The Mu2e Experiment at Fermilab

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Flavor Physics & CP Violation
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Searching for new physics with muons

- Mu2e searches for charged-lepton flavor violation (CLFV) with muons in the presence of a nucleus:

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

- Why muons?

1. Easy to produce: $p + \textbf{target} \to \pi^- \to \mu^-$
2. Large production energies are *not* required
3. Muons are clean — *i.e.* no hadronic final states
4. Muons are relatively long-lived (τ = 2.2 μs)
    - Their trajectories can be harnessed

Comparing Mu2e to other indirect searches

: searches

W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`

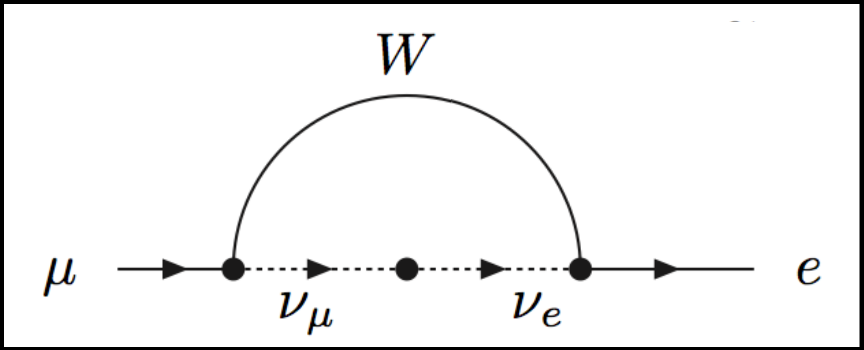
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★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

$\}$ Sizable effects expected for wide range of models.

Charged lepton flavor violation

- In principle, CLFV is not forbidden by massive-ν SM due to neutrino oscillations



- In practice, we will never see the SM process!
  - Transition rate < 10^{-50}

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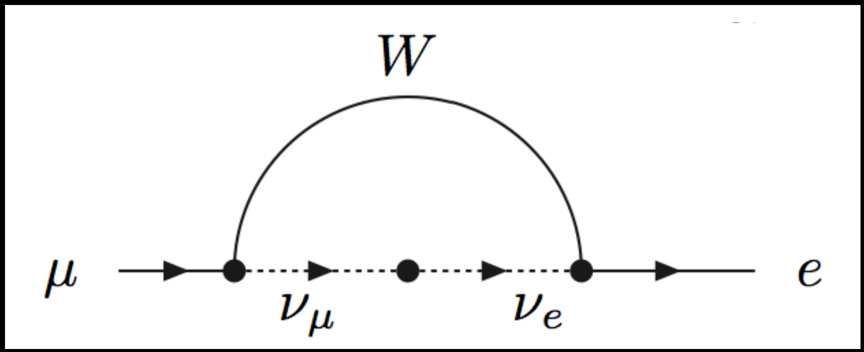

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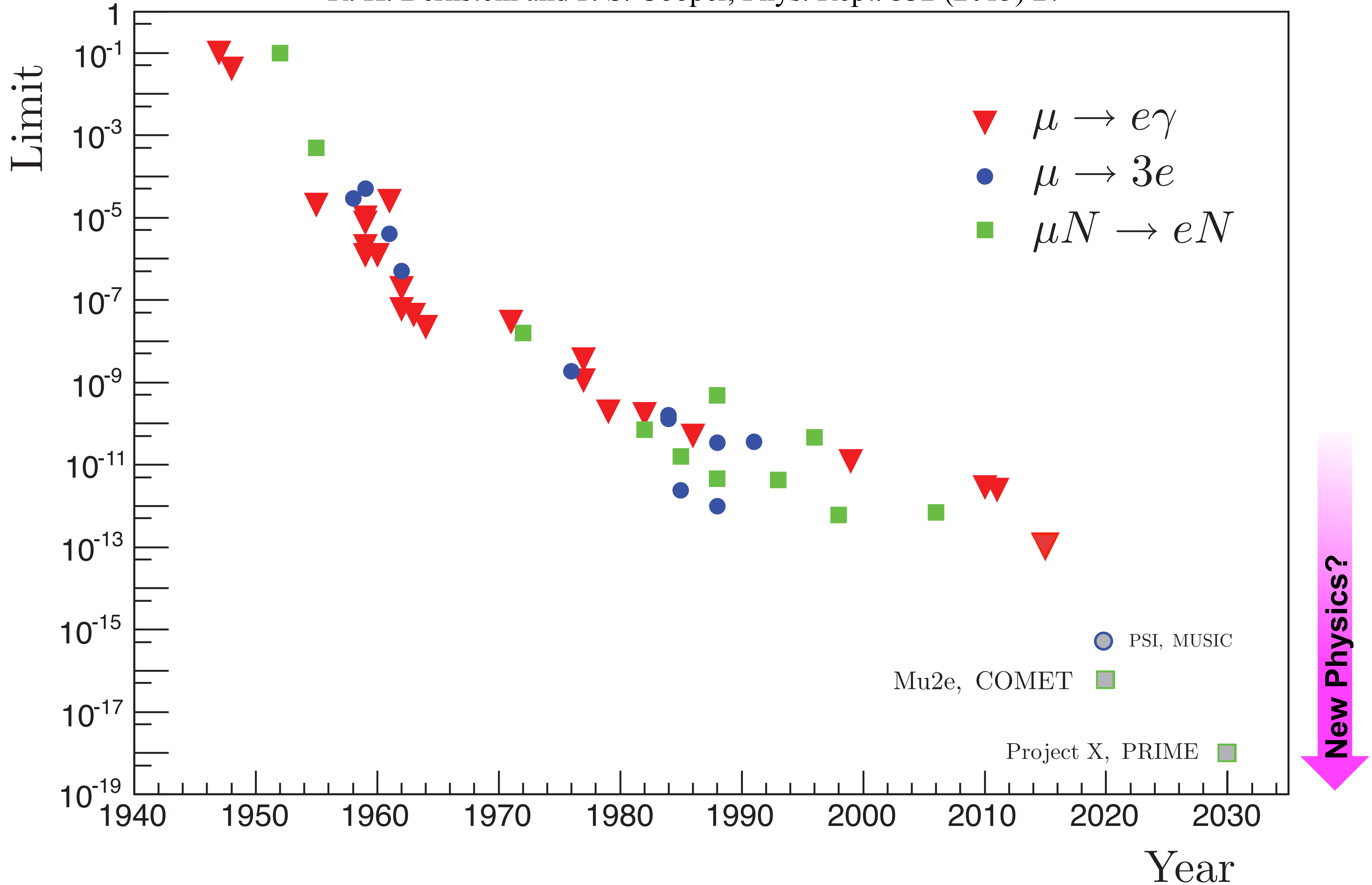
- Various NP models allow CLFV at levels just beyond current CLFV upper limits.
  - SO(10) SUSY
    - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211,** 40 (2012).
  - Scalar leptoquarks
    - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
  - Left-right symmetric model
    - C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

History of CLFV limits with muons

R. H. Bernstein and P. S. Cooper, Phys. Rept. **532** (2013) 27



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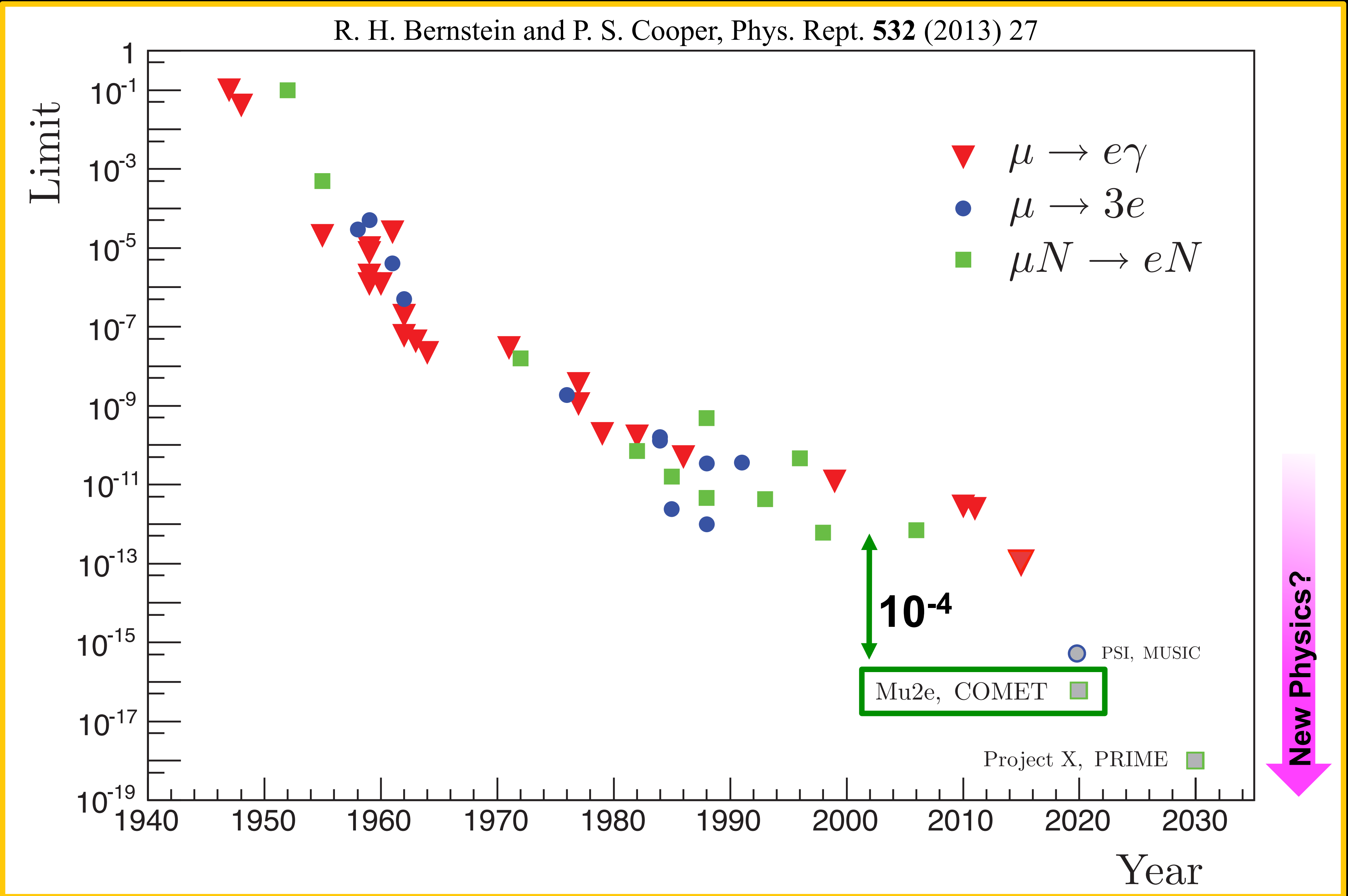

What is Mu2e measuring?

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

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

(NP)

(SM)

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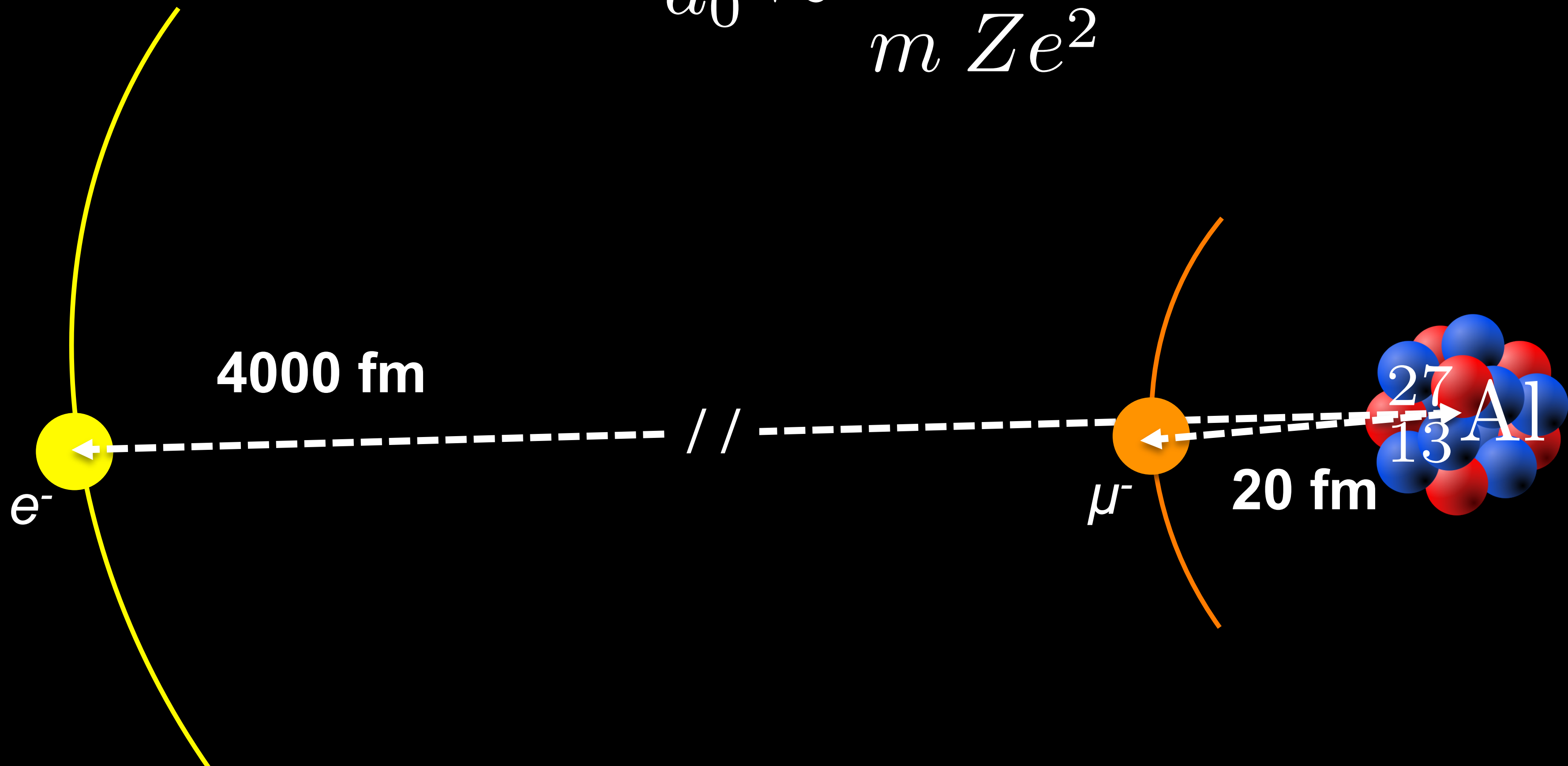
Mu2e goals:

		Improvement wrt. previous experiment
Single-event-sensitivity (SES):	2.5×10^{-17}	(10^4)
Upper limit (90% C.L.):	7×10^{-17}	(10^4)
Discovery sensitivity:	3×10^{-16}	(10^4)
Probe NP eff. mass scales of:	$10^3 – 10^4$ TeV	(10)

Muonic Atoms – a primer

- Bound muon cascades quickly to the 1*s* ground state (emits *X*-rays)
- Bohr radius of ground state:

$$a_0 \sim \frac{1}{m}\frac{\hbar^2}{Ze^2}$$



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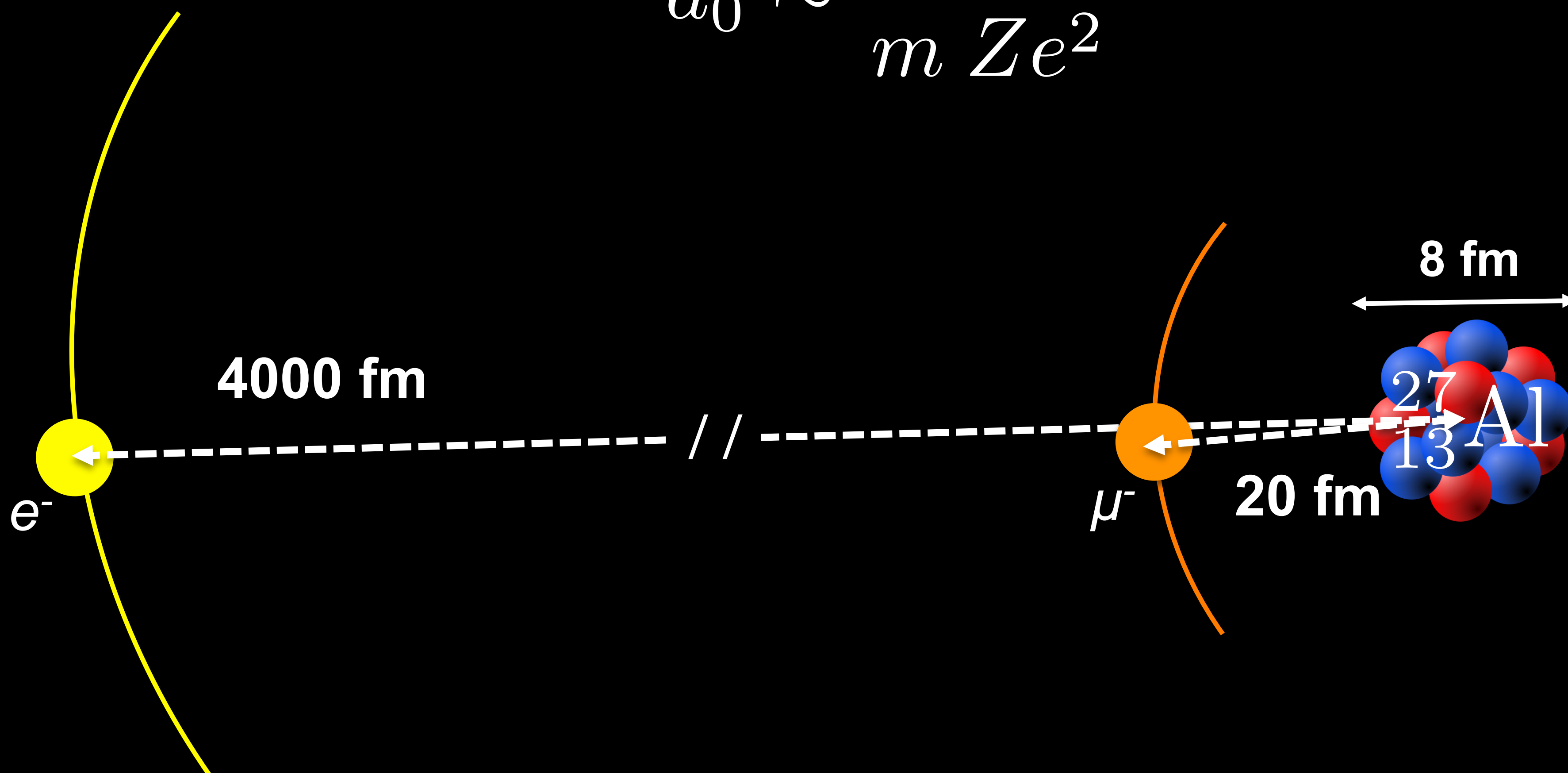
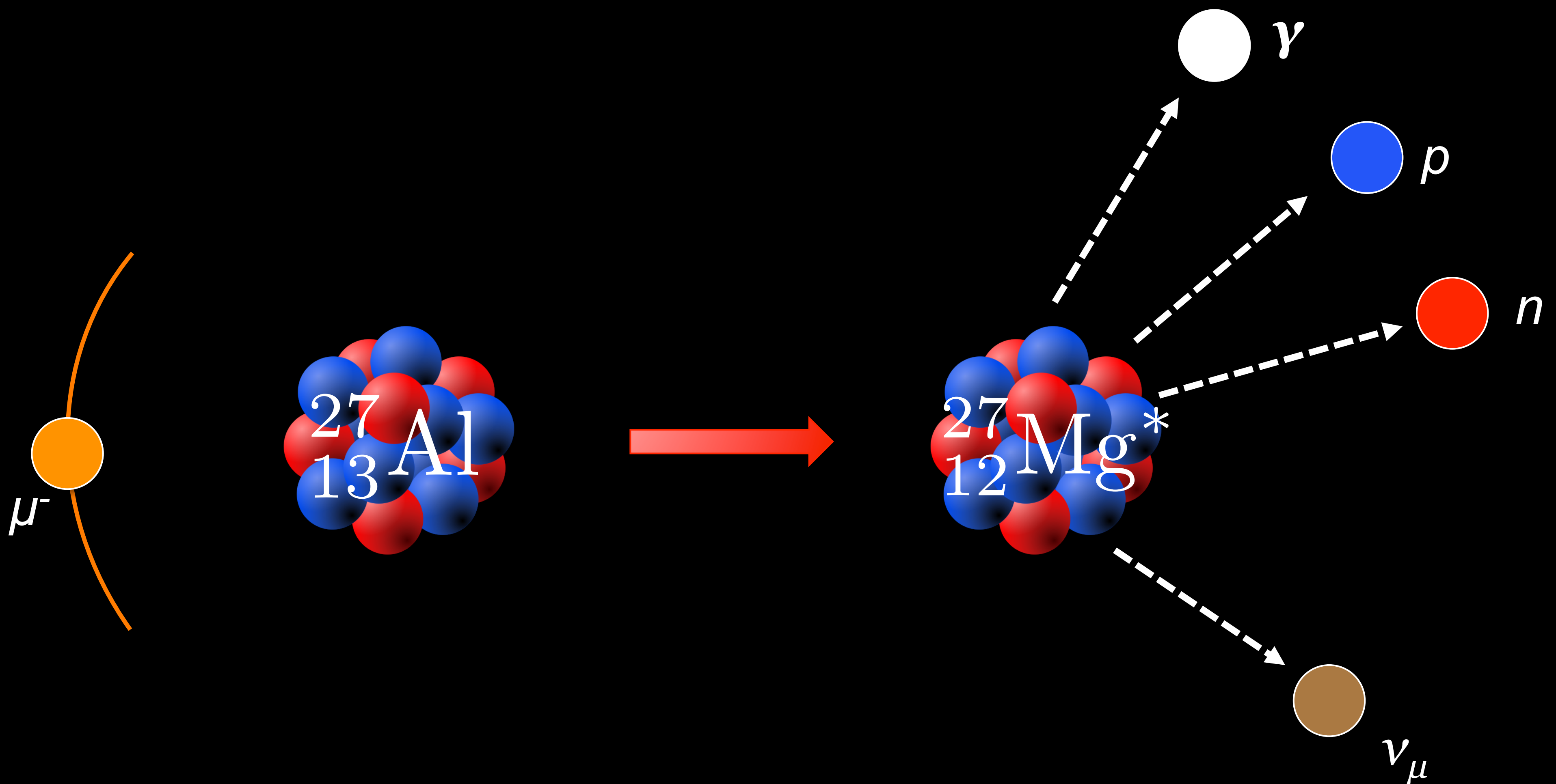


Muonic Atoms

- Nuclear capture (61% of bound muons on Al)

$$\mu^- + N \to \nu_\mu + N'$$

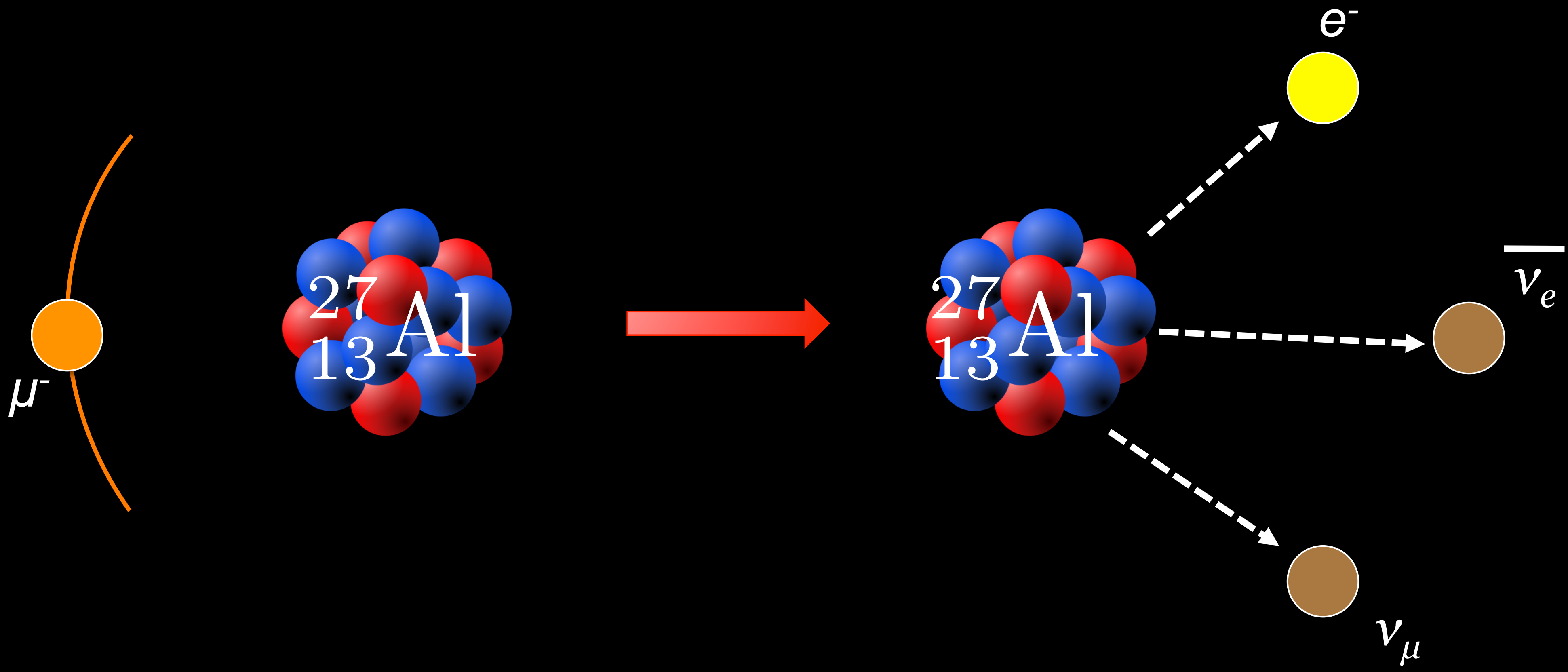


Muonic Atoms

- Decay-in-orbit (39% of bound muons on Al)

Rest of talk: **DIO**

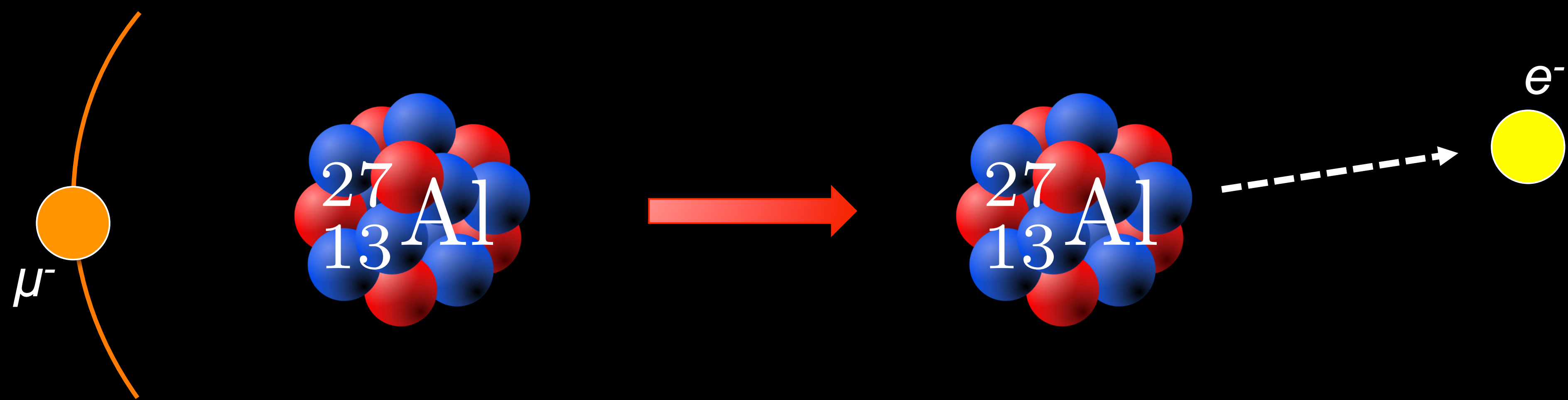
$$\mu^- + N \rightarrow e^- \overline{\nu}_e \nu_\mu + N$$



Muonic Atoms

- Muon to electron conversion

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



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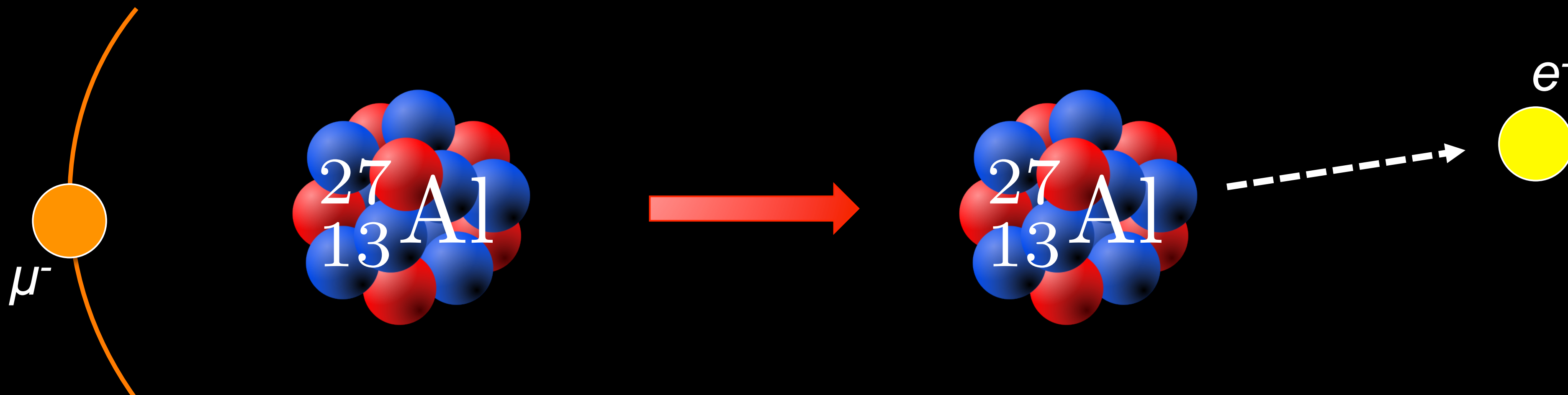

Experimental signature is a mono-energetic electron of energy

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

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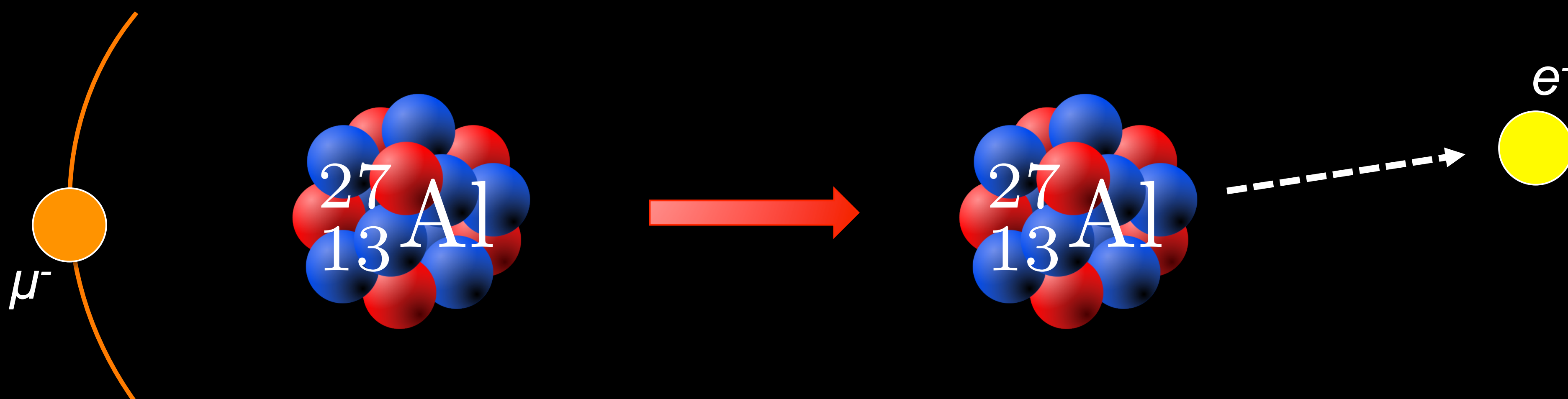

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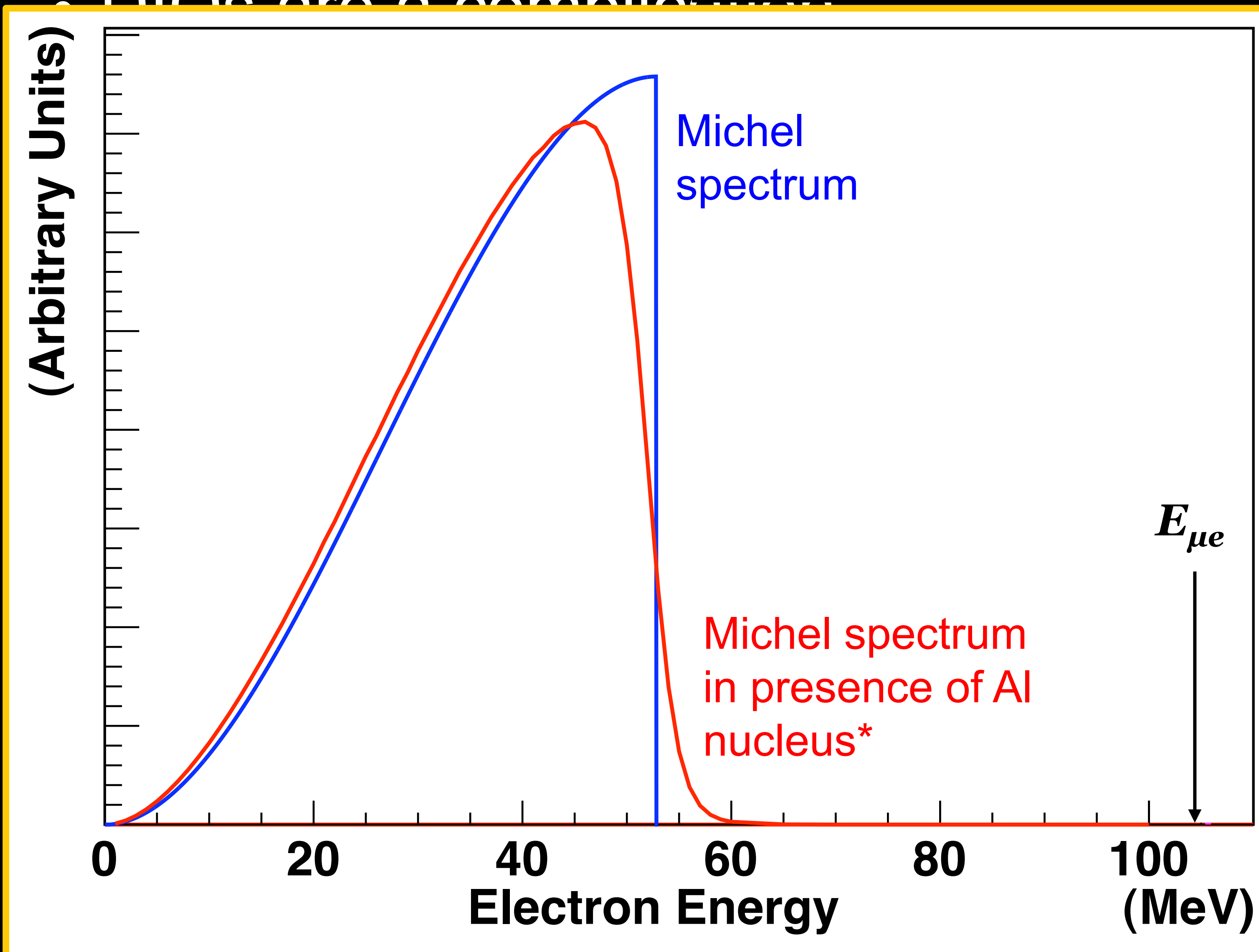
We know *exactly* where to look.

It’s not that simple

- DIOs are a complication
- The energy distribution of electrons from muon decay is given by a (modified) Michel spectrum:
  - Michel spectrum endpoint: 52.8 MeV
  - Presence of atomic nucleus → momentum transfer
  - DIO electron energies up to signal energy $E_{\mu e}$

It’s not that simple

*A. Czarnecki, *et al*, Phys. Rev. D **84**, 013006 (2011).



om muon
spectrum:

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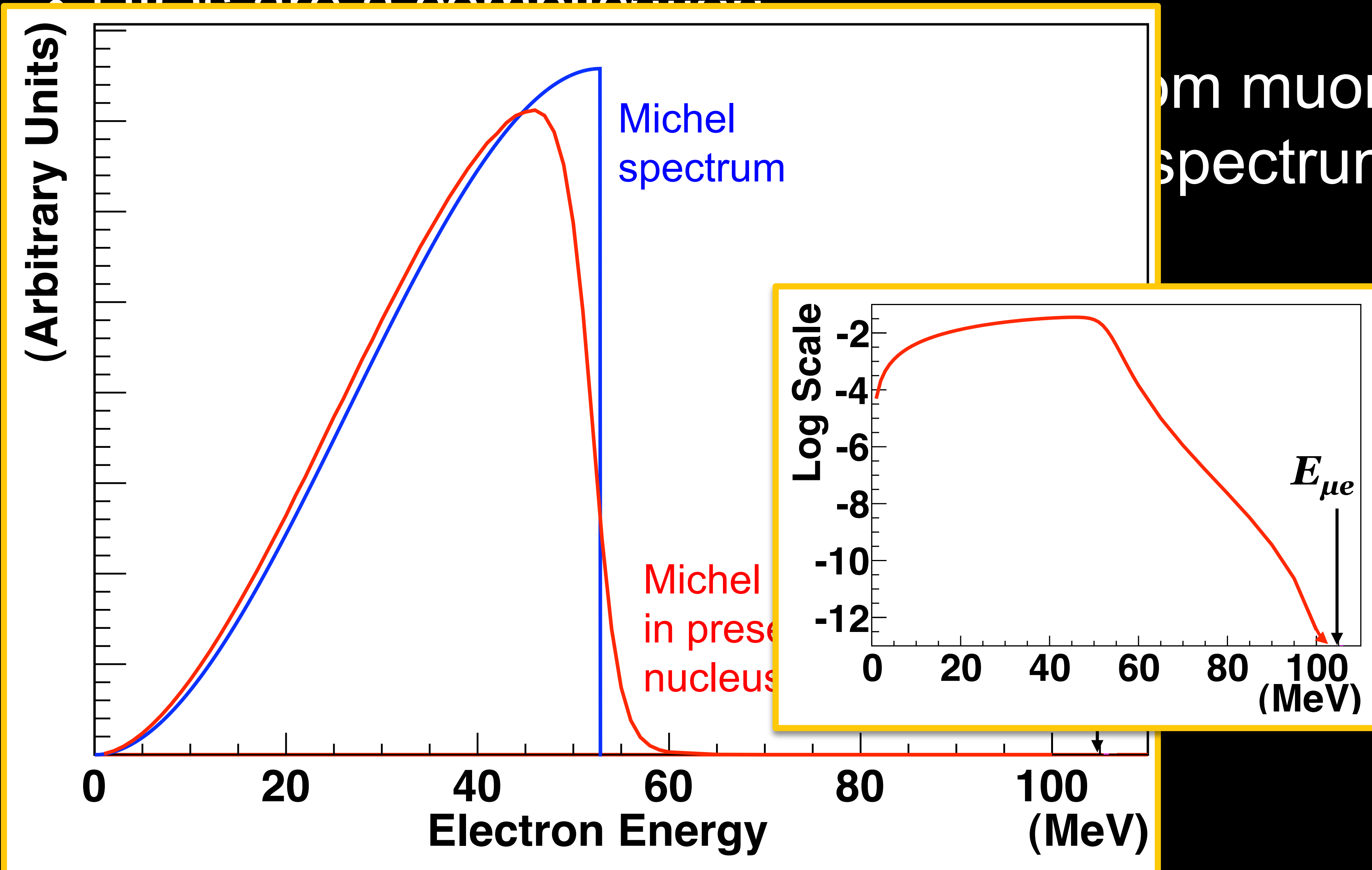
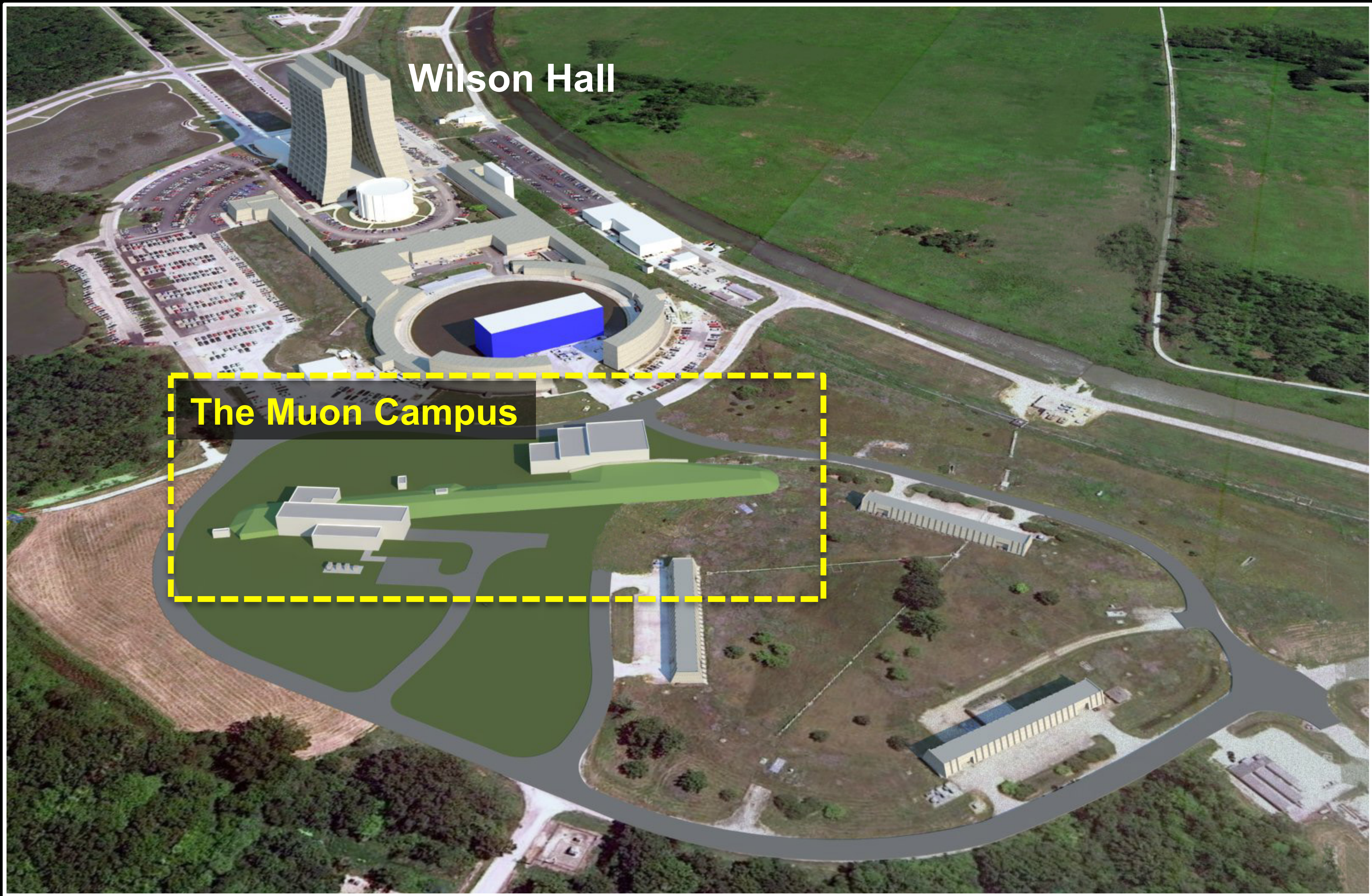


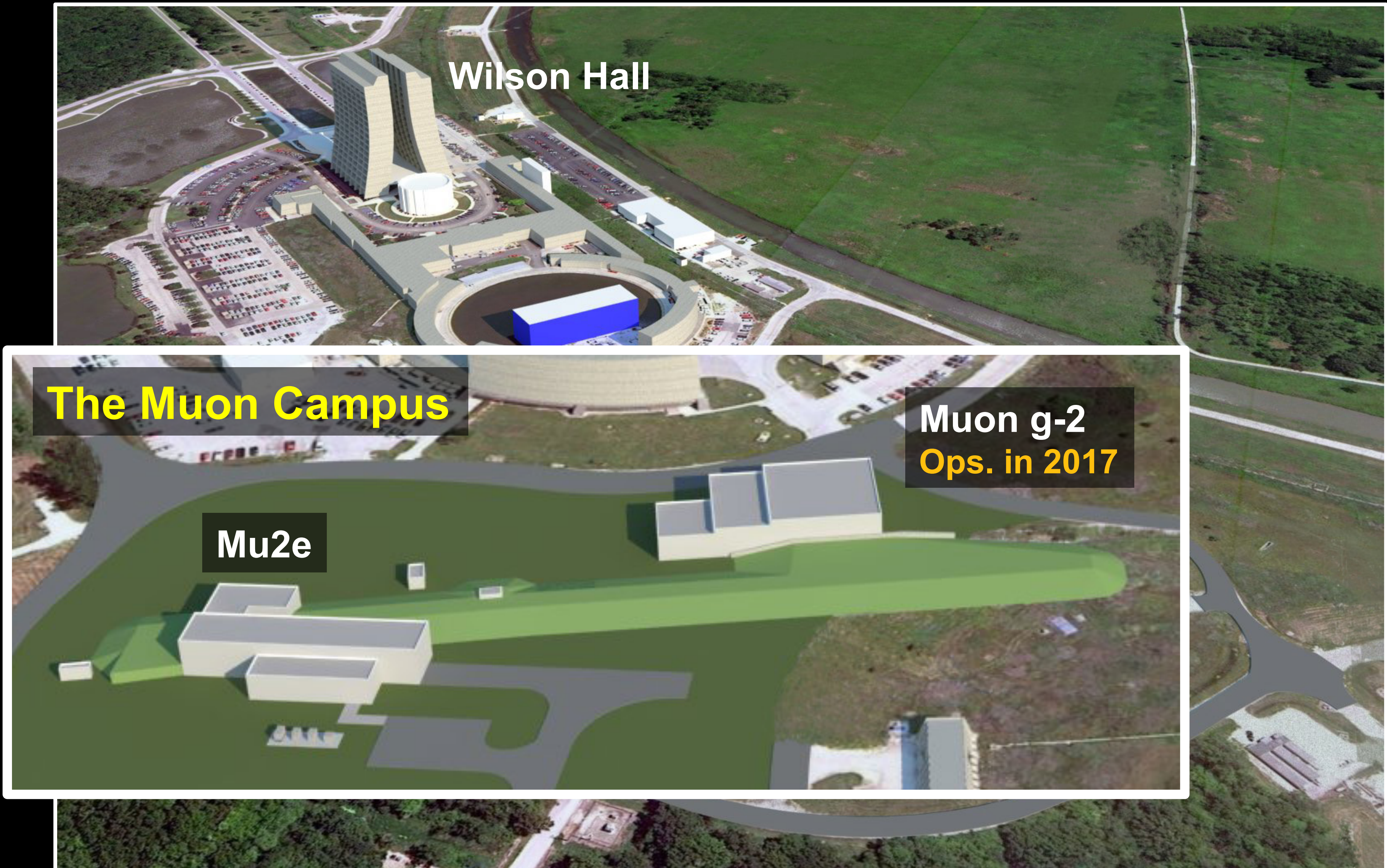
Important design consideration!

The Mu2e Experiment

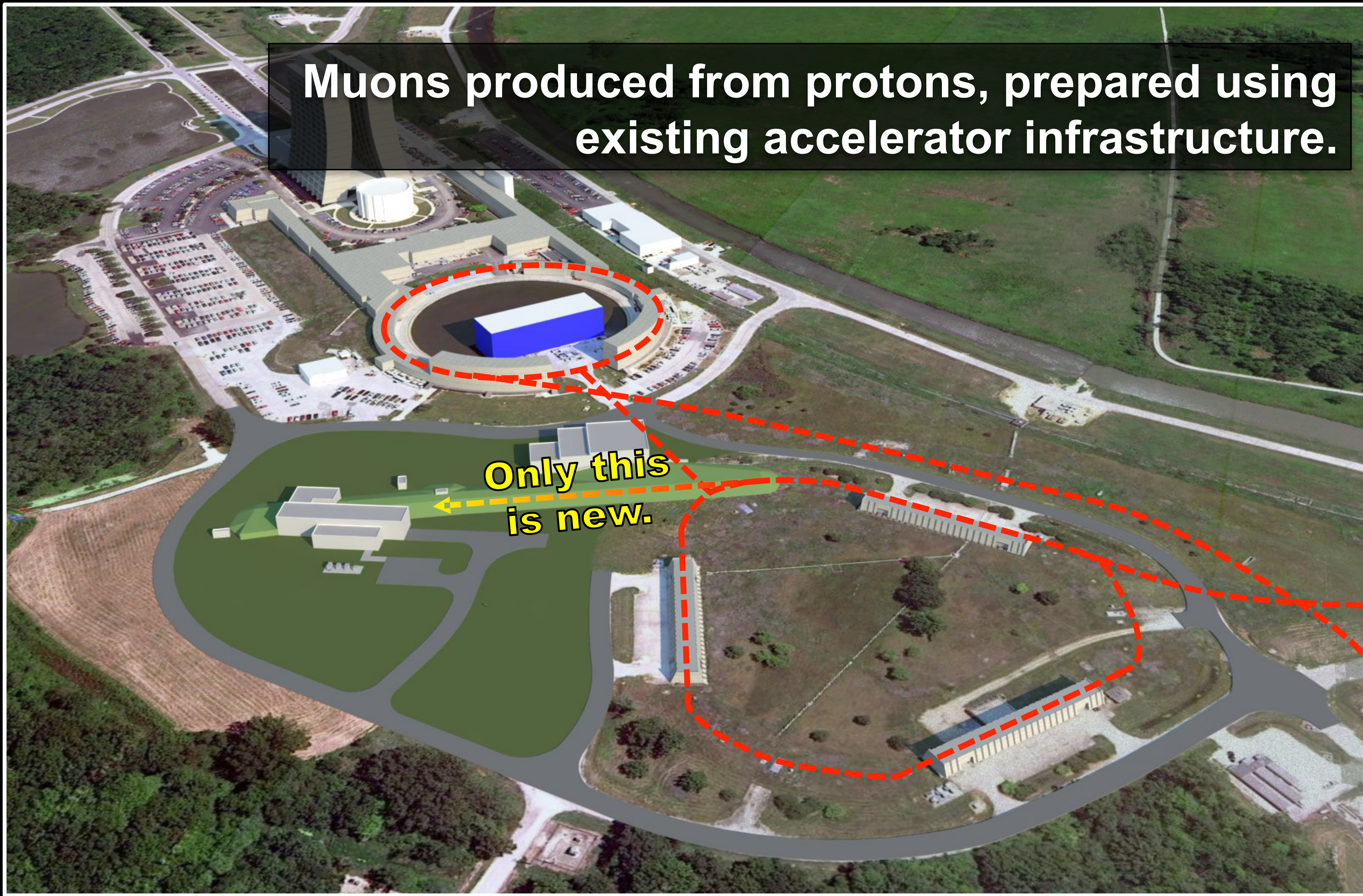
Fermilab in the muon era



Fermilab in the muon era



How do we get the muons?



How do we get the muons?

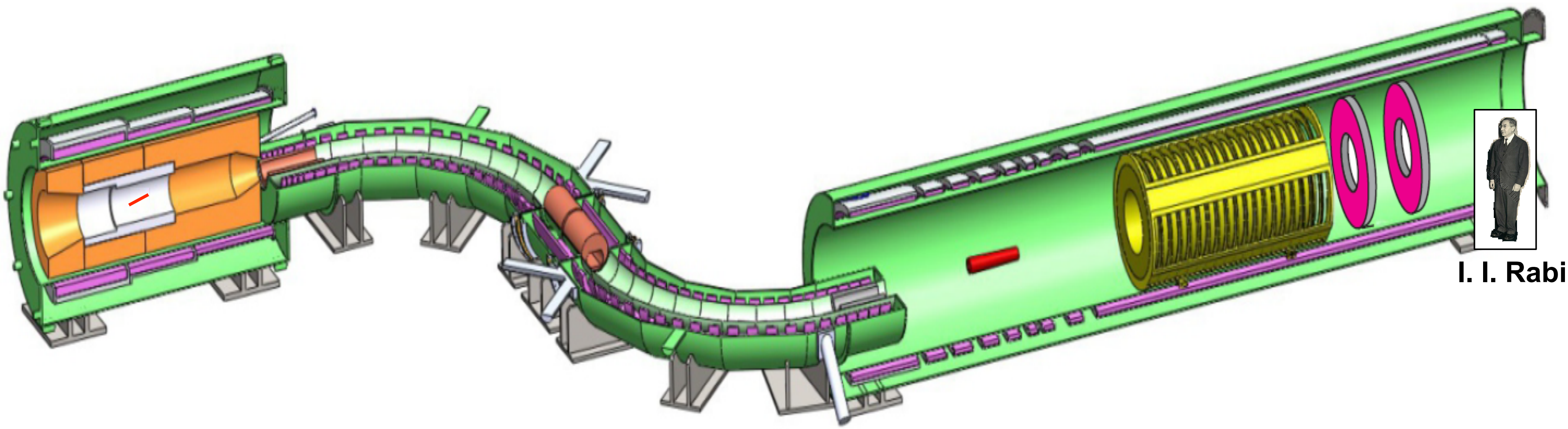
Muons produced from protons, prepared using existing accelerator infrastructure.

Single event sensitivity goal: 2.5×10^{-17}

We need at least 10^{18} Al-bound muons.

For a three-year run, we will need 10^{10} stopped muons/sec.

Mu2e Apparatus



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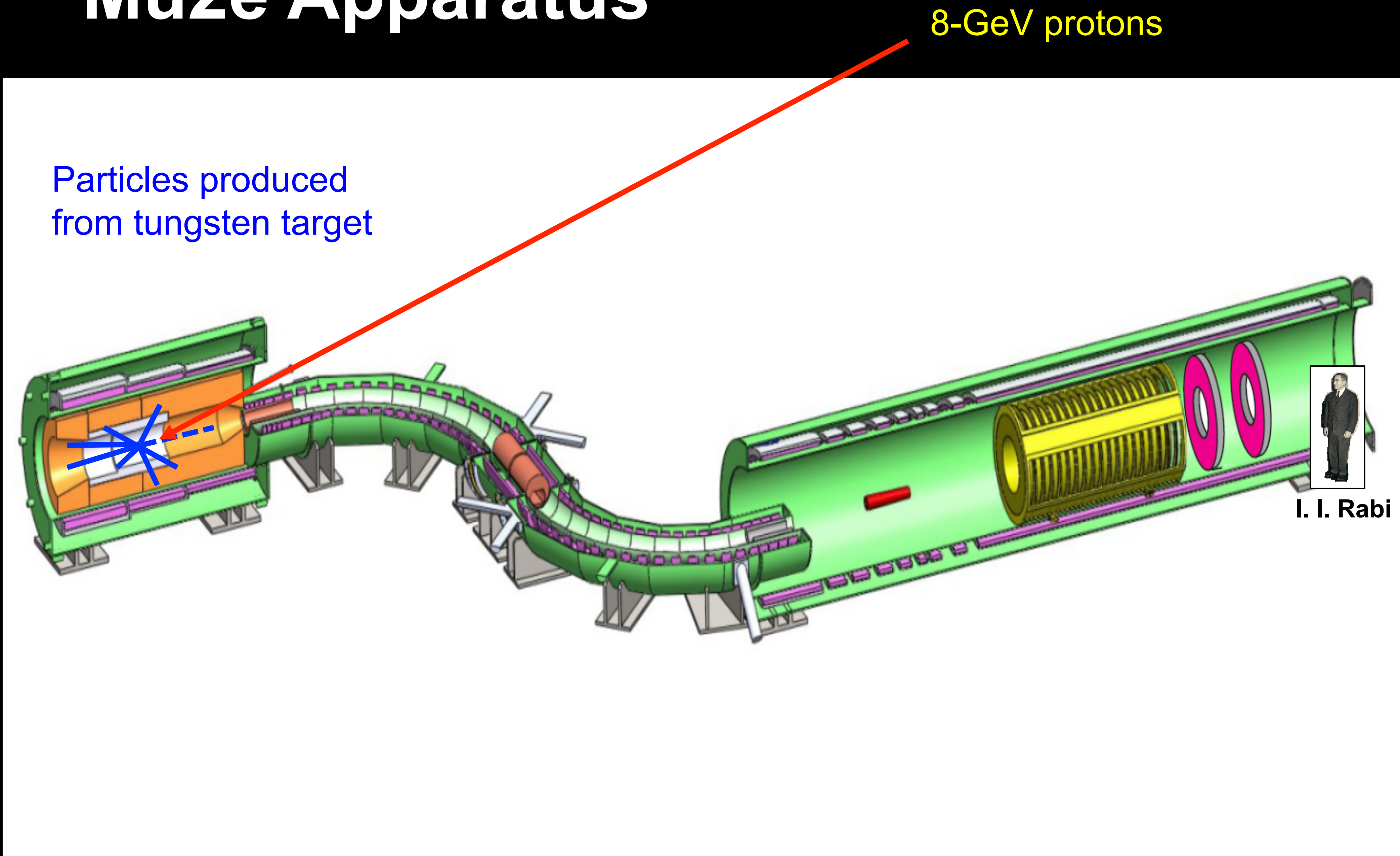
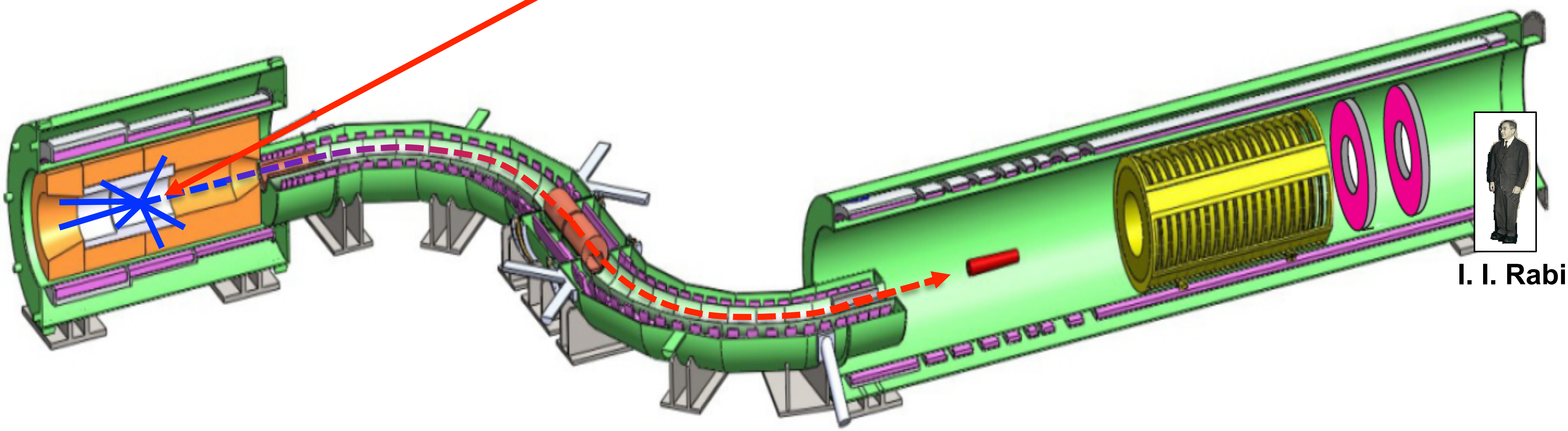


Mu2e Apparatus

8-GeV protons

Particles produced from tungsten target



S-shaped solenoid:
- central collimator selects negative particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

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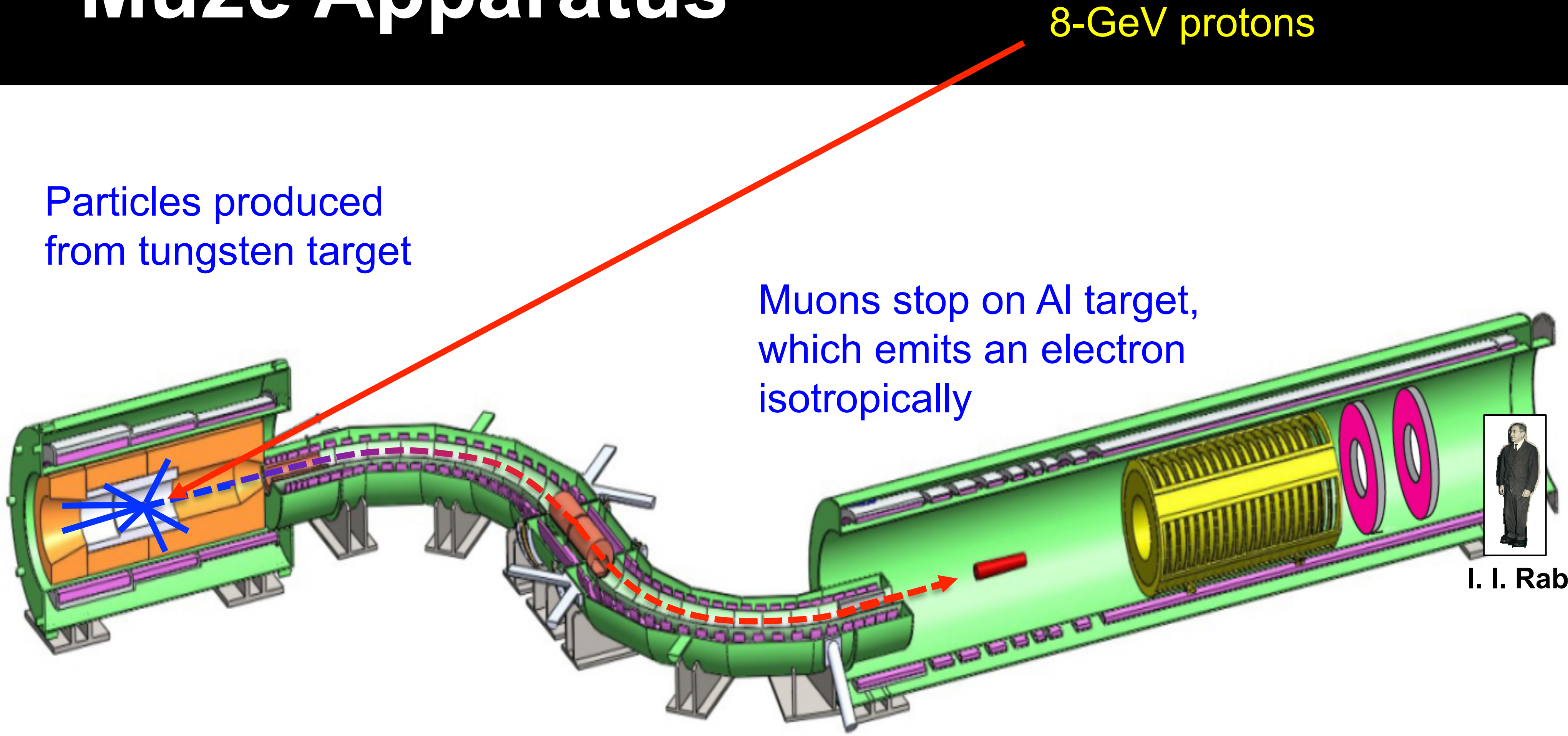

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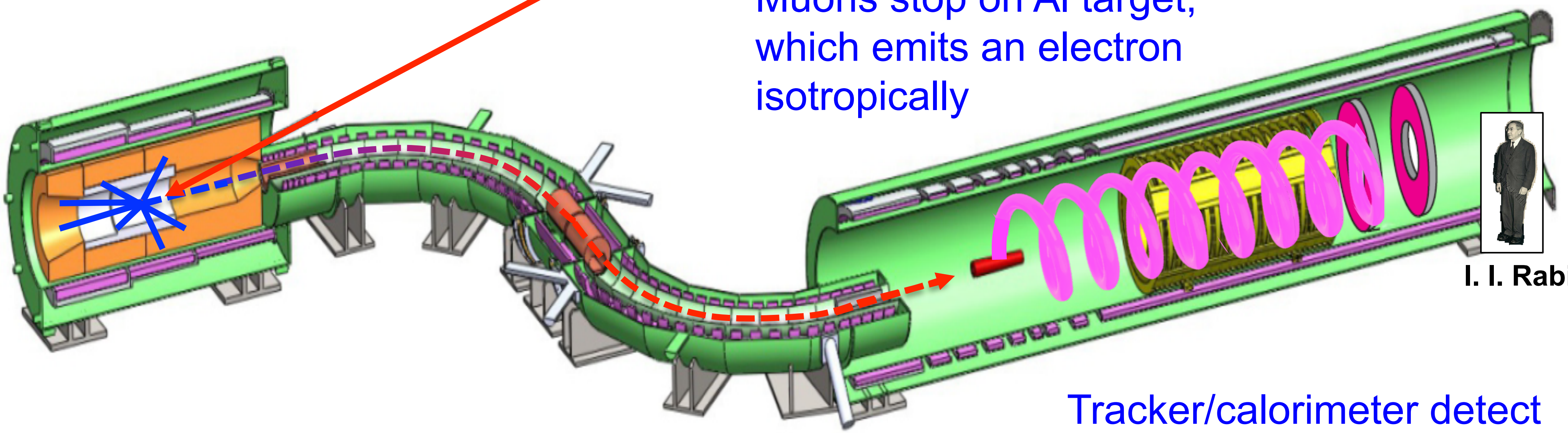
Particles produced from tungsten target

Muons stop on Al target, which emits an electron isotropically



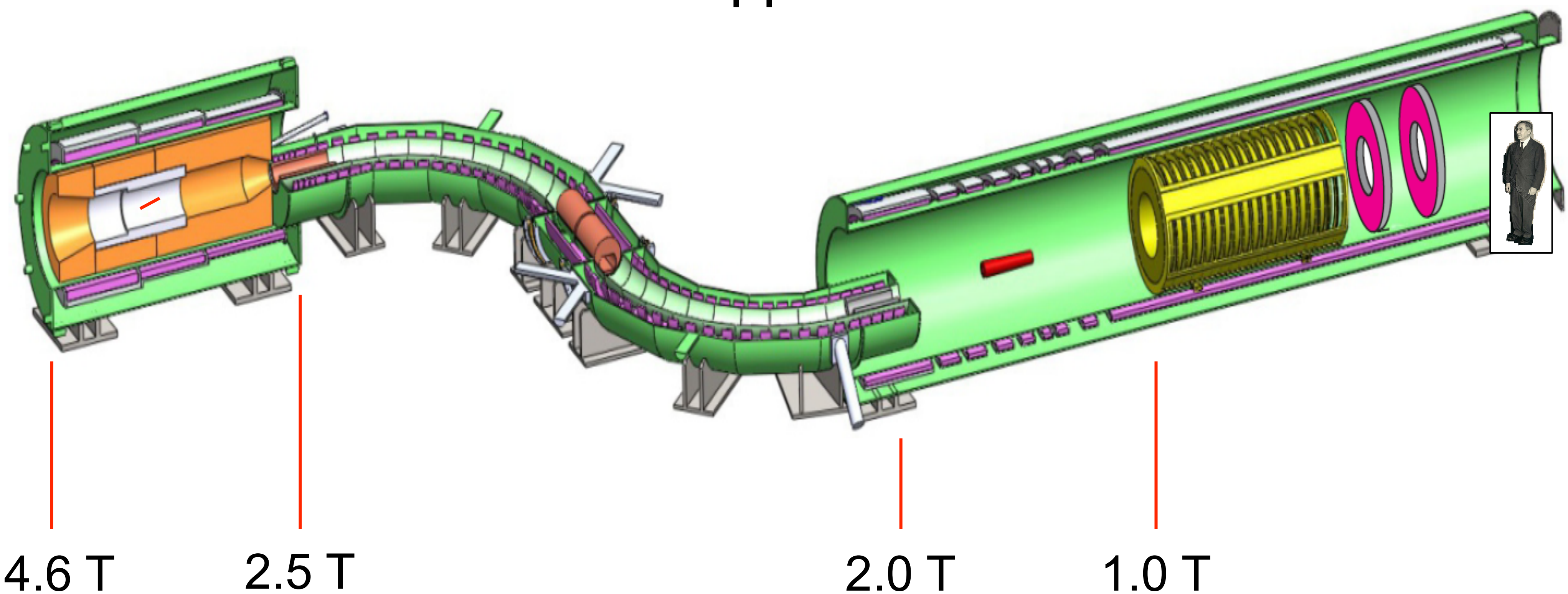
Tracker/calorimeter detect electron signature

S-shaped solenoid:

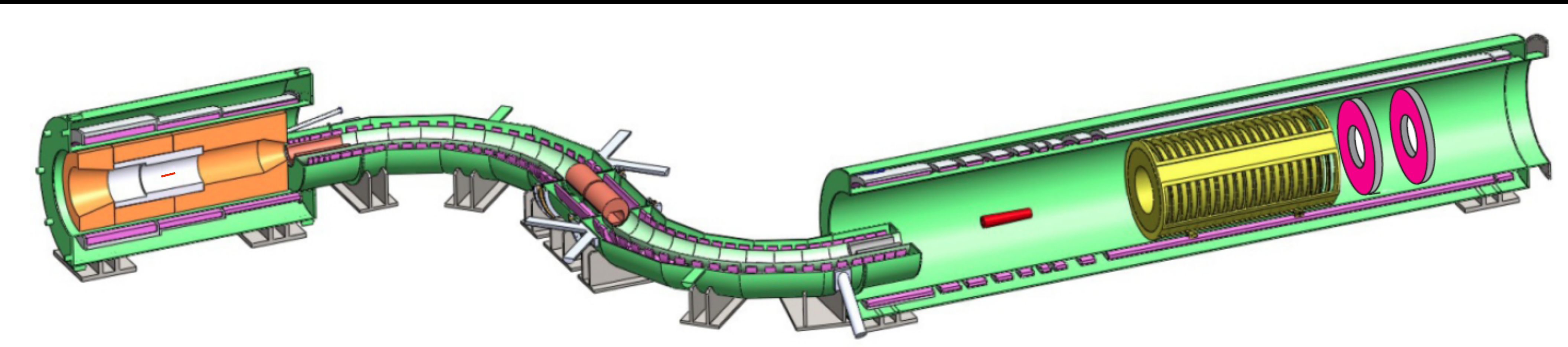
- central collimator selects negative particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

Magnetic fields are important

- To collect as many particles as possible, we use magnetic mirrors, produced by graded magnetic fields in much of the apparatus



A pulsed beam



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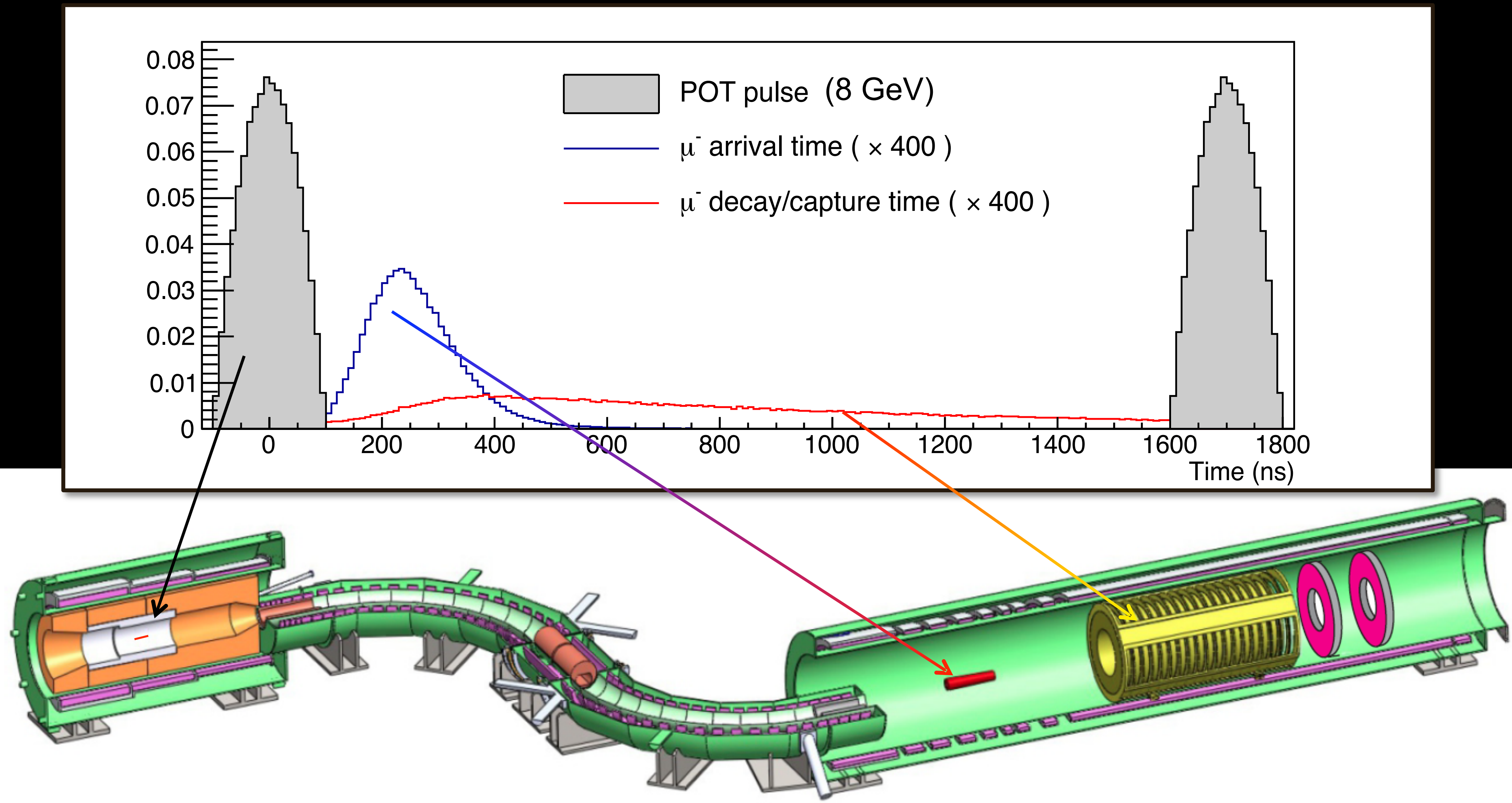

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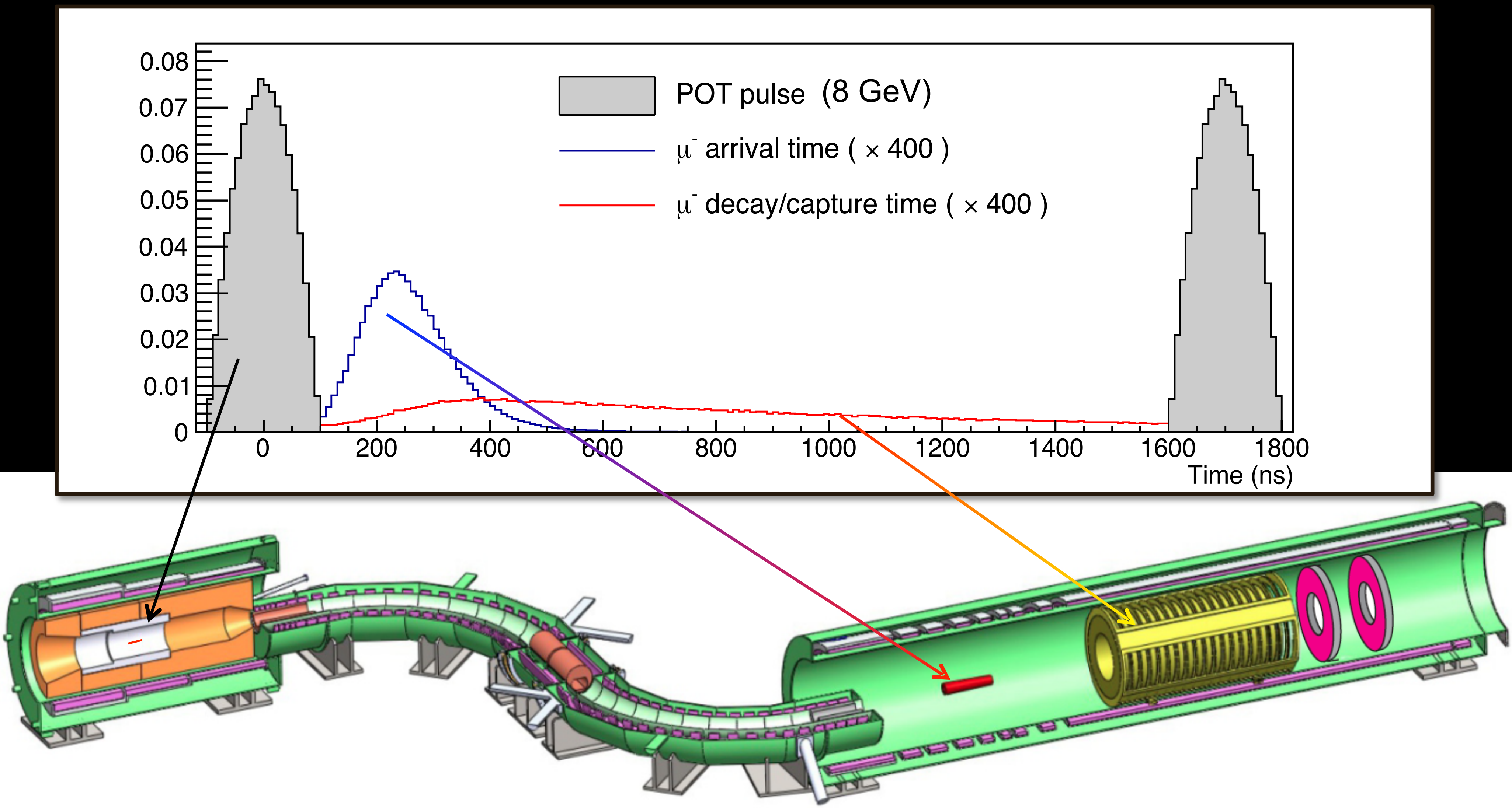
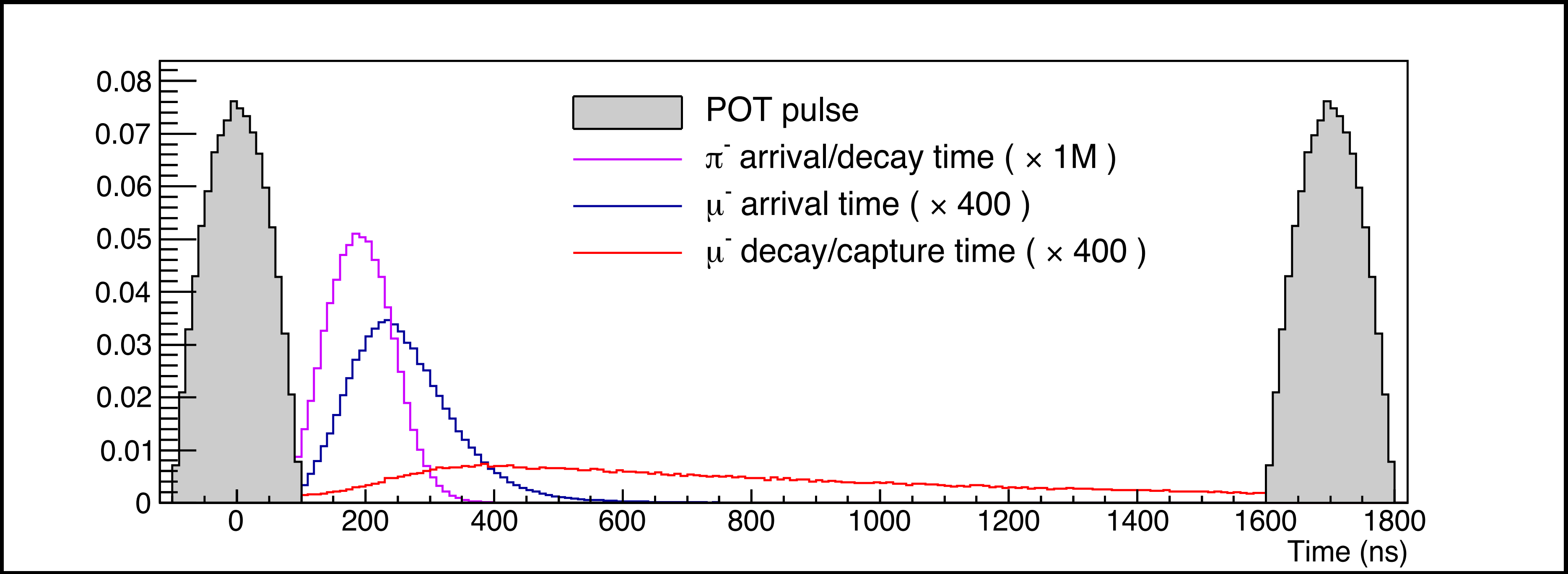


What if a pion doesn't decay but survives and stops in the Al target?

Backgrounds from pion capture



- Pion capture can produce a significant background:

$$\pi^- + N \to \gamma_{e^+e^-} + N'$$

- Can produce electron at same energy as the signal electron!

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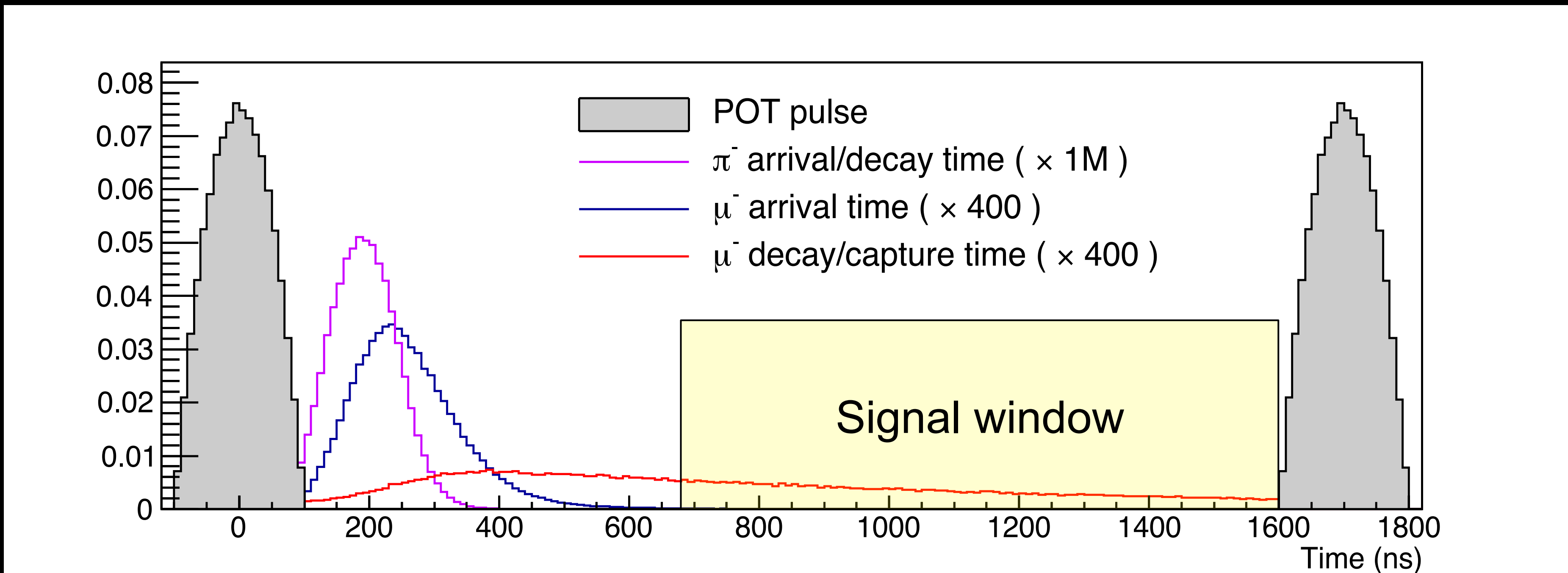


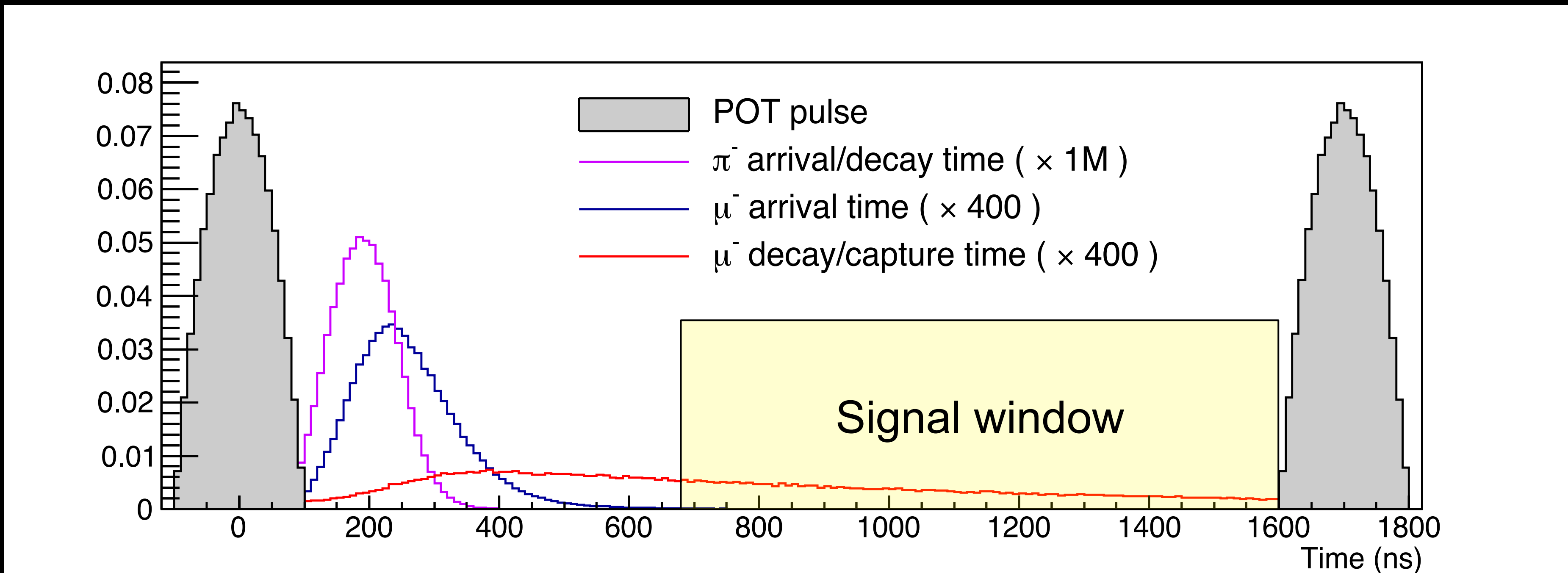
- Pion capture can produce a significant background:

$$\pi^- + N \rightarrow \gamma_{e^+e^-} + N'$$

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

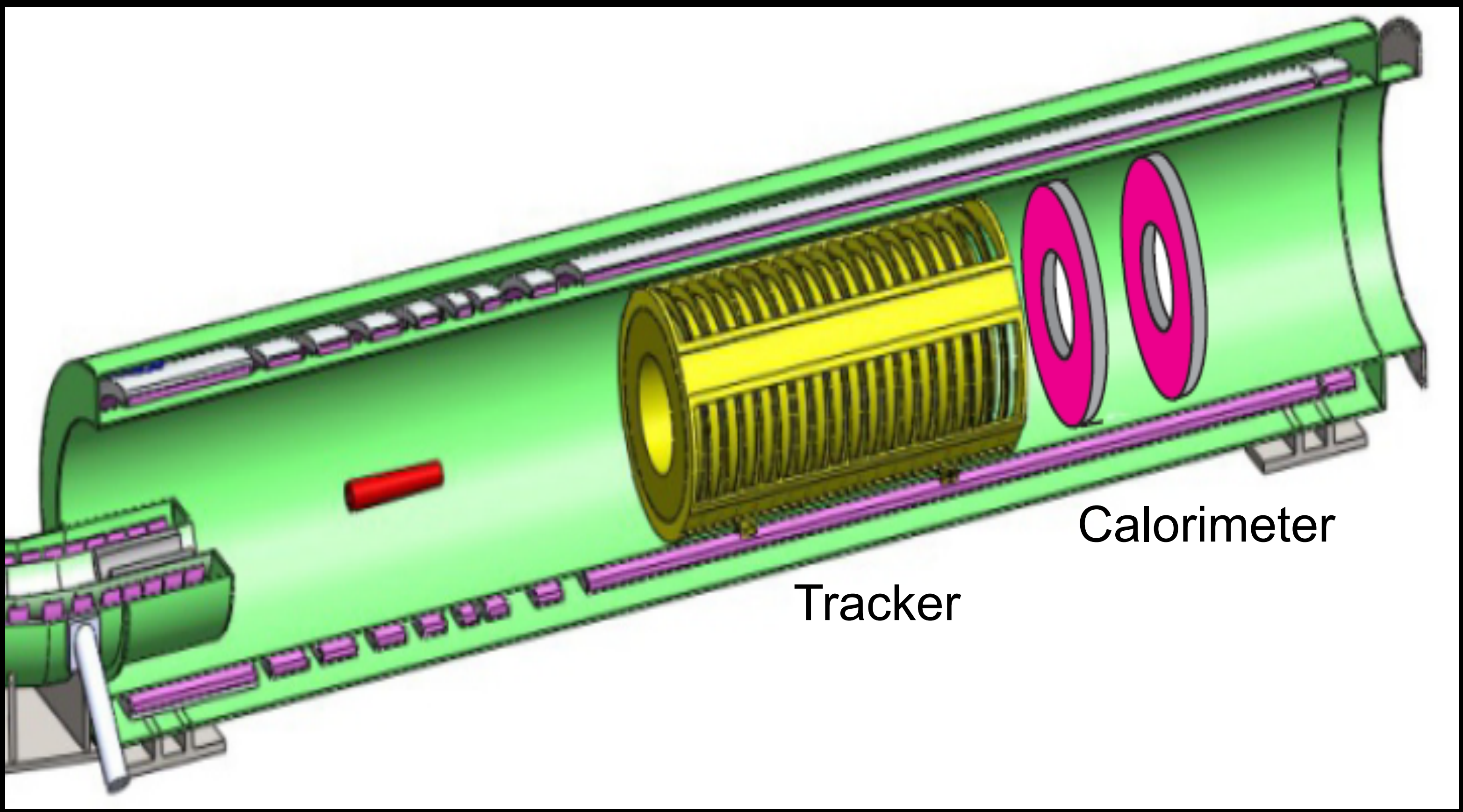
Wait out the pion captures before starting the live gate.

The factor of 10^4 improvement in $\mathcal{R}$…



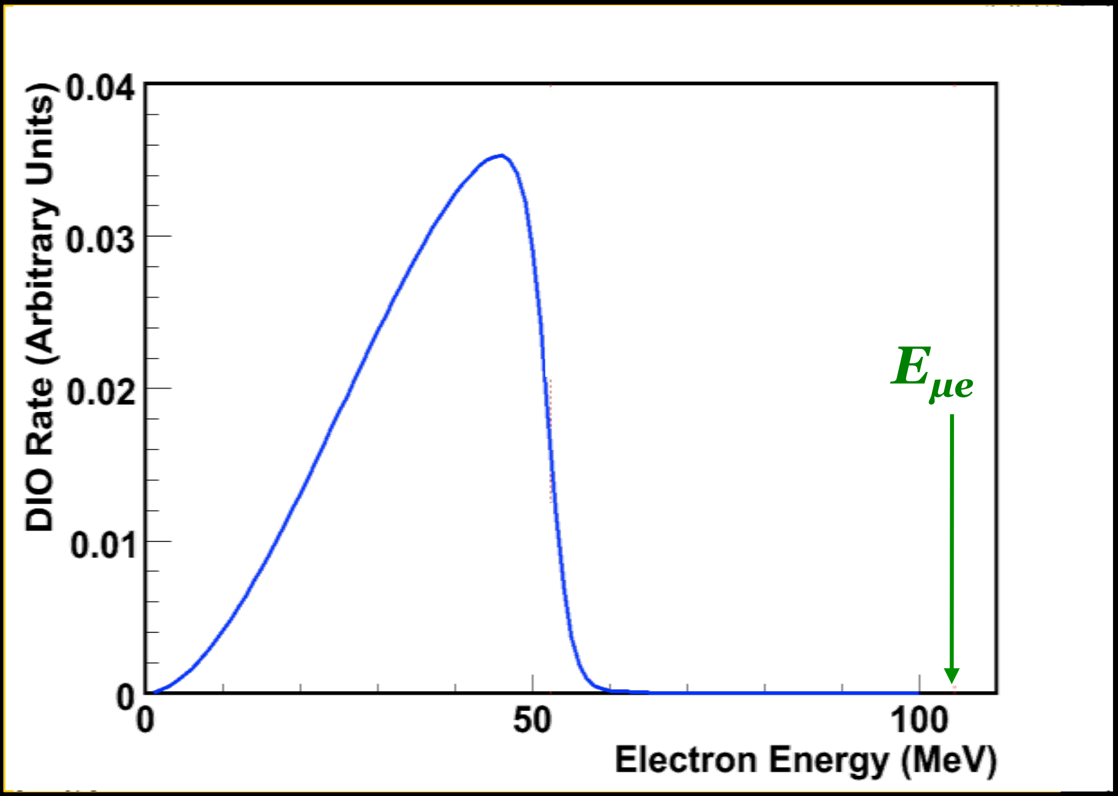
- It's not just more statistics.
- The pulse separation of previous experiment: **20 ns**.
- The 1695 ns proton pulse separation allows various backgrounds to significantly dissipate before we start the livegate.

Designing the tracker and calorimeter



Designing the tracker and calorimeter

- Remember the DIOs.



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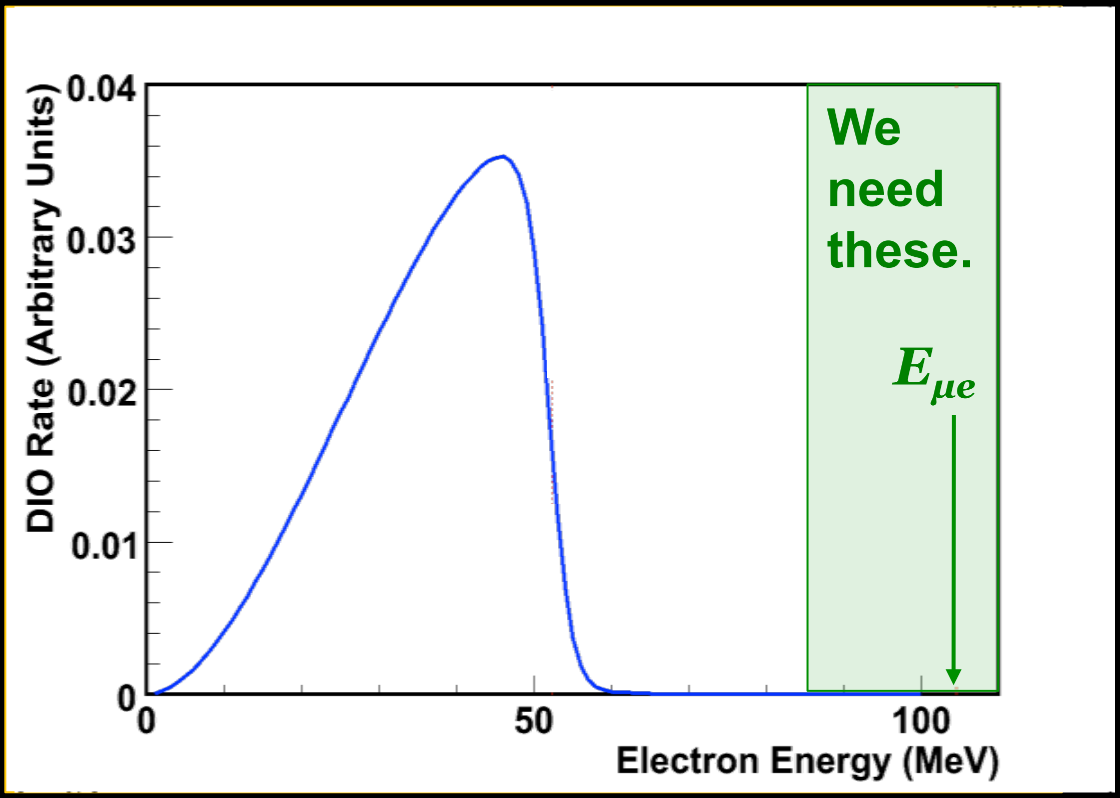

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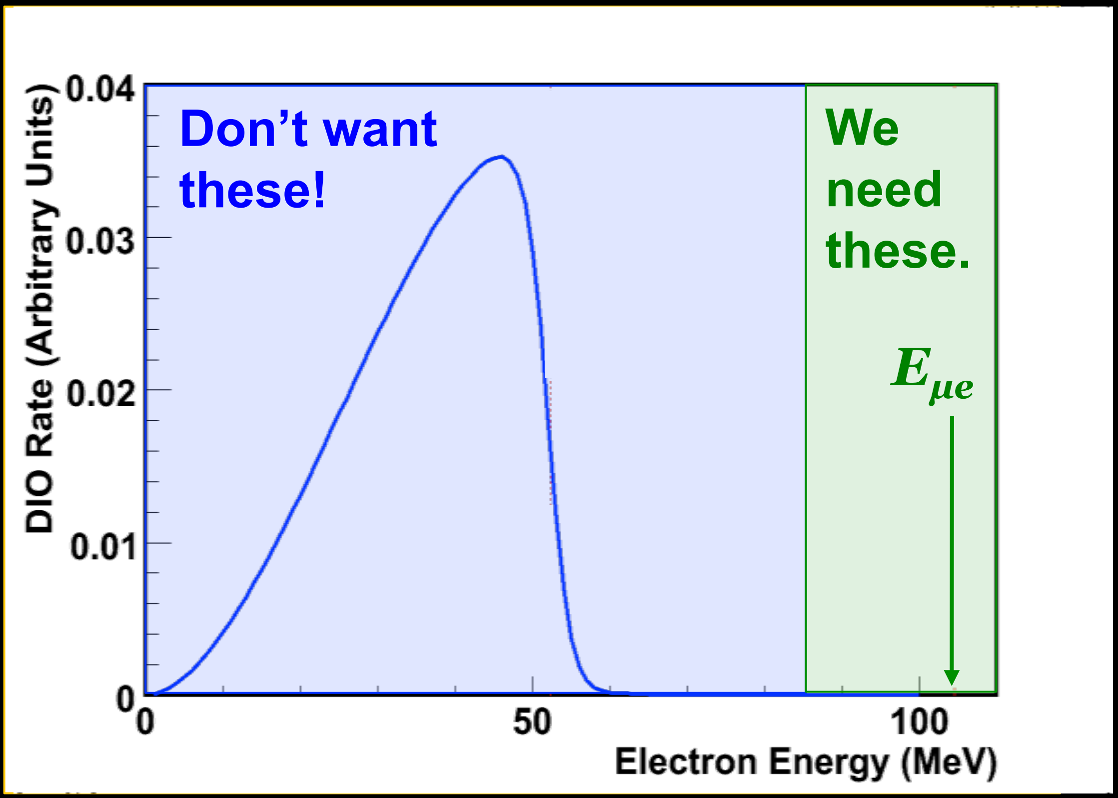

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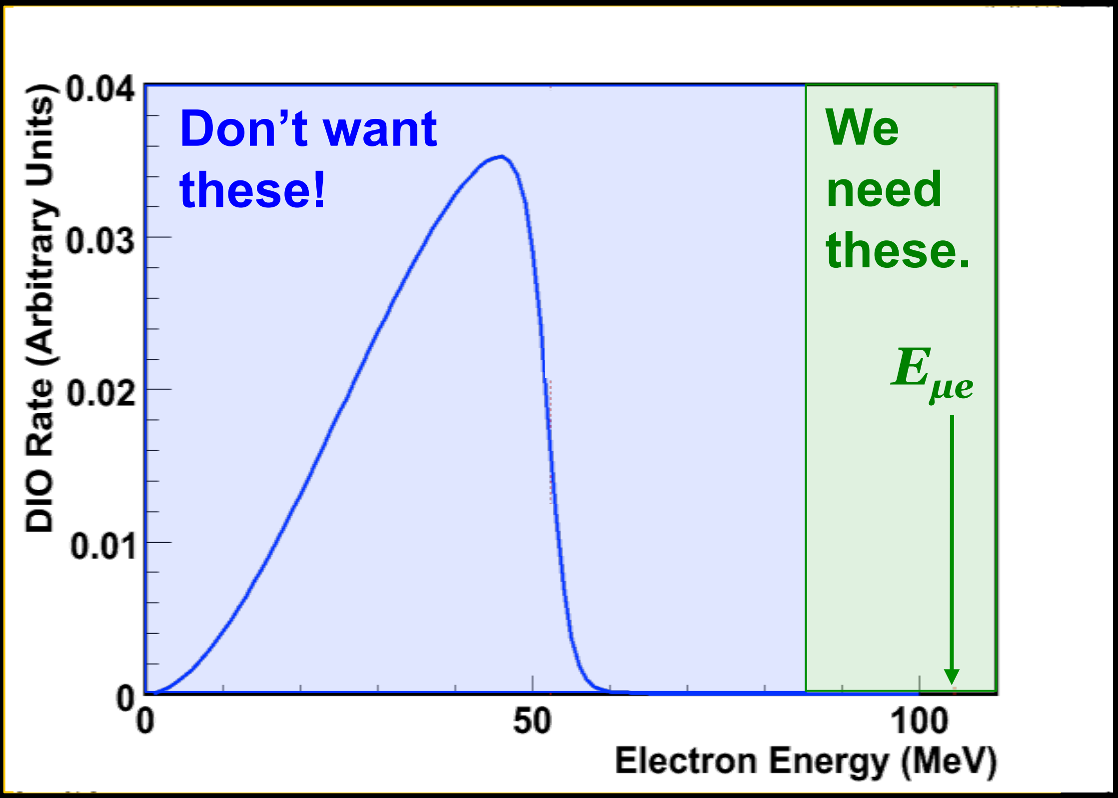
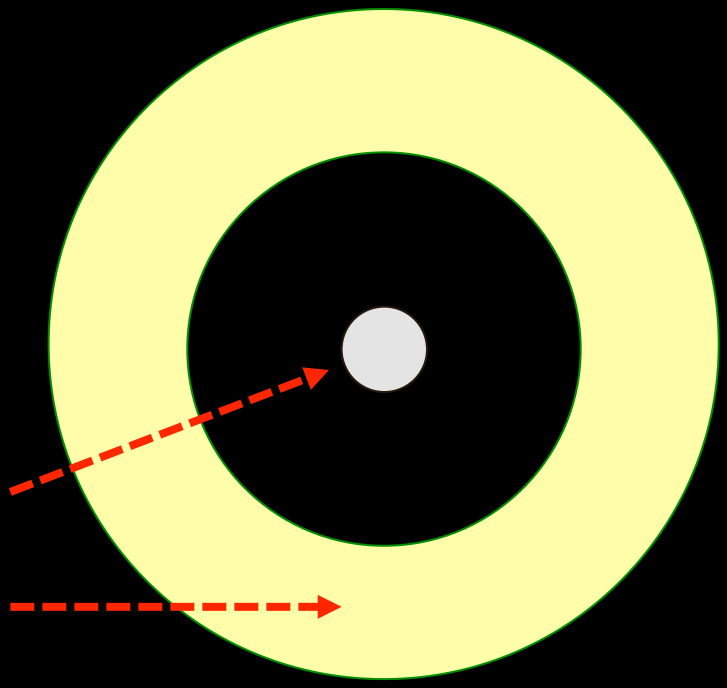


- Since radius of track is proportional to p_T, design the detectors to only see tracks with large enough radii.
  - Annular design



End view of stopping target and detectors

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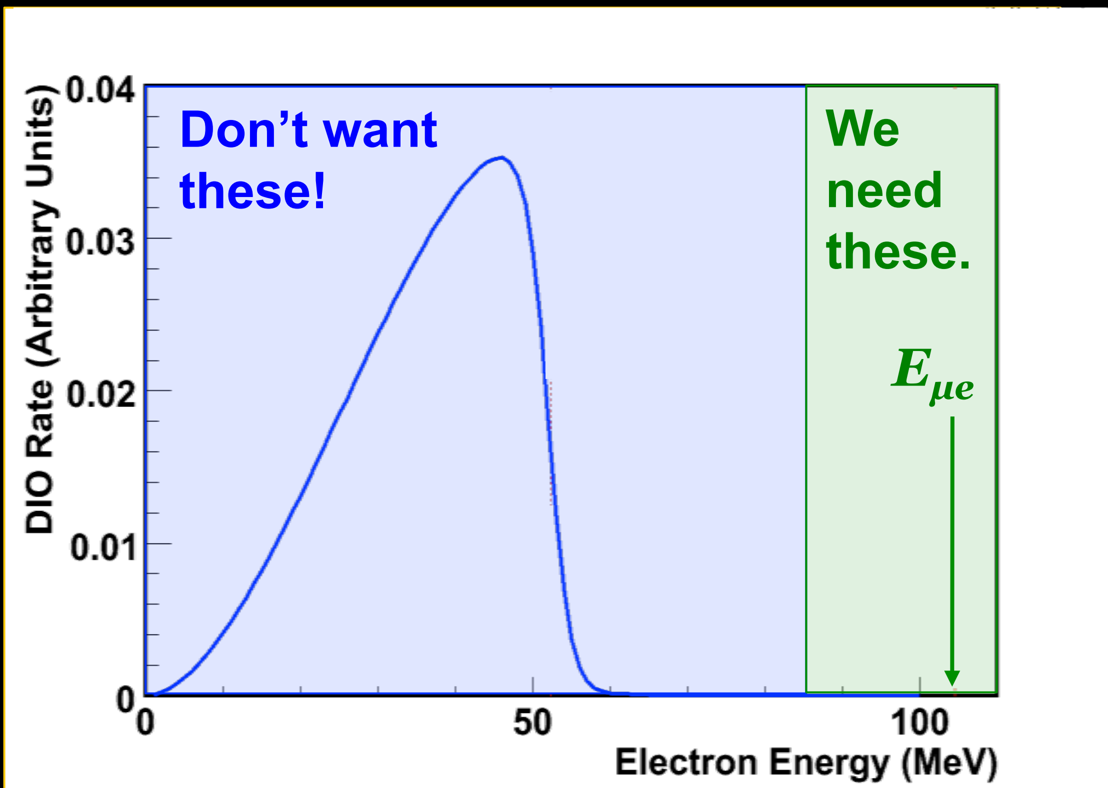

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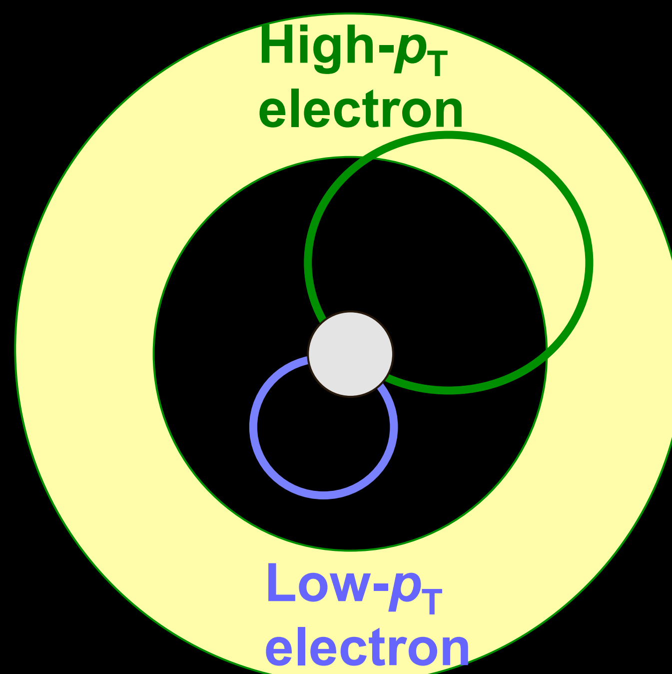
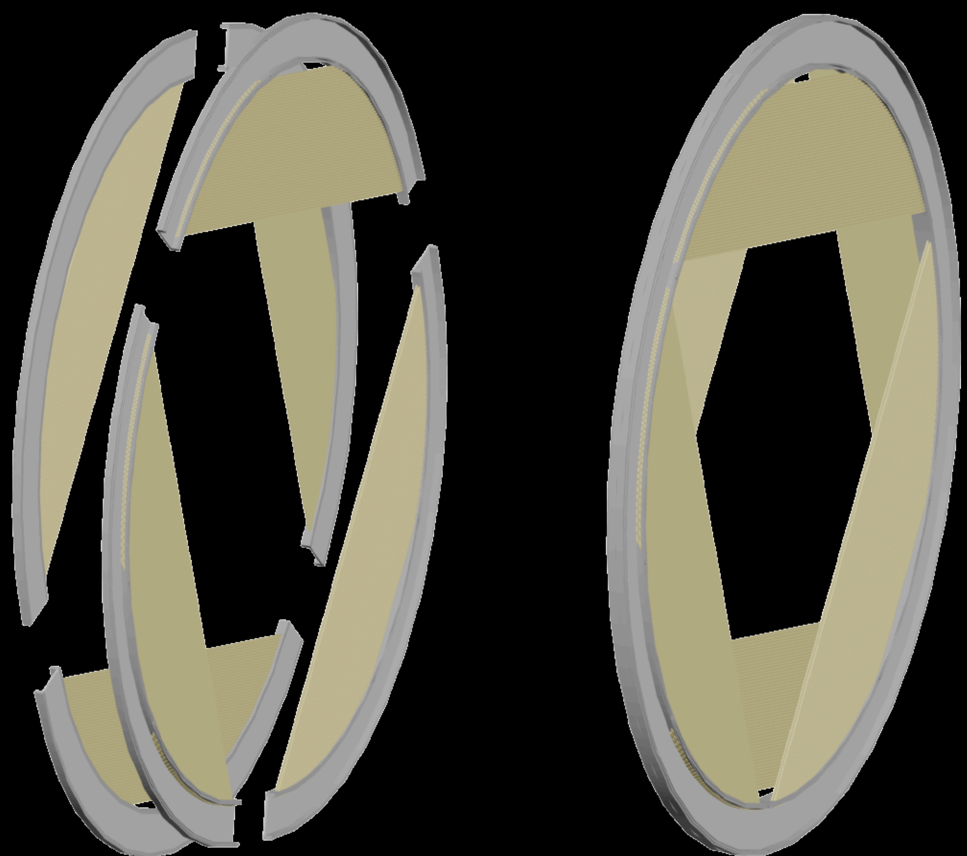
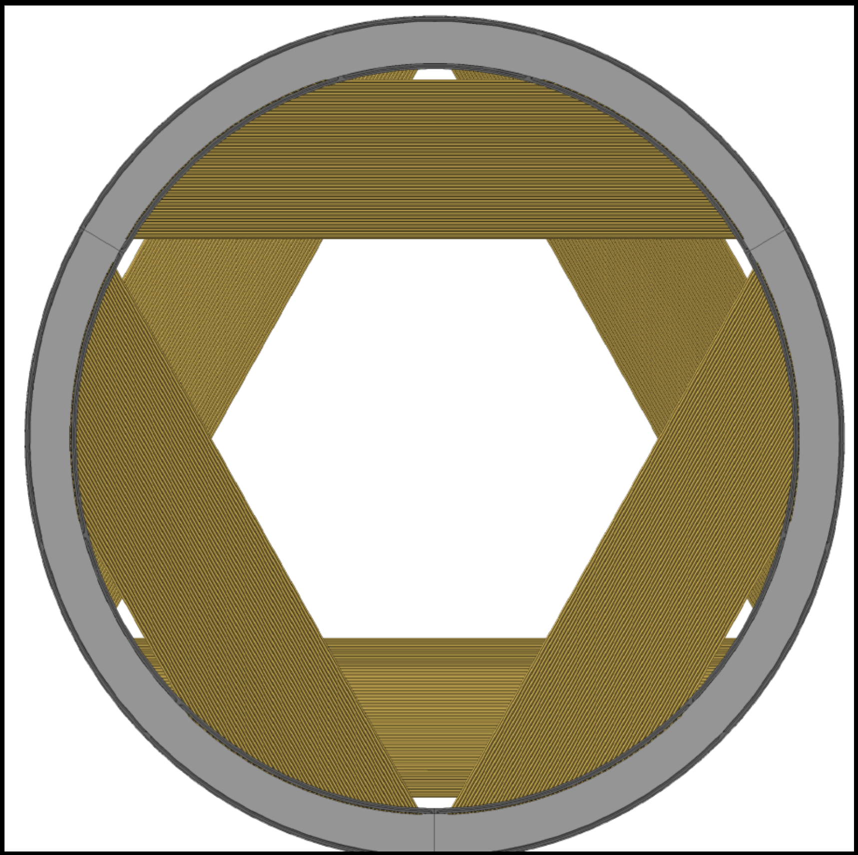


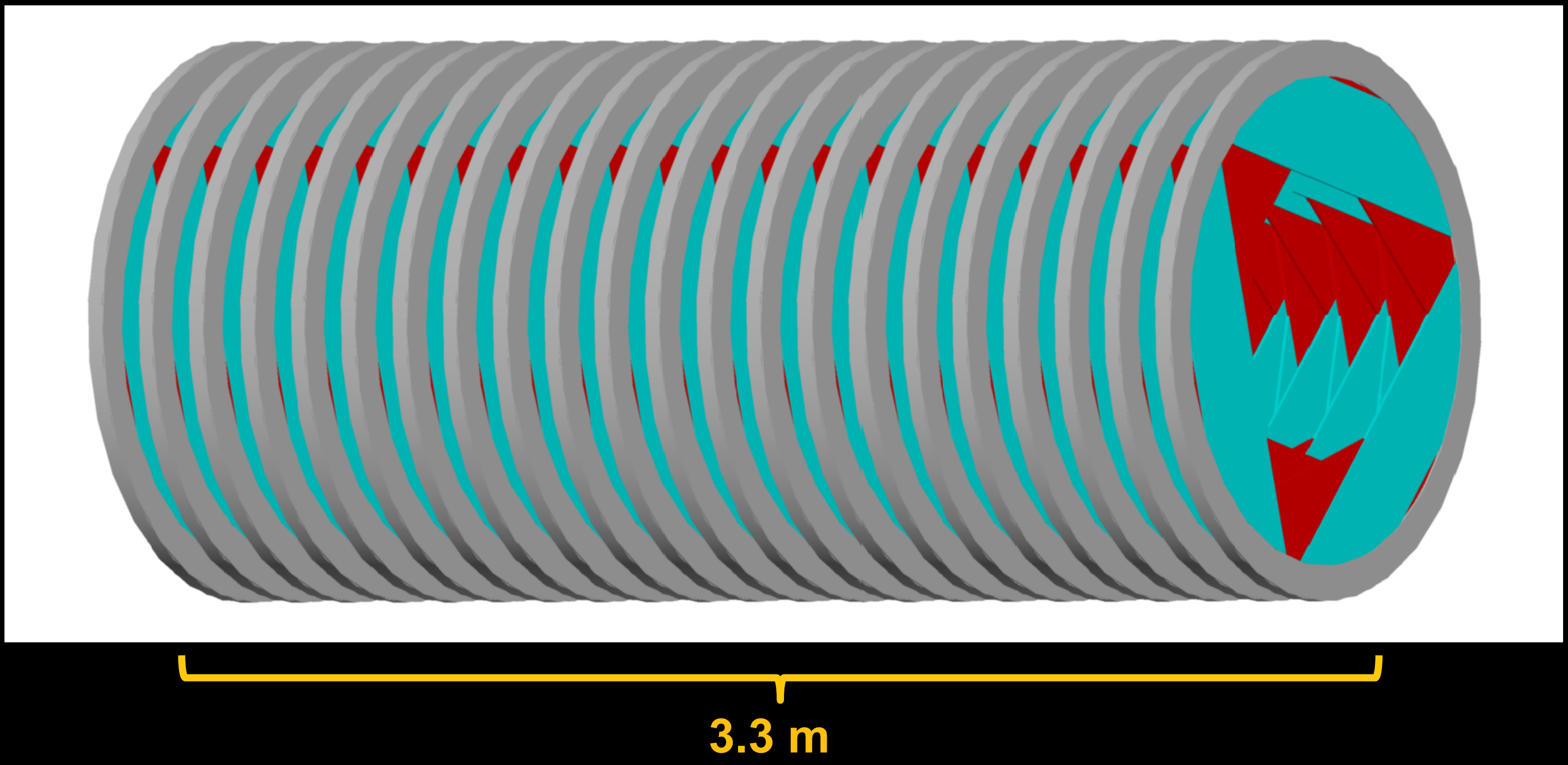
The tracker

- Uses 5-mm diameter straws
  - 15-micron metalized mylar walls
  - 25-micron diameter W central wire
  - Gas mixture of 80:20 Ar CO_2
  - Straws are grouped into panels, 6 of which form a plane





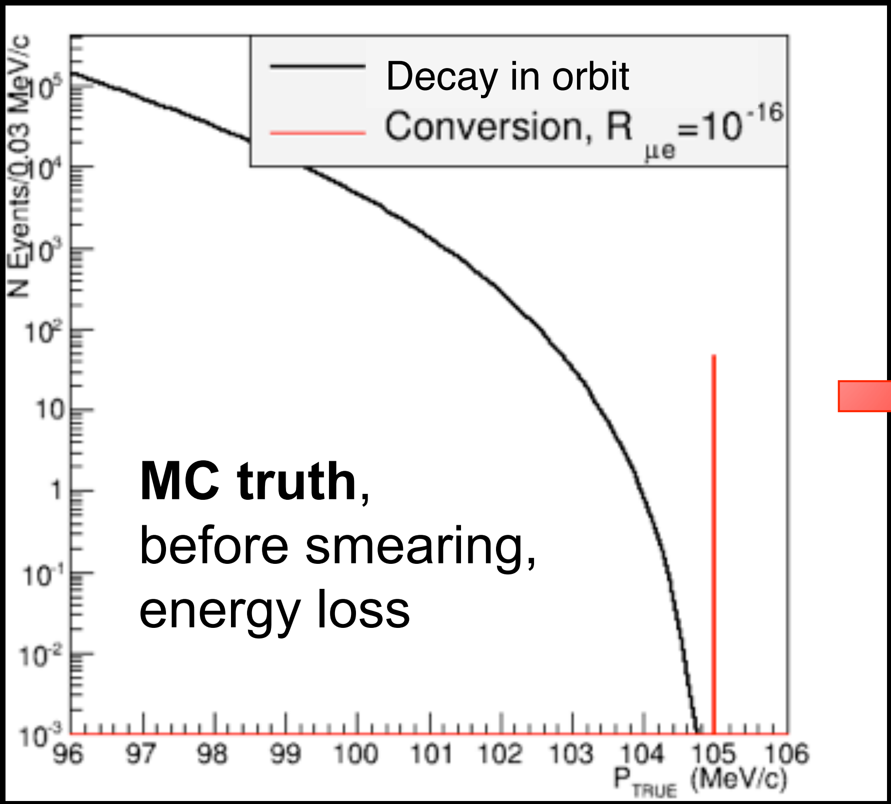
The tracker

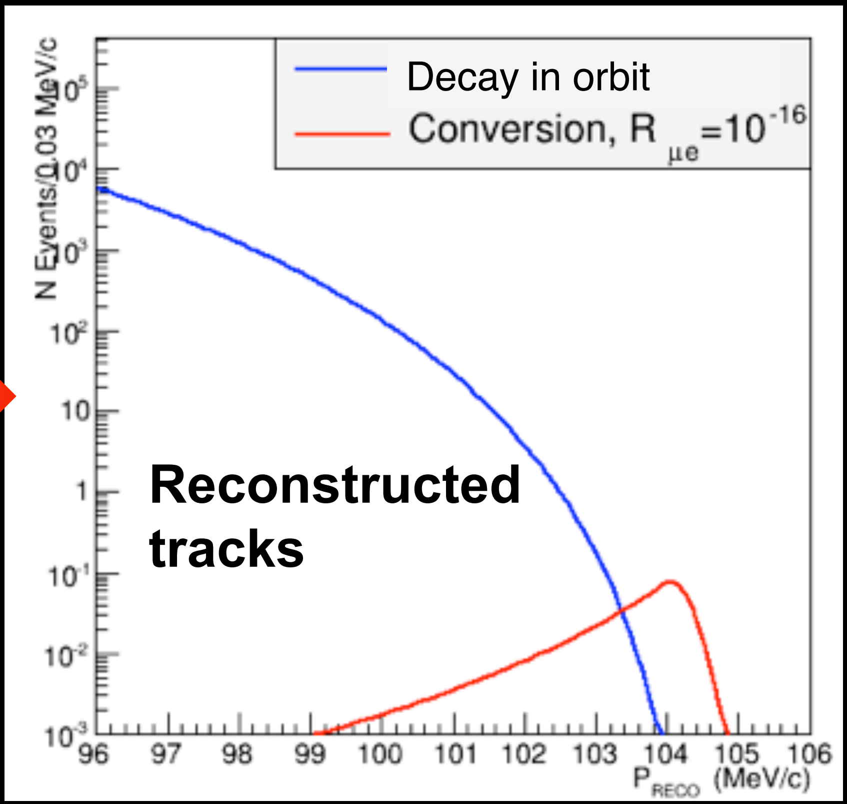


- There are a total of 23K straws in 20 stations.
- Module rotations are optimized to ensure maximum coverage.

What about resolution?

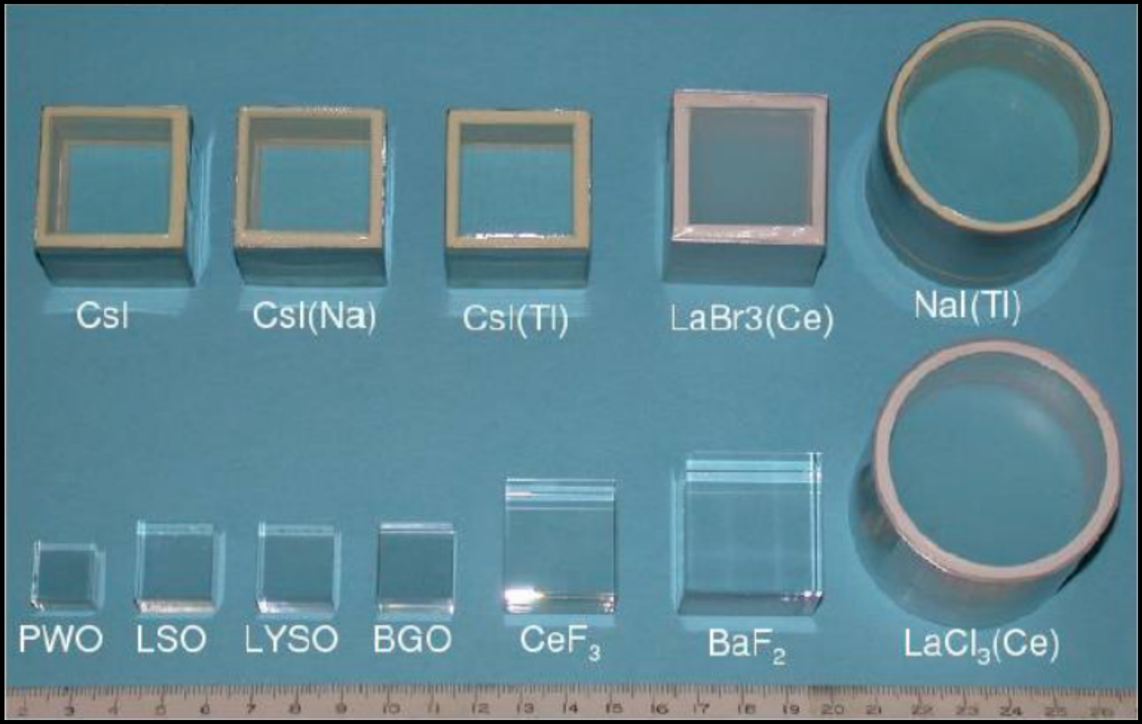
- Energy loss effects result in an overall momentum resolution of ~1 MeV/c.
- If there is a large contribution to the high-side tail of the resolution function, the DIOs can obscure the signal.
    - Detailed simulation indicates this is under control.

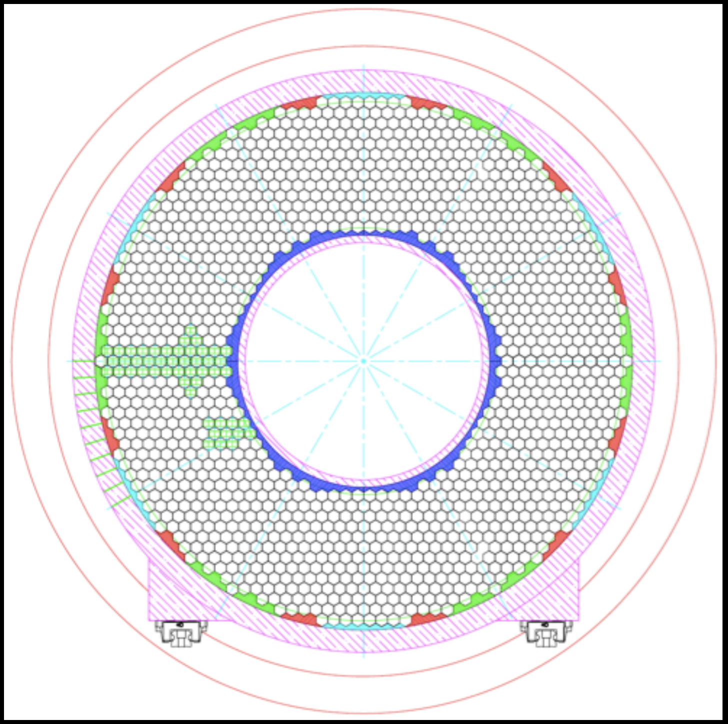




The Calorimeter

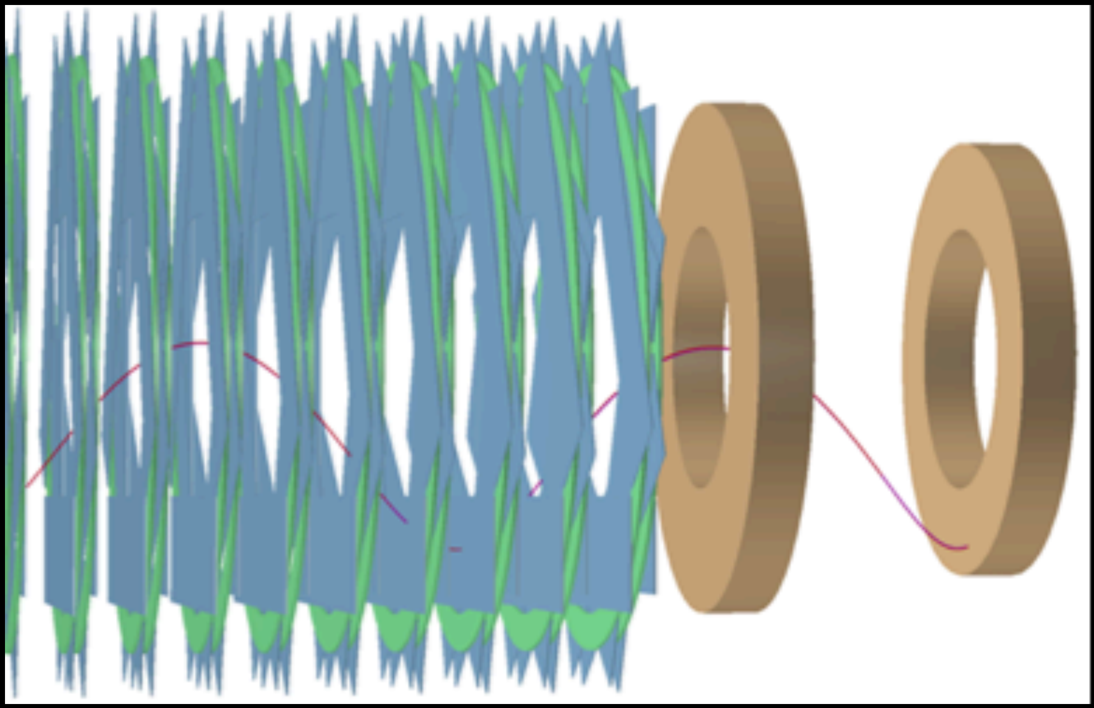
- Disks are comprised of scintillating crystals.
- Need to be fast and radiation hard
  - Use BaF_2, which has a very fast scintillation component (< 1 ns).
- Crystal geometry is hexagonal, which works well with the annular design





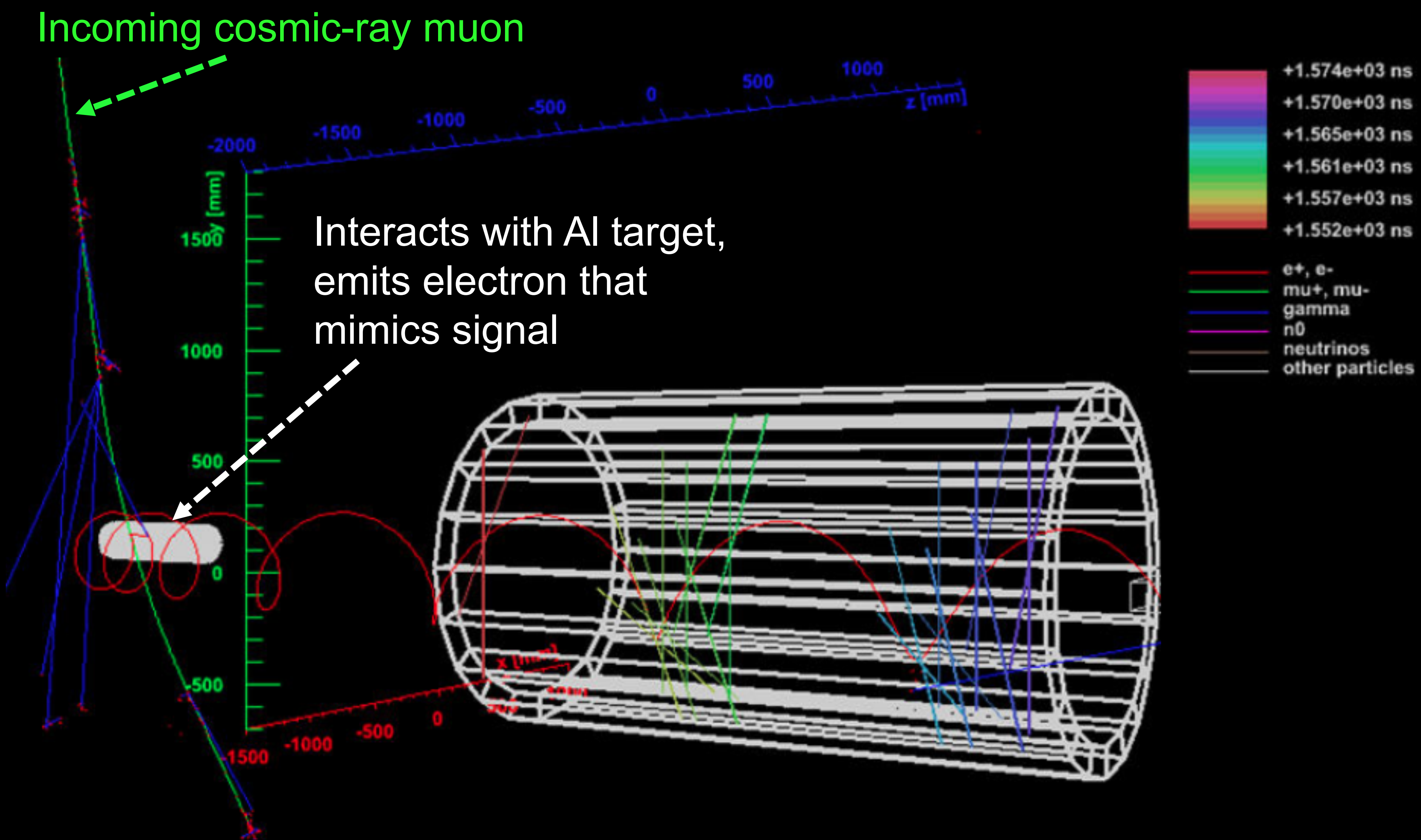
The Calorimeter

- Uses a two-disk arrangement, spaced ½ wavelength apart for (an average) 105 MeV/c particle.



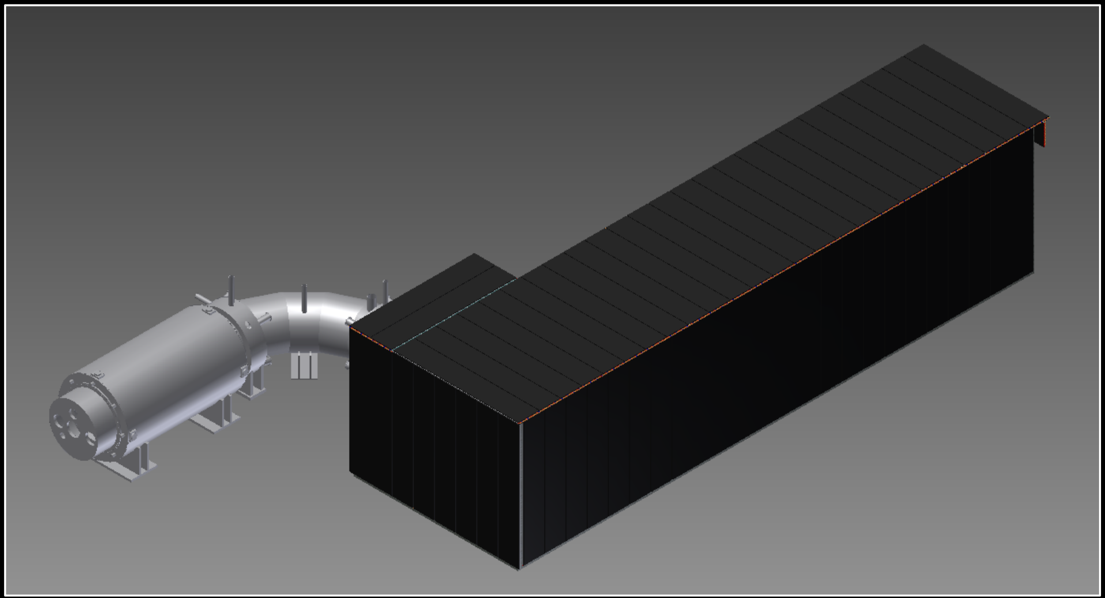
- Calorimeter provides
  - Track reconstruction validation
  - Timing information for background reduction
  - Electron/muon discrimination from cosmic rays…

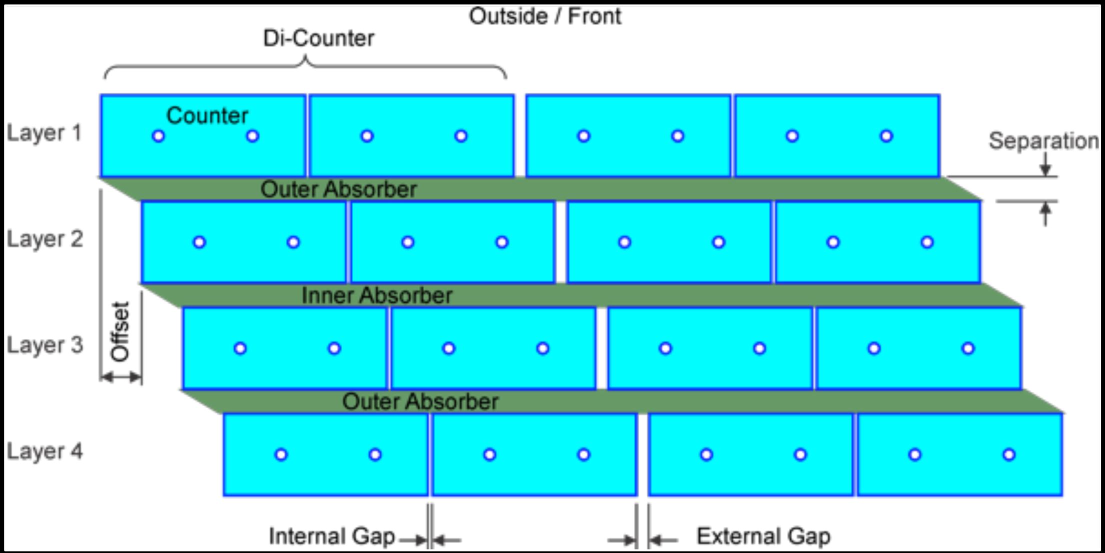
Cosmic ray backgrounds



- This happens once per day!
  - Need cosmic-ray veto (CRV) system.

Cosmic ray veto





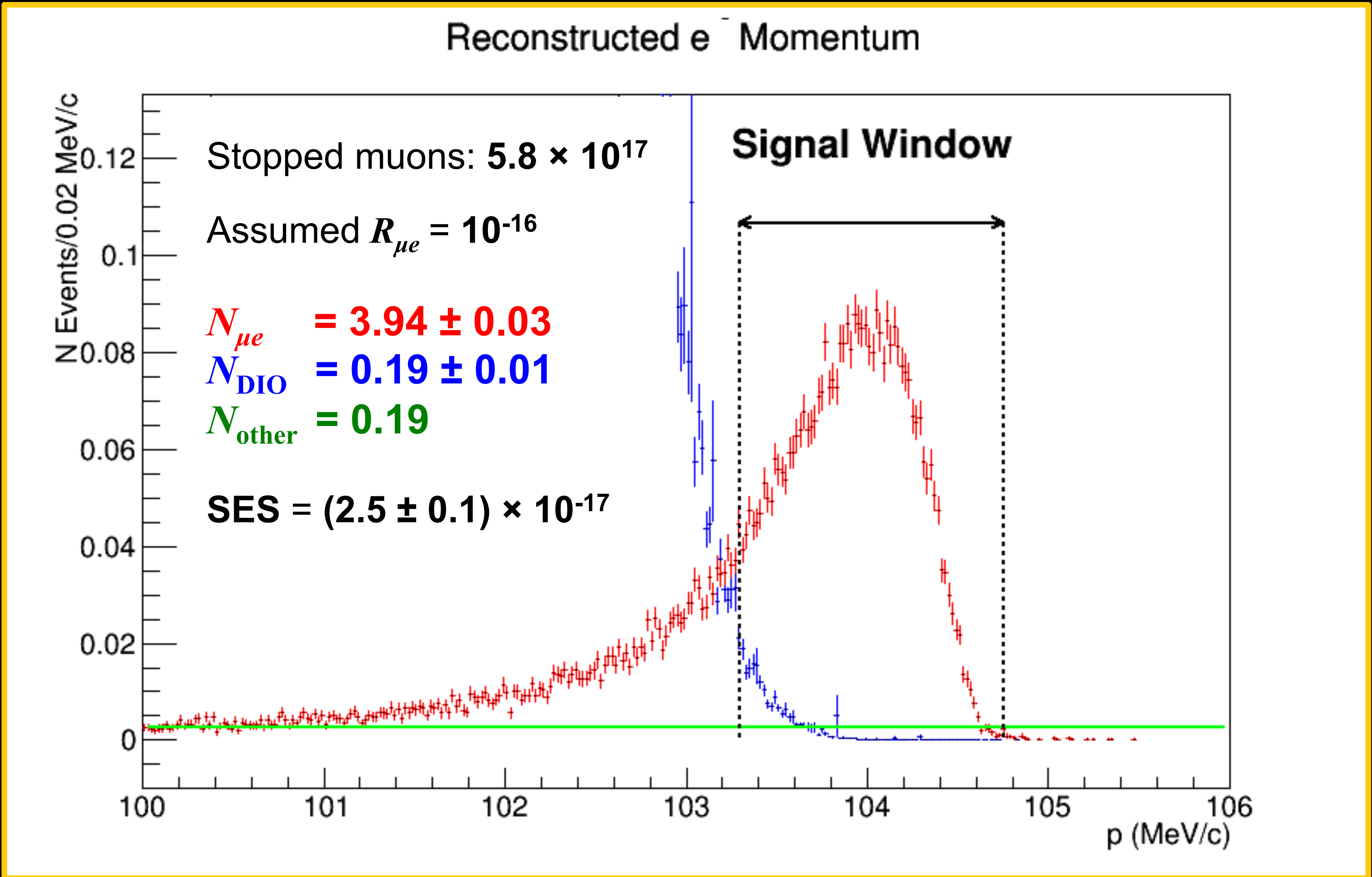
- Surrounds detector area and parts of transport area
- Uses extruded plastic scintillator with wavelength shifting fibers.
- Modules grouped into four layers, separated by aluminum absorbers
- 99.99% veto efficiency required!
- Cosmic ray backgrounds vetoed by rejecting 3-layer coincident signals
- Significant shielding required to protect against neutron/photon radiation from production target, stopping target, etc.

Total backgrounds (for 3 yrs)

Category	Source	Events		
Intrinsic	μ decay in orbit	0.20	$\pm$	0.06
Late-arriving	Radiative π capture	0.04	$\pm$	0.02
	Beam electrons	0.001	$\pm$	0.001
	μ decay in flight	0.010	$\pm$	0.005
	π decay in flight	0.003	$\pm$	0.002
Miscellaneous	Antiproton capture	0.10	$\pm$	0.06
	Cosmic ray	0.050	$\pm$	0.013
Total Background		0.4	$\pm$	0.1

Translates to 90% CL upper limit on *R* of **7×10^{-17}**.

The full simulation



Mu2e Collaboration & Status

Mu2e Collaboration

Mu2e Status

- The experiment was strongly endorsed by P5:
  - **“Recommendation 22: Complete the Mu2e and muon g-2 projects.”**

Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context, p. 15 (May 2014)

- We are working very hard to finalize the technical design report now.
  - Will be released in the next few months
  - We break ground this fall.
- Experiment expected to come online by 2019.

Conclusions

- Mu2e searches for coherent conversion of a muon to an electron (CLFV)
  - An improvement of 10^4 in conversion rate is expected wrt the previous experiment
  - Improvement of 10 in CLFV mass scale
- Experimental design is well along
- Mu2e has been strongly supported by P5
- Operations will begin at end of this decade

…not that far away.

Conclusions

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…not that far away.

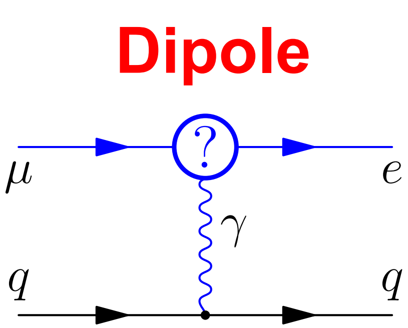
We welcome more collaborators!

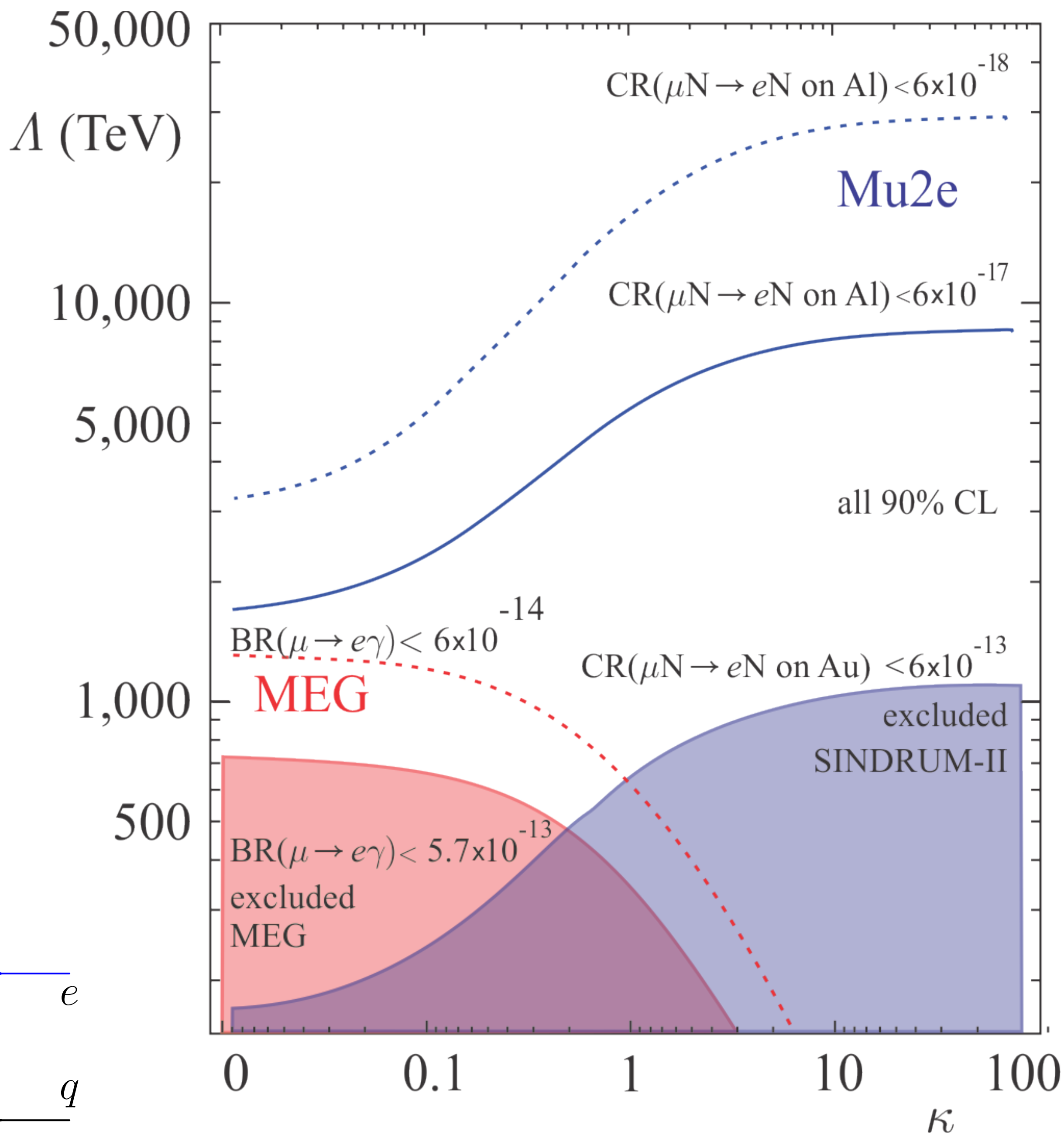
Join us!

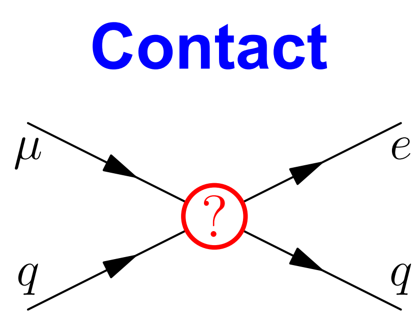
http://mu2e.fnal.gov/

Back-up slides

$\mu \to e\gamma$ **vs.** $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$





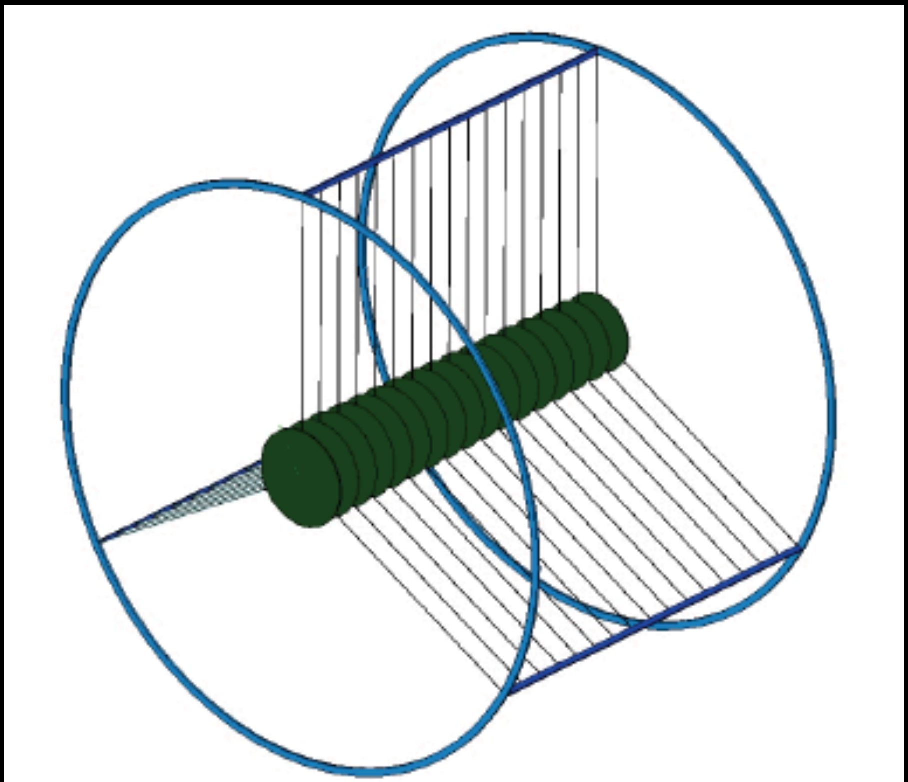


Other backgrounds:

- In-flight decays, late arriving
  - Muons: $\mu^- \rightarrow e^-$
  - Pions: $\pi^- \rightarrow \mu^- \rightarrow e^-$
- Beam electrons, late arriving
  - Electrons that propagate through TS to tracker
- Antiprotons
  - Available kinetic energy is above $p\bar{p}$ threshold
  - Partially mitigated by placement of $\bar{p}$ absorbers in transport area

The stopping target

- Maximize muon stopping rate; but minimize energy loss for electrons
- Chosen geometry:
  - 17 Al foils
    - 0.2 mm thick each
    - Spaced 5 cm apart
    - Radii 6-8 cm
  - Supported by thin, tungsten wires
    - lower DIO energy endpoint
- ***20** out of every **10^4** POTs results in a stopped muon.*

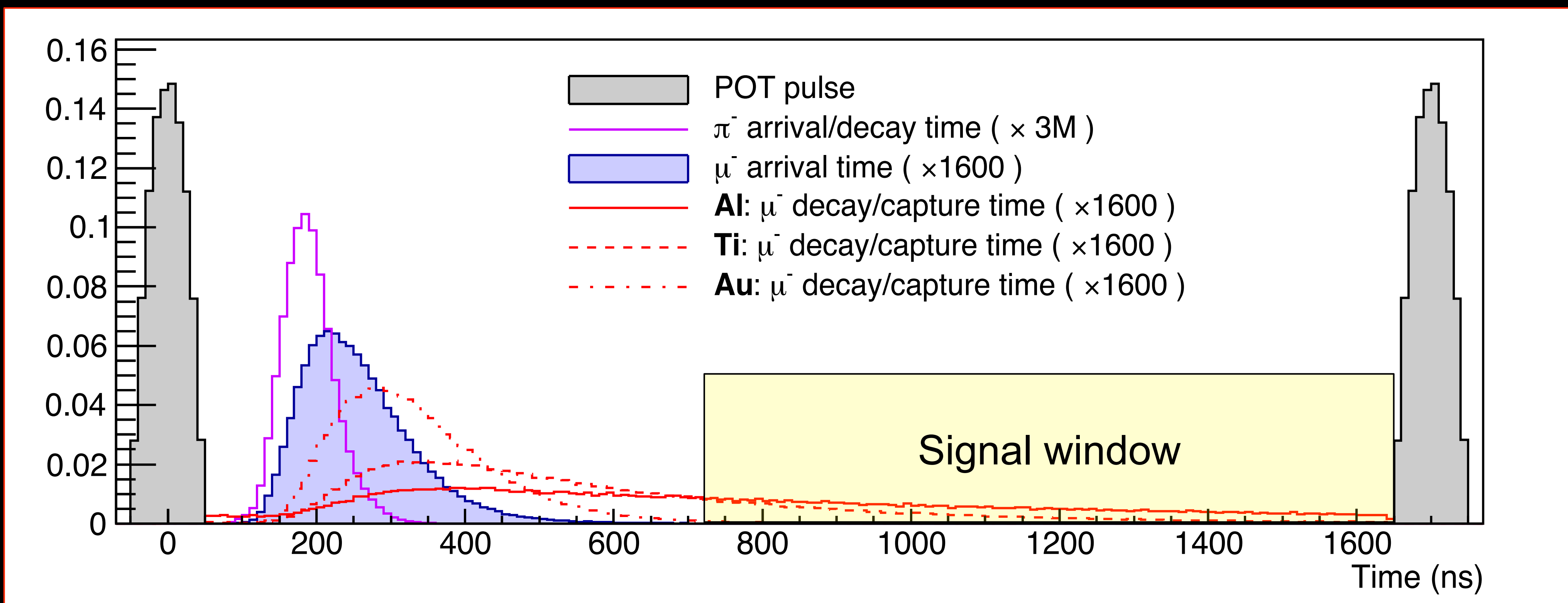


- Electrons emitted isotropically, then travel to the detectors.

Why aluminum?

- Since pion capture process happens very quickly, need a
so
Aluminum is best option

	Al	Ti	Au
Stopped muons that decay	39%	15%	3%
Stopped muon decays in sig. window	50%	30%	1%
Time constant for muon decay	**864 ns**	**329 ns**	**75 ns**



Charged lepton flavor violation

- Allowed by various new physics scenarios
- CLFV parameterized by model-independent Lagrangian:
  - Assume NP appears in dimension-5/6 operators

A. de Gouvea and P. Vogl, Prog. In Particle and Nuclear Physics **71** (2013) 75

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L\boxed{F^{\mu\nu}} +$$

Dipole term

$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

Contact term

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Effective mass scale of CLFV

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Effective mass scale of CLFV

$\boldsymbol{\mu \to e}$ **rate** $\propto \Lambda^{-4}$

Charged lepton flavor violation

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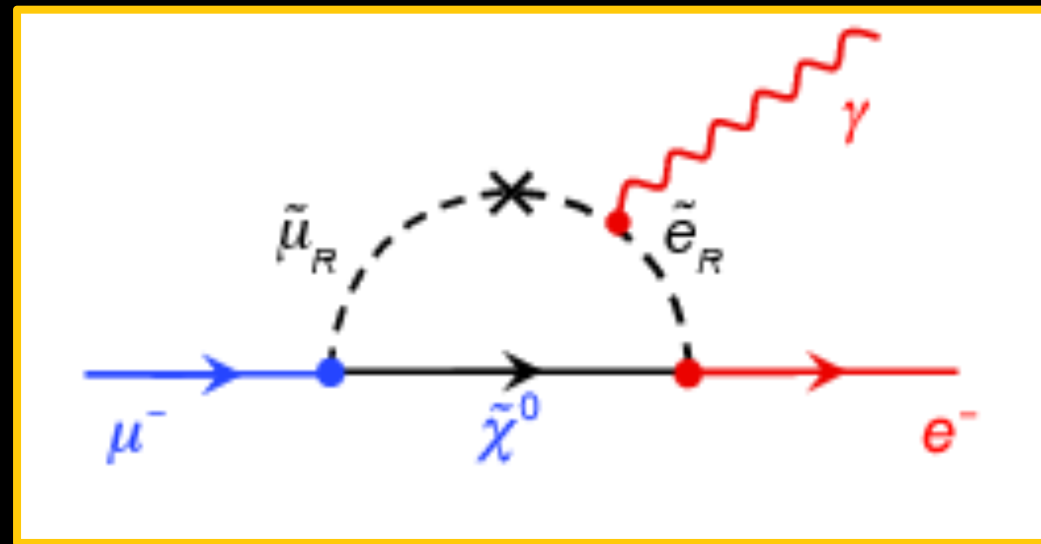
NP parameter regulating "sharing" between operators

Role of κ

- Consider $\mu \rightarrow e\gamma$
- Process requires no quarks, so only dipole operator is relevant

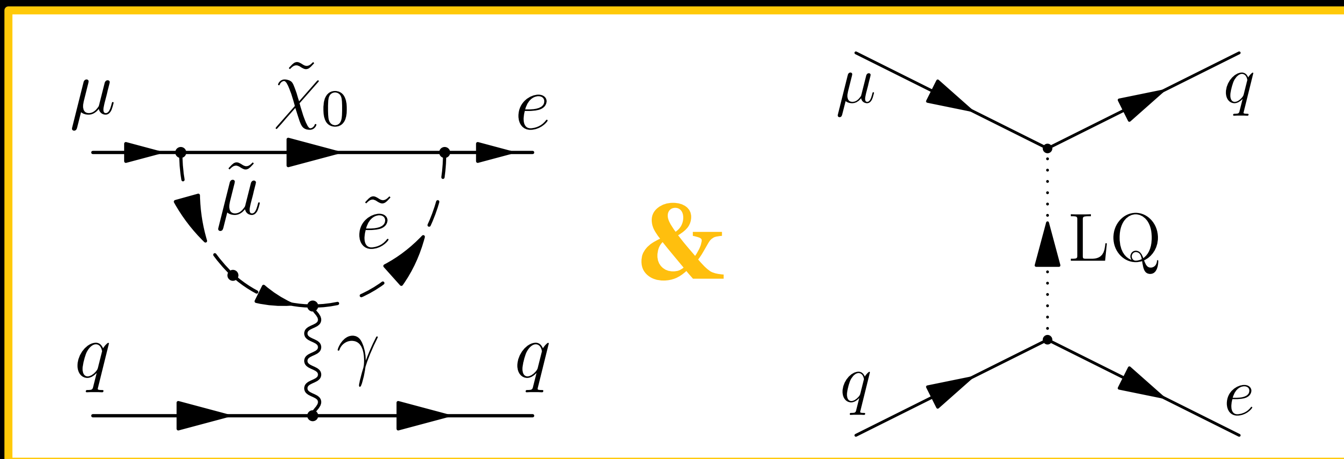


$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

What if κ is very large? Not much sensitivity.

Role of κ

- Consider $\mu N \to e N$
- Sensitive to both kinds of operators.

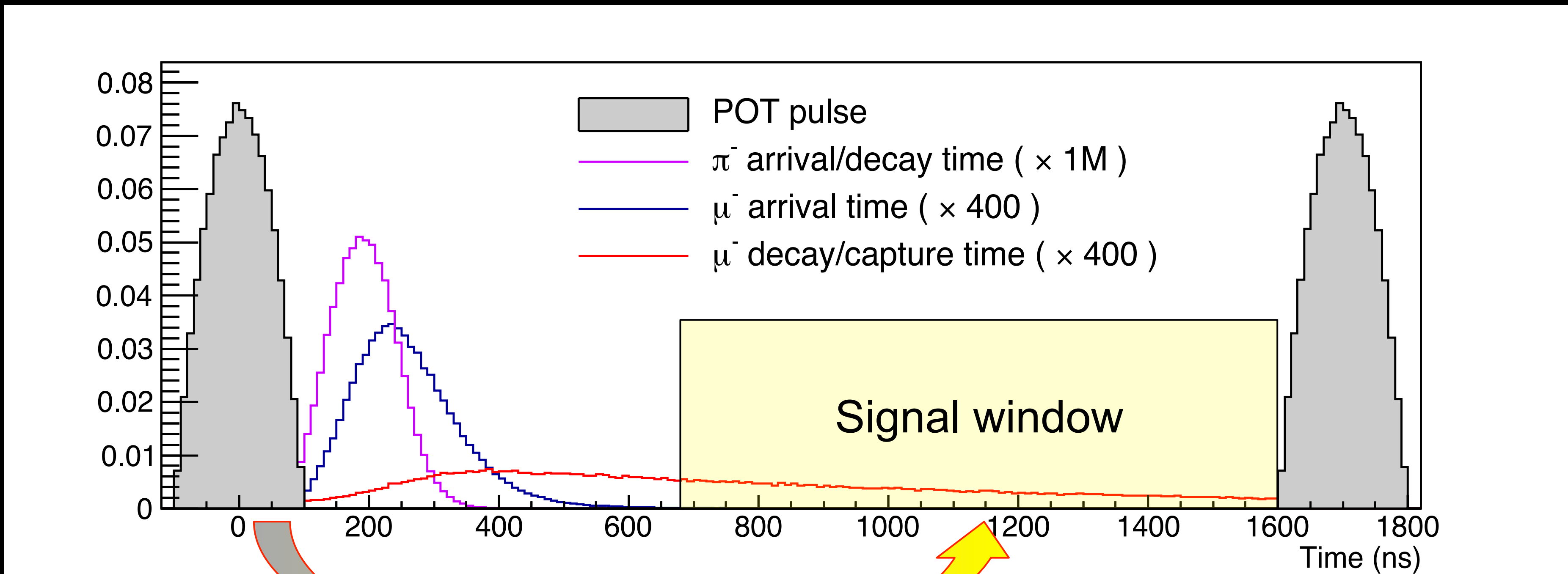


$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L \right)$$

Mu2e is sensitive to all values of κ.

Backgrounds from pion capture

Timing is everything…



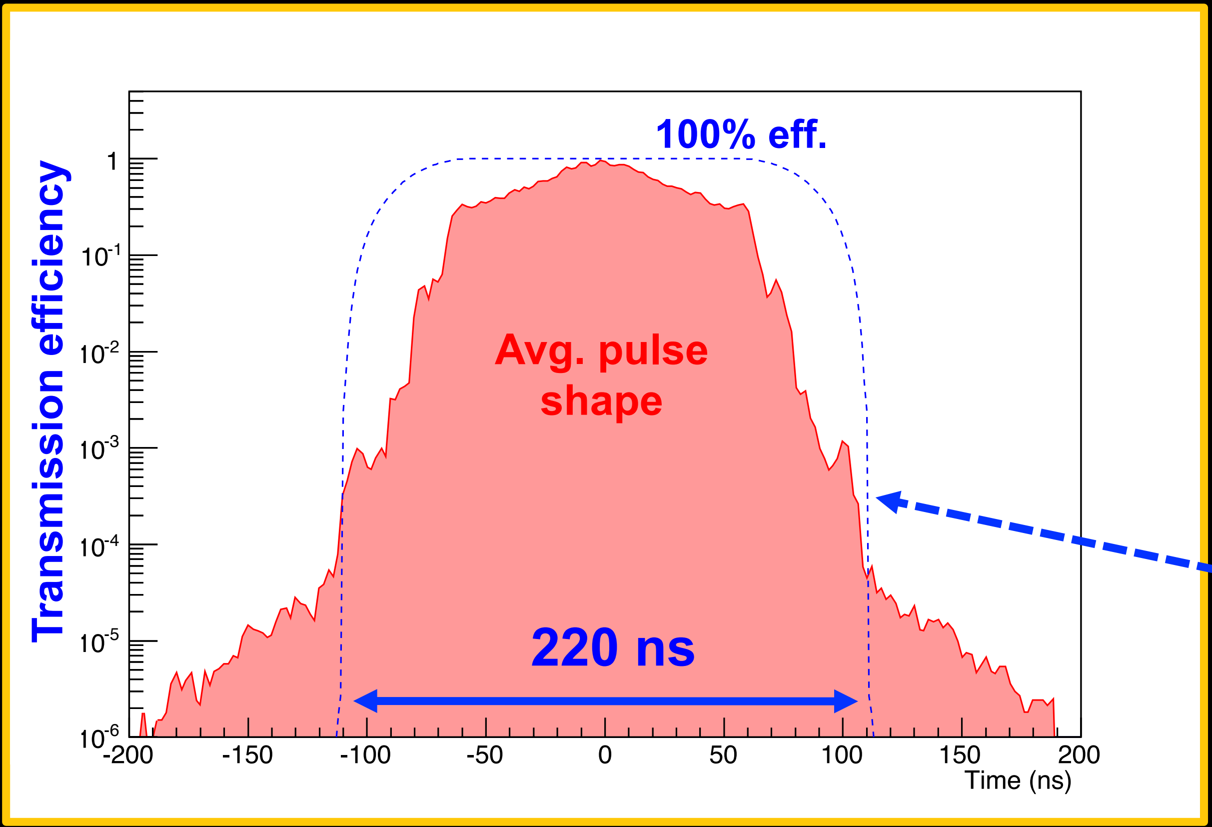
- Significant background is from pion capture
- Can produce … nal electron!
- Trick: Muon decays from Al. are slow; RPCs are fast.

  Wait out the pion captures before starting the live gate.

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

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

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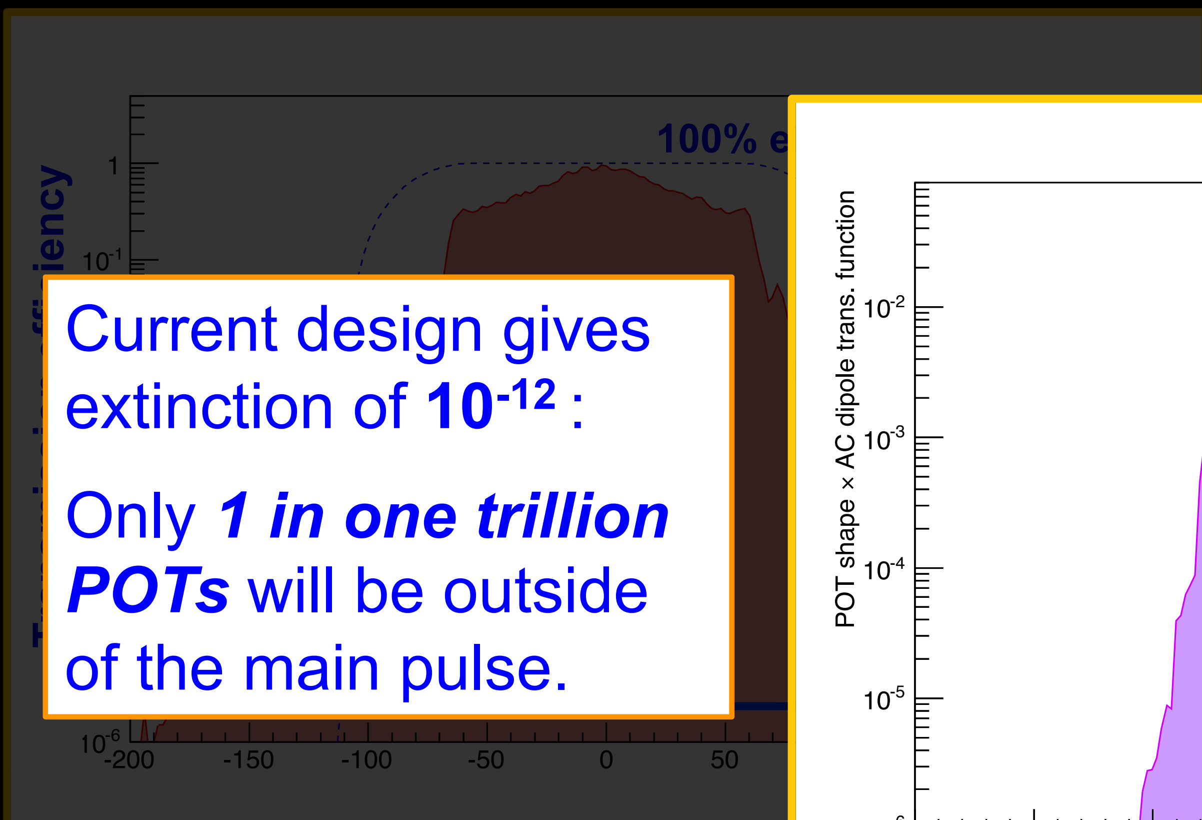
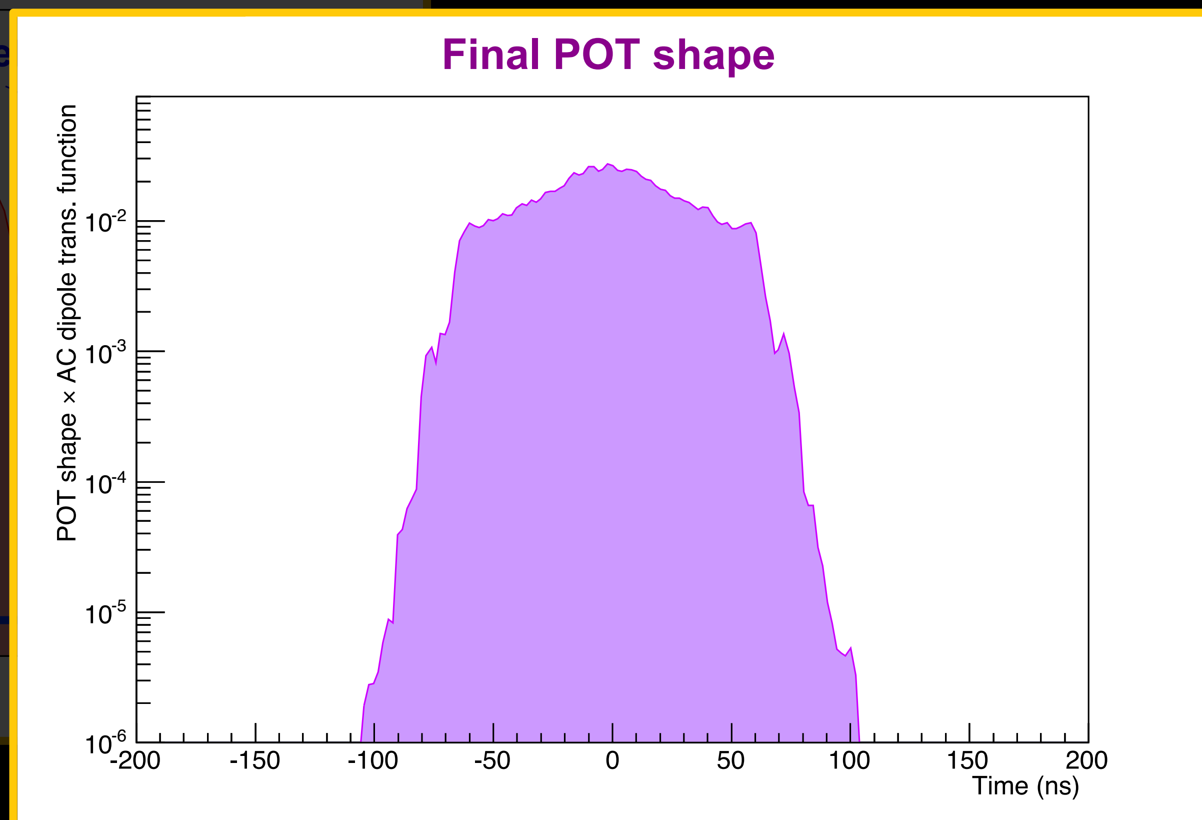
- Need to make sure this doesn't happen!
- Need proton-beam extinction at the level of **10^{-10}**.



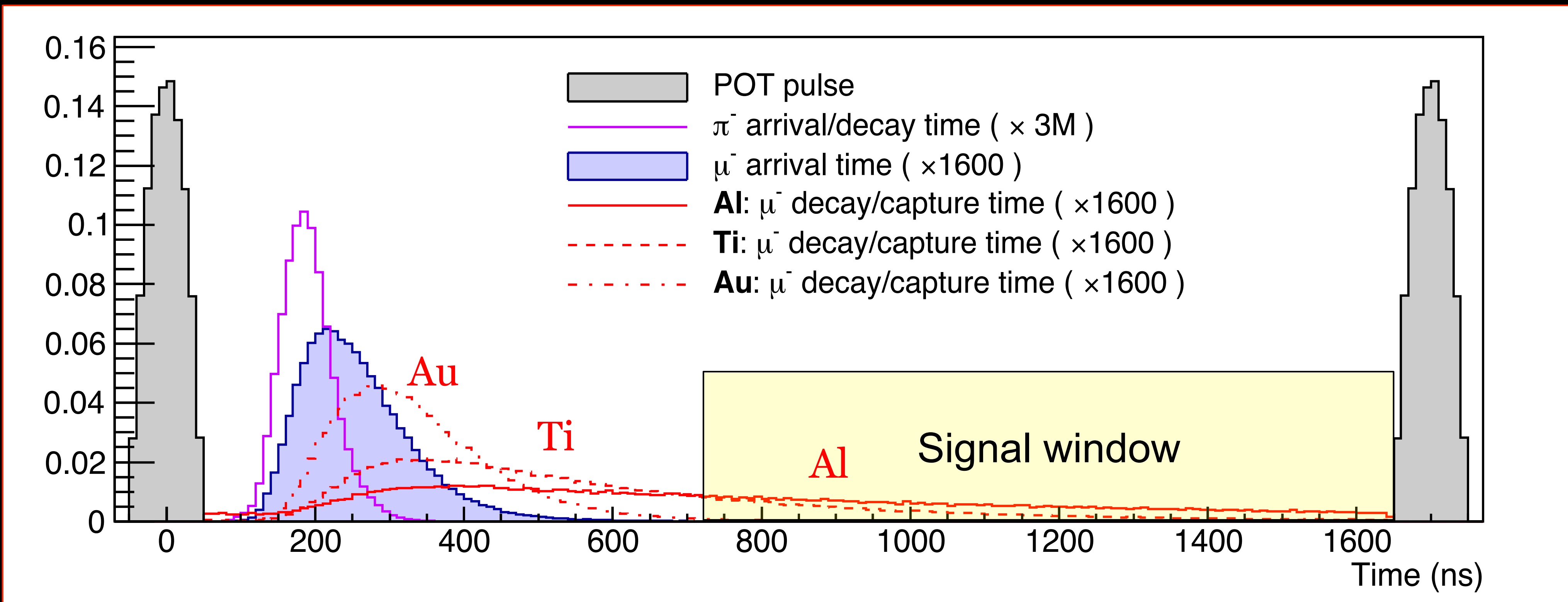
Current design gives extinction of **10^{-12}** :

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

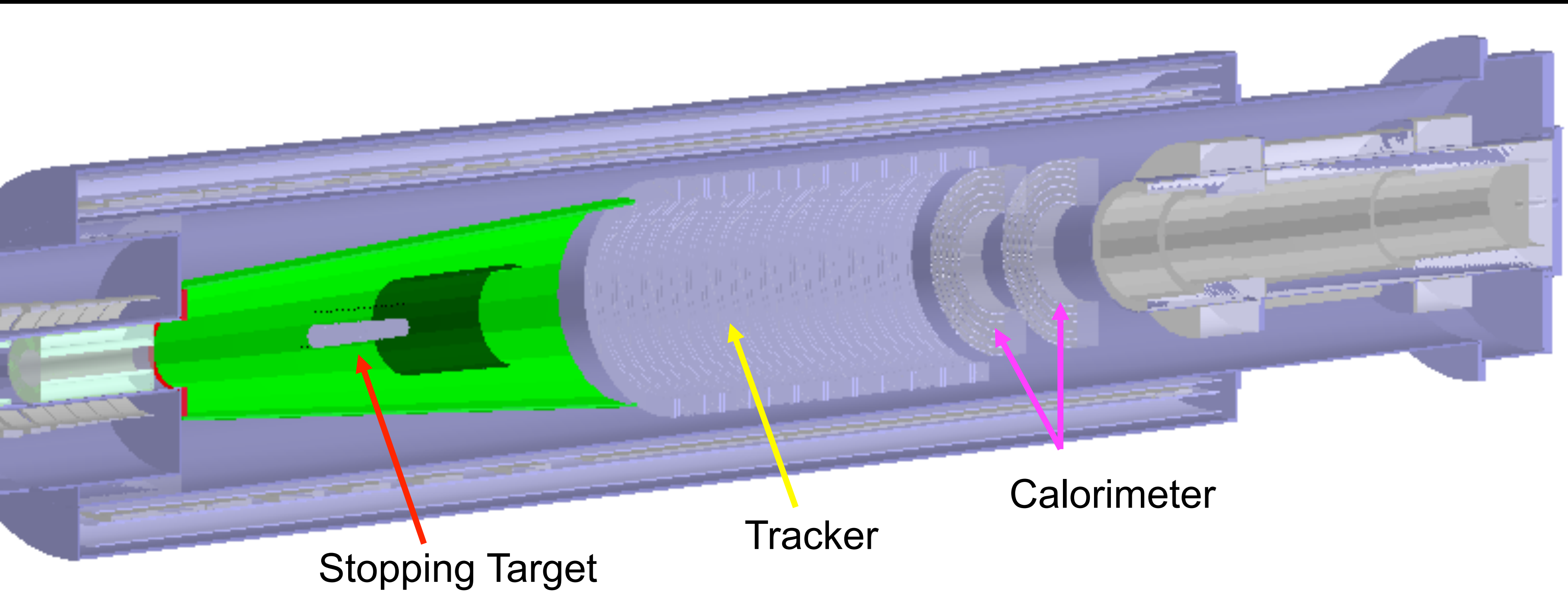


Why aluminum?

- Since pion capture process happens very quickly, need a target where the muon decay/capture happens slowly, so we can collect as many muon decays as possible
  - Aluminum is a good option.



A more realistic view of the detector area



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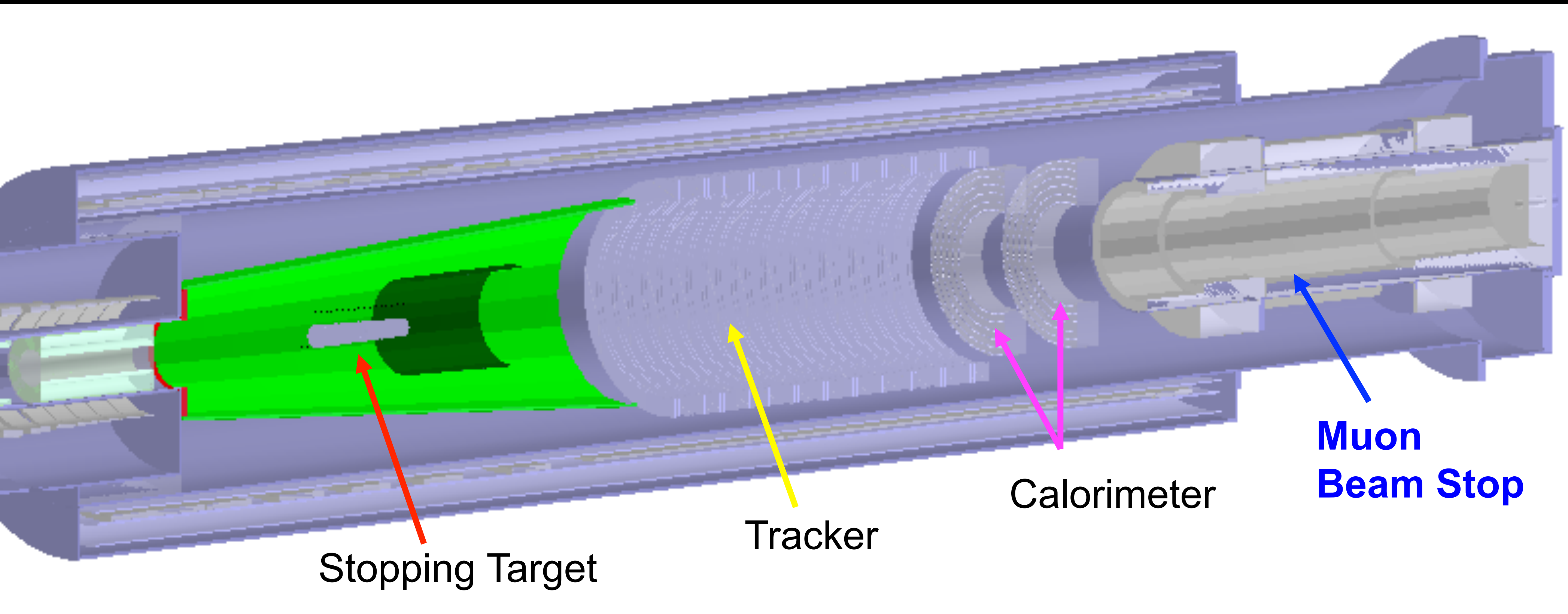
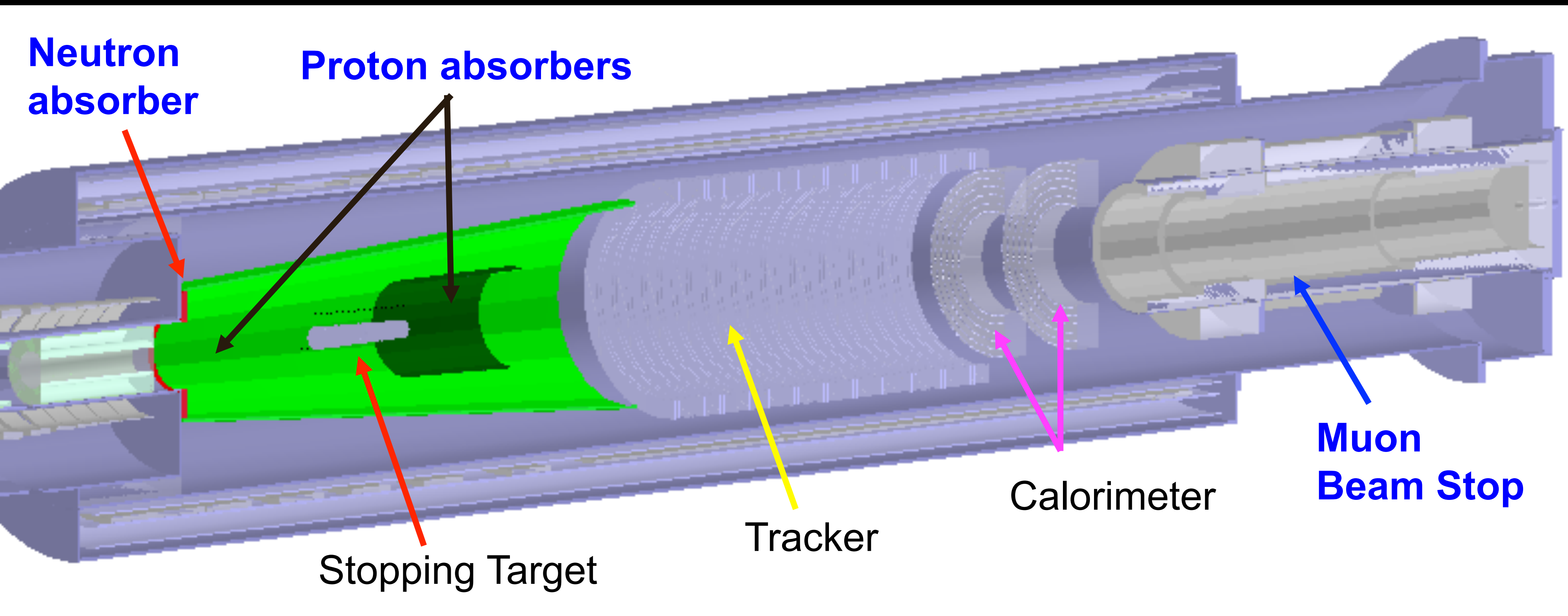


- Muon beam stop absorbs downstream backgrounds
  - Made of polyethylene to reduce neutrons
  - Hollow to reduce albedo from downstream end, and to allow X-ray measurement from atomic transitions of stopped muons

A more realistic view of the detector area



- Neutron and proton absorbers
  - Absorb nucleon backgrounds that unnecessarily increase hit rates/aging in tracker and calorimeters
  - Made of polyethylene-based materials

Mu2e Collaboration

- ~150 collaborators
- 28 institutions

Boston University

Brookhaven National Laboratory

Lawrence Berkeley National Laboratory
& University of California, Berkeley

University of California, Irvine

California Institute of Technology

City University of New York

Duke University

Fermi National Accelerator Laboratory

University of Houston

University of Illinois

Lewis University

University of Massachusetts, Amherst

Muons, Inc.

Northern Illinois University

Northwestern University

Pacific Northwest National Laboratory

Purdue University

Rice University

University of Virginia

University of Washington

Mu2e Collaboration

- ~150 collaborators
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Joint Institute for Nuclear Research, Dubna

Institute for Nuclear Research, Moscow

Laboratori Nazionali di Frascati

INFN, Genova

INFN, Lecce and Universita del Salento

INFN, Lecce and Universita Marconi Roma

INFN, Pisa

Universita di Udine and INFN Trieste/Udine

Next-generation Mu2e

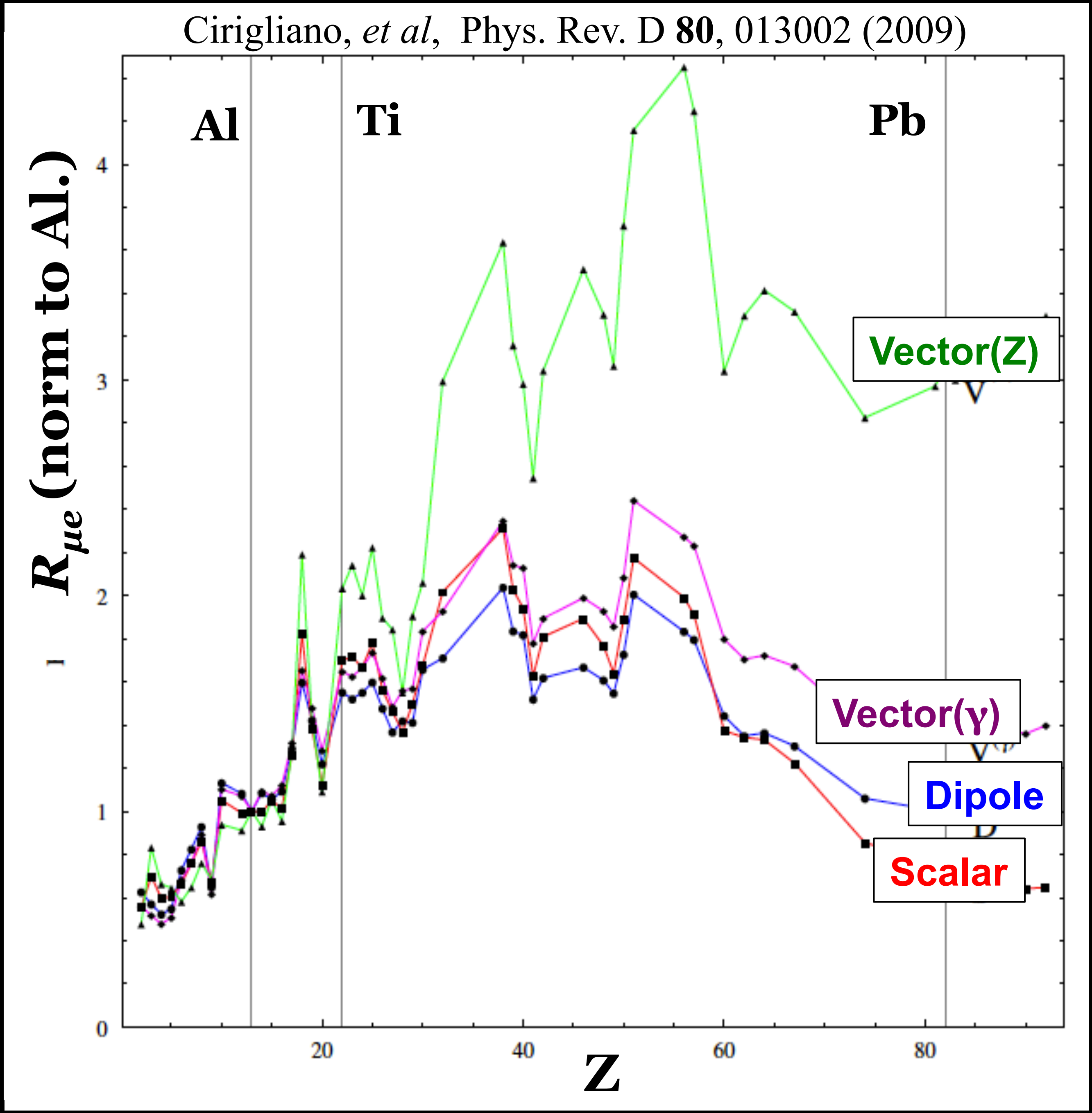
For CSS2013 (*aka* Snowmass)

- We performed a detailed study about the feasibility of a next-generation Mu2e experiment, under the following guidelines:
  - Only modest changes to the baseline design would be implemented.
  - Goal would be a x10 improvement in *R* measurement

- Rationale:
  - If Mu2e discovers CLFV, switch target materials to gain model discrimination (see next page)
  - If Mu2e sees evidence of CLFV, increasing statistics x10 can resolve situation
  - If Mu2e does not see evidence, place more stringent constraints on CLFV

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



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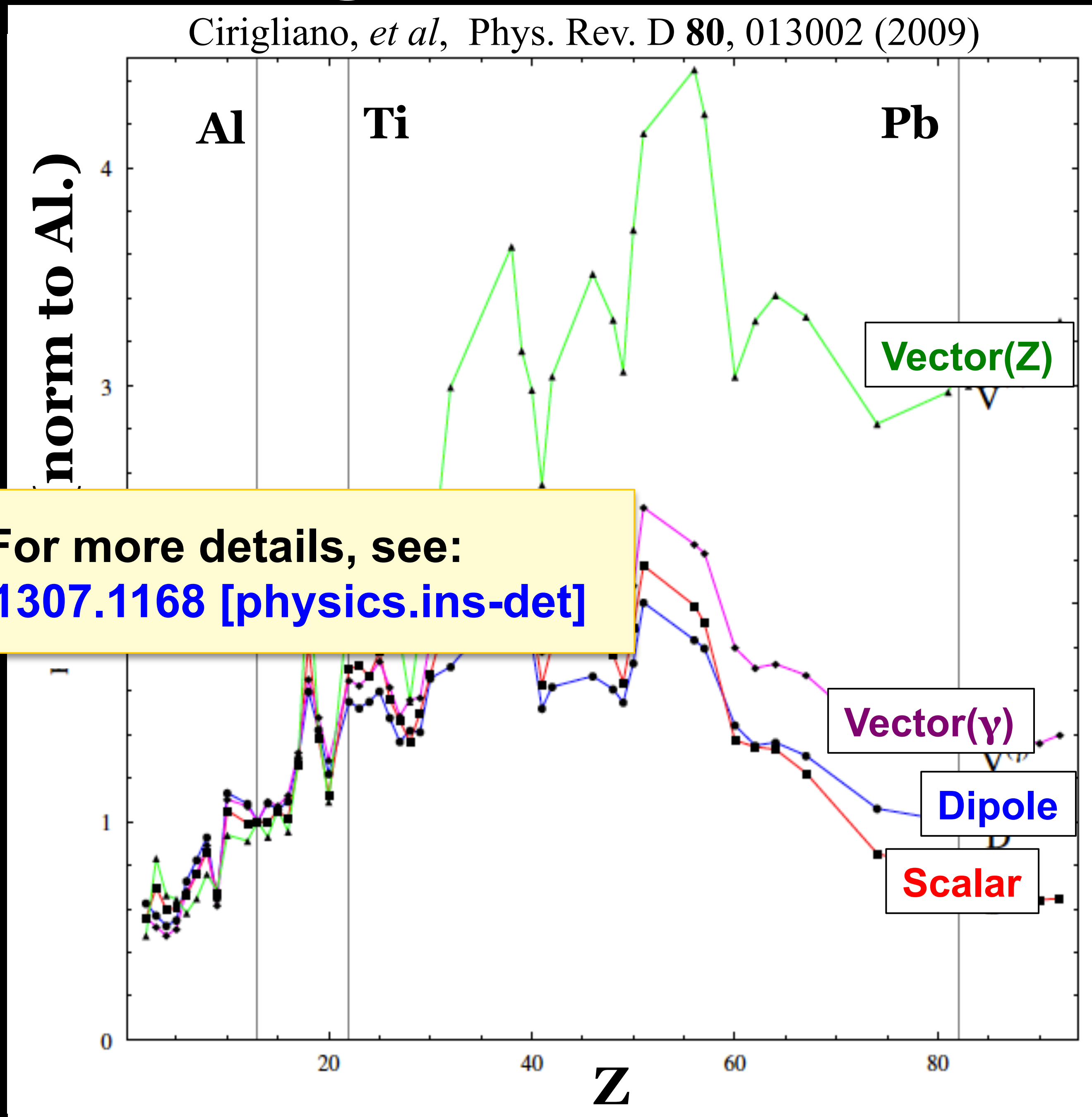

For more details, see:
arXiv:1307.1168 [physics.ins-det]