Big Science On the Move

A Journey to Discovery

Adam Lyon, Fermilab

September 2013

Photo: Hogan Nguyen

Movie removed
(News report from Norfolk)

A little about me

Undergrad:

NC State '91

Grad School:

U Maryland '97

DØ Experiment @ FNAL

Supersymmetry Search

Postdoc:

U Rochester 1997-2002

CLEO Experiment @ Cornell

$b \to s\gamma$

Now:

Fermilab Scientist in the Scientific Computing Division

DØ (Dibosons) and Muon g-2

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VOLUME 83, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1999

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(D0 Collaboration)

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[2]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janiero, Brazil*
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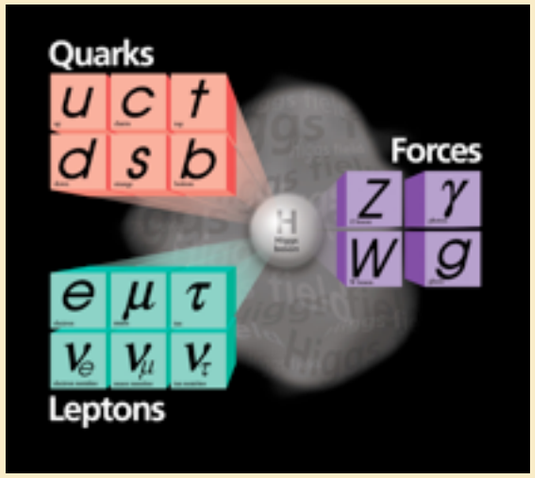
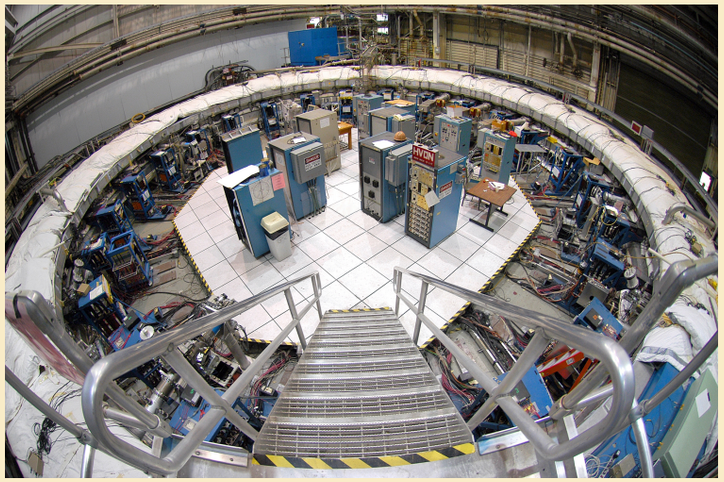
The things we'll talk about today



Quick Intro to Particle Physics



Muons and *g*-2

@ Fermilab

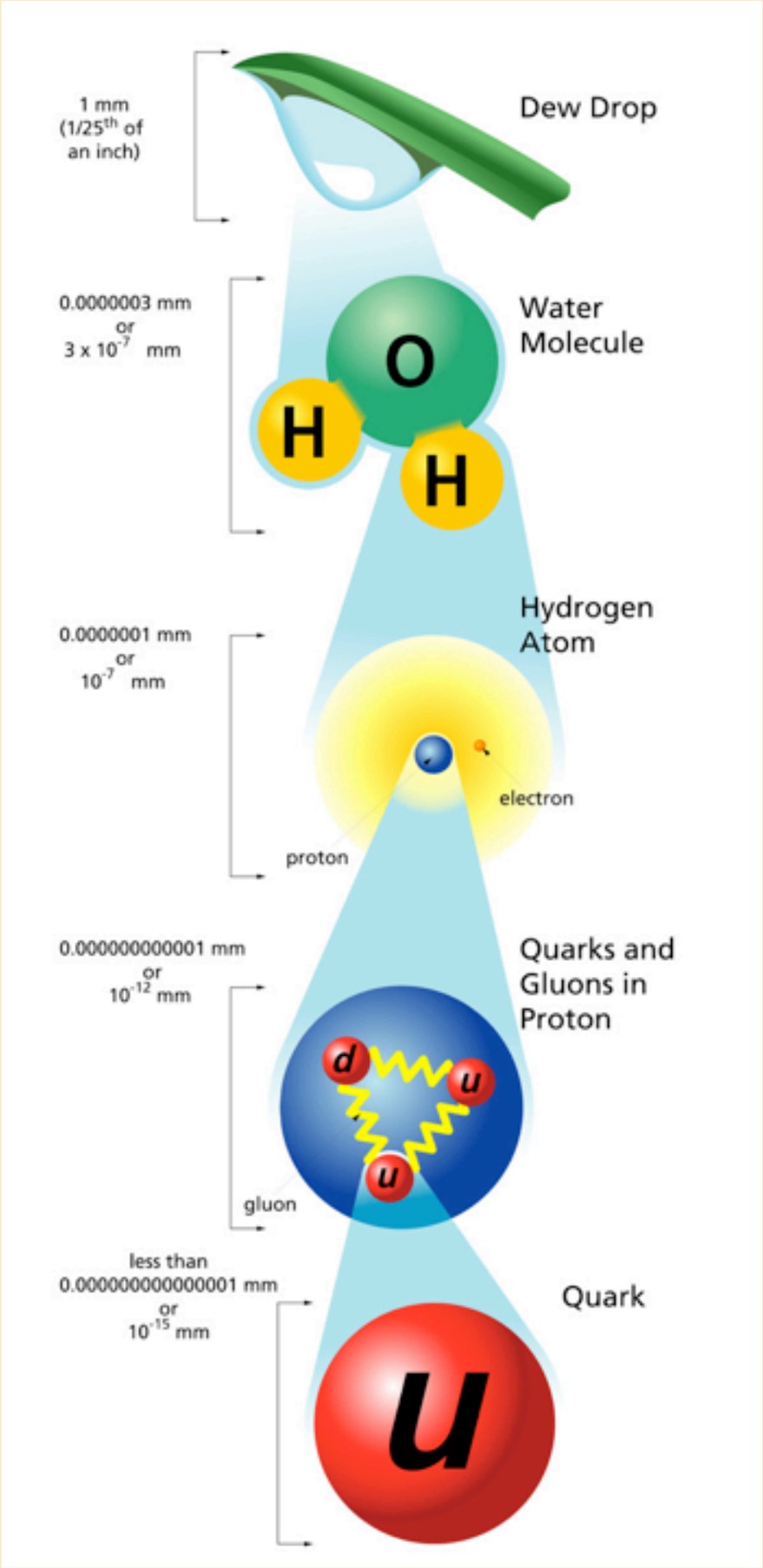
The journey

What happens next

What is Particle Physics?

Q: What is matter?
How does it work?

A: We've learned a lot!



Quarks

Forces

Leptons

Quarks

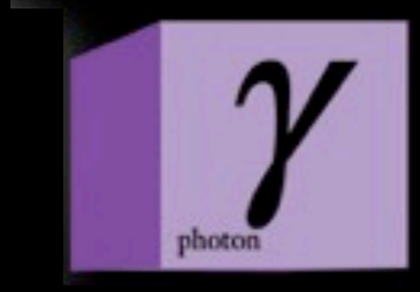
Forces

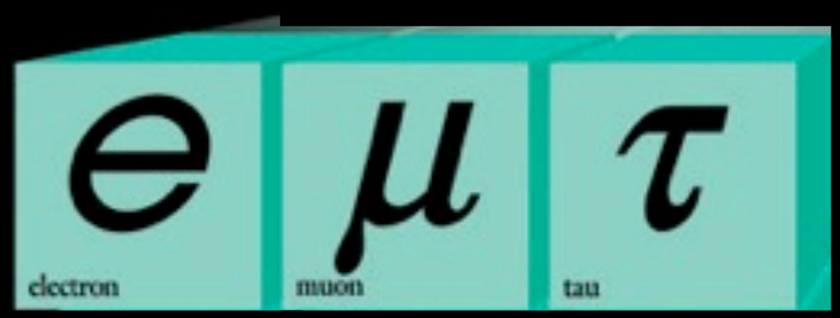
<u>Everything</u> in our everyday world is made up of these particles

Leptons

Quarks

Forces



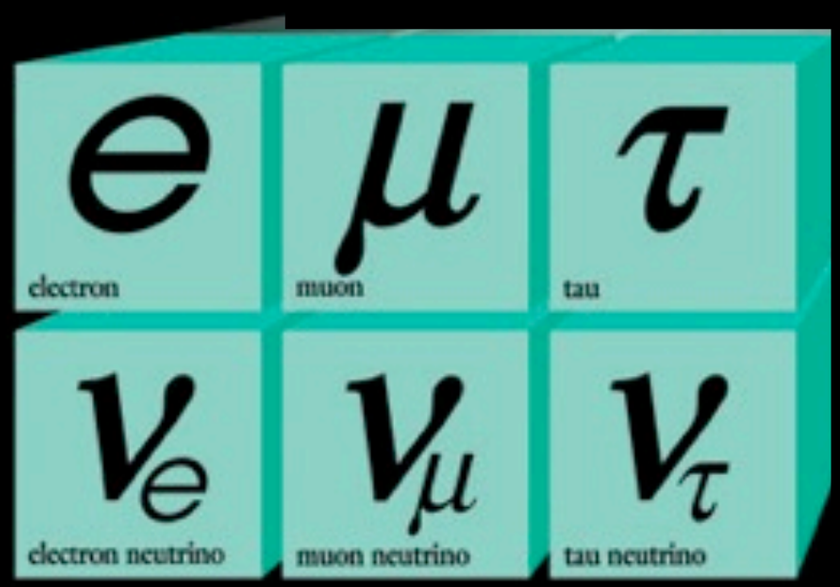


But there are more!

Leptons

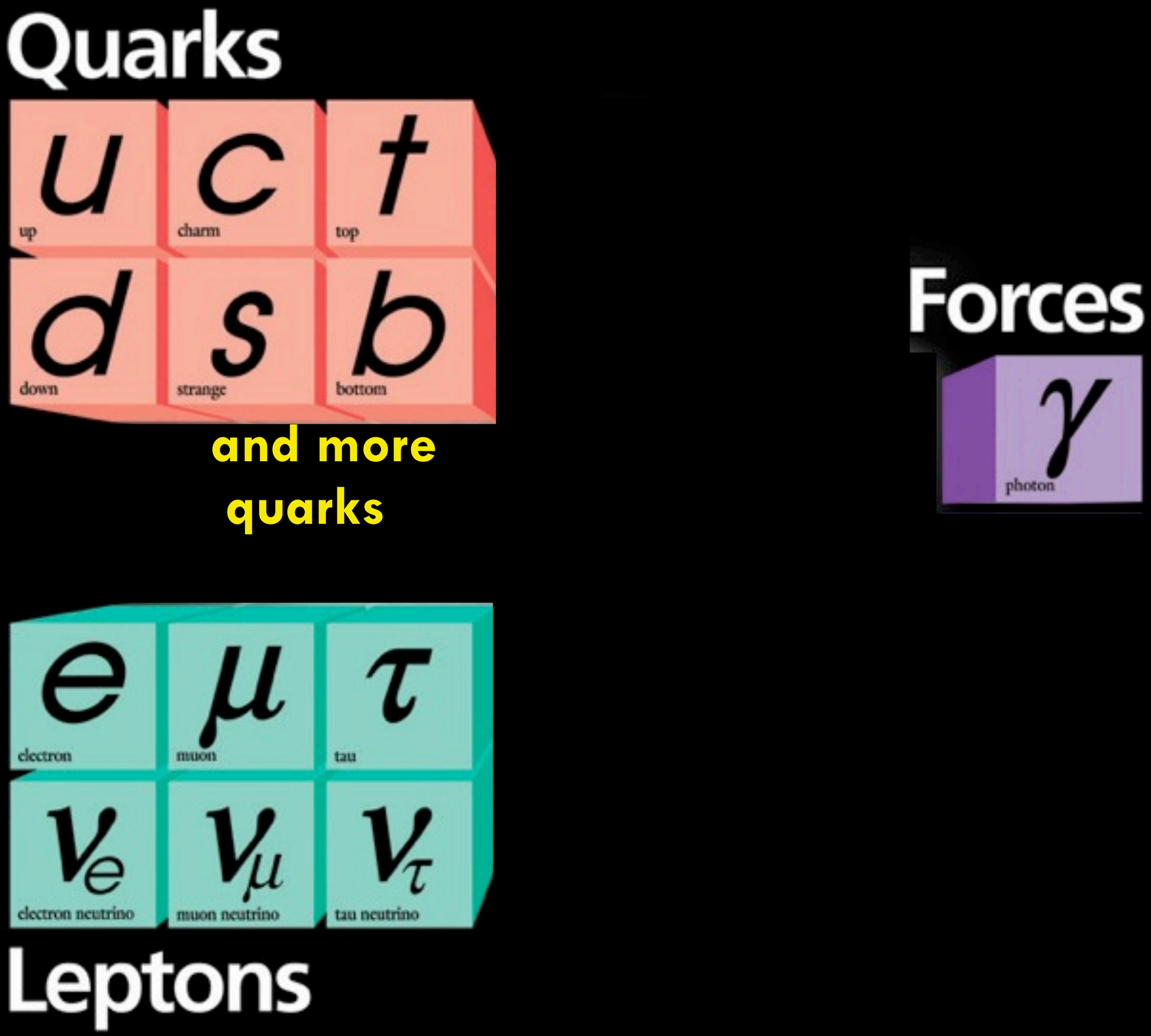
Quarks

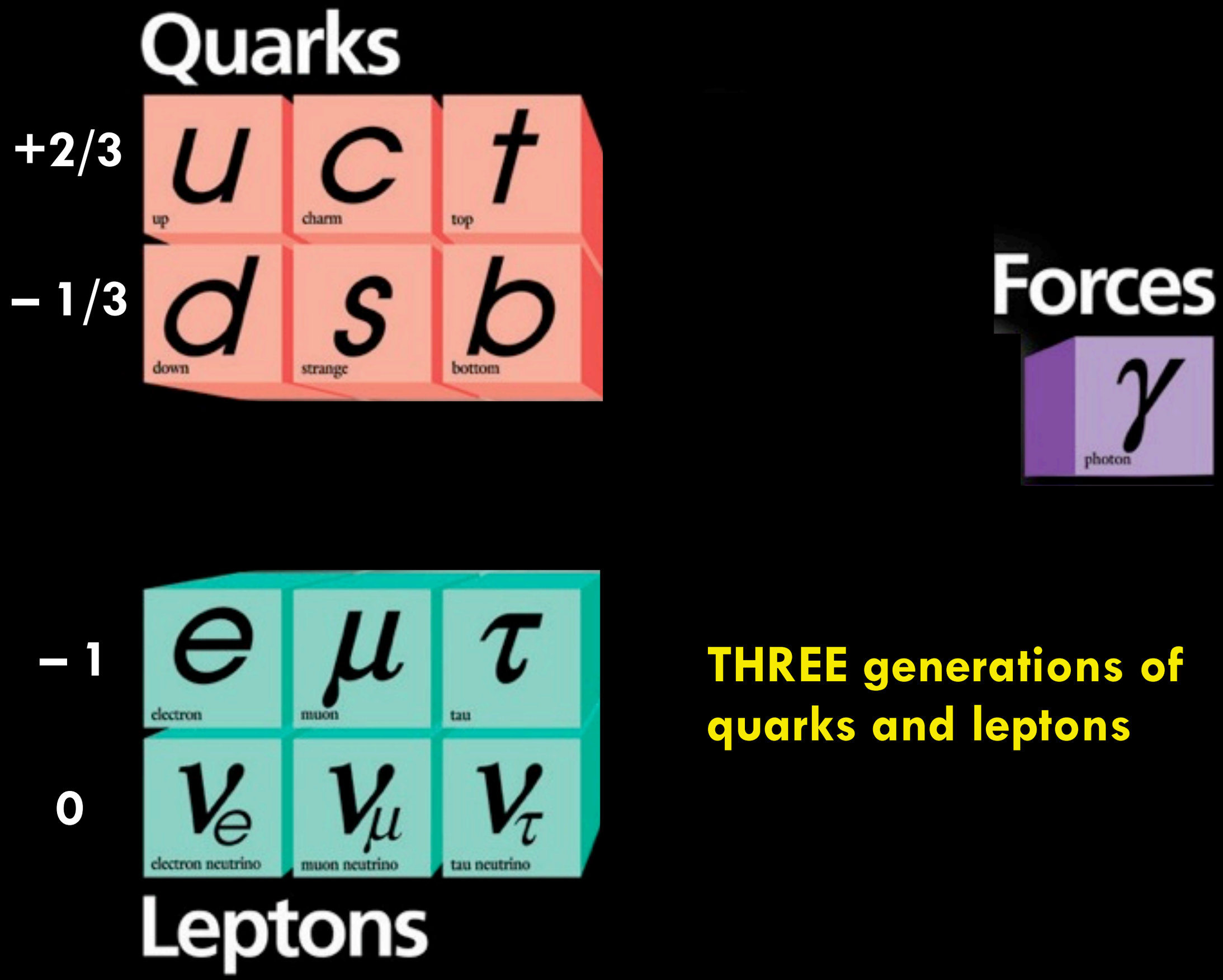
Forces



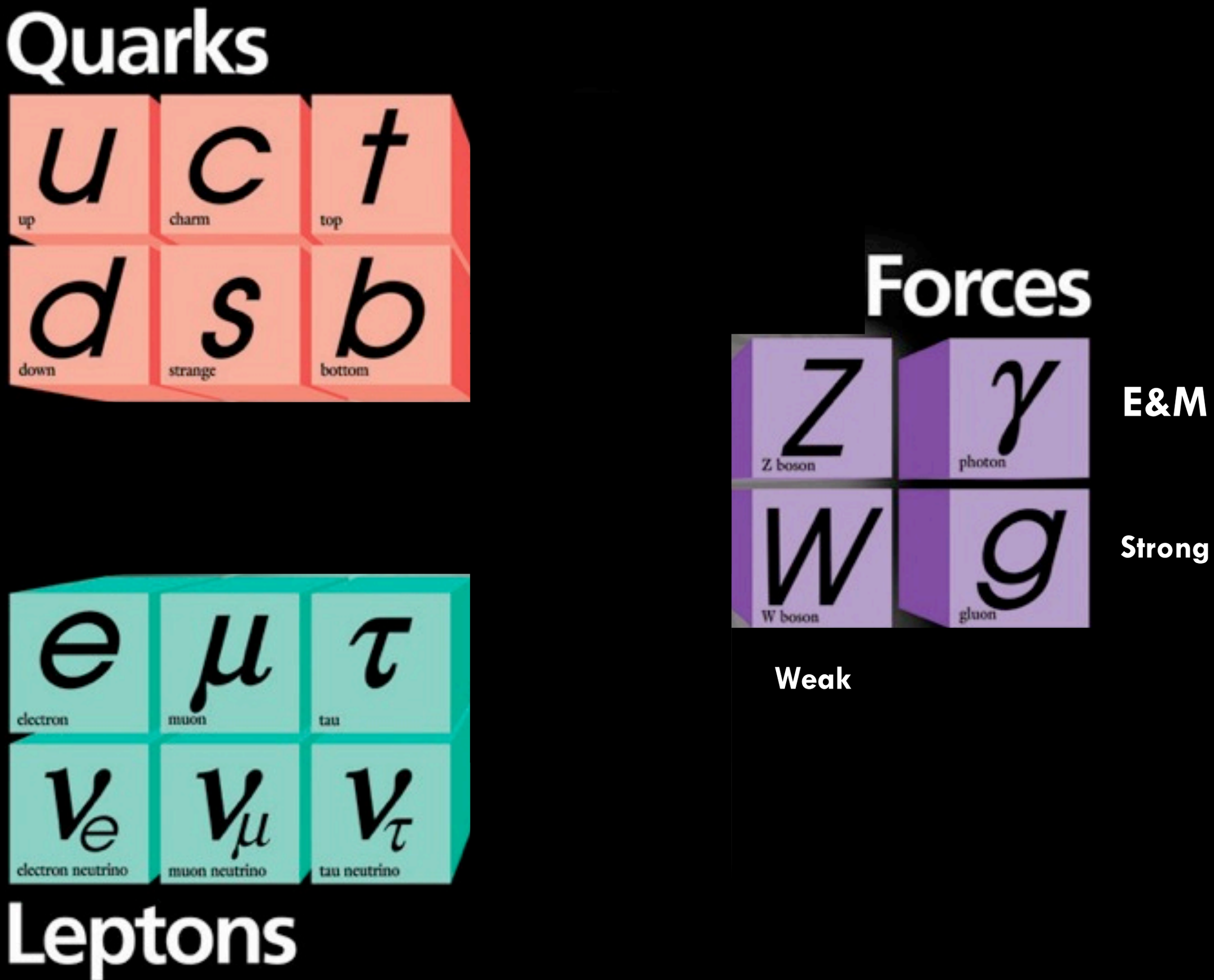
Leptons

and more - neutrinos!

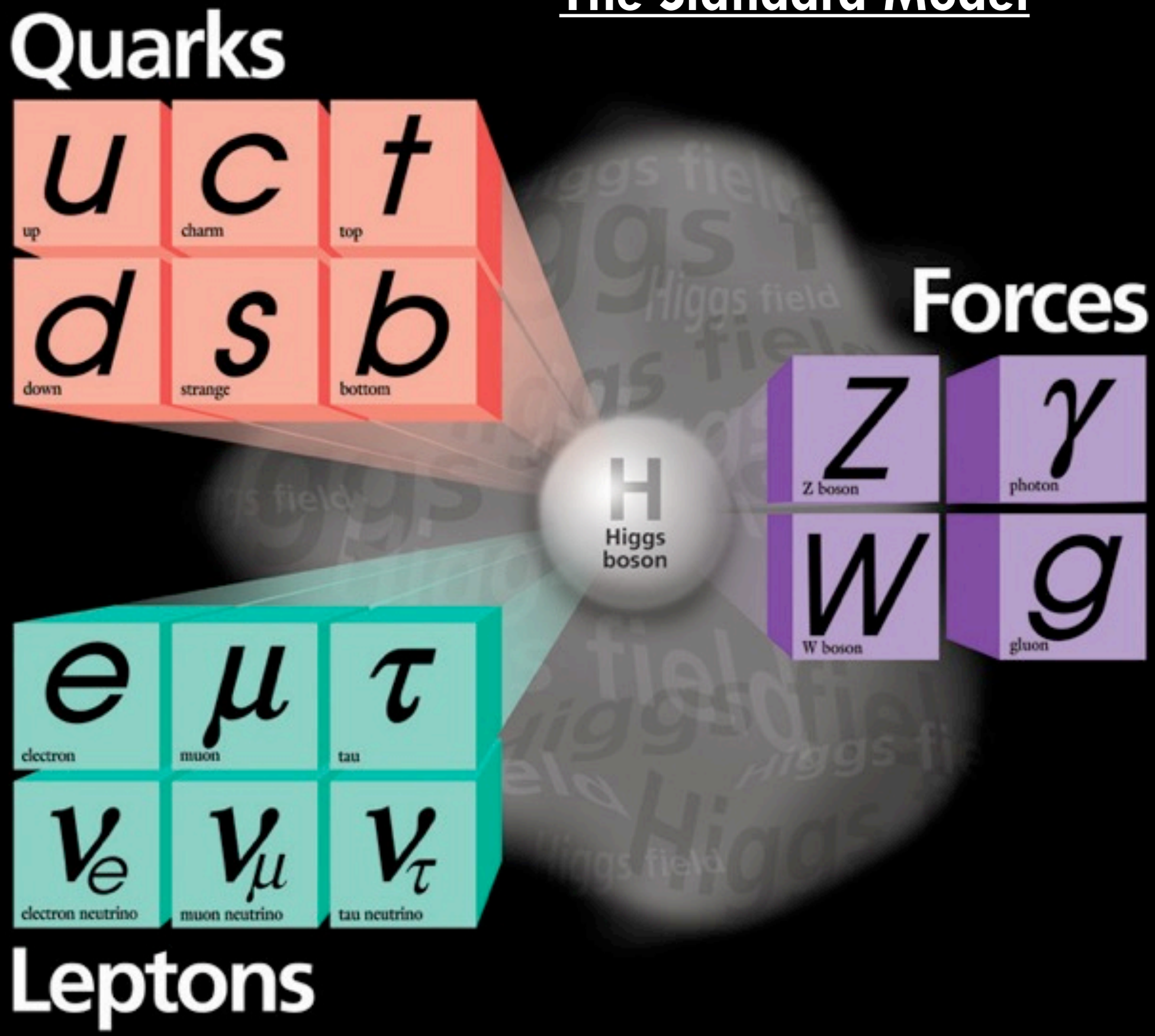

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
and more
quarks
Forces
γ
photon
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons



THREE generations of quarks and leptons

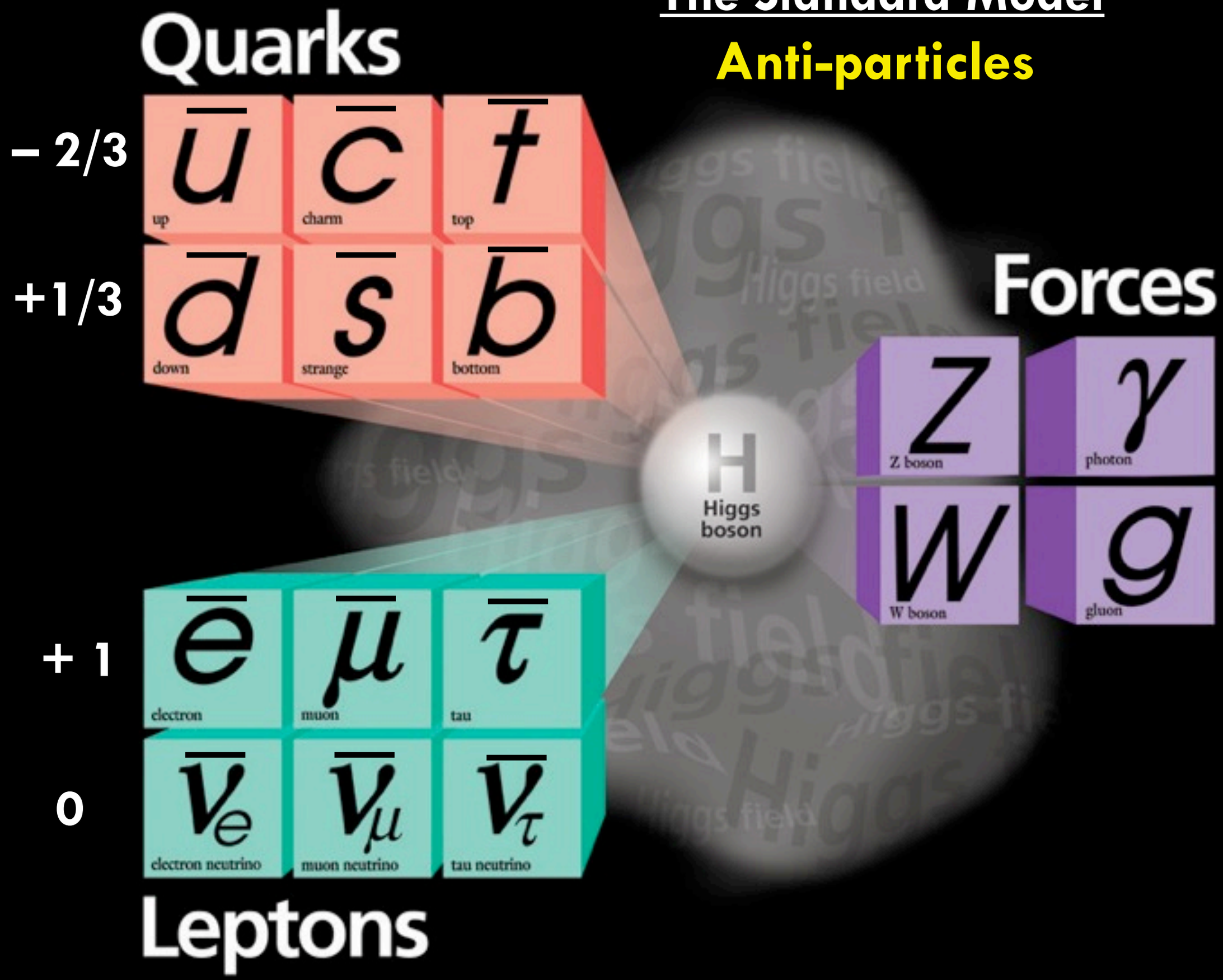

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
E&M
Strong
Weak
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

The Standard Model

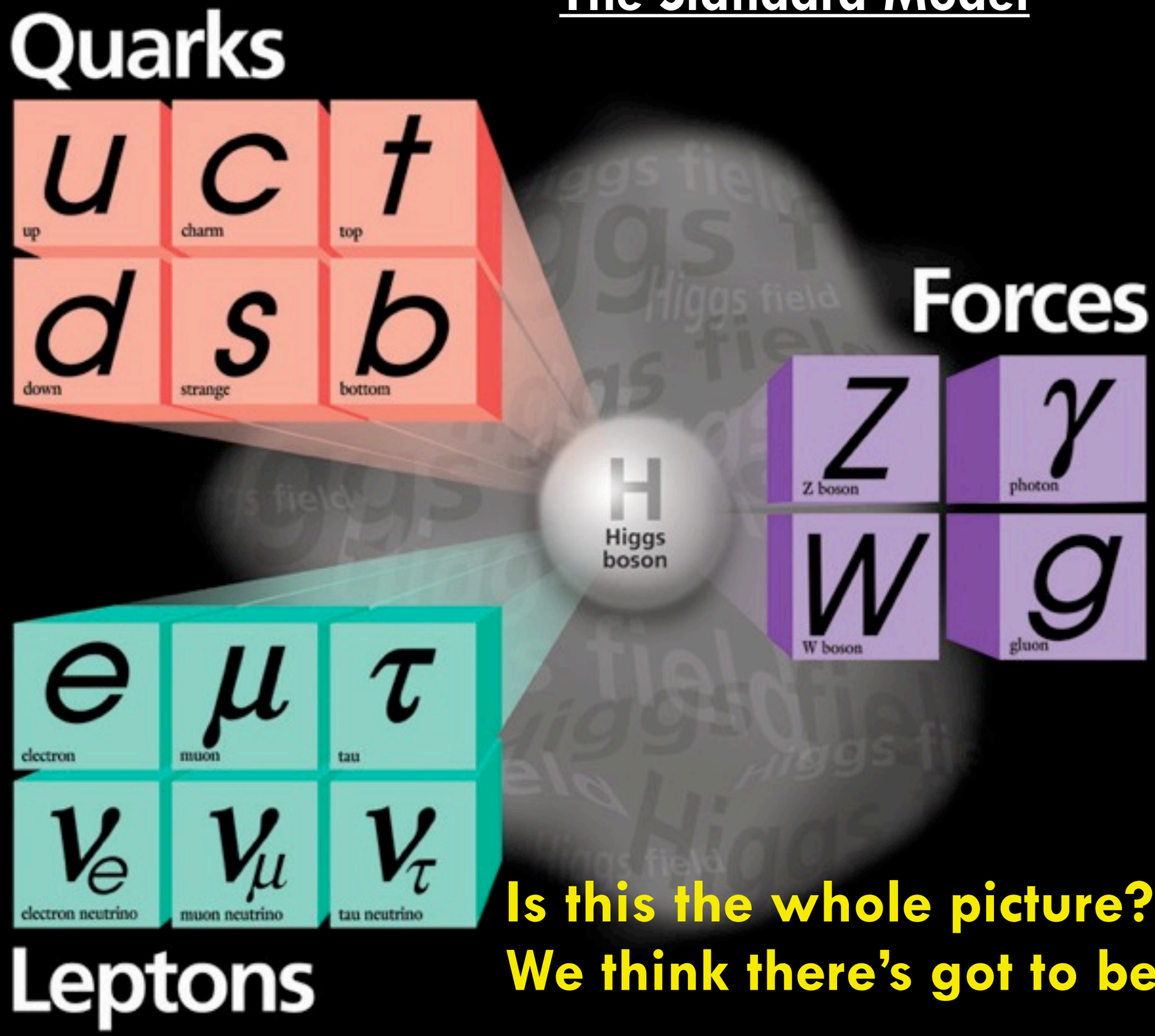


The Standard Model

Anti-particles



The Standard Model

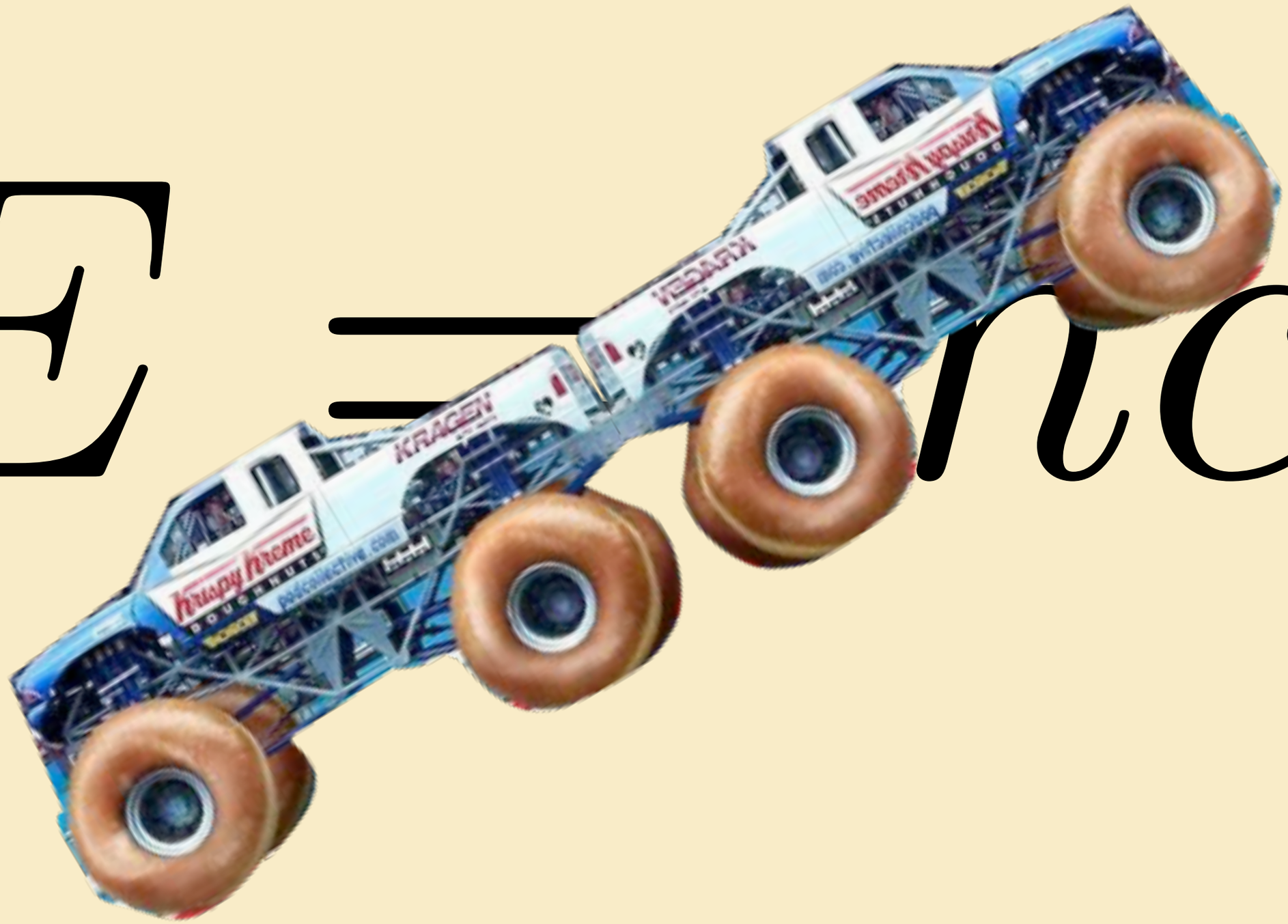


Is this the whole picture?
We think there's got to be more

$$E = mc^2$$

$$E = m \cdot c^2$$

$$E = mc^2$$

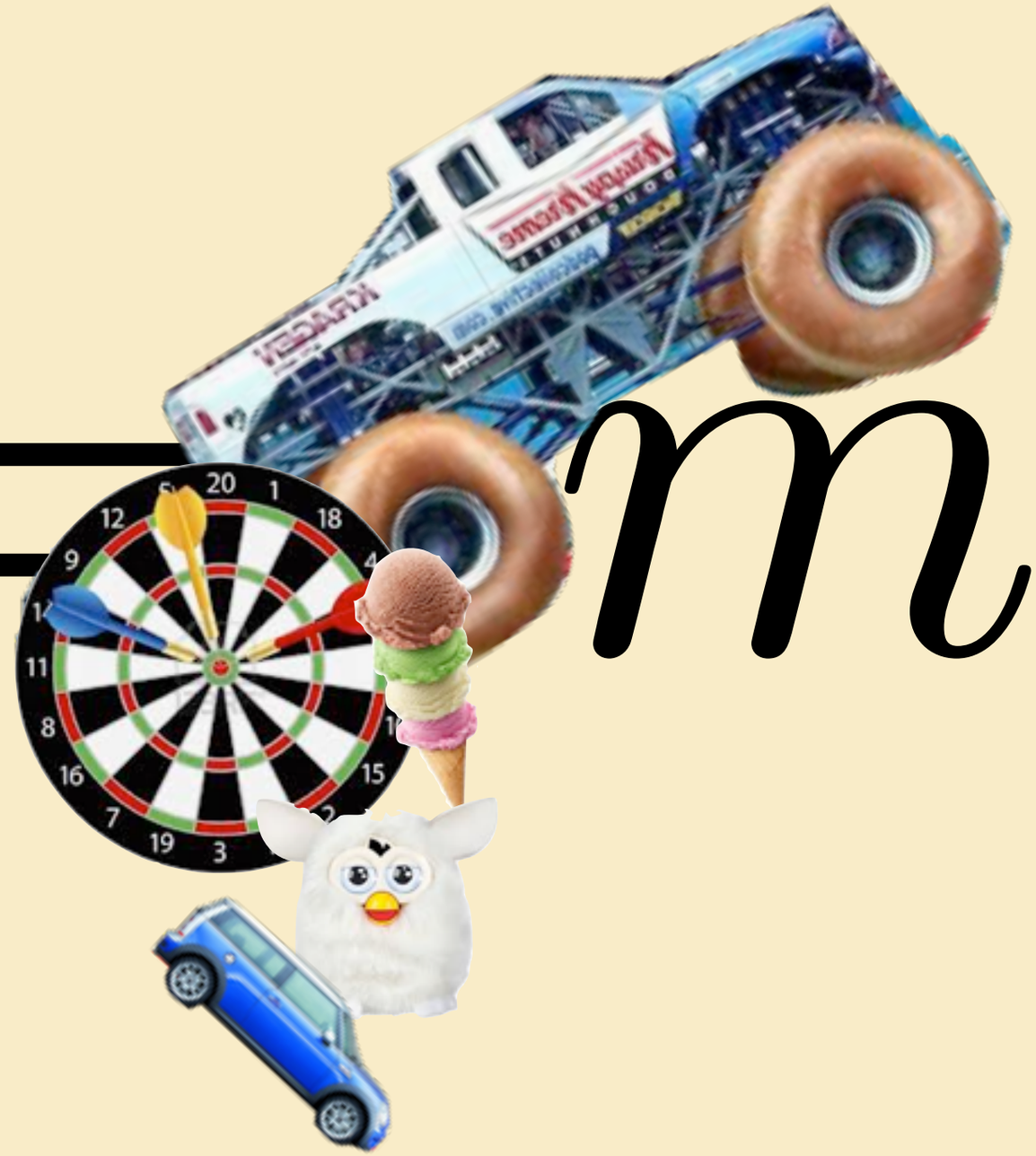


$$E = mc^2$$

$E =$ mc^2

$$E = mc^2$$

$$E = mc^2$$



$$E = mc^2$$

Quantum Mechanics PROBABILITIES

Quantum Mechanics

PROBABILITIES

Quantum Mechanics PROBABILITIES

Quantum Mechanics PROBABILITIES

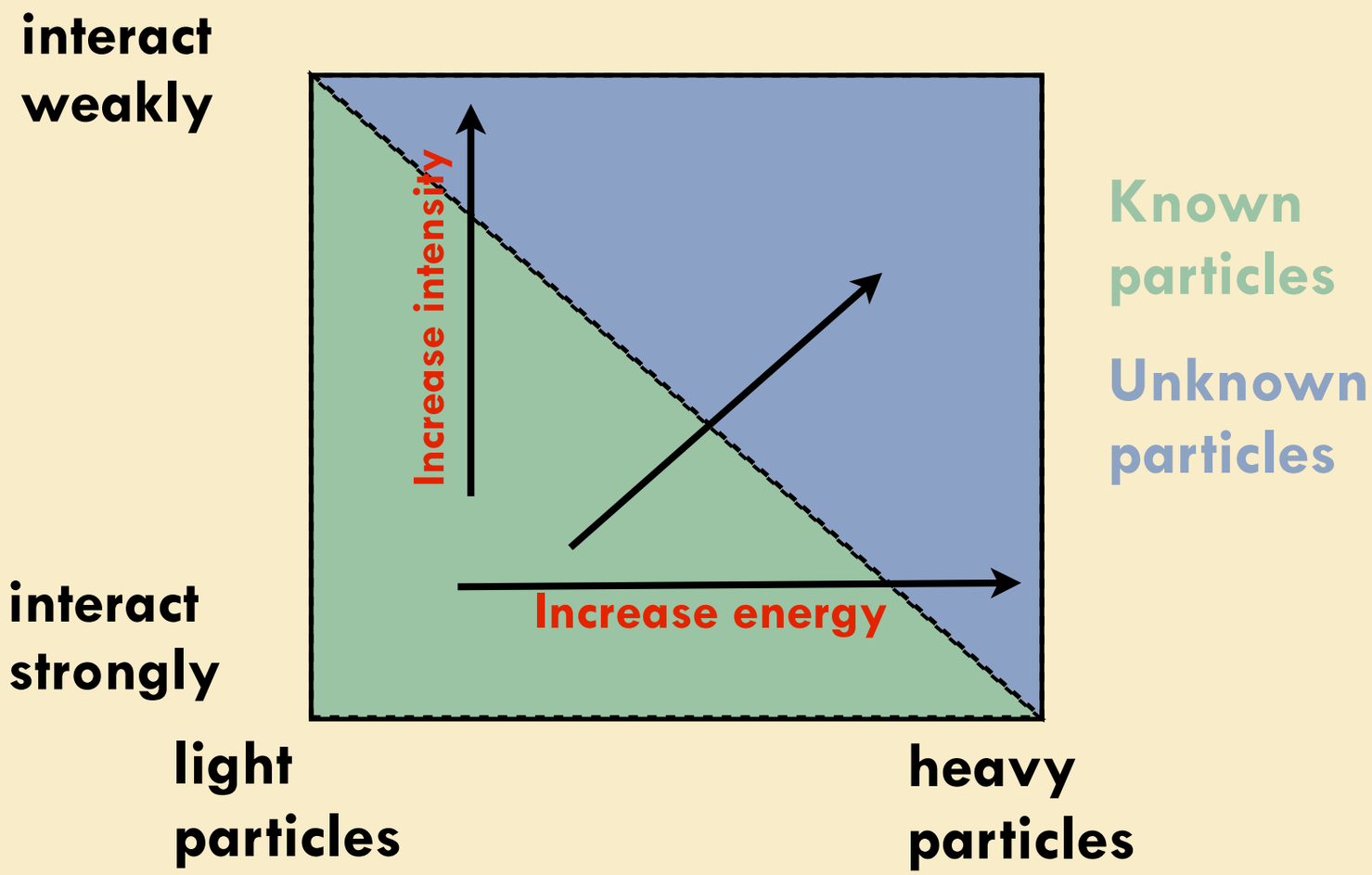
Ways to look for new physics

Find new heavy particles

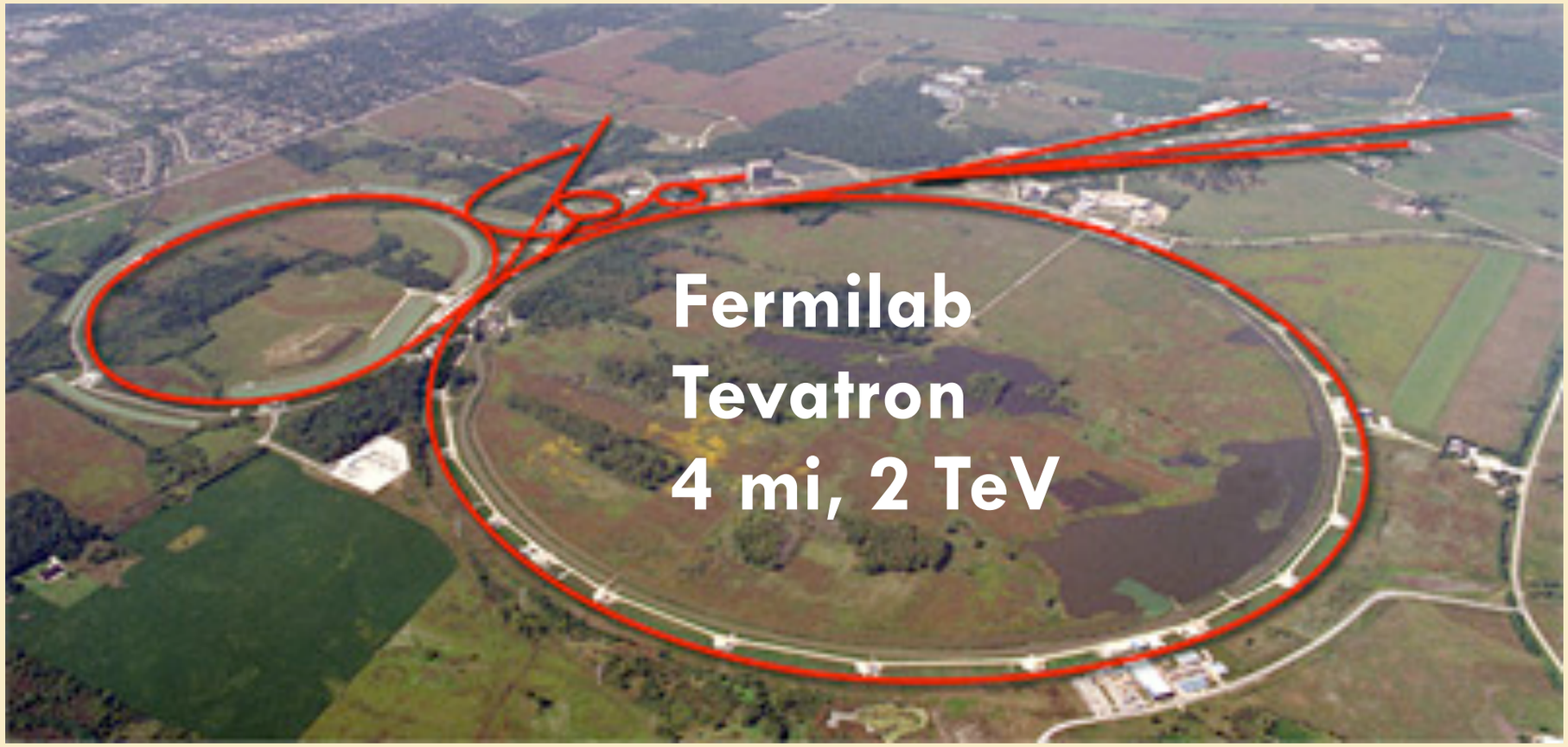
Need to collide at high energy to make them

Find particles that weakly interact

Need to collide LOTS of particles to catch rare interactions



Our typical tools – accelerators



Another way to look for new physics

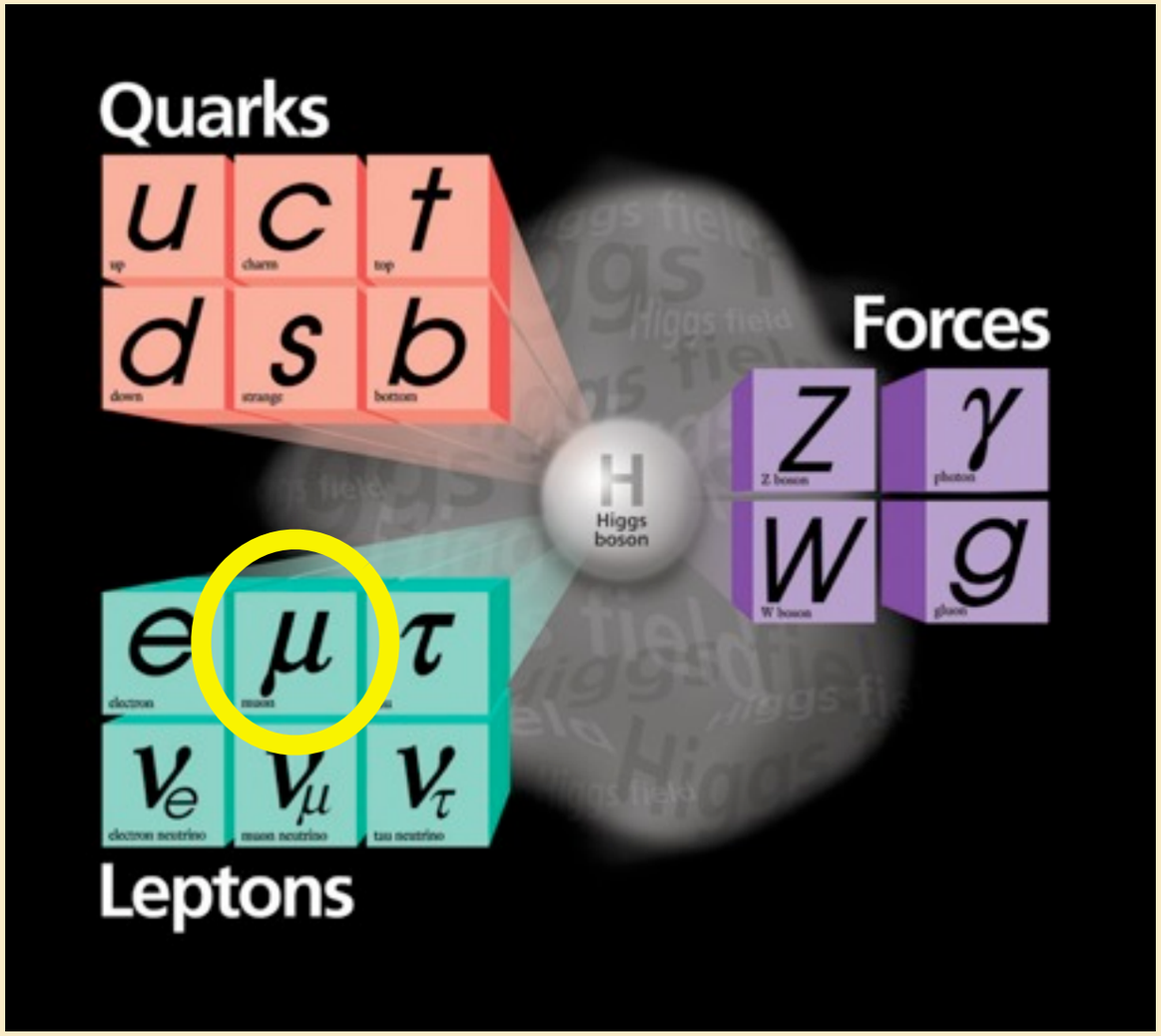
<u>Precision measurements of particle properties</u>

Does particle behavior match Standard Model predictions?

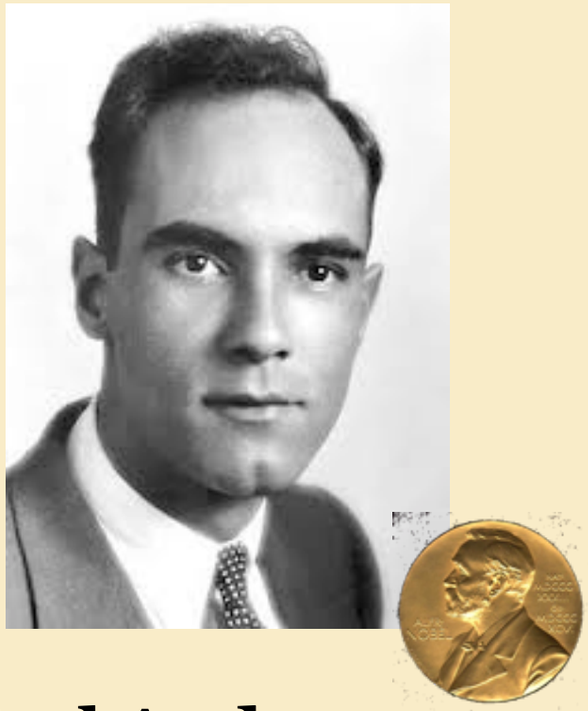
- **Mass?**
- **Production probabilities?**
- **Decay probabilities?**
- **Interactions with other particles**

MUONS are an excellent laboratory for precision studies

Muons are an ideal laboratory!



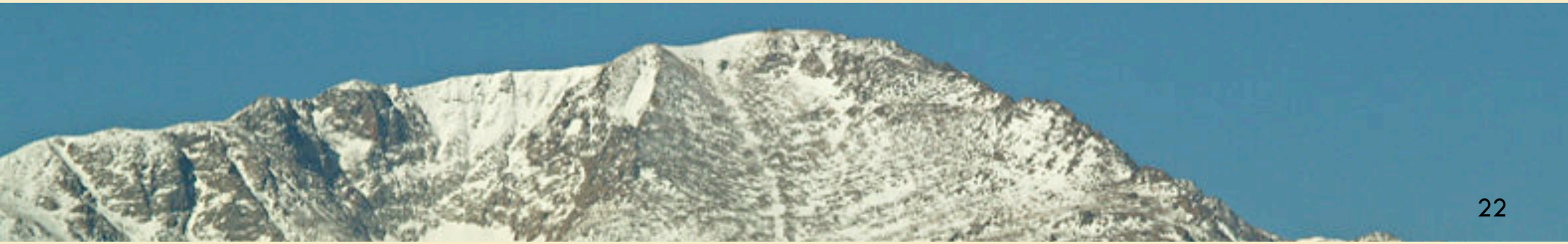
Discovered in 1936 by



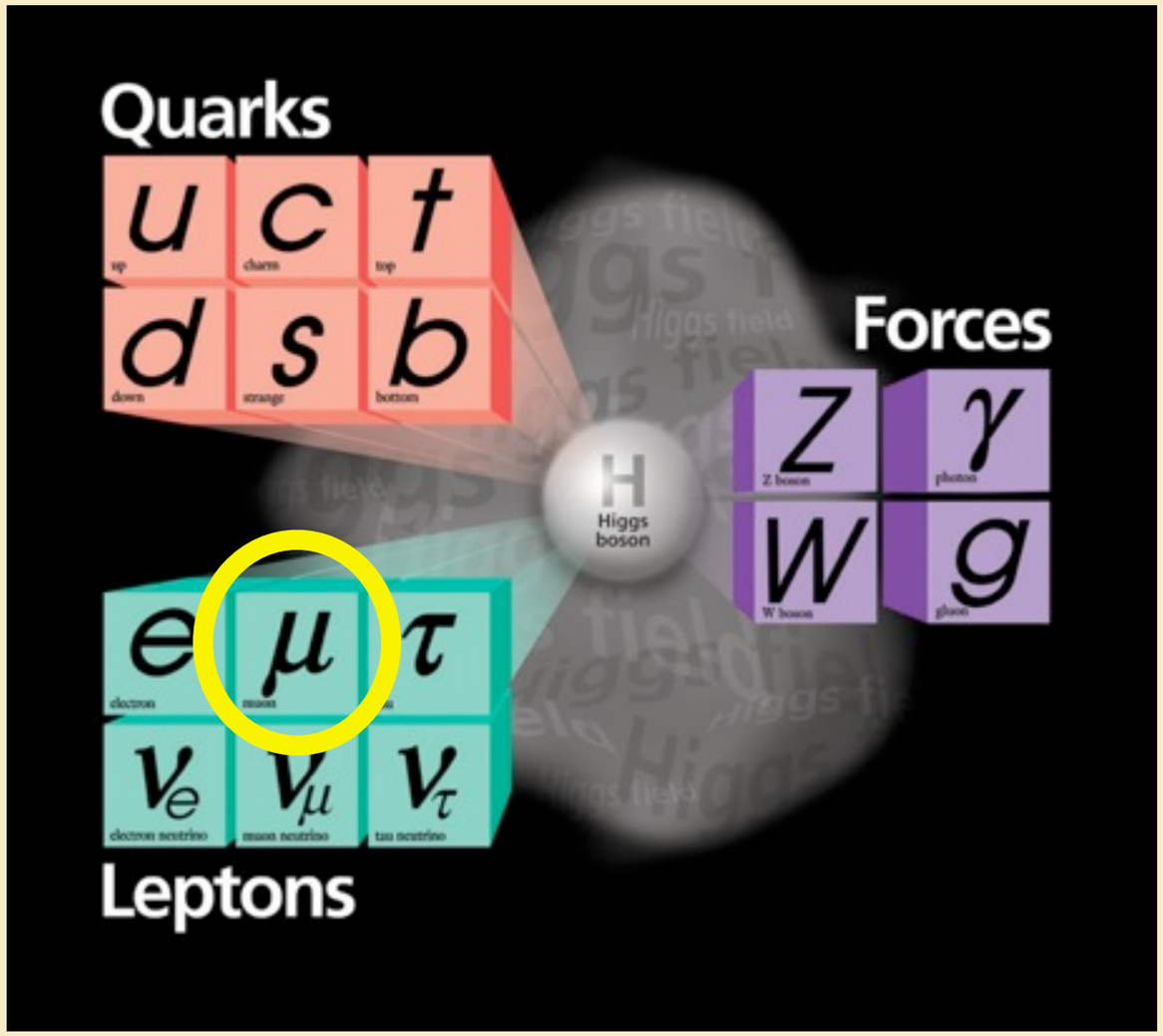
Carl Anderson (Caltech)

Seth Neddermeyer

Studying cosmic radiation on Pikes Peak, Colorado



Why are muons ideal?



Muons are like electrons

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

Muons are unlike electrons

- o Mass is 200x heavier
- o Muons are unstable
  - Decays into an electron and two neutrinos

The spin is the thing to study!

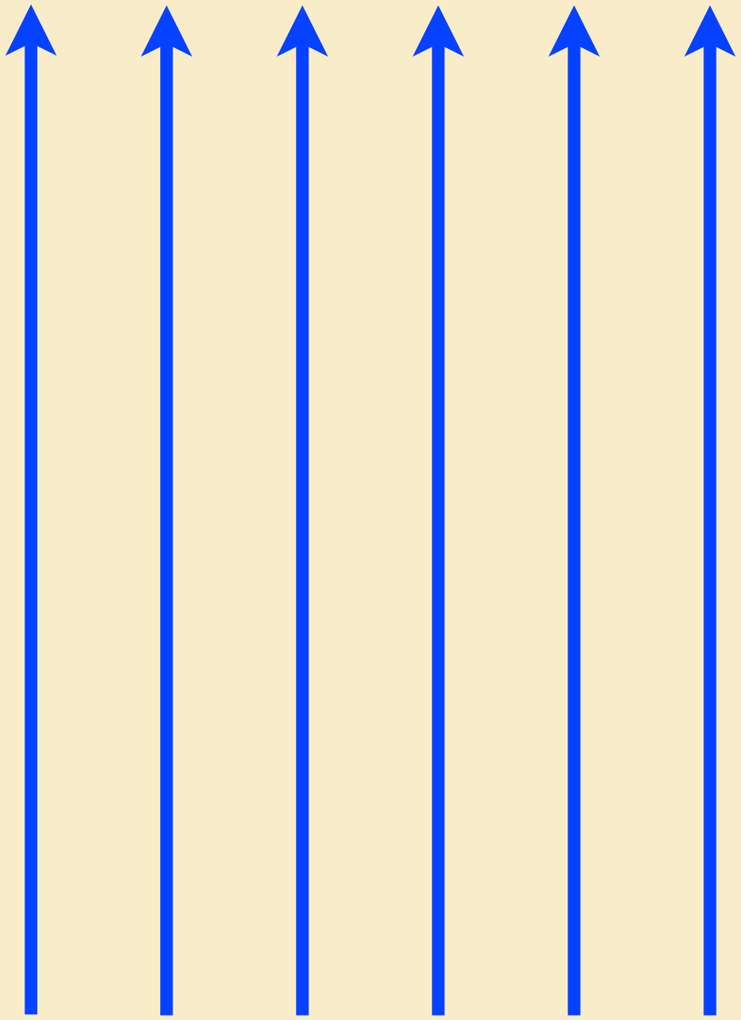
Leptons and Quarks have an internal property called “spin”, like the angular momentum of a spinning top

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



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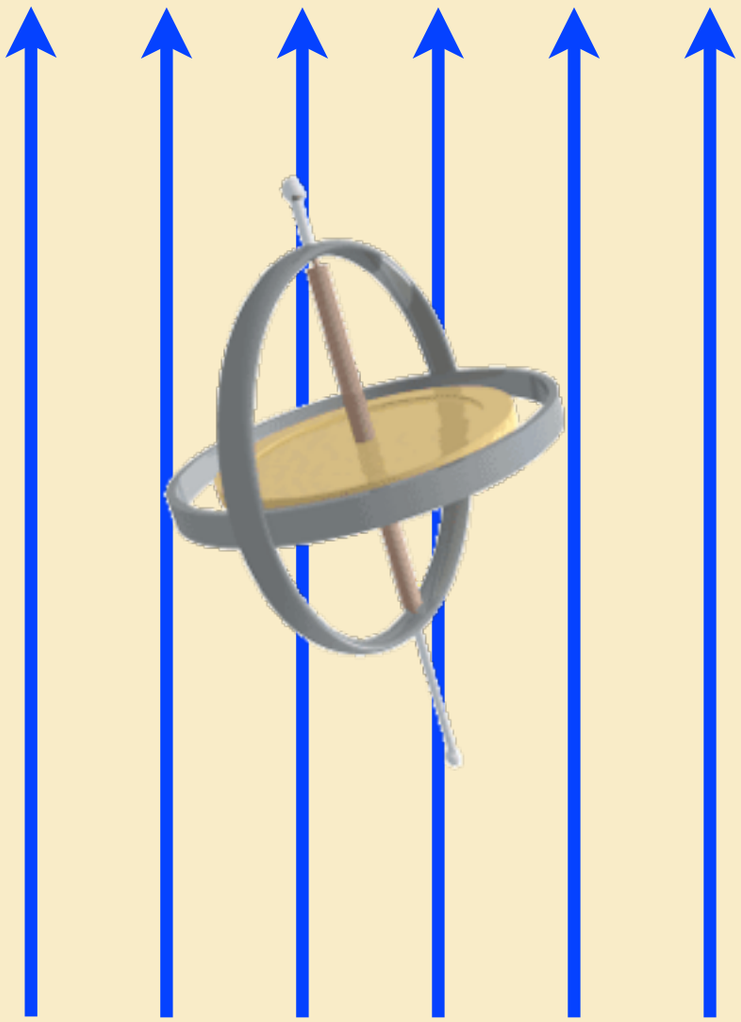


Gyroscope precessing in gravity

Movie removed
(Gyroscope)

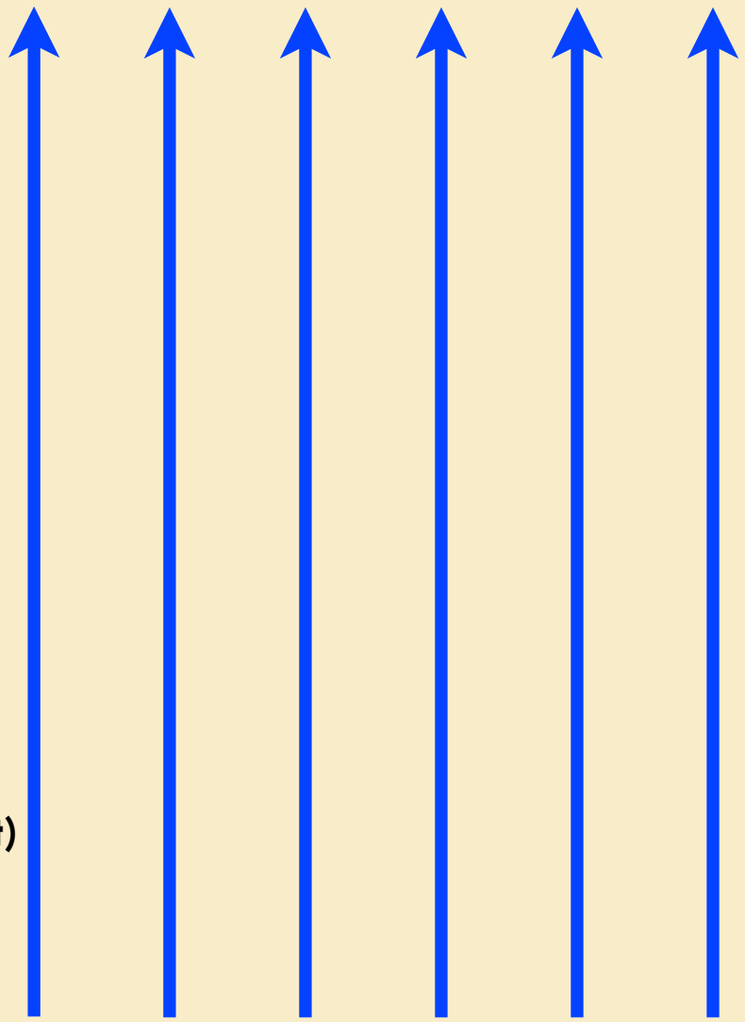
http://www.youtube.com/brusspup

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

Spin in a magnetic field

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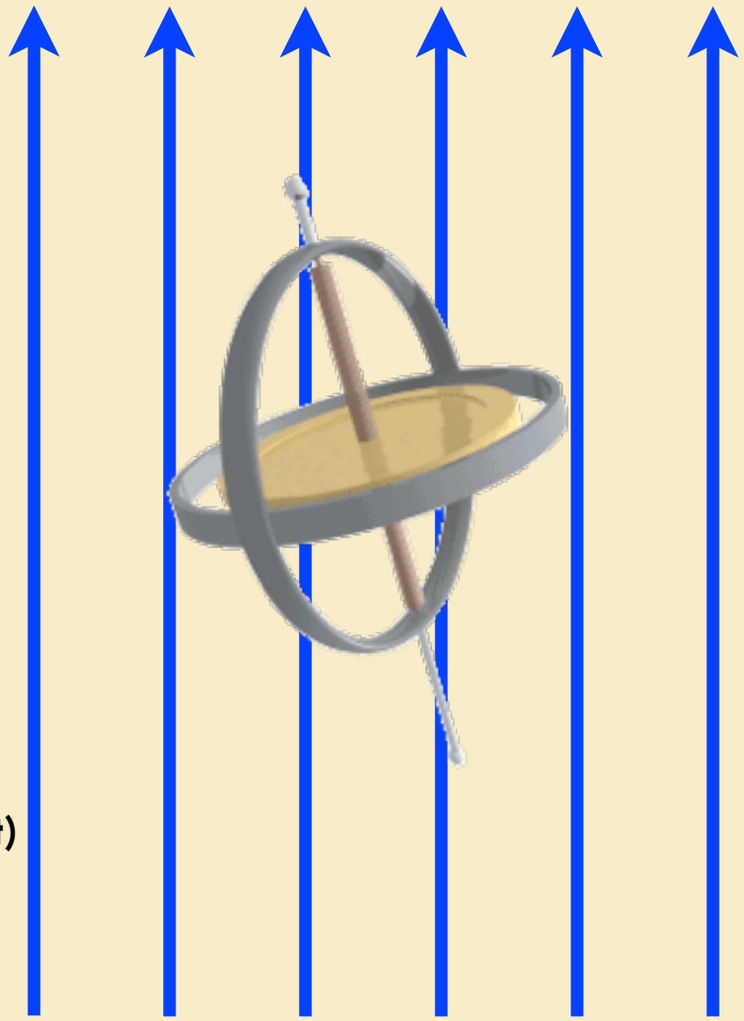


The goal of the *g-2* experiment is to put muons in an exquisite magnetic field and measure the precession frequency with extreme precision

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?

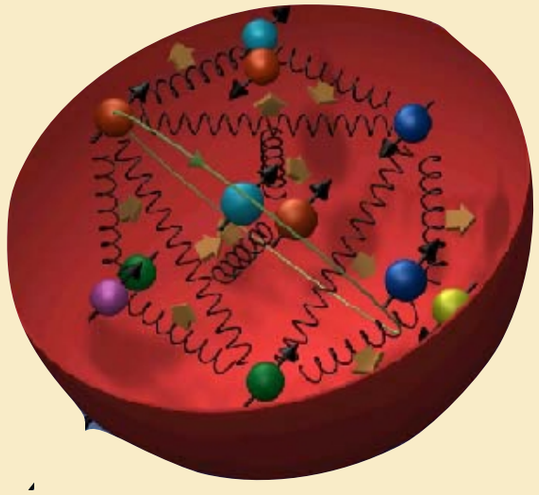
Not quite...

What's with the (almost) 2 ?

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

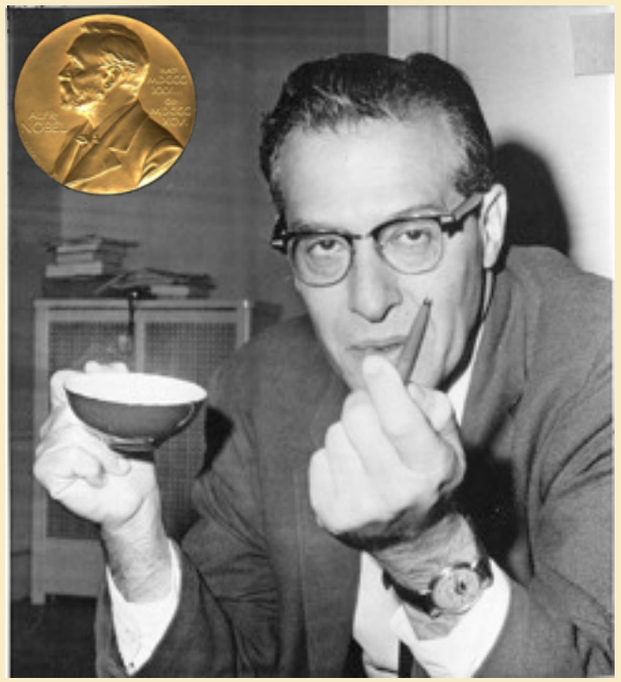
Particles can randomly appear and disappear very quickly (called virtual particles)

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

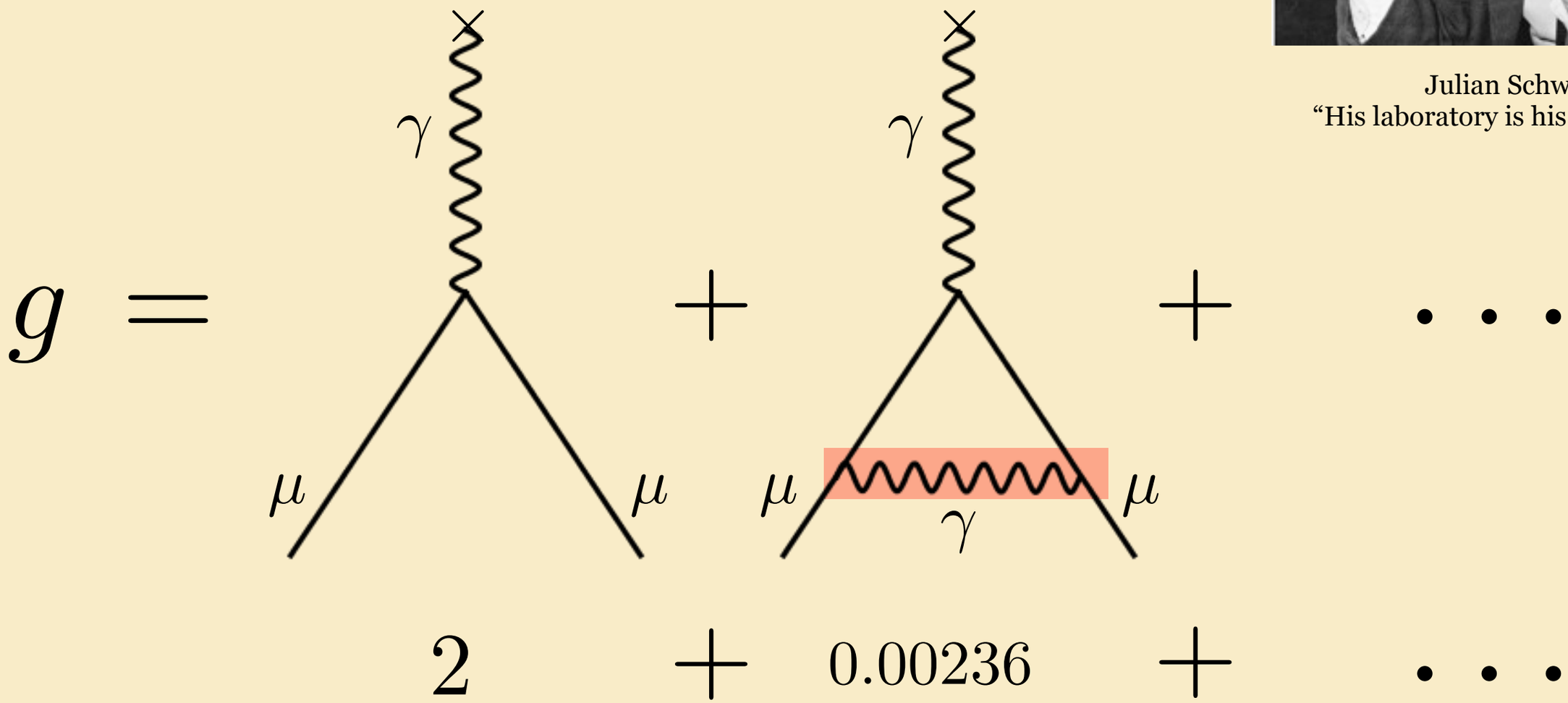
Quantum corrections matter!



Julian Schwinger
"His laboratory is his ballpoint pen"

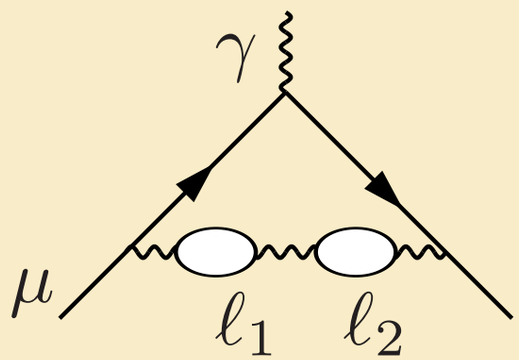
The effect is to "screen" the magnetic field

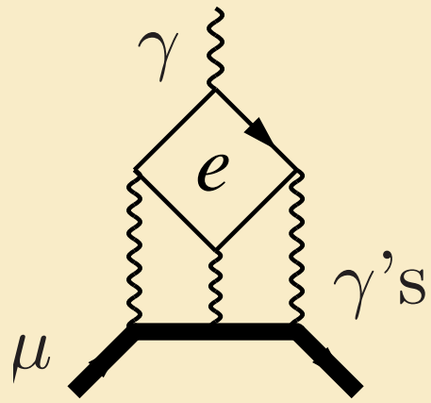
Changes the precession - makes *g* a little bigger



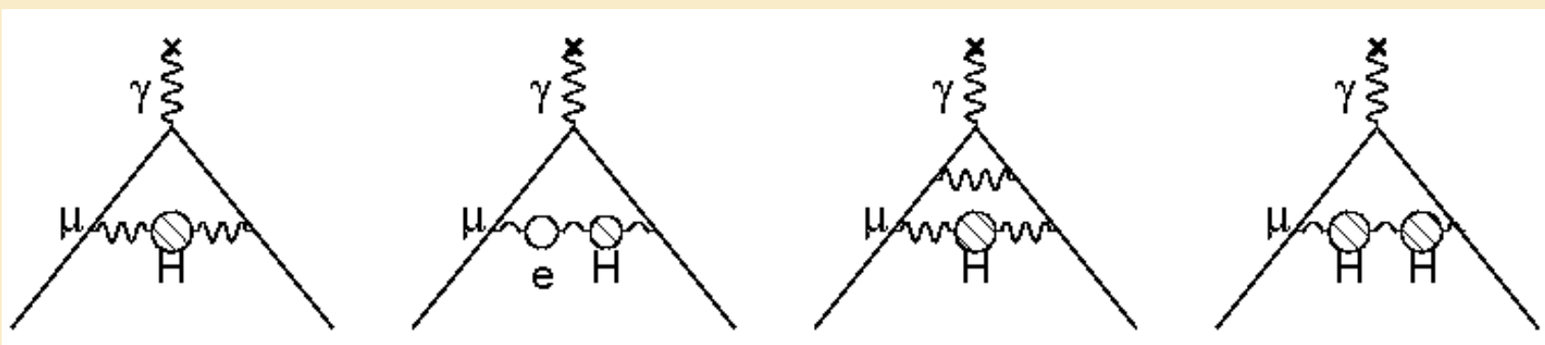
First *g-2* experiments 50's and 60's measured it! g>2 !

But corrections can get really complicated!

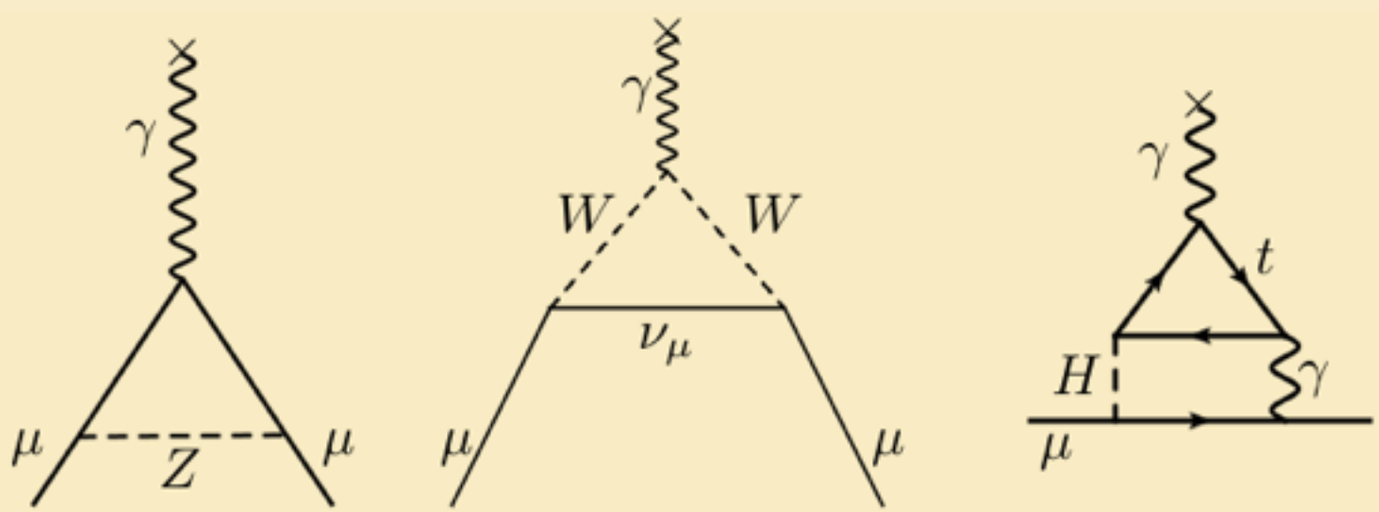




Particle theorists calculate how all these diagrams (and 10,000s more) affect g

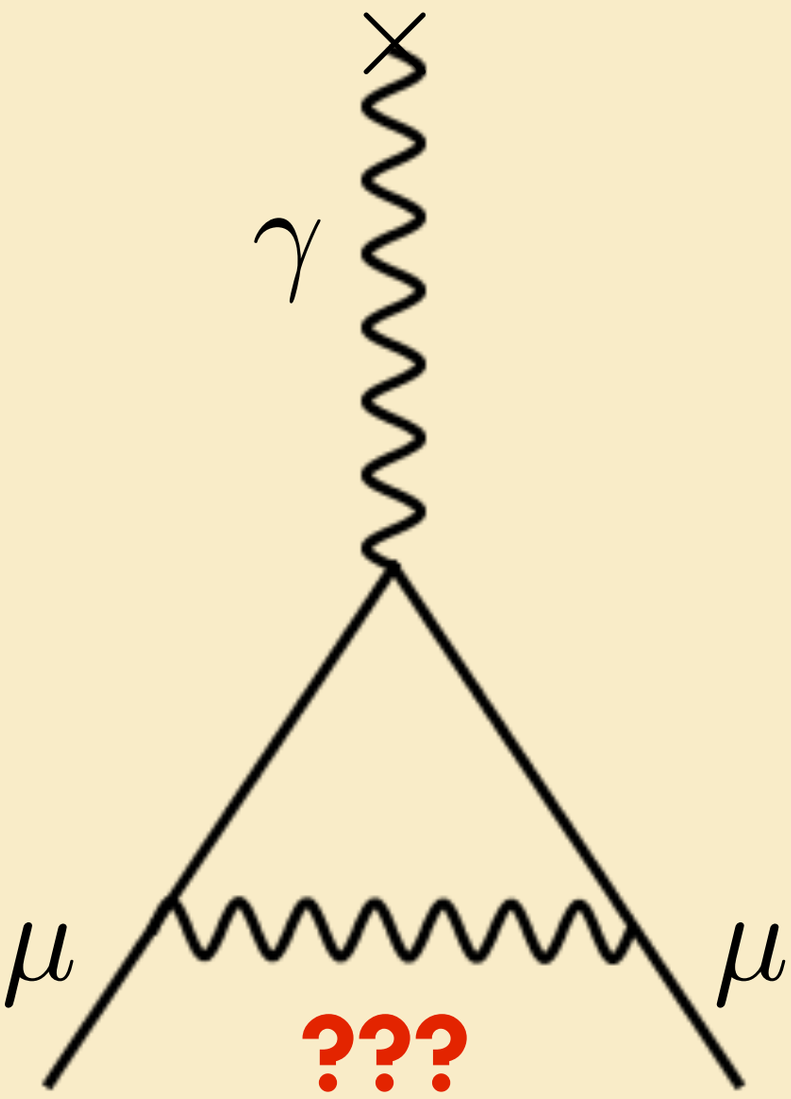


This looks hard! And it is!



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

The BIG question



***g-2* is sensitive to unknown particles**

Are there any?

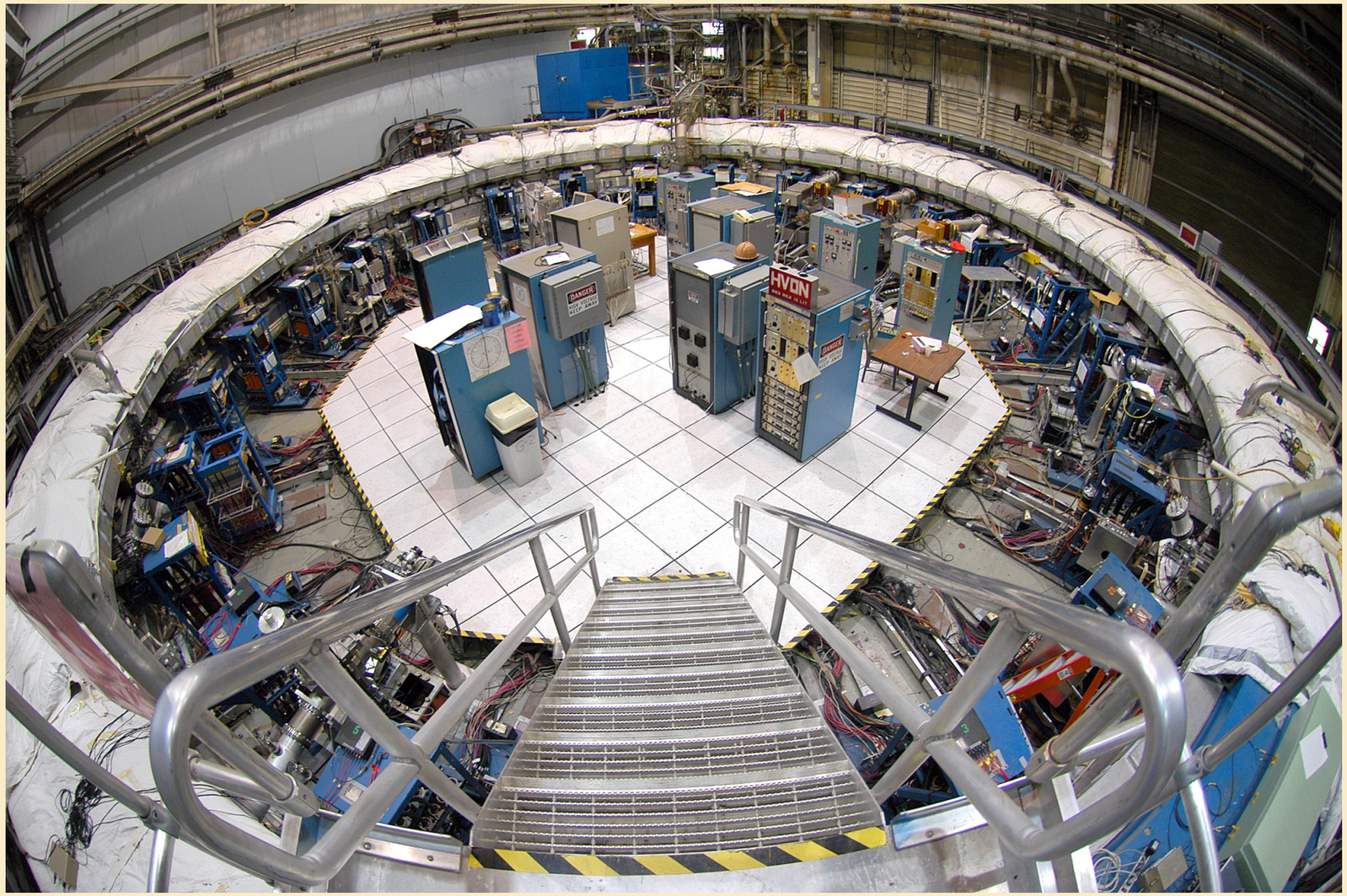
The plan:

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?



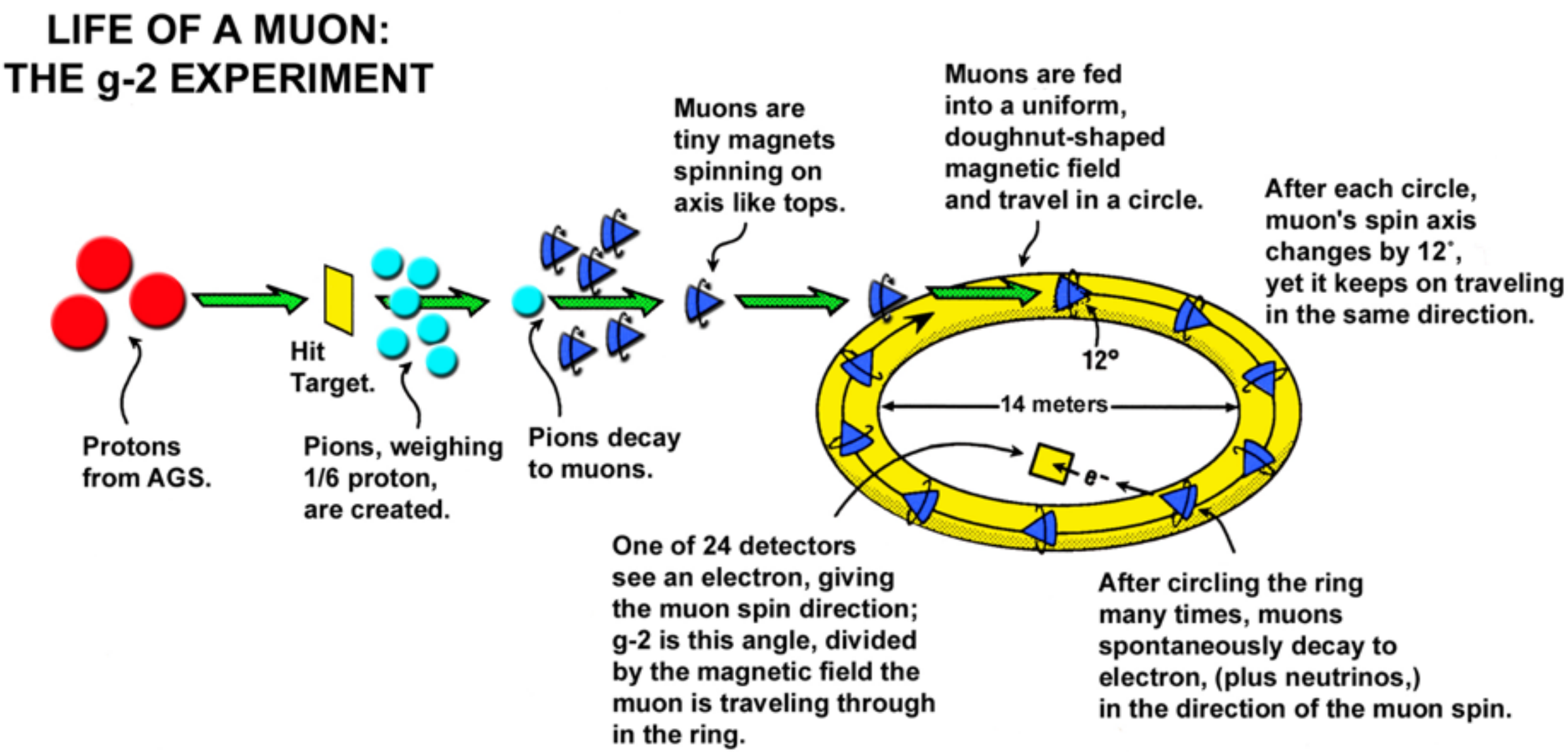
We need a magnetic field to make muons precess

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

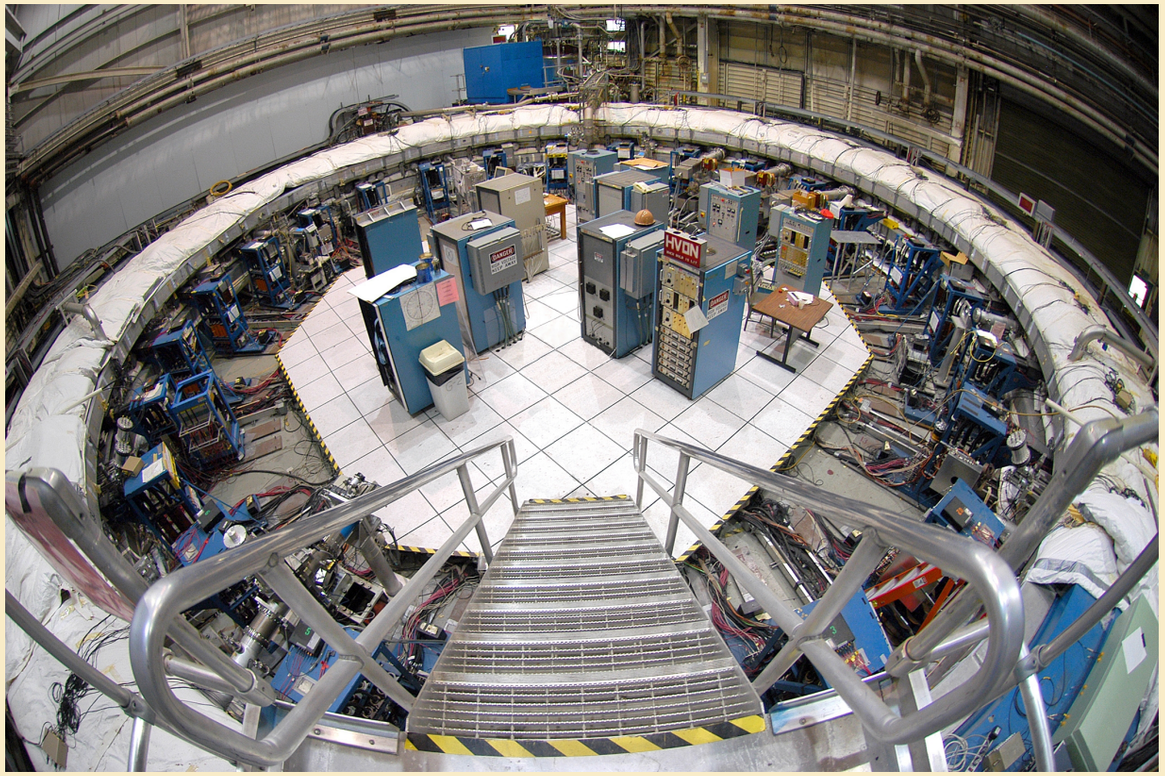
A storage ring does both (the magnets keep muons going in a circle in the ring) !

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

Schematic of the Brookhaven experiment



Ring Fun Facts

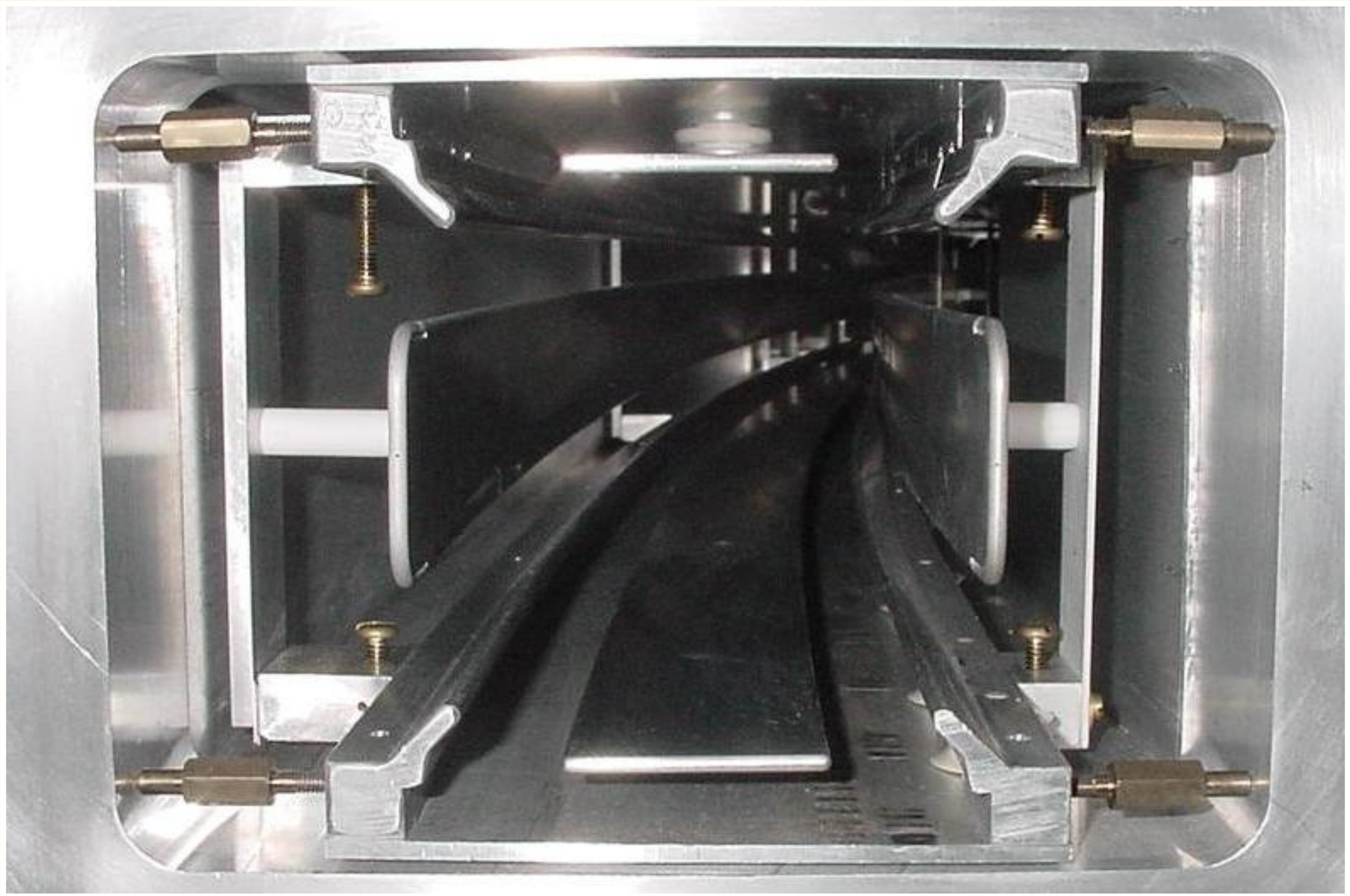


50 feet diameter;
Magnets are 15,000 Gauss
(fridge magnet is 100 G,
earth is ~0.5 G)

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

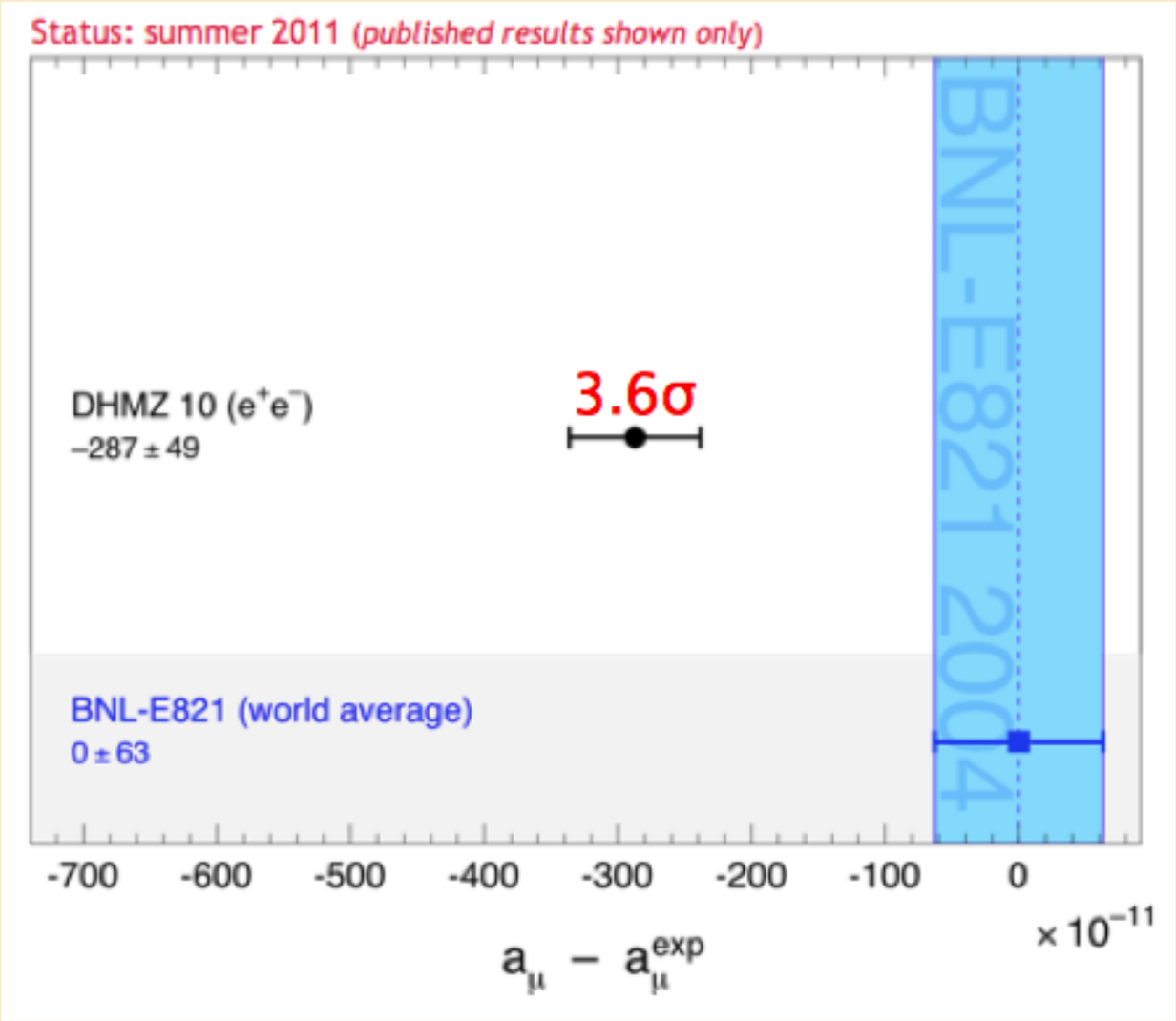
Muons go around the ring every 149 nano-seconds
(would go around 6.7 million times per second)
Travel at 0.99942 c - lifetime is 65 micro-seconds (>2.2)
Muon living for 100 micro-seconds makes 670 turns

Don’t put your head in the beam



4”

The Brookhaven Results (1999-2000)



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

$$a_\mu^{\mathrm{QED}} = 0.00\,116\,584\,718\,09(15)$$
$$a_\mu^{\mathrm{had}} = 0.00\,000\,006\,930(49)$$
$$a_\mu^{\mathrm{EW}} = 0.00\,000\,000\,154(2)$$

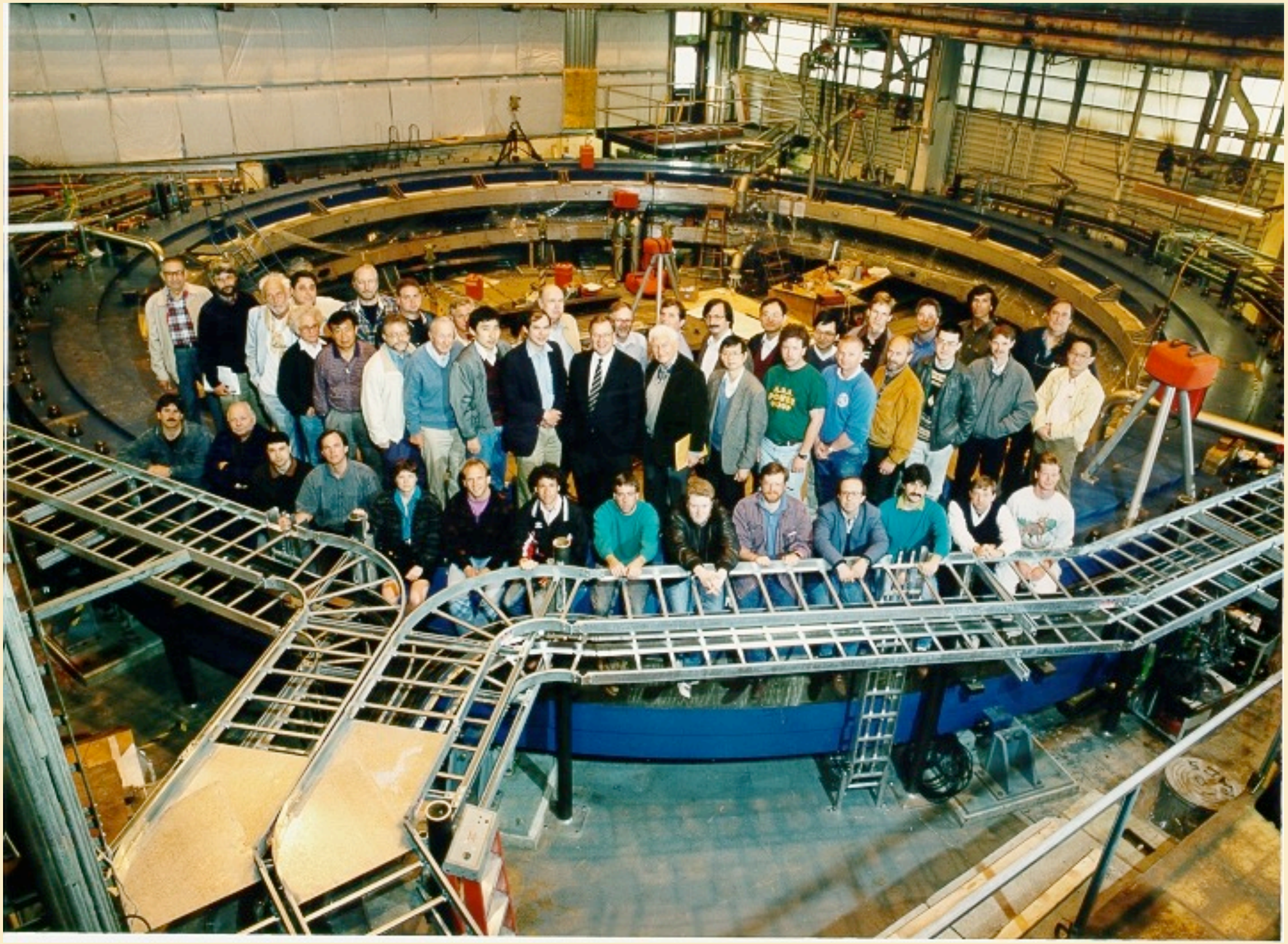
$$a_\mu^{\mathrm{SM}} = 0.00\,116\,591\,802(49)$$
$$a_\mu^{\mathrm{exp}} = 0.00\,116\,592\,089(63)$$

0.54 ppm measurement

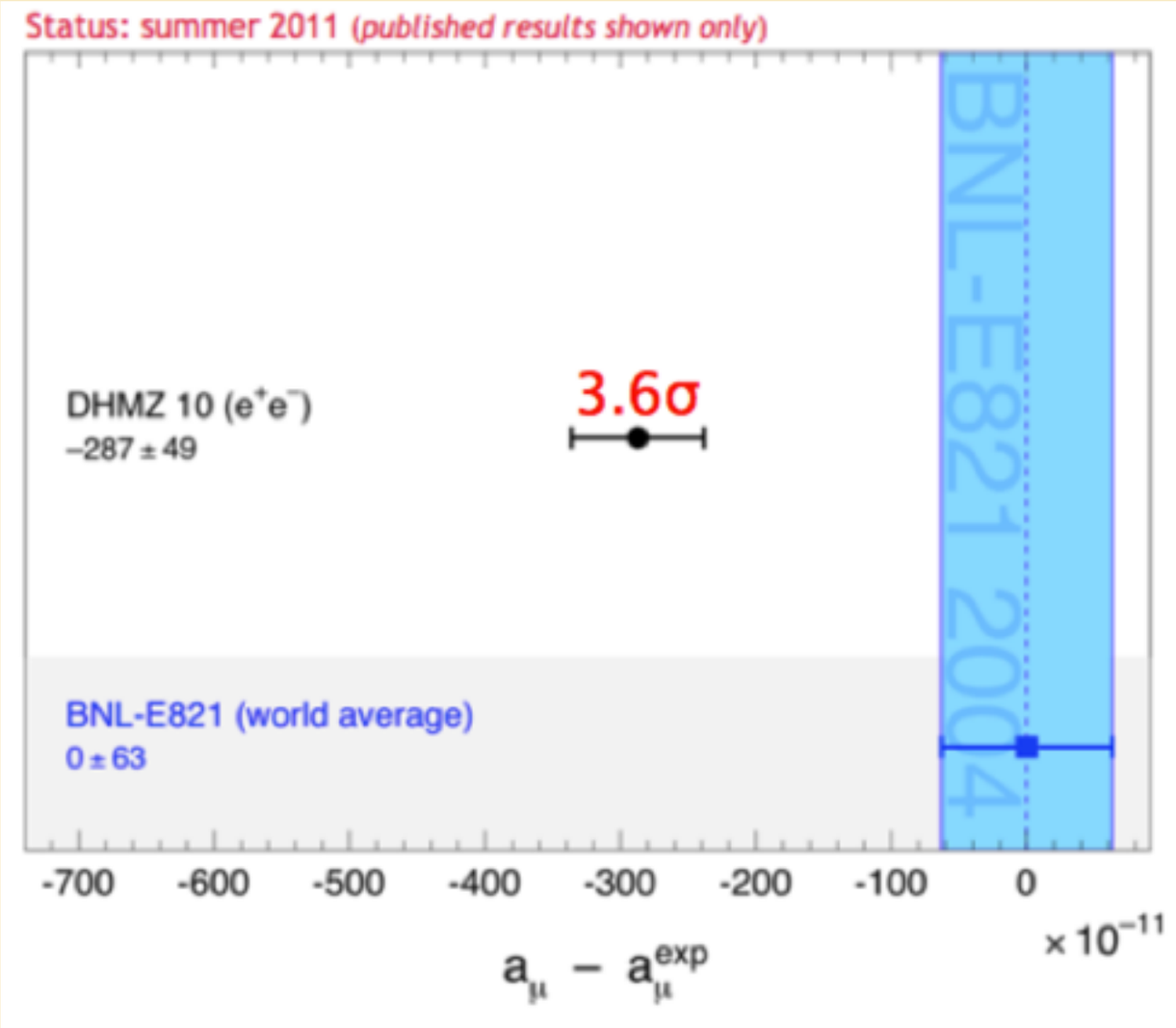
$$\mathbf{a}_\mu^{\mathrm{exp}} - \mathbf{a}_\mu^{\mathrm{SM}} = \mathbf{287(80)} \times \mathbf{10^{-11}}$$

Difference is substantial, but uncertainties are too large to be certain of a discovery

A Job Well Done



Do the experiment again, but better



Want to make the blue uncertainty bar more narrow

Need more muons; better beam

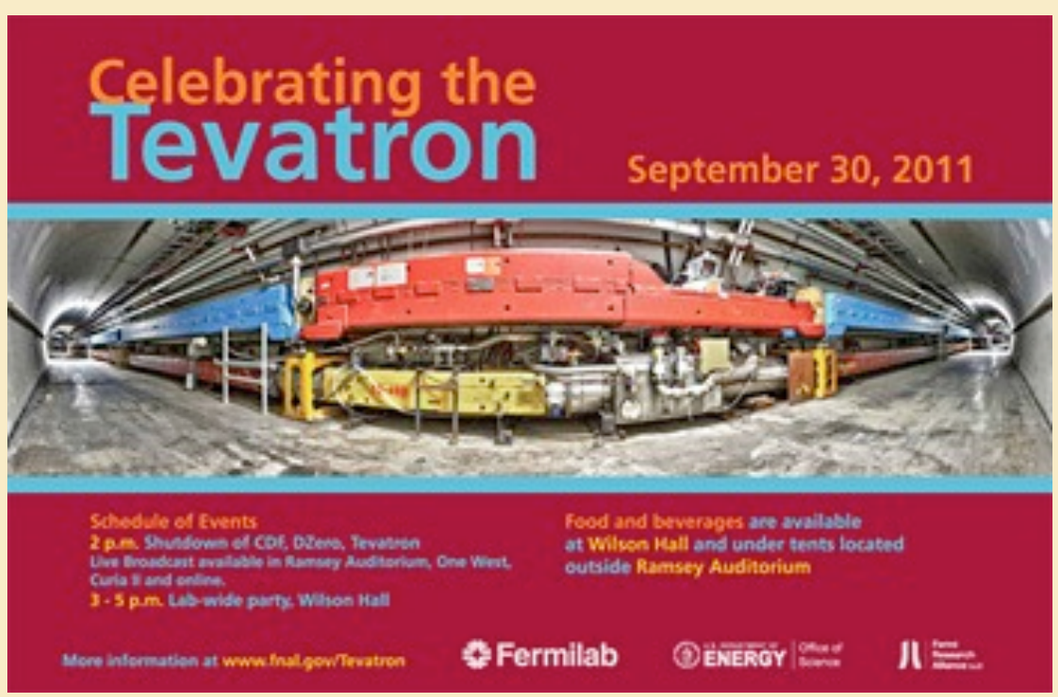
Need "cleaner" environment (move ring further away from target)

But Brookhaven could not provide these improvements in a cost effective way

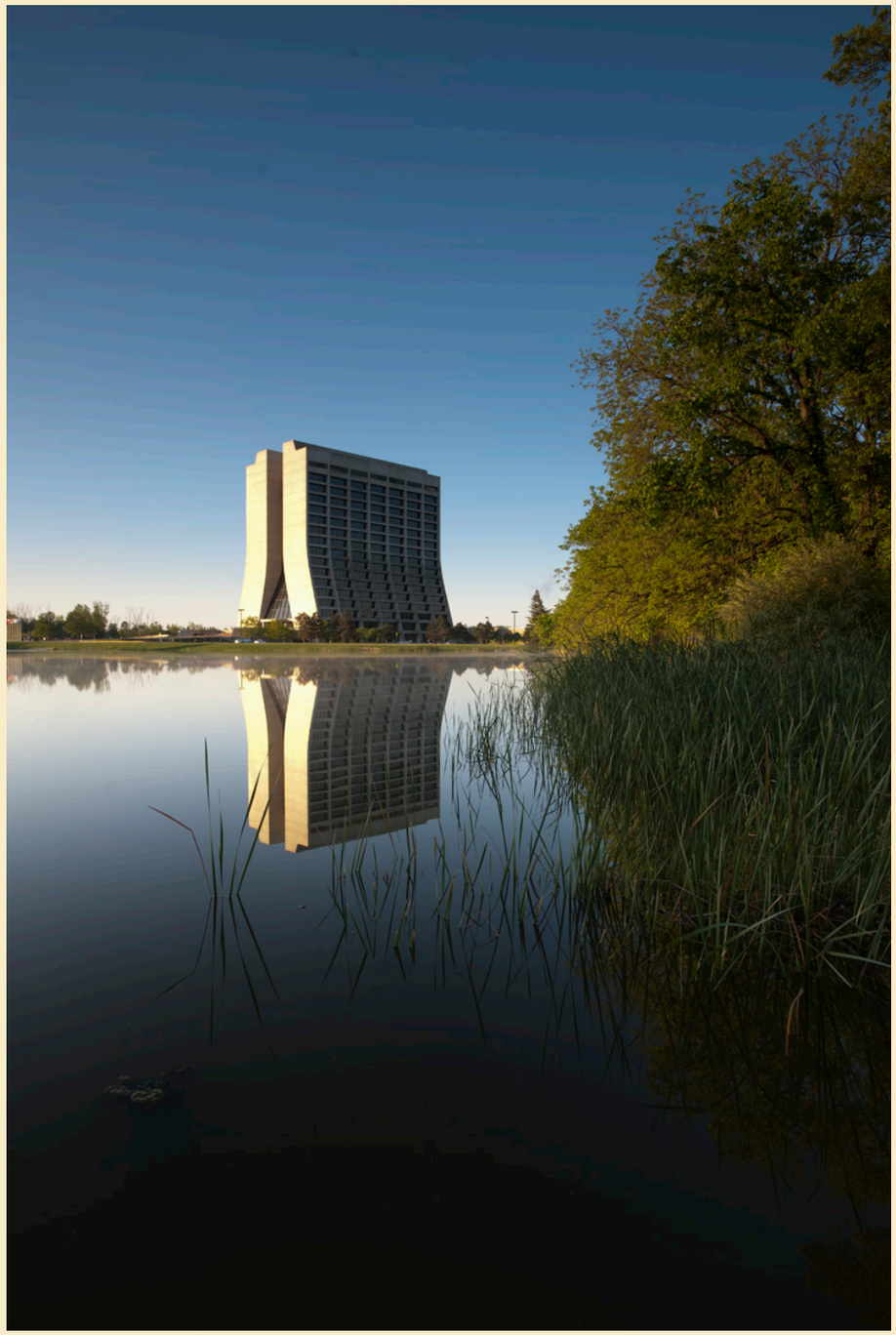
So this amazing and beautiful device sat untouched, gathering dust and raccoons for over a decade

In the meantime at Fermilab

The Tevatron had shutdown after running nearly 30 years
The LHC, by design, makes it obsolete



A little more about Fermilab



Fermi National Accelerator Laboratory

A U.S. Department of Energy,
Office of Science National Laboratory

Started in early 70's. Devoted to Particle Physics
No confidential research

~1700 employees, ~2500 visitors

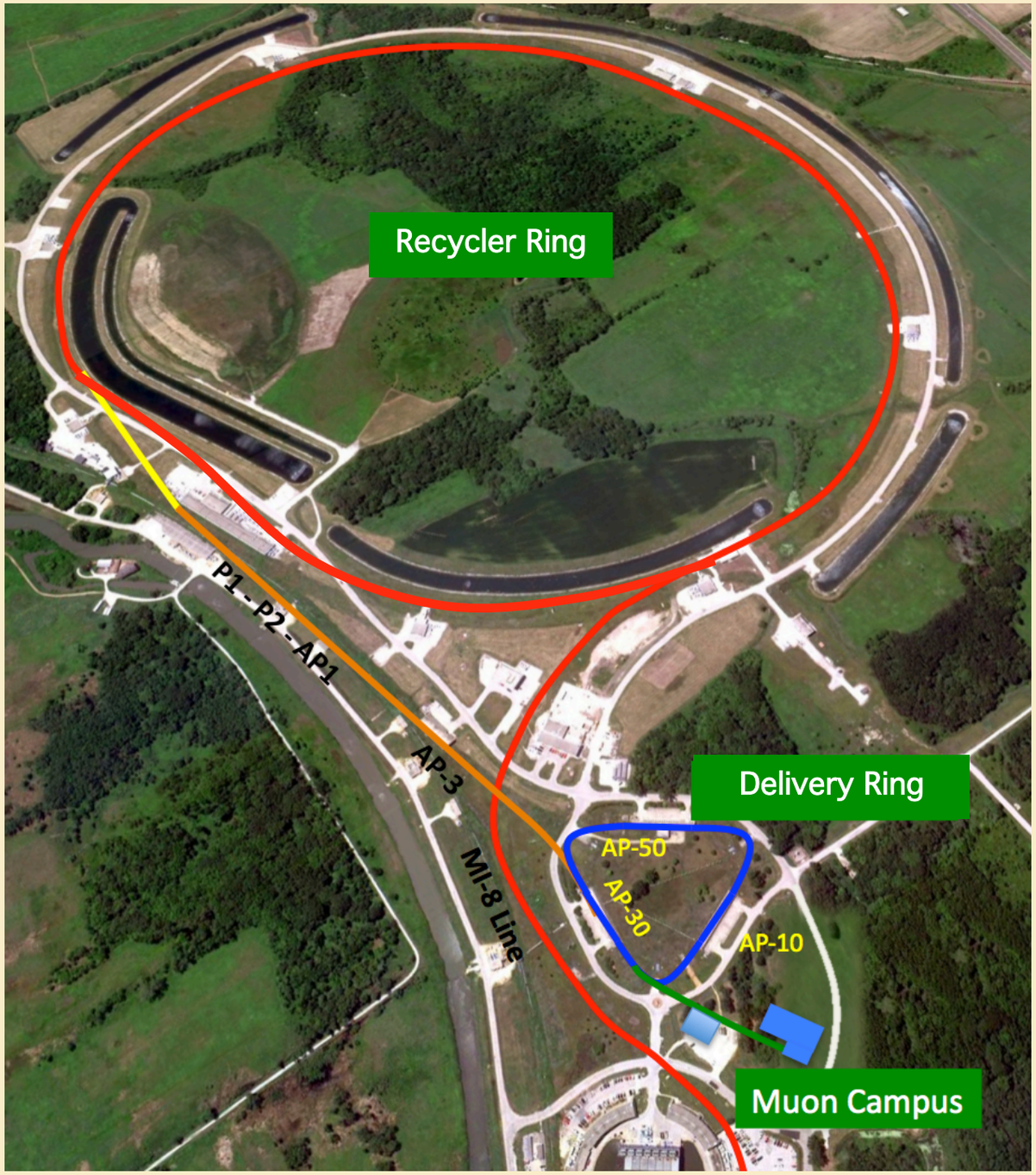
Economic driver for the western suburbs and Illinois

A quite open site (you can drive in –
just be ready to show your driver's license)

Come and see the displays, the bison, and the restored prairie
Bike, fish, canoe, train your dog too!

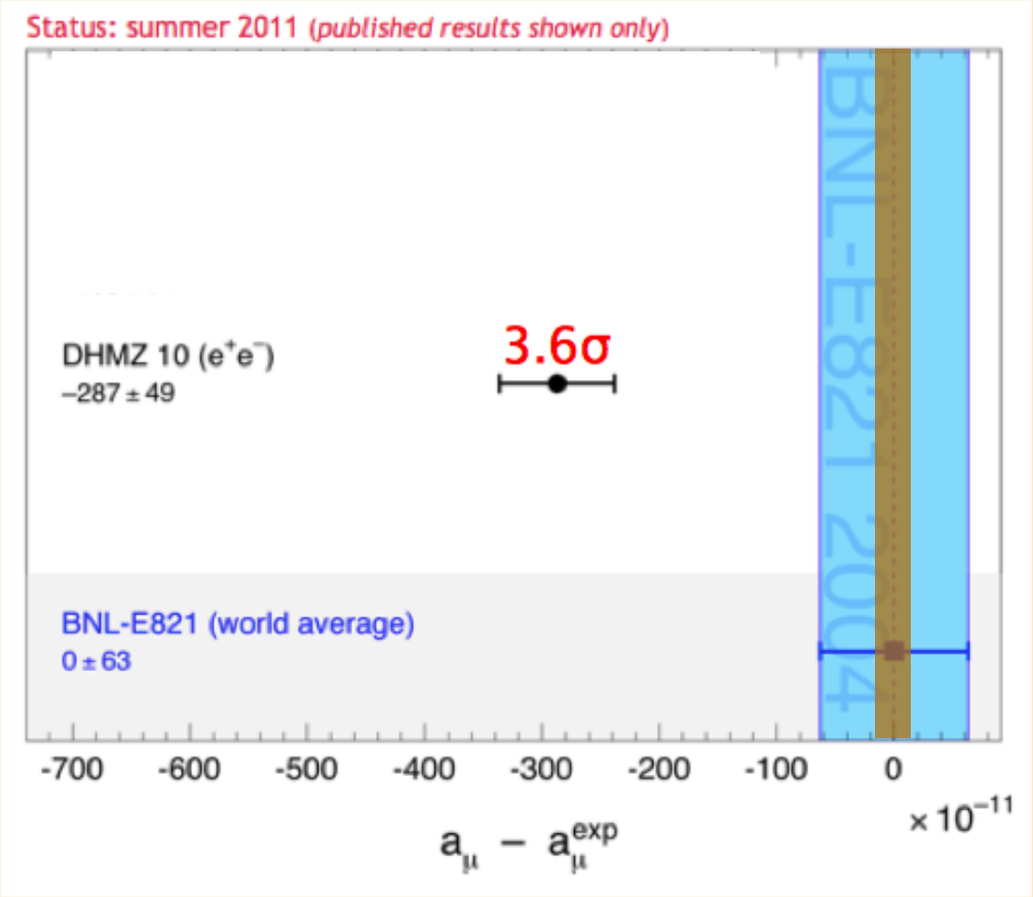
Muon g-2 at Fermilab

Fermilab, the last US laboratory dedicated only to Particle Physics, now had an enormous infrastructure freed up

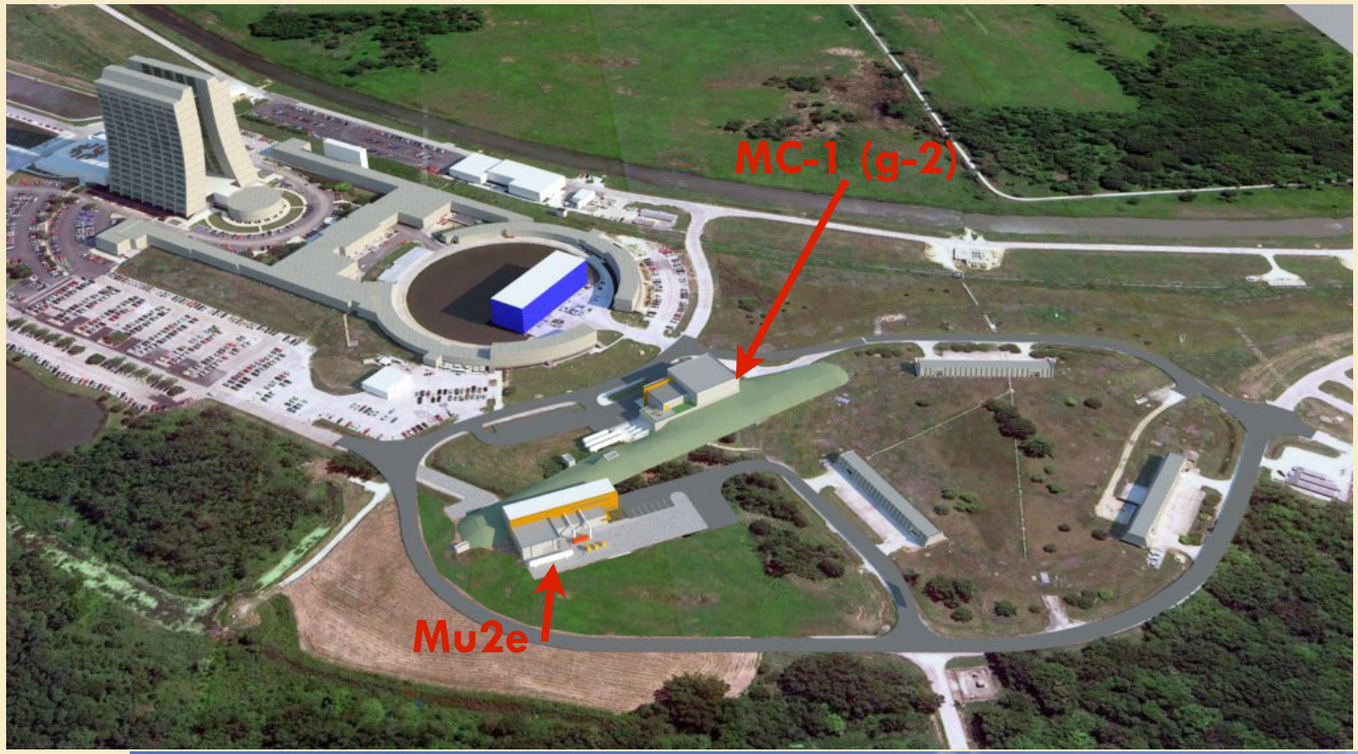


The accelerators and target that made anti-protons for the Tevatron can make muons for *g-2* !!!

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

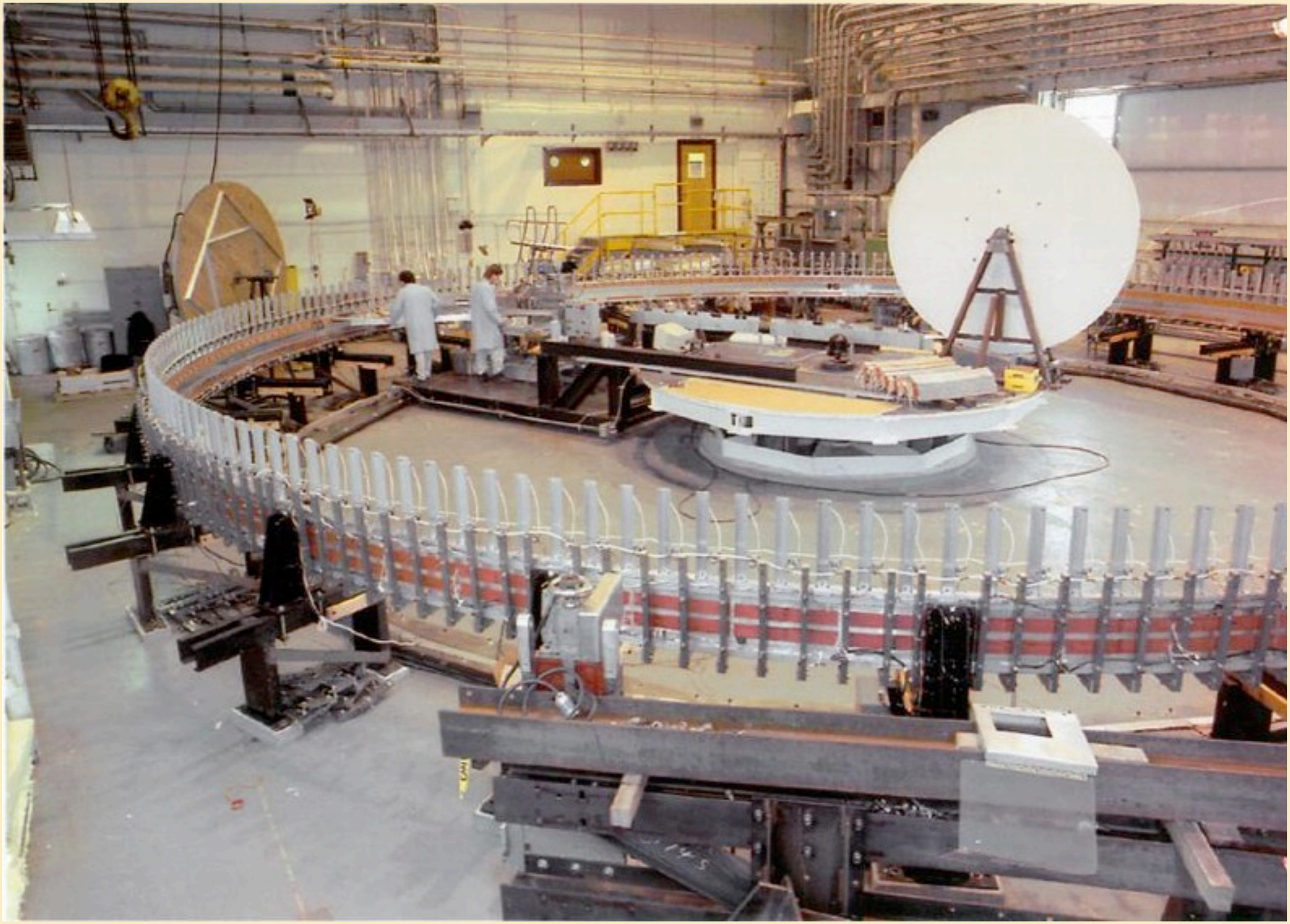
Continuously wound coils, can't break into pieces - can't flex > 3mm

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

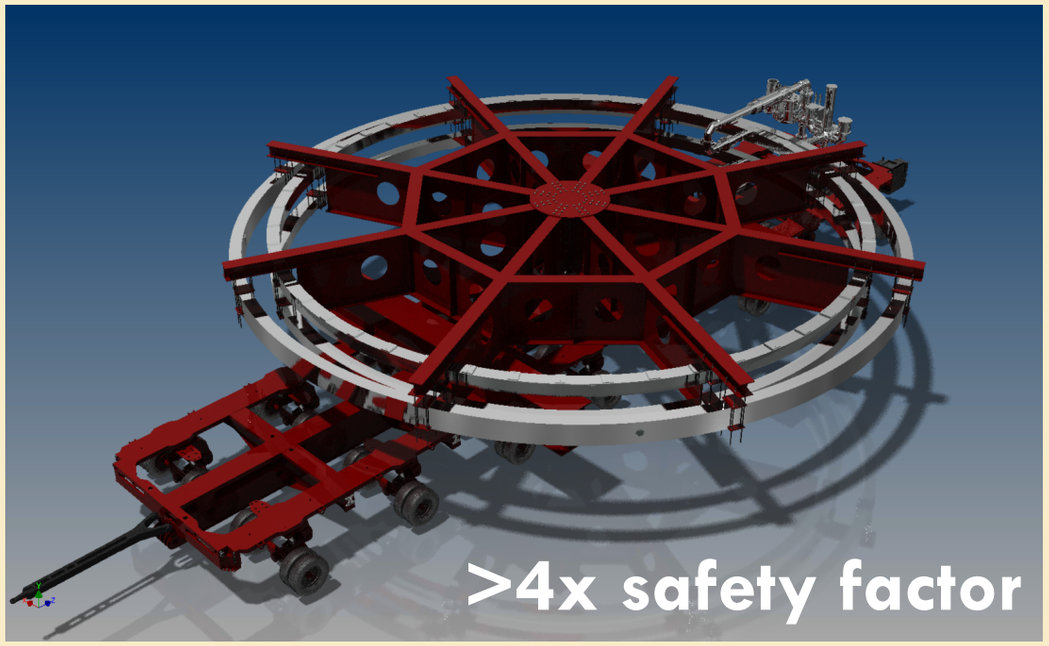
~ $2M to move. 10x more, ~$30M, if we had to build them anew!

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



Disassembly - summer 2011

Photo: Leah Welty-Reiger

Disassembly - spring 2012

Photo: Chris Polly

Assembling the fixture

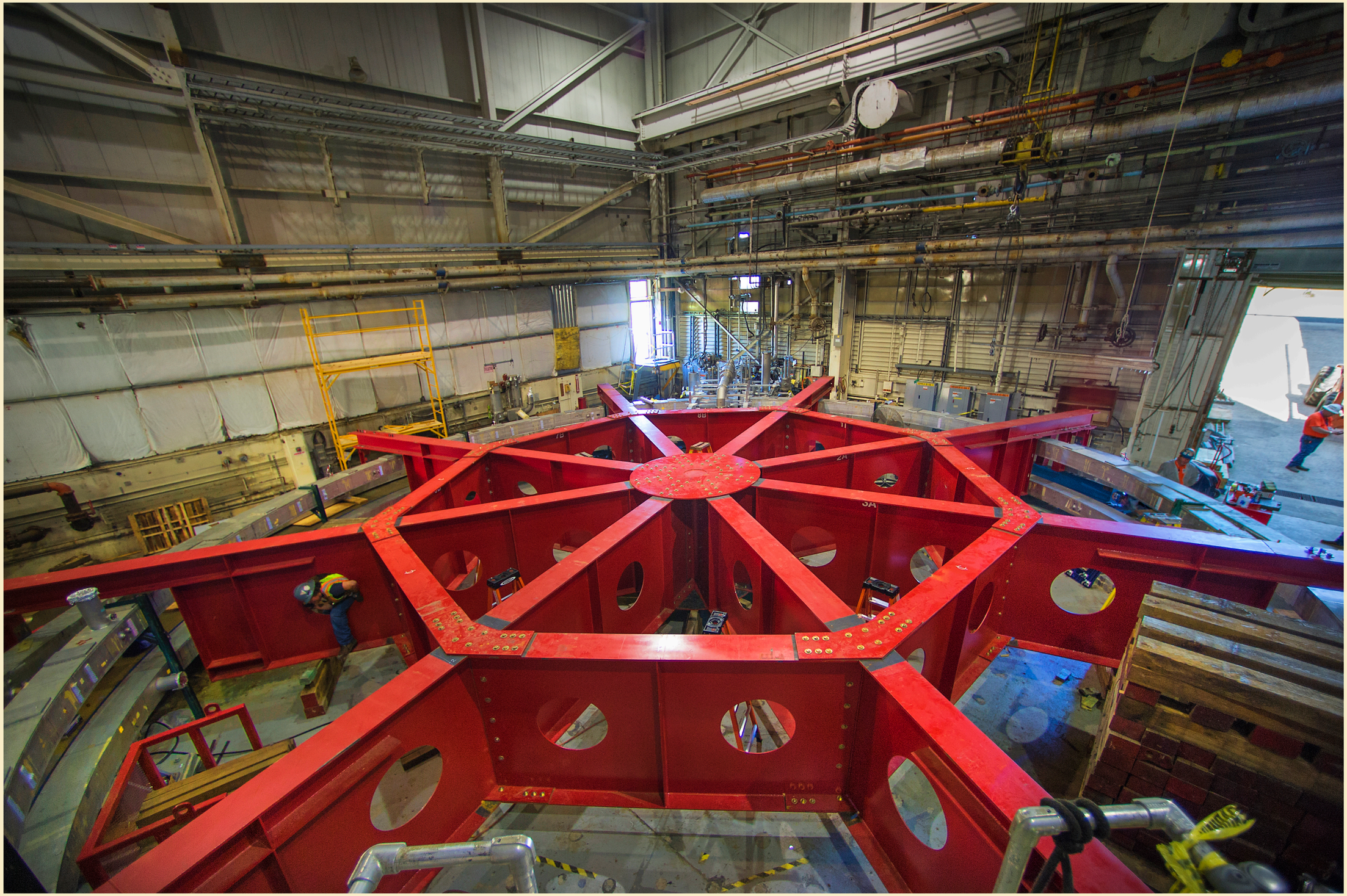


Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

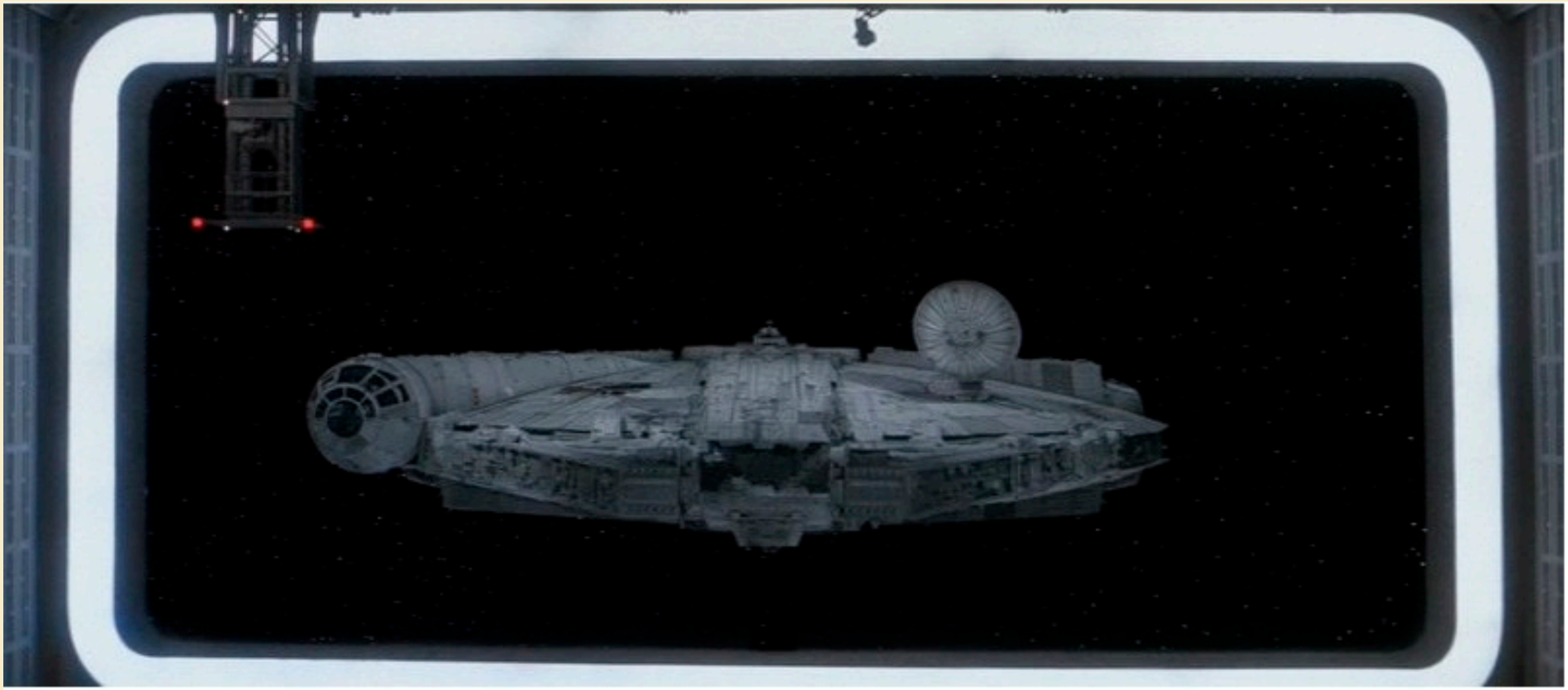


Photo: Darth Vader

It's out

Photo: Brookhaven/Emmert

The fancy trailer

8 axels
64 tires

Auto-leveling
Height control
Independent steering

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

Photos: Brookhaven/Emmert

Off it goes

Photo: Brookhaven/Emmert

A 3200 mile journey 6/22 – 7/26

Making friends while in Norfolk

Photo: Aria Soha's brother

Arrival in Mobile, AL

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

Photo: Darin Clifton

Darin Clifton
July 12 via mobile
near Dauphin Island, AL

Met up with the Trident today at high noon in Mobile Bay & handed off the Muon g-2 to the Katie Ann. Now she's headed up the Tenn-Tom. — with Tifney Clifton and Chuck Paddock.

Share

9 people like this.

Justin Wheeler What is it?
July 12 at 8:18pm via mobile · 1

Darin Clifton Justin - it's a $25m Magnet !! All the way from New York to Illinois by water. Google "Fermilab moves the Magnet"
July 12 at 8:21pm via mobile · 1

Justin Wheeler What kind of dang magnet costs $25m?! Lol
July 12 at 8:21pm via mobile · 1

Chuck Paddock I need to pick up some nails in my drive way
July 12 at 8:22pm via mobile · 2

Justin Wheeler It better be able to pick them up from space! Lol
July 12 at 8:23pm via mobile · 2

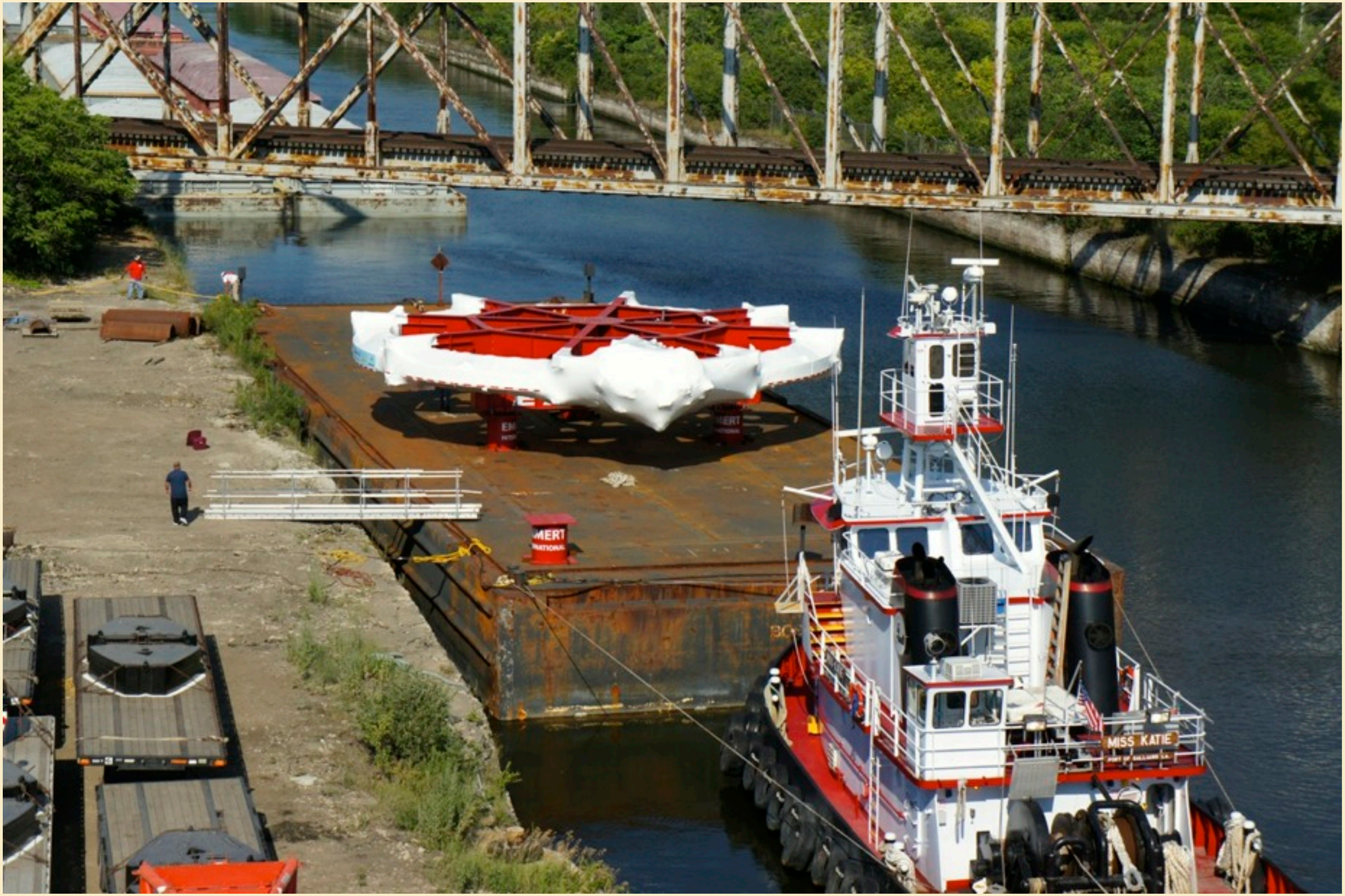
Up the Tenn-Tom Waterway

Photo: Darin Clifton

And Saturday 6/20, finally in Lemont, IL

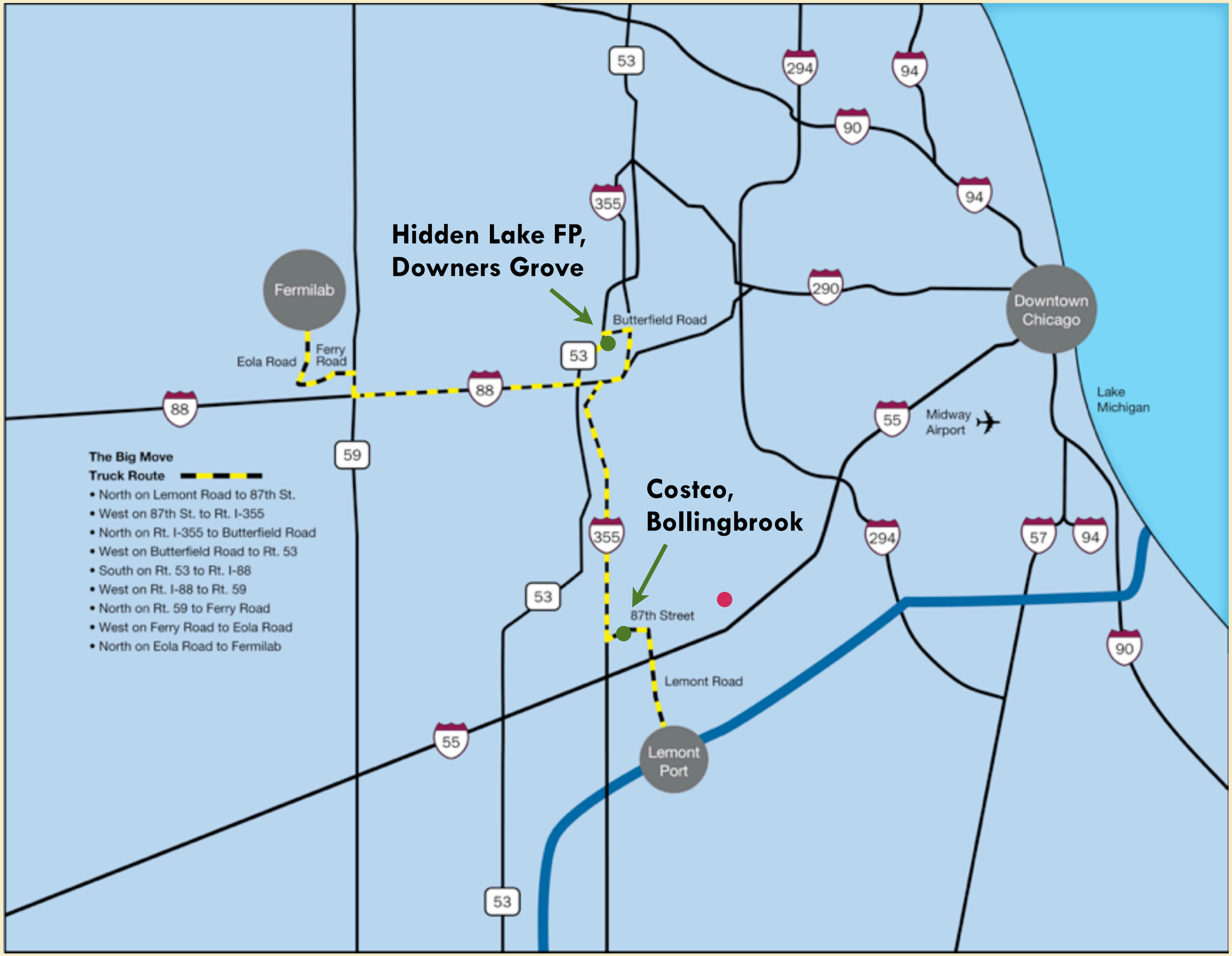
Close up, from Lemont Rd bridge

Arrival in Lemont



Sunday morning, off the barge

Tuesday – Friday: The land route



Tuesday night, on Lemont Rd & 87th St

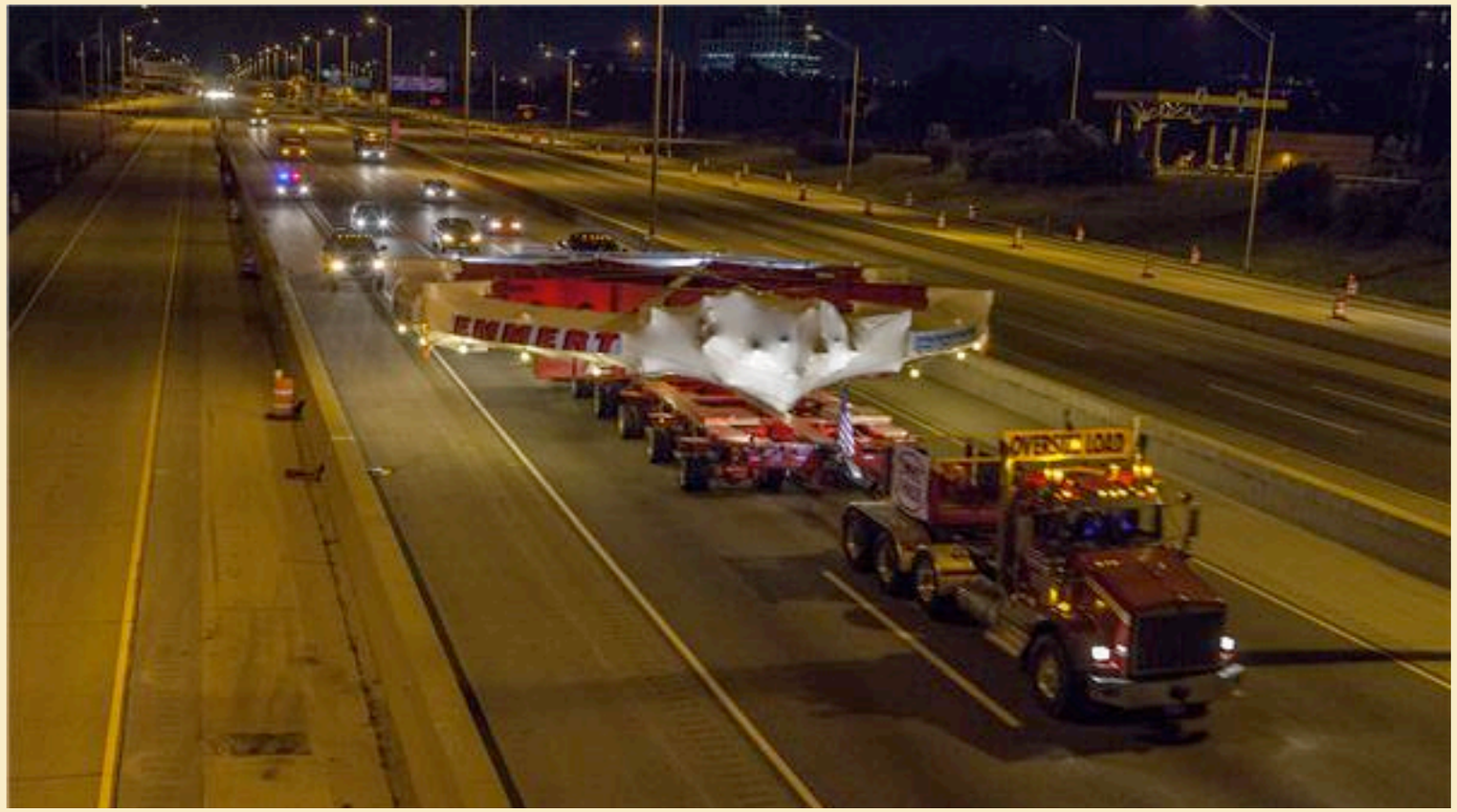
Photos: Fermilab

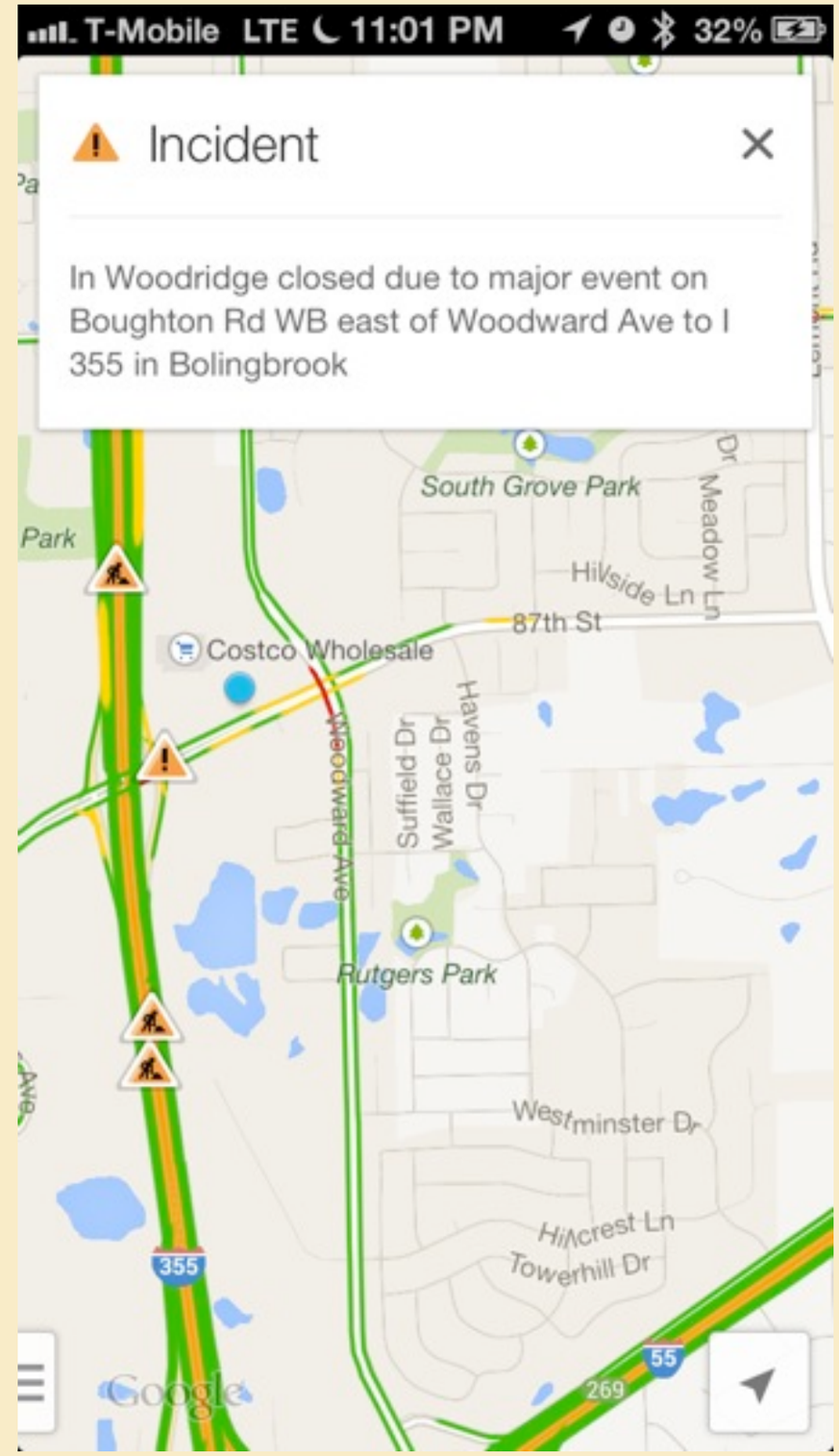
Wednesday, making shopping fun

Wednesday night - on the tollway

Wednesday night - on the tollway

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 onto I-88

20 mph on I-88 !!

Photos: Mike Murphy

Railroad bridge on Ferry Rd

Trying to drive onto the curb

Fermilab
Goldhofer

Fermilab
Goldhofer

Friday, Celebration day!

OVERSIZE LOAD
INNERT

Photo: Fermilab

Photo: Fermilab

What's next?

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

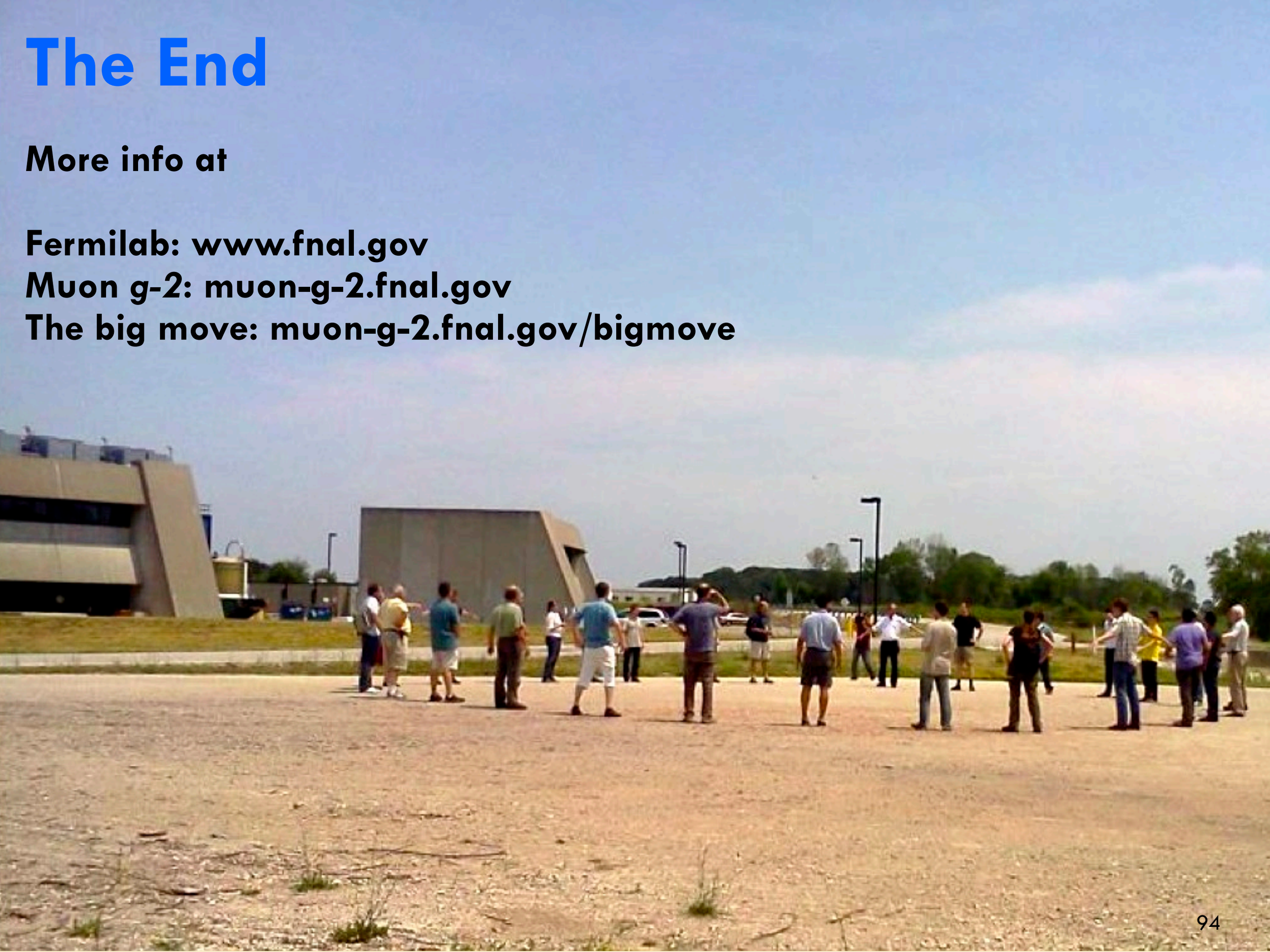
Will take 2+ years to reassemble, test, and "shim"

Data taking starts in 2016 or 2017 for two years !

<u>It takes a collaboration!</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