A search for charged lepton flavor violation in muon to electron conversion

Andrei Gaponenko

2013-12-12

Outline

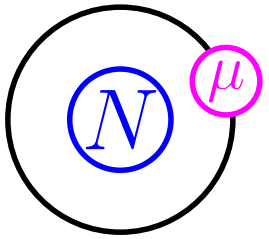
- What and why we measure
  or introduction to charged lepton flavor violation
  (Focus on searches with muons — there are also τ, Z, ...)
- How we do it
  - The concept of Mu2e measurement
  - The challenges—and how we handle them
- Status

Introduction

Mu2e searches for

Coherent muon to electron conversion on nucleus

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



- Initial state is a bound muon
- Nucleus participates in the process
- But remains intact in the end
- Two body decay:

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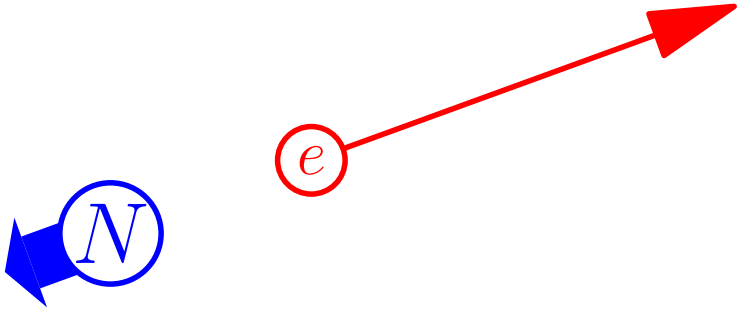

- Initial state is a bound muon
- Nucleus participates in the process
- But remains intact in the end
- Two body decay:

$$E_e = m_\mu - E_b - E_{\text{recoil}} \approx 105 \text{ MeV for Al}$$

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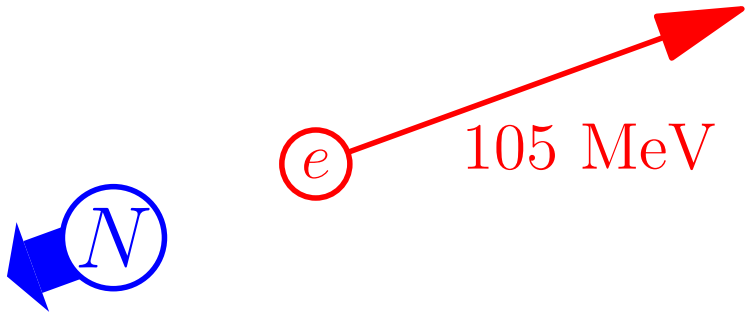

Compare to

Normal muon decay:

$\mu^- \to e^- \bar{\nu}_e \nu_\mu$

Flavor violating decay (MEG)

$\mu^- \to e^- \gamma$

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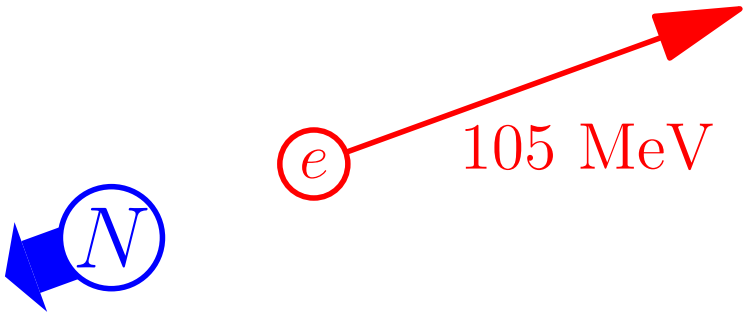

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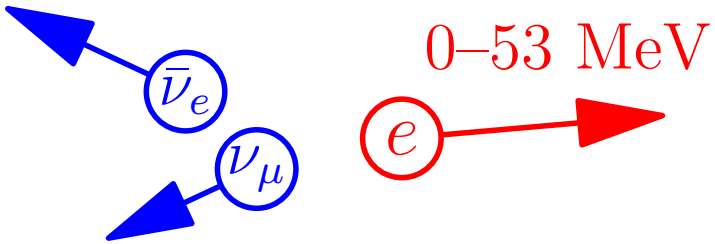

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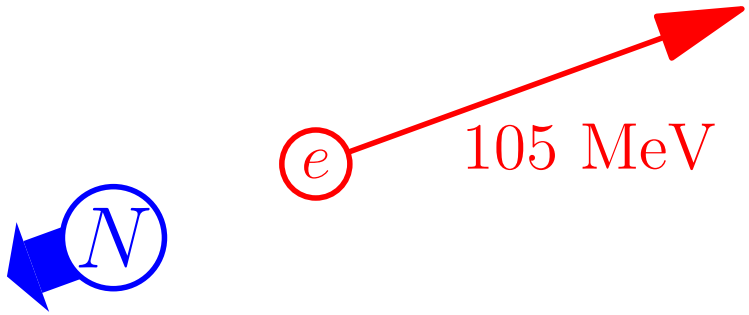

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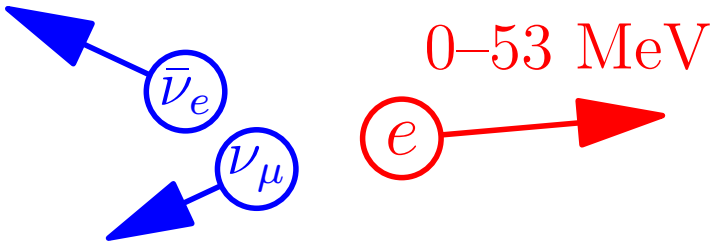

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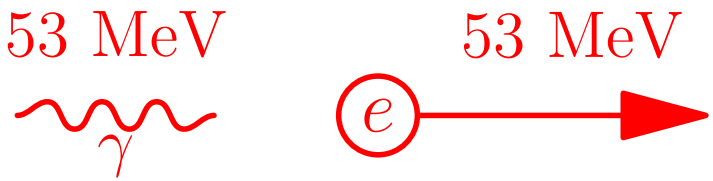


The number we measure

- Signal: coherent muon to electron conversion on nucleus
- Normalization: all nuclear captures
  - reduces theory uncertainty (nuclear wavefunction cancels)

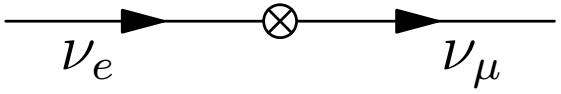
$$R_{\mu e} = \frac{\Gamma[\mu^- + (A,Z) \to e^- + (A,Z)]}{\Gamma[\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)^*]}$$

Simplest capture example:

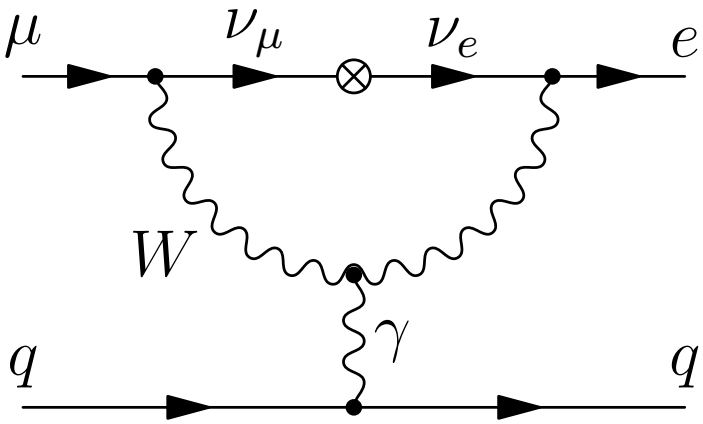
$$\mu^- + p \to \nu_\mu + n$$

Charged lepton flavor violation

- Neutral lepton flavor violation has been observed

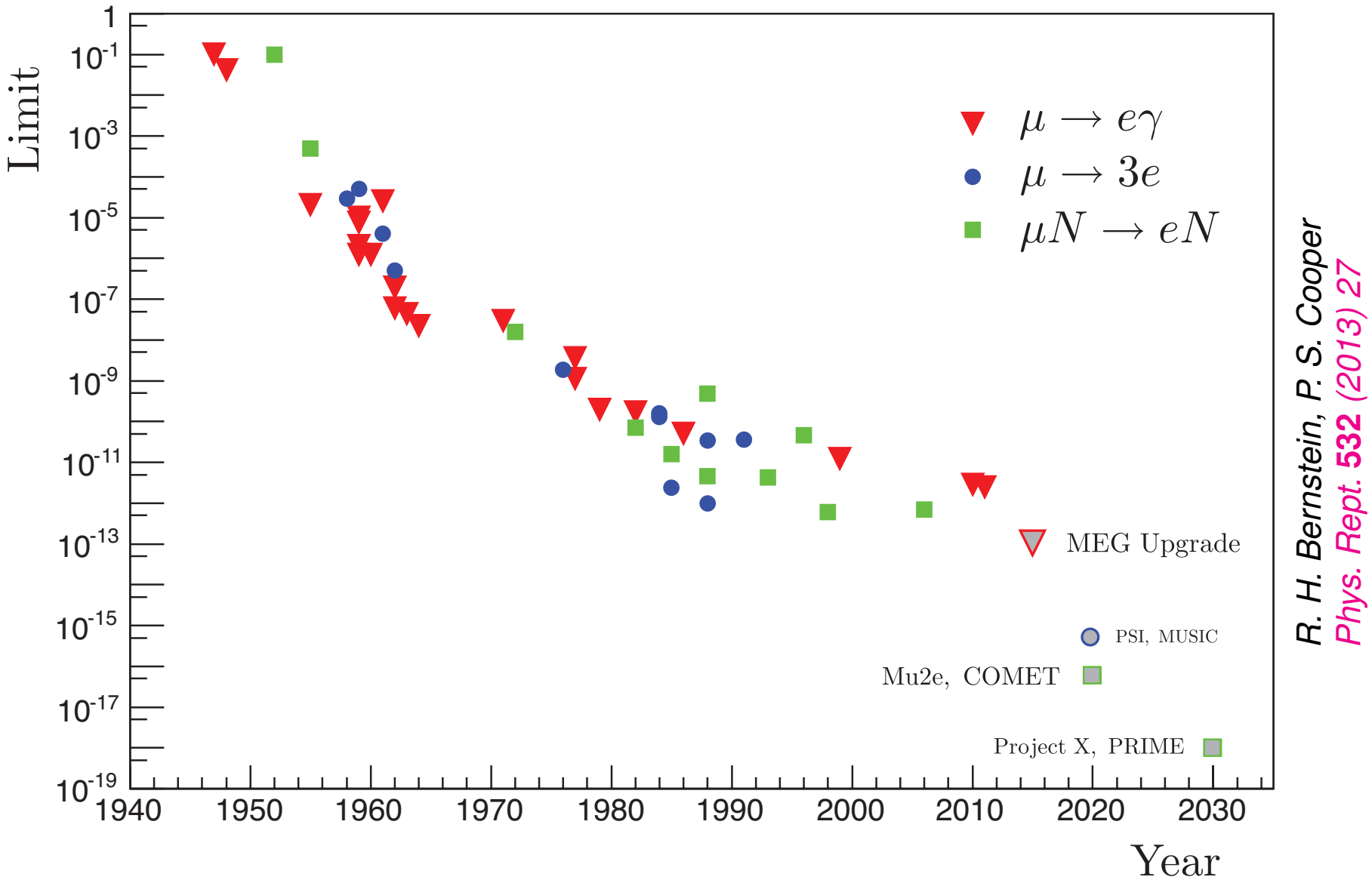


- Induces CLFV



- Induced rate: about 40 orders of magnitude below experimental limits
- CLFV observation would be an unambiguous signal of New Physics

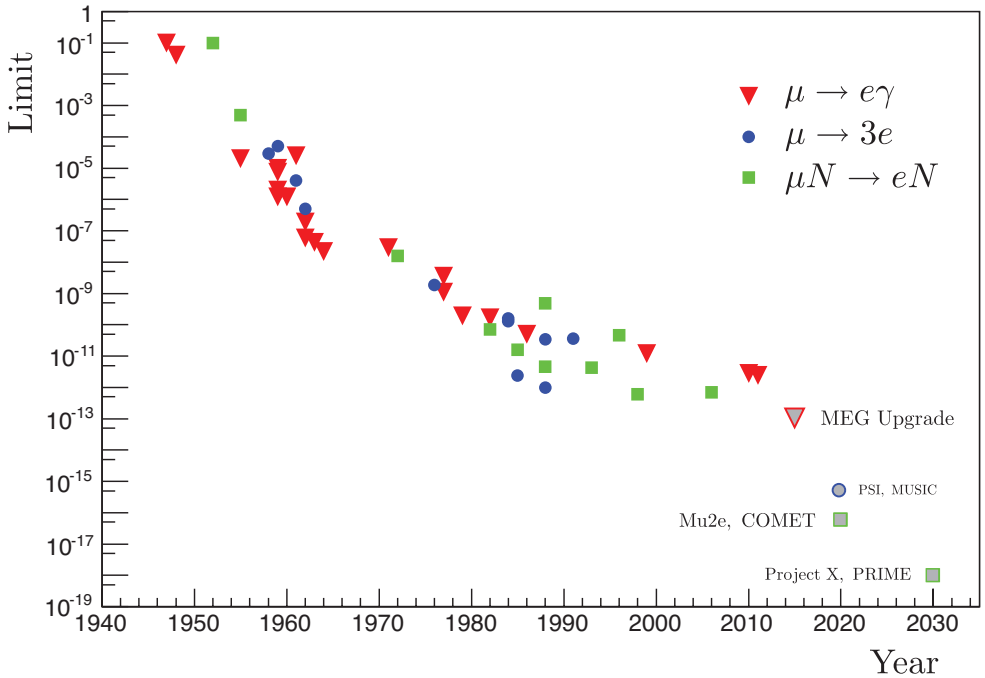
History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



CLFV history

Concept of generations

- Muon is not an excited electron
- $\mu \to e\gamma$ limits: $\nu_e \neq \nu_\mu$ hypothesis



Constraints on models of new physics

Today's best limits (with links)

$R_{\mu e} < 7 \times 10^{-13}$ SINDRUM-II 2006

$Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$ MEG 2013

$Br(\mu \to 3e) < 1 \times 10^{-12}$ SINDRUM-I 1988

Mu2e goal

Single event sensitivity

$R_{\mu e} = \text{few} \times 10^{-17}$

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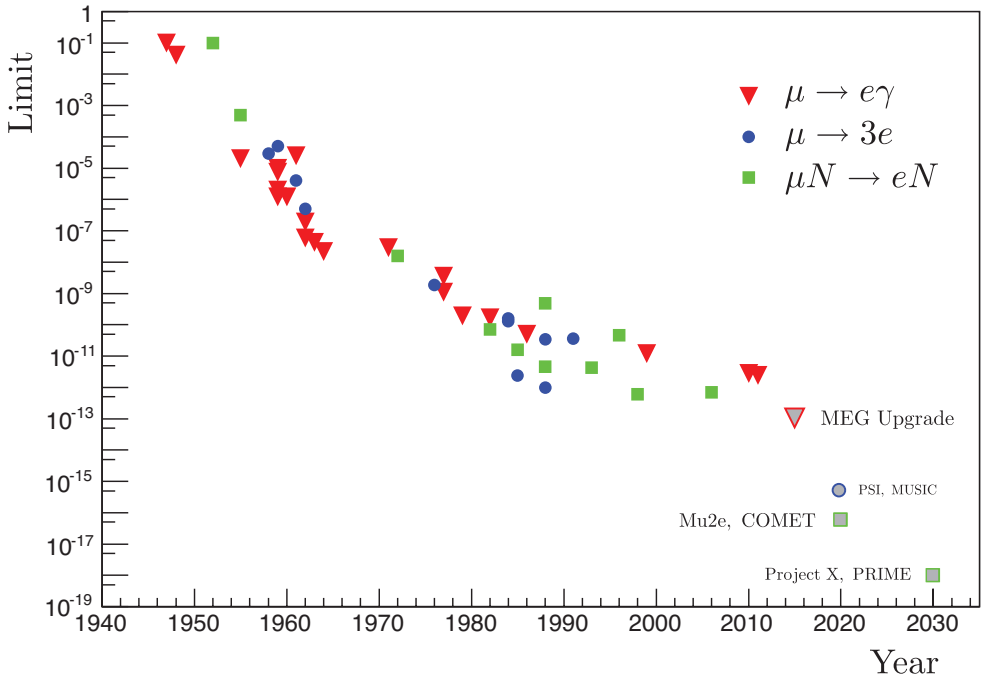


Constraints on models of new physics

Today's best limits (with links)

$R_{\mu e} < 7 \times 10^{-13}$

$Br(\mu \to e\gamma) < 5.$

$Br(\mu \to 3e) < 1 \times$

Relevancy in the LHC era?

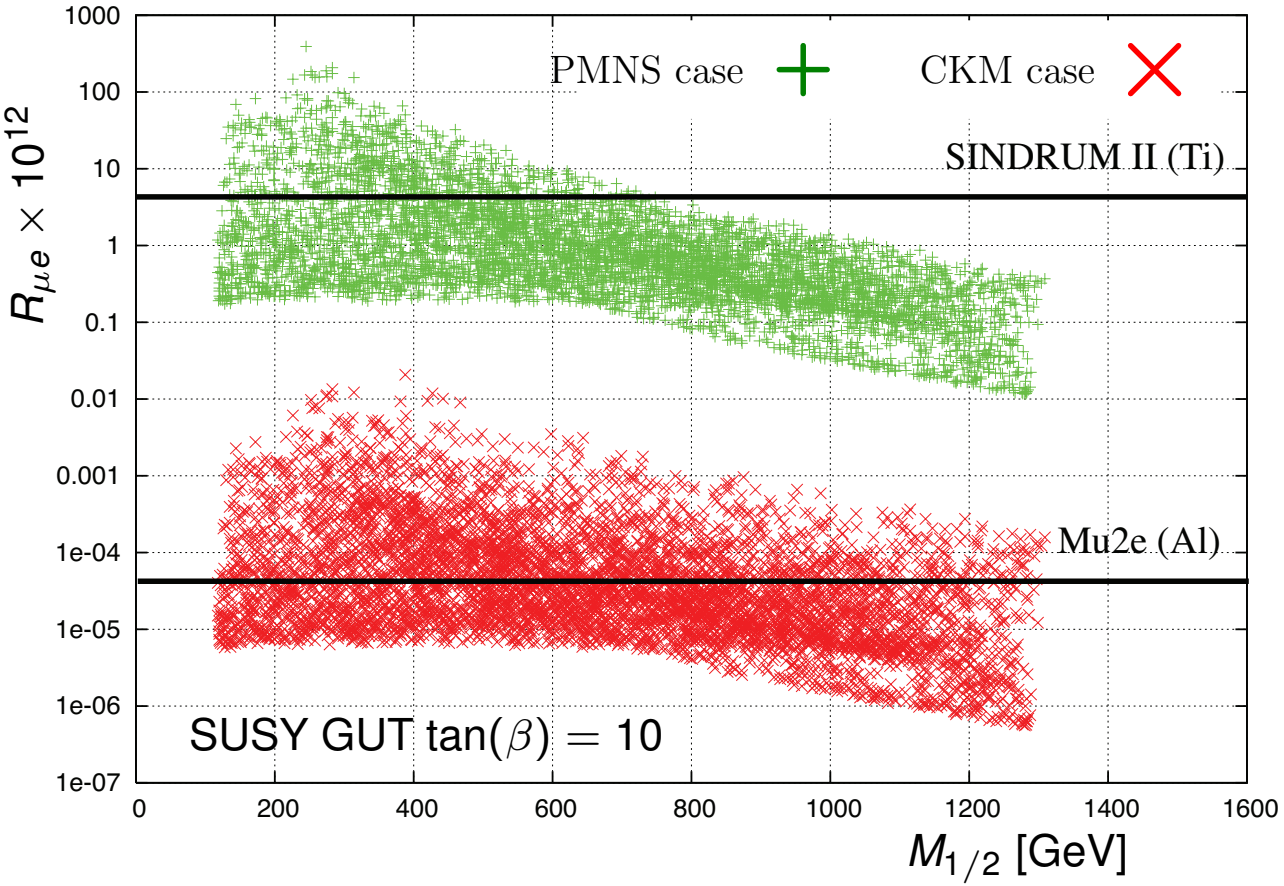
Mu2e goal

vent sensitivity

$\times 10^{-17}$

Mu2e and the LHC

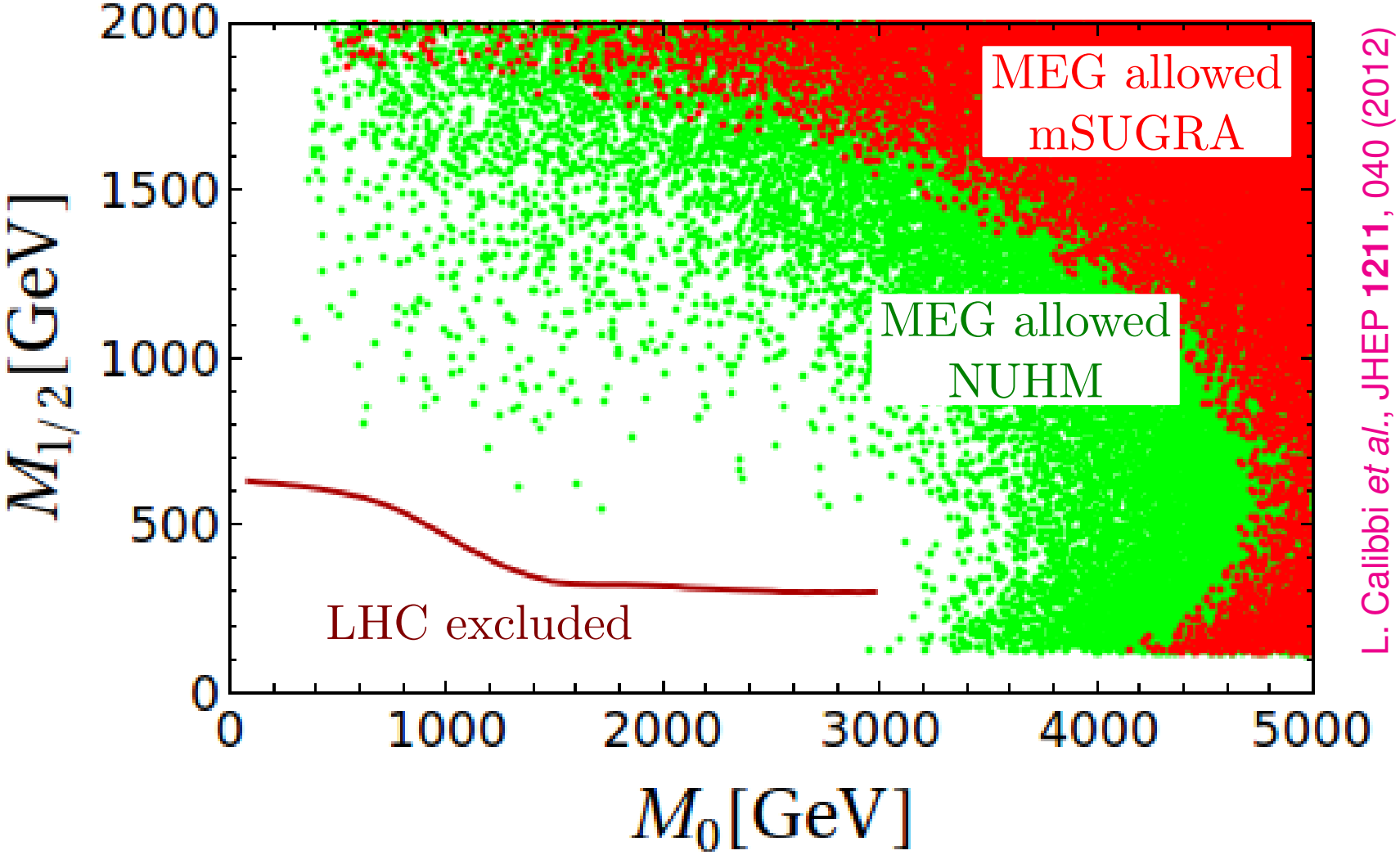
Scan of “LHC accessible” parameter space



*Phys.Rev.**D74** (2006) 116002*

SUSY constraints from MEG 2011

Current Higgs mass, θ_{13}, and $Br(\mu \to e\gamma) < 2.4 \times 10^{-12}$

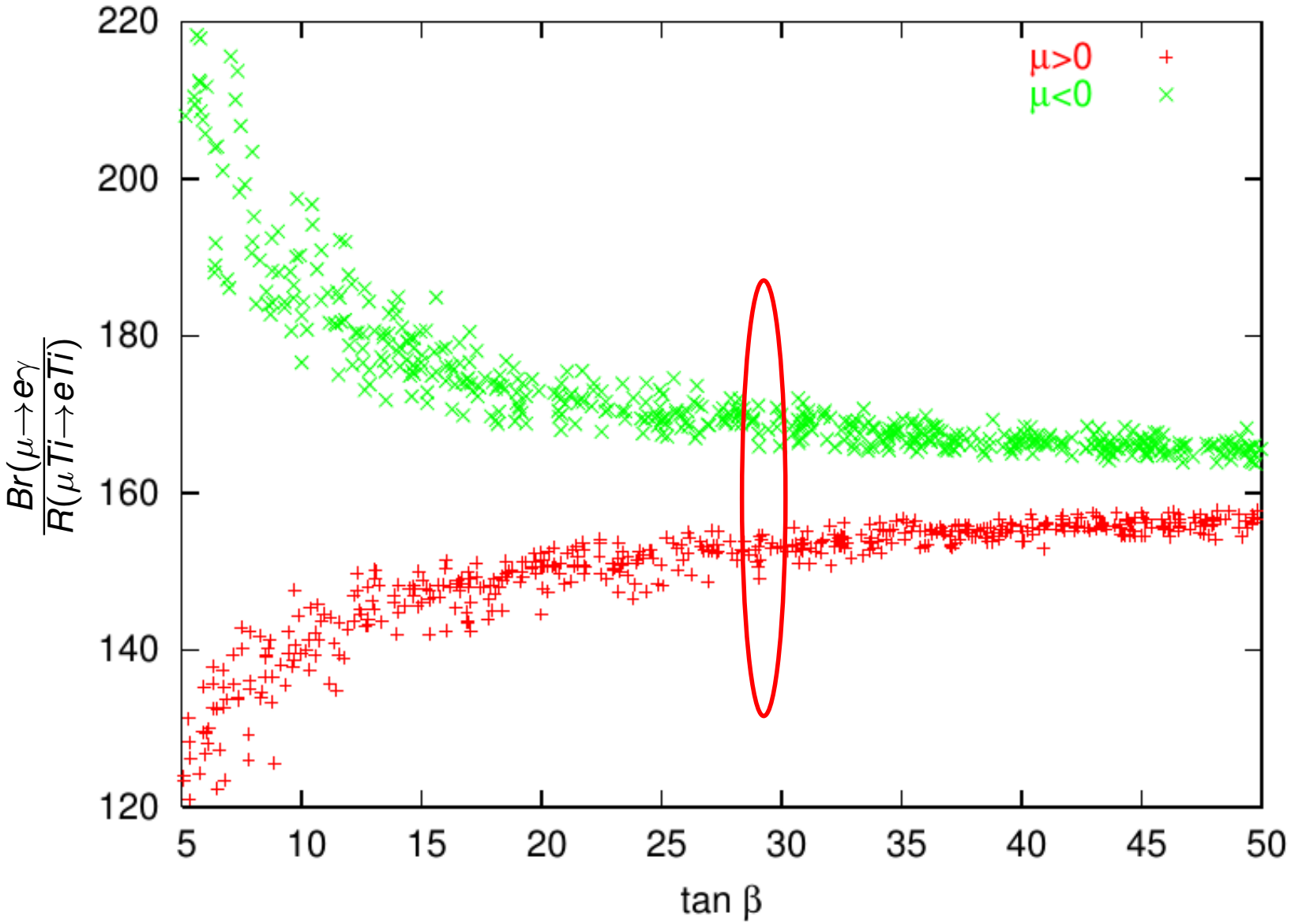


L. Calibbi *et al.*, JHEP **1211**, 040 (2012)

Complementarity with the LHC

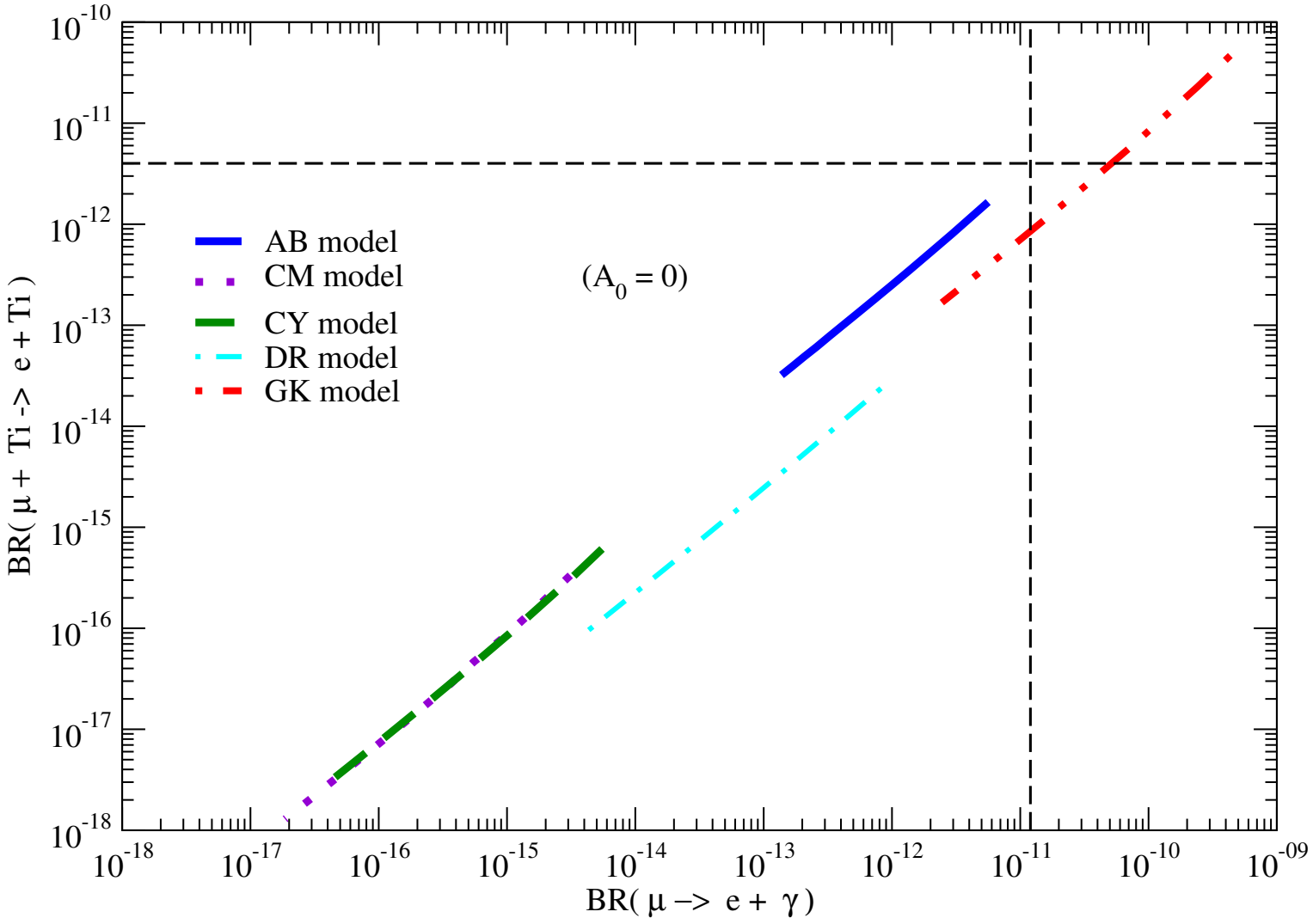
- Today's best constraints
  - Direct searches for some cases
  - CLFV for others
- If new physics is seen at LHC
  - Need CLFV measurements to discriminate models (the inverse LHC problem)
- If no LHC signal
  - Mu2e can still make a discovery

Muon flavor and g-2



C. Yaguna, Int.J.Mod.Phys. A21 (2006) 1283
Bob Bernstein, private communication

Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



C.H. Albright, M.-C. Chen, 2008

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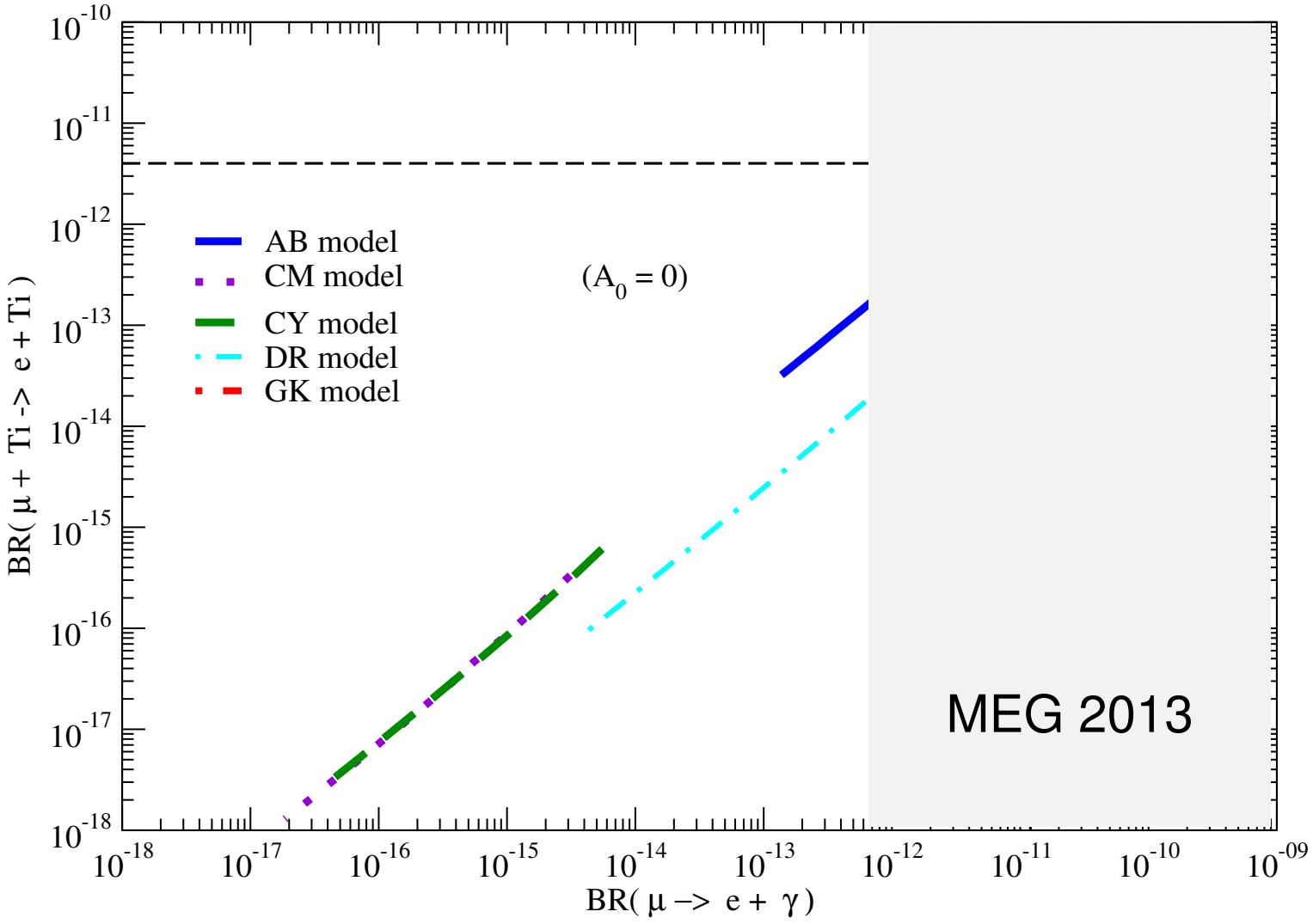

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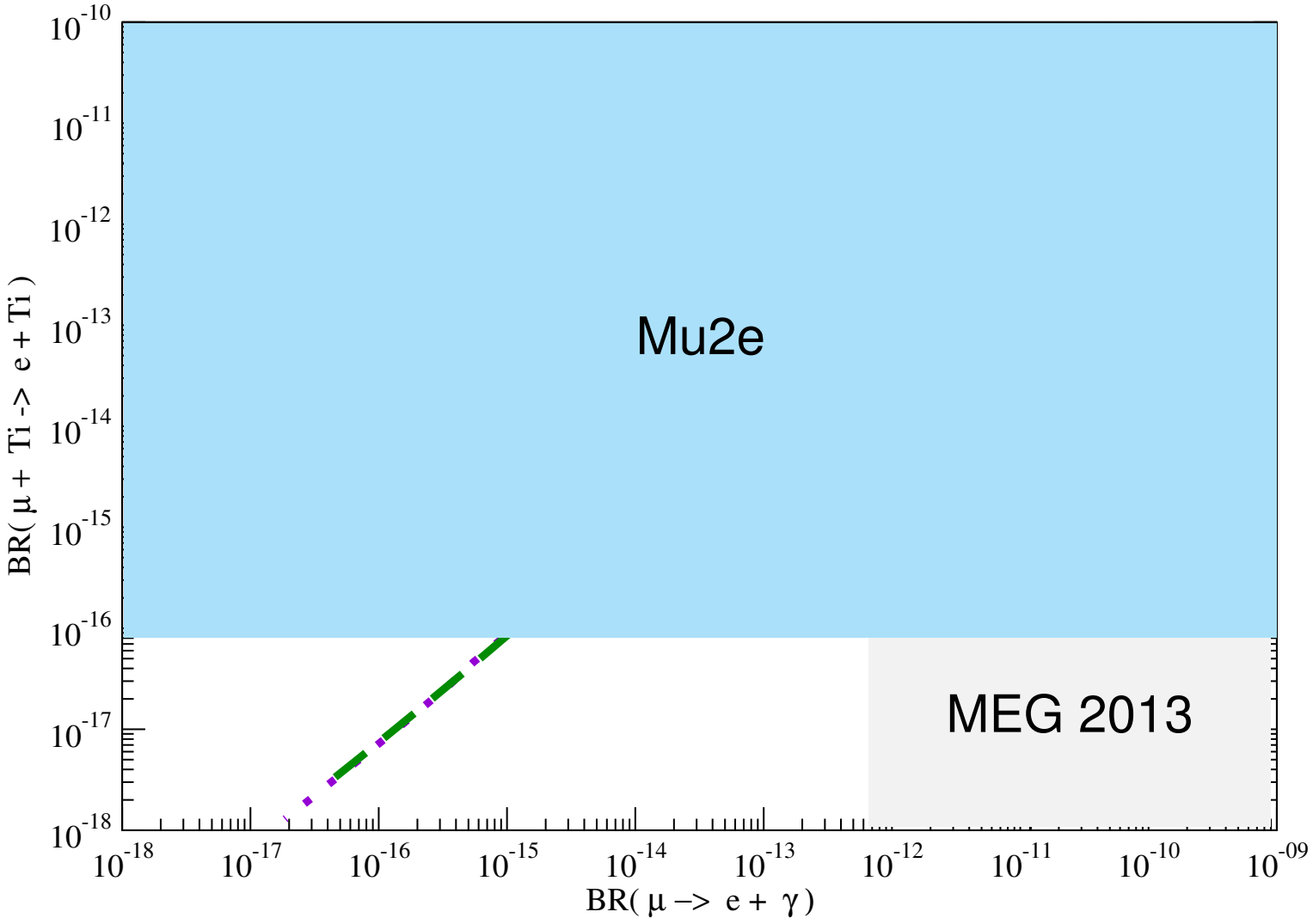
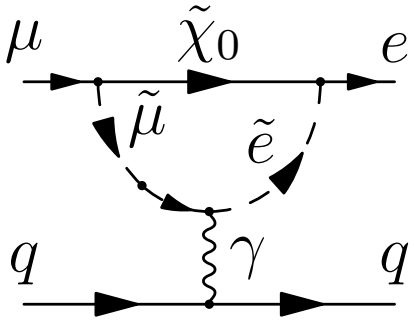


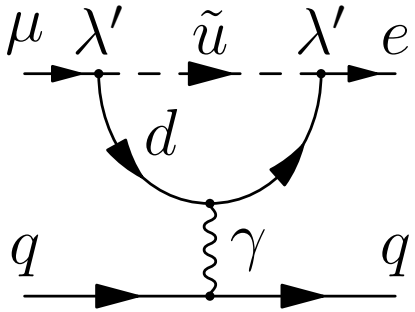
C.H. Albright, M.-C. Chen, 2008

Mu2e can discover

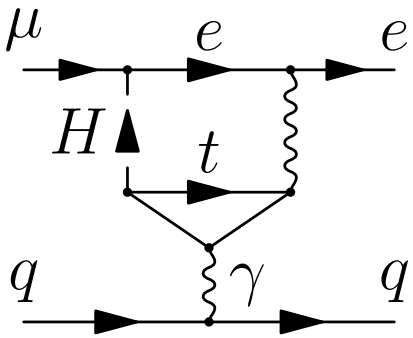
SUSY



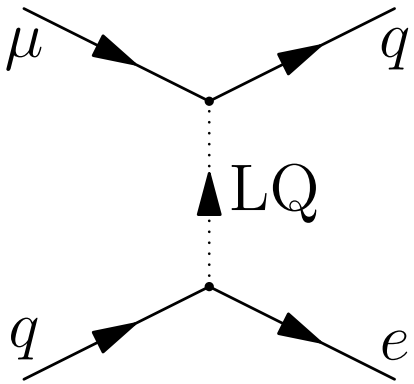
RPV SUSY



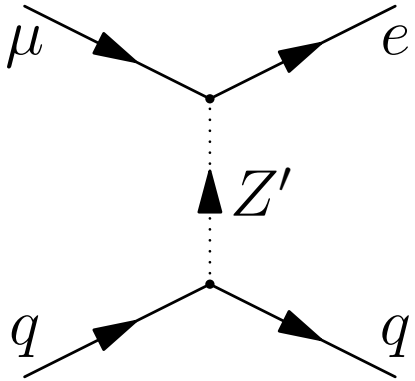
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Some reviews:
Kuno, Okada, 2001
M. Raidal *et al.*, 2008

Mu2e can discover

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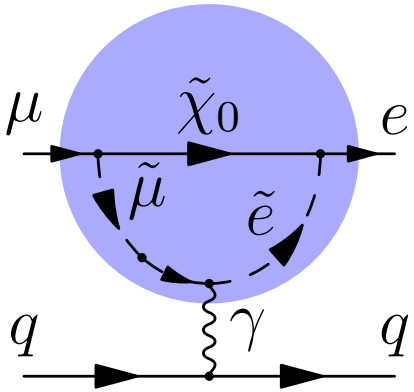

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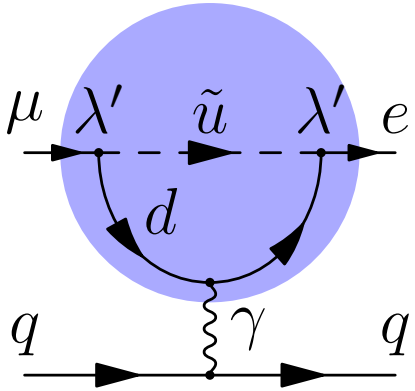

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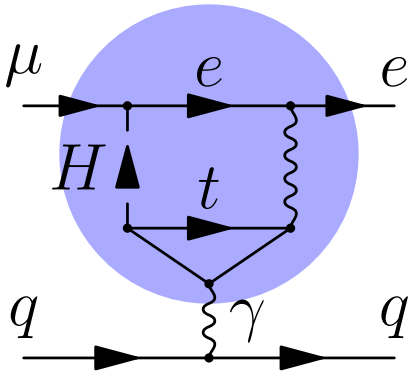

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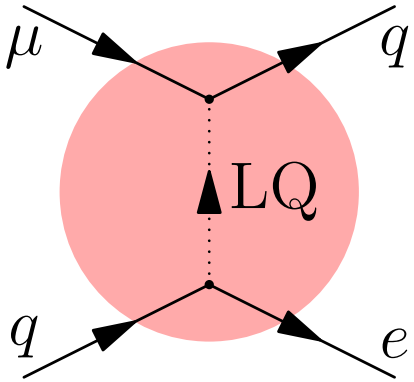

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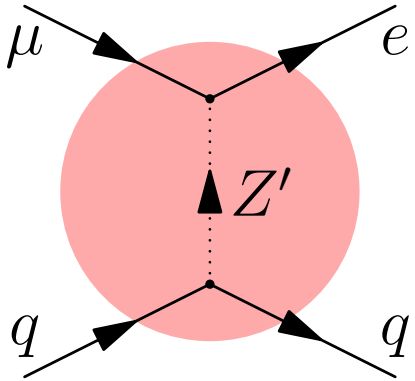

Extra dimensions, etc.

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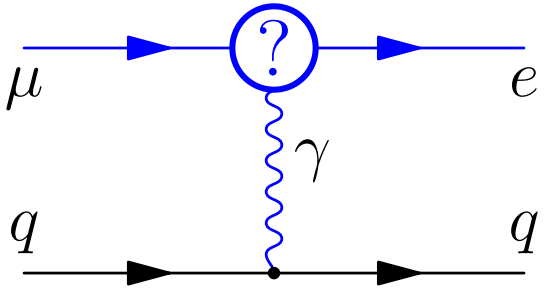
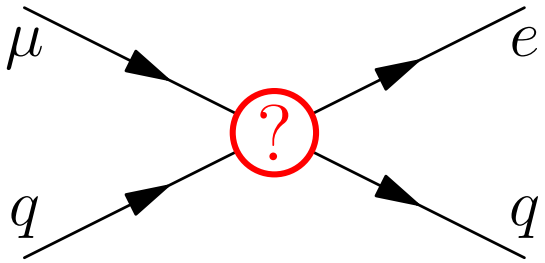
Effective theory

Electromagnetic vertex



Often gives large $Br(\mu \to e\gamma)$

Contact interaction:



May be no $\mu \to e\gamma$ signal

Relative rates of conversion and $\mu \to e\gamma$ are model dependent

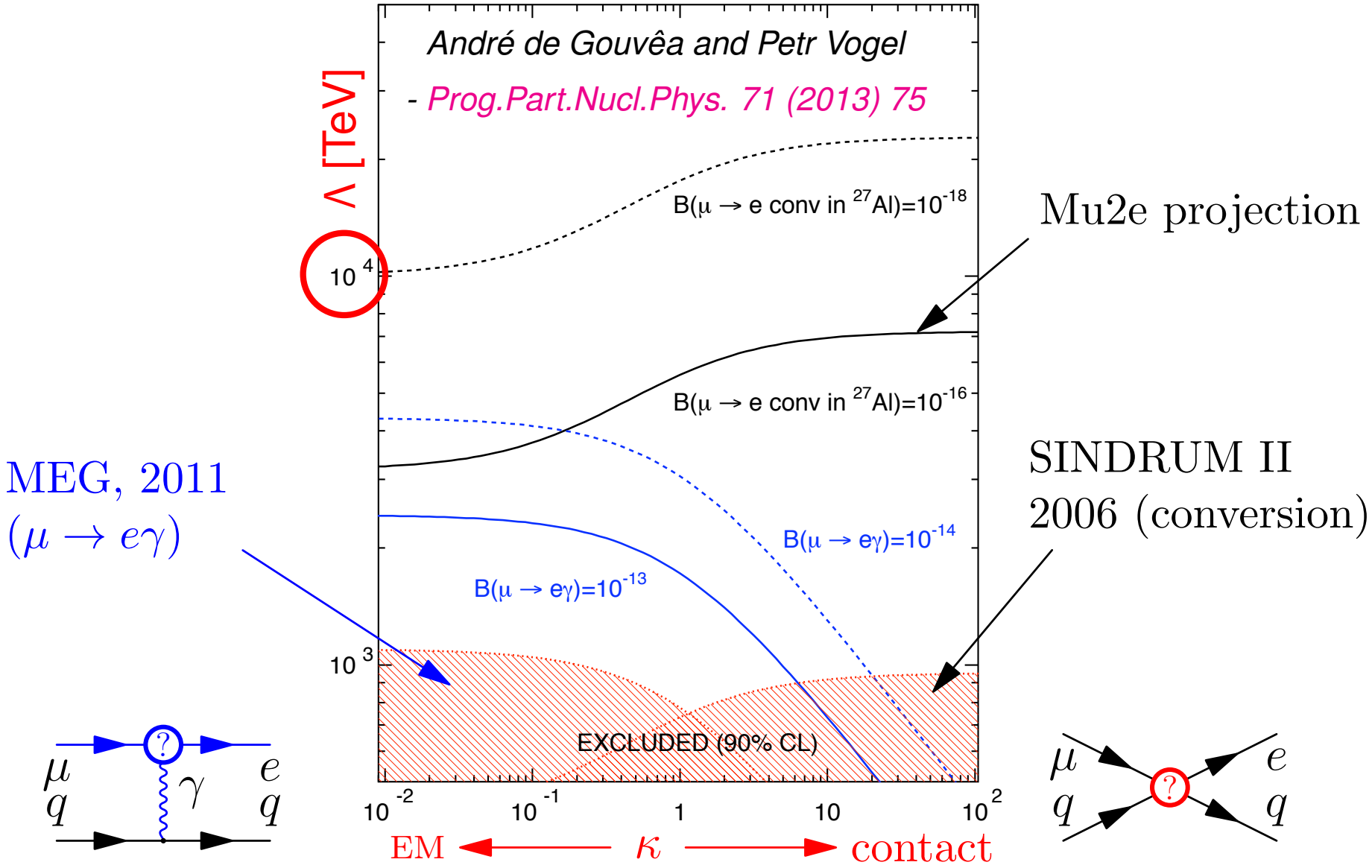
Handle to discriminate New Physics models

Parametrization: $\mathcal{L}_{CLFV} =$

$$\frac{m_\mu}{(1+\kappa)\,\Lambda^2}\,\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\,\Lambda^2}\,\bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

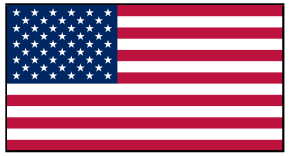
Λ: mass scale, κ: importance of contact term

Muon LFV physics reach



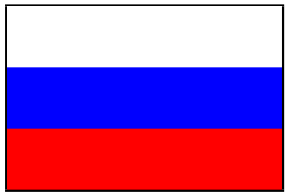
Mu2e experiment

Mu2e collaboration: more than 150 physicists



Boston University
Brookhaven National Laboratory
LBL/UC 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

INFN Genova
INFN Lecce/Università del Salento
INFN Lecce/Università Marconi
INFN Pisa
Universita di Udine/INFN Trieste/Udine
Laboratori Nazionali di Frascati



Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

The concept of Mu2e measurement

- Generate pulsed beam of low momentum negative muons
- Stop muons in thin foils and form muonic atoms
  - μ^- in aluminum: $\tau^{\mathrm{Al}} = 864$ ns
- Wait for prompt backgrounds to decay
- Then measure electron spectrum
  - The signal: mono-energetic electrons at 105 MeV

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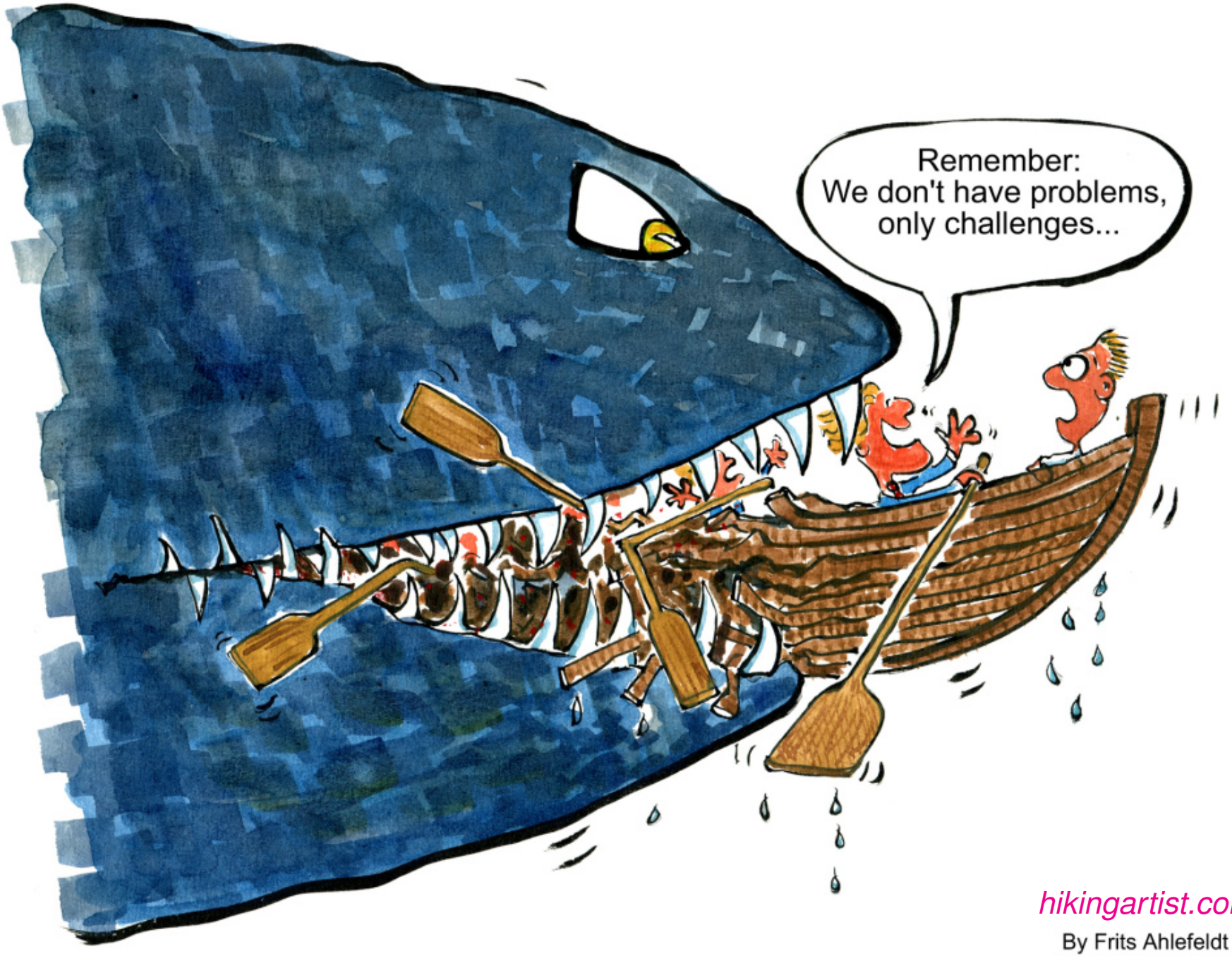
Sounds straightforward...
But achieving a 10^{-17} sensitivity is challenging.



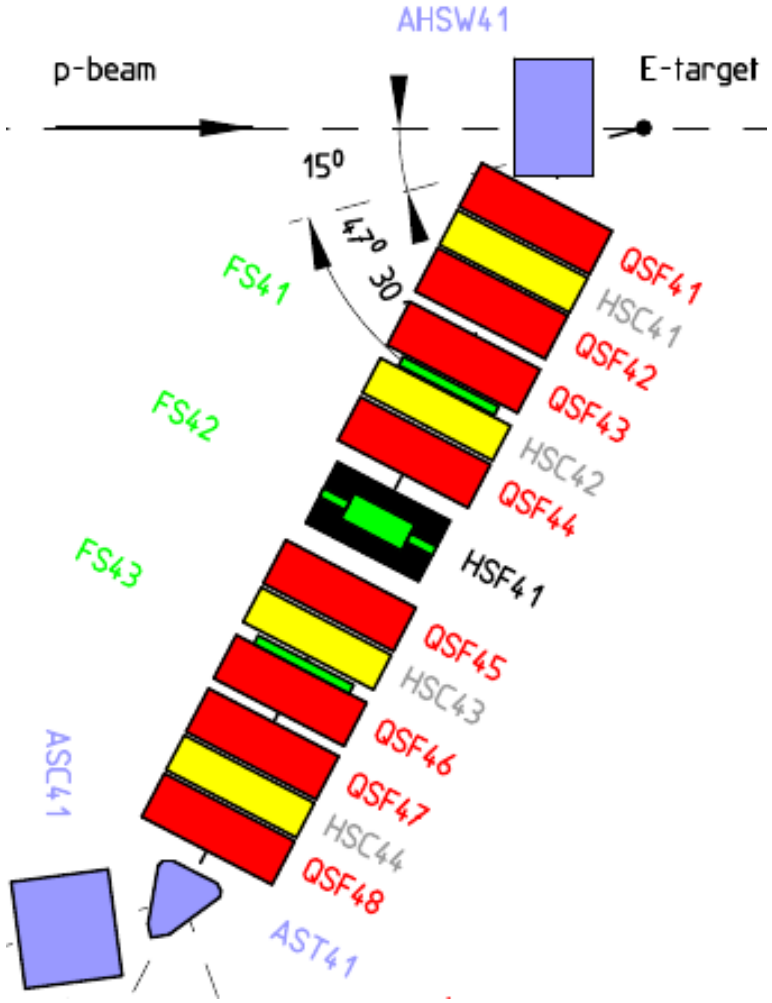
hikingartist.com

By Frits Ahlefeldt

Challenge: getting the muons

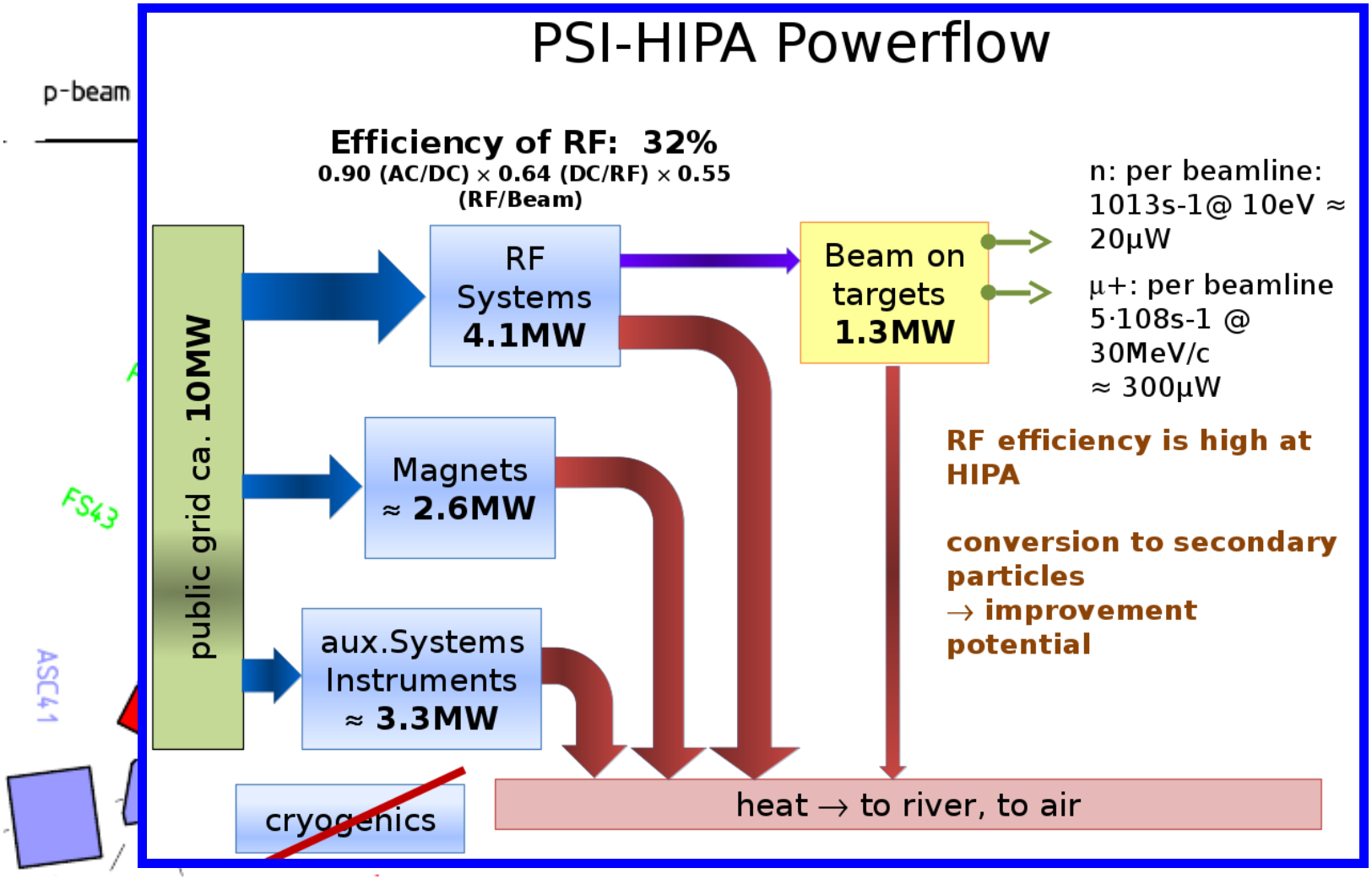
- A 10^{-17} measurement will need $> 10^{17}$ muons
  - Produced by proton beam
- SINDRUM-II: 1 MW proton beam at PSI
- Fermilab will have 8 kW of protons to spare for Mu2e
- How can we be competitive???

The usual way to collect muons



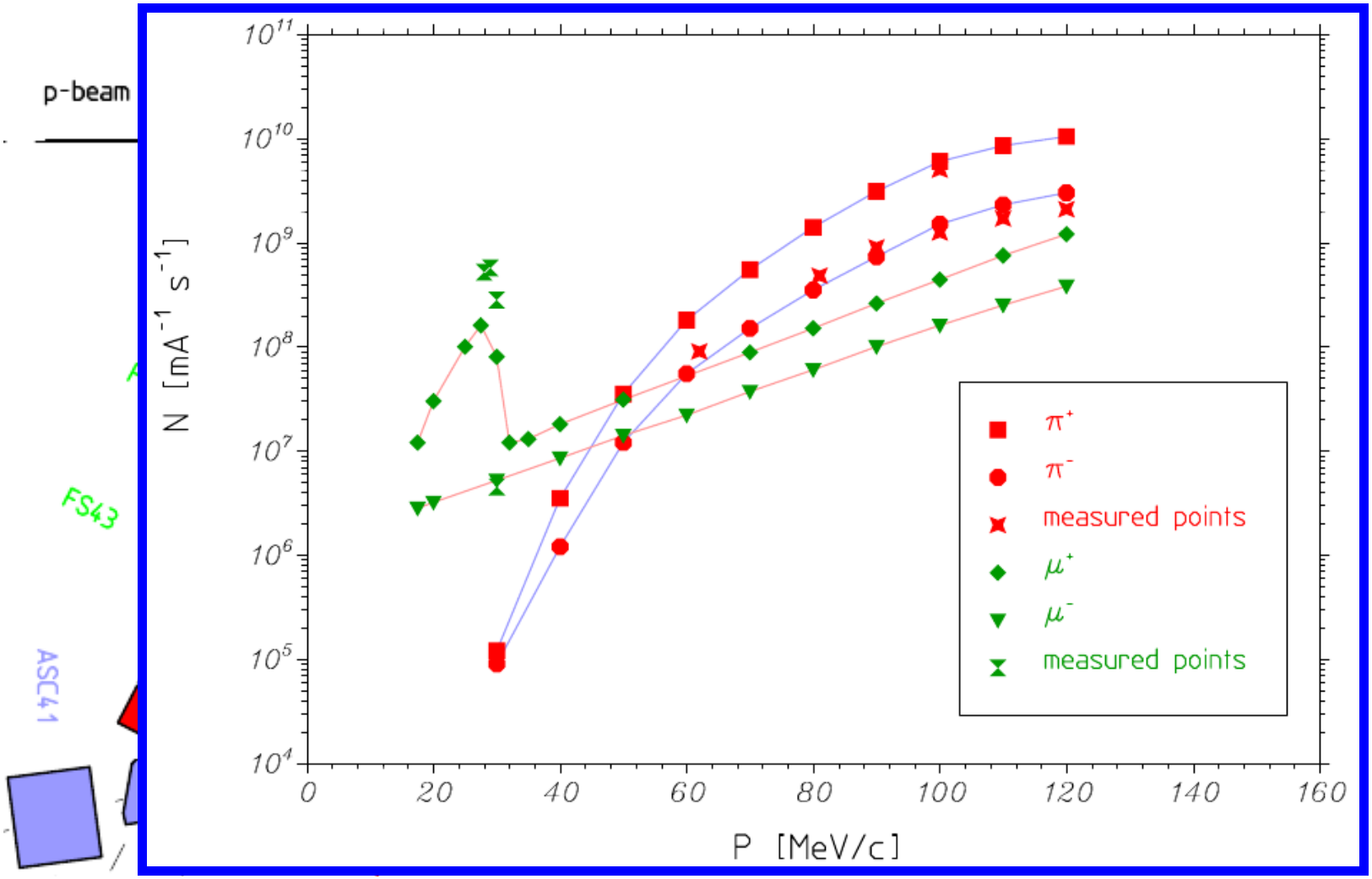
- PSI $\pi E5$ beamline
- Used by SINDRUM II

The usual way to collect muons



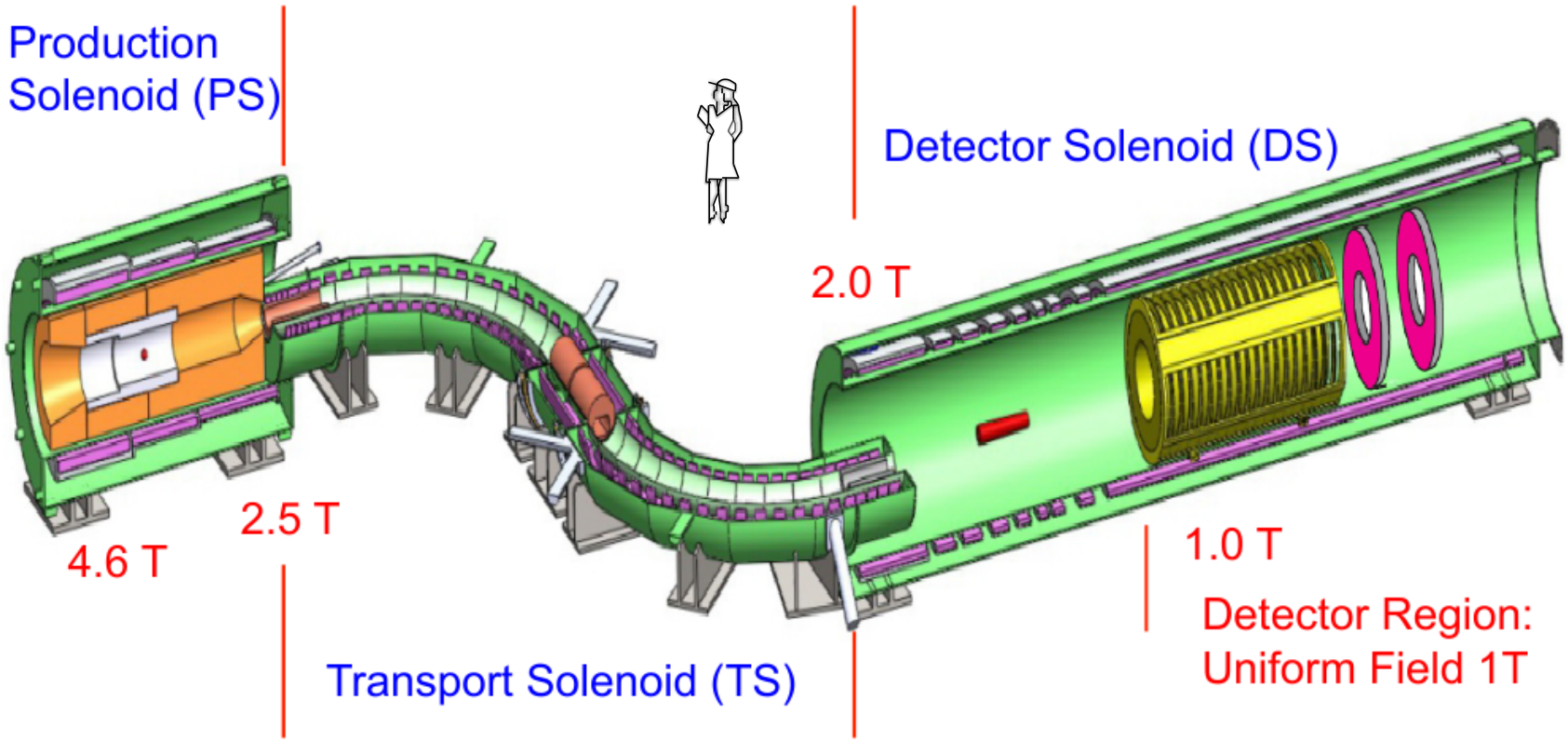
1.3 MW protons $\Longrightarrow$ 300 μW muons [*M. Seidel, PSI-2013*]

The usual way to collect muons



More relevant: $\mathcal{O}(10^7)$ μ^-/s Mu2e: $> 10^{10}$ μ^-/s

Meet Mu2e magnets



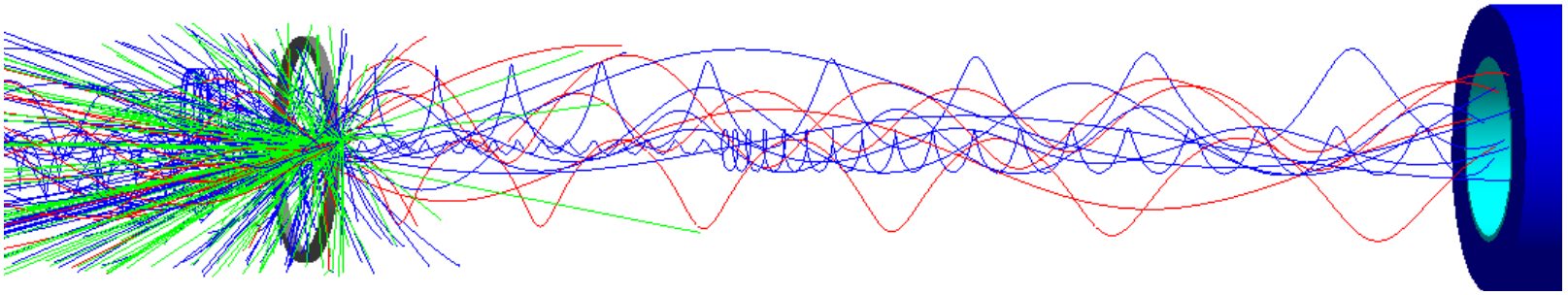
Graded B for most of length

Not shown: Cosmic Ray Veto, Extinction Monitor

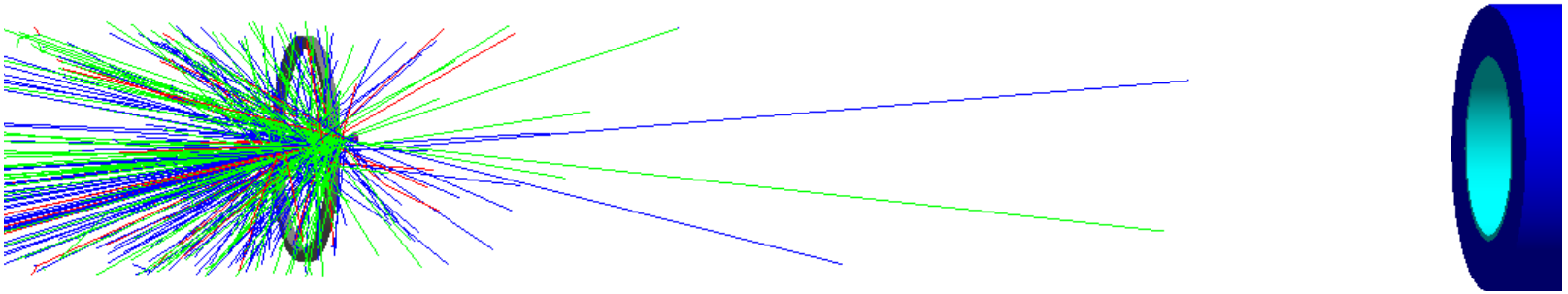
Mu2e muon collection

Proton target in solenoidal $\vec{B}$ field

- Soft pions confined: collect most of resulting muons

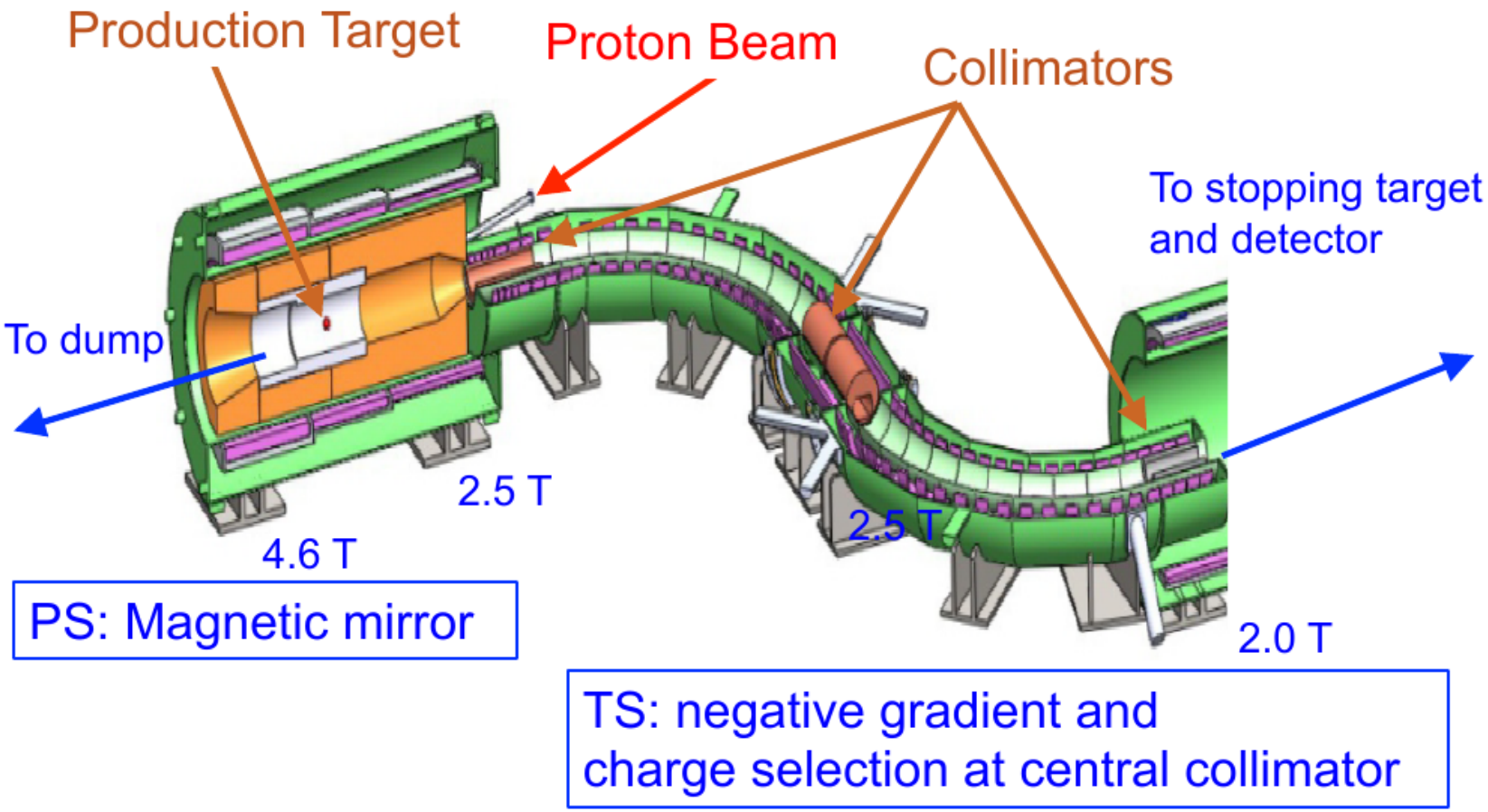


Compare to $\vec{B} = 0$

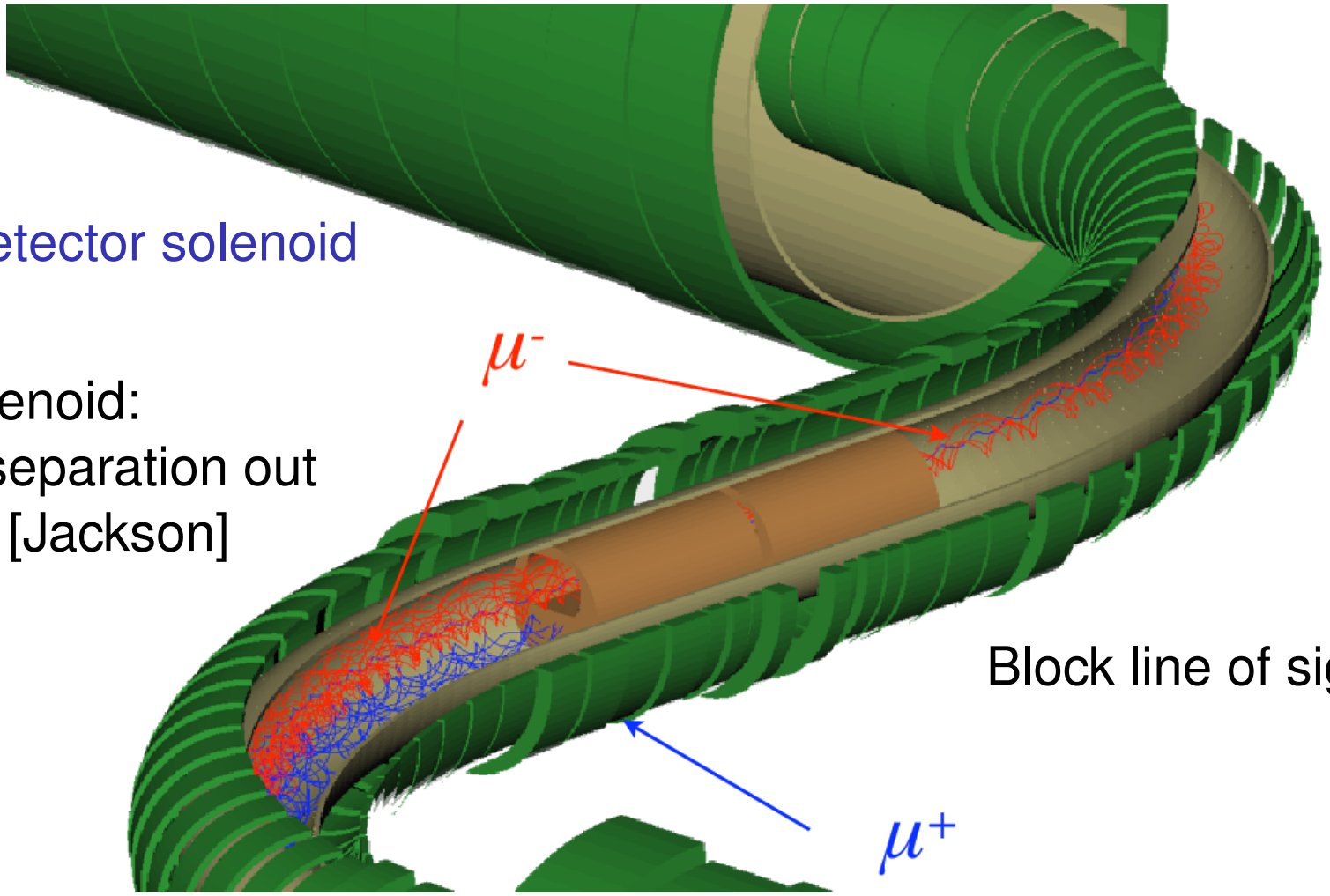


30 protons at 8 GeV: 10^{-6} of Mu2e pulse
γ, $e^{\pm}$, n with $E_k < 100$ MeV not shown

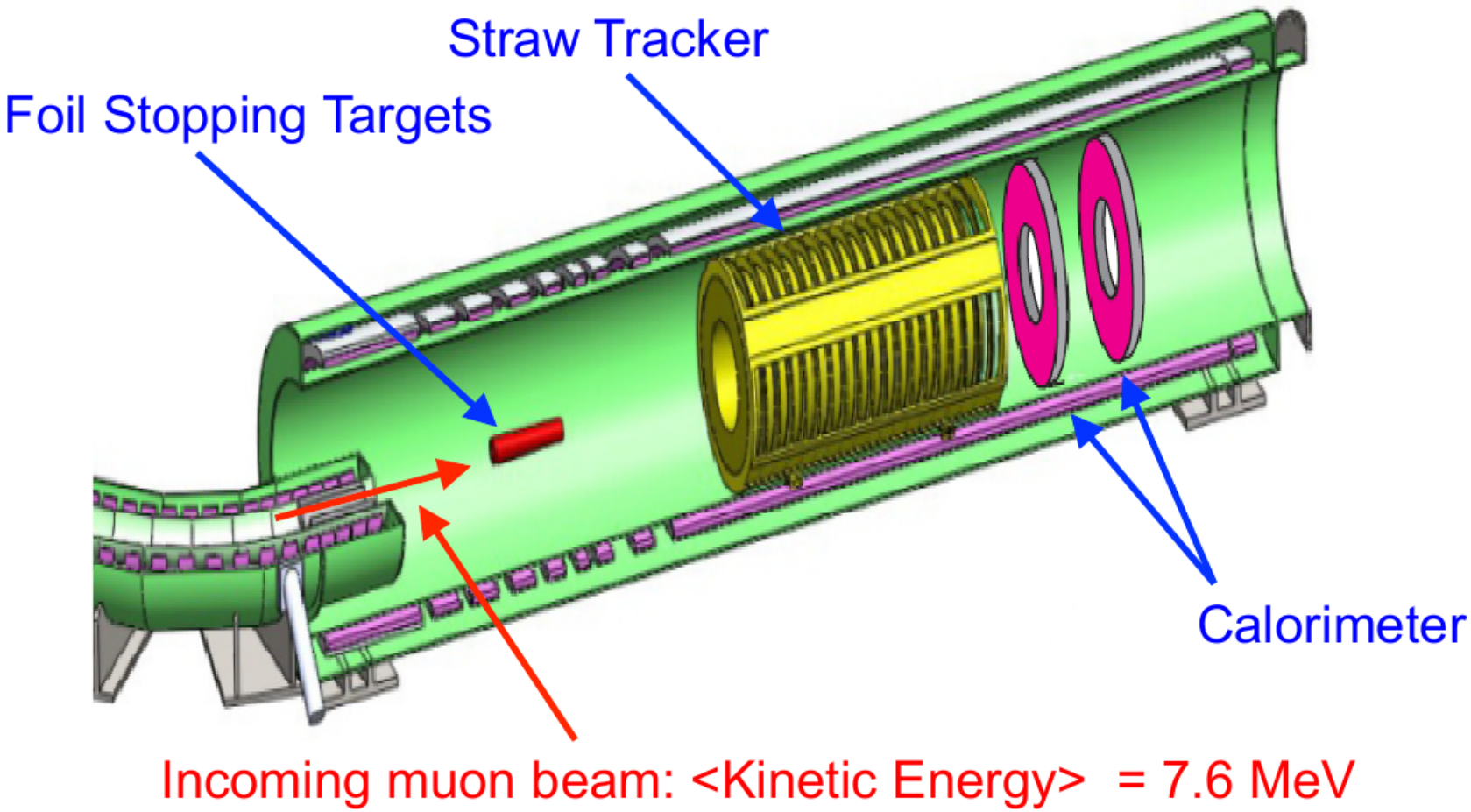
Muon production and delivery



Charge selection

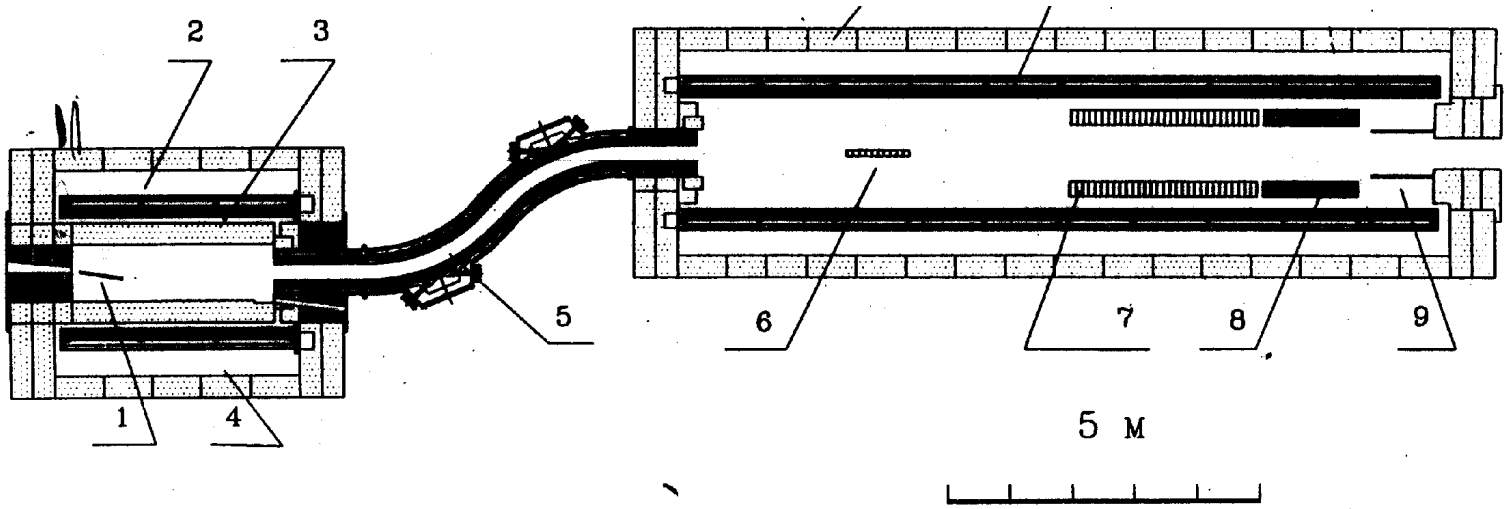


Stopping target and detectors

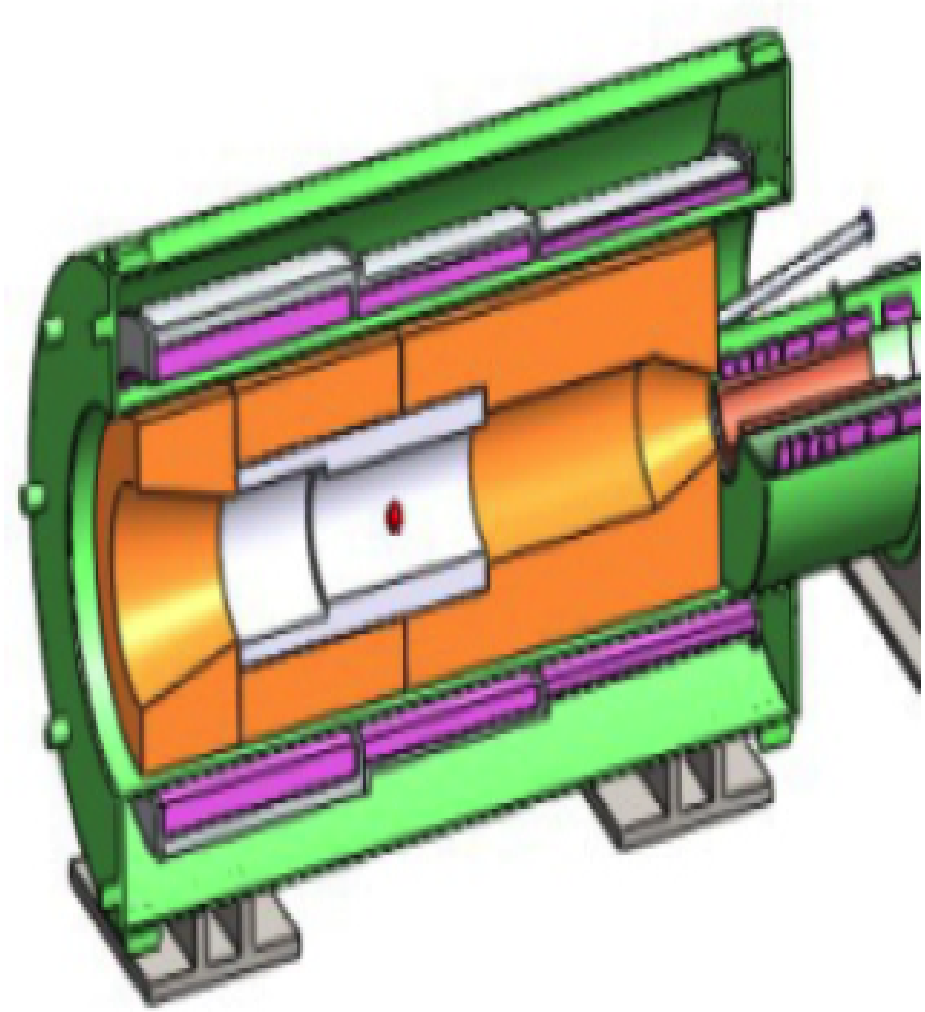


The origins of the concept

- R. M. Dzhilkibaev and V. M. Lobashev, "On the Search for $\mu \to e$ Conversion on Nuclei.," Sov. J. Nucl. Phys. **49**, 384 (1989)
- 1992 MELC experiment proposal:

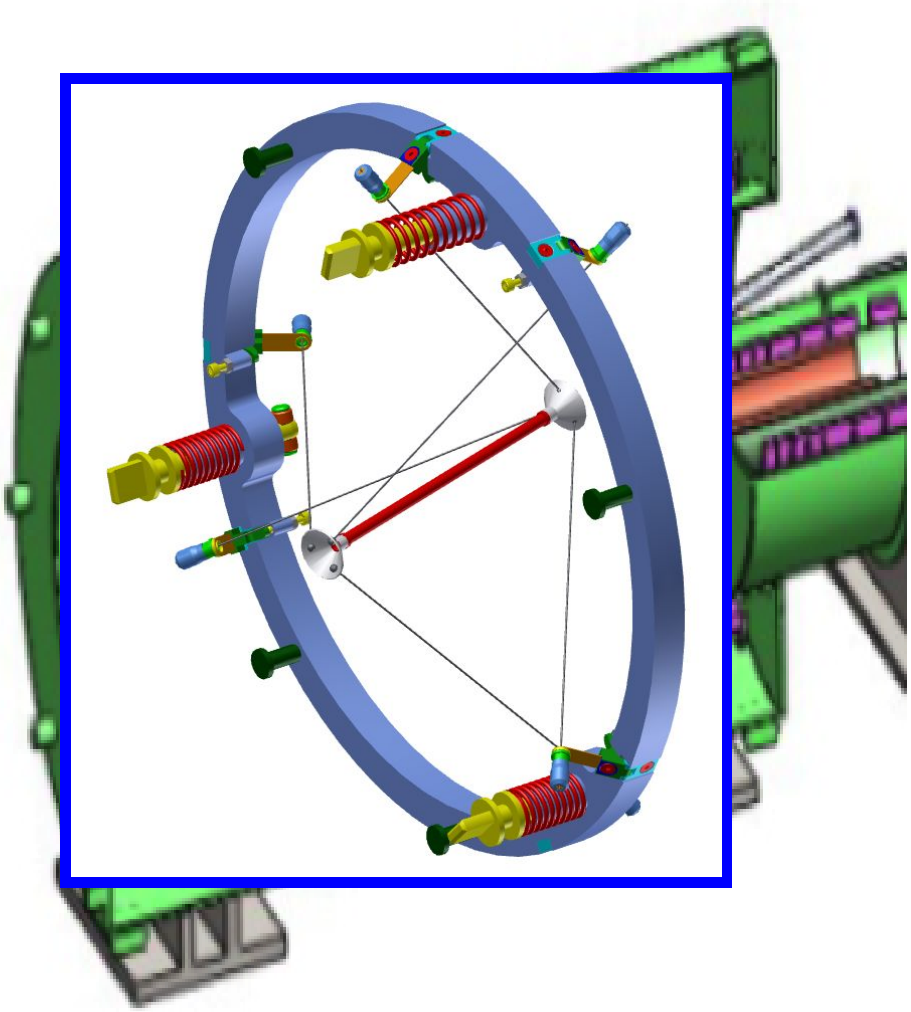


Some of the challenges



- Cold coils
- Near proton target:
  - Heat
  - Radiation damage
    - cable
    - insulation
- Large volume & field:
  - $\mathcal{O}(150)$ t forces
  - Stored energy
- Target life and access

Some of the challenges



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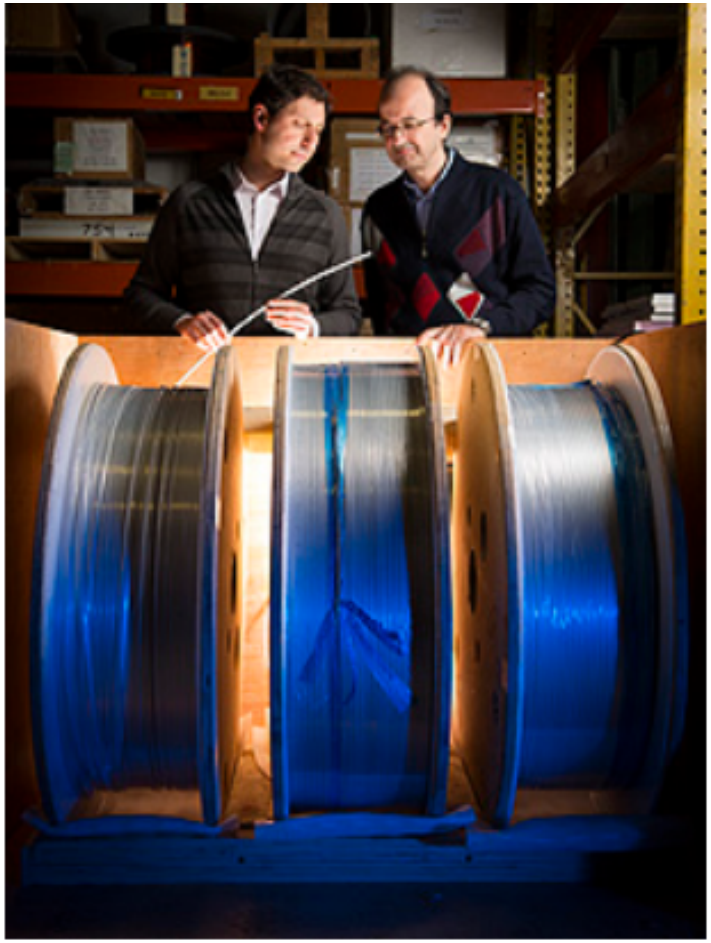
Fermilab Today Tuesday, Dec. 10, 2013



Vito Lombardo and Giorgio Ambrosio lead the development of the Mu2e transport solenoid. In a recent test, the prototype superconducting cable for the solenoid met every benchmark. *Photo: Reidar Hahn*

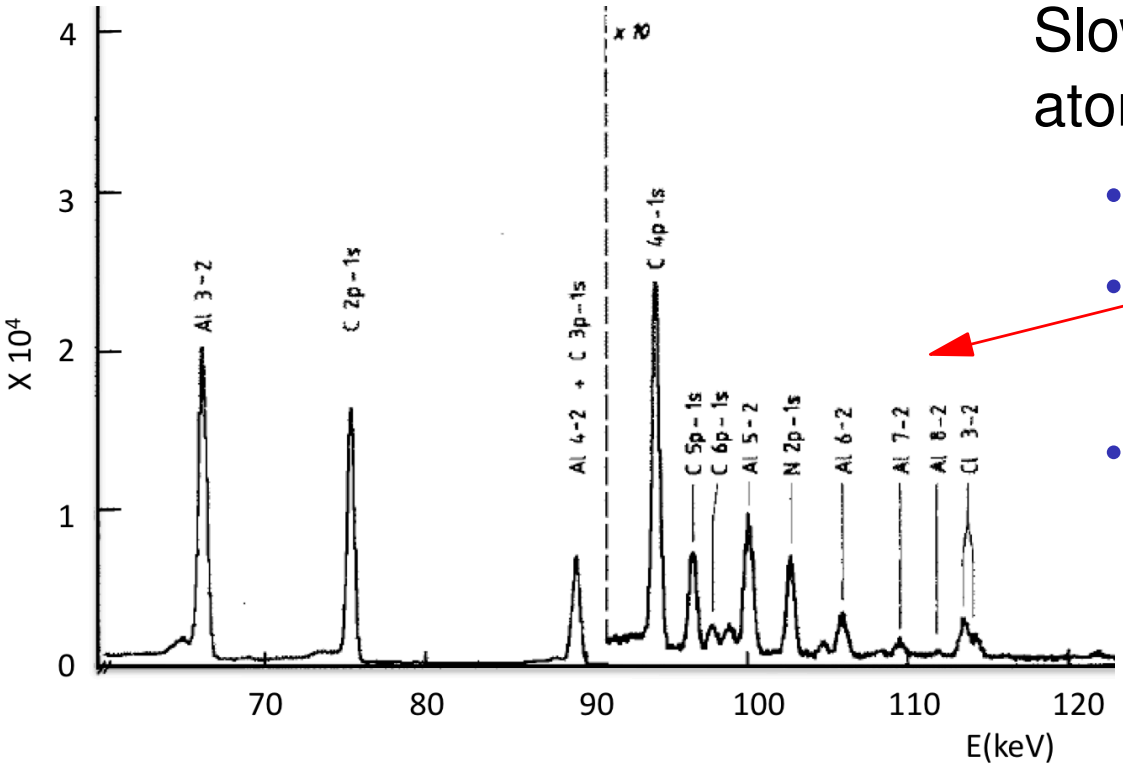
Mu2e superconducting cable prototype successful

Last month, members of the Technical Division conducted final tests on the first batch of prototype superconducting cable for the proposed Mu2e experiment. The cable met every prescribed benchmark, carrying over 6,800 amps of electrical current — well above its design current — at 4.2 Kelvin in a magnetic field of 5 Tesla.

This aluminum-clad niobium-titanium superconductor is a critical component of one of Mu2e's three magnets, the transport solenoid. As the name implies, the transport solenoid will help transport a beam of muons from its production source to the detector, where scientists will study the particle interactions.

"This prototype conductor is an important part of our transport solenoid magnet program," said Giorgio Ambrosio, who is

Muons stopping in Al target



Slow down, form muonic atoms, cascade to 1s state

- picoseconds time scale
- X-rays: use to count stopped muons
- Derive number of captures for normalization

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

Muonic aluminum atom

- 61% Capture:

$$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)^*$$

- 39% Decay in orbit (DIO):

$$\mu^- + (A, Z) \rightarrow e^- \nu_\mu \bar{\nu}_e + (A, Z)$$

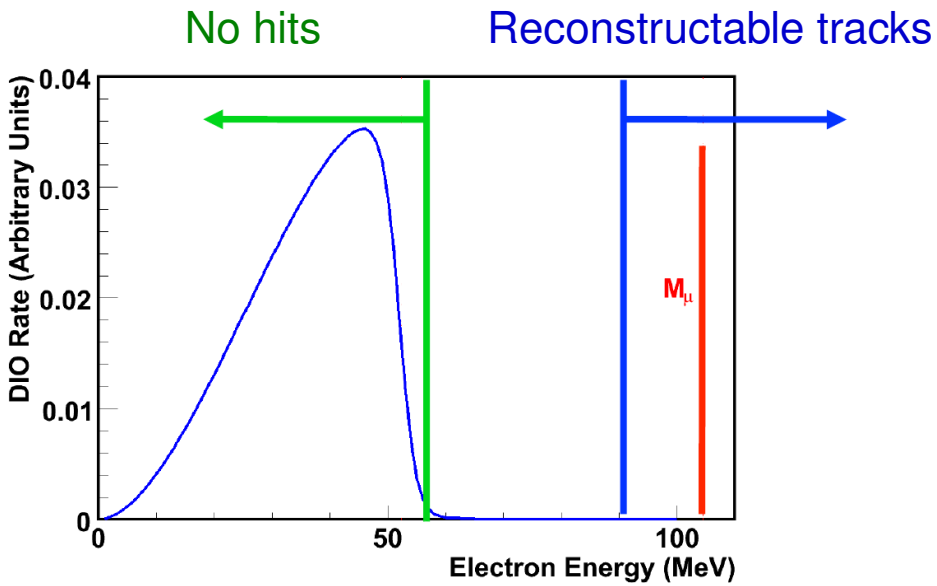
- New Physics: conversion?

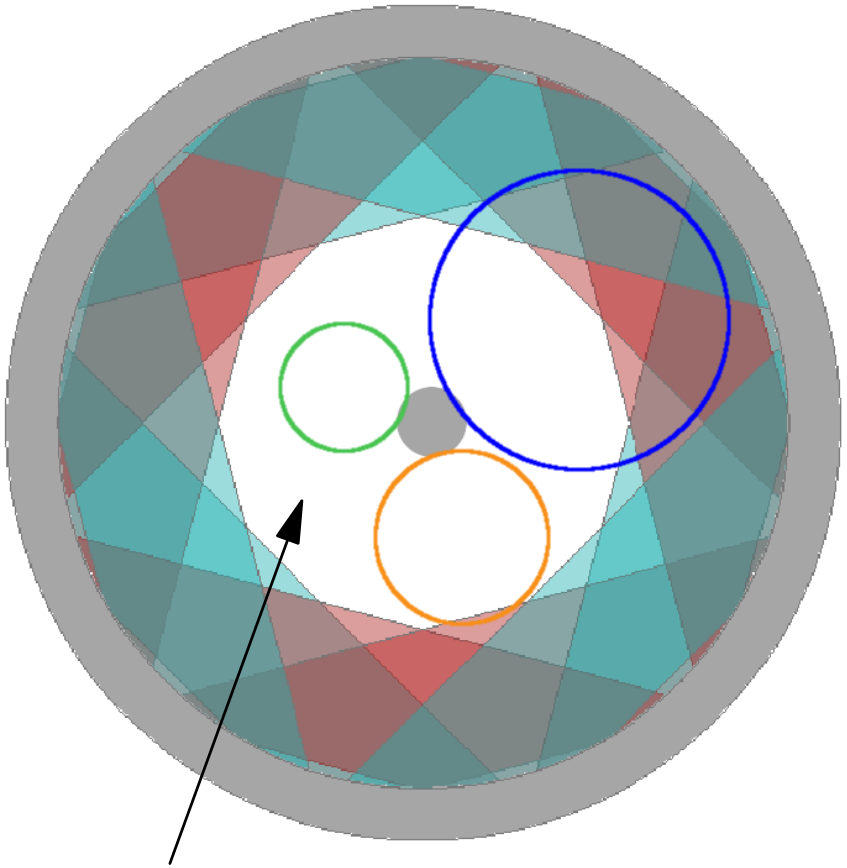
$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

How to handle detector rates from 10^{10} muons/s?

Be blind to most tracks: annular design

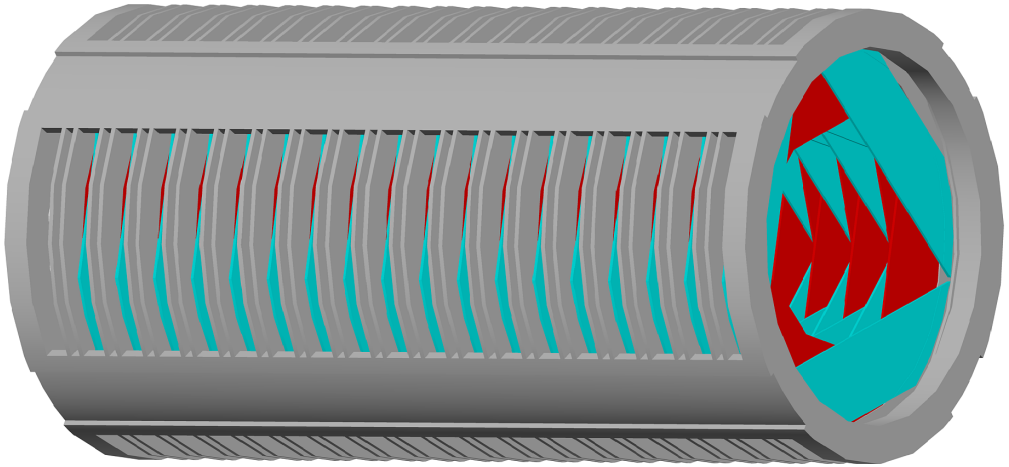
$R_{in} = 38$ cm, $R_{out} = 70$ cm





Vacuum: no scattering

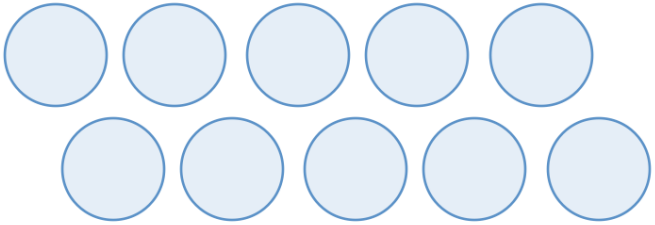
Tracker



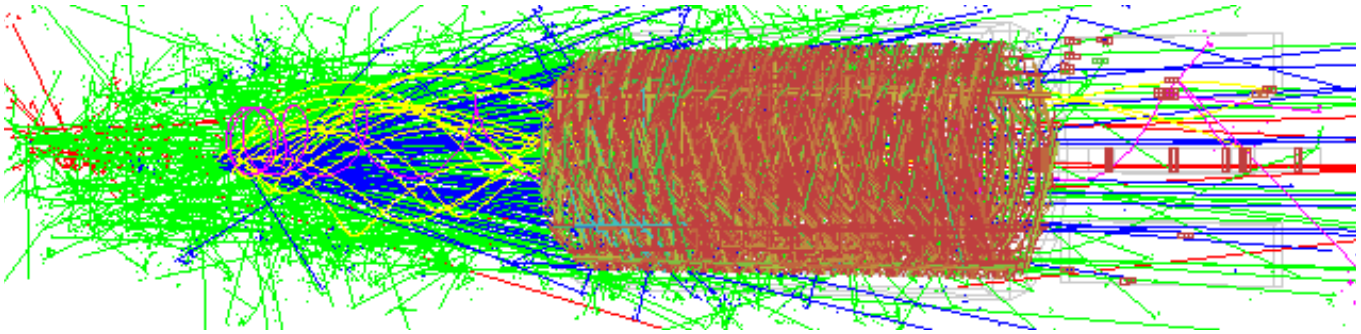
- about 3 m long
- 1 T uniform B field
- "Good" tracks make 2–3 turns
- TDC readout on both ends
  $\Longrightarrow$ along-wire position from Δt
- ADC readout for particle ID

$\approx 25,000$ straw tubes

- 5 mm diameter
- 15 μm wall
- 25 μm wire
- in vacuum

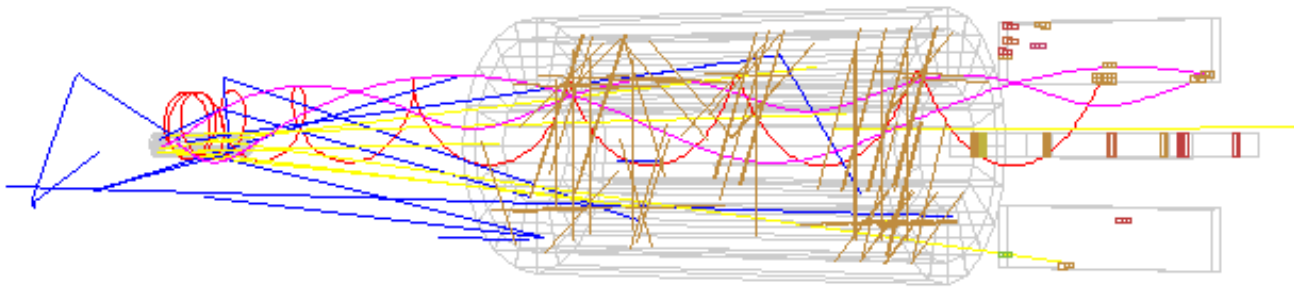


Pattern recognition



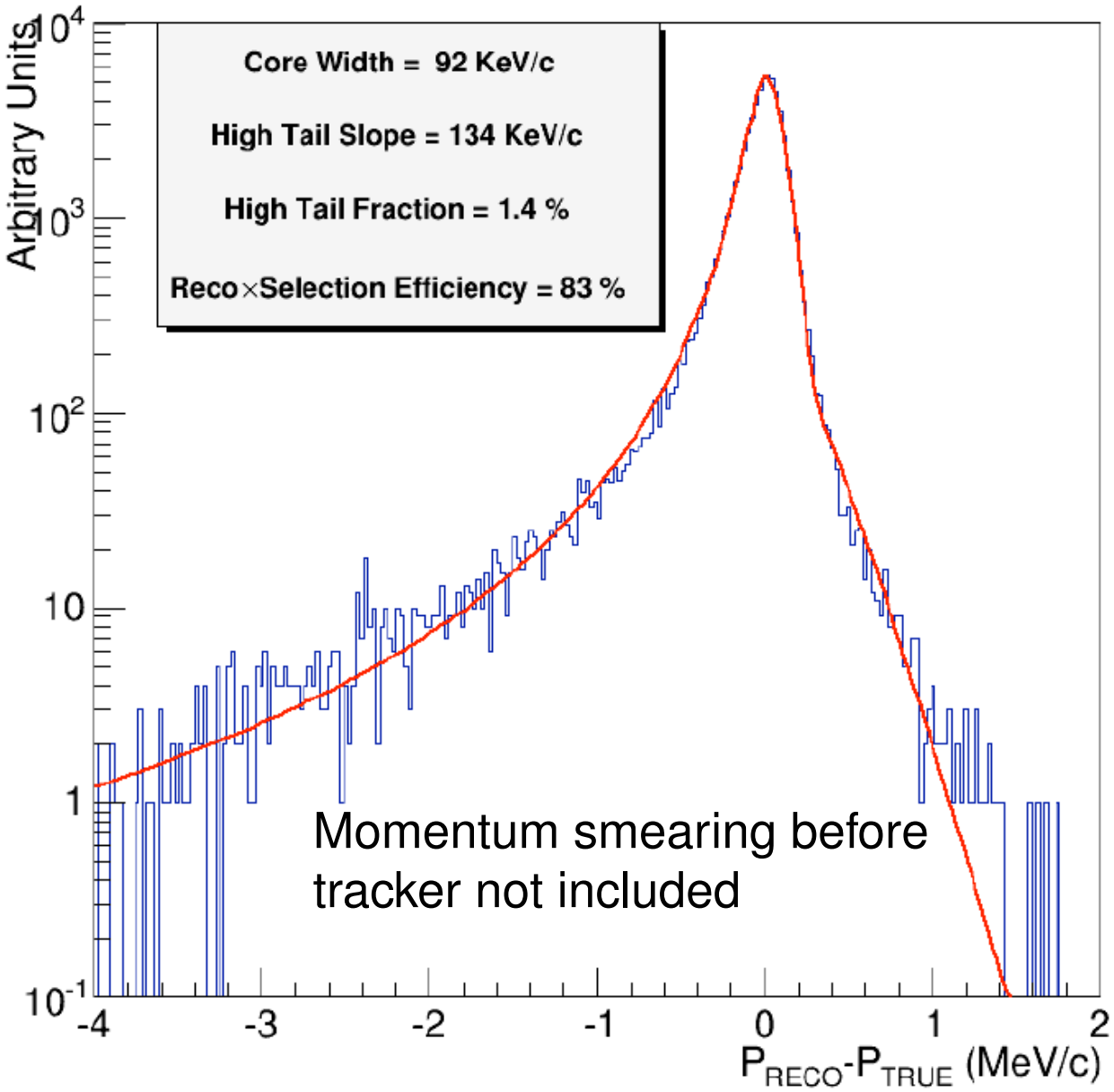
Single proton pulse: particles and hits in 500–1694 ns

Pattern recognition



Single proton pulse: particles and hits in ± 50 ns around conversion

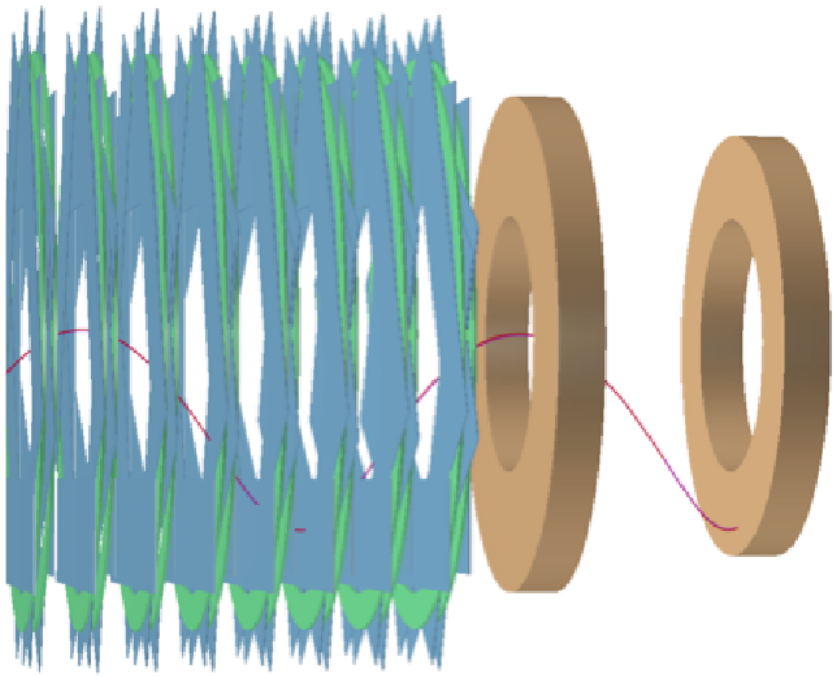
Tracker momentum resolution



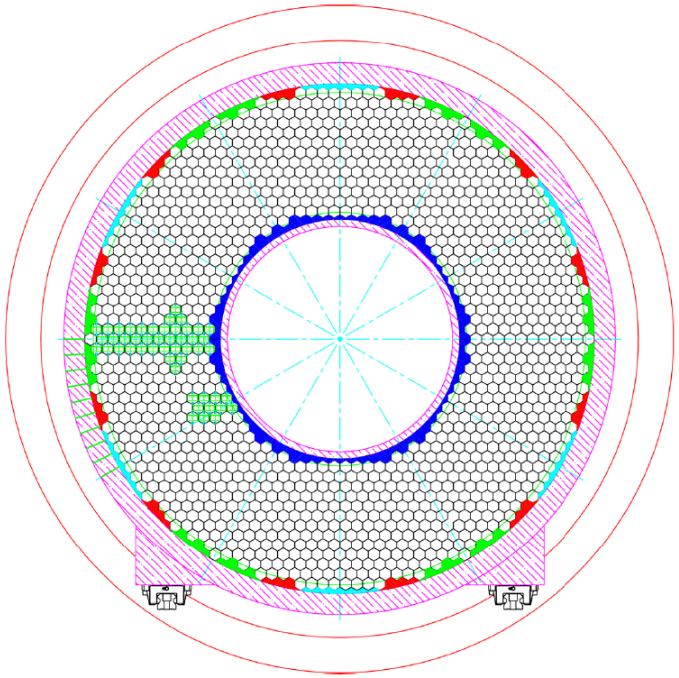
Dave Brown, CLFV2013 (Lecce)

Calorimeter

Two disk geometry



Hex BaF_2 crystals
SiPM or APD readout



Provides precise timing, PID (cosmic rejection), alternate track seed, possible calibration trigger. Discovery: confirms tracker signal events.

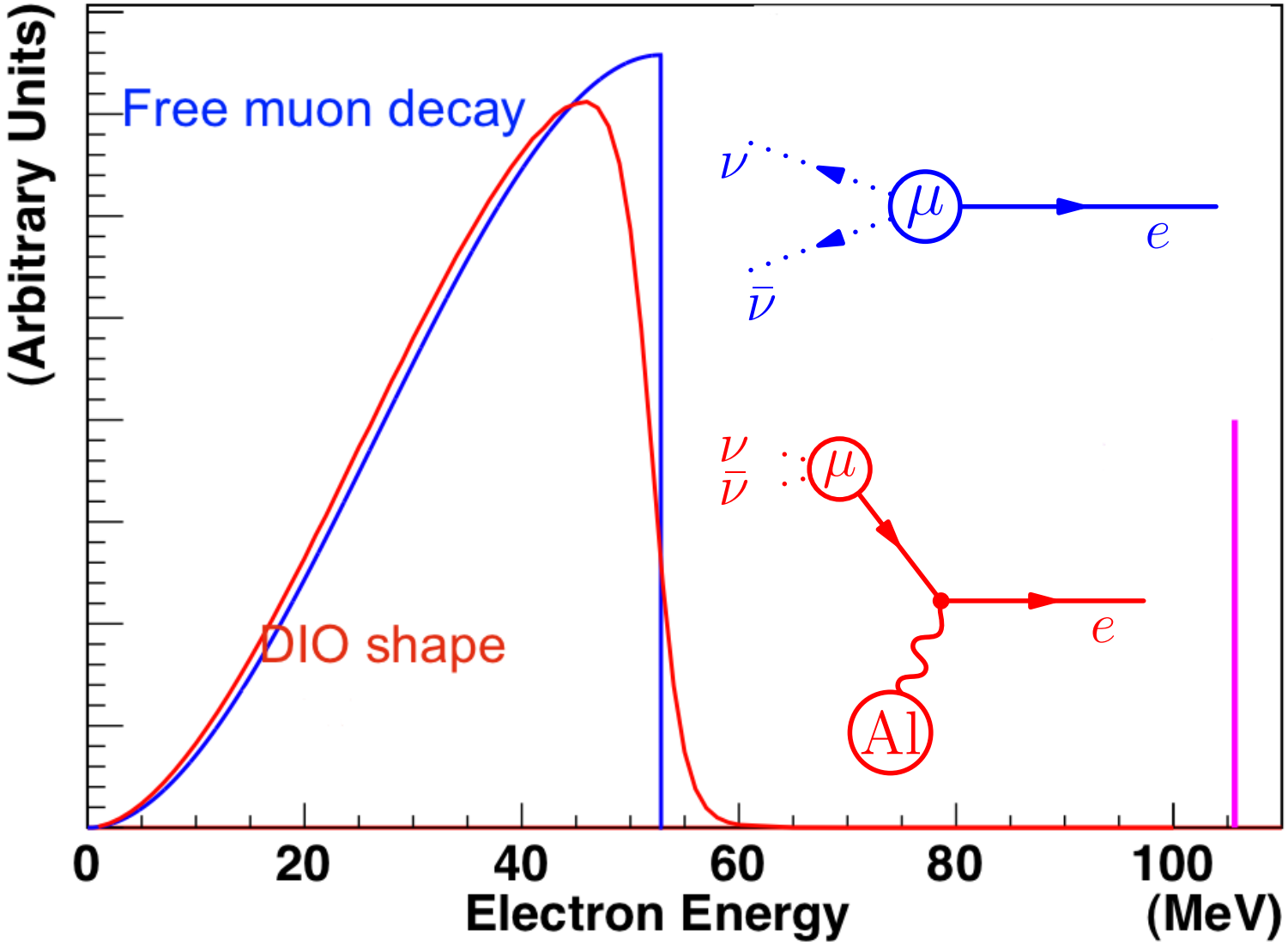
More info: P. Murat's talk 2013-12-18

Got our signal. What about backgrounds?

Types of backgrounds

- Muon induced
  - Muon decay in orbit (DIO)
- Out-of-time protons or long transit secondaries
  - Radiative pion capture
  - Muon decay in flight
  - Pion decay in flight
  - Beam electrons
  - Antiprotons
- Cosmic rays

Electron spectra



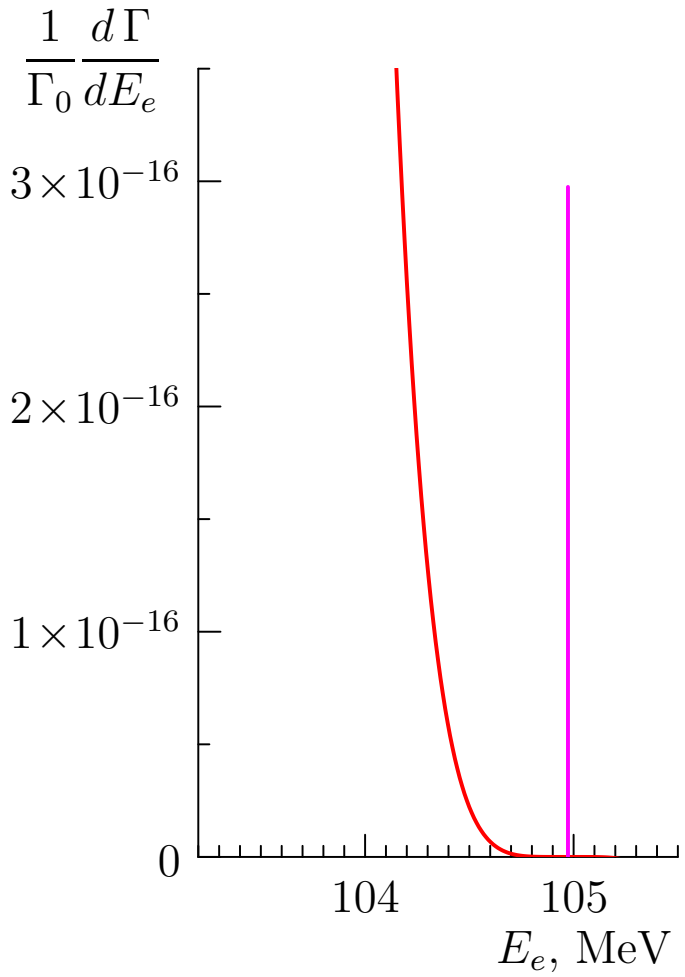
A closer look at DIOs

- Latest spectrum computation: Czarnecki, Tormo, Marciano (2011)
- End point expansion

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e} = B\left(E_\mu - E_e - \frac{E_e^2}{2m_N}\right)^5$$

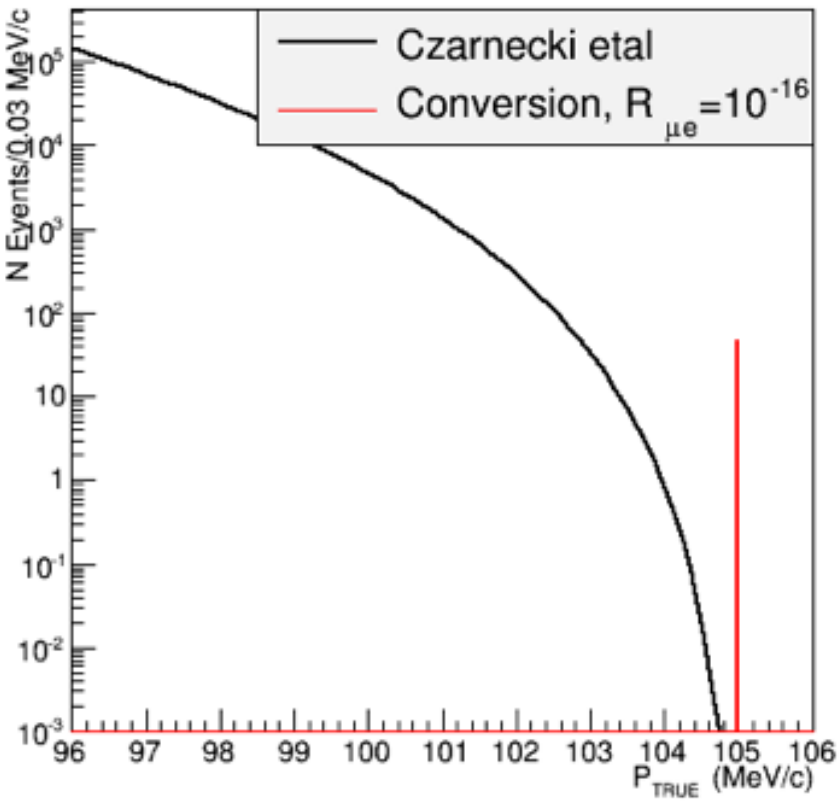
— small but steep tail!

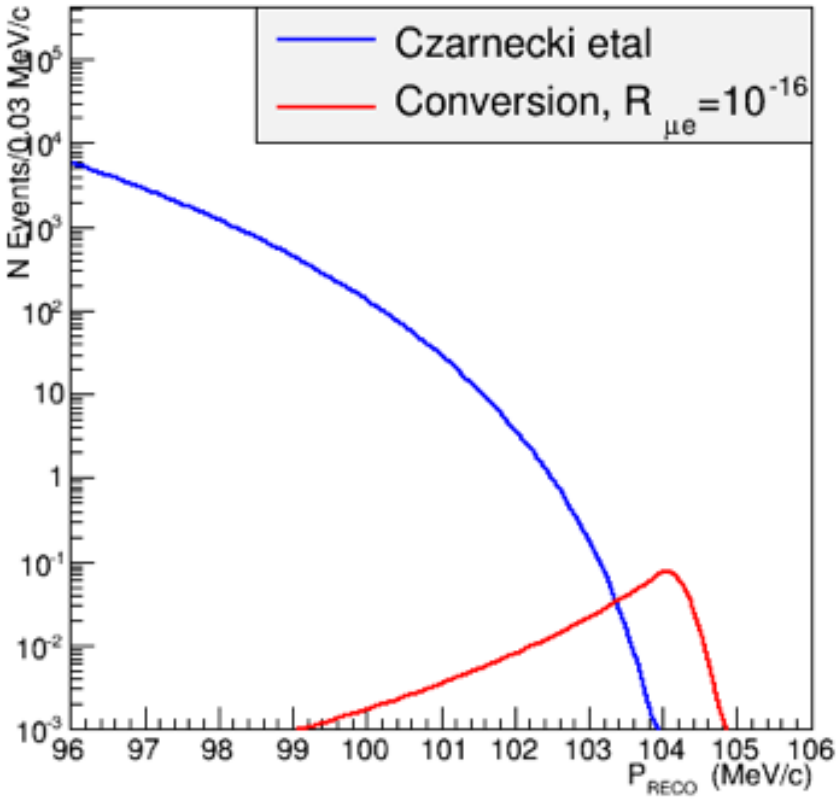
- DIO electron differs from signal only by its p



Momentum resolution is important!

Especially the high side tail: pushes DIOs into the signal region





Prompt backgrounds

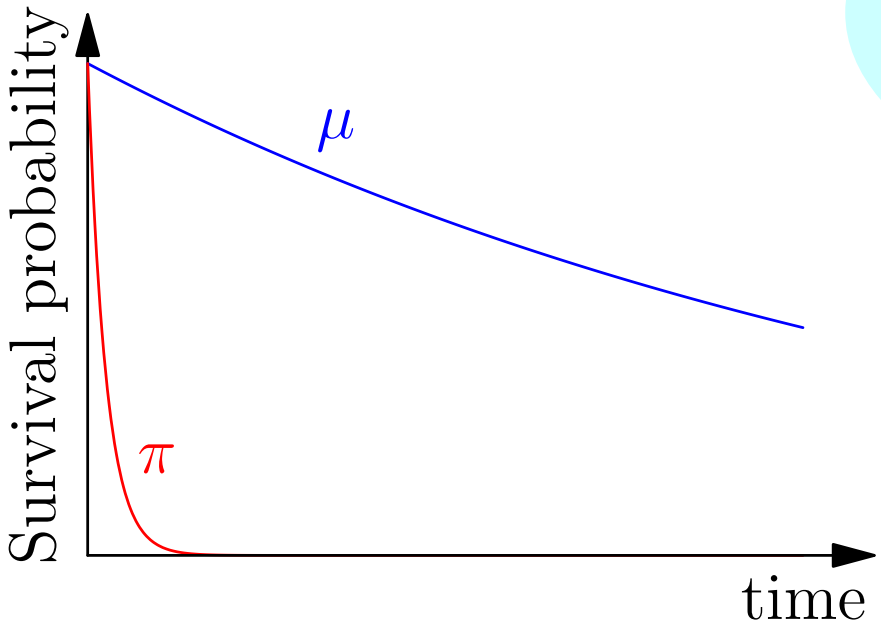
- Signal is a 105 MeV electron
- Many ways for 8 GeV protons to make those
- Example: Radiative Pion Capture

$$pN \longrightarrow \pi^- X$$

$$\pi^- N \xrightarrow{\text{radiative capture}} \gamma N'$$

$$\gamma N \xrightarrow{\text{conversion}} e^- e^+ N$$

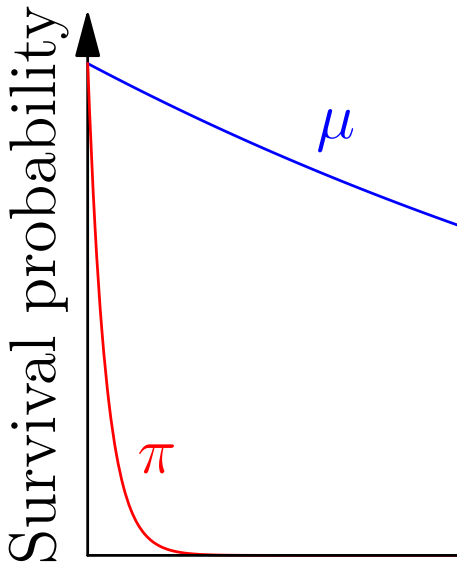
Processes in Al target



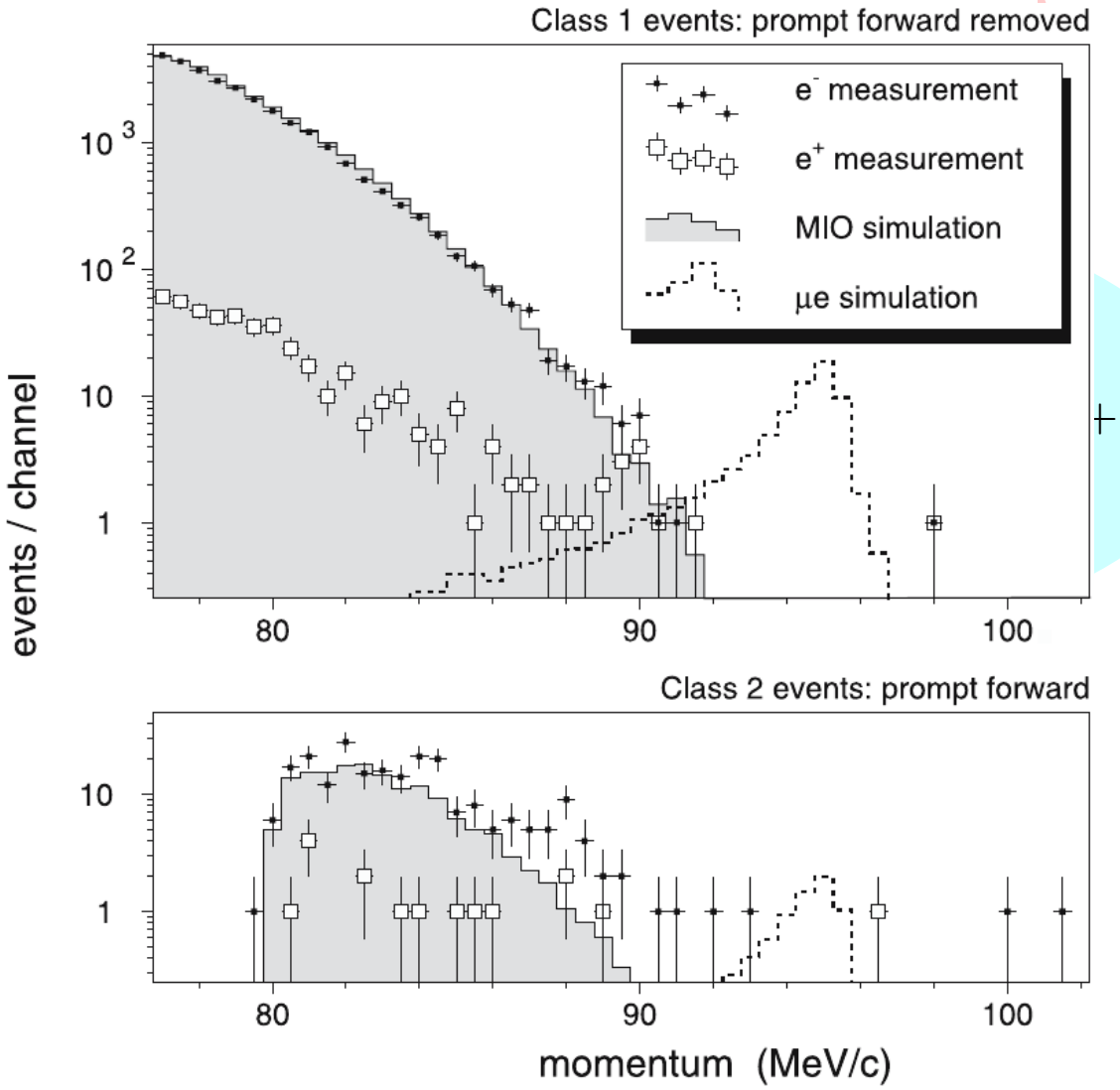
$\Longleftarrow$ Mitigation: wait

Prompt backgrounds

- Signal is a 105
- Many ways for to make those
- Example: Radi Capture

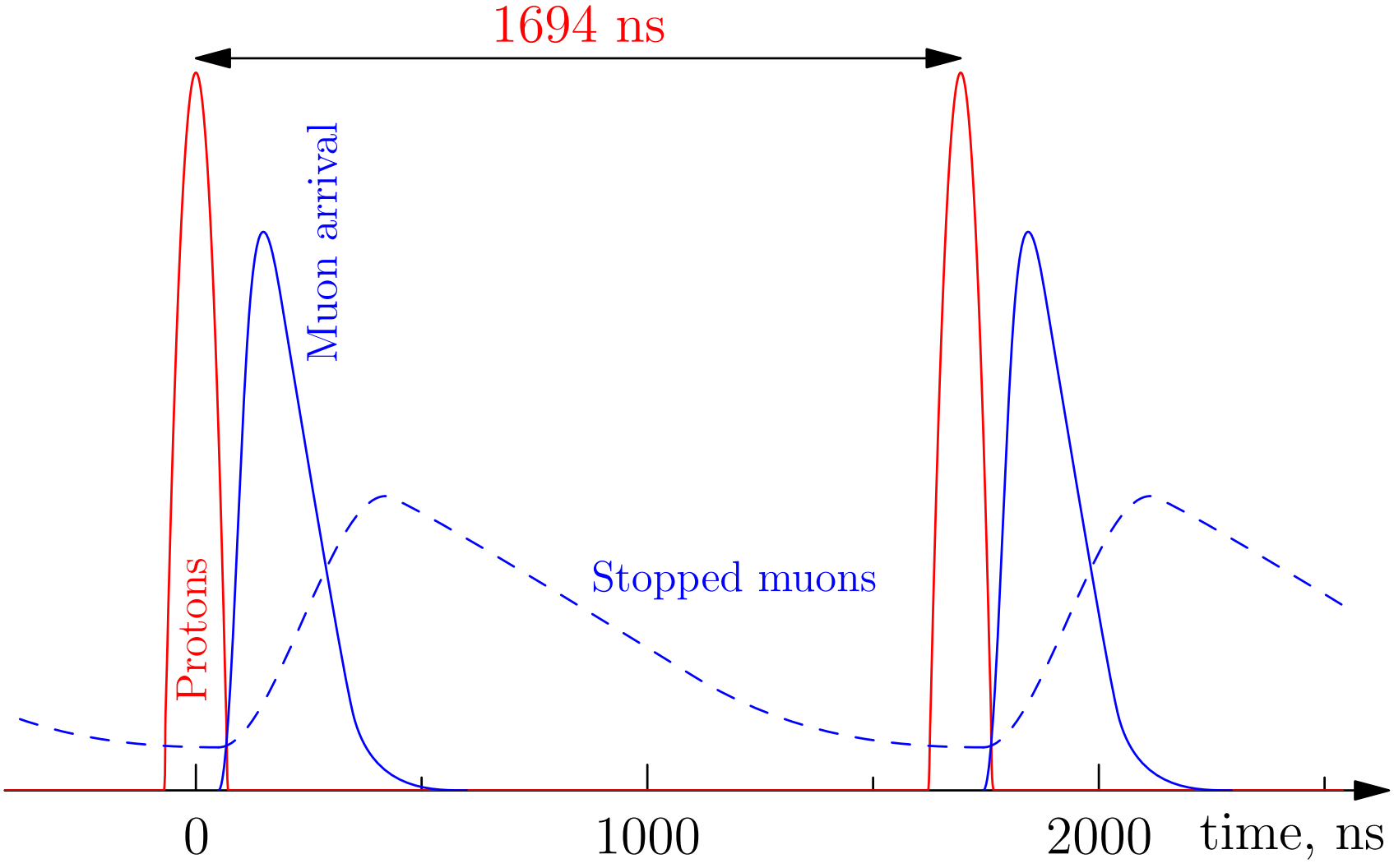


SINDRUM-II spectra



$+N$

Mu2e time structure



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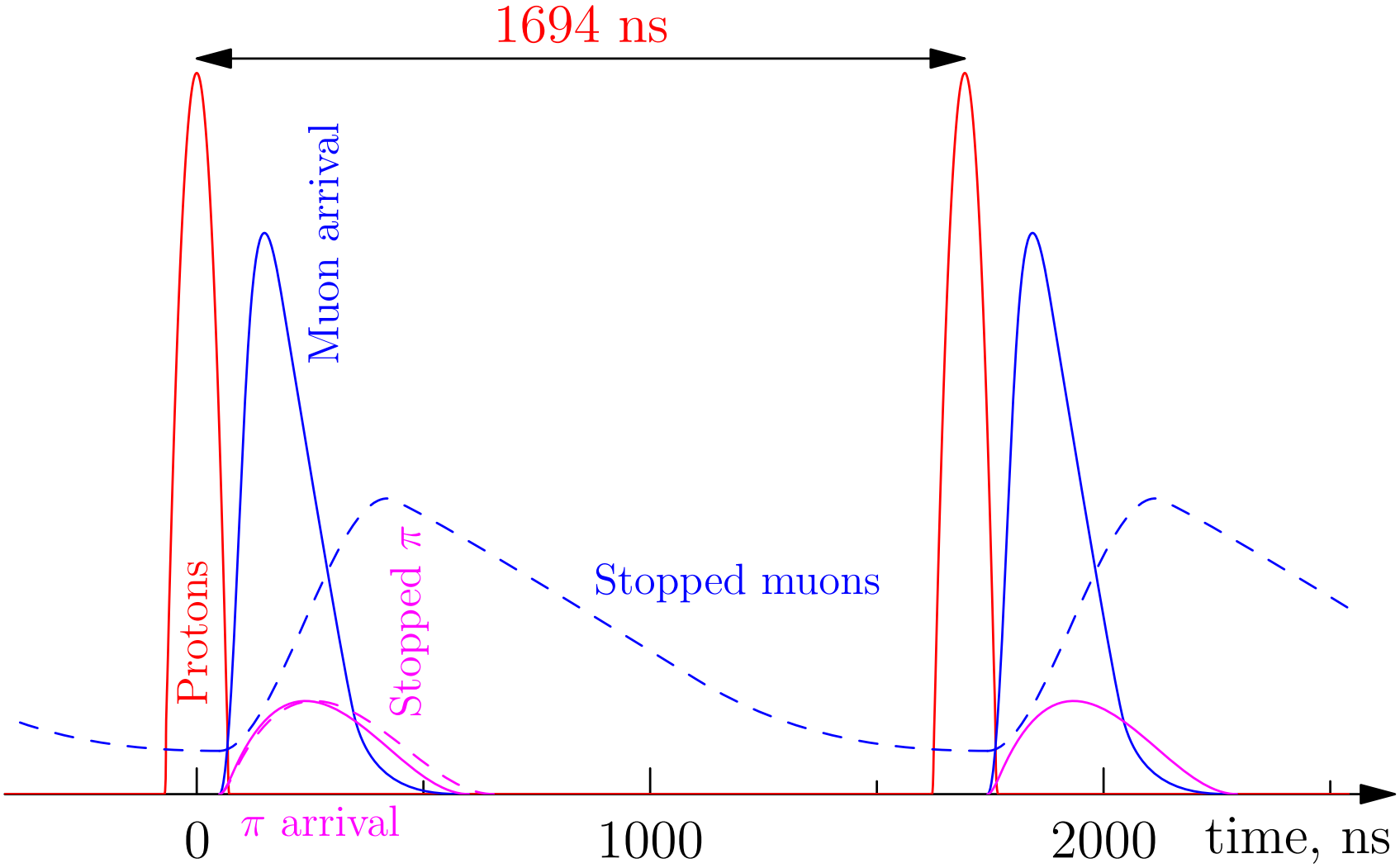

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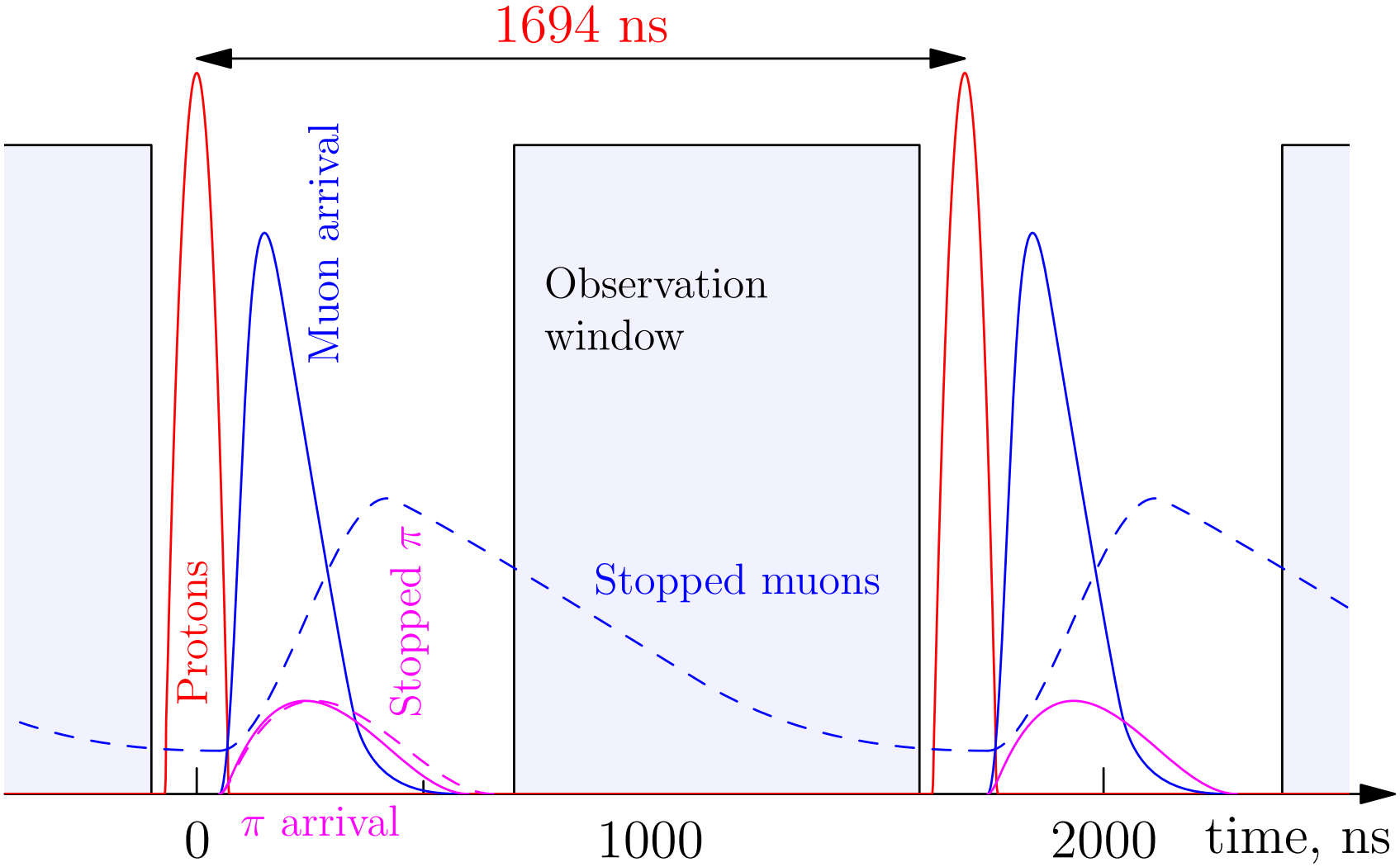
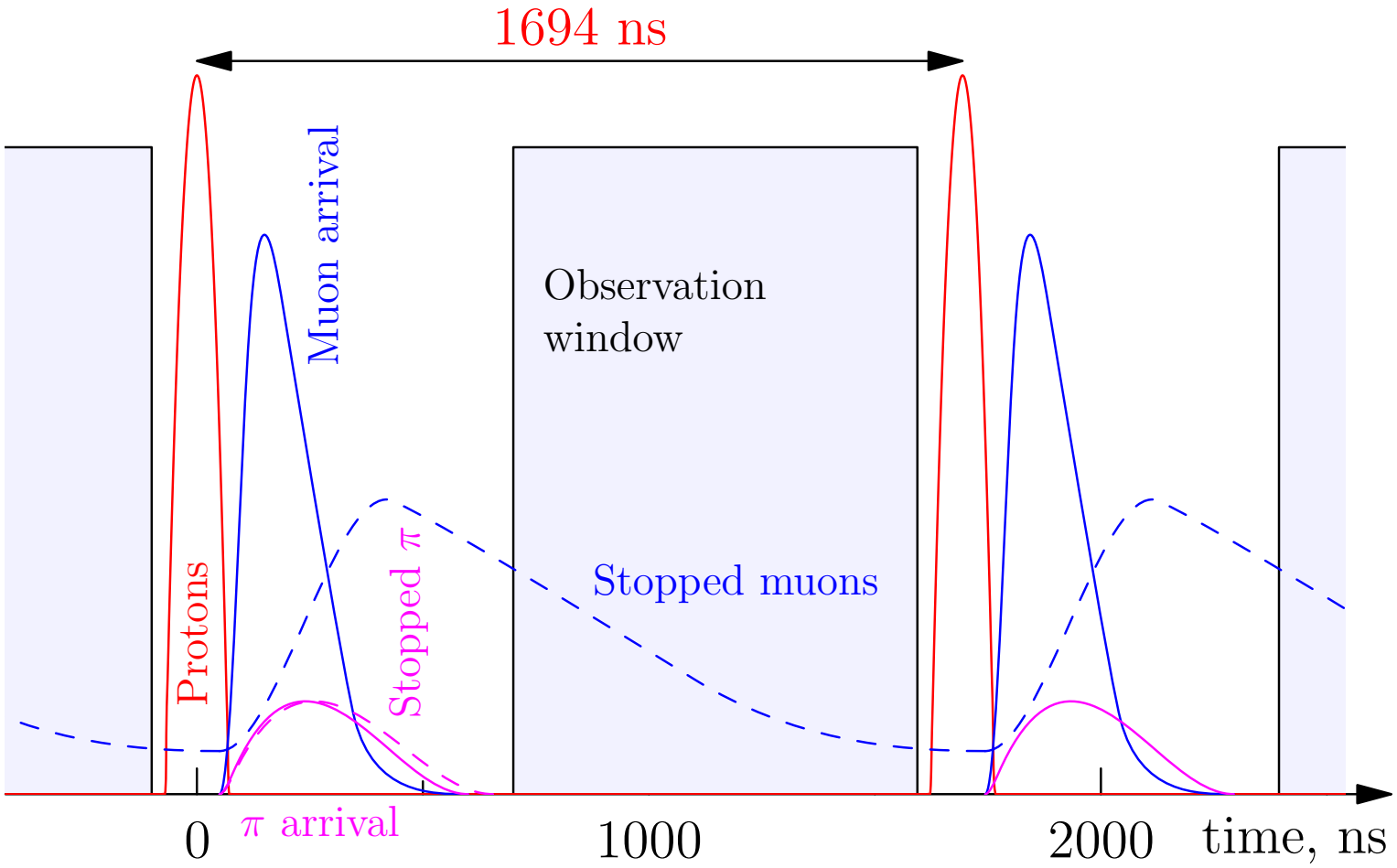


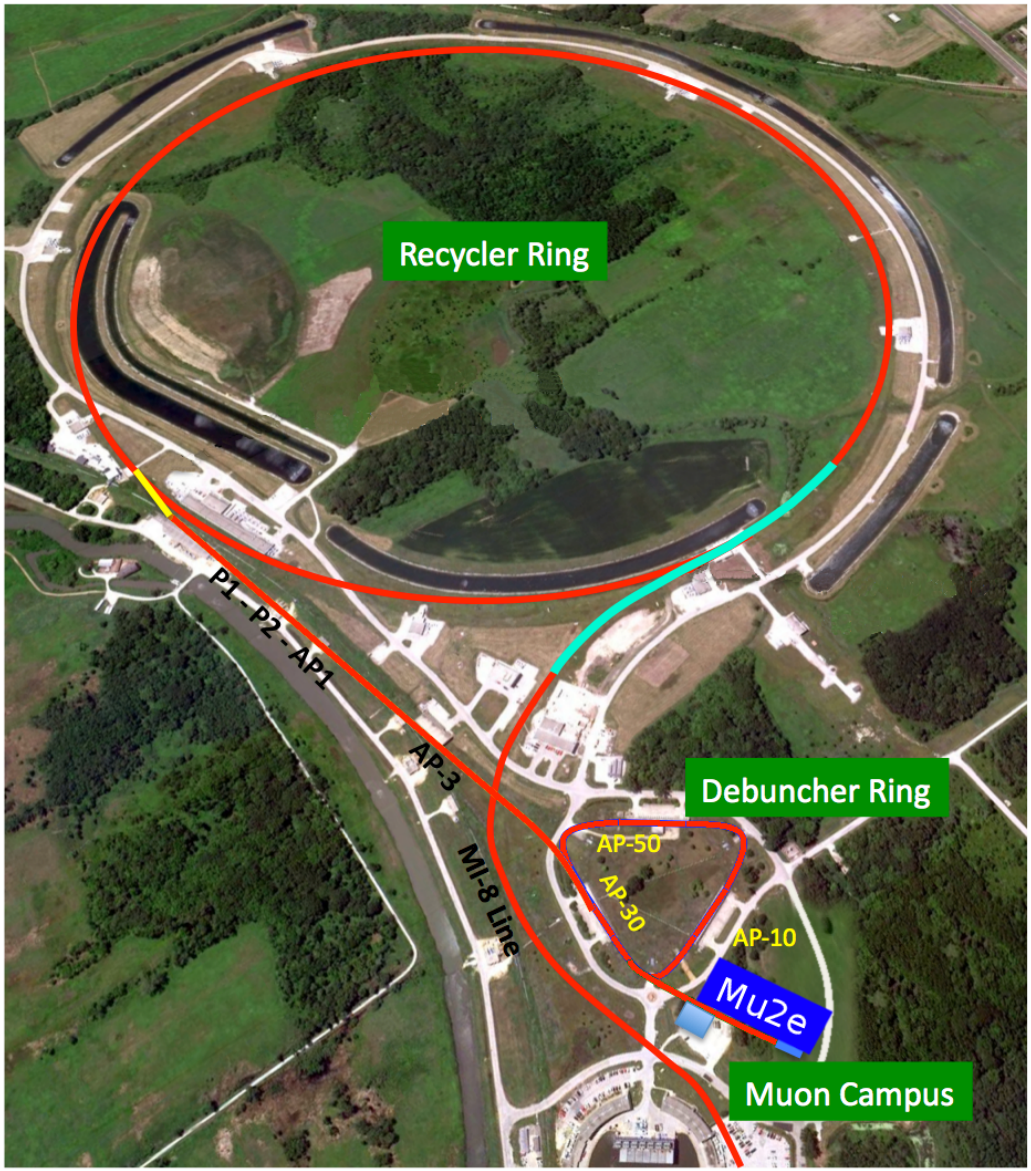
Proton beam extinction



Beam extinction requirement

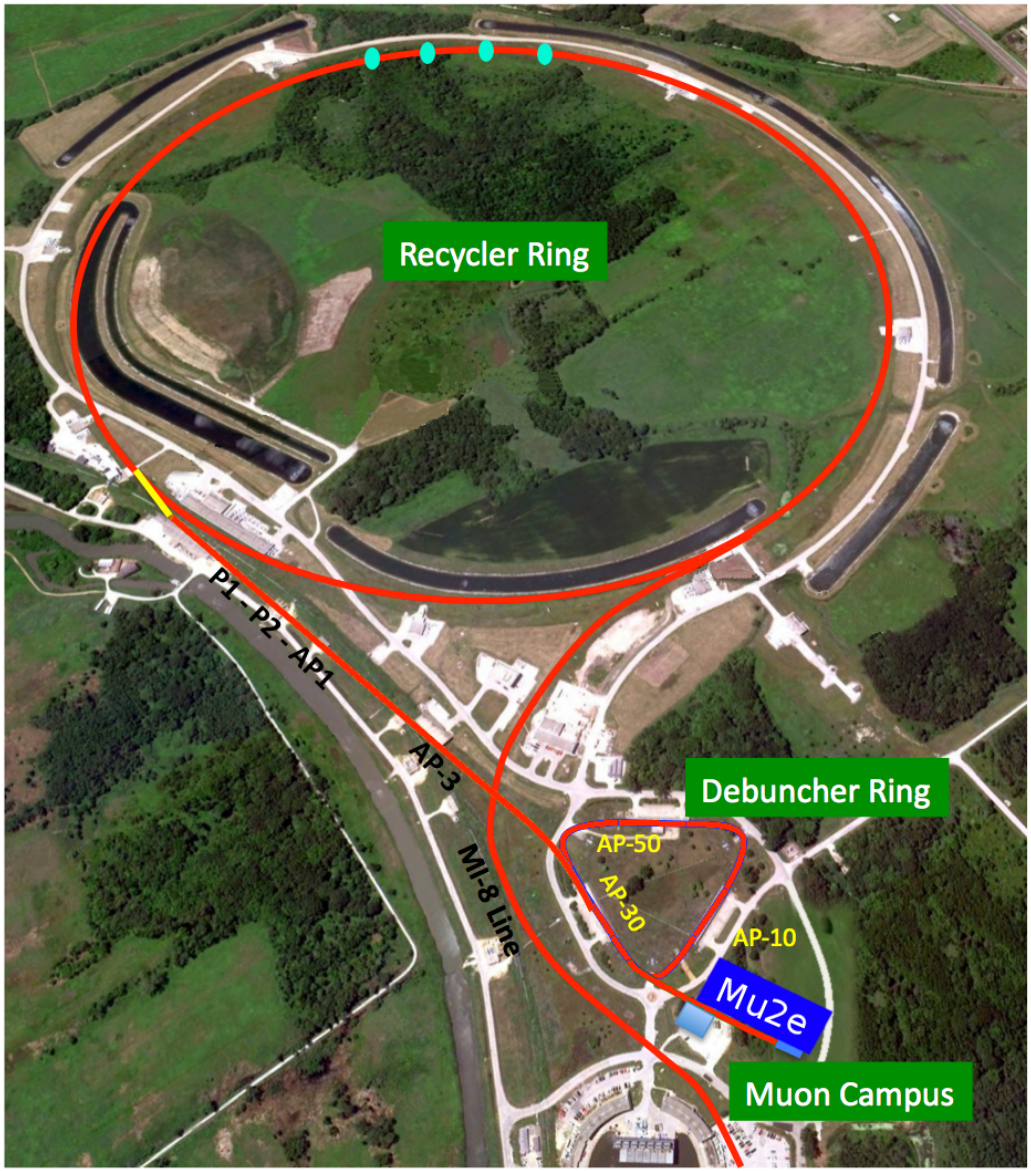
$\epsilon =$ (Num protons between pulses)/(Num in pulses) $< 10^{-10}$

Proton delivery



- Efficient reuse of Tevatron infrastructure
- Muon campus: former antiproton complex
  - g-2 and Mu2e
- A muon experiment can run simultaneously with NOvA
- Ring revolution period is 1694 ns: good match to $\tau^{\mathrm{Al}} = 864$ ns

Proton delivery



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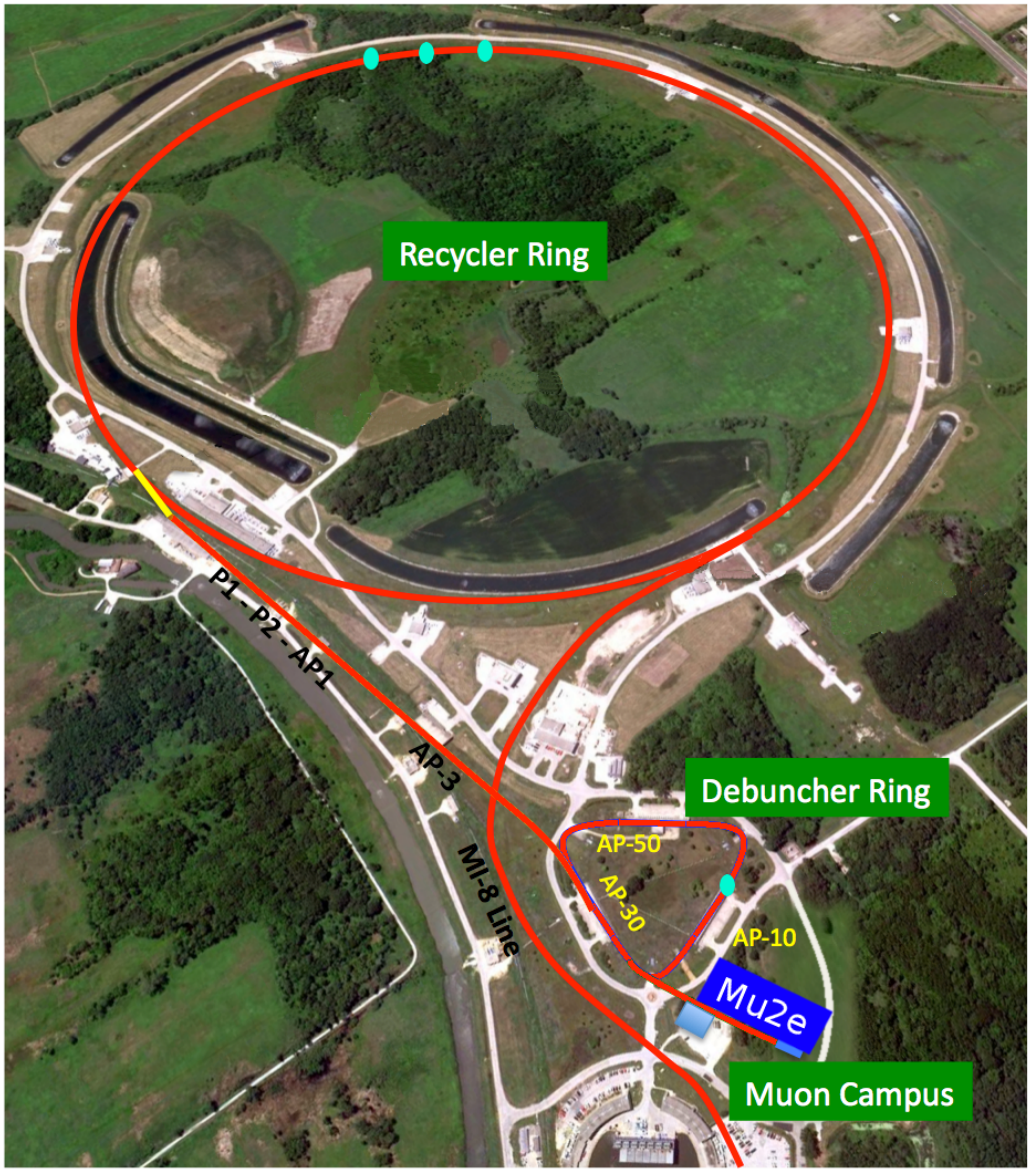

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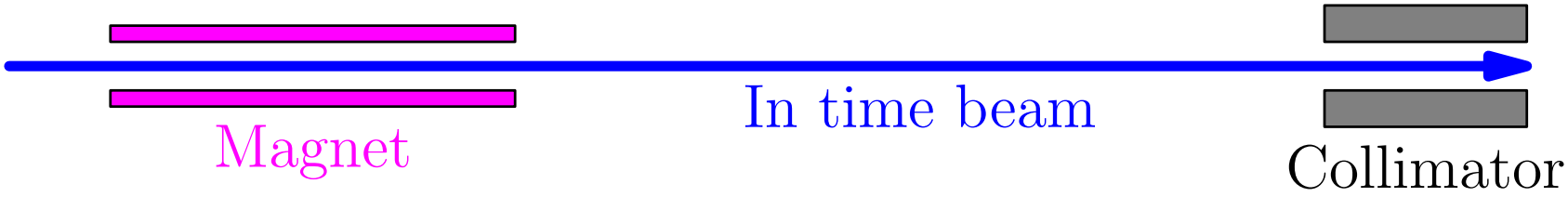
Achieving $\epsilon = 10^{-10}$: two stages

Delivery ring: $\epsilon < 10^{-4}$

- Circulate single bunch
- At injection $\epsilon \approx 10^{-5}$
- Degrades during slow extraction

Extraction beamline:

- Deflect late beam with extinction magnets



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Extraction beamline:

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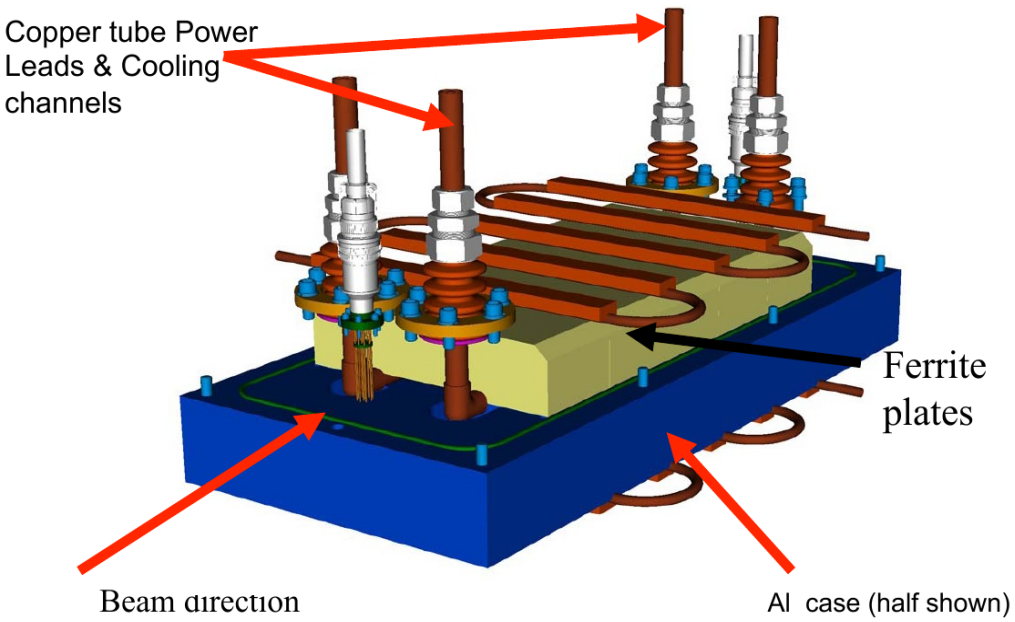
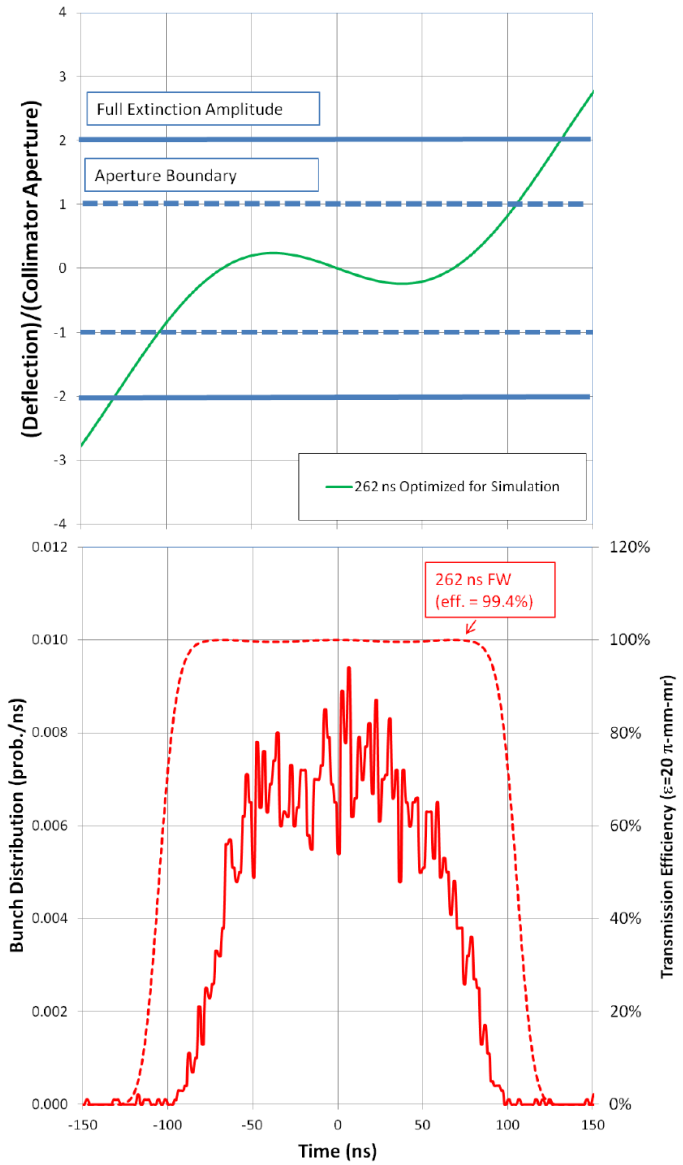
Bunches at 600 kHz:
beyond state of art for kickers

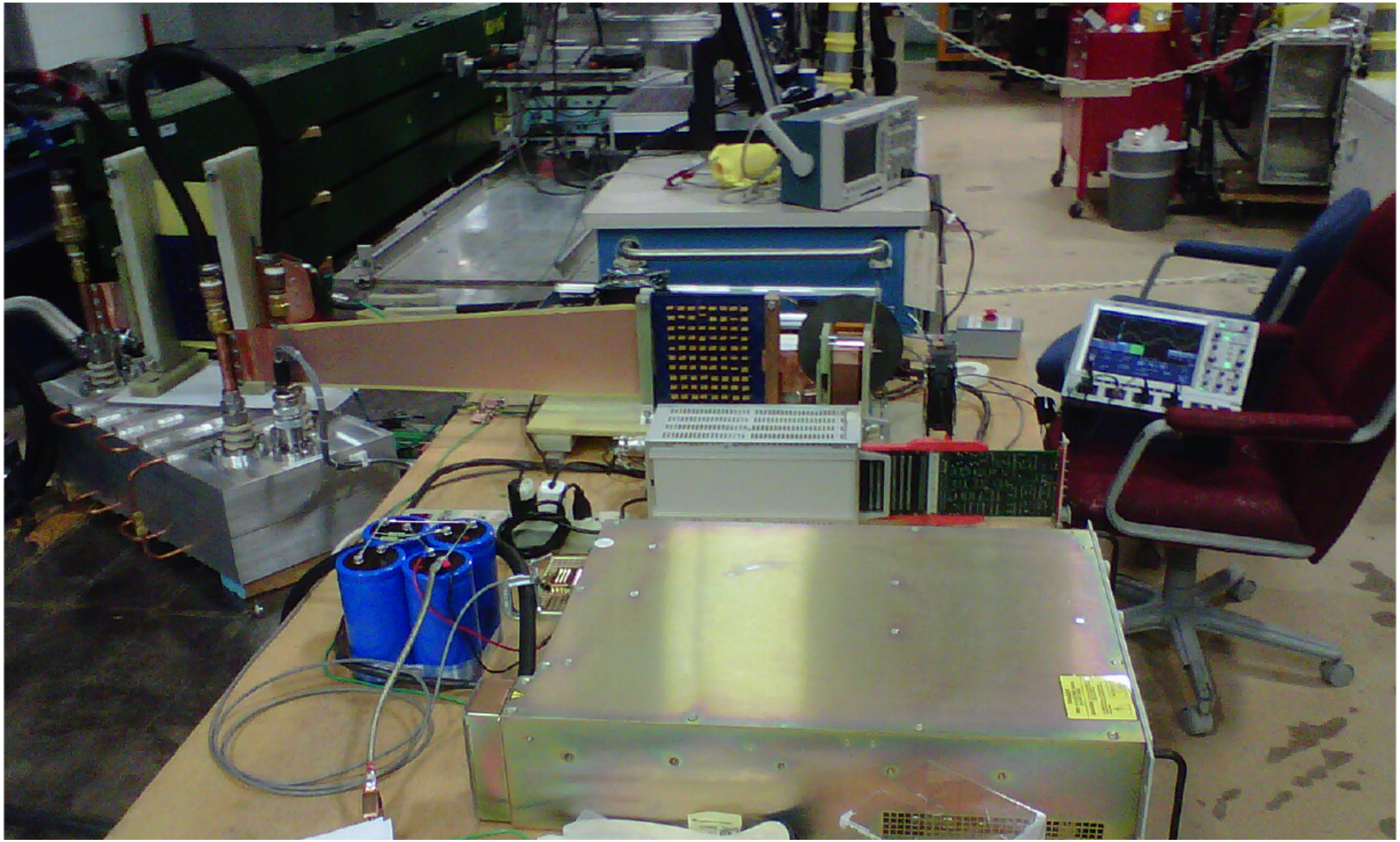
Achieving $\epsilon = 10^{-10}$: use resonant magnets

- Dipole magnets at 300 kHz and 5100 kHz (17th harmonic)
- Extra extinction factor 10^{-7}





Extinction magnets tested



How to monitor $\epsilon = 10^{-10}$

One could try

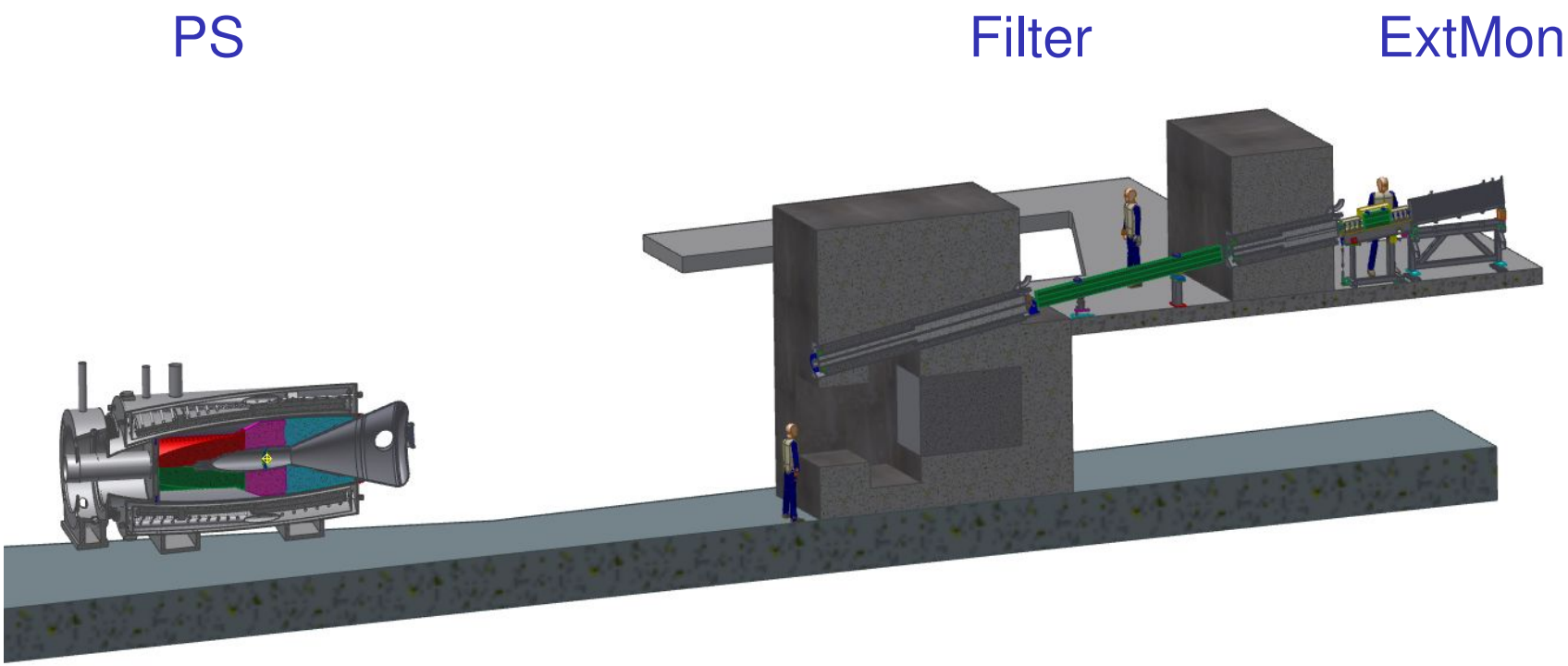
- Count 3×10^7 protons during ≈ 150 ns pulse
- Be sensitive to single proton for the rest of 1694 ns cycle
  - With background $\ll 10^{-3}$ counts/cycle

Mu2e approach: use statistical sampling instead

- Count $\mathcal{O}(30)$ secondary tracks/pulse
- Integrate over $\mathcal{O}(10^9)$ cycles ($\lesssim$ 1 hour)
  - Get 3 out of time secondary tracks/integration at $\epsilon = 10^{-10}$
- Need $\ll 1/\text{integration} = 10^{-9}/\text{cycle}$ backgrounds
  - While monitoring the high intensity proton beam!

Extinction monitor

- Select positive tracks of a few GeV/c originating in the proton target with collimators and a permanent magnet



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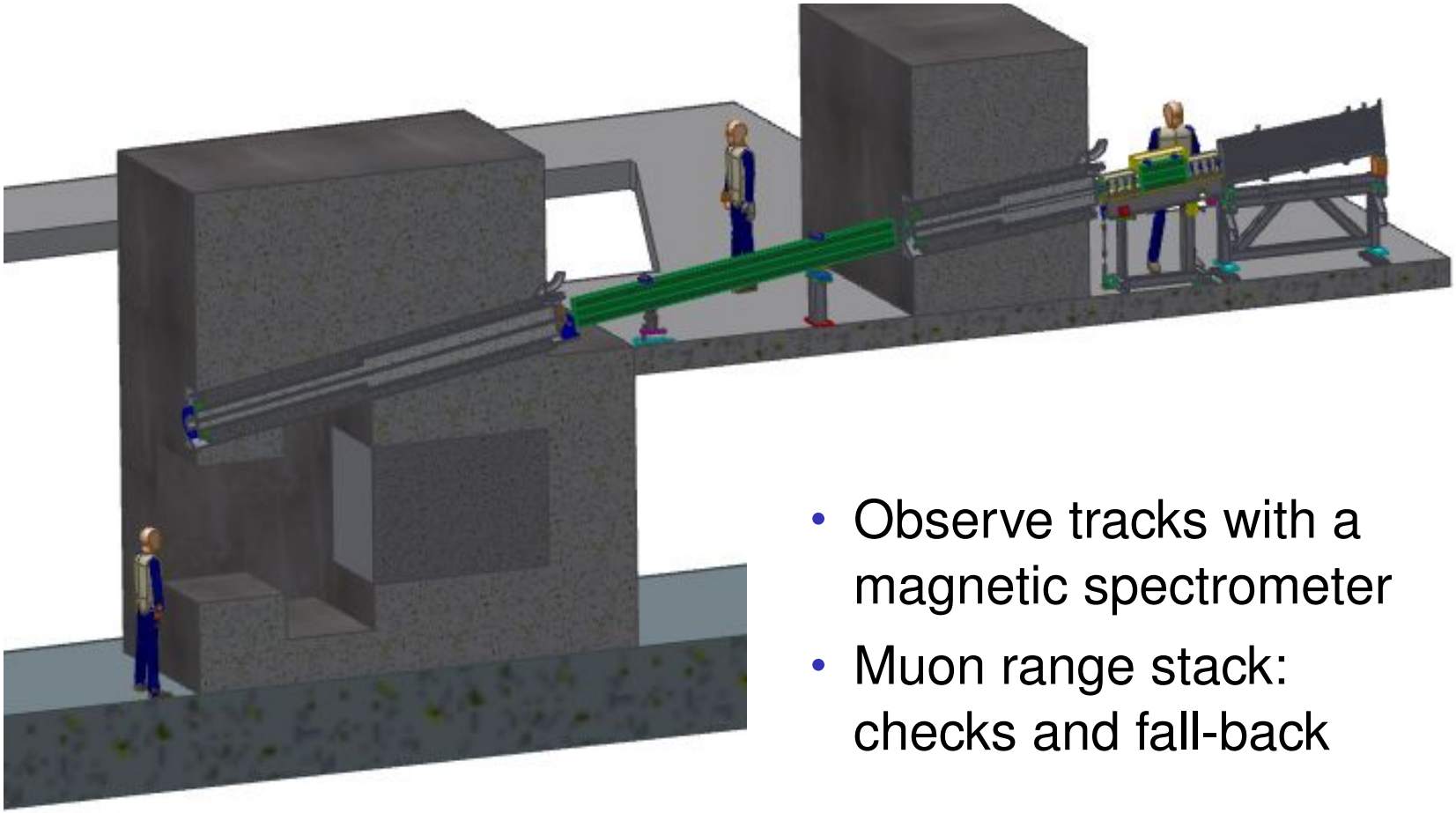


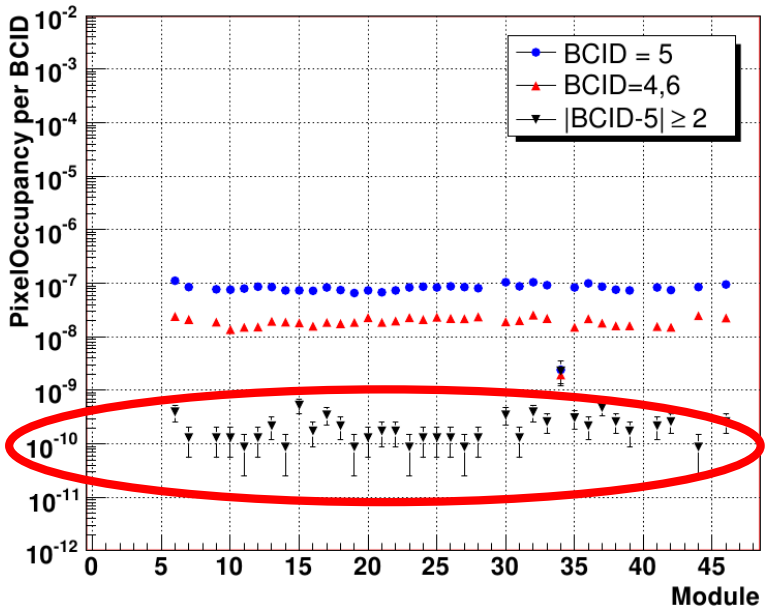
- Observe tracks with a magnetic spectrometer
- Muon range stack: checks and fall-back

ExtMon detector technology

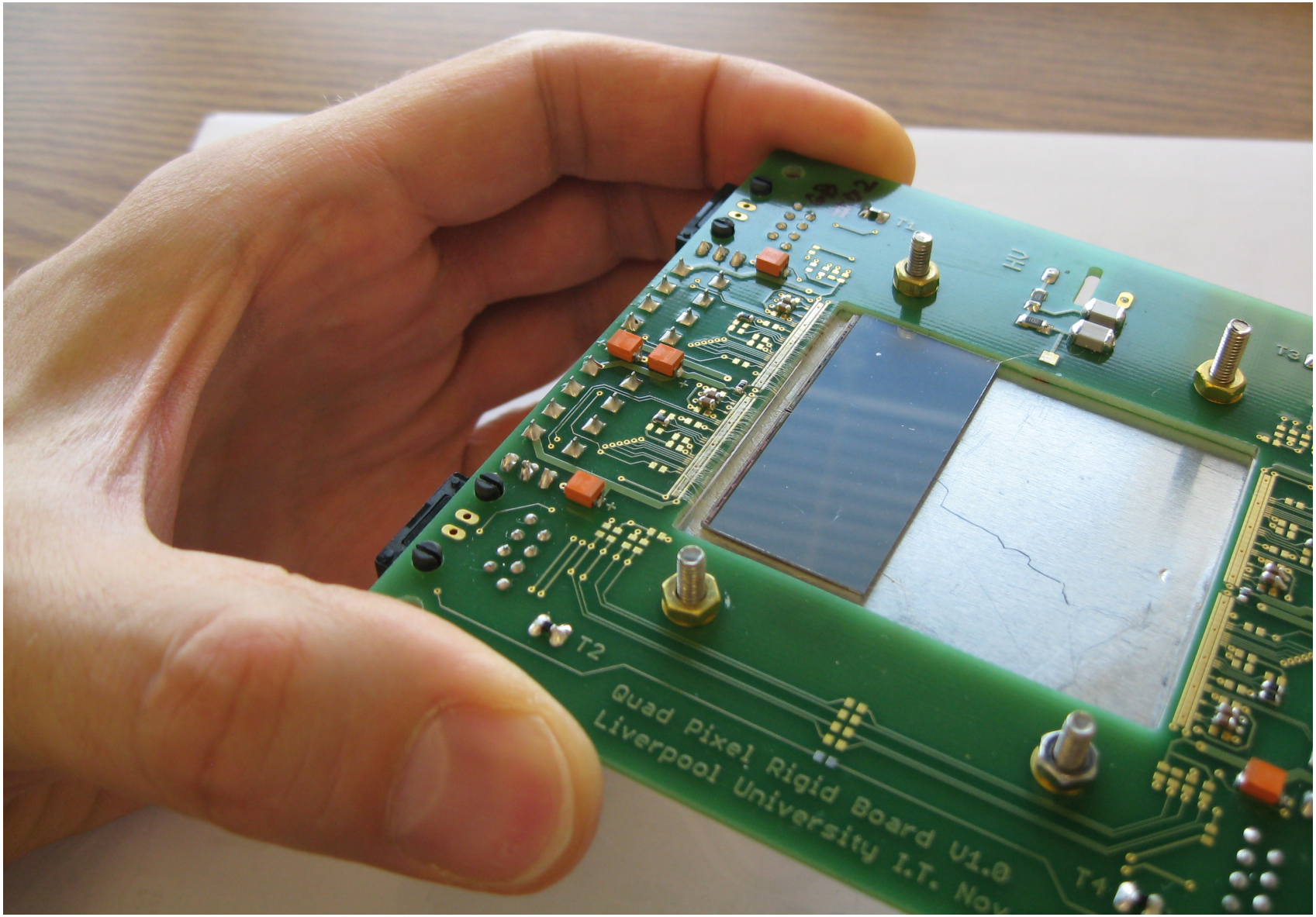
Silicon pixels

- demonstrated noise level 10^{-10} hit/pixel/25 ns
- Radiation hard
- Fine granularity helps to fight backgrounds
- FE-I4 ATLAS IBL upgrade chip is a good match

ATLAS-INDET-PUB-2008-003

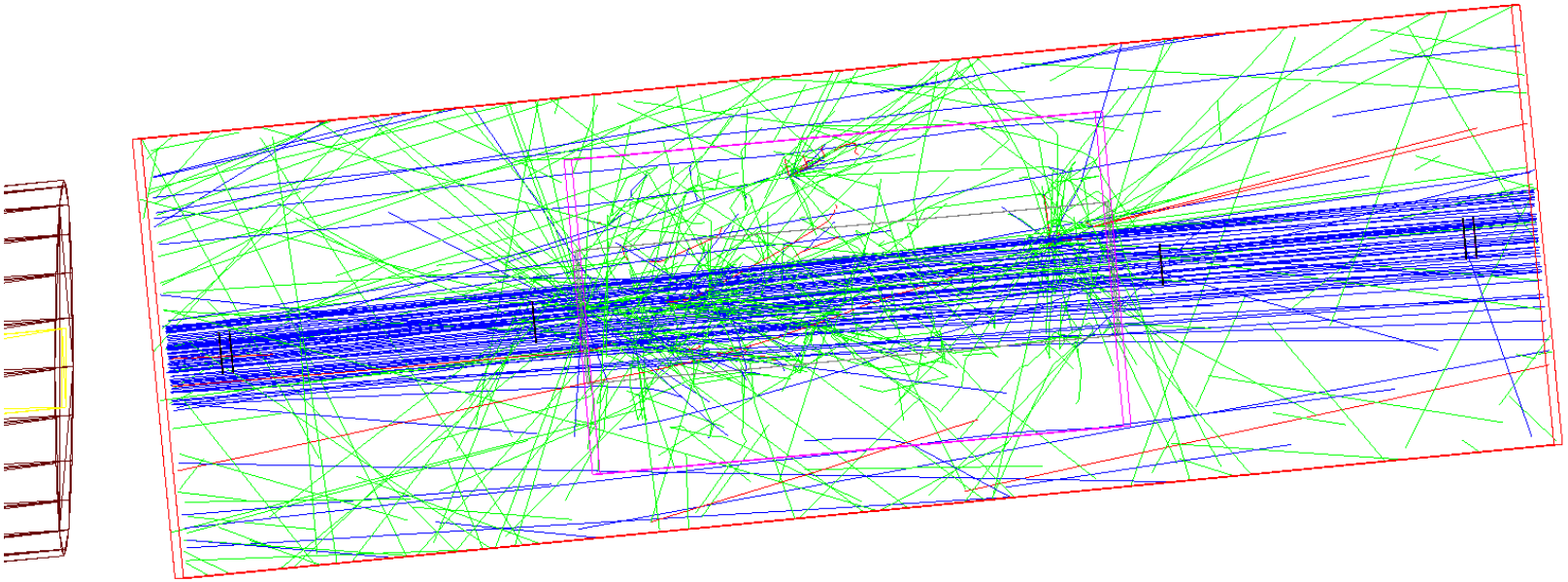


Pixel test module

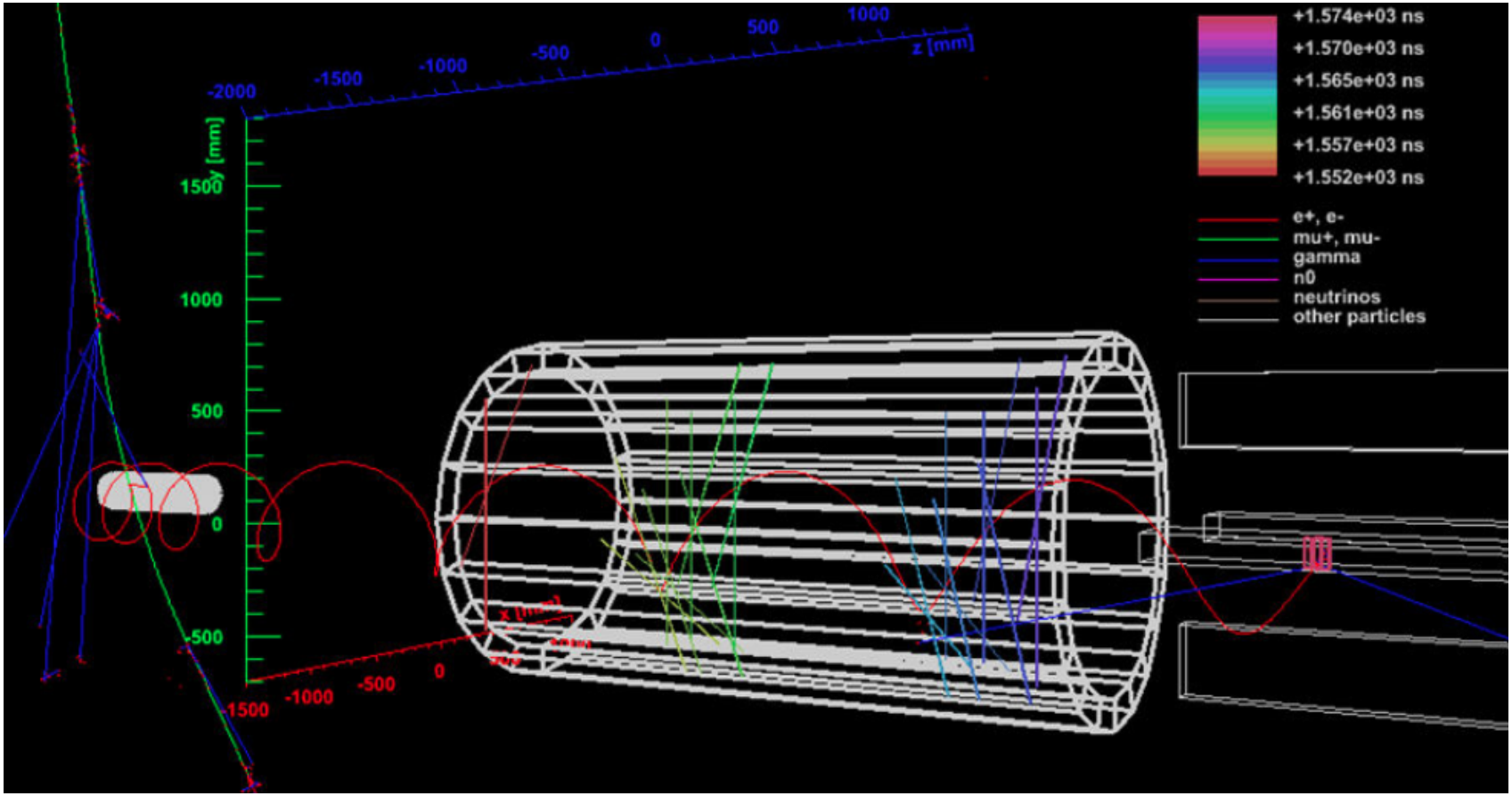


One microbunch in ExtMon spectrometer

- Simulated tracks from 30M primary protons

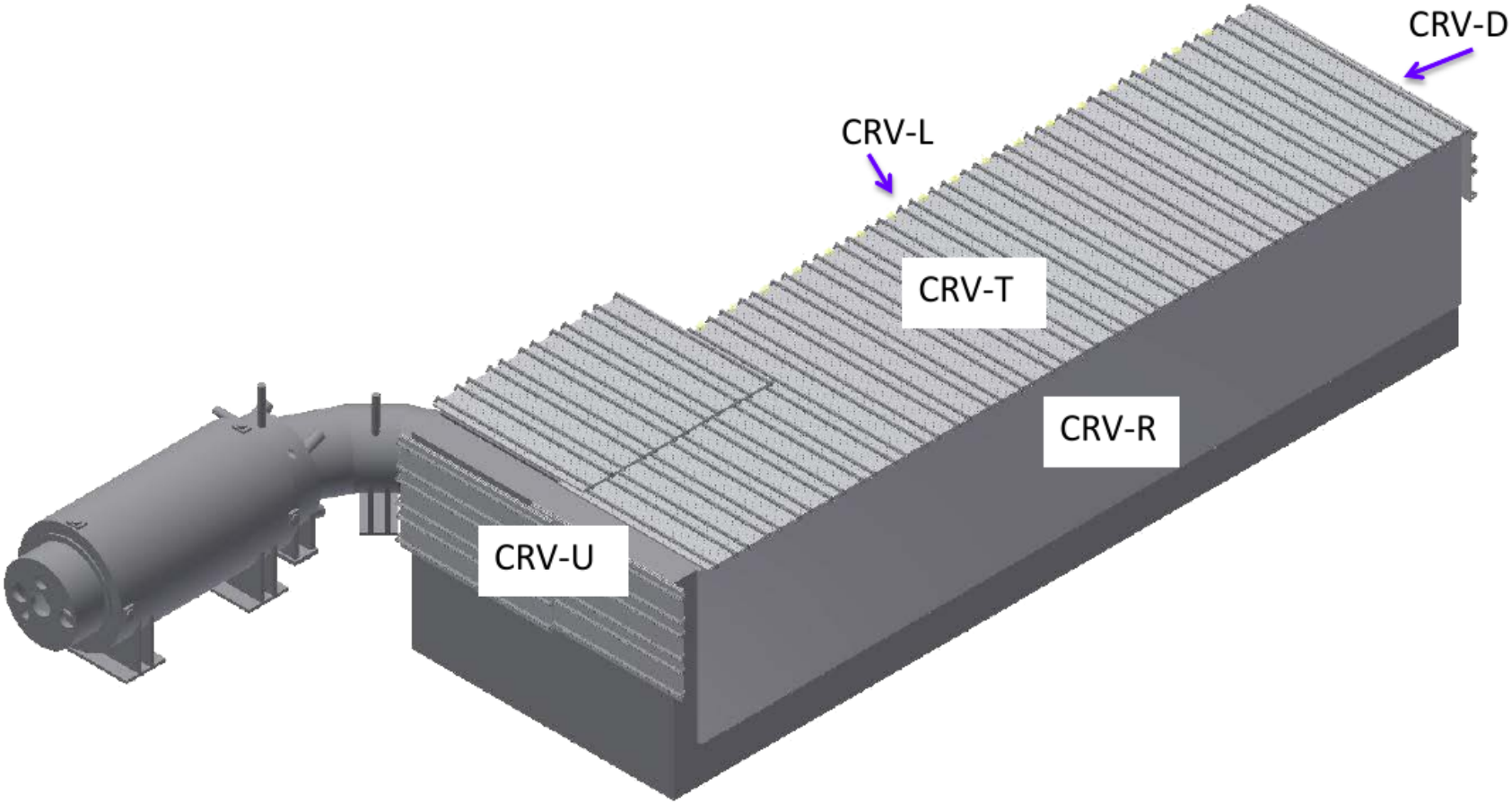


For 10^{-17} need to reject cosmic rays



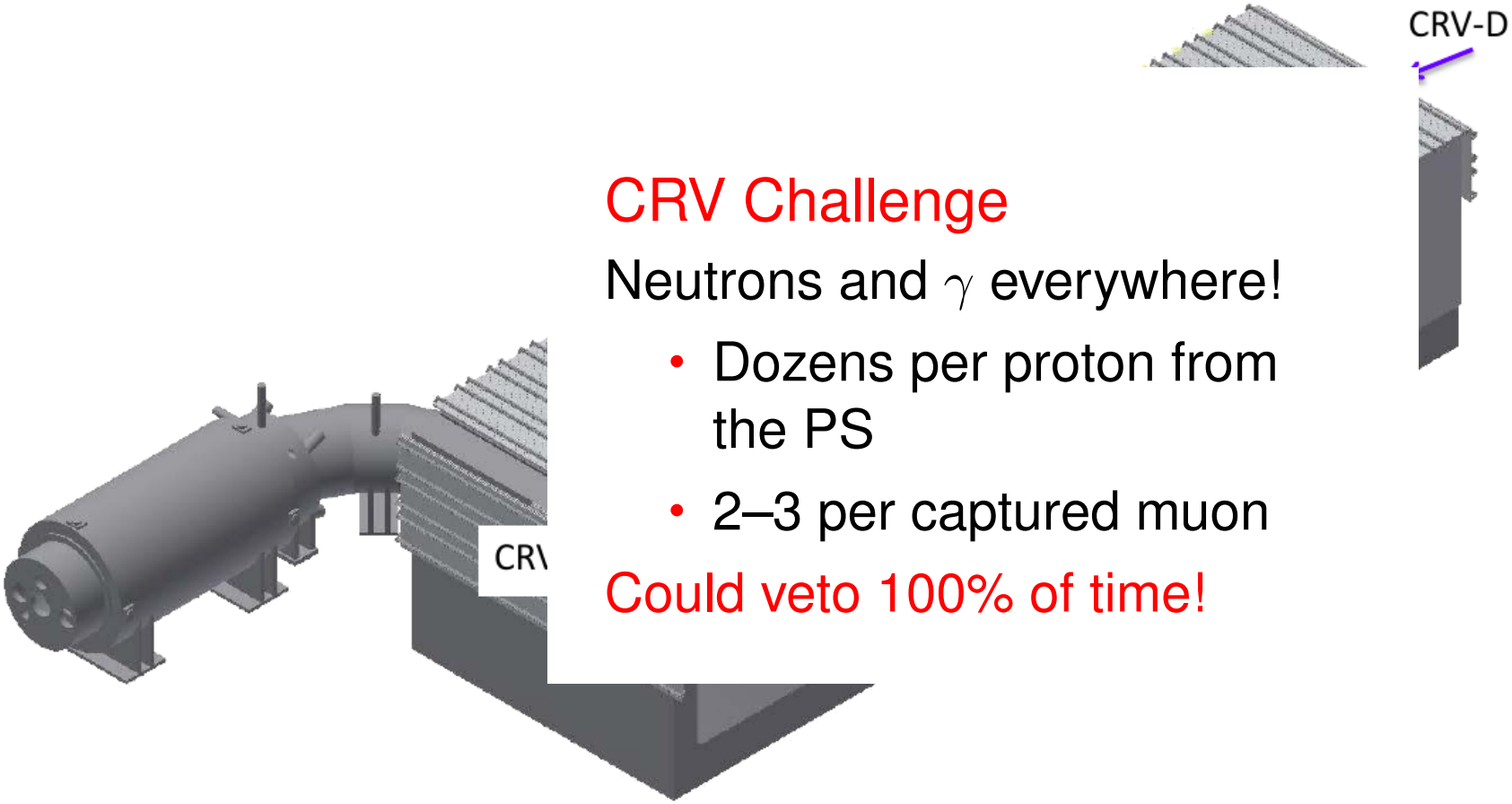
$\sim$ 1 event/day

Cosmic ray veto



- Surround detector with scintillator counters
- Require 99.99% veto efficiency

Cosmic ray veto



CRV Challenge

Neutrons and γ everywhere!

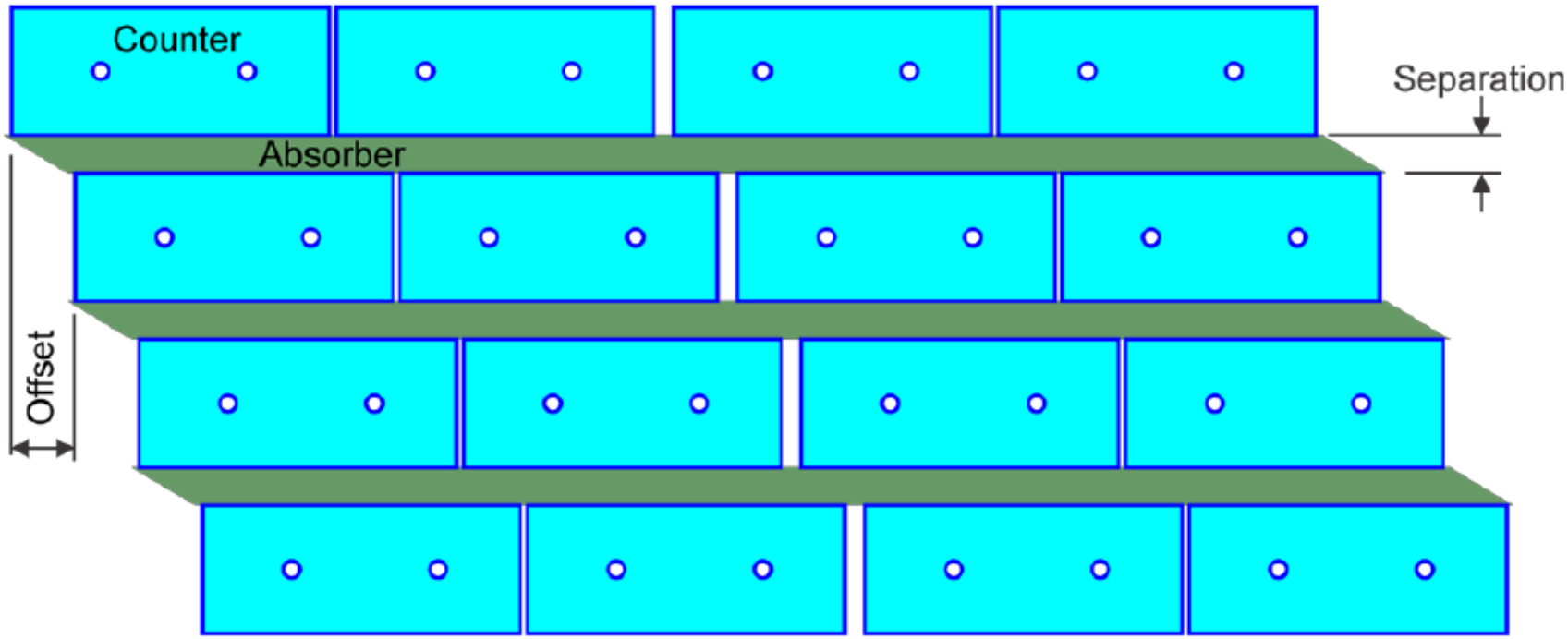
- Dozens per proton from the PS
- 2–3 per captured muon

Could veto 100% of time!

- Surround detector with scintillator counters
- Require 99.99% veto efficiency

CRV mitigation

- Shielding. Lots of it.
- 4 layers, require 3-layer coincidence
- Absorber between layers: reduce correlated hits



Antiprotons

A source of background

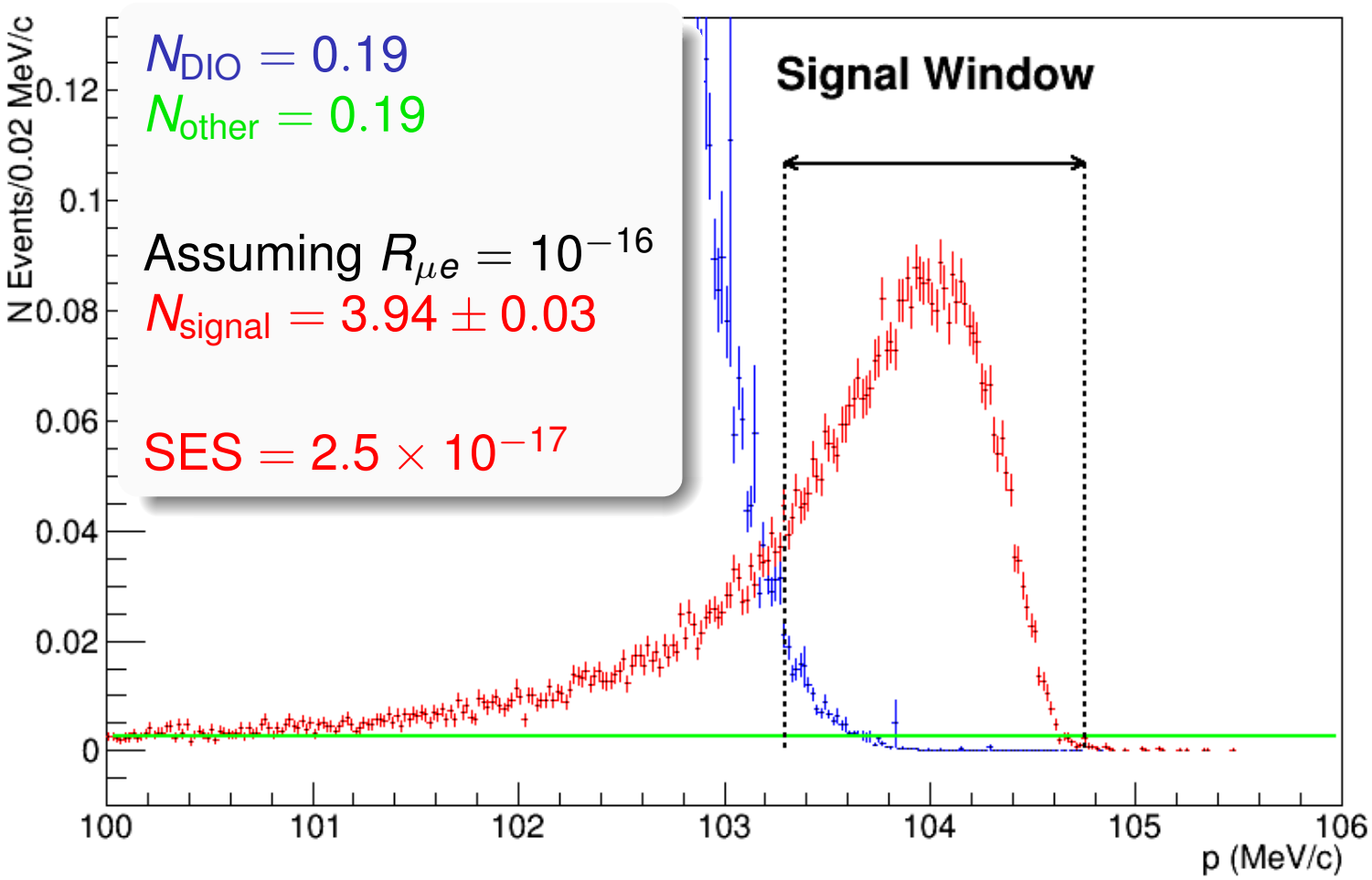
- Negative—go through muon beamline
- Do not decay
- Heavy $\Longrightarrow$ slow
  - Arrive during signal window even for perfect beam extinction
  - 2 GeV shower

Mitigation

- Thin window in the central collimator
- Reduces muon yield
- But effectively annihilates $\bar{p}$

Avoidable: would be nice to have lower energy p beam!

3 year run: 5.8×10^{17} stopped μ^-



Full G4 & reconstruction without truth inputs

$R_{\mu e} = 10^{-16}$: 4 signal events over 0.4 background

Summary of backgrounds

3 years of 1.2×10^{20} protons/year (8 kW beam power)

Background description	Expected events
Muon decay in orbit	0.20 ± 0.06
Antiproton induced	0.10 ± 0.06
Radiative pion capture*	0.04 ± 0.02
Cosmic rays**	0.050 ± 0.013
Beam electrons*	0.001 ± 0.001
Muon decay in flight*	0.010 ± 0.005
Total	0.4 ± 0.1

* Assuming 10^{-10} beam extinction
** For 10^{-4} cosmic ray veto inefficiency

Summary of backgrounds

Another challenge: simulations...

3 years of 1.2×10^{20} protons/year (8 kW beam power)

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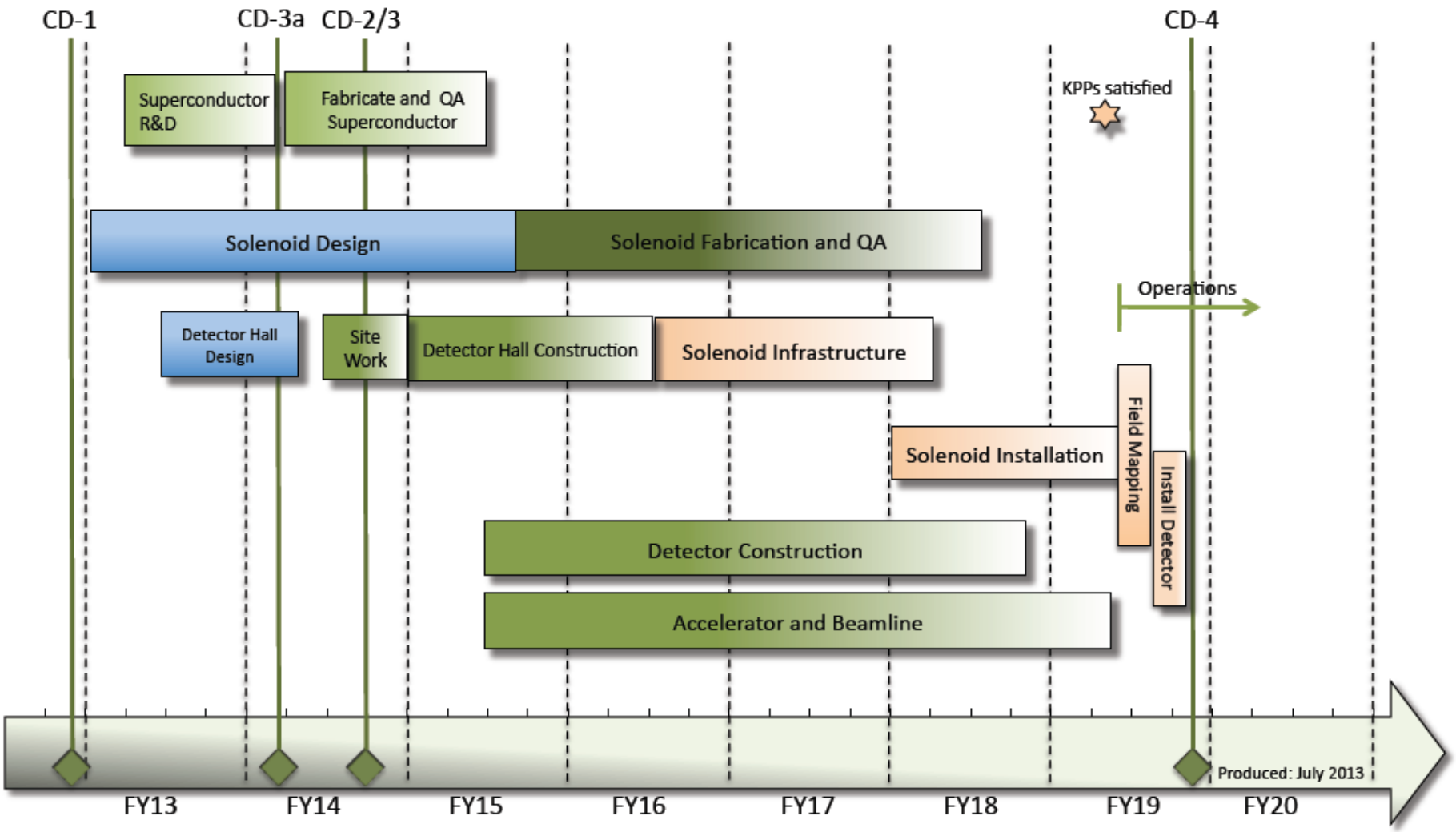
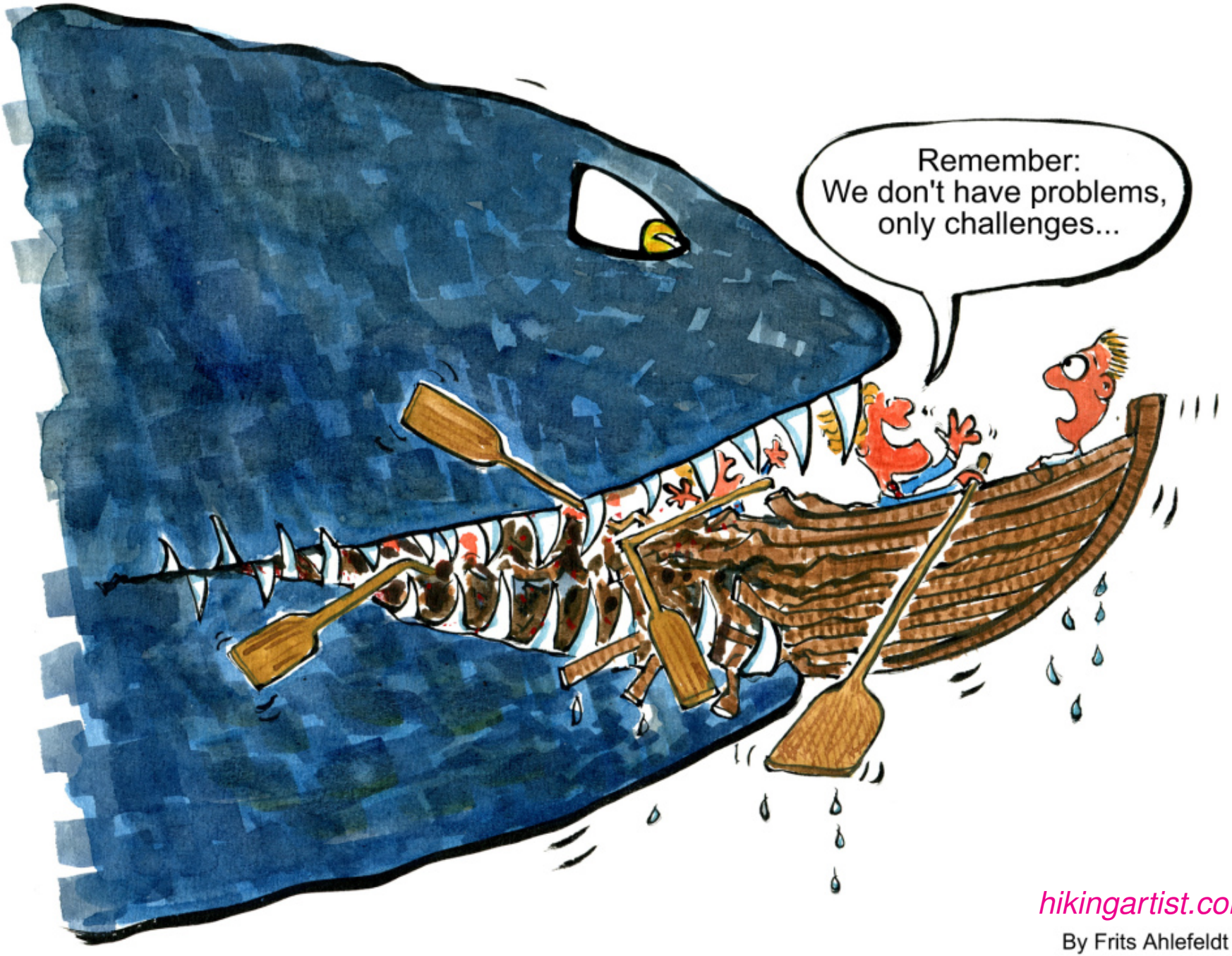
Schedule


CD-1
CD-3a
CD-2/3
CD-4
Superconductor R&D
Fabricate and QA Superconductor
KPPs satisfied
Solenoid Design
Solenoid Fabrication and QA
Operations
Detector Hall Design
Site Work
Detector Hall Construction
Solenoid Infrastructure
Field Mapping
Solenoid Installation
Install Detector
Detector Construction
Accelerator and Beamline
Produced: July 2013
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20

Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aims for 4 orders of magnitude improvement on $R_{\mu e}$ $\Longrightarrow$ $\times$ 10 mass scale reach!
- Conceptual design complete Mu2e CDR arXiv:1211.7019 (DOE CD-1 in July 2012)
- Working towards technical design
- Data taking: about 2019
- Opportunities for new people to join!

`http://mu2e.fnal.gov`



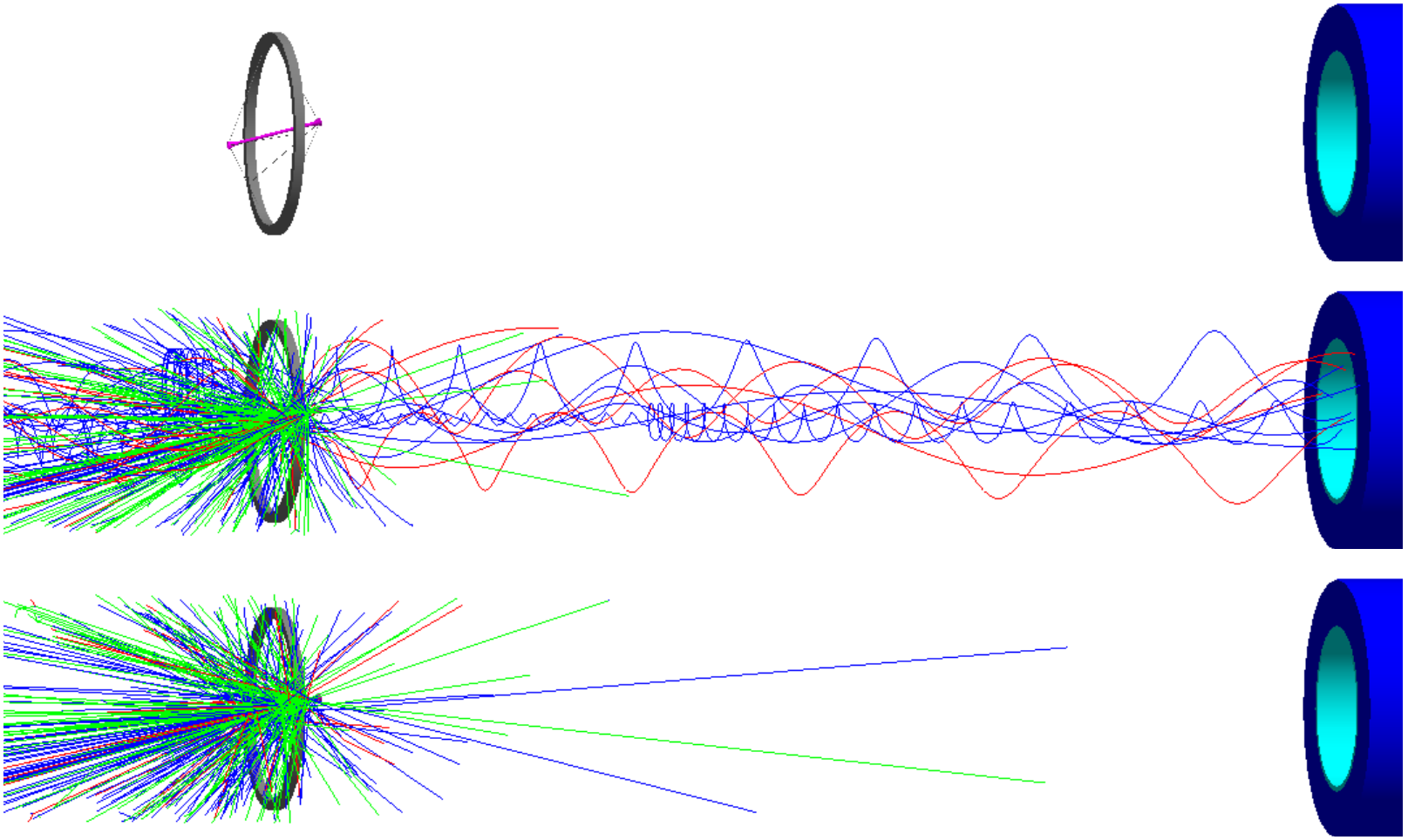
hikingartist.com

By Frits Ahlefeldt

We'll handle our challenges!

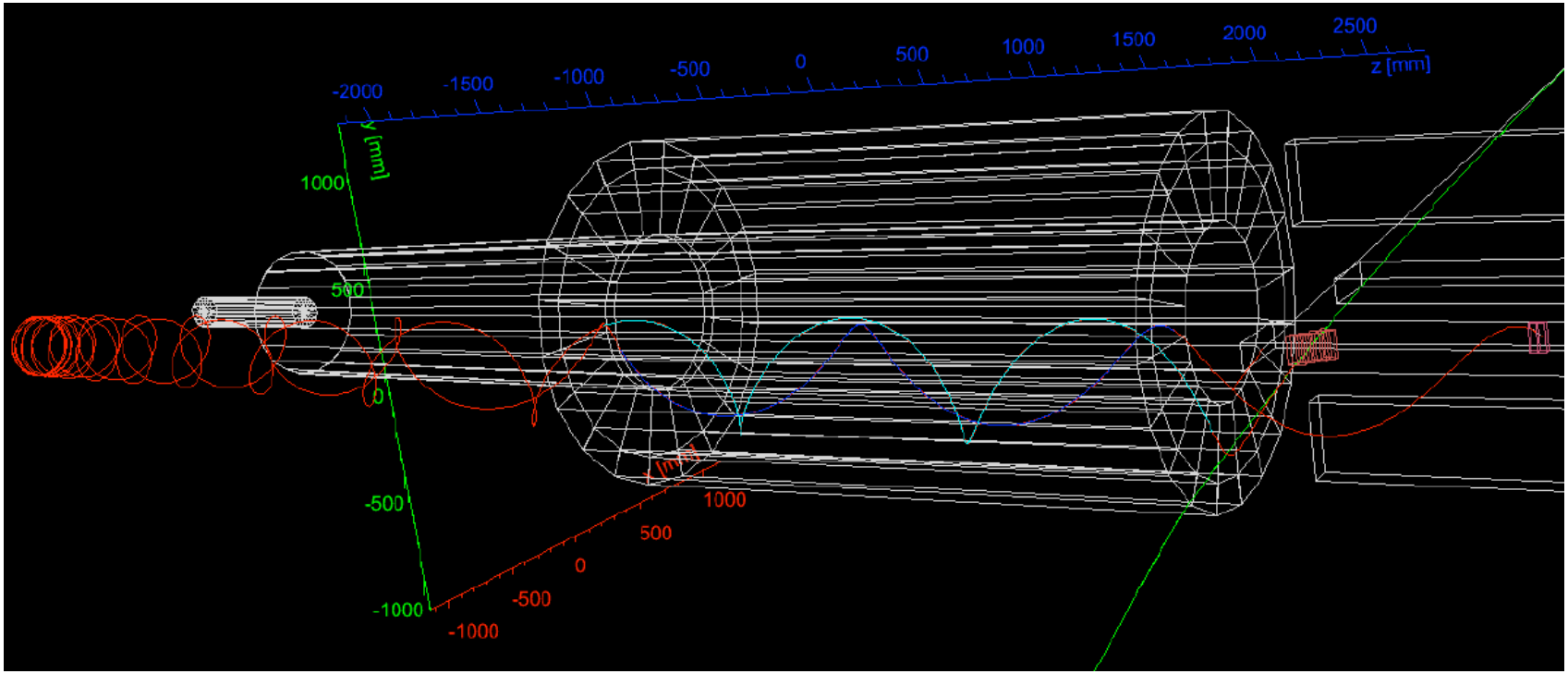
Extra slides

Muon collection

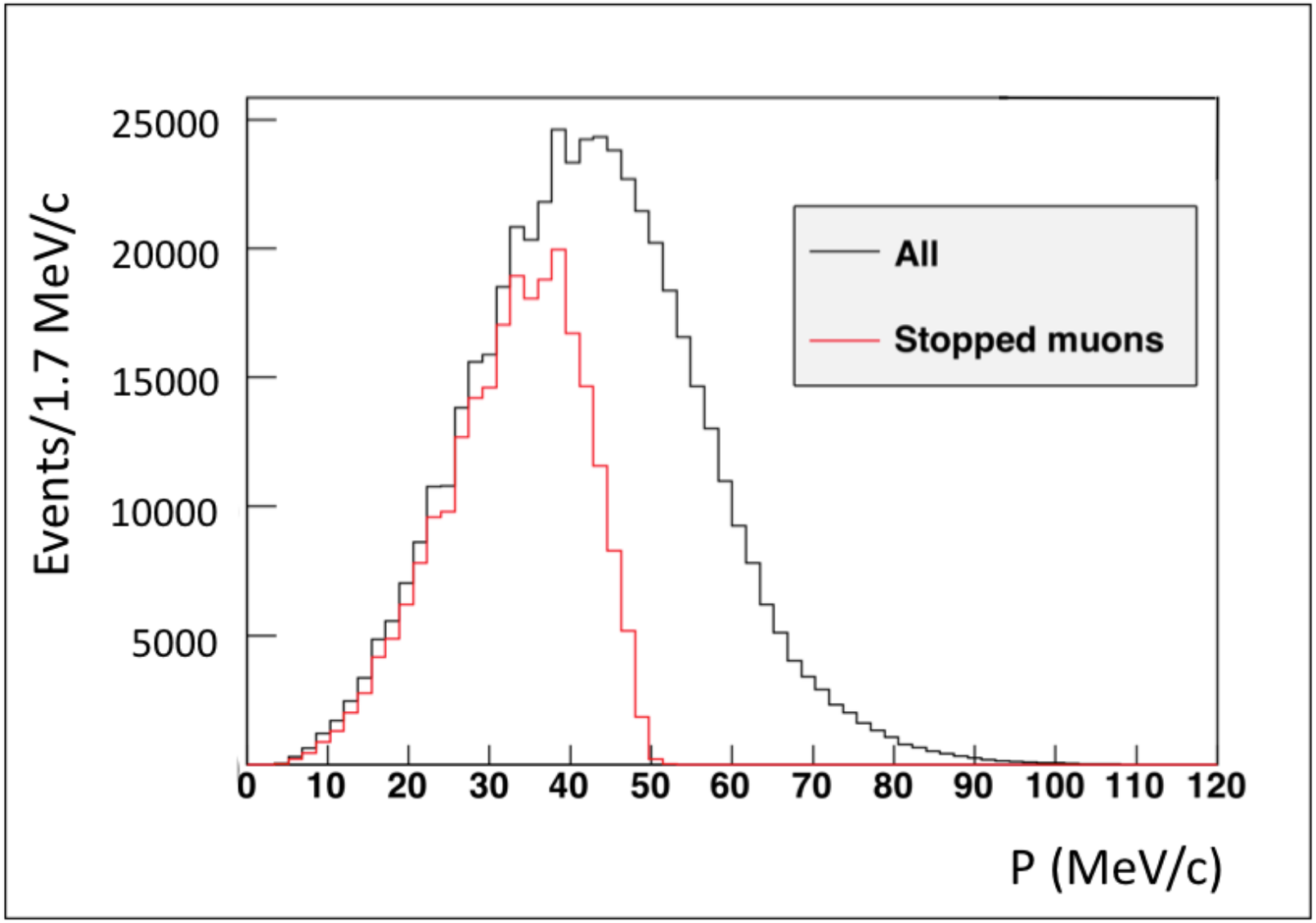


Tracker energy loss calibration

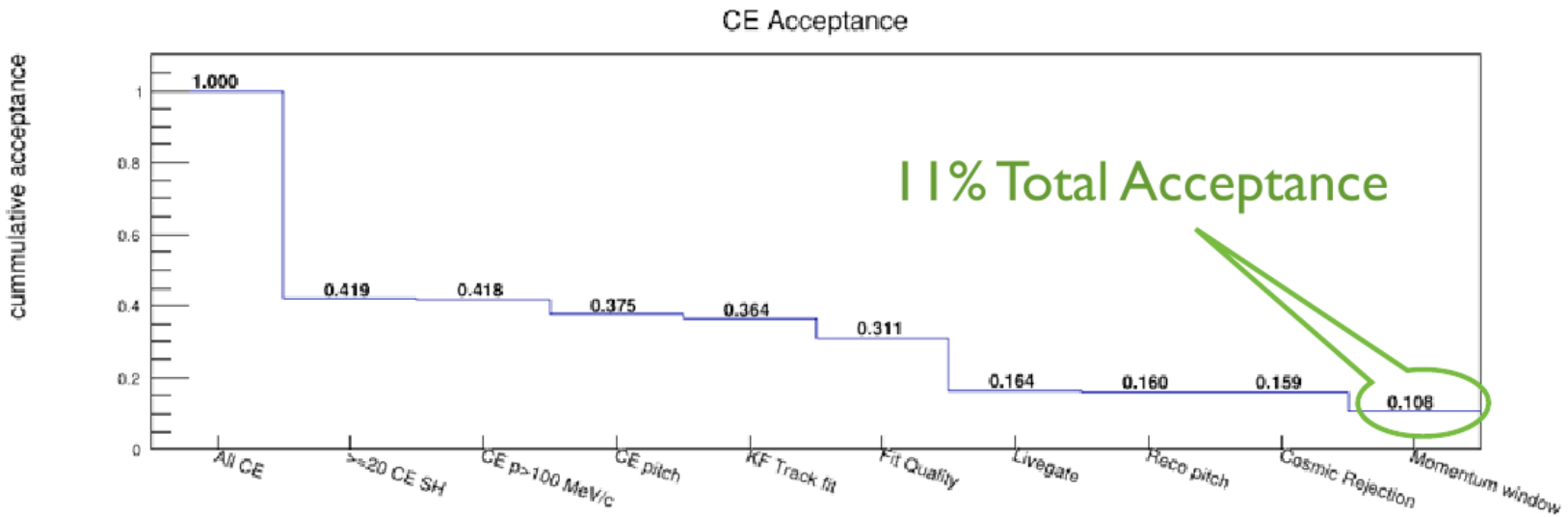
Double-pass of cosmic produced electrons [Dave Brown]

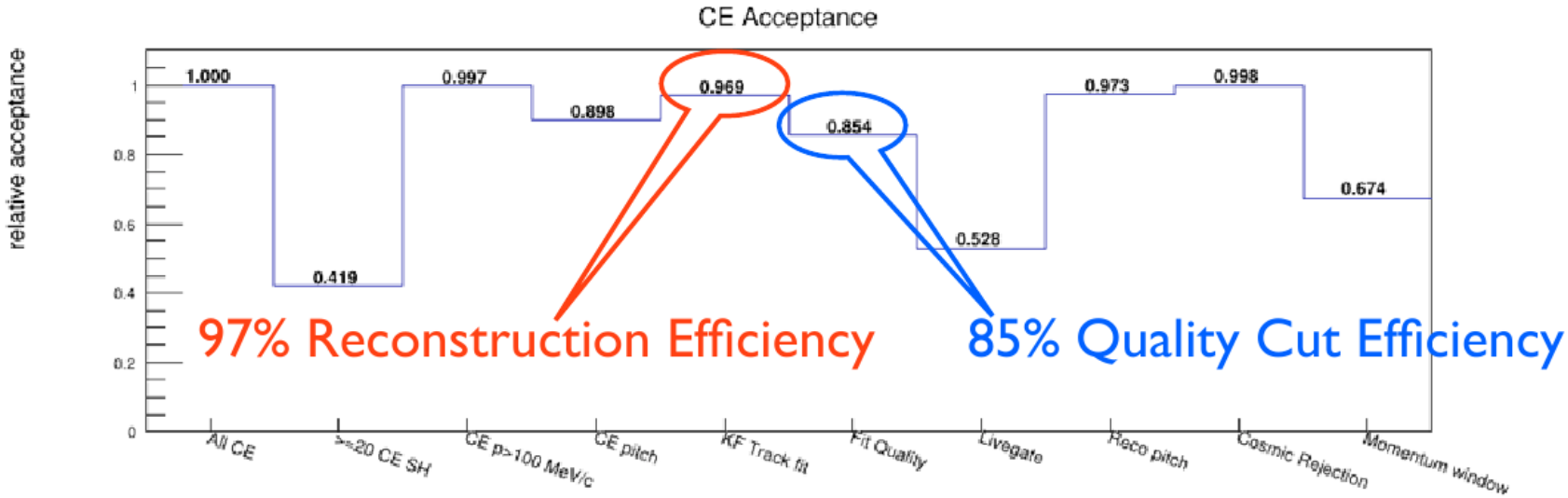


Muon momentum at the stopping target



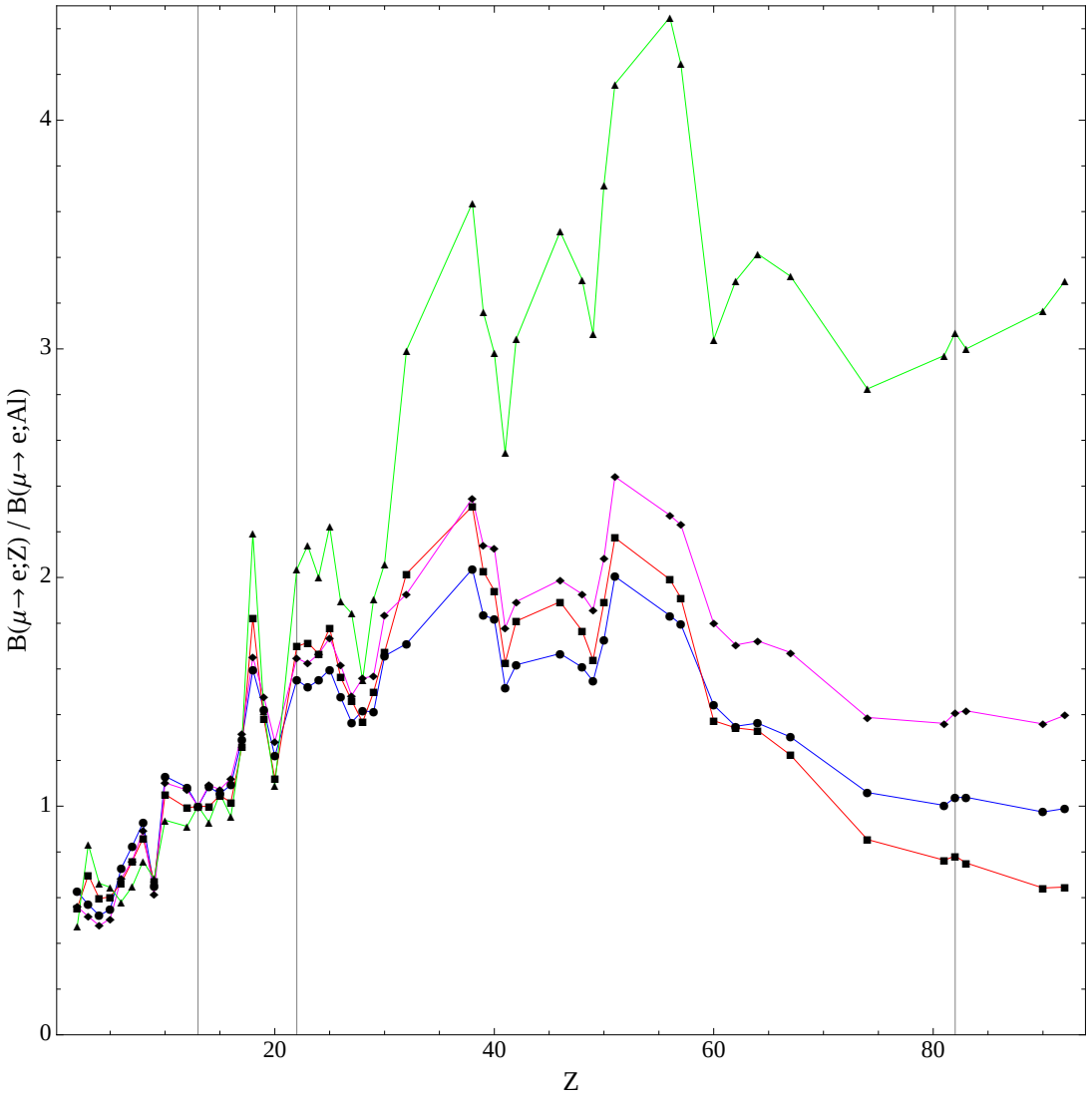
Signal reconstruction efficiency

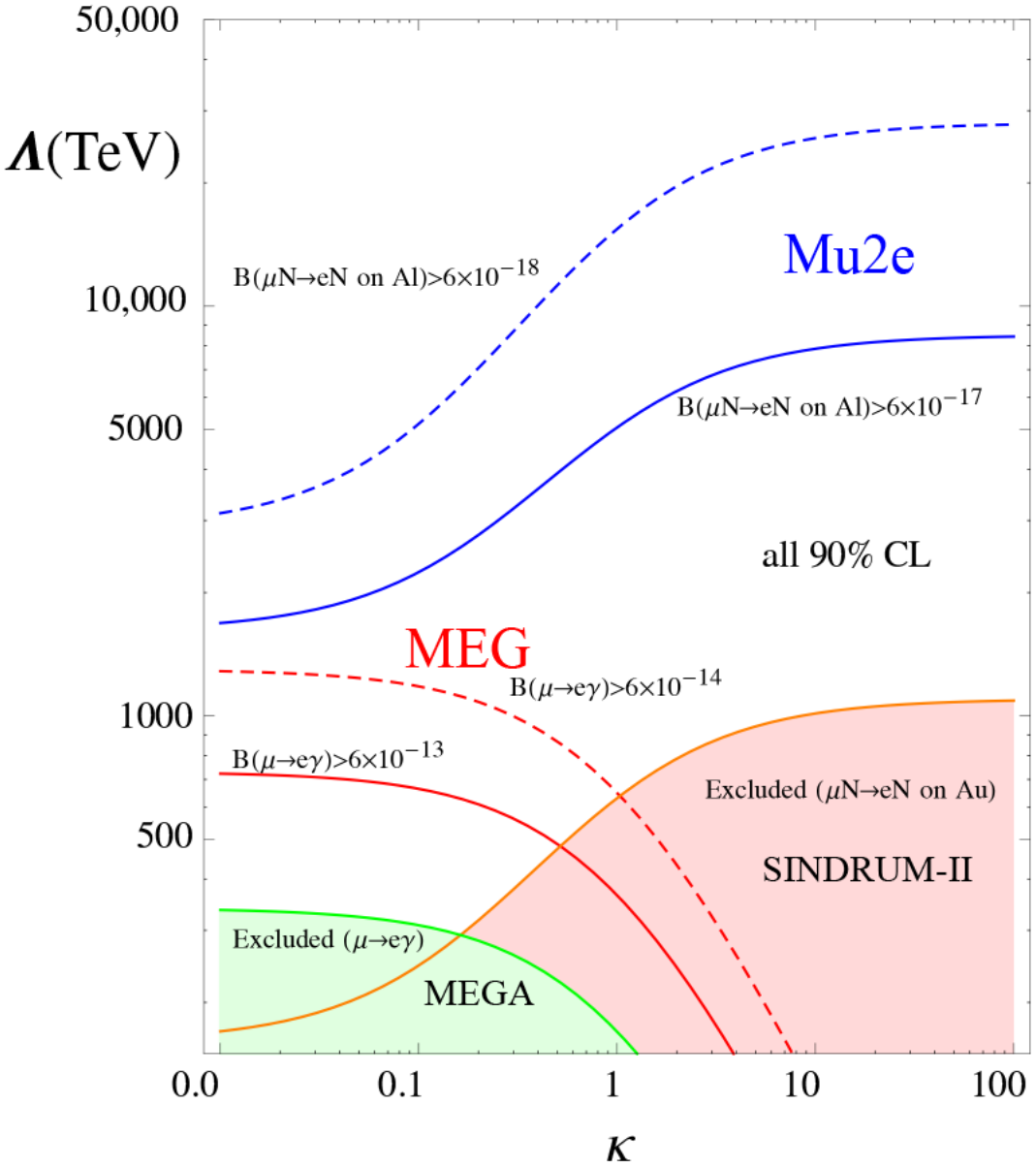




Dave Brown, CLFV2013 (Lecce)

Target Z dependence



V. Cirigliano et al., Phys. Rev. D **80**, *013002 (2009)*

Bob Bernstein's version of Λ vs κ