Mu2e: Search for Muon to Electron Conversion at Fermilab

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Fermilab

(Mu2e Collaboration)

February 22, 2017

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

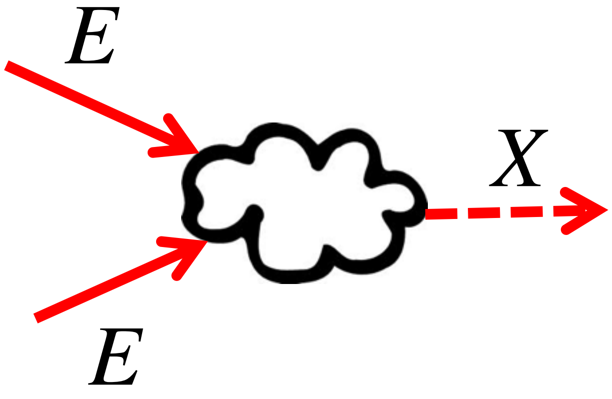
- History and Theoretical Motivation
- Experimental Technique
- Sensitivities
- Mu2e in the context of other experiments
- Conclusion

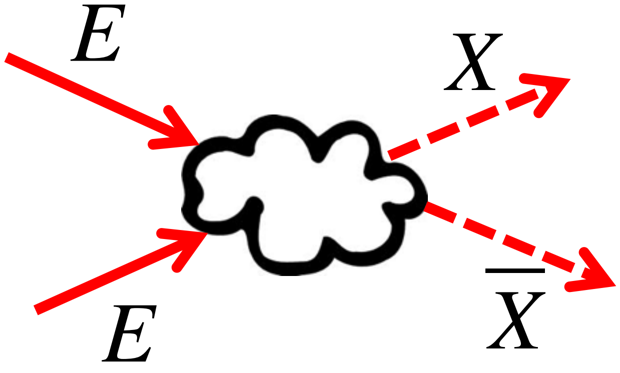
Provocative Comments

- 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➔$\mu^+\mu^-$ 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.

Direct vs. Indirect Observation

Direct

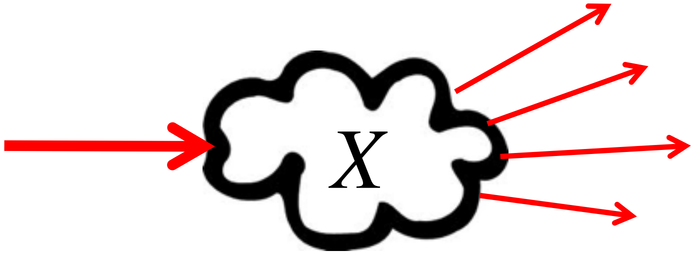




$$\text{probe up to } M_X \approx \frac{E}{c^2}$$

Indirect

$$\Delta t \Delta E \sim \hbar$$

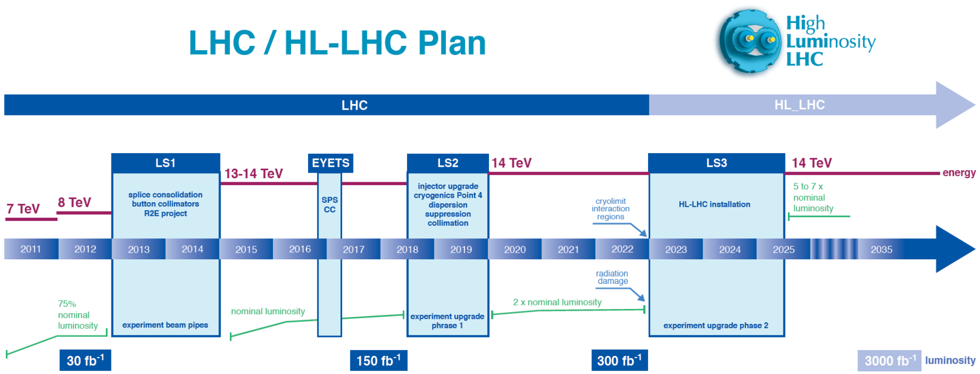


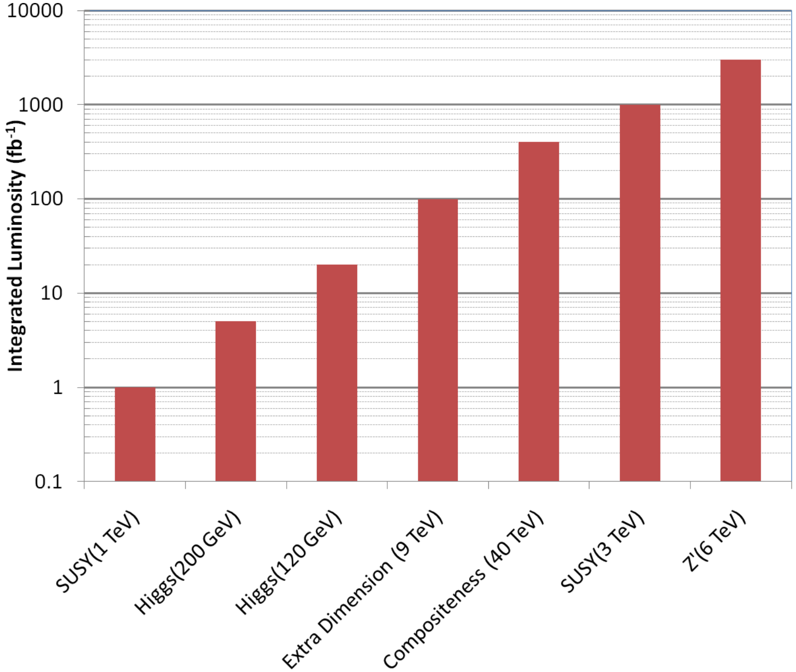
$$M_X c^2 \gg E$$

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

Case in Point…

- The LHC has an upgrade plan and experimental program outlined that extend into the 2030s
  - 3000 fb^{-1} of data at 13-14 TeV CoM Energy





  - HOWEVER:
    - There's no guaranty that it will find anything but the Higgs
    - It's not a major problem if it doesn't (from the physics standpoint)

What then?

- People are already discussing the “Future Circular Collider” (FCC)
  - 100 km circumference
  - 50+50 TeV proton beams
  - Similar luminosity to LHC

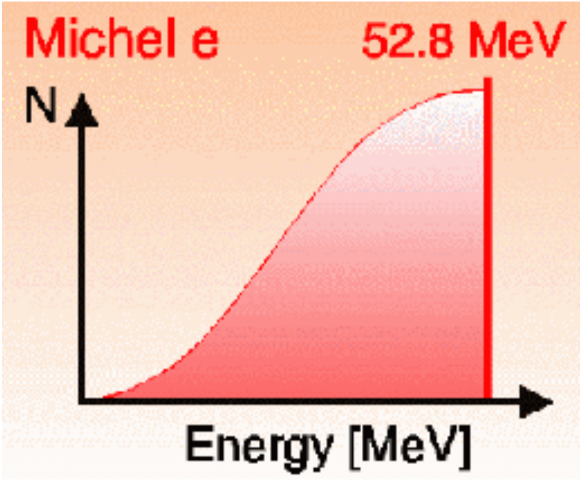
- Is not finding something at a 14 TeV collider enough justification to build a 100 TeV collider?
  - In the absence of guidance, we have no choice but to think logarithmically
    - (LHC to FCC) ~ (Tevatron to LHC) → “meh”
    - Pretty weak scientific argument
    - Non-starter politically

So to summarize…

- Clearly:
  - The LHC has the most promise for discovering new physics in the near future.
  - Because of the complexity of any next generation colliders, we need to start thinking about them now.
- However, it's vital that we pursue a robust and diverse program of indirect studies, to maximize our chances of discovering new physics, and to inform the direction of major research initiatives in the future. These include
  - Rare particle decays
  - Precision studies
  - Tests of fundamental symmetries
- Of all indirect measurements, rare muon processes provide a very attractive mix of experimentally striking signatures and broad discovery potential.
- So without further ado…

History of the Muon

- The muon was originally discovered in 1936 by Anderson and Neddermeyer while studying cosmic ray data
- By studying its penetration properties, they determined that it had a mass roughly 200 times that of the electron.
- The muon was observed to decay to electron+"something invisible" with a spectrum consistent with a three body decay



Mediator of the Strong Force?

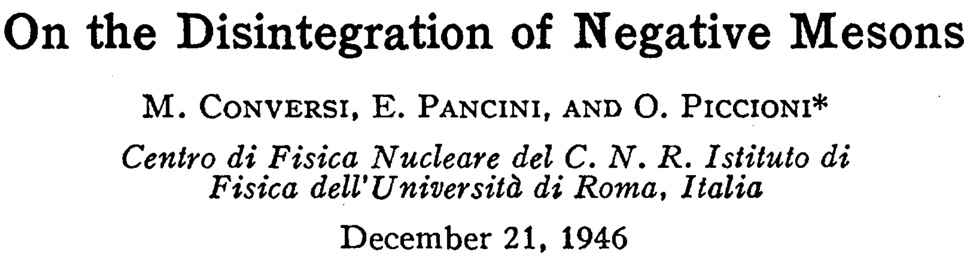
- In 1934, Hideki Yukawa proposed that a massive particle mediated the strong force, resulting in a potential of the form

$\sim 200 m_e$

$$V_{\text{strong}} = -\frac{g^2}{4\pi}\frac{e^{-mr}}{r}$$

The muon was an obvious candidate!

- However, in 1946, Conversi, *et al** showed that muon decays were not consistent with strong interactions

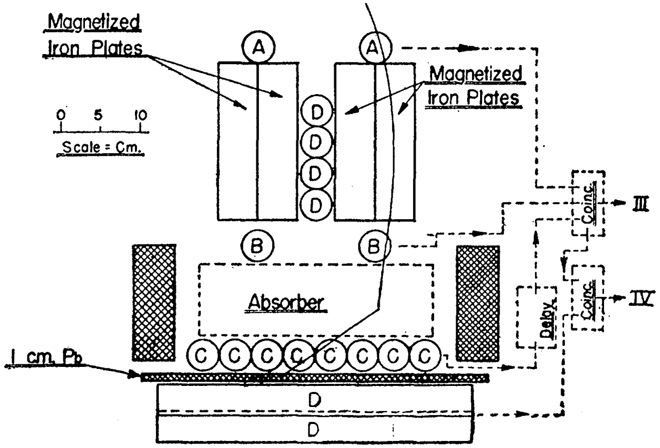


On the Disintegration of Negative Mesons

M. Conversi, E. Pancini, and O. Piccioni*

Centro di Fisica Nucleare del C. N. R. Istituto di Fisica dell'Università di Roma, Italia

December 21, 1946



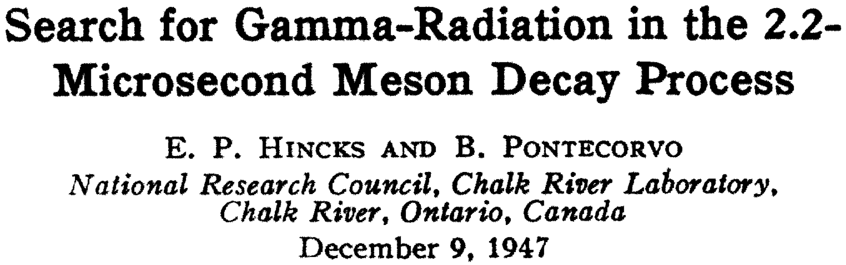
Studied decay rates as a function of target for both positive and negative "mu-mesons". Not consistent with prediction for strongly interacting particles.

- Yukawa's particle turned out to be the pion, discovered in 1947.

*PhysRev.71.209 (1947)

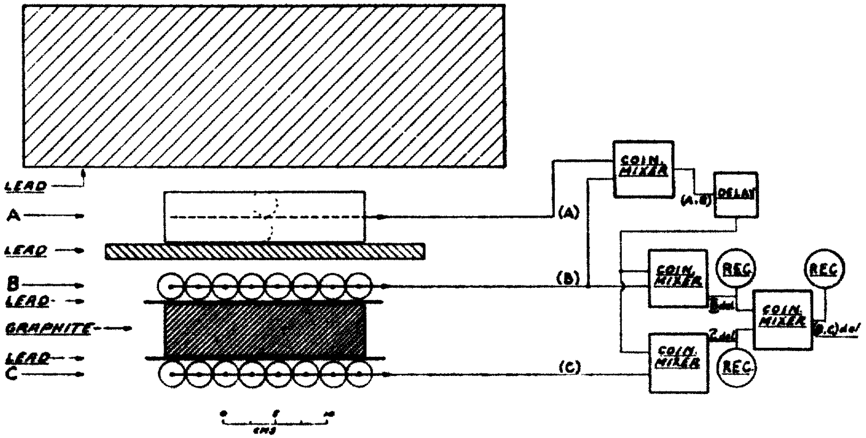
Excited Electron?

- The other working theory was that the muon might be an excited state of an electron.
- In 1947, Hincks and Pontecorvo* looked for gammas associated with stopped muon decay.



Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. HINCKS AND B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
December 9, 1947



- They detected no gammas, leading to the first limit on "Charged Lepton Flavor Violation" (CLFV)

$$\mathrm{Br}(\mu \rightarrow e\gamma) < .06$$

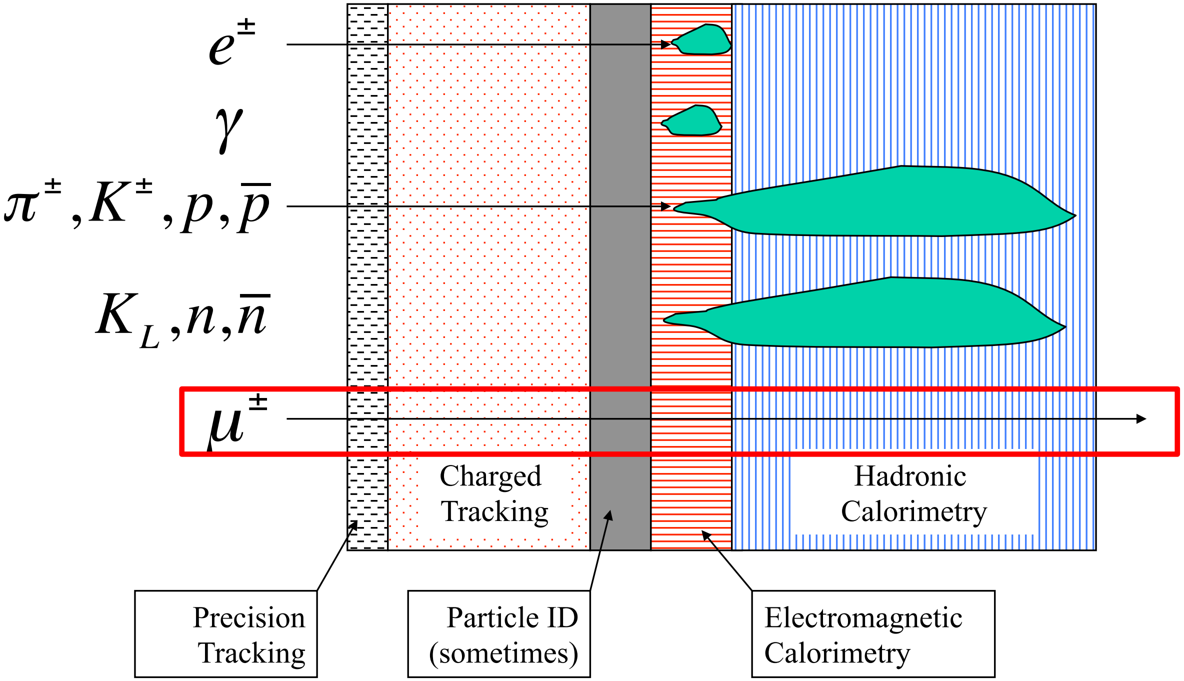
- Conclusion: the muon was a heavier version (flavor) of electron, that interacted only electromagnetically and weakly.

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

*PhysRev.73.257 (1948)

Today's Muon

- Mass: 105.66 MeV/c^2 (~200m_e ~0.1m_p)
- Charge: ±e
- Spin: ½ħ (fermion)
- Lifetime: 2.2 μsec ($c\tau$=660m)
- Interactions: Electromagnetic and Weak, but NOT strong
- Because muons are so much heavier than electrons, they are very penetrating



The Standard Model

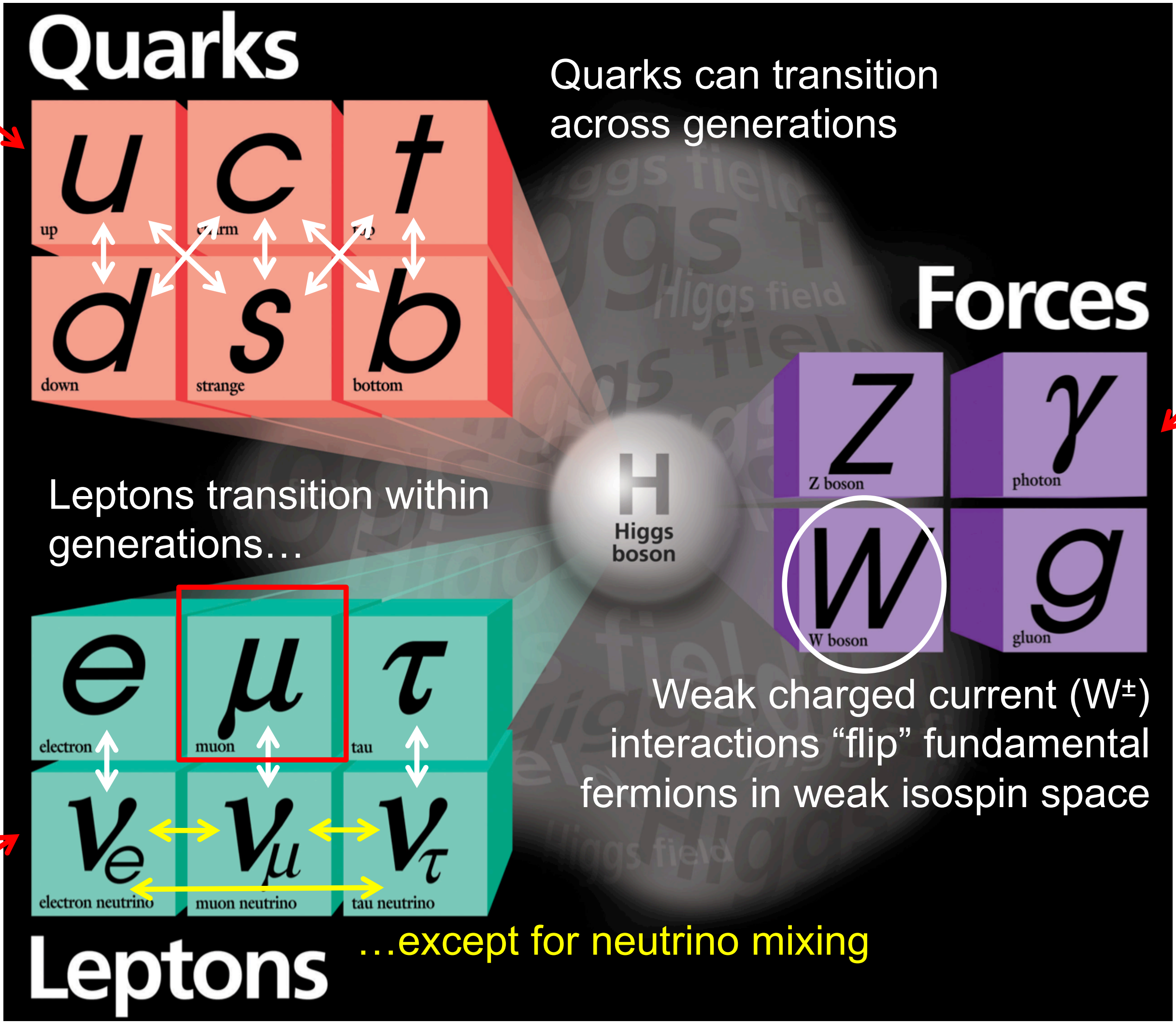
Spin ½ "Fermions"

Spin 1 "Bosons"

Combine to form hadrons

Mediate interactions

Free



Quarks can transition across generations

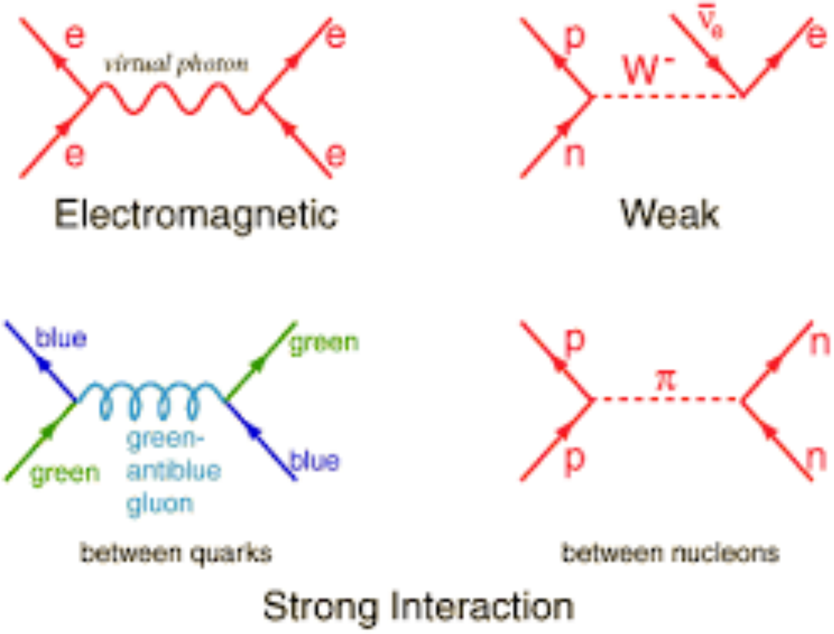
Leptons transition within generations…

Weak charged current ($W^\pm$) interactions "flip" fundamental fermions in weak isospin space

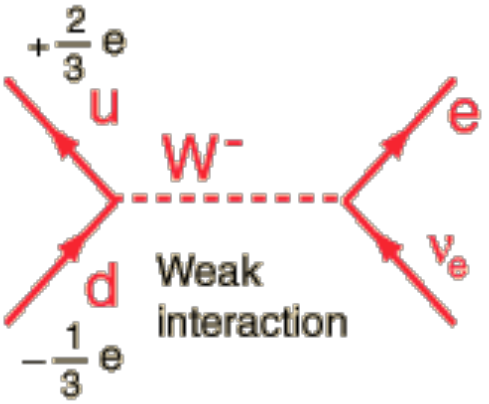
…except for neutrino mixing

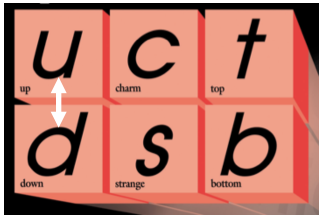
Interactions in the Standard Model

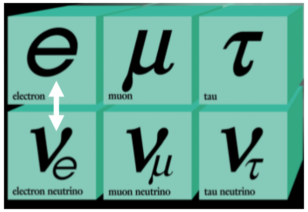
The bosons mediate interactions between the fundamental fermions



W particle causes a weak isospin transition within one *weak* quark or lepton generation







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

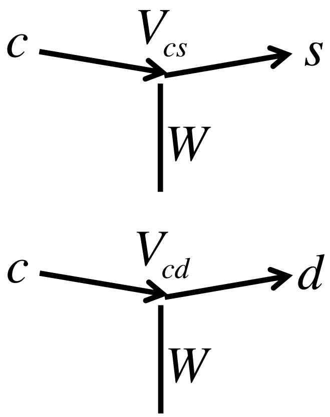
$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

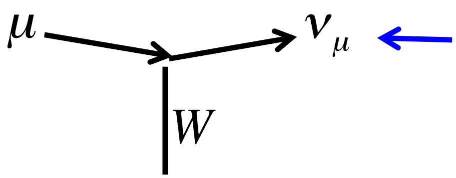
~maximum mixing

- However, because the neutrino masses and their differences are so small, the phenomenology is *very* different

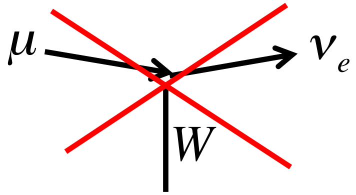
Quarks: generational transitions observed

Leptons: weak transitions and mixing proceed separately





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



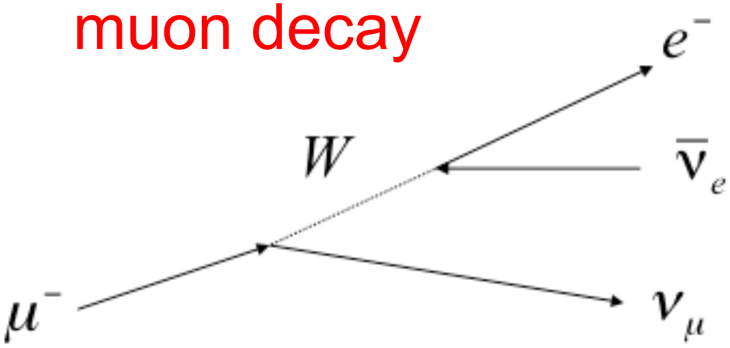
NOT observed!

Lepton Number and Lepton Flavor Number

As a consequence, both lepton number and lepton "flavor" (generation) number are individually conserved*

	l	l_e	l_μ
μ^-	1	0	1
total	1	0	1

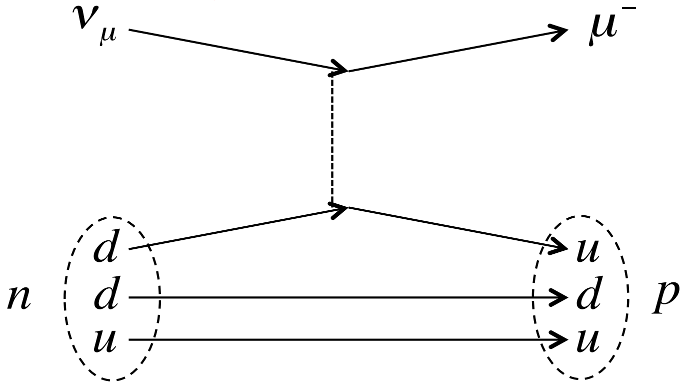
muon decay



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

$\nu_\mu + n \rightarrow \mu^- + p$

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

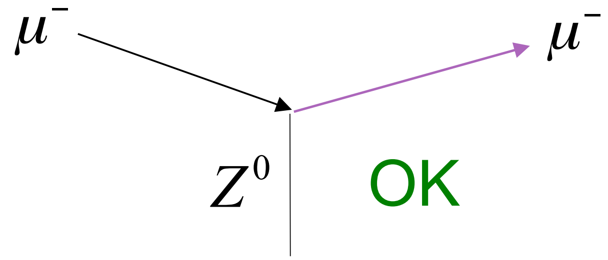


	l	l_e	l_μ
μ^-	1	0	1
p	0	0	0
total	1	0	1

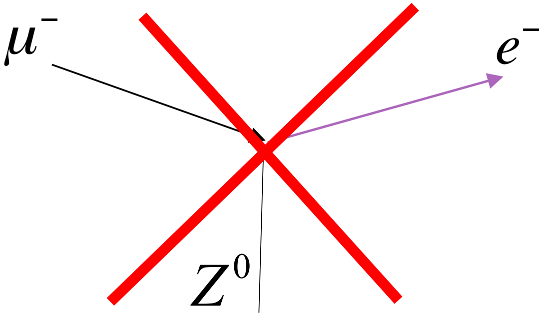
*except in neutrino mixing

Charged Lepton Flavor Violation (CLFV)

The Z^0 mediates neutral current scattering

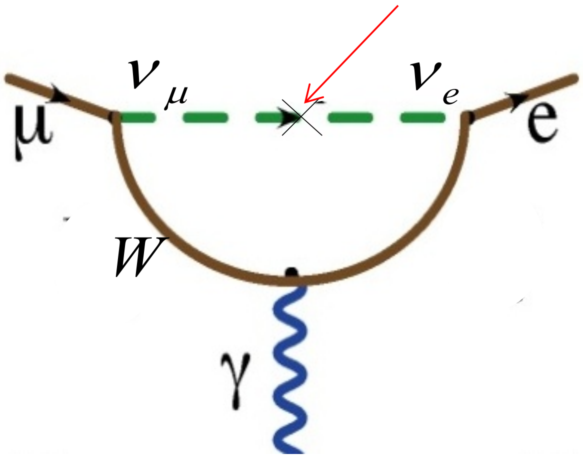


However, "Flavor Changing Neutral Currents" (FCNC):



are forbidden in Standard Model

Note: Observation of neutrino mixing shows CLFV *can* occur


Virtual ν mixing

However, the Standard Model branching ratio is ~$\mathcal{O}(10^{-52})$
(35 orders of magnitude below our goal)

I'm going to shut up about neutrino mixing now!

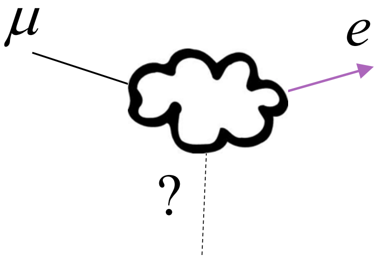
Beyond the Standard Model

- 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 broad physics reach and experimental sensitivity

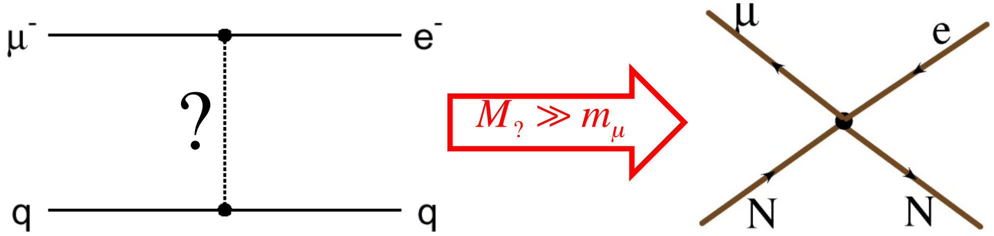
Generic Beyond Standard Model CLFV

There are two broad classes of CLFV reactions…

Flavor Changing Neutral Current

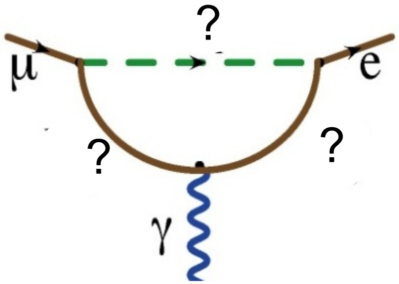


- Mediated by *virtual* massive neutral Boson, e.g.
  - Leptoquark
  - Z'
  - Composite
- Approximated by "four fermi interaction"

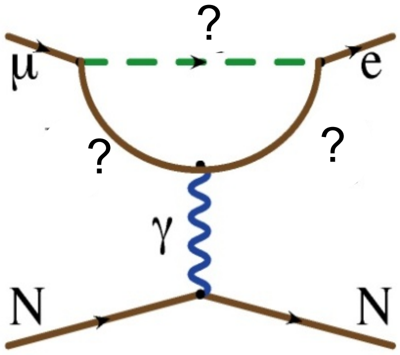


Dipole (penguin)

- Can involve a real photon

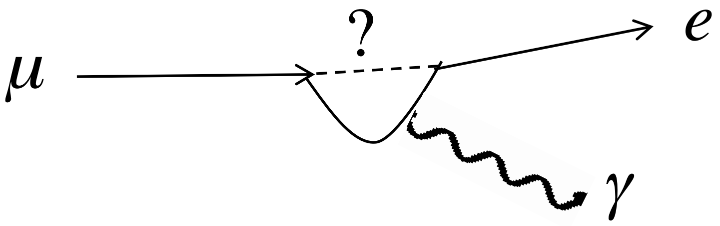


- Or a virtual photon



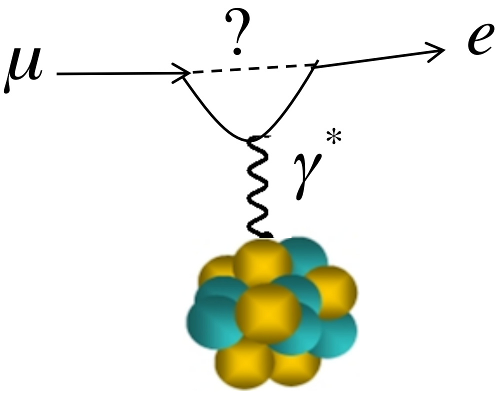
Decay vs. Conversion

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

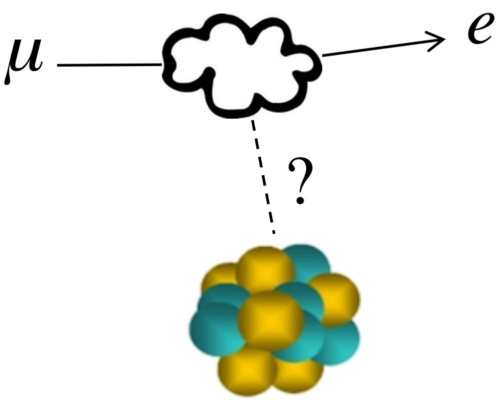


$$\mu \to e + \gamma$$

- However, if we capture a μ^- on a nucleus, it could could "convert" to an e^- via exchange of a virtual particle in both scenarios



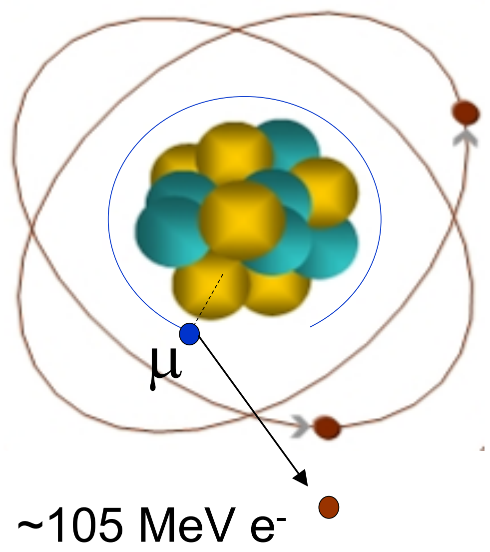
photon



heavy neutral boson

Experimental Signature of μ+N $\rightarrow$ e+N

- When captured by a nucleus, a muon will have an enhanced probability of exchanging a virtual particle with the nucleus.



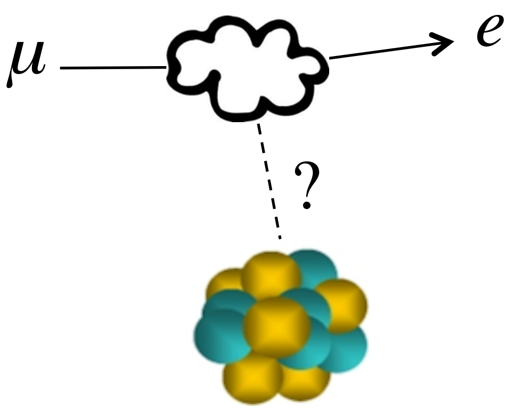
- This reaction recoils against the entire nucleus, producing a *mono-energetic* electron carrying most of the muon rest energy

$$E_e = m_\mu c^2 - \frac{\left(m_e c^2\right)^2}{2 m_N c^2} \sim 105\ \text{MeV}$$

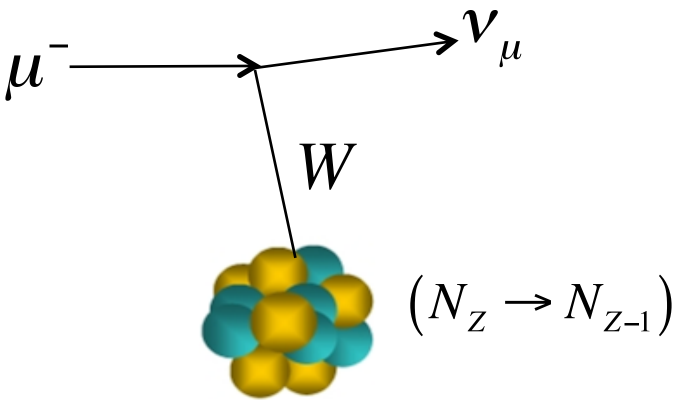
- Very clean experimental signature!

What We (Plan to) Measure

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



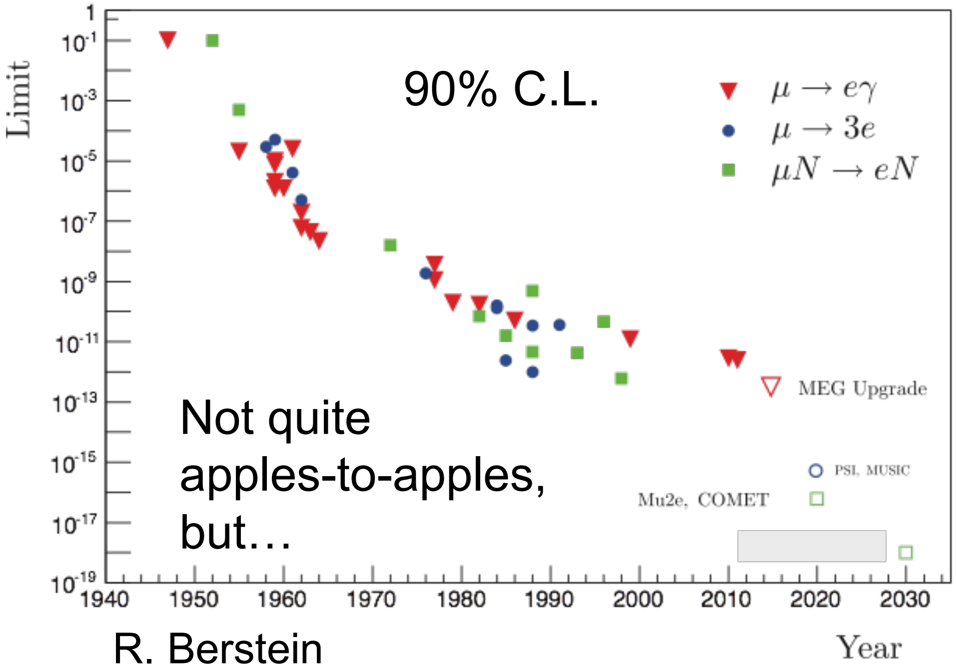
…relative to ordinary μ capture



- 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 (all from PSI)
  - Br(μ➔eγ) < $4x10^{-13}$ (MEG 2016)
  - Br(μ➔3e) < $1x10^{-12}$ (Sindrum-I 1988)
  - $R_{\mu e}$<$7x10^{-13}$ (Sindrum-II 2006)

Four orders of magnitude improvement!

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 $R_{\mu e}=3x10^{-17}$

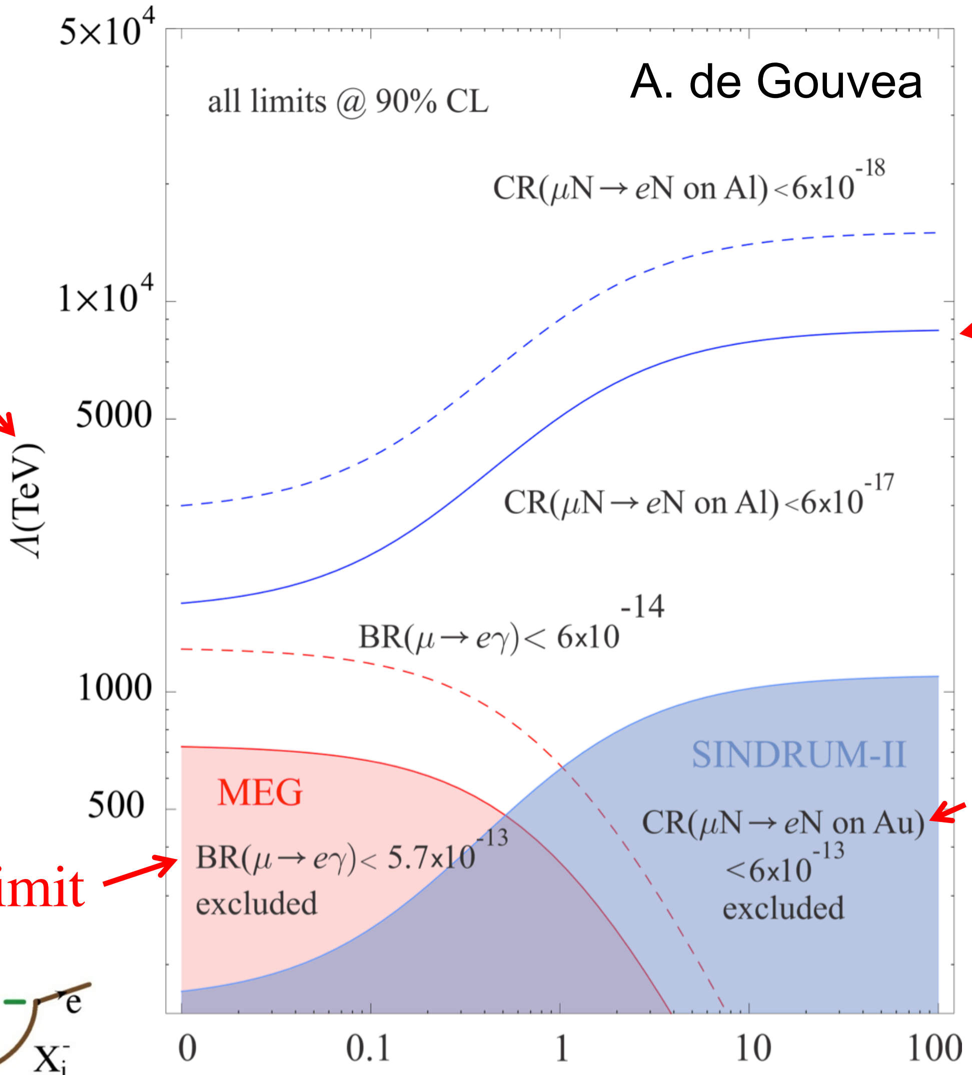
Just to be clear…

- 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 will be *unambiguous evidence of new physics.*
- We are planning for a improvement of roughly four orders of magnitude in sensitivity over the best previous measurement.
- Hard to imagine a single measurement with this much potential.

Dipole vs. Contact Reaction

Mass Scale

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



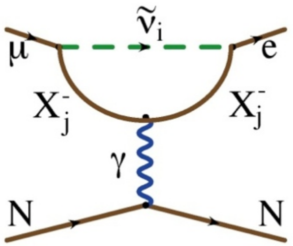
Our goal:

10^4 in rate

10 in mass

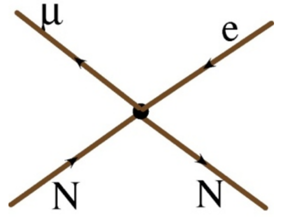
Best $\mu N \rightarrow eN'$ limit

Best $\mu \rightarrow e\gamma$ limit



κ

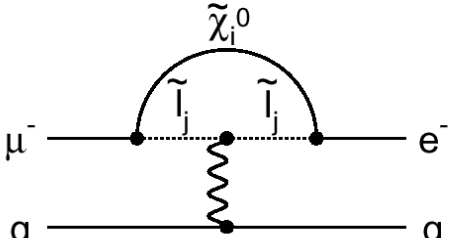
(different for different models)

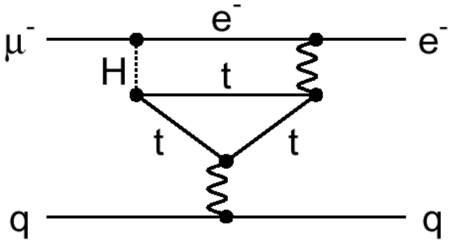


Example Sensitivities*

Supersymmetry

Predictions at 10^{-15}



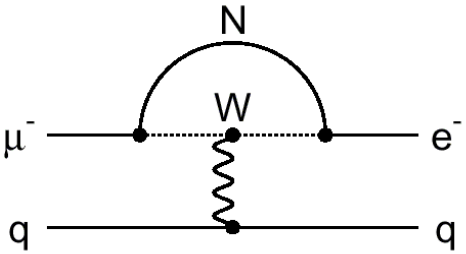


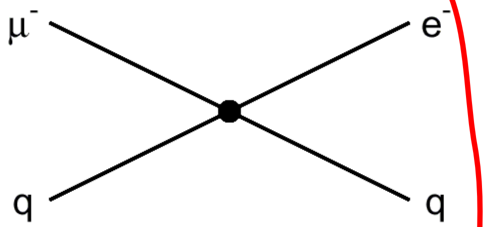
Second Higgs doublet

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

Heavy Neutrinos

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



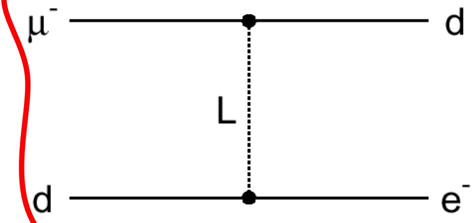


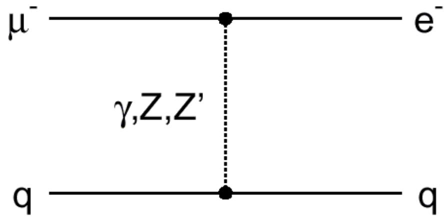
Compositeness

$$\Lambda_C = 3000 \text{ TeV}$$

Leptoquarks

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





Heavy Z', Anomalous Z coupling

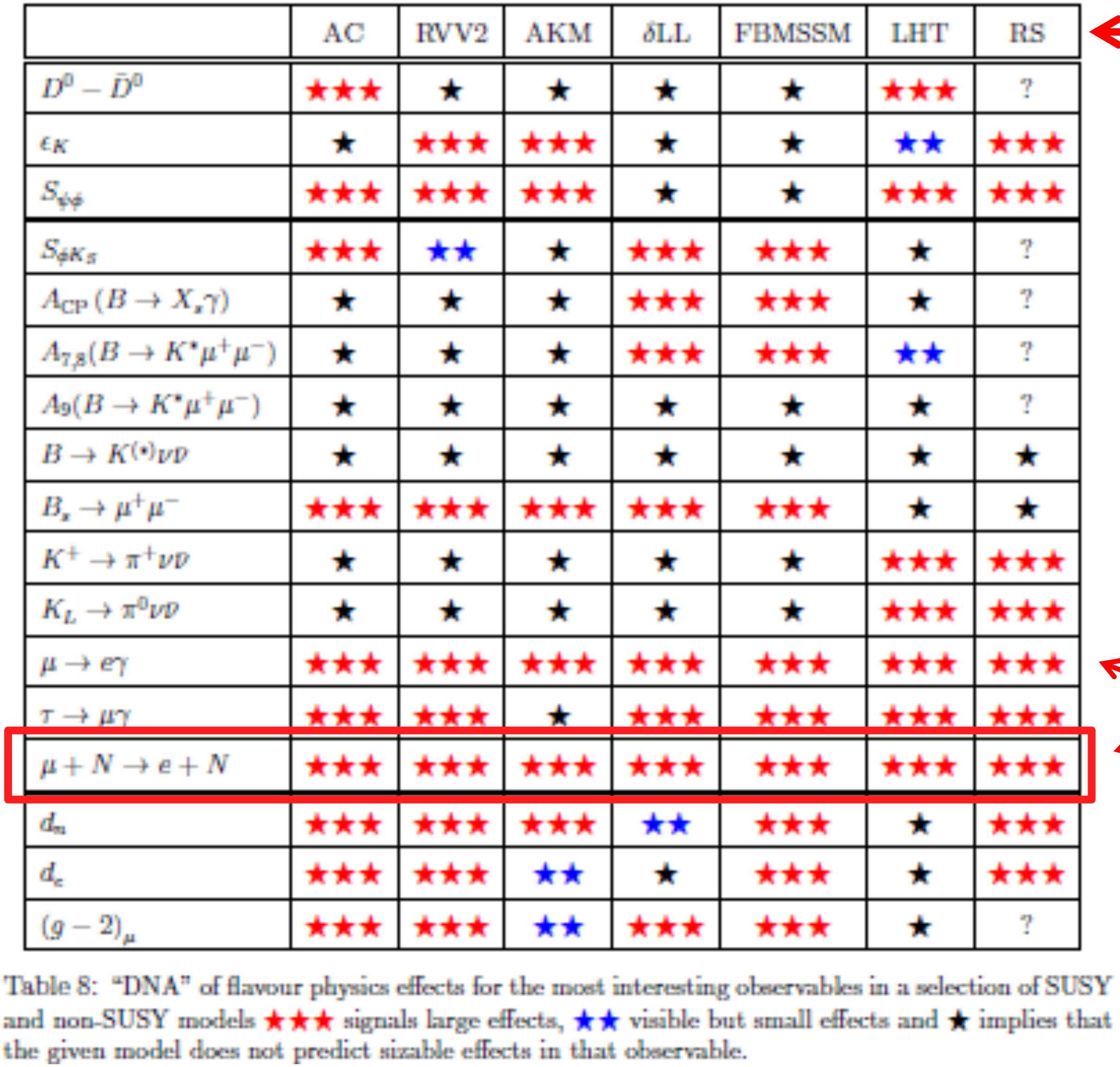
$$M_{Z'} = 3000 \text{ TeV}/c^2$$

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

*After W. Marciano

No μ➔eγ signal

Example: $\mu \rightarrow e$ in Supersymmetry*



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

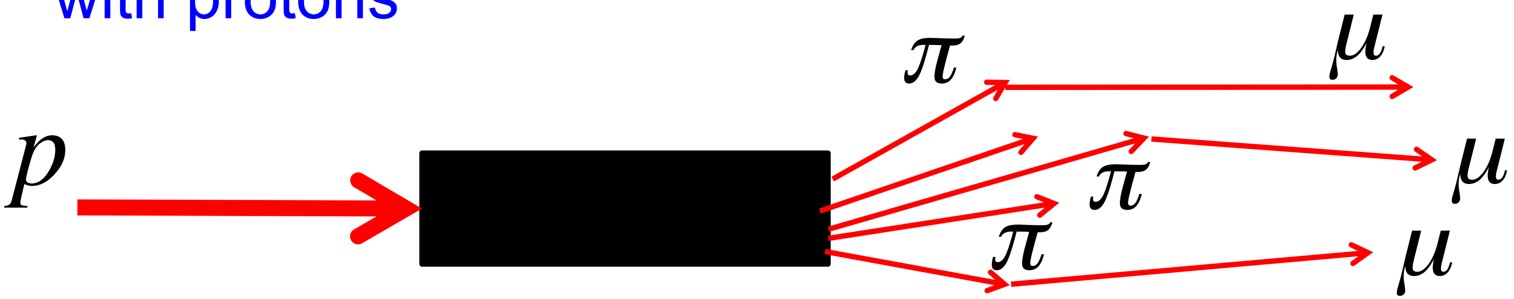
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

SUSY Models

All SUSY models predict both $\mu \rightarrow e\gamma$ and $\mu N \rightarrow eN$

*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

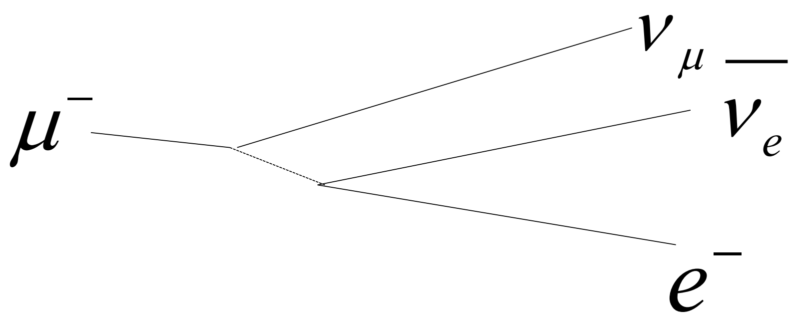
$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \tau_{\pi^\pm} = 26\ \text{ns}$$

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

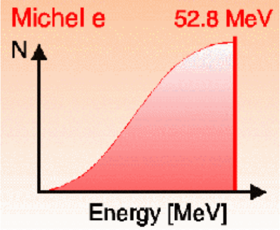
Muons go much further

Biggest Issue: Decay in Orbit (DIO)

Free μ Decay:

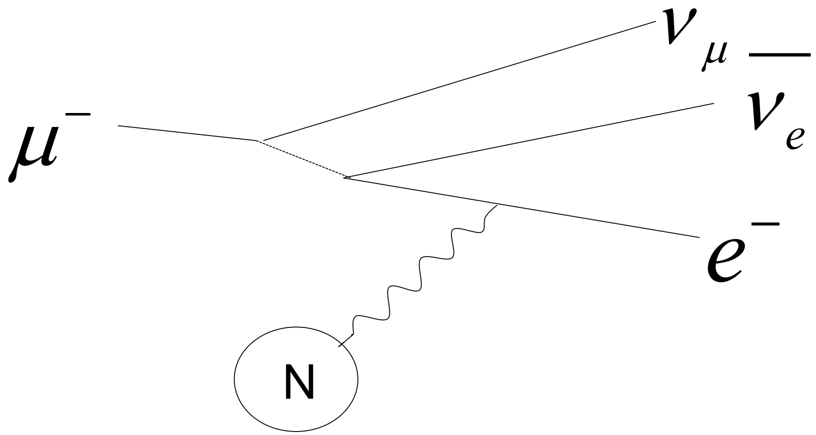


- Very high rate
- "Michel Spectrum"
  - Peak energy ~53 MeV



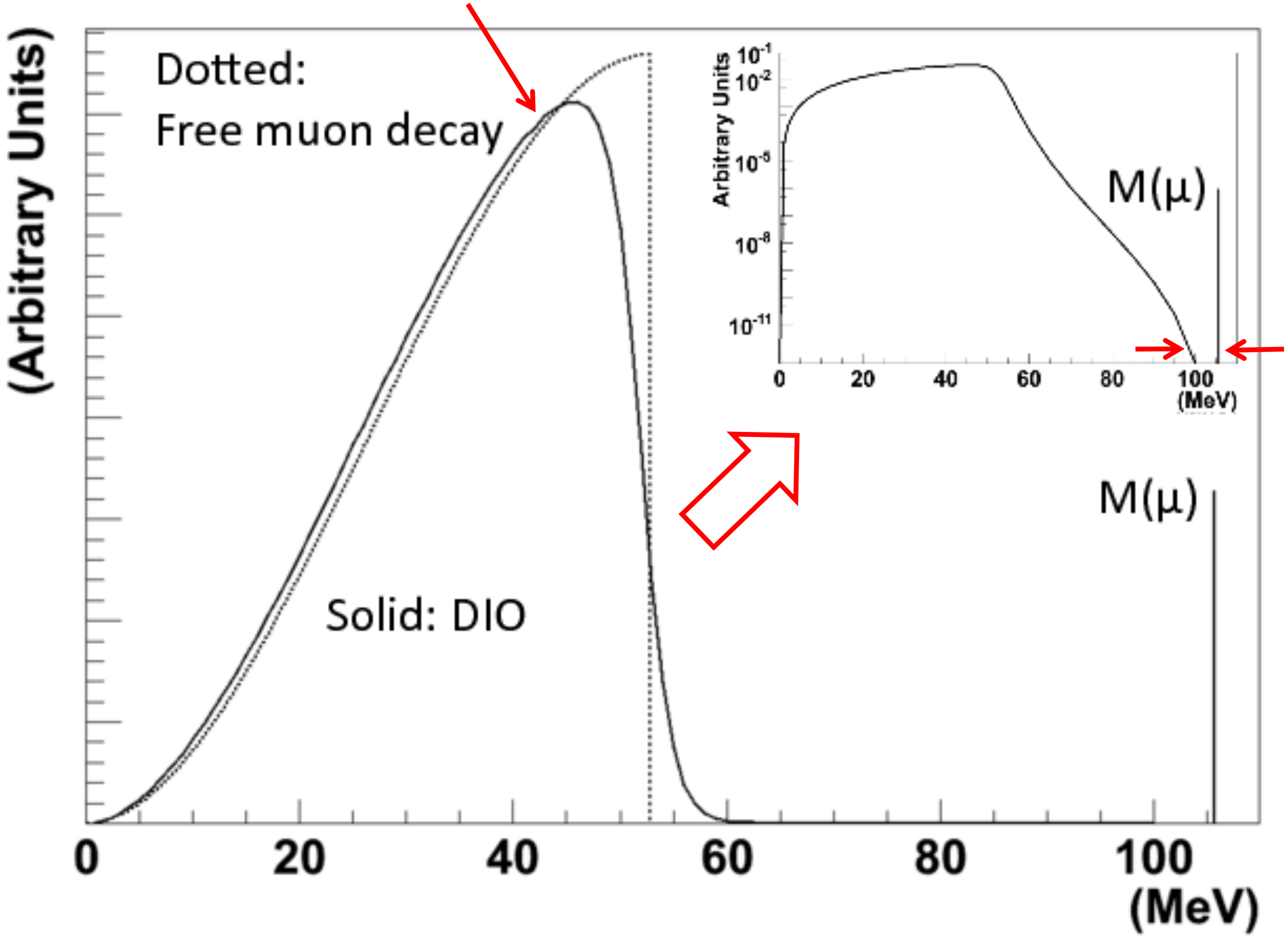
- Must design detector to be very *insensitive* to these.

Coherent DIO:



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

Decay in Orbit Spectrum



We want to be blind to this (acceptance)

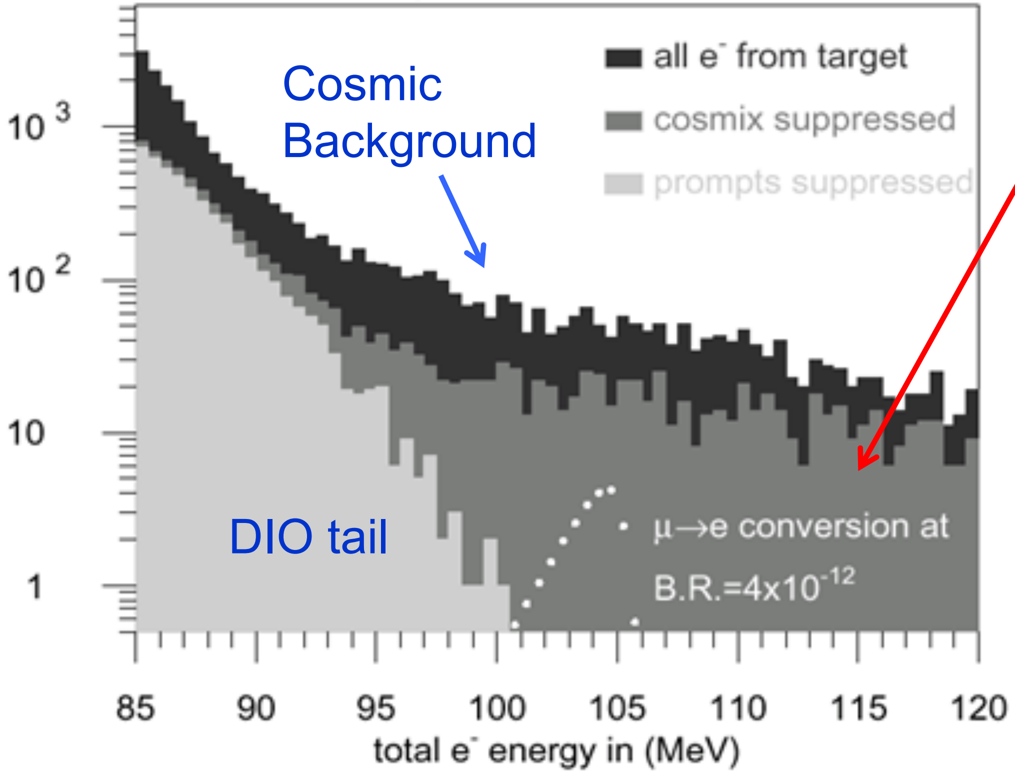
We must resolve this

Prompt Backgrounds

- There are significant backgrounds which are "prompt" with respect to the production and capture of muons:
  - Radiative π- capture
    $\pi^- N \rightarrow N^* \gamma,\ \gamma Z \rightarrow e^+ e^-$
    Biggest worry
  - 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.

Experimental Challenge of “Waiting”

μ–>e Conversion: Sindrum II

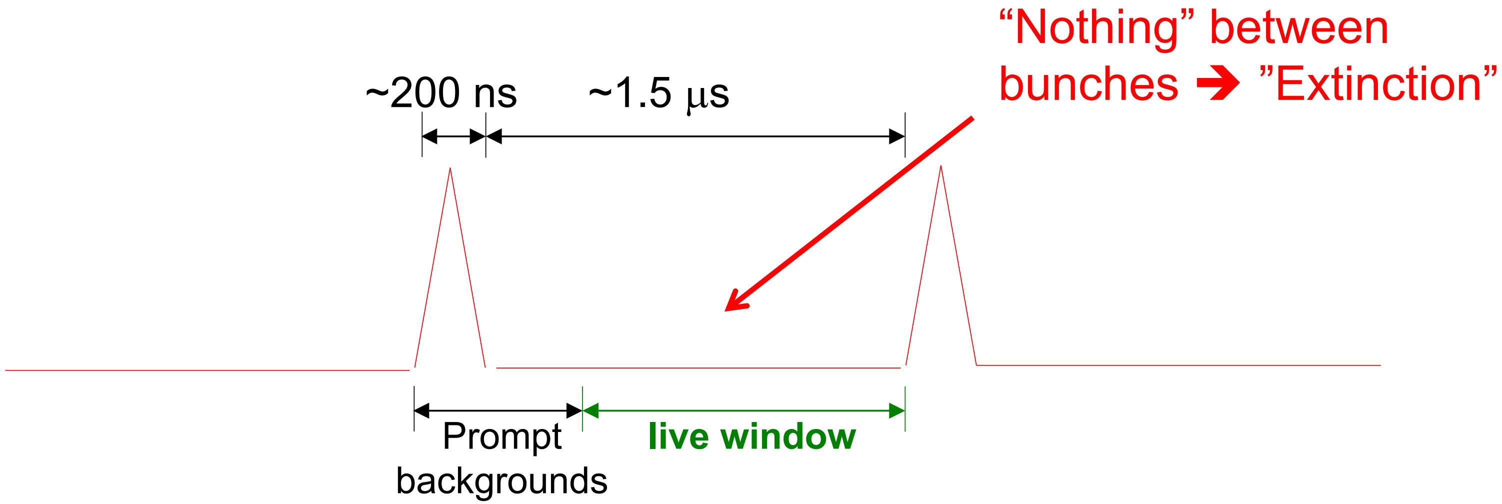


$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- Au \rightarrow e^- Au\right)}{\Gamma\left(\mu^- Au \rightarrow \text{capture}\right)} < 7 \times 10^{-13}$$

- Most backgrounds are ~prompt with respect to the proton 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 charged particle on the capture target*.
  - This leads to a fundamental to a rate limitation.

Pulsed Beams (first proposed for MELC*)

- Replace individual protons with short proton *pulses*, separated by a time on the order of a muon life time.
- Veto the time after the pulse to eliminate prompt backgrounds.



“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.

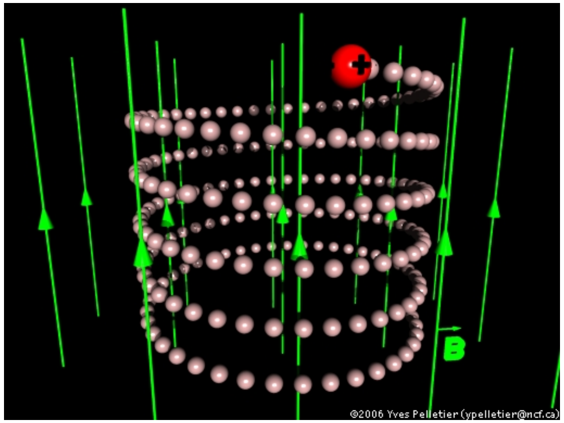
*1992, Moscow Meson Factory

Summary: Experimental Needs

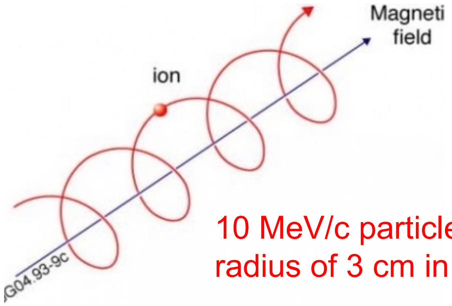
- Proton beam:
  - Bunches, separated by ~muon lifetime with “nothing” in between them.
- Muon transport:
  - Optimize for low momentum, *negative* muons
- Detector:
  - Completely blind to any particle with $p \lesssim 60$ *MeV/c*
  - Excellent energy resolution for *105 MeV* e^-
    - →Very low mass for both target and tracker!

Solenoids!

Refresher: Fun with Solenoids



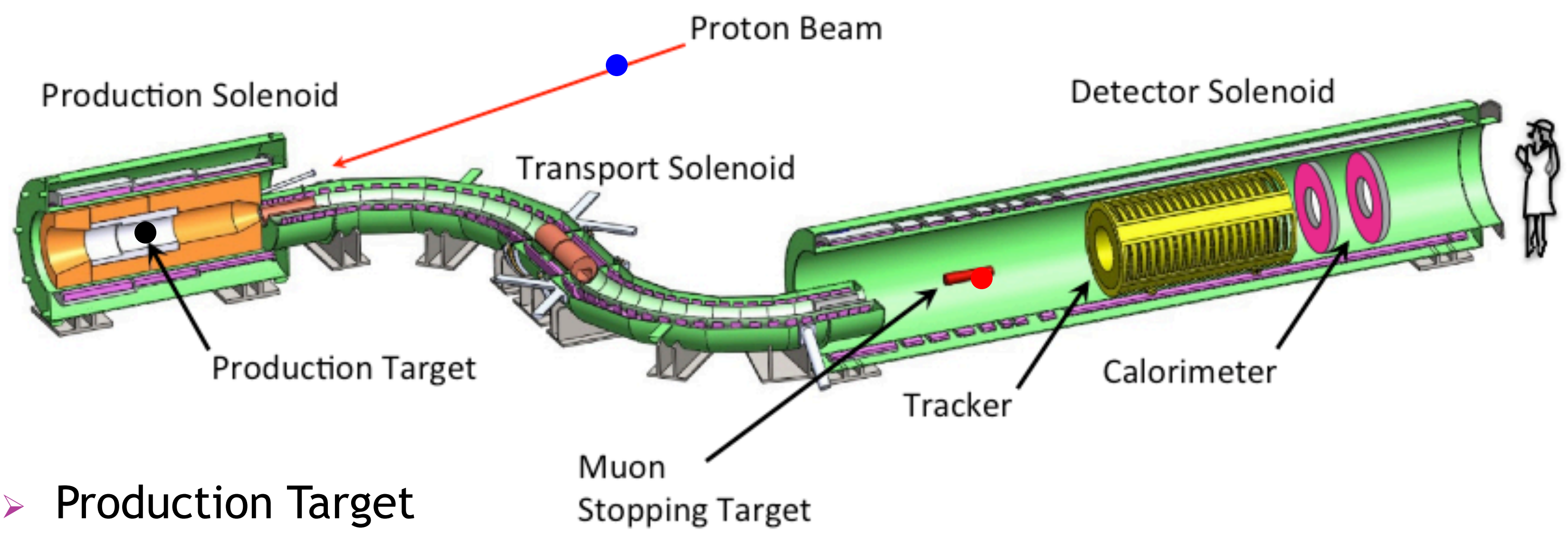
- Particles in a solenoidal field will generally move in a helical path
- Low momentum particles are effectively "trapped" along the field lines
  - We use this to transport muons



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

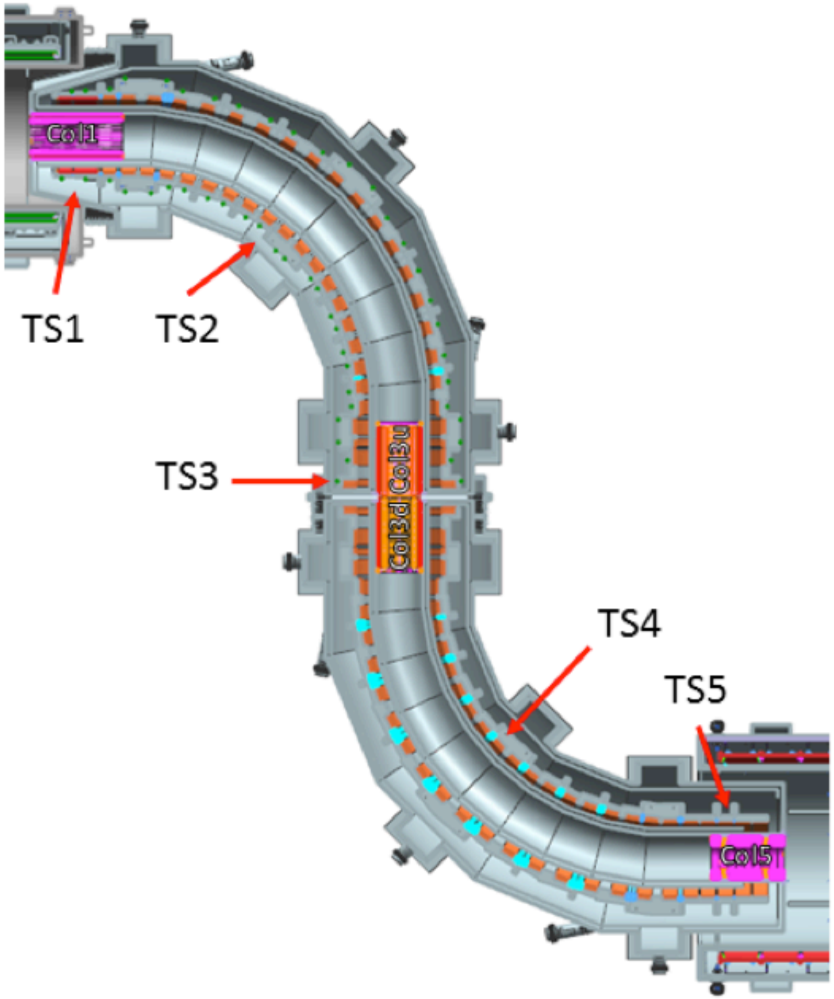
- A particle trapped along a *curved* solenoidal field will drift *out of the plane of curvature*
  - This is how we will resolve muon charge and momentum in the transport line
- For higher momentum particles, the curvature can be used to measure momentum
  - This is how we will measure the momentum of electrons from the capture target

Mu2e: The Big Picture

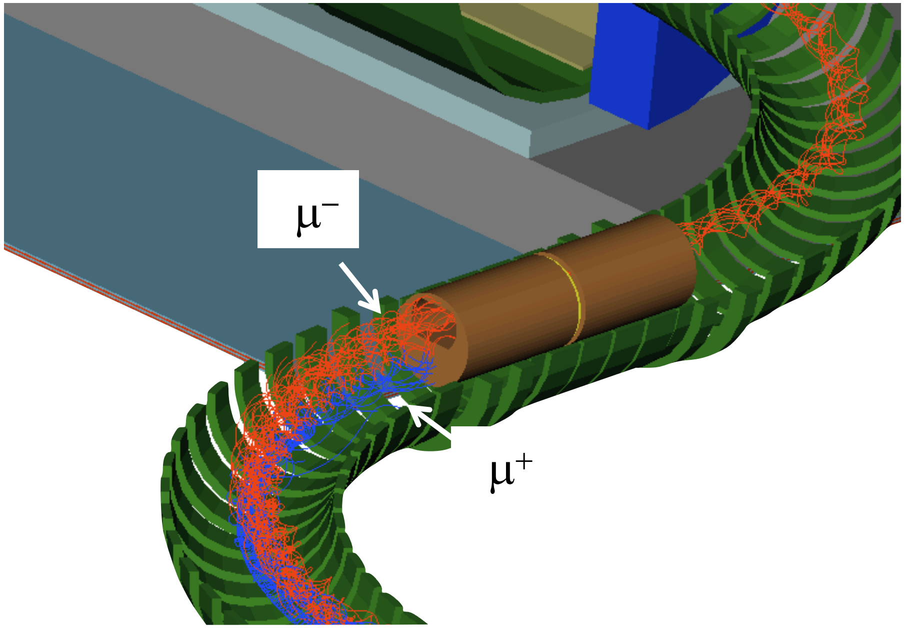


- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on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

Transport Solenoid

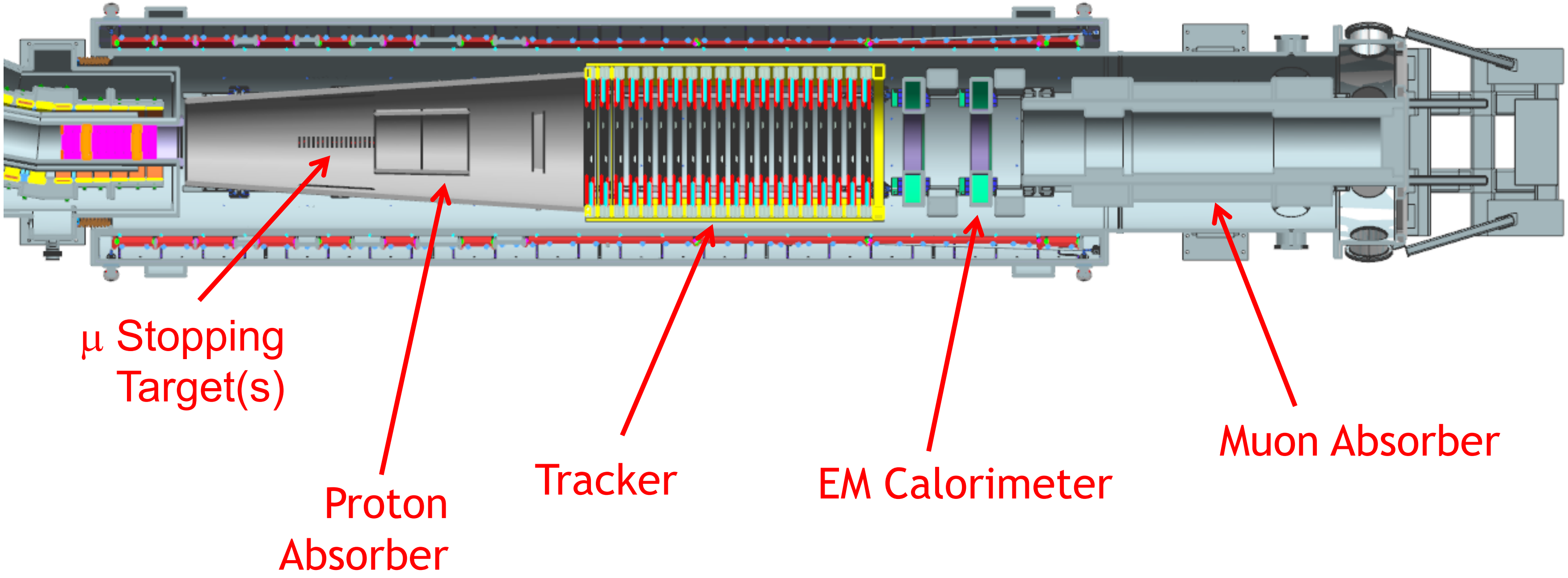


- Transports muons from production target to capture target
- Curved solenoid eliminates line-of-sight backgrounds
- Collimator in center selects low momentum negative muons
  - *RxB* drift causes sign/momentum dependent *vertical* displacement



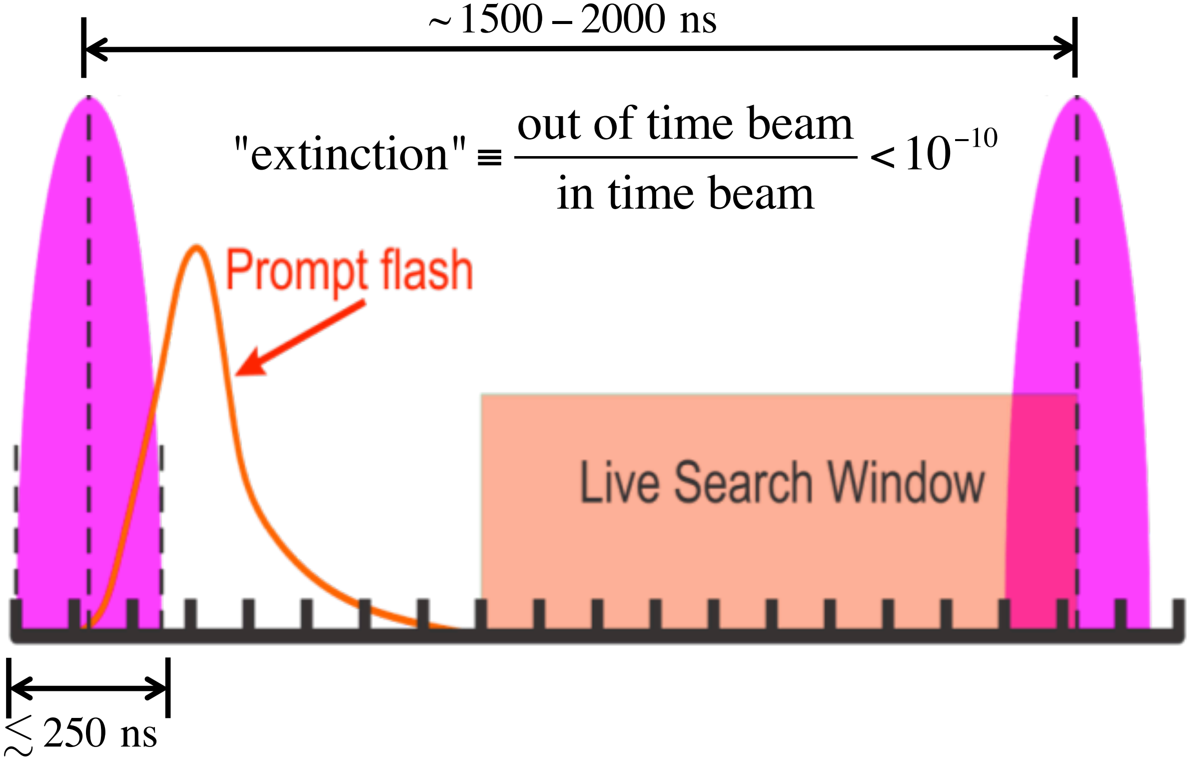
Detector and Detector Solenoid

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



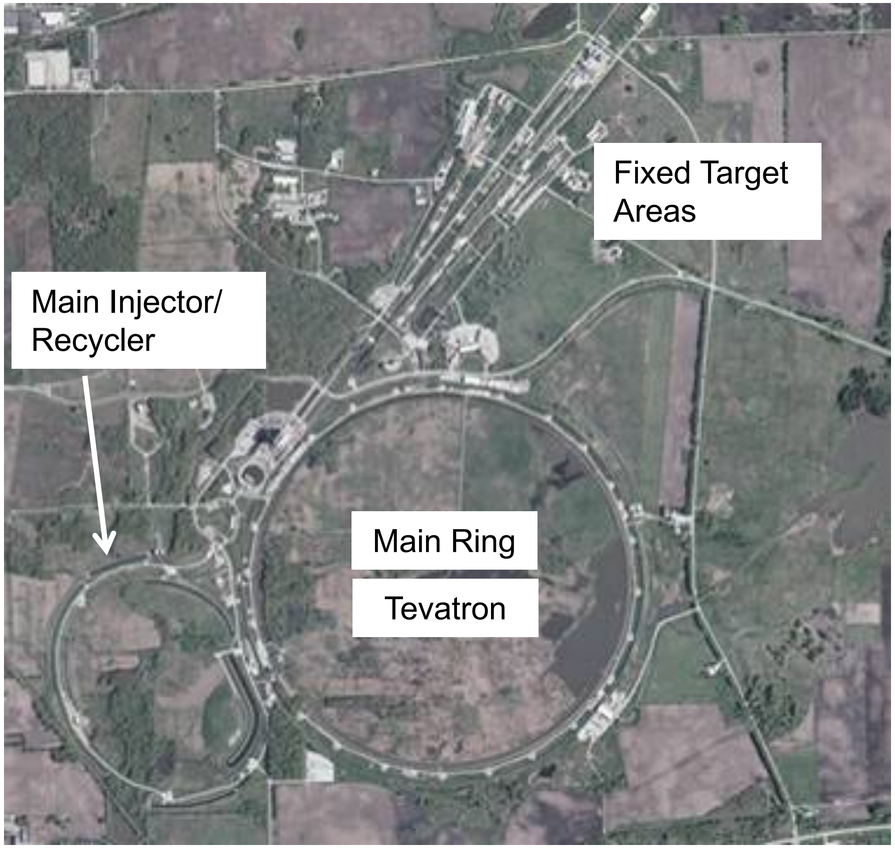
Beam Needs

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

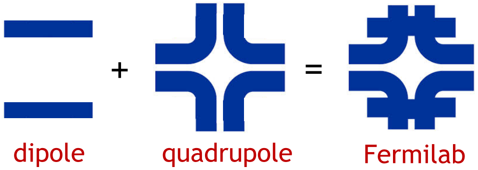


- This is where Fermilab comes in…

A Brief History of Fermilab



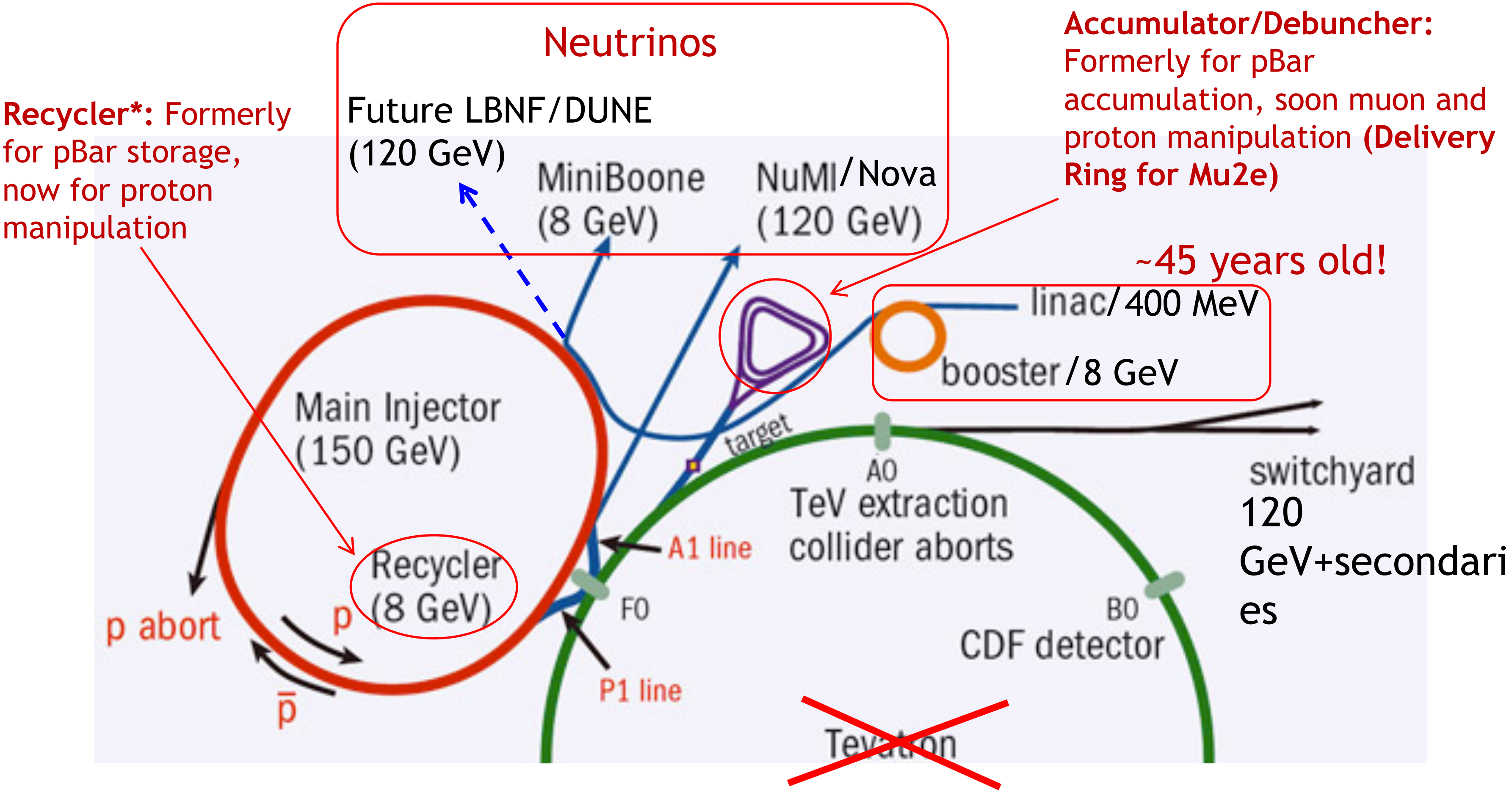
Trivia: original Main Ring was the first “separated function” synchrotron



- 1968: construction begins
- 1972: first beams from Main Ring
  - 200→400 GeV proton beams to fixed targets
  - Highest energy lab for next 36 years!
- ~1985:
  - “Tevatron”: first superconducting synchrotron shares tunnel with Main Ring
  - 900GeV x 900 GeV p-pBar collisions
  - Highest energy collider for 23 years.
- 1997: Major upgrade
  - Main Injector replaces Main Ring -> more intensity
  - 980 GeV x 980 GeV p-pBar collisions
  - Intense neutrino program
- 2011: Tevatron permanently turned off after the LHC came full online.
- So what is the lab doing now?

Fermilab Accelerator Complex Today

- Now that LHC has taken over the Energy Frontier, Fermilab is focusing on intensity-based physics



Recycler*: Formerly for pBar storage, now for proton manipulation

Neutrinos

Future LBNF/DUNE (120 GeV)

MiniBoone (8 GeV)

NuMI/Nova (120 GeV)

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

~45 years old!

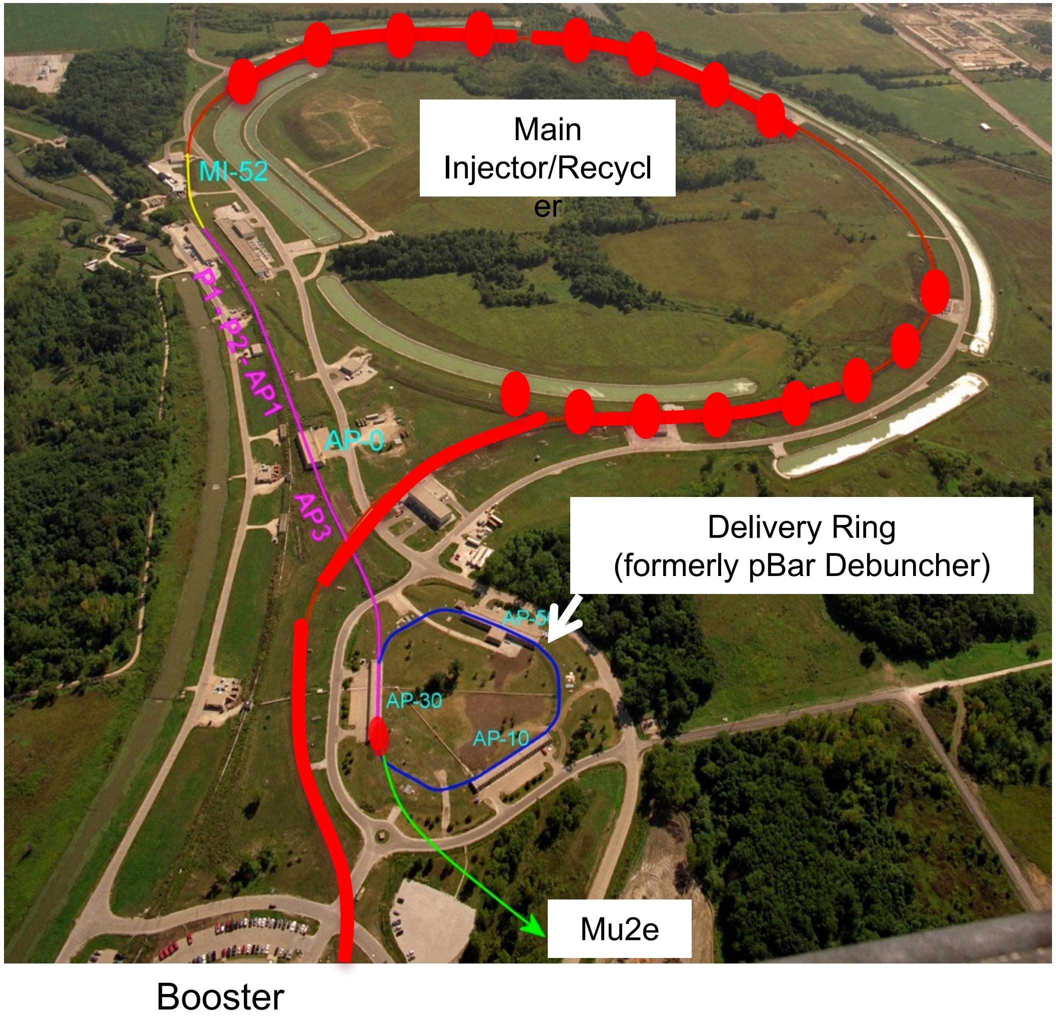
linac/400 MeV

booster/8 GeV

switchyard 120 GeV+secondaries

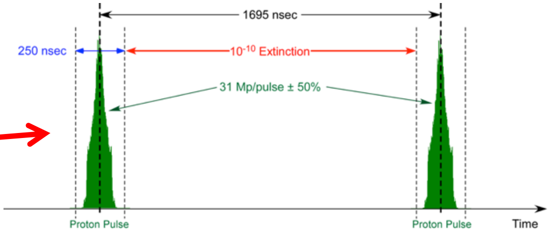
*first permanent magnet storage ring

Mu2e Proton Delivery

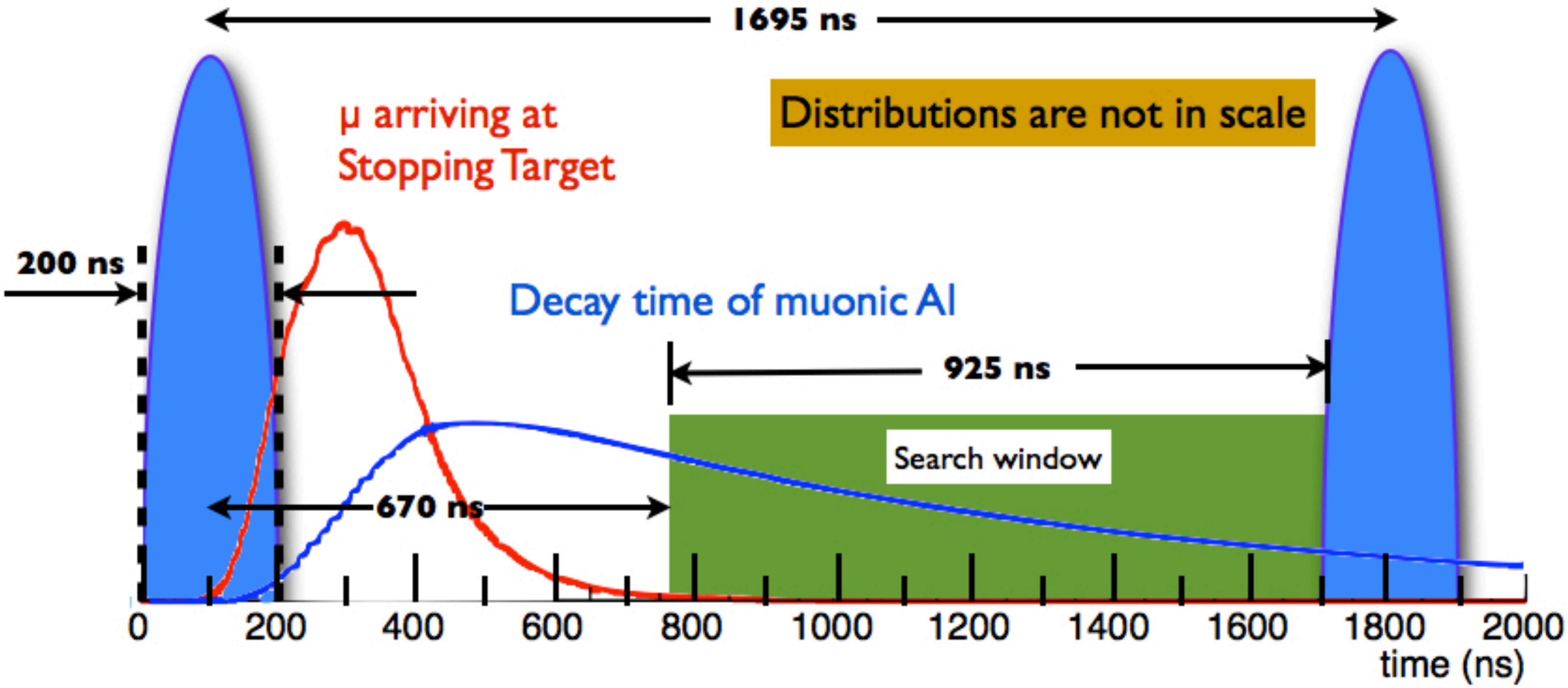


- Two Booster “batches” are injected into the Recycler (8 GeV storage ring). Each is:
  - 4×10^{12} protons
  - 1.7 μsec long
- These are divided into 8 bunches of 10^{12} each
- The bunches are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As the bunch circulates, it is resonantly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

Exactly what we need →



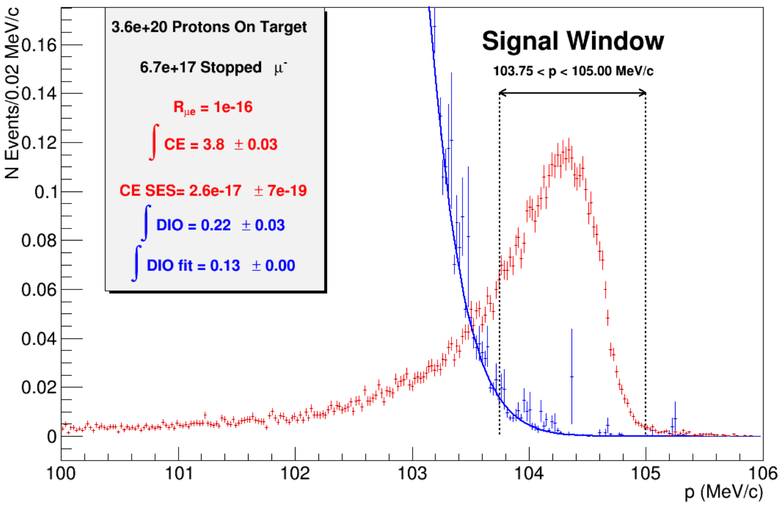
End Product



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

Sensitivity

- Full Simulation (GEANT4)
- $3.6\mathrm{x}10^{20}$ protons on target
  - 3 years nominal running
- Cuts chosen to maximize sensitivity



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

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

Significance

- Backgrounds

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

8 GeV is a stupid energy!

- 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

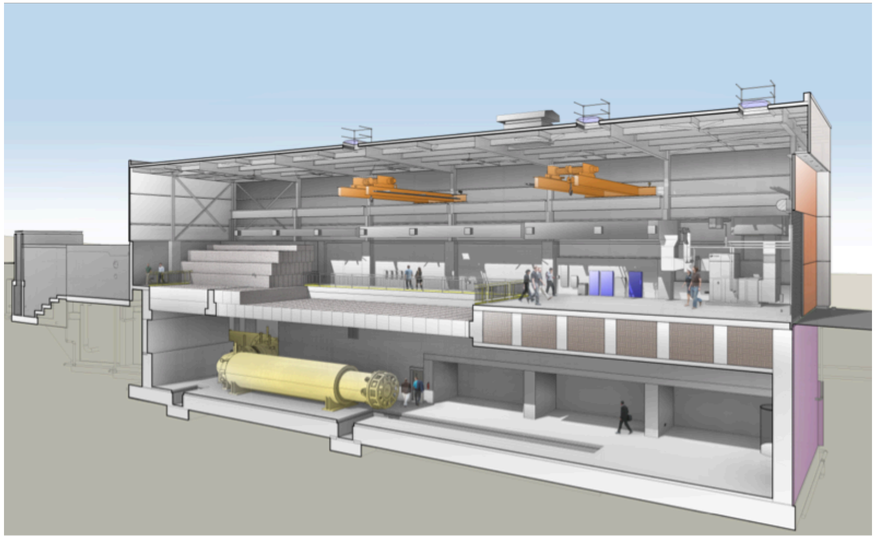
4 order of magnitude improvement!

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 operation)	
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	In DOE project-speak, this is the first "Critical Decision": Statement of mission need = official existence
July 2012	CD-1	
March 2015	CD-2/3b	Approval of baseline and money for long lead elements
June 2016	CD-3c	Full speed ahead!

Finally, things are really happening!

We have a home!



March, 2016

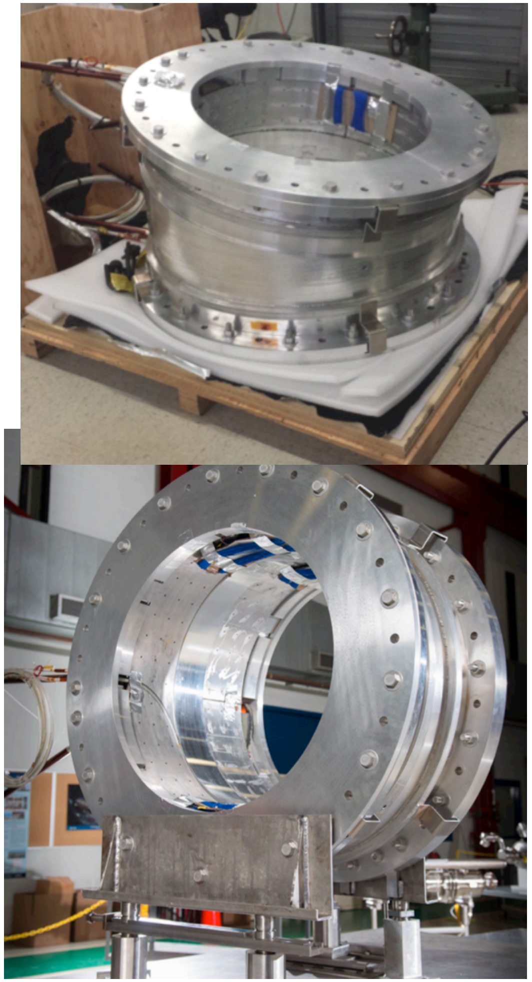
Completed Mu2e hall – Dec 2016

February 10, 2017

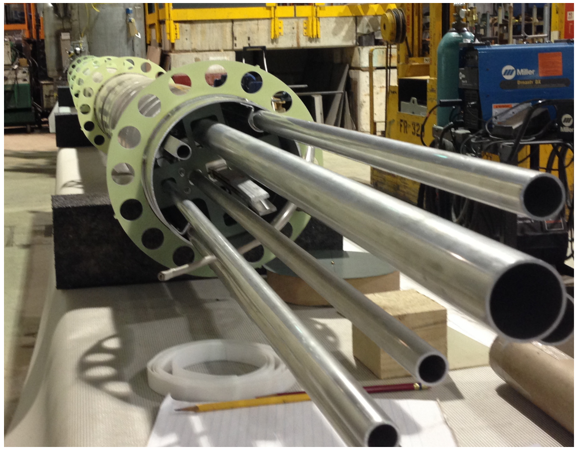
Magnet Procurement and Testing

Cable acceptance

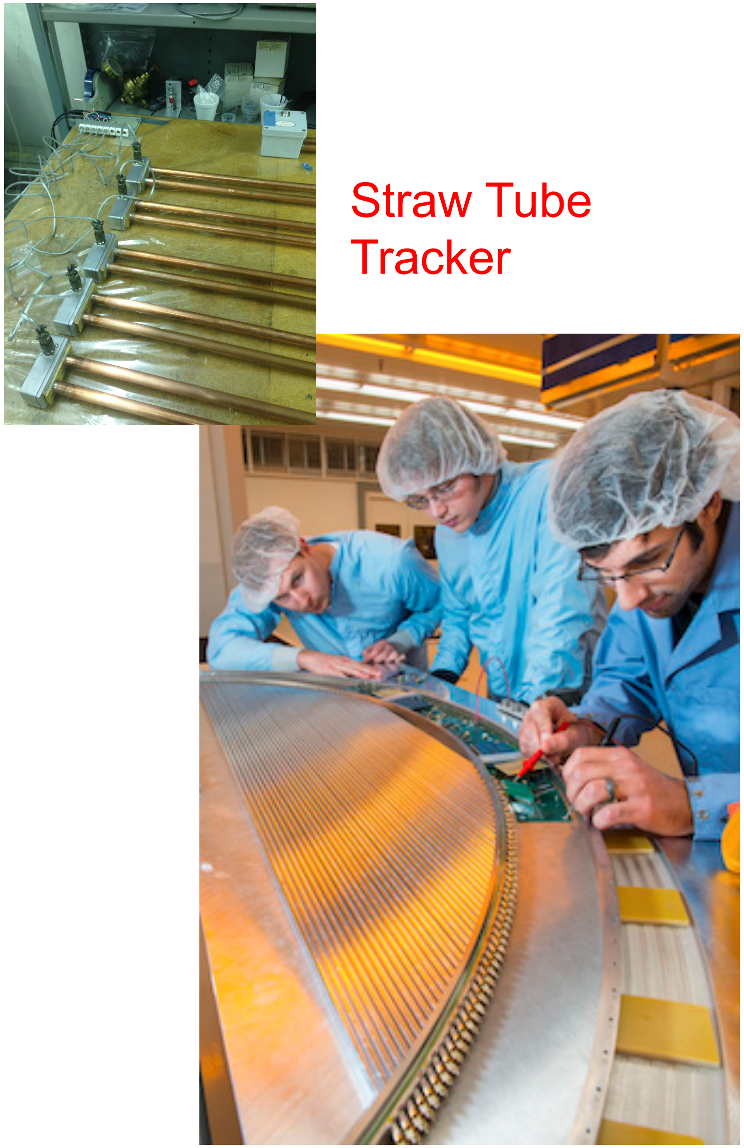
Successful test of Transport Solenoid segment



Prototype of Helium transfer line

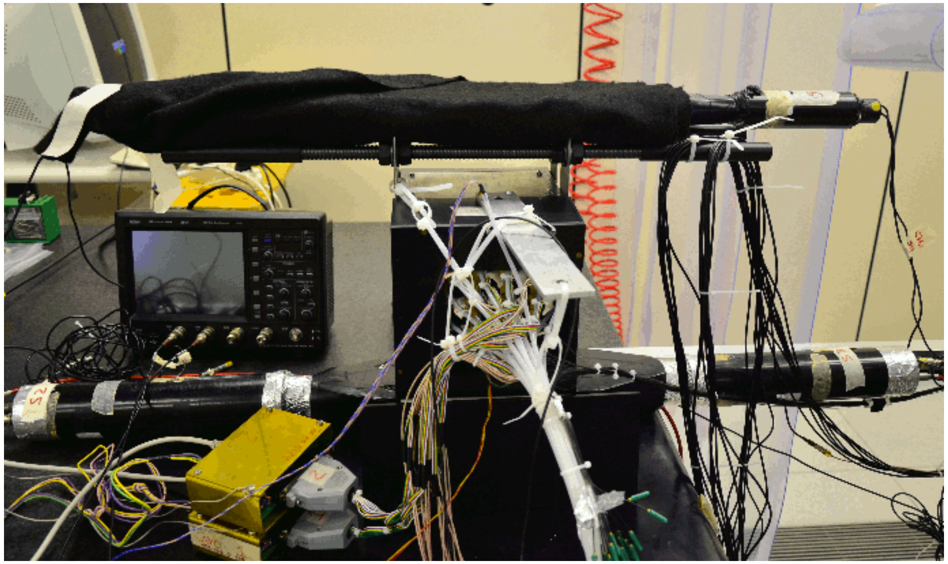


Detectors



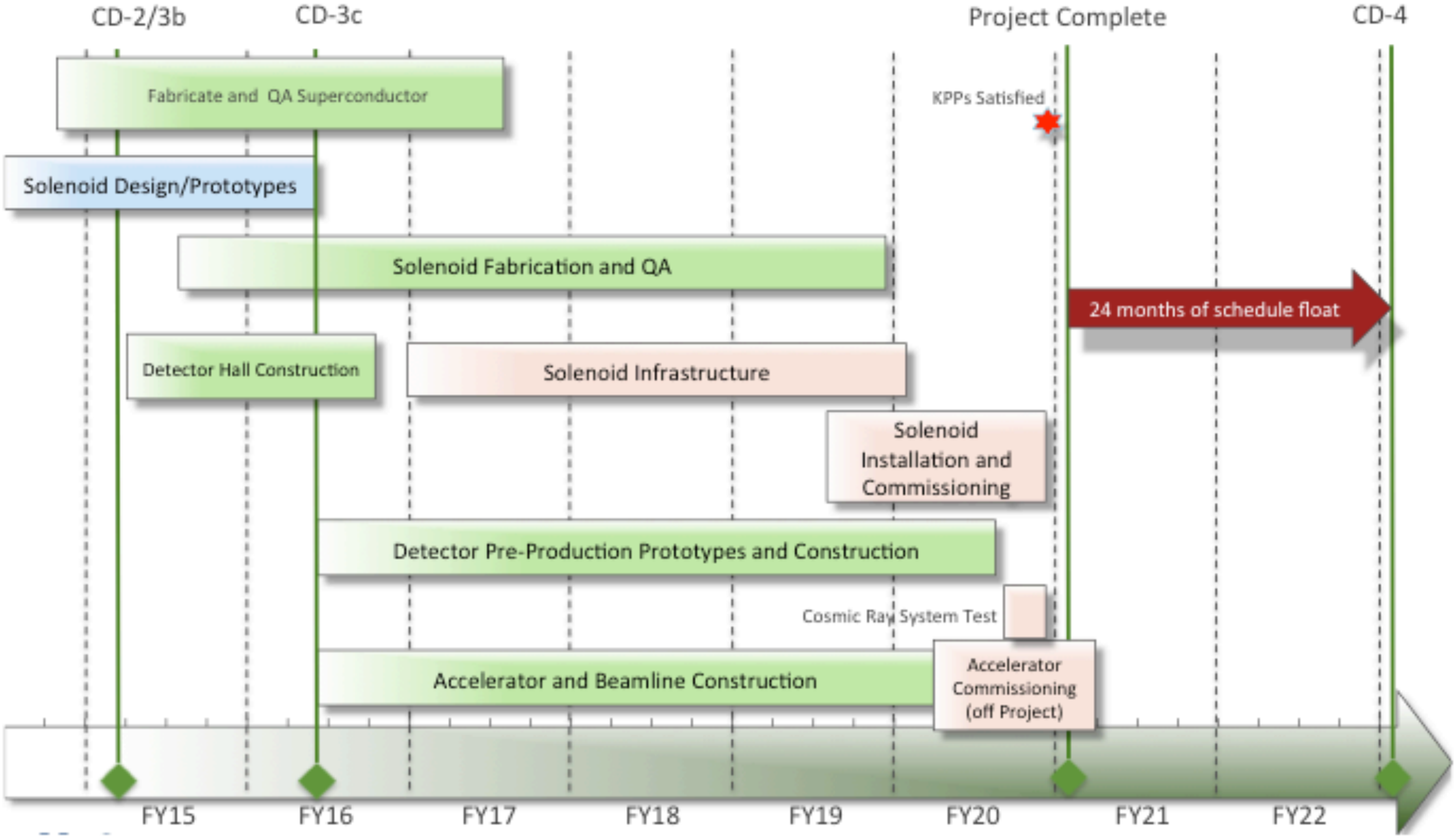
Straw Tube Tracker

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

Some things to think about

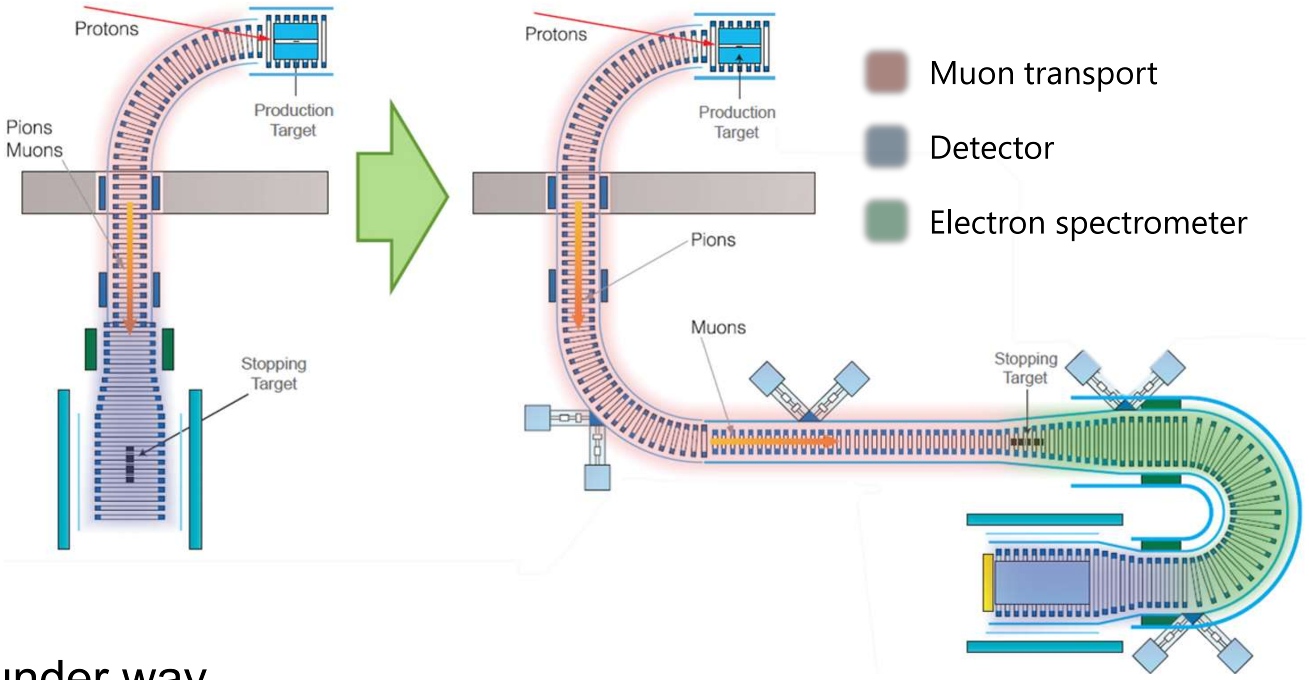
- Mu2e has a nominal plan to run for three years to collect 3.6×10^{20} protons on target.
- This will enable us to measure $R_{\mu\varepsilon}$ with a sensitivity 10,000 times greater than the previous best measurement.
- This means that we will potentially be able to improve on that measurement with *a few hours of running* at nominal intensity.
- We need to develop a plan to roll out results with improved sensitivity of, say 1,10,100,100,10000
- This has implications for how well we will need to understand the detector at each step, our blinding procedures, etc.
- Not a lot of thought has gone into this (yet).

The competition: COMET at J-PARC (Japan)

- The COMET experiment is based on the same principle as Mu2e, and will use 8 GeV beam from the J-PARC Main Ring
- It is currently being planned in two phases*

Phase I

Phase II



🟫 Muon transport

🟦 Detector

🟩 Electron spectrometer

- Well under way
- Beam scheduled for 2019
- Goal: SES = 3×10^{-15}
  - 100 times less sensitive than Mu2e

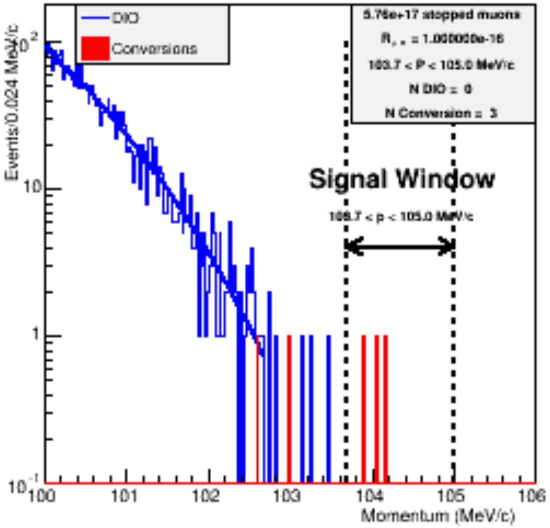
- ~mid 2020s
- Goal: SES = 3×10^{-17}
  - Same as Mu2e

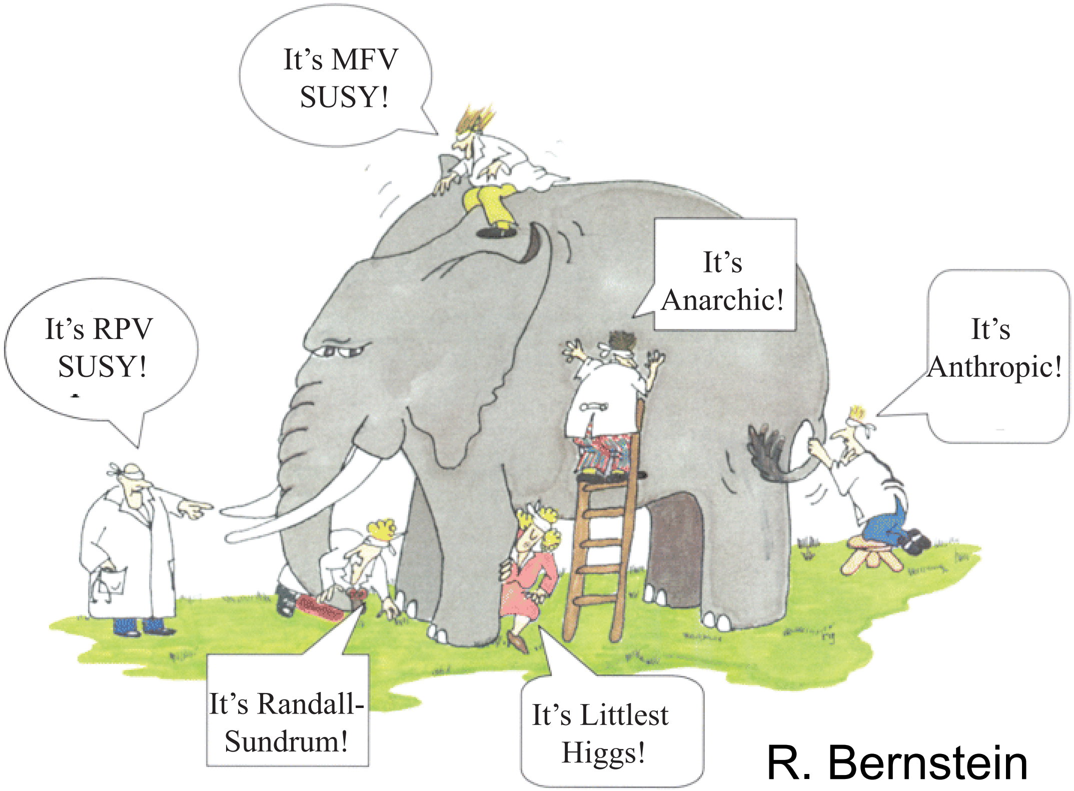
*Phil Litchfield, PASCOS 2016

What if we see something?

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

Toy Mu2e Experiment



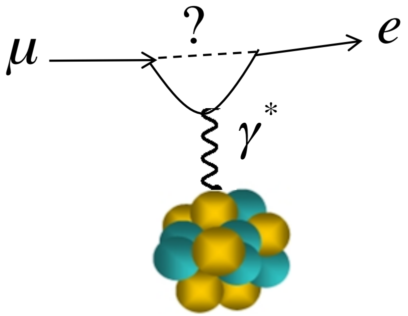


R. Bernstein

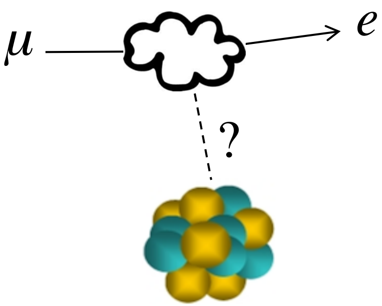
- Next questions:
  - What do other experiments see?
  - What's the target dependence?

First question: what does μ→eγ see?

- If the process is purely of this form (dipole), both the size of the μ→*e*γ signal and the target dependence are tightly constrained (and easily calculated)



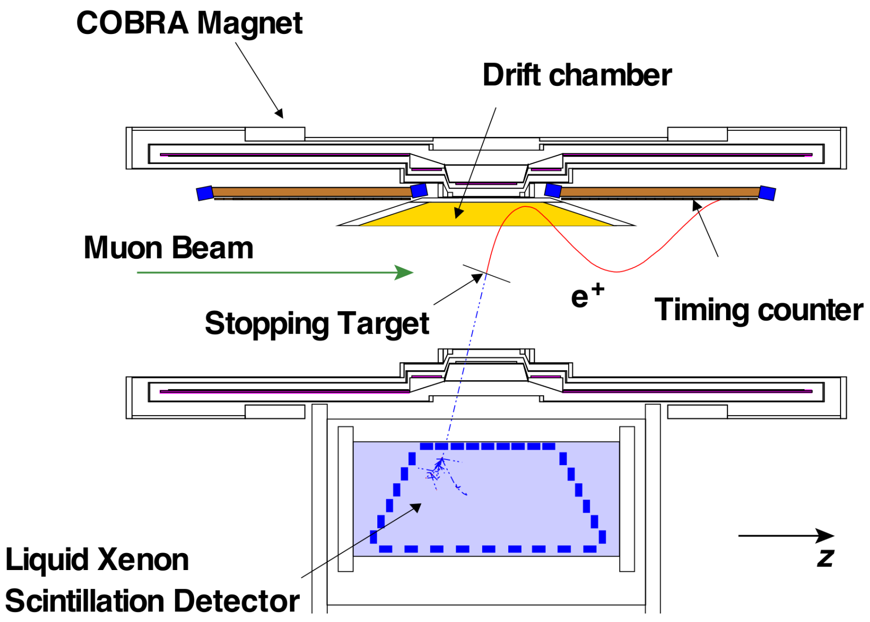
- On the other hand, if the process is of this form (4-Fermi) then μ→*e*γ will never see any signal



- If both experiments see signals, but the relative sizes or target dependence aren't what is predicted, it must be some combination of the two classes.

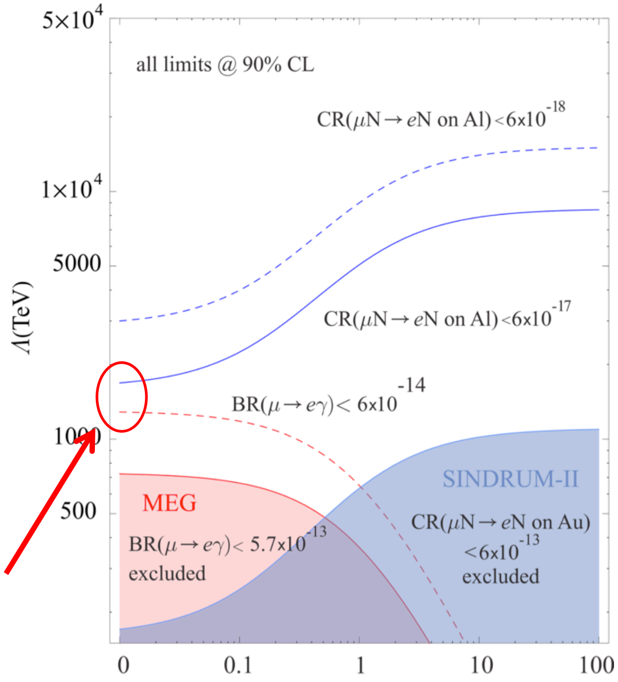
MEG Experiment (PSI, Switzerland)

- The MEG experiment looks for $\mu^+ \rightarrow e^+\gamma$ in stopped muons, produced by the high intensity proton cyclotron at the Paul Scherrer Institute



Latest Results*

- 7.5×10^{14} stopped μ^+
- $BR(\mu^+ \rightarrow e^+\gamma) < 4.2\times10^{-13}$ (90% C.L.)



- Goal: $BR(\mu^+ \rightarrow e^+\gamma) < 5\times10^{-14}$
  - Competitive with Mu2e for dipole reaction

* Eur. Phys. J. C (2016) **76**: 434

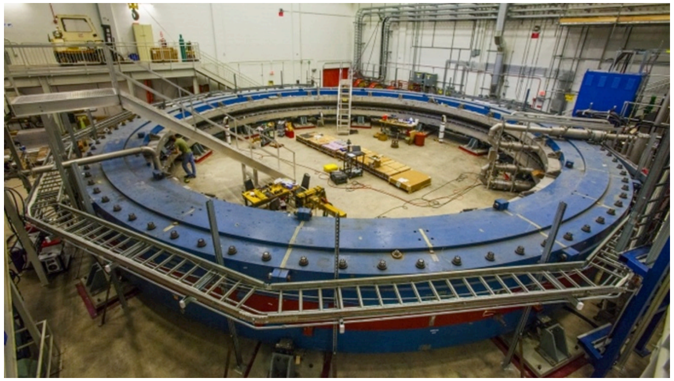
Other non-Standard Model Searches

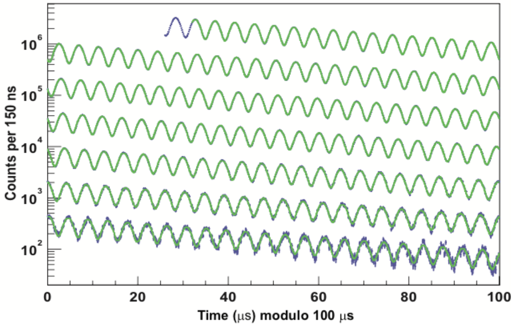
- Other ongoing or proposed experiments are investigating physics beyond the Standard Model, including
  - neutron EDM
  - electron EDM
  - $D \leftrightarrow \bar{D}$ mixing
  - $n \leftrightarrow \bar{n}$ mixing
  - Anomalous rare decays, including $K \rightarrow \pi\nu\bar{\nu}$
  - Anomalous magnetic moment of the muon (g-2)
    - Major initiative at Fermilab…

g-2 at Fermilab

- Along with Mu2e, the g-2 experiment is an important part of the near term plan at Fermilab
  - The muon magnetic moment is given by $\vec{\mu}_\mu = g\frac{e}{2m}\vec{S}$
  - Without higher order corrections, *g* would be exactly 2
  - The difference ("g-2") is sensitive to both Standard Model effects and (potentially) new physics
  - In 2001, an experiment at Brookhaven found a ~3σ discrepancy with the Standard Model
  - That device was moved to Fermilab in 2013, and will soon begin taking data, aiming for 4 times the statistics (3σ→7.5σ)

Arrival: 7/26/2013

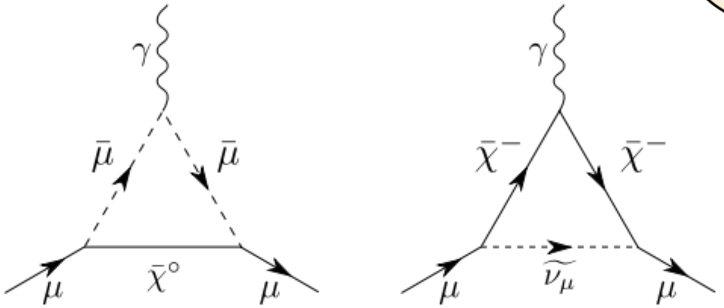




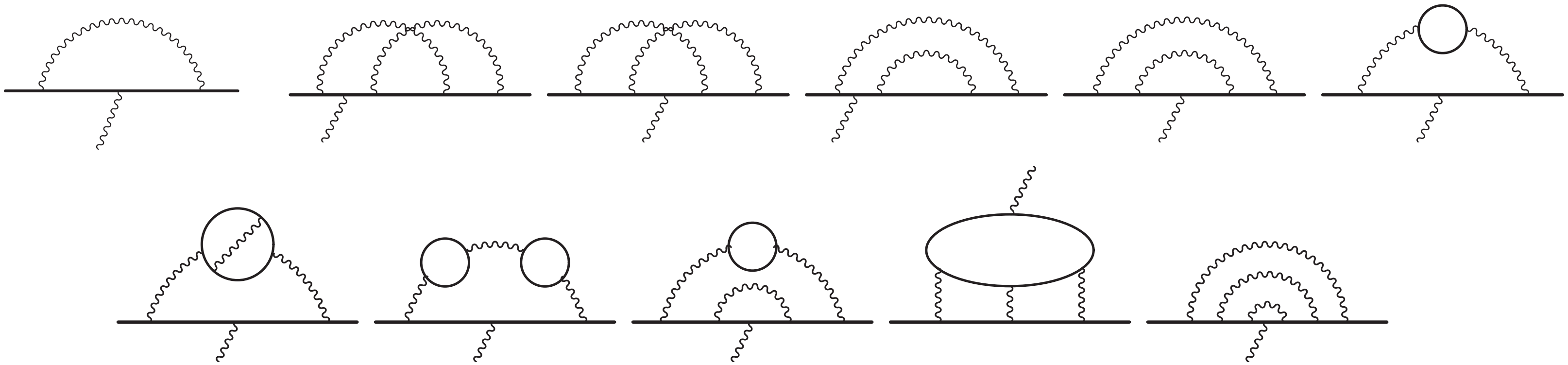
Measure the anomalous precession of muons in a uniform magnetic field

The Challenge of g-2

- g-2 is sensitive to new physics, such as SUSY



- However, you must *first* properly account for the Standard Model contributions, including diagrams like*



where the interior lines can be leptons or quarks, and both theoretical calculations and experimental input are required.

*Aoyama, *et al* ProgTheorExpPhys. 2012, 01A107

Synergy of Mu2e with LHC

- The Mu2e Experiment is well timed with the luminosity upgrade of the LHC
- A limit (null result) from Mu2e would rule out many signals
  - Most flavor violating searches would be ruled out for masses much higher than even the FCC
  - Most of SUSY parameter space would be ruled out except for models specifically concocted to minimize flavor violation (e.g. “CKM models”)
- A positive result would give lots of guidance for searches, and could also set the energy scale of the next machine.

Conclusions

- We have propose a realistic experiment to measure

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

  - 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
  - And would set the scale for future searches
- The absence of a signal would be a very important constraint on proposed new models.
  - And limit the space for new discoveries, even at the highest energies

BACKUP SLIDES

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

← Sindrum limit

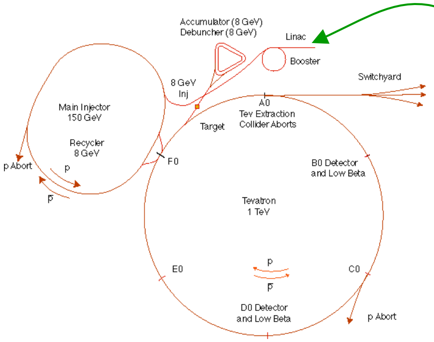
Single event sensitivity of Mu2e

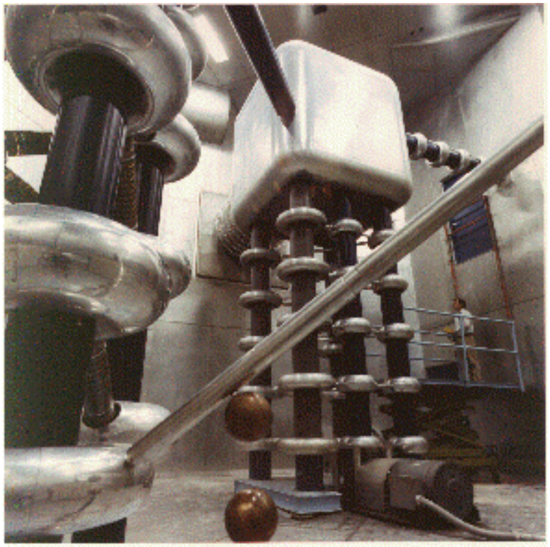
Experimental Challenges for Increased Flux

- 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

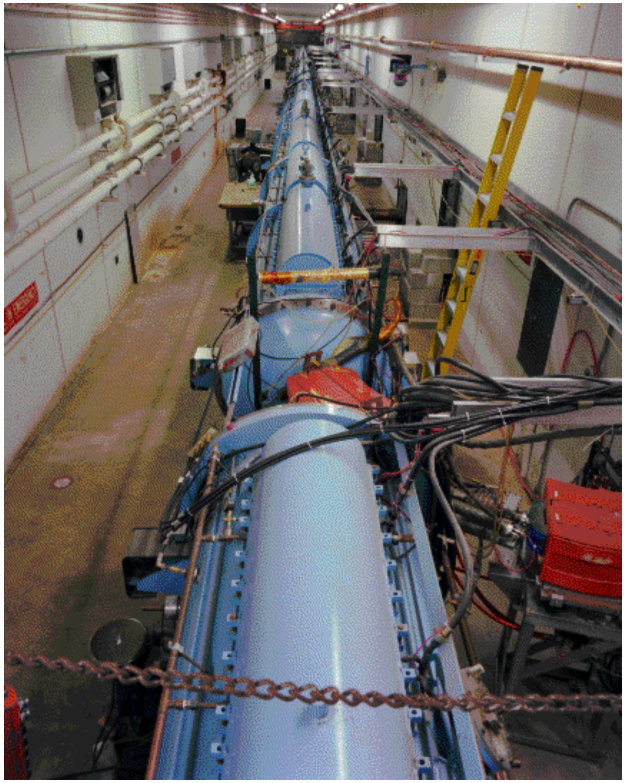
    ➔ go to bunched, mono-energetic muon beam, allowing for thinner target
- Allow longer decay time for pions to decay
- Both of these lead to a decay/compressor ring
- Other issues with increased flux
  - Upgrade target and capture solenoid to handle higher proton rate
    - Target heating
    - Quenching 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 $\mu\to e\gamma$ rate

Preac(cellerator) and Linac



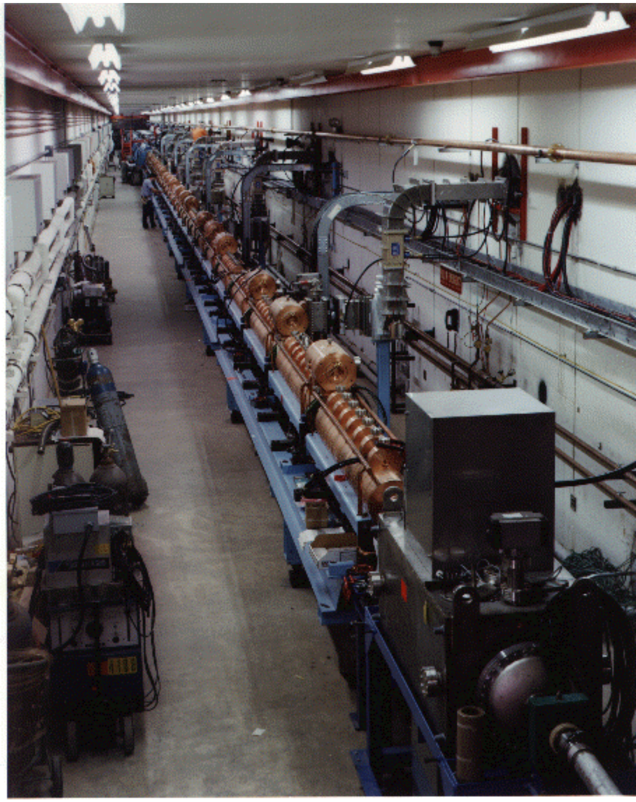


"Preac" - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.

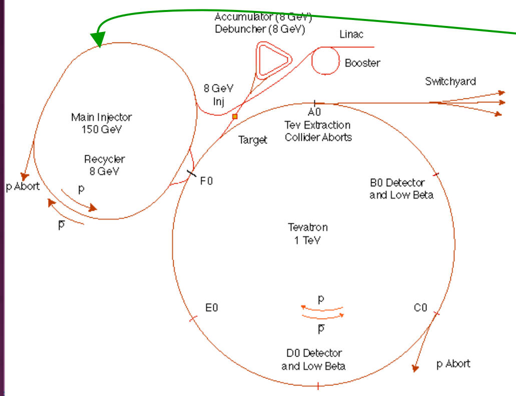


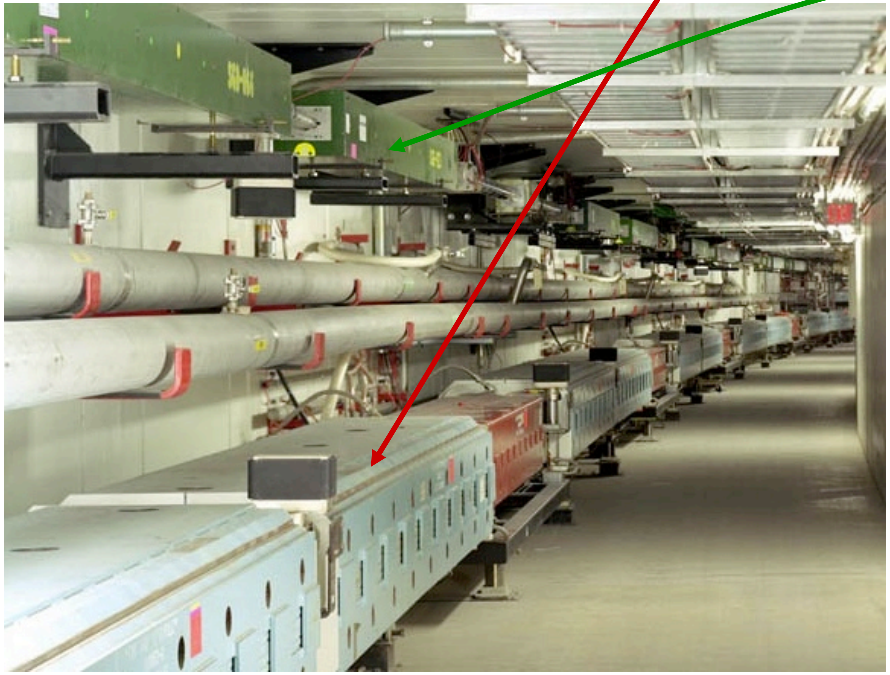
"Old linac"(LEL)- accelerate H- ions from 750 keV to 116 MeV

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



Main Injector/Recycler

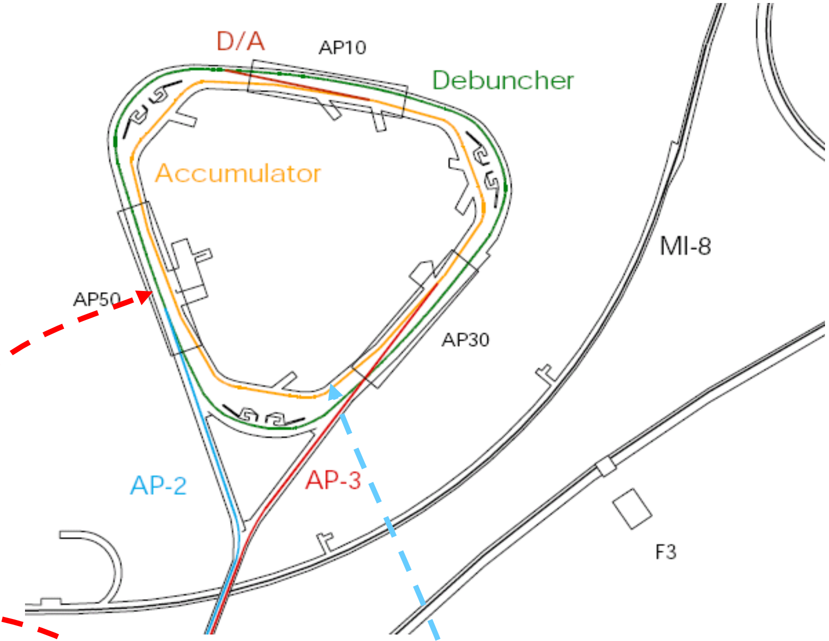


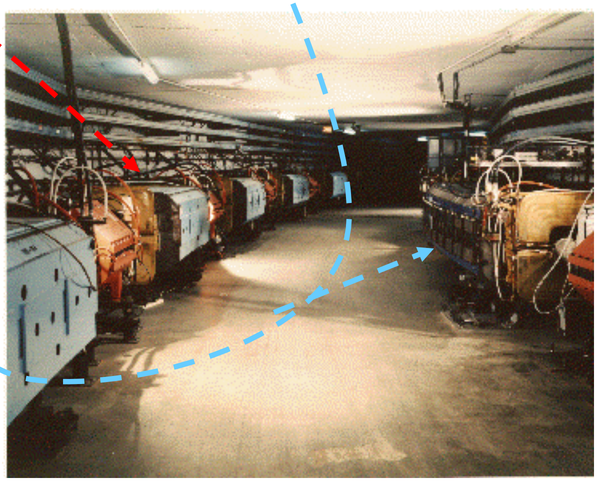


- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The 8 GeV Recycler (which shares the same tunnel and stores antiprotons)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.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

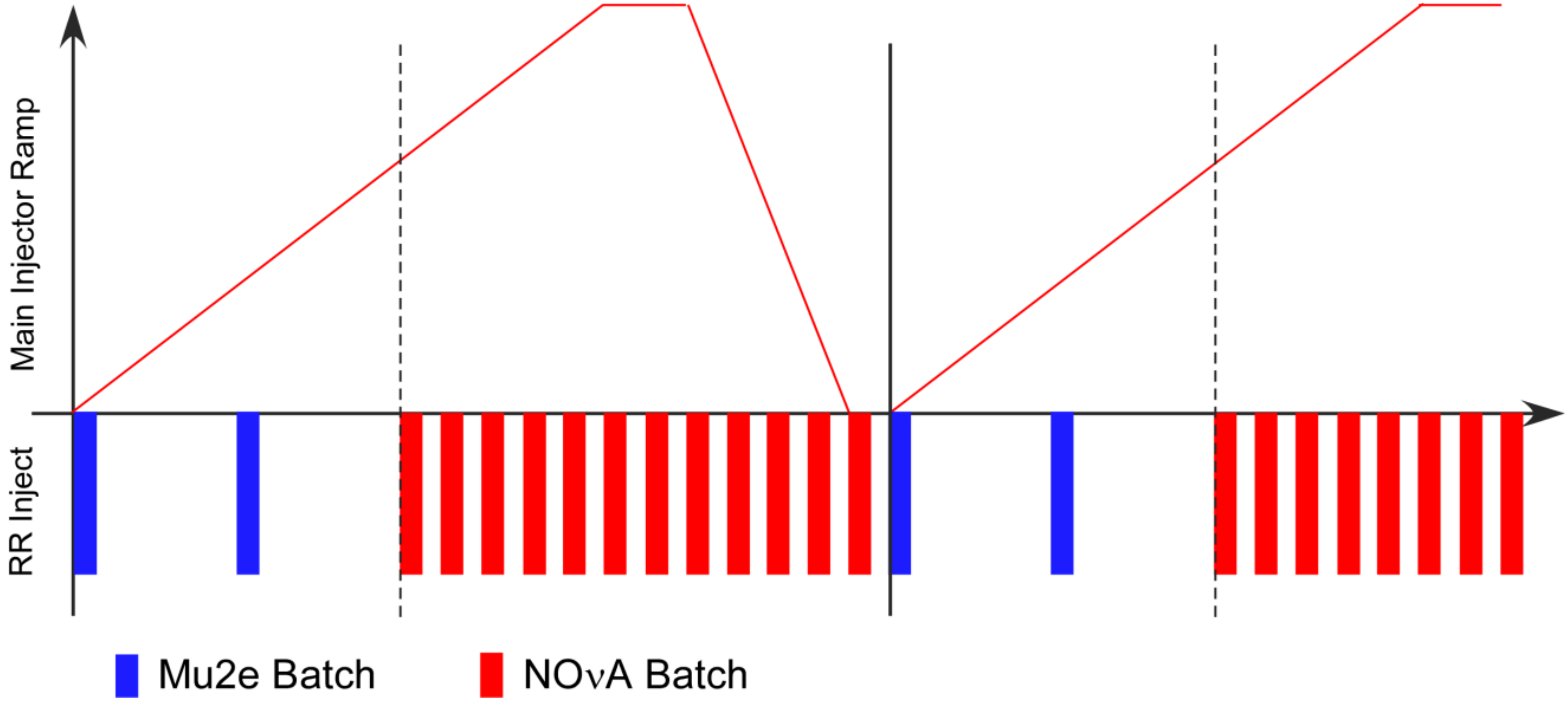
- Protons are accelerated to 120 GeV in Main Injector and extracted to pBar target
- pBars are collected and phase rotated in the "Debuncher"
- Transferred to the "Accumulator", where they are cooled and stacked
- pBars not used after collider.



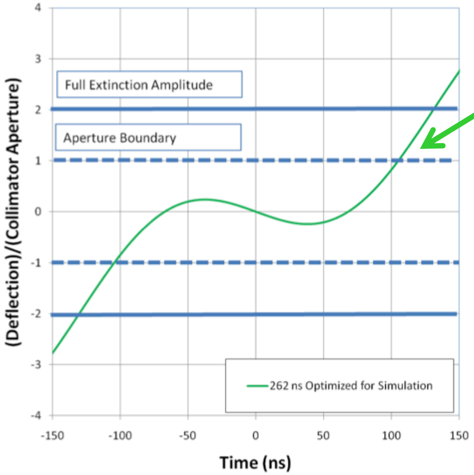


Mu2e in the NOvA era

- Beam Delivered in 15 Hz "batches" from the Fermilab Booster

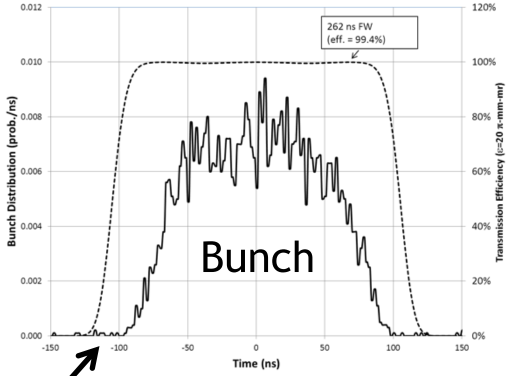


Extinction Performance

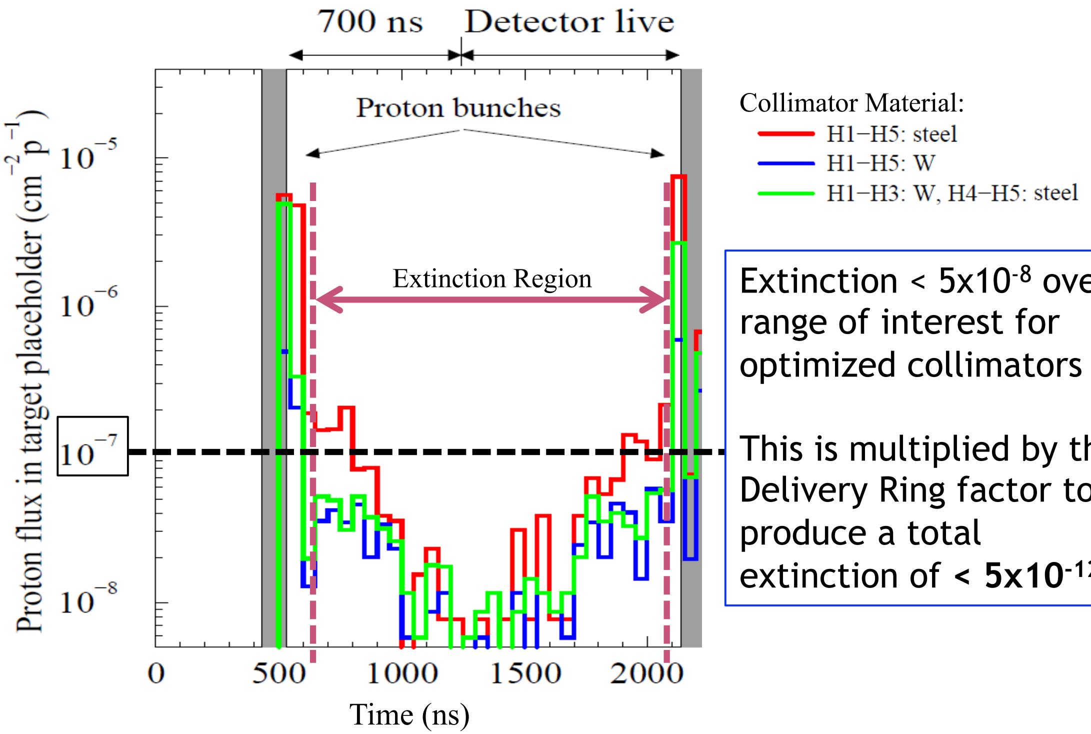


Beam motion in Collimator

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



Transmission Window



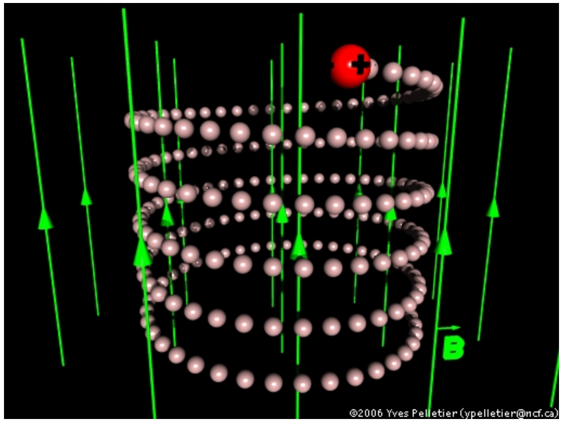
Extinction < 5×10^{-8} over range of interest for optimized collimators

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

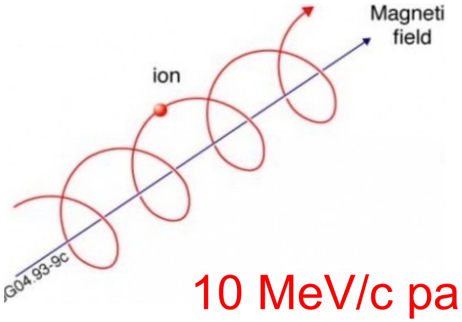
- Additional 10^{-5} extinction from beam delivery system

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



©2006 Yves Pelletier (ypelletier@ncf.ca)



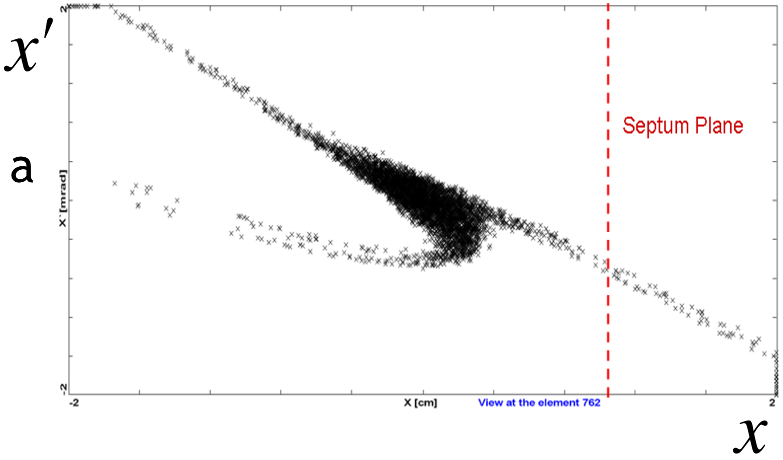
10 MeV/c particle will have a radius of 3 cm in a 1 T field

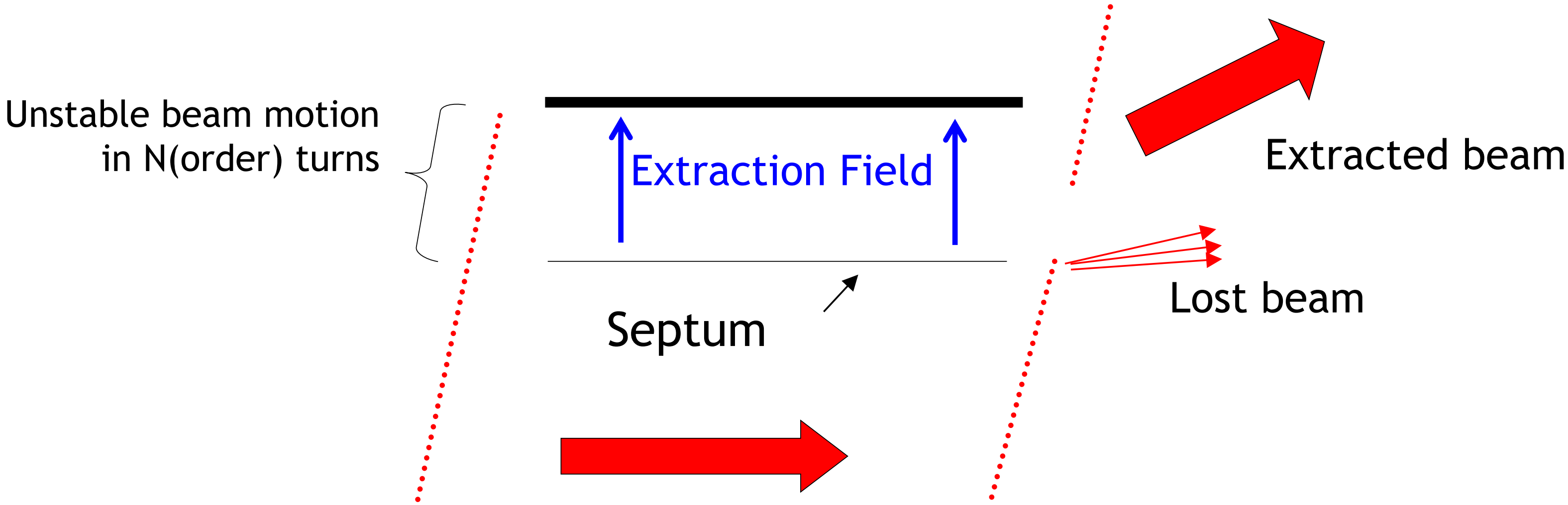
Can be used to resolve charge and momentum!

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

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

Extraction Field

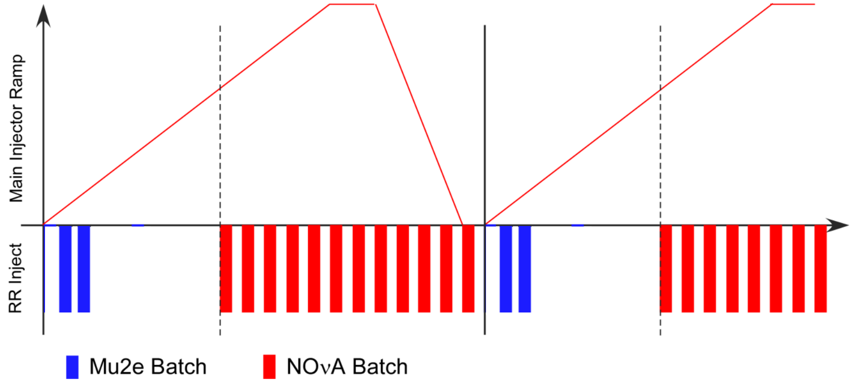
Septum

Extracted beam

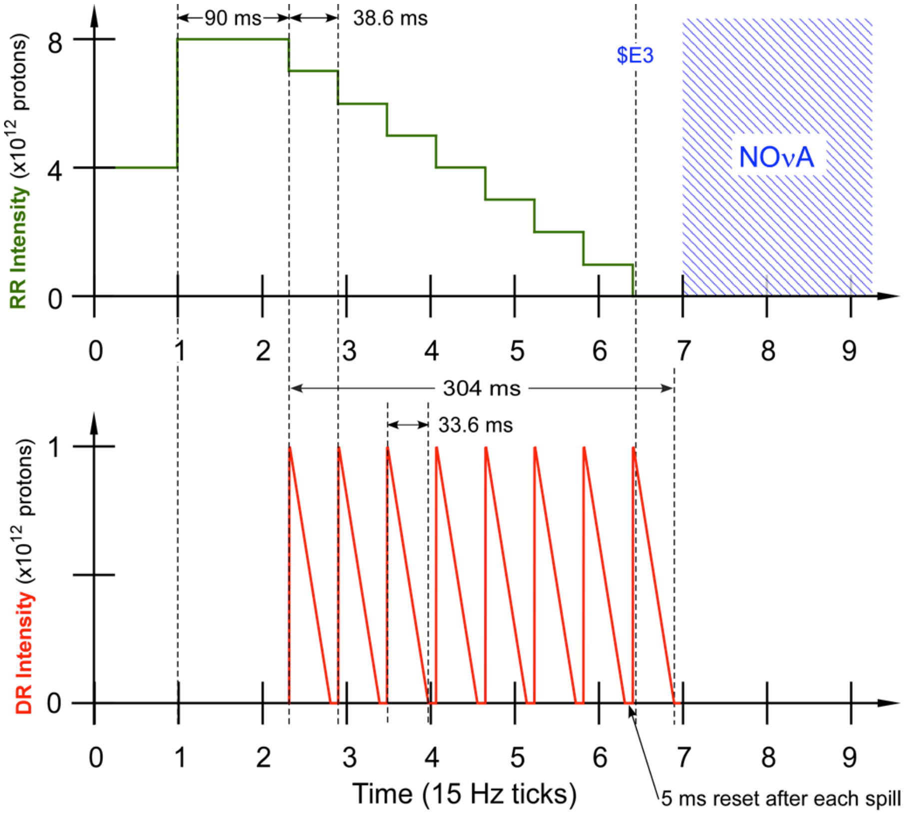
Lost beam

Mu2e Spill Structure

1.33 sec Main Injector cycle

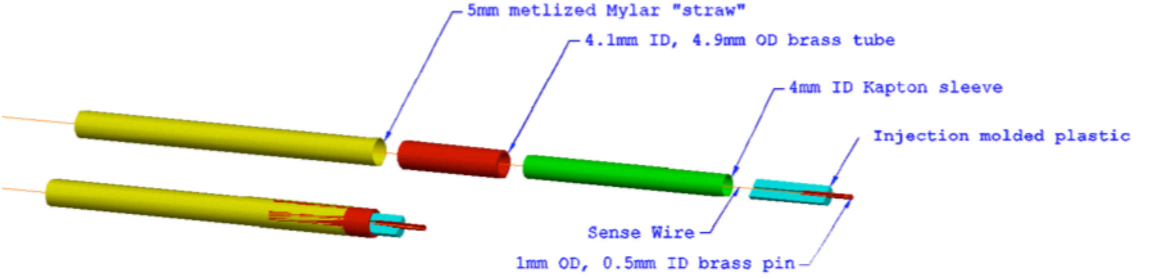


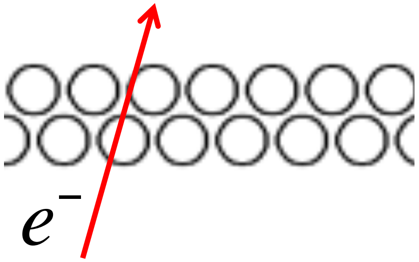
- **Detail:**
  - $3x10^7$ p/bunch
  - 1.7 μsec bunch spacing
  - ~30% duty factor
  - ~$1.2x10^{20}$ protons year



Particle Tracking Technology

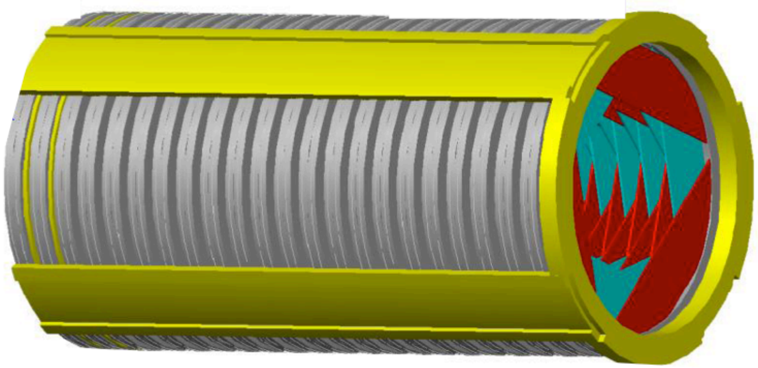
- To achieve the required resolution, must keep mass as low as possible to minimize scattering
- We've chosen transverse planes of "straw chambers" (~23,000 straws)





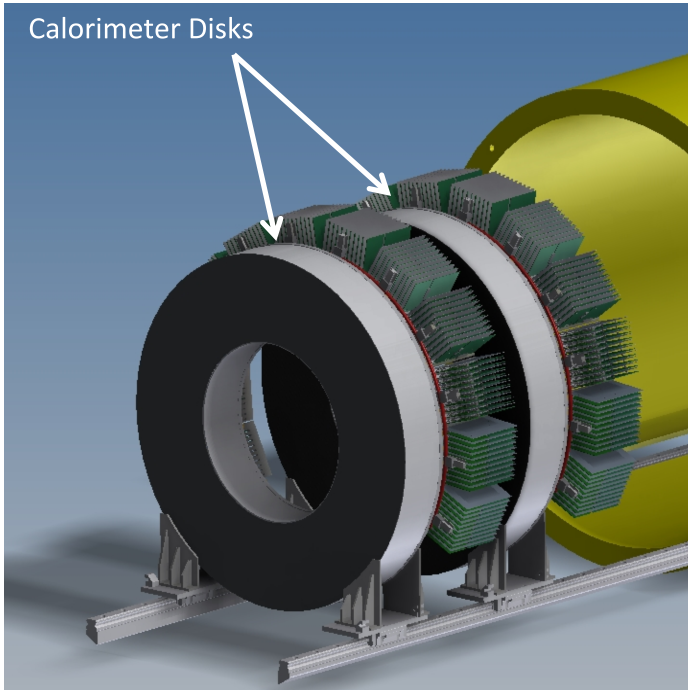
- Track ionizes gas in tube
- Charge drifts to sense wire at center
- Drift time gives precision position

- 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



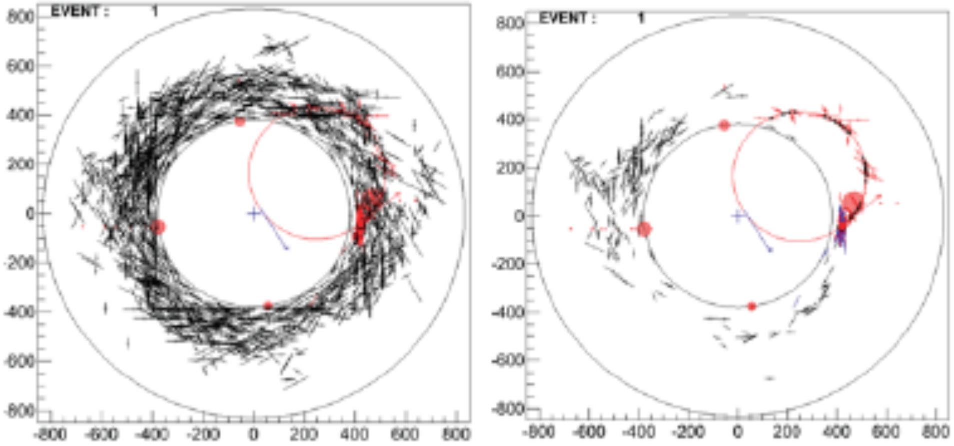
Calorimeter

- 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

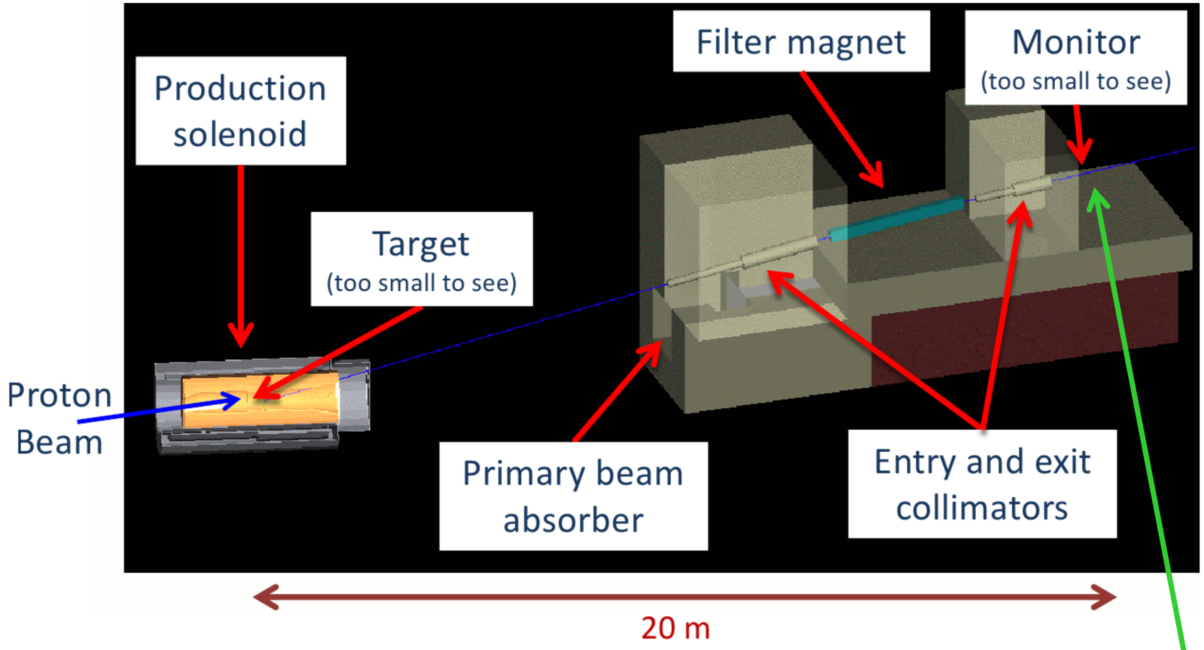
Tracker Hits



Extinction Monitor

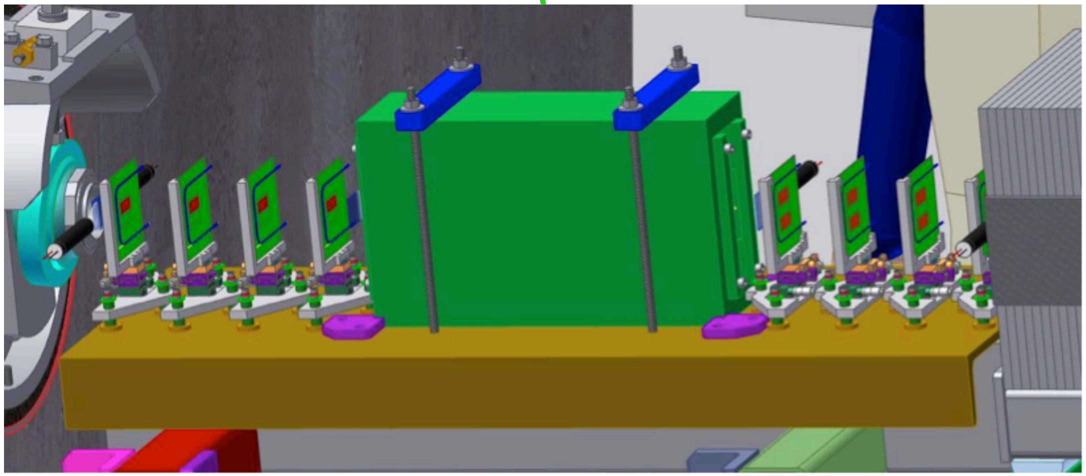
- Achieving 10^{-10} extinction is hard, but it's not useful unless we can verify it.
- Must measure extinction to 10^{-10} precision
  - Roughly 1 proton every 300 bunches!
- Monitor sensitive to single particles not feasible
  - Would have to be blind to the $3\mathrm{x}10^{7}$ particles in the bunch.
- 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 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

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

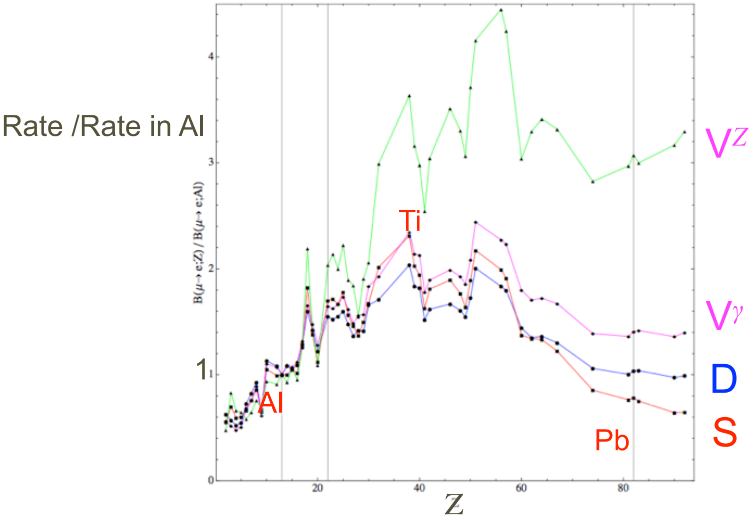
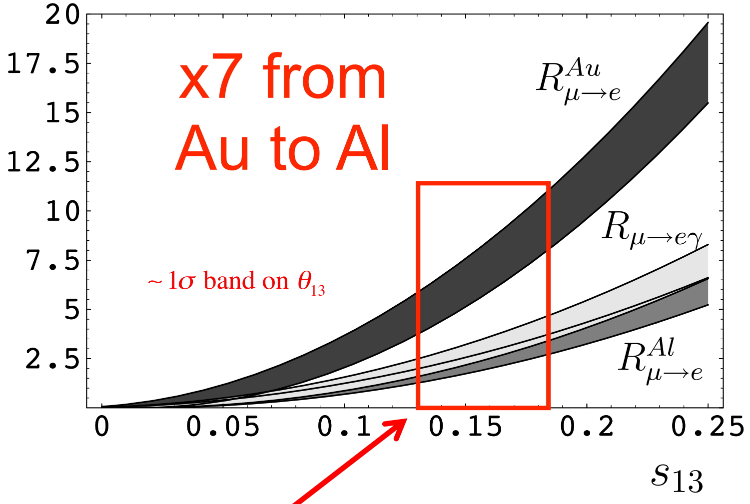


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

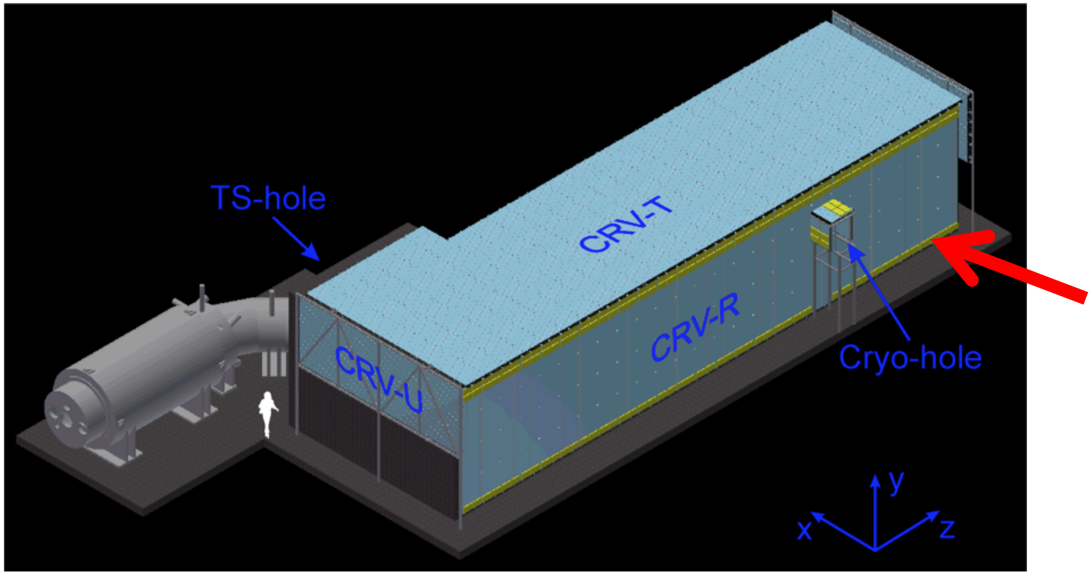


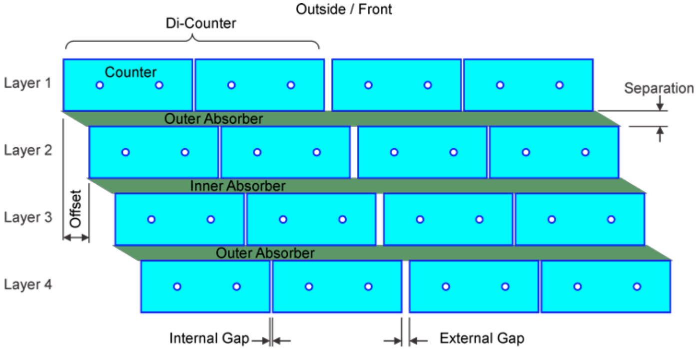
V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005

Now we know this!

Cosmic Ray Veto (CRV)

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





- Efficiency specification: >99.99%

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

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

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

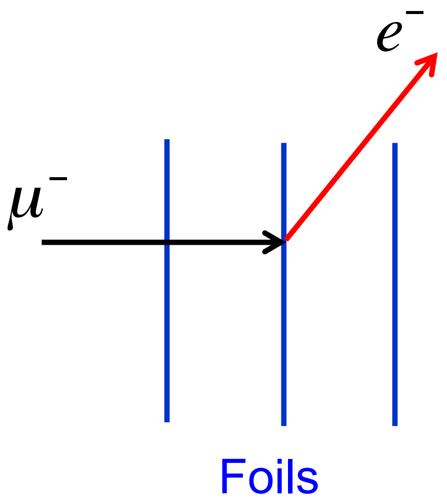
$\Rightarrow$Want M(Z)-M(Z-1) < signal energy

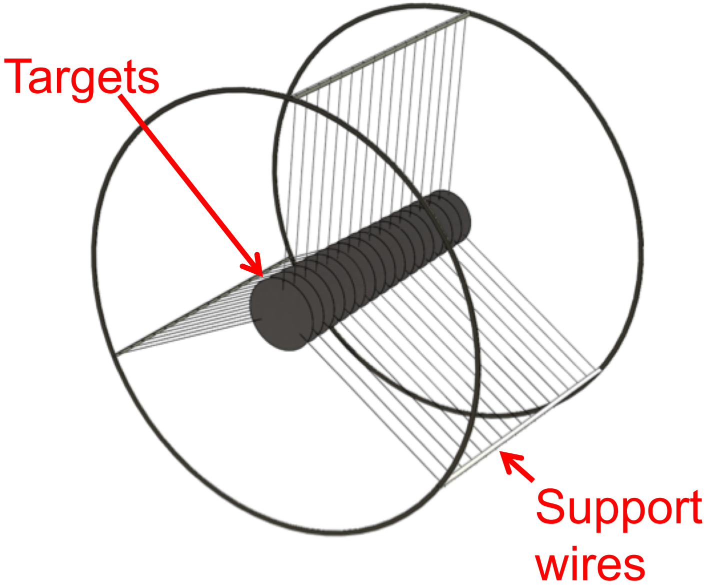
$\Rightarrow$Aluminum is initial choice for Mu2e

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

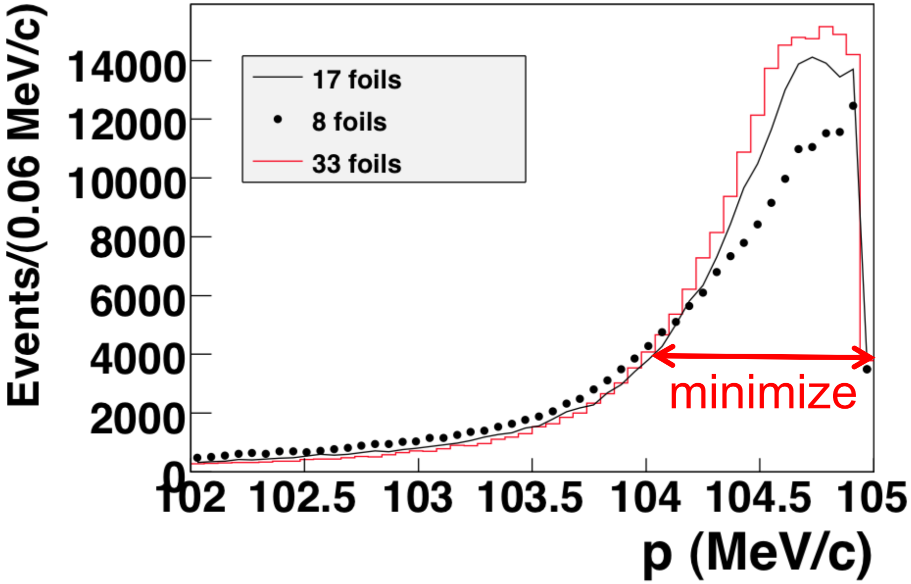
Stopping (capture) Target

- 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

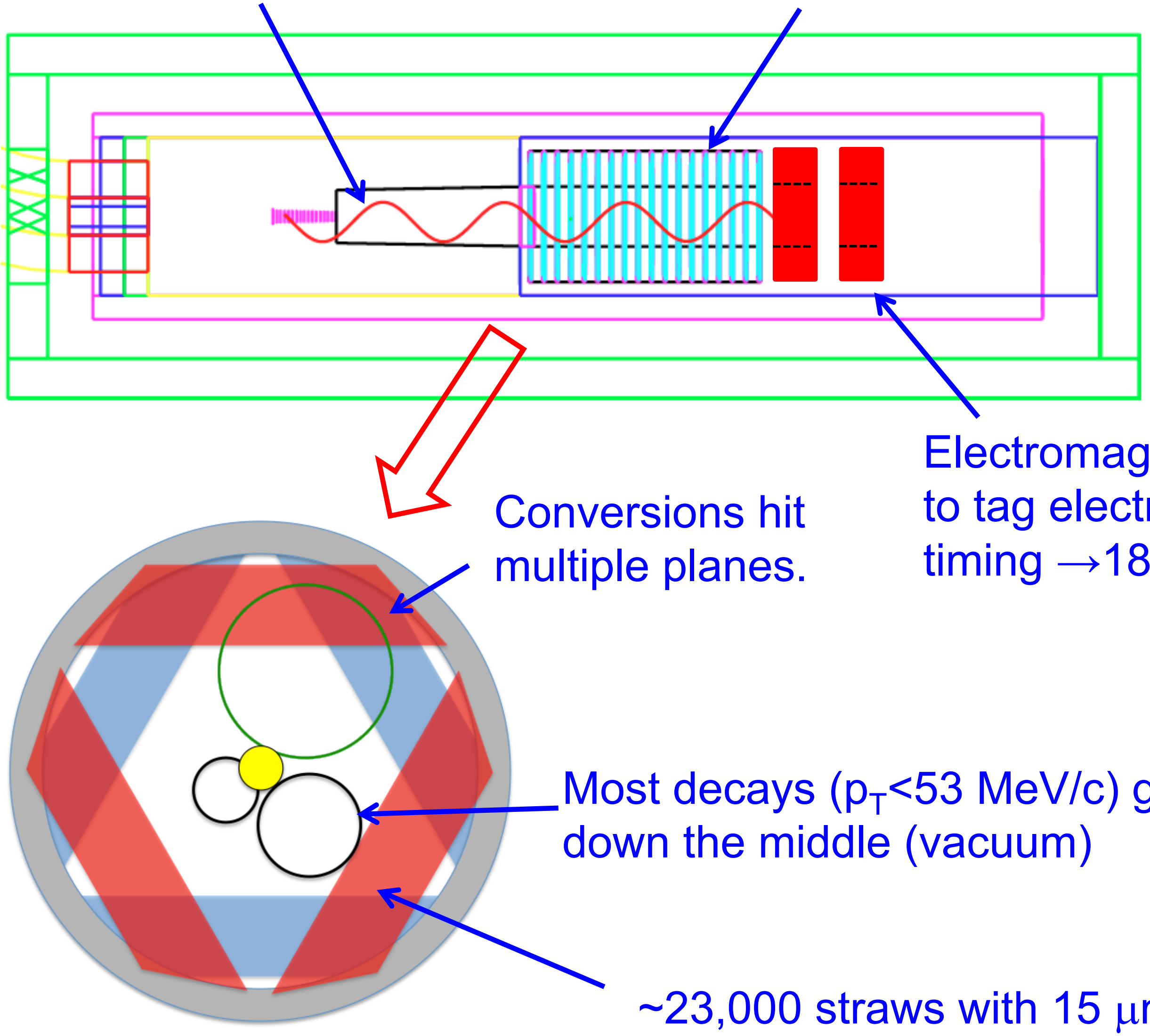




Conversion electron spectrum:



Particle Detector



Helical trajectory

Charged tracking

Electromagnetic Calorimeter to tag electrons and provide timing →1860 BaF_2 crystals

Conversions hit multiple planes.

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

~23,000 straws with 15 μm walls

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 funding scenarios.

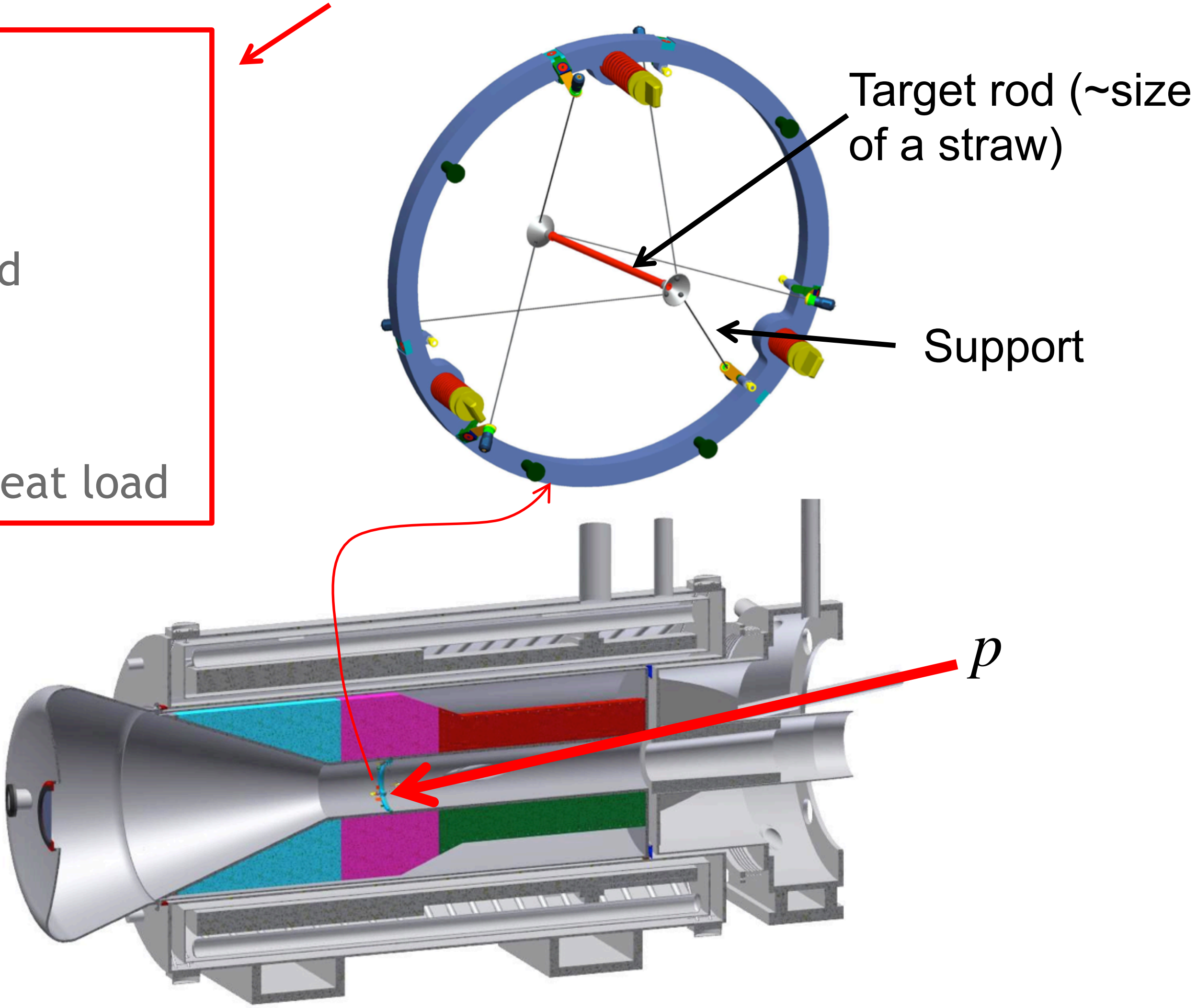
	bleak	flat	fantasy
Project/Activity	**Scenario A**	**Scenario B**	**Scenario C**
Large Projects			
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y
HL-LHC	Y	Y	Y
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced
ILC	R&D only	R&D, possibly small hardware contributions.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

- So… full speed ahead!

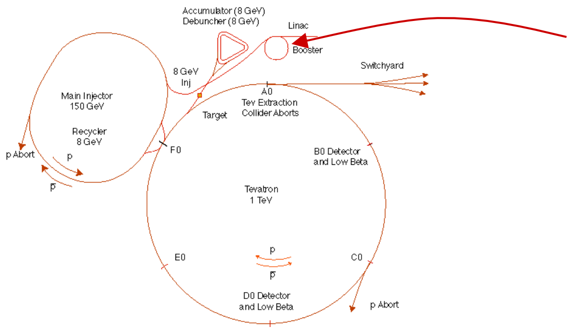
Target and Heat Shield

- 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

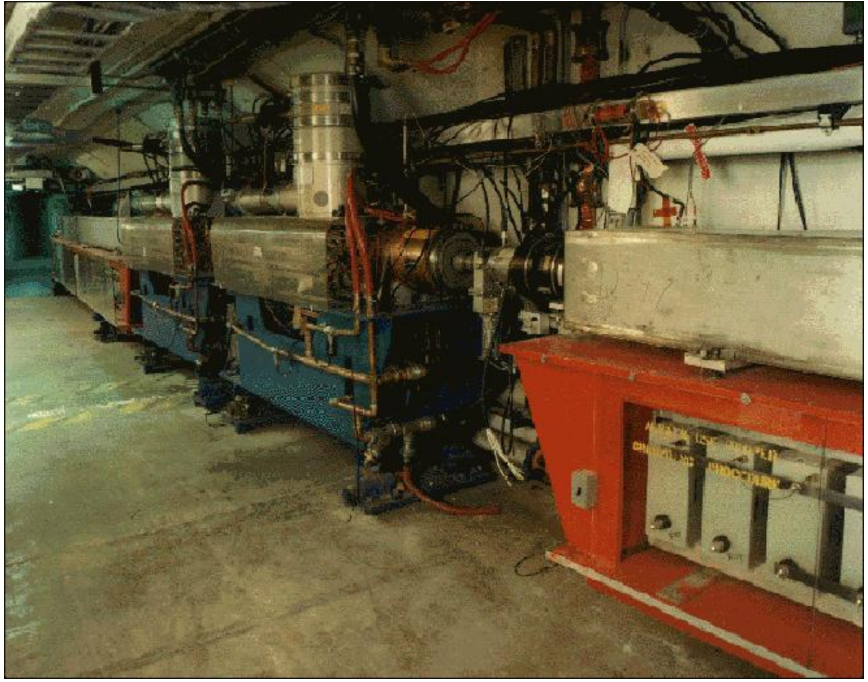
Remember, this is inside a superconducting magnet



Fermilab Booster



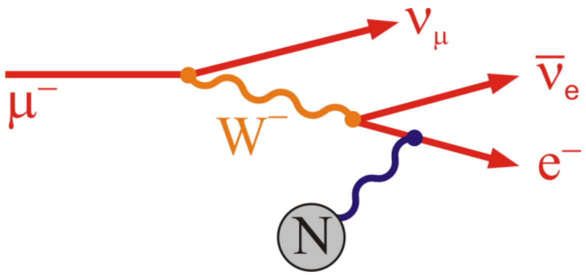
Most "original" part of the complex



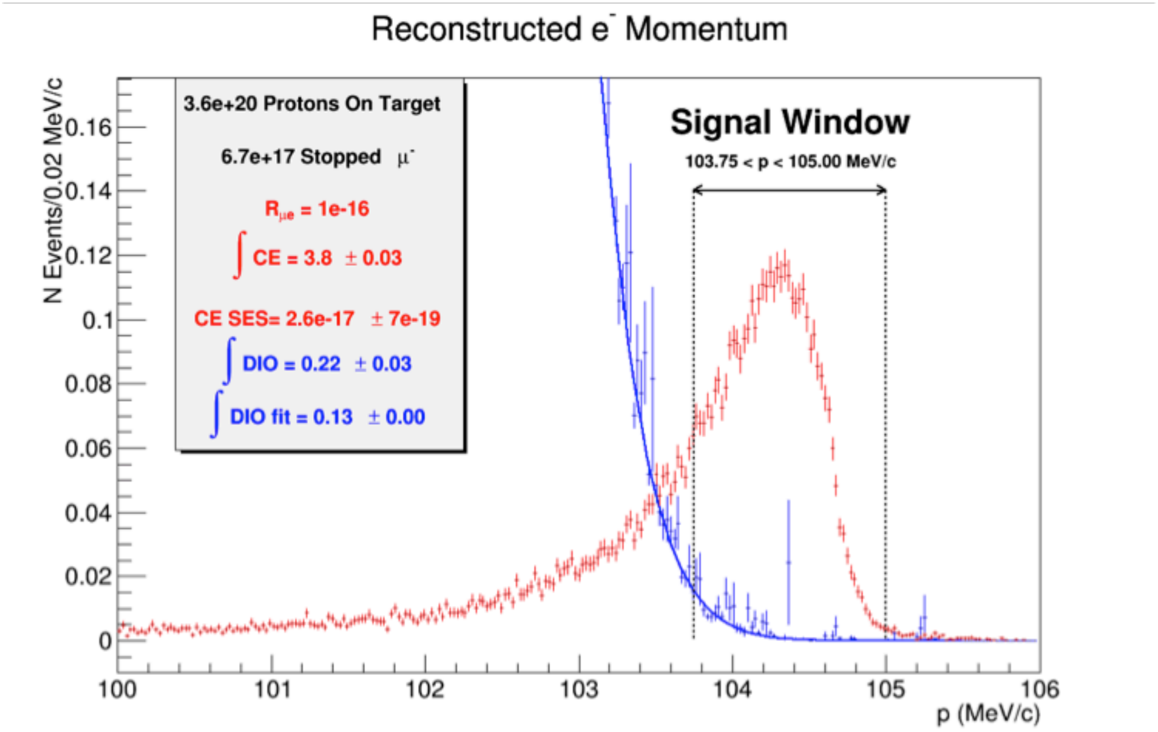
- Accelerates protons from 400 MeV to 8 GeV
- Operates in a 15 Hz resonant circuit
  - No time for beam manipulation
  - Can't make required beam structure
- Sets a fundamental clock for the complex
  - 15 Hz "tick"
- Sets a fundamental unit of protons
  - 1 "batch" = up to ~4x10^{12} protons
- Since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

Major Backgrounds Revisited

1. Muon decay in orbit (DIO)



Defeated by good energy resolution



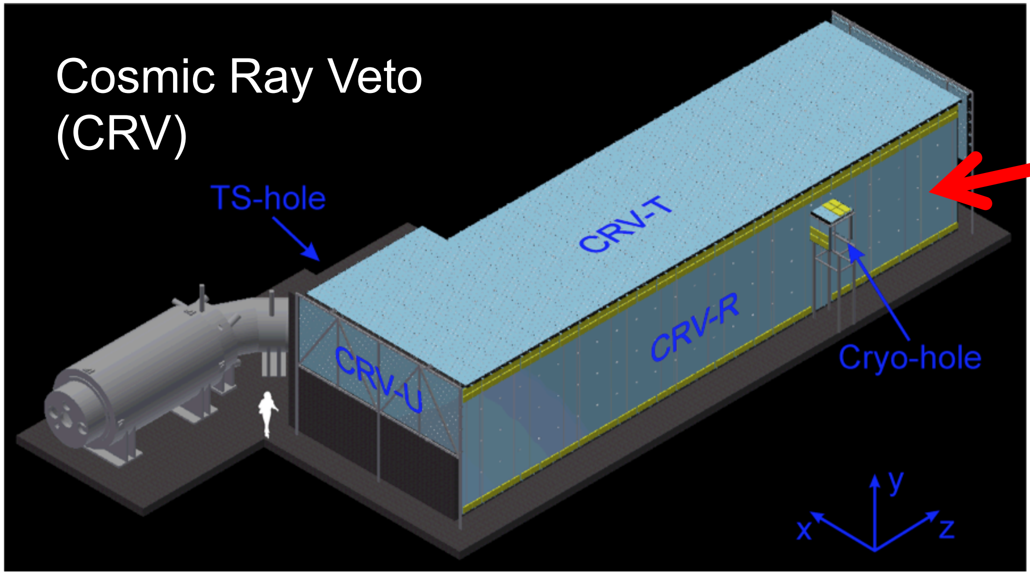
Major Backgrounds (cont'd)

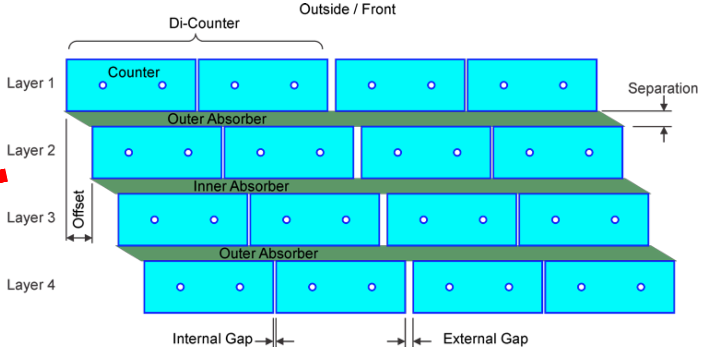
2. Beam Related Backgrounds

Suppressed with 10^{-10} extinction (just talked about this)

3. Asynchronous Backgrounds: Cosmic Rays

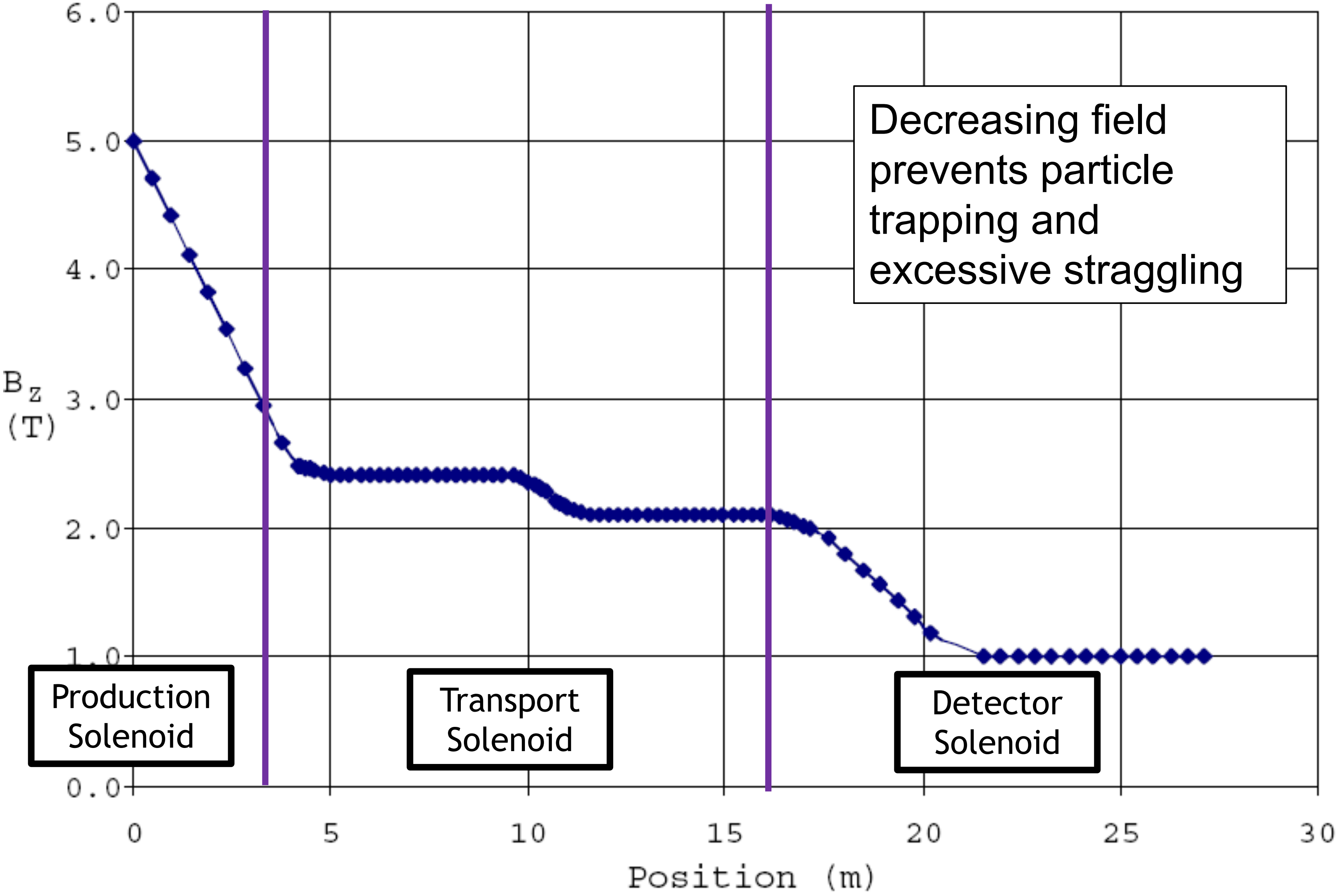
Suppressed by active and passive shielding





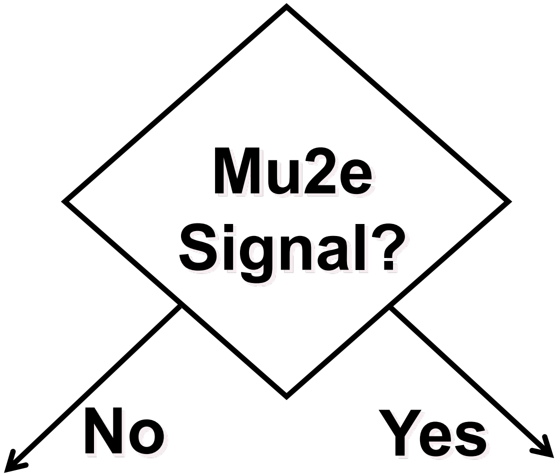
- Four layers of scintillator surround experiment
- Efficiency goal: >99.99%

Magnetic Field Gradient



Decreasing field prevents particle trapping and excessive straggling

Upgrade scenarios



Mu2e Signal?

No

Yes

- Both prompt and DIO backgrounds must be lowered to measure

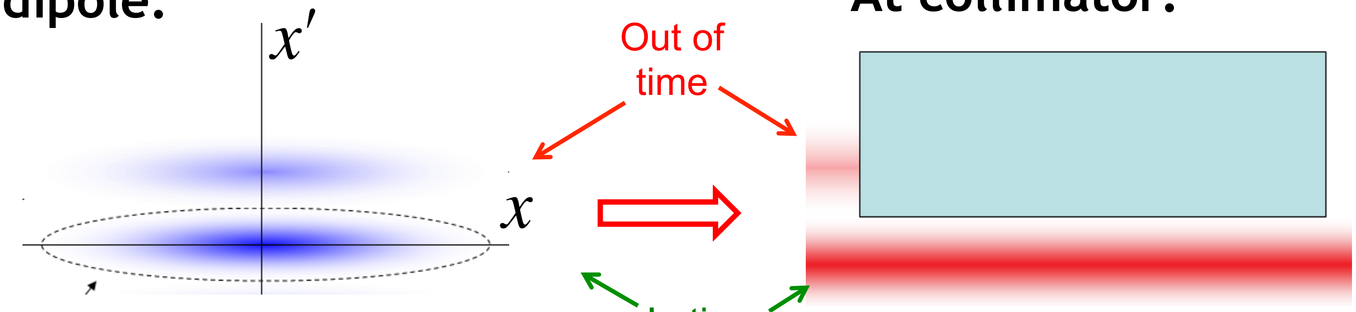
  $R_{\mu e} \sim 10^{-18}$

- 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.

Eliminating out of Time Beam (Extinction)

- The bunches from the Delivery Ring will have ~10^{-5} extinction
  - We need 10^{-10} to make prompt backgrounds small compared to other backgrounds
- A set of resonant dipoles in the beam line will deflect the beam such that only in-time beam is transmitted through a downstream collimator:



At dipole:

At collimator:

Out of time

In time

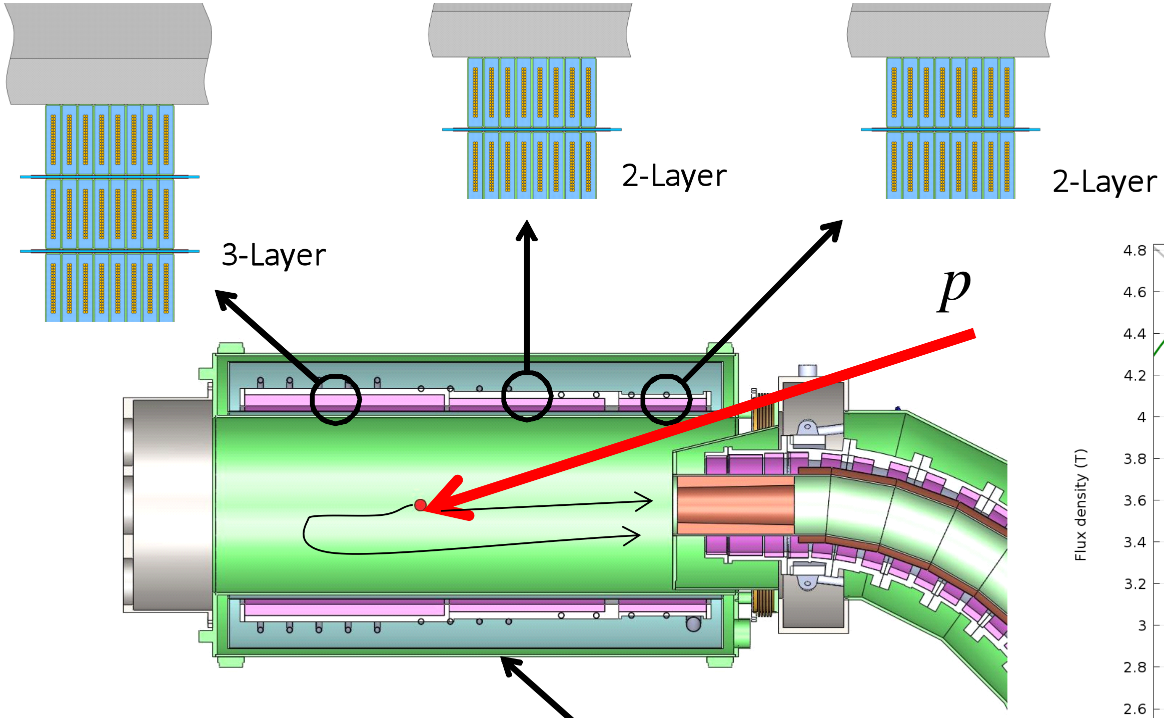
Angular deflection

Spatial offset

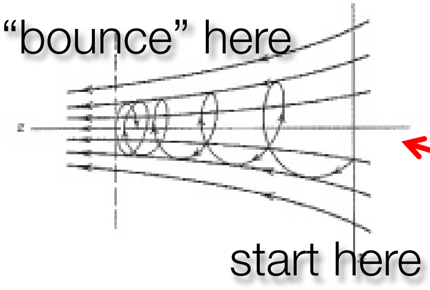
- Think miniature golf

Production Solenoid

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



Cryostat Wall



"bounce" here

start here

Magnetic reflection (pinch confinement)

Magnetic Gradient