Next Generation Mu2e

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27 October 2017

Outline

- Introduction & Motivation
- Summary of work to date
- Beam requirements
- Preparing for next P5

Introduction

Currently constructing Mu2e:

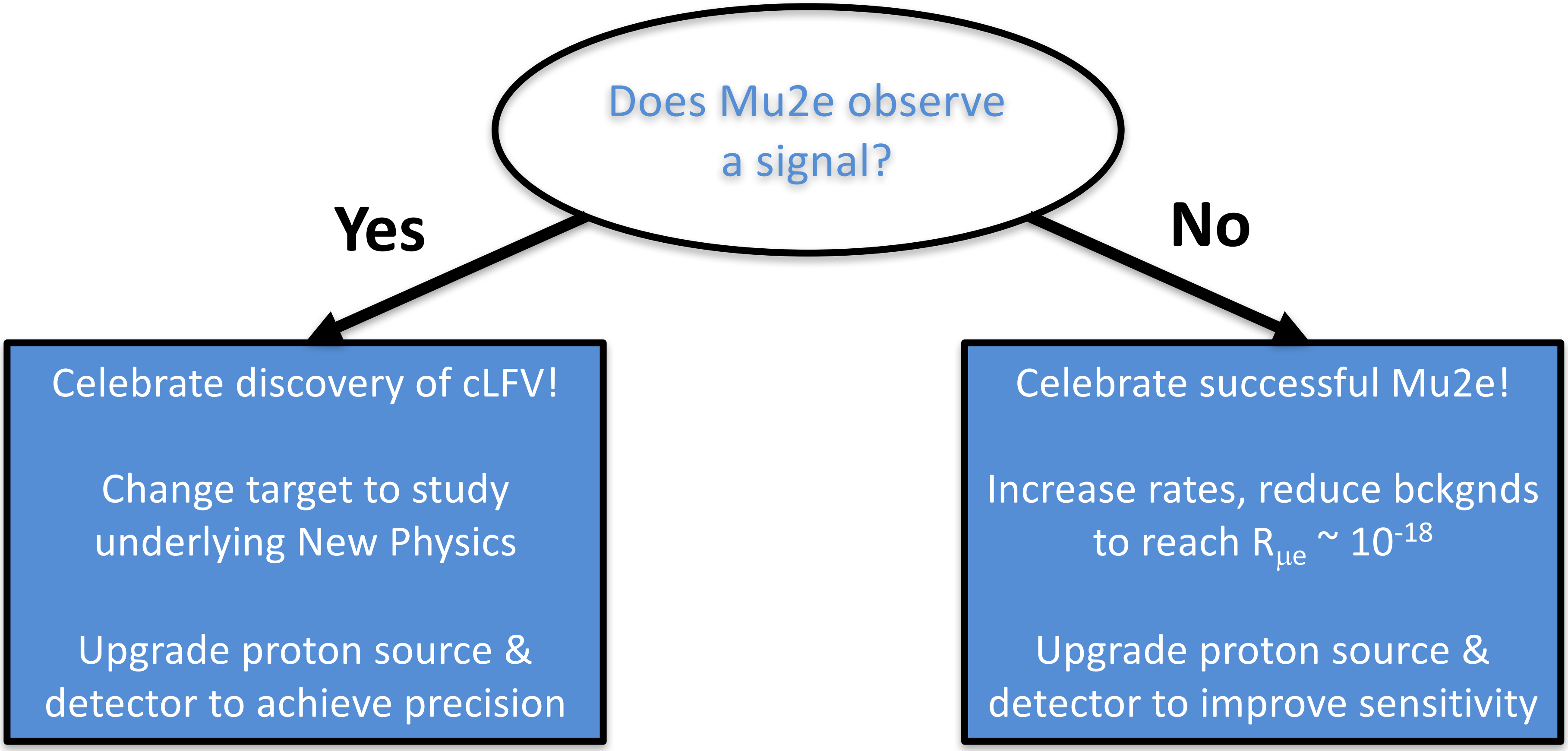
- Utilizes 8 kW of 8 GeV pulsed protons
  - Full-base pulse width 250 ns
  - 1695 ns between pulses
  - Duty factor 30%
  - (# out-of-time protons / #in-time protons) < 1×10^{-10}
- Aluminum stopping target
- Expected sensitivity (with 4×10^{20} POT)
  - Single-event-sensitivity = < 3×10^{-17}
  - Background < 1 events
  - $R_{\mu e} < 7 \times 10^{-17}$ @ 90% CL, or discovery for $R_{\mu e} > 2 \times 10^{-16}$
- Commissioning expected to begin 2021
- Physics running 2022-2026 (no LBNF shutdown)
  2022-2028 (with LBNF shutdown 2024-2026)

Introducing 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

Motivation

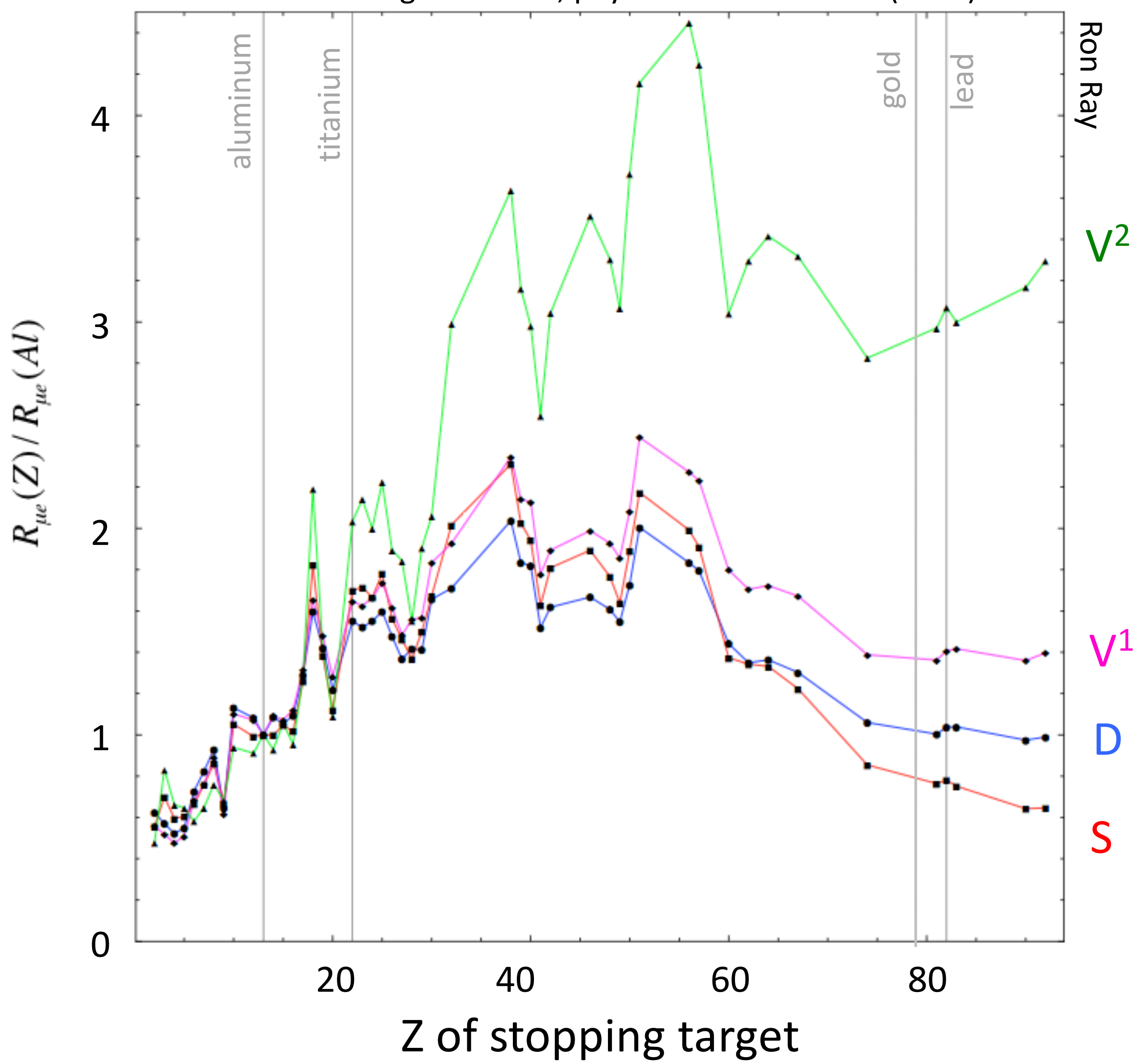


- At conclusion of Mu2e, strong motivation to upgrade proton source and detector to further pursue New Physics

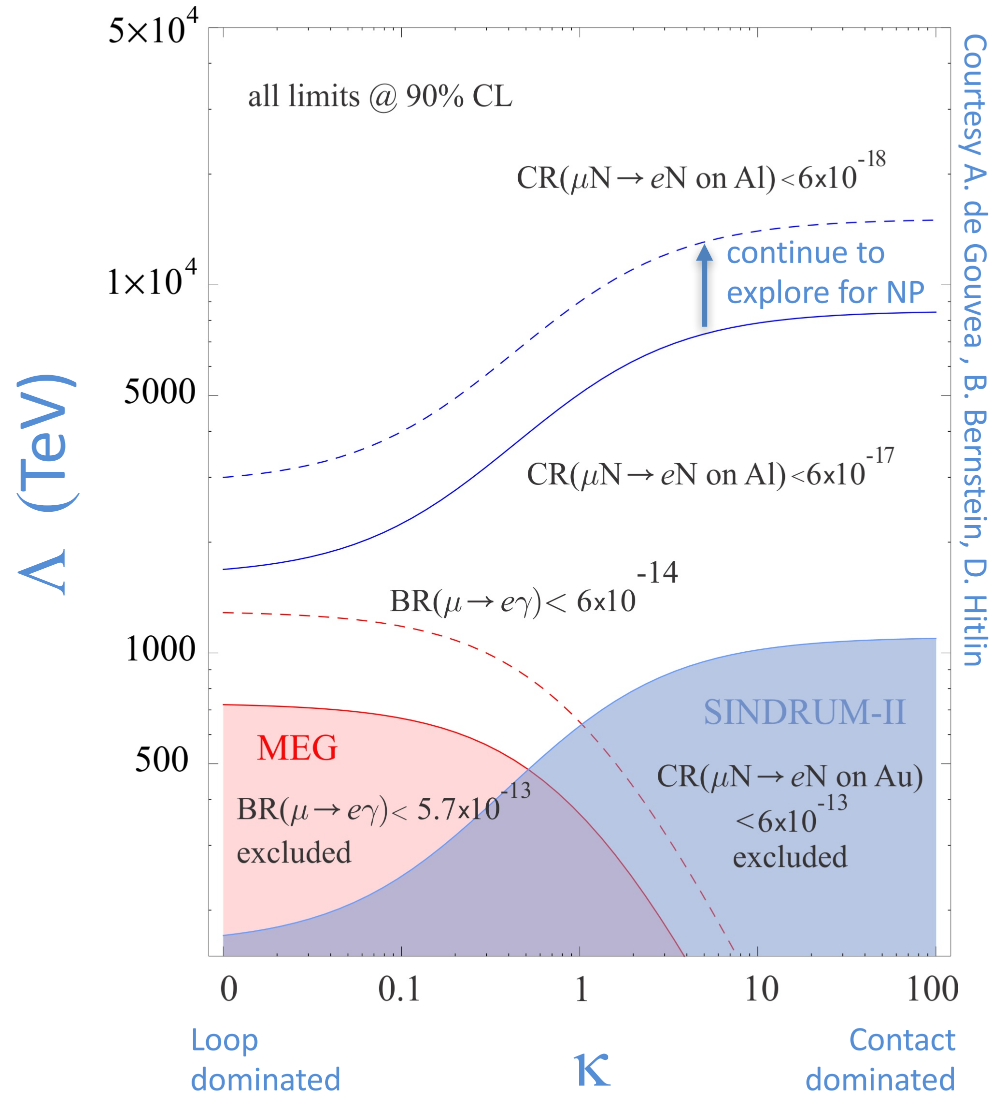
Upgrade Motivation with Mu2e signal

- 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)



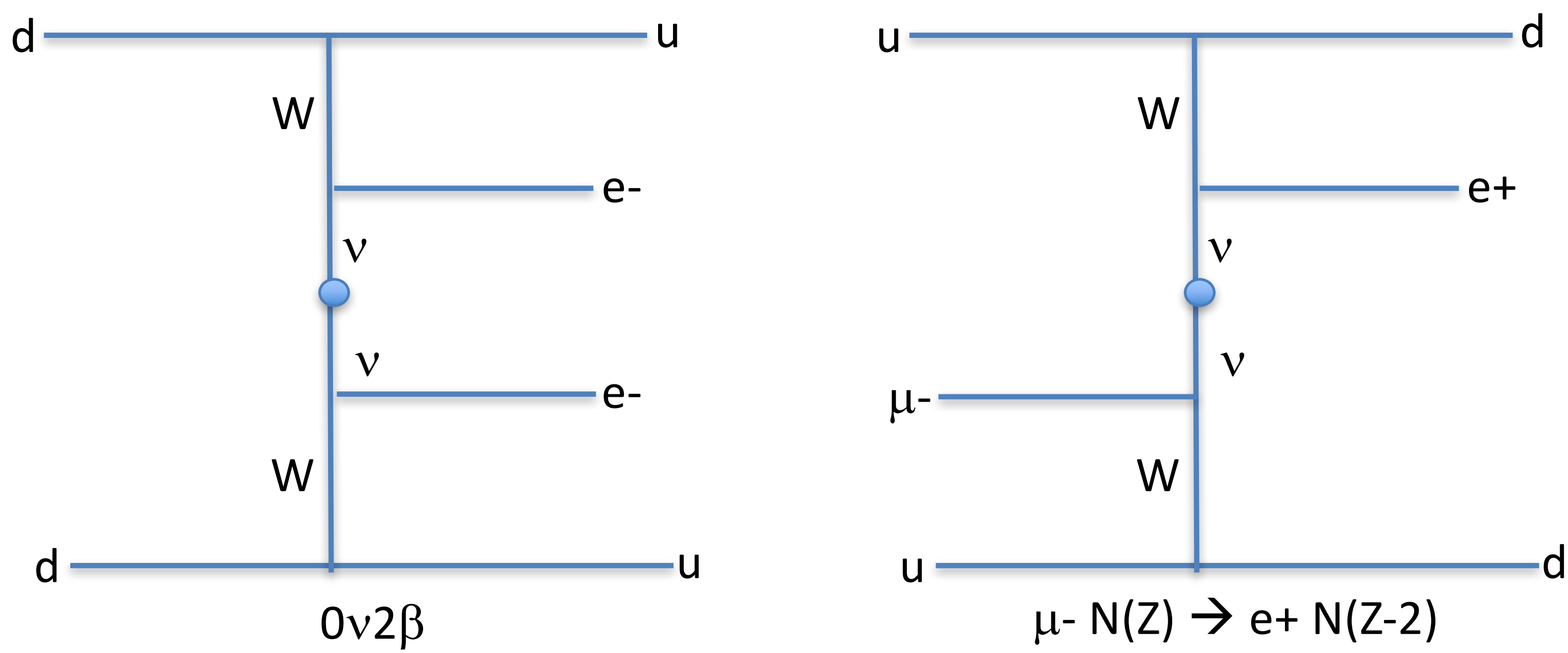
Upgrade Motivation no Mu2e signal



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

Upgrade Motivation – μ^- --> e^+

(We've just begun thinking about this…)



- With increased beam intensity can also pursue a program that utilizes targets optimized for LNV μ^- N(Z)→ e^+N(Z-2) searches (complementary to 0ν2β)

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^{-11} or better
  - Duty factor ~90% or better
  - Strong preference to avoid using Delivery Ring

Preparing for next P5

- Next P5 exercise will likely occur on the 2020-2021 timescale
- We would like to ensure that Mu2e-II is in a strong position to be seriously considered as part of the future HEP program (>2025).
- Necessary steps
  - Formalize interest
  - Advance critical R&D

What's been done so far?

arXiv:1307.1168v1 [physics.ins-det] 3 Jul 2013

Feasibility Study for a Next-Generation Mu2e Experiment

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7], R. Ehrlich[7], M.J. Frank[7], D. Glenzinski[3], R.C. Group[3,7], D. Hedin[6], D. Hitlin[2], M. Lamm[3], J. Miller[1], S. Miscetti[4], N. Mokhov[3], A. Mukherjee[3], V. Nagaslaev[3], Y. Oksuzian[7], T. Page[3], R.E. Ray[3], V.L. Rusu[3], R. Wagner[3], and S. Werkema[3]

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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, 12500
- Workshops
  - IF Workshop (ANL, 04/2013)
  - Snowmass (UM, 08/2013)
  - Mu2e CM (FNAL, 02/2016)

Recent work

- An Expression of Interest is now available for signature
  - Will submit to Fermilab PAC this CY
- Working to address R&D
  - Proposal submitted to INFN for calorimeter R&D
  - Mu2e-II Workshop at ANL on December 8th
  - Brief OHEP in Feb/Mar next year

Proposal to INFN

ERC Consolidator Grant 2017
Research proposal [Part B1]

ICE-DECAF

Innovating the **C**onversion **E**lectron search:
a **DE**monstrator of **CA**lorimetry with barium **F**loride

Cover Page:
- Principal Investigator: **Stefano Miscetti**
- Host Istitution: **Istituto Nazionale di Fisica Nucleare, Italy**
- Duration in months: **60**

The observation of the muon to electron conversion – one of the forbidden Charge Lepton Flavour decays – at the next high intensity frontier would be a striking evidence of new physics shedding light also on direct searches at high energy colliders. This exploration, testing unprecedented mass scales up to 20000 TeV, is setting a series of challenges, pushing experimental requirements well beyond their known limits. Taking advantage of the timely opportunity offered by the Mu2e-II experiment at Fermilab (USA), ICE-DECAF will provide a solution to the outstanding requirements of the high-intensity frontier developing a new concept calorimeter, based on the intriguing characteristics of BaF_2 crystals.

ICE-DECAF will achieve excellent energy ($< 5\%$) and timing (< 500 ps) resolution with very high pile-up discrimination capability (signal output of few ns) for the identification of the 105 MeV conversion electron. Its design will include both space-environment like requirements, such as work under vacuum and in a harsh radiation environment, and the capability of operating inside a region with 1 T magnetic field. To make this a reality, a new technology that take advantage of the fast (0.9 ns) BaF_2 UV scintillating component (220 nm) while achieving "solar-blindness" (SB) for the slow component at longer wavelengths has to be established.

- R&D to demonstrate feasibility of BaF_2 calorimeter with SiPM readout
- 5y, ~3M Euro

Expression of Interest

mu2e-doc-db-10655

Expression of Interest for Evolution of the Mu2e Experiment

Authors TBD.

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment. Mu2e will be the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Introduction

The Mu2e experiment, now under construction at FNAL, will search for the rare muon-to-electron conversion process, $\mu^- + {}^{27}_{13}\mathrm{Al} \rightarrow e^- + {}^{27}_{13}\mathrm{Al}$. If this process were detected it would be the first experimental evidence of Charged Lepton Flavor Violation (CLFV) and a definitive signal of physics beyond the Standard Model. We are submitting this Expression of Interest as a preface to a detailed proposal to upgrade the Mu2e experiment, to improve the sensitivity by an order of magnitude. The new experiment is referred to here as Mu2e-II.

- Finalized this summer
- Committee:

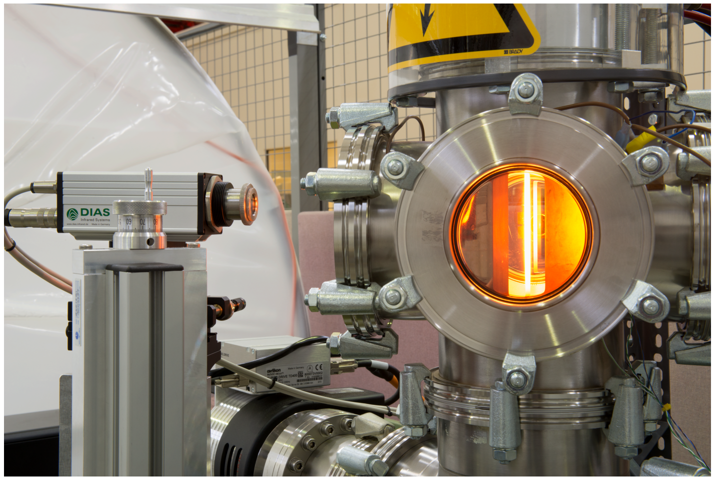
  B. Tschirhart (chair), M. Lancaster, S. Miscetti, V. Glagolev, Z. Yu, Y. Kolomensky, A. Ferrari, D. Brown, S. Werkema
- Collecting signatures

You can add your signature here:
https://docs.google.com/spreadsheets/d/1eQtq7MKmWPvtmtuBlts3Hbx54PfFHTaJkbt_O0IGAbA/edit?usp=sharing

Mu2e-II Workshop

- One day workshop to begin organizing R&D
  - Hosted by Karen Byrum & Rich Talaga at ANL
  - December 8, 2017
- Workshop goals:
  - Summarize experimental challenges
  - Enumerate the high priority R&D needs
  - Brainstorm ideas for addressing these issues
- Registration open to everyone (it's free)
  - Deadline is early Nov
  - Sign-up here:

  https://indico.hep.anl.gov/indico/conferenceDisplay.py?ovw=True&confId=1258



Some Key R&D Issues

- Designing a production target for 100+ kW
  - Current Mu2e production target has an average power density of 150 MW/m^3, DPA~260/yr
  - A Mu2e-II production target would have an average power density of > GW/m^3 and would experience a DPA well beyond current state-of-the-art
- Need to work with RaDIATE consortium and GARD to identify R&D goals of general interest

Some Key R&D Issues

- Measure the extinction from PIP-II "chopper" using the PIP2-IT
  - Utilize LDRD to develop detector that would enable an extinction measurement at 10^{-11} level
  - PIP2-IT will be ready to do this in ~2y… need to start detector development now (interested?)
- Develop beamline design
  - 800 MeV H- beam… need to strip electrons, need to steer 800 MeV onto production target

Additional R&D Issues

- Working to articulate R&D issues for each sub-system
  - Discussed in the Expression of Interest
  - Will have presentations at the ANL workshop

Summary

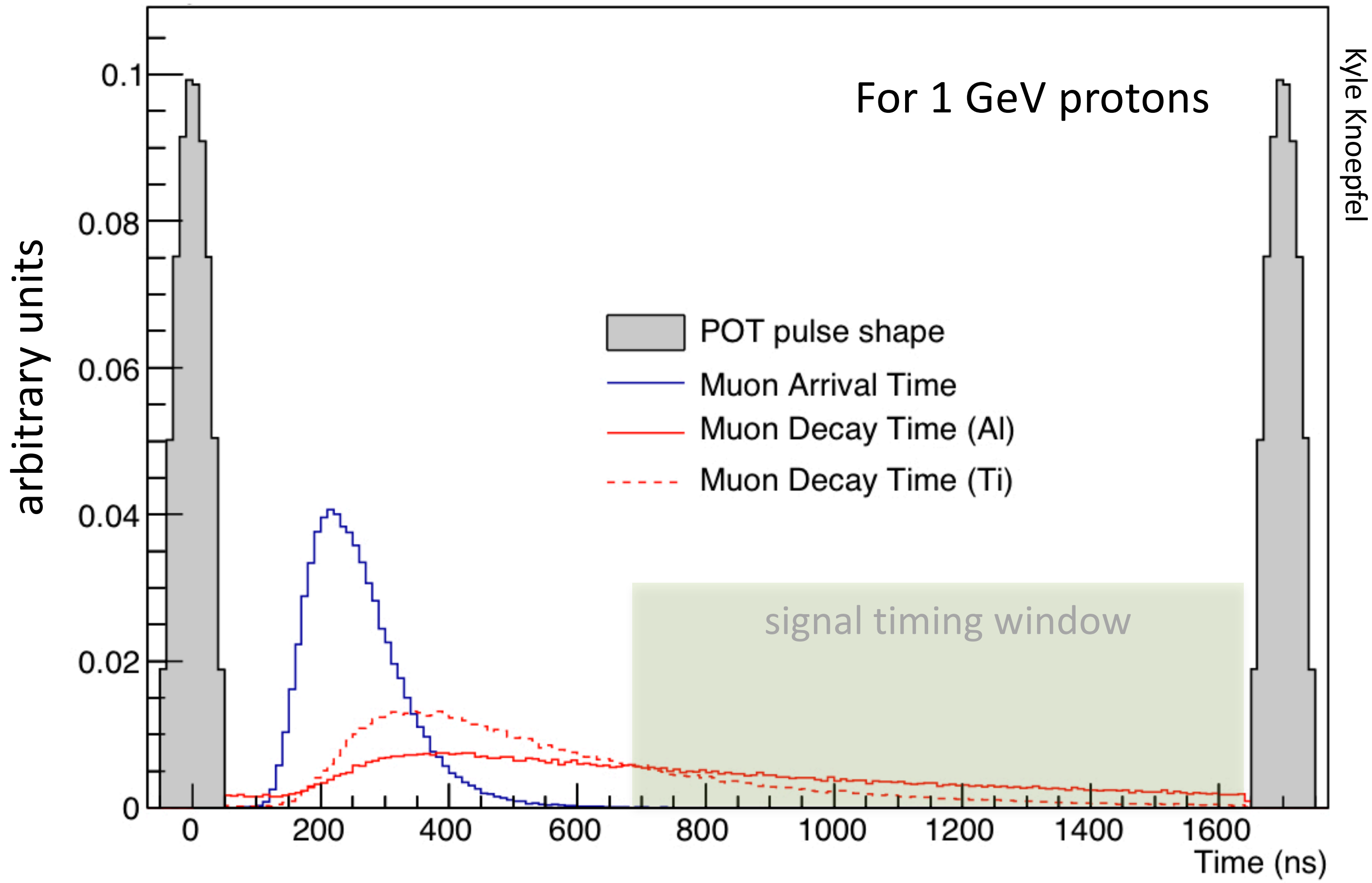
- An upgraded Mu2e (Mu2e-II) with x10 better sensitivity
  - Would reuse as much of Mu2e as possible
  - Would offer powerful probe of New Physics in charged lepton sector
  - Benefits from upgraded proton source
  - Looks feasible based on initial studies (arXiv:1307.1168)
- Expression of Interest is available for signature
  - Will be submitted to FNAL PAC soon
- Developing R&D plan
  - Workshop at ANL December 8
  - Registration is open

Backup Slides

Changing the stopping target

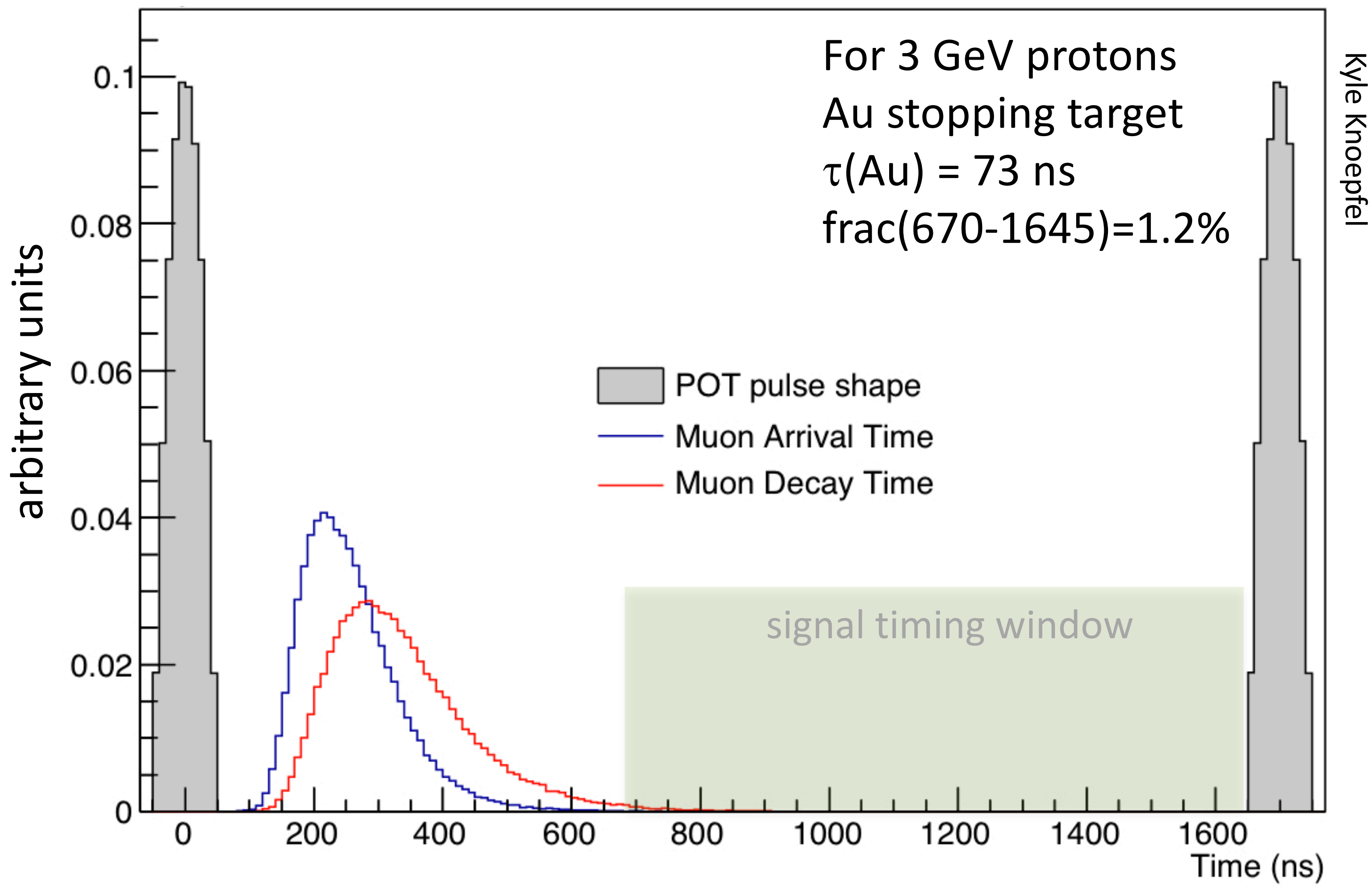
- For an aluminum stopping target
  - Capture fraction : 0.609
  - Decay fraction : 0.391
  - Muonic atom lifetime : 864 ns
  - E_e(signal) = 104.97 MeV
- For a titanium stopping target
  - Capture fraction : 0.850
  - Decay fraction : 0.150
  - Muonic atom lifetime : 329 ns
  - E_e(signal) = 104.27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

muon 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

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.

Endpoint of DIO Spectrum

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

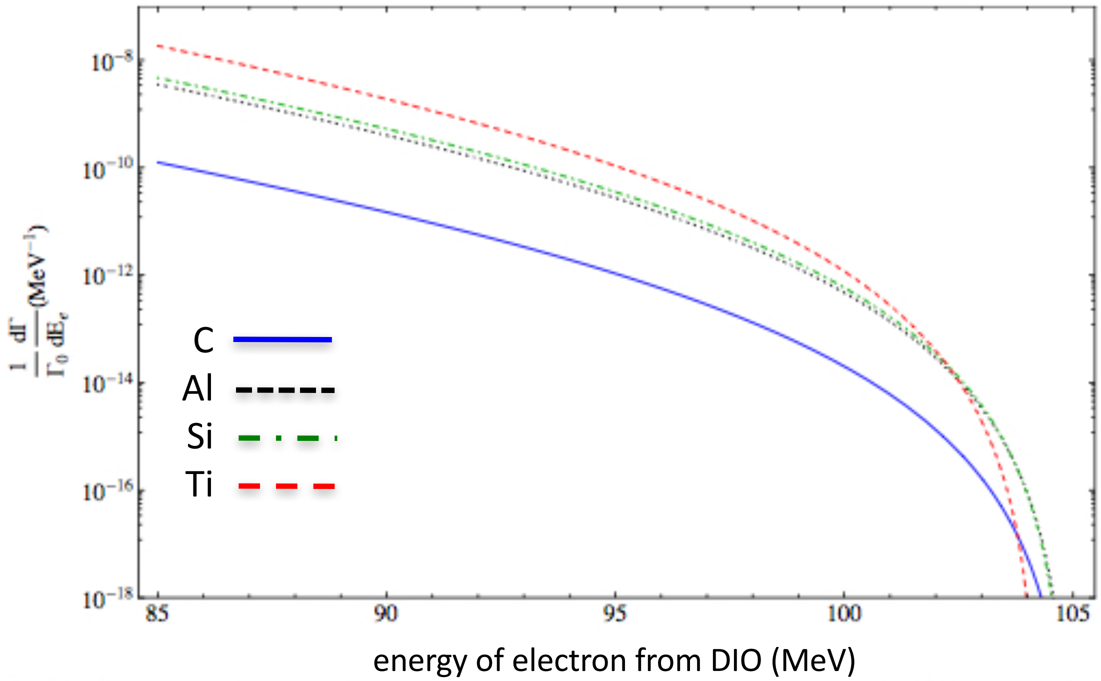
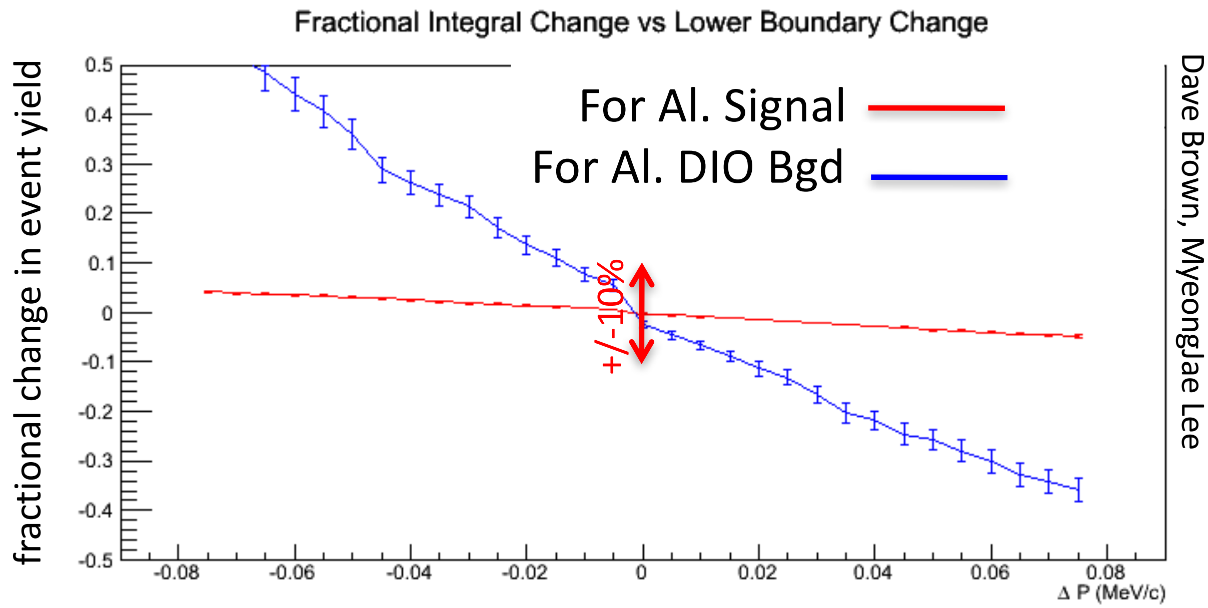


Fig. 1 Electron spectrum, normalized to the free-muon decay rate Γ_0. The solid blue line is for carbon, the black dotted line for aluminum, the green dot-dashed line for silicon and the red dashed line for titanium.

- 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

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 26 ns for CsI
    - 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, D. Hedin, 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).