Next Generation Mu2e

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Outline

- Introduction
- PX muon and pion yields
- Simple estimates of backgrounds
- Necessary upgrades
- Possibly necessary upgrades
- Work List
- Summary

Introduction

- Many people interested in investigating the feasibility of a next generation Mu2e ("Mu2e-II")
- "Next Generation" == modest extension that reuses as much of currently planned facility as possible
  - Assume goal is x10 in sensitivity

Introduction

- Is x10 interesting?
  - Mu2e observes CLFV at >=5σ
    - Switch targets and measure ratio of rate to further discriminate models of underlying physics
  - Mu2e observes hints of CLFV at ~3σ
    - Collect x10 data to definitively resolve the situation
  - Mu2e sets stringent new limit on CLFV
    - Collect x10 data and explore new parameter space

Current Mu2e

- 8 GeV proton beam at 8 kW
  - Full-base beam width 200 ns
  - 1695 ns between pulses
  - Duty factor 30%
  - Intrinsic extinction estimated 1E-4 – 1E-5
  - Total extinction < 1E-10
- Aluminum stopping target
- Momentum resolution $\delta p<120$ keV/c (core) and <1 MeV/c (FWHM) at p=105 MeV/c

Mu2e-II Target Sensitivity

- Current Mu2e:
  - Single-event-sensitivity (ses) = 2.5 E-17
  - Mean expected background = 0.4

- Targets for Mu2e-II:
  - ses(Mu2e-II) = ses(Mu2e)/10 = 2.5 E -18
  - Keep expected background <1 event
  - ie. keep discovery sensitivity scaling linearly with number of stopped muons

Project X Inputs

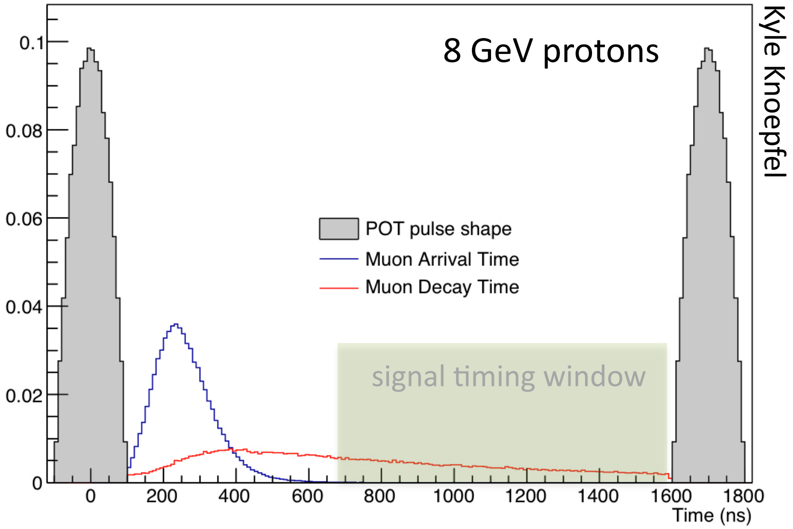
- Assume Project X (PX) delivers
  - Proton pulses with a full-base width of 100 ns
  - Duty factor of 90%
  - Intrinsic extinction <1E-6
    - to yield a total extinction of < 1E-12
  - Protons at 1 or 3 GeV
  - A beam transport scheme to the current Mu2e beamline

PX muon and pion yields

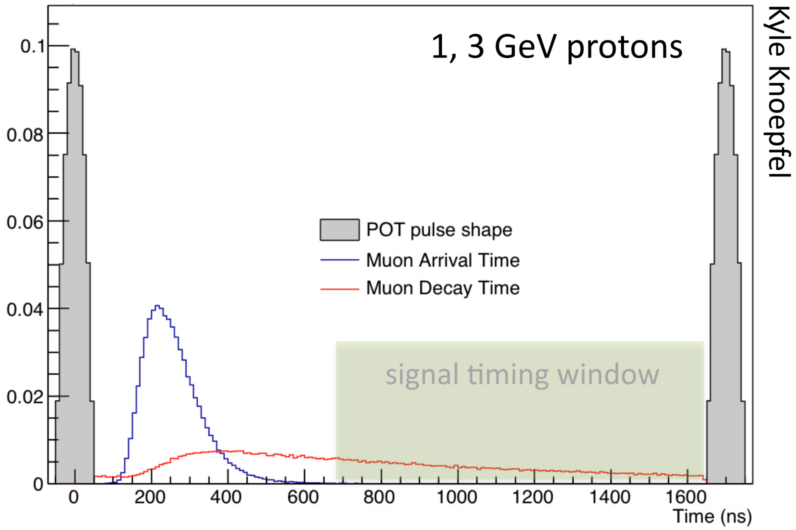
- Kyle Knoepfel (FNAL pdoc) used G4Beamline (Tom Roberts, Muons Inc.) to quantify muon and pion yields at PX
  - Started from current Mu2e simulation including all solenoids, collimators, pbar window, latest magnetic field map, stopping target geometry, internal absorbers
  - Simulated protons at 8, 3, 1 GeV

Signal Timing Windows

- Mu2e: (670, 1595) ns



- Mu2e-II: (670, 1645) ns



PX muon and pion yields: Al target

muons

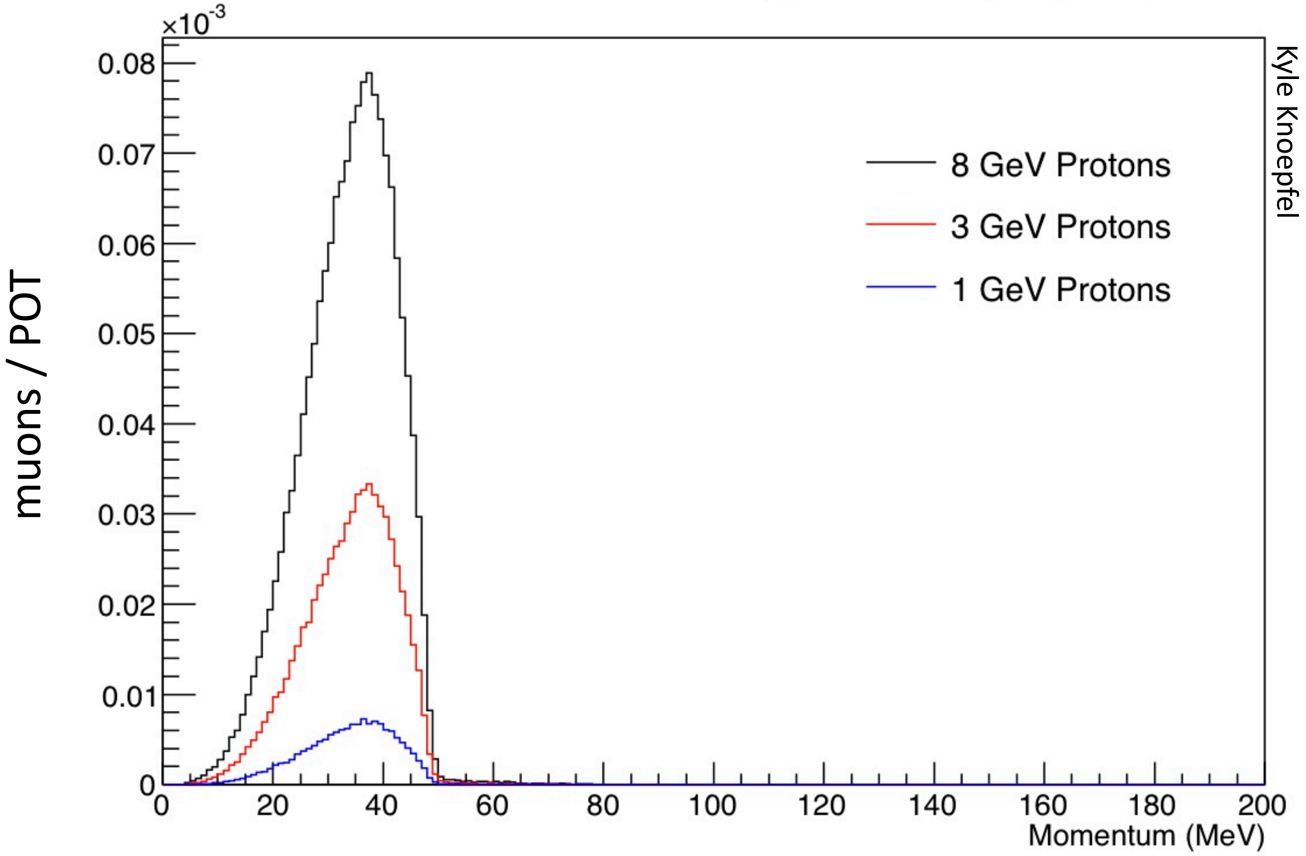
	8 GeV	3 GeV	1 GeV
stops / POT	16.1 E-4	6.7 E-4	1.4 E-4
stops / kW	7.3 E16	8.1 E16	5.2 E16
Capture fraction in window (wrapped modulo 1695 ns)	0.49	0.50	0.50

pions

	8 GeV	3 GeV	1 GeV
stops / POT	68.2 E-8	29.0 E-8	6.4 E-8
stops / kW	3.1 E13	3.5 E13	2.3 E13
fraction of stops in window (wrapped modulo 1695 ns)	3.9 E-11	1.1 E-11	1.4 E-11

- Assumes same stopping target geometry, same 1695 ns proton pulse spacing
- 8 GeV numbers agree with Mu2e CDR to <5%

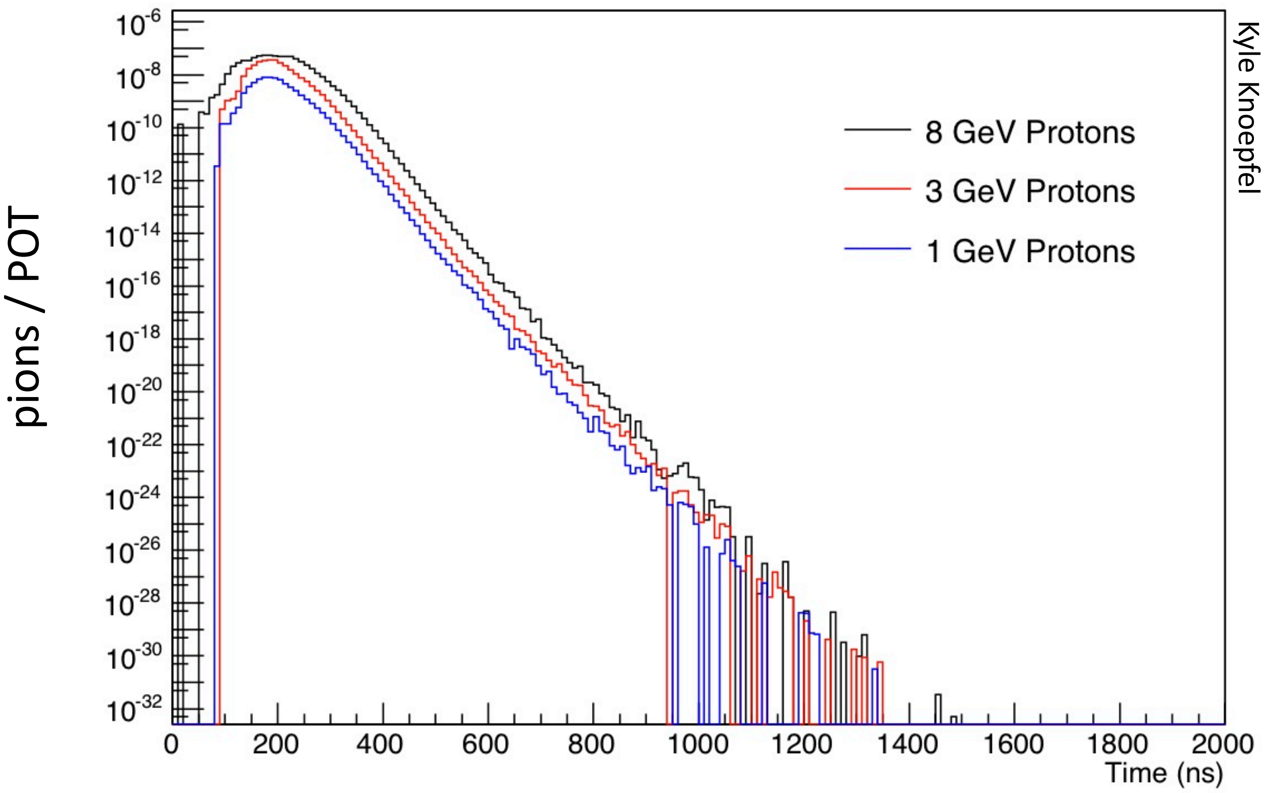
PX distributions



Kyle Knoepfel

- Momentum at DS entrance for muons that stop

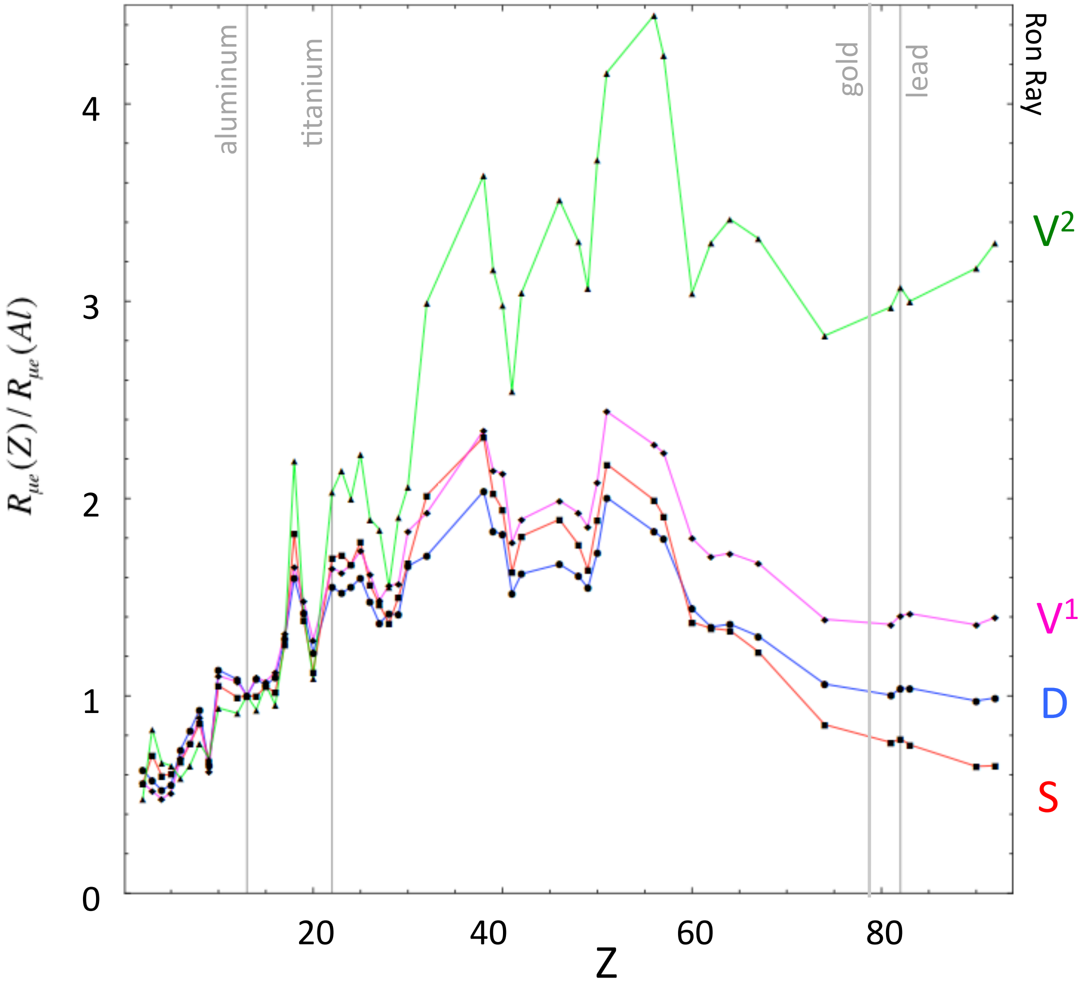
PX distributions



- pion stopping time distribution

Changing the stopping target

- Changing the stopping target provides information about the underlying physics



V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)

Changing the stopping target

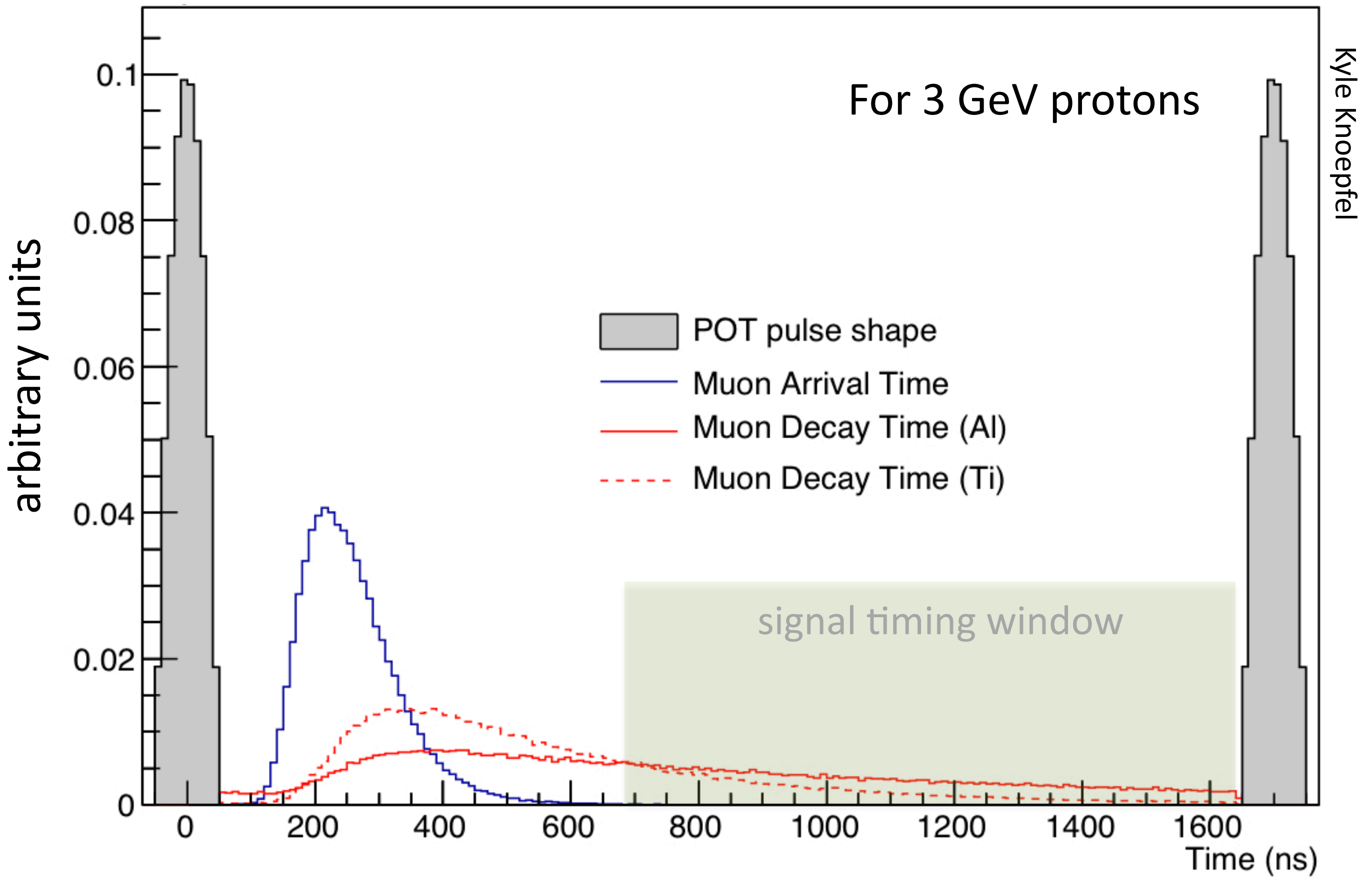
- For an aluminum stopping target
  - Capture fraction : 0.609
  - Decay fraction : 0.391
  - Muonic atom lifetime : 864 ns
  - E_e(signal) = 104.97 MeV
- For a titanium stopping target
  - Capture fraction : 0.850
  - Decay fraction : 0.150
  - Muonic atom lifetime : 329 ns
  - E_e(signal) = 104.27 MeV

PX muon yields: Ti target

		8 GeV	3 GeV	1 GeV
muons	stops /POT	16.1 E-4	6.7 E-4	1.4 E-4
	Capture fraction in window (wrapped modulo 1695 ns)	--	0.28	0.28

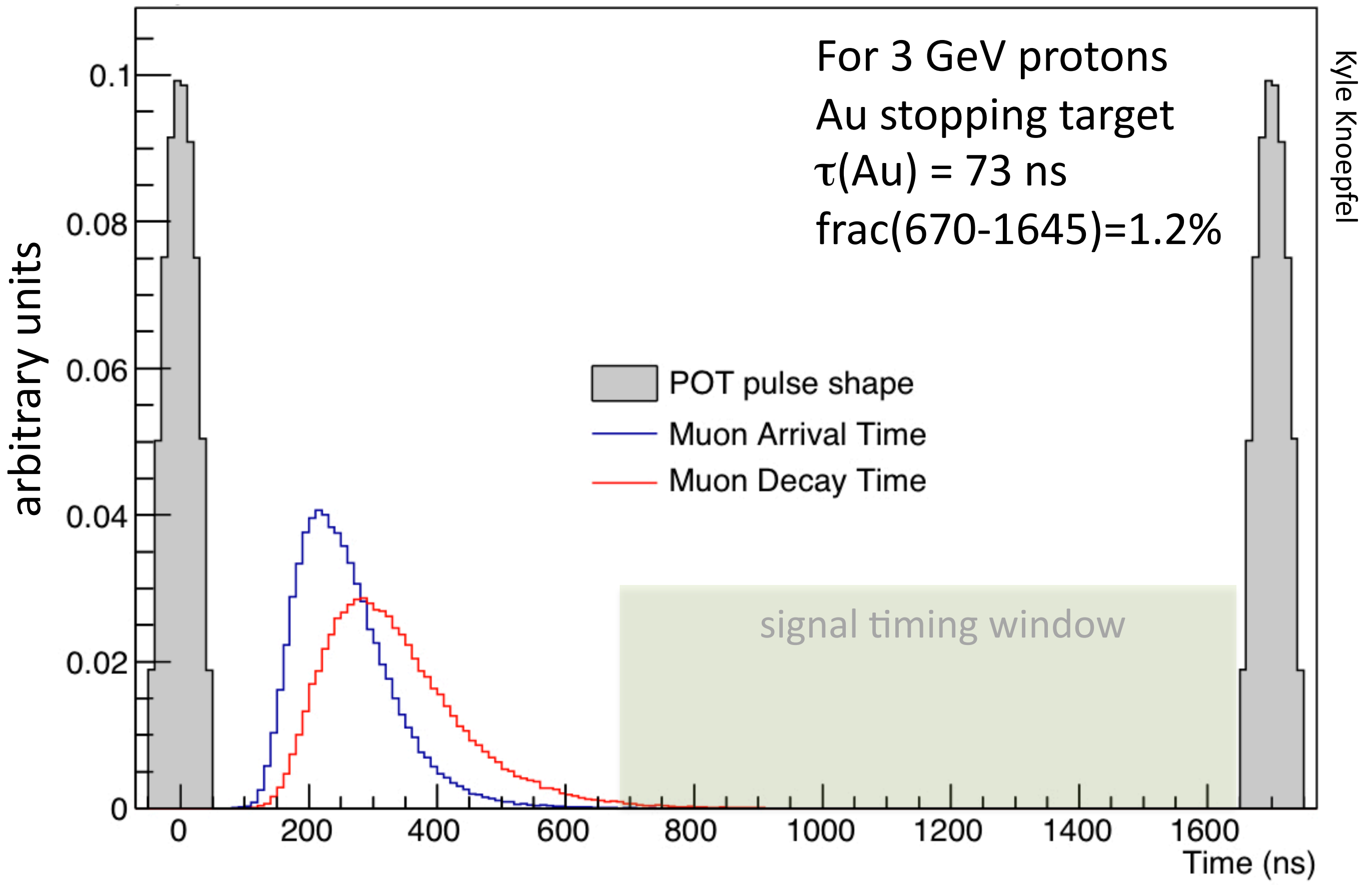
- Assumes same stopping target geometry, same 1695 ns proton pulse spacing
- Used same stops/POT but recalculated capture fraction reweighting decay time distribution
  - $\tau(\mathrm{Al}) = 864$ ns → $\tau(\mathrm{Ti}) = 329$ ns

PX muon timing Al vs Ti



- Decay time of stopped muons

PX muon timing Au



- Due to very short lifetime, really high-Z stopping targets are not a straight forward extrapolation of current Mu2e setup and are not considered further in this talk.

Necessary POT

- Calculate #POT needed to achieve target ses
  - Include differing stopped muon yields/POT
  - Include differing fraction of stops in time window
  - Include differing muon capture fractions
  - Assume reconstruction and selection efficiencies as estimated for Mu2e using full simulation

	Al. target	**Ti. target**
POT (8 GeV)	3.6 E21	
POT (3 GeV)	8.6 E21	10.8 E21
POT (1 GeV)	40.3 E21	50.6 E21

Estimated total POT needed for Mu2e-II to reach ses = 2.5 E-18.
NB. Mu2e estimates it will need 3.6 E20 POT to reach ses = 2.5 E-17.

Beam Power and Instantaneous Rates

	Beam Power	Protons/pulse	Instant. Rates (rel. to Mu2e)
8 GeV (Al)	80 kW	1.0 E8	3.3
3 GeV (Al)	72 kW	2.5 E8	3.4
1 GeV (Al)	112 kW	1.2 E9	3.5
3 GeV (Ti)	90 kW	3.1 E8	4.3
1 GeV (Ti)	140 kW	1.5 E9	4.4

- Assume 3 y run, 2 x 10^7 s run time/yr, 1695 ns proton pulse spacing (peak-to-peak)
- Estimate instantaneous rates at detector by scaling beam power by muon and pion yields (gave same answer to 10%)

Backgrounds

- We have enough ingredients to roughly estimate background contributions
- Assumptions:
  - 1695 ns proton pulse spacing
  - 3y run, 2 x 10^7 s run time/year
  - 90% duty factor
  - Reconstruction and selection efficiency unchanged relative to current Mu2e estimates
  - Momentum resolution unchanged relative to current Mu2e estimates

Backgrounds

- We have enough ingredients to roughly estimate background contributions
- Assumptions:
    - 1695 ns proton pulse spacing
    - 3y run, 2 x 10^7 s run time/year
    - 90% duty factor
    - Reconstruction and selection efficiency unchanged relative to current Mu2e estimates
    - Momentum resolution unchanged relative to current Mu2e estimates

Same as currently planned Mu2e

Current Mu2e Background

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	0.10
	Cosmic Ray	0.05
	Pat. Recognition Errors	<0.01
Total Background		0.41

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
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Miscellaneous	Anti-proton	0.10
	Cosmic Ray	0.05
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Total Background		0.41

Protons at 1,3 GeV are below pbar production threshold [0.10 → 0]

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.05
	Pat. Recognition Errors	<0.01
Total Background		0.31

Scales with live time: x3 for duty factor, x1.05 for larger signal timing window [0.16]

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.16
	Pat. Recognition Errors	<0.01
Total Background		0.42

Scale linearly with Yields*Extinction. At PX that product is expected to be <= 1.

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.16
	Pat. Recognition Errors	<0.01
Total Background		0.42

Two contributions: 1) created during primary proton pulse with long transit time
2) created from out-of-time protons

RPC Background at PX

- From pions produced during primary proton pulse with long transit times (670-1645 ns)

$$\#\mathrm{POT} * \frac{\mathrm{stopped}\ \pi^{-}}{\mathrm{POT}} * f_{\mathrm{stopped}}^{670-1645} * f_{\mathrm{RPC}} * \varepsilon_{\mathrm{reco}} * \varepsilon_{\mathrm{sel.}}$$

- From pions produced by out-of-time protons (assume flat distribution in time)

$$\#\mathrm{POT} * \frac{\mathrm{stopped}\ \pi^{-}}{\mathrm{POT}} * X * f_{\mathrm{livetime}}^{670-1645} * f_{\mathrm{RPC}} * \varepsilon_{\mathrm{reco}} * \varepsilon_{\mathrm{sel.}}$$

RPC Background at PX

Aluminum

	3 GeV	1 GeV
RPC(Long transit)	0.029	0.036
RPC(Out-of-time)	0.001	0.001
RPC Total	0.030	0.038

Titanium

	3 GeV	1 GeV
RPC(Long transit)	0.036	0.046
RPC(Out-of-time)	0.002	0.002
RPC Total	0.038	0.048

- Narrower pulse width and improved intrinsic extinction keep RPC background manageable

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.05
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.16
	Pat. Recognition Errors	<0.01
Total Background		0.44

Depending on scenario (1 GeV vs 3 GeV and Al. vs Ti) varies between 0.03-0.05.

Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03-0.05
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.16
	Pat. Recognition Errors	<0.01
Total Background		0.42-0.44

Scale linearly with number of stopped muons. RMC will remain negligible. DIO… ?

DIO Background at PX

- Estimate DIO yield relative to current Mu2e estimate
  - Correct for different signal timing window widths
  - Correct for differing capture fractions
  - Correct for different lifetimes

	3 GeV	1 GeV
DIO (Al.)	2.1	2.1
DIO (Ti.)	0.58*	0.58*

*estimated using shape of Al. spectrum… see next page

Endpoint of DIO Spectrum

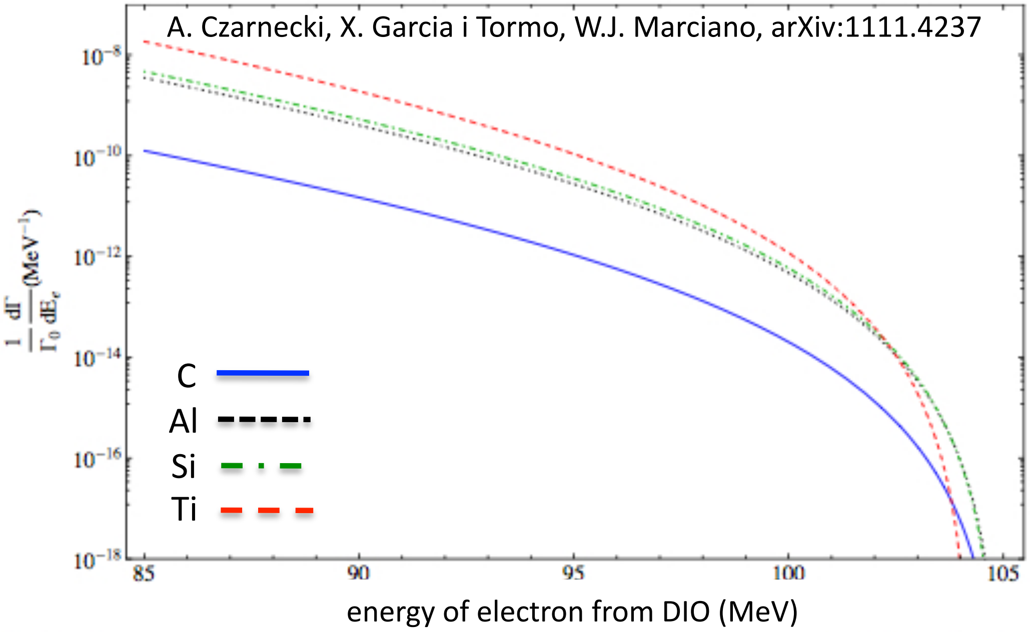

A. Czarnecki, X. Garcia i Tormo, W.J. Marciano, arXiv:1111.4237

Fig. 1 Electron spectrum, normalized to the free-muon decay rate Γ_0. The solid blue line is for carbon, the black dotted line for aluminum, the green dot-dashed line for silicon and the red dashed line for titanium.

- We used the shape of the Al. spectrum from the Mu2e simulation. For Ti. I have *not* accounted for difference in shape of spectrum.

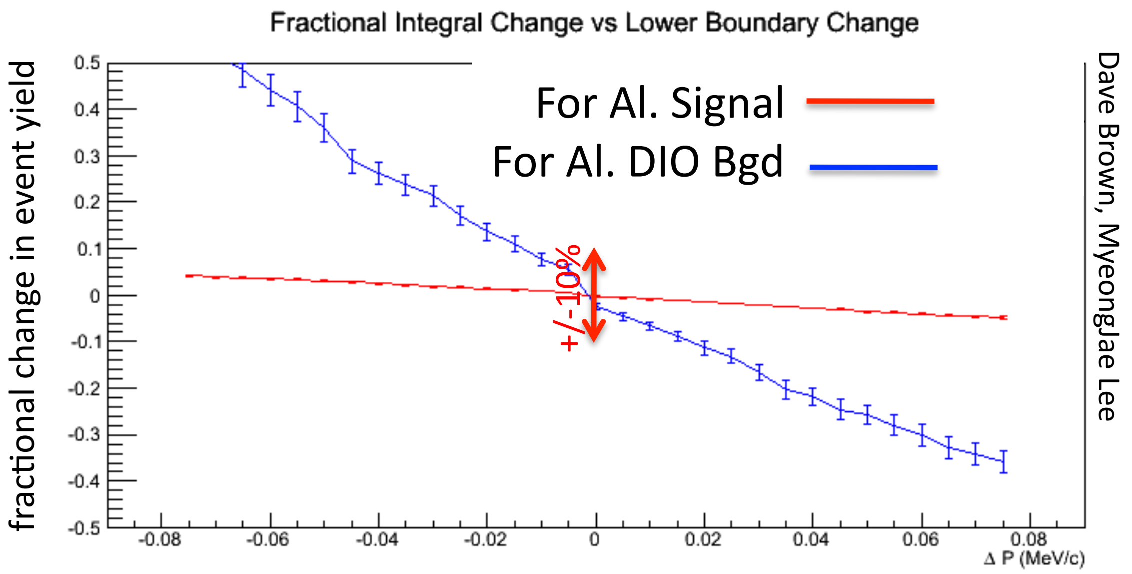
Notes on Mu2e Background at PX

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.58*
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.05
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton	NA
	Cosmic Ray	0.16
	Pat. Recognition Errors	<0.01
Total Background		0.80

*estimated using shape of Al. spectrum… see page 30

Titanium seems viable. Can trade efficiency for DIO background.

DIO Bgd vs Signal Efficiency



- Can reduce DIO background by ~x2 for a ~10% (relative) loss in signal efficiency
- Can also potentially reduce DIO background by optimizing stopping target (e.g. for Ti) and other upstream material and/or building a lower mass tracker

What about the Apparatus?

- OK – so a Mu2e-II with x10 better sensitivity than the currently planned Mu2e seems feasible at PX

- Can the currently planned apparatus handle the increased beam power, rate, etc?

What about the Apparatus?

- We considered
  - Solenoids
  - Tracker
  - Calorimeter
  - Cosmic Ray Veto
- We have not yet considered
  - Stopping target monitor
  - DAQ/Trigger

Solenoids

(M. Lamm, T. Page, N. Mokhov, V.Pronskikh)

- Key Issues
  - Peak power deposition
  - Peak displacements per atom (dpa)
- At x10 sensitivities
  - dpa a significant concern for PS
  - Upgraded heat/radiation shield likely required
- Simulation studies in progress for PX scenarios

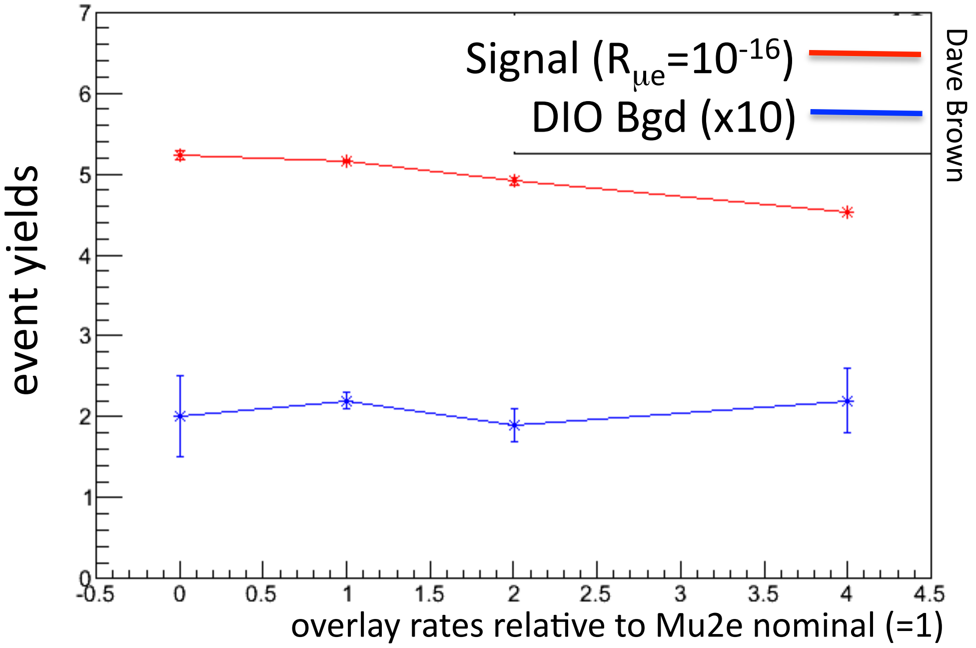
Tracker

(A. Mukherjee, V.Rusu, B.Wagner, D.Brown, M-J.Lee)

- Key issues at higher rates
  - Reconstruction efficiency and momentum resolution [next page]
  - Aging from increased charge deposition [under study]
  - Space-charge effects from increased beam flash [would compromise inner <= 1% of straws for short while]
  - Voltage sag from increased beam flash [calculated to be small]

    [mitigations in mind for these]
- Punchline
  - Current tracker probably workable for Mu2e-II scenarios unless significantly lower mass required to meet a more stringent momentum resolution requirement (e.g. to further mitigate DIO backgrounds)

Tracker performance



Dave Brown

- For the current Mu2e tracker with current reconstruction and track fitting algorithms, modest increases in instantaneous rates leave momentum resolution unchanged and degrade the efficiency at the 5% (relative) level

Calorimeter

(S.Miscetti, D.Hitlin)

- Key issues
  - Performance degradation due to increased neutron rates that overlap the signal events
  - Radiation damage to photo-sensors and FE
- Punchline
  - Existing calorimeter may largely be OK if increased rates only modestly worse than currently planned Mu2e. Would require new FE to shorten the LYSO signal integration time.
  - If rates increase by x10, existing crystals would have to be replaced by something faster. A rad hard example is BaF_2
    - would offer comparable energy resolution
    - 0.9 ns (fast component @ 220nm) vs 40 ns for LYSO
    - Requires development of a photo-sensor with good sensitivity @ 220nm and insensitivity to the slow component @330 nm

Cosmic Ray Veto

(C.Group, C.Dukes, Y.Oksuzian, M.Frank, R.Erhlich)

- Key Issues at higher rates
  - Accidental rates from n and γ interactions in counters [hottest upstream regions will require more shielding or increased granularity]
  - Neutron-induced radiation damage to photo-detectors and FE read-out electronics [replace]
  - Scintillator aging [needs study]
- Punchline
  - Existing CRV likely to require modest upgrades to electronics and redesign in hottest regions assuming no significant aging effects

Necessary Upgrades

- Production Hall (S.Werkema, V.Nagaslaev, G.Ginther, T.Lackowski)
  - Proton beam dump would need improved cooling
  - Production target would need to be redesigned
  - Extinction monitor would need upgrading
  - Production Solenoid Heat and Radiation Shield
  - Hall radiation shielding
- Transport Hall
  - Hall radiation shielding
- Detector Hall (M.Bowden + previous pages)
  - DAQ for higher rates
  - CRV and calorimeter electronics
  - Stopping target monitor would be replaced
  - Limited regions of CRV upgraded to finer granularity
  - Shielding near stopping target would need to be upgraded

Possibly Necessary Upgrades

- Even with upgraded HRS, PS conductor may be at it's physical limit. If so, entire PS would need to be redesigned using a different conductor technology.
- Remote handling system for production target swaps may need to be redesigned depending on compatibility with new production target.
- Depending on magnet heat loads, magnet cooling system may need to be upgraded.

Additional Notes

- The strategy for handling the DIO background depends on whether or not the current Mu2e has observed a signal
  - NO : then DIO background needs to be mitigated by cutting harder, improving momentum resolution, and reducing scattering in upstream material (e.g. stopping target and proton absorber)
  - YES : then can live with some amount of DIO background, depending on expected rate

Additional Notes

- Also depending on the outcome
  - The need to revisit the calibration scheme
  - May not need to increase beam power at all, but instead exploit other features of PX to explore different target materials (NB in this instance the upgrade list would be very different and would likely be substantially shorter).

(Prioritized) Work List

- Heat load/dpa for PS with upgraded HRS and neutron/γ flux for 1 and 3 GeV protons on target
- Simulate more fully the Ti case
- Simulation of a low(er) mass tracker and/or alternative stopping target and proton absorber designs to explore possibilities for mitigating DIO background
- Investigate optimization of pulse spacing
- Investigate high-Z stopping targets like Au or Pb

Summary

- A Mu2e-II at ~x10 better sensitivity relative to currently planned experiment
  - Interesting regardless of Mu2e outcome
  - Looks feasible at Project X
- Feasible because Project X offers important advantages:
  - High duty factor : re-use much of currently planned Mu2e
  - High power at low E_{beam} : get needed #muons without pbars
  - Narrow pulses, high intrinsic extinction: mitigate RPC bgd
- Plenty of work to do - if you're interested, please let us know.
  - Simulation tools exist… you can get started quickly!
  - douglasg@fnal.gov

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Steve Werkema, Vladamir Nagaslaev,
Mike Lamm, Tom Page, Mark Bowden,
George Ginther, Tom Lackowski, Vitaly Pronskikh