Next Generation Mu2e

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Outline

- Introduction & Motivation
- Summary of work to date
- Beam requirements
- Moving forward

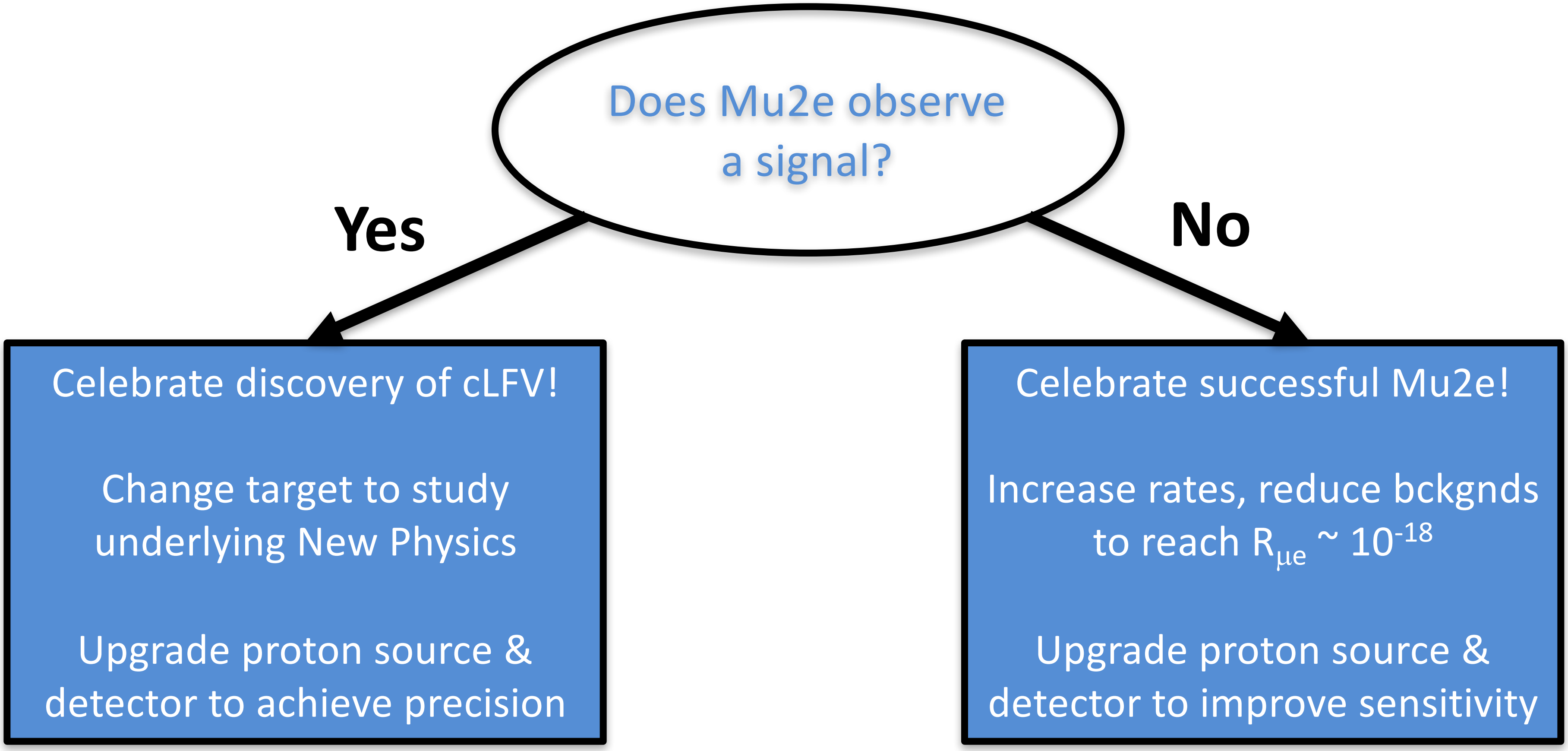
Introduction

Currently constructing Mu2e:

- Utilizes 8 kW of 8 GeV protons
  - Full-base beam width 250 ns
  - 1695 ns between pulses
  - Duty factor 30%
  - (# out-of-time protons / #in-time protons) < 1×10^{-10}
- Aluminum stopping target
- Expected sensitivity (with 4×10^{20} POT)
  - Single-event-sensitivity = < 3×10^{-17}
  - Background < 1 events
  - $R_{\mu e} < 7 \times 10^{-17}$ @ 90% CL, or discovery for $R_{\mu e} >$ few $\times 10^{-16}$
- Commissioning expected to begin 2021
- Physics running 2022-2026 (no LBNF shutdown)

  2022-2028 (with LBNF shutdown 2024-2026)

Motivation

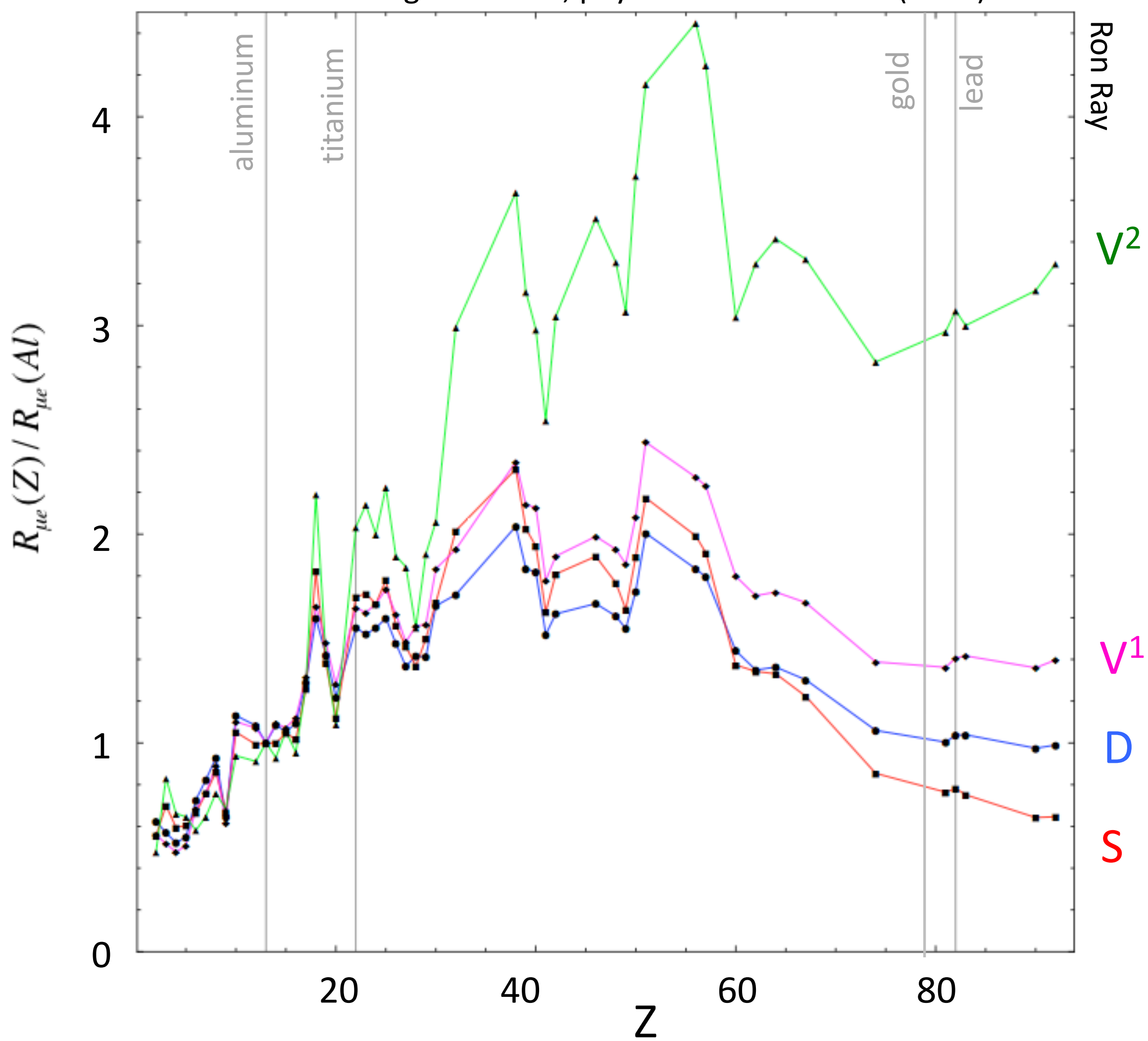


- At conclusion of Mu2e, strong motivation to upgrade proton source and detector to further pursue New Physics

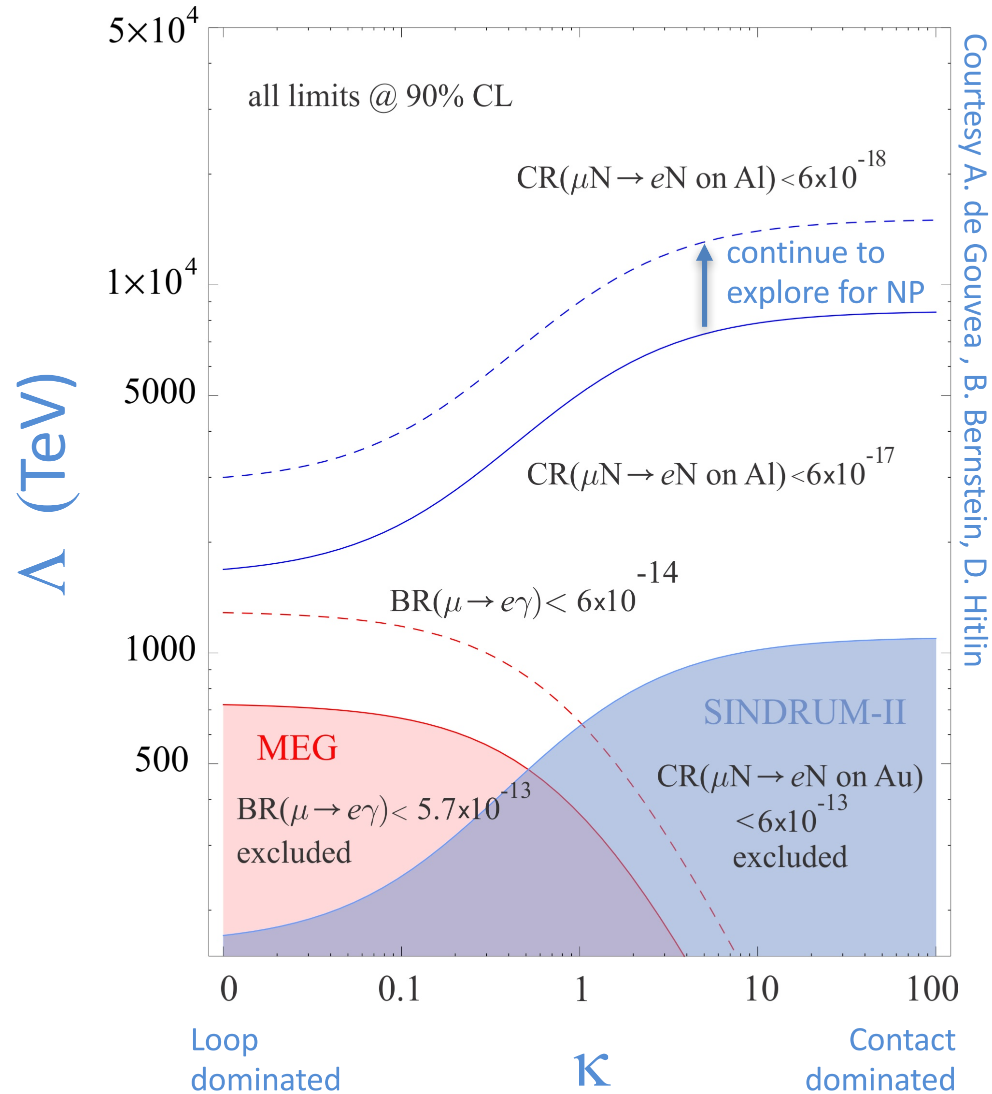
Upgrade Motivation with Mu2e signal

- A x10 improvement in sensitivity allows measuring $R_{\mu e}$ to ~10%
  - will probe underlying New Physics operators

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



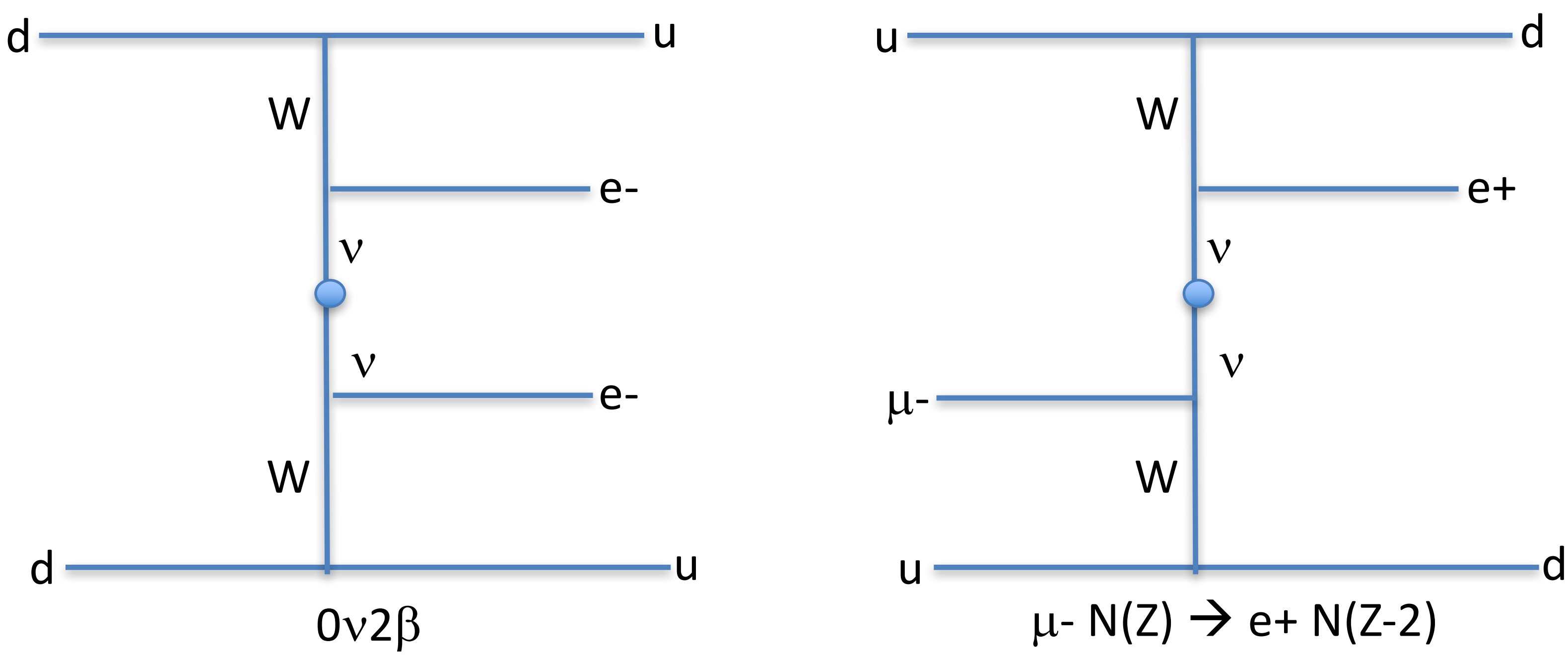
Upgrade Motivation no Mu2e signal



- A x10 improvement in sensitivity allows probing $R_{\mu e}$ to ~10^{-18}
  - will further probe New Physics parameter space

Upgrade Motivation – $\mu^- \text{-->} e^+$

(We've just begun thinking about this…)



- With increased beam intensity can also pursue a program that utilizes targets optimized for LNV $\mu^- N(Z) \rightarrow e^+ N(Z-2)$ searches (complementary to $0\nu2\beta$)

Mu2e-II

- An upgrade to current Mu2e construction that
  - Uses 100-150 kW of PIP-II protons
  - Leverages as much of Mu2e investment as it can
  - Achieves x10 improvement in sensitivity (ie. probe $R_{\mu e} \sim 10^{-18}$ level)

- Timescale
  - Assume 2y from End-Mu2e to Start-Mu2e-II
  - (3+1) y of data taking at full intensity
  - Could occur on 2030 timescale

What's been done so far?

Feasibility Study for a Next-Generation Mu2e Experiment

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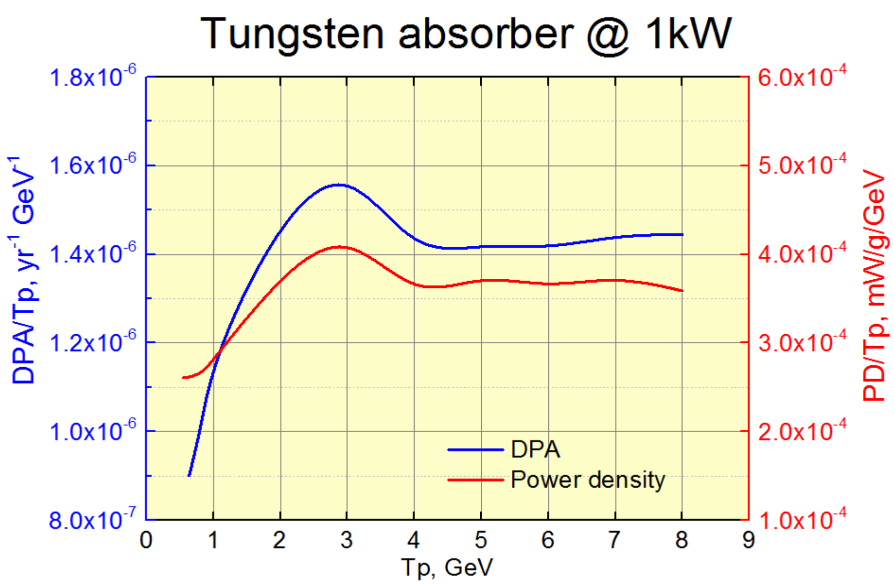
Submitted as part of the APS Division of Particles and Fields Community Summer Study
(dated: July 5, 2013)

We explore the feasibility of a next-generation Mu2e experiment that uses Project-X beams to achieve a sensitivity approximately a factor ten better than the currently planned Mu2e facility.

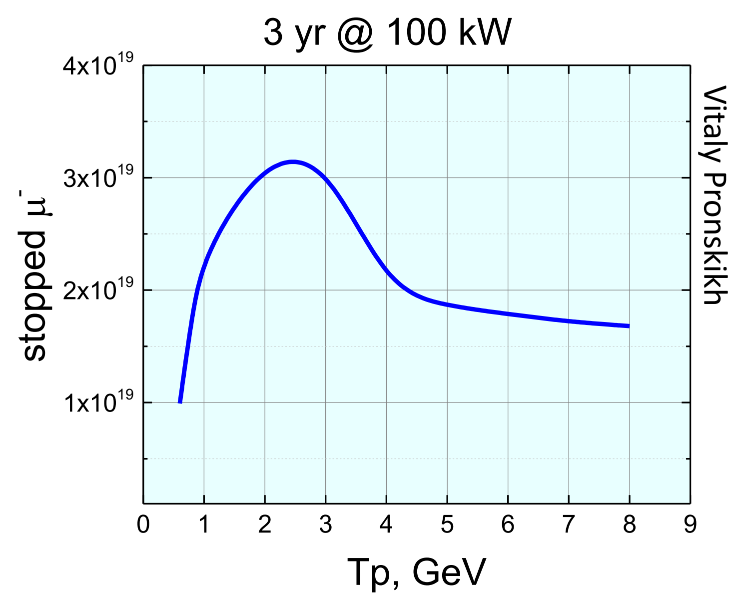
- A background & sensitivity study was performed assuming a 1 or 3 GeV proton beam
  - arXiv:1307.1168
- Studies of μ and π yields and solenoid rad. damage vs proton beam energy
  - arXiv:1612.08931
- Preliminary targeting studies
  - mu2e-doc-db-6810
  - Conference ref. xxxx
- Workshops
  - IF Workshop (ANL, 04/2013)
  - Snowmass (UM, 08/2013)
  - Mu2e CM (FNAL, 02/2016)

Studies of coil damage and μ yields

(assuming no change in HRS geometry or production target)



(nb. PS conductor can tolerate ~5×10^{-4} DPA/yr and ~3×10^{-2} mW/g Peak Power density)



- Optimal beam energy is 1-3 GeV
- Strongly prefer an energy below pbar production threshold ($T_p < 4$ GeV)
- 800 MeV beam of PIP-II can be made to work

(from arXiv:1612.08931)

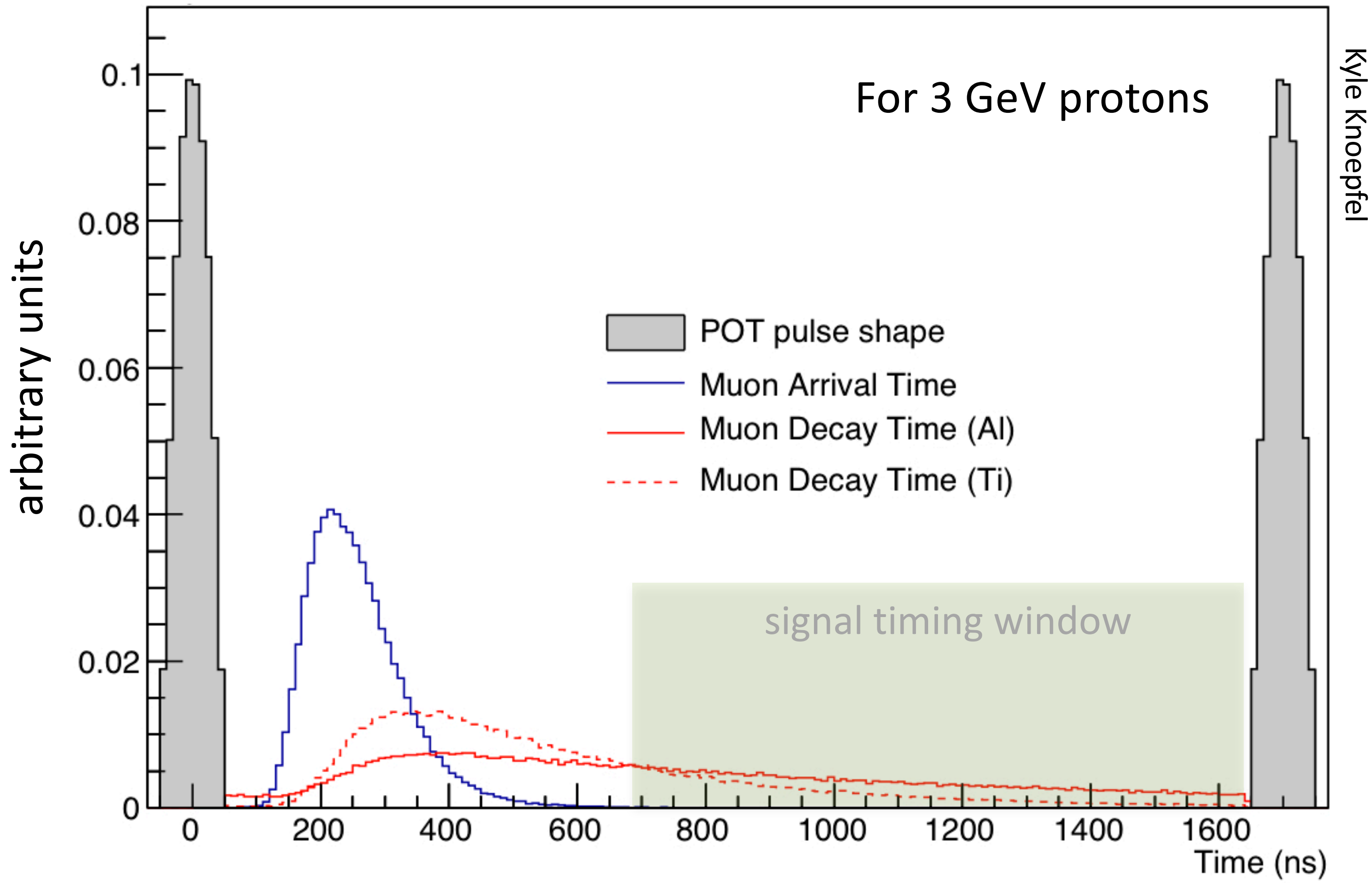
muon and pion yields: Al target

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%

muon timing Al & Ti stopping target



- Choice of stopping target material affects muon decay time distribution
  - τ(Al) = 864 ns, τ(Ti) = 329 ns, τ(Au) = 73 ns
  - Also affects spectrum of electrons from dominant "decay-in-orbit" (DIO) background process

Mu2e-II Background Estimates

		CDR	X10 sensitivity	
		Mu2e	Mu2e-II	
		8 GeV	1 or 3 GeV	
		Al.	Al.	Ti.
Category	Source	Events		
Intrinsic	μ decay in orbit	0.22	0.26	1.19
	radiative μ capture	< 0.01	< 0.01	< 0.01
Late Arriving	radiative π capture	0.03	0.04	0.05
	beam electrons	< 0.01	< 0.01	< 0.01
	μ decay in flight	0.01	< 0.01	< 0.01
	π decay in flight	< 0.01	< 0.01	< 0.01
Miscellaneous	anti-proton induced	0.10	–	–
	cosmic-ray induced	0.05	0.16	0.16
	pat. recognition errors	< 0.01	< 0.01	< 0.01
Total Background		0.41	0.46	1.40

(from arXiv:1307.1168)

- The Mu2e-II DIO numbers assume the tracker has 8 μm thick walls. For current (15 μm thick) walls the DIO background estimate is >2 events for both Al and Ti stopping targets.
- Assumes out-of-time protons are suppressed by 10^{-12} or more
- Estimates for 1 and 3 GeV are the same within 10% of each other
- Total uncertainty on the total background estimate is ~30%

Mu2e-II Beam Requirements

- Pulsed proton beam
  - Kinetic energy < 4 GeV
  - Sufficient beam power to achieve few x 10^{18} stopped muons in 3 years of full intensity running
  - Pulsed with spacing of ~1700 ns
    (a tunable spacing in the range 800-1700 ns even better)
  - Full width ~100 ns (ie. +/- 50 ns around center)
  - Suppress out-of-time protons by 10^{-12} or better
  - Duty factor ~90% or better
  - Strong preference to avoid using Delivery Ring

Moving Forward

- Writing an Expression of Interest to be submitted to the Fermilab PAC this summer
  - Will circulate outside of Mu2e collaboration
- Developing a list of required R&D
  - Even lower mass tracker, faster calorimeter
  - 100-150 kW capable target station
    - Actively cooled production target
    - New HRS or new Production Solenoid
    - Associated target handling and radiation safety
  - Etc.
- Additional simulation work
  - Particularly regarding production target region

Summary

- Muon Campus will be dedicated to Mu2e running through 2028 (assuming LBNF shutdown 2024-26)
- An upgraded Mu2e (Mu2e-II) with x10 better sensitivity
  - Would reuse as much of Mu2e as possible
  - Would offer powerful probe of New Physics in charged lepton sector
  - Benefits from upgraded proton source
  - Looks feasible based on initial studies (arXiv:1307.1168)
- Expression of Interest in preparation

Backup Slides

Changing the stopping target

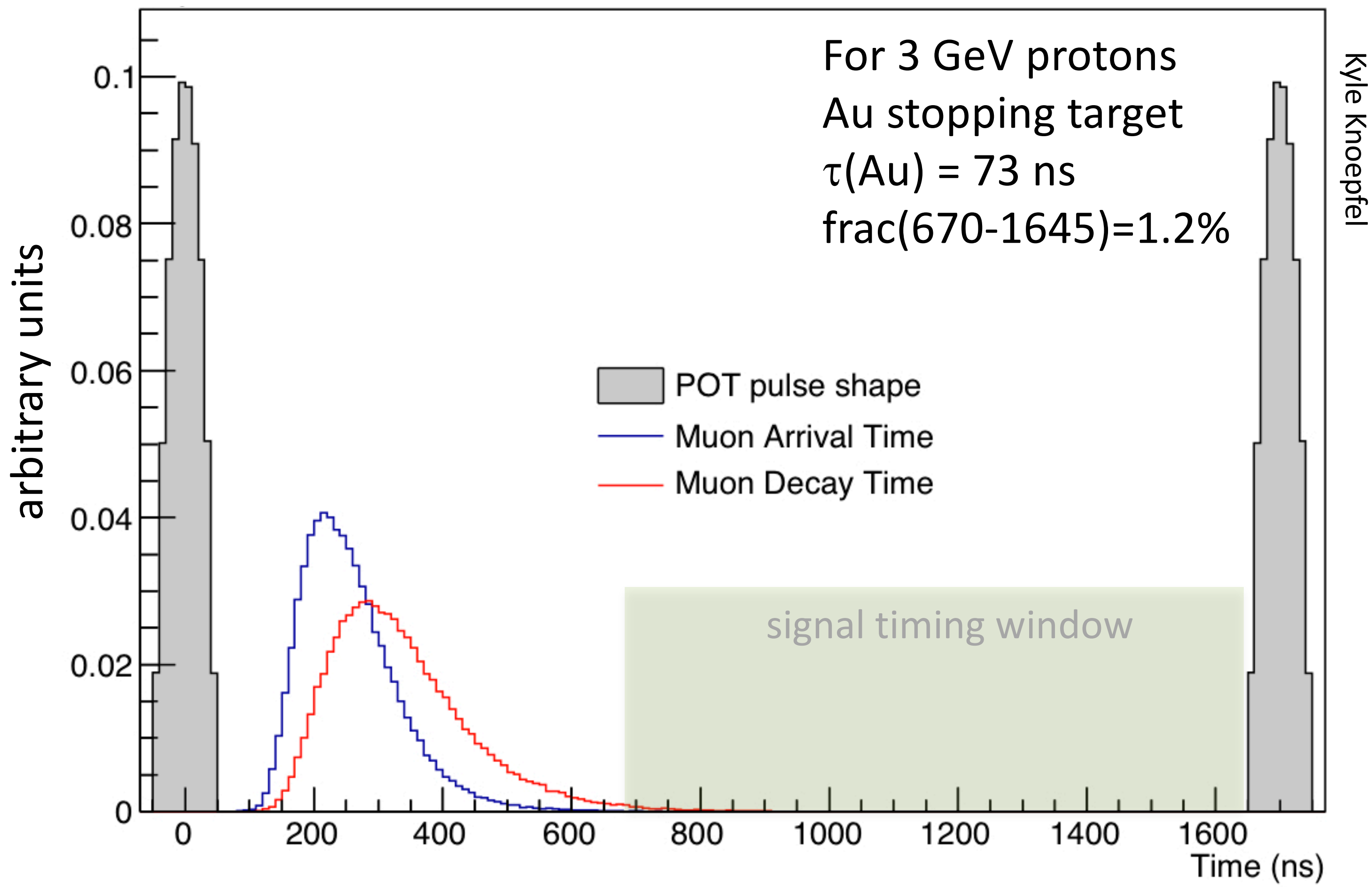
- For an aluminum stopping target
  - Capture fraction : 0.609
  - Decay fraction : 0.391
  - Muonic atom lifetime : 864 ns
  - E_e(signal) = 104.97 MeV
- For a titanium stopping target
  - Capture fraction : 0.850
  - Decay fraction : 0.150
  - Muonic atom lifetime : 329 ns
  - E_e(signal) = 104.27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

muon yields: Ti target

muons		8 GeV	3 GeV	1 GeV
	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
  - τ(Al) = 864 ns → τ(Ti) = 329 ns

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

Endpoint of DIO Spectrum

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

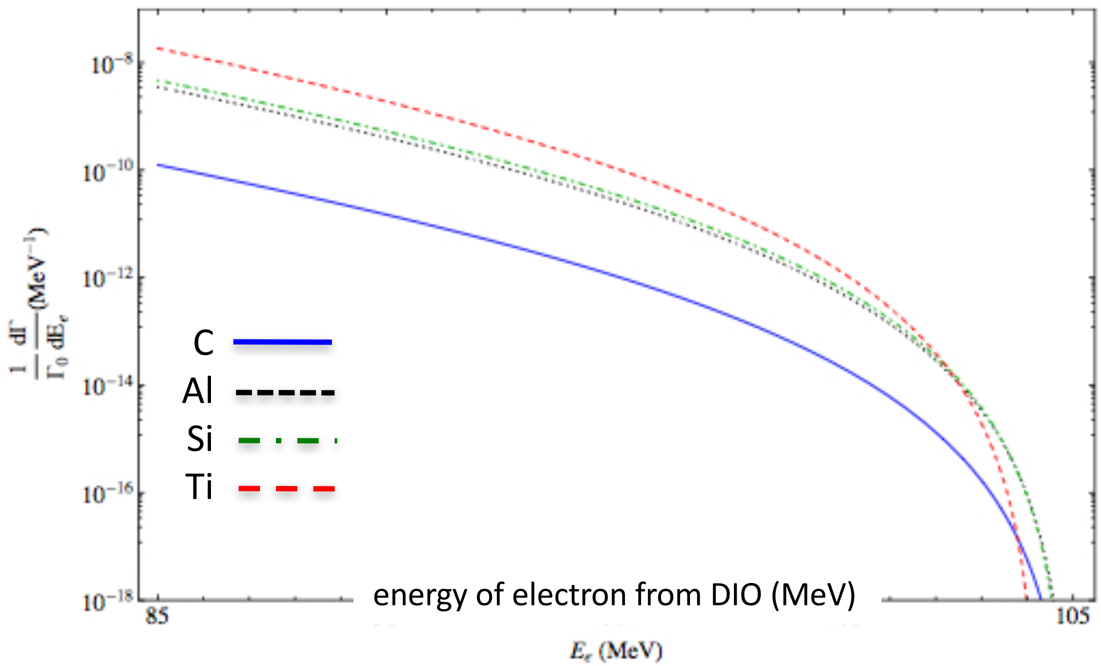
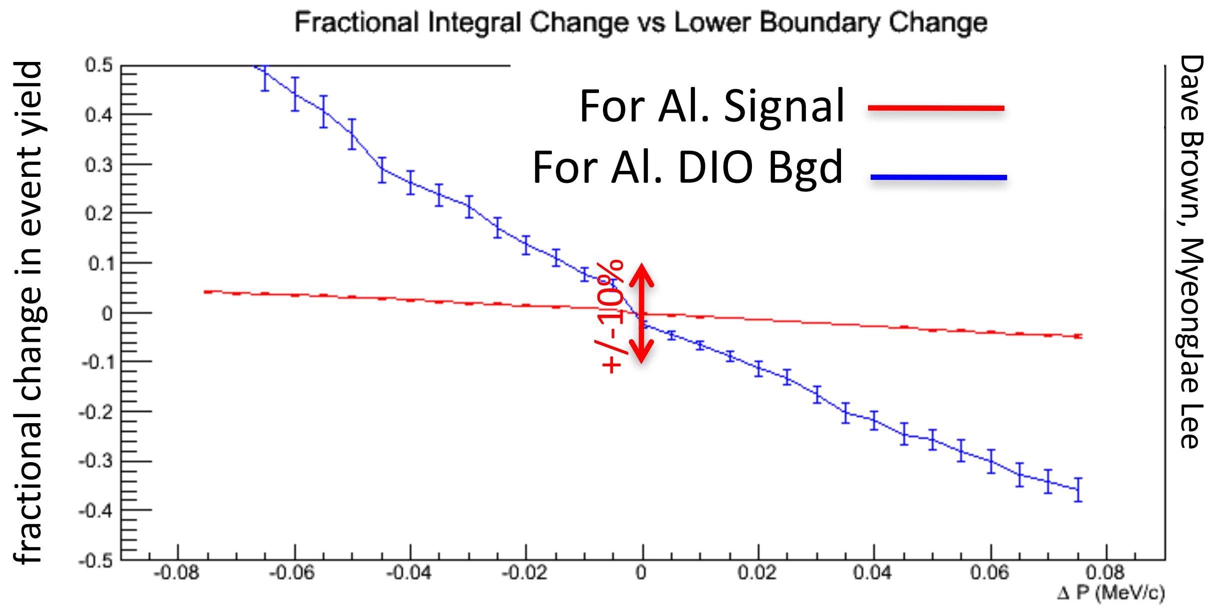


Fig. 1 Electron spectrum, normalized to the free-muon decay rate Γ_0. The solid blue line is for carbon, the black dotted line for aluminum, the green dot-dashed line for silicon and the red dashed line for titanium.

- We used the correct shape for Al and Ti spectrum
  - Included overlays from increased (beam-related) occupancy and utilized full pattern recognition and track fitting for 15 μm and 8 μm thick tracker straw walls

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?

- We considered
  - Solenoids
  - Tracker
  - Calorimeter
  - Cosmic Ray Veto
- We have not yet considered
  - Stopping target monitor
  - Extinction 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)

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 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 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 PIP-II to explore different target materials (NB in this instance the upgrade list would be very different and would likely be substantially shorter).