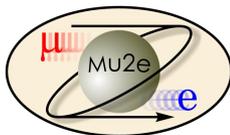


# The Mu2e Experiment

## A search for charged lepton flavor violation at FNAL

For the Mu2e Collaboration  
Kevin Lynch  
Boston University  
2010 Fermilab Users' Meeting  
June 2-3, 2010

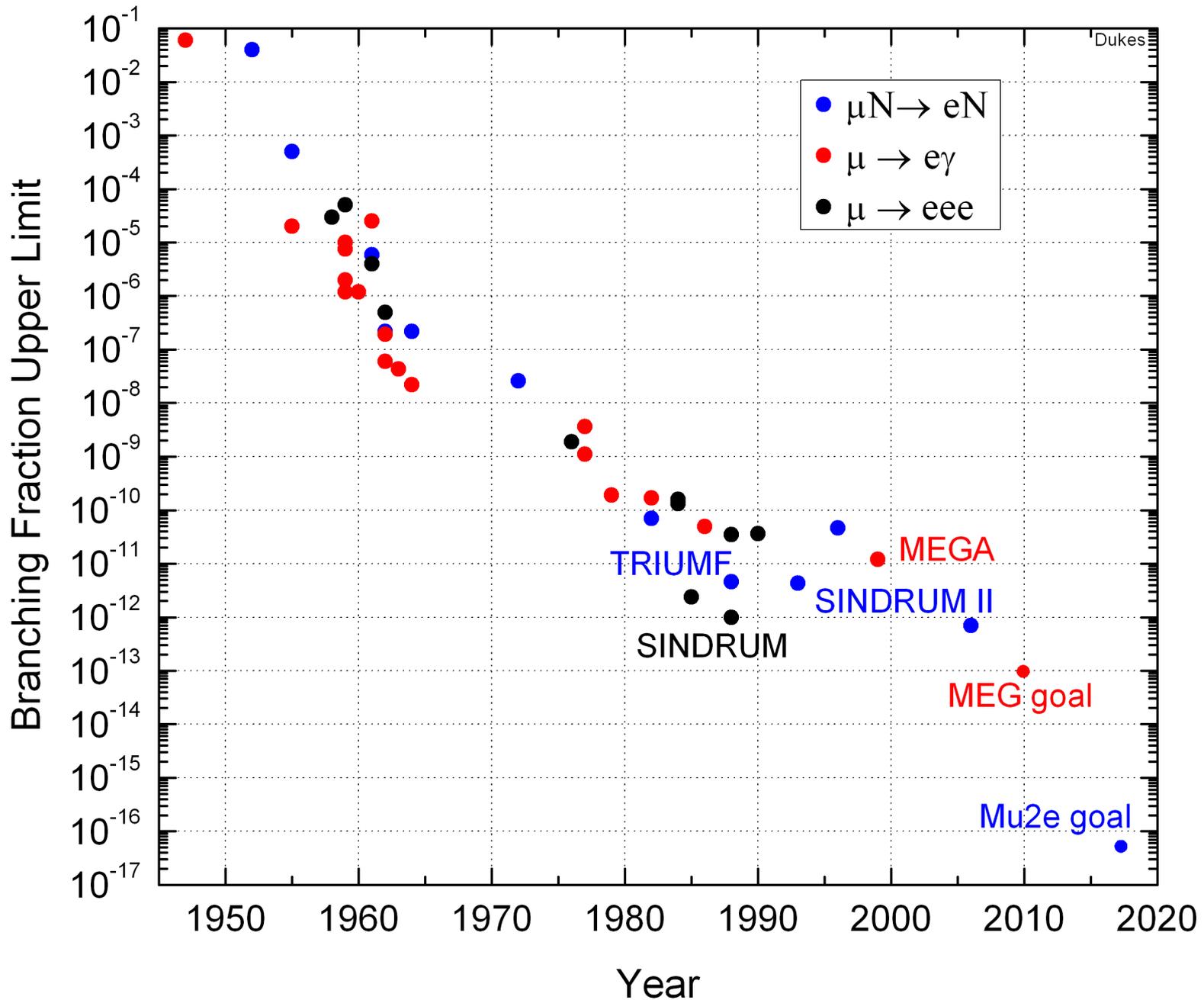


# The roadmap for this talk...

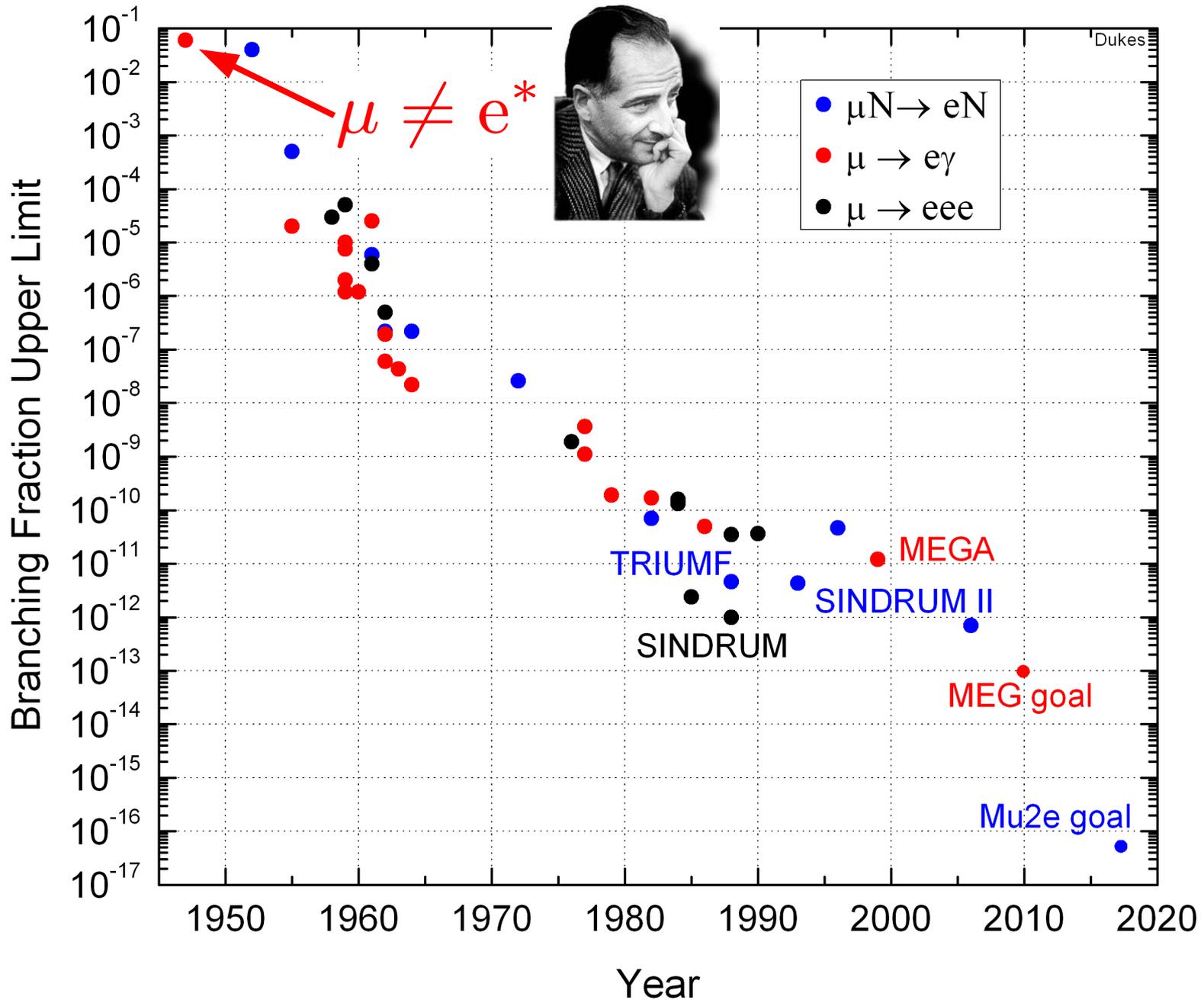
- Lepton Flavor Violation
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The mystery of lepton flavor has been with us for many decades

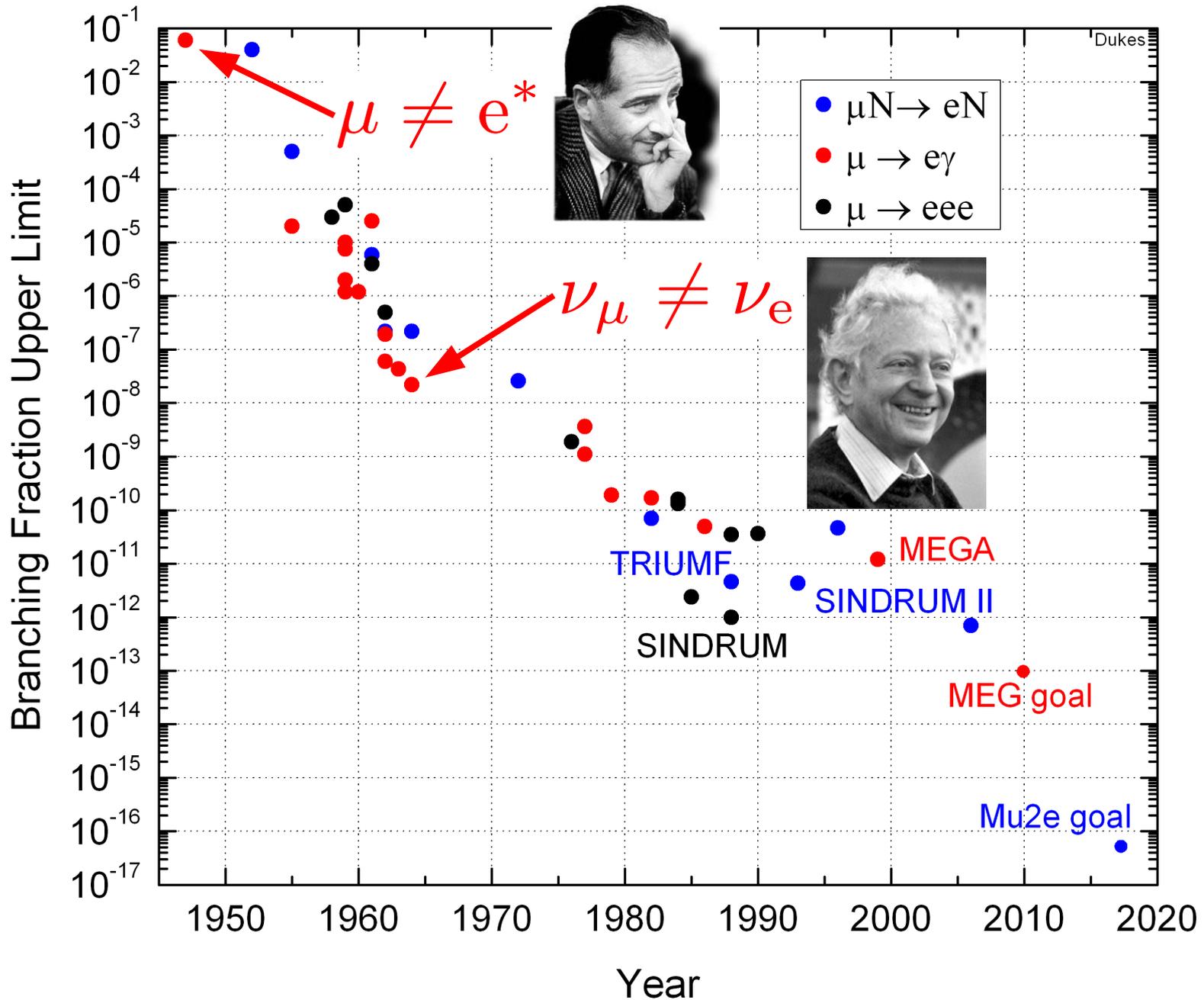
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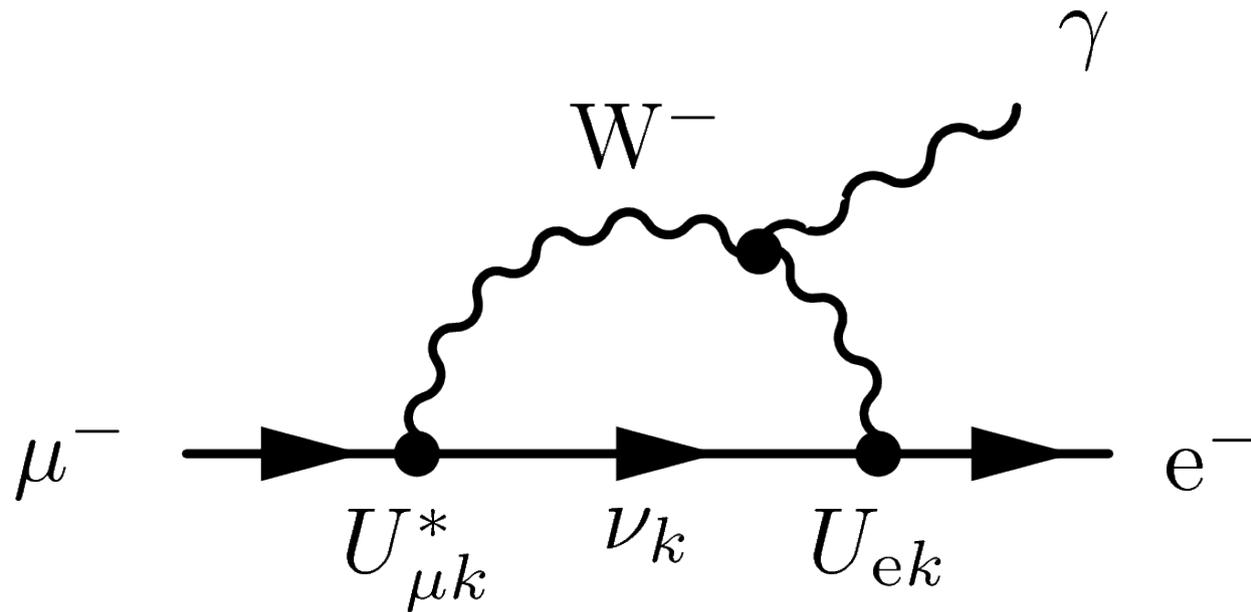
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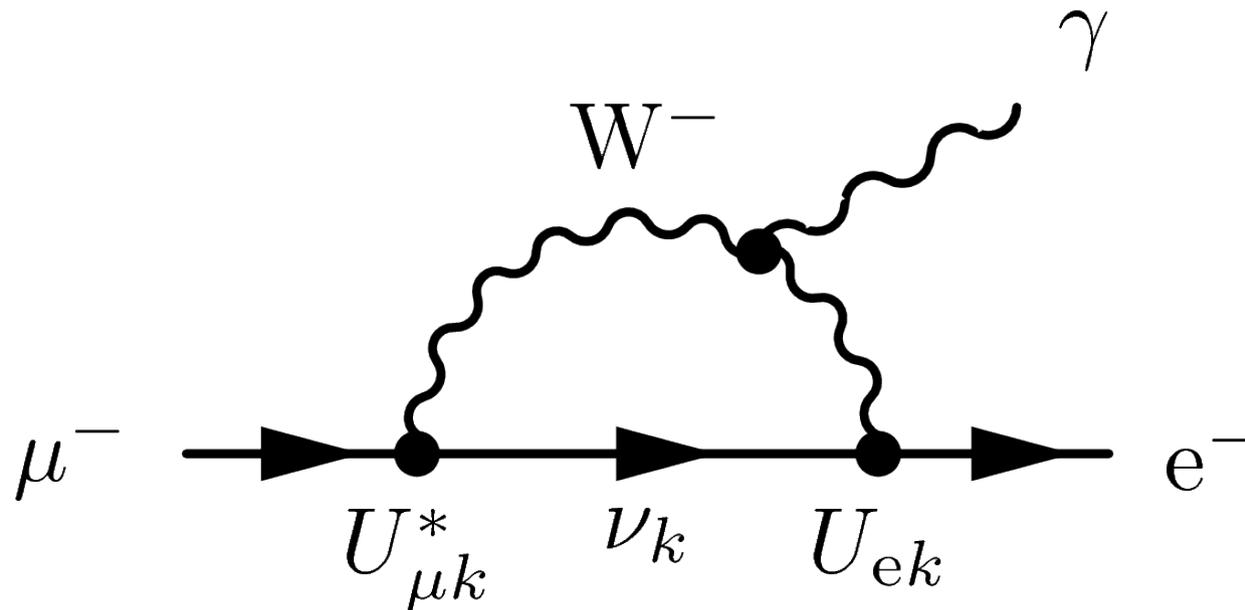
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However, the predicted SM rates are unobservably small:

$$\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U_{\mu k}^* U_{ek} \frac{\Delta m_{1k}^2}{M_W^2} \right|^2 < 10^{-54}$$

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MEG at PSI

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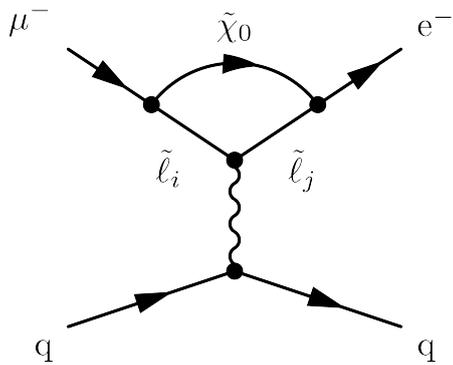
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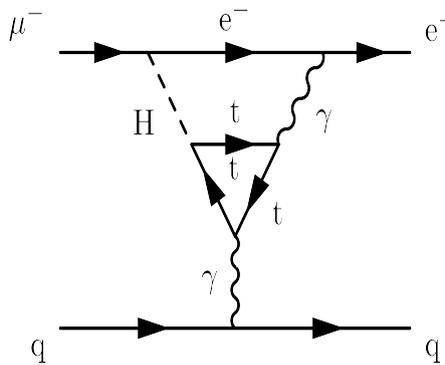
COMET/PRISM at JPARC  
Mu2e at FNAL

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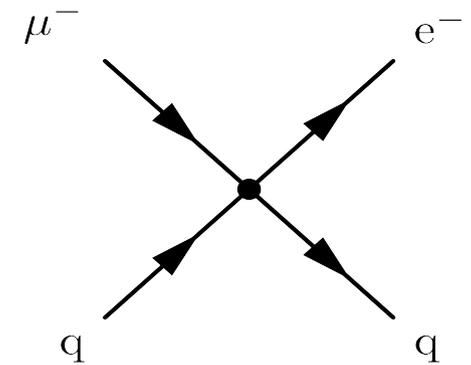
# Muon conversion arises in many new physics scenarios



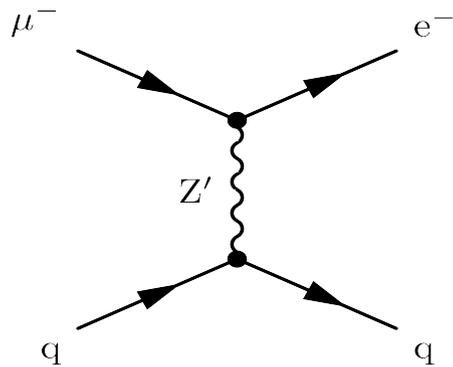
SUSY



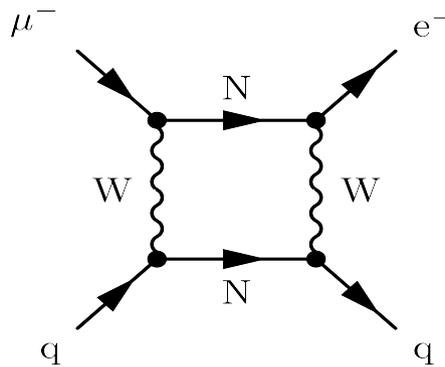
Second Higgs Doublet



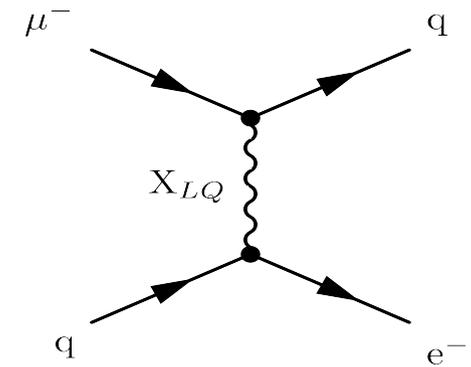
Compositeness



Heavy Gauge Bosons

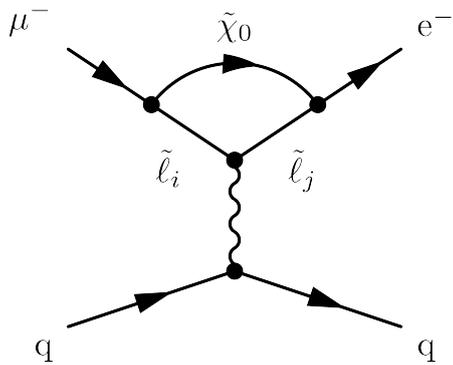


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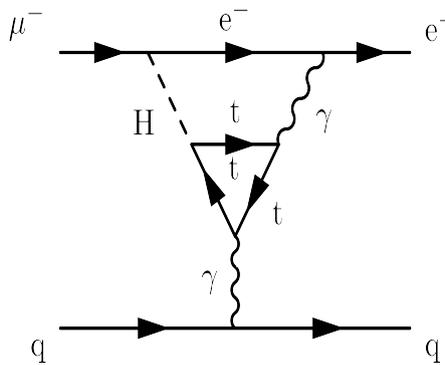


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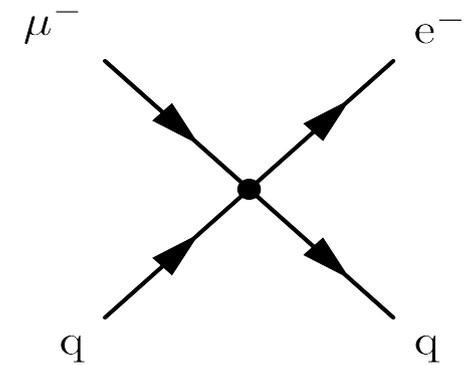
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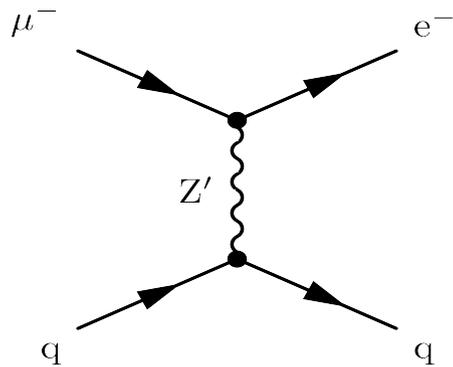
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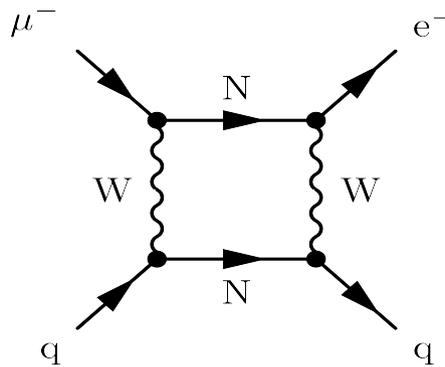
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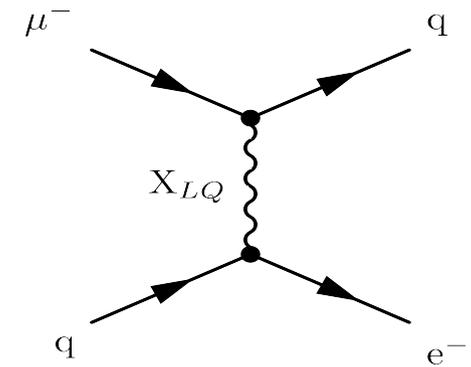
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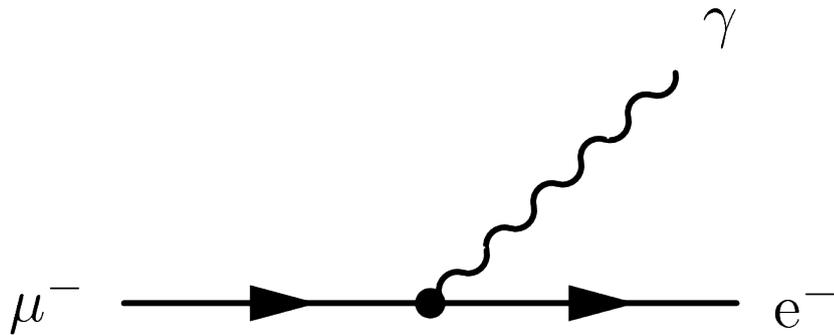
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The discovery of Weak scale SUSY at LHC would imply observable cLFV rates

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

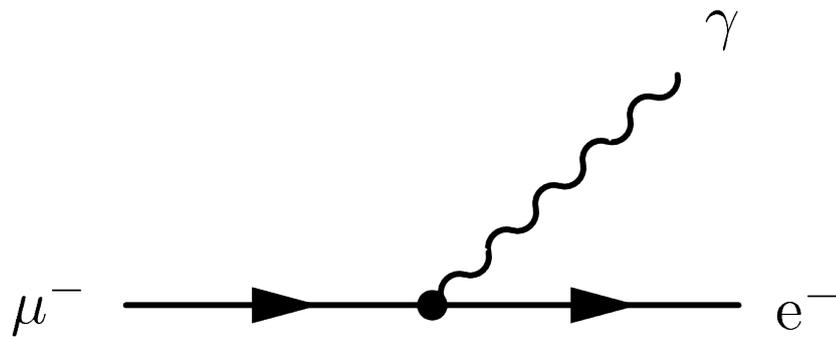
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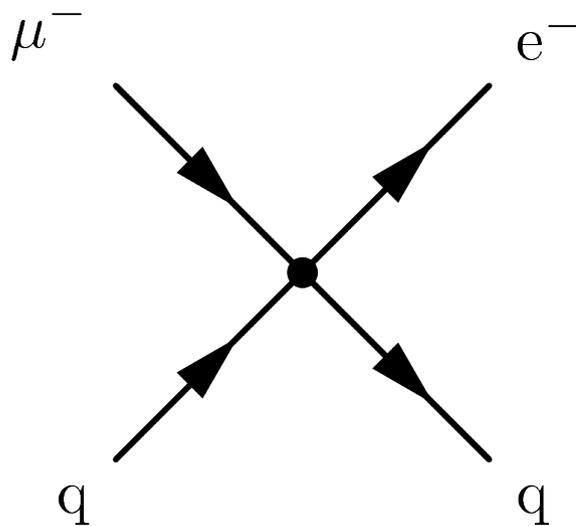


A dimension 5  
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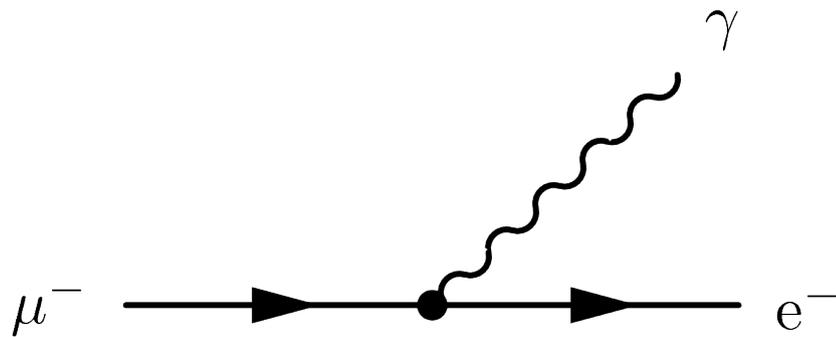


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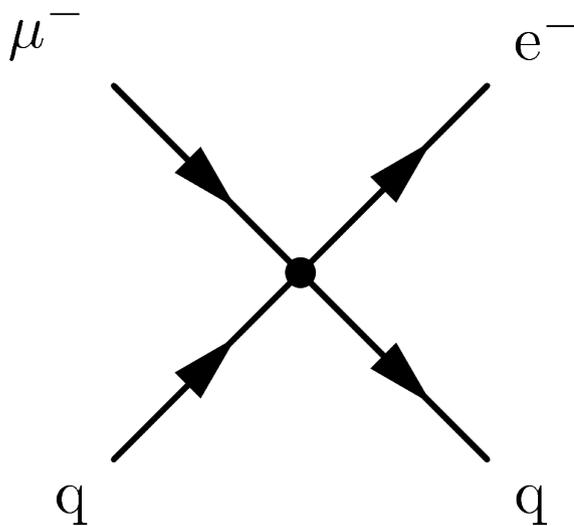
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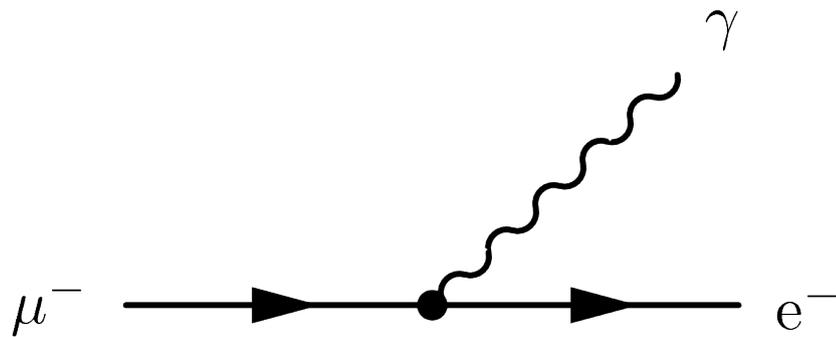
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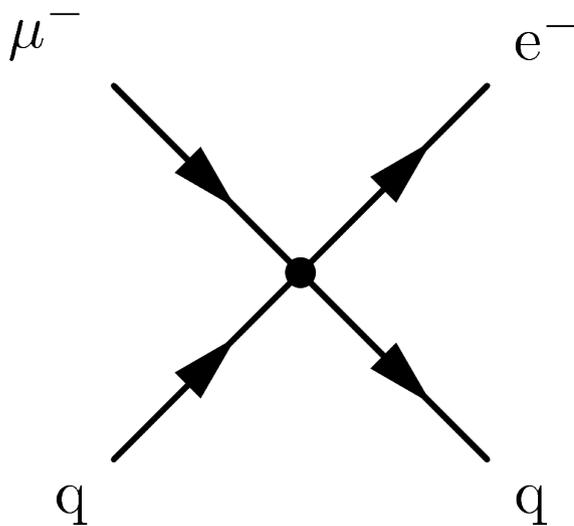
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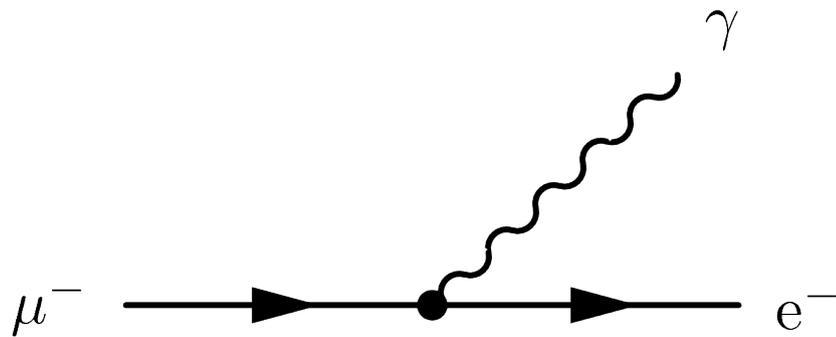
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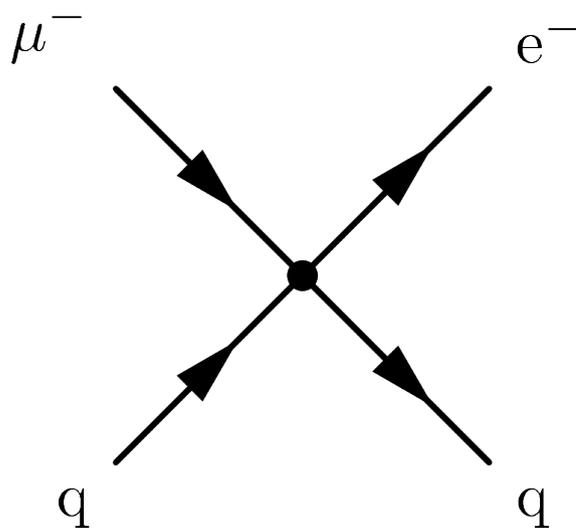
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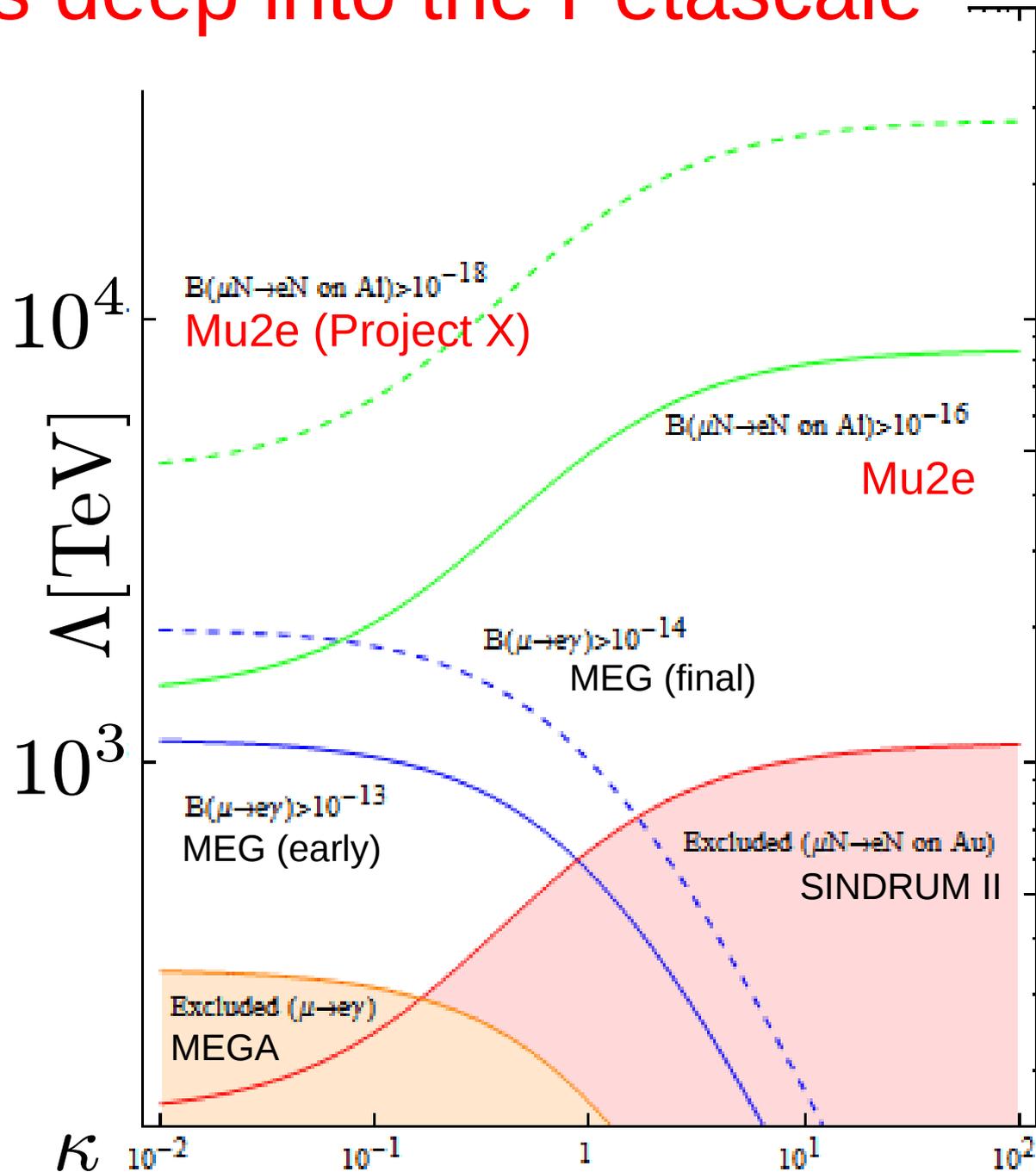


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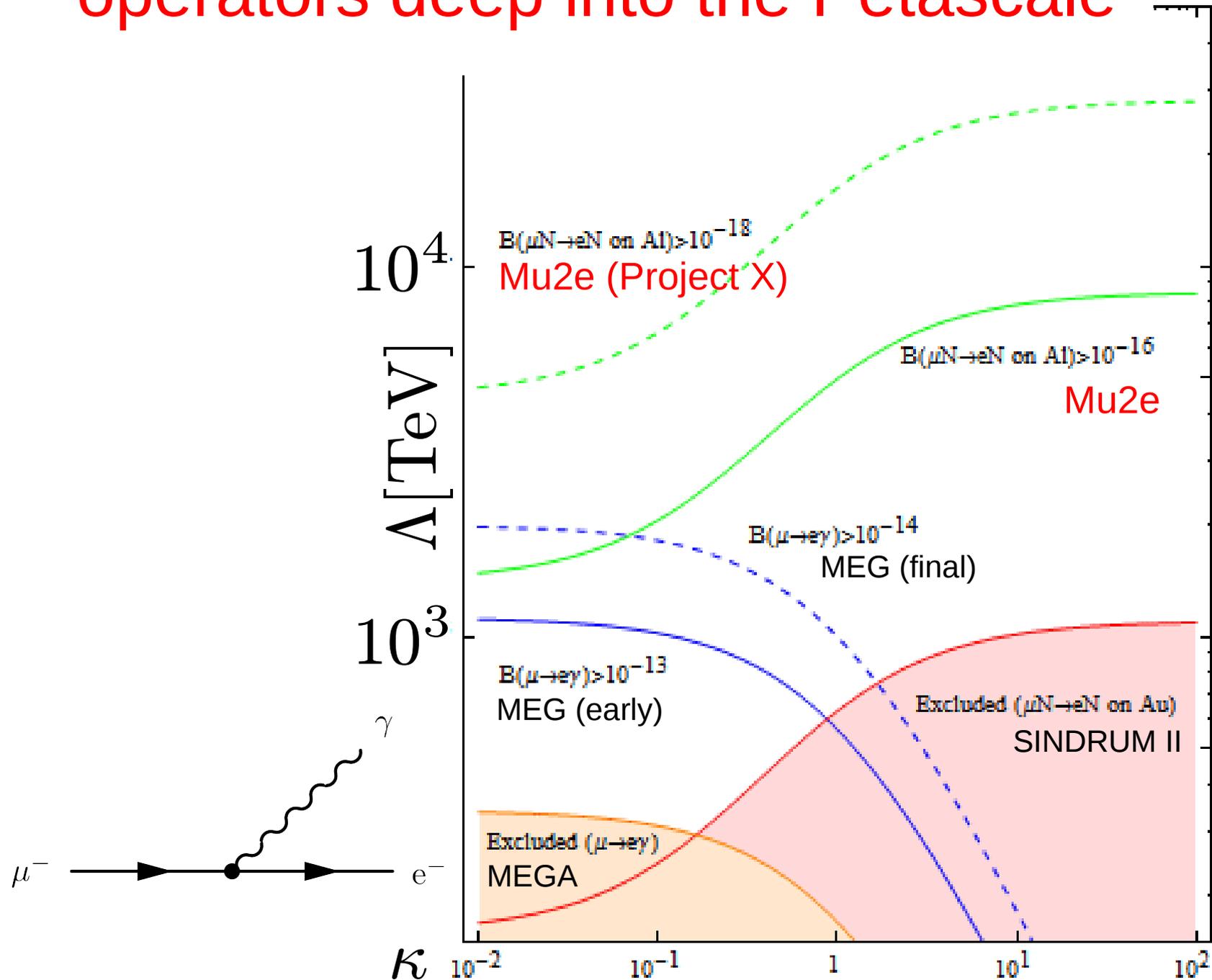
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$$\frac{1}{\kappa + 1}$$
$$\updownarrow \kappa$$
$$\frac{\kappa}{\kappa + 1}$$

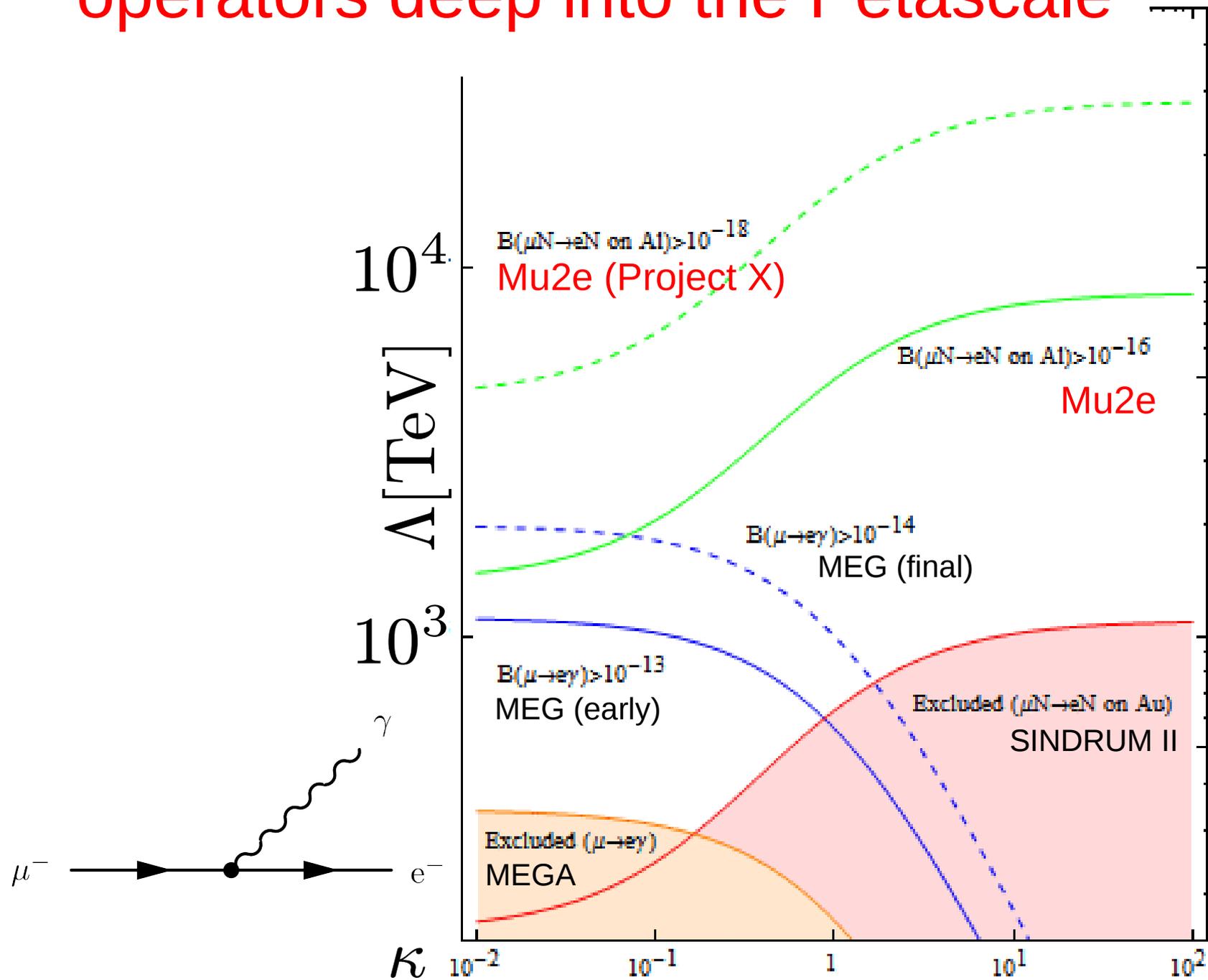
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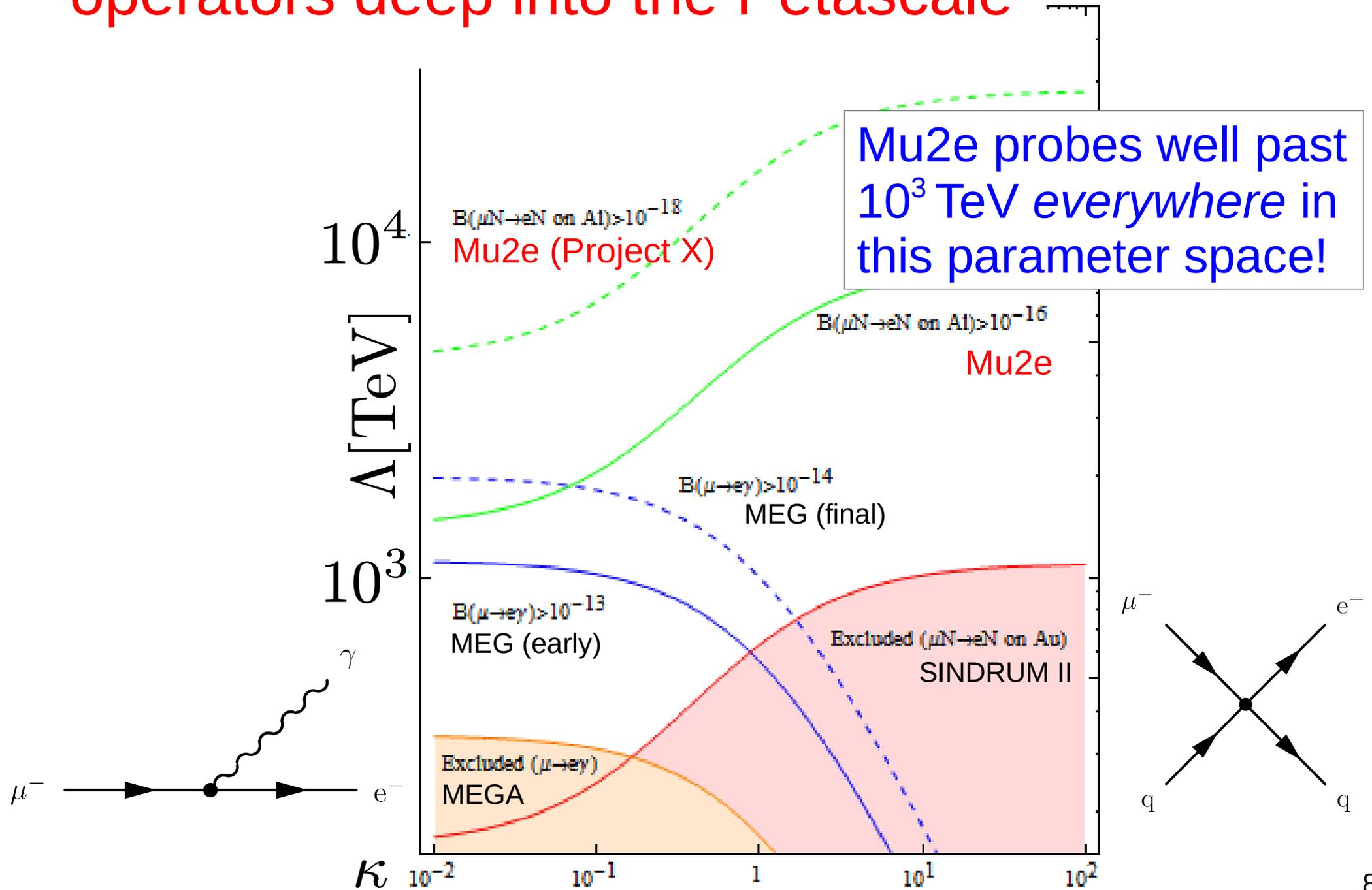
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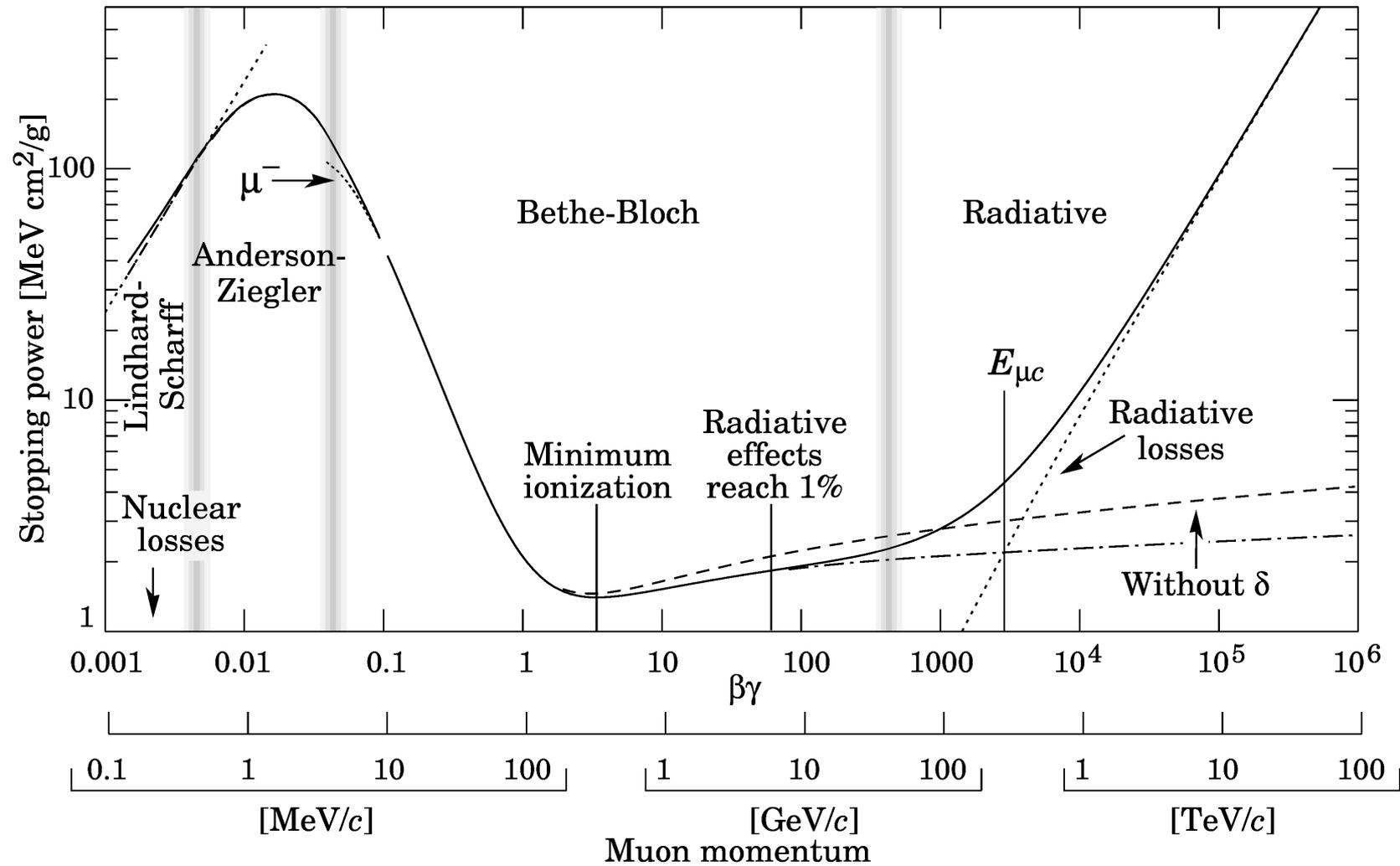


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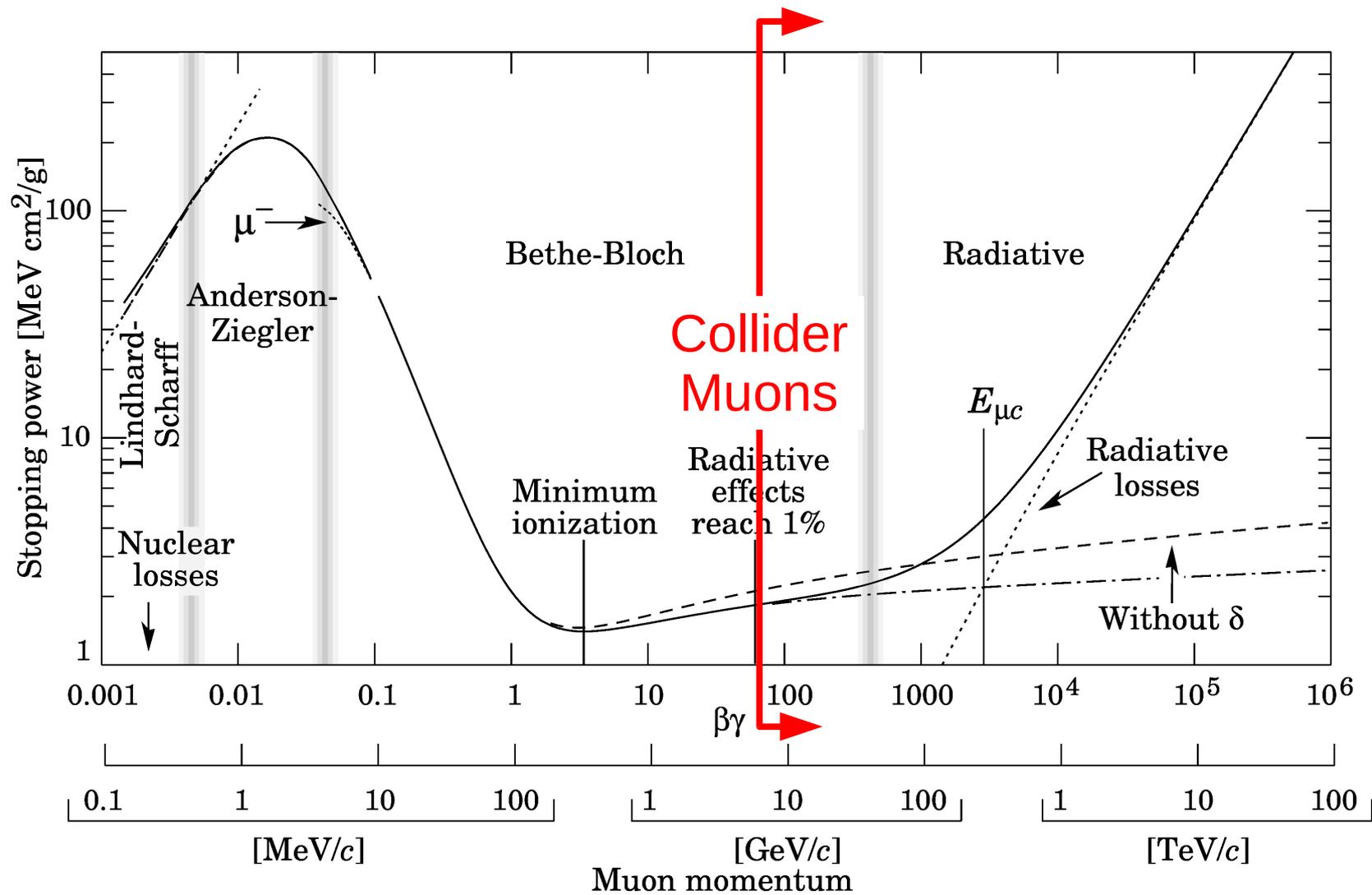
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Our muons are not like your muons...

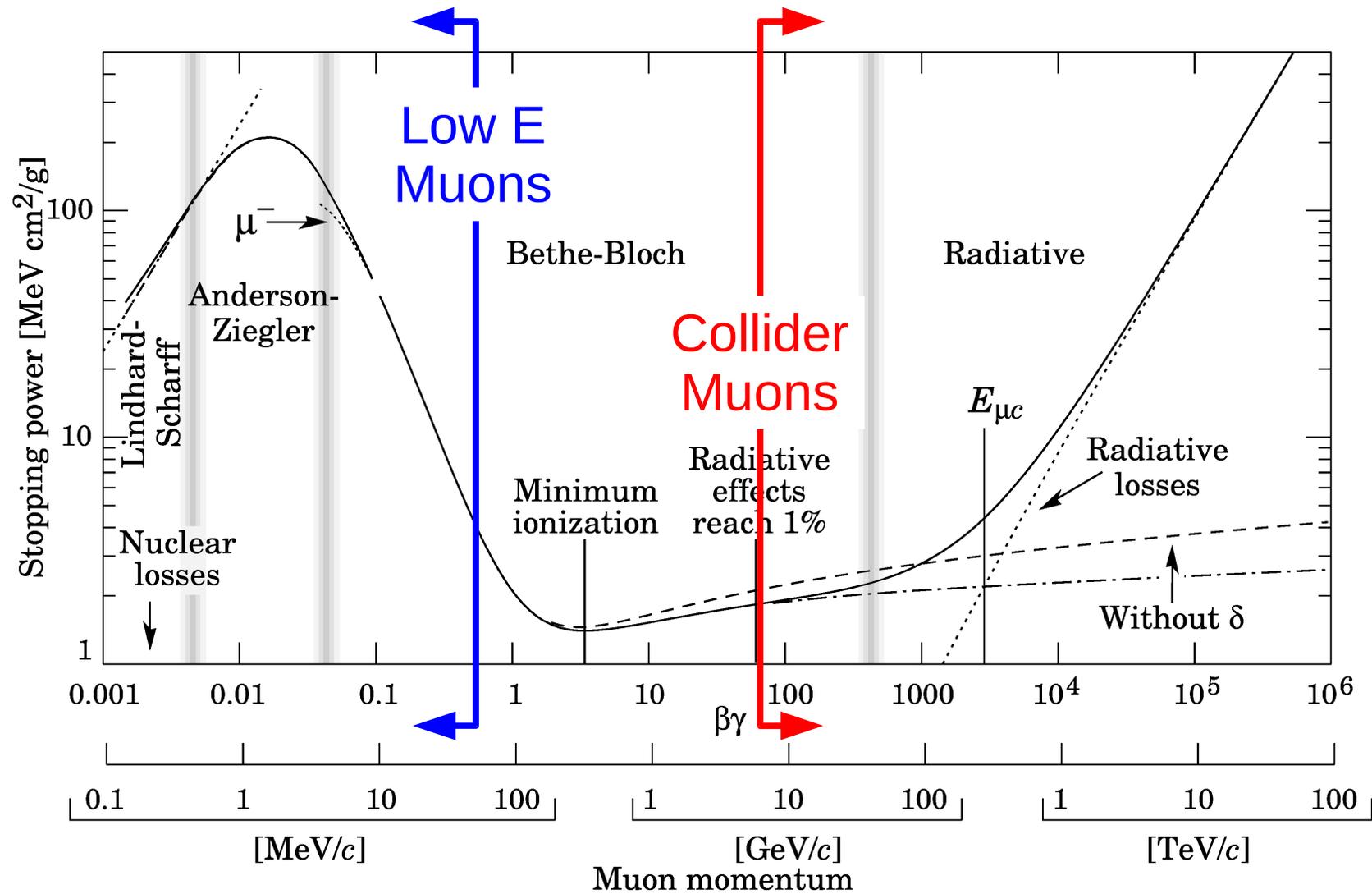
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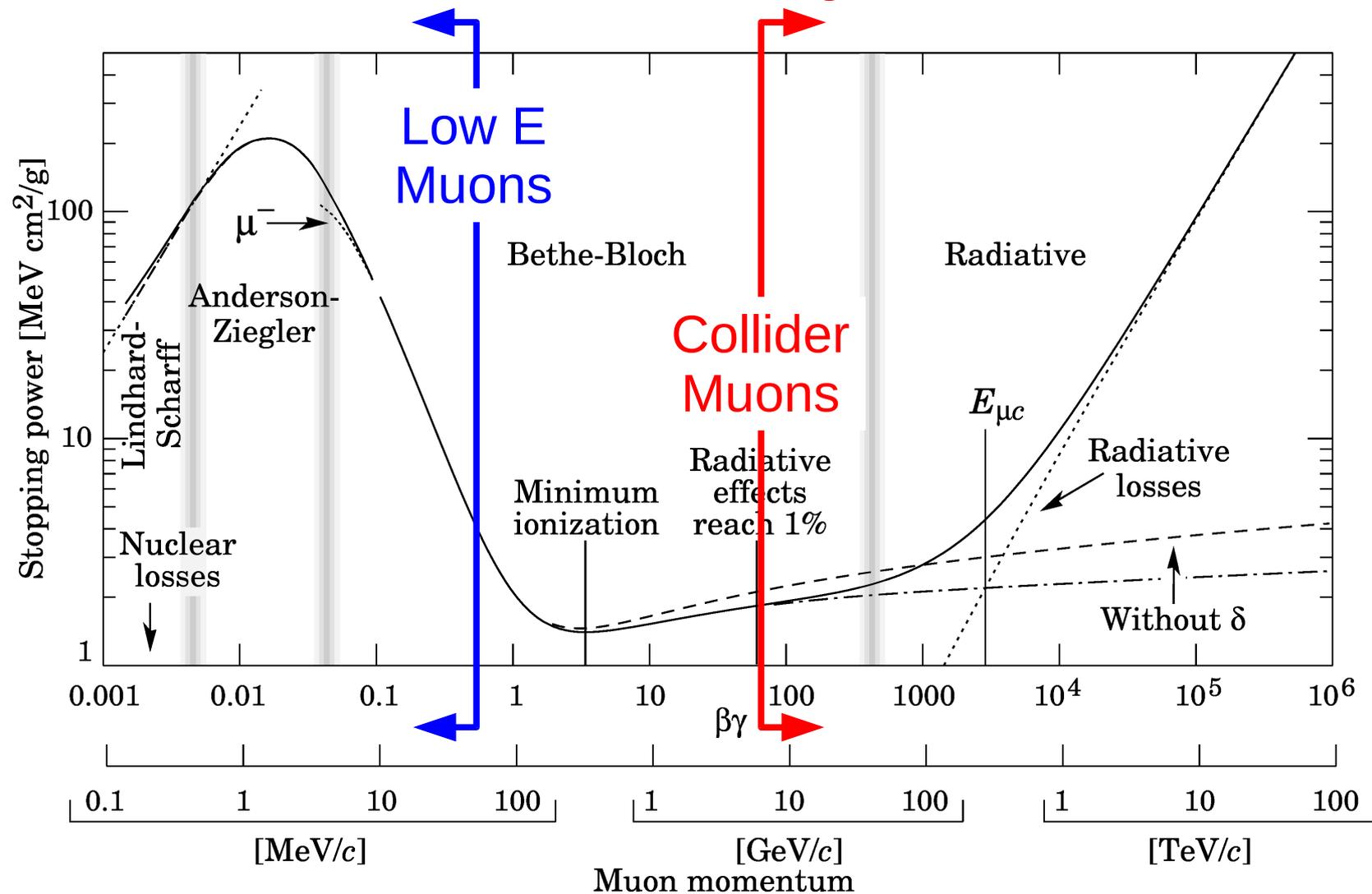
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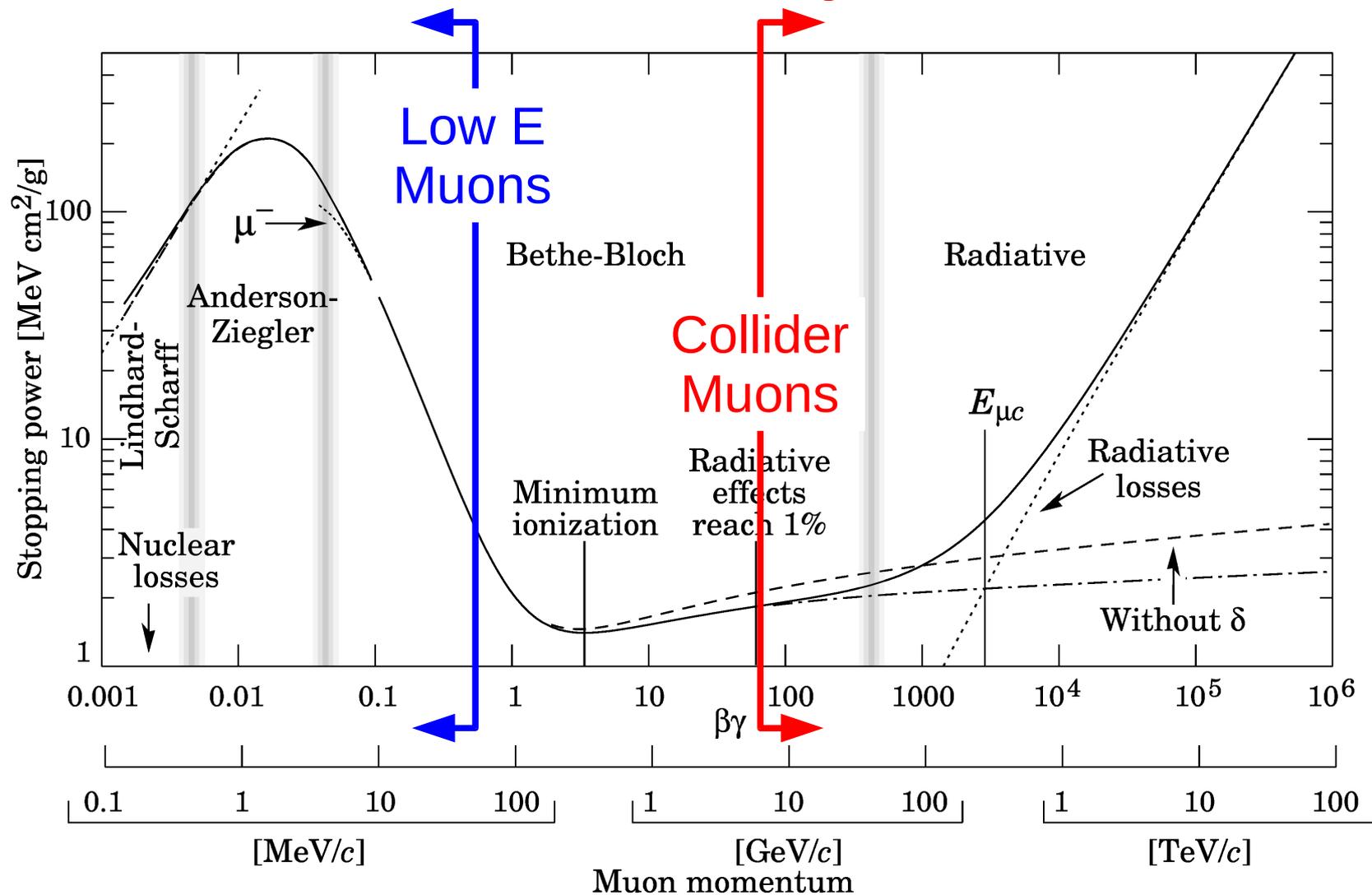


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Negative muons rapidly stop, capture on atoms, and cascade to the 1s state.

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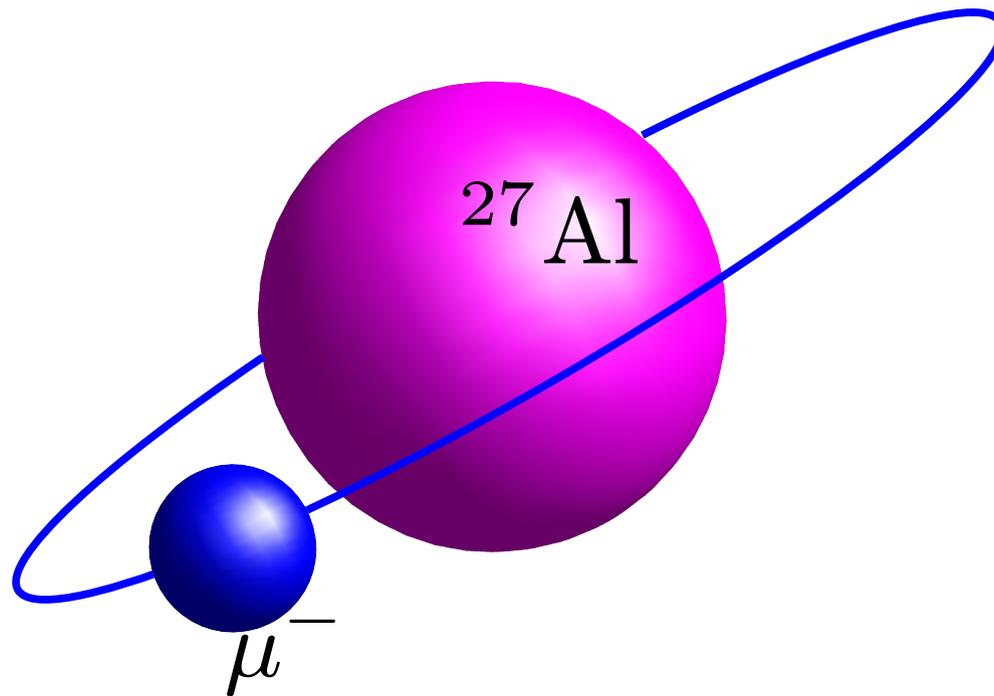


Negative muons rapidly stop, capture on atoms, and cascade to the 1s state.

$$E_{1s} = -Z^2 2.7 \text{ keV}$$

# Coherent conversion kinematics

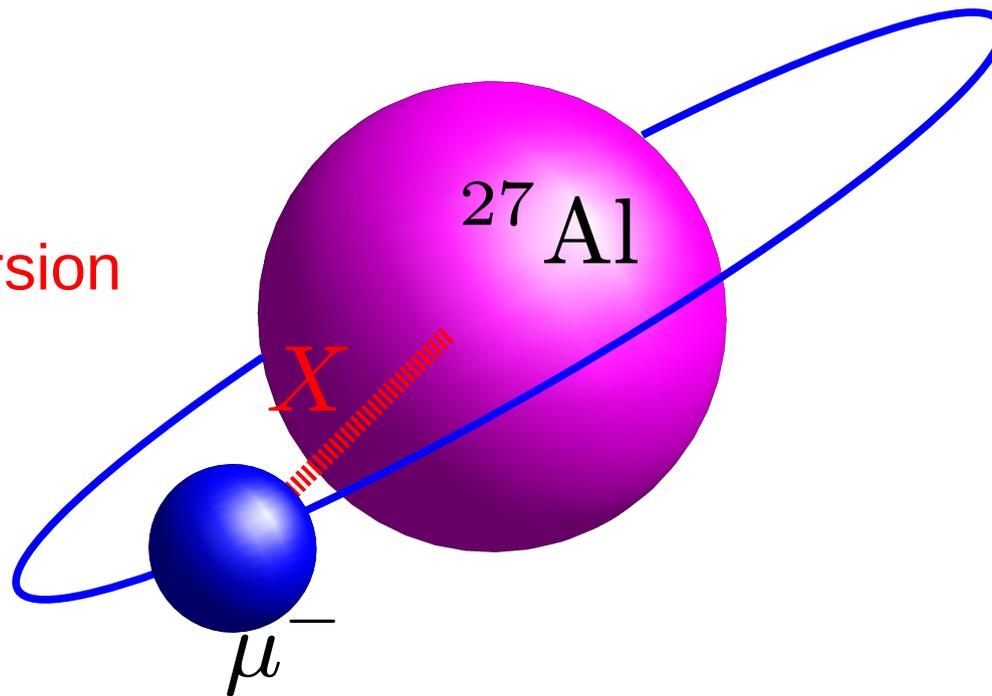
Starting with a  
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# Coherent conversion kinematics

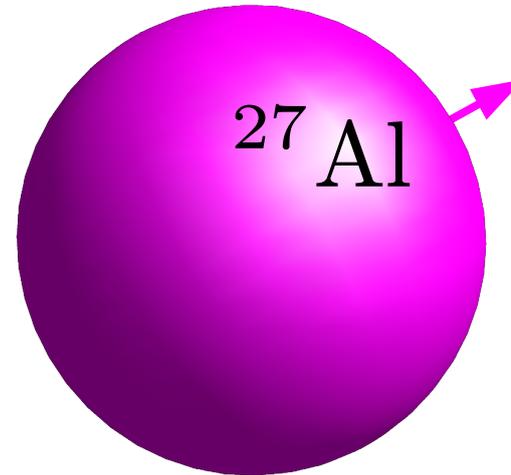
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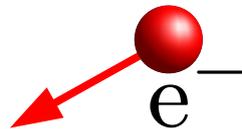


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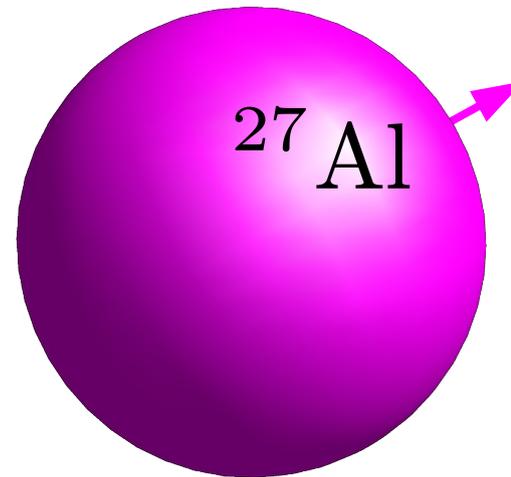
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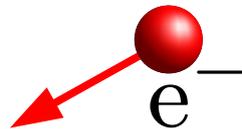
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# Coherent conversion kinematics

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... a 1-to-2 process producing monochromatic electrons!

$$E_e = m_\mu - E_{1s} - E_{A(Z,N)}$$

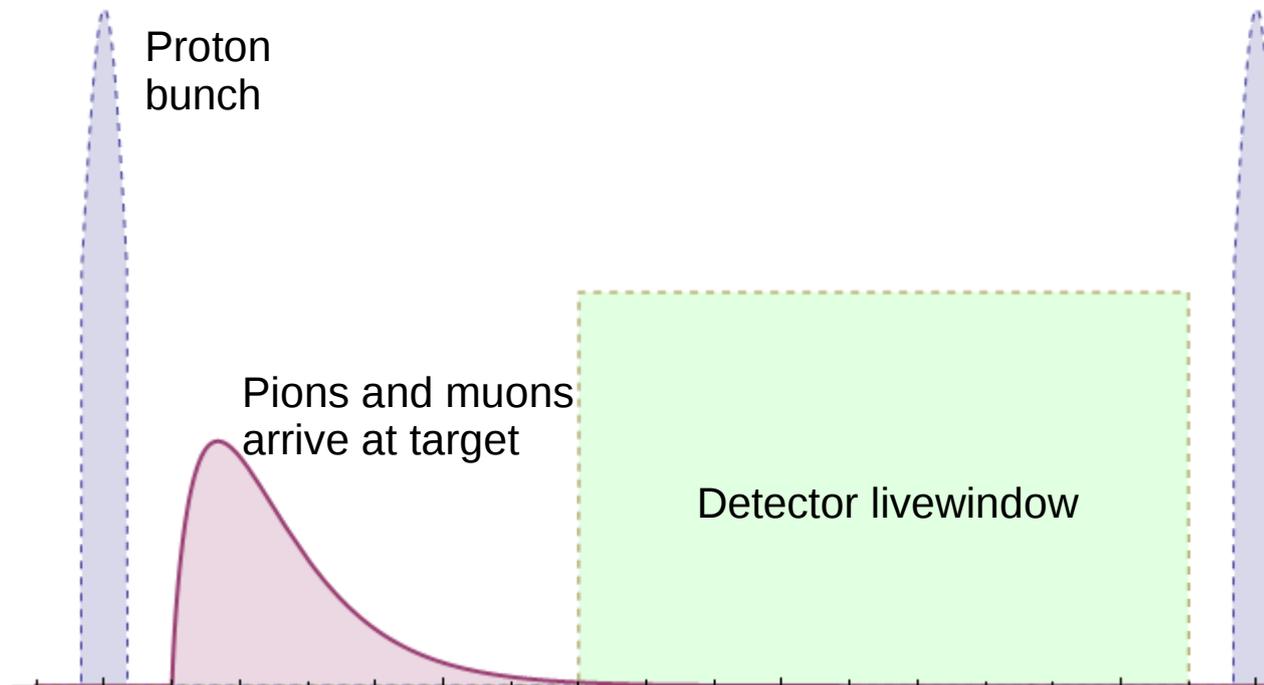
$$E_e(^{27}\text{Al}) = 104.97 \text{ MeV}$$

The two most dangerous backgrounds have very different timing properties.

The FNAL accelerator complex produces proton beams with a pulsed structure.

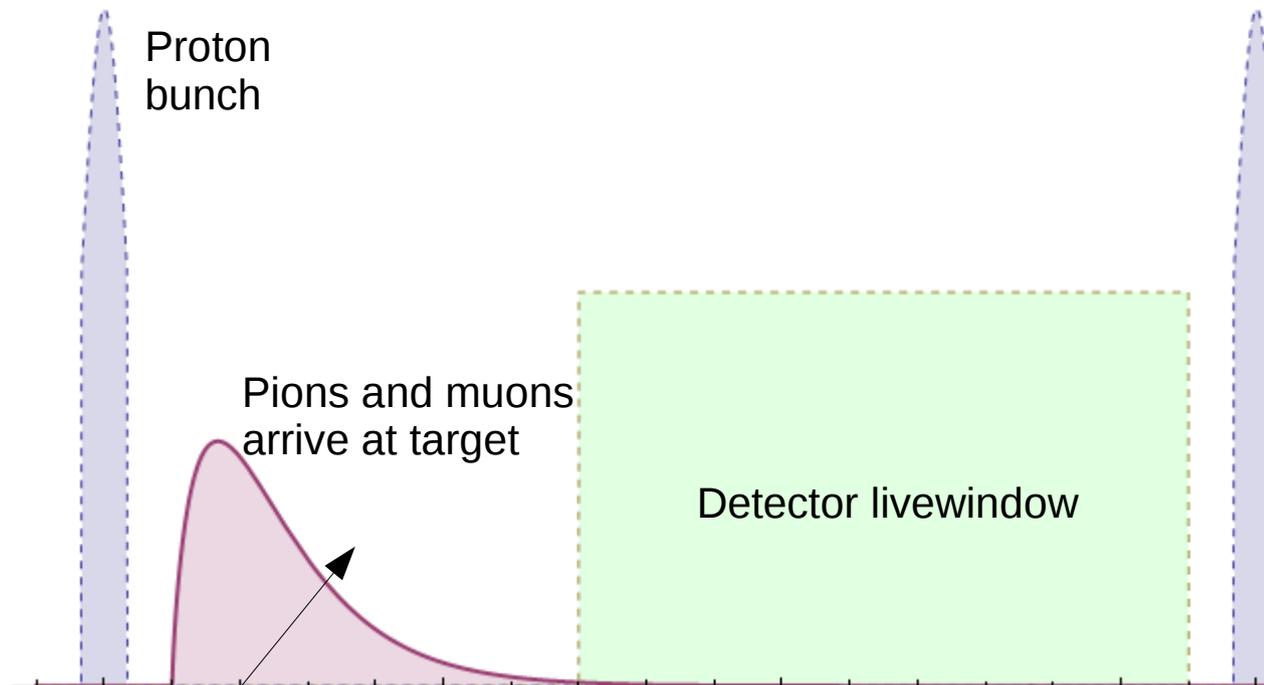
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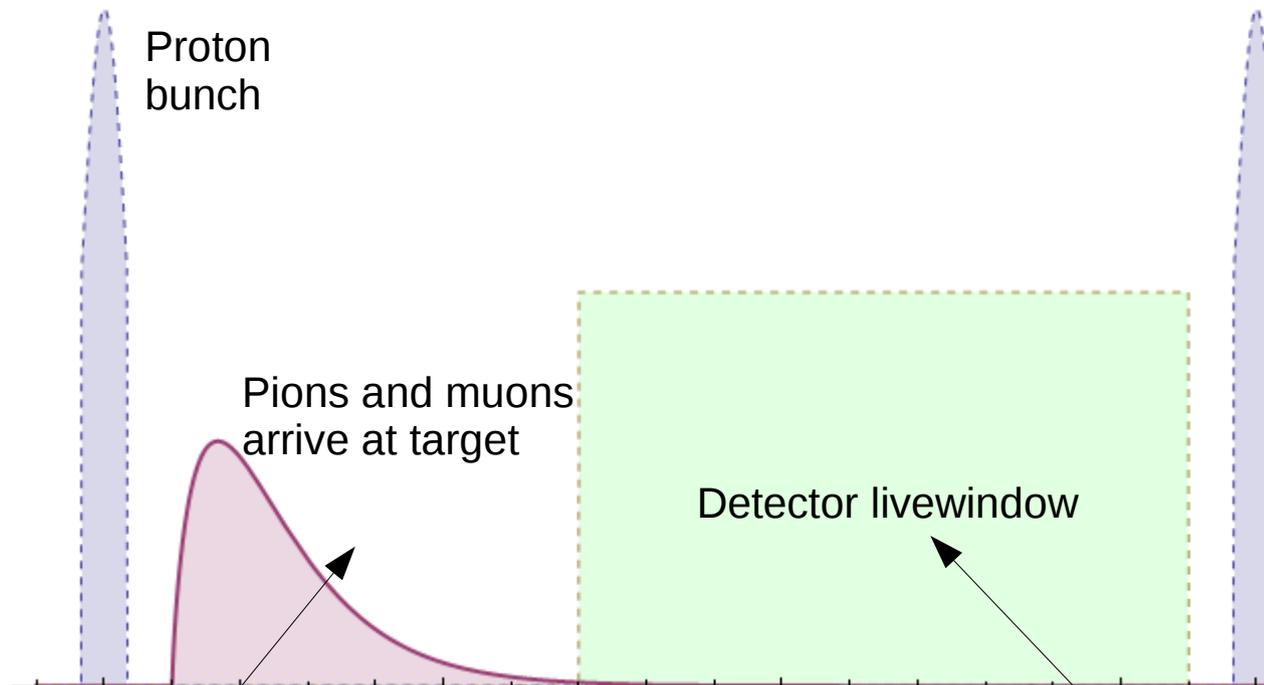
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Prompt: Radiative Pion Capture with pair production

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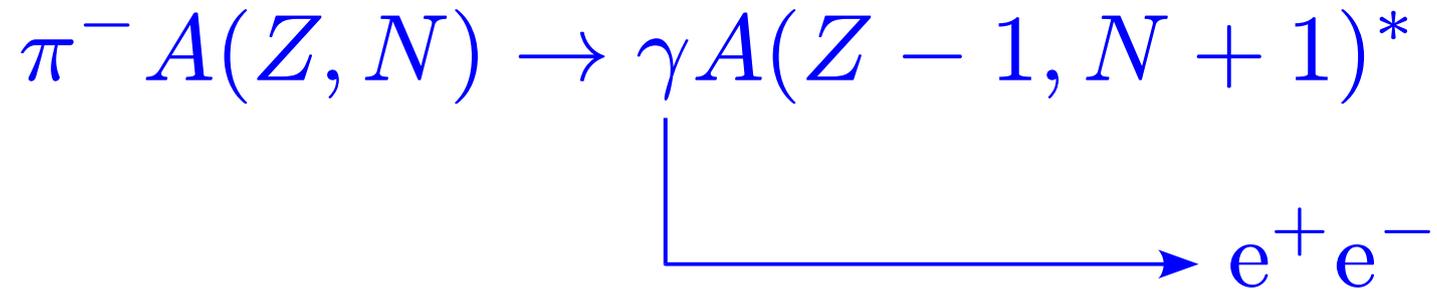
Prompt: Radiative Pion Capture with pair production

Delayed: Muon Decay-in-Orbit

Radiative pion capture can produce electrons near the conversion energy

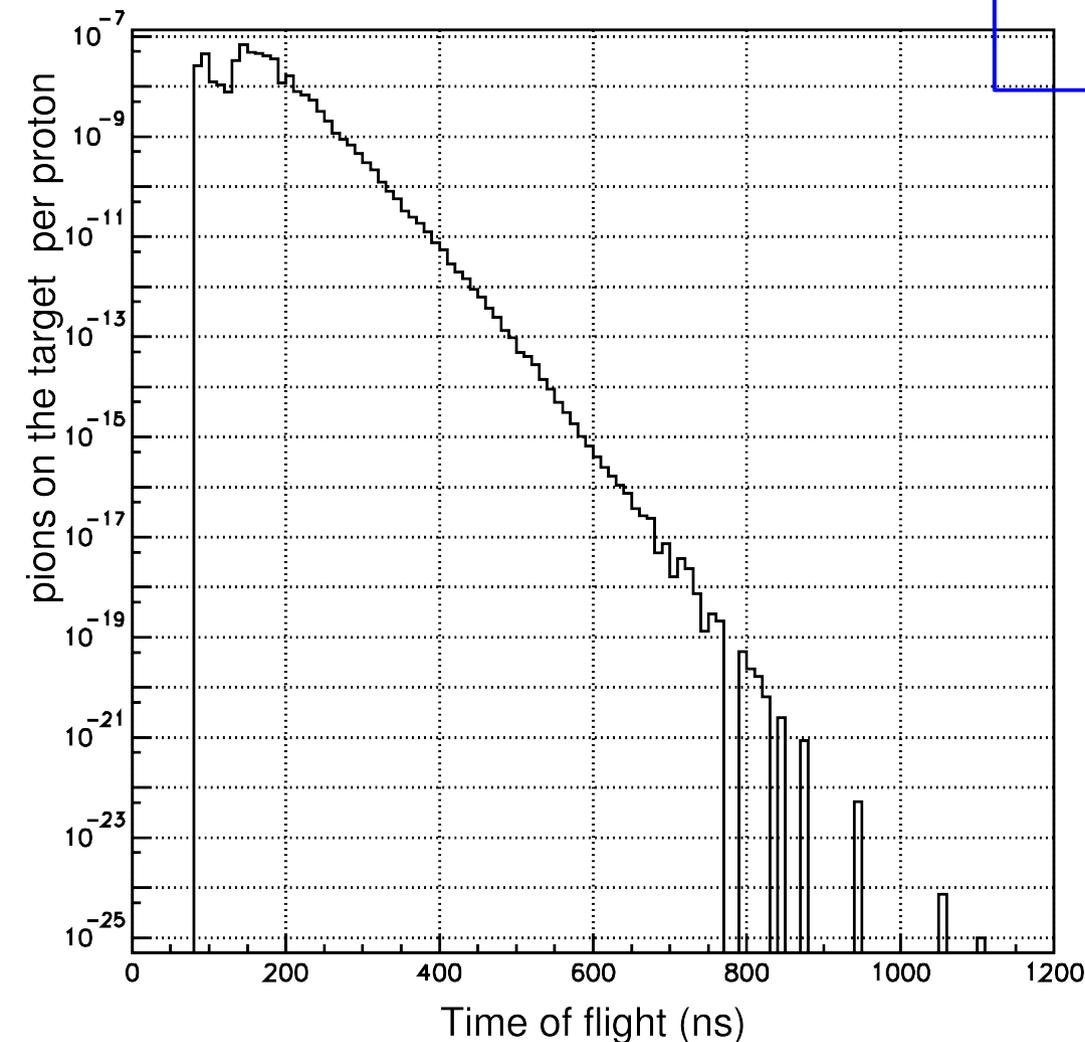


# Radiative pion capture can produce electrons near the conversion energy



The electron spectrum extends out to nearly  $m_\pi$

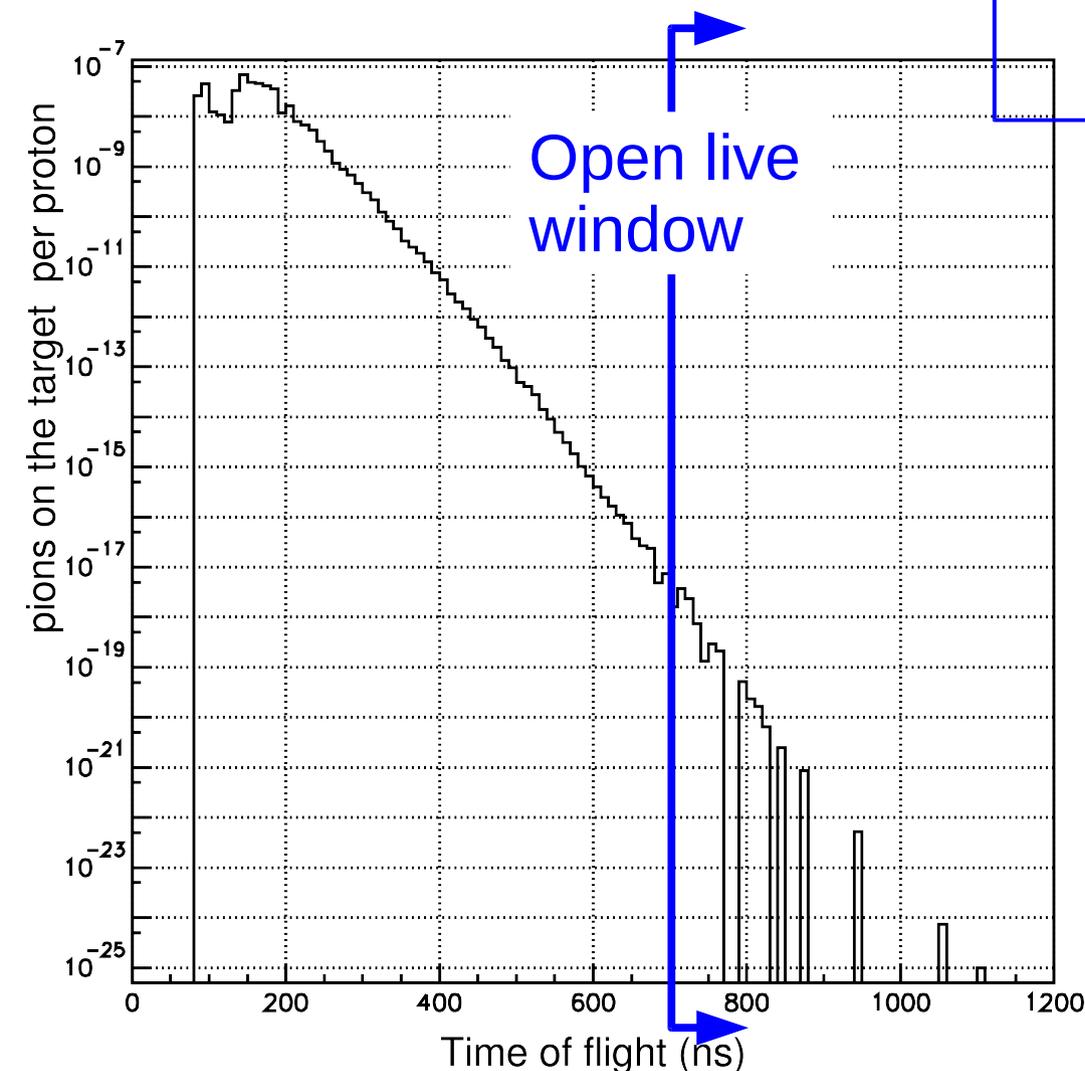
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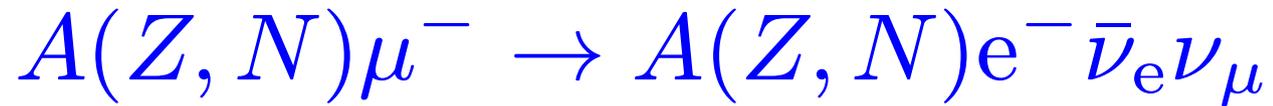


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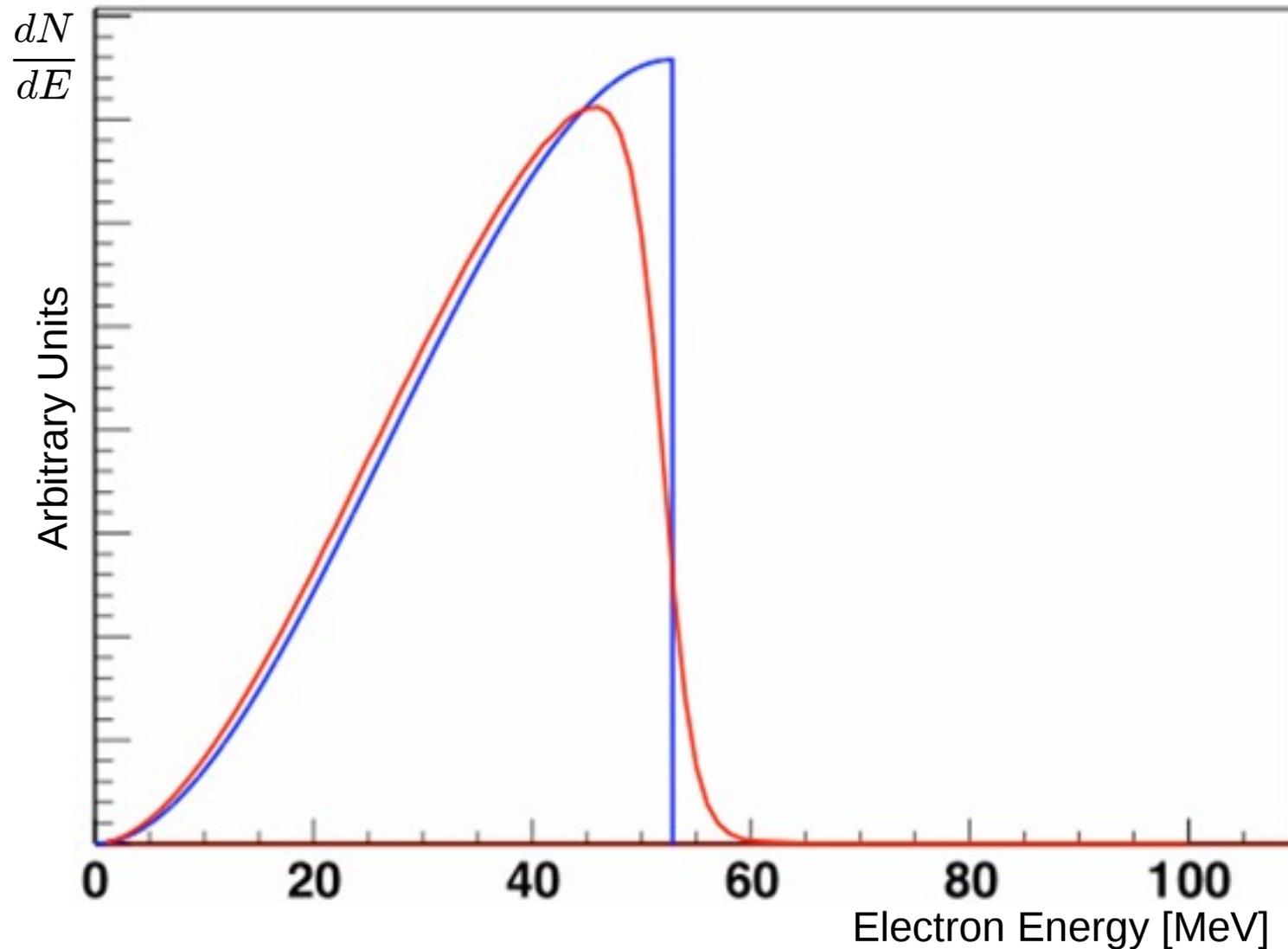
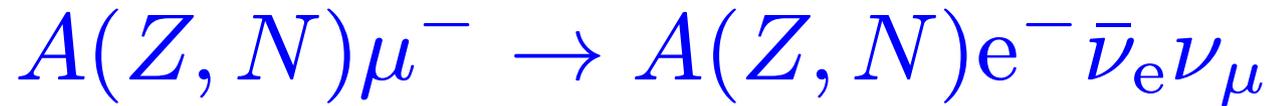
The electron spectrum extends out to nearly  $m_\pi$

This (and other) prompt backgrounds are eliminated by keeping the DAQ dead until the background rate has fallen below some threshold.

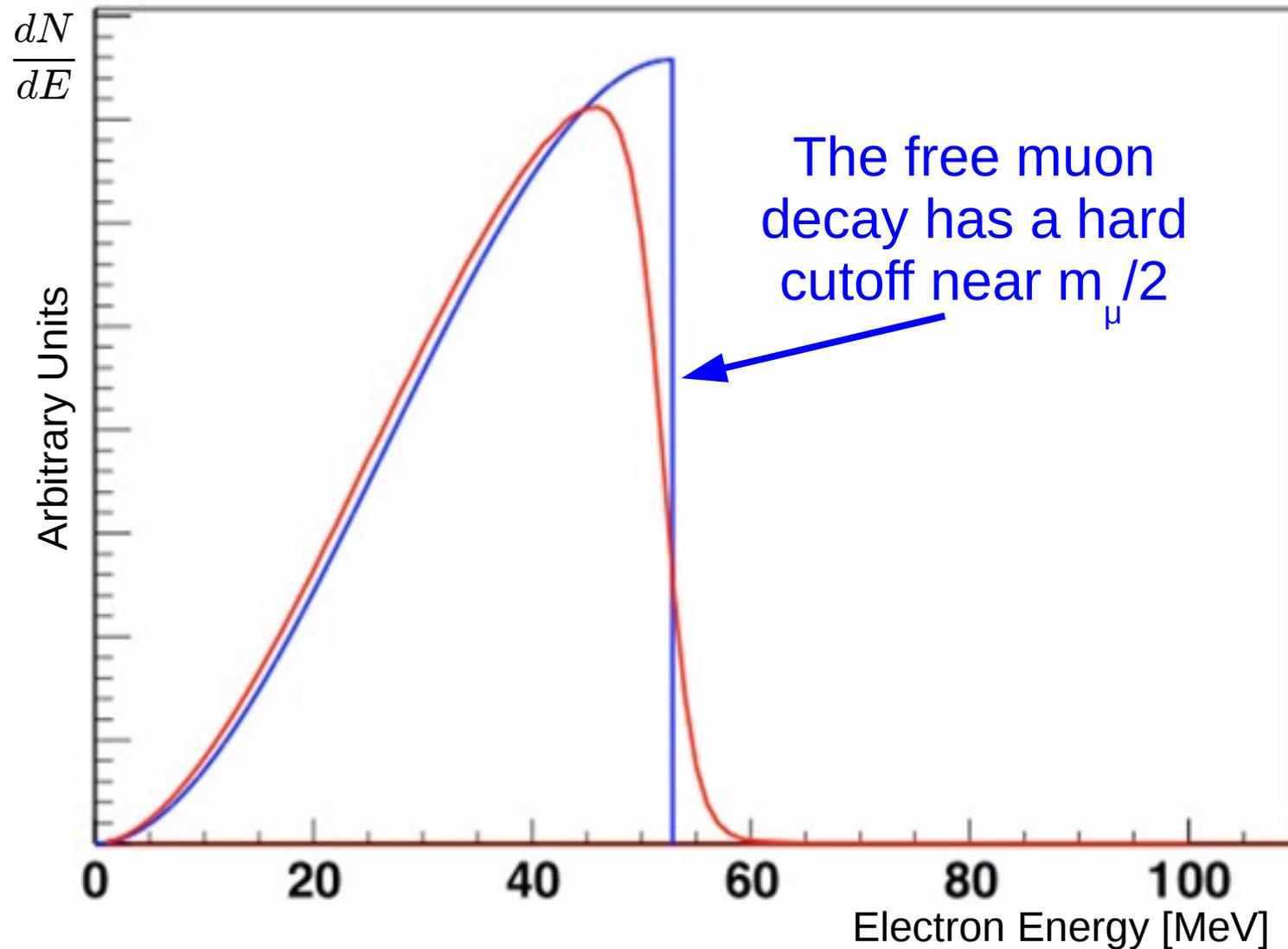
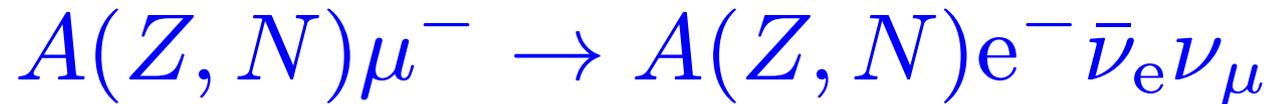
Decay-in-Orbit is the major source of delayed background in the live window



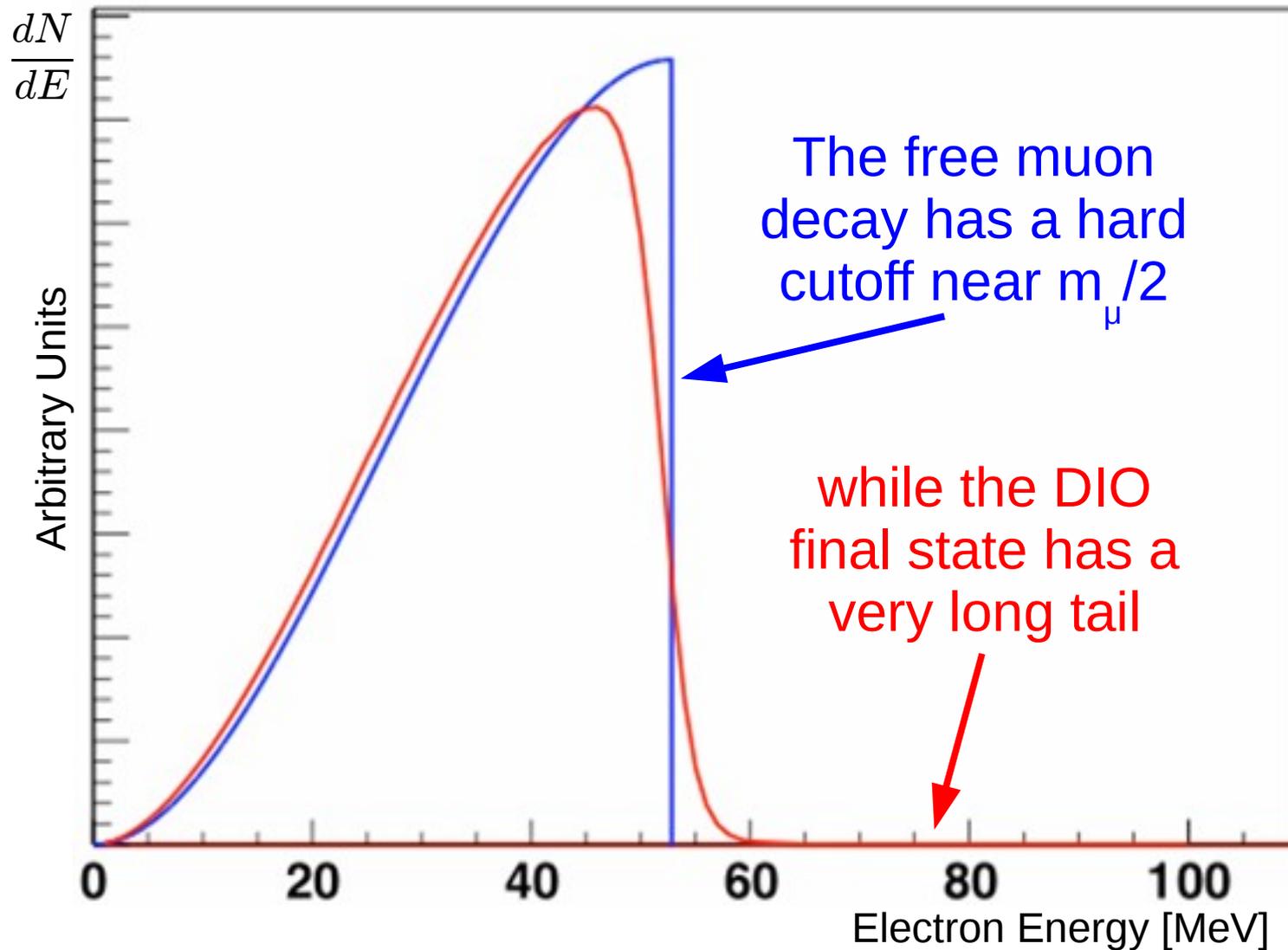
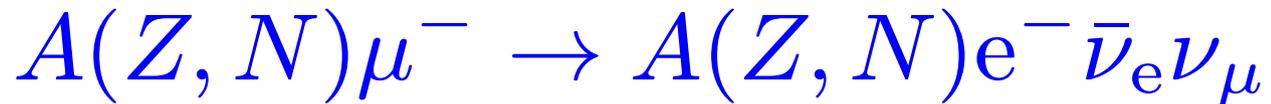
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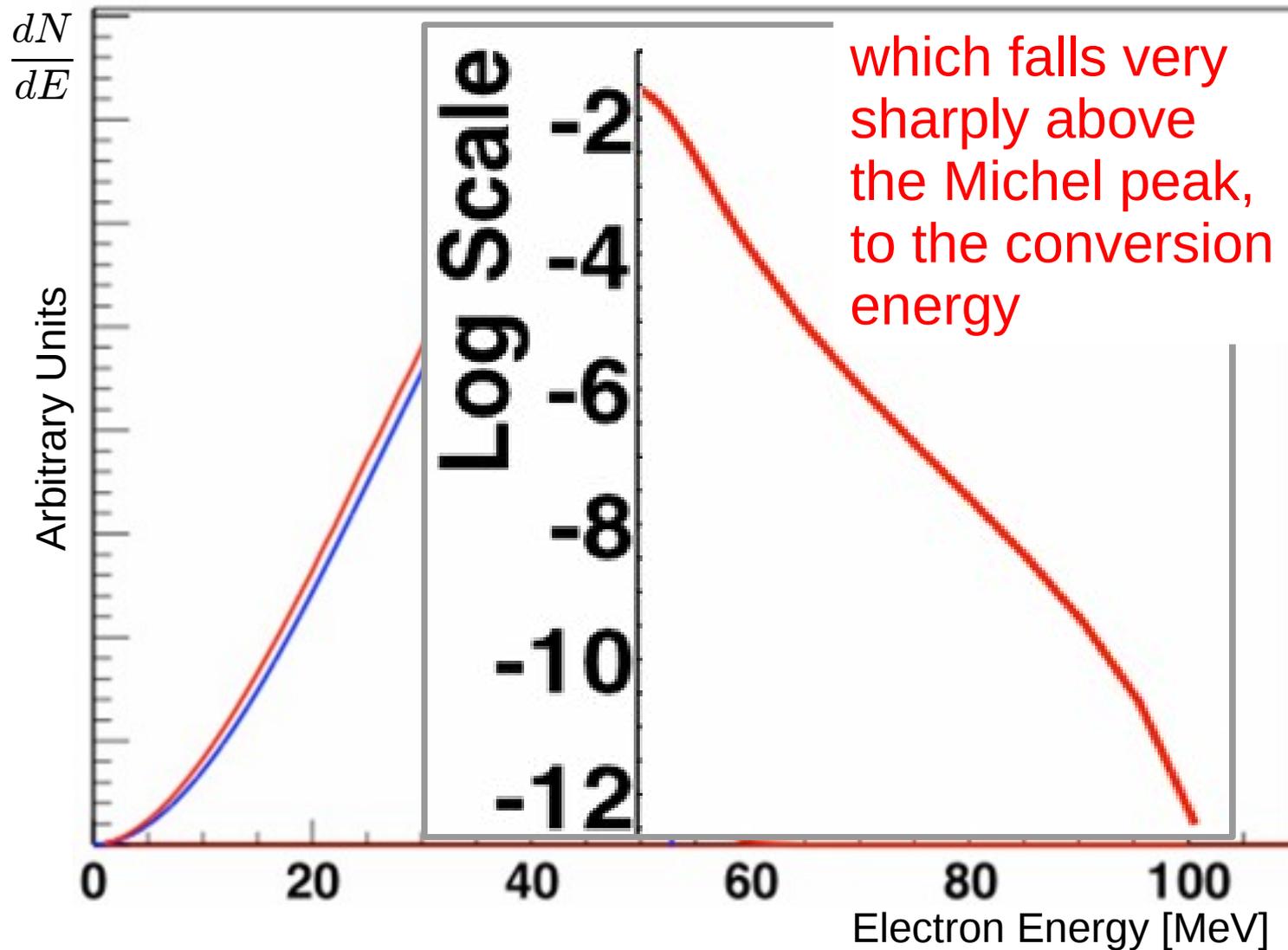
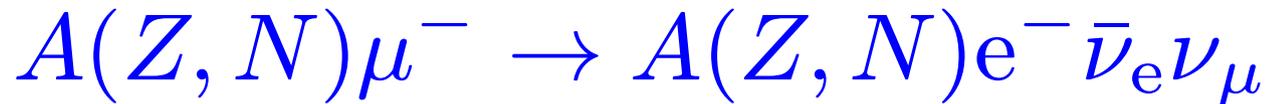
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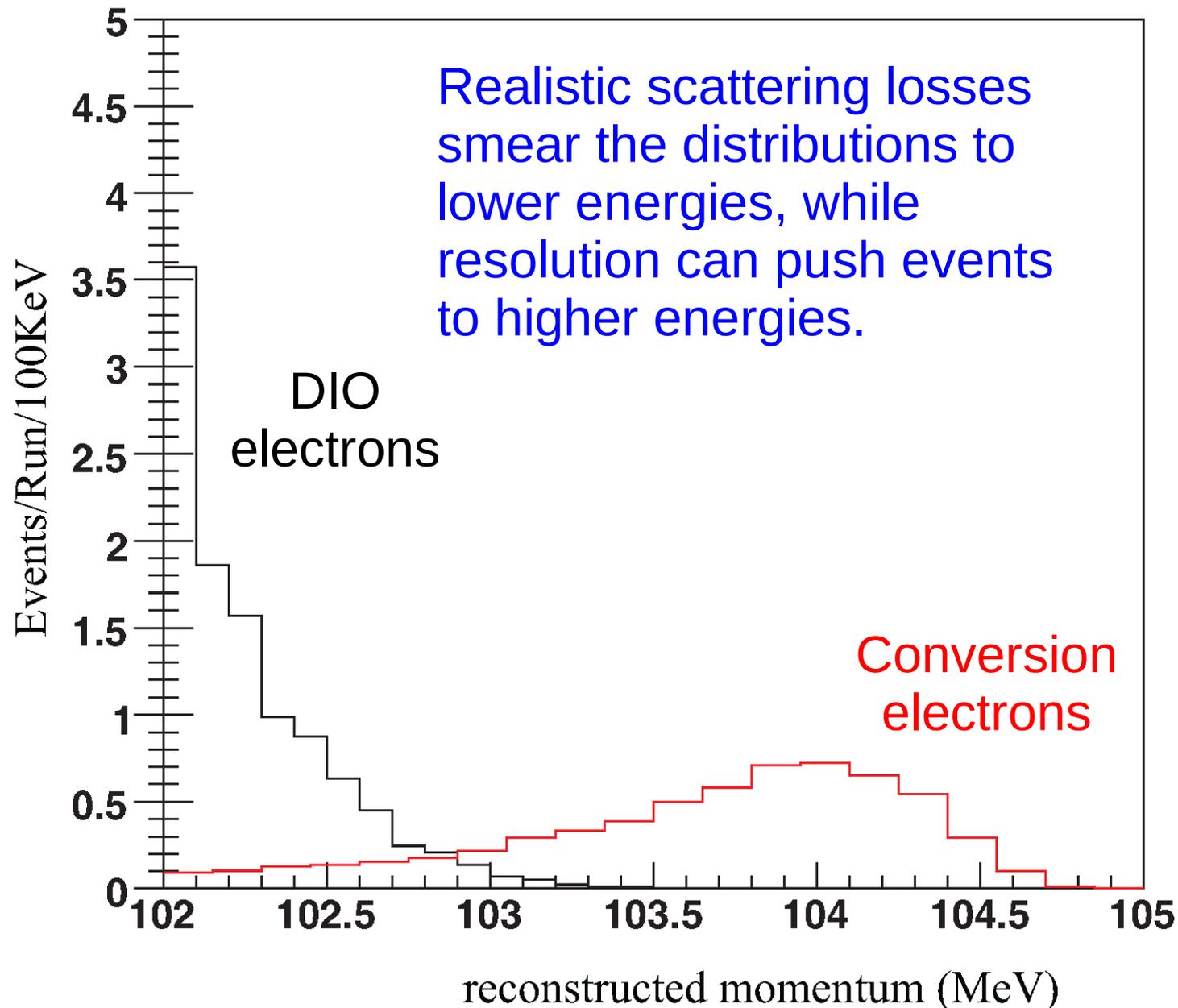
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# An experimental reality check



The backgrounds and resolutions constrain the design and reach of the experiment

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- Spectrometer design:
  - Track momentum resolution:  $O(200\text{keV})$
- Beam transport
  - Out-of-time particle suppression:  $10^9$

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In two years of running

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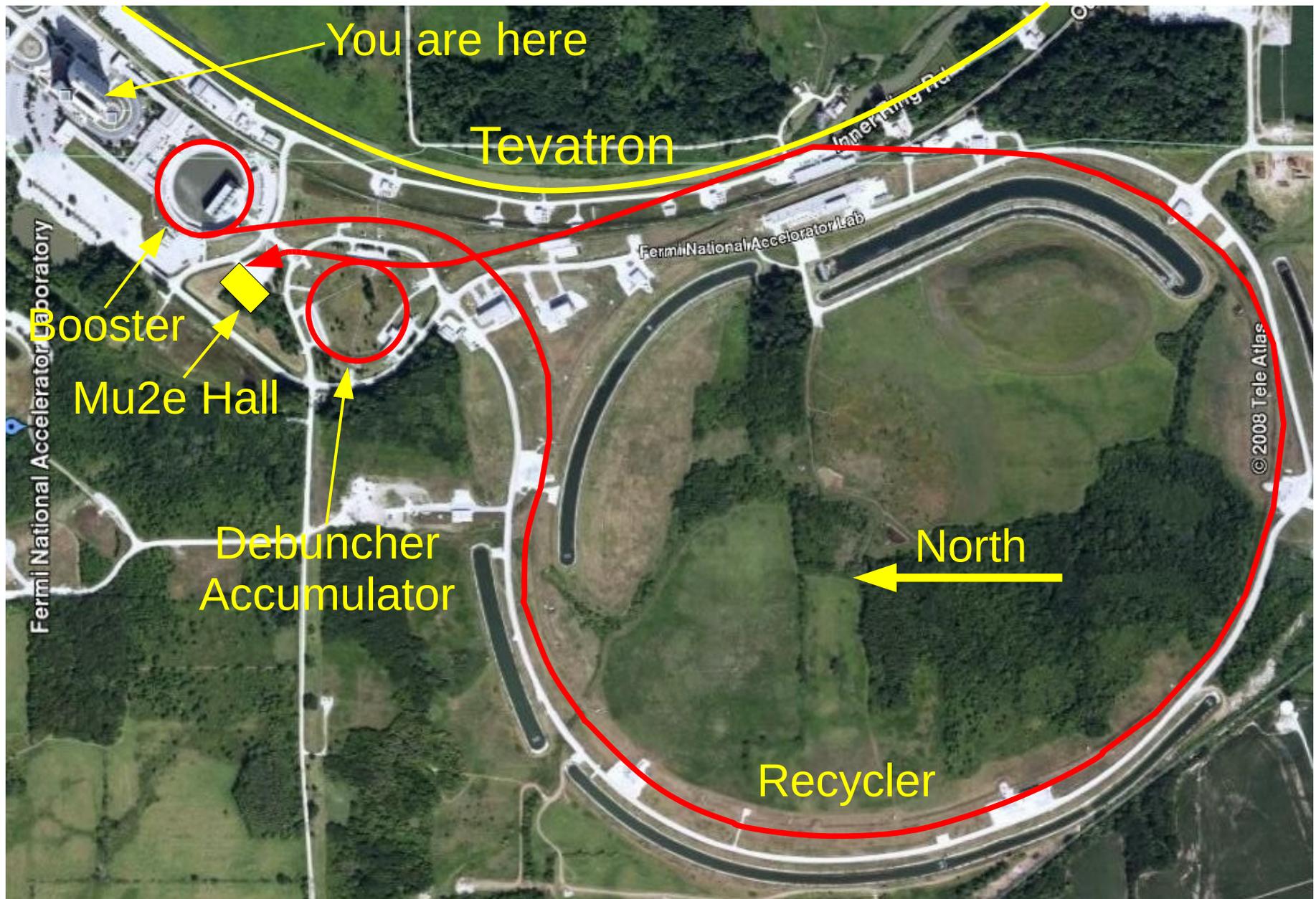
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This is a factor  $10^4$  improvement  
on the current limit!

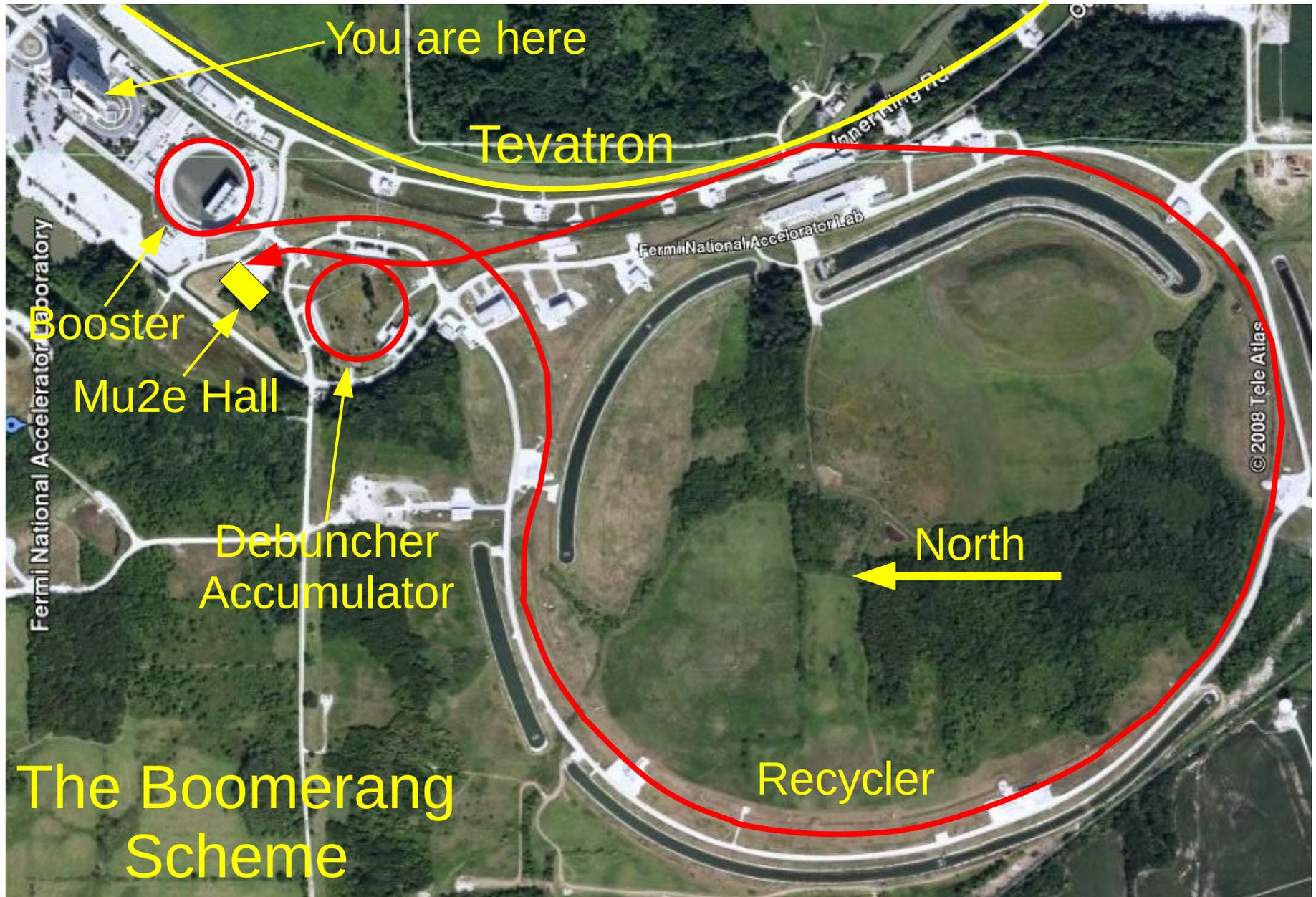
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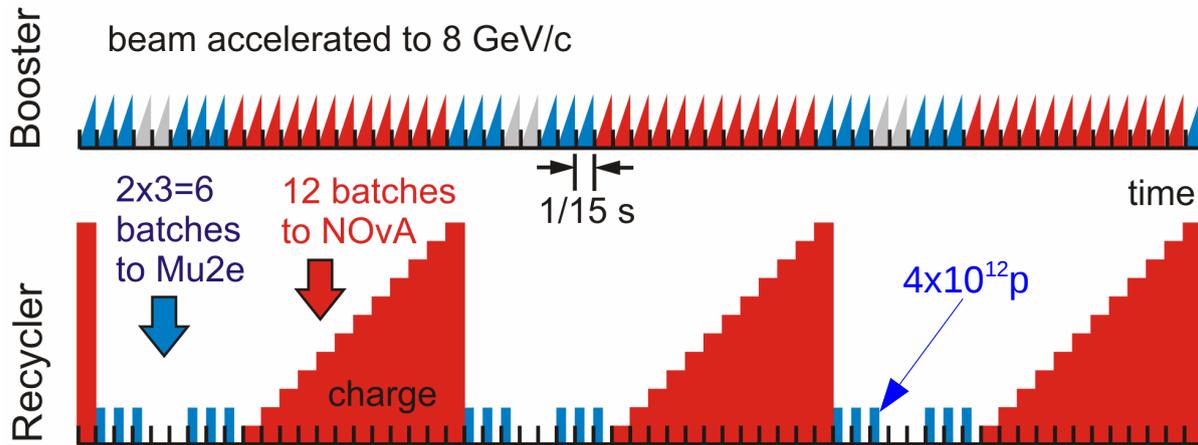


# Where are we going to build this thing?

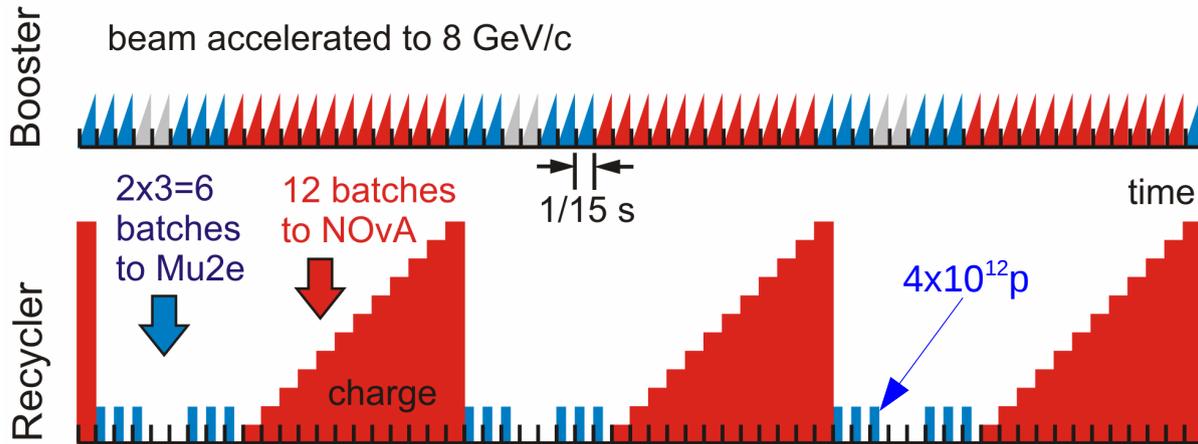


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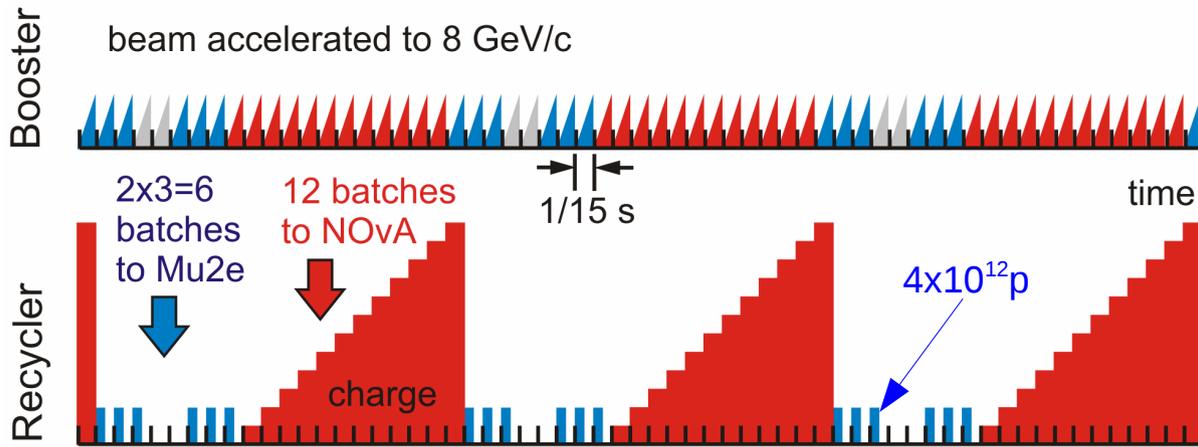


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*Mu2e running does not impact the neutrino program!*

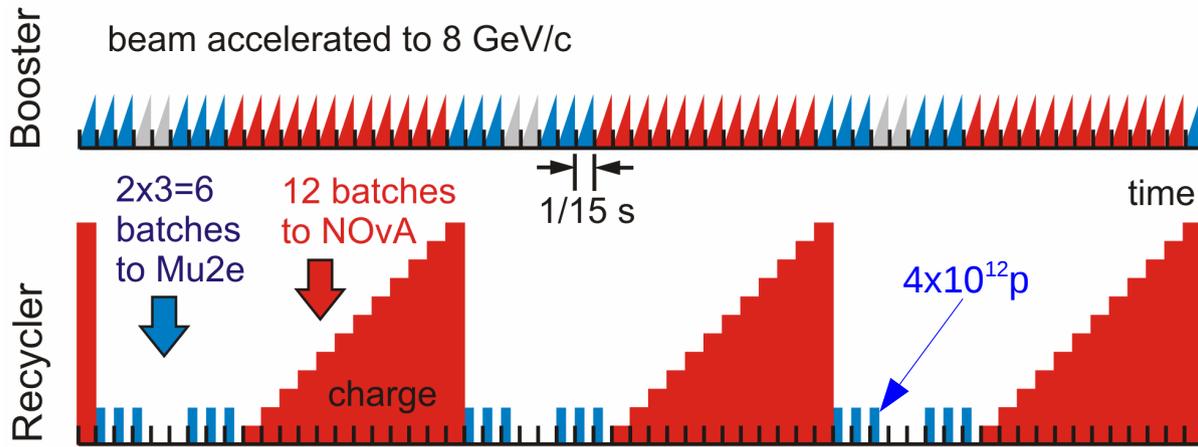
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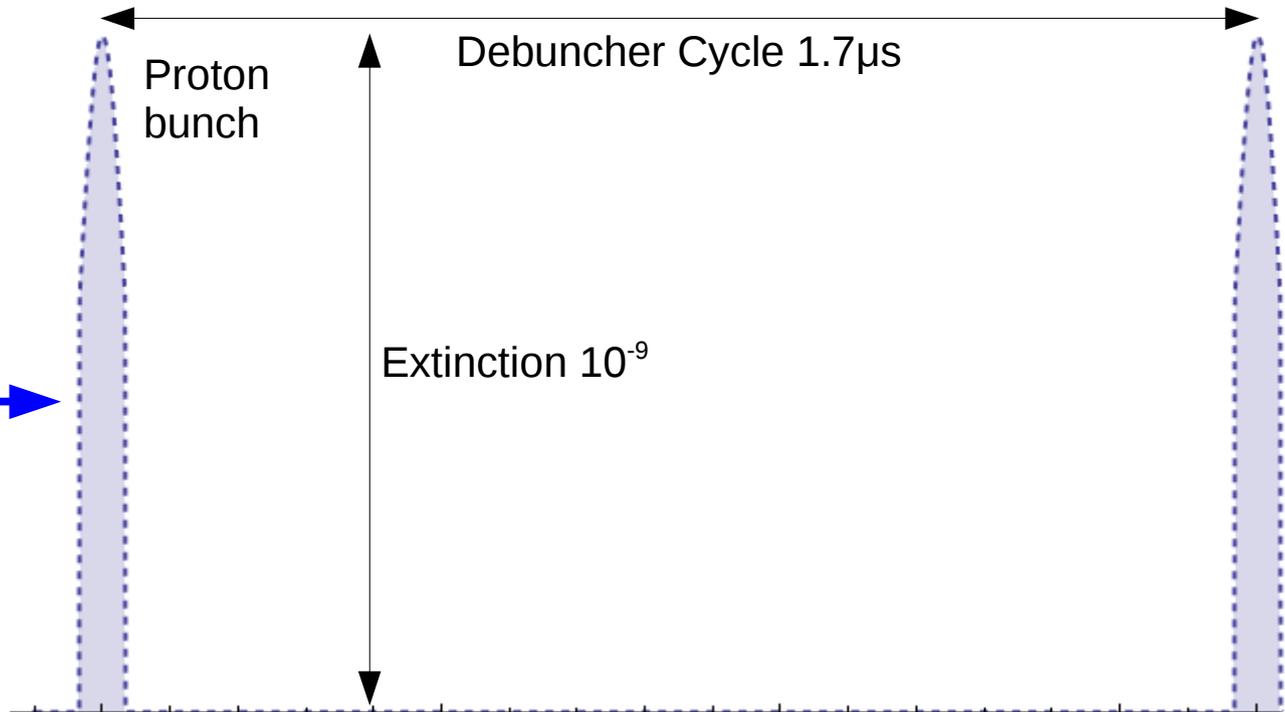
These batches are stacked and bunched in the accumulator, then transferred to the debuncher for slow extraction to Mu2e

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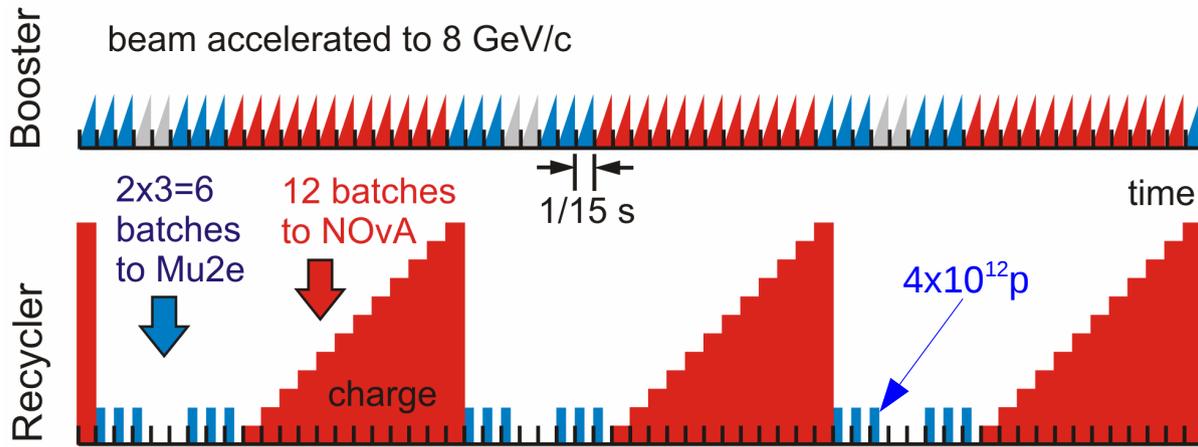


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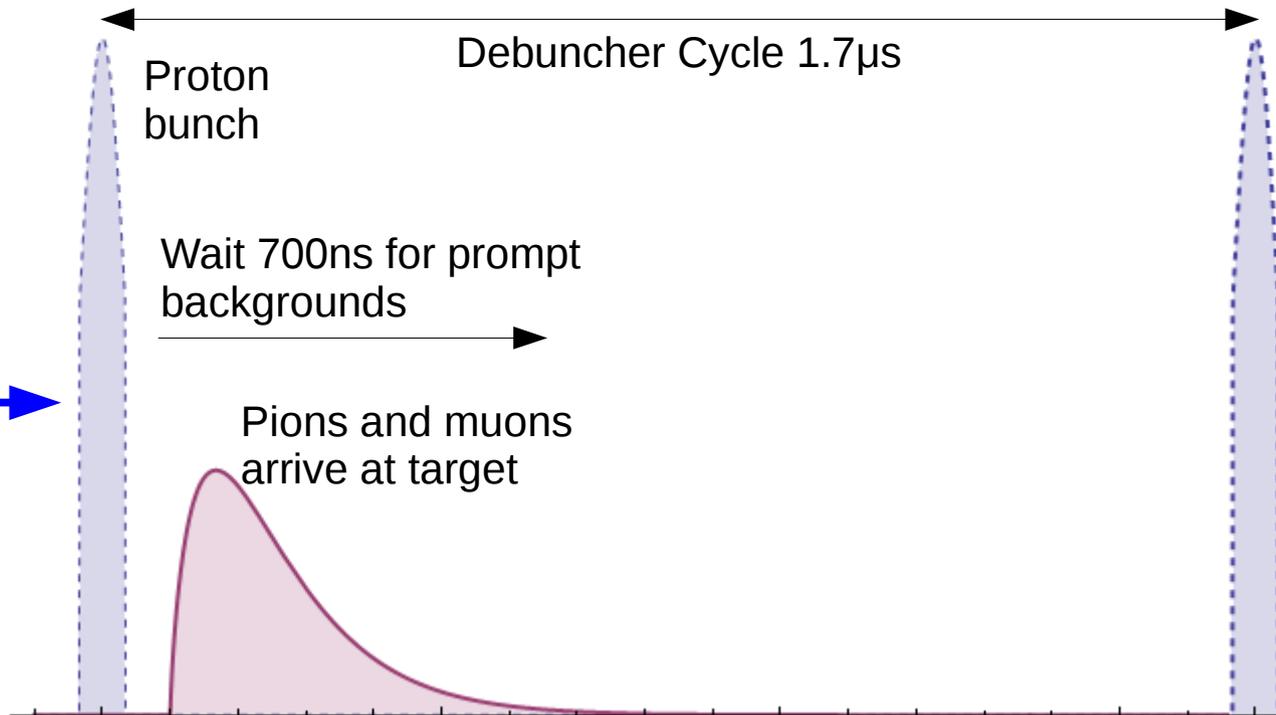


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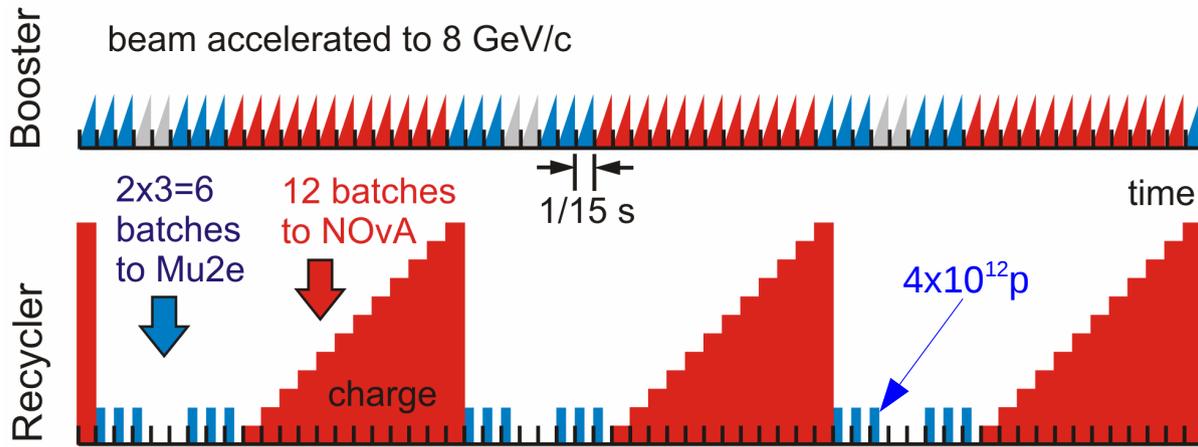


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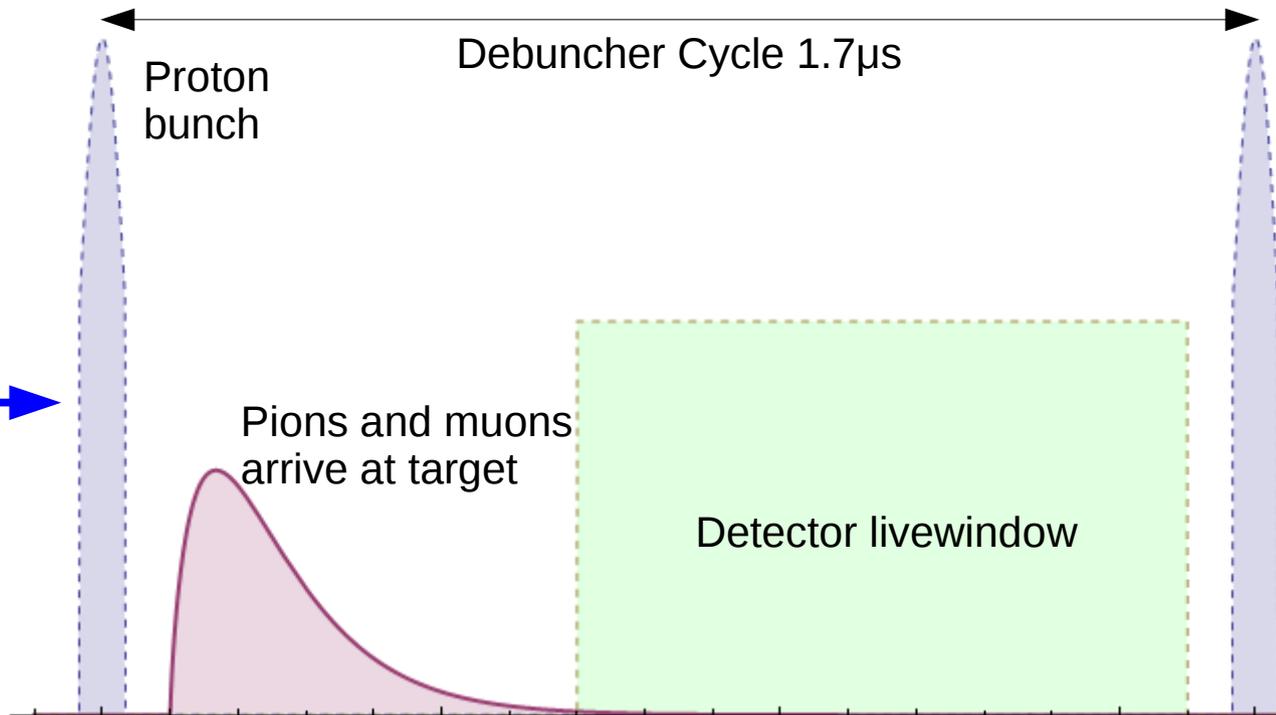


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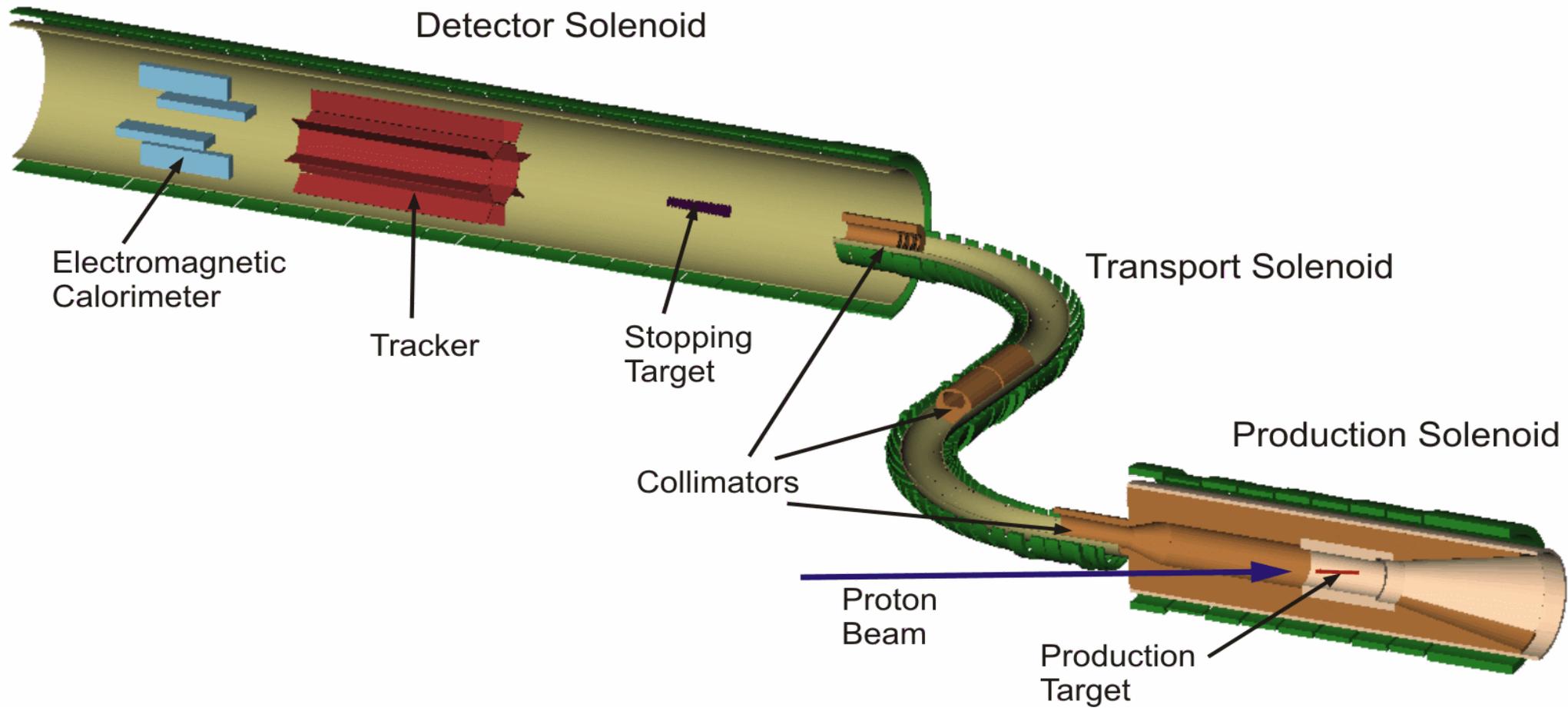


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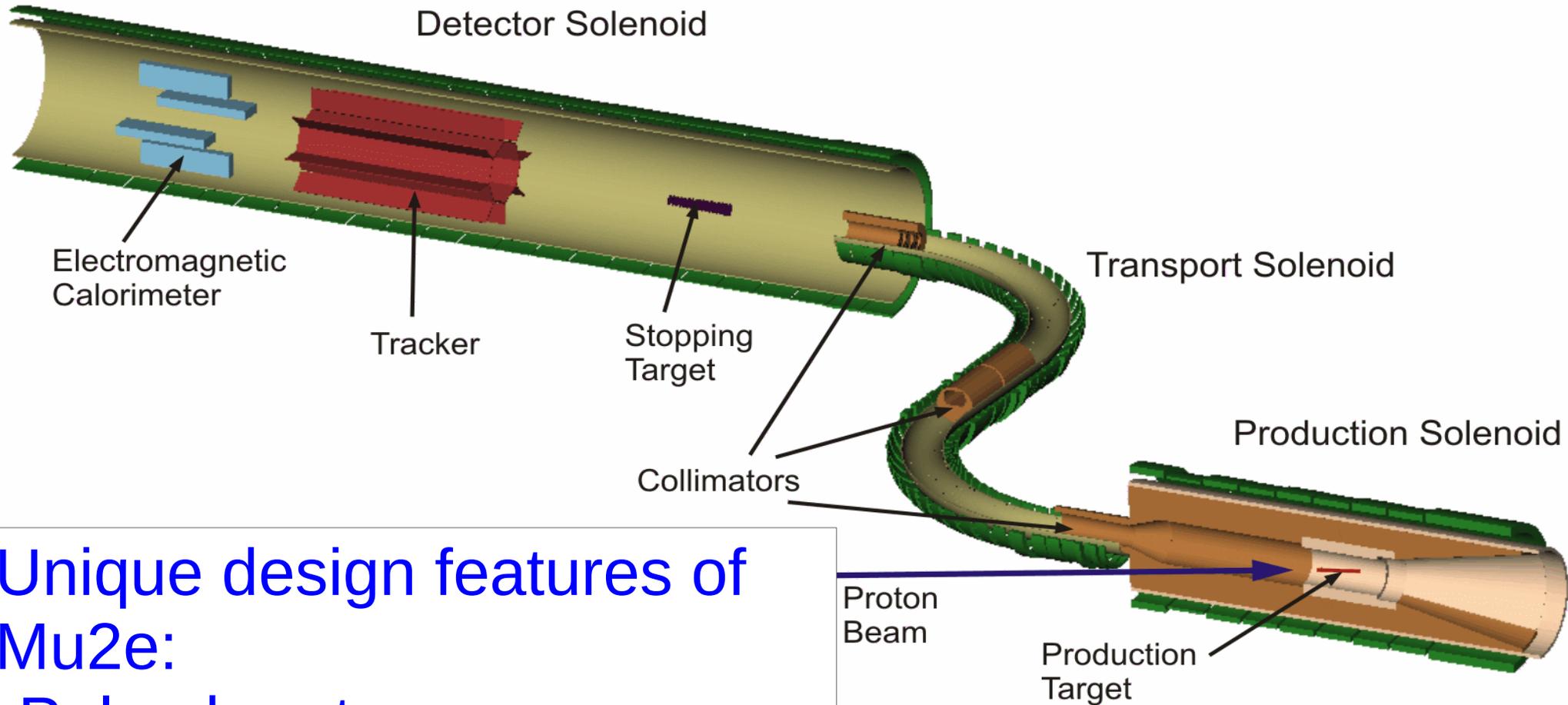
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# What goes in the hall?



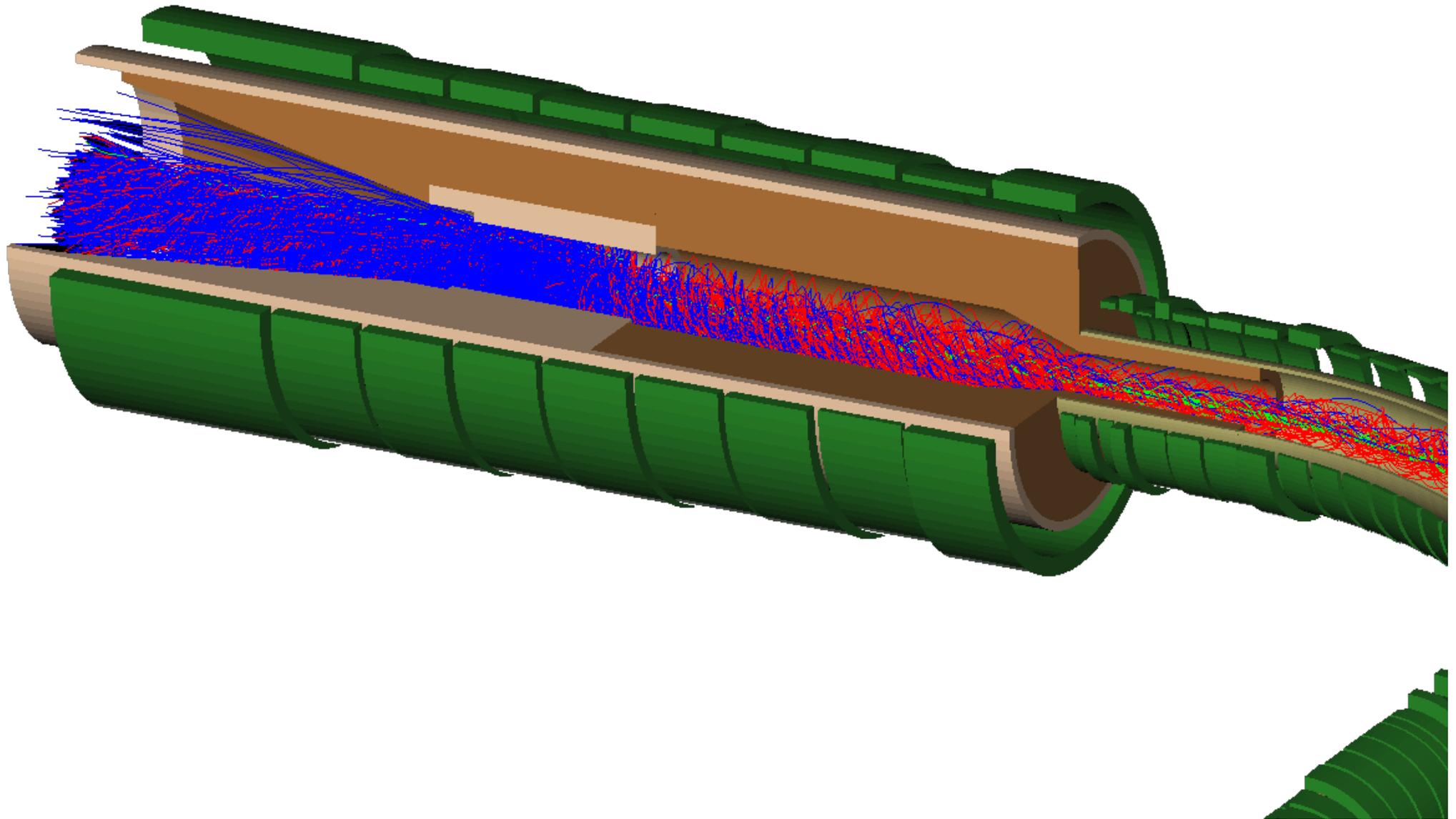
# What goes in the hall?



## Unique design features of Mu2e:

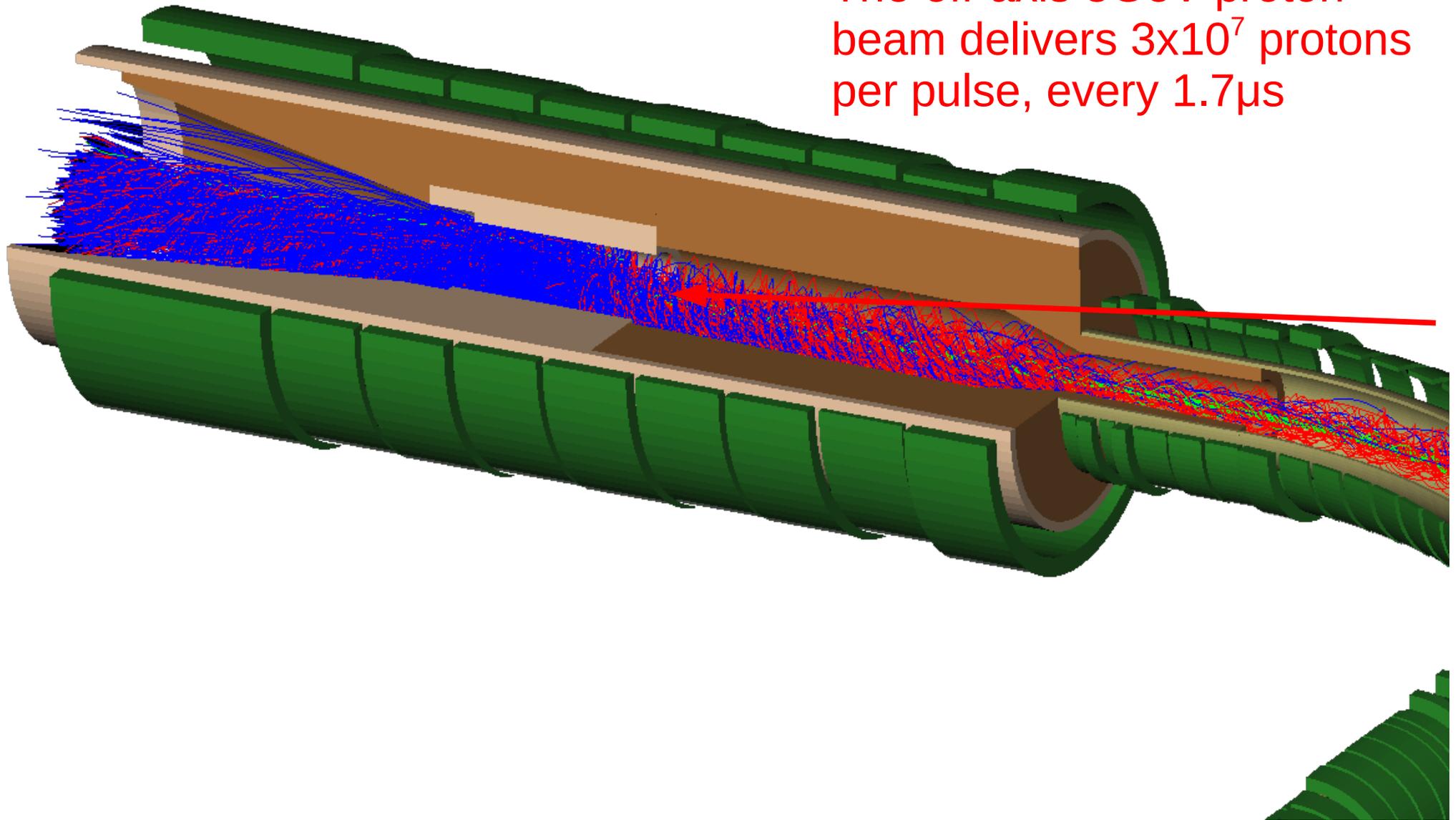
- Pulsed proton source
- Curved transport solenoid
- Graded production and detector solenoid fields

# Muon production solenoid



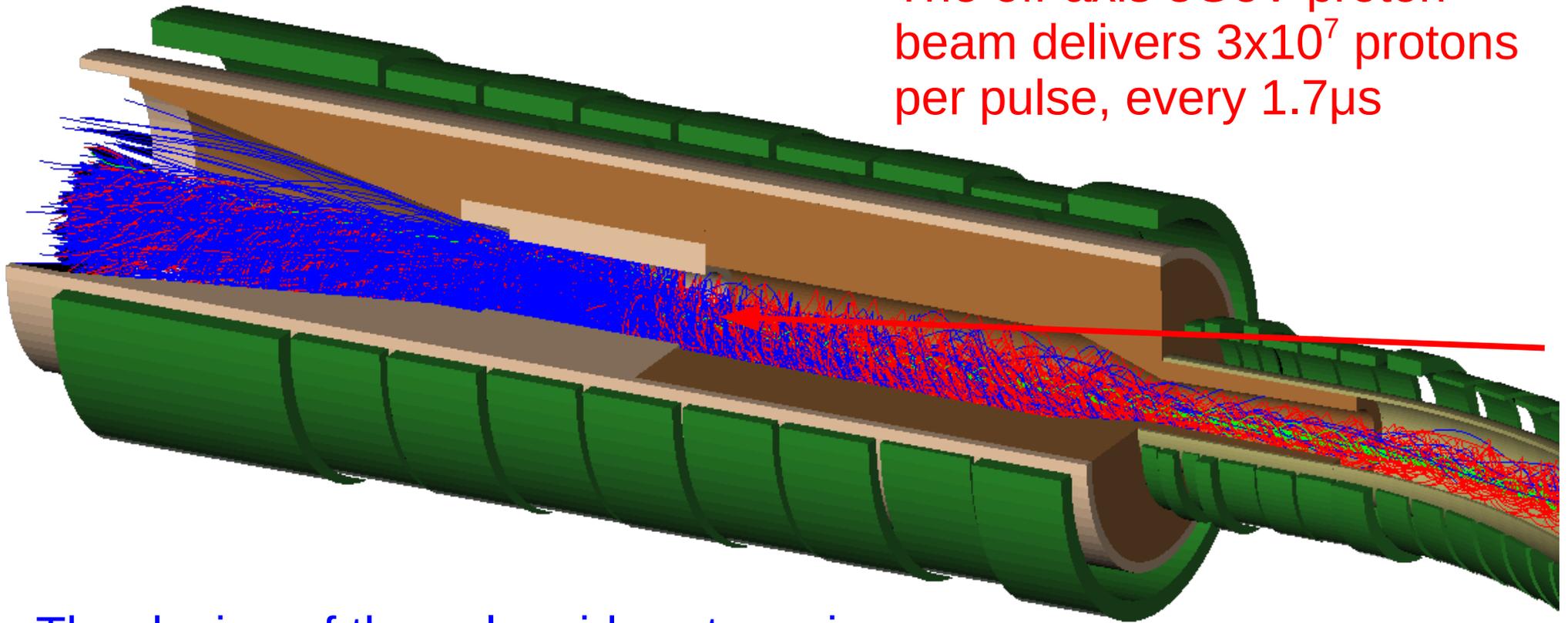
# Muon production solenoid

The off-axis 8GeV proton beam delivers  $3 \times 10^7$  protons per pulse, every  $1.7 \mu\text{s}$



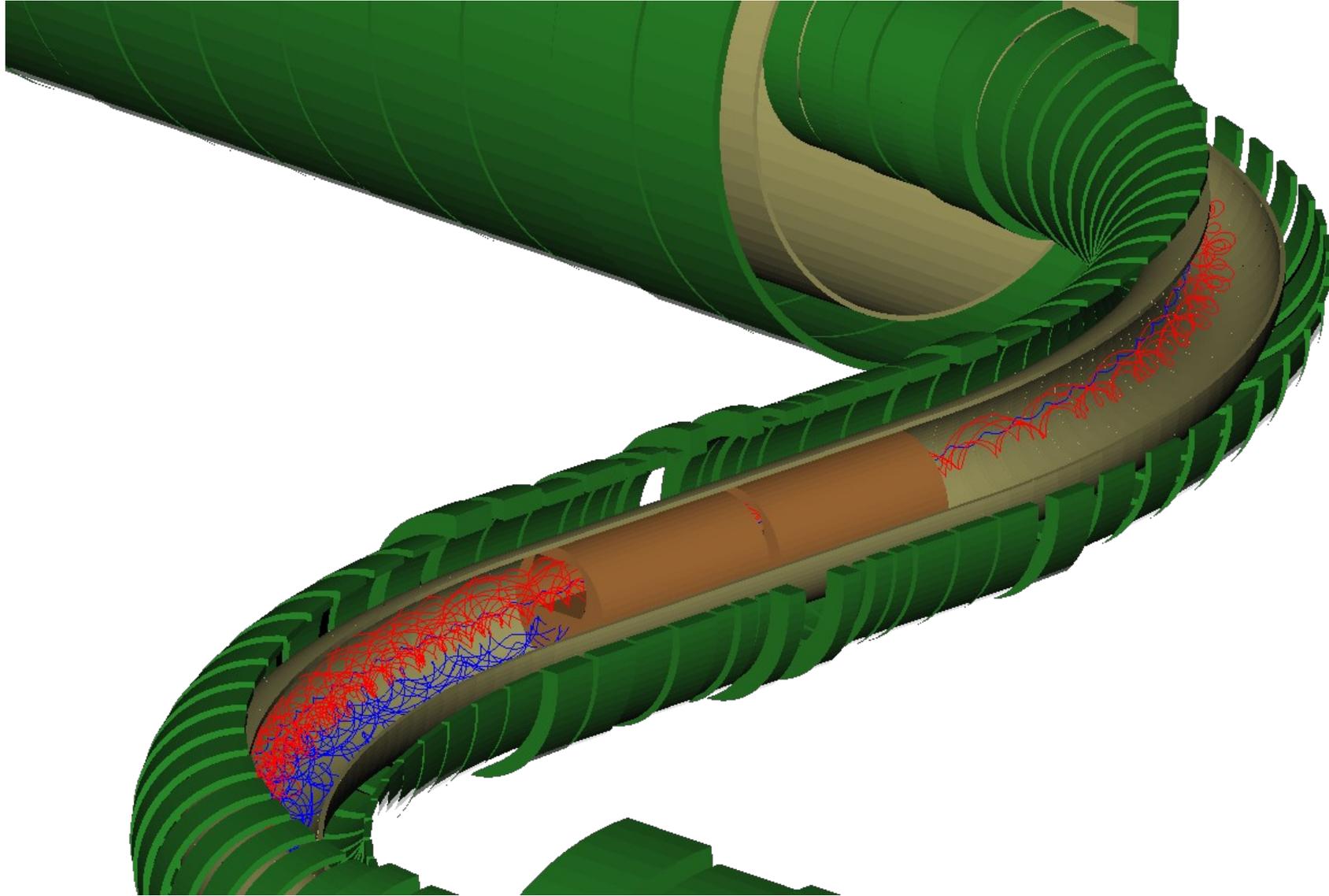
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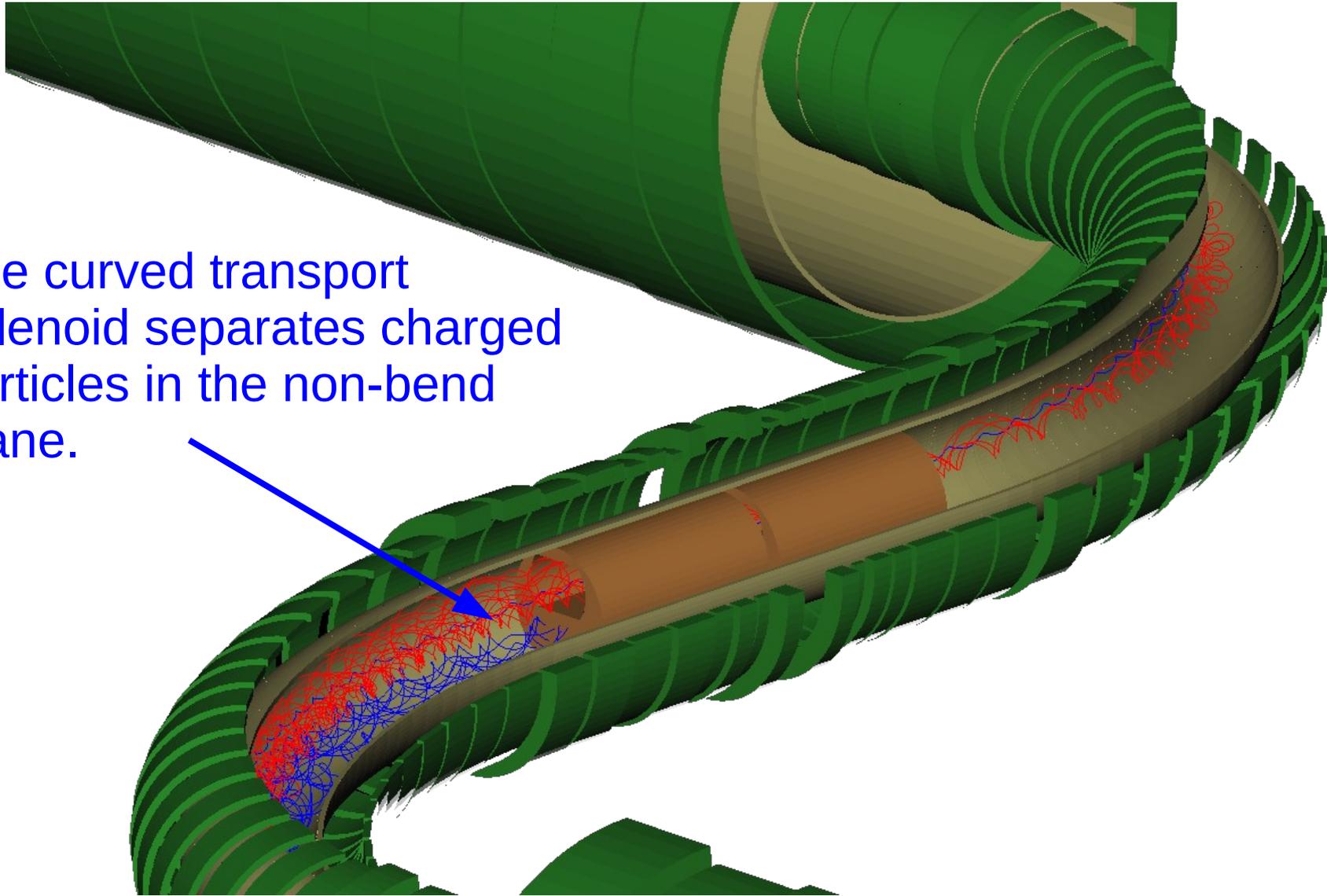
The design of the solenoid systems is a collaborative effort among TD, AD, and Physicists: “It's not just a big gizmo for TD to build ... we need University people to get involved!”

# Transport solenoid



# Transport solenoid

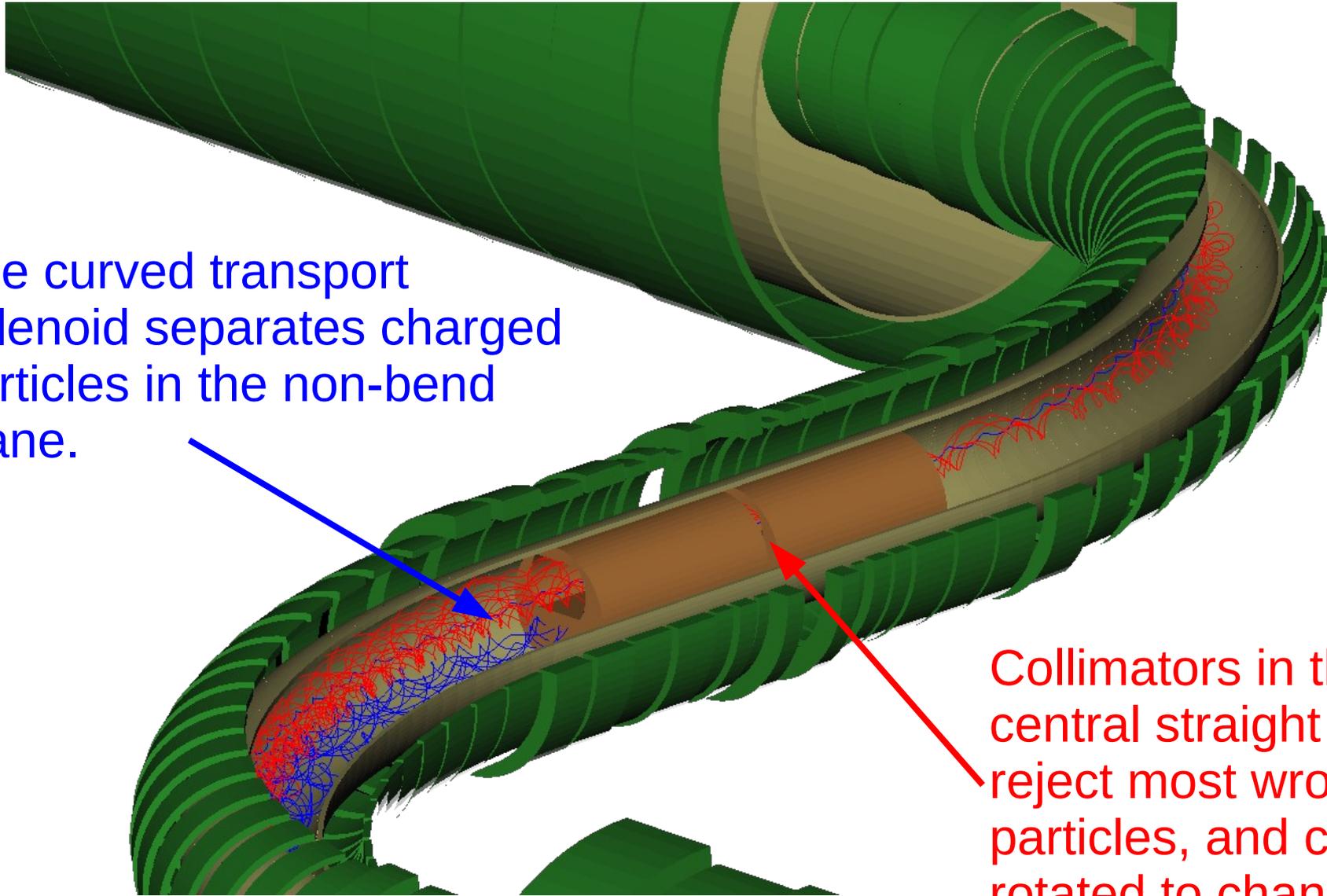
The curved transport solenoid separates charged particles in the non-bend plane.



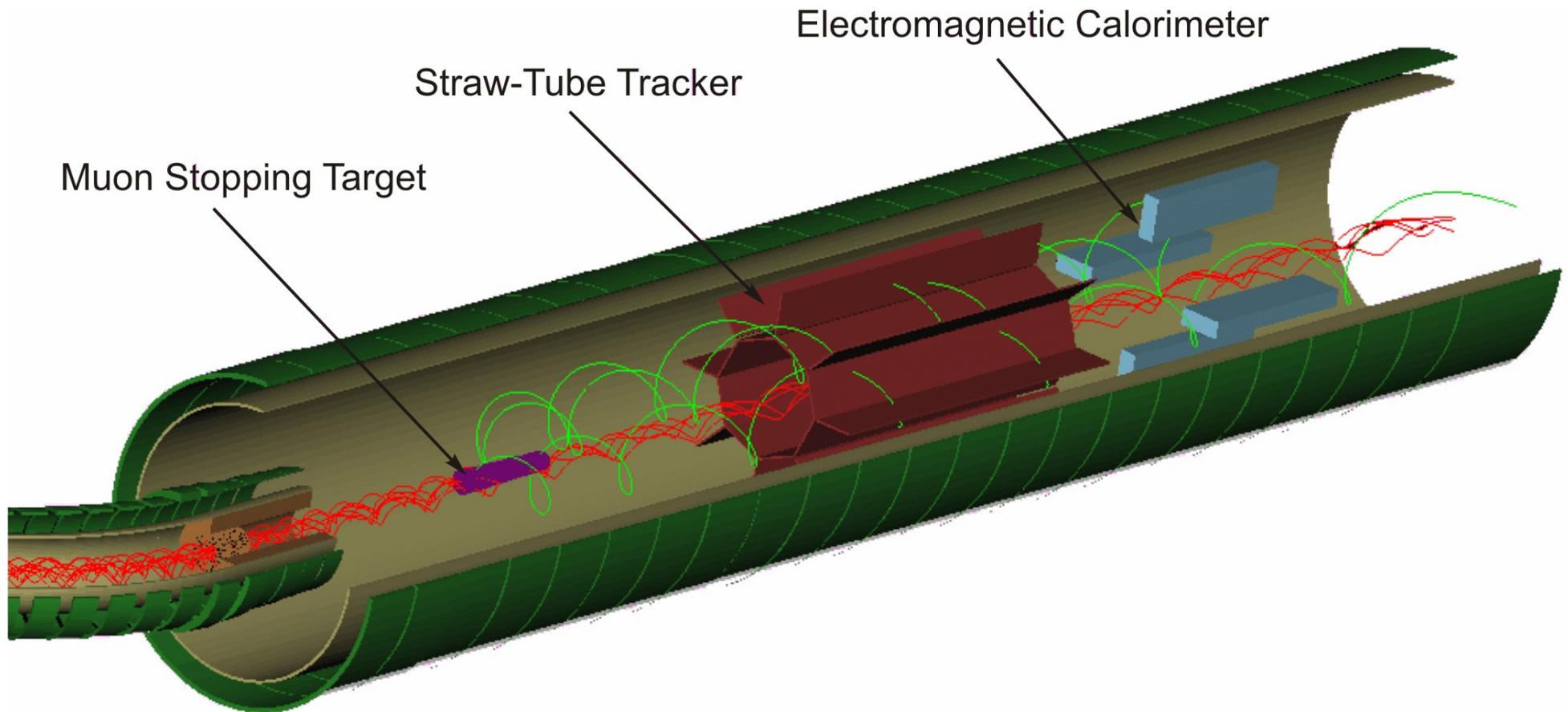
# Transport solenoid

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

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

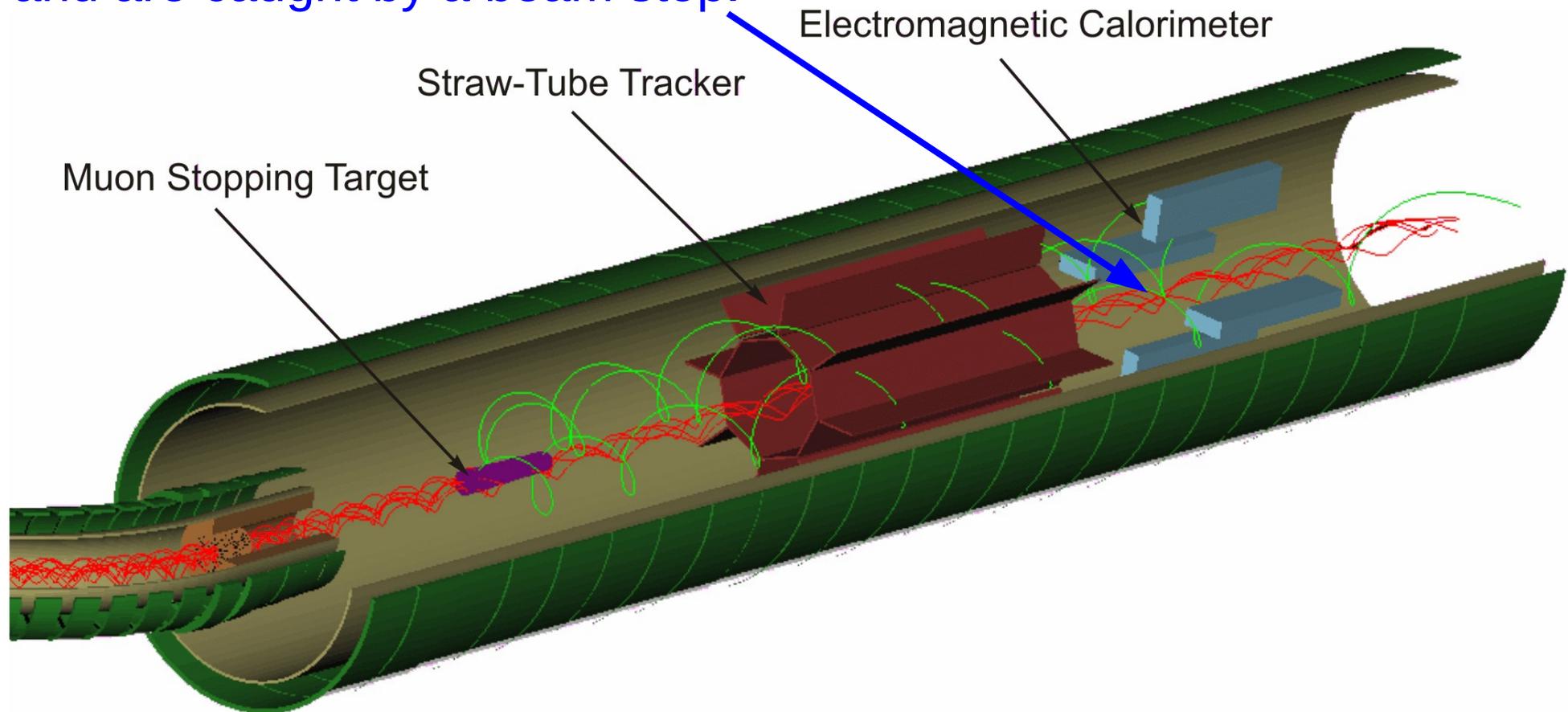


# The detector solenoid and stopping target



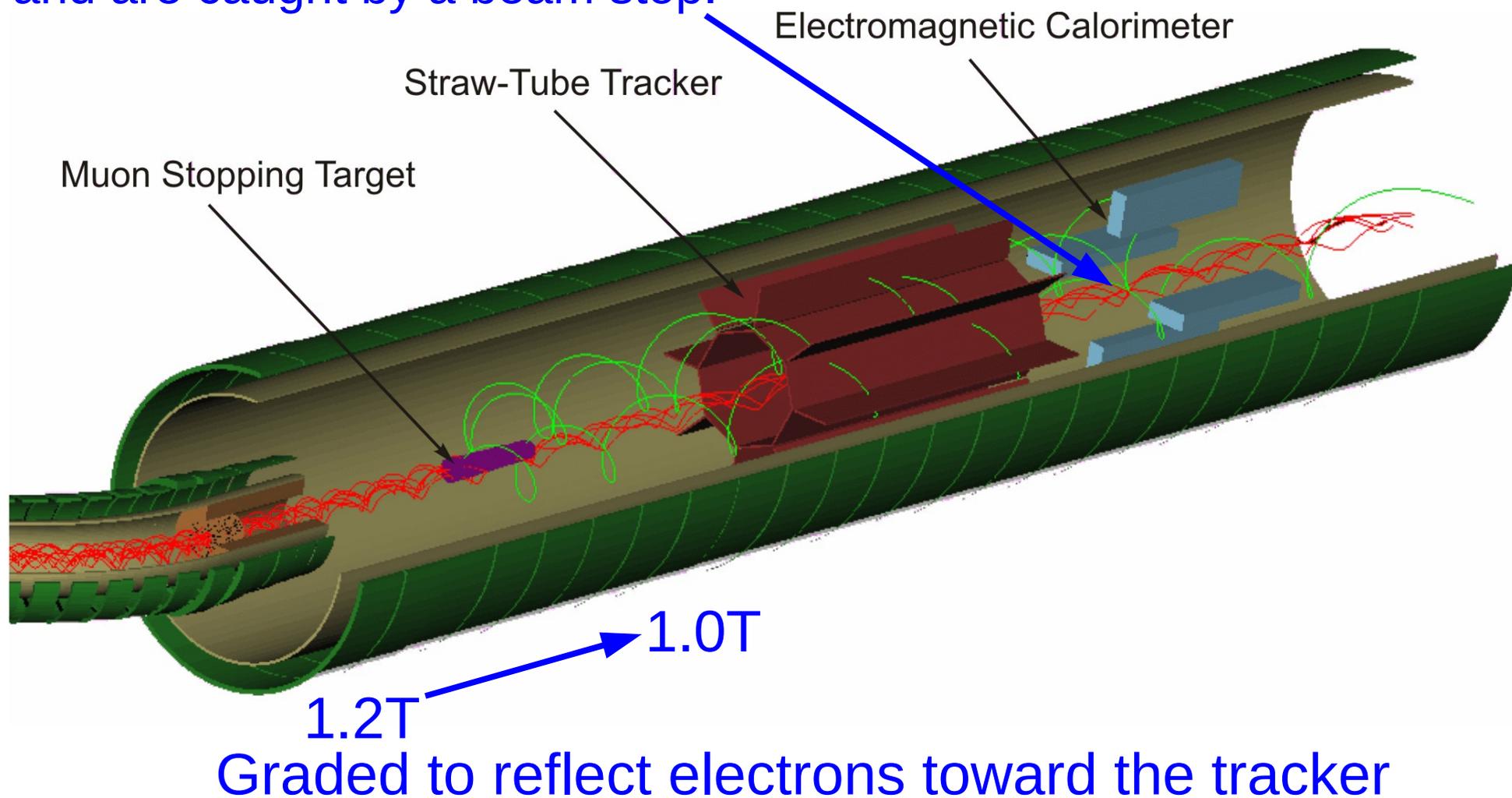
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The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.



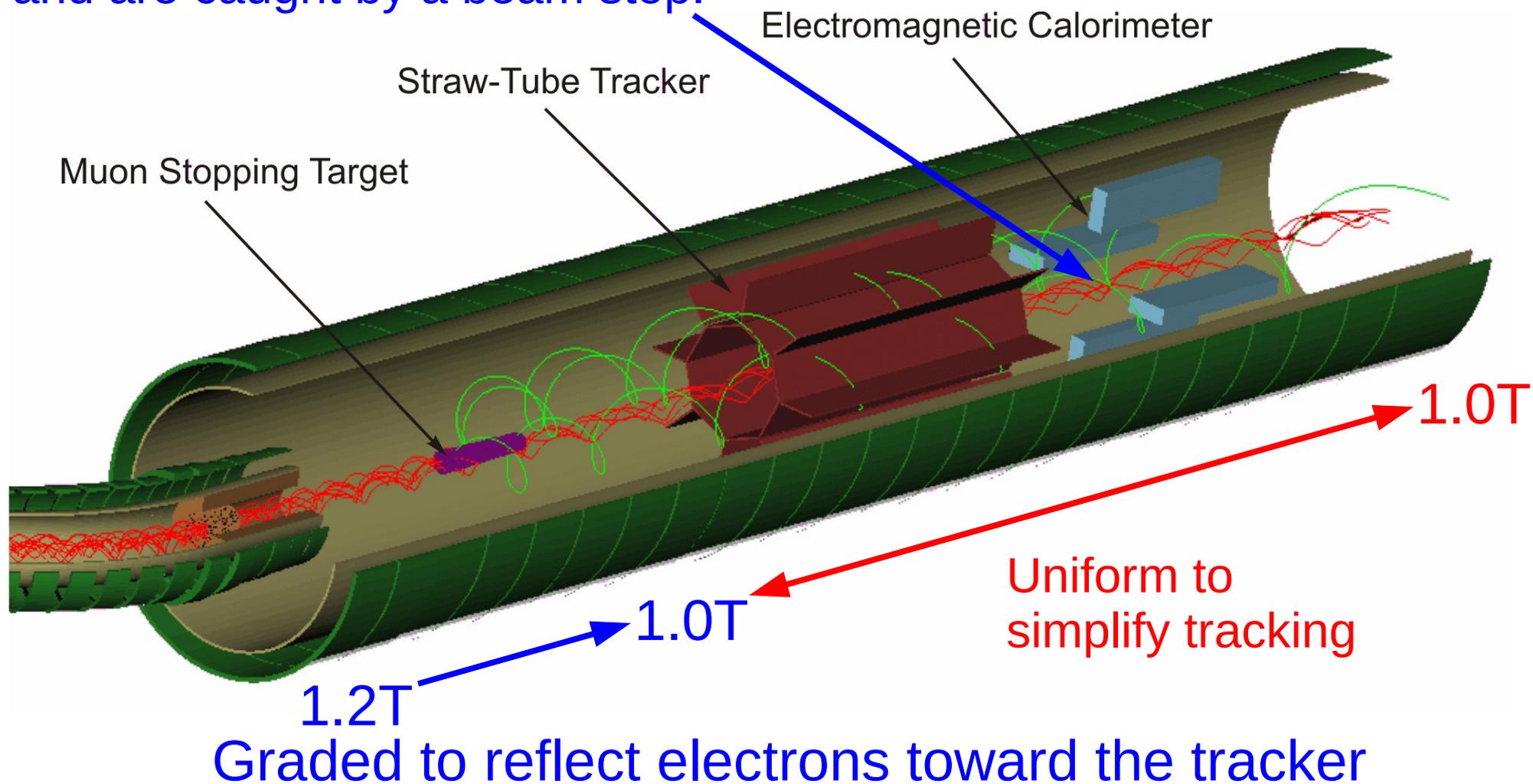
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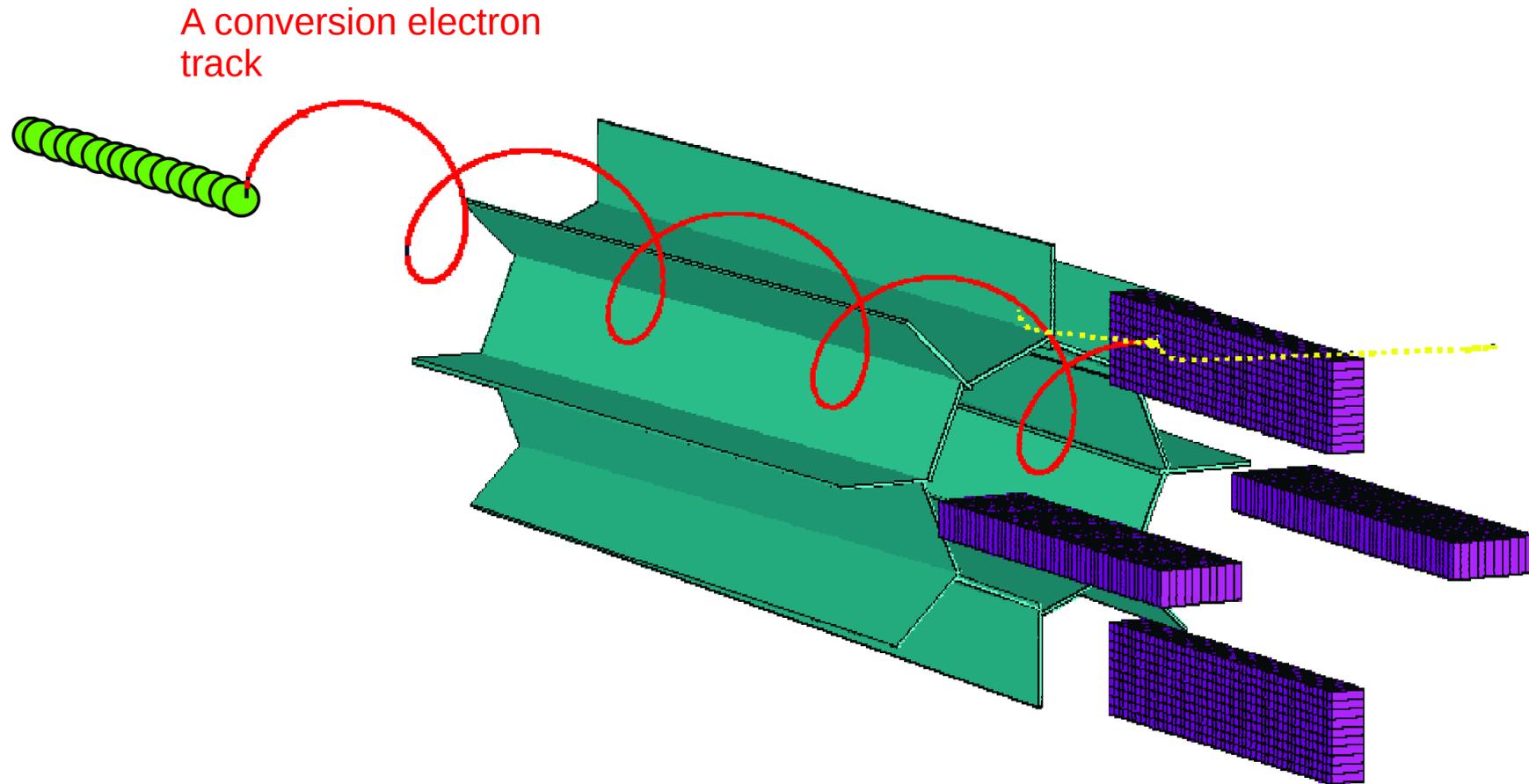


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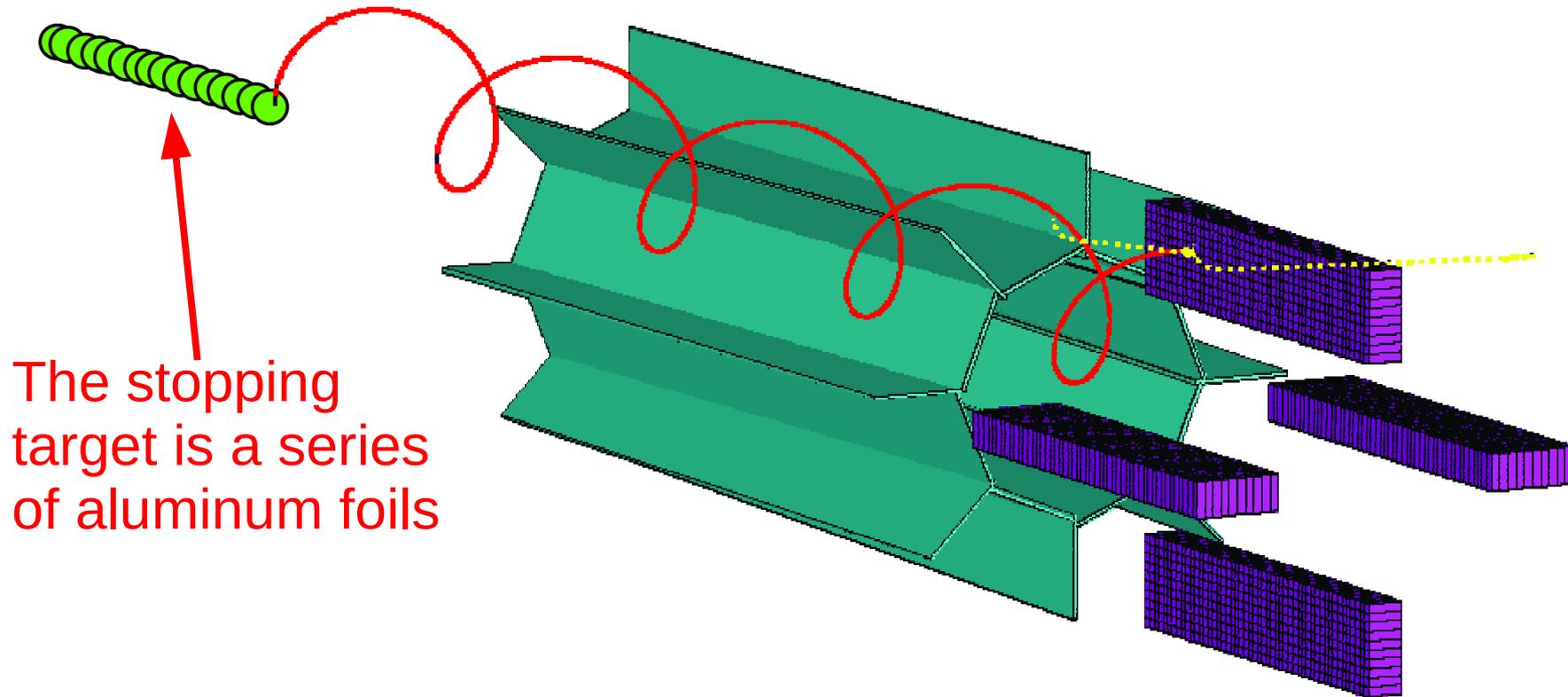


# The target and detectors



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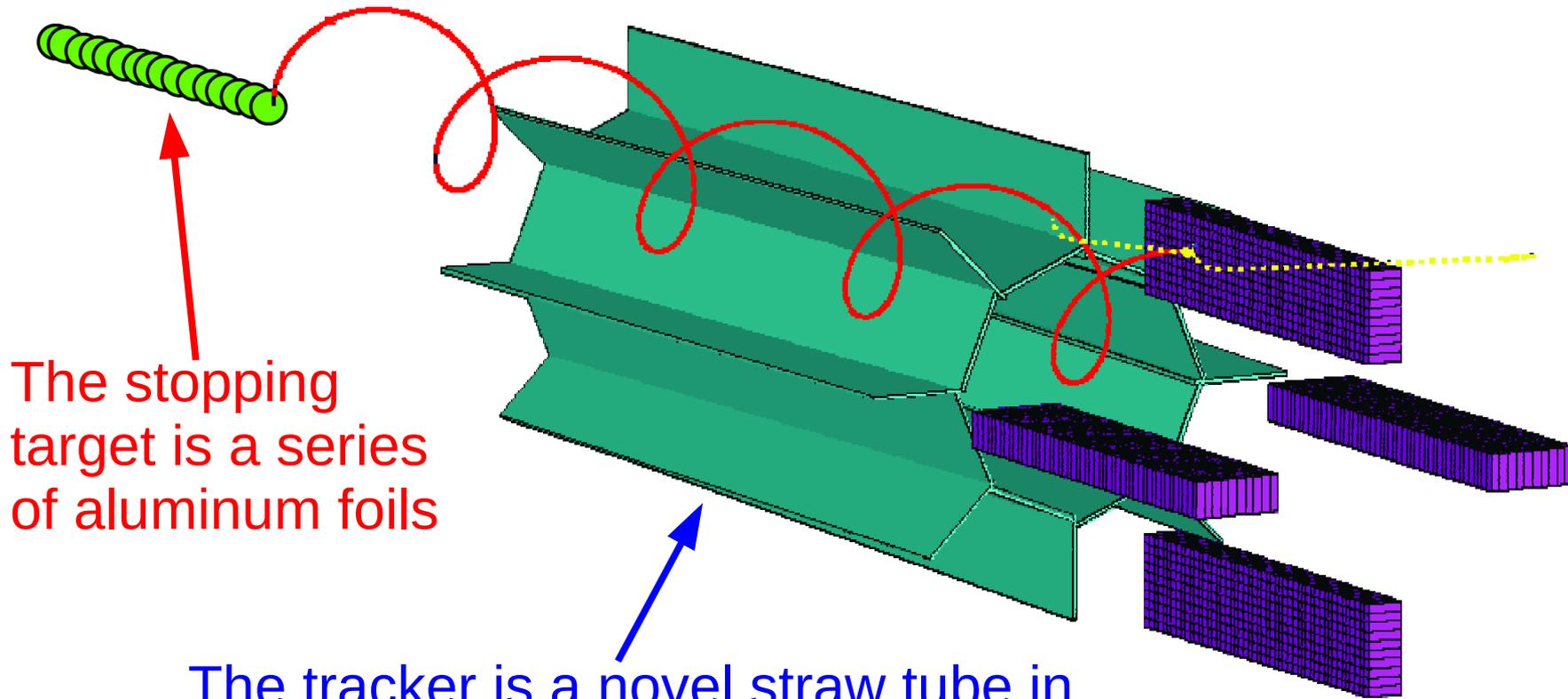
A conversion electron track



The stopping target is a series of aluminum foils

# The target and detectors

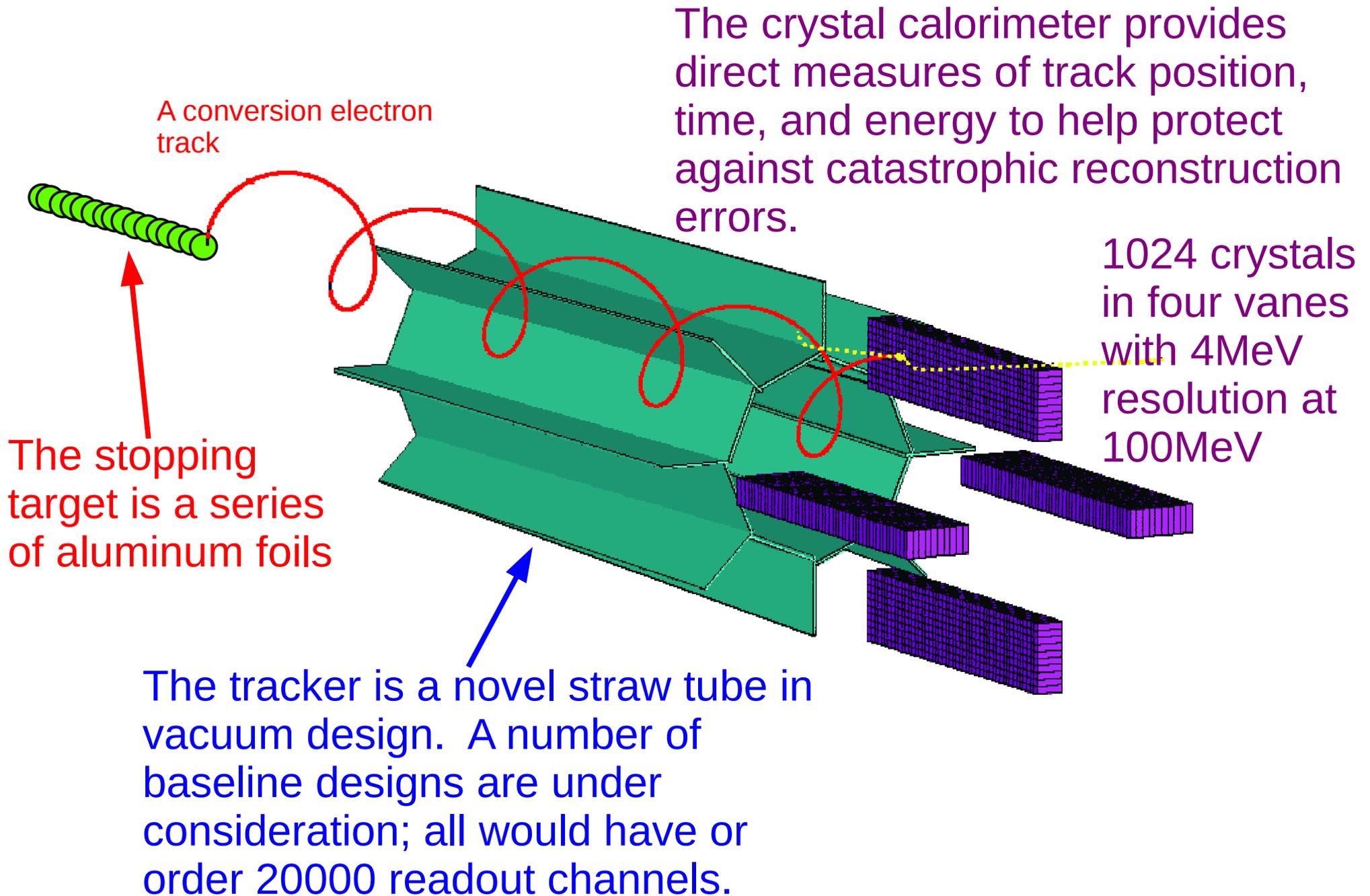
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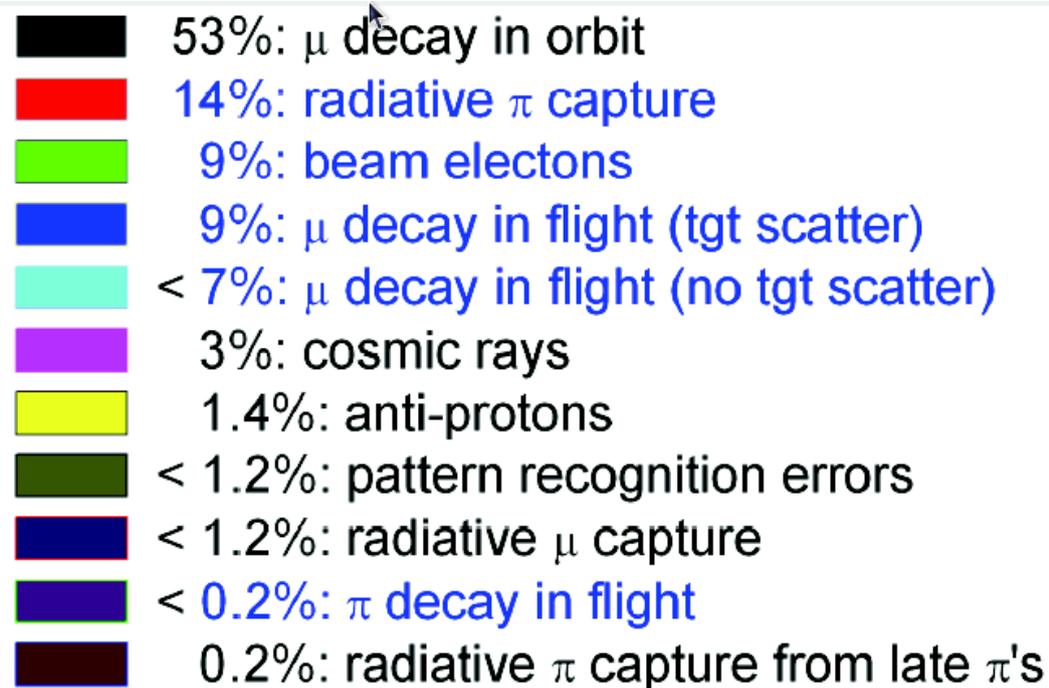
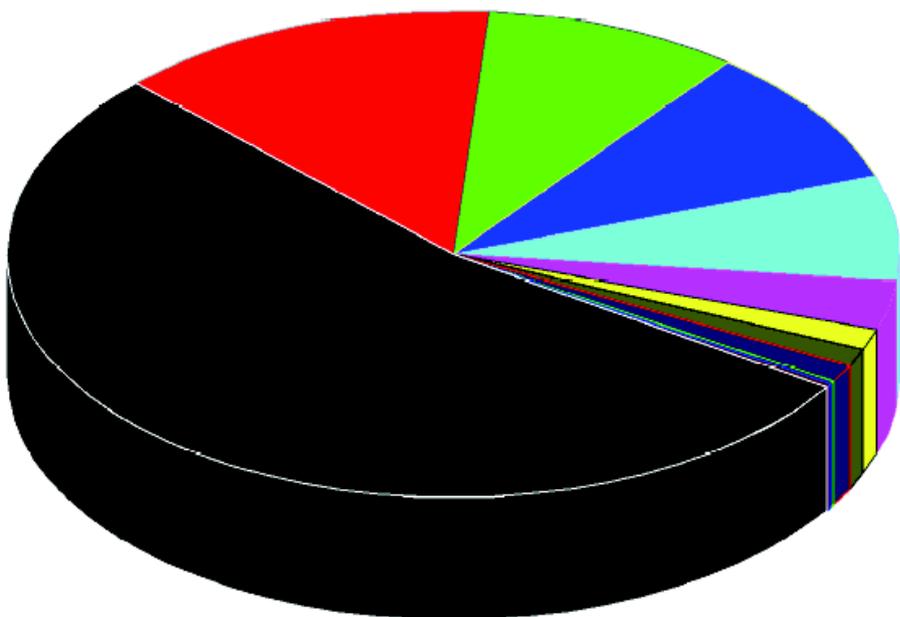
The tracker is a novel straw tube in vacuum design. A number of baseline designs are under consideration; all would have or order 20000 readout channels.

# The target and detectors



With this design, the background rates are indeed very small!

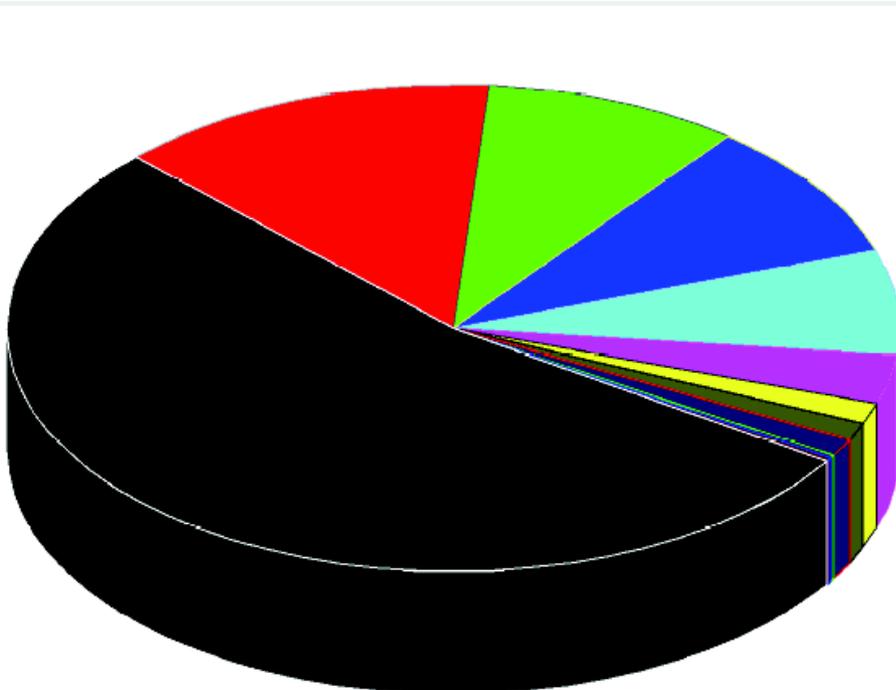
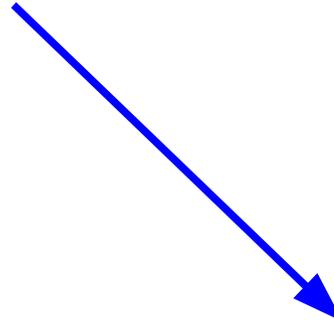
Background	Events per $2 \times 10^7$ s
$\mu$ DIO	0.225
Radiative $\pi$ capture	0.072
$\mu$ DIF	0.072
Scattered beam e	0.035
<b>Total</b>	<b>0.41</b>



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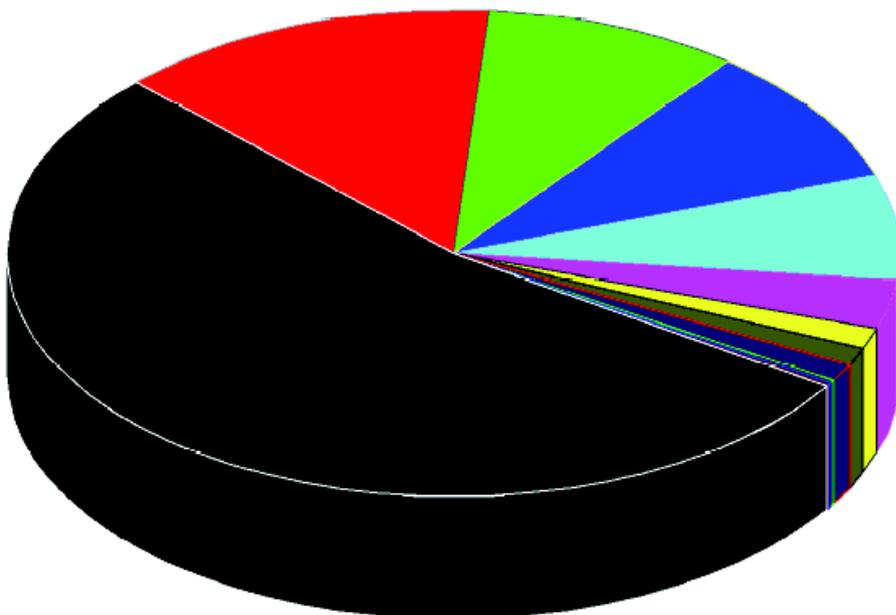
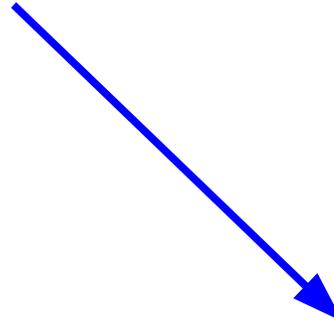
- 53%:  $\mu$  decay in orbit
- 14%: radiative  $\pi$  capture
- 9%: beam electrons
- 9%:  $\mu$  decay in flight (tgt scatter)
- < 7%:  $\mu$  decay in flight (no tgt scatter)
- 3%: cosmic rays
- 1.4%: anti-protons
- < 1.2%: pattern recognition errors
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- 0.2%: radiative  $\pi$  capture from late  $\pi$ 's

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In two years of running, we expect fewer than one background event in the signal region.

If  $R_{\mu e} = 10^{-15}$ , we will see 40 signal events

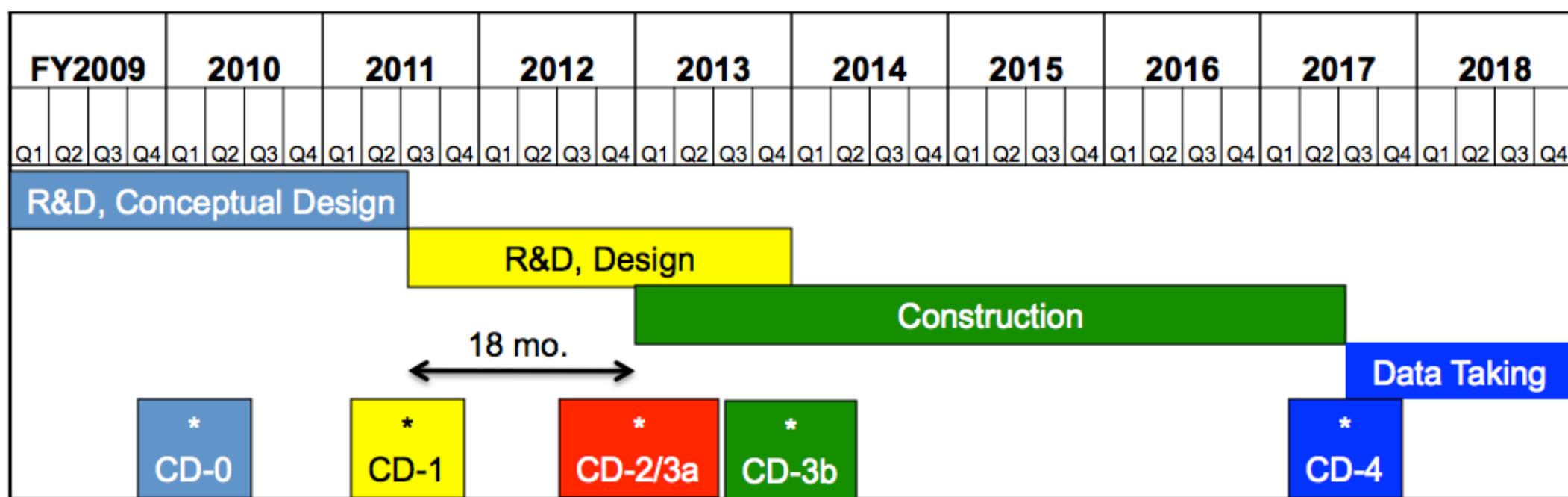
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# The schedule is technically driven

- We have received both Stage 1 approval and CD-0.
- Magnet design and construction remain the schedule drivers.



# Summer 2010 R&D

- Tracker Development
  - Straw thickness and composition
  - Winding and sealing
  - Time/charge division and TDC/ADC evaluation
- Simulation and software
- Cosmic Ray Veto
  - Efficiency
- Extinction Monitor
  - Studying SiPMs
- Calorimeter studies
- Solenoid design



In the Project X era ...

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... beam power will increase 10-100 fold. Mu2e naturally extends into this era, regardless of the first generation results.

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## With no signal

- All backgrounds must be further suppressed to reach  $R_{\mu e}$  of  $10^{-18}$
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## With no signal

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## If we do see a signal

- Change target material to determine structure of new physics amplitudes
- All detector and transport systems will need upgrades to handle the higher rates

# Please join us!

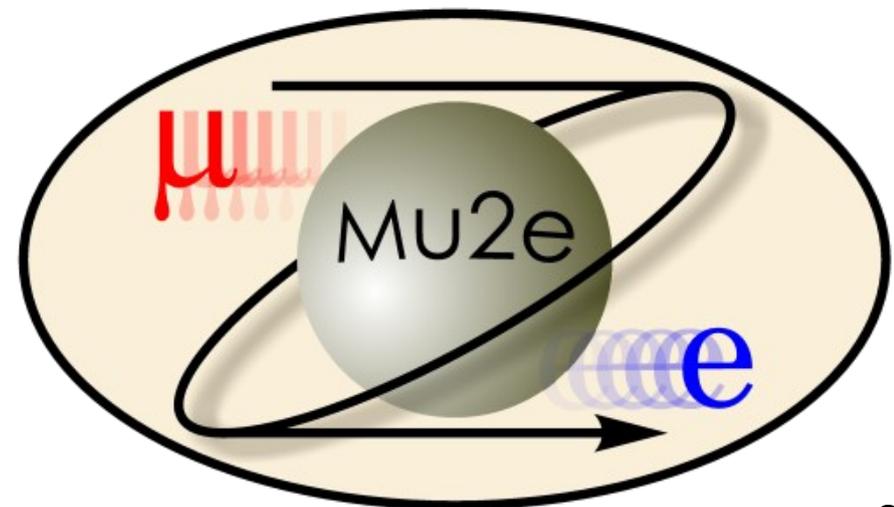
- Boston University
- Brookhaven National Laboratory
- City University of New York
- College of William & Mary
- Fermi National Accelerator Laboratory
- Idaho State University
- Istituto Nazionale di Fisica Nucleare, Lecce
- Istituto Nazionale di Fisica Nucleare, Pisa
- Institute for Nuclear Research, Moscow
- Joint Institute for Nuclear Research, Dubna

- Laboratori Nazionali di Frascati
- Los Alamos National Laboratory
- Muons Inc.
- Northwestern University
- Rice University
- Syracuse University
- University of California, Berkeley
- Lawrence Berkeley National Laboratory
- University of California, Irvine
- University of Illinois
- University of Massachusetts, Amherst
- University of Virginia

Contact:

**Bob Bernstein**, [rhbob@fnal.gov](mailto:rhbob@fnal.gov),  
or

**Jim Miller**, [miller@bu.edu](mailto:miller@bu.edu).



Backup Slides

We normalize the conversions with the captures

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

Events in signal window

Acceptance for signal events

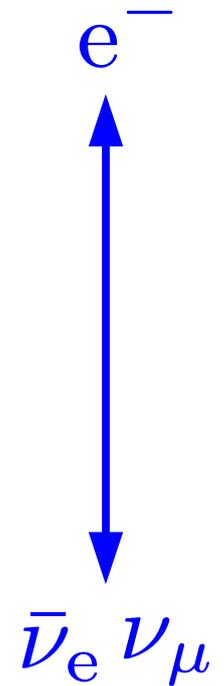
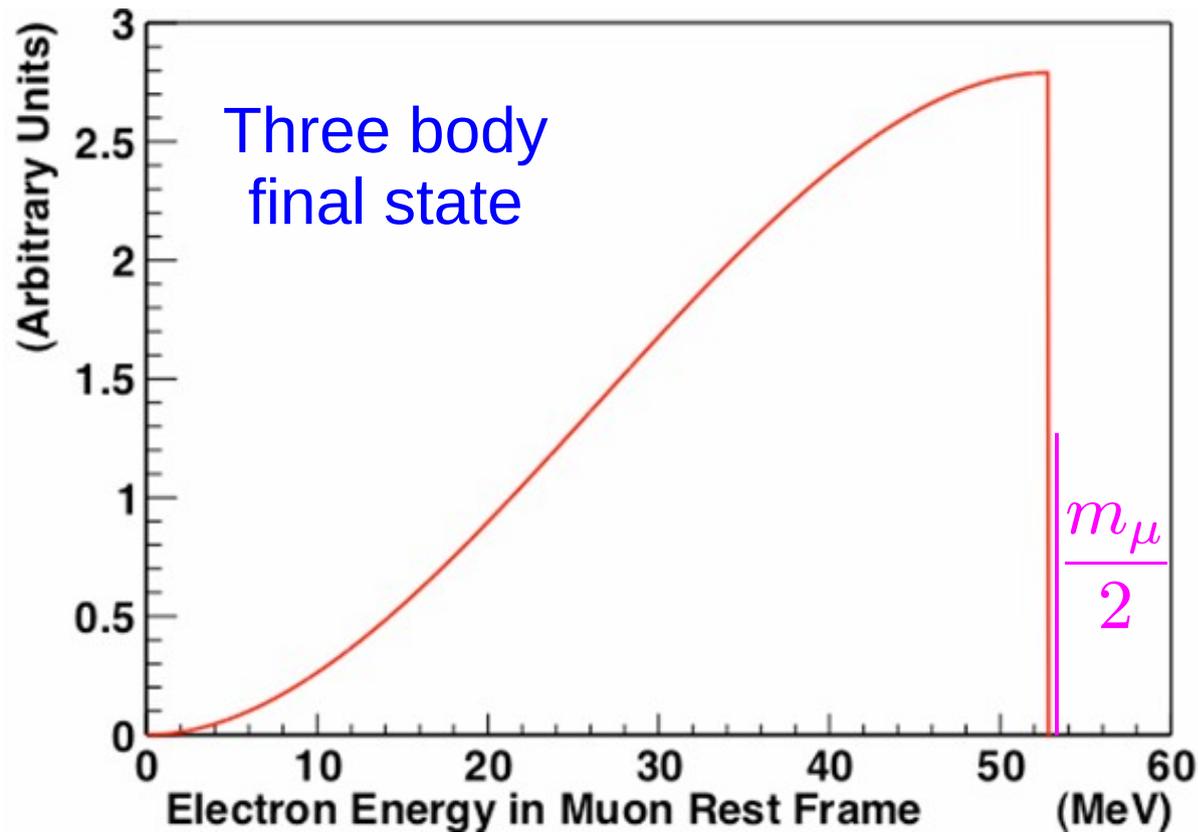
$$= \frac{N_{\mu e} / \epsilon_{\mu e}}{N_{\text{stops}} / \epsilon_{\text{stops}} (\Gamma_{\mu\nu} / \Gamma_{\text{total}})}$$

Directly measured via cascade X-Rays

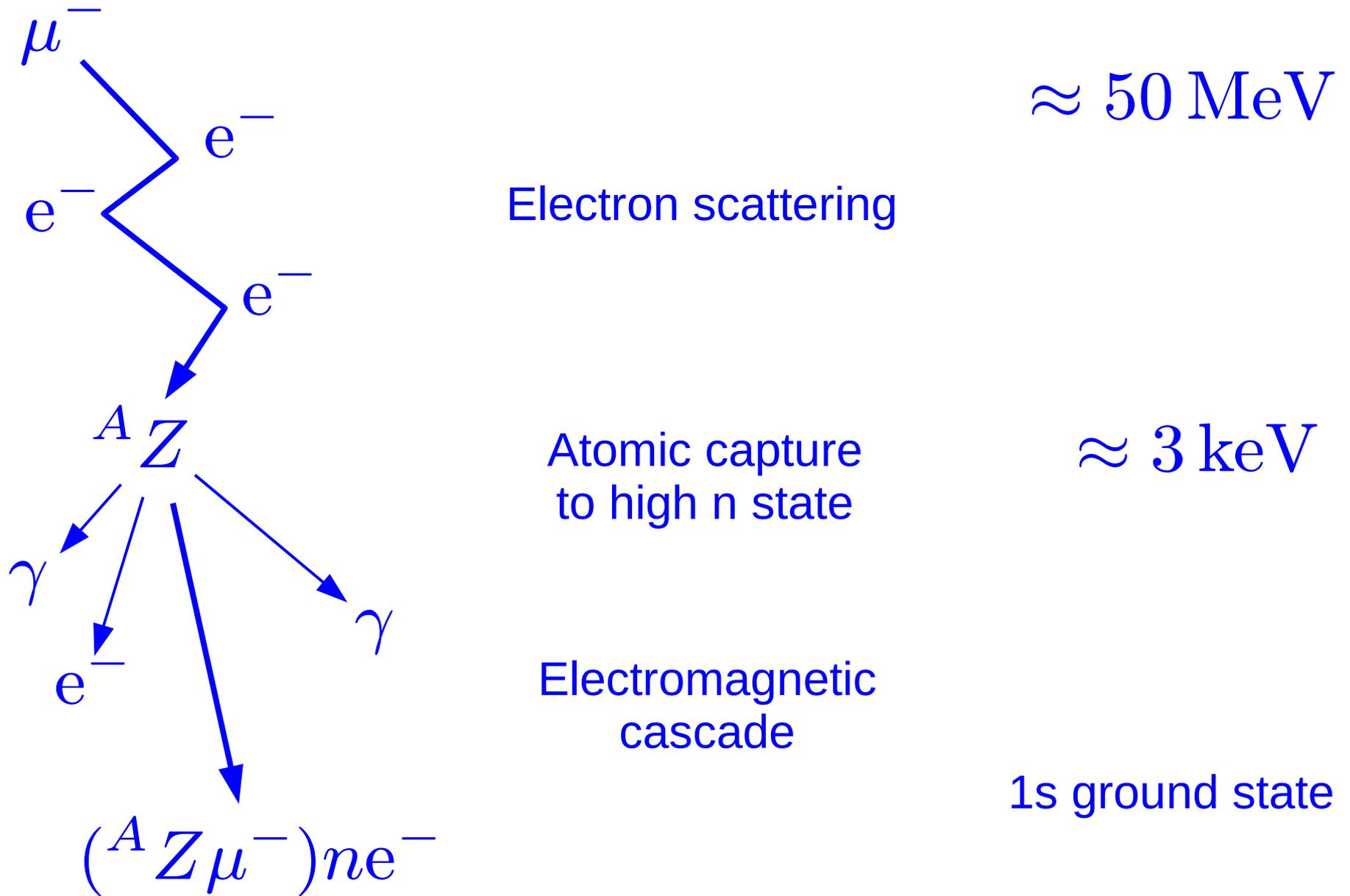
Well known nuclear capture ratio

# Muon Decay-in-Orbit

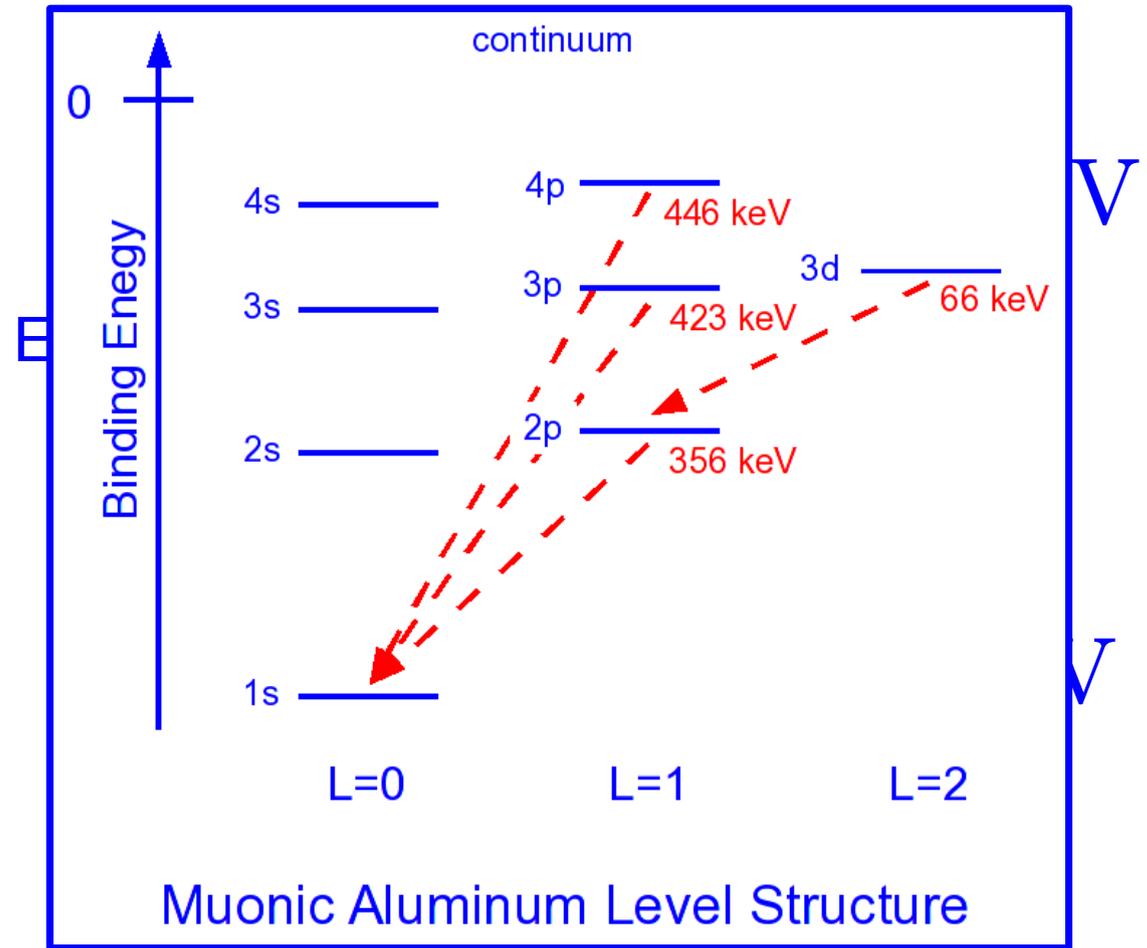
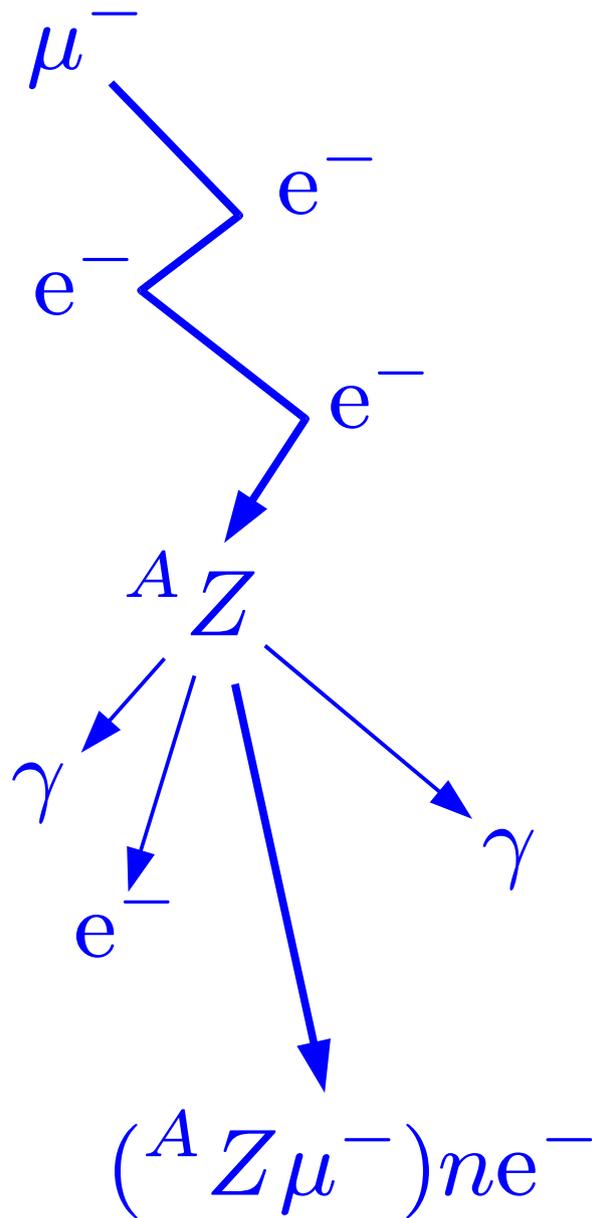
First, consider the free decay



# Negative muon stopping in matter



# Negative muon stopping in matter



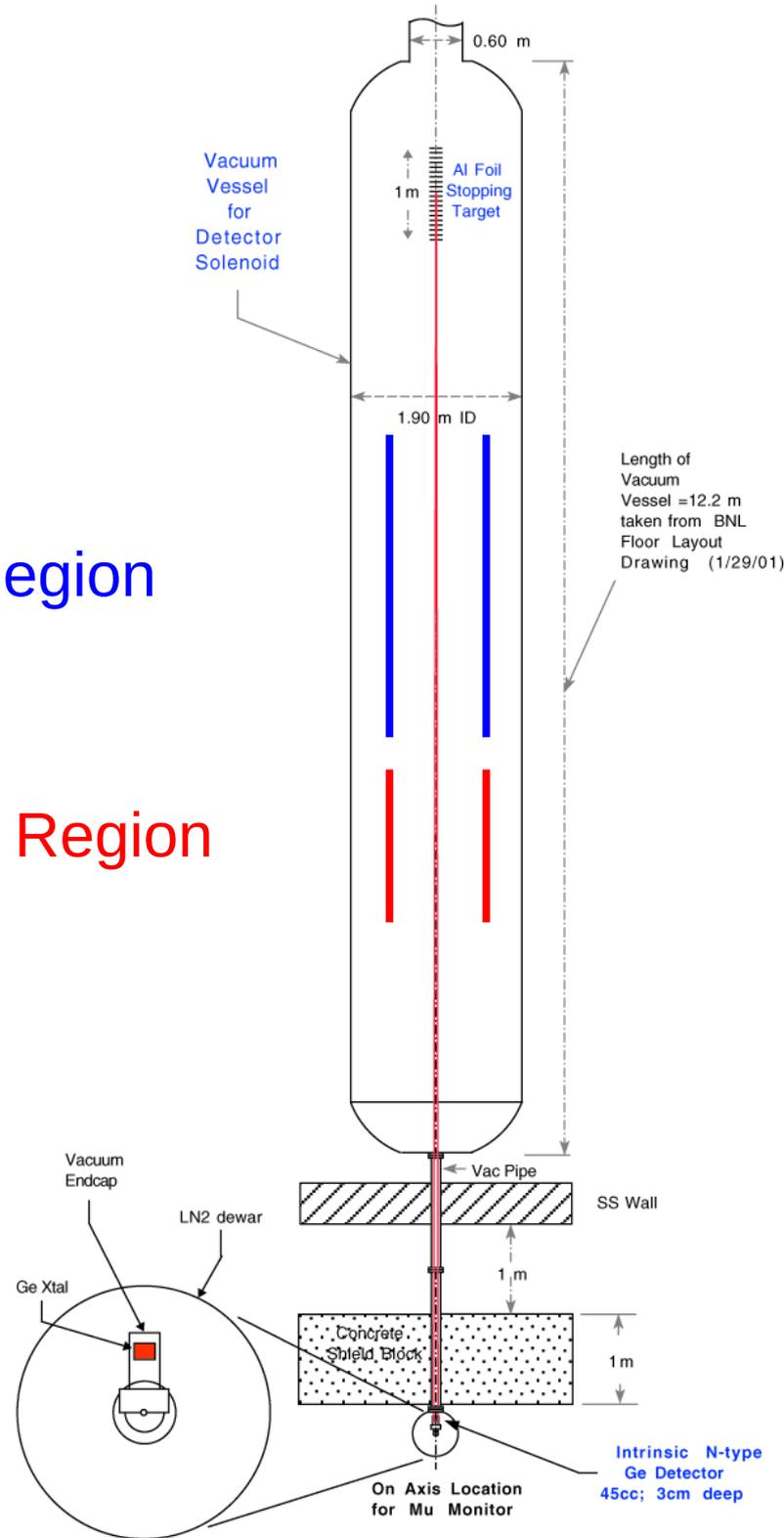
Electromagnetic cascade

1s ground state

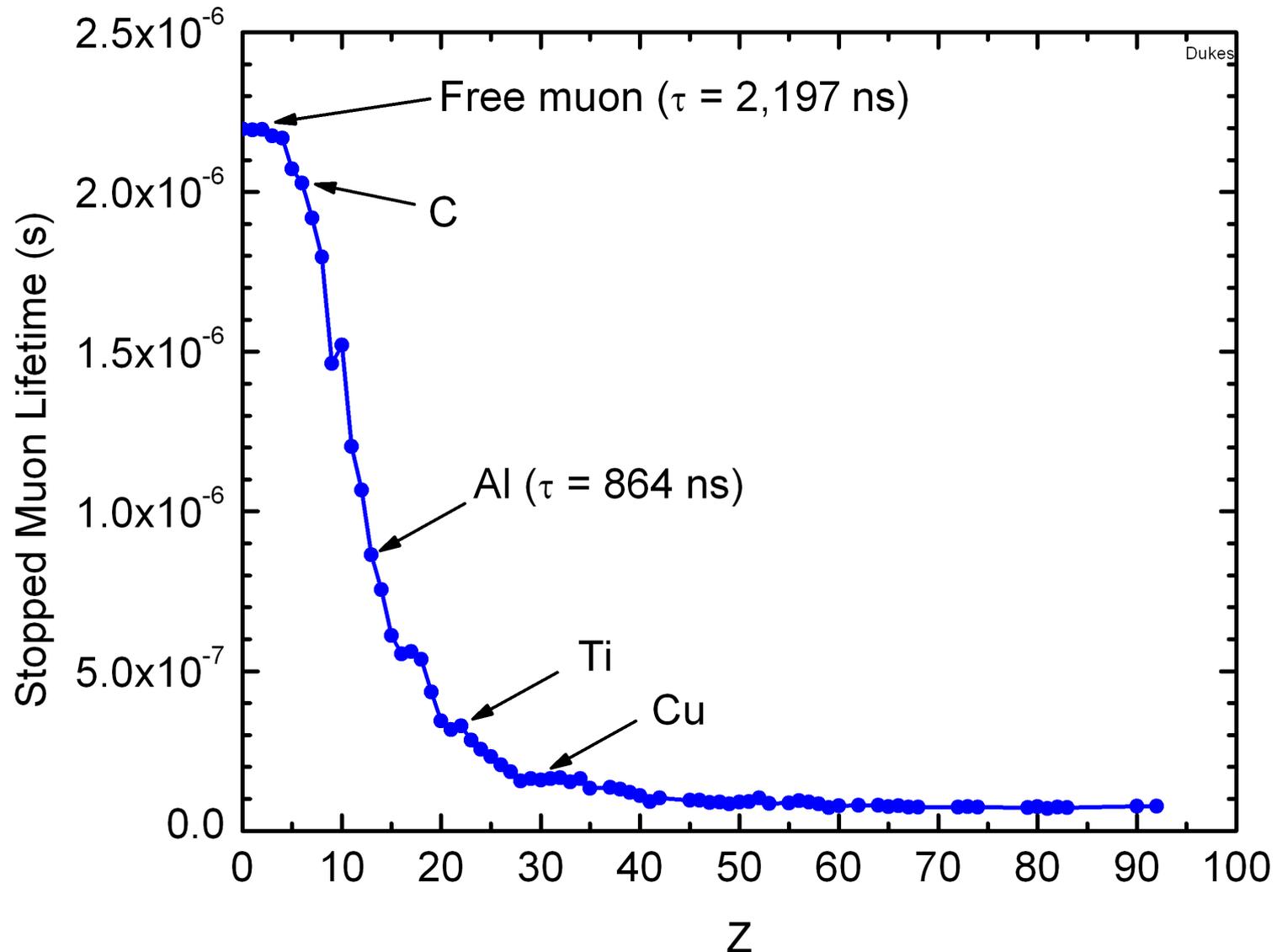
# Monitoring the muon stopping rate

Tracker Region

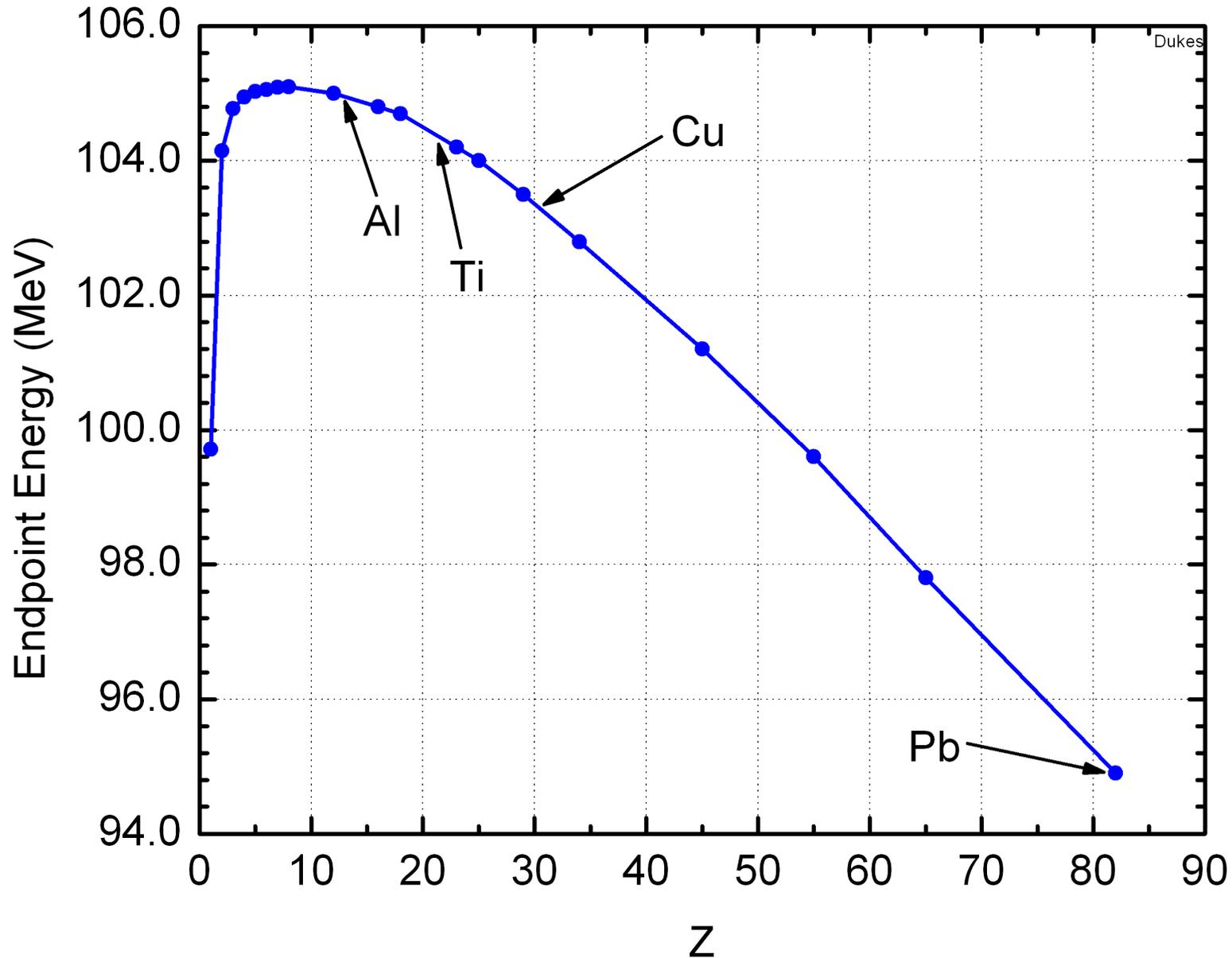
Calorimeter Region



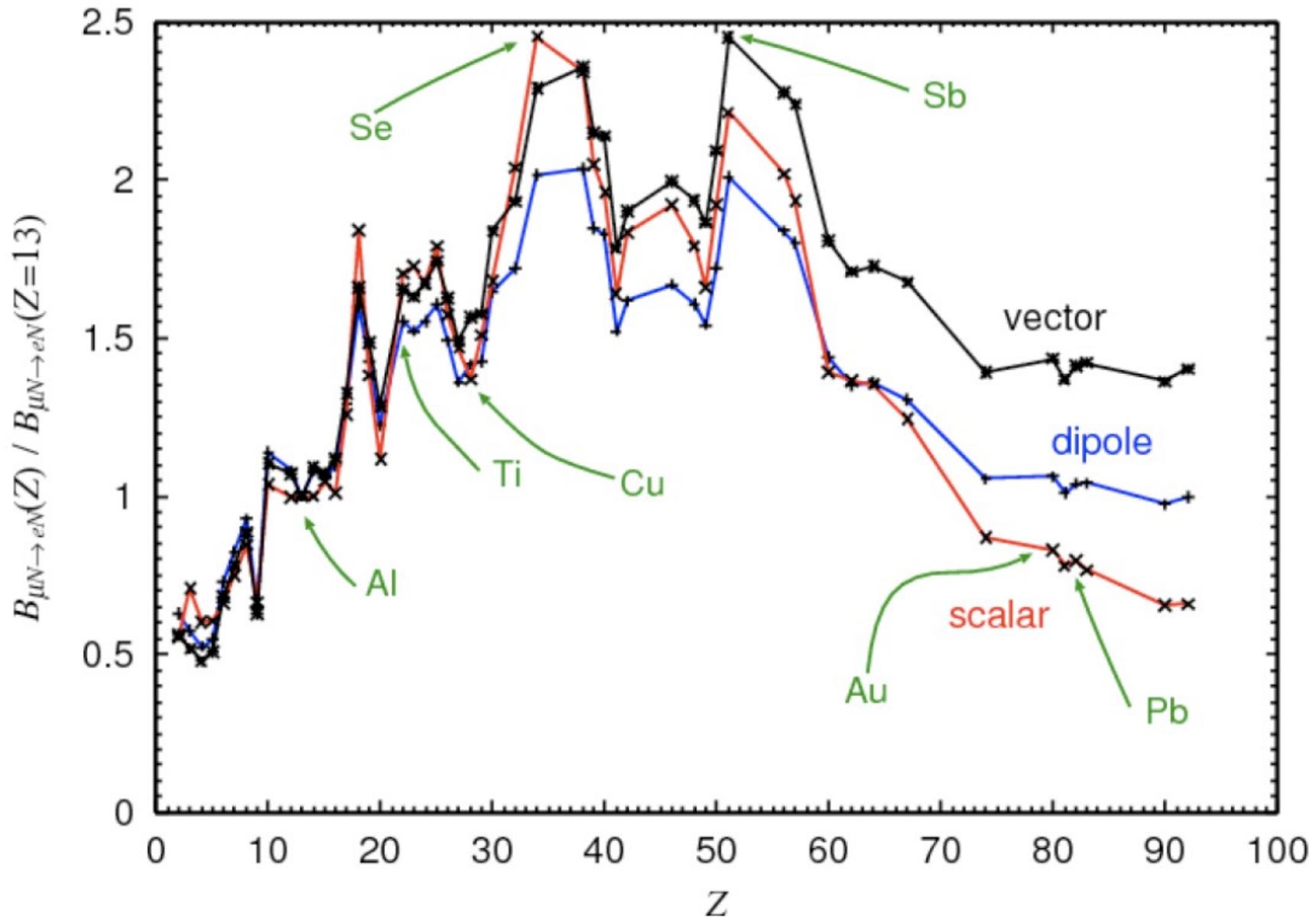
# The choice of Al is well matched to the FNAL beam time structure



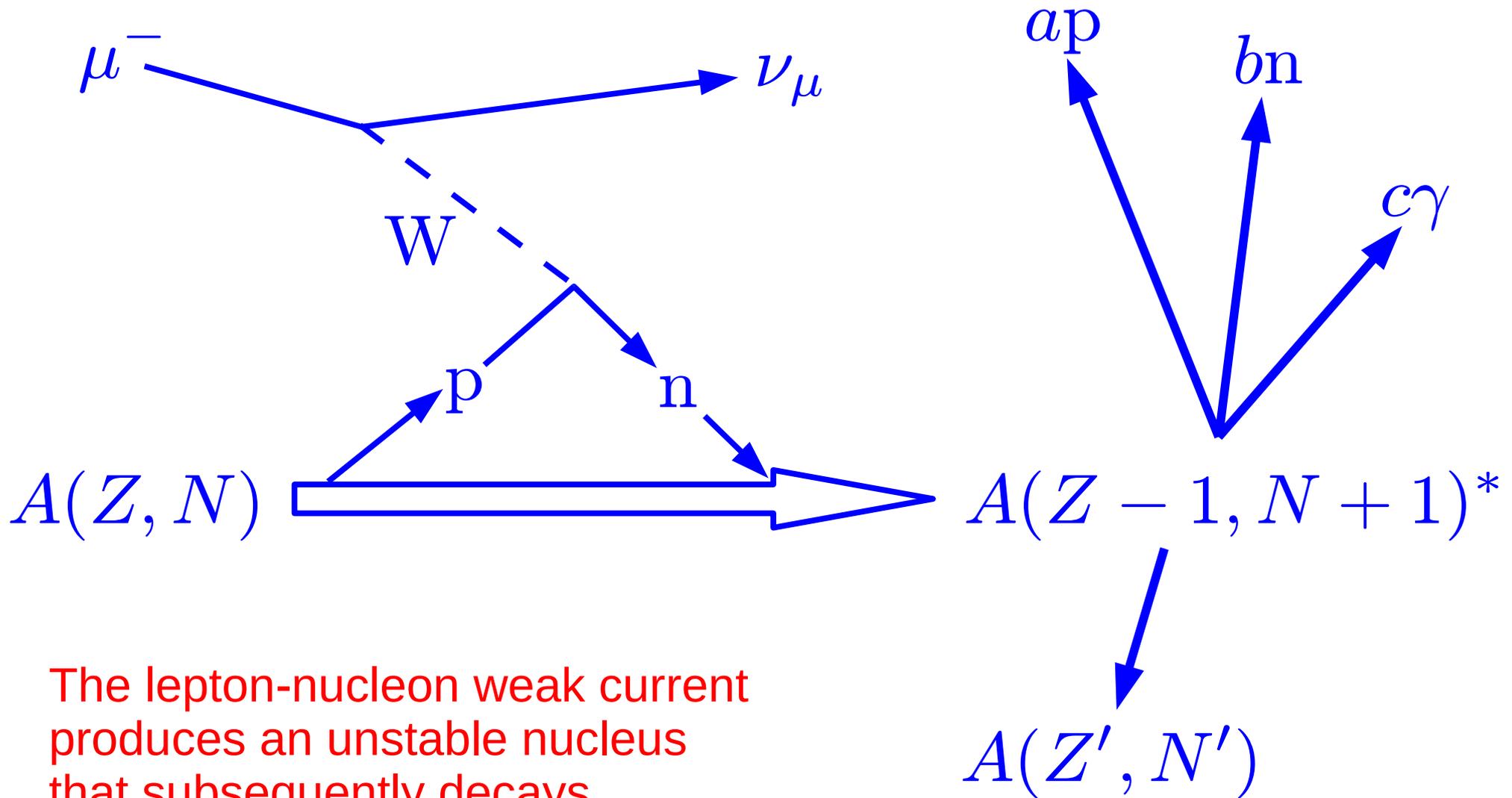
# The endpoint energy is material dependent



# Different materials are sensitive to different operators

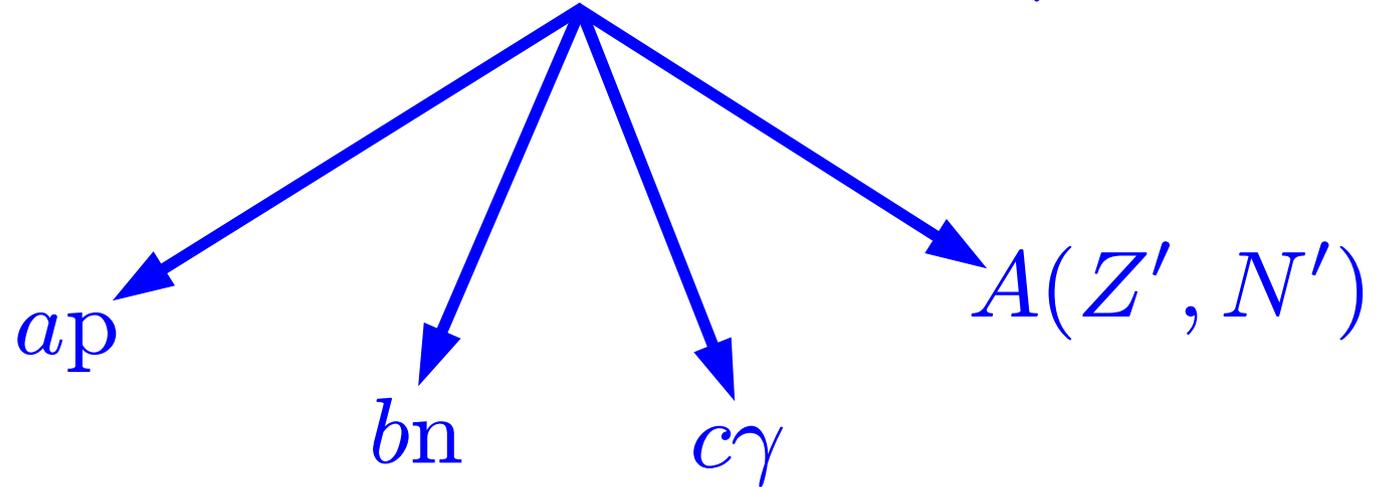


Nuclear capture is both normalization and a source of inefficiency due to extra hits



The lepton-nucleon weak current produces an unstable nucleus that subsequently decays

Nuclear capture is both normalization and a source of inefficiency due to extra hits

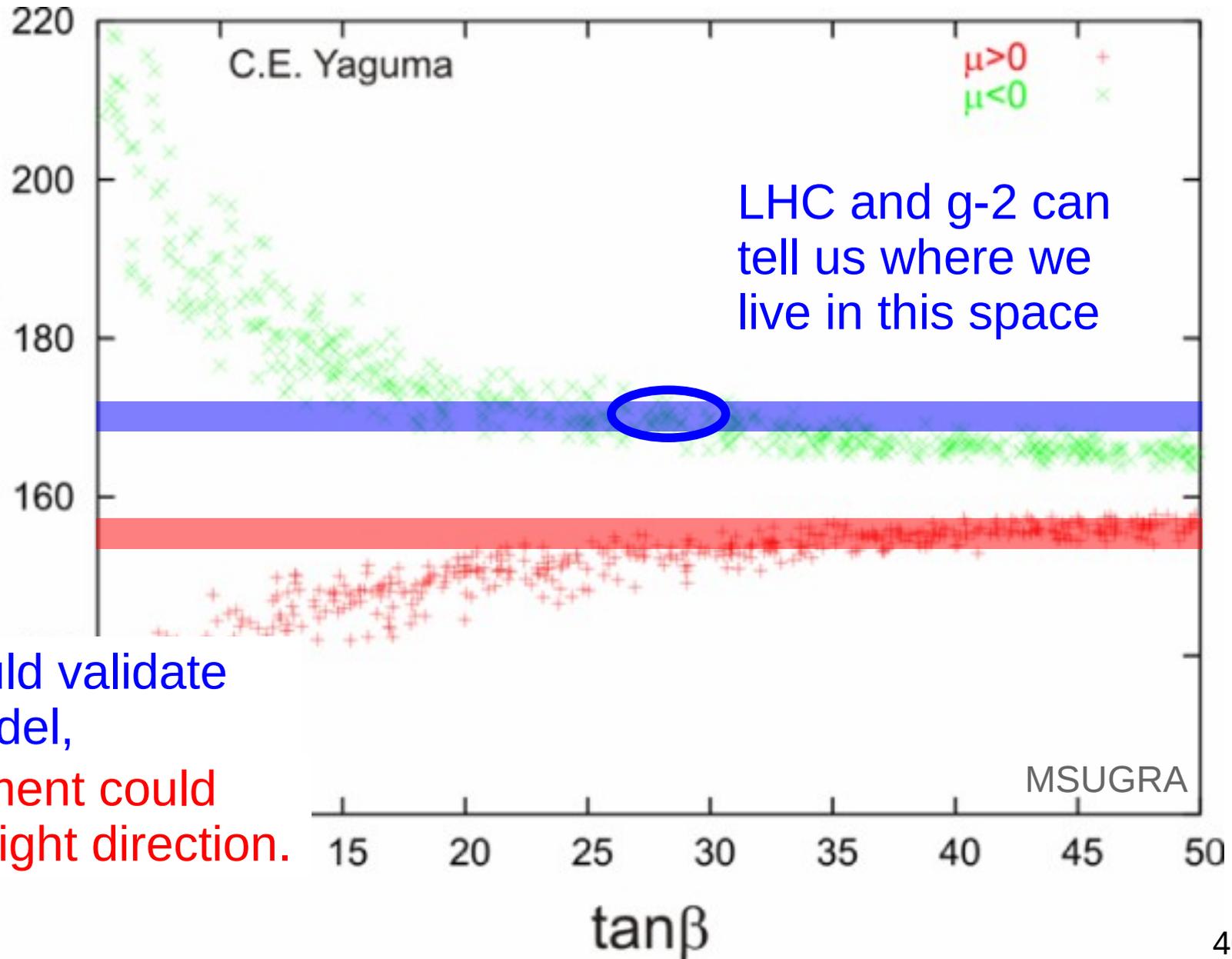


For an  $^{27}\text{Al}$  target, the average capture results in 0.1p, 2n, and 2γ. These result in additional hits in the detectors, potentially leading to inefficiency and pattern recognition errors.

# Conversion is just one complementary piece of the flavor puzzle

The ratio of MEG to Mu2e observations

$$\frac{BR(\mu \rightarrow e\gamma)}{R(\mu\text{Ti} \rightarrow e\text{Ti})}$$



Agreement would validate any leading model, while disagreement could point us in the right direction.

# Different cLFV processes are driven by different operators

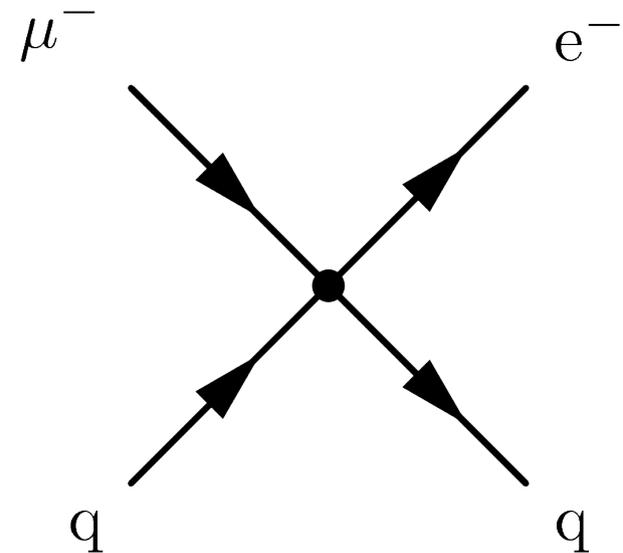
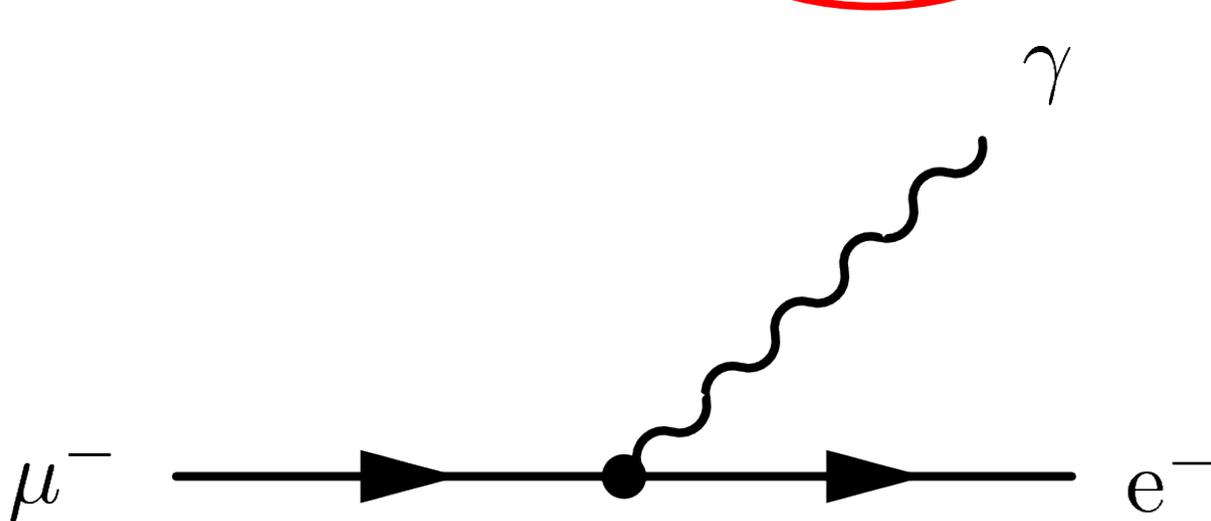
Hence, measurements of the different processes tell us about the underlying physics

$$\mathcal{L}_{\text{cLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\alpha\beta} e_L F^{\alpha\beta} +$$

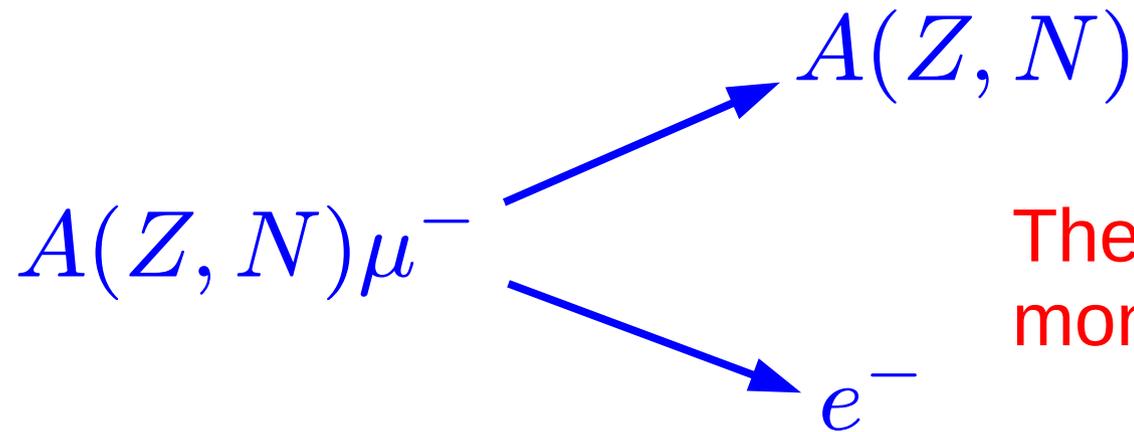
Chirality violating dipole interaction

Chirality preserving contact interaction

$$\frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\alpha e_L (\bar{u}_L \gamma^\alpha u_L + \bar{d}_L \gamma^\alpha d_L)$$



# Coherent conversion kinematics



The 1-to-2 process produces monochromatic electrons!

$$E_e = m_\mu - E_{1s} - E_{A(Z, N)}$$

$$E_e(^{27}\text{Al}) = 104.97 \text{ MeV}$$

This energy is well above the vast bulk of the muon decay backgrounds!

# But the DIO endpoint is the conversion energy

