Overview and Challenges for Upgrades: Muon-Electron Conversion at FNAL

R. Bernstein
Fermilab
for the Mu2e Collaboration

Collaboration

R.M. Carey, K.R. Lynch, J.P. Miller*, B.L. Roberts
Boston University

W. Marciano, Y. Semertzidis, P. Yamin
Brookhaven National Laboratory

Yu.G. Kolomensky
University of California, Berkeley

C.M. Ankenbrandt , R.H. Bernstein*, D. Bogert, S.J. Brice, D.R. Broemmelsiek, R. Coleman, D.F. DeJongh, S. Geer, R. Kutschke, M. Lamm, M.A. Martens, S. Nagaitsev, D.V. Neuffer, M. Popovic, E.J. Prebys, M. Syphers, R.E. Ray, R. Tschirhart, H.B. White, K. Yonehara, C.Y. Yoshikawa
Fermi National Accelerator Laboratory

D. Dale, K.J. Keeter, E. Tatar
Idaho State University

W. Molzon
University of California, Irvine

P.T. Debevec, G. Gollin, D.W. Hertzog, P. Kammel
University of Illinois, Urbana-Champaign

F. Cervelli, R. Carosi, M. Incagli, T. Lomtadze, L. Ristori, F. Scuri, C. Vannini
Istituto Nazionale di Fisica Nucleare Pisa, Università Di Pisa

V. Lobashev
Institute for Nuclear Research, Moscow, Russia

D.M. Kawall, K.S. Kumar
University of Massachusetts, Amherst

R.J. Abrams, M.A.C. Cummings, R.P. Johnson, S.A. Kahn, S.A. Korenev, T.J. Roberts, R.C. Sah
Muons, Inc.

J.L. Popp
City University of New York, York

A. DeGouvea
Northwestern University

M. Corcoran
Rice University

R.S. Holmes, P.A. Souder
Syracuse University

M.A. Bychkov, E.C. Dukes, E. Frlez, R.J. Hirosky, A.J. Norman, K.D. Paschke, D. Pocanic
University of Virginia

G4beamline

64 collaborators
16 institutions

Outline

- The search for muon-electron conversion
- Experimental Technique
- Project X Upgrades and Mu2e
- 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)
- Related Processes:
    - μ or τ → eγ, e^+e^-e, $K_L \rightarrow \mu e$, and more

Endorsed in US Roadmap

FNAL has proposed muon-electron conversion as a flagship program for the next decade

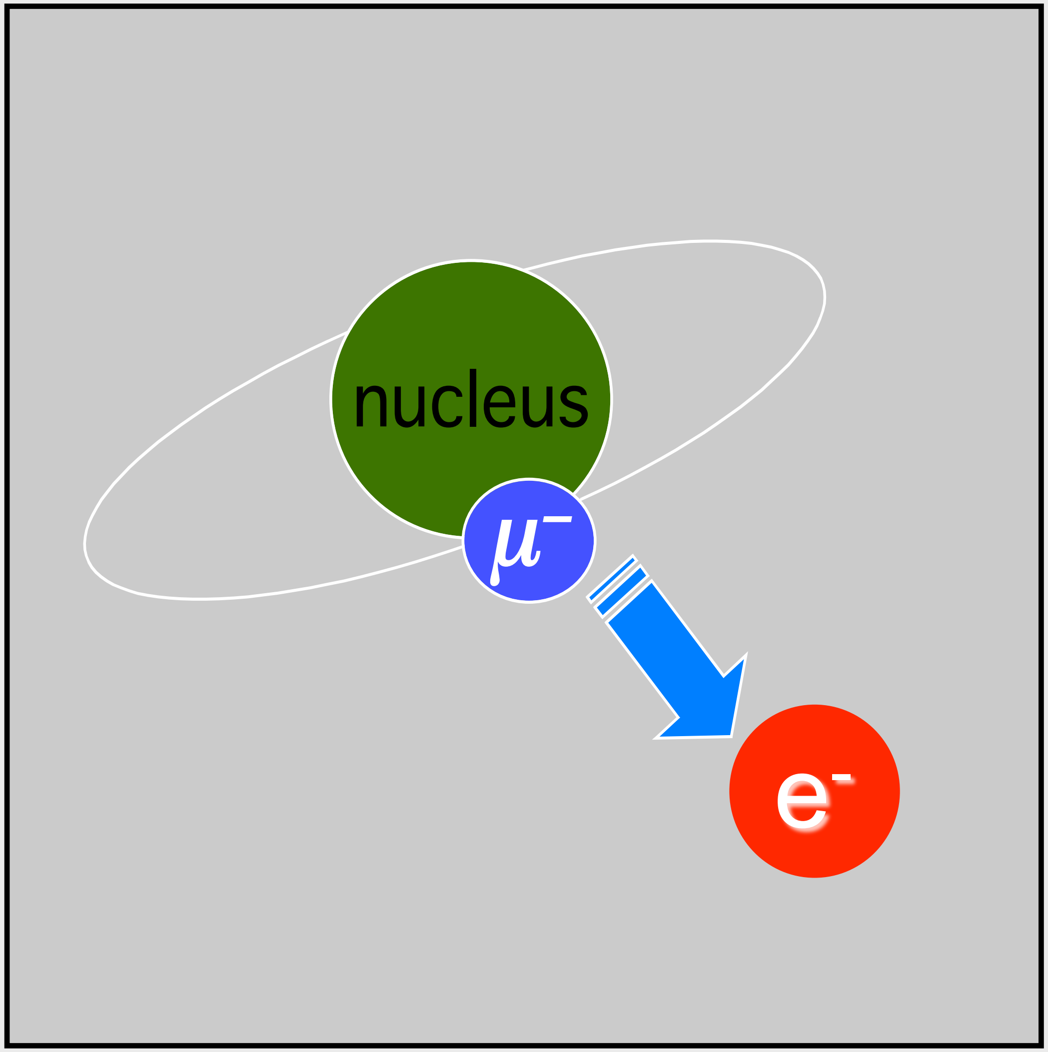
Strongly endorsed by P5:

"The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. **The panel recommends pursuing the muon-to-electron conversion experiment... under all budget scenarios considered by the panel**"

Mu2e is a central part of the future US program

Experimental Signal

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

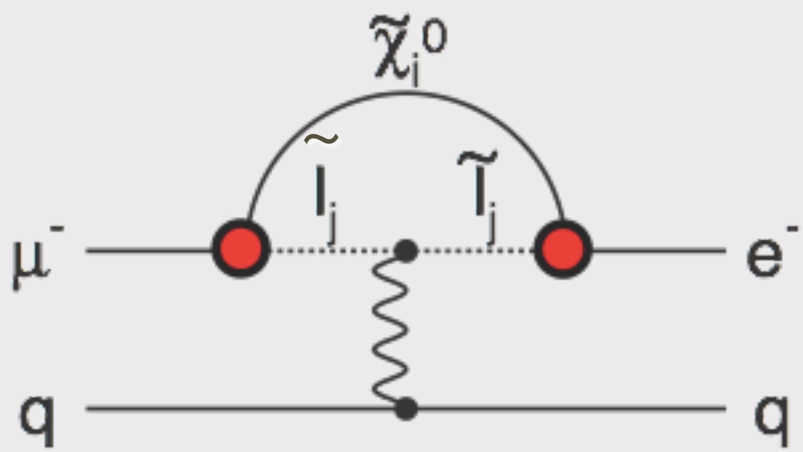


- A Single Monoenergetic Electron
- If N = Al, E_e = 105. *MeV*
  - electron energy depends on Z

LFV, SUSY and the LHC

Supersymmetry

rate ~ 10^{-15}



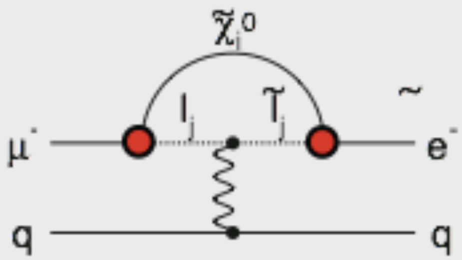
Access SUSY through loops:

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

Contributions to μe Conversion

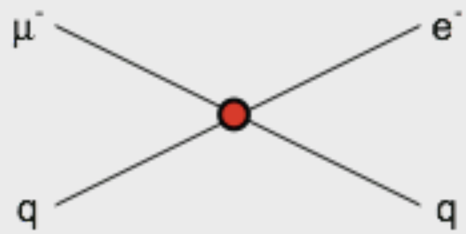
Supersymmetry

rate ~ 10^{-15}



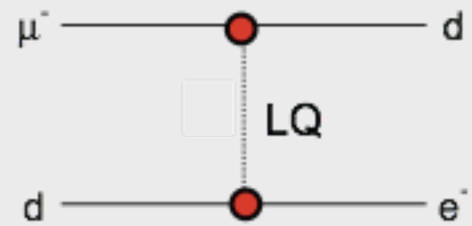
Compositeness

$\Lambda_c \sim 3000$ TeV



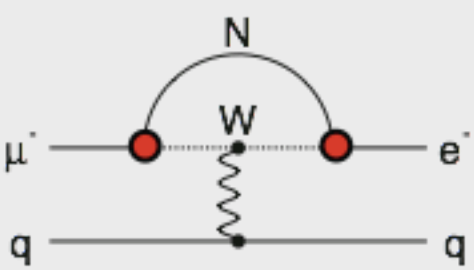
Leptoquark

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



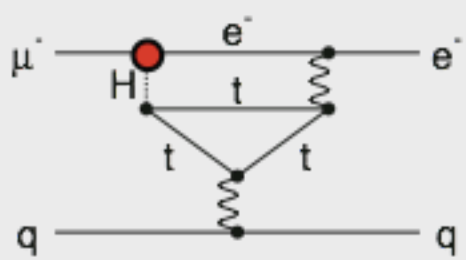
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



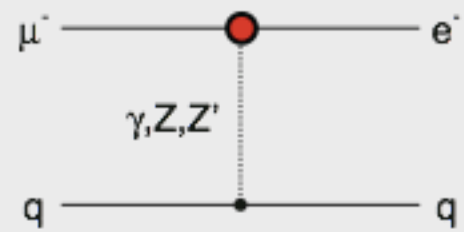
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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

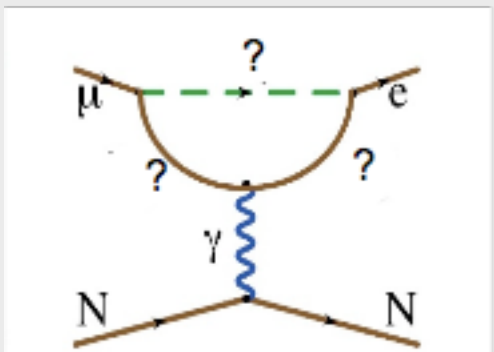


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

“Model-Independent” Picture

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

“Loops”

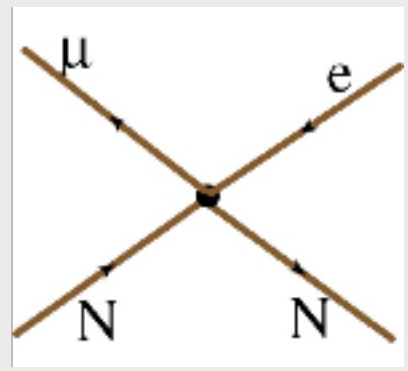


κ

Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

“Contact Terms”



Λ

Exchange of a new, massive particle

Does not produce μ→eγ

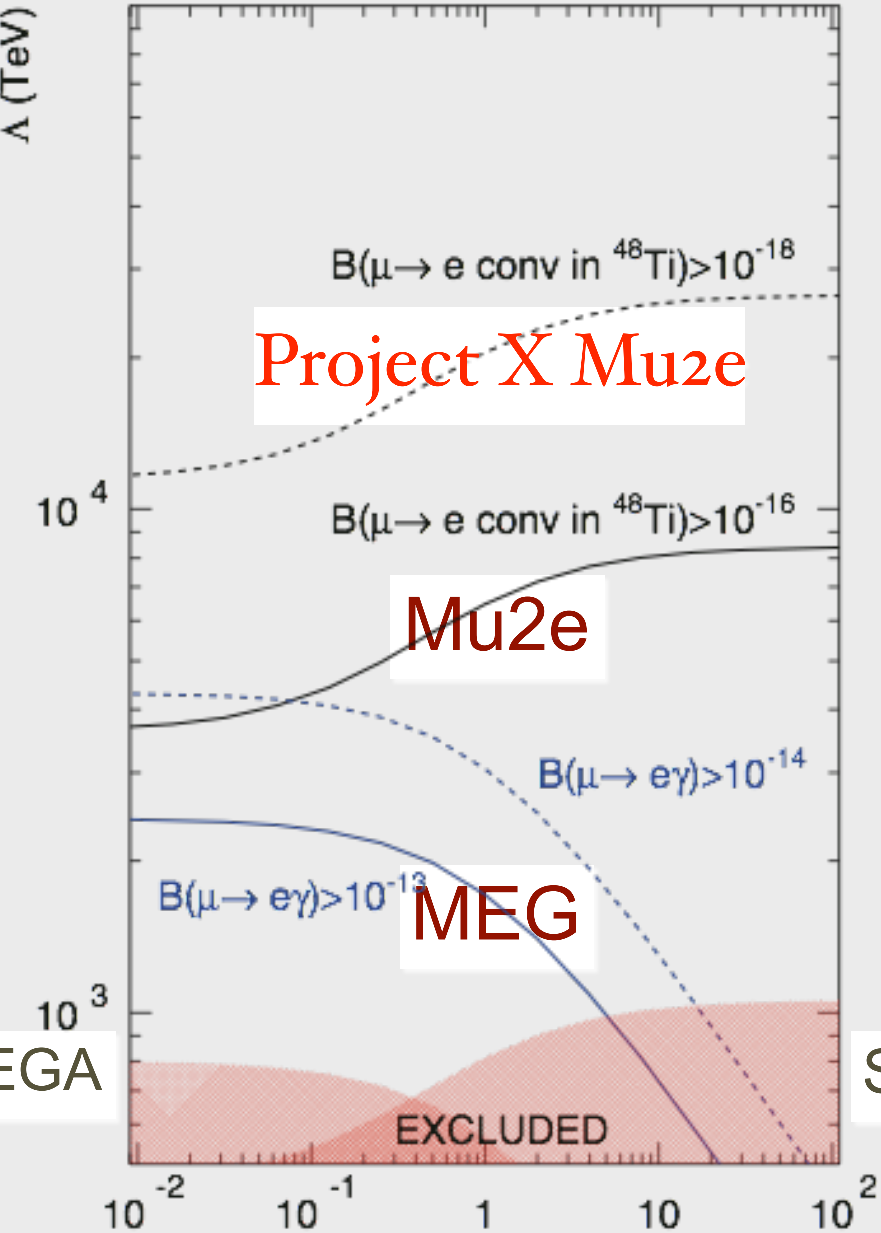
Quantitative Comparison?

μe Conversion and μ→eγ

1) Mass Reach to ~10^4 TeV

2) about x2 beyond MEG in loop-dominated physics

Λ (TeV)



MEGA

SINDRUM

higher mass scale

André de Gouvêa, Project X Workshop Golden Book

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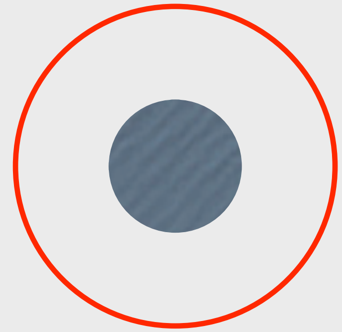
Overview Of Processes

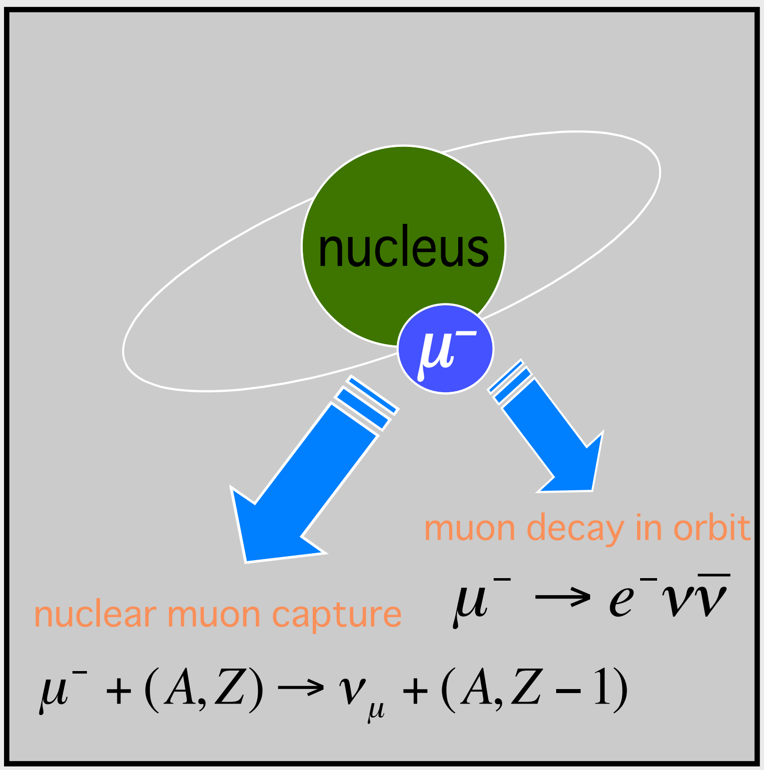
μ^- stops in thin Al foil

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

μ^- in 1s state



Al Nucleus
~4 fm



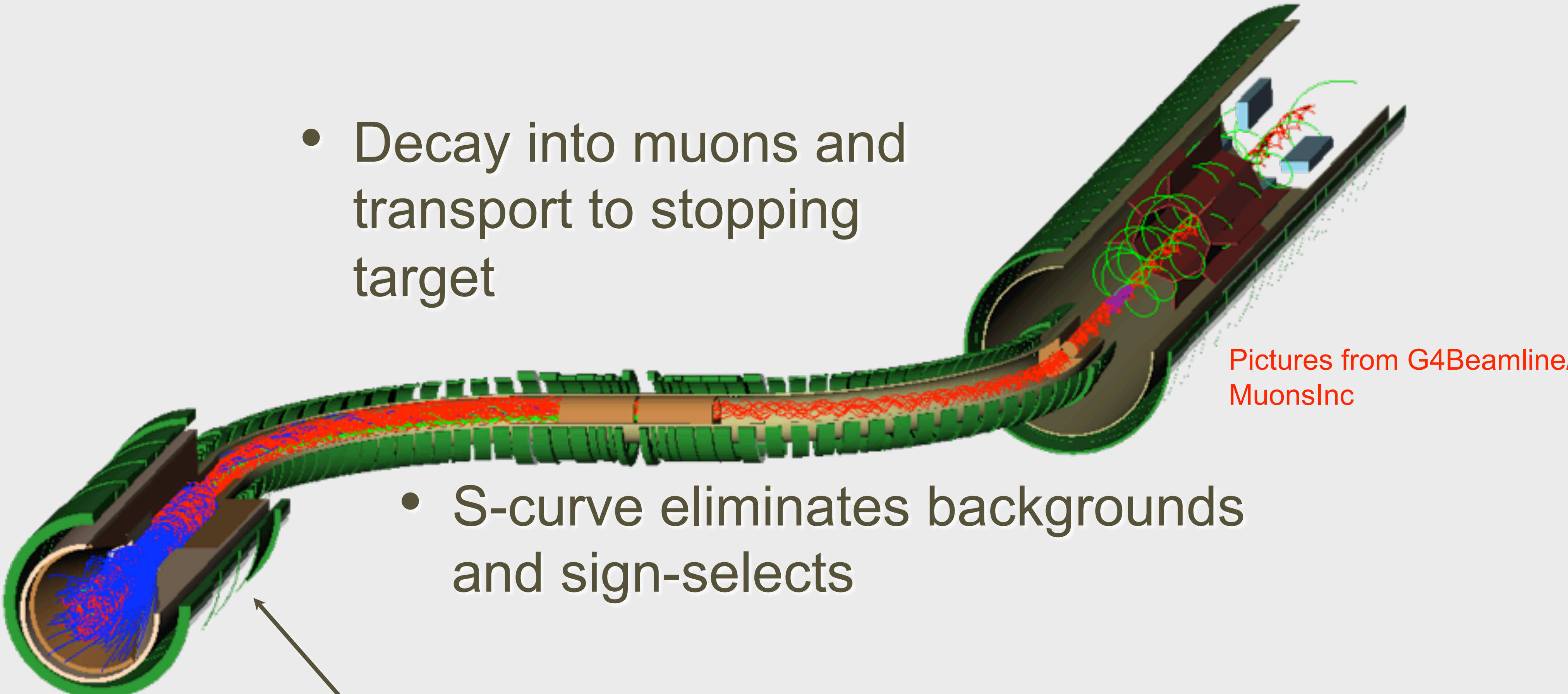
60% capture
40% decay

muon capture,
muon “falls into”
nucleus:
normalization

Decay in Orbit:
background

Detector and Solenoid

- Tracking and Calorimeter



- Decay into muons and transport to stopping target
- S-curve eliminates backgrounds and sign-selects
- Production: Magnetic mirror reflects π's into acceptance

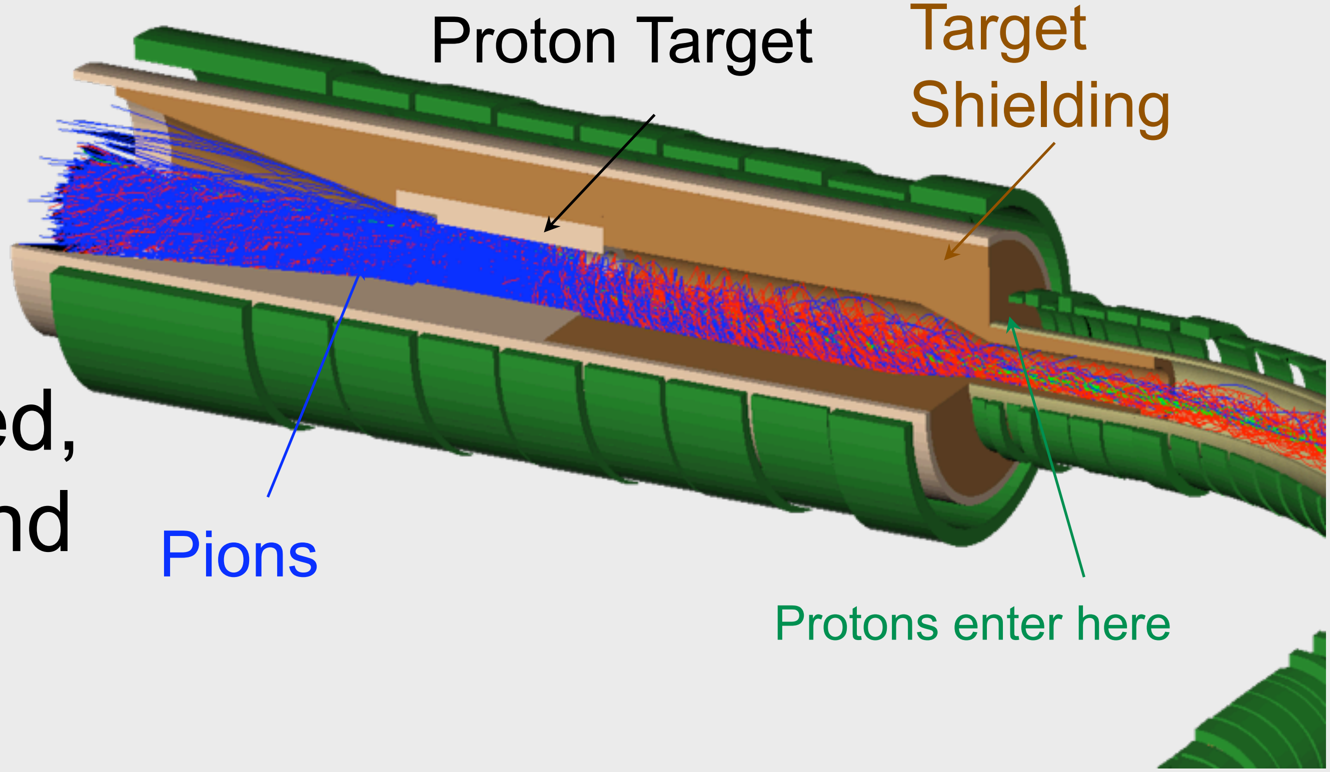
Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave through thin window

π's are captured, spiral around and decay

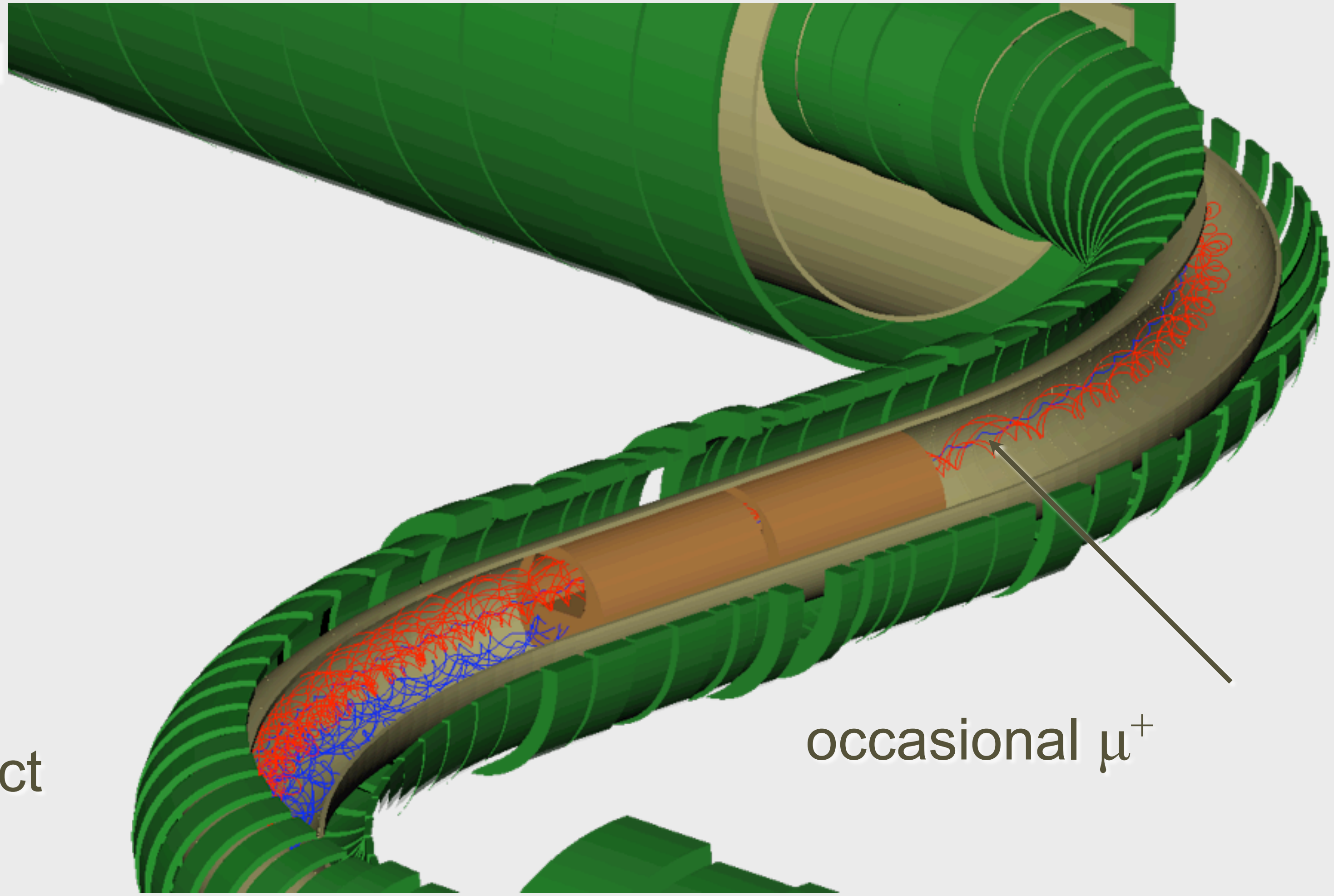
muons exit to right



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

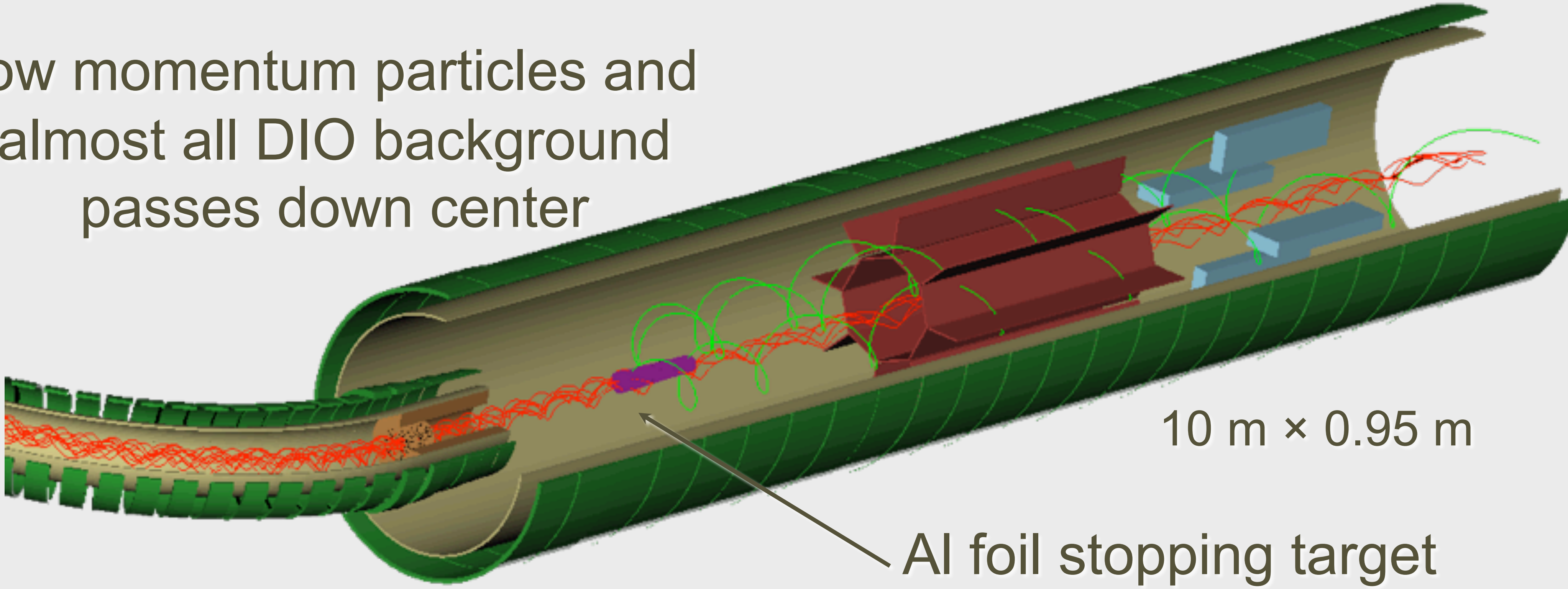


13.1 m along axis × ~0.25 m

Detector Solenoid

octagonal tracker surrounding central region:
radius of helix proportional to momentum

low momentum particles and almost all DIO background passes down center



10 m × 0.95 m

Al foil stopping target

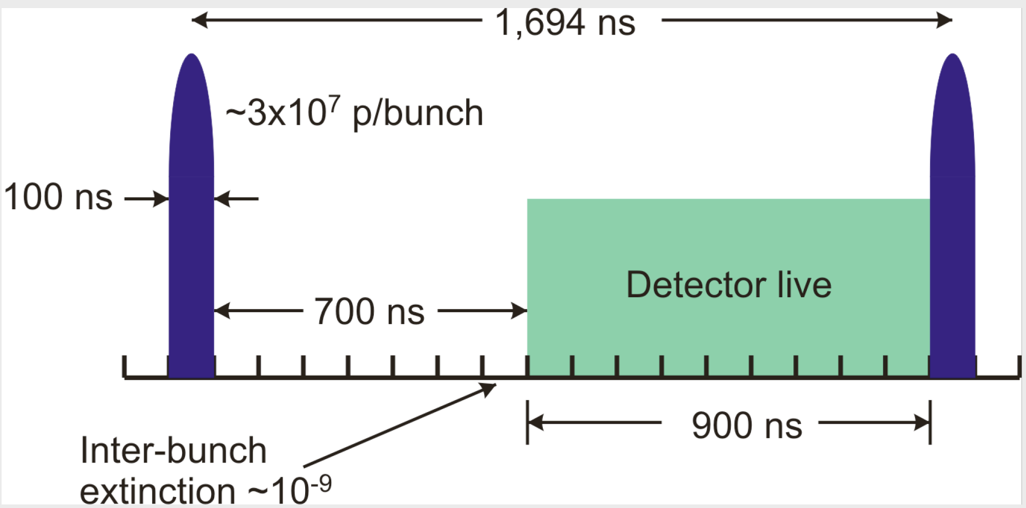
signal events pass through octagon of tracker and produce hits

Two Classes of Backgrounds

	Prompt	Decay-In-Orbit
Source	Mostly π's produced in target	Physics Background nearly indistinguishable from signal
Solution	Design of Muon Beam, formation, transport, and time structure	Spectrometer Design: resolution and pattern recognition

Pulsed Beam Structure

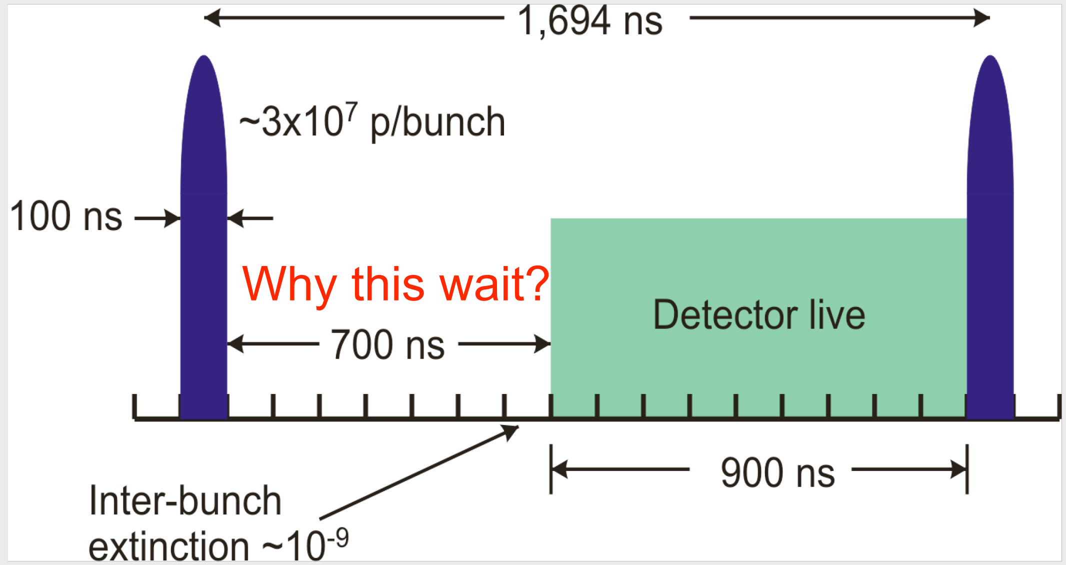
- Tied to prompt rate and machine: FNAL near-perfect
- Want pulse duration << $\tau_\mu^{\rm Al}$, pulse separation ≥ $\tau_\mu^{\rm Al}$
  - FNAL Debuncher has circumference 1.7μsec !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse



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

Prompt Backgrounds

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

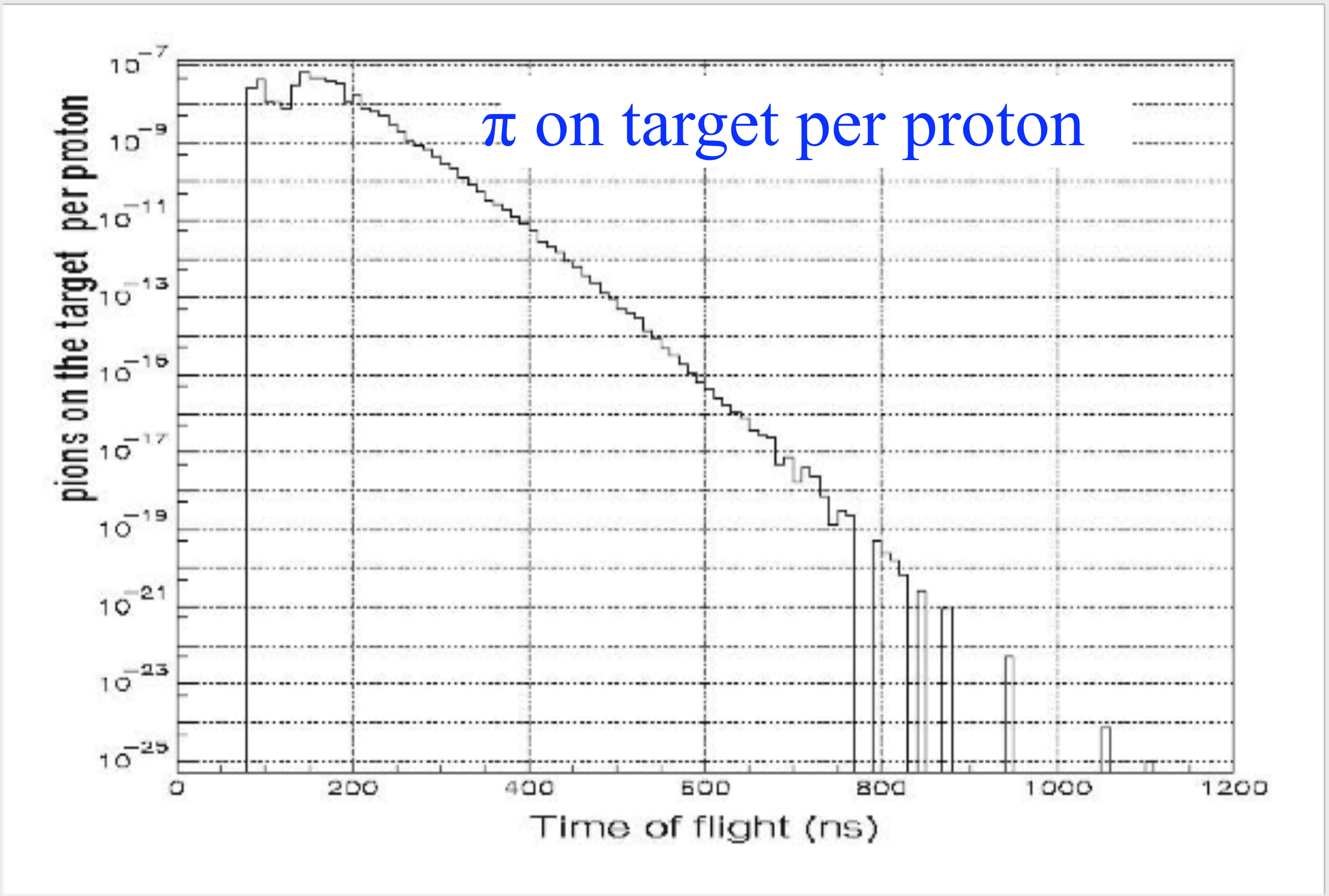


Radiative pion capture

- π-$+A(N,Z) \rightarrow \gamma + X$.
  - γ up to m_π, peak at 110 MeV; $\gamma \rightarrow e+e-$;
  - if one electron ~ 100 MeV in the target, looks like signal: limitation in best existing experiment, SINDRUM II?

Radiative π vs. Time

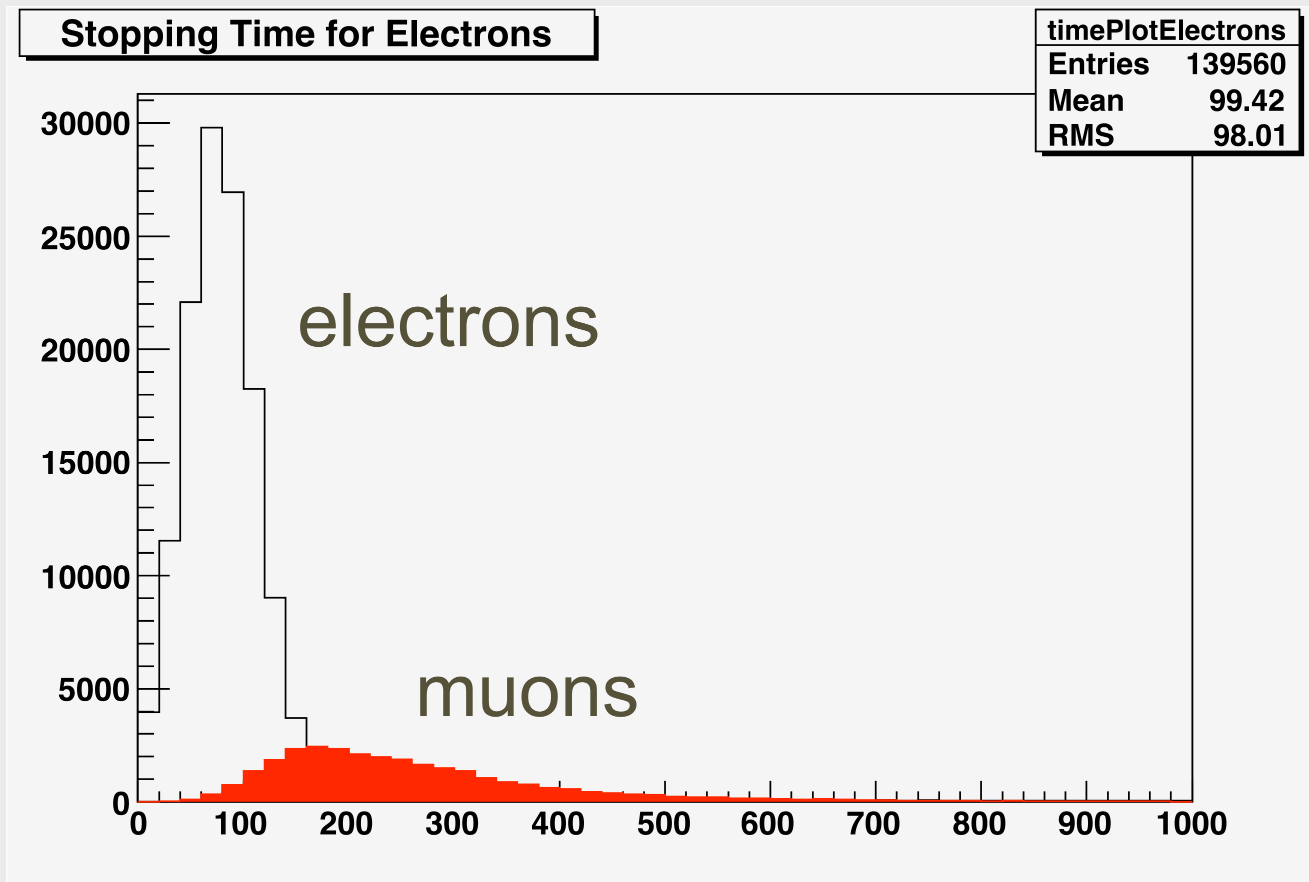
- This is a main reason why we have to wait 700 nsec
- would be really nice to eliminate pions another way!!



Gain 10^{11} in π rejection by waiting 700 nsec

Beam Flash

- Beam electrons: incident on the stopping target and scatter into the detector region.
- Need to suppress e^- with E>100 MeV near 105 MeV signal



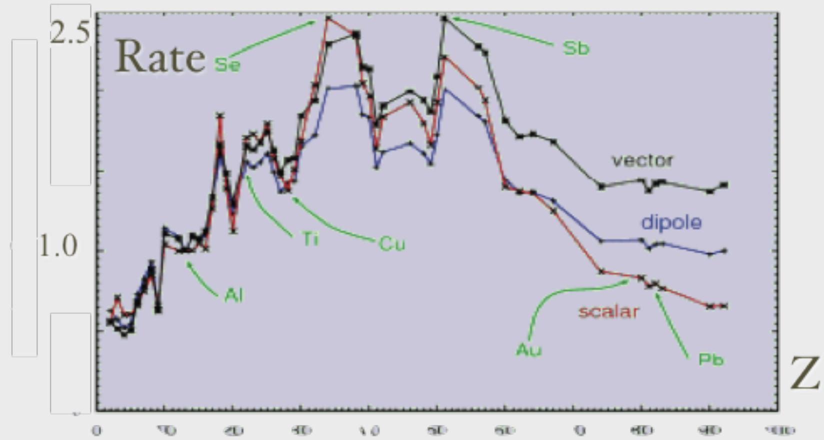
Other Backgrounds

- In-flight muon decays yielding electrons
  - If p_μ > 76 MeV/c, can get > 100 MeV electron
- Late arriving electrons from spiraling in field
- Momentum selection and a tighter timing distribution would help!

Choice of Stopping Material: rate vs wait

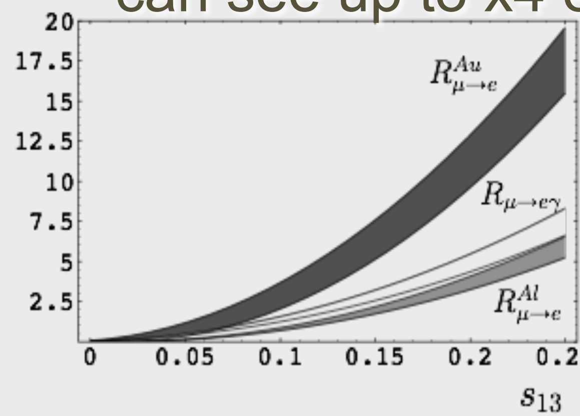
- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

rate normalized to Al



Kitano, et al.,PRD 66, 096002 (2002)

can see up to x4 effect!



s_{13} is NOvA mixing angle < 0.2 or so

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005. e-Print: hep-ph/0507001

Prompt Background and Choice of Z

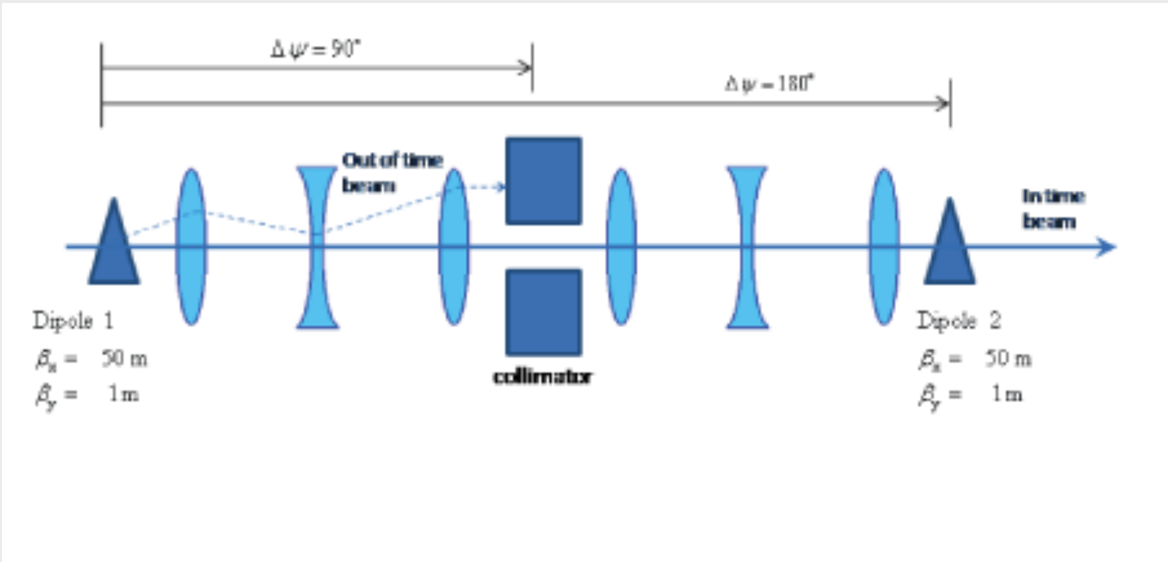
- choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

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 Too short!	95.56 MeV	negligible

Extinction Scheme

achieving 10^{-9} is hard; normally get $10^{-2} - 10^{-3}$

- Eliminate protons in beam in-between pulses:



CDR under development

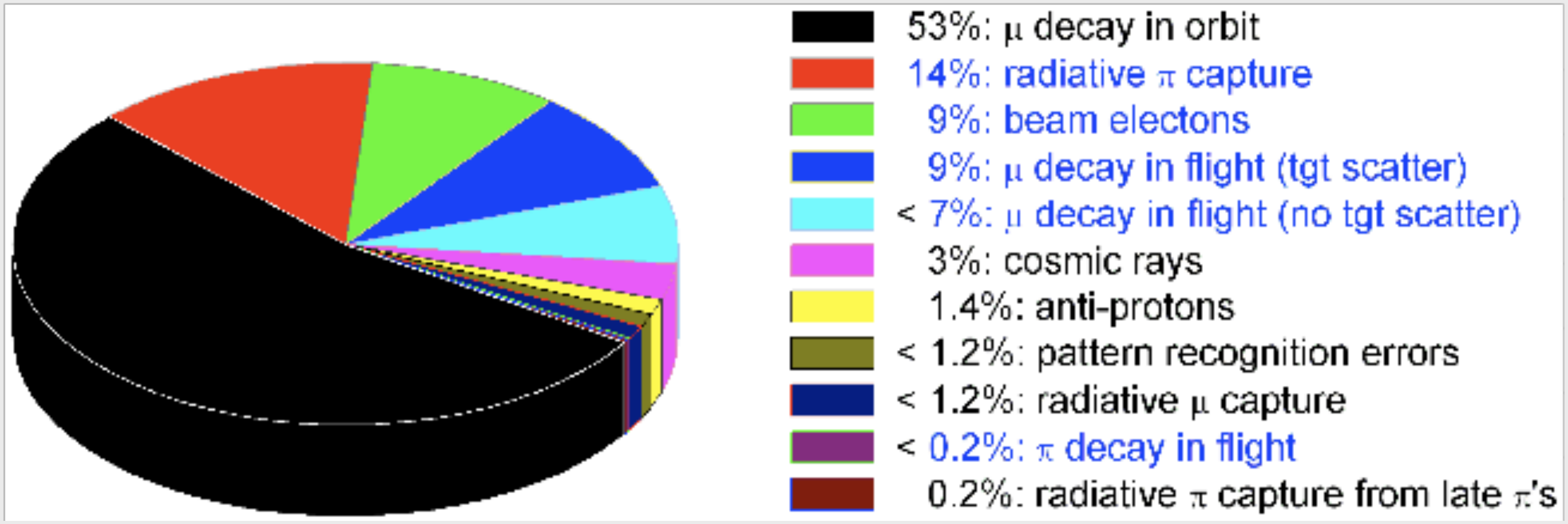
- "Switch" dipole timing to switch signal and background: accept only out-of-time protons for direct measurement of extinction
- Continuous Extinction monitoring techniques under study
  - Cerenkov light with gated PMT for beam flash

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



Outline

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- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
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Project X Timing

- Must run and analyze Mu2e Phase I
- We will continue to refine our existing design and look for new ideas
    - solenoid? tracking? time structure?
- Finish analysis Phase I around 2020 then
- Project X makes a program possible, improving as we learn

Mu2e Upgrades

Signal?

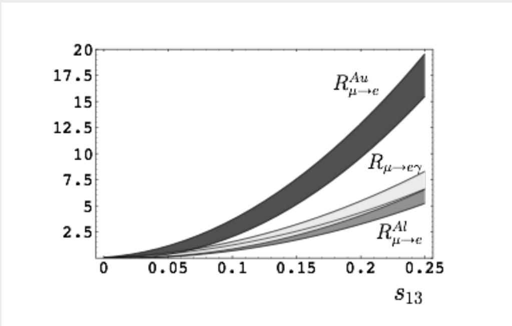
Yes

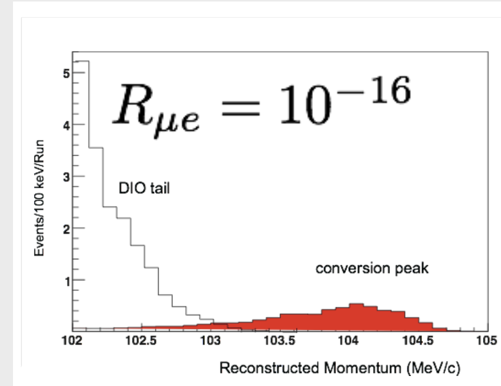
1. Change Z of Target to determine source of new physics
2. Need Project X to provide statistics

No

1. Probe additional two orders of magnitude made possible by Project X
2. Need upgrades to muon transport and detector

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

Upgrade Challenges

- If we want higher Z targets, must shorten the 700 nsec wait time, perhaps 700 → 70 nsec
  - Beam flash
  - Radiative pi capture
- But without a signal, *also* need to improve resolution from decay-in-orbit background
  - Just the beam improvements are not enough: would only reduce radiative pi background x2
  - Resolution of spectrometer and pattern recognition algorithms; new hardware?
- Extinction: need ~x100 better

Conclusions (physics)

- Mu2e will:
  - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6\times10^{-17}$ @ 90% C.L.)
  - Discover unambiguous proof of Beyond Standard Model physics or provide important information either complementing the LHC or probing up to 10^4 GeV mass scales
- Technically limited schedule: data-taking 2016:
  - We plan to use existing scheme, not major variations for beam delivery

Conclusions (upgrade)

- Resolution and background issues are critical
- Project X will get at least x10 in statistics,
  - *With a signal*
    a) Explore different targets
    b) Reduce radiative pion background
    c) Decrease time spread of muons
  - *And with a limit,* the beam related sources are only ½ of background – resolution/misreconstructions becomes the limiting problem