The New Muon g-2 Experiment at Fermilab

Photo: Hogan Nguyen

Adam Lyon, Fermilab

NCSU Physics Colloquium

9/23/13

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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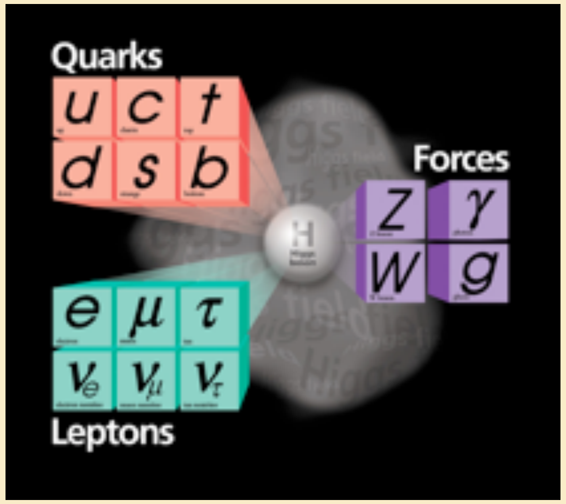
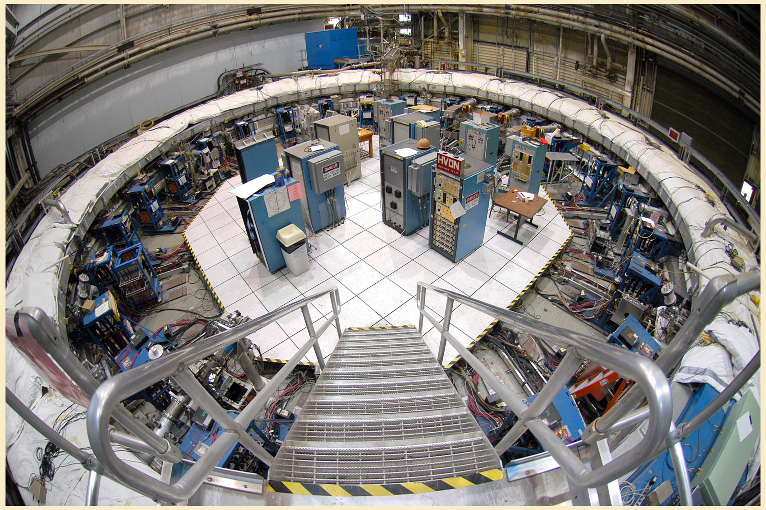
Outline of this Colloquium



Motivation



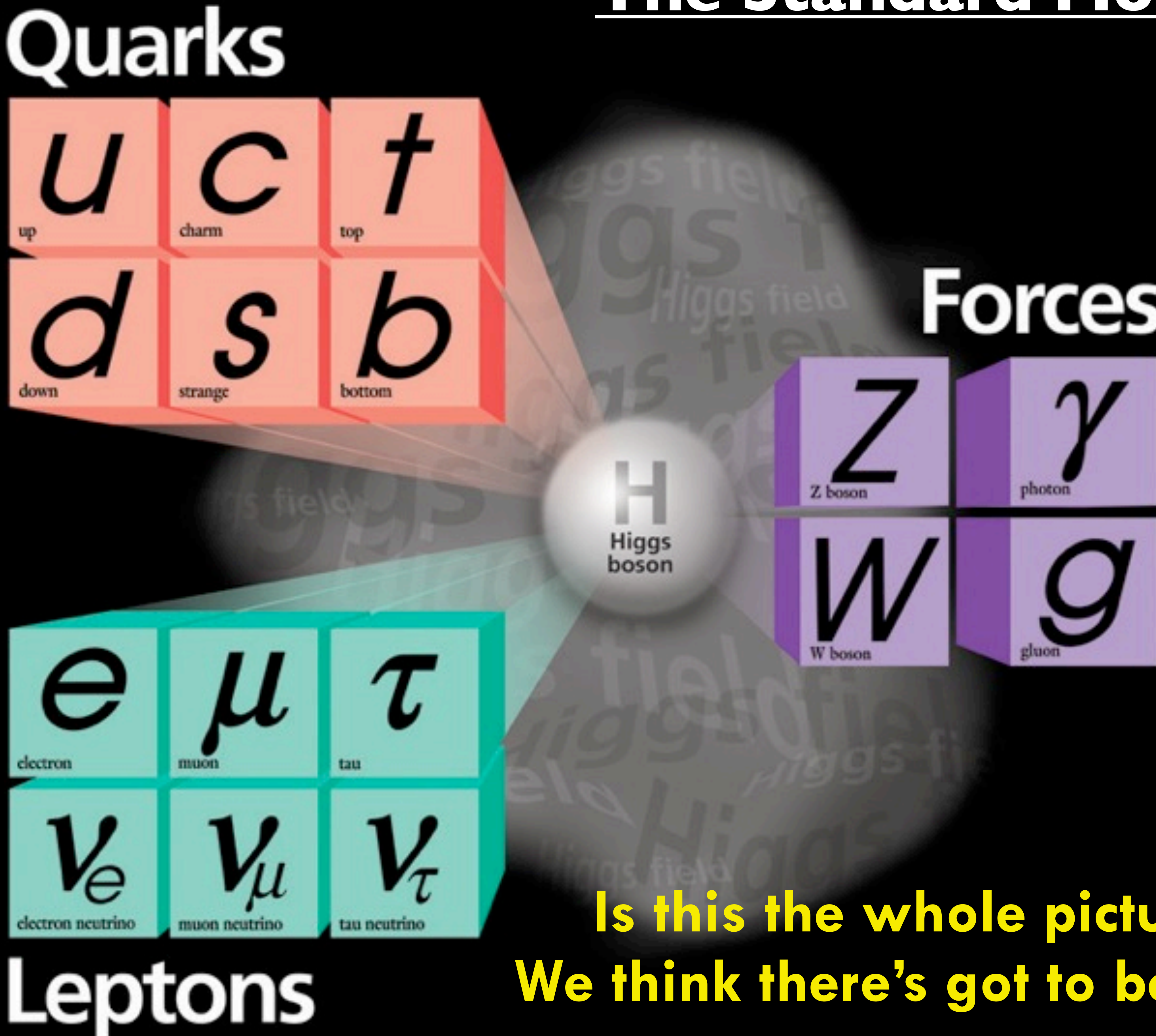
Muons and *g*-2

@ Fermilab

A journey

The future

The Standard Model

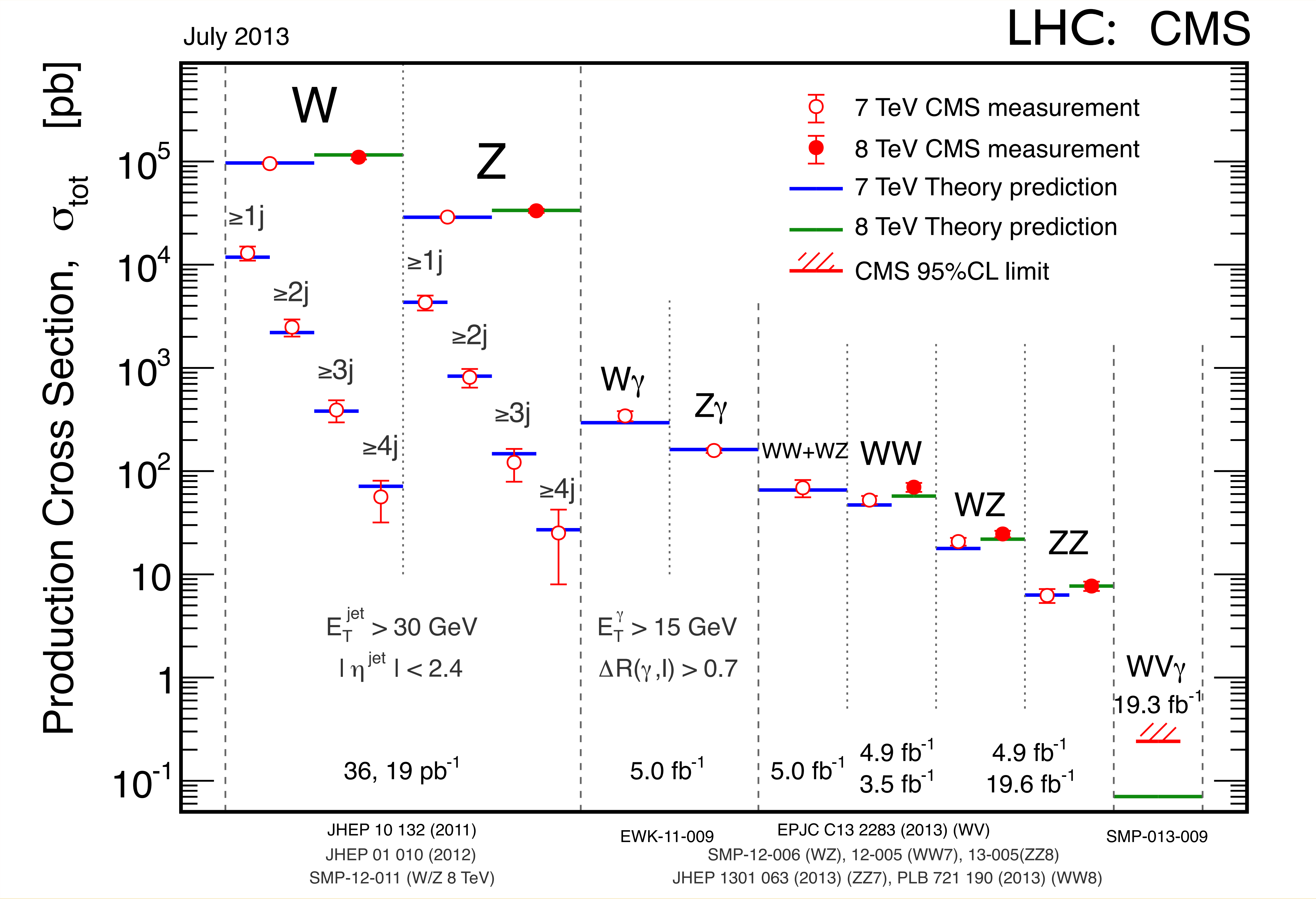


Is this the whole picture?

We think there's got to be more

Why do we look beyond the SM?

Despite being an incredibly successful model…

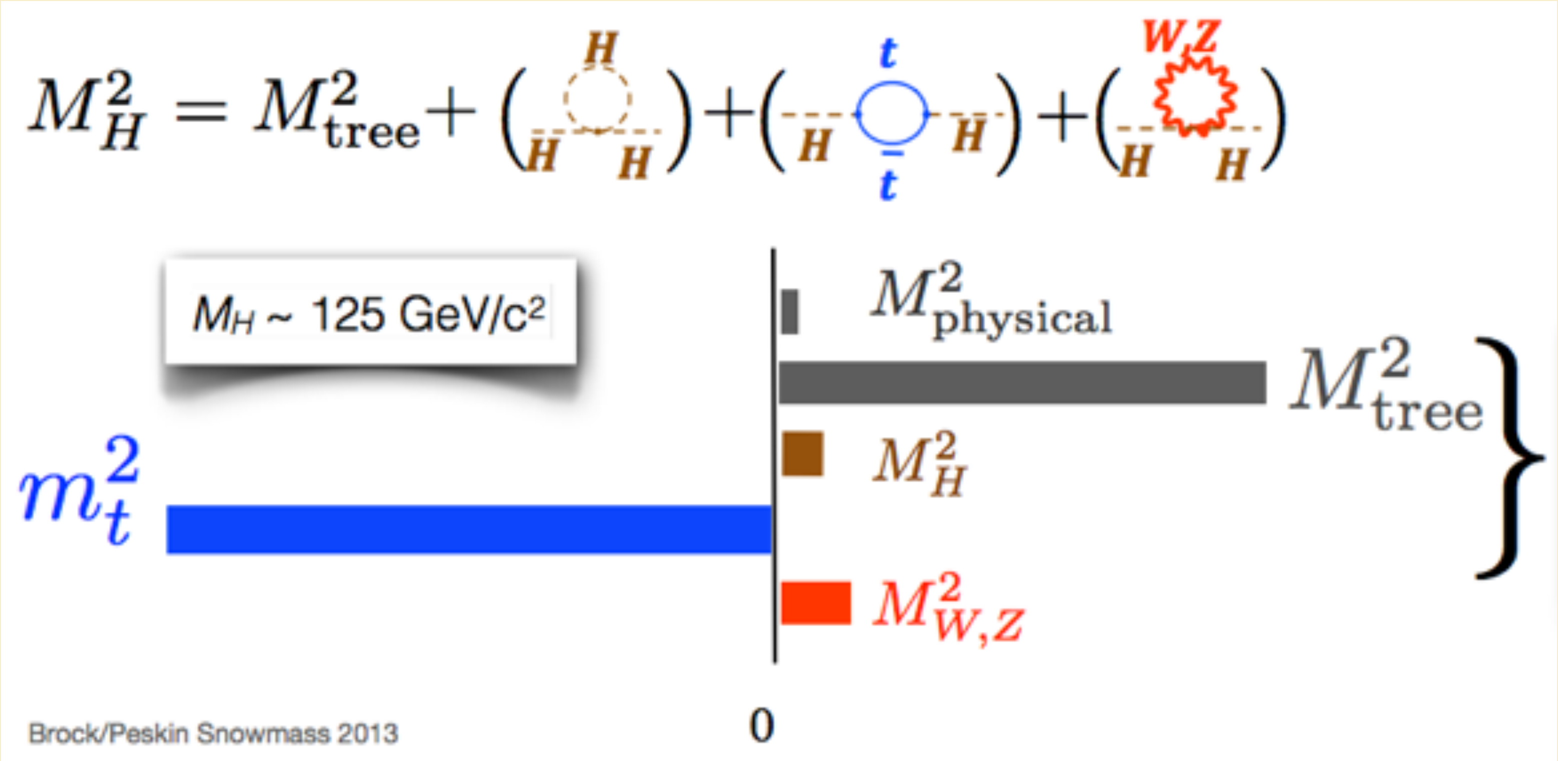


Why do we look beyond the SM?

… it doesn't predict everything we want:

o Gravity? Dark matter? Dark energy? Neutrino masses? Matter/antimatter asymmetry?

… and it gives theorists some headaches



Fine tuning necessary for Higgs mass to come out right

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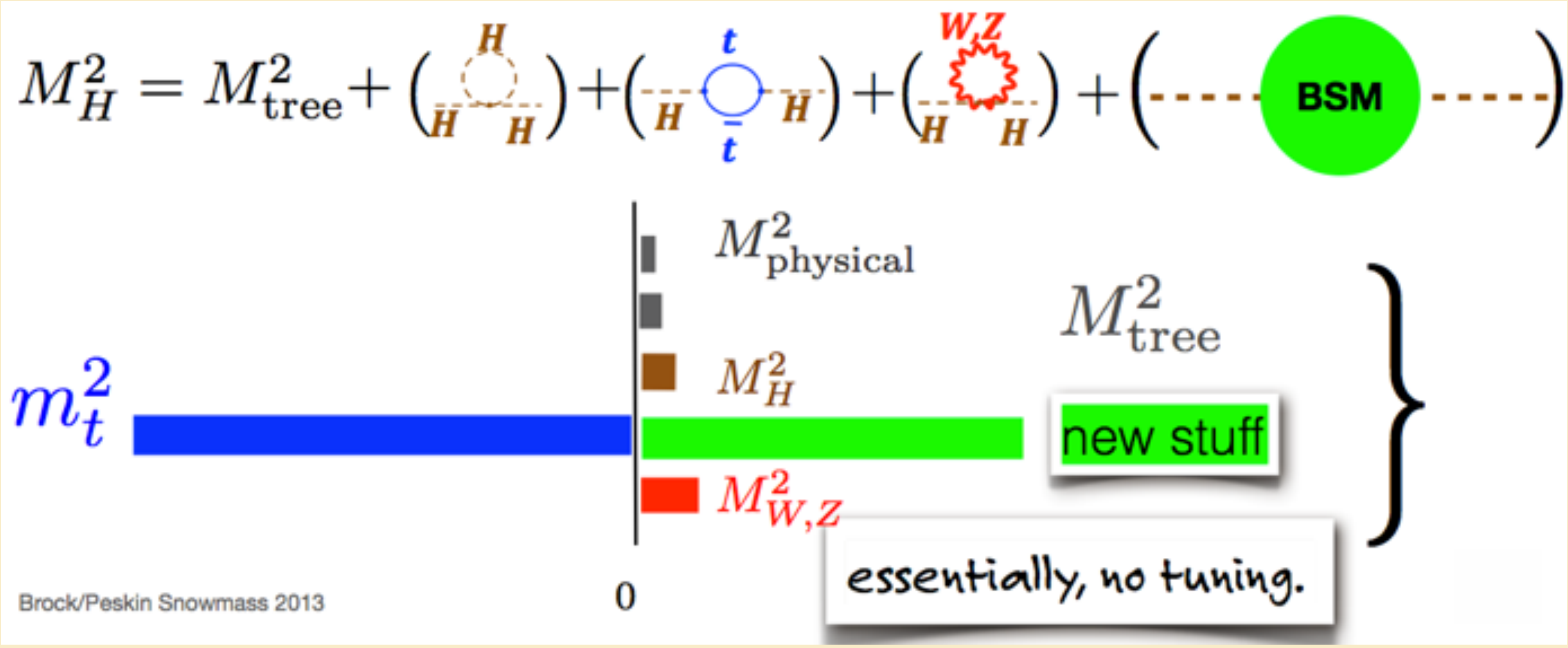
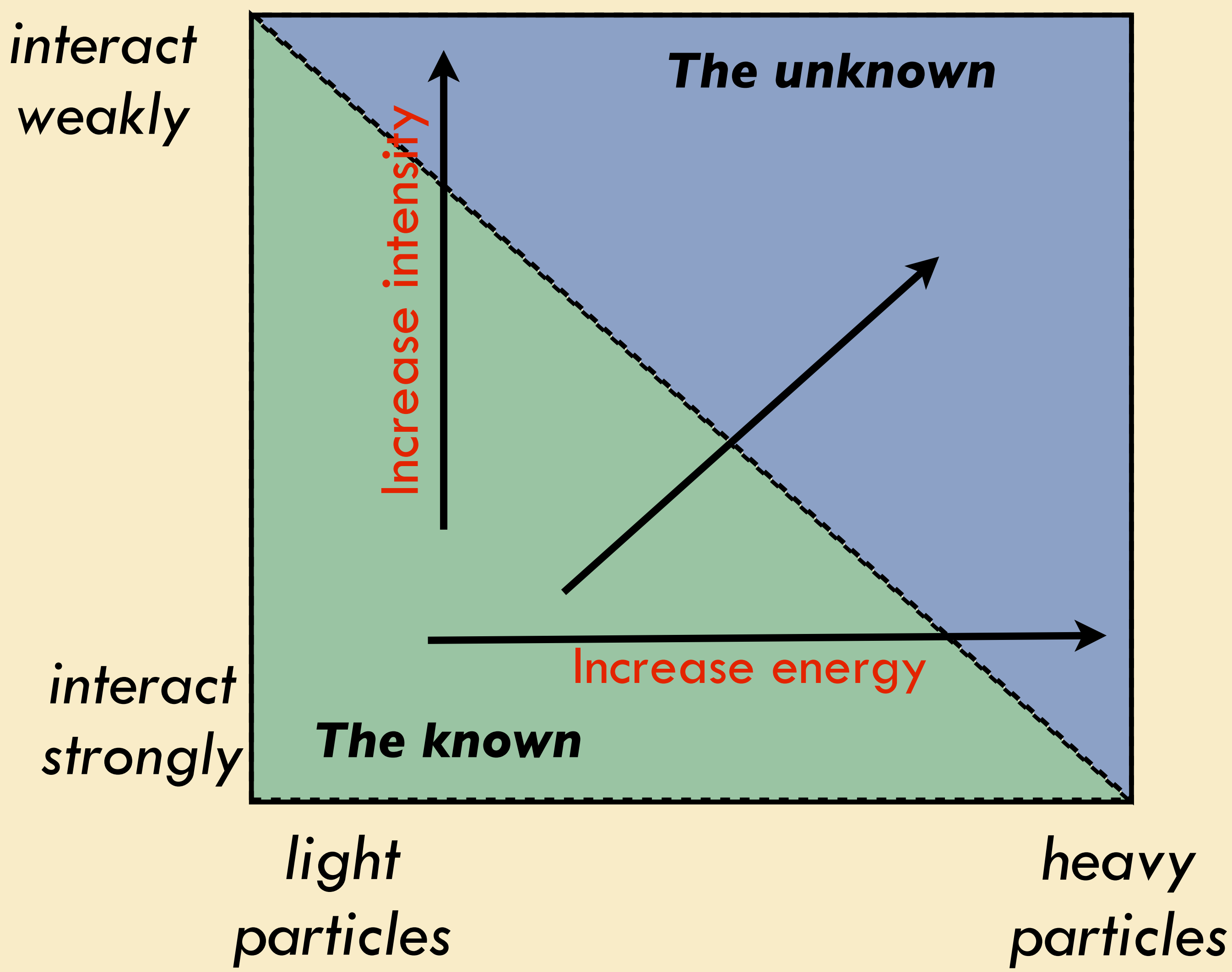


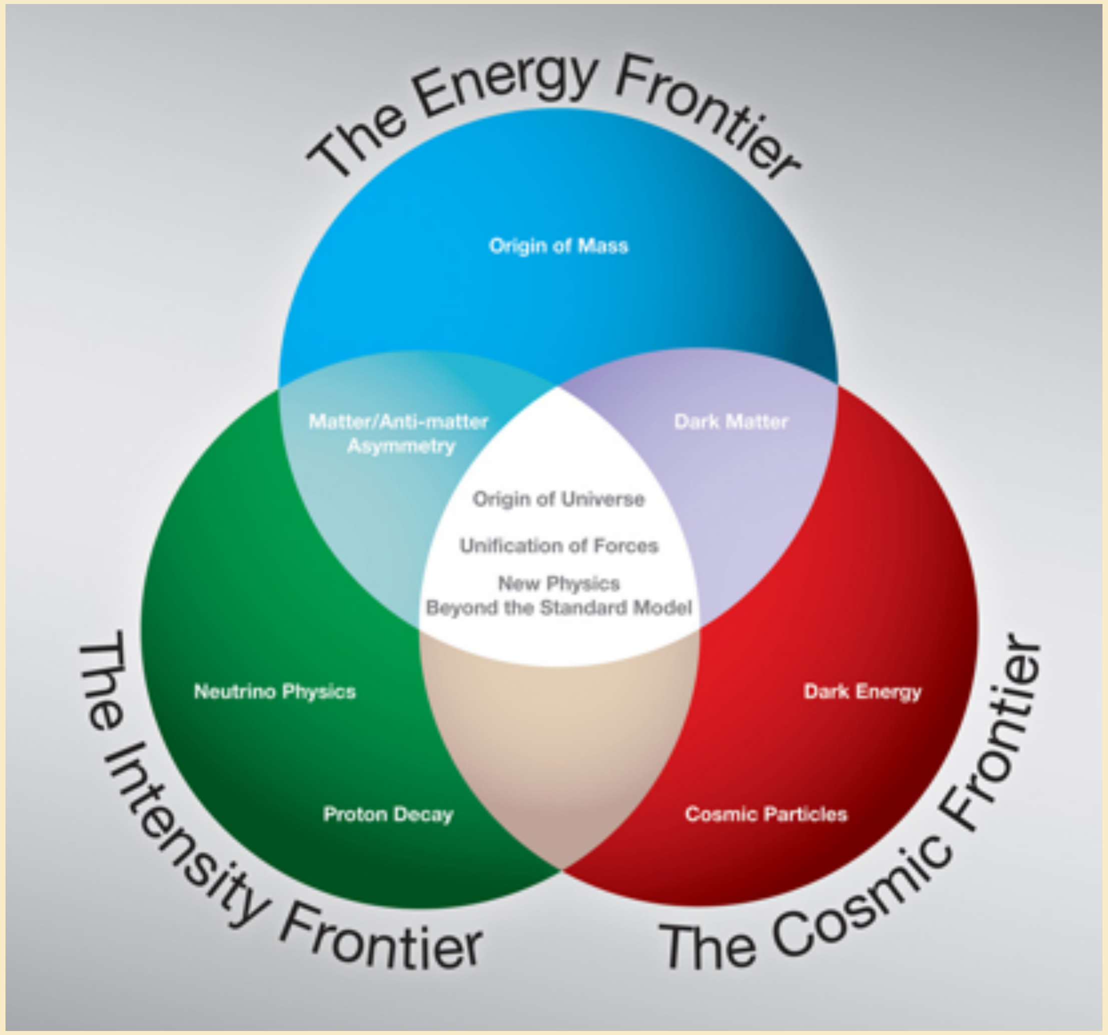
Avoid fine-tuning through Beyond SM (BSM) physics
[e.g. Supersymmetry]

Some ways to look for new physics

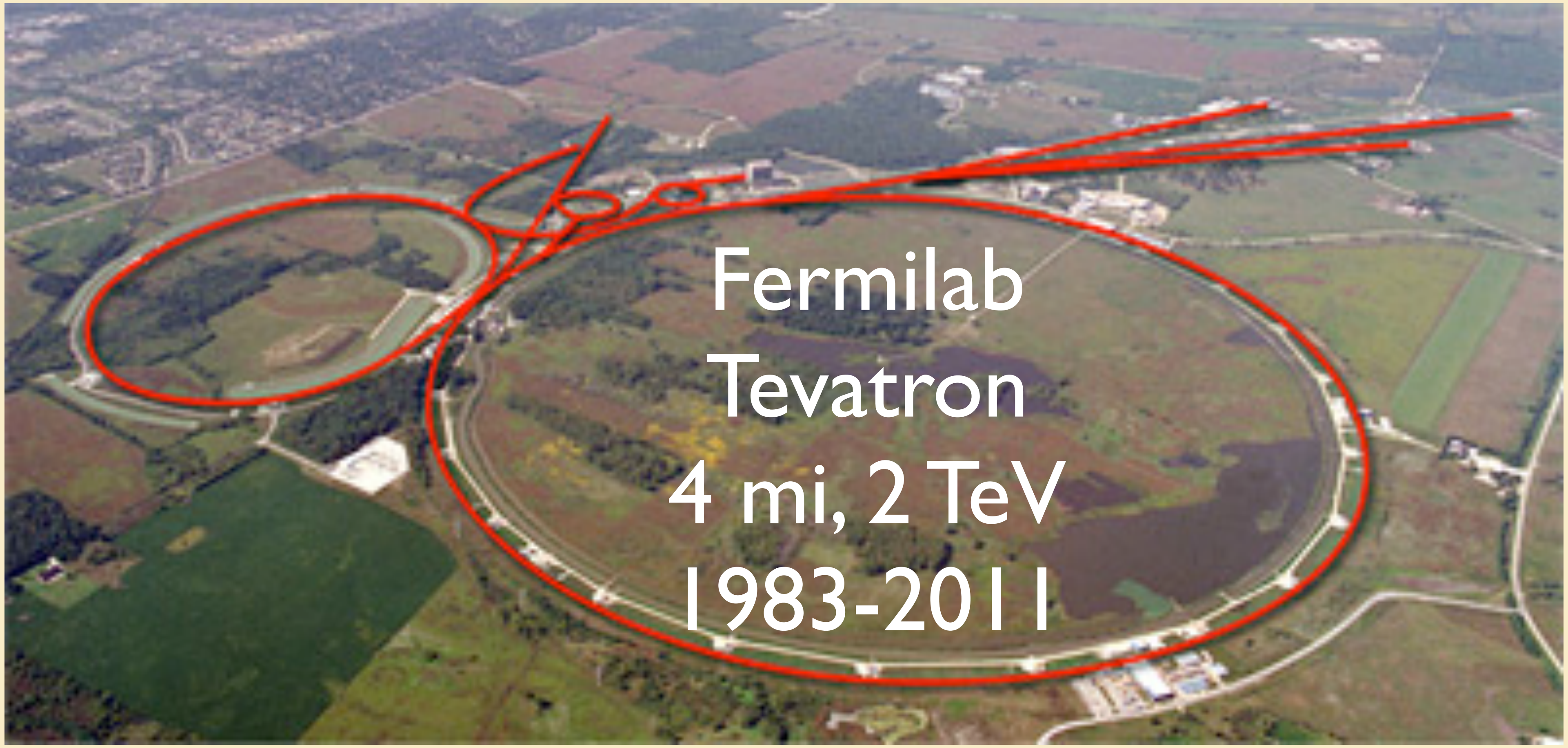
Find new high mass particles
Need to collide at high energy to make them

Probe interactions that occur very rarely (interact weakly)
Need lots of interactions to catch the rare ones

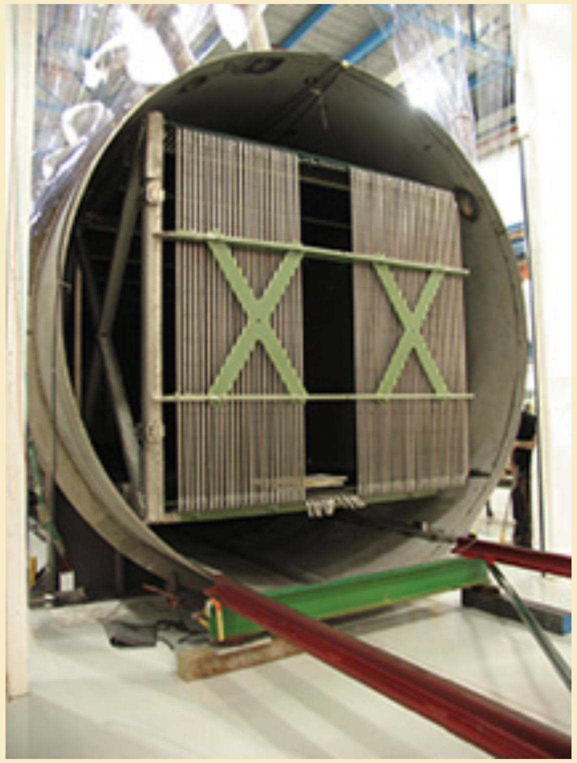


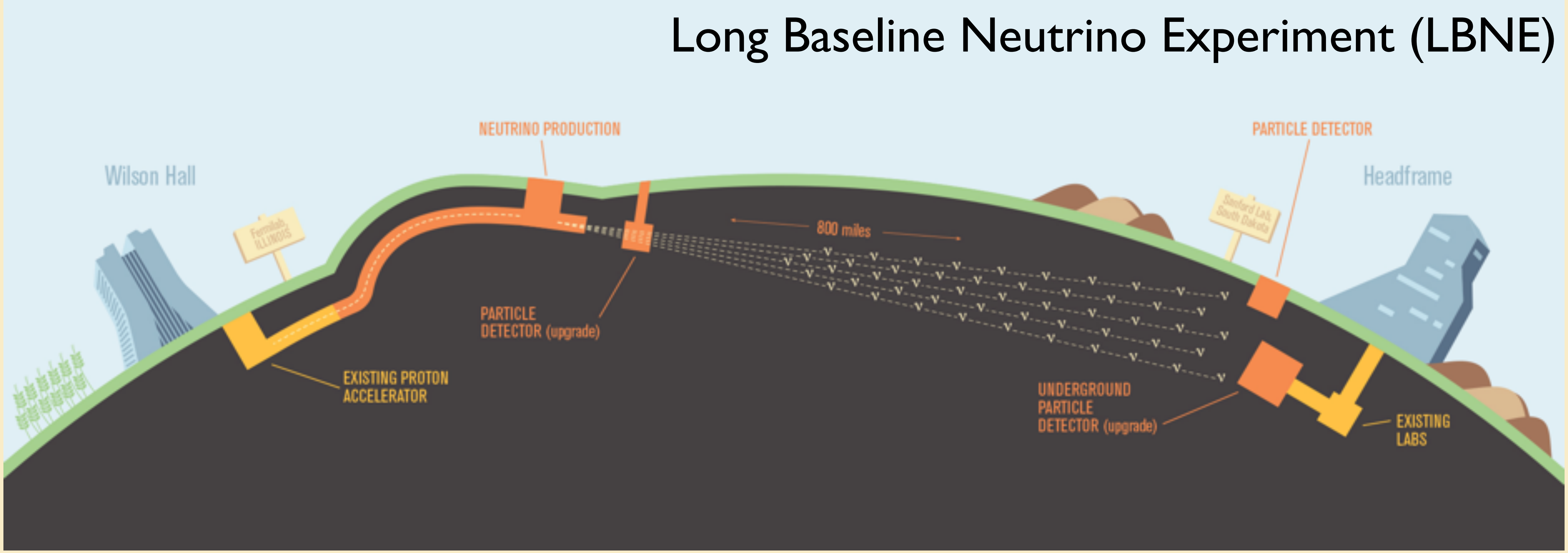


The Energy Frontier

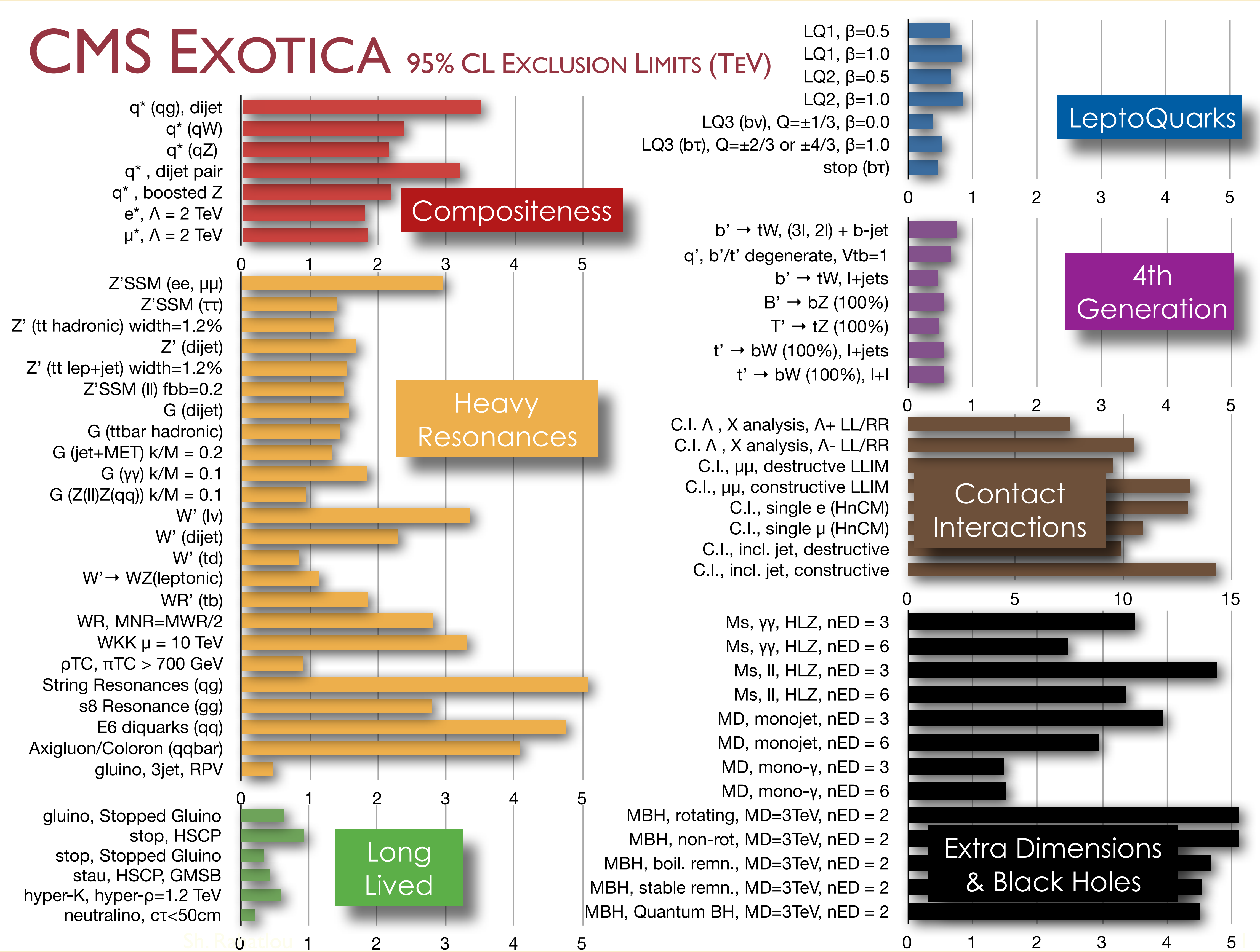


The Intensity Frontier





No obvious new physics, yet



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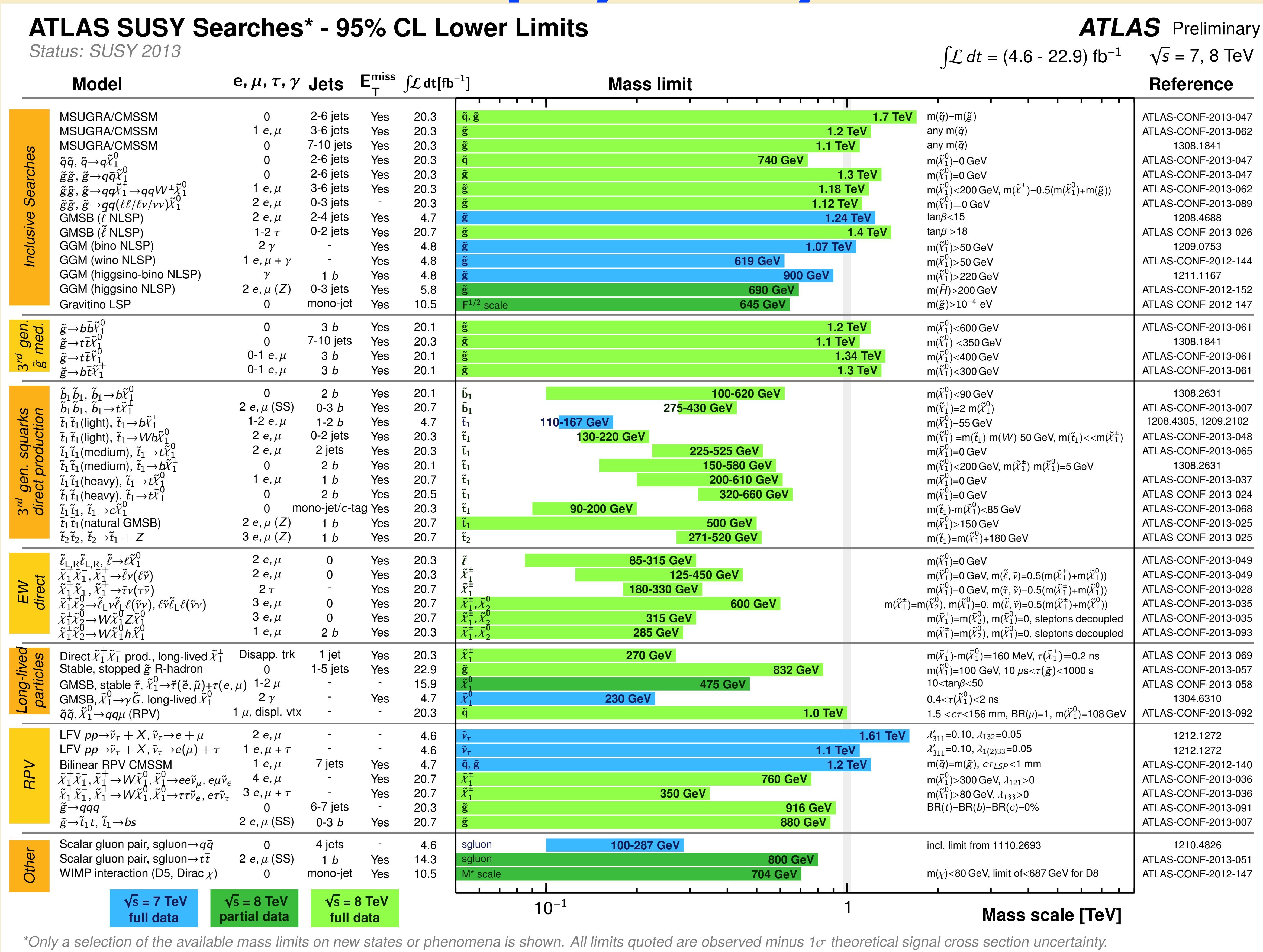


Another way to look for new physics

A “Precision” Frontier

Does particle behavior match Standard Model predictions?

- **o Mass?**
- **o Production rates?**
- **o Decay rates?**
- **o Interactions with other particles or fields (e.g. magnetic moment)**

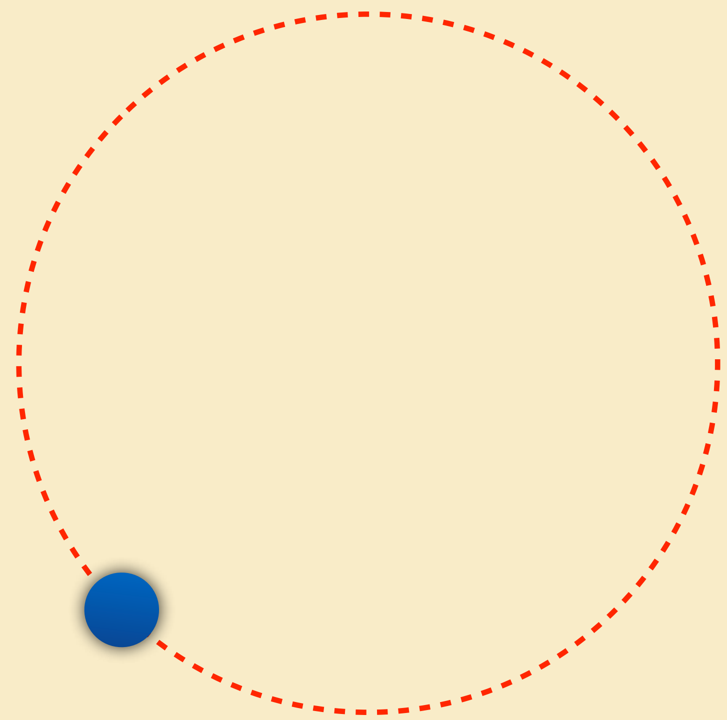
The predictions depend on contributions from particles that we know about

A discrepancy may indicate contributions from particles that we don’t know about (already a hint of something new)

The basics of the "*g-factor*"

Orbiting charged particle:

$$\vec{\mu_L} = \vec{I}A = \frac{q}{2m}\vec{L} \qquad \gamma = \frac{q}{2m}$$



Particle with spin has an *intrinsic* magnetic moment:

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

Classical system: *g* = 1

For the electron: *g* = 2 was known from Stern-Gerlach and spectroscopy experiments

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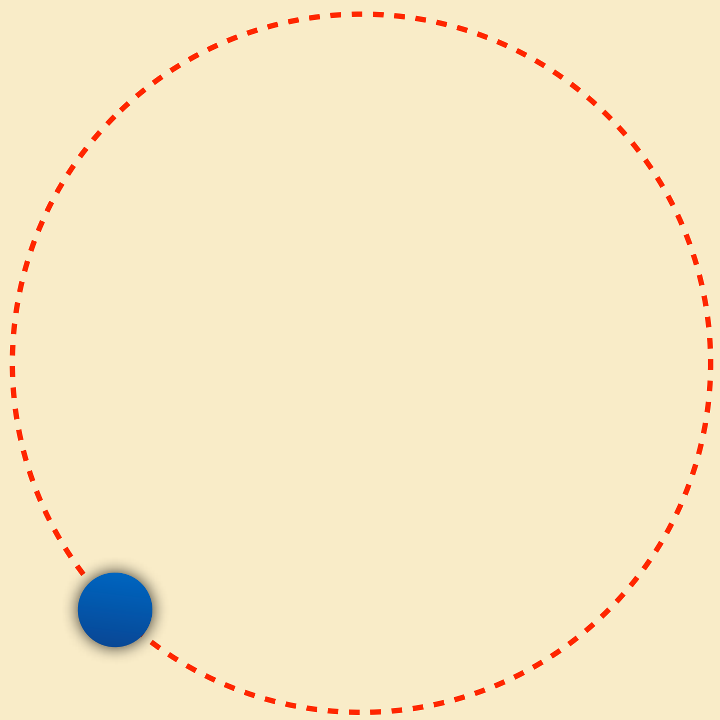

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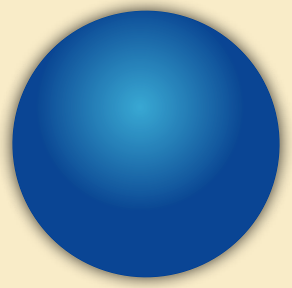

$$\vec{\mu_S} = g\frac{q}{2m}\vec{S}$$

Classical system: *g* = 1

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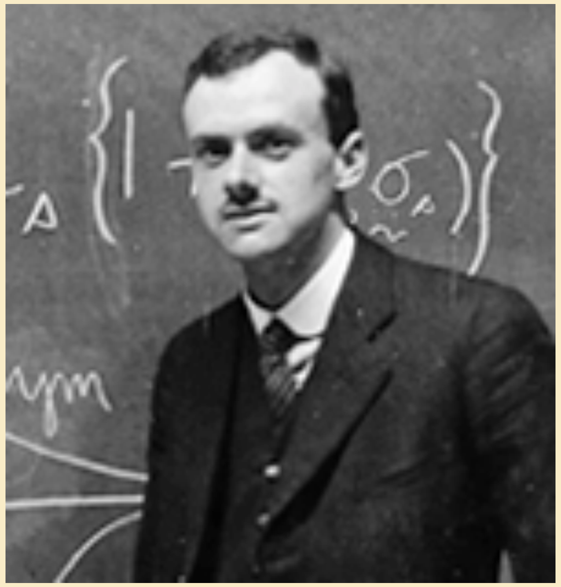
Why does g = 2?

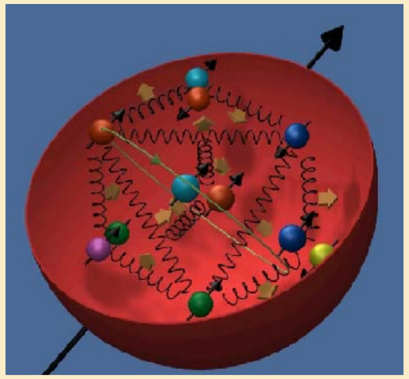
Predicted theoretically by Dirac in 1928


Paul Dirac

$$\left(\gamma^\nu (p_\nu - \frac{e}{c} A_\nu) - mc\right)\psi = 0$$

$$i\frac{\partial \psi}{\partial t} = \left[\frac{1}{2m}(\vec{p} - e\vec{A})^2 - 2\frac{e}{2m}\vec{S}\cdot\vec{B}\right]\psi$$

Aside: In 1933, measured for proton *g* = 5.6,
neutron (by measuring deuteron) *g* = – 3.8
Protons and Neutrons are not like Electrons!



For the <u>electron</u>, *g* remained = 2 for twenty years

QED corrections push g

But, there's more to this story ...

1948 - Kusch and Foley measure $g_e > 2$ by 0.12% in spectroscopy

Henry Foley

Polykarp Kusch

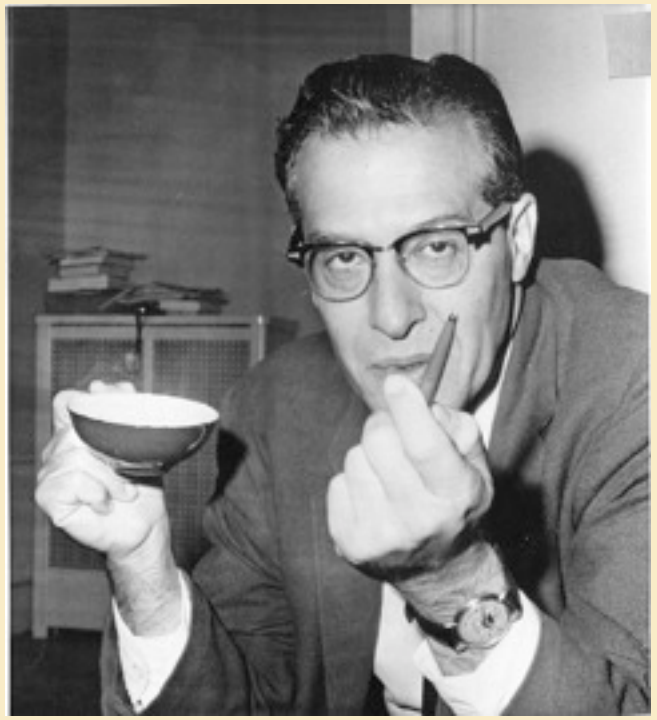
$$g_e = 2.00238(10)$$

An <u>anomalous</u> magnetic moment

$$a = \frac{g-2}{2} \qquad a_e = 0.00119(5)$$

Soon after, Schwinger calculates first order QED correction

$$a_e = \alpha/2\pi = 0.00118$$

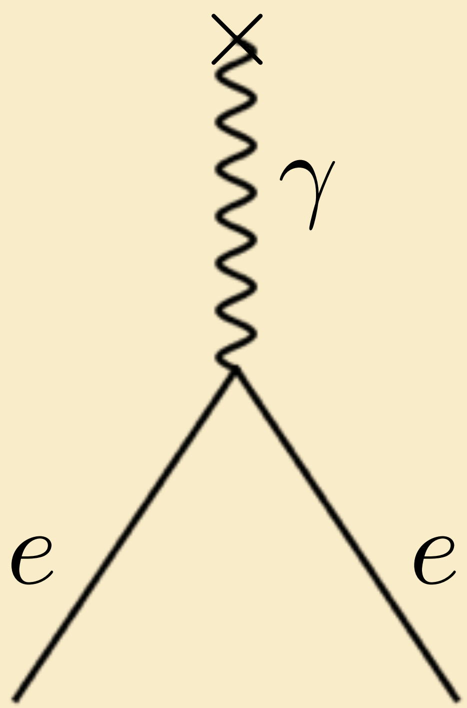


Julian Schwinger
"His laboratory is his ballpoint pen"

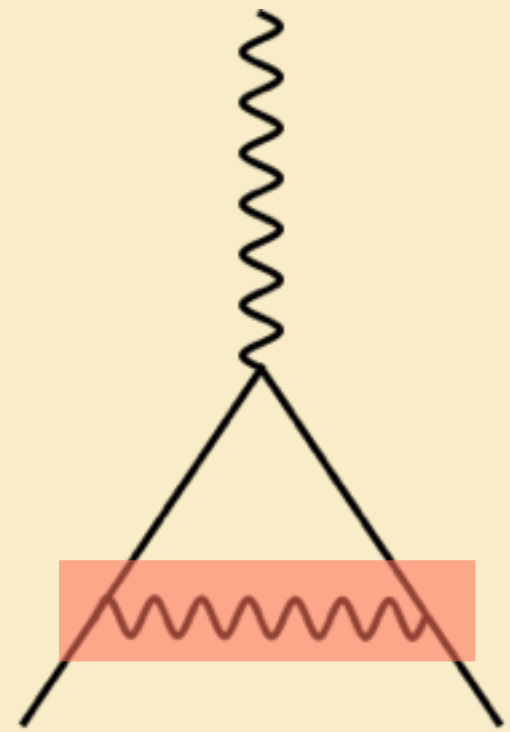
A new understanding begins

Empty space is not empty

$g_e =$



$+$



$+ \cdots$

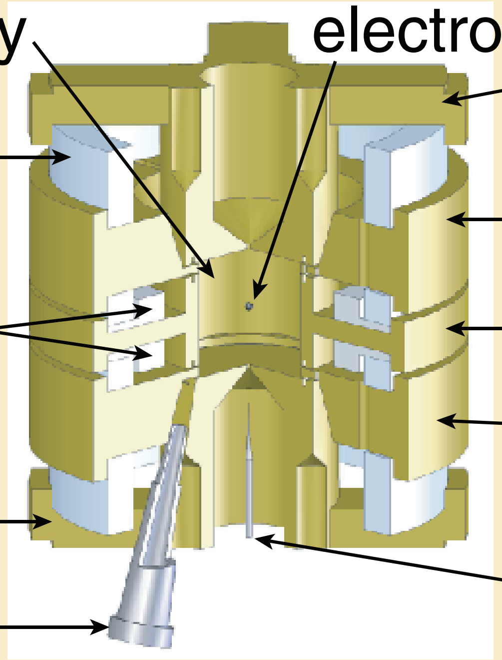
$$2 + 0.00236 + \cdots$$

The beginnings of QED and the Standard Model

Currently, a_e is known to sub-ppb

Gabrielse (2006 & 2008):

Previous result was 20 years prior



$$a_e = 1159652180.73(28) \times 10^{-12} \quad 0.3 \text{ ppb}$$

Hanneke et al., PRL100 (2008) 120801

Agrees with SM. So are we done?

Beyond electrons are muons

Weak and hadronic corrections to a_e are tiny

$1.628(20) \times 10^{-12}$ $0.0297(5) \times 10^{-12}$ **See M.Passera INT2008**

Hadronic correction   **Weak correction**

But for the muon, sensitivity goes as $(m_\mu/m_e)^2 \approx 40,000$

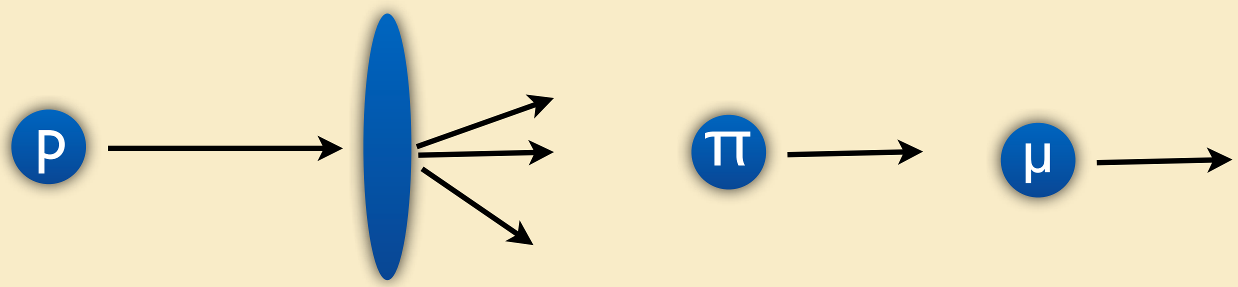
So look at muons!

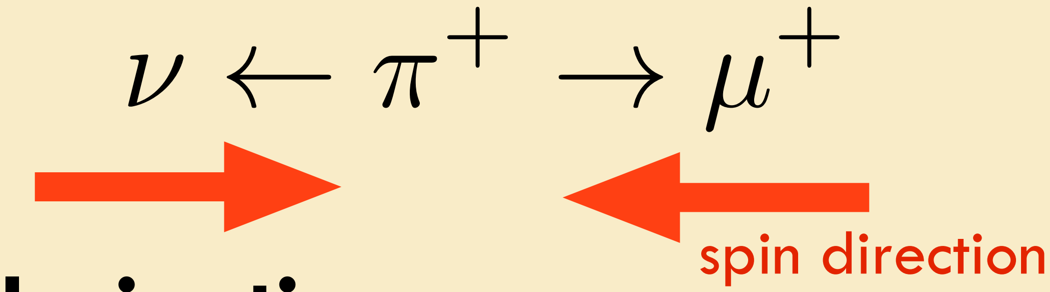
Taus would be even better, but lifetime and production rates are too small to be useful here

Muons are the only particle left for this type of fundamental measurement!

With Muons, we can control spin and measure it

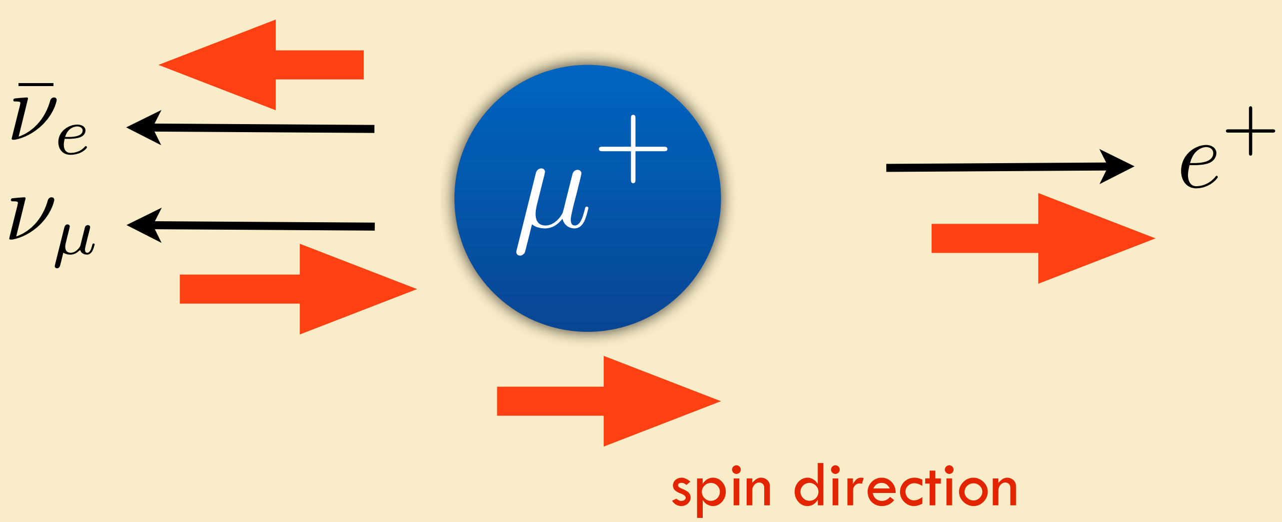
Production: **Muons from** $\pi^+ \to \mu^+ \nu$ **are polarized**





97% polarization

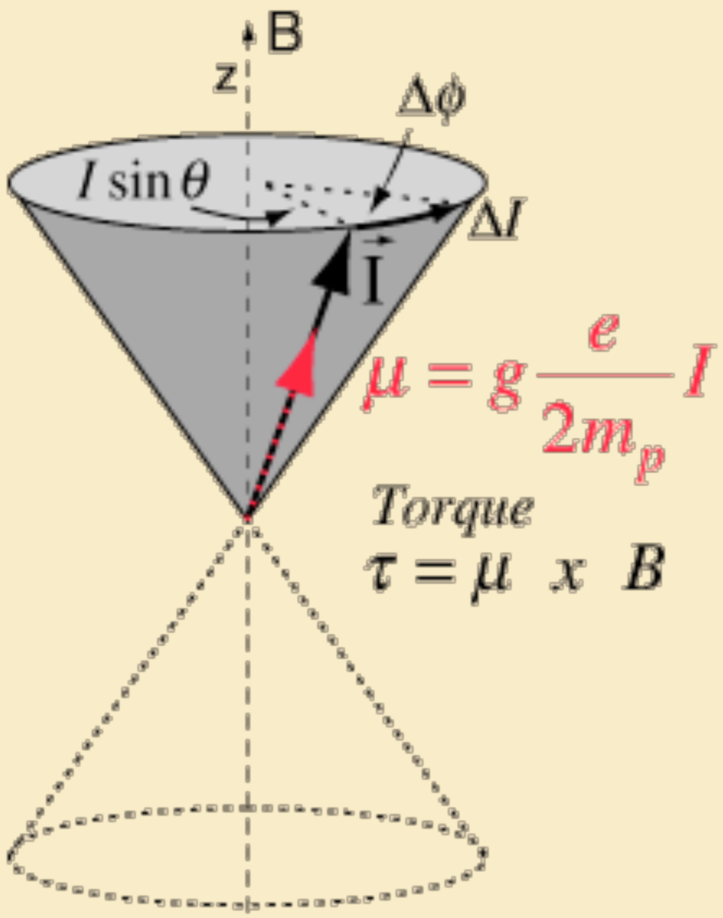
Decay: "Self analyzing" $\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$



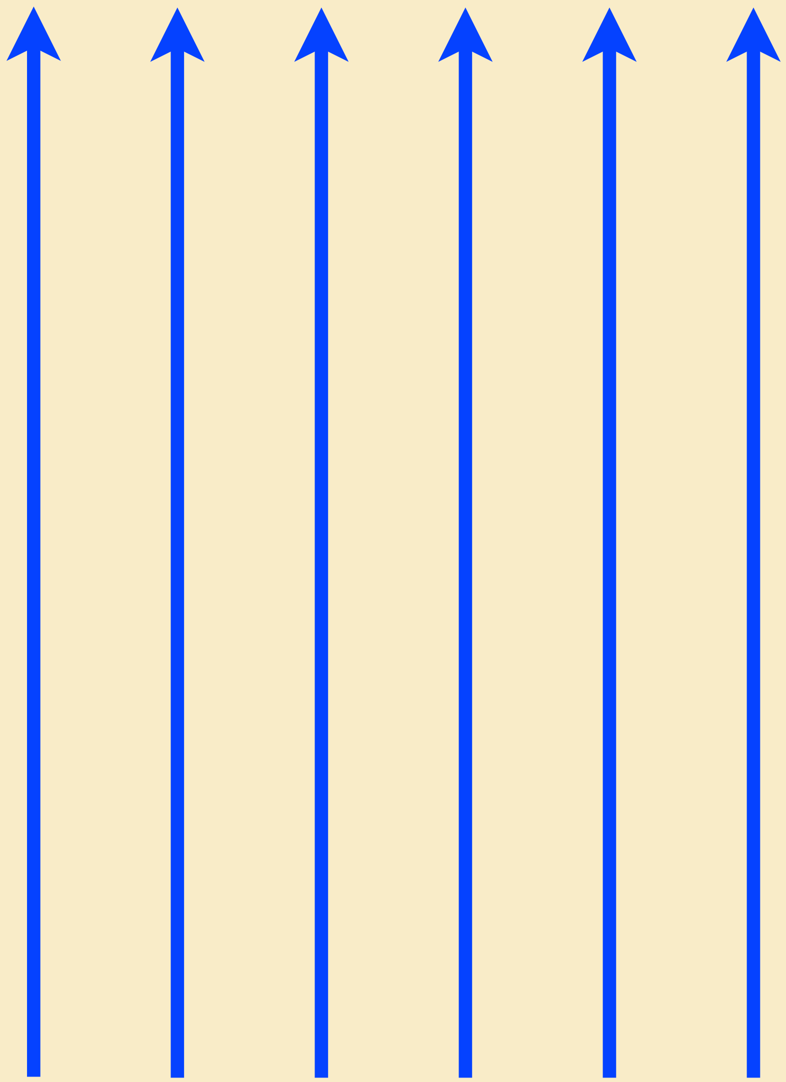
Highest energy positrons emitted along muon's spin direction (in Muon center of mass frame)

How to measure a_μ

Idea: Put polarized muons in a magnetic field and measure Larmor precession



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



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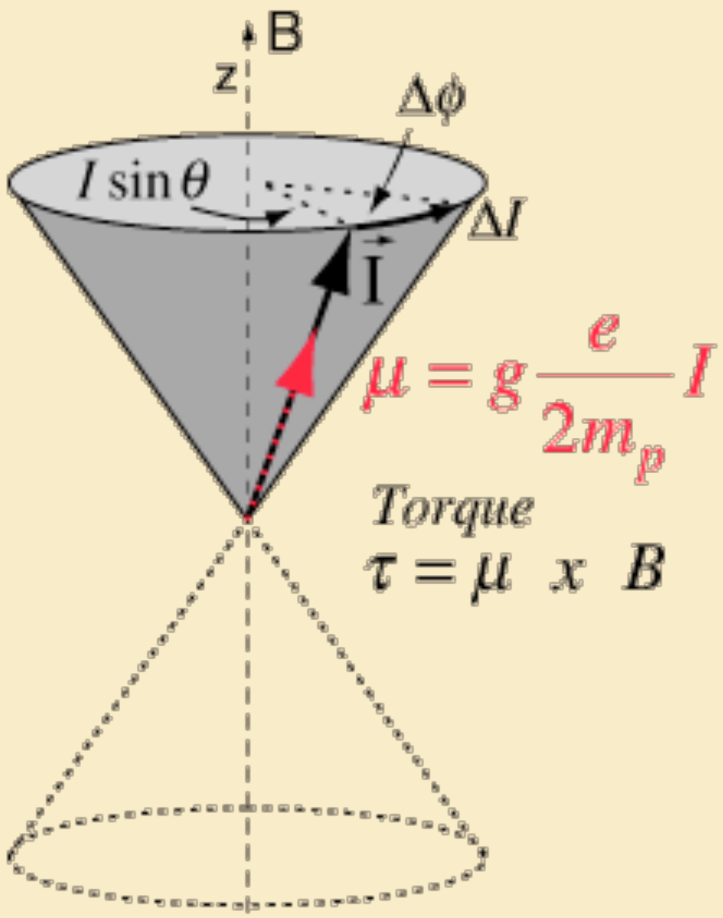

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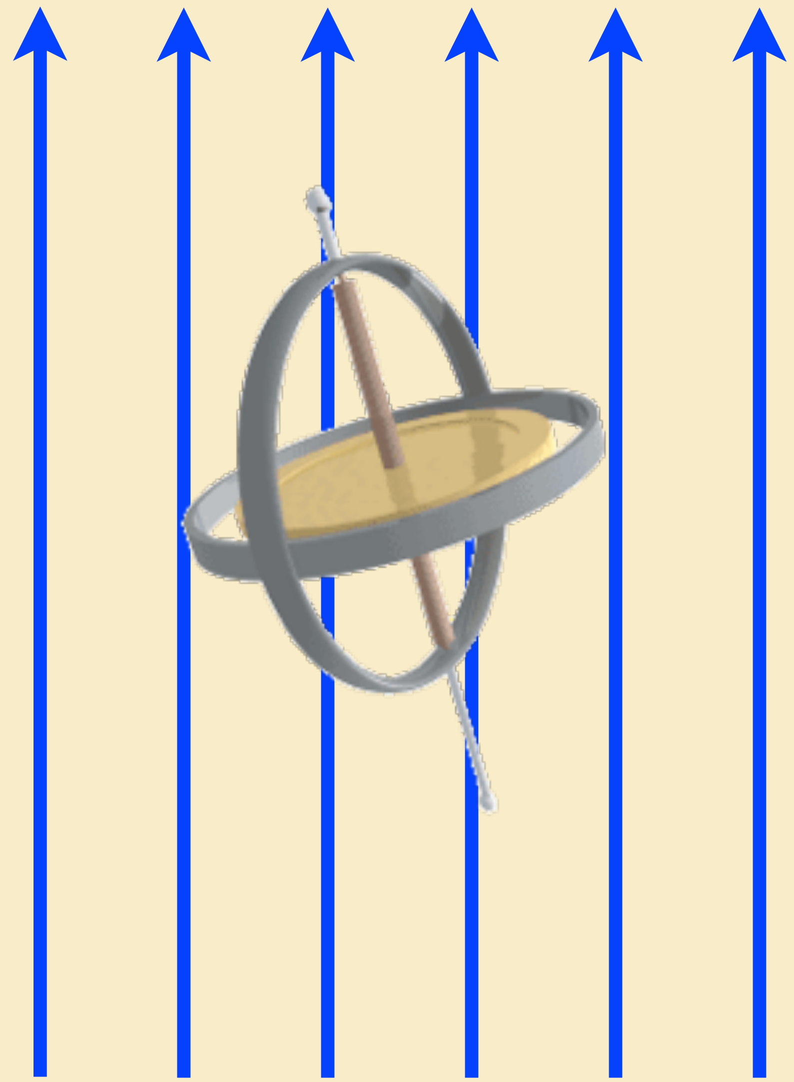
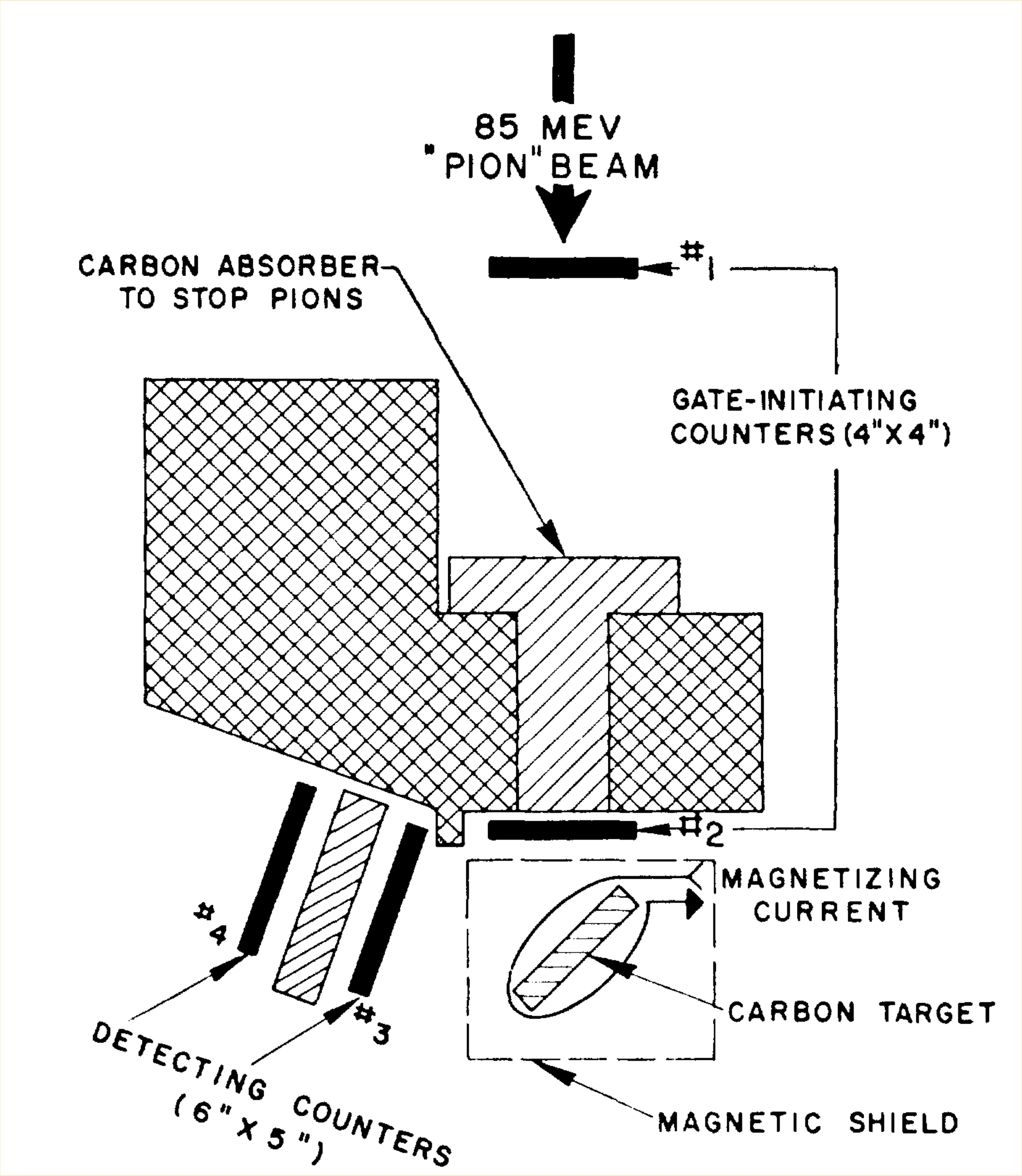
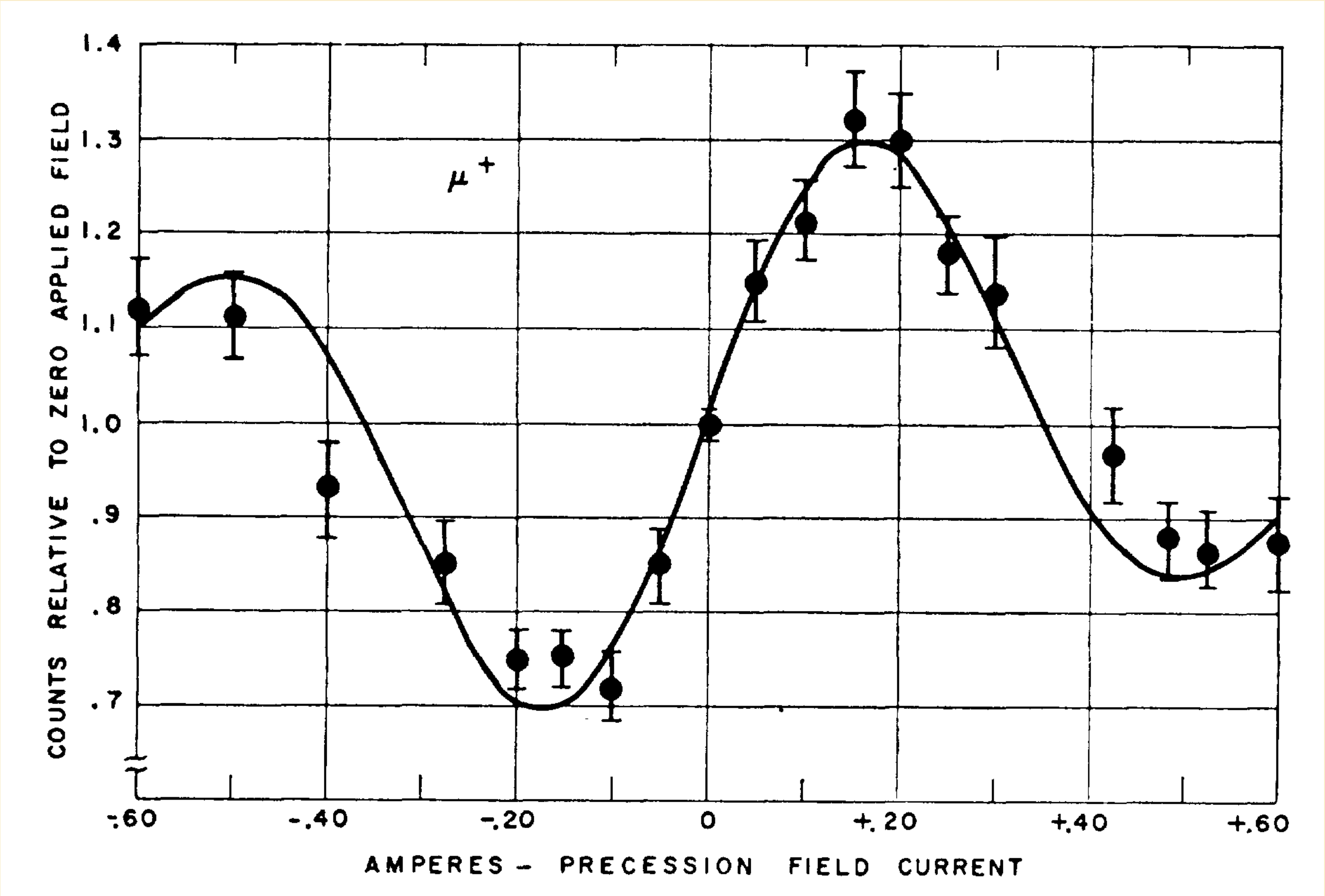


The first experiments for a_μ

1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)



Direct measurement of *g* -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

5% uncertainty

muons behave like electrons

The first experiments for a_μ

Such experiments continued at Nevis and CERN until 1965

Best measurement CERN I (1965)

$$a_\mu = 0.001\,162(5)\ \ (\pm 4300\,\mathrm{ppm})$$

Just like the electron!
Sensitive to 2nd order QED

Time for a new idea...

The first CERN g-2 team: Sens, Charpak, Muller, Farley, Zichichi (CERN/1959)

Storage rings enter the picture

Muon momentum precession rate (cyclotron frequency) for particle in a *B* field

$$\omega_c = \frac{eB}{m_\mu c \gamma}$$

Muon spin precession rate

$$\omega_s = \frac{g_\mu eB}{2m_\mu c} + (1-\gamma)\frac{eB}{m_\mu c\gamma}$$

Larmor precession — Thomas precession

Storage rings enter the picture

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Muon spin precession rate

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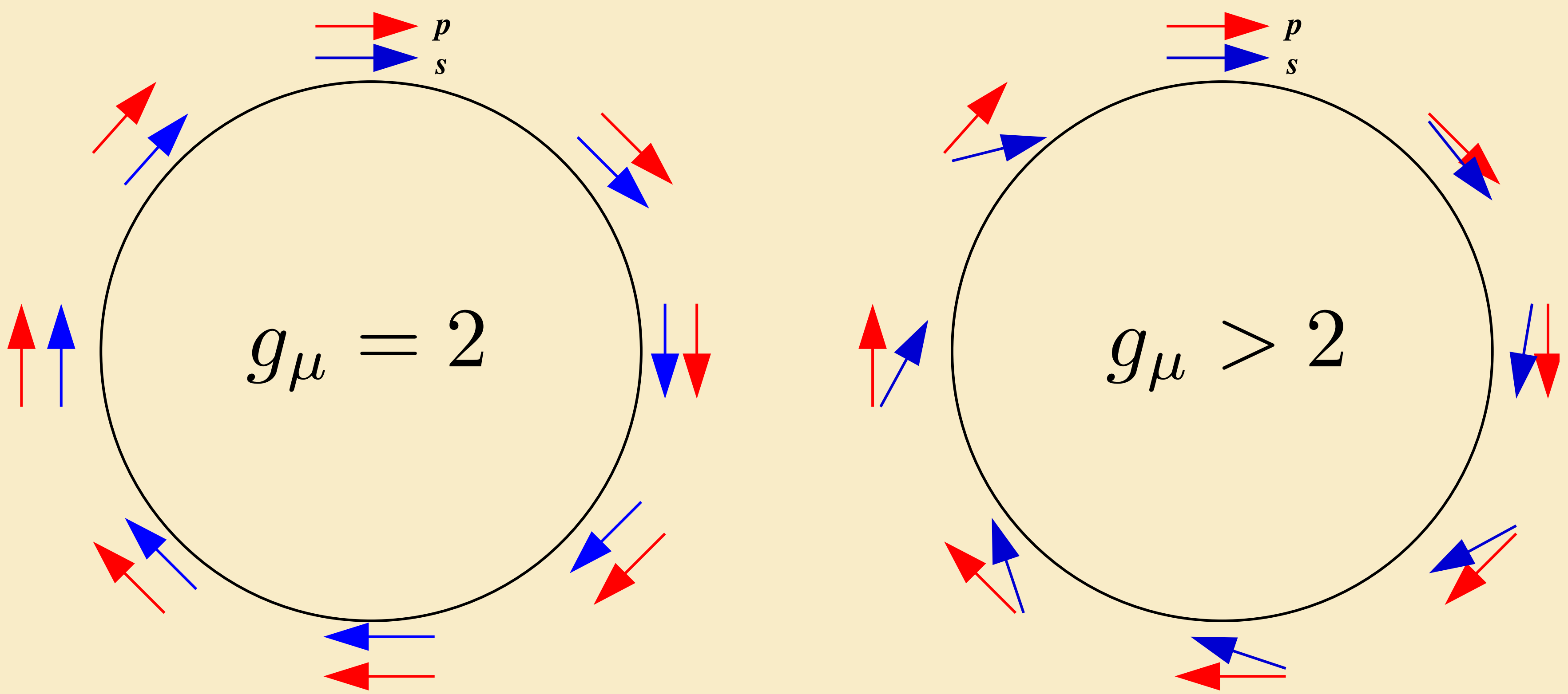
Larmor precession

Thomas precession

Taking their difference...

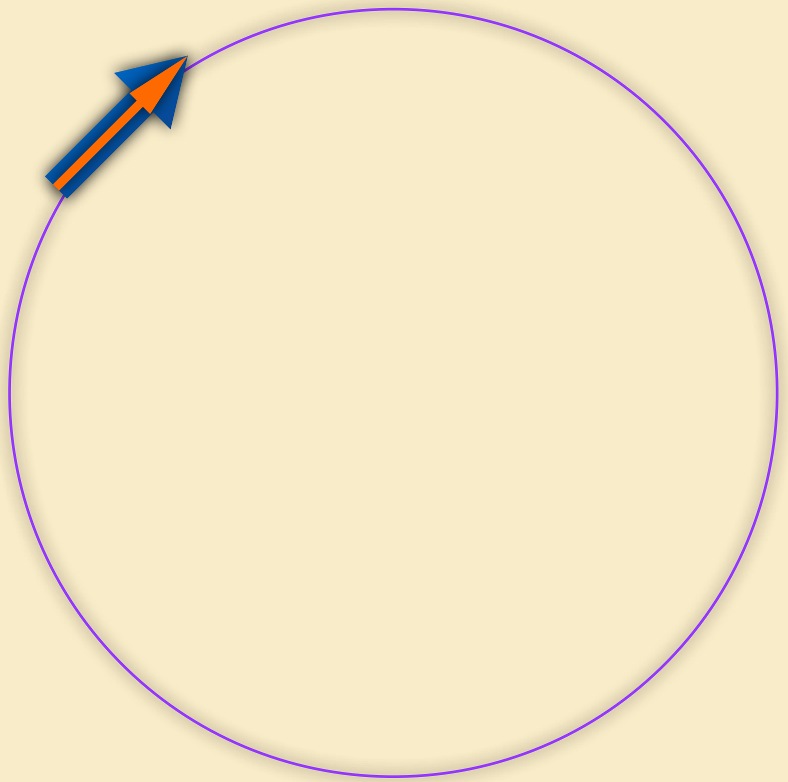
A fortuitous simplification

$$\omega_a = \omega_s - \omega_c = \frac{g_\mu - 2}{2} \frac{eB}{m_\mu c} = a_\mu \frac{eB}{m_\mu c}$$



True for any size ring and any muon momentum

The measurement plan

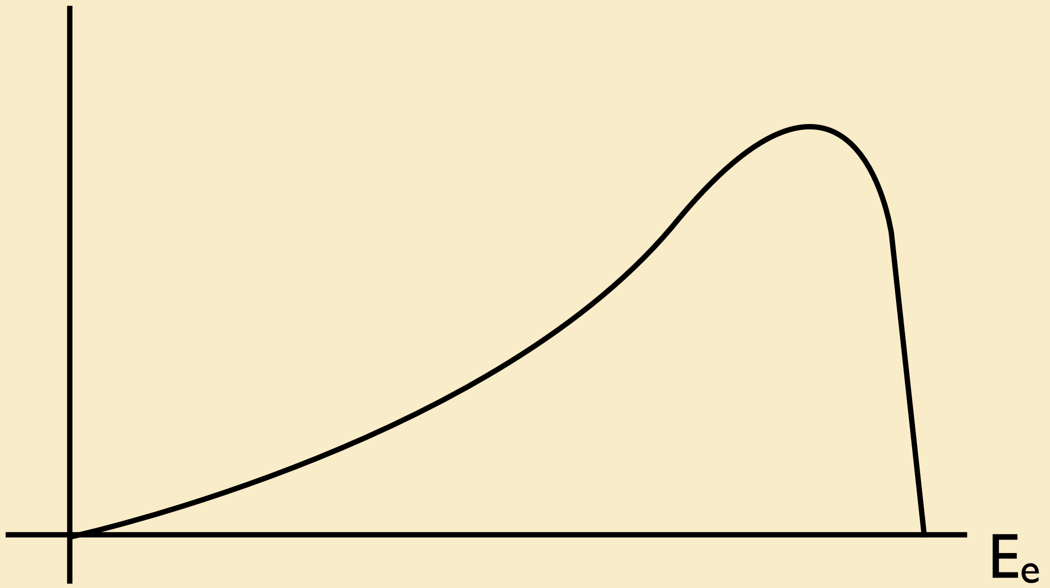


Muons circle the ring and decay to positrons, which travel inward hitting detectors

Remember highest energy positrons are emitted in direction of muon spin

Boost to the lab frame gives *E* a boost

If anomaly exists, maximum *E* oscillates at ω_a



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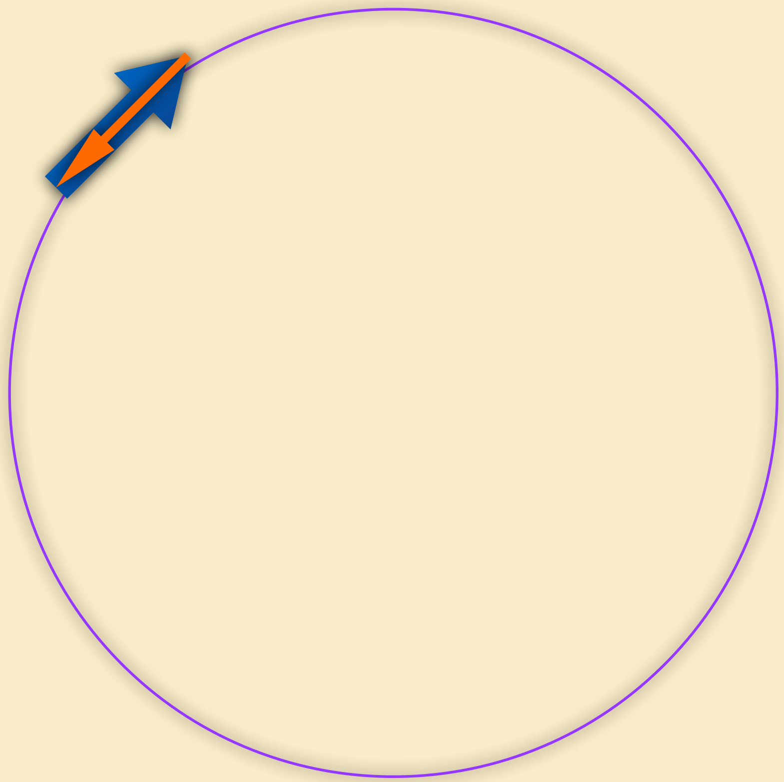

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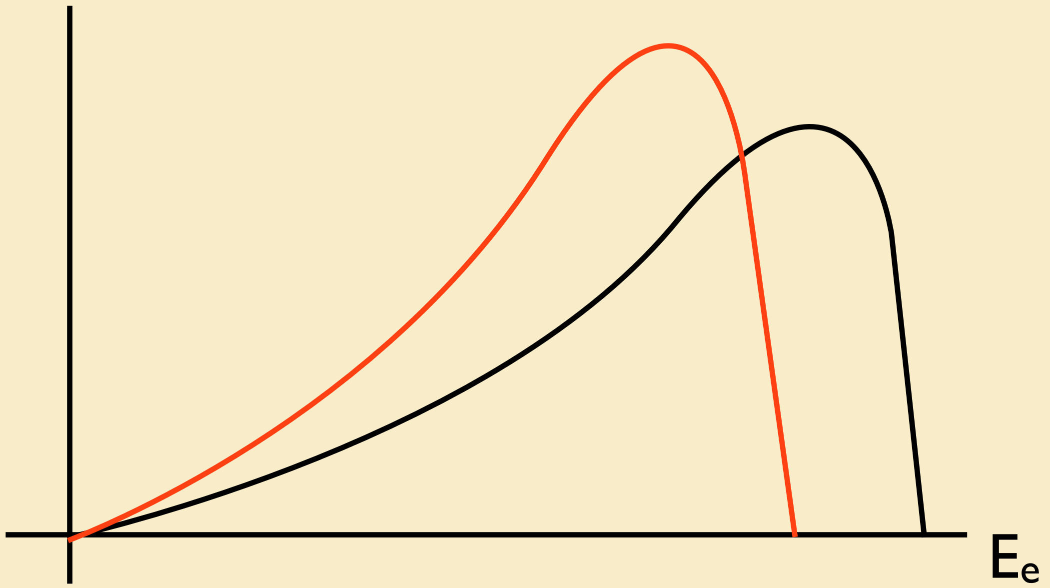

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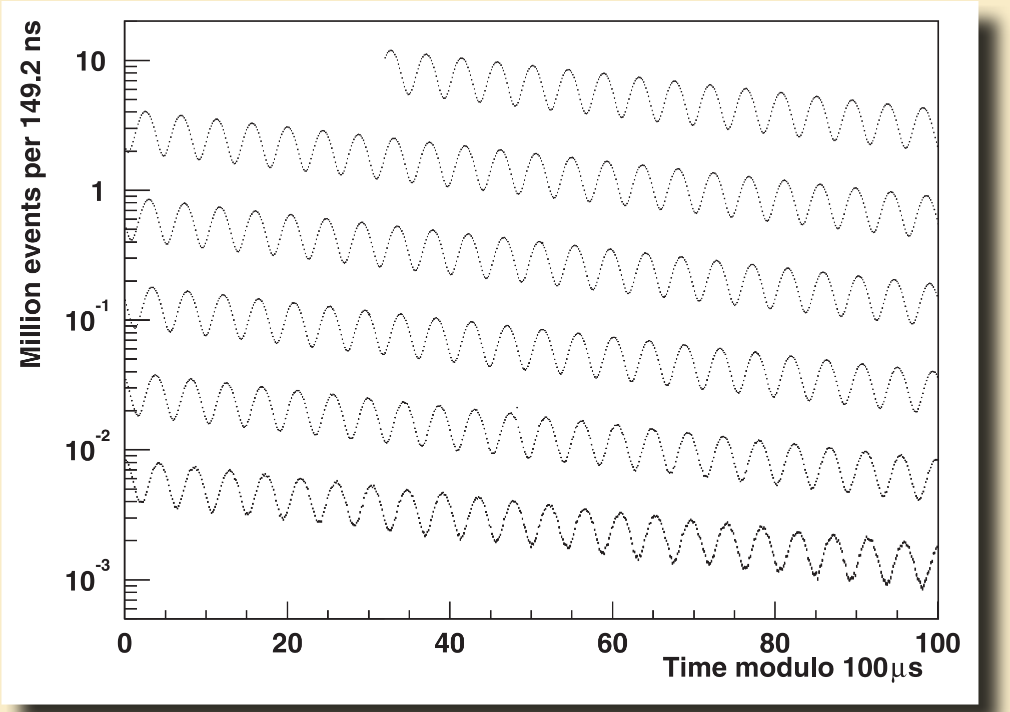
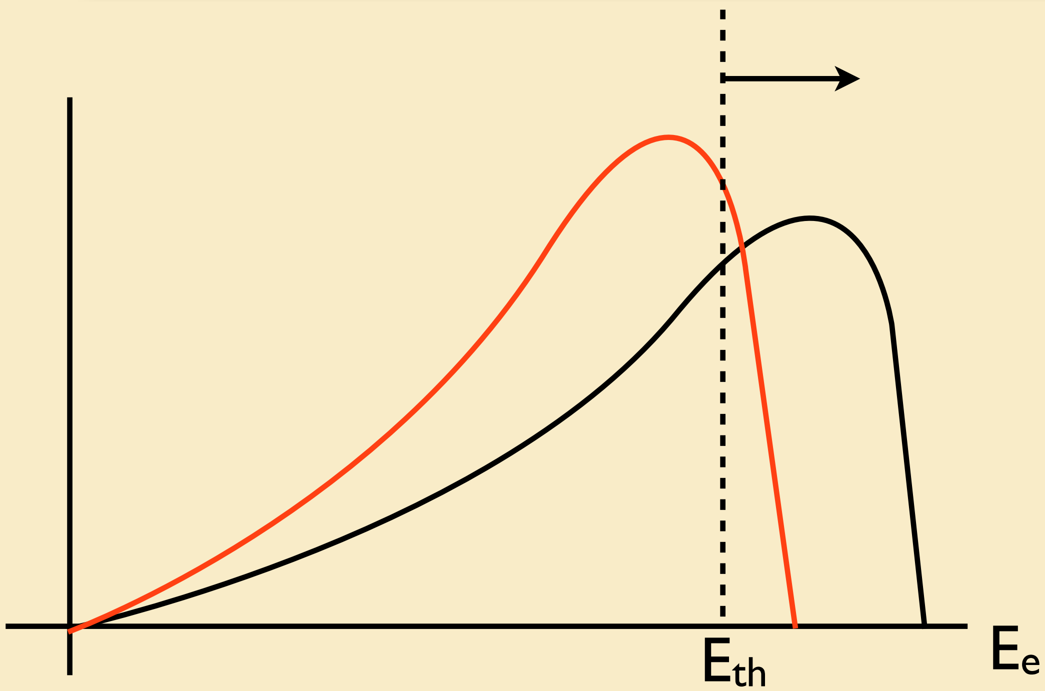
Count above fixed threshold. Oscillation rate $\propto a_\mu$





Thanks to Lawrence Gibbons for cool animation

Improvements for free

$$\omega_a = a_\mu \frac{eB}{m_\mu c}$$

Since $a_\mu \approx g_\mu/800$ measuring ω_a gives x1000 in precision over measuring g

We can avoid the uncertainty in muon charge to mass ratio by,

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}} \qquad \mathcal{R} = \omega_a/\omega_p,\ \lambda = \mu_\mu/\mu_p$$

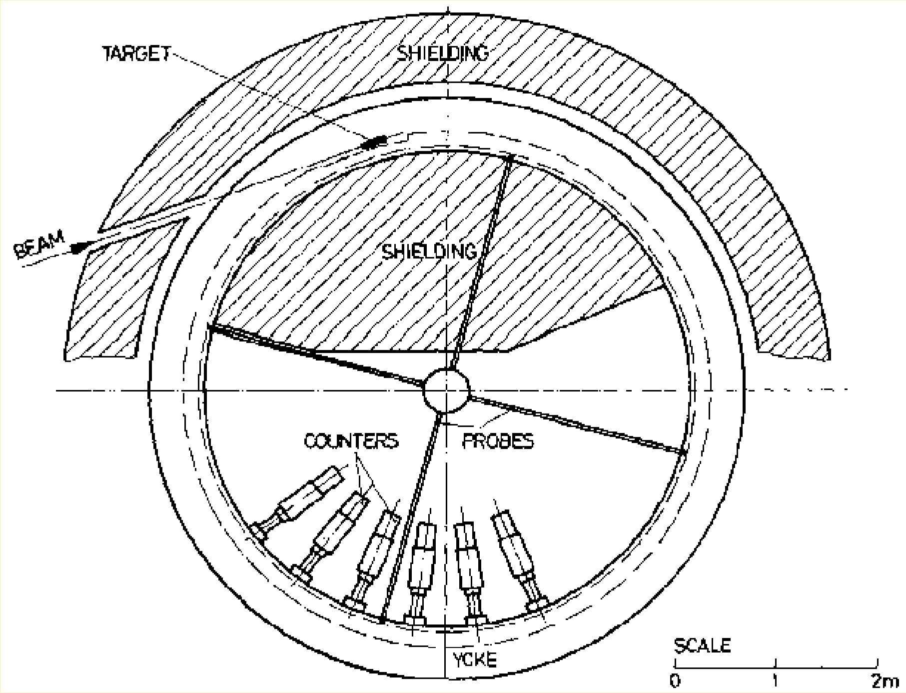
ω_p **is proton Larmor precession (can measure with NMR) is essentially the magnetic field**

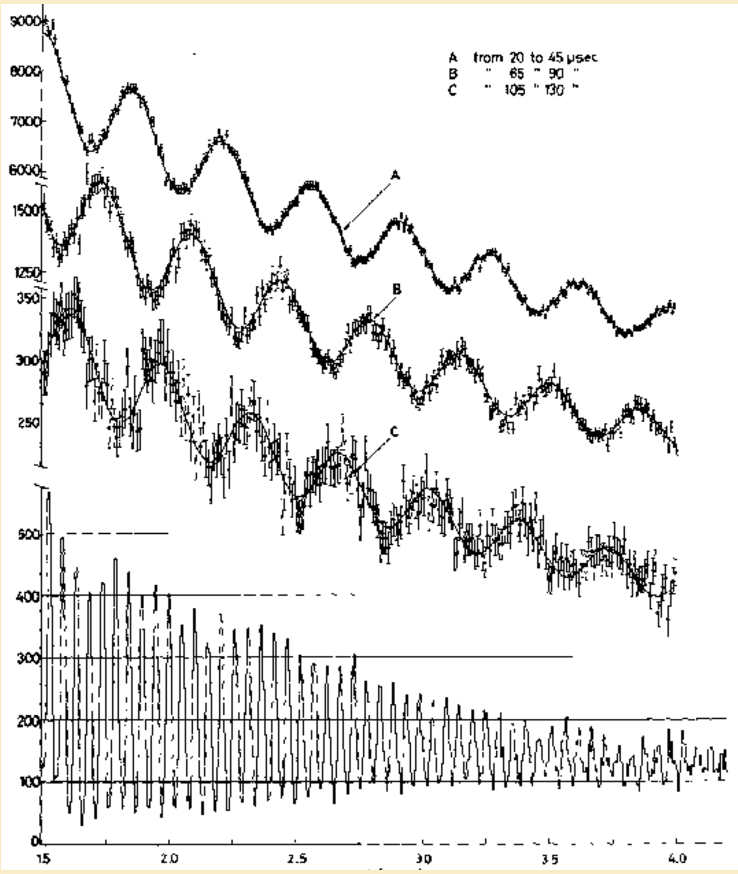
λ **is muon to proton magnetic moment ratio. Get from hyperfine muonium structure (Liu) 26 ppb**

Second CERN experiment results (1968)

$$p_\pi = 1.27\ \mathrm{GeV}/c$$
$$B = 1.7\ \mathrm{T}$$

Electrons go inward to detectors





130 μs of wiggles

$$a_\mu = 0.001\,166\,16(31),\ \pm 270\ \mathrm{ppm}$$

Sensitive to 3rd order QED and light-by-light scattering

A miracle happens here

How to keep the muons vertically confined?
2nd CERN used radial variation in *B* field (big systematic)

Use electrostatic quadrupoles - but adds complications

$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

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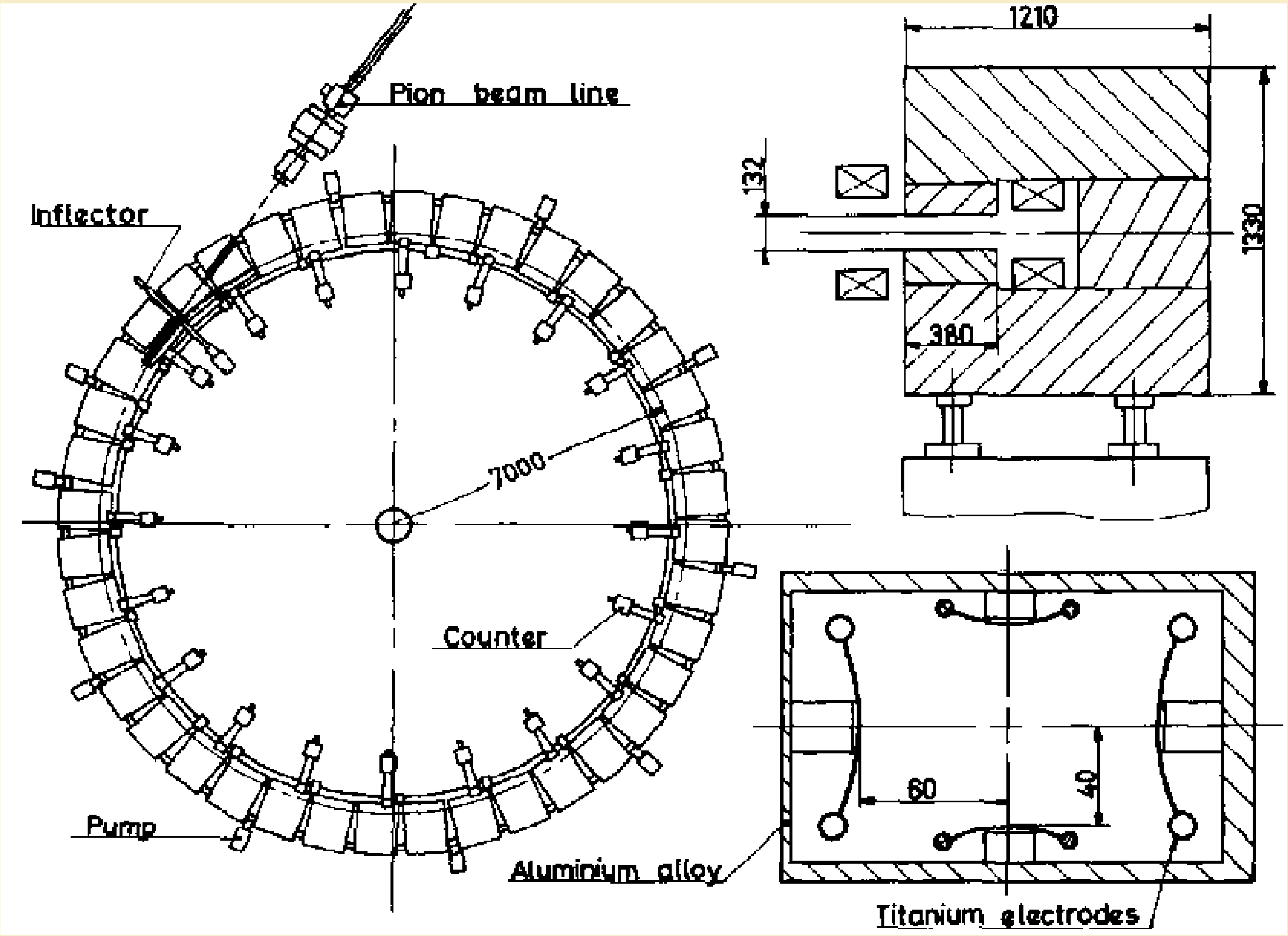
$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

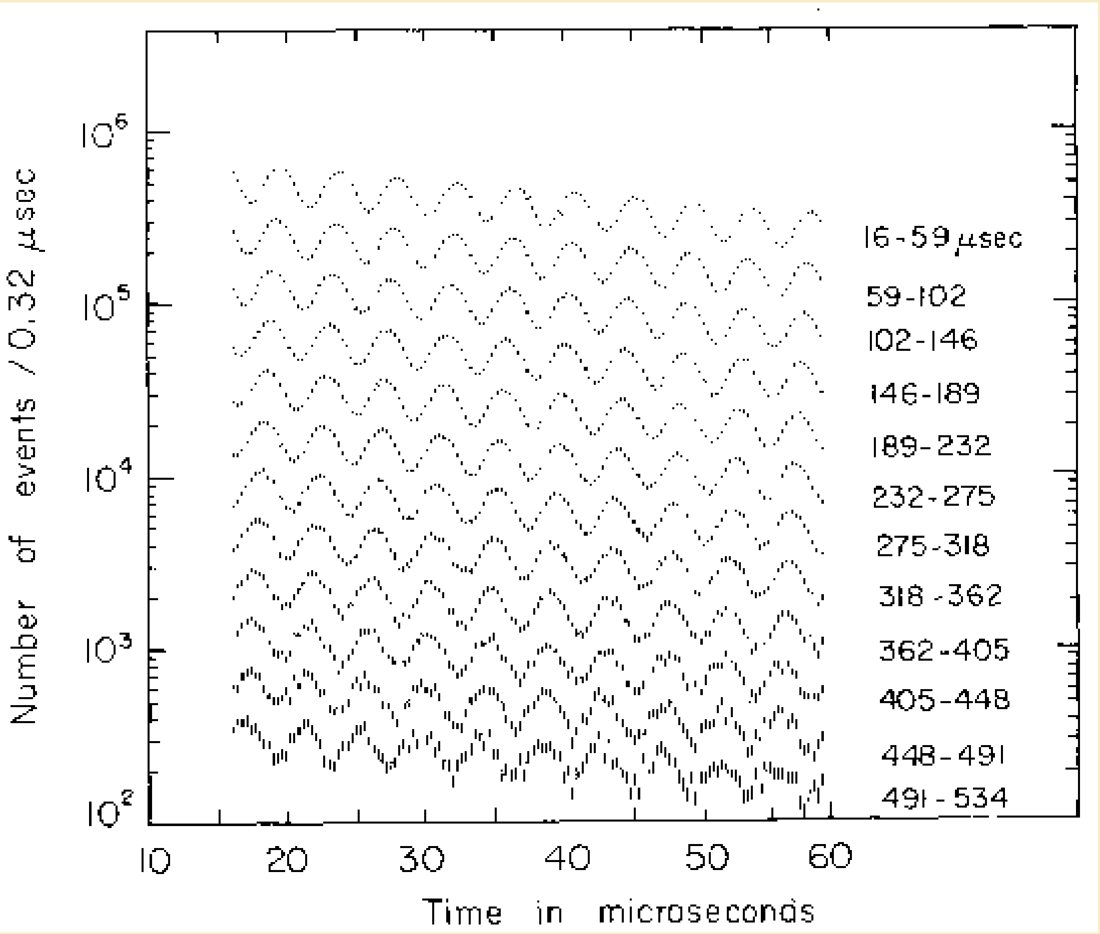
If we choose $\gamma = 29.3 \;\; (p_\mu = 3.09 \text{ GeV}/c)$
then coefficient vanishes! The MAGIC momentum!

So we can worry less about the electric field (but still will need corrections)
Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

Third CERN Experiment (1969-79)

Muon lifetime dilates to 64 μs (nice!)





> 500 μs

$$a_\mu = 0.001\,165\,924(8.5),\ \pm 7\ \text{ppm}$$

Sensitive to hadronic vacuum polarization (adv. muons!)

Large systematic due to field at magnet edges

Setting the stage for Brookhaven E821

In 1984, QED was calculated to fourth order

Hadronic uncertainties were greatly reduced

Time for new experiment at Brookhaven at the AGS at sub ppm

Figure 1.10: A picture from 1984 showing the attendees of the first collaboration meeting to develop the BNL g-2 experiment. Standing from left: Gordon Danby, John Field, Francis Farley, Emilio Picasso, and Frank Krienen. Kneeling from left: John Bailey, Vernon Hughes and Fred Combley.

Improvements:

Much higher intensity

3 superconducting coils

Inject muons into ring with inflector and kicker

***in-situ B* measurements with NMR probes**

15 years until first pub in 1999

Brookhaven E821 g-2 Experiment

Steps of the experiment for measuring a_μ

Inject muons into the storage ring

Measure ω_a and determine corrections

Measure ω_p

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}}$$

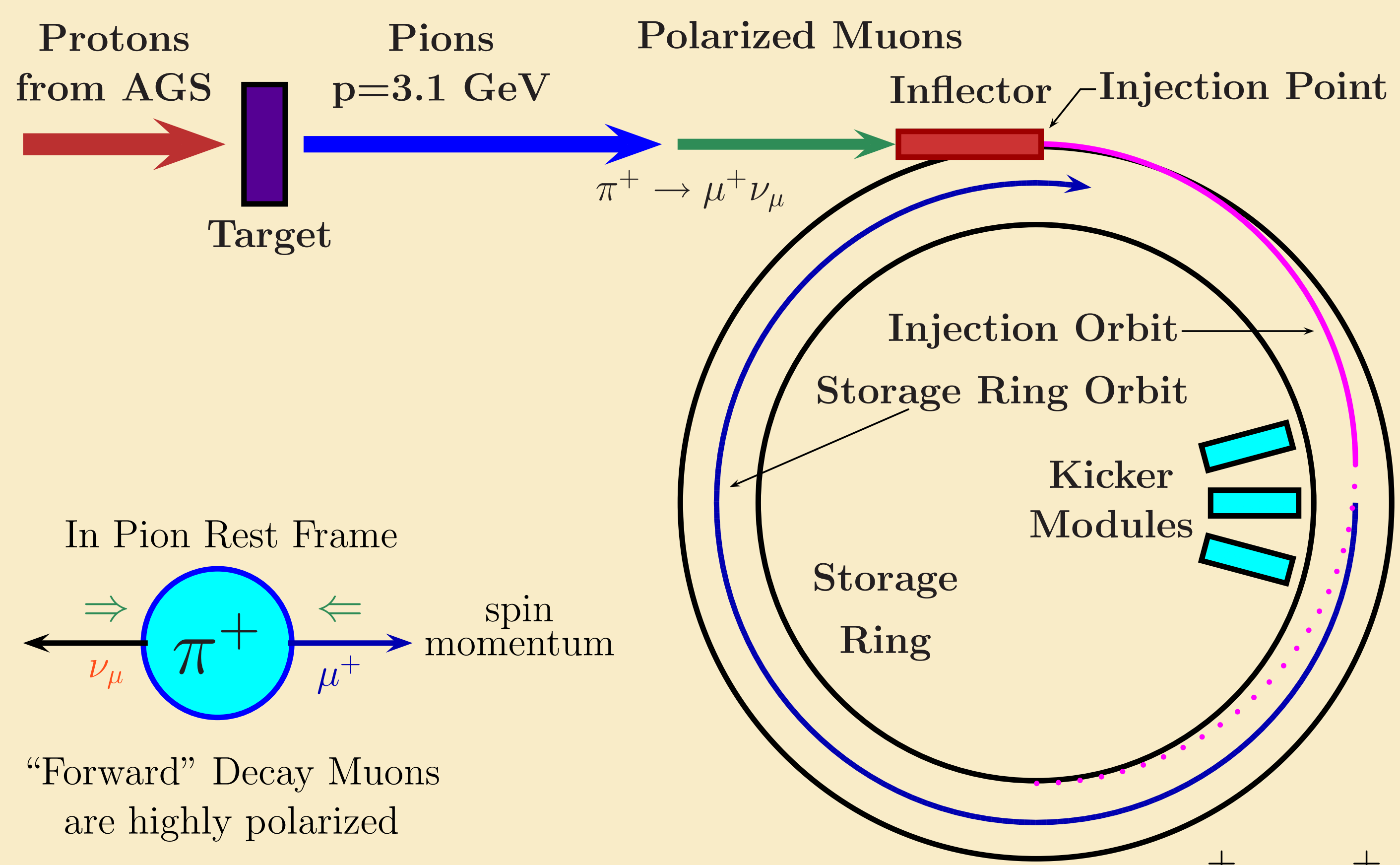
Get λ from friends

$$\mathcal{R} = \omega_a/\omega_p, \ \lambda = \mu_\mu/\mu_p$$

Determine systematics

Think about the next experiment

Experiment in cartoons



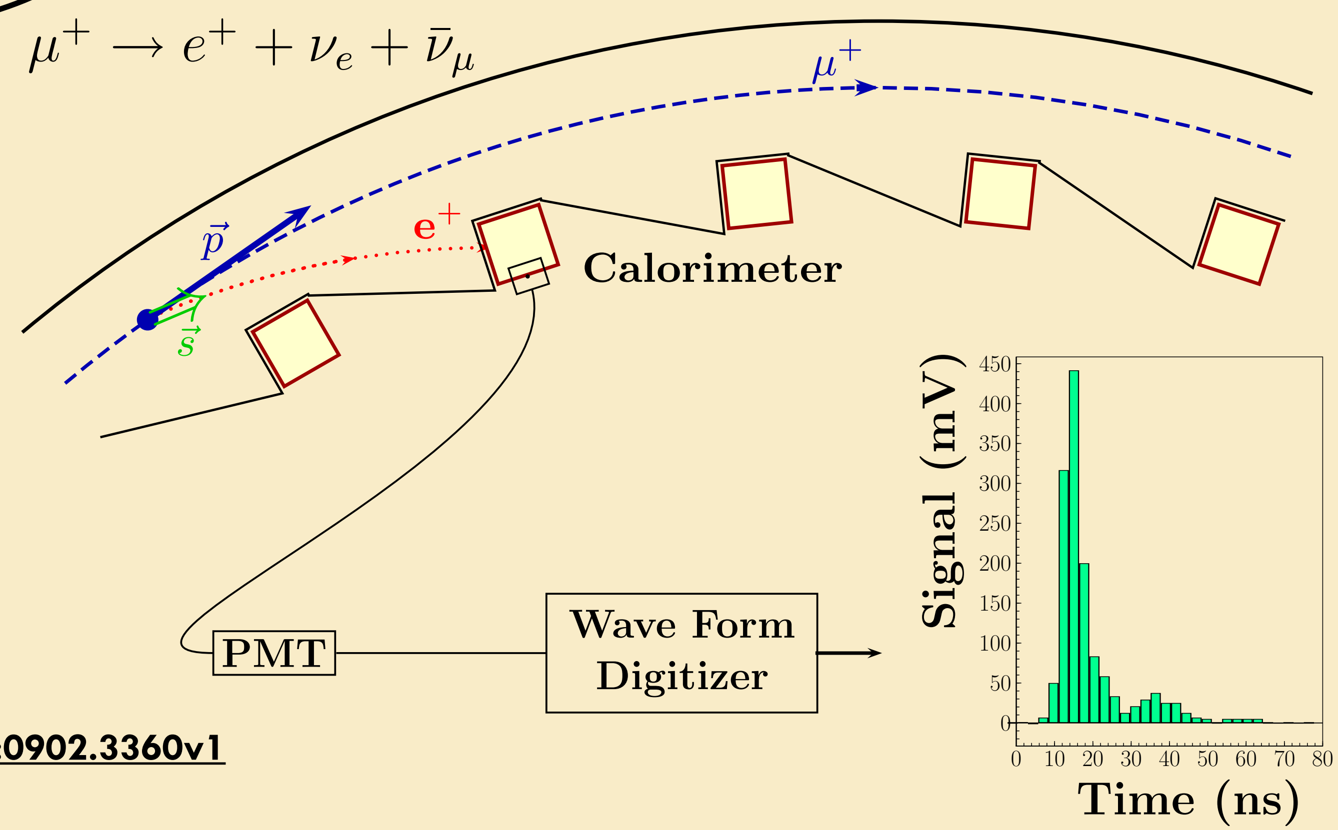
3 data runs (# e^+'s)

1999 (950M),

2000 (4000M),

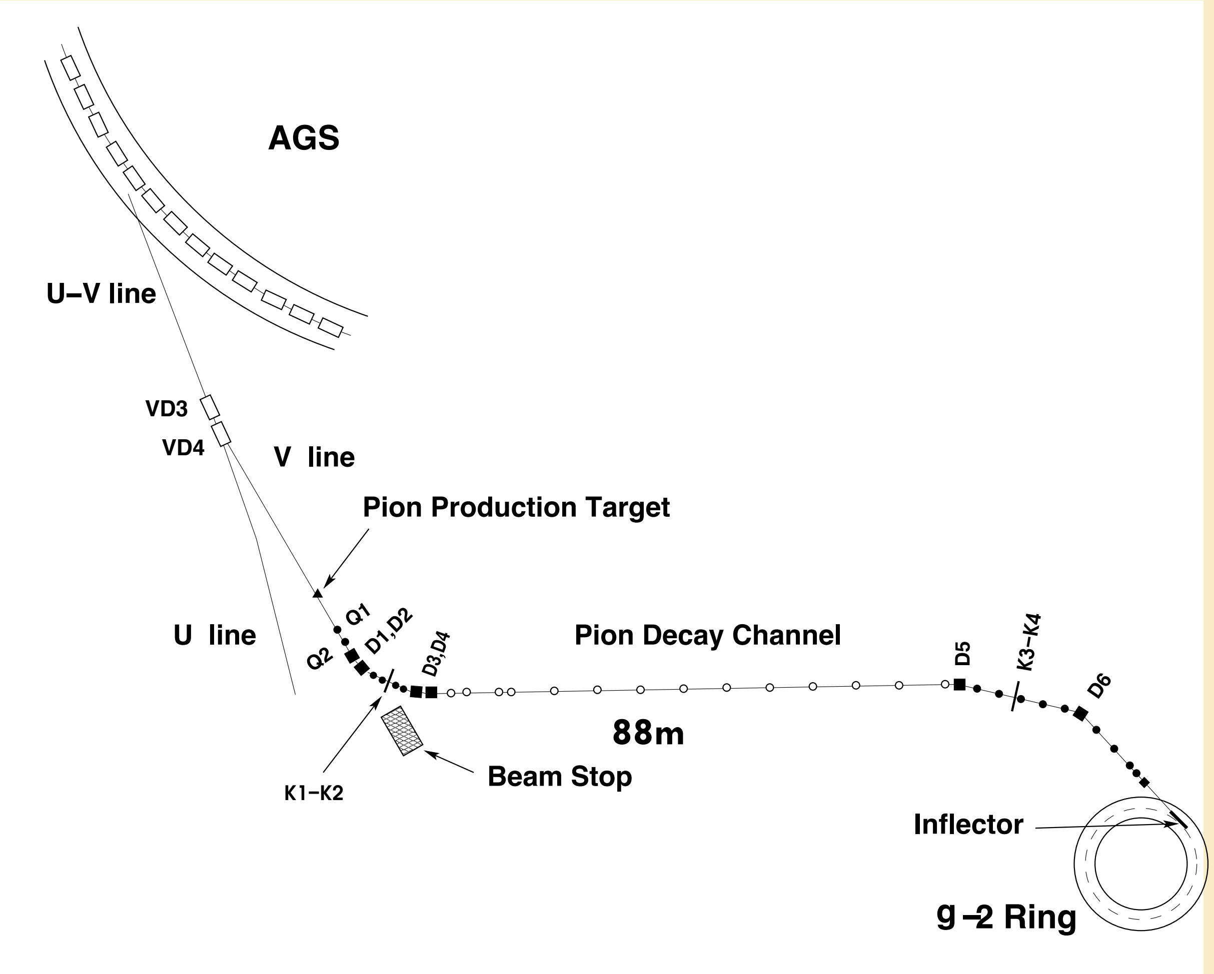
2001 (3600M e^-)

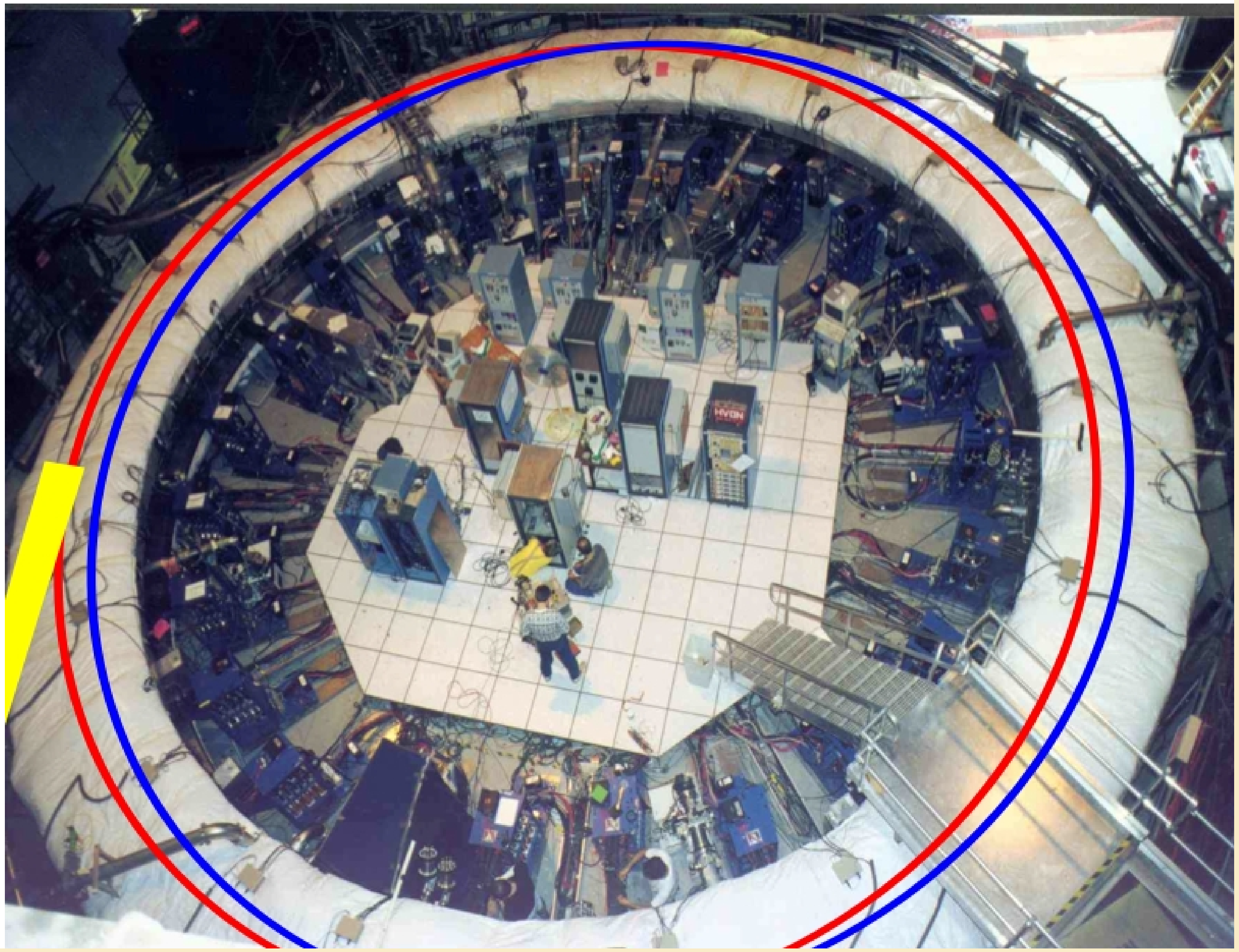
8550M events total

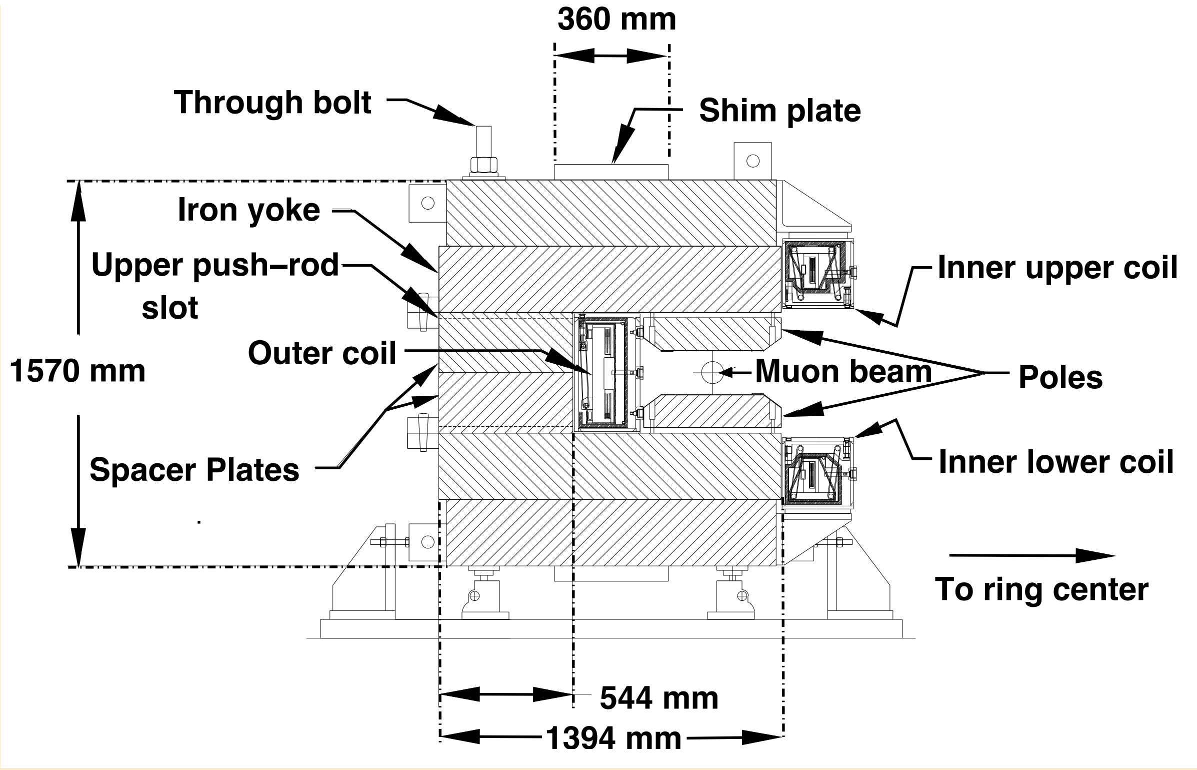


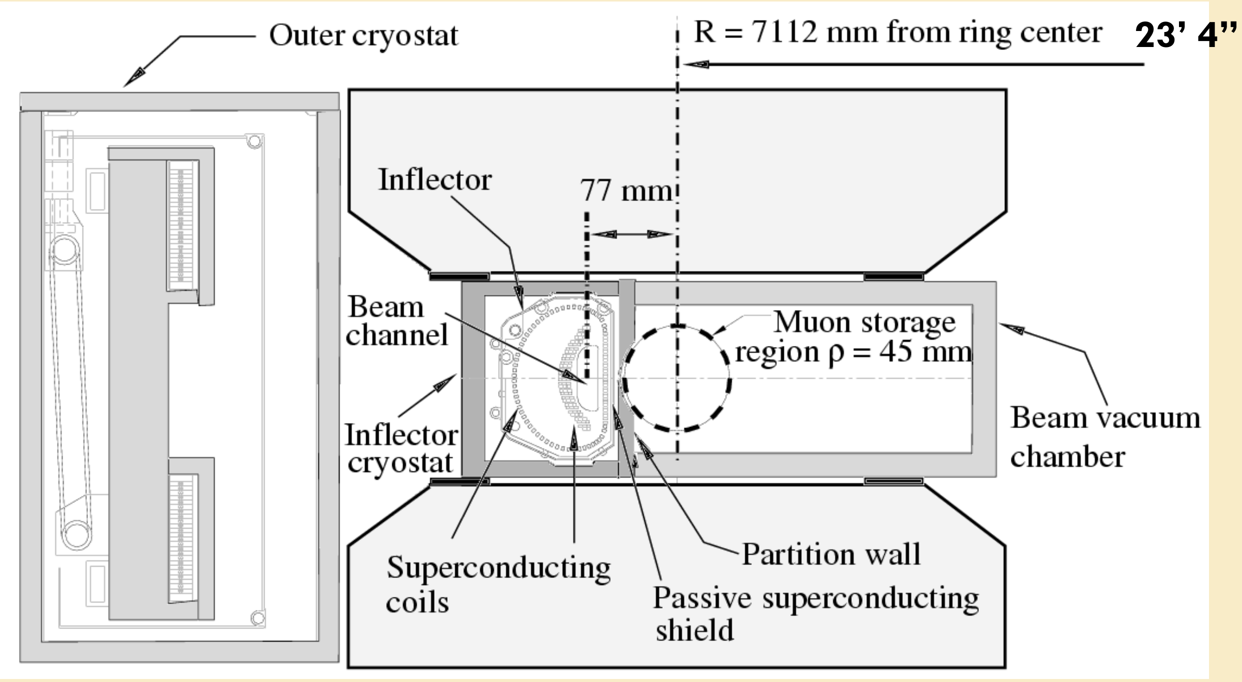
Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, arXiv:0902.3360v1

Injection into the storage ring

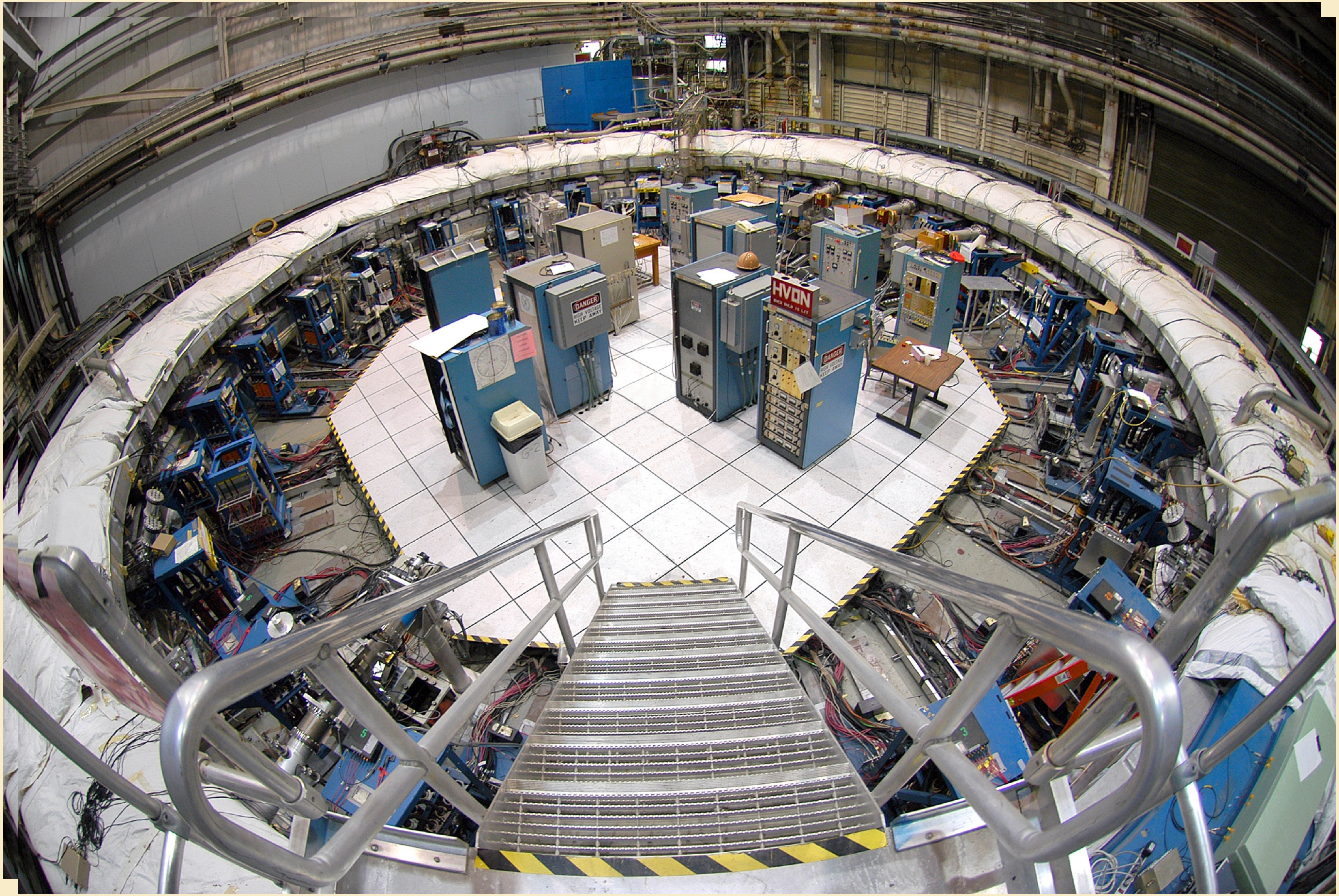




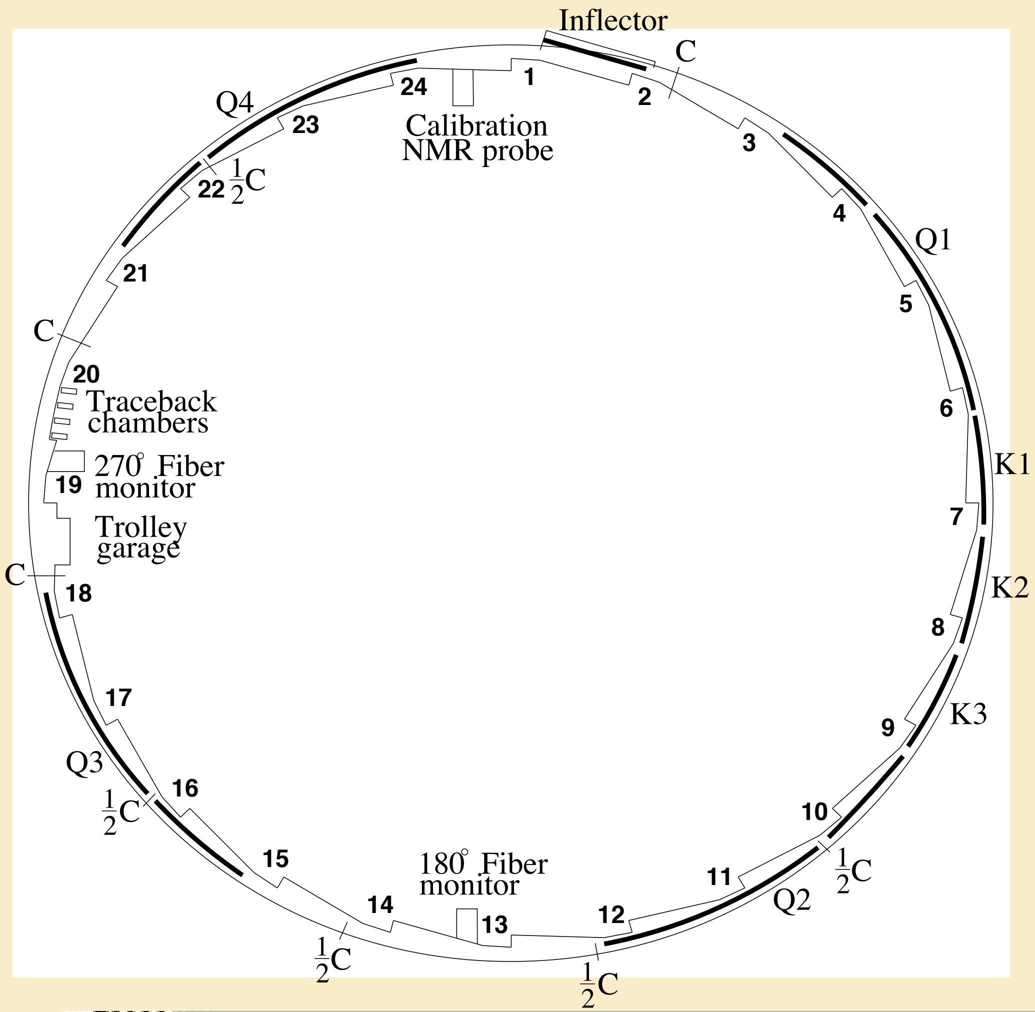


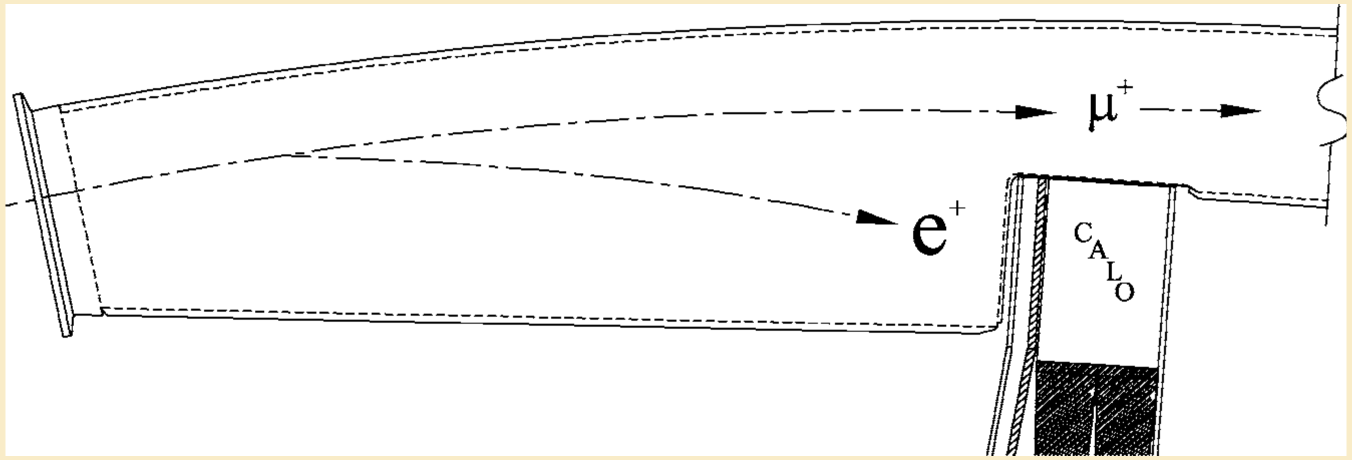


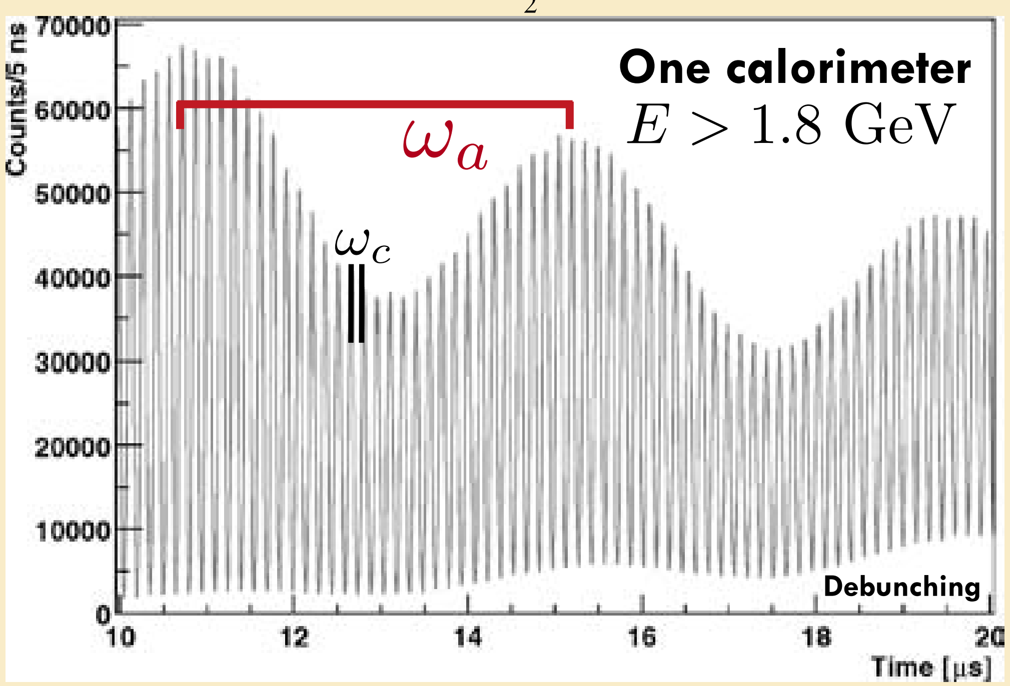
The storage ring

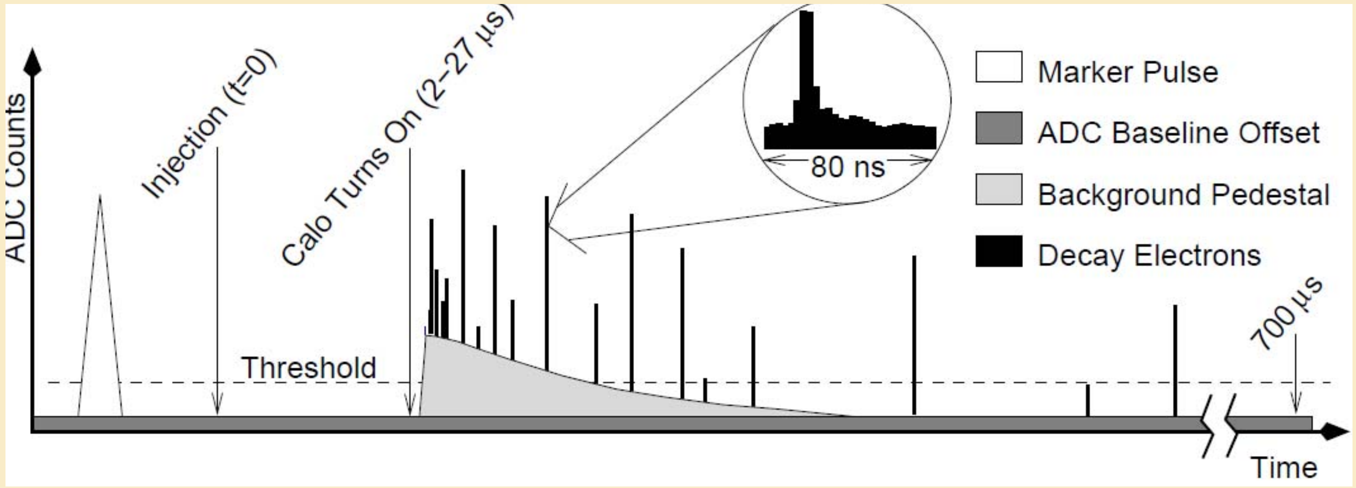


Measuring ω_a

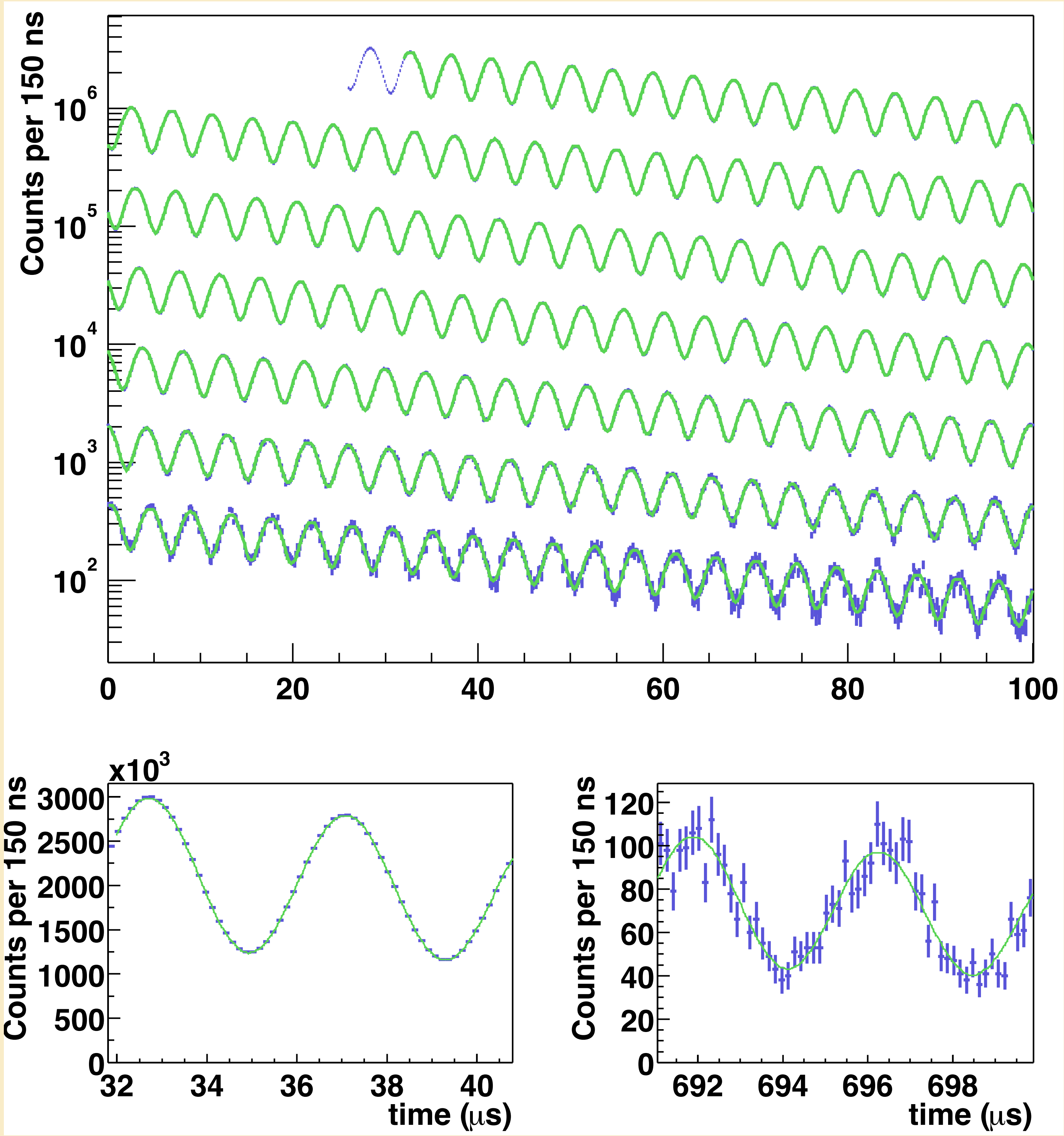








Measuring ω_a



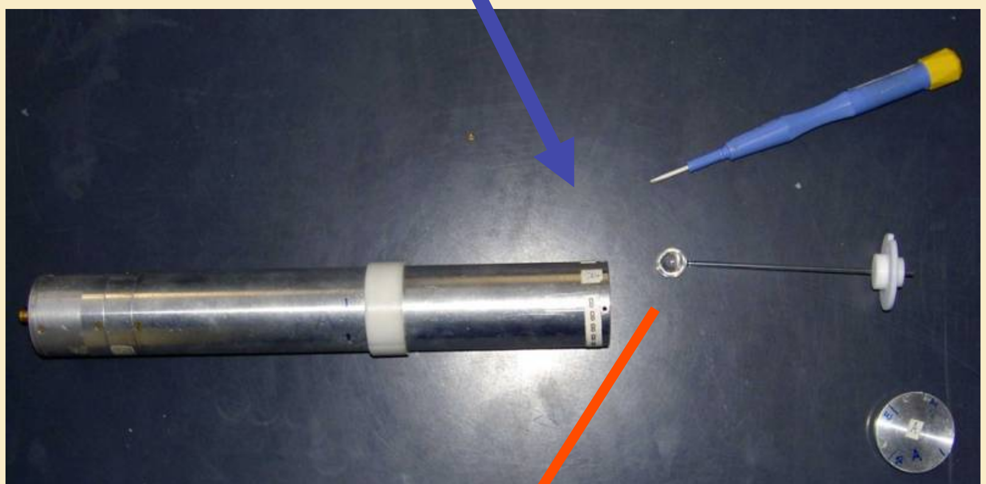
2000 data,

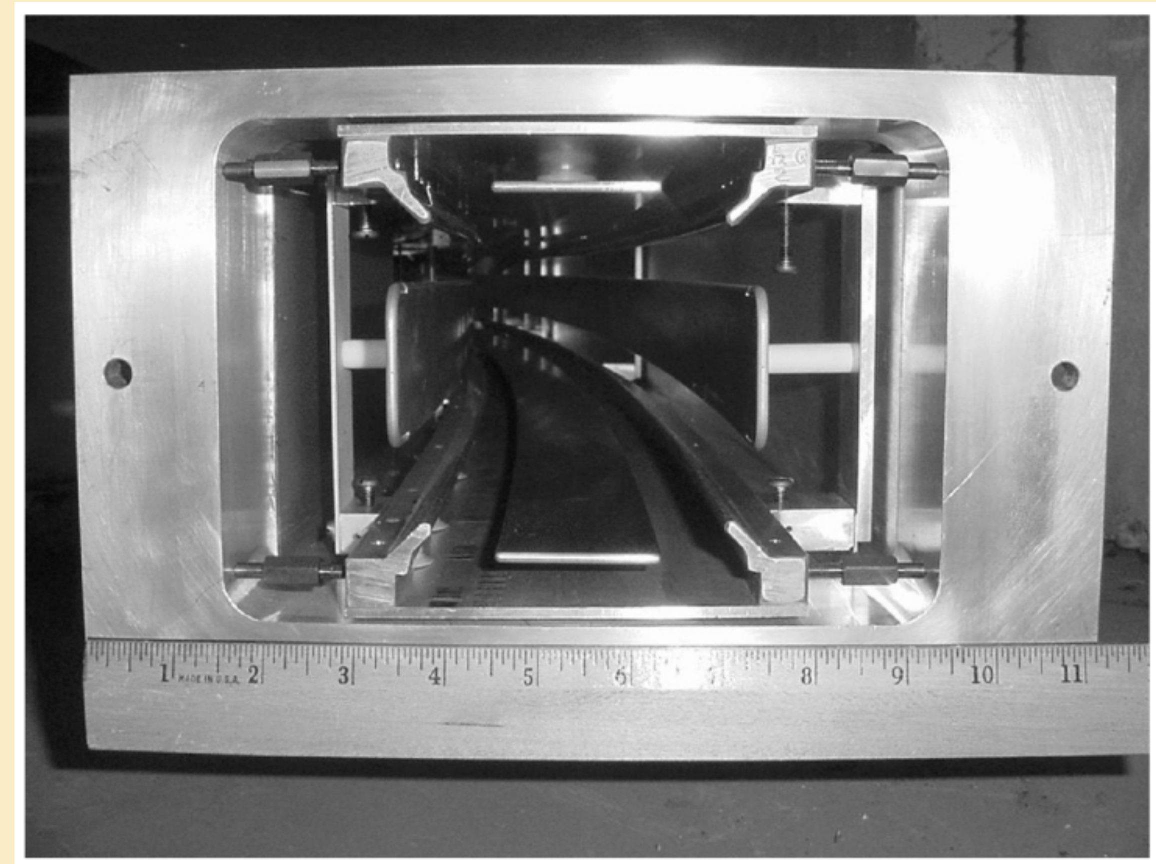
4 billion decays,

5 parameter fit

Measuring ω_p - Measuring the B field

Absolute Calibration Probe: a Spherical Water Sample





Trolley with matrix of 17 NMR Probes

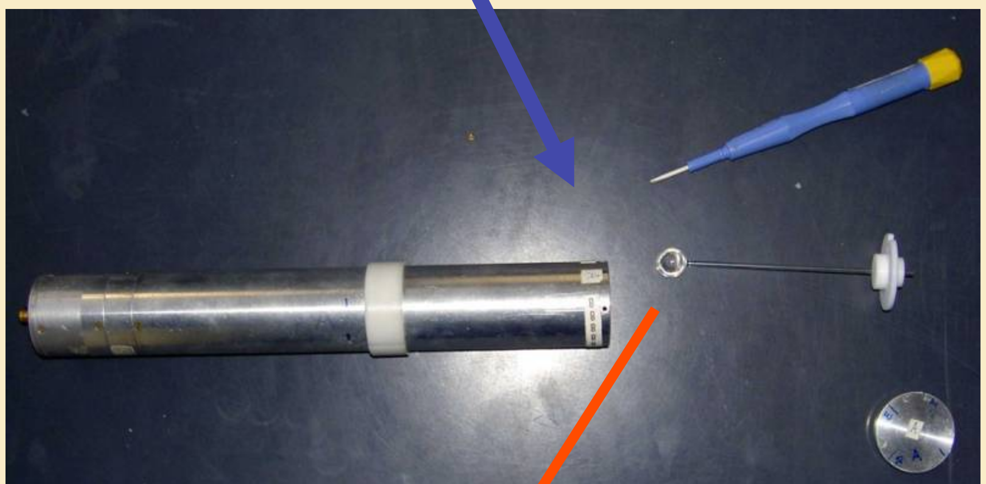
Electronics, Computer & Communication

Position of NMR Probes

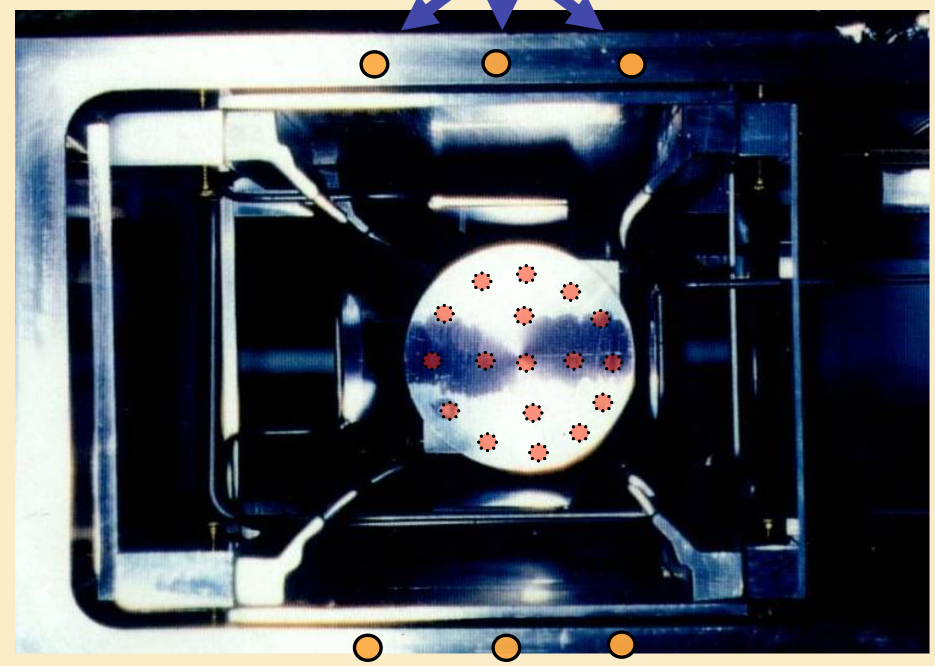
In vacuum, 6000 azimuthal measurements, Calibrated against plunging probe

Measuring ω_p - Measuring the B field

Absolute Calibration Probe:
a Spherical Water Sample



Fixed Probes in the walls of the vacuum tank



360 fixed probes, 150 most reliable

Trolley with matrix of 17 NMR Probes

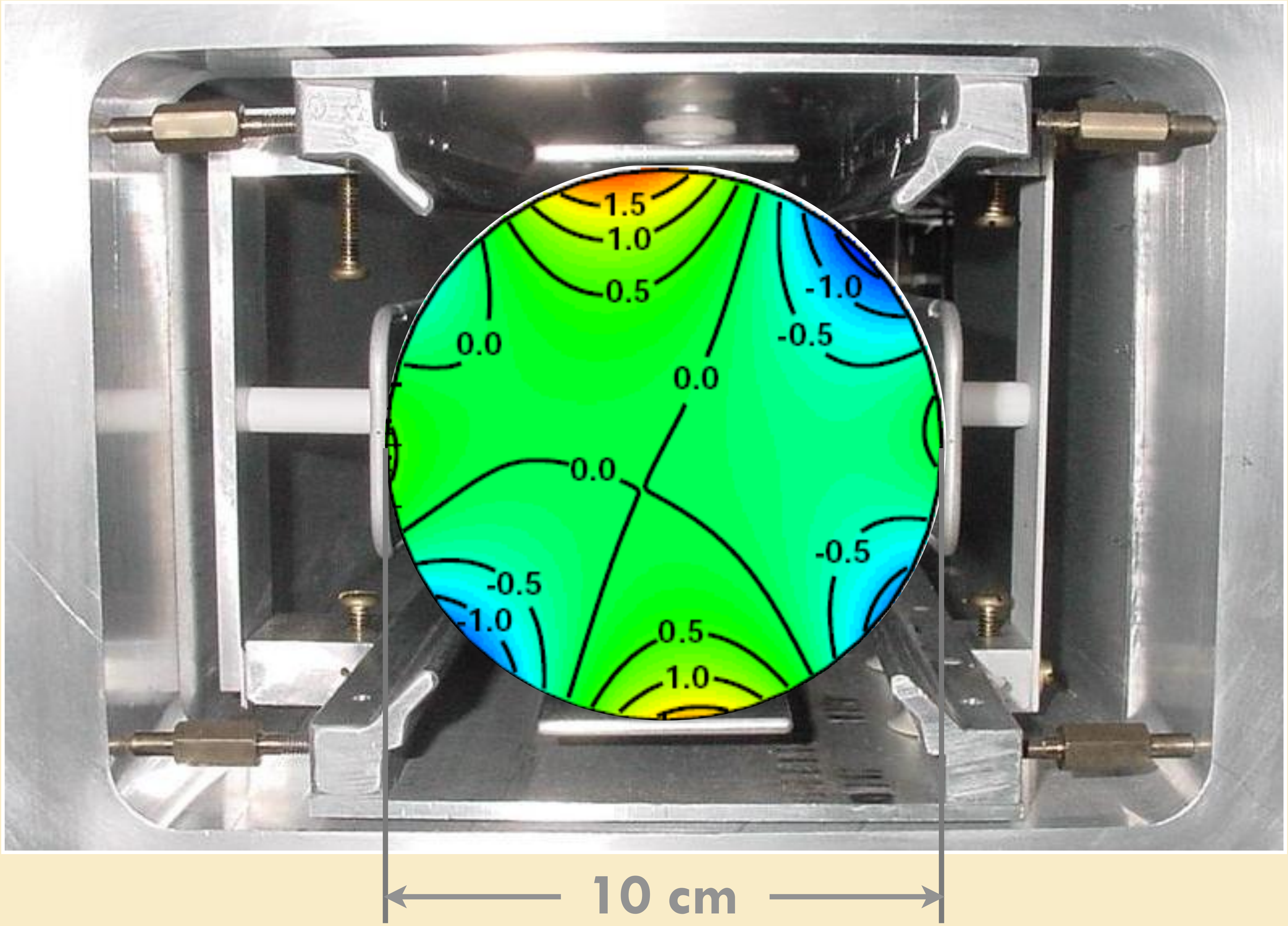
Electronics, Computer & Communication

Position of NMR Probes

In vacuum, 6000 azimuthal measurements, Calibrated against plunging probe

Measuring ω_p

Contours are ppm



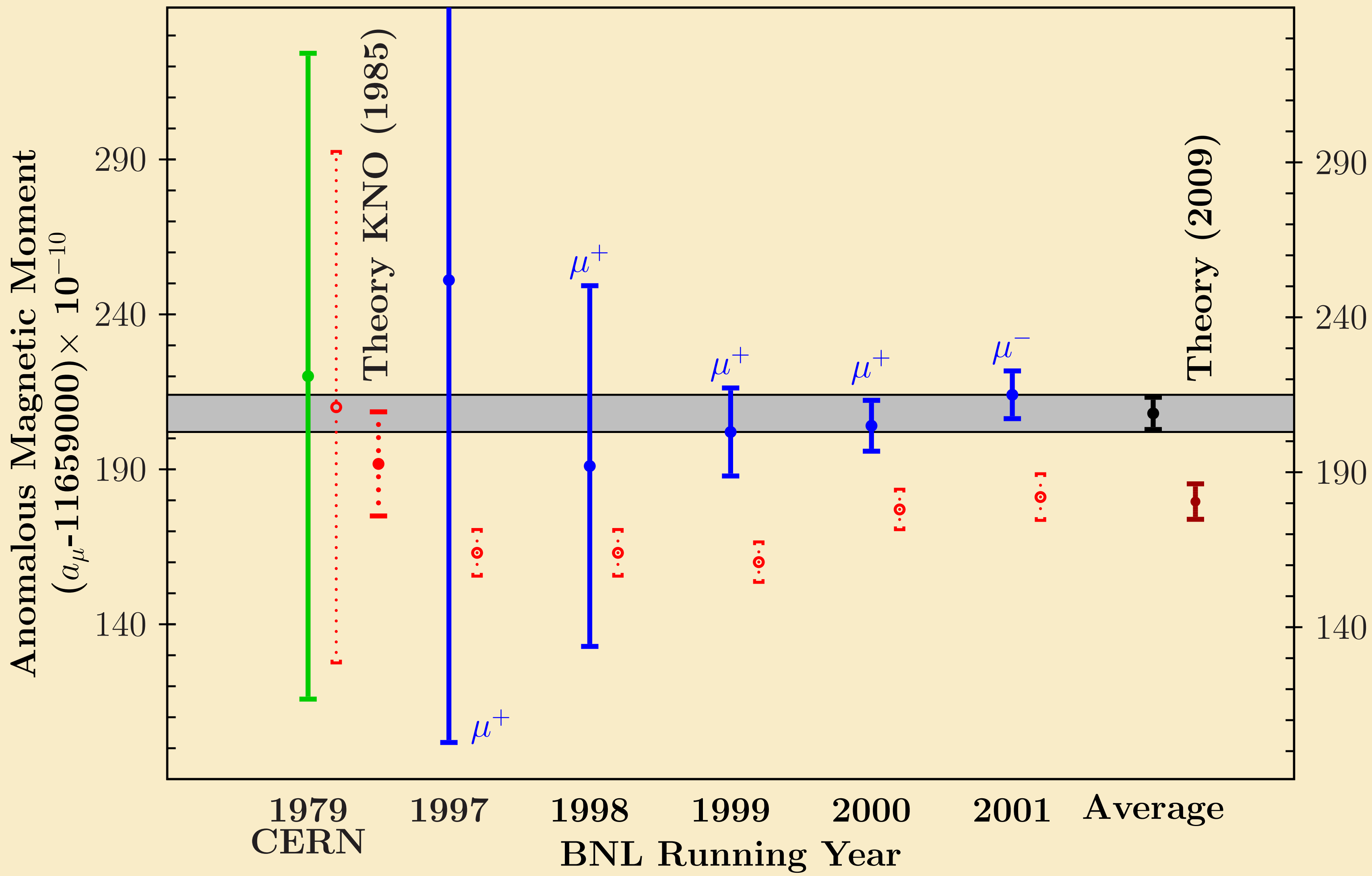
Blind analysis with separate groups (no one person knows both ω_a and ω_p)

Brookhaven E821 Results

PRD 73, 072003 (2006)

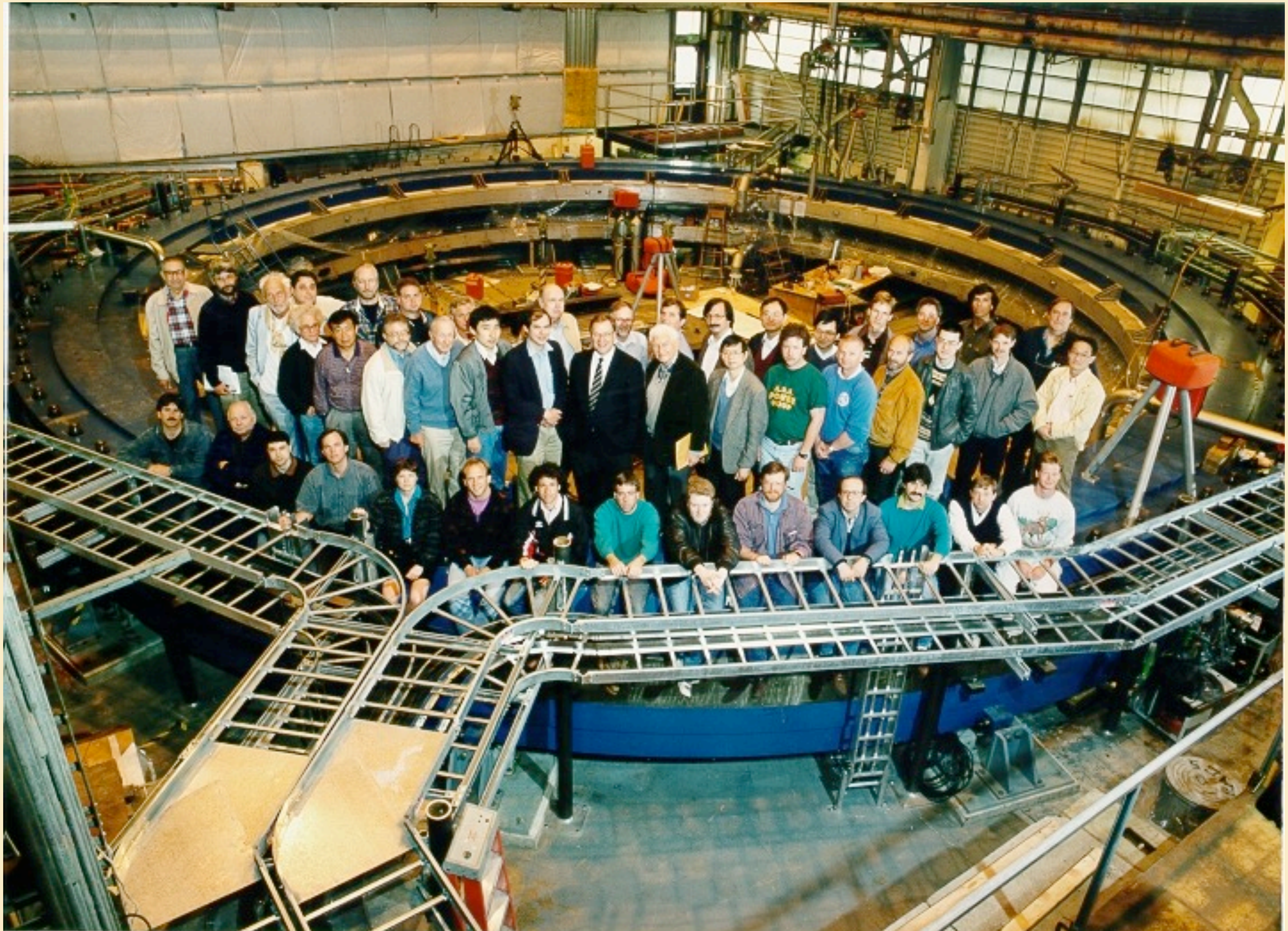
$$a_\mu^{\exp} = 116\,592\,089(63) \times 10^{-11} \;\; (0.54 \text{ ppm})$$

0.46 ppm statistics, 0.28 ppm systematic



$$g_\mu^{\exp} = 2.002\,331\,841\,78(126)$$

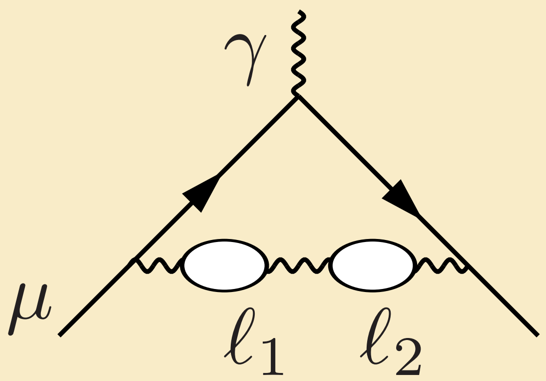
A Job Well Done

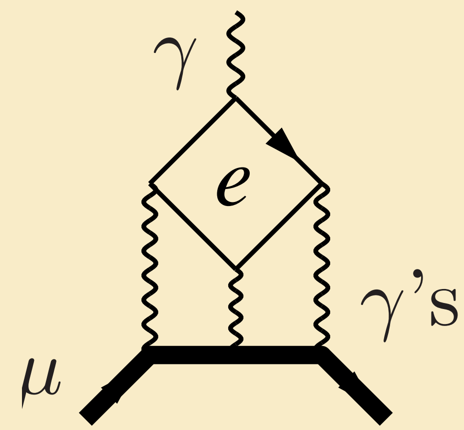


Comparing to Theory

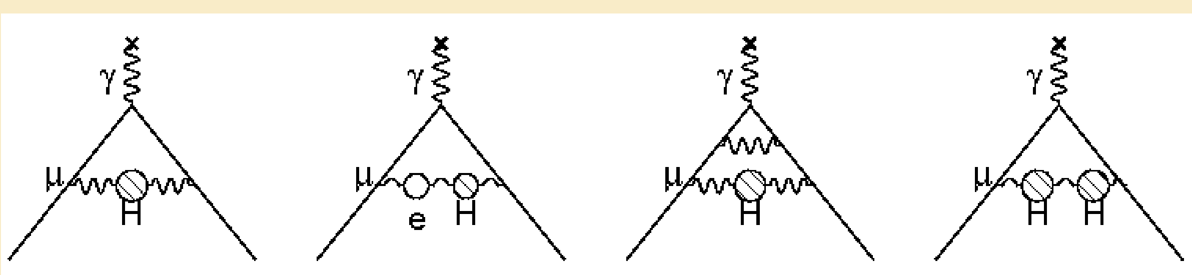
$$a_\mu^{\mathrm{th}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{had}} + a_\mu^{\mathrm{weak}} + a_\mu^{???}$$

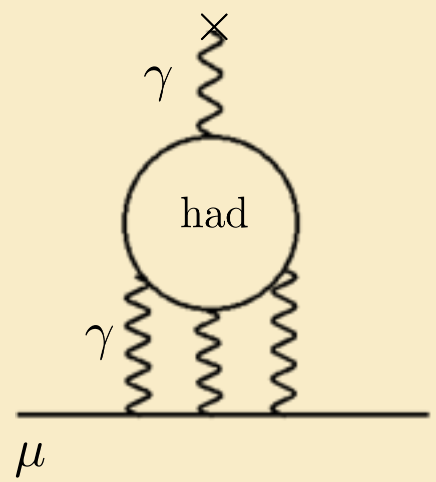
Theoretical contributions get complicated





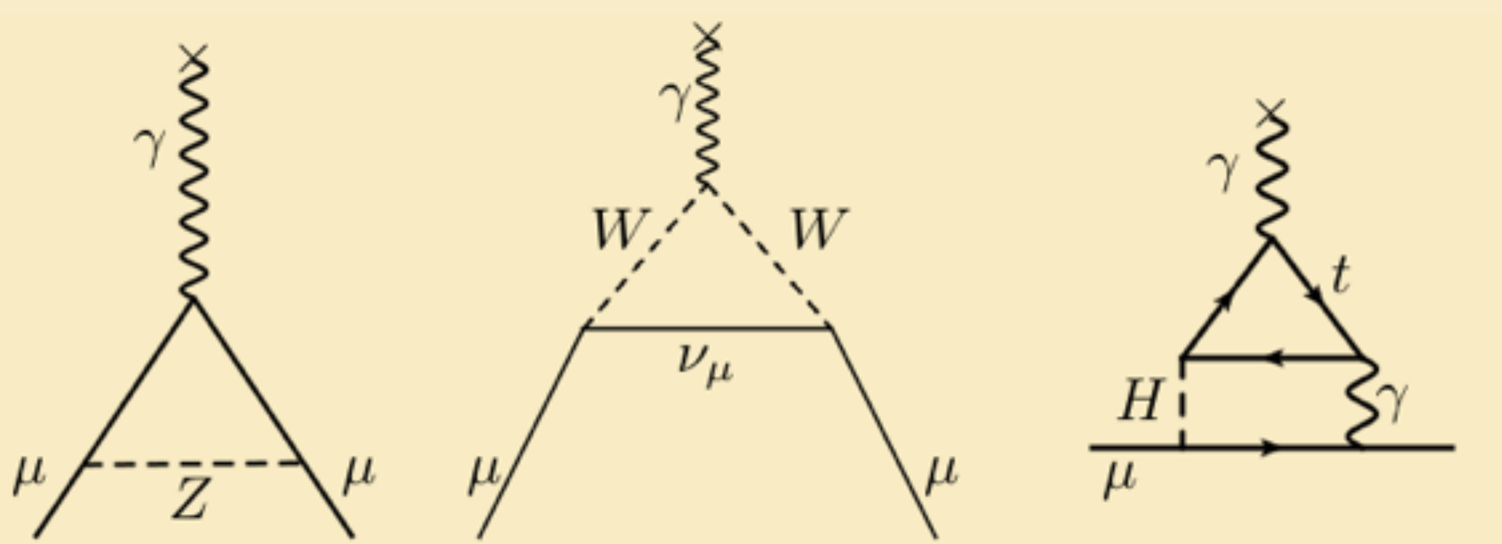
Theorists calculate
how all these diagrams (and
10,000s more)
affect g





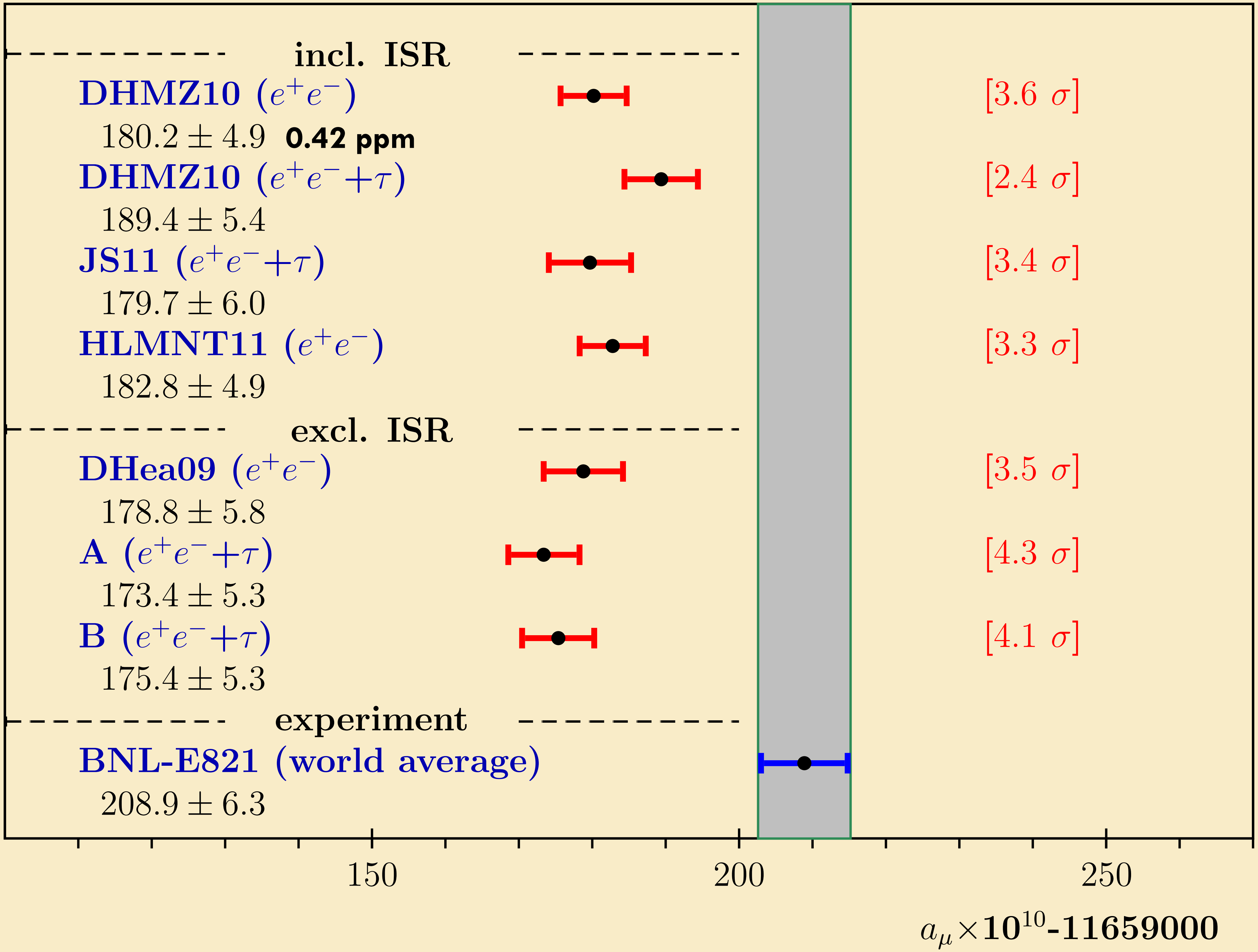
A fortunate rule:
The more extreme the
diagram, the less it changes *g*
(whew!)

Still, muons are very
sensitive to these diagrams



Theorists and experimentalists
work really hard at this and
improvements are in the
works.

Comparison to experiment



Benayoun, et. al., Eur. Phys. J **C72**, 1848 (2012)

Comparison to experiment

$$\mathbf{a}_\mu^{\rm exp} - \mathbf{a}_\mu^{\rm SM} = \mathbf{287(80)} \times \mathbf{10^{-11}} \quad > \mathbf{3}\sigma$$

Difference is ~ twice electroweak contribution!

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

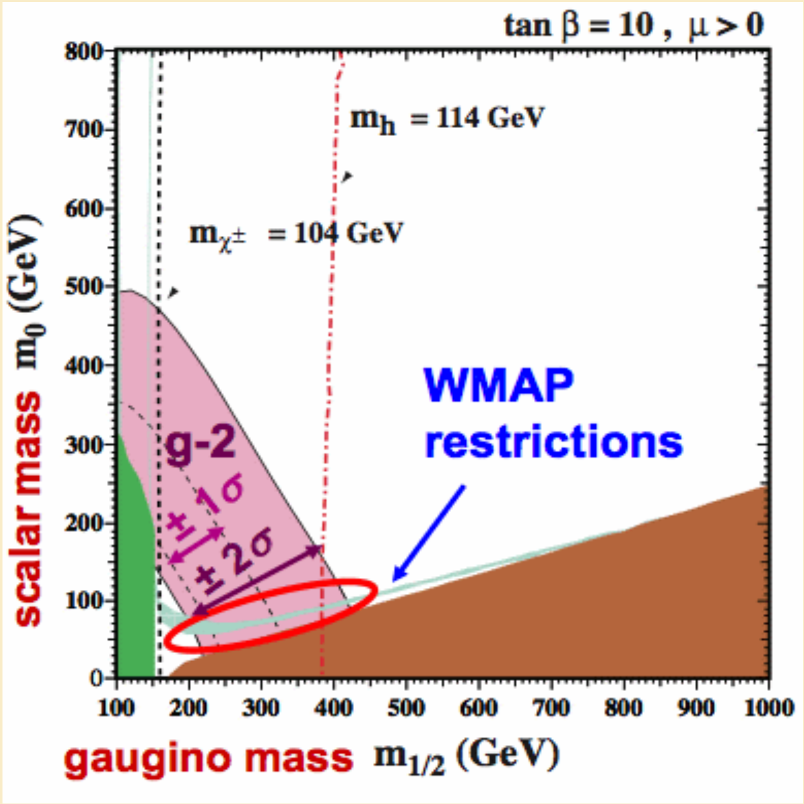
If this is new physics, why haven't we seen it elsewhere?

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

a_μ **is sensitive to ratio of coupling / mass scale**

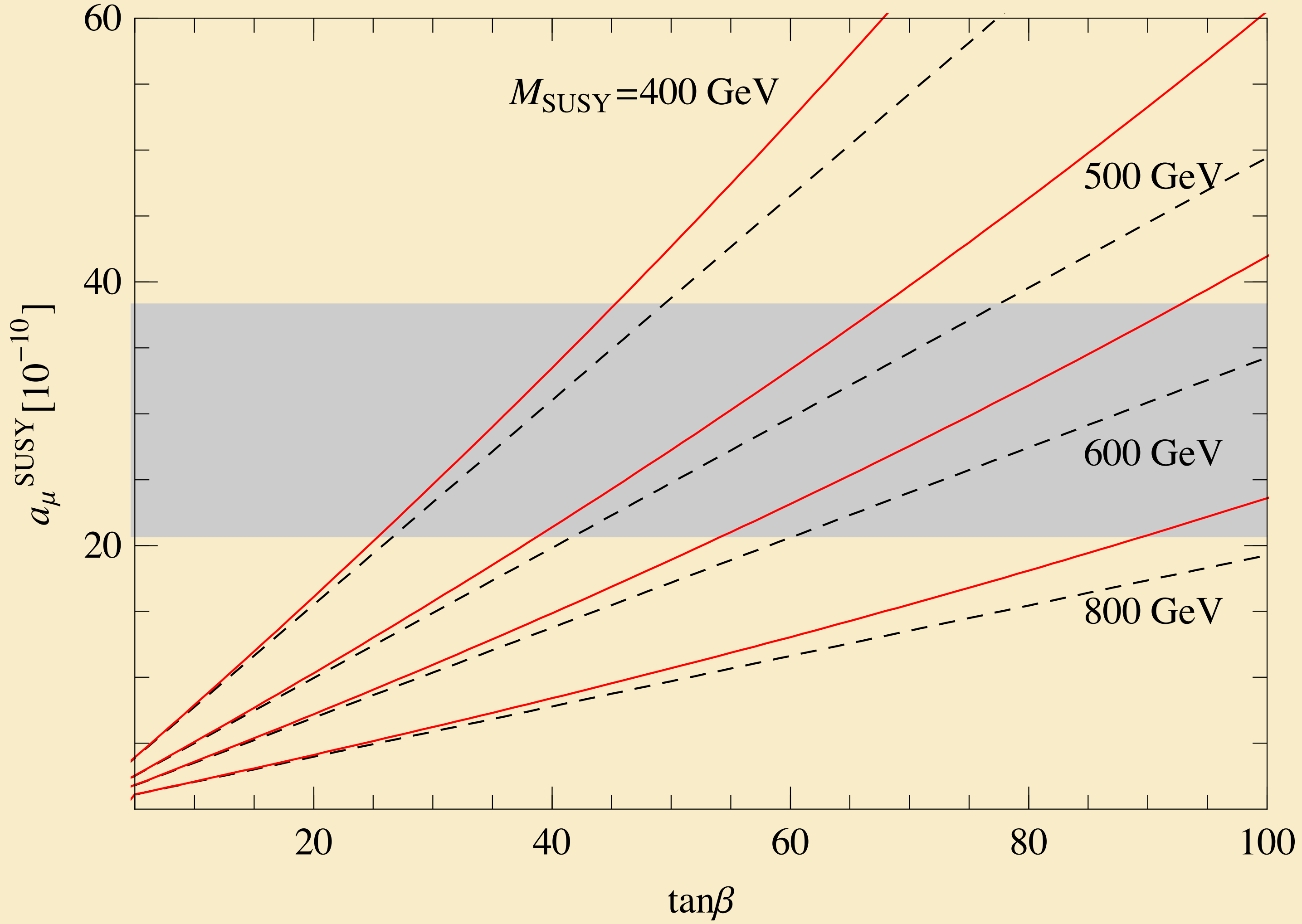
Perhaps mass scale is large and/or coupling is small

New Physics: SUSY?

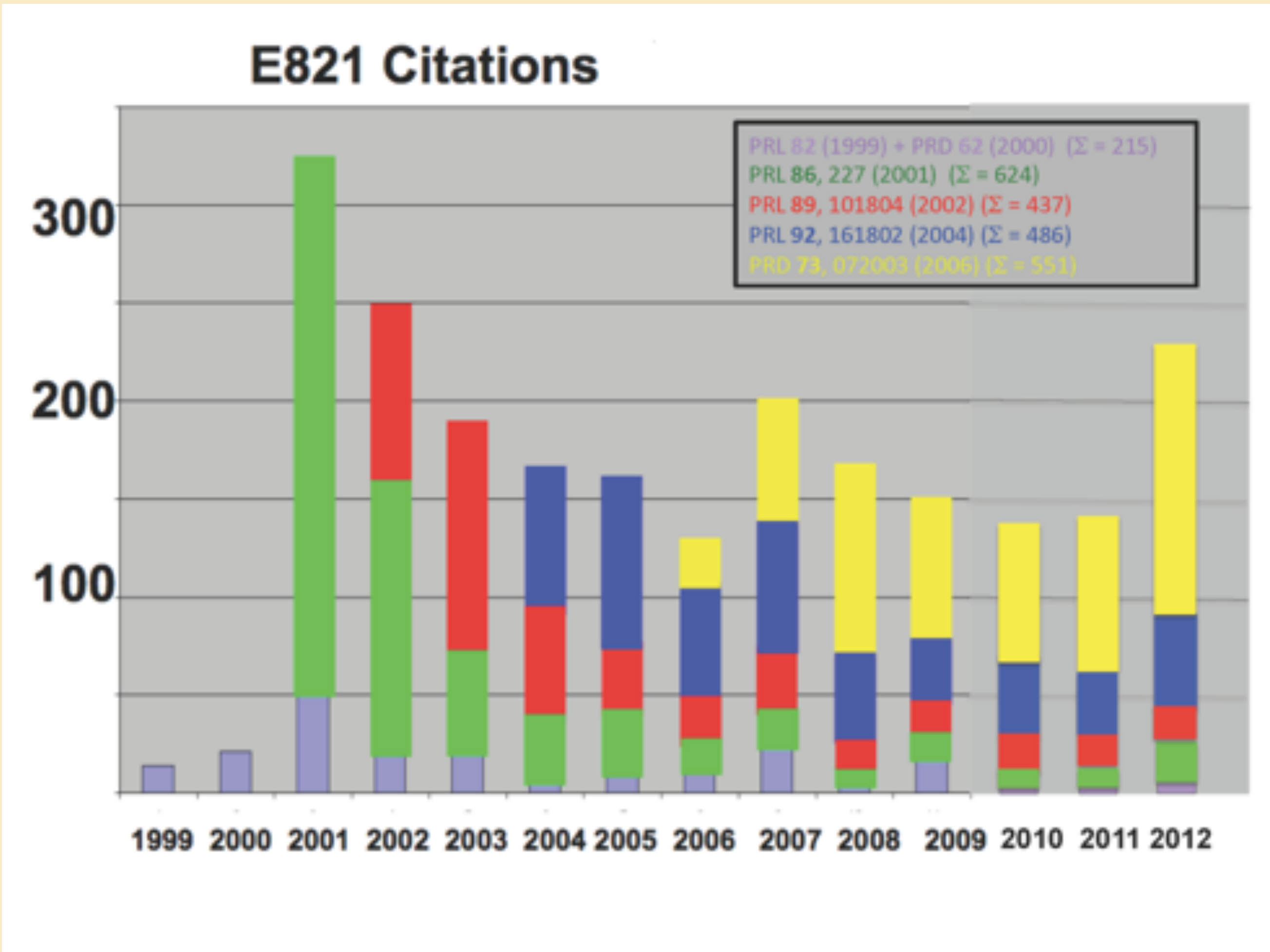


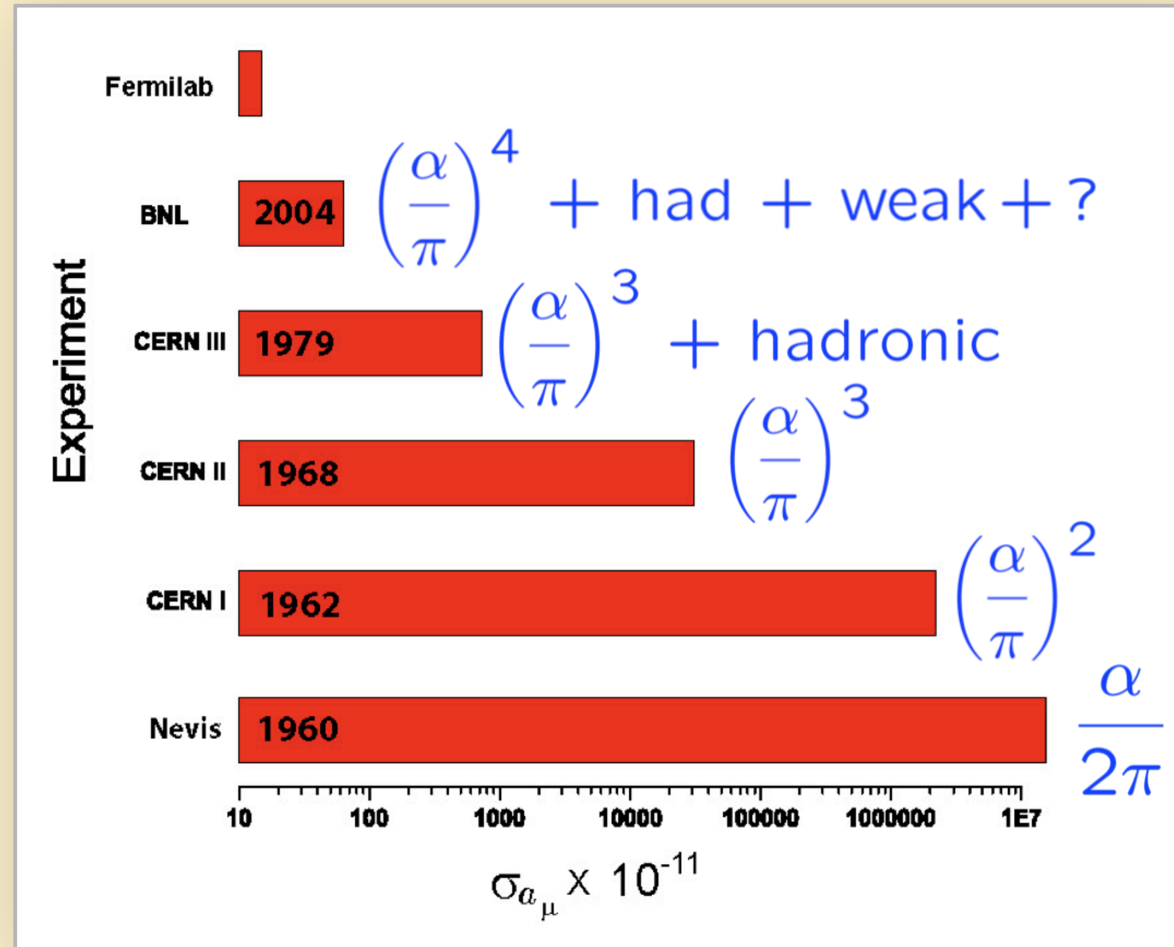
SUSY with mass scale of several 100 GeV is consistent with discrepancy

$$a_\mu^{\rm SUSY} \approx 13 \times 10^{-10}\,{\rm sign}(\mu)\left(\frac{100\ {\rm GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$



Enormous interest in the result

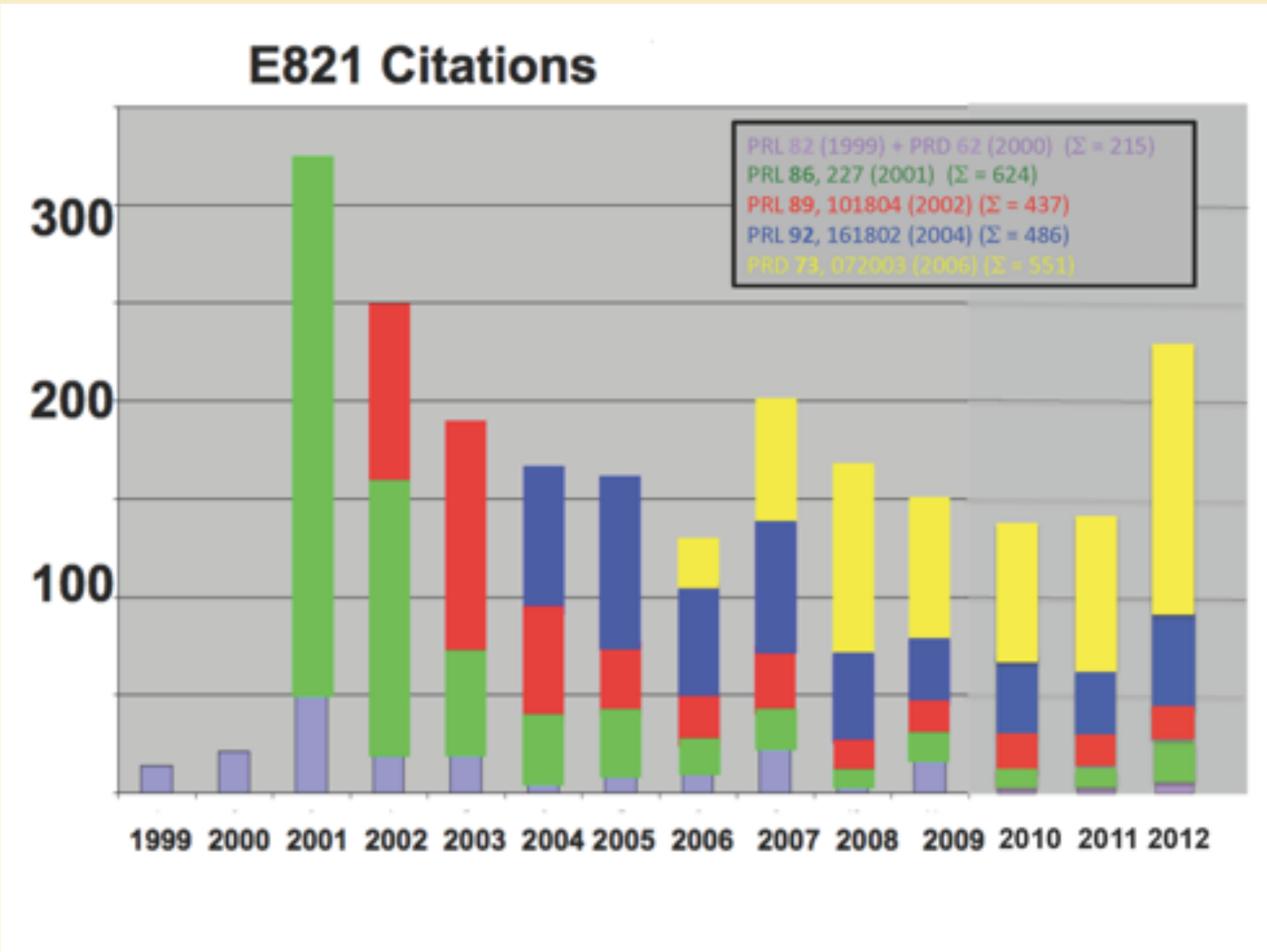


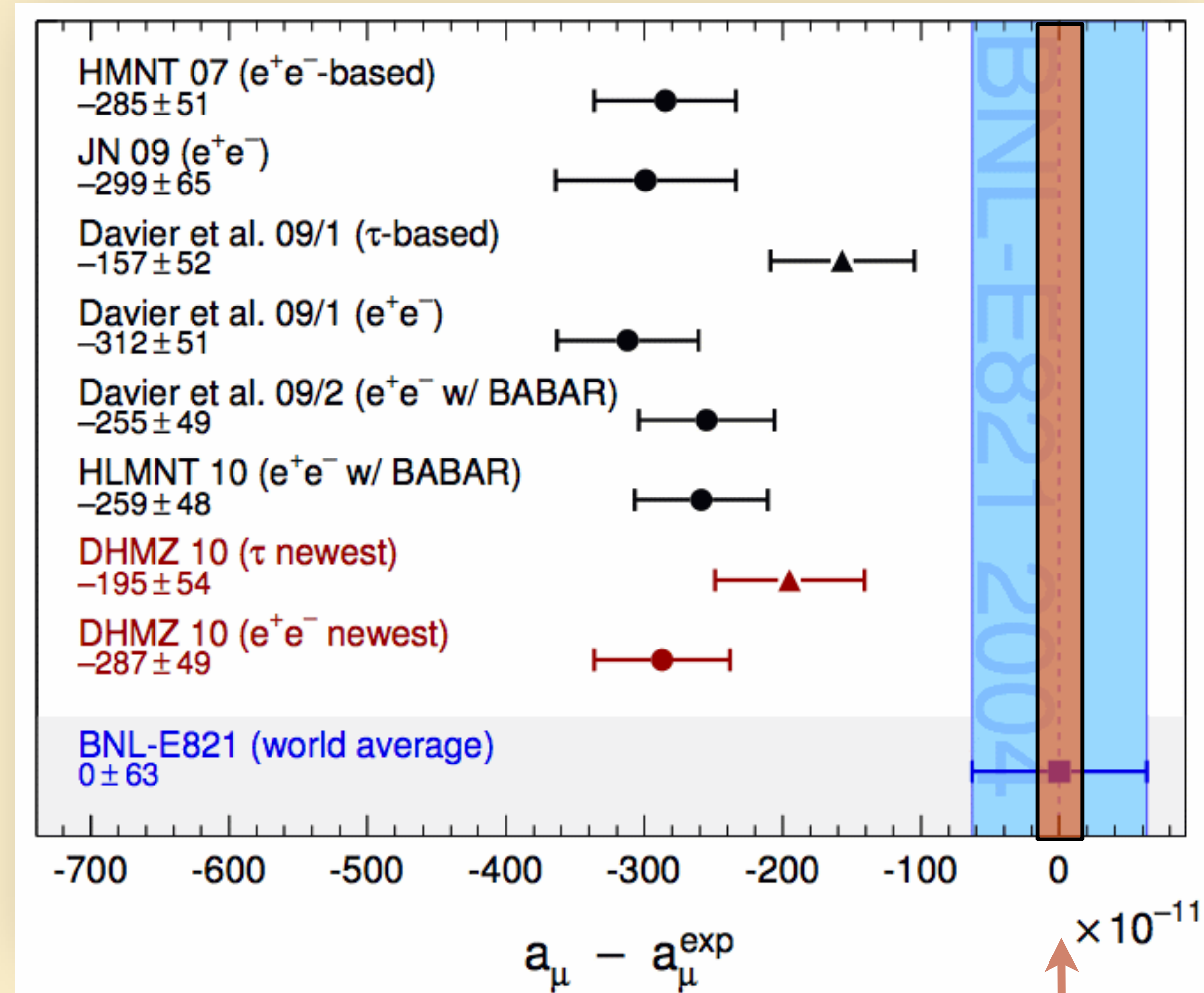


Difference is intriguing, but inconclusive

Redo the experiment even better than before!

Enormous interest in the result





Difference is intriguing, but inconclusive

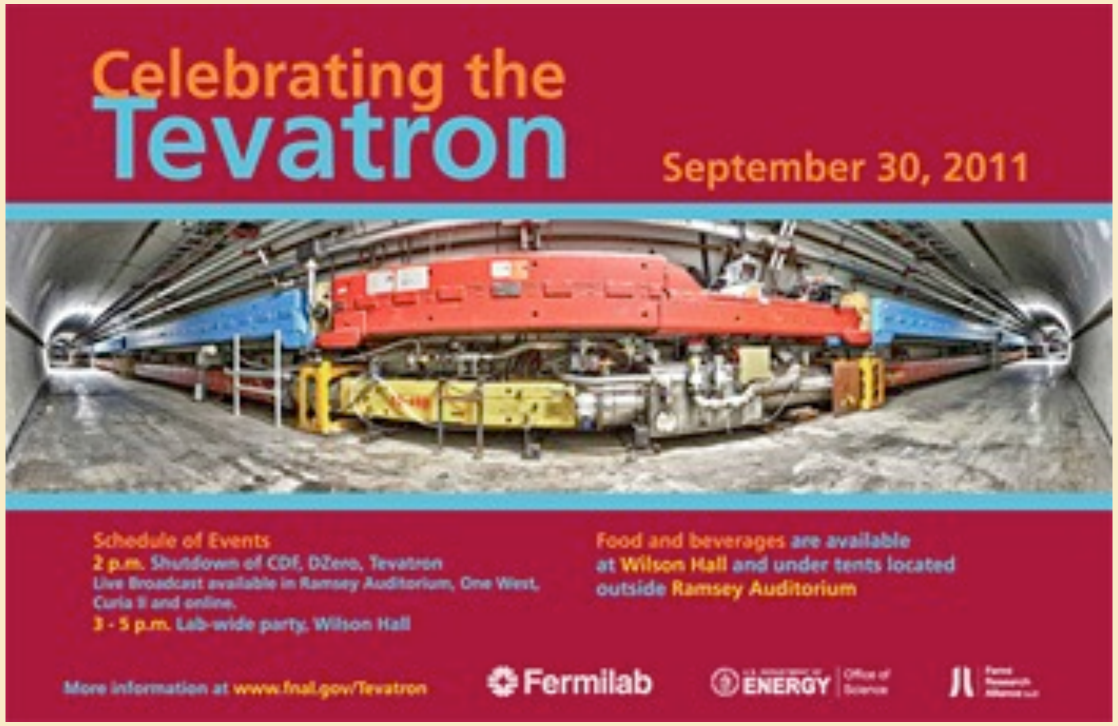
Redo the experiment even better than before!

With a 0.14 ppm measurement current difference becomes 5.6σ (7.5σ if theory improves to 0.3 ppm)

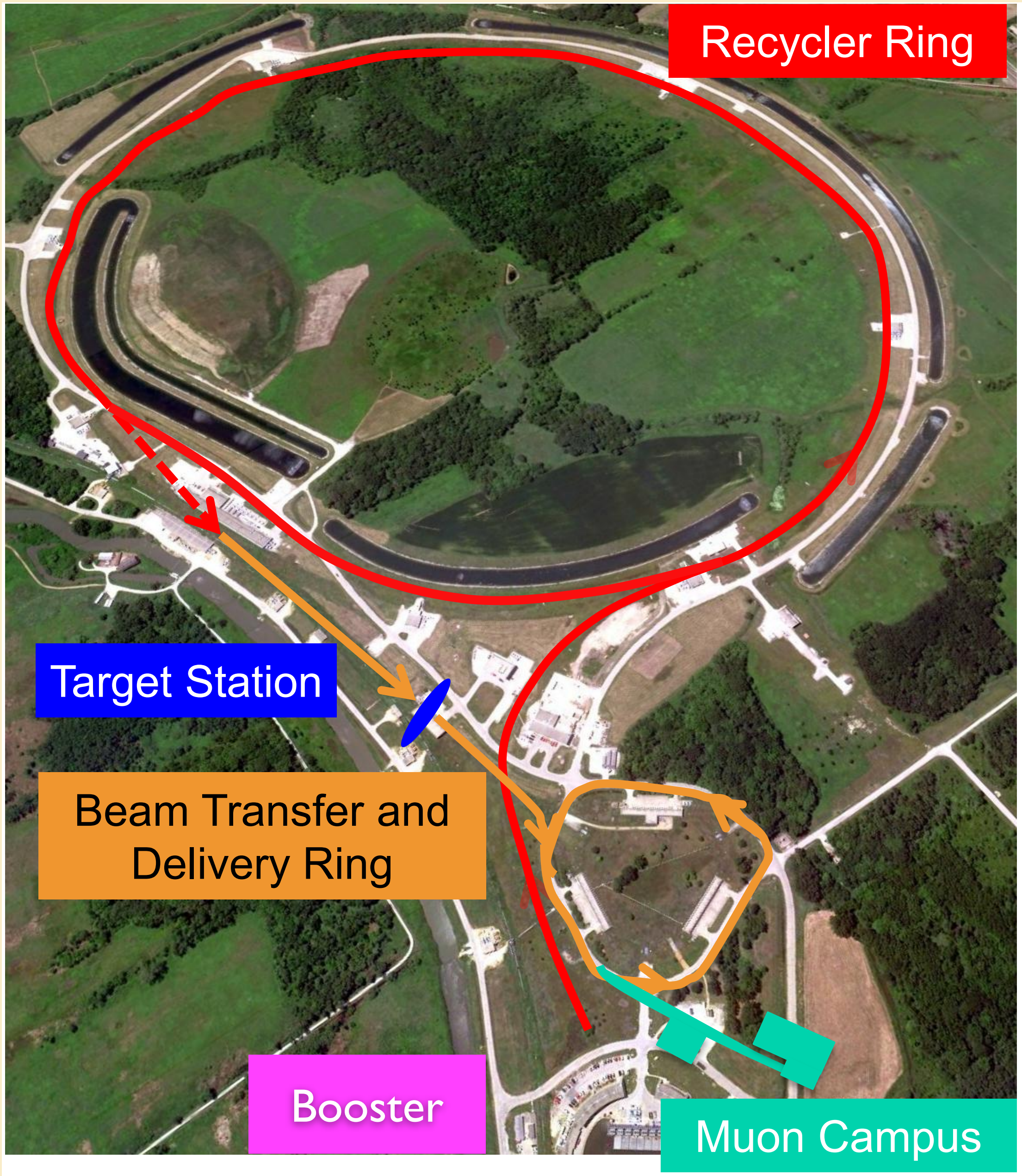
If difference persists, then a major discovery!

In the meantime at Fermilab

The Tevatron shut down in 2011 after running nearly 30 years



Antiproton source repurposed for μ^+



- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

Delivery ring was the antiproton debuncher

<u>Use the Ring from Brookhaven with the Fermilab infrastructure</u>
900m pion decay path (10x BNL; improves mu/p by 2x)
Much purer muon beam and heavily suppressed hadronic flash
1T protons per bunch on target -- 6000 muons in ring (6x eff of BNL) -- 700 good e^+
16 fills / 1.33s (booster cycle)
2 year run: ~ 1 T positron decays total, 0.18 T "good"

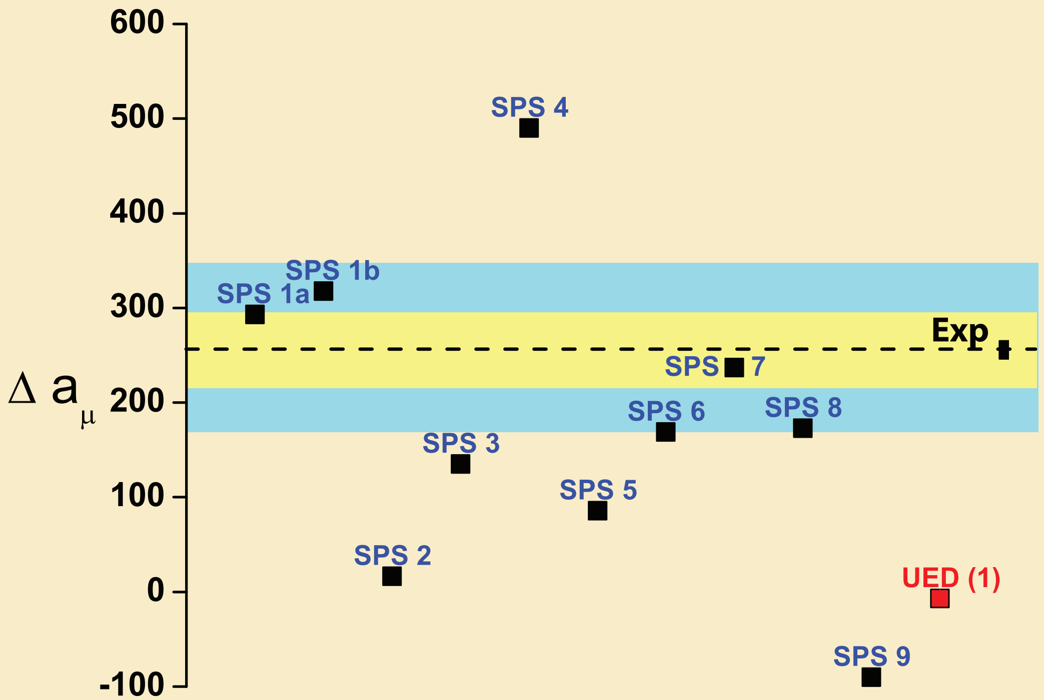
A new home at the Fermilab Muon Campus

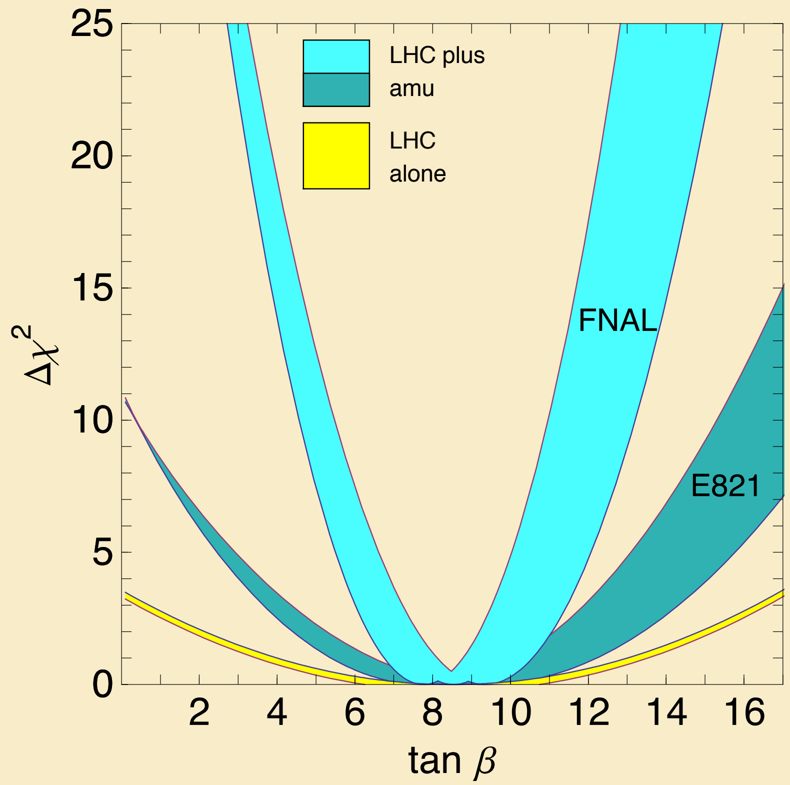
Ring arrives summer 2013

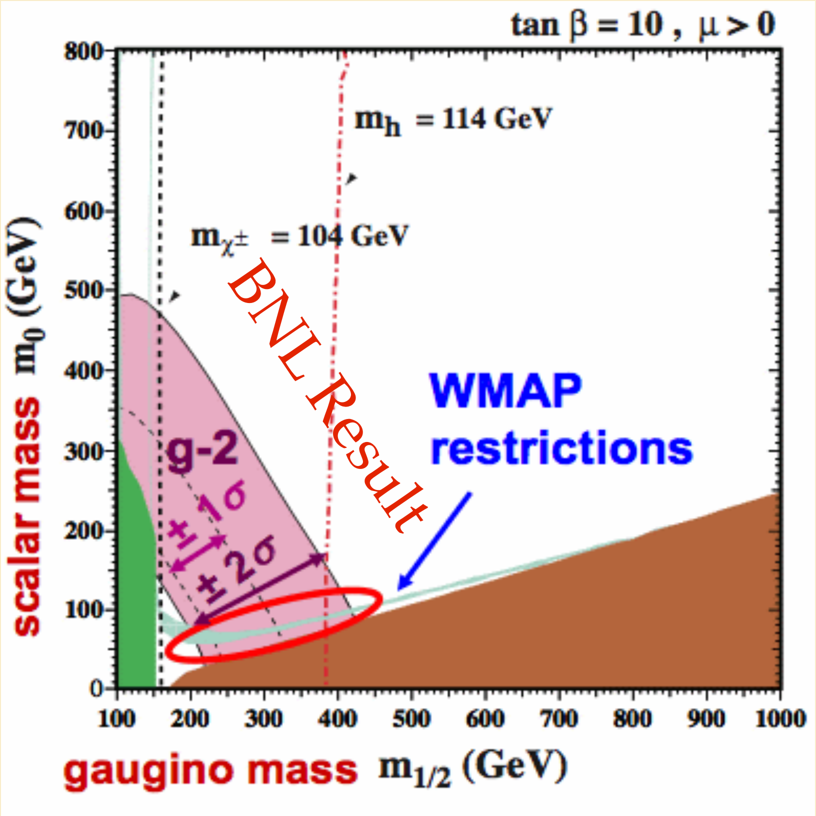
Building complete 2014

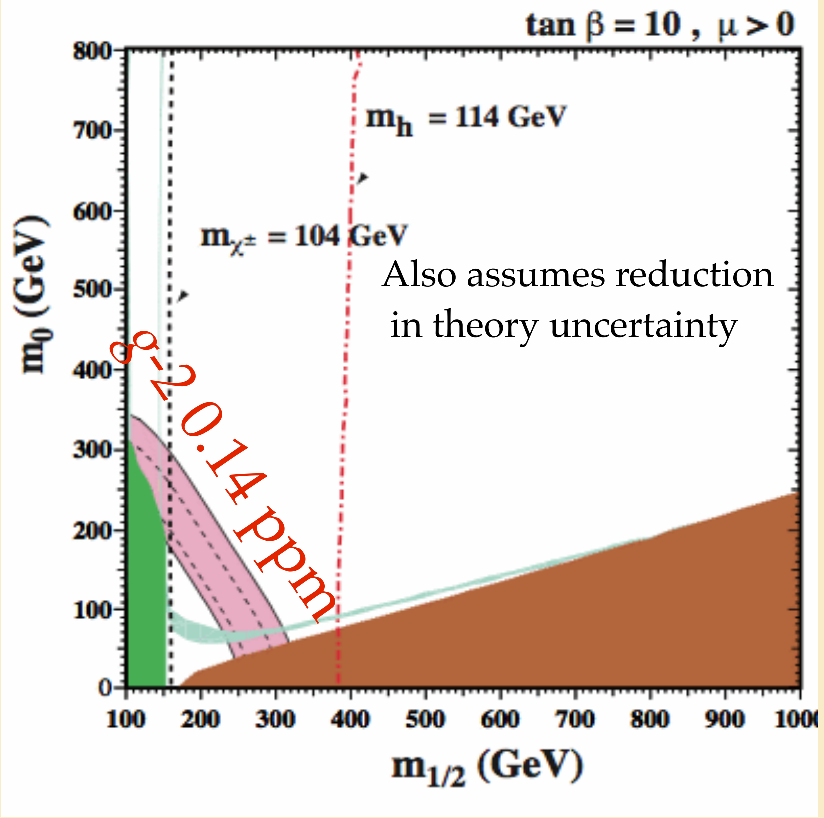
New physics with 0.14 ppm

Complementary to LHC









New Muon g-2 experiment justification

Discrepancy with SM and complementarity with LHC makes for easy physics motivation. If there is new physics, LHC + Muon $g - 2$ will be a powerful combination

BNL E821 was statistics limited

Factor of 4 is about the limit of the current apparatus

Need 21x statistics to achieve this goal !!!

Gotta get more beam! Move to Fermilab -- Literally!

Many BNL E821 collaborators have joined Fermilab E989

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

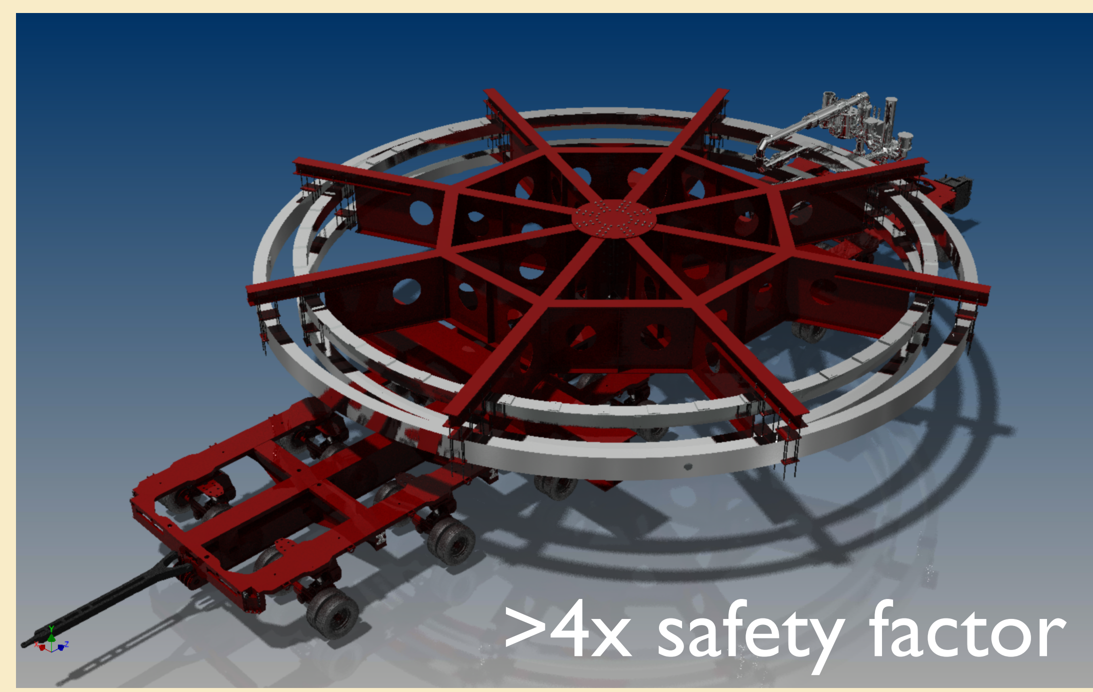
They aren't dangerous: nonmagnetic when unpowered, not radioactive, no dangerous chemicals (aluminum, niobium [hypoallergenic], tin), inert

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

The ultimate road/water/road trip

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

"We can move that"



June 2013 - Assembling the fixture

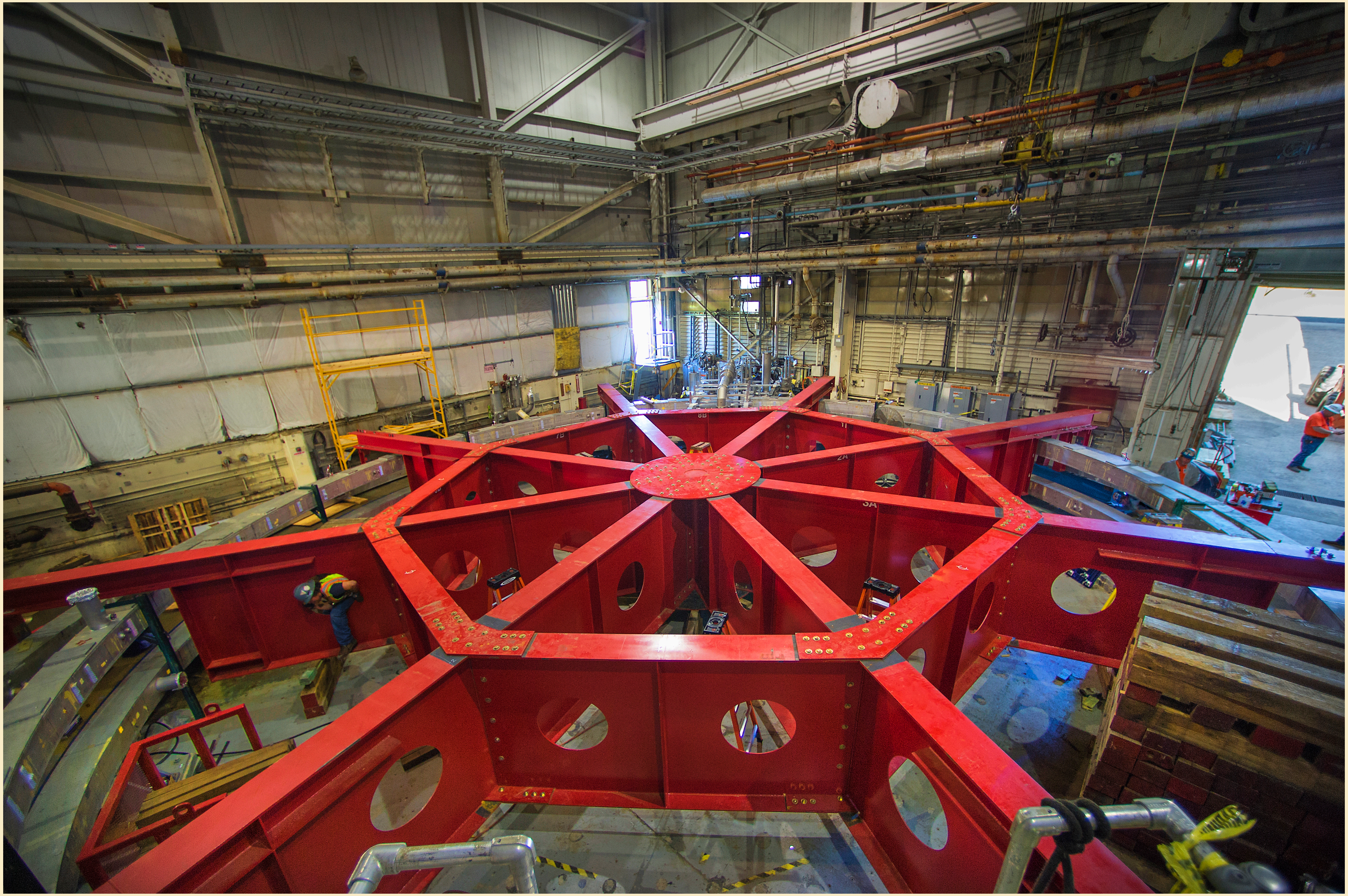


Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

Photo: Brookhaven/Emmert

Rolling out of the building

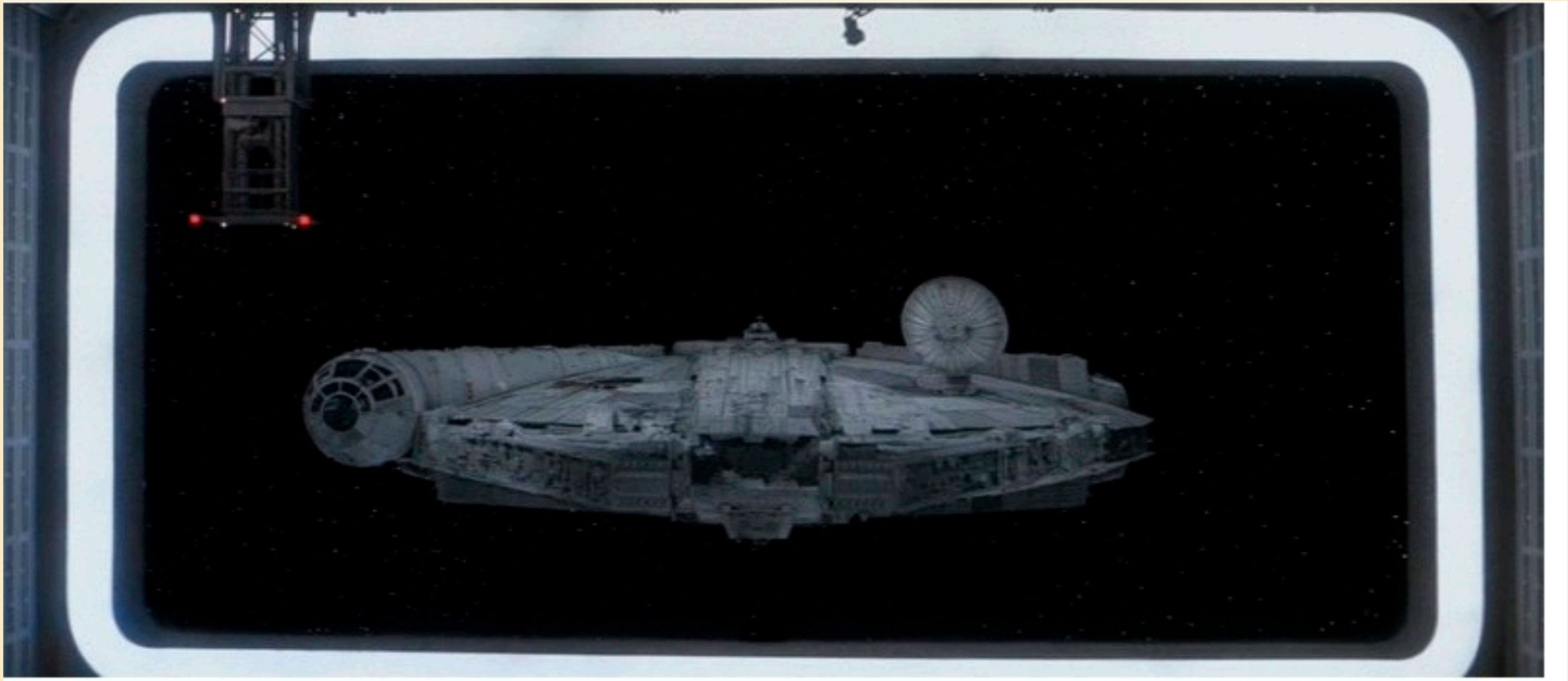


Photo: Darth Vader

It's out !!

Photo: Brookhaven/Emmert

The fancy trailer

8 axels
64 tires

Auto-leveling
Height control
Independent steering
Way cool!

Photos: Brookhaven/Emmert

Traversing Brookhaven National Lab

Photo: Brookhaven

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)

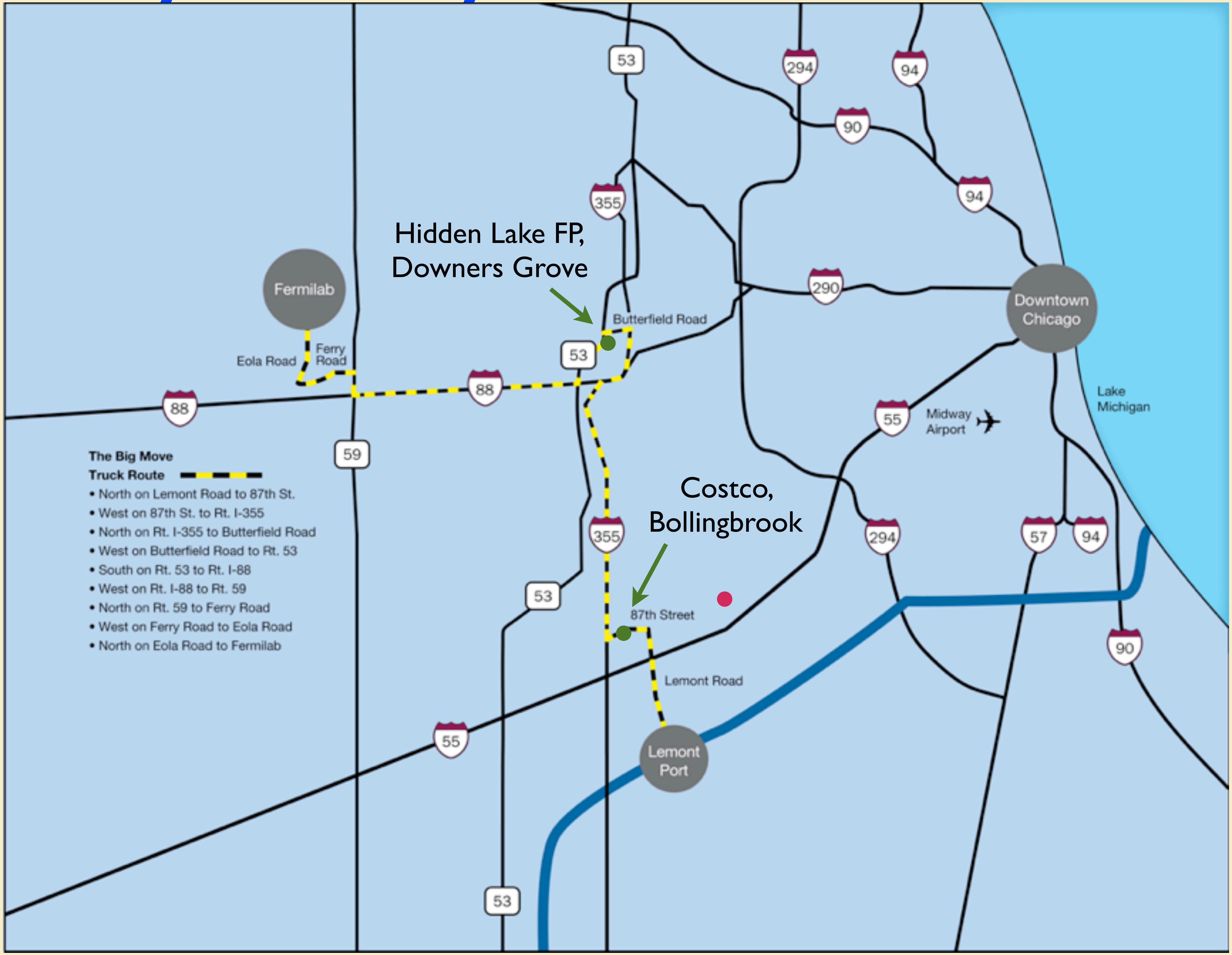
Up the Tenn-Tom Waterway

Photo: Darin Clifton

And Saturday 6/20, finally in Lemont, IL

Sunday morning, off the barge

Tuesday – Friday: The land route



Tuesday night, on Lemont Rd & 87th St

Photos: Fermilab

Wednesday, shopping at Costco

Wednesday night, on the Tollway

“Muon Down the Road!”

Thursday night, to the lab!

20 mph
on I-88 !!

Photos: Mike Murphy


Fermilab
Goldhofer

Friday, Celebrate at Fermilab!

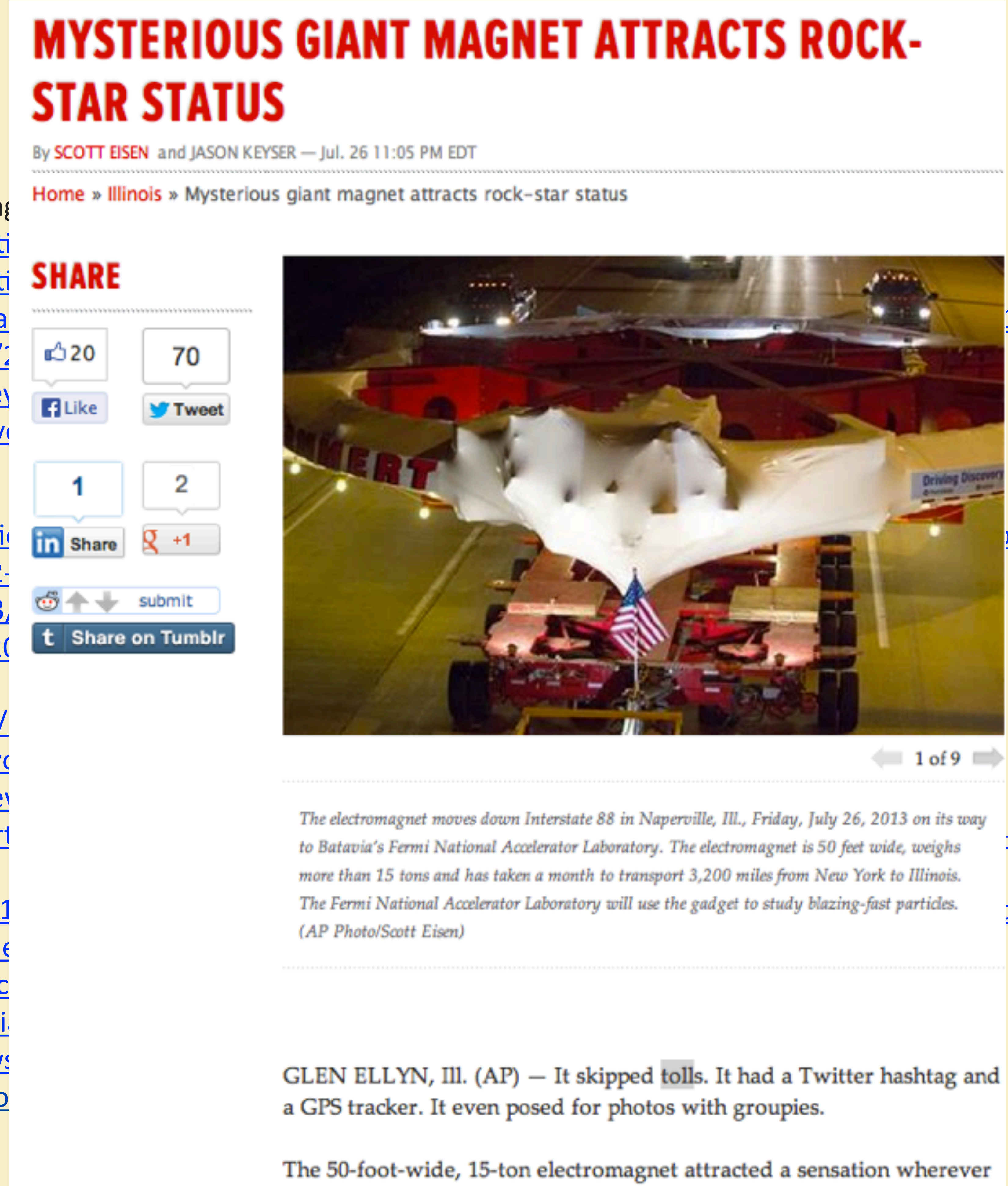
Photo: Fermilab

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 1
http://chicago.cbslocal.com/2013/07/2
http://wgntv.com/2013/07/23/journey
http://wgntv.com/2013/07/27/massive

Print and Web coverage:
http://www.washingtonpost.com/nati om-
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/nationwc
http://napervillesun.suntimes.com/nev
http://www.natureworldnews.com/art -goes-
video.htm
http://articles.chicagotribune.com/201 ional-
accelerator-laboratory-monster-magne
19040101_Giant_magnet_set_to_reac
http://hamptonroads.com/2013/07/gi
http://heraldnews.suntimes.com/news
http://bigsto



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

SHARE

20 Like | 70 Tweet | 1 Share | 2 +1 | submit | Share on Tumblr

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

Improving ω_a

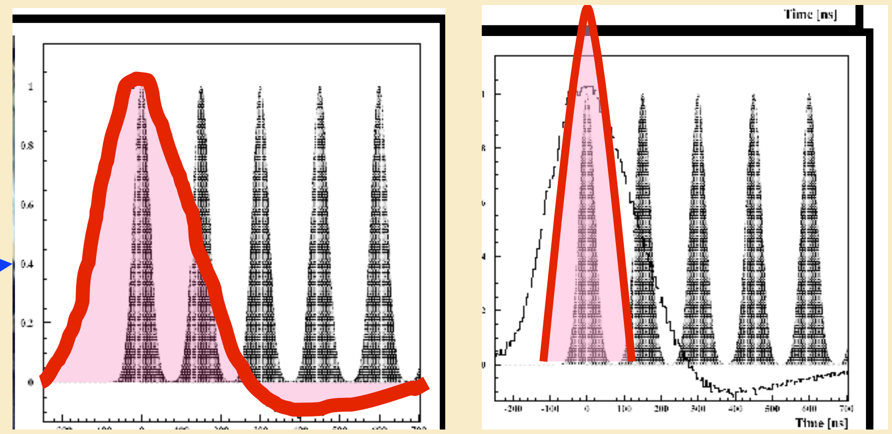
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

+ No hadronic flash, better laser calibration

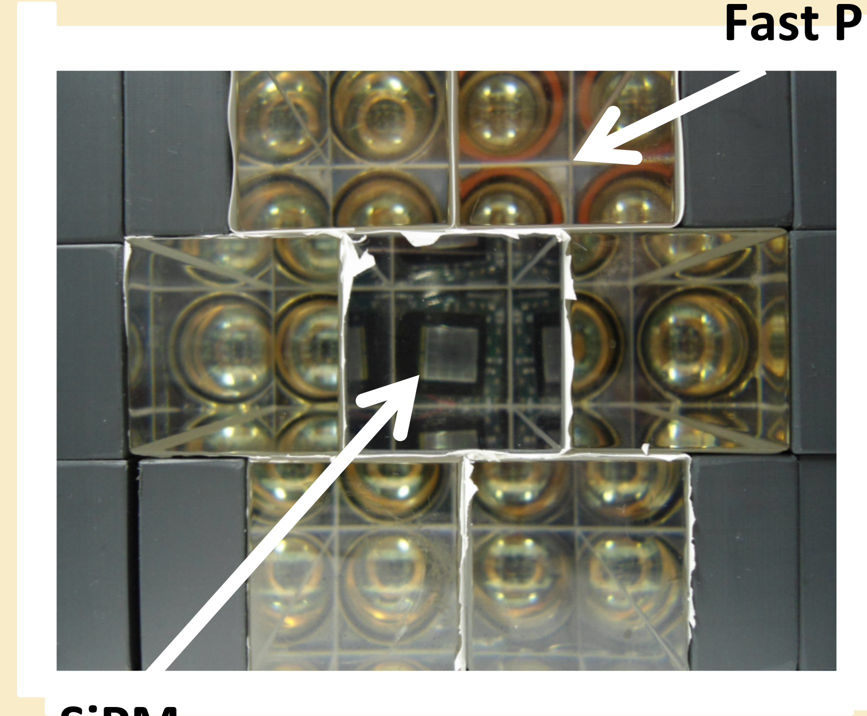
+ New tracking, open inflector, scraping

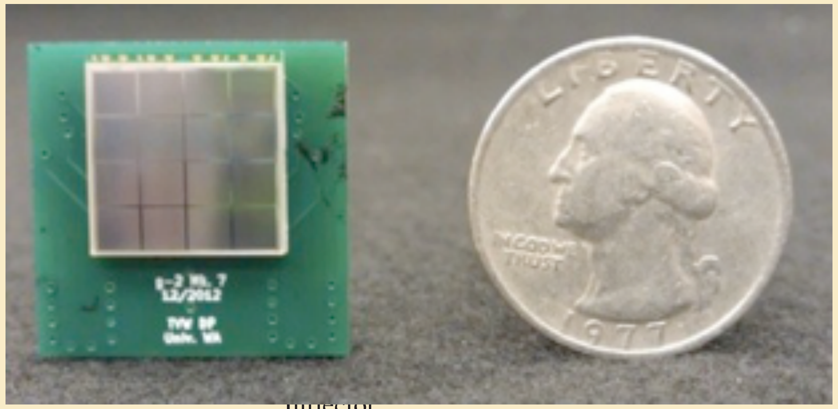
+ Segmented calorimeters

+ Improved kickers



Segmented calorimeters



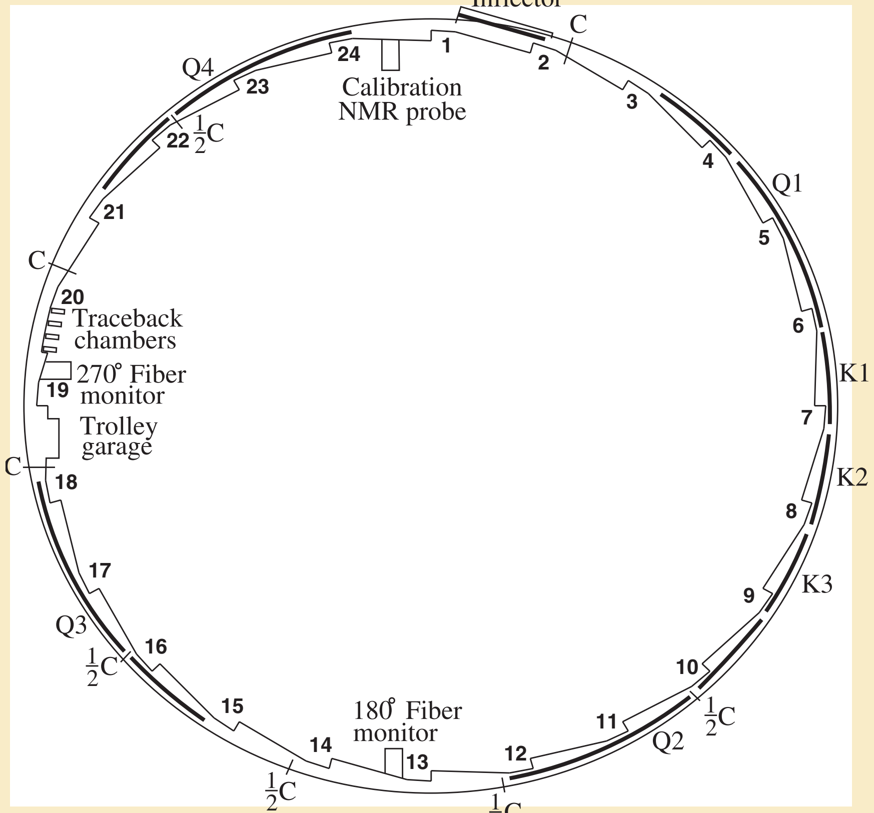


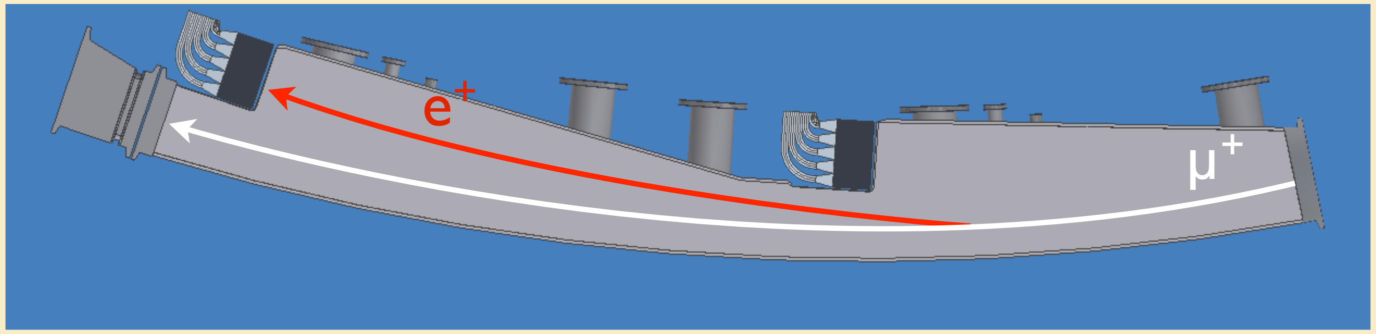
24 Calorimetry stations (E and t)

- **9x6 (2.5x2.5) cm PbF_2 array (X_0 = 0.93 cm)**
- **Silicon Photomultipliers**
- **500 MSPS waveform digitizers**

Improvements over E821

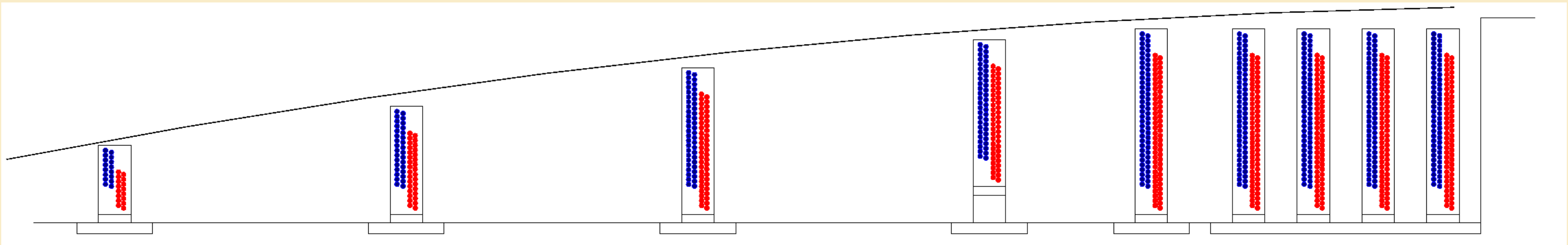
- **Improved gain control and laser monitoring**
- **Pileup suppression via segmentation**
- **lower thresholds, reduced pion "flash"**

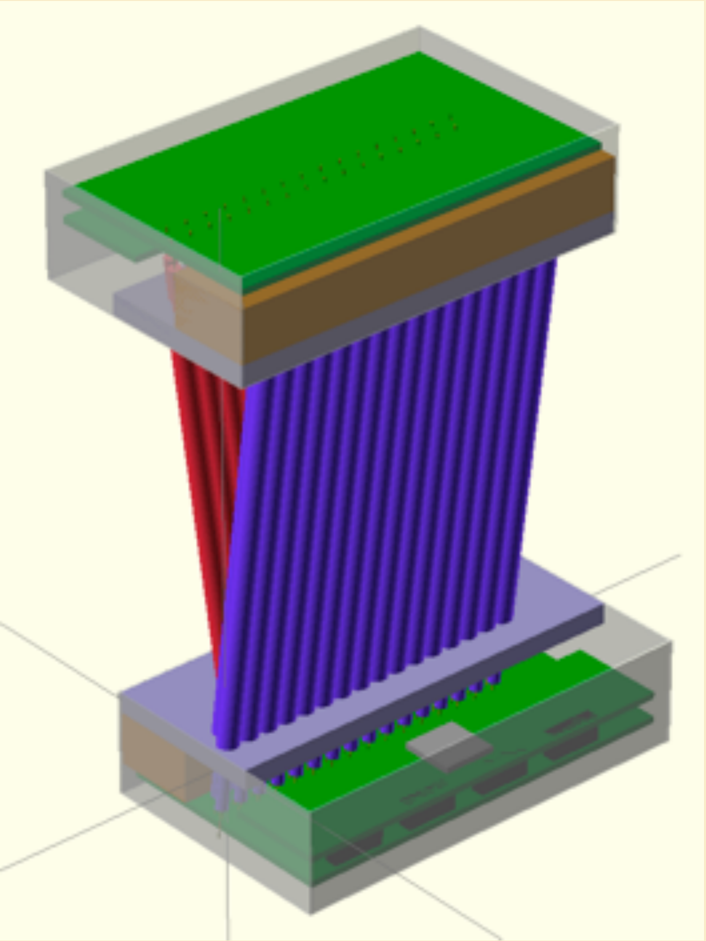




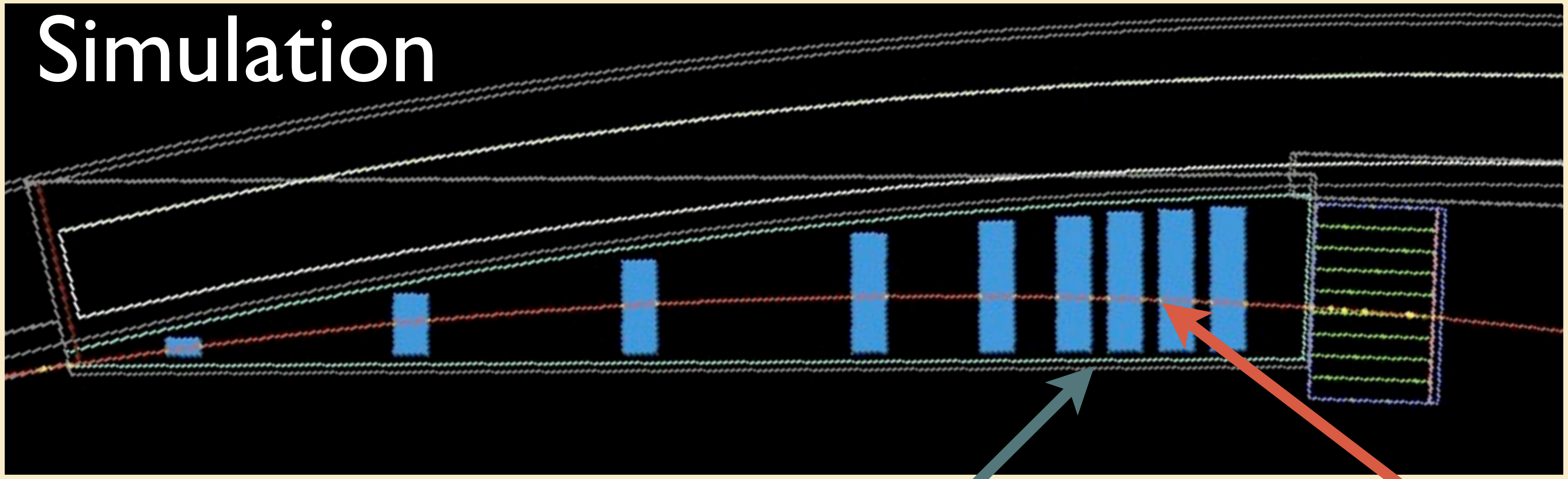
Tracking Traceback detectors

Each station is a doublet of UV straw chambers.





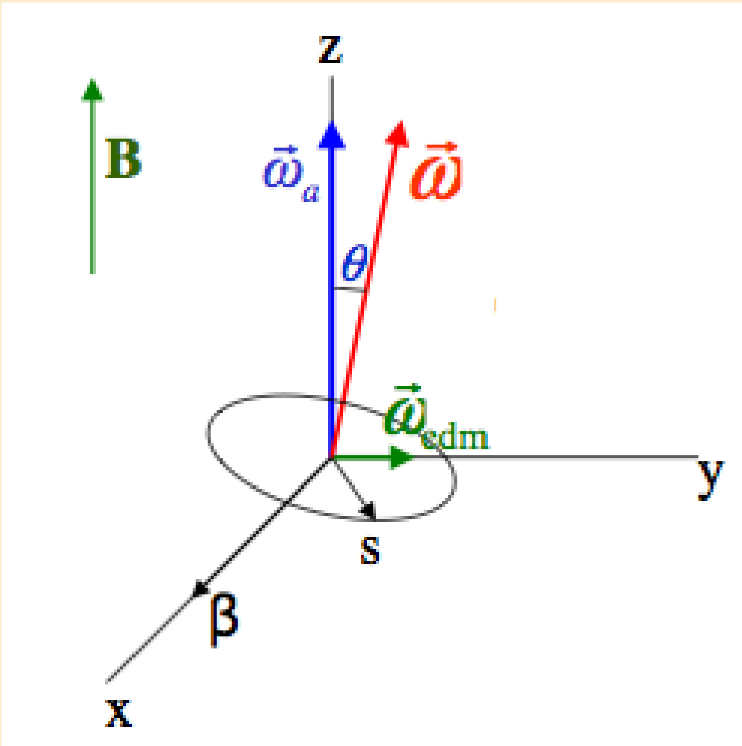
Important for pitch systematic, pileup, lost muons and Muon EDM

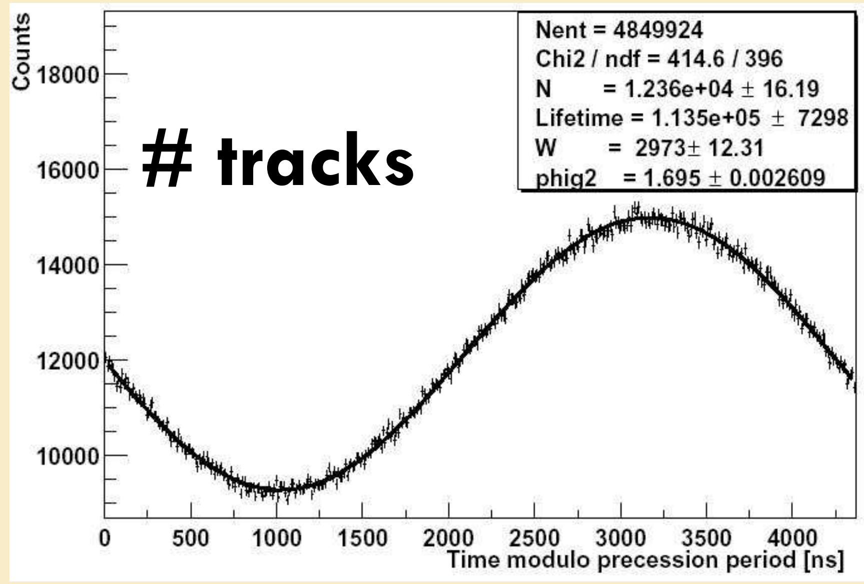


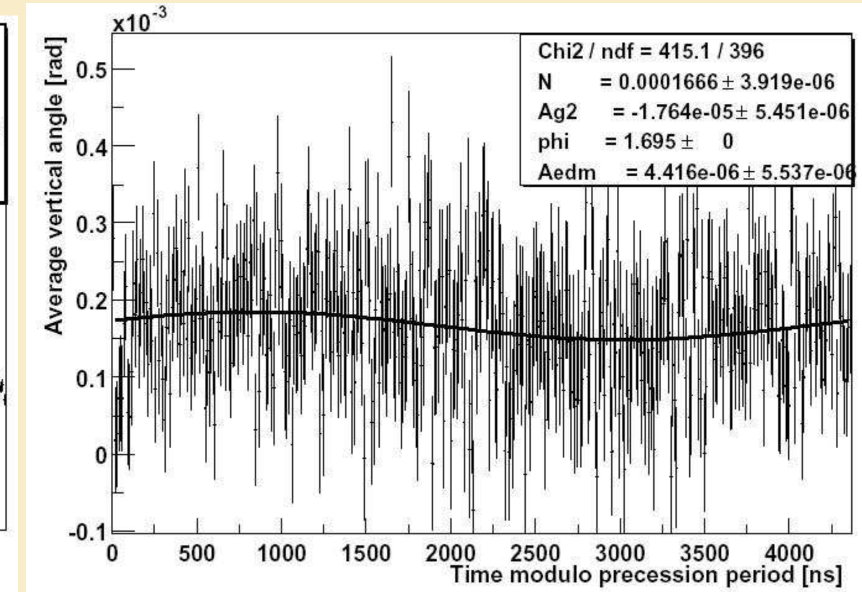
Geant4 Sensitive tracking detectors in place and easy to move for testing purposes.

Track!

Muon Electric Dipole Moment







vertical angle of tracks

Precession plane tilted, vertical out of phase oscillation of ω_a

Current best limit from E821

$$|d_\mu| < 1.8 \times 10^{-19}\, e \text{ cm } (95\% \text{ C.L.})$$

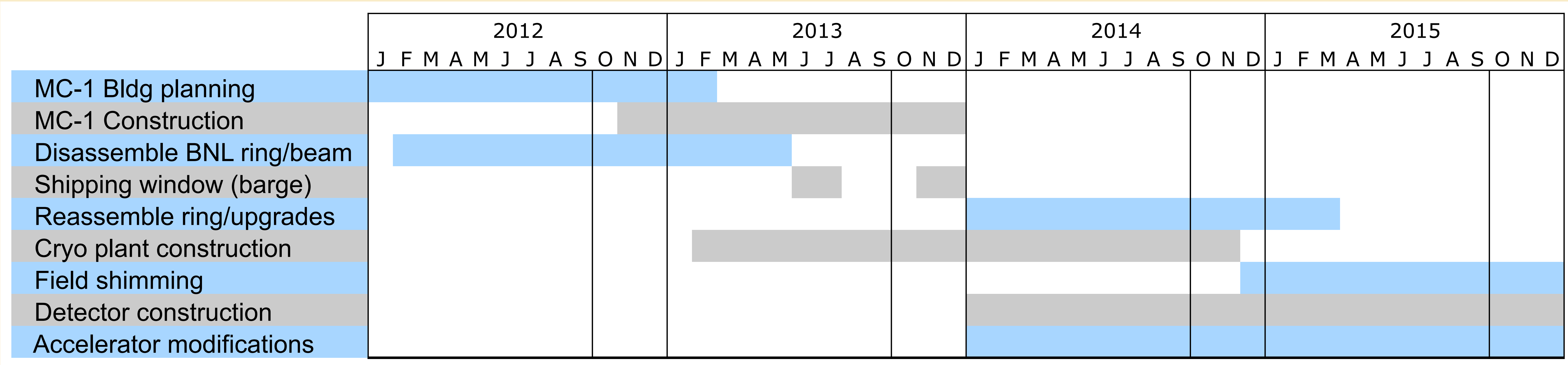
Expect < few 10^{-21}

EDMs do not exist in Standard Model

Existence implies Time and CP violation

Status and timeline

Just passed DOE CD-1 Review!



Building is progressing

Summary

Exciting times ahead!

A new era for Fermilab with Muon Physics!

Lots more pictures and movies of the Ring Transport at muon-g-2.fnal.gov/bigmove