Expression of Interest for the Evolution of Mu2e – Mu2e-II

D. Glenzinski (Fermilab)

On behalf of Mu2e-II Signatories

Mu2e-II Definition

- An upgrade to current Mu2e construction that
  - Uses ~100 kW of PIP-II protons
  - Leverages as much of Mu2e investment as reasonably possible
  - Achieves an order of magnitude improvement in sensitivity (ie. probes $R_{\mu e} \sim 10^{-18}$ level, extends Λ_{NP} reach by x2)

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

Our goal

We want Mu2e-II to be a serious part of the next P5 discussion.

For that to occur we need to address the following:

- Is there interest in the community?
- Is the science compelling?
- Is the experimental concept sound?
- Is the scope understood?
- Is the remaining R&D specified?

In the remainder of this talk I'll address each of these issues.

Community Interest

Expression of Interest – Mu2e-II

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

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, providing 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.

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, providing 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.

- Submitted to PAC 09 February 2018
- arXiv:1802.02599, Fermilab-FN-1052
- **130 Signatories, 36 Institutions, 6 Countries**

Science Motivation

Science Motivation

- CLFV is a deep & unique probe of New Physics (NP) parameter space
  - Next generation experiments planned in Europe, Asia, and Americas
  - Probes complementary regions of NP space relative to rest of HEP program
  - Measured rates provide model discrimination

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)}$	$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^3$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^3$	$\mathcal{O}(10^3)$
LFV Higgs	Loop†	Loop$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

arXiv:1709.00294v2[hep-ph]

from L. Calibbi and G. Signorelli, Riv. Nuovo Cimento, 41 (2018) 71

TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). It is indicated whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to Eq. (40, 41). † A tree-level contribution to this process exists but it is subdominant.*

Science Motivation

- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - –Provides best sensitivity to CLFV
  - –Probes broad array of NP models
  - –Can provide unique information regarding underlying NP operators

Science Motivation

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  - Provides best sensitivity to CLFV

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 4.4 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \rightarrow \mu\mu\mu$	BR < 2.1 E-8	
$\tau \rightarrow eee$	BR < 2.7 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	NA62
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 2.8 E-9	LHCb, Belle II
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG-II)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-15} (μ3e Phase-I)
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET Phase-II)

(Current Limits taken from the PDG)

Science Motivation

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(Current Limits taken from the PDG)

Science Motivation

- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - Mu2e-II would provide the best sensitivity to CLFV in foreseeable future

Process	Current Limit	Next Generation exp
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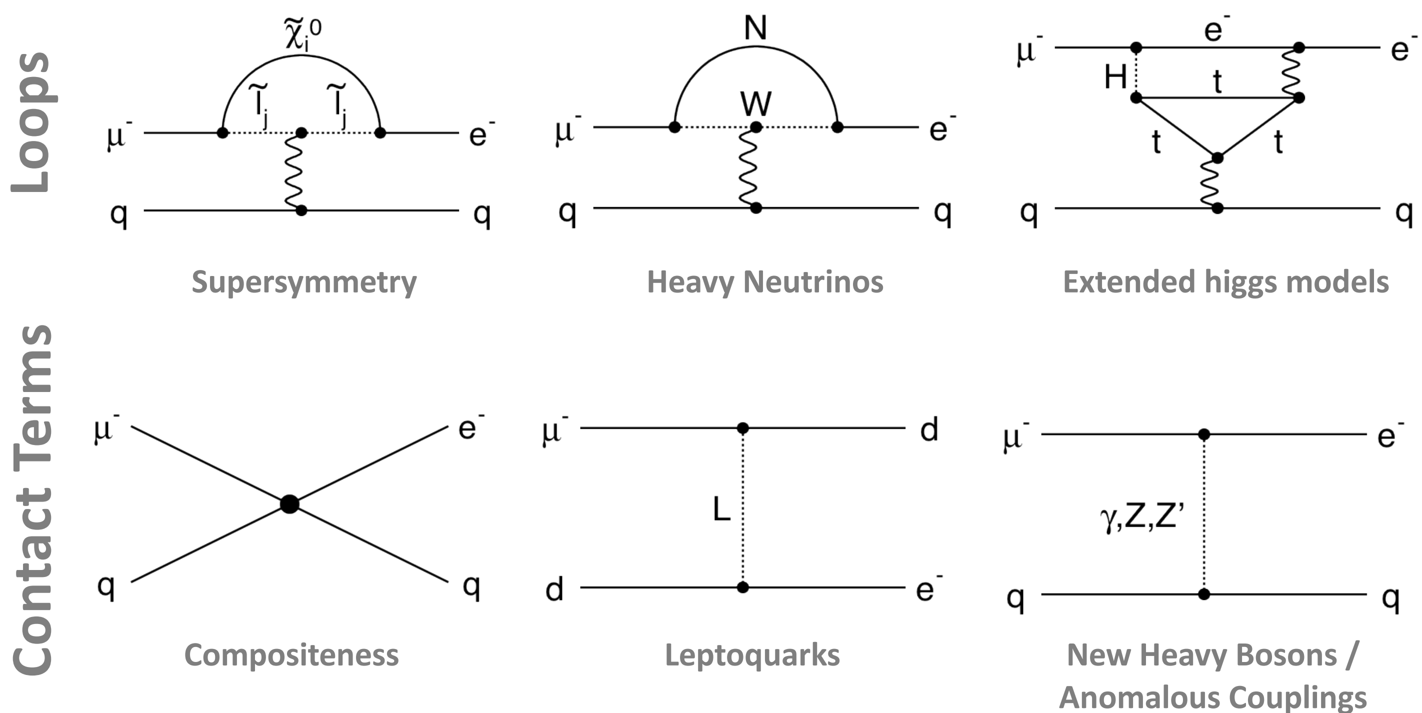
10^{-18} Mu2e-II

(Current Limits taken from the PDG)

Science Motivation

- Direct μ→e conversion is the "Golden Channel" of CLFV
  - Sensitive to broad array of New Physics models



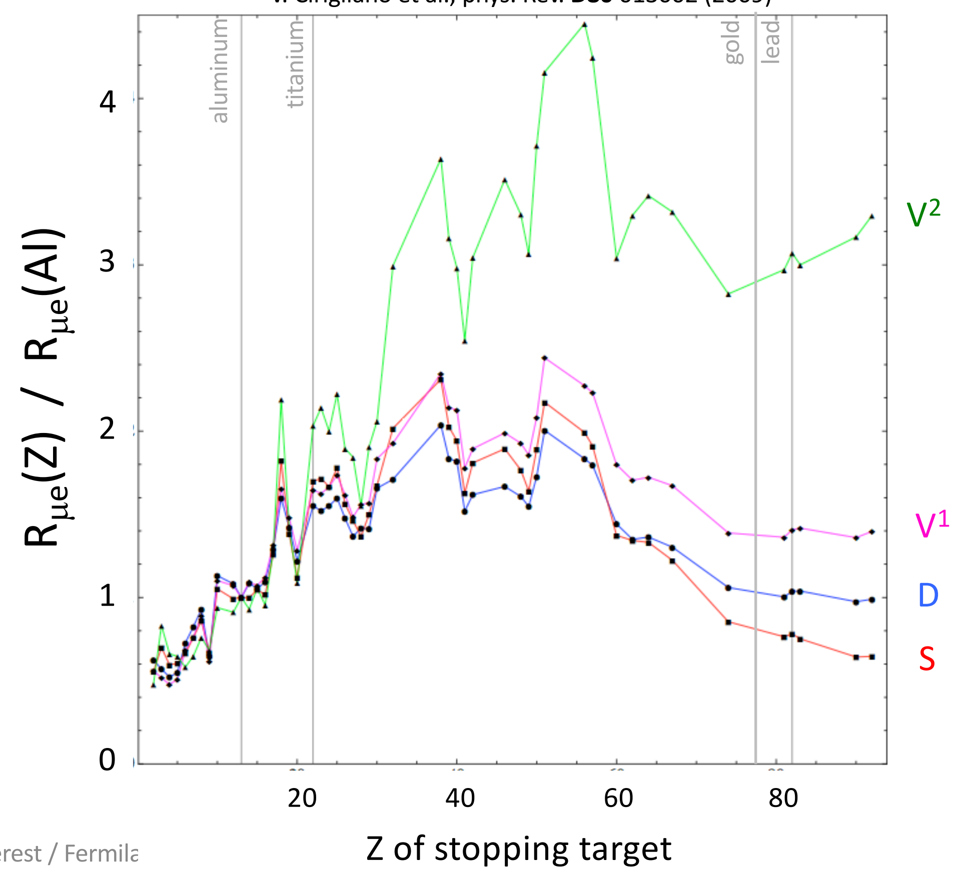
Science Motivation

- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - Once an observation is made, can change stopping target to probe underlying NP operator

	S	D	V^1	V^2
$\frac{B(\mu \to e, \mathrm{Ti})}{B(\mu \to e, \mathrm{Al})}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu \to e, \mathrm{Pb})}{B(\mu \to e, \mathrm{Al})}$	$0.69 \pm 0.02_{\rho_n}$	1.04	1.41	$2.67 \pm 0.06_{\rho_n}$

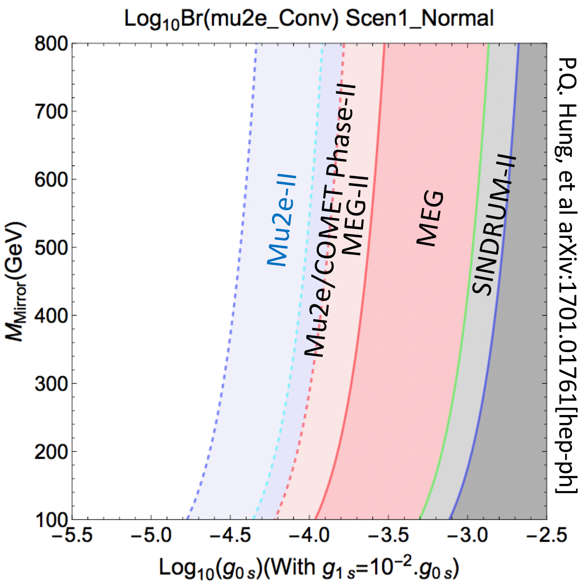
y = nuclear scalar form factor, ρ_n = nuclear neutron density

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

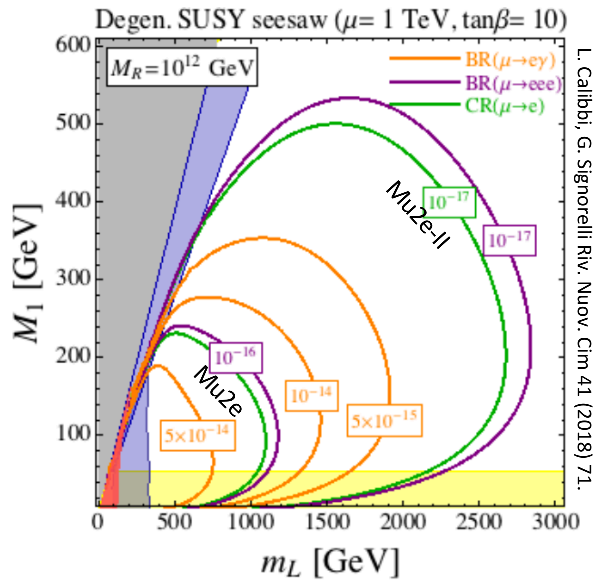


Science Motivation

Mirror Leptons



SUSY Seesaw



Composite Higgs

C. Hagedorn, M Serone JHEP 10 (2011) 83.

Z Prime

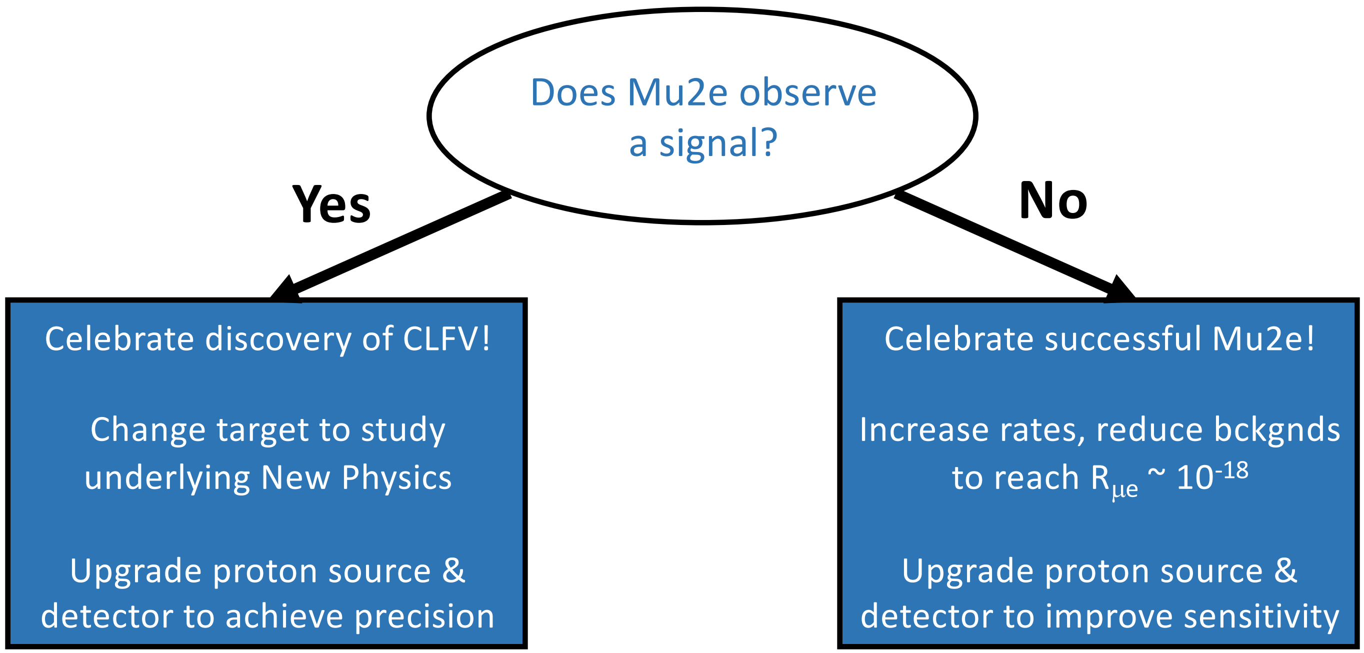
A. Falkowski, M. Nardeccia, R. Ziegler, JHEP 11 (2015) 173.

LeptoQuarks

A. Crivellin, et al., PRD 97 (2018) 015019.

- Mu2e-II will have discovery sensitivity in broad array of New Physics models

Mu2e-II Motivation



- **At conclusion of Mu2e there's a strong motivation to upgrade proton source and detector to further pursue New Physics – Mu2e-II**

Experimental Concept

Feasibility of Mu2e-II Experimental Concept

arXiv:1307.1168[hep-ex]

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]

[1] *Boston University, Boston, Massachusetts 02215, USA*
[2] *California Institute of Technology, Pasadena, California 91125, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[5] *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6] *Northern Illinois University, DeKalb, Illinois 60115, USA*
[7] *University of Virginia, Charlottesville, Virginia 22906, USA*

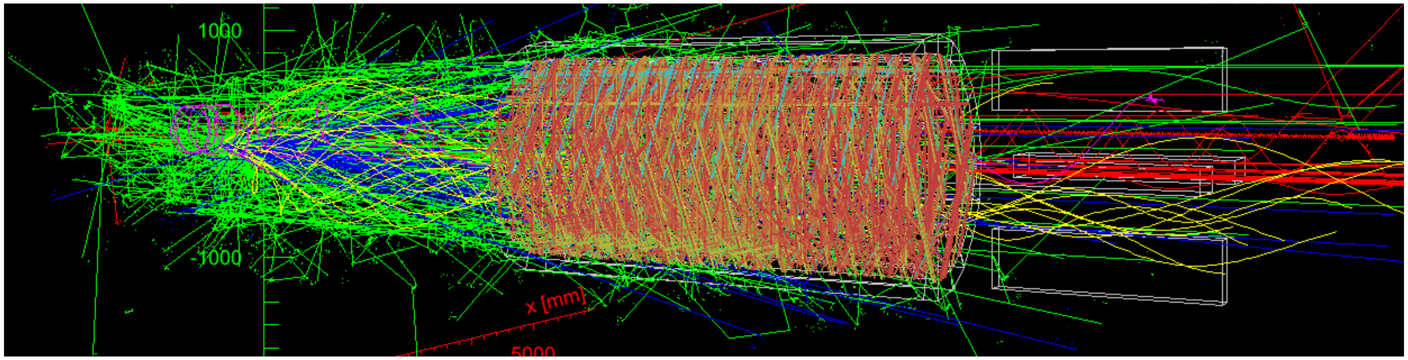
Submitted as part of the APS Division of Particles and Fields Community Summer Study (dated: September 27, 2013)

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.

- Mu2e-II Experimental concept is straightforward extension of Mu2e
- White Paper arXiv:1307.1168
  - Associated workshops (April-2013, July-2013)
  - Follow-up workshops (July-2015, March-2016, June-2017)
- Used Mu2e simulation & reconstruction framework to estimate backgrounds at Mu2e-II rates
  - Includes all sources of background: from, μ, π, beam e, & cosmic ray

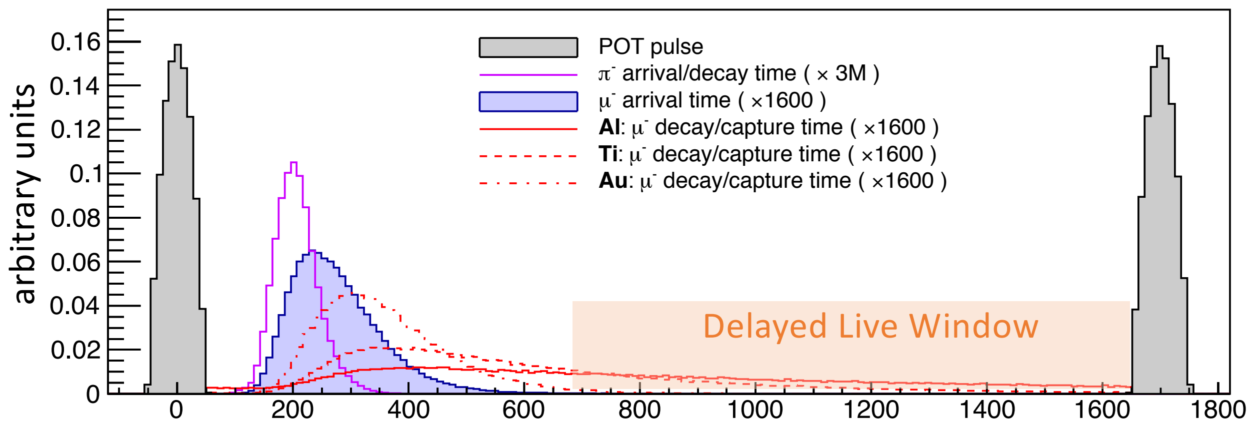
Feasibility of Mu2e-II Experimental Concept

Mu2e-II studies utilized full sophistication of Mu2e simulations and reconstruction software.

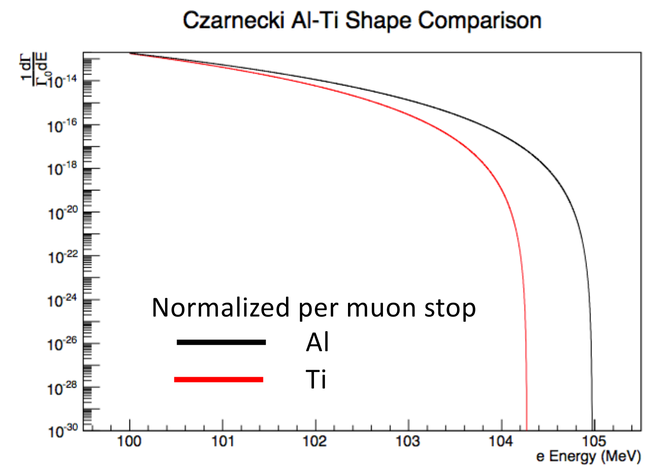


- A signal electron, together with all the other "stuff" occurring simultaneously (e.g. beam backgrounds, products from muon nuclear capture, DIOs), integrated over 500-1695 ns window
  - On average Mu2e (Mu2e-II) ~2500 (7500) hits in tracker during this time period
    - Capture products : 50% | Beam flash : 40% | other muon stops : 9% | DIO : 1%
    - On average a signal track leaves ~45 hits in tracker

Feasibility of Mu2e-II Experimental Concept



K. Knoepfel, *et al.*, arXiv:1307:1168 (2013).



Element ($^A_Z N$)	Density (ρ_N)	Decay fraction (f_N)	Lifetime (τ_N)
$^{27}_{13}$Al	2.70 g/cm^3	0.39	864 ns
$^{46-50}_{22}$Ti	4.51 g/cm^3	0.15	329 ns

A. Czarnecki, X. Garcia I Tormo, & W.J. Marciano, PRD 84 (2011) 013006.

- Aluminum & Titanium stopping targets investigated
  - Accounted for differences in density, decay fraction, end-point energy, DIO spectrum
- **Total background can be kept ~1 event**
  - **Discovery sensitivity continues to scale linearly with single-event-sensitivity**

Upgrade Scope and Required R&D

Proton Beam

Challenges associated with primary beam

Discussed and documented in EOI & in AD Impact Statement

- Does PIP-II meet the beam requirements?
- What level of secondary extinction is required after the PIP-II chopper?
- Is H- stripping necessary and if so how & where is it accomplished?
- What are implications of steering 800 MeV beam to the production target?
- What are implications for the production target at the required beam power?
- What modifications are required to the heat & radiation shield and/or production solenoid to keep superconductor functioning stably?
- What are the requirements for the proton beam absorber and radiation shielding for an upgraded proton beam?

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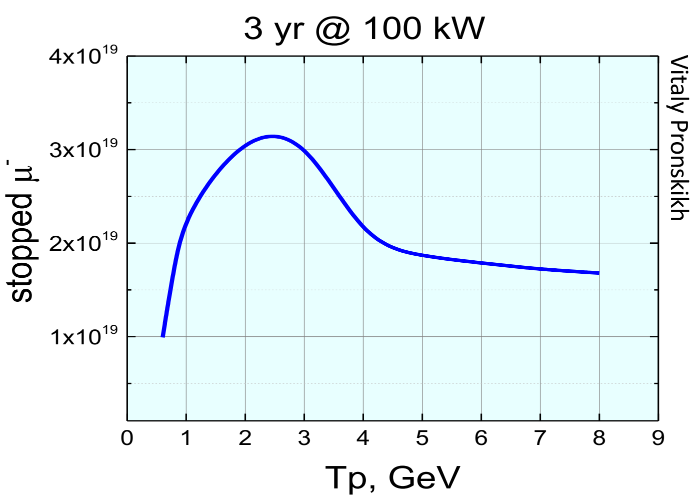
Studies completed or in progress

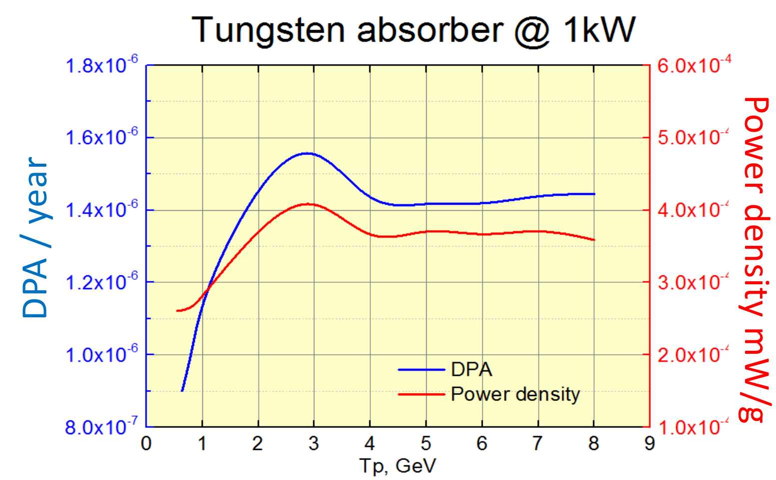
Studies of proton beam energy (arXiv:1612.08931)

(assuming no change in geometry of Heat & Radiation Shield or production target)

Muon Yield Studies



Coil Damage Studies



(nb. PS conductor can tolerate ~5x10^{-5} DPA/yr and ~3 x 10^{-2} mW/g Peak Power density)

- Muon yield at 0.8 GeV is ~same as at 8 GeV, while coil damage is ~30% smaller
- Strongly prefer an energy below pbar production threshold (Tp < 4 GeV)
- Upgrades required so that Production Solenoid can tolerate 100 kW

Beam requirements

	Mu2e	Mu2e-II	Comments
source	Slow extracted from Delivery Ring	H- direct from PIP-II Linac	Mu2e-II will need to strip H- ions upstream of production target
beam energy (MeV)	8000	800	optimal beam energy 1-3 GeV
Total POT (3+1)y	4.7E+20	4.40E+22	approximate, depends on mu-stop yield
run duration (yr)	3	3	
run time (sec/yr)	2.0E+07	2.0E+07	
experimental duty factor	25%	>90%	important for keeping instantaneous rates under control
p pulse full width (ns)	250	<= 100	
p pulse spacing (ns)	1695	1695	assumes an Al. target; shorter spacing better for Ti or Au targets
extinction	1.0E-10	1.0E-11	ratio of (out-of-time / in-time) protons
average beam power (kW)	8	100	100kW is approximate; will depend on production target design and transport, which will affect mu-stop yield

- Total POT and beam power are approximate – will depend on details of production target design and transport, which affect the stopped-μ yield

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- High spill-time fraction important in keeping instantaneous rates under control

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- Narrow pulses & better extinction important for reducing π background

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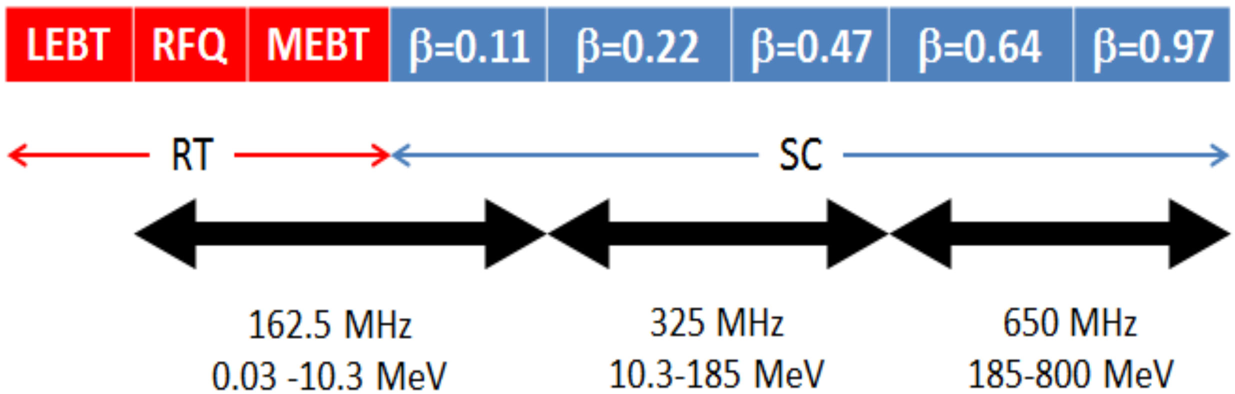
- PIP-II capable of meeting these requirements

PIP-II Capabilities

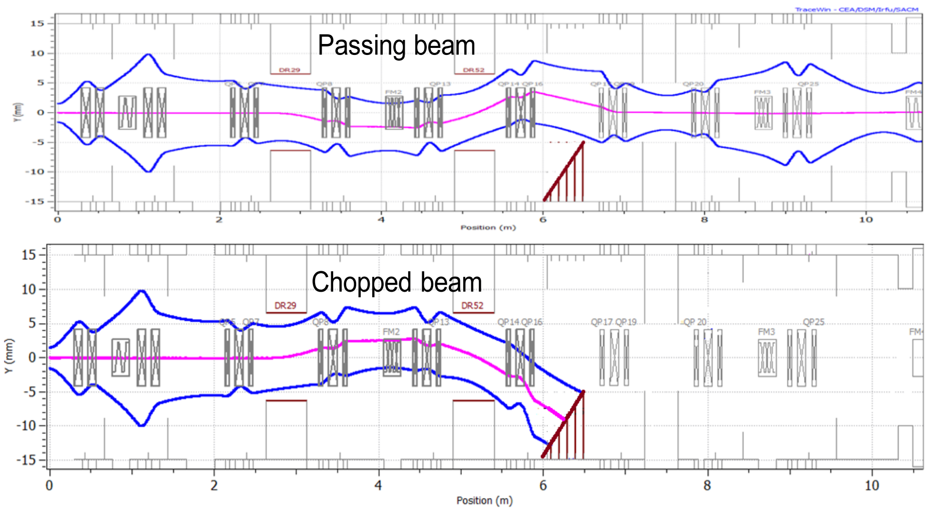


- PIP-II is capable of running in CW mode (with sufficient cooling)
  - 2 mA average current (H^-) at 800 MeV (1.6 MW)
  - LBNF/DUNE needs 1.2 MW at 60-120 GeV
  - **100 kW of 800 MeV beam for Mu2e-II is readily available with high spill fraction**

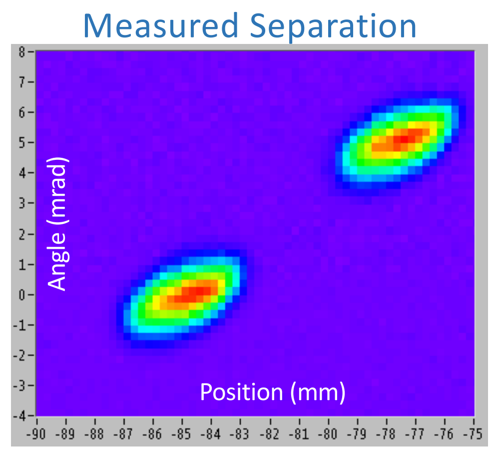
PIP-II Capabilities

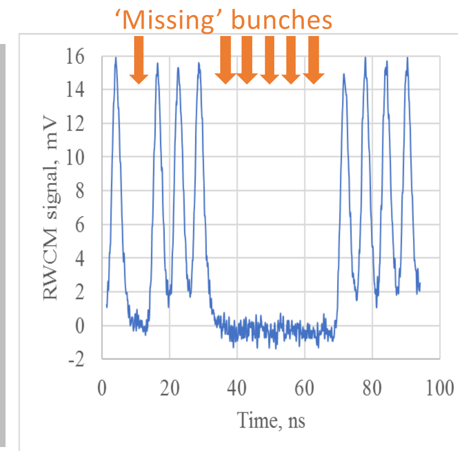
Figures from Paul Derwent

Chopper design optics



Measured performance at PIP2-IT



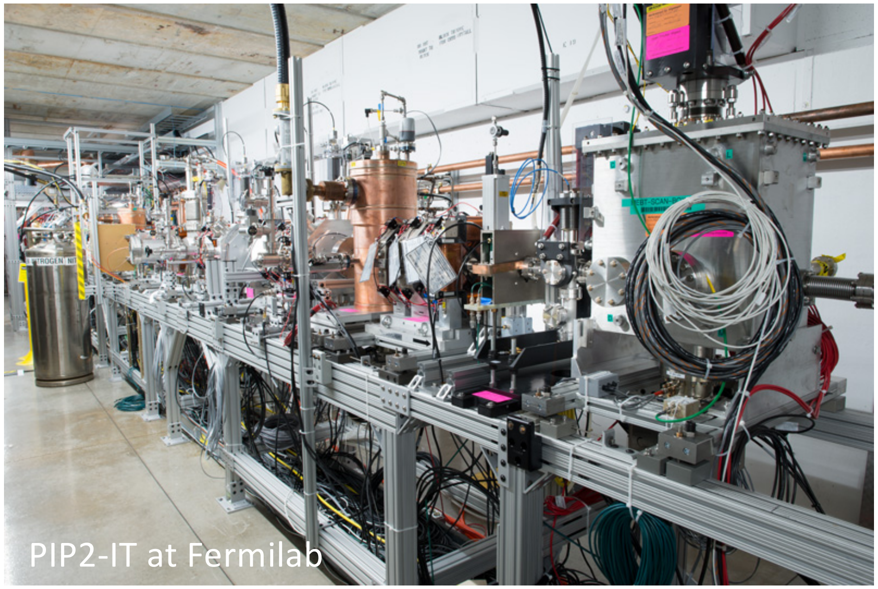


Possible Mu2e-II scenario: 6 full buckets+270 empty buckets = 40 ns wide pulses every 1.7 µs

- PIP-II is capable of delivering customized pulsed time structure
  - Utilizes a bunch-by-bunch "chopper" at end of MEBT section
  - **Prototype built & demonstrated to work at PIP2-IT facility**
  - **Required R&D: What's the level of extinction achieved by chopper alone?**

Required R&D – Extinction from Chopper

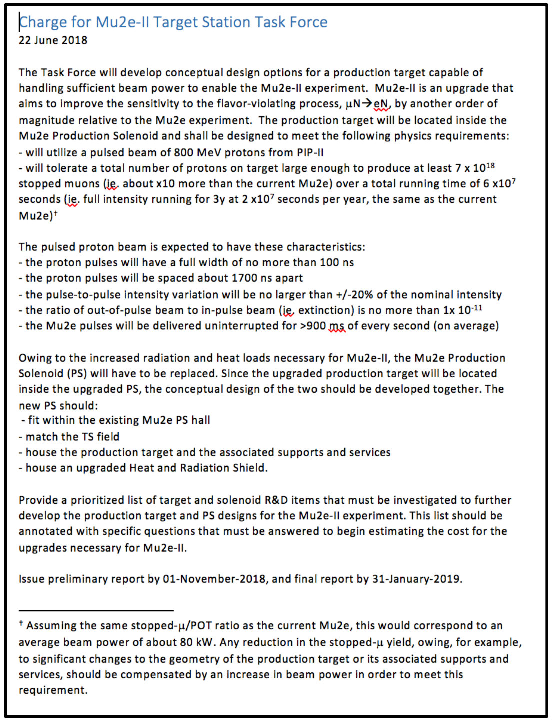
- LDRD proposal in preparation
- Myron Campbell (U. Michigan) Paul Derwent (Fermilab)
- Will measure intrinsic extinction from chopper using PIP2-IT


PIP2-IT at Fermilab

- Important to understand the chopper extinction performance early
  - Relevant for any PIP-II era experiment
- Beam line design may need to incorporate additional extinction capabilities.
  - Resonant AC dipole (a la Mu2e)
  - Stripping of H^- upstream of production target
  - Beam transport studies in progress

Required R&D – Production Target

- Main issue: need to tolerate x10 more power, which brings the power density and radiation damage "beyond state-of-the-art"
- Worked with lab Directorate to establish a Mu2e-II Task Force
  - Pursue integrated approach, target+solenoid+beamline
  - Charge : develop conceptual design options for Mu2e-II target station, provide prioritized R&D plan for target and solenoid
  - Chairs : S. Werkema, B. Zwaska
  - Final report by 31 January 2019



Charge for Mu2e-II Target Station Task Force

22 June 2018

The Task Force will develop conceptual design options for a production target capable of handling sufficient beam power to enable the Mu2e-II experiment. Mu2e-II is an upgrade that aims to improve the sensitivity to the flavor-violating process, $\mu N \rightarrow eN$, by another order of magnitude relative to the Mu2e experiment. The production target will be located inside the Mu2e Production Solenoid and shall be designed to meet the following physics requirements:

- will utilize a pulsed beam of 800 MeV protons from PIP-II
- will tolerate a total number of protons on target large enough to produce at least 7×10^{18} stopped muons (ie. about x10 more than the current Mu2e) over a total running time of 6×10^{7} seconds (ie. full intensity running for 3y at 2×10^{7} seconds per year, the same as the current Mu2e)†

The pulsed proton beam is expected to have these characteristics:

- the proton pulses will have a full width of no more than 100 ns
- the proton pulses will be spaced about 1700 ns apart
- the pulse-to-pulse intensity variation will be no larger than +/-20% of the nominal intensity
- the ratio of out-of-pulse beam to in-pulse beam (ie. extinction) is no more than 1×10^{-11}
- the Mu2e pulses will be delivered uninterrupted for >900 ms of every second (on average)

Owing to the increased radiation and heat loads necessary for Mu2e-II, the Mu2e Production Solenoid (PS) will have to be replaced. Since the upgraded production target will be located inside the upgraded PS, the conceptual design of the two should be developed together. The new PS should:

- fit within the existing Mu2e PS hall
- match the TS field
- house the production target and the associated supports and services
- house an upgraded Heat and Radiation Shield.

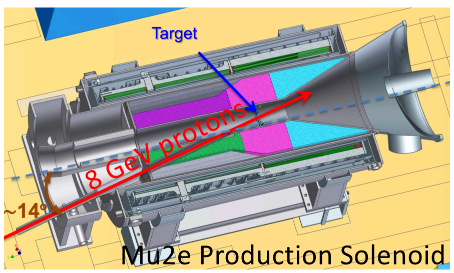
Provide a prioritized list of target and solenoid R&D items that must be investigated to further develop the production target and PS designs for the Mu2e-II experiment. This list should be annotated with specific questions that must be answered to begin estimating the cost for the upgrades necessary for Mu2e-II.

Issue preliminary report by 01-November-2018, and final report by 31-January-2019.

† Assuming the same stopped-μ/POT ratio as the current Mu2e, this would correspond to an average beam power of about 80 kW. Any reduction in the stopped-μ yield, owing, for example, to significant changes to the geometry of the production target or its associated supports and services, should be compensated by an increase in beam power in order to meet this requirement.

Required R&D – Beam delivery

- Main issue: need to steer 0.8 GeV beam to hit the production target
- Internal studies (mu2e-doc-db-16205, 16328) have found solutions
  - Require modifications to various components of target station region
  - Exact solution will depend on details of production target & solenoid
  - Now beginning studies of stripping & secondary extinction options



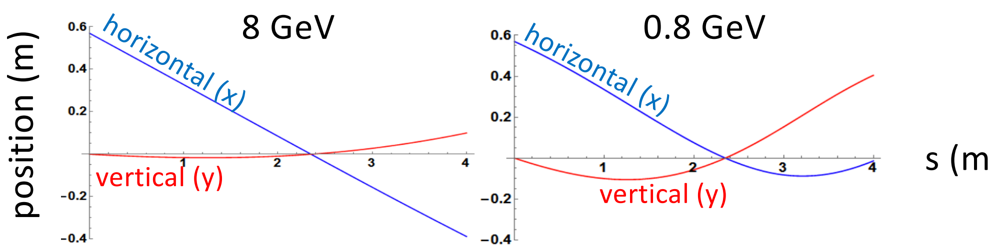


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at =2.35m

TABLE 1. Trajectories for 8 GeV and 800 MeV protons. (target at s=2.35m)

Position	8 GeV (x, y)	8 GeV (x', y')	800 MeV (x,y)	800 MeV (x', y')
s=0 entrance	0.57, 0.0 m	-13.6 °, -1.4°	0.57, 0.0	-11.4, -8.3°
s=2.35 target	0.0, 0.0 m	-13.6°, 1.8°	0.0, 0.0	-9.6°, 10.9 °
s=4m exit	-0.39, 0.08 m	-12.7°, 5.1 °	-0.01, 0.40	10.2 °,11.4 °

Table & Figures from Dave Neuffer

Upgrade Scope and Required R&D

Mu2e-II apparatus

Upgrade Scope and Required R&D

- Hosted Mu2e-II Workshop at ANL, December 2017
  - >70 participants (~15% non-Mu2e)

- Workshop Goals:
  - Summarize experimental challenges
  - Brainstorm ideas for addressing these challenges
  - Enumerate high-priority R&D needs


Mu2e-II Workshop @ ANL, December 2017

Experimental Challenges

Challenges for Mu2e-II apparatus are known:

- Solenoids & collimators: heat & radiation loads
- Target station: convectively cooled production target, HRS, remote handling, proton beam absorber, radiation safety
- Tracker: lower mass, increased charge deposition, beam flash
- Calorimeter: background rates, light yield & SiPM vs dose
- Cosmic Ray Veto: accidental rates, scintillator & SiPM aging
- TDAQ: increased rates and occupancies
- Electronics : radiation tolerance (~3 Mrad, $10^{12} – 10^{13}$ $n_{1MeV\text{-}eq}/cm^2$)
- Beam monitors : rates (STM), sensitivity & feasibility (ExtMon)
- Detector Shielding : accidental rates in CRV, tracker, calorimeter

Mu2e-II Workshop at ANL

Full agenda –
lots of ideas for addressing challenges

Agenda for Mu2e-II Workshop at ANL (08 December 2017)

Time	Speaker	Title
8:30	M. Demarteau	Welcome
8:40	J. Miller	Overview of Experimental Challenges
9:00	S. Werkema	High Priority Accelerator R&D Needs
9:20	D. Brown	High Priority Detector R&D Needs
9:40	B. Tschirhart	Research Funding Overview
10:00		Coffee Break
10:15	D. Neuffer	Wedge Absorber to Increase Muon Acceptance and PIP-II beamline
10:50	K. Lynch	Pion Productin Targets at 800 MeV
11:15	D. Stratakis	Improvements in Performance of the Muon Campus Beamline
11:40	G. Drake	Radiation Tolerance Requirements for Mu2e-II
12:00		Lunch
13:00	S. Miscetti	R&D Challenges and Technical Specifications for Mu2e-II Calorimeter
13:25	R-Y. Zhu	A Very Fast and Radiation Hard BaF2-based Calorimeter
13:50	S. Magill	Nanoparticle Readout for the Fast UV Component of BaF2 Crystals
14:15	M. Minot	Update on LAPPD Pilot Production
14:40		Coffee Break
15:00	L. Xia	High Rate Resistive Plate Chambers for Cosmic Ray Veto
15:25	J. Bono	Design Considerations for Mu2e-II Tracker
15:50	P. Murat	Quantum Dot / Semiconductor-based Scintillators
16:15	J-F. Caron	Mu2e-II Tracker with Molybdenum Sense Wires
16:35	D. Ambrose	Feasibility of Making thinner Straws for Mu2e-II
16:55	K. Byrum	Brainstorming and Discussion
17:30		Adjourn

Workshop agenda

- Summary Report : mu2e-doc-db-15582
  http://mu2e-docdb.fnal.gov/cgi-bin/ShowDocument?docid=15582
- Action Items:
  1) Develop plan for beam delivery
  2) Develop plan for and pursue R&D for 100 kW production target
  3) Engage labs & funding agencies to identify resources for detector R&D
  4) Formulate list of high priority simulations tasks

Next Workshop – Northwestern University

- 29-30 August, 2018

- Goal:
  - Formalize Mu2e-II detector R&D plan by specifying tasks & objectives and identifying interested institutions
- Agenda includes working sessions for each major sub-system
- Finalizing talks, identifying session conveners

To Further Define Mu2e-II Scope:

- Complete Task Force work and then identify resources to pursue the TF recommendations (e.g. for target R&D)
- Measure extinction from chopper using PIP2-IT (e.g. via LDRD)
- Develop conceptual design for beam line – extinction, final focus to target
- Develop conceptual design for production solenoid + heat & radiation shield

- Based on the above can then
  - Estimate Heat & radiation loads on collimators, proton beam stop, muon beam stop, detector materials
  - Estimate Detector occupancies and the effect on backgrounds and sensitivity
  - Estimate Required radiation tolerance of electronics components
  - Understand the radiation safety needs
  - Develop remove & replace plans

- In parallel, identify and initiate high priority detector R&D

Summary

Mu2e-II offers compelling science

- **Provides the deepest probe of CLFV in the foreseeable future**
  - An order of magnitude more sensitive than any other experiment
- **Offers additional insights into New Physics parameter space, independent of Mu2e outcome**
  - If Mu2e discovery: Mu2e-II achieves precision to explore underlying NP operators
  - If Mu2e limits: Mu2e-II extends sensitivity of $R_{\mu e}$ another order of magnitude, Λ_{NP} by factor 2

Mu2e-II can be an important part of FNAL program in ~2030s

- **Science goals can be achieved utilizing an upgraded Mu2e**
  - Experimental concept established using detailed simulation and full sensitivity estimate
  - PIP-II capable of providing required proton beam
  - Leverages significant investment in Mu2e and Fermilab Muon Campus

Punchline

We want Mu2e-II to be a serious part of the next P5 discussion.

For that to occur we need to address the following:

- [x] Community interest
- [x] Compelling science
- [x] Science goal achievable
- [x] Scope understood
- [x] R&D specified

We need the strong support of the laboratory and the funding agencies to complete work necessary to define scope & initiate required R&D studies.

Backup Slides

European Planning

- Spoke with Halina Abramowicz, chair of European Particle Physics Strategy Update
  - Was aware of Mu2e and Mu2e-II and our significant European participation
  - Discussed complementarity of $\mu N \rightarrow eN$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$
  - Commented that a joint white paper would be most useful to committee

- We contacted our colleagues at PSI and JPARC and have organized a joint submission with Mu2e(II), MEG, μ3e, & COMET
  - Will explicitly discuss Mu2e-II as possibility of future FNAL program
  - Will detail possible European contributions to Mu2e-II
  - Mu2e(II) points-of-contact : S. Miscetti (Italy), M. Lancaster (UK)
  - First draft expected in August

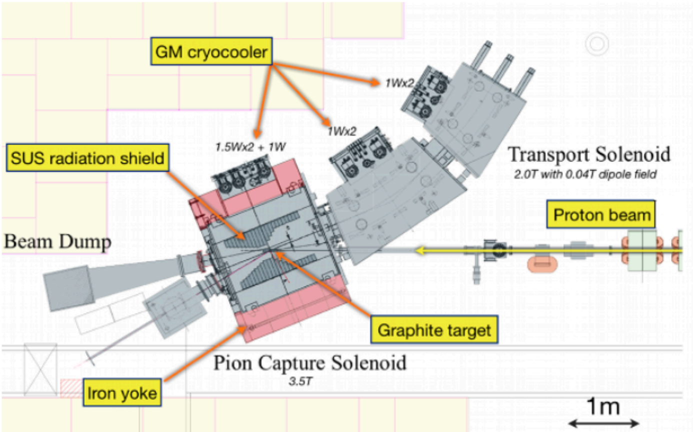
Mu2e-II Background estimates

Category	Source	Events (Al)	Events (Ti)
Intrinsic	μ decay in orbit	0.26	1.19
	Radiative μ capture	<0.01	<0.01
Late Arriving	Radiative π capture	0.04	0.05
	Beam electrons	<0.01	<0.01
	μ decay in flight	<0.01	<0.01
	π decay in flight	<0.01	<0.01
Miscellaneous	Anti-proton induced	--	--
	Cosmic ray induced	0.16	0.16
Total Background:		**0.46**	**1.40**

Table 1: Estimated background yields for the Mu2e-II experiment assuming an aluminum (Al) or a titanium (Ti) stopping target. These studies were performed for a proton beam energy of 1 GeV. The total uncertainty is about 20%. Reproduced from arXiv:1307.1168. Note that, unlike in the case of aluminum, the titanium analysis has not yet been rigorously optimized.

- From Feasibility study (arXiv:1307.1168)
  - Assumes BaF_2 calorimeter, 8 μm thick straw walls for tracker, extinction 10^{-12}, CR veto efficiency of 99.99%, μ-stop/POT is same as Mu2e

Demonstration of technique



- MuSIC facility at RCNP (Japan) measured stop-μ rate (S. Cook, et al., J. Phys. Conf. **408** (2013) 012079)
  - 1 nA of 392 MeV proton
  - 3.5 T solenoid with graphite production target
  - 8.5×10^5 stop-μ / W / s
  - Agrees with simulation estimates <30%