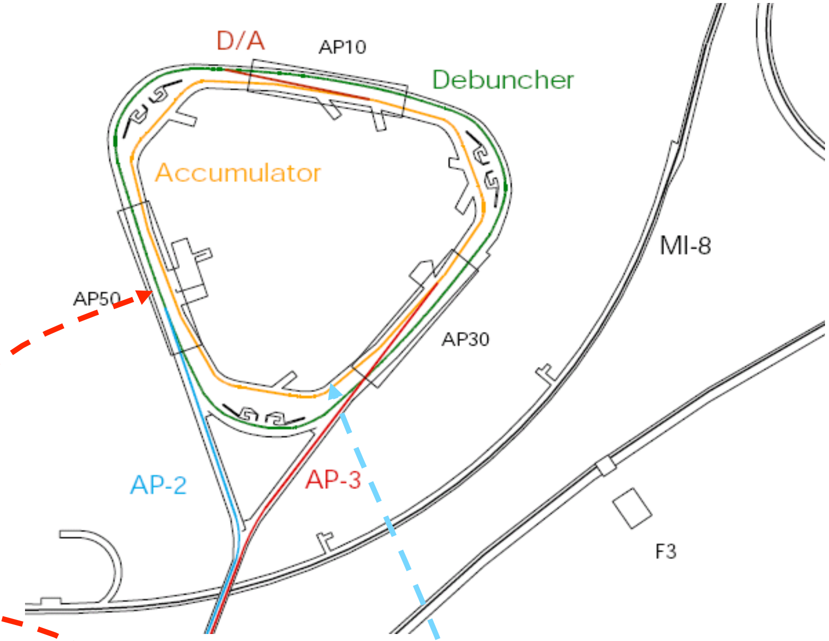


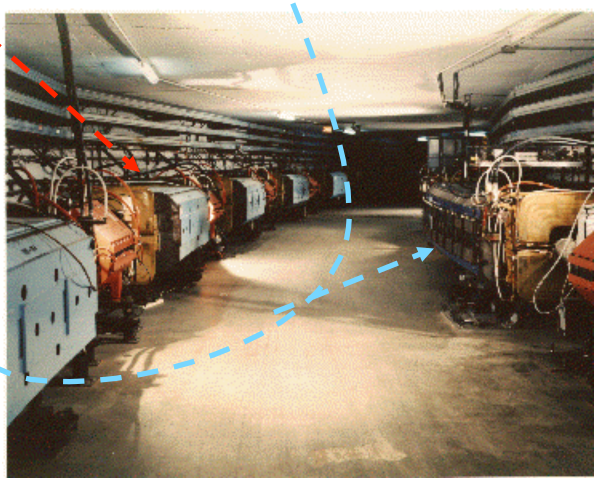


- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The 8 GeV Recycler (which shares the same tunnel and stores antiprotons)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - The fixed target area.
  - The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.

Present Operation of Debuncher/ Accumulator

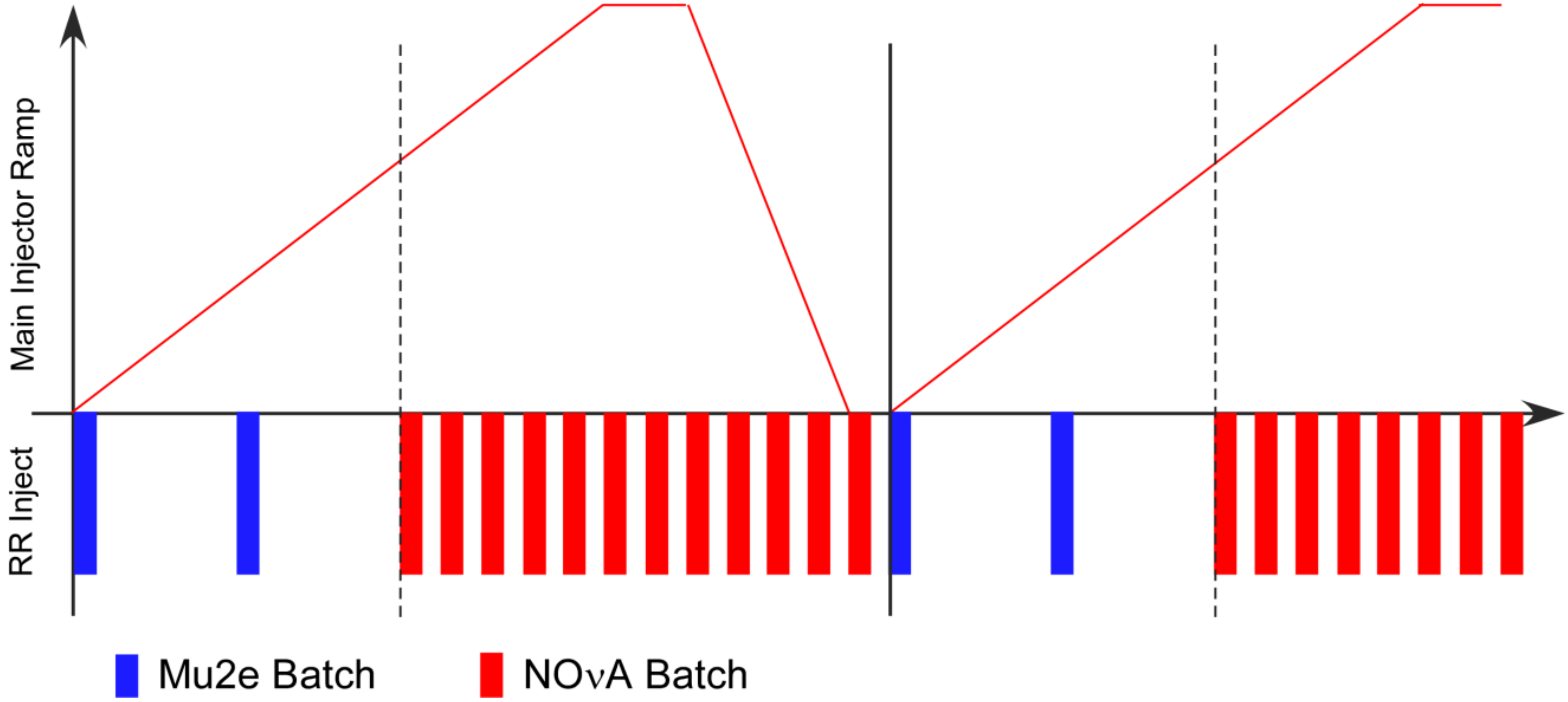
- Protons are accelerated to 120 GeV in Main Injector and extracted to pBar target
- pBars are collected and phase rotated in the “Debuncher”
- Transferred to the “Accumulator”, where they are cooled and stacked
- pBars not used after collider.





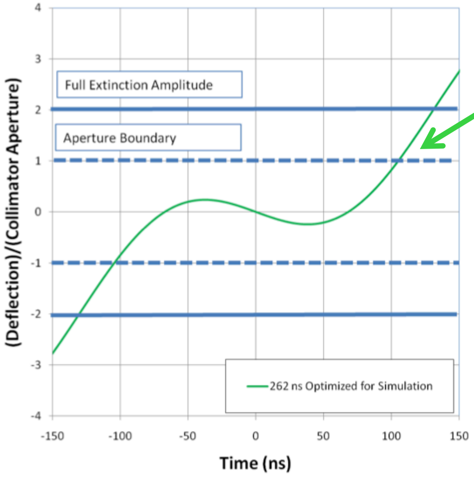
Mu2e in the NOvA era

- Beam Delivered in 15 Hz “batches” from the Fermilab Booster



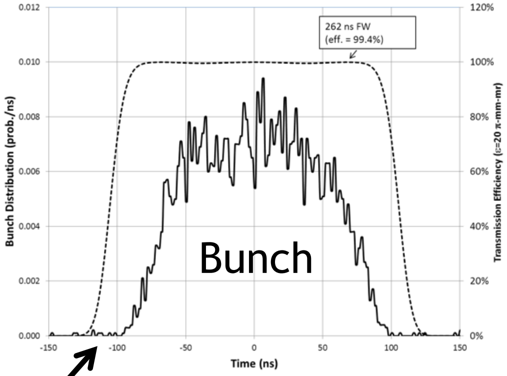
🟦 Mu2e Batch 🟥 NOνA Batch

Extinction Performance

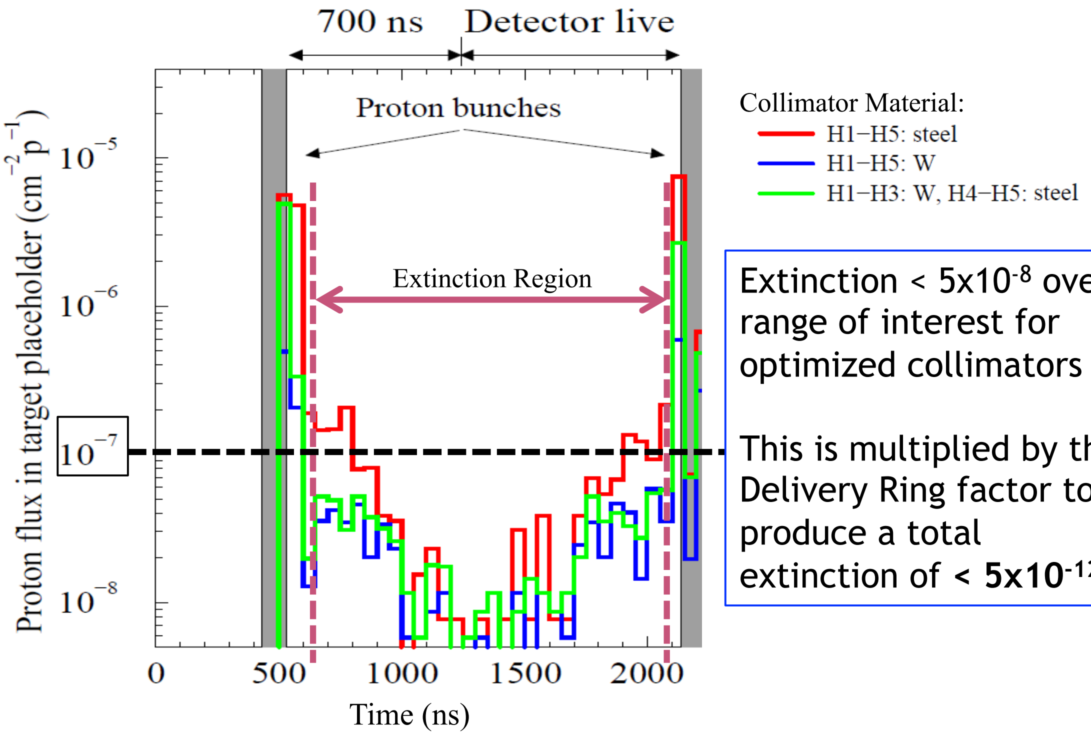


Beam motion in Collimator

Component	Length	Frequency	Peak Field
Low Frequency	3 m	300 kHz	108 Gauss
High Frequency	3 m	3.8 MHz	13 Gauss



Transmission Window



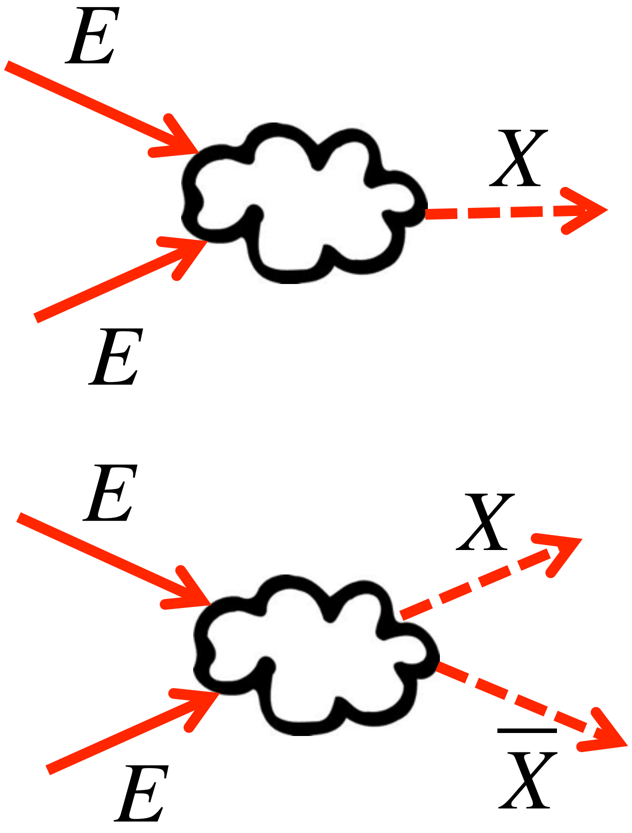
Extinction < 5×10^{-8} over range of interest for optimized collimators

This is multiplied by the Delivery Ring factor to produce a total extinction of **< 5×10^{-12}**

- Additional 10^{-5} extinction from beam delivery system

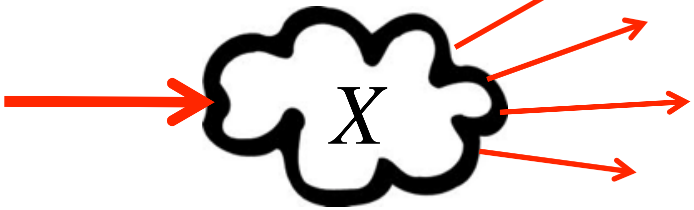
Direct vs. Indirect Observation

Direct



probe up to $M_X \approx \dfrac{E}{c^2}$

Indirect

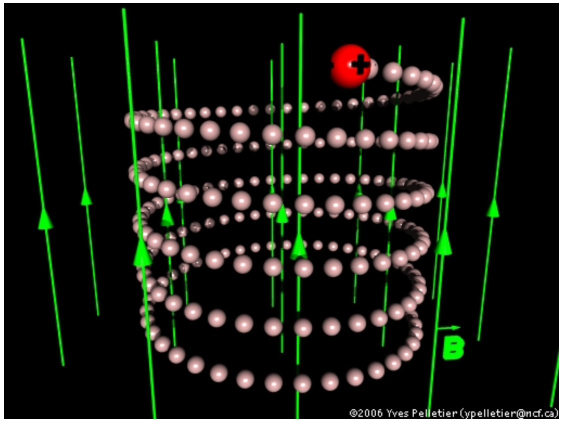


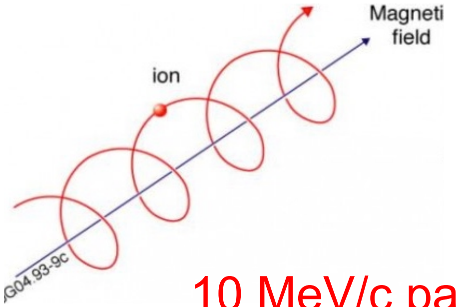
$$M_X c^2 \gg E$$

$$\text{Rate} \propto \frac{1}{M_x^4}$$

Review: Particle Motion in a Solenoidal Field

- Generally, particles move in a helical trajectory
- For high momentum particles,
- the curvature is used to measure
- the momentum
- Low momentum particles are effectively "trapped" along the field lines
- A particle trapped along a *curved* solenoidal field will drift out of the plane of curvature with a velocity





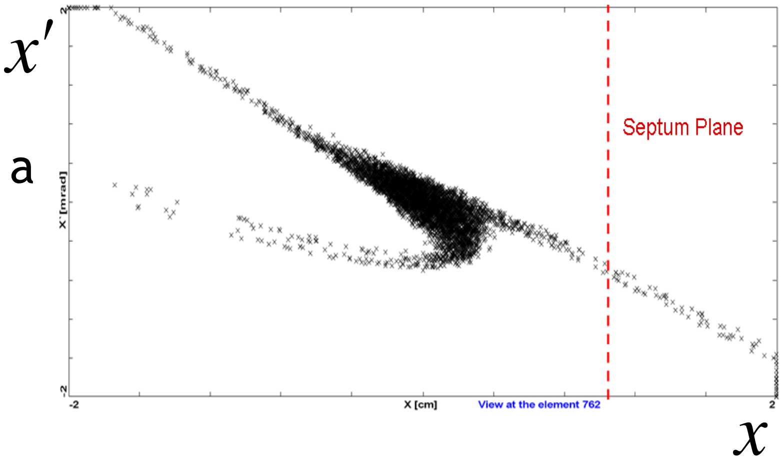
10 MeV/c particle will have a radius of 3 cm in a 1 T field

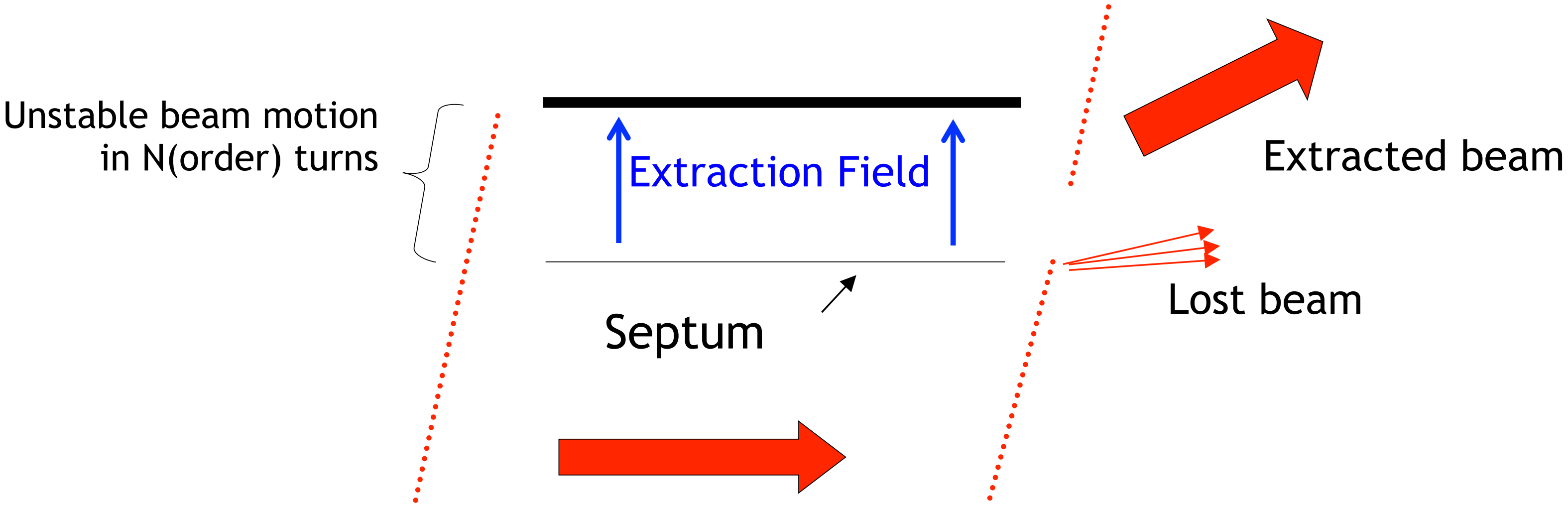
Can be used to resolve charge and momentum! →

$$v_{drift} = \frac{\gamma m}{q}\frac{\hat{R}\times\hat{B}}{RB}\left(v_{\parallel}^{2} + .5v_{\perp}^{2}\right)$$

Resonant Extraction

- Extracting all the beam at once is easy, but we want to extract it slowly over ~60 ms (~35,000 revolutions)
- Use nonlinear (sextupole) magnets to drive a harmonic instability
- Extract unstable beam as it propagates outward
  - Standard technique in accelerator physics




Unstable beam motion
in N(order) turns

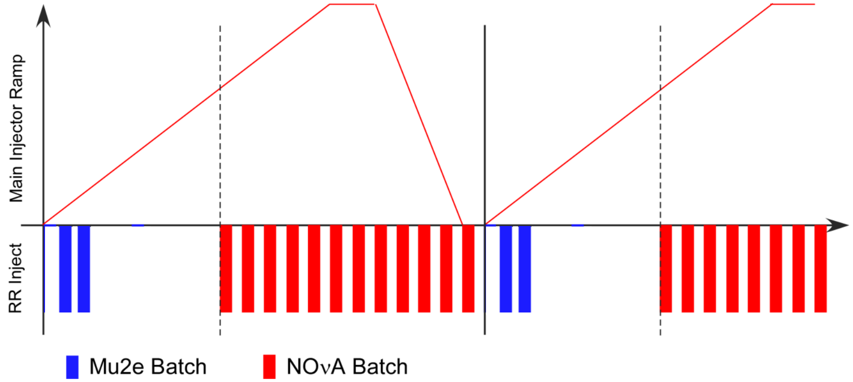
Extracted beam

Lost beam

Septum

Mu2e Spill Structure

1.33 sec Main Injector cycle



- **Detail:**
  - $3\text{x}10^7$ p/bunch
  - 1.7 μsec bunch spacing
  - ~30% duty factor
  - ~$1.2\text{x}10^{20}$ protons year