Mu2e: Search for Muon to Electron Conversion at Fermilab

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Mu2e Student Lunch Talks

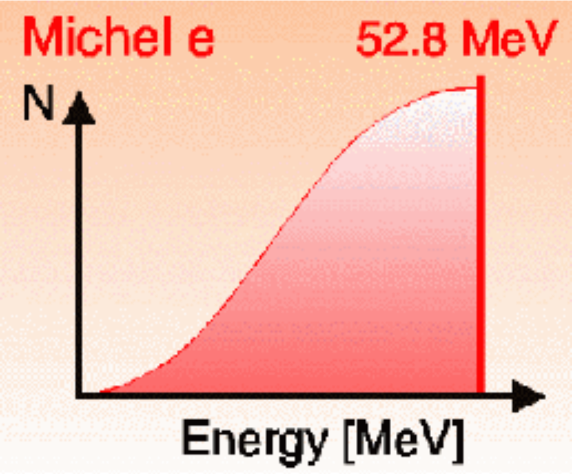
June 22, 2015

Mu2e Student Lunch Talks

- Audience
  - undergrads and incoming graduate students
- Purpose
  - familiarize newcomers with both the underlying physics and the technical details of the Mu2e experiments
- Informal
  - Plan for a short overview of a topic, followed by questions and discussion
  - Later, students can talk about what they're working on.
  - We take requests.

Ancient History

- The muon was originally discovered 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

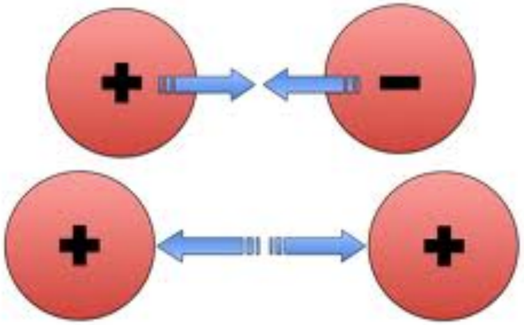


Fast forwarding (and skipping a bunch of stuff)…

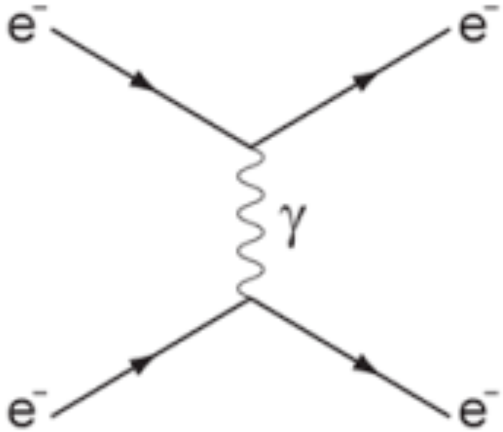
Classical vs. Quantum Interactions (QED)

- Based on the work of Richard Feynman and others, we now view the electric field as the discrete exchange of photons.

Classical picture: charged particles produce "fields", which exert forces on other particles



Quantum picture: charged particles have a probability of exchanging "virtual photons"



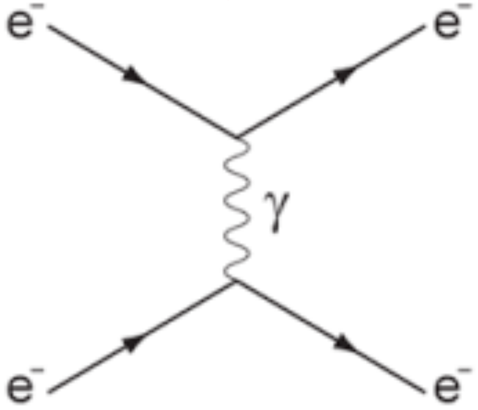
"Feynman Diagram"

- If the probability is high enough, you exchange a lot of photons and quantum → classical again.

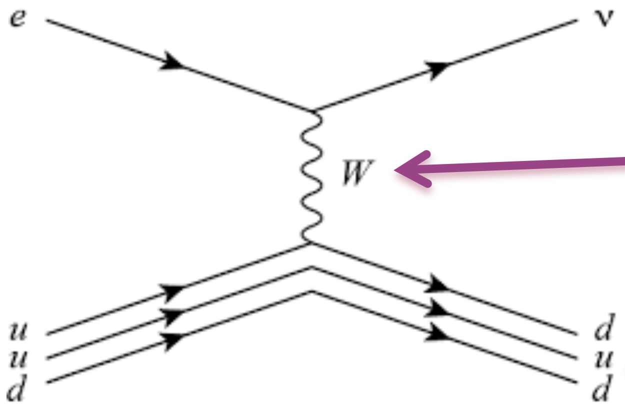
The Rest is History…

- QED became the basis for our models of the other forces.
  - In quantum mechanics, a “force” is something that changes the “state” of a particle, which can sometimes mean changing it into another particle.

QED



Weak Interaction



Neutrino

“W” (like a photon but about 100 times as heavy as the proton!)

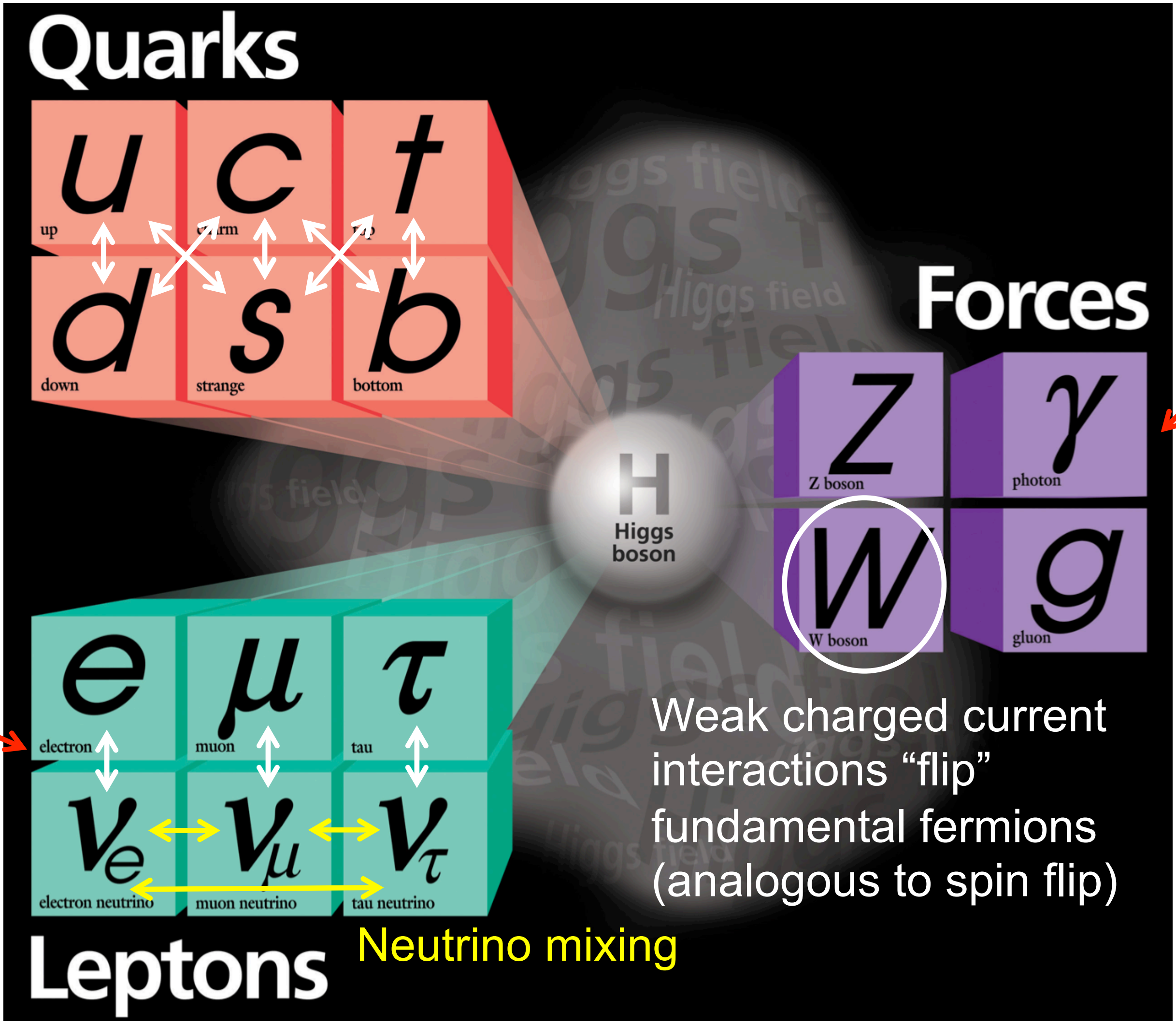
Proton

- And that’s just the beginning…

The Standard Model

Fermions

Bosons



Combine to form hadrons

Mediate interactions

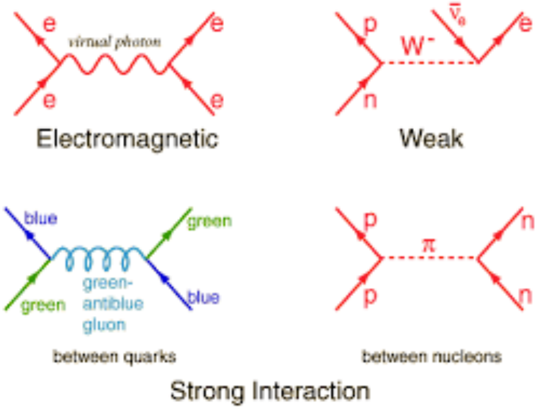
Free

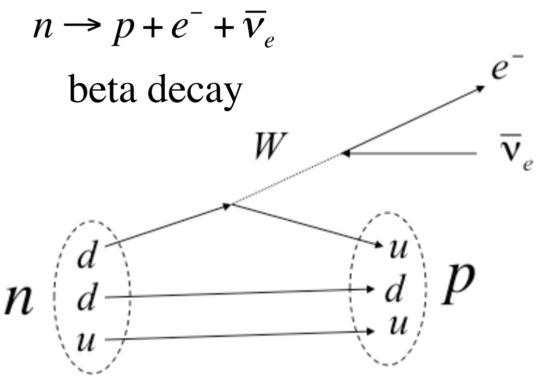
Weak charged current interactions "flip" fundamental fermions (analogous to spin flip)

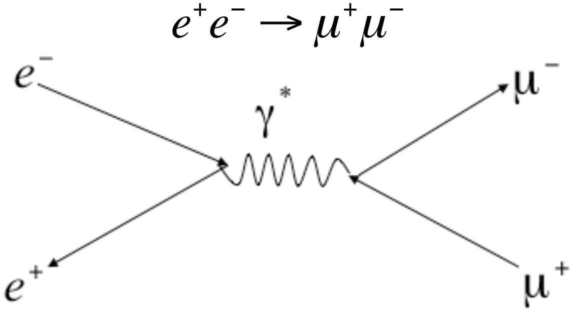
Neutrino mixing

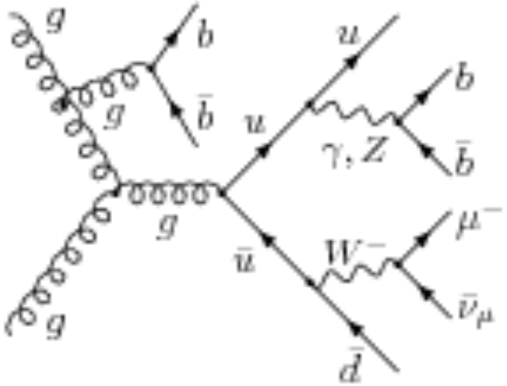
The Standard Model

- We can generalize these Feynman Diagrams and change their orientation to explain every type of particle interaction there is









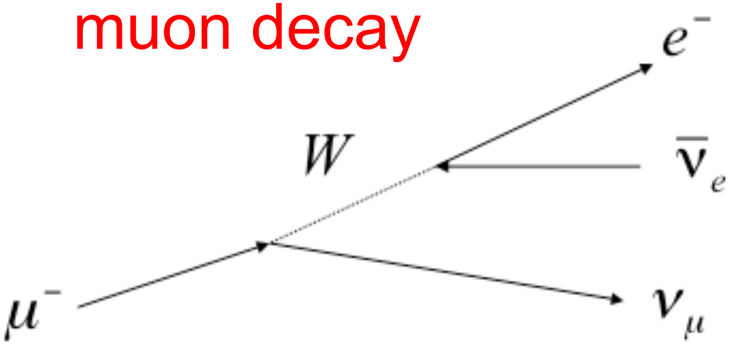
- They’re literally the basis of everything we do here.

Lepton Number and Lepton Flavor Number

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

muon decay

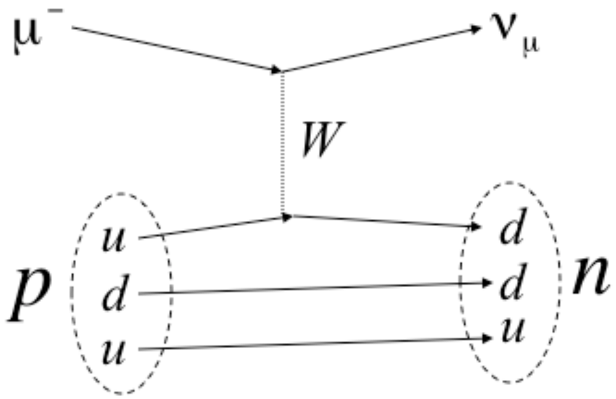
	l	l_e	l_μ
μ^-	1	0	1
total	1	0	1



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

CCQE

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

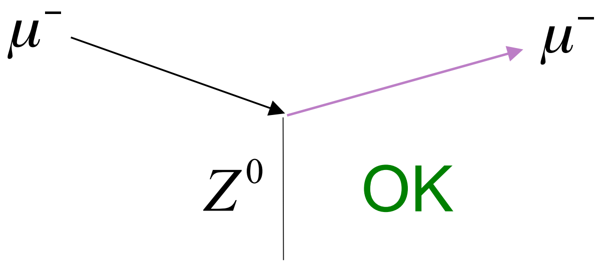


	l	l_e	l_μ
ν_μ	1	0	1
n	0	0	0
total	1	0	1

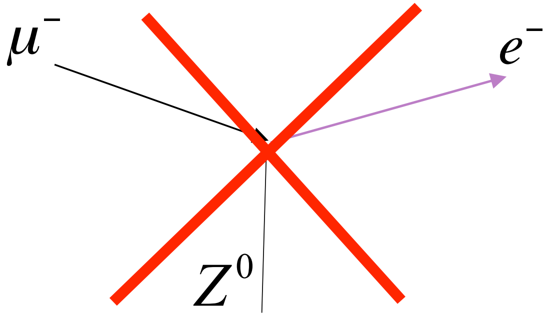
*except in neutrino mixing

Charged Lepton Flavor Violation

Neutral Current Scattering

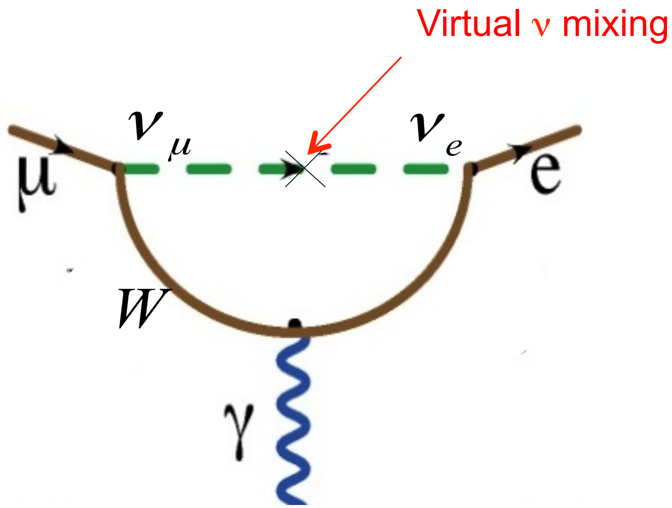


Flavor Changing Neutral Current (FCNC):



- Forbidden in Standard Model

Higher order dipole “penguin”:



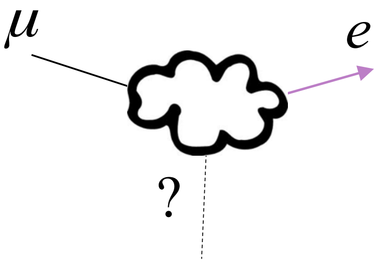
- Observation of neutrino mixing shows this can occur at a *very small* rate
- Photon can be real (μ->eγ) or virtual (μN->eN)
- Standard model branching ration ~$\mathcal{O}(10^{-52})$ (effectively zero)

Beyond the Standard Model

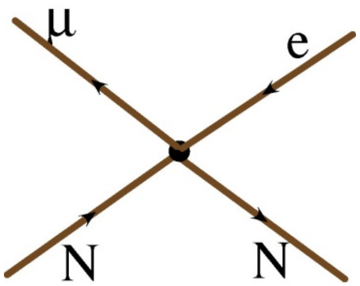
- Because extensions to the Standard Model couple the lepton and quark sectors, Charged Lepton Flavor Violation (CLFV) is a nearly universal feature of such models.
- The fact that it has not yet been observed already places strong constraints on these models.
- CLFV is a powerful probe of multi-TeV 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

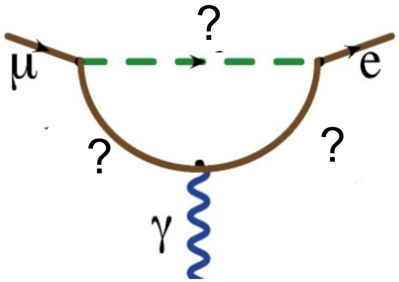


- Mediated by massive neutral Boson, e.g.
  - Leptoquark
  - Z'
  - Composite
- Approximated by "four fermi interaction"

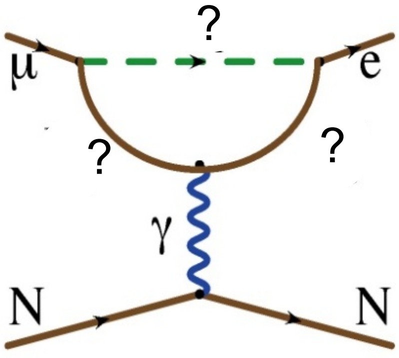


Dipole (penguin)

- Can involve a real photon

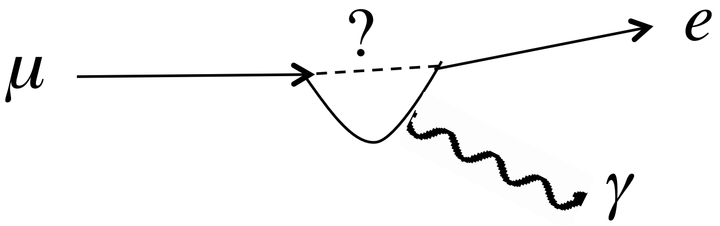


- Or a virtual photon



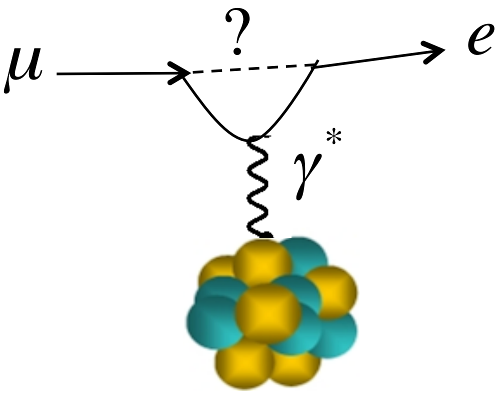
Decay vs. Conversion

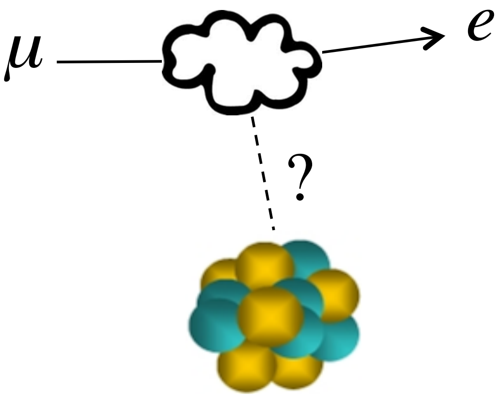
- Only the "dipole"-like reactions can lead to a decay



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

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

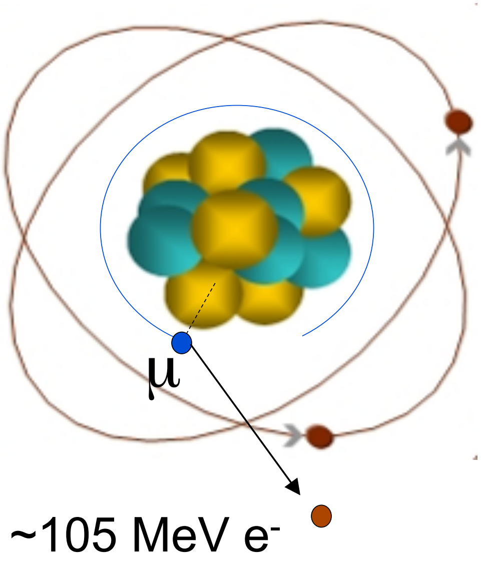




Experimental Signature of μ+N → e+N

- 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

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

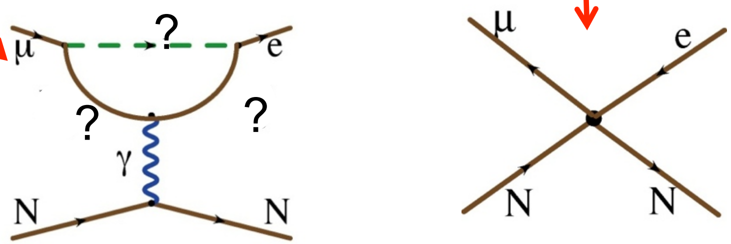


- Similar to μ→eγ, with important advantages:
  - No combinatorial background.
  - Because the virtual particle can be a photon *or* heavy neutral boson, this reaction is sensitive to a broader range of new physics.
- Relative rate of μ→eγ and μN→eN is the most important clue regarding the details of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

μ→e Conversion vs. μ→eγ

- We can parameterize the relative strength of the dipole and four fermi interactions.

$$\boxed{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}} + \boxed{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)}.$$

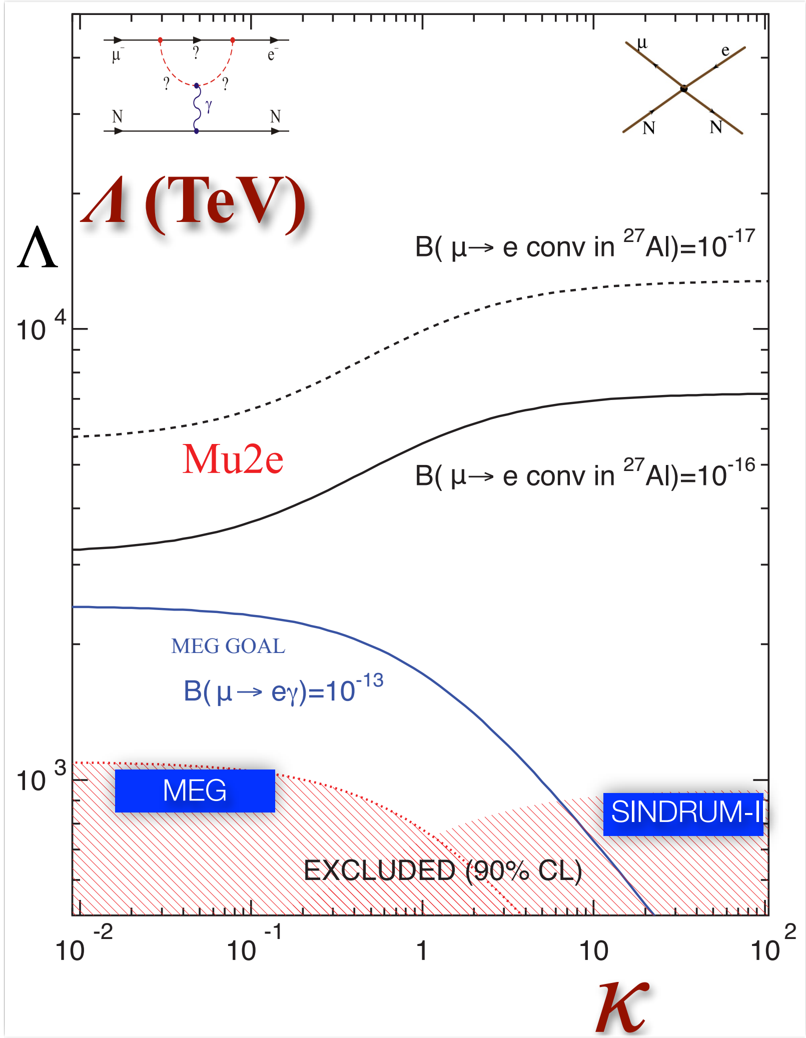


$\Lambda \equiv$ "mass scale" of intermediate particle(s)

$\kappa \equiv$ relative strength of two terms (1 ~ equal)

$$\text{Total rate} \propto \frac{1}{\Lambda^4}$$

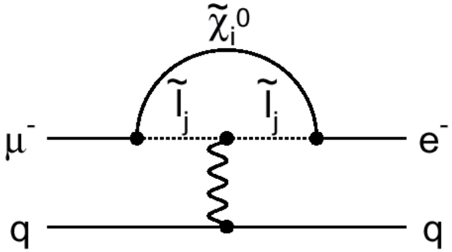
Courtesy: A. de Gouvea

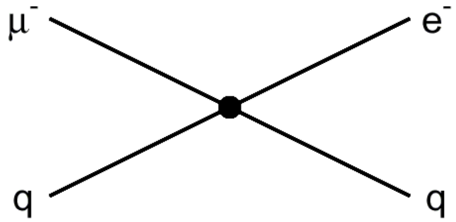


Example Sensitivities*

Supersymmetry

Predictions at 10^{-15}



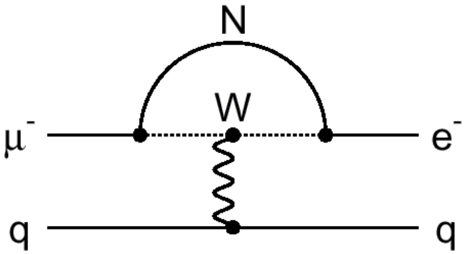


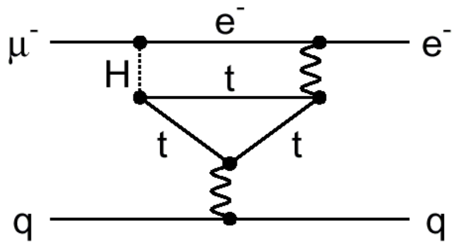
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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





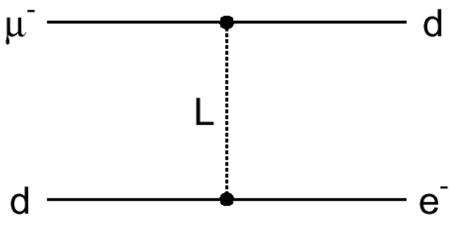
Second Higgs doublet

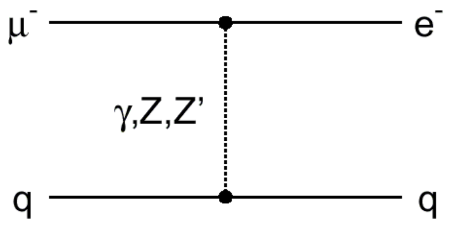
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L =$

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





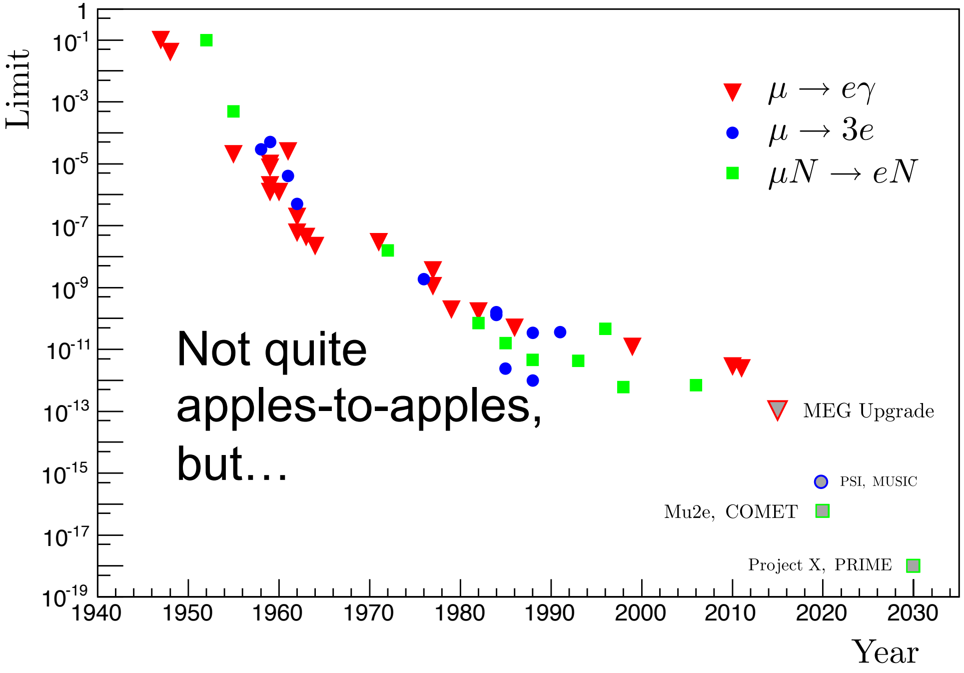
Heavy Z', Anomalous Z coupling

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

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

*After W. Marciano

History of Lepton Flavor Violation Searches



Not quite apples-to-apples, but…

- **Best Limits**
  - $R_{\mu e} < 7\times10^{-13}$ (Sindrum-II 2006)
  - $Br(\mu \rightarrow e\gamma) < 2.4\times10^{-12}$ (MEG 2011)
  - $Br(\mu \rightarrow 3e) < 1\times10^{-12}$ (Sindrum-I 1988)

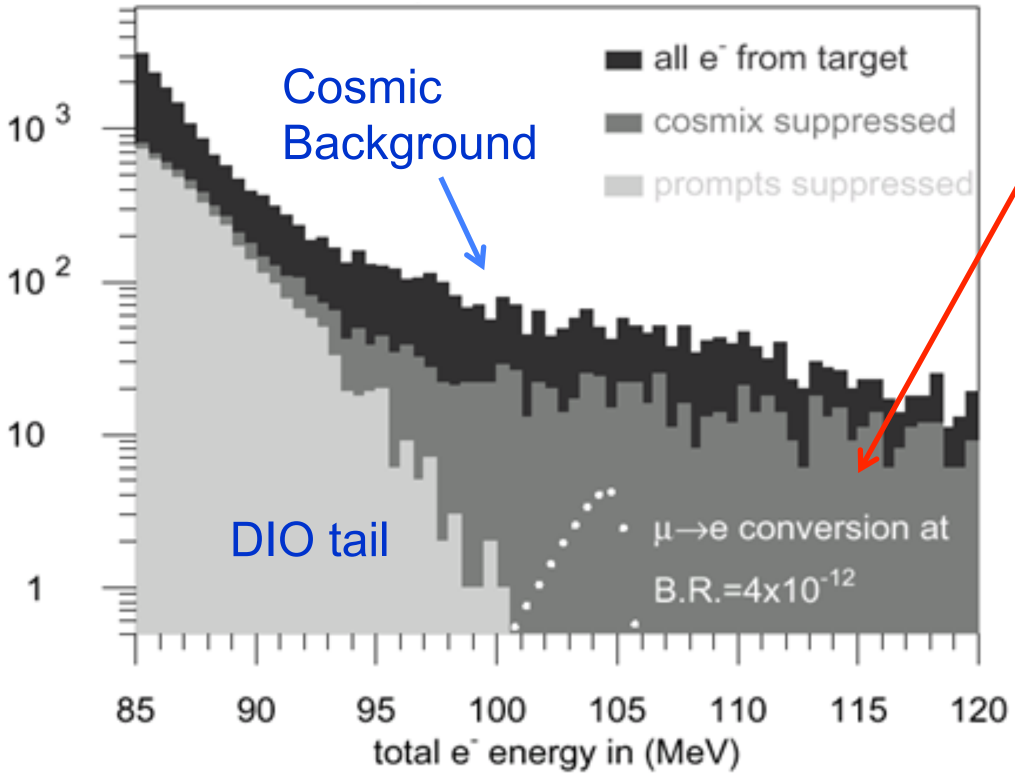
Mu2e will measure:

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

Goal: single even sensitivity of $R_{\mu e}$=“a few”$\times10^{-17}$

Limits of Previous Experiments

μ−>e Conversion: Sindrum II

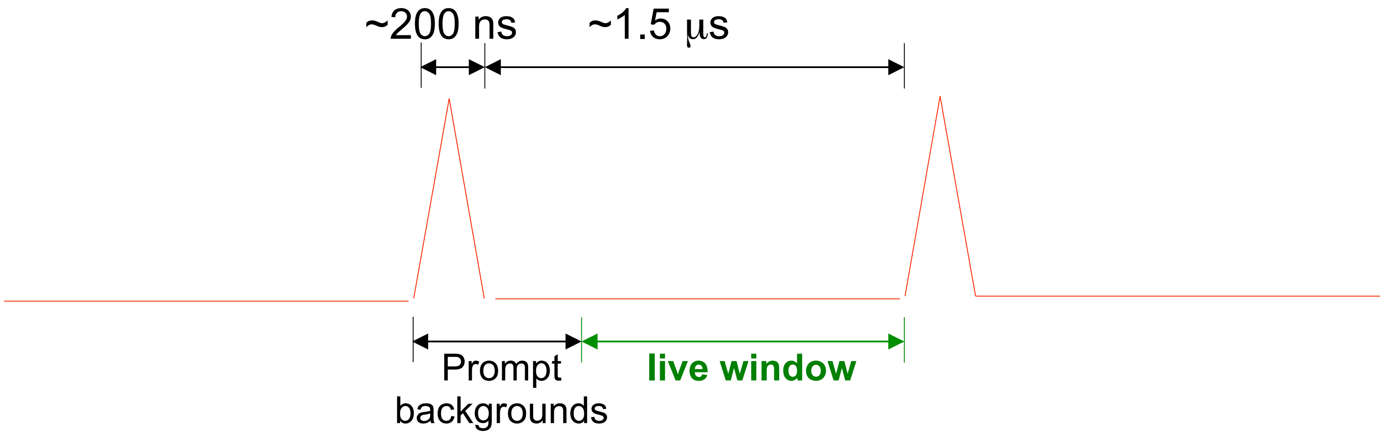


$$\boxed{R_{\mu e} \equiv \frac{\Gamma\left(\mu^- Ti \rightarrow e^- Ti\right)}{\Gamma\left(\mu^- Ti \rightarrow \text{capture}\right)} < 4.3\times10^{-12}}$$

- Most backgrounds are prompt with respect to the beam
  - Caused either by production or capture or muons
- 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.

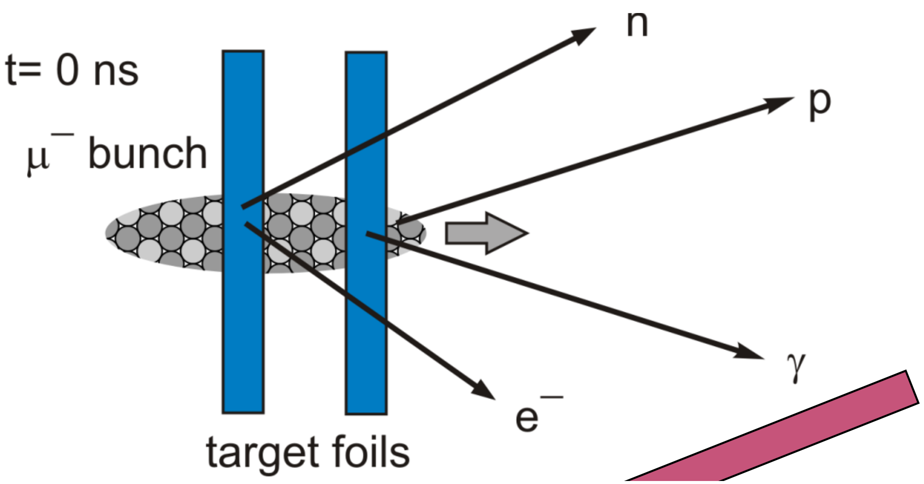
Mu2e (MELC) Experimental Technique

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



- 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

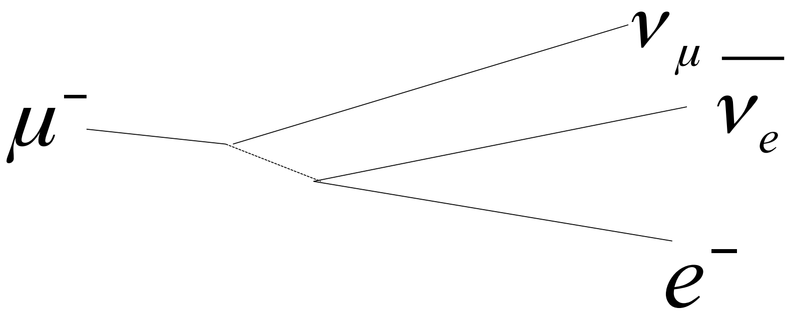
Signal



- Muons from bunch are captured on nuclei in target
- Wait for prompt backgrounds to subside
- Look for muons to decay (or convert!)

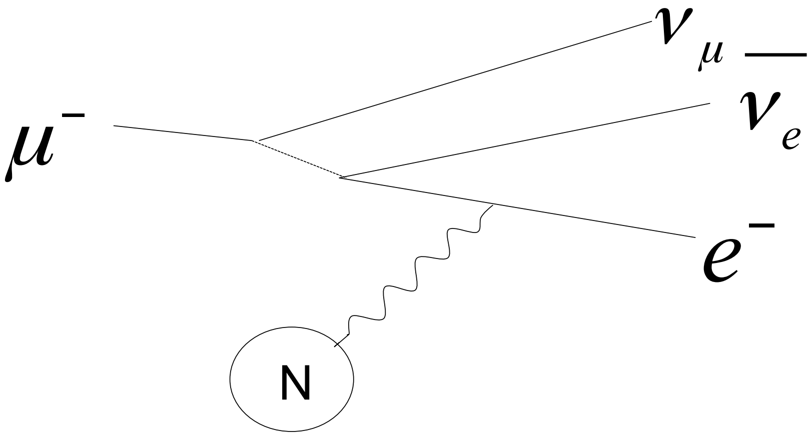
Our Biggest Issue: Decay in Orbit (DIO)

In-flight Decay:



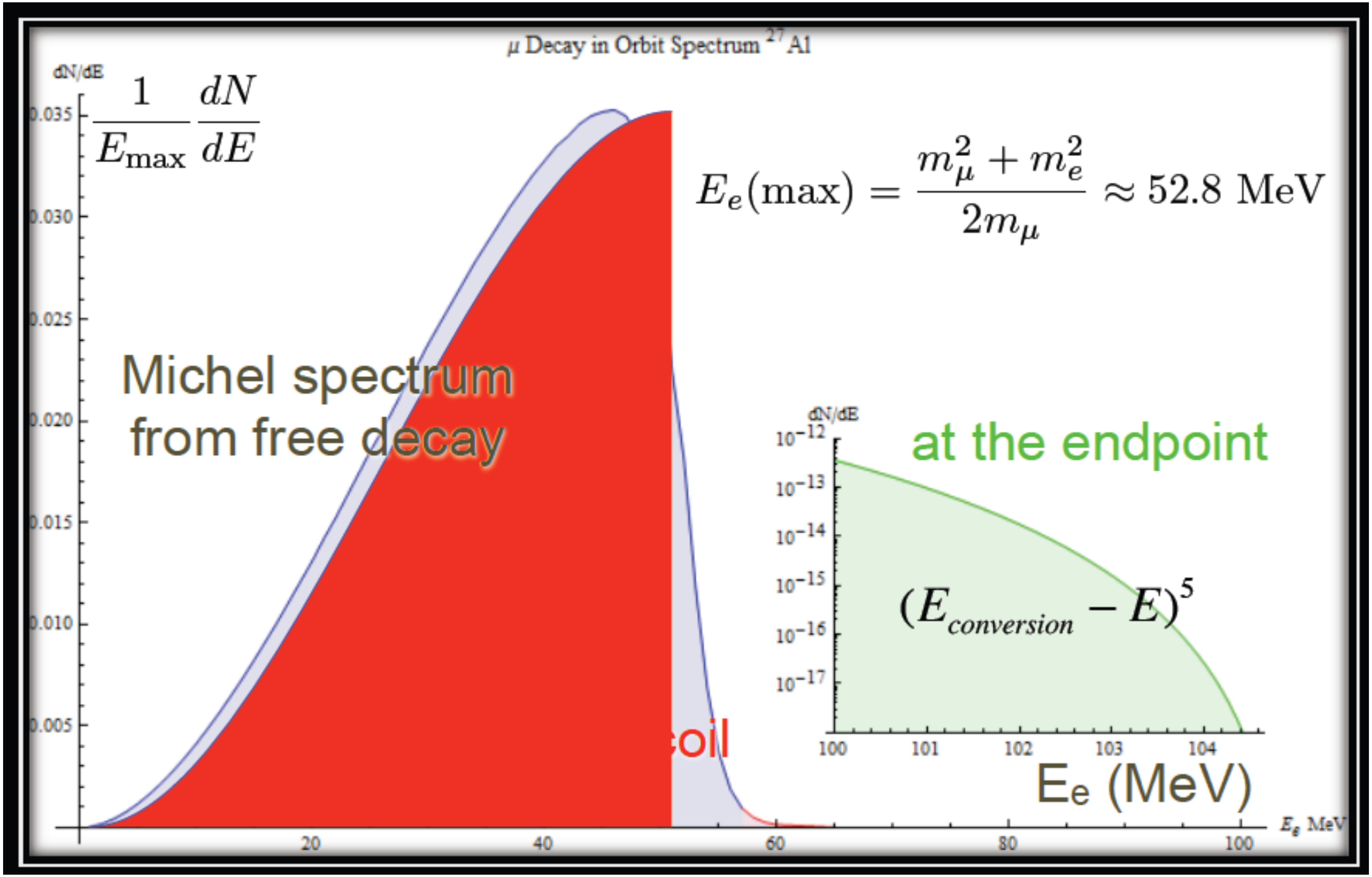
- Very high rate
- Peak energy 52 MeV
- Must design detector to be very *insensitive* to these.

Coherent DIO:



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

DIO Spectrum



$$\frac{1}{E_{\max}}\frac{dN}{dE}$$

$$E_e(\max) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

Michel spectrum from free decay

at the endpoint

$$(E_{conversion} - E)^5$$

Ee (MeV)

Choosing the Capture Target

- Determining the Z dependence is very important, but
- Lifetime is *shorter* for high-Z
  - Decreases useful live window
- Also, need to avoid background from radiative muon capture

$$\mu N \rightarrow \nu_\mu N'\gamma$$

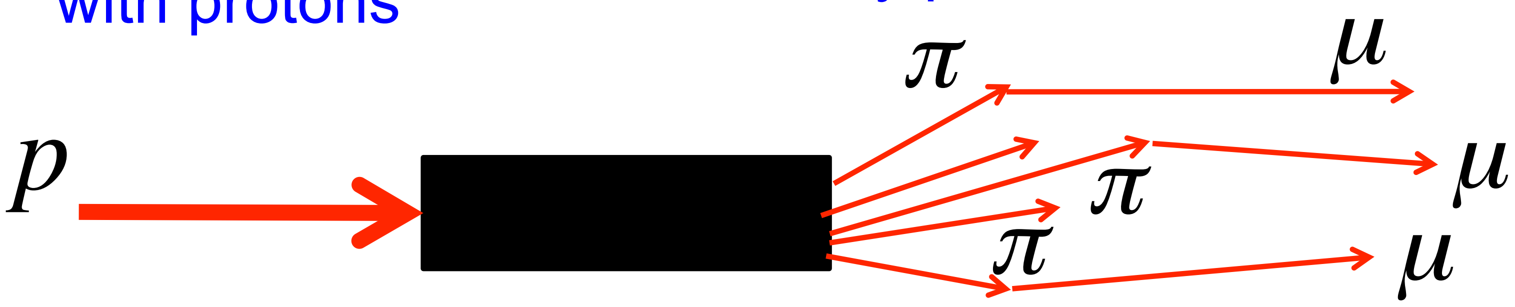
$$\hookrightarrow e^+ \boxed{e^-}$$

⇒Want M(Z)-M(Z-1)
< signal energy

⇒Aluminum is nominal 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

How do we make muons?



Hit a target with protons

This produces mostly pions

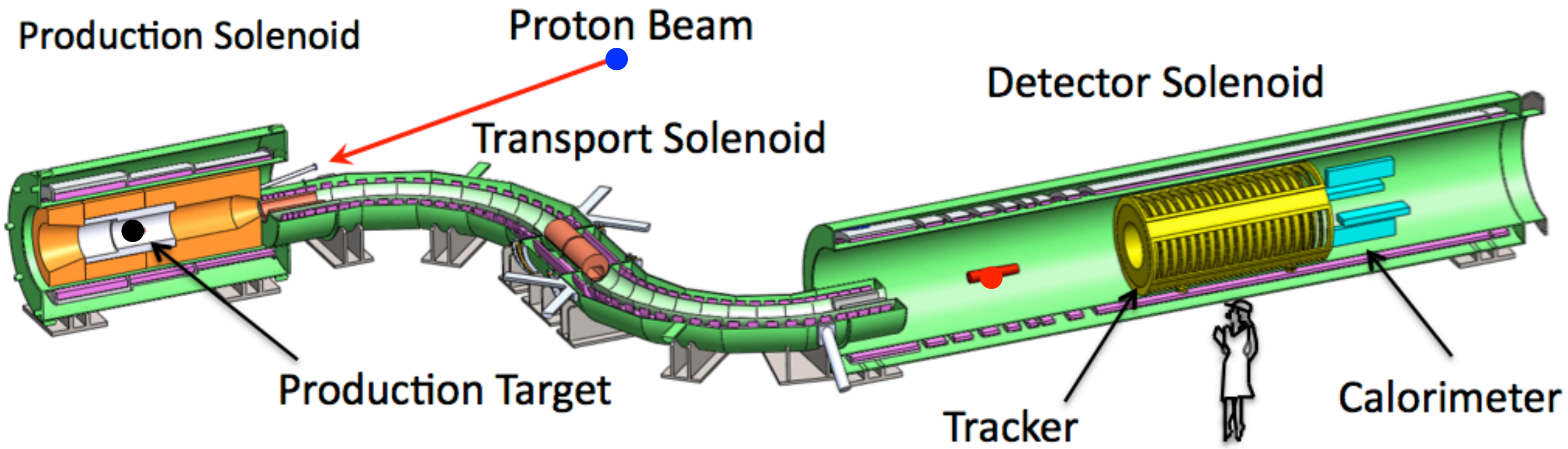
These quickly decay to muons

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau_{\mu^\pm} = 2.2\ \mu\text{s}$$

Muons go much further

Muon Beam Line and Mu2e Detector

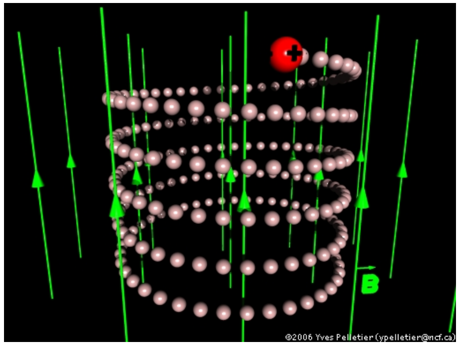


- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on Aluminum 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 $E \sim m_\mu c^2$

Review: Particle Motion in a Solenoidal Field

- Generally, particles move in a helical trajectory

$$\rho = \frac{p}{qB};\ \rho[m] = \frac{p[MeV/c]/299}{B[T]}$$



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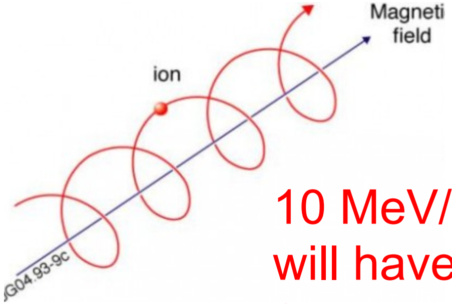
- For high momentum particles, the curvature is used to measure the momentum
- Low momentum particles are effectively “trapped” along the field lines



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

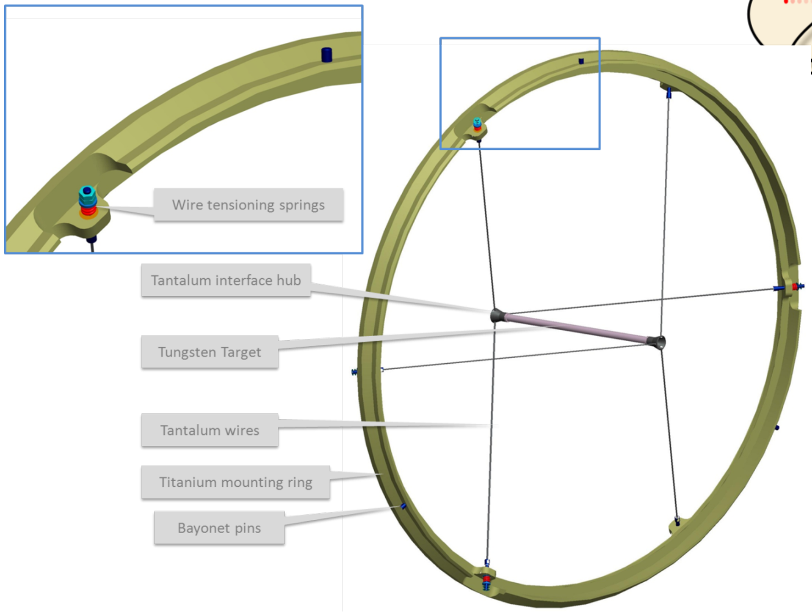
- A particle trapped along a *curved* solenoidal field will drift out of the plane of curvature with a velocity

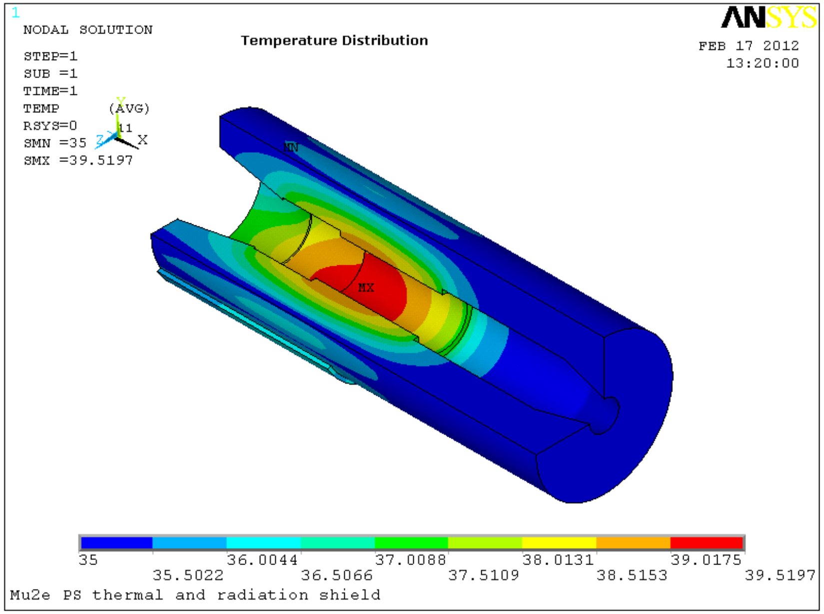
$$v_{drift} = \frac{\gamma m}{q}\frac{\hat{R}\times\hat{B}}{RB}\left(v_{\parallel}^2 + .5v_{\perp}^2\right)$$

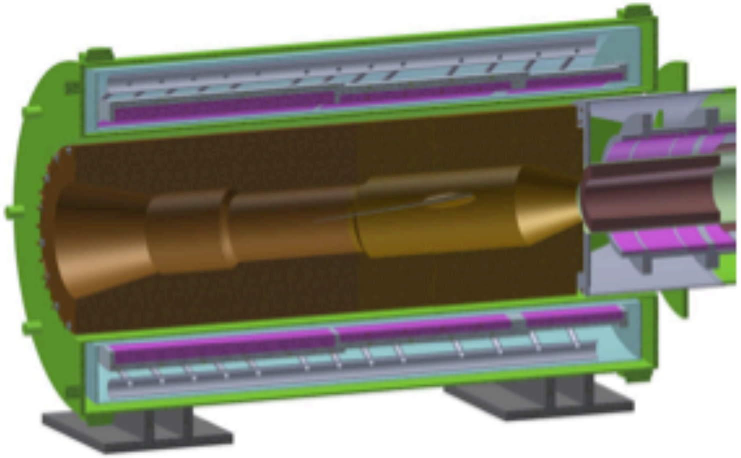
Can be used to resolve charge and momentum!

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

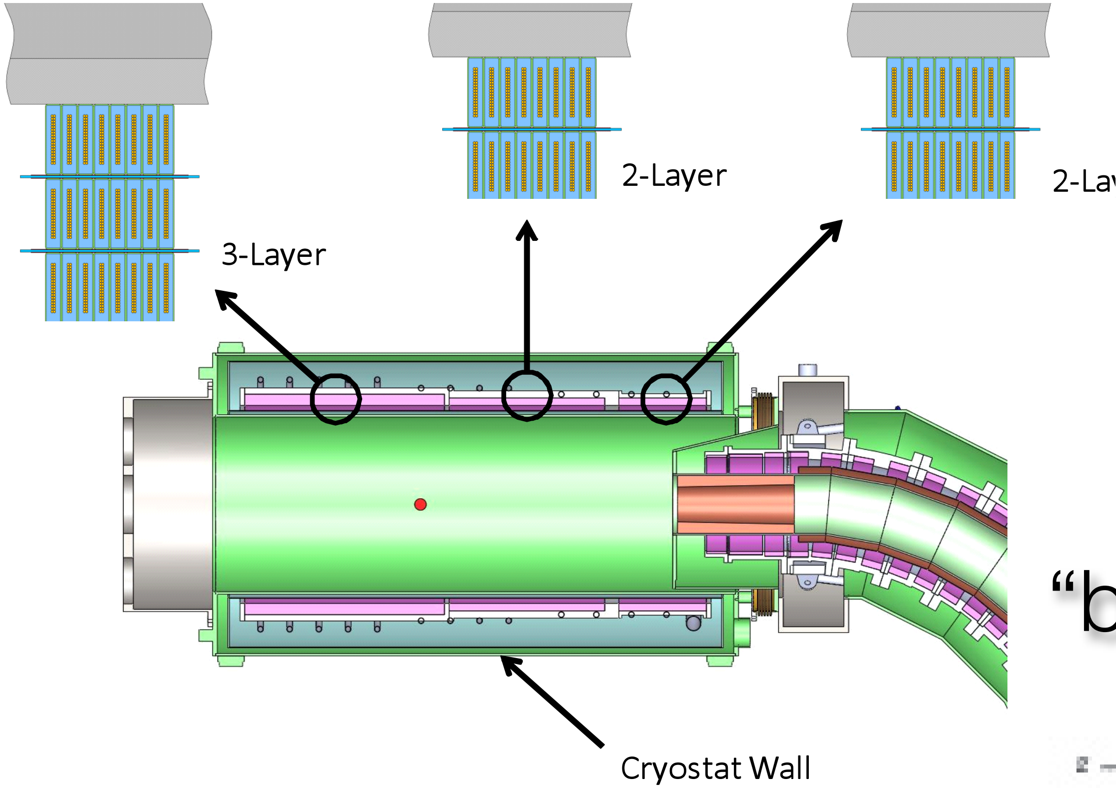




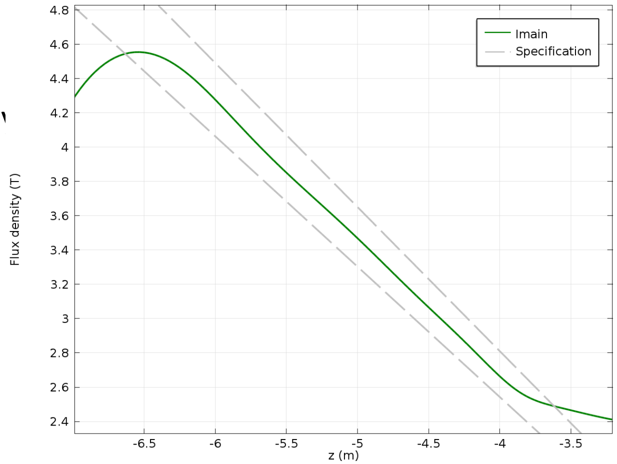


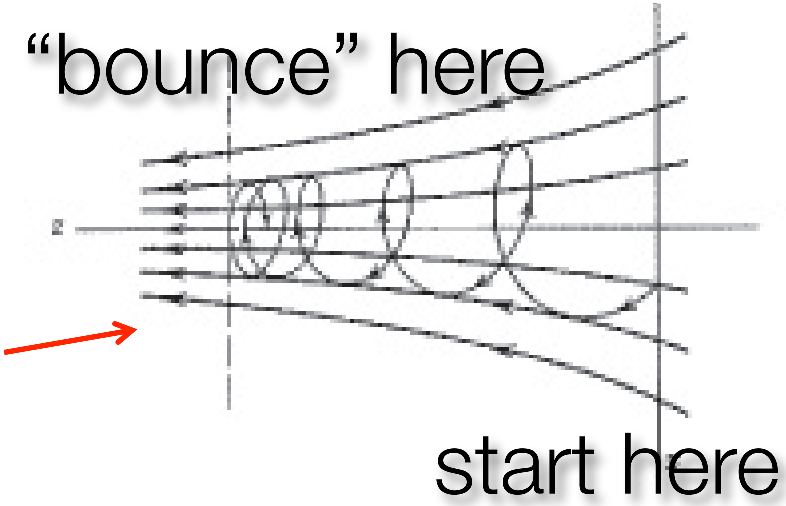
Production Solenoid

- Axially graded ~5 T solenoid captures low energy backward and *reflected* pions and muons, transporting them toward the stopping target



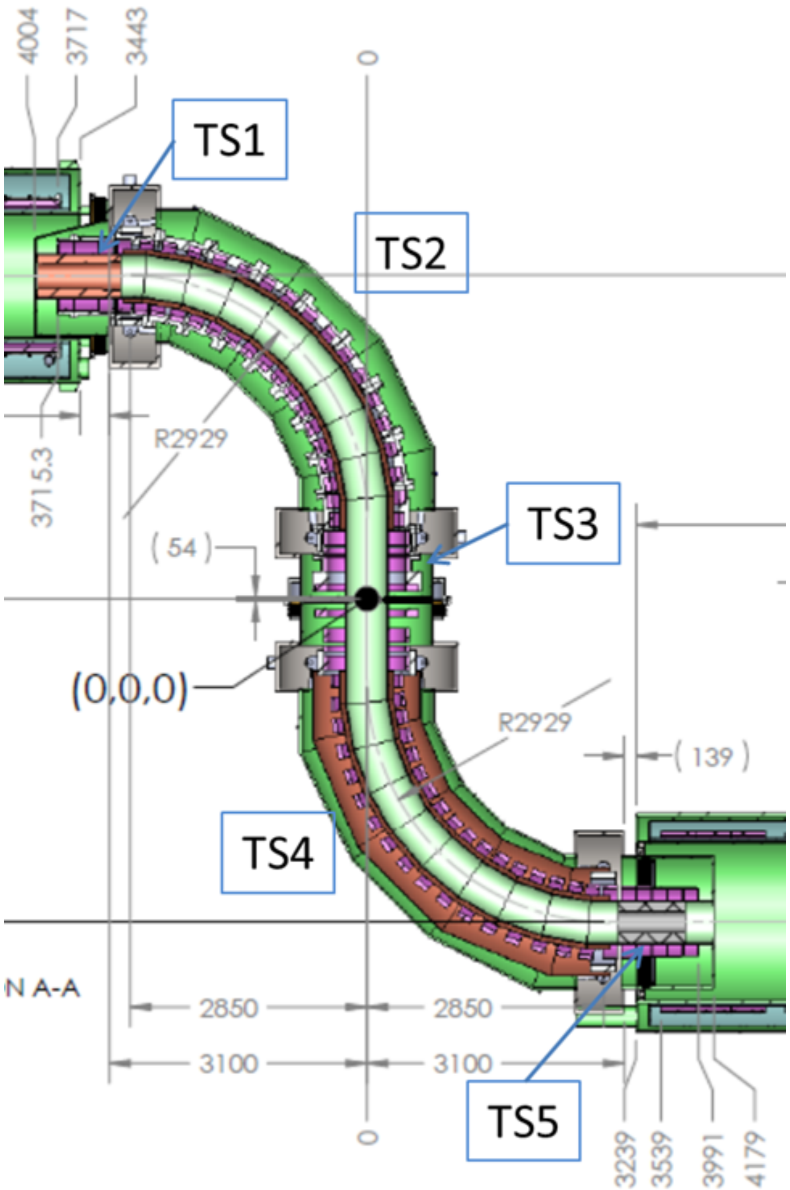
Magnetic Gradient



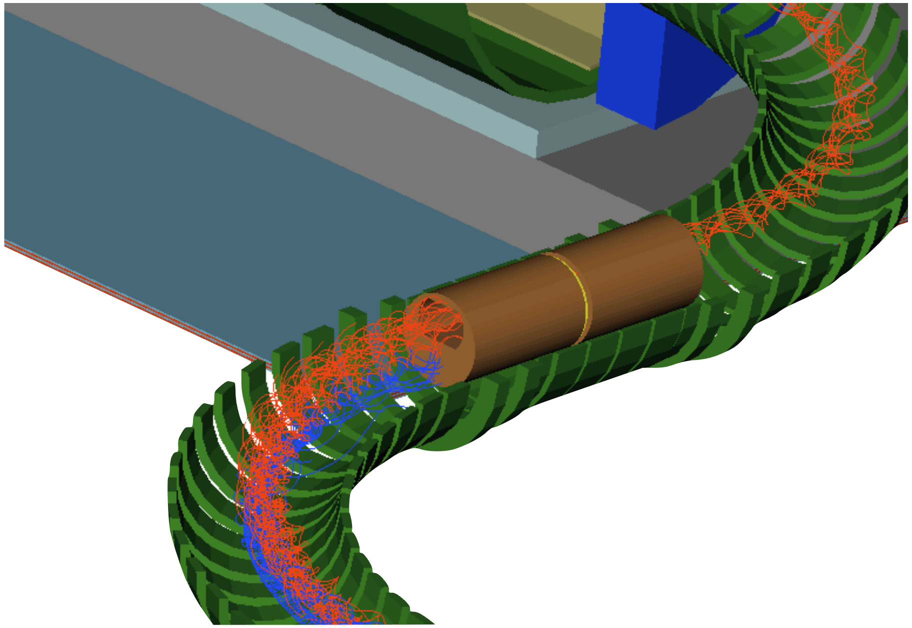


Magnetic reflection (pinch confinement)

Transport Solenoid

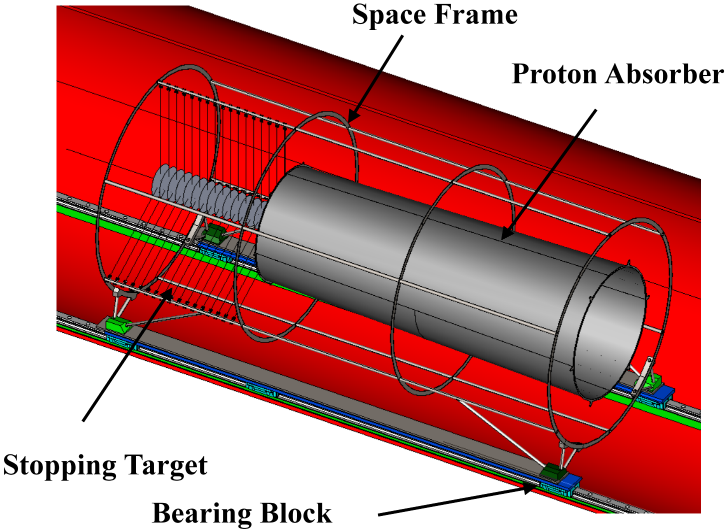


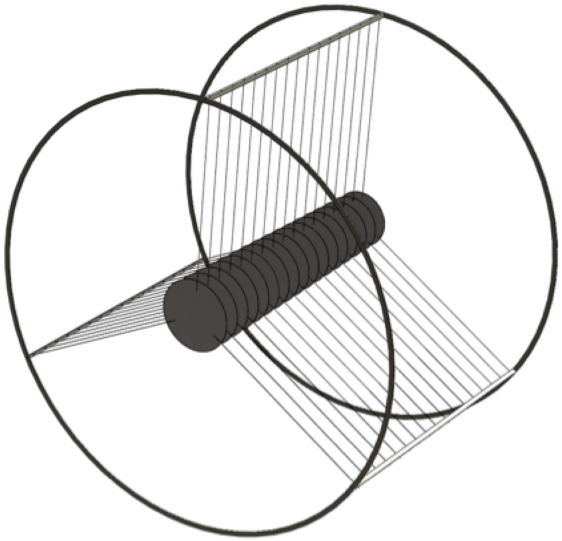
- Transports muons from production target to capture target
- Curved solenoid eliminates line-of-sight backgrounds
- Collimator in center selects low momentum negative muons
  - *RxB* drift causes sign/momentum dependent *vertical* displacement



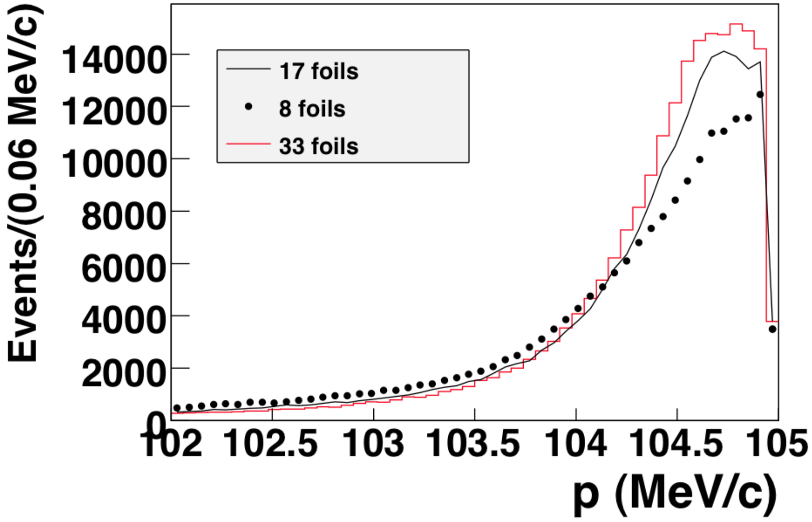
Stopping (capture) Target

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



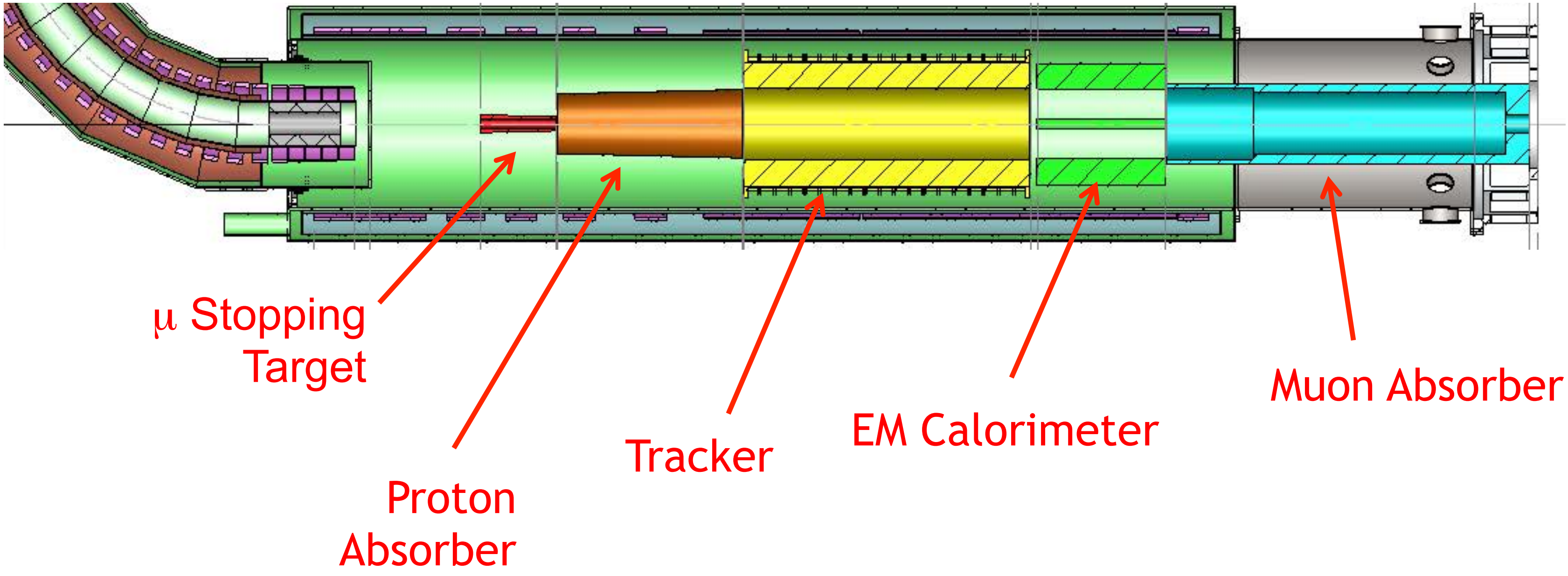


Conversion electron spectrum:

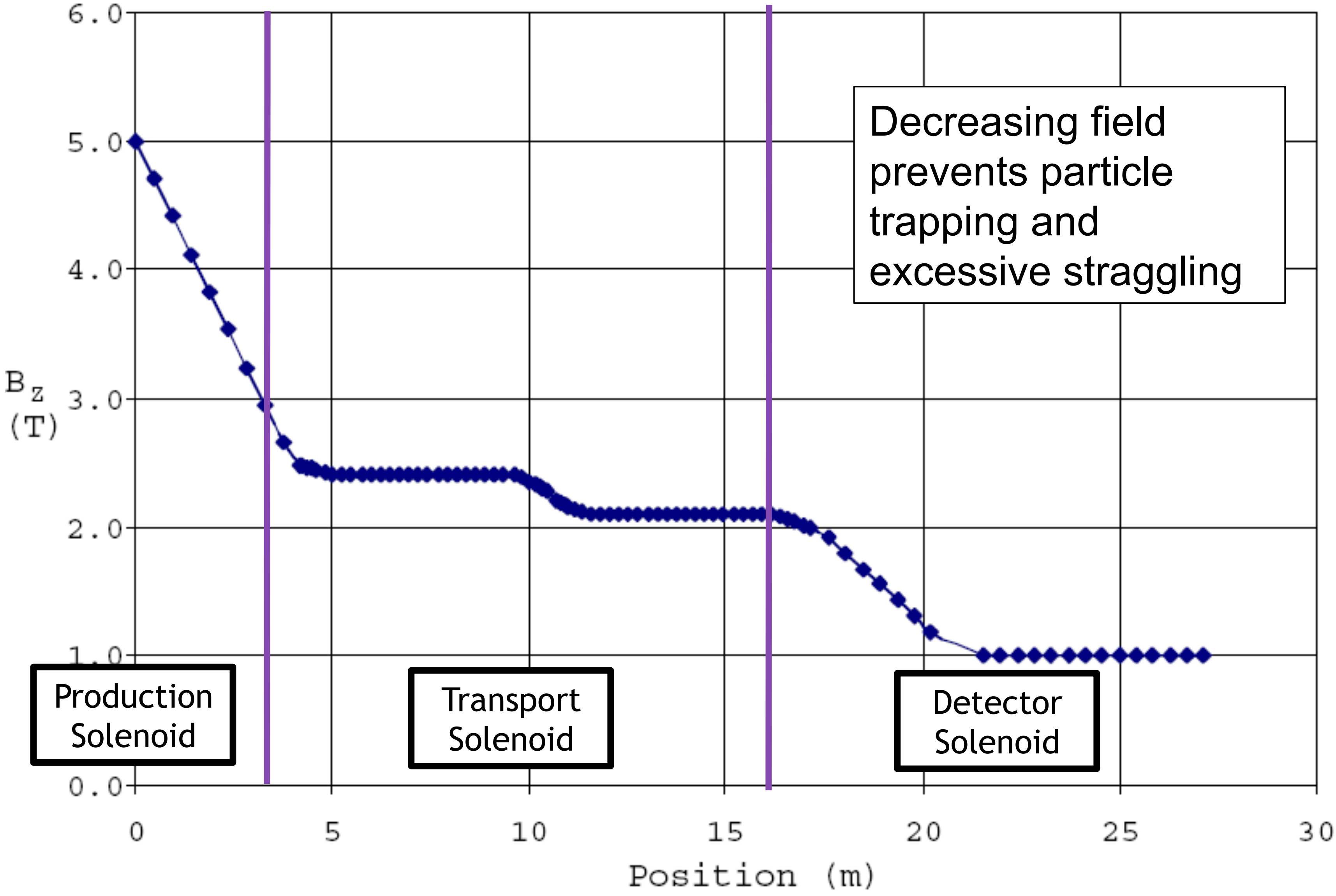


Detector and Detector Solenoid

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



Magnetic Field Gradient



Decreasing field prevents particle trapping and excessive straggling

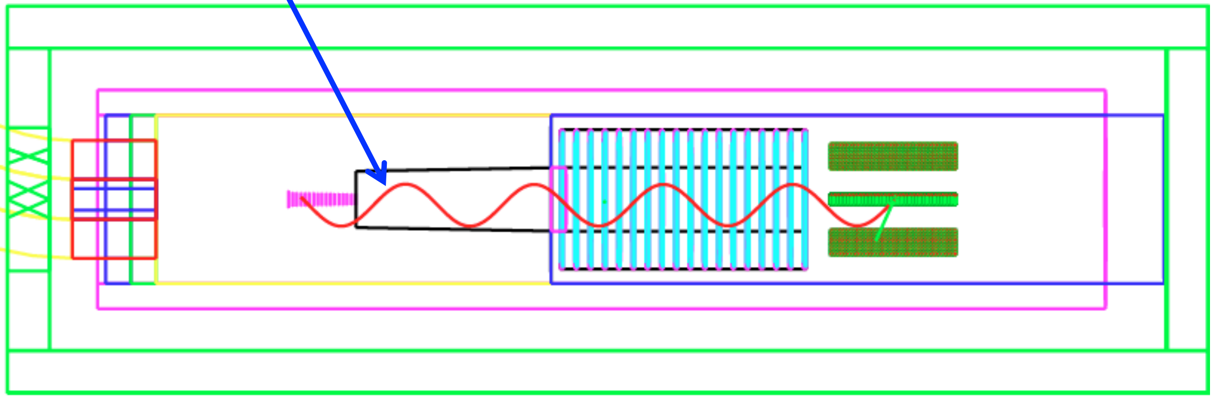
Production Solenoid

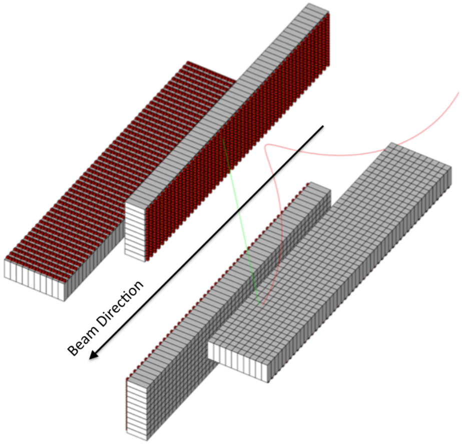
Transport Solenoid

Detector Solenoid

Particle Detector

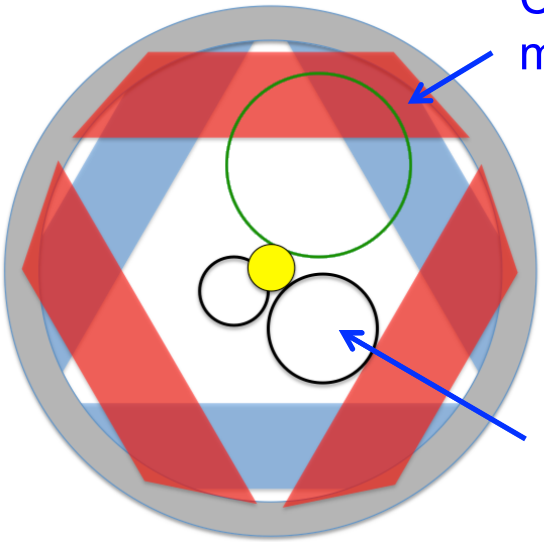
Helical trajectory





Electromagnetic Calorimeter to tag electrons

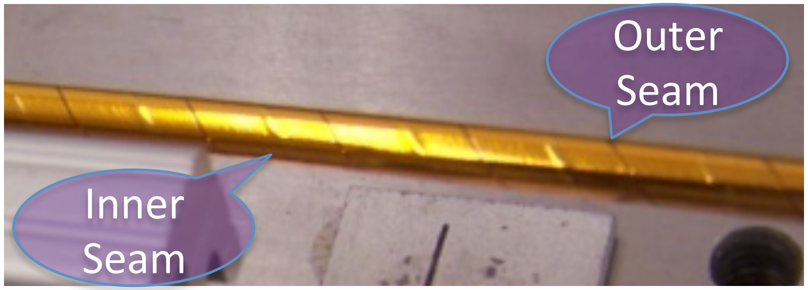
Conversions hit multiple planes.

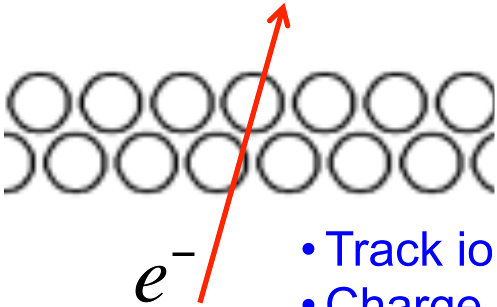


Most decays (p_T<53 MeV/c) go down the middle (vacuum)

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" (21,600 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

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
October 2007	Mu2e letter of intent submitted to Fermilab
Fall 2008	Mu2e Proposal submitted to Fermilab
November 2008	Stage 1 approval. Formal Project Planning begins
November 2009	DOE Grants CD-0
2013	DOE Grants CD-1
2015	DOE Grants CD-2/3b

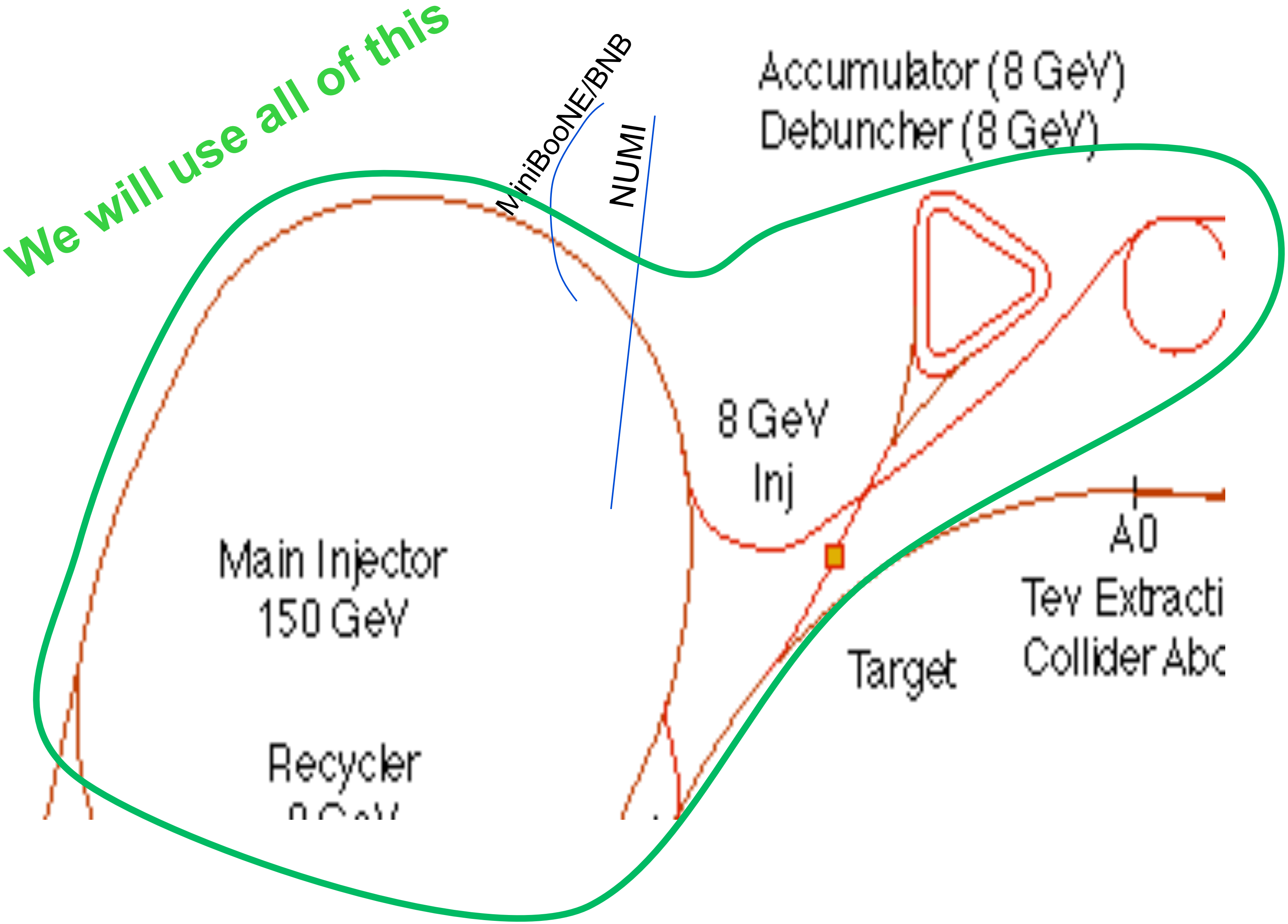
Start civil and magnet construction

Context (evolving slide)

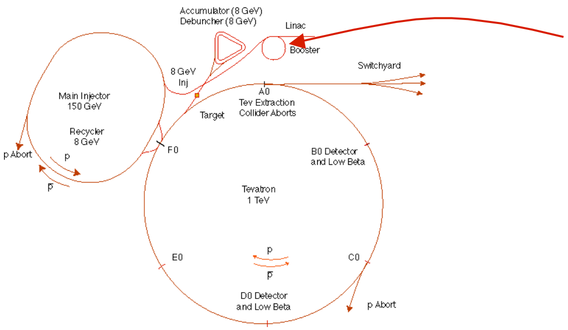
- Fermilab
  - Built ~1970
    - 200 GeV proton beams
    - Eventually 400 GeV
  - Upgraded in 1985
    - 900GeV x 900 GeV p-pBar collisions
    - Most energetic in the world ~~ever since~~ until recently
  - Upgraded in 1997
    - Main Injector-> more intensity
    - 980 GeV x 980 GeV p-pBar collisions
    - Intense neutrino program
  - ~~For awhile~~ ~~Soon~~ ~~the *second* most powerful collider~~
    - What next???

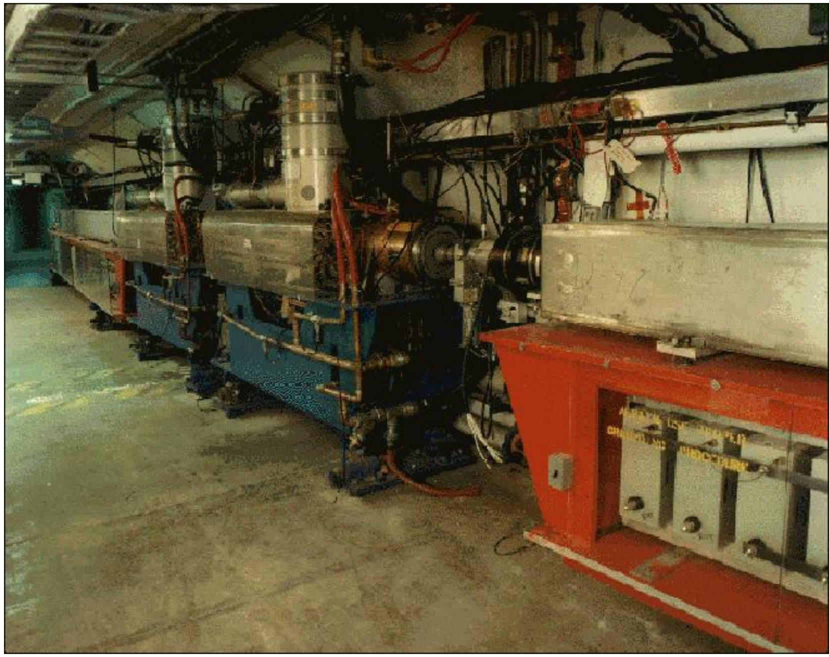
- With the LHC now the highest energy collider, Fermilab must focus on different types of physics.

The Fermilab Accelerator Complex



Booster

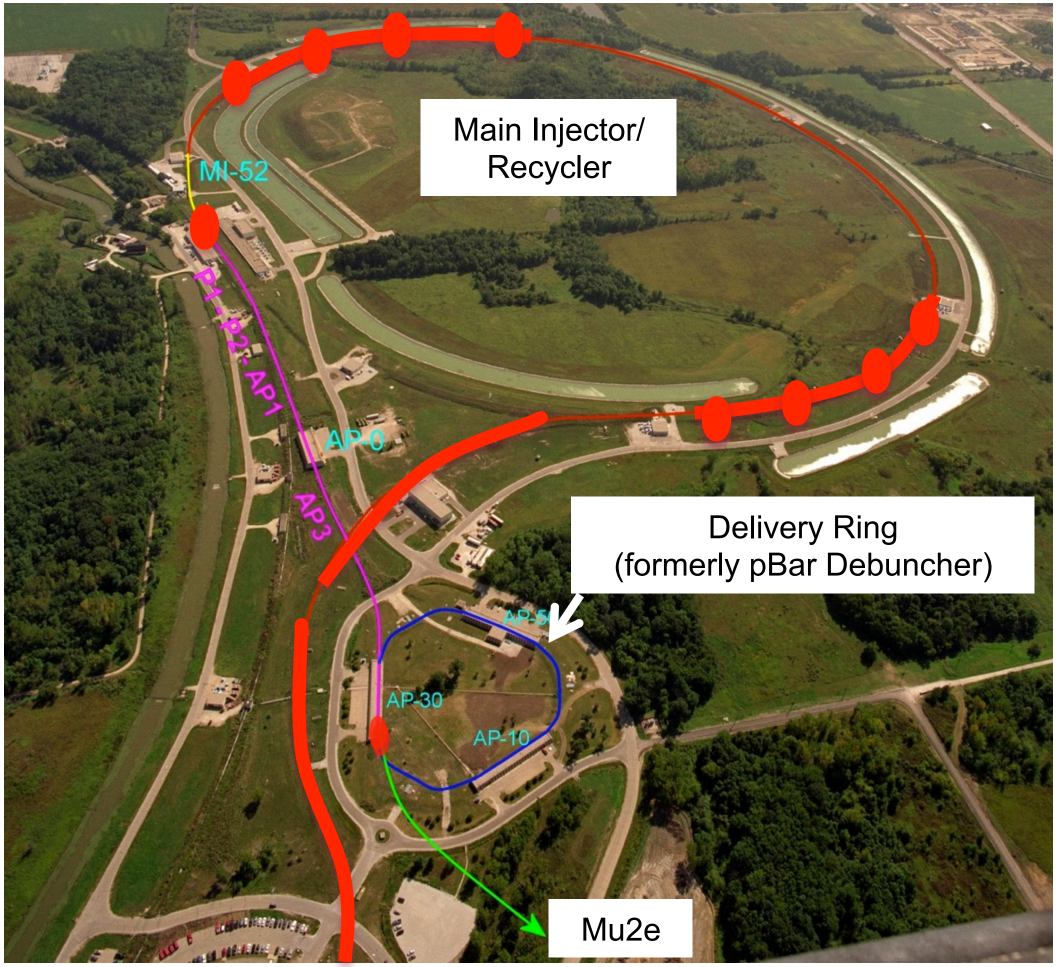




- Accelerates the 400 MeV beam from the Linac to 8 GeV
  - Operates in a 15 Hz offset resonant circuit
    - Cannot make required beam structure
    - That’s why MECO wasn’t proposed there
  - Sets fundamental clock of accelerator complex
- More or less original equipment
  - 40+ years old
- Supplying beam to neutrino program and Mu2e will require ~doubling output
  - Hardware limits ➔ Improve RF system
  - Radiation limits ➔ Improve acceleration efficiency

➔ “Proton Improvement Plan” (whole separate talk)

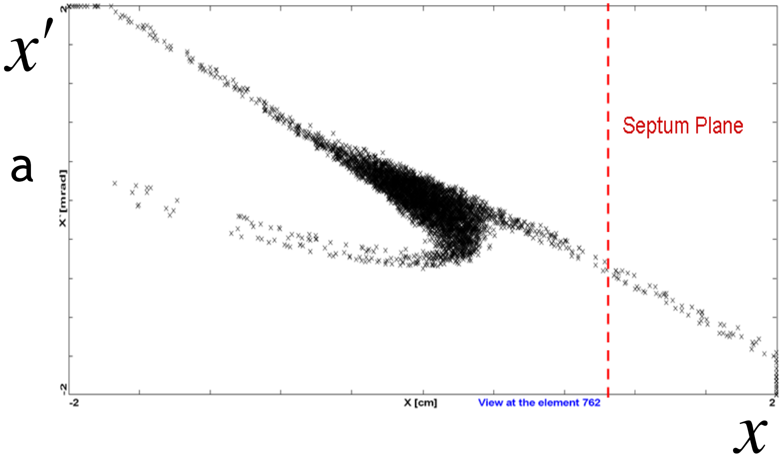
Mu2e Proton Delivery

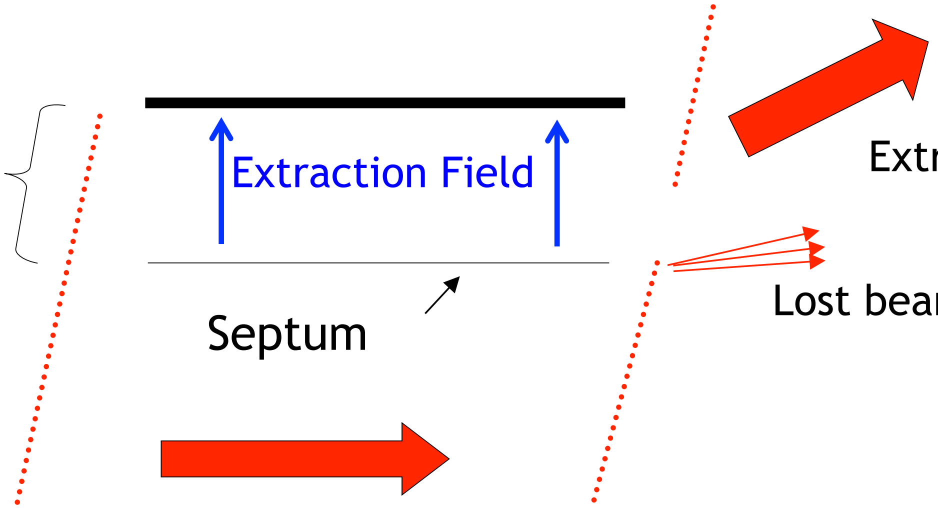


- One Booster “batch” is injected into the Recycler (8 GeV storage ring).
  - $4\text{x}10^{12}$ protons
  - 1.7 μsec long
- It is divided into 4 bunches of 10^{12} each
- These are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As a bunch circulates, it is resonantly extracted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

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

Extraction Field

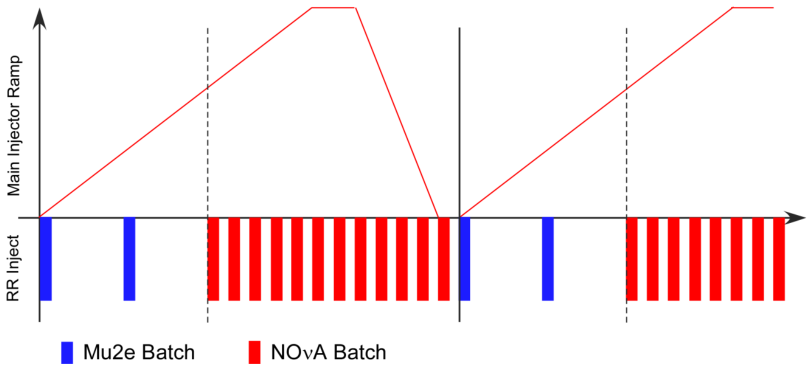
Septum

Extracted beam

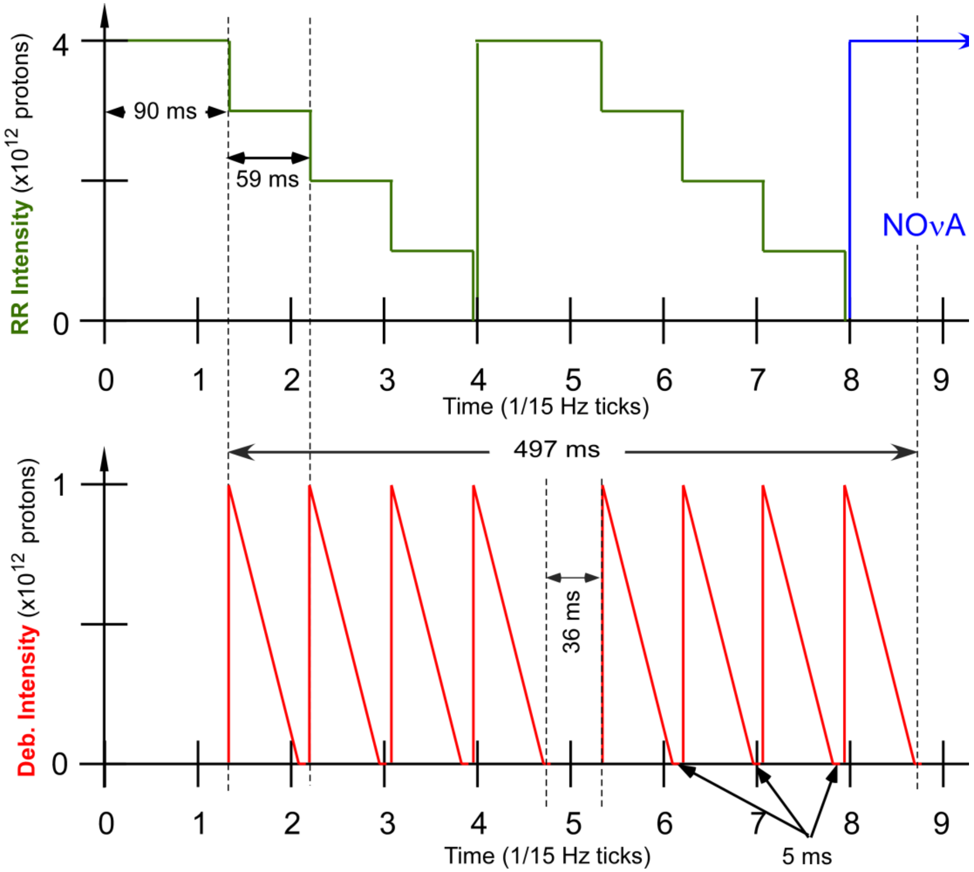
Lost beam

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

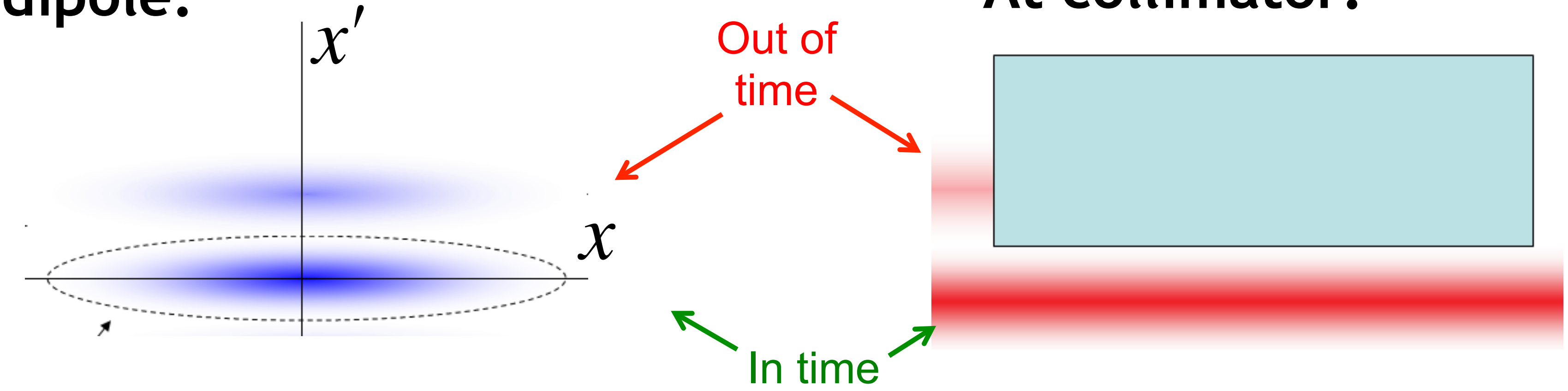


Beam line extinction

- 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!

At dipole:

At collimator:



Out of time

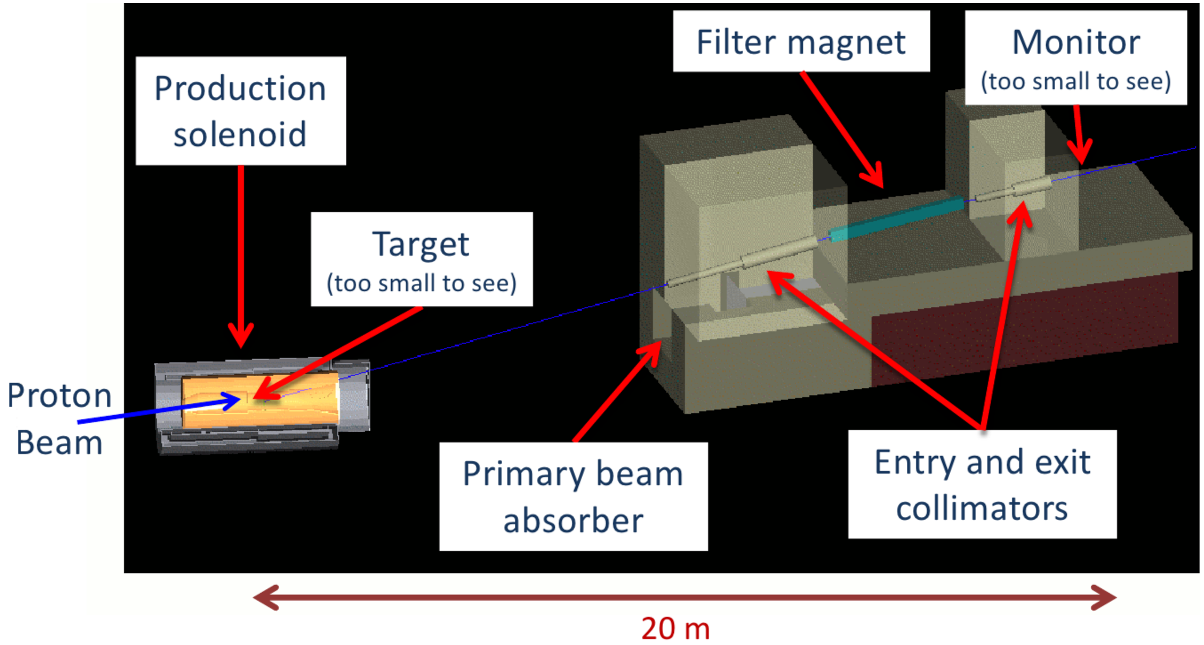
In time

- Use resonant dipoles at two frequencies
  - ½ bunch frequency to sweep out of time beam into collimators
  - High harmonic to reduce motion during transmission window

Extinction Monitor

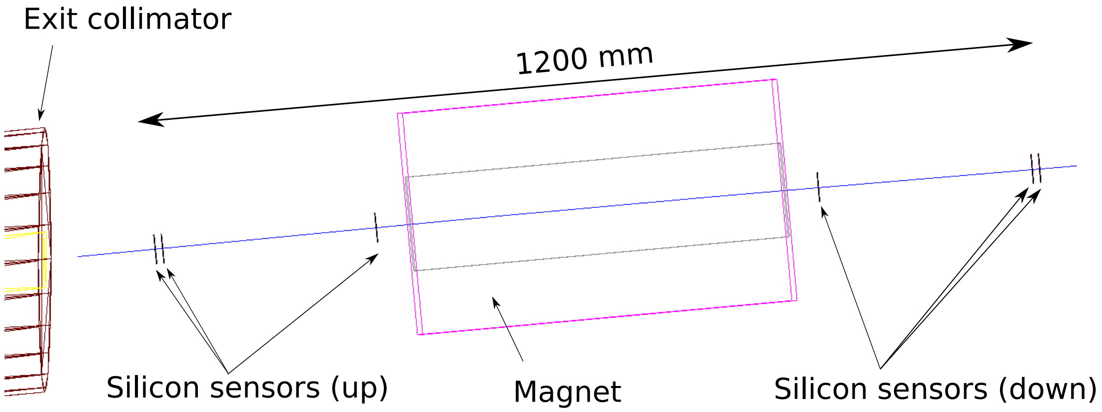
- Must measure extinction to 10^{-10} precision
  - Roughly 1 proton every 300 bunches!
- Monitor sensitive to single particles not feasible
  - Would have to be blind to the $3\text{x}10^{7}$ particles in the bunch.
- Focus on statistical technique
  - Design a monitor to detect a small fraction of 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 one hour.

Extinction Monitor Design



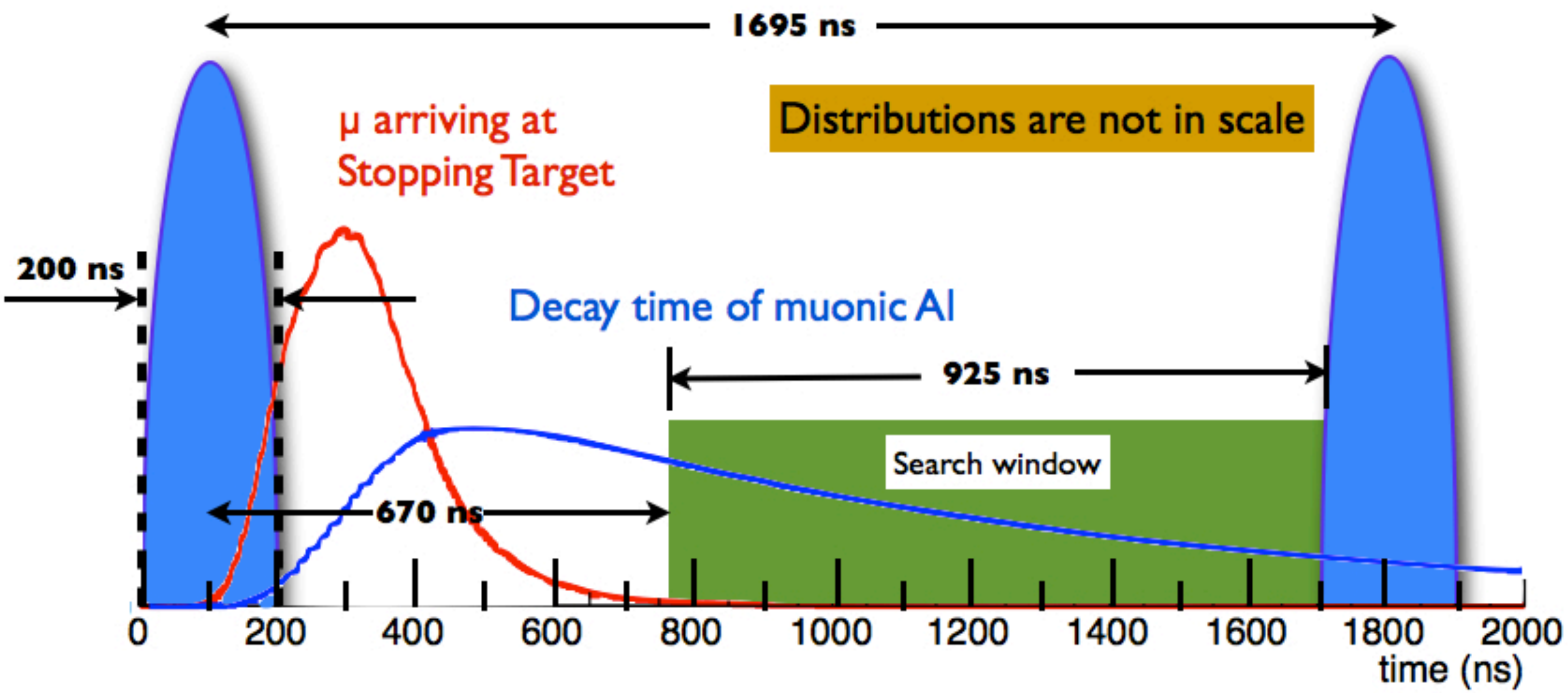
Peter Kasper, NUFACT-2012

Selection channel built into target dump channel



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

End Product



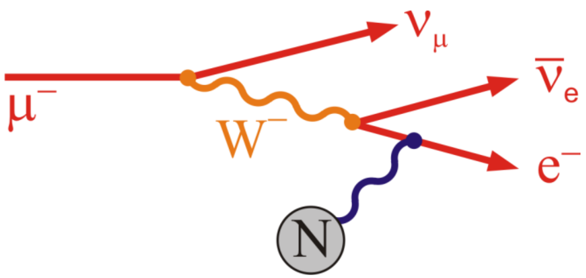
- μ^- are accompanied by e^-, π^-, …
- Extinction system makes prompt background ~equal to all other backgrounds
  - 1 out of time proton per 10^{10} in time protons.
- Lifetime of muonic Al: 864 ns.

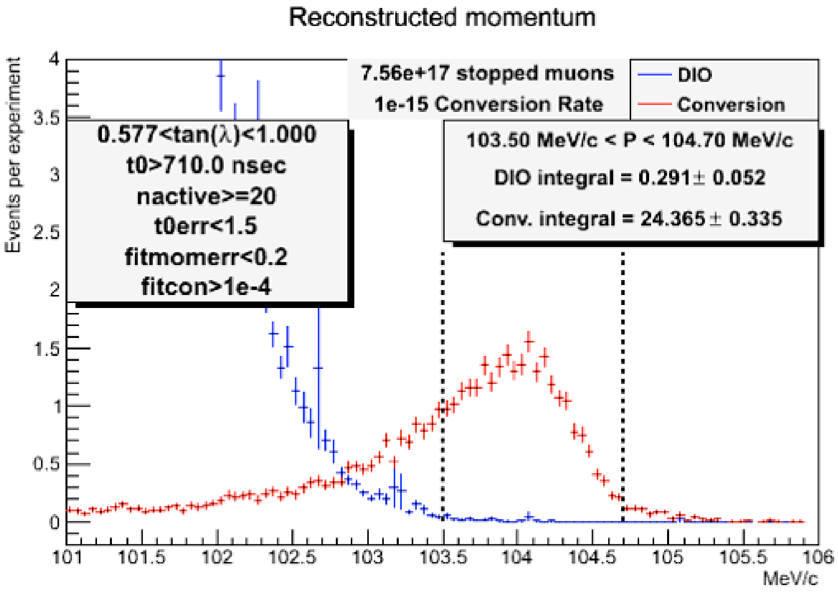
Major Backgrounds

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 ~ 5×10^{-15}
- Defeated by good energy resolution



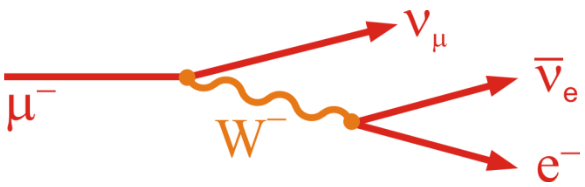


Backgrounds (cont'd)

2. Beam Related Backgrounds

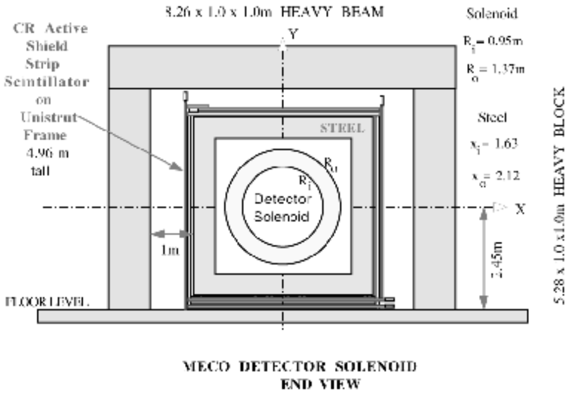
Goal: Prompt background ~equal to all other backgrounds

- 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)



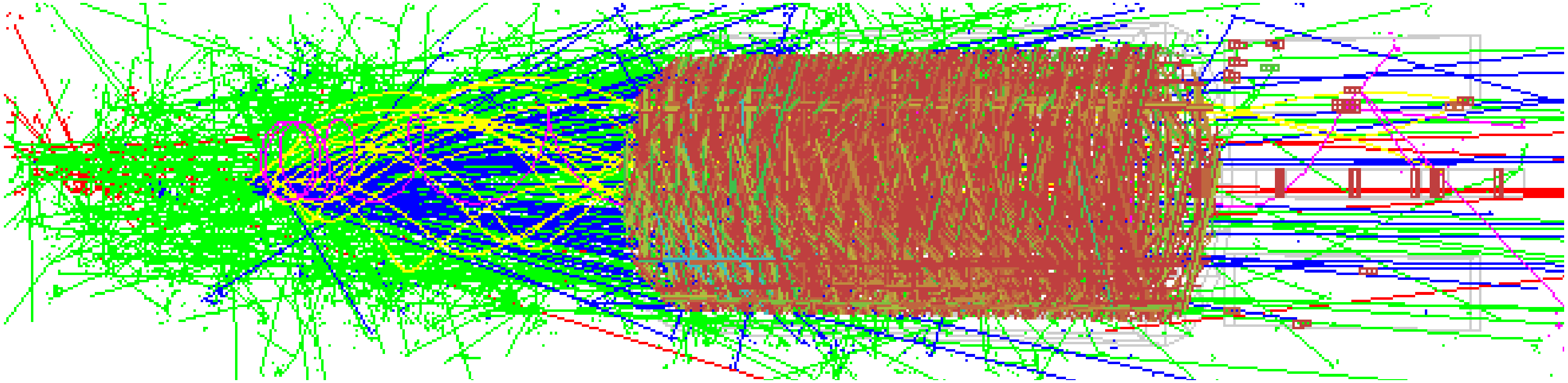
3. Asynchronous Backgrounds

- Cosmic rays
  - suppressed by active and passive shielding

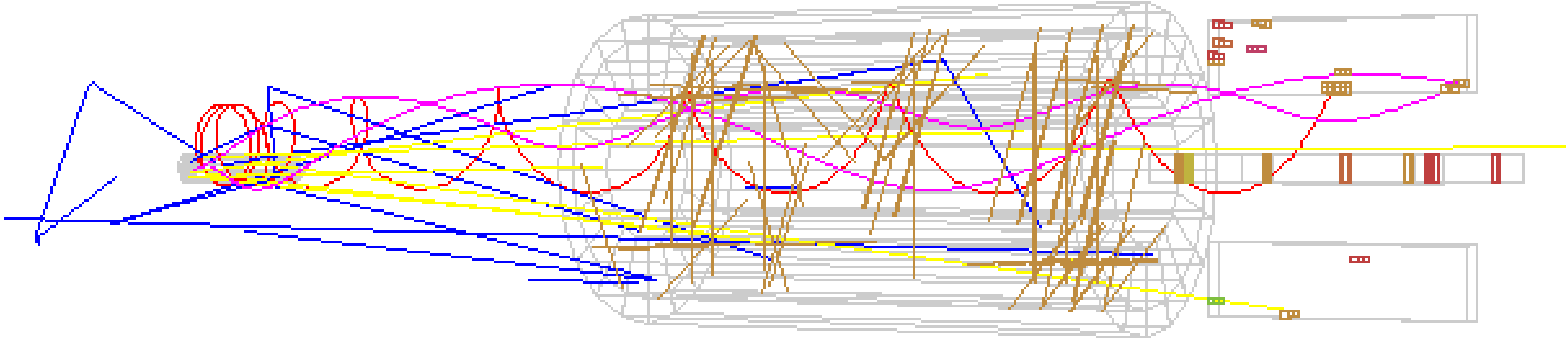


Pattern Recognition

- All hits from 500-1694 ns

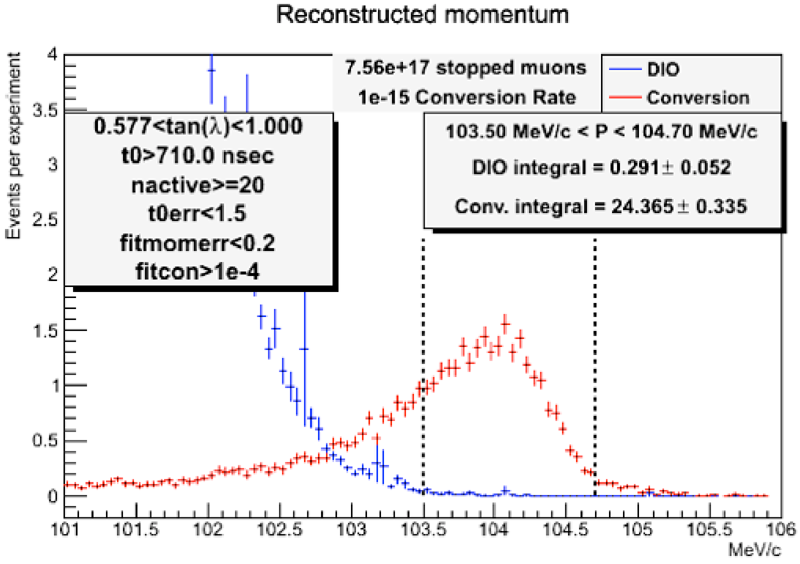


- Hits within ±50 ns conversion electron



Sensitivity

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



Parameter	Value
Running 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	0.0016
μ^- capture probability	0.609
Fraction of muon captures in live time window	0.51
Electron Trigger, Selection, and Fitting Efficiency in Live Window	0.10

Single Event Sensitivity: $R_{\mu e} = 2 \times 10^{-17}$

Significance

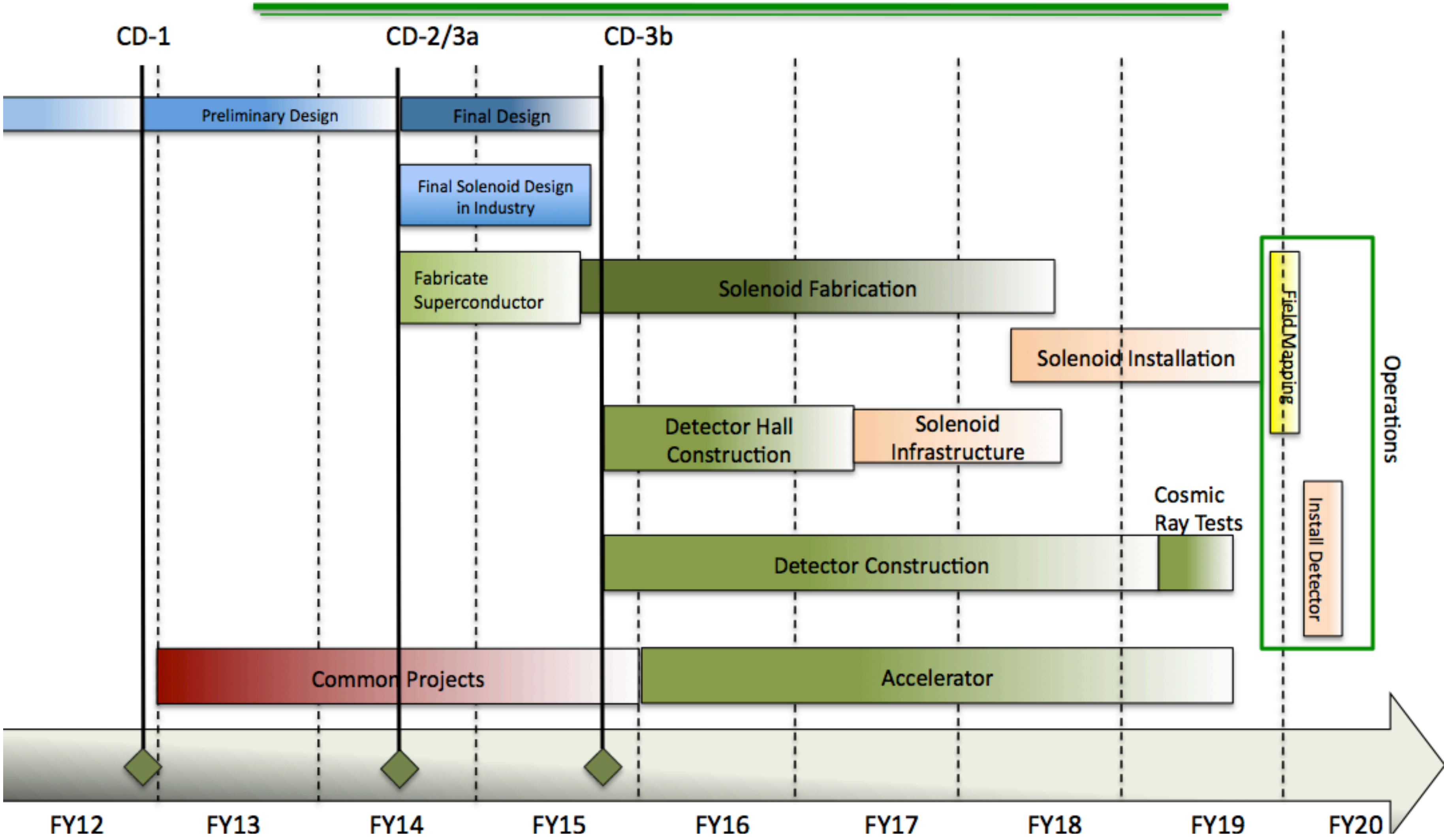
- Backgrounds

Background description	Expected events
Muon decay in orbit	0.22 ± 0.06
Antiproton induced	0.10 ± 0.05
Cosmic rays	0.05 ± 0.013
Radiative pion capture	0.03 ± 0.007
Muon decay in flight	0.01 ± 0.003
Pion decay in flight	0.003 ± 0.0015
Beam electrons	0.0006 ± 0.0003
Radiative muon capture	$< 2 \times 10^{-6}$
Total	0.41 ± 0.08

- Bottom line:
  - Single event sensitivity: $R_{\mu e}=2x10^{-17}$
  - 90% C.L. (if no signal) : $R_{\mu e}<6x10^{-17}$
  - Typical SUSY Signal: ~50 events or more

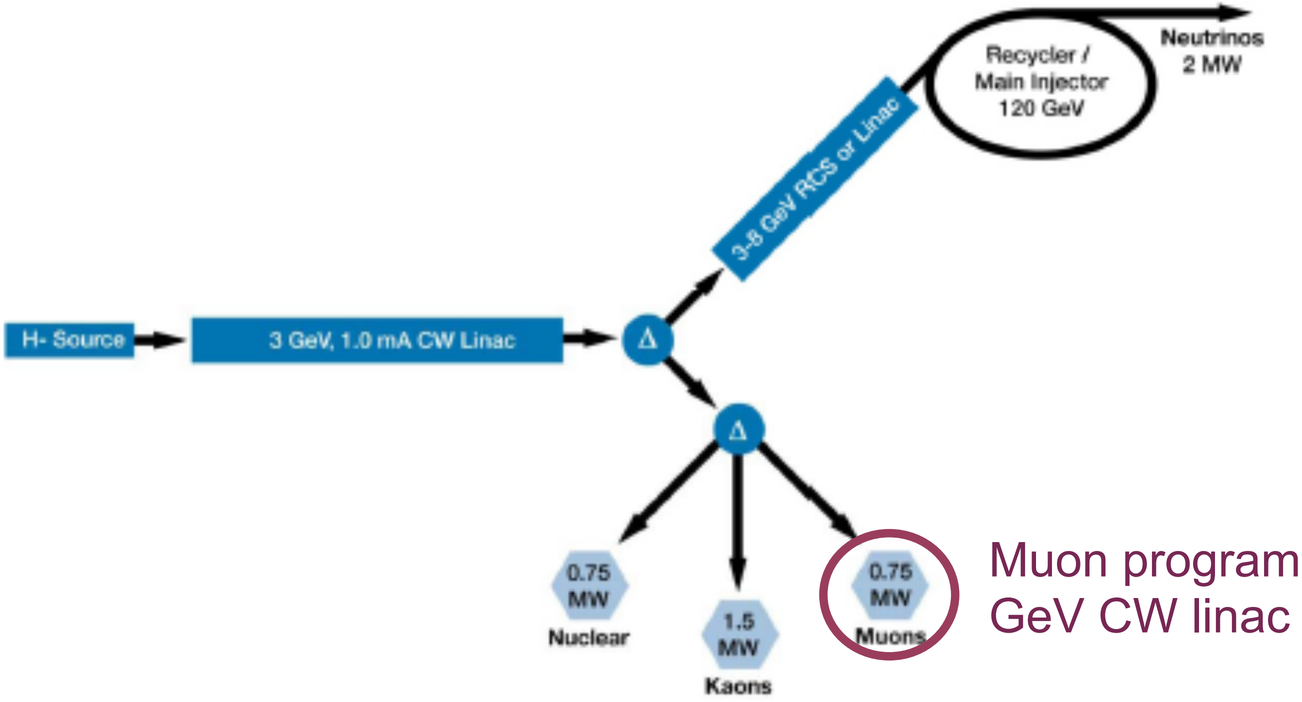
4 order of magnitude improvement!

Mu2e Schedule



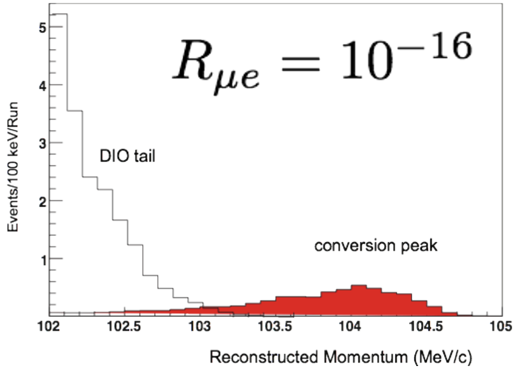
Looking toward the future: Project X

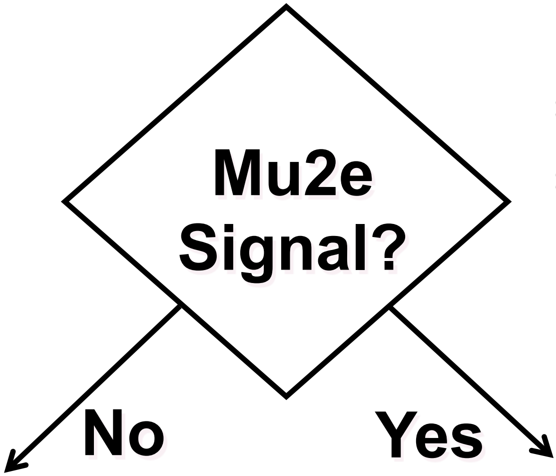
- Maximizing the intensity of the Main Injector will require replacing Fermilab’s aging proton source.
- In 2007 the Fermilab Long Range Steering committee endorsed a design based on a linac incorporating ILC RF technology
  - *Temporarily* named “Project X”
- Specification has undergone many iterations. Current incarnation



Muon program driven by 3 GeV CW linac beam

Upgrade scenarios

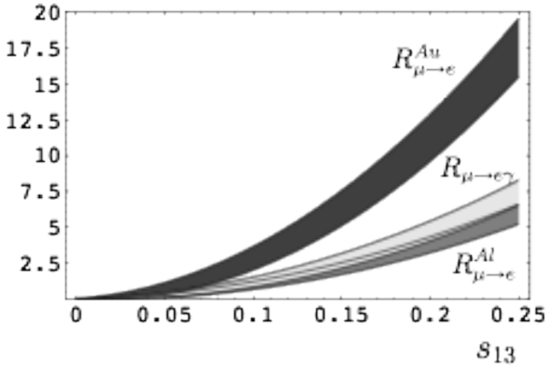




Mu2e Signal?

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

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

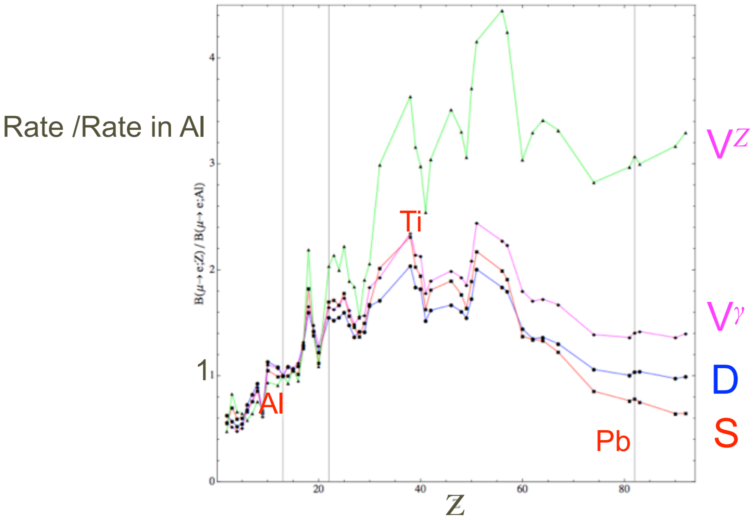
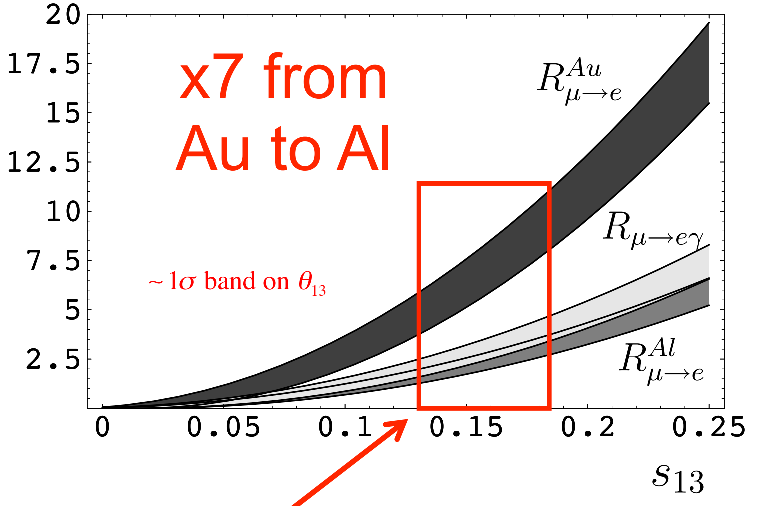


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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



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

Now we know this!

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

Conclusions

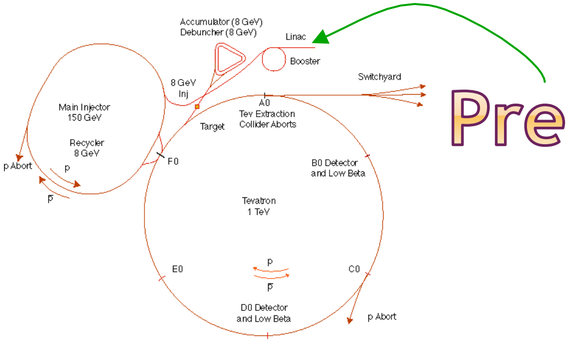
- We have proposed a realistic experiment to measure

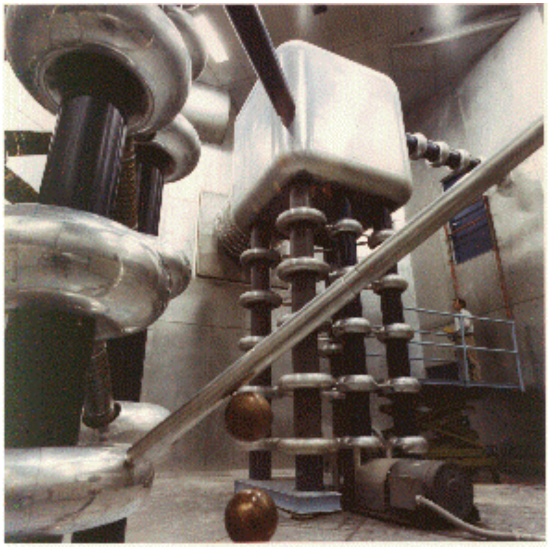
$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^{-}\mathrm{Al} \rightarrow e^{-} + \mathrm{Al}\right)}{\Gamma\left(\mu^{-}\mathrm{Al} \rightarrow \ \left(\text{All Captures}\right)\right)}$$

  - Initial single event sensitivity of $R_{\mu e}=2\times10^{-17}$
  - 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
    - 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.

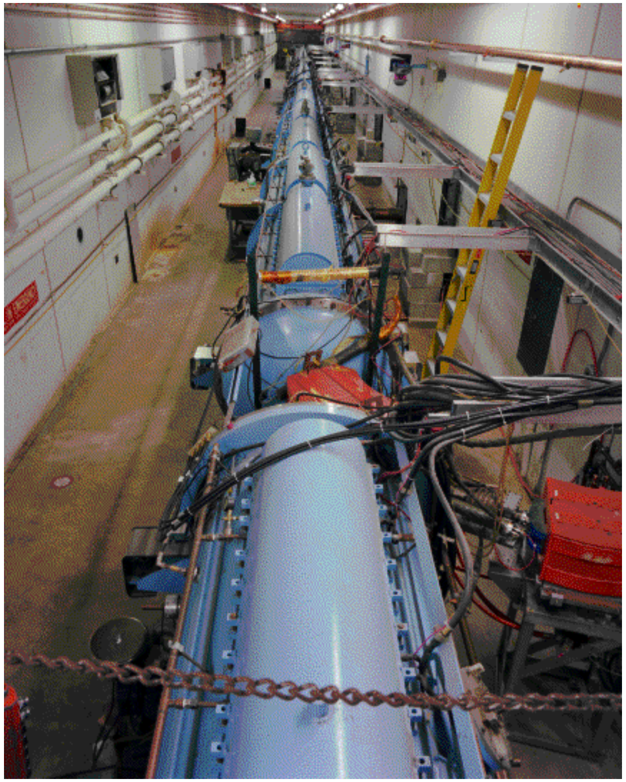
BACKUP SLIDES

Preac(cellerator) and Linac



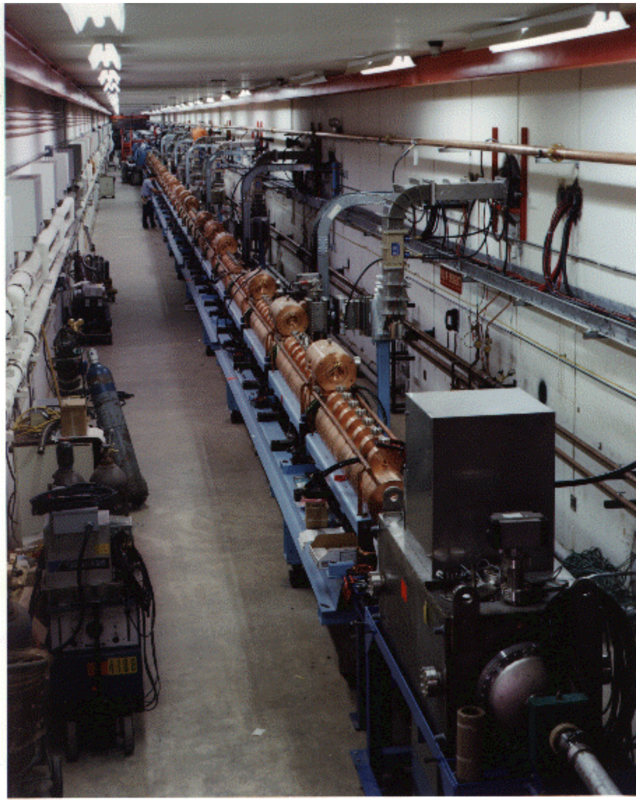


“Preac” - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.

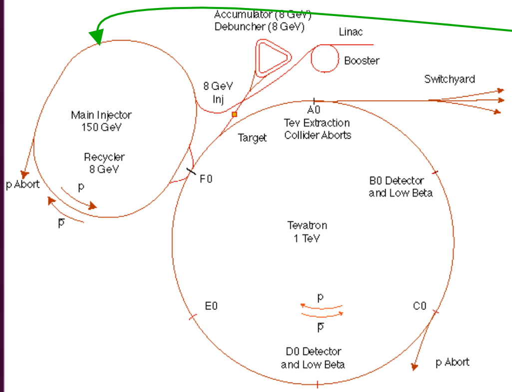


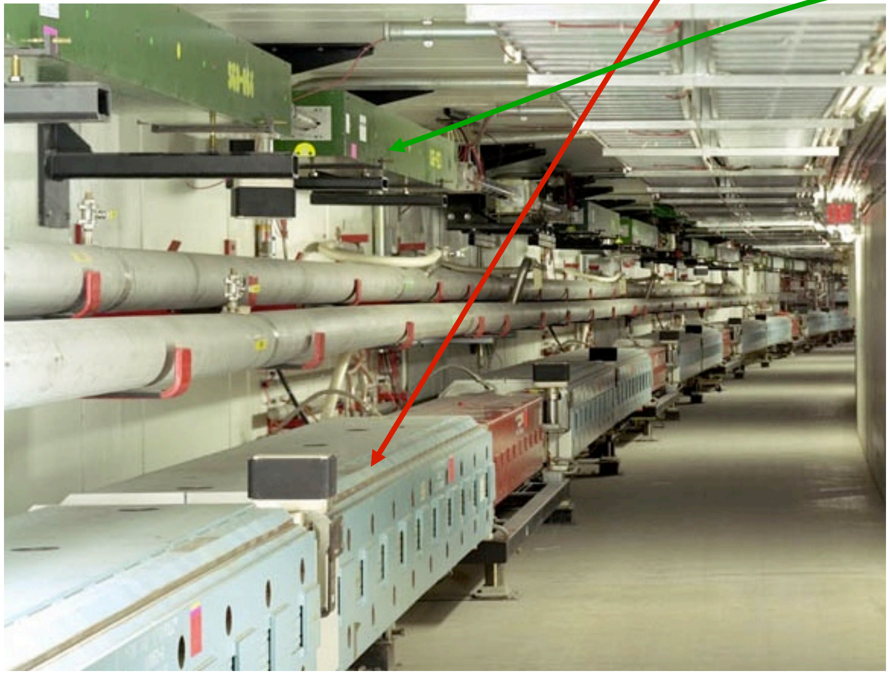
“Old linac”(LEL)- accelerate H- ions from 750 keV to 116 MeV

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



Main Injector/Recycler

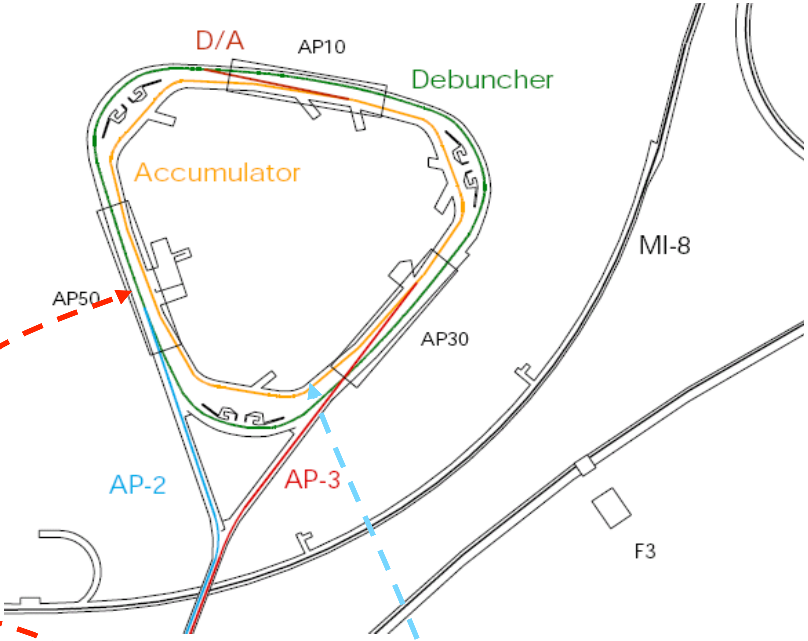


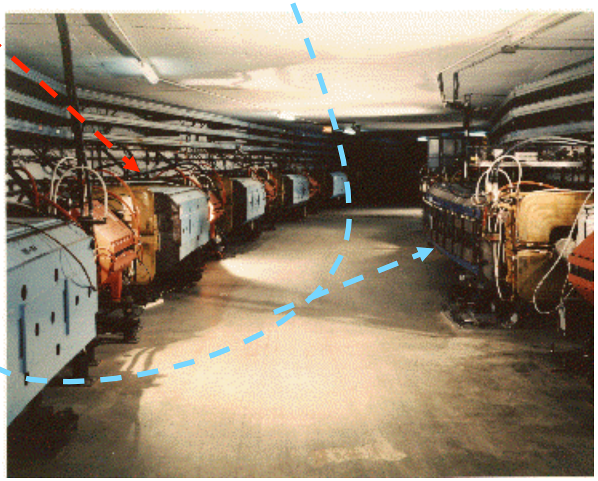


- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The 8 GeV Recycler (which shares the same tunnel and stores antiprotons)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.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

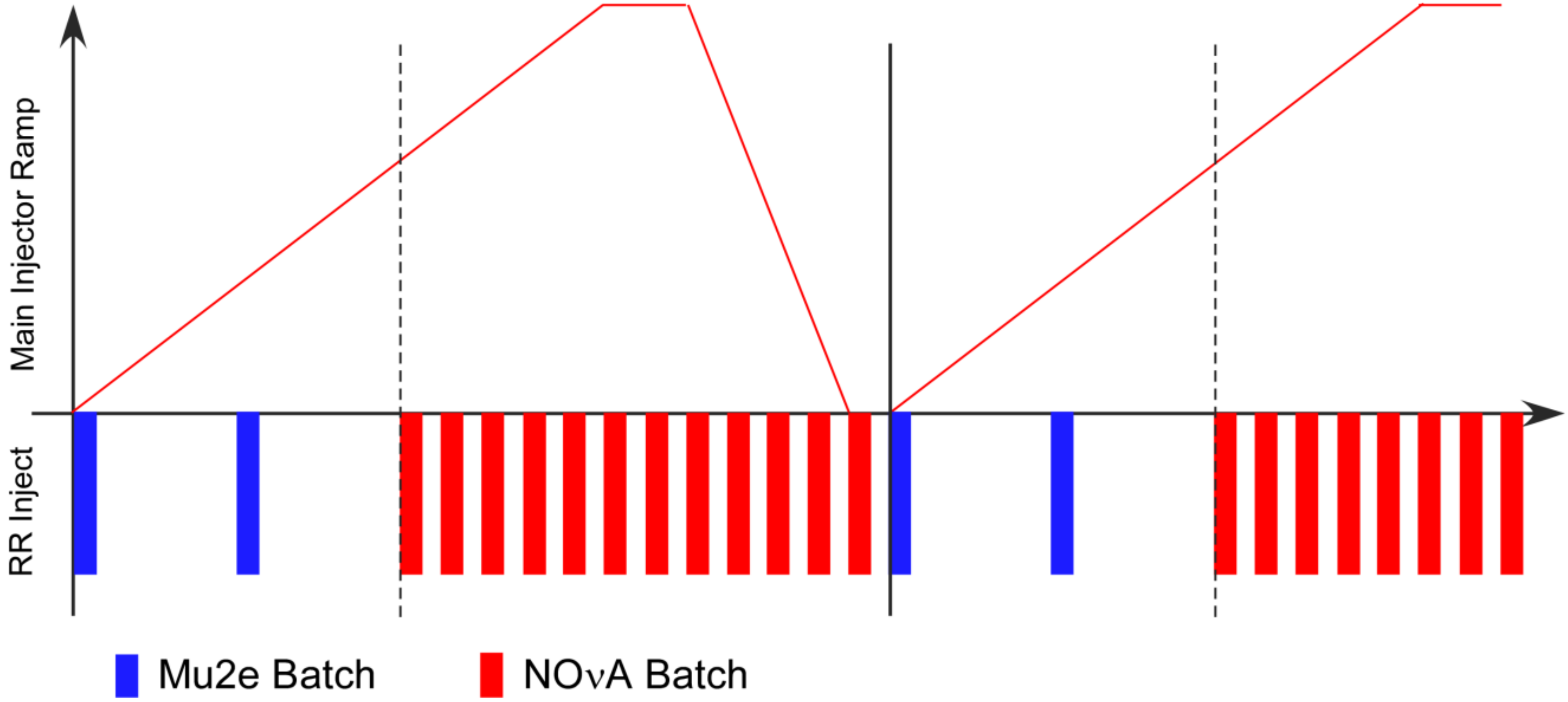
- Protons are accelerated to 120 GeV in Main Injector and extracted to pBar target
- pBars are collected and phase rotated in the "Debuncher"
- Transferred to the "Accumulator", where they are cooled and stacked
- pBars not used after collider.



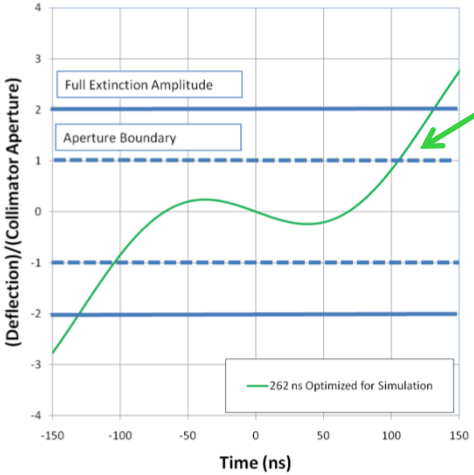


Mu2e in the NOvA era

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

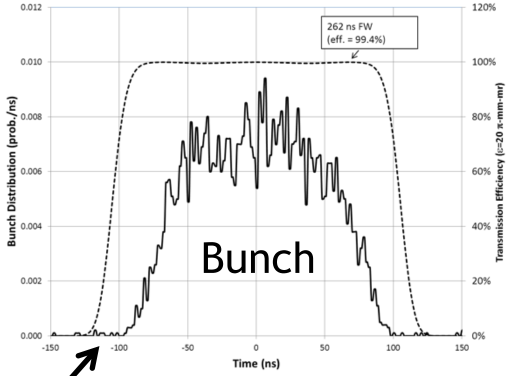


Extinction Performance

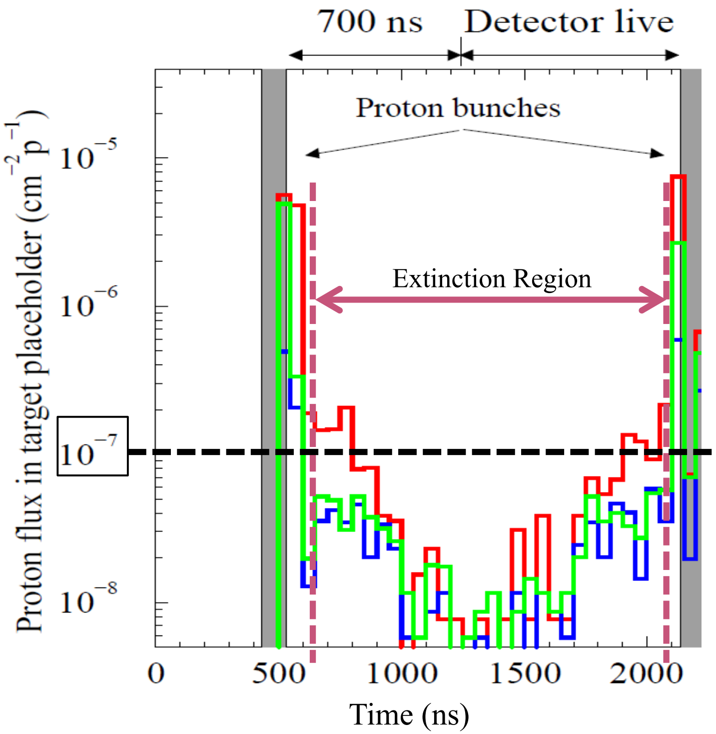


Beam motion in Collimator

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



Transmission Window



Collimator Material:
- H1–H5: steel
- H1–H5: W
- H1–H3: W, H4–H5: steel

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