Big Science On the Move

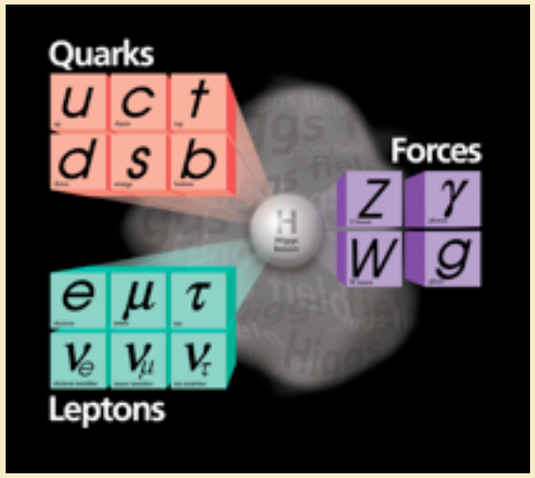
Transporting the Muon g-2 Magnet

Adam Lyon, FNAL SCD

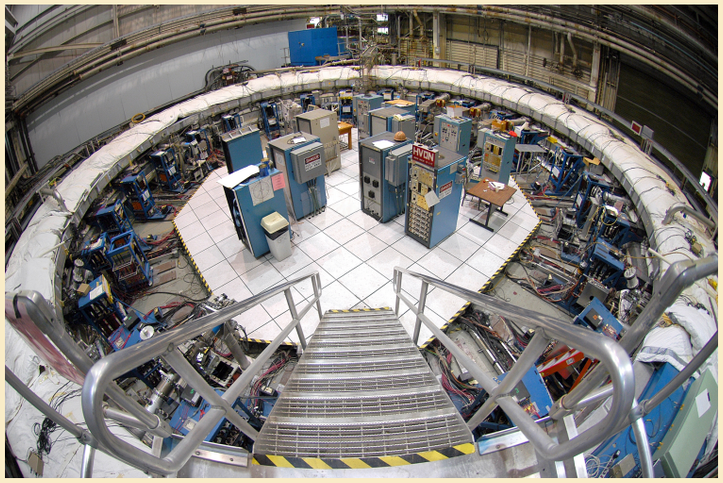
August 2013

Photo: Hogan Nguyen

The things we'll talk about today



What's the big idea?



Muons and *g*-2

@ Fermilab

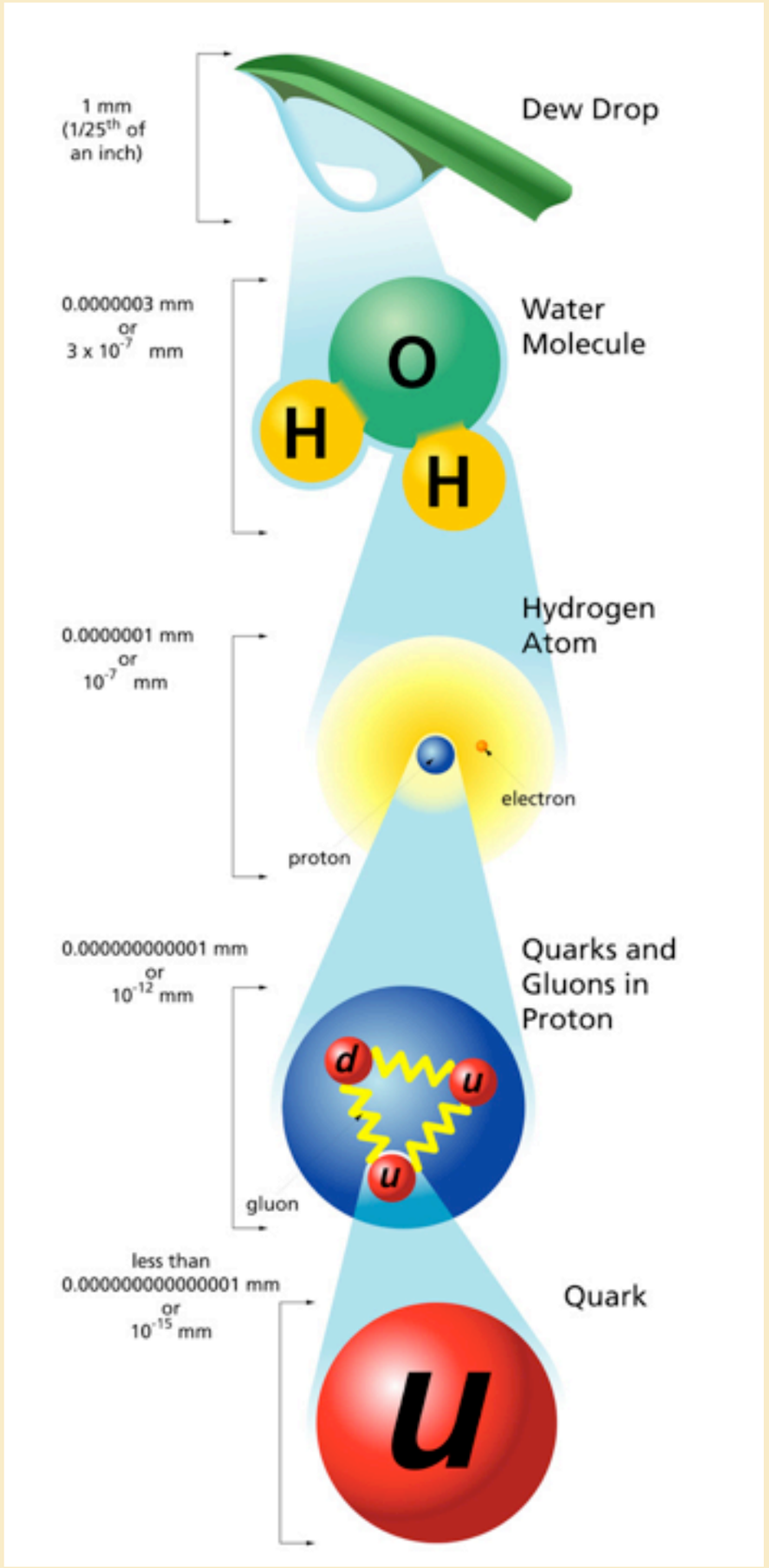
The journey

What happens next

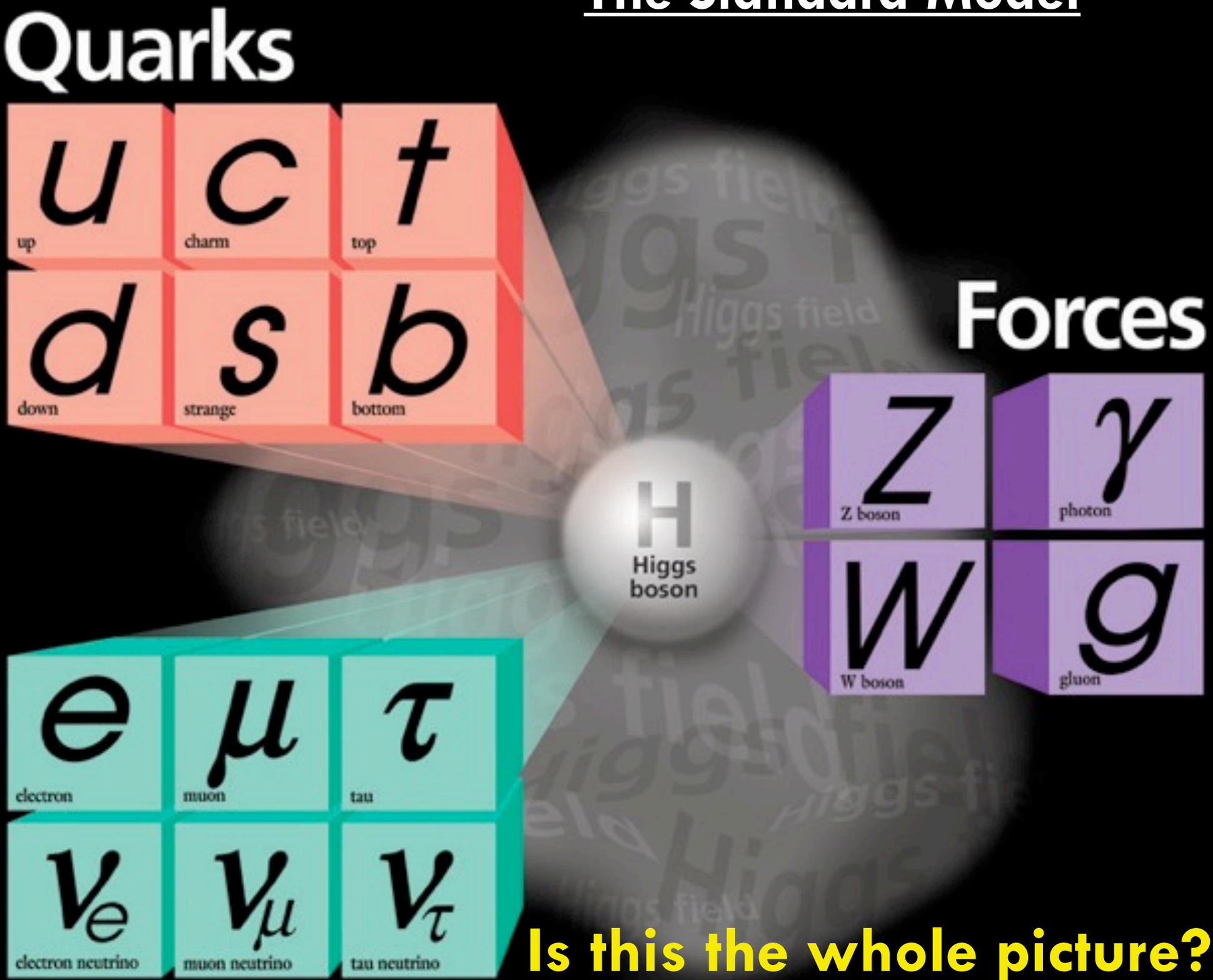
What is Particle Physics?

Q: What is matter?
How does it work?

A: We've learned a lot!



The Standard Model



Is this the whole picture?
We think there's got to be more

One way to look for new physics

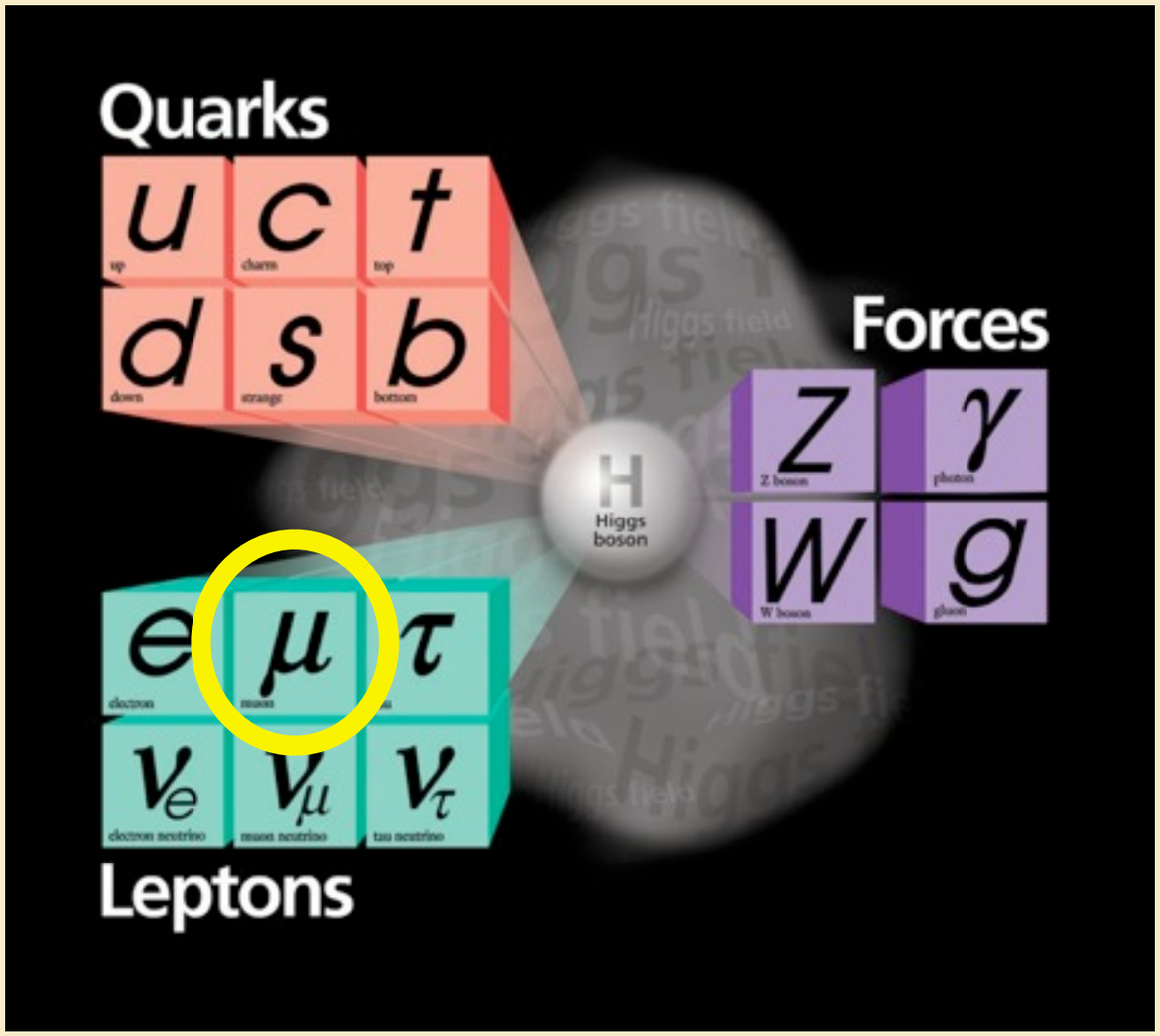
Precision measurements of particle properties

Does particle behavior match Standard Model predictions?

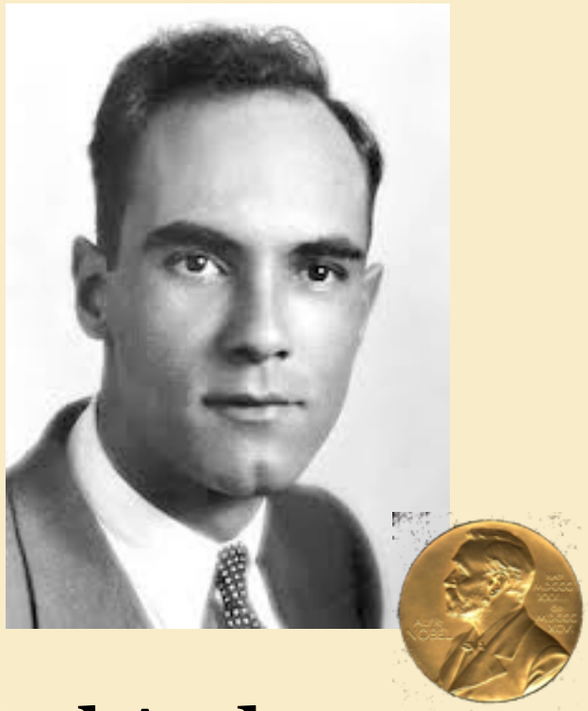
- **Mass?**
- **Production probabilities?**
- **Decay probabilities?**
- **Interactions with other particles**

MUONS are an excellent laboratory for precision studies

Muons are an ideal laboratory!



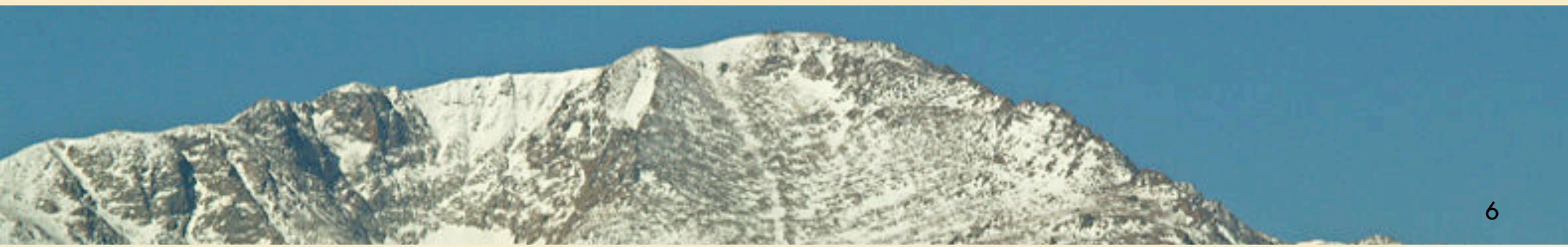
Discovered in 1936 by



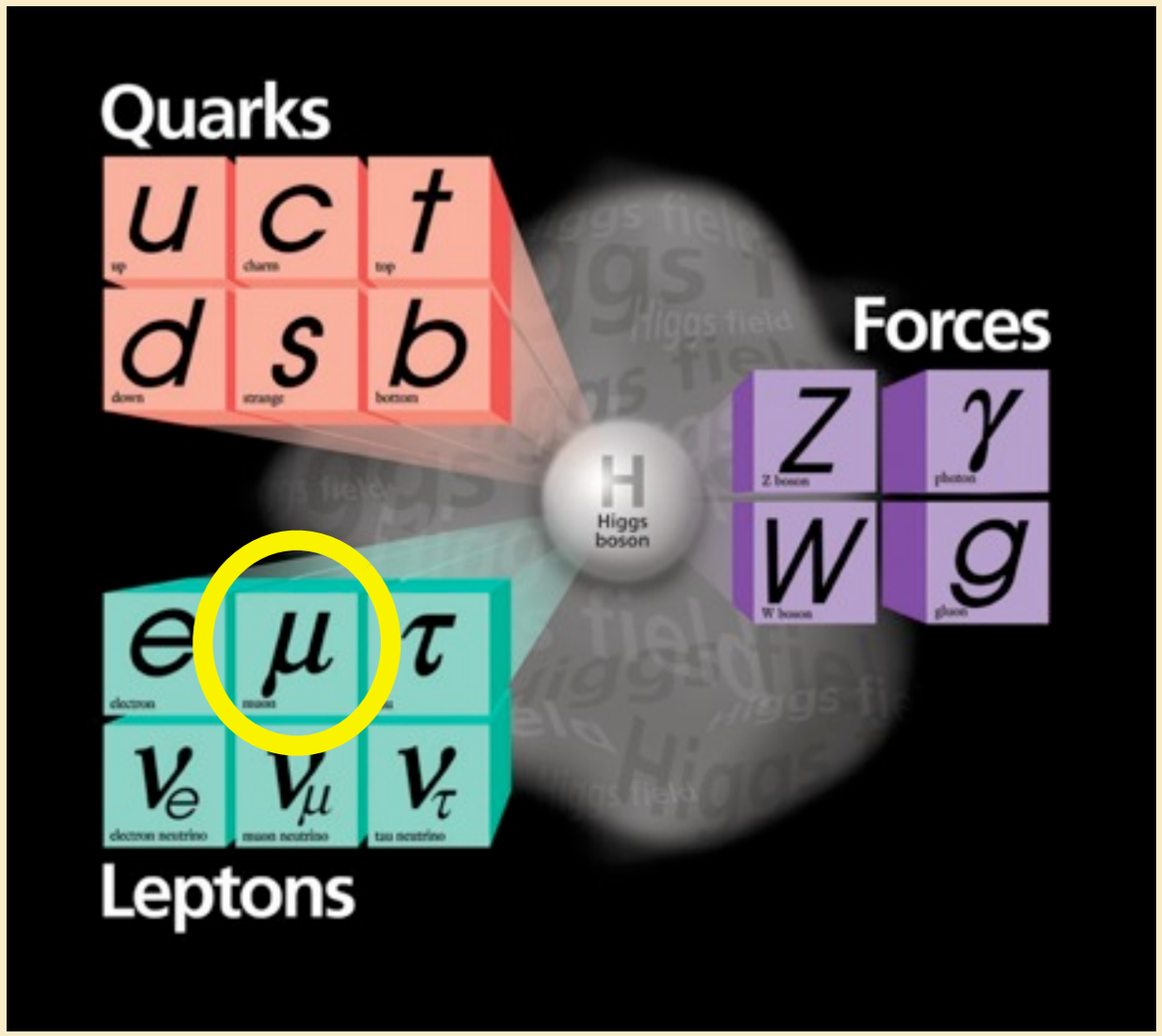
Carl Anderson (Caltech)

Seth Neddermeyer

Studying cosmic radiation on Pikes Peak, Colorado



Why are muons ideal?



Muons are like electrons

- **Same charge**
- **Also seem fundamental**
- **Have spin like electron (more in a moment)**

Muons are unlike electrons

- **Mass is 200x heavier**
- **40,000x more sensitive than electrons to subtle physics**
- **Muons are unstable**
  Decays into an electron and two neutrinos

The spin is the thing to study!

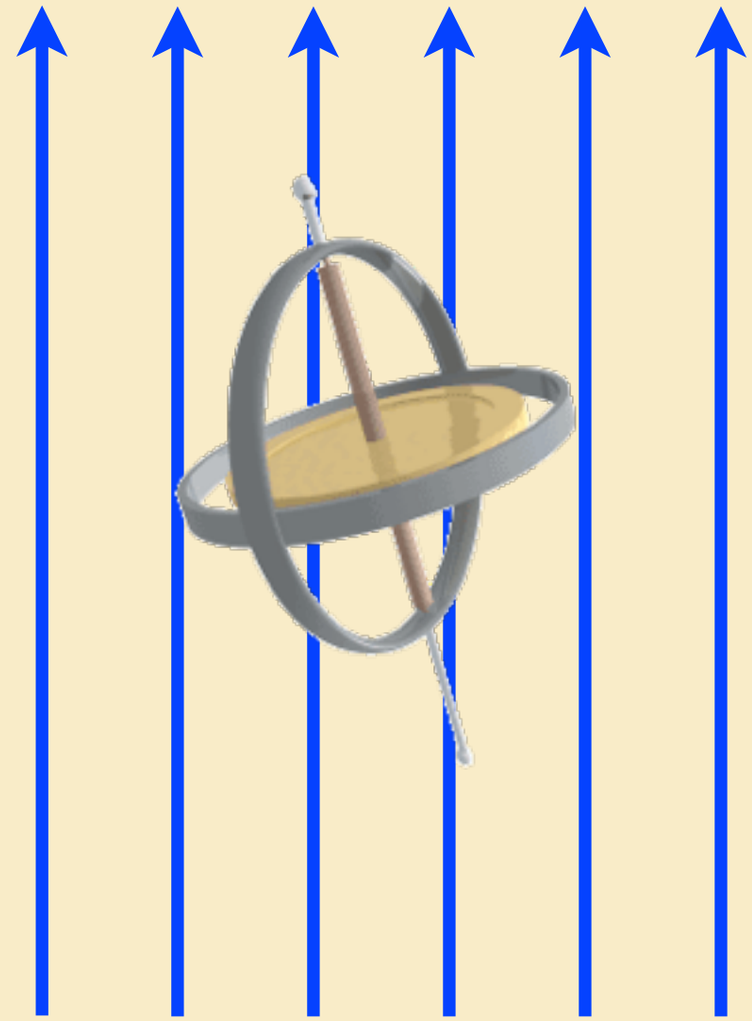
Leptons and Quarks have an internal property called “spin”, like the angular momentum of a spinning top

Not easy to think about, but the analogy works

Spin in a magnetic field

Put a muon in a magnetic field, its spin will "precess"

Just like a gyroscope or top in gravity

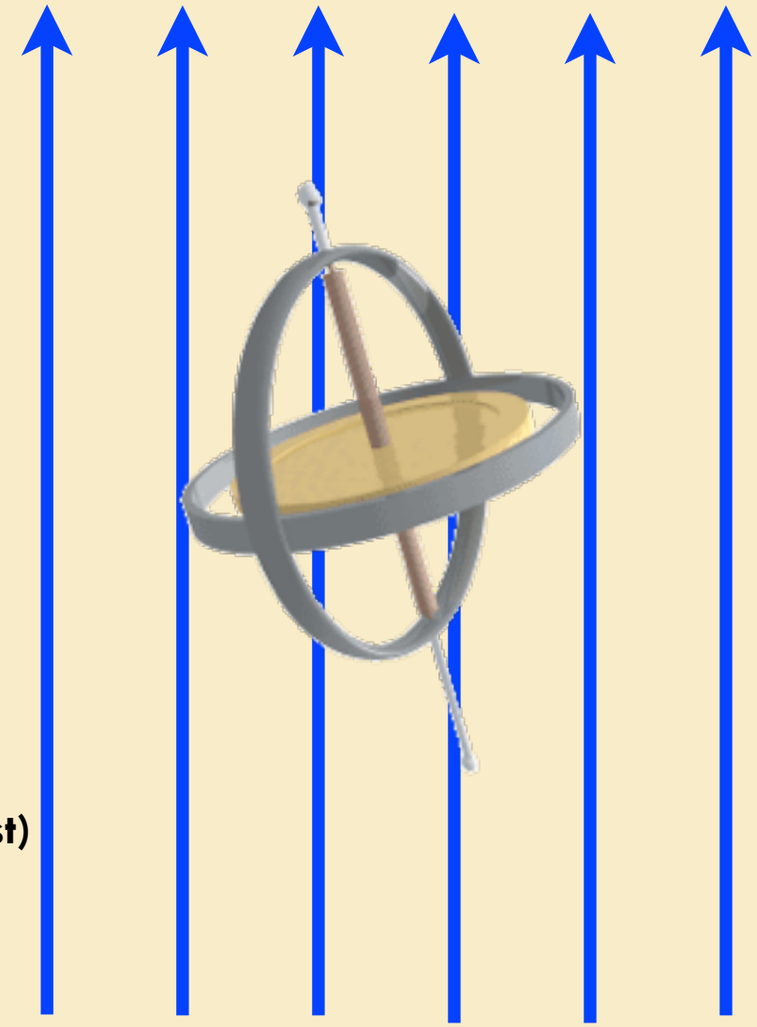


Spin in a magnetic field

Put a muon in a magnetic field, its spin will "precess"

Just like a gyroscope or top in gravity

The precession frequency of the muon is characterized by the "g-factor" for which quantum mechanics predicts 2 (almost)



The goal of the g-2 experiment is to put muons in an exquisite magnetic field and measure the precession frequency with extreme precision

What's with the (almost) 2 ?

An example with a bottle of wine...
Drink the wine (be careful not to precess!)

Pump out <u>all</u> of the air (pretend you have a perfect pump)

You'd think the bottle is empty, right?

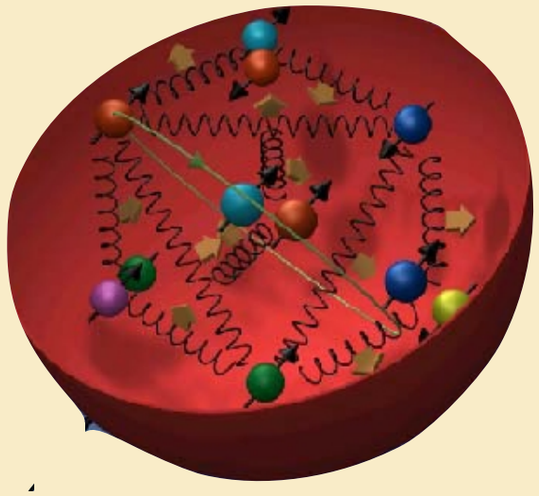
Not quite...

What's with the (almost) 2 ?

Quantum mechanics says that empty space is not empty !!!!!

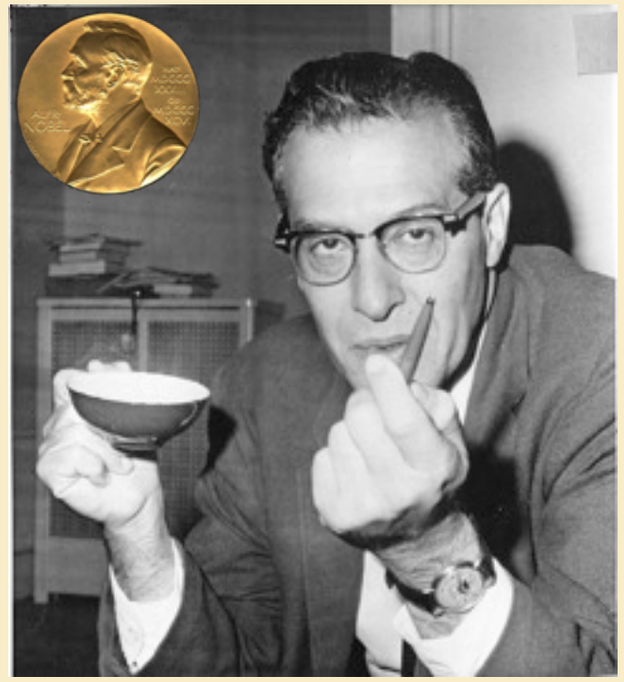
Particles can randomly appear and disappear very quickly (called virtual particles)

Strange, but it's true! We observe it often in particle physics experiments



The proton has u, u, d quarks, and lots of other stuff appearing and disappearing. Sometimes, we hit that stuff in collision experiments

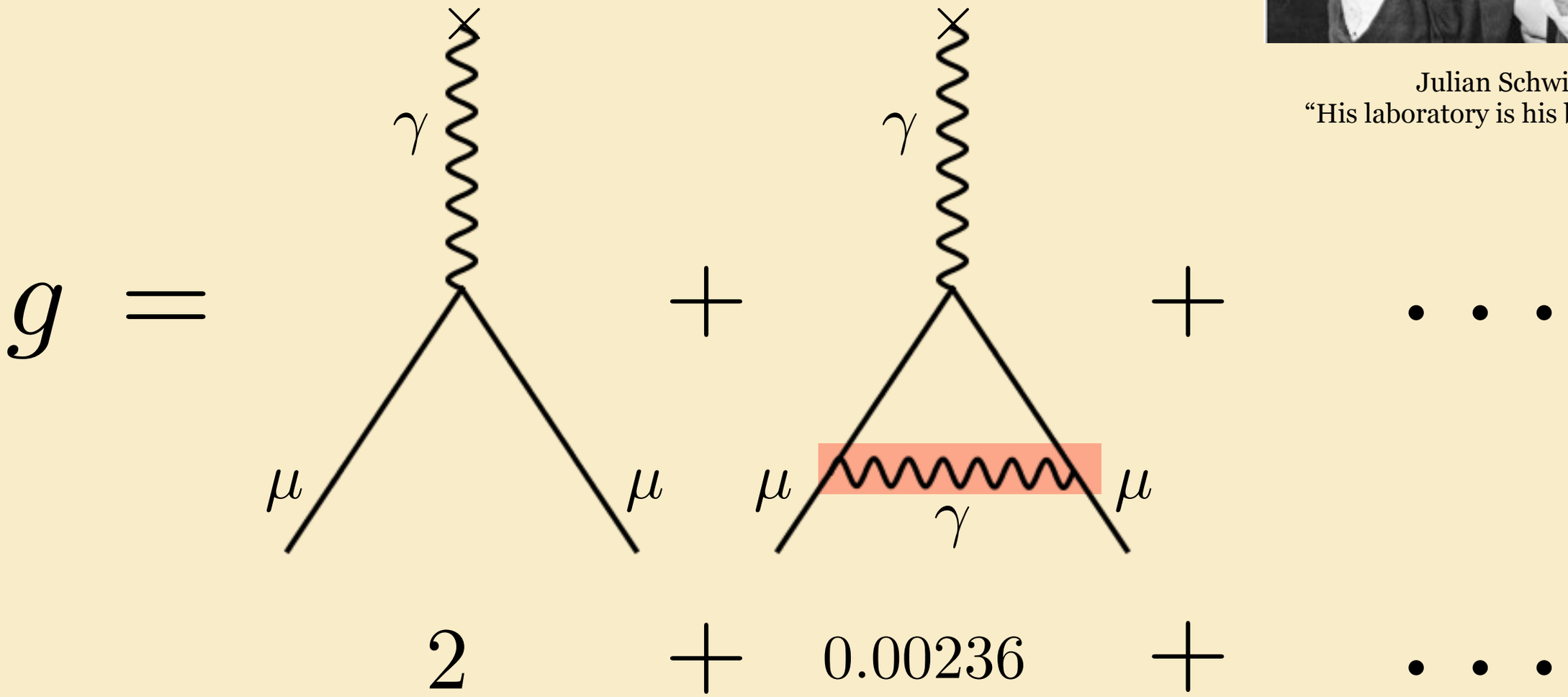
Quantum corrections matter!



Julian Schwinger
"His laboratory is his ballpoint pen"

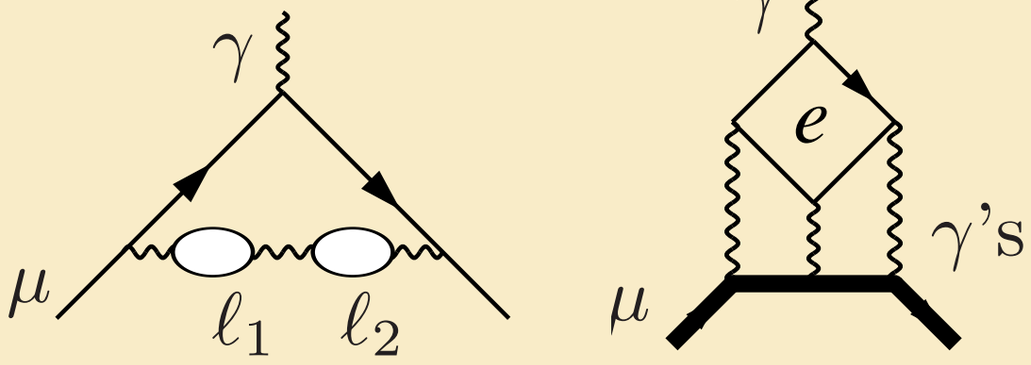
The effect is to "screen" the magnetic field

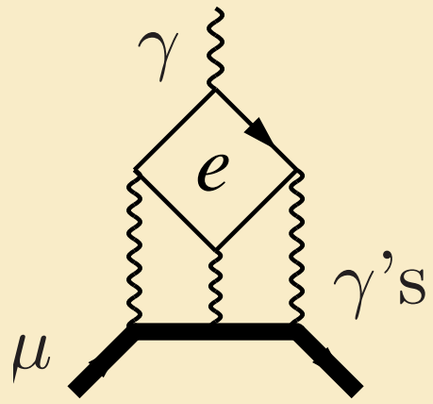
Changes the precession - makes *g* a little bigger



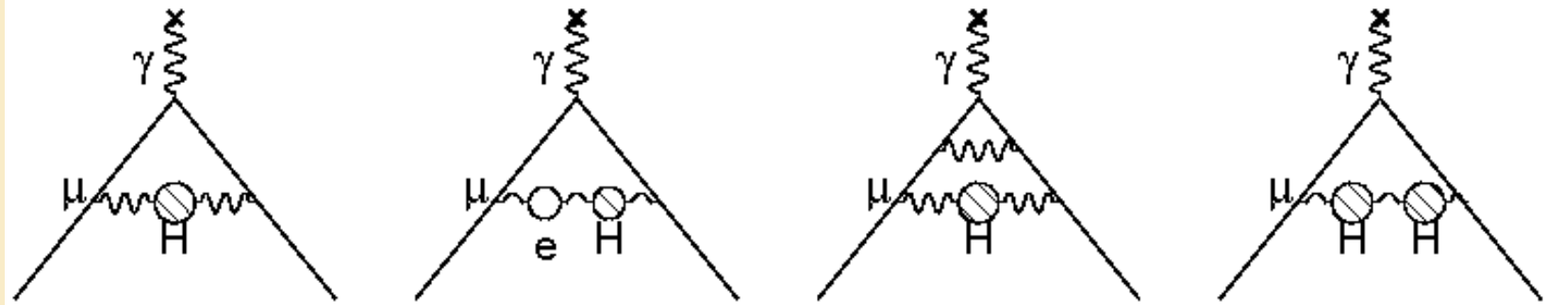
First *g-2* experiments 50's and 60's measured it! g>2 !

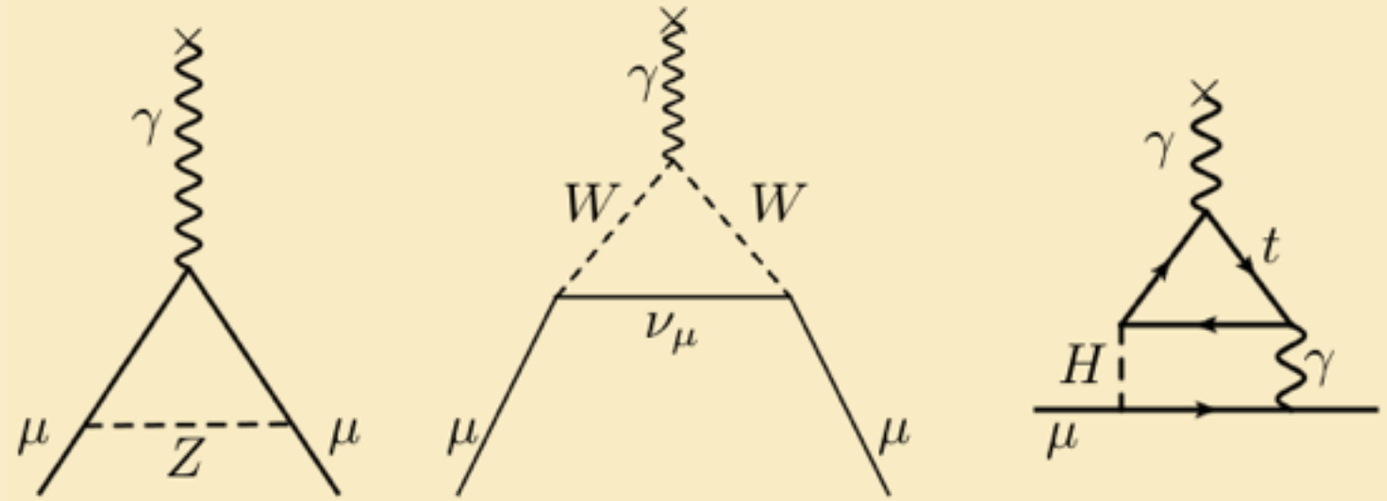
But corrections can get really complicated!





Particle theorists calculate how all these diagrams (and 10,000s more) affect *g*



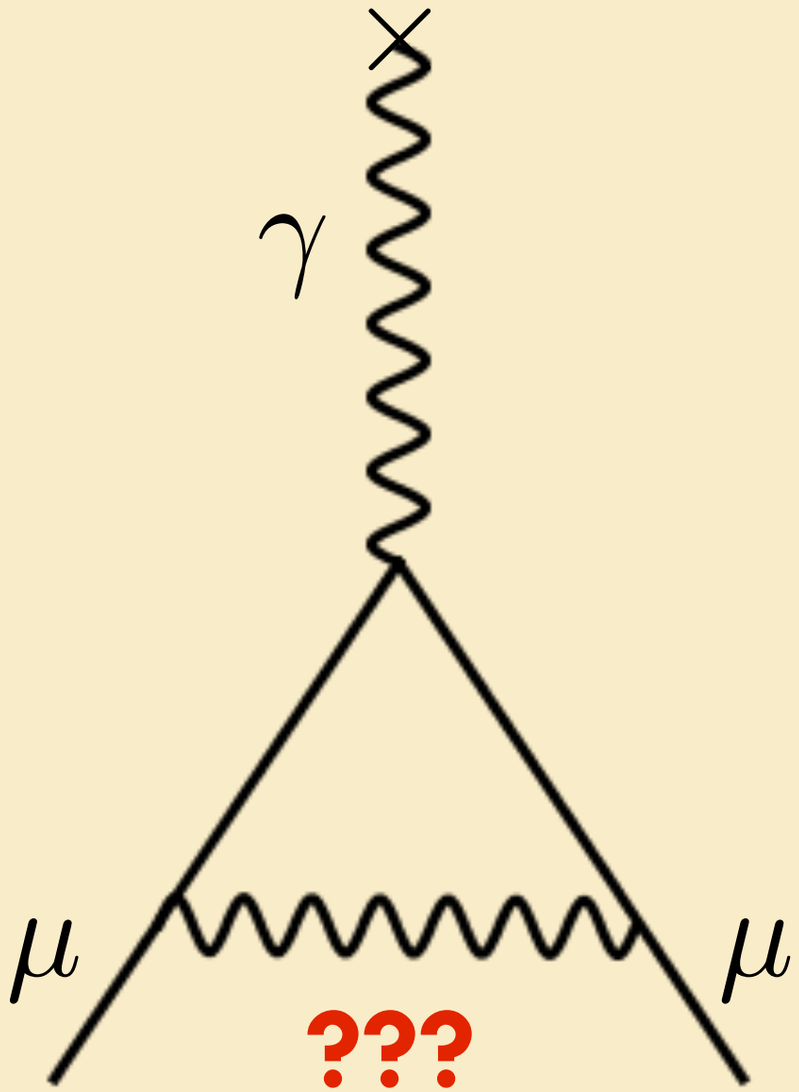


A fortunate rule: The more extreme the diagram, the less it changes *g*
(whew!)

Still, muons are very sensitive to these diagrams

Theorists work really hard at this!

The BIG question



g-2 is sensitive to unknown particles

Are there any?

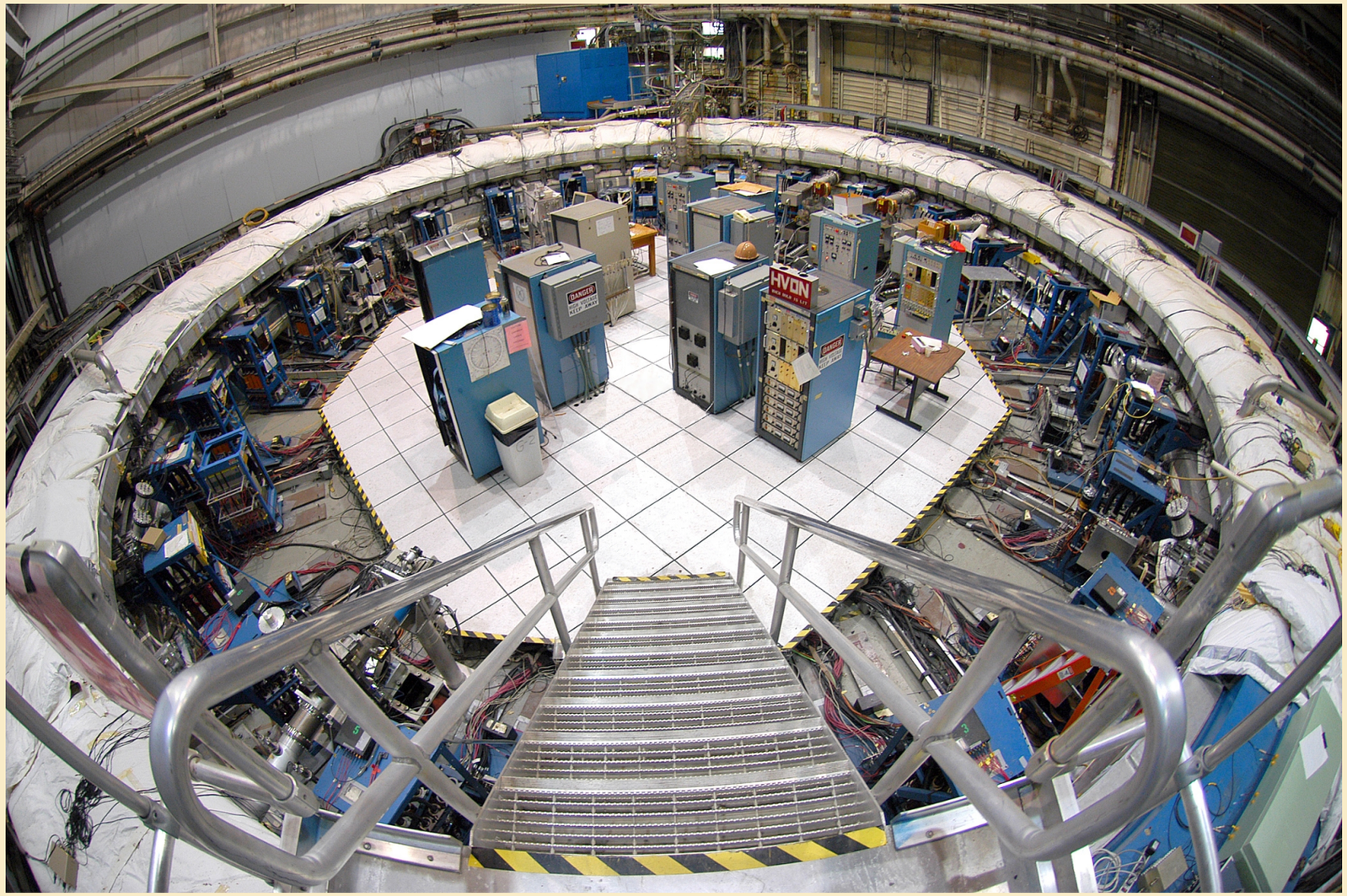
The plan:

1. Theorists calculate g-2 of the muon with corrections from all of the particles that we know about (Standard Model)

2. Experimentalists <u>measure</u> g-2 of the muon with great precision

If there's a difference, maybe New Physics is responsible!

How do we measure g-2?



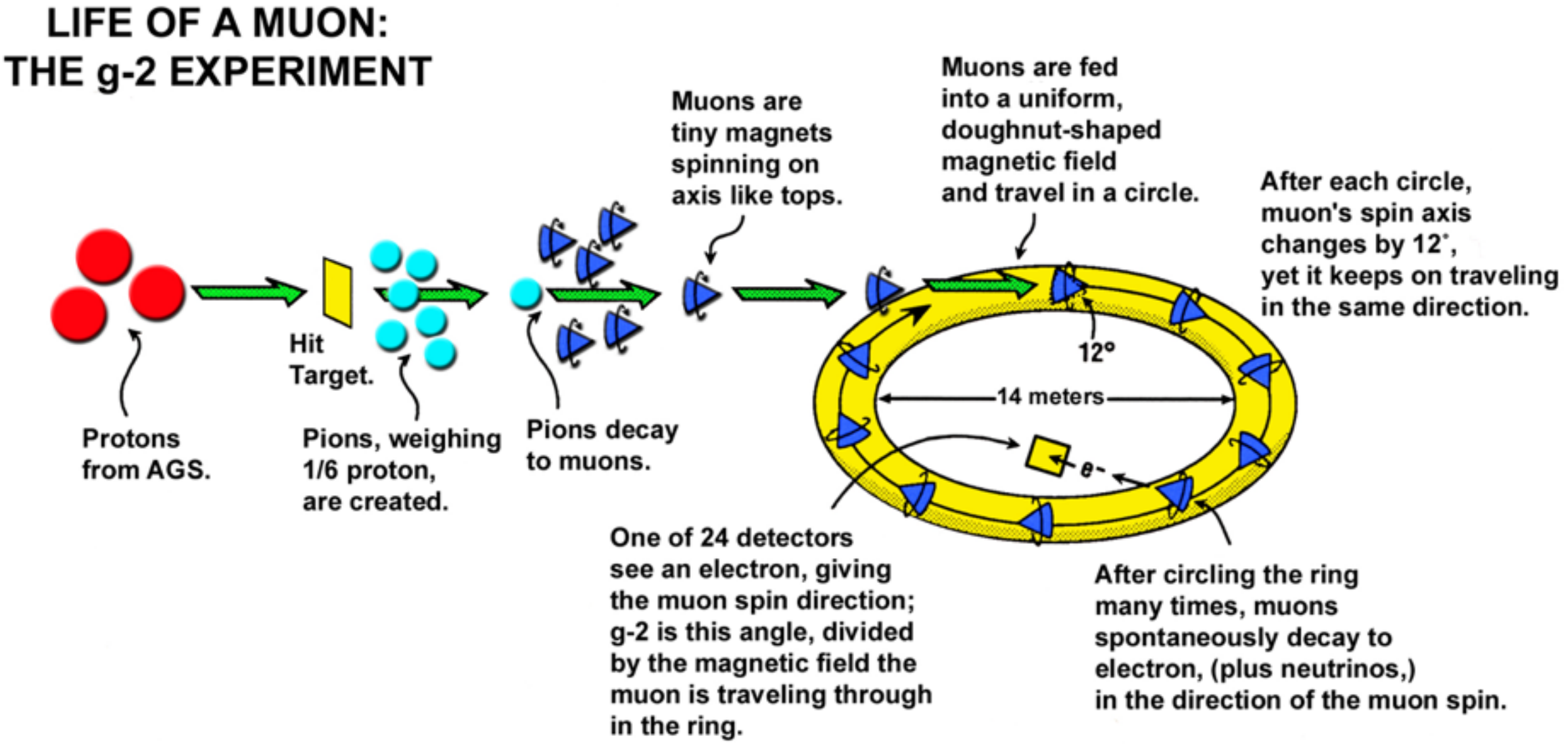
We need a magnetic field to make muons precess

We need a way to "store" the muons to watch them

A storage ring does both (the magnets keep muons going in a circle in the ring) !

Most recent experiment was 1999–2001 at Brookhaven National Laboratory on Long Island, NY

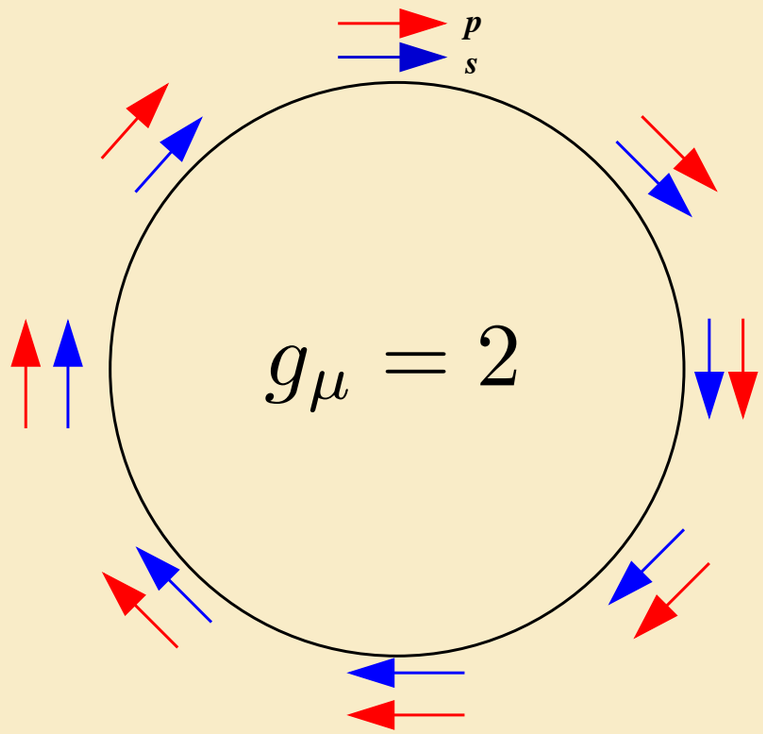
Schematic of the Brookhaven experiment

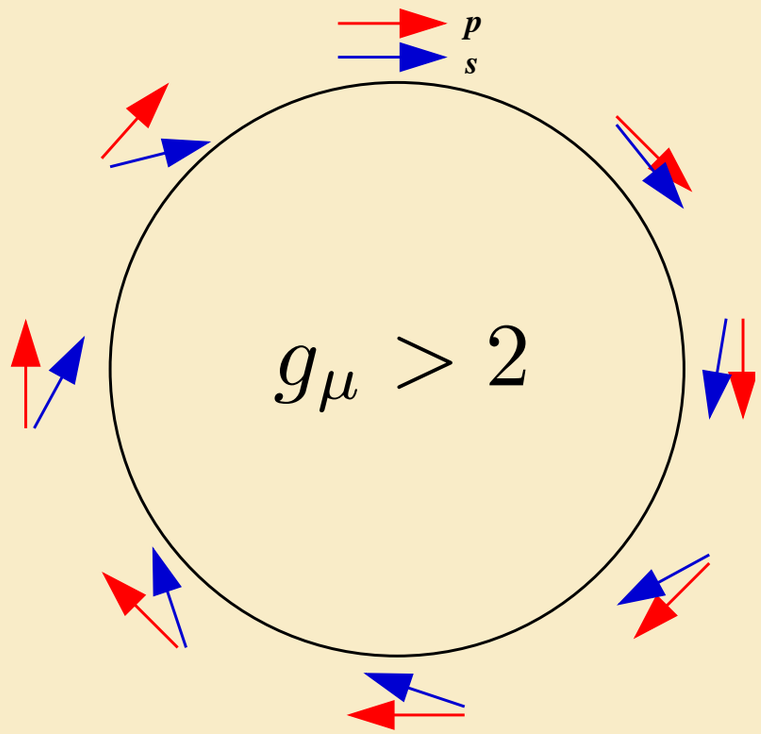


Spin direction diverges for g>2

direction of travel (*p*)

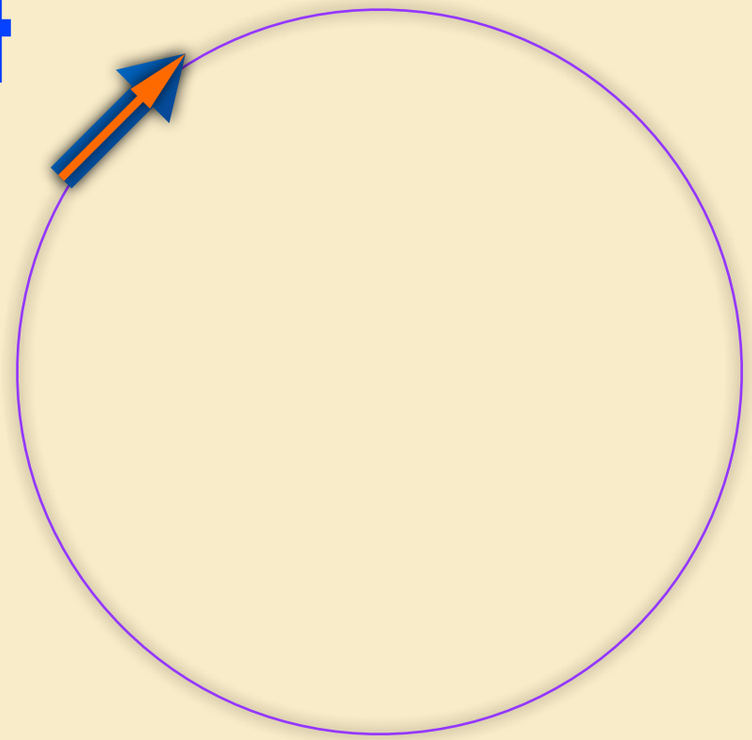
direction of spin (*s*)





- True for any size ring and any muon momentum
- At the measured *g* Muons go around 29 times for one spin cycle

Making the "wiggle" plot

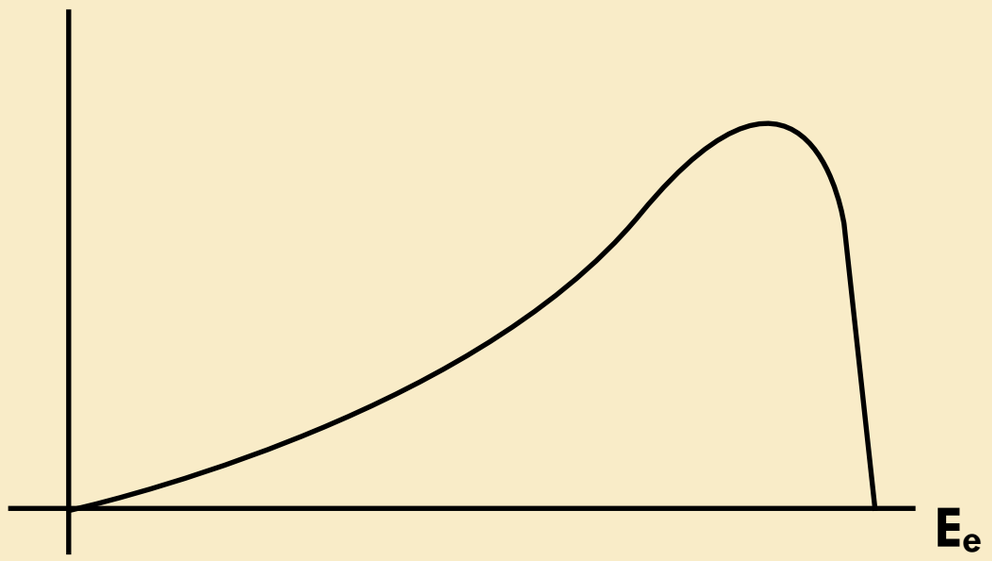


Muons circle the ring and decay to positrons, which travel inward hitting detectors

Highest energy positrons are aligned with muon spin

Boost to the lab frame gives *E* a boost

If anomaly exists, maximum *E* oscillates at ω_a



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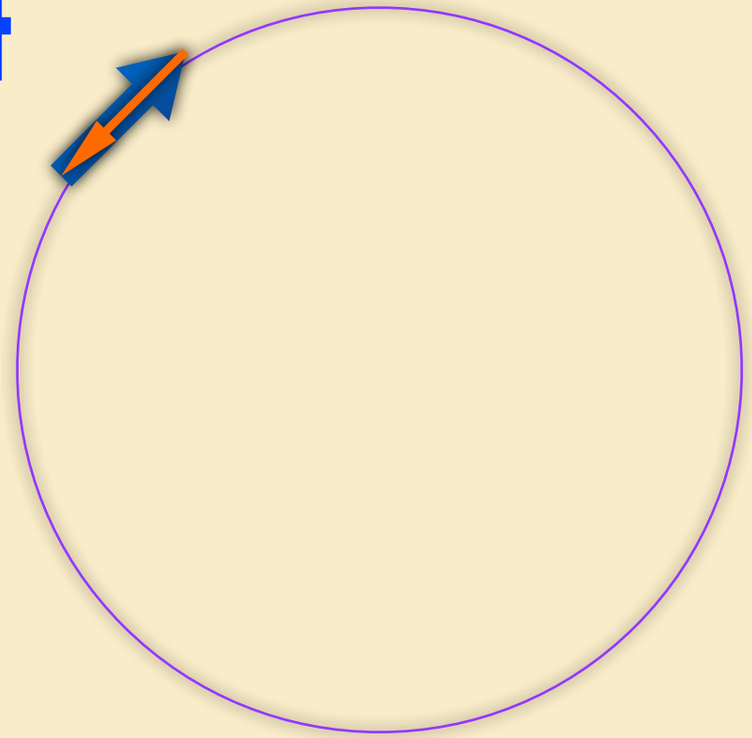

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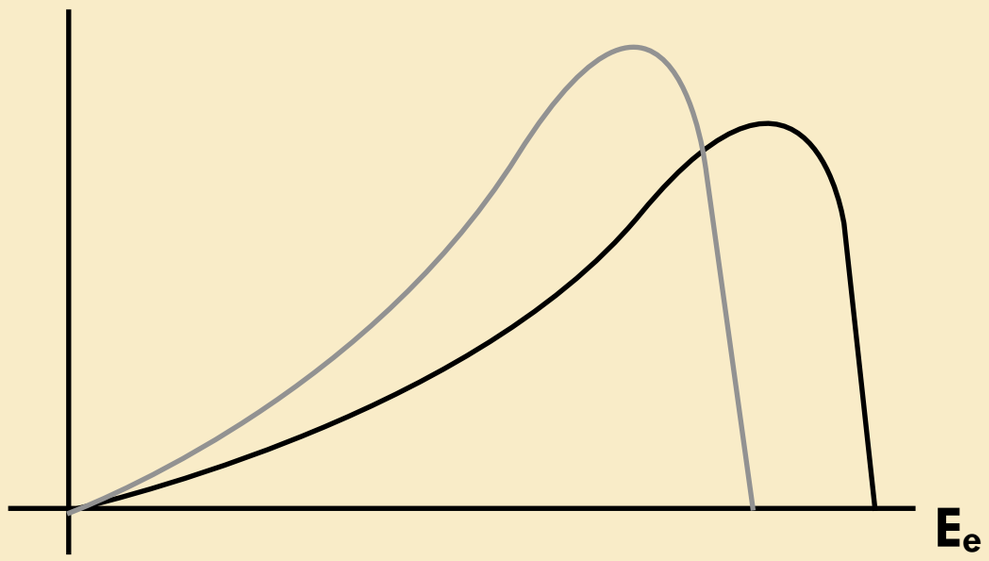

Making the "wiggle" plot

Count above fixed threshold. Oscillation rate ∝ g-2

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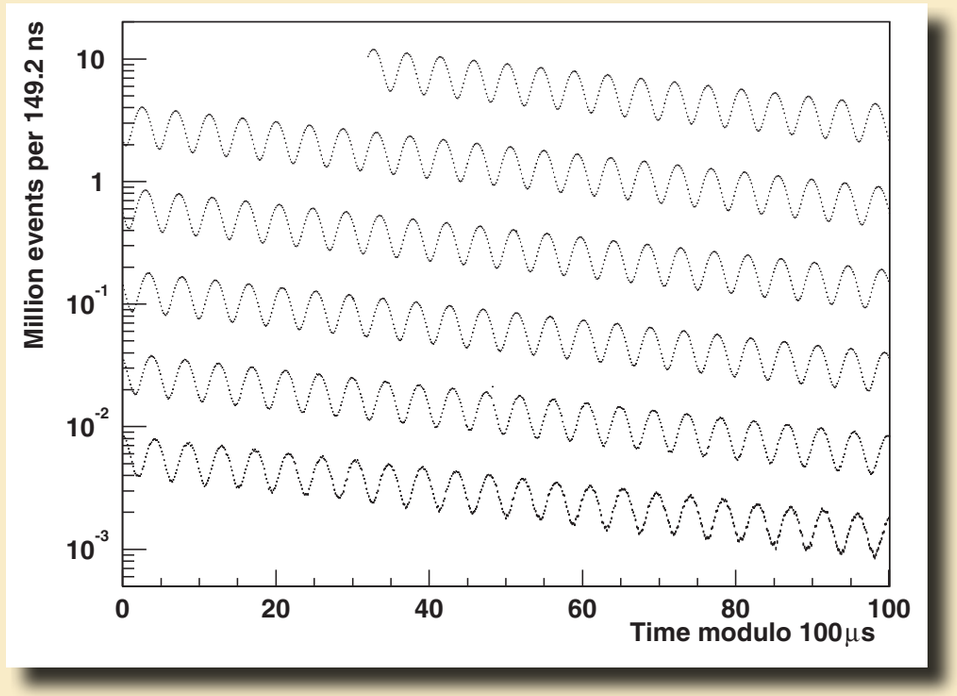
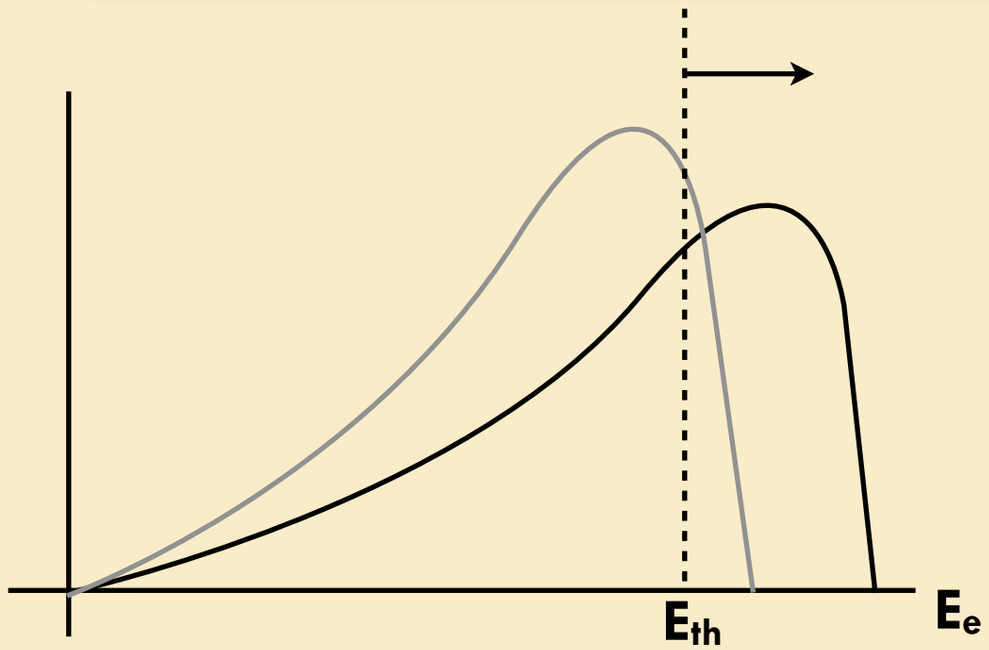
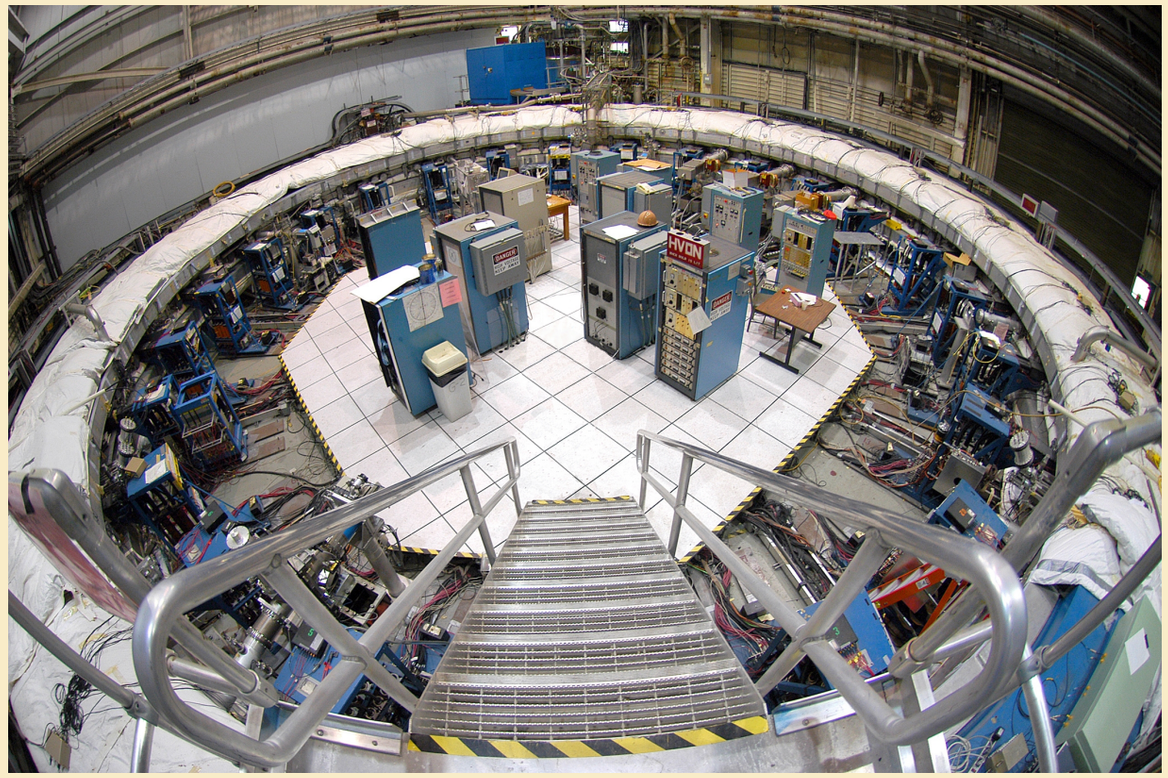




Thanks to Lawrence Gibbons for cool animation

Ring Fun Facts

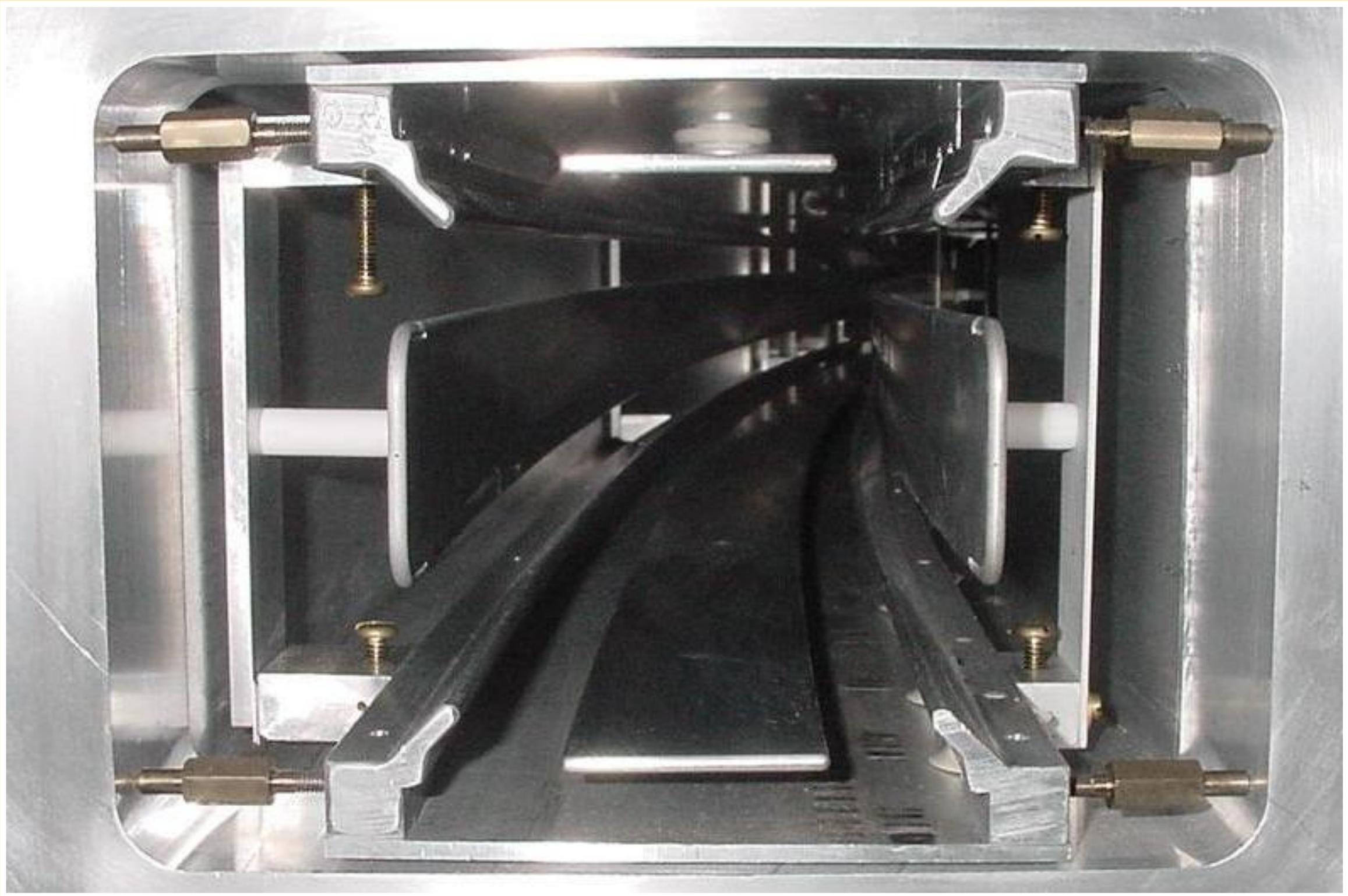


50 feet diameter;
Magnets are 15,000 Gauss
(fridge magnet is 100 G,
earth is ~0.5 G)

Electric current in wire coils make magnetic field
5200 Amps needed (a wall plug does 15-20A)
Coils are made from Niobium-Titanium Superconducting wire
Kept cold with Liquid Helium (5 K, – 450 F)

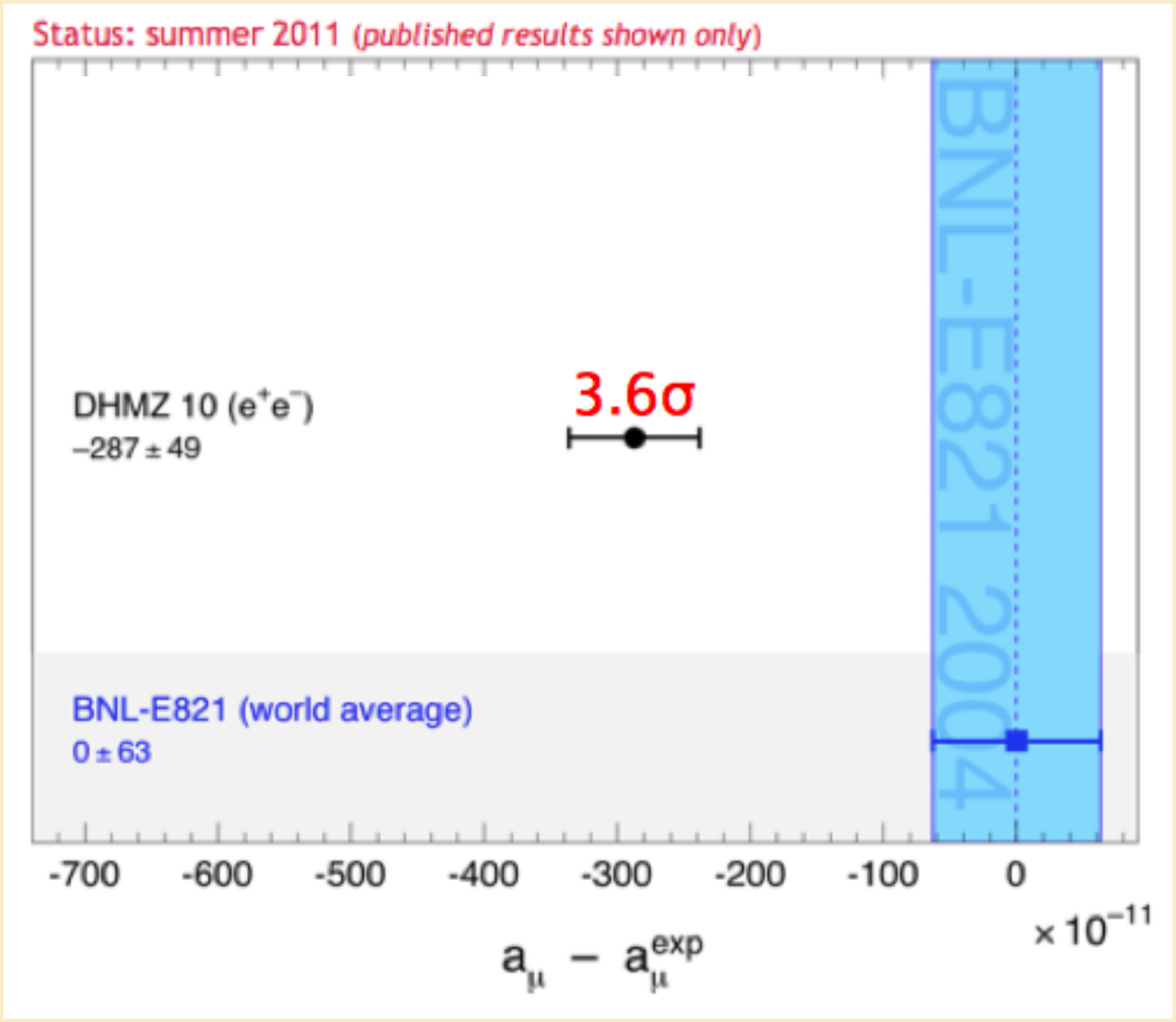
Muons go around the ring every 149 nano-seconds
(would go around 6.7 million times per second)
Travel at 0.99942 c - lifetime is 65 micro-seconds (>2.2)
Muon living for 100 micro-seconds makes 670 turns

Don’t put your head in the beam



4”

The Brookhaven Results (1999-2000)



$$a_\mu = (g-2)/2$$

$$a_\mu^{\rm QED} = 0.00\,116\,584\,718\,09(15)$$

$$a_\mu^{\rm had} = 0.00\,000\,006\,930(49)$$

$$a_\mu^{\rm EW} = 0.00\,000\,000\,154(2)$$

$$a_\mu^{\rm SM} = 0.00\,116\,591\,802(49)$$

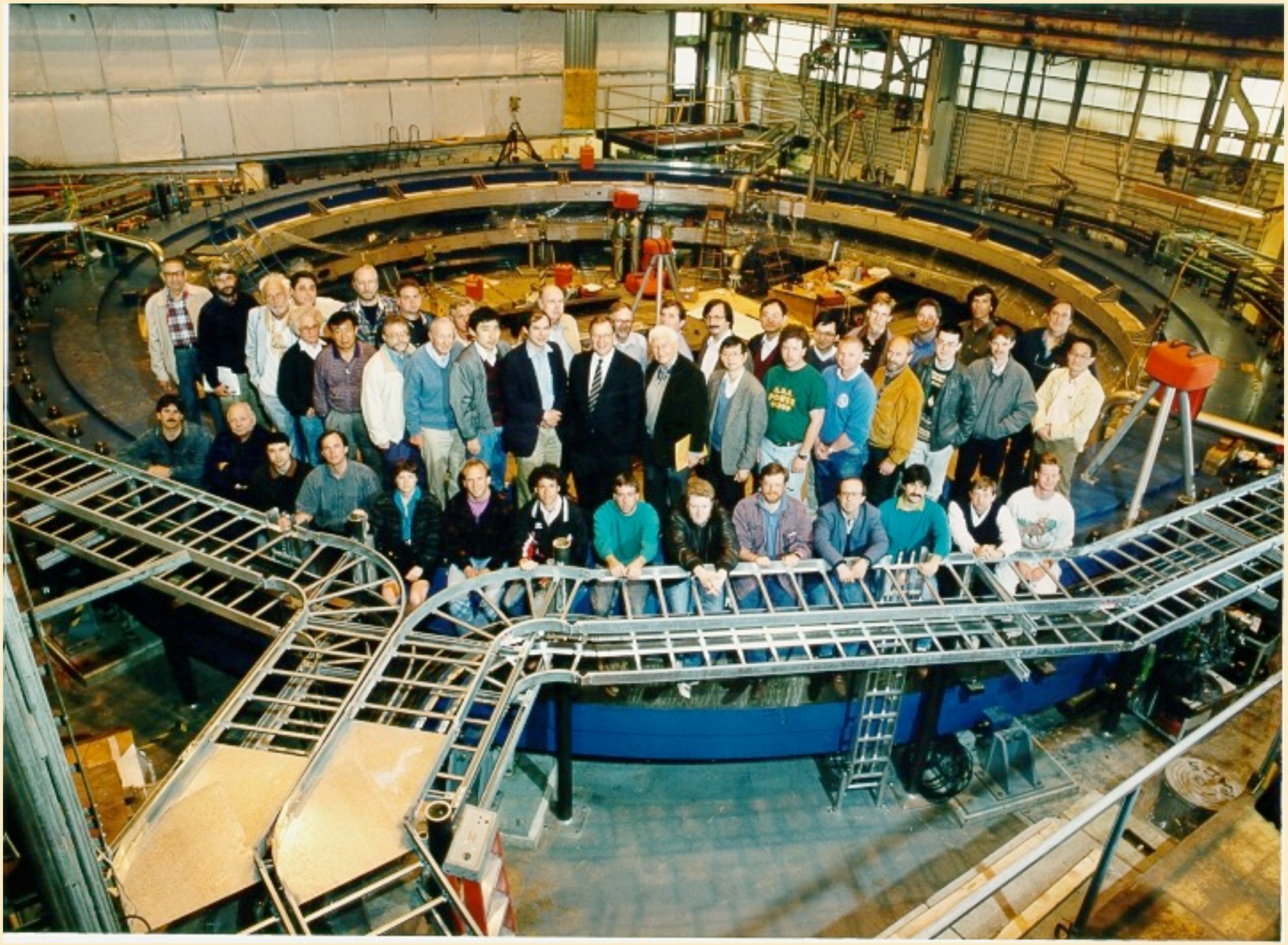
$$a_\mu^{\rm exp} = 0.00\,116\,592\,089(63)$$

0.54 ppm measurement

$$\mathbf{a_\mu^{exp} - a_\mu^{SM} = 287(80) \times 10^{-11}}$$

Difference is substantial, but uncertainties are too large to be certain of a discovery. Still, this is one of the only hints of physics beyond the Standard Model

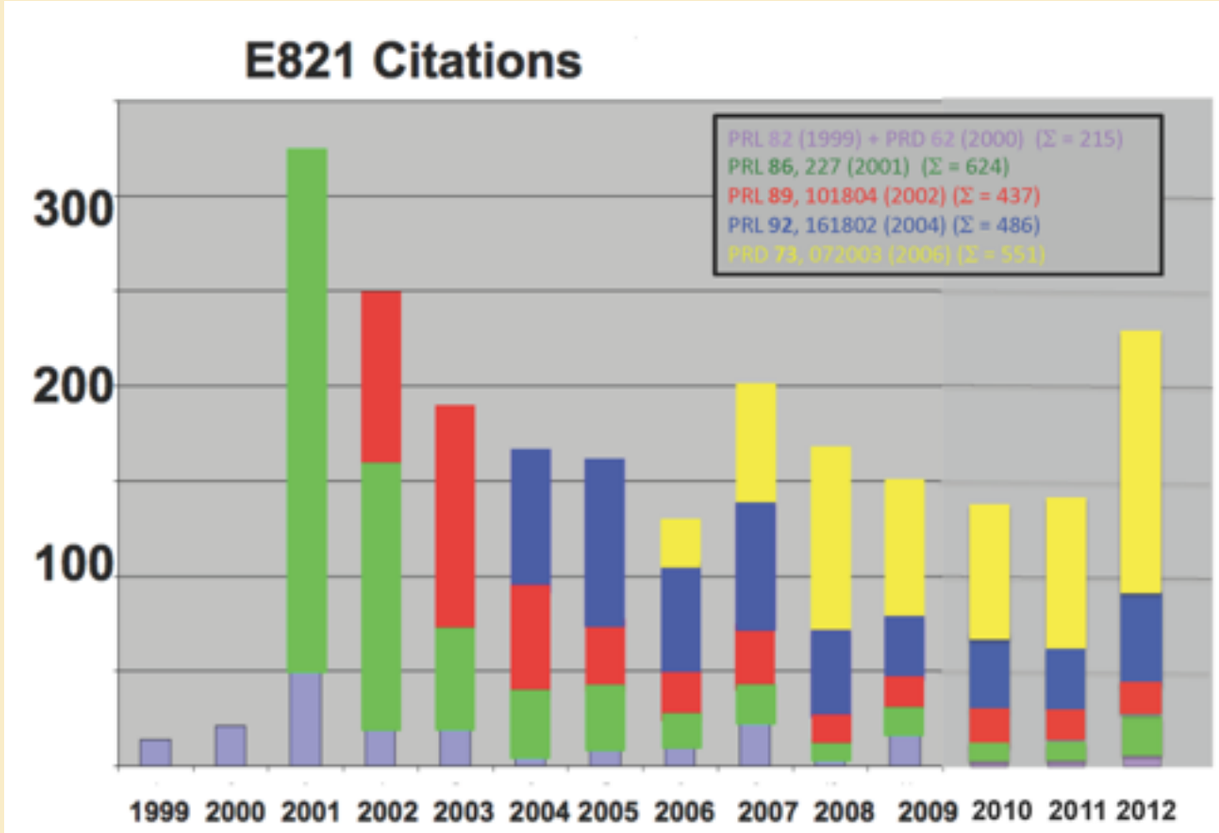
A Job Well Done

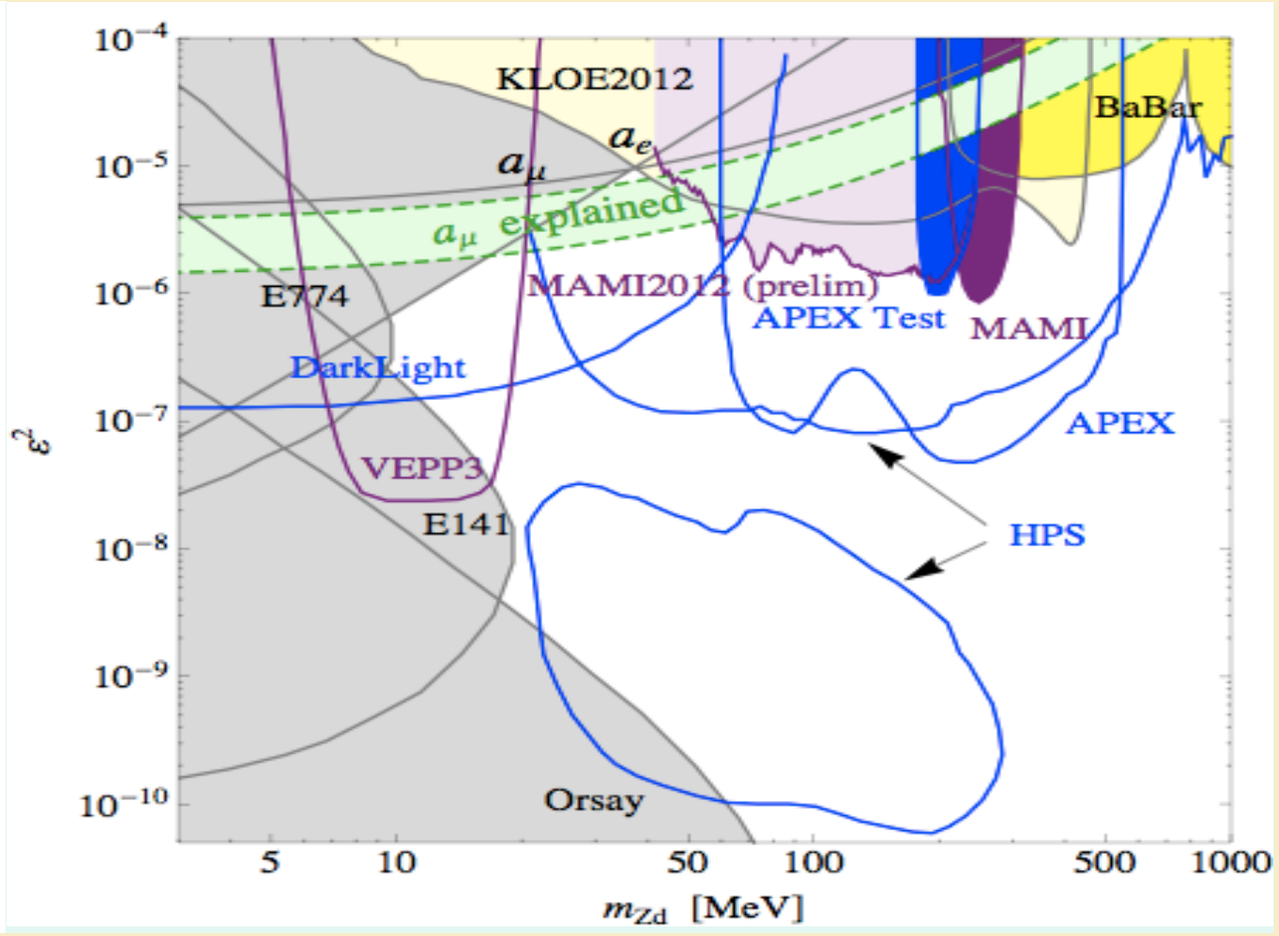


Impact of Brookhaven Results

This result is one of the few hints that there may be physics beyond the Standard Model

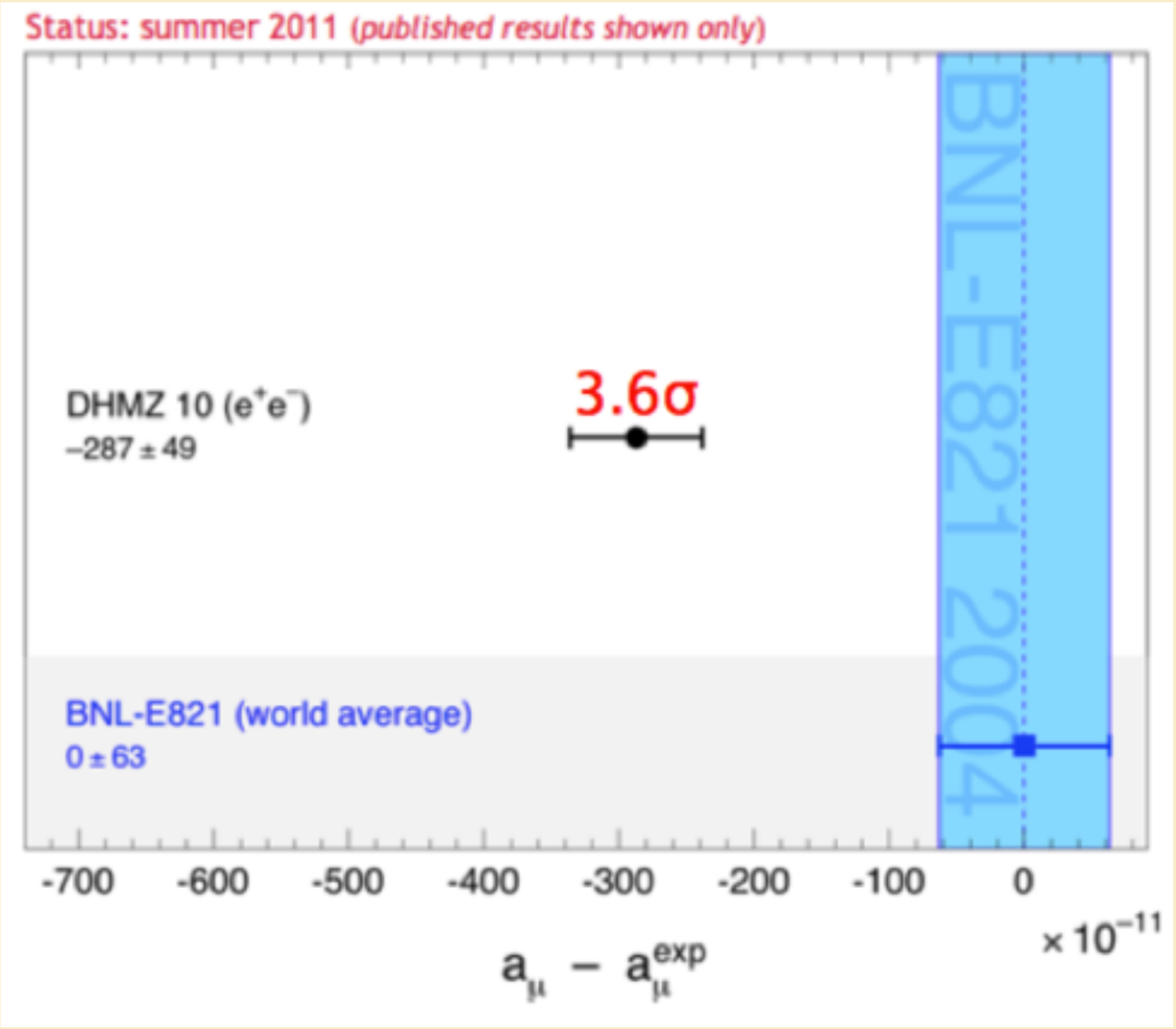
Enormous interest over the years





Huge impact on theories being developed and proposed for interpretation of LHC results (Muon *g-2* is complementary to the LHC)

Do the experiment again, but better



Want to make the blue uncertainty bar more narrow

Need more muons; better beam

Need "cleaner" environment (move ring further away from target)

But Brookhaven chose to invest in other things

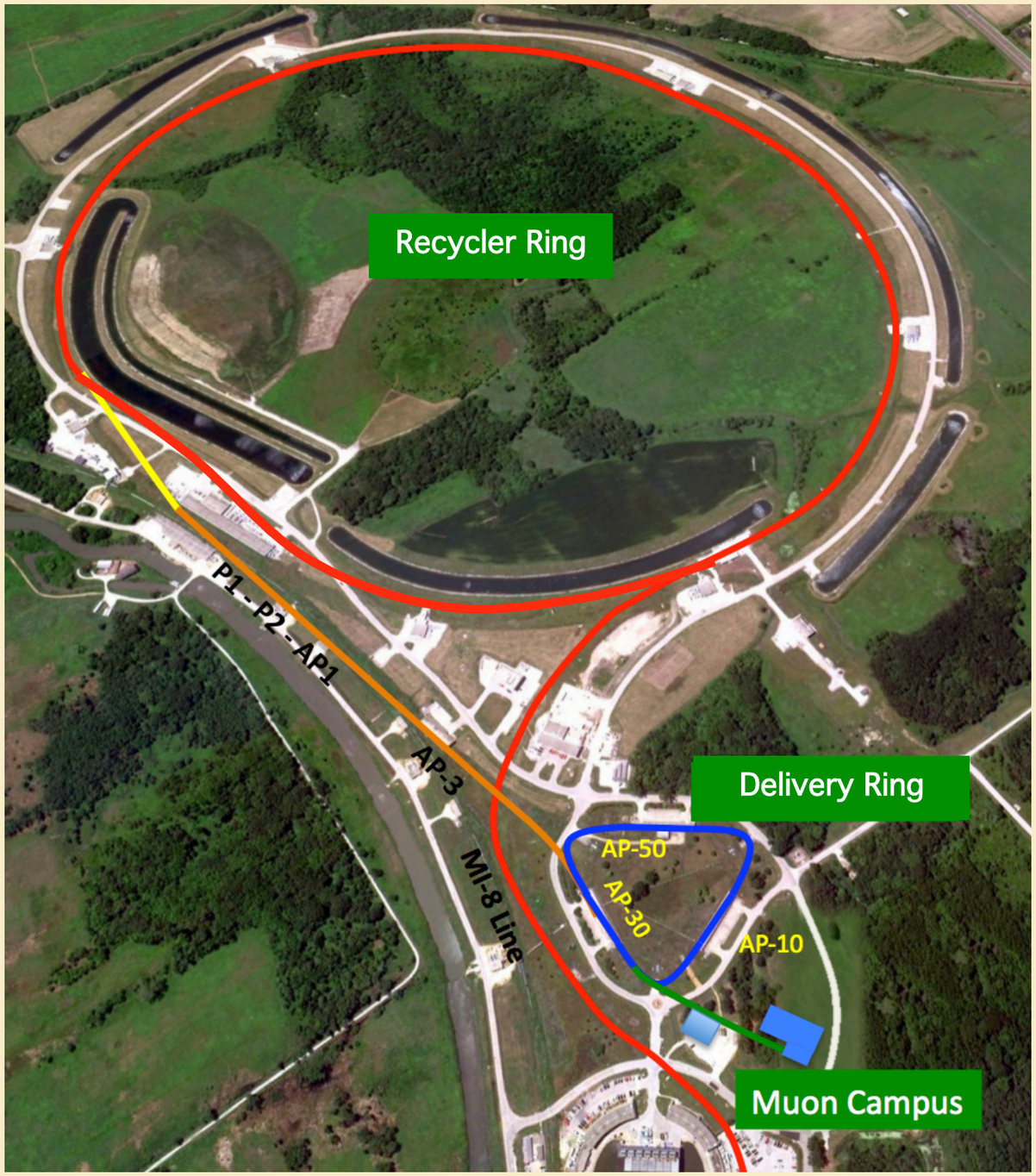
So this amazing and beautiful device sat untouched, gathering dust and raccoons for over a decade

In the meantime at Fermilab

The Tevatron shut down in 2011 after running nearly 30 years

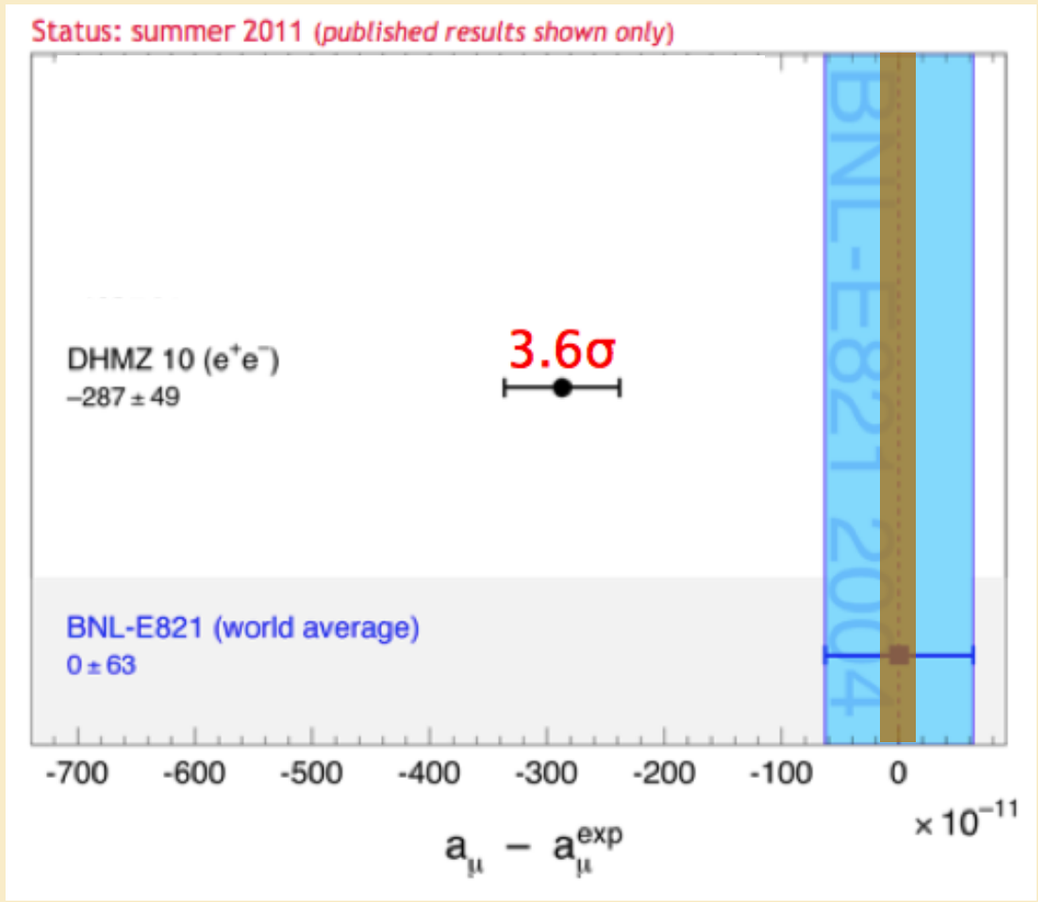
Muon g-2 at Fermilab

The Tevatron infrastructure is now available to do other things!

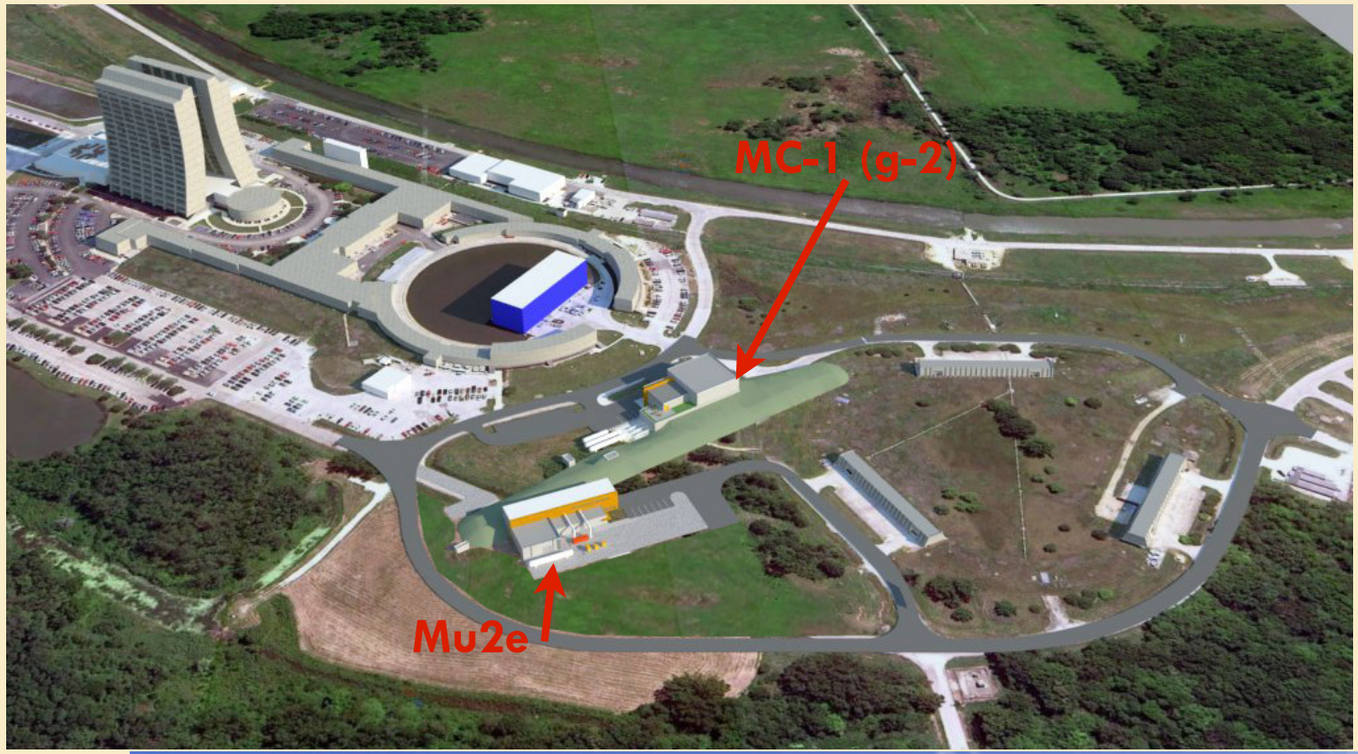


The accelerators and target that made anti-protons for the Tevatron can make muons for *g-2* !!!

And MUCH improved over Brookhaven!



A new home at the Fermilab Muon Campus



Ring arrives summer 2013

Building complete 2014

Moving the ring from Brookhaven to Fermilab

The hard part is moving the three superconducting coils

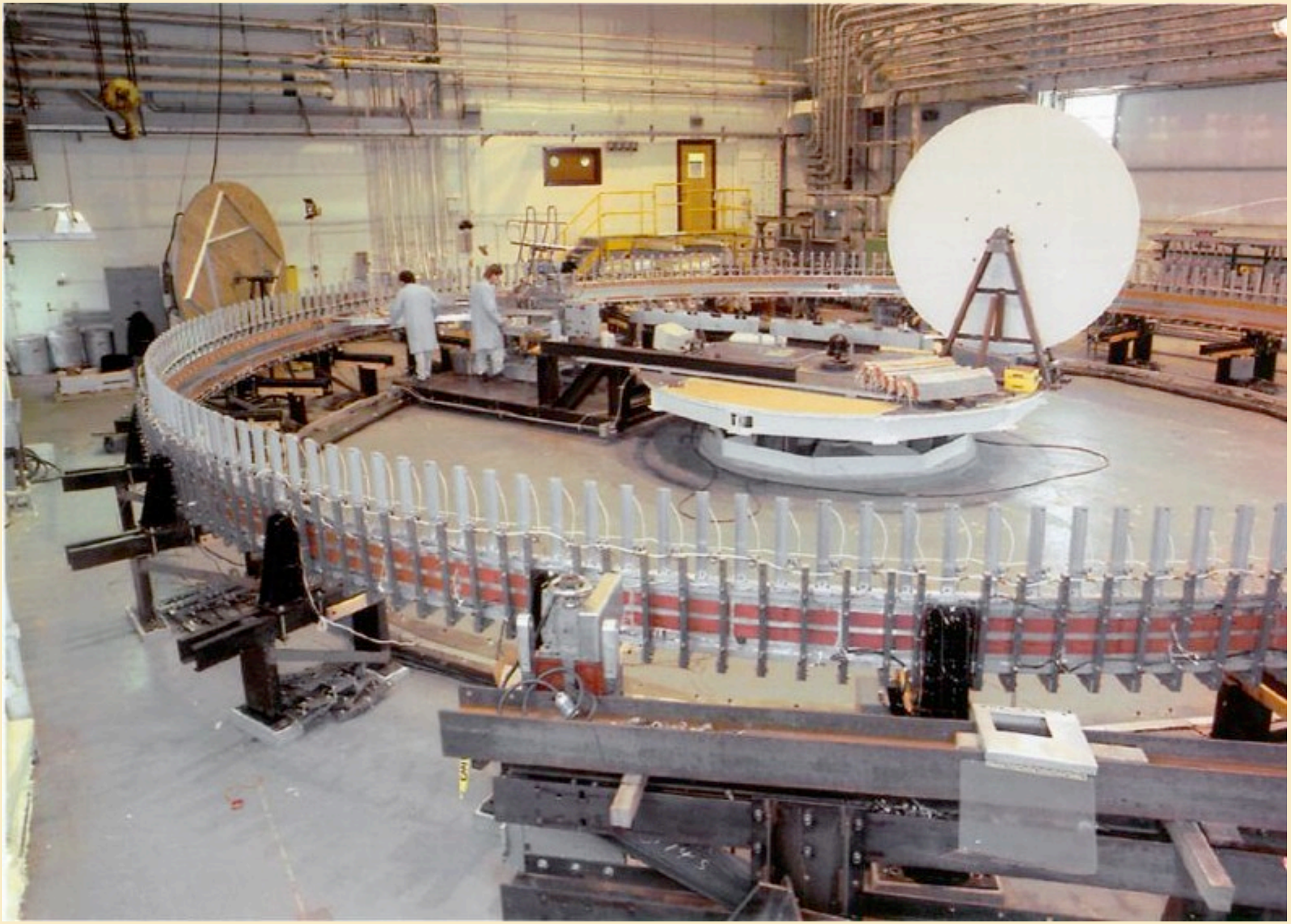
Continuously wound coils, can't break into pieces - can't flex > 3mm

They're big!
50 ft diameter
(takes up ~ 4 lanes on the highway). Not terribly heavy at 15 tons

They aren't dangerous: nonmagnetic when unpowered, not radioactive, no dangerous chemicals (aluminum, niobium [hypoallergenic], tin), inert

~ $2M to move. 10x more, ~$30M, if we had to build them anew!

Moving the ring from Brookhaven to Fermilab



The ultimate road/water/road trip

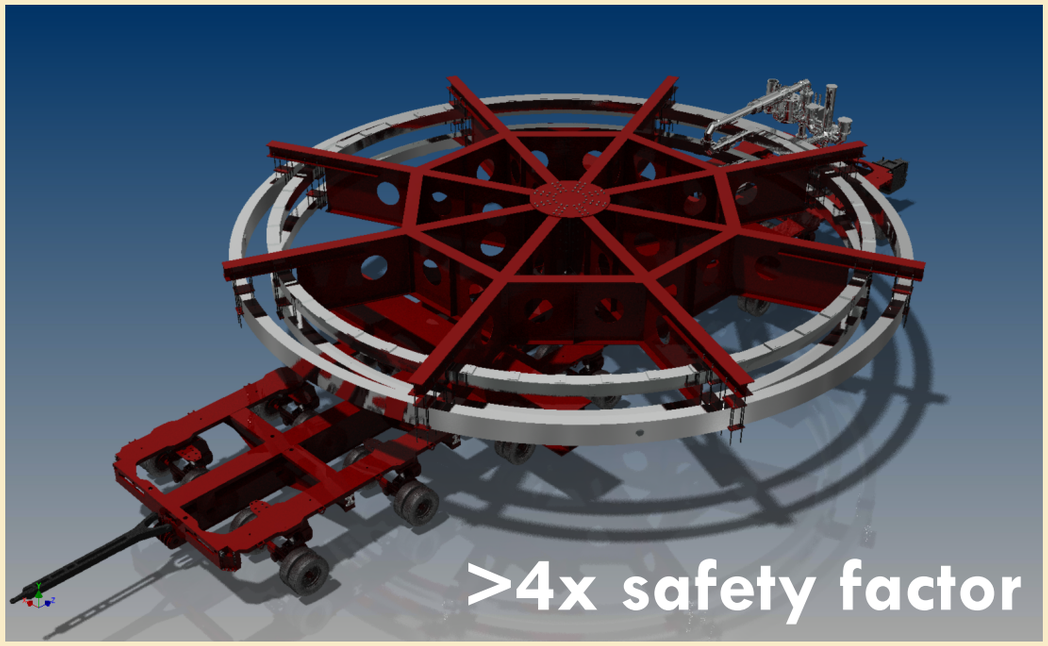
Coils must not flex more than 3mm. Ring is 15 tons, fixture is 40 tons

EMMERT INTERNATIONAL

"We can move that"

Decision to avoid lower Mississippi was made 2 weeks prior to departure

Instead, take the Tennessee–Tombigbee



Disassembly - summer 2011

Photo: Leah Welty-Reiger

Disassembly - spring 2012

Photos: Chris Polly

Disassembly - spring 2012

Photo: Chris Polly

June 2013 - Assembling the fixture

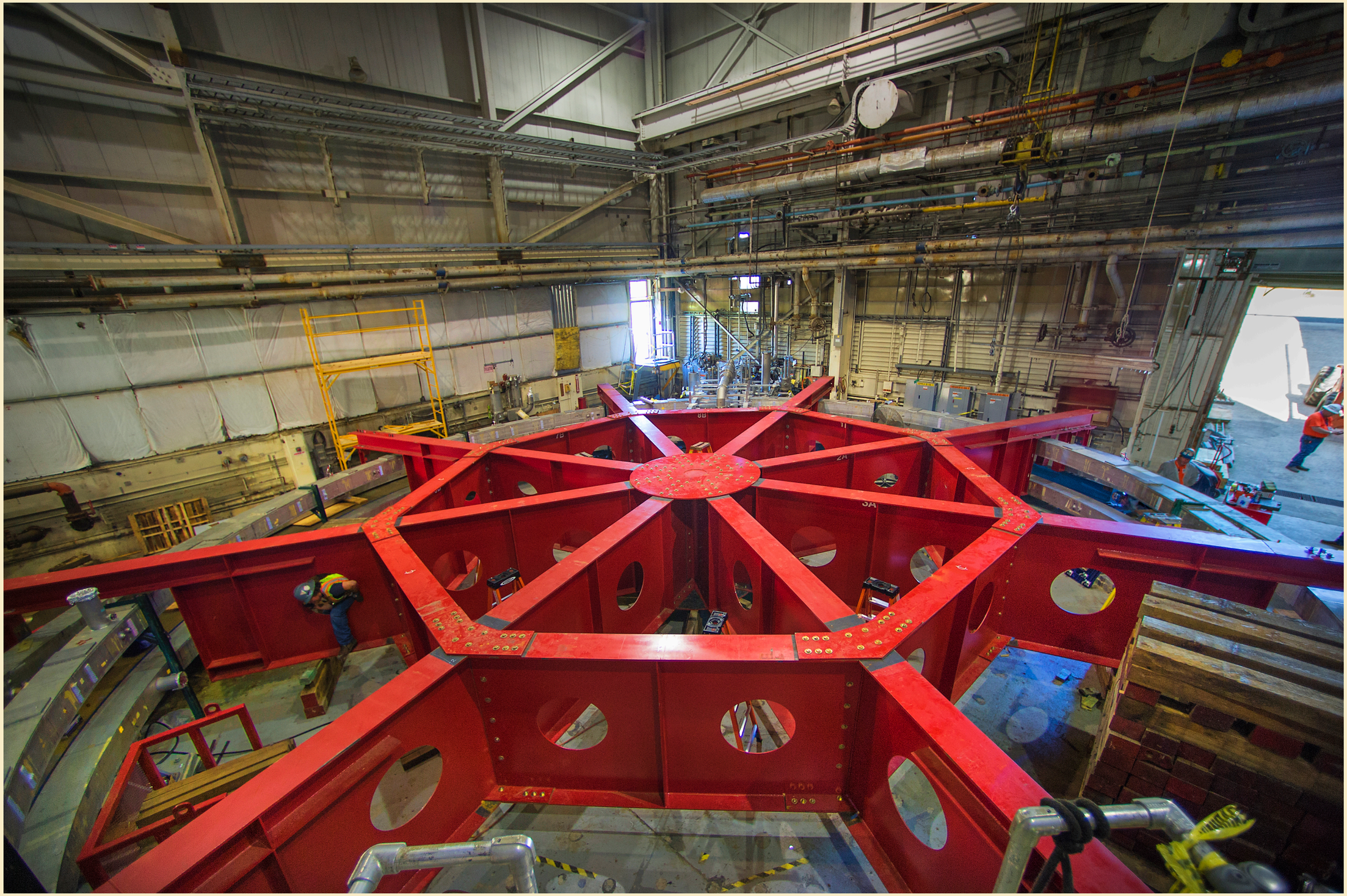


Photo: Brookhaven/Emmert

Removing the coils

Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

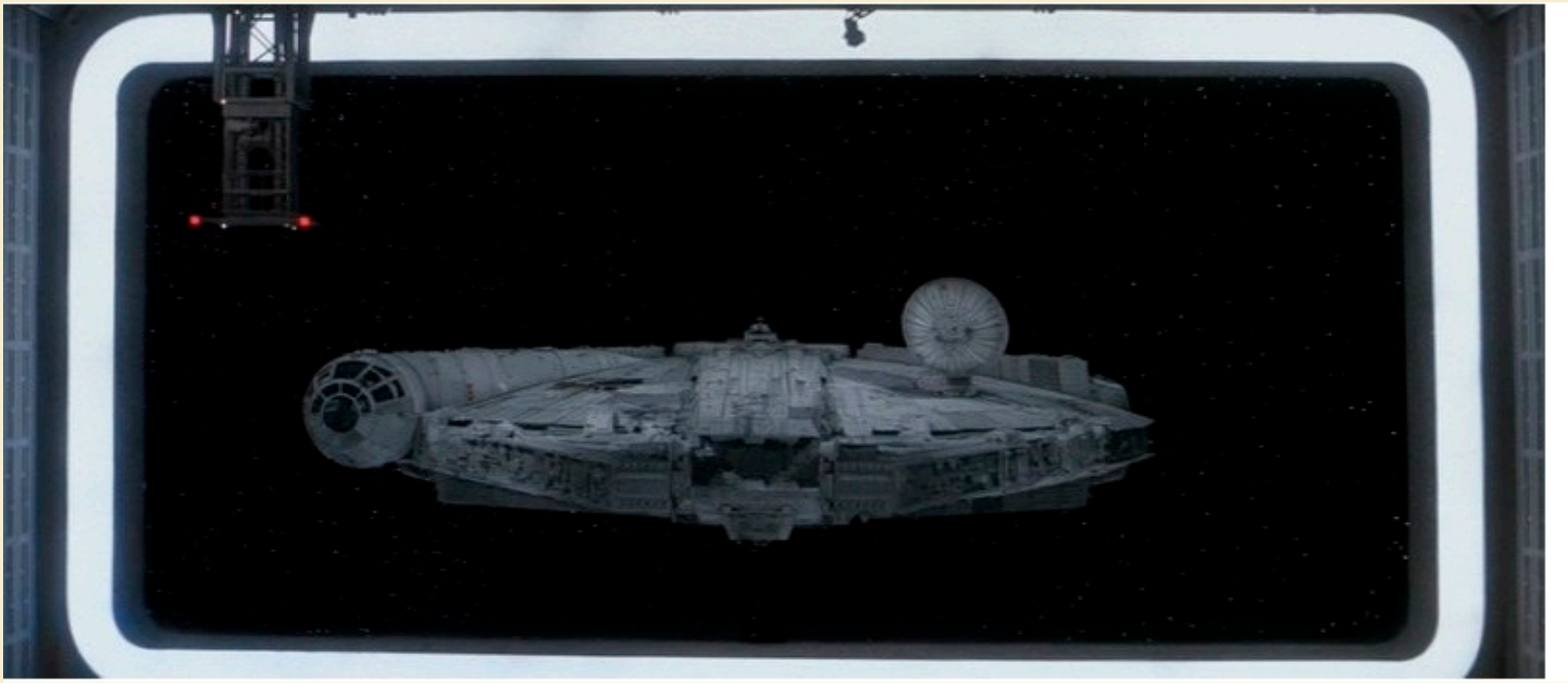


Photo: Darth Vader

It’s out !!

Photo: Brookhaven/Emmert

The fancy trailer

8 axels
64 tires

Auto-leveling
Height control
Independent steering
Way cool!

Photos: Brookhaven/Emmert

Wrapped up and ready to roll

Photo: Brookhaven/Emmert

Traversing Brookhaven National Lab

Photo: Brookhaven

Driving on the William Floyd Pkwy to port

Photo: Brookhaven

Hoisting onto the barge

Photos: Brookhaven/Emmert

On the barge

Photo: Brookhaven/Emmert

Off it goes

Photo: Brookhaven/Emmert

A 3200 mile journey 6/22 – 7/26

GPS update every two hours

4 days in port at Norfolk ($1000/hr)

Our instrumentation aside from GPS failed

Emmert's coarse instrumentation ok

Making friends while in Norfolk

Photo: Aria Soha's sister-in-law

Arrival in Mobile, AL

Handoff from the Trident (ocean tug) to the Miss Katie (river tug)

Photo: Darin Clifton

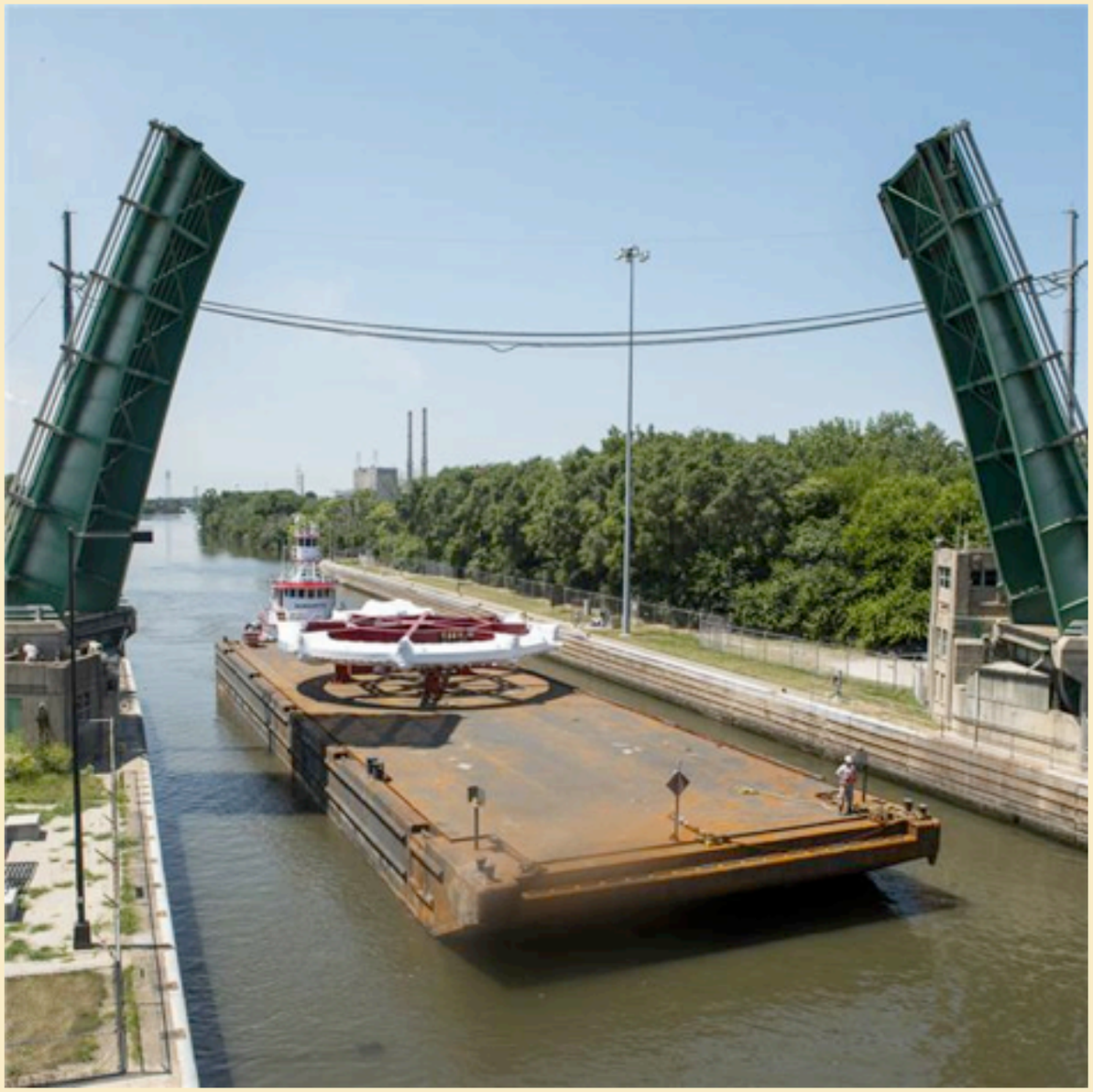
Up the Tenn-Tom Waterway

Photo: Darin Clifton

See you in St. Louis

Photo: Hogan Nguyen

On the Illinois Waterway

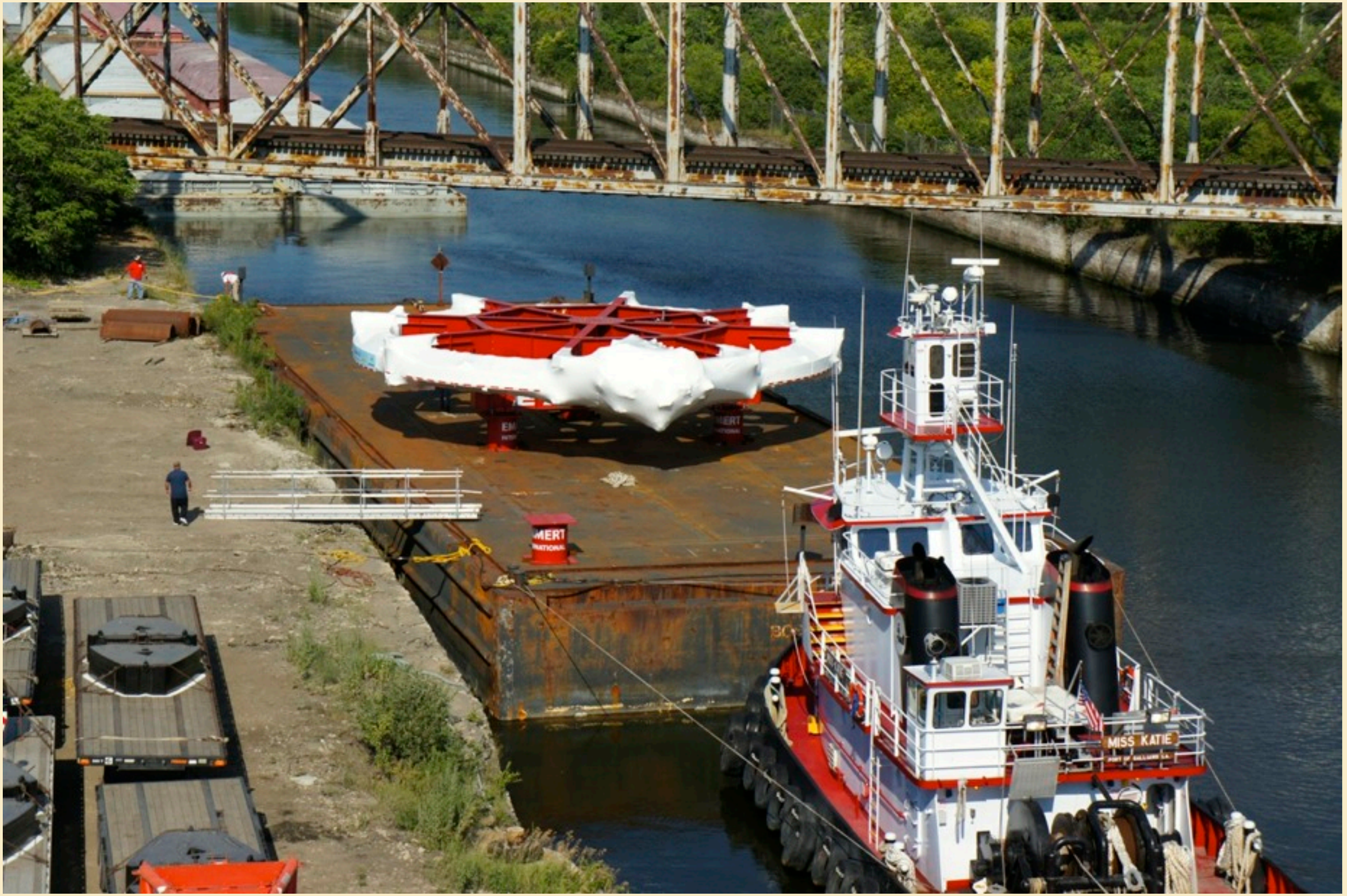


Photos: Fermilab

And Saturday 6/20, finally in Lemont

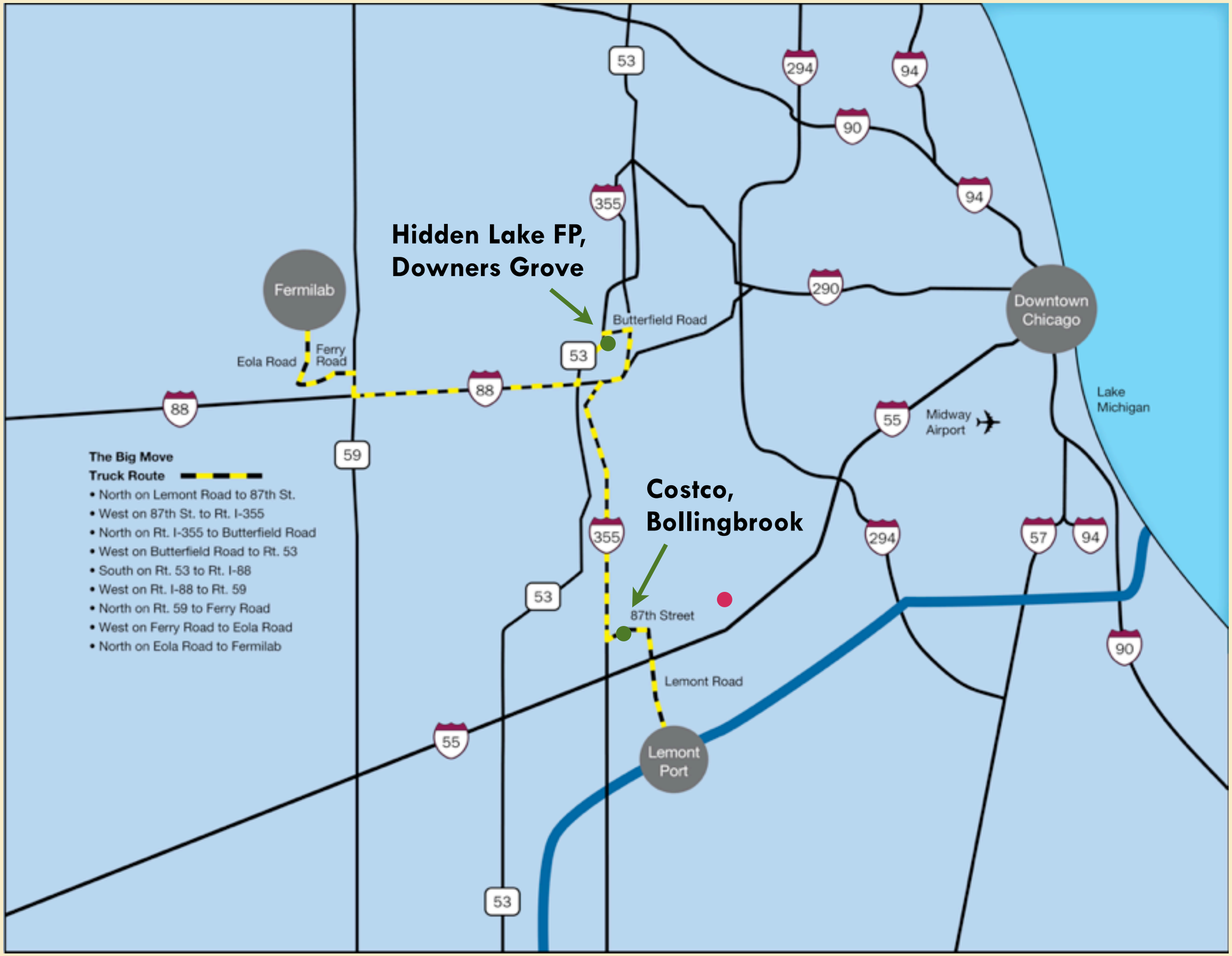
Close up, from Lemont Rd bridge

Arrival in Lemont



Sunday morning, off the barge

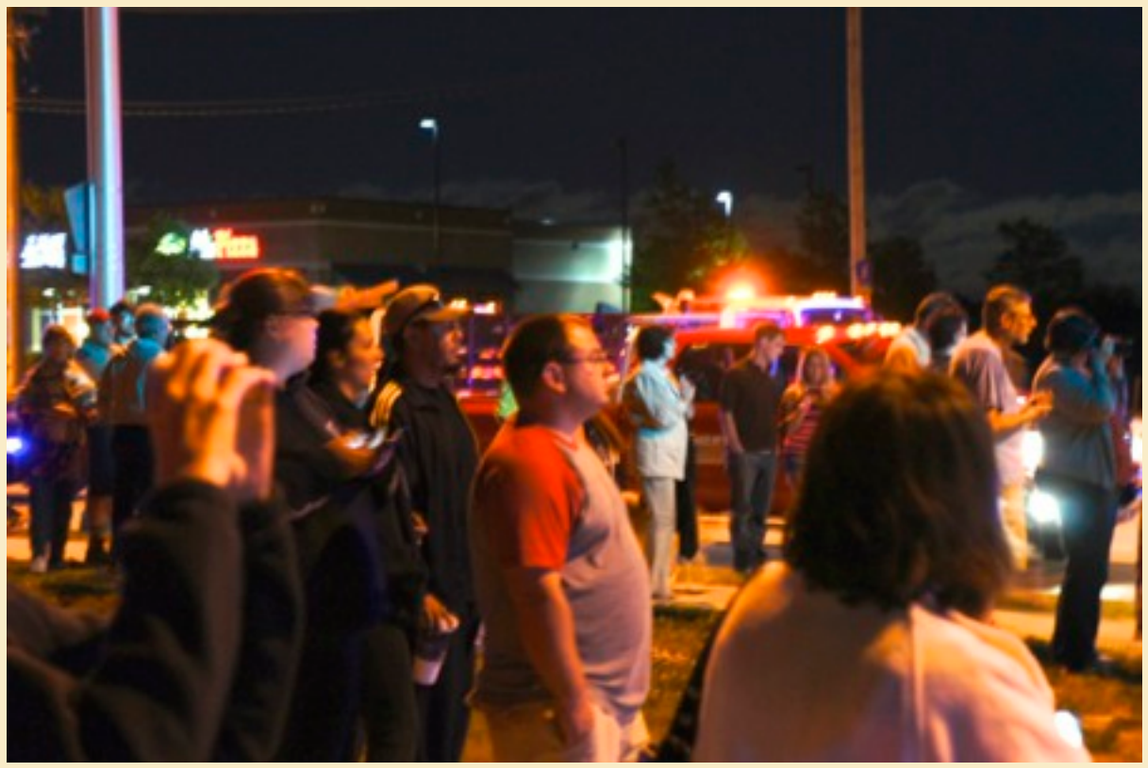
Tuesday – Friday: The land route



Tuesday night, on Lemont Rd & 87th St

Photos: Fermilab

Arriving at Costco in Bollingbrook



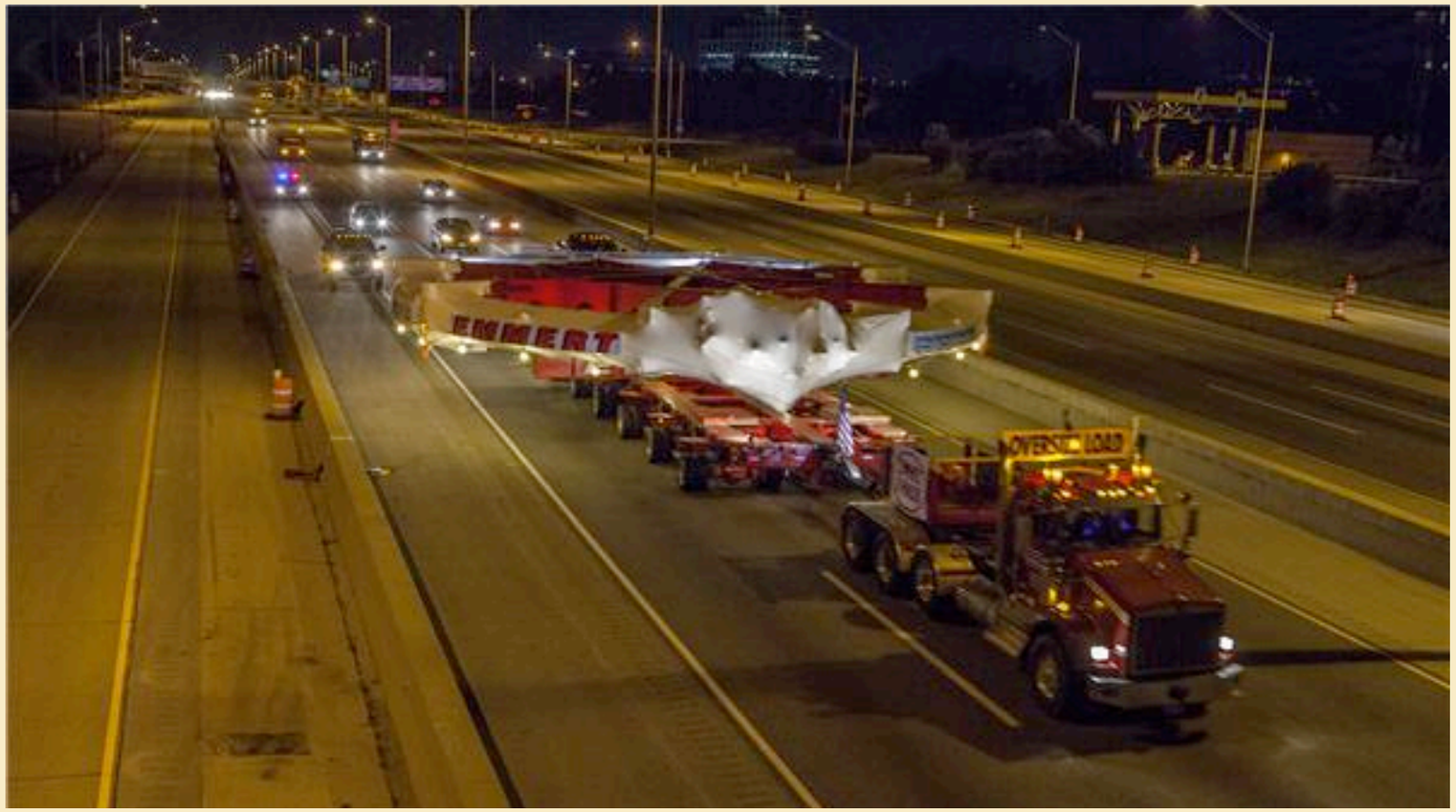
Arriving at Costco in Bollingbrook

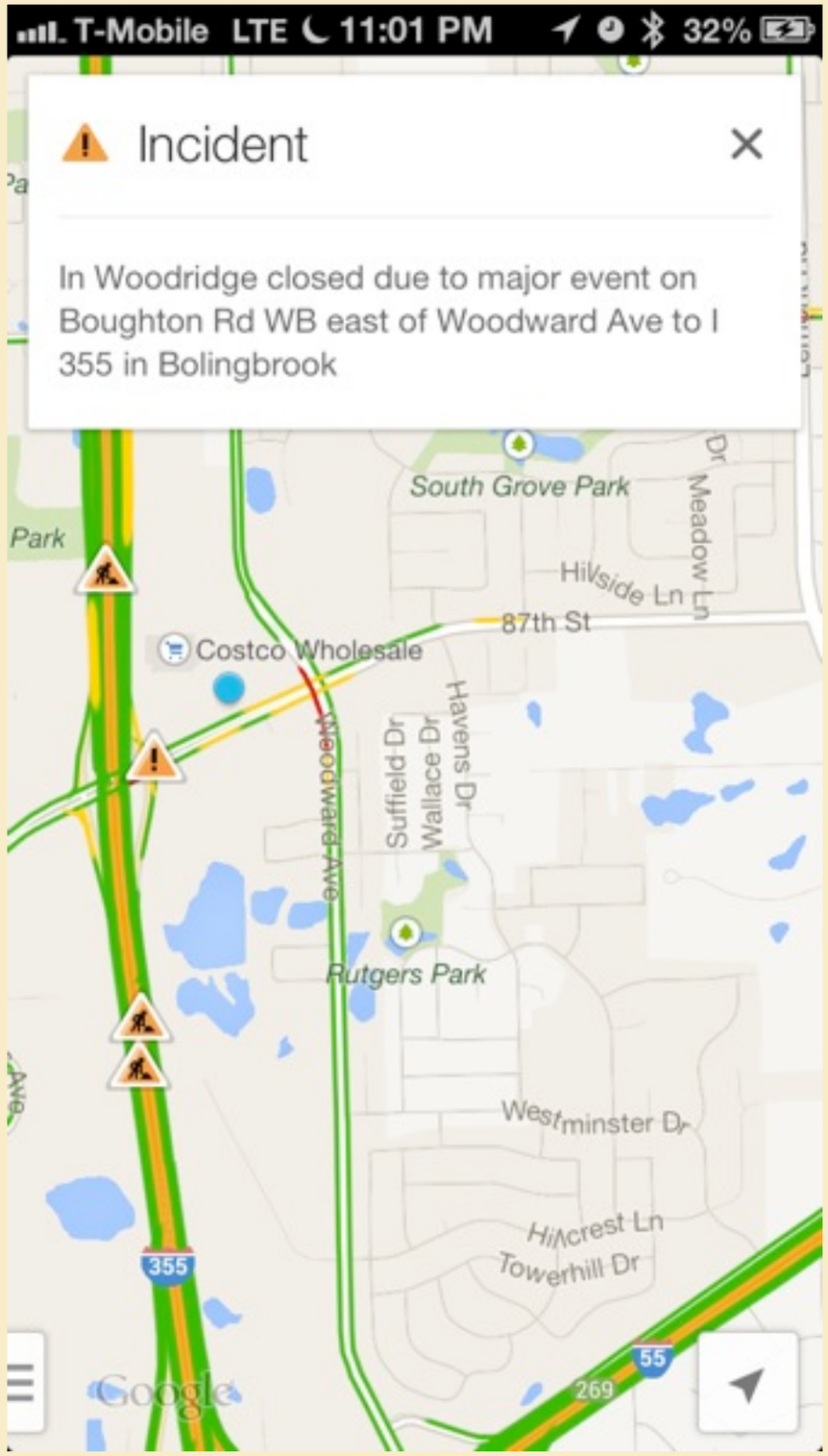
Wednesday, making shopping fun

Wed night, the biggest toll violation ever!

Photos: Fermilab

Wed night, on I-355 to Hidden Lake FP





Photos: Fermilab

Thursday night, ride-along Hidden Lake FP to Fermilab

“Muon Down the Road!”

Leaving Hidden Lake FP

IL-53 to I-88 exit ramp

Backing up the IL-53/I-88 exit ramp

Backing onto I-88

20 mph on I-88 !!

Photos: Mike Murphy

IL-59 exit ramp

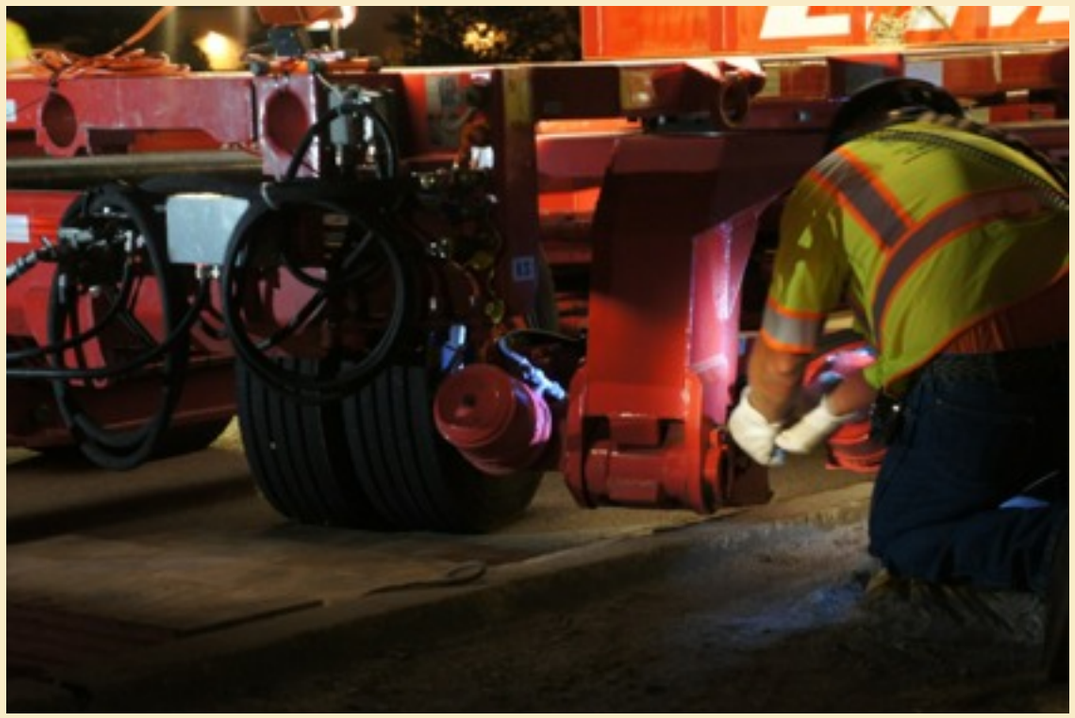
Turning onto Ferry Rd

Railroad bridge on Ferry Rd

Turning onto Eola / Wrong siding on Eola on curb to avoid median trees

Trying to drive onto the curb

Fermilab
Goldhofer



Fermilab
Goldhofer

Removing the Fermilab Eola Rd Gate

Friday, Celebration day!

OVERSIZE LOAD
INERT

Photo: Fermilab

Rock star!

Coverage by local TV stations, including
http://abclocal.go.com/wls/story?secti
http://abclocal.go.com/wls/story?secti
http://www.nbcnews.com/science/gia
http://chicago.cbslocal.com/2013/07/2
http://wgntv.com/2013/07/23/journey
http://wgntv.com/2013/07/27/massiv

Print and Web coverage:
http://www.washingtonpost.com/nati
new-york/2013/07/26/8e86095e-f5c2-
http://www.huffingtonpost.com/2013/
http://www.upi.com/Science_News/20
UPI-96121374874502/?spt=hs&or=sn
http://news.sciencemag.org/2013/07/
http://www.denverpost.com/nationwo
http://napervillesun.suntimes.com/ne
http://www.natureworldnews.com/art
video.htm
http://articles.chicagotribune.com/201
accelerator-laboratory-monster-magne
19040101_Giant_magnet_set_to_reac
http://hamptonroads.com/2013/07/gi
http://heraldnews.suntimes.com/news
http://bigstory.ap.org/article/giant-ma

MYSTERIOUS GIANT MAGNET ATTRACTS ROCK-STAR STATUS

By SCOTT EISEN and JASON KEYSER — Jul. 26 11:05 PM EDT

Home » Illinois » Mysterious giant magnet attracts rock-star status

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1 Share 2 +1

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1 of 9

The electromagnet moves down Interstate 88 in Naperville, Ill., Friday, July 26, 2013 on its way to Batavia's Fermi National Accelerator Laboratory. The electromagnet is 50 feet wide, weighs more than 15 tons and has taken a month to transport 3,200 miles from New York to Illinois. The Fermi National Accelerator Laboratory will use the gadget to study blazing-fast particles. (AP Photo/Scott Eisen)

GLEN ELLYN, Ill. (AP) — It skipped tolls. It had a Twitter hashtag and a GPS tracker. It even posed for photos with groupies.

The 50-foot-wide, 15-ton electromagnet attracted a sensation wherever

Rock star!

Coverage by local TV stations, including live coverage by ABC and CBS:
http://abclocal.go.com/wls/story?section=news/local&id=9186274
http://abclocal.go.com/wls/story?section=news/local&id=9185326
http://www.nbcnews.com/science/giant-electromagnet-ends-circuitous-month-long-trip-arrives-fermilab-6C10761191
http://chicago.cbslocal.com/2013/07/26/massive-electromagnet-completes-arduous-trip-to-fermilab/
http://wgntv.com/2013/07/23/journey-of-giant-magnet-coming-to-an-end/
http://wgntv.com/2013/07/27/massive-magnet-arrives-at-fermilab/

Print and Web coverage:
http://www.washingtonpost.com/national/giant-magnate-set-to-reach-new-illinois-home-after-3200-mile-journey-from-new-york/2013/07/26/8e86095e-f5c2-11e2-81fa-8e83b3864c36_story.html
http://www.huffingtonpost.com/2013/07/26/giant-electromagnet-set-t_n_3658331.html?utm_hp_ref=chicago
http://www.upi.com/Science_News/2013/07/26/Giant-electromagnet-finishes-long-distance-US-move-for-science/UPI-96121374874502/?spt=hs&or=sn
http://news.sciencemag.org/2013/07/after-6-week-journey-giant-magnet-arrives-fermilab
http://www.denverpost.com/nationworld/ci_23741073/15-ton-electromagnet-completes-cross-country-trip-fermilab
http://napervillesun.suntimes.com/news/magnet-NAP-07262013:article
http://www.natureworldnews.com/articles/3140/20130724/massive-magnet-makes-way-chicago-causing-roadblocks-goes-video.htm
http://articles.chicagotribune.com/2013-07-24/news/ct-met-fermilab-electromagnet-20130724_1_fermilab-fermi-national-accelerator-laboratory-monster-magnet http://www.staradvertiser.com/news/breaking/19040101_Giant_magnet_set_to_reach_new_home_in_Illinois.html
http://hamptonroads.com/2013/07/giant-magnet-stopped-norfolk-finishes-journey
http://heraldnews.suntimes.com/news/21416840-418/fermilabs-prized-supermagnet-arrives-in-lemont.html
http://bigstory.ap.org/article/giant-magnate-set-reach-new-home-illinois

What's next?

The ring will sit outside until the building is finished early next year (no problem being outside)

Will take 2+ years to reassemble, test, and "shim"

Data taking starts in 2016 or 2017 for two years !

<u>It takes a collaboration, and help from you!</u>

Building is progressing

The End

More info at

Fermilab: www.fnal.gov
Muon g-2: muon-g-2.fnal.gov
The big move: muon-g-2.fnal.gov/bigmove