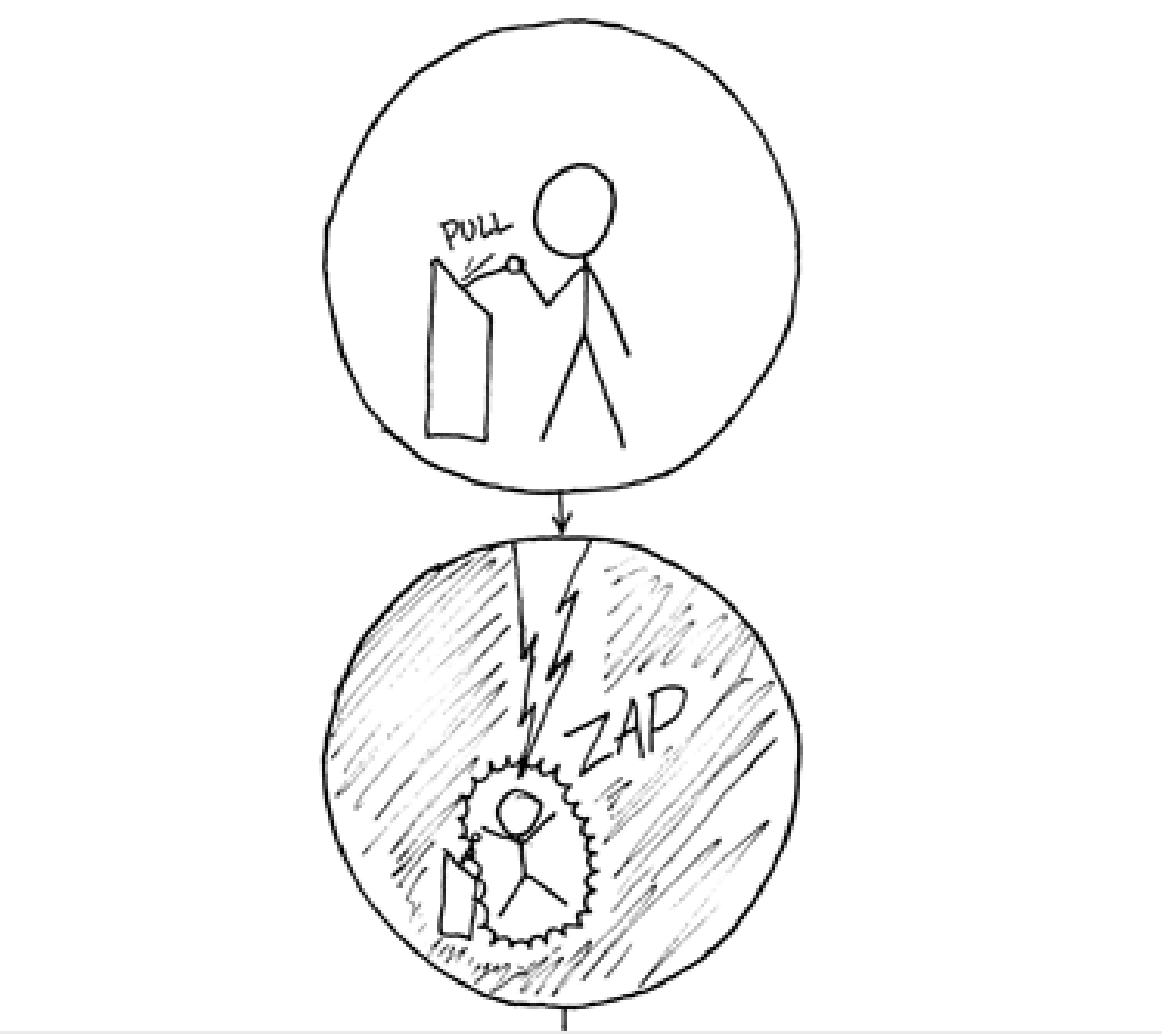
Standing on the Shoulders of Giants: Future Charged Lepton Flavor Violation Experiments

R. Bernstein
Fermilab

http://lccn.loc.gov/50041709

Alternative Title and Def'n of Insanity

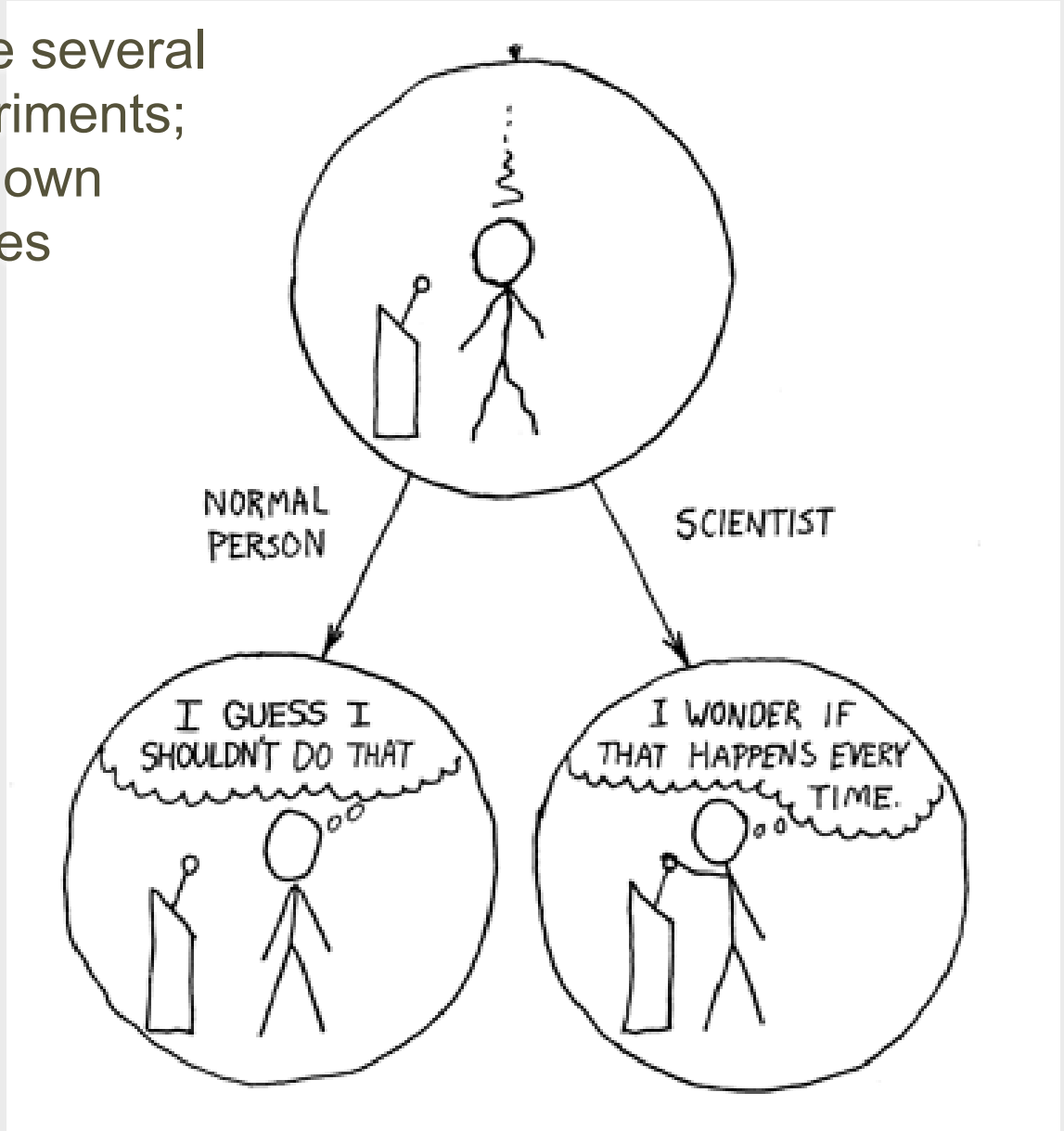
http://xkcd.com/242/



Alternative Title and Def'n of Insanity

Peter has done several of these experiments; draw your own inferences

http://xkcd.com/242/



Problem with Review Talks

leave out someone's favorite topic

cover everything

I will do both, but one promise:

Will Not Talk About Reviews

Kepler at CD review

Last Disclaimer

- Unless otherwise stated, none of these are official Mu2e (not official $\mu 2e$ slides) and have not been vetted

Outline

- Review:
  - experimental methods and limitations
- New Methods for Muon-to-Electron Conversion
  - new designs and new problems
- Back to the Future
  - $\mu \to e\gamma$ and $\mu \to ee^+e^-$

What is μe Conversion?

muon converts to electron in the field of a nucleus

$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Standard Model Background of 10^{-54}
- Charged Lepton Flavor Violation (CLFV)
  - can measure a signal with SES of 2.3×10^{-17}
- Related Processes: μ or $\tau \rightarrow e\gamma$, $\tau \rightarrow 3l$, $K_L \rightarrow \mu e$, and more

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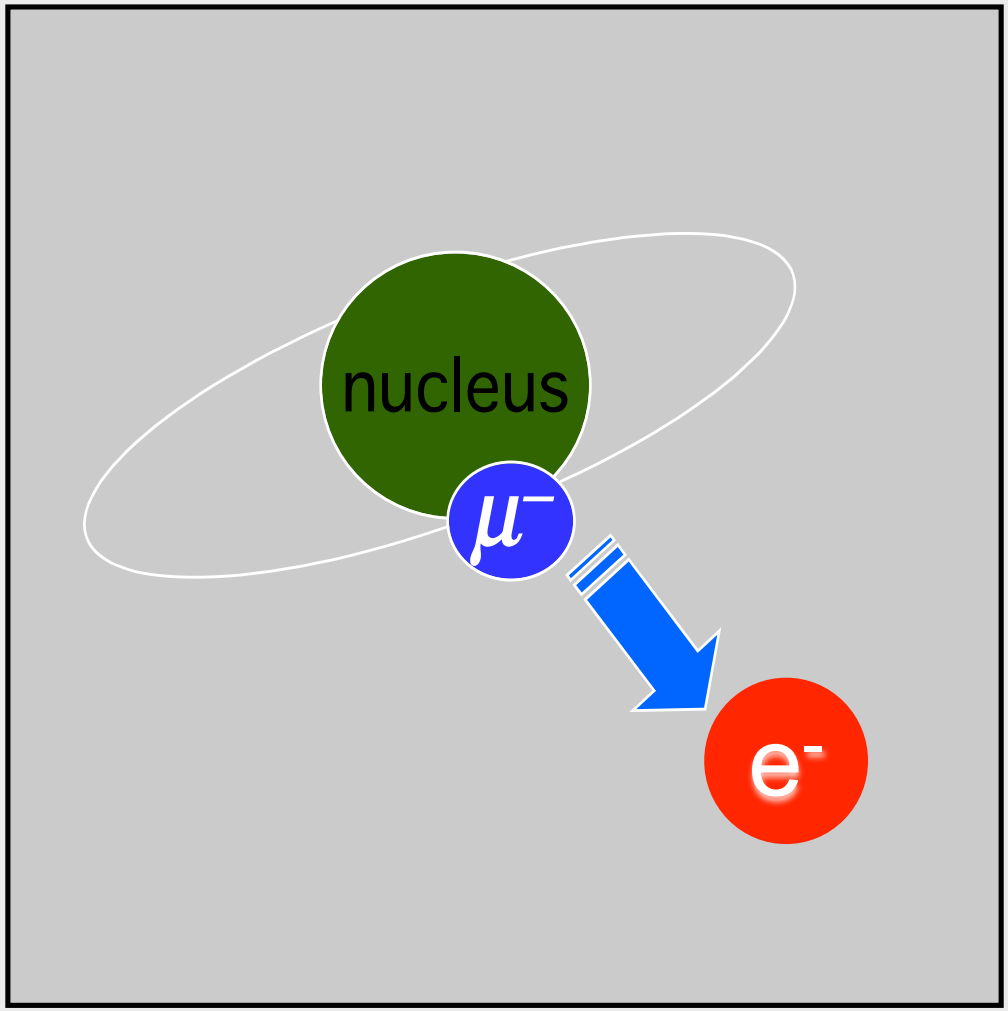
Experimental Signal

$$\mu^- N \rightarrow e^- N$$

- A Single Monoenergetic Electron
- If *N* = Al, E_e = 105. MeV
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



A Sketch of the Experiment

- Get muons in a 1s state around a nucleus
- Let them interact
- Measure a ratio of how often conversion happens normalized to something we can
  - detect
  - calculate

Understanding the Normalization

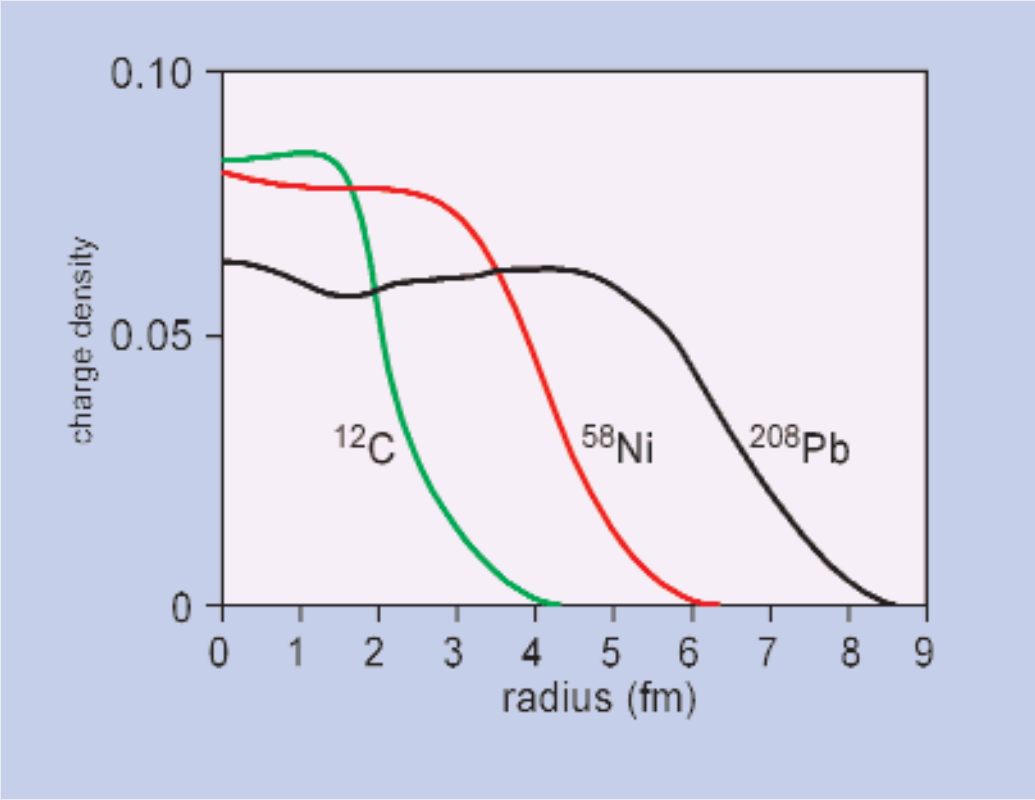
- How does the muon get captured by the nucleus?
  - through the weak interaction
    - (and many details cancel in the ratio we measure)
- But first the wave functions have to overlap:
  - what's the Bohr radius for a 1s muon in Aluminum?

$$a_0 = \frac{\hbar^2}{Z m_\mu c^2} = 0.529\,\mathring{A} \times \left(\frac{m_e}{m_\mu}\right) \times \frac{1}{13} = 2 \times 10^{-4}\,\mathring{A}$$

$$= 20 \text{ fermi}$$

How Big Is A Nucleus?

- A few fermi for the relevant nuclei
- I wish I hadn't completely avoided nuclear physics as an undergrad and grad student ☹



http://www.nupecc.org/pans/Data/CHAPT_4.PDF

How Long Does this Take?

- What's the Hamiltonian?

$$H = H_{\text{muon decay}} + H_{\text{capture}}$$

  - 2.2 μsec is from the strength of the weak interaction and G_F
  - 0.864 μsec is measured
  - and then the branching fractions are:

$$\frac{dN}{dt} = \frac{dN}{dt}_{\text{muon decay}} + \frac{dN}{dt}_{\text{capture}} = -\Gamma N(t)$$

so with $\tau = 1/\Gamma$

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{muon decay}}} + \frac{1}{\tau_{\text{capture}}}$$

$$= \frac{1}{2.2\ \mu\text{sec}} + \frac{1}{1.4\ \mu\text{sec}}$$

or

$$\tau = 864 \text{ nsec}$$

$$B_{\text{capture}} = \frac{0.864}{1.4} = 0.61$$

$$B_{\text{decay}} = \frac{0.864}{2.2} = 0.39$$

What Happens Now?

- The muon and nuclear wave functions overlap

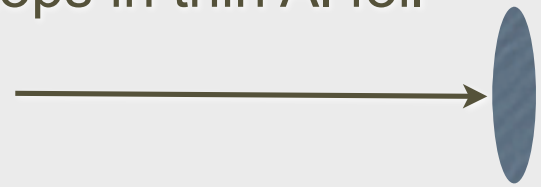
probability of overlap:

~ 0.001 for a muon vs 10^{-13} for an electron

- *Don't try to do this calculation at home*
  - doing it right involves relativistic wave functions and Dirac spinors (especially if new physics!!)
- *In fact, a theorist got it wrong and a team of experimenters worked for a year as a result*
  - hint: don't trust theorists (most important thing to learn)

Overview Of Processes

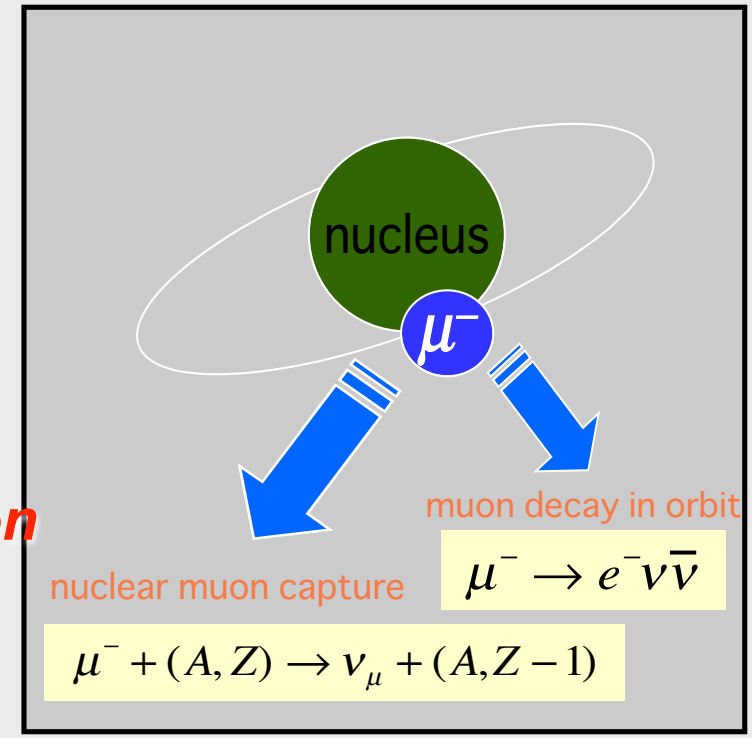
μ^- stops in thin Al foil



the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

μ^- in 1s state

Al Nucleus
~4 fm



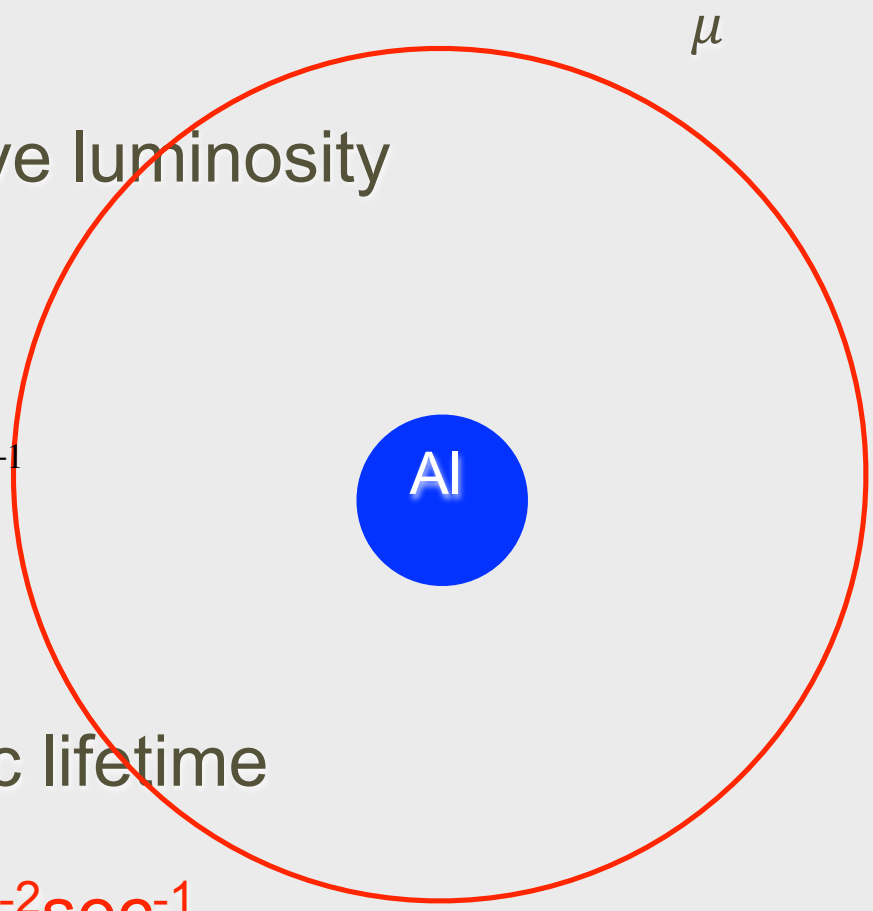
muon capture,
muon "falls into"
nucleus: ***normalization***

60% capture
40% decay

Decay in Orbit:
background

Measuring 10^{-17} in Collider Units

- The captured muon is in a 1s state and the wave function overlaps the nucleus (picture ~ to scale)



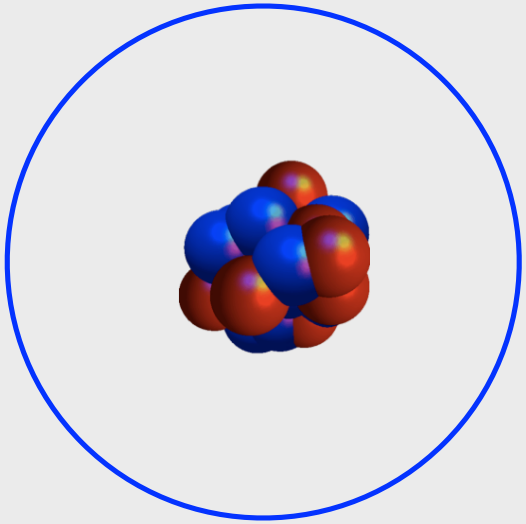
- We can turn this into an effective luminosity
- Luminosity = density x velocity

$$|\psi(0)|^2 \times \alpha Z = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} = 8 \times 10^{43}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

- Times 10^{10} muons/sec X 2 μsec lifetime
- Effective Luminosity of 10^{48} $cm^{-2}sec^{-1}$

A. Czarnecki, clfv.le.infn.it

Three Possibilities: Normalization



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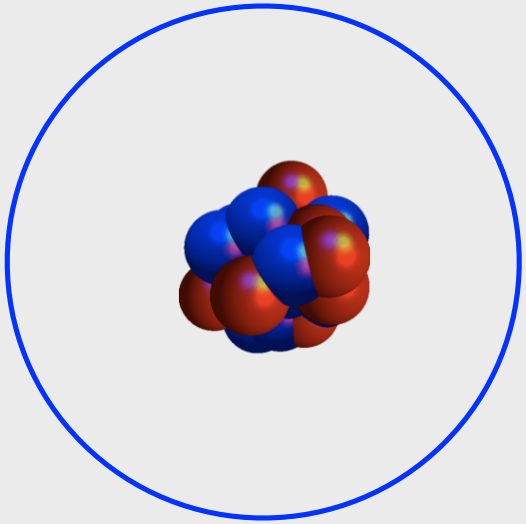
muon stops



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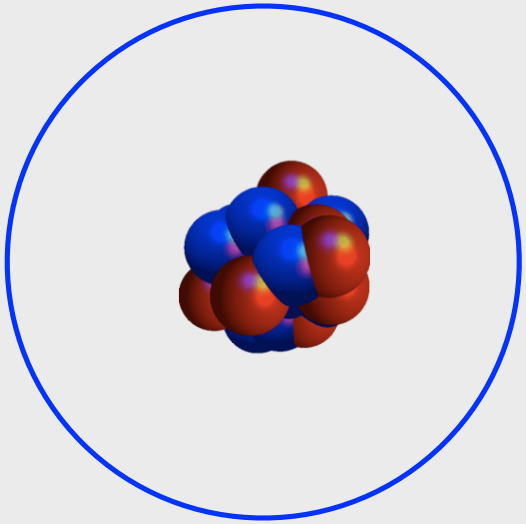

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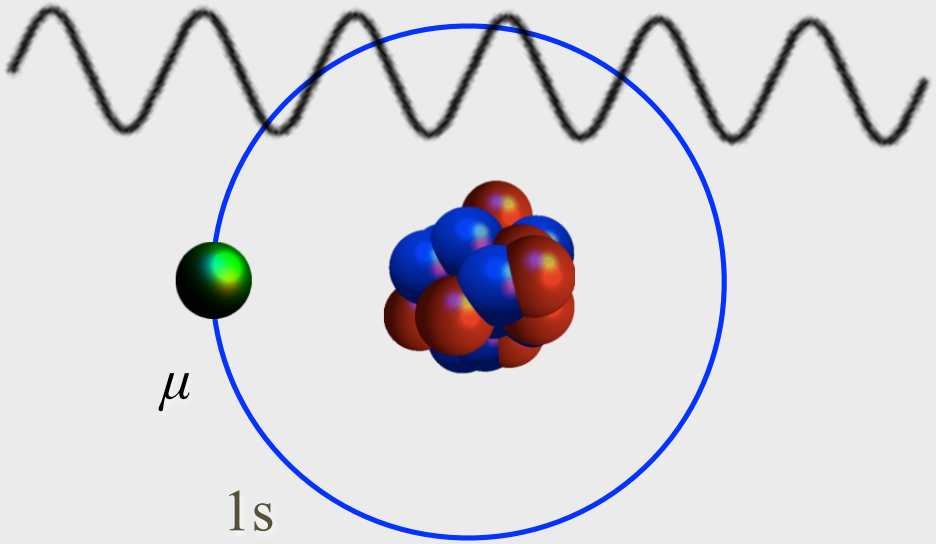
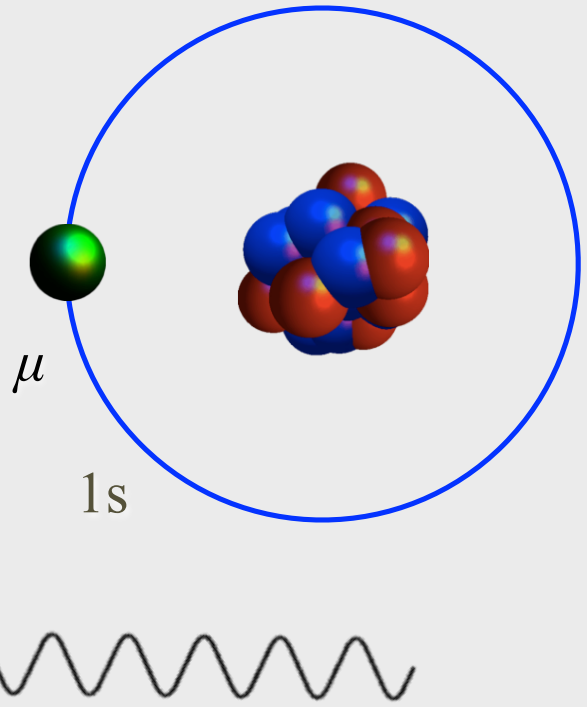


Three Possibilities: Normalization

X-Rays from cascade (occurs in <psec)

detect these for normalization

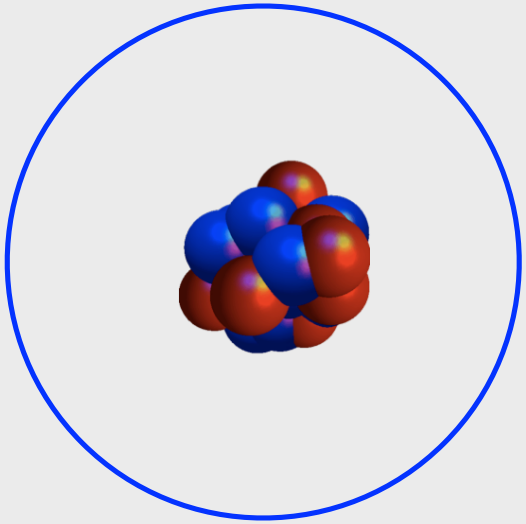
Transition	Energy
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV



Normalization to Nuclear Capture

1) measure stop rate 2) calculate capture rate/stop

Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110



$$\text{then compute } R_{\mu e} = \frac{\mu N \to e N}{\mu N \to \text{ all captures}}$$

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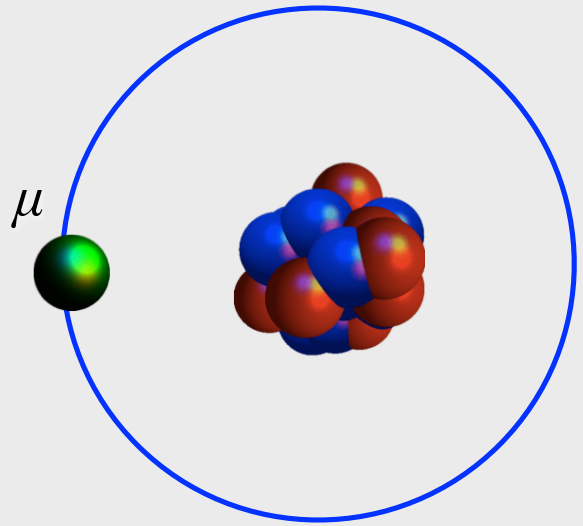

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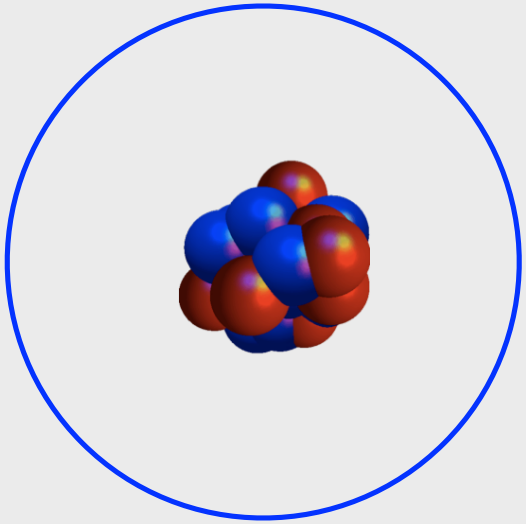

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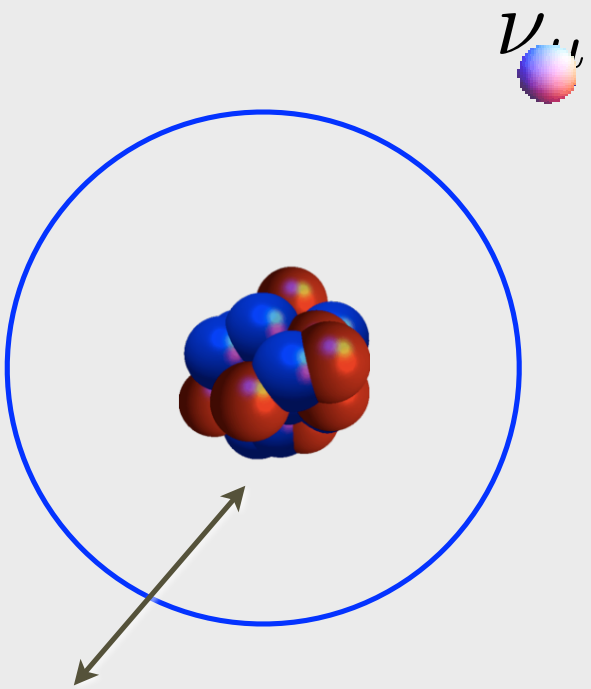


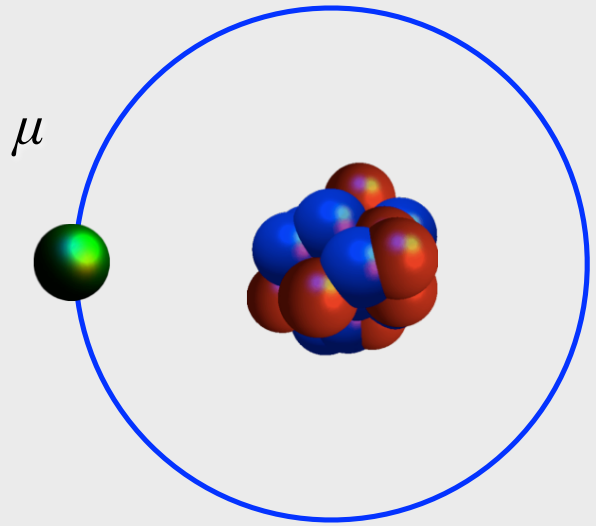
$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow eN}{\mu N \rightarrow \text{ all captures}}$$

Counting Stops

- Easier Said than Done
- Very High Rate Germanium
  - technically challenging
  - expensive?
  - work in progress
- Normalize to DIO instead?
  - use region where calculation robust
  - then subject to theory uncertainty but does not harm discovery potential; just a bad measurement of conversion rate...

Three Possibilities: Signal



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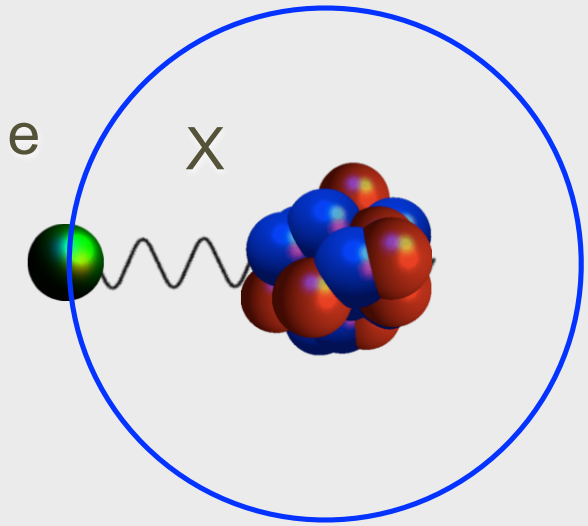
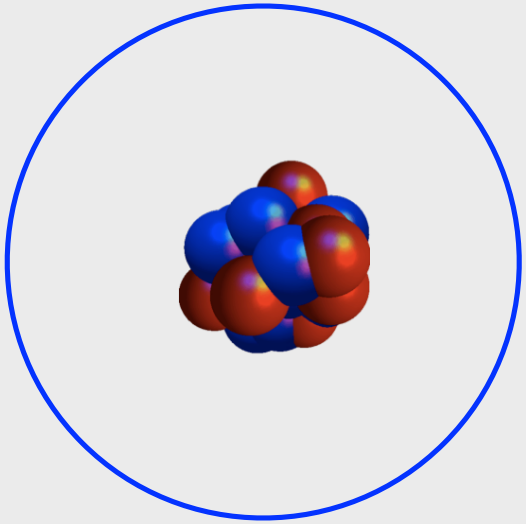


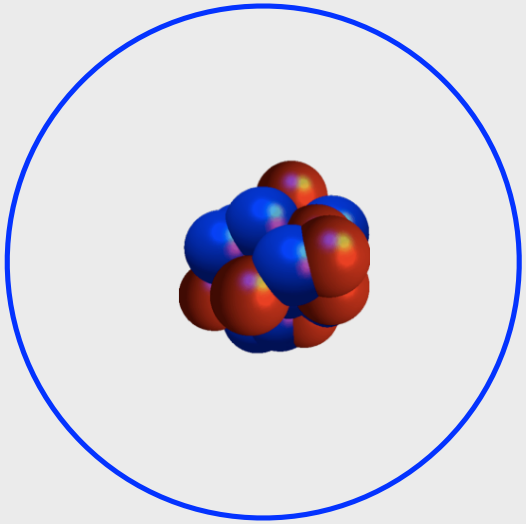
Three Possibilities: Signal

e



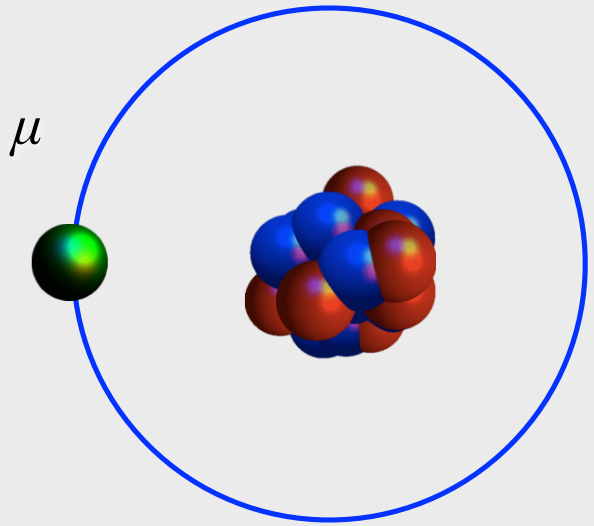
Three Possibilities: Signal

e *off to detector!*



coherent recoil of nucleus

Three Possibilities: Background



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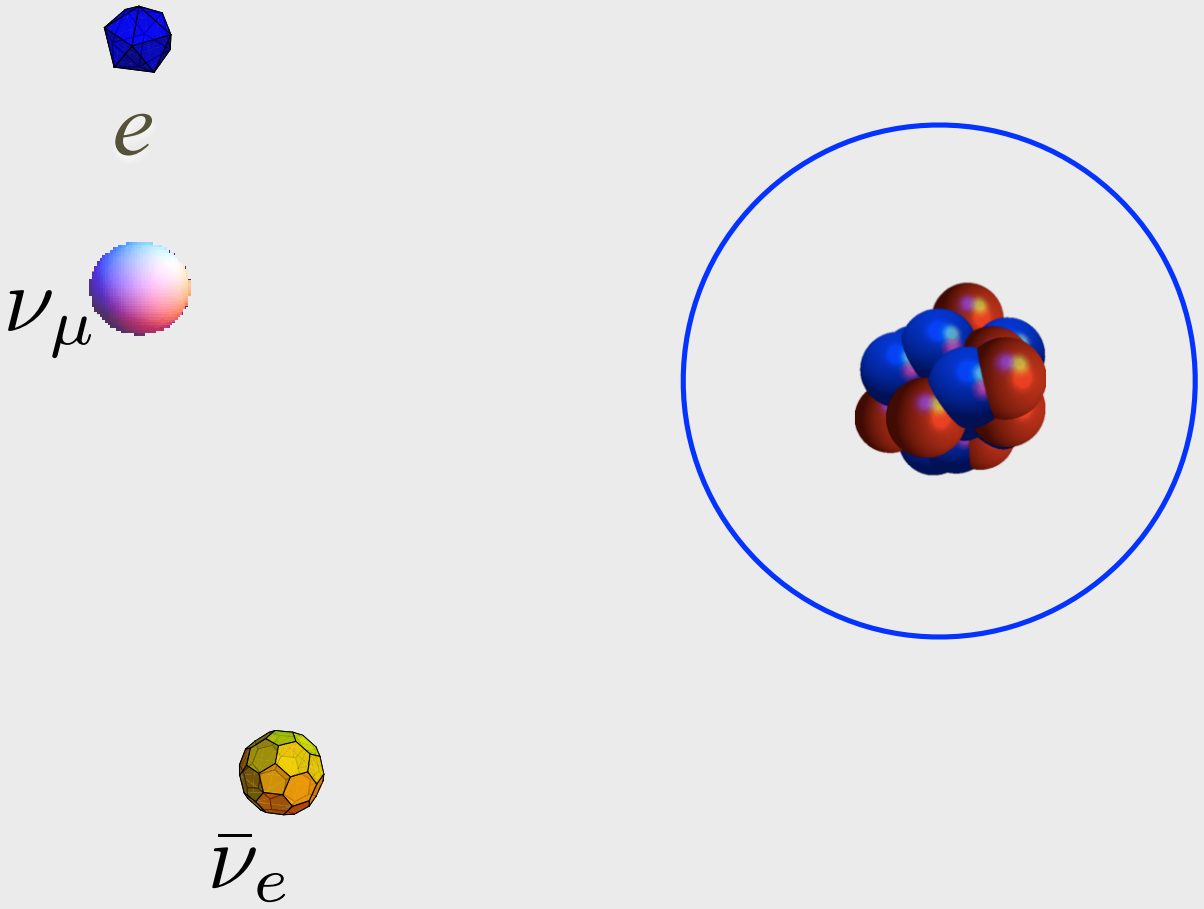
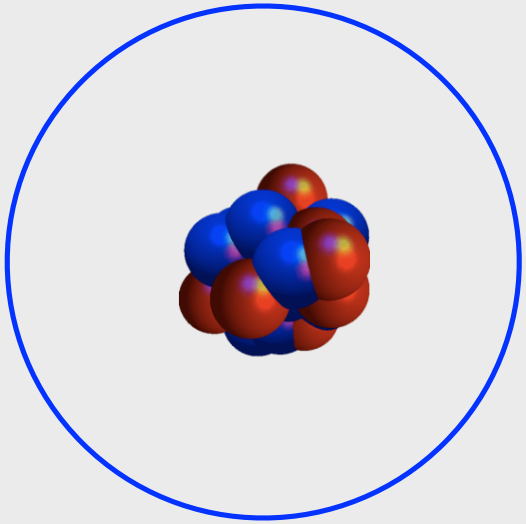


Three Possibilities: Background

this electron can be background;
let's see how

e

ν_μ



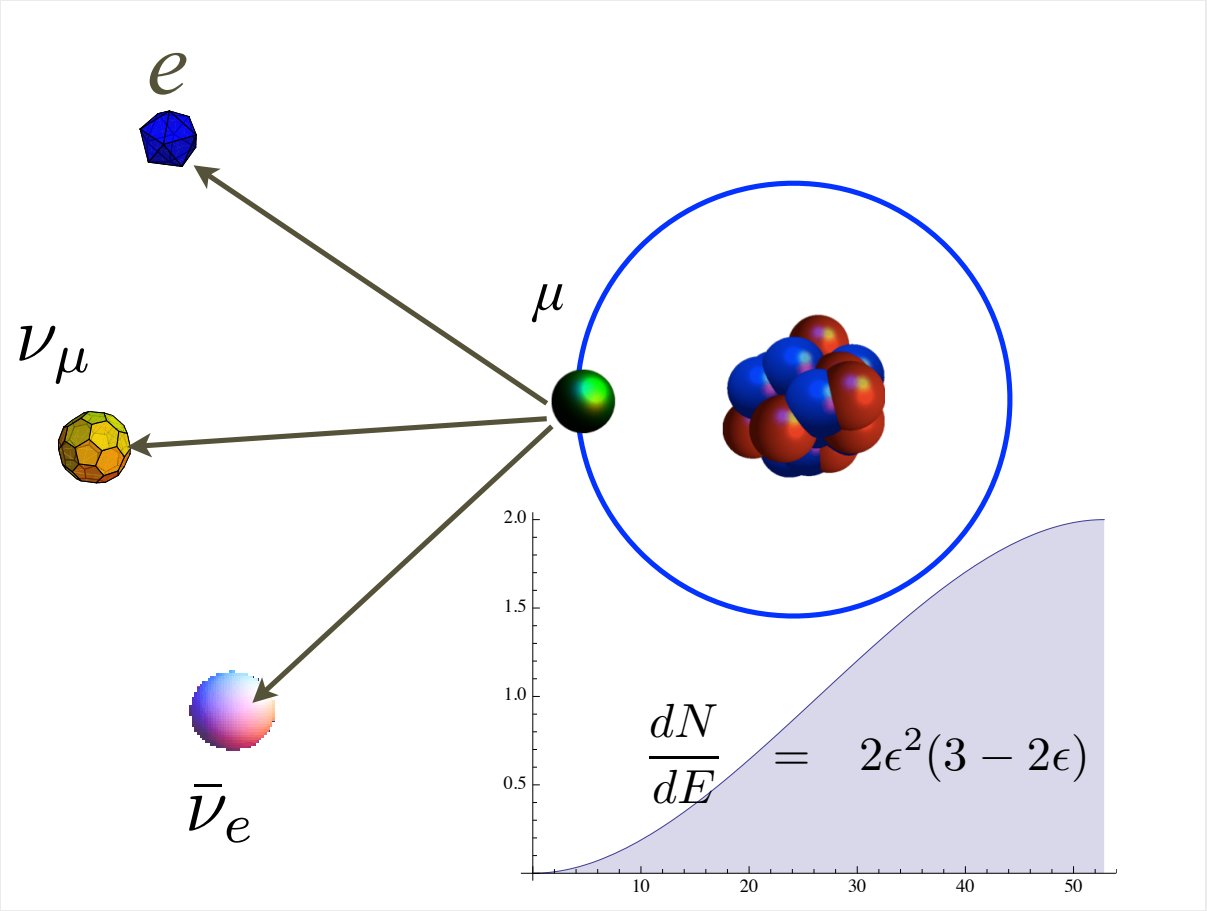
$\bar{\nu}_e$

Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- Detector will be insensitive to electrons at this energy
- Recall *signal* at 105 MeV>>52.8 MeV



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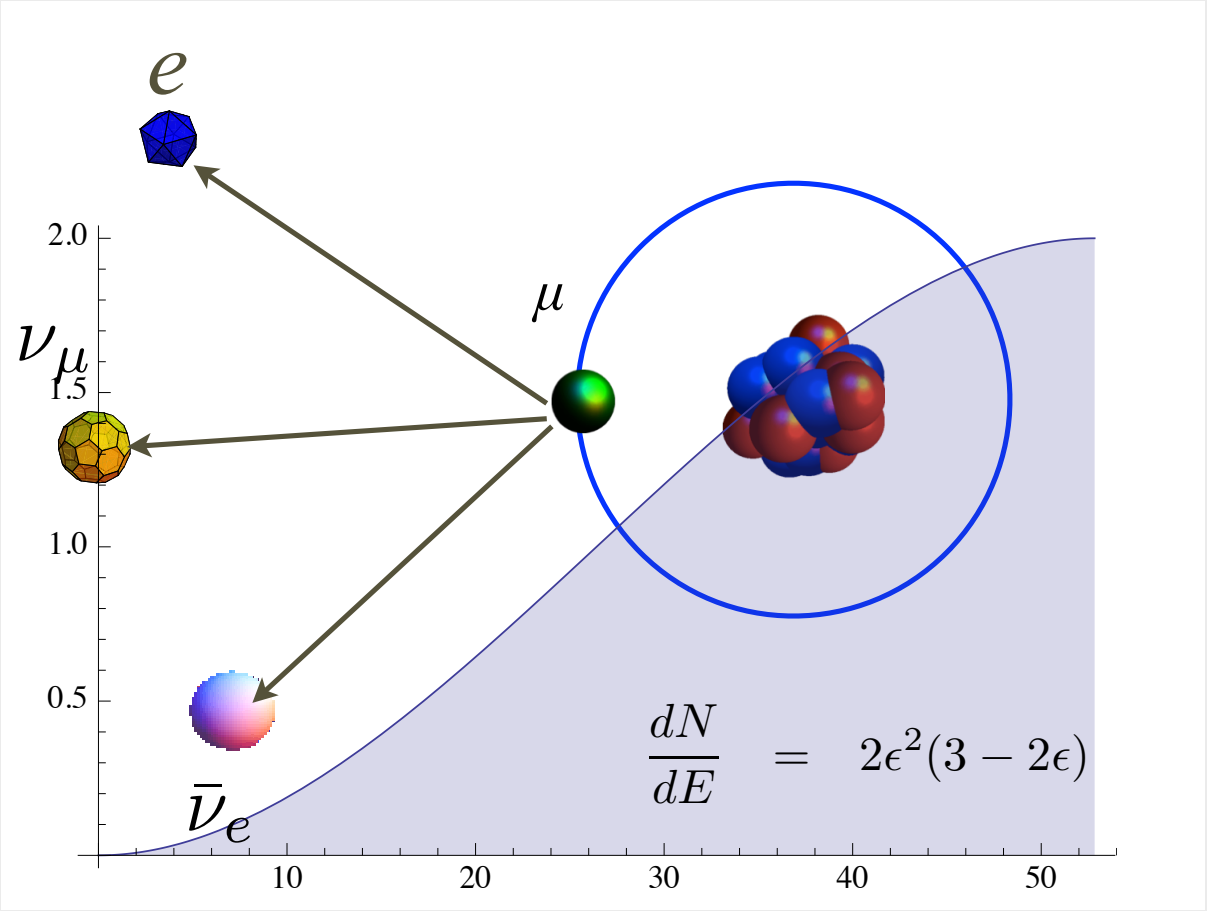
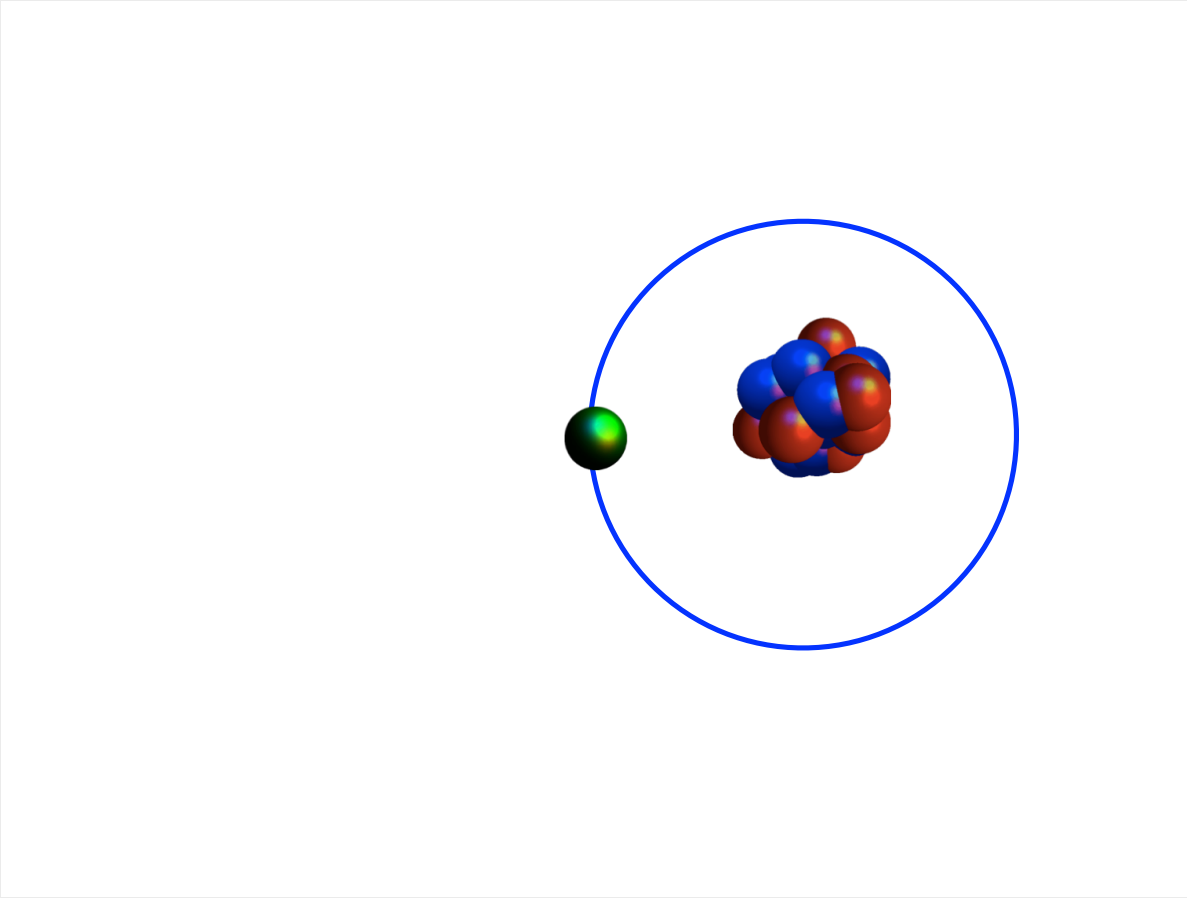


Decay-In-Orbit Background

- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, the DIO electron can be exactly at conversion energy (up to neutrino mass)



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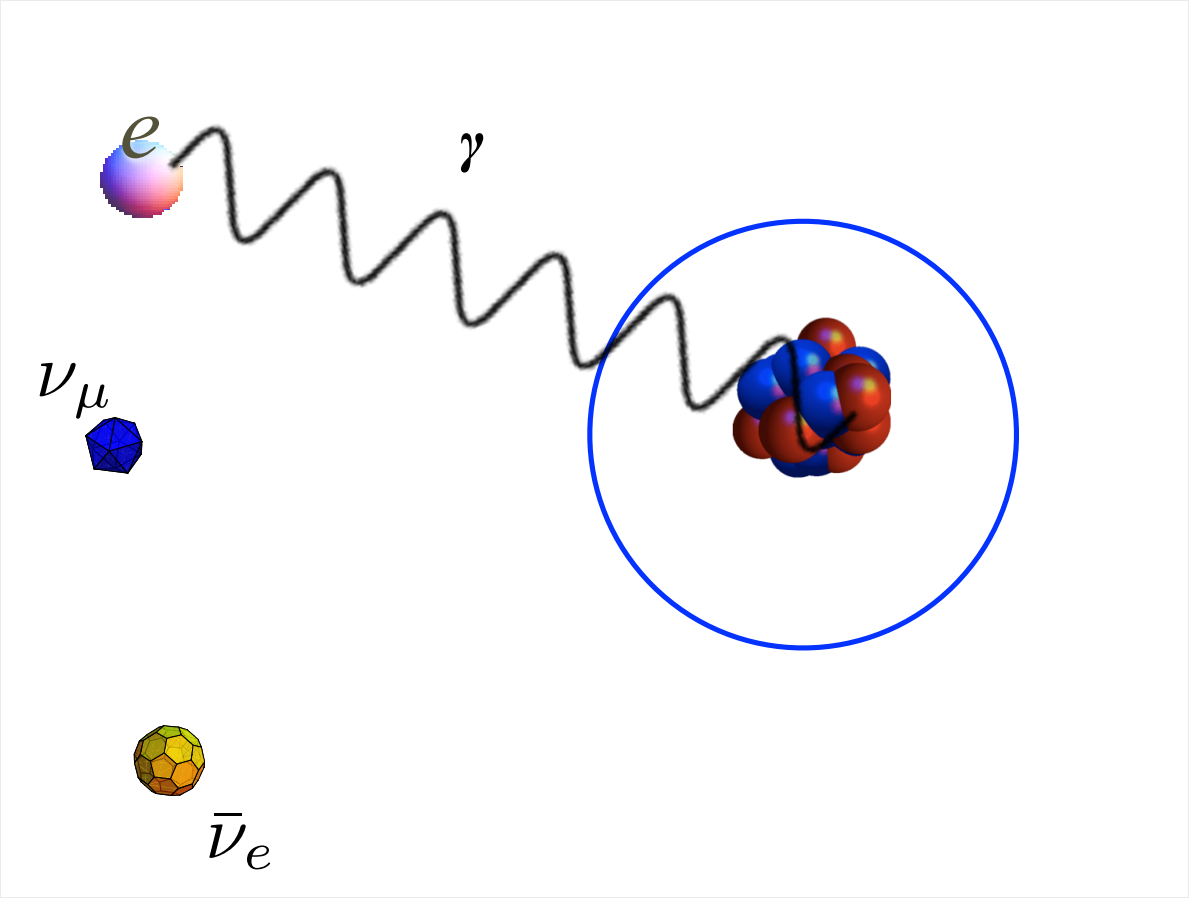

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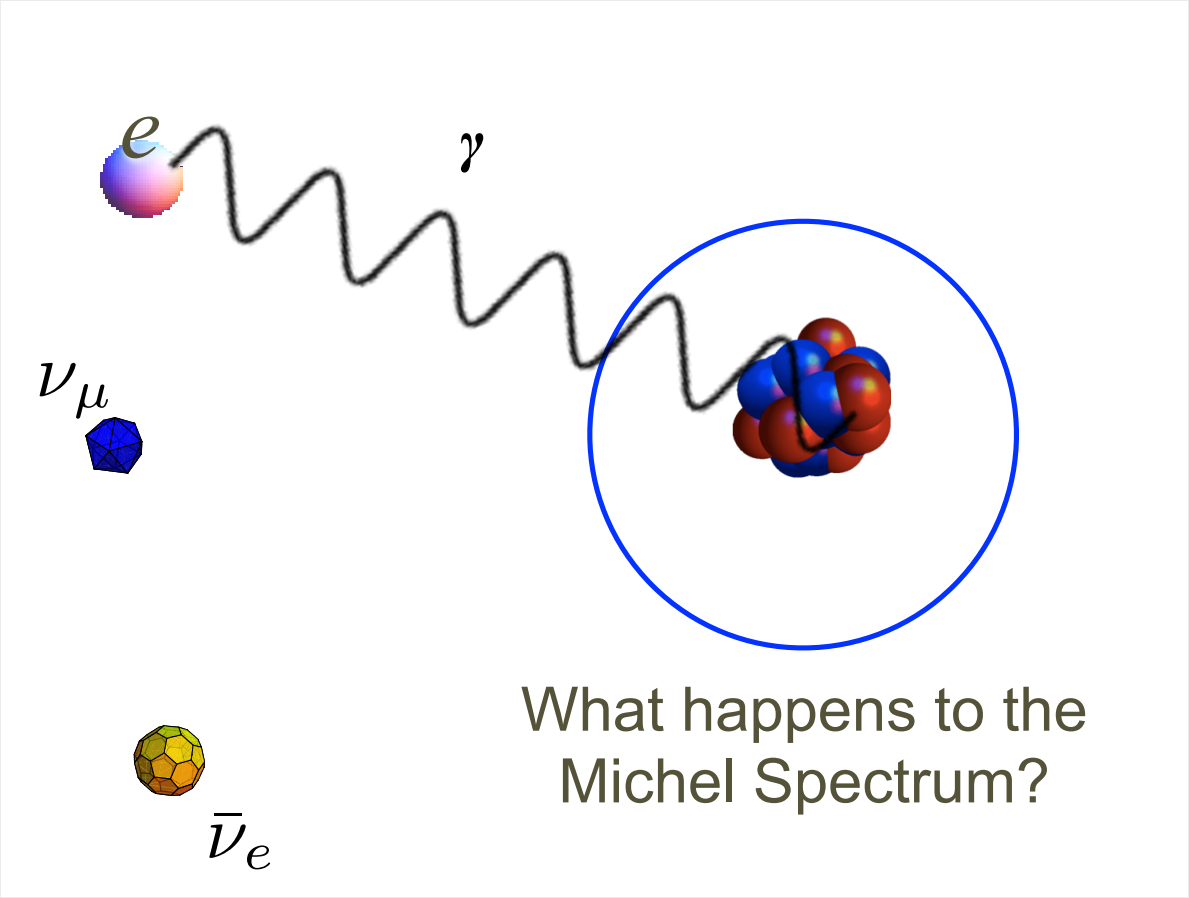
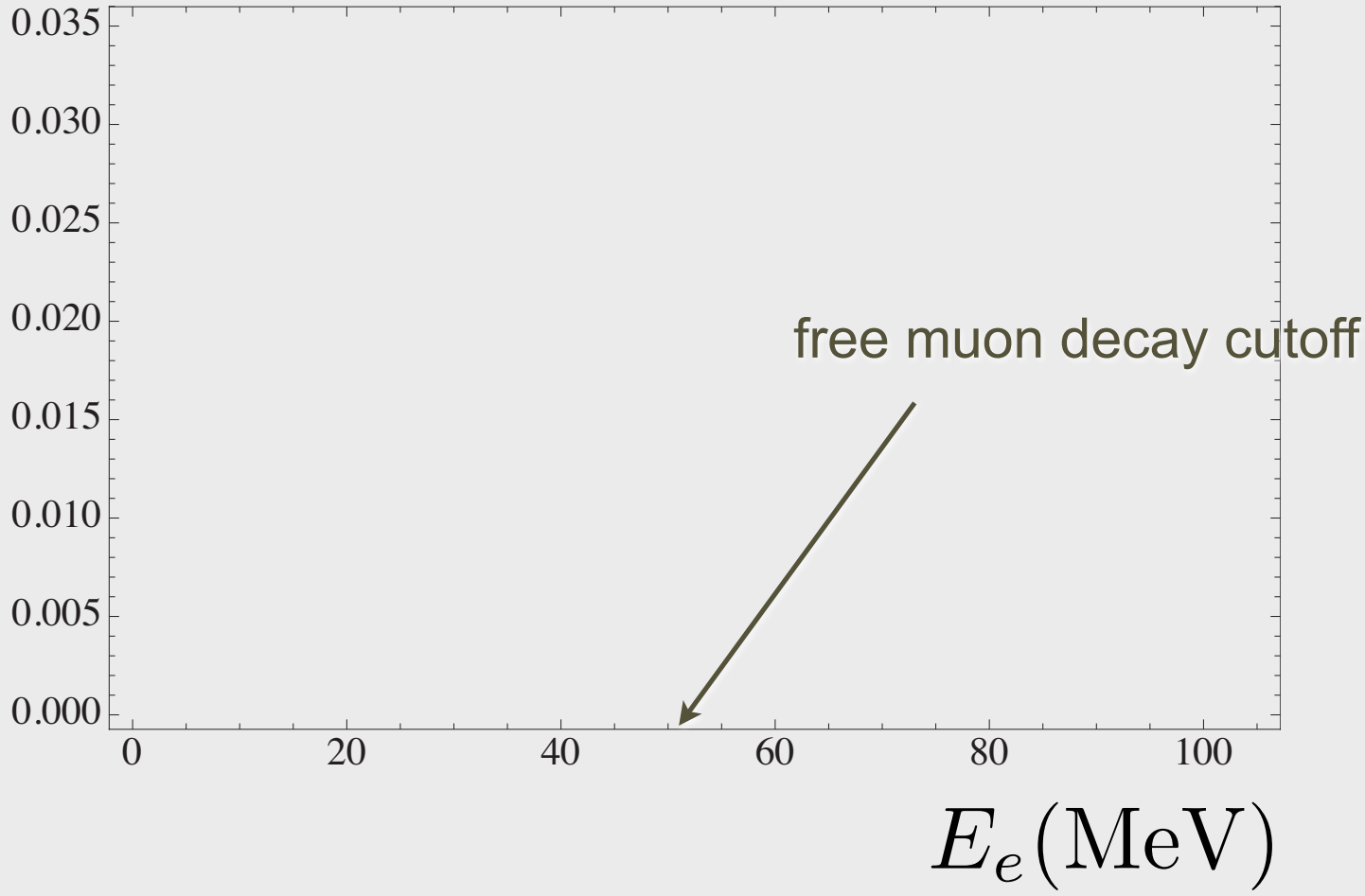


Decay-in-Orbit Shape

Czarnecki et al., arXiv:1106.4756v2 [hep-ph] Phys. Rev. D 84, 013006 (2011)

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE}$$



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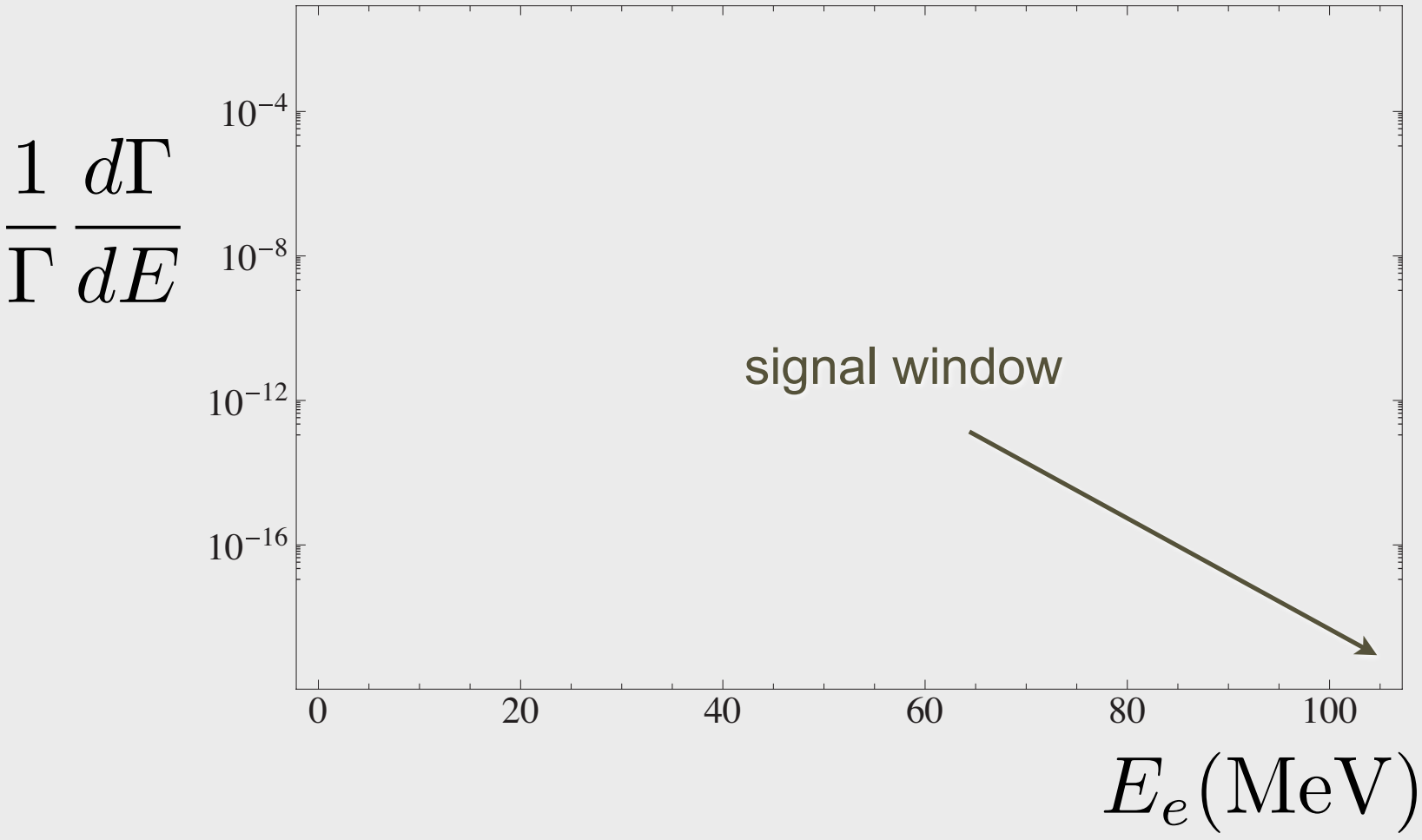
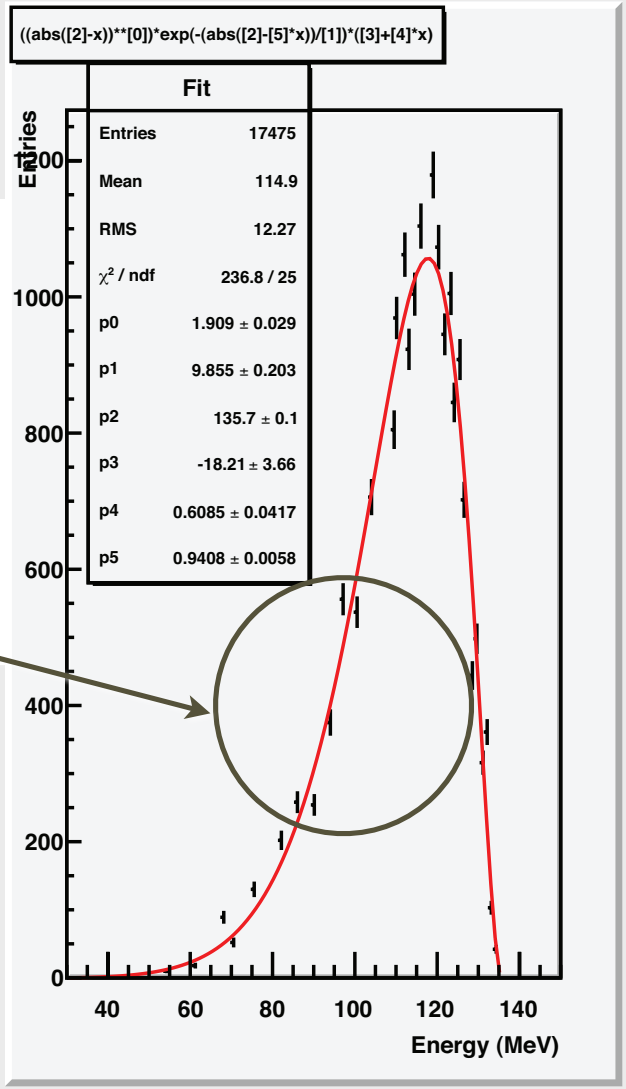


Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars

- **Radiative pion capture**, $\pi^- + A(N,Z) \rightarrow \gamma + X$.
  - γ up to mπ, peak at 110 MeV; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal: ***limitation in best existing experiment, SINDRUM II?***



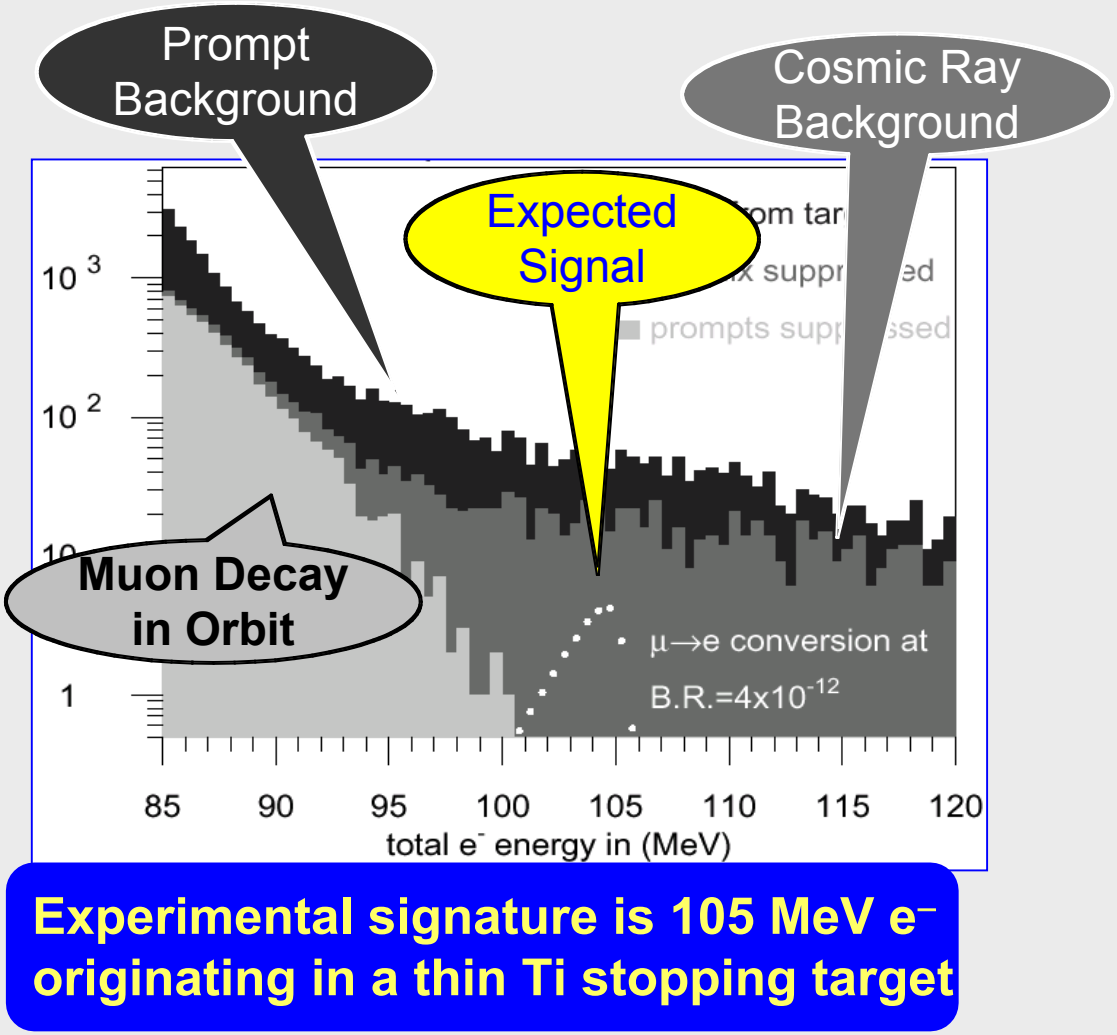
energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

also included internal conversion, $\pi^- N \rightarrow e^+ e^- X$

Previous Best Experiment

SINDRUM-II

- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



SINDRUM-II Results

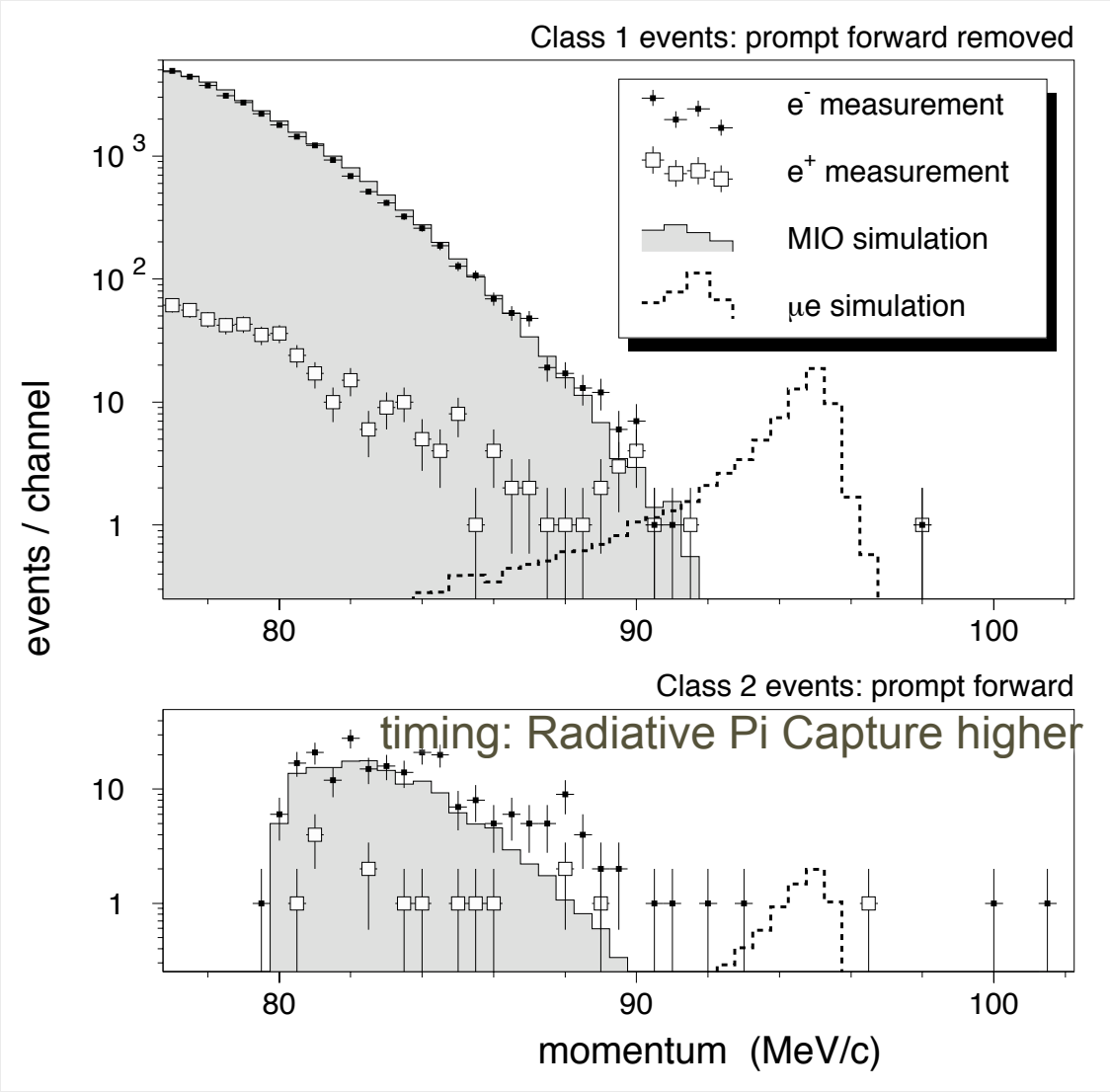
- Final Results on Au:

$$B_{\mu e}^{\mathrm{Au}} \quad < \quad 7 \times 10^{-13} \ @ \ 90\% \ \mathrm{CL}$$

51 MHz (20 nsec) repetition rate, width of pulse ~0.3 nsec

little time separation between signal and prompt background

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



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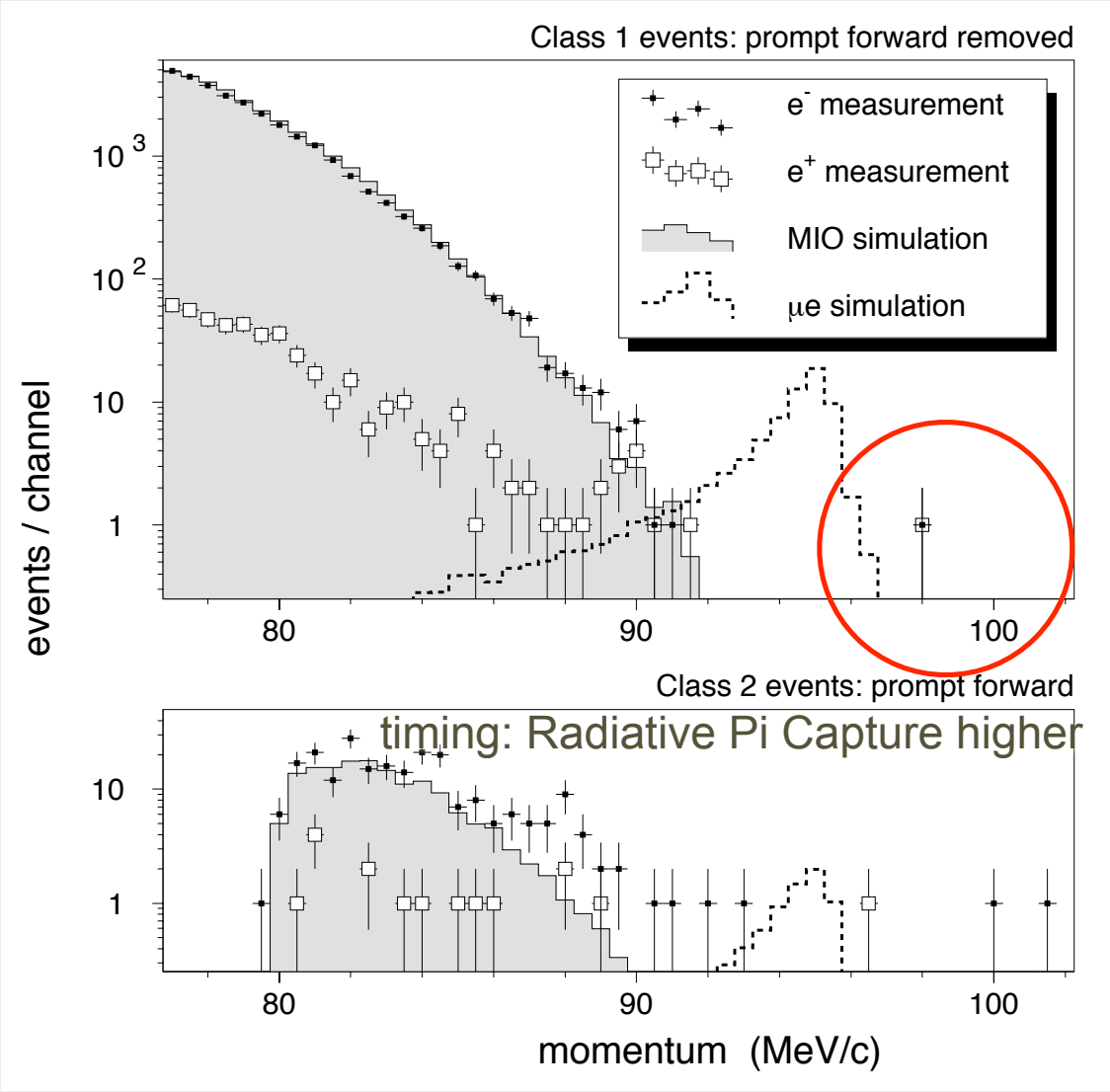


How Can We Do Better?

>10^3 increase in muon intensity from SINDRUM

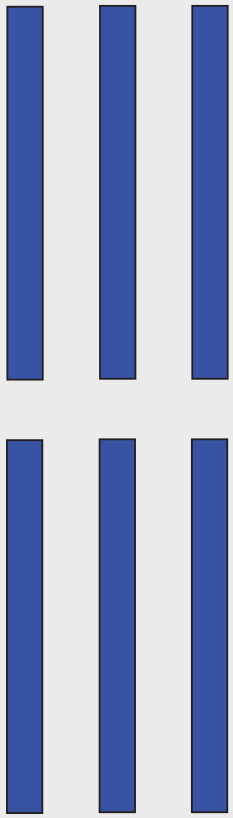
Requiring

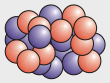
Pulsed Beam to Eliminate prompt backgrounds like radiative π capture and CR

protons out of beam pulse/ protons in beam-pulse < 10^{-10} *and we must measure it*

Prompt backgrounds and Pulsed Beam

target foils: muon converts here

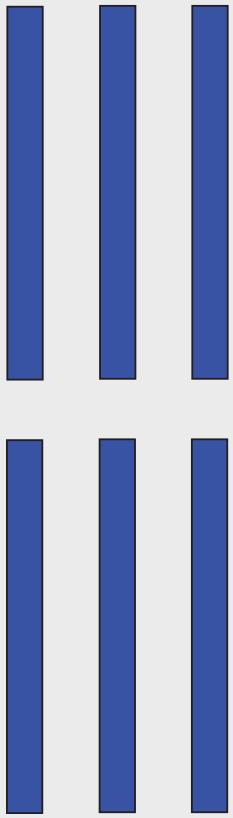


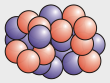
 = muons, electrons, pions

pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

Prompt backgrounds and Pulsed Beam

target foils: muon converts here

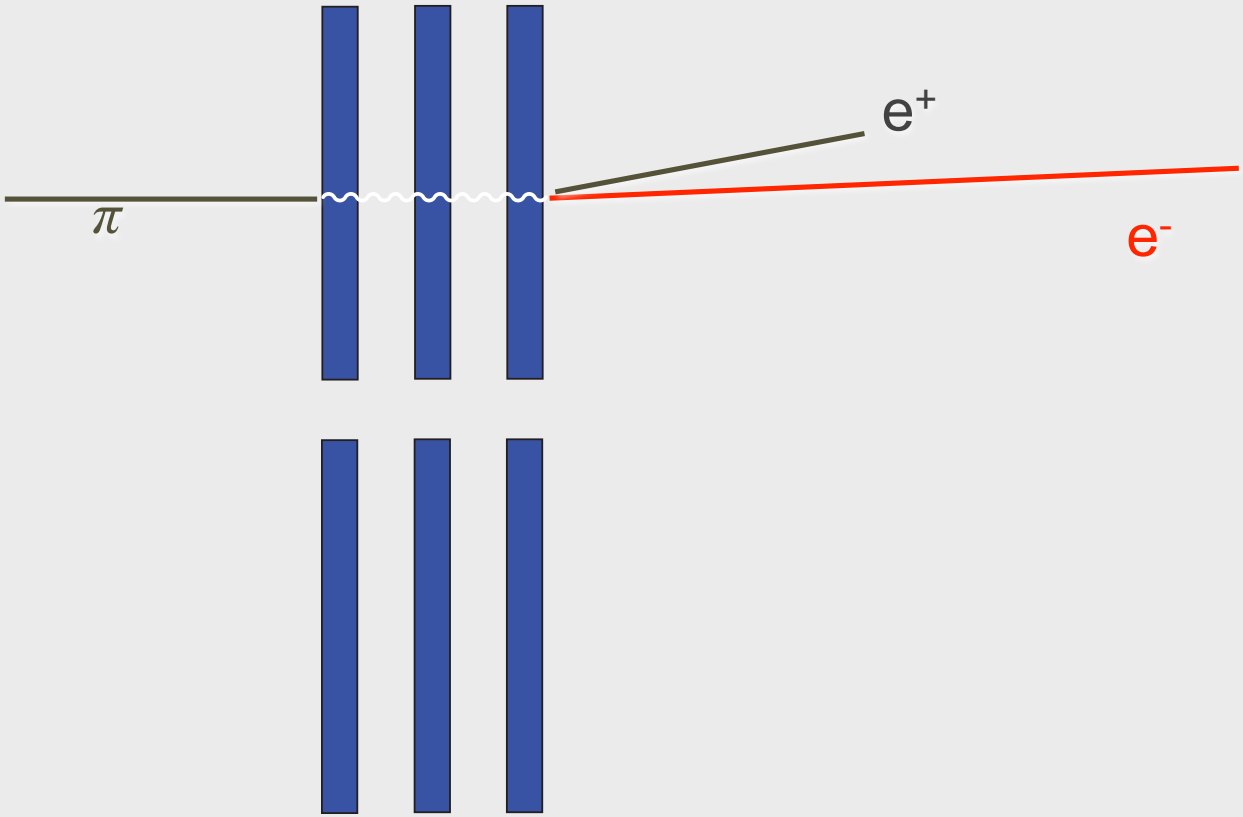


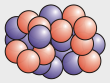
 = muons, electrons, pions

pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

Prompt backgrounds and Pulsed Beam

target foils: muon converts here



 = muons, electrons, pions

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Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

$\gamma \rightarrow e^+ e^-$ *in foils*

Prompt backgrounds and Pulsed Beam

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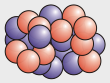

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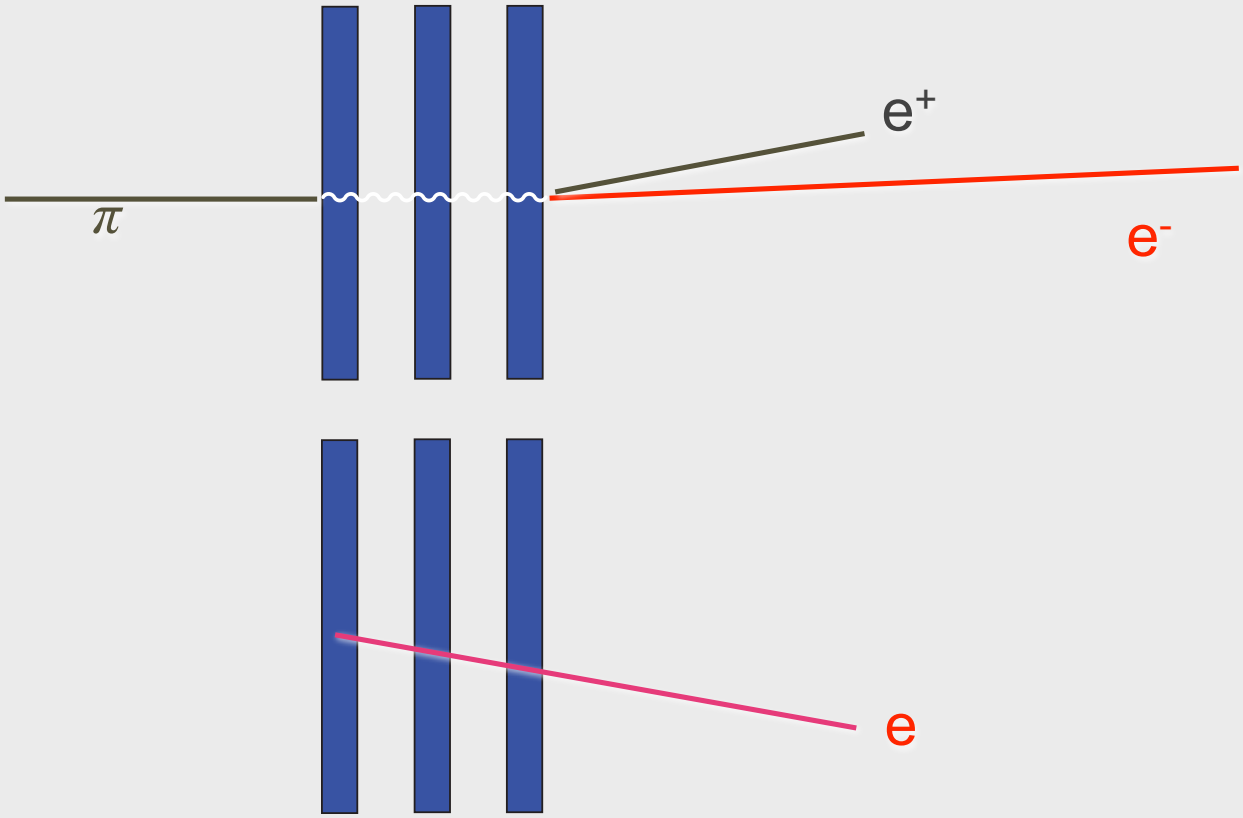


pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

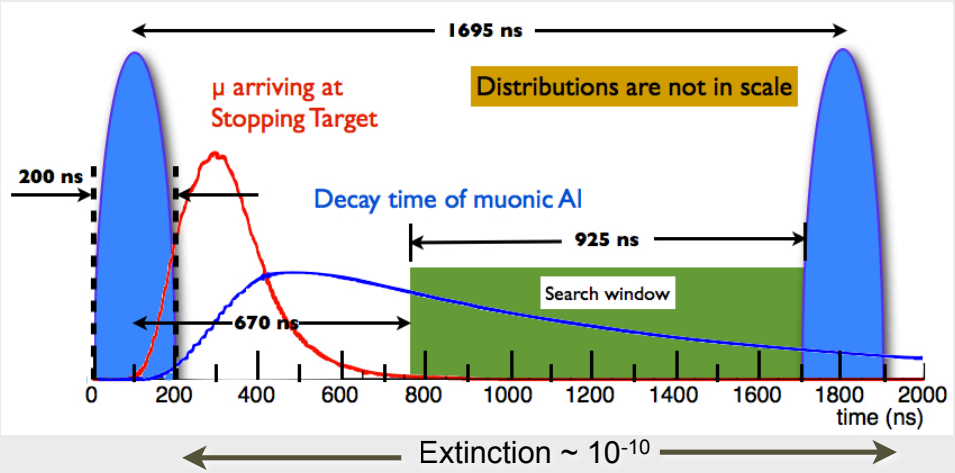
$\gamma \rightarrow e^+ e^-$ *in foils*

delayed 105 MeV electron

Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7μsec , ~x2 τ_μ^{Al}
- Extinction between pulses < 10^{-10} needed

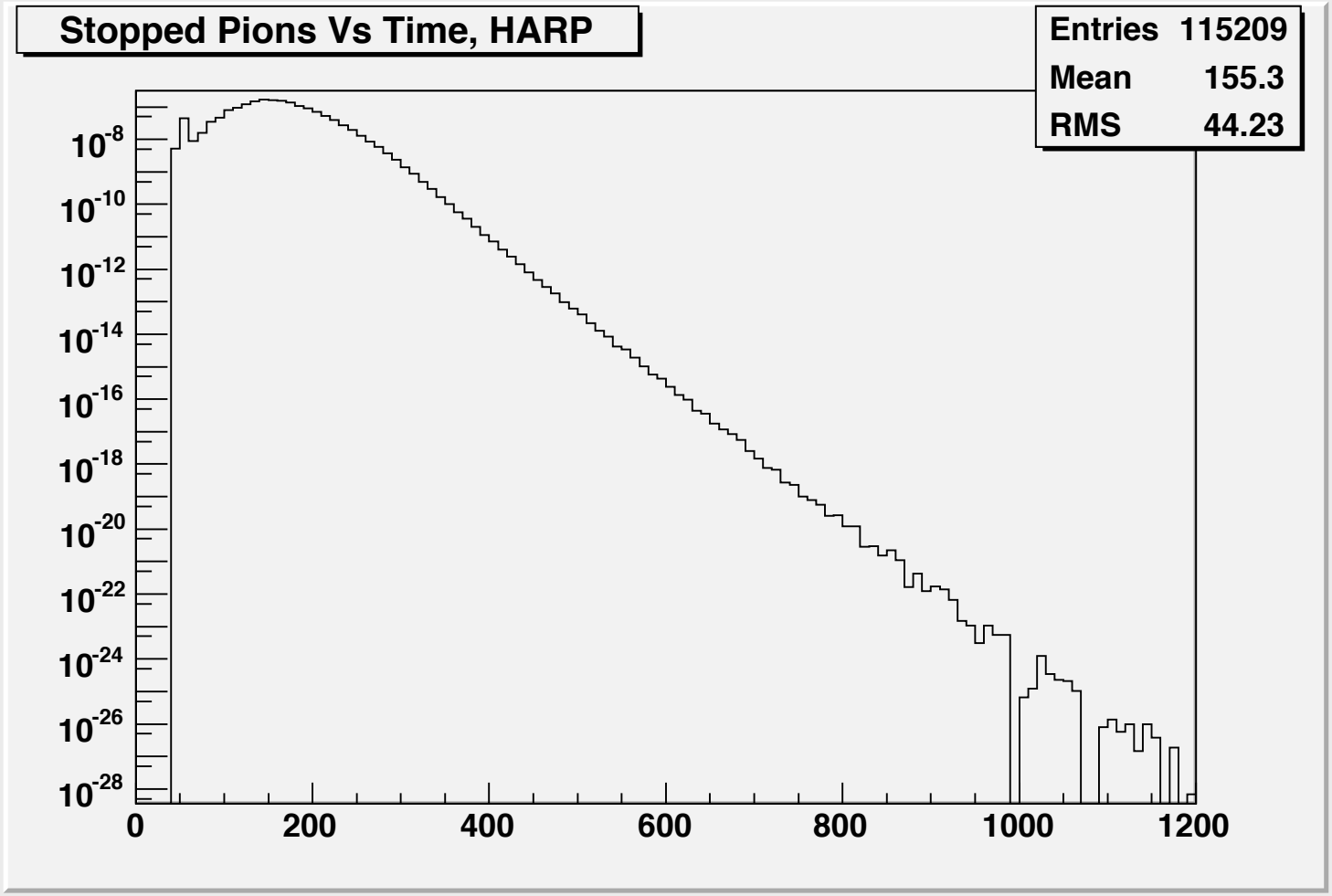
  = # protons out of pulse/# protons in pulse



- 10^{-10} based on simulation of prompt backgrounds and beamline

Pulsed Beam Structure and Radiative π Capture

$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+ e^-$$



need a beam that lets us wait this long: pulsed with long spacing

Pulsed Beam Structure and Radiative π Capture

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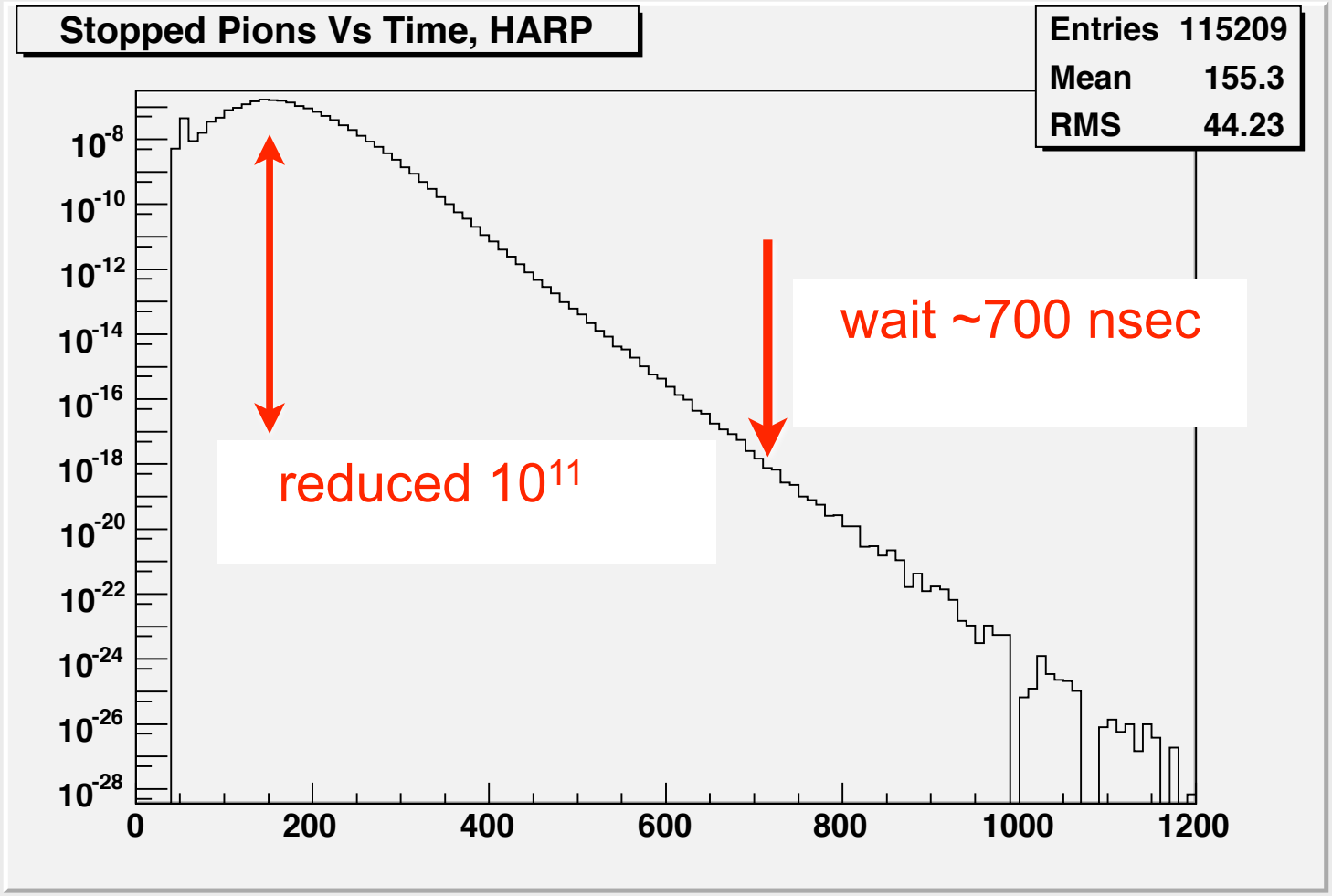
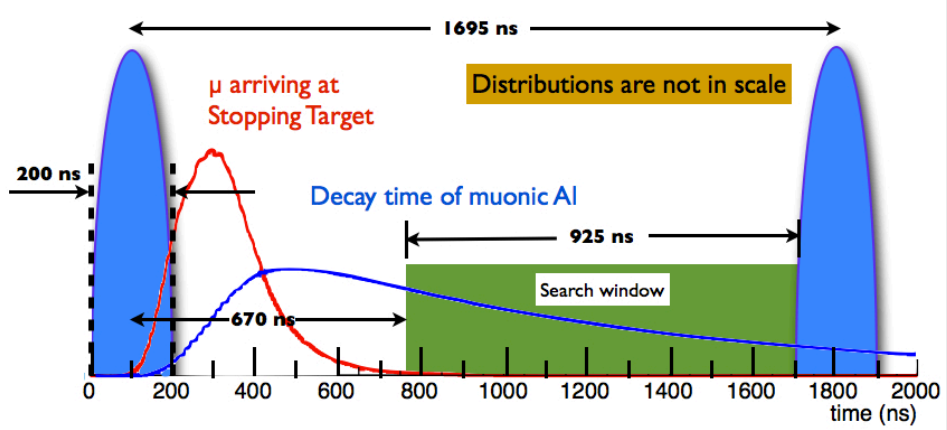


need a beam that lets us wait this long: pulsed with long spacing

Prompt Background and Choice of Z

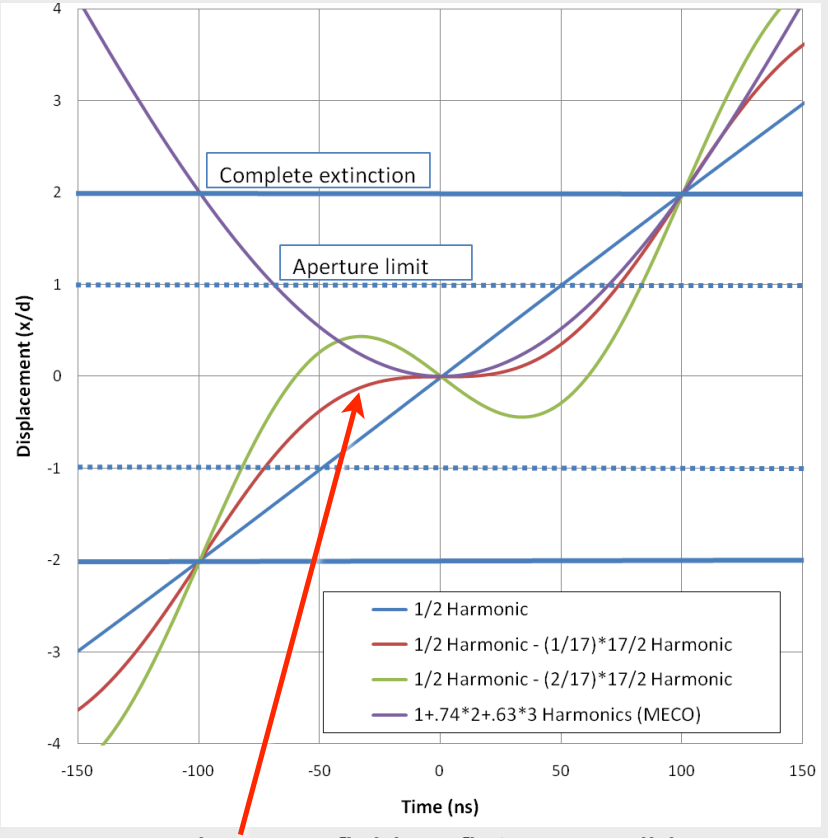
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds



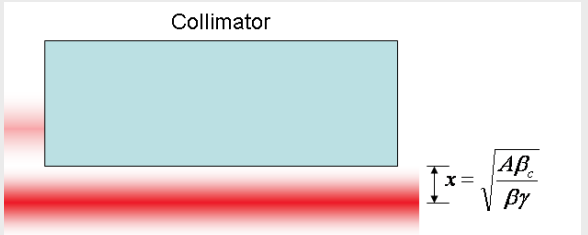
Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1.0	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

Extinction Scheme

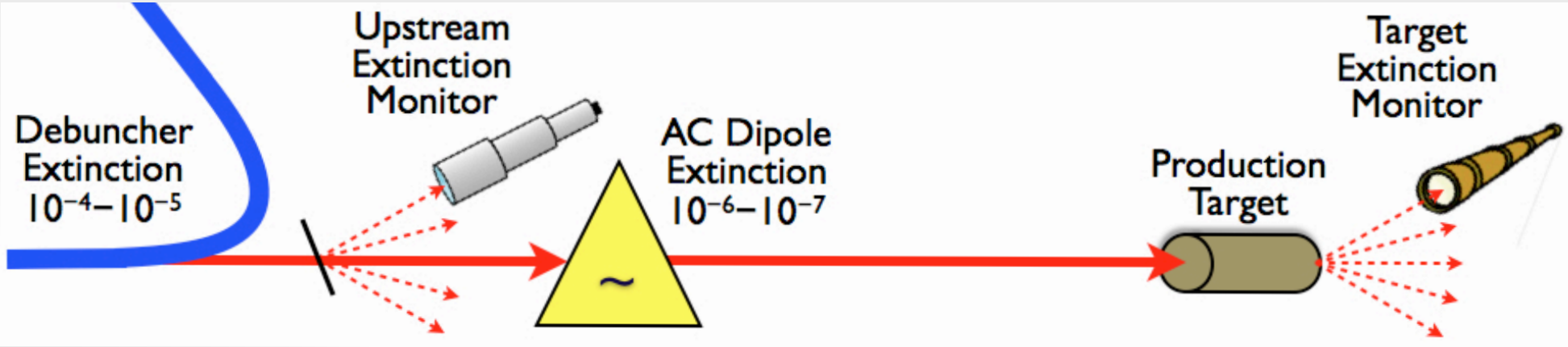
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
- Calculations (MARS) show this combination gets ~10^{-12}



choose a field as flat as possible during the pulse that kicks beam out as quickly as possible



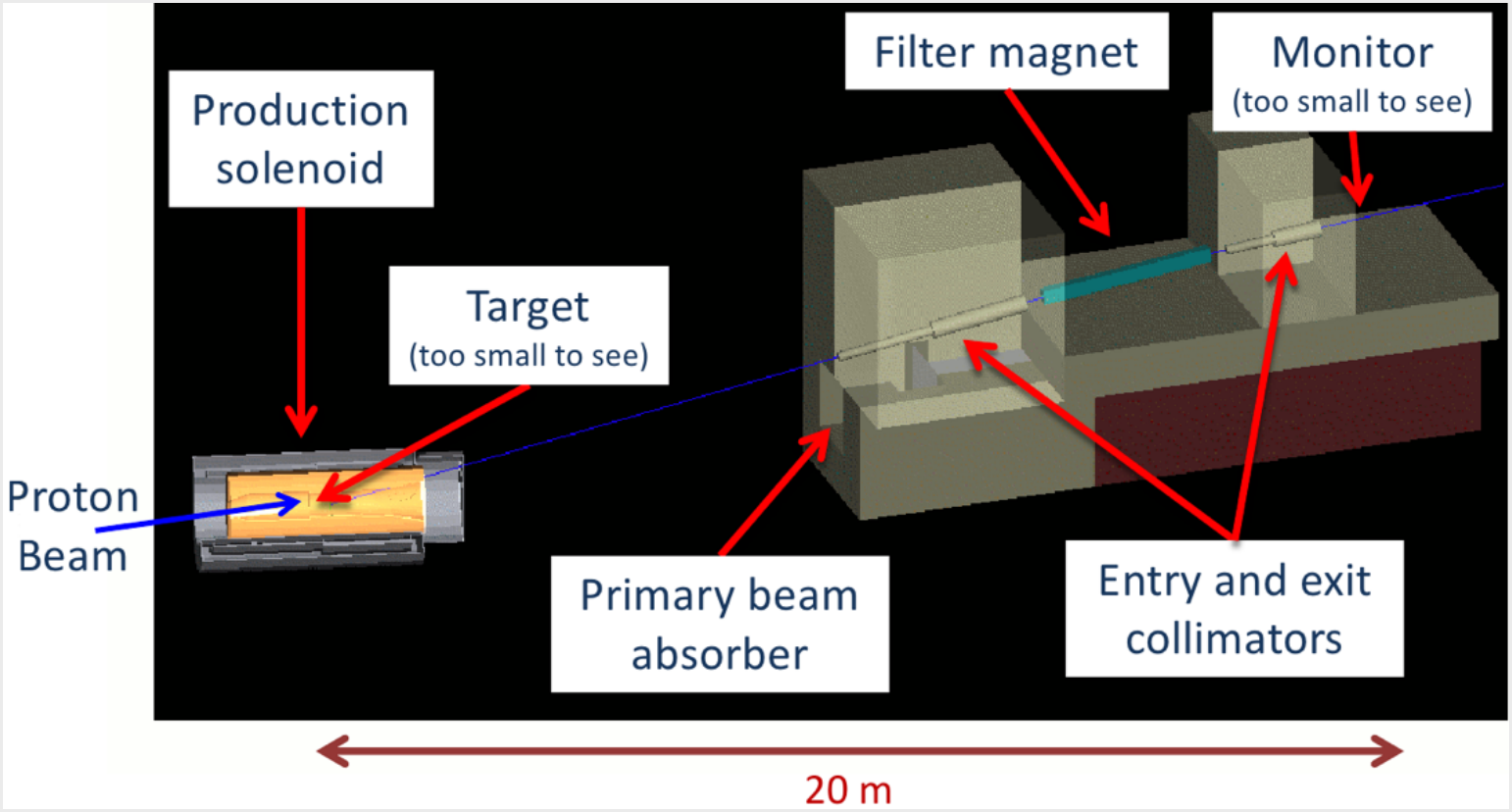
Extinction Measurement



- Beam Formation and AC-Dipole provide extinction
- Measure with:
  - Thin foils in 8 GeV transport line (fast feedback on machine performance)
  - Off-axis telescope looking at production target (time scale of hour)
    - pixel-based telescope looking at few GeV protons

Extinction Detector

- Si pixel telescope spectrometer with narrow view of target
- Measure extinction to 10^{-10} in ~1 hour



Mu2e Overview

V. Lobashev, MELC 1992:

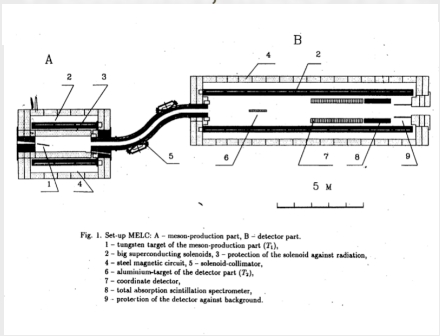
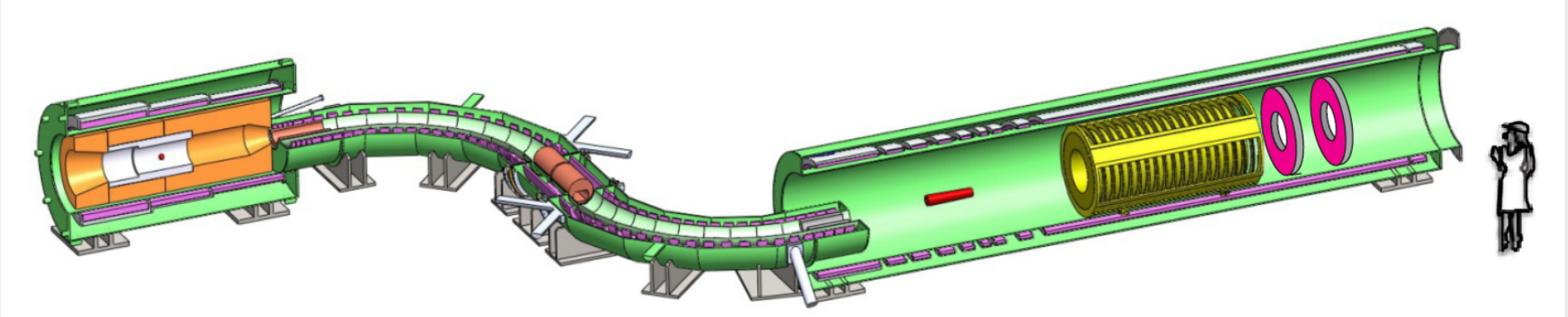


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

- *Production*: Magnetic mirror traps π's, which decay into accepted μ's

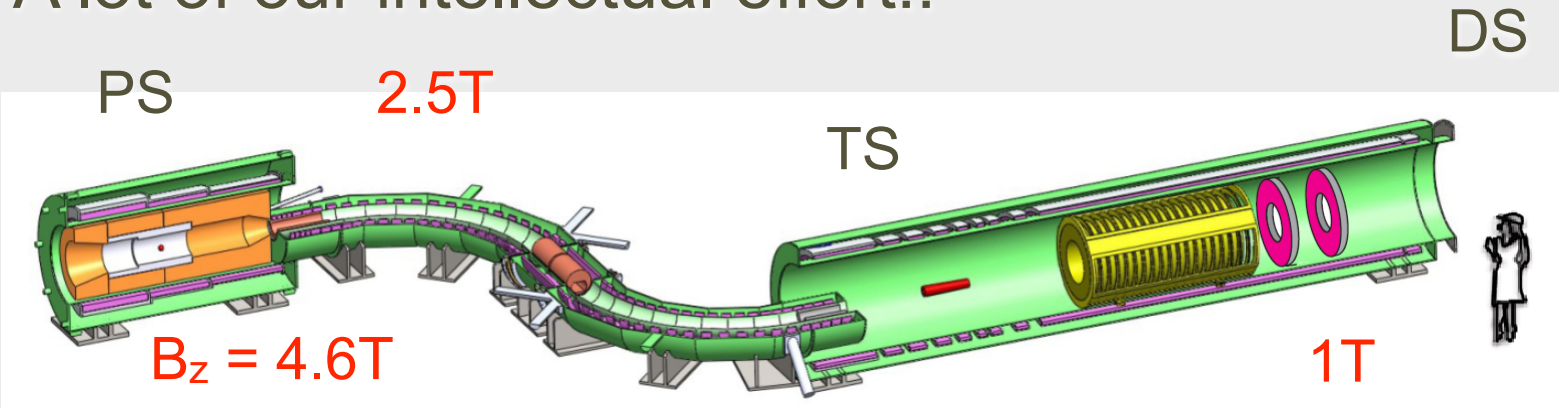


- *Transport:* S-curve eliminates backgrounds and sign-selects
- *Detector:* Stopping Target, Tracking and Calorimeter

entire system in vacuum < 10^{-4} torr

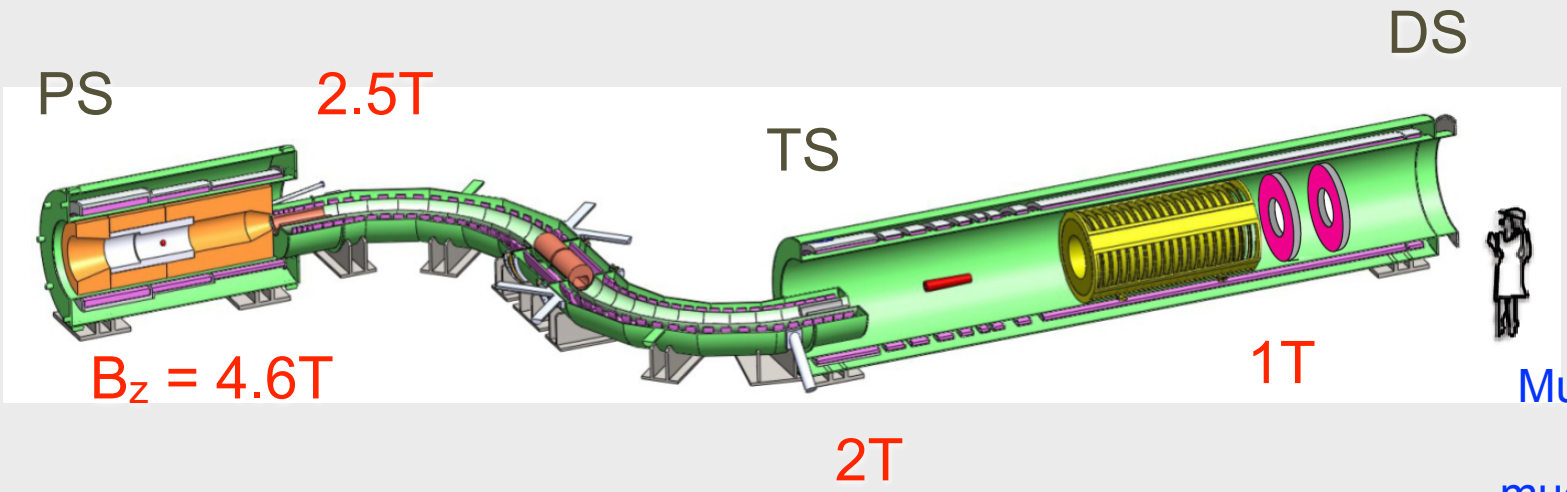
Gradient Fields in Mu2e

- Play a vital role throughout the design
- A lot of our intellectual effort!!

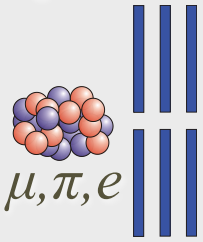


- "push" muons out of PS into TS and into DS so we can study them
- keep particles from spiraling around, arriving late
- conversions are isotropic in stopping target; the gradient over stopping target "reflects" backward going muons and nearly doubles the acceptance

Mu2e Muon Beam: Three Solenoids and Gradient



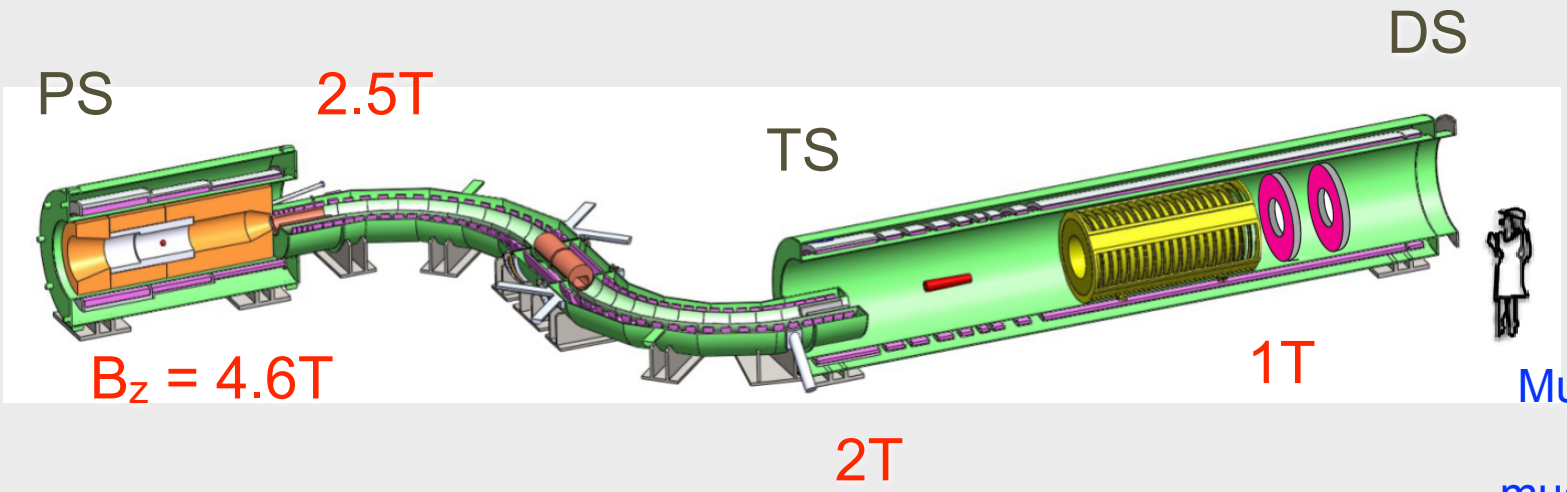
Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

Mu2e Muon Beam: Three Solenoids and Gradient

4.6T ⟶ B-field gradient ⟶ 1T



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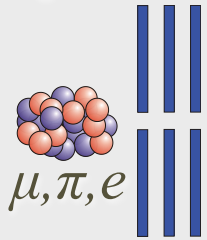

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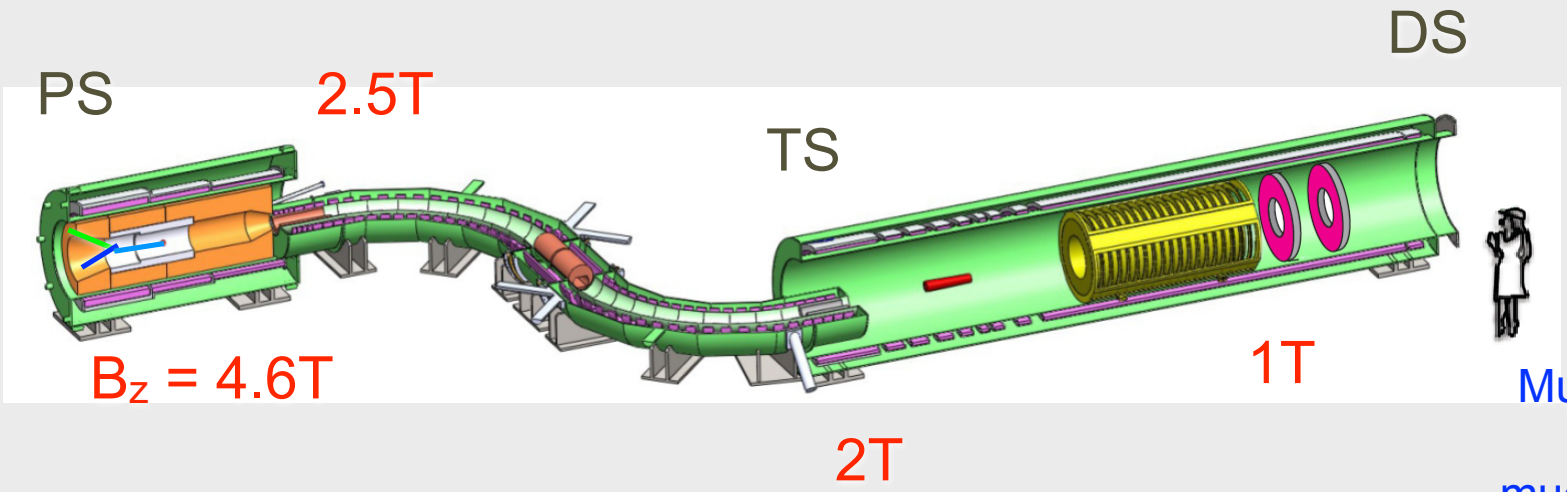

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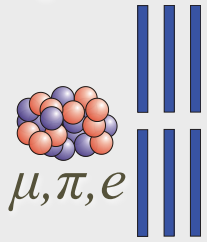

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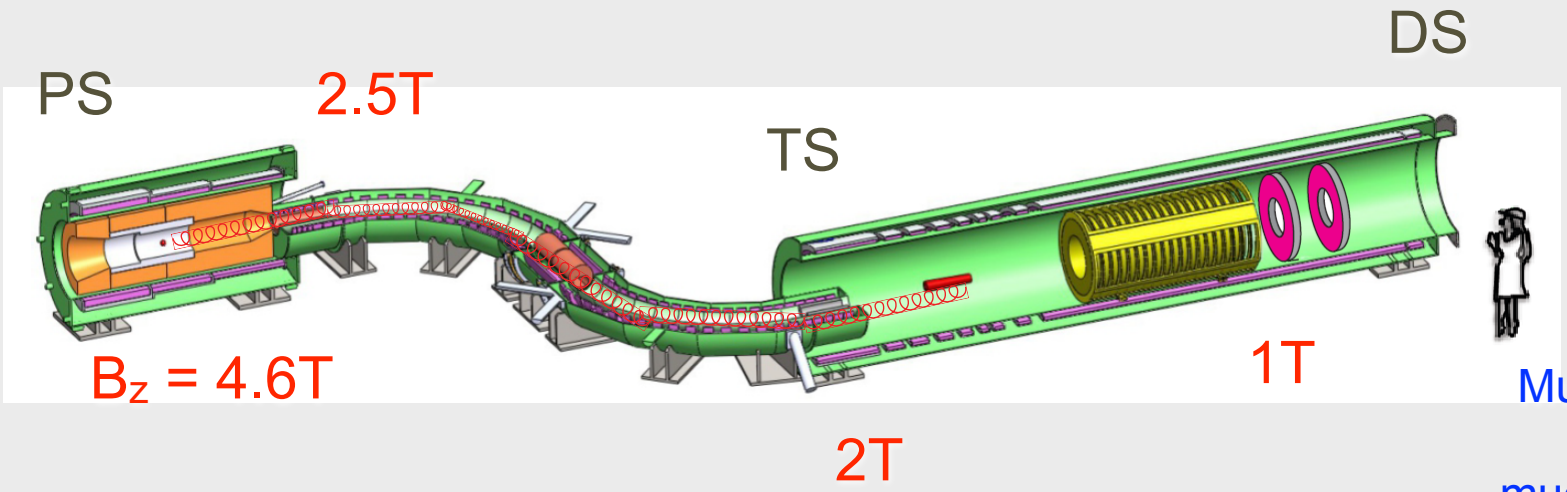

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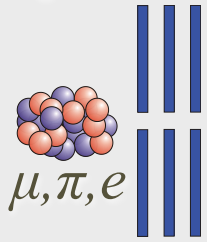

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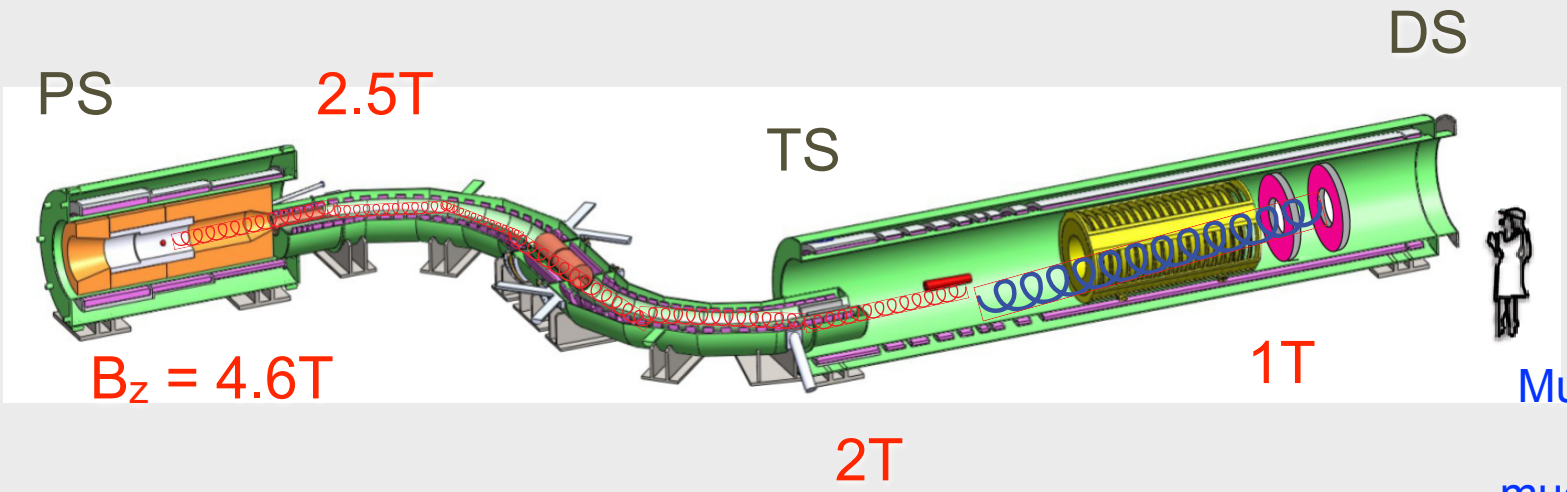

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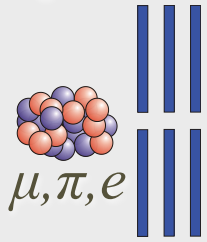
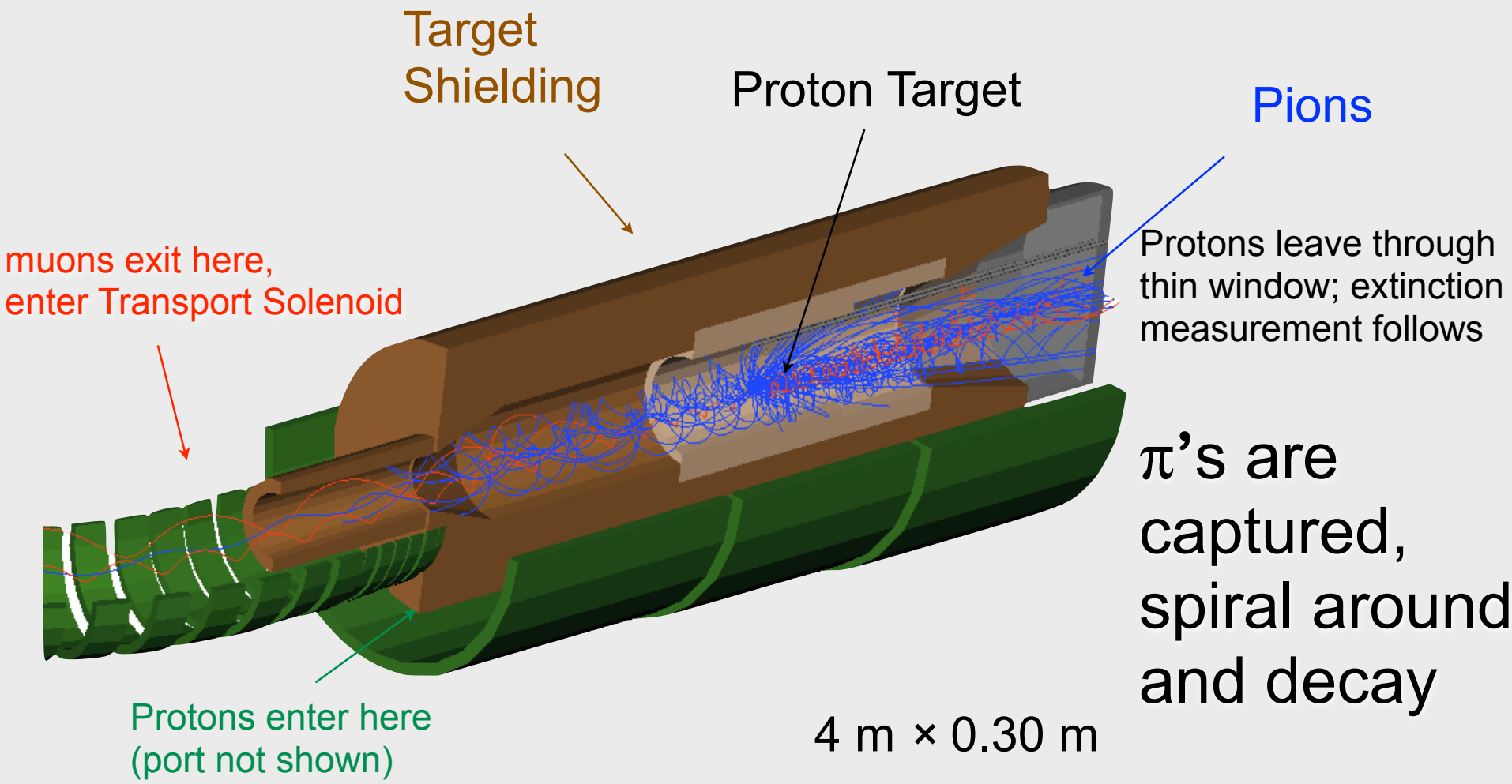


Production Solenoid:

old picture, design has changed a little

Protons enter opposite to outgoing muons

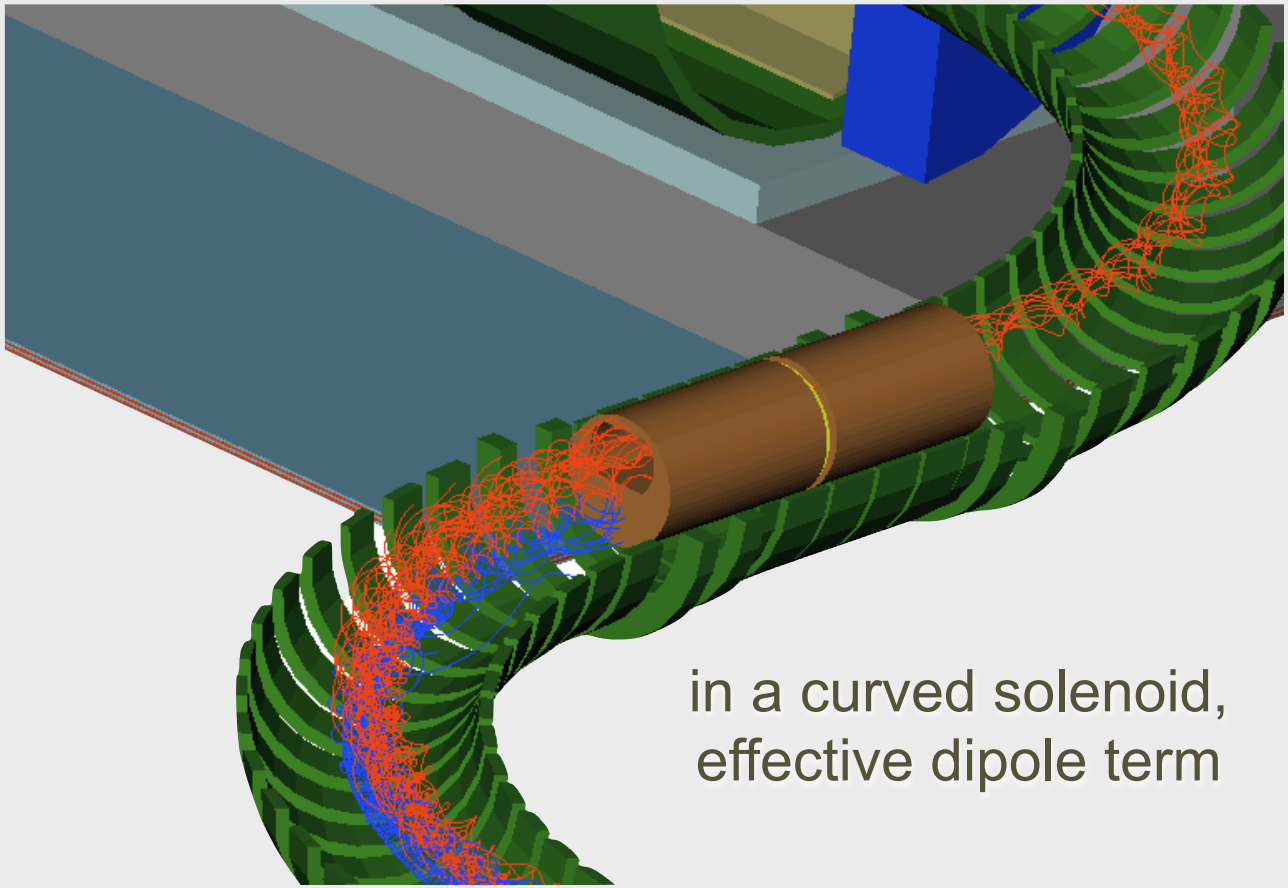


π's are captured, spiral around and decay

Transport Solenoid

old picture, design has changed a little

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam



in a curved solenoid, effective dipole term

13.1 m along axis × ~0.25 m

Detector Solenoid

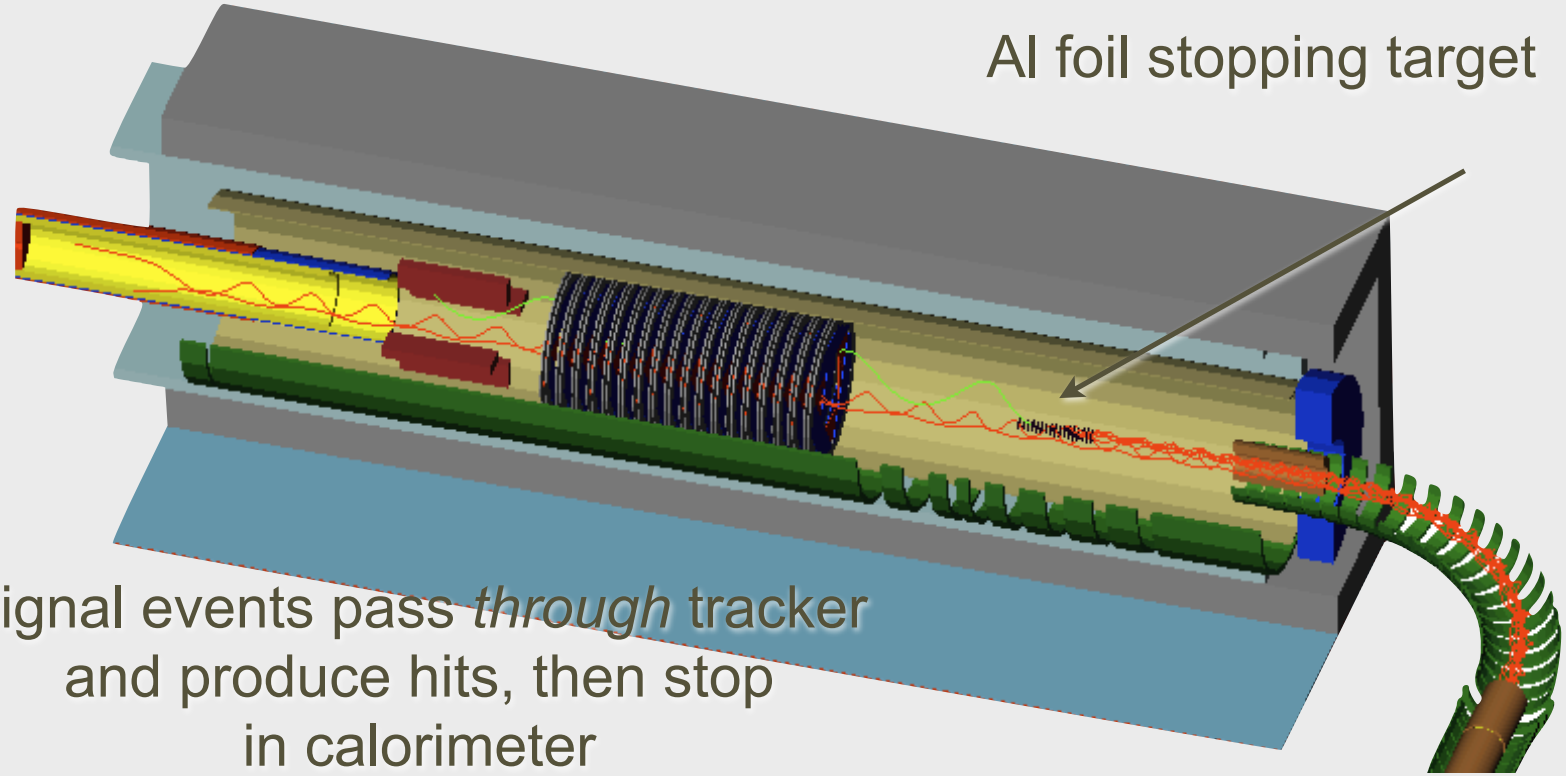
octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

old picture, calorimeter design has changed

10 m × 0.95 m

low momentum particles and almost all DIO background passes down center

Al foil stopping target



signal events pass *through* tracker and produce hits, then stop in calorimeter

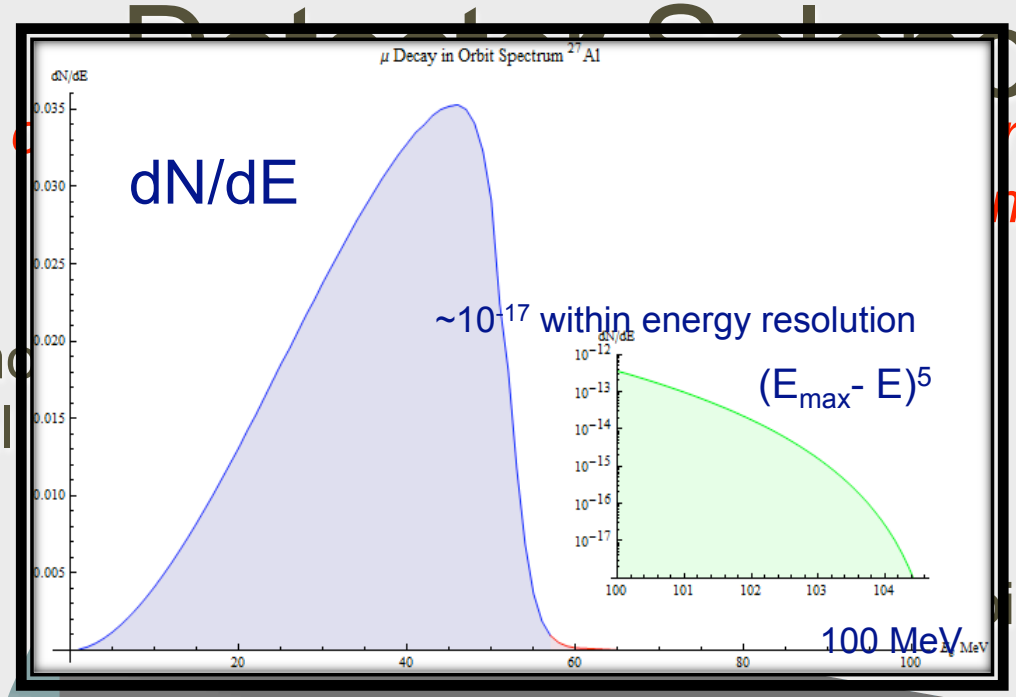
Detector Solenoid

region:
ntum,

old picture, calorimeter design has changed

10 m × 0.95 m

low mo
almost al



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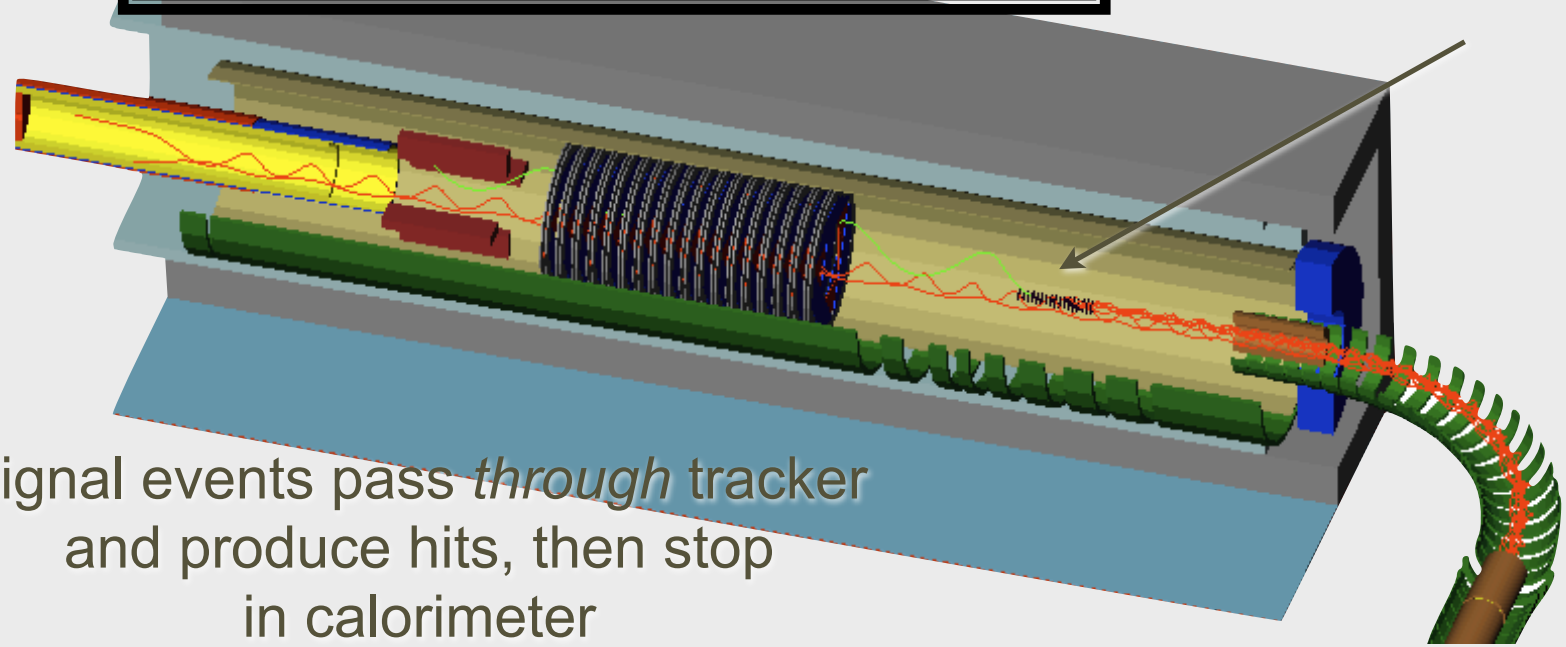

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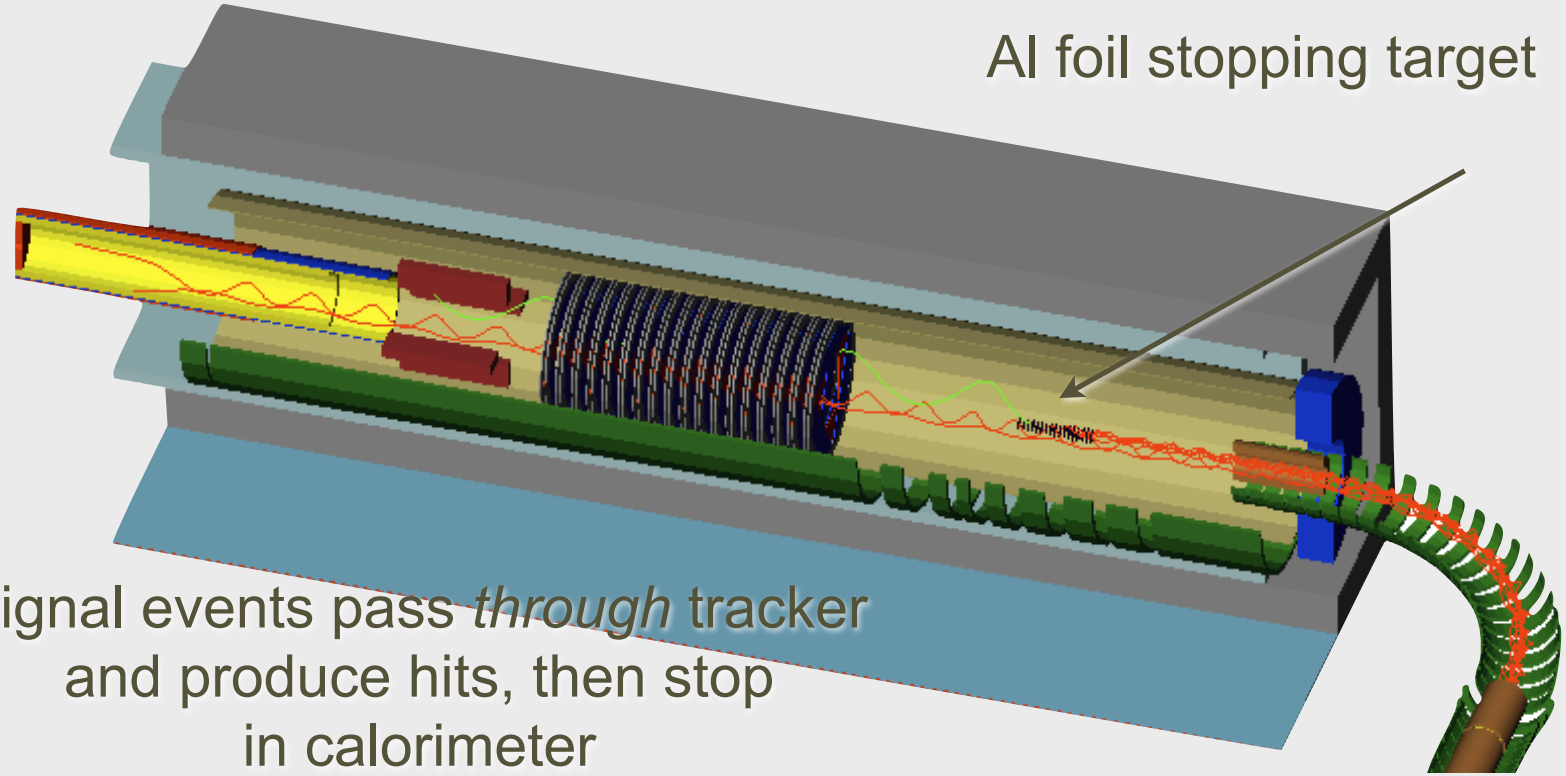


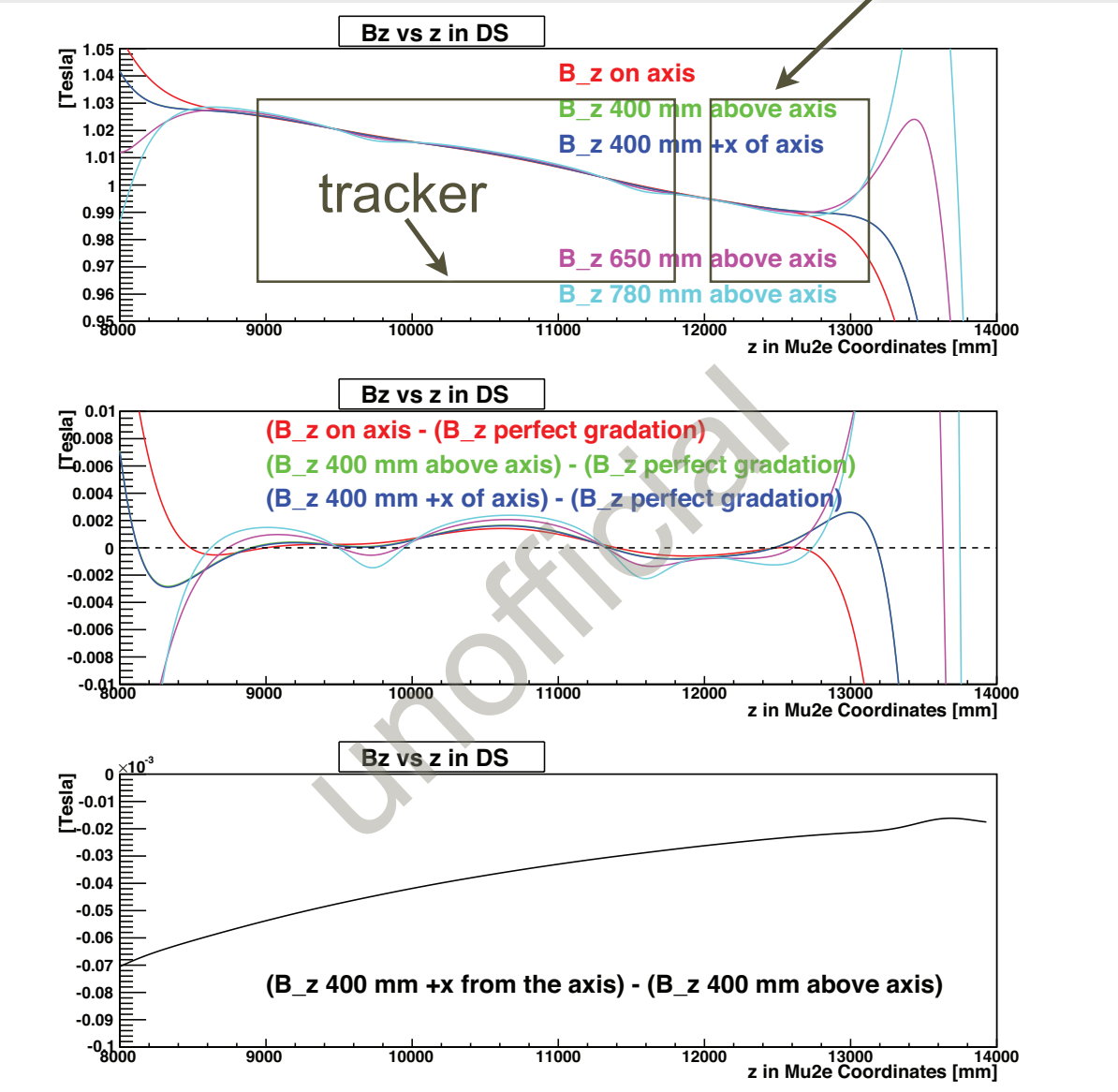
signal events pass *through* tracker and produce hits, then stop in calorimeter

Sculpting Magnetic Fields

- Overall, the field is solenoidal steadily decreasing until we get to the tracker and then keep it as constant as possible
- This also “pushes” particles along the system
  - avoids trapped particles looping around and ending up getting to the detector late
- After that, tons of details

Tracker, Calorimeter and Field

- Actually put slight gradient over tracker region to minimize small negative gradients and trapped particles
- Can see coil structure
- >100 Person-years



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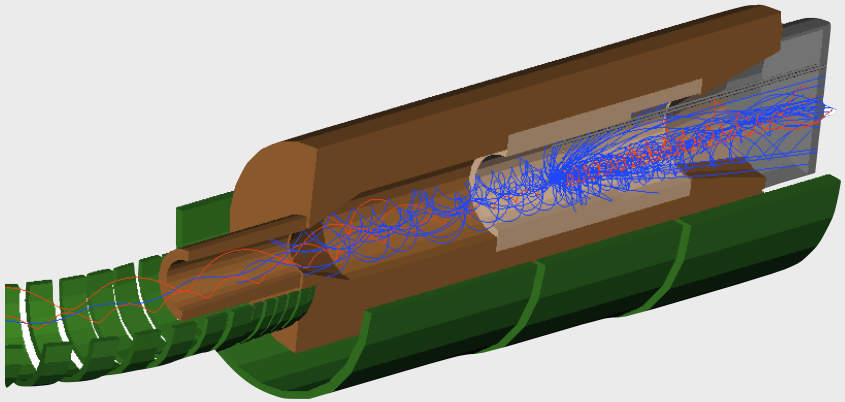


- In PS:
  - proton beam enters *in opposite direction* from solenoid system
  - extinction measurement out the back
  - solenoidal field increases along proton direction, creating a magnetic mirror, but ~80-85% of flux from backwards going pions
    - cross-sections are poorly known (+- 20%)

Magnetic Mirror

- Magnetic Fields do no work! (ever hear that?)
- See Jackson, 2nd Ed. Sec. 12.4. If the field changes sufficiently slowly,

$$Ba^2$$

$$p^2{}_\perp / B$$

$$\gamma\mu \text{ (the magnetic moment of the current loop)}$$

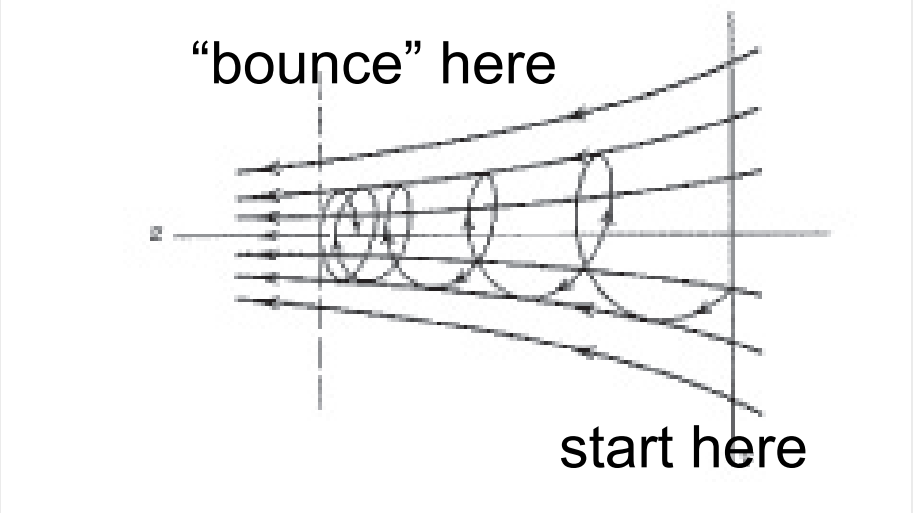
are adiabatic invariants

Therefore for Our Solenoids

$$v_{\parallel}^2 + v_{\perp o}^2 = v_o^2$$

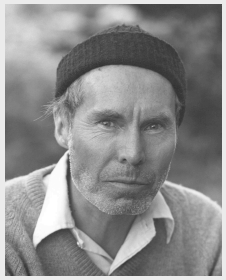
$$\frac{v_{\perp o}^2}{B(z)} = \frac{v_o^2}{B_o}$$

$$v_{\parallel}^2 = v_o^2 - v_{\perp o}^2 \frac{B(z)}{B_o}$$



as *B* grows, $v_{\parallel}$ goes to zero
and the particle turns around with constant $|\vec{p}|$ – a magnetic mirror

Selecting Negative Muons



- E&M to the rescue:
  - Jackson, 2nd Ed., Sec 12.5: particle drifts in Nonuniform, Static Magnetic Fields
  - Curve of Solenoid gives “centrifugal acceleration” from an effective electric field

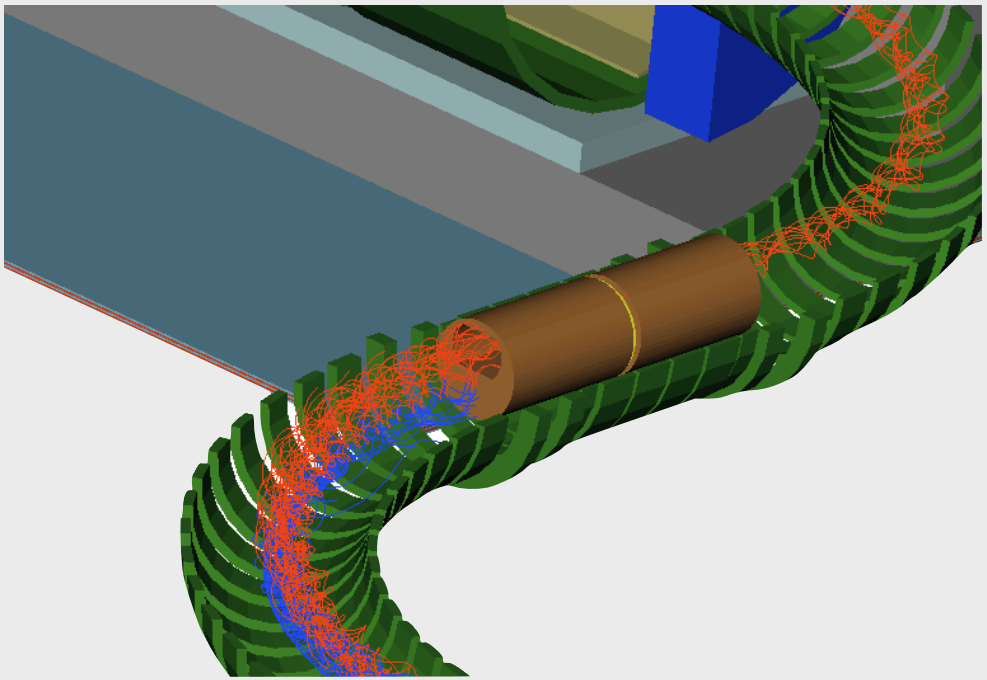
$$\vec{E}_{\text{effective}} = \frac{\gamma m}{e}\frac{\vec{R}}{R^2}\mathrm{v}^2_{\parallel}$$

note the sign
of the field flips with the
sign of the charge

So This is What Happens:

- Negative muons go one way, positive muons the other
- A rotatable collimator lets us pick one charge or the other: see calibration discussion later
- And the 2nd half of the "S" brings the beam back on axis

13 m along the axis, 25 cm across

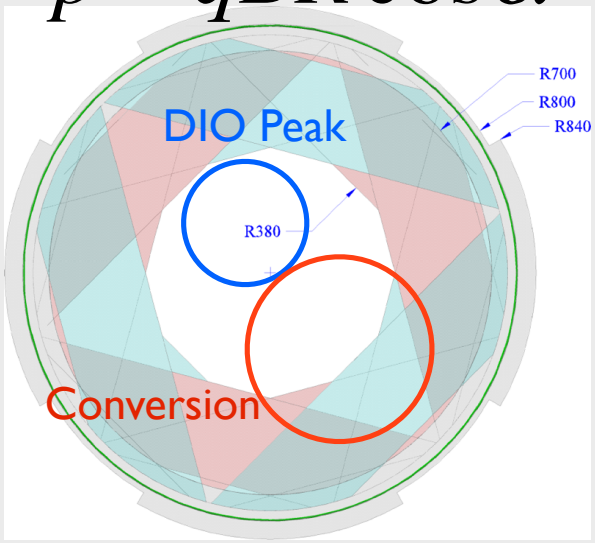


green represents the coils of superconducting cable

Design and Getting to 10^{-17}

- The trick, of course, is not to have to reject 10^{17} events
- There are multiple ways to solve this problem.
- Mu2e:
  - use a central hole
  - only see ~few x 10^5 events
  - 10^5 << 10^{17}

$$p = qBR\cos\alpha$$

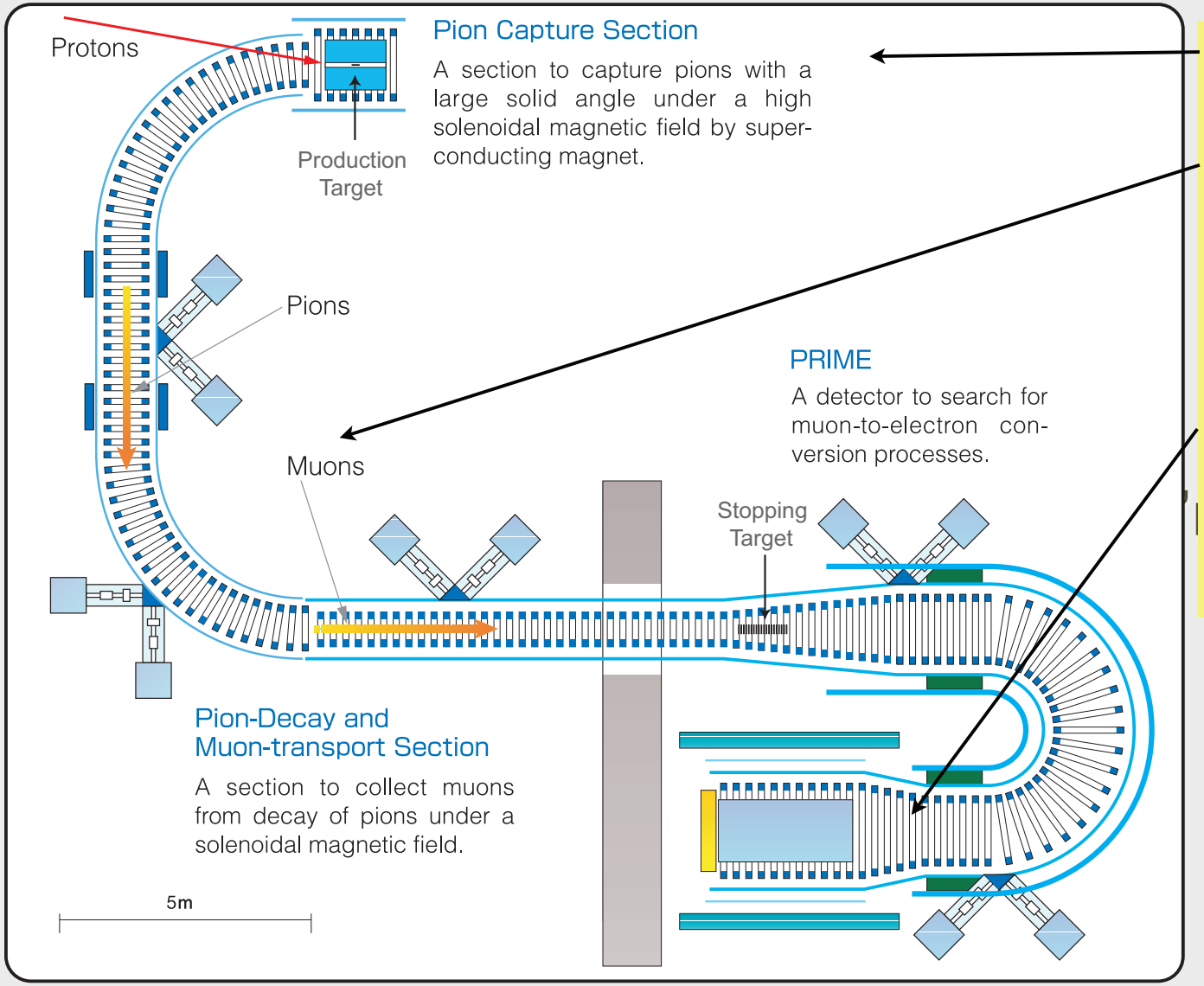


DIO's up to ~ 80 MeV/c stay in central hole;
conversions seen by tracker

Theme and Variations: COMET

- Here's another way: (not as good but I'm biased)

Theme and Variations: COMET



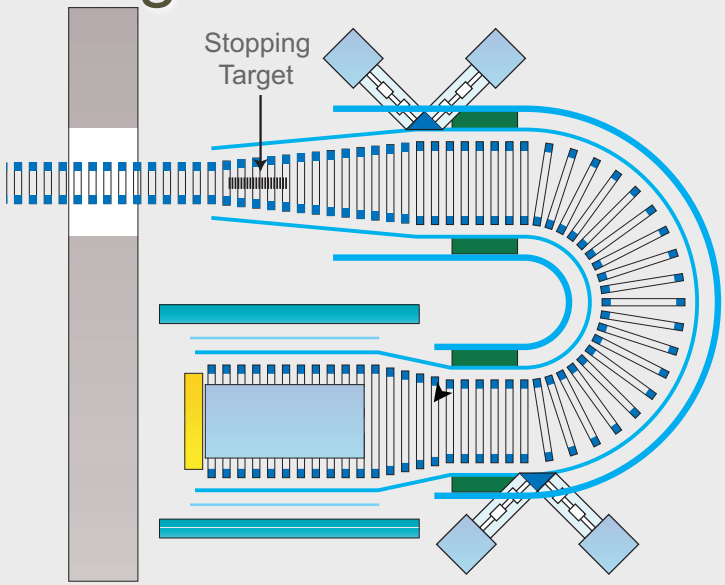
Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

2nd Bend

- DIO's below some momentum hit walls of solenoid and never make it to the tracker
- Tracker has no hole
- But a "DIO-blocker" is needed inside bend, creating accidental activity and reducing acceptance; design not final and effect not included



For the Astute

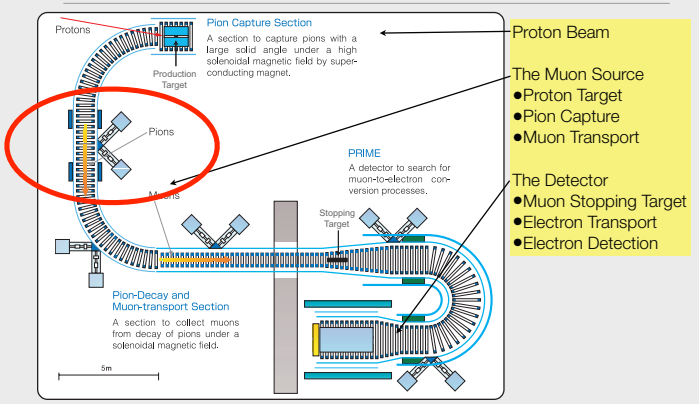
- You'll notice I said the second part of the Mu2e "S" brought the muons back on axis
- COMET has a C: are the muons drifting off somewhere?
  - No, they have (IM¬HO) a complicated dipole correction system

$$D(s) = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

apply compensating dipole field

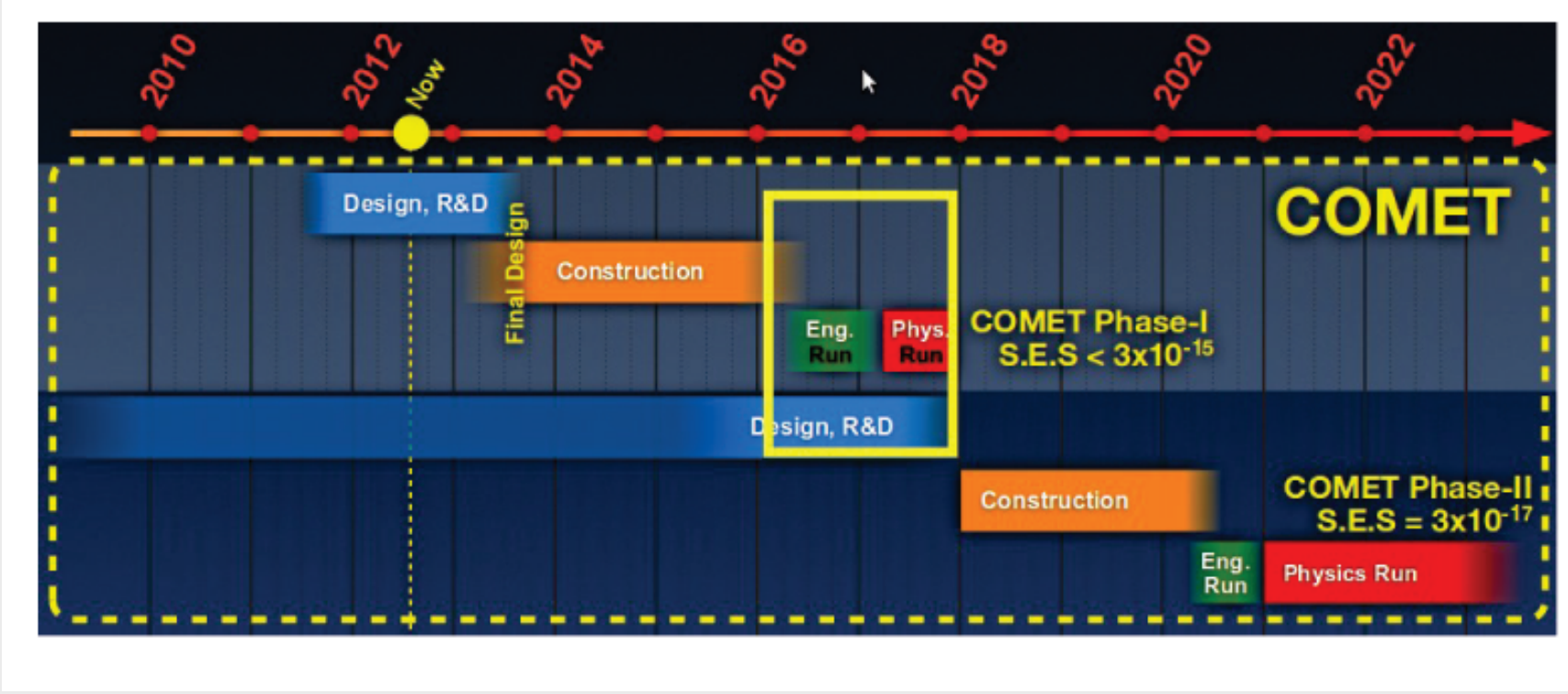
$$\mathrm{B} = \frac{1}{qR}\frac{p_0}{2}\left(\cos\theta_0 + \frac{1}{\cos\theta_0}\right)$$

COMET Status

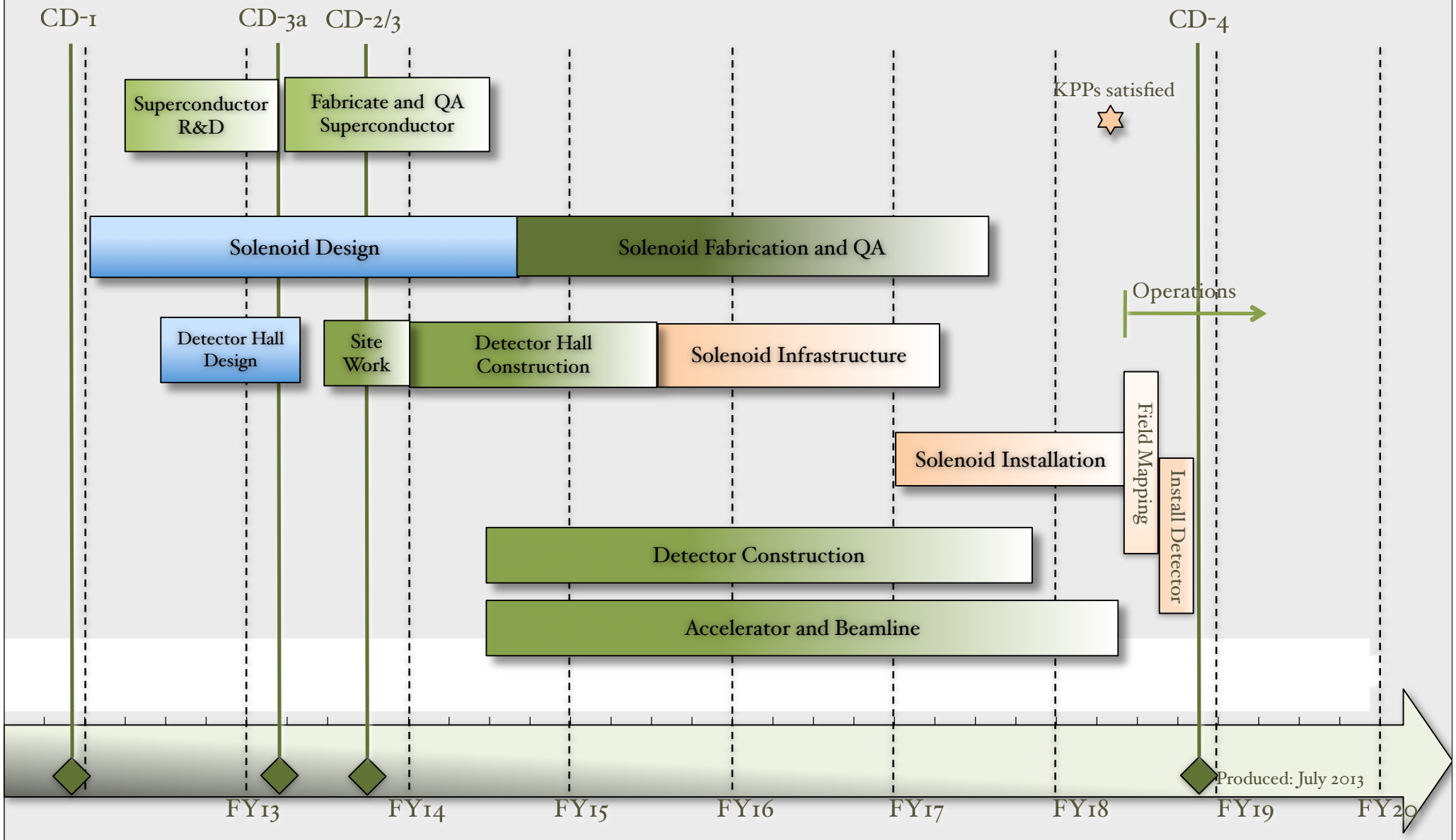


- Broken into two phases:
  - Phase I: up through central bend
    - Want to do measurements of flux with one detector and a second detector to do ~x100 better than SINDRUM, same style of cylindrical detector as SINDRUM >= 2017
  - Phase II: full detector as shown >=2021
- Design of Phase I in progress
  - a test coil is in the purchase process

COMET Schedule



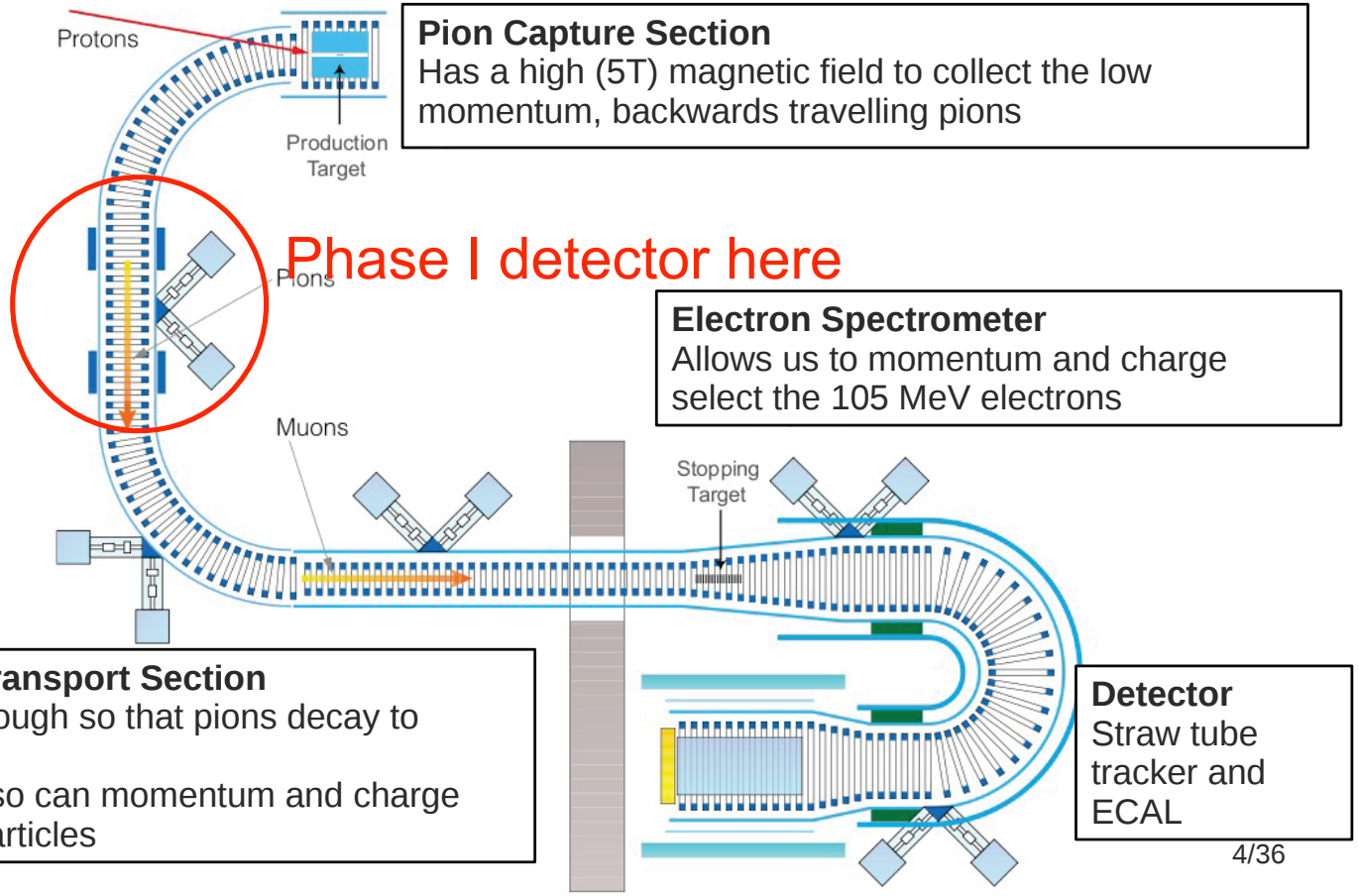
Mu2e Schedule



COMET Phase I

Starting in 2020
Measurement in 2022
S.E.S = 3×10^{-17}

COMET (Phase-II)



Pion Capture Section
Has a high (5T) magnetic field to collect the low momentum, backwards travelling pions

Electron Spectrometer
Allows us to momentum and charge select the 105 MeV electrons

Muon Transport Section
Long enough so that pions decay to muons
Curved so can momentum and charge select particles

Detector
Straw tube tracker and ECAL

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