The Muon g-2 Experiment at Fermilab

Adam Lyon, Fermilab

UMN Physics Colloquium

April 2016

Photo: Hogan Nguyen, Fermilab

A little about me

Undergrad:

- NC State '91

Grad School:

- U Maryland '97 / N. Hadley
- DØ Experiment @ FNAL
- Supersymmetry Search

Postdoc:

- U Rochester 1997-2002 / E. Thorndike
- CLEO Experiment @ Cornell
- $b \to s\gamma$

Now:

- Fermilab Scientist in the Scientific Computing Division
- Formerly on DØ (Dibosons)
- Now Muon g-2

VOLUME 83, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1999

Search for Squarks and Gluinos in Events Containing Jets and a Large Imbalance in Transverse Energy

B. Abbott,[40] M. Abolins,[37] V. Abramov,[15] B. S. Acharya,[8] I. Adam,[39] D. L. Adams,[49] M. Adams,[24] S. Ahn,[23] G. A. Alves,[2] N. Amos,[36] E. W. Anderson,[30] M. M. Baarmand,[42] V. V. Babintsev,[15] L. Babukhadia,[16] A. Baden,[33] B. Baldin,[23] S. Banerjee,[8] J. Bantly,[46] E. Barberis,[17] P. Baringer,[31] J. F. Bartlett,[23] A. Belyaev,[14] S. B. Beri,[6] I. Bertram,[26] V. A. Bezzubov,[15] P. C. Bhat,[23] V. Bhatnagar,[6] M. Bhattacharjee,[42] N. Biswas,[28] G. Blazey,[25] S. Blessing,[21] P. Bloom,[18] A. Boehnlein,[23] N. I. Bojko,[15] F. Borcherding,[23] C. Boswell,[20] A. Brandt,[23] R. Breedon,[18] G. Briskin,[46] R. Brock,[37] A. Bross,[23] D. Buchholz,[26] V. S. Burtovoi,[15] J. M. Butler,[34] W. Carvalho,[2] D. Casey,[37] Z. Casilum,[42] H. Castilla-Valdez,[11] D. Chakraborty,[42] S. V. Chekulaev,[15] W. Chen,[42] S. Choi,[10] S. Chopra,[21] B. C. Choudhary,[20] J. H. Christenson,[23] M. Chung,[24] D. Claes,[38] A. R. Clark,[17] W. G. Cobau,[33] J. Cochran,[20] L. Coney,[28] W. E. Cooper,[23] D. Coppage,[31] C. Cretsinger,[41] D. Cullen-Vidal,[46] M. A. C. Cummings,[25] D. Cutts,[46] O. I. Dahl,[17] K. Davis,[16] K. De,[47] K. Del Signore,[36] M. Demarteau,[23] D. Denisov,[23] S. P. Denisov,[15] H. T. Diehl,[23] M. Diesburg,[23] G. Di Loreto,[37] P. Draper,[47] Y. Ducros,[5] L. V. Dudko,[14] S. R. Dugad,[8] A. Dyshkant,[15] D. Edmunds,[37] J. Ellison,[20] V. D. Elvira,[42] R. Engelmann,[42] S. Eno,[33] G. Eppley,[49] P. Ermolov,[14] O. V. Eroshin,[15] V. N. Evdokimov,[15] T. Fahland,[19] M. K. Fatyga,[41] S. Feher,[23] D. Fein,[16] T. Ferbel,[41] H. E. Fisk,[23] Y. Fisyak,[43] E. Flattum,[23] G. E. Forden,[16] M. Fortner,[25] K. C. Frame,[37] S. Fuess,[23] E. Gallas,[47] A. N. Galyaev,[15] P. Gartung,[20] V. Gavrilov,[13] T. L. Geld,[37] R. J. Genik II,[37] K. Genser,[23] C. E. Gerber,[23] Y. Gershtein,[13] B. Gibbard,[43] B. Gobbi,[26] B. Gómez,[4] G. Gómez,[33] P. I. Goncharov,[15] J. L. González Solís,[11] H. Gordon,[43] L. T. Goss,[48] K. Gounder,[20] A. Goussiou,[42] N. Graf,[43] P. D. Grannis,[42] D. R. Green,[23] H. Greenlee,[23] S. Grinstein,[1] P. Grudberg,[17] S. Grünendahl,[23] G. Guglielmo,[45] J. A. Guida,[16] J. M. Guida,[46] A. Gupta,[8] S. N. Gurzhiev,[15] G. Gutierrez,[23] P. Gutierrez,[45] N. J. Hadley,[33] H. Haggerty,[23] S. Hagopian,[21] V. Hagopian,[21] K. S. Hahn,[41] R. E. Hall,[19] P. Hanlet,[35] S. Hansen,[23] J. M. Hauptman,[30] C. Hebert,[31] D. Hedin,[25] A. P. Heinson,[20] U. Heintz,[34] R. Hernández-Montoya,[11] T. Heuring,[21] R. Hirosky,[24] J. D. Hobbs,[42] B. Hoeneisen,[4,+] J. S. Hoftun,[46] F. Hsieh,[36] Tong Hu,[27] A. S. Ito,[23] J. Jaques,[28] S. A. Jerger,[37] R. Jesik,[27] T. Joffe-Minor,[26] K. Johns,[16] M. Johnson,[23] A. Jonckheere,[23] M. Jones,[22] H. Jöstlein,[23] S. Y. Jun,[26] C. K. Jung,[42] S. Kahn,[43] G. Kalbfleisch,[45] D. Karmanov,[14] D. Karmgard,[21] R. Kehoe,[28] S. K. Kim,[10] B. Klima,[23] C. Klopfenstein,[18] W. Ko,[18] J. M. Kohli,[6] D. Koltick,[29] A. V. Kostritskiy,[15] J. Kotcher,[43] A. V. Kotwal,[39] A. V. Kozelov,[15] E. A. Kozlovsky,[15] J. Krane,[38] M. R. Krishnaswamy,[8] S. Krzywdzinski,[23] S. Kuleshov,[13] Y. Kulik,[42] S. Kunori,[33] F. Landry,[37] G. Landsberg,[46] B. Lauer,[30] A. Leflat,[14] J. Li,[47] Q. Z. Li,[23] J. [illegible] Lima, [illegible] coln,[23] S. L. Linn,[21] J. Linnemann,[37] R. Lipton,[23] F. Lobkowicz,[41] A. Lucotte,[42] L. Lu[illegible]ng,[23] A. L. Lyon,[33] A. [illegible] K. A. Maciel,[2] R. J. Madaras,[17] R. Madden,[21] L. Magaña-Mendoza,[11] V. Manankov,[14] [illegible] Mani,[18] H. S. M[illegible],[†] R. Markeloff,[25] T. Marshall,[27] M. I. Martin,[23] K. M. Mauritz,[30] B. May,[26] A. A. Mayorov, [illegible] McCarthy,[42] J. McDonald,[21] T. McKibben,[24] J. McKinley,[37] T. McMahon,[44] H. L. Melanson,[23] M. Merkin,[14] K. W. Merritt,[23] C. Miao,[46] H. Miettinen,[49] A. Mincer,[40] C. S. Mishra,[23] N. Mokhov,[23] N. K. Mondal,[8] H. E. Montgomery,[23] P. Mooney,[4] M. Moztafa,[1] H. da Motta,[2] C. Murphy,[24] F. Nang,[16] M. Narain,[34] V. S. Narasimham,[8] A. Narayanan,[16] H. A. Neal,[36] J. P. Negret,[4] P. Nemethy,[40] D. Norman,[48] L. Oesch,[36] V. Oguri,[3] N. Oshima,[23] D. Owen,[37] P. Padley,[49] A. Para,[23] N. Parashar,[35] Y. M. Park,[9] R. Partridge,[46] N. Parua,[8] M. Paterno,[41] B. Pawlik,[12] J. Perkins,[47] M. Peters,[22] R. Piegaia,[1] H. Piekarz,[21] Y. Pischalnikov,[29] B. G. Pope,[37] H. B. Prosper,[21] S. Protopopescu,[43] J. Qian,[36] P. Z. Quintas,[23] R. Raja,[23] S. Rajagopalan,[43] O. Ramirez,[24] S. Reucroft,[35] M. Rijssenbeek,[42] T. Rockwell,[37] M. Roco,[23] P. Rubinov,[26] R. Ruchti,[28] J. Rutherfoord,[16] A. Sánchez-Hernández,[11] A. Santoro,[2] L. Sawyer,[32] R. D. Schamberger,[42] H. Schellman,[26] J. Scully,[40] E. Shabalina,[14] C. Shaffer,[21] H. C. Shankar,[8] R. K. Shivpuri,[7] D. Shpakov,[42] M. Shupe,[16] H. Singh,[20] J. B. Singh,[6] V. Sirotenko,[25] E. Smith,[45] R. P. Smith,[23] R. Snihur,[26] G. R. Snow,[38] J. Snow,[44] S. Snyder,[43] J. Solomon,[24] M. Sosebee,[47] N. Sotnikova,[14] M. Souza,[2] G. Steinbrück,[45] R. W. Stephens,[47] M. L. Stevenson,[17] F. Stichelbaut,[43] D. Stoker,[19] V. Stolin,[13] D. A. Stoyanova,[15] M. Strauss,[45] K. Streets,[40] M. Strovink,[17] A. Sznajder,[2] P. Tamburello,[33] J. Tarazi,[19] M. Tartaglia,[23] T. L. T. Thomas,[26] J. Thompson,[33] T. G. Trippe,[17] P. M. Tuts,[39] V. Vaniev,[15] N. Varelas,[24] E. W. Varnes,[17] A. A. Volkov,[15] A. P. Vorobiev,[15] H. D. Wahl,[21] G. Wang,[21] J. Warchol,[28] G. Watts,[46] M. Wayne,[28] H. Weerts,[37] A. White,[47] J. T. White,[48] J. A. Wightman,[30] S. Willis,[25] S. J. Wimpenny,[20] J. V. D. Wirjawan,[48] J. Womersley,[23] E. Won,[41] D. R. Wood,[35] Z. Wu,[23,†] R. Yamada,[23] P. Yamin,[43] T. Yasuda,[35] P. Yepes,[49] K. Yip,[23] C. Yoshikawa,[22] S. Youssef,[21] J. Yu,[23] Y. Yu,[10] B. Zhang,[23,†] Z. Zhou,[30] Z. H. Zhu,[41] M. Zielinski,[41] D. Zieminska,[27] A. Zieminski,[27] E. G. 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(D0 Collaboration)

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[3]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

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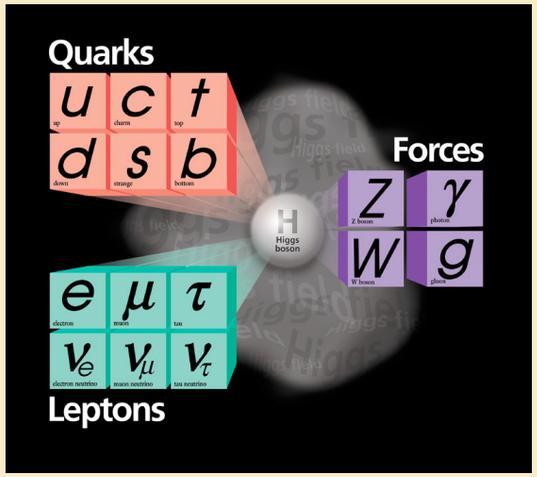
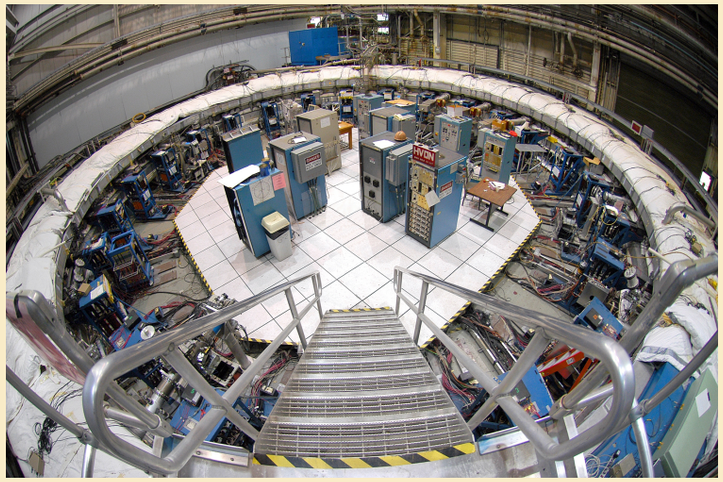
Outline of this Colloquium

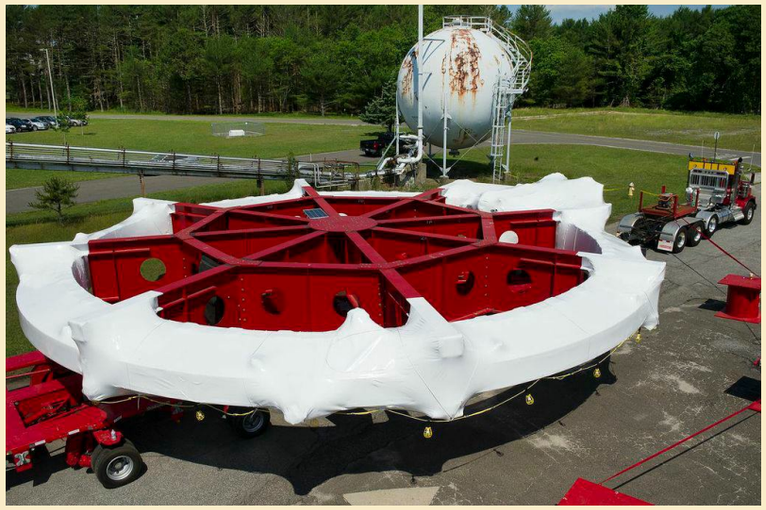


Motivation

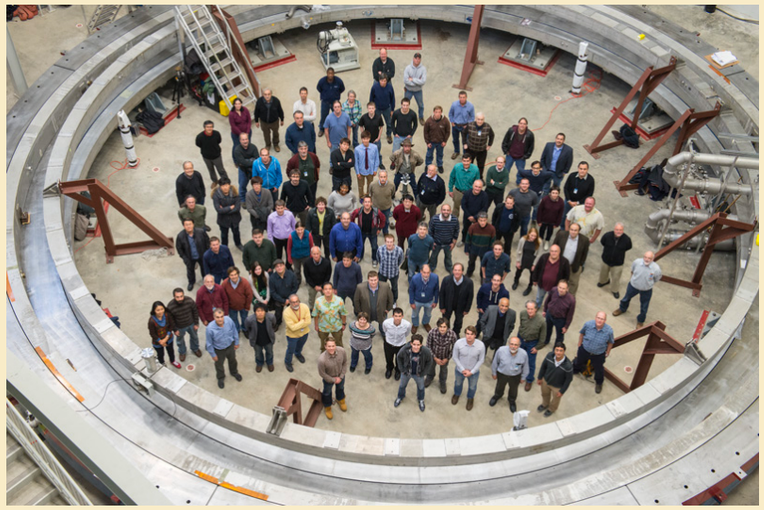


Muons and *g*-2

@ Fermilab



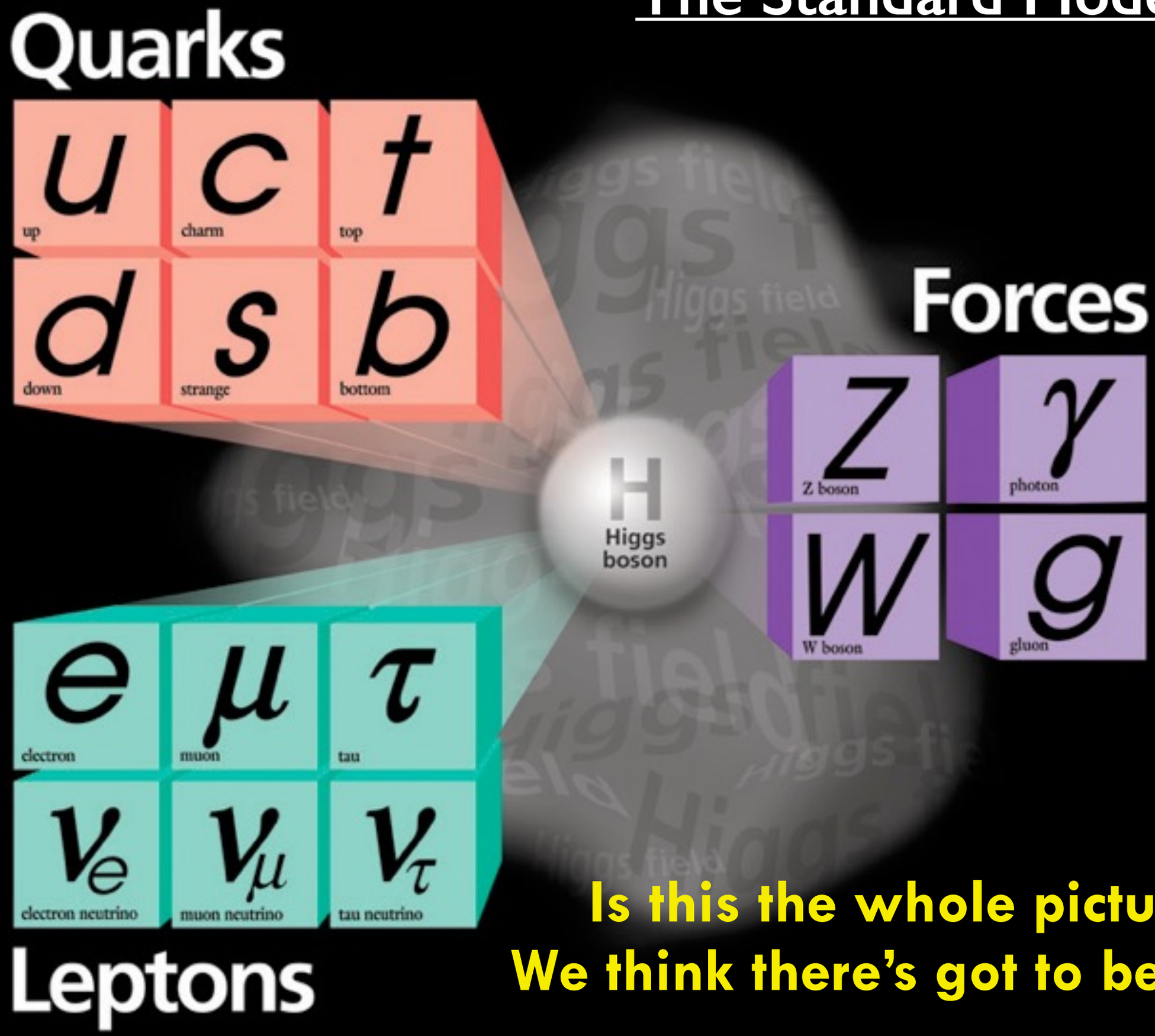
A journey



Assembly

To first muons

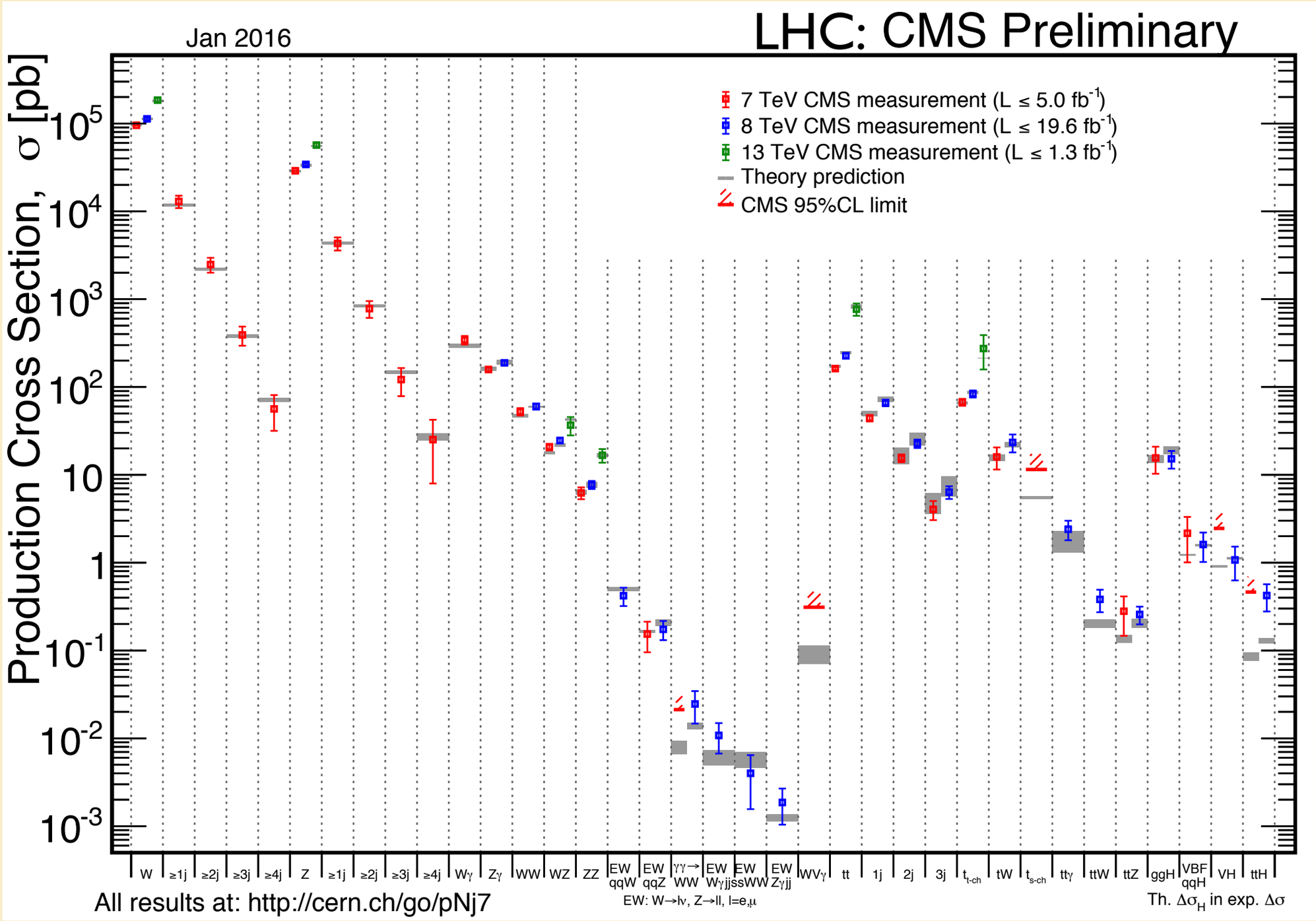
The Standard Model



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

Why do we look beyond the SM?

Despite being an <u>incredibly</u> successful model...

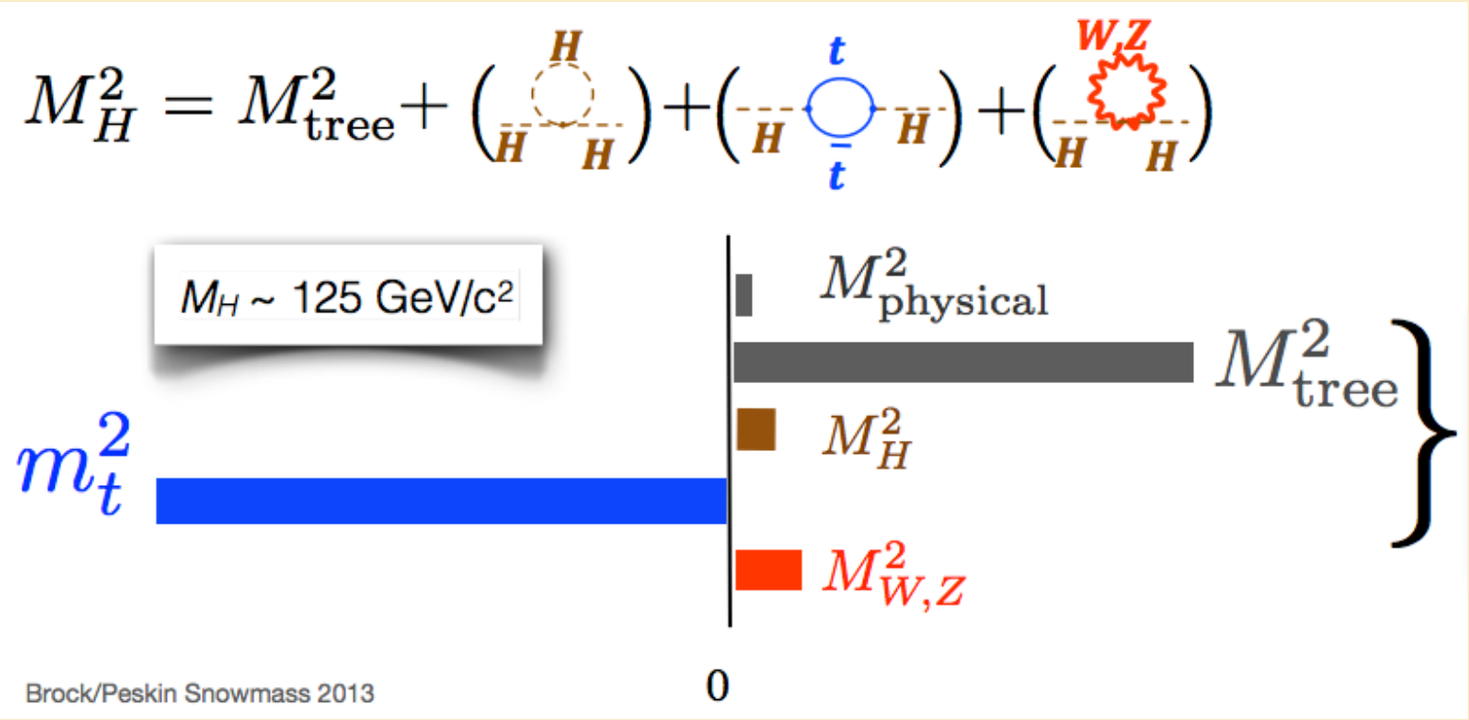


Why do we look beyond the SM?

... it doesn't predict everything we want:

- **Gravity? Dark matter? Dark energy? Neutrino masses? Matter/antimatter asymmetry?**

... and SM generates some headaches



Fine tuning necessary for Higgs mass to come out right

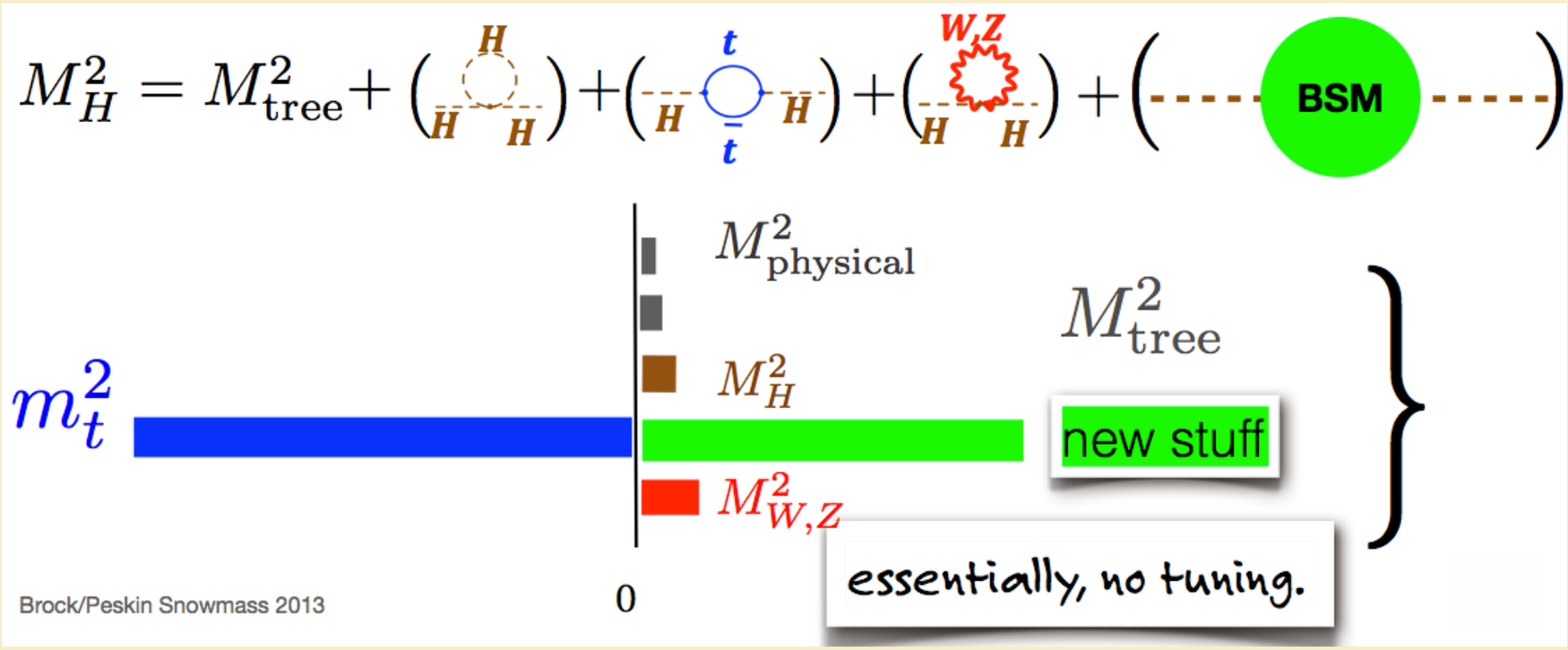
Naturalness/Hierarchy problem

Why do we look beyond the SM?

... it doesn't predict everything we want:

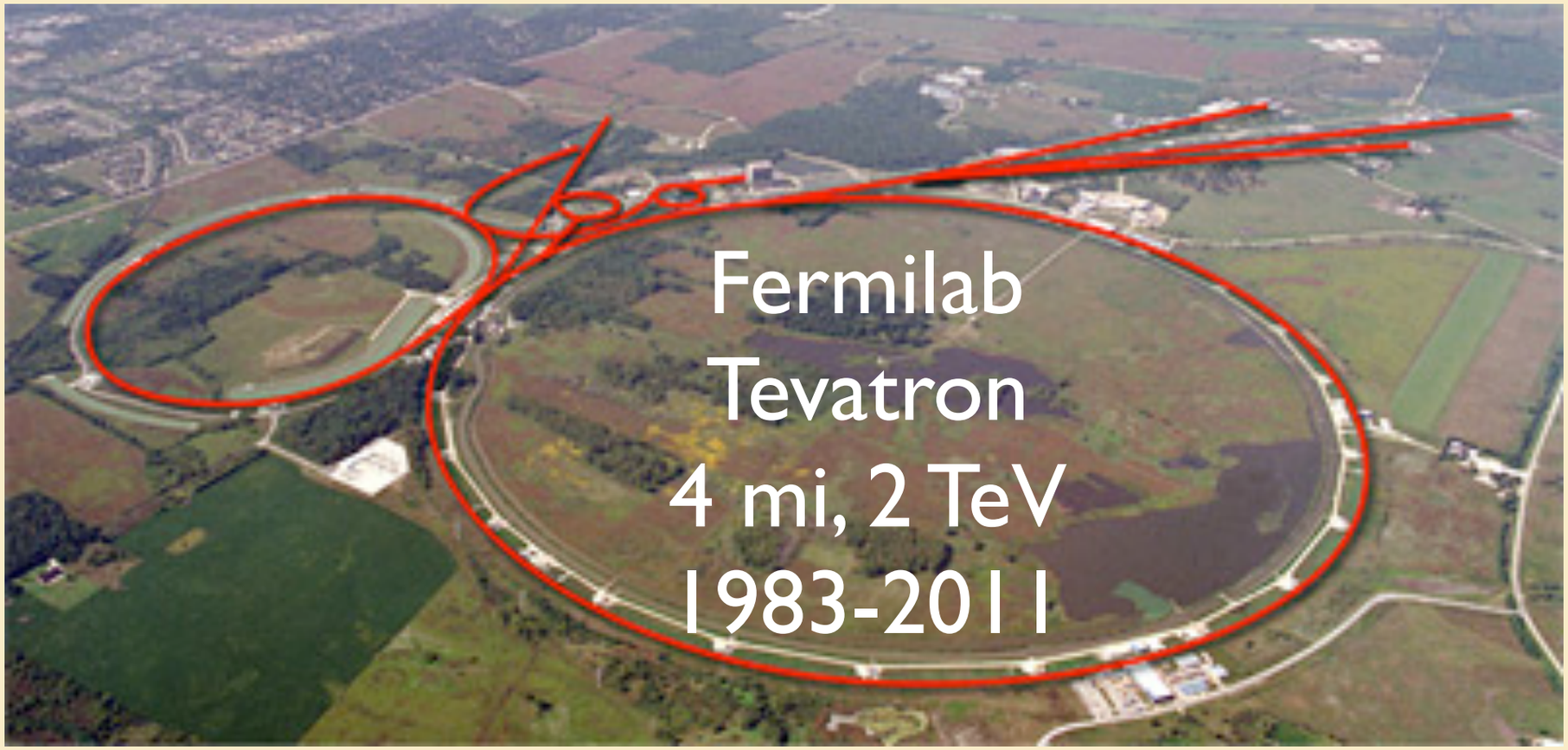
o Gravity? Dark matter? Dark energy? Neutrino masses? Matter/antimatter asymmetry?

... and SM generates some headaches

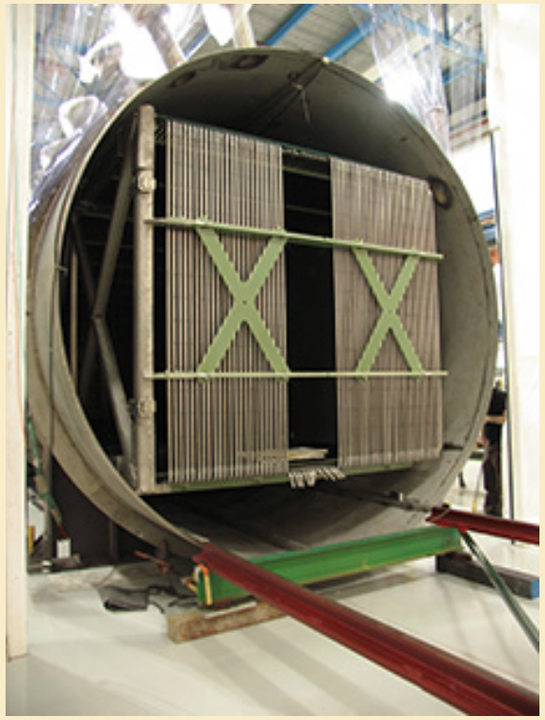


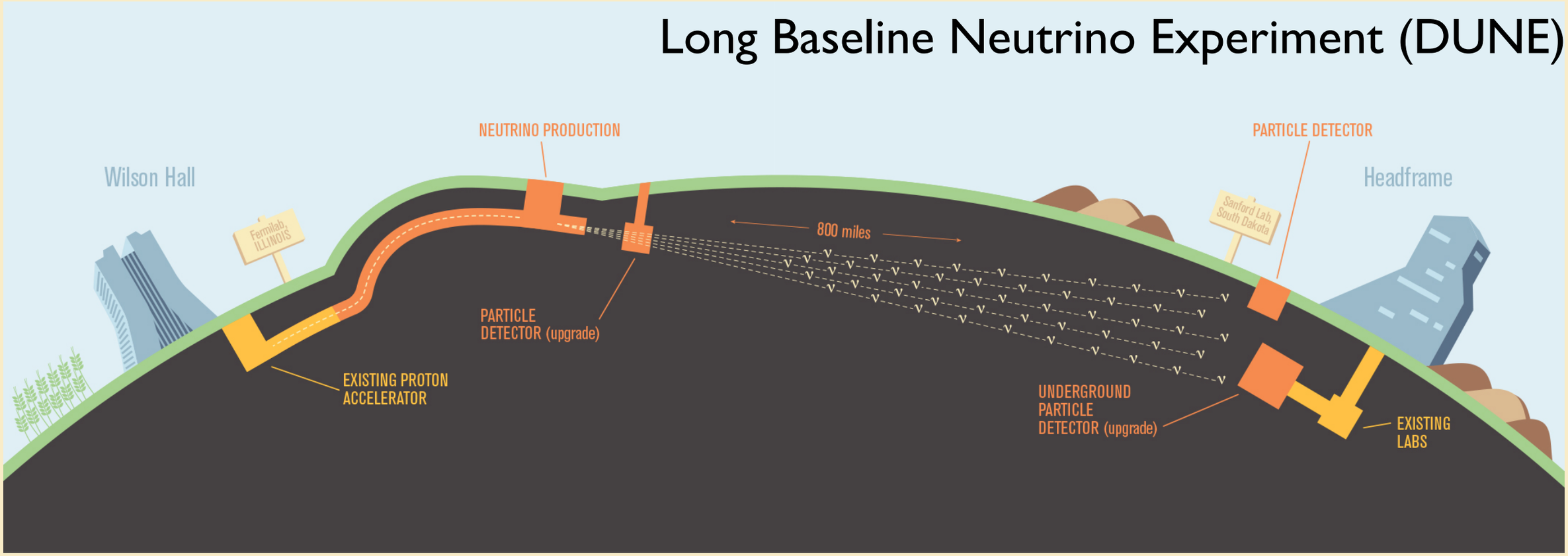
Avoid fine-tuning through Beyond SM (BSM) physics [e.g. Supersymmetry]

The Energy Frontier

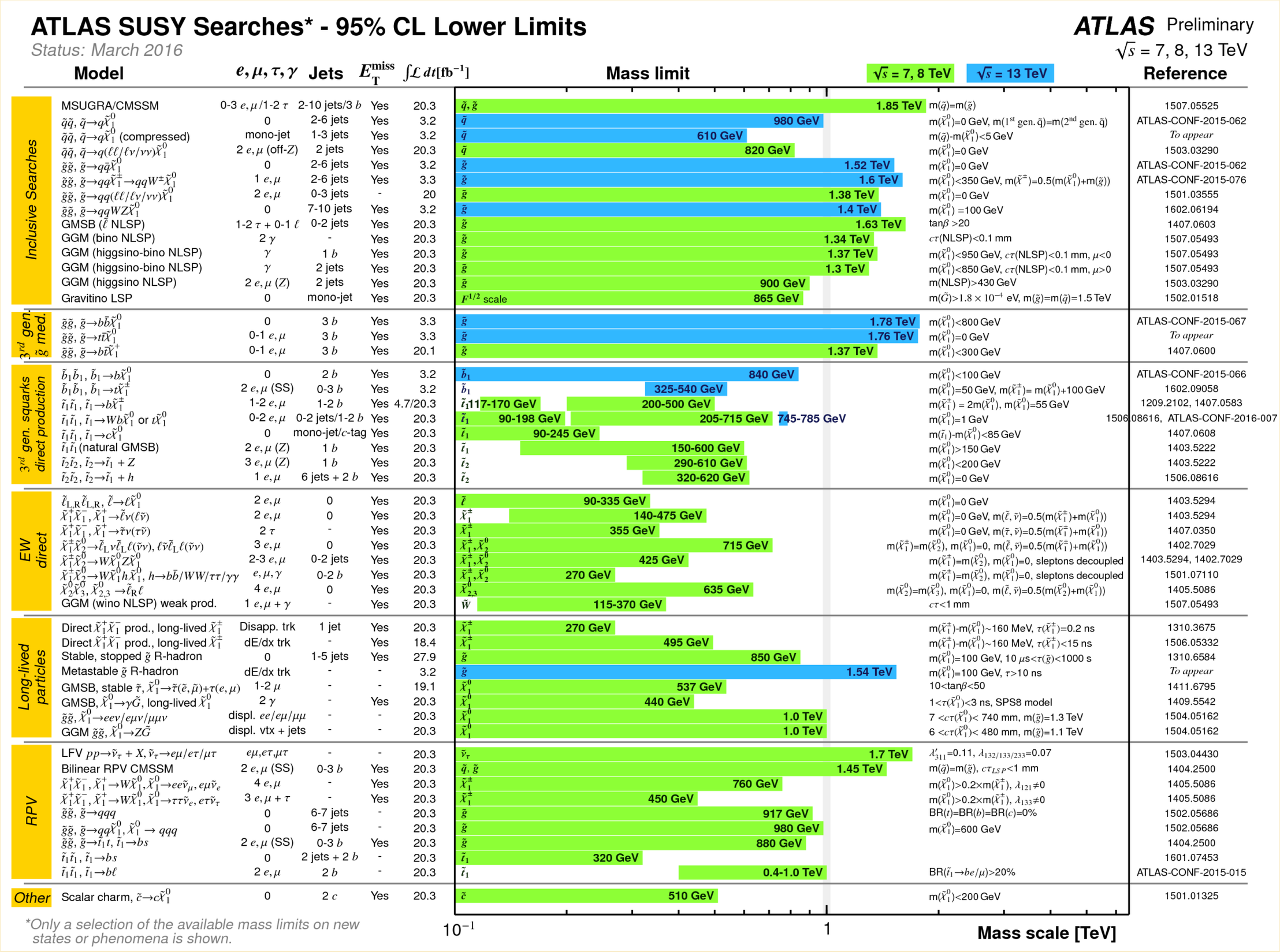


The Intensity Frontier





No obvious new physics, yet



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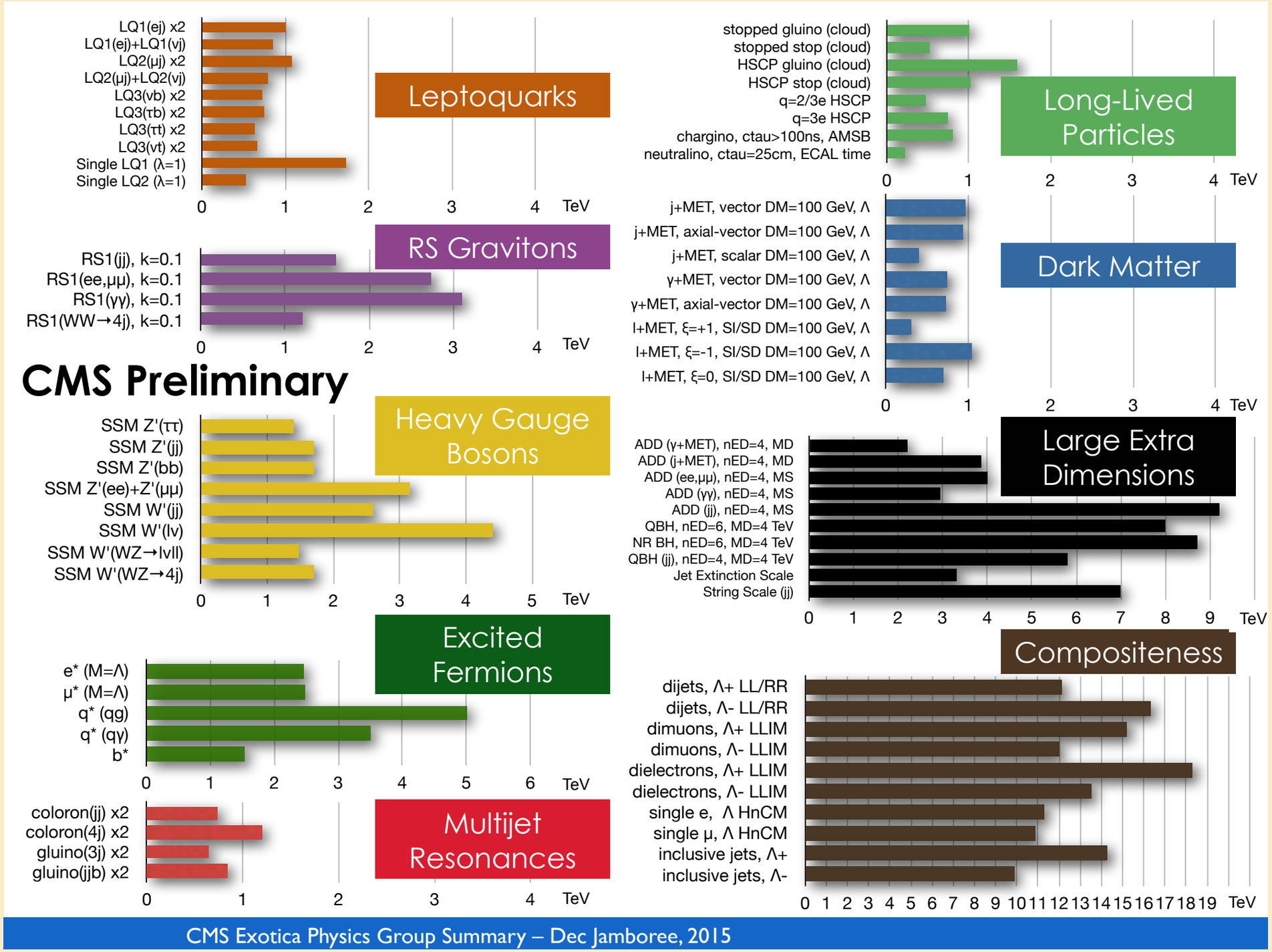


(well, 750 GeV excess? We'll see)

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 perhaps a hint of something new with "g-2")

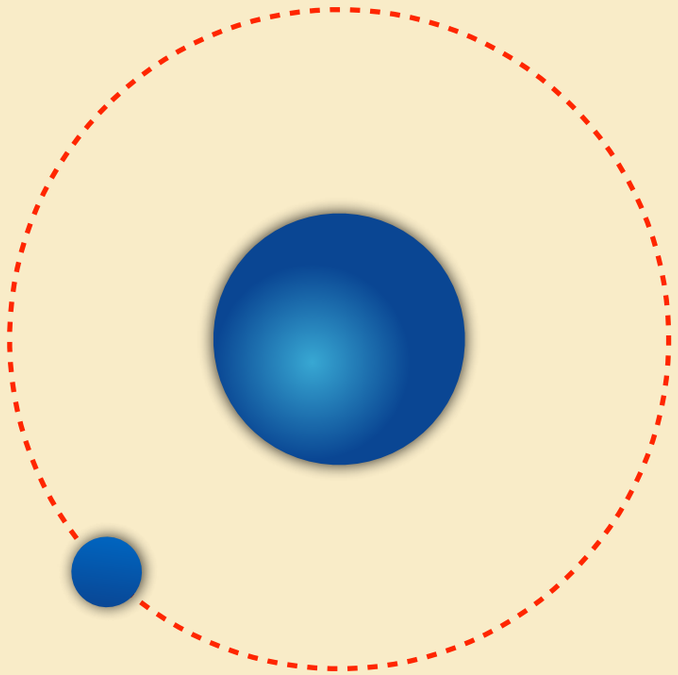
The basics of the "*g-factor*"

Orbiting charged particle:

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

Particle with spin has an *intrinsic* magnetic moment:

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

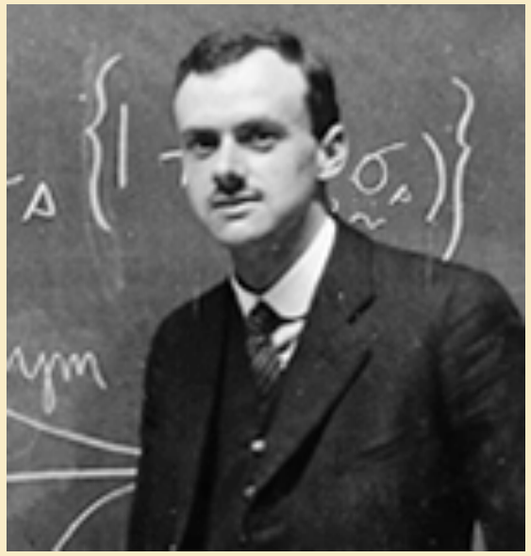


Classical system: g = 1

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

Why does g = 2?

Predicted theoretically by Dirac in 1928

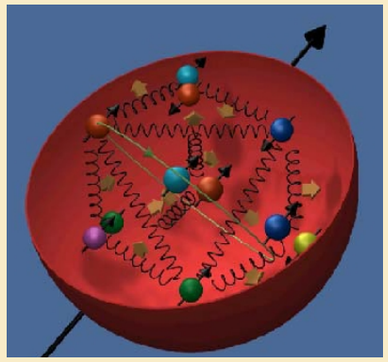


Paul Dirac

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

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

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

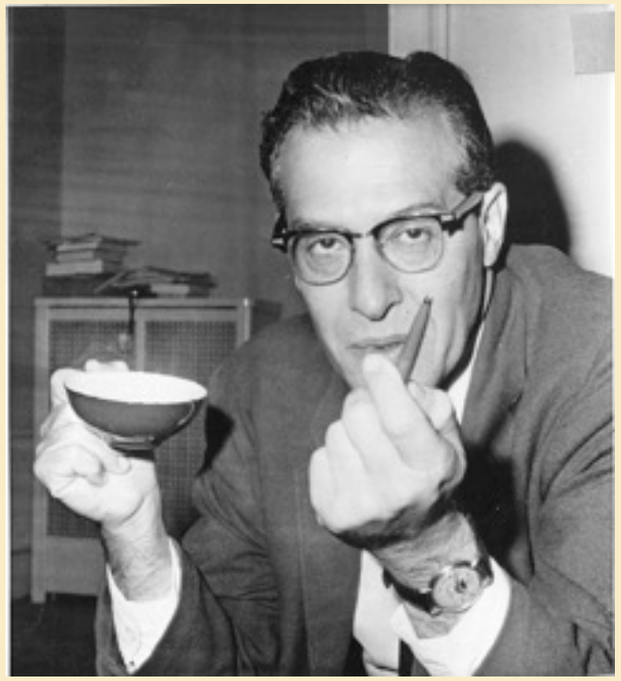
$$g_e = 2.00238(10)$$

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

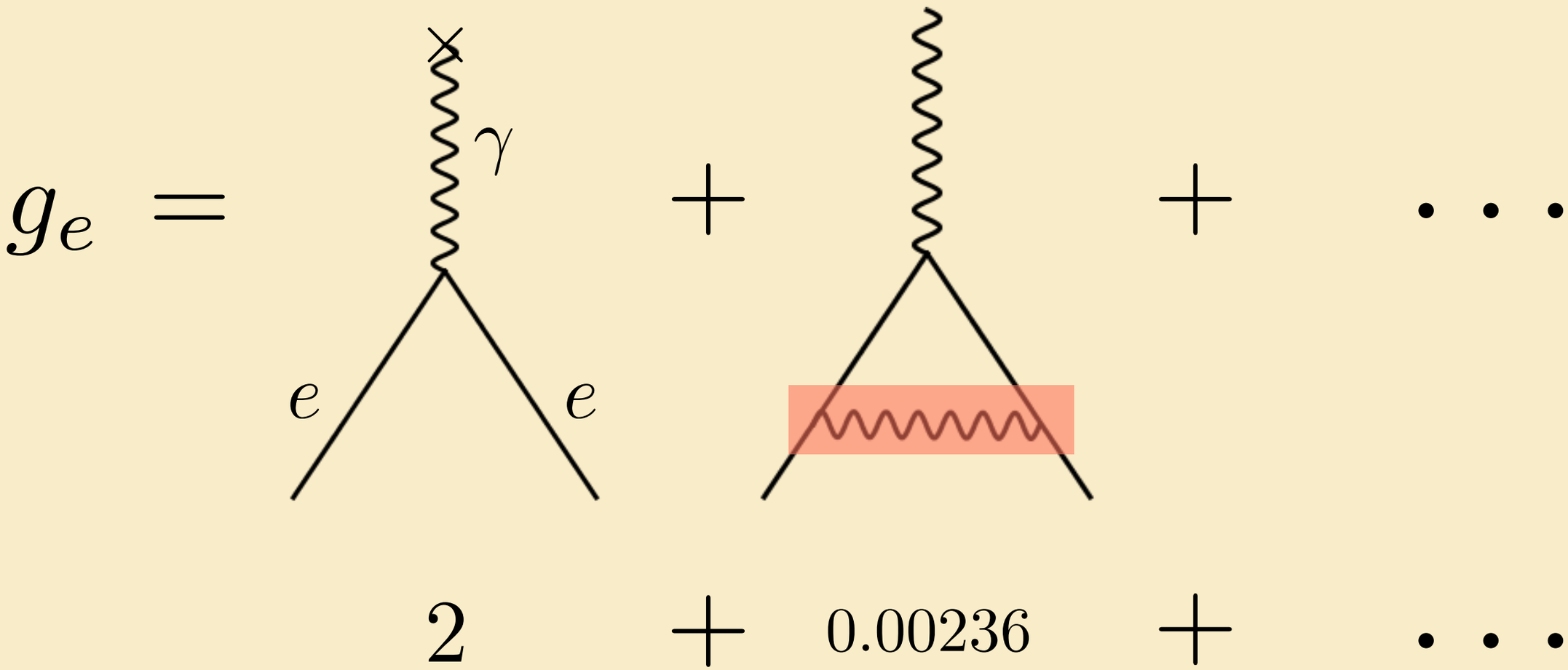
$$a_e = \alpha/2\pi = 0.00118$$



Julian Schwinger
"His laboratory is his ballpoint pen"

A new understanding begins

Empty space is not empty

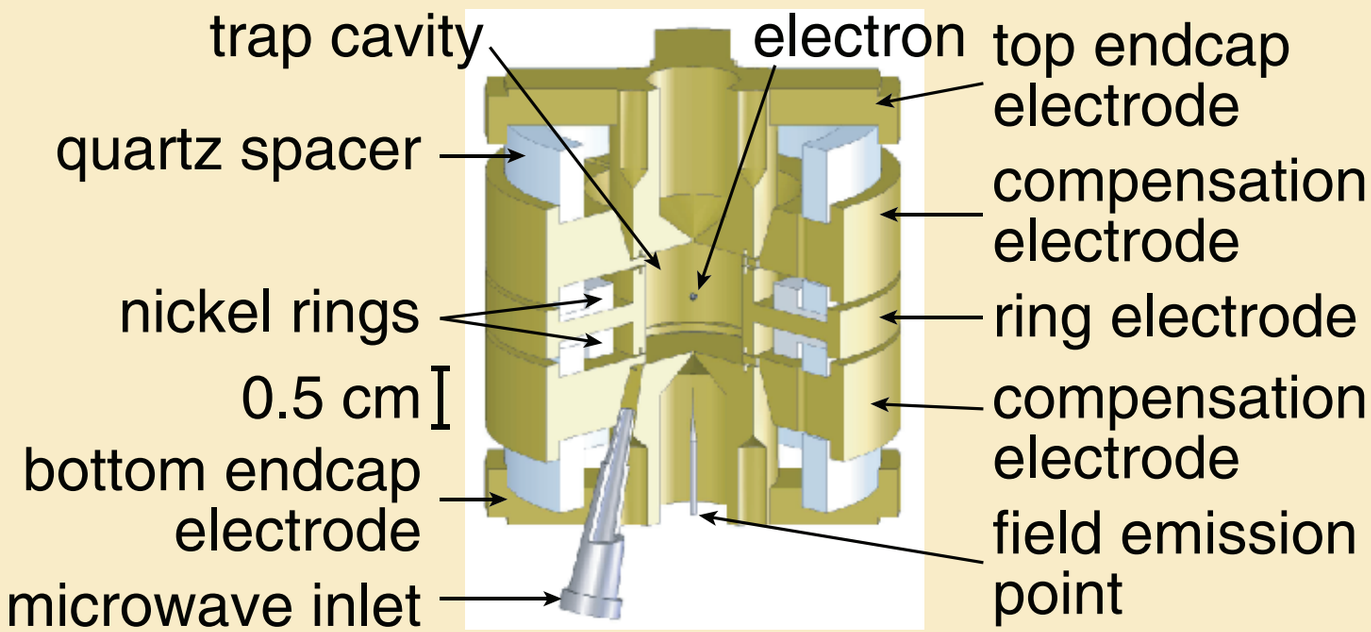


The beginnings of QED and the Standard Model

Currently, a_e is known to sub-ppb

Gabrielse (2006 & 2008):

Previous result was 20 years prior



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

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

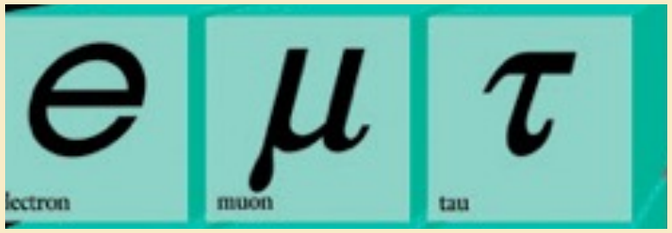
$1.628(20) \times 10^{-12}$ **Hadronic correction**

$0.0297(5) \times 10^{-12}$ **Weak correction**

See M.Passera INT2008

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

So look at muons!

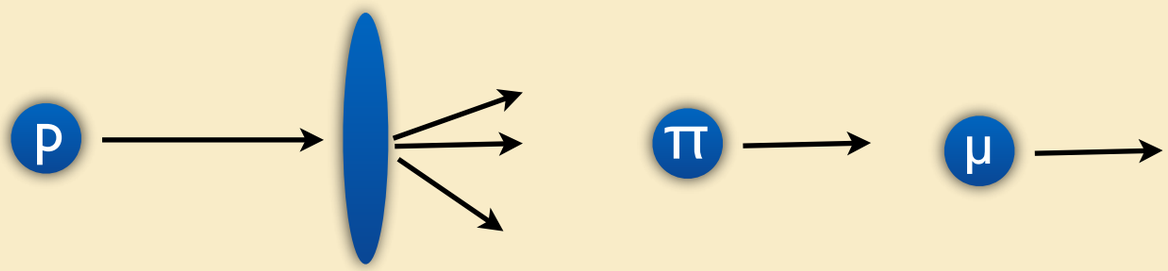


Taus would be even better, but lifetime and production rates are too small to be useful here

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

With Muons, we can control spin and measure it (weak interaction, parity violation)

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

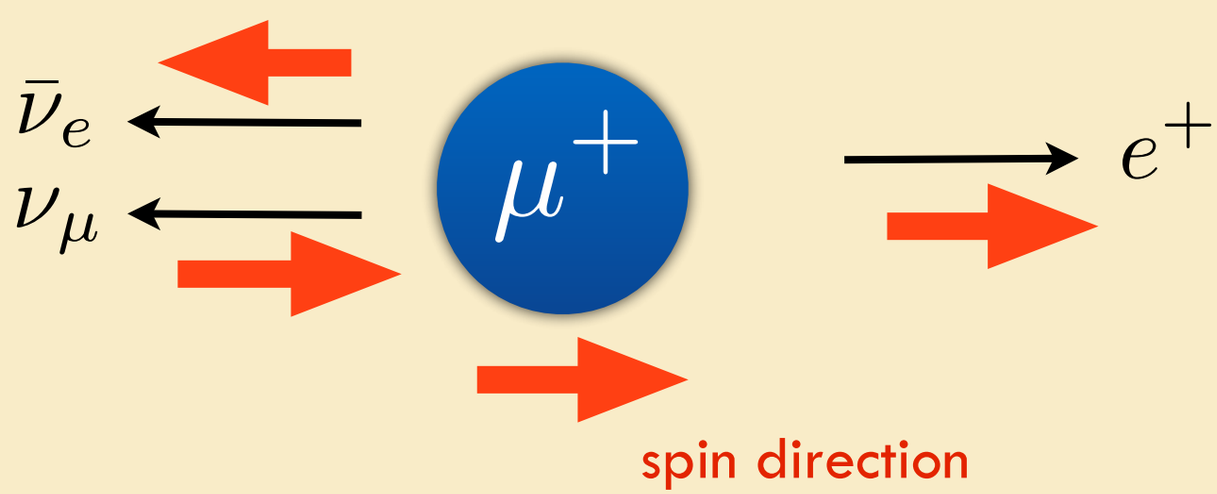


target

$$\nu \leftarrow \pi^+ \rightarrow \mu^+$$

97% polarization

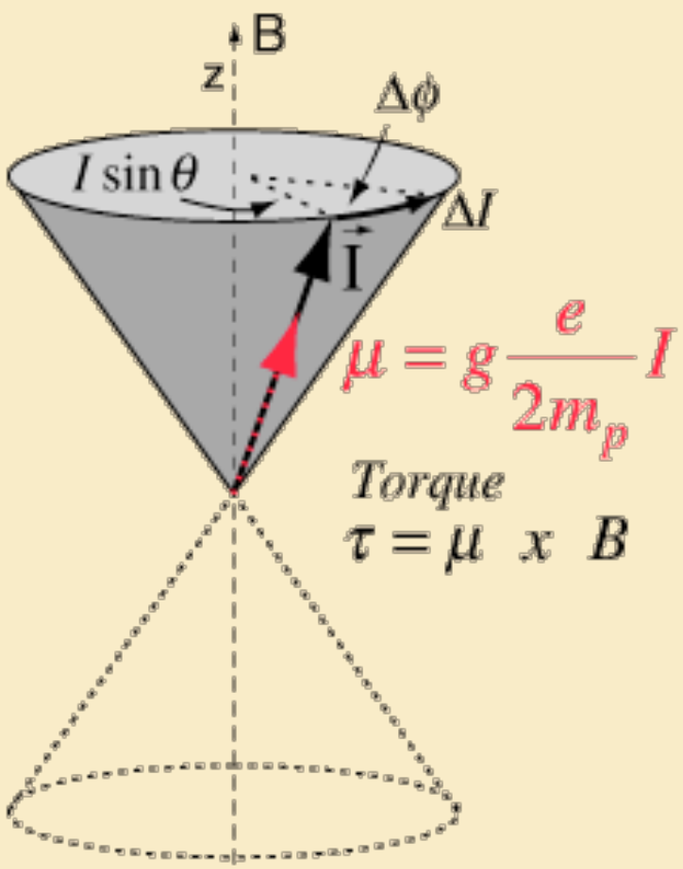
Decay: "Self analyzing" $\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$



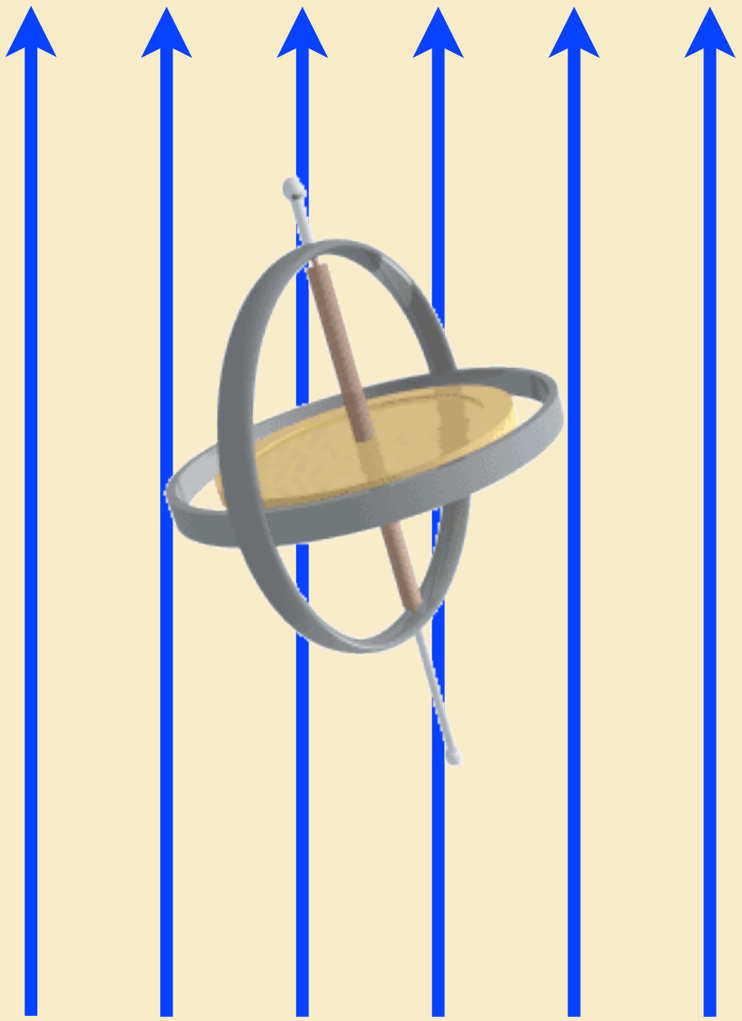
Highest energy positrons emitted along muon's spin direction (in Muon center of mass frame)

How to measure a_μ

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

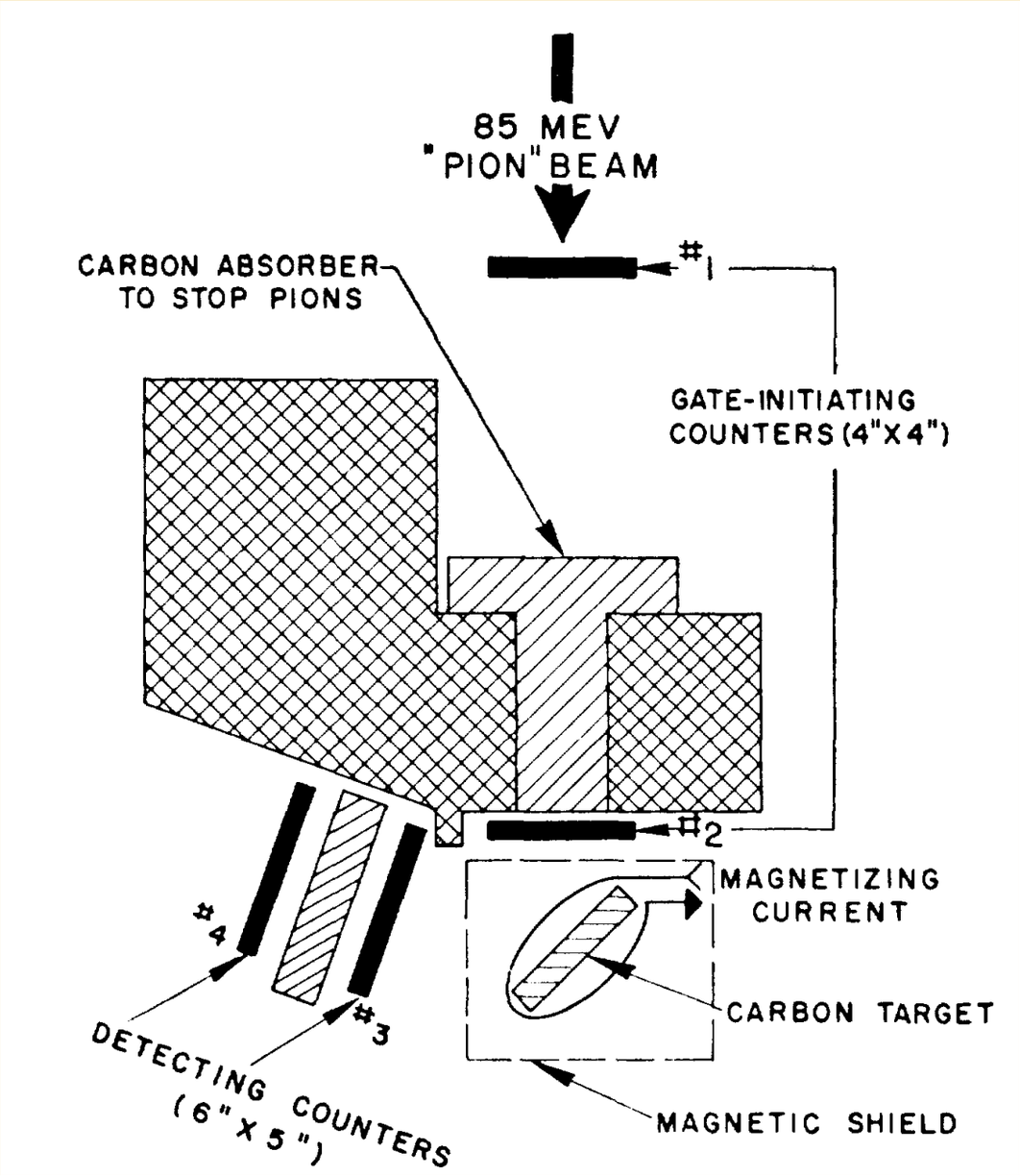


$$\omega_s = g \frac{eB}{2mc}$$

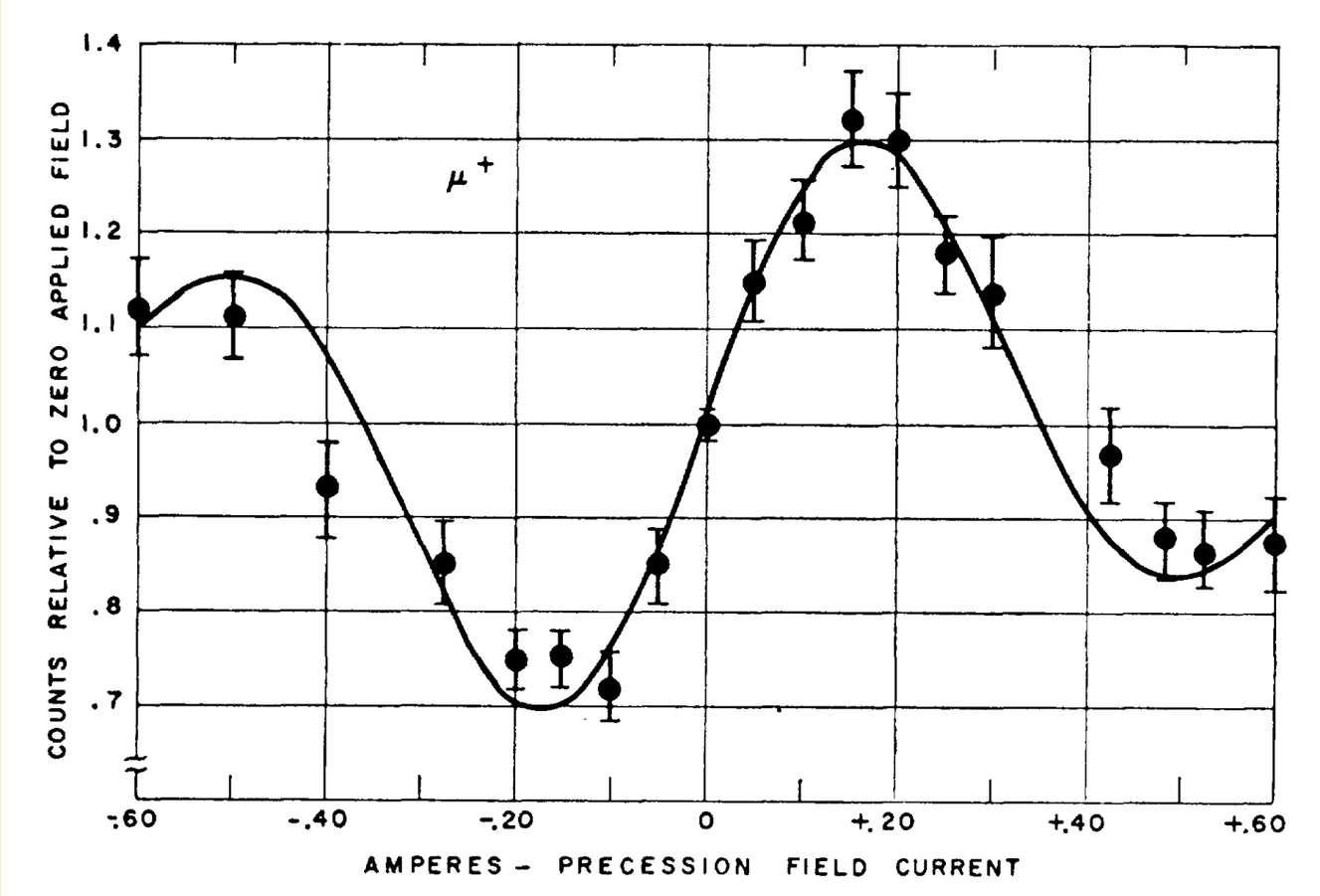


The first experiments for a_μ

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

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

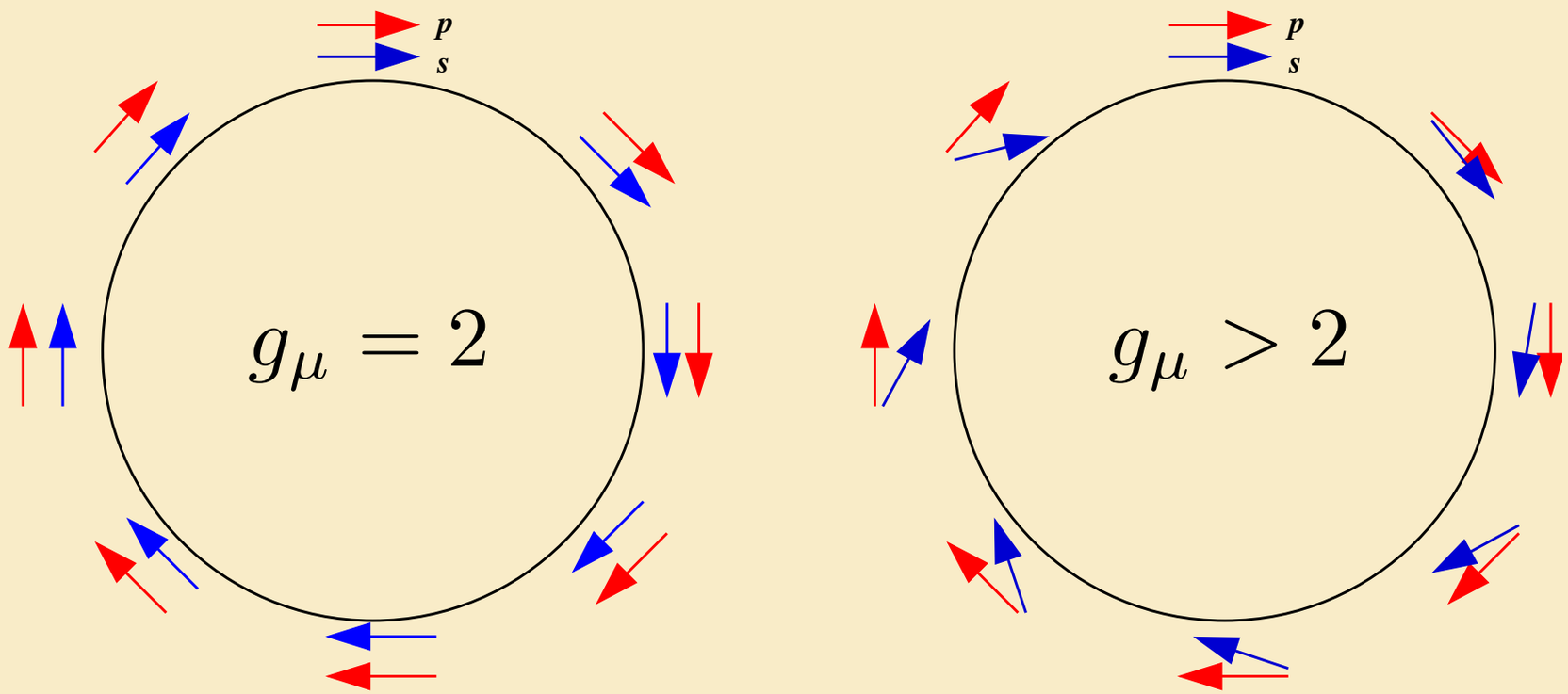
Larmor precession

Thomas precession

Taking their difference...

A fortuitous simplification

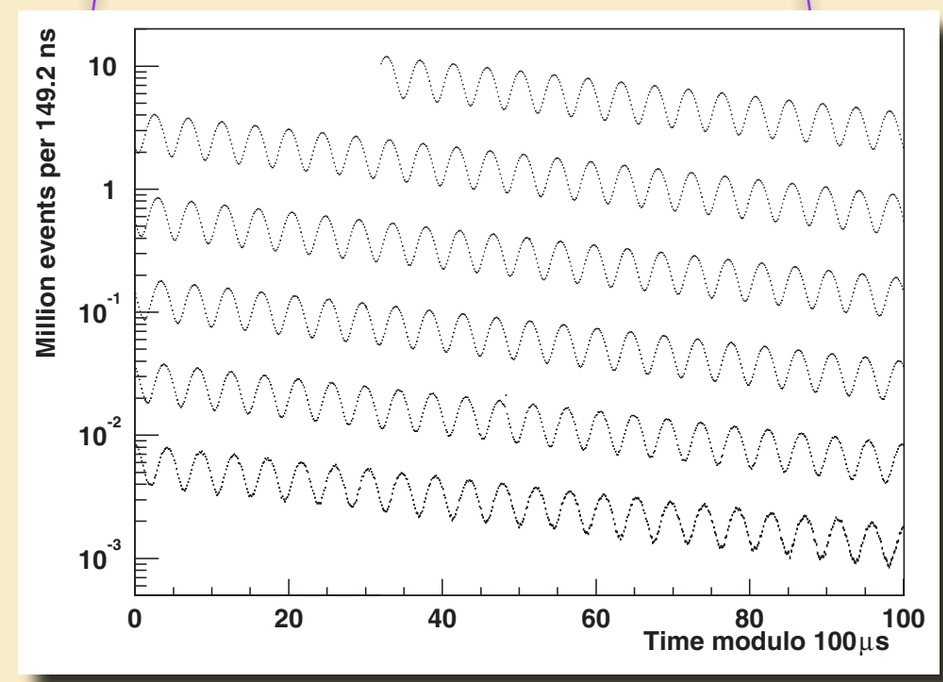
$$\omega_a = \omega_s - \omega_c = \frac{g_\mu - 2}{2}\frac{eB}{m_\mu c} = a_\mu \frac{eB}{m_\mu c}$$



True for any size ring and any muon momentum

The measurement plan

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

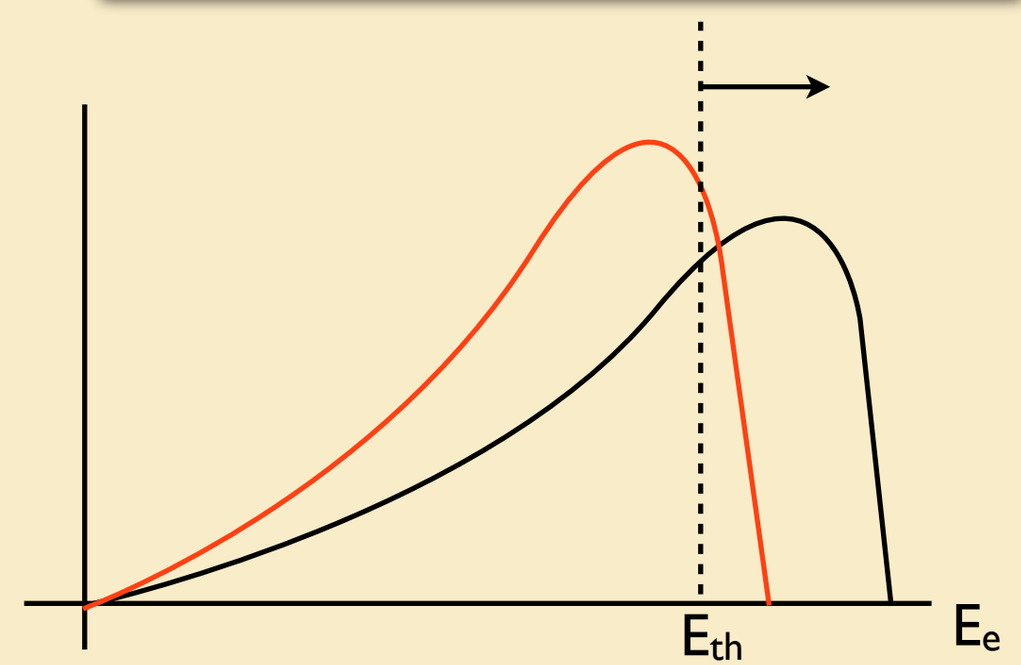


Muons circle the ring and decay to positrons, which travel inward hitting detectors

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



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 <u>NMR</u>) is essentially the magnetic field

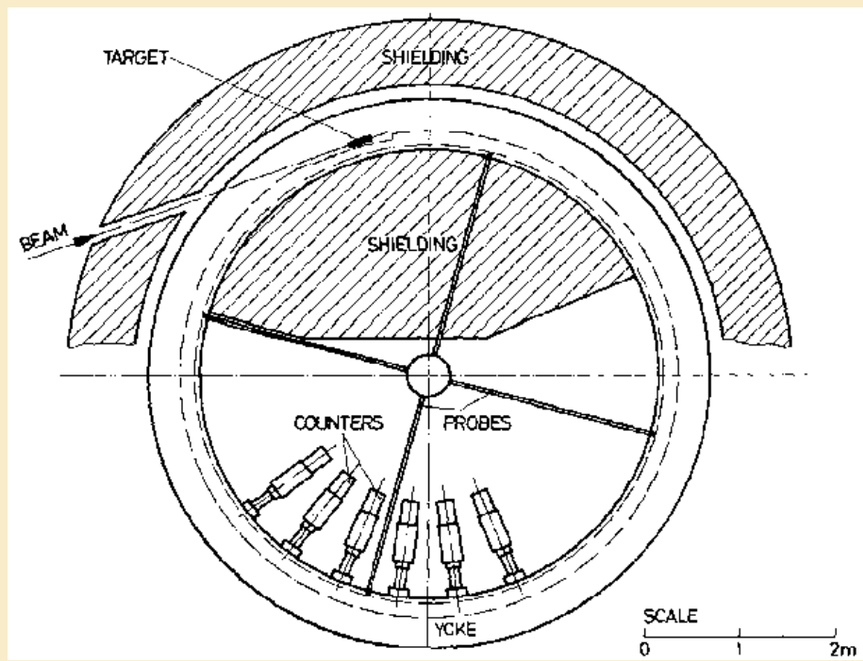
λ is muon to proton magnetic moment ratio. Get from muonium hyperfine splitting structure (Liu) 26 ppb

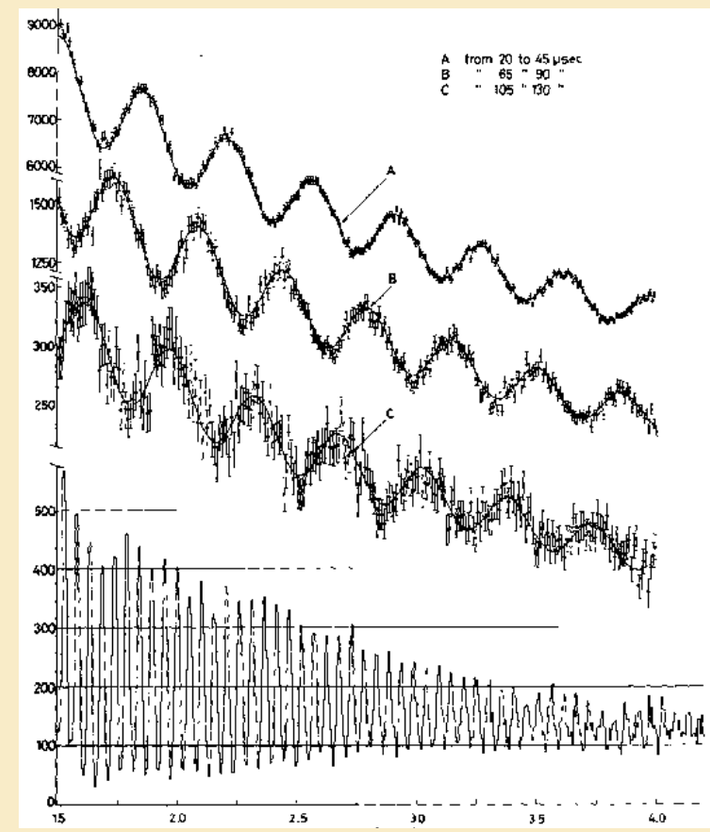
Second CERN experiment results (1968)

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

$$B = 1.7\ \mathrm{T}$$

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

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

A miracle happens here

How to keep the muons vertically confined?
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Use electrostatic quadrupoles - but adds complications

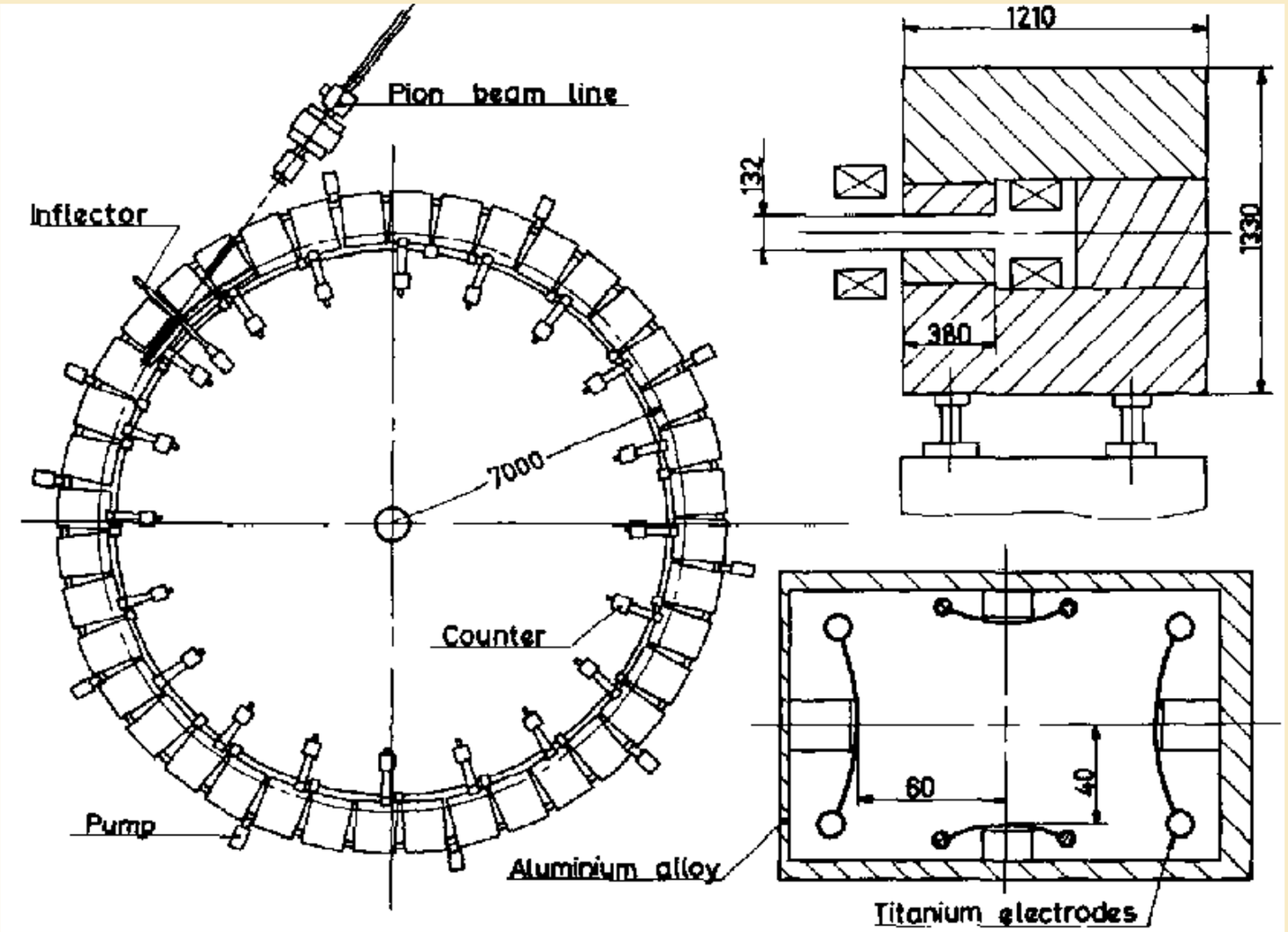
$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

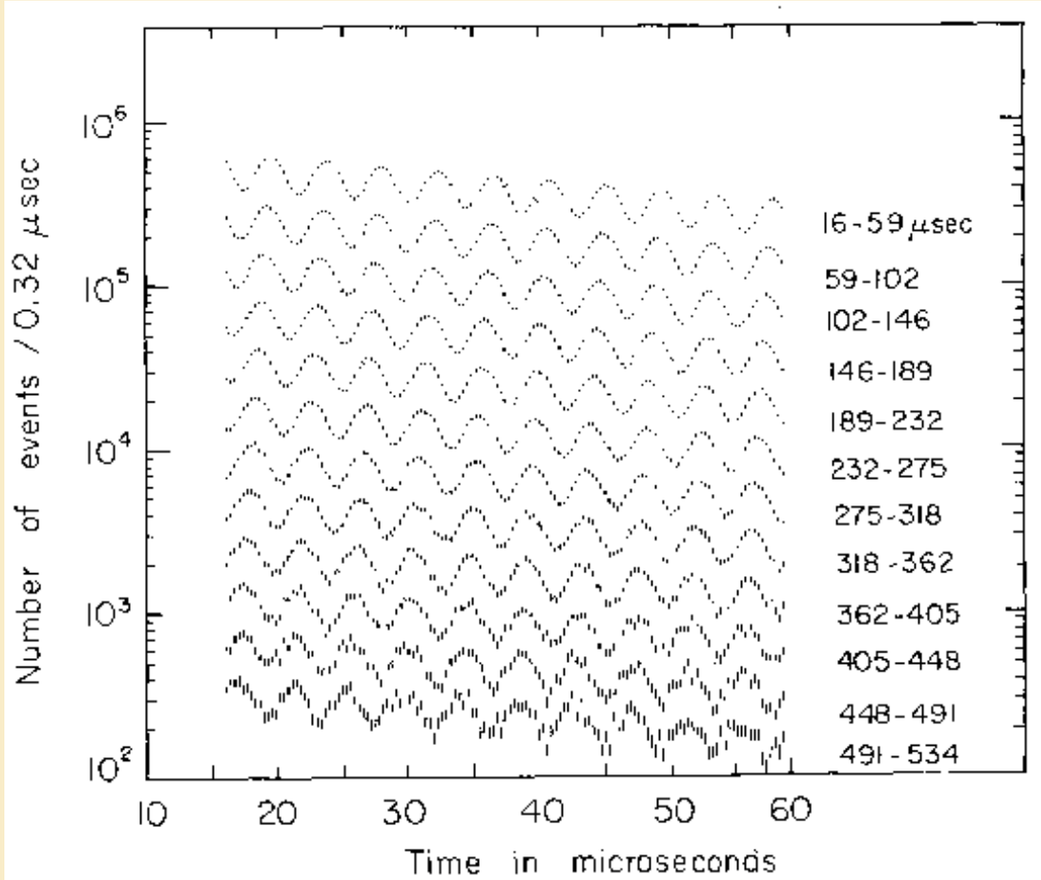
If we choose $\gamma = 29.3 \;\; (p_\mu = 3.09\ \mathrm{GeV}/c)$
then coefficient vanishes! The MAGIC momentum!

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 (!!!)





> 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.

<u>Improvements</u>:

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 Muonium Hyperfine

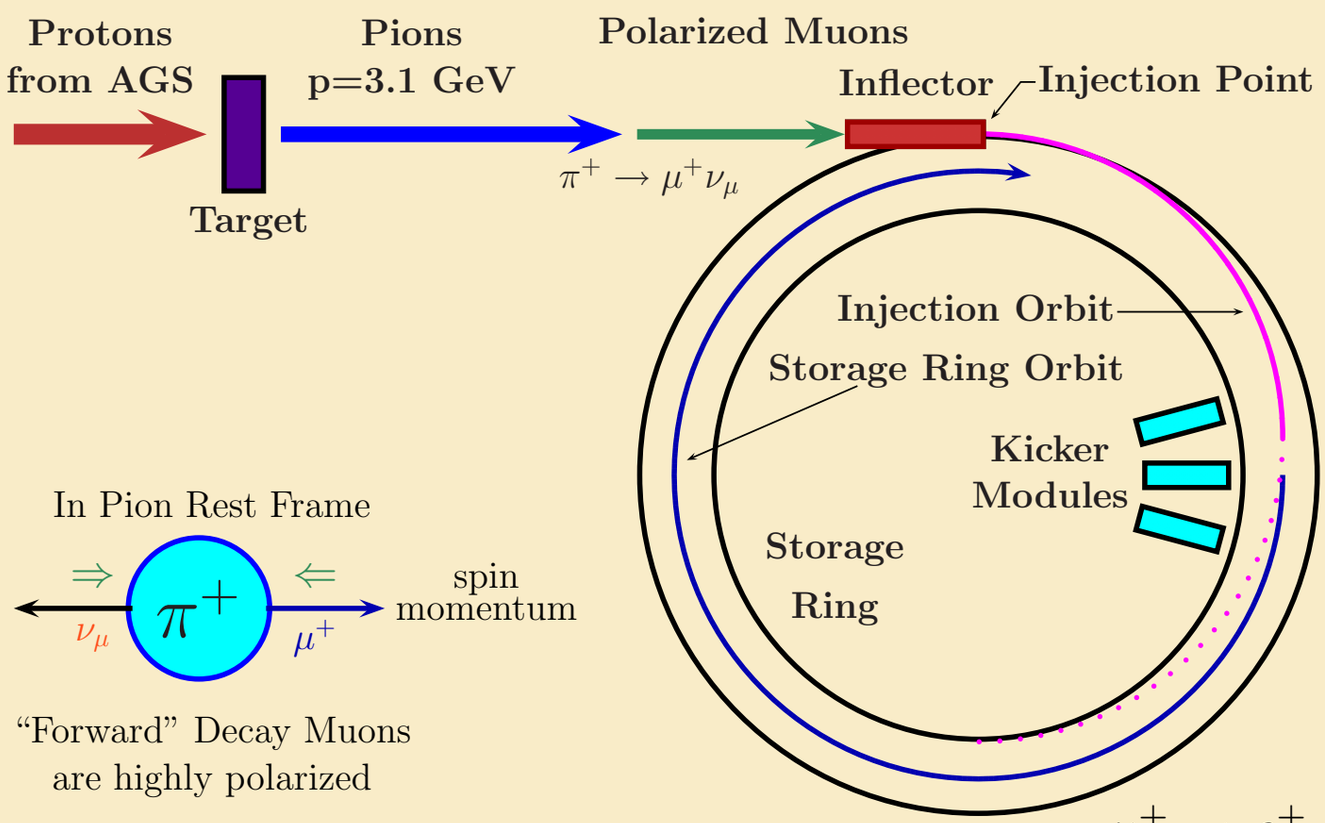
$$\mathcal{R} = \omega_a/\omega_p, \ \lambda = \mu_\mu/\mu_p$$

Determine systematics

Think about the next experiment

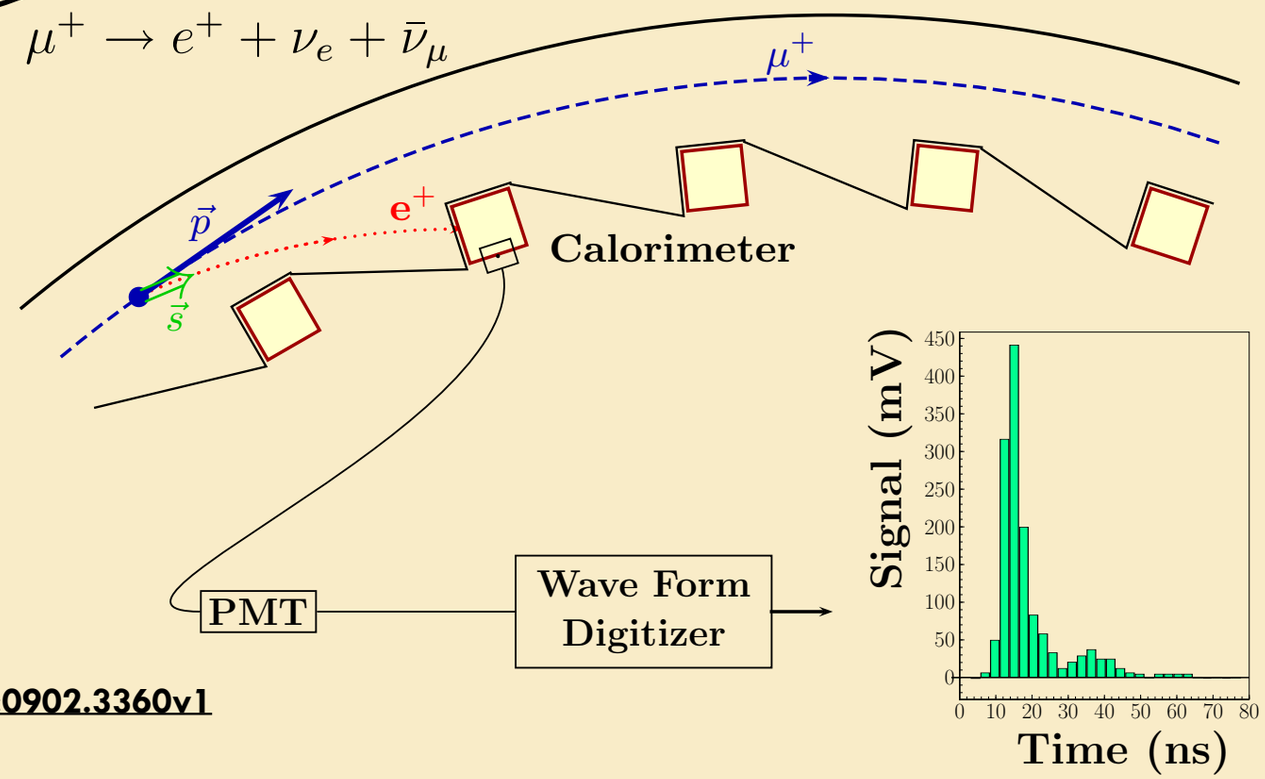
Experiment in cartoons

3 data runs (# e^+'s)
1999 (950M),
2000 (4000M),
2001 (3600M e^-)
8550M events total



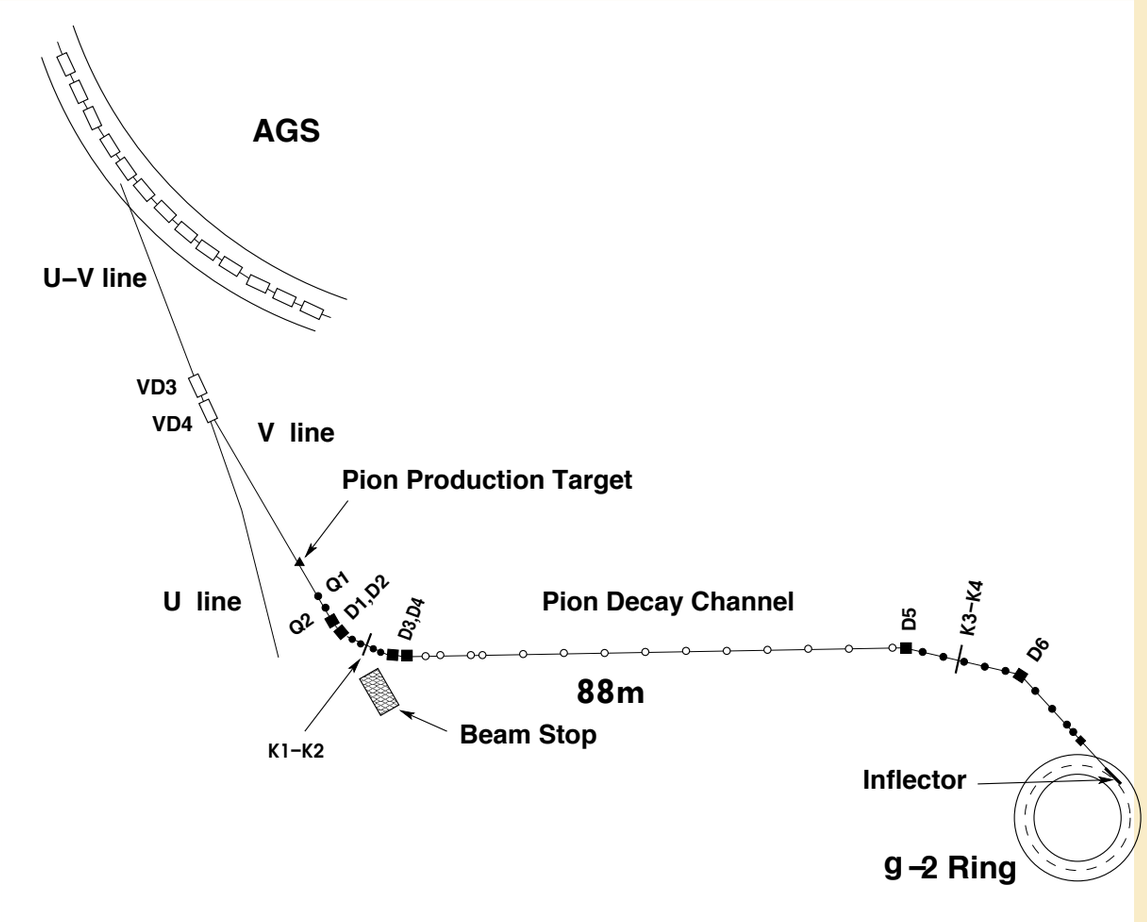
"Forward" Decay Muons
are highly polarized

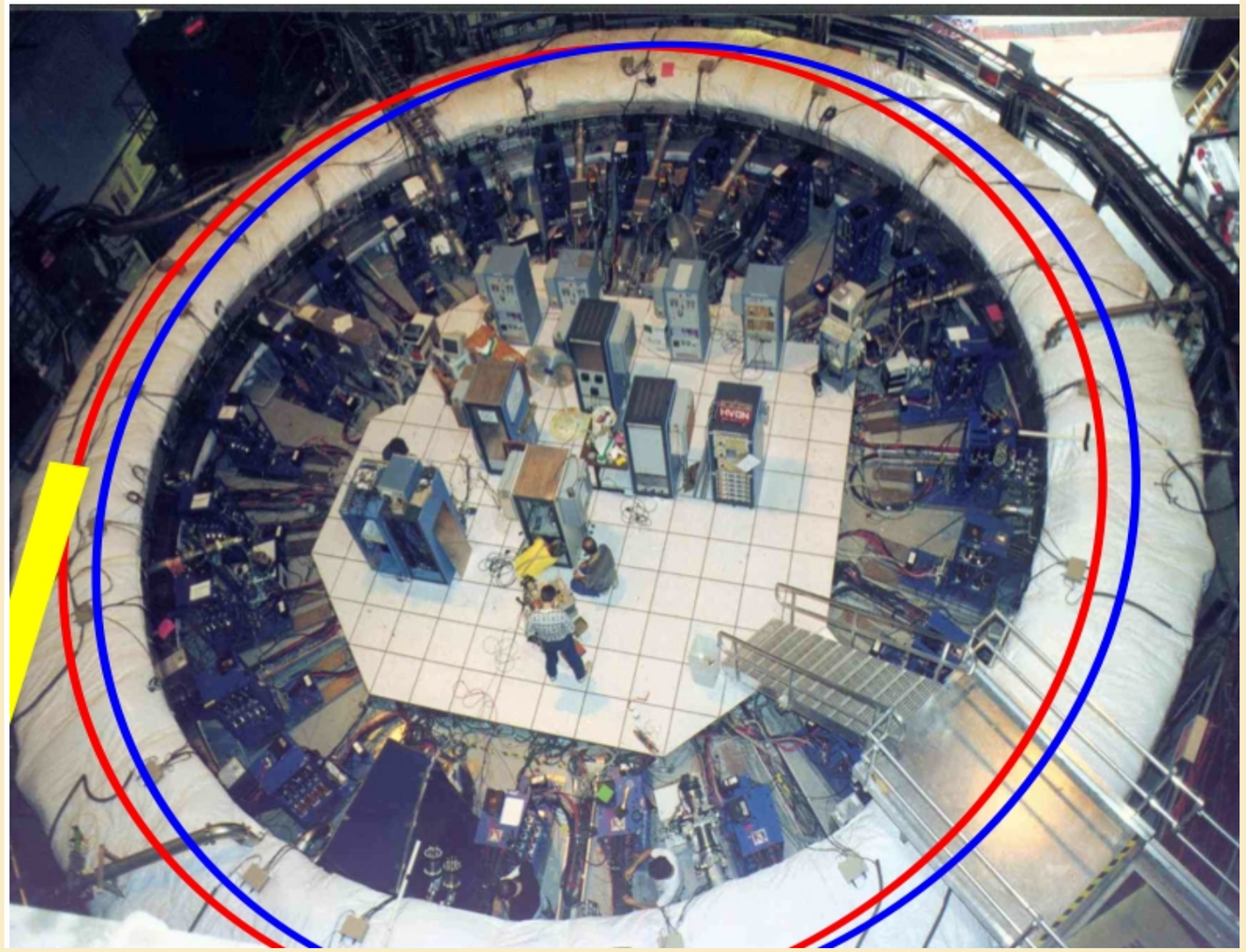
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

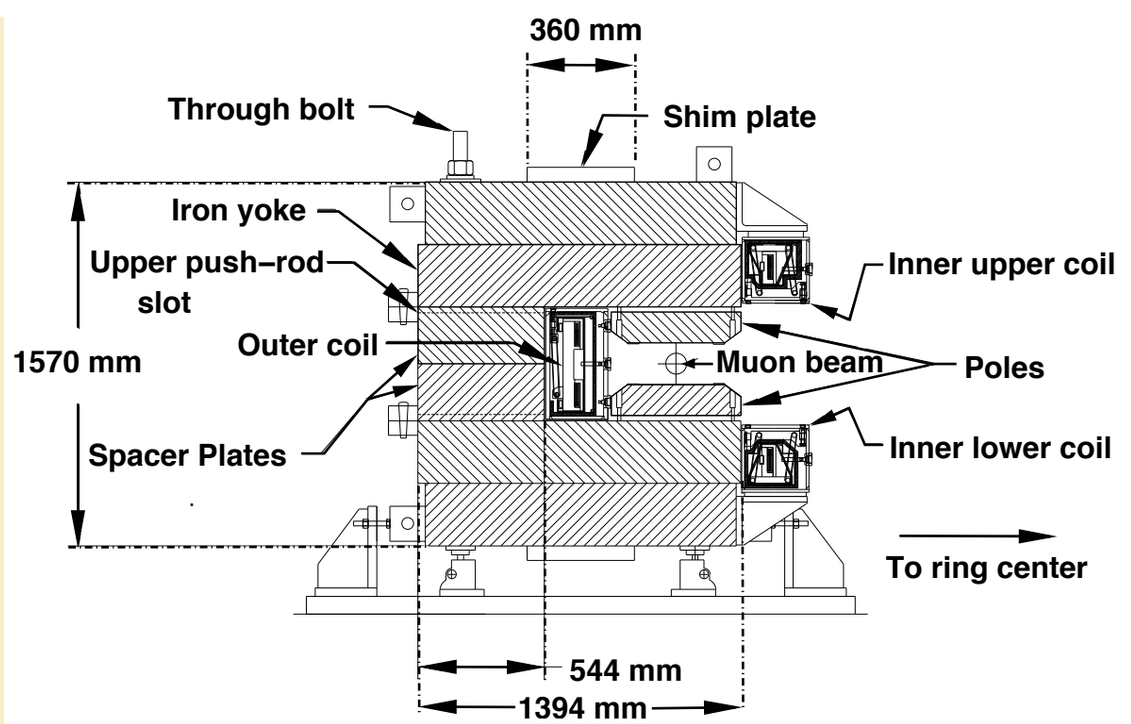


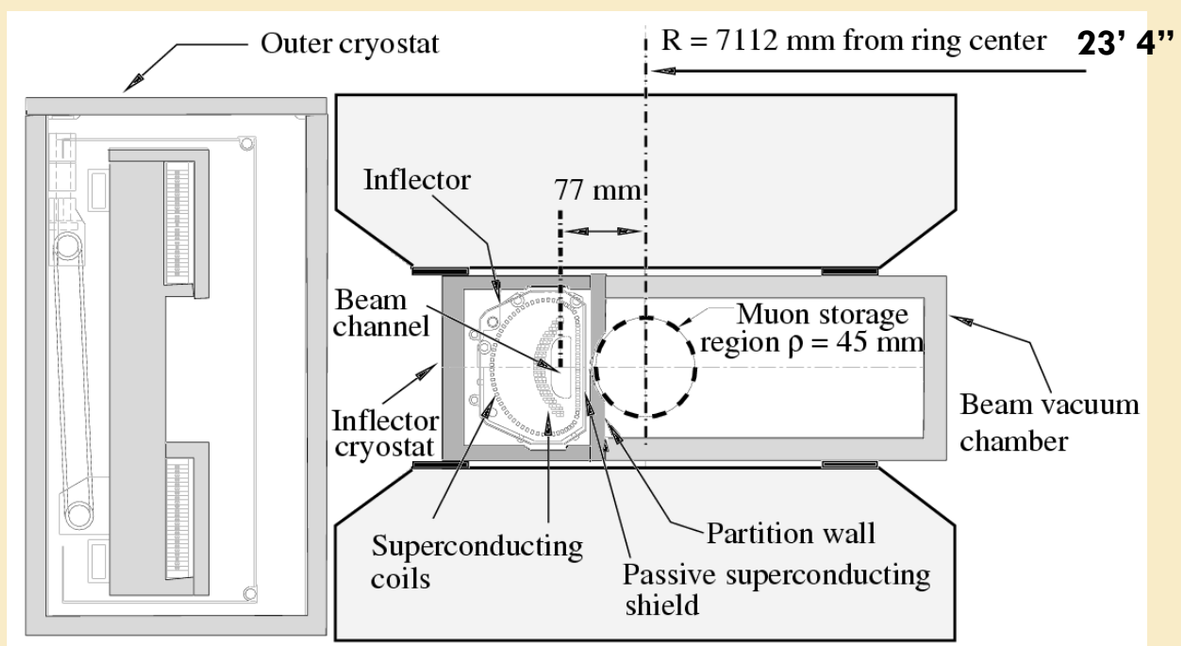
Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, arXiv:0902.3360v1

Injection into the storage ring

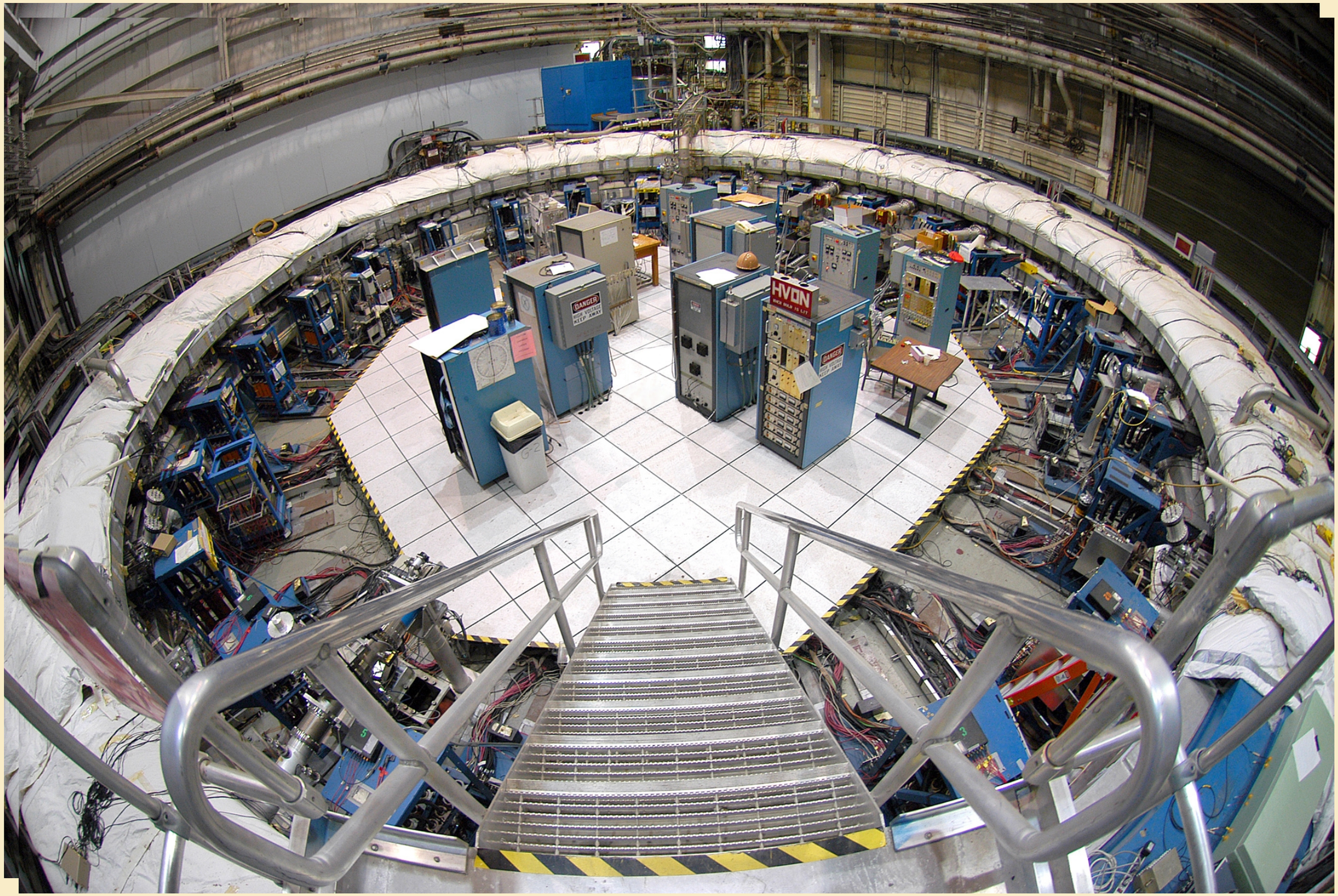




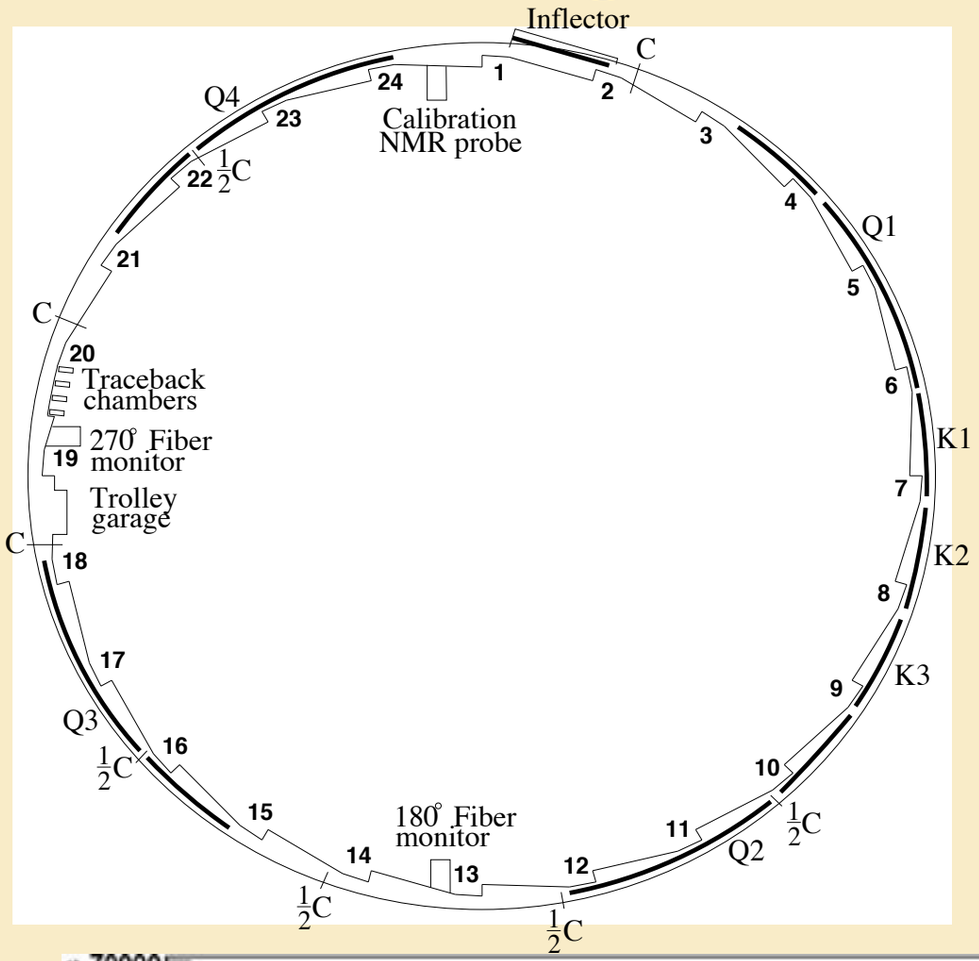


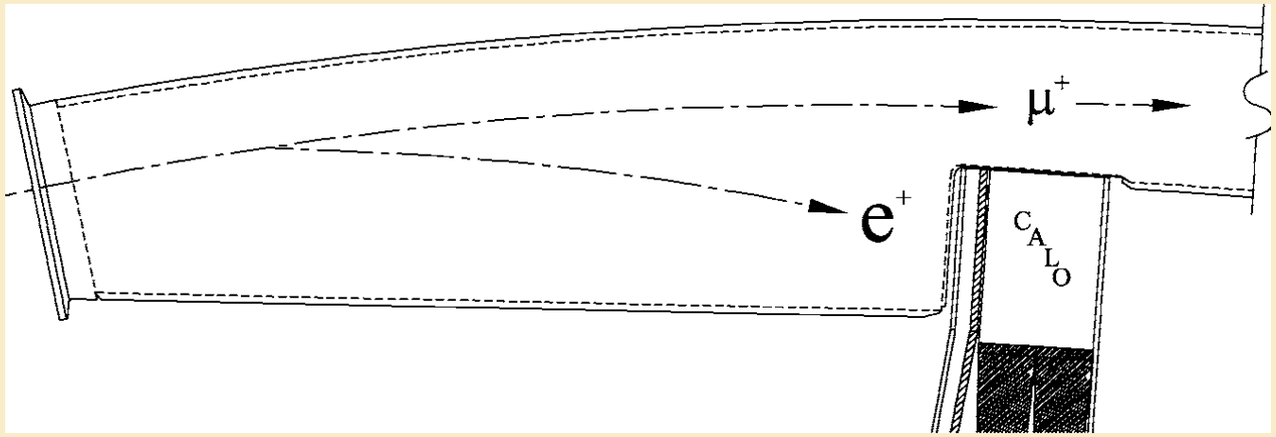


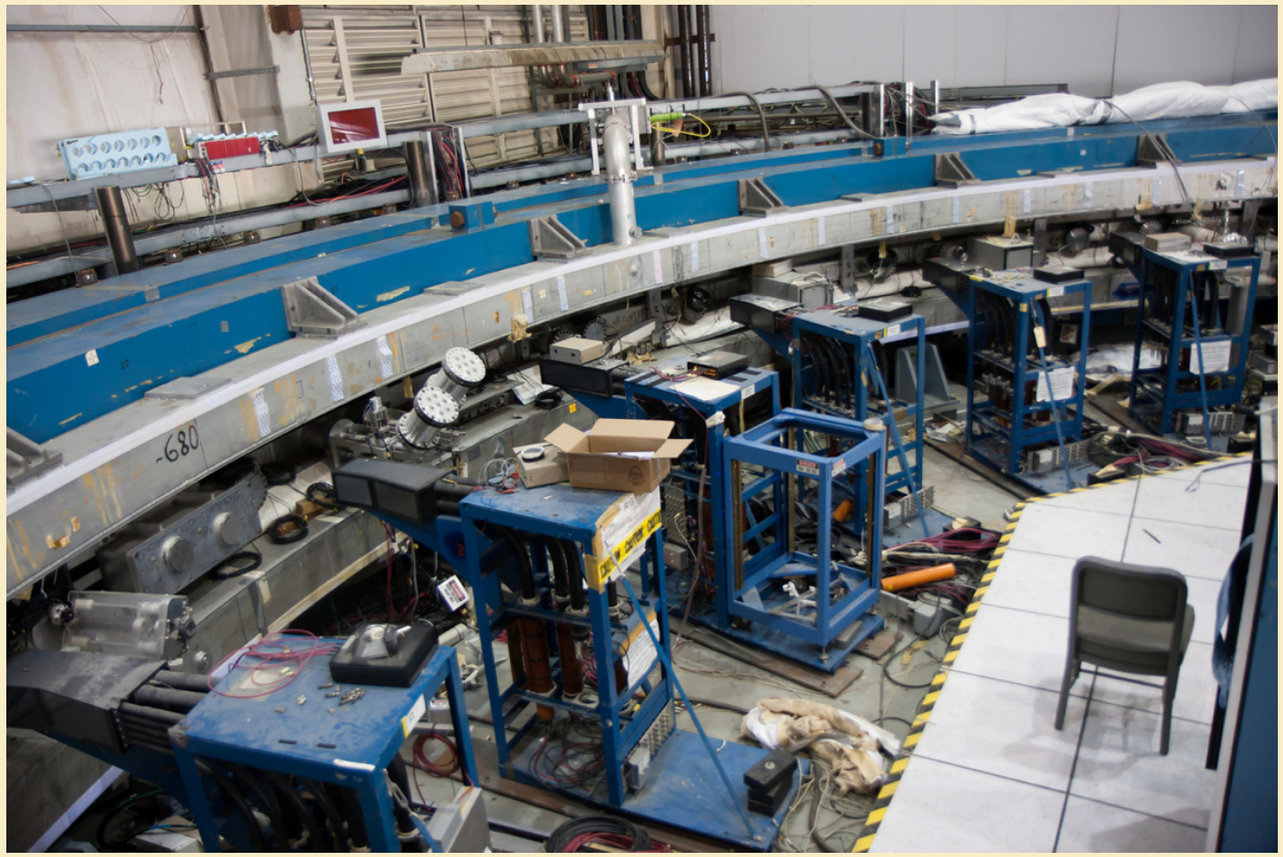
The storage ring

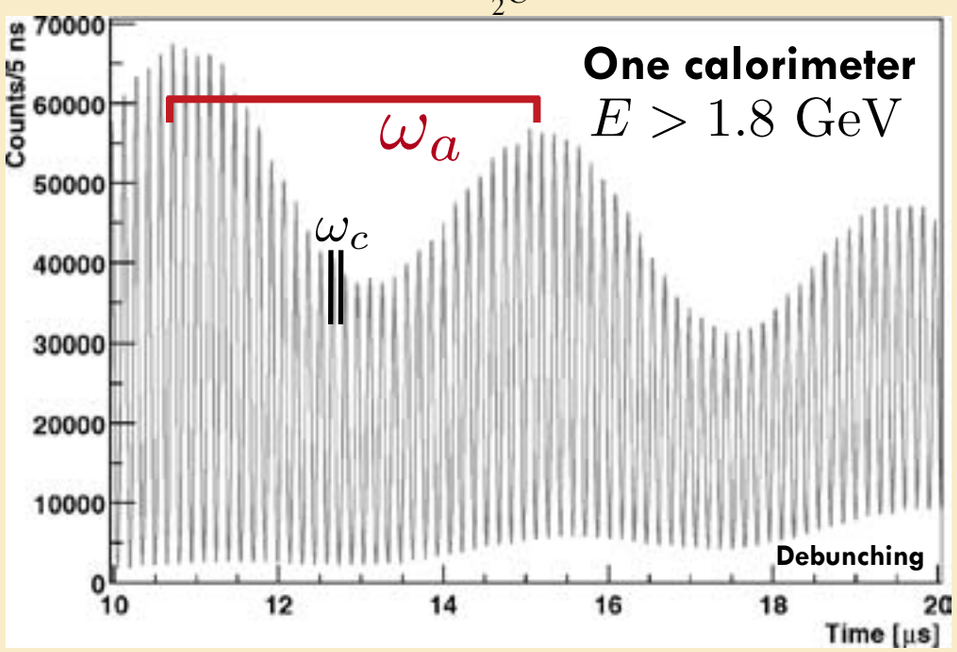


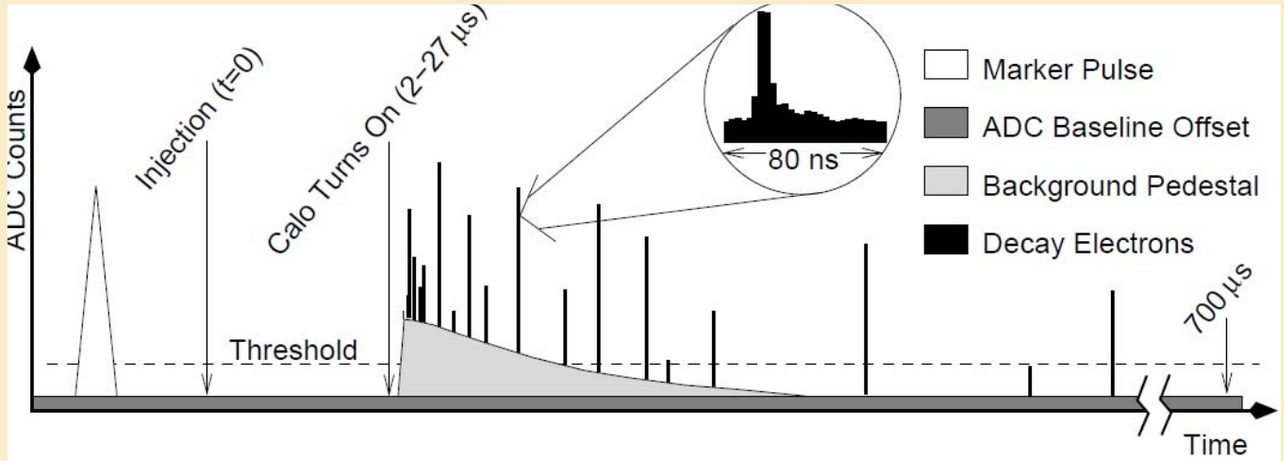
Measuring ω_a



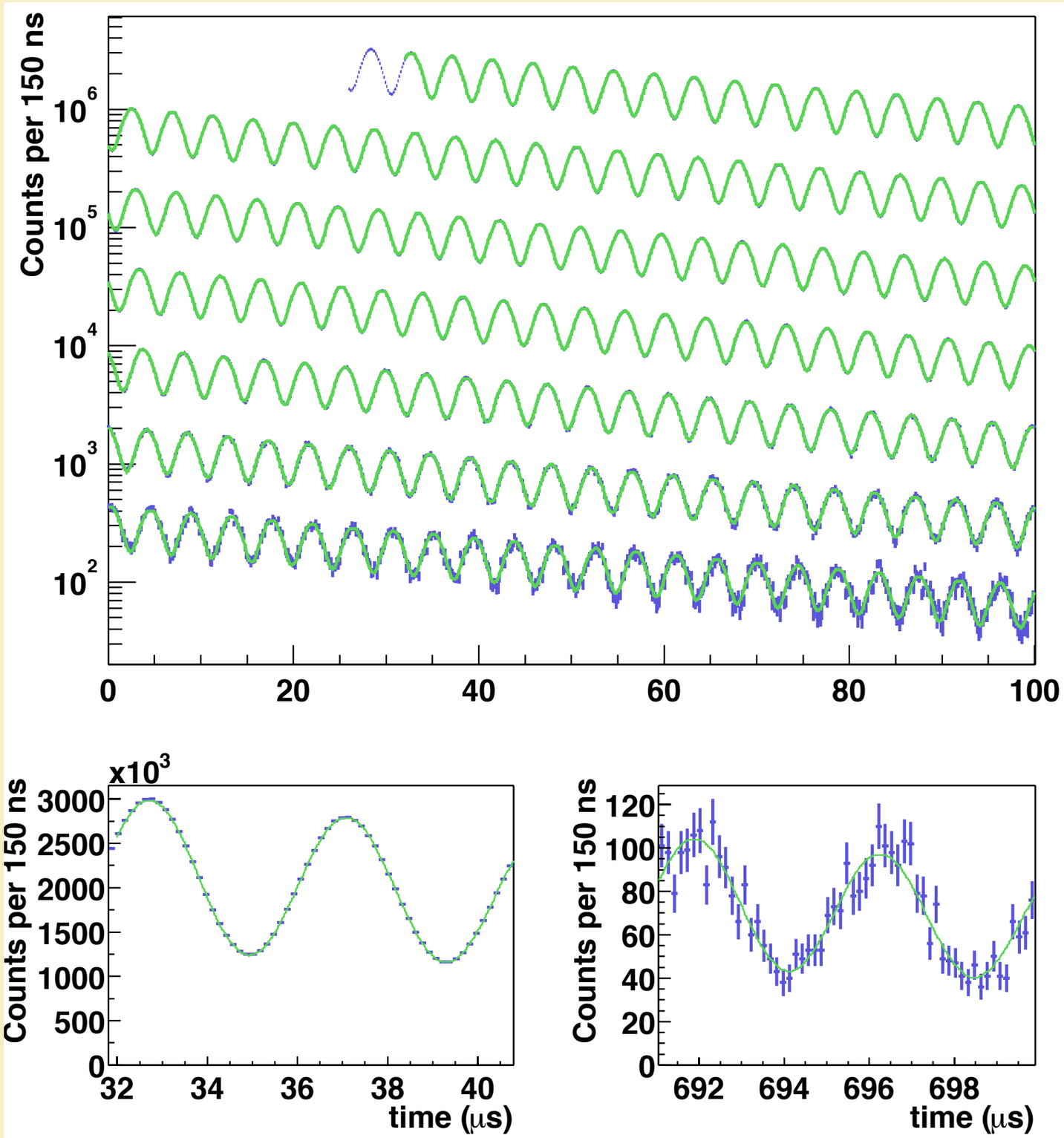








Measuring ω_a



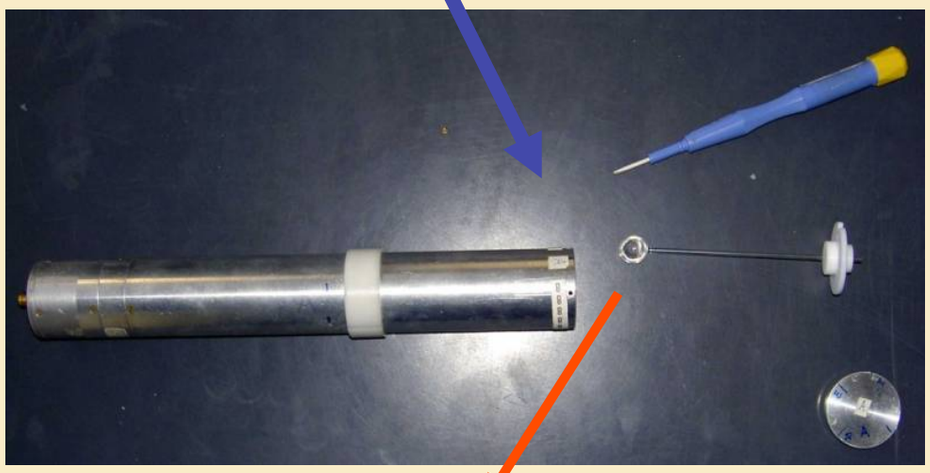
2000 data,

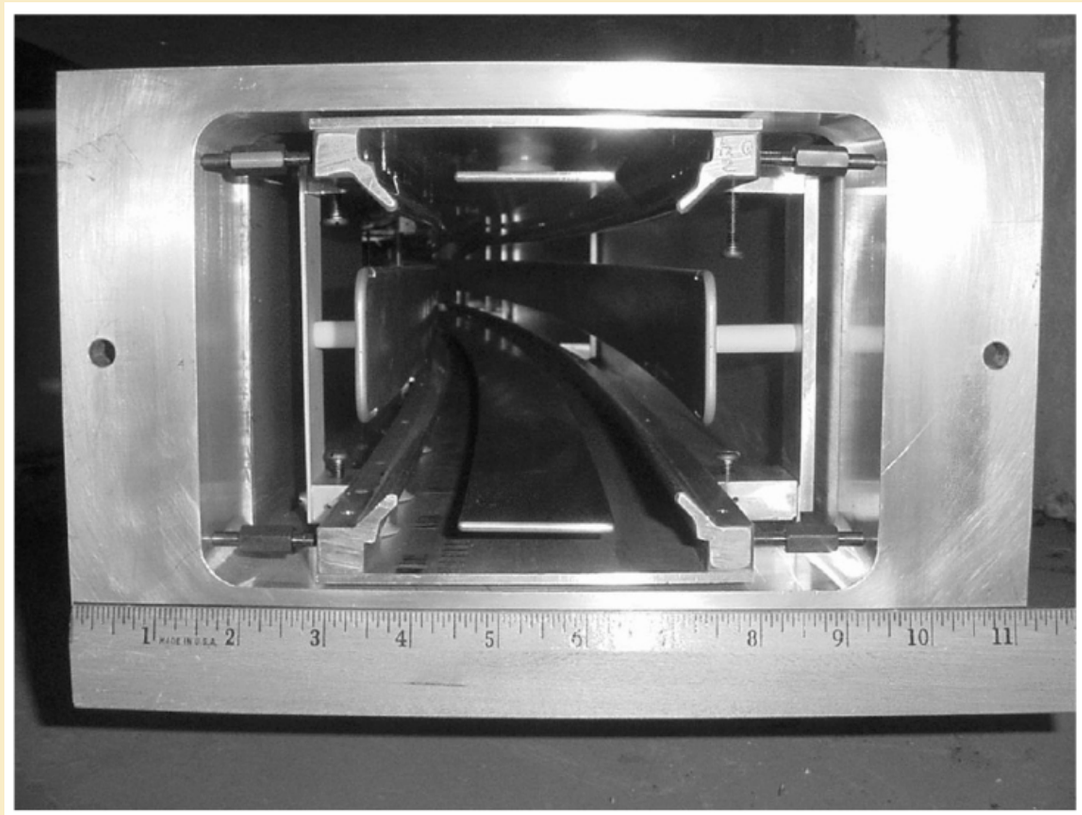
4 billion decays,

5 parameter fit

Measuring ω_p - Measuring the B field

Absolute Calibration Probe:
a Spherical Water Sample





Trolley with matrix of 17 NMR Probes

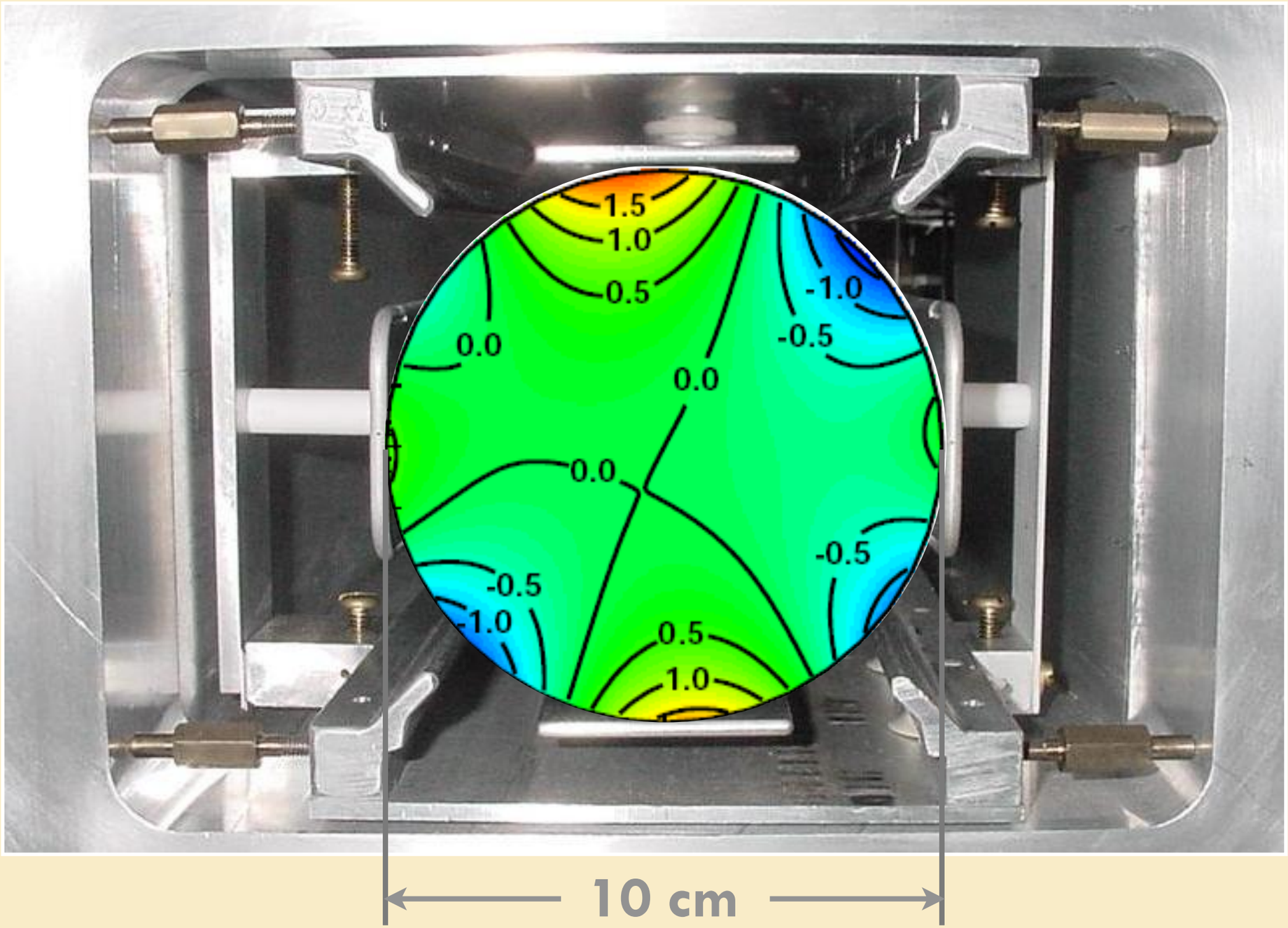
Electronics, Computer & Communication

Position of NMR Probes

In vacuum, 6000 azimuthal measurements,
Calibrated against plunging probe

Measuring ω_p

Contours are ppm



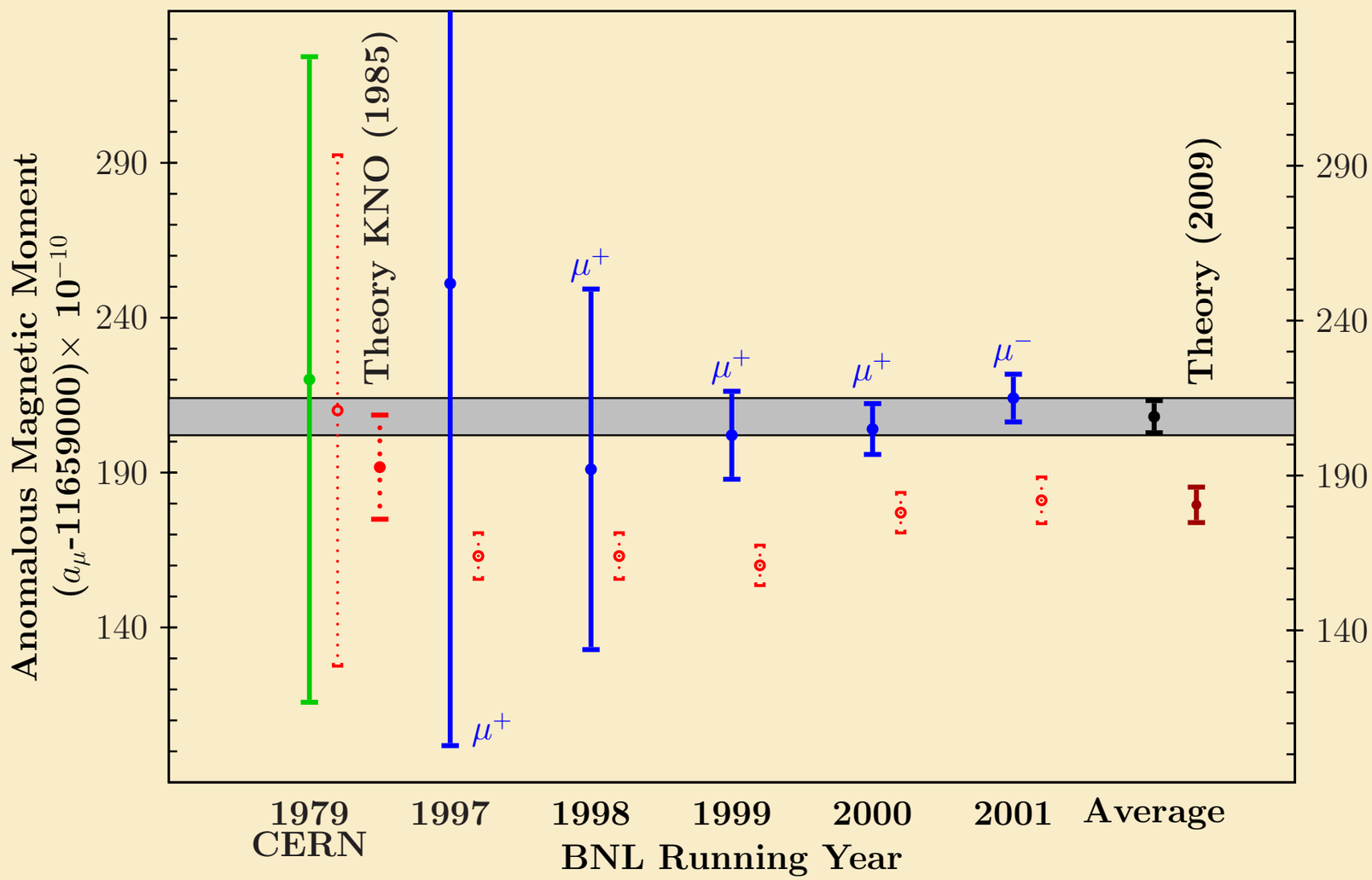
Blind analysis with separate groups (no one person knows both ω_a and ω_p)

Brookhaven E821 Results

PRD 73, 072003 (2006)

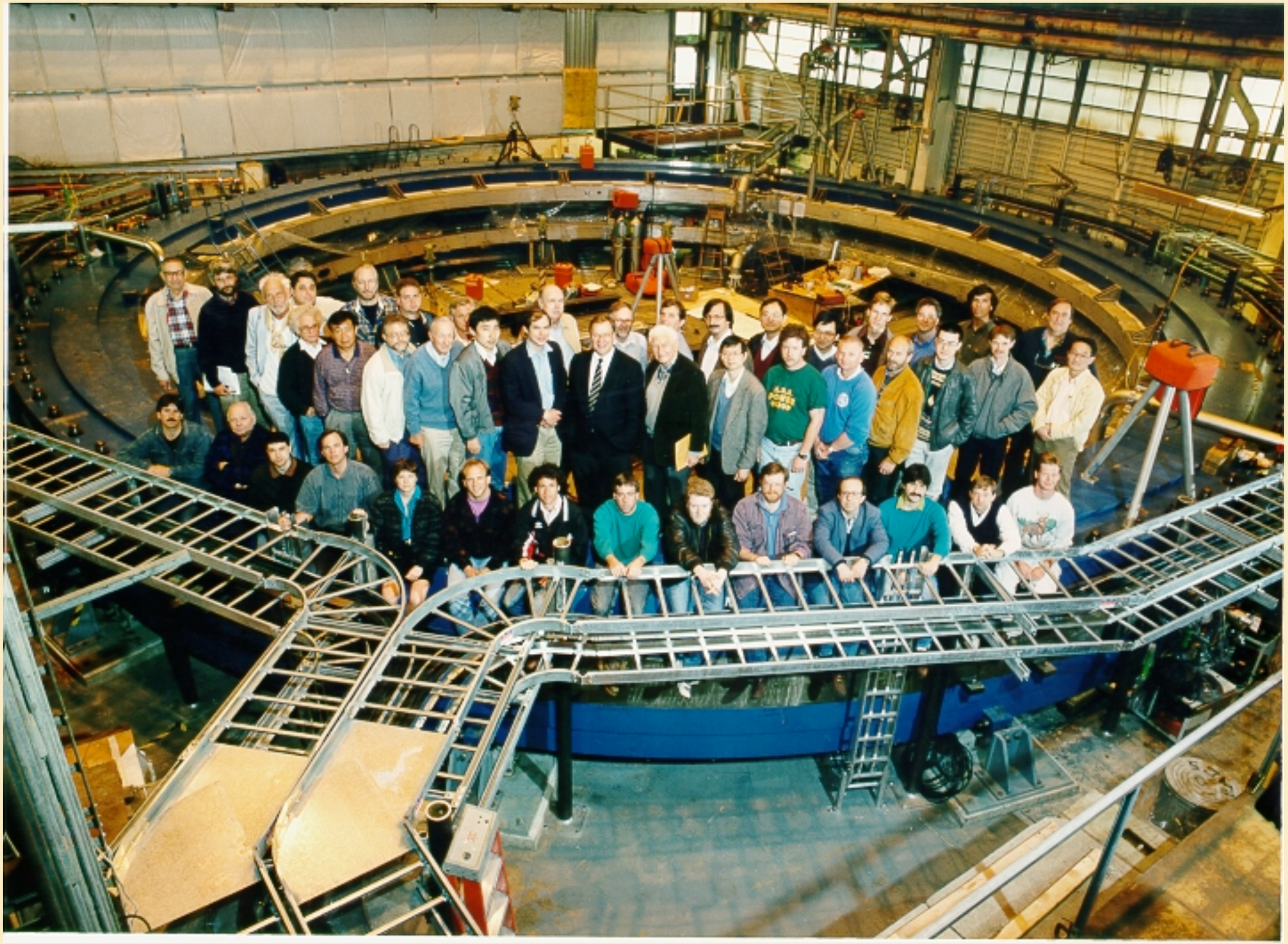
$$a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\ \text{ppm})$$

0.46 ppm statistics, 0.28 ppm systematic



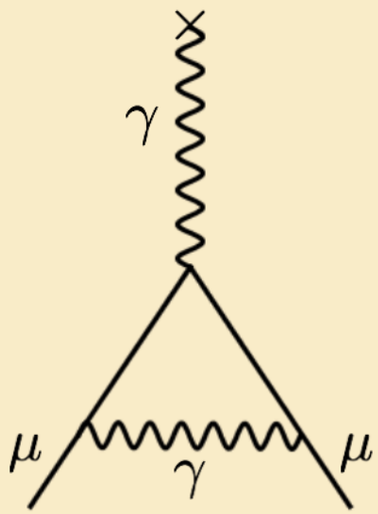
$$g_\mu^{\rm exp} = 2.002\,331\,841\,78(126)$$

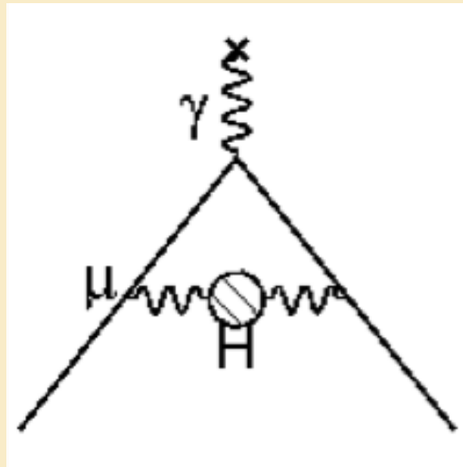
A Job Well Done

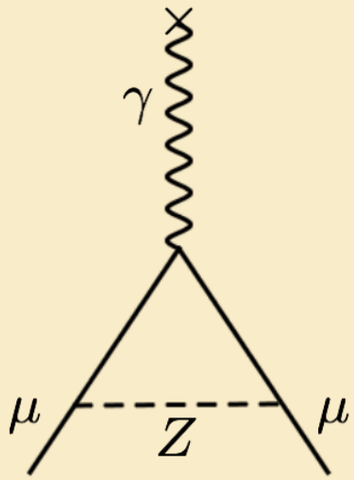


Comparing $a_\mu^{\rm exp} = 0.00\,116\,592\,089\,(63)$ to Theory

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







$$a_\mu^{\rm QED} = 0.00\,116\,584\,718\,951(80)$$ **10th order**

$$a_\mu^{\rm had} = 0.00\,000\,006\,930(49)$$ **Hadronic Vacuum Polarization, Light-by-light**

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

Quick theory features

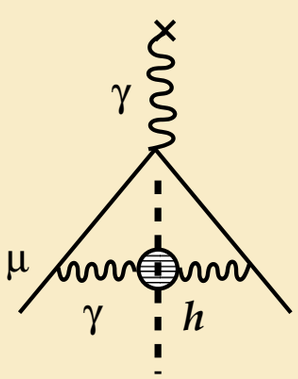
From Blum, et al., arXiv:1311.2198, "Snowmass Whitepaper"

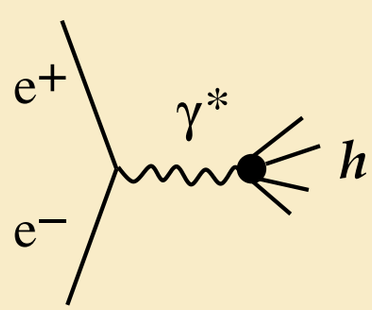
Two treatments of HVP(LO) [20] M. Davier, et al.; [21] K. Hagiwara, et al

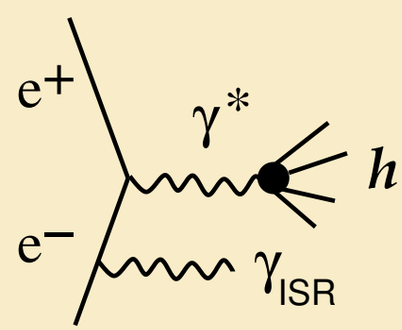
	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_{\alpha}$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

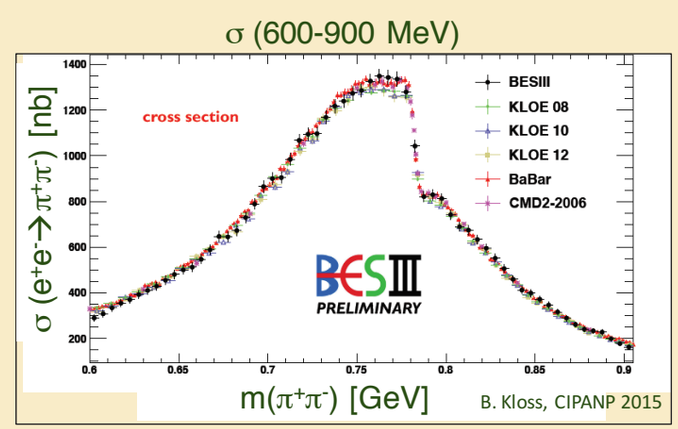
Leading contribution to a_μ

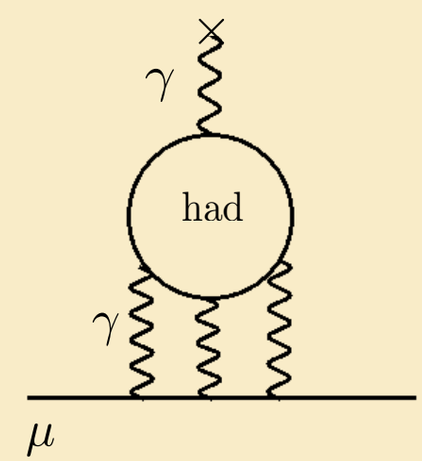
Leading contribution to δa_μ



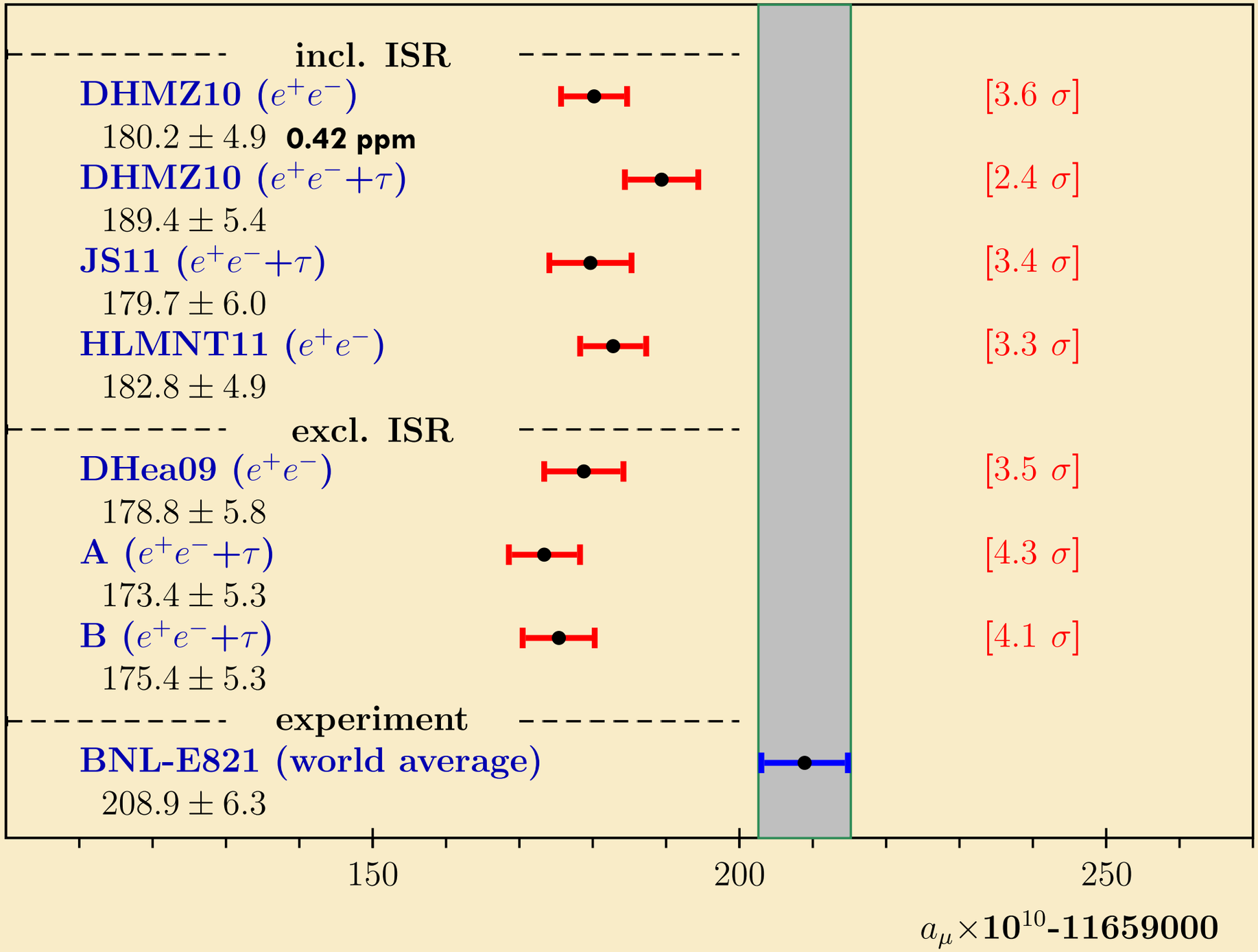








Comparison to experiment



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

Comparison to experiment

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

Difference is ~ twice electroweak contribution!

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

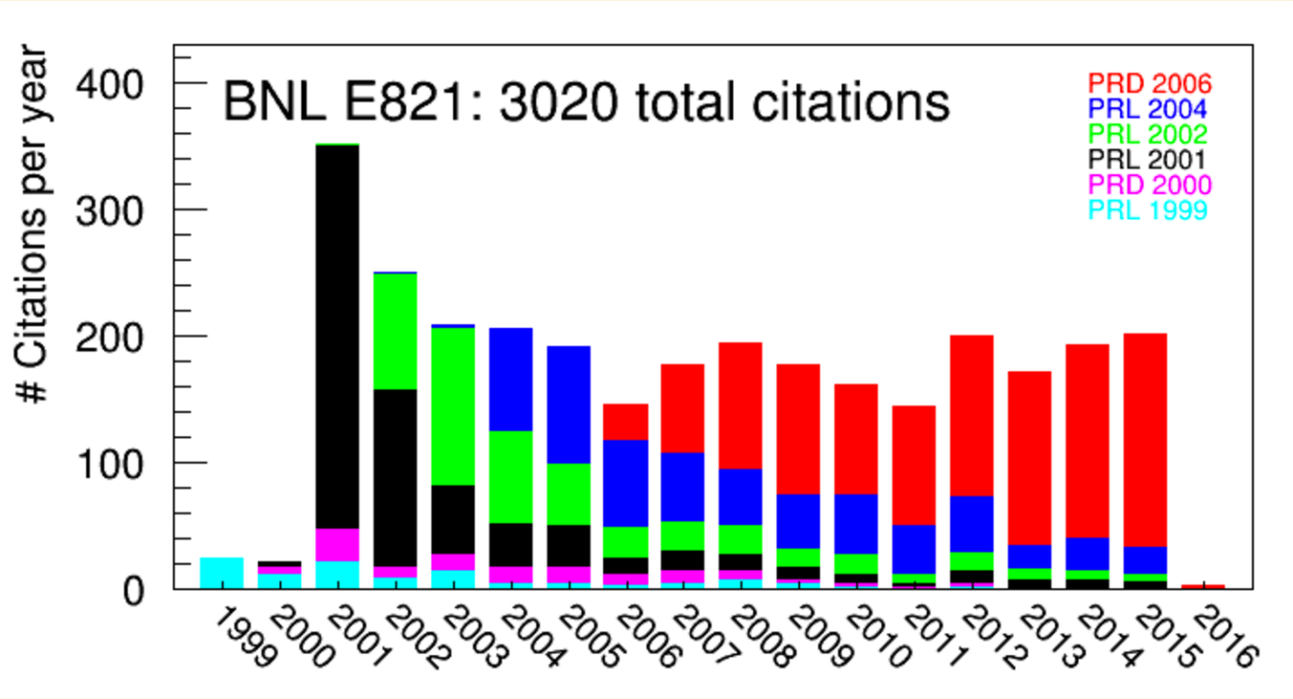
If this is new physics, why haven't we seen it elsewhere?

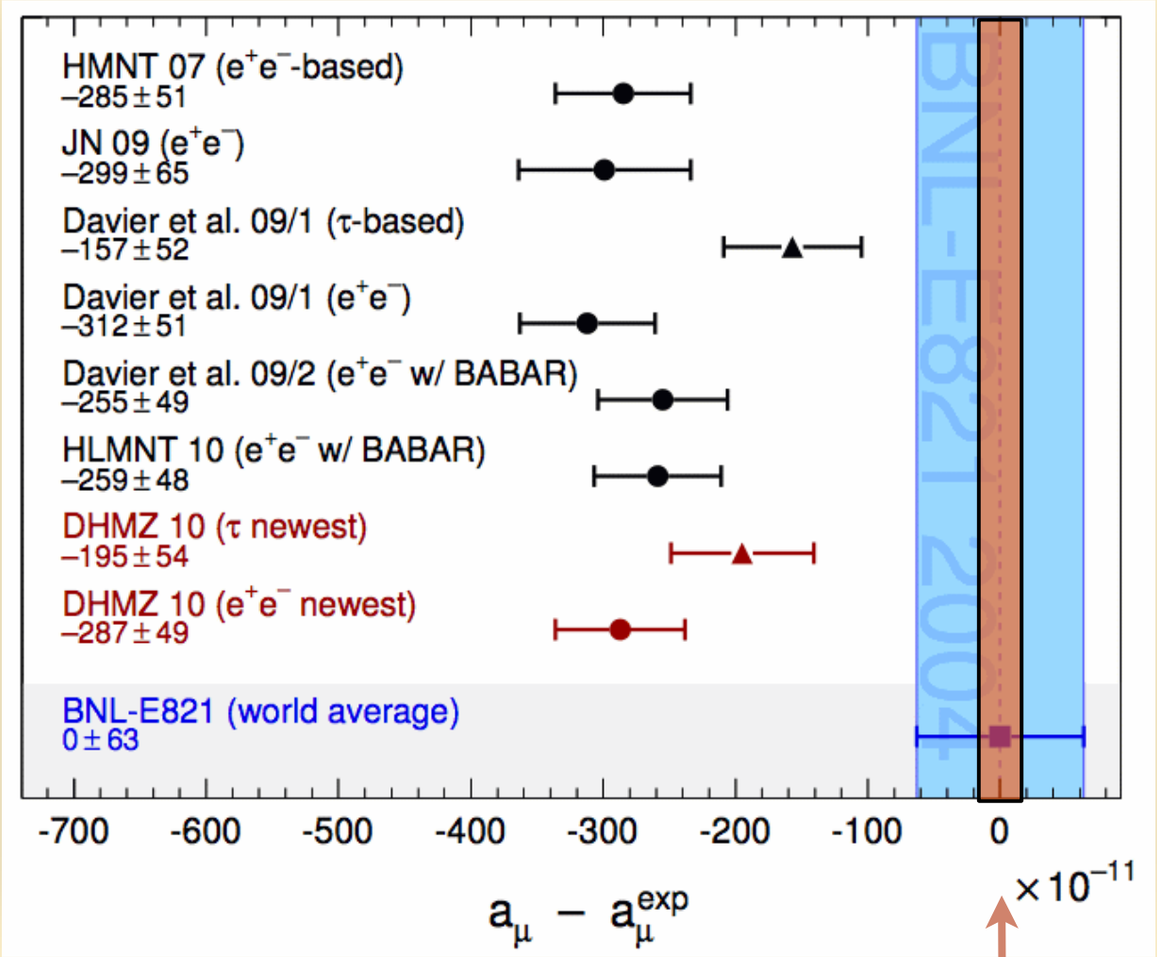
$$a_\mu^{\mathrm{SM}} = 0.00\,116\,591\,802(49)$$
$$a_\mu^{\mathrm{exp}} = 0.00\,116\,592\,089(63)$$

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

Perhaps mass scale is large and/or coupling is small

Enormous interest in the result





Difference is intriguing, but inconclusive

Redo the experiment even better than before!

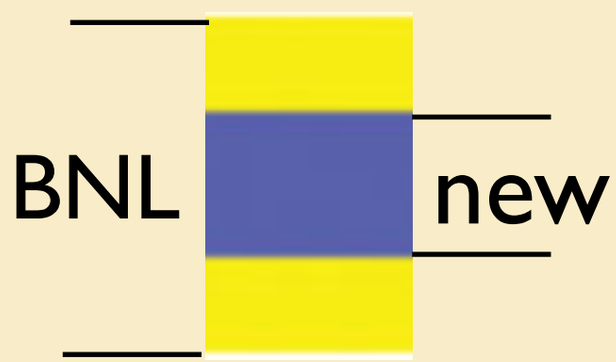
With a 140 ppb measurement current difference becomes 5.6σ (7.5σ if theory improves to 0.3 ppm)

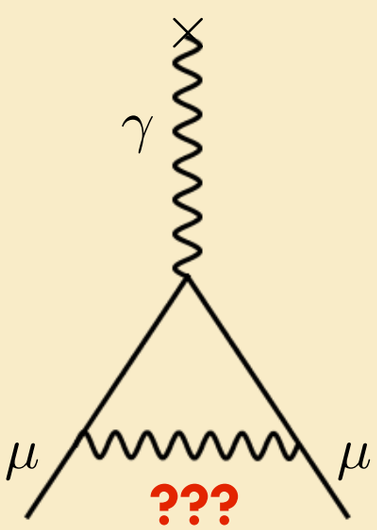
If difference persists, then a major discovery!

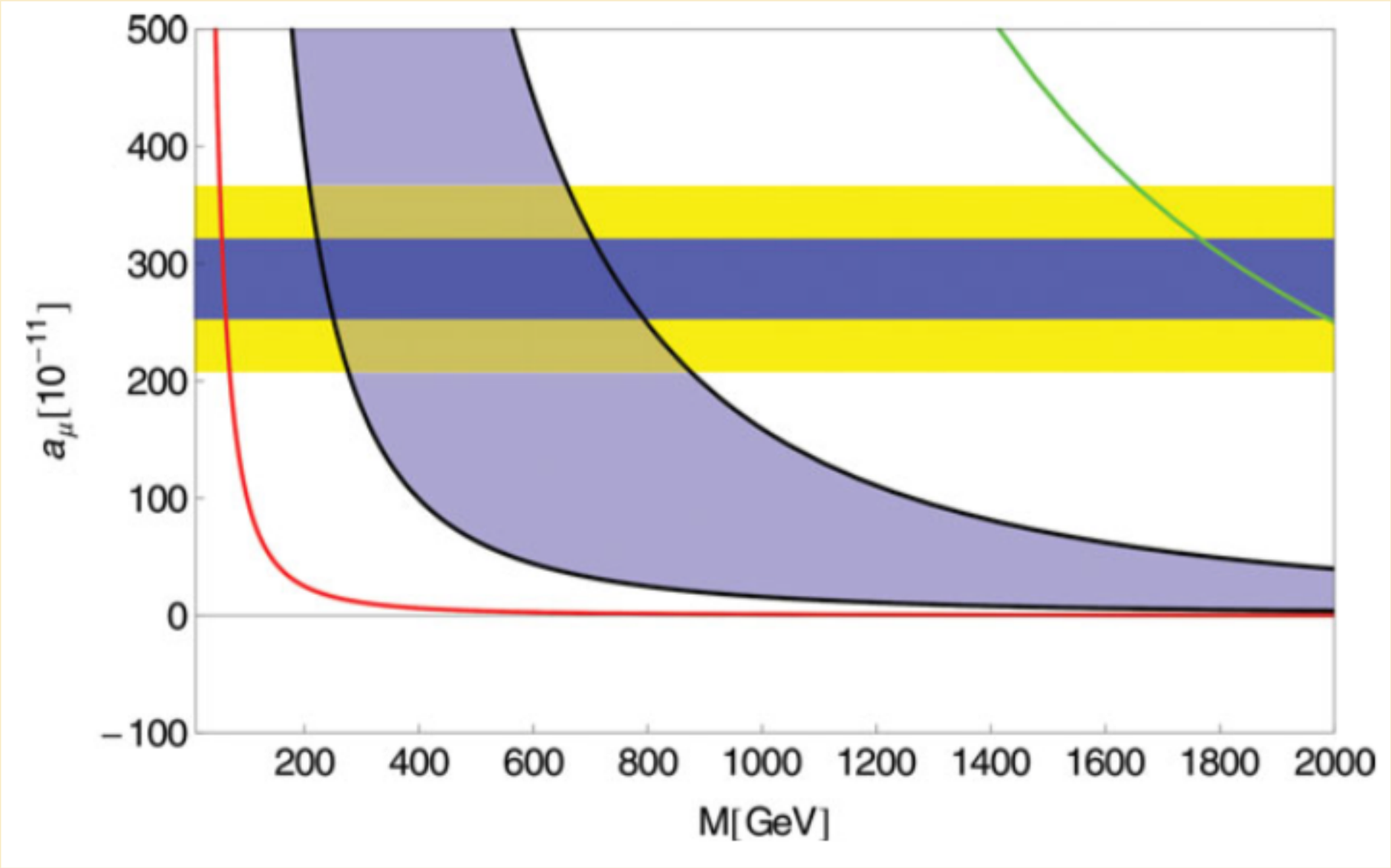
New Physics?

TeV Scale Models

- ***Z', W', Extra Dimensions, Littlest Higgs Models with typical weak couplings***
- ***Radiative Muon Mass Generation (e.g. Multi-higgs doublet models)***
- ***Unparticles, Extra dimension models, SUSY*** *(width of band from tan β: 5–50)*



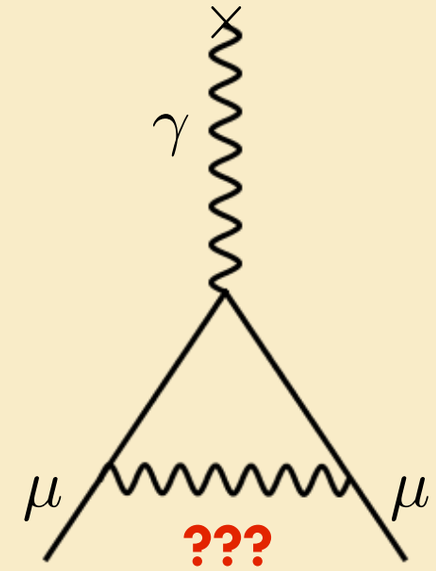




D. Hertzog, Ann. Phys (Berlin) 2015, plot courtesy D. Stockinger

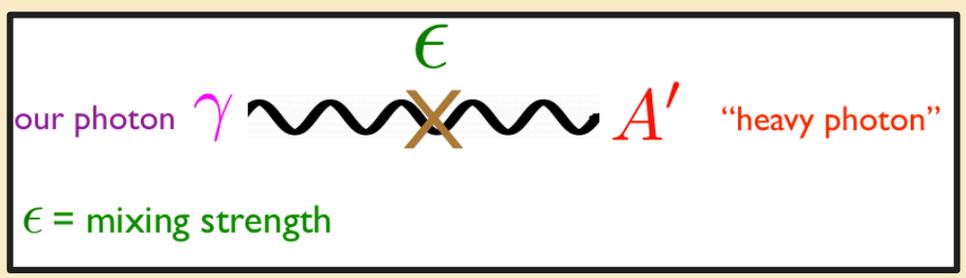
New Physics?

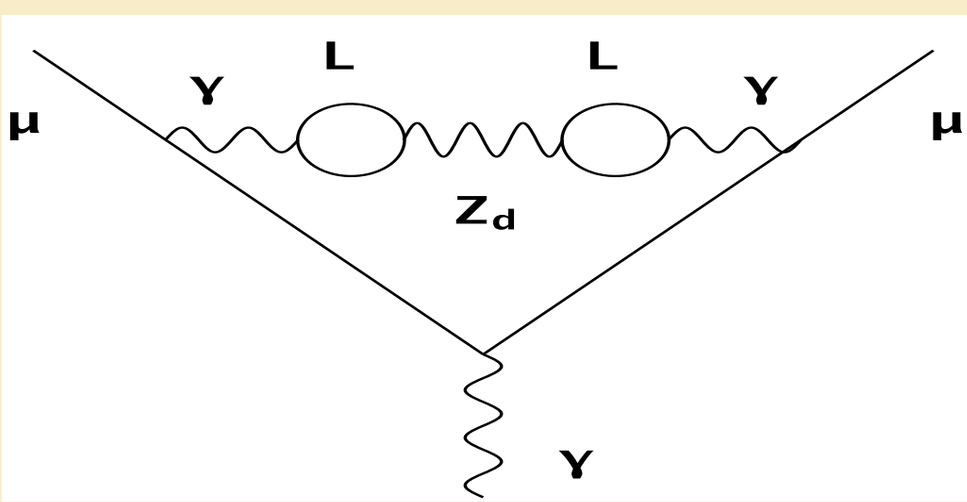
$$a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm had} + a_\mu^{\rm weak} + \boxed{a_\mu^{???}}$$



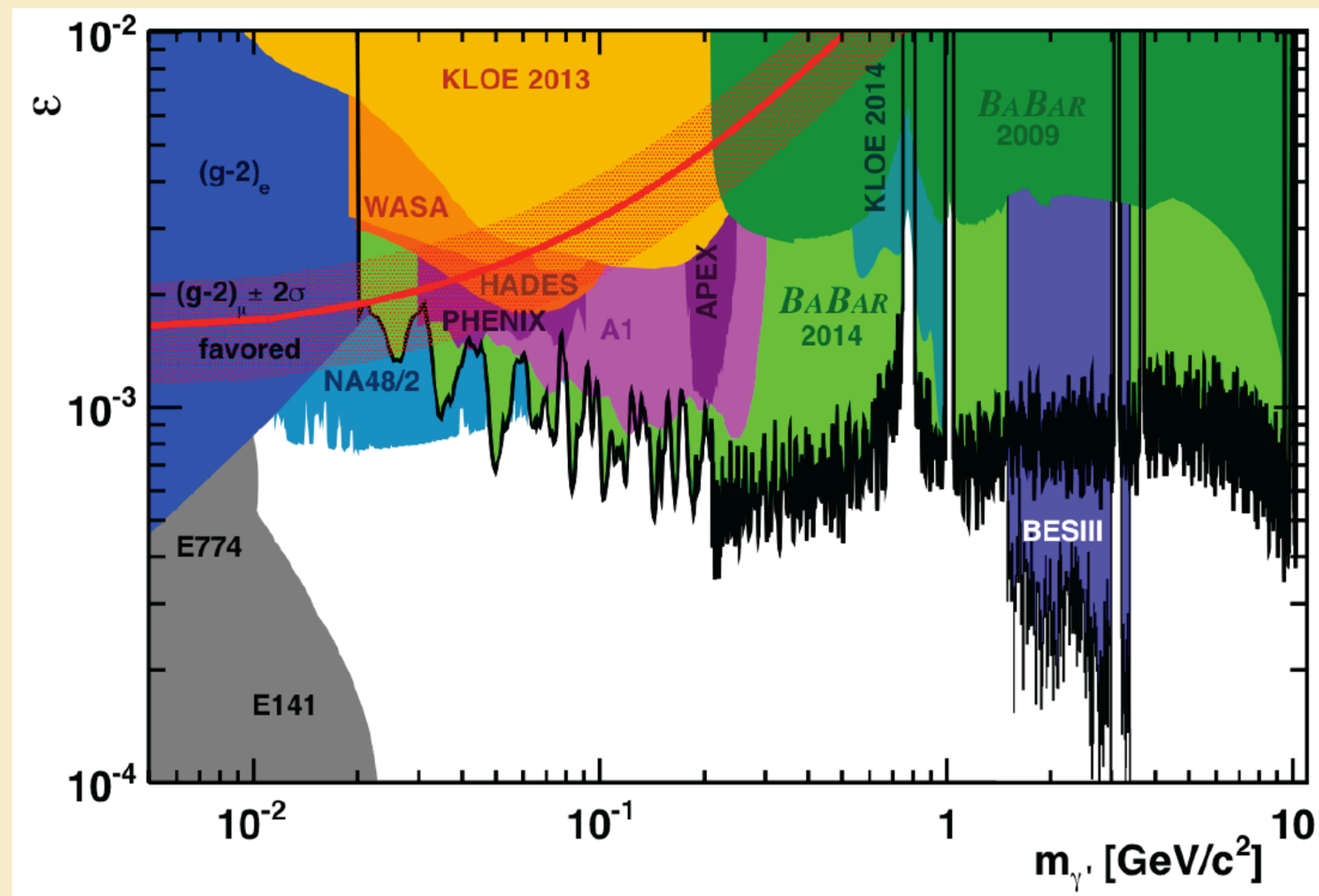
Dark Bosons?

<u>Light</u> hidden sector U(1) bosons that interact <u>very weakly</u> with SM





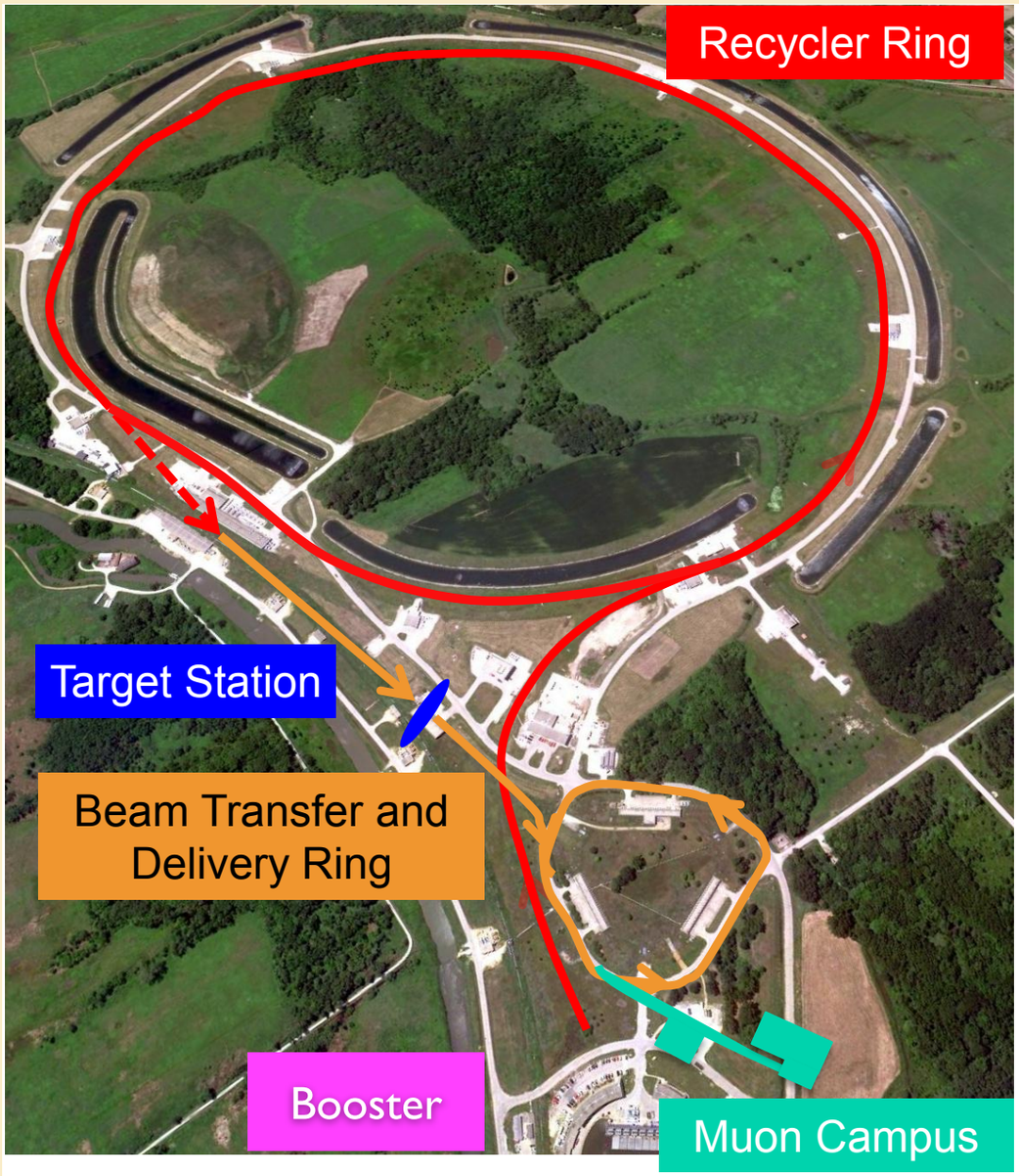
"Dilbert Diagram"



Meanwhile at Fermilab…

The Tevatron shut down in 2011 after running nearly 30 years

Antiproton source repurposed for μ^+

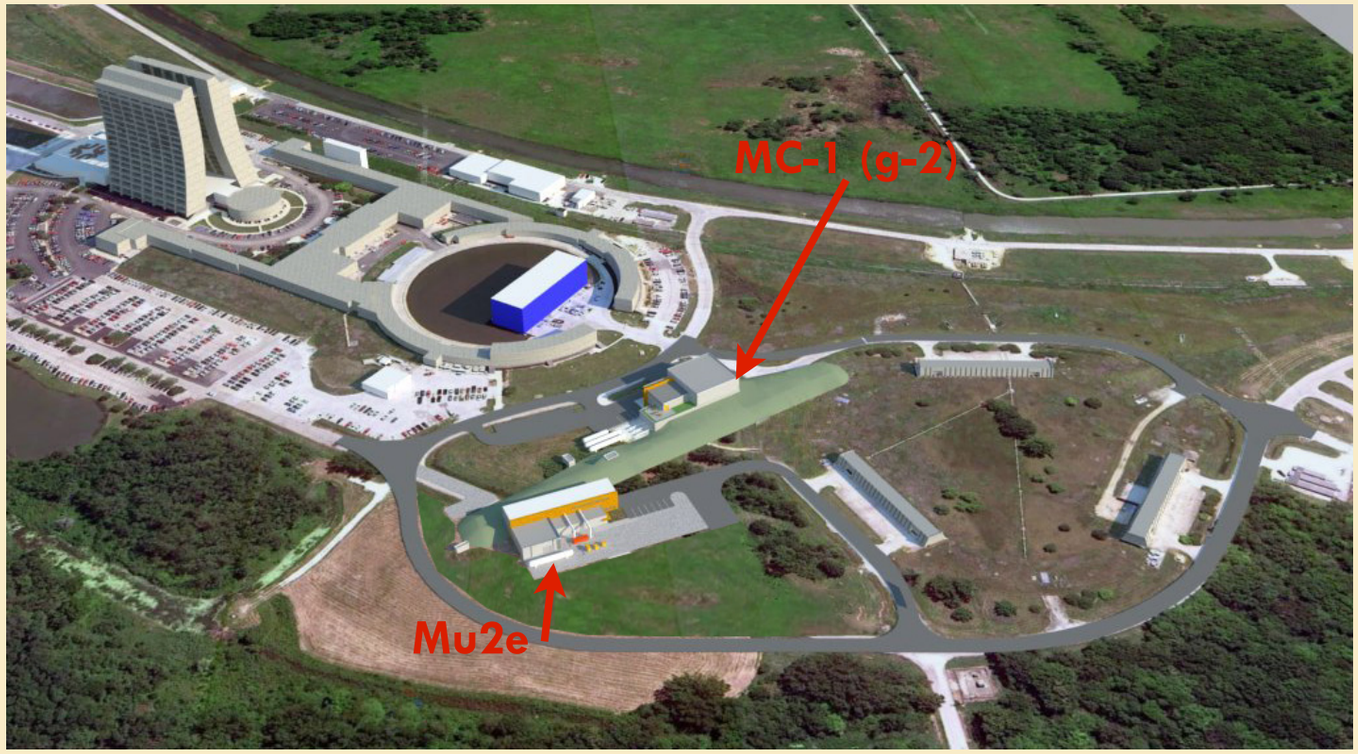


- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - 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 -- 10000 muons in ring (6x eff of BNL) -- 1000 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



Building completed early 2014

New Muon g-2 experiment justification with 140 ppb

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

The Muon g-2 Collaboration

35 Institutes, 155 Members

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- Yale
- York College

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab

Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Russia:

- Dubna
- Novosibirsk

England

University College London

Liverpool

Oxford

Korea

KAIST

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!

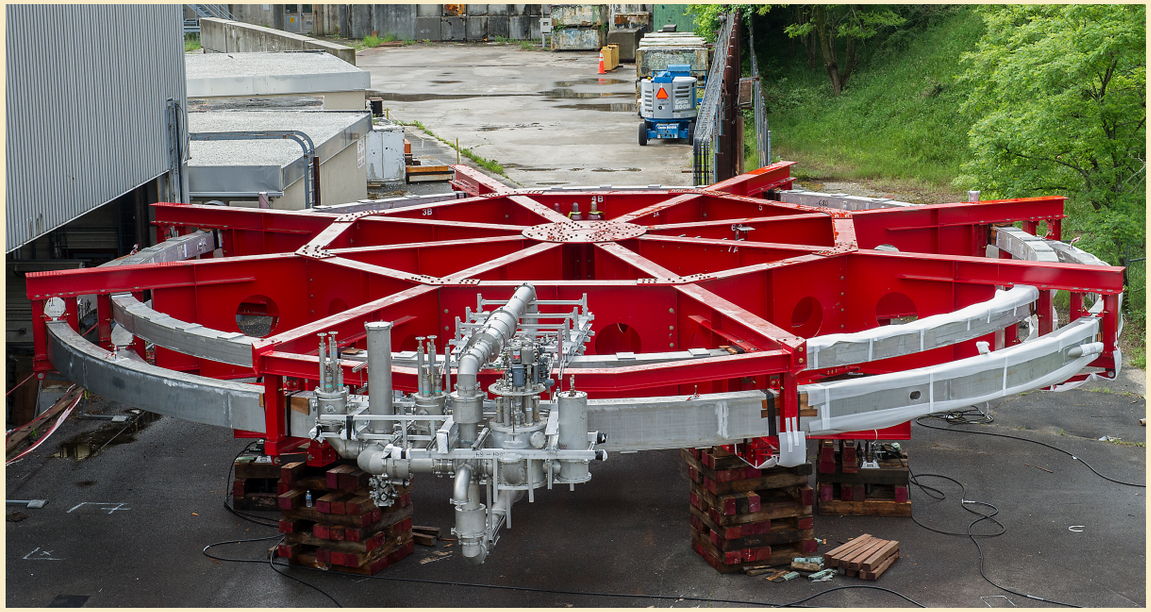
The ultimate road/water/road trip

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

EMMERT INTERNATIONAL

"We can move that"

3200 Mile Journey
6/22/13 – 7/26/13



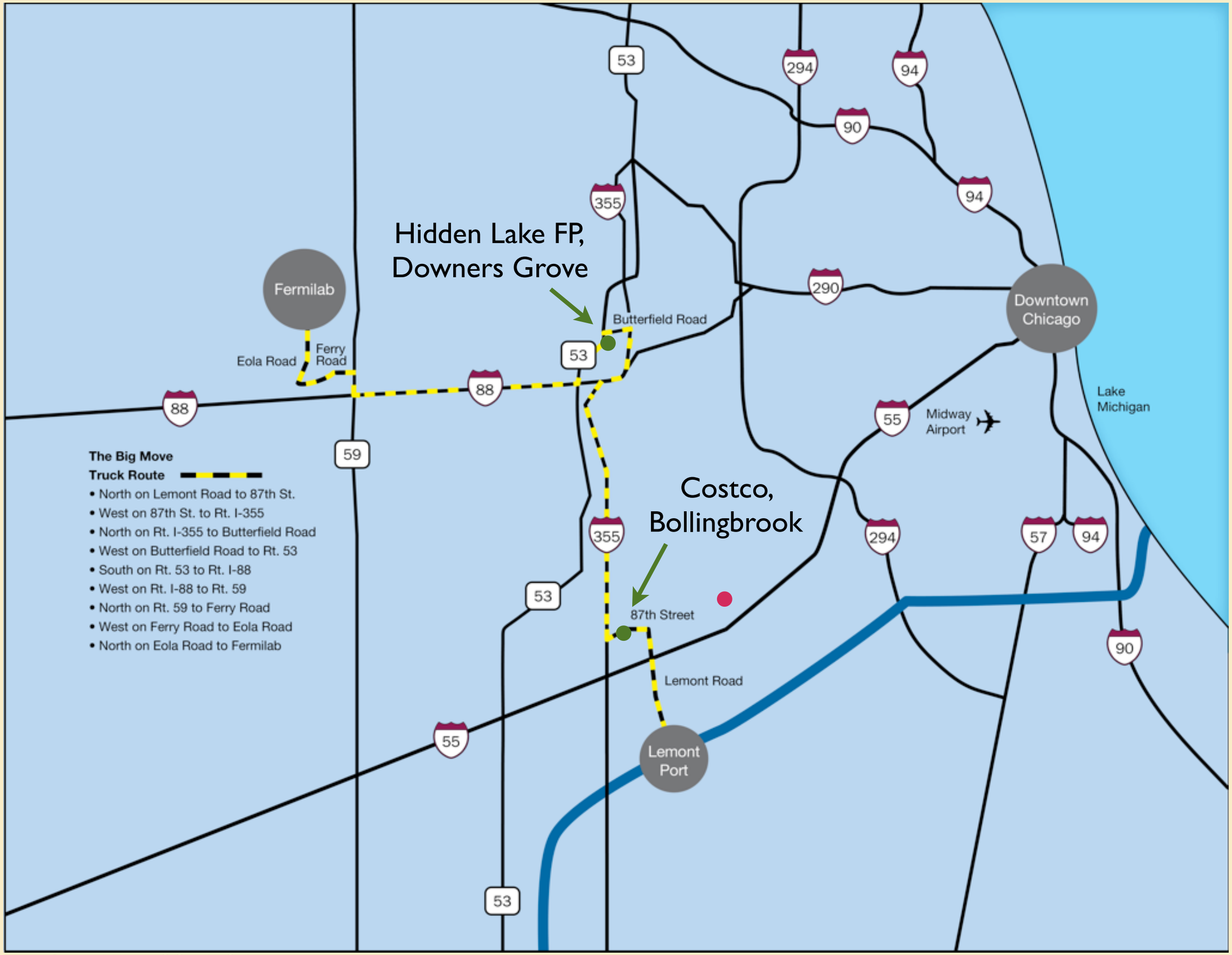
NEW AT 11
11:23 78°

On the water

Photo: Brookhaven/Emmert

And Saturday 7/20, finally in Lemont, IL

Tuesday 7/23 – Friday 7/26: The land route



Tuesday night, on Lemont Rd & 87th St

Photos: Fermilab

Wednesday, shopping at Costco

Toll Violation!

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/giar
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/natic m-new-
york/2013/07/26/8e86095e-f5c2-11e2
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 onal-
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

Muon g-2 @ Fermilab: Improving ω_a

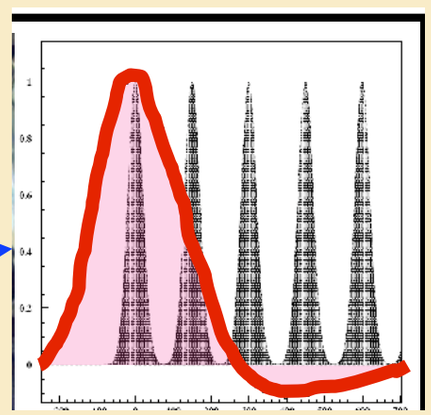
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme;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

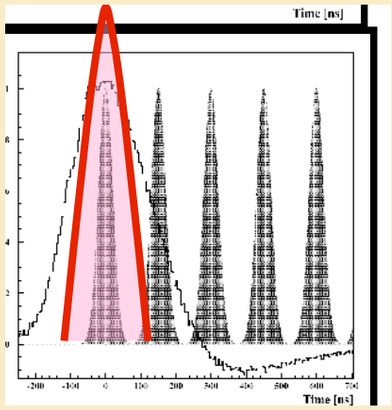
+ No hadronic flash, better laser calibration

+ New tracking, open inflector, scraping

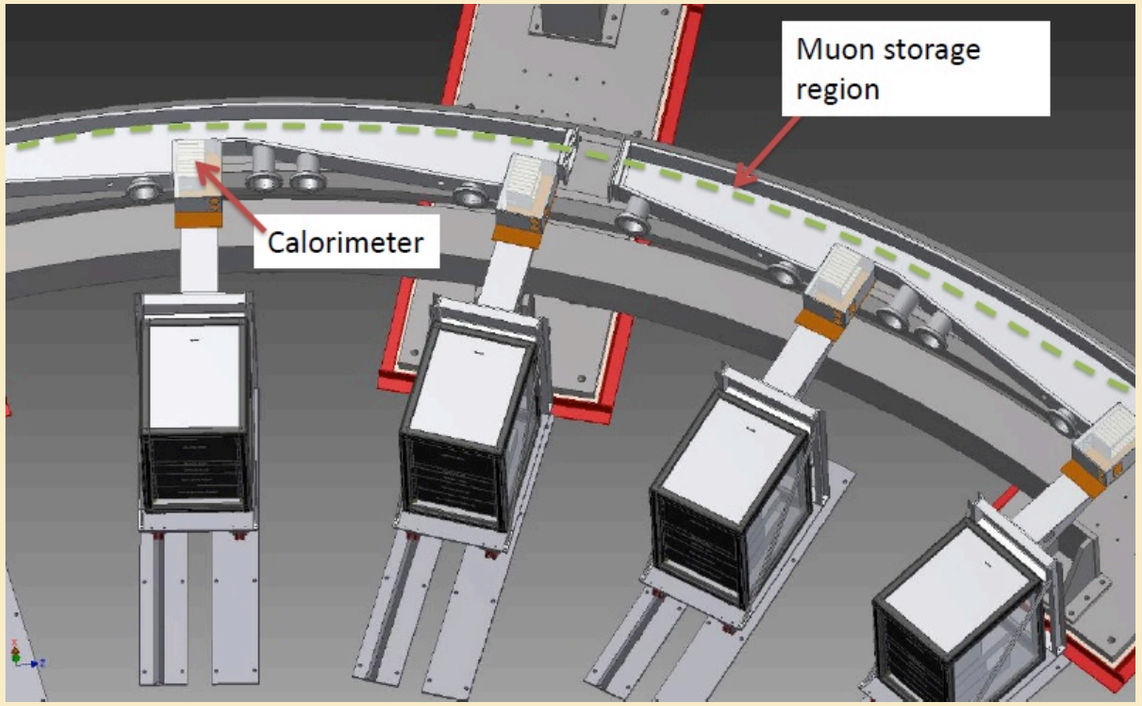
+ Segmented calorimeters

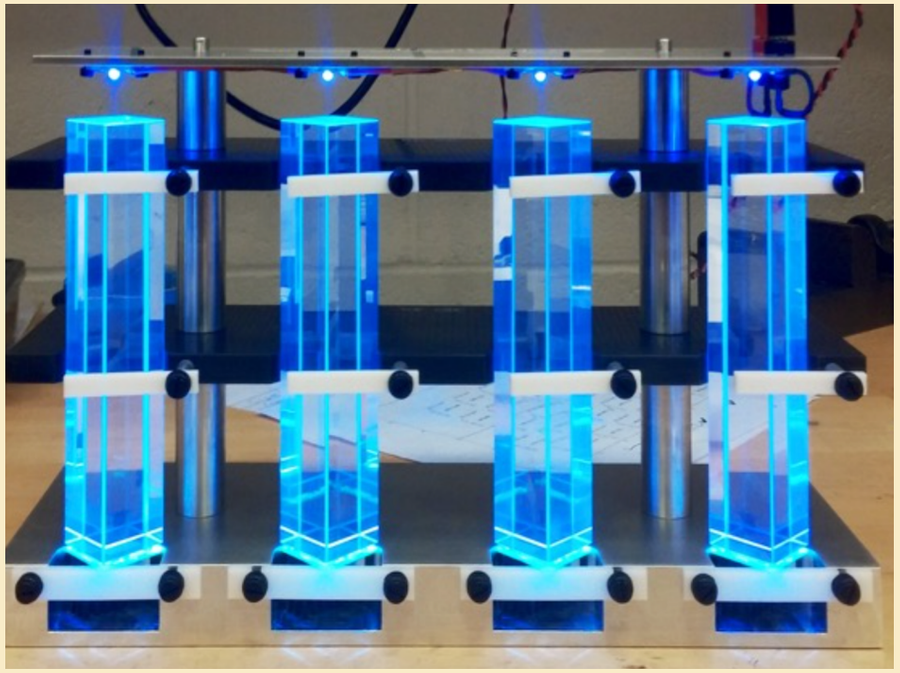
+ Improved kickers

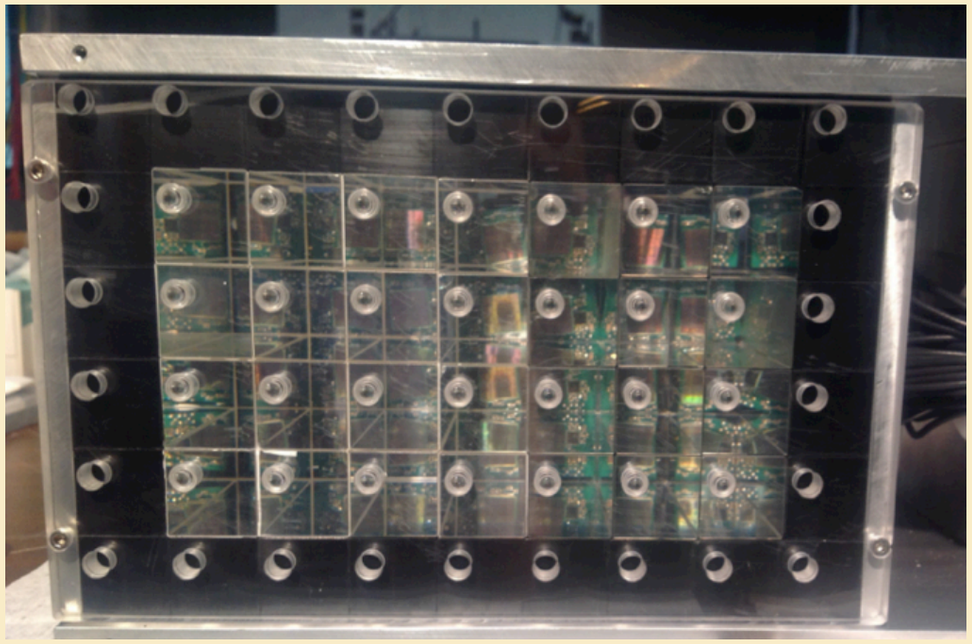




Instrumentation upgrades







24 Calorimetry stations (E and t)

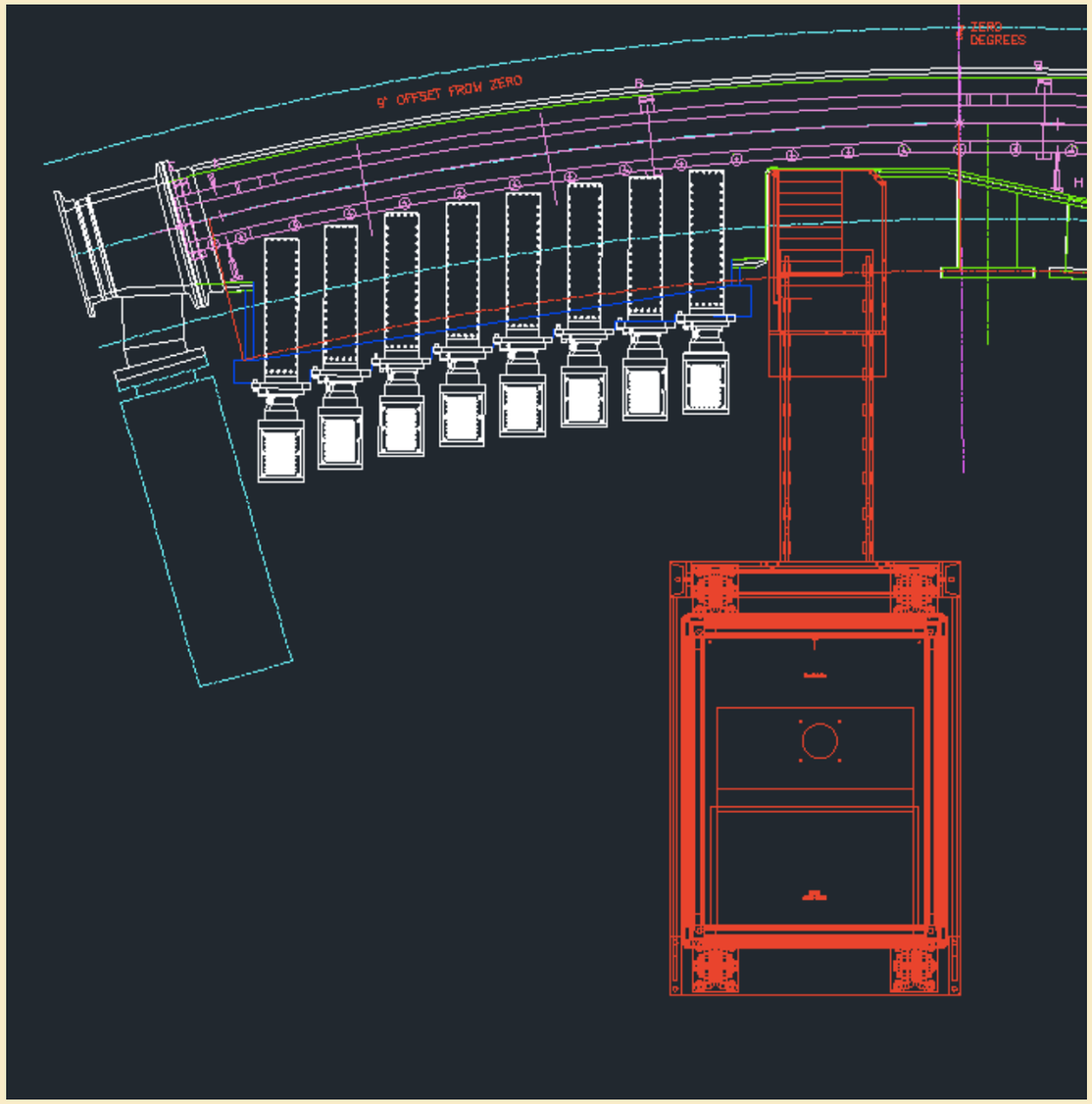
- **6x9 (2.5x2.5 cm) PbF_2 array (X_0 = 0.93 cm)**
- **SiPM Readout**
- **800 MSPS waveform digitizers**
- **Res: Energy: 2.8% @ 3.5 GeV, Spatial: 3 cm, Time: ns**

Improvements over E821

- **Laser for tracking gain stability**
- **Pileup suppression via segmentation**
- **lower thresholds, reduced pion "flash"**

Instrumentation upgrades

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

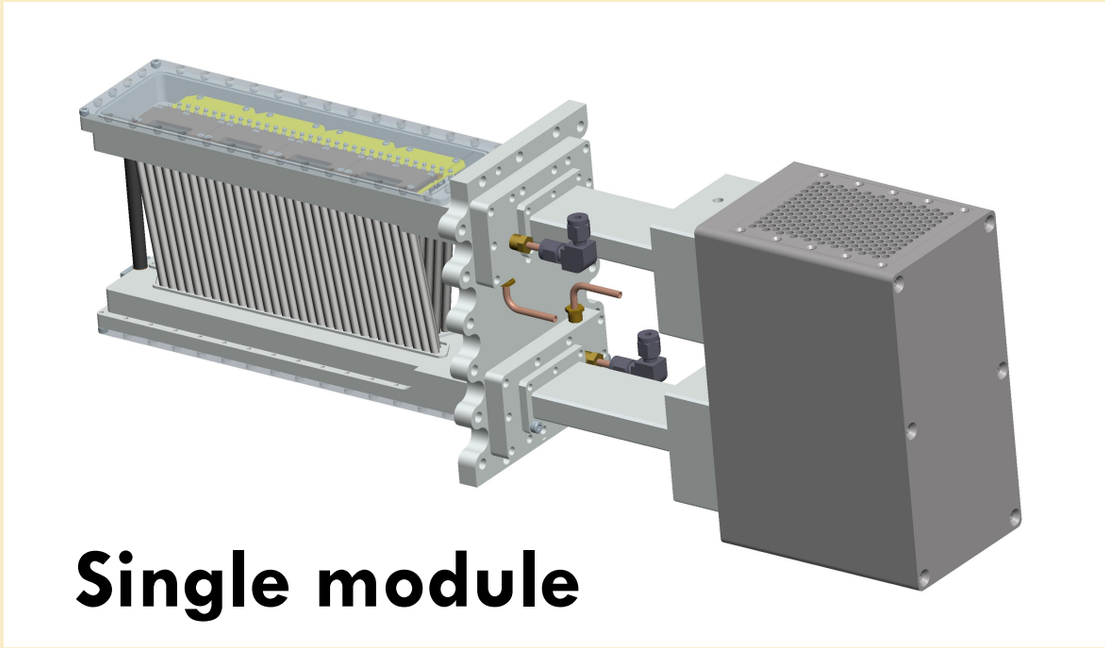


8 modules per tracker system

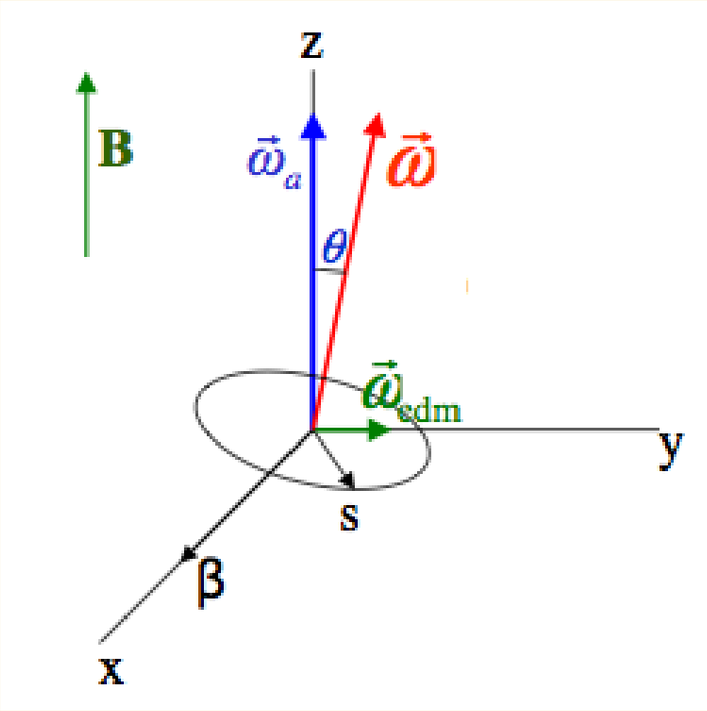
128 straws per tracker

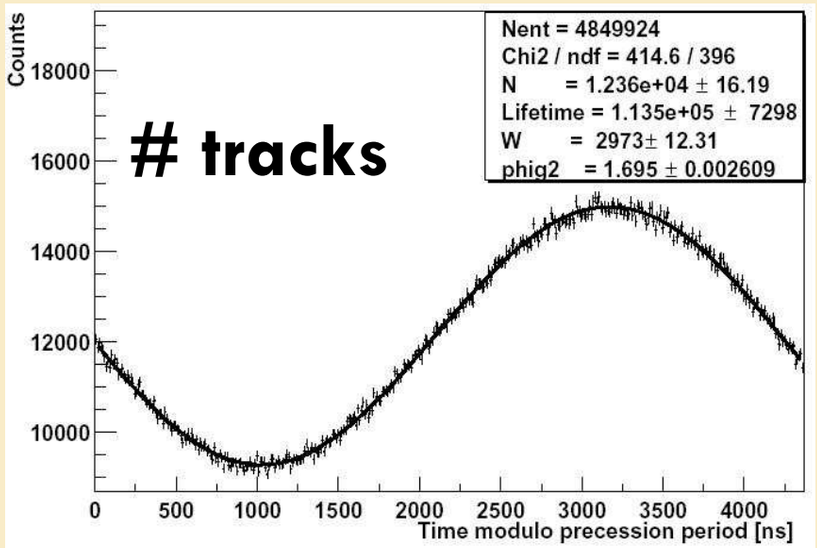
Preamps at end of straws

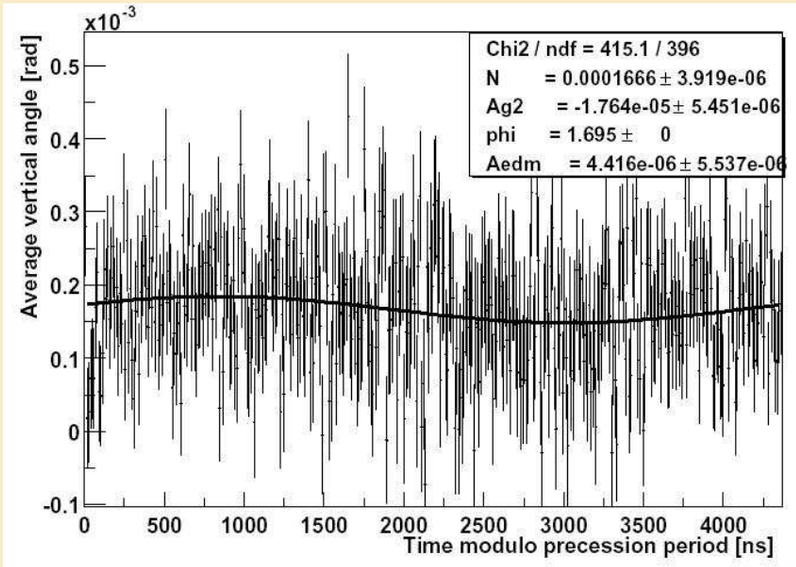
FPGA based TDCs just outside



Muon Electric Dipole Moment







vertical angle of tracks

Precession plane tilted, vertical out of phase oscillation of ω_a

Current best limit from E821

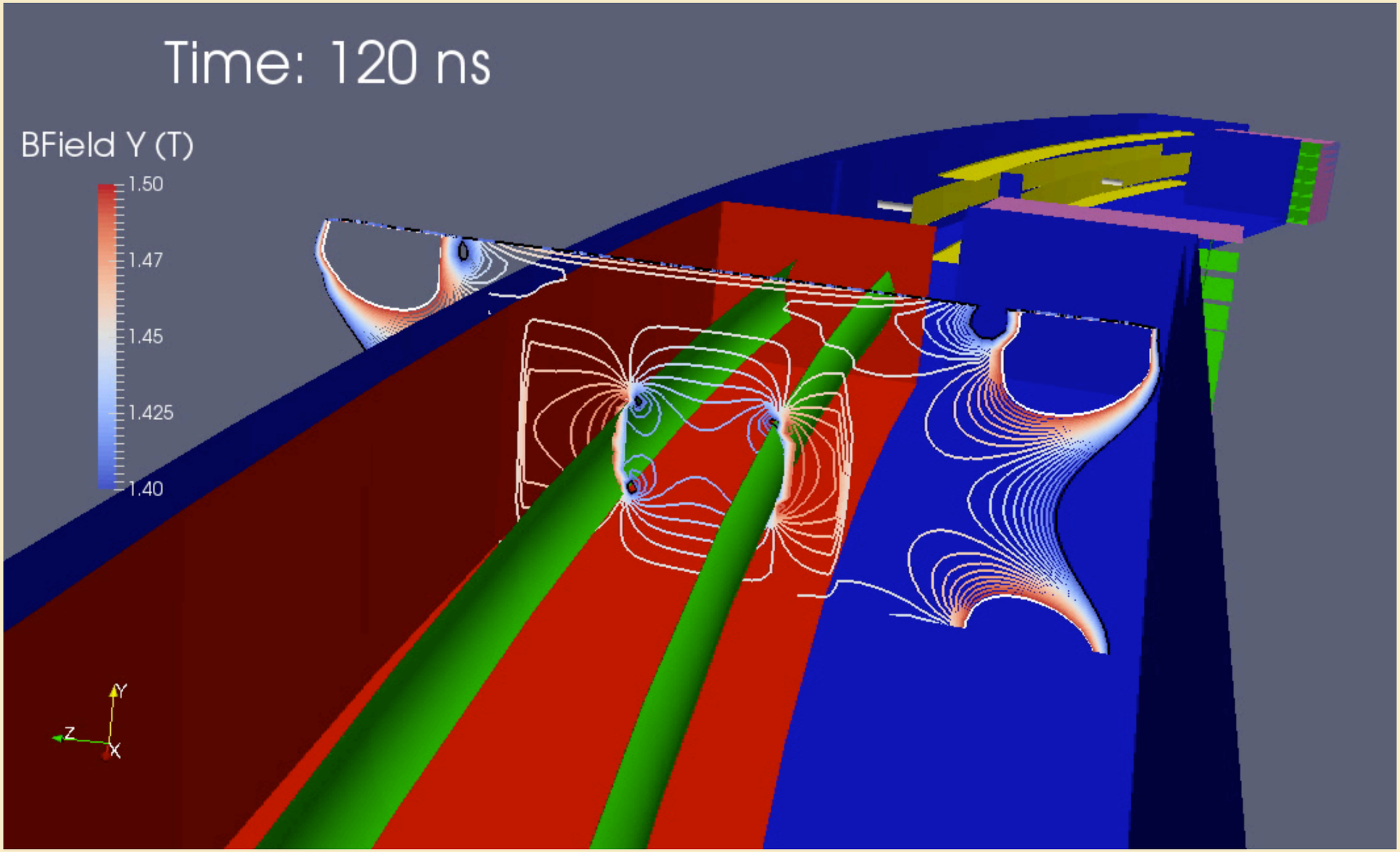
$$|d_\mu| < 1.8 \times 10^{-19}\, e \text{ cm } (95\% \text{ C.L.})$$

<u>Expect < few 10^{-21}</u>

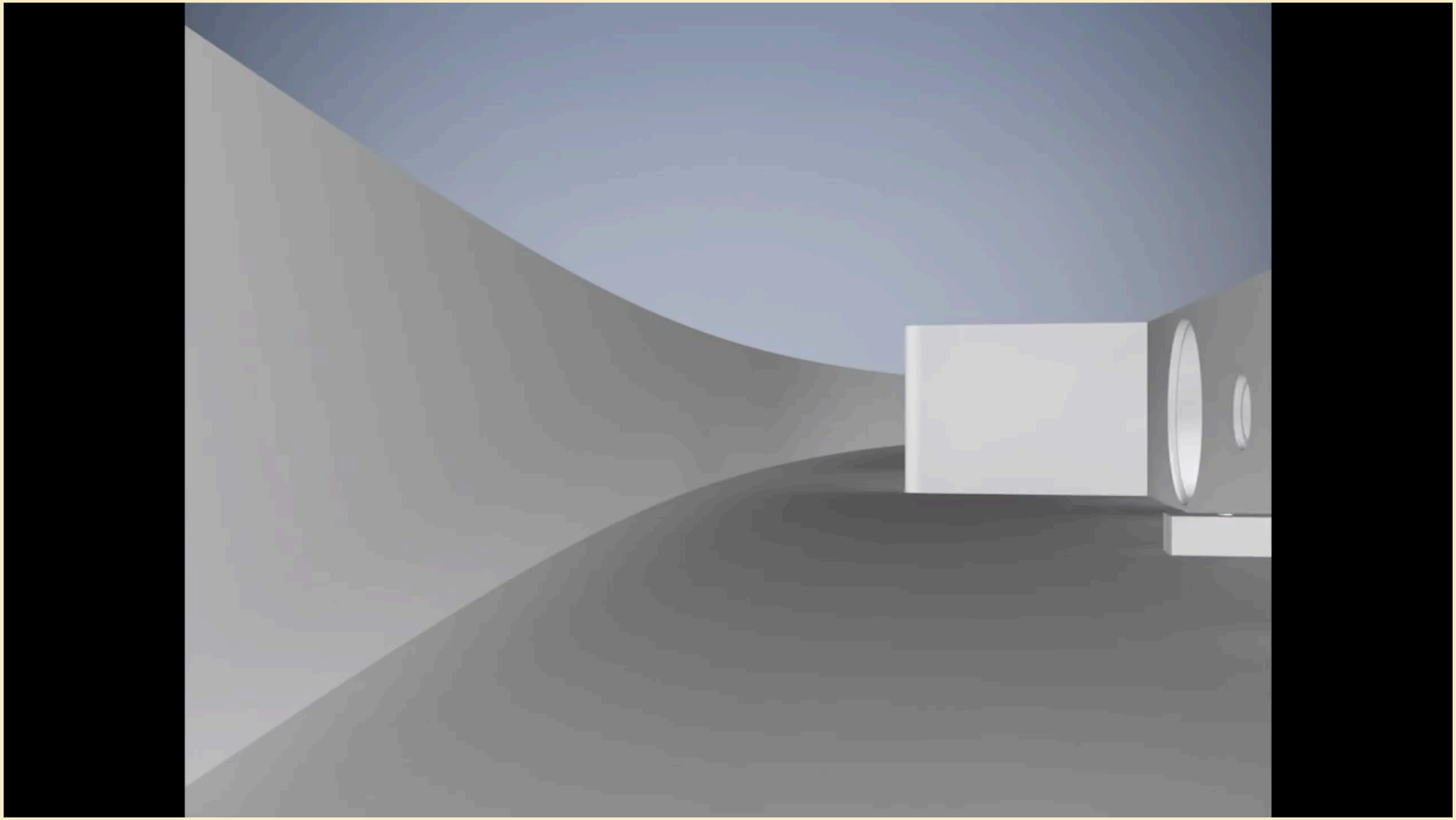
EDMs do not exist in Standard Model
Existence implies Time and CP violation

Simulations

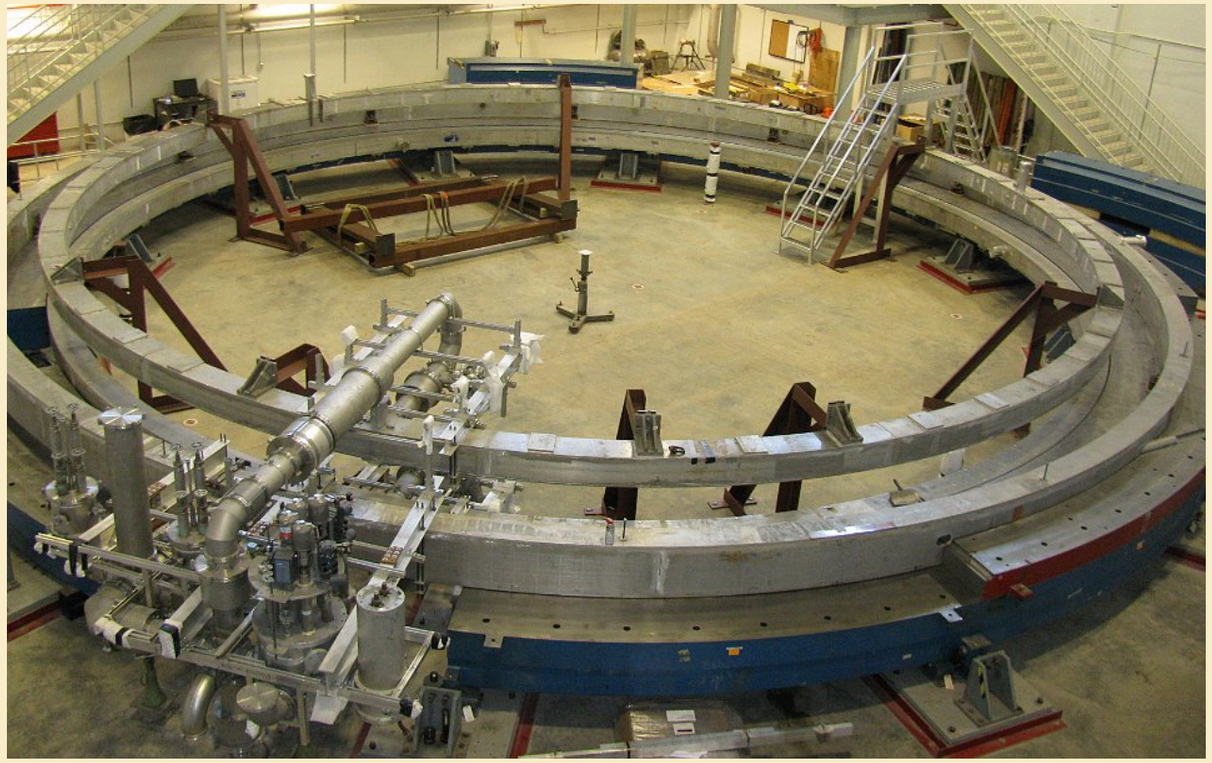
Detailed Geant4 based simulations of Beamline and Ring

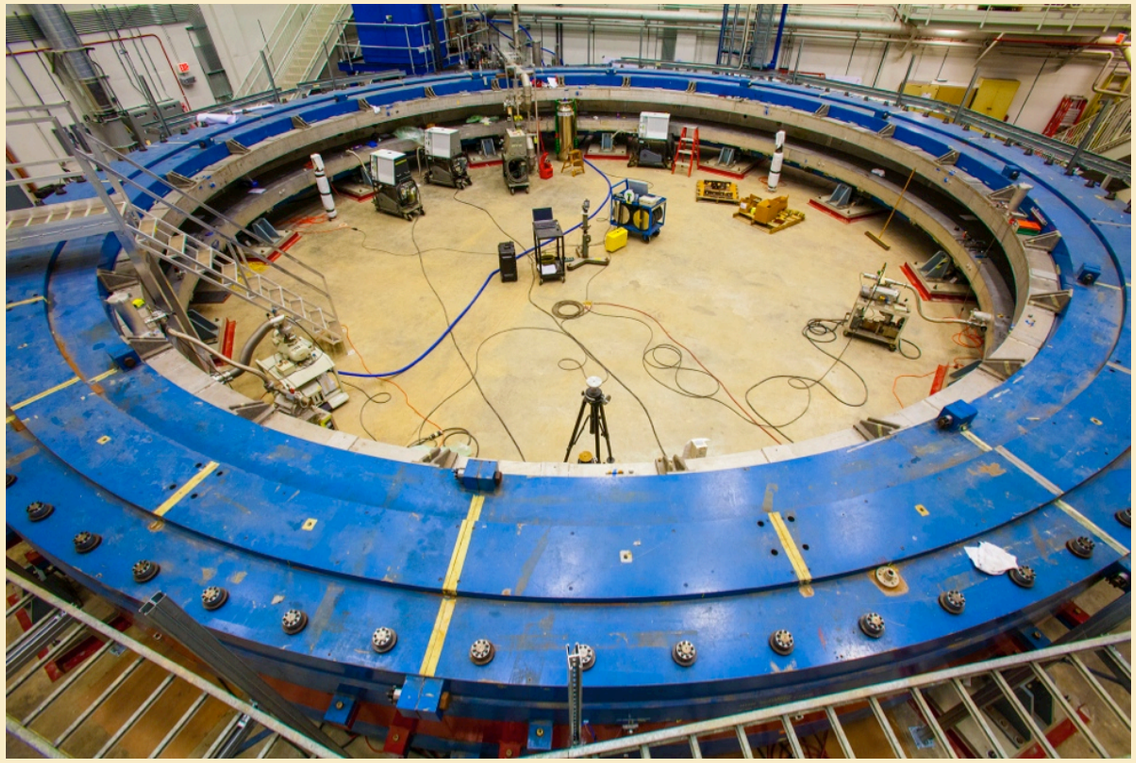


If I was a muon…

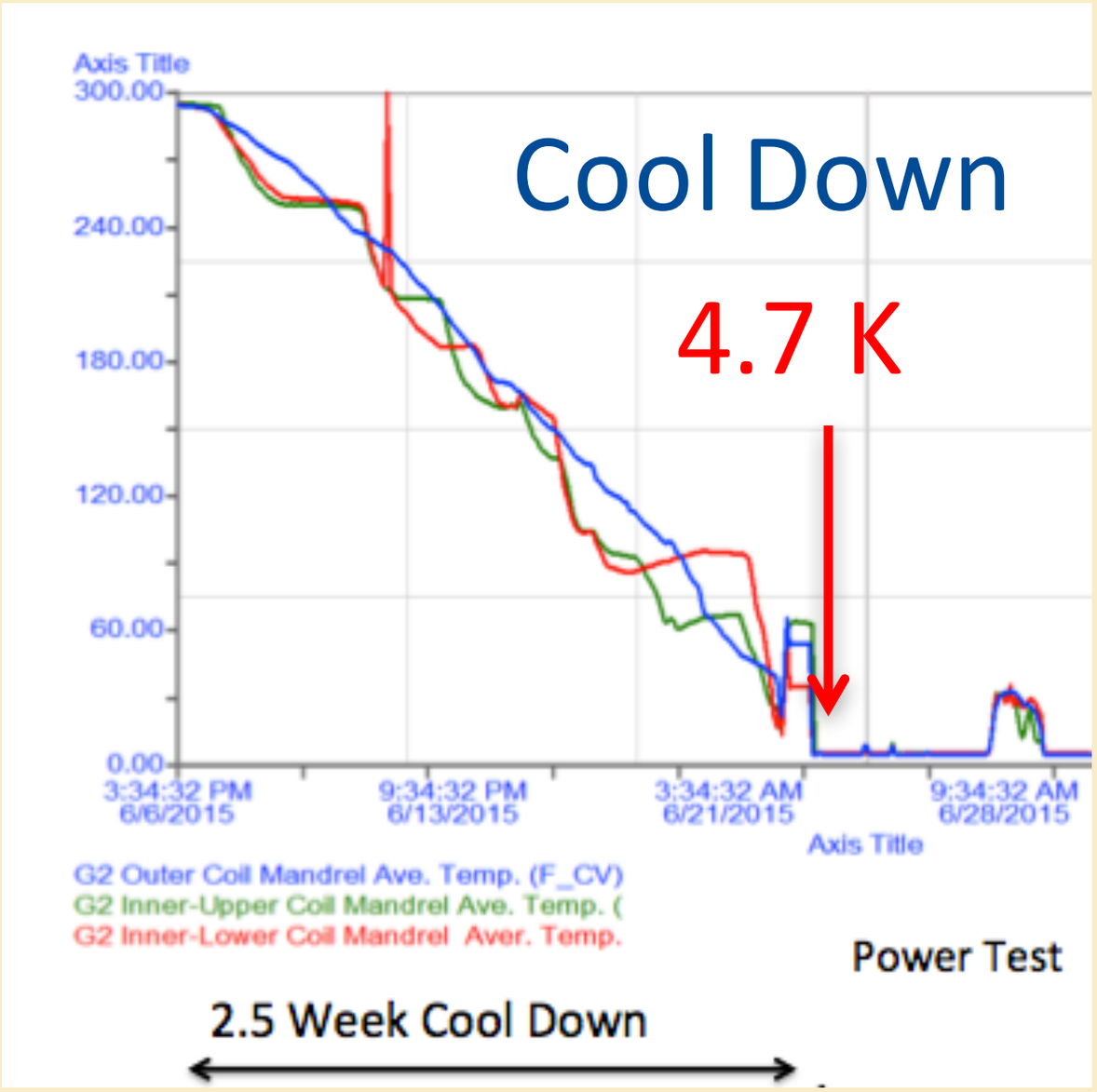


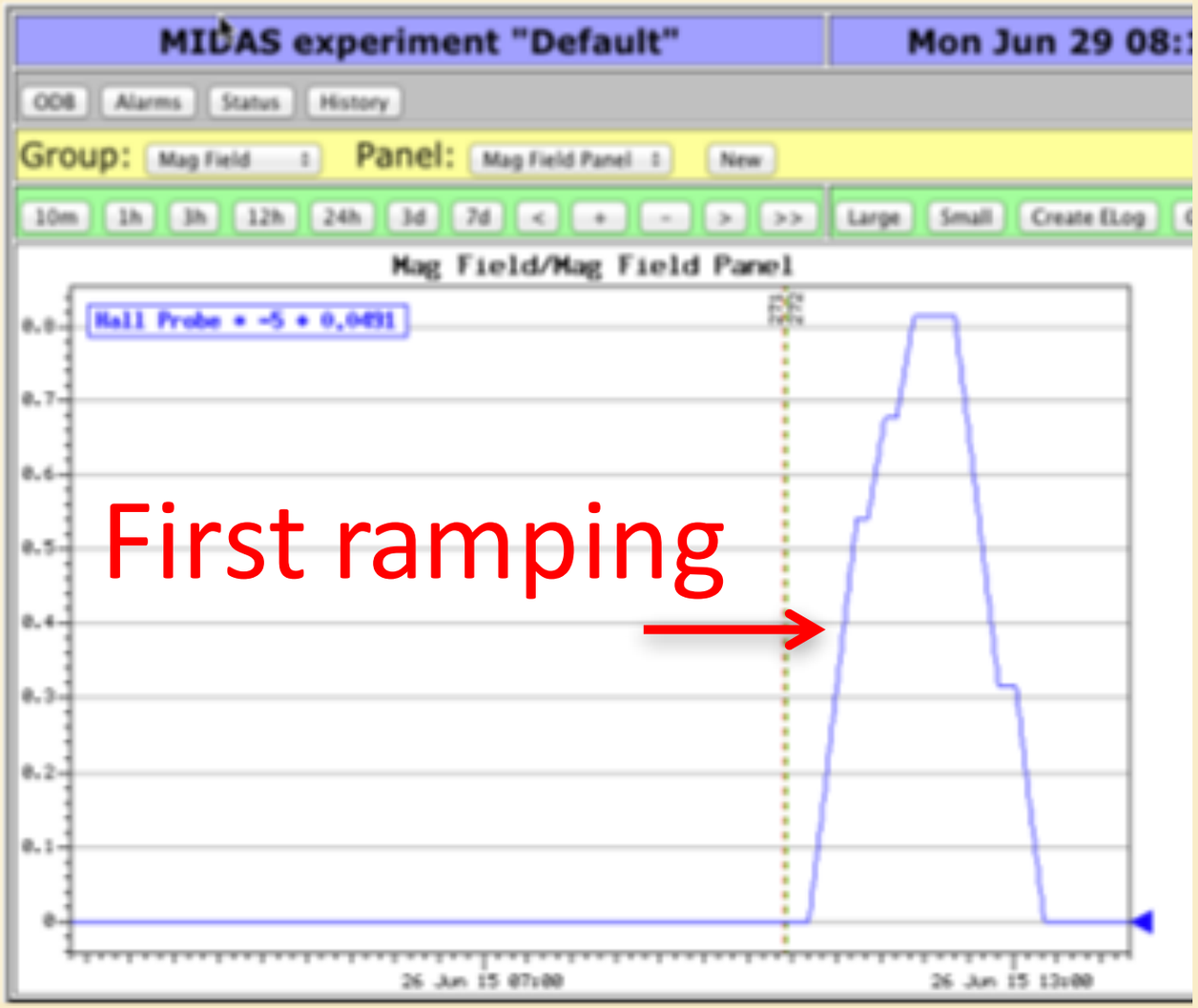
Installation/Assembly (7/14 – 6/15)





Summer 2015 - Power on!





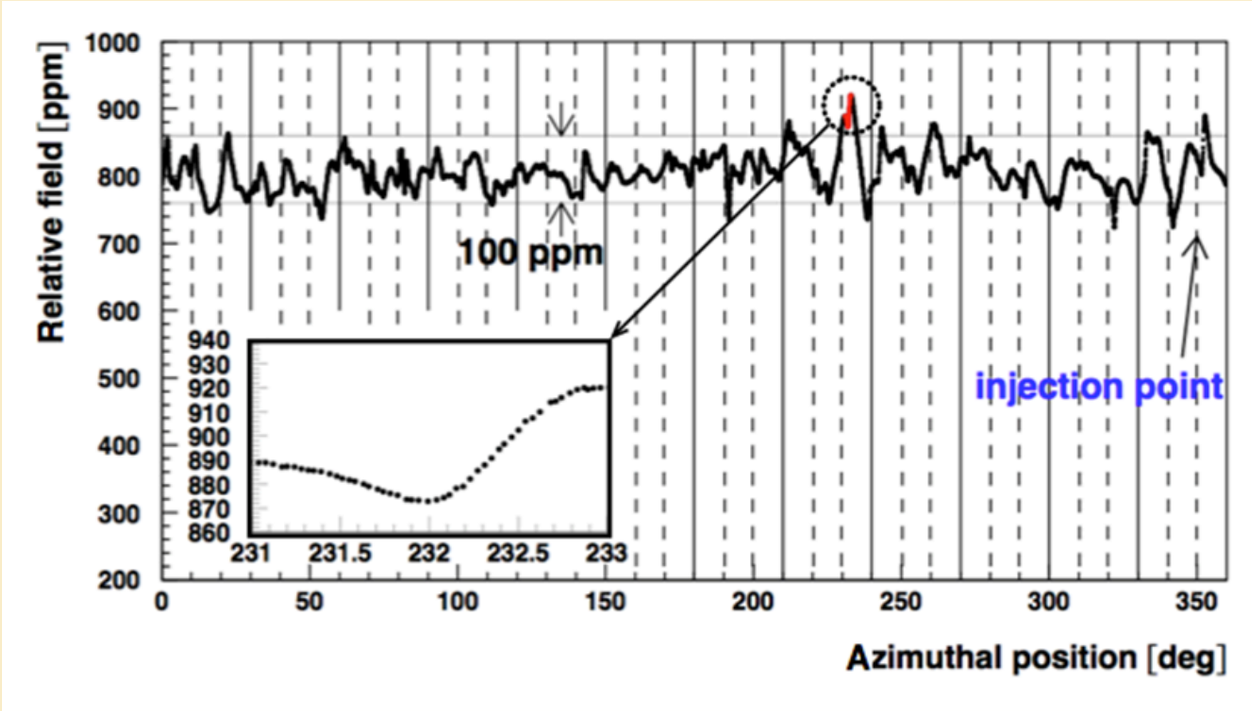
Full Field reached 9/21/15

Shimming the field

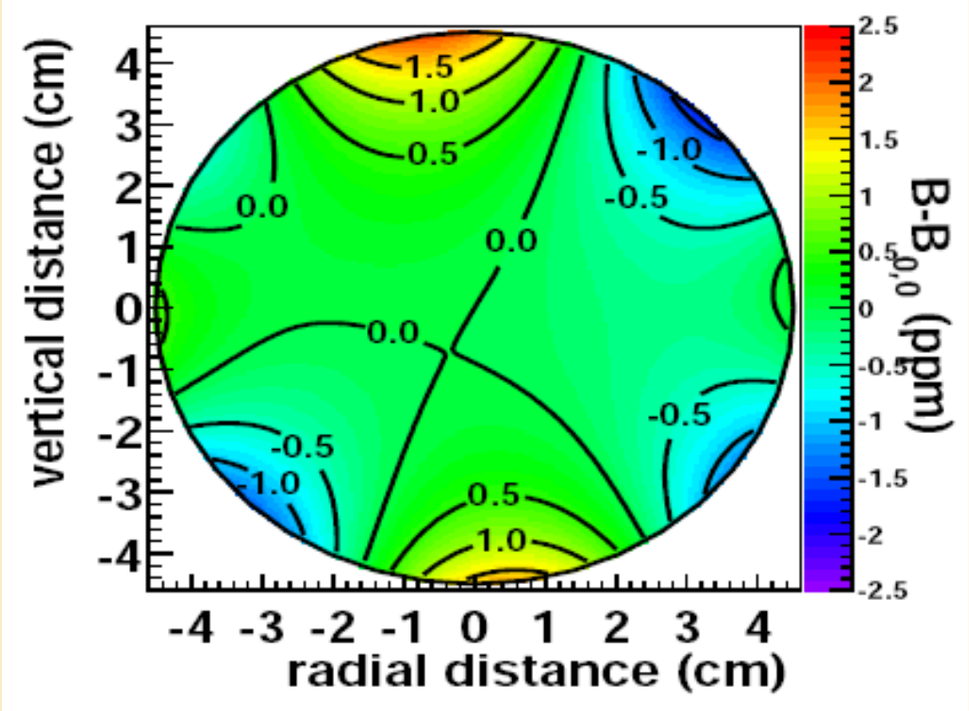
Field uniformity around the ring is crucial

From BNL:

Field vs. Azimuth



Azimuthally Averaged Field vs r,z

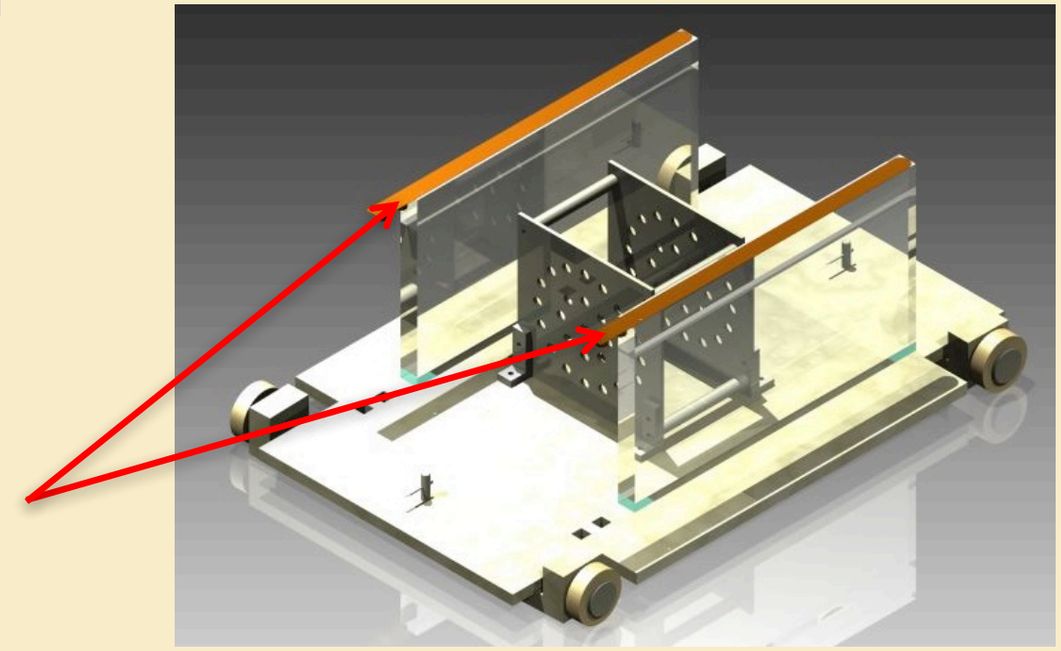


Bennett et al. 10.1103/PhysRevD.73.072003

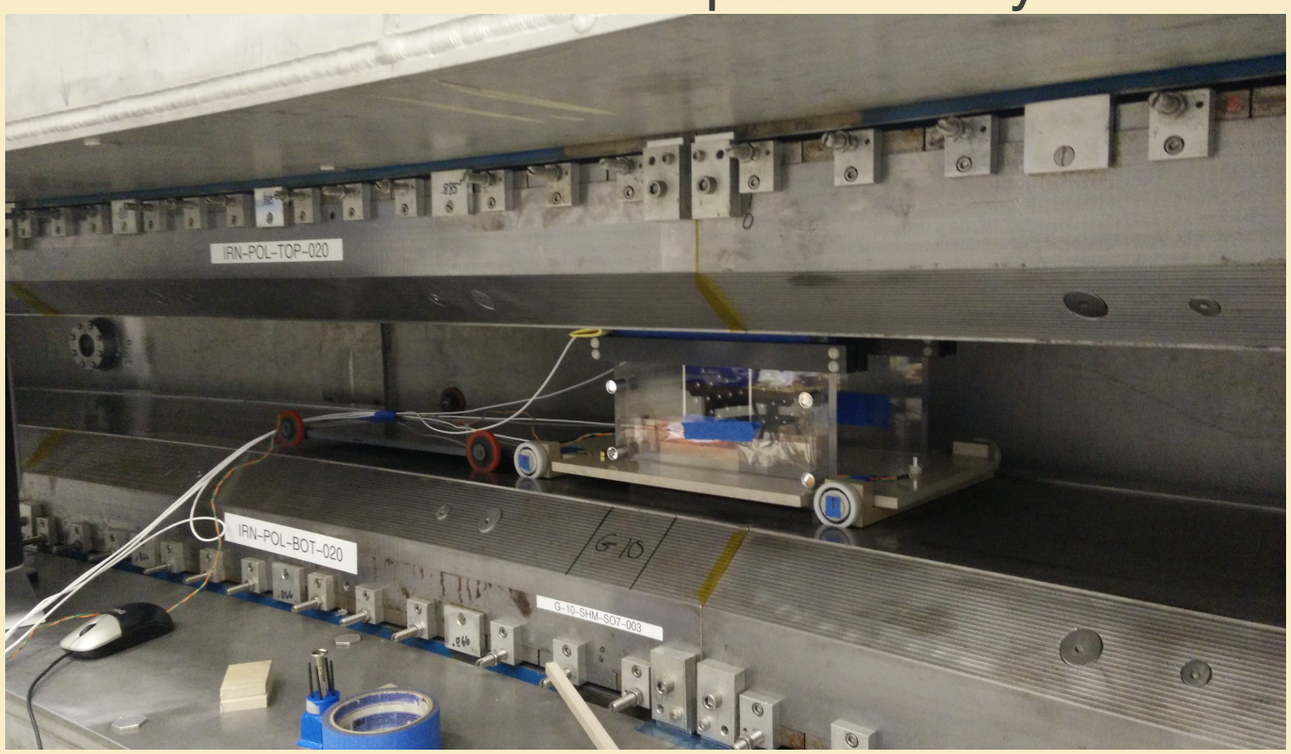
Our Goal +/- 25 ppm

Our Goal +/- 0.5 ppm

Shimming Equipment



- Multipurpose instrument
  - 25 **NMR Probes** for field
  - 4 **capacitive gap sensors**
    - Measure pole alignment
    - 70 nm resolution
    - Few micron reproducibility



4 Position sensors

- Corner cube reflectors
- ~ 25 μm res
- Cart r,θ,z

Thousands of knobs!

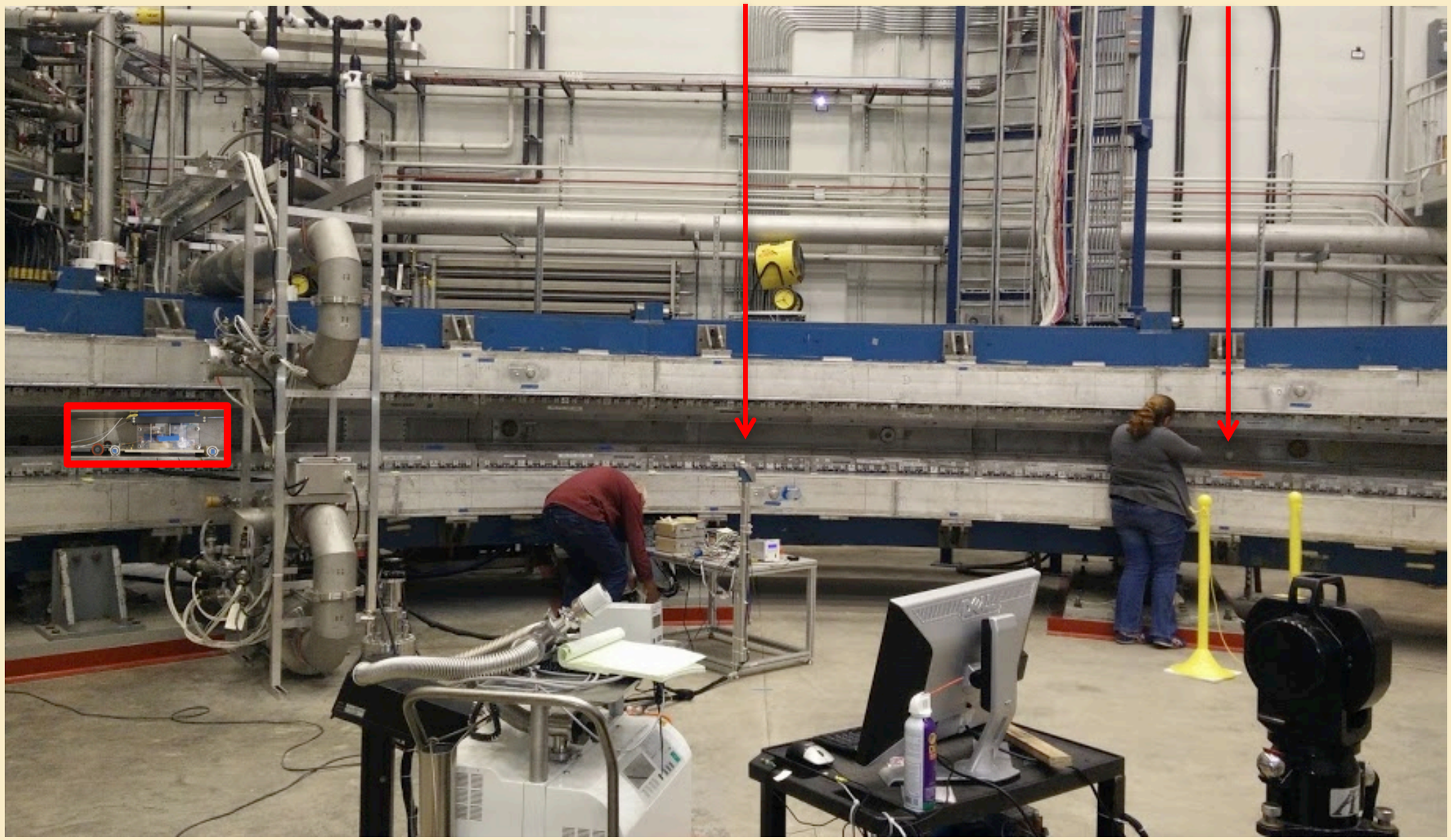
Slide from B. Kiburg

Shimming

Shimming Cart

Stepper Motor

Pulley



Tether

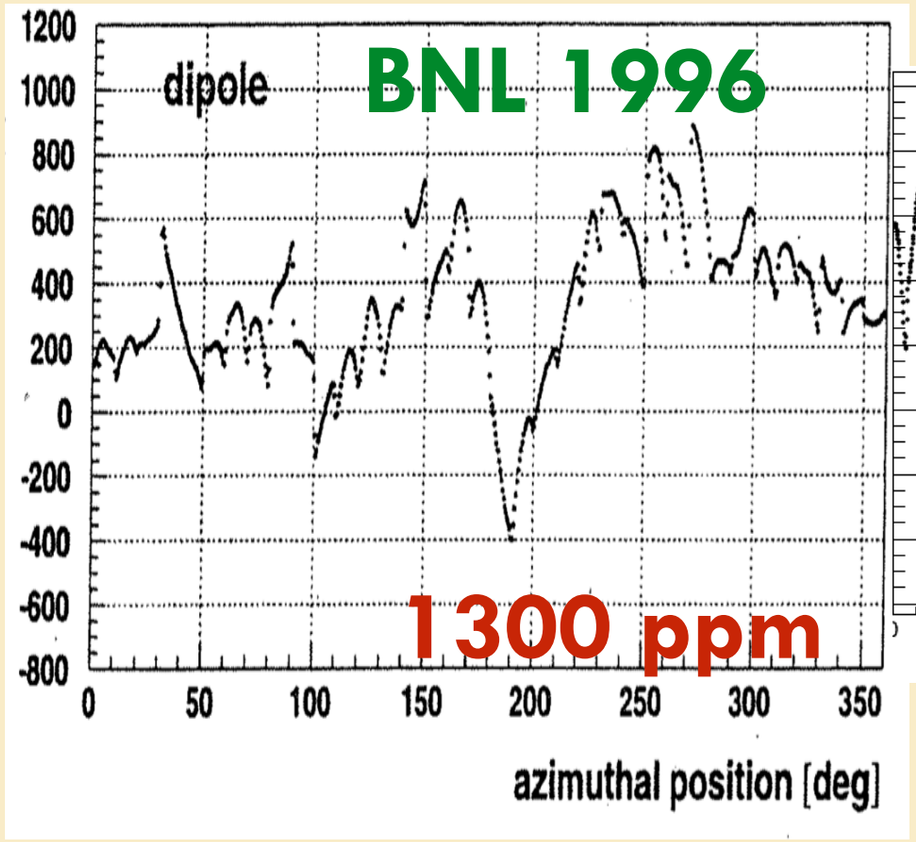
NMR Multiplexors, Electronics Table

Laser DAQ

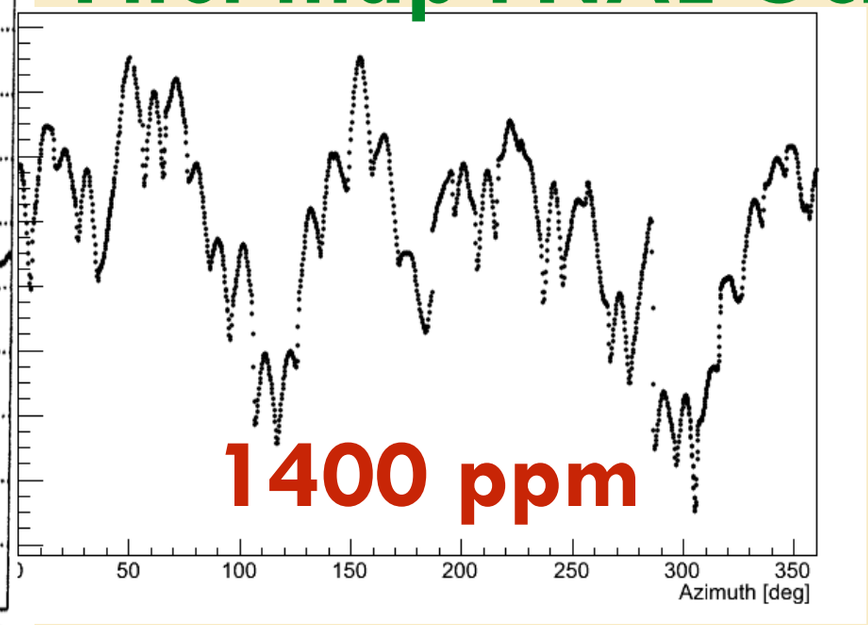
Laser Tracker

Slide from B. Kiburg

Shimming Progress

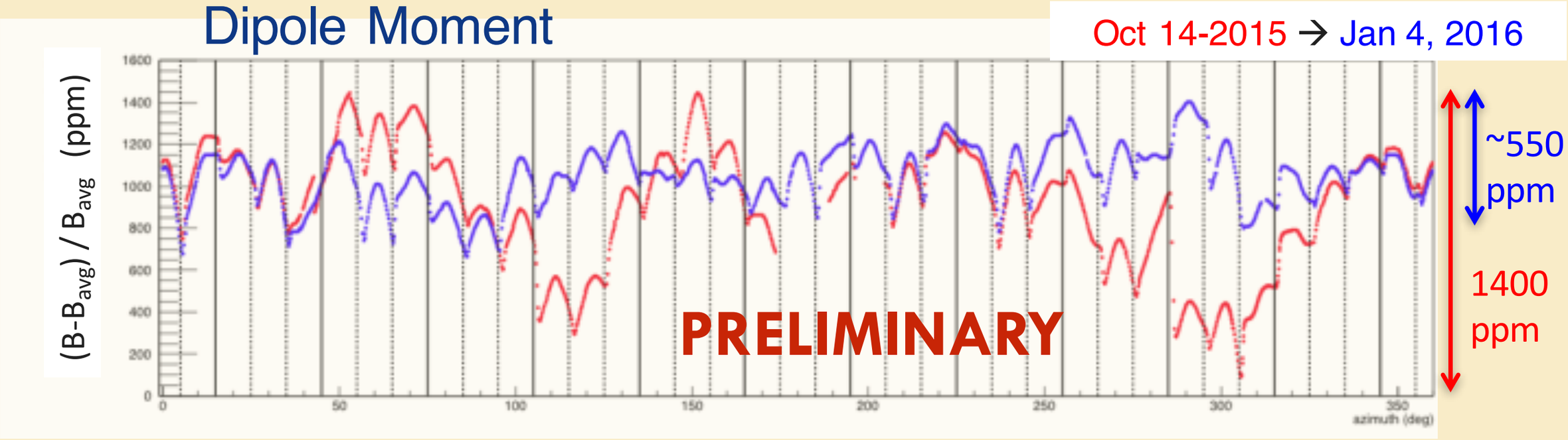


First map FNAL Oct. 2015



Dipole Moment

Oct 14-2015 → Jan 4, 2016



Plots from B. Kiburg

The timeline

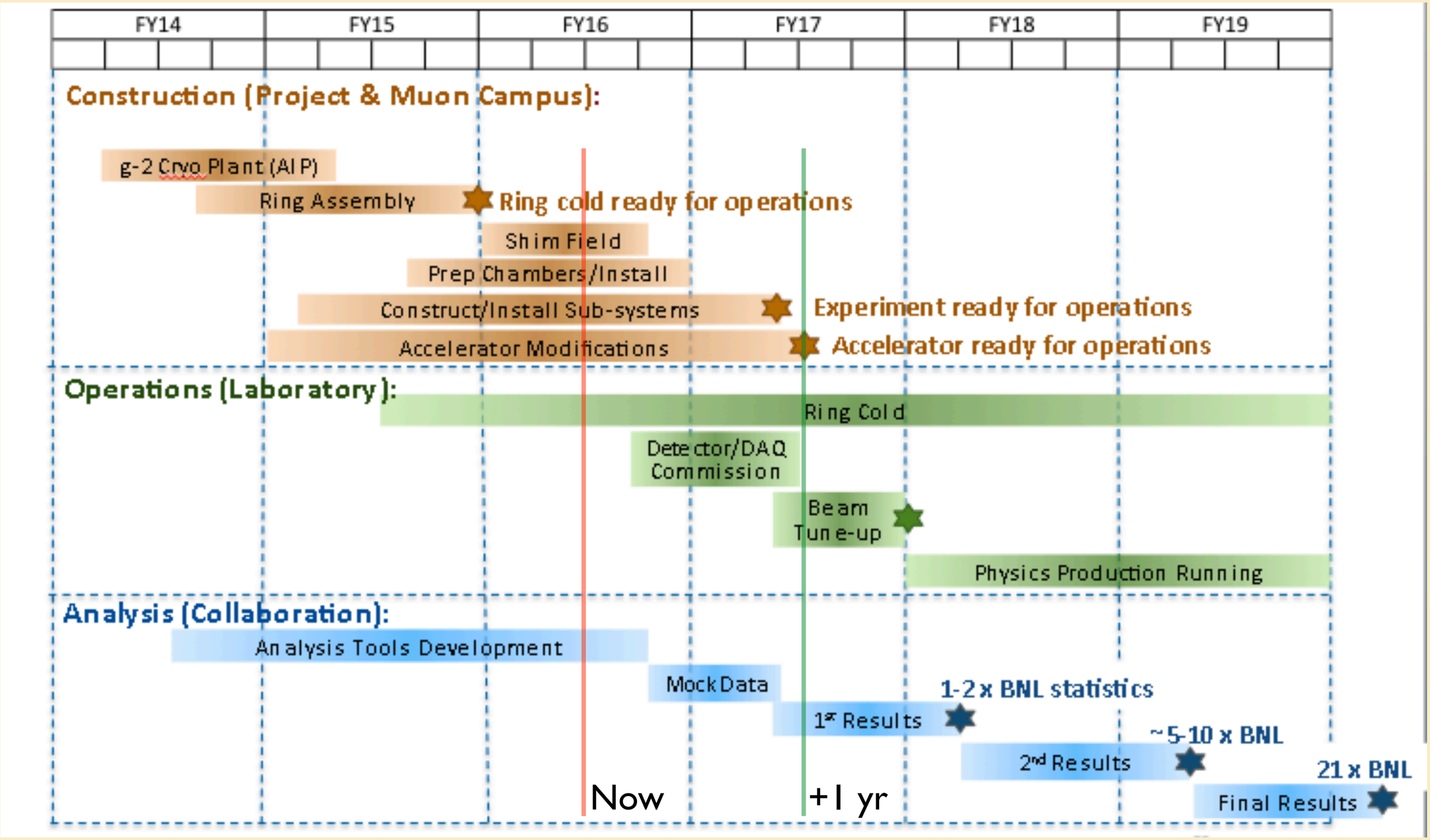


Photo: Fermilab

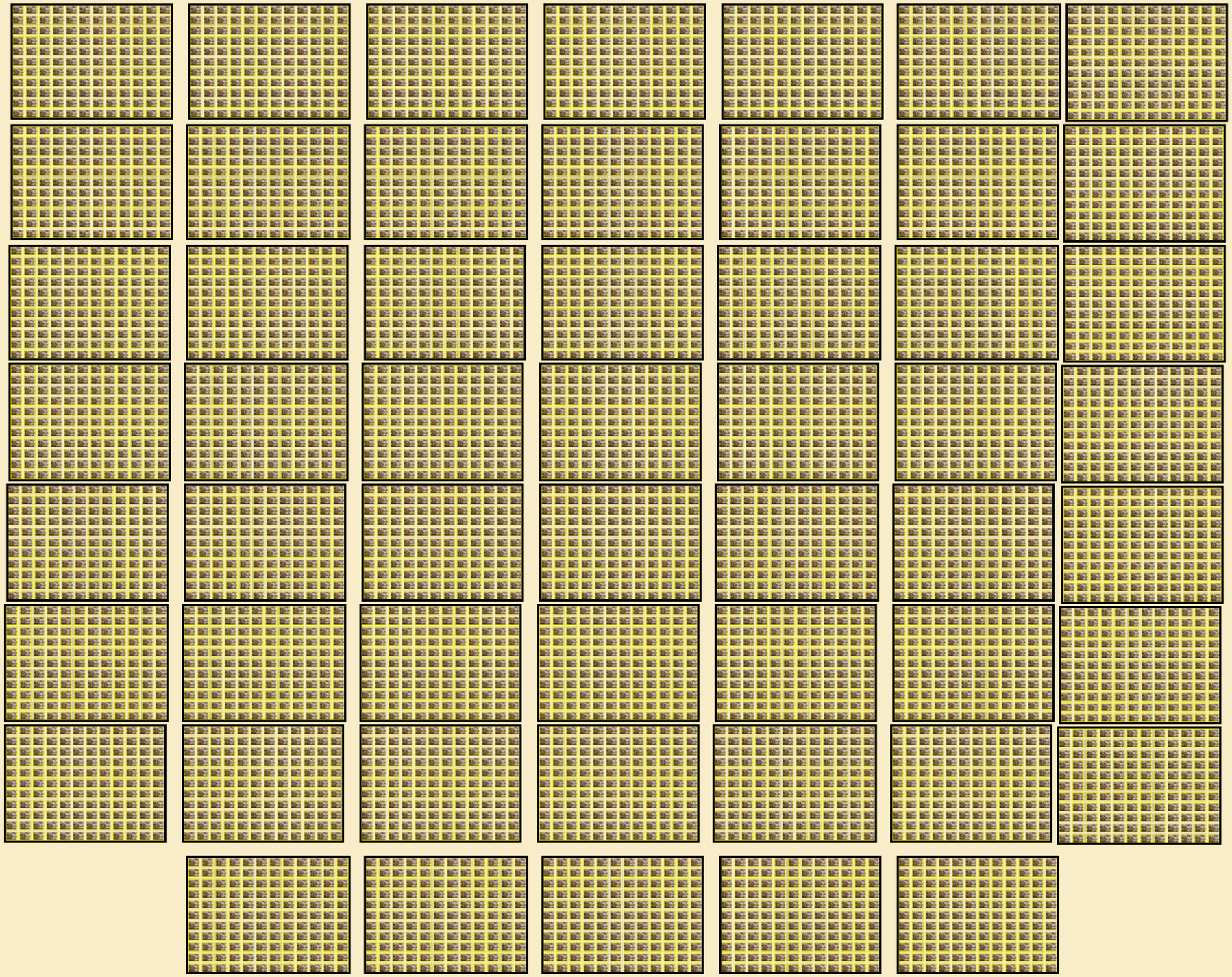
Understanding 140 ppb (a la Dave Hertzog)

1000 piece puzzle; 2 missing; 0.2% systematic

Understanding 140 ppb (a la Dave Hertzog)

142 puzzles; 1 missing piece; 7 ppm (CERN III result)

Understanding 140 ppb (a la Dave Hertzog)



7128 puzzles; 1 missing piece; 140 ppb - Our Goal!!

Acknowledgements

Thanks to these papers and web sites from whom I "borrowed" images

Wikipedia

http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

Chris Polly's thesis

CERN image archives

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

Hertzog & Morse, Annu. Rev. Nucl. Part. Sci. 2004. 54:141–74

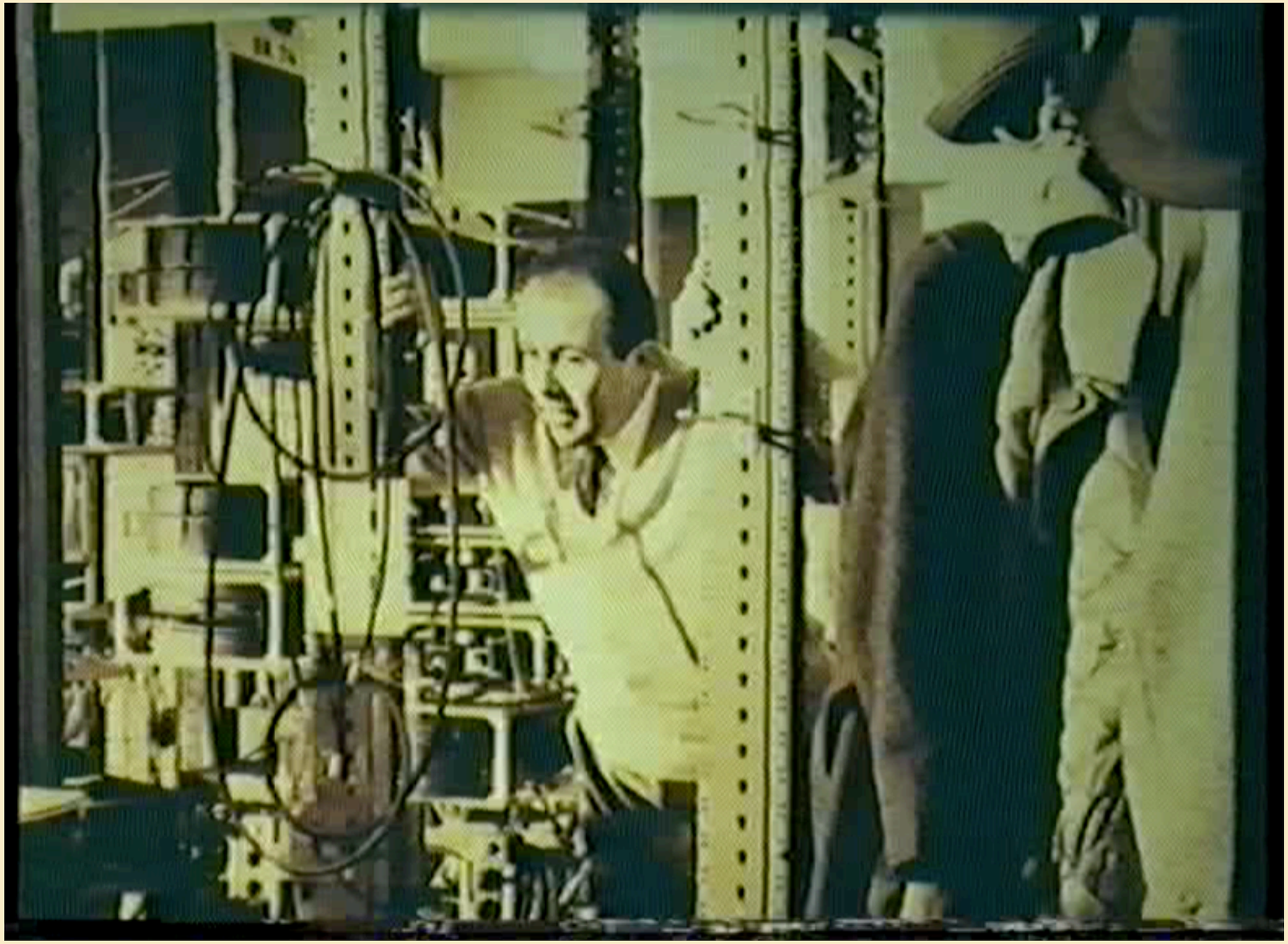
E989 Proposal document and Conceptual Design Report

Various talks by Chris Polly, Dave Hertzog, Brendan Casey, Mary Convery, Hogan Nguyen, Lawrence Gibbons, Leah Welty-Rieger

BACKUP SLIDES

Installation

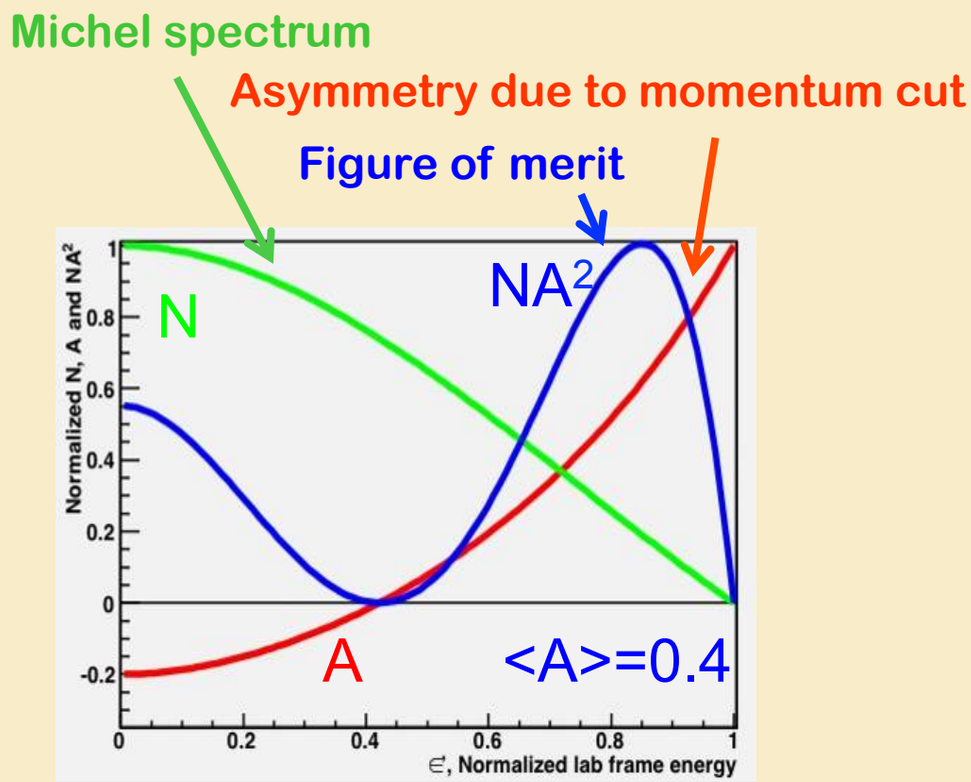
Second CERN experiment results



<u>In the Heart of CERN in 1967</u> **with Emilio Picasso (LEP Project Leader)**

$$N(t) = N_0 e^{-t/\tau} \left[1 + A\cos(\omega_a t + \phi)\right]$$

Positrons over threshold



positron momentum fraction

Cut at 1.8 GeV

Systematics

σ_{syst} ω_p	1999 (ppm)	2000 (ppm)	2001 (ppm)	σ_{syst} ω_a	1999 (ppm)	2000 (ppm)	2001 (ppm)
Inflector fringe field	0.20	-	-	Pile-Up	0.13	0.13	0.08
Calib. of trolley probes	0.20	0.15	0.09	AGS background	0.10	0.01	‡
Tracking B with time	0.15	0.10	0.07	Lost muons	0.10	0.10	0.09
Measurement of B_0	0.10	0.10	0.05	Timing shifts	0.10	0.02	‡
μ-distribution	0.12	0.03	0.03	E-field/pitch	0.08	0.03	‡
Absolute calibration	0.05	0.05	0.05	Fitting/binning	0.07	0.06	‡
Others†	0.15	0.10	0.07	CBO	0.05	0.21	0.07
				Beam debunching	0.04	0.04	‡
				Gain changes	0.02	0.13	0.12
Total for ω_p	0.4	0.24	0.17	Total for ω_a	0.3	0.31	0.21

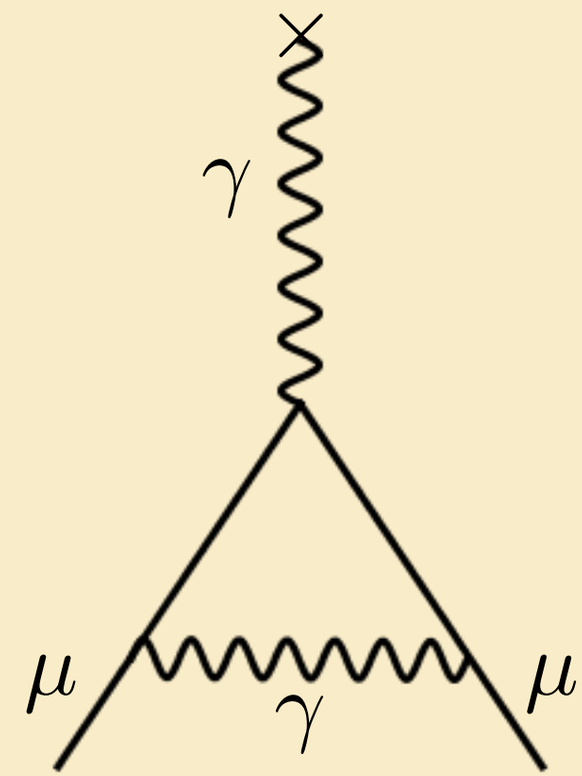
Total 0.28 ppm systematic

1st order QED

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

Lowest order QED is

$$a_\mu^{\rm LO\ QED} = \alpha/2\pi = 0.00118$$



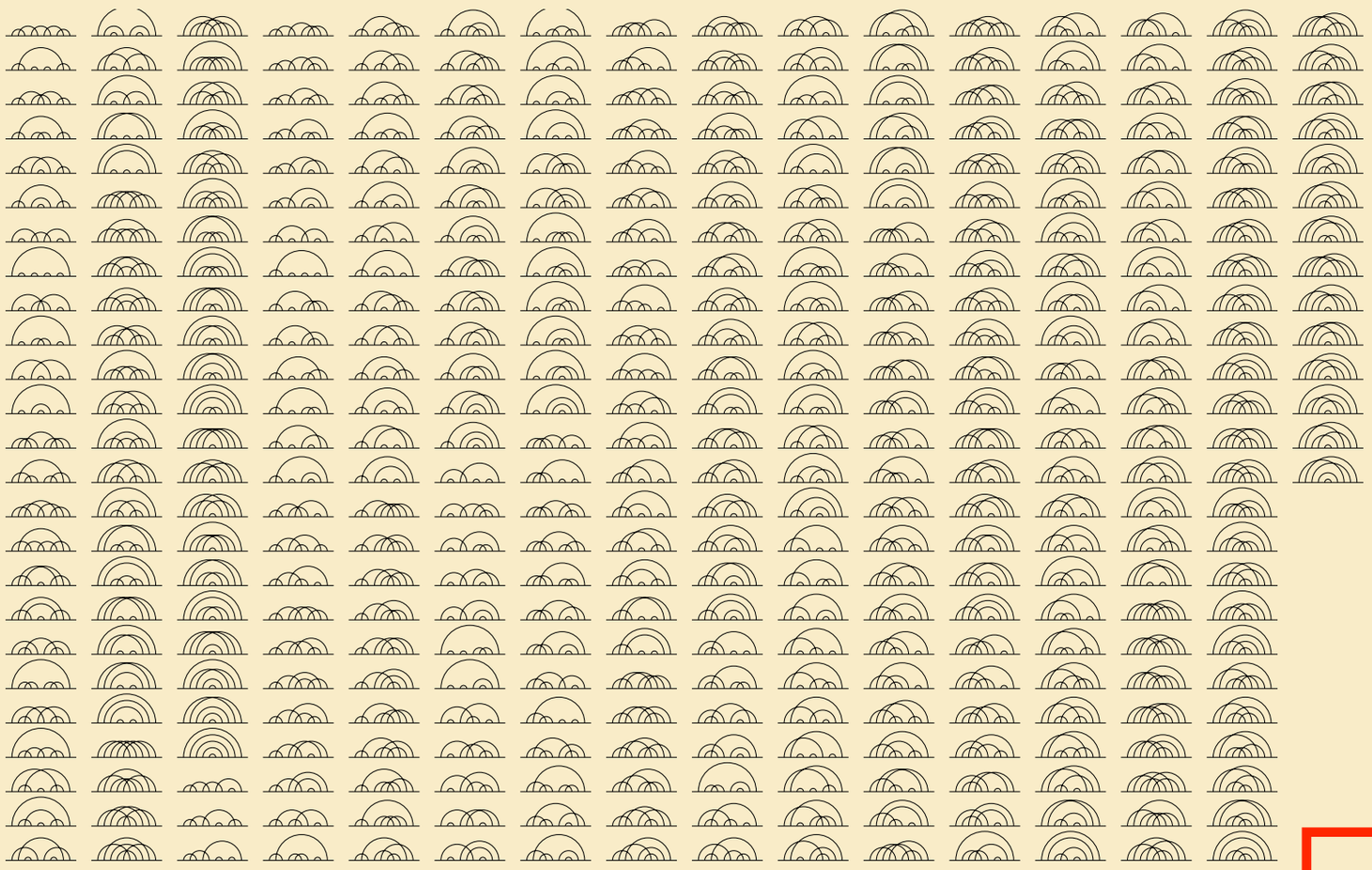
$$a_\mu^{\rm exp} = 0.00\boxed{116}592\,089(63)$$

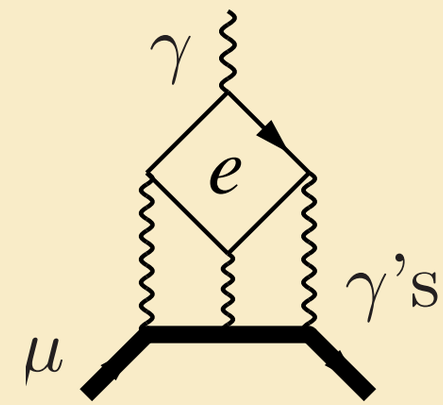
$$a_\mu^{\rm LO\ QED} = 0.00\boxed{118}$$

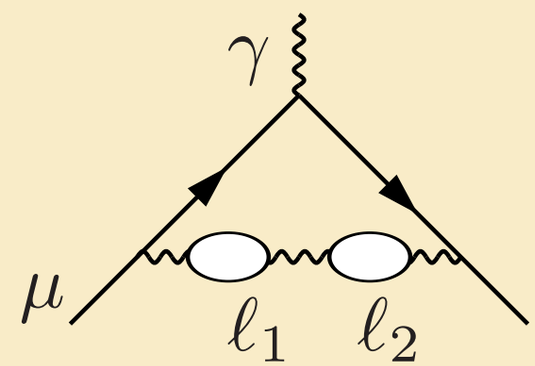
QED contributions

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

QED corrections computed to $O(\alpha^5)$ 10th order contribution (12,672 diagrams contribute)







Aoyama, Hayakawa, Kinoshita, Nio (2012)

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

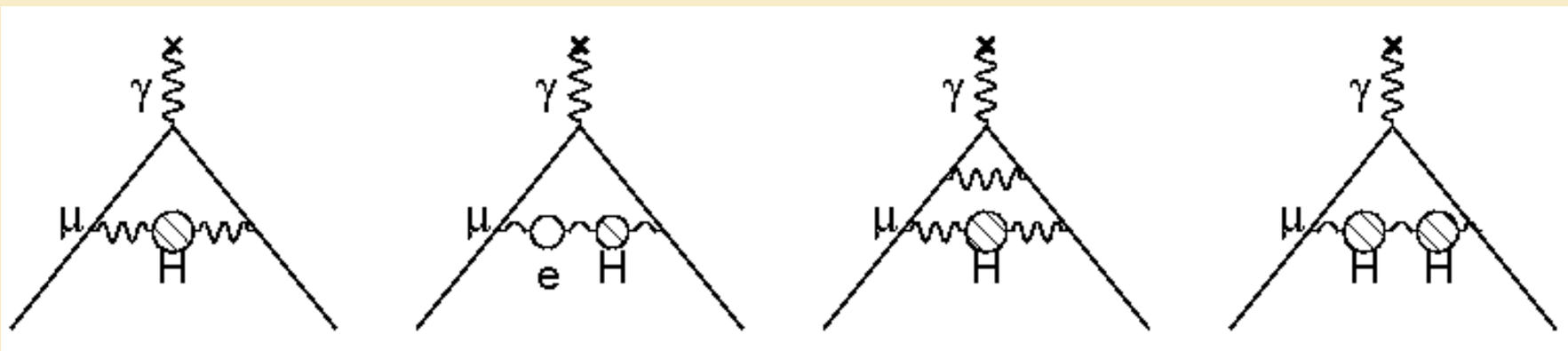
$$a_\mu^{\rm QED} = 0.00\,116\,584\,718\,951(80)$$

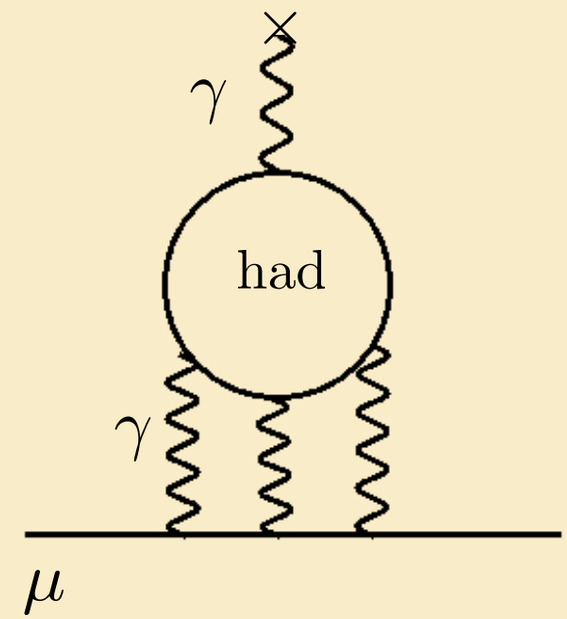
Hadronic contributions

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

Hadronic contribution has the largest uncertainty

Hadronic Vacuum polarization, Hadronic light-by-light

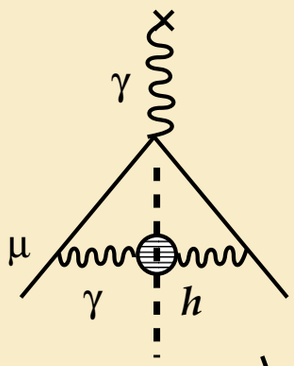


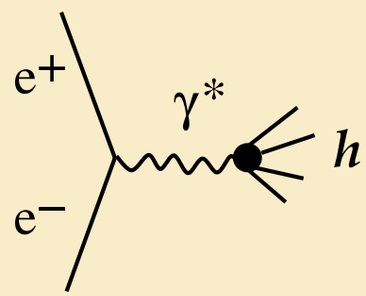


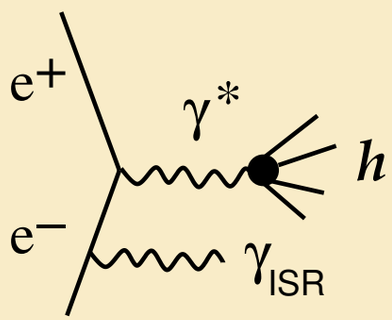
Virtual hadron energy scale is well below perturbative region of QCD

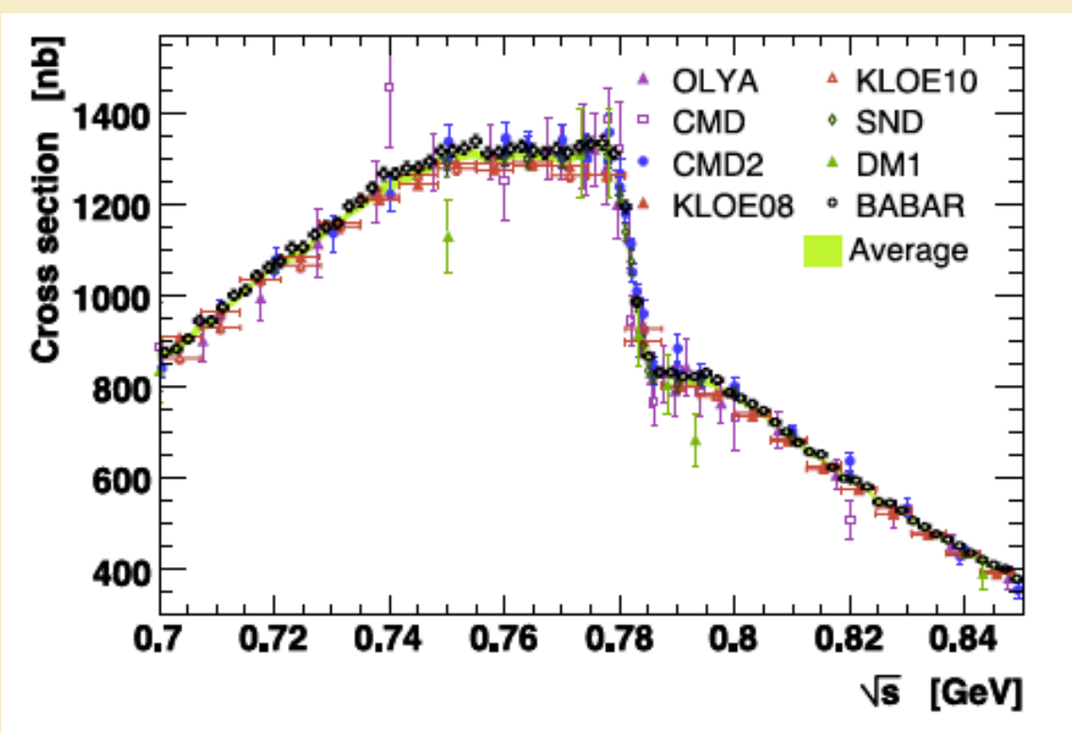
Hadronic contributions

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









$$a_\mu^{\rm HVPLO} = (692.3 \pm 4.2) \times 10^{-10}$$

$$a_\mu^{\rm HVPNLO} = (-9.8 \pm 0.1) \times 10^{-10}$$

$$a_\mu^{\rm HLBL} = (10.5 \pm 2.6) \times 10^{-10}$$

$$a_\mu^{\rm had} = (693.0 \pm 4.9) \times 10^{-10}$$

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

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

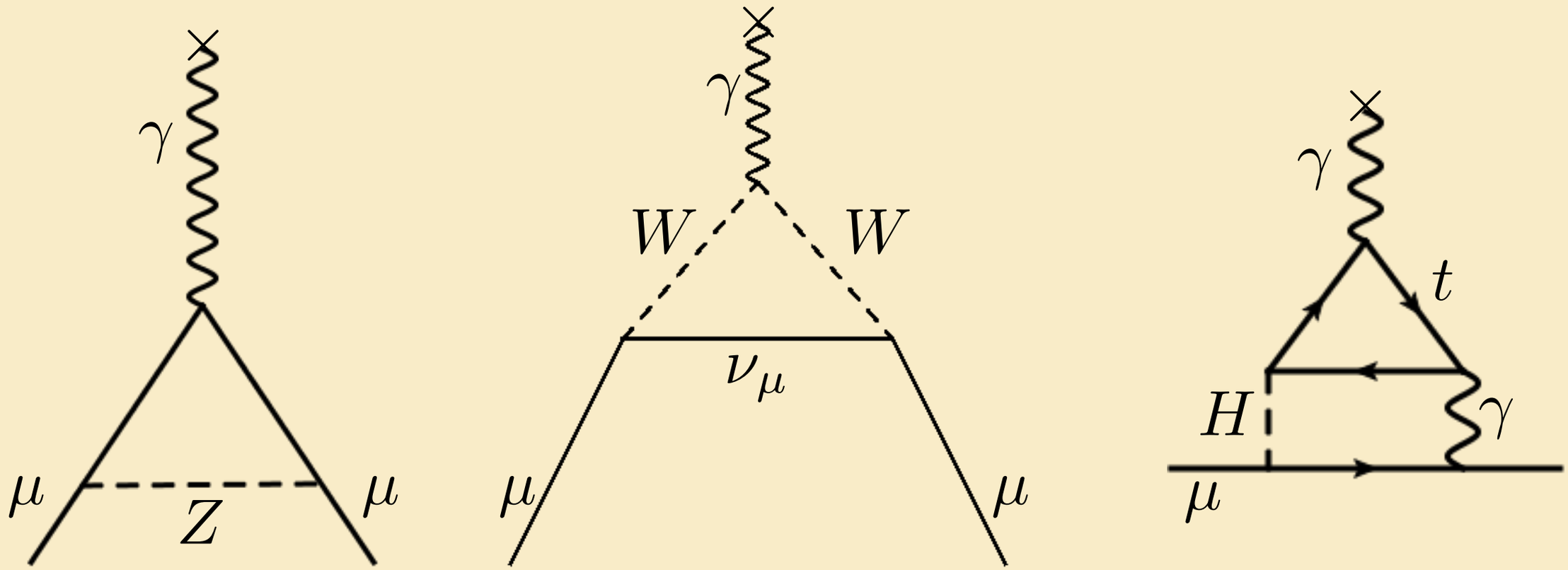
Significant improvements coming!

Including Lattice QCD work

Electroweak contributions

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

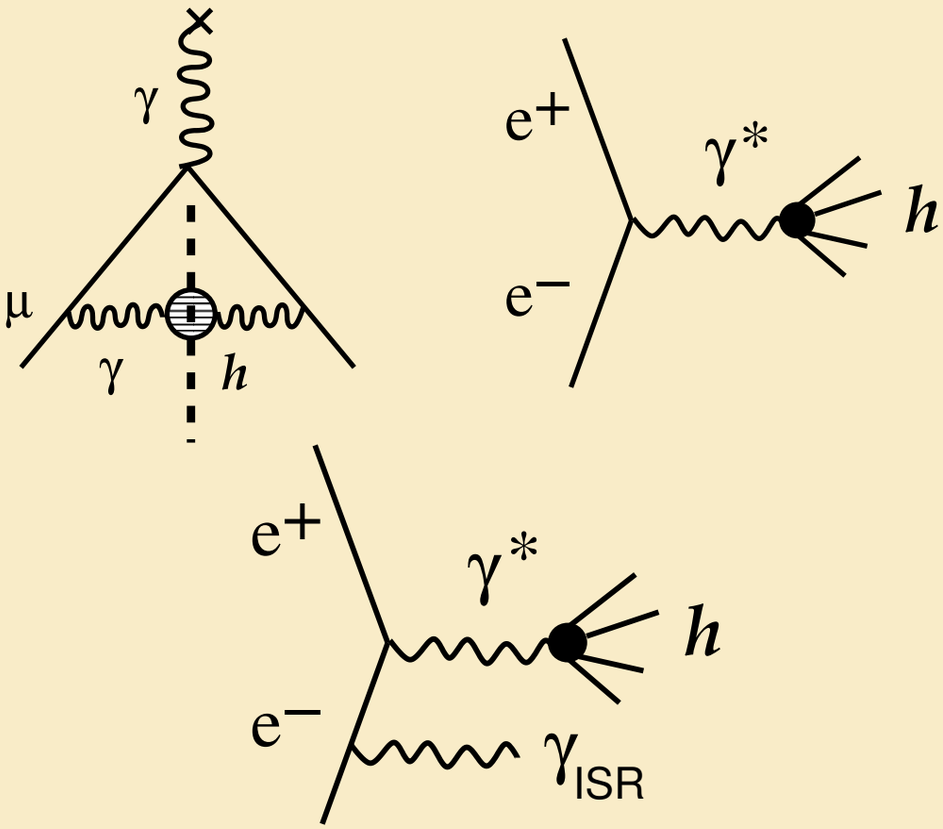
Unambiguously calculable - BNL experiment sensitive



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

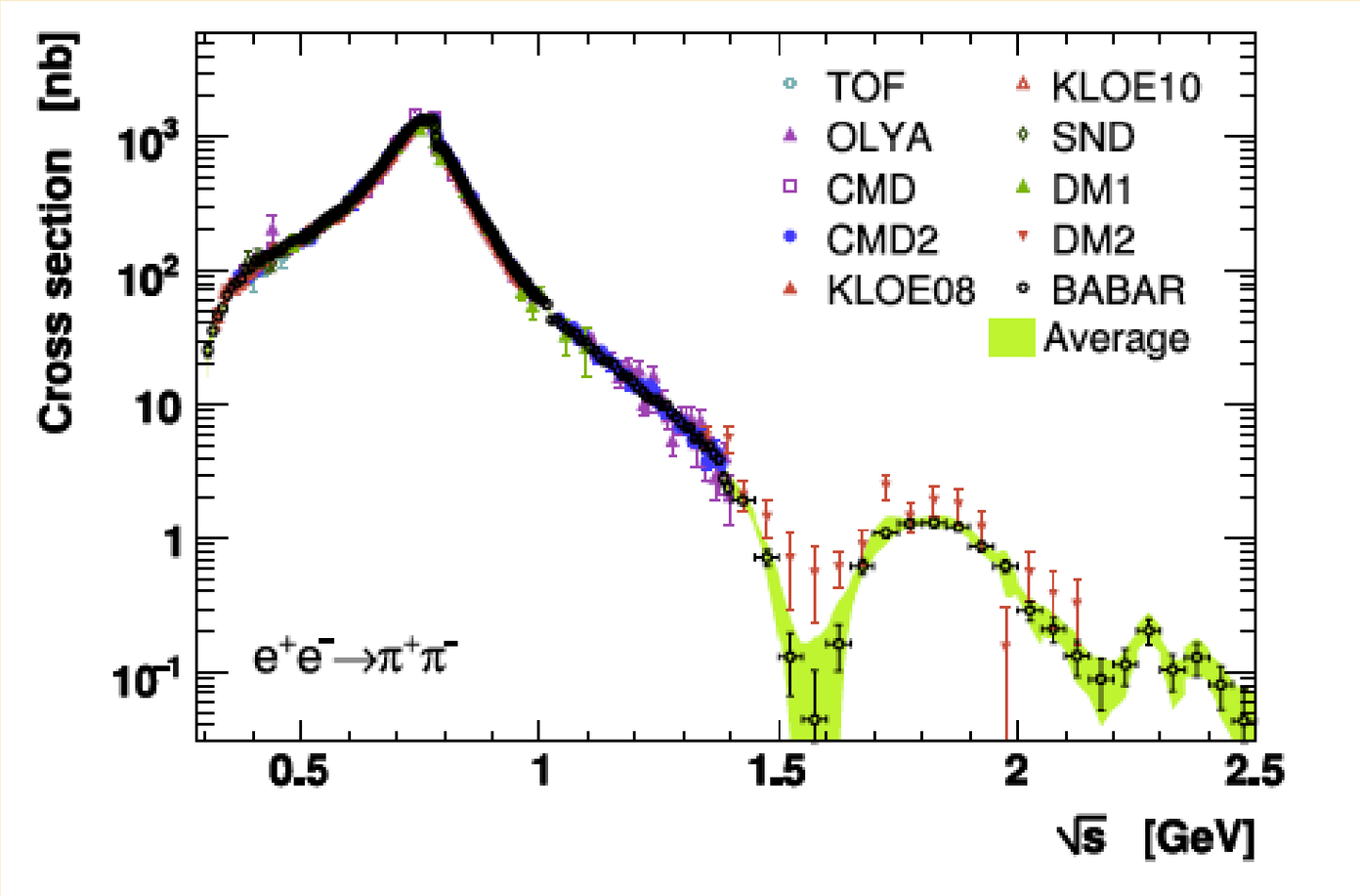
$$a_\mu^{\rm EW} = 0.00\,000\,000\,\boxed{154}(2)$$

Hadronic vacuum polarization

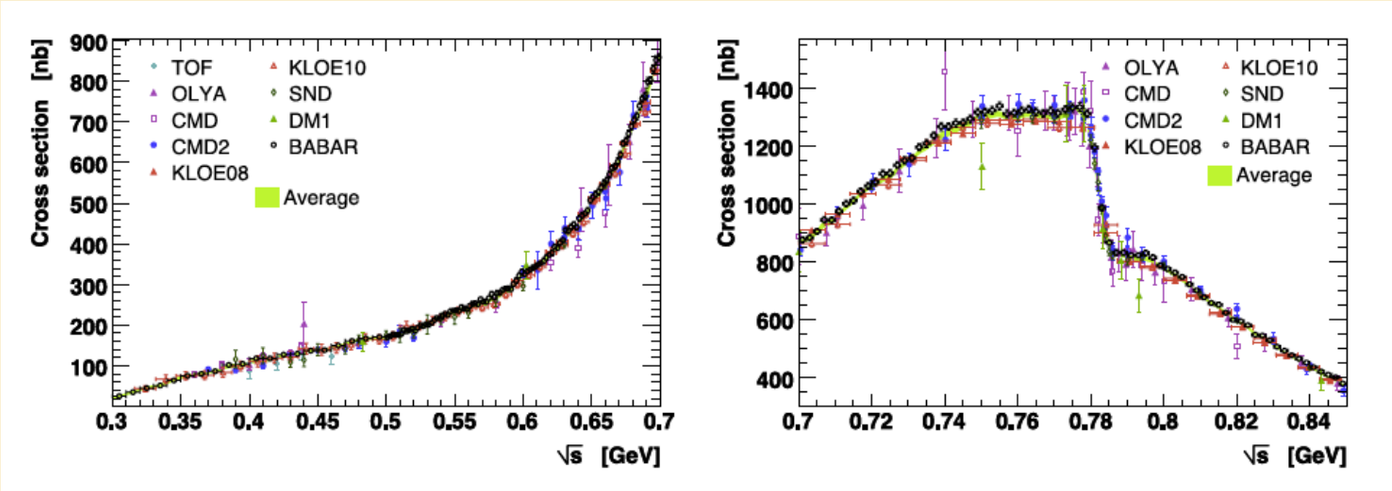


$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}R(s),$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

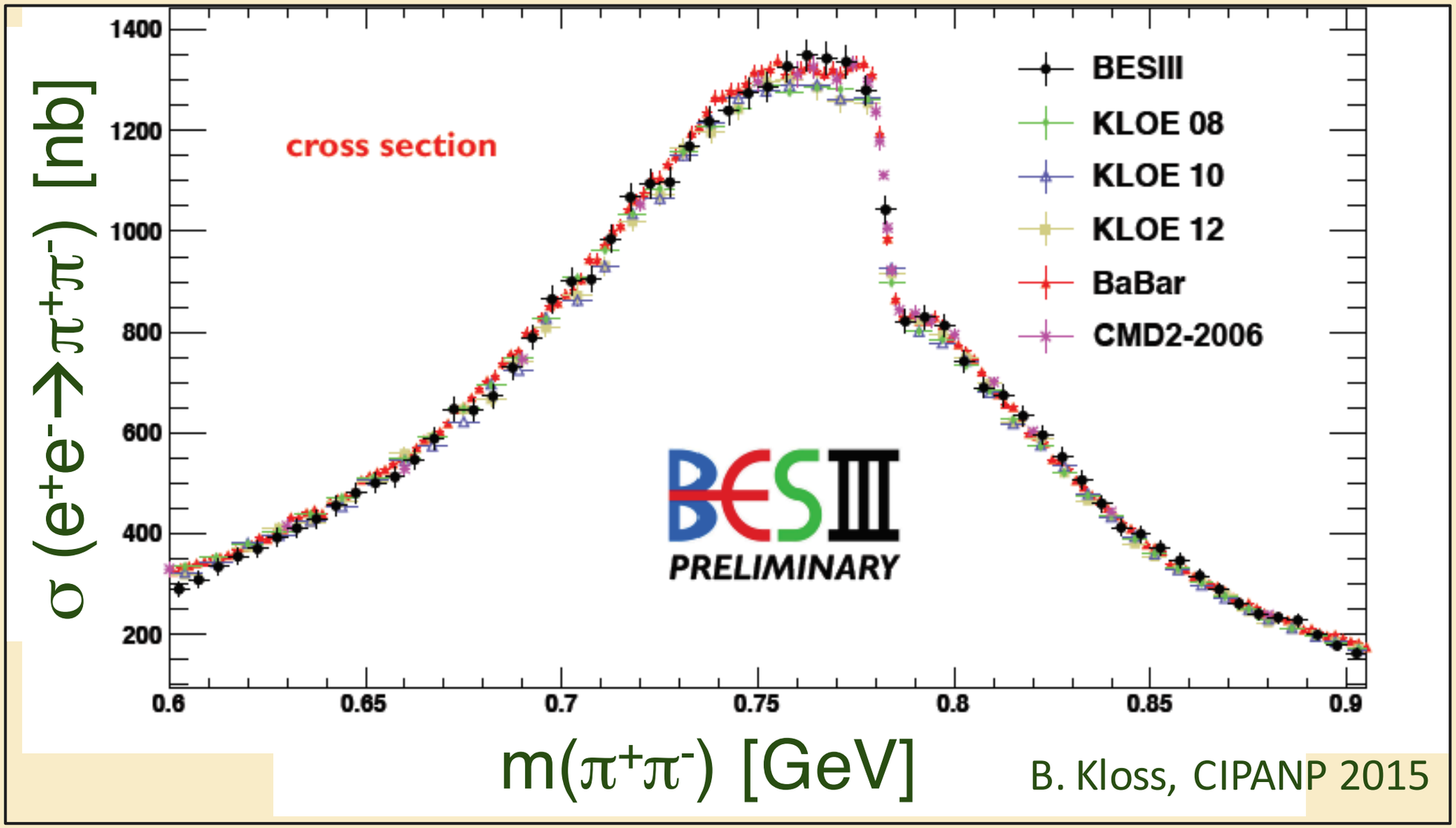


(a)



HVP

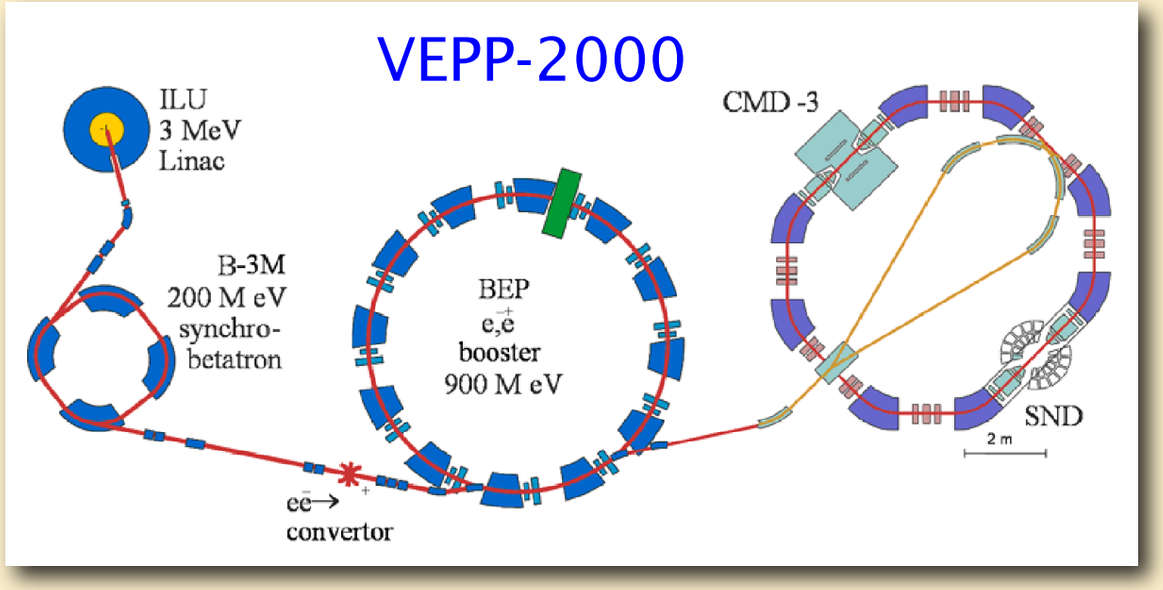
σ (600-900 MeV)



B. Kloss, CIPANP 2015

HVP(LO & NLO)

Results from taus compare well too, but with some differences



Huge 15 year effort has paid off with factor of 4 error reduction

Prospects for more improvements are good

- **New VEPP-2000 at Novosibirsk (x10-100 better stats, energy up to 2 GeV)**
- **New CMD3 and SND2000 detectors**

HVP(NLO) is similar and uses much of the same data

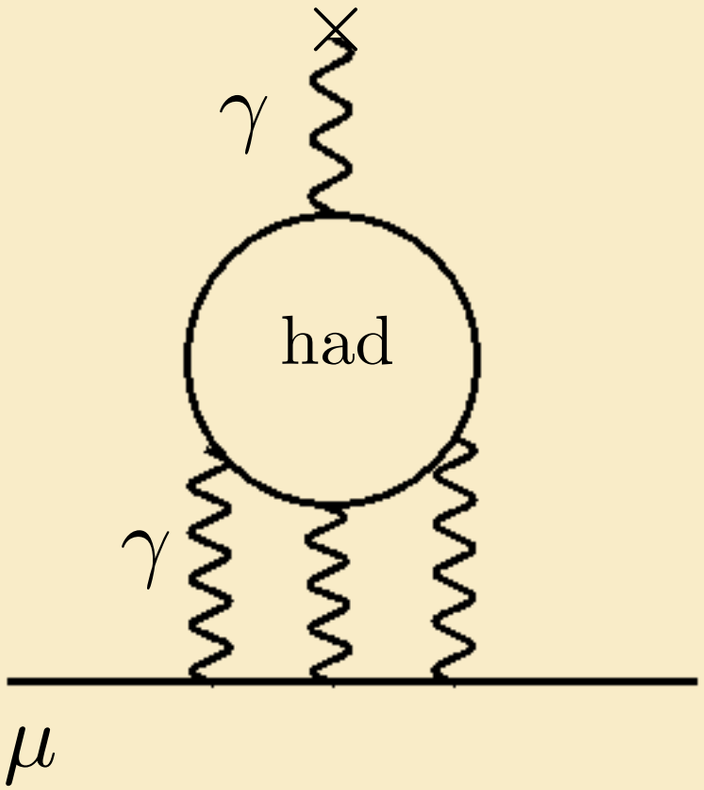
$$a_\mu^{\mathrm{HVPLO}} = (692.3 \pm 4.2) \times 10^{-10}$$
$$a_\mu^{\mathrm{HVPNLO}} = (-9.8 \pm 0.1) \times 10^{-10}$$

M. Davier, Hagiwara

Hadronic light-by-light

Model dependent calculations
Now an industry!

Future prospects:
KLOE to measure $\gamma^*\gamma^* \to \text{hadrons}$
at q^2~0 will provide first constraints



Lattice QCD calculations are under study

$$a_\mu^{\text{HLBL}} = (10.5 \pm 2.6) \times 10^{-10}$$

Prades, deRafael, Vainshtein (and others)

Comparing models and ingredients

Hadronic light-by-light scattering in the muon $g-2$: Summary

Some results for the various contributions to $a_\mu^{\mathrm{LbyL;had}} \times 10^{11}$:

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops +subl. N_C	–	–	–	0 ± 10	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

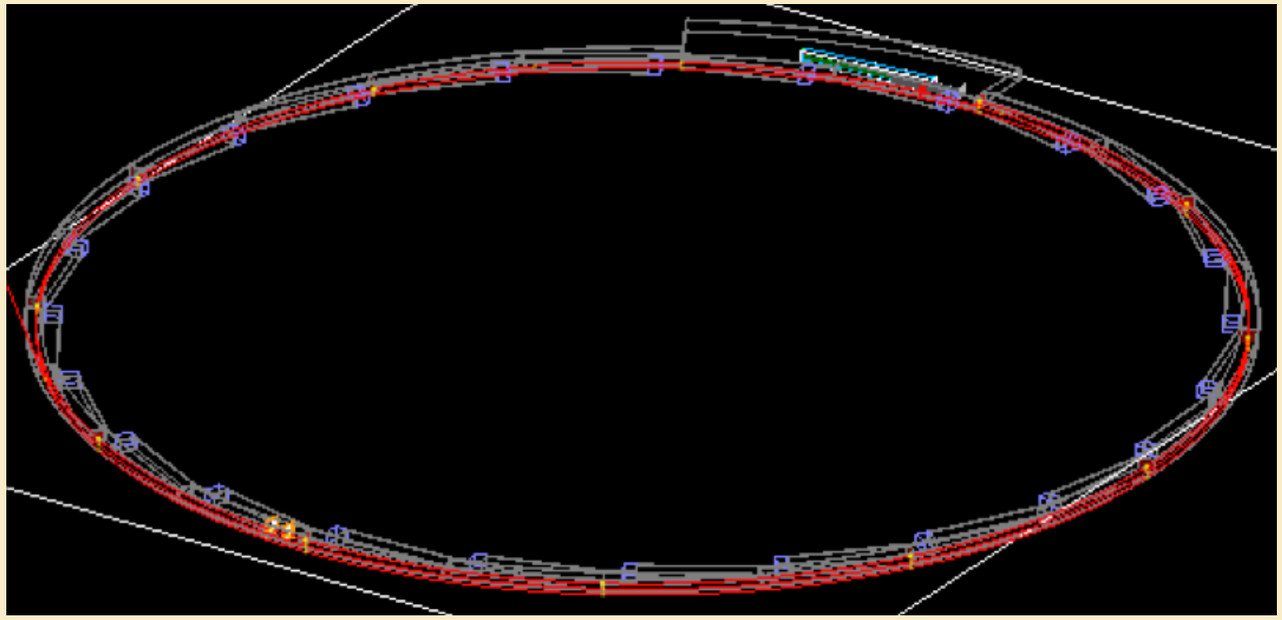
- Pseudoscalar-exchange contribution dominates numerically (except in FGW). But other contributions are not negligible. Note cancellation between π, K-loops and quark loops !
- PdRV: Do not consider dressed light quark loops as separate contribution ! Assume it is already taken into account by using short-distance constraint of MV '04 on pseudoscalar-pole contribution. Added all errors in quadrature ! Like HK(S). Too optimistic ?
- N, JN: New evaluation of pseudoscalars. Took over most values from BPP, except axial vectors from MV. Added all errors linearly. Like BPP, MV, BP, MdRR. Too pessimistic ?
- FGW: new approach with Dyson-Schwinger equations. Is there some double-counting ? Between their dressed quark loop (largely enhanced !) and the pseudoscalar exchanges.

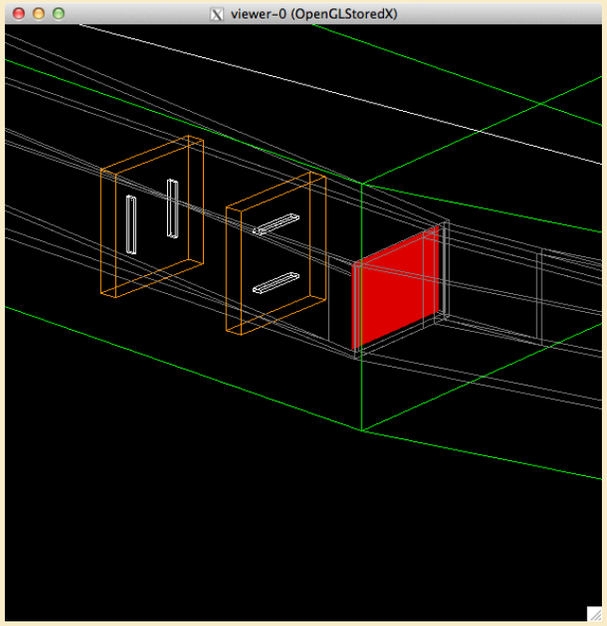
Nyffeler talk @ INT

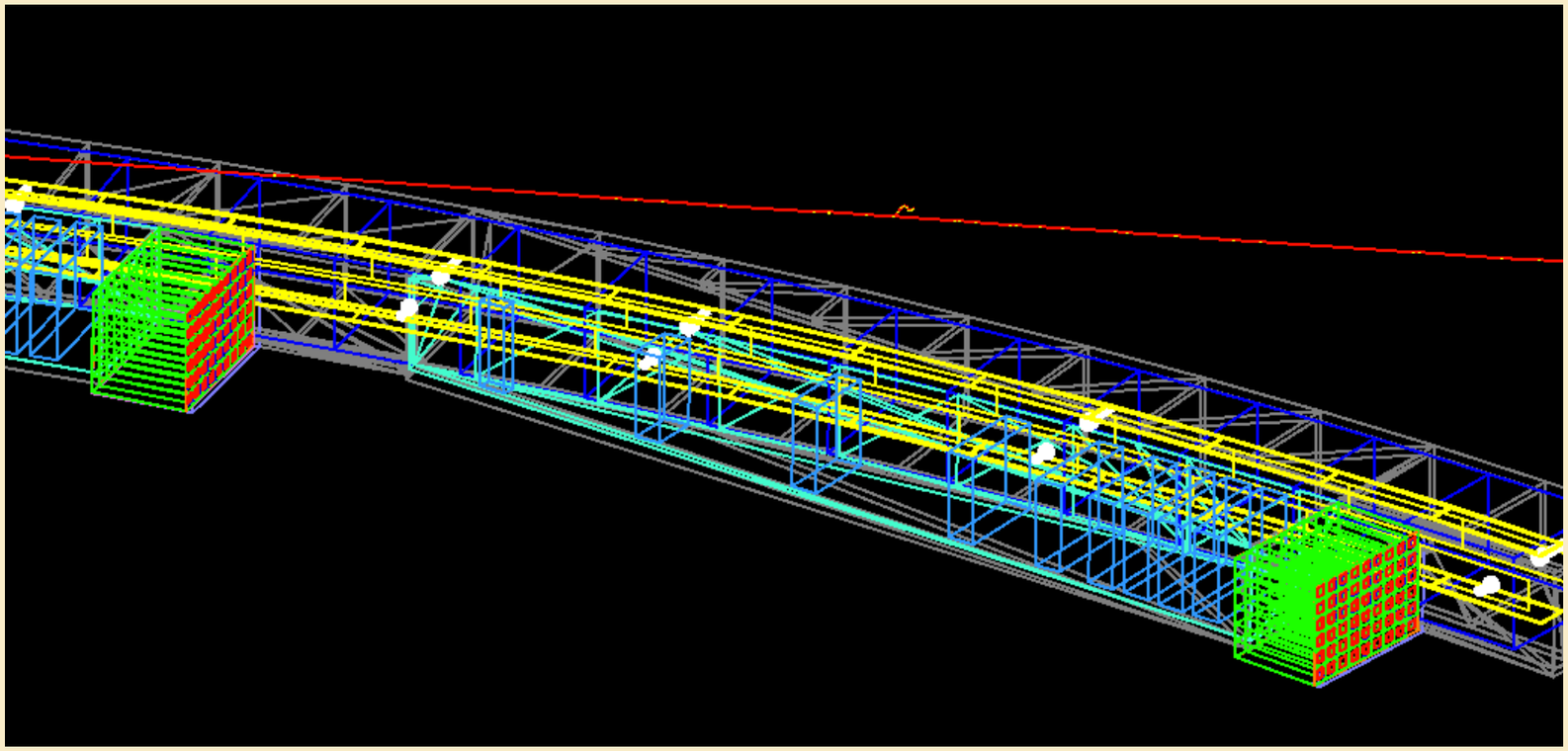
Geant4 Simulations

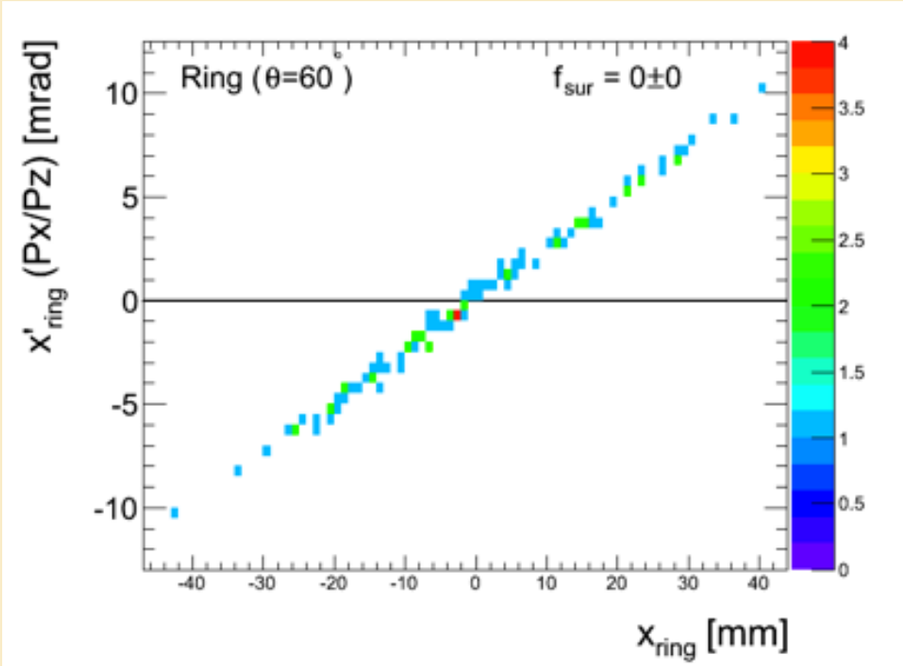
Entire ring is simulated

Uses common ART (CMS-LITE) framework









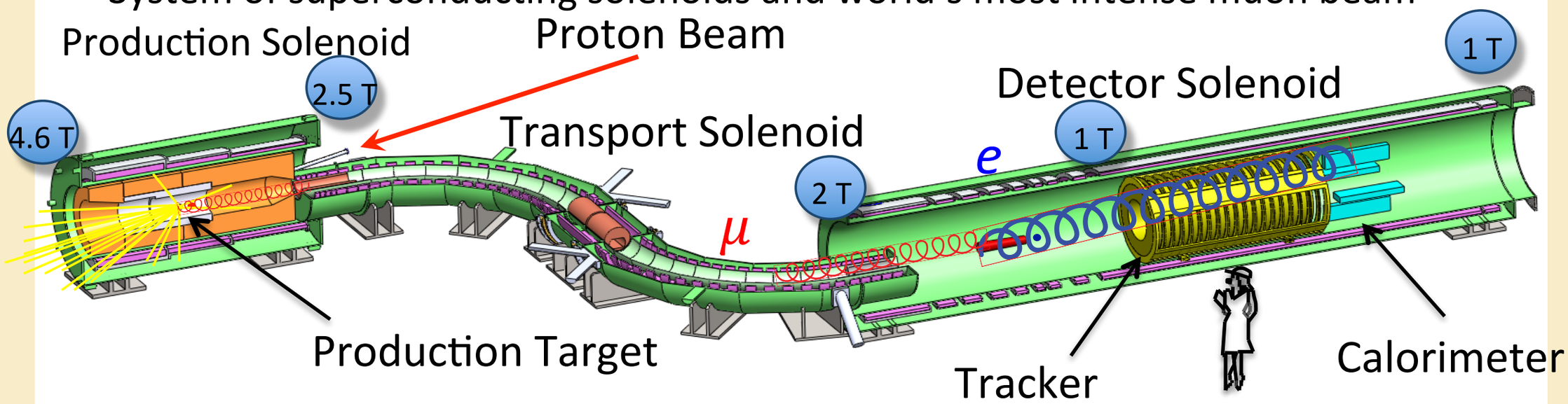
Mu2e

Starts with FNAL Booster; upgrades at Project X

X10,000 improvement over previous measurements

mu2e.fnal.gov

System of superconducting solenoids and world's most intense muon beam

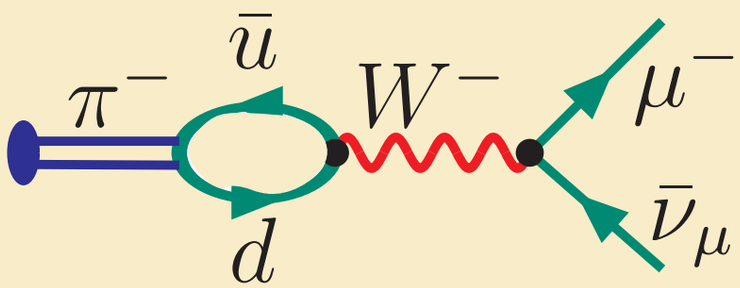


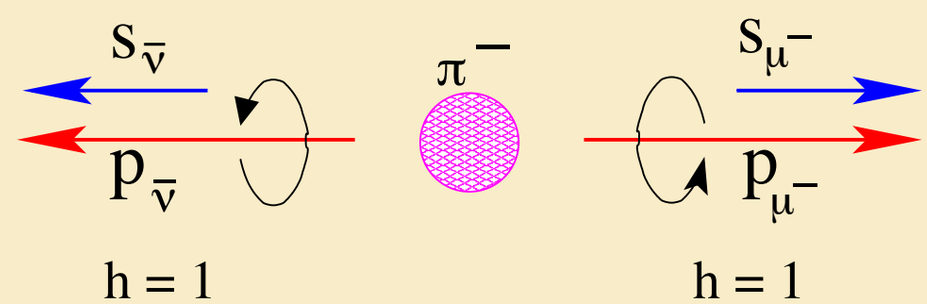
- Charged Lepton Flavor Violation: Search for $\mu N \rightarrow eN$ at 6×10^{-17}
  - Quarks and neutrinos violate flavor: why don't the charged leptons?
  - Uniquely sensitive to both SUSY and non-SUSY new physics
  - Complements LHC and probes mass scales to 10^4 TeV/c^2
  - A powerful discriminator among models
- CD1/Conceptual Design Summer 2012; CD2 scheduled for early 2014; construction to start 2014; physics data-taking to start early 2020 for 2-3 years

Muons and spin are an ideal match

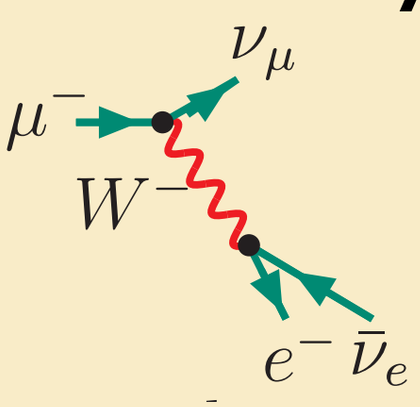
Some lucky breaks from parity violation:

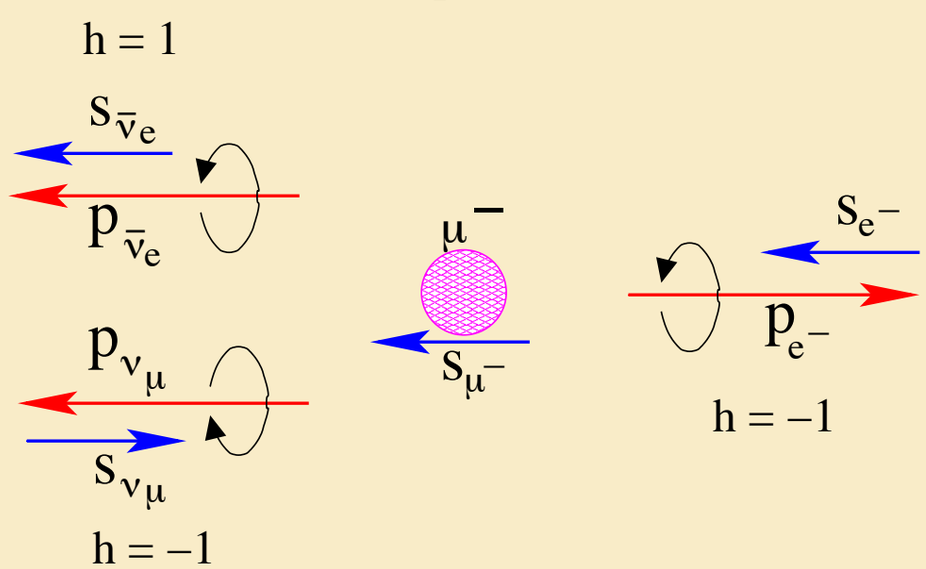
High momentum muons from pion decays are longitudinally polarized





Muon decays are "self-analyzing"



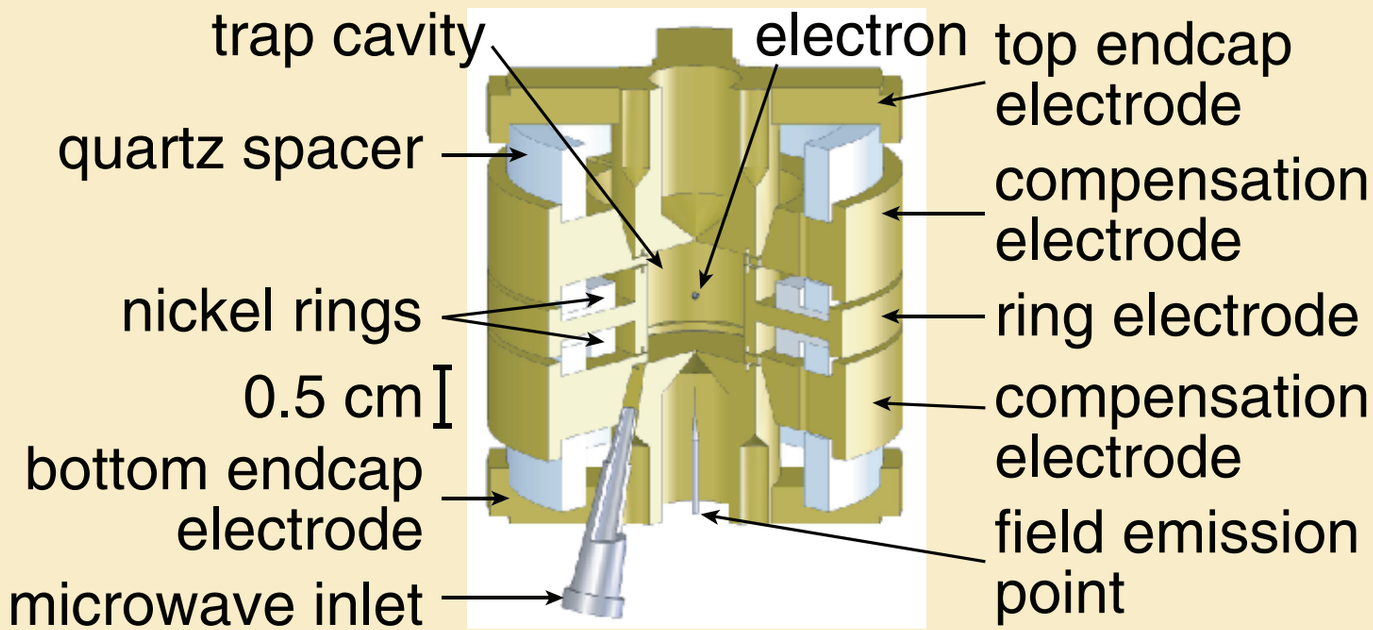


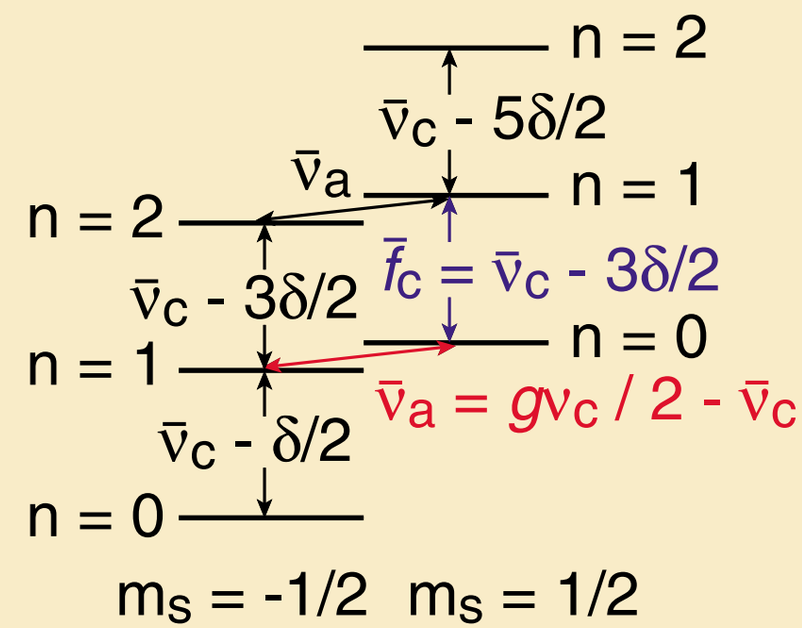
Highest energy electrons are emitted along (opposite) direction of muon+(-) spin in muon rest frame

Currently, a_e is known to sub-ppt

Gabrielse (2006 & 2008):

Previous result was 20 years prior





Single electron trapped for months

Quantum nondemolition measurement

e orbits horizontally in *B* field at 150 GHz

Oscillates in z at 200 MHz with electric quadrupole

Observe quantum jump spectroscopy

$$a_e = 0.00115965218073(28)$$

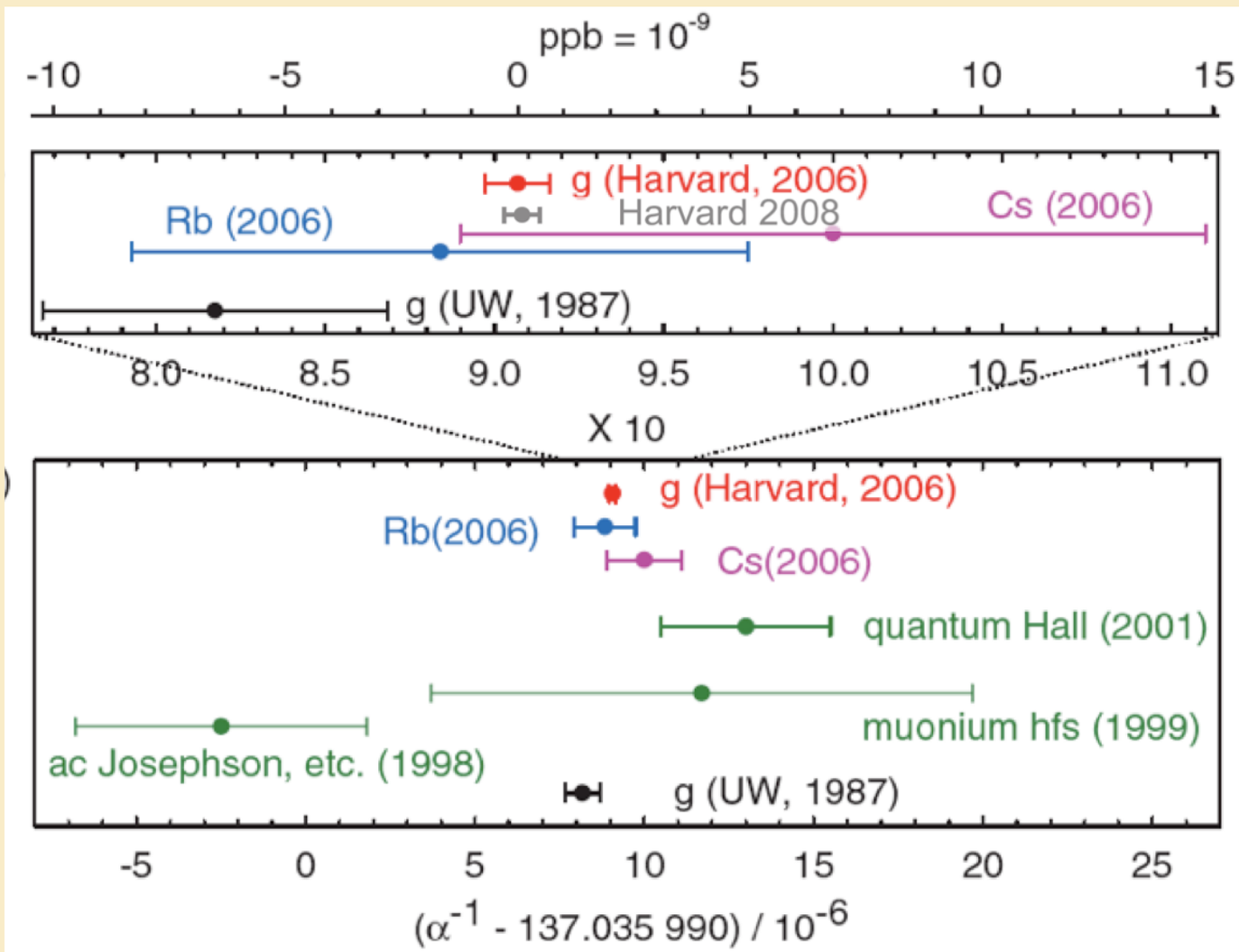
Hanneke et al., PRL100 (2008) 120801

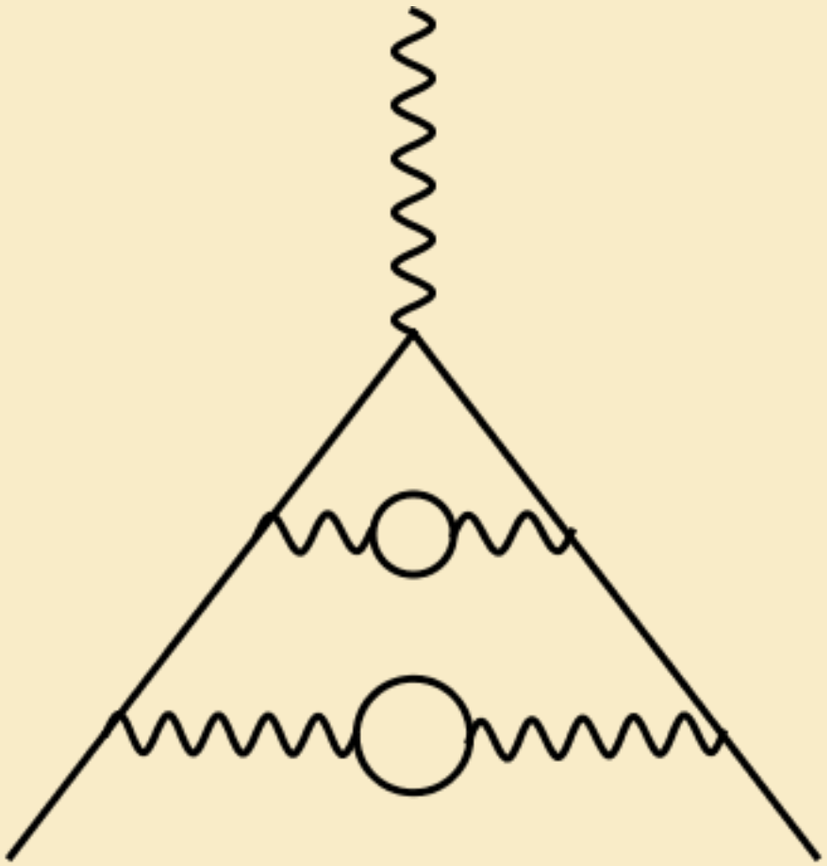
The most accurate value of alpha is obtained

$$g/2 = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + \alpha_{\text{hadronic}} + \alpha_{\text{weak}}$$

$$\alpha^{-1} = 137.035\,999\,084\,(33_{\text{exp}})(39_{\text{th}})$$

Compare to other independent extractions





Are we done?
No, lots more
to this story...

Third CERN experiment ('69-79)

Observe $N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$

over threshold

Fractional uncertainty is $\dfrac{\delta\omega_a}{\omega_a} = \dfrac{\sqrt{2}}{\omega_a A \tau \sqrt{N}}$

Increase momentum to magic (dilates lifetime to 64 μs)

Increase *B* field, *N*

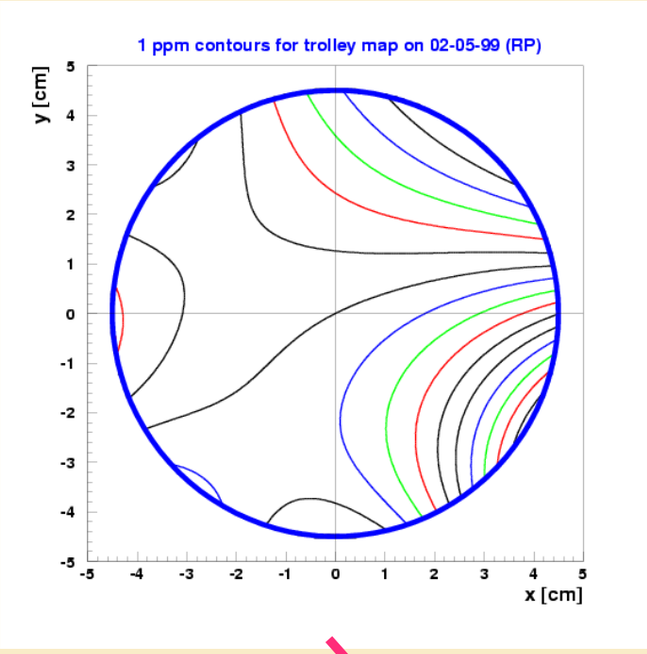
Improved λ (13 ppm to 2.6 ppm)

Target outside of ring - inject pions - better polarization

Differences between BNL and 3rd CERN

Quantity	E821	CERN
Magnet	Superconducting	Room Temperature
Yoke Construction	Monolithic Yoke	40 Separate Magnets
Magnetic Field	1.45 T	1.47 T
Magnet Gap	180 mm	140 mm
Stored Energy	6 MJ	
Field mapped in situ?	yes	no
Central Orbit Radius	7112 mm	7000 mm
Averaged Field Uniformity	± 1 ppm	± 10 ppm
Muon Storage Region	90 mm Diameter Circle	120×80 mm^2 Rectangle
Injected Beam	Muon	Pion
Inflector	Static Superconducting	Pulsed Coaxial Line
Kicker	Pulsed Magnetic	$\pi \rightarrow \mu\ \nu_\mu$ decay
Kicker Efficiency	$\sim 4\%$	125 ppm
Muons stored/fill	10^4	350
Ring Symmetry	Four-fold	Two-fold
$\sqrt{\beta_{\rm max}/\beta_{\rm min}}$	1.03	1.15
Detectors	Pb-Scintillating Fiber	Pb-Scintillator "Sandwich"
Electronics	Waveform Digitizers	Discriminators
Systematic Error on B-field	0.17 ppm	1.5 ppm
Systematic Error on ω_a	0.21 ppm	Not given
Total Systematic Error	0.28 ppm	1.5 ppm
Statistical Error on ω_a	0.46 ppm	7.0 ppm
Final Total Error on a_μ	0.54 ppm	7.3 ppm

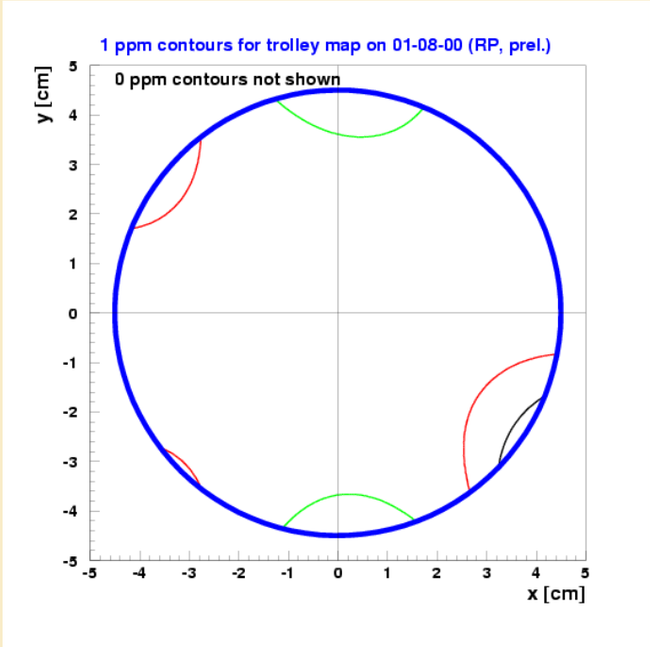
Measuring ω_p - Shimming the field



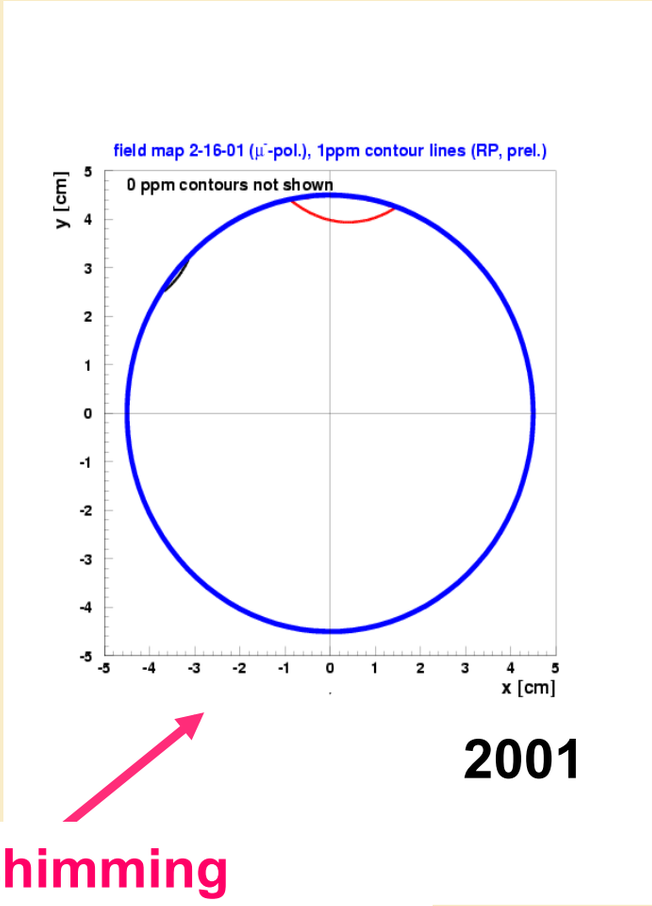
1999

1ppm contours are avg of B over 2π in muon storage region 10cm x 10cm

2000



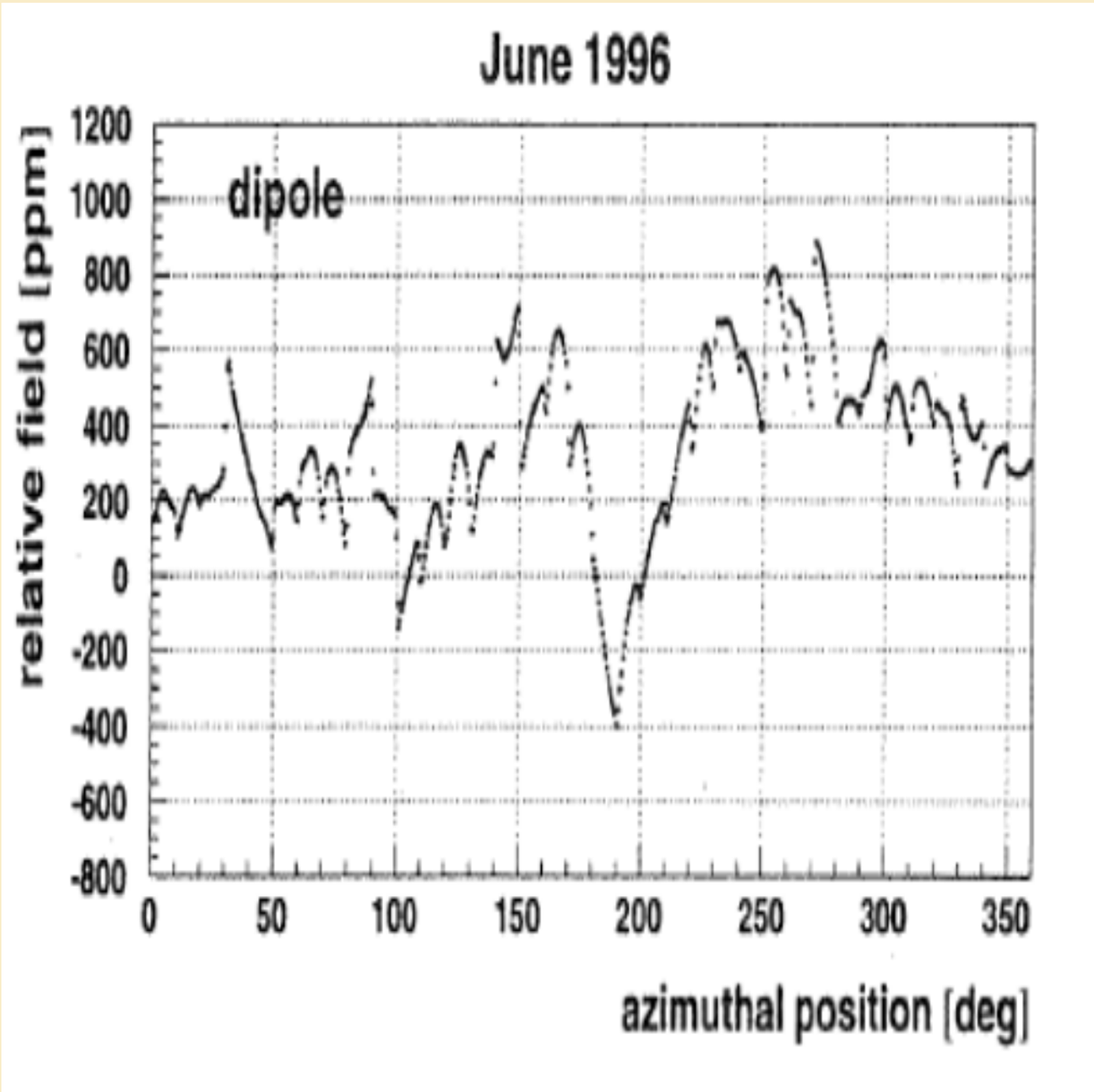
shimming

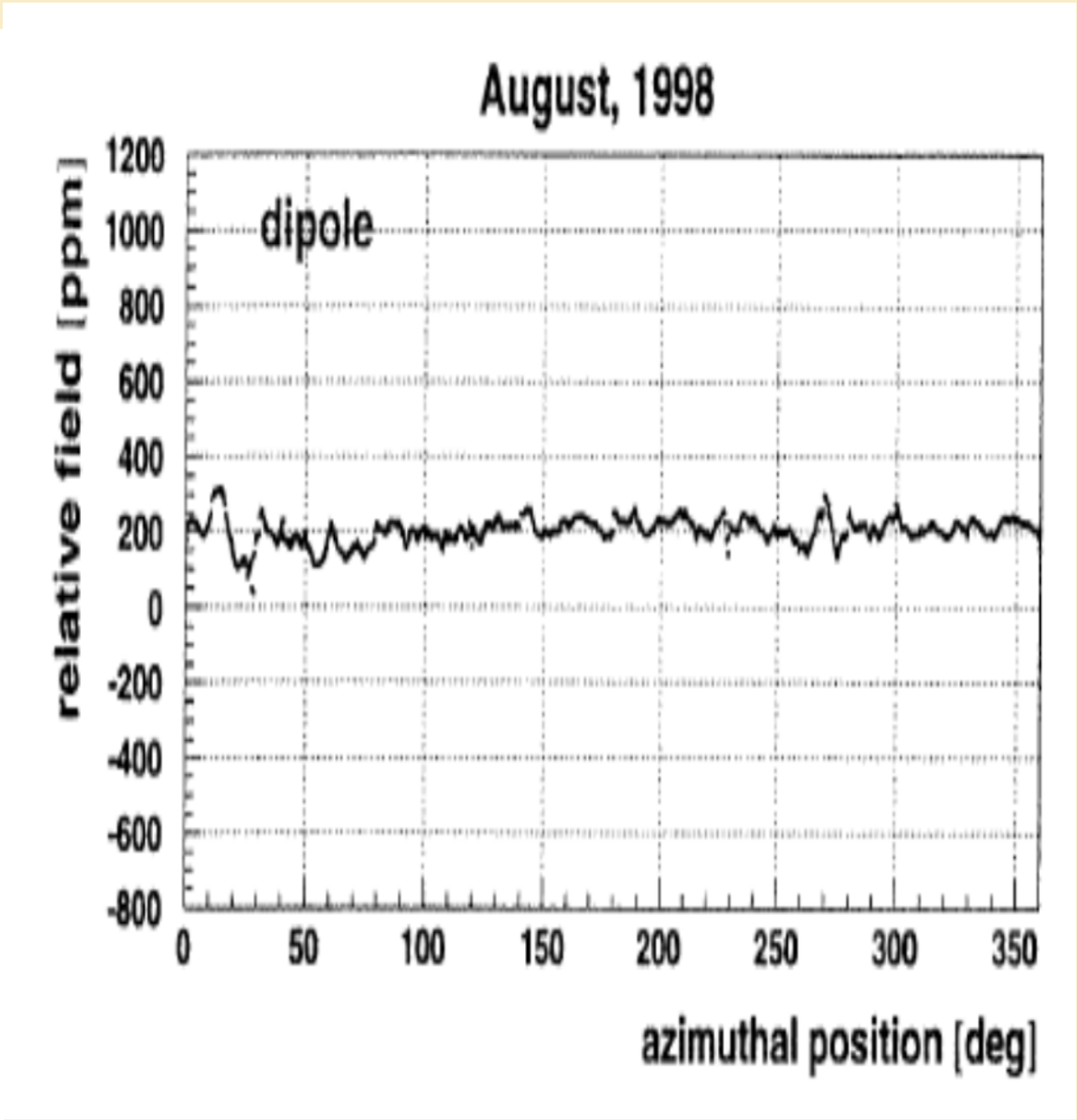


2001

shimming

Shimming Kits to Achieve Desired Uniformity



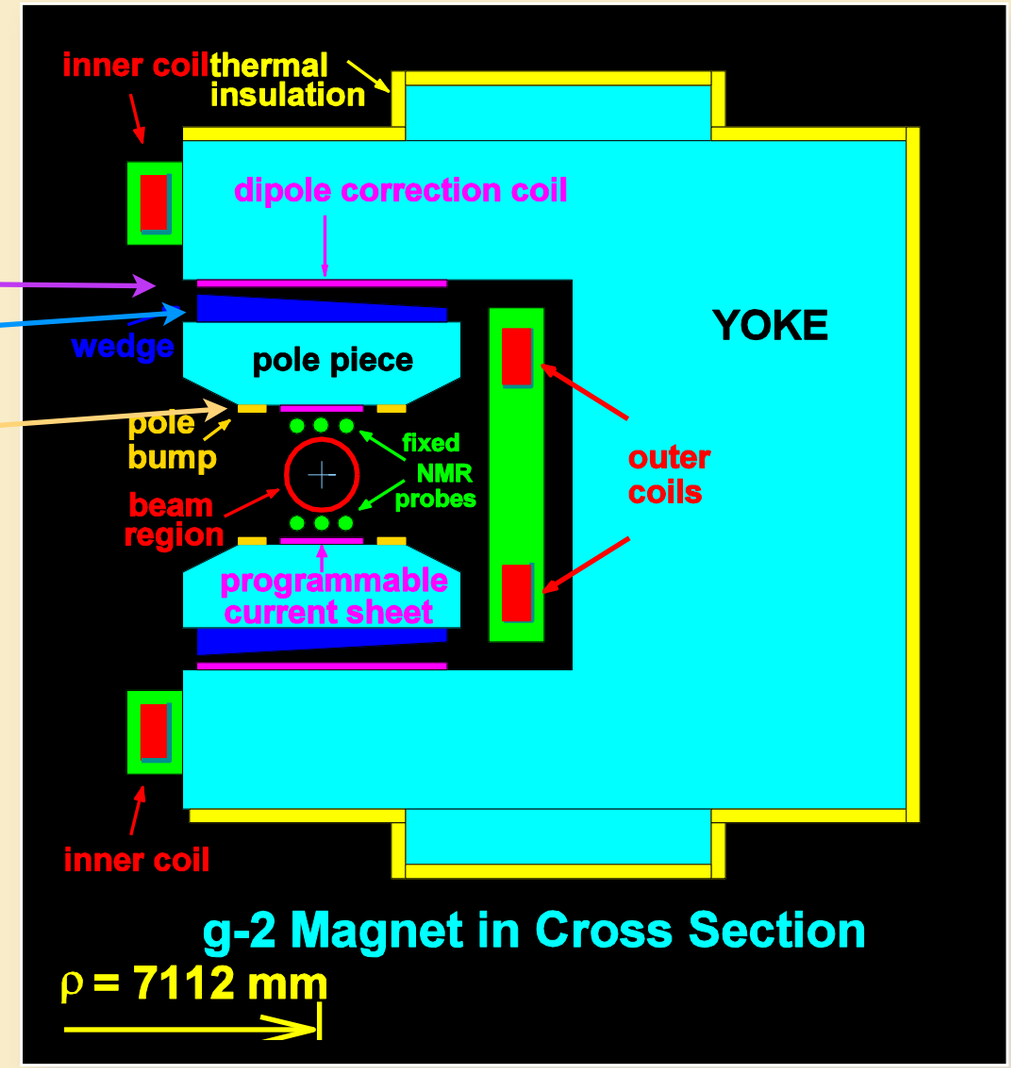


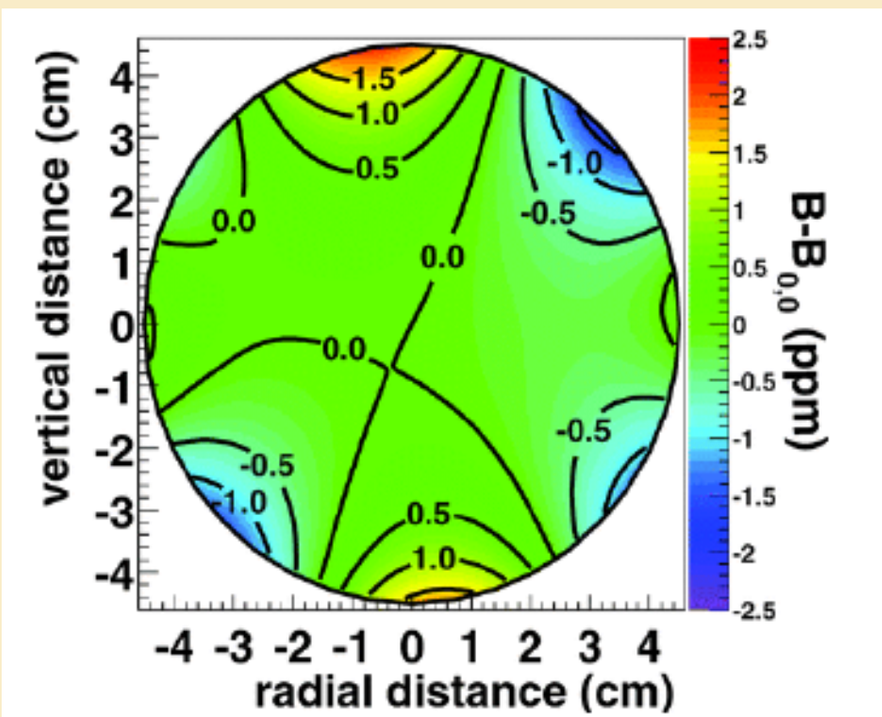
100 ppm = 1.45 Gauss out of 1.45 Tesla

~1 year to shim

independent shimming for

- dipole
- quadrupole
- sextupole

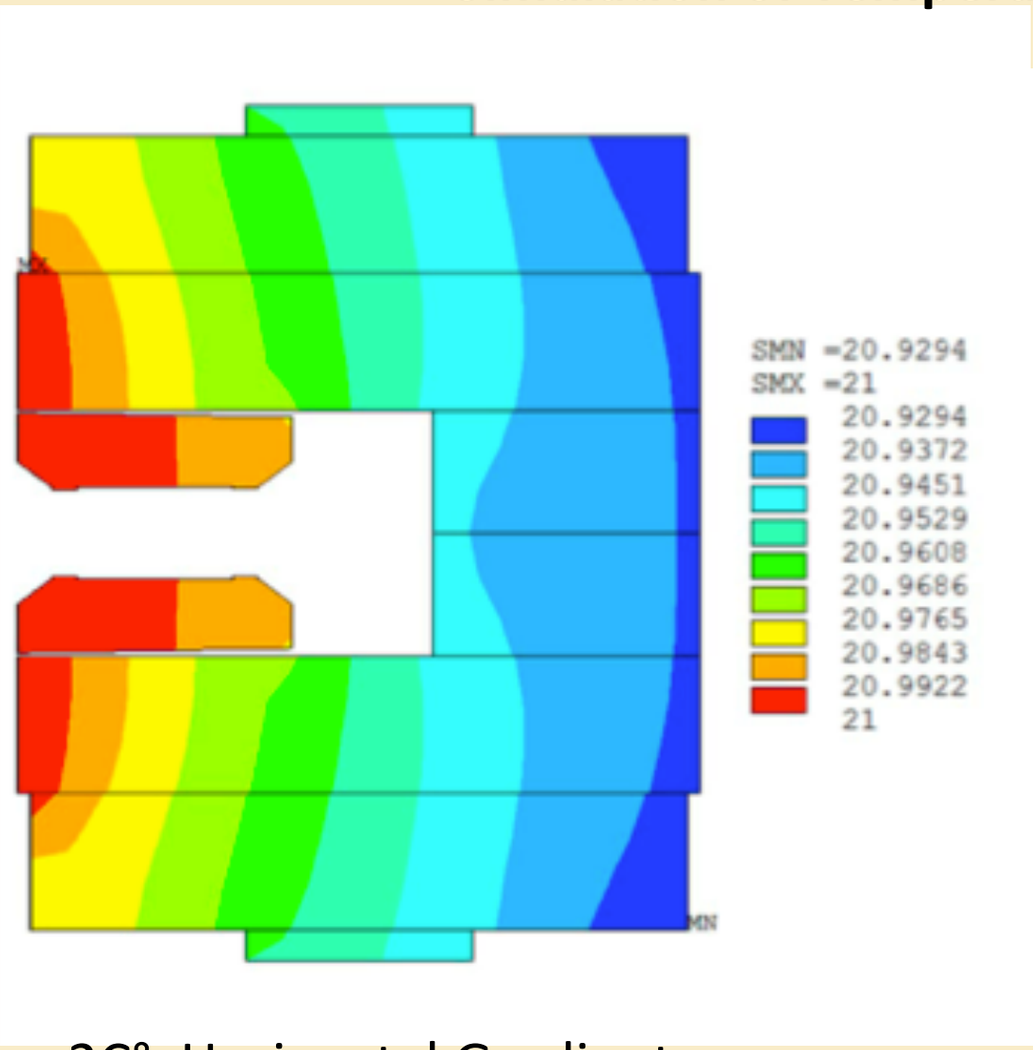




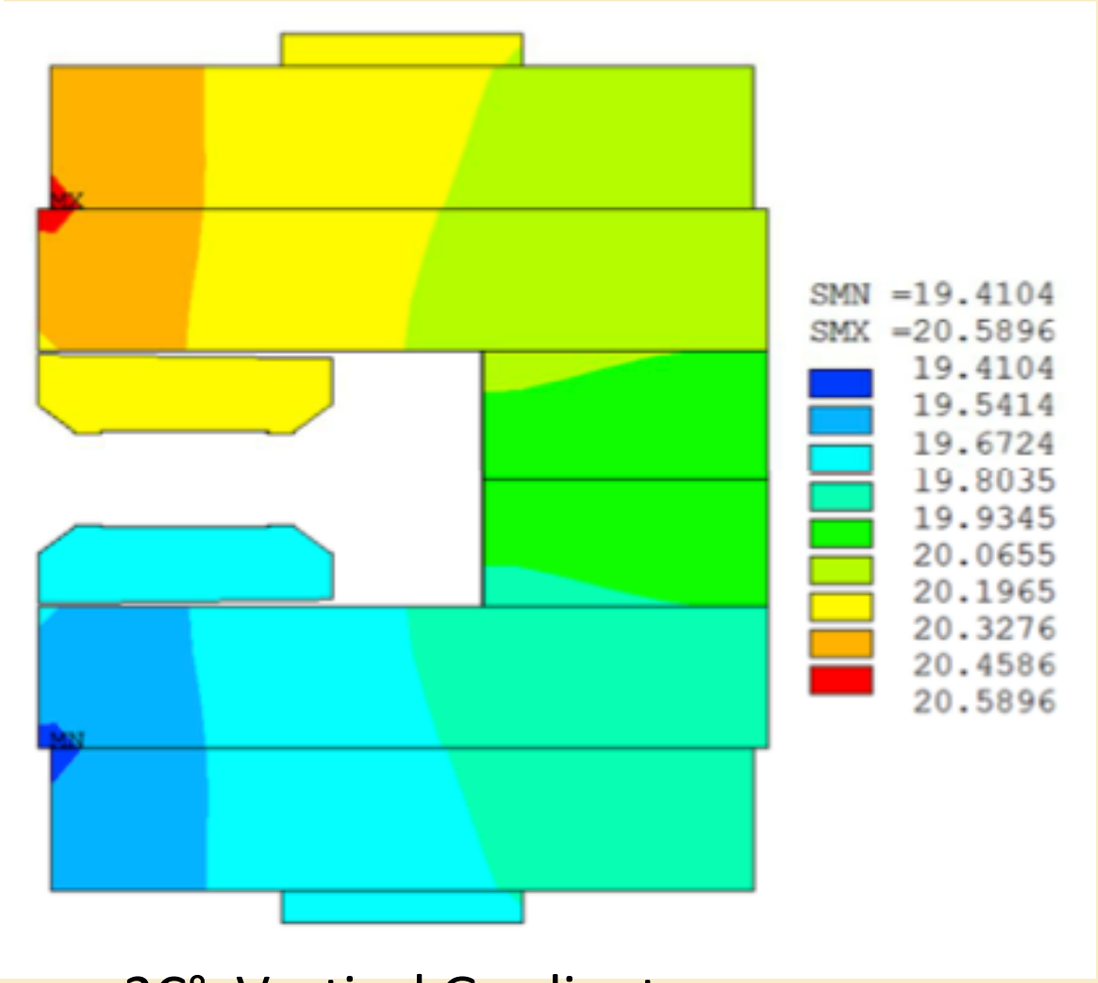
Achieved ppm uniformity

FNAL Improvements: Hall Temperature Control (+/- 1 C)
Temperature Uniformity
Magnet Iron Insulation

Simulation of Temperature Profiles

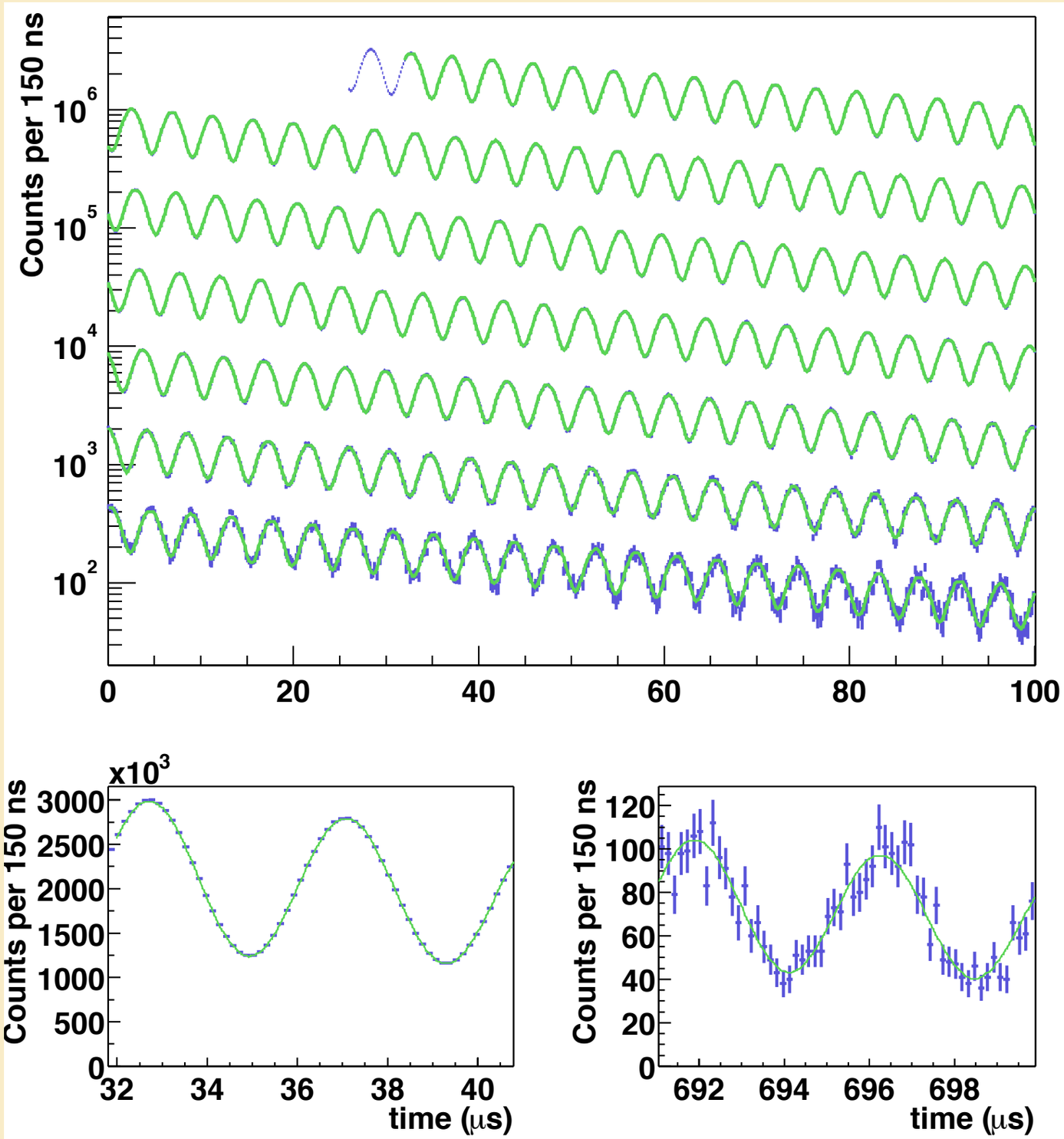


2C° Horizontal Gradient



2C° Vertical Gradient

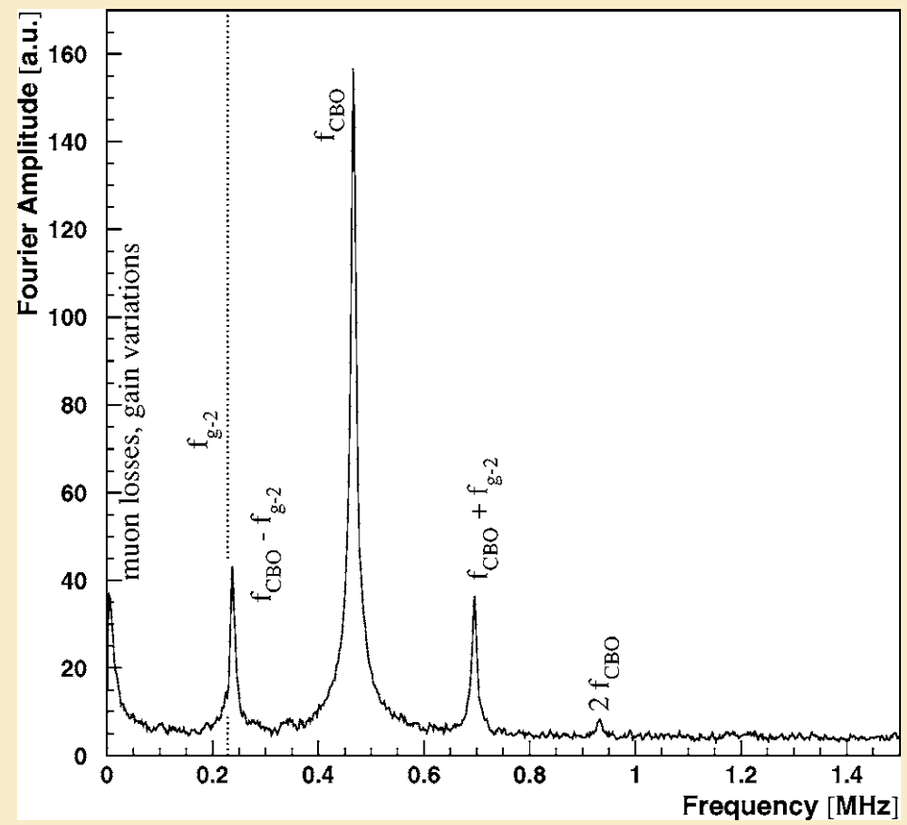
Measuring ω_a



2000 data, 4 billion decays

5 parameter fit

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$



Coherent betatron oscillation sideband near g-2 found in 2000 data. Tune changed for 2001 run to move CBO away

Corrections to ω_a

Not all muons exactly at magic - measure cyclotron frequency distribution, correct ω_a

Pitch correction due to vertical betatron motion - measured with traceback system (4 straw chambers to trace location of muon decay)

Fast rotation - bunch structure can remain - apply random small offset (< bin width) to t_0

Multiparticle pileup - allows low energy e's (with different phase) in fit, more early, less late - keep raw WFD data – subtract constructed pileup hypothesis

Lost muons - escape before decay - leads to incorrect lifetime - Hodoscopes in front of calorimeters measure rate (coincidence of 3 adjacent hodoscopes)

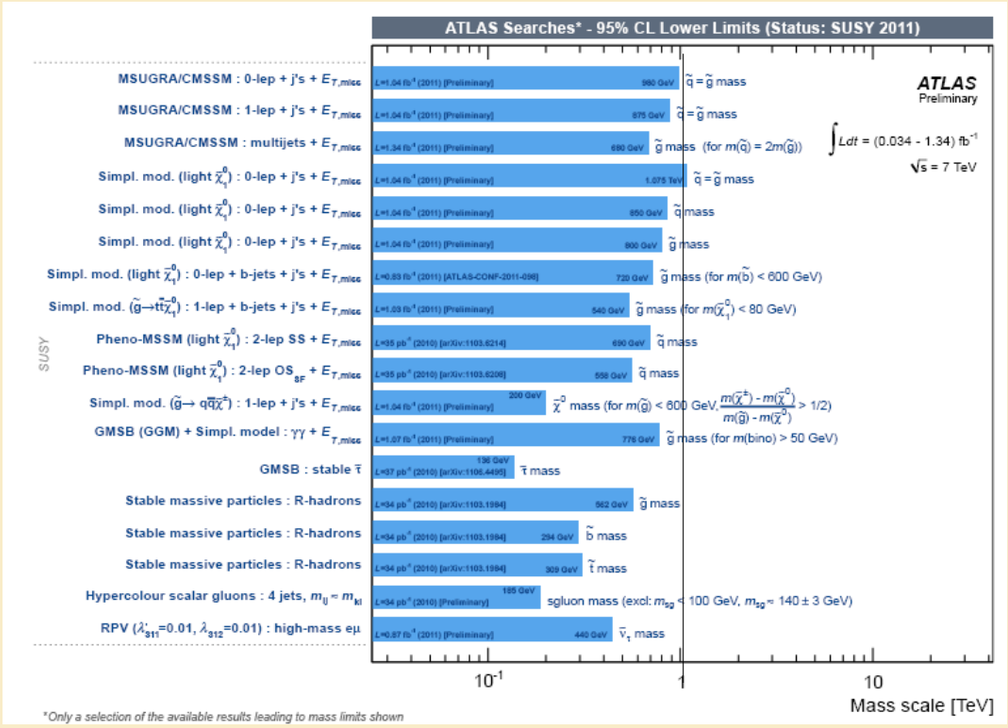
EDM - tilts precession plane - causes vertical oscillation of polarization - Traceback detector saw none

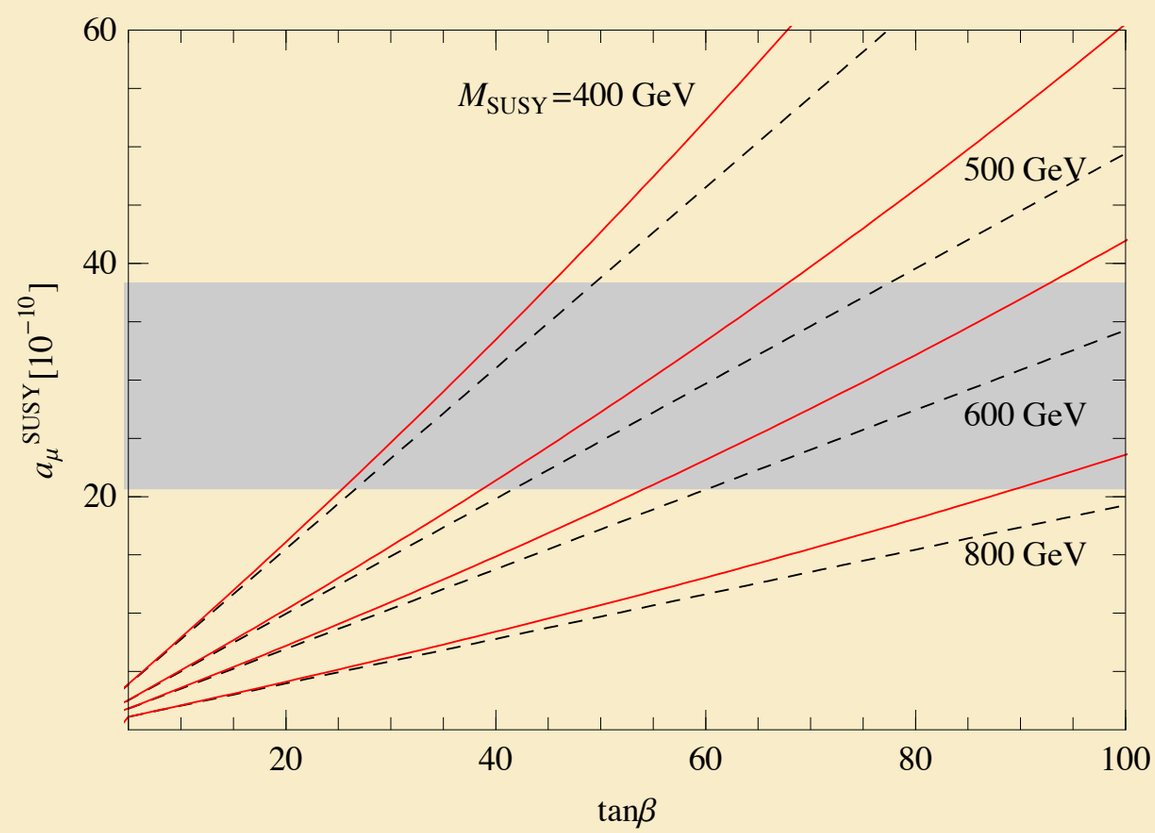
SUSY?

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

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

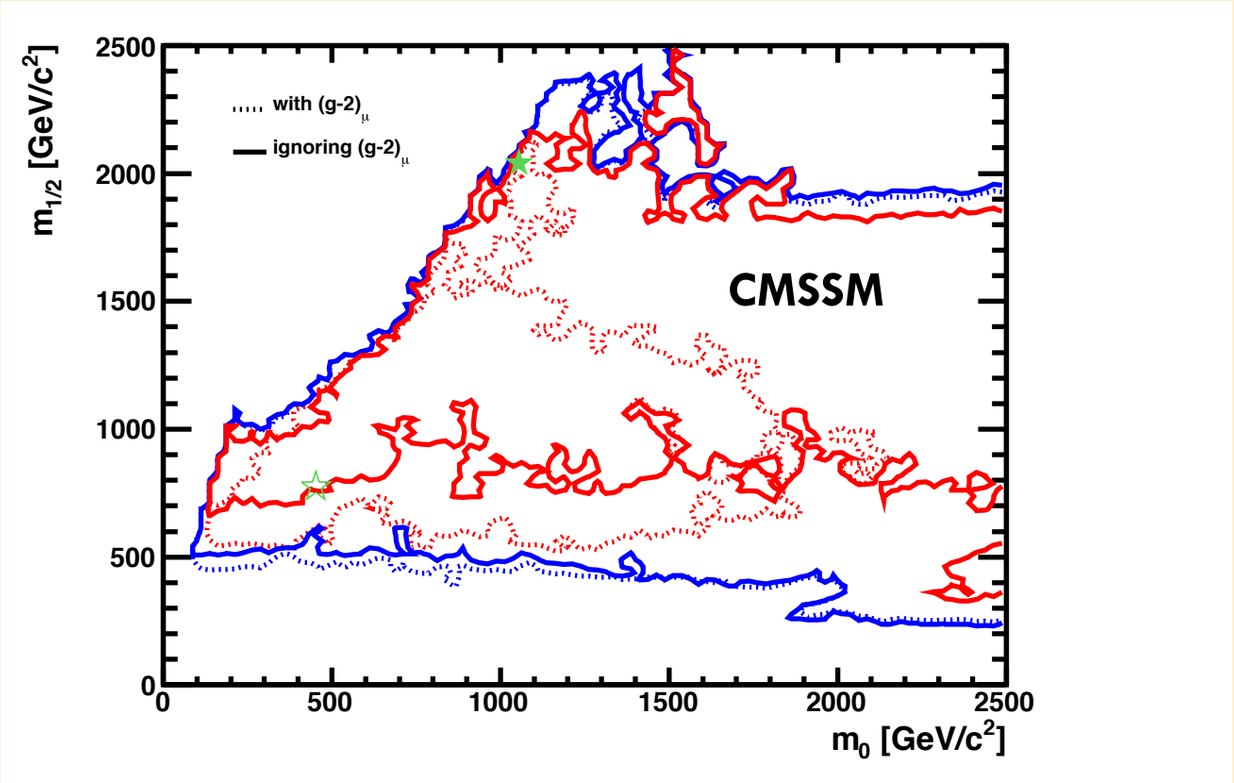
But LHC results require large $\tan\beta$

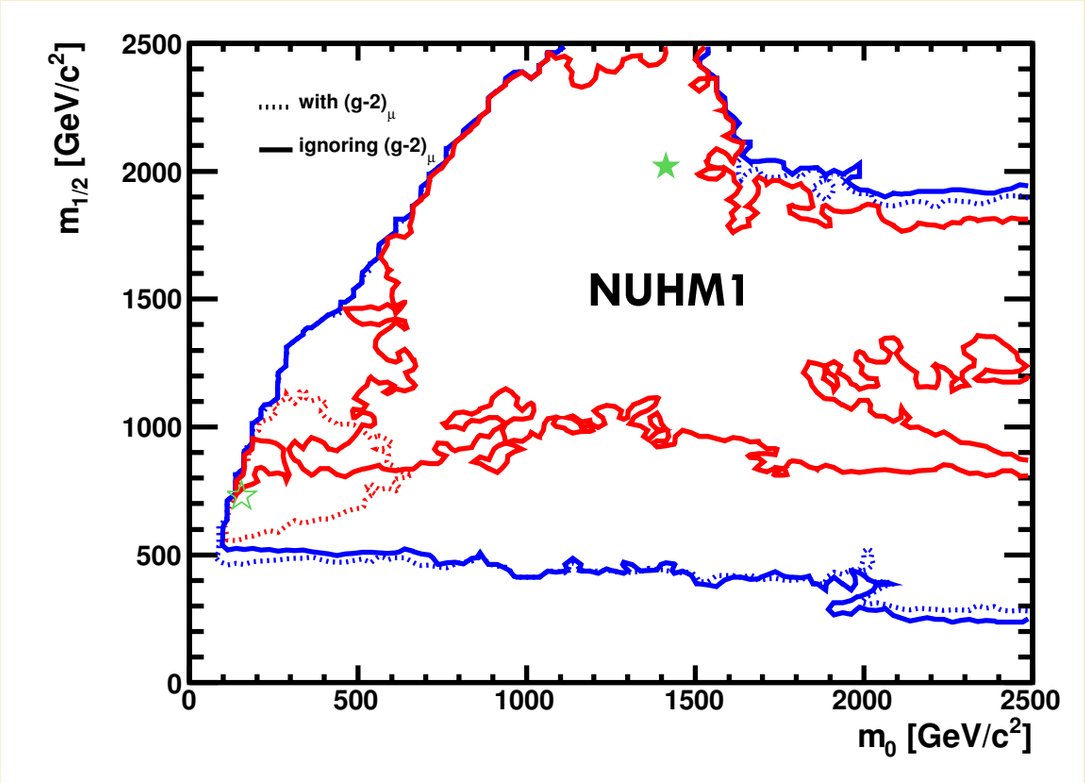




SUSY?

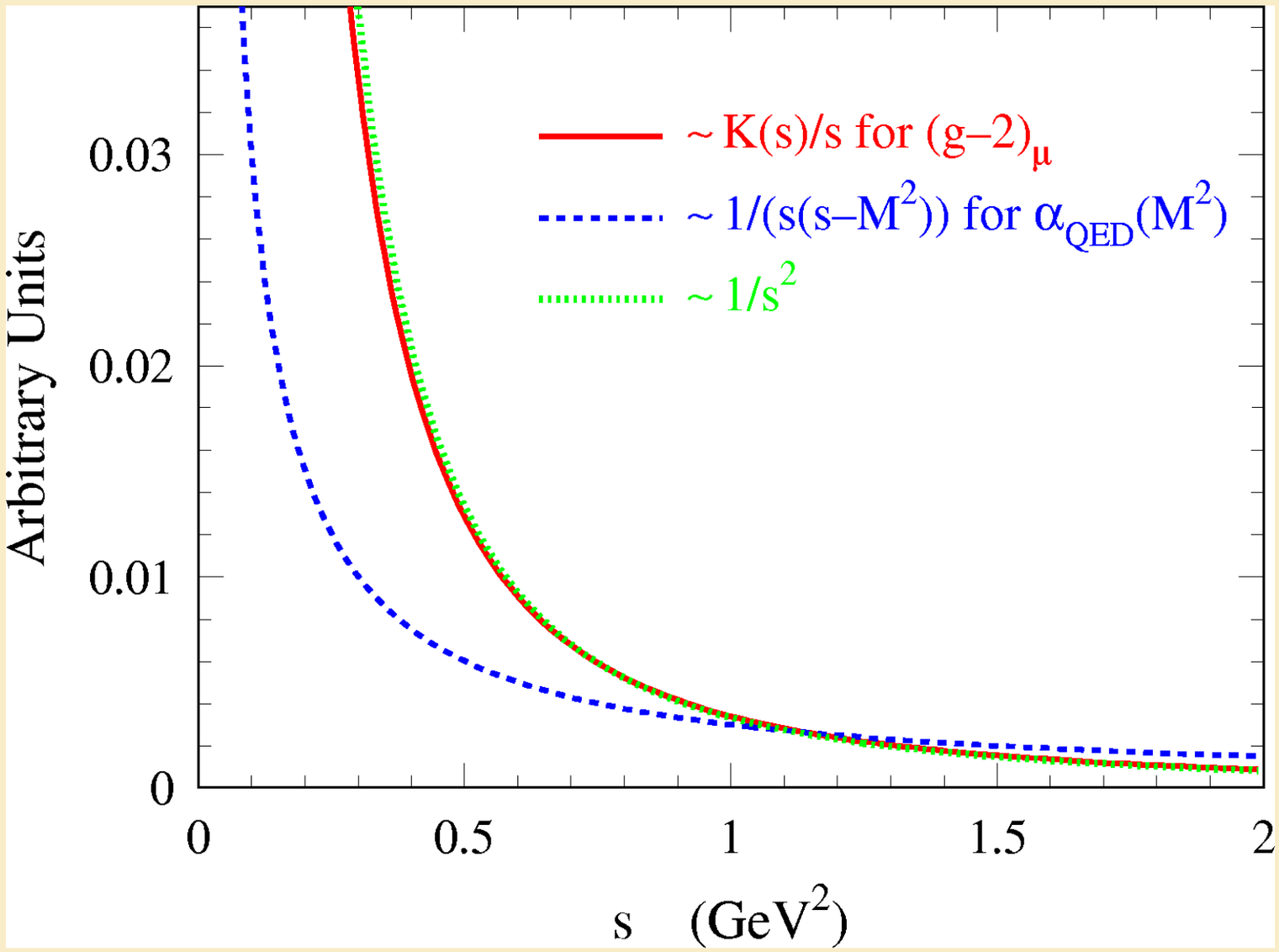
Buchmueller et. al. arXiv:1110.3568v1 [hep-ph]





Global fit for best SUSY points given recent Atlas, CMS, LHCb, and other data, including g-2

HVP(LO) K(s)



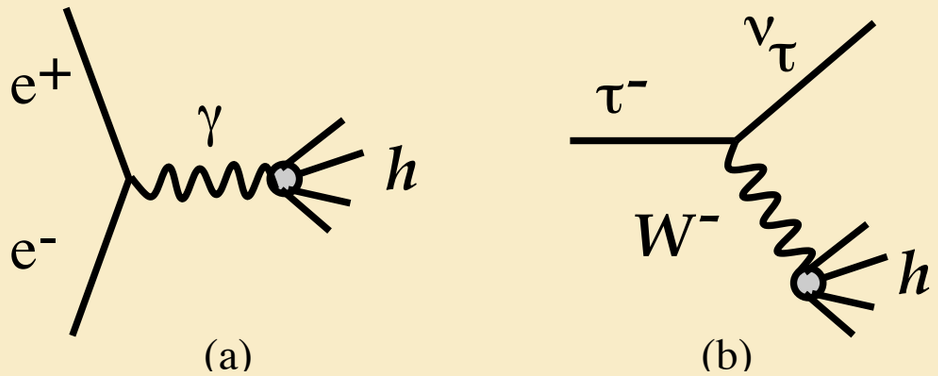
M. Davier

Taus for HVPLO

Differences between e+e- and tau data.

Taus need isospin corrections

But predictions of tau to pions branching fractions with CVC (Conserved Vector Current) Hypothesis disagree with experiment at few-sigma level.



Explore the discrepancy with a next experiment

~ 3σ discrepancy - a hint of something new?

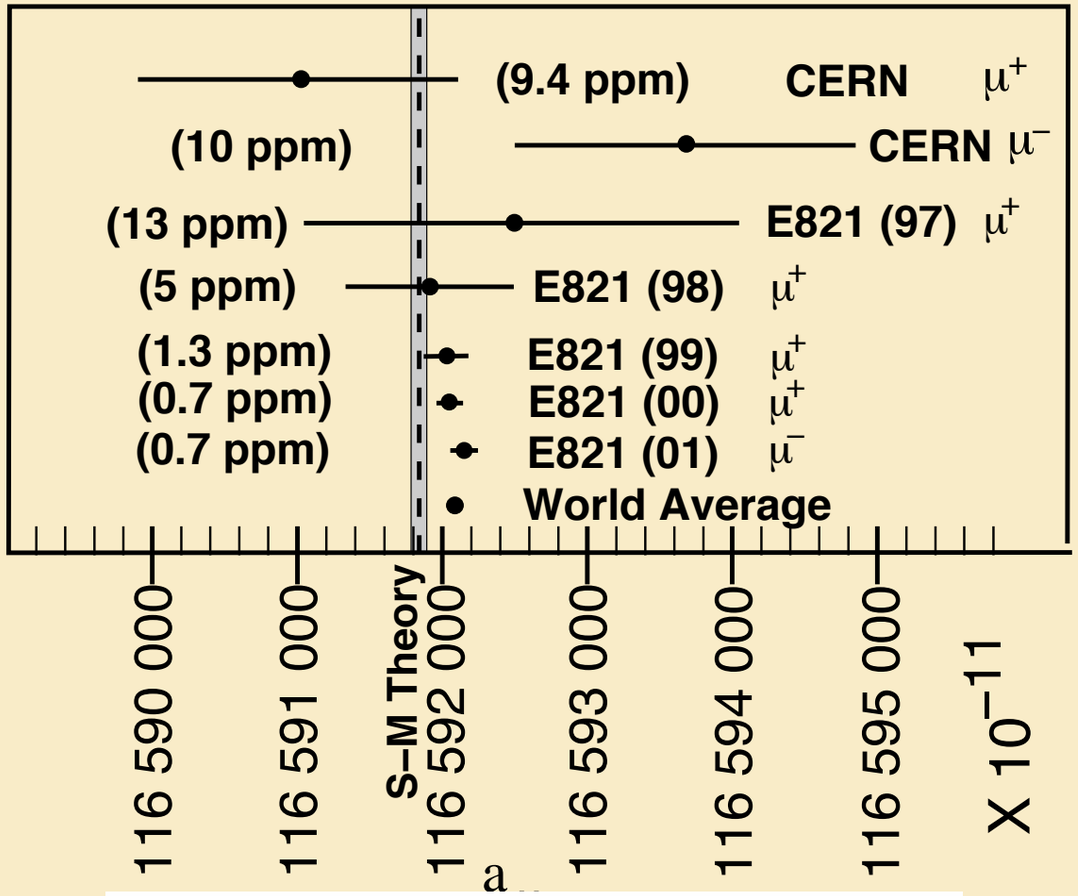
Time for another experiment!

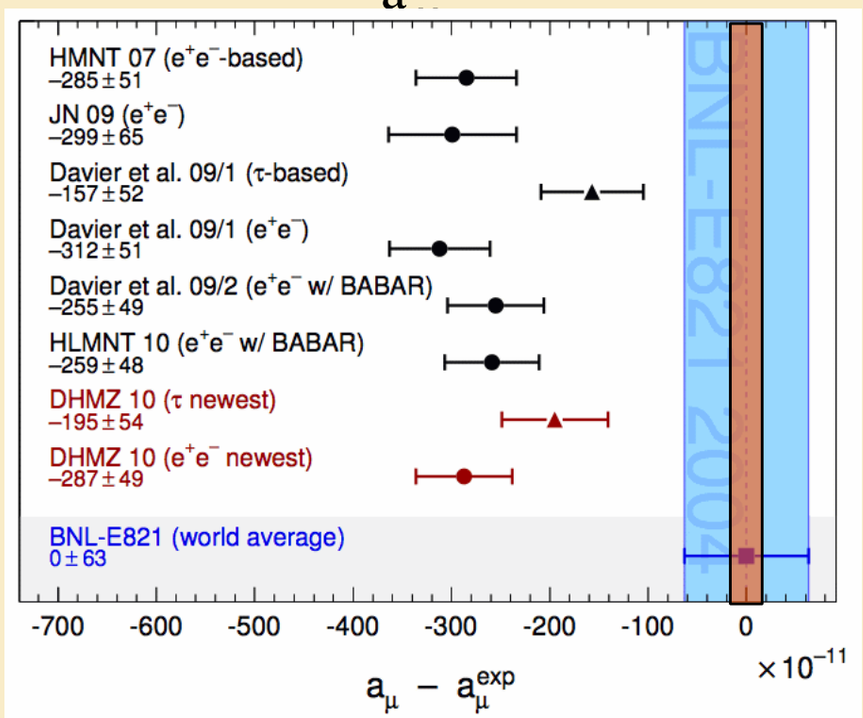
Goal: a_μ to $\pm 16 \times 10^{-11}$ (0.14 ppm)

0.10 ppm stat, 0.07 ppm systematic on both ω_a and ω_p

With a 0.14 ppm measurement, current discrepancy becomes 5.6σ (7.5σ if theory drops to 0.3 ppm)

What can you do with a factor of 4 better experimental result?



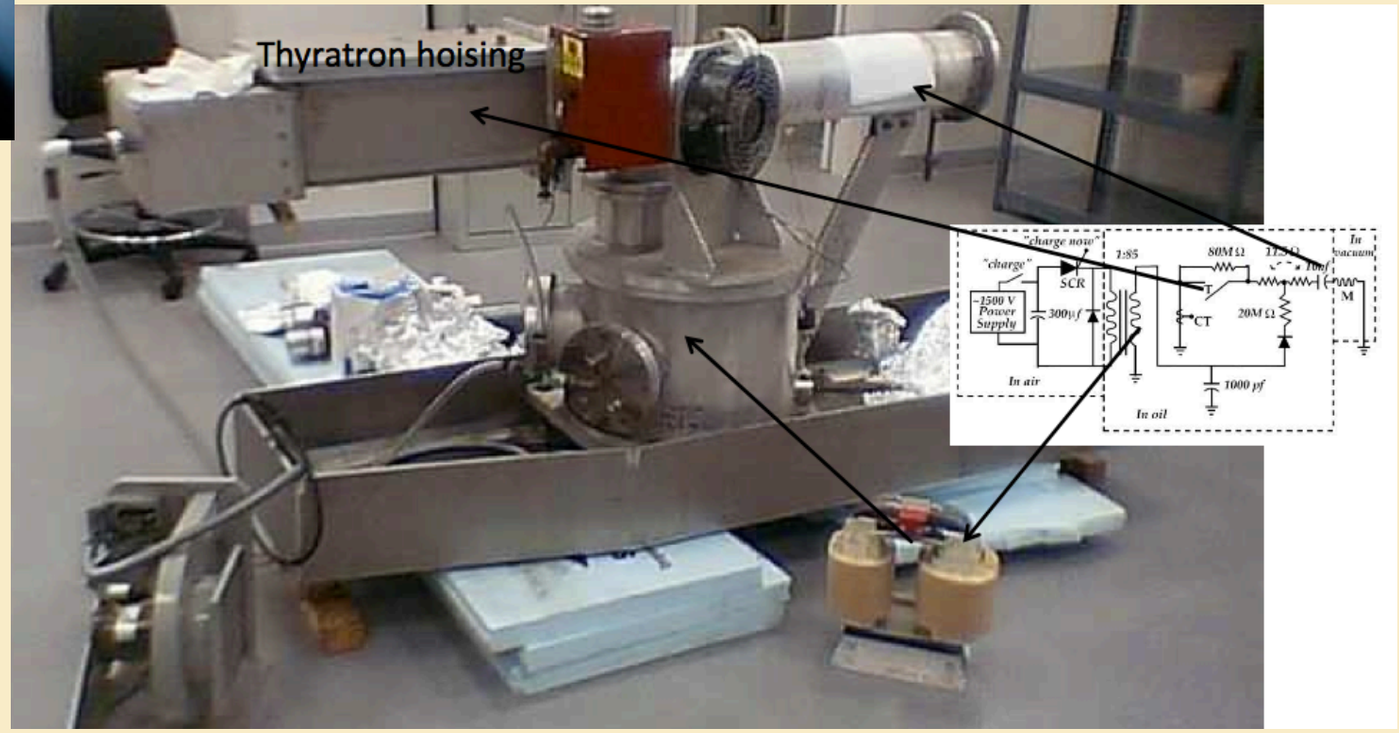


M. Davier

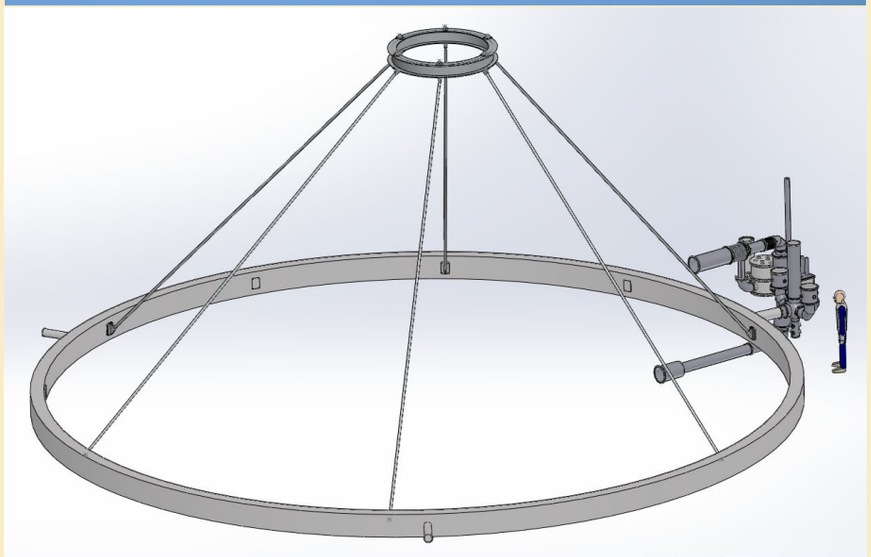
And studying old parts

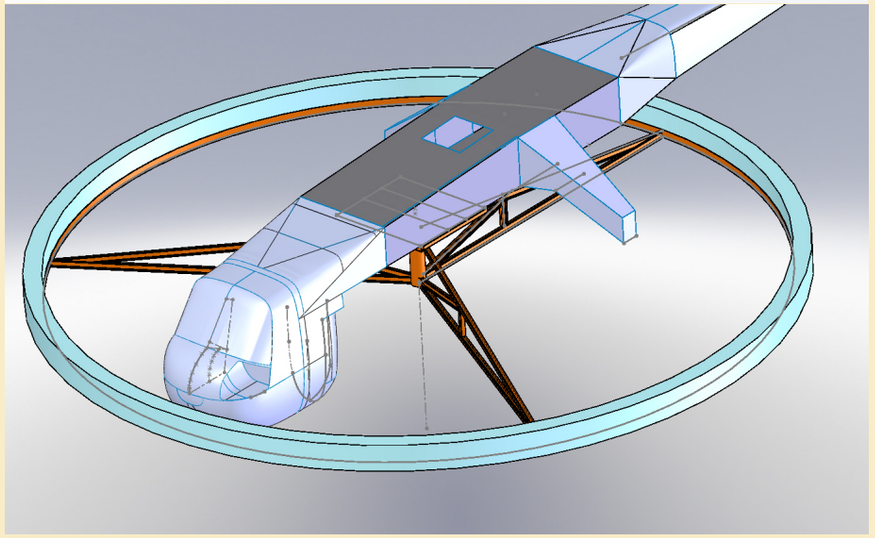
Cornell got this box of stuff

And reconstructed a kicker



Helicopter?





Feasibility study by Erickson Air Crane

<u>PROS</u>:

Skycrane has sufficient lift (coils aren't that heavy)

No need to remove traffic obstructions and no tree trimming

Pretty economical

Way cool

<u>CONS</u>:

FAA requires 300' no-habitation zone under copter; would require tollway closure during day

Very weather dependent

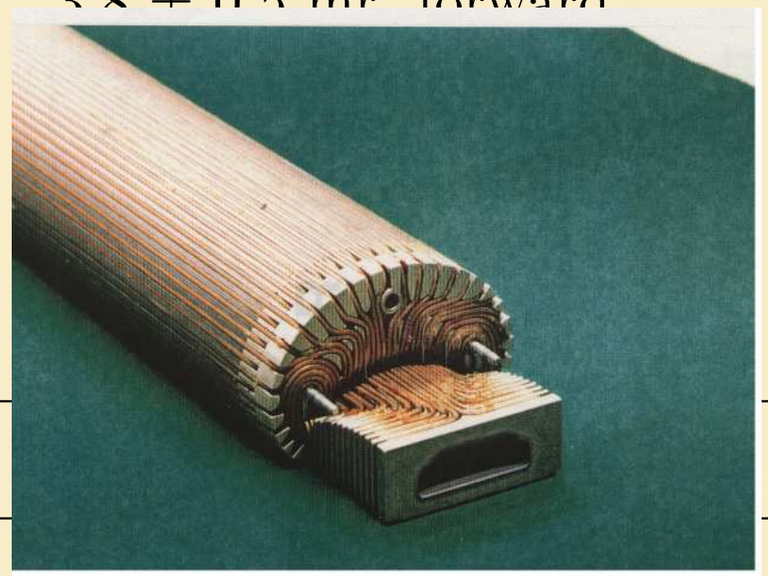
Vibrations a concern

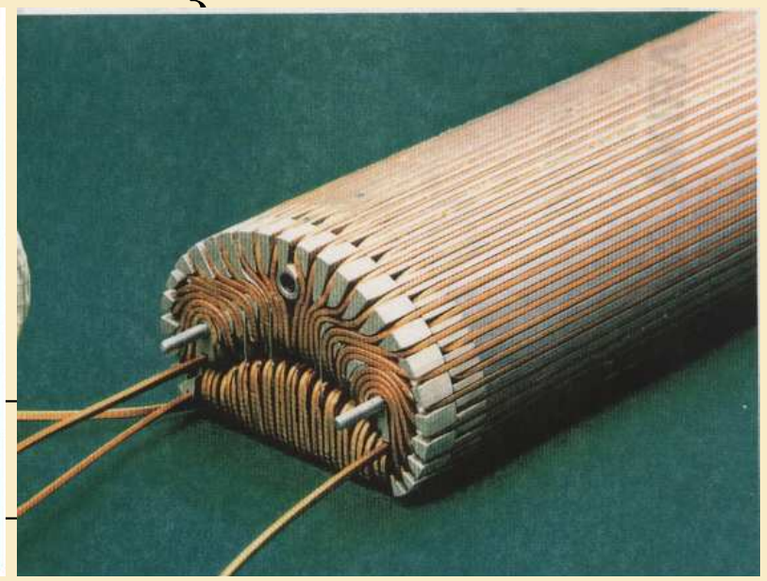
More risk and more DOE hurdles (attention from the DOE inspector general)

A better beam from Fermilab

Need 180B positron decays
With 4 x 10^{20} Protons on target in 2 year run,
need to improve μ/p by factor of 6 (11 to be safe)

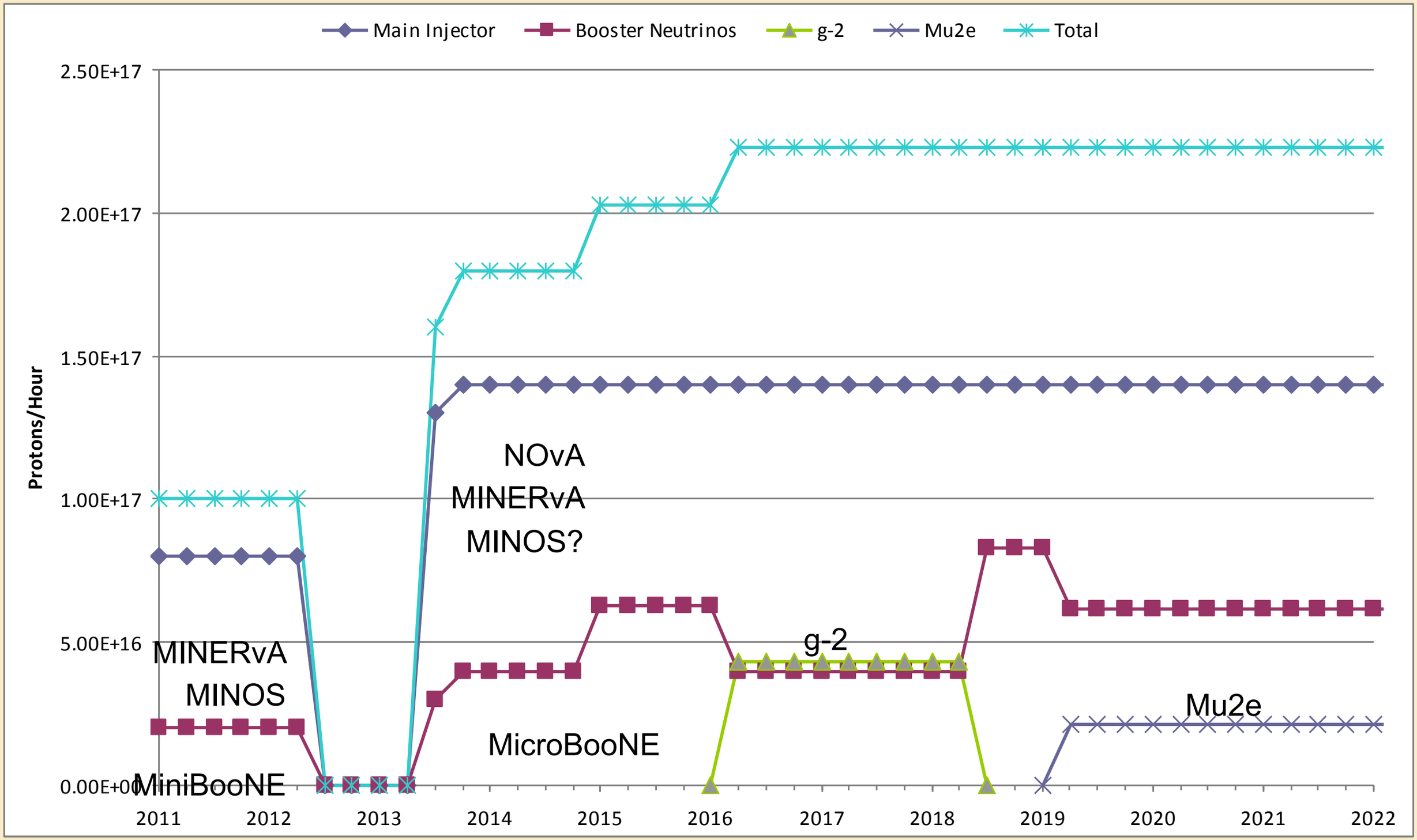
parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	≈ 2.7E-5	≈ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band			
FODO lattice spacing			
inflector			
total			





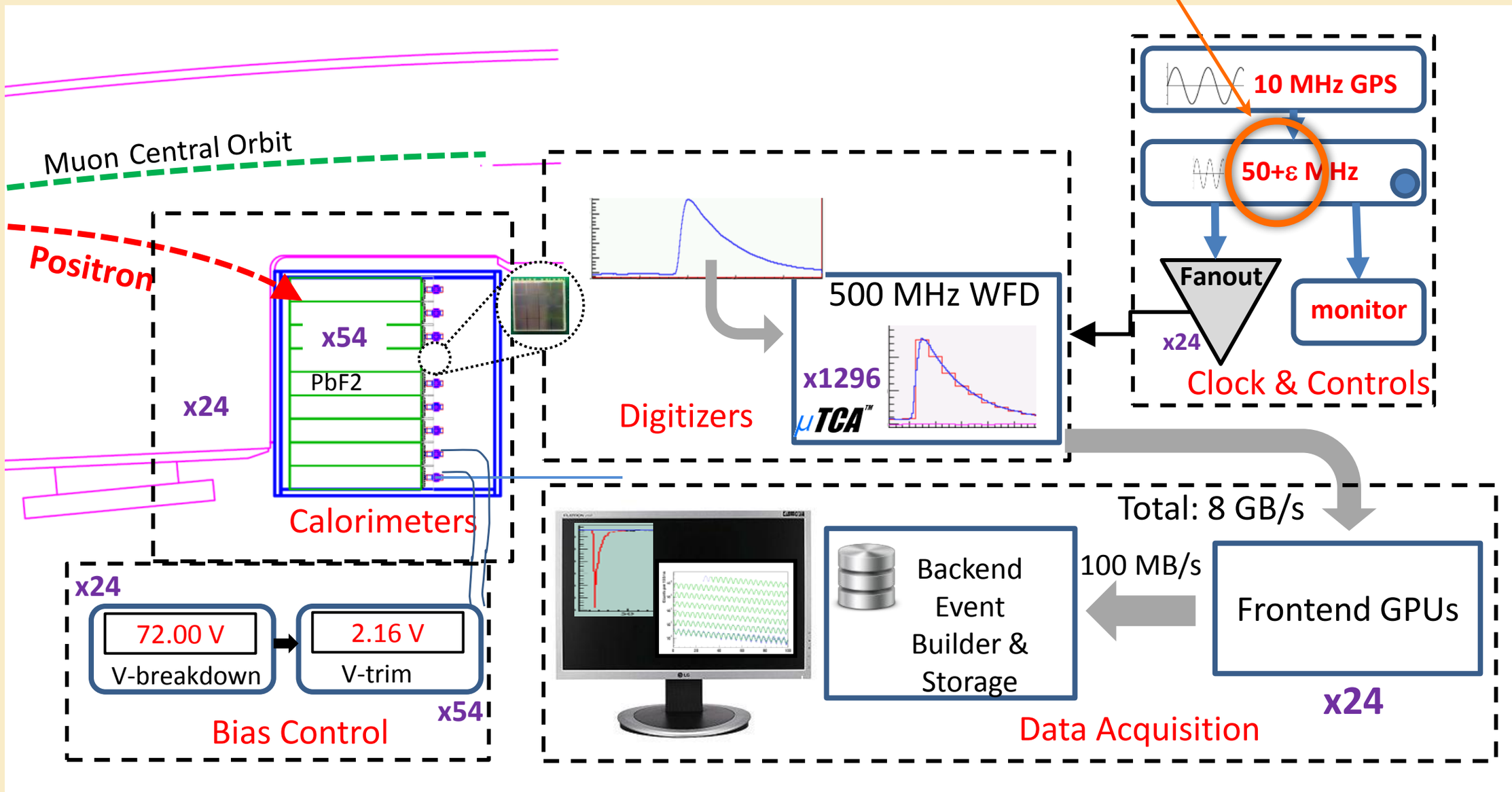
Improved kicker magnets too!

Who gets beam when? REMOVE

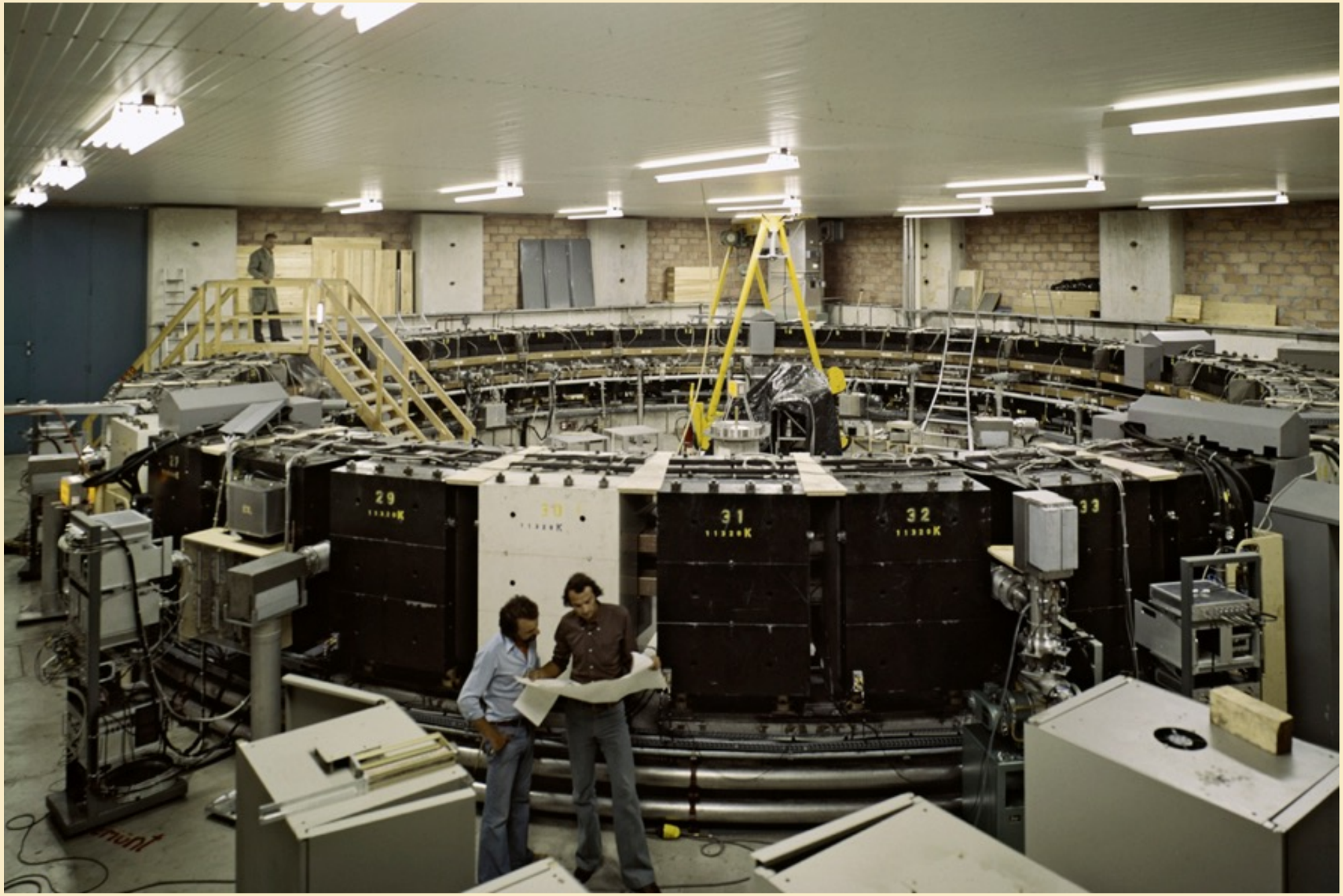


Measuring ω_a

Time base blinded



Third CERN Muon g-2 Experiment (–1979)



Sensitive to hadronic vacuum polarization (adv. muons!)

A huge recycling project

Make excellent use of existing Tevatron infrastructure

- g-2 ring
- g-2 beamline
- Debuncher Ring
- Magnets, pumps, stands and other Accumulator Ring components
- AP transfer lines
- AP-0 Target Station
- AP-2 beamline magnets
- Main Injector RF ferrites
- Tevatron satellite refrigerators
- Tevatron N_2 and He storage tanks
- Tevatron cryo line
- Tevatron High Temperature Superconducting leads
- Tevatron vacuum equipment
- Tevatron loss monitors
- Tevatron BPM electronics
- Tevatron electronics crates
- Tevatron control cards
- Tevatron damper system
- Misc. Tevatron Instrumentation
- Shielding steel
- Transformers

Beam line from BNL

Synergies between g-2 and Mu2e

Proton Improvement Plan (PIP)

- Currently Booster limited by RF system to <9 Hz operation
- Proton Improvement Plan will allow 15 Hz operation of the Booster
- NOvA needs 9 Hz, leaving 5e20 POT/yr available for other programs
  - MicroBooNE (2014) – up to 6 Hz
  - g-2 (2016) – 3 Hz
  - Mu2e (2019) – 1.5 Hz

Experiment	Total Beam Request	Available Protons/year	Time Needed
MicroBooNE*	6.7 e20	Up to 5.0 e20	< 3 years
Muon g-2	4.0 e20	2.4 e20	2 years
Mu2e	3.6 e20	1.2 e20	3 years

* MicroBooNE can run in parallel with g-2 or Mu2e, but g-2 and Mu2e have to run separately

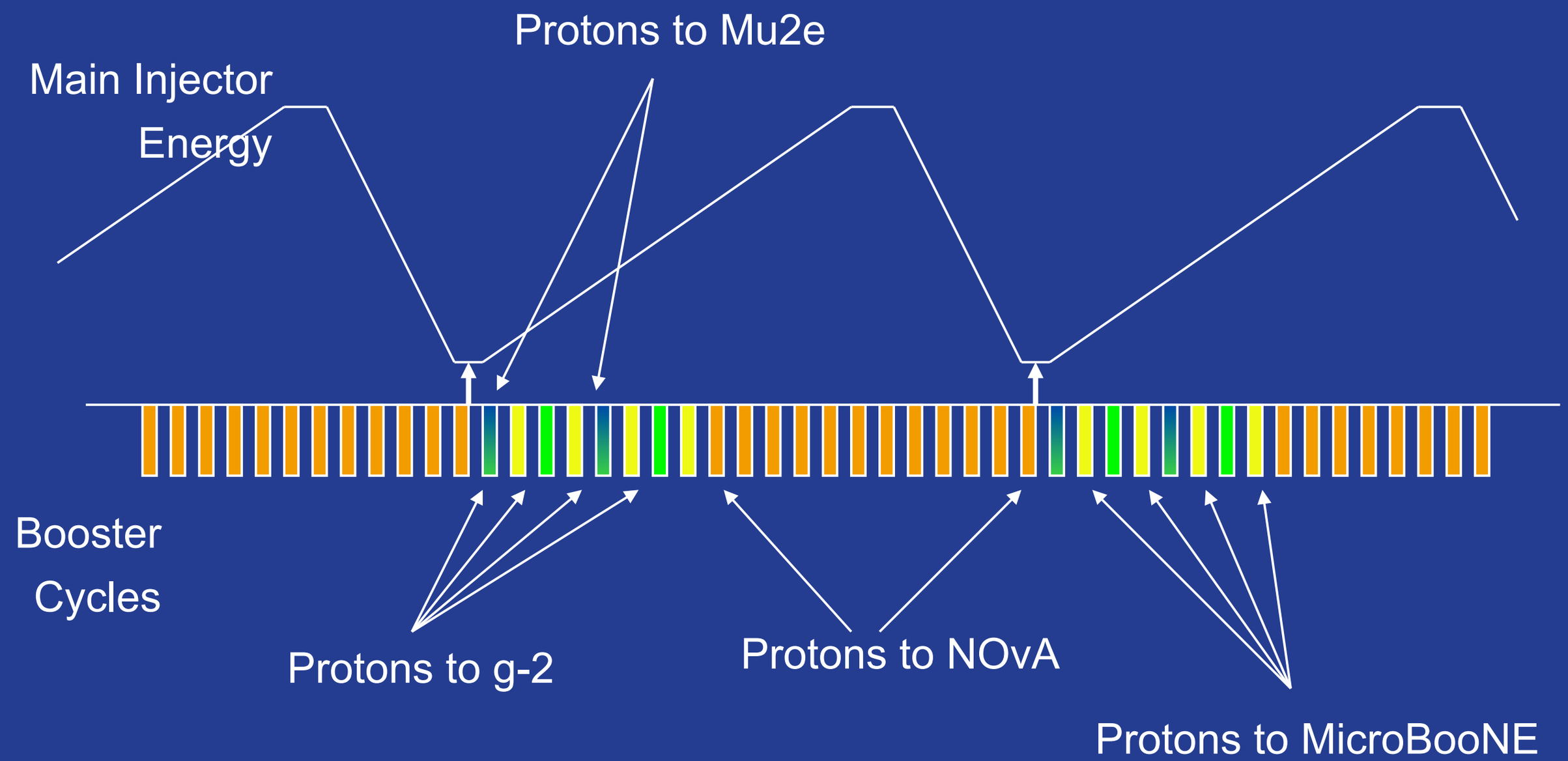
Booster beam structure

20 Booster cycles per NOvA cycle (1.33 sec)

12 NOvA cycles stored in Recycler before transfer to MI

Remaining 8 Booster cycles available for other experiments

MiniBooNE experience, 1 Booster cycle -> 0.6e20 POT/year



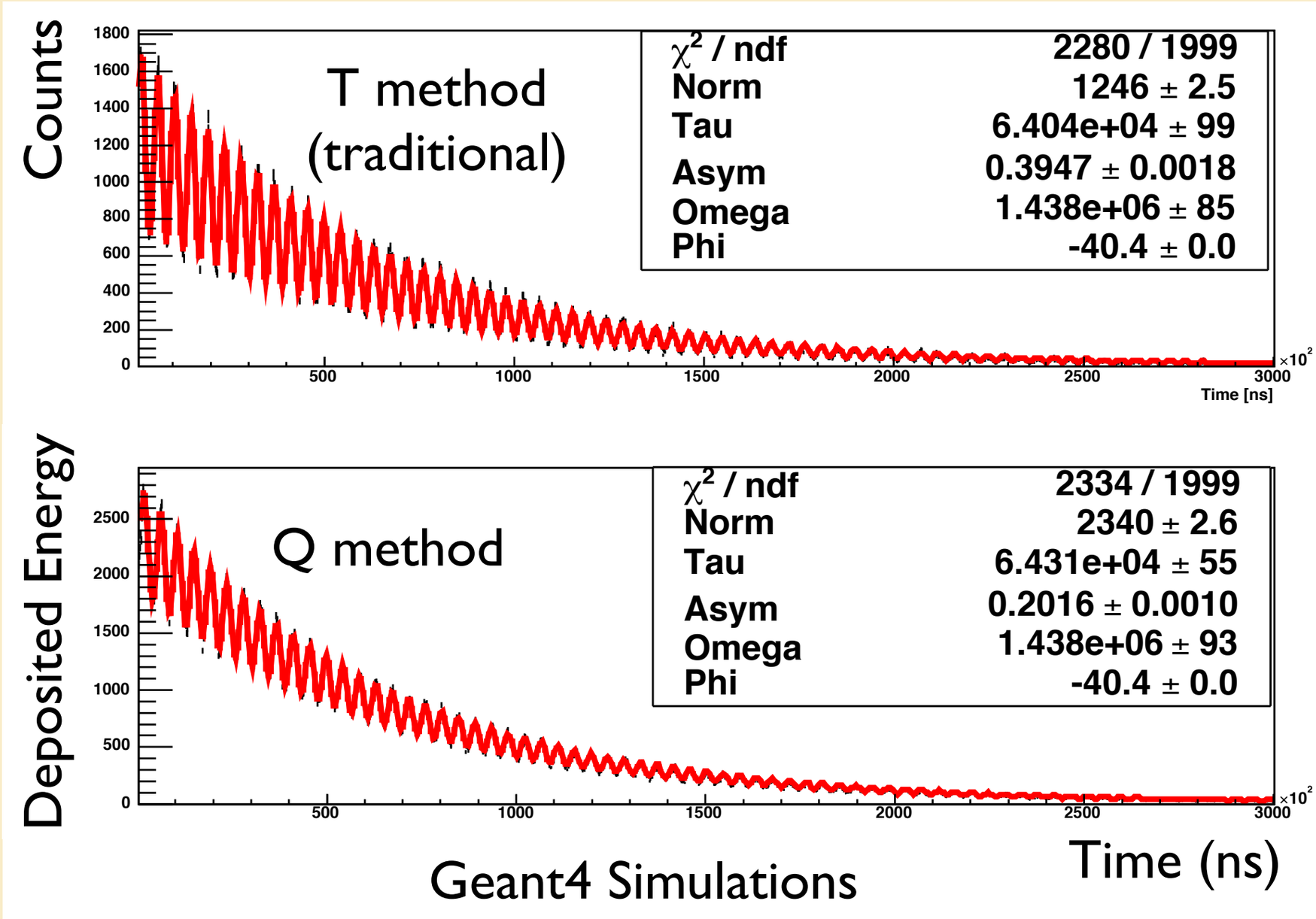
Event rate calculation

Item	**Factor**	**Net**	**Note**
Booster cycle - 15 Hz operation	1.33 s/cycle	0.75 Hz	1
Batches to $g-2$	6	4.51 Hz	2
Protons on target	4×10^{12} p/batch	1.80×10^{13} p/s	3
Bunches (each bunch provides 1 fill of the ring)	4 /batch	18 fills/s	4
BNL stored muons per proton	1×10^{-9} μ/p	1000 μ/Tp	5
Minimum stored μ/p improvement FNAL *vs.* BNL	6.0	6000 μ/Tp	6
Positrons with $t > 30$ μs and $E > 1.8$ GeV	10 %	603 e^+/fill	7
DAQ / Expt. production and uptime	66 %		8
Time to collect 1.8×10^{11} events (2×10^7s/y)		1.25 years	9
Commissioning time		0.1 years	10
FNAL running years		1.35 years	11
Total Protons on Target		4×10^{20} **POT**	12

T's and Q's

New Q method: Total cal E vs time (no threshold) will see wiggle too

Net asymmetry is half of T method, but N is larger.



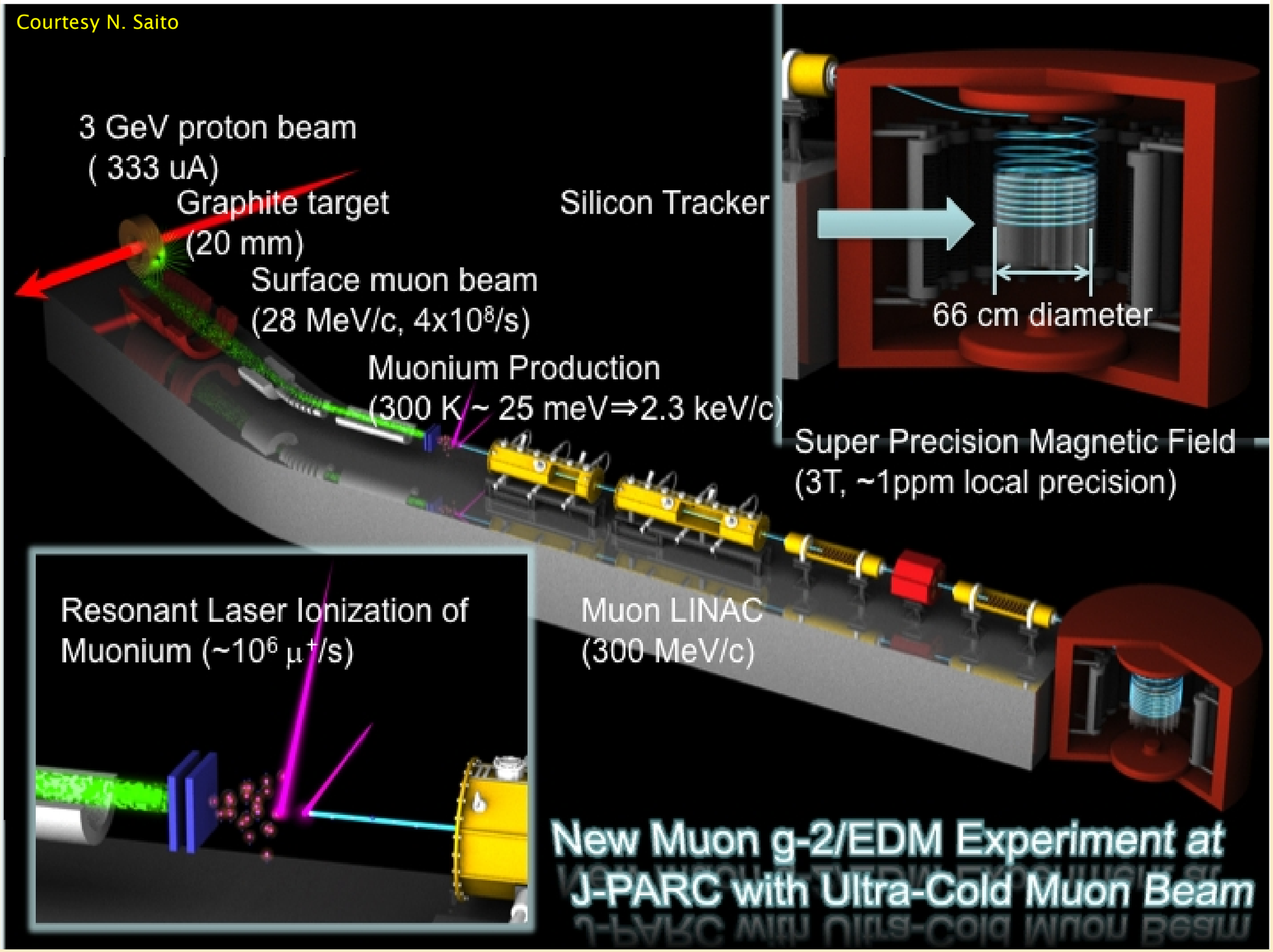
Statistically weaker than T method by 9%, but no Pileup correction necessary!! Will other systematics emerge?

Improving ω_p

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

To get to 0.07 ppm, more probes, mapping, shimming, temp control

g-2 at JPARC (no E-fields)



JPARC

Have to contend with higher rate in smaller device

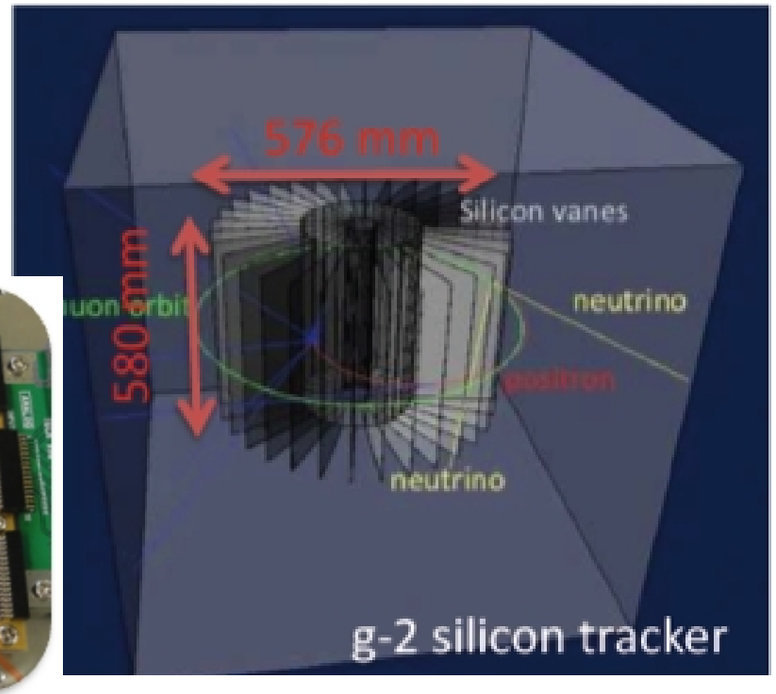
$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

N. Saito NuFact 2011

$$\Rightarrow \quad \sigma_\omega = \frac{\sqrt{2}}{A\,\gamma\,\tau_\mu\sqrt{N}}$$

Lower γ means higher statistics required

Also need to repolarize muon source or compensate lower A

Highly granular Si tracker, Belle II DSSD under evaluation