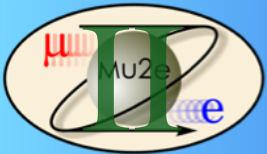


Mu2e-II : next generation muon conversion experiment

Yuri Oksuzian
NuFact 2019



■ What is Mu2e-II?

- ▶ Upgrade to Mu2e that improves $R_{\mu e}$ sensitivity by x10, extending λ_{NP} reach by x2
- ▶ Refurbish as much of Mu2e infrastructure as possible
- ▶ Upgrade Mu2e components to handle higher beam intensity

■ When?

- ▶ 2 years after the end of Mu2e run
- ▶ Start taking data sometimes in 2030 decade
- ▶ Expected 3+1 years of physics run

■ Where?

- ▶ Mu2e will utilize 100kW proton beam from Proton Improvement Plan-II (PIP-II) at Fermilab

- PIP-II will power both DUNE and other experiments like Mu2e-II
- The project received CD-1 approval from the U.S. Department of Energy in July 2018
- PIP-II is planned to deliver beam in the middle of the next decade
- Groundbreaking for the project occurred in March 2019



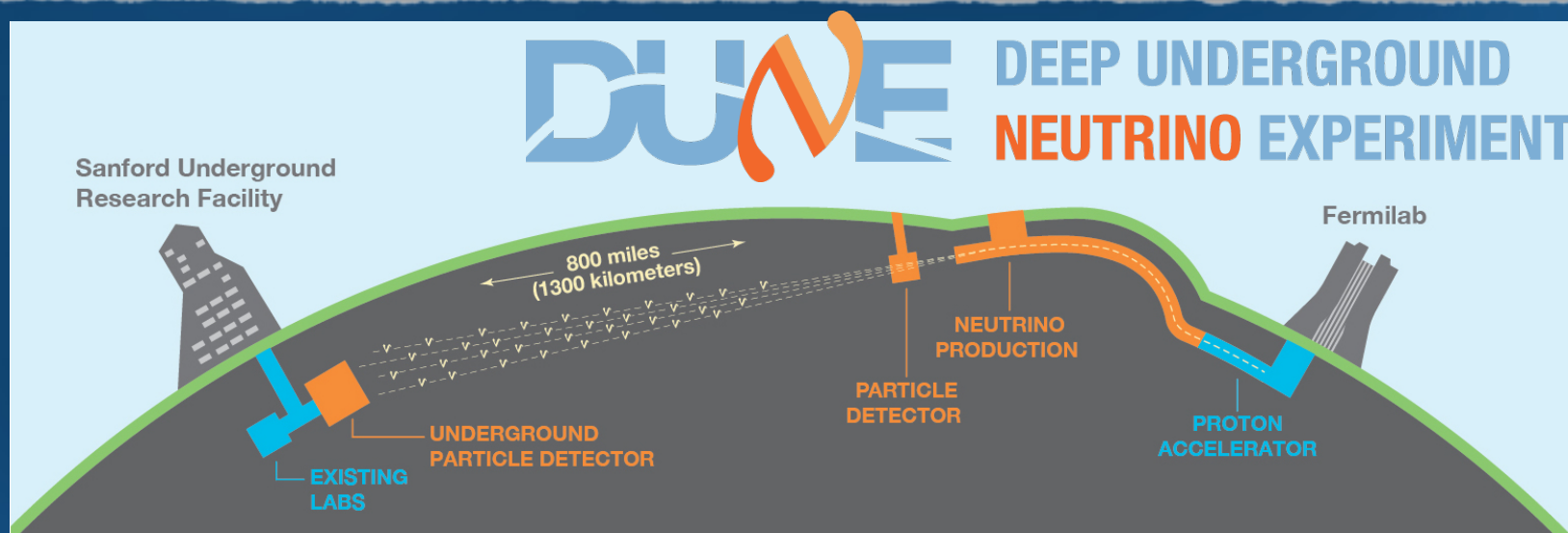
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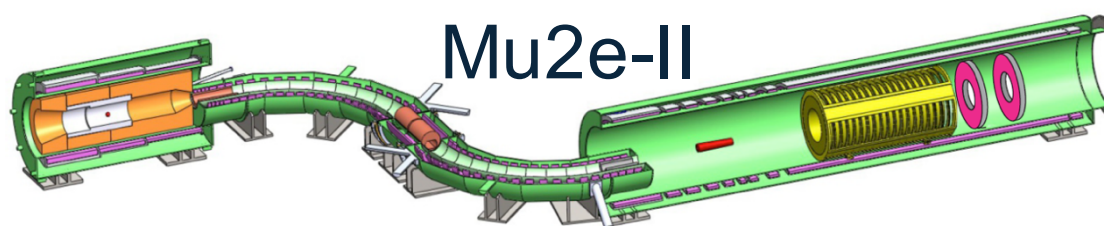
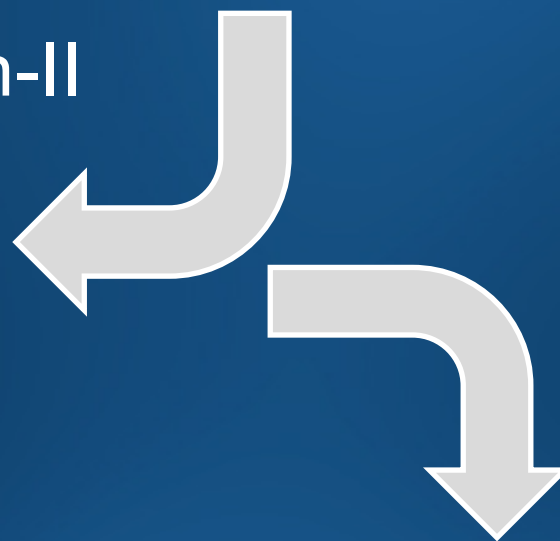
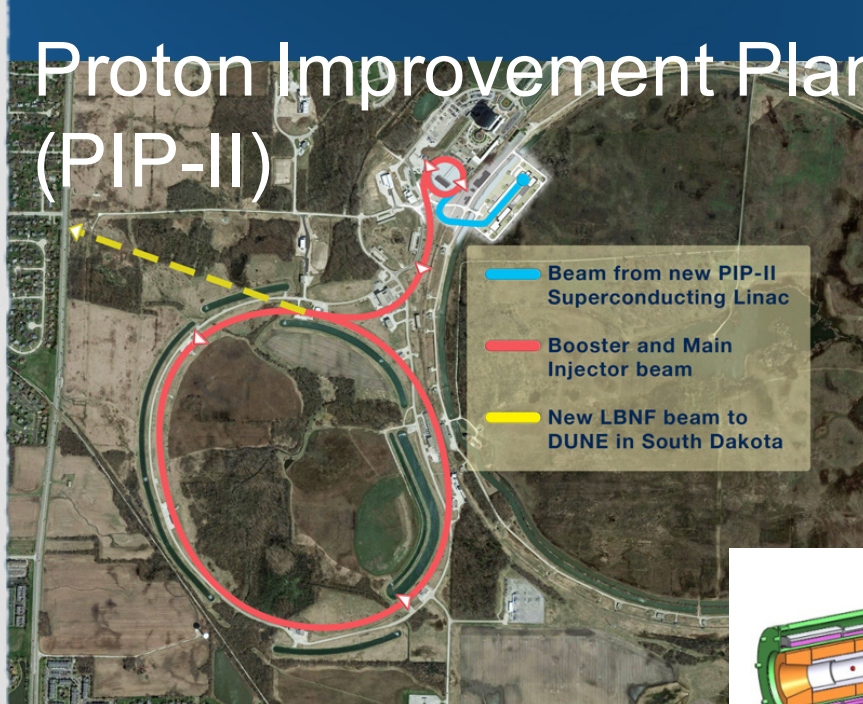
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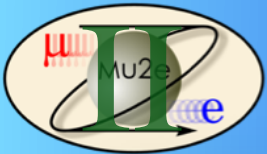
Robert R. Wilson holds a worm he has found while breaking ground for the Main Ring.



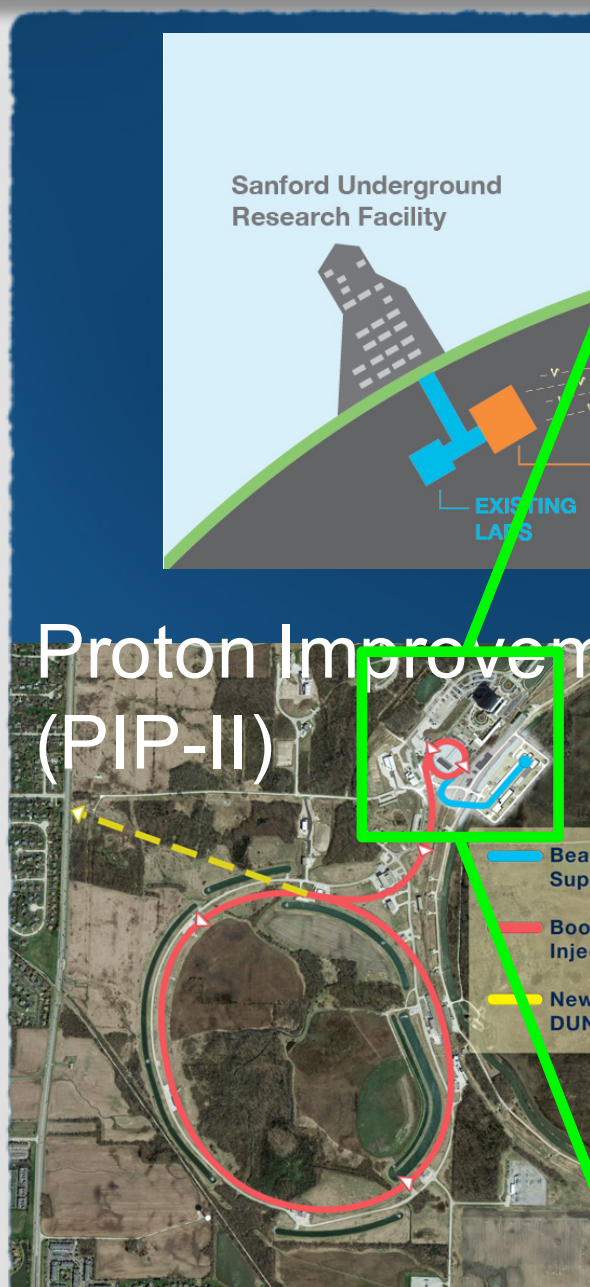
Proton Improvement Plan-II (PIP-II)



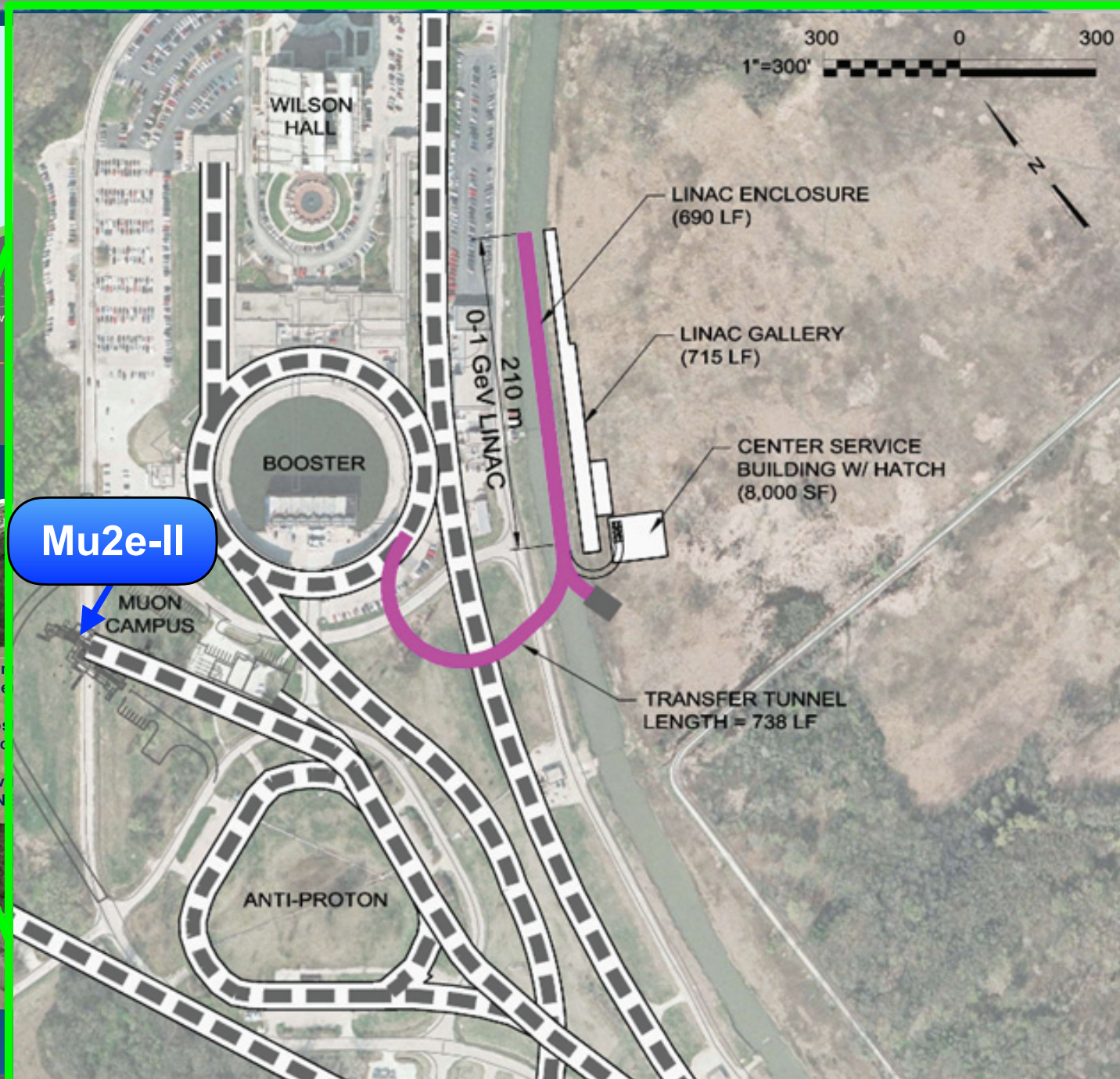
MyeongJae Lee



PIP-II @ Mu2e-II

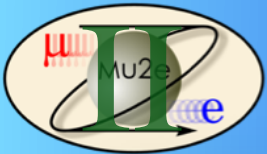


Proton Improvement
(PIP-II)



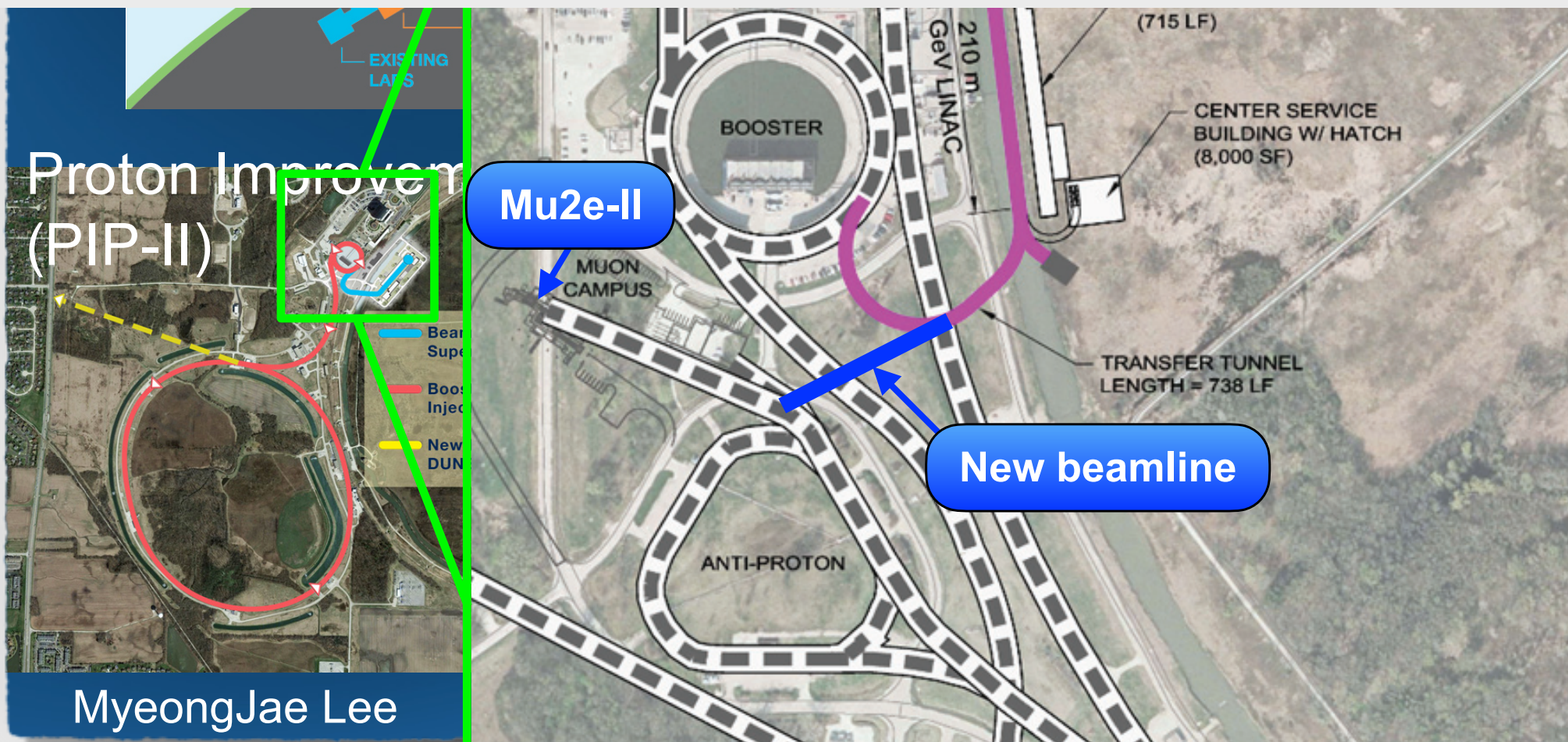
Mu2e-II

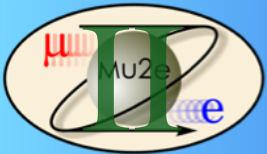
MyeongJae Lee



PIP-II @ Mu2e-II

- PIP-II designed to deliver 800 MeV H- beam to the Booster
 - Capable of running in CW mode with 2 mA average current at 1.6 MW
 - Beam chopper can provide 8 pulses over 50 ns
- Mu2e-II will get a beam at upstream end of transfer line to Booster
 - Need to build a beamline to deliver beam to M4 enclosure





- Mu2e-II is a natural extension of Mu2e
- White Paper arXiv:1307.1168
 - ▶ Estimated backgrounds at Mu2e-II rates, using current simulation framework
- Mu2e-II workshops in:
 - ▶ IF Workshop (ANL, 04/2013)
 - ▶ Snowmass (UM, 08/2013)
 - ▶ Mu2e (FNAL, 02/2016)
 - ▶ Mu2e II Workshop (ANL, 12/2017)
 - ▶ Mu2e-II Workshop (NWU, 08/2018)

arXiv:1307.1168[hep-ex]

Feasibility Study for a Next-Generation Mu2e Experiment

K. Knoepfel³, V. Pronskikh³, R. Bernstein³, D.N. Brown⁵, R. Coleman³, C.E. Dukes⁷,
R. Ehrlich⁷, M.J. Frank⁷, D. Glenzinski³, R.C. Group^{3,7}, D. Hedin⁶, D. Hitlin², M. Lamm³,
J. Miller¹, S. Miscetti⁴, N. Mokhov³, A. Mukherjee³, V. Nagaslaev³, Y. Oksuzian⁷,
T. Page³, R.E. Ray³, V.L. Rusu³, R. Wagner³, and S. Werkema³

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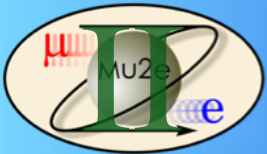
⁵ Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

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.



Expression of Interest

Expression of Interest for Evolution of the Mu2e Experiment[†]

F. Abusalma²³, D. Ambrose²³, A. Artikov⁷, R. Bernstein⁸, G.C. Blazey²⁷, C. Bloise⁹, S. Boi³³, T. Bolton¹⁴, J. Bono⁸, R. Bonventre¹⁶, D. Bowring⁸, D. Brown¹⁶, D. Brown²⁰, K. Byrum¹, M. Campbell²², J.-F. Caron¹², F. Cervelli³⁰, D. Chokheli⁷, K. Ciampa²³, R. Ciolini³⁰, R. Coleman⁸, D. Cronin-Hennessy²³, R. Culbertson⁸, M.A. Cummings²⁵, A. Daniel¹², Y. Davydov⁷, S. Demers³⁵, D. Denisov⁸, S. Denisov¹³, S. Di Falco³⁰, E. Diociaiuti⁹, R. Djilkibaev²⁴, S. Donati³⁰, R. Donghia⁹, G. Drake¹, E.C. Dukes³³, B. Echenard⁵, A. Edmonds¹⁶, R. Ehrlich³³, V. Evdokimov¹³, P. Fabbicatore¹⁰, A. Ferrari¹¹, M. Frank³², A. Gaponenko⁸, C. Gatto²⁶, Z. Giorgio¹⁷, S. Giovannella⁹, V. Giusti³⁰, H. Glass⁸, D. Glenzinski⁸, L. Goodenough¹, C. Group³³, F. Happacher⁹, L. Harkness-Brennan¹⁹, D. Hedin²⁷, K. Heller²³, D. Hitlin⁵, A. Hocker⁸, R. Hooper¹⁸, G. Horton-Smith¹⁴, C. Hu⁵, P.Q. Hung³³, E. Hungerford¹², M. Jenkins³², M. Jones³¹, M. Kargiantoulakis⁸, K. S. Khaw³⁴, B. Kiburg⁸, Y. Kolomensky^{3,16}, J. Kozminski¹⁸, R. Kutschke⁸, M. Lancaster¹⁵, D. Lin⁵, I. Logashenko²⁹, V. Lombardo⁸, A. Luca⁸, G. Lukicov¹⁵, K. Lynch⁶, M. Martini²¹, A. Mazzacane⁸, J. Miller², S. Miscetti⁹, L. Morescalchi³⁰, J. Mott², S. E. Mueller¹¹, P. Murat⁸, V. Nagaslaev⁸, D. Neuffer⁸, Y. Oksuzian³³, D. Pasciuto³⁰, E. Pedreschi³⁰, G. Pezzullo³⁵, A. Pla-Dalmau⁸, B. Pollack²⁸, A. Popov¹³, J. Popp⁶, F. Porter⁵, E. Prebys⁴, V. Pronskikh⁸, D. Pushka⁸, J. Quirk², G. Rakness⁸, R. Ray⁸, M. Ricci²¹, M. Röhrken⁵, V. Rusu⁸, A. Saputi⁹, I. Sarra²¹, M. Schmitt²⁸, F. Spinella³⁰, D. Stratakis⁸, T. Strauss⁸, R. Talaga¹, V. Tereshchenko⁷, N. Tran², R. Tschirhart⁸, Z. Usubov⁷, M. Velasco²⁸, R. Wagner¹, Y. Wang², S. Werkema⁸, J. Whitmore⁸, P. Winter¹, L. Xia¹, L. Zhang⁵, R.-Y. Zhu⁵, V. Zutshi²⁷, R. Zwaska⁸

06 February 2018

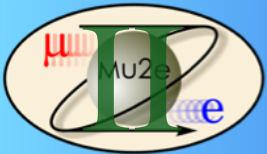
[arXiv:1802.02599](https://arxiv.org/abs/1802.02599)

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 Expression of Interest in 2018
- 130 signatures, 36 institutions
- Positive feedback from Fermilab Physics Advisory Committee: "The PAC endorses the Mu2e-II request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources"



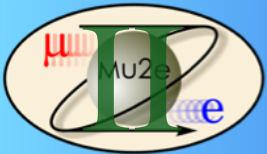


Backgrounds at Mu2e-II

- Mu2e-II assumes 3 years of running
- Total muon stopped muons: $6 \cdot 10^{18}$
- Single event sensitivity: $3 \cdot 10^{-18}$
 - Total background needs to be kept <1 event

Dominant Background Sources

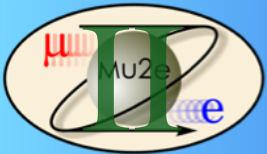
Category	Source	Mu2e	Mu2e-II	Assumption
Intrinsic	μ decay in orbit	0.144	0.26	Improved tracker resolution and thinner ST
Late Arriving	Radiative π capture	0.02	0.04	Extinction $<10^{-11}$
Miscellaneous	Anti-protons	0.04	0	Beam energy below \bar{p} threshold
	Cosmic rays	0.21	0.16	Improved veto efficiency with 3x live-time



Beam requirement for Mu2e-II

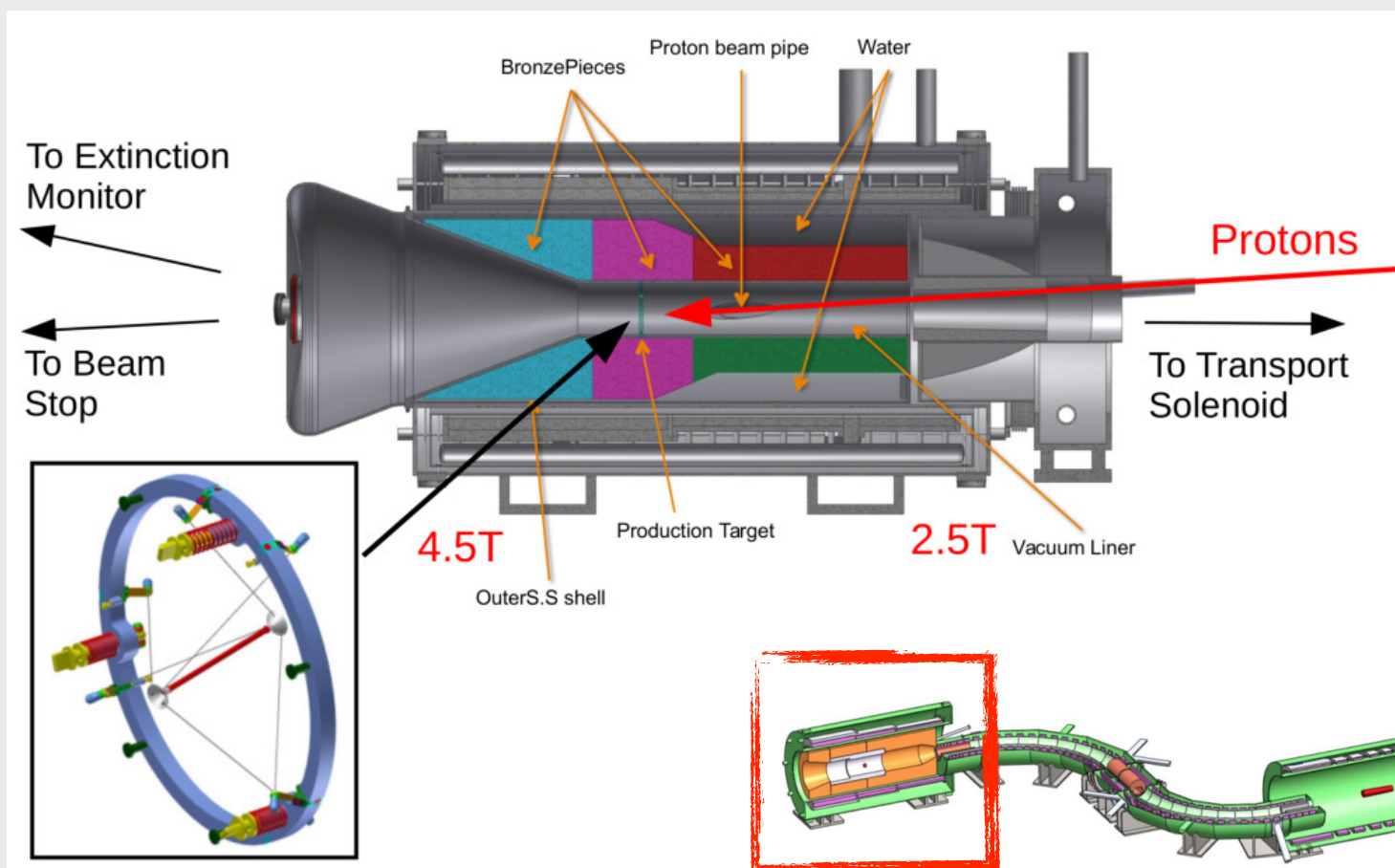
	Mu2e	Mu2e-II	Comments
source	Slow extracted from Delivery Ring	H- direct from PIP-II Linac	Mu2e-II will need to strip H- ions upstream of production target
beam energy (MeV)	8000	800	optimal beam energy 1-3 GeV
Total POT (3+1)y	4.7E+20	4.40E+22	approximate, depends on mu-stop yield
run duration (yr)	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	~ 1700	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

- PIP-II can deliver these requirements to Mu2e-II

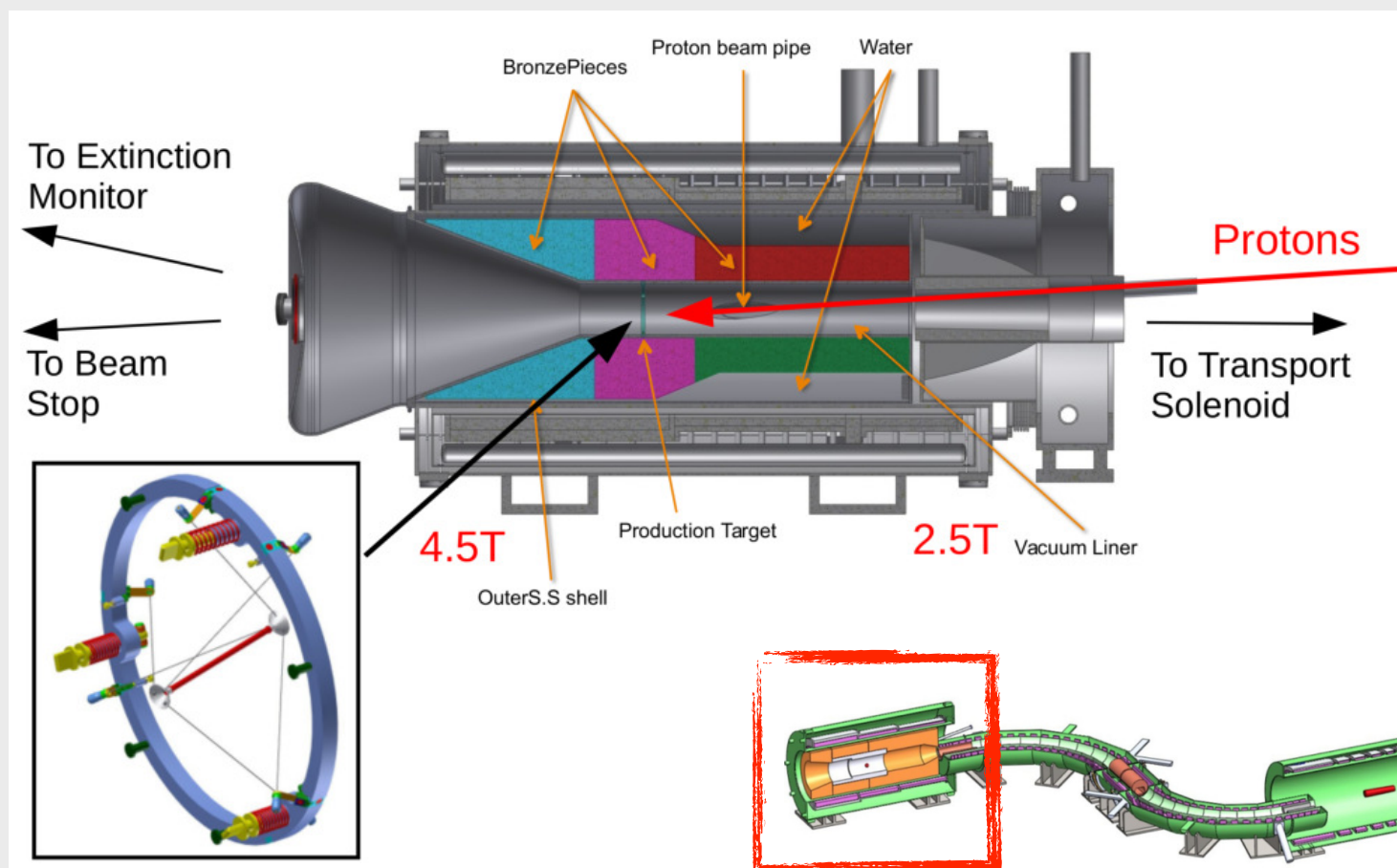


Beam production and transport

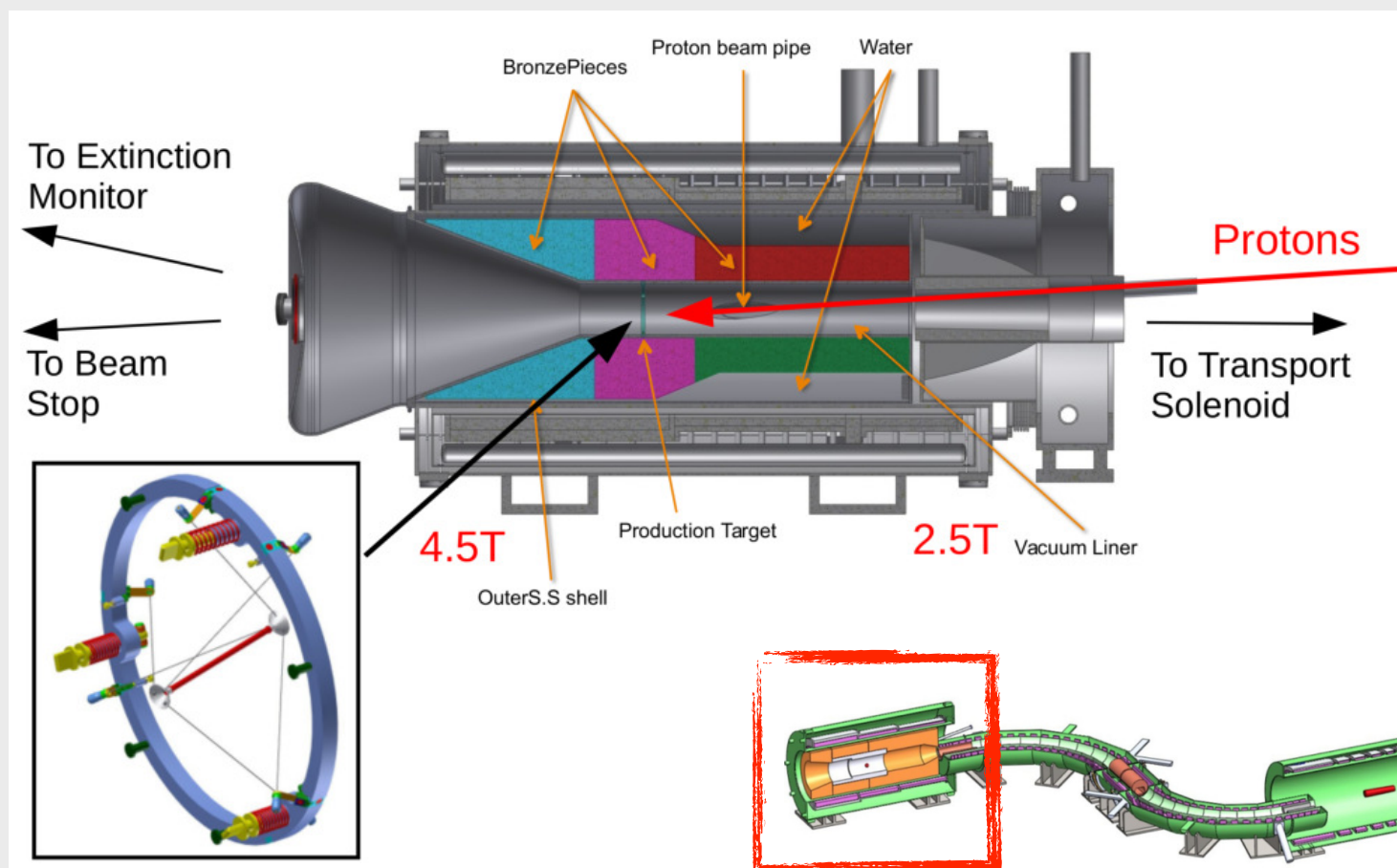
- Need to tolerate x10 beam more power
 - Power density and radiation damage imposes challenges
- Target station:
 - Active cooling (water or helium), liquid target and/or rasterizing the beam on the target face

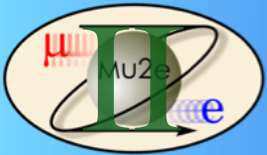


- PS Solenoid: radiation damage and heat load in super-conducting coils
 - Simulations indicate that change of Heat Radiation Shield from brass to tungsten may be adequate
- Remote target handling
- Radiation safety (overburden)



- Aiming the beam on target: 0.8 GeV (Mu2e-II) vs 8 GeV (Mu2e)
 - ▶ Studies suggest that Mu2e-II off-axis beam injection may address the aiming issue
 - ▶ Impacts the position of beam dump and extinction monitor position

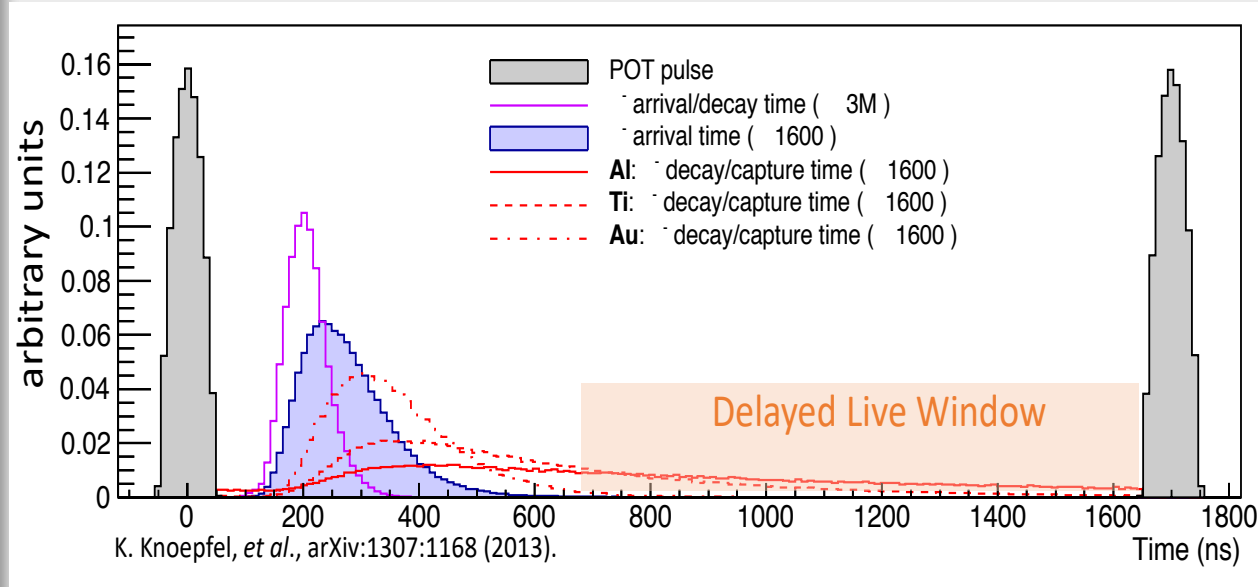
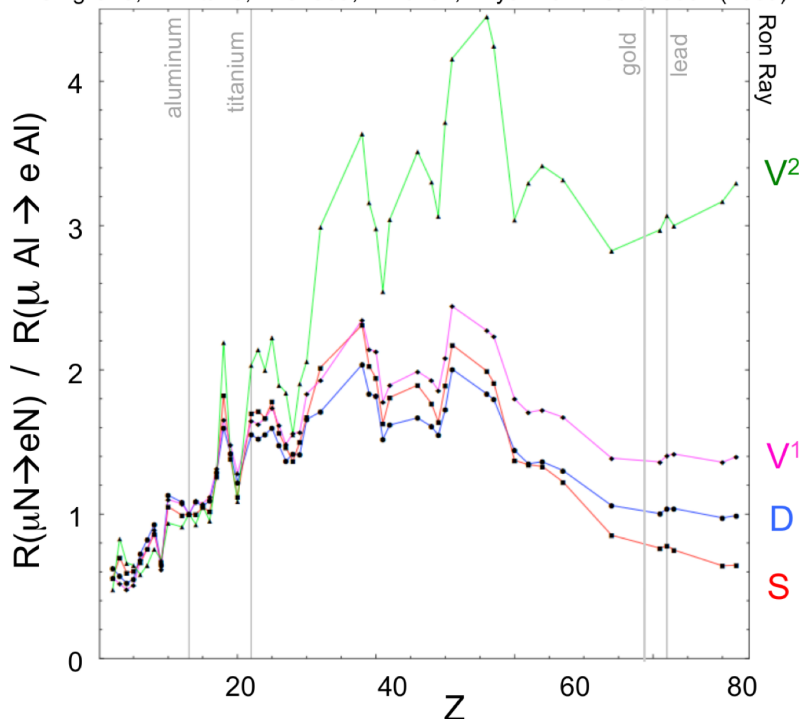


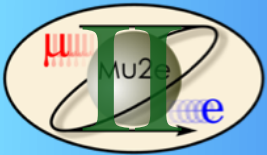


Stopping target

- Mu2e-II will need thinner stopping target, to improve momentum resolution and suppress Decay In Orbit (DIO) background
- If the signal is observed, will change stopping target to probe underlying NP operator
 - ▶ Aluminum & Titanium stopping targets investigated
- Will adjust the micro-bunch length period to accommodate the muon lifetime on Titanium: 329 ns

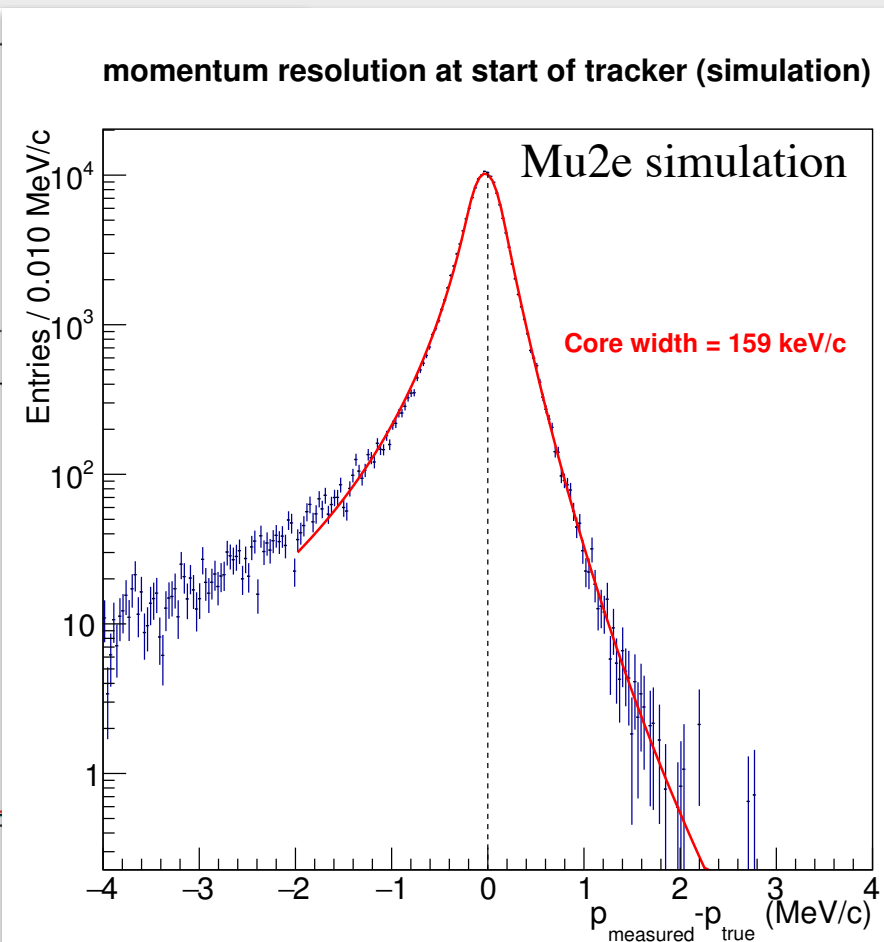
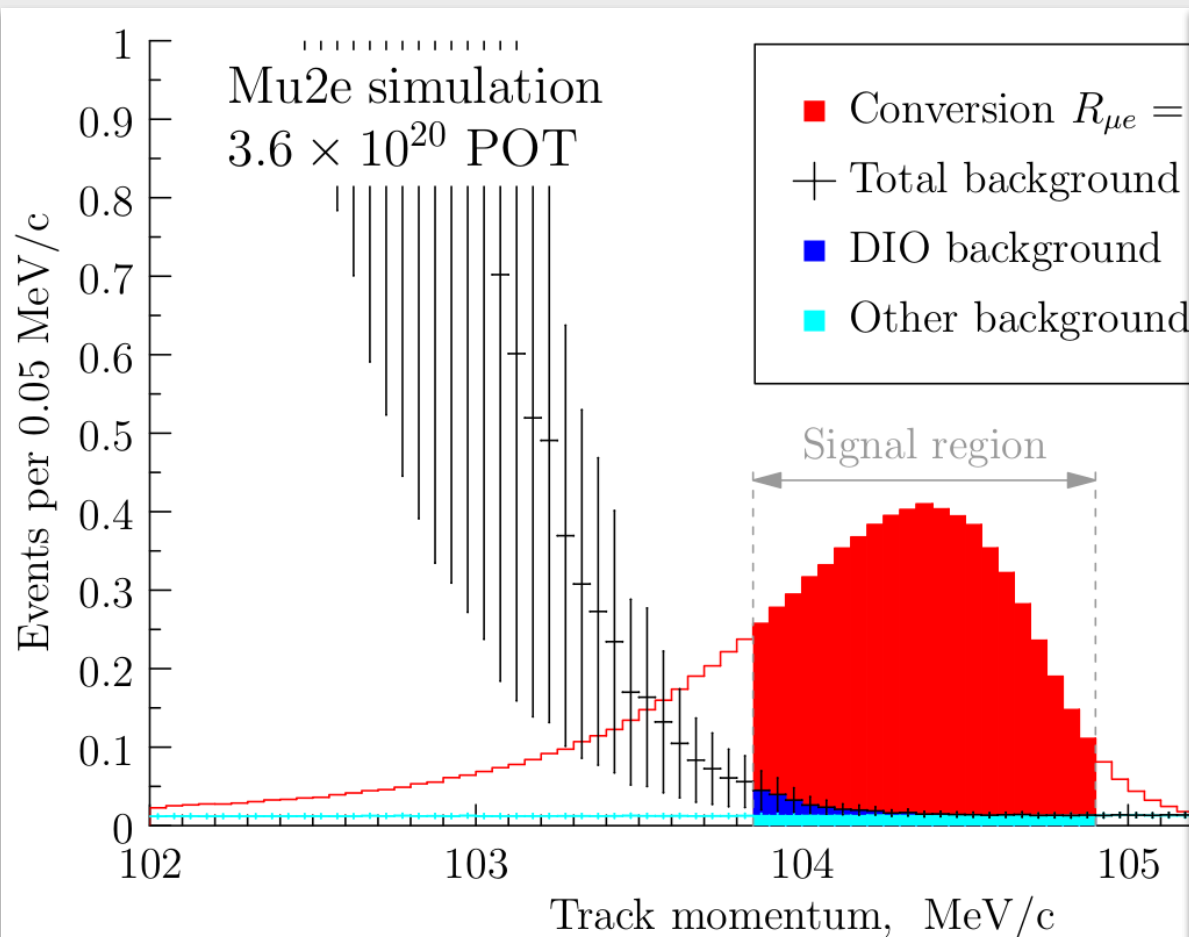
V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)

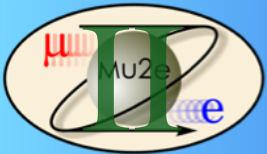




Tracker

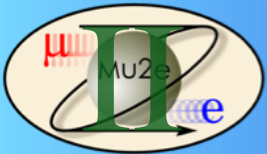
- Mu2e tracker features <200 KeV momentum resolution to suppress DIO background
- DIO scales with the number of stopped muon
- Expected DIO background at Mu2e: 0.14 events





Tracker

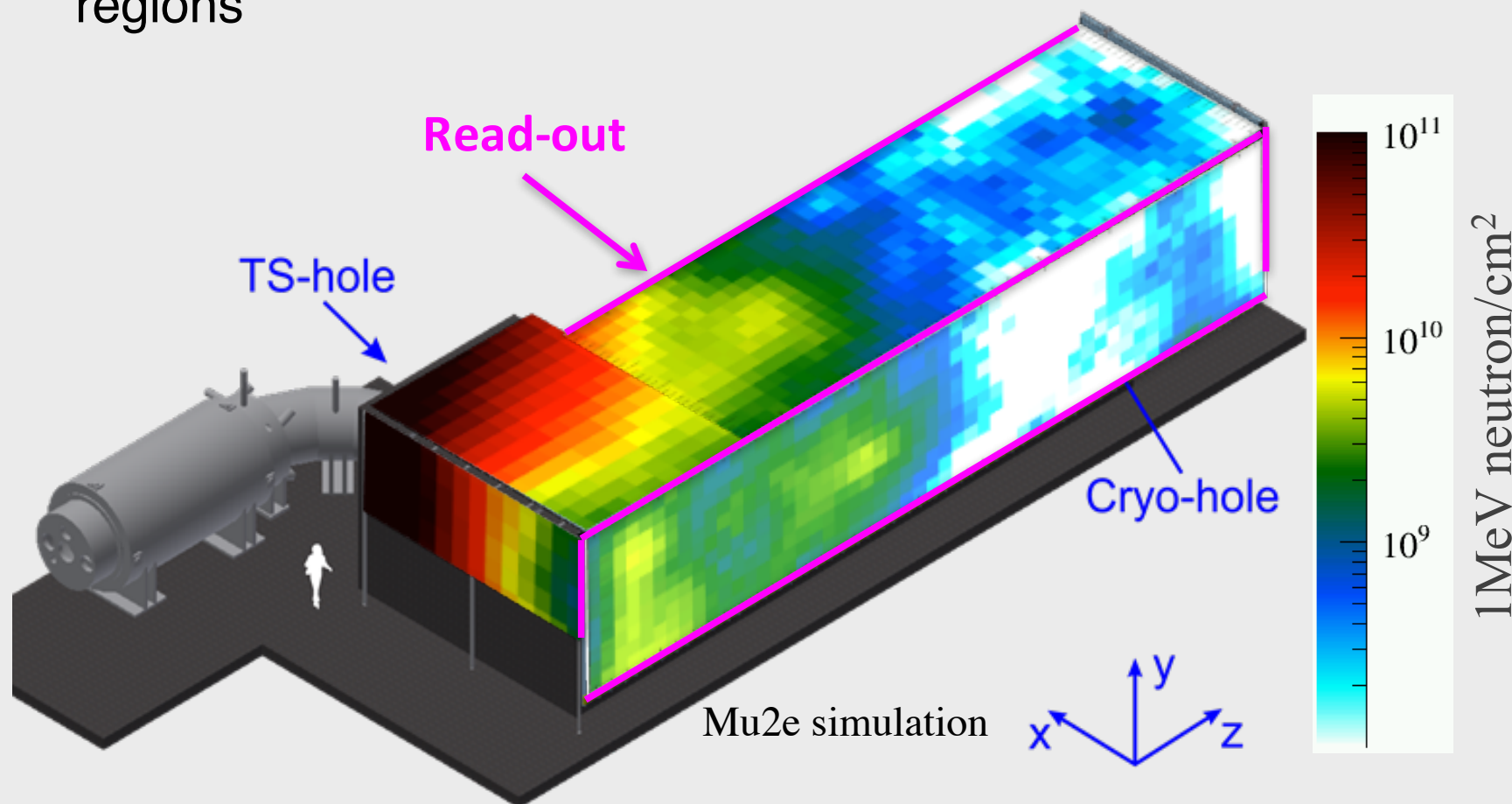
- Mu2e tracker features <200 KeV momentum resolution to suppress DIO background
- DIO scales with the number of stopped muon
- Expected DIO background at Mu2e: 0.14 events
- DIO background would increase 10x at Mu2e-II, linear to the number of stopped muons
- Improve momentum resolution to suppress DIO to 0.26 events by reducing tracker straws thickness: $15 \mu m \rightarrow 8 \mu m$
 - ▶ Additional R&D is required to address challenges with: vacuum tightness, long term stability and large scale production
- Radiation levels would likely exceed the safety factor
 - ▶ Expected 3 Mrad does will damage some commercial off-the-shelf tracker components
 - ▶ Consider using application-specific integrated circuit electronics to handle the radiation levels in the Mu2e-II environment
- Investigate other detector alternatives

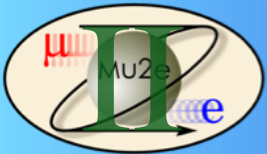


Calorimeter

- Calorimeter is used for PID and cosmic ray suppression
- Fast timing is used to seed tracking and provide a fast trigger
- The radiation doses and rates at Mu2e-II are high for CsI crystals used at Mu2e
- R&D choice has been investigated:
 - ▶ BaF₂ is an excellent upgrade choice, if slow visible scintillation component is suppressed
 - ▶ Suppress the slow scintillation component by doping BaF₂ with Yttrium
 - ▶ Develop photosensor sensitive to the UV component only
 - SiPM with an external filter
 - UV-sensitive photocathodes
 - Solar-blind MCP

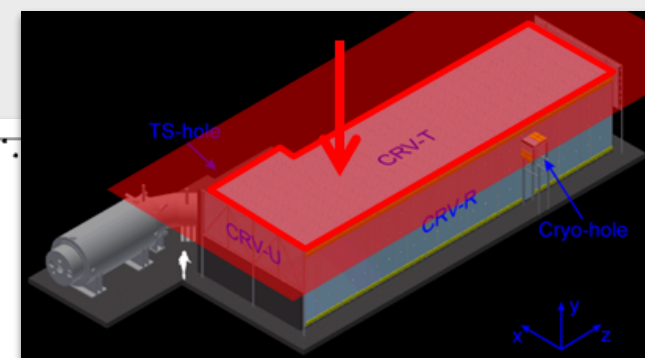
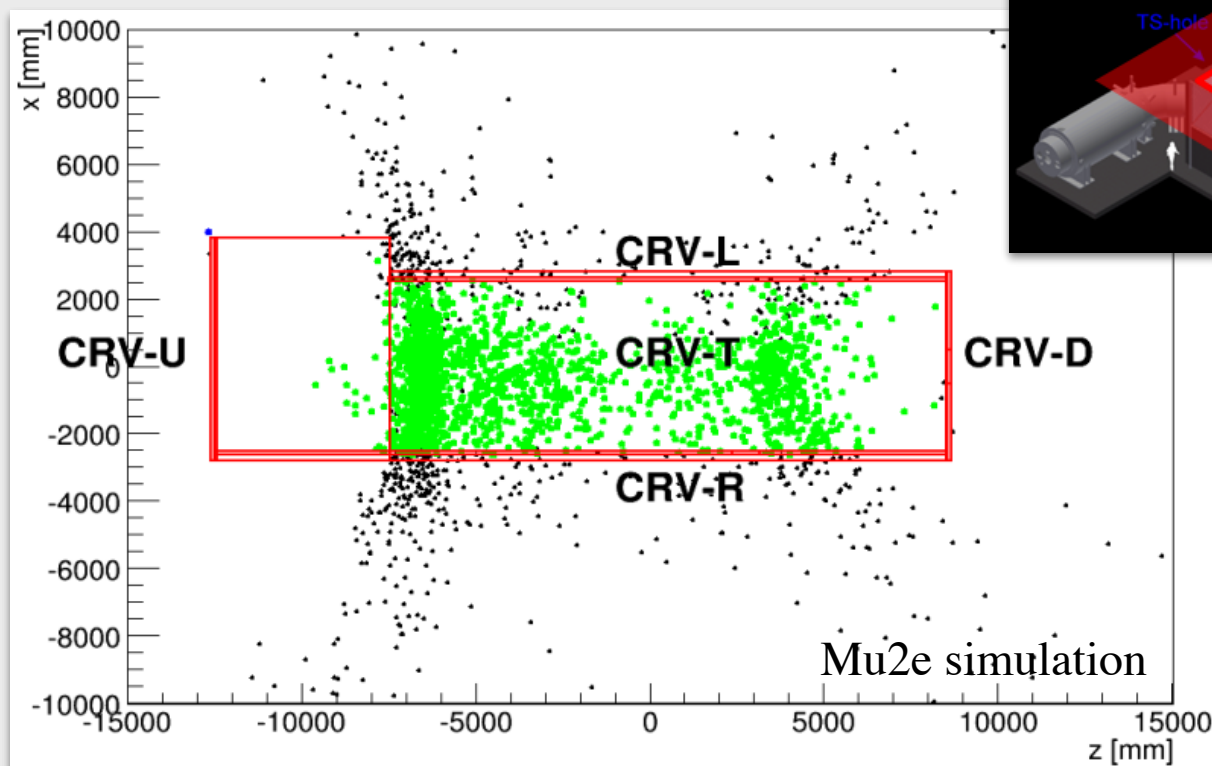
- Higher noise rates impose challenges: higher DAQ rates, rad damage to electronics and induced dead-time by CRV
 - ▶ Consider enhanced shielding
 - ▶ Explore other detector technologies to withstand higher rates in 'hot' regions

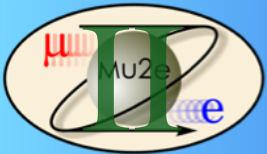




Cosmic Ray Veto (CRV)

- Cosmic ray (CR) background scales with the live-time
- Expected CR background on Mu2e: 0.21 events
- Expected live-time and therefore CR background will be $\sim 3\times$ higher for Mu2e-II
 - Need enhance CRV efficiency in the most critical regions
- The light yield degradation in currently used CRV scintillating counters will impact the CRV performance
 - Large portion of CRV needs to be replaced for Mu2e-II





Summary

- Mu2e-II will advance CLFV search in $\mu \rightarrow e$ channel
 - ▶ Order of magnitude in $R_{\mu e}$ with SES $\sim 3 \cdot 10^{-18}$
- Physics case of Mu2e-II is compelling, regardless of Mu2e's findings
 - ▶ Study underlying physics, if Mu2e sees signal
 - ▶ Extend the sensitivity reach, if Mu2e doesn't observe New Physics
- Mu2e-II has a support from muon physics community and Fermilab's PAC
- Broad R&D program has been identified
 - ▶ No showstoppers
- If approved, Mu2e-II expects to start data taking in the first half of 2030.