Who Ordered That?

Mu2e: A Search for Charged Lepton Flavor Violation with Sensitivity $< 10^{-16}$

R. Bernstein
Fermilab
for the Mu2e Collaboration

What is This Talk About?

- Muon-to-Electron Conversion
- What's That?
  - a muon changing into an electron
- Who Cares?
  - it happens all the time in normal muon decay...

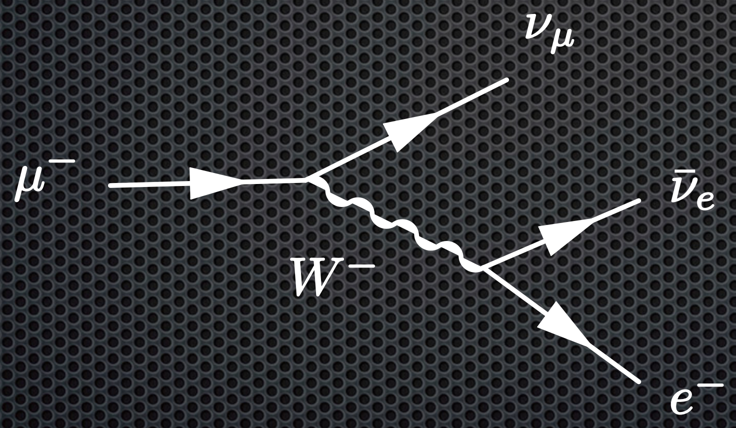
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- But this is different: $\mu^- N \rightarrow e^- N$

Why is this important?

- Because there are no neutrinos in $\mu^- N \rightarrow e^- N$
- Muons interact by gravity, E&M, and the weak force

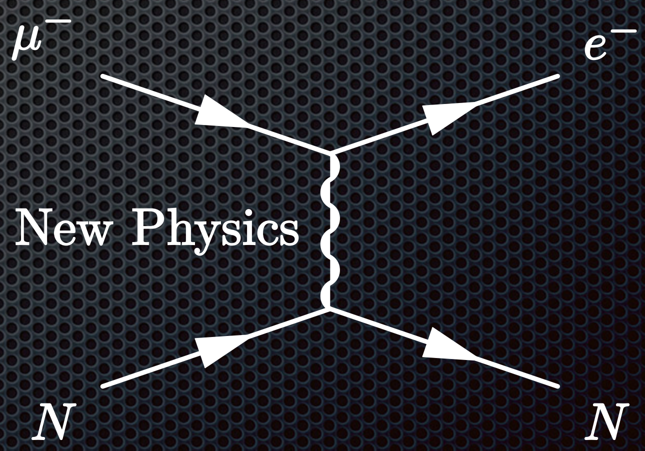
muon decay in the Weak Interaction



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

R.Bernstein /Fermilab

muon-to-electron Conversion

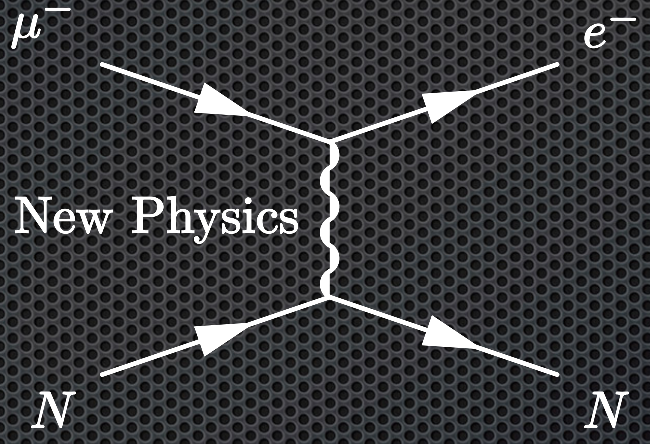


$$\mu^- N \rightarrow e^- N$$

Mu2e

Mu2e Look For New Physics:

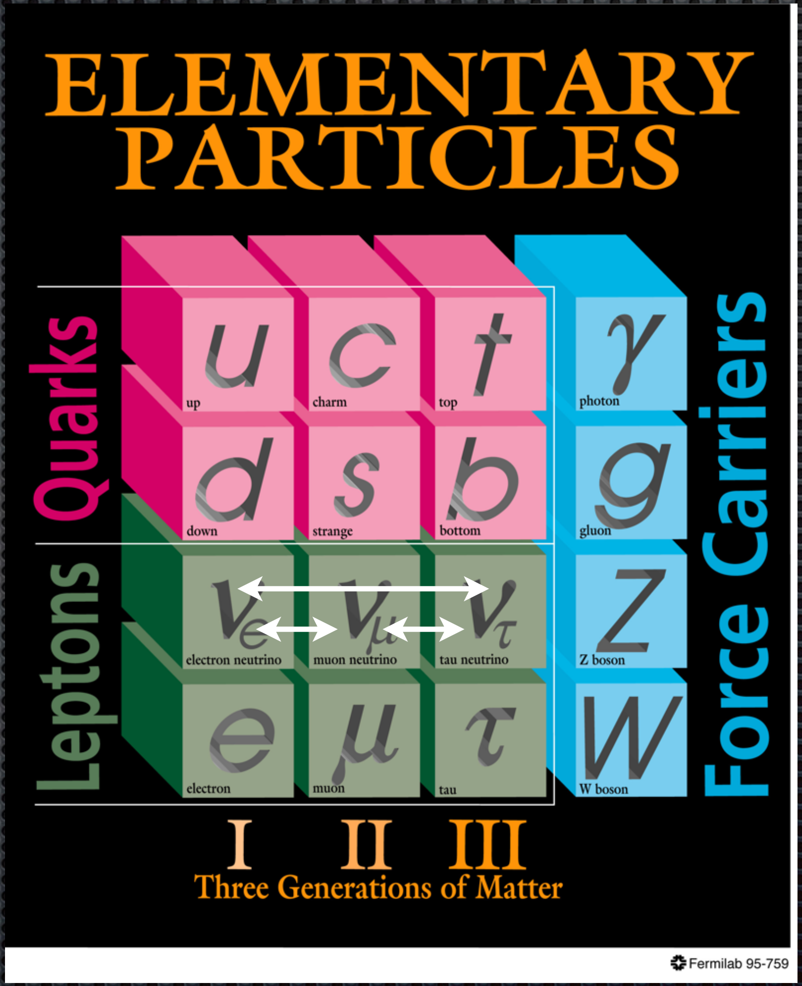
- Unlike Standard Model muon decay, no one has ever seen:



- We propose to set a limit at ~10^{-17} and can make a discovery at a few 10^{-16}

Why is this important?

- We think we have a good understanding of the constituents of matter
- modulo particle physics arrogance given that this is 5% of the Universe



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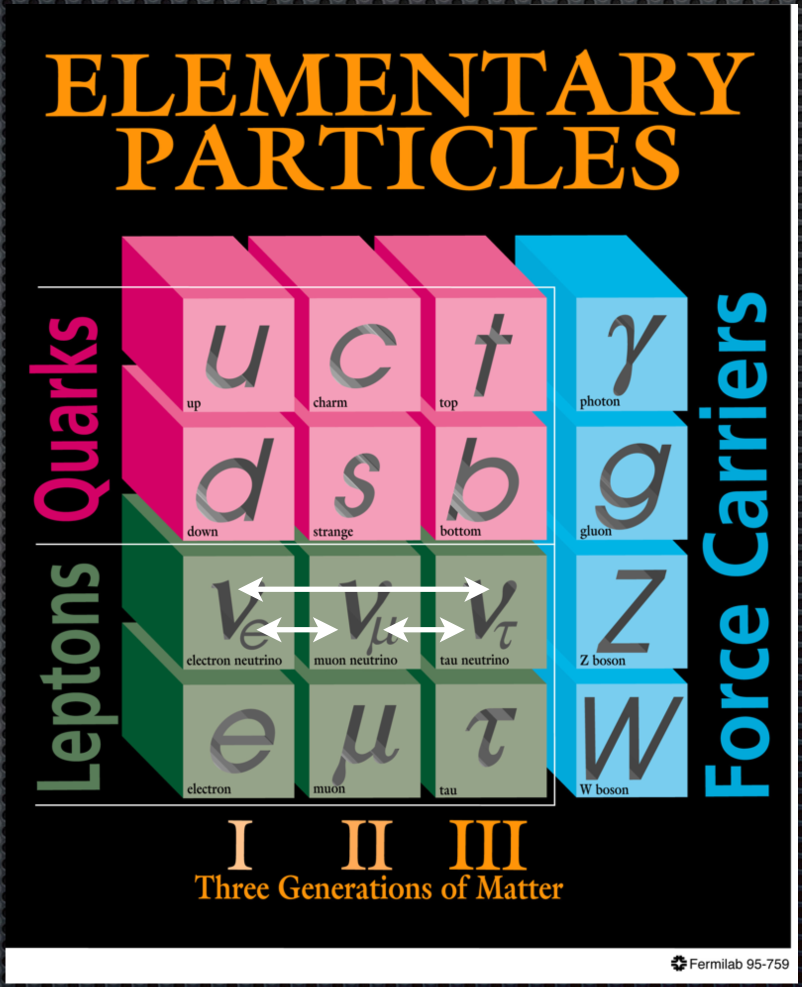

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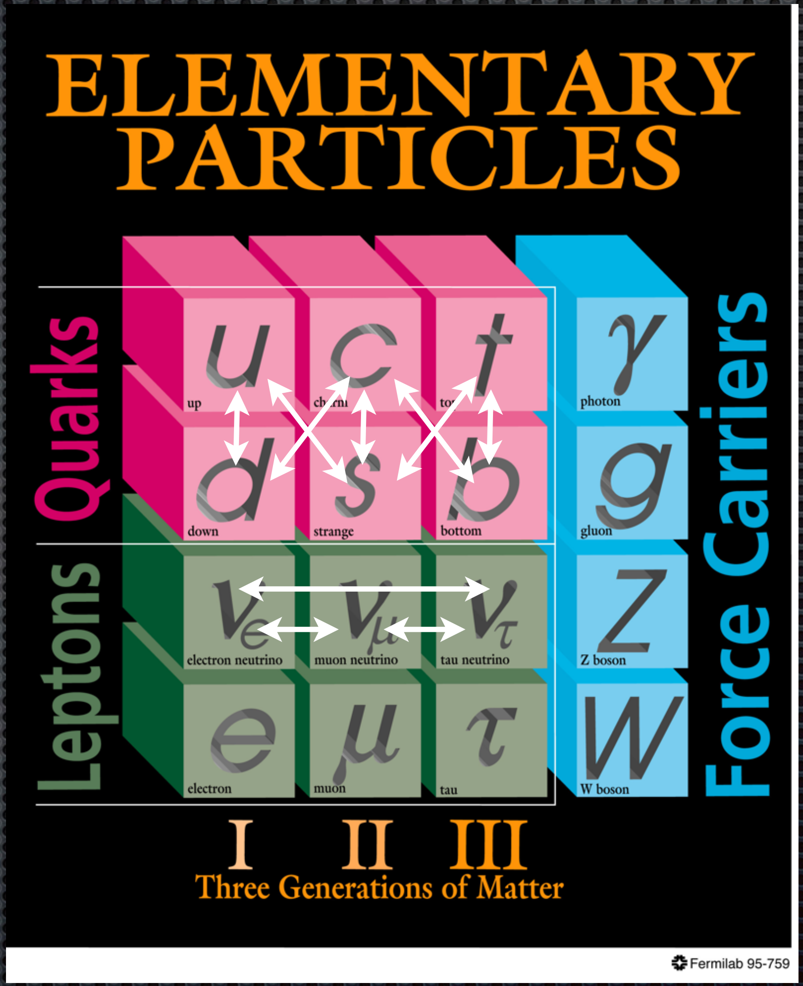

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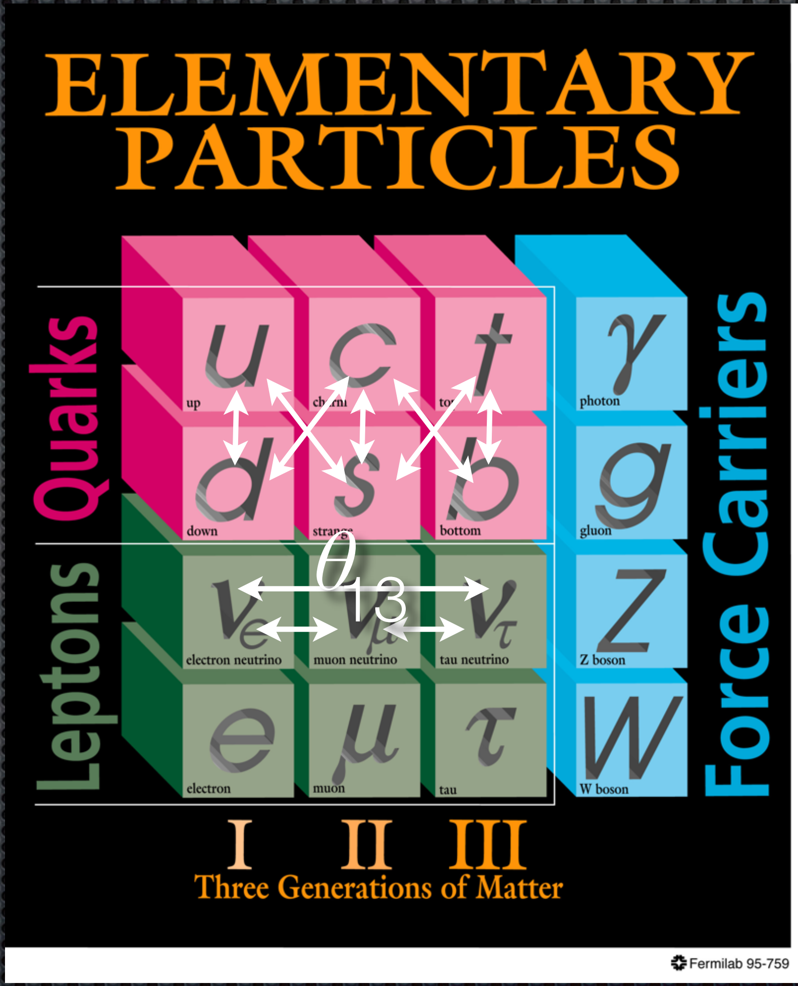

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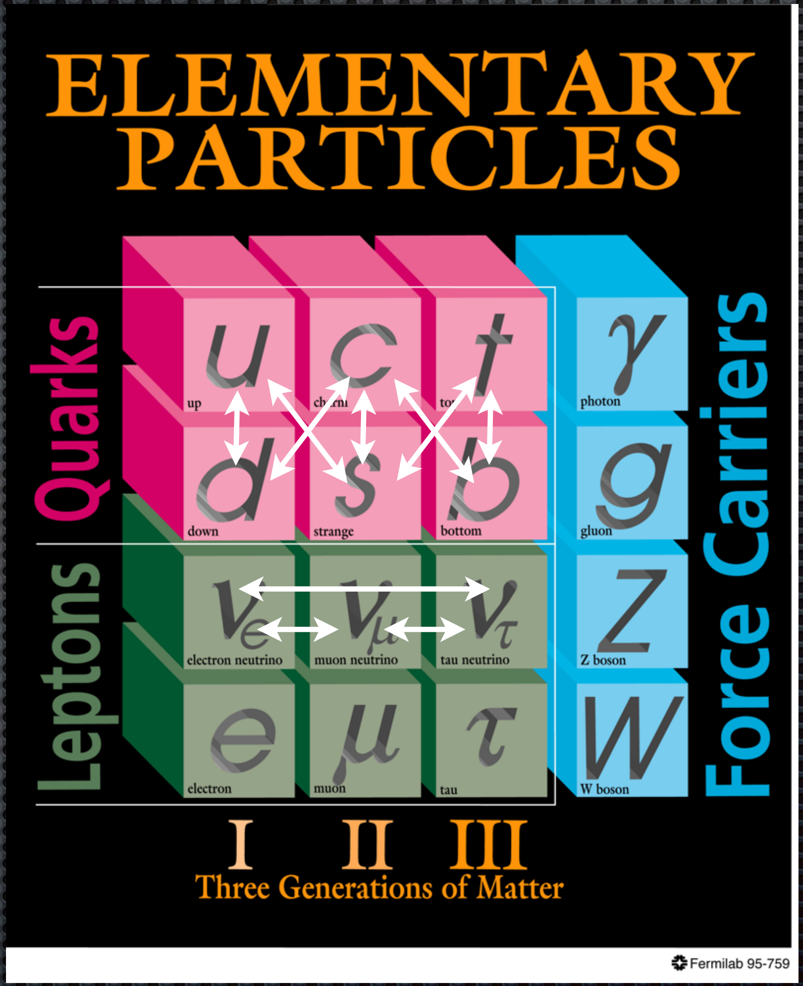

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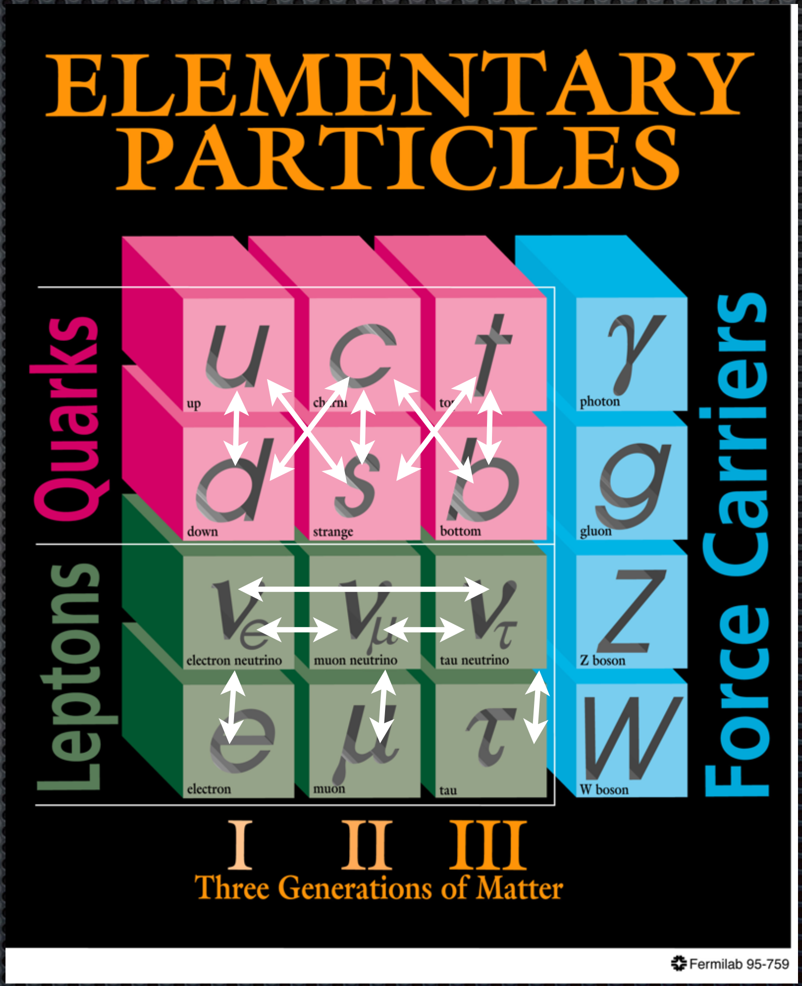
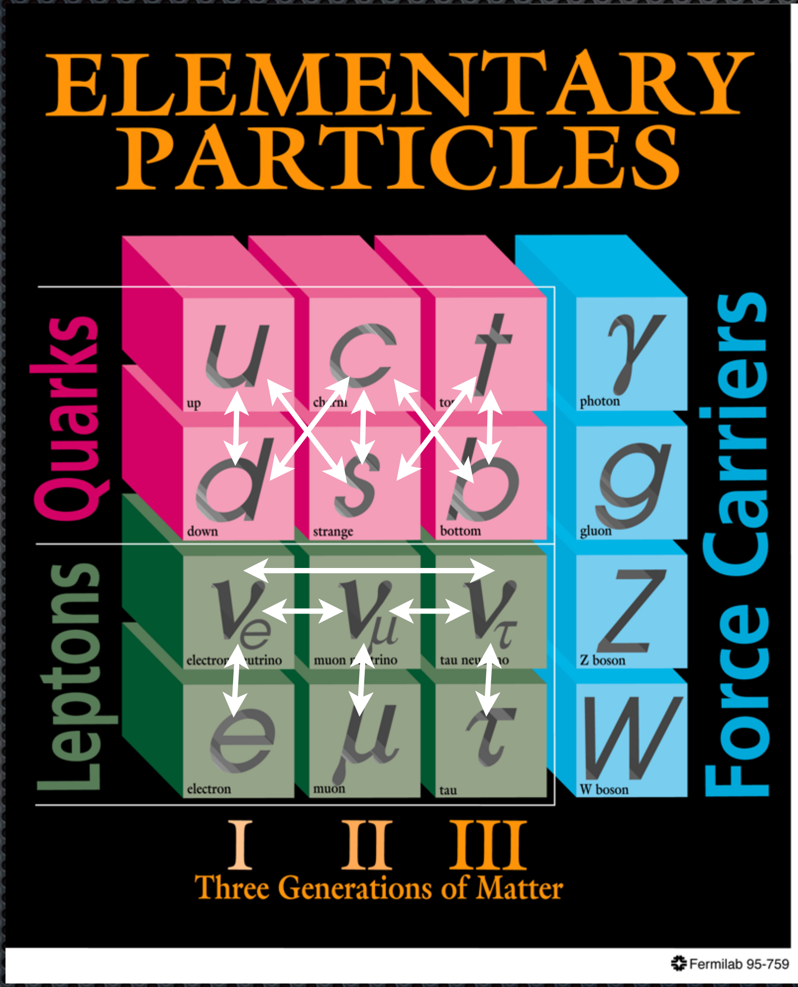


- Quarks change type, or mix (via the *W*)
- Neutrinos mix(neutrino oscillations)
- And neutrinos change into their charged partners

What's Wrong With this Picture?



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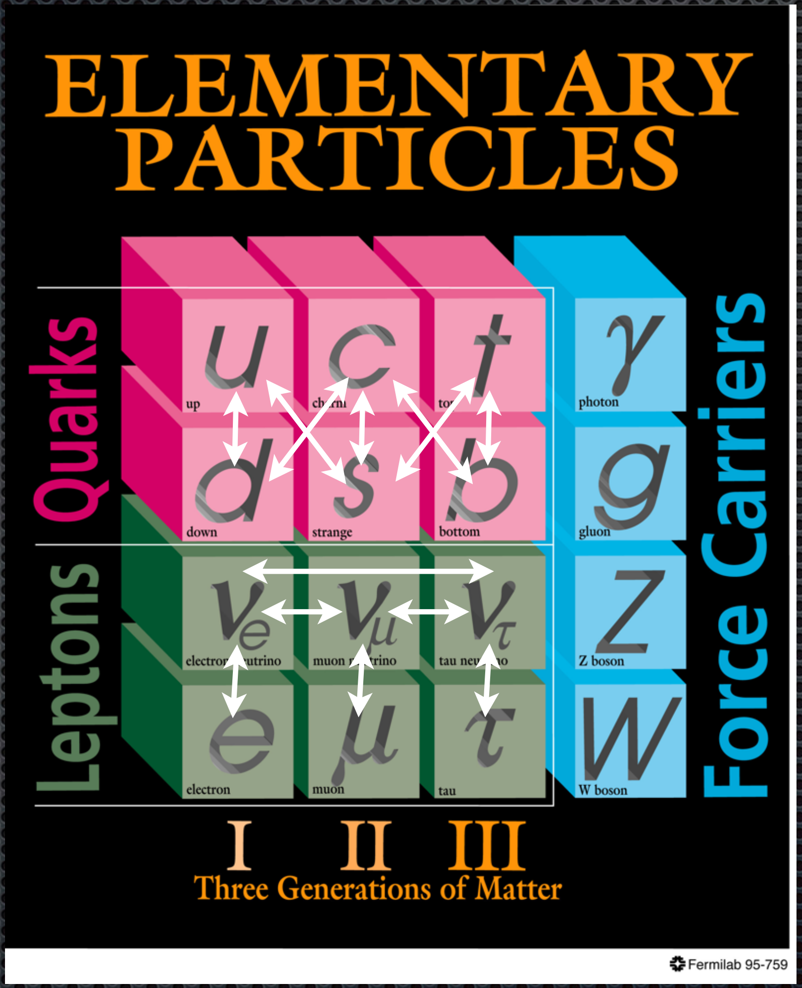
- What's going on with charged leptons?



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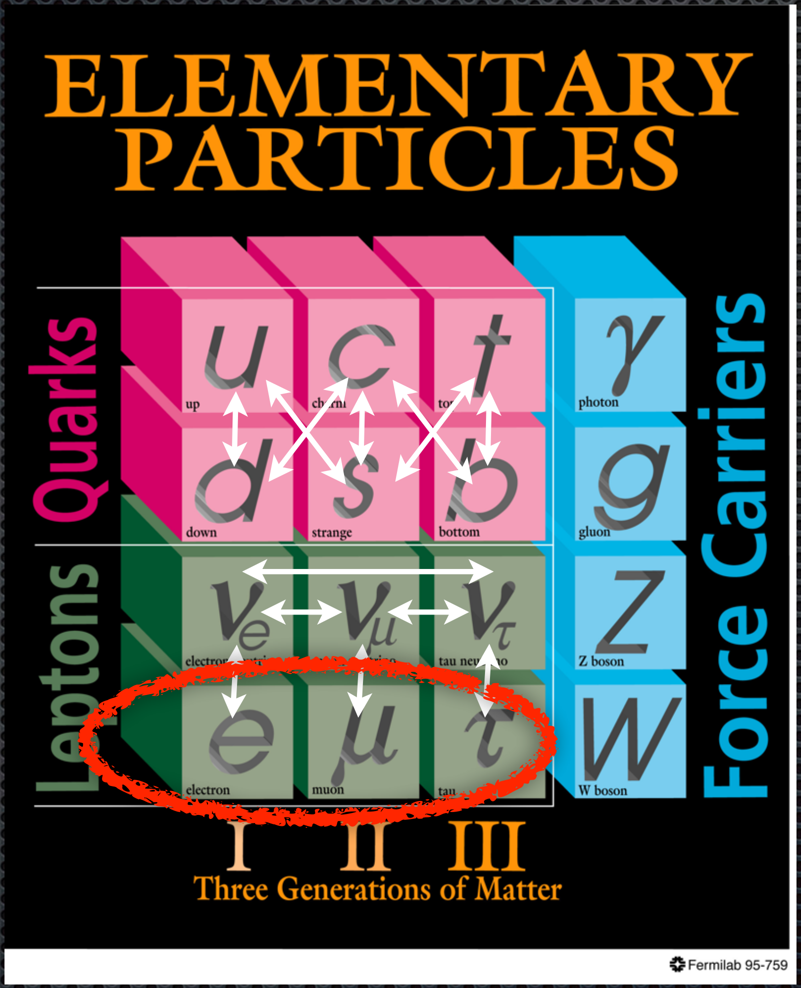

- They don't mix

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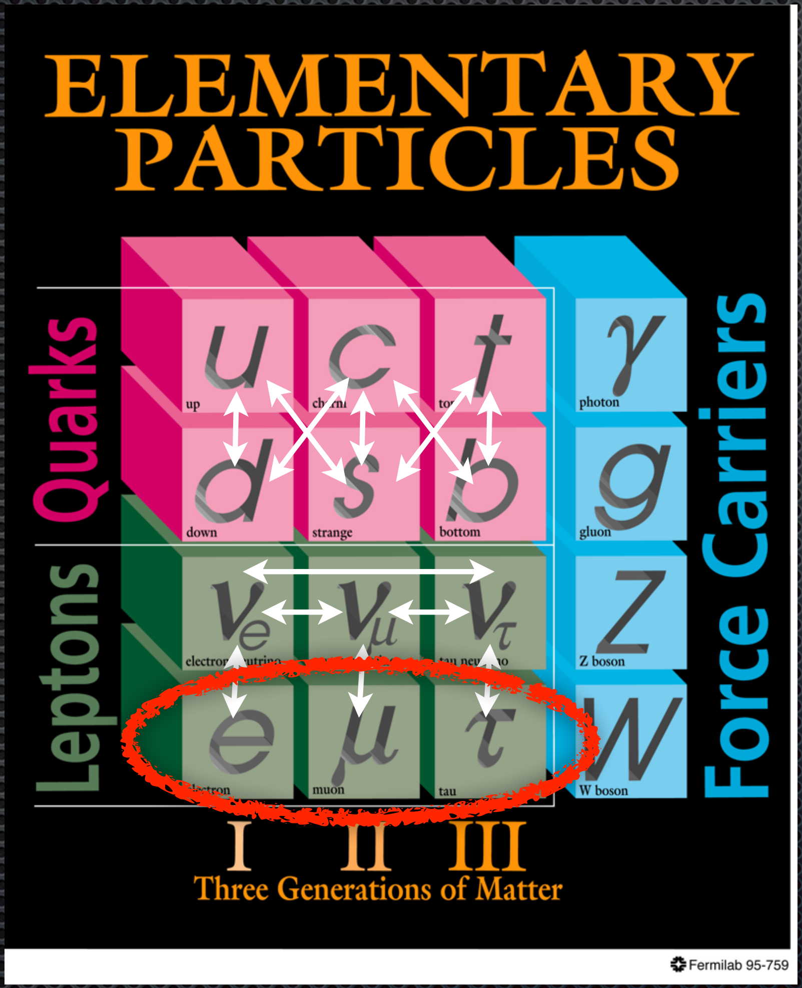
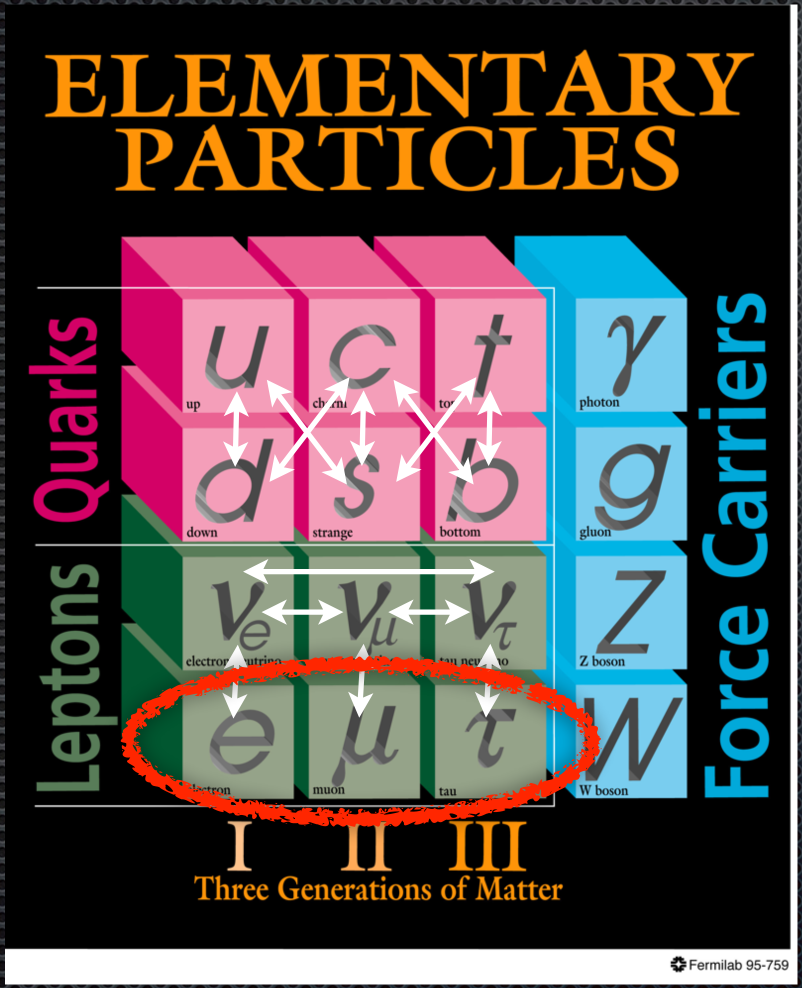
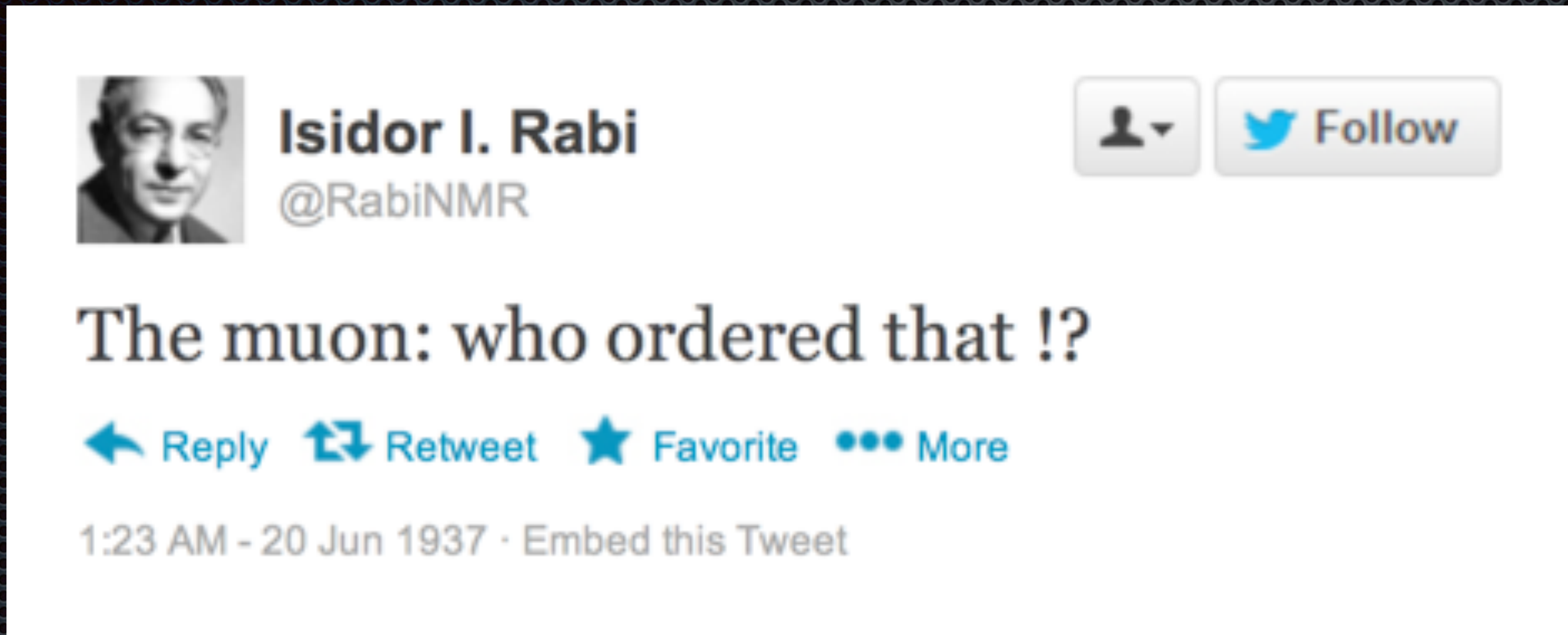


What's Wrong With this Picture?

- why are there three generations?



Sound Bite Format:



- Why are there three generations (flavors)?
- We can't come up with a sensible theory that doesn't mix charged leptons, *aka* charged lepton flavor violation (CLFV)
- If it doesn't exist, we need to know; and if it does, why is it so small?

Neutral and charged lepton flavor violation

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect $BR(\mu \to e\gamma) \approx 10^{-4}$
- Unless another ν, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)
  - same as GIM mechanism!

Neutral and charged lepton flavor violation

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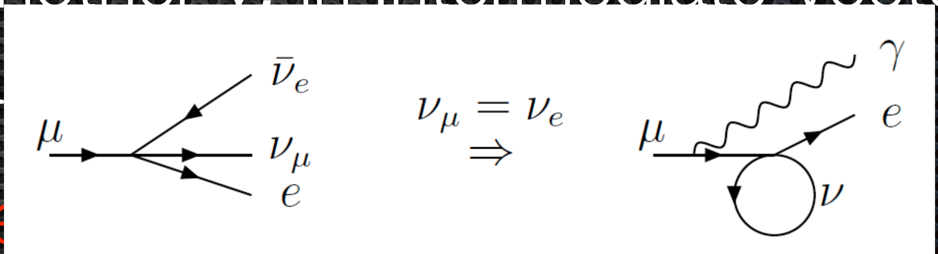
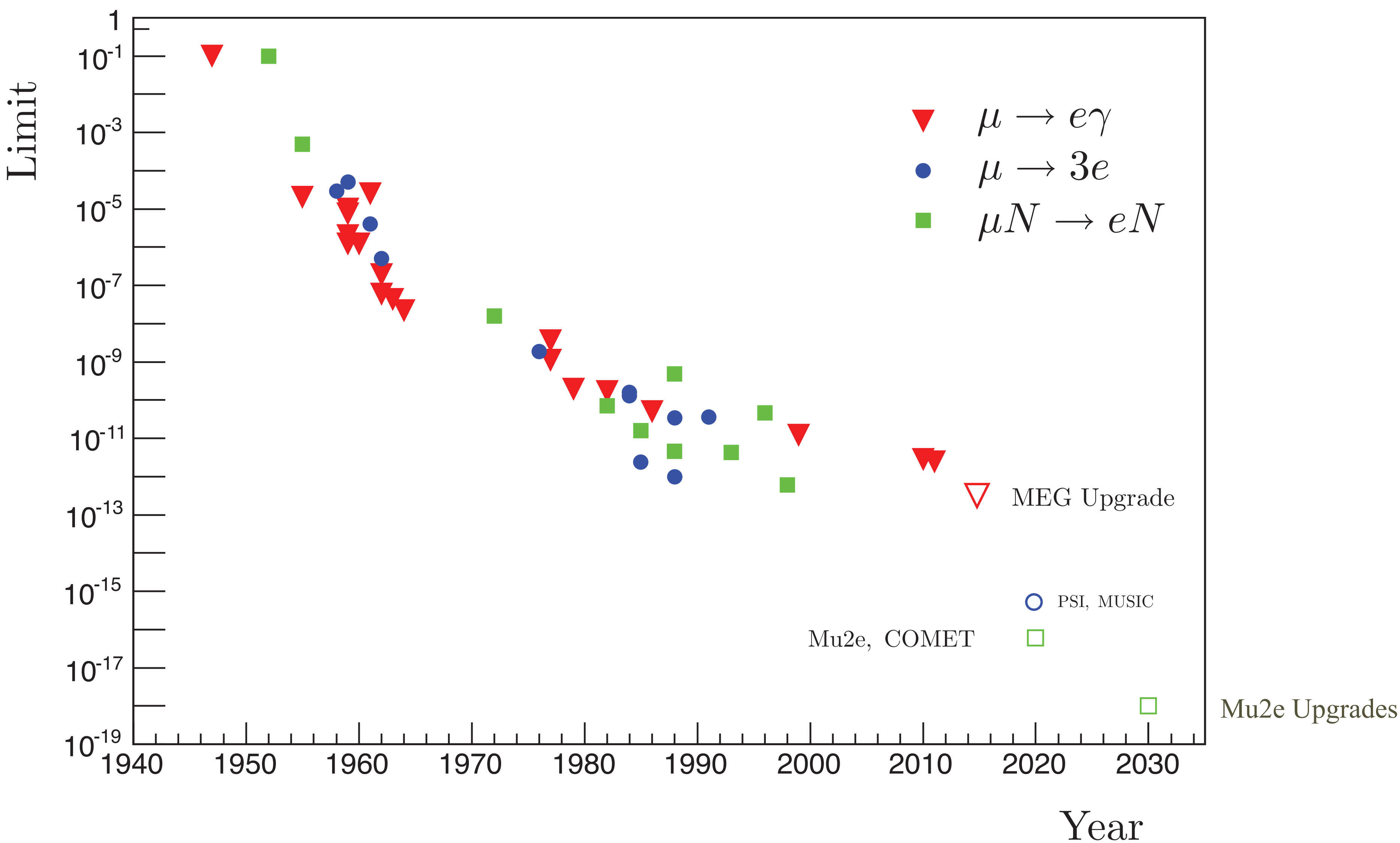


[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

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



RHB and P.S. Cooper, Phys Rept C (1307.5787)

What is μe Conversion?

muon converts to electron in the field of a nucleus

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

- Standard Model (neutrino oscillations) Background of 10^{-54}
- Charged Lepton Flavor Violation (CLFV)
- Related Processes: μ or $\tau \rightarrow e\gamma$, μ or $\tau \rightarrow 3l$, $K_L \rightarrow \mu e$, and more

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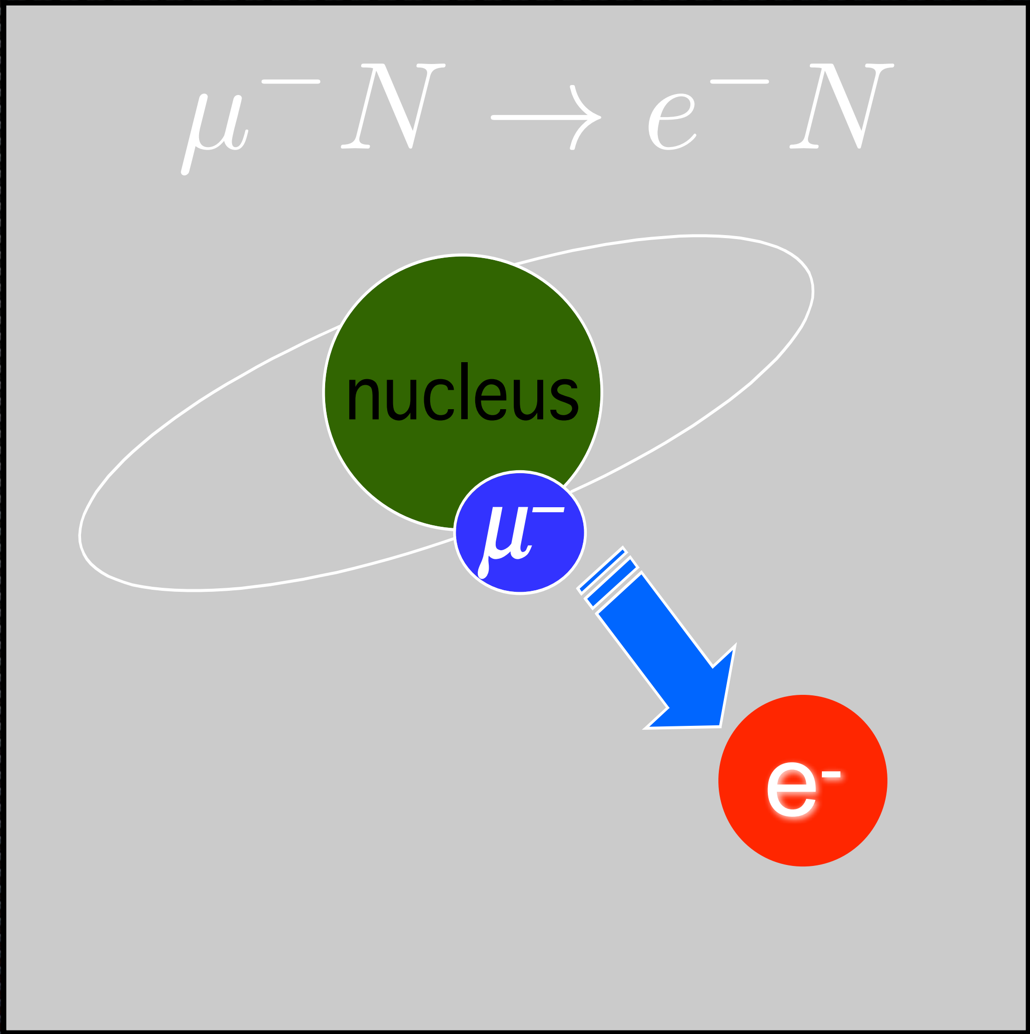
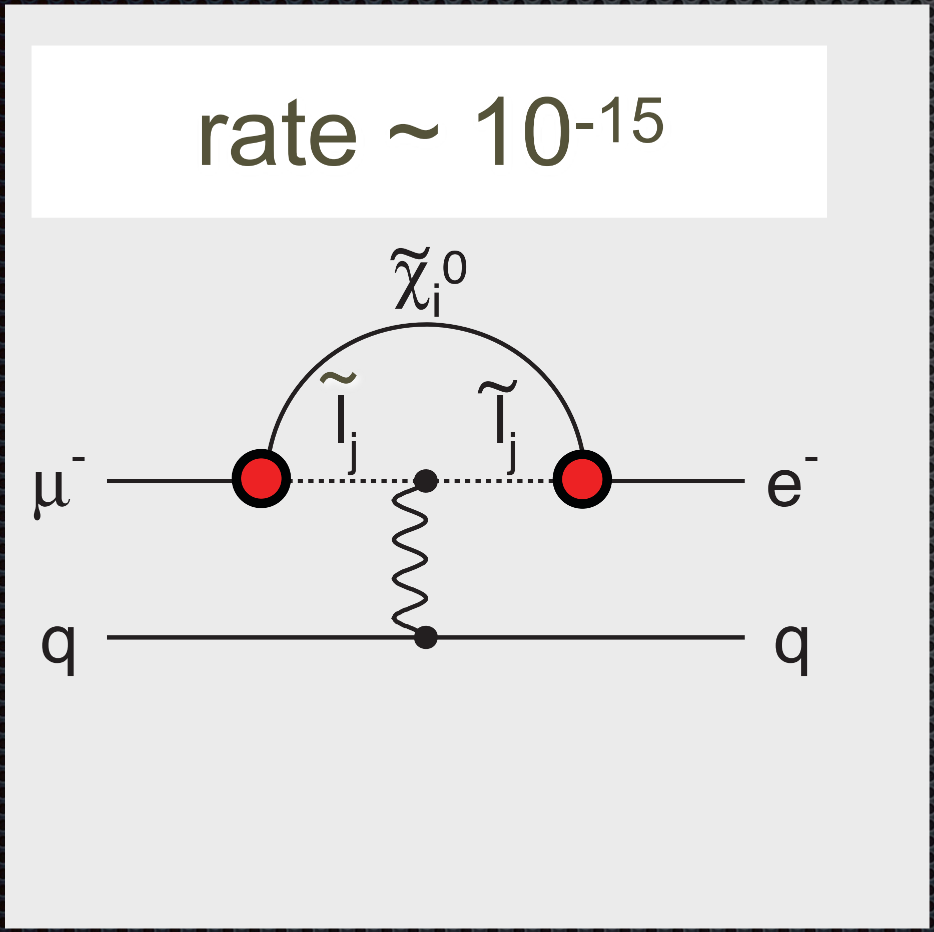
Experimental Signal

- A Single Monoenergetic Electron
- E_e ~ muon mass of 105 MeV/c^2
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



LFV, SUSY and the LHC

Supersymmetry

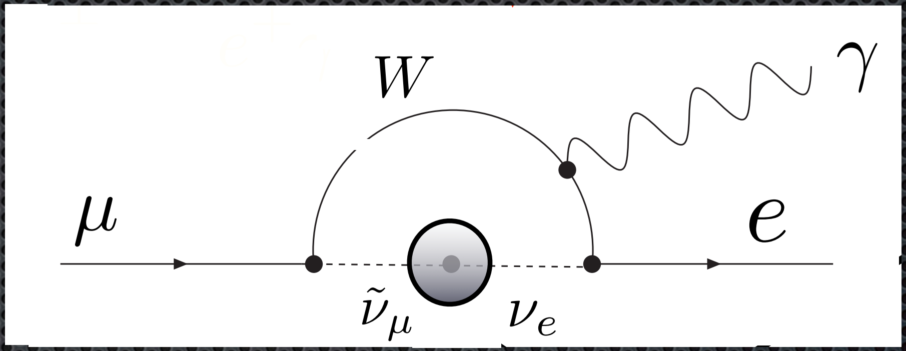


Access SUSY through loops:

signal of Terascale at LHC implies ~40 event signal / <0.5 bkg in this experiment

Neutrino Oscillations and Muon-Electron Conversion

- ν's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



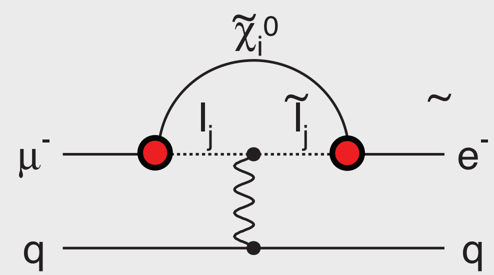
No Standard Model Background

$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Sources of Muon-to-Electron Conversion

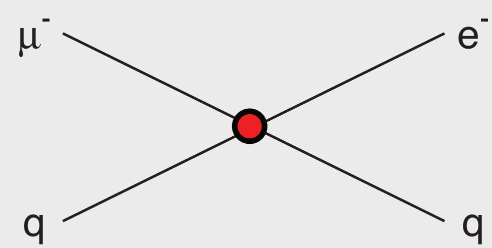
Supersymmetry

rate ~ 10^{-15}



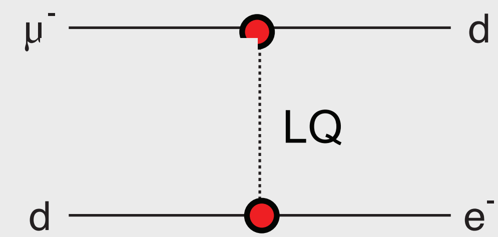
Compositeness

Λ_c ~ 3000 TeV



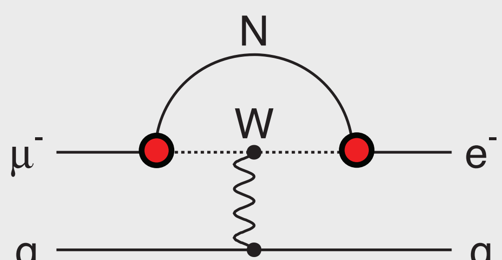
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



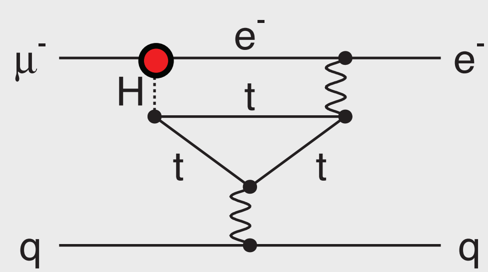
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ $8\text{x}10^{-13}$



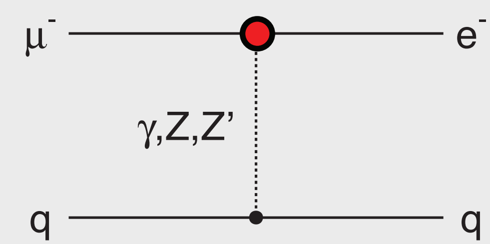
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



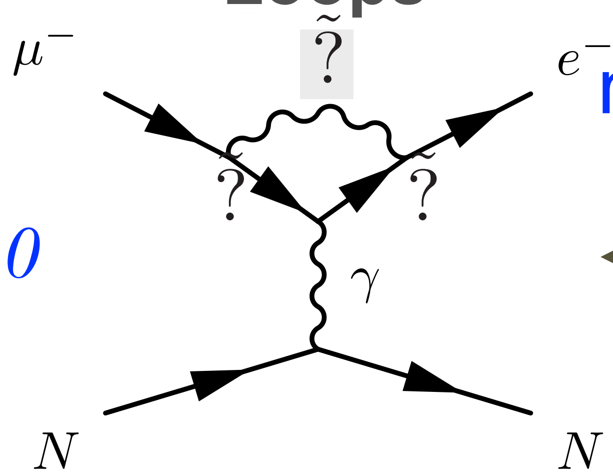
also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

“Model-Independent” Form

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

“Loops”

$\kappa = 0$

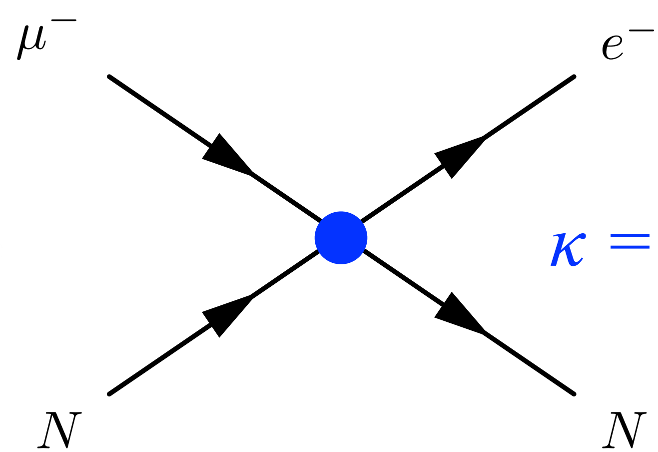


Supersymmetry and Heavy Neutrinos

mass scale Λ

κ

“Contact Terms”



$\kappa = \infty$

New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Contributes to $\mu \to e\gamma$

Does not produce $\mu \to e\gamma$

MEG at PSI, world’s best CLFV experiment

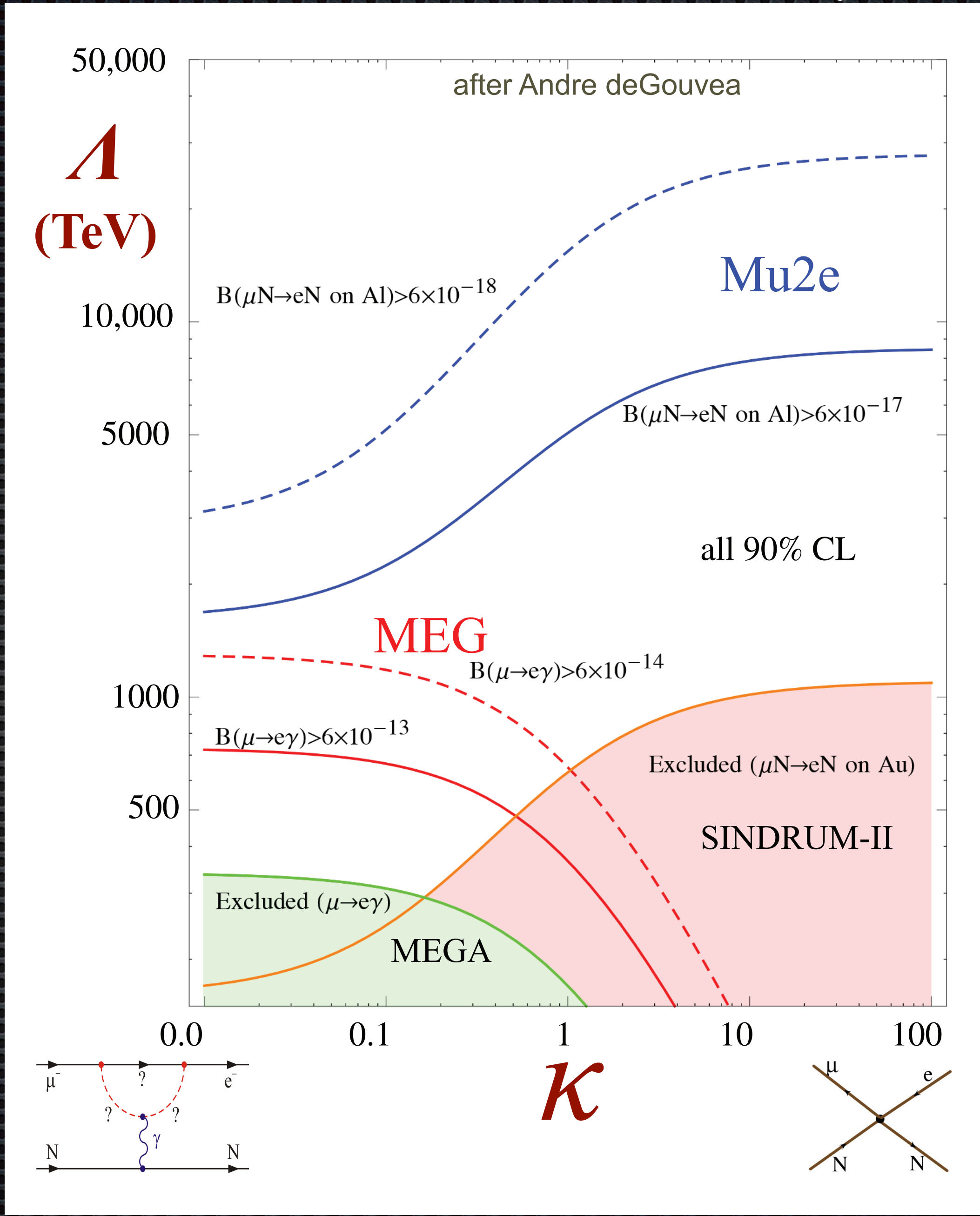
Quantitative Comparison?

μe Conversion and $\mu \rightarrow e\gamma$

1) Mass Reach to ~10^4 TeV

2) roughly equal to MEG upgrade in loop-dominated physics

3) Mu2e is a discovery experiment: ~ 10^{-16}



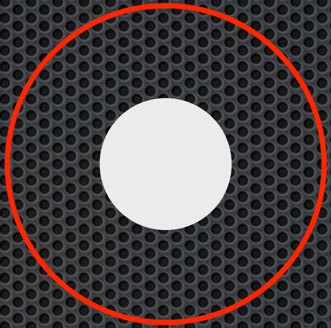
higher mass scale

Overview Of Processes

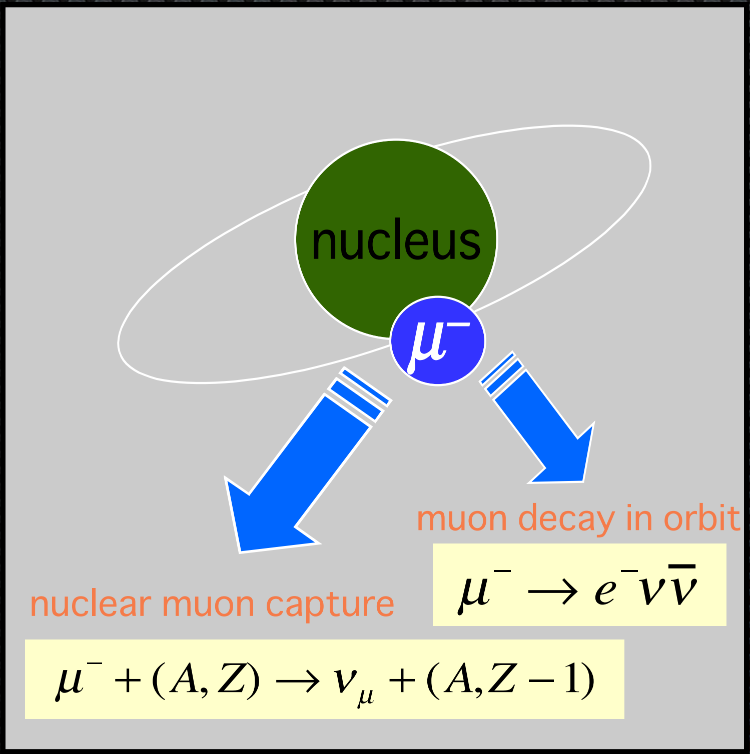
μ^- stops in thin Al foil

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

μ^- in 1s state



Al Nucleus
~4 fm



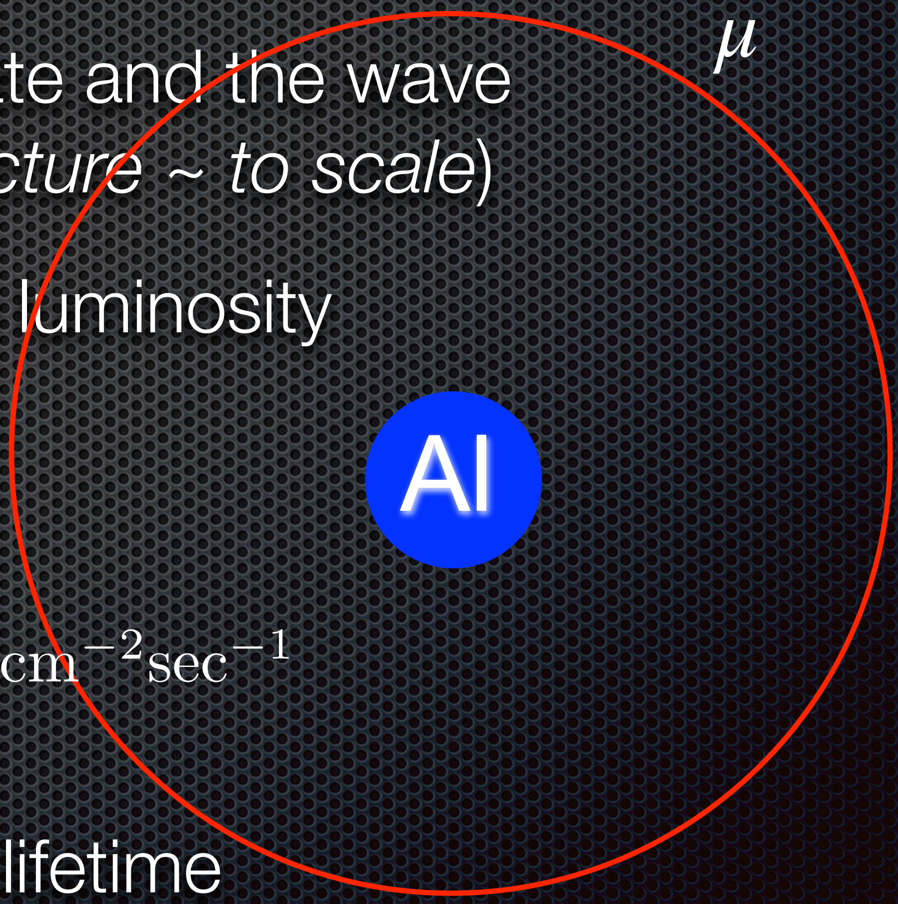
muon capture,
muon "falls into" nucleus:
normalization

60% capture
40% decay

Decay in Orbit:
background

Measuring 10^{-16} 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}

Getting the Luminosity

- 1st Year QM:

$$\psi(r) = \frac{1}{\sqrt{\pi}} a_o^{-3/2} e^{-r/a_0};$$

$$a_o = \frac{\hbar^2}{me^2} \to \frac{\hbar^2}{Zm_\mu e^2} \to \frac{1}{Zm_\mu \alpha};$$

$$a_o^{-3/2} = \frac{Z^3 m_\mu{}^3 \alpha^3}{\pi}$$

velocity in a 1s state?

$$\frac{Ze^2}{r^2} = \frac{m\mathrm{v}^2}{r}; m\mathrm{v}r = n\hbar;$$

or

$$\mathrm{v} = Z\alpha$$

then finally

$$|\psi(0)|^2\ \mathrm{v} = \frac{m_\mu^3 Z^4 \alpha^4}{\pi}$$

for extra credit:
what happens for Z>137?

Understanding the Normalization

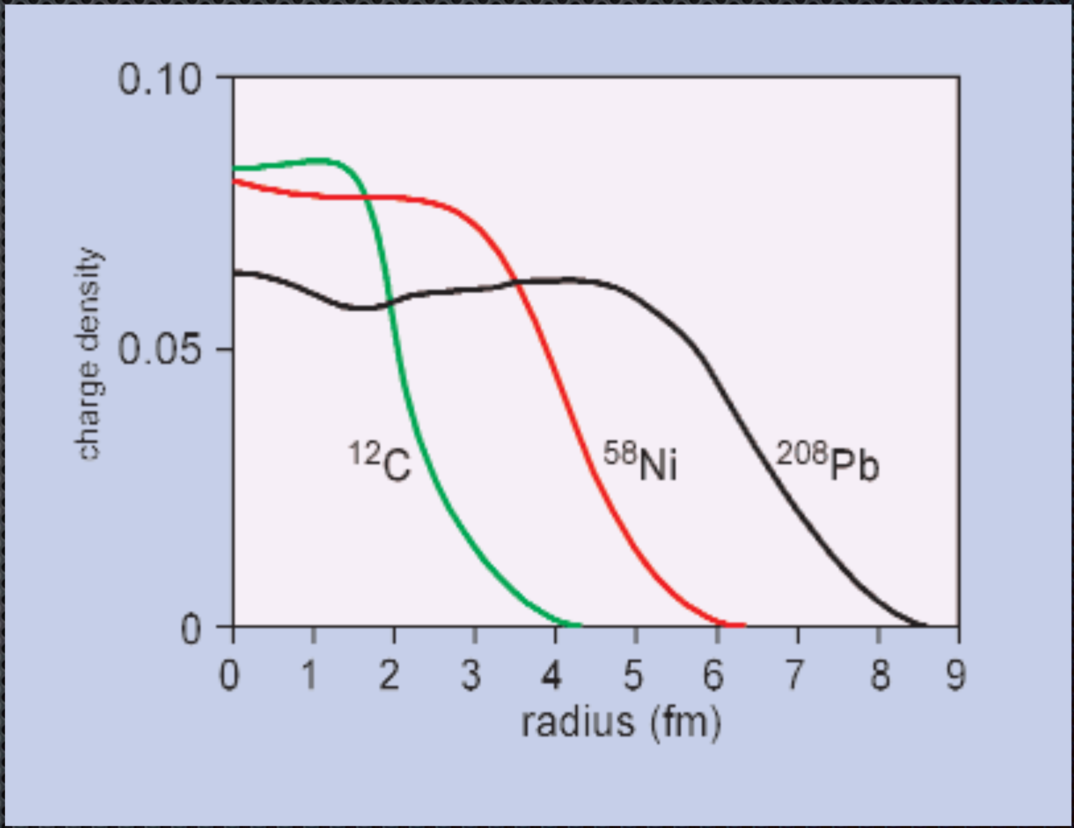
- The muon gets captured by the nucleus
  - and many details cancel in the ratio we measure
  - (we actually detect the muon falling into the 1s state from X-rays, before capture)
- But first the wave functions have to overlap:
  - what’s the Bohr radius for a 1s muon in Aluminum?

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

$$= 20 \text{ fermi}$$

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:

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

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 I'm Going to Tell You

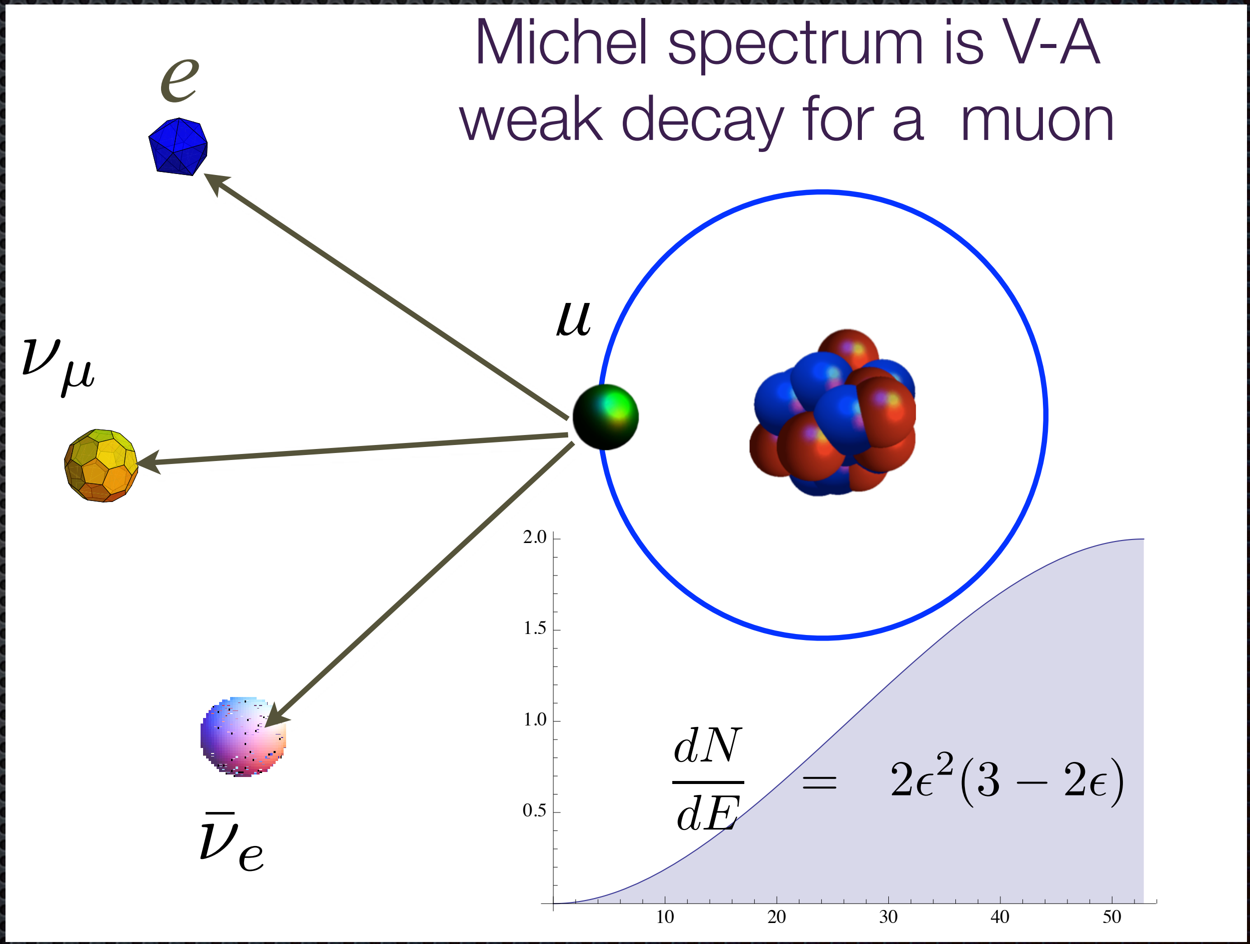
- There are two backgrounds that determine how the experiment works
  - one is intrinsic, and comes from the same muons we study in searching for conversion. It determines the detector design, required resolutions, and how the spectrometer works.
  - the other is beam-related. In order to improve on the existing limits we need an entirely new way to make a muon beam.

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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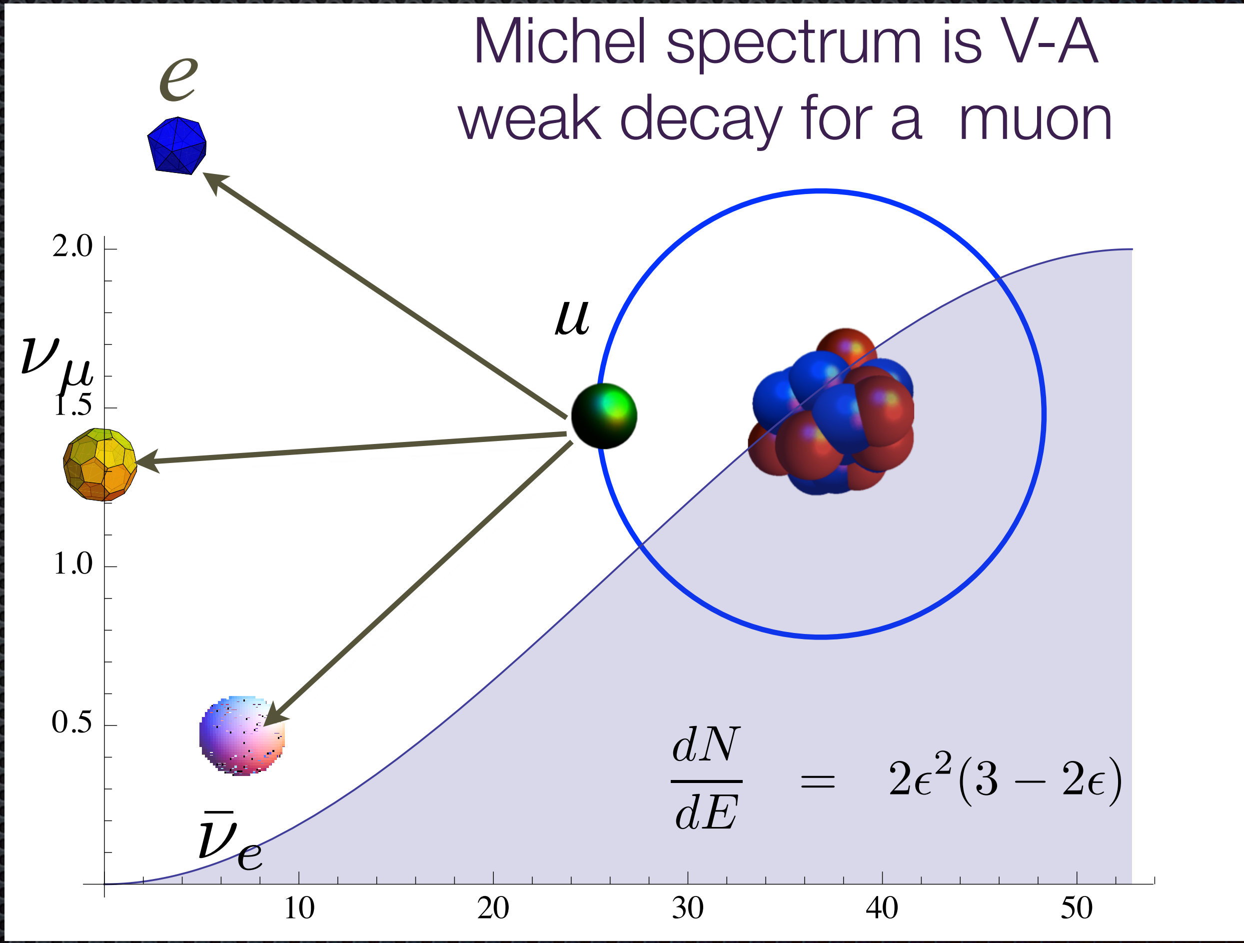

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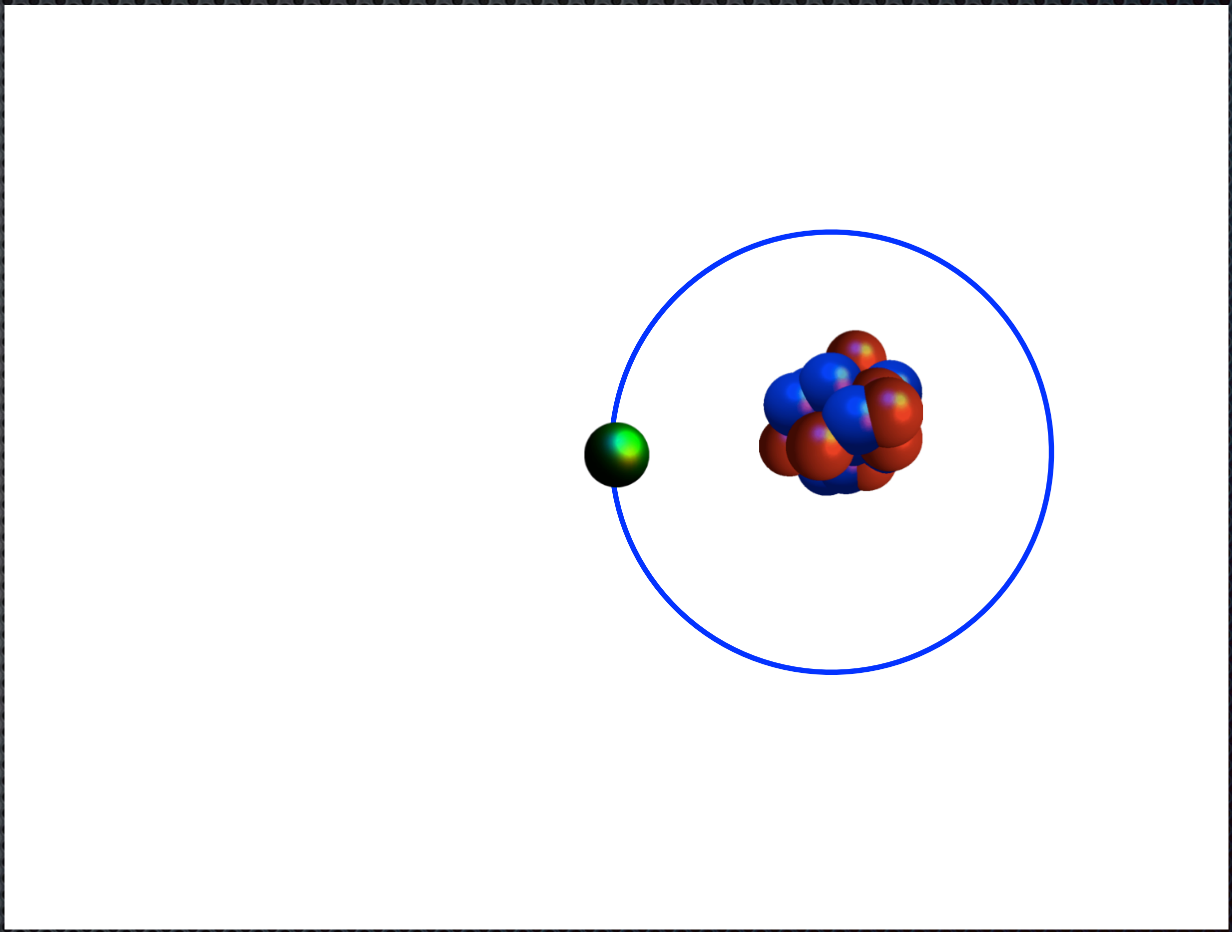
- Same process as before
- This time, include recoil of outgoing electron off nucleus (exchange of photon)



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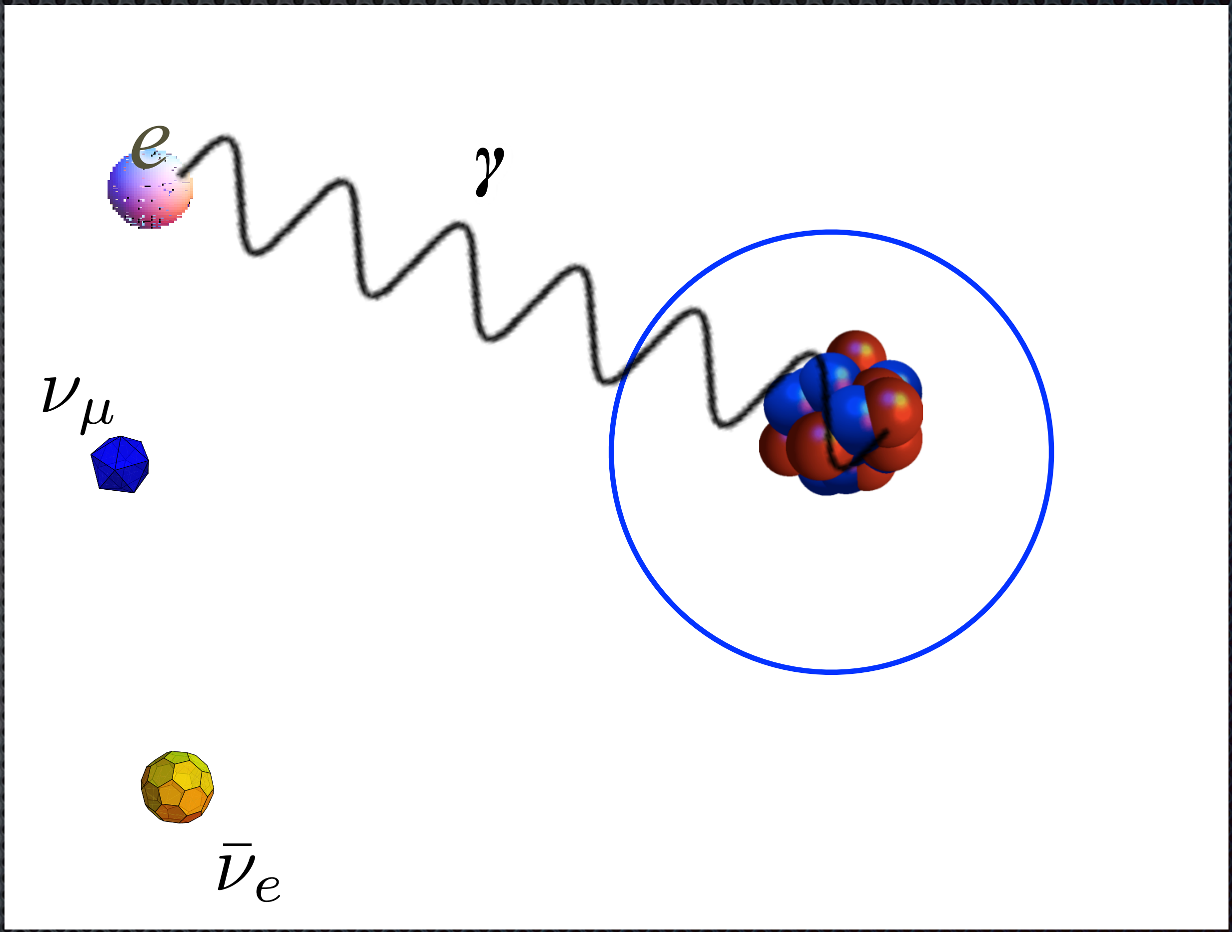

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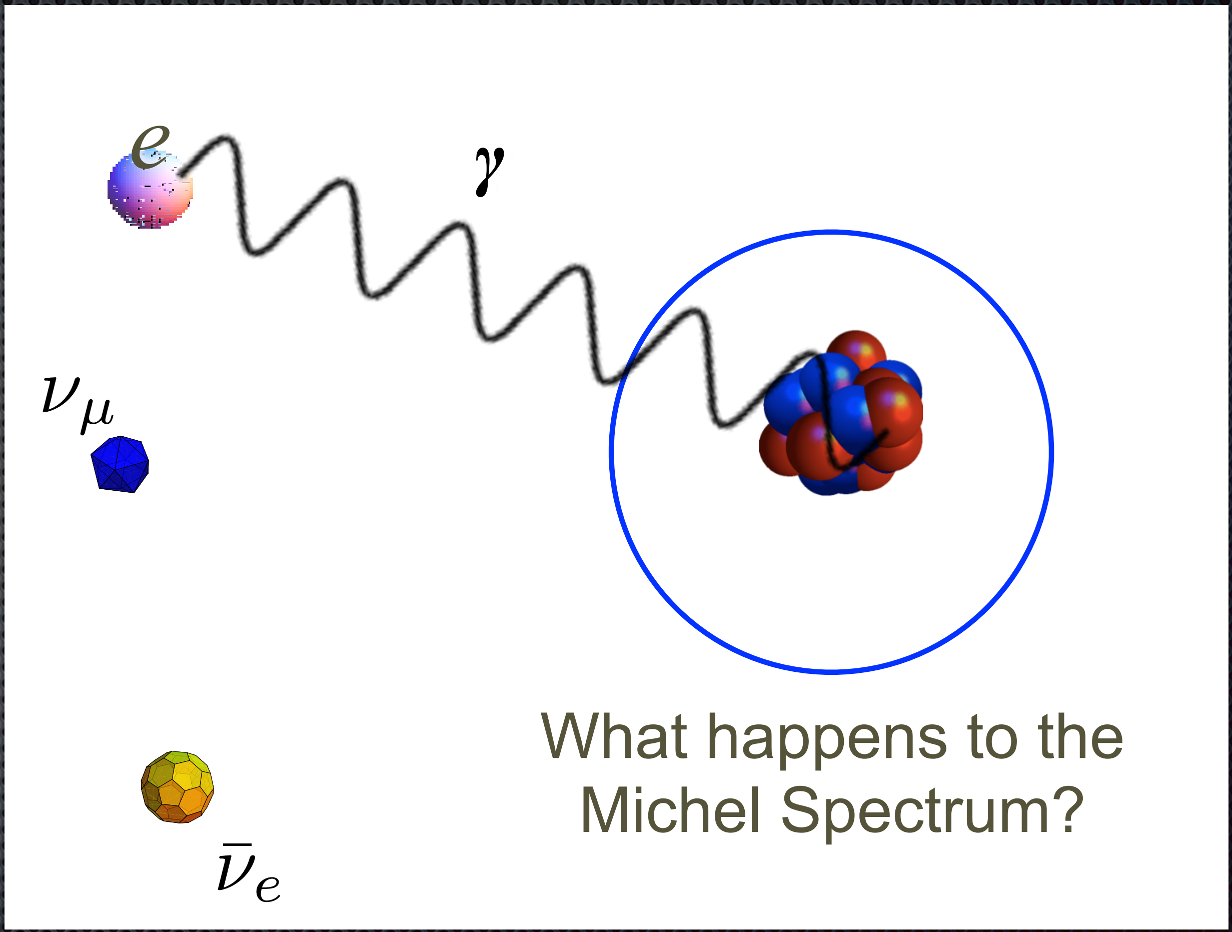
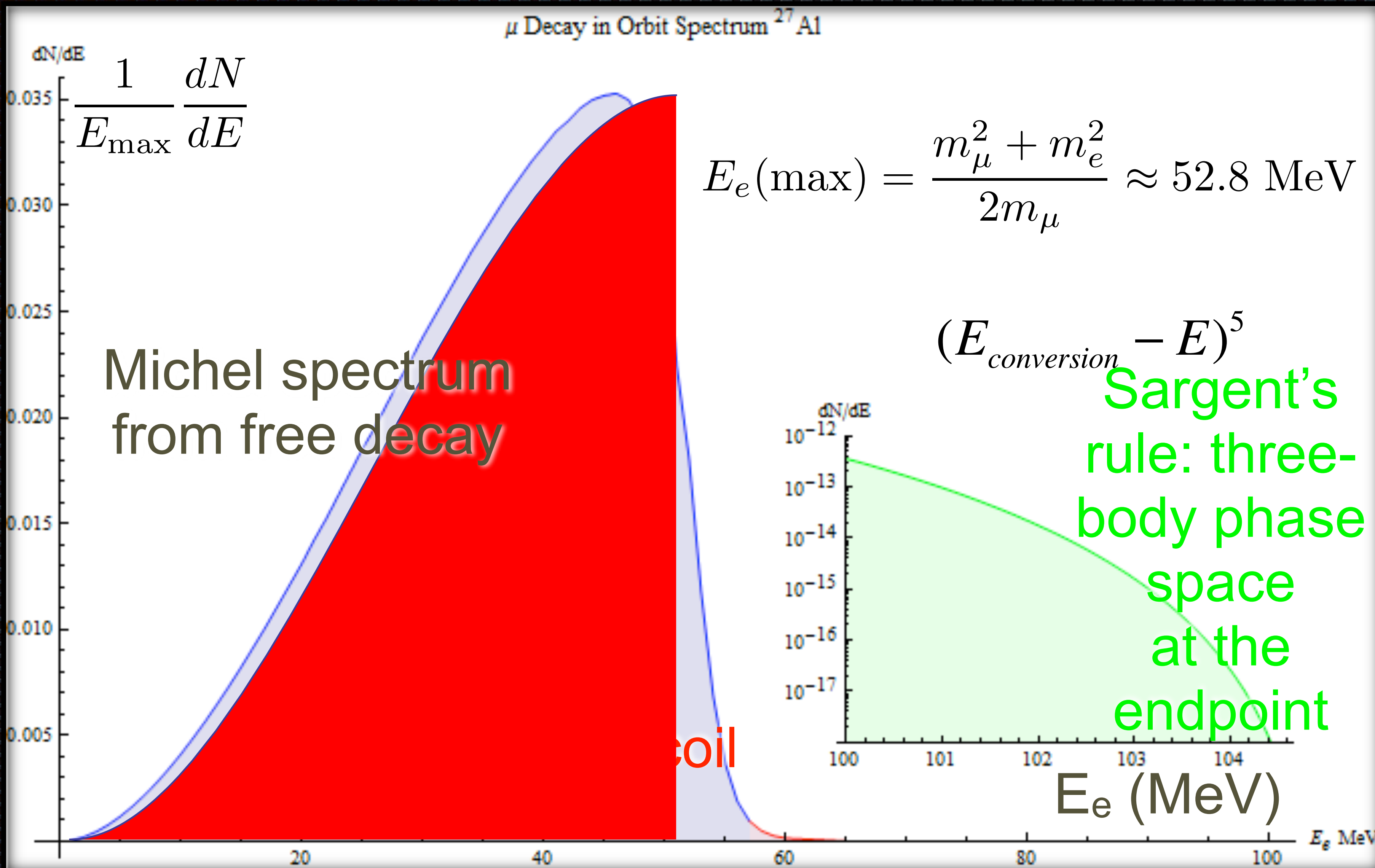


Decay-in-Orbit Shape

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



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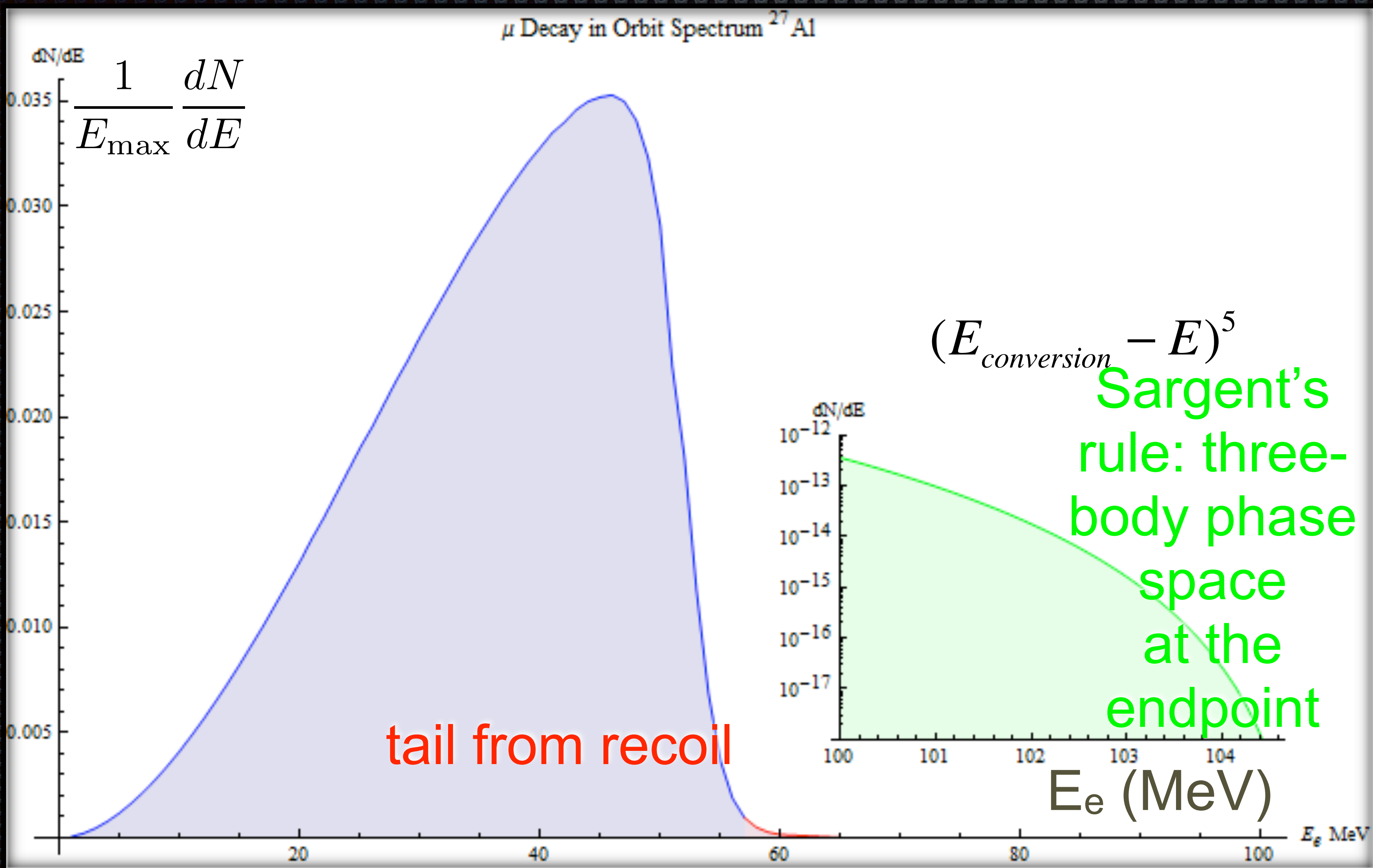


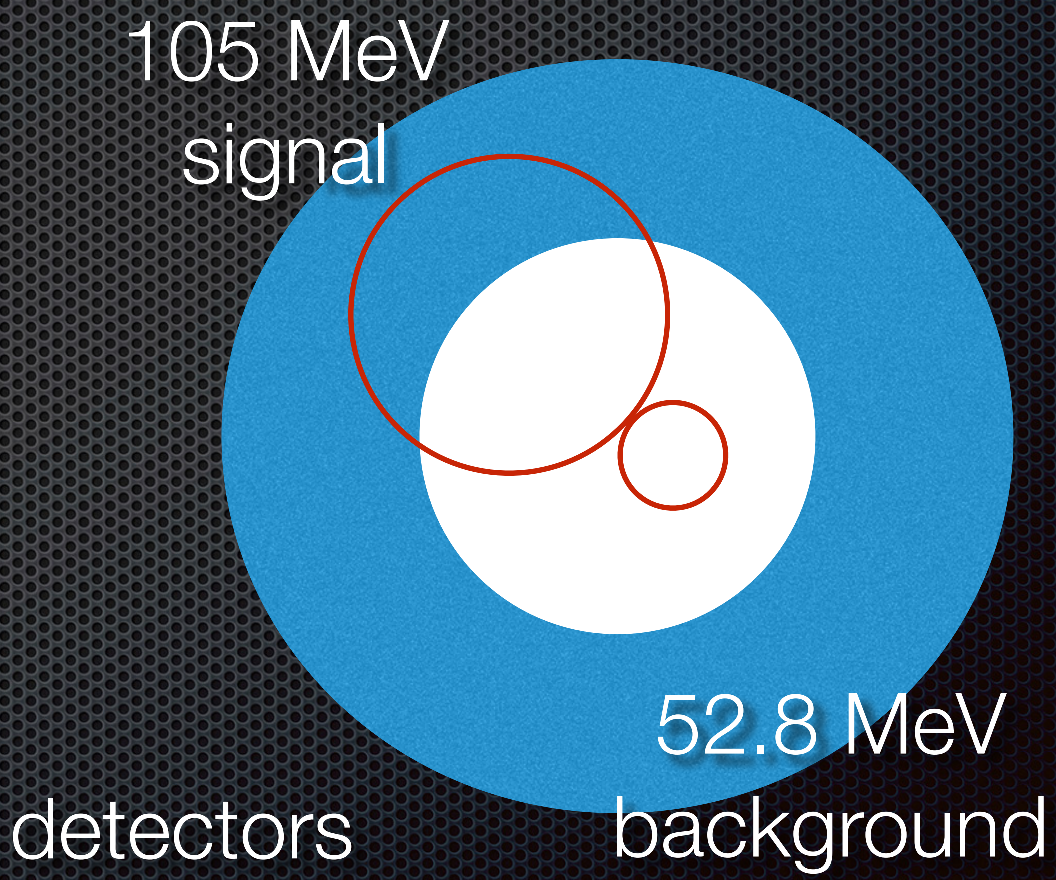
How Do We Suppress DIO?

- Best possible energy resolution: we do not want DIO events near the endpoint resolution smeared upwards and promoted into the signal region, so we are sensitive to both the “gaussian width” and especially to “high side tails”
- We use a solenoidal field and annular detectors
  - p=qBR; p for Michel edge at 52.8 MeV is about 1/2 of conversion energy of 105 MeV.

In pictures

- This design gives us a few 10^5 muons to reconstruct instead of ~ 10^{18} from the distorted DIO spectrum
- Making it possible to have a small DIO background
- See Pasha's talk!

Looking along detector axis



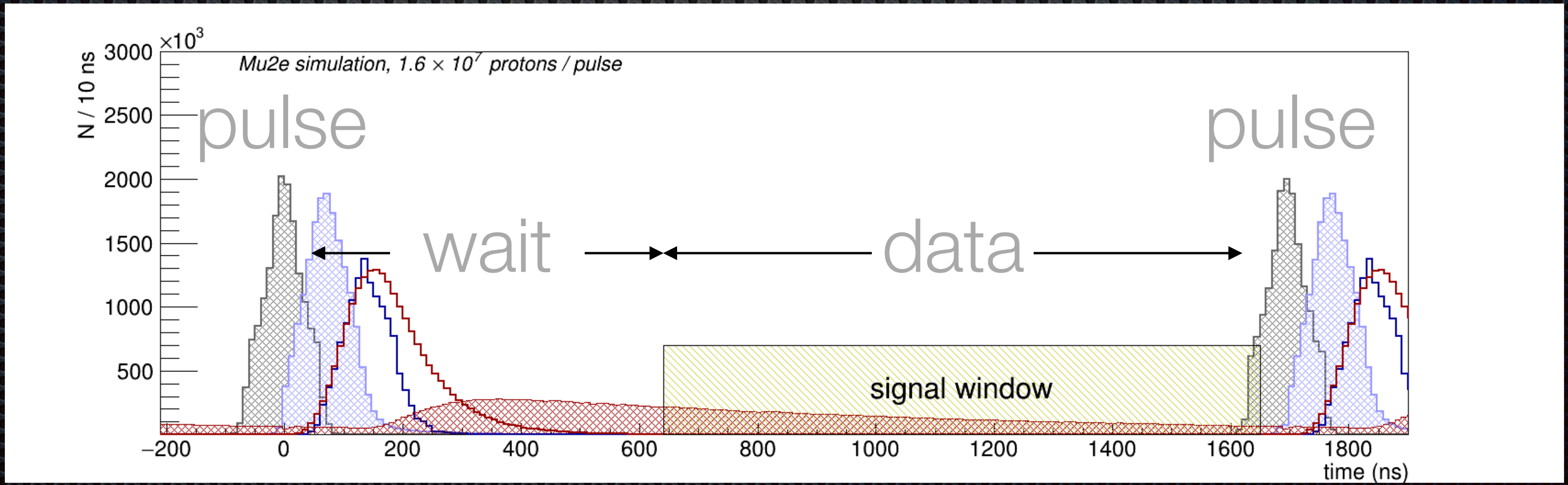
What Is the 2nd Background?

- When protons collide with a target, you make a lot of pions; pions decay into muons, and those are the muons we use
- But some pions live a long time and make it to our Aluminum
  - they can produce a background through “radiative pion capture” (RPC) and sometimes the electron is at the conversion signal energy

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

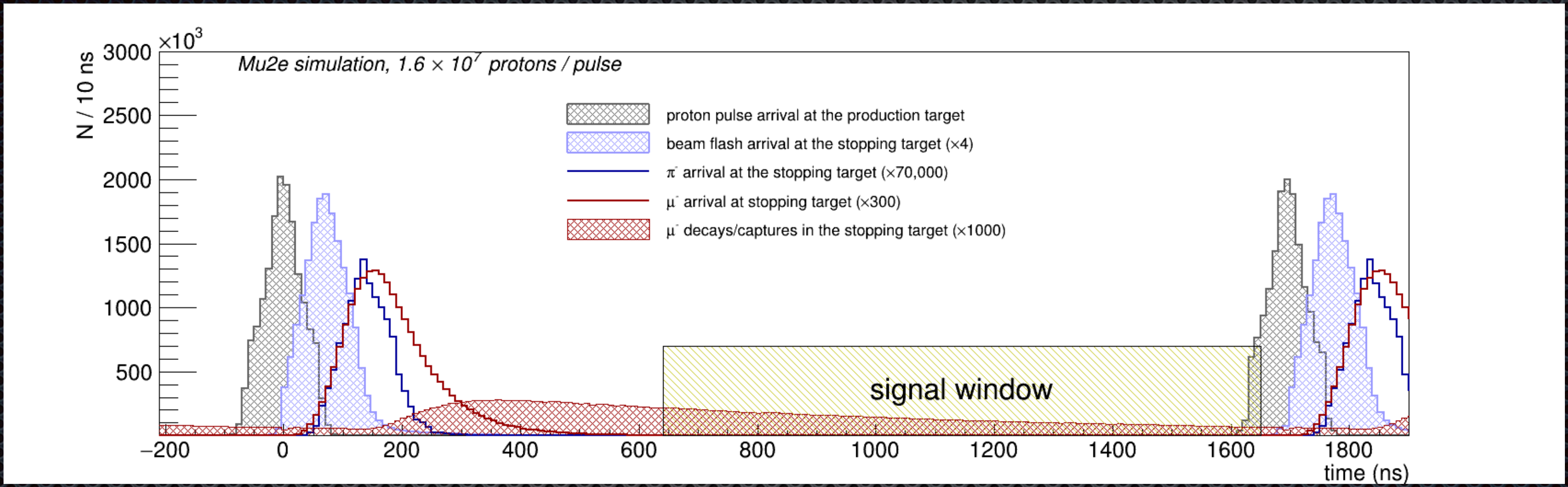
How Do We Suppress RPC?

- With a pulsed beam — this is a key improvement over all previous conversion experiments
  - recall muon lifetime is 2.1 μsec; pion lifetime is 26 nsec
- Pion backgrounds are suppressed by ~ 10^{11} by waiting



Extinction

- When you make a proton pulse, sometimes protons get through outside the pulse



- Late-arriving proton "restarts the clock" and we get a smaller suppression from the pion lifetime

- Extinction is suppressing these protons; need in-time/out of time $< 10^{-10}$

Extinction

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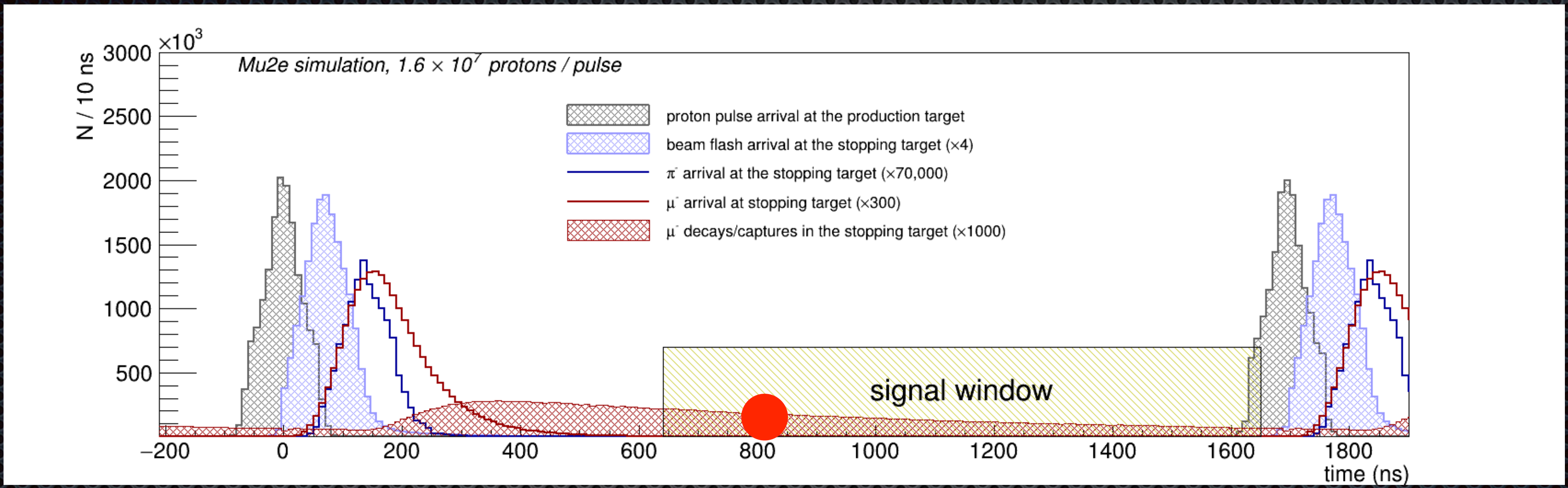

- Late-arriving proton "restarts the clock" and we get a smaller suppression from the pion lifetime

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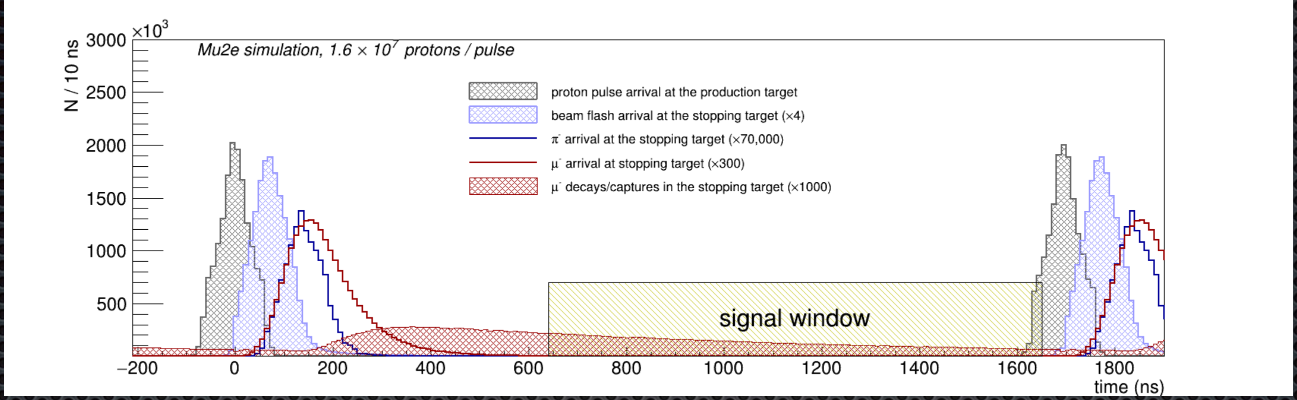
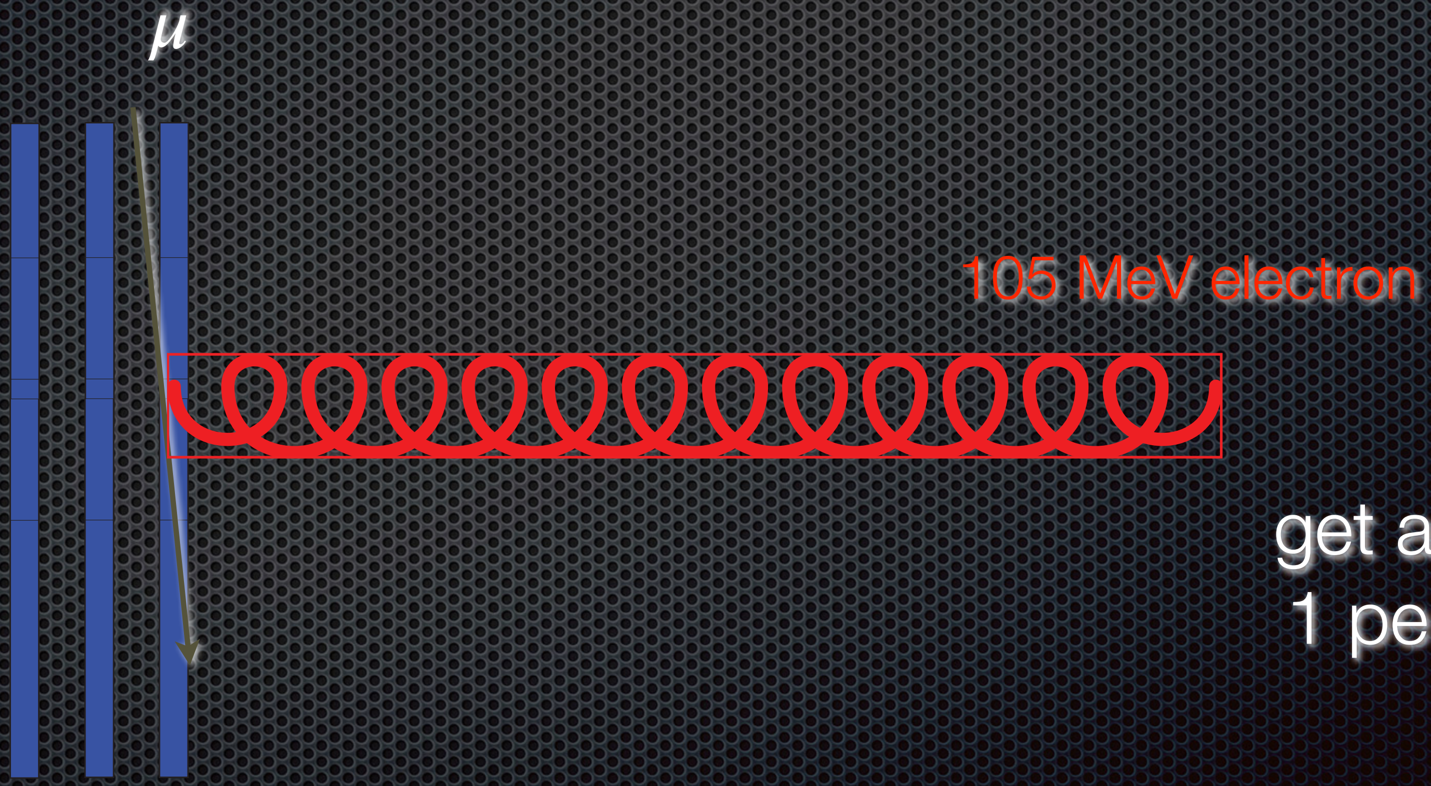
Prompt Background and Choice of Z



Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1	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

Cosmic Ray Veto

- At 10^{-17} there's a lot of rare backgrounds; here's one that is surprising but not too rare



get about
1 per day

Cosmic Ray Veto

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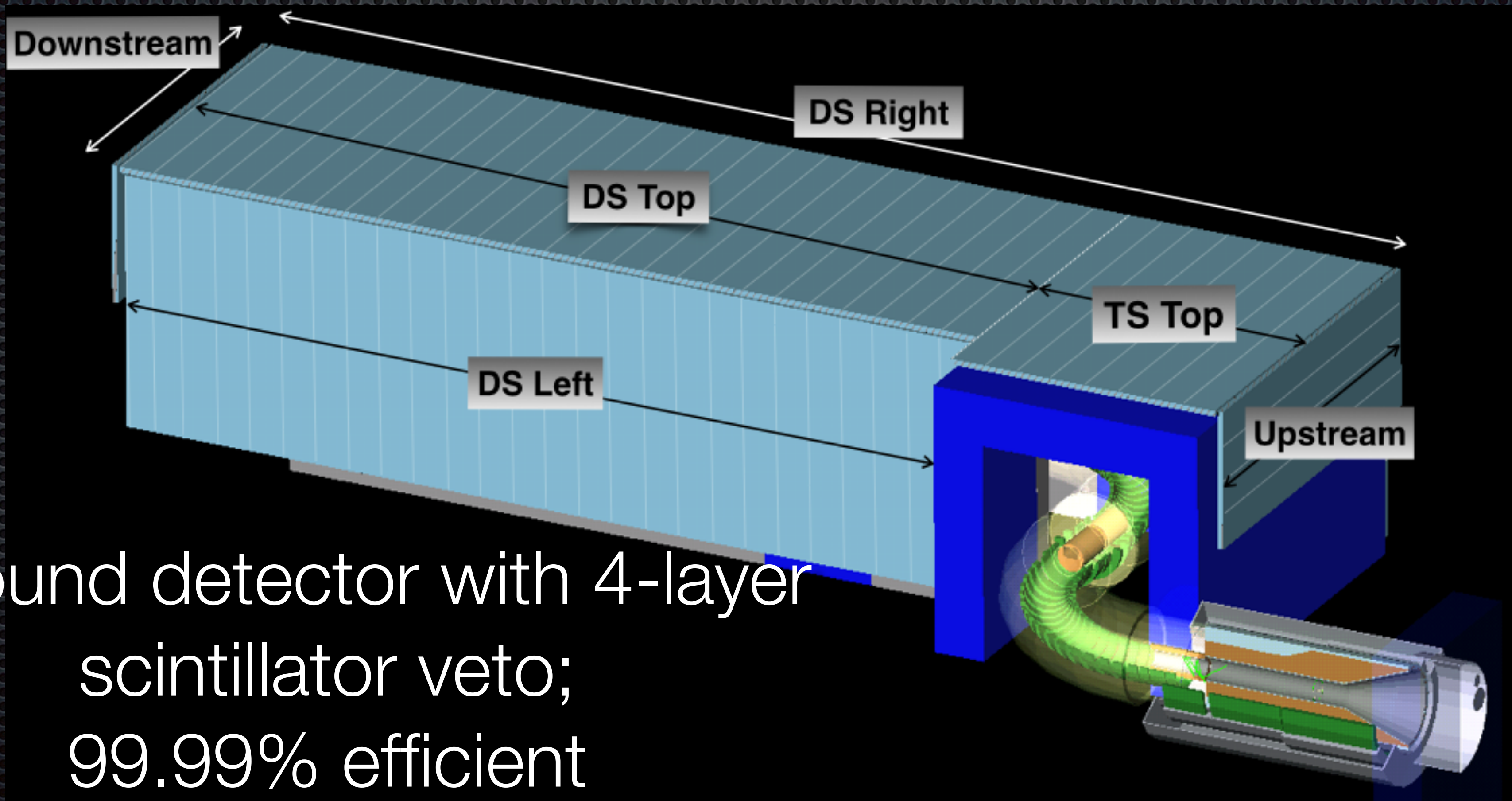


surround detector with 4-layer scintillator veto; 99.99% efficient

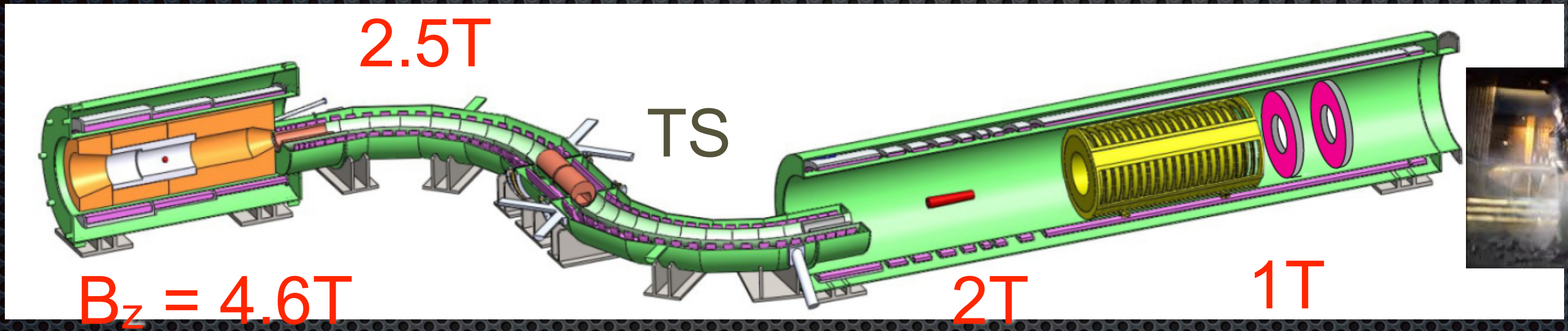
Mu2e Muon Beam: Three Solenoids and Gradient

~ scale, typical physicist at work

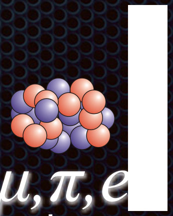
PS

DS

V. Lobashev, MELC 1992:



- 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



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

Mu2e Muon Beam: Three Solenoids and Gradient

~ scale, typical physicist at work

4.6T ⟶ B-field gradient ⟶ 1T

PS

DS

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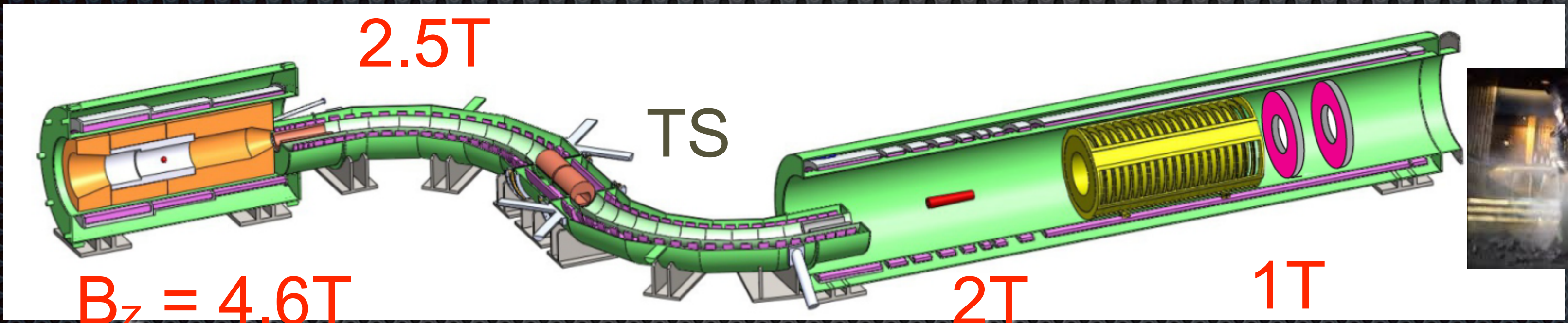

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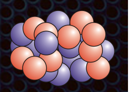

μ, π, e

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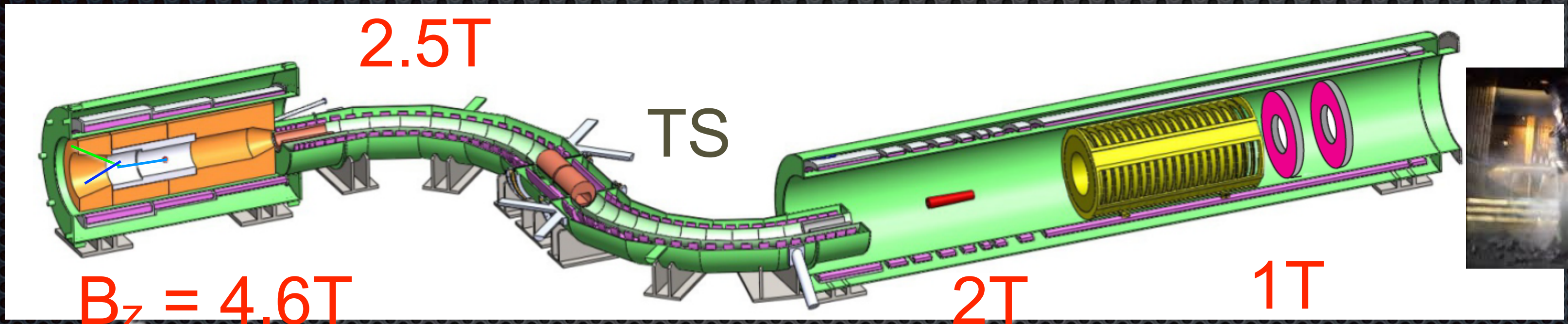

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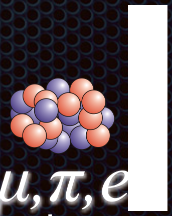

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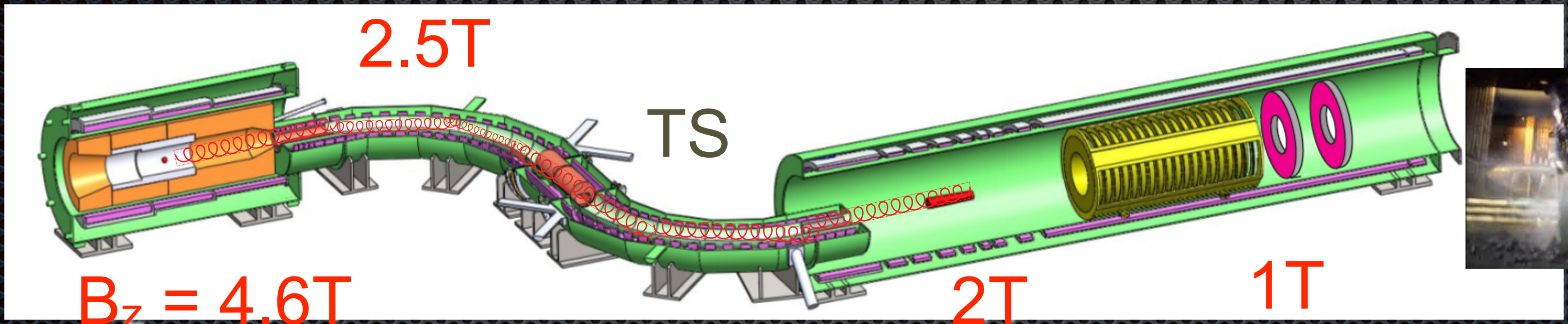

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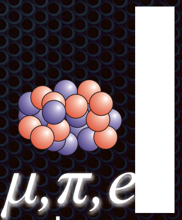

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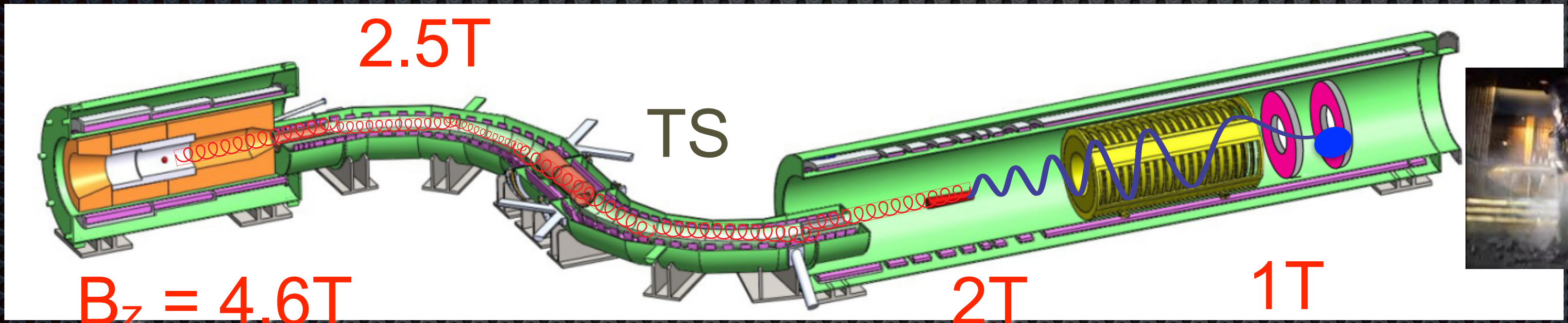
PS **DS**



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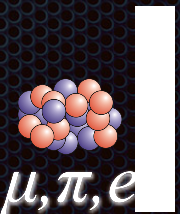
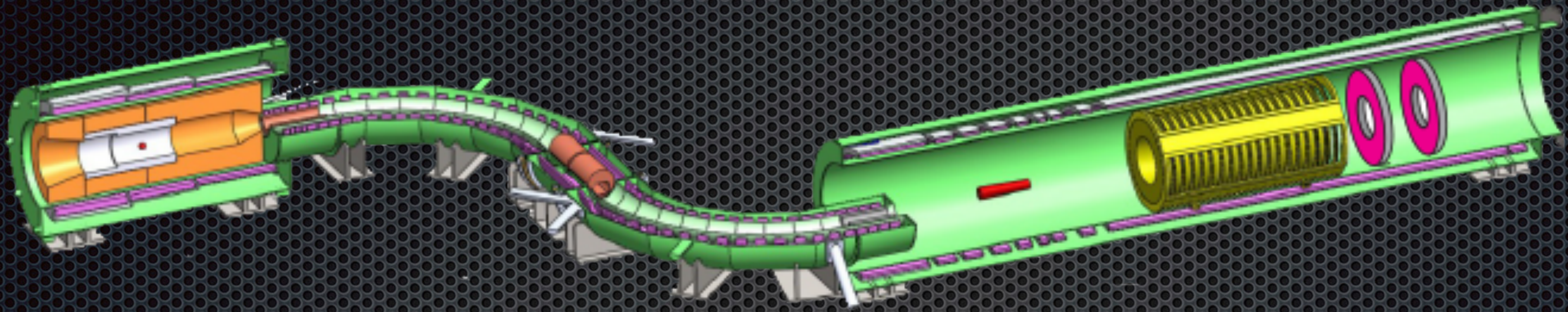


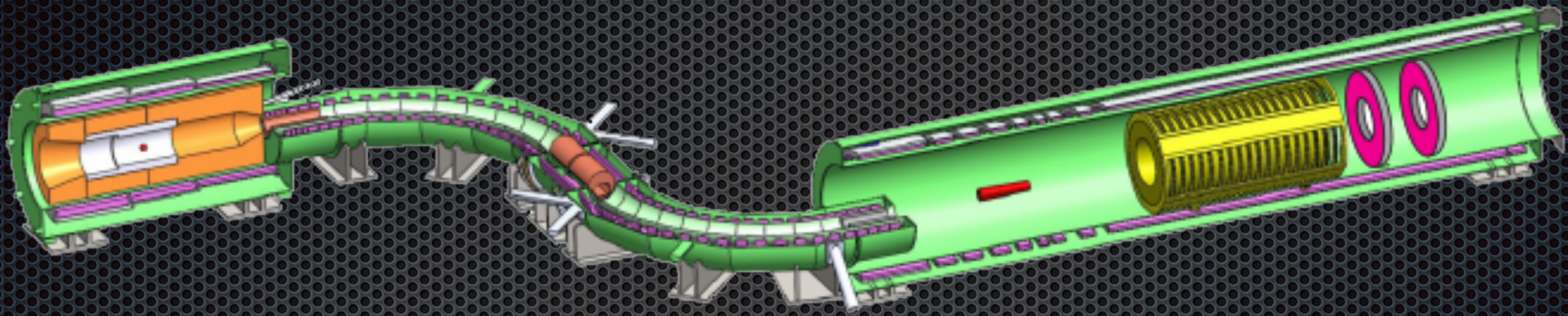
Muon Momentum ~ 50 MeV/c: muons range out in Aluminum

Why is this hard?



- We have 8 kWatts in a superconducting magnet
  - enough heat to make superconductor go normal, so we need complicated cooling and shielding of the superconductor. This is "state of the art"
  - And the protons are pointed away from the detector to keep it from being overwhelmed by debris

What Happens Next?

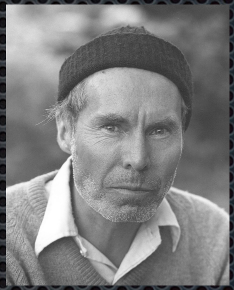


- The muons are in a solenoidal field, $B = B_Z$ more or less
  - in the x-y plane, $p_T = qBR$, so they circle
- But they also have p_L along the z-axis, so they spiral

What's In the Middle?

- Remember we want a negative muon beam so the muons will be captured by the atoms and fall into a 1s state
- But the muons at the production target are both positive and negative
- How Do We Select Negative Muons?

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

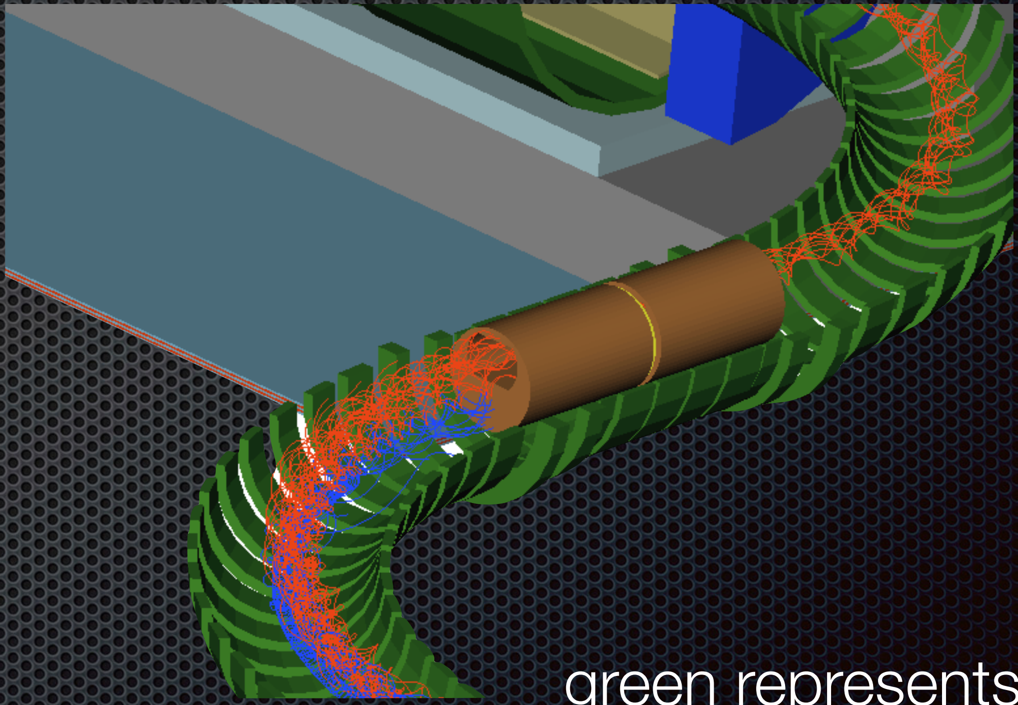
$$\vec{E}_{\text{effective}} = \frac{\gamma m}{e}\frac{\vec{R}}{R^2}\mathrm{v}_{\|}^2$$

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

So This is What Happens:

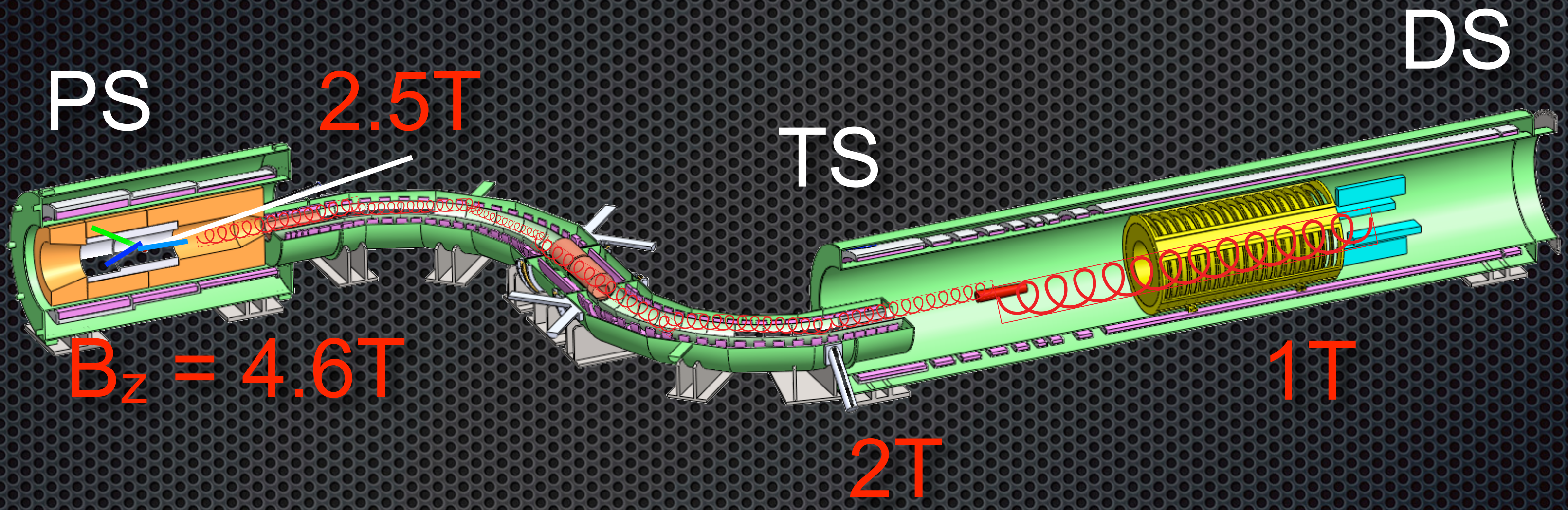
- Negative muons go one way, positive muons the other
- A rotatable collimator lets us pick one charge or the other
- And the 2nd half of the "S" brings the beam back on axis

13 m along the axis, 25 cm across



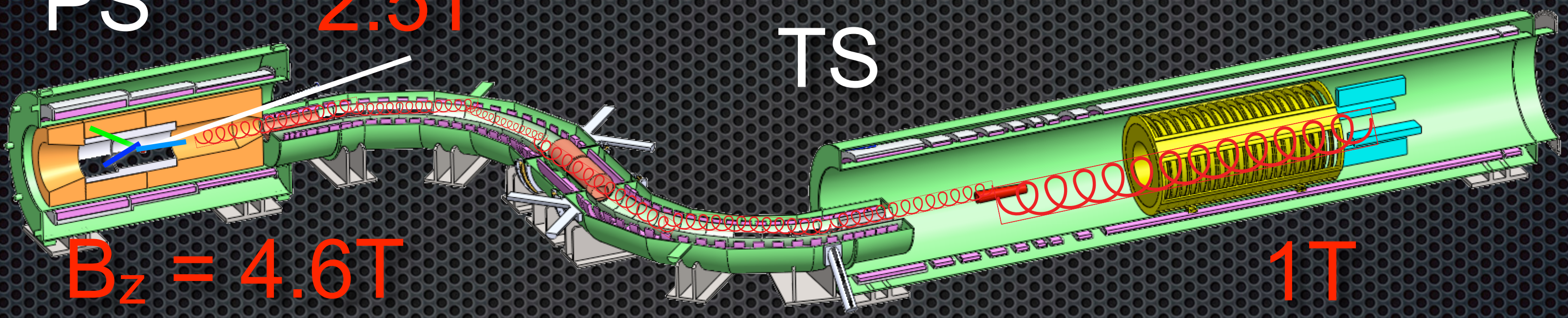
green represents the coils of superconducting cable

Why is the electron spiral bigger?



- The muons had momentum 40 MeV/c; the signal electron has momentum 105 MeV/c
- Now apply p = qBR to get the big spiral

Why Is The Field Graded?



- If the field were constant, particles could become "trapped" and just circle around; this leads to backgrounds
- The dB/ds <0 (graded) field tends to "push" particles in the region of lower field, moving them along.

An even better reason...

- The electron in a conversion travels out isotropically, since there's no preferred direction
- Half travel *away* from the detector and would be lost ☹
- But the gradient, which we need to send particles toward the detector anyway, gets them back!

How? A Magnetic Mirror

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

$$Ba^2$$

$$p_{\perp}^2 / B$$

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

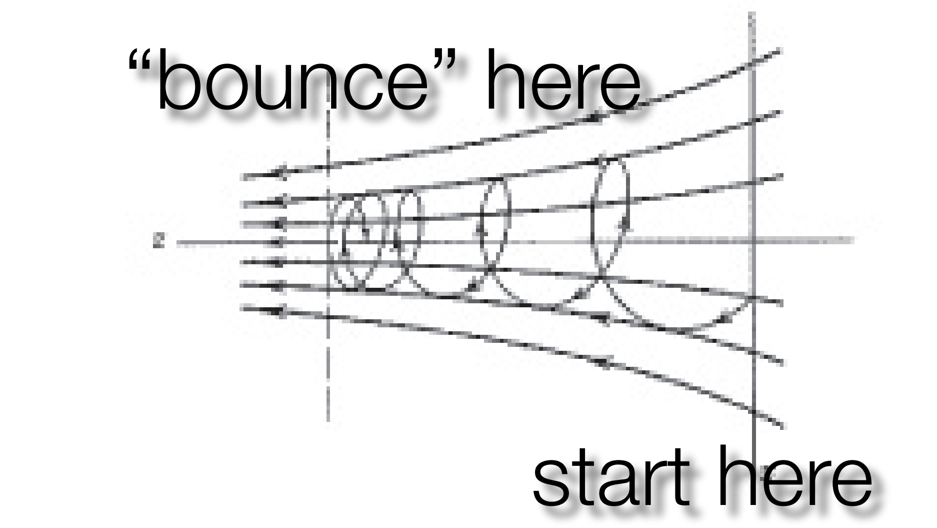
are adiabatic invariants

Therefore

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

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

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



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

What Does A Solenoid Really Look Like?

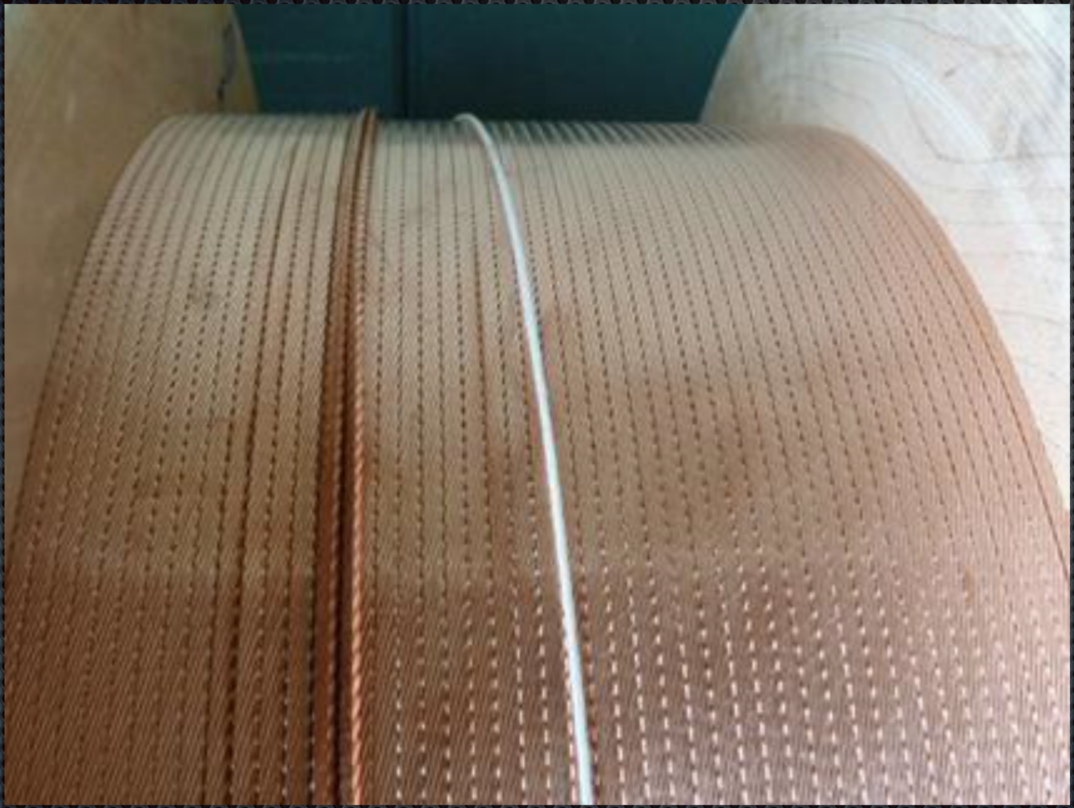
- Start with conductor, held in place by Al

R.Bernstein /Fermilab

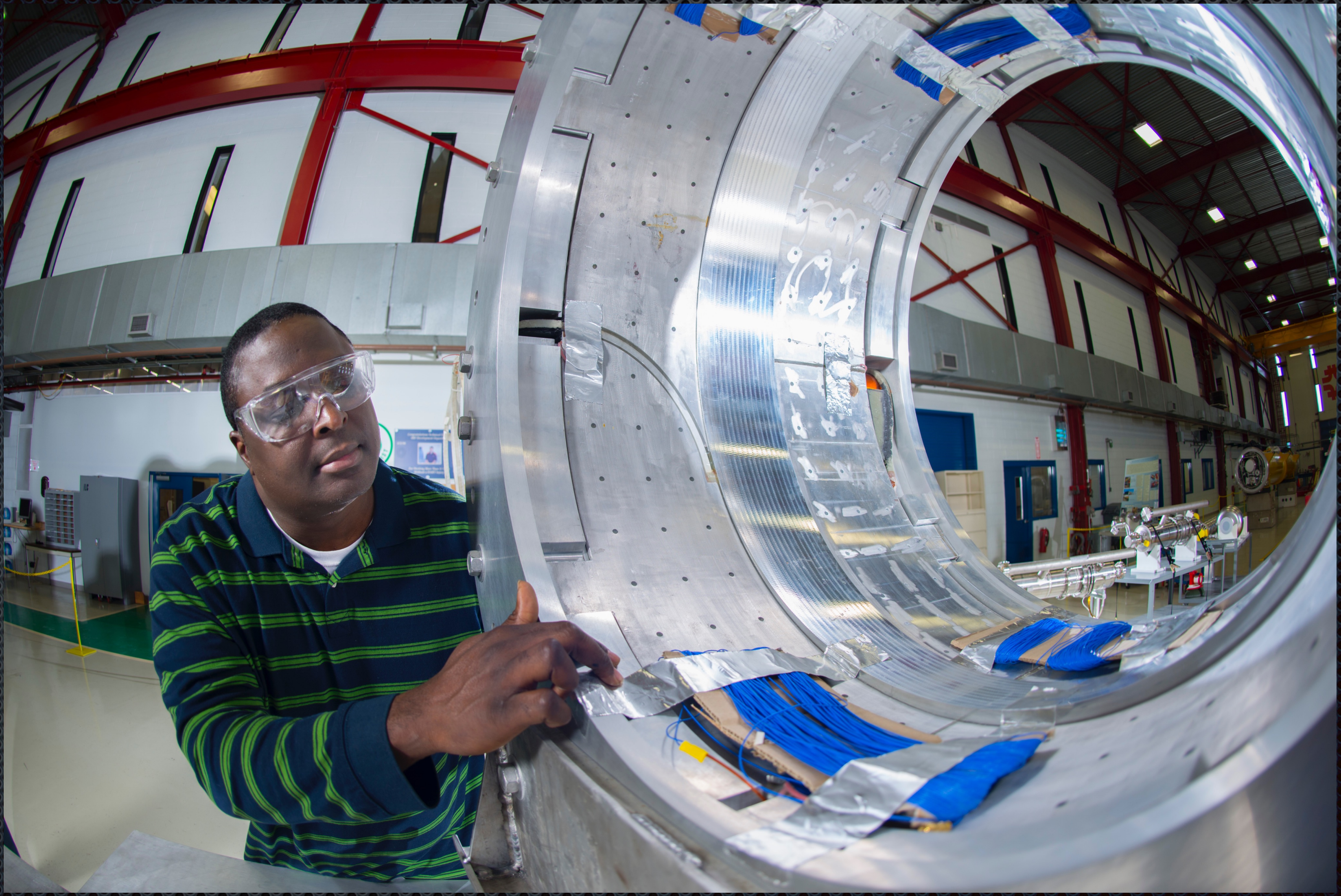
Mu2e

Then

- Wind it into about 75 km (45 miles) of cable, all in custom-designed sections and lengths

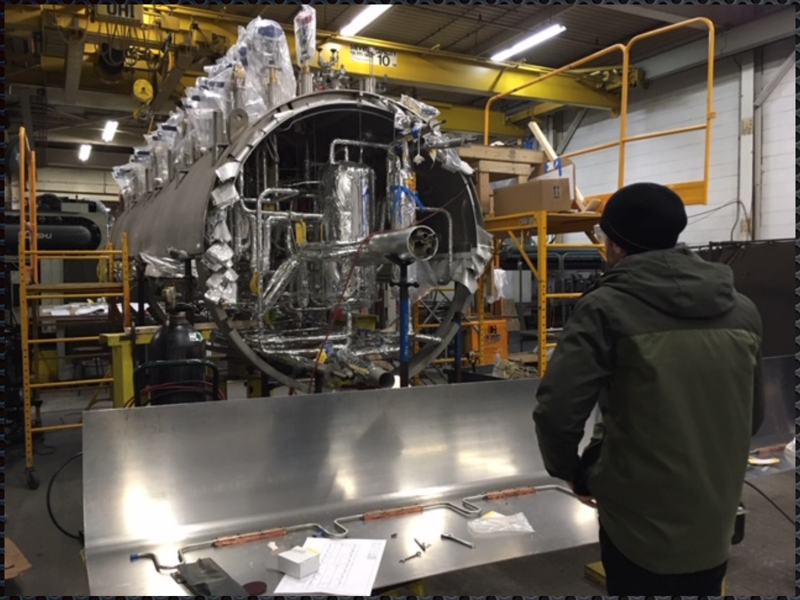


Wind into Coils

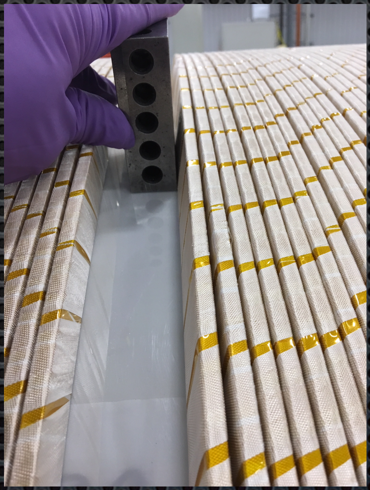


Production Solenoid

- Winding coils is non-trivial!



cryogenics distribution



Heat and Radiation Shield

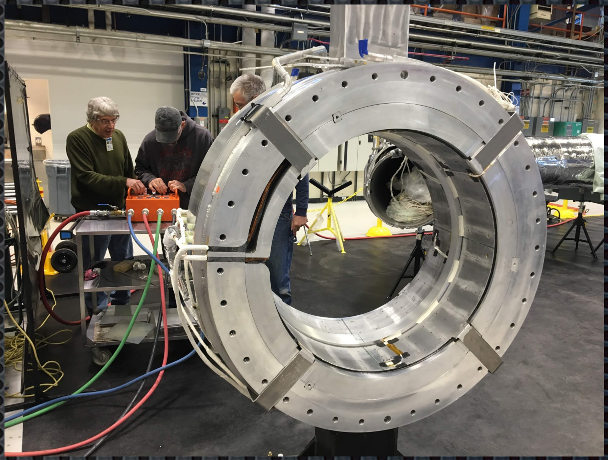
- Fits inside Production Solenoid
- Protects it from 8 kW of beam
- Delivered!

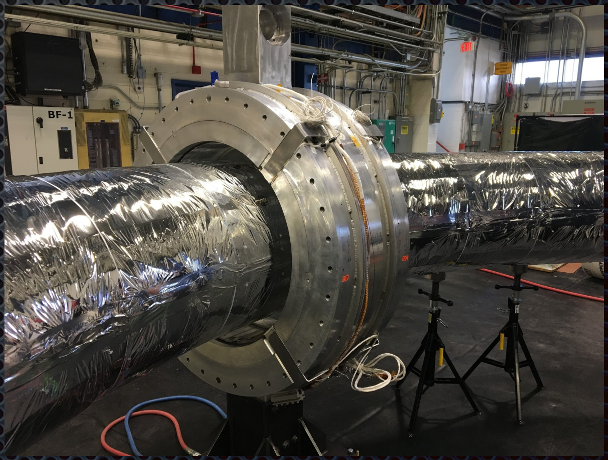
this is where proton beam enters

Transport Solenoid

- Upstream side complete and modules under test (downstream started)

Cold mass assembly at Fermilab

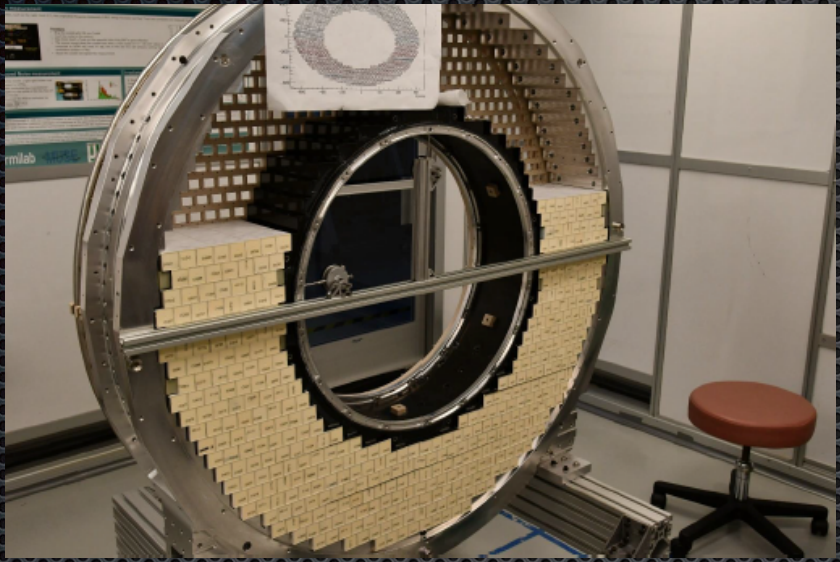


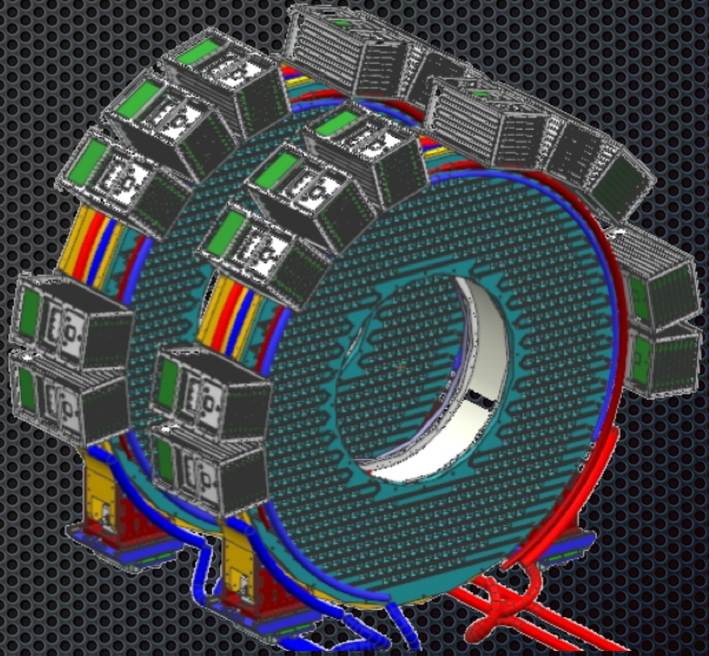


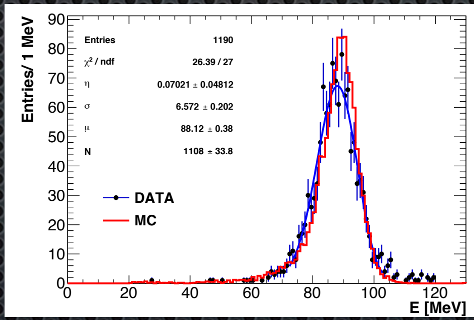
- First test unit assembled on warm bore; alignment ongoing

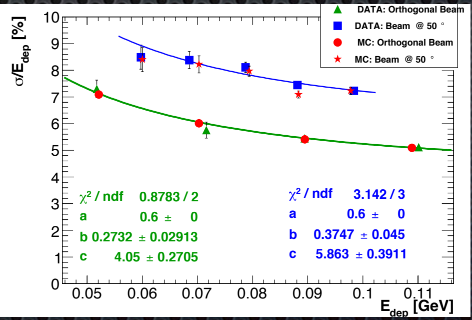
Calorimeter R&D/Construction

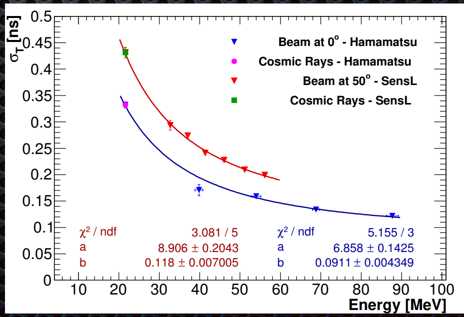
- Probably the best run system on the experiment (and by INFN)
- See Ivano's talk











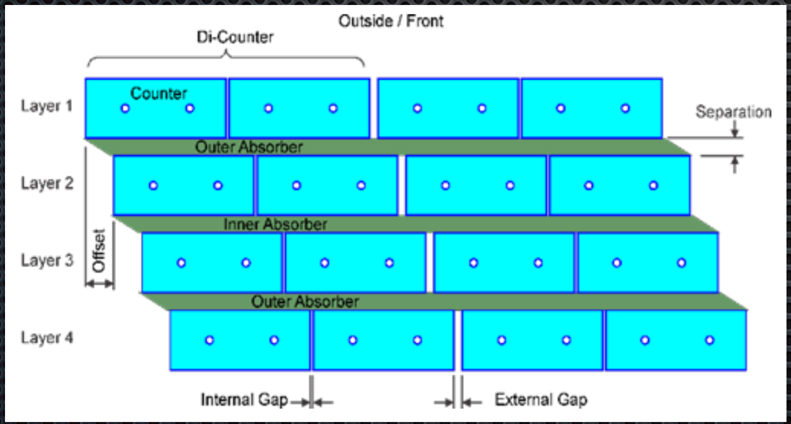
51 crystal prototype tested at Frascati

students needed here! we are testing light yield of modules

Cosmic Ray Veto

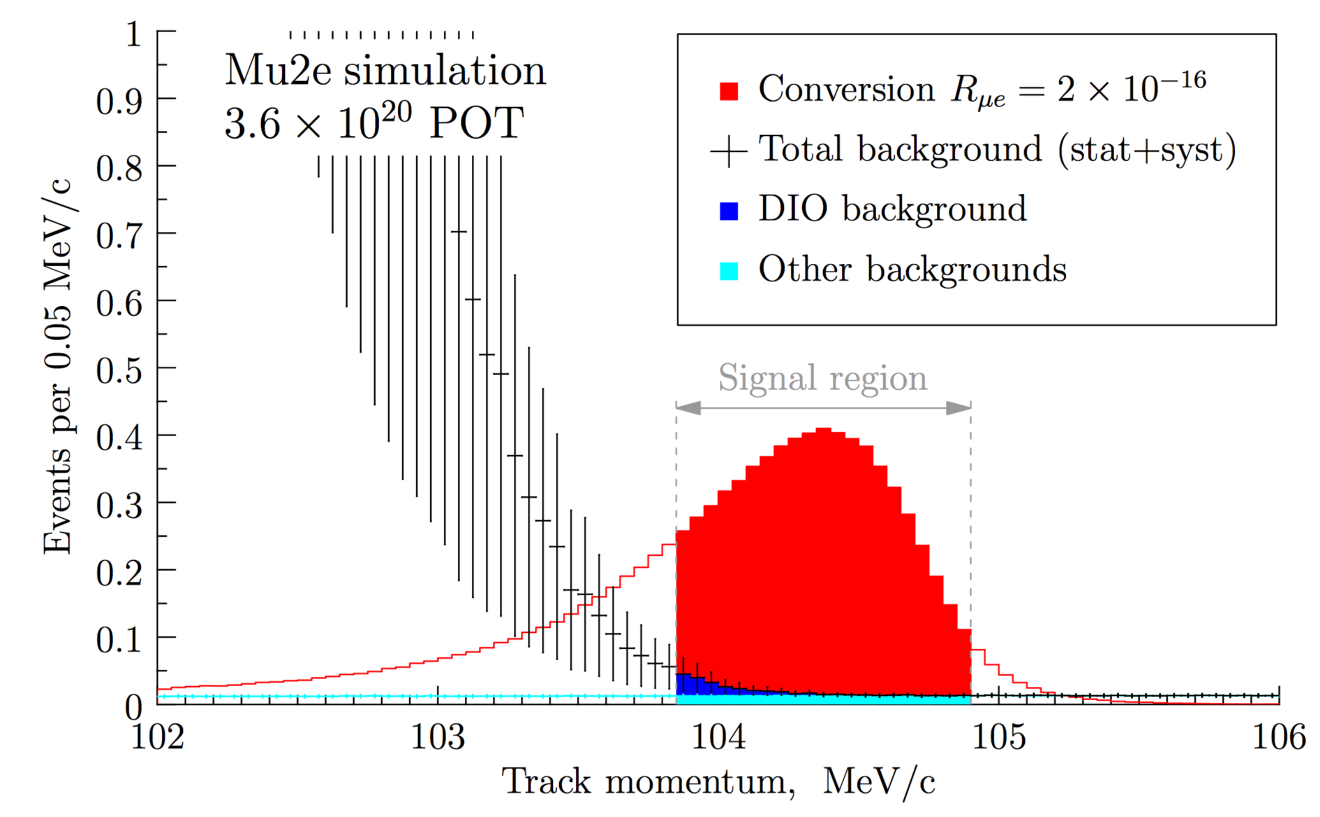
- Modules now at FNAL

- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards



Expected Reach

- 90% CL ~ 8 X 10^{-17}; 5σ ~ 2.5 X 10^{-16} (7.5 events)



Schedule

students have a lot they could do!

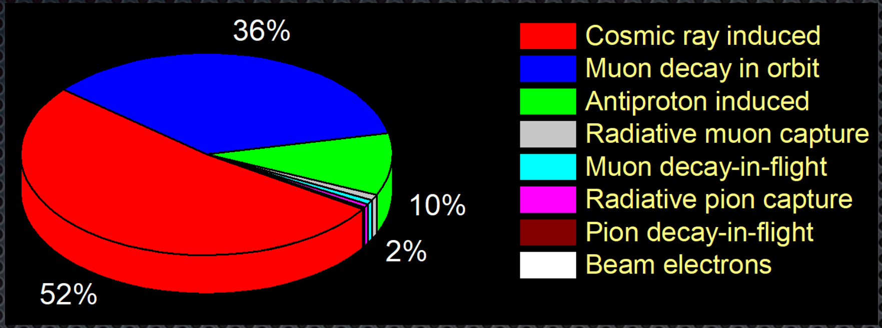
Commission Beamline	2023-2024
Commission Detector	2024
First Data-Taking	2025
Finish Data Taking	end of decade

Conclusions

- Mu2e will either:
  - *Reduce the limit for $R_{\mu e}$ by four orders of magnitude ($R_{\mu e}$ <8x10^{-17} @ 90% C.L.)*
  - *Discover unambiguous proof of Beyond Standard Model physics and*
  - *Provide important information either complementing LHC results or probing up to 10^4 TeV mass scales*
- We are examining upgrades to go another order of magnitude or study a signal


QUESTIONS
FOUND IN GOOGLE AUTOCOMPLETE
WHY DO WHALES JUMP
WHY ARE WITCHES GREEN
WHY ARE THERE MIRRORS ABOVE BEDS
WHY DO I SAY UH
WHY IS SEA SALT BETTER
WHY ARE THERE TREES IN THE MIDDLE OF FIELDS
WHY IS THERE NOT A POKEMON MMO
WHY IS THERE LAUGHING IN TV SHOWS
WHY ARE THERE DOORS ON THE FREEWAY
WHY ARE THERE SO MANY SVCHOST.EXE RUNNING
WHY AREN'T THERE ANY COUNTRIES IN ANTARCTICA
WHY ARE THERE SCARY SOUNDS IN MINECRAFT
WHY IS THERE KICKING IN MY STOMACH
WHY ARE THERE TWO SLASHES AFTER HTTP
WHY ARE THERE CELEBRITIES
WHY DO SNAKES EXIST
WHY DO OYSTERS HAVE PEARLS
WHY ARE DUCKS CALLED DUCKS
WHY DO THEY CALL IT THE CLAP
WHY ARE KYLE AND CARTMAN FRIENDS
WHY IS THERE AN ARROW ON AANG'S HEAD
WHY ARE TEXT MESSAGES BLUE
WHY ARE THERE MUSTACHES ON CLOTHES
WHY ARE THERE MUSTACHES ON CARS
WHY ARE THERE MUSTACHES EVERYWHERE
WHY ARE THERE SO MANY BIRDS IN OHIO
WHY IS THERE SO MUCH RAIN IN OHIO
WHY IS OHIO WEATHER SO WEIRD
WHY AREN'T THERE DINOSAUR GHOSTS
WHY DO IGUANAS DIE
WHY DO TESTICLES MOVE
WHY ARE THERE PSYCHICS
WHY ARE HATS SO EXPENSIVE
WHY IS THERE CAFFEINE IN MY SHAMPOO
WHY DO YOUR BOOBS HURT
WHY ARE THERE SLAVES IN THE BIBLE
WHY DO TWINS HAVE DIFFERENT FINGERPRINTS
WHY ARE AMERICANS AFRAID OF DRAGONS
WHY IS YKK ON ALL ZIPPERS
WHY IS HTTPS CROSSED OUT IN RED
WHY IS THERE A LINE THROUGH HTTPS
WHY IS THERE A RED LINE THROUGH HTTPS ON FACEBOOK
WHY IS HTTPS IMPORTANT
WHY AREN'T MY ARMS GROWING
WHY ARE THERE WEEKS
WHY DO I FEEL DIZZY
WHY IS THERE PHLEGM
WHY ARE THERE SO MANY CROWS IN ROCHESTER, MN
WHY AREN'T ECONOMISTS RICH
WHY DO AMERICANS CALL IT SOCCER
WHY ARE MY EARS RINGING
WHY ARE THERE SO MANY AVENGERS
WHY ARE THE AVENGERS FIGHTING THE X MEN
WHY IS WOLVERINE NOT IN THE AVENGERS
WHY IS THERE LAVA
WHY IS PSYCHIC WEAK TO BUG
WHY DO CHILDREN GET CANCER
WHY IS POSEIDON ANGRY WITH ODYSSEUS
WHY IS THERE ICE IN SPACE
WHY ARE THERE ANTS IN MY LAPTOP
WHY IS THERE NO KING IN ENGLAND
WHY ARE DOGS AFRAID OF FIREWORKS
WHY IS EARTH TILTED
WHY IS SPACE BLACK
WHY IS OUTER SPACE SO COLD
WHY ARE THERE PYRAMIDS ON THE MOON
WHY IS NASA SHUTTING DOWN
WHY ARE THERE GHOSTS
WHY ARE THERE FEMALE MR MIMES
WHY IS THERE AN OWL IN MY BACKYARD
WHY IS THERE AN OWL OUTSIDE MY WINDOW
WHY IS THERE AN OWL ON THE DOLLAR BILL
WHY DO OWLS ATTACK PEOPLE
WHY ARE AK 47s SO EXPENSIVE
WHY ARE THERE HELICOPTERS CIRCLING MY HOUSE
WHY ARE THERE GODS
WHY ARE THERE TWO SPOCKS
WHY ARE MY BOOBS ITCHY
WHY ARE CIGARETTES LEGAL
WHY ARE THERE DUCKS IN MY POOL
WHY IS JESUS WHITE
WHY IS THERE LIQUID IN MY EAR
WHY DO Q TIPS FEEL GOOD
WHY DO GOOD PEOPLE DIE
WHY IS LIFE SO BORING
WHY ARE THERE MALE AND FEMALE BIKES
WHY ARE THERE BRIDESMAIDS
WHY DO DYING PEOPLE REACH UP
WHY AREN'T THERE VARICOSE ARTERIES
WHY ARE OLD KLINGONS DIFFERENT
WHY ARE THERE SQUIRRELS
WHY IS THERE HELL IF GOD FORGIVES
WHY ARE THERE TINY SPIDERS IN MY HOUSE
WHY DO SPIDERS COME INSIDE
WHY ARE THERE HUGE SPIDERS IN MY HOUSE
WHY ARE THERE LOTS OF SPIDERS IN MY HOUSE
WHY ARE THERE SPIDERS IN MY ROOM
WHY ARE THERE SO MANY SPIDERS IN MY ROOM
WHY DO SPIDER BITES ITCH
WHY IS DYING SO SCARY
WHY IS MT VESUVIUS THERE
WHY DO THEY SAY T MINUS
WHY ARE THERE OBELISKS
WHY ARE WRESTLERS ALWAYS WET
WHY ARE OCEANS BECOMING MORE ACIDIC
WHY IS ARWEN DYING
WHY AREN'T MY QUAIL LAYING EGGS
WHY AREN'T MY QUAIL EGGS HATCHING
WHY AREN'T THERE ANY FOREIGN MILITARY BASES IN AMERICA
WHY AREN'T THERE GUNS IN HARRY POTTER
WHY ARE ULTRASOUNDS IMPORTANT
WHY ARE ULTRASOUND MACHINES EXPENSIVE
WHY IS STEALING WRONG
WHY IS PROGRAMMING SO HARD
WHY IS THERE A 0 OHM RESISTOR
WHY DO AMERICANS HATE SOCCER
WHY DO RHYMES SOUND GOOD
WHY DO TREES DIE
WHY IS THERE NO SOUND ON CNN
WHY AREN'T POKEMON REAL
WHY AREN'T BULLETS SHARP
WHY DO DREAMS SEEM SO REAL
WHY IS THERE NO GPS IN LAPTOPS
WHY DO KNEES CLICK
WHY AREN'T THERE E GRADES
WHY IS ISOLATION BAD
WHY DO BOYS LIKE ME
WHY DON'T BOYS LIKE ME
WHY IS THERE ALWAYS A JAVA UPDATE
WHY ARE THERE RED DOTS ON MY THIGHS
WHY IS LYING GOOD
WHY IS GPS FREE
WHY IS SEX SO IMPORTANT

Background Estimates



Craig D.!

Process	Expected Number
Cosmic Ray Muons	$0.21 \pm 0.02 \pm 0.06$
DIO	$0.14 \pm 0.03 \pm 0.11$
Antiprotons	$0.04 \pm 0.001 \pm 0.020$
RPC	$0.021 \pm 0.001 \pm 0.002$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam Electrons	$2.1 \pm 1.0 \times 10^{-4}$
Total	0.41 ± 0.03

BACKUPS

Choice of Stopping Material: rate vs wait

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics (more later)
- Why start with Al?

V. Cirigliano et al., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

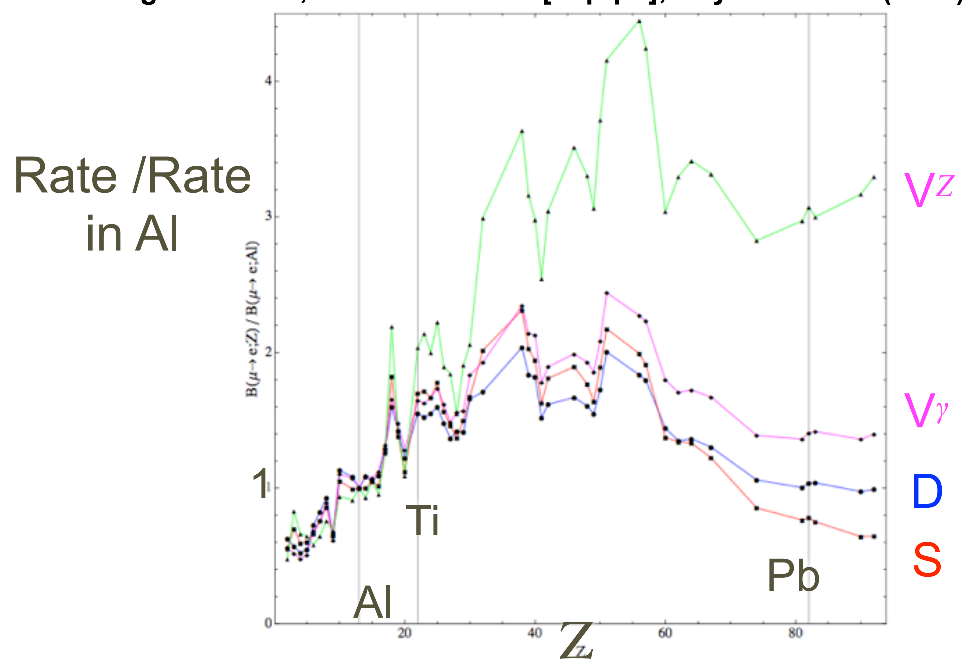


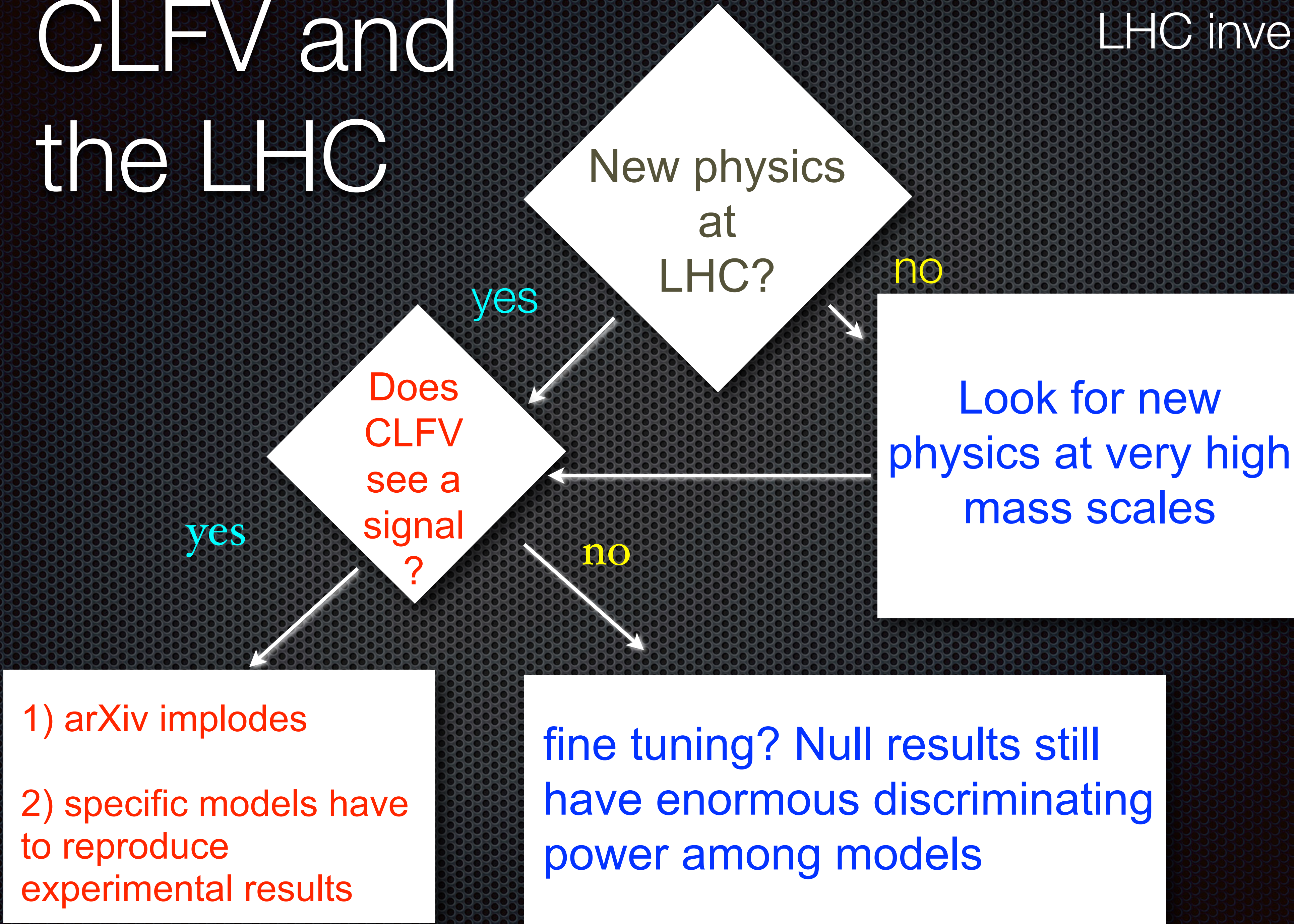
Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

Mu2e Upgrades

- Next Step in CLFV program

CLFV and the LHC

LHC inverse



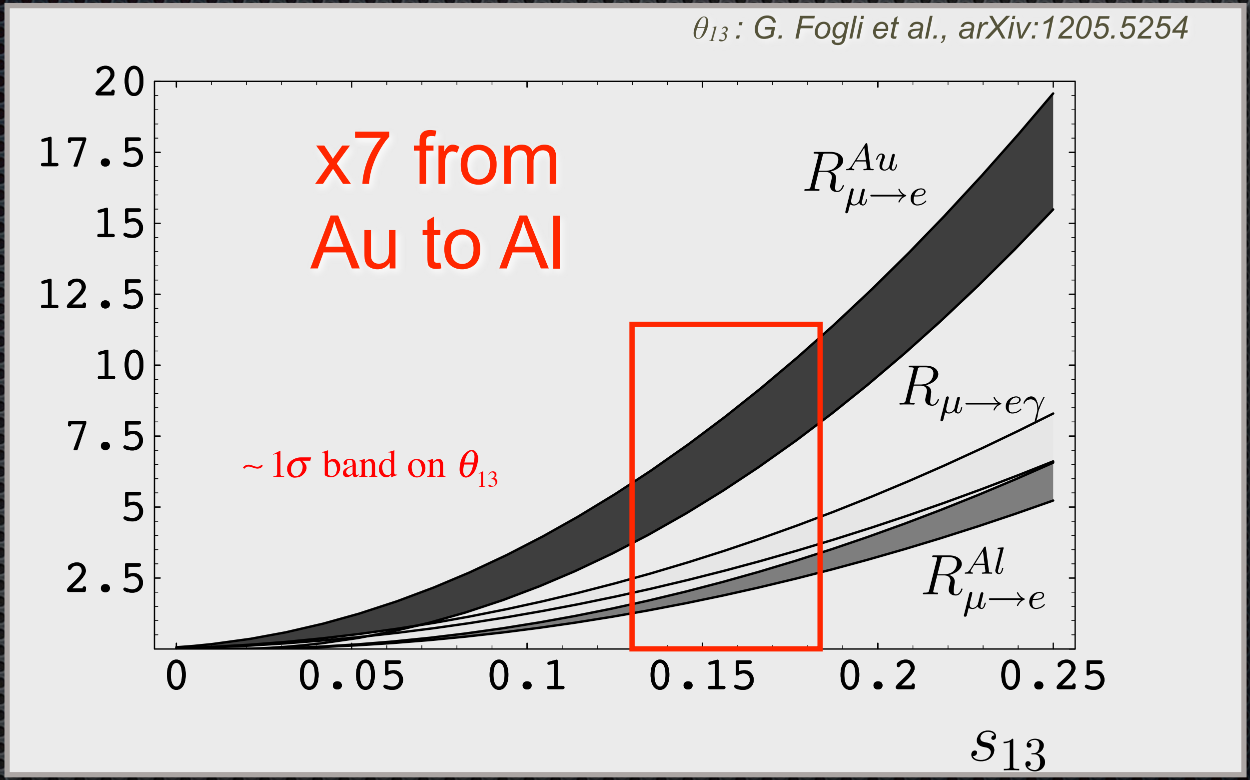
Studying a Signal

- *Vary Z to probe new physics*

FNAL Upgrades and new beams!

Studying a Signal

- *Vary Z to probe new physics*



V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005

FNAL Upgrades and new beams!

Tracker resolution

- A high-side tail promotes DIO into signal region
- Can only understand this tail with measurements, which is why we measure straw properties and perform a "first-principles" simulation