The Mu2e Experiment at Fermilab

Kevin Lynch
For the Mu2e Collaboration
Phenomenology 2015
University of Pittsburgh
May 4-6, 2015

YORK College
THE CITY UNIVERSITY OF NEW YORK

Mu2e holds a prominent place in the near term US HEP program

Building for Discovery

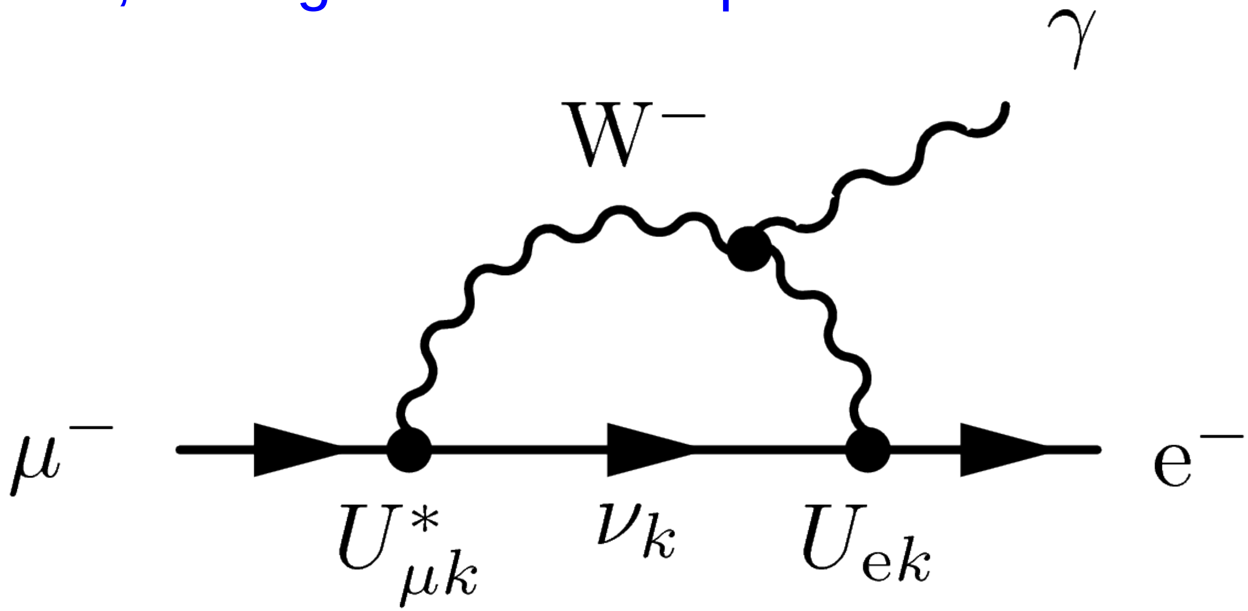
Strategic Plan for U.S. Particle Physics in the Global Context

P5 Report Recommendation 22: Complete the Mu2e and muon g-2 projects.

Why this emphasis on muon physics?

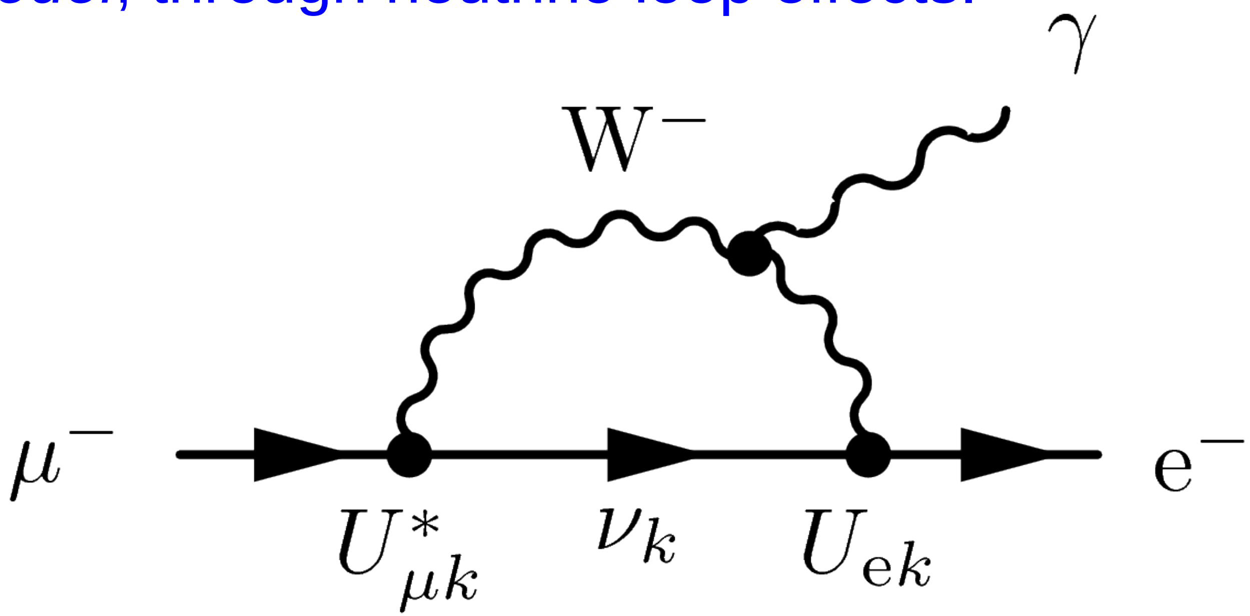
Mu2e is a search for charged lepton flavor violation with *discovery potential*

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



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:

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

Any observation of cLFV is a direct signal of new physics!

$$\mu^\pm \to \mathrm{e}^\pm \gamma$$

$$\mu^\pm \to \mathrm{e}^\pm \mathrm{e}^+ \mathrm{e}^-$$

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

Any observation of cLFV is a direct signal of new physics!

$$\mu^{\pm} \rightarrow \mathrm{e}^{\pm}\gamma$$

MEG at PSI

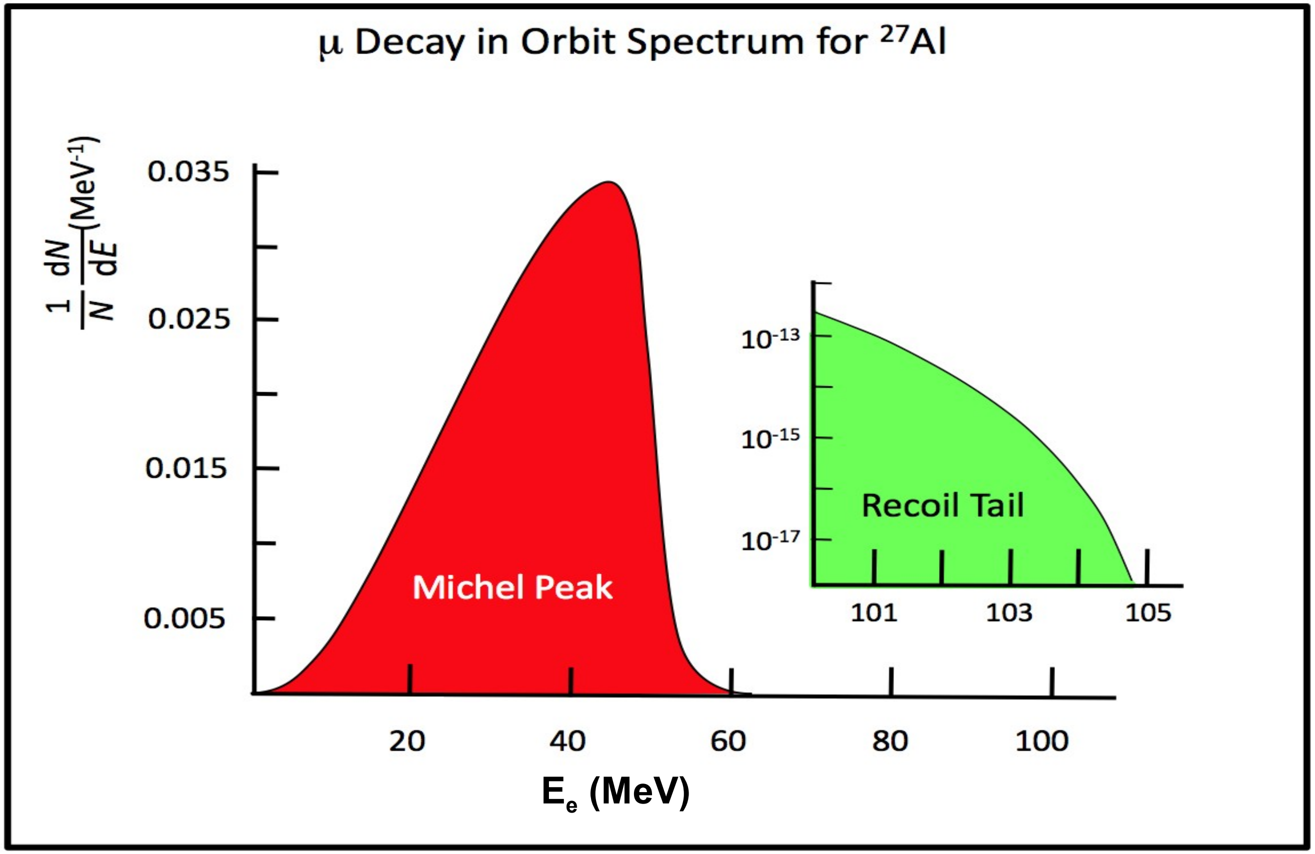
$$\mu^{\pm} \rightarrow \mathrm{e}^{\pm}\mathrm{e}^{+}\mathrm{e}^{-}$$

Mu3e at PSI

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

COMET at JPARC
Mu2e at FNAL

Any observation of cLFV is a direct signal of new physics!



$\mu^{\pm} \rightarrow e^{\pm}\gamma$

MEG at PSI

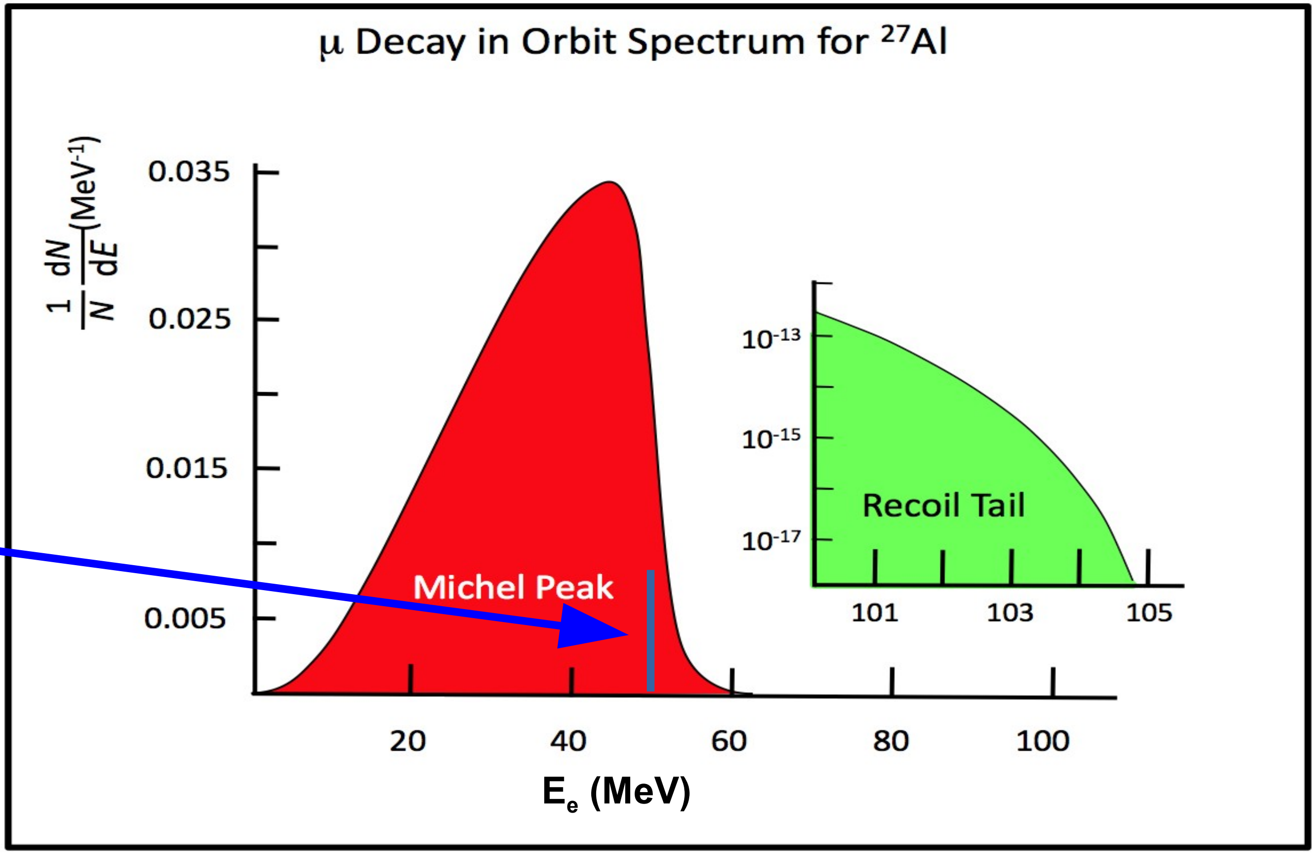
$\mu^{\pm} \rightarrow e^{\pm}e^{+}e^{-}$

Mu3e at PSI

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

COMET at JPARC
Mu2e at FNAL

Any observation of cLFV is a direct signal of new physics!



$\mu^\pm \to e^\pm \gamma$

MEG at PSI

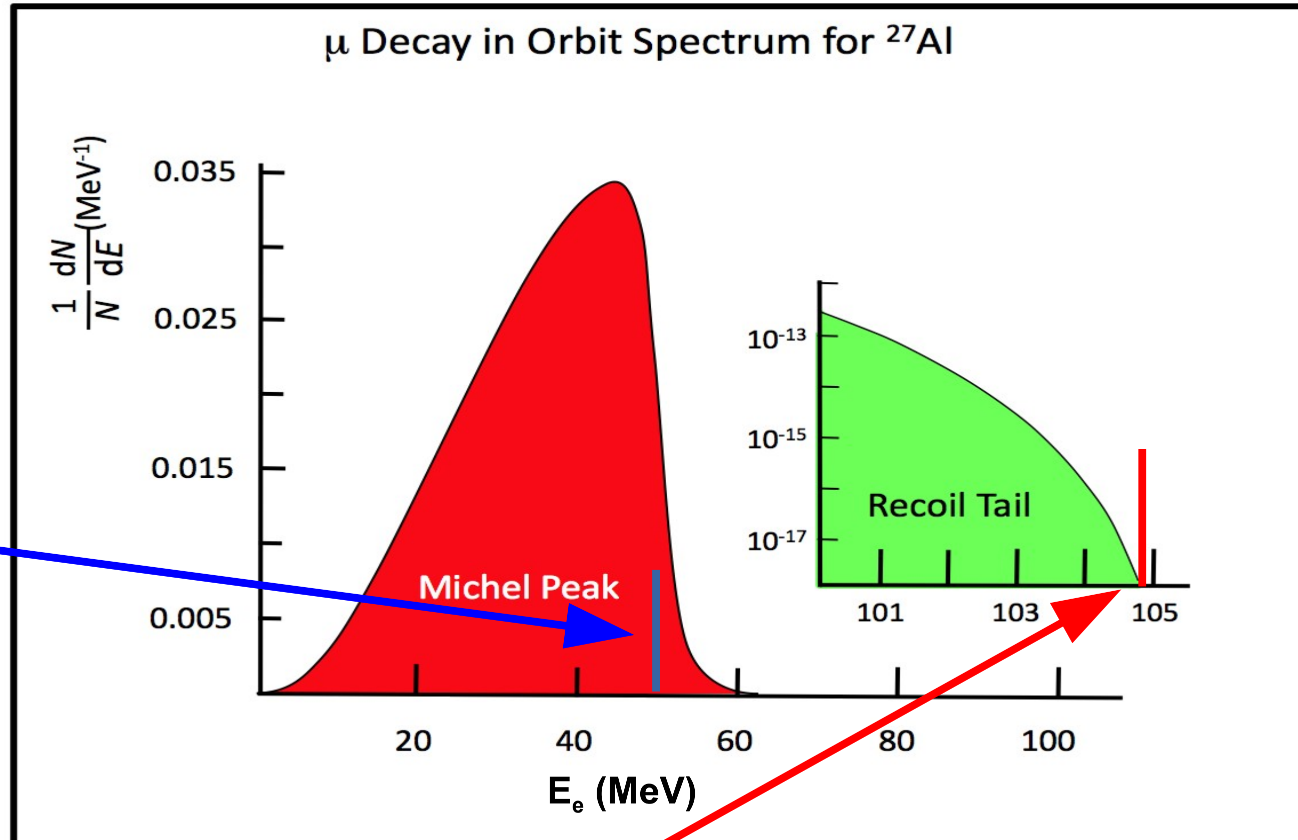
$\mu^\pm \to e^\pm e^+ e^-$

Mu3e at PSI

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

COMET at JPARC
Mu2e at FNAL

Any observation of cLFV is a direct signal of new physics!



$$\mu^{\pm} \to \mathrm{e}^{\pm}\gamma$$

MEG at PSI

$$\mu^{\pm} \to \mathrm{e}^{\pm}\mathrm{e}^{+}\mathrm{e}^{-}$$

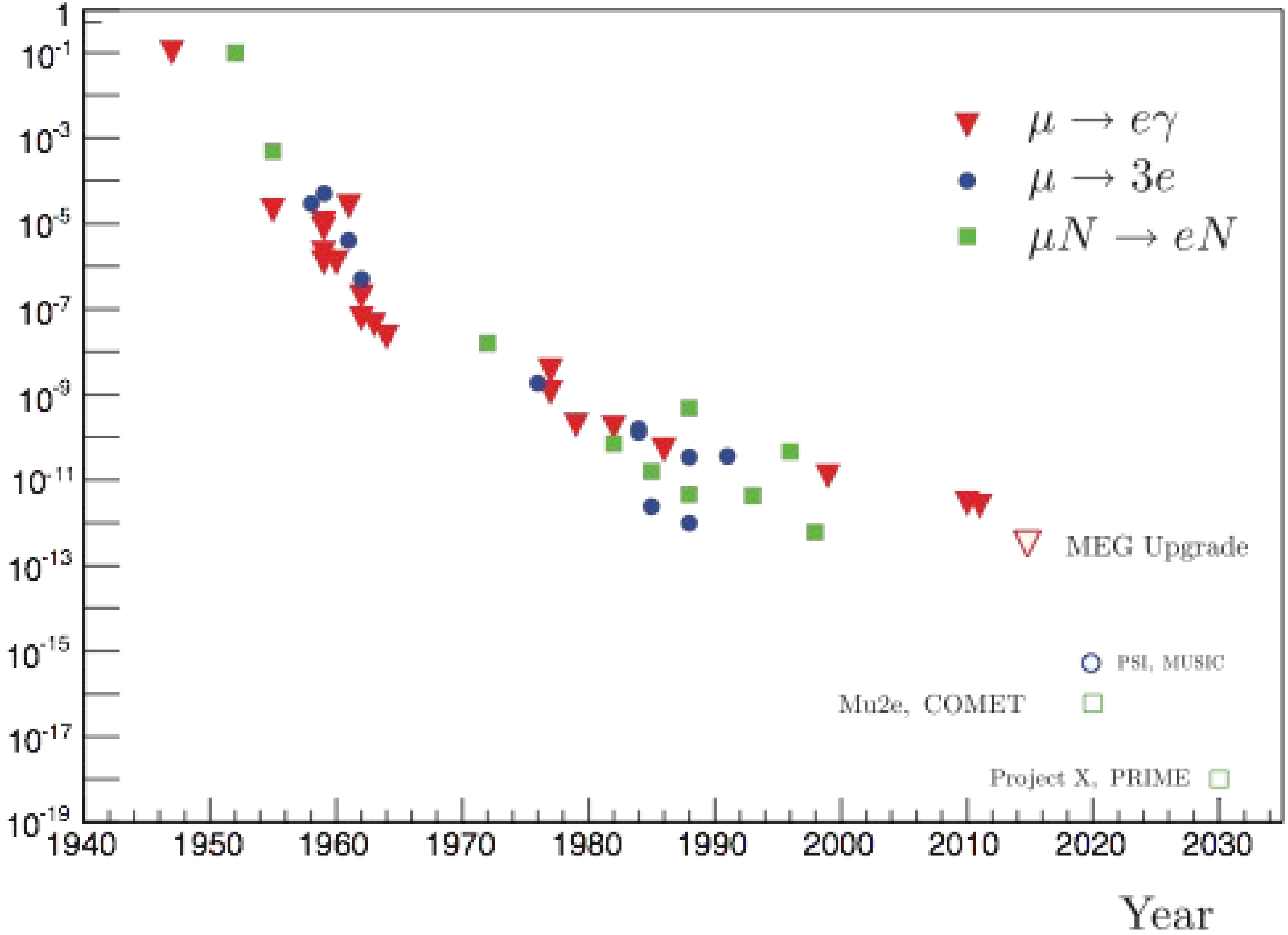
Mu3e at PSI

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

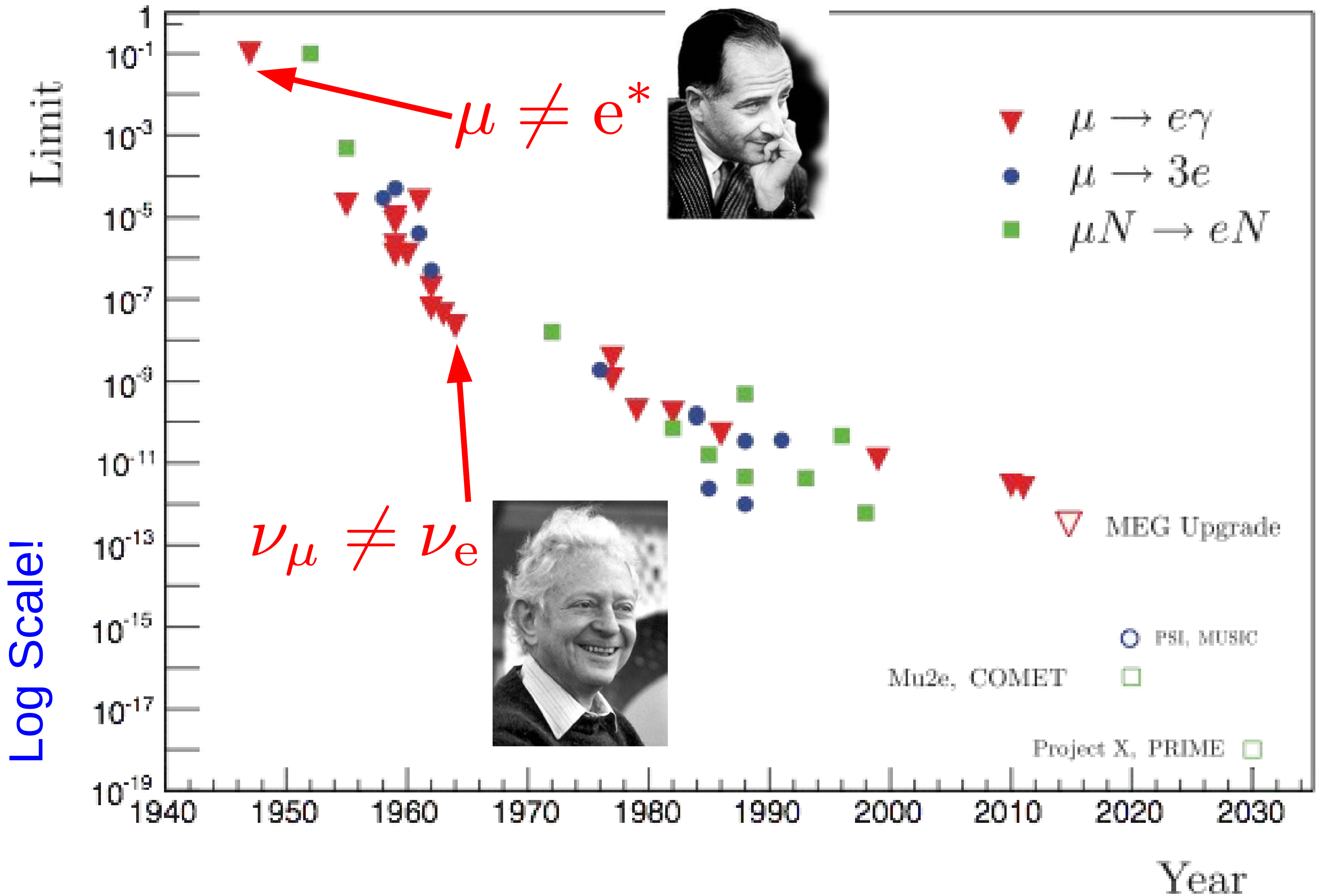
COMET at JPARC
Mu2e at FNAL

Mu2e joins a long line of experiments designed to understand the mystery of lepton flavor

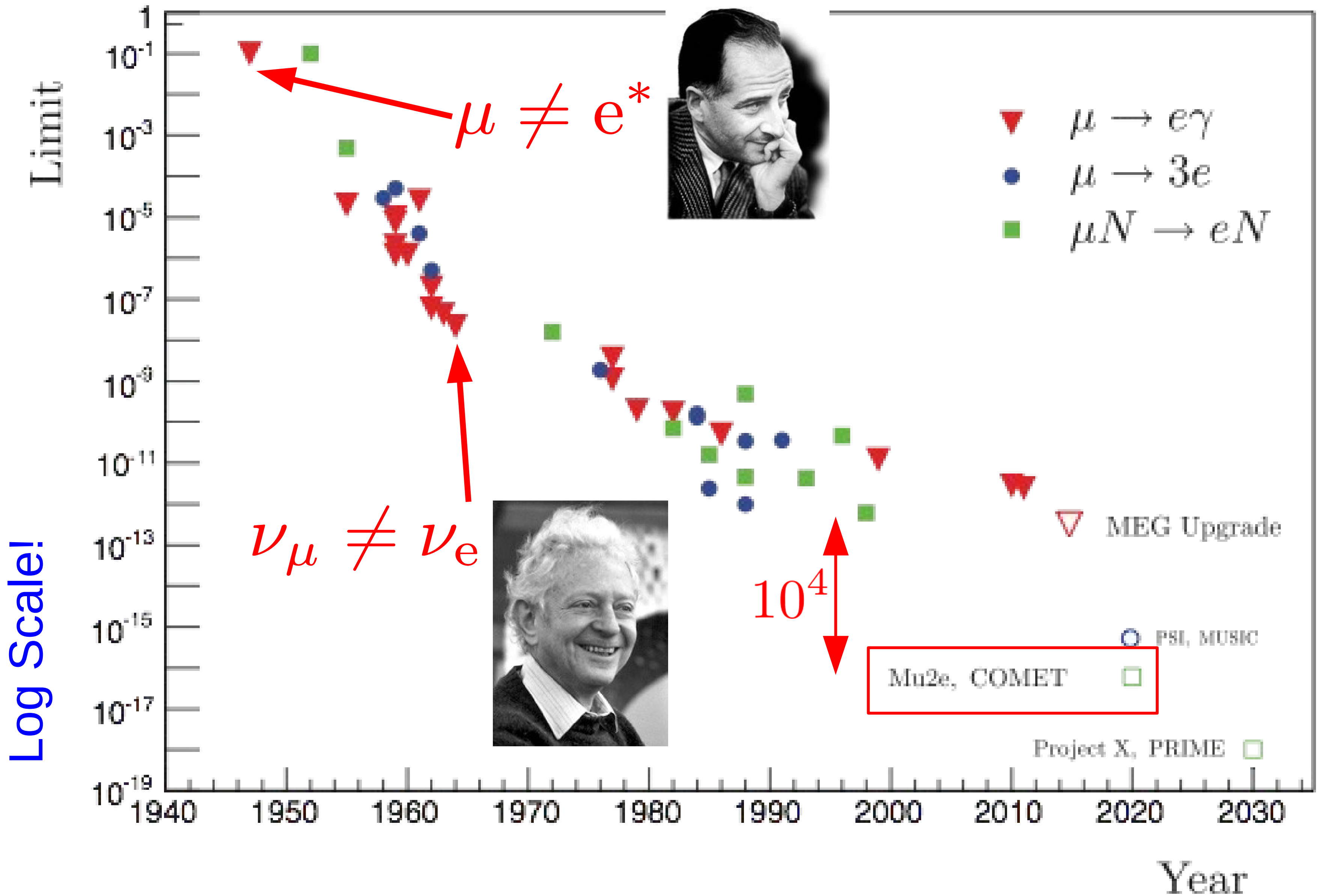
Log Scale!



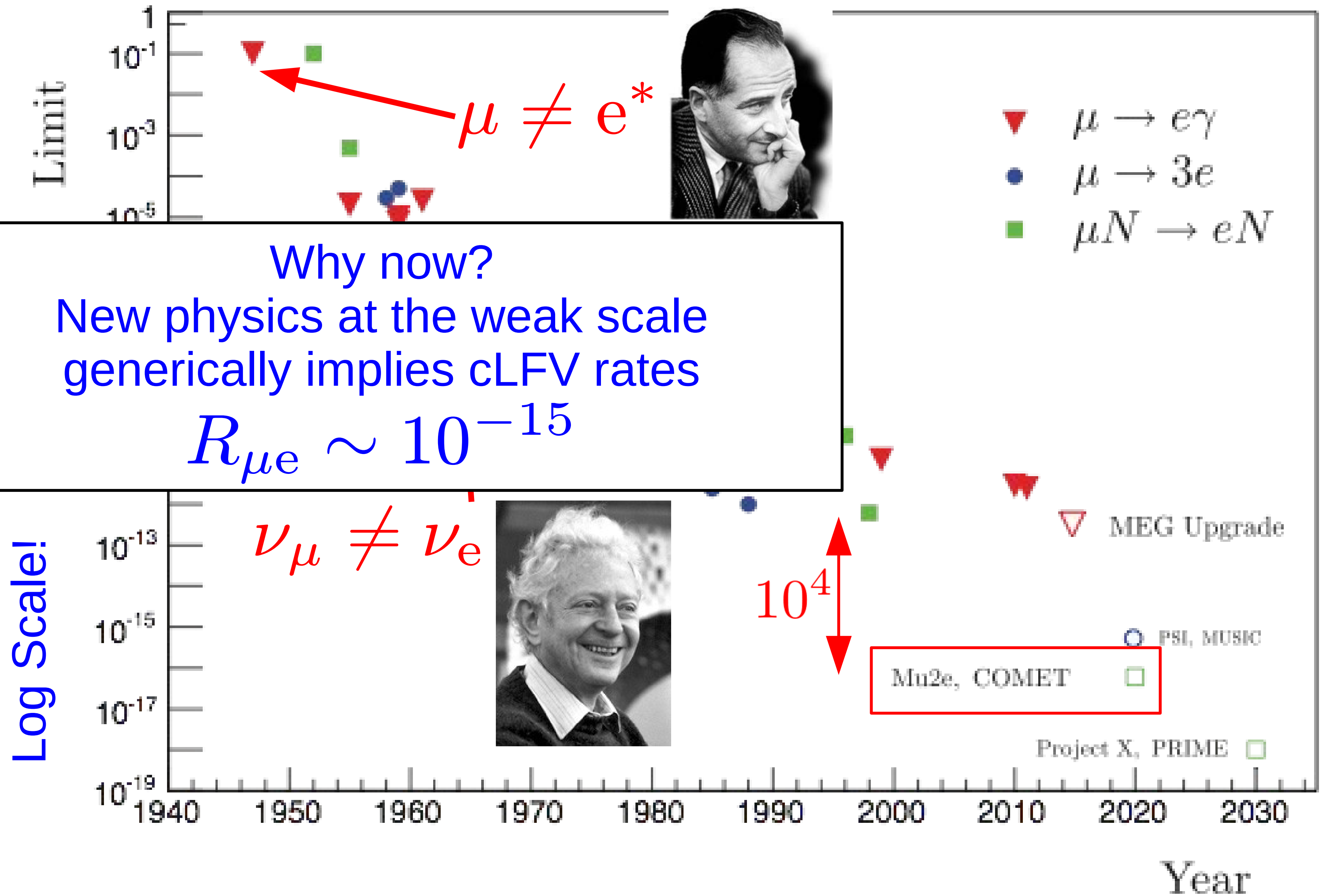
Mu2e joins a long line of experiments designed to understand the mystery of lepton flavor



Mu2e joins a long line of experiments designed to understand the mystery of lepton flavor



Mu2e joins a long line of experiments designed to understand the mystery of lepton flavor



Why now?

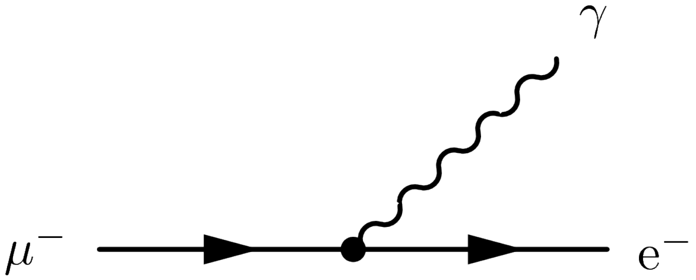
New physics at the weak scale generically implies cLFV rates

$$R_{\mu e} \sim 10^{-15}$$

In terms of energy reach, what does 10^4 sensitivity improvement gain us?

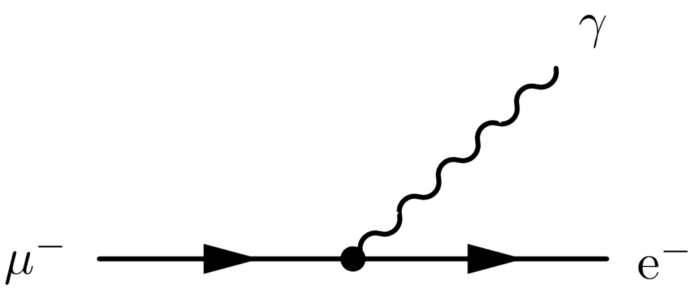
In terms of energy reach, what does 10^4 sensitivity improvement gain us?

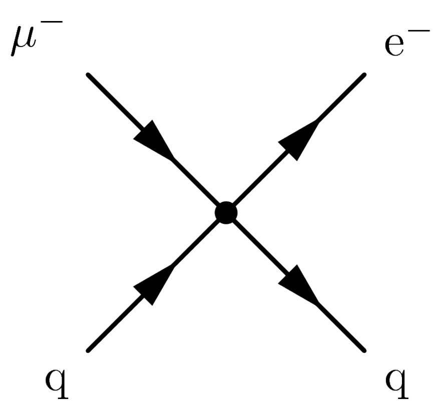
$$\mathcal{L}_{\mathrm{cLFV}} = \frac{1}{\kappa + 1}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\alpha\beta}\mathrm{e}_L F^{\alpha\beta} +$$



In terms of energy reach, what does 10^4 sensitivity improvement gain us?

$$\mathcal{L}_{\mathrm{cLFV}} = \frac{1}{\kappa+1}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\alpha\beta}\mathrm{e}_L F^{\alpha\beta} + \frac{\kappa}{\kappa+1}\frac{1}{\Lambda^2}\bar{\mu}_L\gamma_\alpha\mathrm{e}_L\left(\bar{\mathrm{u}}_L\gamma^\alpha\mathrm{u}_L + \bar{\mathrm{d}}_L\gamma^\alpha\mathrm{d}_L\right)$$

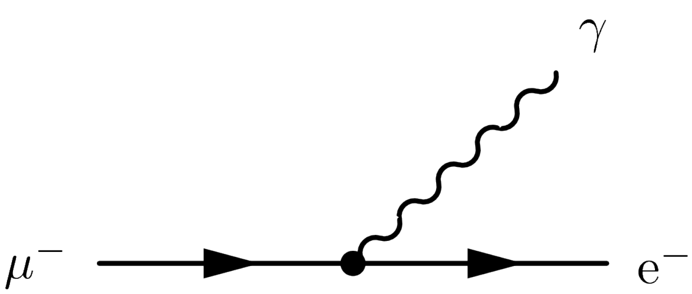


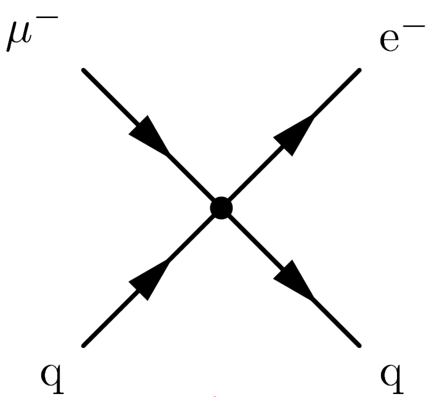


In terms of energy reach, what does 10^4 sensitivity improvement gain us?

$$\mathcal{L}_{\mathrm{cLFV}} = \frac{1}{\kappa+1}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\alpha\beta}\mathrm{e}_L F^{\alpha\beta} + \frac{\kappa}{\kappa+1}\frac{1}{\Lambda^2}\bar{\mu}_L\gamma_\alpha \mathrm{e}_L\left(\bar{\mathrm{u}}_L\gamma^\alpha \mathrm{u}_L + \bar{\mathrm{d}}_L\gamma^\alpha \mathrm{d}_L\right)$$

We set their relative strength with a dimensionless interpolating factor κ





$$\frac{1}{\kappa+1} \longleftrightarrow \frac{\kappa}{\kappa+1}$$

In terms of energy reach, what does 10^4 sensitivity improvement gain us?

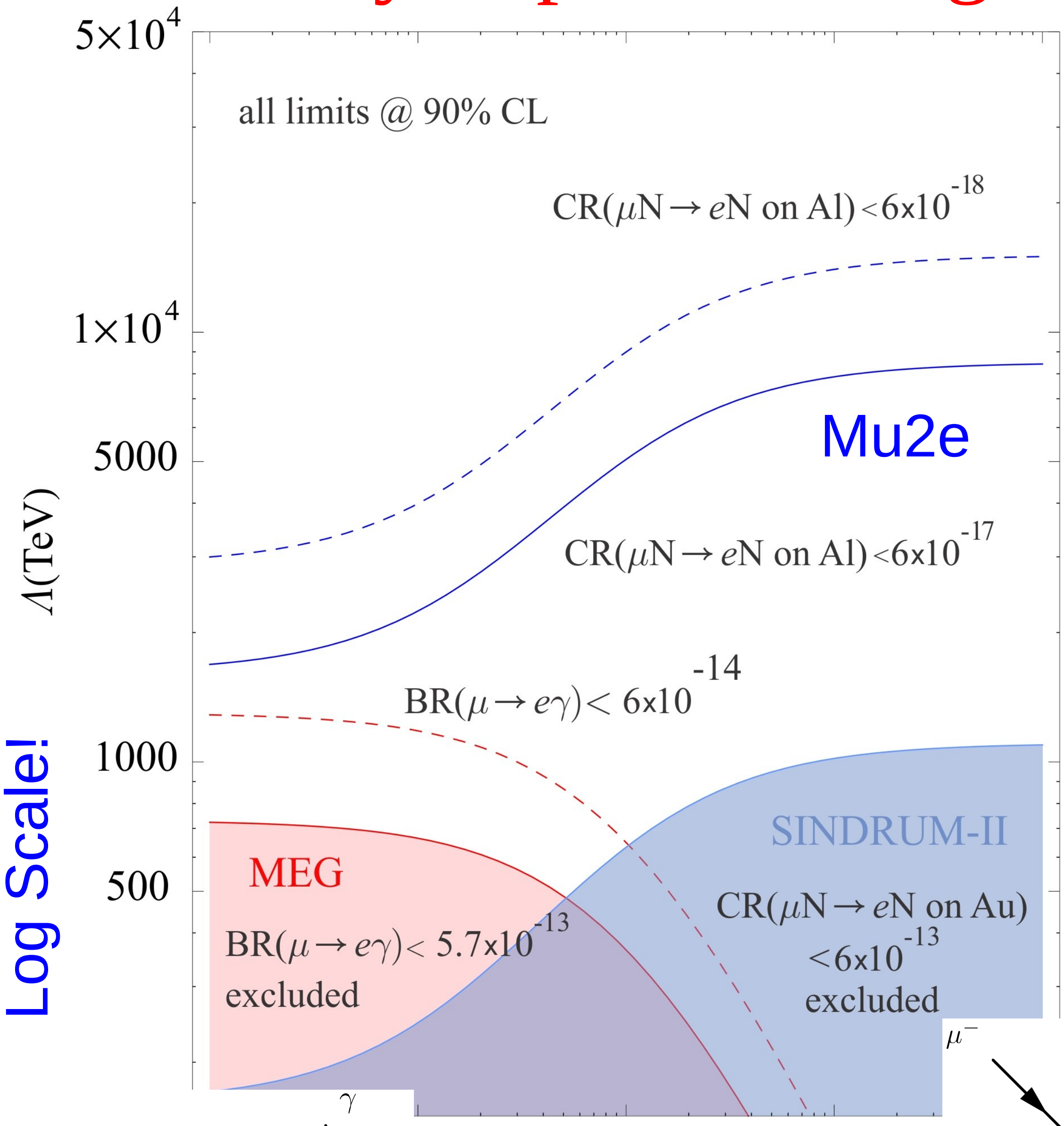
In terms of energy reach, what does 10^4 sensitivity improvement gain us?

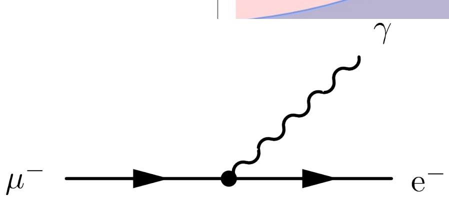
Improving the rate measurement by four orders of magnitude extends our reach in energy by an order of magnitude

$$r \propto \frac{1}{(\Lambda^2)^2}$$

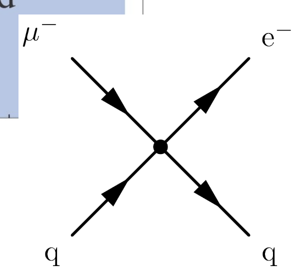
In terms of energy reach, what does 10^4 sensitivity improvement gain us?

Log Scale!





$\kappa = 1$

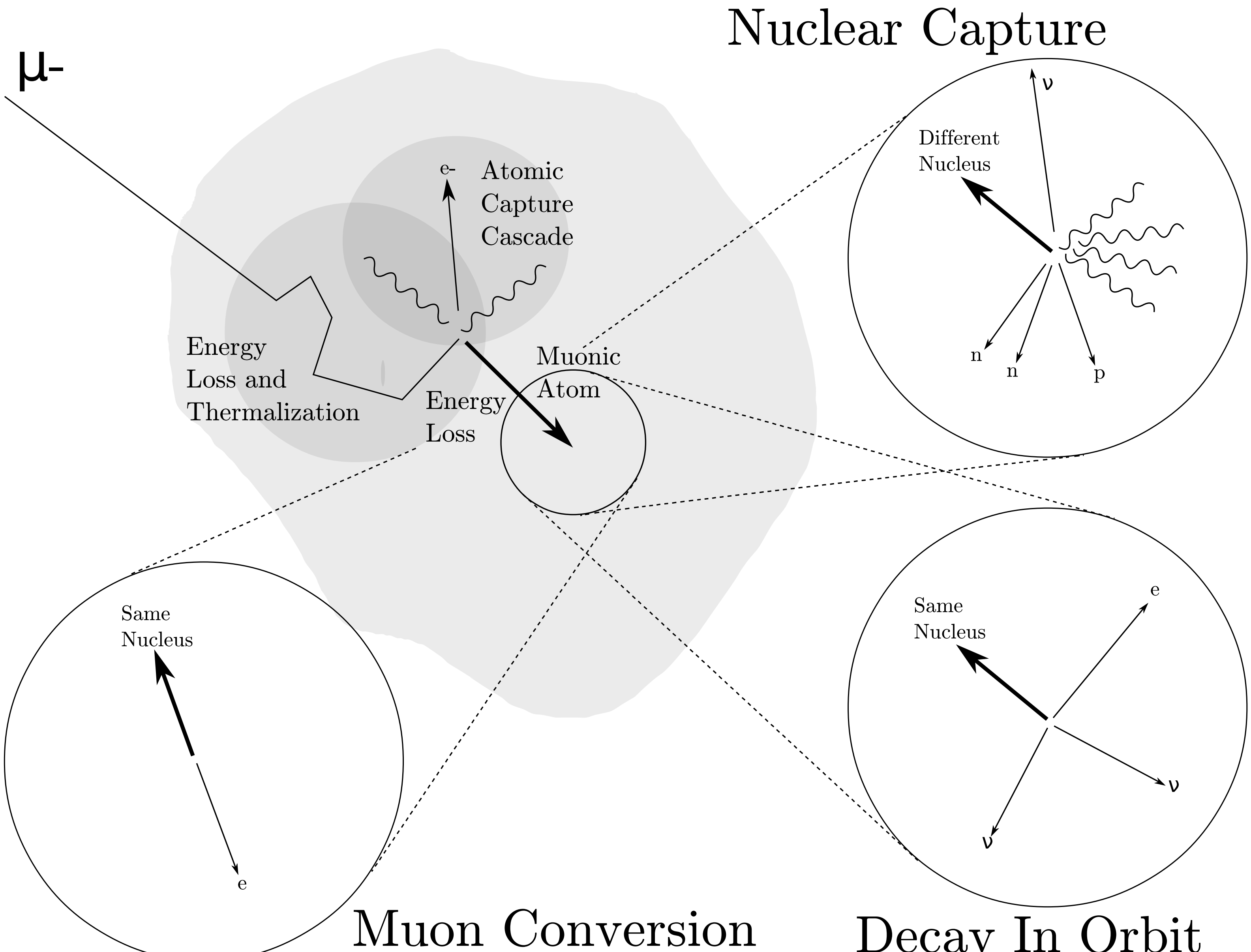


Improving the rate measurement by four orders of magnitude extends our reach in energy by an order of magnitude

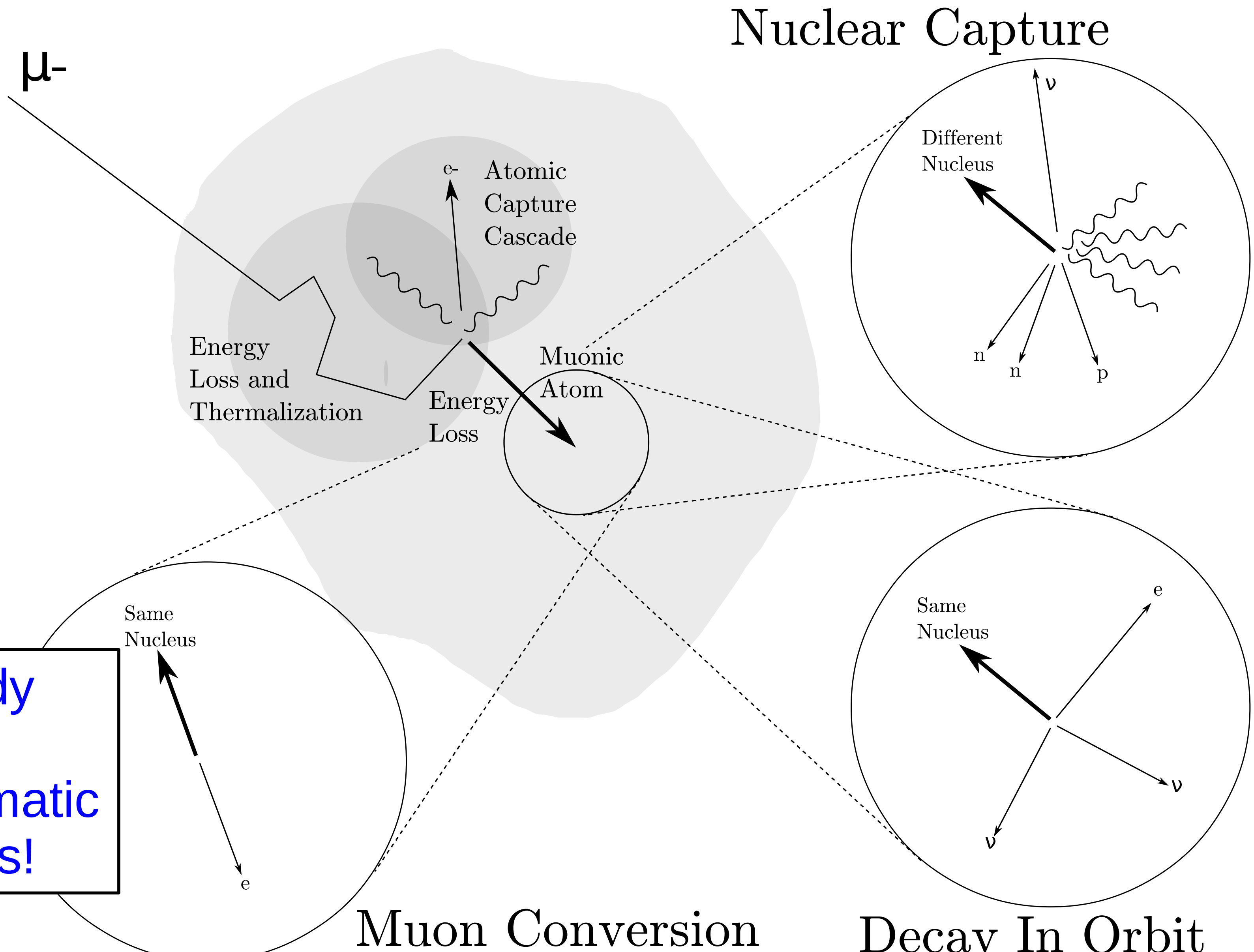
$$r \propto \frac{1}{(\Lambda^2)^2}$$

A. de Gouvêa and P. Vogel,
Prog. Part. Nucl. Phys. 71, 75 (2013).

The atomic, nuclear, and particle physics of μ⁻ drive the design of the experiment

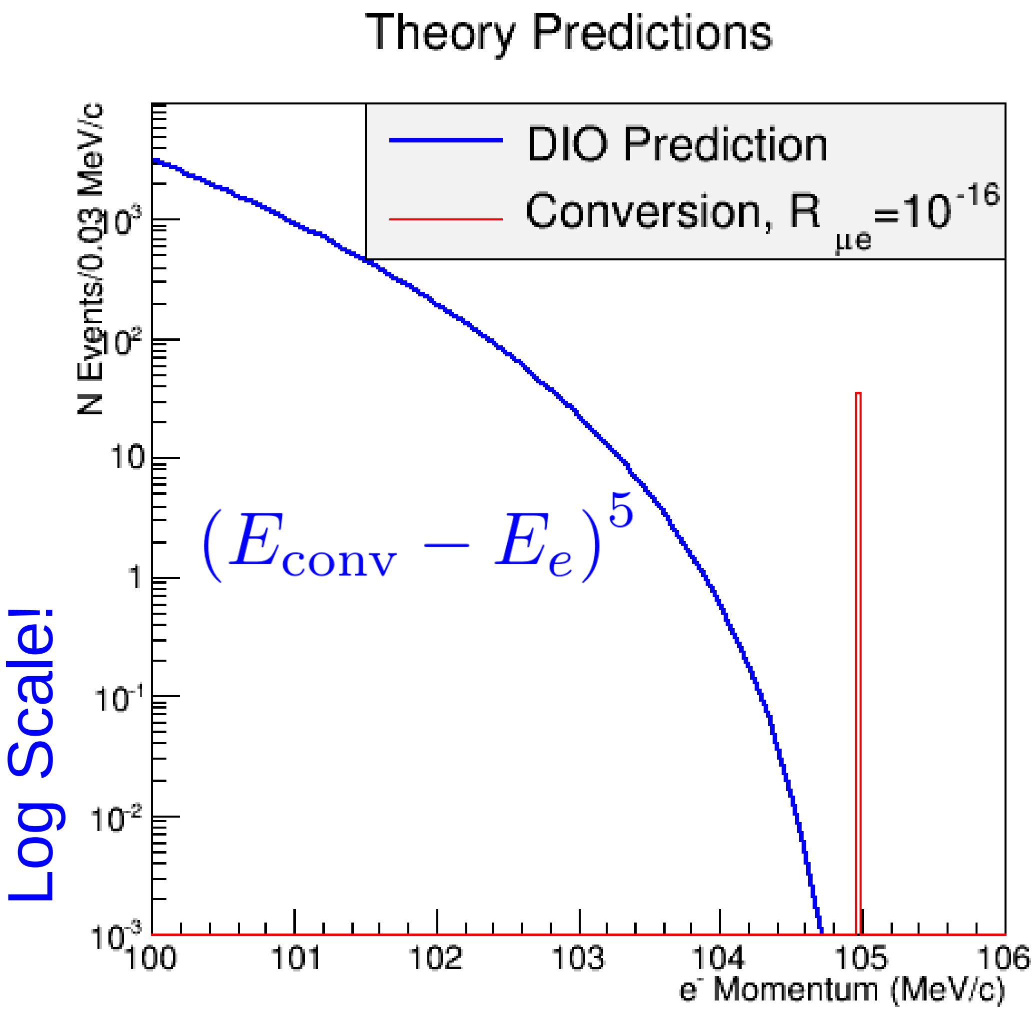


The atomic, nuclear, and particle physics of μ^- drive the design of the experiment

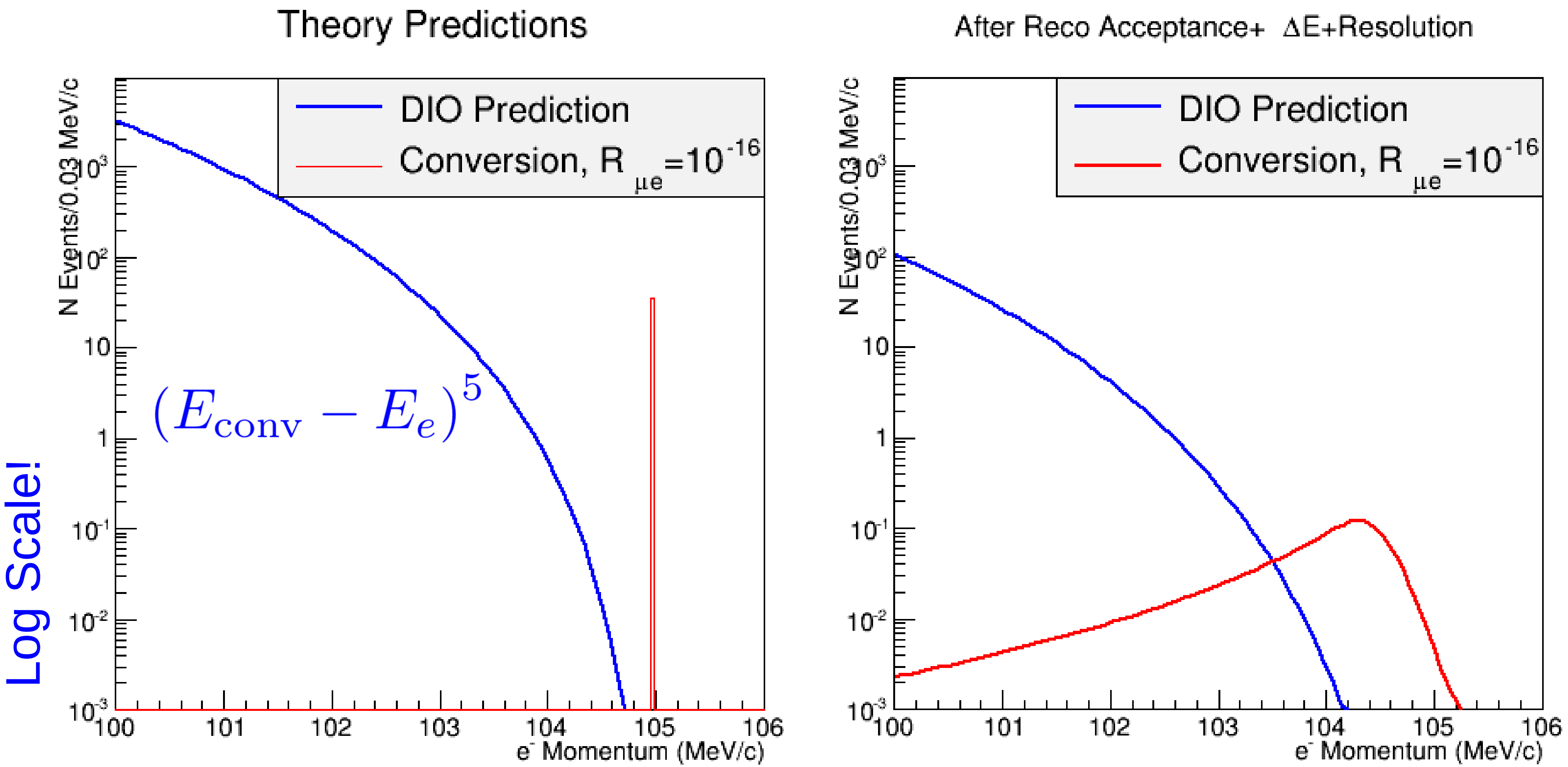


Two body decay: monochromatic electrons!

Electron momentum resolution is a big driver of the experiment design



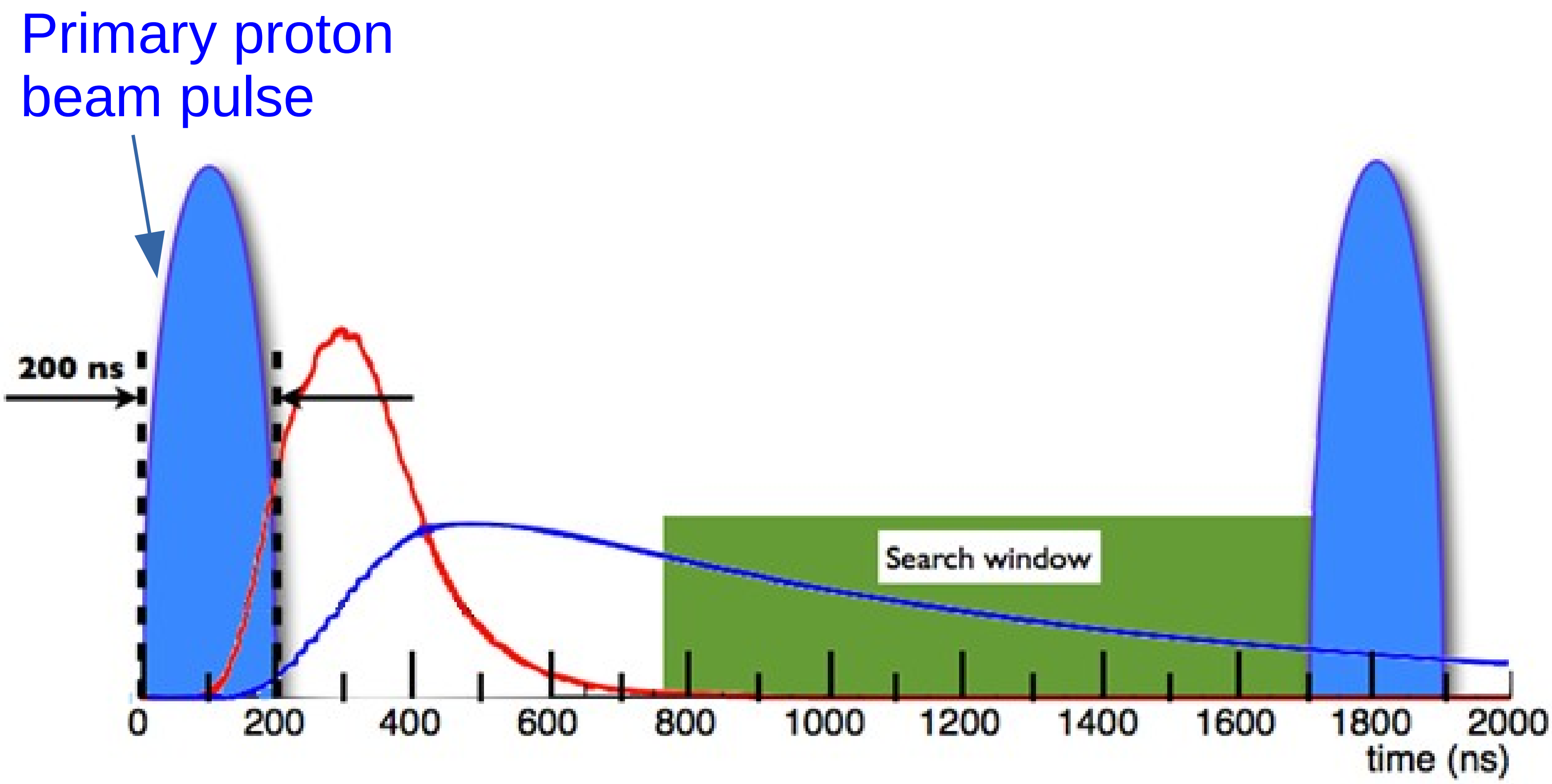
Electron momentum resolution is a big driver of the experiment design



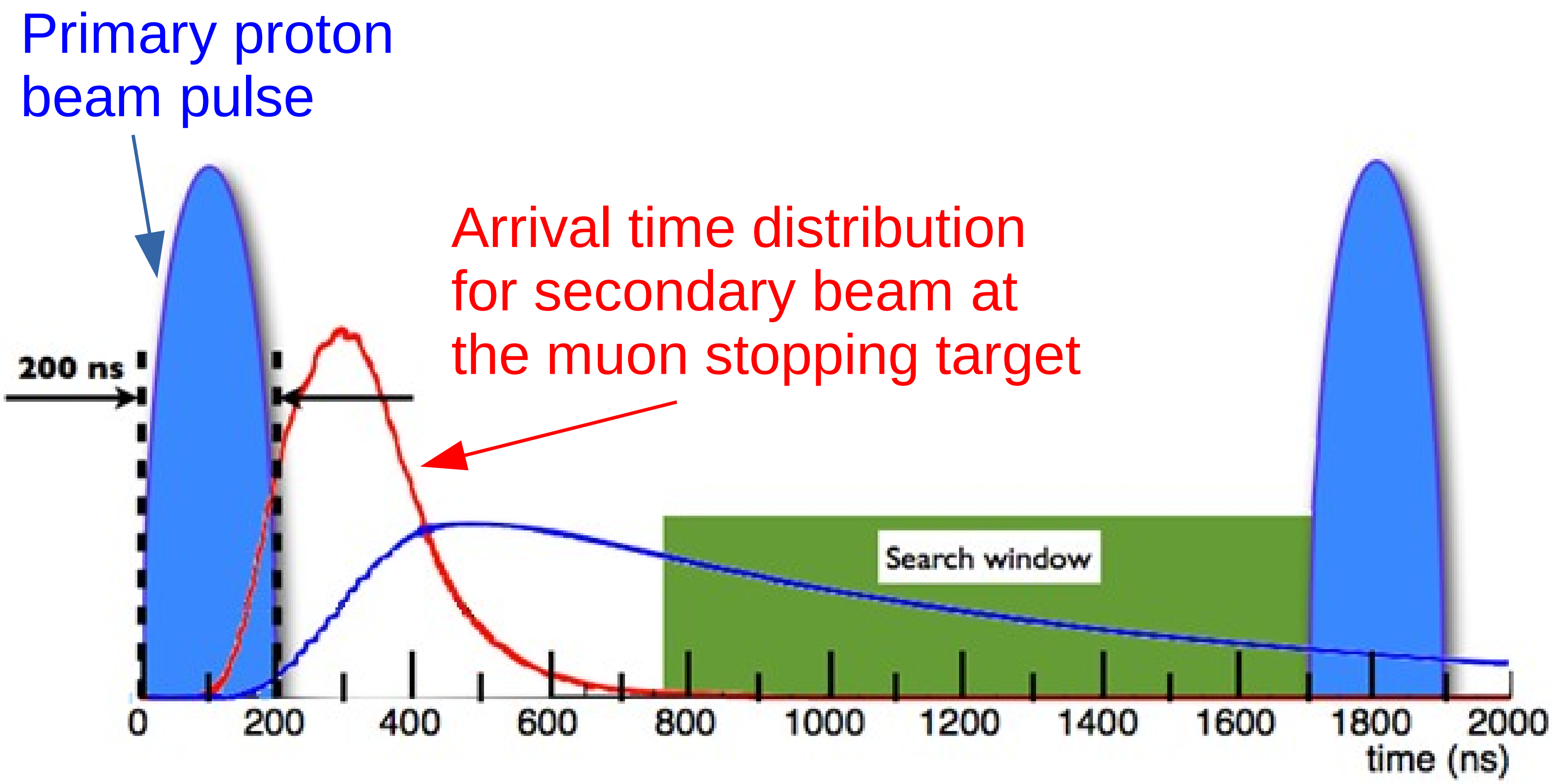
We need a low mass detector design to minimize energy loss and resolution smearing!

The reduction of prompt backgrounds demands a pulsed beam structure

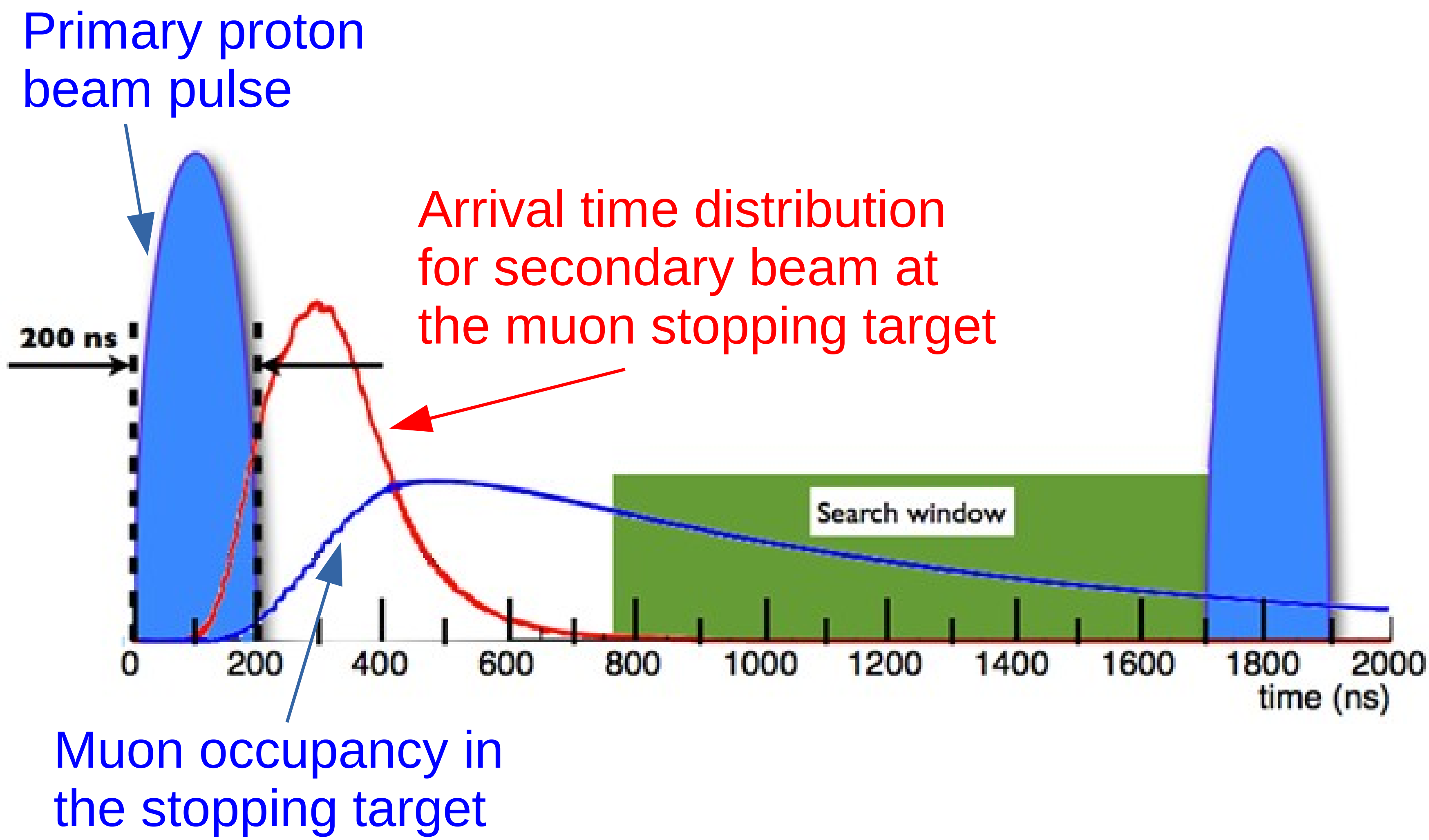
The reduction of prompt backgrounds demands a pulsed beam structure



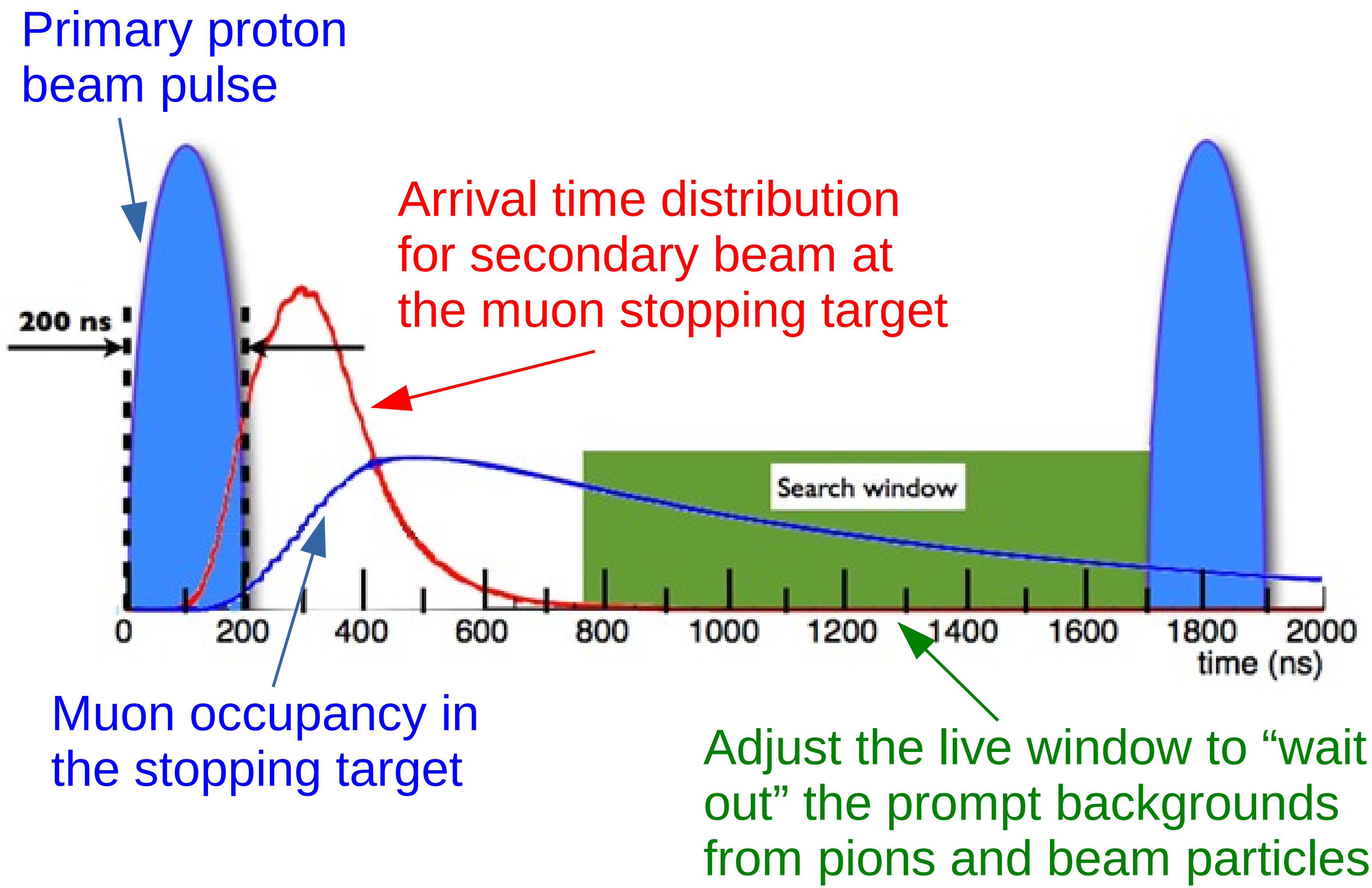
The reduction of prompt backgrounds demands a pulsed beam structure



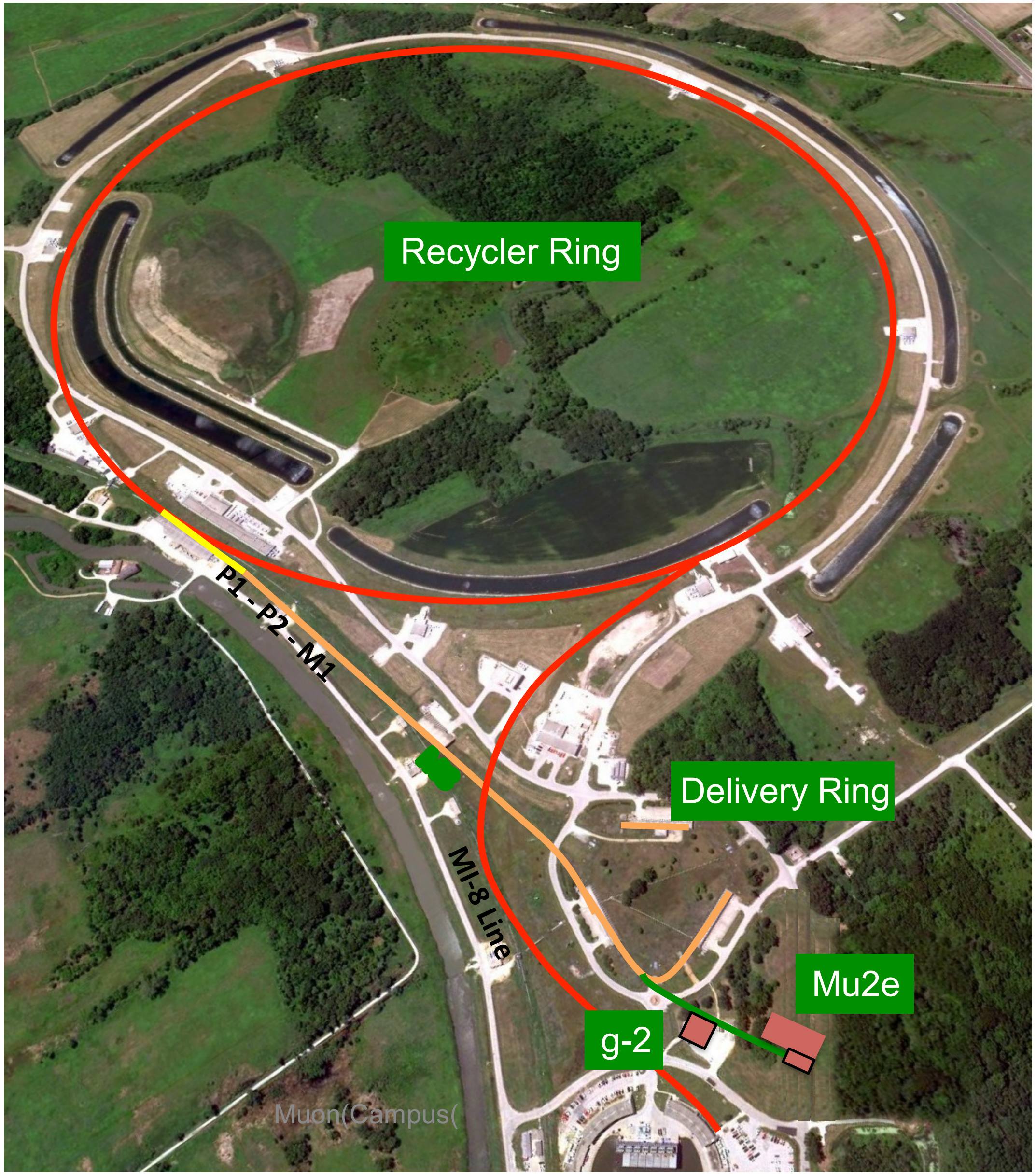
The reduction of prompt backgrounds demands a pulsed beam structure



The reduction of prompt backgrounds demands a pulsed beam structure

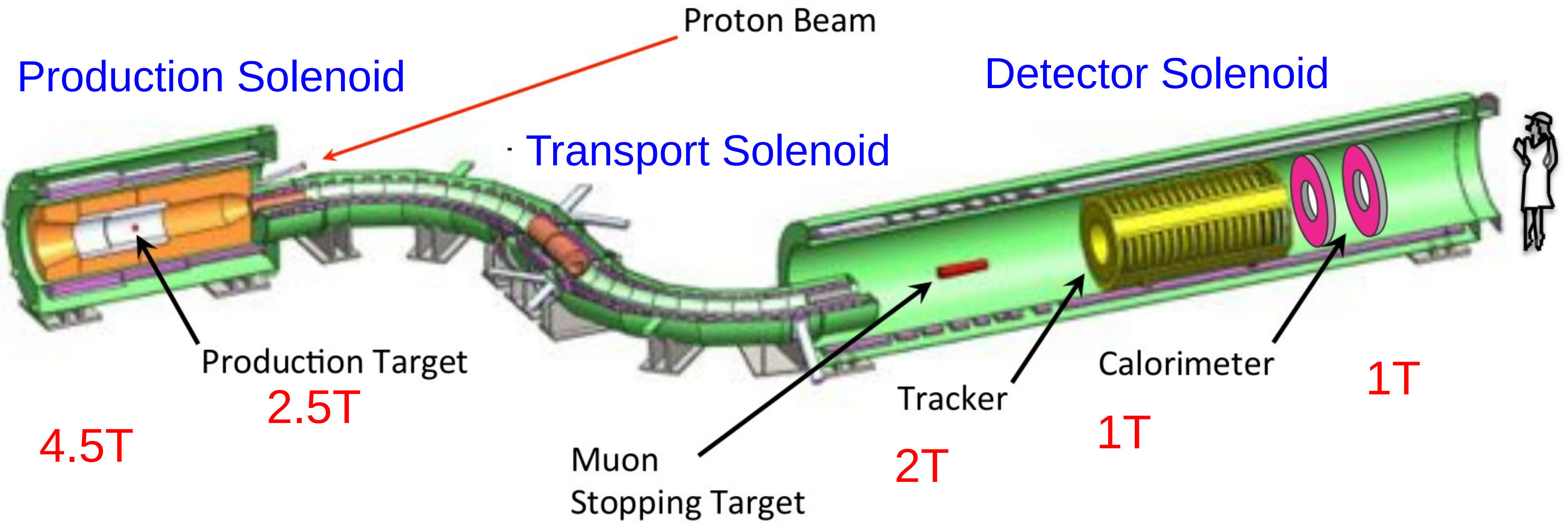


We can get this beam structure from the Fermilab accelerator complex



We can get this beam structure from the Fermilab accelerator complex

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



If there is new weak scale physics, Mu2e is in an excellent position to observe cLFV

For a 3 year run with 3.6×10^{20} POT, we expect a nearly background free signal:

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

If there is new weak scale physics, Mu2e is in an excellent position to observe cLFV

For a 3 year run with 3.6×10^{20} POT, we expect a nearly background free signal:

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

The single event sensitivity goal is 2.5×10^{-17}; our current estimate is 2.9×10^{-17}

If there is new weak scale physics, Mu2e is in an excellent position to observe cLFV

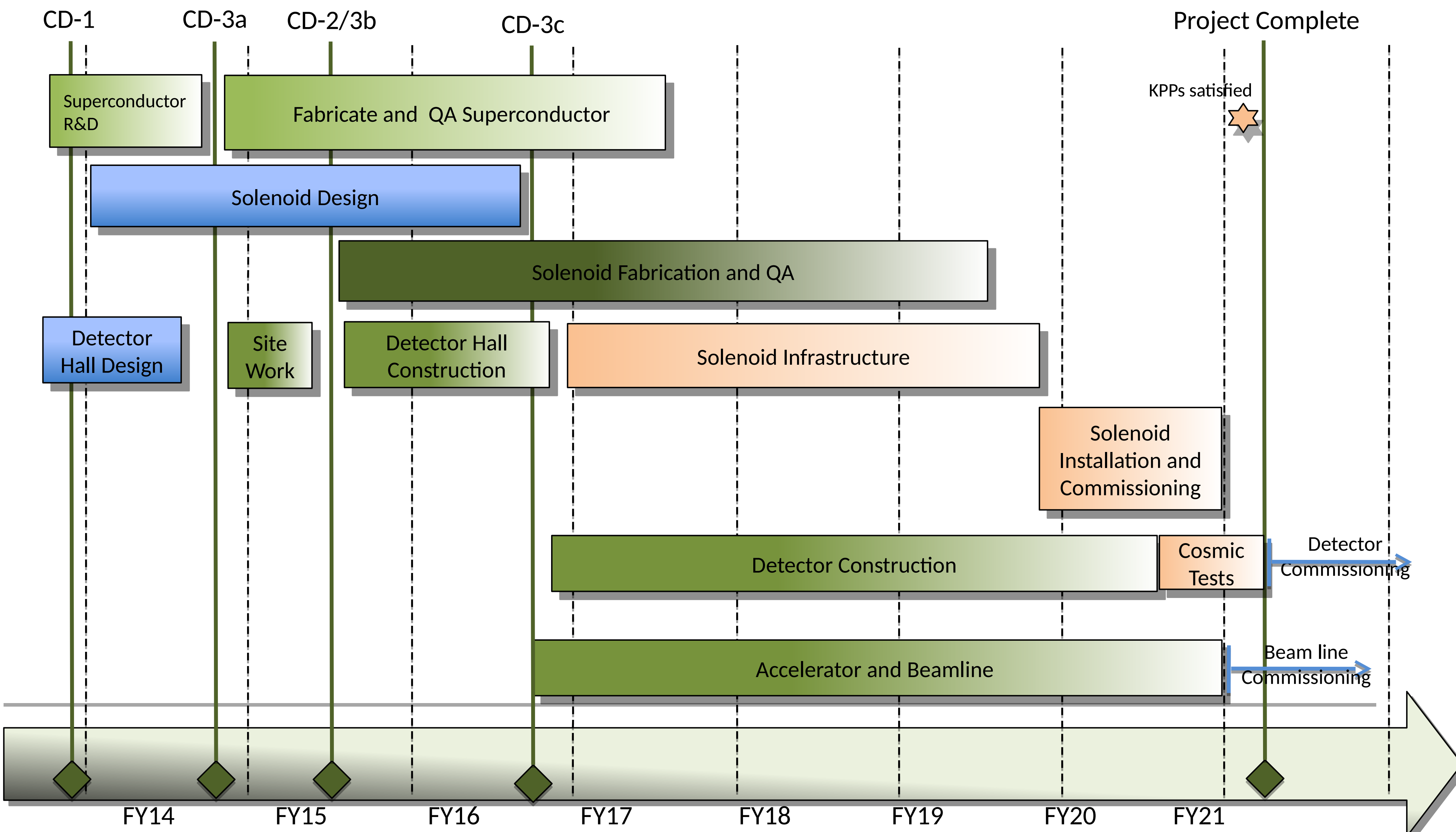
For a 3 year run with 3.6×10^{20} POT, we expect a nearly background free signal:

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

The single event sensitivity goal is 2.5×10^{-17}; our current estimate is 2.9×10^{-17}

We'll see a signal of 50 or more events for models that predict conversion at the 10^{-15} level

Mu2e has a technically limited schedule that will lead to data very early in the 2020s



Produced: February 2015

Mu2e recently achieved two major milestones: CD2/3b Approval from DOE

Office of High Energy Physics
Office of Science
Critical Decision 2 (CD-2)
Approve Performance Baseline and
Critical Decision 3b (CD-3b)
Approve Start of Phased Construction/Fabrication
Muon to Electron Conversion (Mu2e) Project

Approval

Based on the information presented in this approval document and at ESAAB Equivalent Review, CD-2, Approve Performance Baseline and CD-3b, Approve Start of Phased Construction/Fabrication, for the Mu2e Project is approved.

Patricia M. Dehmer, Acquisition Executive
Acting Director
Office of Science

3/4/2015
Date

Mu2e recently achieved two major milestones: Groundbreaking on the detector hall

We are making significant progress on R&D and prototypes in preparation for CD3 review

In summary

Within the next 10 years, Mu2e will either unambiguously discover cLFV or push the limit on muon conversion by four orders of magnitude.

For more information

•Mu2e Homepage: http://mu2e.fnal.gov

•Technical Design Report: http://arxiv.org/abs/1501.05241

Contact:

Doug Glenzinski, *douglasg@fnal.gov*,

or

Jim Miller, *miller@bu.edu*.

We normalize the conversions with the captures

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

Events in signal window

Acceptance for signal events

$$= \frac{N_{\mu e}/\epsilon_{\mu e}}{N_{\text{stops}}/\epsilon_{\text{stops}}\ \left(\Gamma_{\mu\nu}/\Gamma_{\text{total}}\right)}$$

Directly measured via cascade X-Rays

Well known nuclear capture ratio

Current conversion limits come from SINDRUM II at PSI

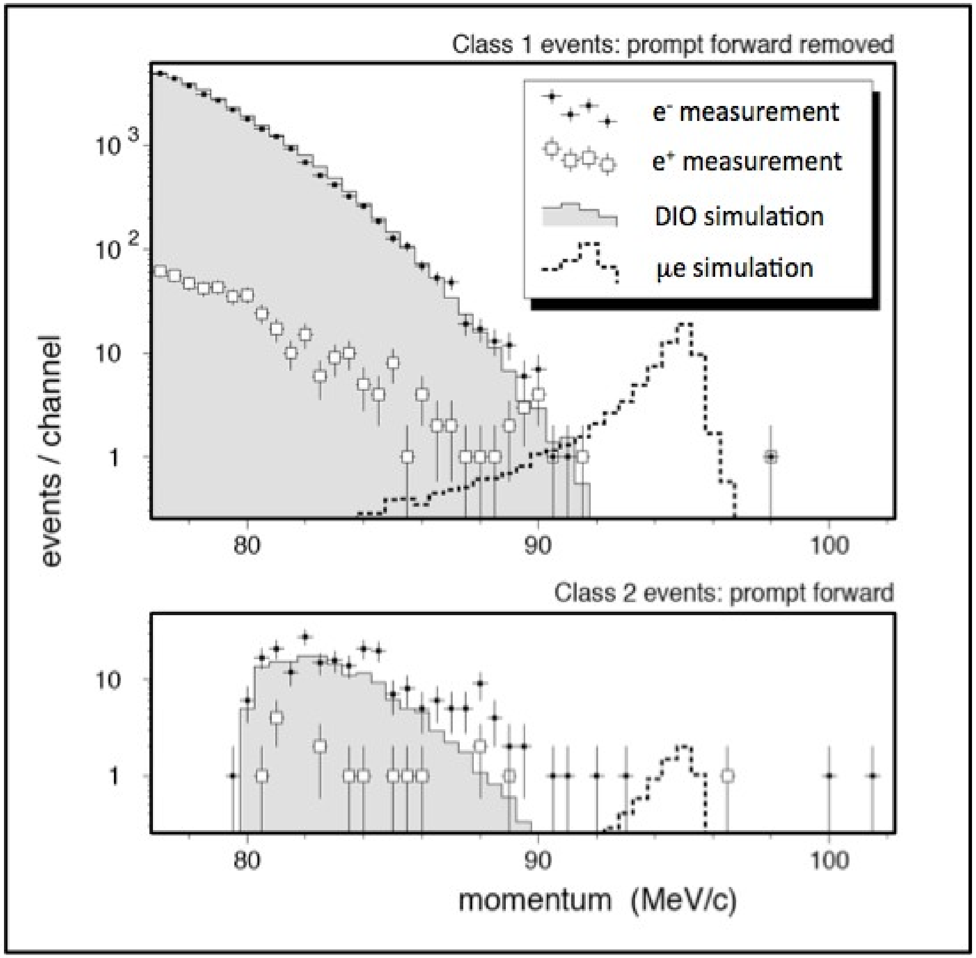
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

Final results on Au:

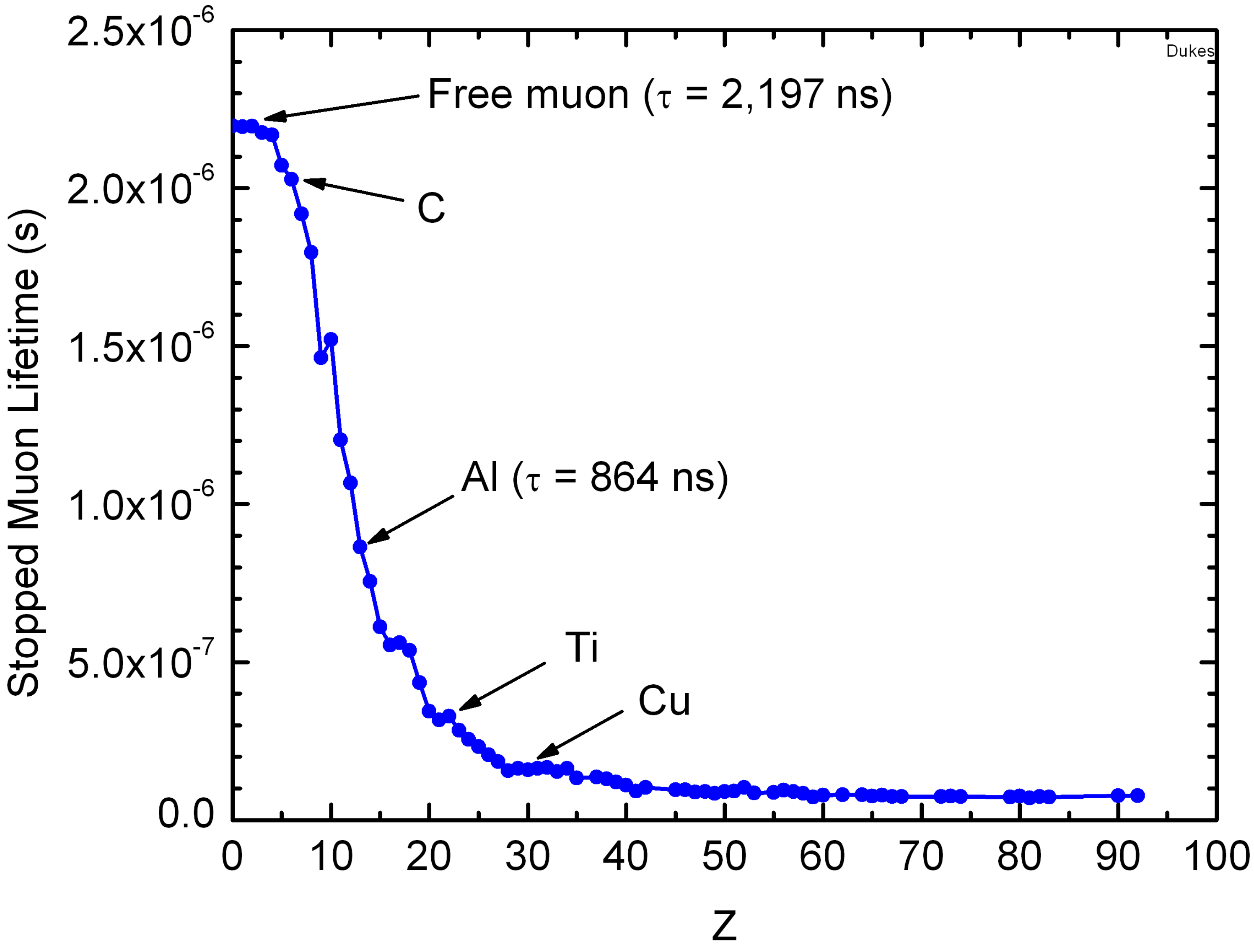
$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

One candidate event past the end of the spectrum. Pion capture, cosmic ray?

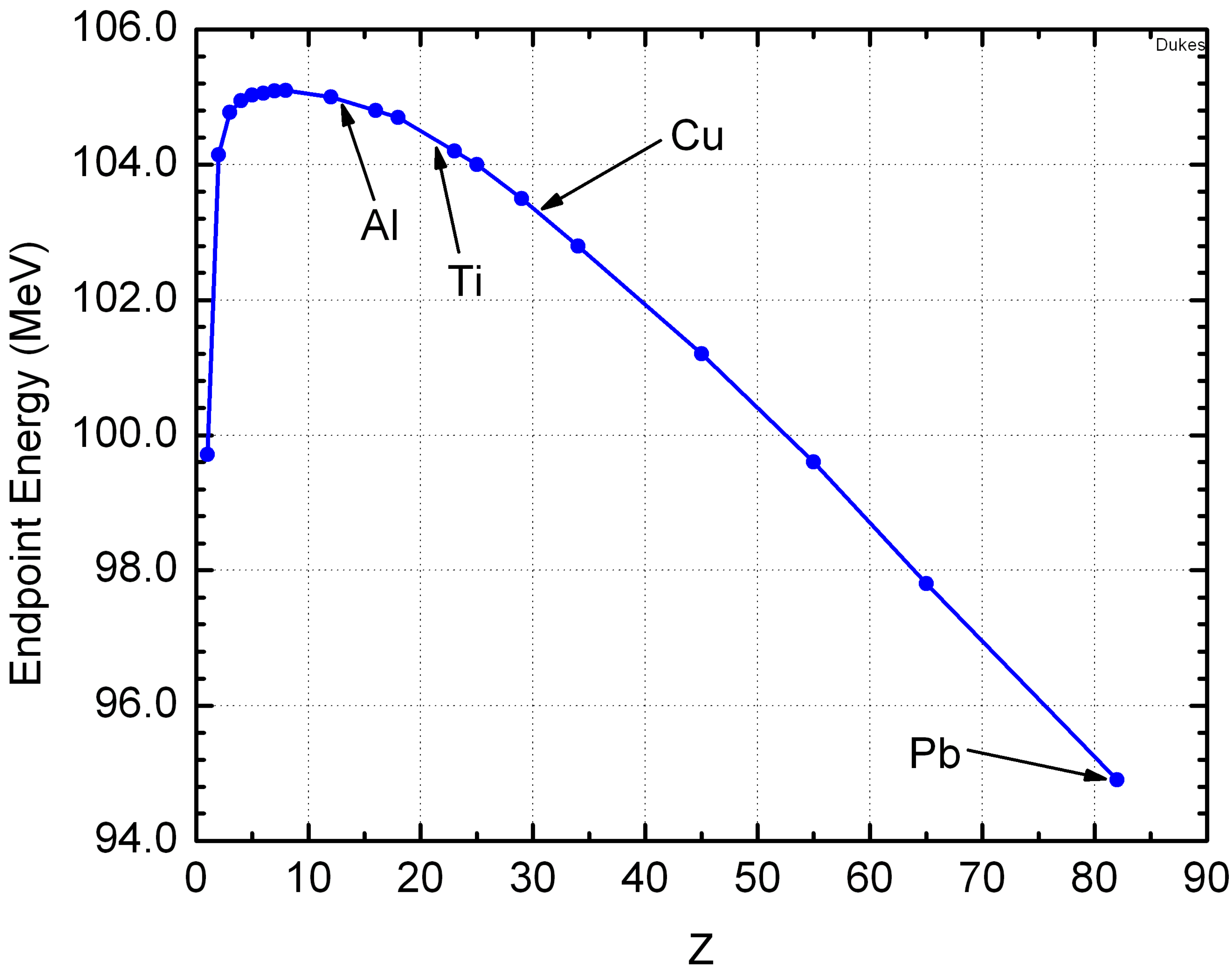
Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)



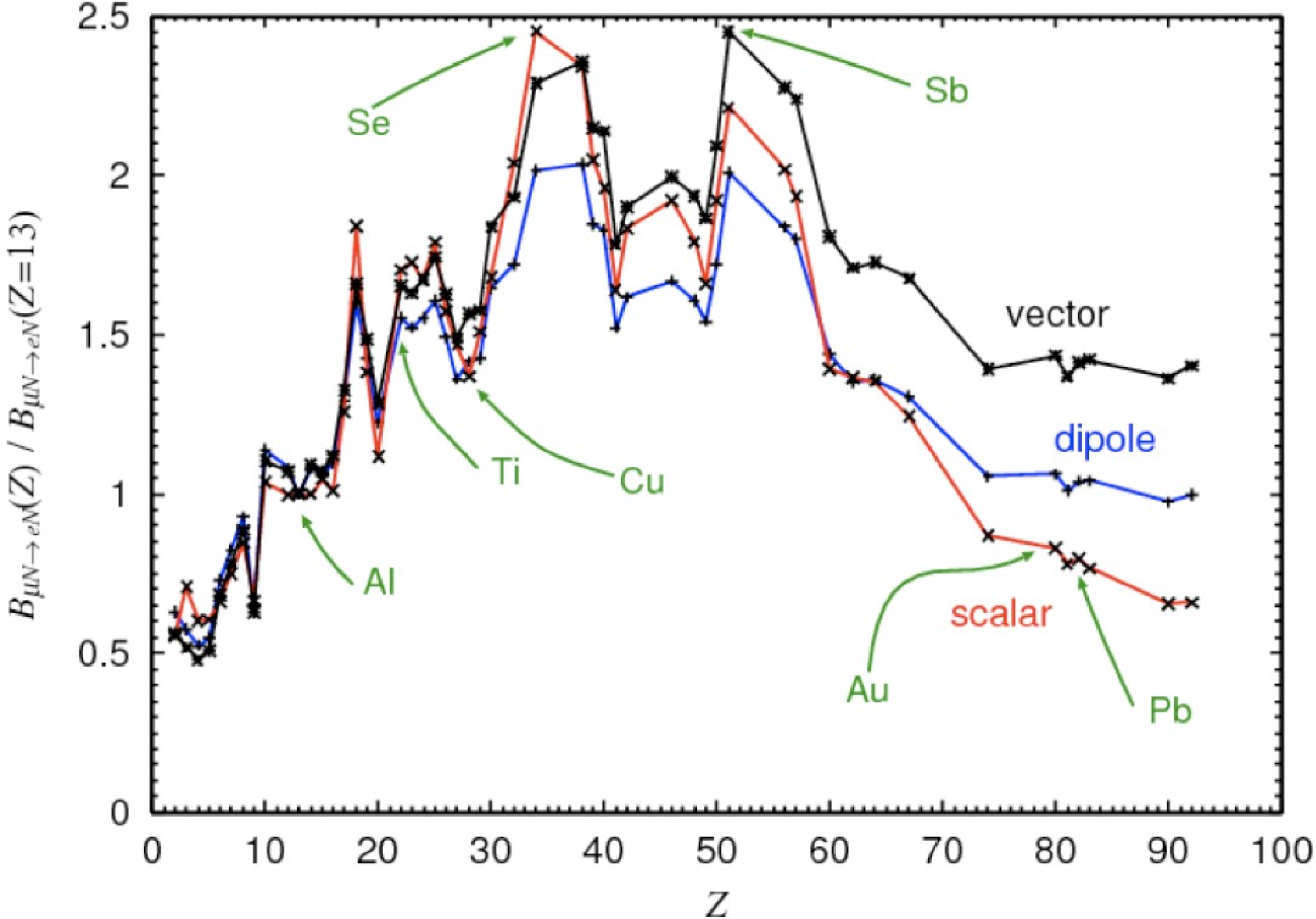
The choice of Al is well matched to the FNAL beam time structure



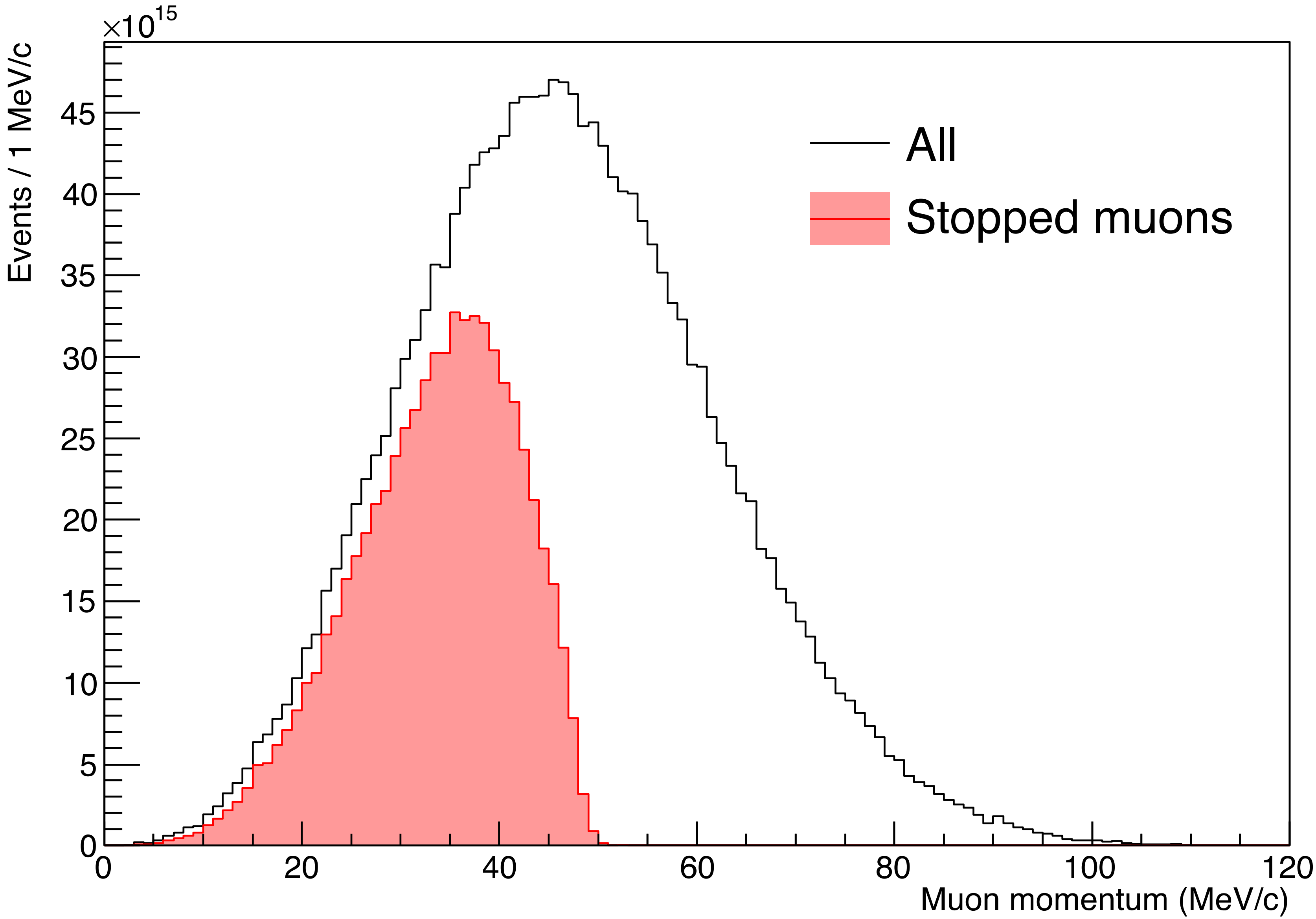
The endpoint energy is material dependent



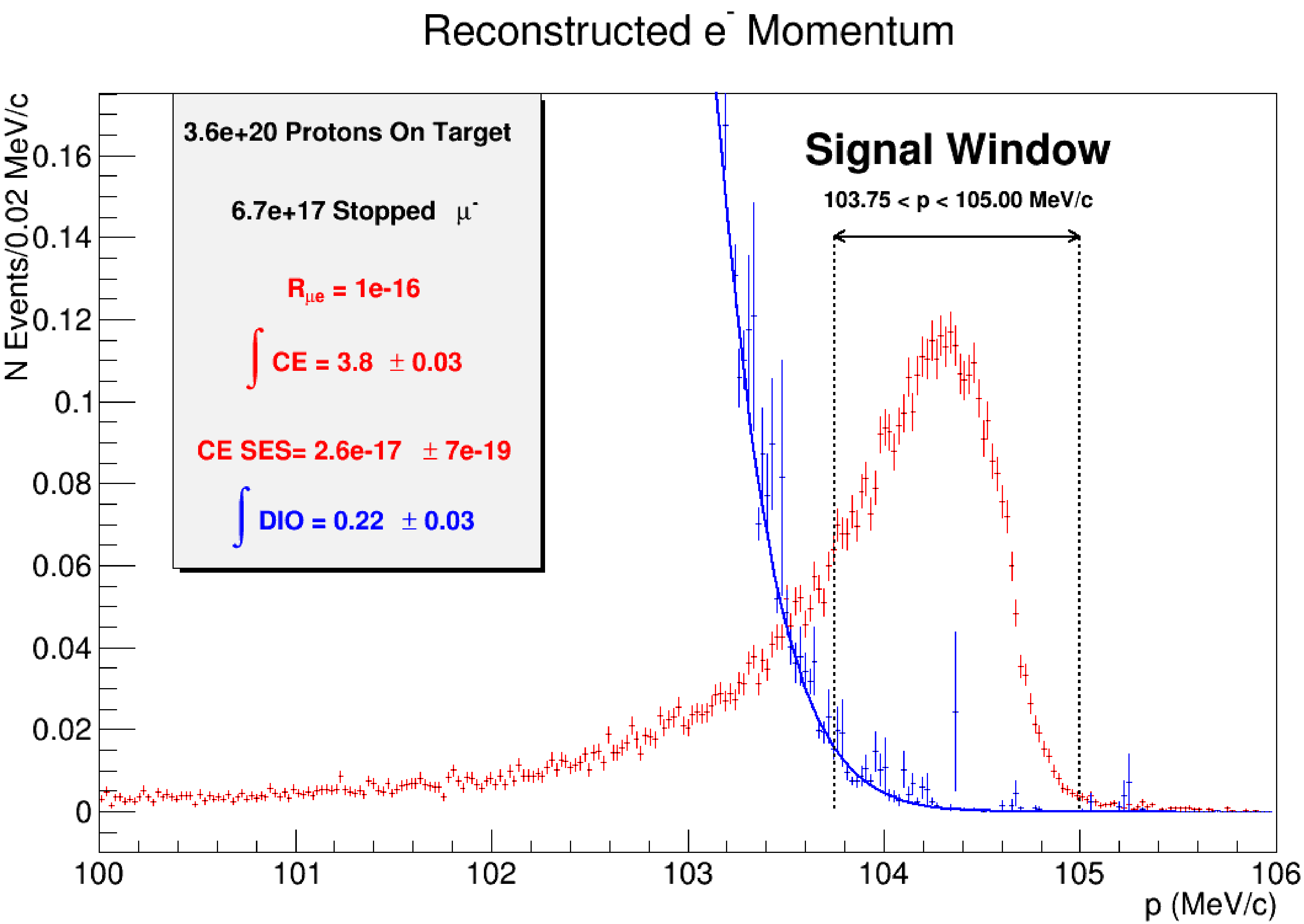
Different materials are sensitive to different operators



Muon momentum distributions at the stopping target



The signal box



Why cLFV searches?

Different SUSY and non-SUSY BSM models

★★★ Large effects

★★ Visible, but small

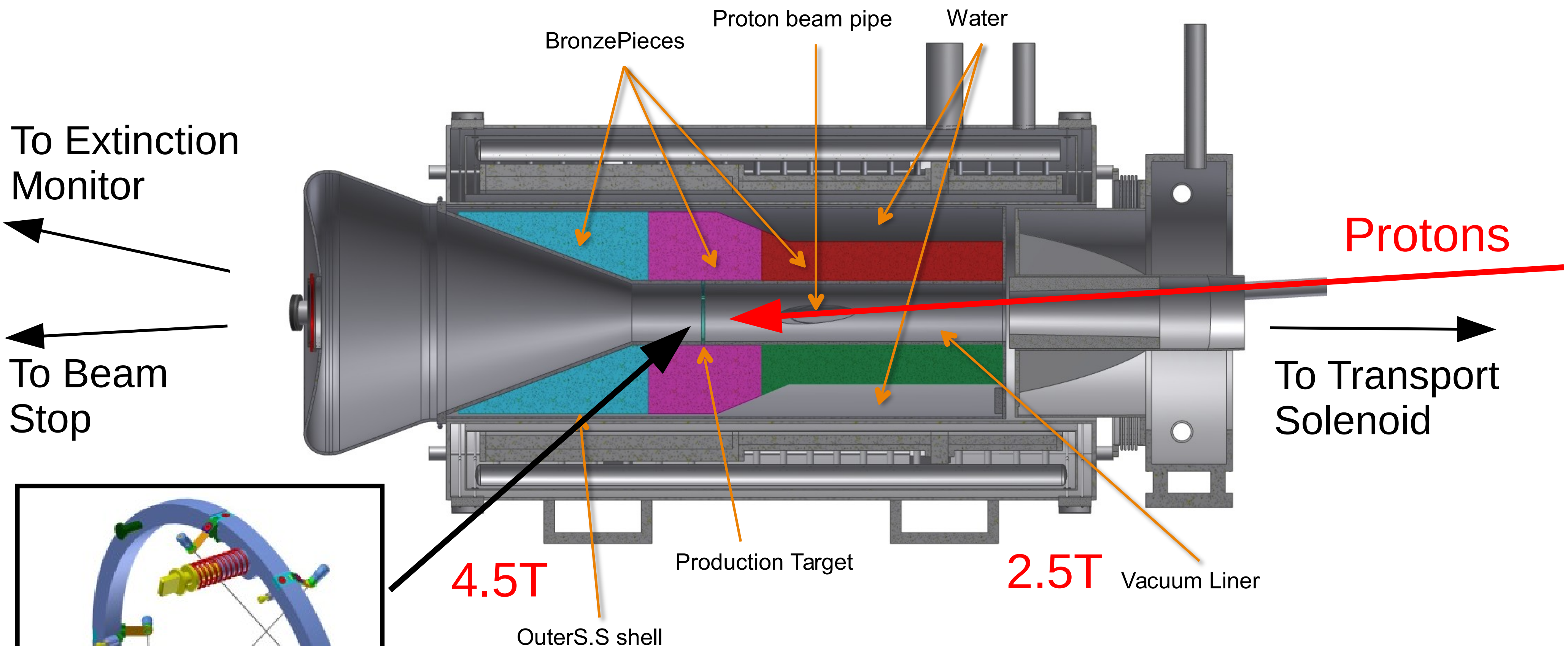
★ No sizable effect

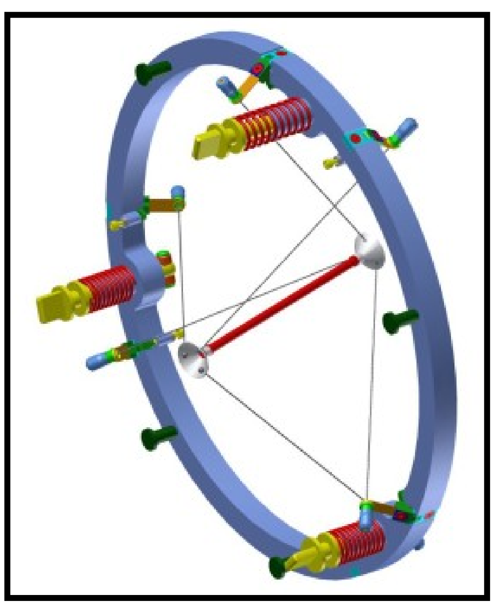
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Altmannshofer et al., NPB 830, 17 (2010)

The production solenoid produces a backward beam to reduce backgrounds

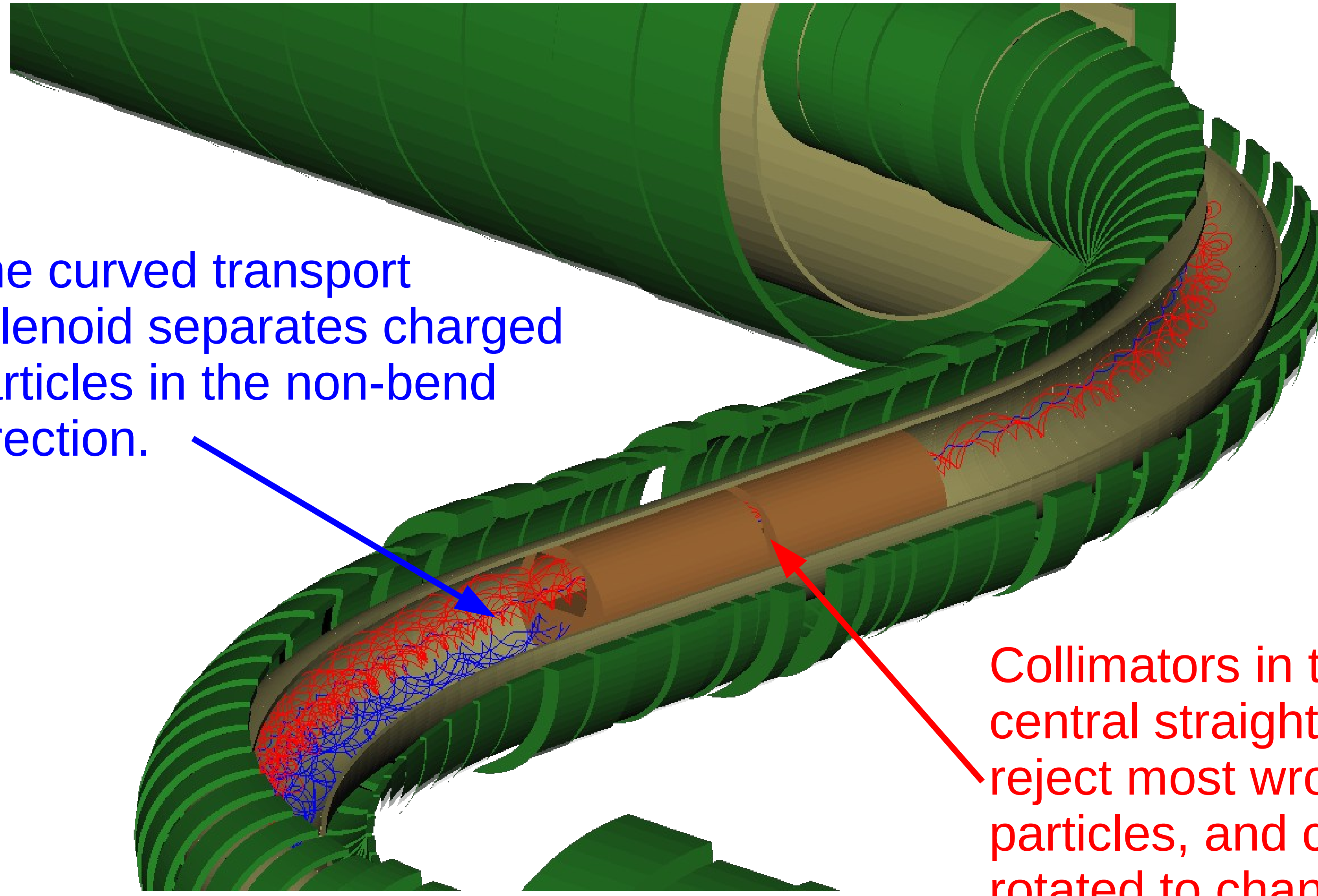




The tungsten production target is about the size of a pencil

The graded field acts as a “mirror” for charged particles, increasing the flux of muons into the TS

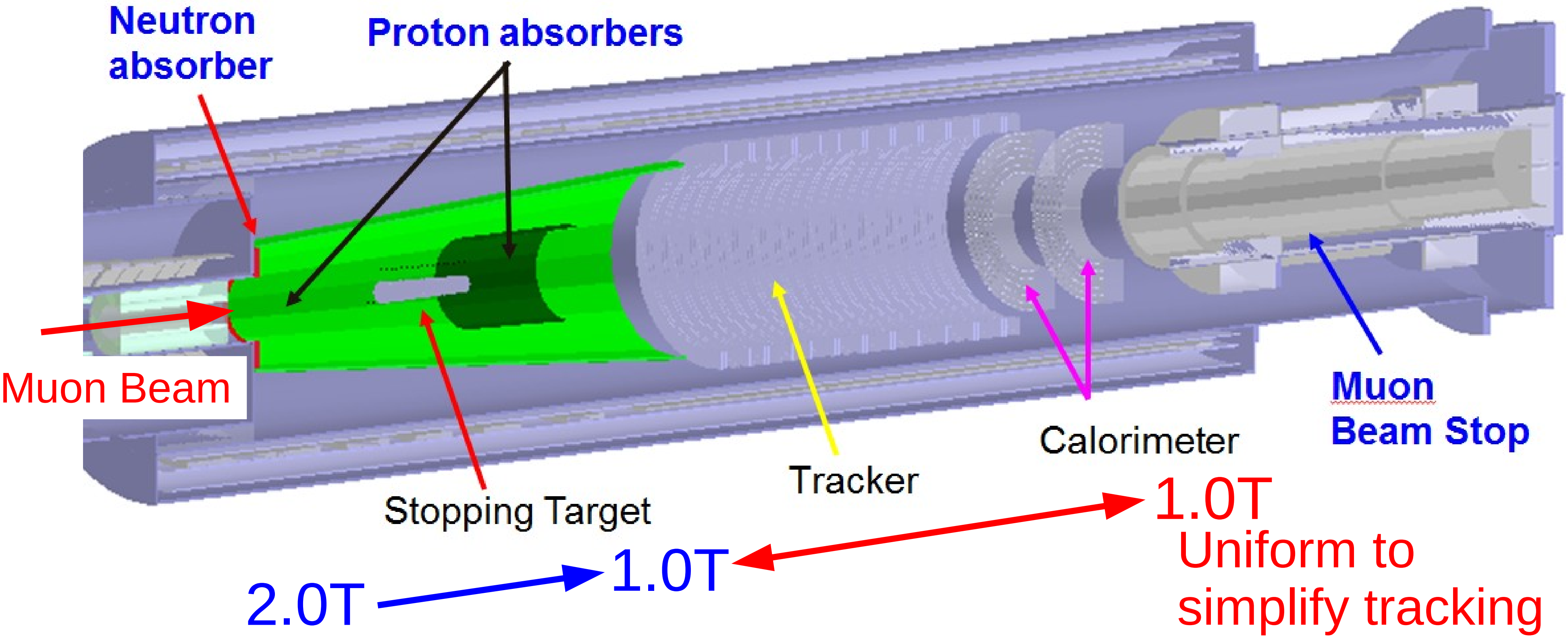
The transport solenoid sign selects charged particles



The curved transport solenoid separates charged particles in the non-bend direction.

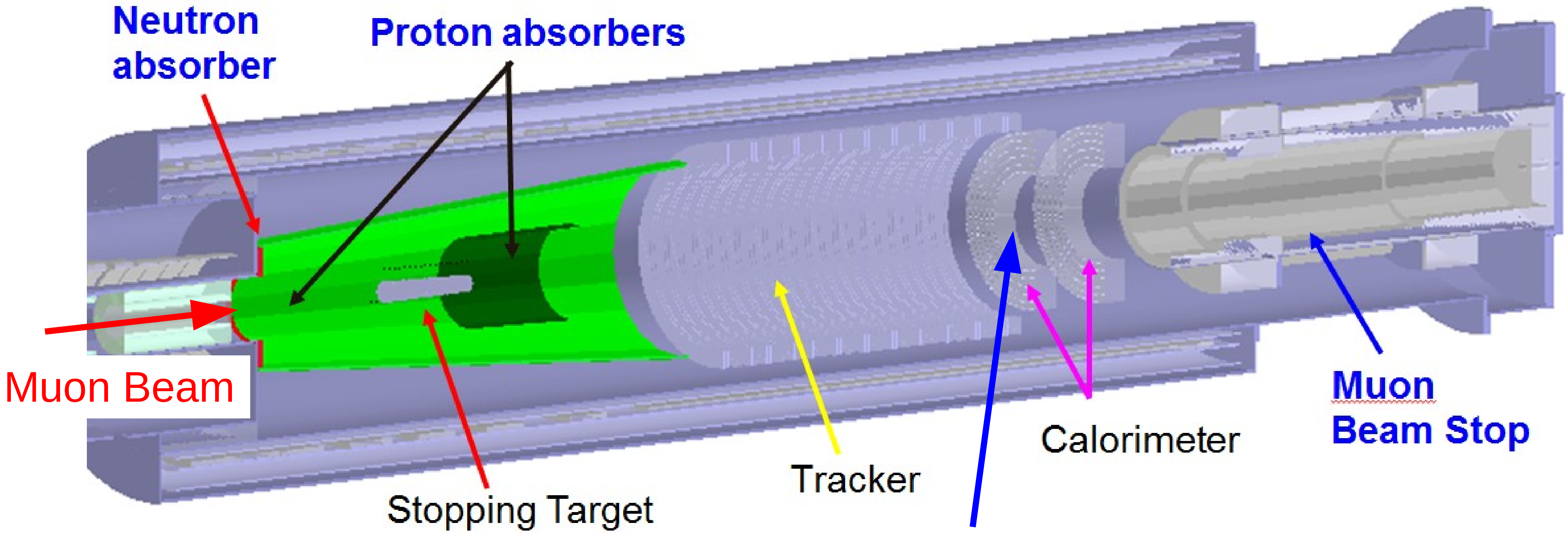
Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

The detector solenoid forms the heart of the experiment

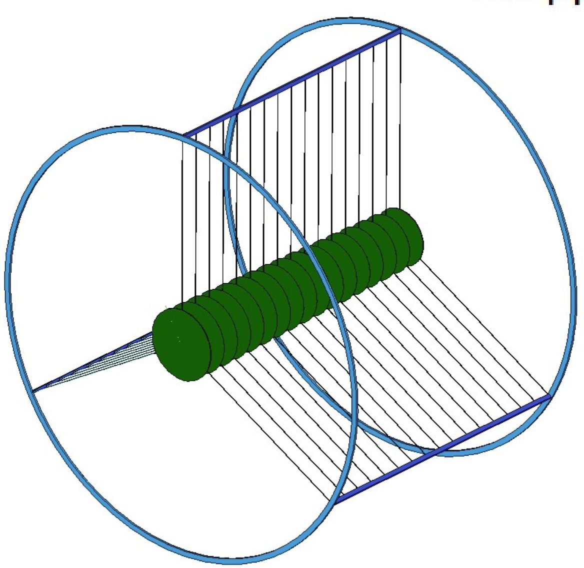


Graded to reflect electrons toward the tracker

The detector solenoid forms the heart of the experiment

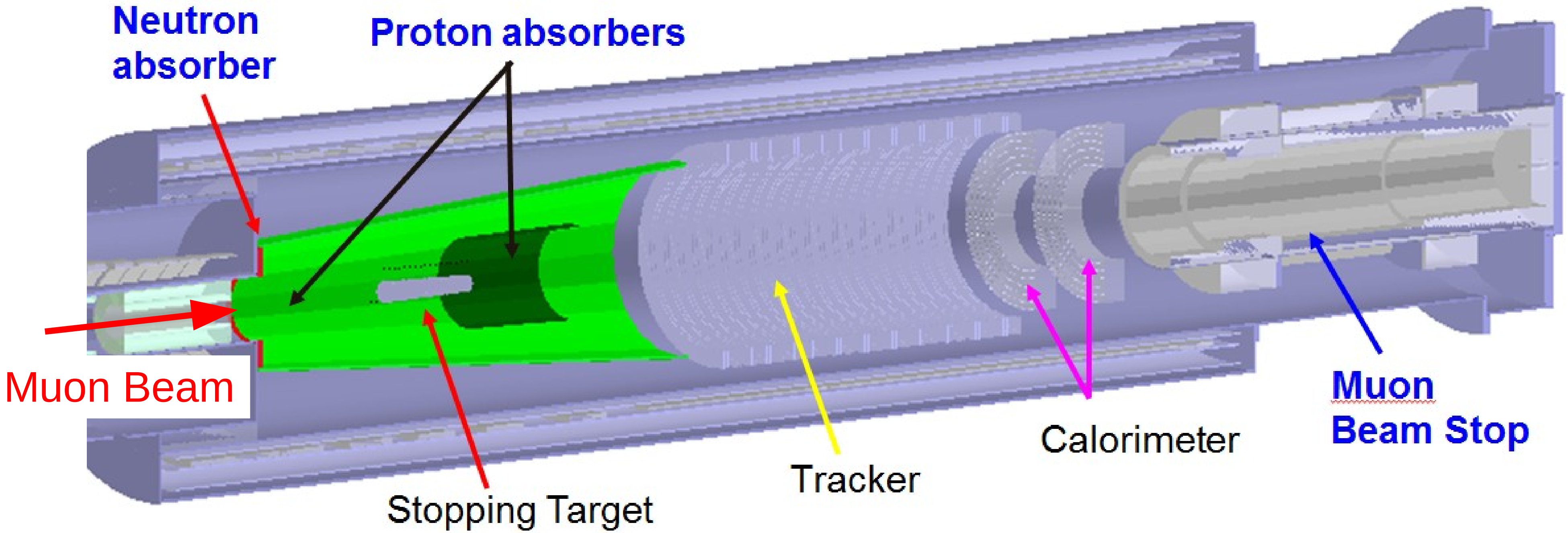


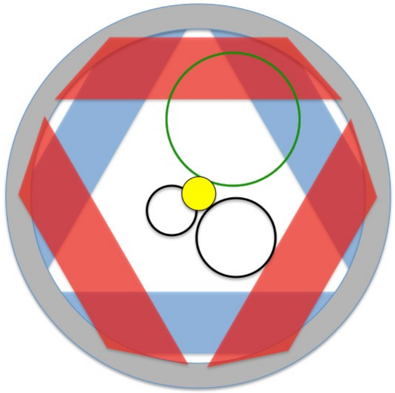
The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.

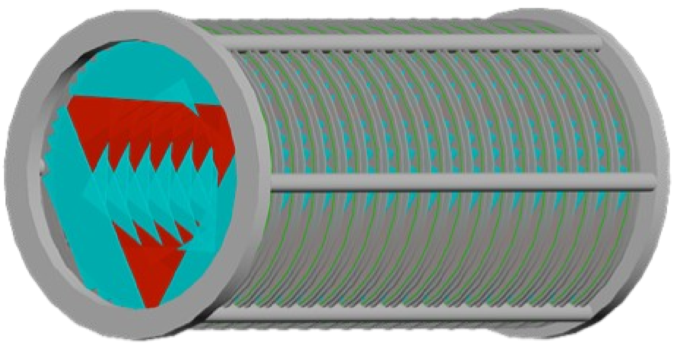


The stopping target is 17 Al foils to intercept and stop the secondary beam

The detector solenoid forms the heart of the experiment

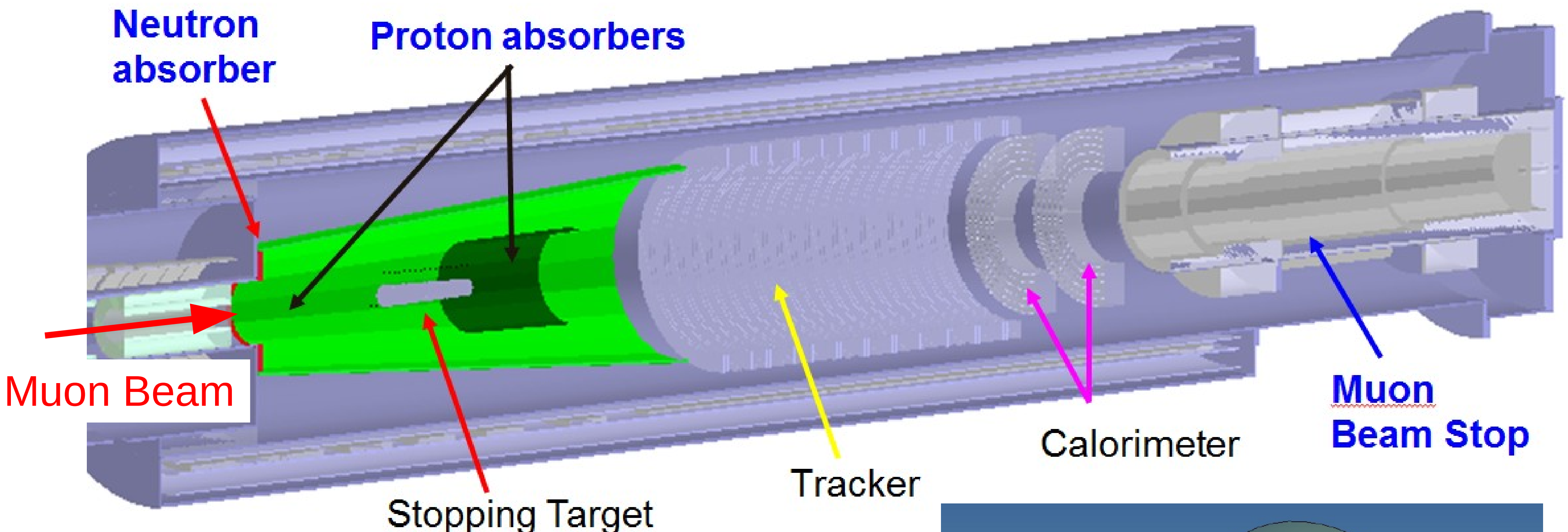




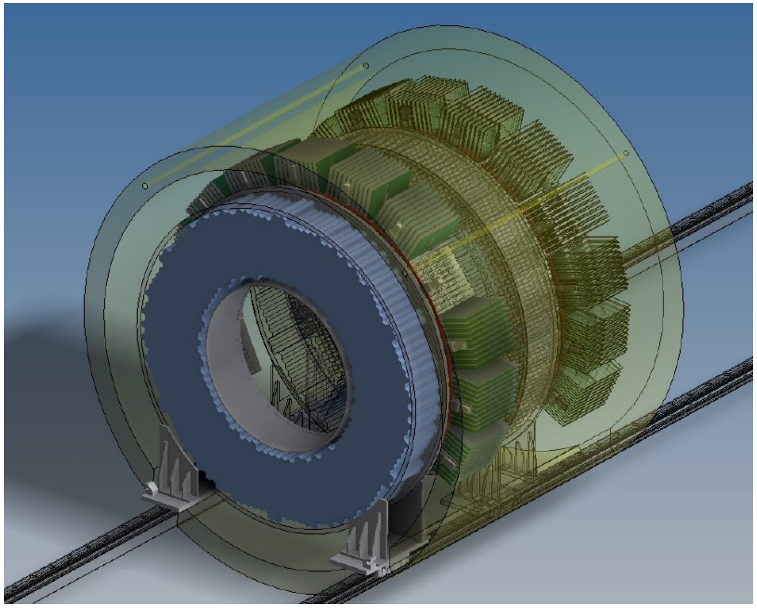


The electron tracker is a low mass straw tube design with 18 planes of tubes transverse to the secondary beam

The detector solenoid forms the heart of the experiment



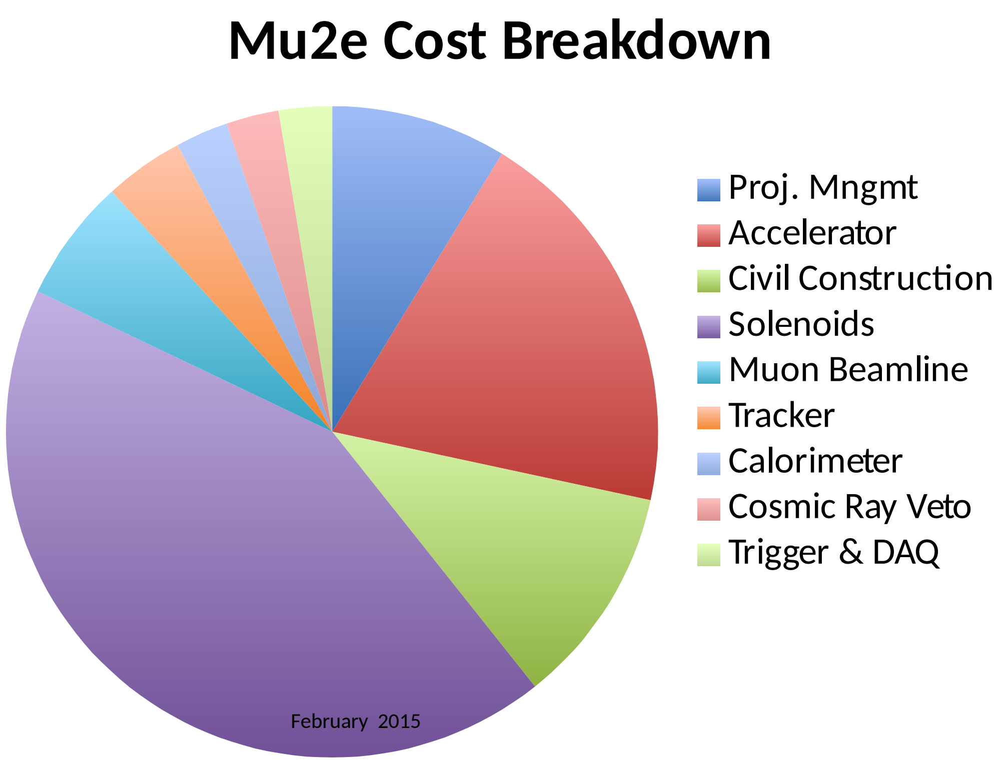
The calorimeter is a two layer, annular crystal calorimeter



Mu2e Total Project Cost

	Total Cost (AY)
Project Management	$21M
Accelerator	$40M
Civil Construction	$21M
Solenoids	$88M
Muon Beamline	$19M
Tracker	$12M
Calorimeter	$5M
Cosmic Ray Veto	$7M
Trigger & DAQ	$5M
Sub-Total	$218M
Contingency	$56M
Total	$274M

February 2015



- All figures are escalated and include overheads