A Mu2e Upgrade Plan for the Project X Era

Chuck Ankenbrandt
Muons, Inc. and Fermilab
January 28, 2009

Introduction

- Synergies among NFs, MCs, and a Mu2e Upgrade:
  - All three need an intense proton source.
    - At Fermilab, that will be Project X (1 MW @ 8 GeV).
    - Project X needs an 8-GeV "customer".
    - That could be the Mu2e experiment.
    - The same 8-GeV ring(s) could be used for all three.
  - All three (or two!) will benefit from muon cooling.
    - Cooling may be provided by a helical cooling channel.
    - The Mu2e application is easier than that of the MC.
    - The Mu2e need is earlier than that of the MC.
- Multiple uses of bright muons build HEP support.
  - Muon cooling technology will enable a diverse program.
  - The other kind of lepton collider is a one-trick pony.
- We should come to praise spinoffs, not bury them.

MANX/Mu2e @ AAC Meeting

- There will be a session on MANX at the Fermilab Accelerator Advisory Committee meeting next week.
- MANX proposes to test a helical cooling channel.
- The same kind of HCC might be used to upgrade the Mu2e experiment.
- I will talk about a Mu2e upgrade plan at that meeting.
- Bob Bernstein, co-spokesperson for Mu2e, has allowed me to show you some of the slides that he prepared for that meeting.
- Jim Miller, our other co-spokesperson, has allowed me to use some of his slides from a recent PAC meeting.

Structure of this talk

- Introduction
- Mu2e Baseline Design
- A Mu2e Upgrade Plan
- Summary/Conclusions

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

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G4beamline

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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:

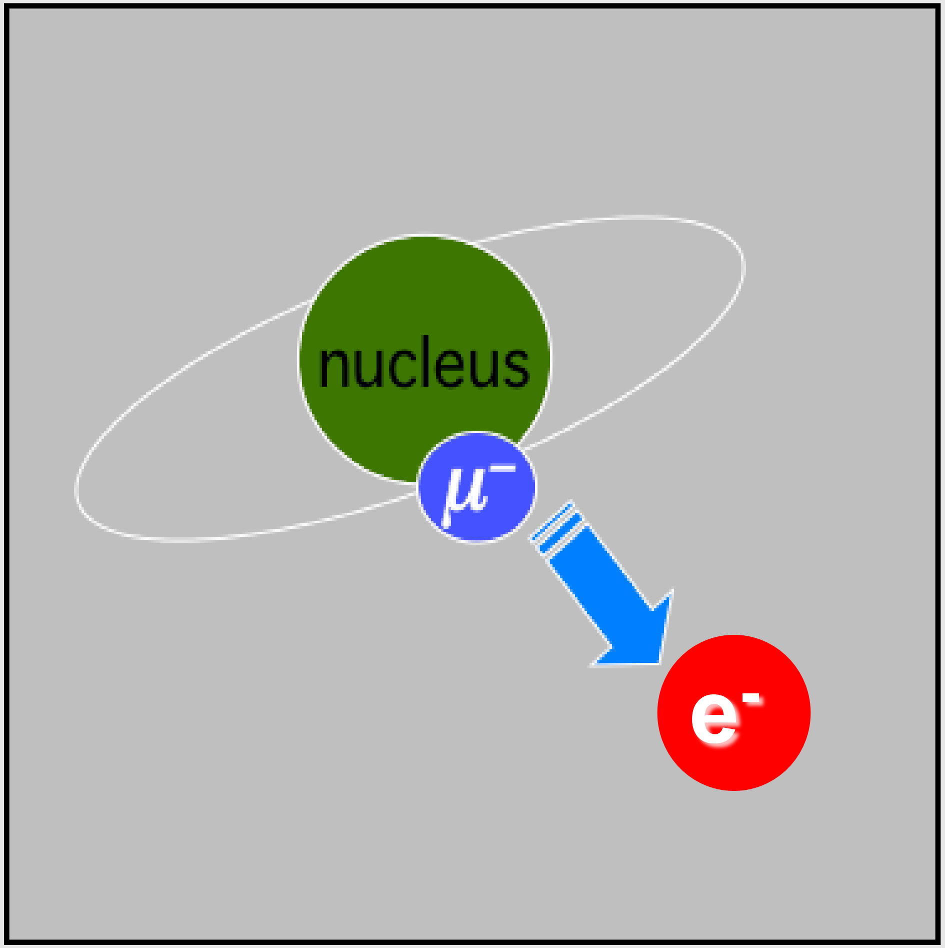
"The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. The panel recommends pursuing the muon-to-electron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

Mu2e is a central part of the future US program

Experimental Signal

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

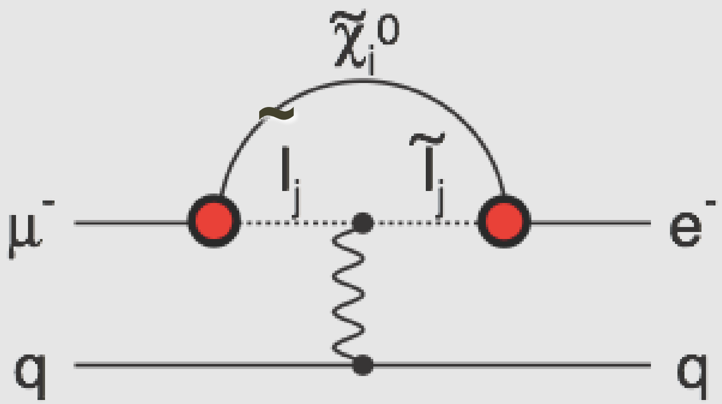
- A Single Monoenergetic Electron
- If N = Al, E_e = 105. *MeV*
    - electron energy depends on Z



LFV, SUSY and the LHC

Supersymmetry

rate ~ 10^{-15}



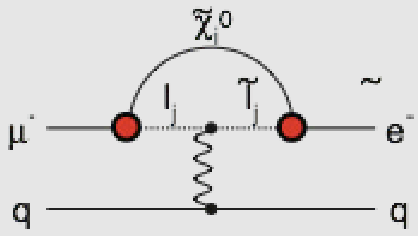
Access SUSY through loops:

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

Contributions to μe Conversion

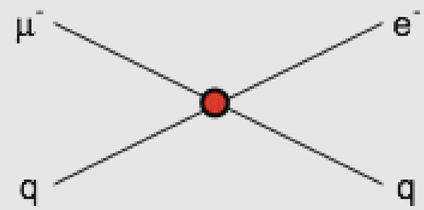
Supersymmetry

rate ~ 10^{-15}



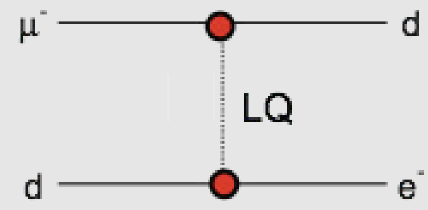
Compositeness

$\Lambda_c \sim 3000$ TeV



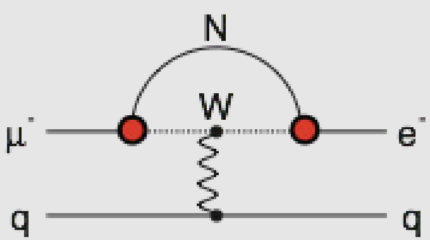
Leptoquark

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



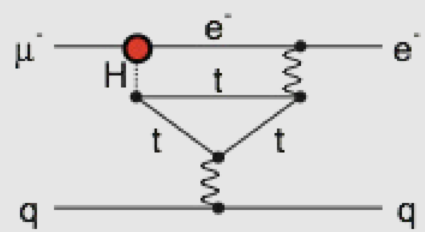
Heavy Neutrinos

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



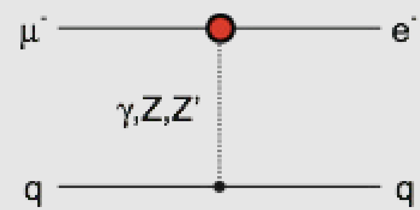
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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

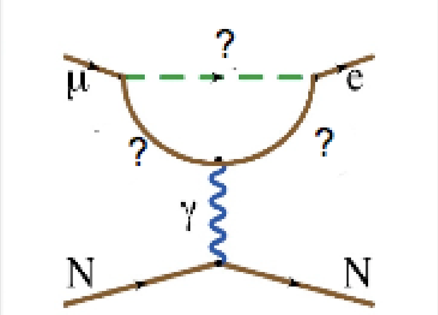


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

“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” | **“Contact Terms”**



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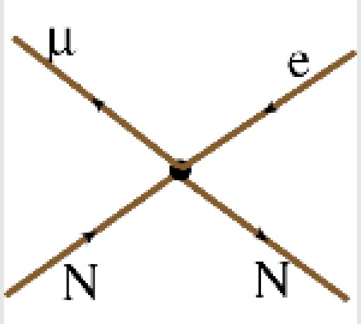


Λ

Supersymmetry and Heavy Neutrinos

Exchange of a new, massive particle

Contributes to μ→eγ

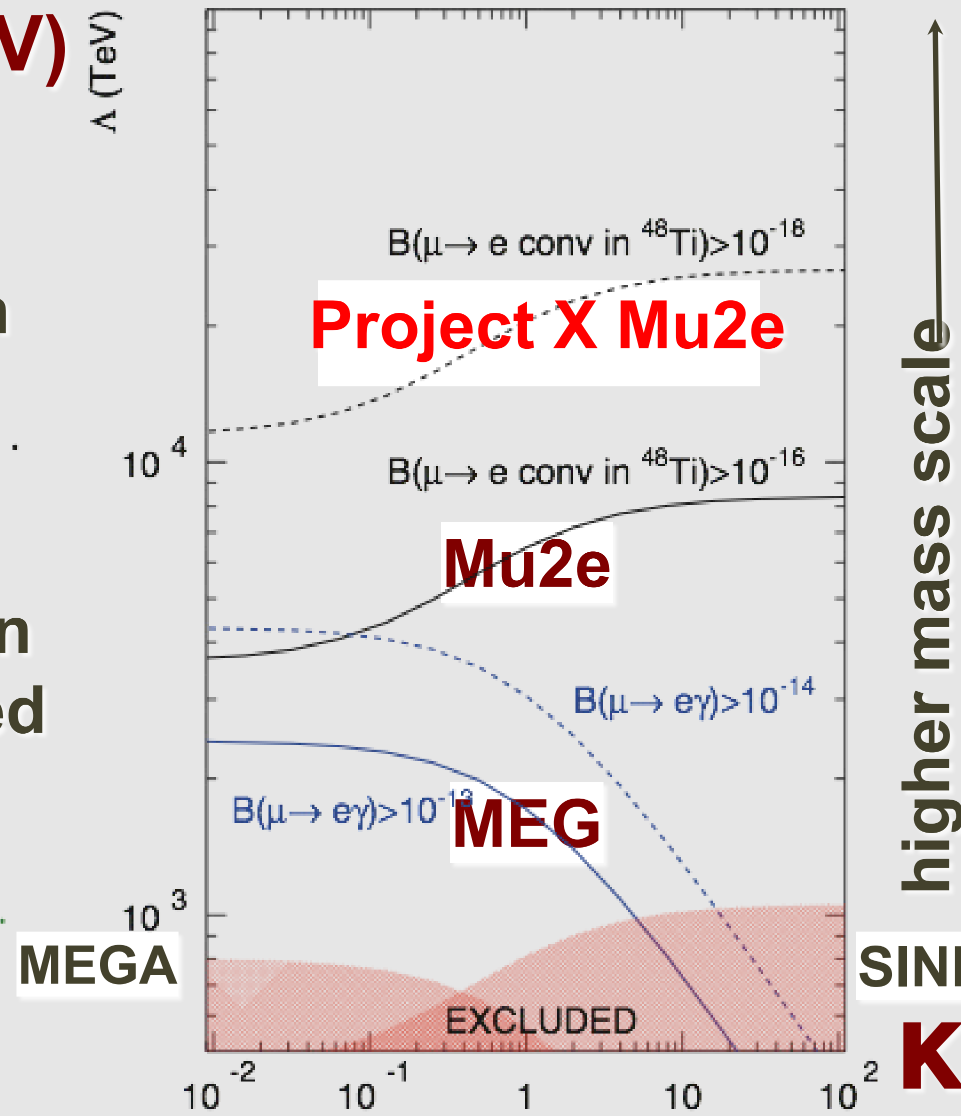
Does not produce μ→eγ

Quantitative Comparison?

μe Conversion and μ→eγ

1) Mass Reach to ~10^4 TeV

2) about x2 beyond MEG in loop-dominated physics



André de Gouvêa, Project X Workshop Golden Book

Outline

- The search for muon-electron conversion
- Experimental Technique
- Project X Upgrades and Mu2e
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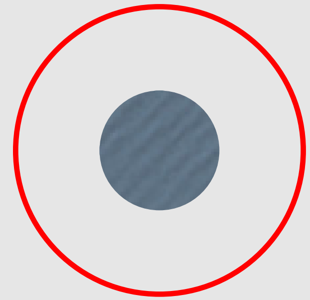
Overview Of Processes

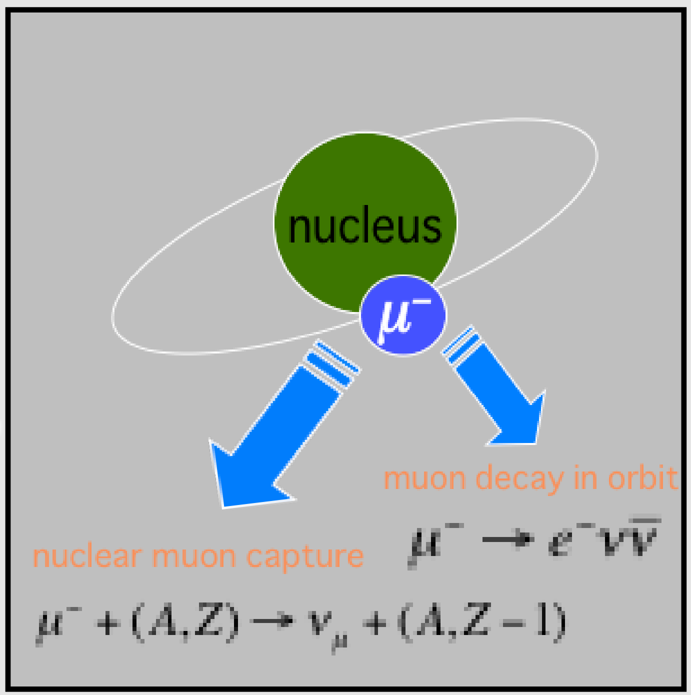
μ⁻ stops in thin Al foil

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

μ⁻ in 1s state



Al Nucleus
~4 fm



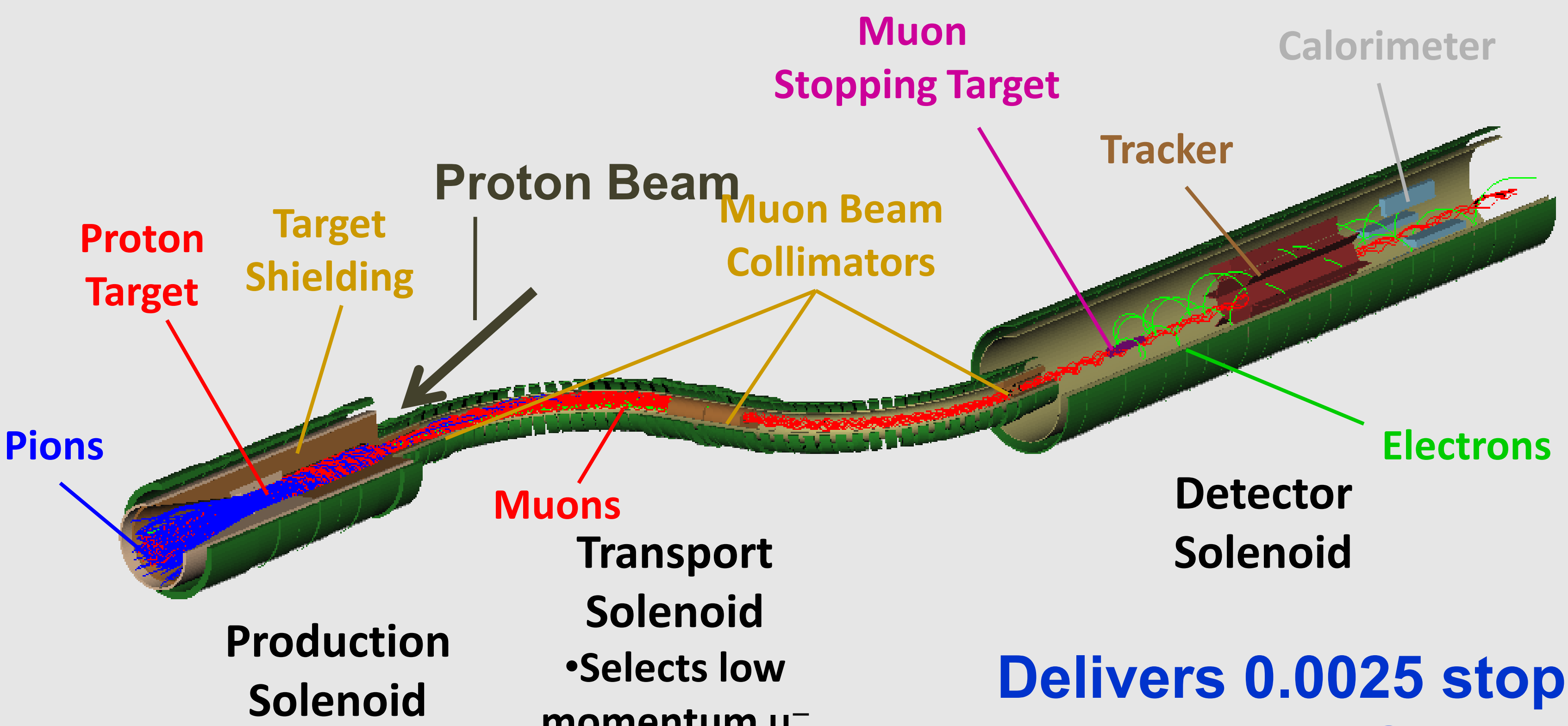
60% capture
40% decay

muon capture, muon “falls into” nucleus: **normalization**

Decay in Orbit: **background**

Mu2e Muon Beamline- follows MECO design

Muons are collected, transported, and detected in superconducting solenoidal magnets



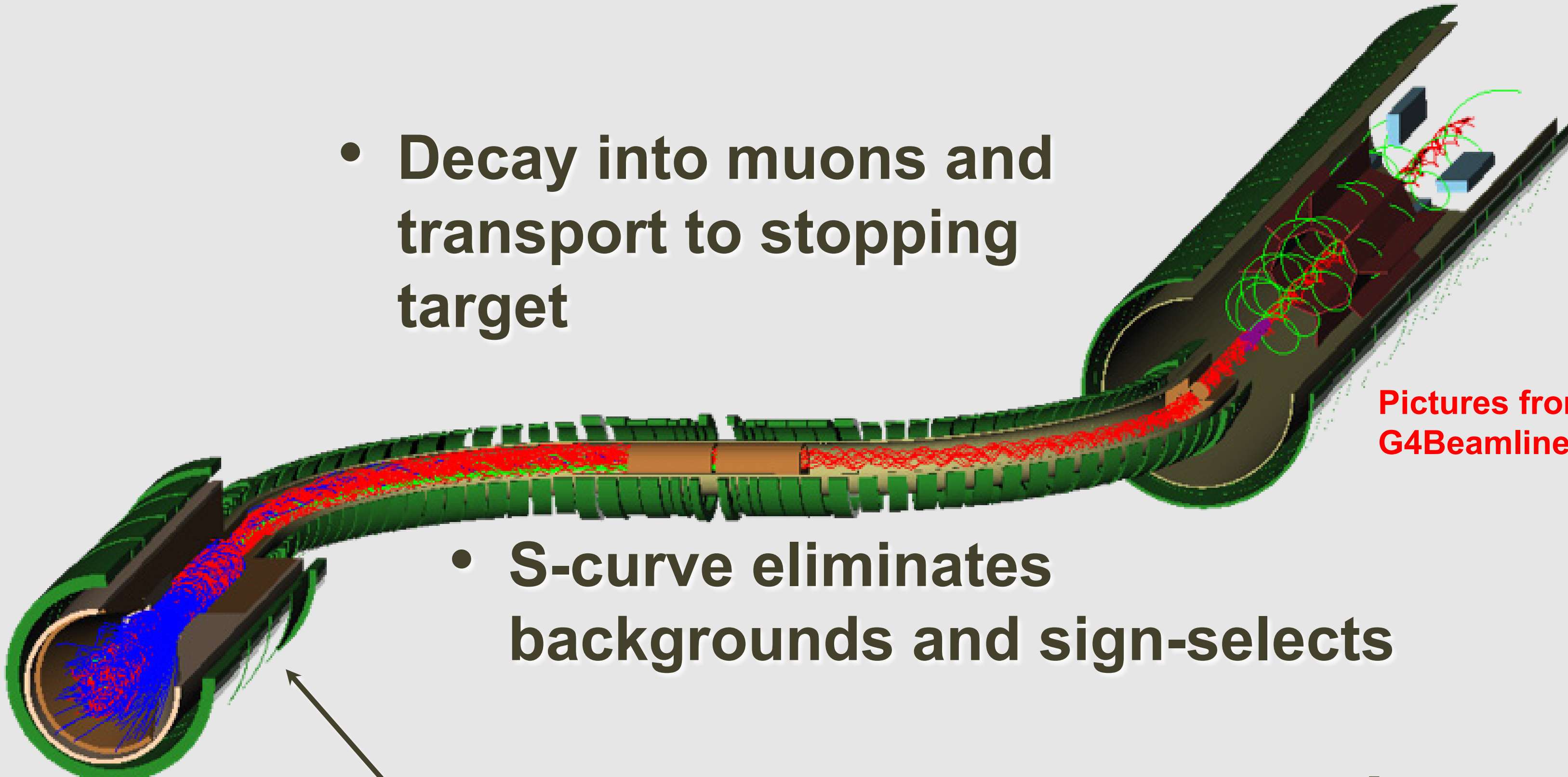
- Selects low momentum μ^-
- Avoids straight line from production target to detectors

Delivers 0.0025 stopped muons per 8 GeV proton

Detector and Solenoid

- Tracking and Calorimeter

- Decay into muons and transport to stopping target



Pictures from G4Beamline/MuonsInc

- S-curve eliminates backgrounds and sign-selects

- Production: Magnetic mirror reflects π's into acceptance

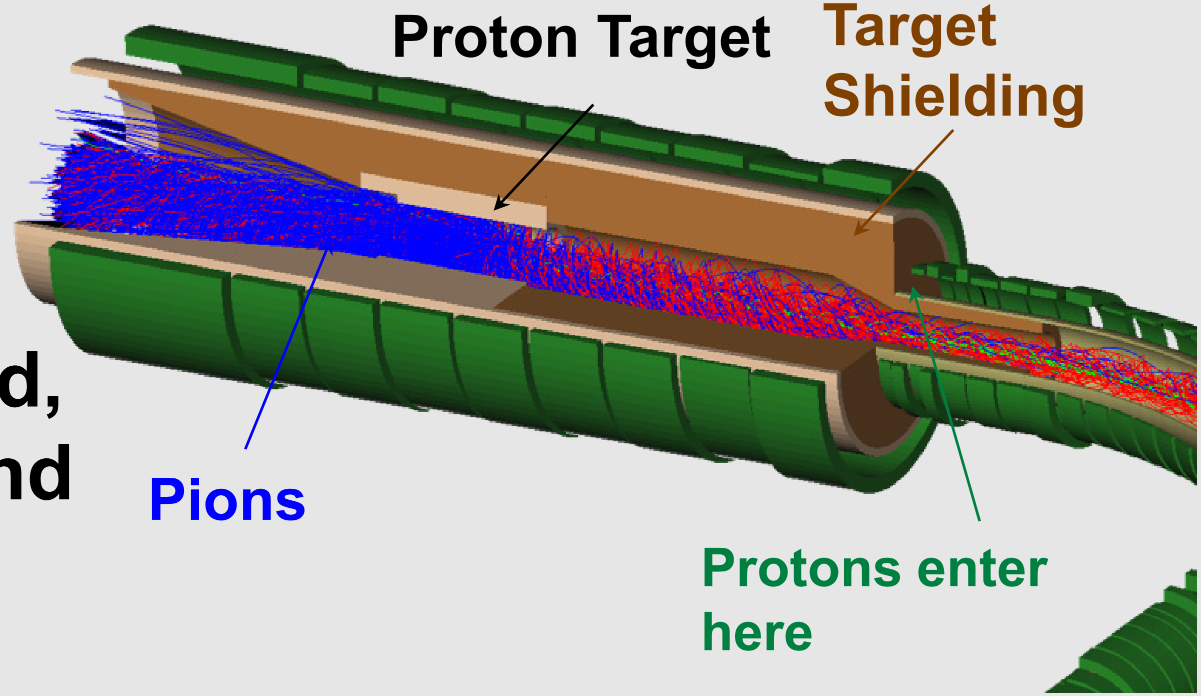
Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave through thin window

π's are captured, spiral around and decay

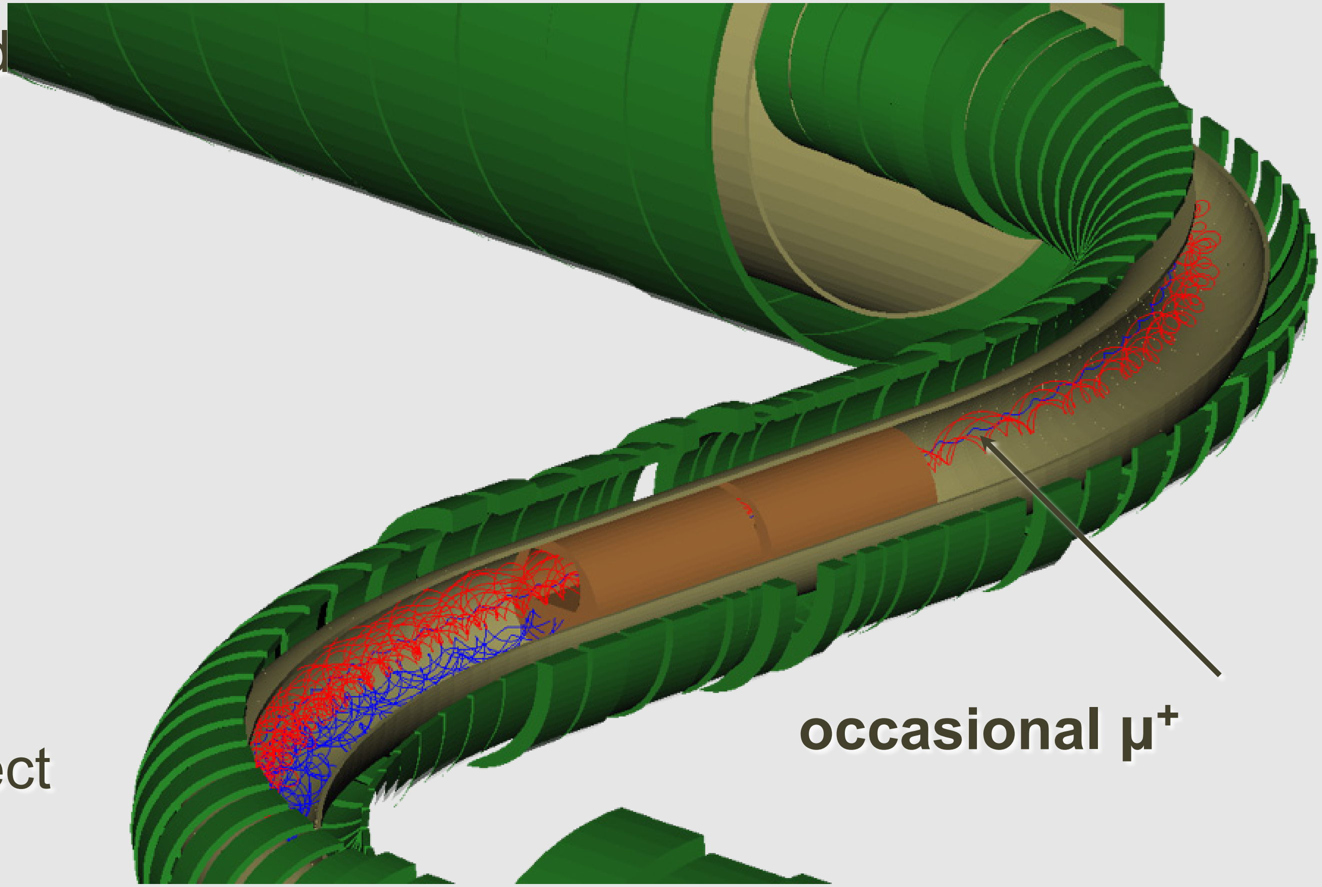
muons exit to right



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



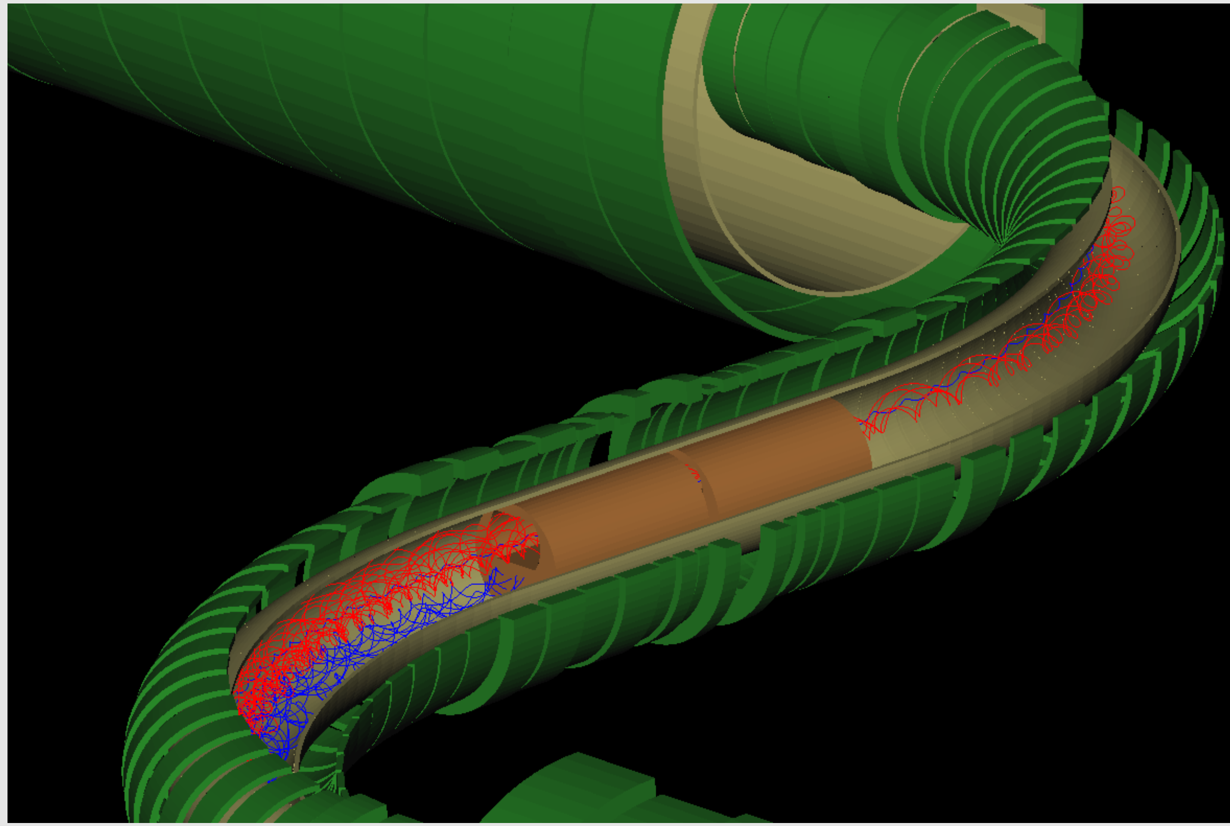
occasional μ^+

13.1 m along axis × ~0.25 m

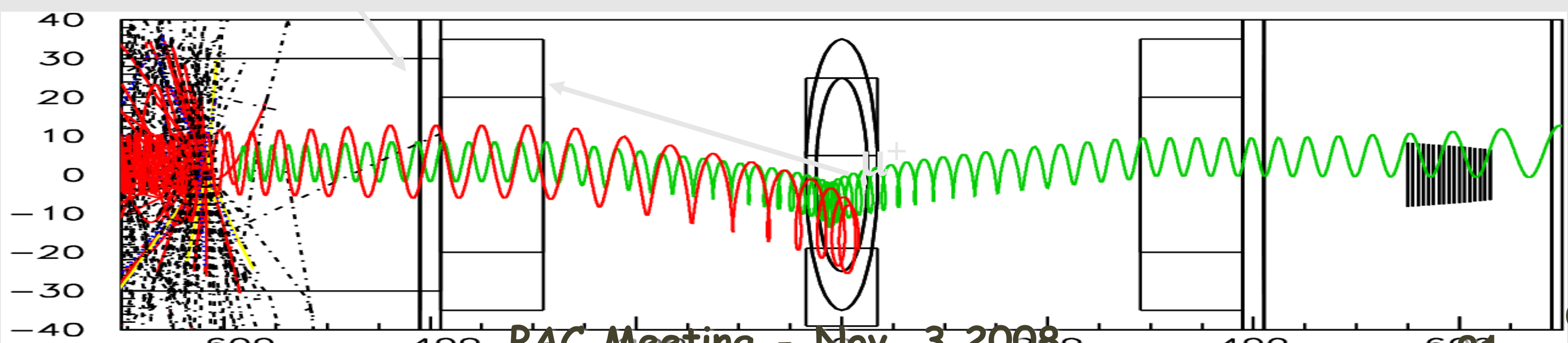
Separation of μ^- from μ^+

$$\text{pitch} = \alpha = \frac{p_l}{p}$$

$$D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p(\frac{1}{\alpha} + \alpha).$$



cm

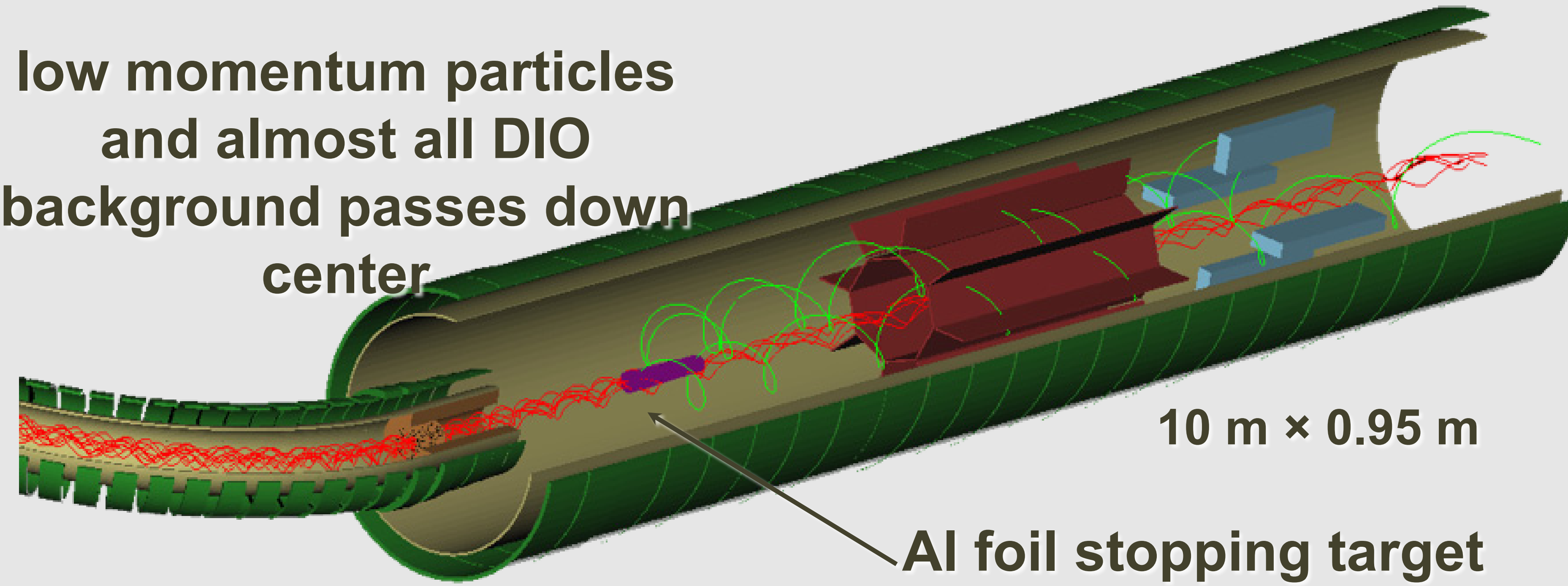


cm

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

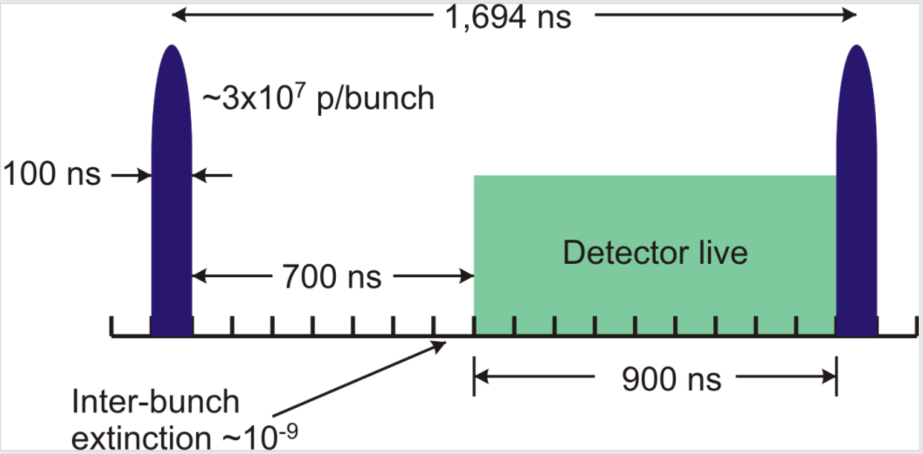
signal events pass through octagon of tracker and produce hits

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

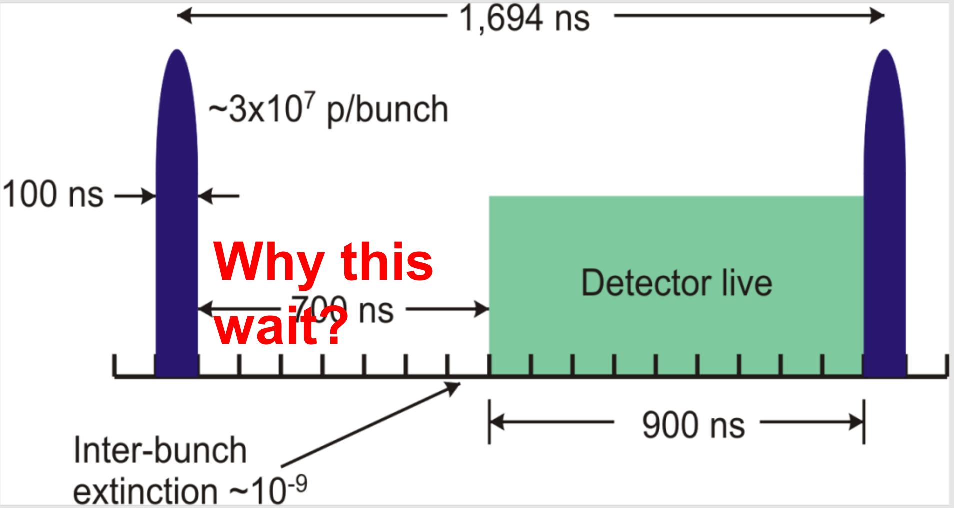
- Tied to prompt rate and machine: FNAL near-perfect
- Want pulse duration << τ_μ^{Al} , pulse separation ≥ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7 μsec !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse



- **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

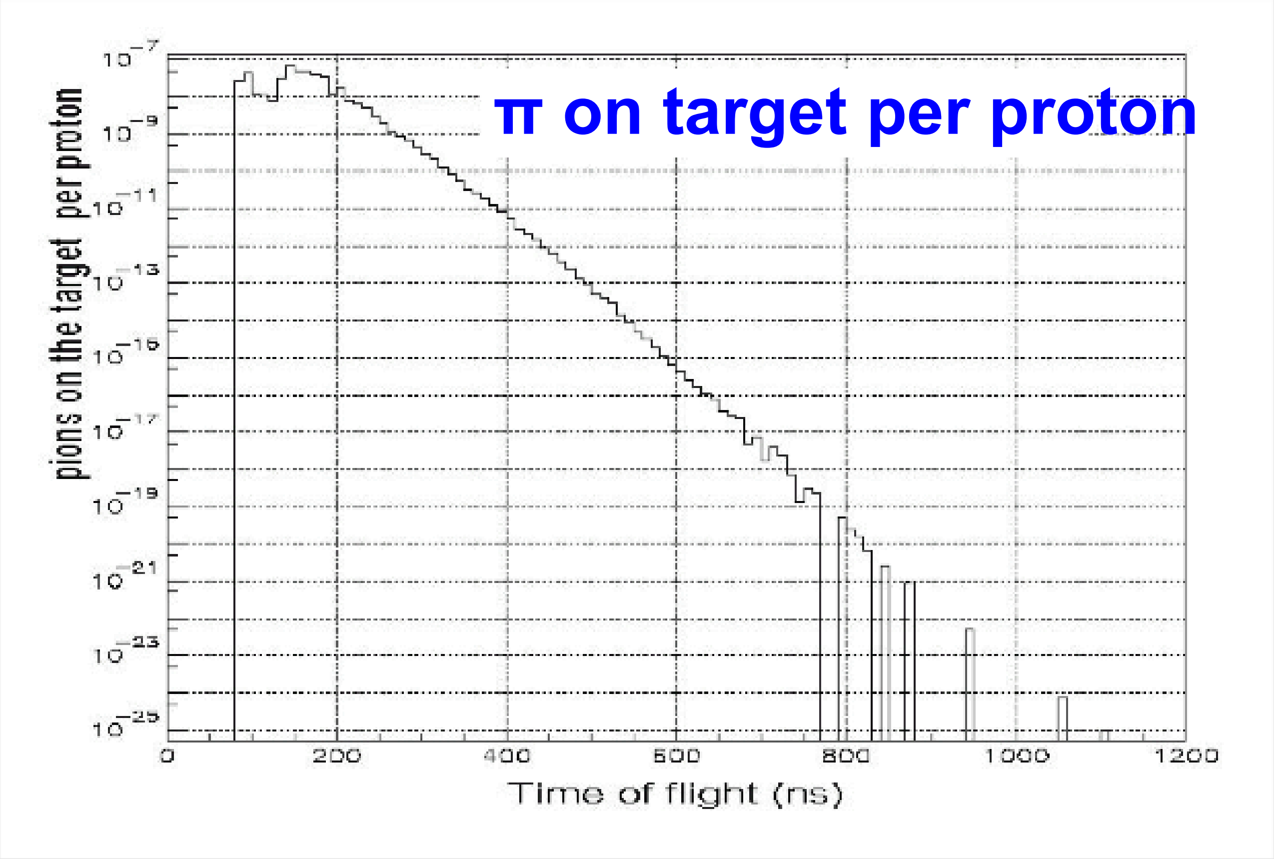
- $\pi^- + A(N,Z) \rightarrow \gamma + X.$
  - γ up to m_π, peak at 110 MeV; $\gamma \rightarrow e^+e^-$;
  - if one electron ~ 100 MeV in the target, looks like signal: limitation in best existing experiment, SINDRUM II?

Radiative π vs. Time

- This is a main reason why we have to wait 700 nsec

Upgrade alert!

- would be really nice to eliminate pions another way!!



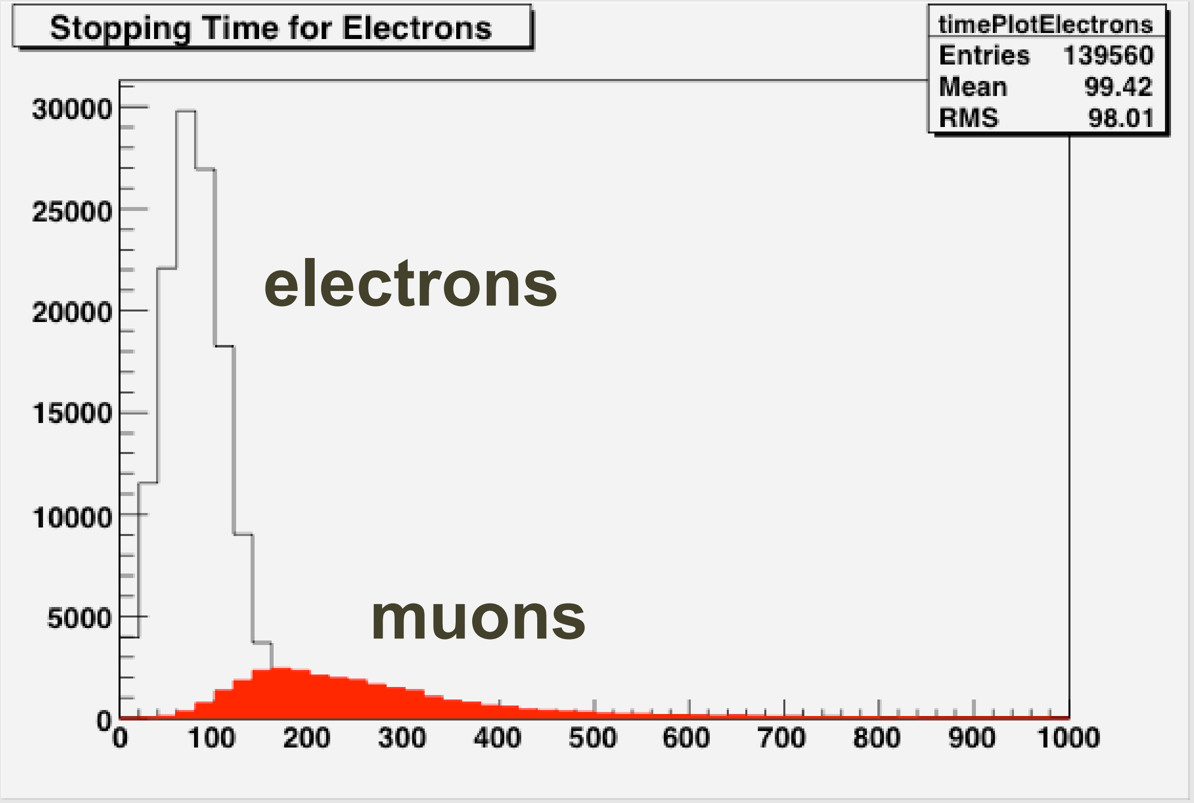
Gain 10^{11} in π rejection by waiting 700 nsec

Beam Flash

- Beam electrons: incident on the stopping target and scatter into the detector region.

Upgrade alert!

- 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!

Upgrade alert!

Backgrounds from Stopped Muons(Cont'd)

- Ordinary muon capture on the nucleus

$$\mu^- + A(N,Z) \rightarrow A'(N',Z') + \nu_\mu + an + bp + c\gamma,\ \langle a\rangle \sim 2,\ \langle b\rangle \sim 0.1,\ \langle c\rangle \sim 2$$

  - In aluminum, 40% capture, 60% decay, lifetime = 864 ns
  - n, p are low energy, γ are mostly low energy, well below conversion electron energy: create high rate background in detectors, potential track recognition errors
    - Neutral background (n, γ) is reduced by displacing detectors downstream from the stopping target **Upgrade alert!**
    - Protons are reduced by placing thin absorbers in their path
  - Muon radiative decay, γ near conversion energy, prob ~ few x 10^{-5}; endpoint for aluminum 102.4 MeV, 2.5 MeV below conversion electron energy. Smaller event rate but still significant compared to DIO.
- In-flight muon decay
  - p_μ>75 MeV/c can decay to >100 MeV electron

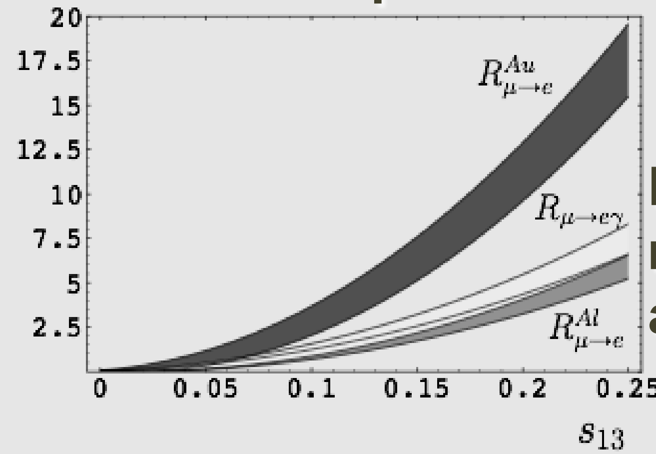
Long Transit Time Background

- Particles with low longitudinal velocity can take a long time to traverse the beam line, arriving at the stopping target during the measurement period
  - Antiprotons and radiative pion capture:
    - Antiprotons are stopped by a thin window in middle of transport
    - Adjust measure start time until most long-transit time pions decay
- Example of a potential problem
  - Pion decays into a muon early in the transport solenoid
  - Muon can have small pitch and progress very slowly downstream
  - Muon can decay after a long time into an electron
  - Decay electron can be >100 MeV if p_μ>75 MeV/c
  - Electron could scatter in collimators, arriving at the target late during the measurement period, where it could scatter into the detector acceptance
- To suppress this…
  - Straight sections of solenoids have dB_s/ds<0.02 T/m **Upgrade alert!**
    - Greatly reduces number of particles (e.g. $\pi \rightarrow \mu$) with small pitch
    - Gradient criterion not necessary in curved solenoid sections, low pitch particles are swept away vertically by dB_s/dr field gradient.

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 **Upgrade alert!**
- Why start with Al?

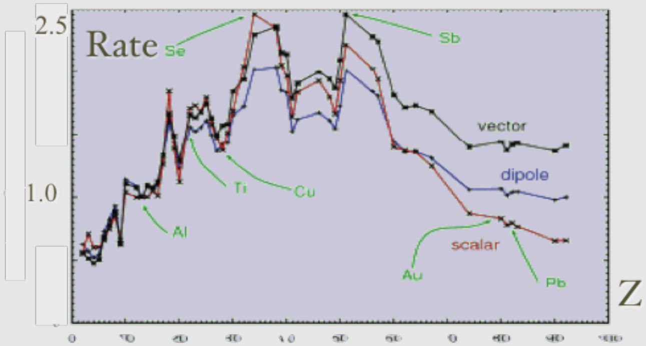
can see up to x4 effect!



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

rate normalized to Al



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

Prompt Background and Choice of Z

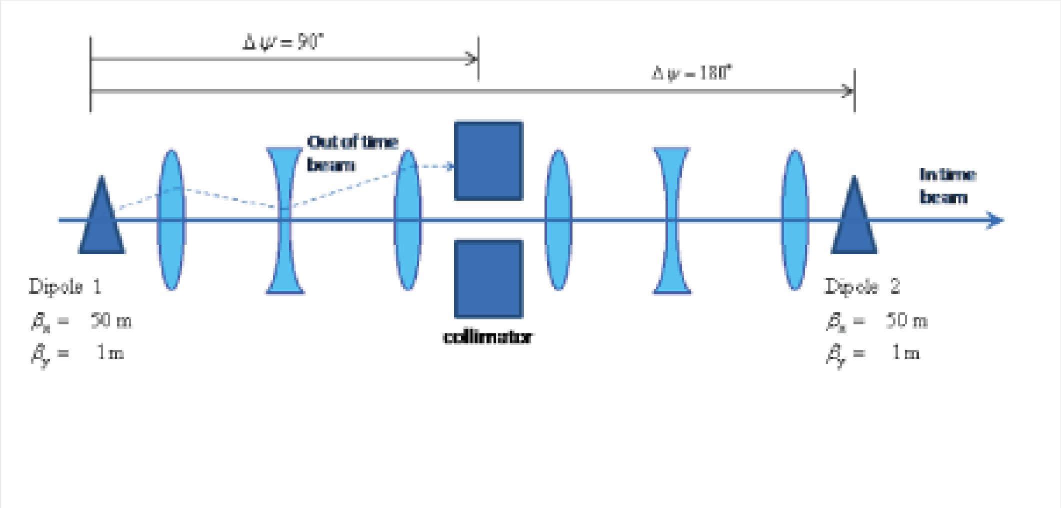
- choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

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

- Eliminate protons in beam in-between pulses:



CDR under development

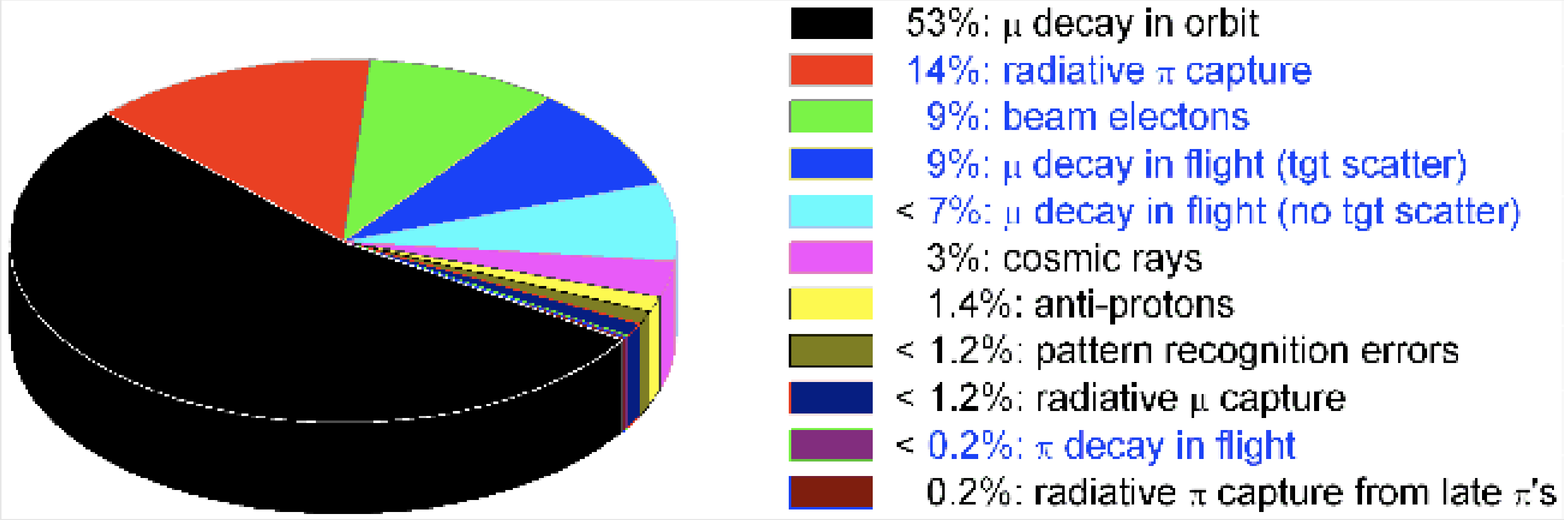
- "Switch" dipole timing to switch signal and background: accept only out-of-time protons for direct measurement of extinction
- Continuous Extinction monitoring techniques under study
  - Cerenkov light with gated PMT for beam flash

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

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

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

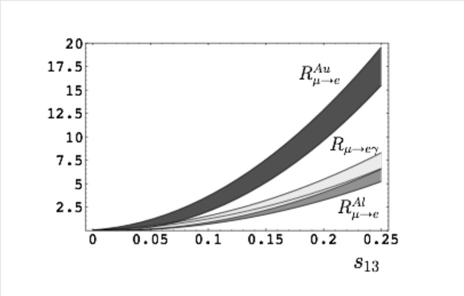
2. Need Project X to provide statistics

No

1. Probe additional two orders of magnitude made possible by Project X

2. Need upgrades to muon transport and detector

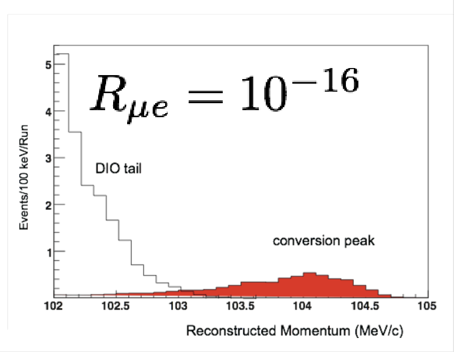
Upgrade Plans...



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 background x2
  - Resolution of spectrometer and pattern recognition algorithms; new hardware? **Upgrade alert!**
- Extinction: need ~x100 better

Conclusions (physics)

- Mu2e will:
  - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 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 becomes the limiting problem

Upgrade alert!

Structure of this talk

- Introduction
- Mu2e Baseline Design
- A Mu2e Upgrade Plan (rethink everything)
- Summary/Conclusions

Major components of the plan

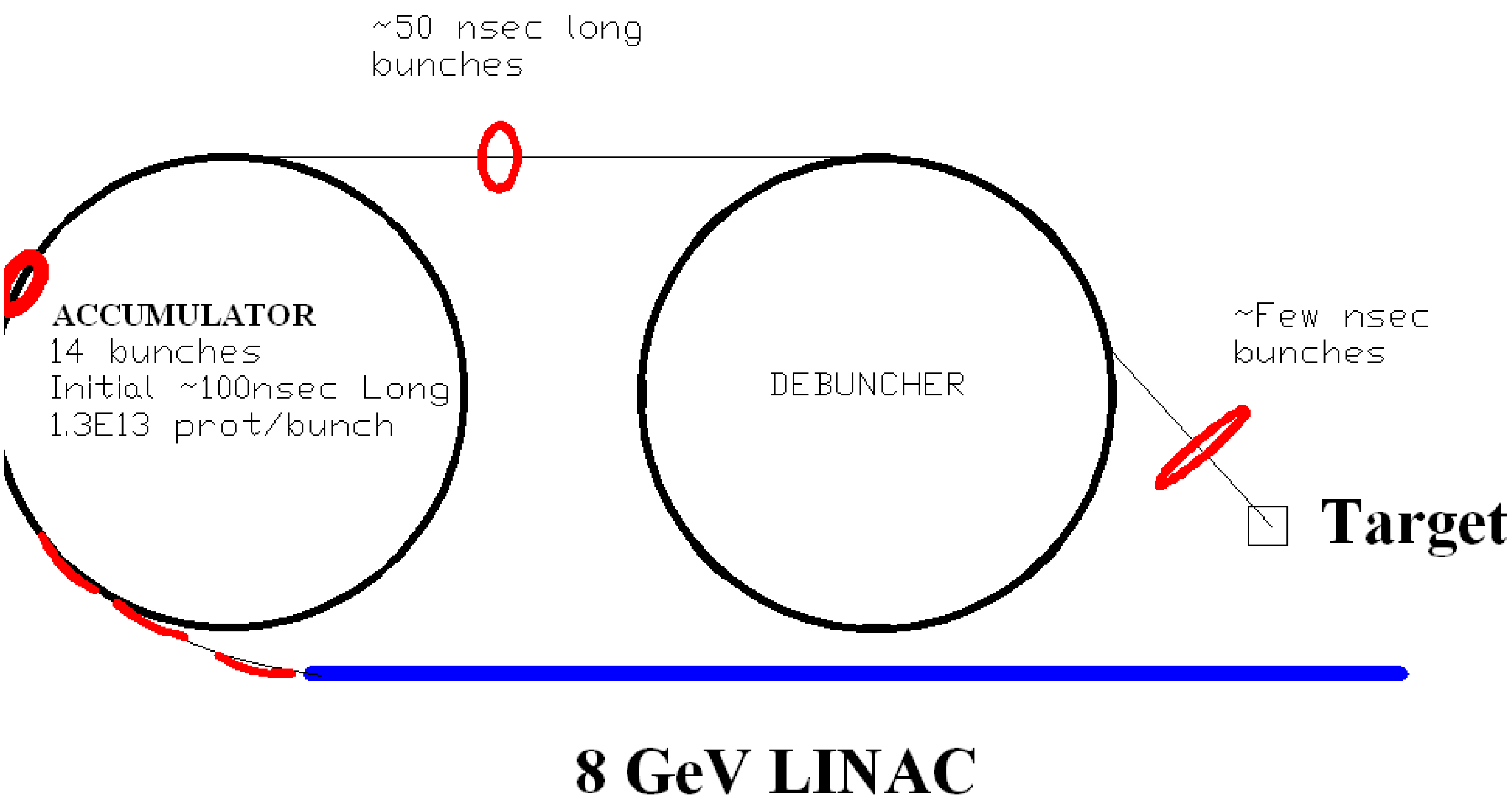
- Accumulate protons from linac into bunches
  - No. bunches can be optimized vs Z of the target.
    - !st ring: accumulate and form N bunches
    - Bunch rotate into shorter bunches
    - Transfer M bunches at a time to 2nd ring and extract
- Two-stage slow extraction
- Produce pions in dipole plus wedge system
- Match quasi-monochromatic pion beam into HCC
  - (matching section is also decay volume)
- Cool and degrade muons in HCC
- Match into stopping target solenoid
- Use S-bend a la MECO to transport e's to detector

Project X

- Parameters
  - 8-GeV H^- Linac
  - 1 MW of beam power initially
    - 5 Hz repetition rate
    - ~1.3 msec beam pulse
    - ~20 mA beam current during pulse
  - Upgrade Path to 4 MW for NF/MC
    - 10 Hz?
    - 2.5 msec?
- Must “repackage” the beam to meet NF/MC needs.
- Can use same bunching rings for Mu2e.

Providing p Bunches for a ν Factory or a μ Collider

- Accumulate protons from linac into N bunches



Two-stage resonant extraction

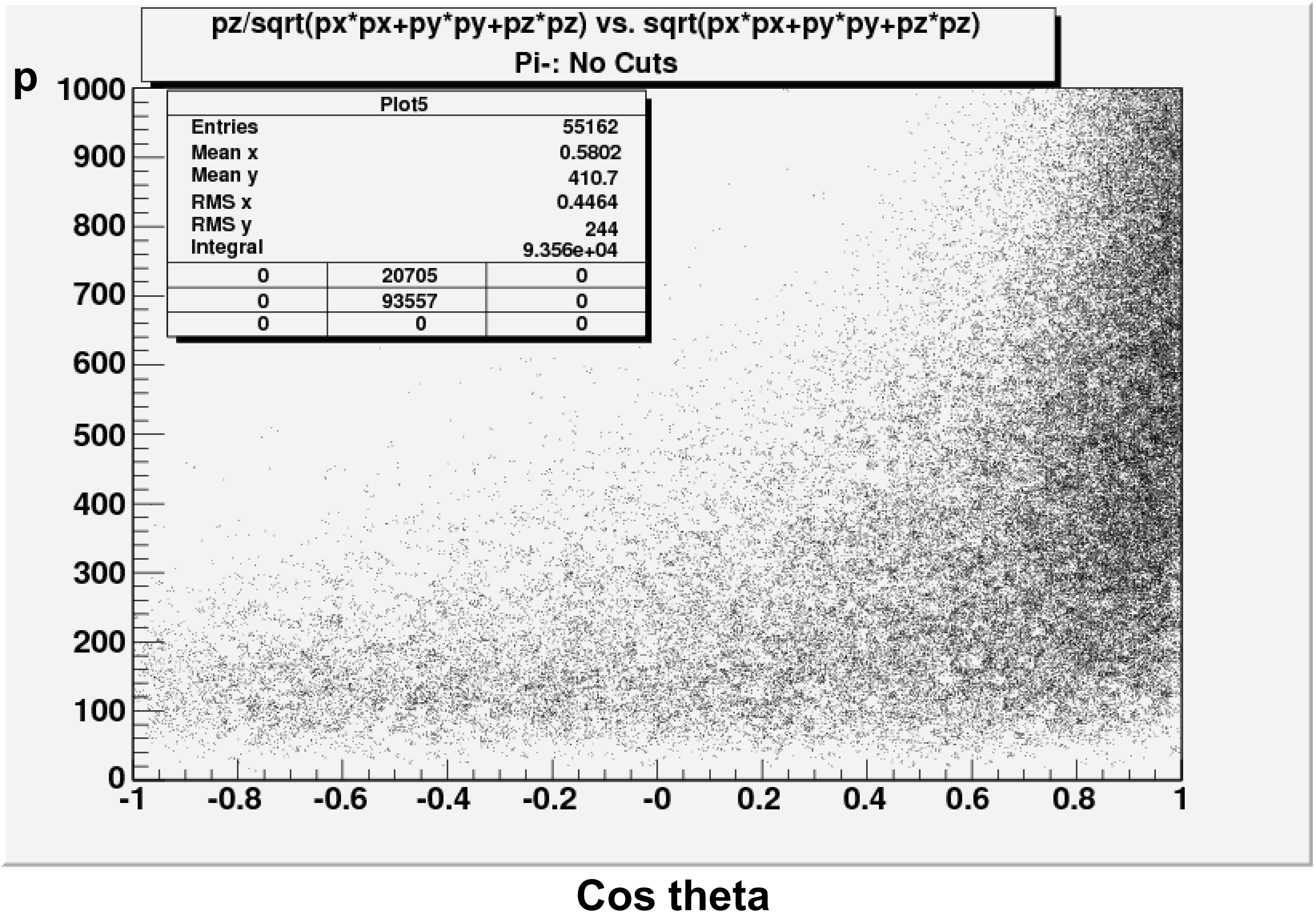
- Extraction loss fraction ~ septum width/step size ~ 1%
  - Losses of 10 kW in ring would be serious.
- Protons hitting wires get partial deflection by E field
  - Worse than interactions and multiple scattering
- Those protons are likely to hit the Lambertson septum
- Brute force: reduce width, increase step size
- New concept: two-stage extraction
  - Move Lambertson ~ 270 degrees downstream from 1st septum
  - Add second electrostatic device ~ 90 degrees from 1st septum
  - Second device has two wire septa, with E field in between
    - Circulating and extracting protons are undeflected
    - "Damaged" protons are deflected by second device to dump or to test beam area

Stopping Muon Beams 101

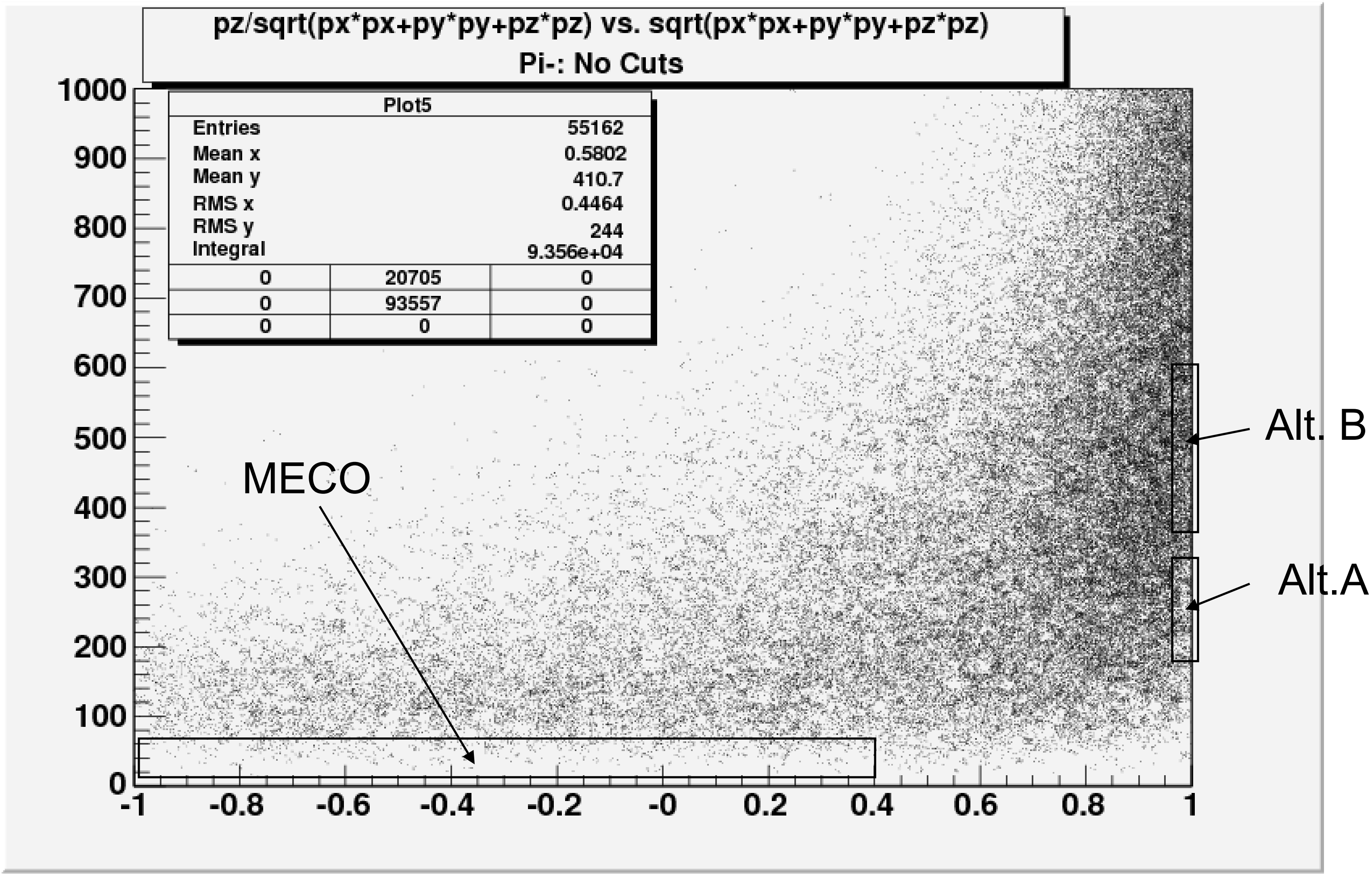
(Taken from Talk At Project X Physics Workshop)

- $p + A \rightarrow \pi + X$
- ~One charged pion of each sign per 8-GeV proton
- Pion decay length is 7.8 meters for p = mc
- $\pi \rightarrow \mu + \nu$ decay kinematics in lab:
    - Less than 29 MeV/c of transverse momentum
    - Longitudinal momentum distribution of muons is uniform between about 60% and about 100% of pion momentum
    - Polarization correlates completely with longitudinal momentum
- Passing the muons through material causes the momentum spread to grow (dE/dx causes longitudinal heating)
- Where the pions are: cf. next slide

Momentum vs. Cosine of production angle (from C. Yoshikawa)



Momentum vs. Cosine of production angle (from C. Yoshikawa)

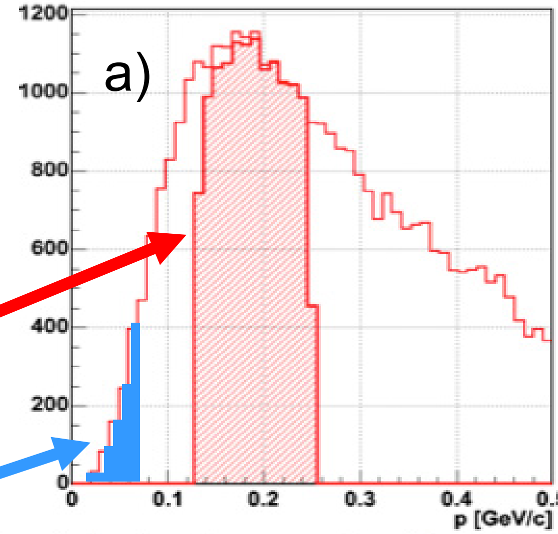


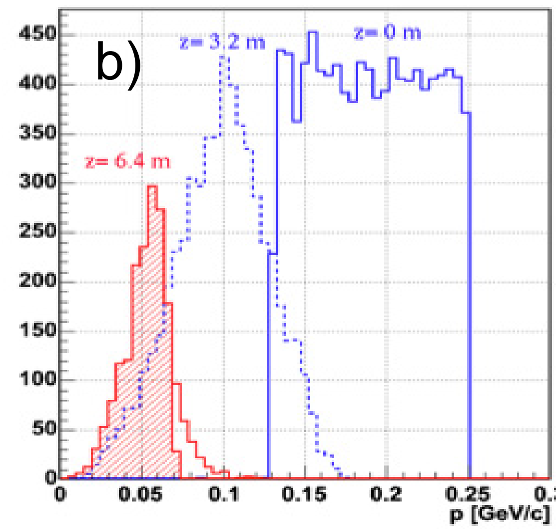
Concepts

- (a) π/μ production
  (b) momentum evolution

HCC acceptance

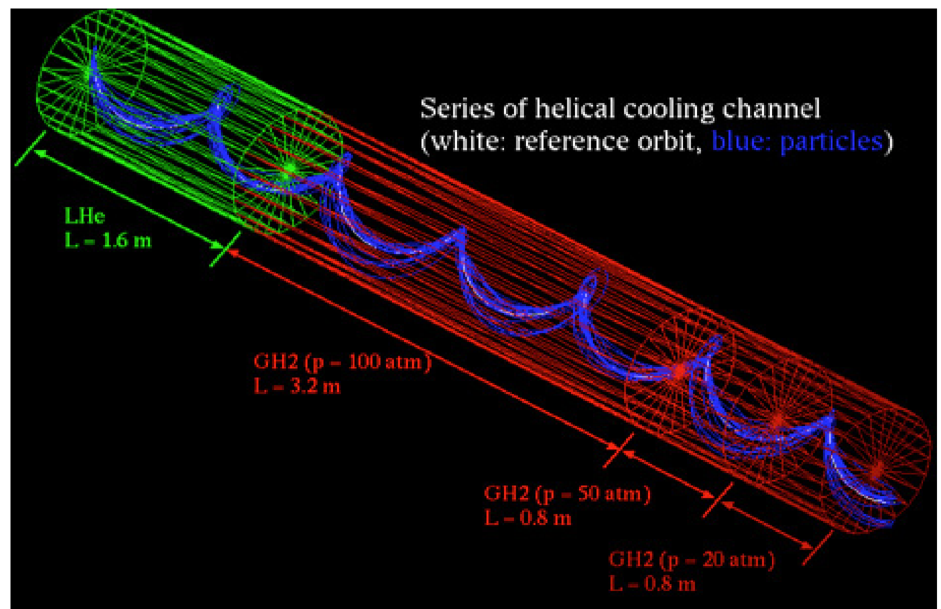
MECO acceptance





- SBIR Cooling Concept:
  - 6D particle density increase
  - Absorber density decrease

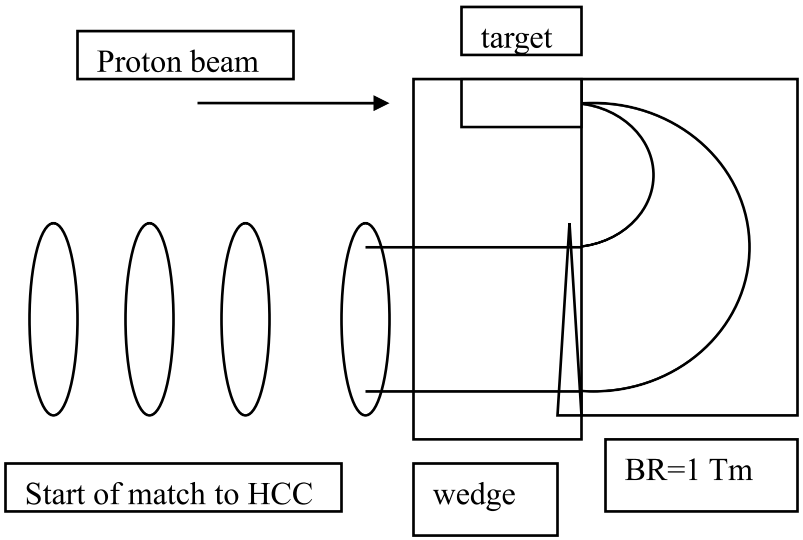
(From Mary Anne Cummings)



However, …

- Above example used collider target solenoid (20 T)
  - Not a fair comparison with MECO (5 T)
  - Perhaps not practical for mu2e
- Also, collaborators dislike proton beam pointed at detector
- Ergo, explore other concepts:

Target + Wedge @ Dipole Edge



Followed by low-Z absorber in HCC to cool the beam and reduce its energy.

SBIR: Stopping Muon Beams

Phase II-SBIR/STTR Fiscal Year 2008
(All information provided on this page is subject to release to the public.)

FIRM NAME: **Muons, Inc**

RESEARCH INSTITUTION: **Fermi National Accelerator Laboratory**
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PROJECT TITLE: **Stopping Muon Beams**

TECHNICAL ABSTRACT (Limit to space provided)

Statement of the problem or situation that is being addressed - typically, one to three sentences.

Physics experiments often use low-energy beams of unstable particles that stop in a target in order to provide high sensitivity to rare processes with reduced backgrounds. However, the stopping rate in the target is limited by the dynamics of the production process and by multiple scattering and energy straggling in the material used to slow the particles. As a result the event rates and sensitivity to rare processes are limited.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects

In this project, we will apply new six-dimensional beam cooling inventions, improved capture techniques, and our new simulation tools to develop designs for low-energy beam lines to stop many muons in small volumes.

What was done in Phase I – typically, two to three sentences.

G4beamline, our Geant4 based program, was used to simulate the mu2e experimental design as a baseline for comparison with the proposed method using a helical cooling channel (HCC) and for general improvements. An entirely new concept for reducing the energy spread of the secondary pion beam was invented and is under development to provide better protection from many sources of background that could limit the sensitivity of the experiment and also to provide the possibility for highly polarized stopping muon beams.

What is planned for the Phase II project - typically, two to three sentences.

We will develop the HCC and the newer pion momentum spread reduction schemes for experiments like mu2e and others that require polarization. We will use G4beamline to improve the mu2e experimental sensitivity and to develop methods to study rare background events.

Dipole + Wedge Results

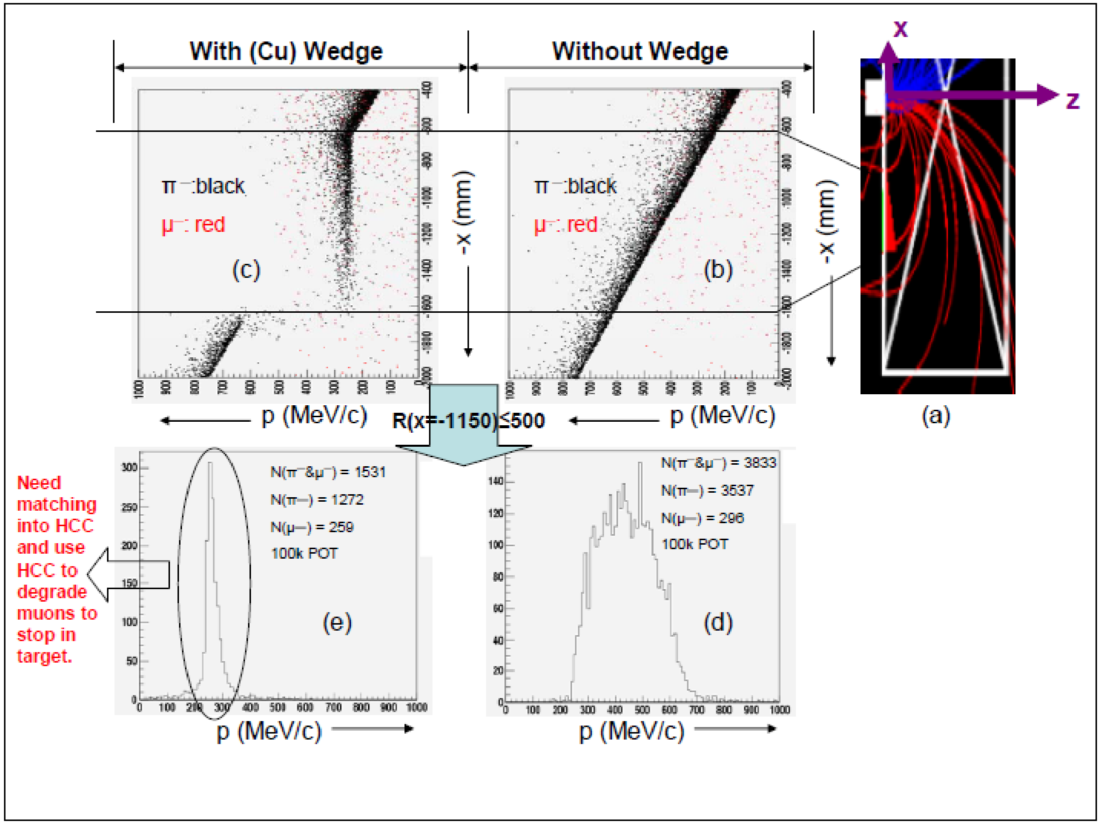

Fig. 2:(a) G4beamline top view of dipole and wedge. Negatively charged particles (red) are bent through dipole (2.5T; 1m aperture) with those in the momentum range 244 MeV/c ≤ p ≤ 619 MeV/c hitting the Cu wedge (red triangle). (b) Projection of particle momentum vs. location of dipole exit in absence of wedge. (c) Projection of particle momentum vs. location of dipole exit when Cu wedge is in place. (d) Momentum of particles in circular aperture (r = 500 mm) with same center as where wedge would be placed. (e) Momentum of particles in circular aperture (r = 500 mm) with same center as wedge that have gone through wedge.

Momentum vs Range in LiH

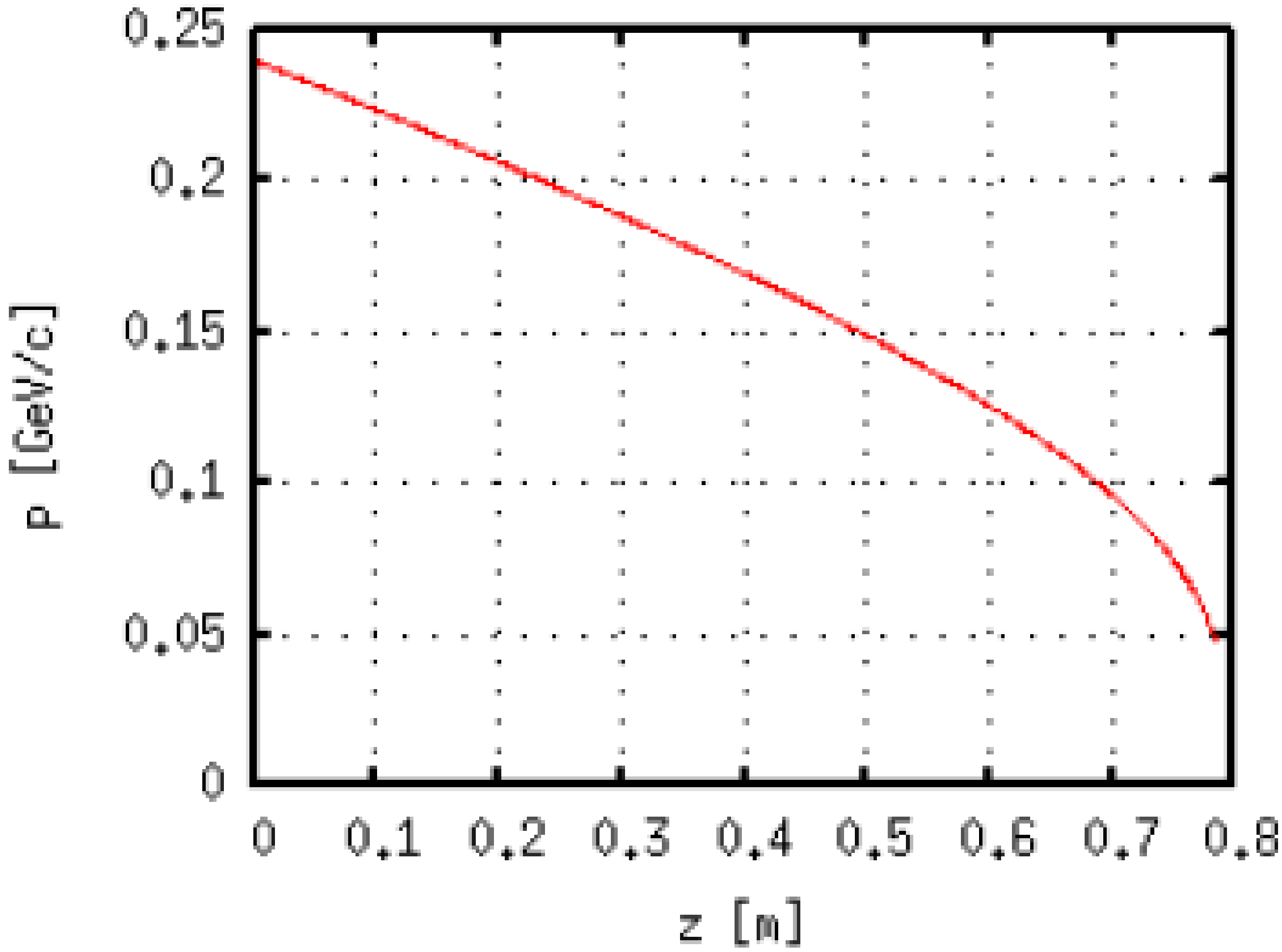

Fig. 1: Muon momentum vs absorber length for a continuous LiH absorber.

Muons, Inc.

Advantages of Wedge@edge

- Hard momentum cutoff at ~ 150 MeV/c
- Eliminates wrong-sign particles
- Full width of target magnet is used: magnetic field volume is not wasted
- Particles heavier than muons stop in degrader, not in stopping target; thus much better hadron background rejection than in MECO design
- Electrons get eaten by high-Z wedge, thus probably not a problem.
- Better background suppression means might live with higher intensity
- Little dispersion in muon arrival times
- May have better mu/proton ratio:
- Uses pions at peak of momentum distribution
- Uses pions produced near zero degrees
- May be less expensive than MECO (maybe even fly under P5 radar?)
- Probably can operate with shorter deadtime after proton arrival
  =>More usable muons per proton
  =>Could use titanium or other material having Z greater than Aluminum
- Proton beam points away from experiment and is easily dumped.
- Produces polarized stopping muon beam
- Polarization can be varied by changing the thickness of the degrader

Transmit muons to stopping target

- Match quasi-monochromatic pion beam into HCC
  - (matching section is also pion decay volume)
- Cool and degrade muons in HCC
- Match into stopping target in solenoid

Reconfigure stopping target/detector

- Use S-bend a la MECO to transport e's to detector.
  - Perhaps can reuse muon transport solenoid from Phase I.
- Remove proton catcher around stopping target.
- Many advantages result…

Advantages

- Much higher proton flux is available (thanks to Project X) and usable.
- The production target configuration is easily shielded.
- The coils of the production dipole are shielded by iron pole tips.
- The pions are produced forward, so we don't need a small-radius target.
  - So it's easier to handle ~ 1 MW of beam power.
- Wrong-sign particles from the production target are eliminated.
- Hi-Z wedge suppresses electrons from production target.
- There's much less straggling in flight times of muons and pions.
- Angles in beam are small, so we don't need precise fields to avoid trapping.
- Hadronic "flash" is suppressed; they stop upstream, in the degrader.
- The protons from muon capture are eliminated in the S-bend solenoid.
  - (5 MeV protons have p~100 MeV/c.)
- Since we don't need a proton catcher around the stopping target, the energy resolution for the signal electrons is better.
  - Helps suppress background from muon decay in orbit.
- (Can make polarized muon beam for other applications.)

In conclusion:

- A promising Mu2e Upgrade concept has emerged.
  - The concept seems to have many advantages.
  - No disadvantages are obvious to the naked eye.
- The ideas are synergistic with the Project X initial configuration and with the subsequent evolution of the facility for a neutrino factory and/or a muon collider.
- Support for the development of the concept is requested.
  - Extensive design and simulation work is needed.
  - Experimental testing of the muon transport and cooling would be useful.

Backup slides