Studies toward a next-generation Mu2e experiment

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Roadmap

- The next-generation study
- The physics of Mu2e
- The Mu2e experiment
- Why PIP-II is important to Mu2e
- Studies toward Mu2e-II

In what follows…	
Mu2e	Current (baseline) Mu2e experiment
Mu2e-II	Next-generation Mu2e using Project-X/PIP-II

The Project-X Mu2e study (2013)

- A concentrated study was undertaken by Mu2e collaborators to determine the feasibility of a next-generation Mu2e experiment.
  - Dedicated session at Snowmass for next-gen. Mu2e
- Our work is summarized here:
  - K. Knoepfel, *et al*, "Feasibility Study for a Next-Generation Mu2e Experiment", `arXiv:1307.1168`
  - A. Kronfeld, *et al*, "Project X: Physics Opportunities", `arXiv:1306.5009`
- Since then, the Mu2e collaboration has been working hard toward DOE CD2 approval (TDR) of the <u>baseline</u> experiment.

The Project-X Mu2e study (2013)

- A concentrated study was undertaken by Mu2e collaborators to determine the feasibility of a next-generation Mu2e experiment.
- u2e
  68
  es”,

(1) The studies shown today are based on those done for Snowmass – *i.e.* not 800 MeV.

(2) For today I concentrate on issues that are downstream of the primary beamline.

- Since then, the Mu2e collaboration has been working hard toward DOE CD2 approval (TDR) of the <u>baseline</u> experiment.

Beamline assumptions

	Baseline Mu2e	
Beam kinetic energy	8	GeV
Beam power	8	kW
Protons-on-target (POTs)	**3.6×10^{20}**	
Run duration	3	years
Run time	2×10^{7}	sec/year
Duty factor	0.32	
POT pulse full width	200	ns
POT pulse spacing	1695	ns
POT extinction*	$< 10^{-10}$	

*fraction of POTs between proton pulses

Beamline assumptions

	Baseline Mu2e		Project X (Al)	
Beam kinetic energy	8	GeV	1	GeV
Beam power	8	kW	112	kW
Protons-on-target (POTs)	**3.6×10^{20}**		**4.0×10^{22}**	
Run duration	3	years	3	years
Run time	2×10^{7}	sec/year	2×10^{7}	sec/year
Duty factor	0.32		0.90	
POT pulse full width	200	ns	100	ns
POT pulse spacing	1695	ns	1695	ns
POT extinction*	$< 10^{-10}$		$< 10^{-12}$	

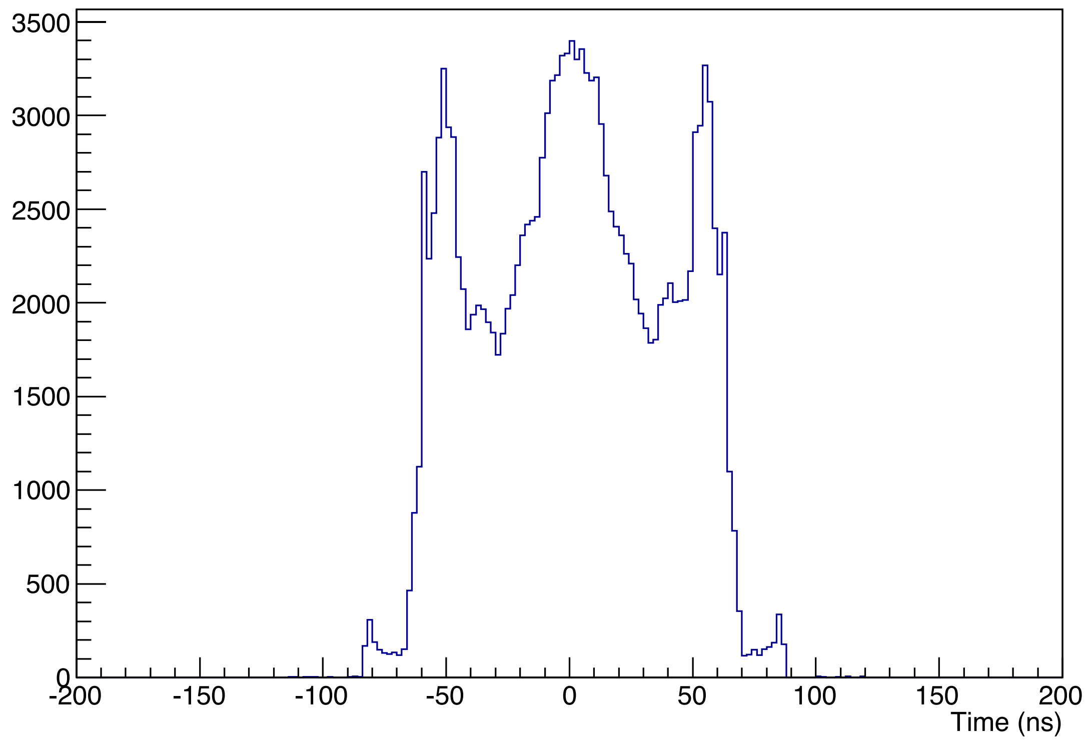
*fraction of POTs between proton pulses

Beamline assumptions

	Baseline Mu2e		Project X (Al)		PIP-II	
Beam kinetic energy	8	GeV	1	GeV	800	MeV
Beam power	8	kW	112	kW	100	kW
Protons-on-target (POTs)	**3.6×10^{20}**		**4.0×10^{22}**		4.5×10^{22}	
Run duration	3	years	3	years	3	years
Run time	2×10^{7}	sec/year	2×10^{7}	sec/year	2×10^{7}	sec/year
Duty factor	0.32		0.90			
POT pulse full width	200	ns	100	ns		
POT pulse spacing	1695	ns	1695	ns		
POT extinction*	$< 10^{-10}$		$< 10^{-12}$		$< 10^{-12}$	

*fraction of POTs between proton pulses

Assumed POT time distribution



- Timing structure due to artifacts of matching the 53 MHz beam from booster to the 2.5 MHz bucket in the recycler.
- For more details, see:

Mu2e Conceptual Design Report, Ch. 5.
`arXiv:1211.7019 [physics.ins-det]`

The physics

- Mu2e is an experiment searching for charged lepton flavor violation (CLFV) in muons:

$$\mu^- + \mathbf{Al} \rightarrow e^- + \mathbf{Al}$$

- This reaction is suppressed by the standard model (SM) to a level smaller than $\mathbf{10^{-50}}$.

- Allowed by many beyond-the-SM (BSM) models at levels just beyond current experimental limits.

- Excellent avenue for new physics exploration.

What is Mu2e measuring?

- Measure ratio of $\mu \rightarrow e$ conversions (CLFV) to the number of μ captures (SM).

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)]}$$

(BSM)

(SM)

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- Mu2e goal for *R*:
  - Single-event-sensitivity: 2.5×10^{-17}
  - Upper limit (90% C.L.): $\sim 1 \times 10^{-16}$
  - Probe BSM eff. mass scales of: $10^3 - 10^4$ TeV/c^2

- Experimental signature?

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- Experimental signature?

Need at least **10^{18}** muons.

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- Experimental signature?

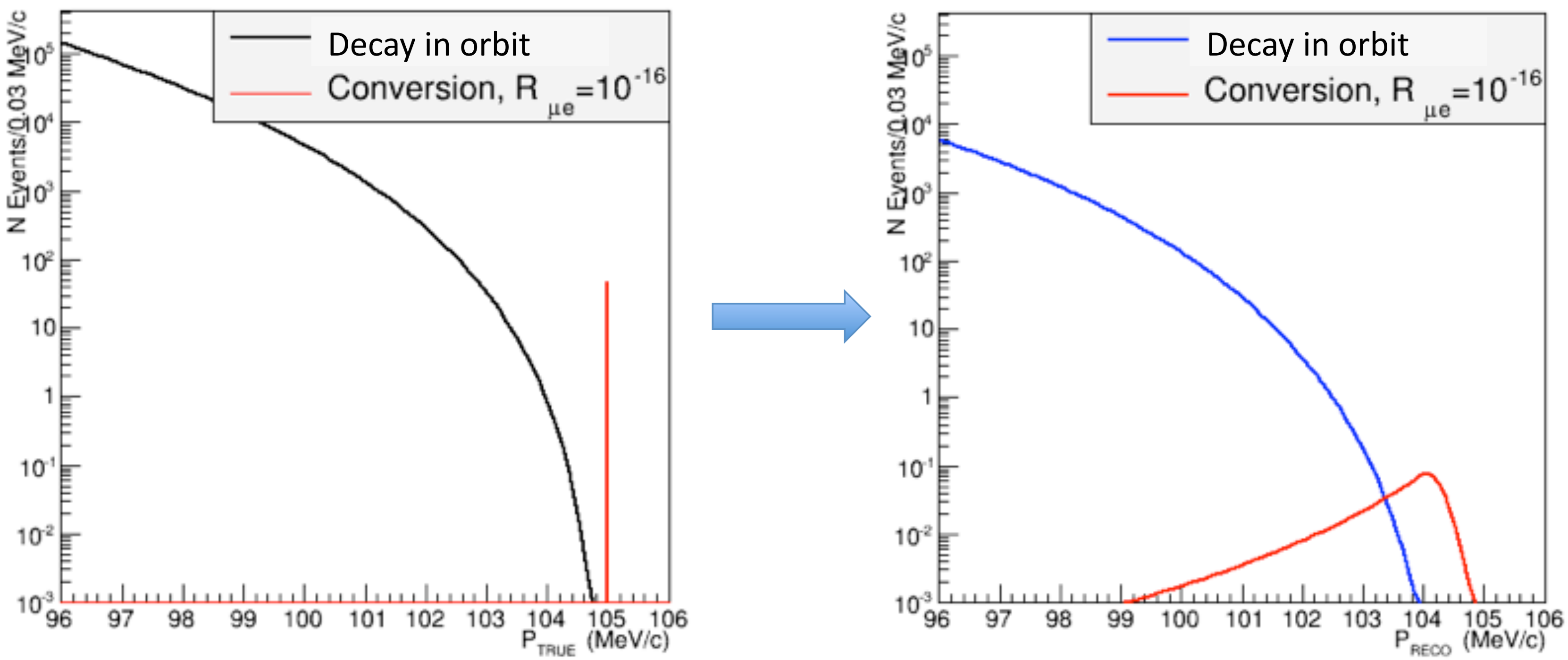
$$\begin{aligned} E_e &= m_\mu c^2 - E_b - E_{\mathrm{recoil}} \\ &= 104.973 \text{ GeV} \quad (\text{for Al}) \end{aligned}$$

What is Mu2e measuring?

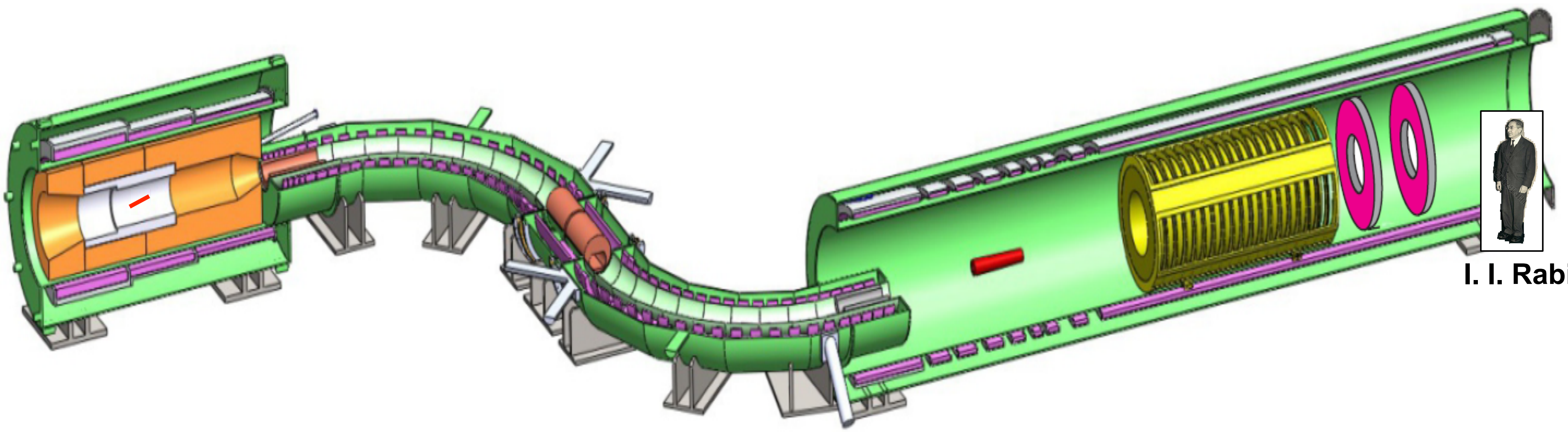
- Measure ratio of μ→e conversions (CLFV) to the

- Other effects decrease and smear out the mono-energetic peak
- Signal peak runs into another background from muon decays-in-orbit

$$\mu^- + N \rightarrow e^- \overline{\nu}_e \nu_\mu + N$$



Baseline Mu2e Apparatus



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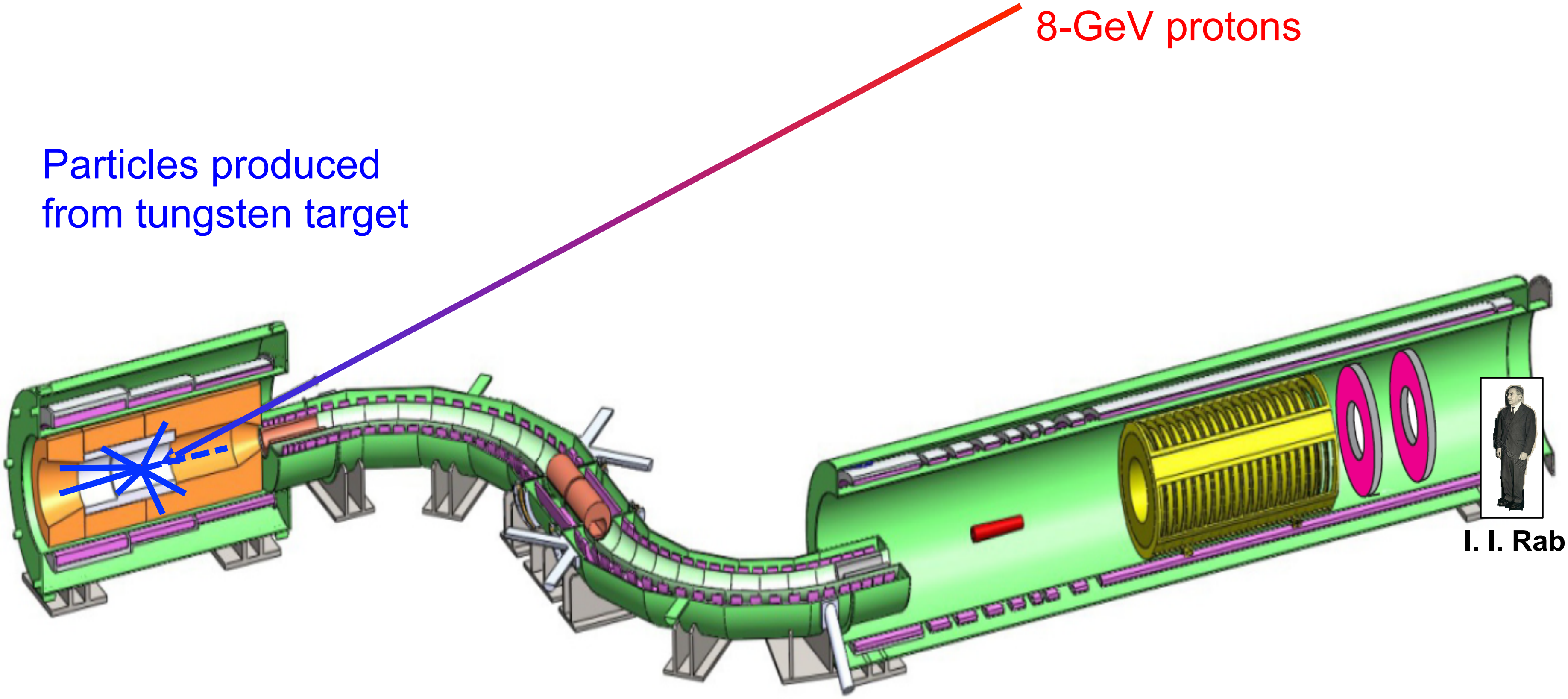

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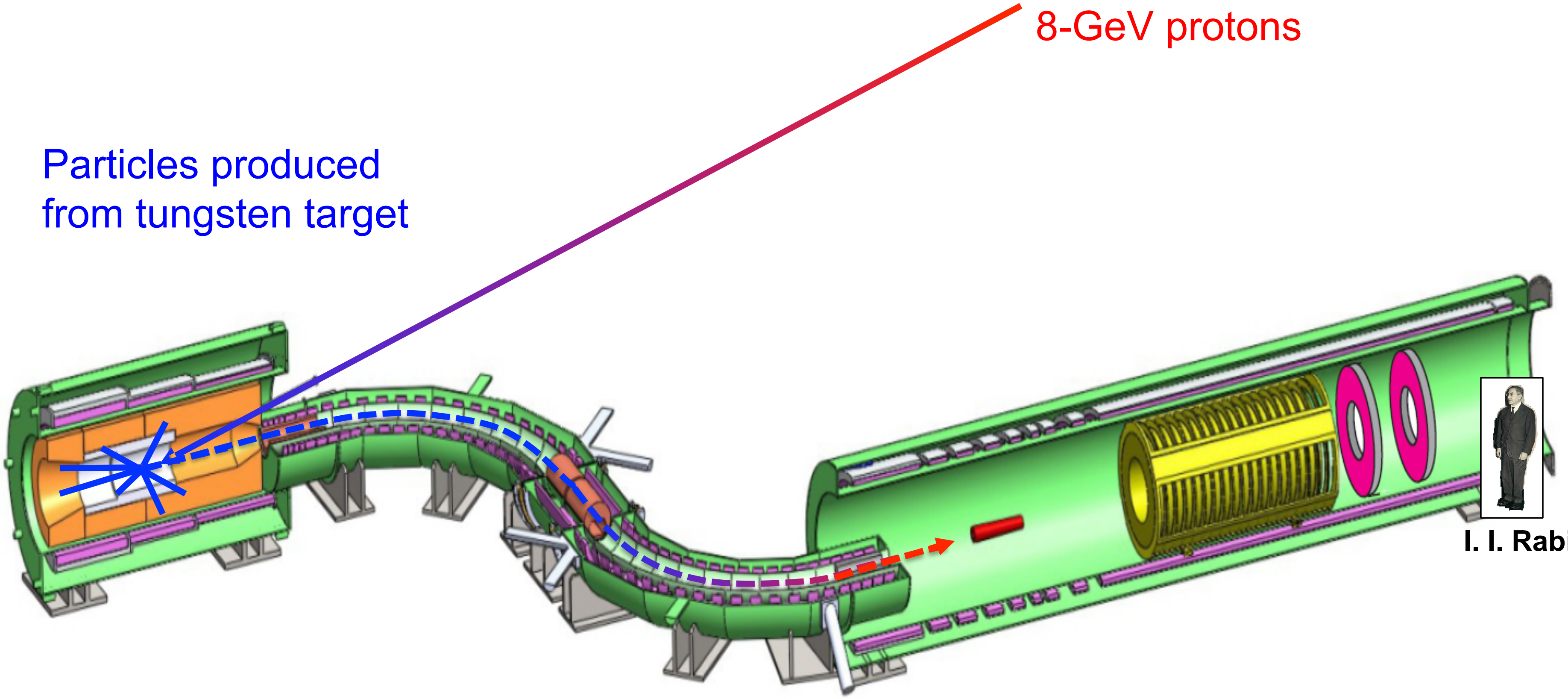
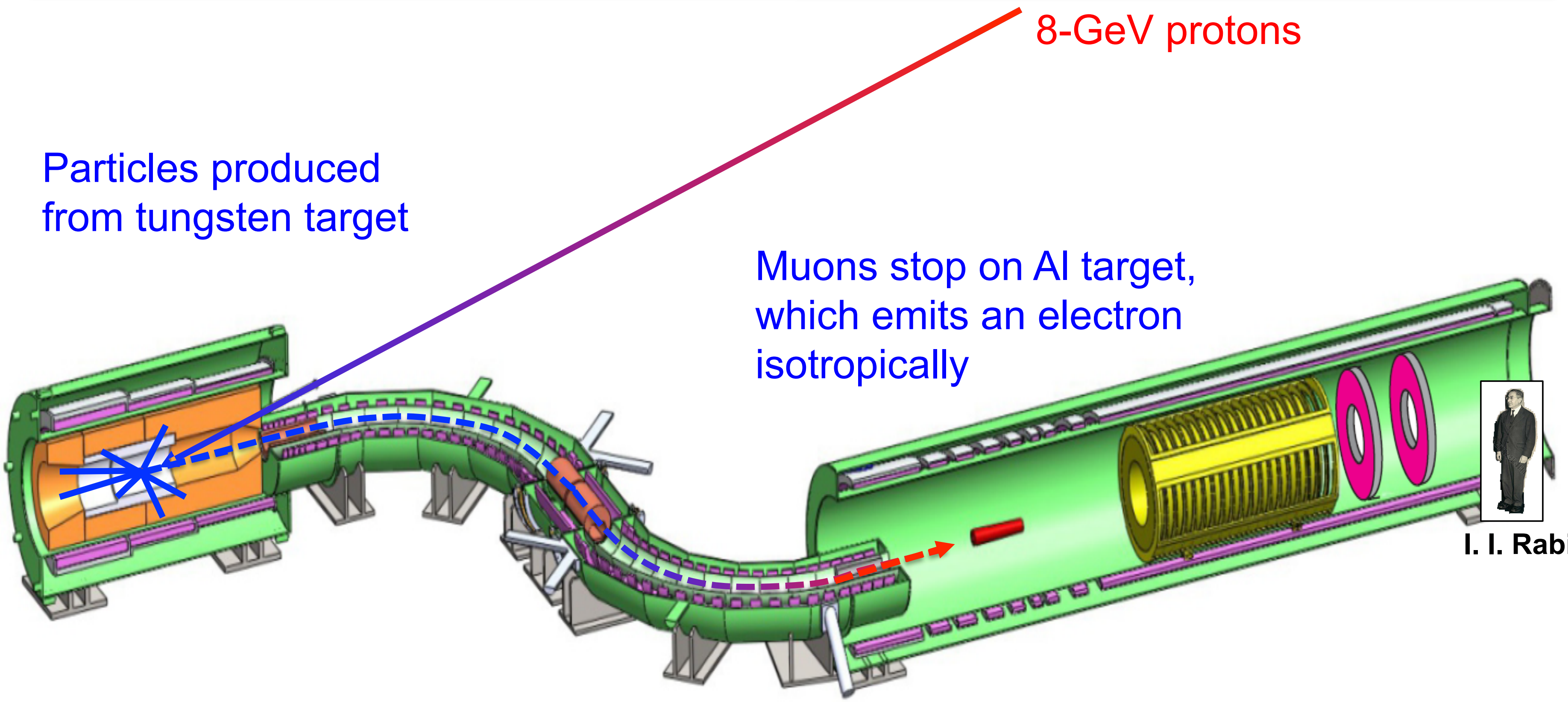


S-shaped solenoid:

- collimator selects negatively-charged particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

Baseline Mu2e Apparatus



S-shaped solenoid:
- collimator selects negatively-charged particles
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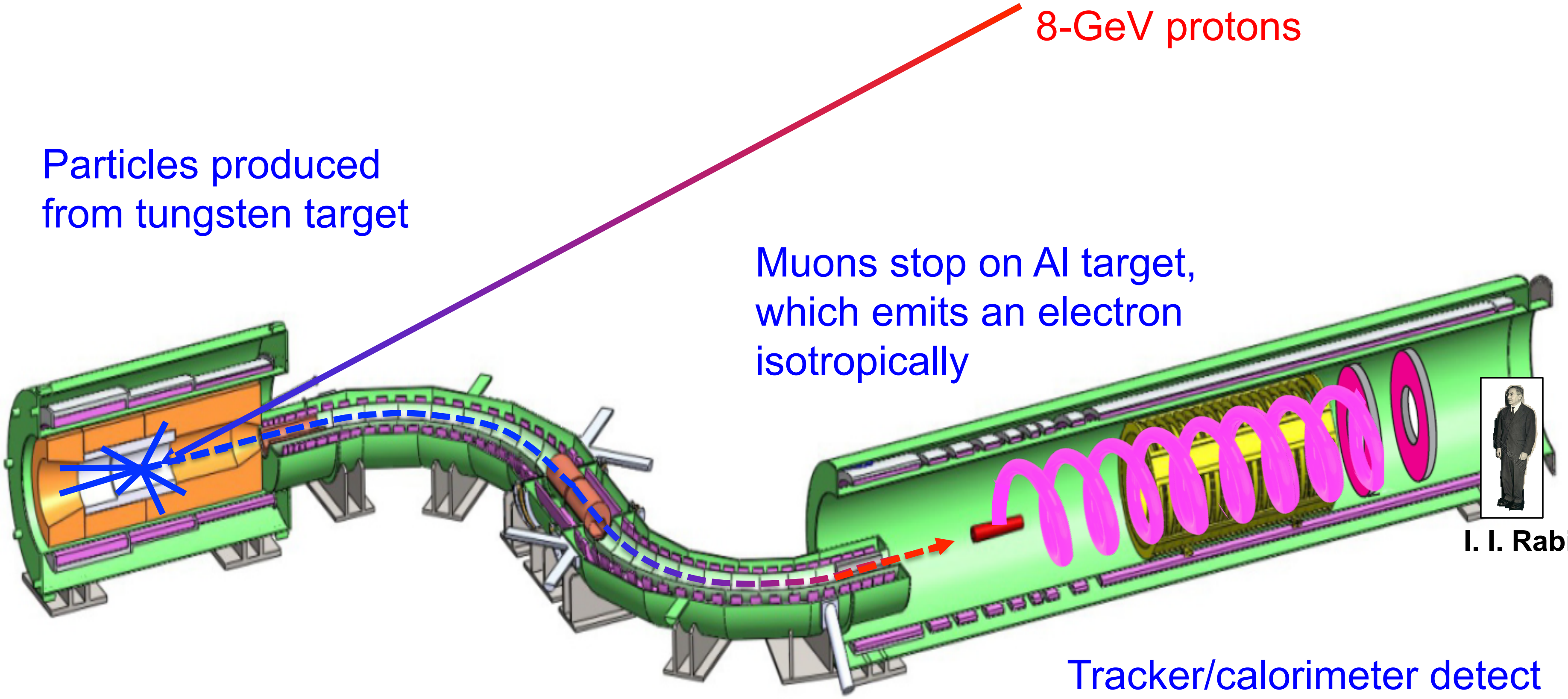
Baseline Mu2e Apparatus

Particles produced
from tungsten target

Muons stop on Al target,
which emits an electron
isotropically



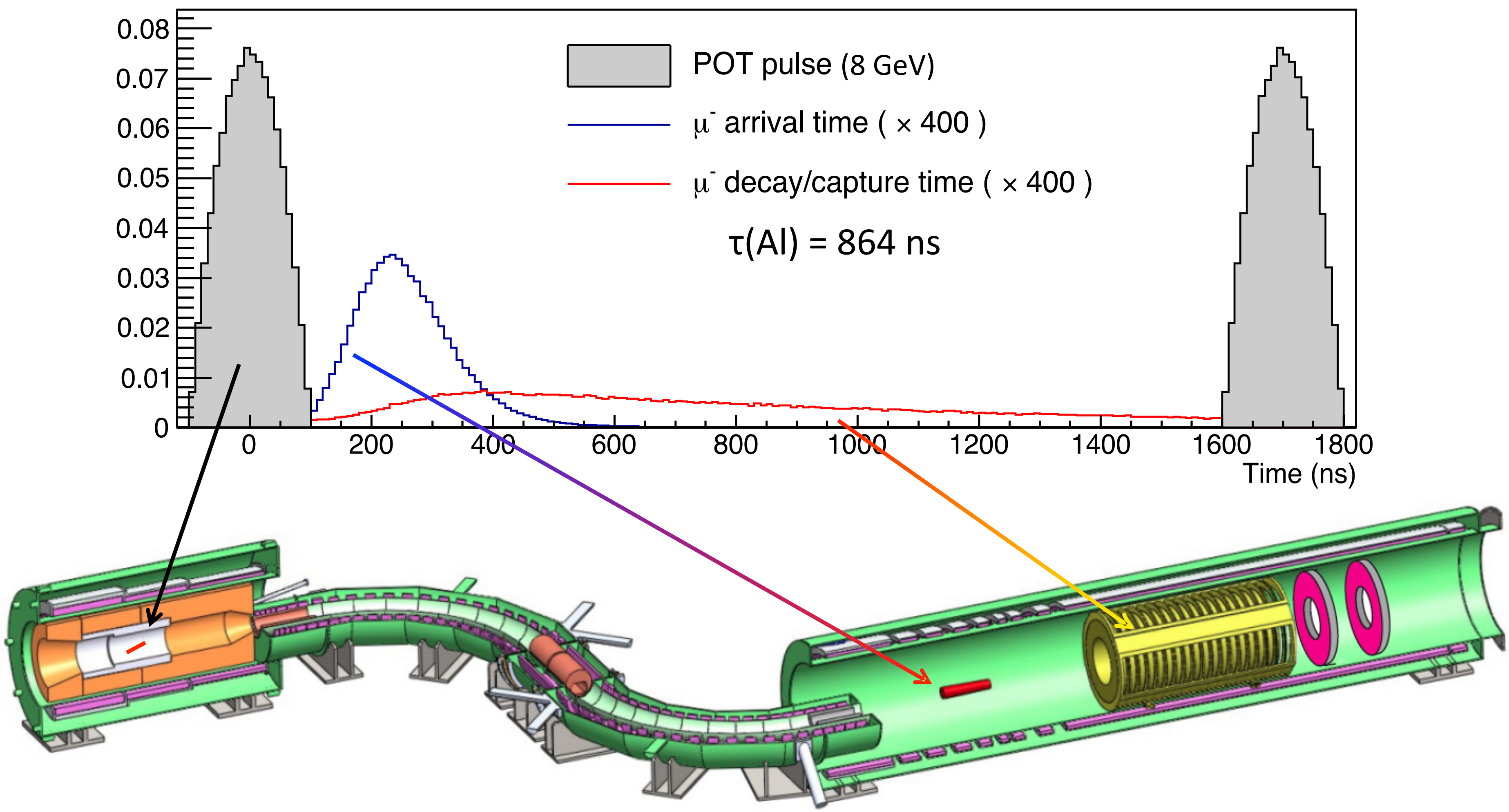
Tracker/calorimeter detect
electron signature

S-shaped solenoid:

- collimator selects negatively-charged particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

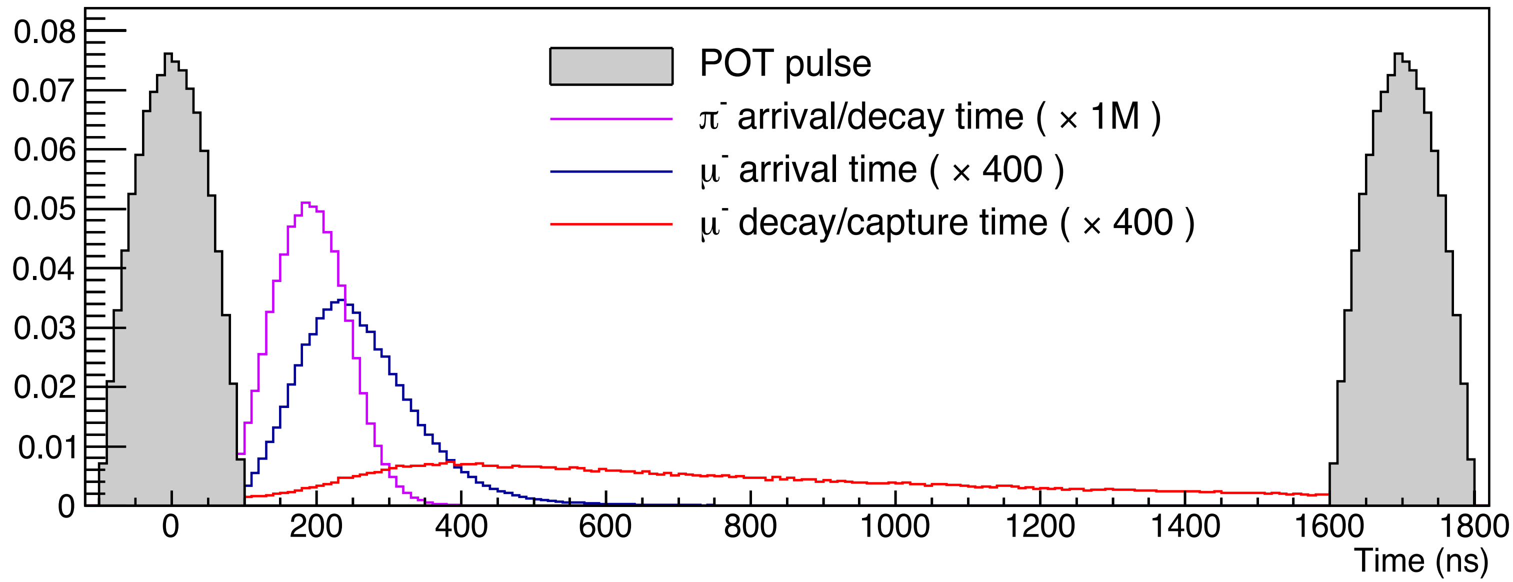
Baseline Mu2e Apparatus

Timing is important…



Baseline Mu2e

Timing is important…



- Significant background is radiative pion capture (RPC)

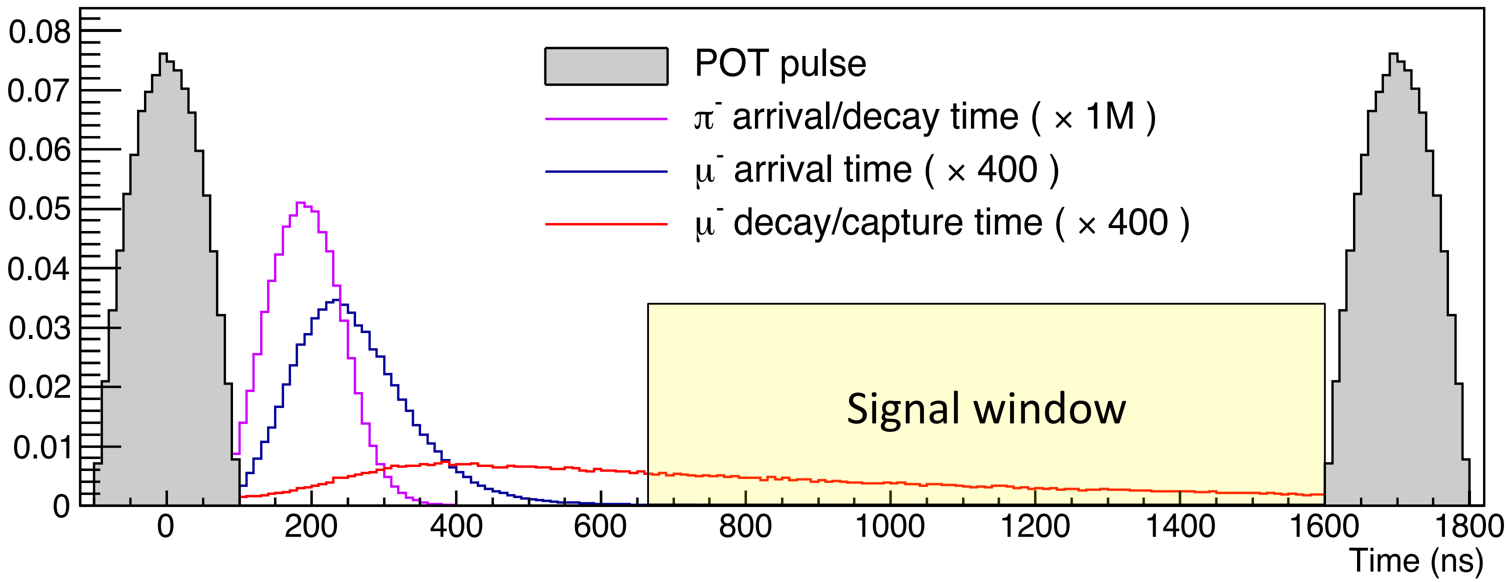
$$\pi^- + \mathbf{Al} \rightarrow \gamma^{(*)}_{e^+e^-} + \mathbf{Mg}^*$$

- Can produce electron at same energy as the signal electron
- Trick: Muon decays from Al are slow; RPCs are fast.

Wait out the RPCs before starting the live gate.

Baseline Mu2e

Timing is important…



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- Can produce electron at same energy as the signal electron
- Trick: Muon decays from Al are slow; RPCs are fast.

Wait out the RPCs before starting the live gate.

Total backgrounds (for 3 yrs)

Category	Source	Events
Intrinsic	μ decay in orbit	0.22
	Radiative μ capture	< 0.01
Late-arriving	Radiative π capture	0.03
	Beam electrons	< 0.01
	μ decay in flight	0.01
	π decay in flight	< 0.01
Miscellaneous	Antiproton	0.10
	Cosmic ray	0.05
	Pat. Recognition Errors	< 0.01
Total Background		0.41

Why consider next-generation Mu2e?

- Regardless of the Mu2e result, Mu2e-II is important:
  - Mu2e observed CLFV at ≥ 5σ
    - Switch targets and measure ratio of rates to further disciminate models of underlying physics
  - Mu2e observes hints of CLFV at 3σ
    - Collect ×10 data to definitively resolve the situation
  - Mu2e sets stringent new limit on CLFV
    - Collect ×10 data and explore new parameter space

Our guidance:

- The goal was to study a next-gen. experiment according to the assumptions:

  1. Only modest changes to the Mu2e design would be implemented.

  2. The requisite number of POTs would be delivered so that Mu2e-II would have ×10 sensitivity wrt Mu2e.

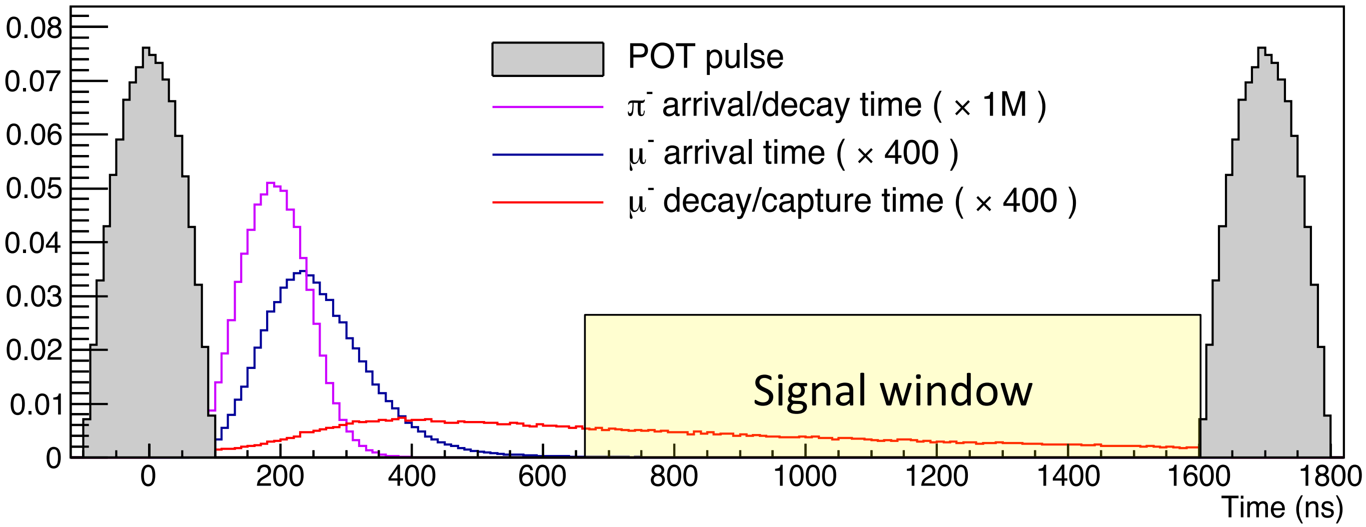
  3. We did not consider *how* the protons would make it to the primary target.

  4. Desire less than 1 background event.

What is important for Mu2e-II?

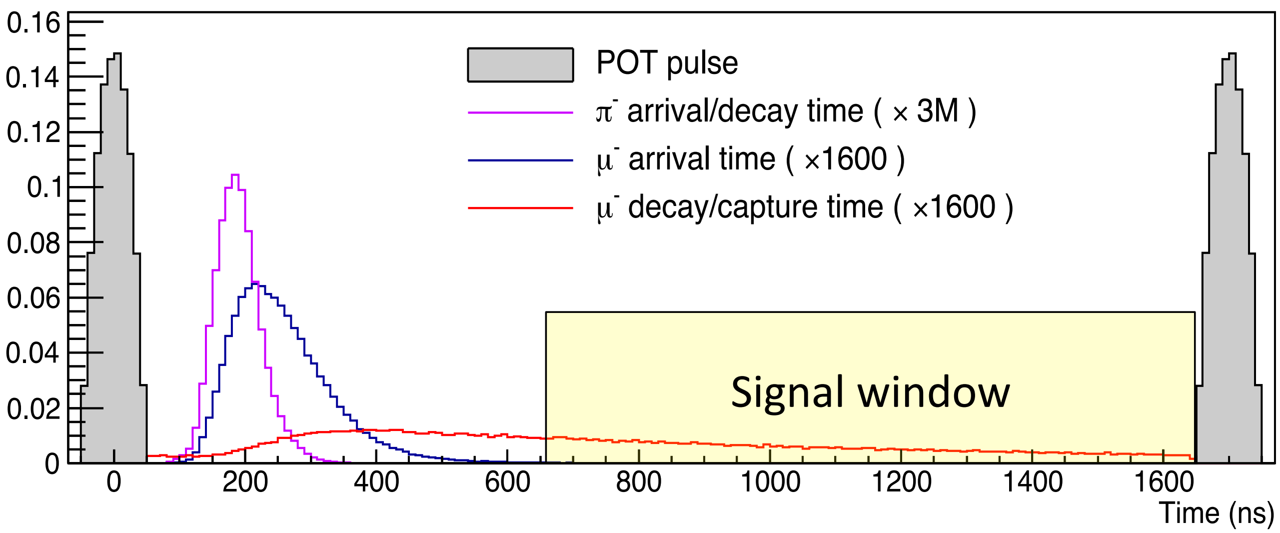
- Mu2e-II is not just about getting more protons-on-target.
- There are beam properties that are important:
  - Kinetic energy is 8 GeV for Mu2e baseline:
    - Above proton-antiproton production threshold
    - 25% of estimated background
    - This is not a problem with PIP-II
  - Timing structure is important:
    - Pion backgrounds and muon acceptance

Moving to Project X



Baseline:
8 GeV POTs

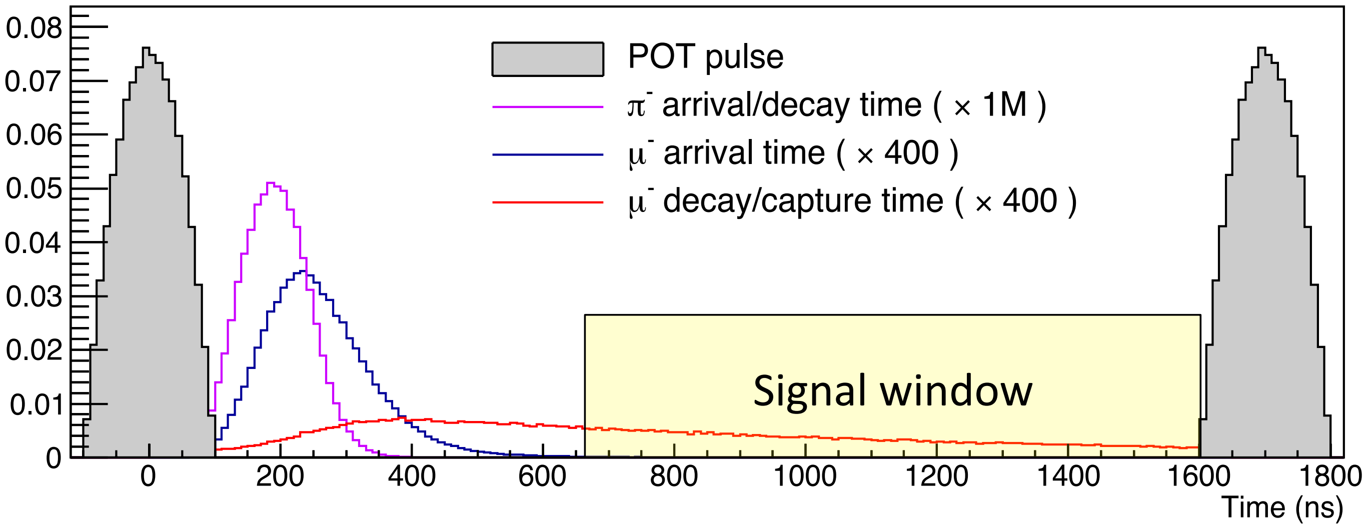
Proton bunch contained within ± 100 ns



Project X:
1 GeV POTs

Proton bunch contained within ± 50 ns (assume same shape)

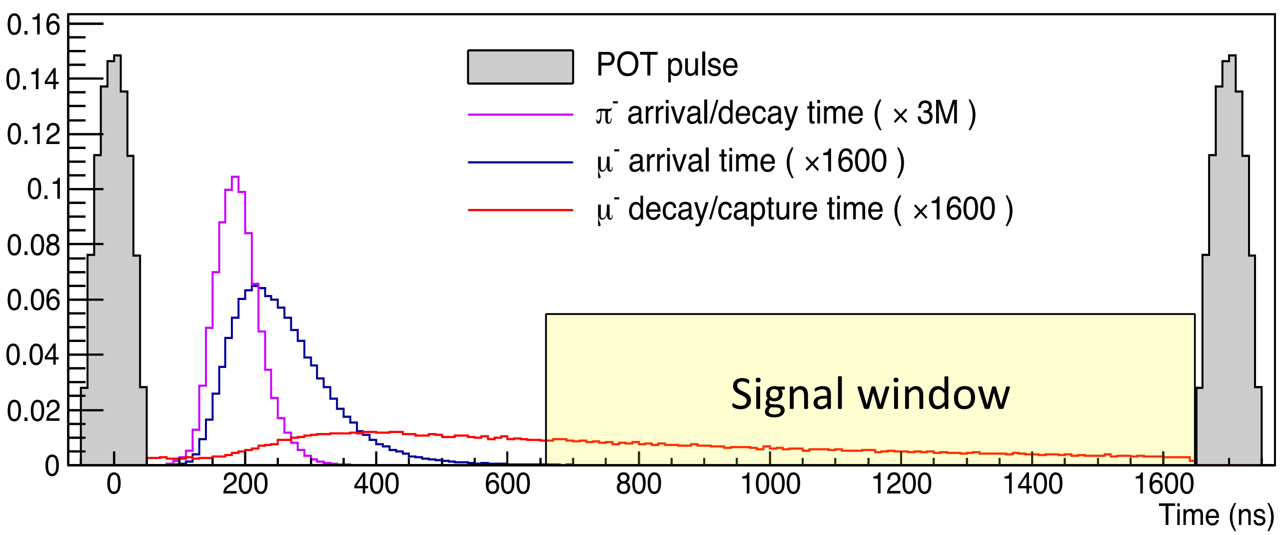
Moving to Project X



Baseline:

30% duty cycle

Ext. < 10^{-10}



Project X:

90% duty cycle

Ext. < 10^{-12}

How the backgrounds change

Category	Source	Events Current
Intrinsic	μ decay in orbit	0.22
	Radiative μ capture	< 0.01
Late-arriving	Radiative π capture	0.03
	Beam electrons	< 0.01
	μ decay in flight	0.01
	π decay in flight	< 0.01
Miscellaneous	Antiproton	0.10
	Cosmic ray	0.05
	Pat. Recognition Errors	< 0.01
Total Background		0.41

Using same event selection with Project-X, we get…

How the backgrounds change

Category	Source	Events Current	Events PX (Al)
Intrinsic	μ decay in orbit	0.22	2.14
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	0.04
	Beam electrons	< 0.01	< 0.01
	μ decay in flight	0.01	0.01
	π decay in flight	< 0.01	< 0.01
Miscellaneous	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
	Pat. Recognition Errors	< 0.01	< 0.01
Total Background		0.41	2.36

How the backgrounds change

Category	Source	Events: Current	Events: PX (Al)
Intrinsic	μ decay in orbit	0.22	2.14
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	0.04
	Beam electrons	< 0.01	< 0.01
	μ decay in flight	0.01	0.01
	π decay in flight	< 0.01	< 0.01
Miscellaneous	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
	Pat. Recognition Errors	< 0.01	< 0.01
Total Background		0.41	2.36

Dominant background by far is DIO for PX (Al).

Some options to reduce DIO

- Reduce acceptance window
  - Significant reduction in signal acceptance

- Improve momentum resolution
  - Reduce stopping target material amount, but need more protons to have enough stopped muons.

  - Reduce the size of tracker straw walls
    - By moving from 15 μm to 8 μm walls, we obtain a significant improvement in DIO background:

      2.14 → 0.26 events

      giving an overall background of **0.46** events over three years running.

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What if we observe BSM signal with Mu2e (Al)?

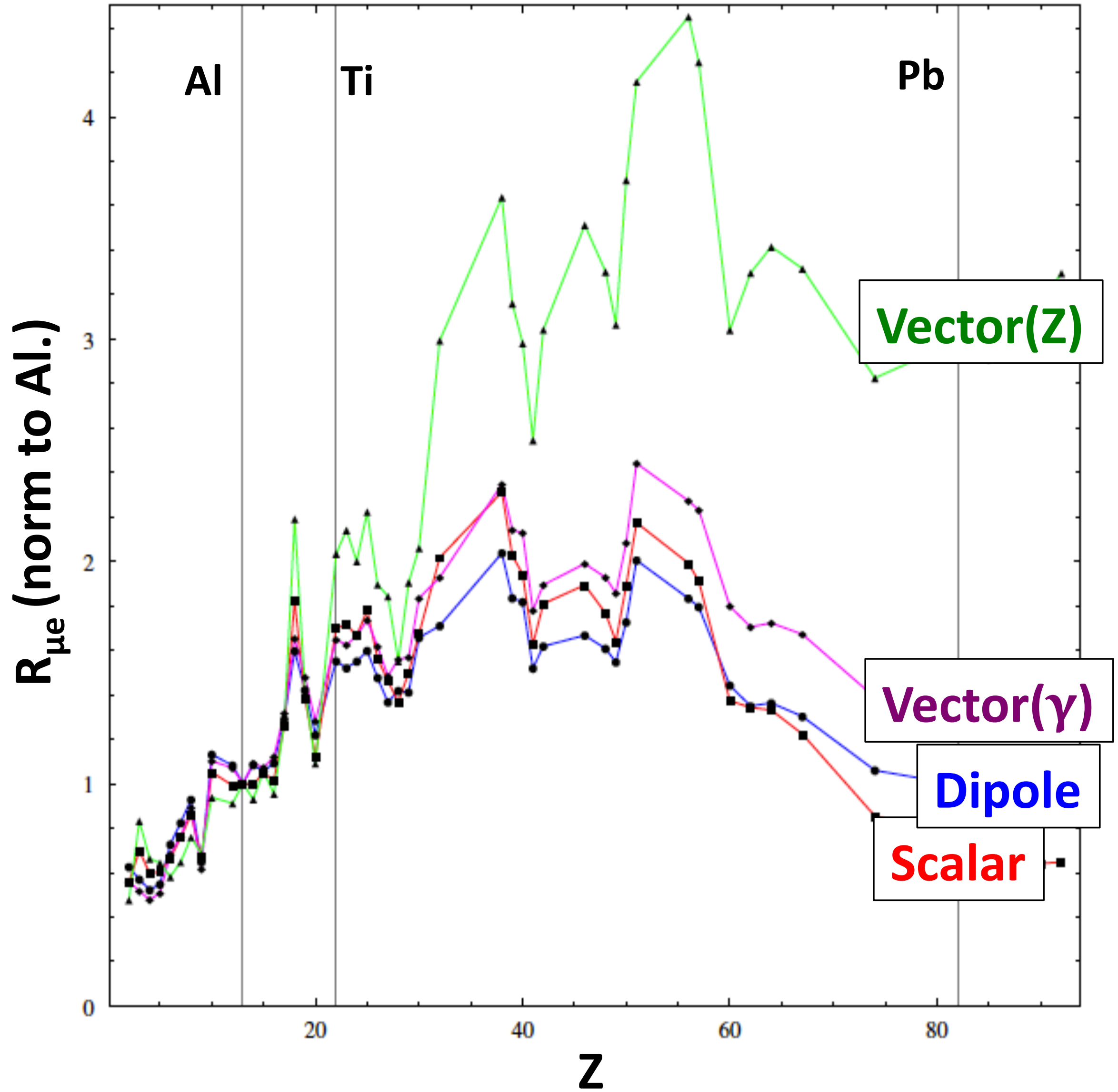
We want to switch stopping target materials.

Why use different targets?

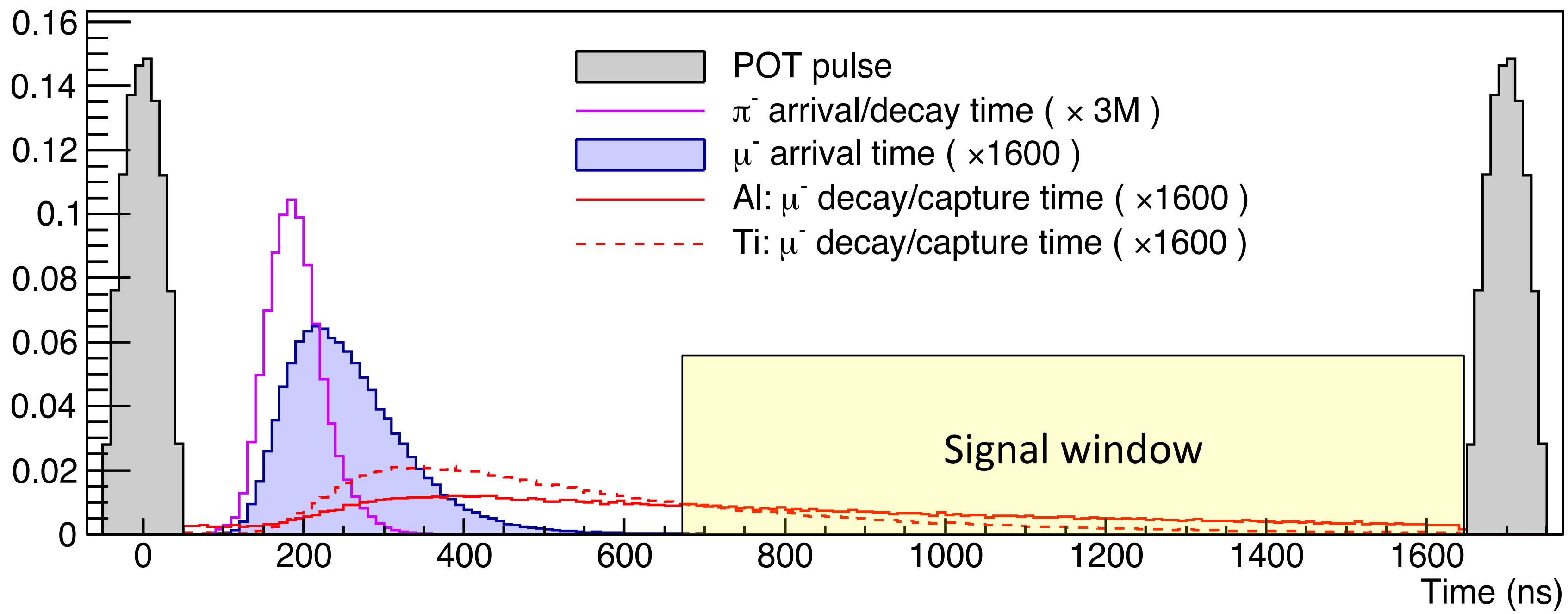
- *R* is *Z*-dependent, and depends on the dominant operator in the Lagrangian

- Measuring *R* for different-*Z* targets gives some discrimination in pinning down the model

Cirigliano, et al PRD **80**, 013002 (2009)



Moving to a different target



	Aluminum	Titanium
Stopped muons/POT (norm. to Al.)	1	1.3
% muons that decay	39%	15%
% of decays in sig. window	50%	30%
Time constant for muon decay	864 ns	297 ns

How the backgrounds change

Category	Source	Events Current	Events PX (Ti)
Intrinsic	μ decay in orbit	0.22	2.25
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	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	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
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Total Background		0.41	2.46

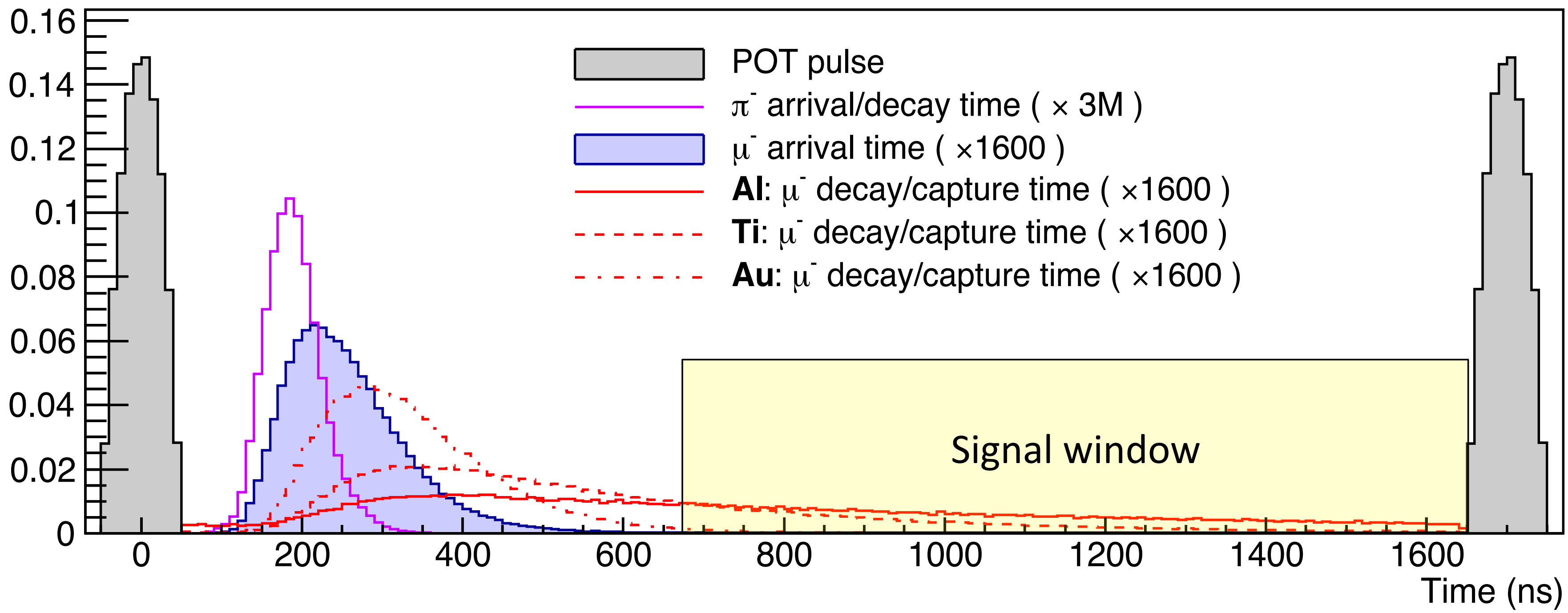
Baseline Mu2e configuration; moving to narrower straw walls…

How the backgrounds change

Category	Source	Events	
		Current	PX (Ti)
Intrinsic	μ decay in orbit	0.22	1.19
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	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	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
	Pat. Recognition Errors	< 0.01	< 0.01
Total Background		0.41	1.40

Larger than 1 background event, but an improvement.

What would gold look like?



- Awfully difficult:
  - Only ~1% of muon decays are in signal window.
  - Can we sharpen the arrival time distributions?

Things to explore

- How would we get protons to the primary target?
  - Currently under study.
- For PIP-II we are not constrained to the 1695 ns time cycle.
  - What would be ideal for Mu2e-II?
  - For Ti, perhaps a shorter time cycle would be better.
- How can material upstream/part of tracker be optimized to improve momentum resolution?

Summary

- Mu2e will be sensitive to CLFV at new-physics mass scales of 10^3 – 10^4 TeV.
- Single-event sensitivity of 2.5×10^{-17} expected.
- PIP-II would be ideally suited for Mu2e-II:
  - No antiproton backgrounds
  - Proton timing structure can be tuned to reduce backgrounds/ increase muon acceptance as much as possible.
- Improving sensitivity by a factor of 10 is conceivable through a Project-X-like facility with only modest upgrades to the currently planned facility.
- Preliminary Project-X studies were performed indicating Ti is a possibility.

Summary

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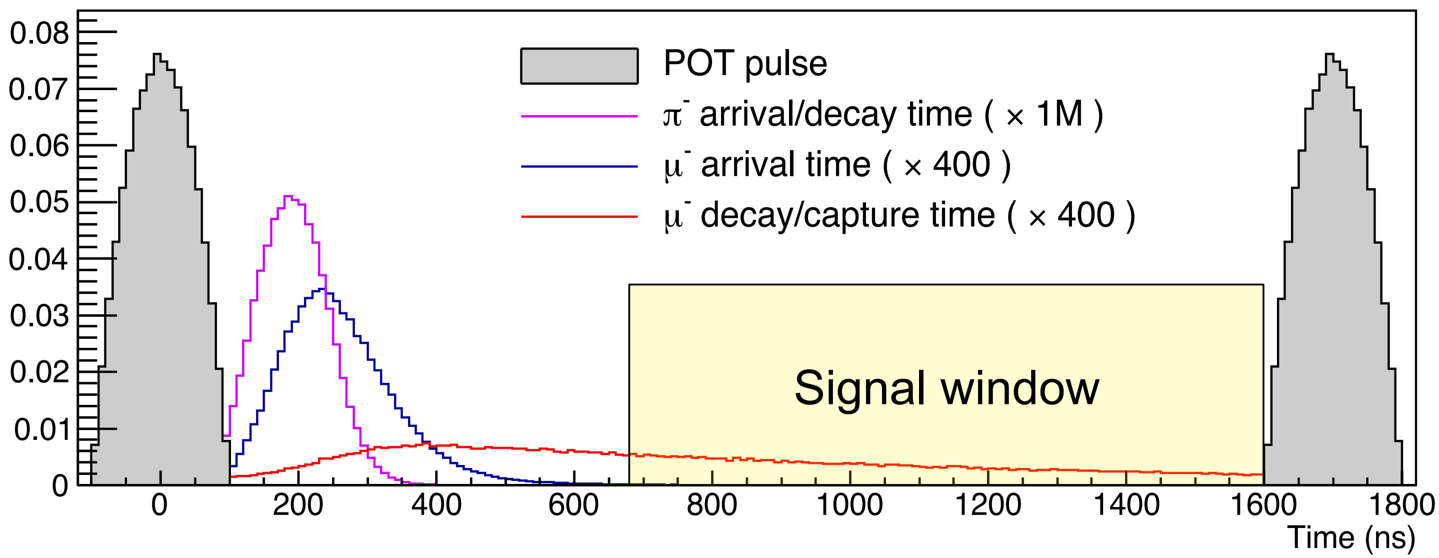
Thank you.

http://mu2e.fnal.gov

Back-up Slides

Factor 10 improvement in *R*



- It's not just more statistics.
- The pulse separation of previous experiment: **20 ns**.
- The 1695 ns proton pulse separation allows various backgrounds to significantly dissipate before we start the livegate.

Charged Lepton Flavor Violation

- Forbidden by Standard Model

  suppressed to the 10^{-54} level
- Allowed by various new physics scenarios
- CLFV parameterized by model-independent Lagrangian:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L \left(\sum_{q=u,d}\overline{q}_L\gamma^\mu q_L\right)$$

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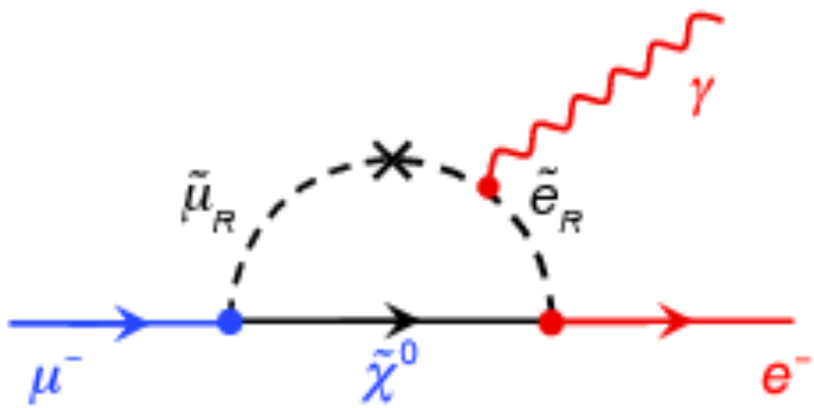


$\mu \to e\gamma$ proportional to dipole term only

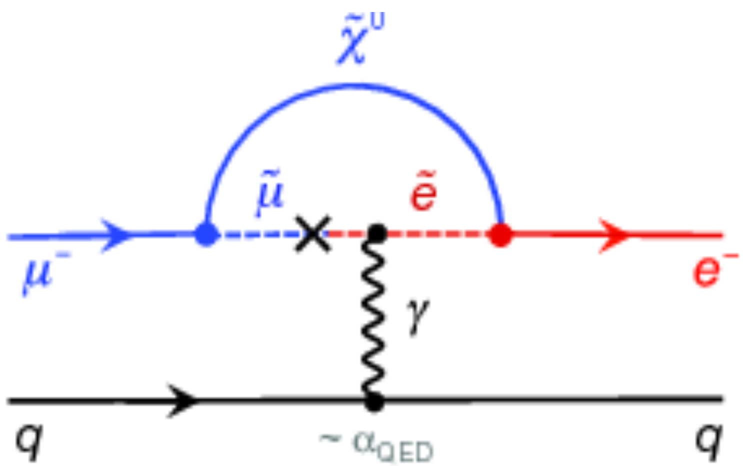
No sensitivity if κ is large

Charged Lepton Flavor Violation

- Forbidden by Standard Model

  suppressed to the 10^{-54} level
- Allowed by various new physics scenarios
- CLFV parameterized by model-independent Lagrangian:

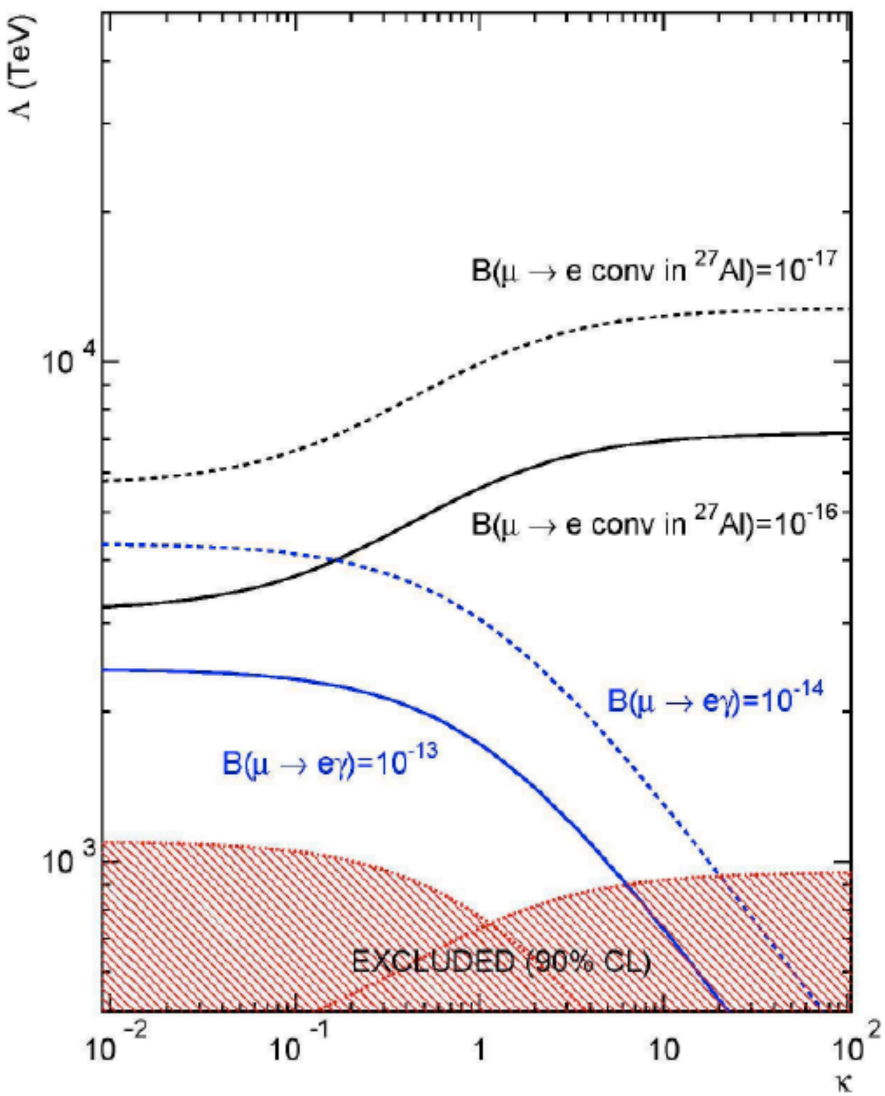
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\overline{q}_L\gamma^\mu q_L\right)$$



$\mu N \to eN$ proportional to both terms

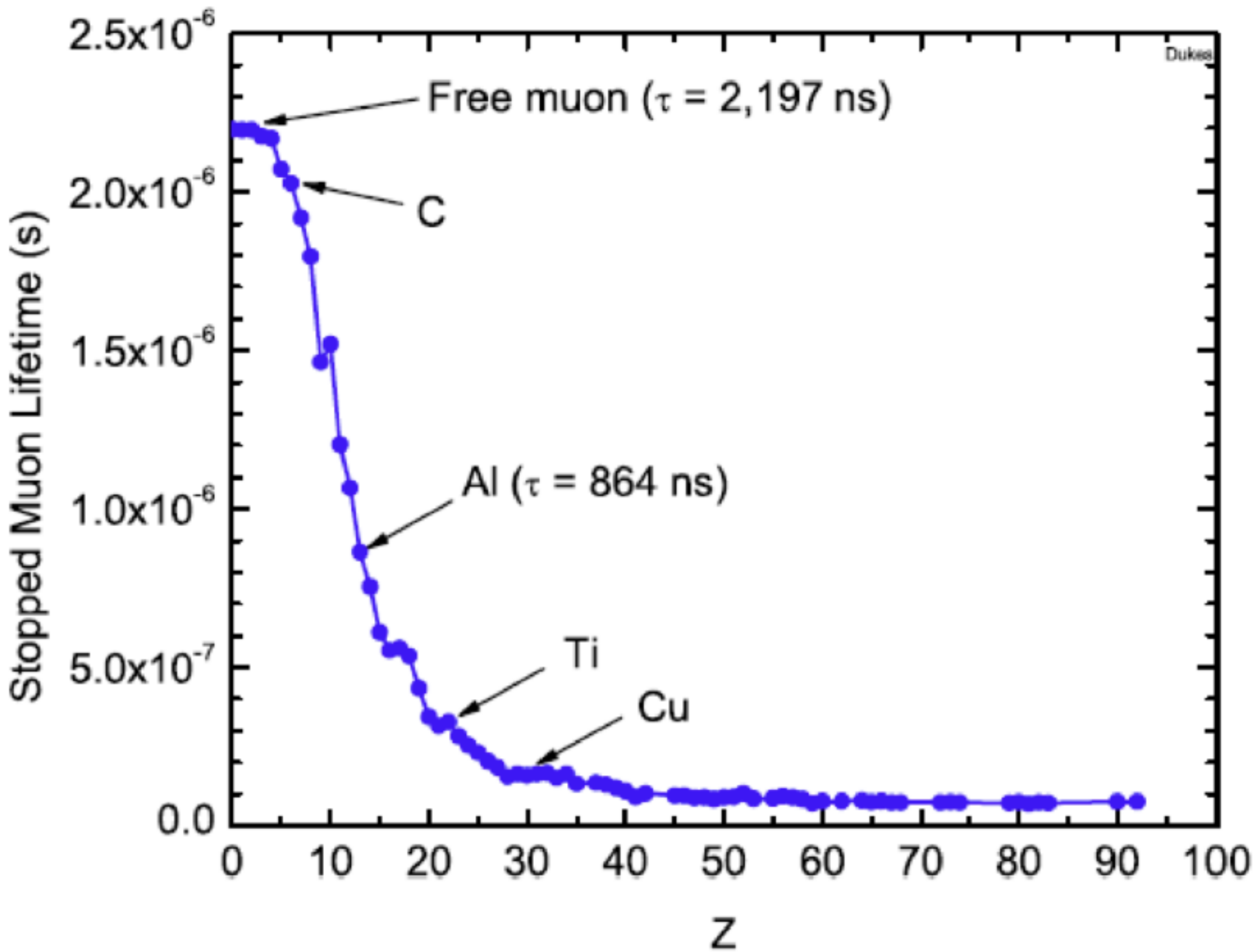
Sensitivity for all κ

How far can CLFV experiments reach?



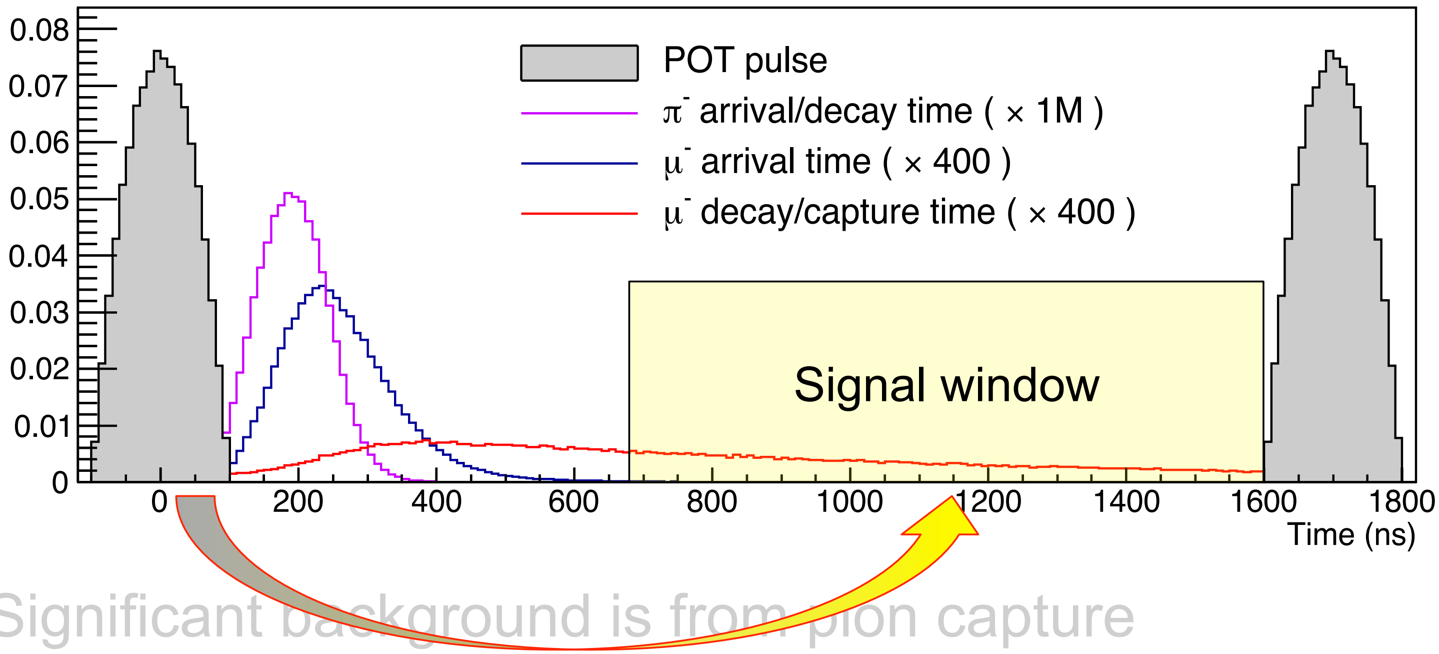
- Direct observation of CLFV new physics at LHC constrained to ~few TeV.
- Baseline Mu2e will exclude CLFV mass scales greater than 3×10^3 TeV.
- Factor 10 improvement in sensitivity pushes exclusion up to 6×10^3 TeV.

Stopped muon lifetime



Backgrounds from pion capture

Timing is everything…



- Significant background is from pion capture

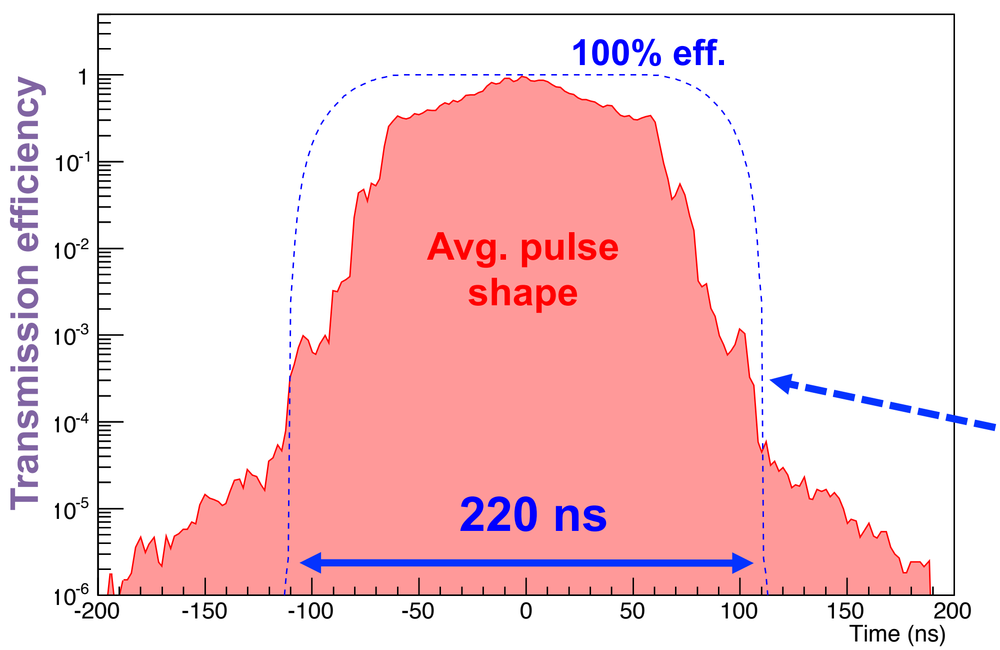
What happens if an out-of-time proton enters the signal window?

- Can produce electron at same energy as the signal electron!
- Trick: Muon decays from Al. are slow; RPCs are fast.

Wait out the pion captures before starting the live gate.

Out-of-time protons

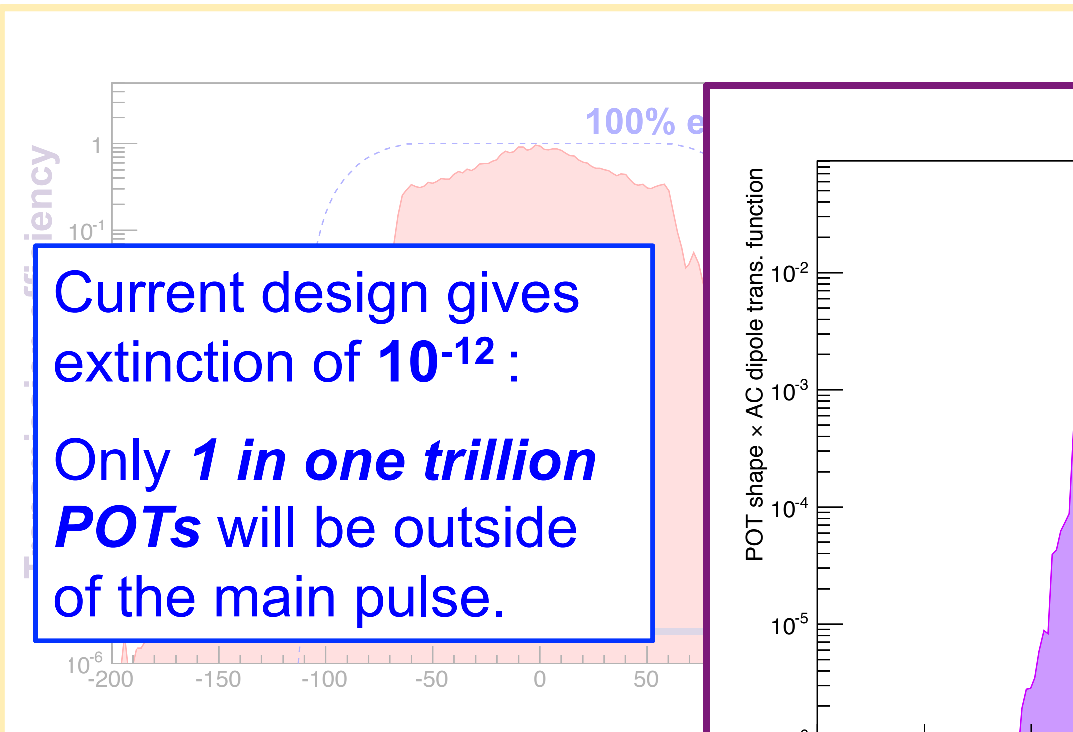
- Can create RPC backgrounds we cannot reject.
- Need to make sure this doesn't happen!
- Need proton-beam extinction at the level of **10^{-10}**.



Series of AC dipole magnets "kick" out-of-time protons out of the way.

Out-of-time protons

- Can create RPC backgrounds we cannot reject.
- Need to make sure this doesn't happen!
- Need proton-beam extinction at the level of **10^{-10}**.



Current design gives extinction of **10^{-12}** :

Only ***1 in one trillion POTs*** will be outside of the main pulse.