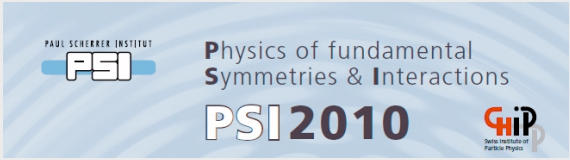
A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
Fermilab
for the Mu2e Collaboration



Collaboration

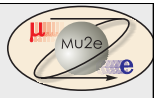
Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
City University of New York
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
Northwestern University
INFN Frascati
INFN Pisa, Università di Pisa, Pisa, Italy
INFN Lecce, Università del Salento, Italy
Rice University
Syracuse University
University of Virginia
College of William and Mary
University of Washington, Seattle

~110 collaborators

Outline

- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions

What is μe Conversion?



muon converts to electron in the presence of a nucleus

$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

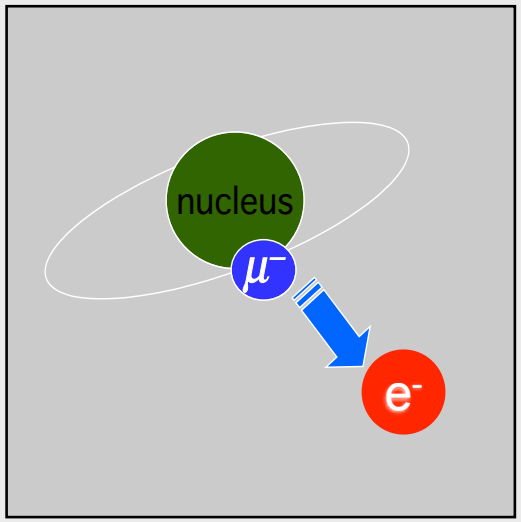
- Charged Lepton Flavor Violation (CLFV)
  - will measure $R_{\mu e} < 6 \times 10^{-17}$ @ 90%CL
- Related Processes:

μ or $\tau \rightarrow e\gamma$, e^+e^-e, $K_L \rightarrow \mu e$, and more

Experimental Signal

$$\mu^- N \rightarrow e^- N$$

- A Single Monoenergetic Electron
- If *N* = Al, E_e = 105. MeV
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



will use this many times, so take a moment

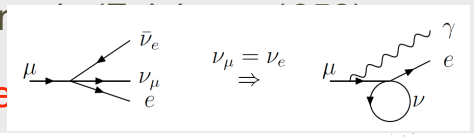
"Who ordered that?"

– I.I. Rabi, 1936

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect BR(μ→$e\gamma$) ≈ 10^{-4}
- Unless another ν, in Intermediate Vector Boson Loop, car

➡ same



[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

this is really the question of flavor and generations: why?

Current and Planned Lepton Flavor Violation Searches

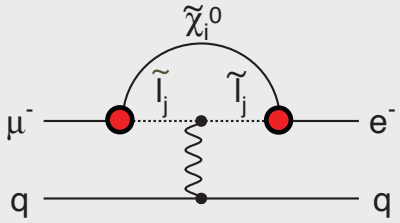
- CLFV in SUSY
- LFV with τ's/ e^+ e^-
- MEG and $\mu \rightarrow e\gamma$
- Mu2e:
  - Strengths of muon-electron conversion
  - Complementarity to other processes

what's going on in the world now?

LFV, SUSY and the LHC

Supersymmetry

rate ~ 10^{-15}



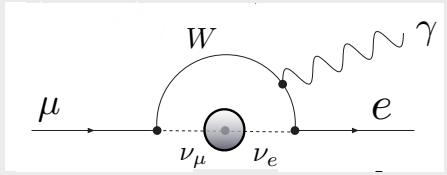
Access SUSY through loops:

signal of Terascale at LHC implies ~40 event signal / 0.4 bkg in this experiment

let's look at some specific models

Neutrino Oscillations and Muon-Electron Conversion

- ν's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



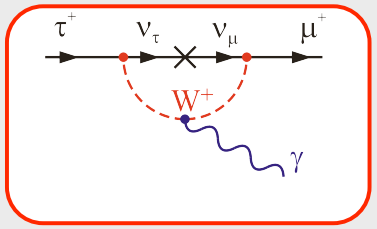
NO STANDARD MODEL BACKGROUND!

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

CLFV and Tau Decays

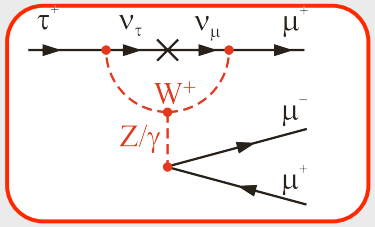
Highly suppressed in Standard Model

Lee, Shrock
Phys.Rev.D16:1444,1977



SM ~ 10^{-40}

Milder
GIM
Cancellations



SM ~ 10^{-14}

Pham, hep-ph/9810484

Good News:
BSM rates are several orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce:
~10^{10} τ/*yr* vs ~10^{11} μ/*sec* in fixed-target experiments (Mu2e/COMET)

also e→τ at electron-ion collider?

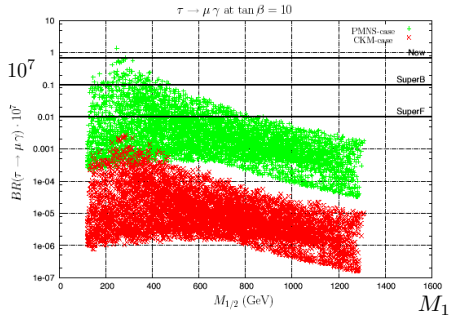
M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063v1

Supersymmetry in Tau LFV

L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

$\mathrm{BR}(\tau \to \mu\gamma) \times 10^7$



$\tan\beta = 10$

$M_{1/2}$ (GeV)

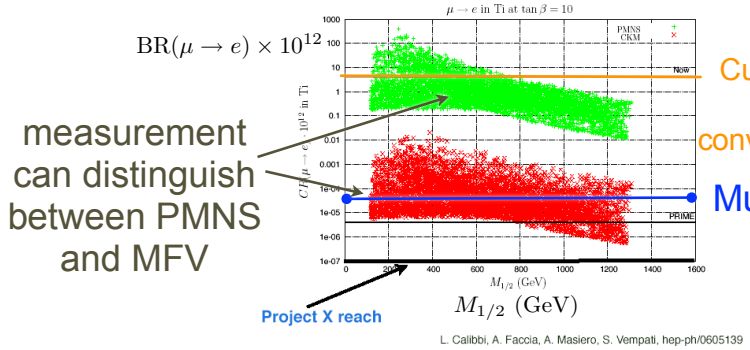
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

neutrino mass via the see--saw mechanism, analysis is performed in an SO(10) framework

And Muon-Electron Conversion

$\tan\beta = 10$

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)



Current μe conversion

Mu2e

measurement can distinguish between PMNS and MFV

Project X reach

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

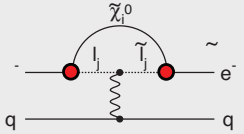
complementarity between Lepton Flavor Violation (LFV) and LHC experiments

squarks and gluinos ~ 1 TeV should be visible at LHC and Mu-e gamma, 2-2.5 TeV perhaps beyond LHC but effects detectable in mu-e conversion

Contributions to μe Conversion

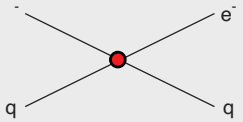
Supersymmetry

rate ~ 10^{-15}



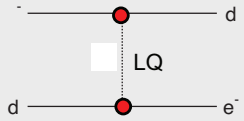
Compositeness

Λ_c ~ 3000 TeV



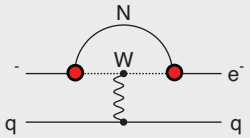
Leptoquark

M_{LQ} = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



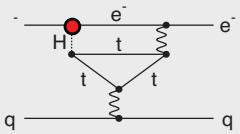
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



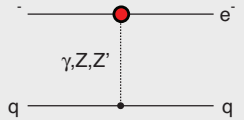
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

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



also see Flavour physics of leptons and dipole moments, arXiv:0801.1826
and Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

note both loop processes and new particle exchange, will come back to this next slide. note article or excellent discussion

"Model-Independent" Form

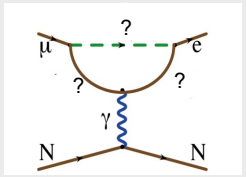
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

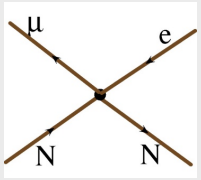
"Loops" **"Contact Terms"**

mass scale Λ

κ

$\kappa=0$





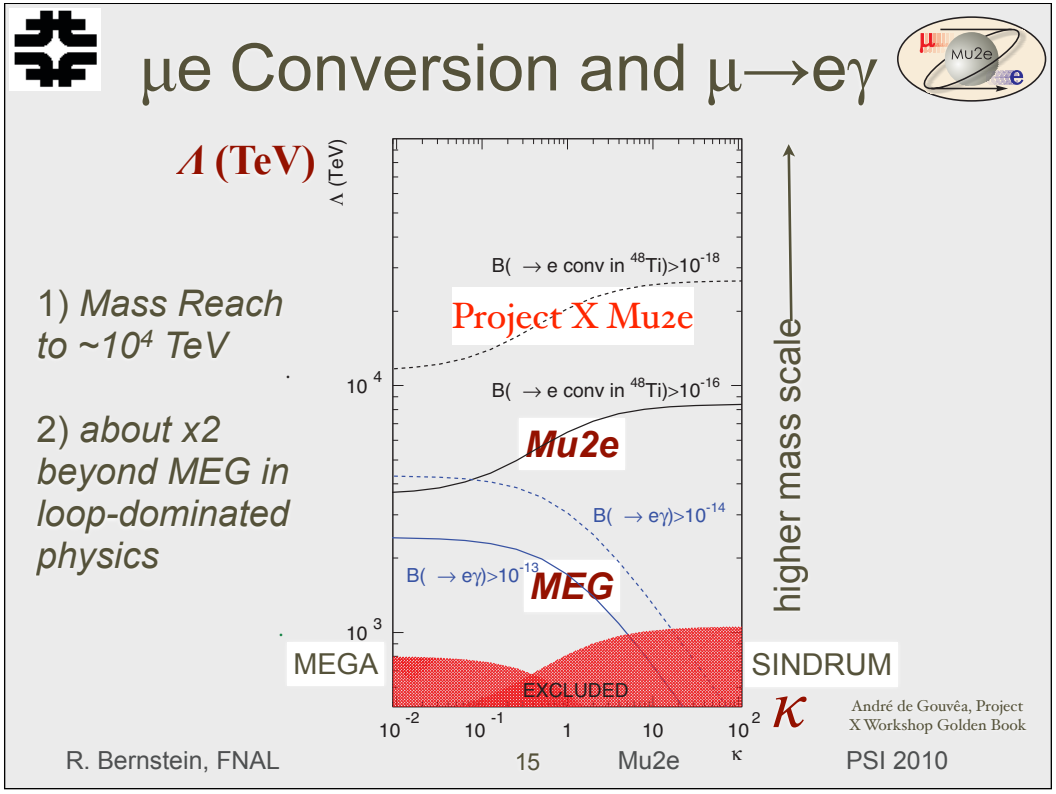
$\kappa=1$

Supersymmetry and Heavy Neutrinos

Contributes to $\mu\to e\gamma$

Does not produce $\mu\to e\gamma$

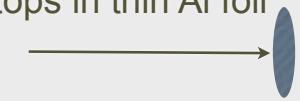
Quantitative Comparison?



generally acknowledge for experimental reasons mu e gamma will not get much better -- this improvement is only a factor of 5 --point to MEG/MEGA, but mu-e conversion can improve by 10,000 --SINDRUM to Mu2e. Independent of model! If supersymmetry, great -- but if not, can reach to 10^4 TeV for new physics. This is a unique contribution made by mu-e conversion. You know about COMET/PRISM proposed here in Japan: different design, similar sensitivities.

Overview Of Processes

μ^- stops in thin Al foil

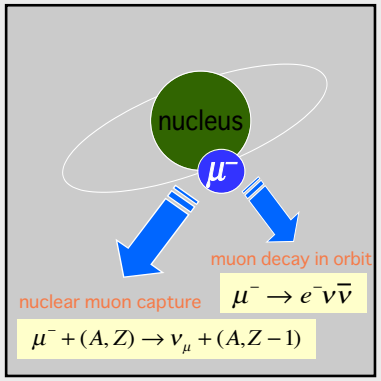


the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

μ^- in 1s state

Al Nucleus
~4 fm

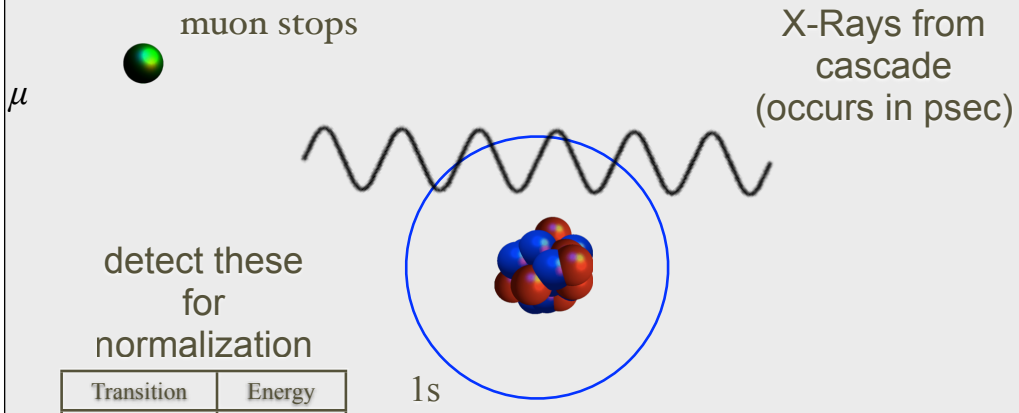
muon capture, muon "falls into" nucleus:
normalization



60% capture
40% decay

Decay in Orbit:
background

Three Possibilities: Normalization



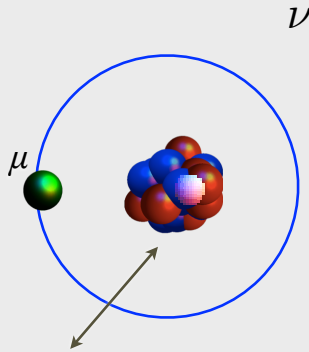
detect these for normalization

Transition	Energy
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV

Normalization to Nuclear Capture

1) measure stop rate 2) calculate capture rate/stop

Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110

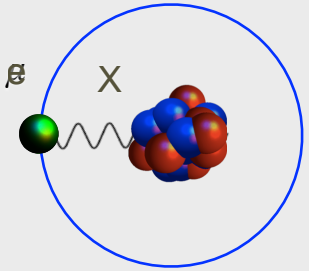


$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow e N}{\mu\ \mathrm{Al}(27,13) \rightarrow \nu_\mu\ \mathrm{Mg}(27,12)}$$

Three Possibilities: Signal

off to detector!

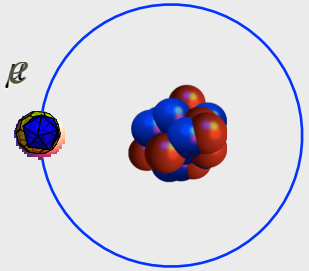


coherent recoil of nucleus

Three Possibilities: Background

this electron can be background; let's see how

ν_μ



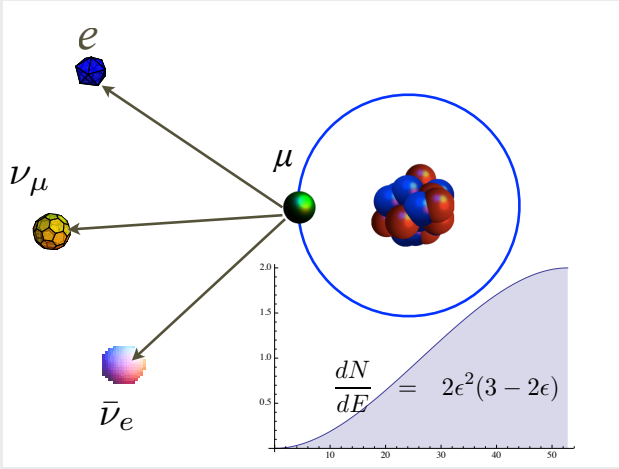
$\bar{\nu}_e$

Decay-In-Orbit: Not Normally Background

- Peak and Endpoint of Michel Spectrum is at

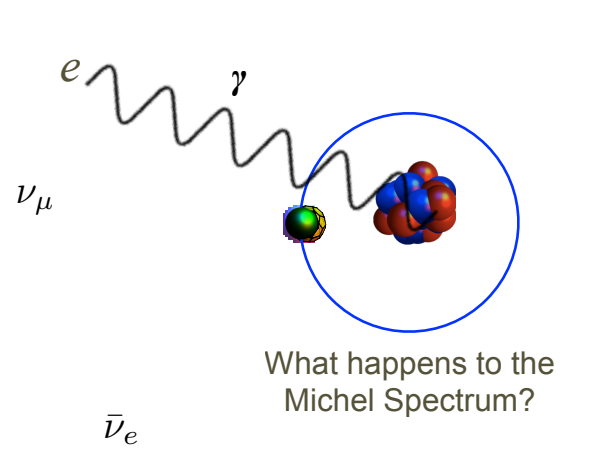
$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- Detector will be insensitive to electrons at this energy
- Recall *signal* at 105 MeV>>52.8 MeV



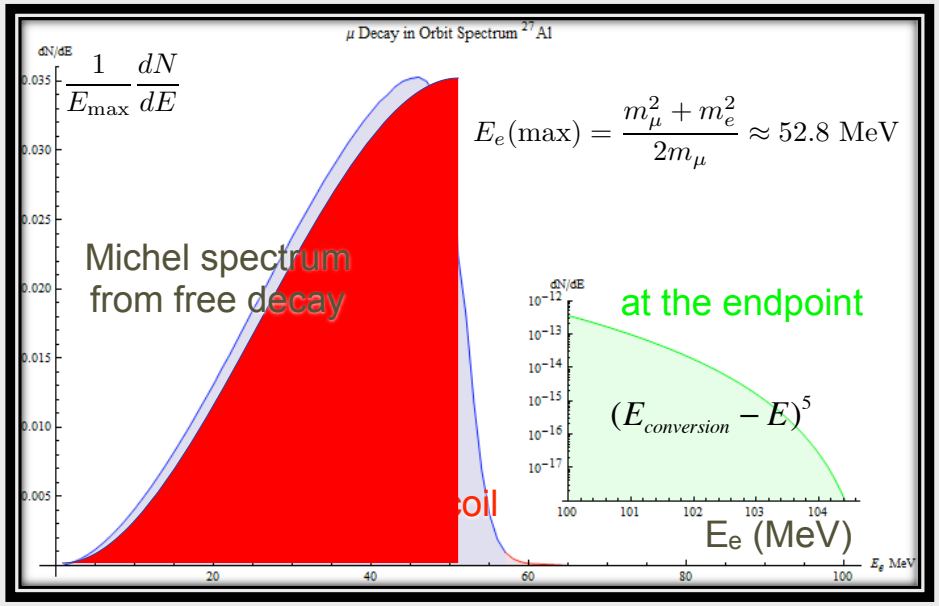
Decay-In-Orbit Background

- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, the DIO electron can be exactly at conversion energy (up to neutrino mass)



What happens to the Michel Spectrum?

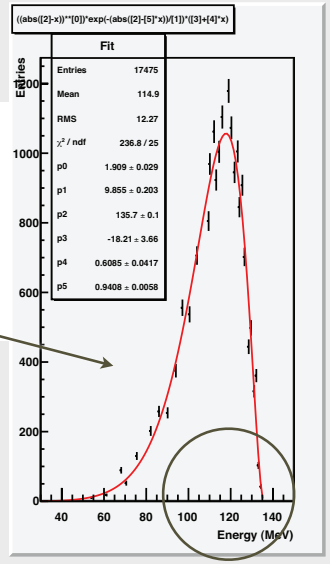
Decay-in-Orbit Shape



Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars

- **Radiative pion capture**, $\pi^- + A(N,Z) \rightarrow \gamma + X$.
  - γ up to m_π, peak at 110 MeV; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal



energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

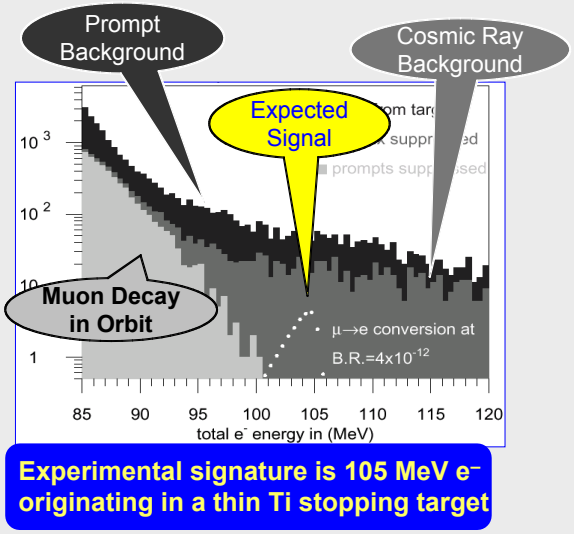
also included internal conversion, $\pi^- N \rightarrow e^+ e^- X$

76 MeV from relativistic kinematics

Current Best Experiment

SINDRUM-II

- $R_{\mu e} < 7 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



Experimental signature is 105 MeV e^- originating in a thin Ti stopping target

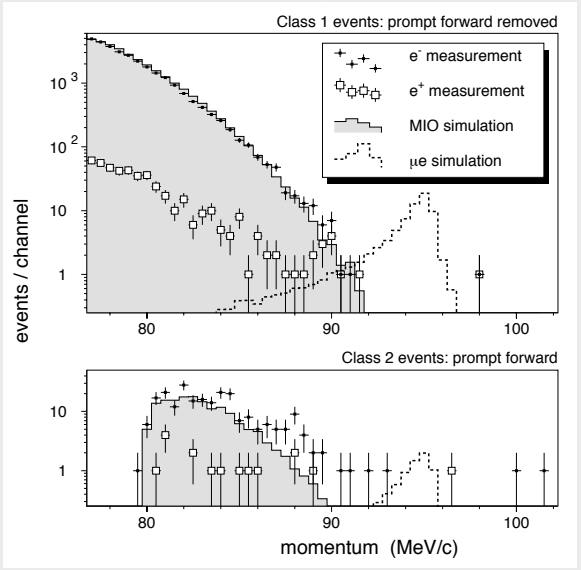
SINDRUM-II Results

- Final Results on Au:

$$B_{\mu e}^{\mathrm{Au}} \quad < \quad 7 \times 10^{-13} \ @ \ 90\% \ \mathrm{CL}$$

- Note events beyond signal region
  - can't just repeat at higher statistics

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)



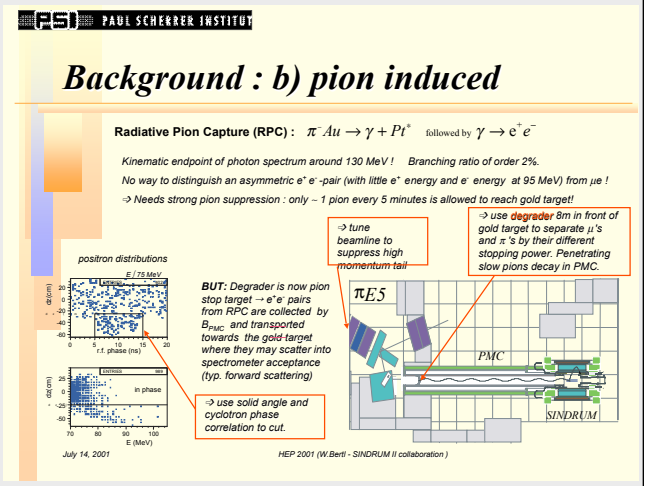
What Limited SINDRUM-II?

51 MHz
width ~0.3 nsec

little time separation between signal and prompt background

Two Pion Backgrounds:
1)radiative π capture

2)π decay in flight$\rightarrow e\nu$



cosmic rays also an issue; need excellent veto, ~99.9%

point to radiative pi capture in b), explain degrader and veto. We use a different method, beam extinction,

Review: Two Classes of Backgrounds

	Decay-In-Orbit	Prompt
Source	Intrinsic Physics Background	Radiative π Capture: Mostly π's produced in production target
Solution	Spectrometer Design: resolution and pattern recognition	Design of Muon Beam, formation, transport, and time structure

How Can We Do Better? Pulsed Beam Structure

>10^3 increase in muon intensity from SINDRUM

Requiring

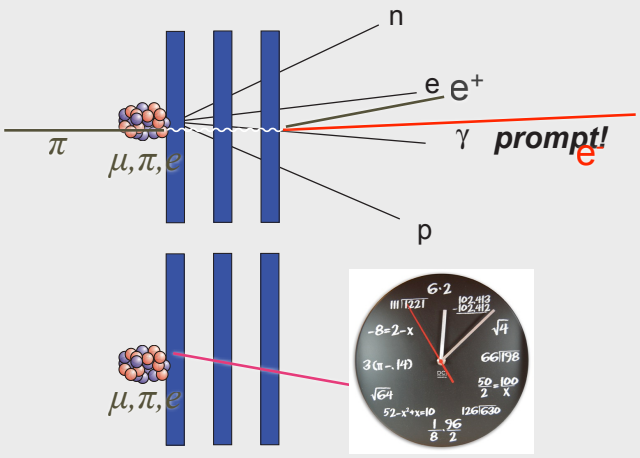
Pulsed Beam with waiting period to
Eliminate radiative π capture

protons out of beam pulse/ protons in beam-pulse < 10^{-10}
and we must measure it

Advantage of Pulsed Beam

target foils: muon converts here

= muons, electrons, pions



pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

RPC:

$\pi N \rightarrow \gamma N$

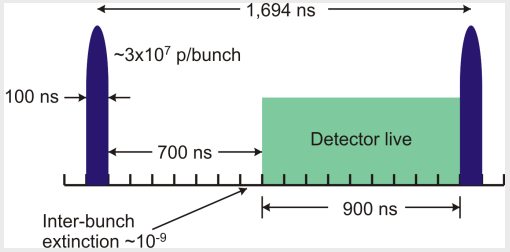
$\gamma \rightarrow e^+e^-$ *in foils*

delayed 105 MeV electron

Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL “perfect”
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7μsec , ~x2 τ_μ^{Al}
- Extinction between pulses < 10^{-9} needed

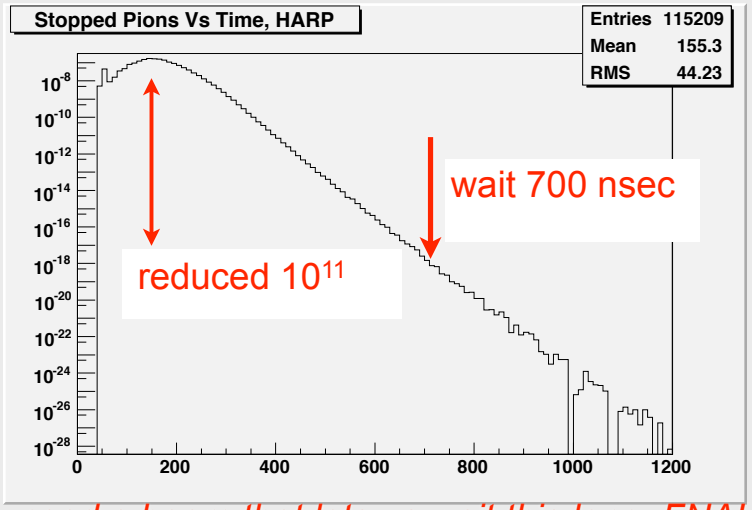
  = # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds and beamline

Pulsed Beam Structure and Radiative π Capture

$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+e^-$$

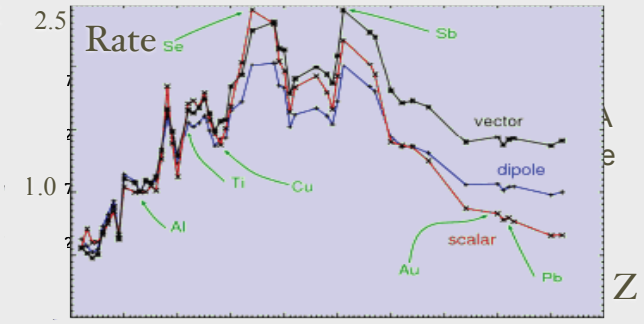


need a beam that lets us wait this long: FNAL

Choice of Stopping Material: rate vs wait

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

rate normalized to Al



V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**.
Kitano et al. PRD 66, 096002 (2002)
e-Print: **hep-ph/0307001**

shape governed by relative conversion/capture rate, form factors, ...

Prompt Background and Choice of Z

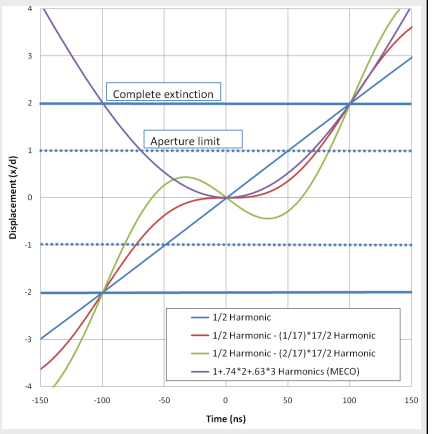
choose Z based on tradeoff between rate and lifetime:
longer lived reduces prompt backgrounds

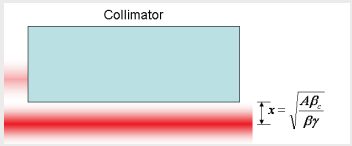
Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

Extinction Scheme

achieving 10^{-10} is hard; normally get $10^{-2} - 10^{-3}$

- Internal (momentum scraping)
- External:
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
  - Calculations (MARS) show this sufficient



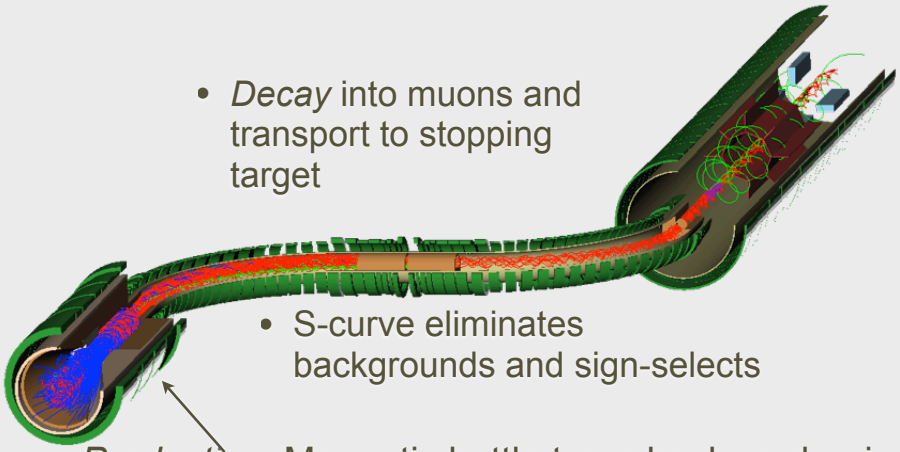


Extinction Measurement

- Continuous Extinction monitoring techniques under study
  - Statistical
    - Off-axis telescope looking at production target
    - Thin foils in 8 GeV transport line before and after AC-dipole
  - Proton-by-Proton count
    - hard to handle dynamic range of beam-on to beam-off

Detector and Solenoid

- *Tracking and Calorimeter*



- *Decay* into muons and transport to stopping target
- S-curve eliminates backgrounds and sign-selects
- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

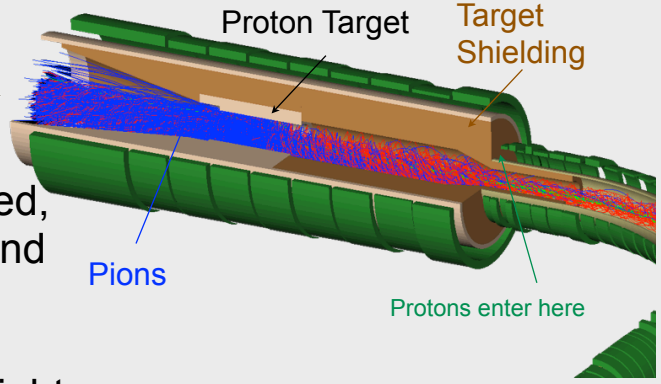
Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave through thin window

π's are captured, spiral around and decay

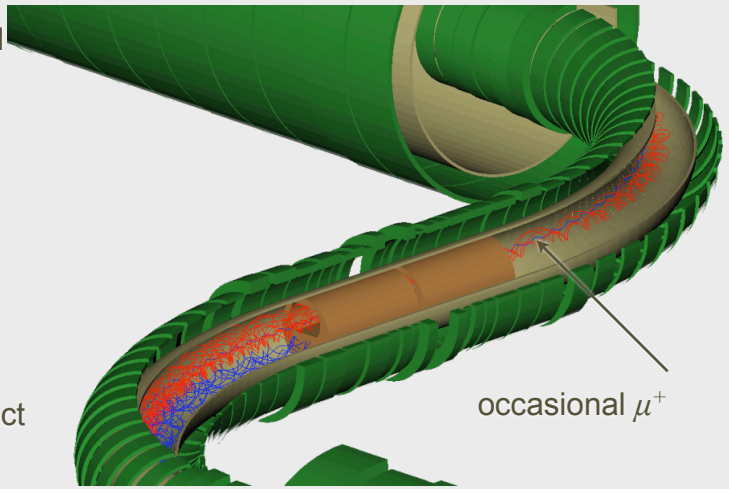
muons exit to right



4 m × 0.30 m

Transport Solenoid

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam

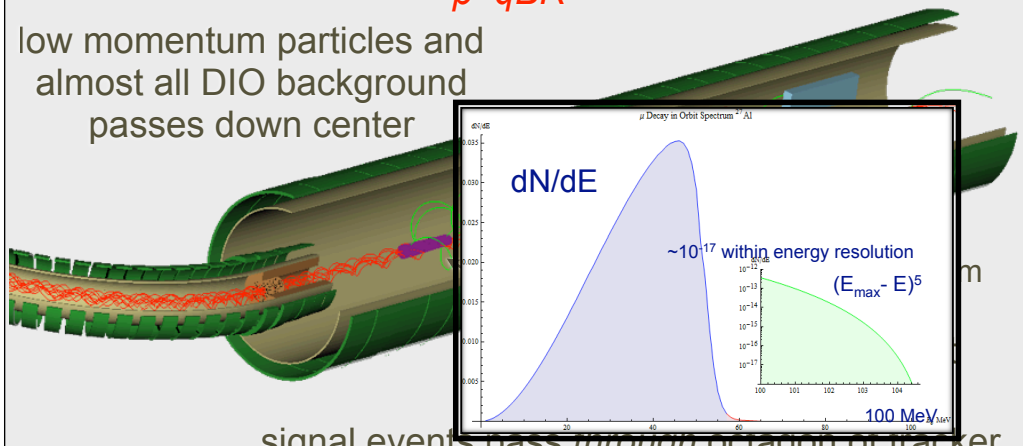


13.1 m along axis × ~0.25 m

Detector Solenoid

octagonal tracker surrounding central region:
radius of helix proportional to momentum,
p=qBR

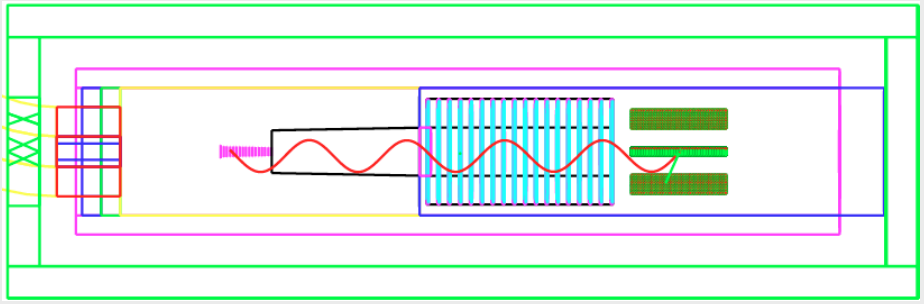
low momentum particles and
almost all DIO background
passes down center



signal events pass *through* octagon of tracker
and produce hits

so background goes down center and signal spirals out to tracker

Detector



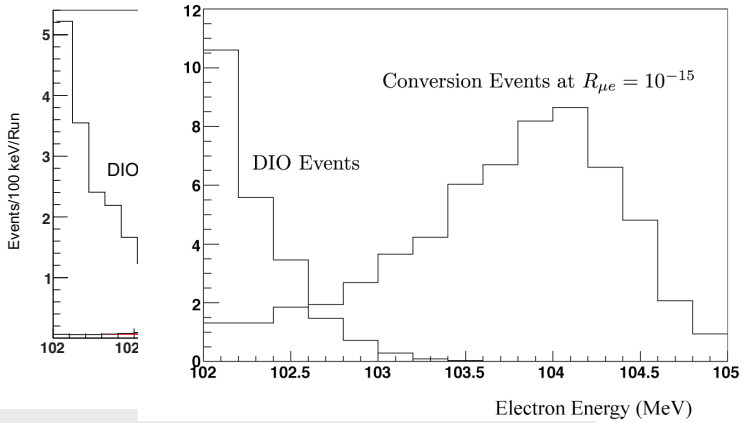
- Immersed in solenoidal field, so electrons follow near-helical path
- Conversion Electron born in Stopping Target
- Tracker followed by Calorimeter

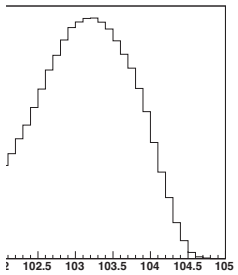
- Tracker: (straw tubes with axes transverse to beam)
  - 216 sub-planes
    - sixty 5 mm diameter conducting straws
    - length from 70-130 cm
    - total of 13,000 channels
- Calorimeter:
  - 1024 $3.5 \times 3.5 \times 12$ cm $PbWO_4$ or LYSO
  - 4--5% resolution

Signal and Background

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

$\frac{S}{B} \sim 5.5$



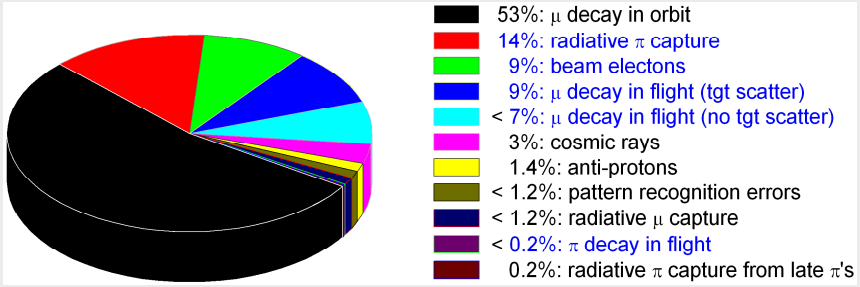


energy loss in stopping target and other material shifts electron down to ~104 MeV

Final Backgrounds

- For $R_{\mu e}$ = 10^{-15}
  ~40 events / 0.4 bkg
  (LHC SUSY?)
- For $R_{\mu e}$ = 10^{-16}
  ~4 events / 0.4 bkg

Source	Number
DIO	0.225
Radiative π capture	0.072
μ decay-in-flight	0.072
Scattered e-	0.035
π decay in flight	<0.0035



FNAL Beam Delivery

- FNAL has unique, major strength:

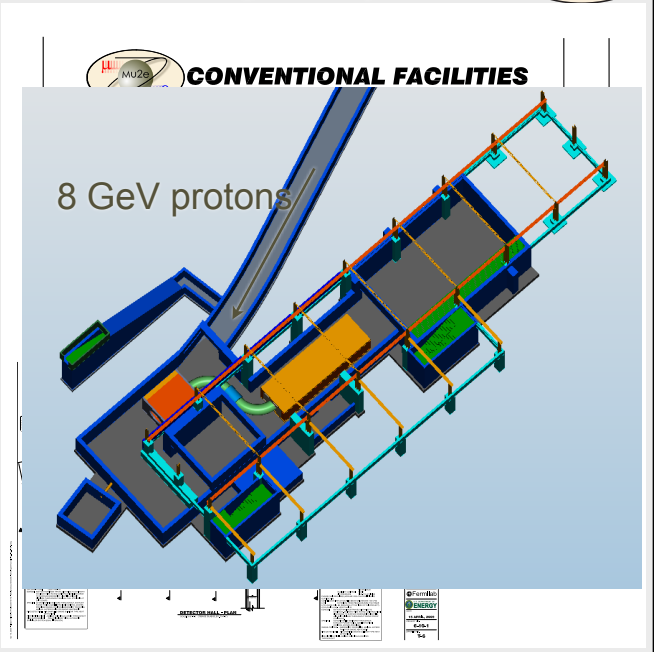
  Multiple Rings

  - *no interference* with NOvA neutrino oscillation experiment: we use beam NOvA can't use
  - reuse existing rings with only minor modifications
    - antiprotons for TeV use two rings and we will use those
    - we do not need access before Run III would end

big strength of FNAL: can run without interference

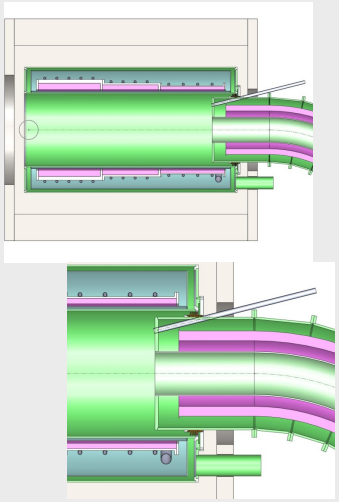
Site and Building Layout

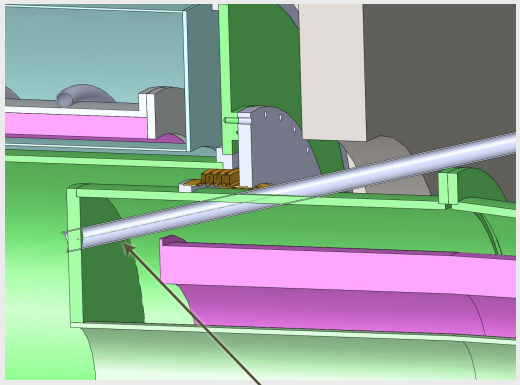
- Looking hard at variety of options
- Technical and cost considerations



Much Progress in Solenoid Design

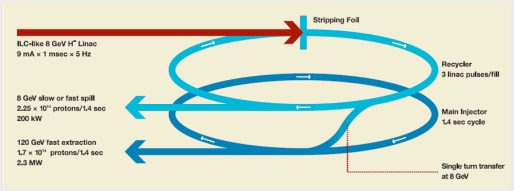
- Starting to talk with vendors about construction of solenoids; much interest in bids

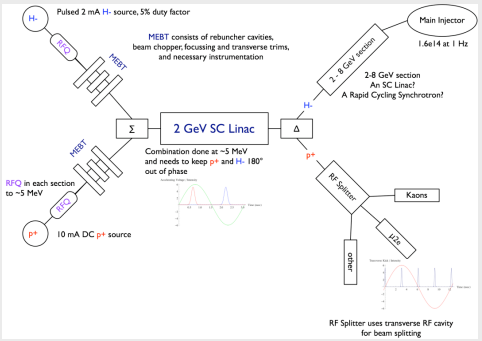




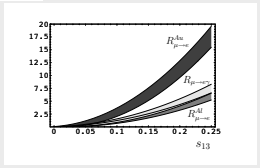
Upgrades at Project X

- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- Can drive next generation experiments in intensity frontier physics: rare processes, neutrinos
- Potential to upgrade Mu2e by *x100*
  - *study new physics*
  - *set stronger limit*





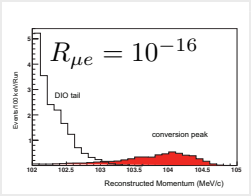
Upgrade Plans...



Signal?

Yes

No



1. Change Z of Target to determine source of new physics

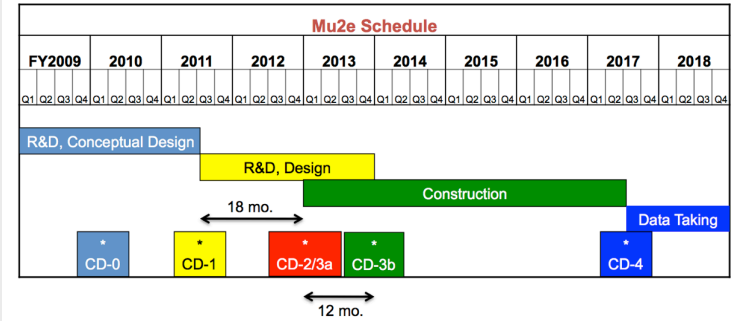
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

1. Both Prompt and DIO backgrounds must drop to measure $R\mu e \sim 10^{-18}$

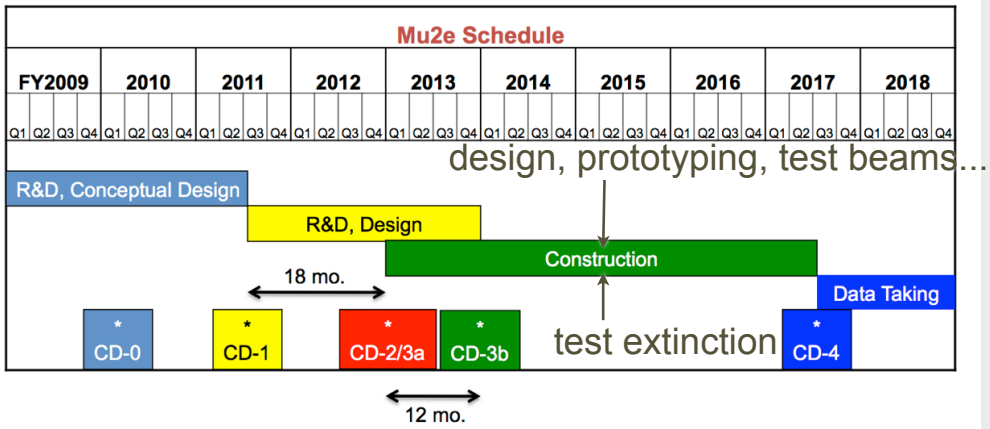
2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

Cost and Schedule

- ***This is a technically limited schedule***
- Critical Path is Superconducting Solenoids
- $200M “fully-loaded” Total Cost



What Does This Mean?



Conclusions

- Mu2e will either:
  - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)*
  - *Discover unambiguous proof of Beyond Standard Model physics and*
  - *Provide important information either complementing LHC results or probing up to 10^4 TeV mass scales*
- With upgrades, we could extend the limit by up to two orders of magnitude or study the details of new physics

And Perhaps Answer Rabi's Question about the physics of flavor and generations

Who ordered that?