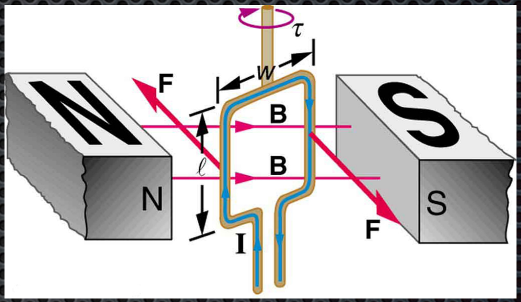
Part 2: g-2 and CLFV

g-2 and Muon Magnetic Moment

- Magnetic Field exerts torque on magnetic moment, causing spin to precess

$$\vec{\Gamma} = \vec{\mu} \times \vec{B} = \gamma \vec{J} \times \vec{B}; \quad \omega = -\gamma B$$

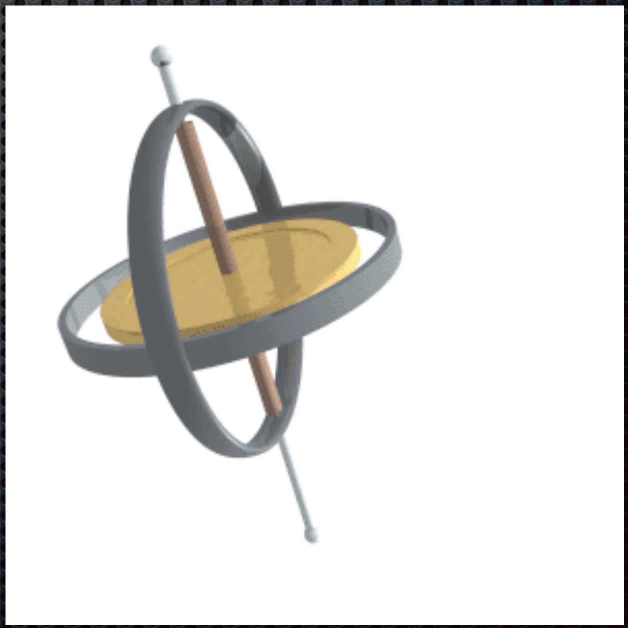


- For a system of classical charged particles:

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c} \vec{L}_i$$

for spin,

$$\vec{\mu} = g \frac{q\hbar}{4mc} \vec{\sigma}_i \, ; \vec{S} = \frac{\hbar}{2} \vec{\sigma}$$



- The Landé *g* factor relates the magnetic moment to the frequency of Larmor precession (angular momentum precesses about field direction)

$$\omega_s = g \frac{eB}{2mc}$$

Clear Prediction, Definitive Check of *g*-factor

- For a spin 1/2 point particle $g=1$
- From Stern-Gerlach, clear $g=2$
  - relativistic treatment! (Thomas precession)
- So for Dirac particles, $g=2.$
  - well, not quite

Physics on Your Tombstone

- Kusch and Foley: g_e= 2.00238(6)
  - yikes…
- Schwinger to the rescue: one—loop

$$g_e \approx 2\left(1+\frac{\alpha}{2\pi}\right) \approx 2.00232$$

define anomaly as

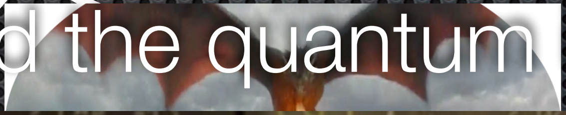
$$a_\mu = \frac{g-2}{2}$$

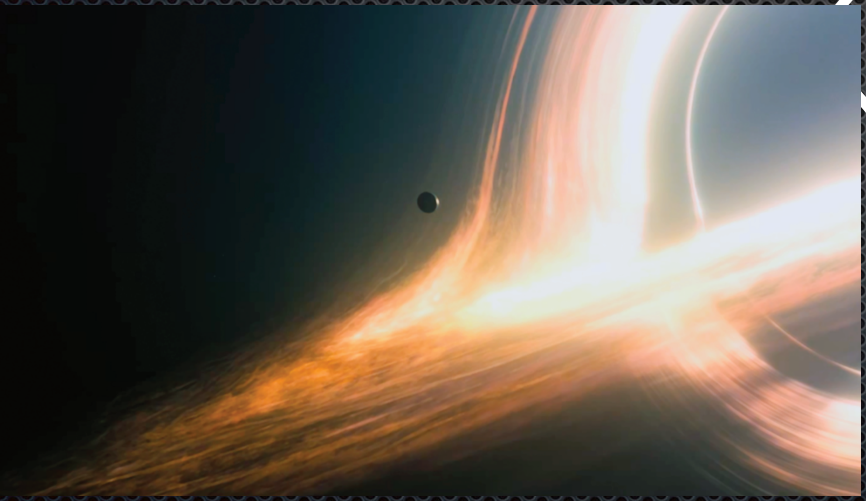
g-2:Muon Magnetic Moment

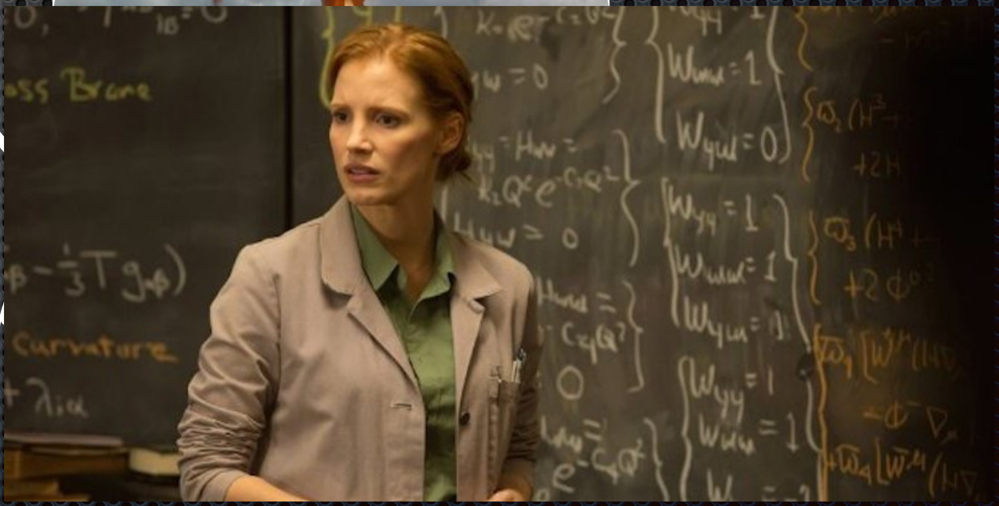
- The anomaly *a* grows with particle mass^2, so muons are about 40,000 times as sensitive to new physics as electrons

- What’s in that loop?

we need the quantum information



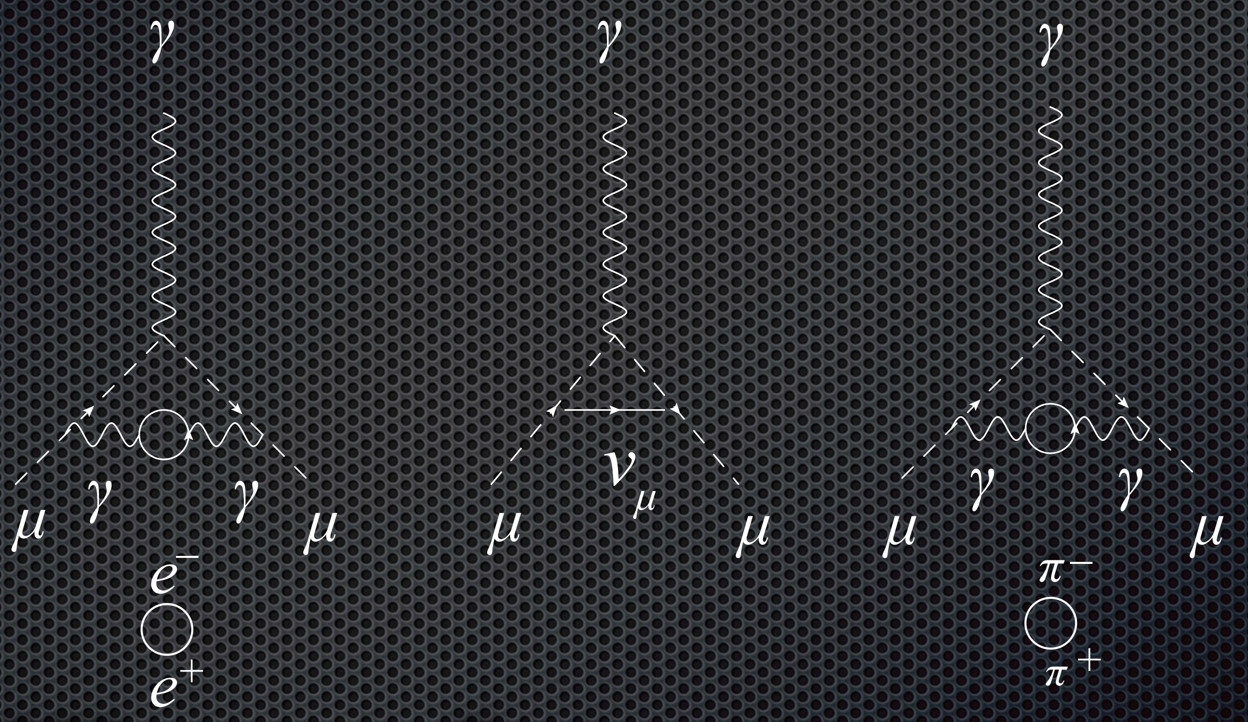




As usual, things are difficult

- First take out known physics:

this last piece is data based; cut the hadron loop and look at $e^+e^- \rightarrow \pi^+\pi^-$



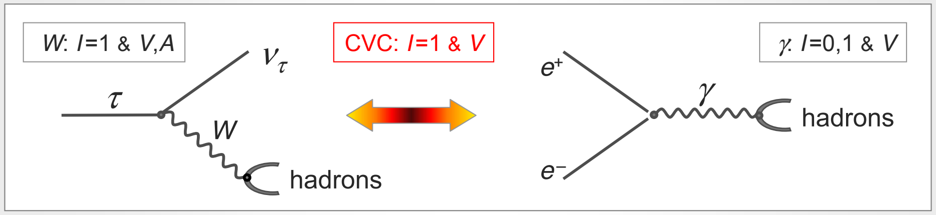
QED Electroweak Hadronic

$$a_\mu = a_\mu^{\mathrm{SM}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HLBL}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{New\ Physics}}$$

Digression: tau vs e^+e^-

- This was a source of concern for a long time: apparent discrepancy

Using also Tau Data through CVC – SU(2)



Hadronic physics factorizes in Spectral Functions :

Isospin symmetry connects $I=1$ e^+e^- cross section to vector τ spectral functions:

$$\sigma^{(I=1)}\left[e^+e^- \to \pi^+\pi^-\right] = \frac{4\pi\alpha^2}{s}\,\upsilon\left[\tau^- \to \pi^-\pi^0\nu_\tau\right]$$

Experimentally: τ and e⁺e⁻ data are complementary with resp. to normalisation and shape uncertainties

$$\upsilon\left[\tau^- \to \pi^-\pi^0\nu_\tau\right] \propto \frac{\mathrm{BR}\left[\tau^- \to \pi^-\pi^0\nu_\tau\right]}{\mathrm{BR}\left[\tau^- \to e^-\bar{\nu}_e\nu_\tau\right]}\;\frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds}\;\frac{m_\tau^2}{\left(1-s/m_\tau^2\right)^2\left(1+s/m_\tau^2\right)}$$

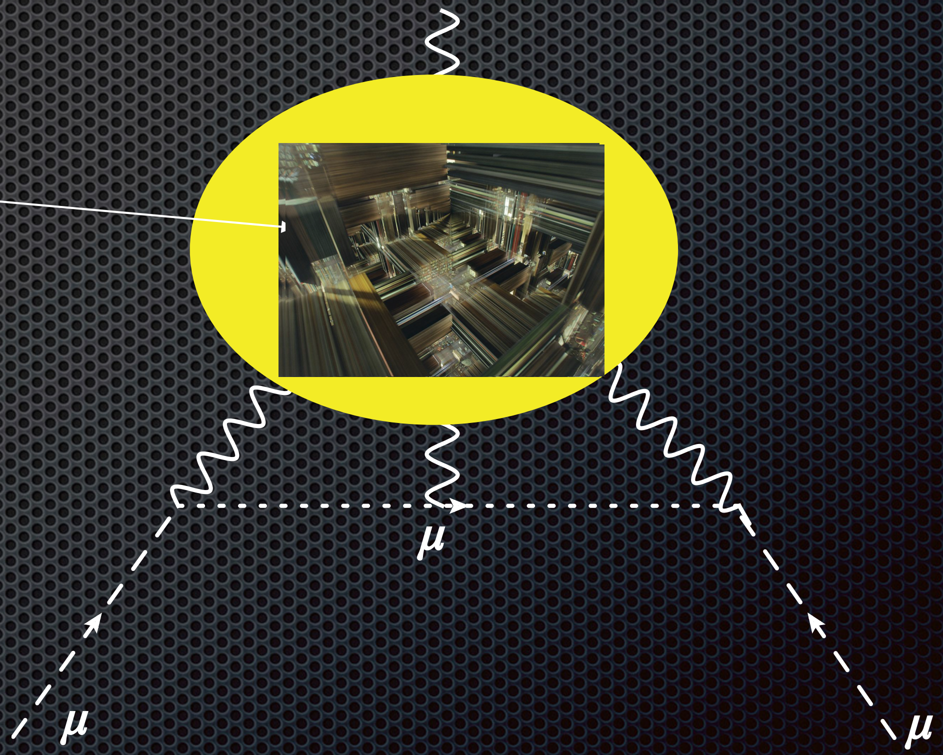
branching fractions — mass spectrum — kinematic factor (PS)

Flavour & LHC, October 9-11, 2006, CERN — A. Höcker — Hadronic Contribution to the Muon $(g-2)$ — 12

- This “theory” error is dominated by experimental errors. Data have more or less converged

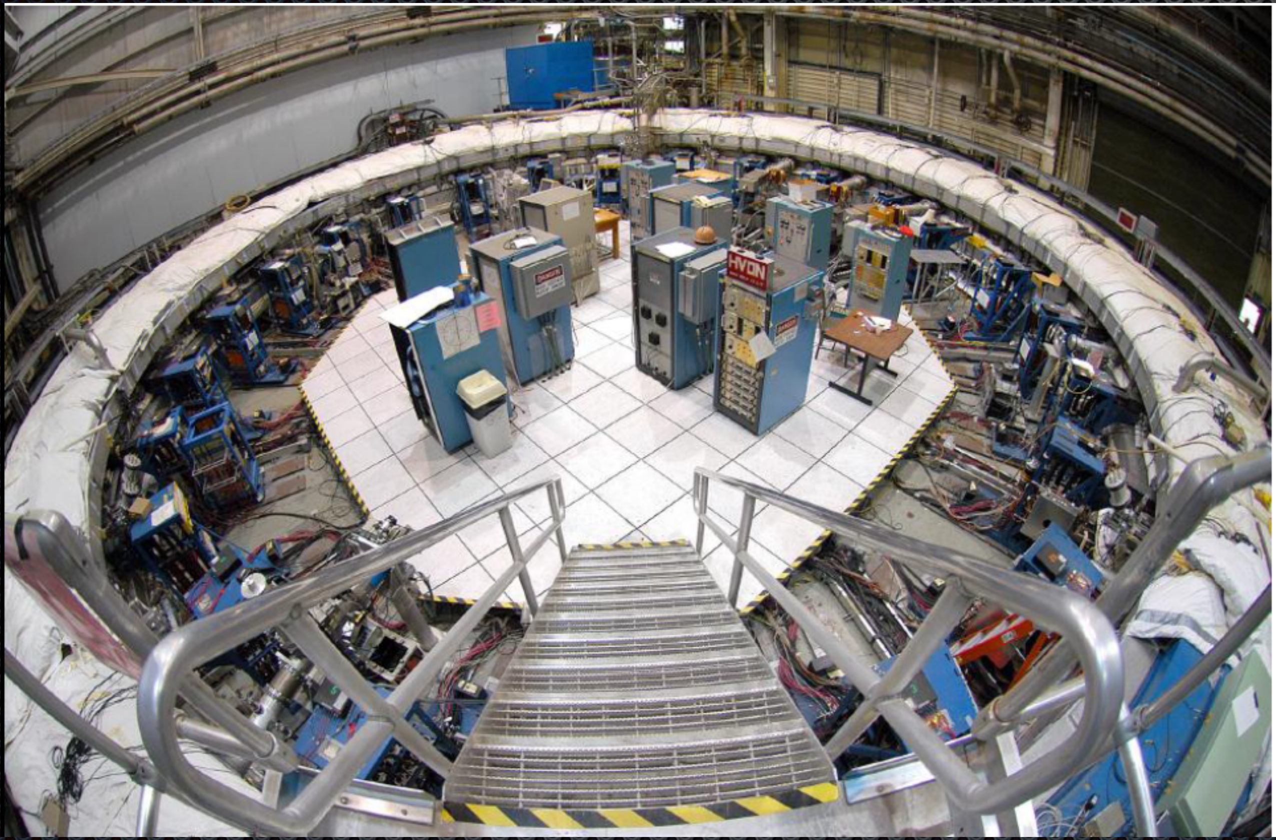
Hadronic Light-By-Light

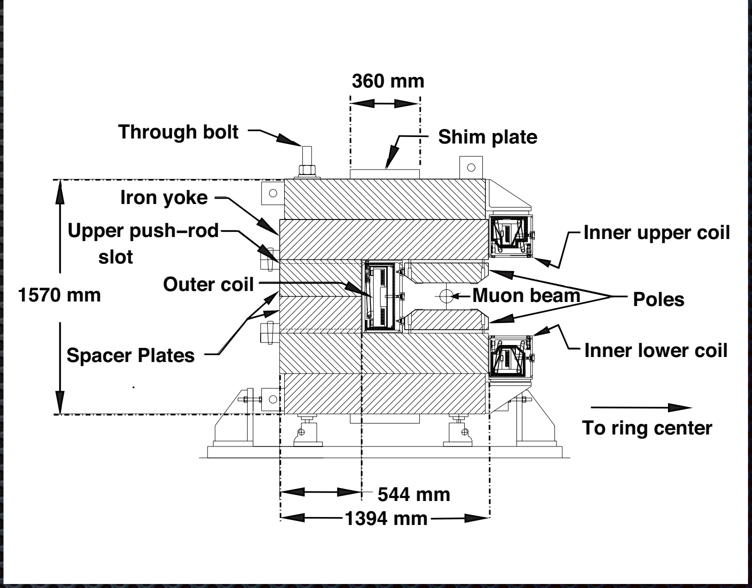
- What people focus on
- Calculations done on the lattice and many naively assume that they are wrong
  - Lattice QCD has improved greatly in last decade
- But existing calculations would have to be very far off; if so, interesting for lattice QCD.



Muon g-2 at BNL

- Used a muon storage ring





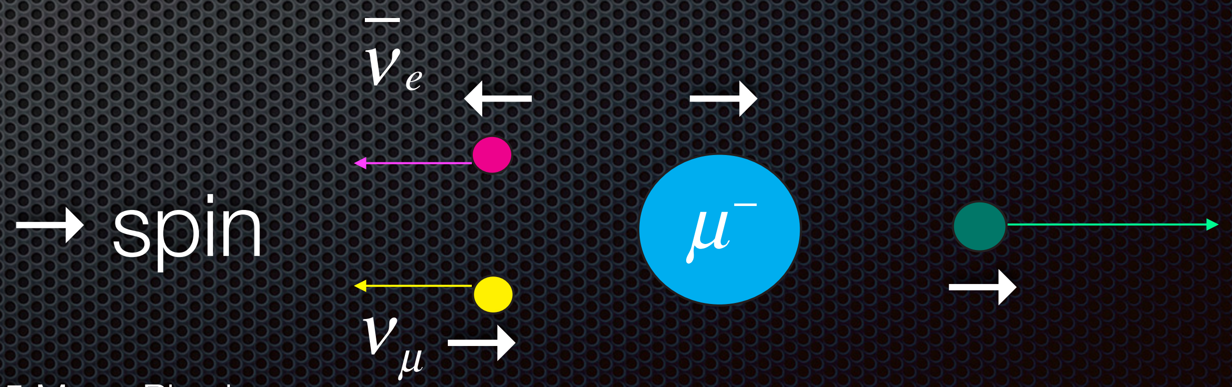
long history of experiments. First storage ring *g*-2

Nucl.Phys. B150 (1979) 1
Print-79-0088 (CERN)
DOI: 10.1016/0550-3213(79)90292-X

http://cds.cern.ch/record/133132/files/CM-P00063992.pdf

Principles and "Magic γ"

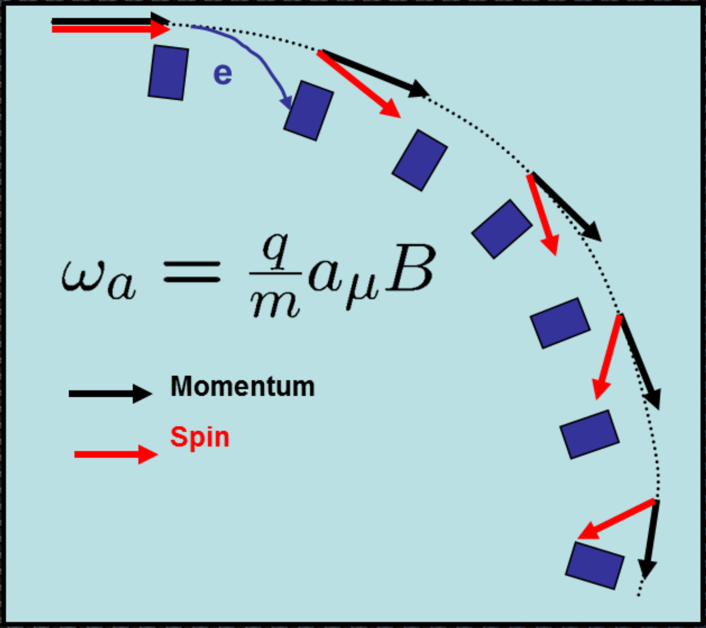
- The muon momentum rotates as the muon circulates around the ring
  - The spin is initially aligned with the momentum
- Measure relative precession of spin and momentum
  - $a_\mu^{\text{predicted}}$ vs. a_μ^{measured}



Expressed in equations,

- Basic expressions

$$\omega_c = \frac{eB}{mc}\left(\frac{1}{\gamma}\right)$$ cyclotron frequency



$$\omega_L = \frac{eB}{mc}\left(\frac{1}{\gamma} + \frac{g-2}{2}\right)$$ Larmor frequency with Thomas Precession; this is the relativistic γ

$$\omega_a = \omega_L - \omega_c$$

and

$$a = \frac{g-2}{2}$$

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] - \eta\frac{e}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$

precession perpendicular to orbit plane, sensitive to EDM.

Bargmann-Michel-Telegdi Eqn

Magic γ

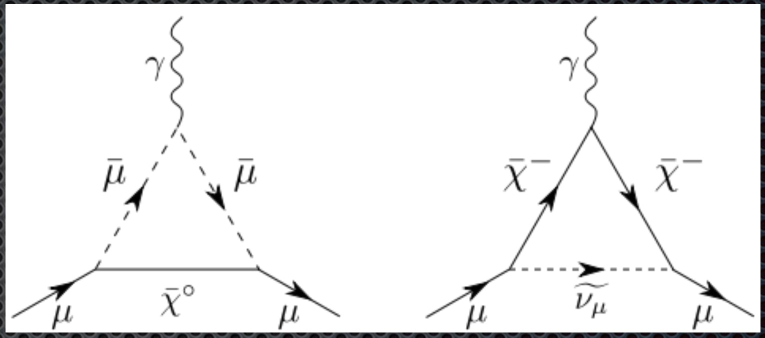
- Problem: E-field needed to keep muons in storage ring
  - but $\vec{\beta} \times \vec{E}$ looks like $\vec{B}$ (1st year E&M)
  - so *choose* γ to cancel : "magic γ"

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right] \quad \gamma = 29.3,\ p_\mu = 3.094\ \mathrm{GeV/c}$$

  - there are other ways to do the experiment: cold muons, don't need electric field, under study at JPARC

Deviation and SUSY

- Supersymmetry can produce effects like *g*-2 anomaly.
- Deviation roughly the right size for EWSB-scale SUSY.



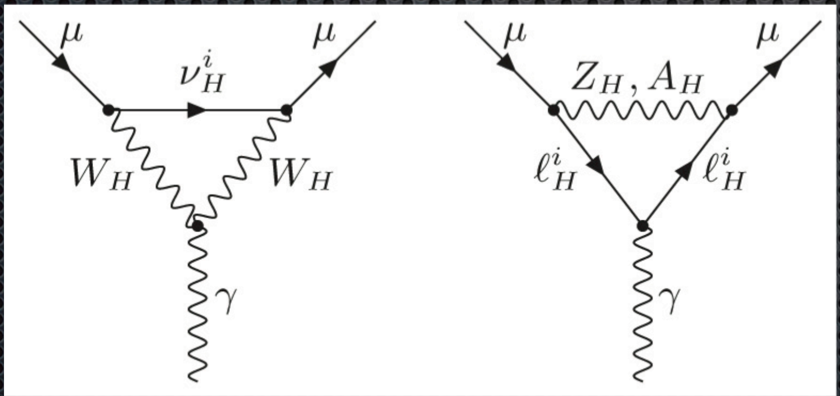
$$a_\mu(\mathrm{SUSY}) \approx (\mathrm{sgn}\,\mu)\times 130\times 10^{-11}\tan\beta\left(\frac{100\,\mathrm{GeV}}{\tilde{m}}\right)$$

A. Czarnecki and W. Marciano, Phys. Rev. D 64, 013014 (2001)

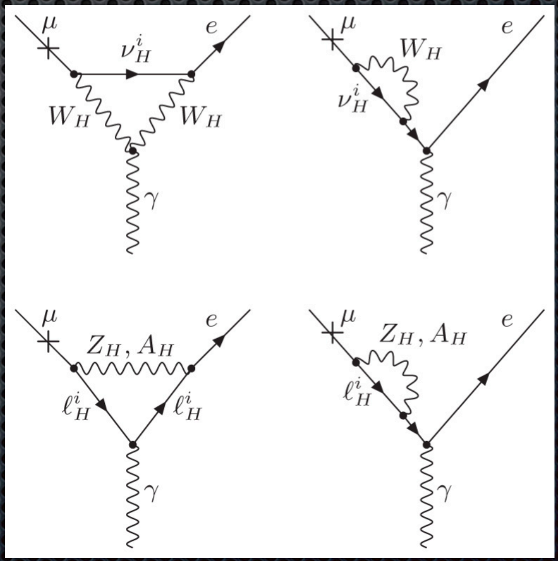
More than SUSY

- g-2 terms can come from many sources

$$a_\mu(\text{New Physics}) = O(1)\left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu}{m_\mu}\right)$$



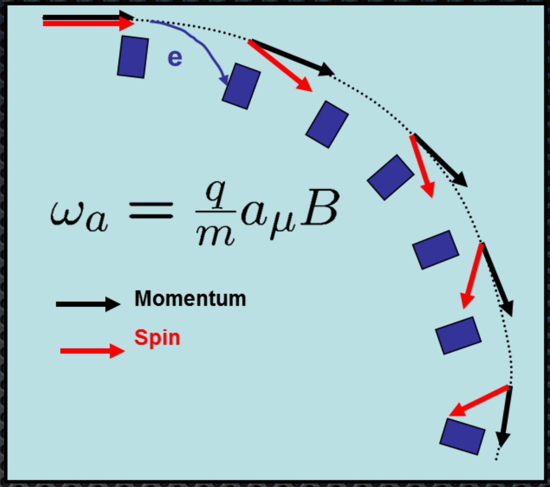
Littlest Higgs



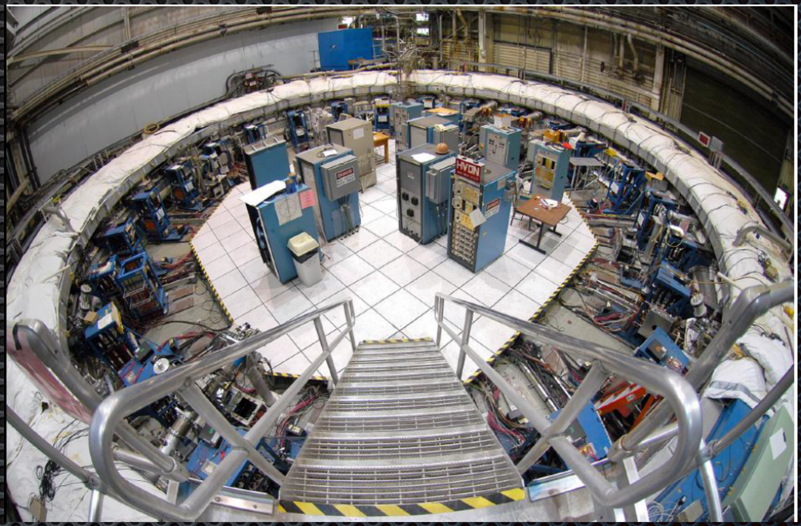
$\mu \to e\gamma$

we'll talk about this later

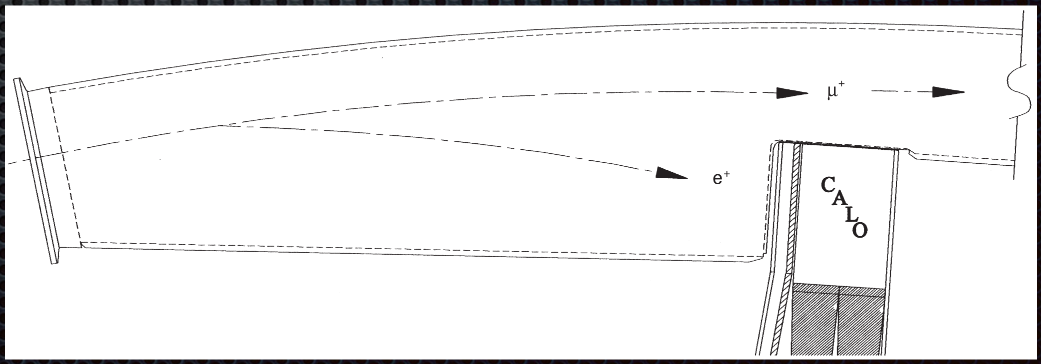
Measurement:



- Every electron has a smaller momentum than its parent muon
  - Therefore it curls to the inside of the storage radius



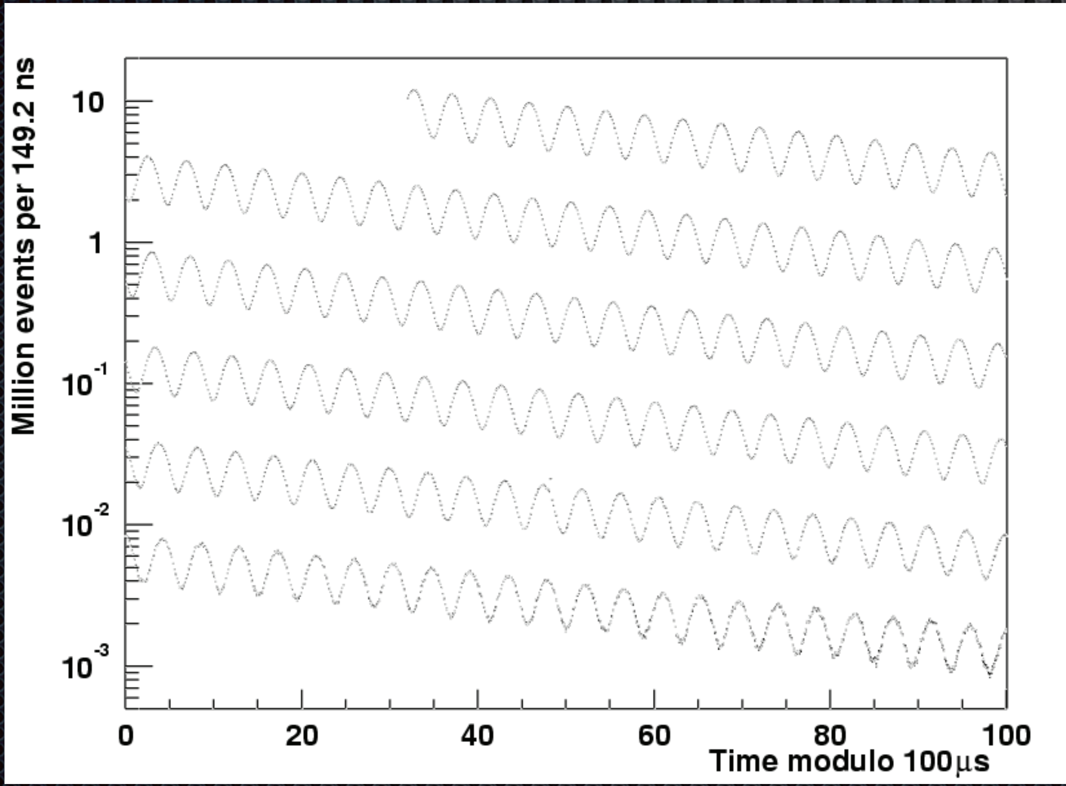
- A set of calorimeters along the inner circumference measures the energy



Data

- Watch precession as muons decay in ring by detecting number of electrons vs. time

$$N(t) = N_o e^{-t/\gamma\tau_\mu}\left[1 - A\cos(\omega_a t + \phi)\right]$$



$$\frac{dP(y,\theta)}{d\epsilon\, d\Omega} = \frac{1}{2\pi} n(\epsilon)\left(1 - \alpha(\epsilon)\cos\theta\right)$$

$$\alpha(\epsilon) = q\,\frac{2\epsilon - 1}{3 - 2\epsilon}$$

P is probability for electron to head off at a given angle and energy

n.b.: *we see again that angular distribution is a function of* ε

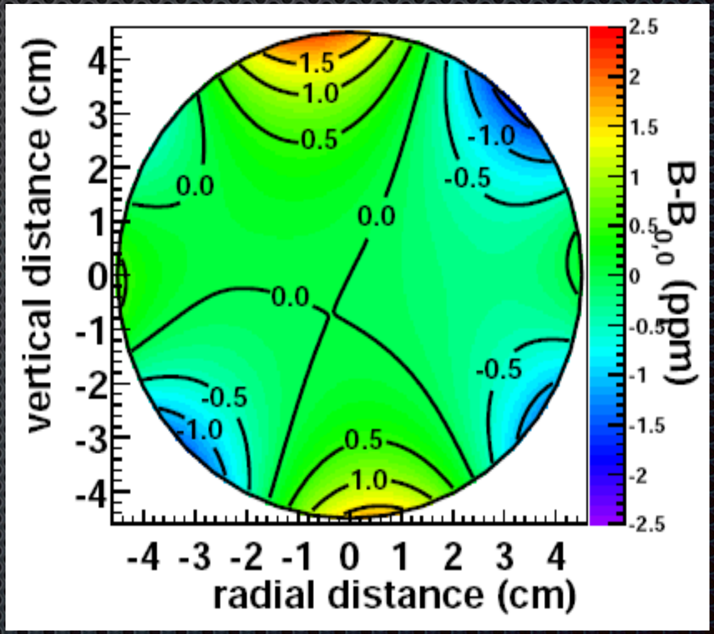
What Do You Measure (2)

- Two choices:
    1. you can count number above a threshold energy
    2. you can measure the spectrum
- Experiment chose to count the number
    - threshold energy error is still a systematic
        - you need to know the energy calibration to determine fraction of spectrum above threshold

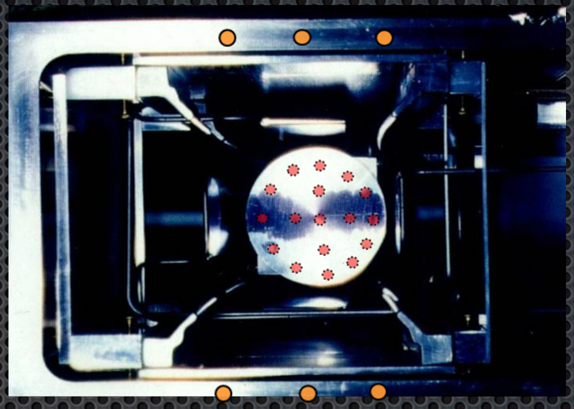
Extracting a_μ

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B}\right]$$

- We have ω_a: $N(t) = N_o e^{-t/\gamma\tau_\mu}\left[1 - A\cos(\omega_a t + \phi)\right]$
- Now must extract a_μ
- This requires knowing *B*:
  - detailed field maps
  - absolute scale
  - shimming to get field right in this large ring to < ppm



Extracting Absolute Field



- Need *absolute* field scale.
- Used trolley to measure absolute field along ring by observing proton precession
  - but trolley and other effects distort field. Field seen by test protons not the same as field seen by muons
  - Correct for these effects by measurement of the proton sample in special spherical water sample

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a}$$

$$a_\mu = \frac{\omega_a / \tilde{\omega}_p}{\omega_L / \tilde{\omega}_p - \omega_a / \tilde{\omega}_p} = \frac{R}{\lambda - R}$$

obtain

$$\lambda = \omega_L / \omega_P = 3.18334539(10) \text{from muonium } (\mu^+ e^-) \text{ HFS}$$

FNAL experiment will improve the systematics here

New Trolley

- Picture to scale

Brendan Kliburg, from whom I stole much of the talk yesterday

Result:

$$a_\mu(\text{exp}) = 116{,}592{,}089\ (63) \times 10^{-11} (0.54\text{ppm})$$
$$a_\mu(\text{thy}) = 116{,}591{,}802\ (49) \times 10^{-11} (0.42\text{ppm})$$

- 3.6 σ deviation(theory updated since PRD, exp't unchanged)
  - signal of SUSY?
  - DM?
  - ?
- No clear experimental problem to point at. Will discuss errors in a moment
- Must repeat experiment, attacking dominant errors

Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL
Muon g-2 Collaboration (G.W. Bennett (Brookhaven) *et al.*). Feb 2006. 96 pp.
Published in **Phys.Rev. D73 (2006) 072003**
DOI: 10.1103/PhysRevD.73.072003
e-Print: **hep-ex/0602035 | PDF**

Summary of Method

- Recall four ingredients:
  1. polarized (97% in practice)
  2. parity violation in decay gives spin direction to electron
  3. measure precession of spin wrt momentum
  4. use magic γ **and** momentum of 3.094 GeV/c
- Extract *g-2*

Limiting Errors

Phys.Rev.D73:072003,2006
DOI:10.1103/PhysRevD.73.072003
arXiv:hep-ex/0602035

- Experiment: 540 ppb
  - Statistical: 460 ppb
  - Systematic: 280 ppb
- Theory: 494. Error dominated by HVP, not HLBL

dominant errors	theory	experimental
HVP	420	
HLBL	260	
Gains		120
Pileup		80
Beam		114
Statistics		460

Next Step: New *g*-2 at FNAL

- Get to 140 ppb (x4 better)
  - improve statistics x21
  - improve experimental systematics
    - on ω_a from 200 ppb to 70 ppb
      - field variations, energy scale,…
    - on ω_p from 170 ppb to 70 ppb
      - scale of B-field

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a}$$

$$a_\mu = \frac{\omega_a / \tilde{\omega}_p}{\omega_L / \tilde{\omega}_p - \omega_a / \tilde{\omega}_p} = \frac{R}{\lambda - R}$$

~10K muons circulating in ring, ~18 Hz

Where is Fermilab?

aka Fermi National Accelerator Laboratory

What Does it Look Like?

Fermilab's Accelerator Chain

Linac	400 MeV	Half a ^{235}U fission	Protons at 0.7c
Booster	8 GeV	KE of a dime falling a foot	g -2/ Mu2e protons live here
Main Injector	120 GeV	~ rest energy of Higgs	used for neutrino oscillations through Earth
Tevatron	1 TeV	~KE of a mosquito	∑KE of tank armor-piercing shell; modern colliders

Typical Fermilab Denizens

- We have a bison herd on site
- And cooling ponds to carry away heat from magnets in the accelerators

and physicists

You Can See this from Space

~a 10k run
around the ring

Getting Ring to FNAL:

- The ring is expensive: recycle!
- *Move* ring from BNL to FNAL
- Lots of fun and very exciting!
  - BNL to barge
  - across ocean
  - barge to FNAL

Actual GPS of journey

hang out waiting for storm to pass

Big But Delicate

- Move 50 ft diameter rings without flexing > 1/8 inch

The barge deck Flexed more than the Ring!

In Lemont, IL at canal

- Famous resting place of Chicago luminaries (?) who somehow ended up in canal

And then it had to deal with Chicago traffic

- Ring transported at night over two Interstates
- Waited during day; Made stop at my Costco for provisions

only a inch or two to spare

Big Public Event!

- Emmert International is family-owned firm that did all this

Marketing (are you surprised?)

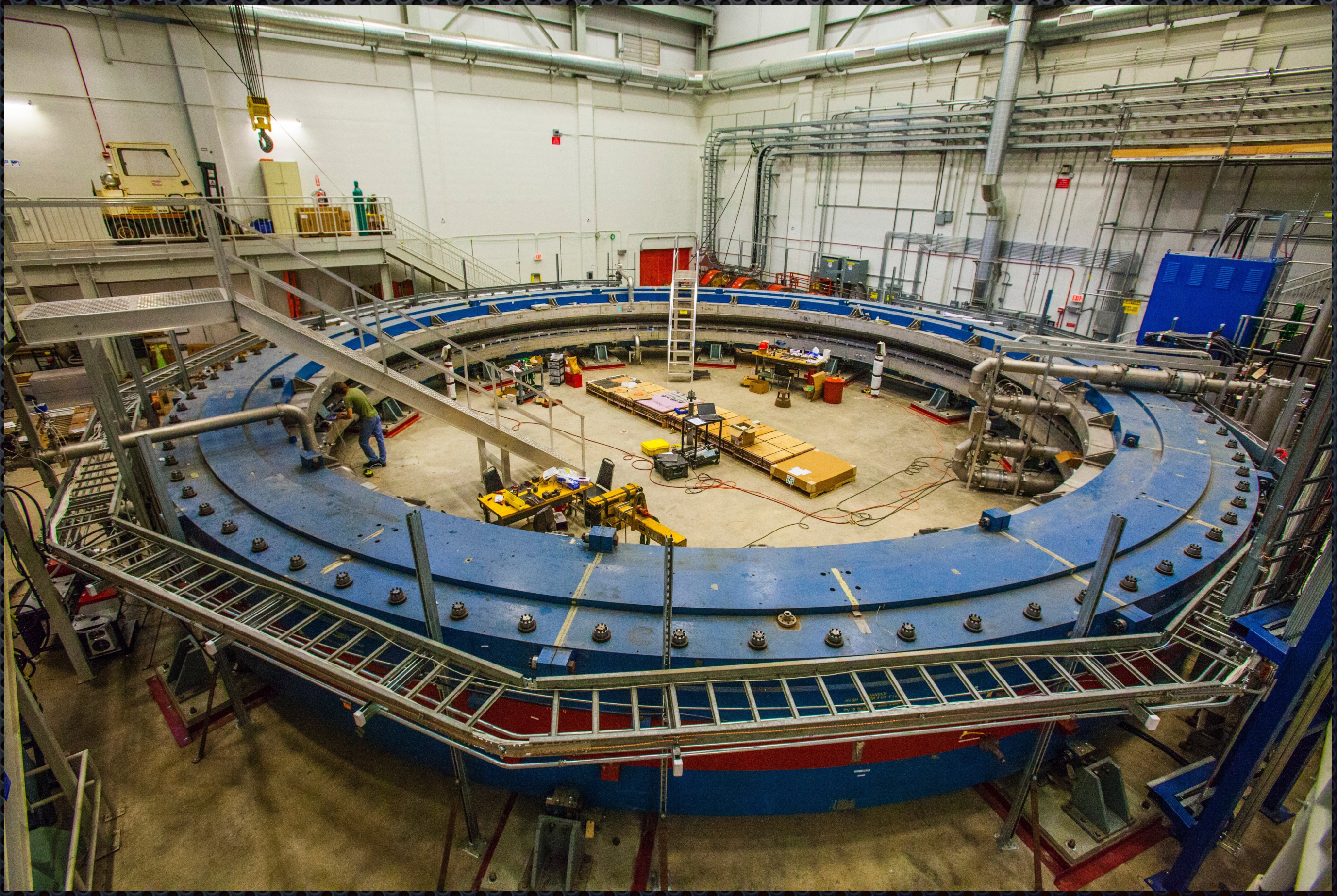
- Local microbrewery Two Brothers

But the excitement died down

- And then the ring got left in a parking lot at Fermilab where any random could walk right up to it…

Cooled Down and operated at 3400 A (5200 operating)

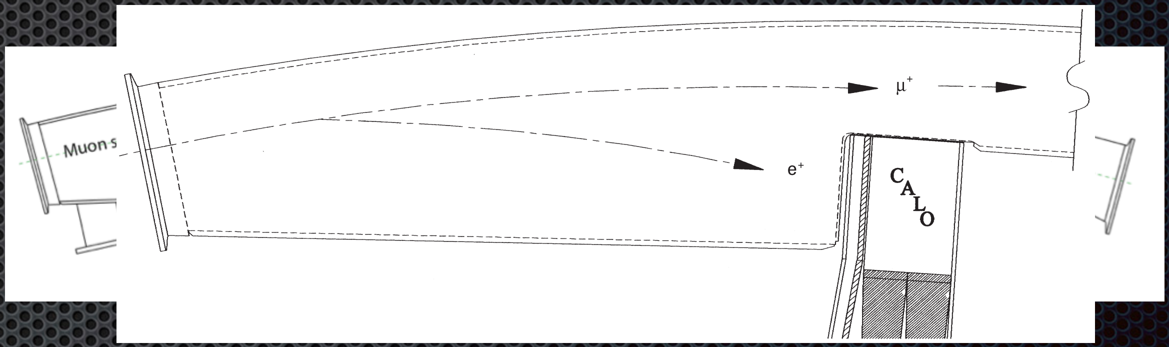
- Field measured at 0.94±0.05 T/1.45T in their nifty new building



432 shim pairs in 360°, 24 pairs installed

Detector Improvements

- new calorimeter PbF_2
- tracking chambers
  - also good for out-of-plane and EDM
- more frequent trolley runs than BNL
  - better NMR probes
- Better absolute calibration

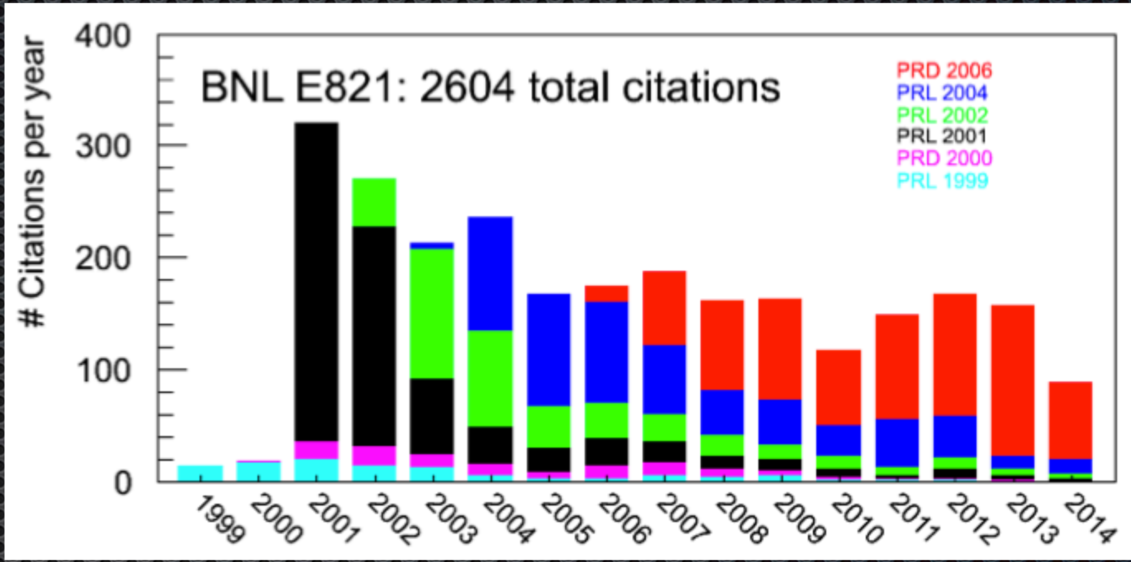


New PbF_2 Calorimeter

- Brendan Kiburg’s thesis on MuCap; Peter Winter gave this lecture two years ago; photographer Volodya Tishchenko g-2, MuLan

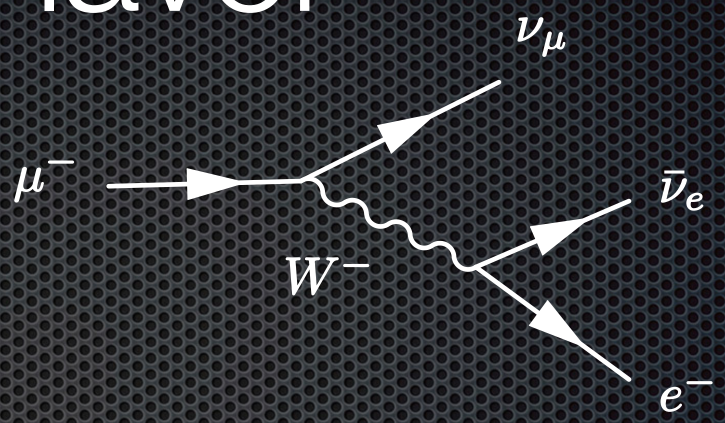
g-2 Conclusions

- One of most-cited results
- Theory Error is shrinking
- Many significant experimental improvements
- Stay tuned for first results in about two years



May
or May Not Contain
New Physics

Charged Lepton Flavor Violation



- We'll concentrate on muon decay without neutrinos
- Muons interact by gravity, E&M, and the weak force
  - if an electron is produced it's not gravity or E&M
  - weak interactions of muons make neutrinos
  - if no neutrinos, it's not the weak force

no neutrinos means new physics

Rabi: on the discovery of the muon

- Why are there three generations (flavors)?
- How are they related?

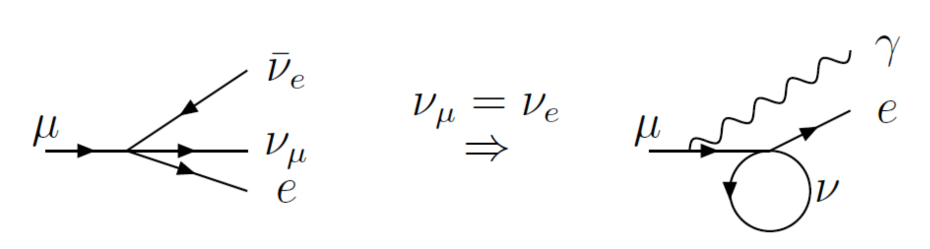
-Roni Harnik

Rabi discovered NMR and was key in the invention of the magnetron (think microwave oven), without which we would all starve. students: Schwinger, Ramsey, Perl. Look him up.

Who *Did* Order That?

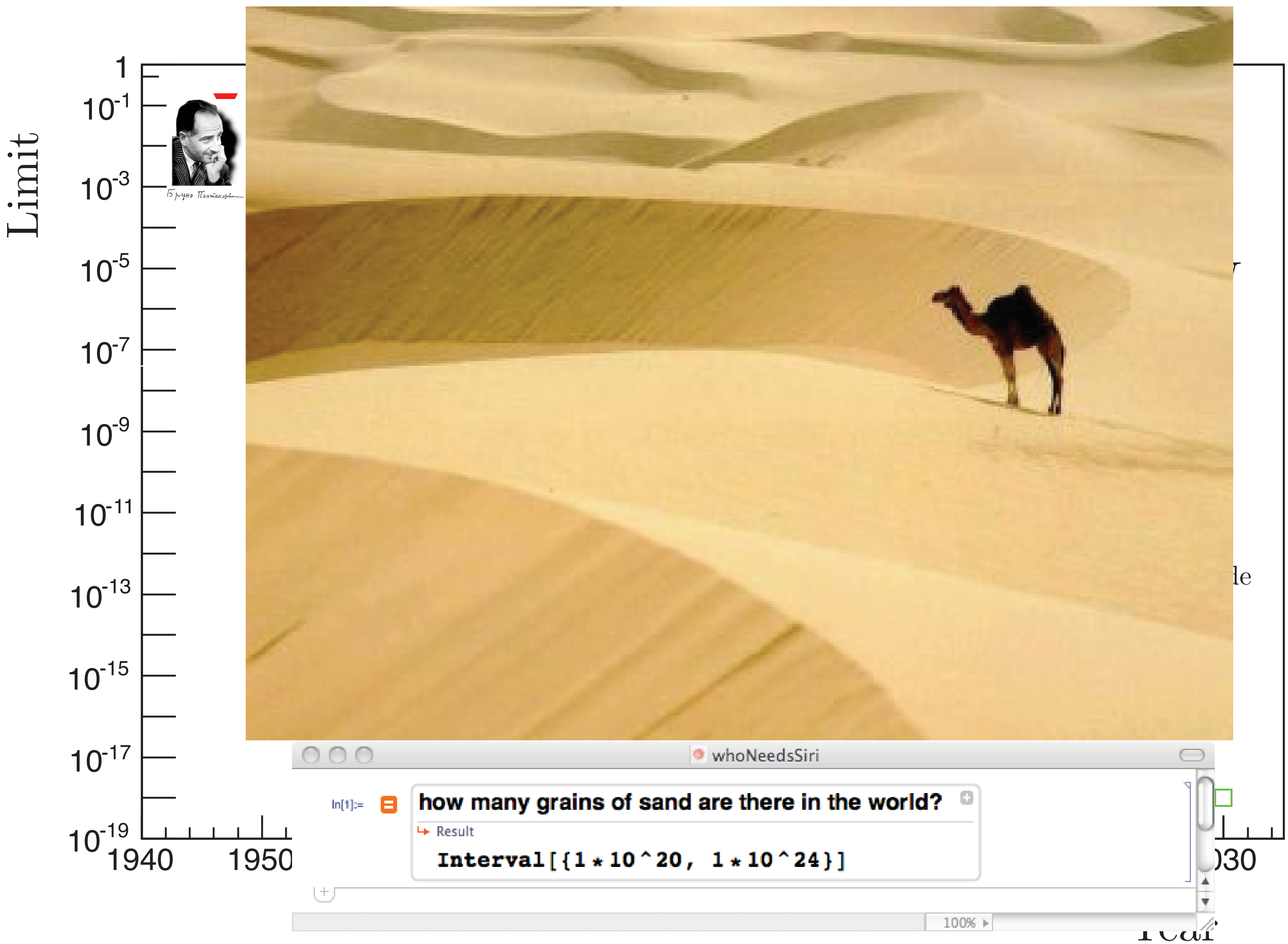
After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect BR($\mu \rightarrow e\gamma$) ≈ 10^{-4}
- Unless another ν, in Intermediate Vector Boson Loop, car
  - same



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

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

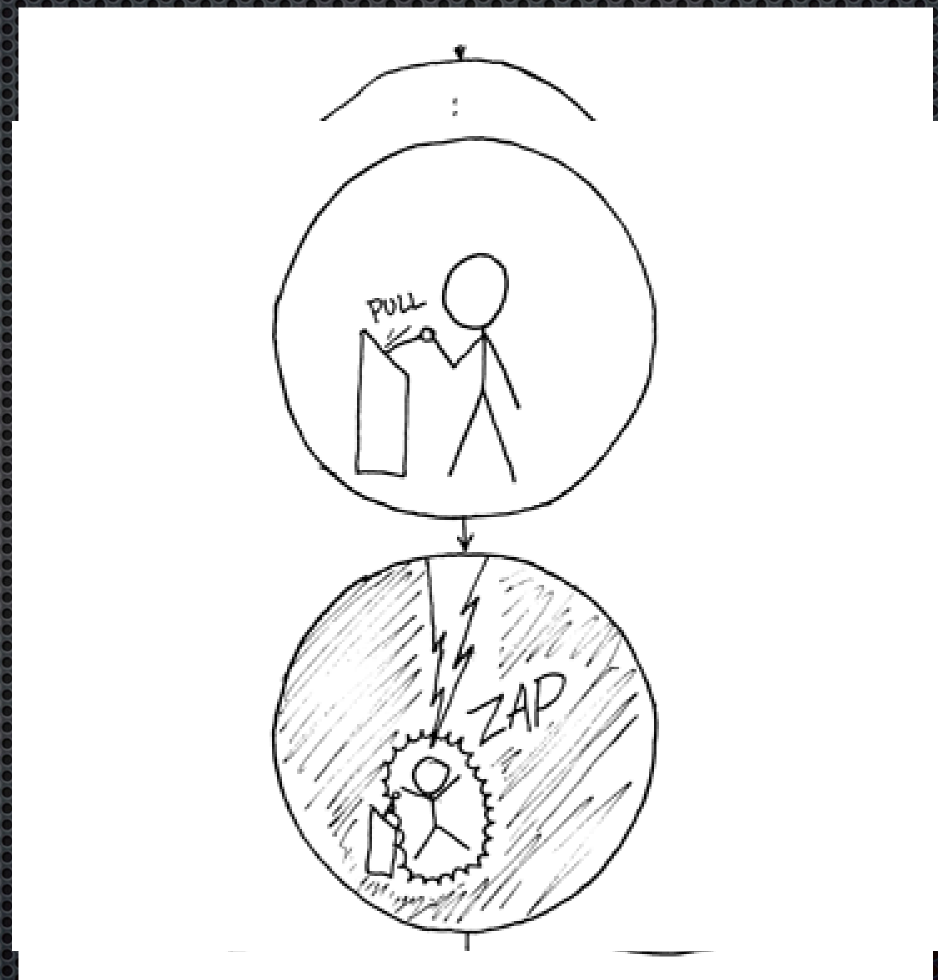


need about 10^{21} muons to get to 10^{-17}

Muons and Charged Lepton Flavor Violation Experiments

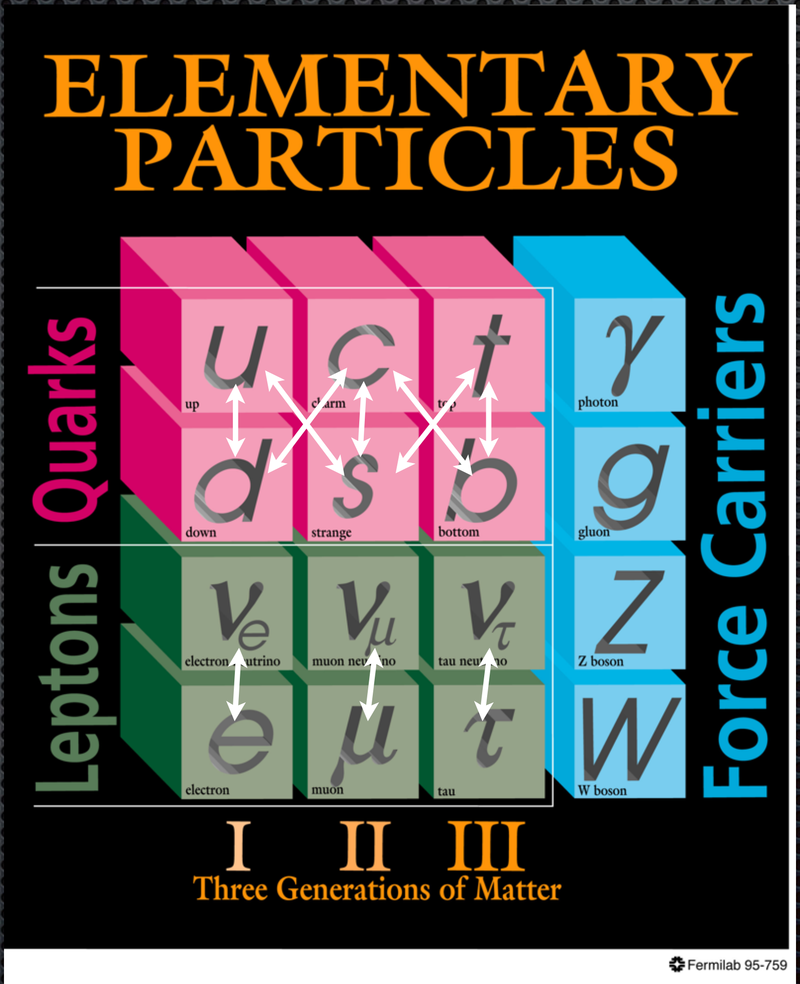
- A very long history, as you see!

- What's that definition of insanity?



Why is CLFV Interesting?

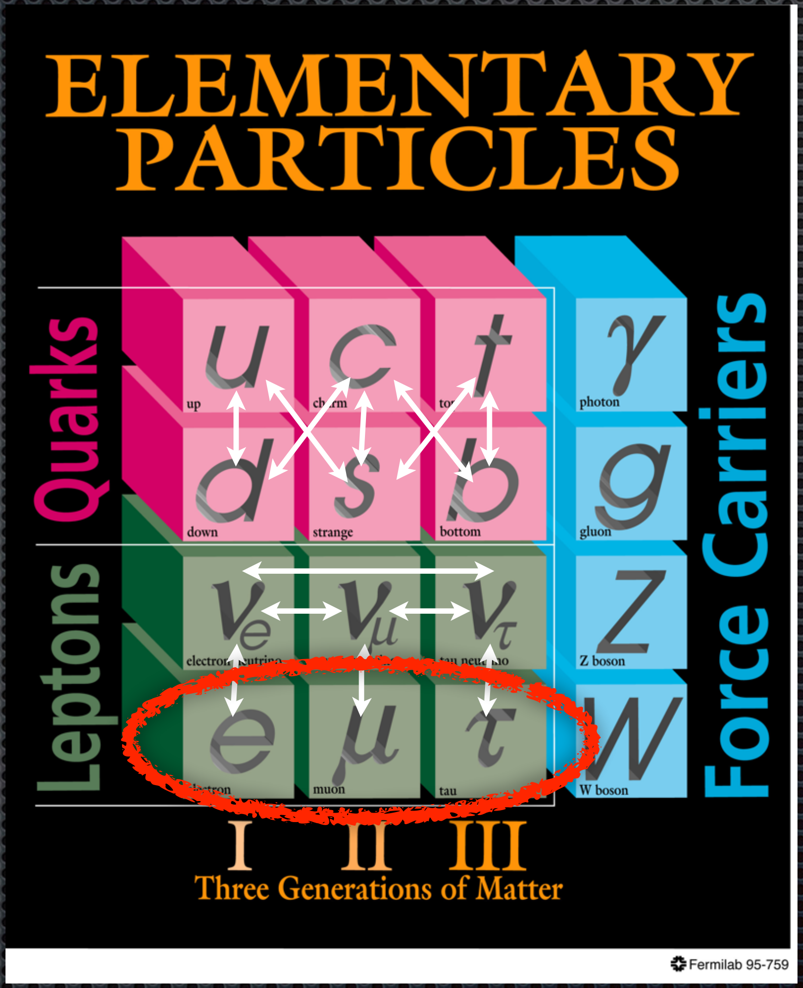
- We think we have a good understanding of the constituents of matter
  - modulo particle physics arrogance given that this is 5% of the Universe and we're essentially clueless about Dark Energy



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

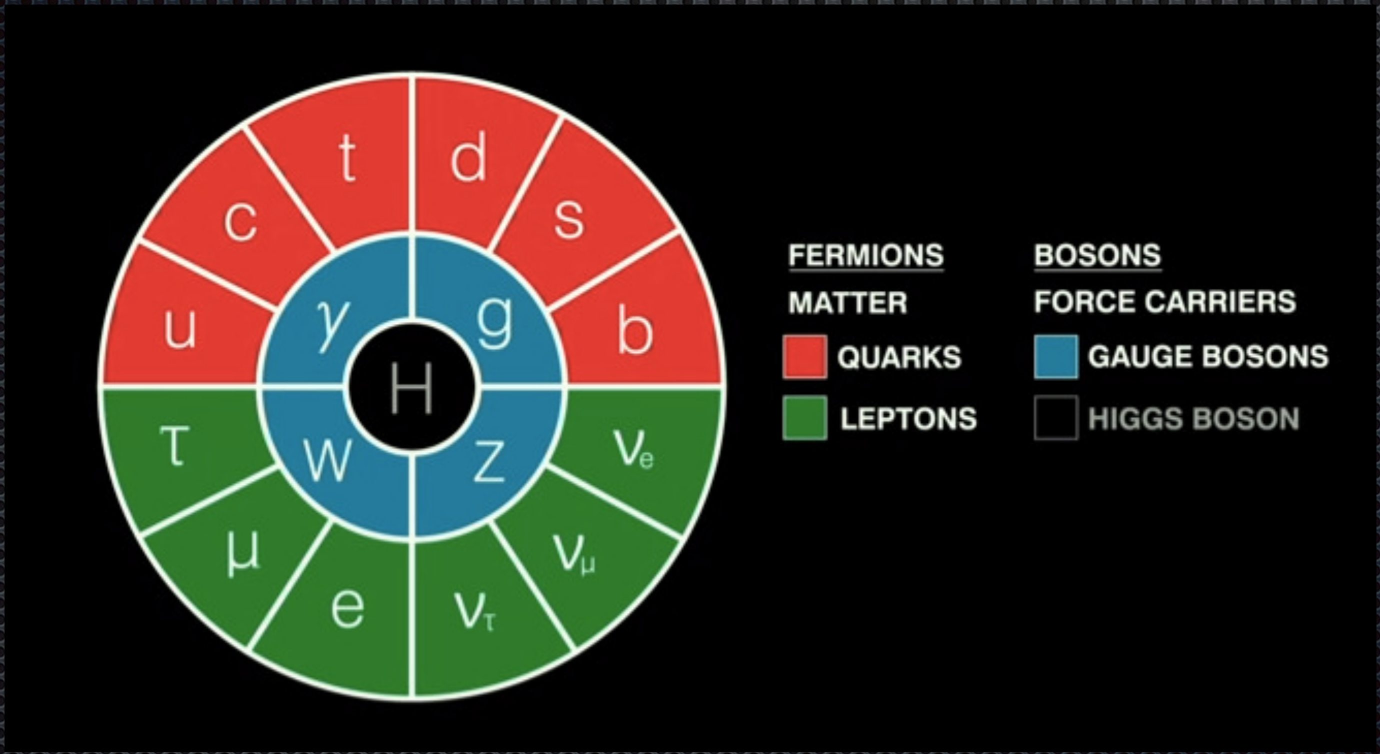
What Don't We Know?

- What's going on with charged leptons?



- They don't mix

studying the relationships among generations is *flavor physics*



I heard people complaining about this image (twice!) yesterday; I'm not crazy about it either

Why is Flavor Physics Important?

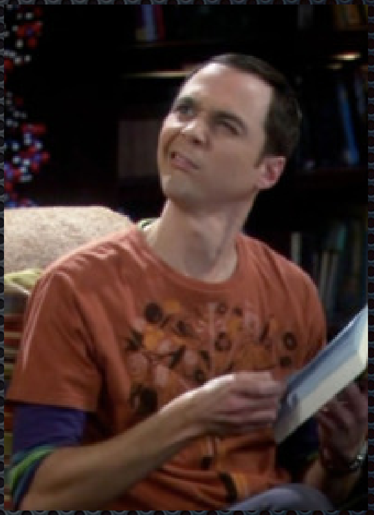
- Because it speaks to the generation puzzle:
  - why is there more than one generation of quarks and leptons?
- Because knowing a mass scale is not enough:

dim-6

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\text{flavor structure, Yukawas, couplings}}{\Lambda^6}$$

  - the Lagrangian has a numerator and a denominator (we tend to focus on the denominator)
- Because flavor physics provides discovery and discrimination

Flavor Physics and Mass Scales:



- There's already a problem:
  depends on numerator!
  - the hierarchy problem: $\Lambda \sim \quad 1\ TeV/c^2$
  - flavor bounds: $\Lambda > 10\text{-}10^5\ TeV/c^2$
- BSM ideas must explain the flavor problem:
  - "Natural" to have seen flavor effects already
  - Back to the numerator: Minimal Flavor Violation, for example, is an assumption
  - Flavor is an *input*, not an *output*

What Might Cause (c)LFV?

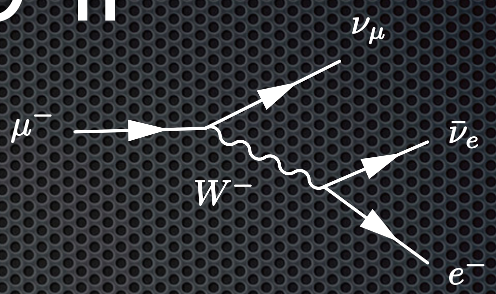
- Loop Diagrams:
  - SUSY
  - Littlest Higgs
  - Seesaw
  - GUT/Leptoquarks
  - …
- Tree Diagrams:
  - Higgs Triplets
  - New Heavy Vector Bosons
  - Extra Dimensions

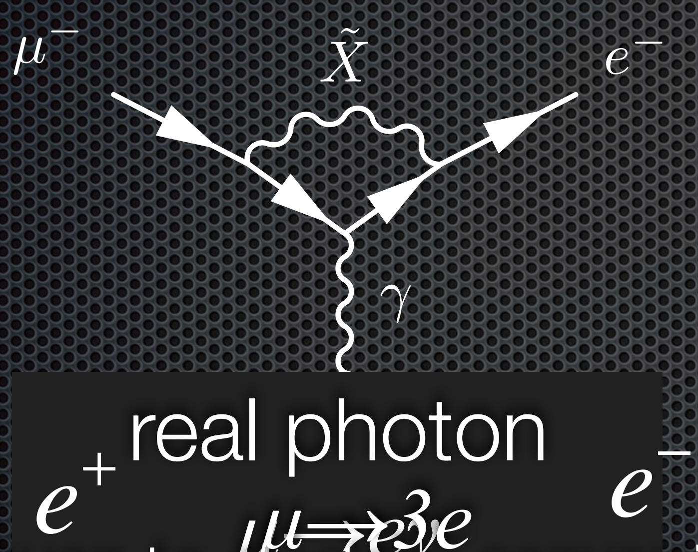
Some Sample Experiments

Just Muons!	Dedicated experiment	Multi-purpose experiment
New Physics if any signal	$\mu \to e\gamma$ $\mu \to 3e$ $\mu^- N \to e^- N$	$\tau \to \mu, e\,\gamma$ $K_L^0 \to \mu e$ $\tau \to 3l$ $Z' \to \mu e$ $H \to \mu e$
New Physics if deviations from SM (and SM errors now apply, not just exp't)	μ EDM $(g-2)_\mu$ $\dfrac{\pi, K \to e\nu}{\pi, K \to \mu\nu}$ $K_L^0 \to \pi^0 \nu\bar{\nu}$	$B \to \mu\mu$ $\dfrac{\tau \to e\nu\nu}{\tau \to \mu\nu\nu}$ $K^+ \to \mu^+\mu^+\pi^-$

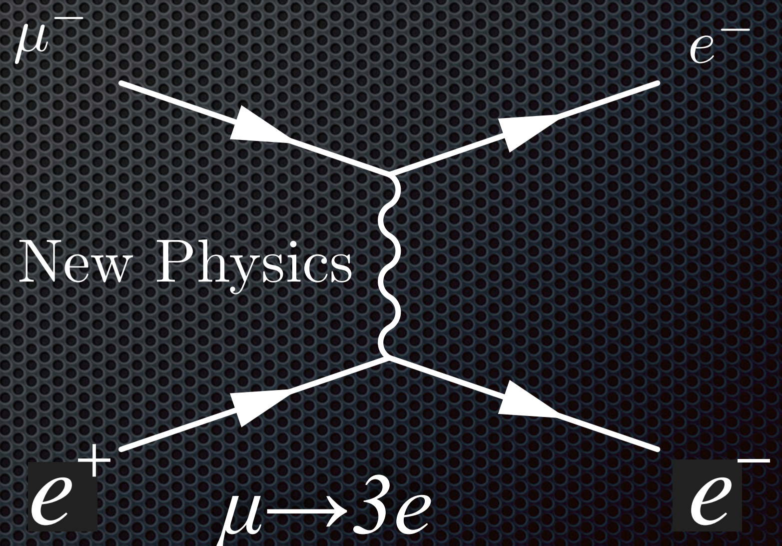
Three Processes We'll Examine

muon Decay via
Weak Interaction





muon-to-electron conversion
virtual photon, *H,* other neutral

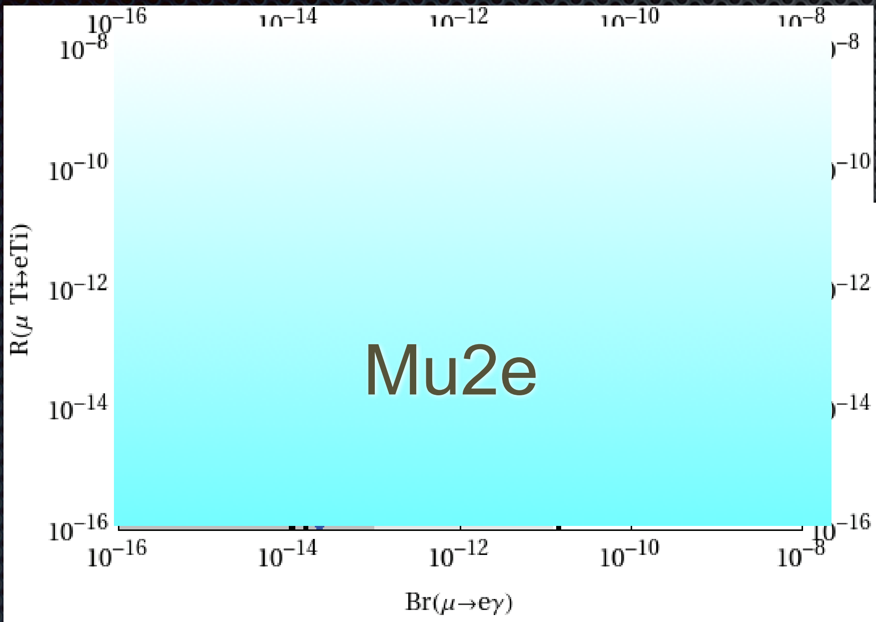


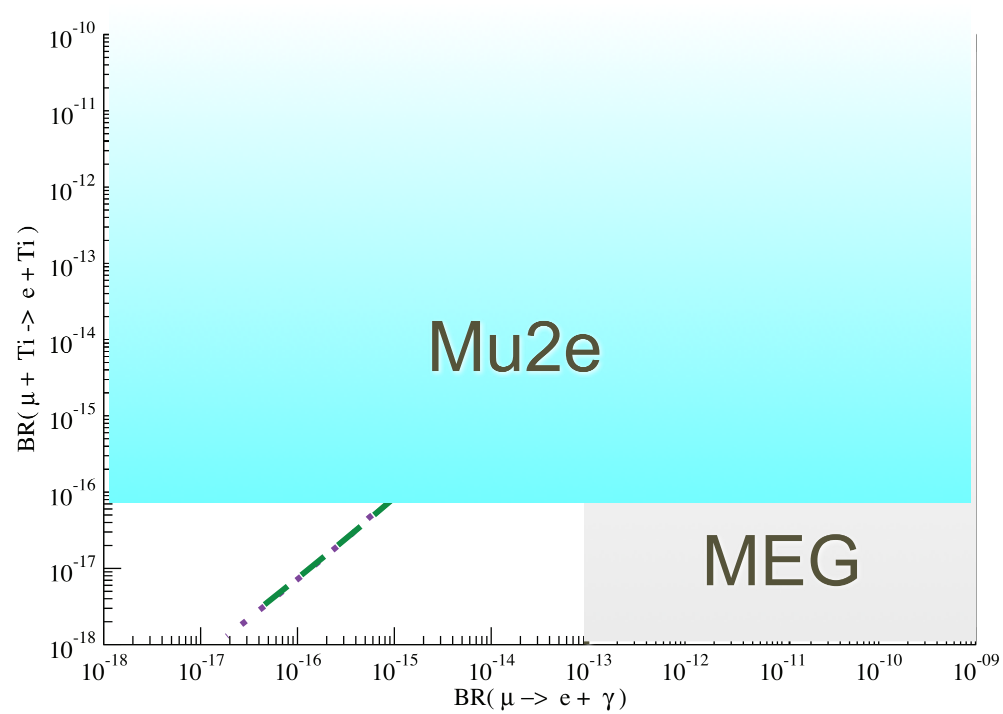
muon-to-electron conversion

Combining μ→eγ with $\mu \rightarrow e$ Conversion

Littlest Higgs

Monika Blanke, Andrzej J. Buras, Bjoern Duling, Stefan Recksiegel, Cecilia Tarantino, Acta Phys.Polon.B41:657,2010,arXiv:0906.5454v2 [hep-ph]



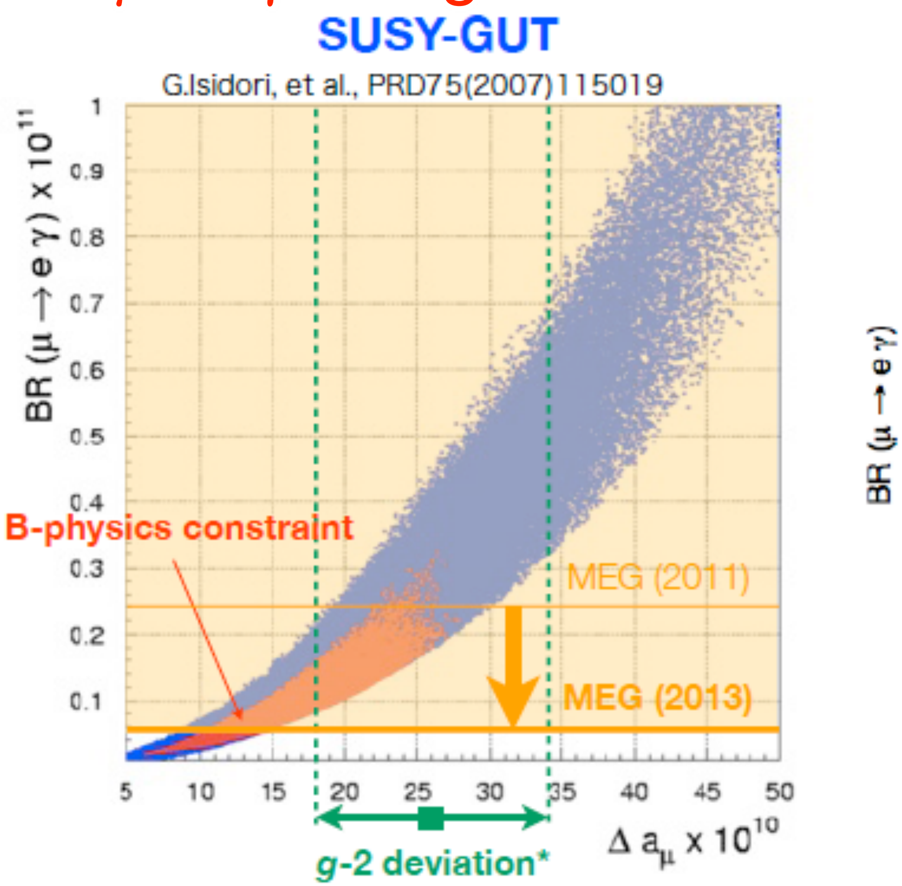


SO(10) models:

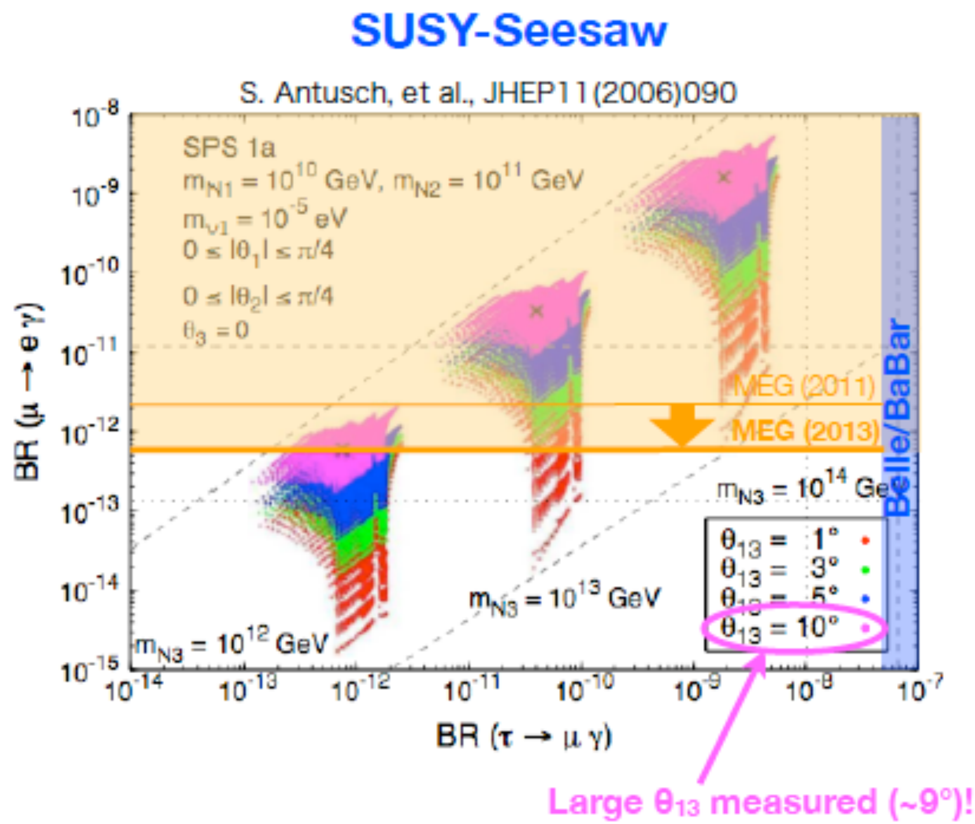
C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

Combining Experiments:

$\mu \rightarrow e\gamma$ and g-2



* a_μ(EXP):PRD73(2006)072,
a_μ(SM):Hagiwara et al., JPG38(2011)085003

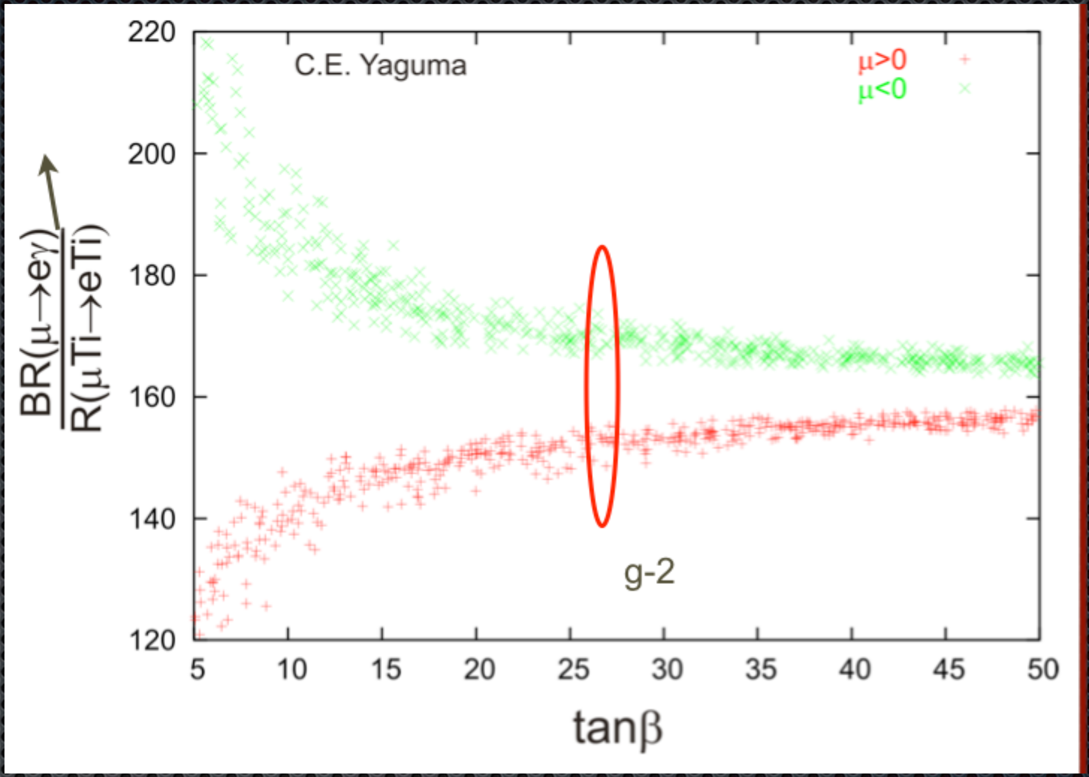


$\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ and θ_{13}

Mu2e, g-2, and $\mu \to e\gamma$

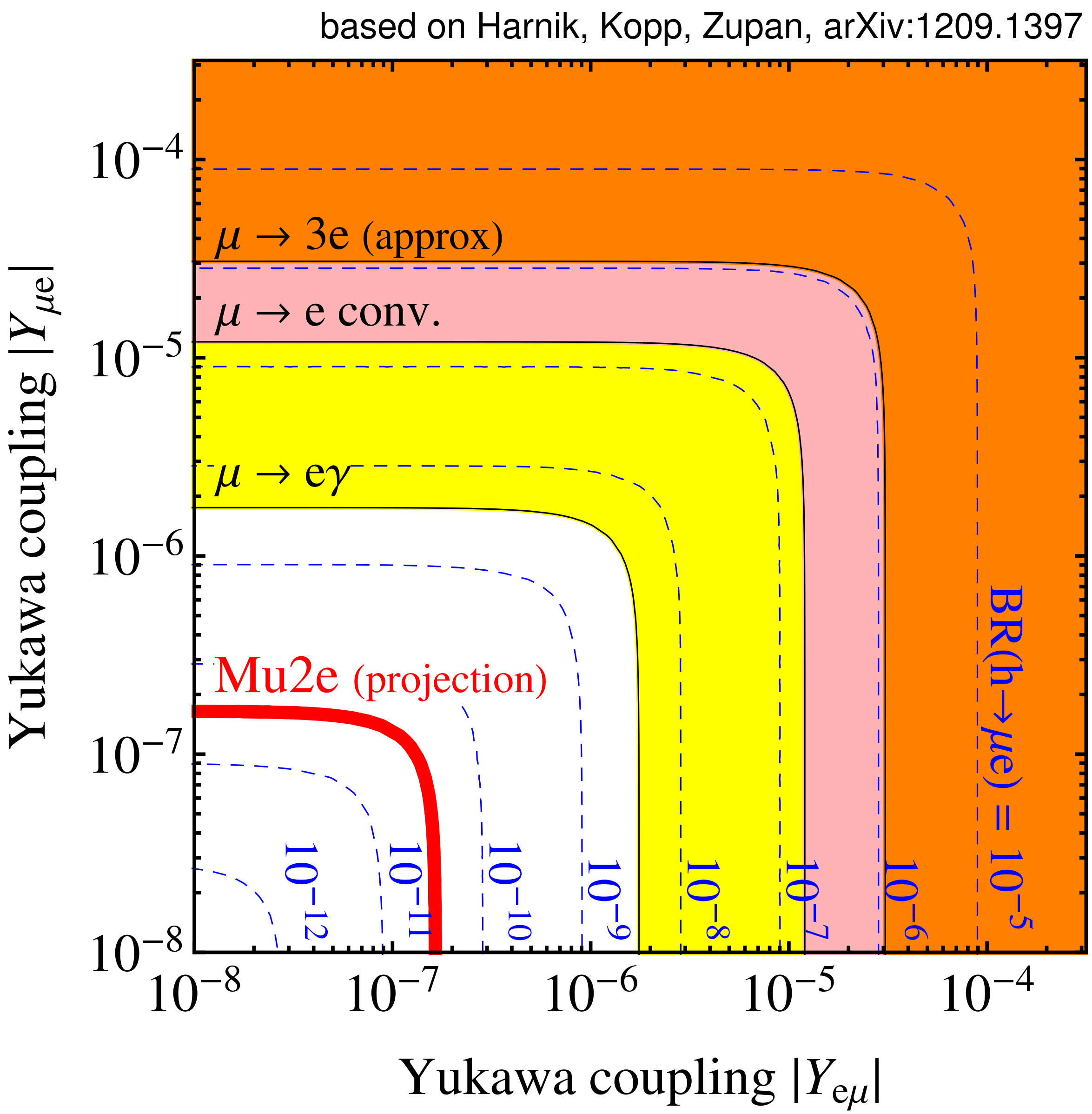
Yaguna, hep-ph/0502014v2

MSSM w mSUGRA



- Need:
  - observation of CLFV in more than one channel, and/or
  - evidence from LHC, g-2, or elsewhere
- to allow discrimination among different models

Higgs couplings to μe



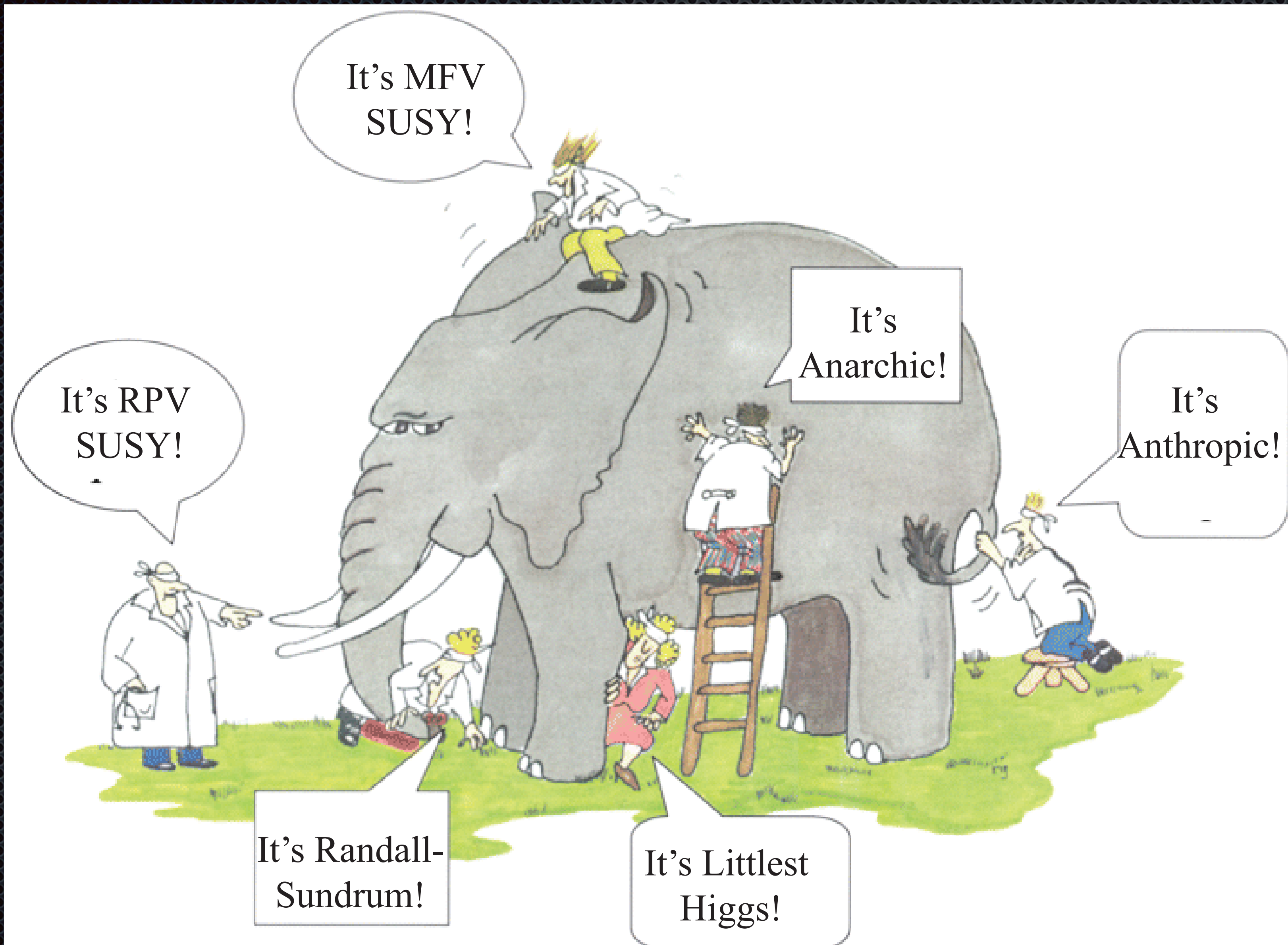
Outside of LHC reach. BR's of 10^{-11}!

Probing "natural" models:

$Y_{\mu e}^2 \ll Y\mu\ Ye$

(that line is off the plot)

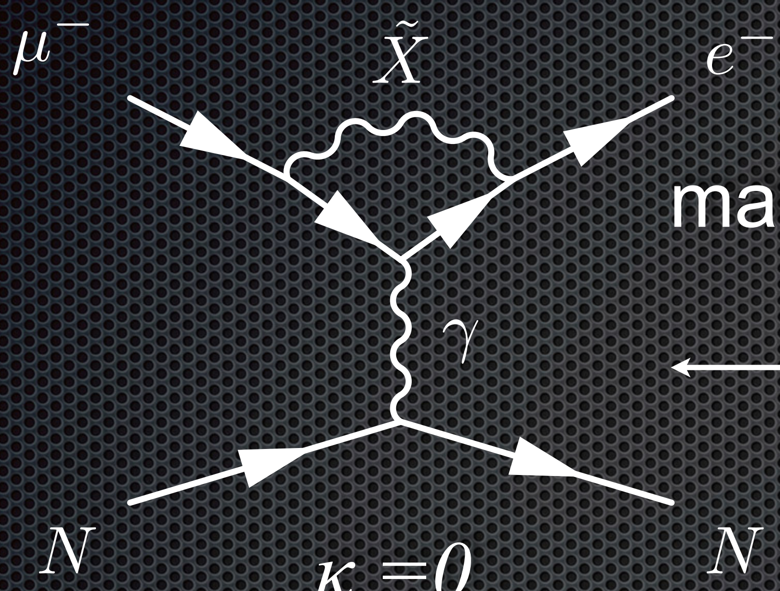
Problem with Single Measurements



"General" Form:

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

"Loops"



$\kappa = 0$

mass scale Λ

κ

$\longleftrightarrow$

"Contact Terms"

$\kappa = \infty$

Supersymmetry

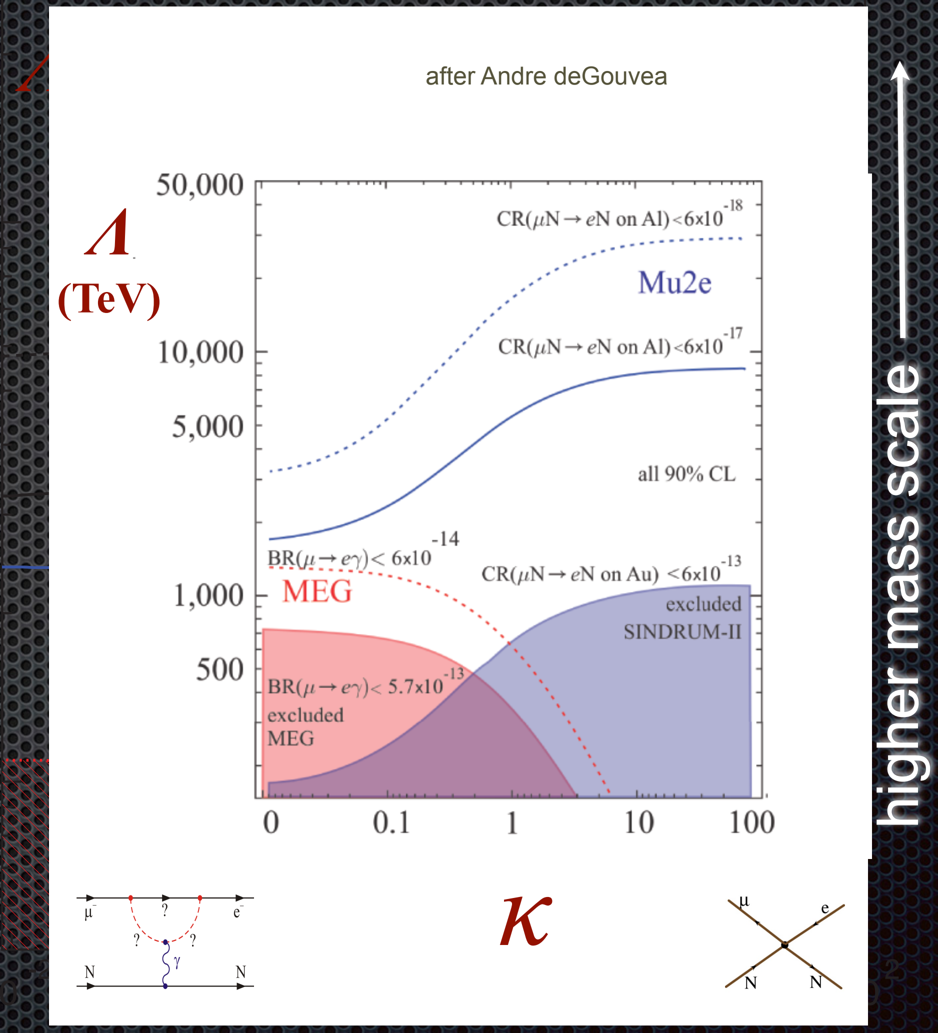
Contributes to $\mu \to e\gamma$
if the photon is "real", not attached to a nucleus

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

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

Muon-Electron Conversion and $\mu \rightarrow e\gamma$

- *Mu2e is ~ 10^4 TeV*
- *LHC is ~ 10 TeV*
- Need multiple experiments to pin down theory
- Both of these are discovery experiments: designed to see a signal



$\mu \to e\gamma$

- First mode searched for soon after muon discovery
  - natural hypothesis: the muon is an excited electron
- Kinematics simple: back to back γ and e in time

Backgrounds

- If you go high enough in rate, can create fake event from random γ and e in time and within cuts
- Radiative Muon Decay: produces γ

$$\mu^+ \to e^+ + \gamma + \nu_e + \bar{\nu}_\mu \qquad (1.4 \pm 0.4\%)$$

- Kinematics + time resolution + energy resolution conspire to produce background

As an Equation

- Background is driven by these resolutions:
  - This is proportional to "1/number of muons to see one background event"

$$B \propto \left(\frac{R_\mu}{D}\right)\left(\Delta t_{e\gamma}\right)\left(\frac{\Delta E_e}{m_\mu / 2}\right)\left(\frac{\Delta E_\gamma}{15 m_\mu / 2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

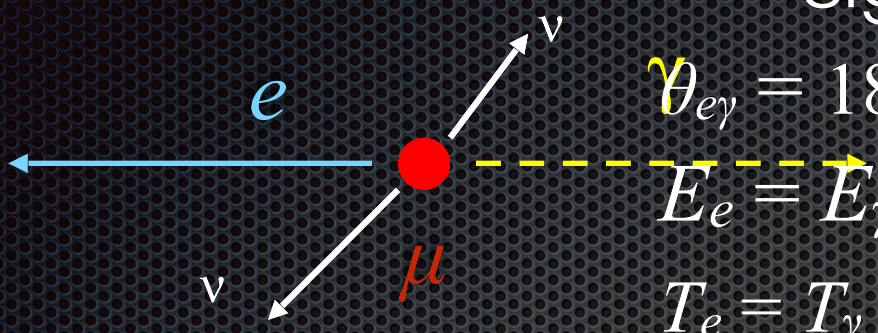
    - Rate/Duty Factor linear (less time for same rate increases accidental coincidences)
    - time, electron energy linear
    - angle, photon energy resolution quadratic

MEG Beam

- Muon surface beam
  - pulse of a few hundred psec every 20 nsec
  - Effectively constant, DC-beam for the experiment
  - but we'll see this time structure is not optimal for muon-to-electron conversion

Two Kinds of Background

signal



$\theta_{e\gamma} = 180°$

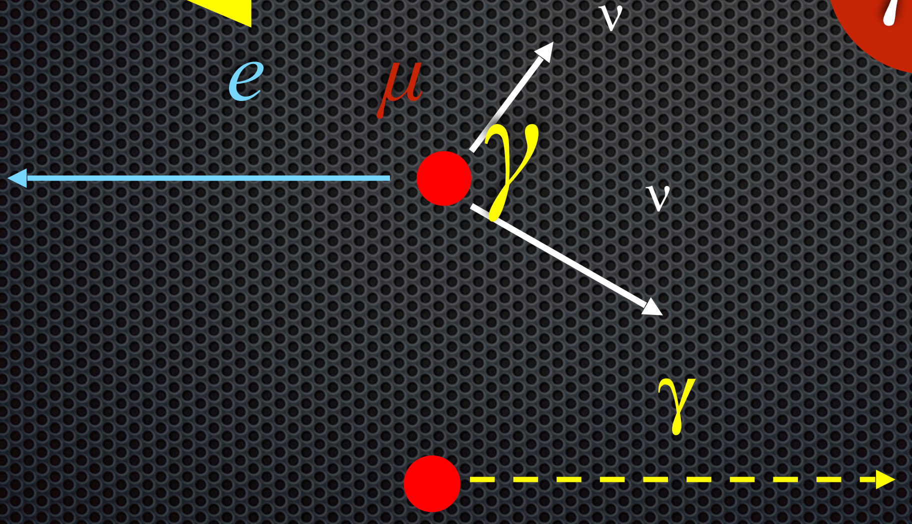
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

correlated

$\mu \longrightarrow e\,\gamma\,\nu\,\nu$

uncorrelated



$\mu \longrightarrow e\,\nu\,\nu$

$$\left\{\begin{array}{l} \mu \longrightarrow e\,\gamma\,\nu\,\nu \\ ee \longrightarrow \gamma\gamma \\ eN \longrightarrow eN\gamma \end{array}\right.$$

Background Derived

$$B \propto \left(\frac{R_\mu}{D}\right)\left(\Delta t_{e\gamma}\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

1. The time difference between any two stops is essentially random, hence the $\Delta t_{e\gamma}$ term and the R_μ/D dependences.

2. The Michel spectrum is $\Gamma(\epsilon)\, d\epsilon \propto (3-2\epsilon)\epsilon^2\, d\epsilon$, where $\epsilon = 2E_e/m_\mu$. Near $\epsilon = 1$ at the maximum the derivative is zero. Hence the $\Delta E_e/(m_\mu/2)$ dependence.

3. the radiative decay $\mu \to e\nu\nu\gamma$ near the zero-energy neutrino edge is a bremsstrahlung term that behaves as $(1-y)\, dy$ where $y = 2E_\gamma/m_\mu$. Hence the background under the $\mu \to e\gamma$ peak is proportional to the integral over the resolution window of width Δ: $\int_{(1-\Delta)}^{1}(1-y)\, dy$ which is just proportional to Δ^2.

4. The angular term is simple as well. Since the direction of the photon in a $\mu \to e\gamma$ decay is opposite to the direction of the electron, the area of the angular phase space is a small patch of area $\Delta\theta_{e\gamma}\Delta\phi_{e\gamma}$, yielding a quadratic dependence in angular resolution. The precise form will depend on whether the photon is converted and details of the apparatus.

Do You Convert the Photon?

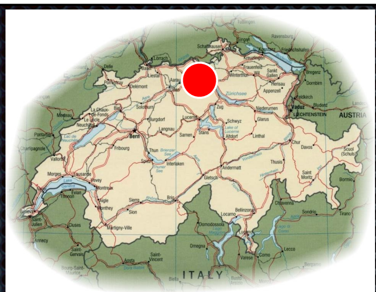
- Resolution of
  - momentum-analyzed e^+e^- is ~0.1%
  - photon energy in calorimeter is ~3%
  - photon position at COG is ~ 1 cm from shower
- Therefore no measured vertex; extrapolate electron to stopping target and draw line from calorimeter, look for intercept

No Perfect Answer

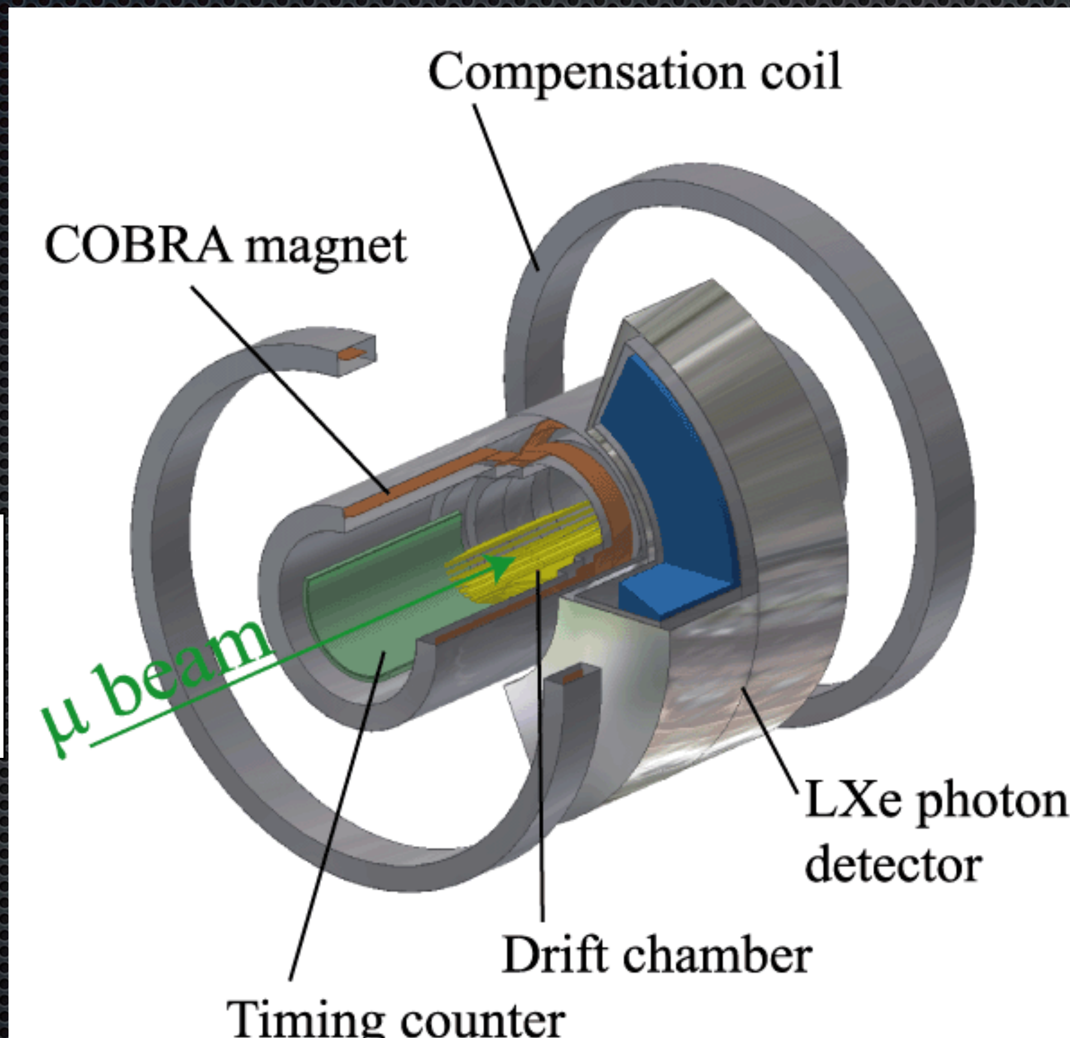
- This all sounds like you should convert. Why not?
  - statistics. Need resolution, so thin converters, so low rate.
- Experiments have gone back and forth on this issue.
  - depends on the muon beam intensity, capability of detector. Not a right/wrong answer.

Most Modern: MEG

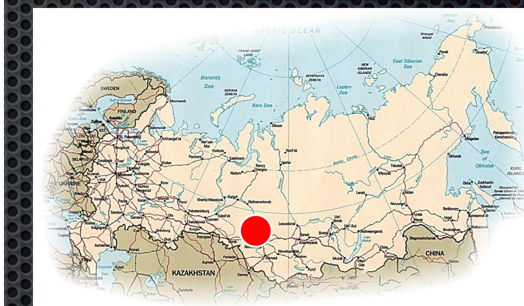
Switzerland
Drift Chambers
Beam Line
DAQ



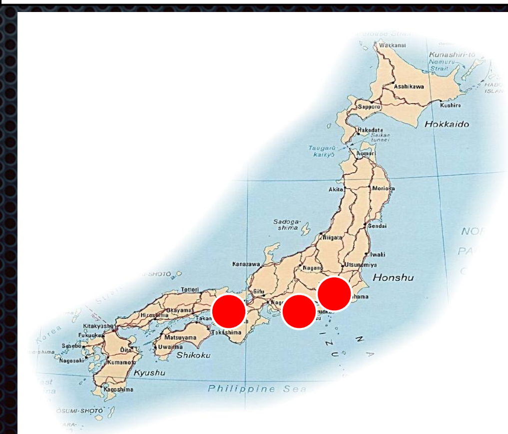
Italy
e+ counter
Trigger
LXe Calorimeter



Russia
LXe Tests
Purification

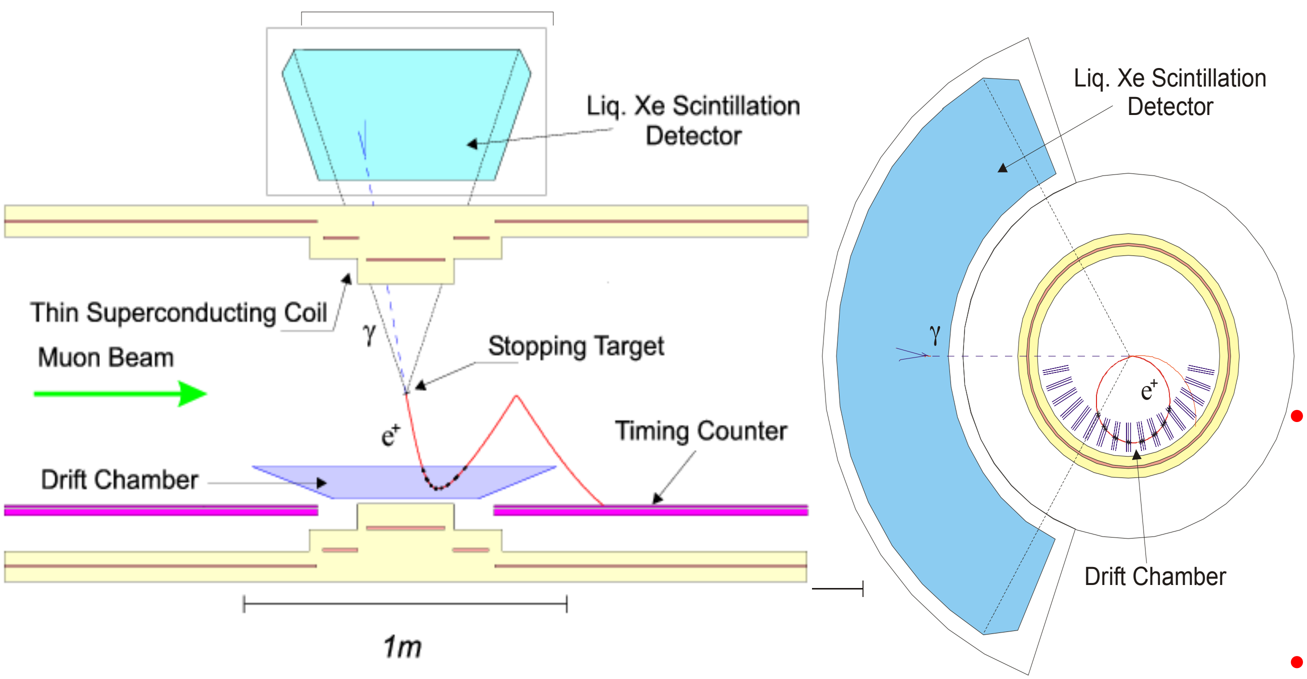


Japan
LXe Calorimeter,
Magnetic spectrometer



Experimental method

Signal selection with μ^+ at rest

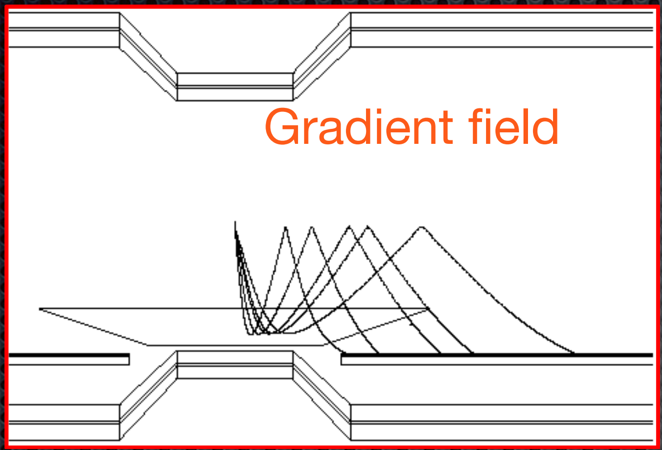


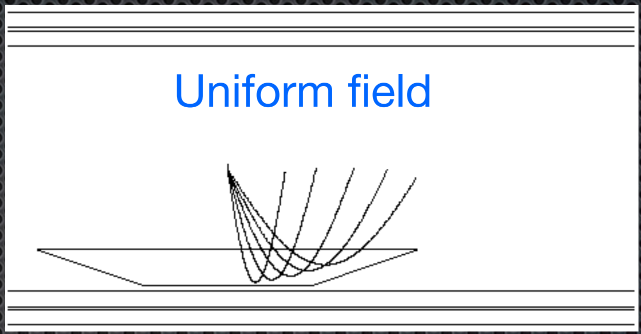
Detector outline

- Stopped beam of $>10^7$ μ / sec in a 150 μm target
- Liquid Xenon calorimeter for γ detection (scintillation)
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- Solenoid spectrometer & drift chambers for e^+ momentum
- Scintillation counters for e^+ timing

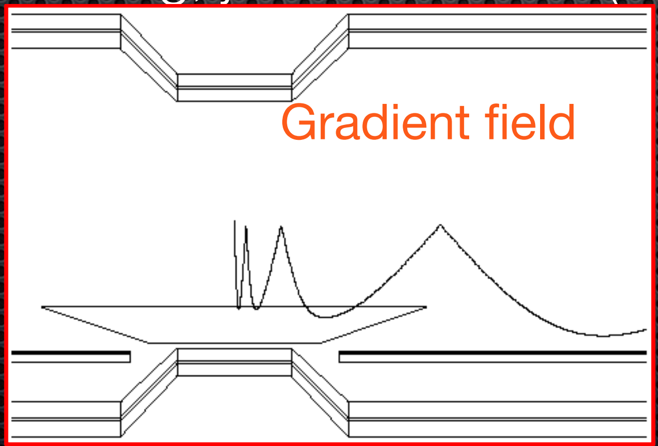
COBRA spectrometer

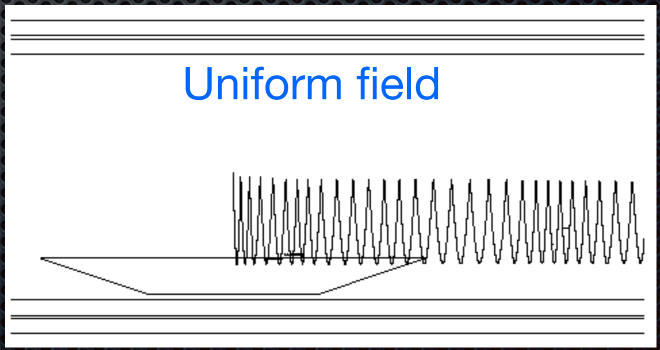
COnstant Bending RAdius (COBRA) spectrometer





- Constant bending radius independent of emission angles
- High p_T positrons quickly swept out
  - at p_L=0, just orbits in a circle! these produce many hits and overwhelm tracking, just ask MEGA (earlier generation at Los Alamos)





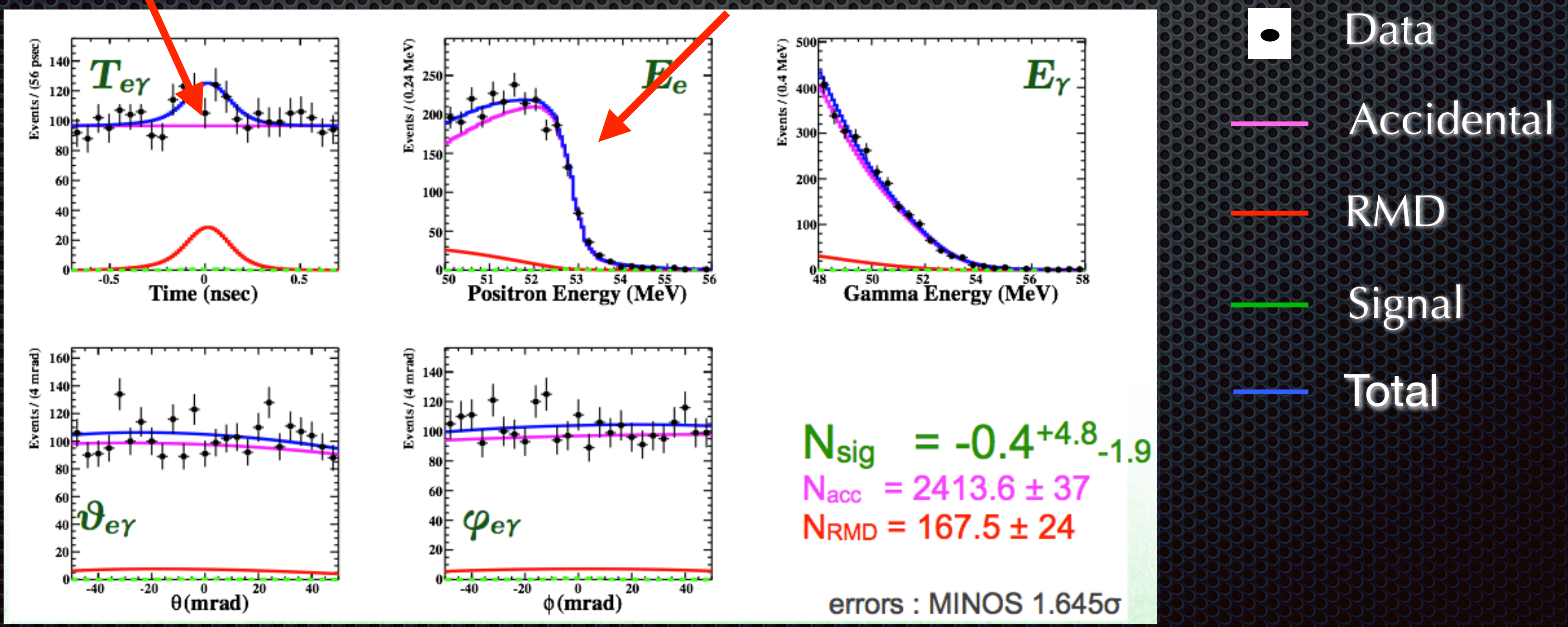
Data

Radiative Muon Decay

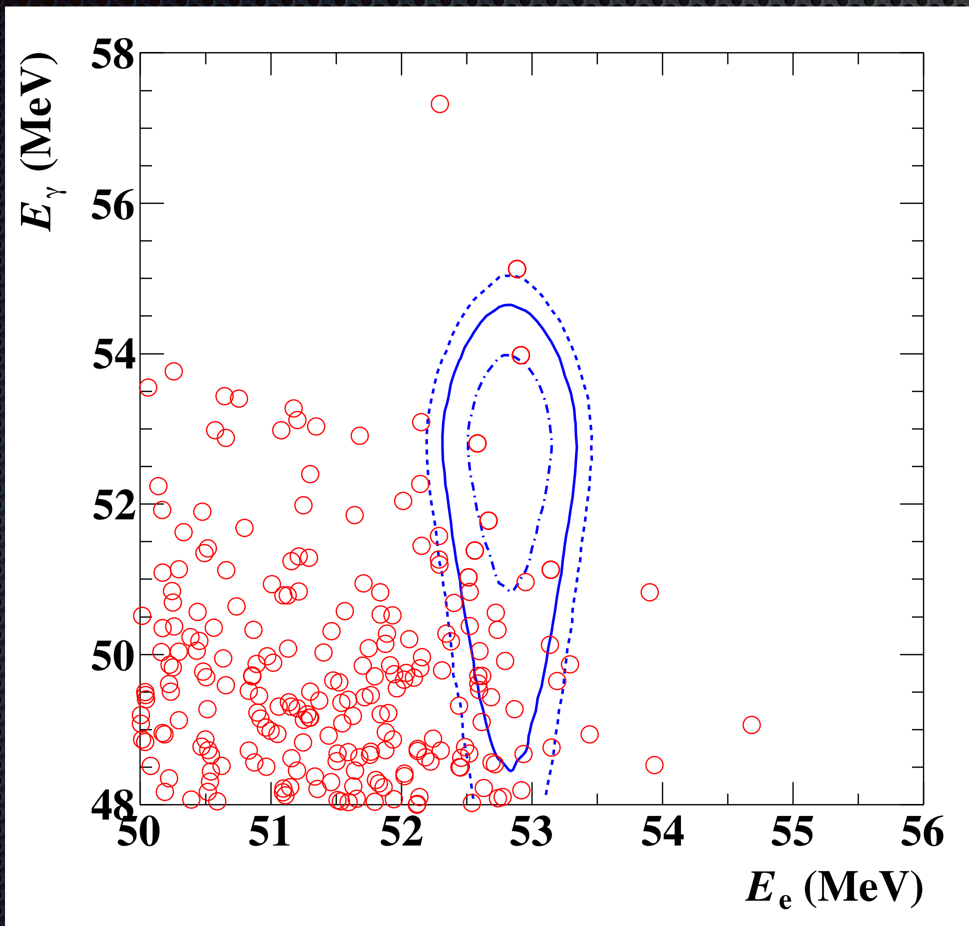
$$\mu^+ \rightarrow e^+ + \gamma + \nu_e + \bar{\nu}_\mu \qquad (1.4 \pm 0.4\%)$$

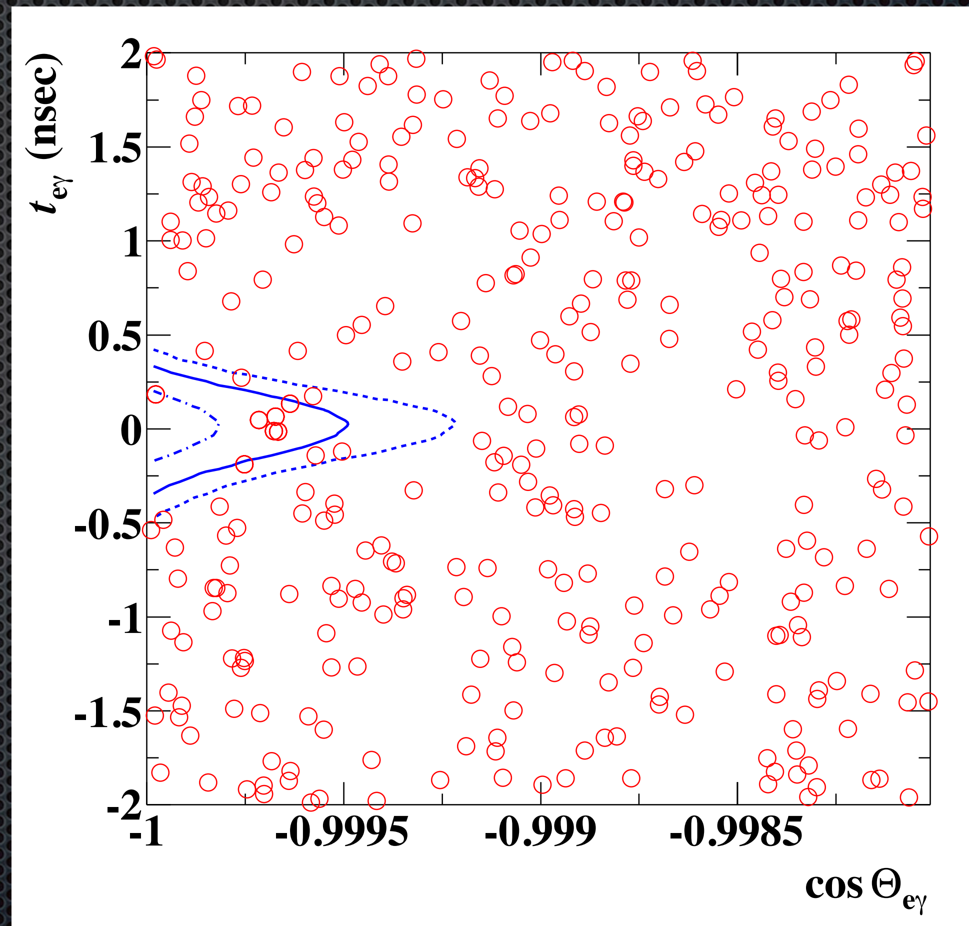
- Backgrounds fitted from sidebands and simulations
- Note features we've discussed

what's this peak? Michel Spectrum



Data: to get better need push on all ingredients



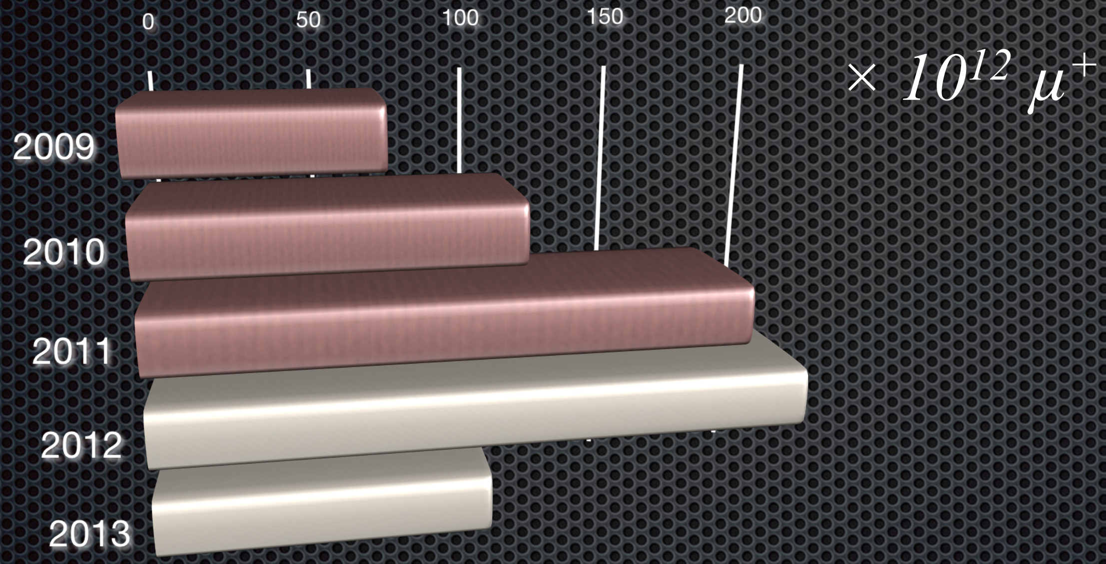


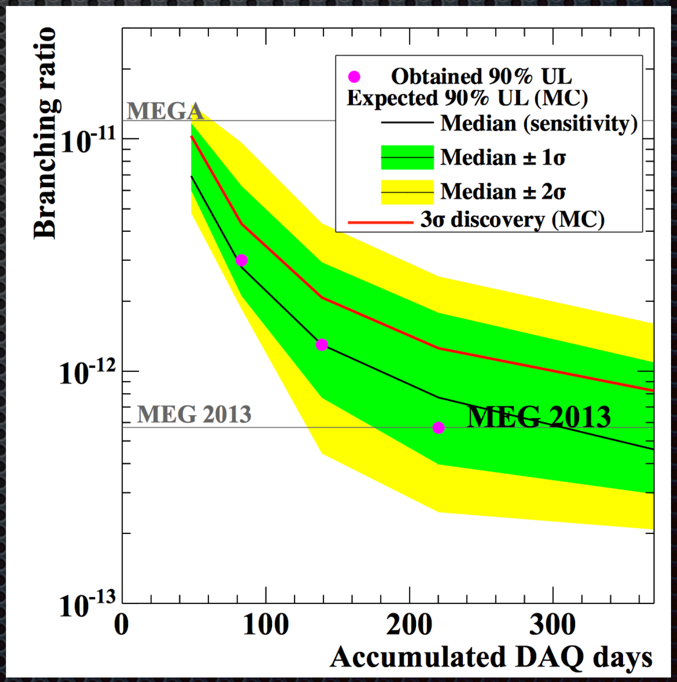
MEG Collab, PRL 110(2013) 201801 or 1303.0754

MEG result

$$\frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 5.7\times 10^{-13} \text{ at } 90\% \text{ CL}$$

- 5×10^{14} μ-stops collected 2009-2013





- Analysis of full data set in progress, results after this summer

MEG Upgrades

- Finished data taking in 2013; upgrades required to improve search.

μ

1. Increasing μ^+–stops on target
2. Reducing target thickness to minimize e^+ MS & bremsstrahlung
3. Replacing the e^+ tracker reducing the radiation length and improving its granularity and resolutions

e

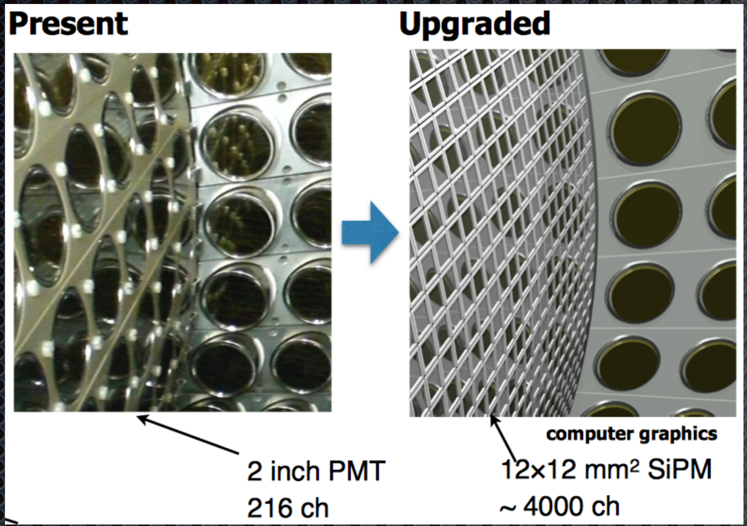
4. Improving the timing resolution between e^+ and γ
5. Improving the γ acceptance, energy, and position resolution
   - improved granularity, reconfiguration, and other upgrades

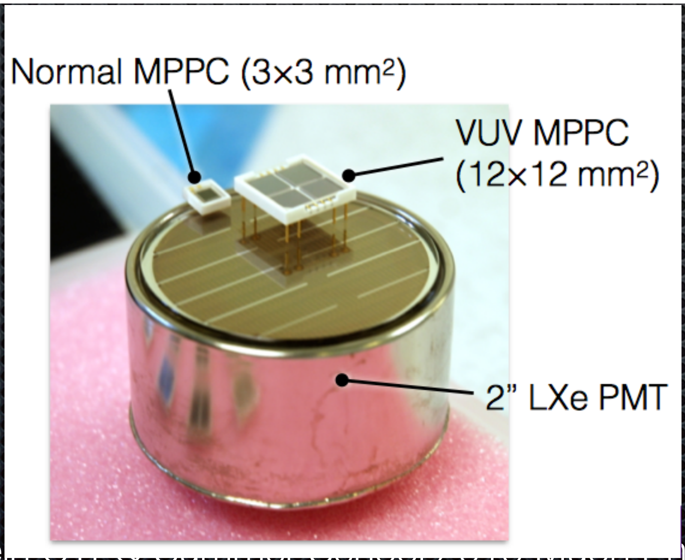
γ

$$B \propto \left(\frac{R_\mu}{D}\right)\left(\Delta t_{e\gamma}\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

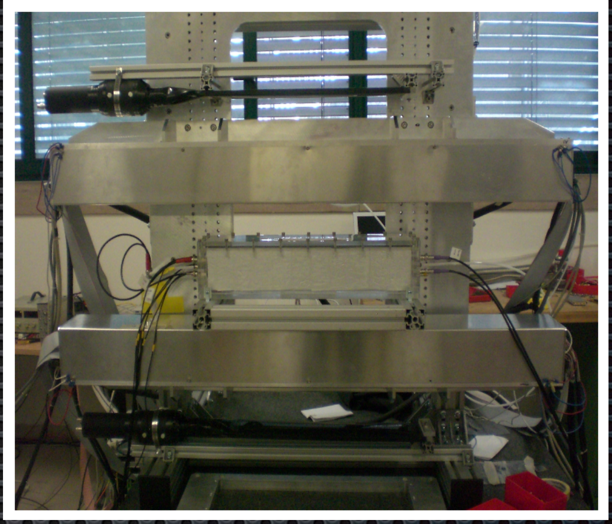
MEG II highlights

- LXe calorimeter
  - x2 better energy/position resolution
  - 10% higher efficiency

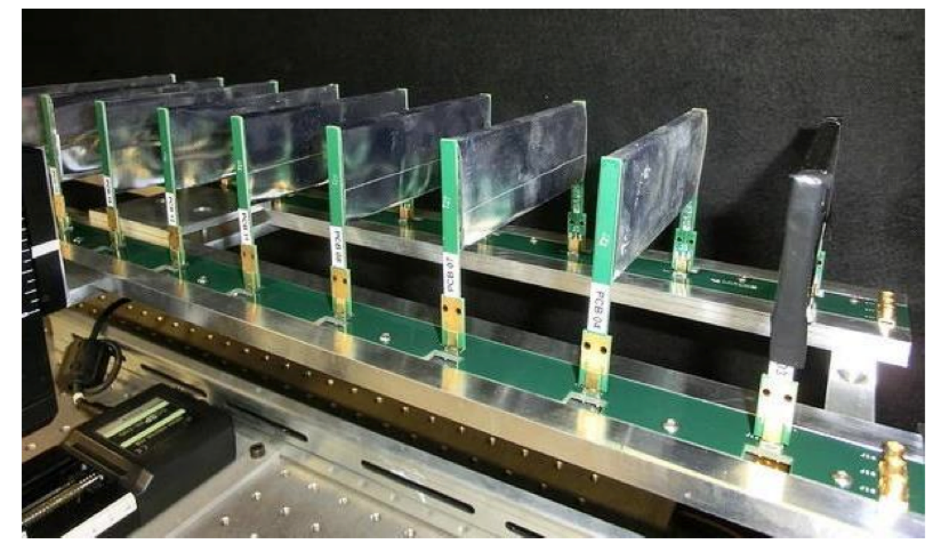




- Cylindrical Drift Chamber
  - single hit resolution ~120 μm



- Pixelated timing counters
  - σ ~ 40 ps

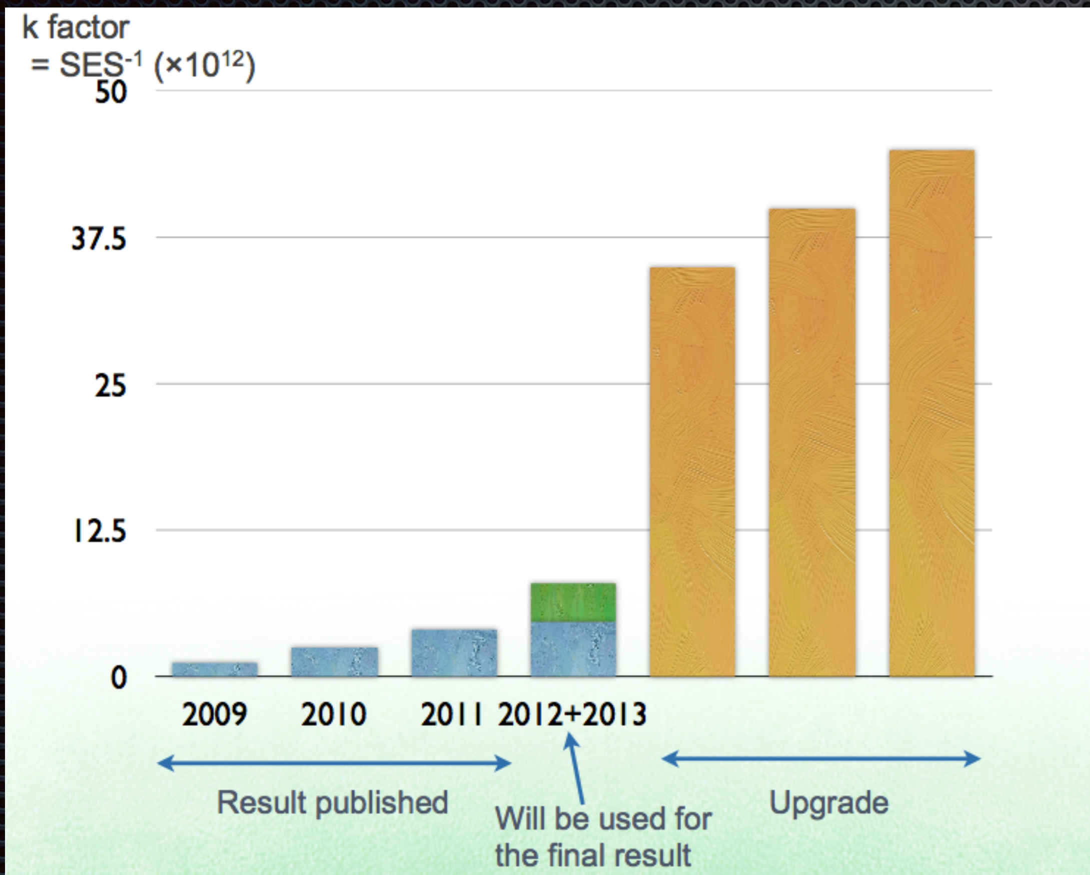


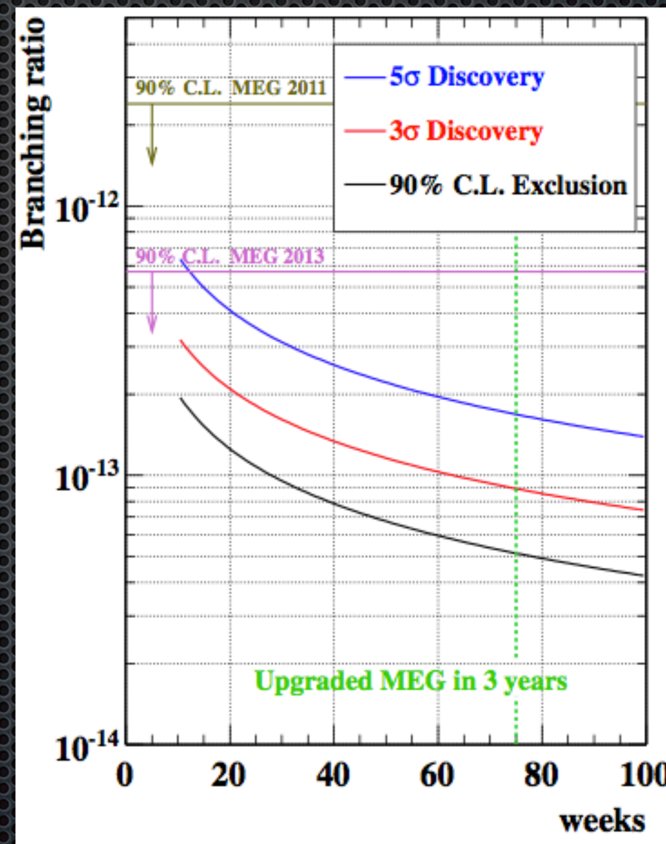
MEGII sensitivity

L. Galli

- New resolutions and acceptances ⇒ ultimate sensitivity at the few x 10^{-14} level
- Engineering run 2015
- Data taking 2016-2018

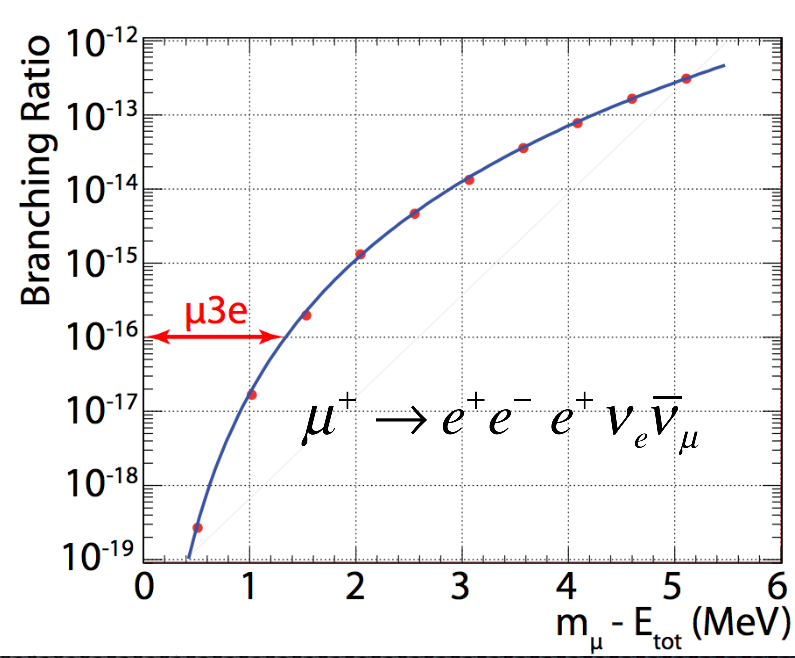
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |

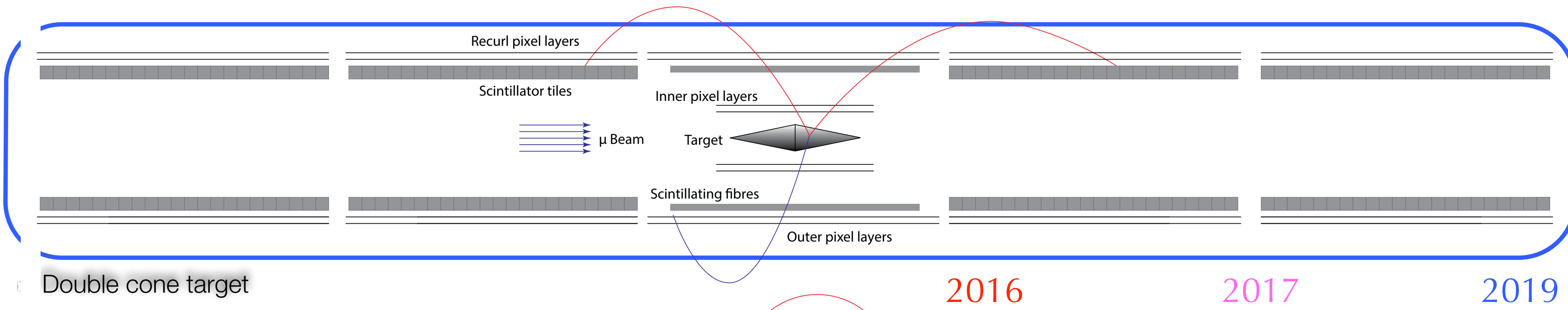




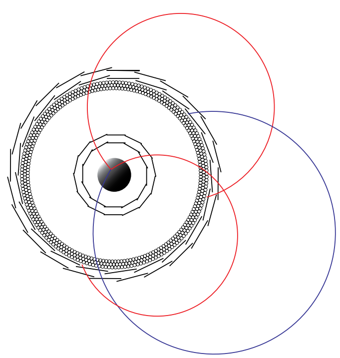
Mu3e at PSI

- Search for $\mu \to e\, e\, e$
  - 10^{-15} sensitivity in phase IA / IB
  - 10^{-16} sensitivity in phase II





- Double cone target
- HV-MAPS ultra thin silicon detectors
- Scintillating fibers timing counter (tiles from phase IB)
- O(6 hits!) for electron - positron tracks

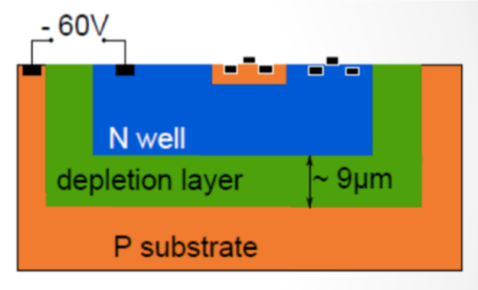


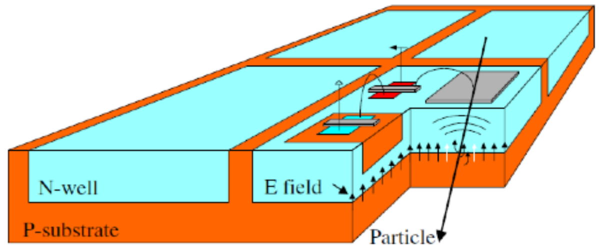
Mu3e detector technology

- Ultra-thin devices are necessary to suppress multiple scattering
- HV-MAPS
  - thinned down to 50 μm
  - amplification and digitization on chip
  - fast readout to get a <50 ns timestamp

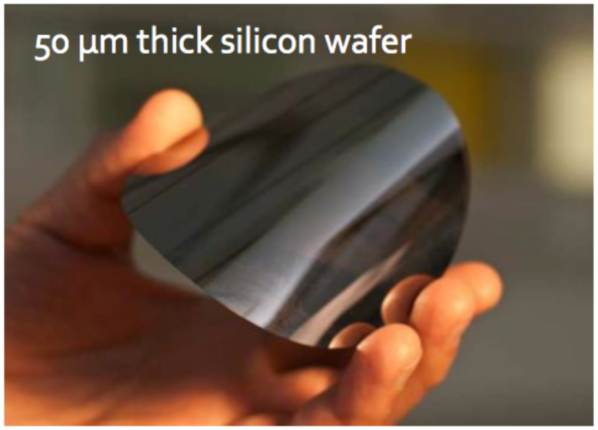
- 50 μm Silicon sensor
- 25 μm Kapton flexprint
- 25 μm Kapton support frame

$\rightarrow \sim 1$ ‰ Radiation length





(High voltage monolithic active pixel sensors)
I. Peric et.al. NIMA 582 (2007) 876

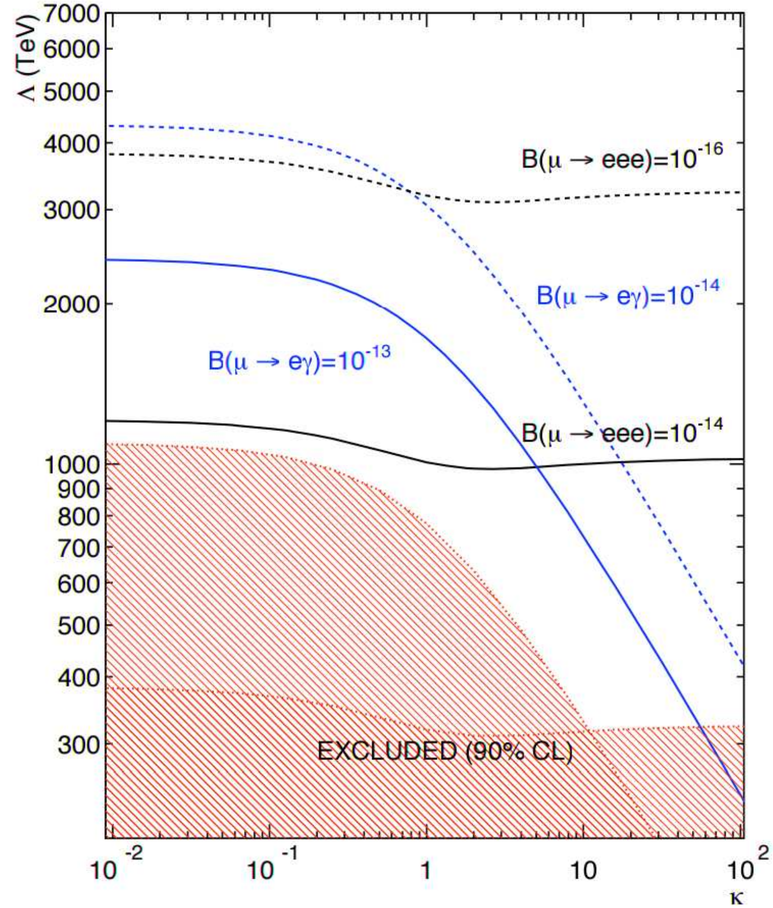


Physics Reach

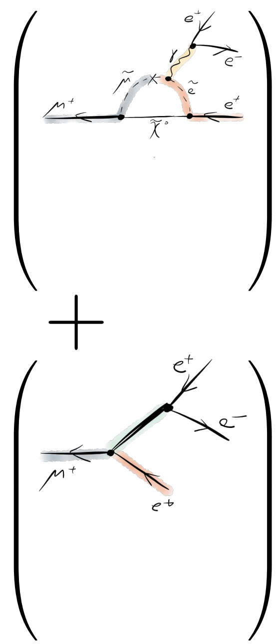
- Have to be a little careful about comparisons since diagrams are different, but in same range as other muon experiments

Mu3e/MEG Processes

Corrodi, BLV2015



$$\frac{m_\mu}{1+\kappa}\Lambda^2$$



$+$

$$\frac{\kappa}{1+\kappa}\Lambda^2$$

A. Gouvea1 and P. Vogle, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model, arXiv:1303.4097 (2013)

1 / 3

Long Section on My Expt

Muon to Electron Conversion

muon converts to electron in the field of a nucleus

nucleus does not change

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

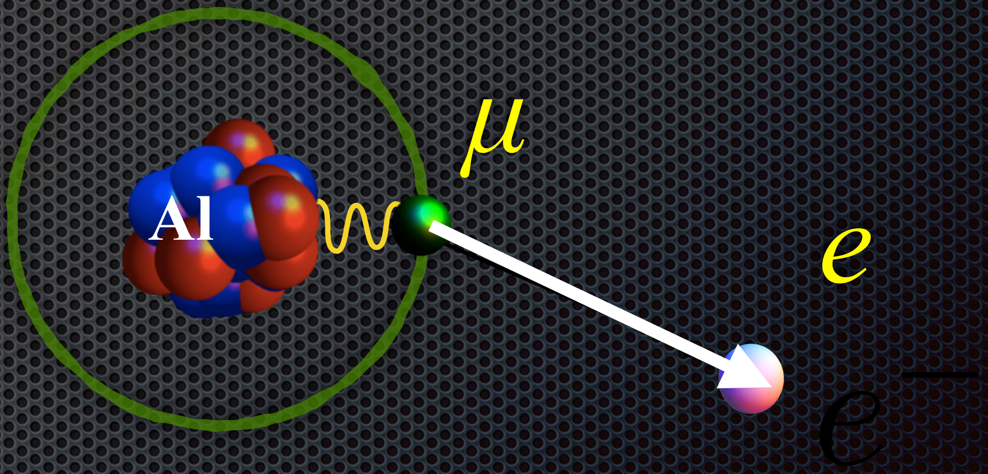
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Charged Lepton Flavor Violation (CLFV)
  - goal: measure a signal with SES of 2.4×10^{-17}
- Standard Model Background of 10^{-52}
- Related Processes: μ *or* $\tau \rightarrow e\gamma$, $\tau \rightarrow 3l$, $K_L \rightarrow \mu e$, and more

Experimental Signal

- A Single Monoenergetic Electron
- If N=Al, E_e = 105. MeV
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup
- Note this is a negative, *captured* muon unlike the positive, *stopped* muon in $\mu \to e\gamma$

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



Requirements

- $R_{\mu e} = 2.9 \times 10^{-17}$ (7×10^{-17} @ 90% C.L.)
- Statistics
  - Requires ~10^{18} stopped muons
  - Requires ~3.6×10^{20} protons on target
  - 3 years data taking
  - Fewer than 1 expected background events
- Discovery sensitivity: $R_{\mu e} >$ few x 10^{-16}

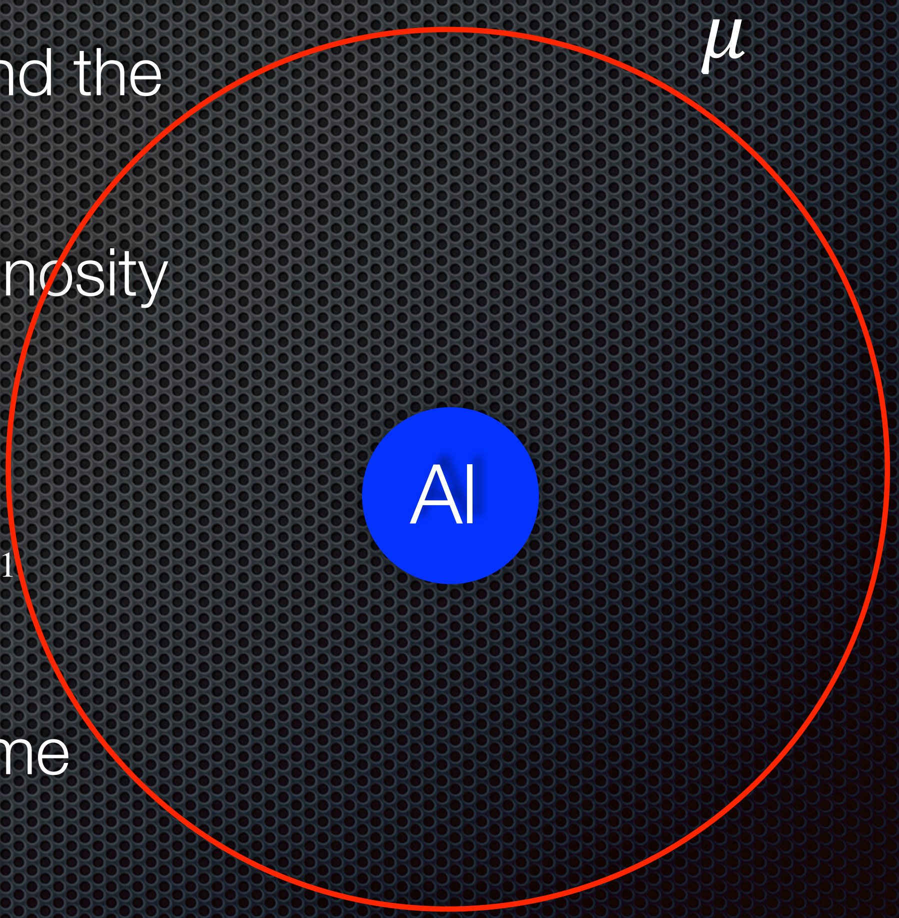
Measuring 10^{-17} in Collider Units

pic close to scale

- The captured muon is in a 1s state and the wave function overlaps the nucleus
- 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} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$



A. Czarnecki, clfv.le.infn.it

Understanding the Normalization

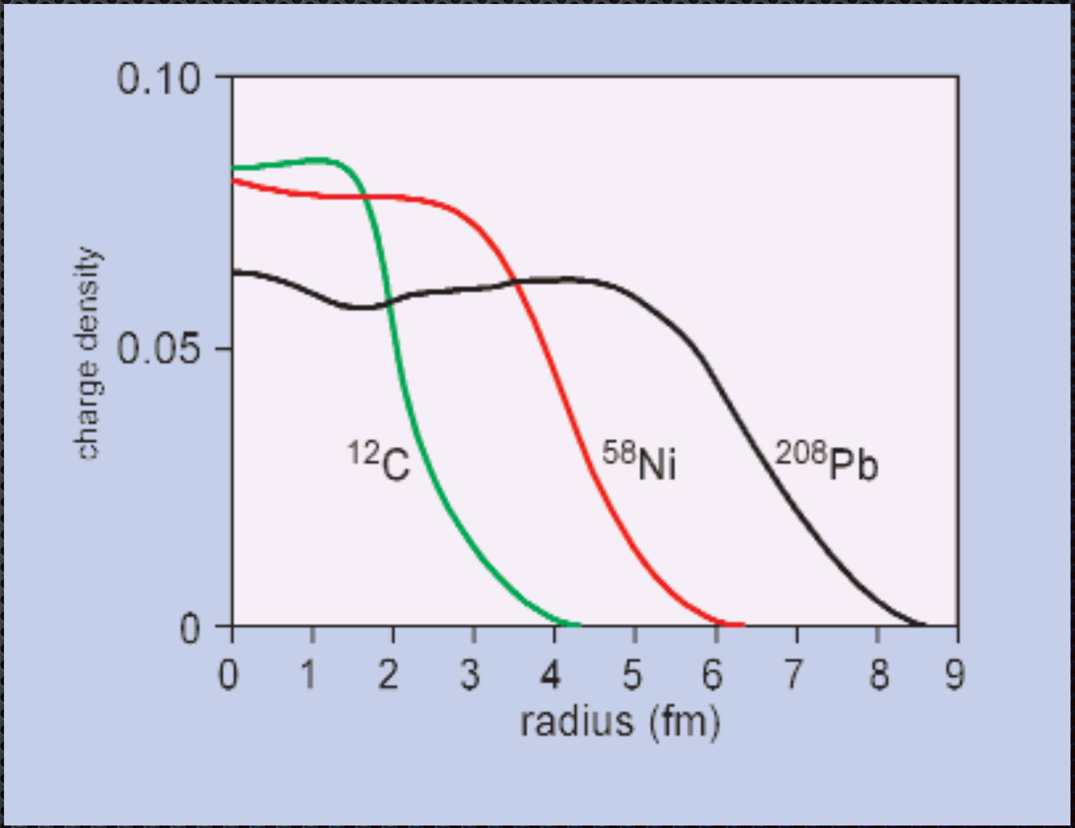
- How does the muon get captured by the nucleus?
  - through the strong interaction
    - (and many details cancel in the ratio we measure)
- But first the wave functions have to overlap:
  - what's the Bohr radius for a 1s muon in Aluminum?

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

$$= 20 \text{ fermi}$$

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:

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

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

τ = 864 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:

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

- *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 famous theorist got it wrong and a team of experimenters worked for a year as a result*
  - hint: don't trust your profs to do everything right

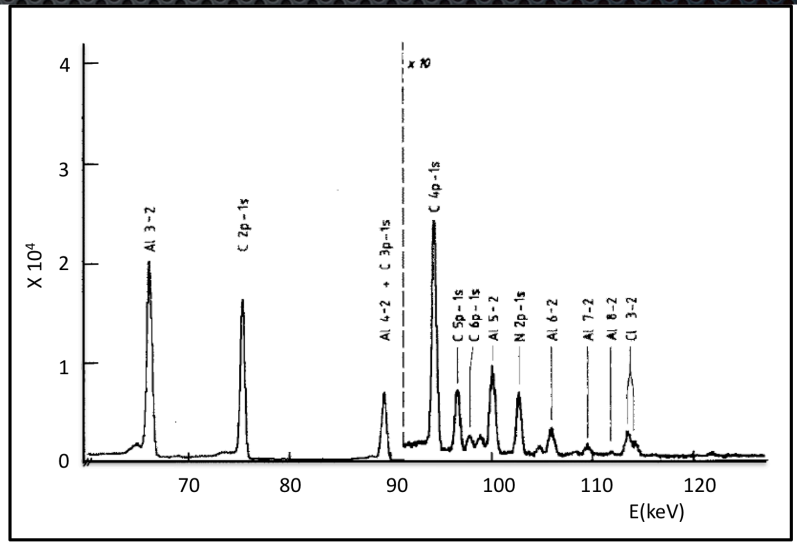
What Can Happen to a Muon in the 1s State?

- The muon can
  - be captured and “fall in” to the nucleus
    - *this is our normalization*
  - magically convert into an electron
    - *this is our signal*
  - decay while in the 1s state
    - *this is our background*

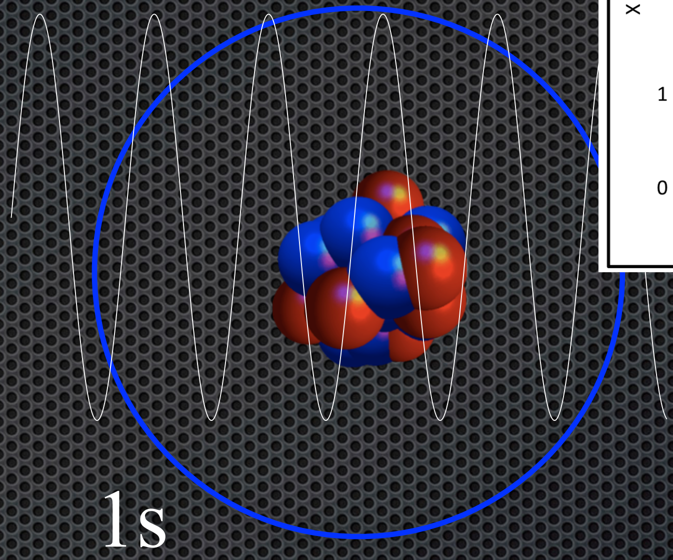
The Capture Process, part 1:

muon stops by dE/dx

μ



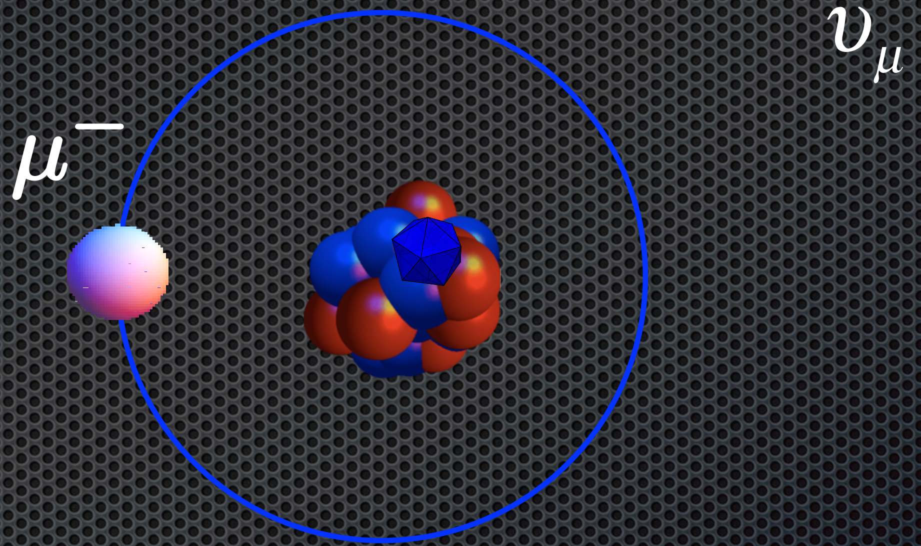
detect photons for normalization



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

X-Rays from cascade (occurs in ≤ psec)

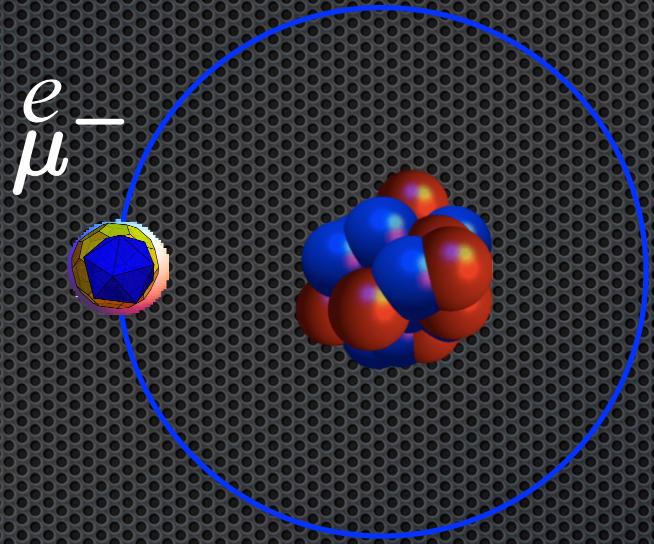
The Capture Process, part 2:



Al(27,13) →Mg(27,12)

What Does a Decay Look Like?

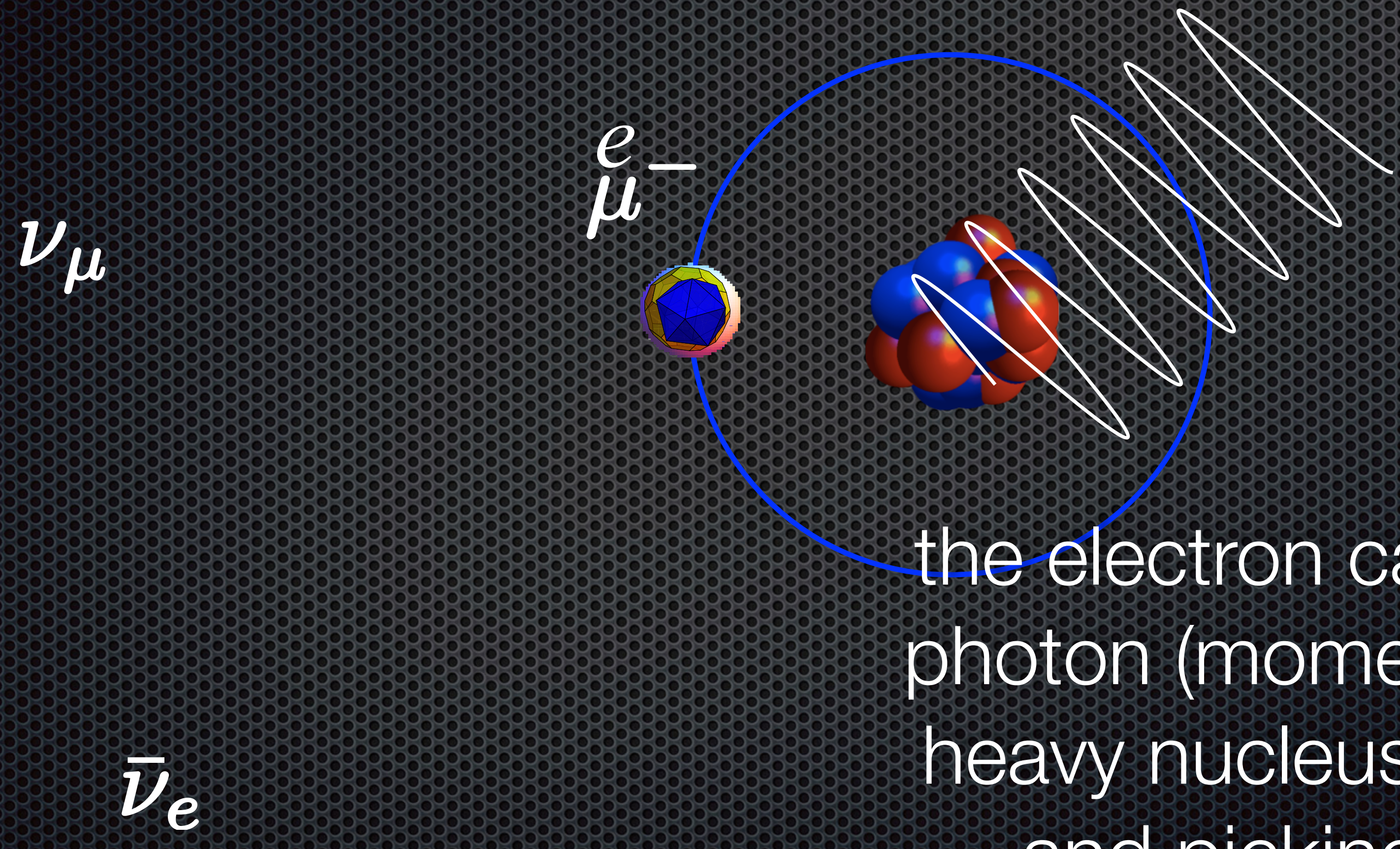
ν_μ



$\bar{\nu}_e$

How Does This Change Near A Nucleus?

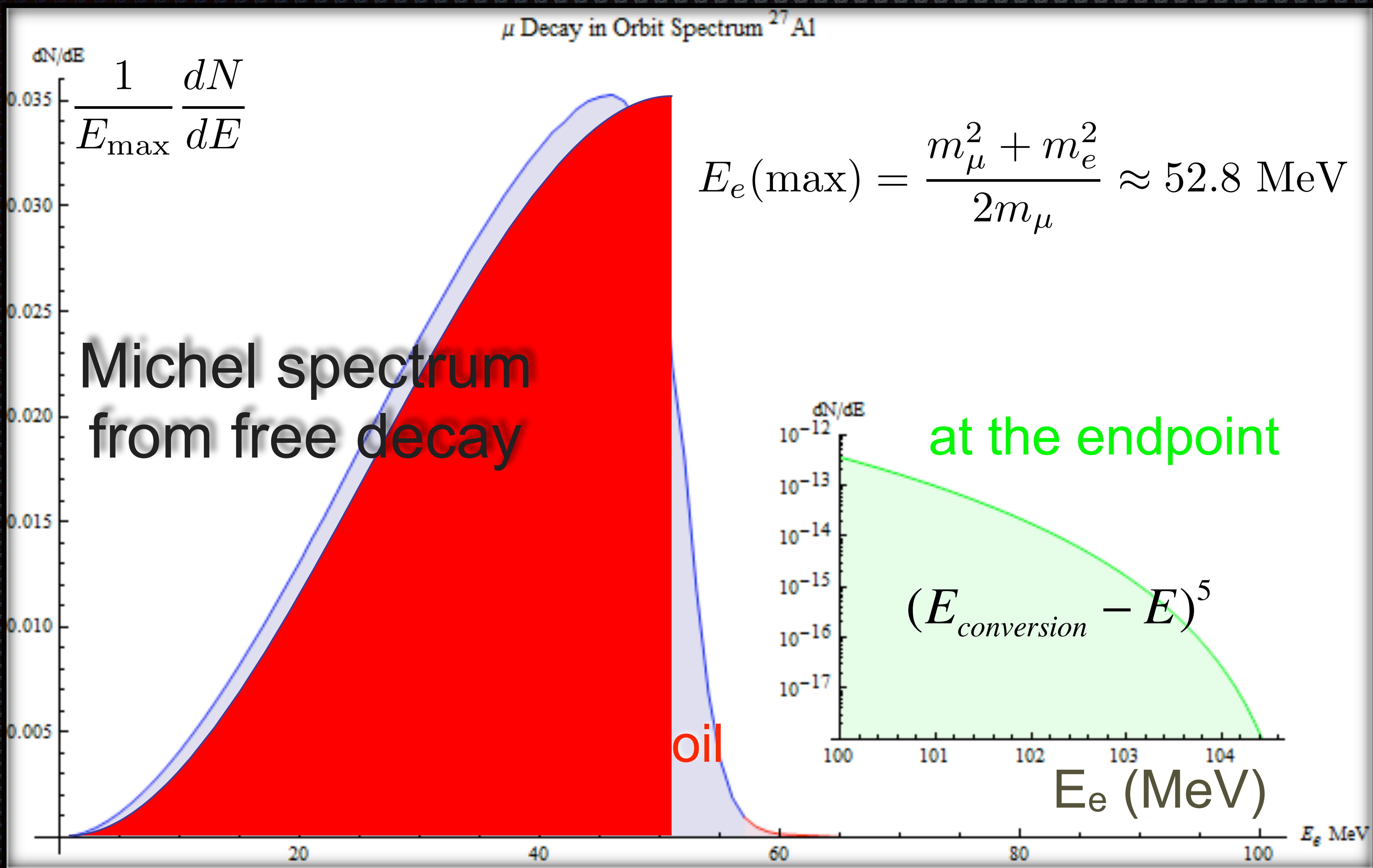
Background



the electron can exchange a photon (momentum) with the heavy nucleus, bouncing off and picking up energy

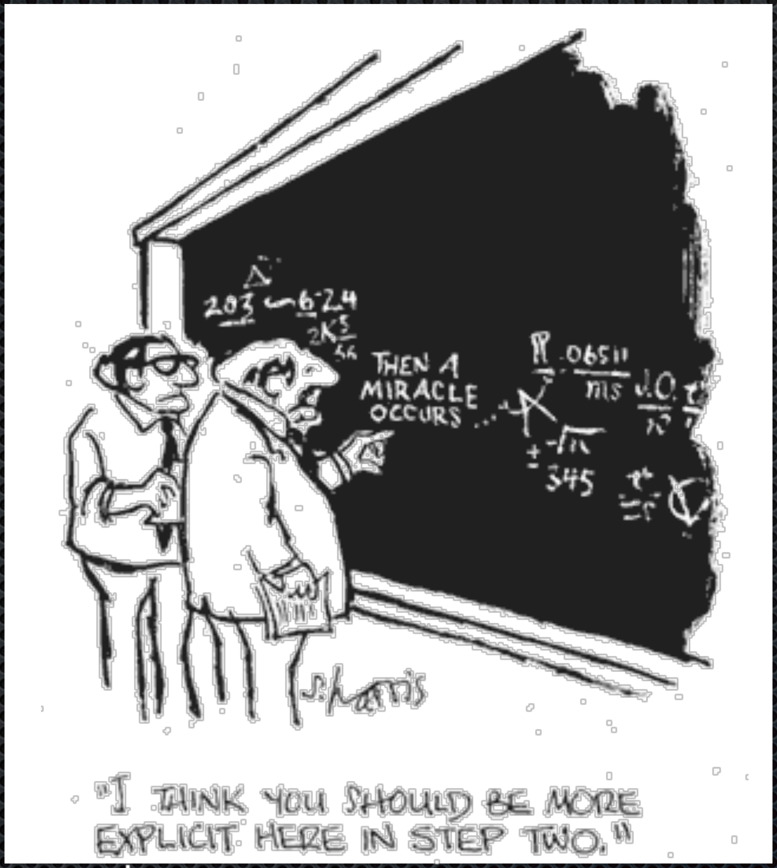
Decay-in-Orbit Shape

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



What Does a Conversion Look Like?

first it's a muon



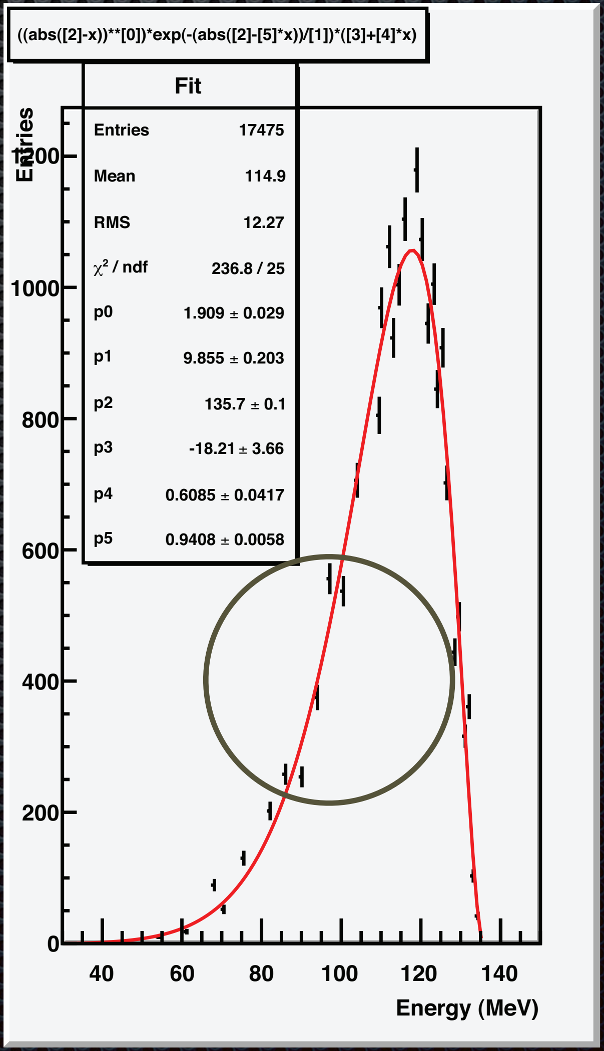
then it's an electron

e^-

new physics!

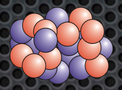
Prompt Backgrounds

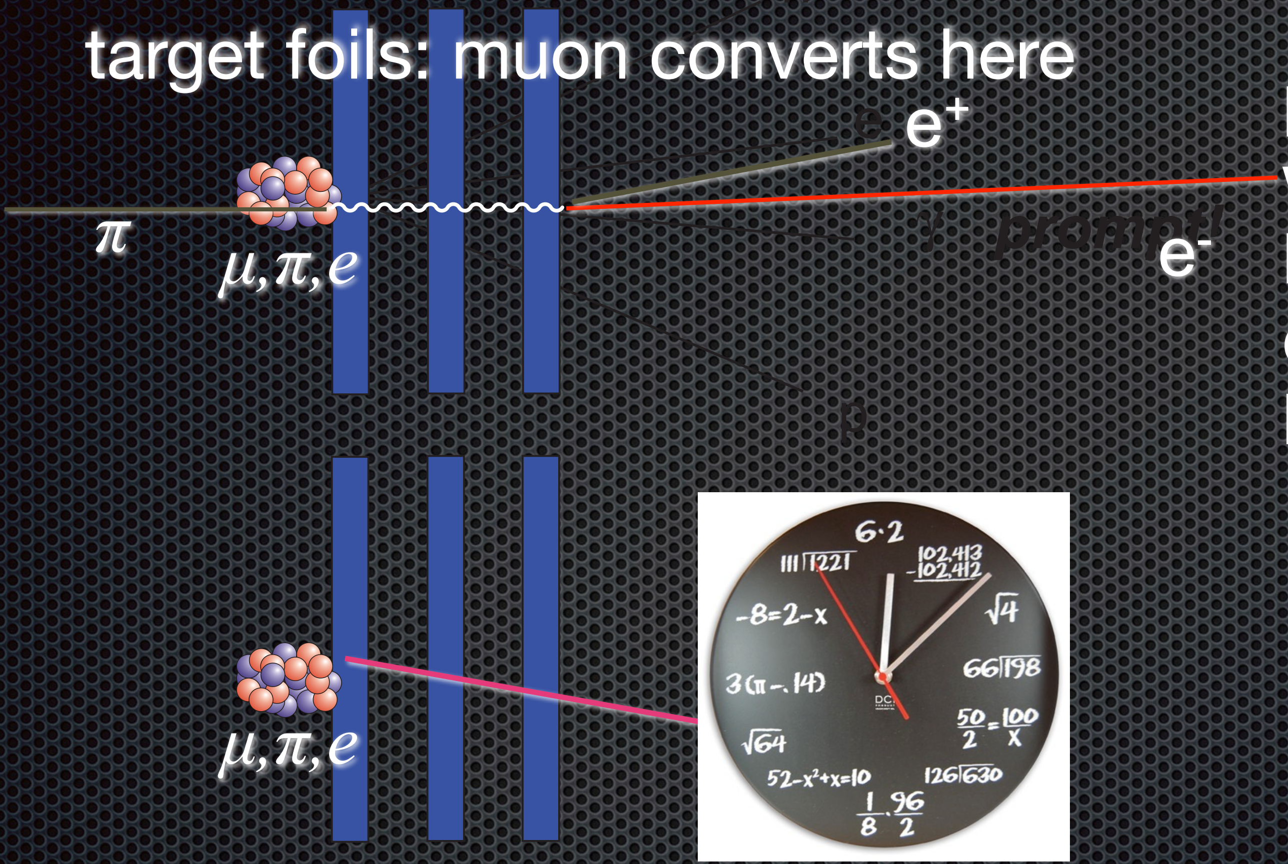
- Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars
- Radiative pion capture, $\pi^- + A(N,Z) \rightarrow \gamma + X$.
  - γ up to m_π, peak at 110 MeV; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like 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)

Prompt backgrounds and Pulsed Beam

 = muons, electrons, pions



delayed 105 MeV electron

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

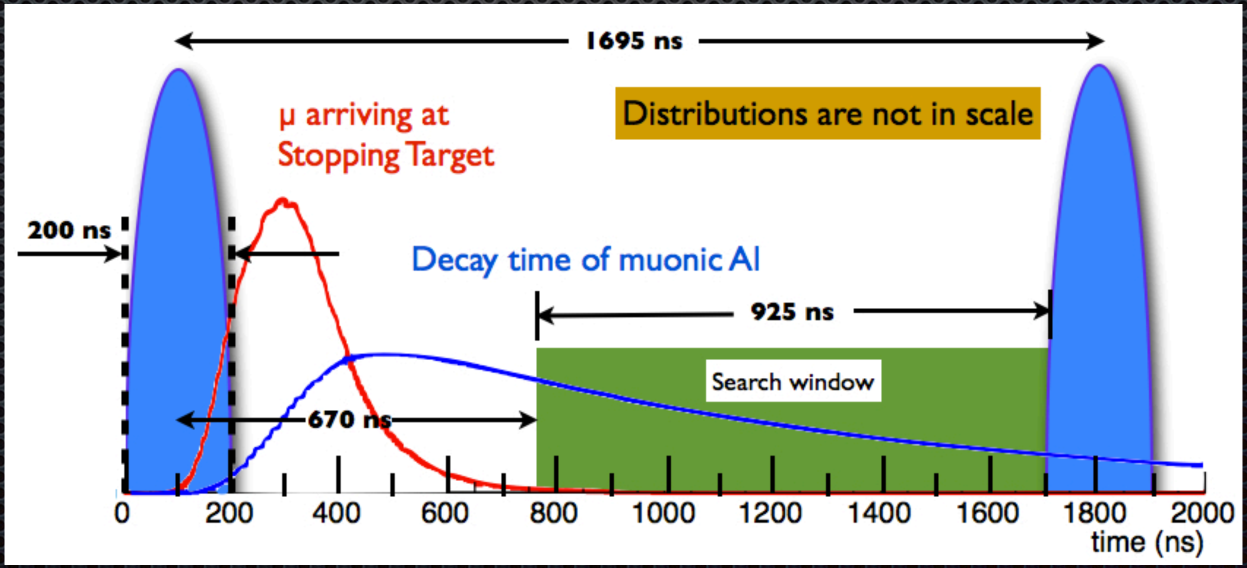
Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

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

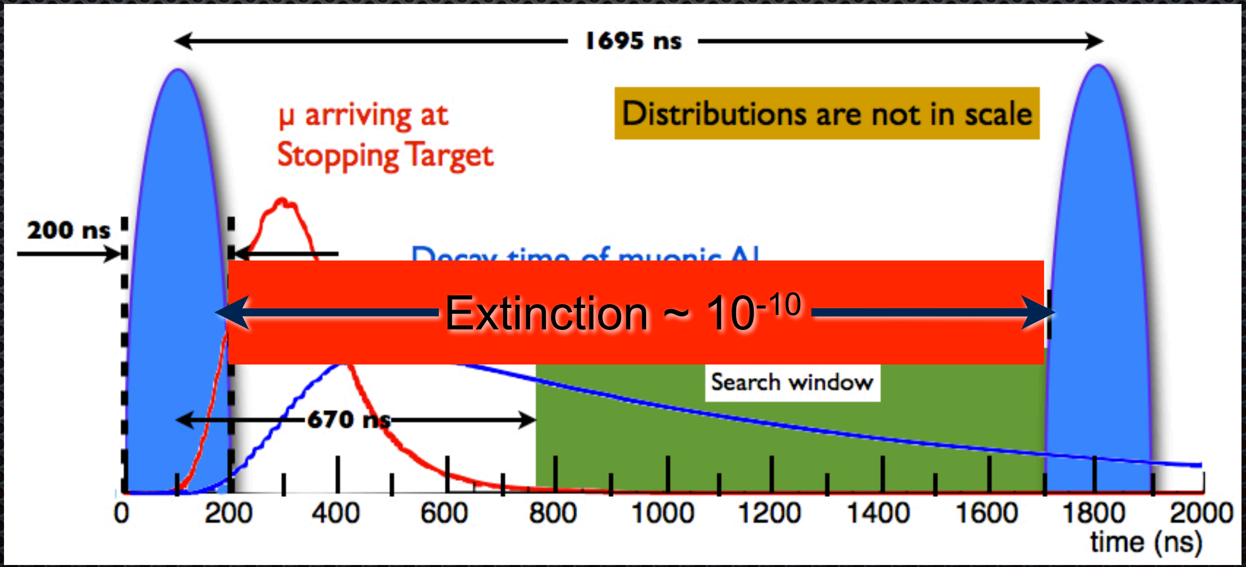
Pulsed Beam Structure

- Pulsed beam suppresses many "prompt" backgrounds for muon capture experiments
  - different from MEG (stopped muons)
- Want pulse duration << τ_μ^{Al}, pulse separation ≈ τ_μ^{Al}
  - FNAL time structure: 1.7μsec , ~x2 τ_μ^{Al} = 2(864 nsec)



Extinction

- No "new" beam after initial pulse, since it would reset clock and remove advantage of waiting out short pion lifetime
- Can't use kicker as in MuCap: 2 μsec lifetime too fast
- Have a dipole oscillating at beam frequency to sweep beam into collimators



Antiprotons

- If antiprotons get to the stopping target, annhiliations make pions; pions make RPC
- Antiprotons are very slow, don't decay, and evade the extinction suppression, unlike pions born in production target
- These pions are estimated to be the second largest background
- Suppress with collimators and thin windows along beam

Cosmic Ray Veto

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

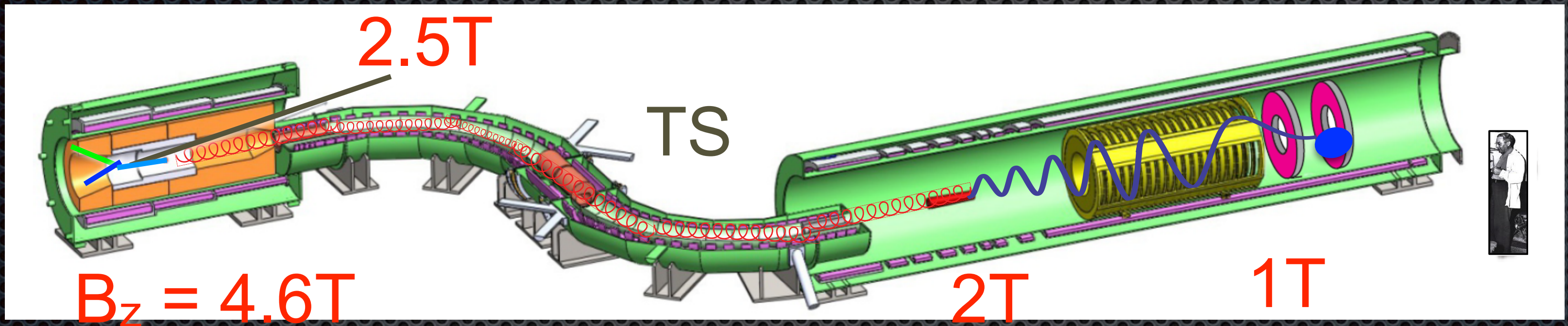
- therefore the experiment needs a 99.99% efficient veto
- in an environment with 10^{10} neutrons/cm^2/sec

Mu2e Muon Beam: Three Solenoids and Gradient

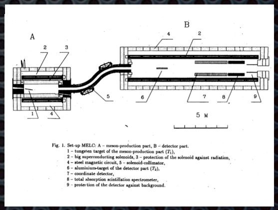
4.6T ⟶ B-field gradient ⟶ 1T

PS

DS



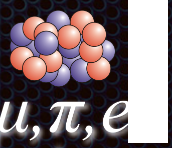
V. Lobashev, MELC 1992:



- 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

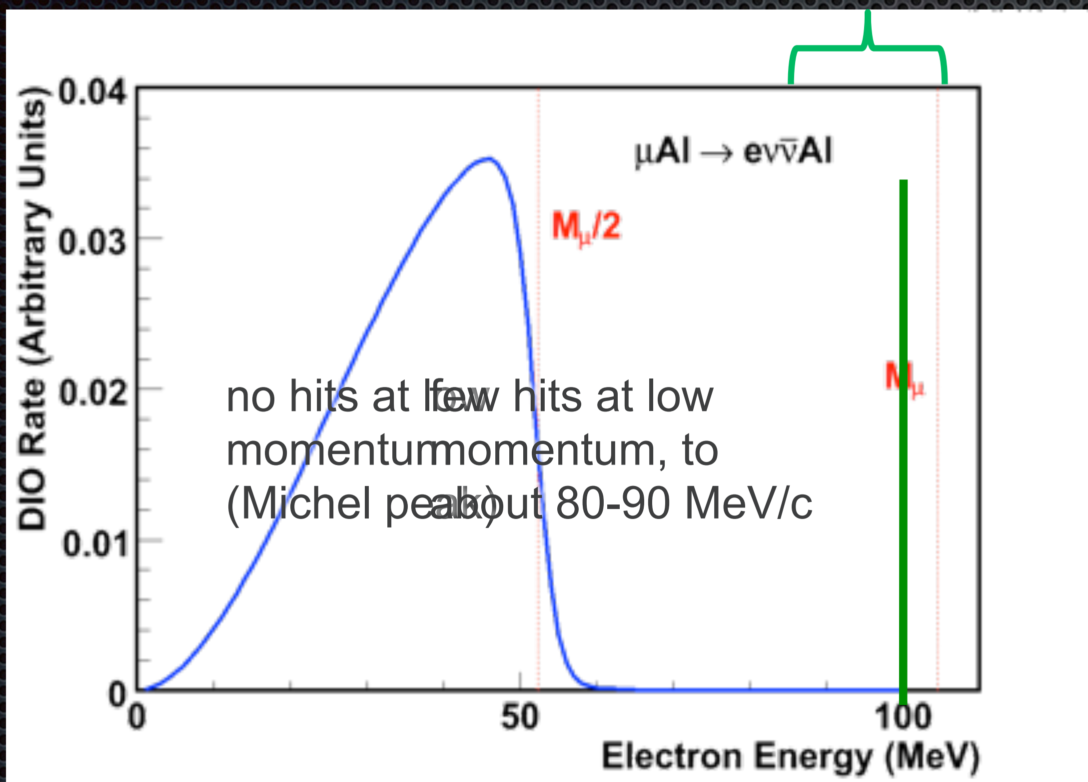


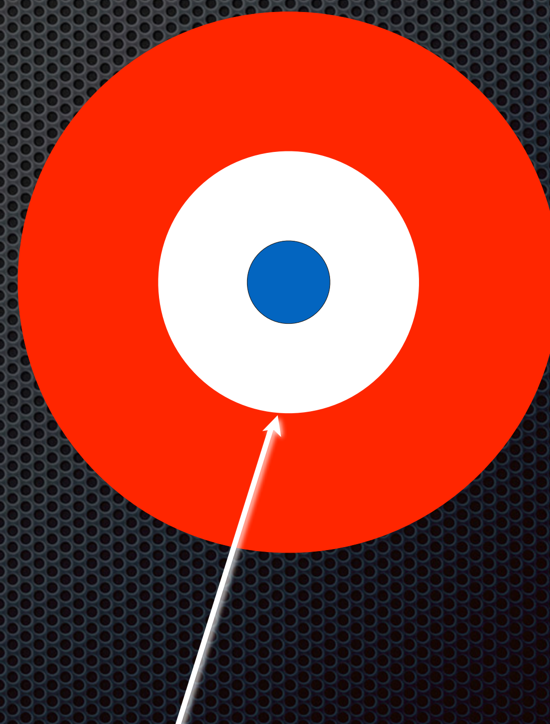
Muon Momentum ~ 50 MeV/c: muons range out in Aluminum

Why An Annular Design?

$p_T = 0.3\ qBR$

> 20 hits
near signal
Reconstructable

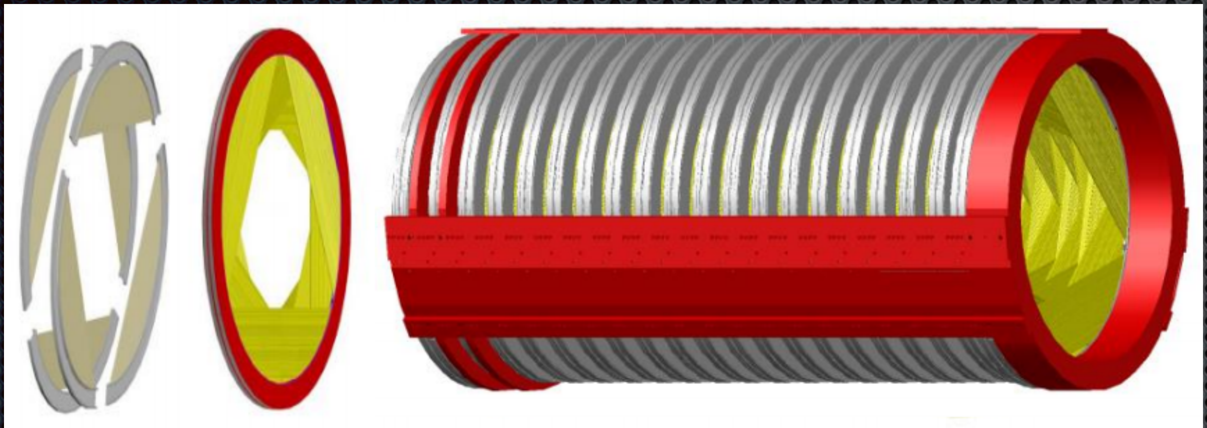


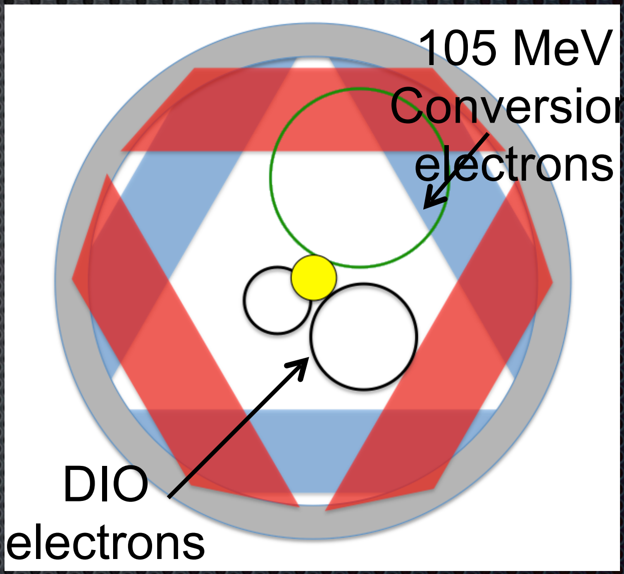


minimum radius to make hits = 38 cm

Tracker

Tracker Structure

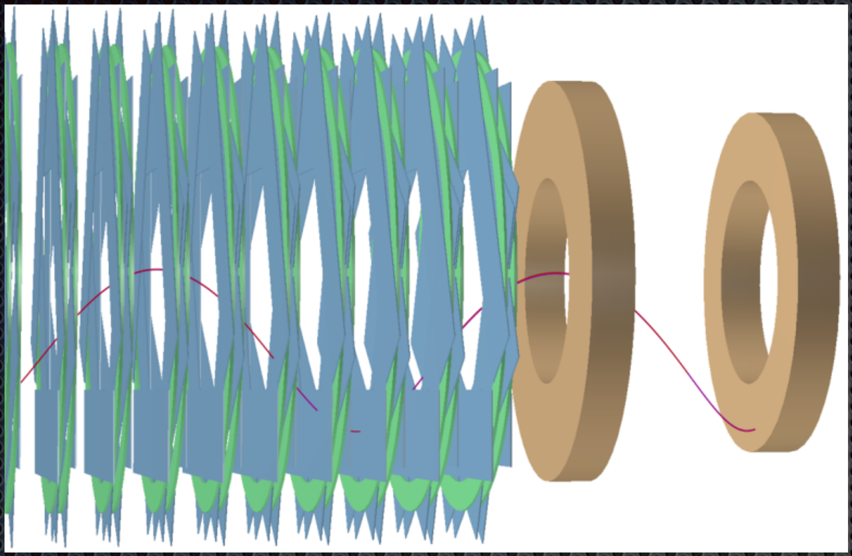


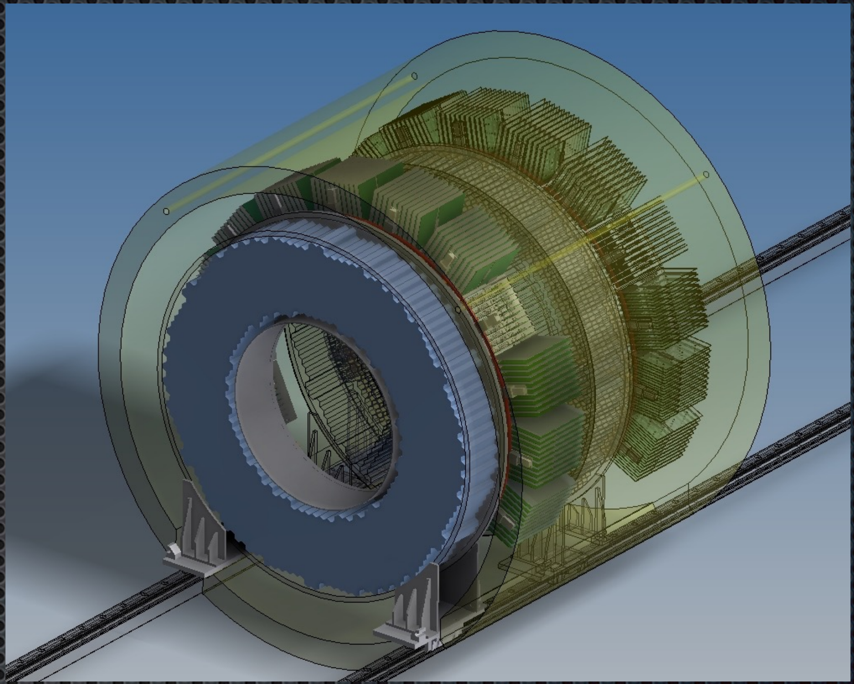


- 5 mm diameter straw drift tubes
- 15 μm Mylar walls, filled with Ar/CO_2
- 18 stations, 2 planes/station, 6 panels / plane
- Blind to beam flash and >97% DIO
- Expect 100 μm hit resolution

Straw Tube

Calorimeter

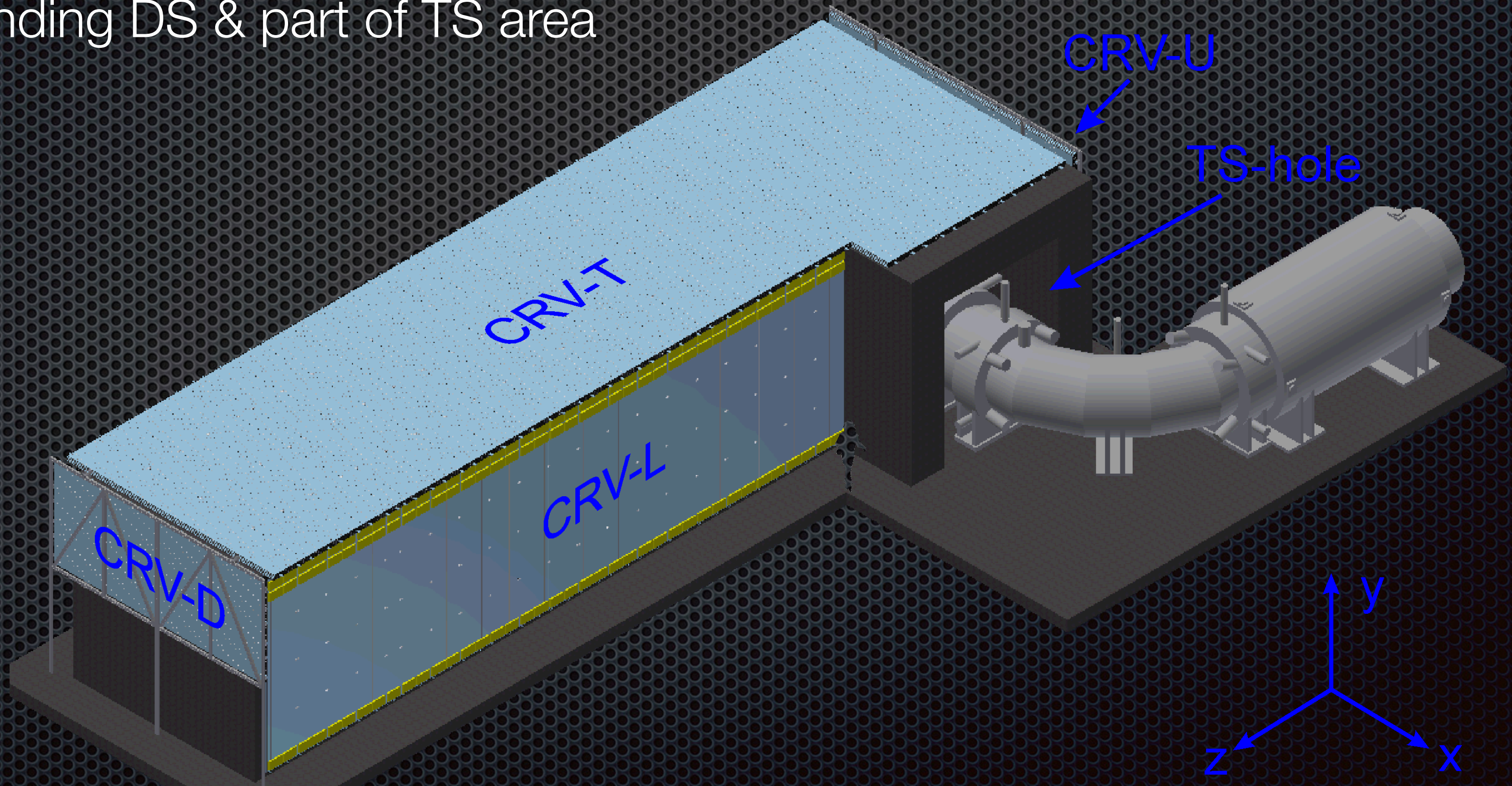




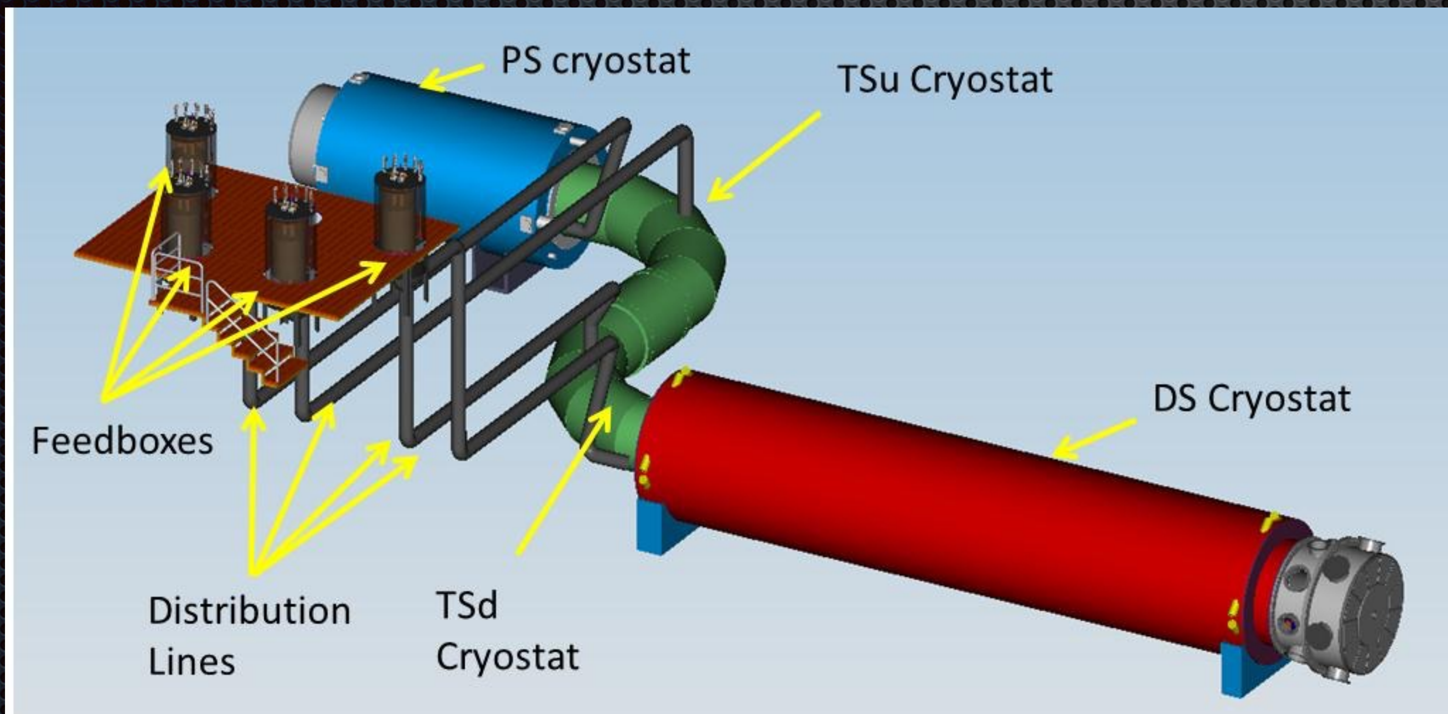
- Two disks composed of square BaF_2 crystals
- Provides independent energy (up to 5%), time (0.5ns) and position (1cm) measurements
- Particle ID, Cosmic Ray rejection, tracking seed
- Independent trigger

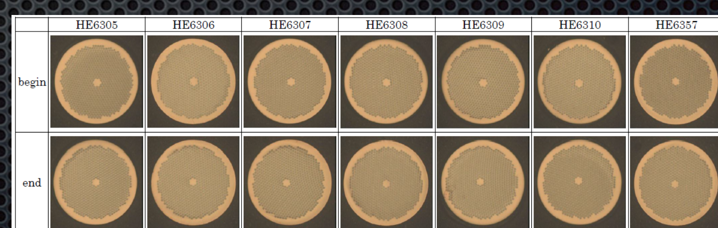
Cosmic Ray Veto

- Cosmic ray background ~1 event / day
- Requires <10^{-4} inefficiency → 0.1 event in 3 years
- Cosmic Ray Veto (CRV) made of 4 layers of overlapping scintillators
- Surrounding DS & part of TS area

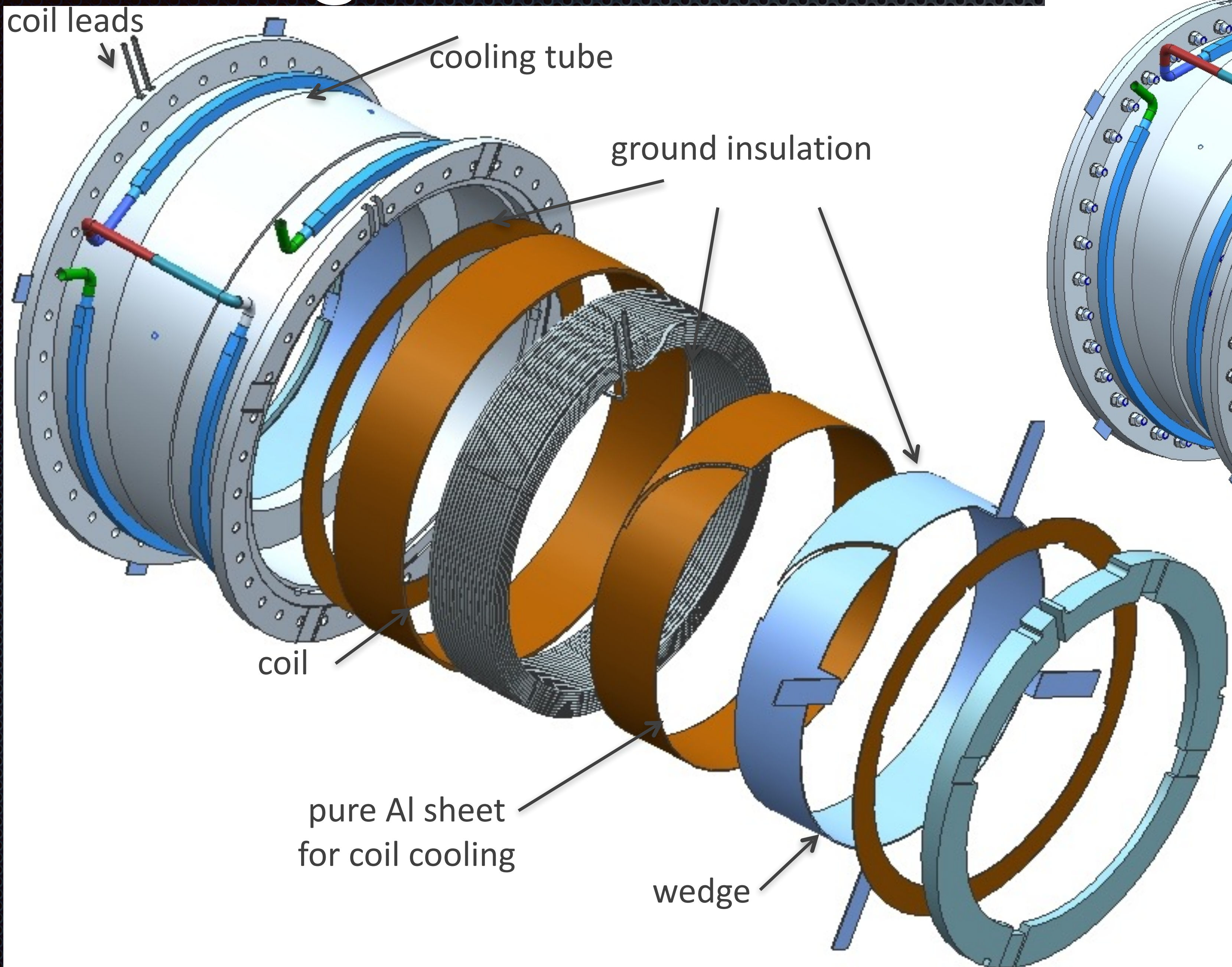


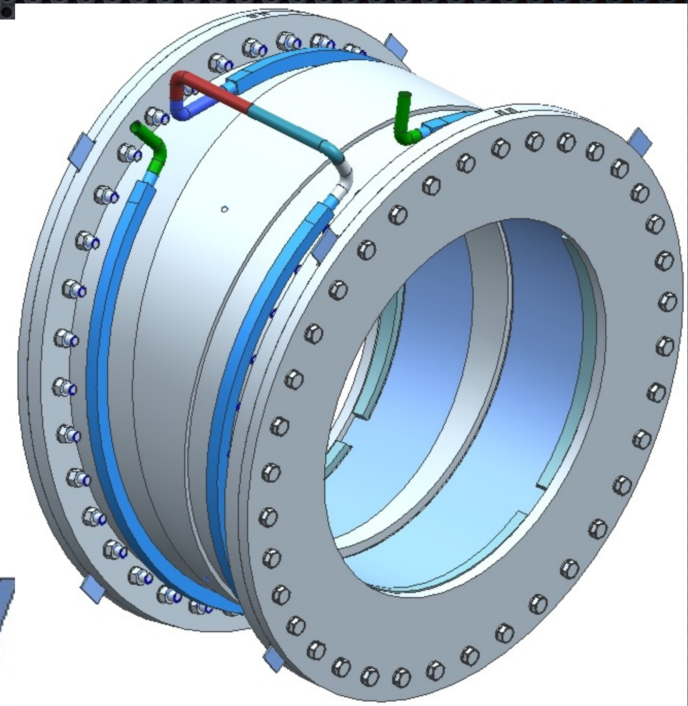
A Few Words About Solenoids





Design – Coil Module



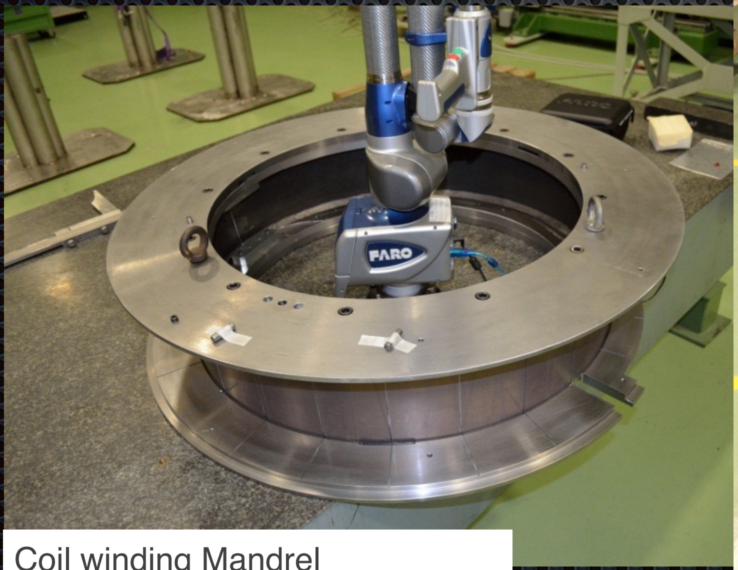


TS Prototype Coil Module Collage

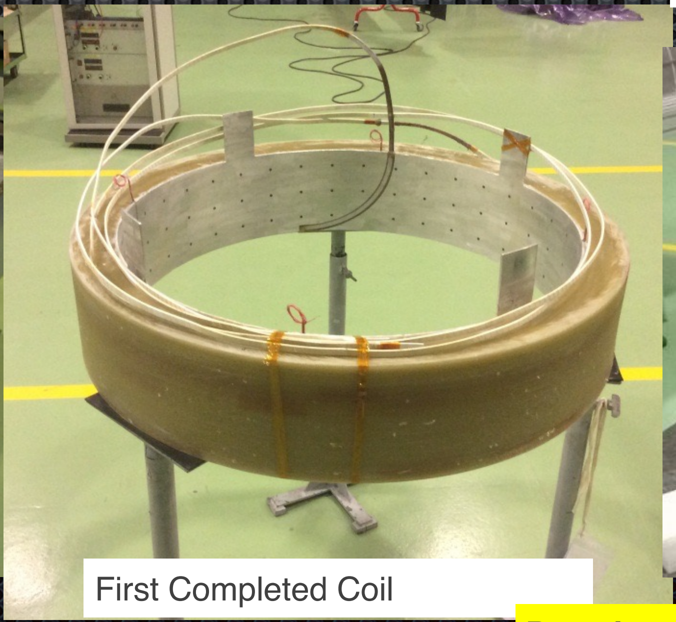
Outer support cylinder casting pre-machined

Machined shell ready for inspection

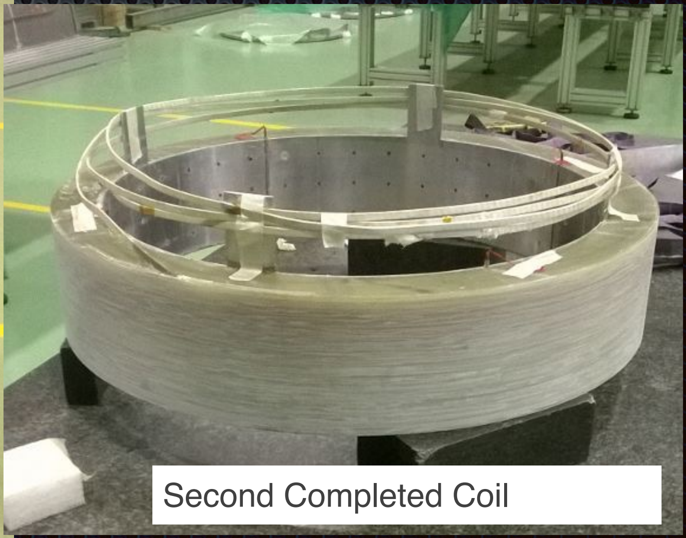
Computer model of outer support cylinder



Coil winding Mandrel



First Completed Coil



Second Completed Coil

Proprietary Assembly tooling not shown!

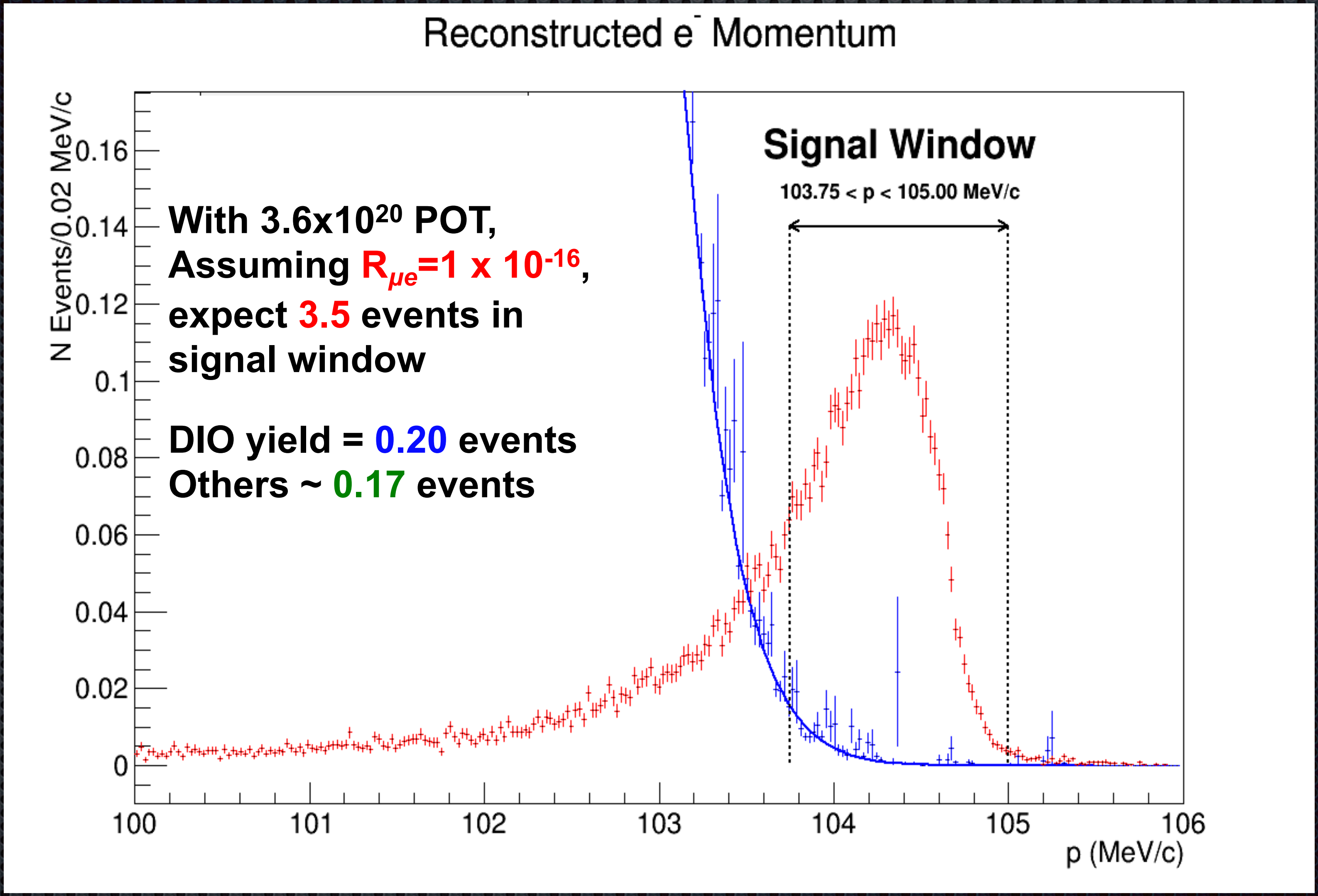
TS Module

Can see wound cable and current lead

Production Orders

	Prototype Length	Production lengths needed for coil winding	Spare production lengths	Total Production Length
Transport Solenoid	*3x1000m*	*14x1540mm* *22x800*	*2x1540m* *2x800m*	*~ 44km*
Detector Solenoid 1	*200m*	*8x1100m*	*1x1100m*	*~ 10km*
Detector Solenoid 2	*200m*	*3x1750m*	*1x1750m*	*~ 7km*
Production Solenoid	*200m*	*3x1700m* *2x1300m* *1x1500m*	*3x1700m*	~ 14km

Signal and Backgrounds



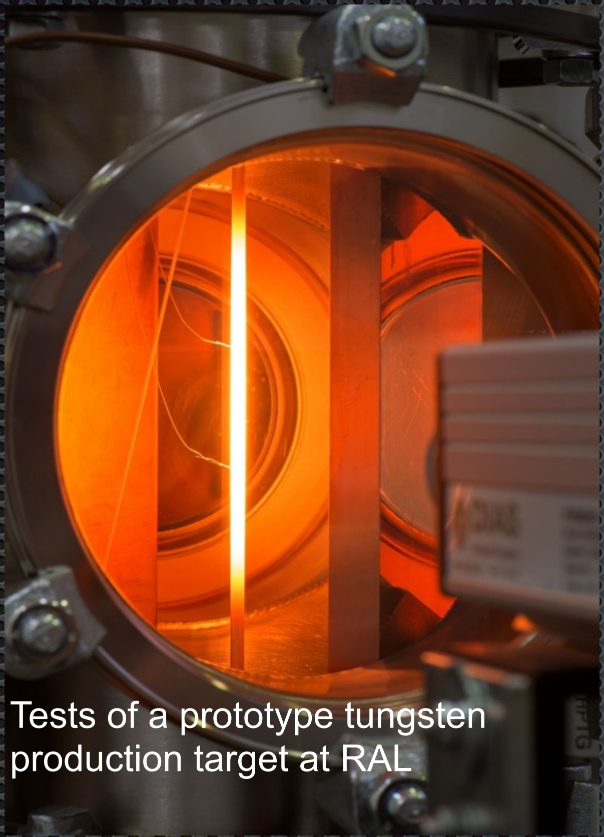
Full Geant4 simulation and reconstruction : Background overlaid on signal

All Backgrounds

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

- Numbers normalized to 3 year run, 3.6×10^{20} POT events
- Expect to start data-taking ~2020

Mu2e Prototypes

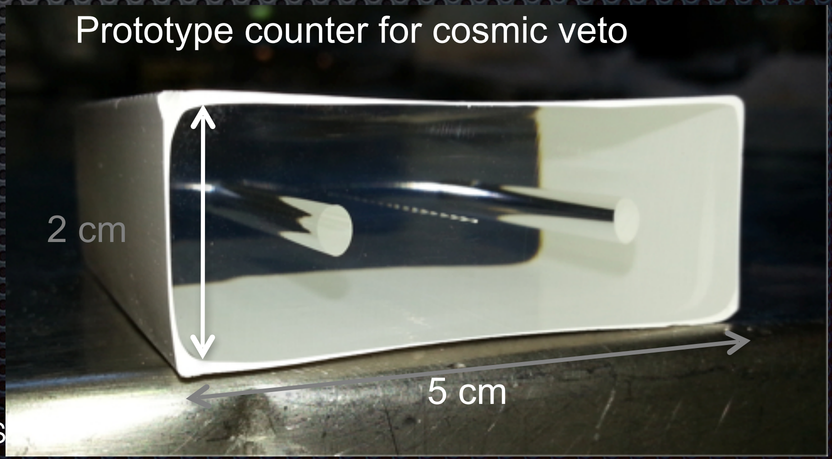


Tests of a prototype tungsten production target at RAL

panel prototype (96 straws) for vacuum tests

TS Coil Module prototype at Fermilab

Prototype counter for cosmic veto



Mu2e Status

Groundbreaking!

Mu2e Technical Design Report

October 2014

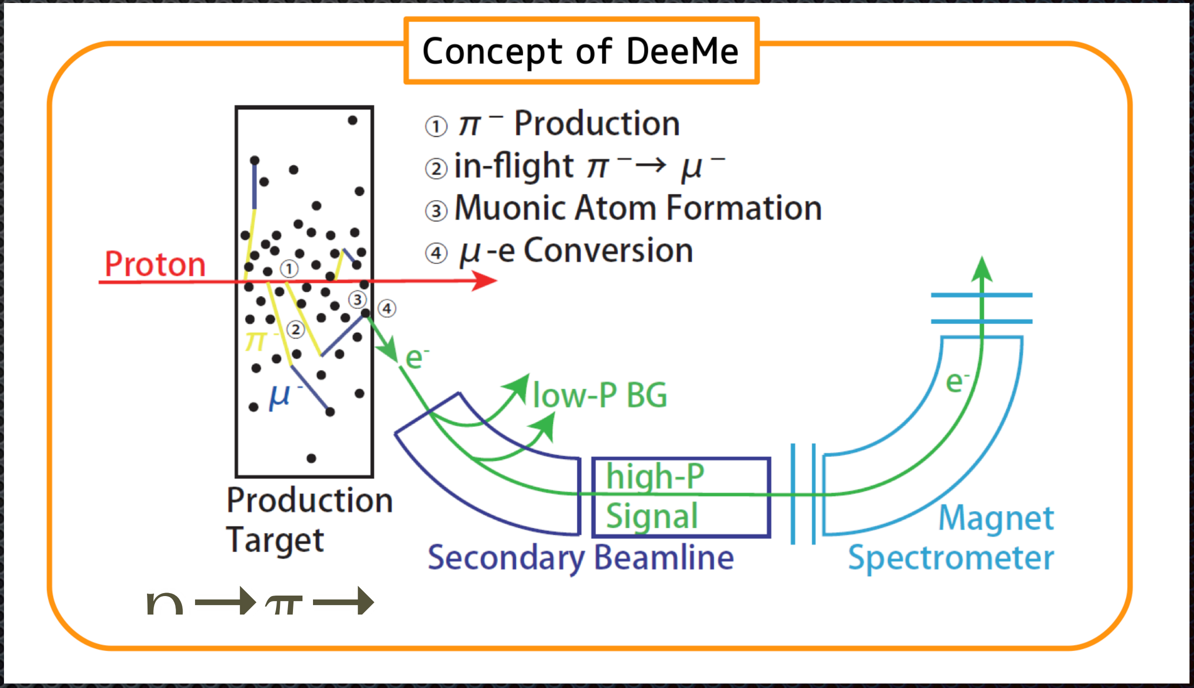
Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

U.S. DEPARTMENT OF ENERGY | Office of Science
INFN
Fermilab

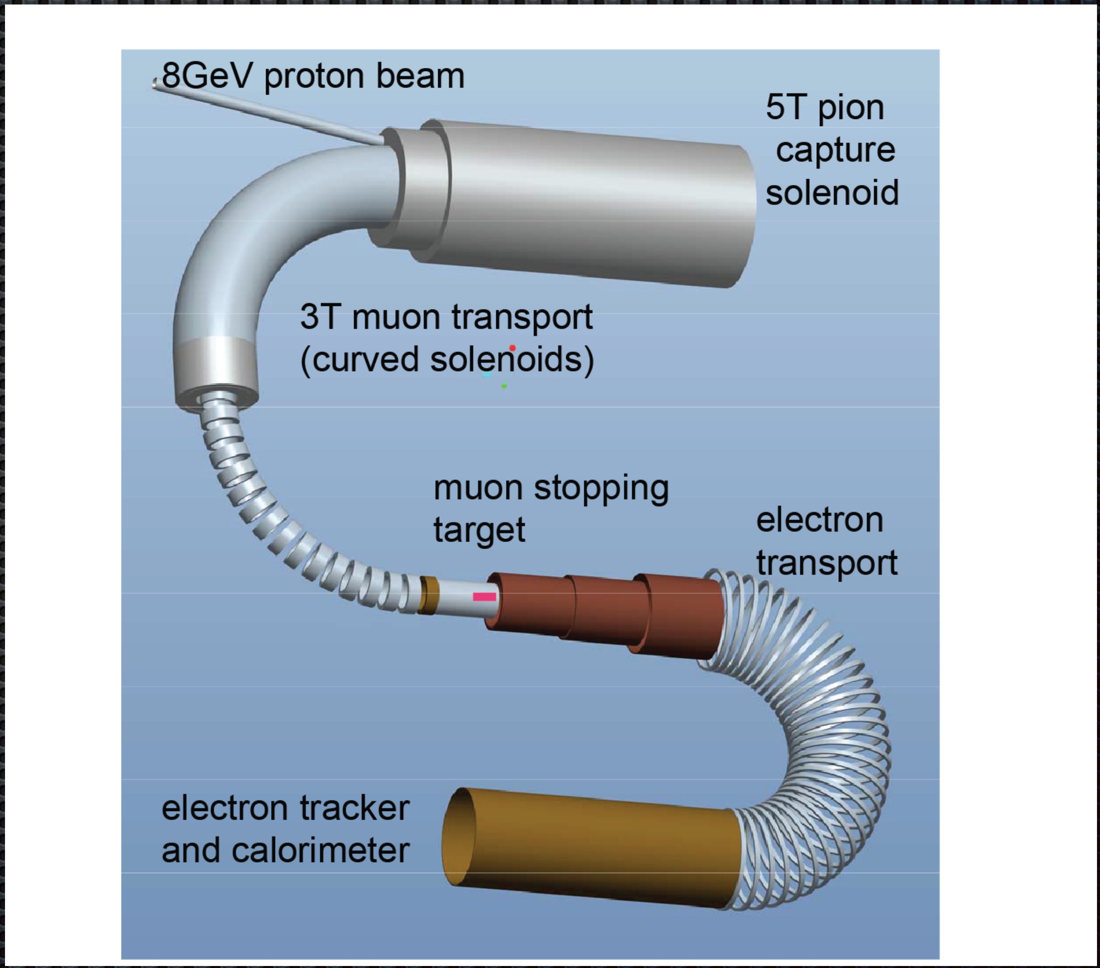
DeeMe

- DeeMe at J-PARC $\mu N \rightarrow eN$ with a 2 x 10^{-14} sensitivity
- production target and conversion target are the same
- rotating Silicon Carbide target
- physics data taking planned to start in 2016

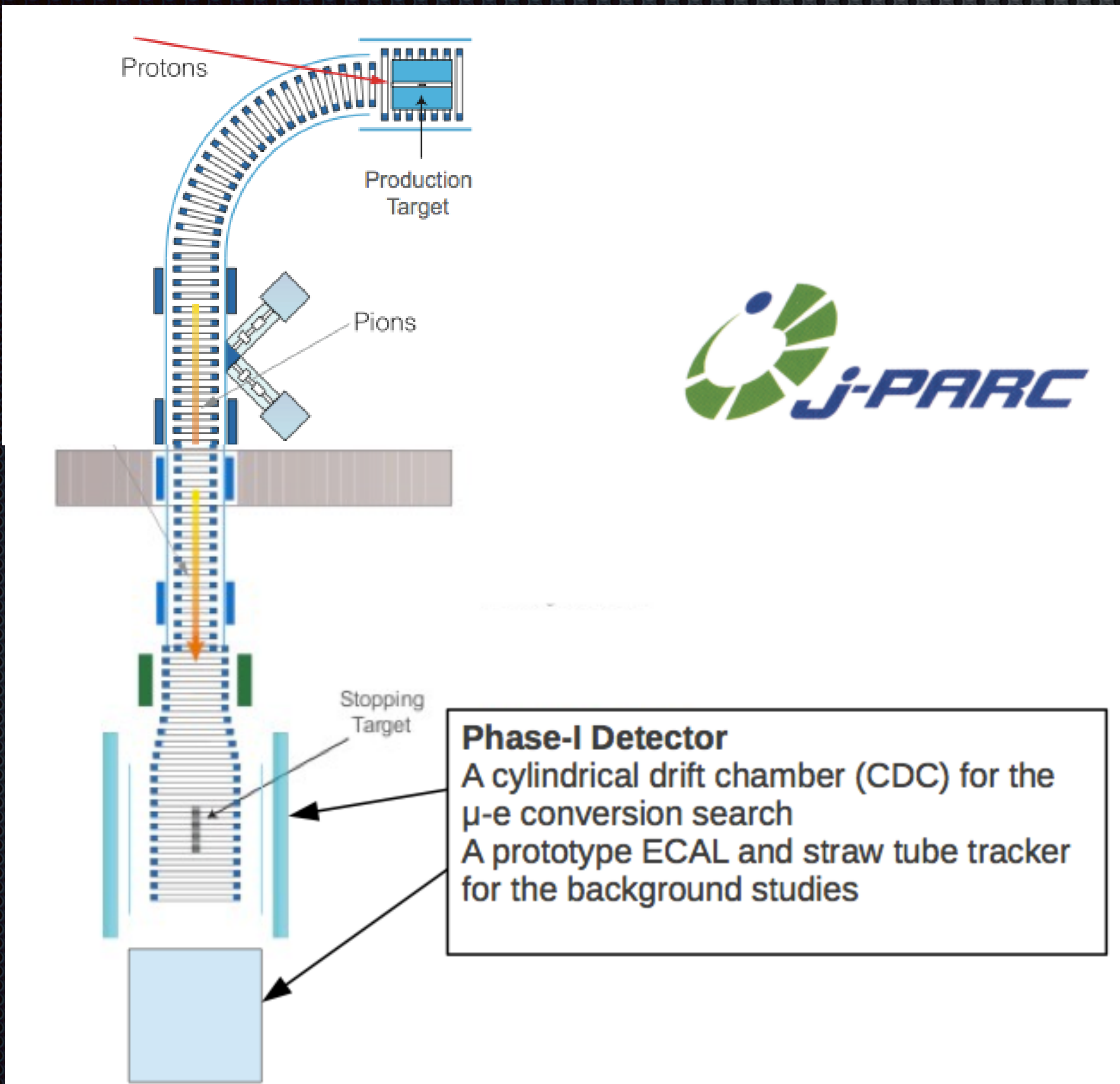


COMET: Theme and Variations

- Japanese Effort at J-PARC
- C-shaped solenoid instead of Mu2e S-shaped
  - don't require annular detector
- Propose to run at x7 Mu2e power
- Stage Experiment
  - first run to "center"
  - then full run



COMET: phase I

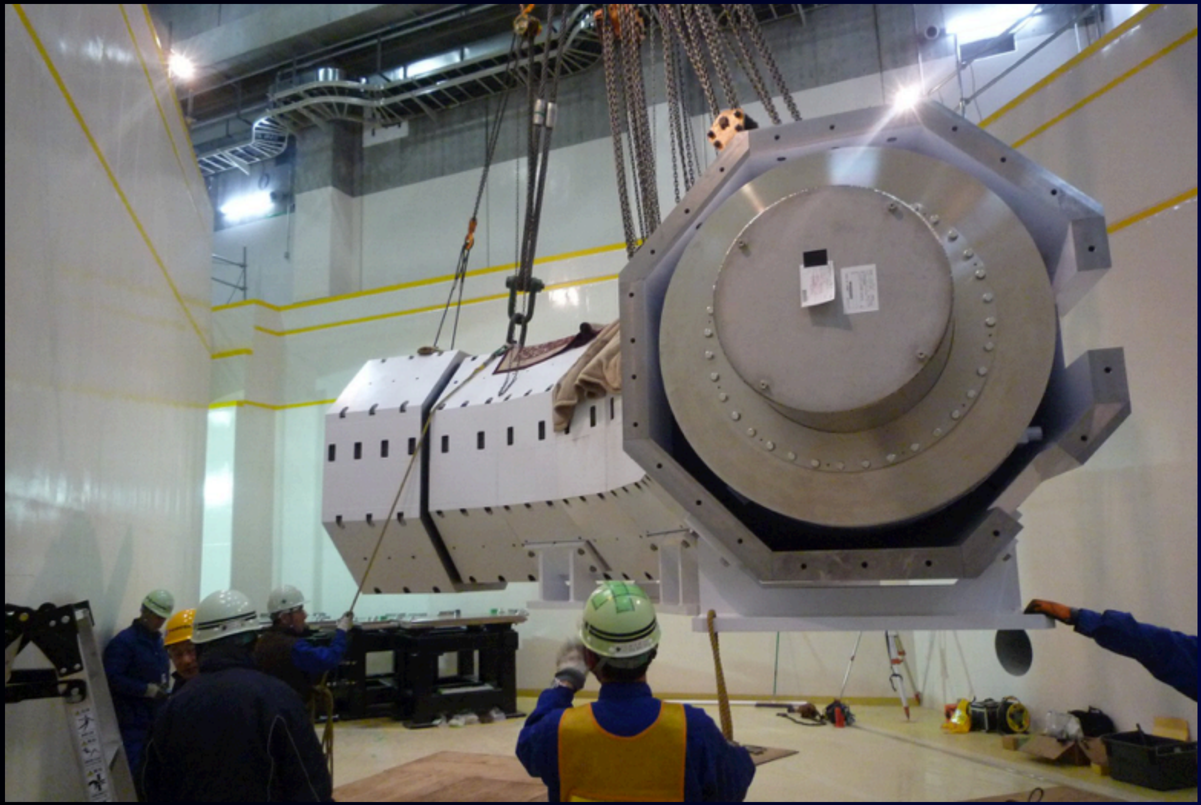


Starts in 2016
~ 1 month of data-taking

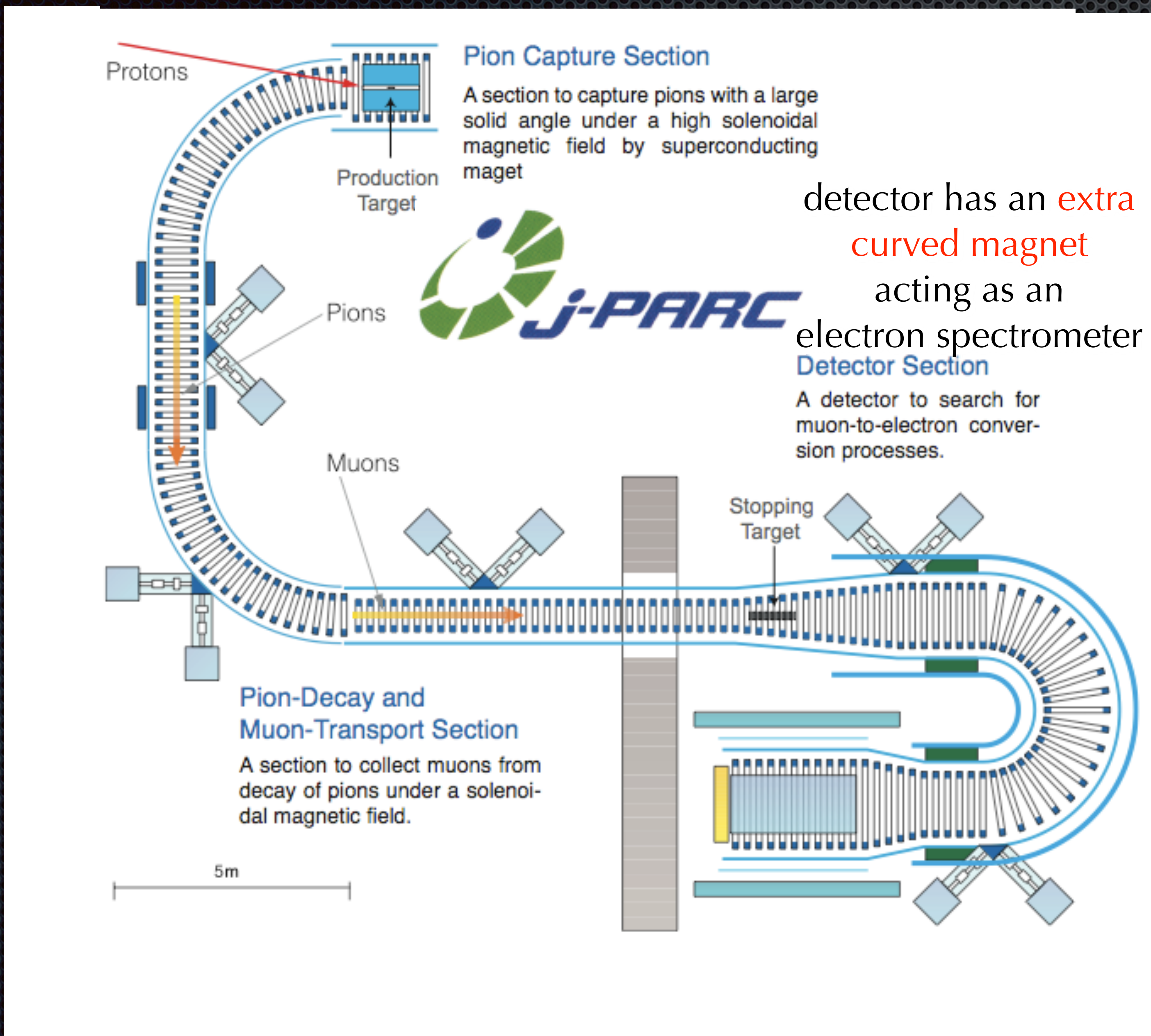
Study backgrounds
Sensitivity ~10^{-15}

COMET Progress

Muon Transport Solenoid at J-PARC



COMET: phase II



detector has an extra curved magnet acting as an electron spectrometer

Starts in 2016

Starts in 2020

~1 month of data-taking

Data in 2022

Study Backgrounds

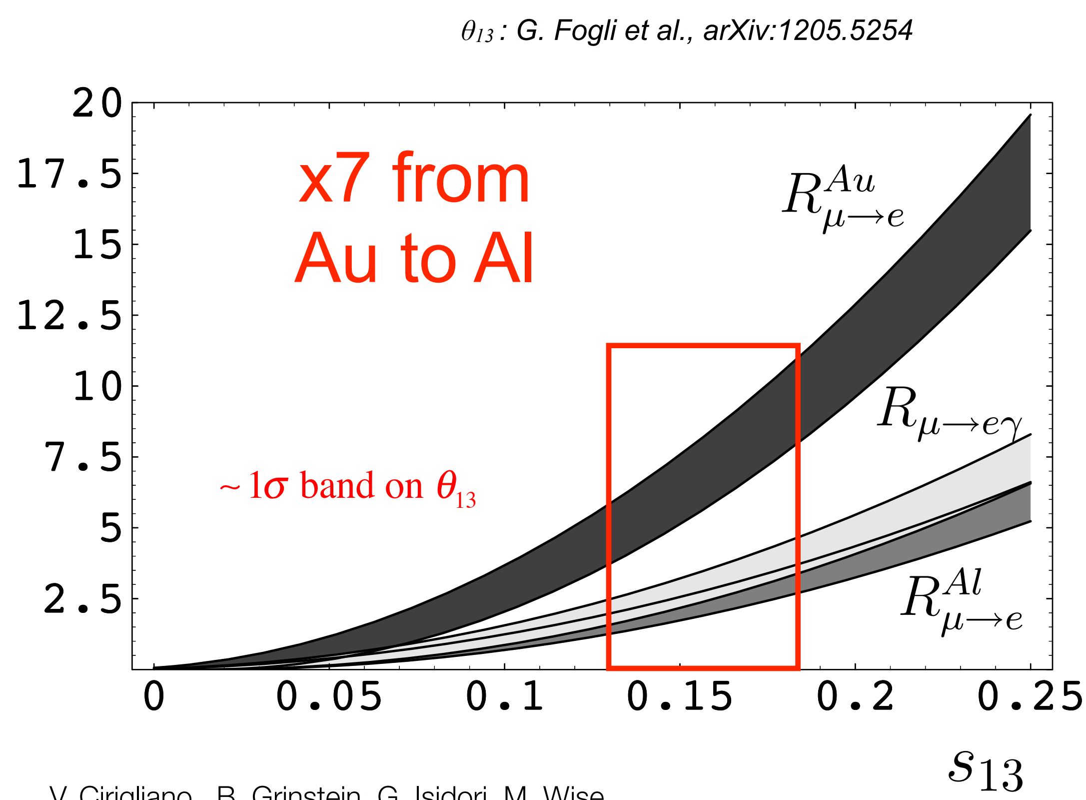
Sensitivity ~ 6×10^{-17}

Sensitivity $\sim 10^{-15}$

Studying a Signal

- Vary Z to probe new physics

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

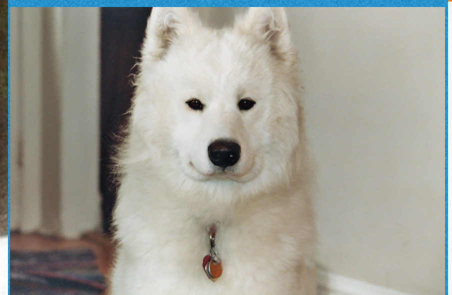


V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
Nucl.Phys.B728:121-134,2005

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).

ule

My Dog

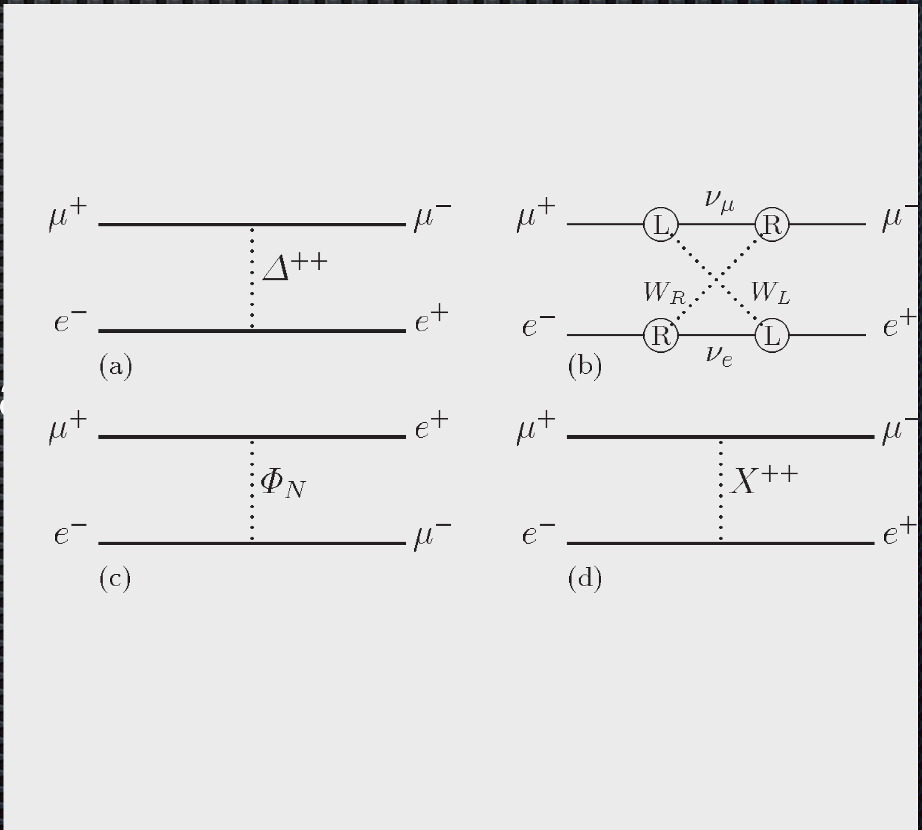


Kuno-san’s dog

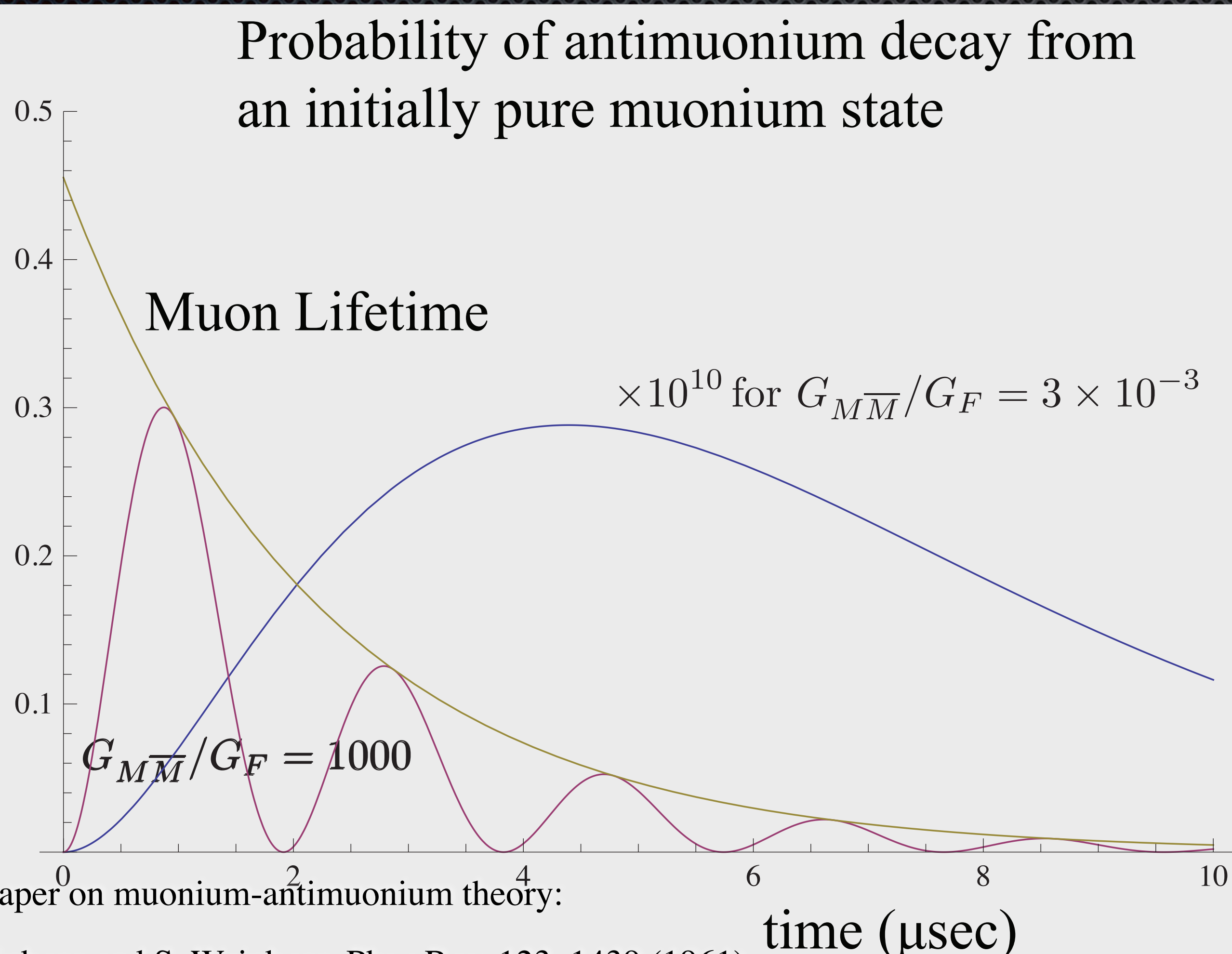
Osaka University

Muonium-Antimuonium

- $\mu^+ e^- \leftrightarrow \mu^- e^+$
  - Leptoquarks, doubly charged Higgs, Heavy Majorana neutrinos,...
  - New interactions break degenera
  - Not unlike K^0 $\overline{K}^0$ system
  - Usually parameterize interaction strength as G/G_F



Math



best paper on muonium-antimuonium theory:

G. Feinberg and S. Weinberg, Phys.Rev. 123, 1439 (1961).

Relevant Equations

$$\frac{\delta}{2} = \frac{8\,G_F}{\sqrt{2}n^2\pi a_o^3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

where n is the principal quantum number and a_o is the Bohr radius of the muonium atom. For $n = 1$,

$$\delta = 2.16 \times 10^{-12}\,\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\ \mathrm{eV}$$

Assuming an initially pure μ^+e^- state, the probability of transition is given by:

$$\mathcal{P}(t) = \sin^2\left(\frac{\delta t}{2\hbar}\right)\ \lambda_\mu e^{-\lambda_\mu t}$$

where λ_μ is the muon lifetime. Modulating the oscillation probability against the muon lifetime tells us the maximum probability of decay as anti-muonium occurs at $t_{\max} = 2\tau_\mu$. The overall probability of transition is

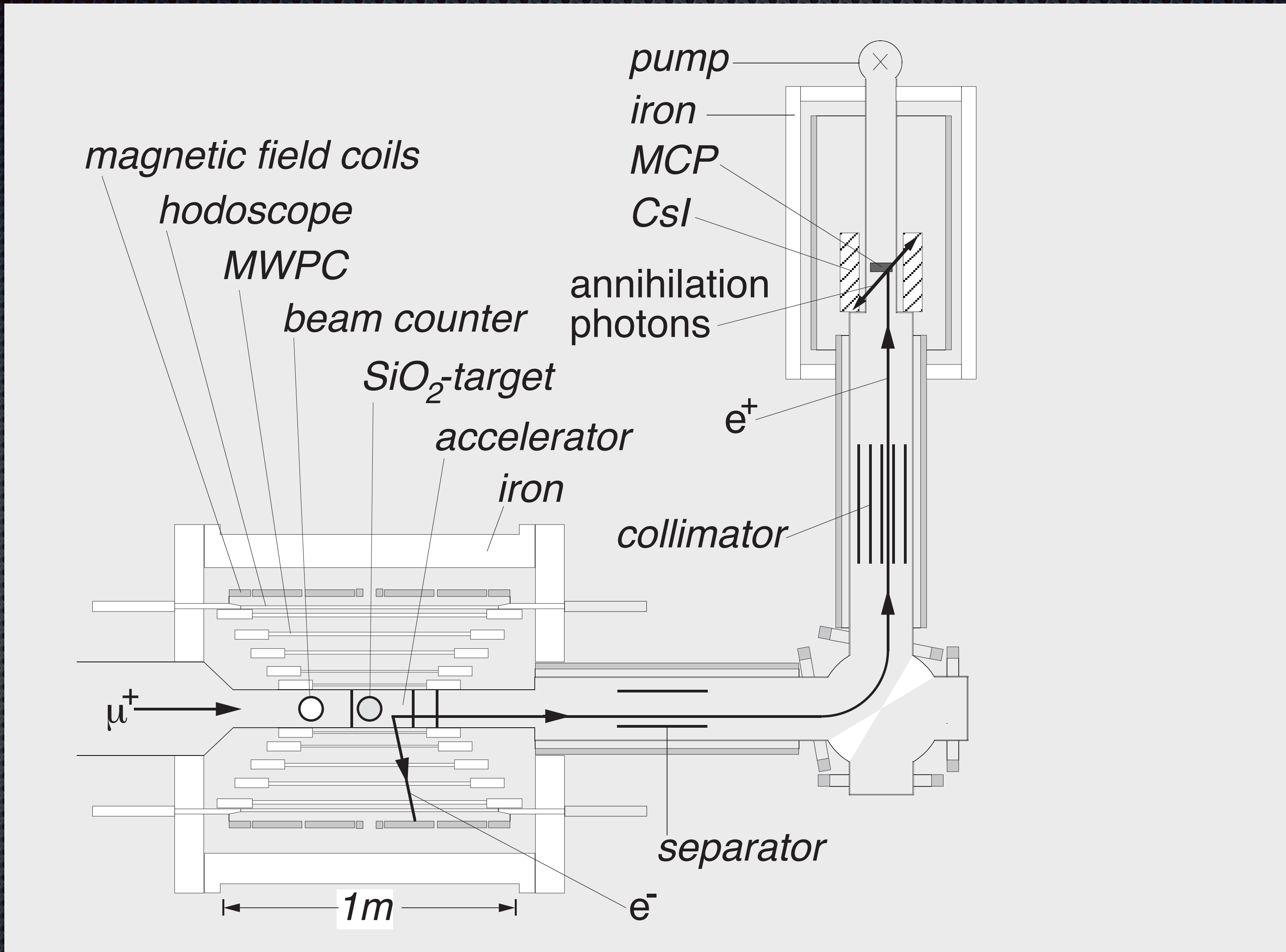
$$P_{\mathrm{total}} = 2.5 \times 10^{-3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

Beautiful Experimental Methods

- How do you make muonium?
  - make a sub-surface beam
    - sub-surface beams stop inside, not on surface, and have a lower momentum distribution than surface beams
    - this yields a smaller straggling by $\Delta R \sim p^{3.5}$ and a tighter spatial stopping distribution (MEG is considering this)
  - let the positive muons stop in SiO_2 powder, a technique invented at TRIUMF
  - The powder structure stops the positive muon and the voids permit the muonium to escape
  - Other new ideas, but no time... see RHB and Cooper article and J-PARC work

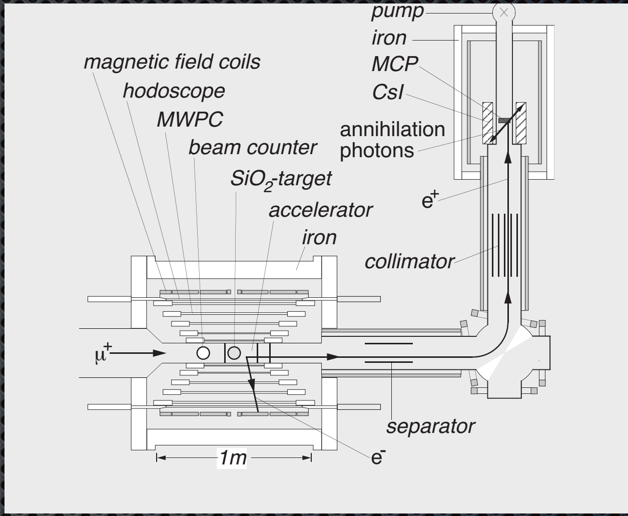
Experiment

- MACS at PSI



Signal and Background

$$G/G_F < 3\times10^{-3} \text{ at } 90\% \text{ CL}$$



Willmann, L., et al. (1999), Phys. Rev. Lett. 82, 49.

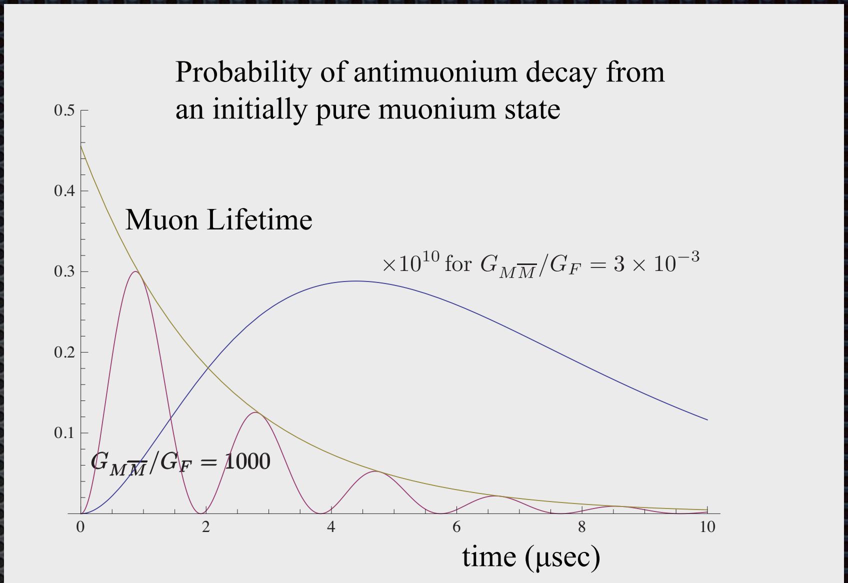
- Signal:
  - μ^- decay (e^- near Michel peak) in coincidence with e^+
- Backgrounds:

1. The rare decay mode $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ with a branching ratio of 3.4×10^{-5}. If one of the positrons has low kinetic energy and the electron is detected, this channel can fake a signal.

2. The system starts as muonium, hence $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ yields a positron. If the e^+ undergoes Bhabha scattering, an energetic electron can be produced. Background results from the coincidence of that scattering with a scattered e^+. The positron's time-of-flight is is used to reject background.

$e^+e^- \to e^+e^-$, annihilation or scattering

How to do better?



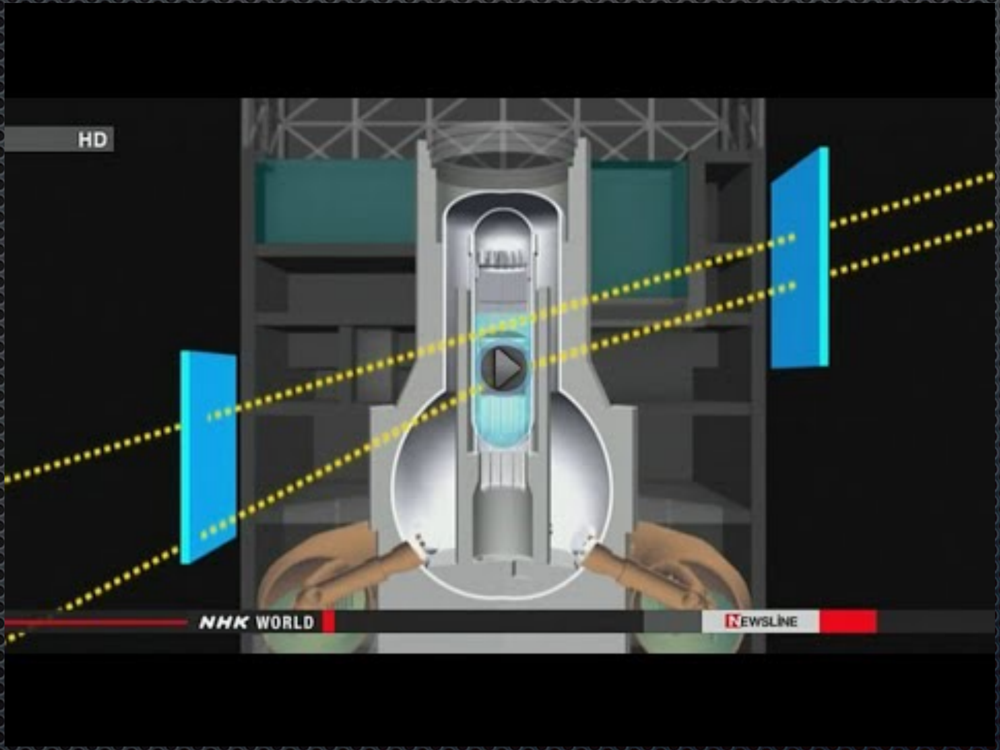
- Both backgrounds can be suppressed with a pulsed beam and by waiting for the muon lifetime to suppress the muon decay
  - can make up the muon flux at a hotter beam, which did not exist at the time of MACS
- Modern detectors have much better resolution
- discussions with experts: x100 should be achievable

Topics I have left out

- Muon Spin Rotation
- Muon Tomography
- Muonium Hyperfine Splitting
- Muonium-Antimuonium Oscillations

Muon Tomography

at Fukushima, for example



Summary

- We've covered a lot; hope not too much or not enough depth
- Muon physics covers a span from nuclear physics to QCD to searches at the highest mass scales
- A vibrant field and will only get better in the next decade

Final Thought

- Again from Rabi:

Rabi, the son of poor immigrants, reported that his mother made him a scientist. Every day when he returned home from school, rather than ask (as most mothers did), “What did you learn today?” Rabi’s mother asked, “Izzy, did you ask any good questions?”

muon physics is about great questions