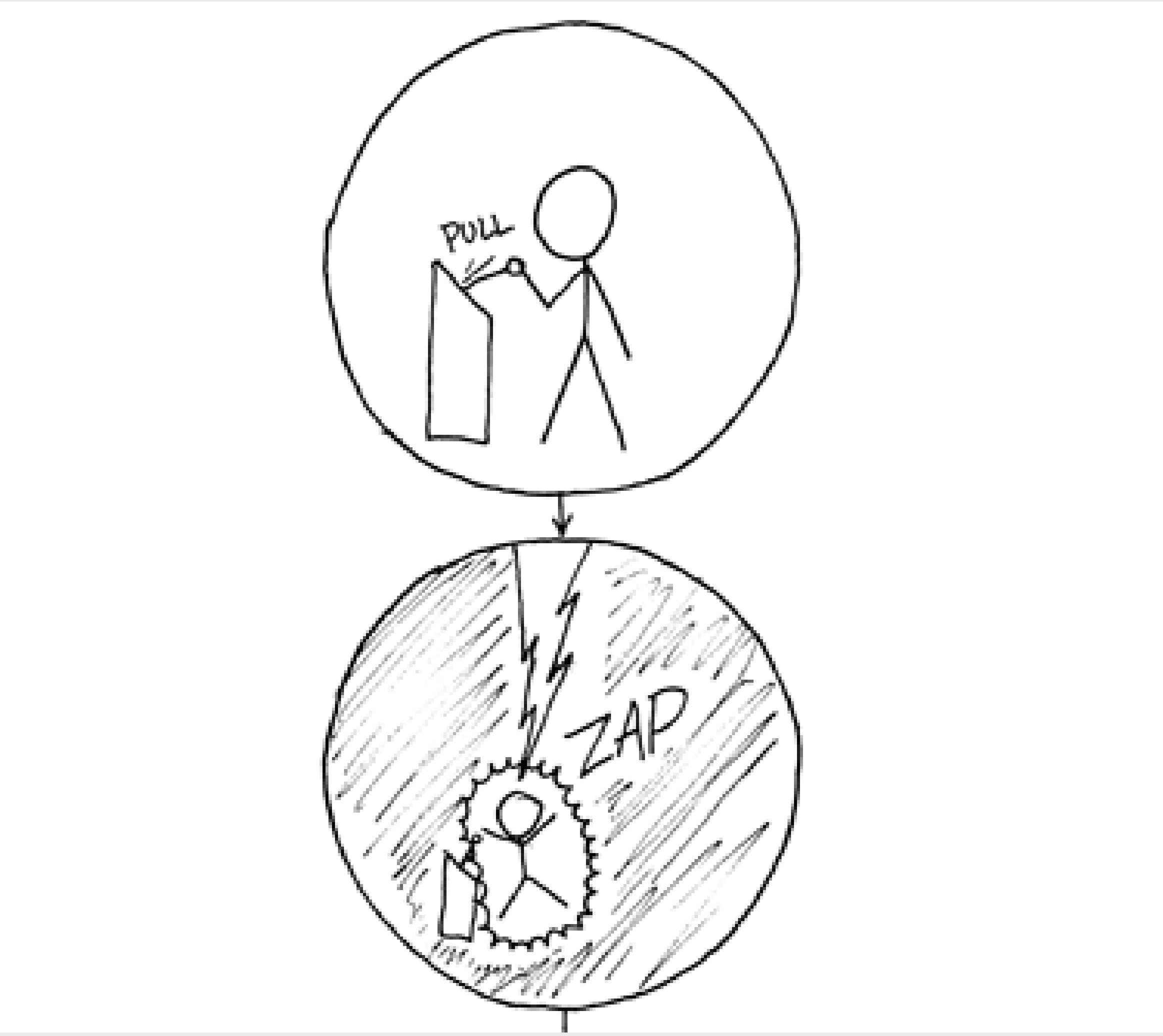
Standing on the Shoulders of Giants: Future Charged Lepton Flavor Violation Experiments

http://lccn.loc.gov/50041709

R. Bernstein
Fermilab

Alternative Title and Def'n of Insanity

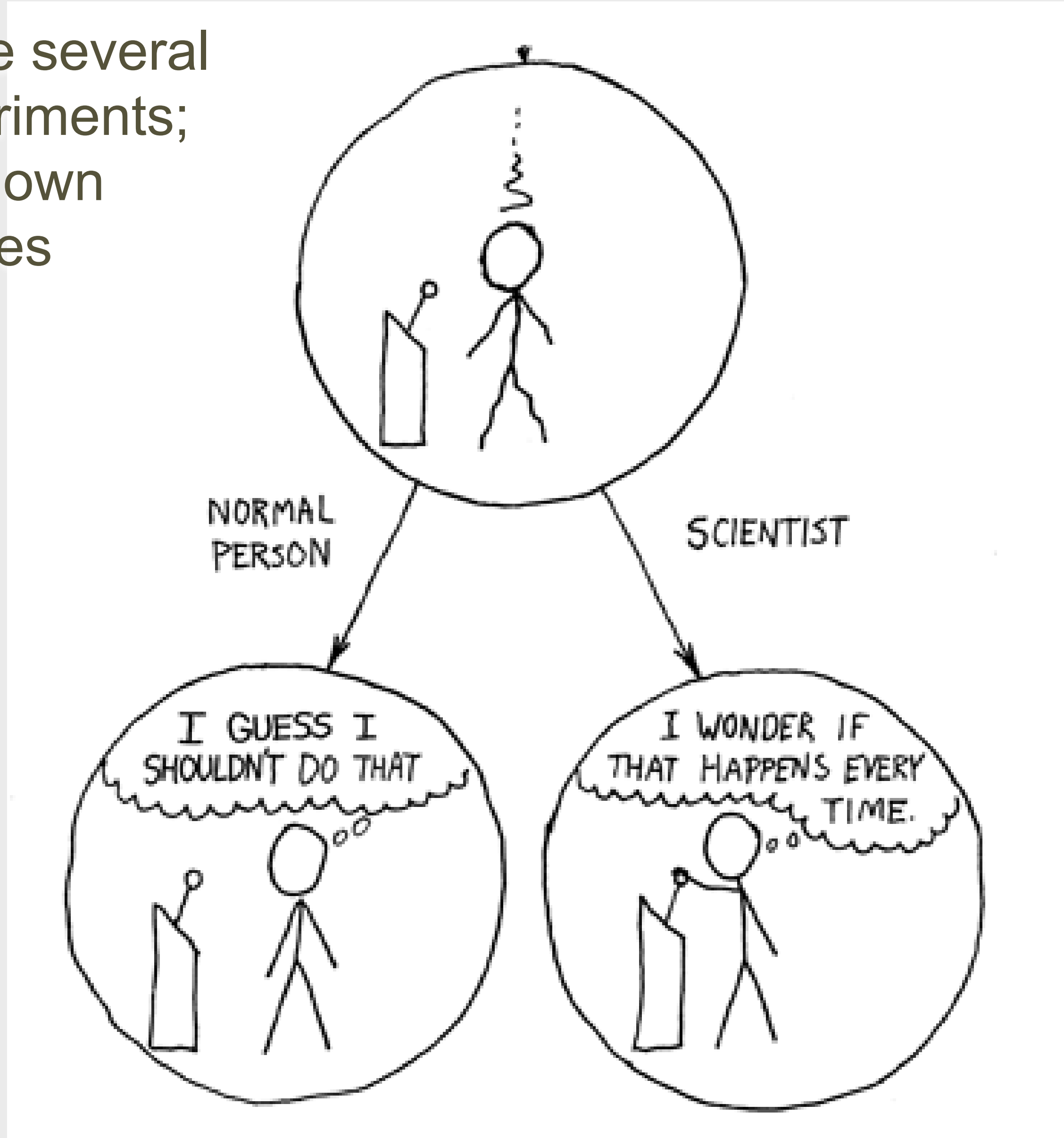
http://xkcd.com/242/



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

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

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

- 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 $\tau \to e\gamma$, $\tau \to 3l$, $K_L \to \mu e$, and more

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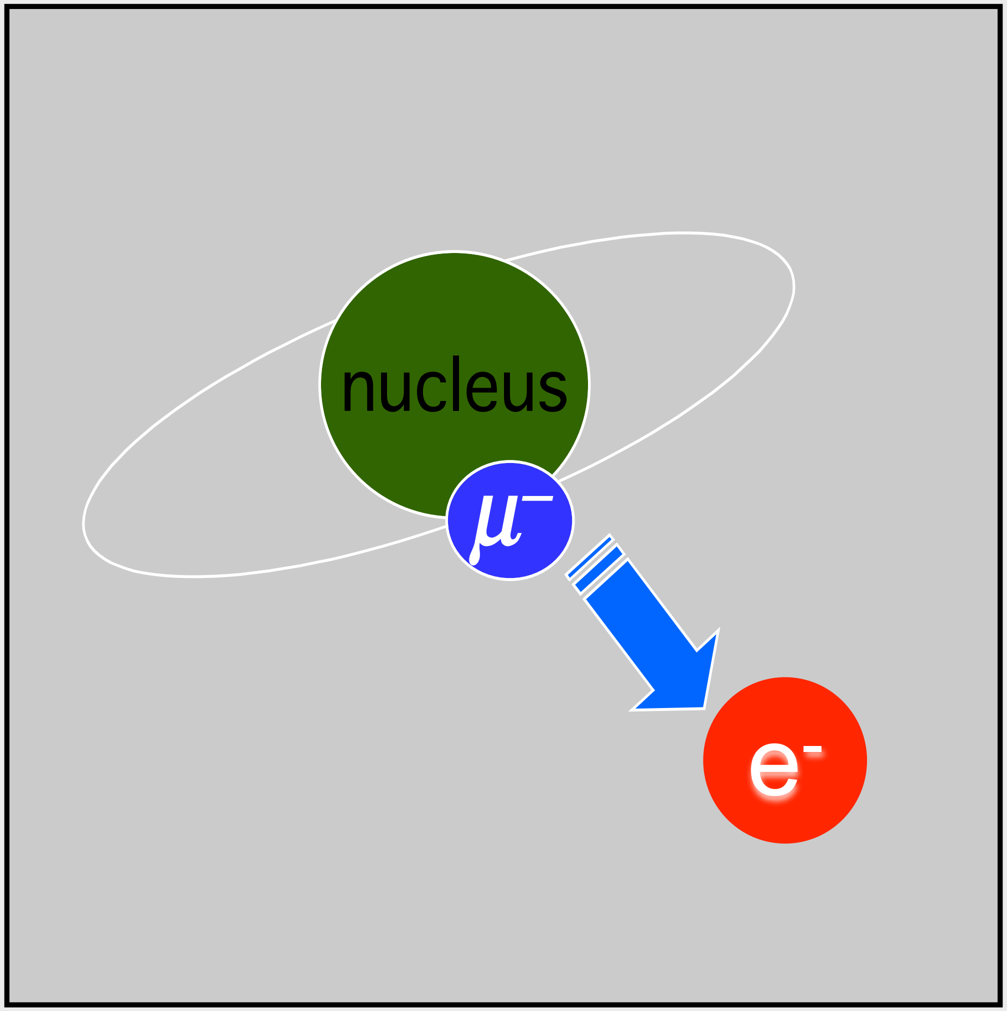
Experimental Signal

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

- 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

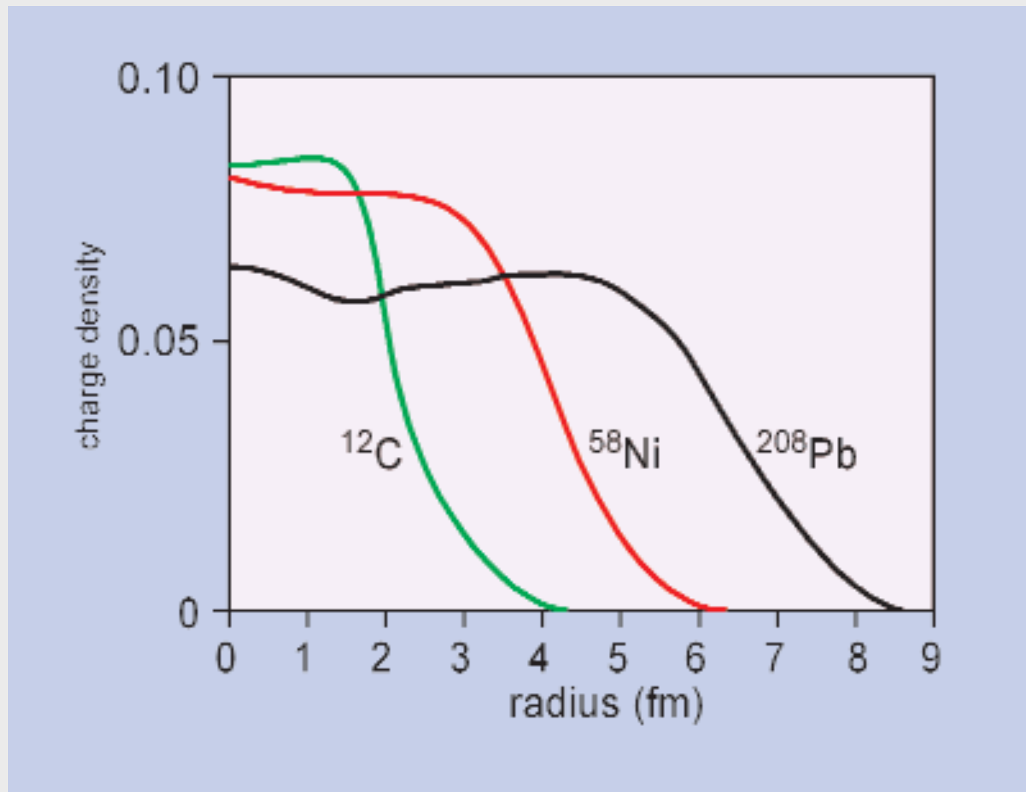
- How does the muon get captured by the nucleus?
  - through the weak interaction
    - (and many details cancel in the ratio we measure)
- But first the wave functions have to overlap:
  - what's the Bohr radius for a 1s muon in Aluminum?

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

$$= 20 \text{ fermi}$$

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

$$\text{probability of overlap:}$$

$$\sim 0.001 \text{ for a muon vs } 10^{-13} \text{ for an electron}$$

- *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)

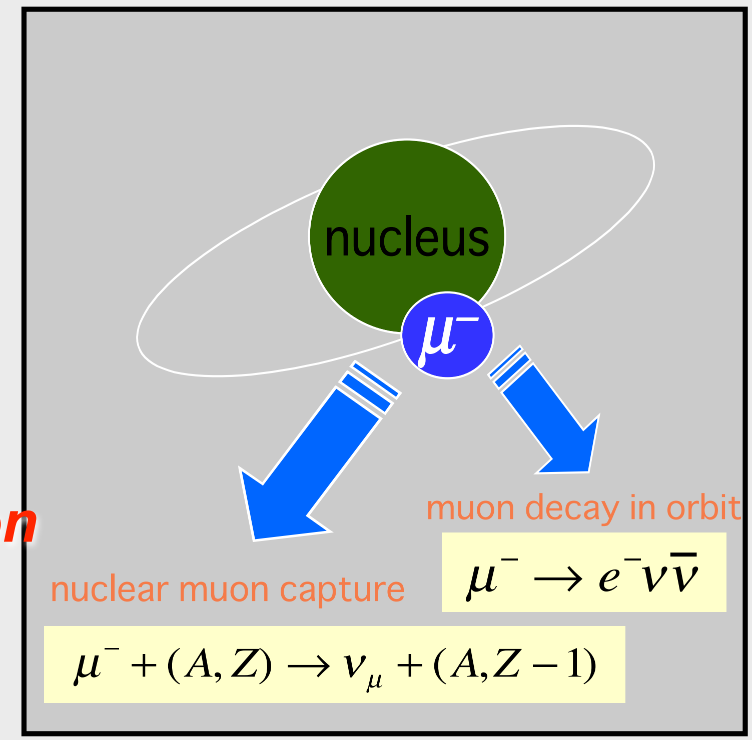
Overview Of Processes

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



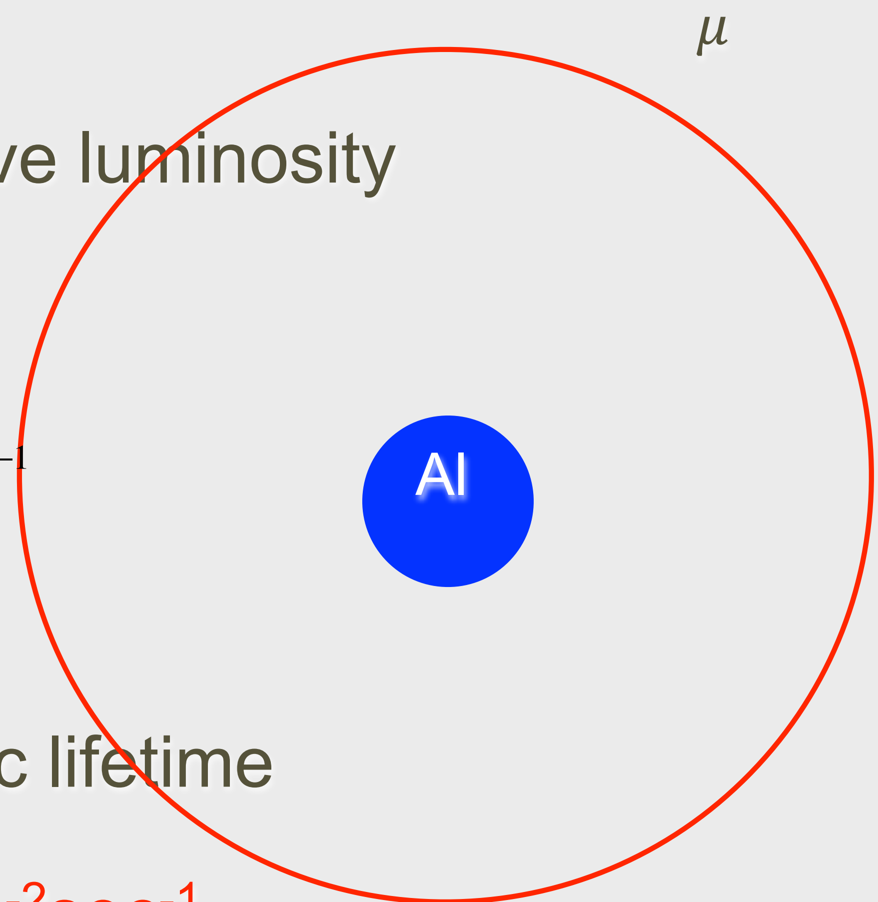
muon capture,
muon “falls into”
ucleus: ***normalization***

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)



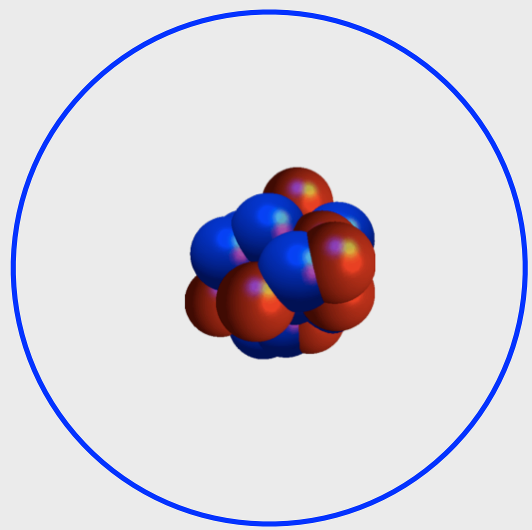
- We can turn this into an effective luminosity
- Luminosity = density x velocity

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

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

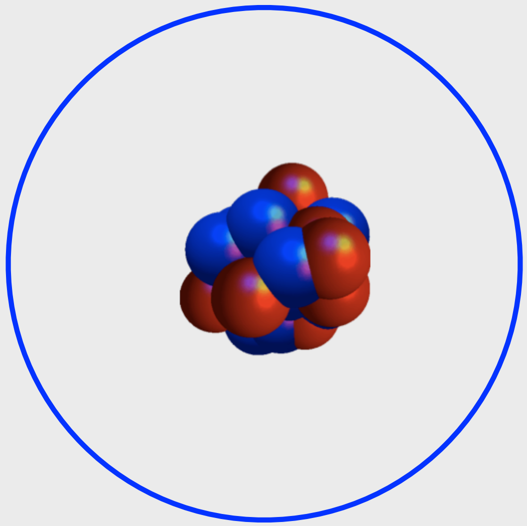
A. Czarnecki, clfv.le.infn.it

Three Possibilities: Normalization



Three Possibilities: Normalization

muon stops



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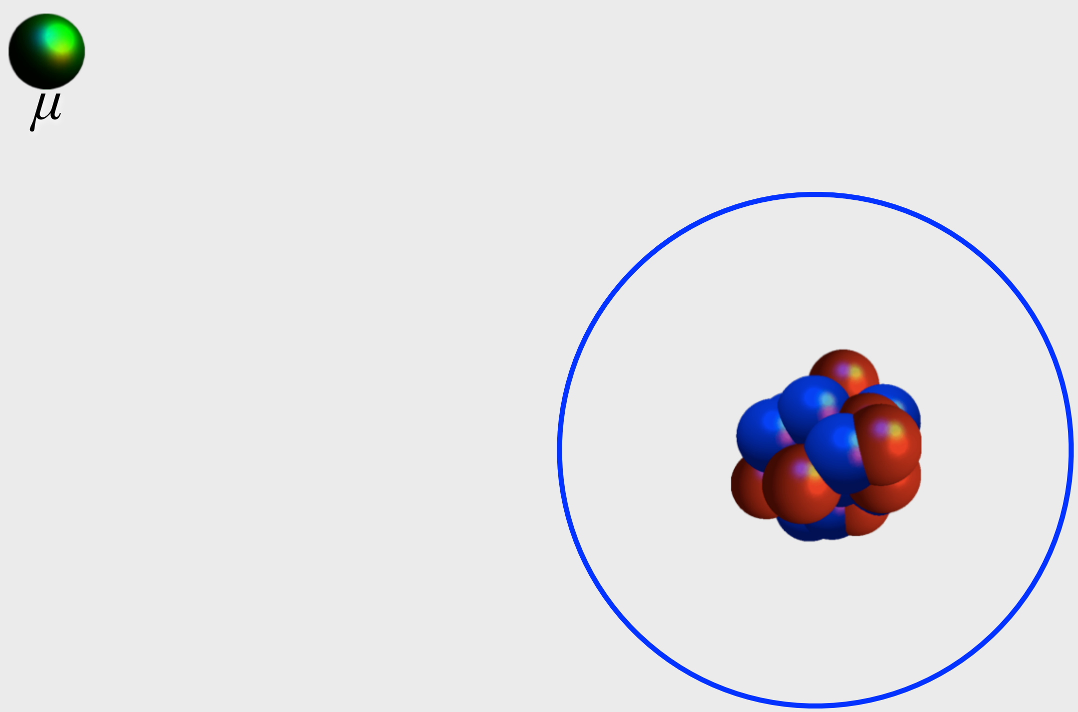

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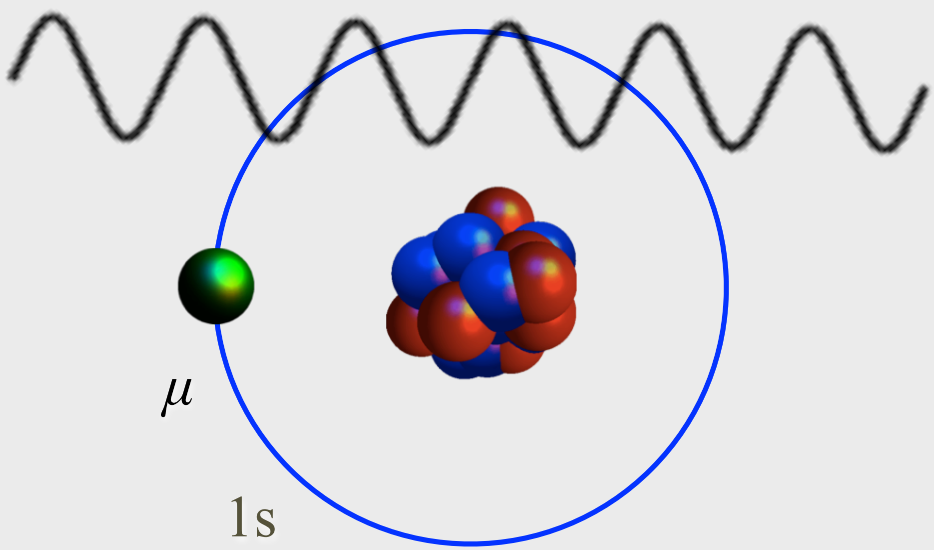
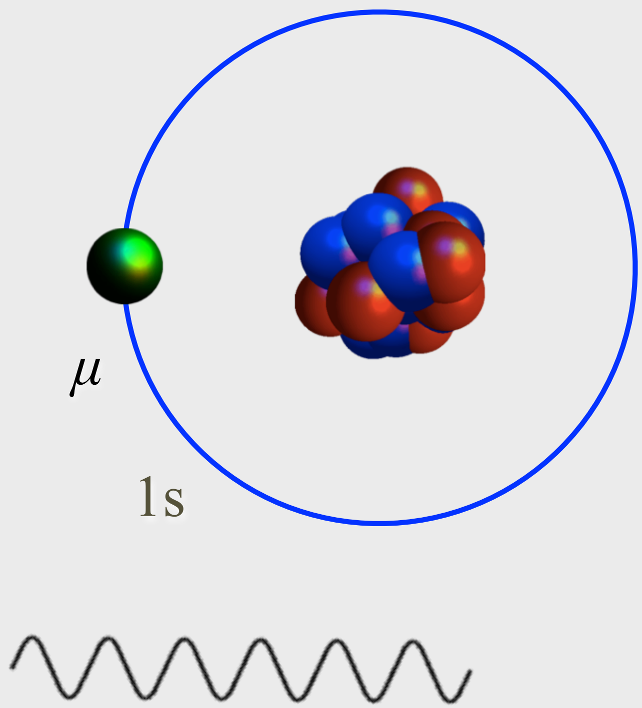


Three Possibilities: Normalization

X-Rays from cascade (occurs in <psec)

detect these for normalization

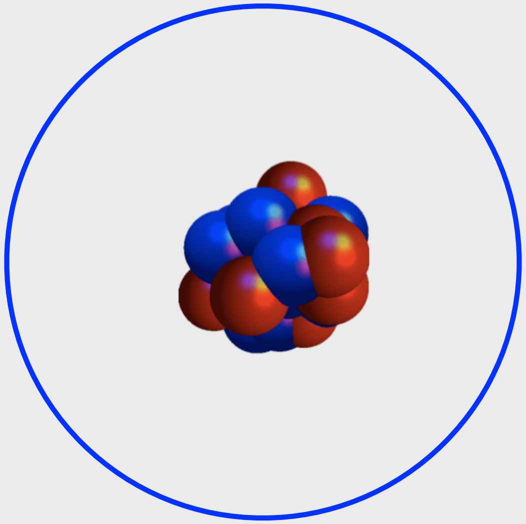
Transition	Energy
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV



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



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

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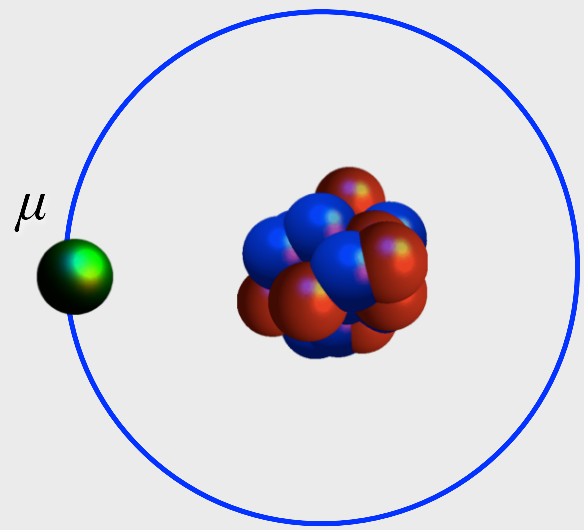

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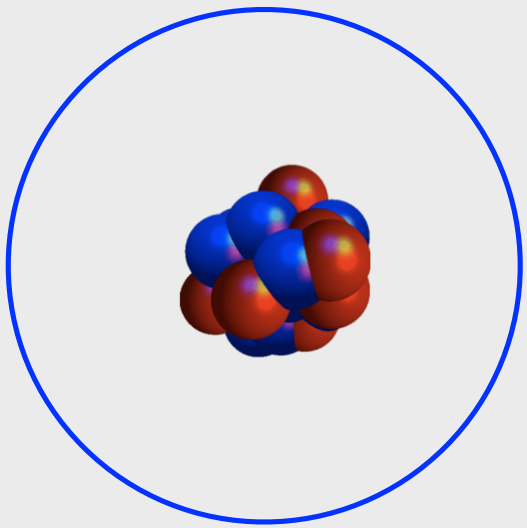

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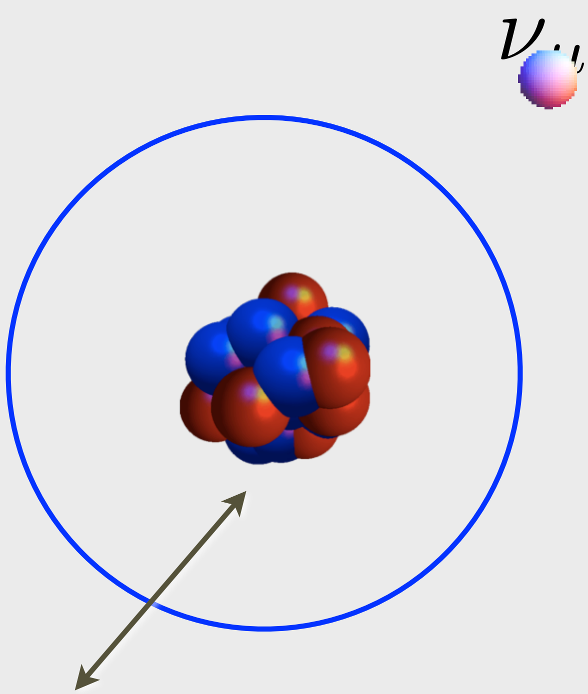


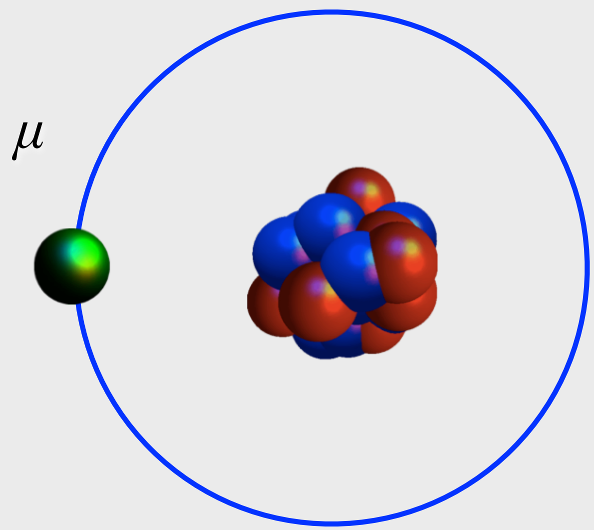
$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

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

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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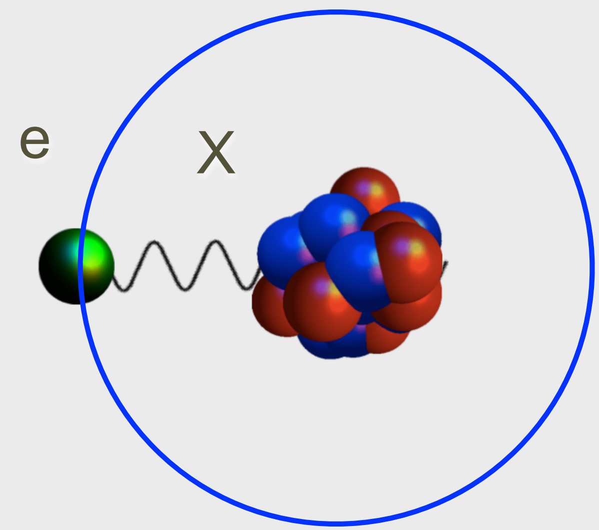

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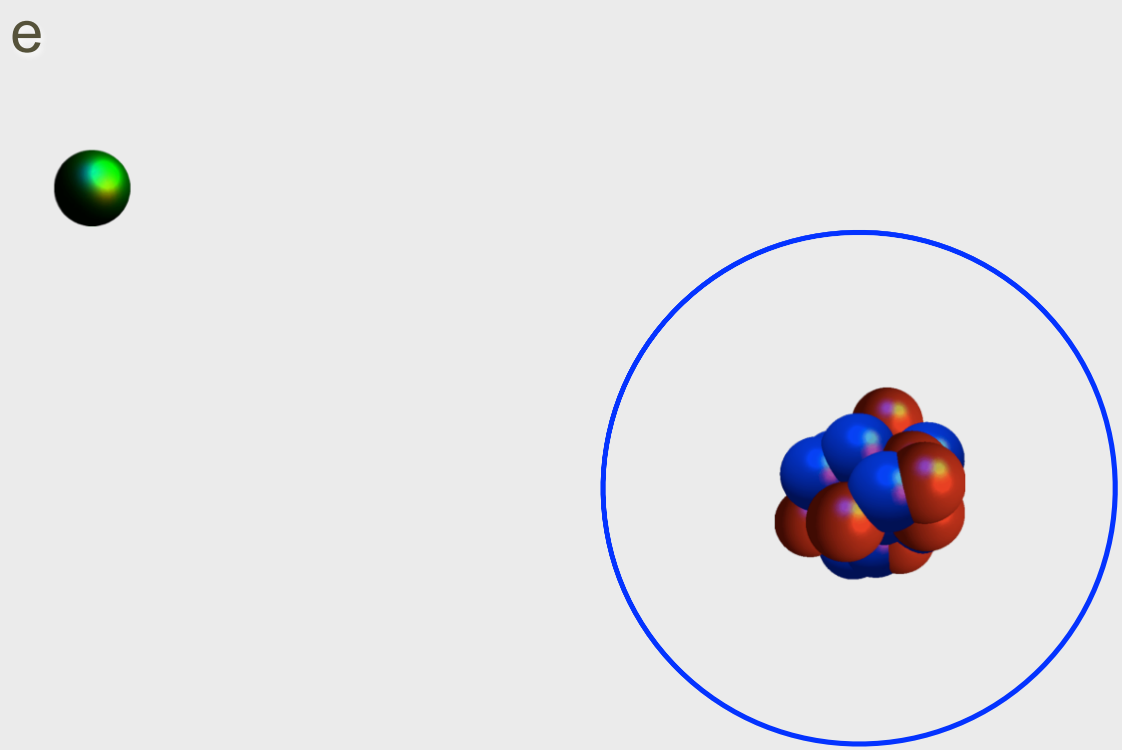
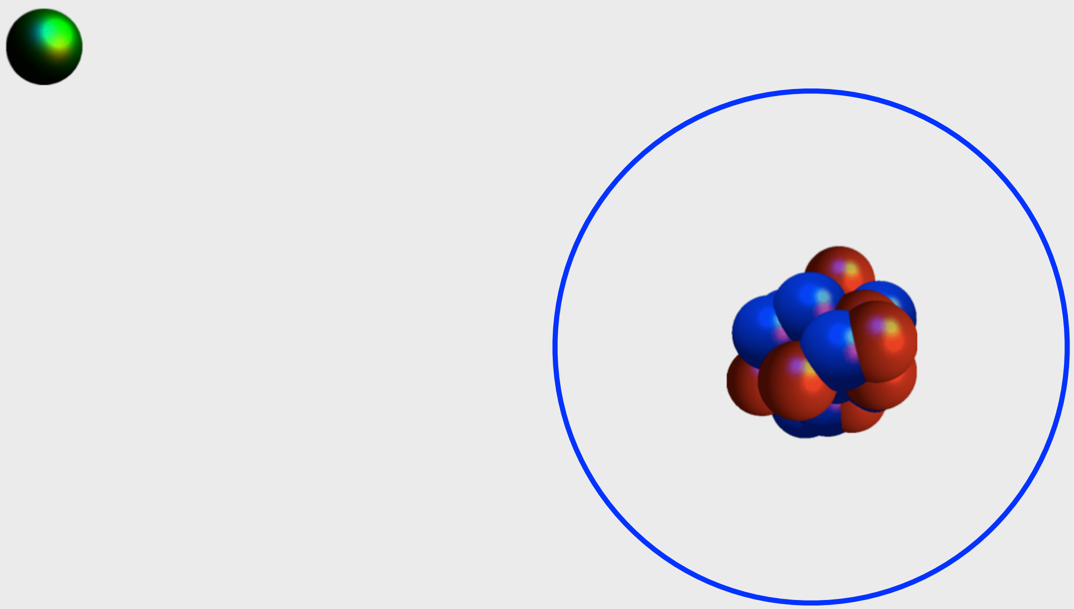


Three Possibilities: Signal

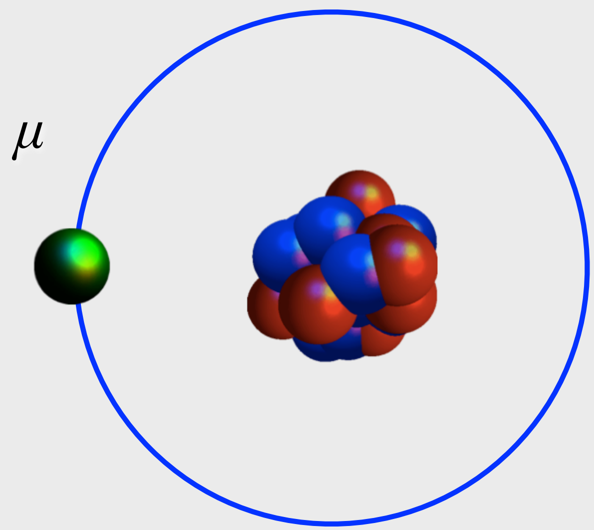
e

off to detector!



coherent recoil of nucleus

Three Possibilities: Background



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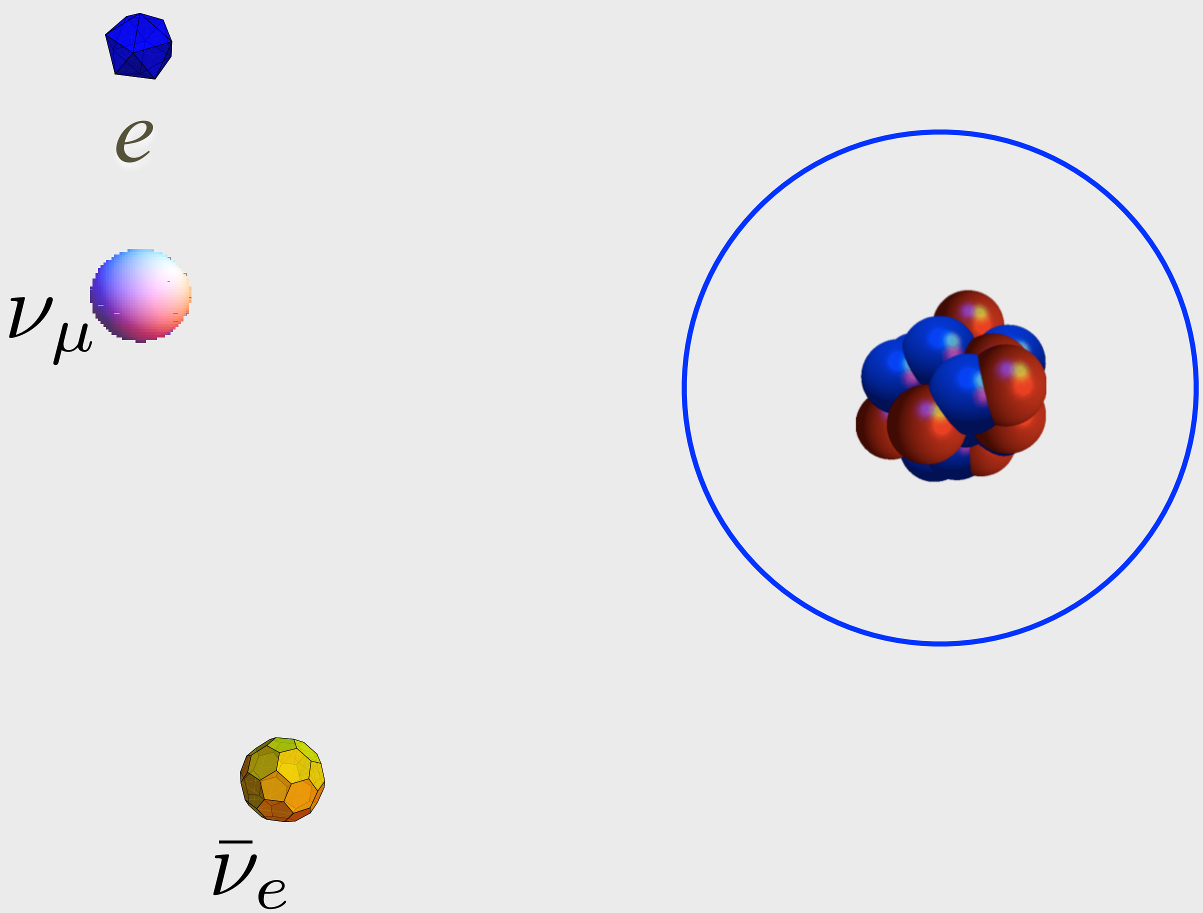
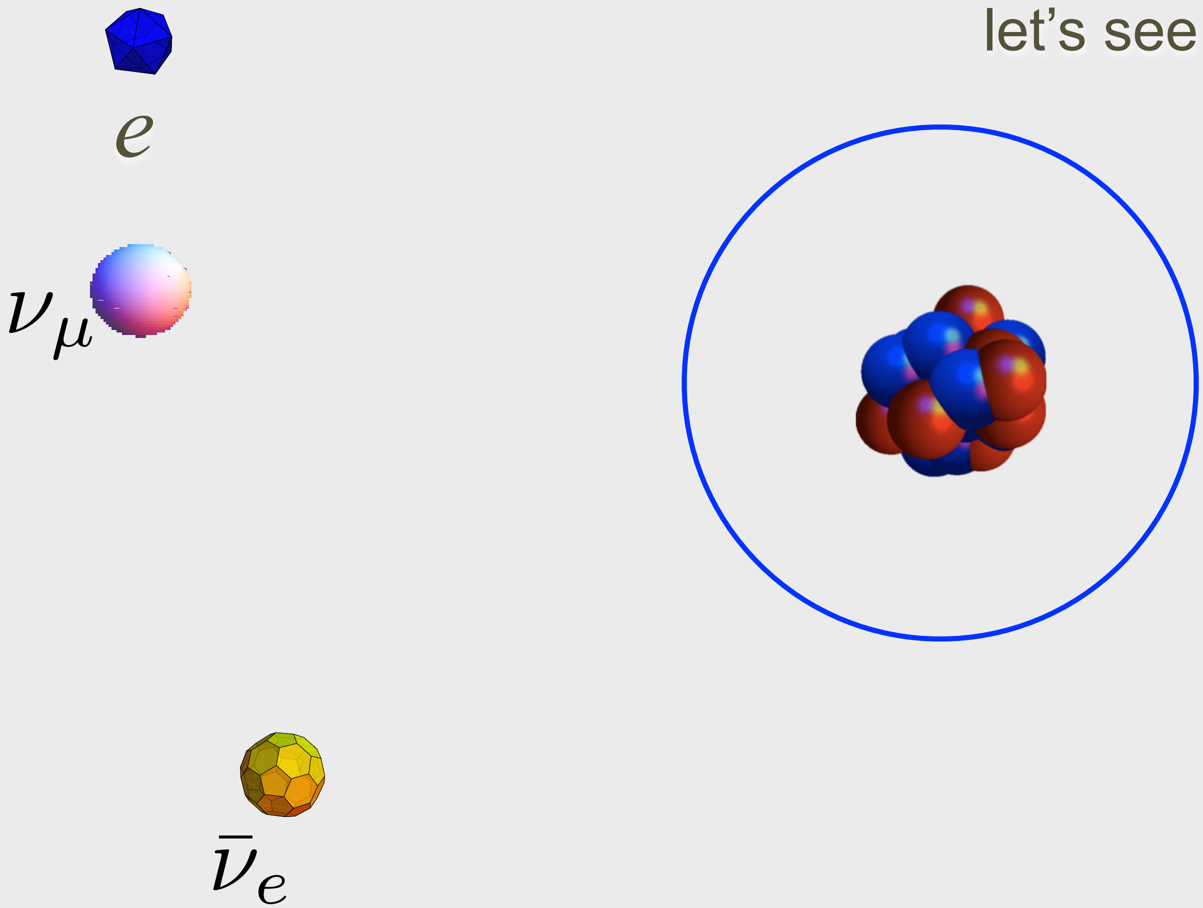


Three Possibilities: Background

this electron can be background;
let’s see how

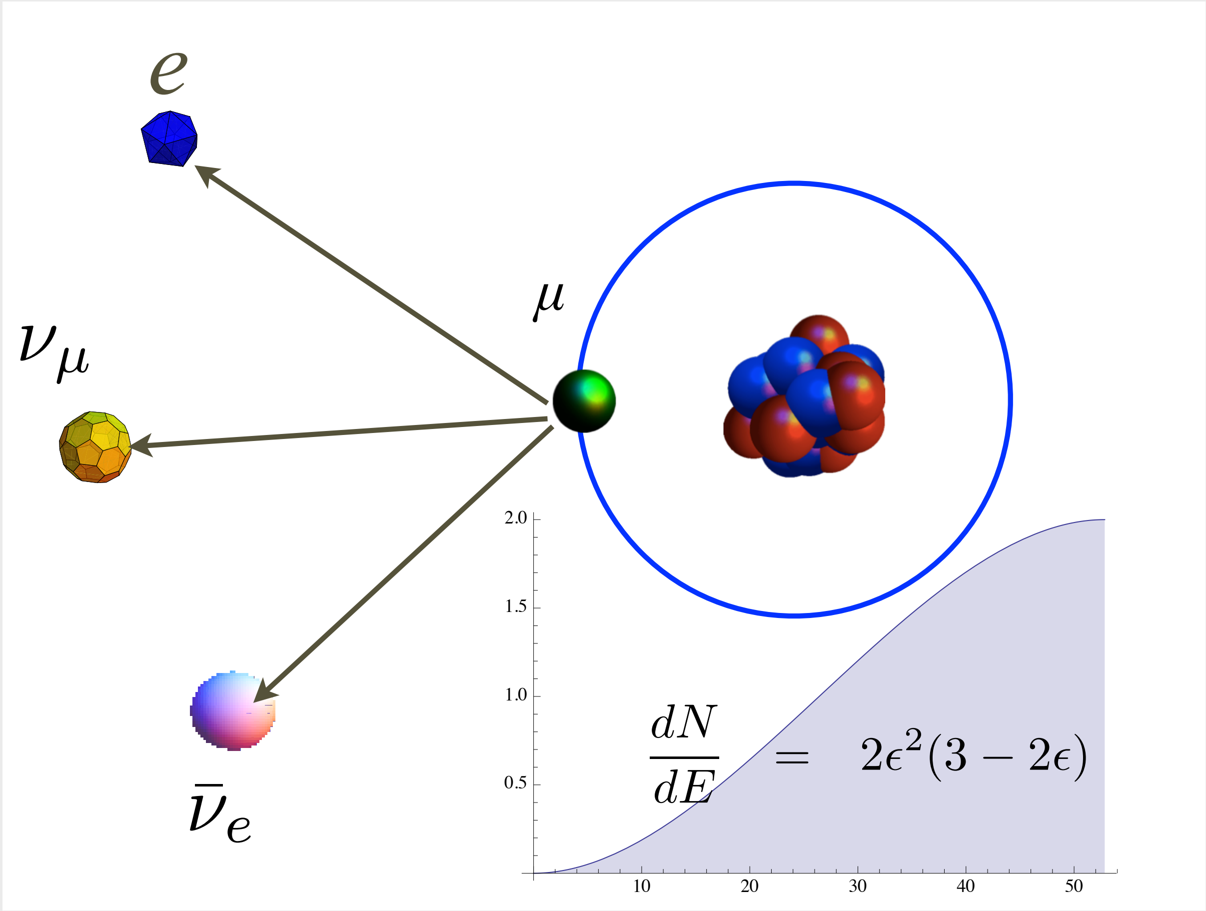


Decay-In-Orbit: Not always Background

- 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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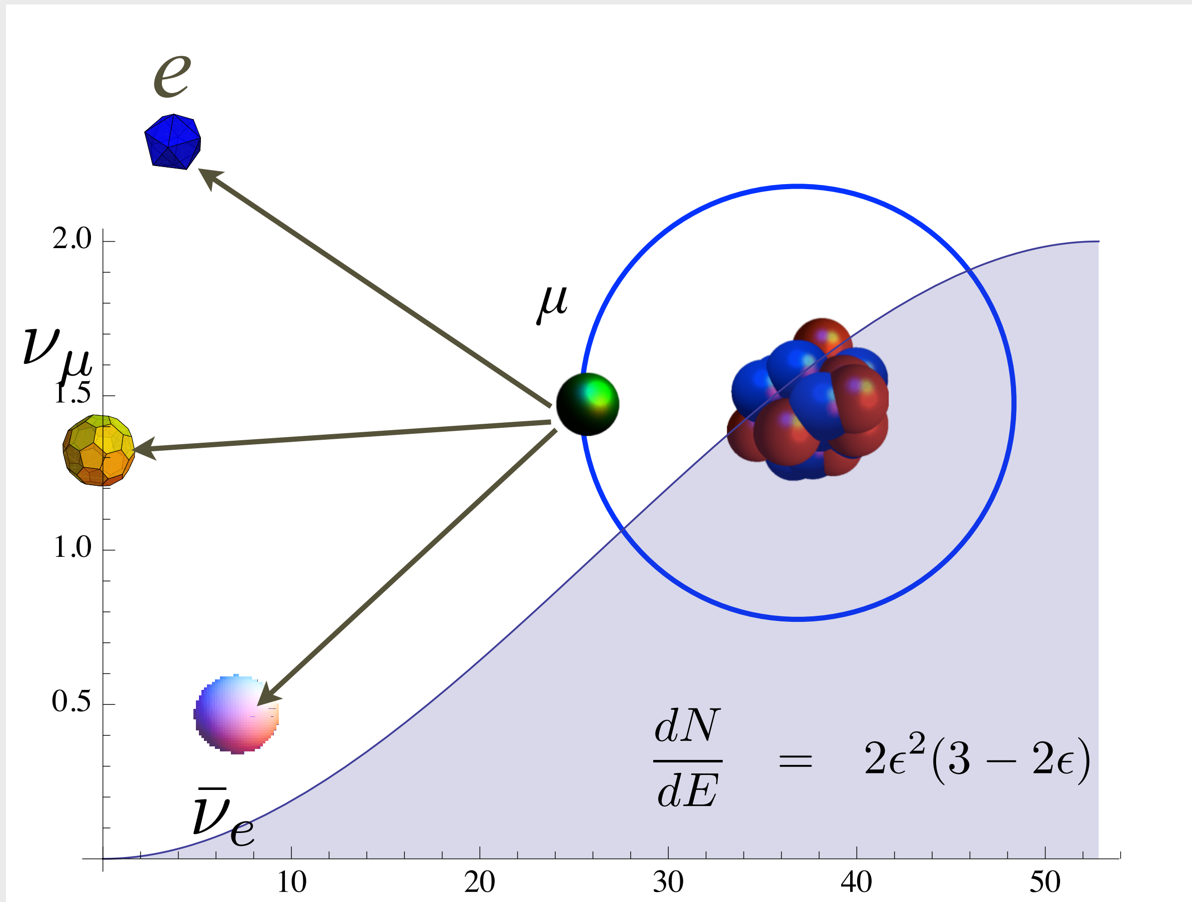
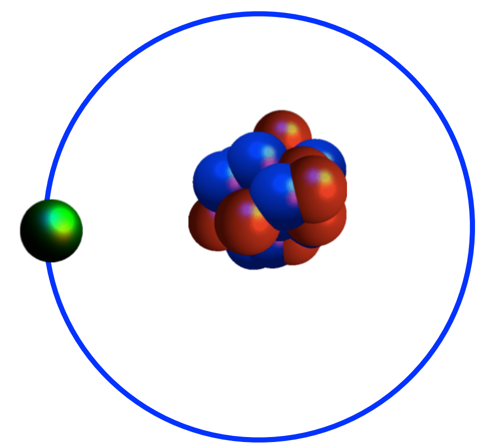


Decay-In-Orbit Background

- 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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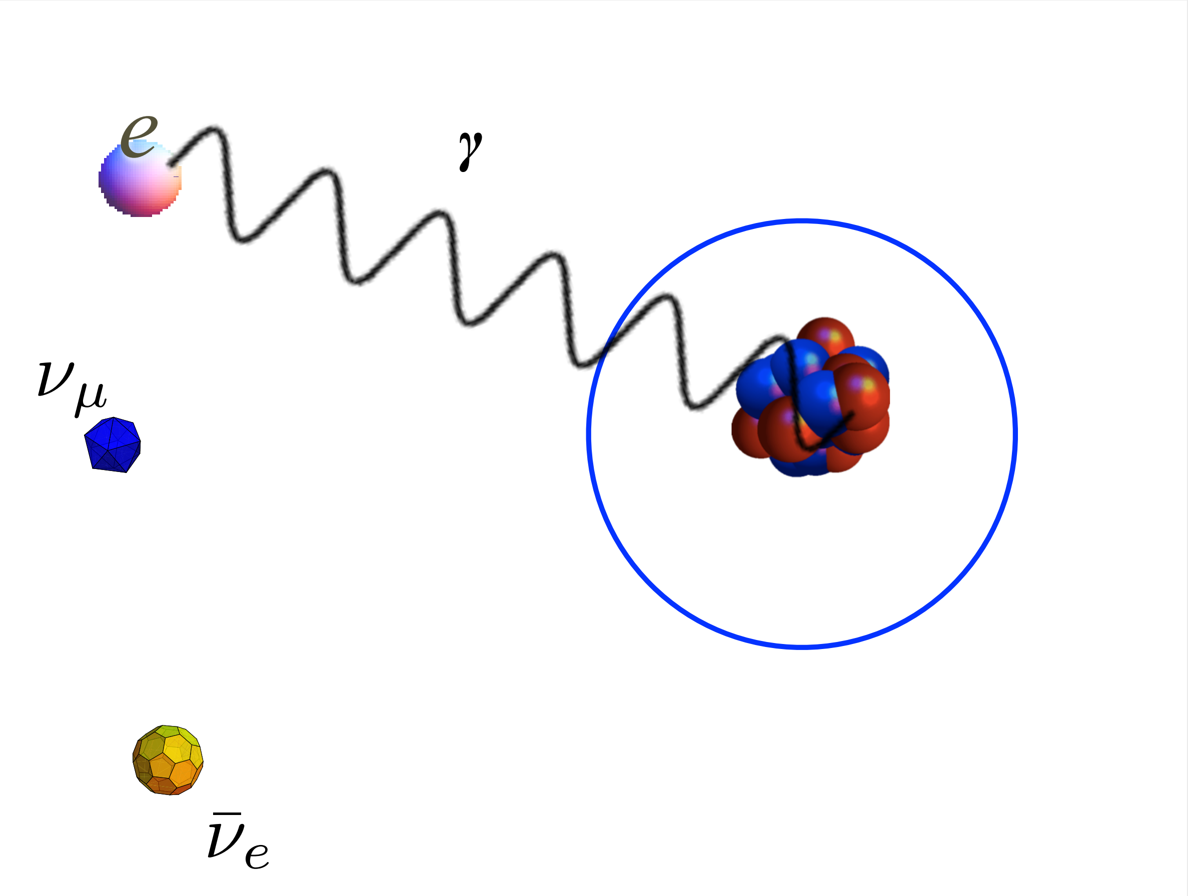

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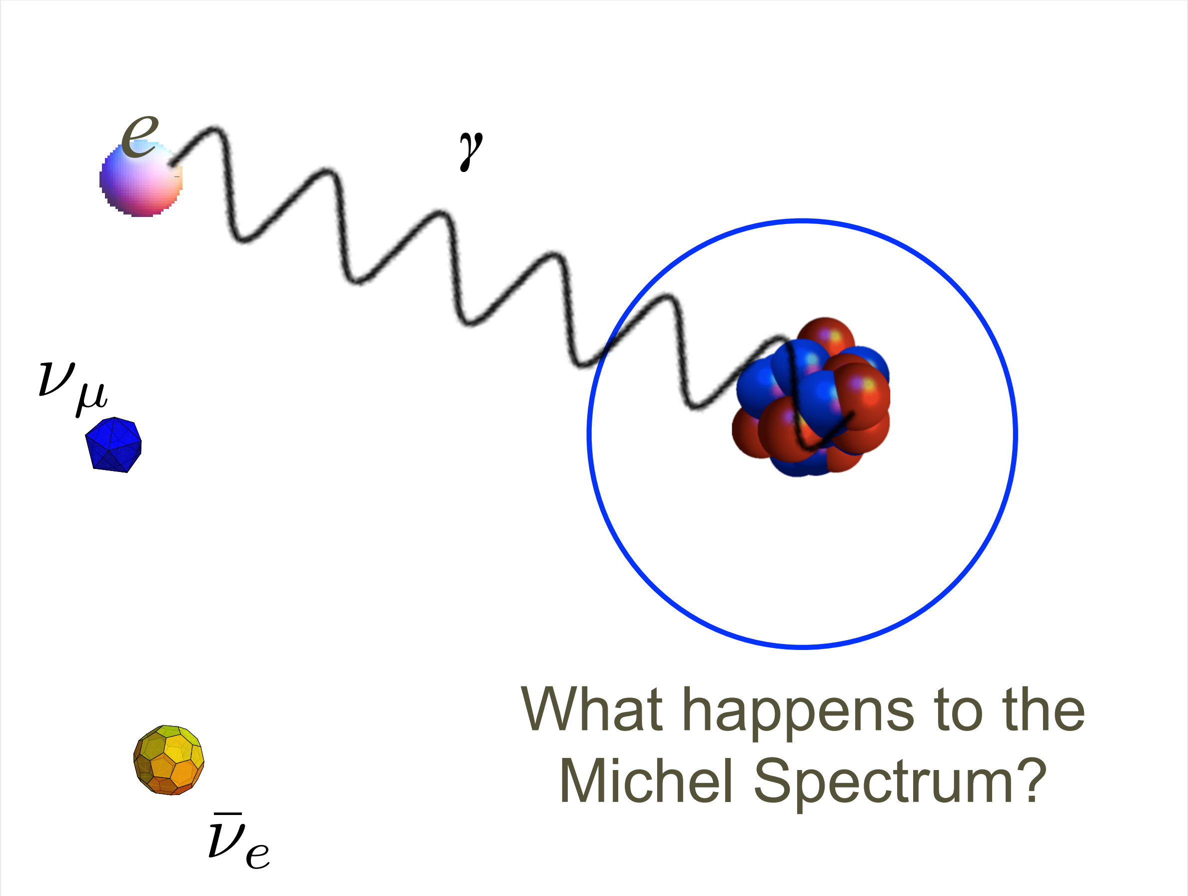
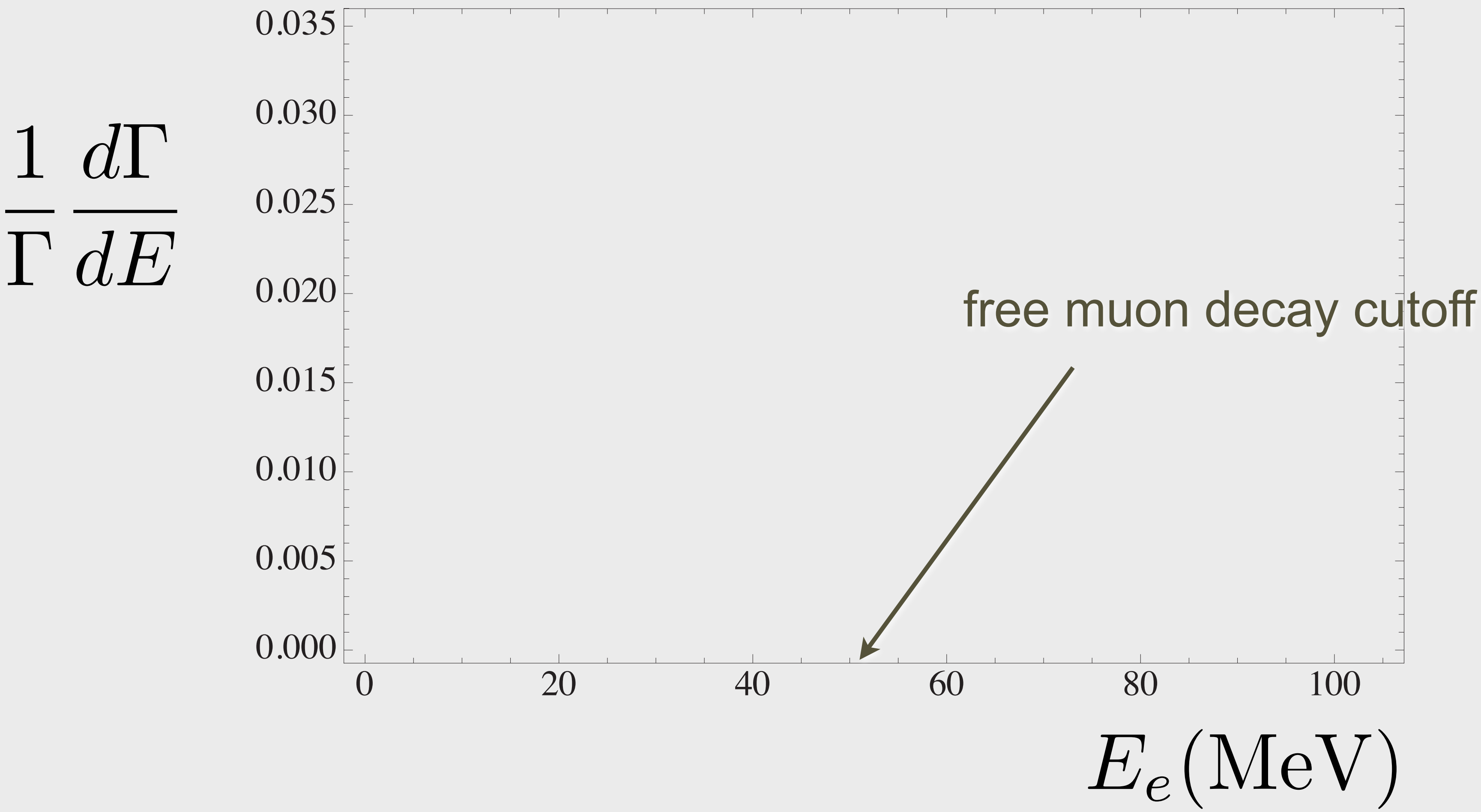


Decay-in-Orbit Shape

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



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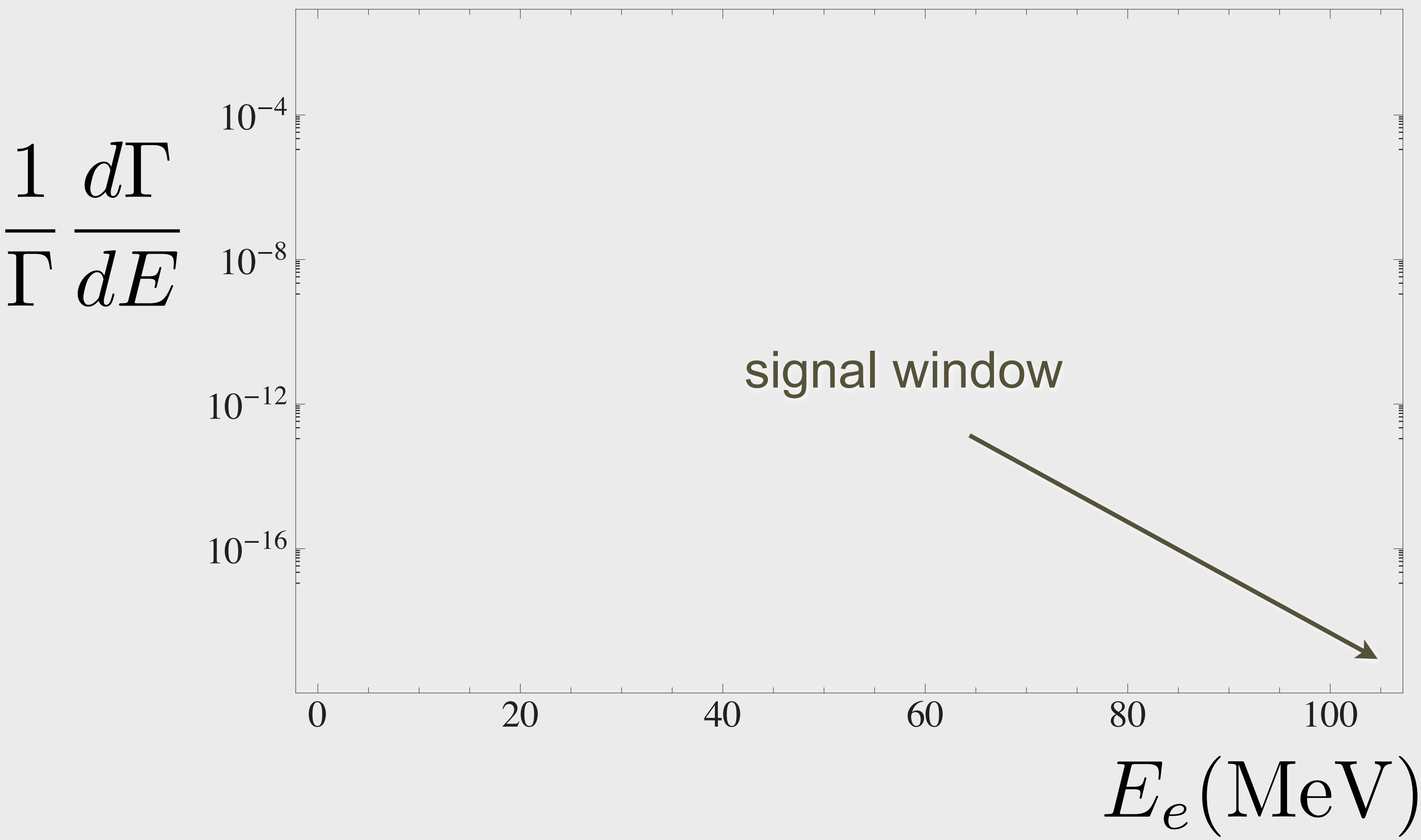
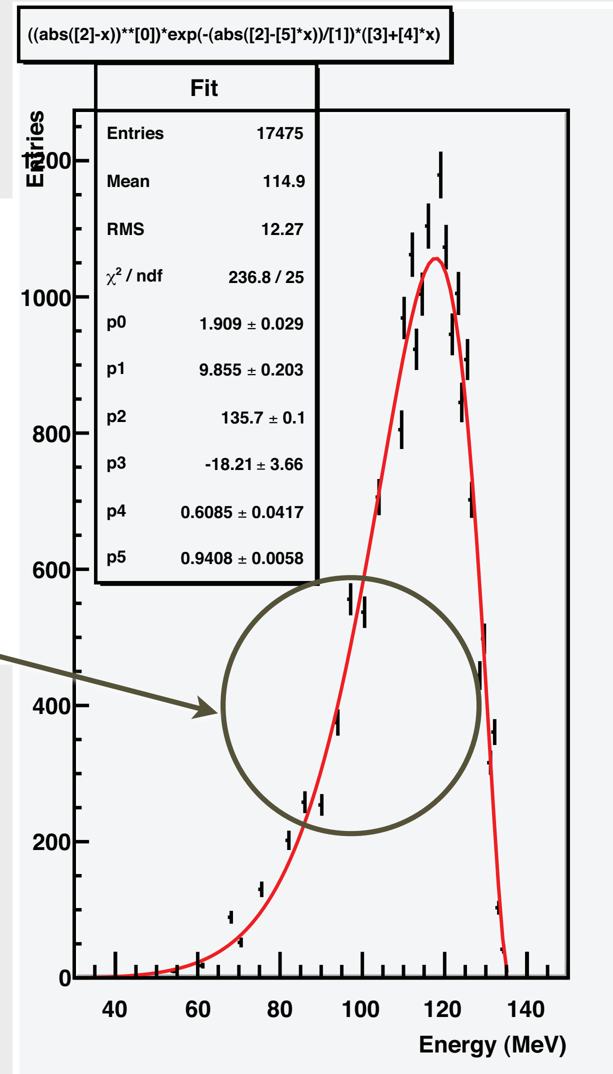


Prompt Backgrounds

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 m_π, 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?***



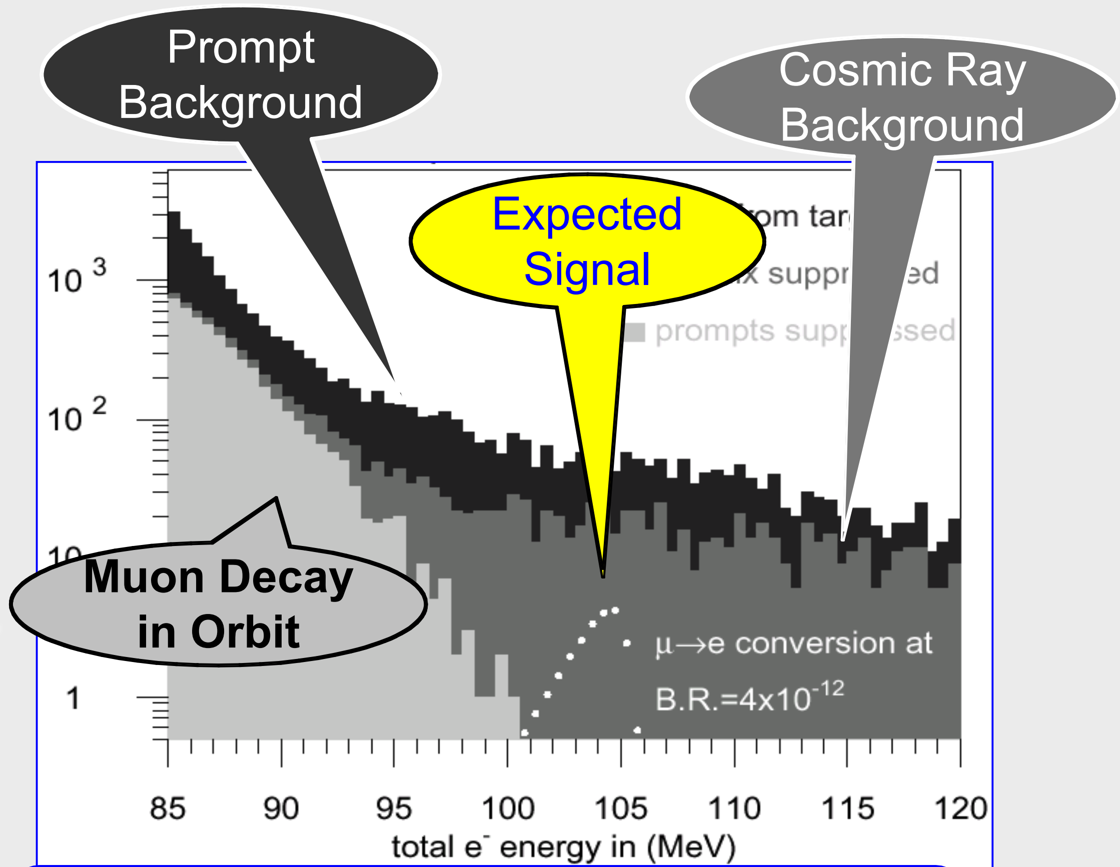
energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

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



Experimental signature is 105 MeV e⁻ originating in a thin Ti stopping target

SINDRUM-II Results

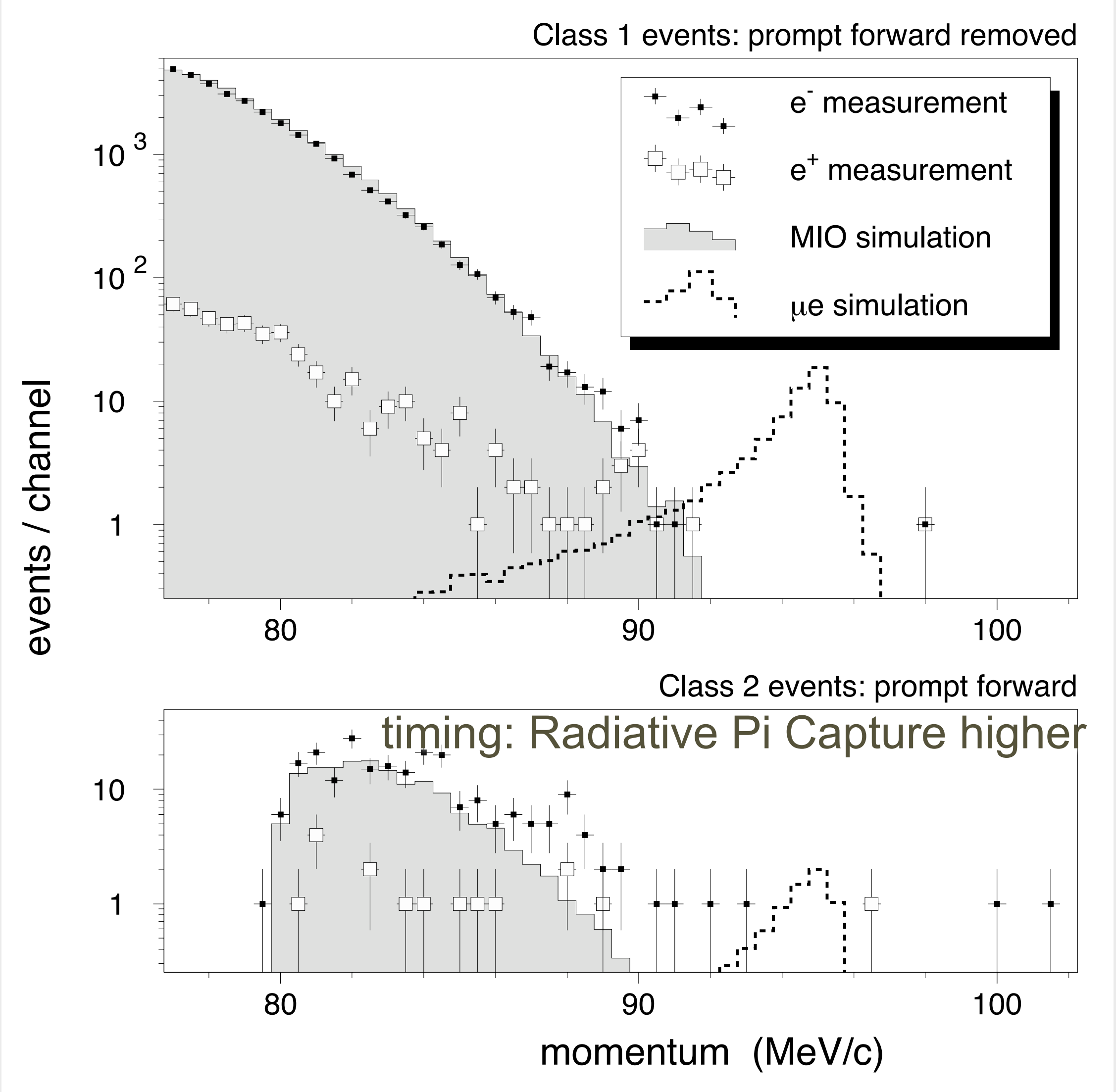
- Final Results on Au:

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

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)



timing: Radiative Pi Capture higher

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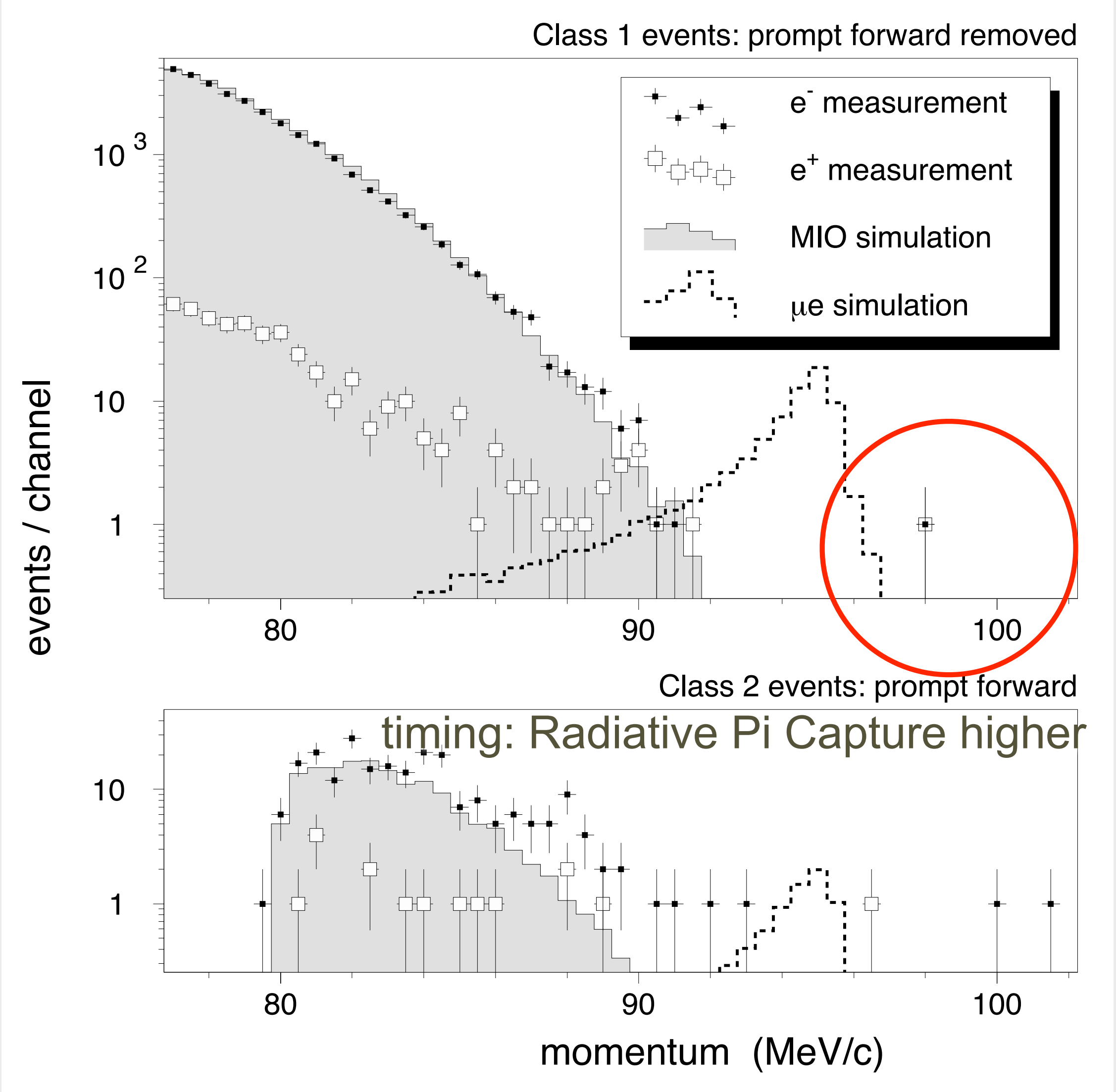


How Can We Do Better?

$>10^3$ increase in muon intensity from SINDRUM

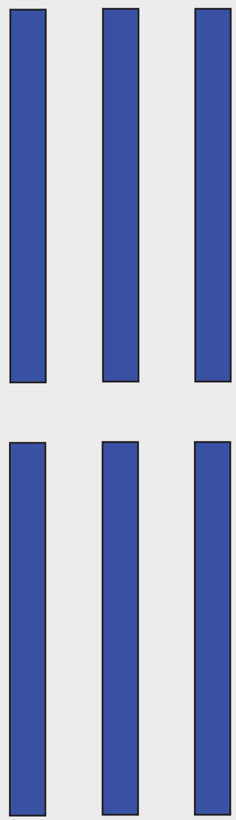
Requiring

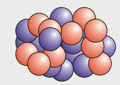
Pulsed Beam to Eliminate prompt backgrounds like radiative π capture and CR

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

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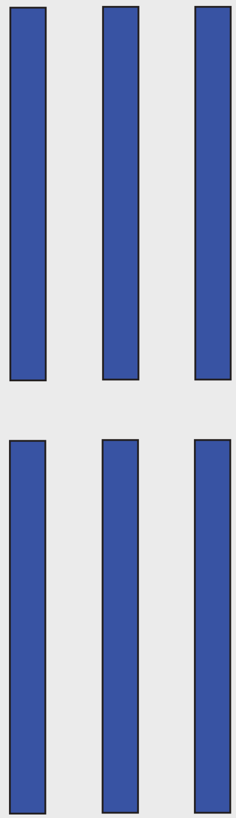

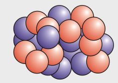 = muons, electrons, pions

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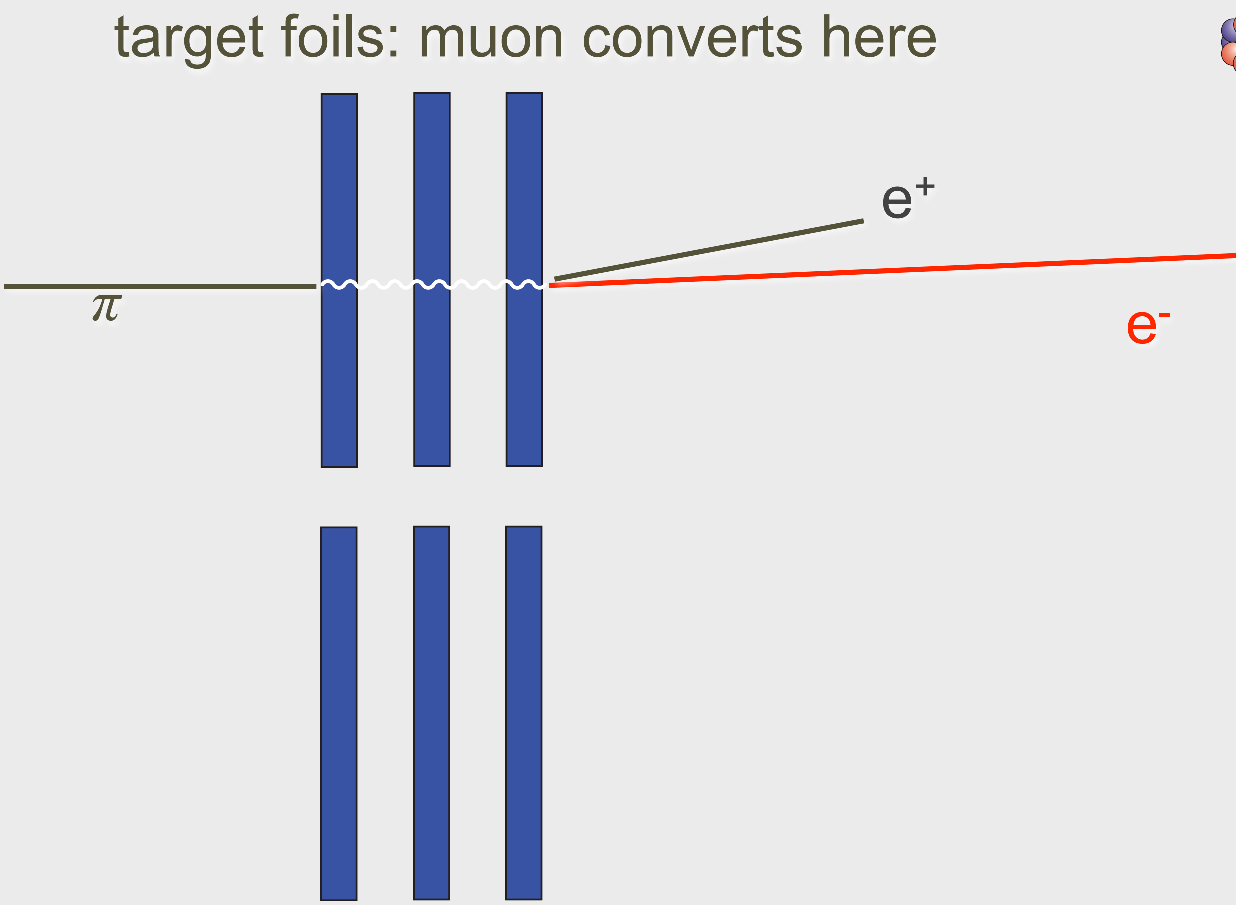


pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

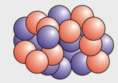
Radiative Pion Capture:

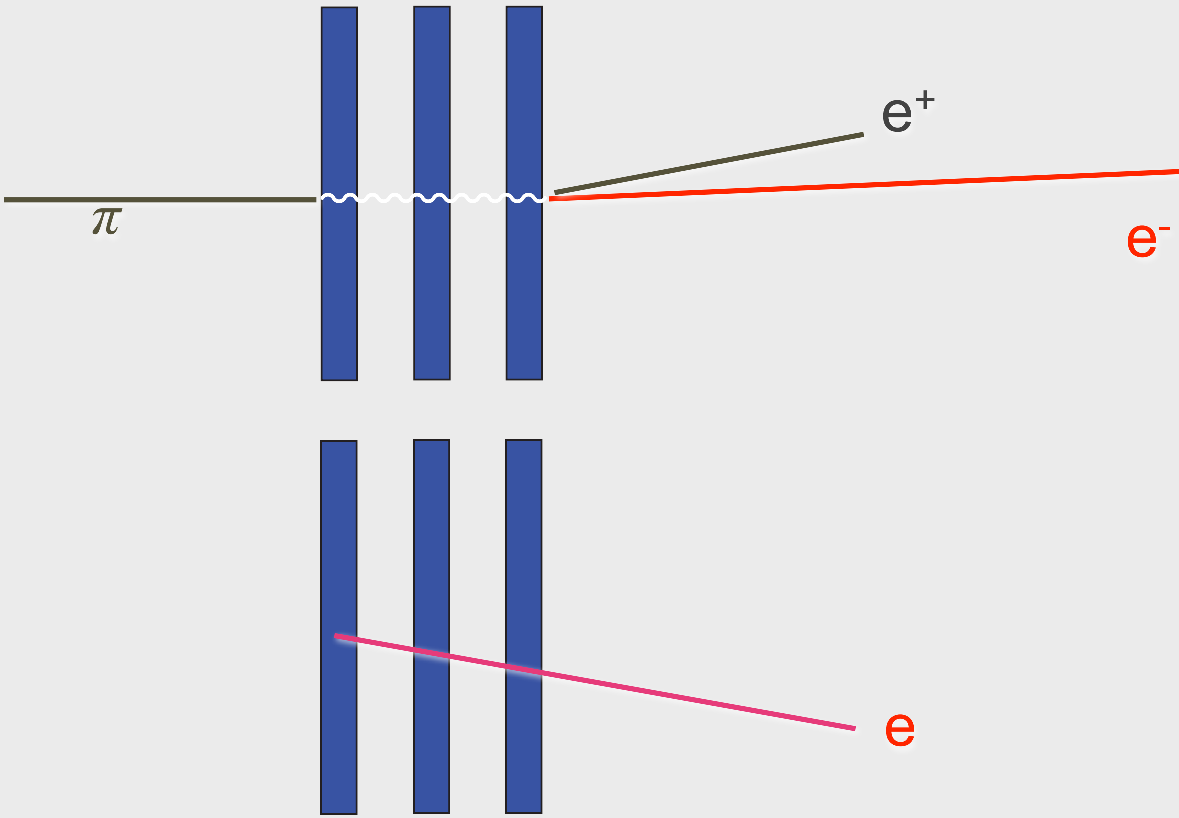
$\pi N \rightarrow \gamma N$

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

Prompt backgrounds and Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



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Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

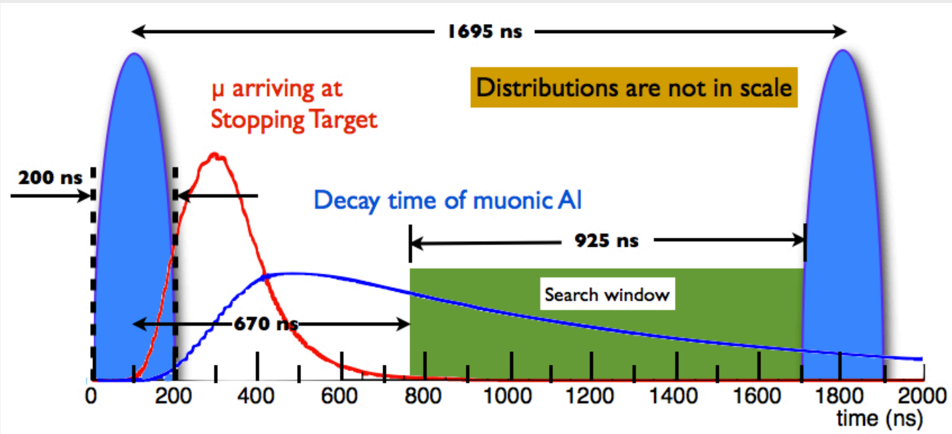
$\gamma \rightarrow e^+ e^-$ *in foils*

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

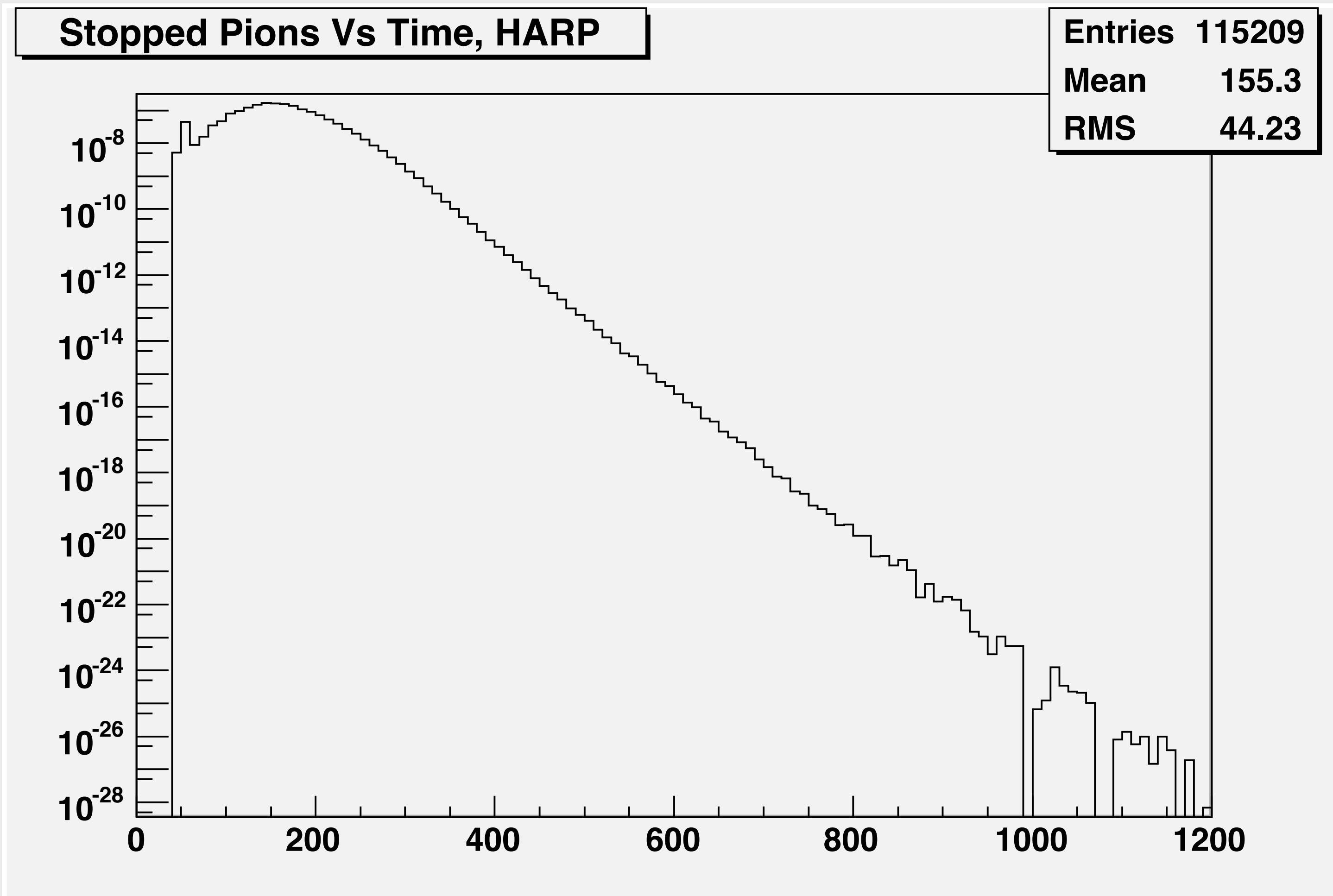


Extinction ~ 10^{-10}

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

Pulsed Beam Structure and Radiative π Capture

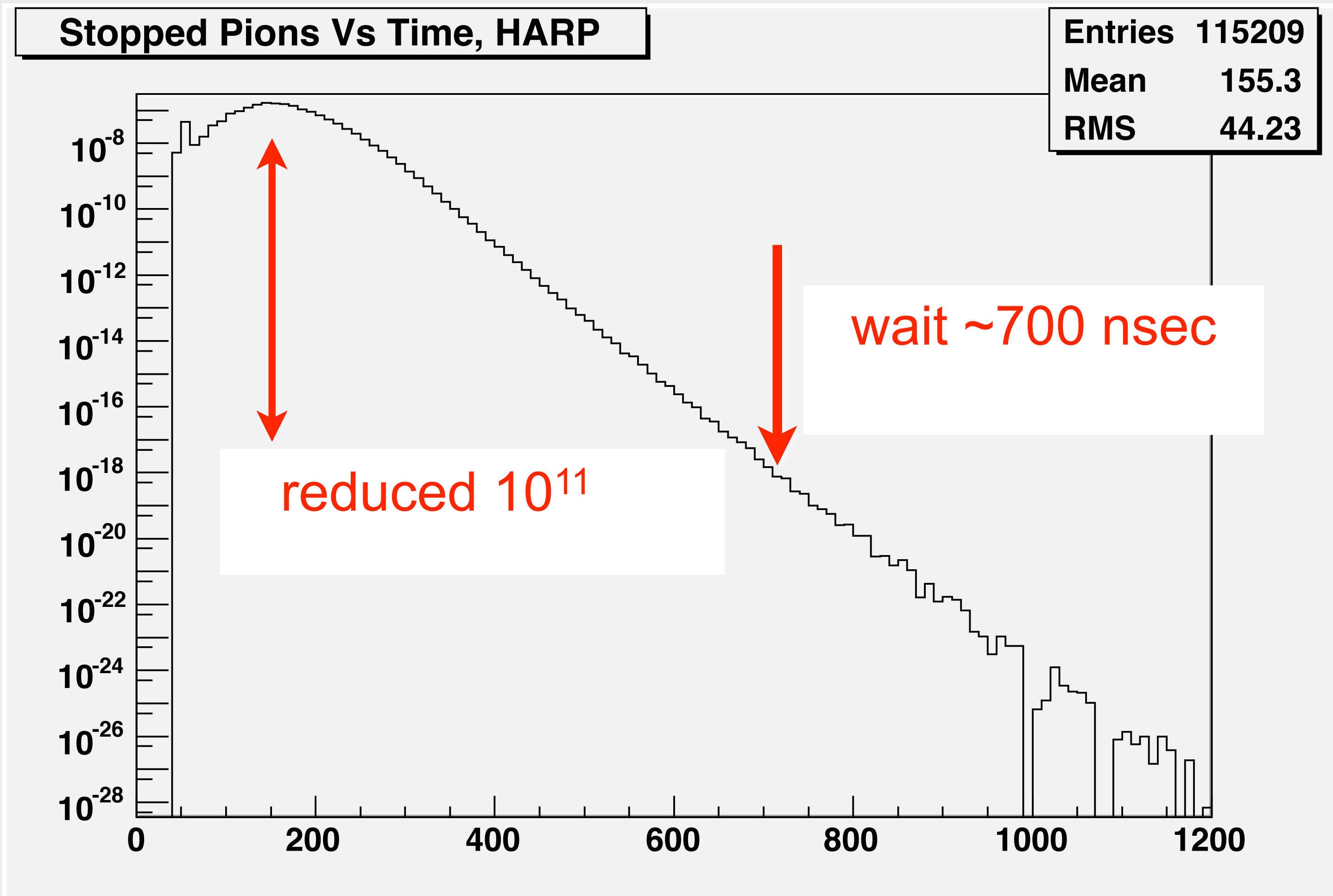
$$\pi N \to \gamma N, \gamma \to e^+ e^-$$



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

Pulsed Beam Structure and Radiative π Capture

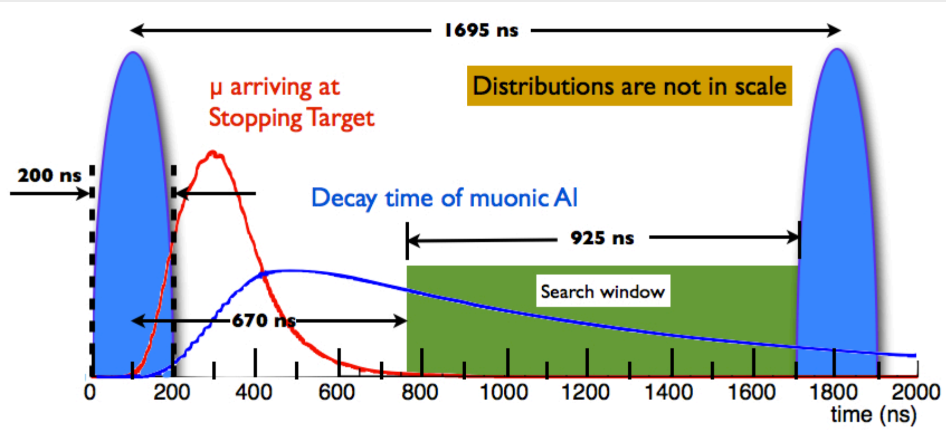
$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+e^-$$



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

Prompt Background and Choice of Z

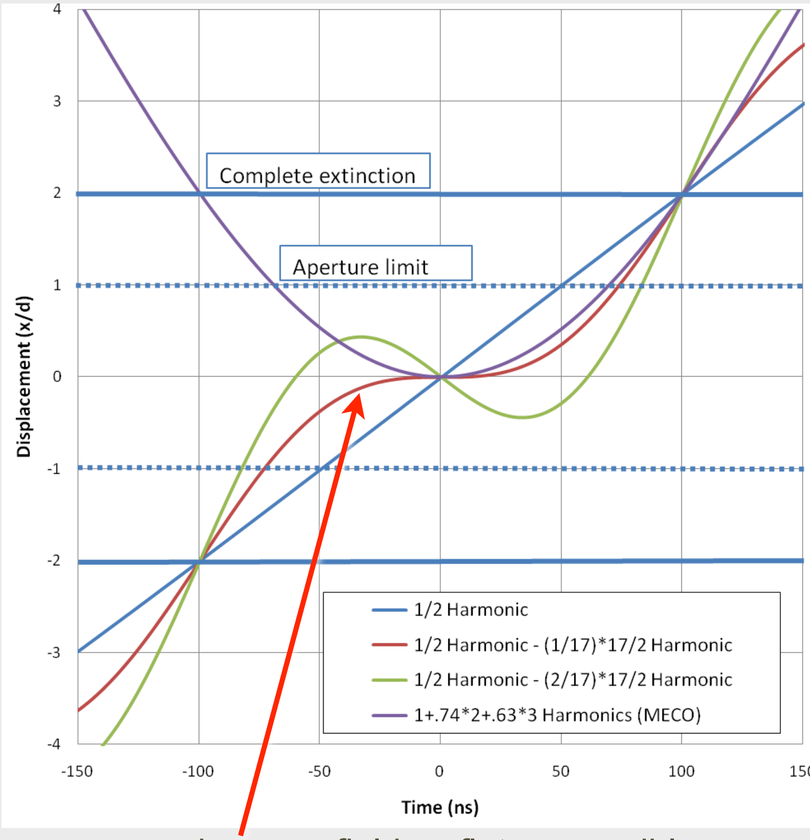
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds



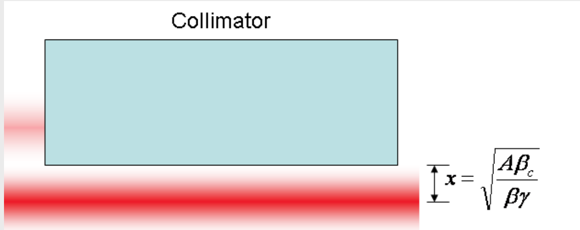
Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1.0	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

Extinction Scheme

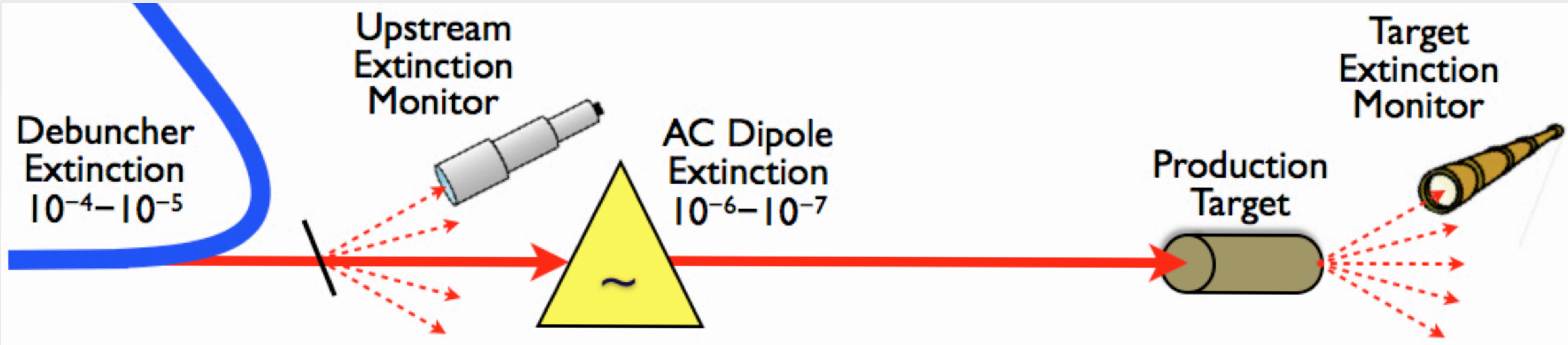
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
- Calculations (MARS) show this combination gets ~10^{-12}



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



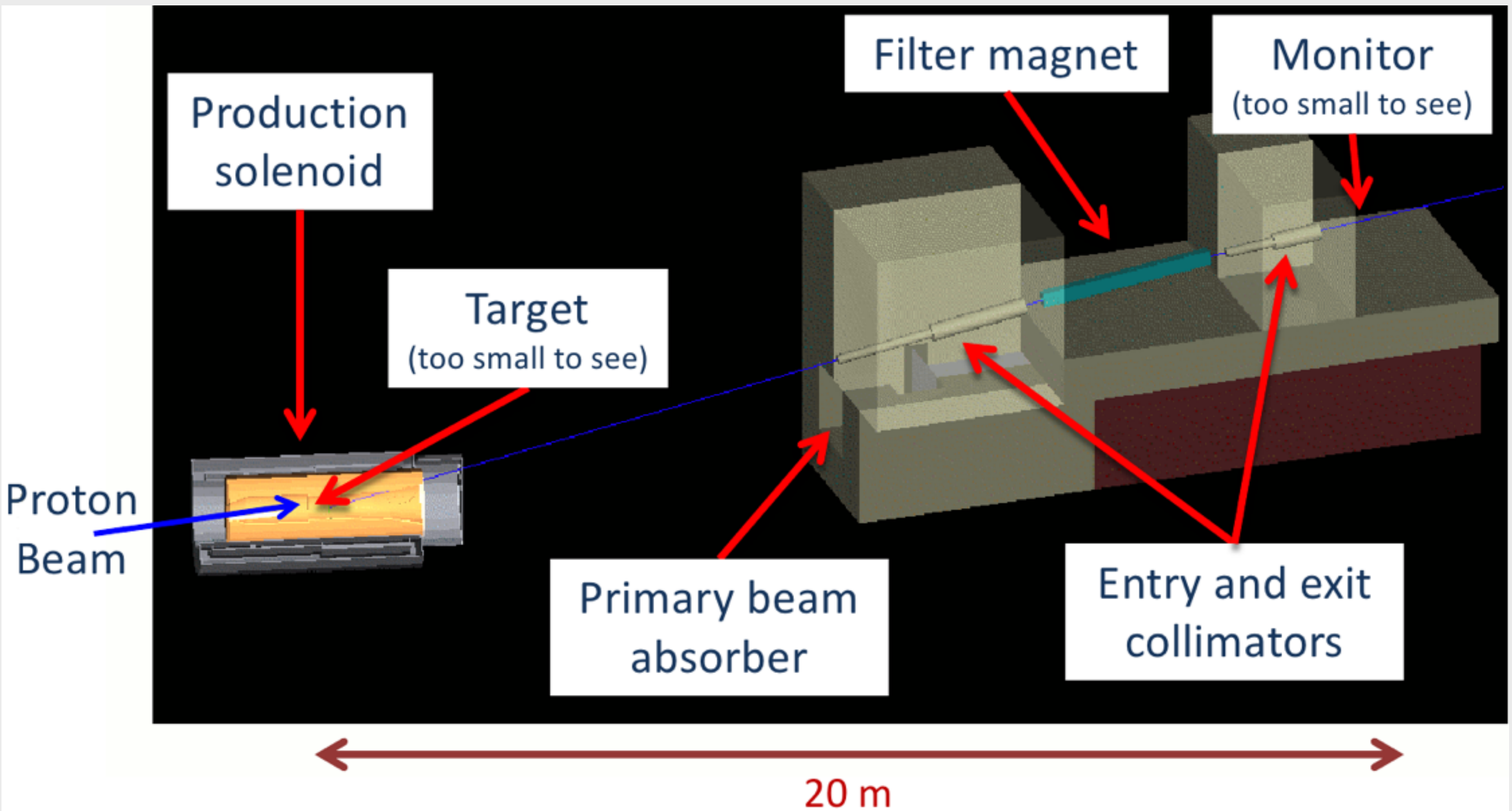
Extinction Measurement



- 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:

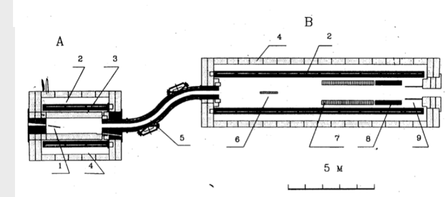
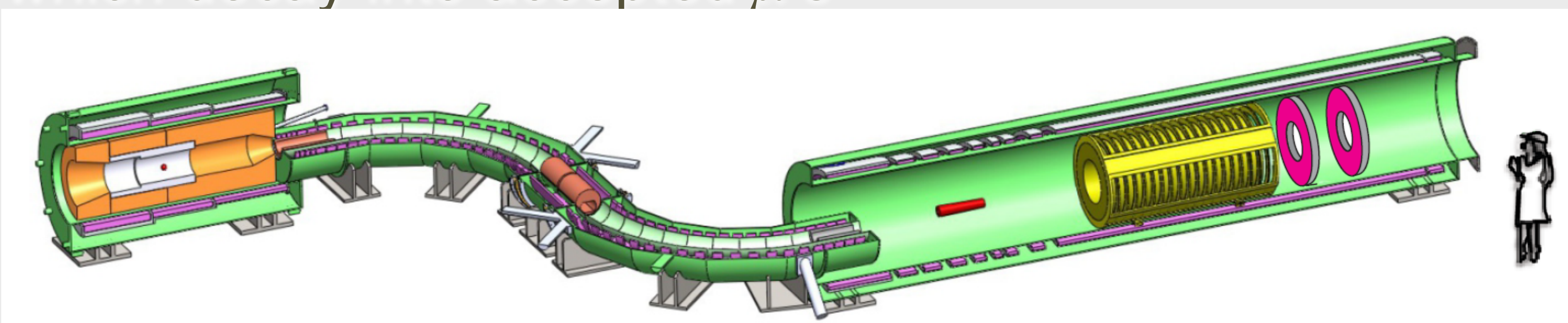


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part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



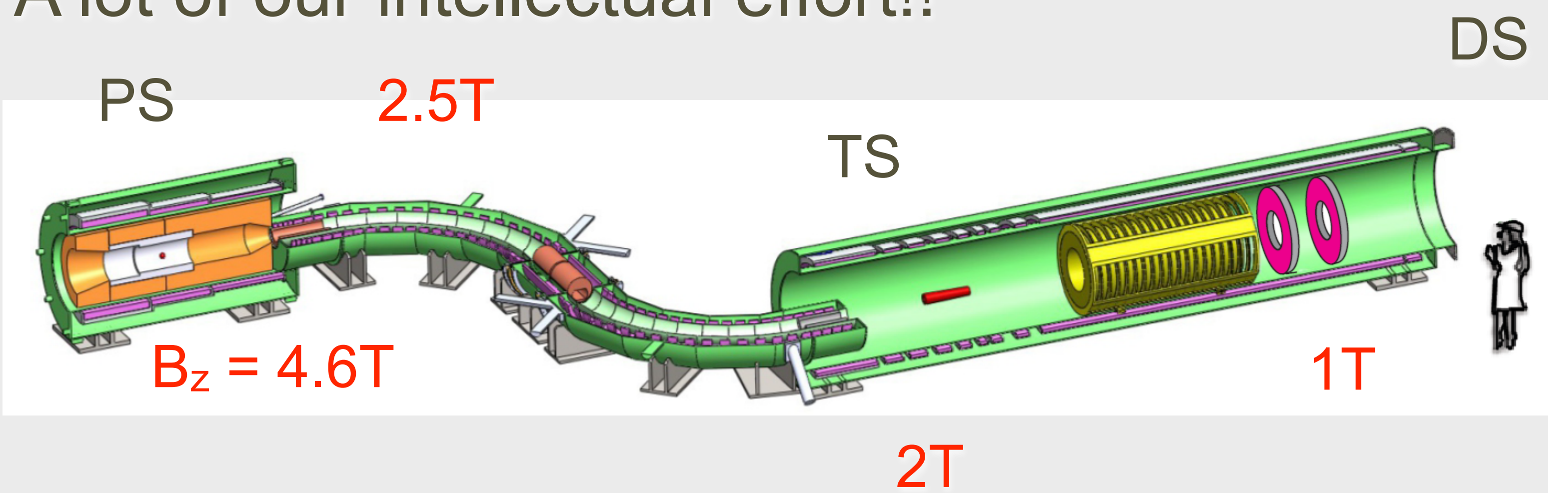
- *Transport:* S-curve eliminates backgrounds and sign-selects

- *Detector:* Stopping Target, Tracking and Calorimeter

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

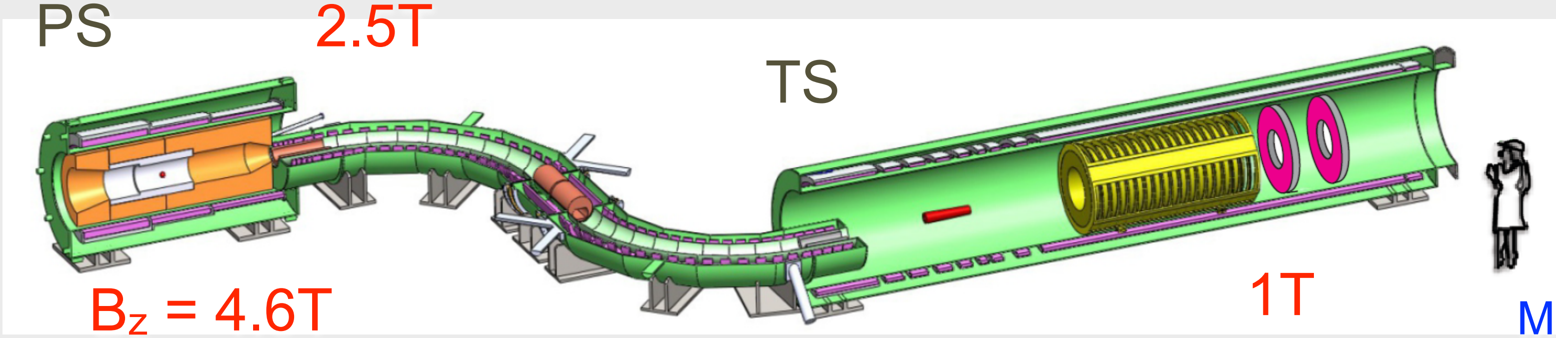
Gradient Fields in Mu2e

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

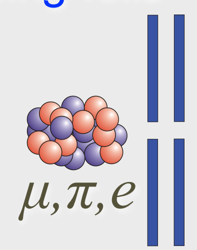


- "push" muons out of PS into TS and into DS so we can study them
- keep particles from spiraling around, arriving late
- conversions are isotropic in stopping target; the gradient over stopping target "reflects" backward going muons and nearly doubles the acceptance

Mu2e Muon Beam: Three Solenoids and Gradient



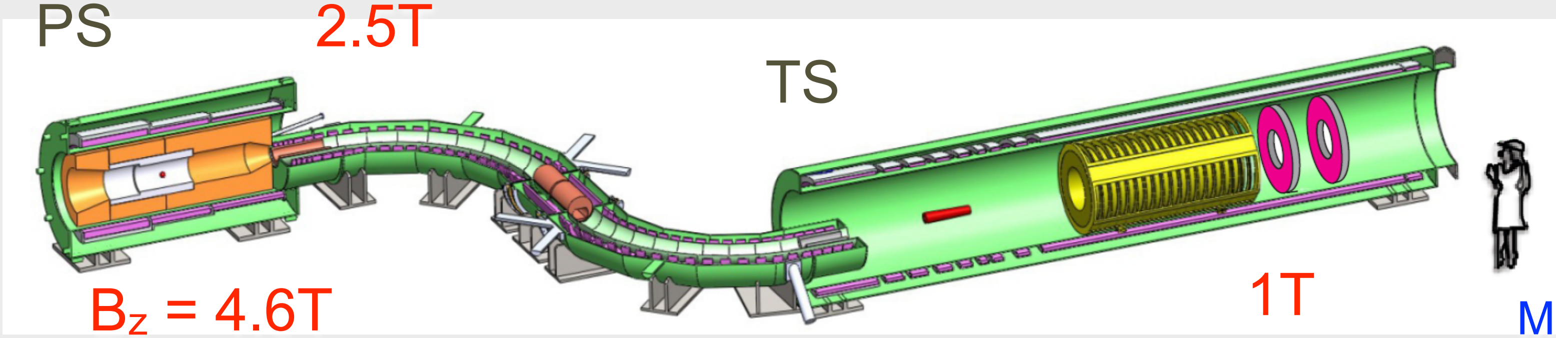
Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



- 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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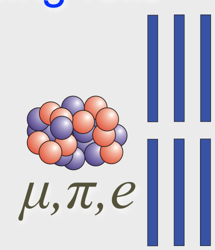

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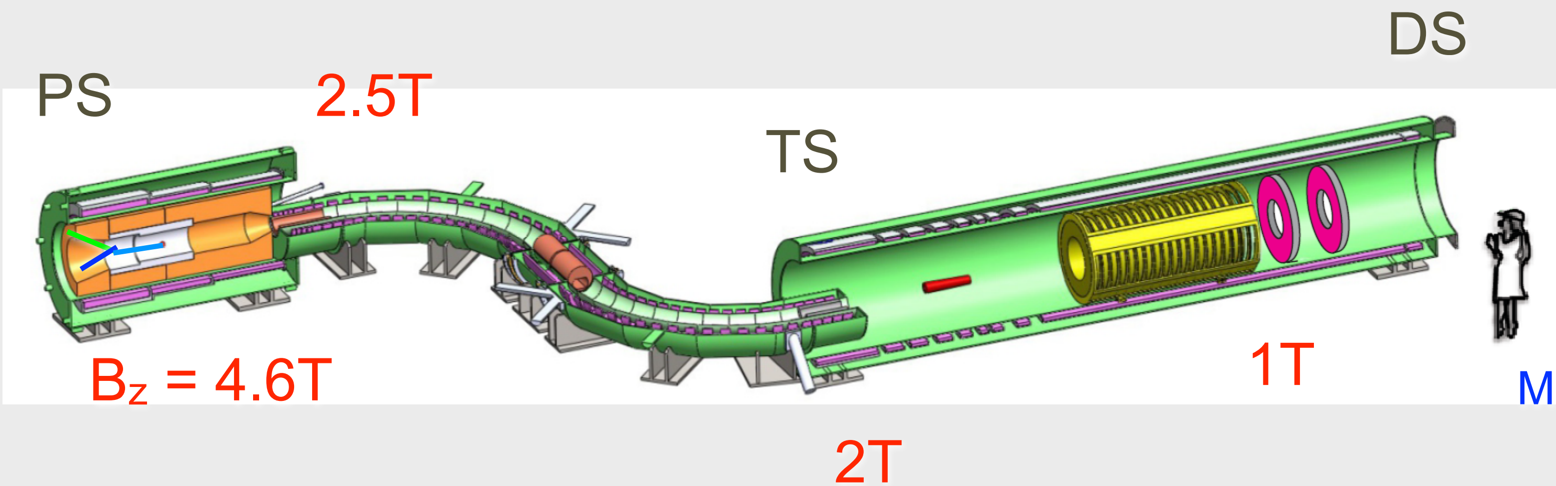

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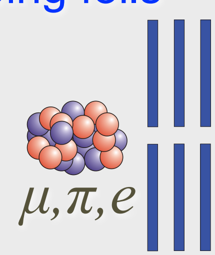

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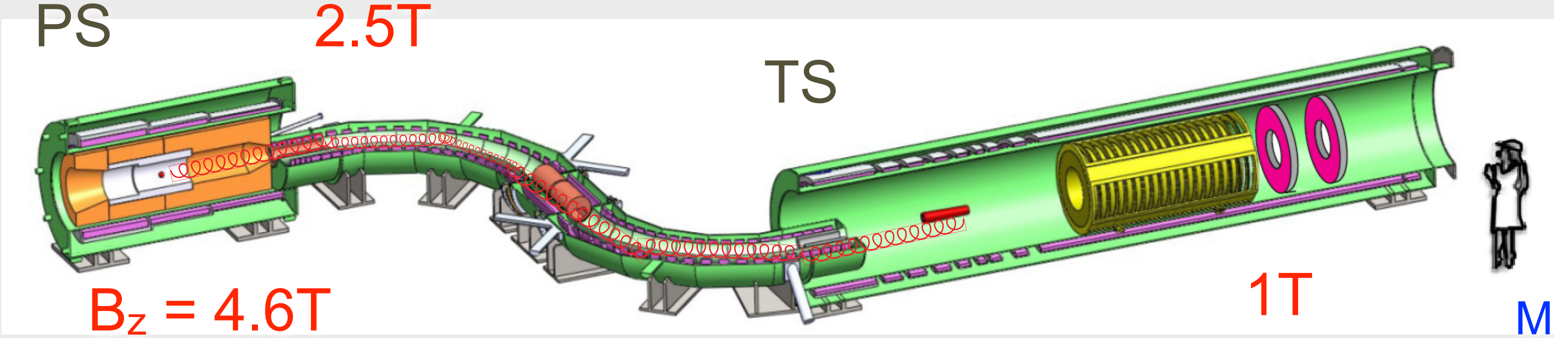

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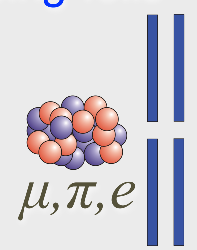

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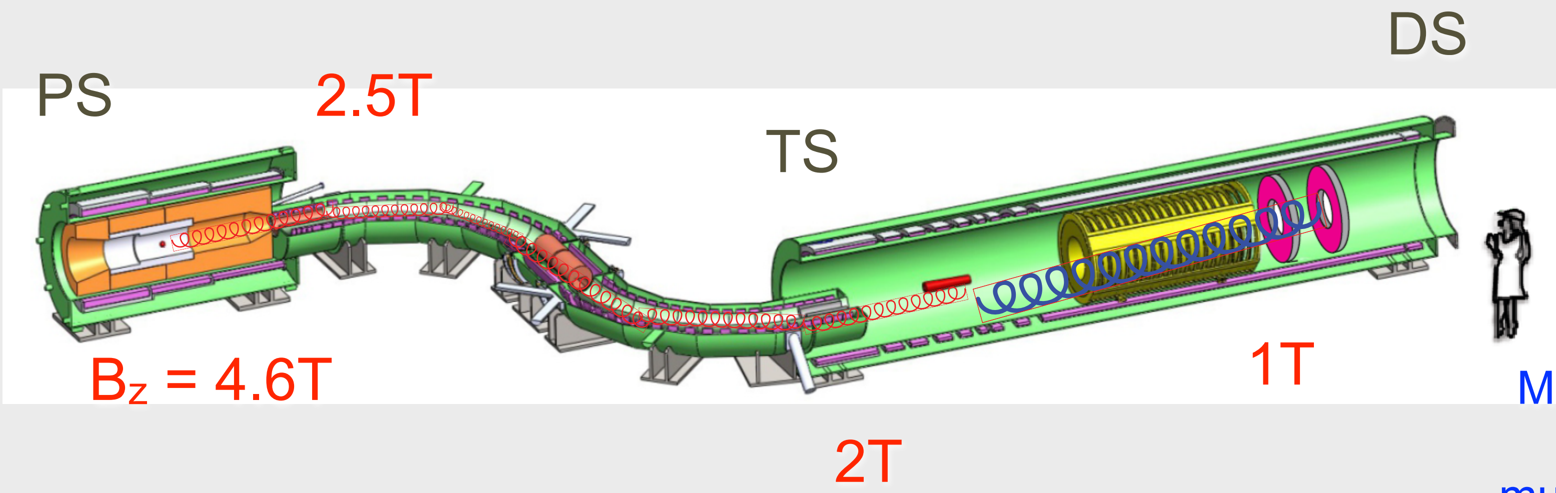

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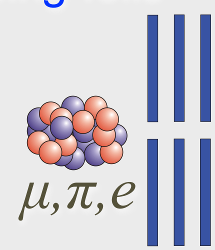
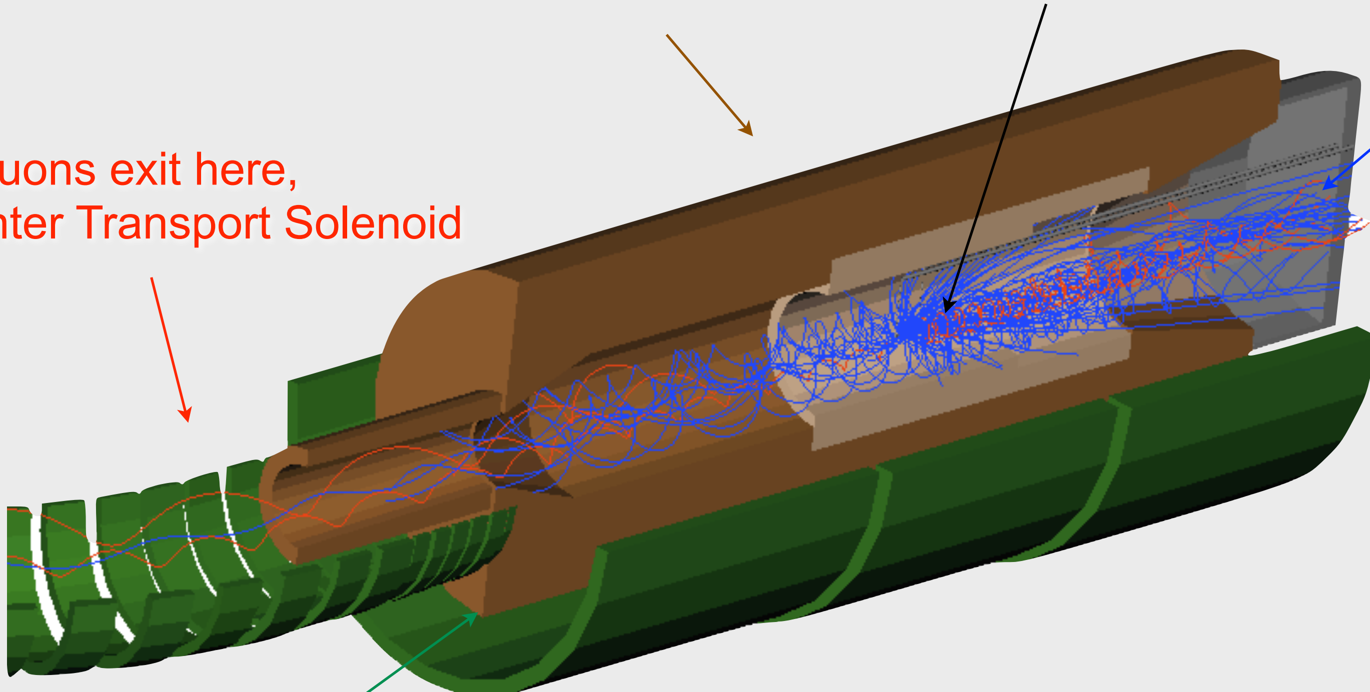


- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

Production Solenoid:

old picture, design has changed a little

Protons enter opposite to outgoing muons



π's are captured, spiral around and decay

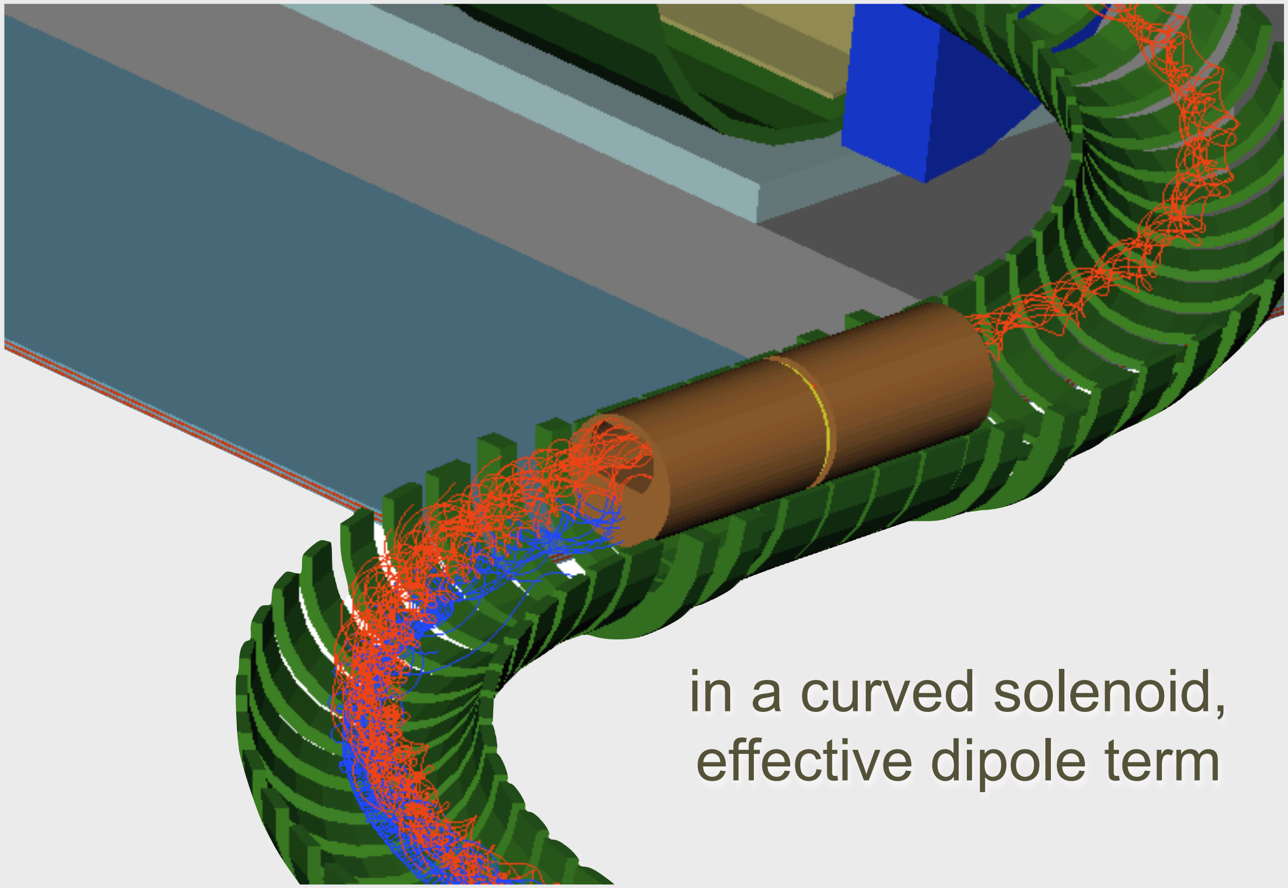
4 m × 0.30 m

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

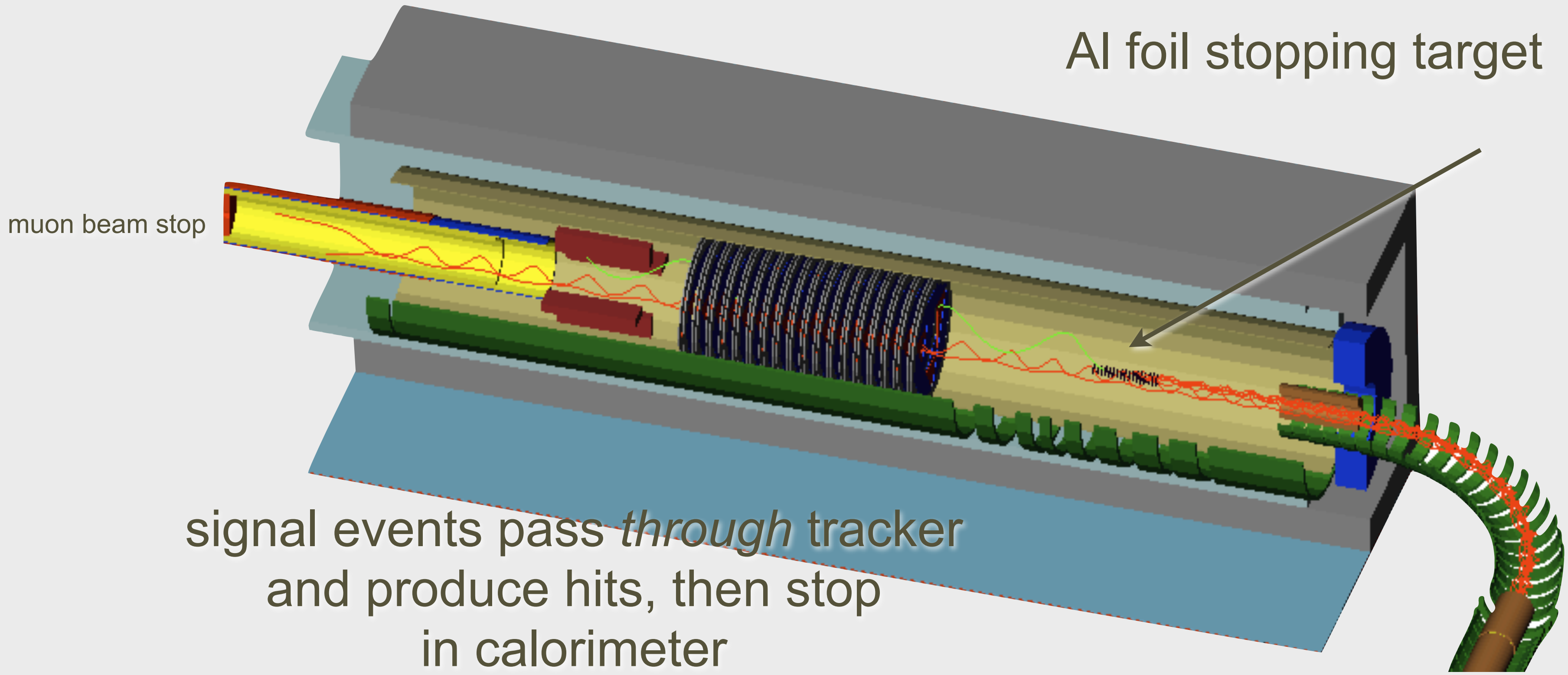
Detector Solenoid

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



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

...oid

...region:

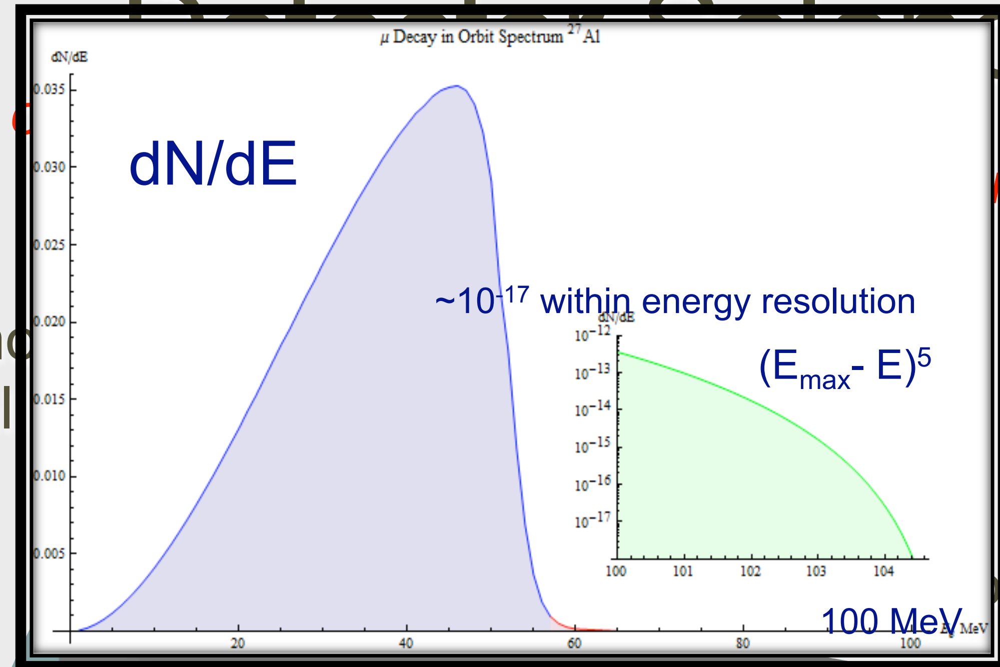
...ntum,

old picture, calorimeter design has changed

10 m × 0.95 m

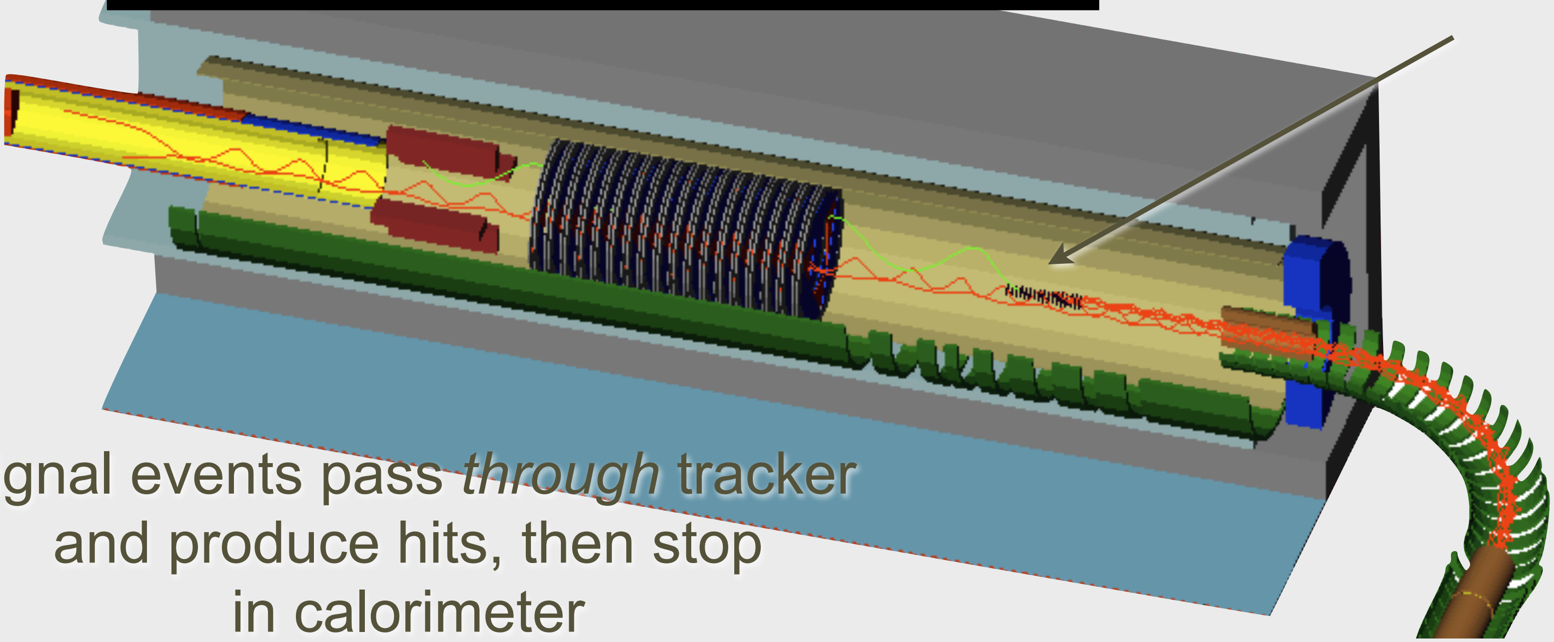
low mo...

almost al...



...il stopping target

muon beam stop



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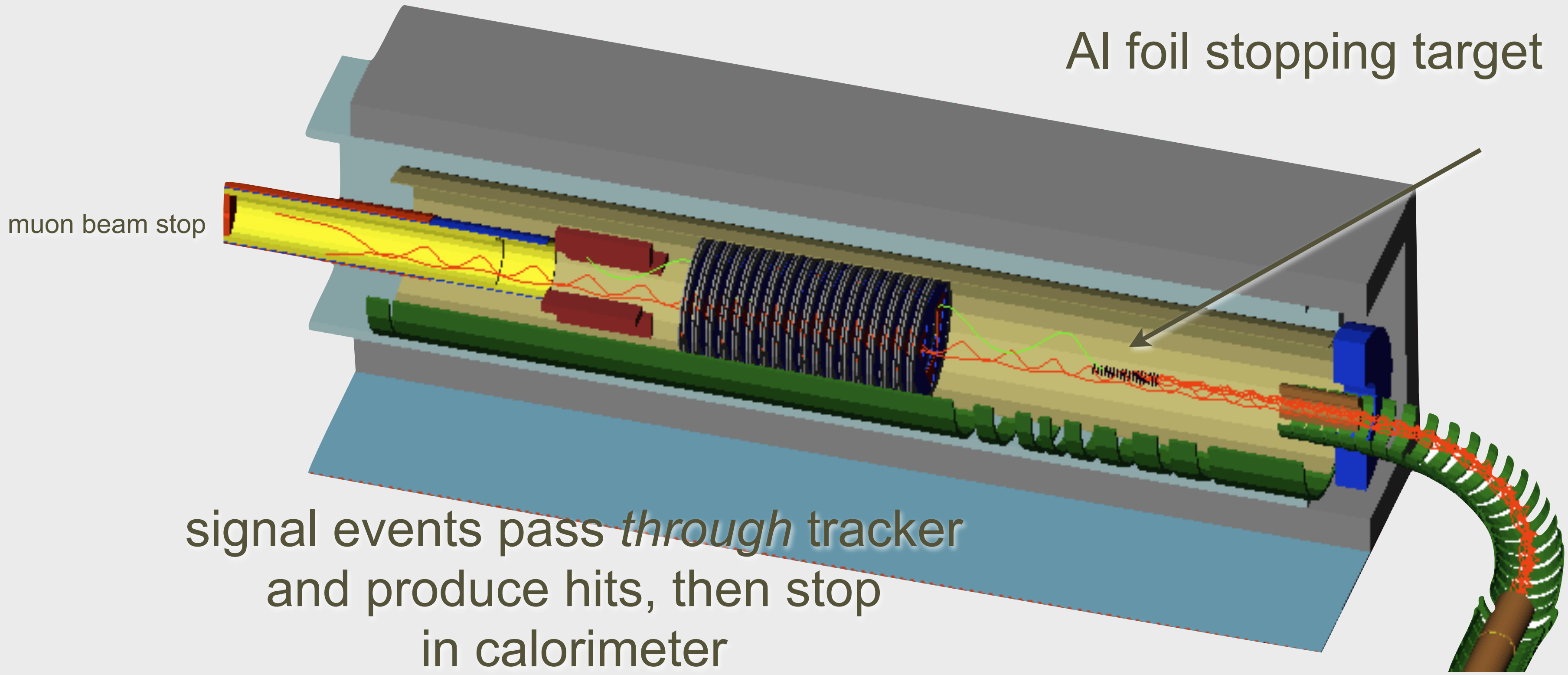


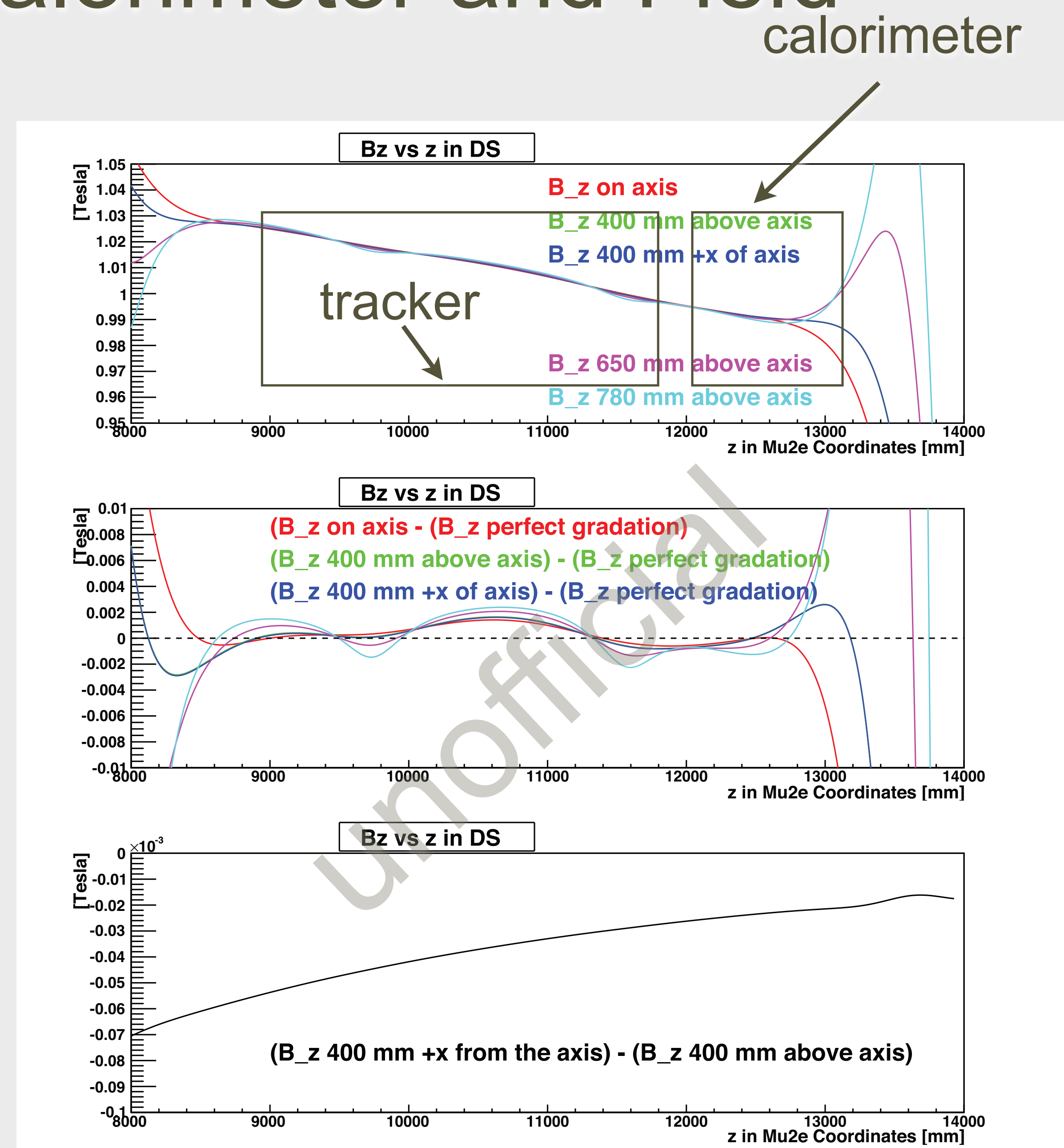
signal events pass *through* tracker and produce hits, then stop in calorimeter

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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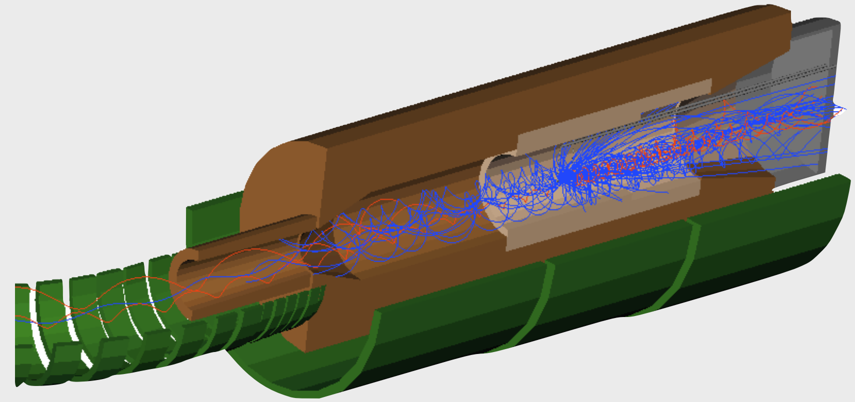


- In PS:
  - proton beam enters *in opposite direction* from solenoid system
  - extinction measurement out the back
  - solenoidal field increases along proton direction, creating a magnetic mirror, but ~80-85% of flux from backwards going pions
    - cross-sections are poorly known (+- 20%)

Magnetic Mirror

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

$$Ba^2$$

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

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

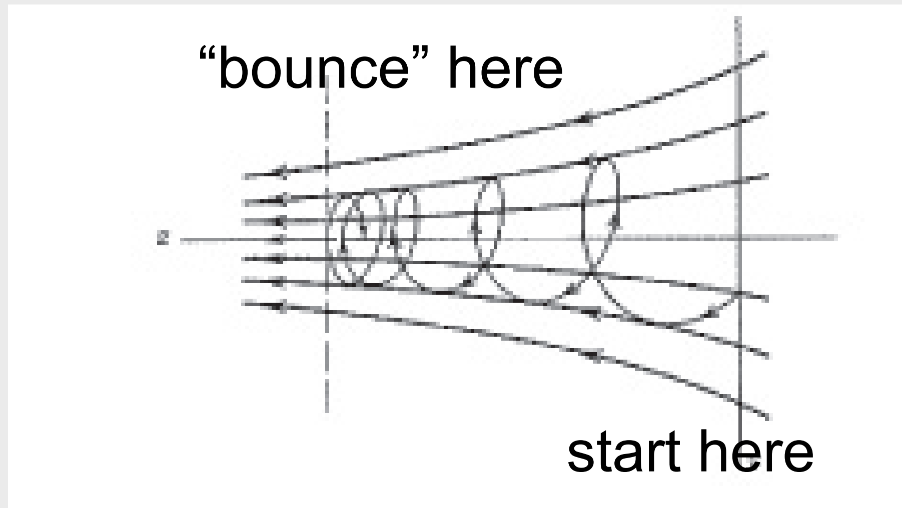
are adiabatic invariants

Therefore for Our Solenoids

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

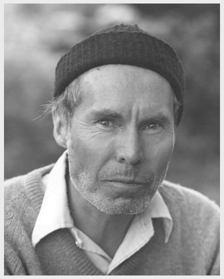
$$\frac{v_{\perp o}^2}{B(z)} = \frac{v_o^2}{B_o}$$

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



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

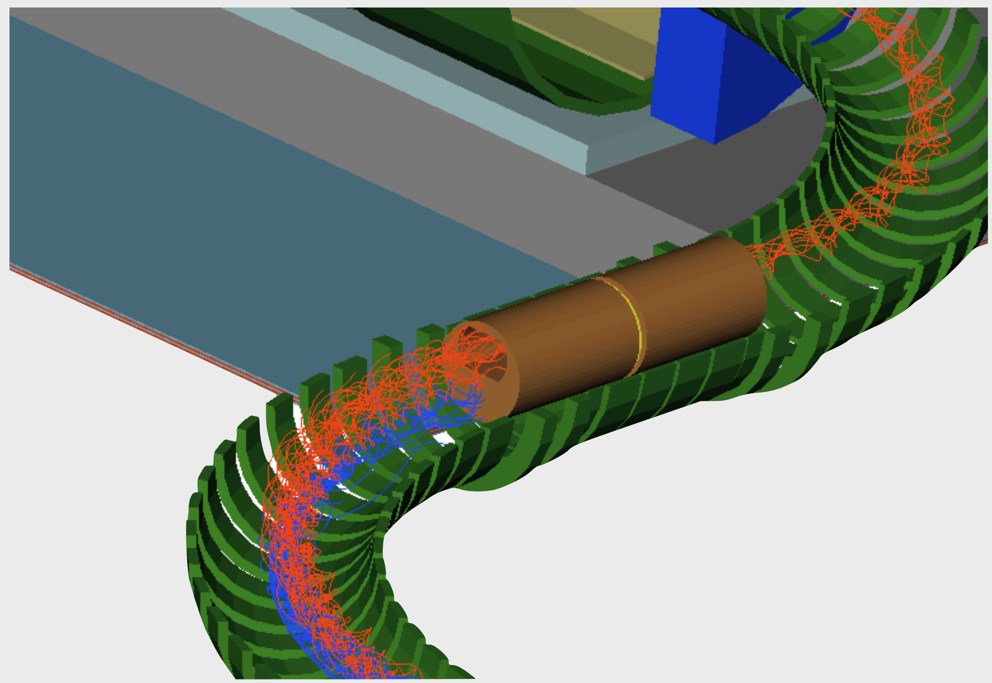
$$\vec{E}_{\text{effective}} = \frac{\gamma m}{e} \frac{\vec{R}}{R^2} \mathrm{v}^2_{\parallel}$$

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

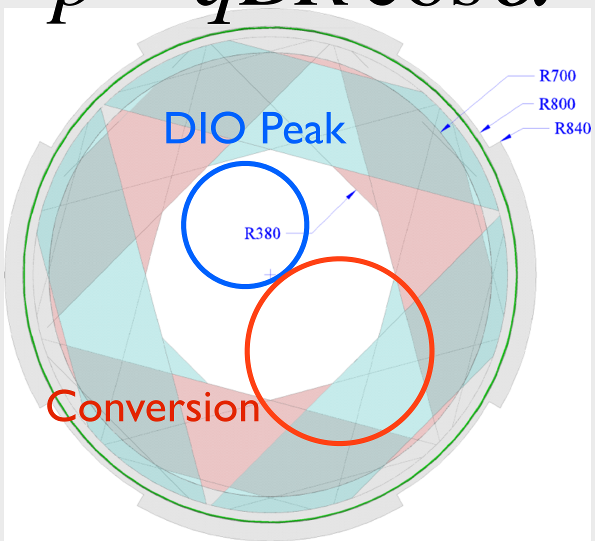


green represents the coils of superconducting cable

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
  - $10^5 << 10^{17}$

$$p = qBR\cos\alpha$$

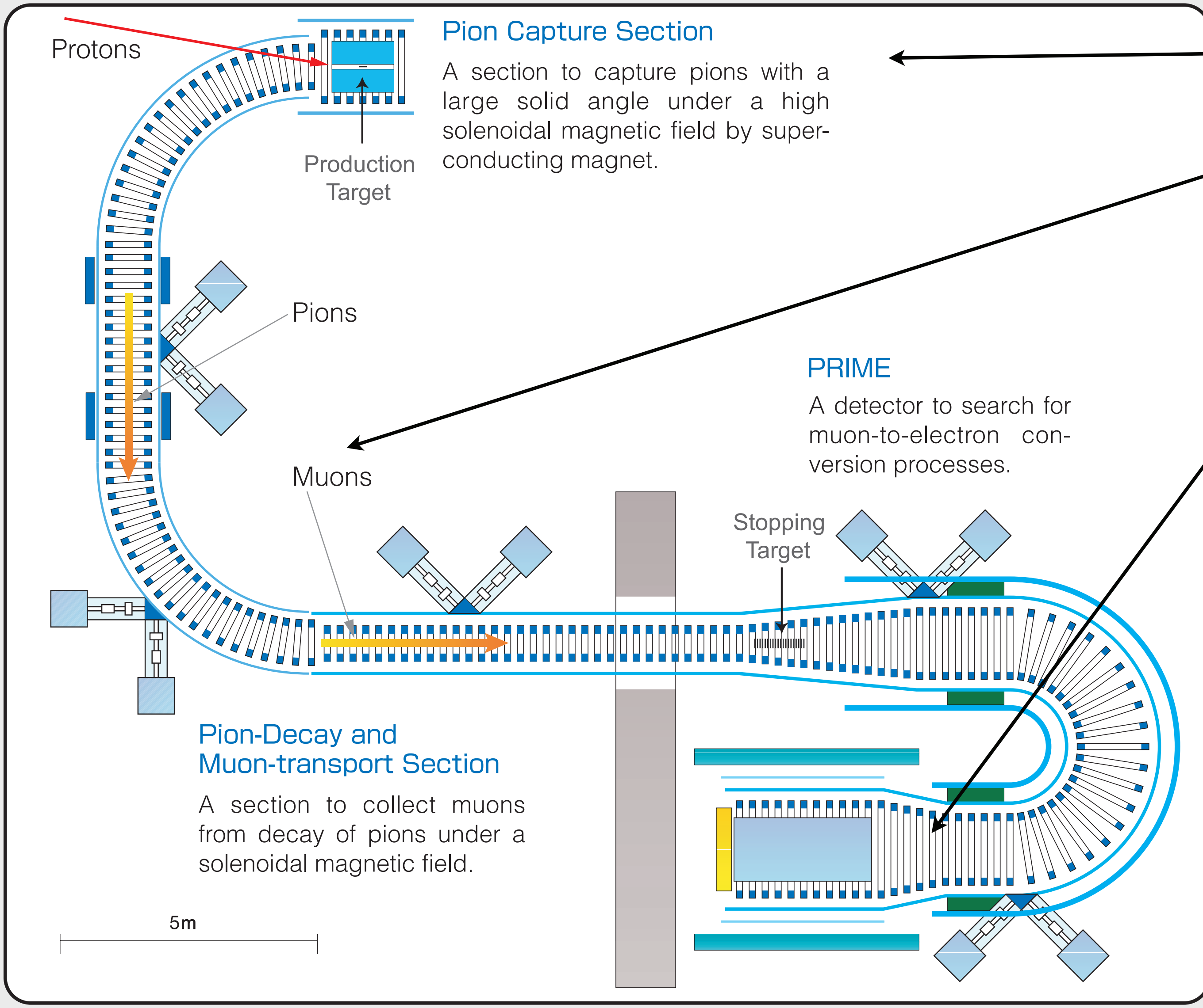


DIO's up to ~ 80 MeV/c stay in central hole; conversions seen by tracker

Theme and Variations: COMET

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

Theme and Variations: COMET



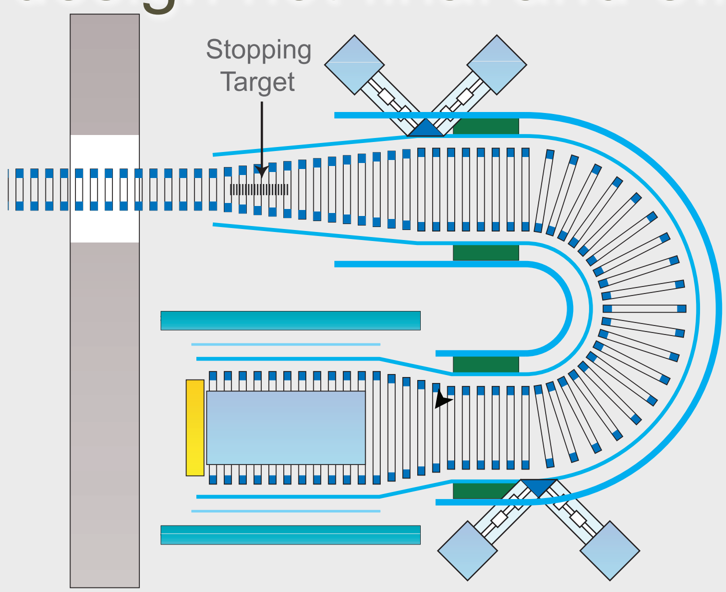
Proton Beam

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

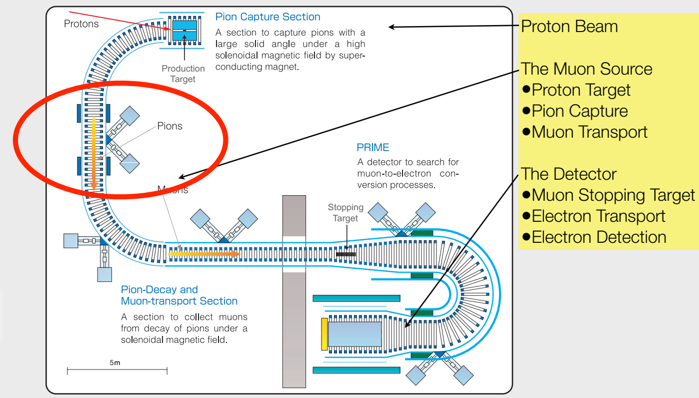
- You'll notice I said the second part of the Mu2e "S" brought the muons back on axis
- COMET has a C: are the muons drifting off somewhere?
  - No, they have (IM¬HO) a complicated dipole correction system

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

apply compensating dipole field

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

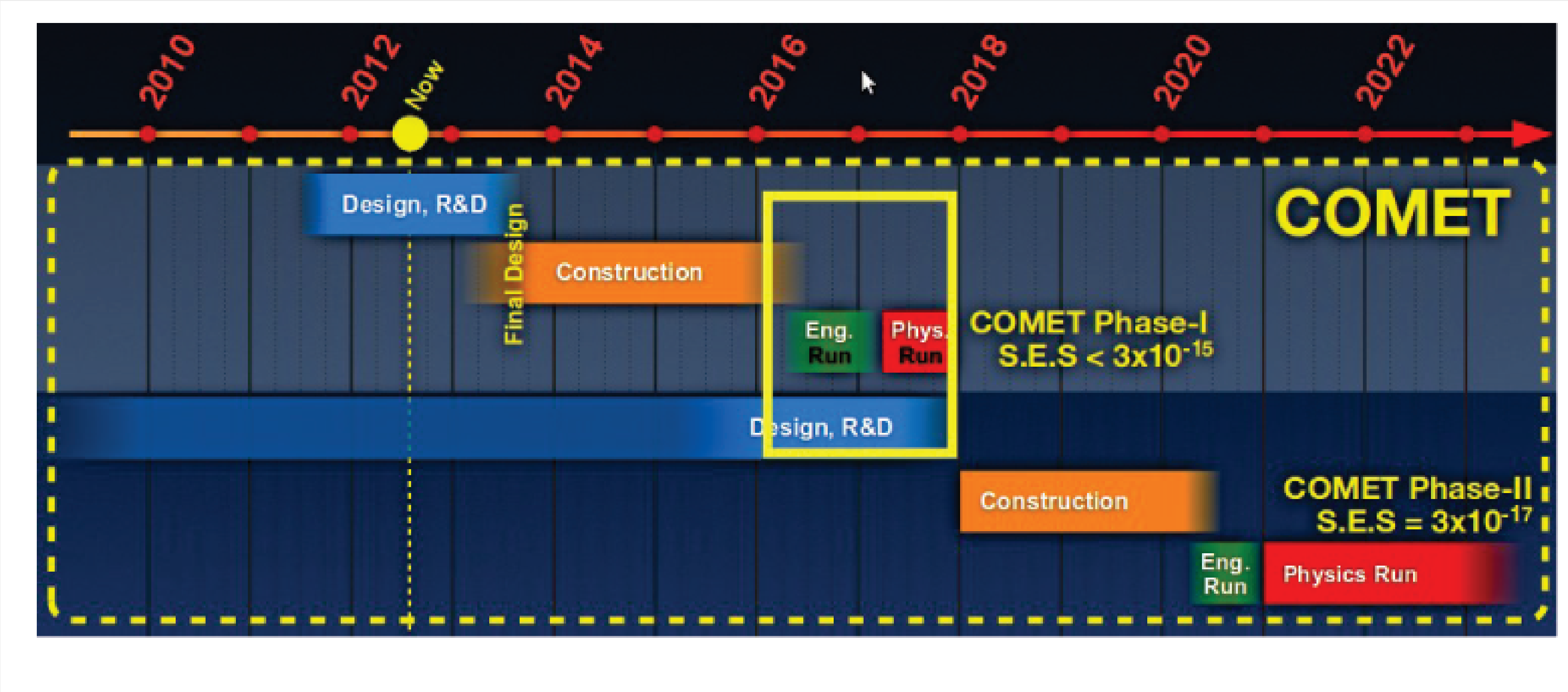
COMET Status



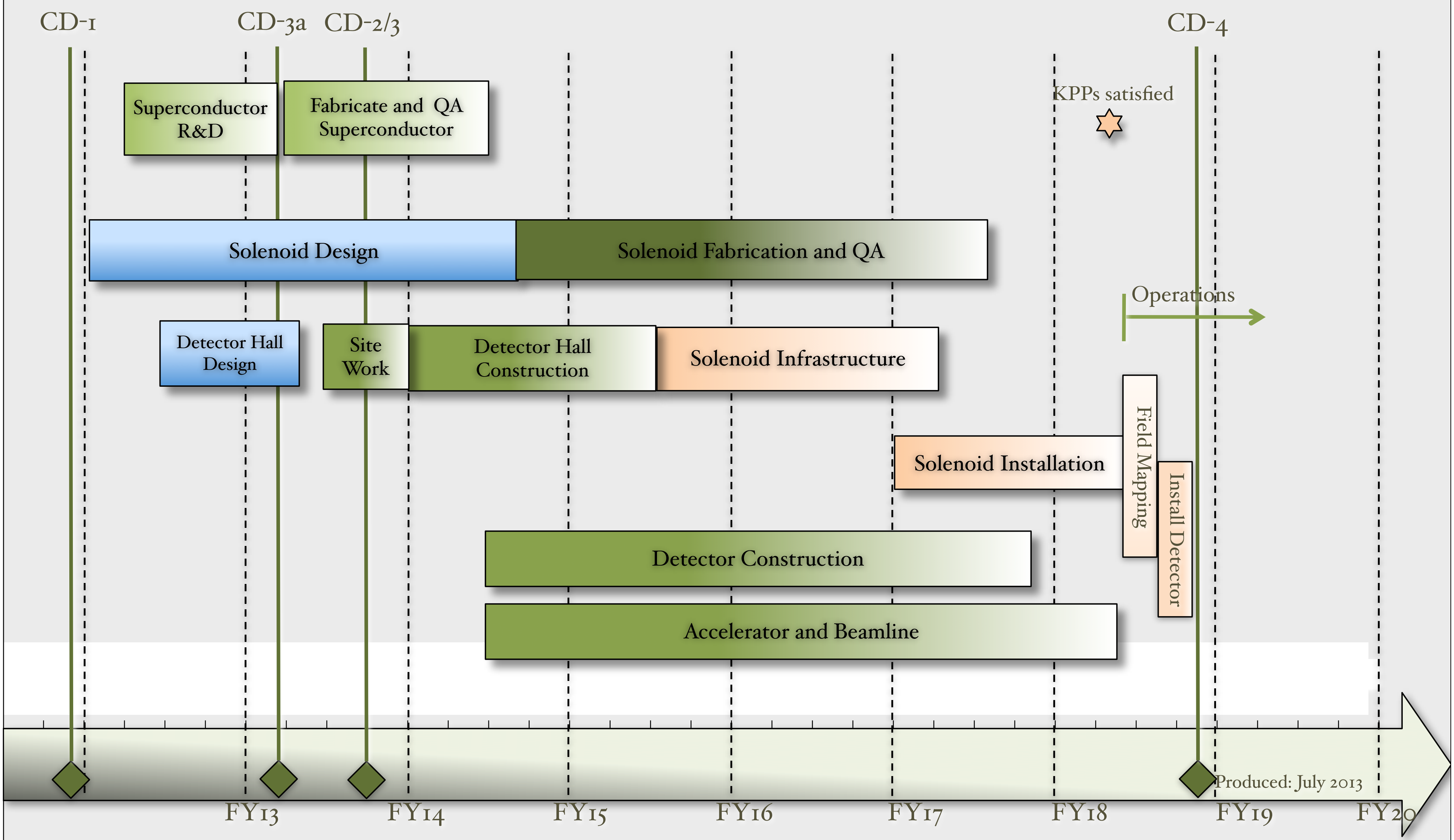
- Broken into two phases:
  - Phase I: up through central bend
    - Want to do measurements of flux with one detector and a second detector to do ~x100 better than SINDRUM, same style of cylindrical detector as SINDRUM

      >= 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 x 10^{-17}