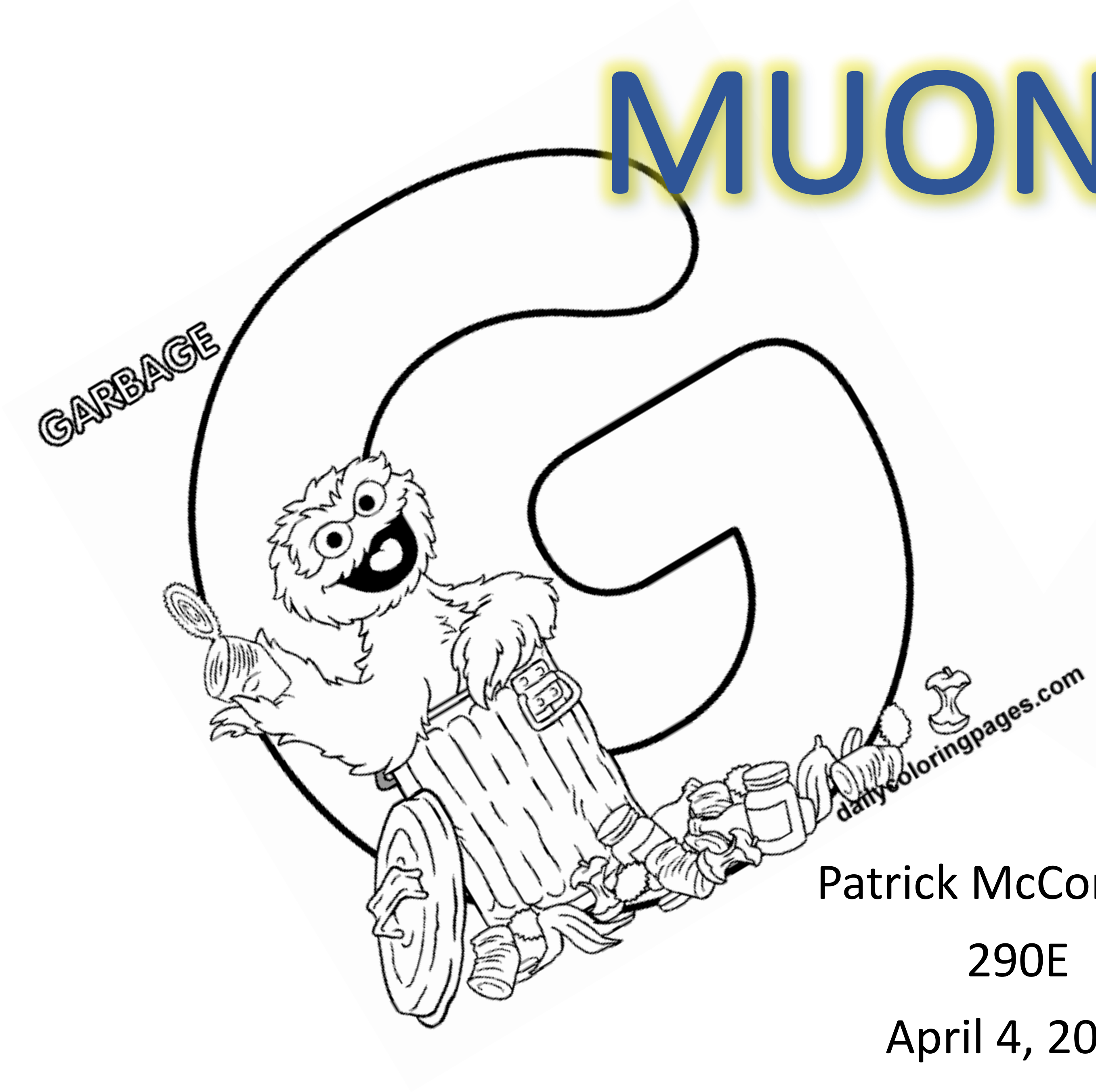
MUON G-2



Patrick McCormack

290E

April 4, 2018

Find G

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

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There it is

Find G

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

This is the magnetic moment of charged, spinning particles.

Dirac famously calculated:

g = 2

(for the electron at least)

Go with the Schwing

- What is it we really care about again?

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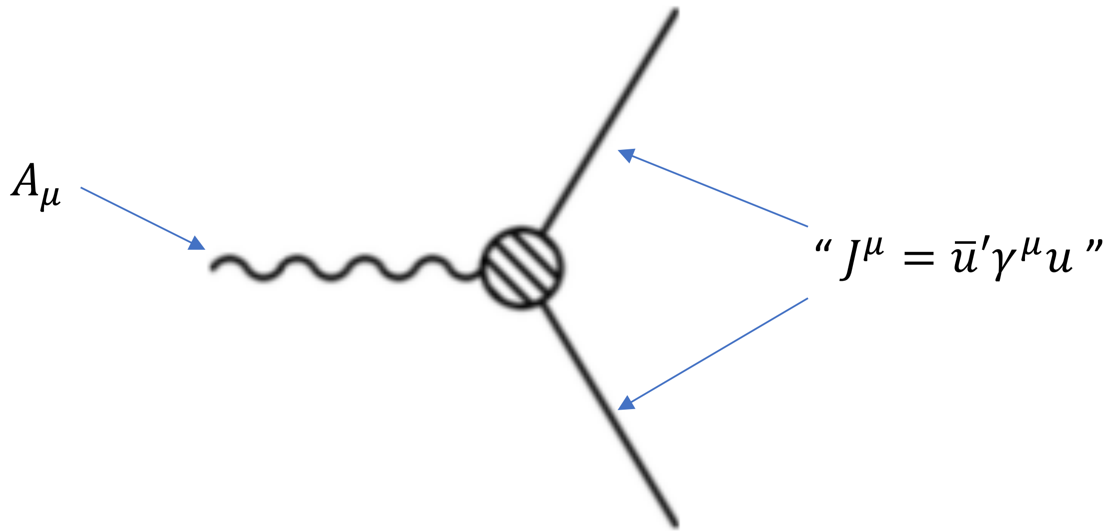
  - How a muon couples to an external magnetic field



Go with the Schwing

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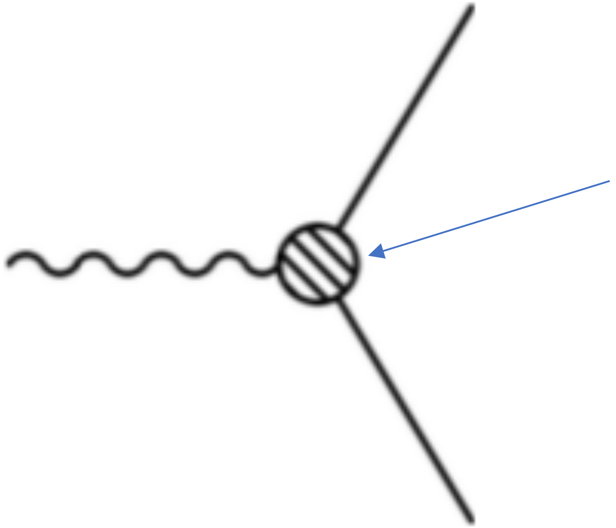
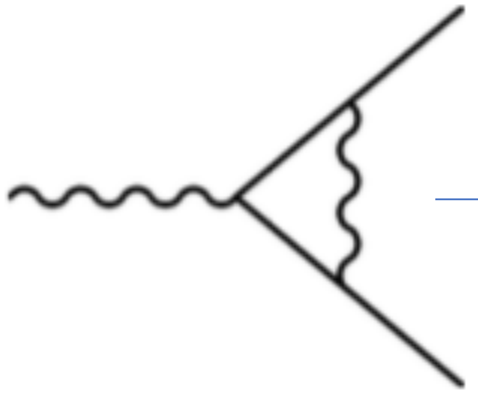


Field Theory tells us how to calculate this vertex

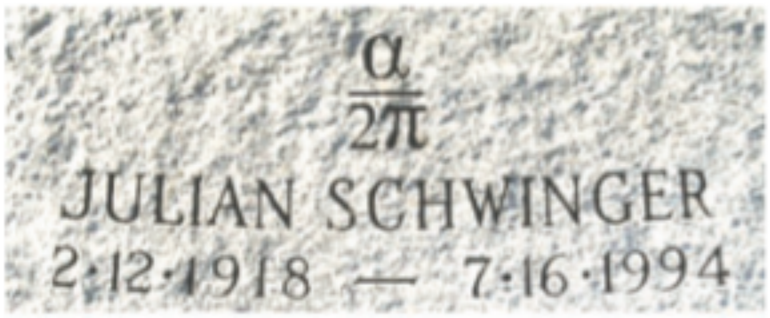
Go with the Schwing

- To one-loop order:



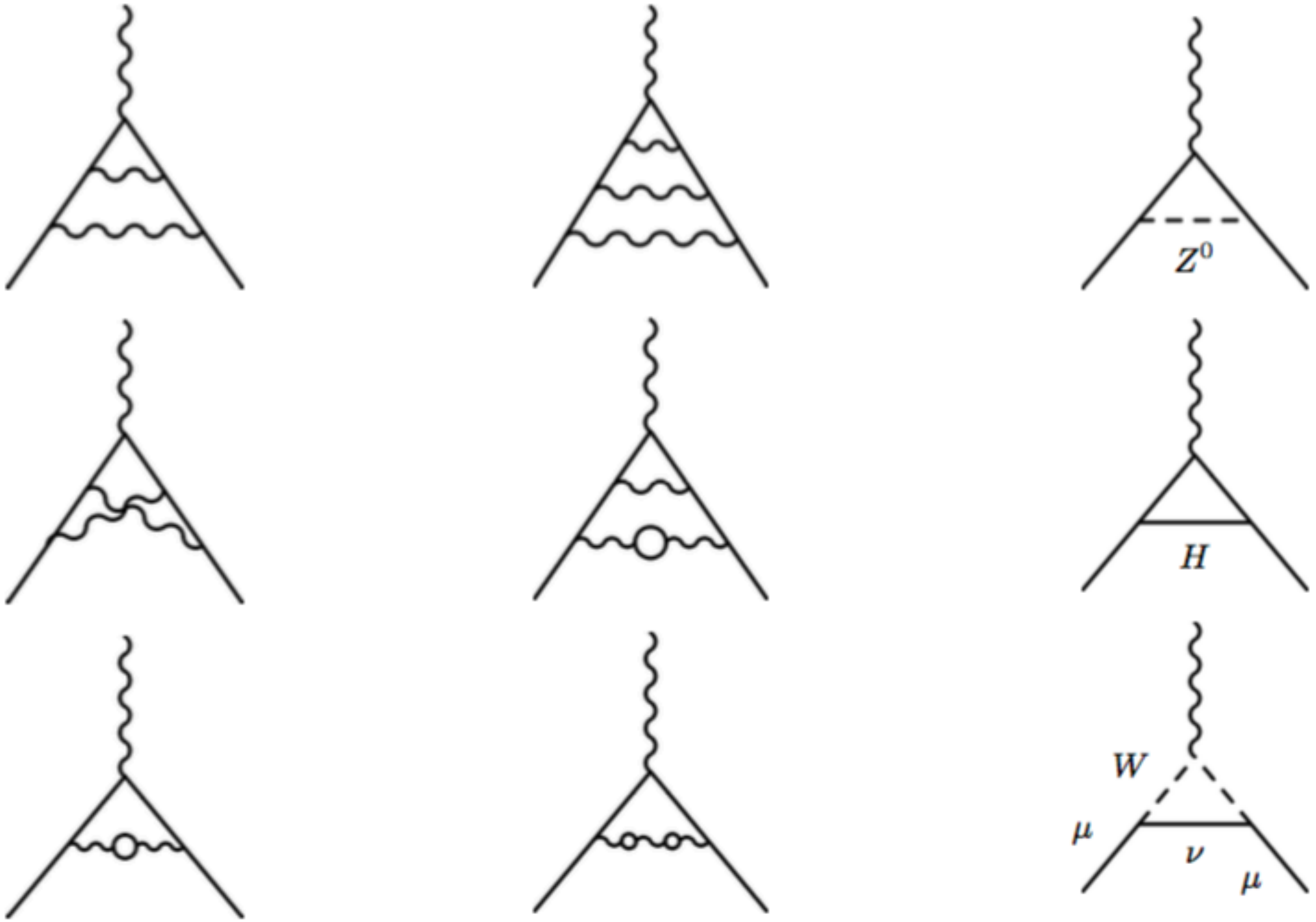
Dirac g is modified by factor:

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



To higher order and beyond

- We can compute MANY diagrams using the whole Standard Model



Etc., etc., etc...

To higher order and beyond

Table 2 SM contributions

Contribution	Result in 10^{-11} units
QED (leptons)	116 584 718.09 ± 0.15
HVP(lo)[e^+e^-]	6 923 ± 42
HVP(ho)	−98.4 ± 0.7
HLbyL	105 ± 26
EW	153 ± 1
Total SM	116 591 801 ± 49

Abbreviations: EW, electroweak; HLbyL, hadronic light-by-light scattering; ho, highest order; HVP, hadronic vacuum polarization; lo, lowest order; SM, Standard Model.

Note that the 1-loop correction is 116,140,973.29 (0.04) of this!!

Is this a theory talk?

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- No

Why should we care?

- The standard model offers an extremely precise calculation of the muon's g-factor
  - What if it was… WRONG?

How can you make a precision measurement of g-2?

- For simplicity, define $\mu = (1+a)\frac{e\hbar}{2m}$, **where $\boldsymbol{a} = \frac{(\boldsymbol{g}-2)}{2}$ is what we're looking for**
- The torque on a dipole is $\vec{\tau} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$

Potential electric dipole moment term
(let's ignore this for now)

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- The torque on a dipole is $\vec{\tau} = \vec{\mu} \times \vec{B}$
- Per wikipedia's page on "Larmor precession":
  - $\omega_s = \frac{eB}{m}\left(a + \frac{1}{\gamma}\right)$
- Per wikipedia's page on "Cyclotron":
  - $\omega_c = \frac{eB}{m\gamma}$

Define the Anomalous Precession Frequency:

$$\vec{\boldsymbol{\omega}}_{\boldsymbol{a}} = \vec{\omega}_s - \vec{\omega}_c = \frac{\boldsymbol{e}\vec{\boldsymbol{B}}\boldsymbol{a}}{\boldsymbol{m}}$$

How can you make a precision measurement of g-2?

$$\vec{\omega}_a = \frac{e\vec{B}a}{m}$$

- All we have to do is know $\vec{B}$ and measure $\vec{\omega}_a$!
- So just store a beam of polarized, relativistic muons in a ring and see how they oscillate!
- Well now we're going to want to use an electric field for beam focusing, so:

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

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We can basically eliminate this term by making the muon momentum: $p_{magic} = 3.094$ GeV. So this term is just telling us how fast to make our muons. Neat!

Making (polarized) muons

- We want polarized muons so they're all spinning in the same direction
- **Step 1**: shoot high-energy protons (~8 GeV) at a target to make pions
- **Step 2**: let charged pions decay
  - $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$

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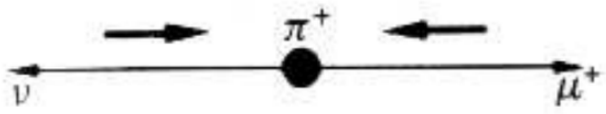
- Lemma: μ^{+} will have helicity - and μ^{-} will have helicity +
  - Sub-Lemma: μ^{+} emitted forward from π^{+} will have spin anti-parallel to momentum and will be more boosted than μ^{+} emitted backwards, which have parallel spin and momentum (everything's opposite for μ^{-})

For clarification, imagine boosting this up or down



Pion rest frame

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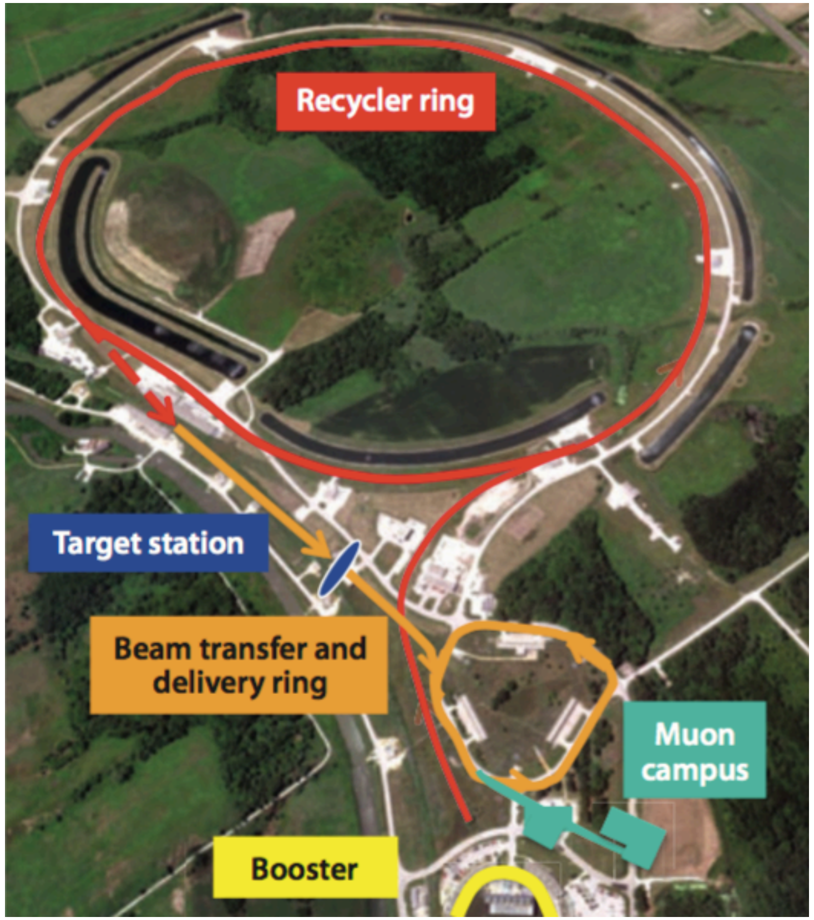
- Lemma: μ^{+} will have helicity - and μ^{-} will have helicity +
  - Sub-Lemma: blah, blah, blah about parallel-ness of spin and momentum
- **Step 3**: siphon off the part of the beam you want (based on charge and relative momentum)
  - By the way: you want to end up with a pulsed beam where the pulse is narrow compared to cyclotron period and pulse separation is wide compared to boosted muon lifetime

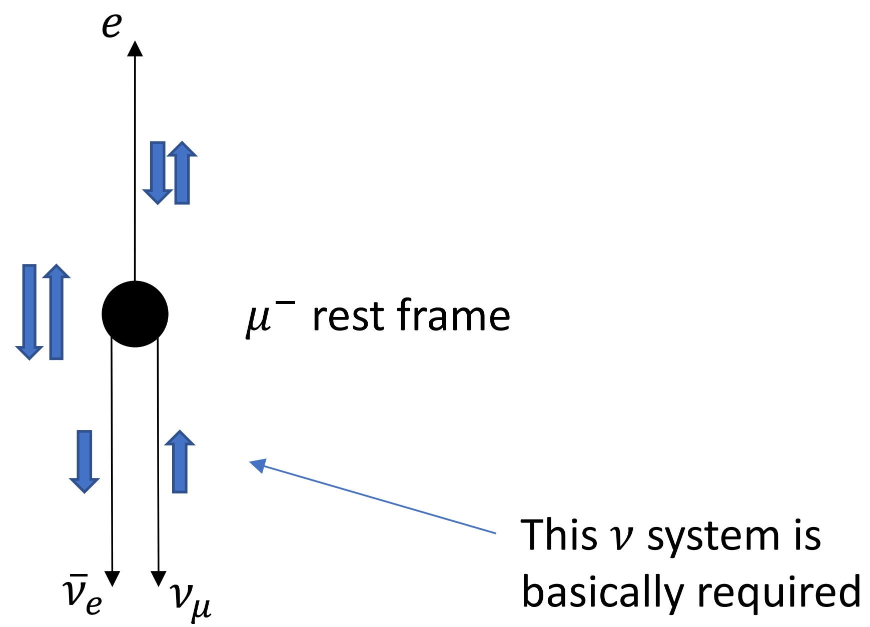
Making (polarized) muons



Example muon-making setup at Fermilab g-2 experiment

How do you measure $\vec{\omega}_a$?

- Now we have muons with $\gamma_{magic} = 29.3$ running around a storage ring
- They will decay via: $\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$
- Lemma: this type of decay maximizes the electron energy:



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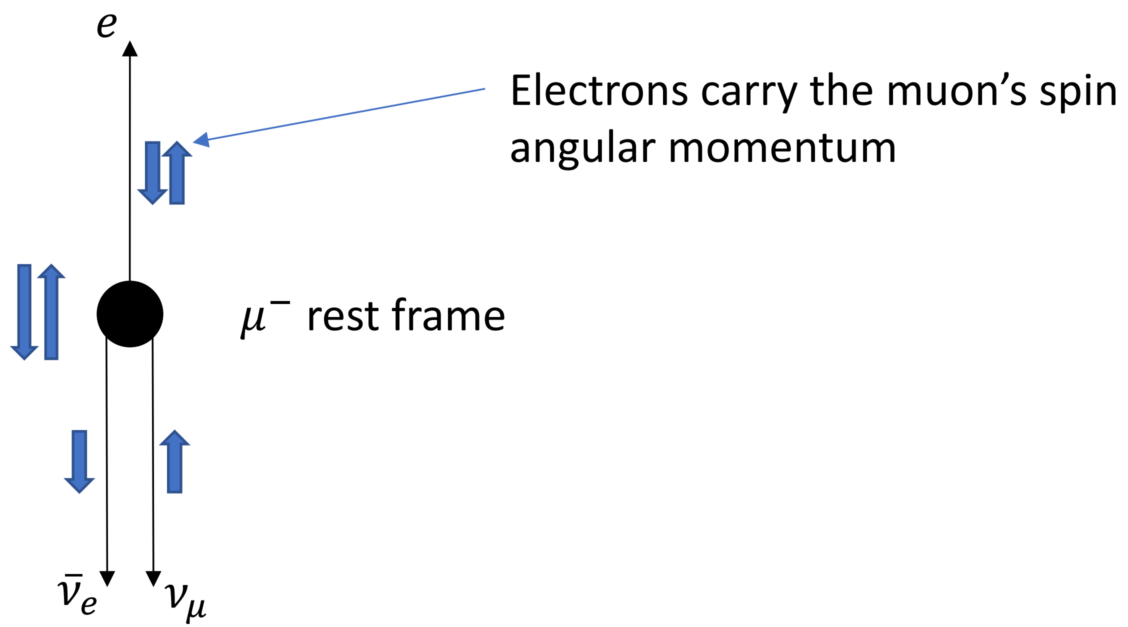

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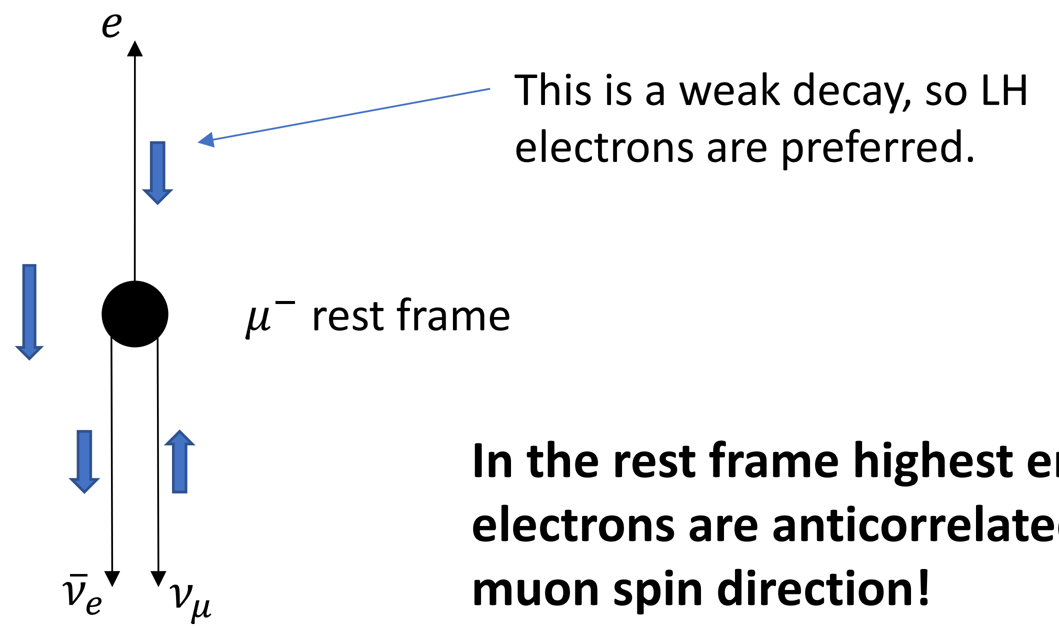

In the rest frame highest energy electrons are anticorrelated with muon spin direction!

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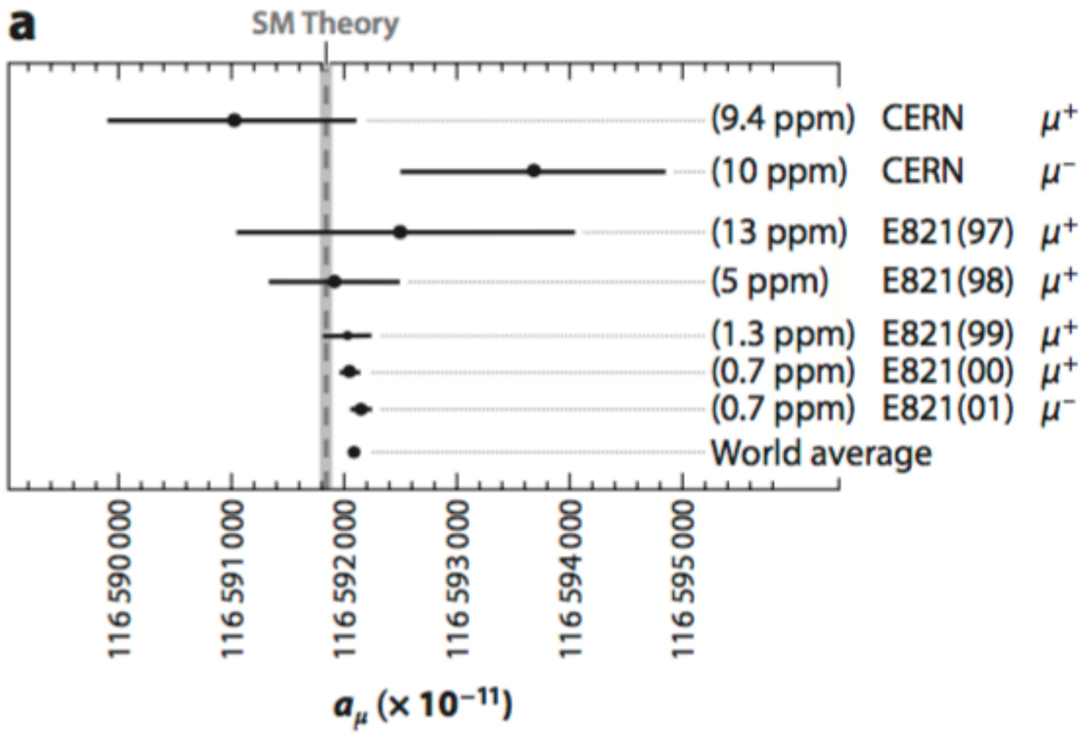
- They will decay via: $\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$
- Corollary: There will be more high-energy electrons when the muon spins are anti-parallel to their momentum!
  - (And fewer when they're parallel)
  - (opposite argument and results for μ^{+})
- So the number of decay electrons over a "high-energy" threshold will oscillate with $\vec{\omega}_a$

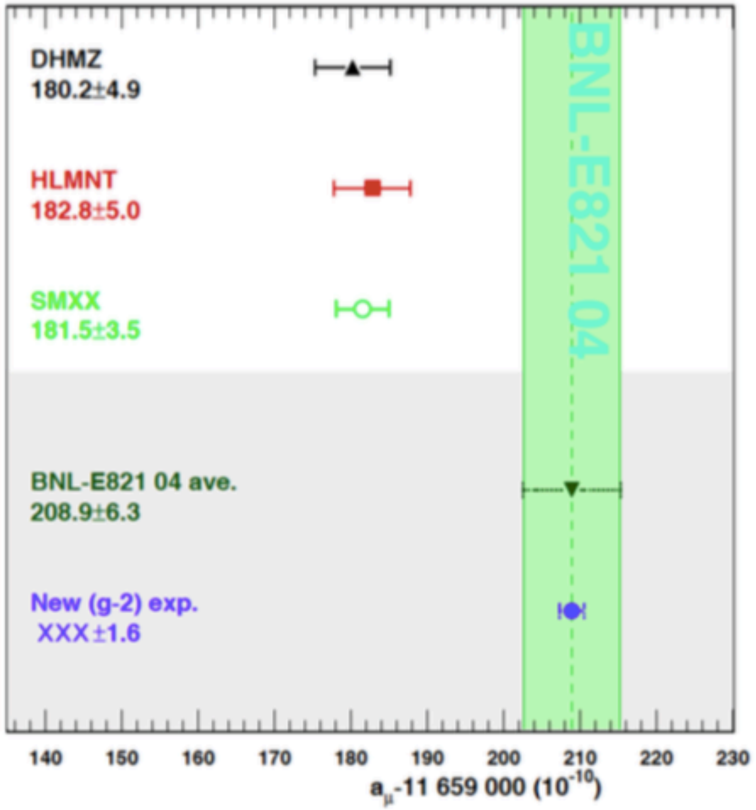
So to summarize (so far)

Shoot protons at target to make pions → Let pions decay to muons → Create pulsed beam of polarized muons → Wait for muons to decay → Count number of high-energy electrons as a function of time

The muon storage ring at currently at Fermilab. It's essentially a large circular dipole magnet outside lead-fluoride electromagnetic calorimeters.

Some quick history

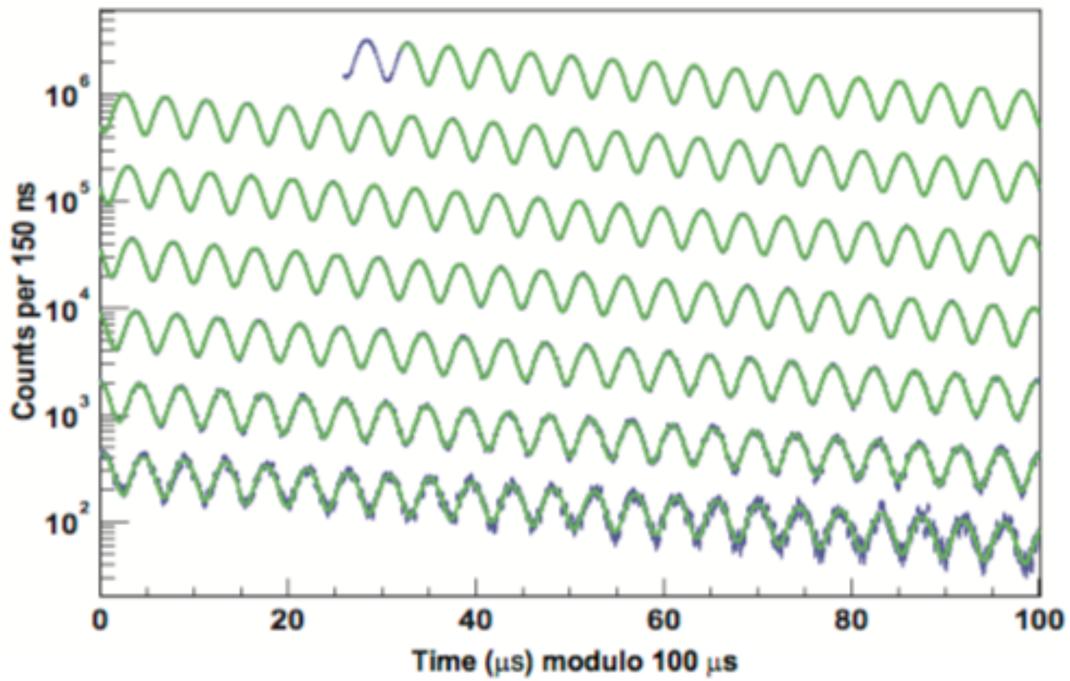




The BNL E821 experiment measured a 3σ deviation from the Standard Model

The Fermilab Plan

- They've essentially moved the BNL setup to Fermilab
- THE PLAN:
  - Gather 21 times the stats of BNL
  - Reduce error on $\vec{\omega}_a$
  - Reduce error on $\vec{B}$



BNL's 2001 high-energy positron vs. time data
(high-energy means greater than 1.8 GeV threshold)

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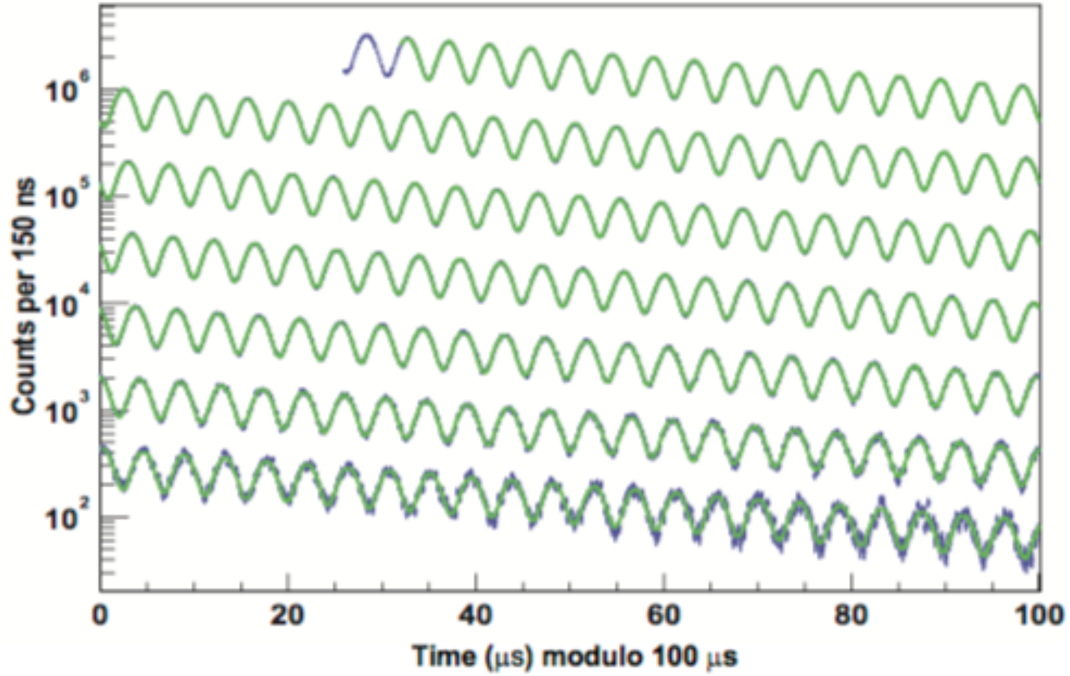
Mostly a matter of increasing the data taking rate



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Reducing uncertainties

- The biggest individual source of uncertainty on $\vec{\omega}_a$ is pileup
  - Here that's two positrons hitting the calorimeter at essentially the same time
  - Goal: eliminate 100% of pileup above 5 ns positron separation
  - Achieve 100 ps hit-time resolution for >100 MeV positron
  - 5% energy resolution at 2 GeV
  - Increase stability over data taking rate (4 orders of magnitude of variation in counting rate to deal with)

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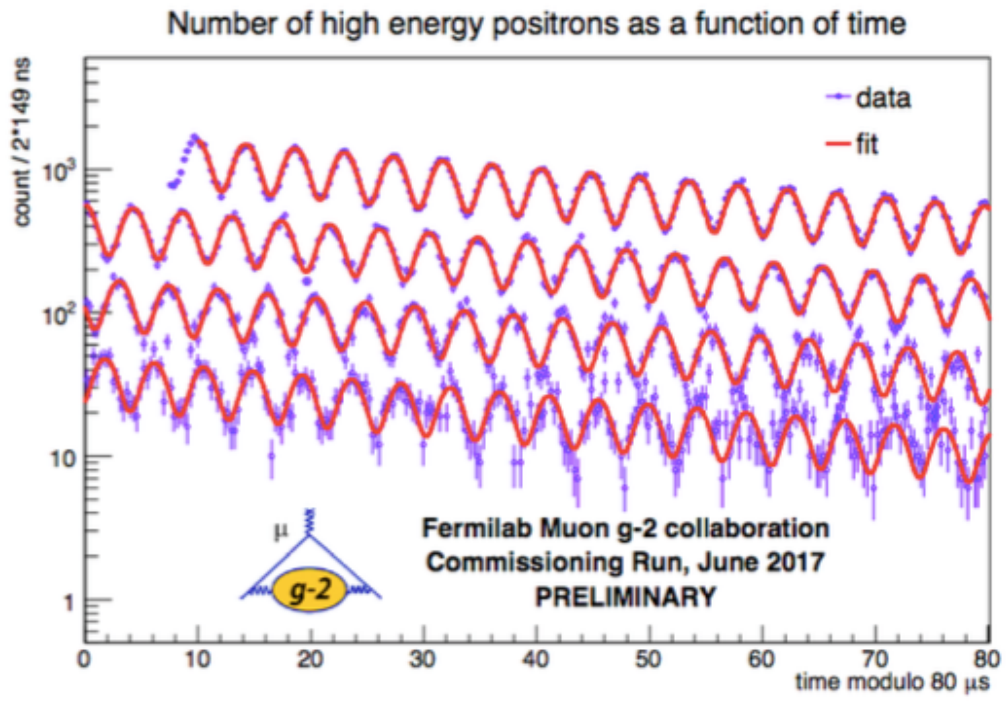
- There will be three tracker stations to study beam shape and muon loss
- Aim to keep uncertainty on $\vec{B}$ below 70 ppb
  - Careful engineering of magnets
  - Feedback adjustments of field
  - Monitoring during data taking
  - Absolute calibration to Larmor frequency of free proton

Fermilab's timeline (headed forward)

- The Fermilab experiment had a two week commissioning run in June 2017
- They will start data taking in Spring 2018 and resolve BNL/SM tension by end of year!
- Hope to finish data taking in 2020



What could it all mean?

- If there’s really discrepancy, that strongly implies BSM physics
- Muon’s g-2 primarily sensitive to 10 MeV - 1000 GeV new particles
- Potentially SUSY?
- Potentially some Z’, W’, or new higgs that couples to the muon?

What could it all mean?

- Or maybe the theorists are just messing up the calculation
- Some guys thinks the curvature of space-time in the earth's gravitational field explains the current tension
  - *Post-Newtonian effects of Dirac particle in curved spacetime - III: the muon g-2 in the Earth's gravity*, T. Morishime et al., arXiv:1801.10246v1 [hep-ph], 30 Jan 2018
- The g-2 collaboration thinks he missed a constant though

Sources

- *The Muon g-2 experiment at Fermilab*, A. Chapelain, arXiv:1701.02807v1 [physics.ins-det] 10 Jan 2017
- *The Muon g-2 Experiment Overview and Status*, J. L. Holzbauer, arXiv:1712.05980v1 [hep-ex] 16 Dec 2017
- *Muon (g − 2): Experiment and Theory*, J. Miller et al., Annu. Rev. Nucl. Part. Sci. 2012. 62:237–64
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- *Muon (g − 2)* , D. Perepelitsa, http://phys.columbia.edu/~dvp/dvp-muon.pdf
- http://muon-g-2.fnal.gov