Production Target Requirements for the Mu2e-II Experiment

Kevin Lynch

For the Mu2e Collaboration

FNAL

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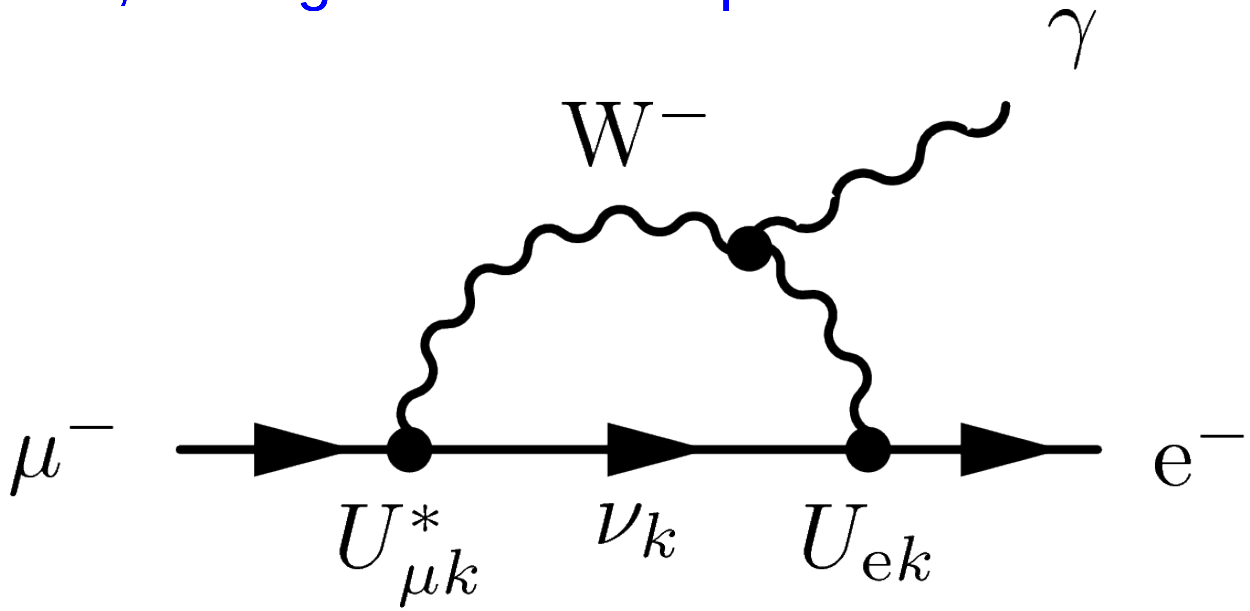
Mu2e is a search for charged lepton flavor violation with *discovery potential*

Although it has never been observed, we know that cLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.

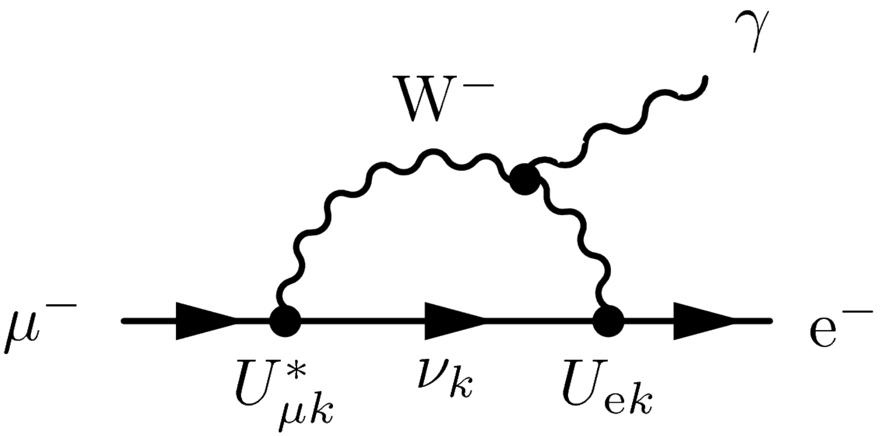


However, the predicted SM rates are unobservably small:

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{k=2,3} U^*_{\mu k} U_{ek} \frac{\Delta m^2_{1k}}{M^2_W}\right|^2 < 10^{-54}$$

This is a good news/bad news story

First, the bad news: we'll never observe this SM process!



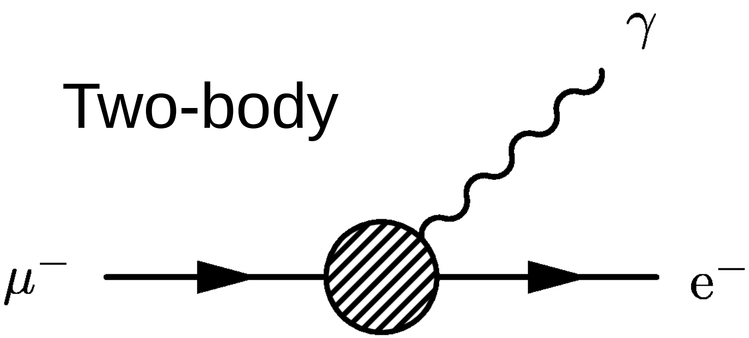
Now, the good news: we'll never observe this SM process!

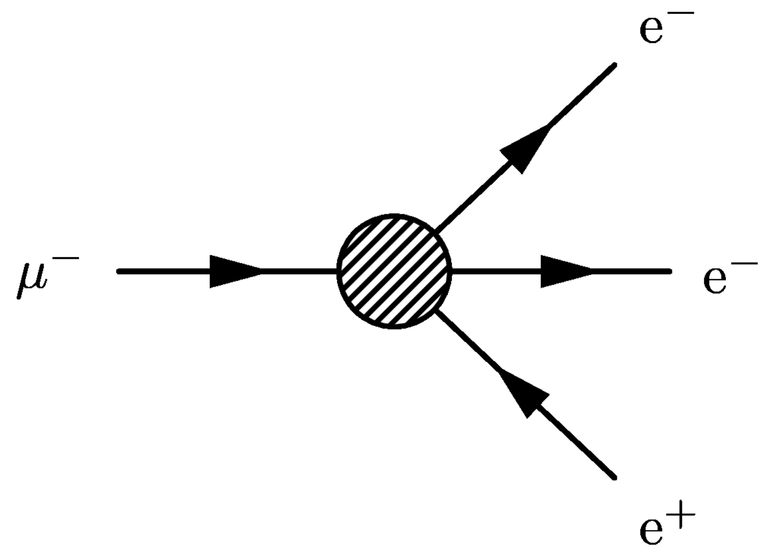
Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!

There are three powerful signatures of CLFV in the muon sector

$$\mu^+ \to e^+\gamma$$

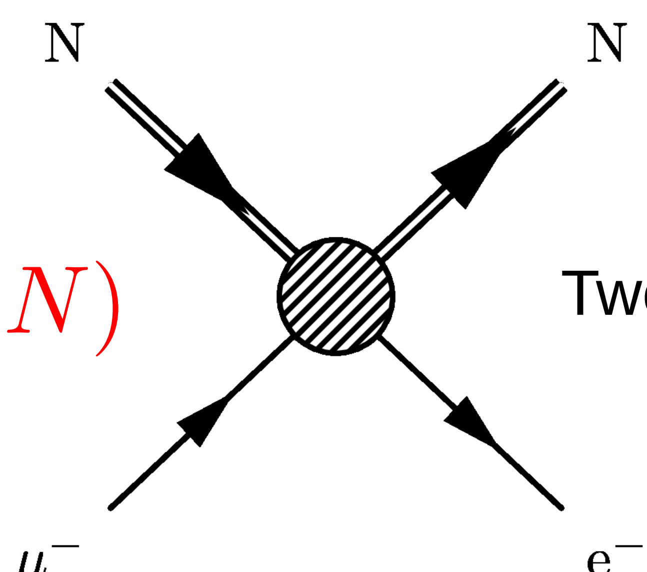
Two-body





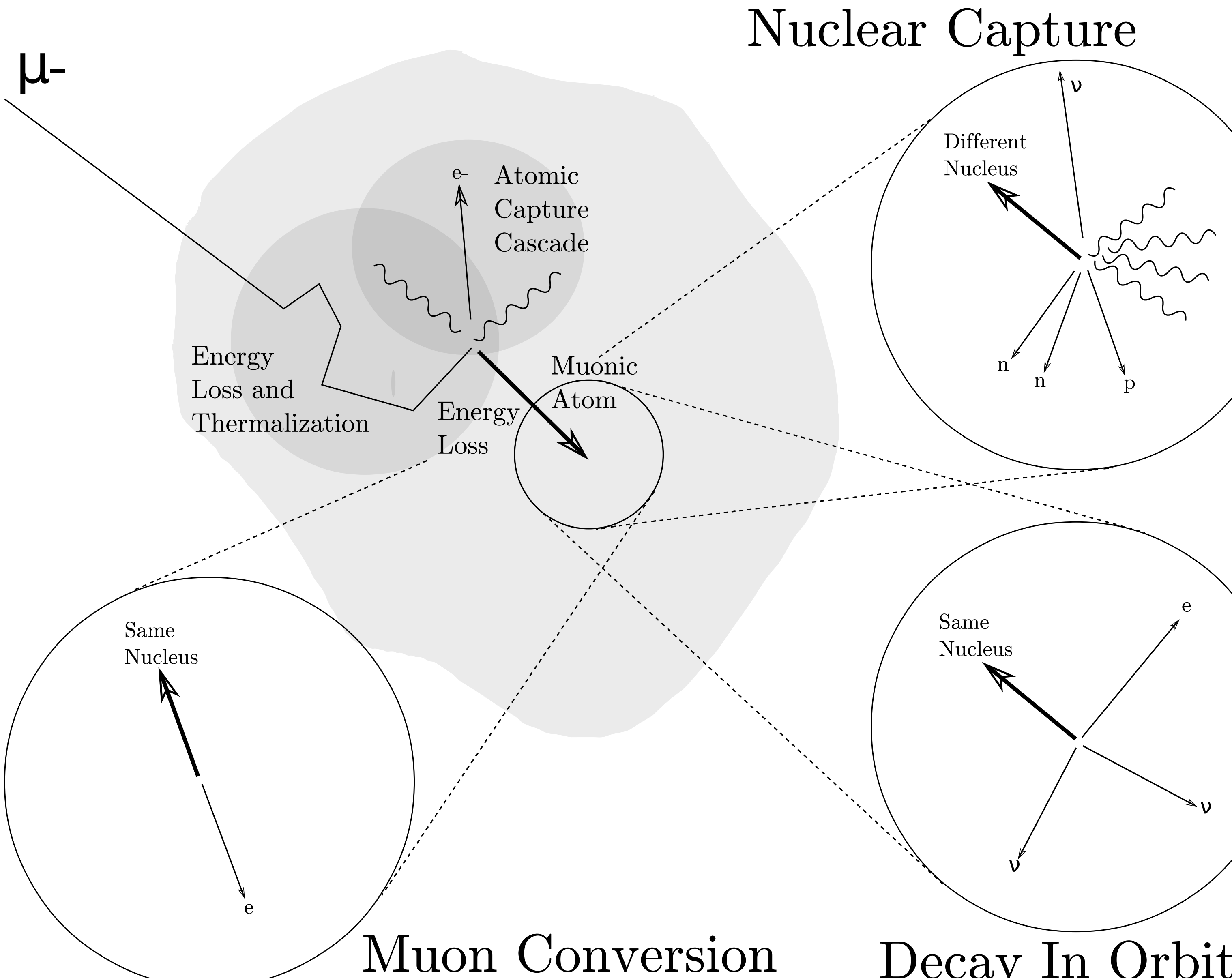
$$\mu^+ \to e^+e^+e^-$$

$$\mu^- A(Z,N) \to e^- A(Z,N)$$

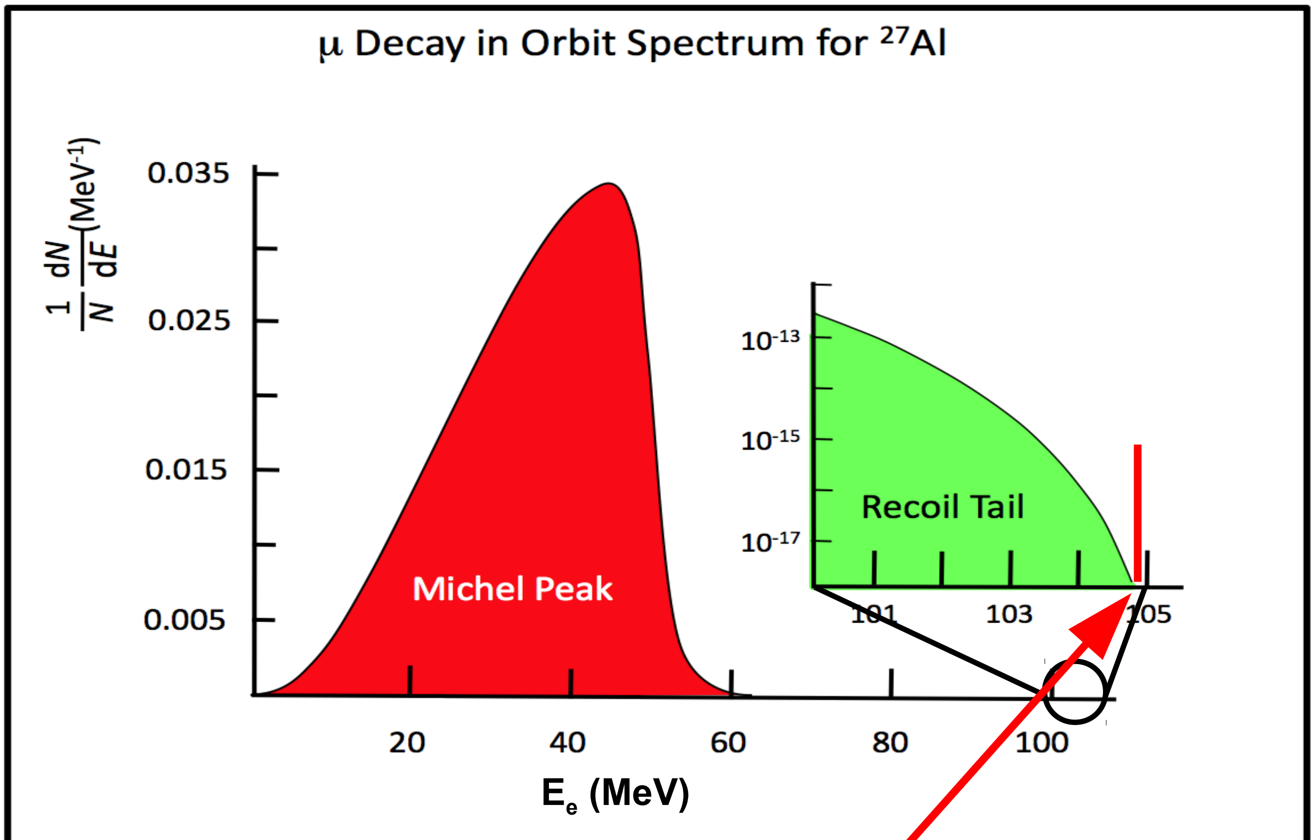


Two-body

Negative muons are "just" heavy electrons, so they also do everything electrons do!



This is our advantage: conversion is kinematically distinct from the background



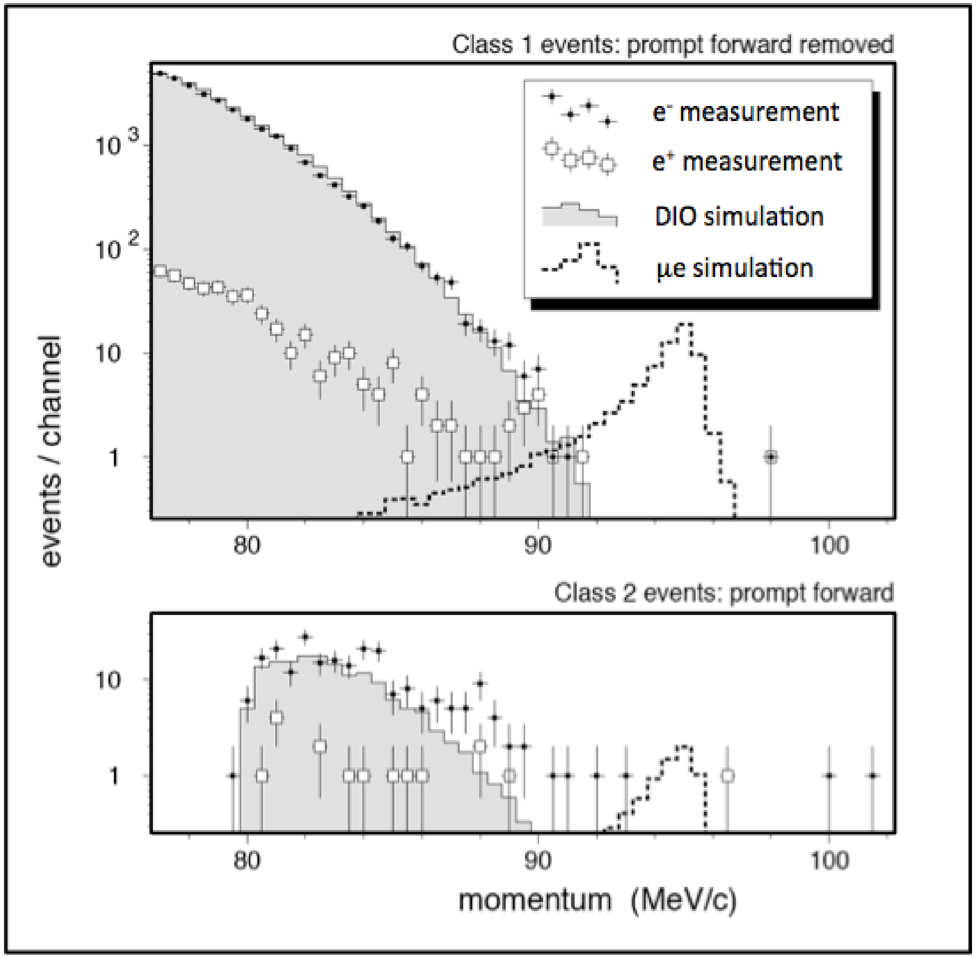
$$\mu^- A(Z,N) \rightarrow \mathrm{e}^- A(Z,N)$$

Our signal is a mono-energetic electron at 105 MeV, above the background tail!

Current conversion limits come from SINDRUM II at PSI

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

$$R_{\mu e} = \frac{\Gamma\left(\mu^- A \to e^- A\right)}{\Gamma\left(\mu^- A \to \nu_\mu A'\right)}$$



The current limit is measured on a gold target:

$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

Mu2e will improve on this limit by four orders of magnitude.

There is clear future value in conversion experiments, whether they see a signal or not

If we see no signal

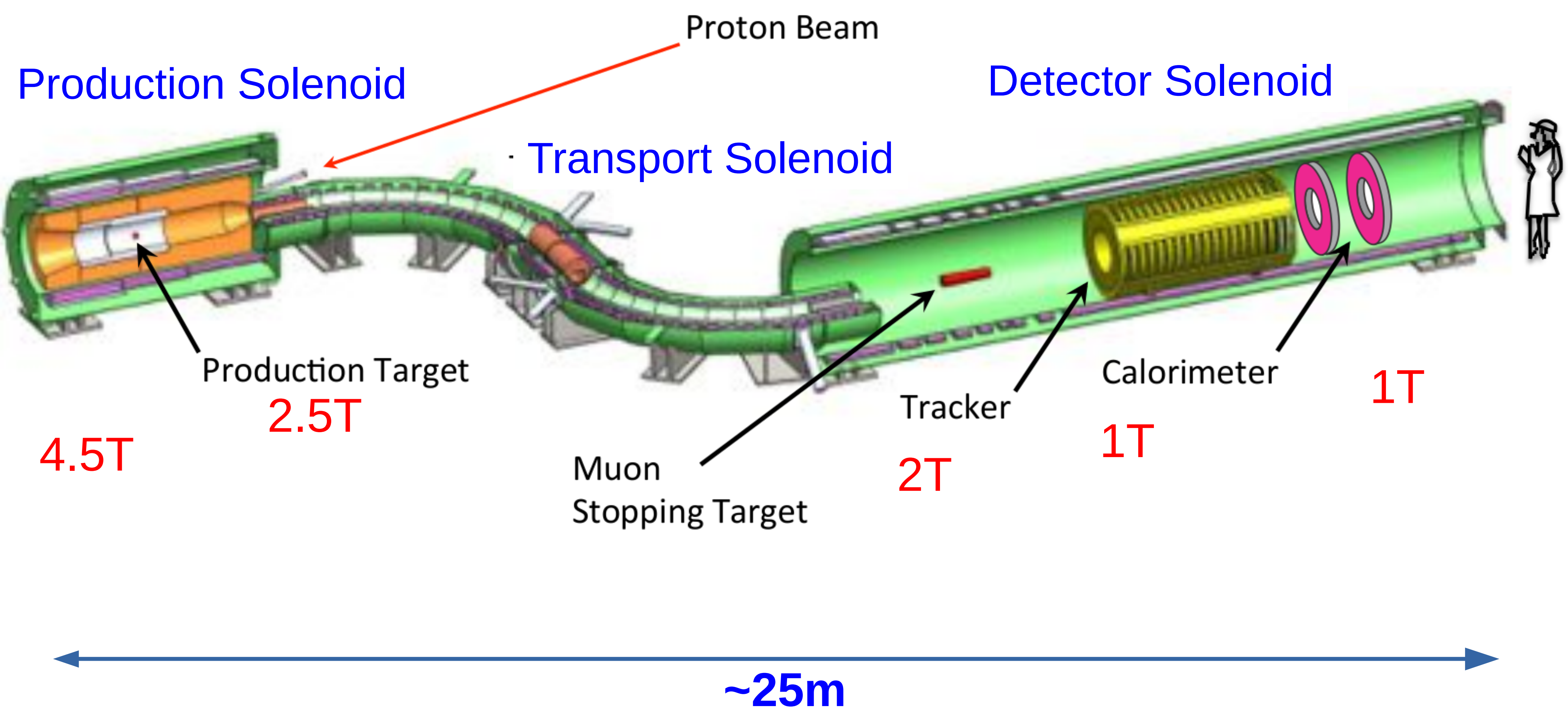
- Significant model space will be ruled out
- Significant background reductions will be needed to strengthen exclusion limits

If we do see a signal

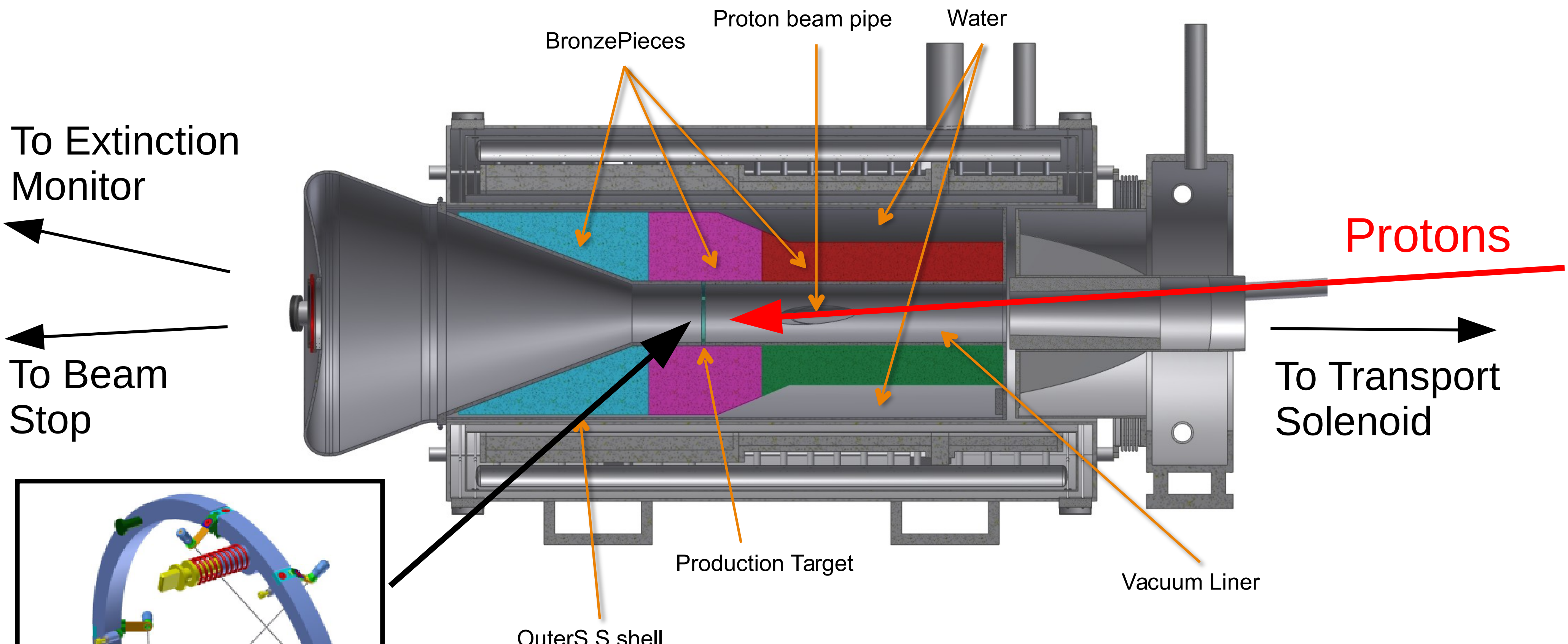
- CLFV will be unambiguously confirmed
- Different target materials can be used to determined the structure of the new amplitudes

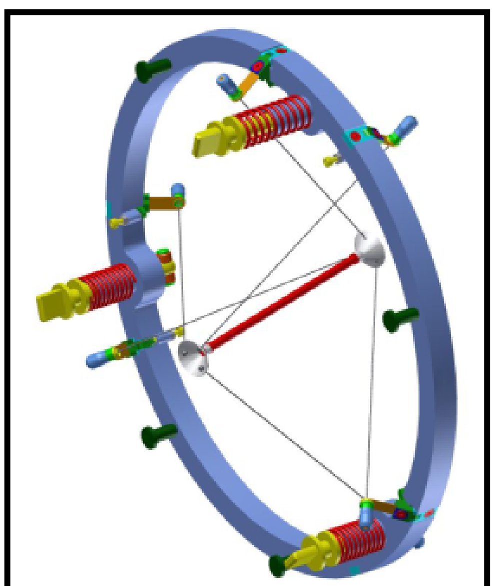
Mu2e-II can gain another order of magnitude reach with modest improvements to the experiment, and the beam power improvements from PIP-II

The Mu2e apparatus separates the production of muons and our observations of their decays



The production solenoid produces a backward beam to further reduce prompt backgrounds

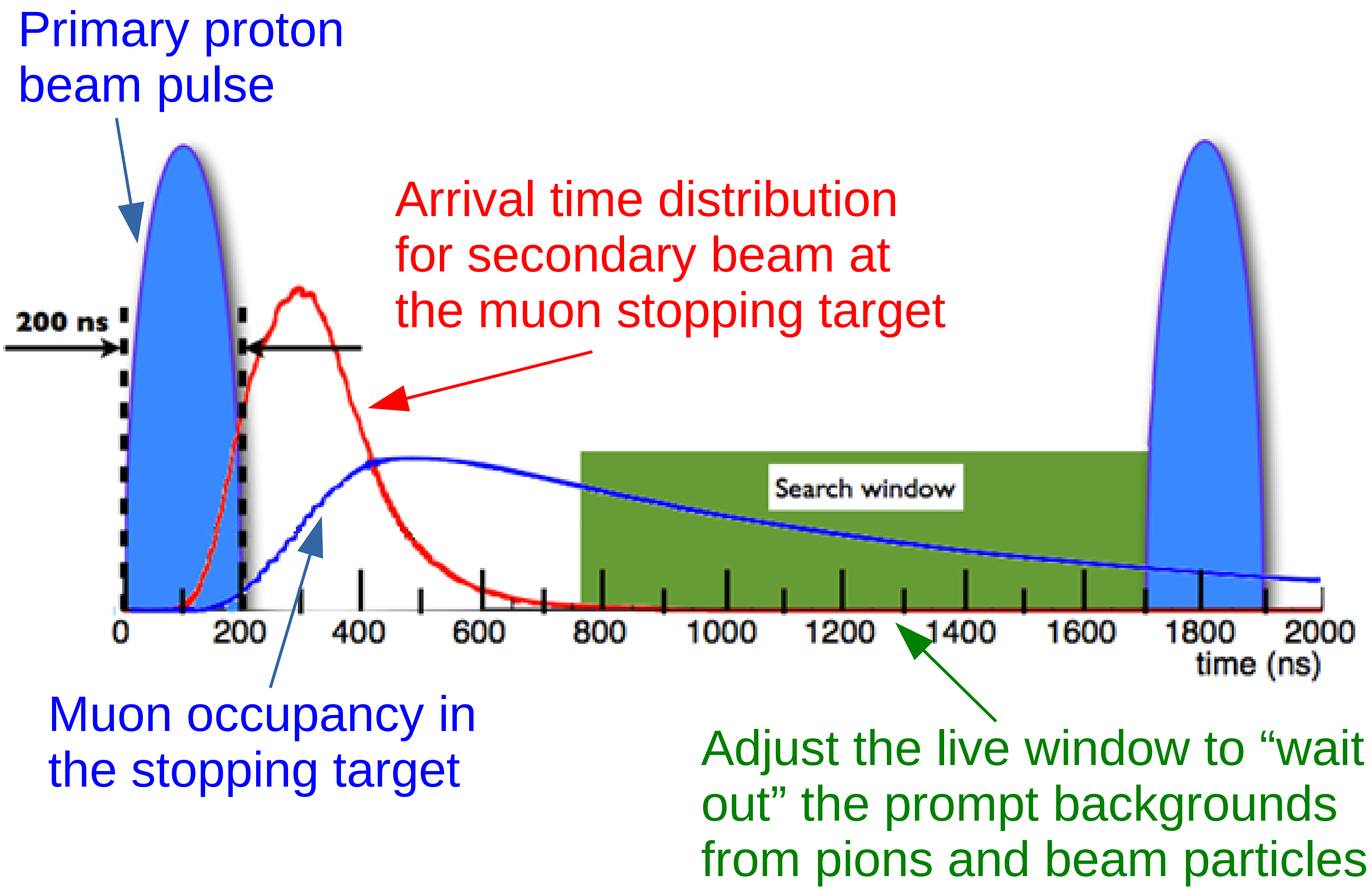




The radiation cooled tungsten production target is about the size of a pencil

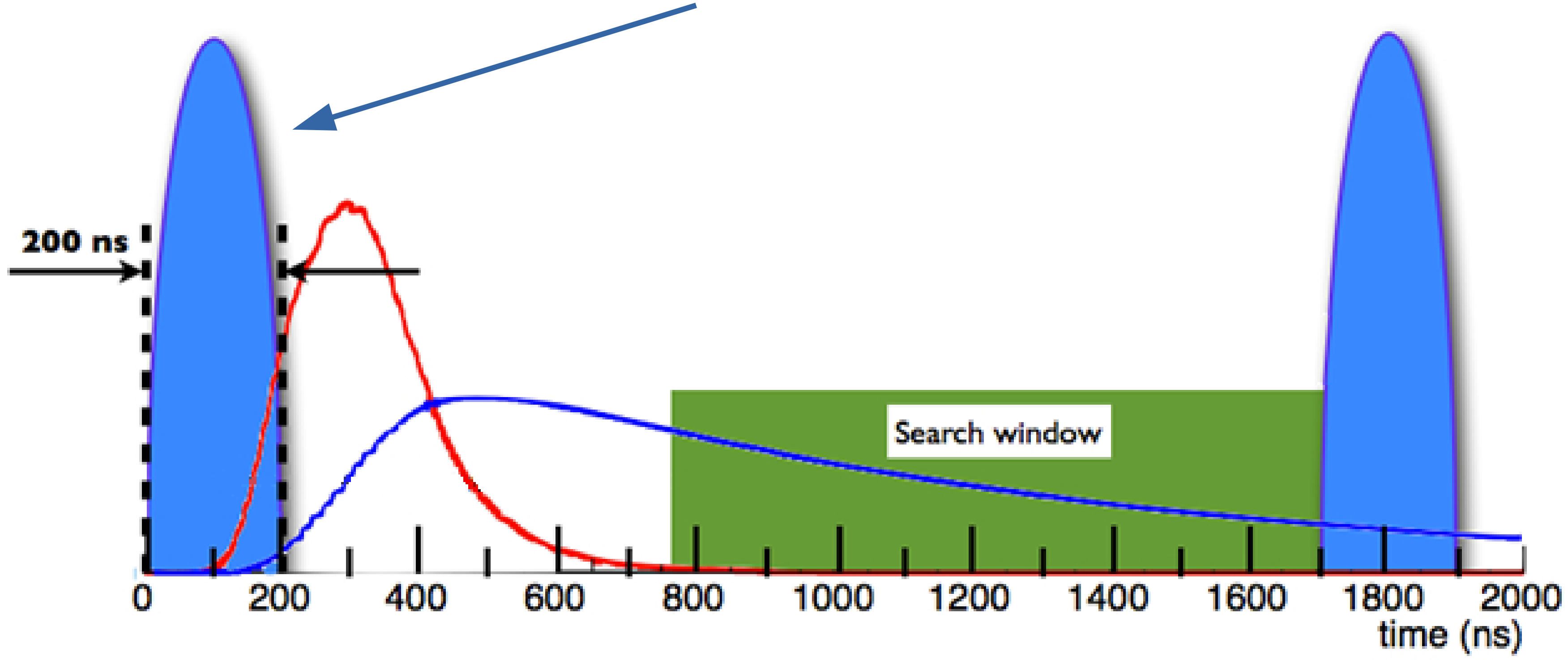
A bronze Heat and Radiation Shield (HRS) protects the superconducting coils from heat and radiation damage

Prompt backgrounds can be reduced with a pulsed beam structure

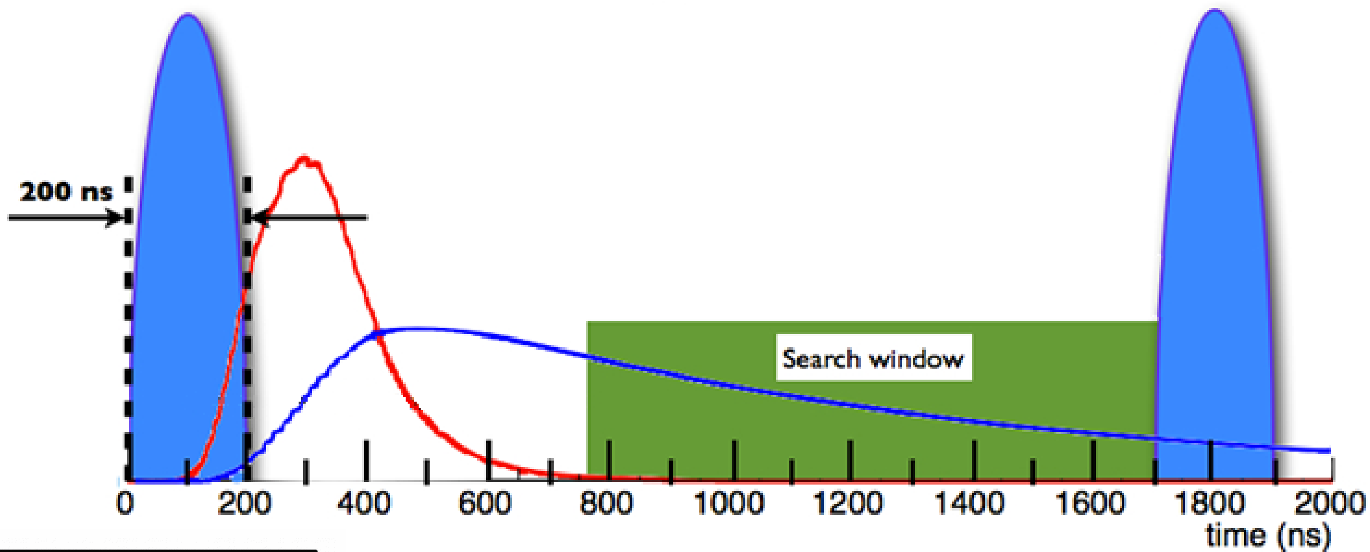


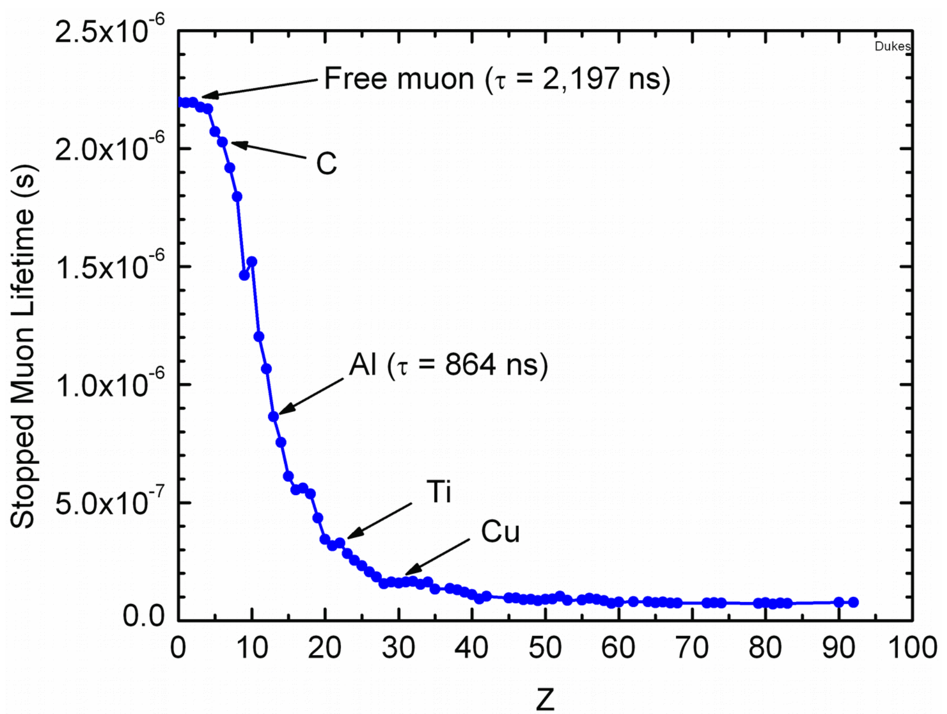
The duration of the prompt backgrounds depends on the width of the proton pulse

Mu2e-II would prefer a 100ns wide proton pulse, with controllable and steady intensity (±10% or better).



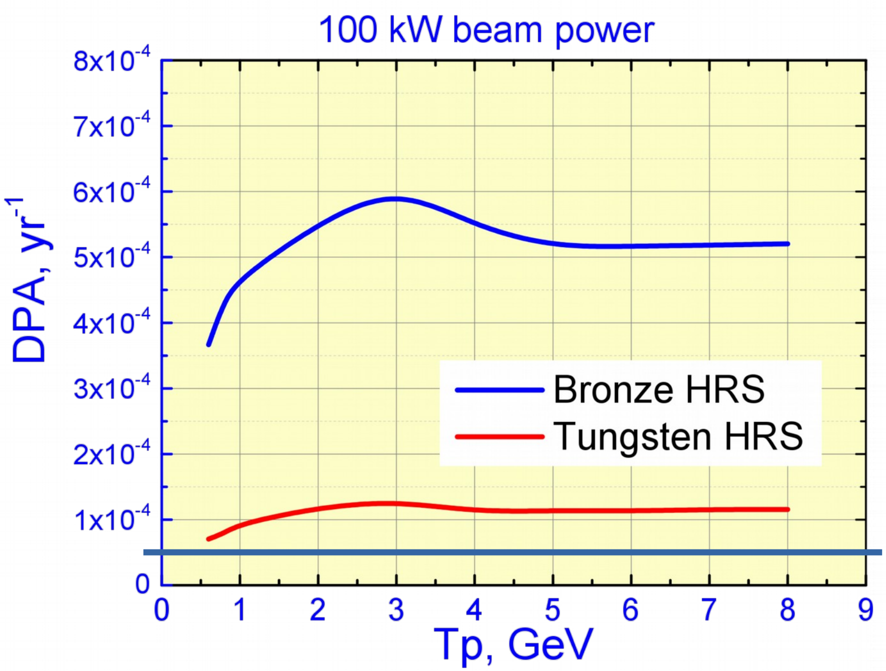
Ideally, the inter-pulse spacing would be variable, with high duty factor

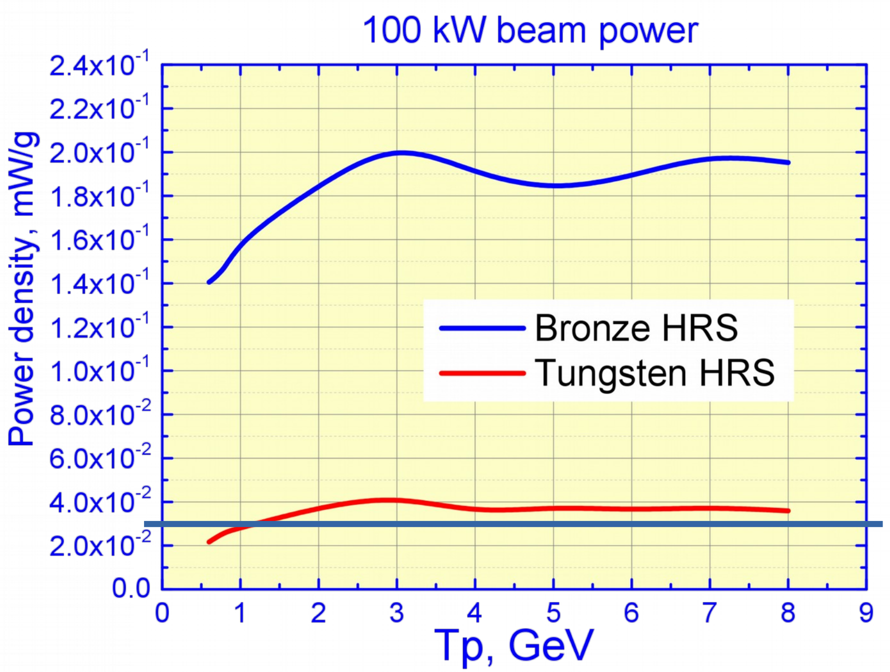




The optimal inter-pulse spacing is about two muon lifetimes in the muon stopping target, which varies by target material …. and we would like to be able to vary the pulse spacing in the range 500-2000ns.

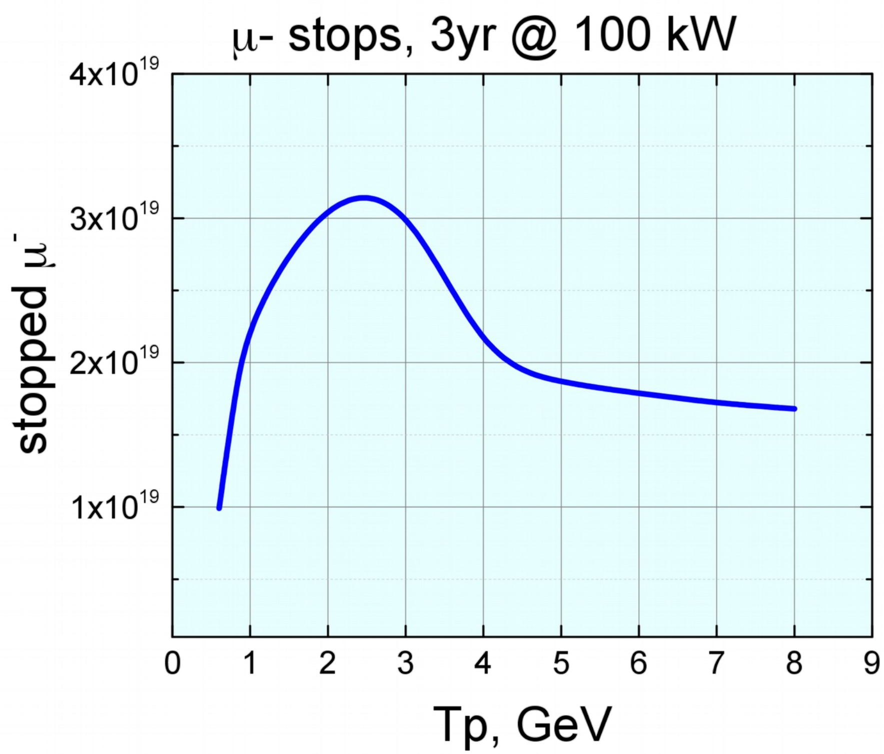
Mu2e-II would prefer a beam energy between 1 and 3 GeV

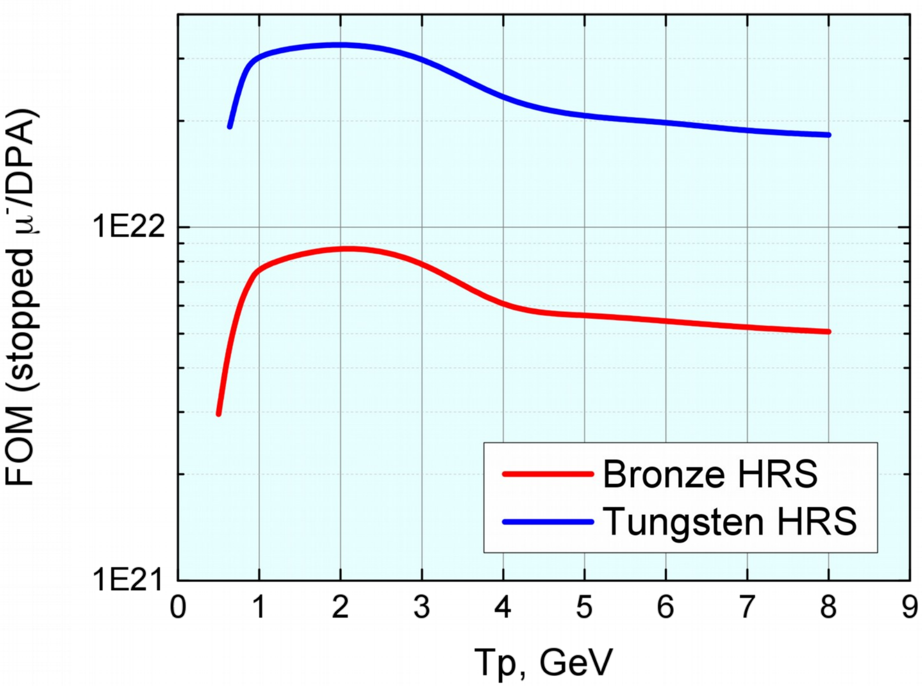




For fixed beam power, annealable radiation damage to the superconductor and deposited power are relatively flat functions of the proton energy ….

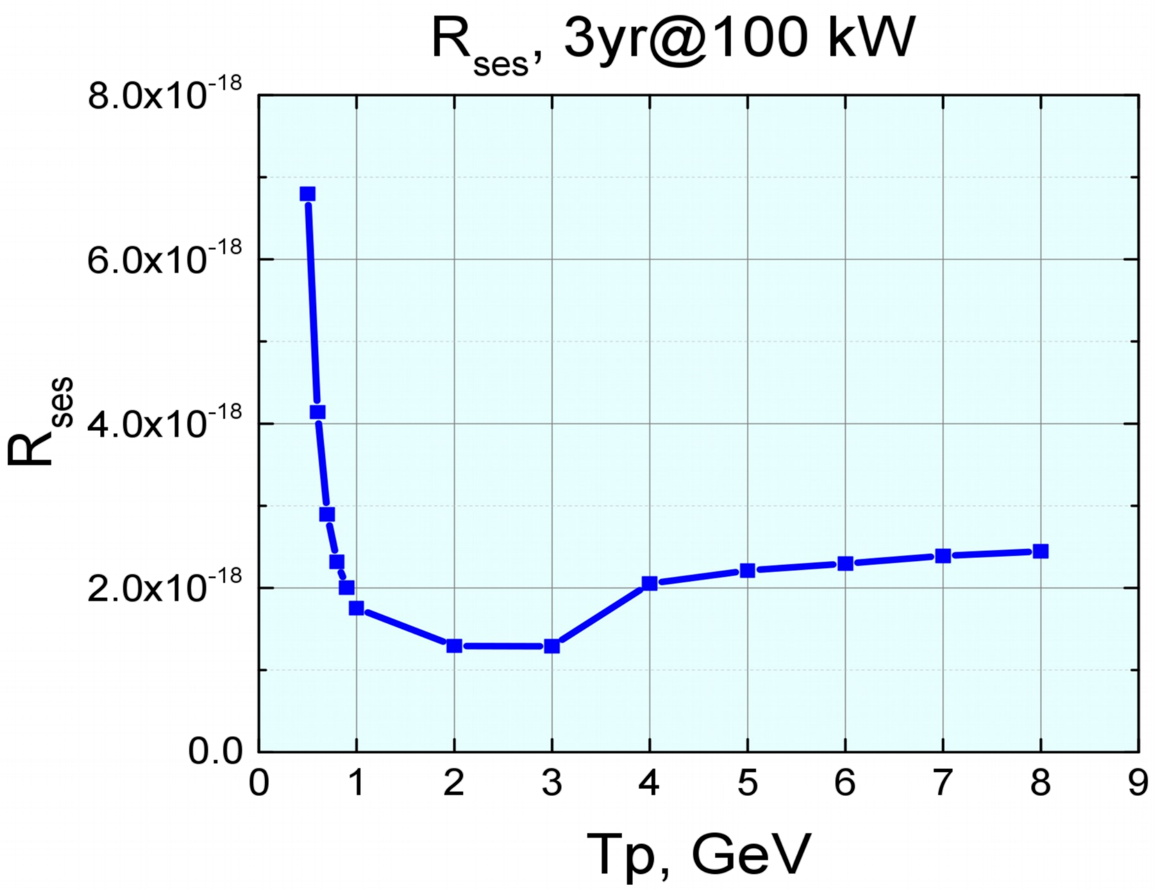
Mu2e-II would prefer a beam energy between 1 and 3 GeV





…. but stopped muons per unit of beam power peaks near 2.5 GeV, and stopped muons per unit of radiation damage has a broad peak between 1 and 3 GeV.

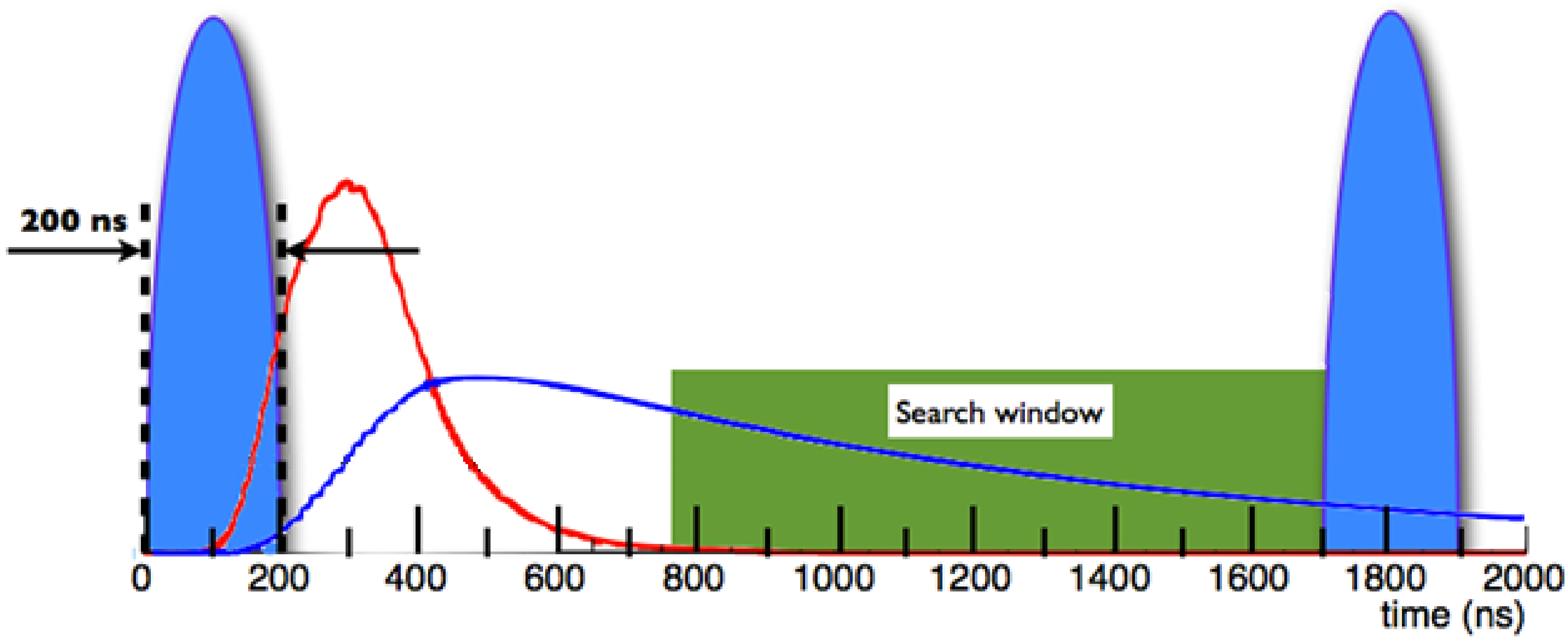
Mu2e-II would prefer a beam energy between 1 and 3 GeV



At 800 MeV and 100kW this requires instantaneous pulse intensities at least 40x greater than in Mu2e …. 10^9 protons per pulse (at 90% duty factor)

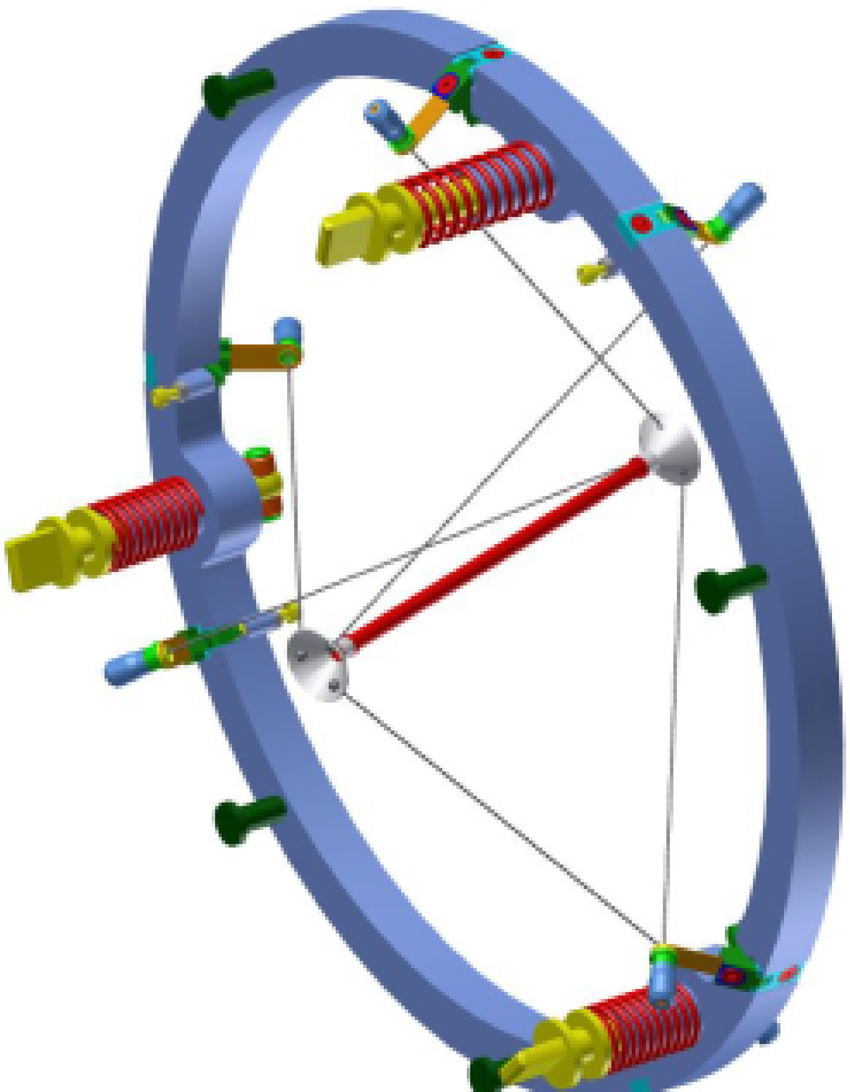
Post talk comment: Lots of assumptions go into this plot, so take the actual values with a grain of salt … but the trends should hold.

We require very high primary beam extinction



The out-of-pulse protons must be a factor of 10^{11} less than the in-pulse count. This is a factor of 10 better than will be achieved by Mu2e. It would be great to measure the extinction of the PIP-II frontend at the PIP2IT facility!

Required Beam and Target R&D



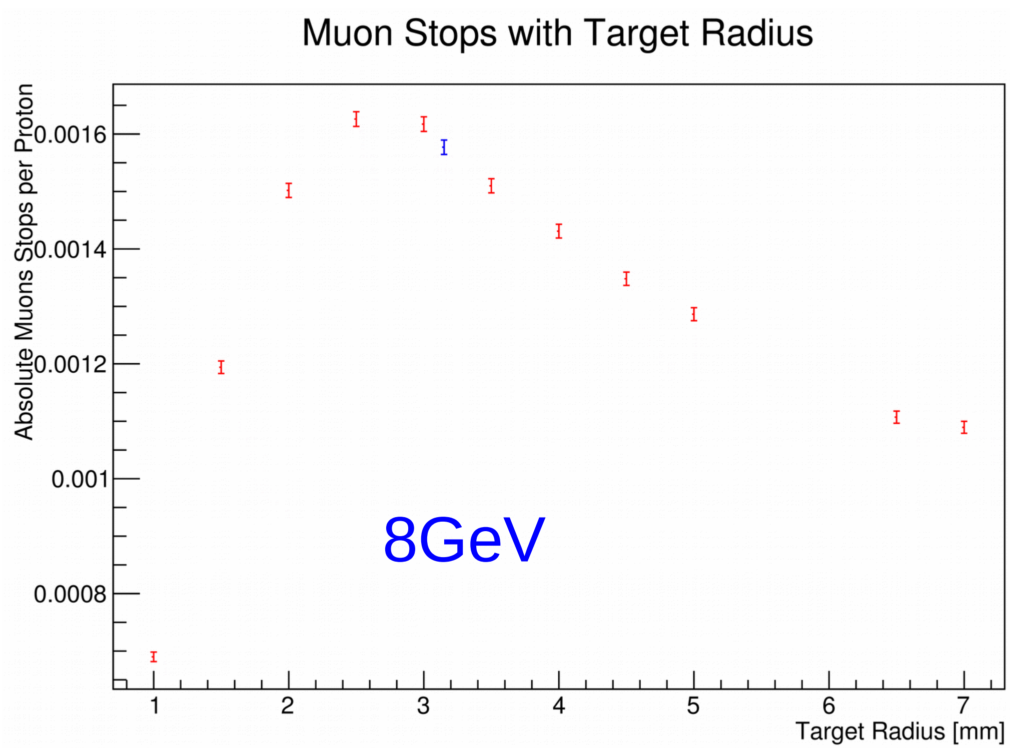
The Mu2e target is a 16cm by 6.3mm radiation cooled tungsten rod … this design will not work at 100kW! We need a new conceptual design for a similarly compact, actively cooled target.

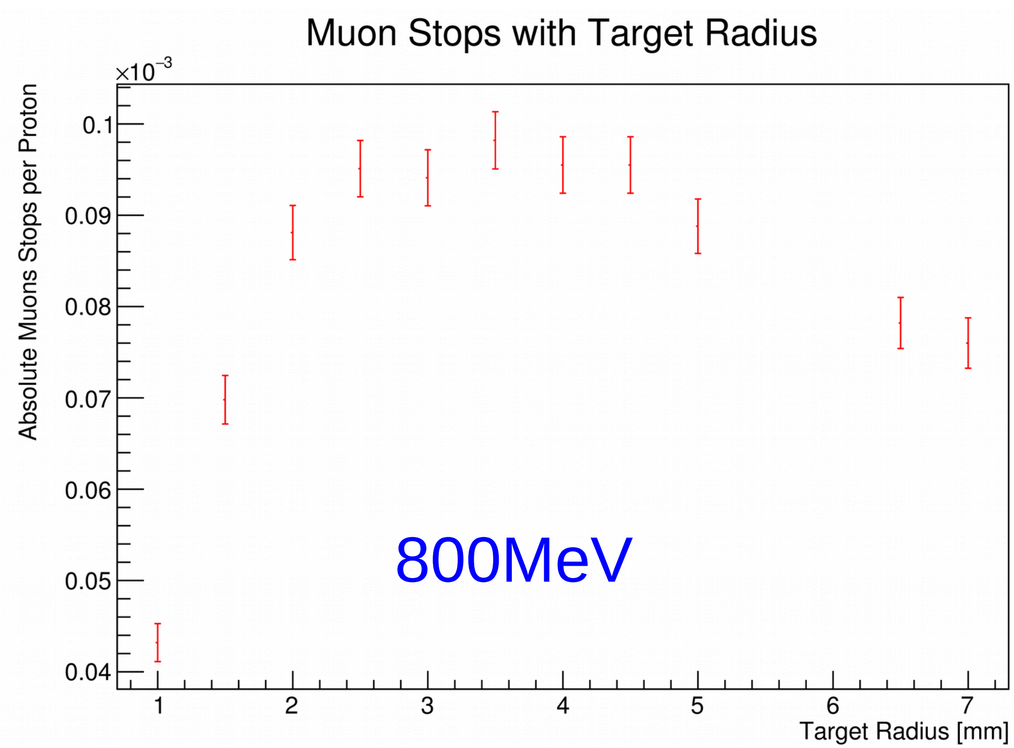
Required Beam and Target R&D

- Solid target with active gas or water cooling?
  - MECO had a water cooled target for 50 kW
  - He cooling also looks promising
  - Mounting/changing the target and its plumbing?
  - We're using Tungsten; MECO planned to use gold.
- Should we consider liquid target technologies?
- We will need a new HRS, and it may even be necessary to replace the PS
- What kind of beam do we need?
  - Small or large beam spot?
  - Rastered across or around target?

What near-term studies can *we* do that would be useful?

Many optimization studies performed for the Mu2e production target can be quickly repeated for Mu2e-II … for example, target radius studies.





Summary

- In the PIP-II era, the physics reach of Mu2e can be extended by an order of magnitude.
- The most pressing R&D issues are
  - Measuring extinction achieved using PIP2IT
  - Develop conceptual designs for a compact, high-Z, actively cooled, 100kW capable production target
- We're excited to be active participants in these studies.

Answers to questions

- Chris Densham asked how we planned to get the HRS and/or the PS out of the hall, as Mu2e plans to weld these objects to each other and to TS. There's no detailed answer to that question yet, as no engineering effort has yet been put into it, but we do acknowledge this as a significant (but likely tractable) issue.
- Bob Tschirhart asked about absorbed energy in the target. At 8GeV/8kW, the target absorbs 760W, which averages to 150MW/m^3. For the same size target at 8GeV/100kW, that should scale directly to about 2GW/m^3. I'm not sure we've done the calculations at other beam energies, but would expect them to be comparable; this is something we can easily study in the near term.
- Although not mentioned in the talk, we will also need to upgrade the beam stop and the target handling systems.

References

- K. Knoepfel, et al. “Feasibility Study for a Next Generation Mu2e Experiment”. 2013. https://arxiv.org/abs/1307.1168
- V. Pronskikh, et al. “A Study of the Energy Dependence of Radiation Damage in Superconducting Coils for a Next Generation Mu2e at PIP-II”. 2016. https://arxiv.org/abs/1612.08931