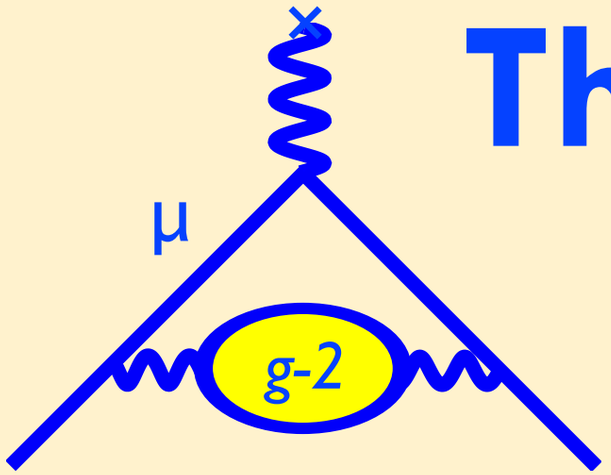


The New g-2 Experiment at Fermilab

Adam Lyon
(Fermilab/Scientific Computing Division)

Argonne HEP Seminar, January 2012

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

Electron?

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

Electron?

Proton?

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

Electron?

Proton?

Neutron?

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

Electron?

Proton?

Neutron?

Crouton?

A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

Electron?

Proton?

Neutron?

Crouton!

A more advanced quiz

Which one of the following is not like the others?

A more advanced quiz

Which one of the following is not like the others?

Electron?

A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

Crouton?

A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

Crouton?

Muon?

A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

Crouton?

Muon????

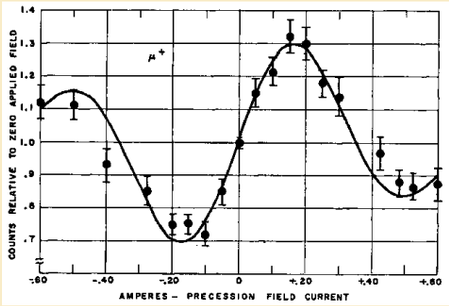
A more advanced quiz

Which one of the following is not like the others?

Isidor I. Rabi

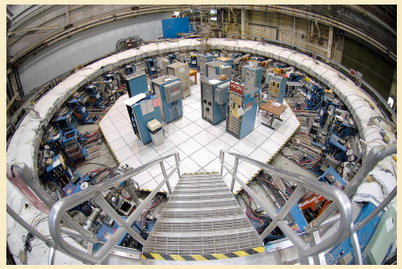
Muon????

Outline of this seminar



1) Introduction to the muon magnetic dipole moment

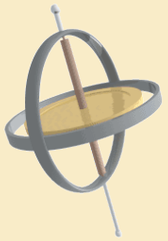
2) Brief history of the measurement

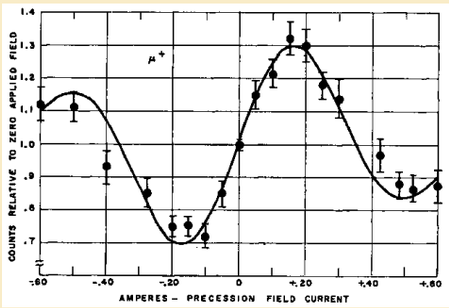


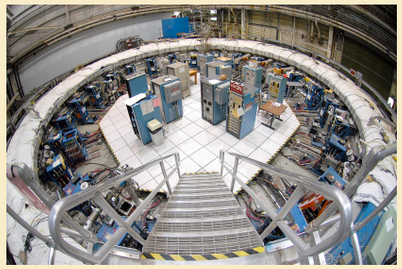
3) Current state of experiment and theory (Brookhaven E821)

4) The future Fermilab E989 Experiment

Outline of this seminar







1) Introduction to the muon magnetic dipole moment

2) Brief history of the measurement

3) Current state of experiment and theory (Brookhaven E821)

4) The future Fermilab E989 Experiment

The basics of the "*g-factor*"

Orbiting charged particle: $\vec{\mu_L} = \frac{q}{2m}\vec{L}$

Particle with spin has an *intrinsic* magnetic moment:

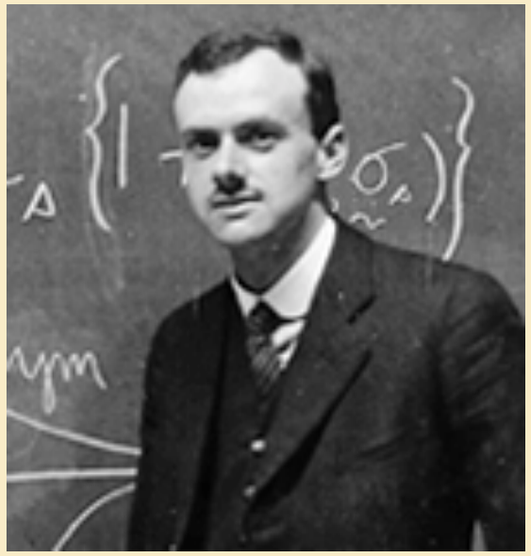
$$\vec{\mu_S} = g\frac{q}{2m}\vec{S}$$

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 electron, g remained = 2 for twenty years

Why does g ≠ 2???

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

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

Henry Foley

Polykarp Kusch

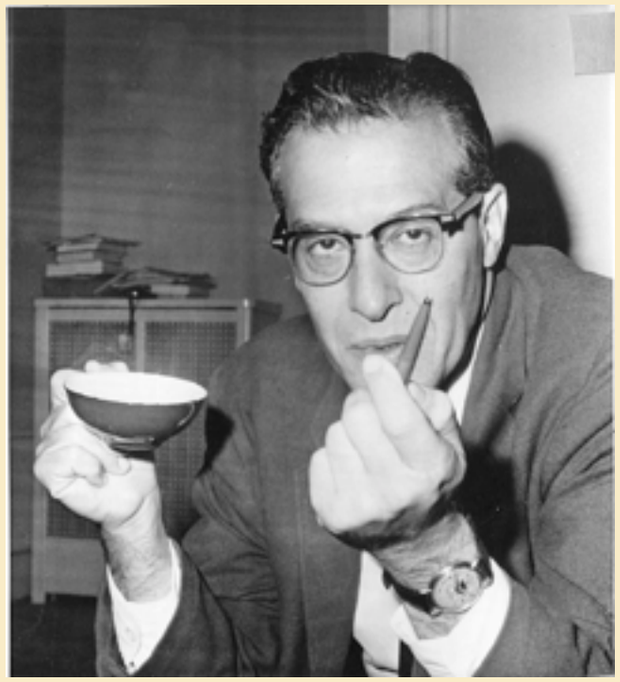
$$g_e = 2.00238(10)$$

An anomalous magnetic moment

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

Soon after, Schwinger calculates first order QED correction

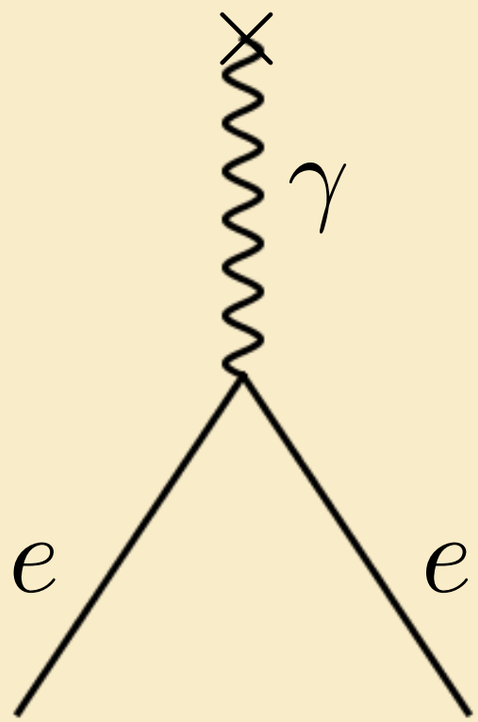
$$a_e = \alpha/2\pi = 0.00118$$

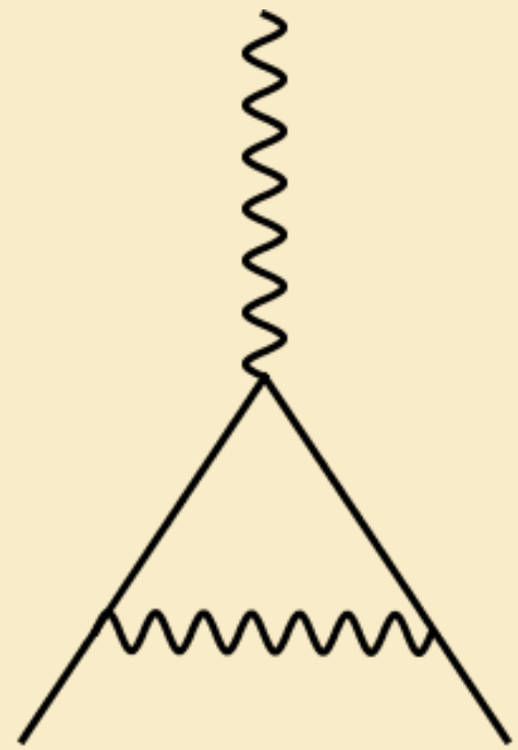


Julian Schwinger

A new understanding begins

Empty space is not empty

$g_e =$ 

$+$  $+ \quad \cdots$

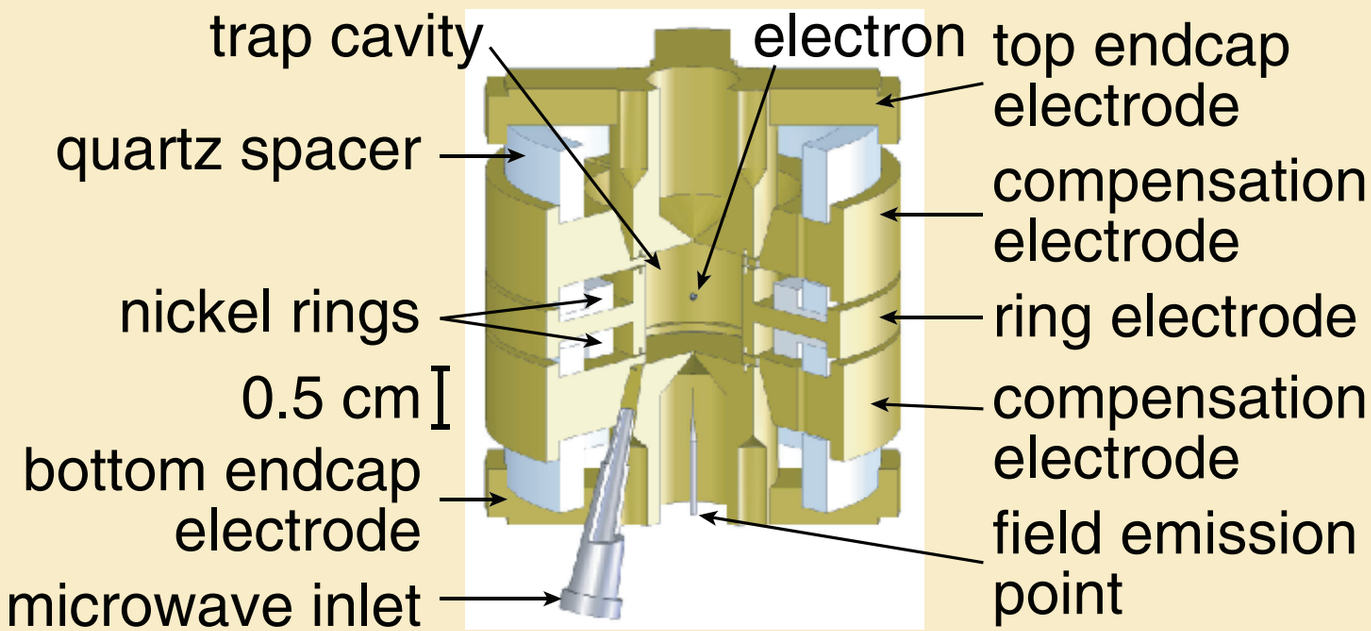
$$2 \quad + \quad 0.00236 \quad + \quad \cdots$$

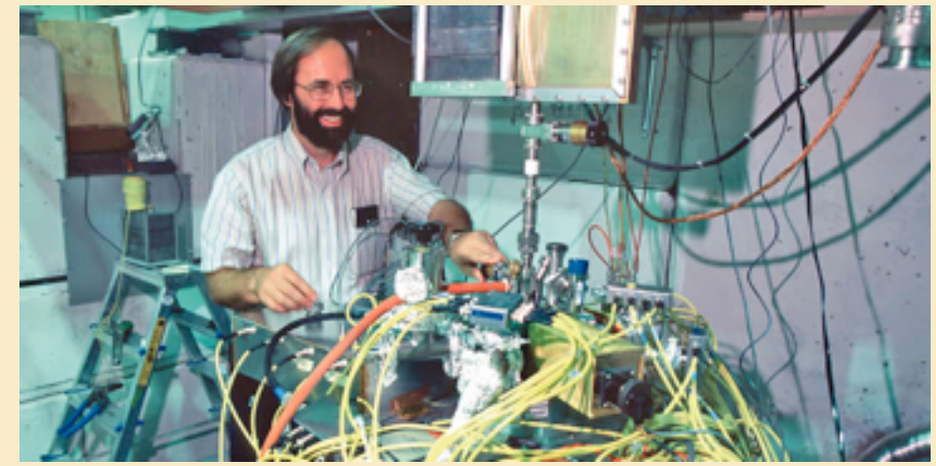
The beginnings of QED and the Standard Model

Currently, a_e is known to sub-ppt

Gabrielse (2006 & 2008):

Previous result was 20 years prior





$$a_e = 0.00115965218073(28)$$

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

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

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

See M.Passera INT2008

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

So look at muons!

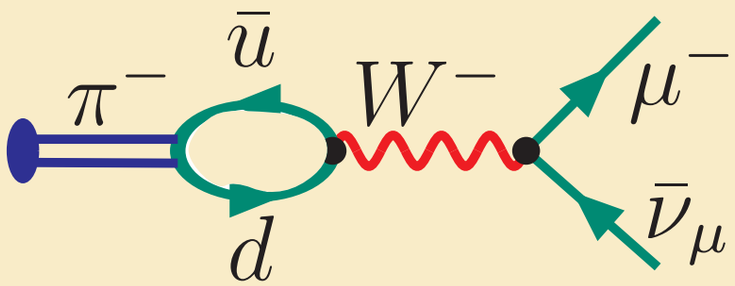
Taus would be even better, but lifetime and production rates are too small to be useful here

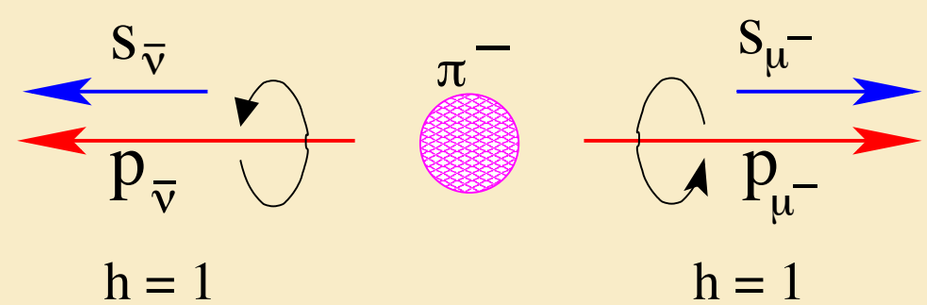
Muons are the only particle left for this type of fundamental measurement!

Muons and spin are an ideal match

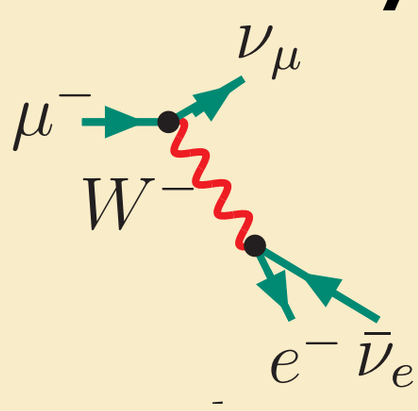
Some lucky breaks from parity violation:

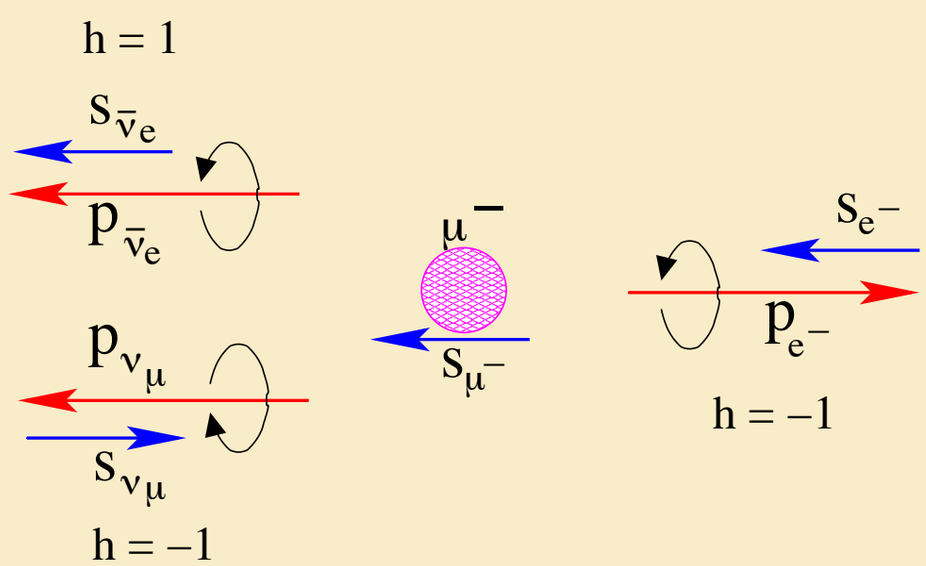
High momentum muons from pion decays are longitudinally polarized





Muon decays are "self-analyzing"

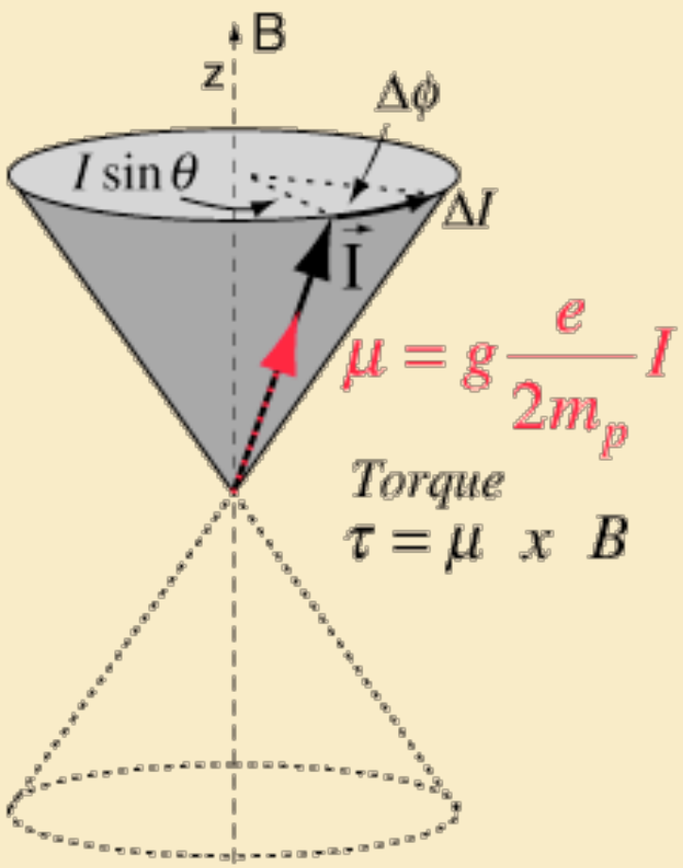




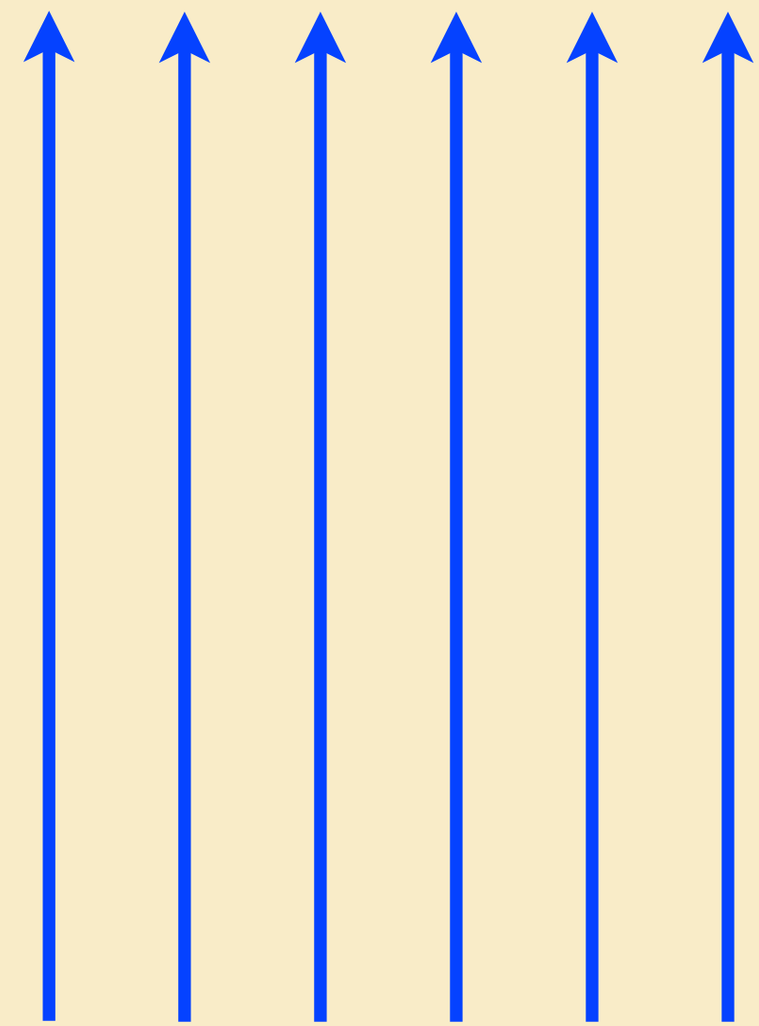
Highest energy electrons are emitted along (opposite) direction of muon+(-) spin in muon rest frame

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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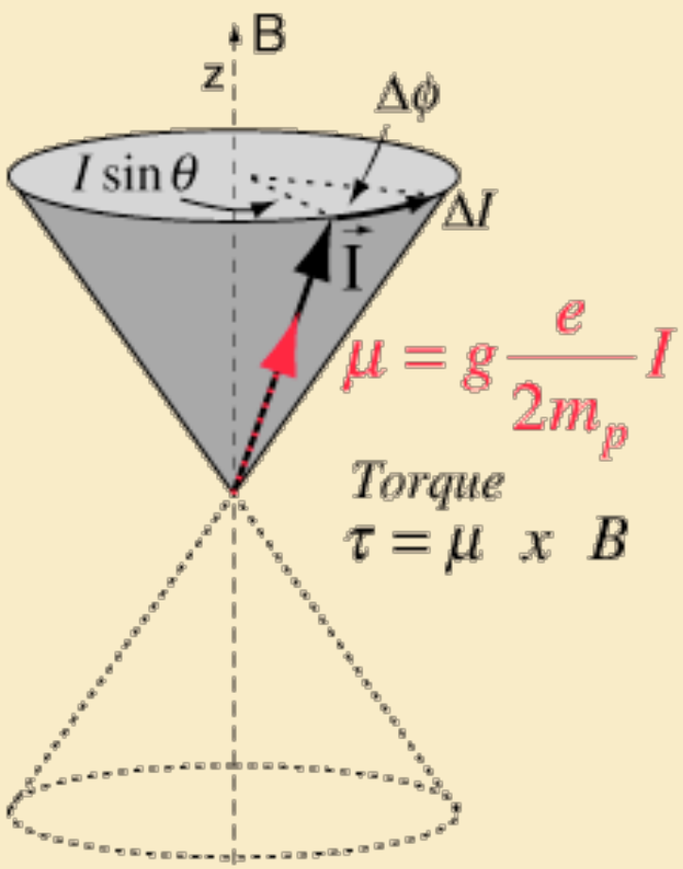

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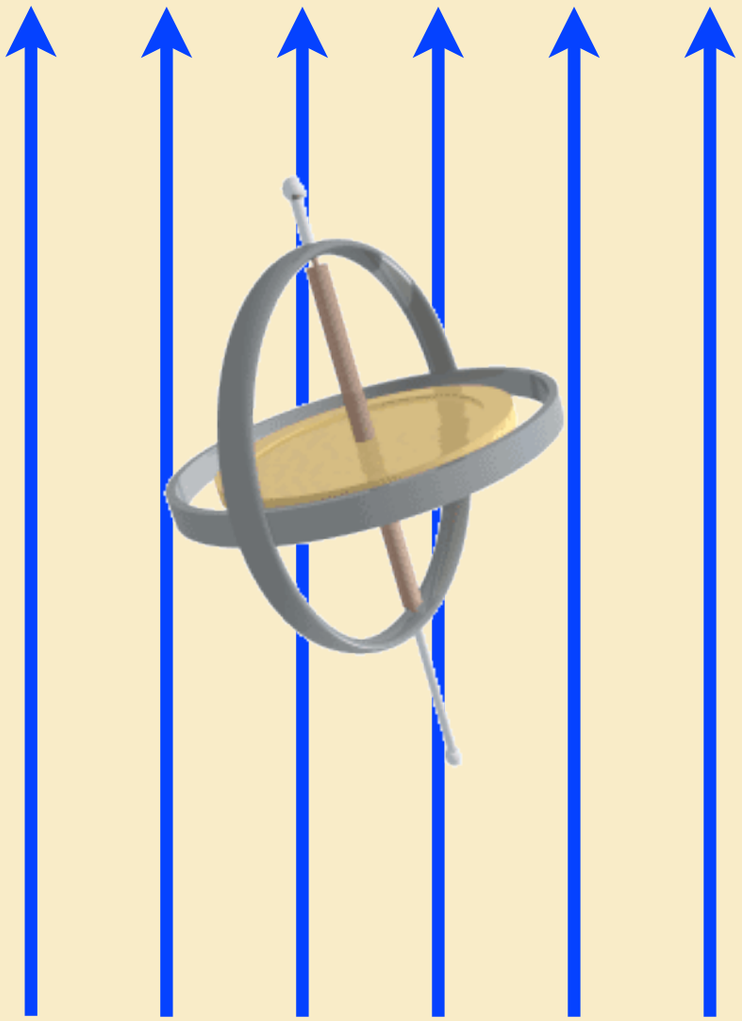
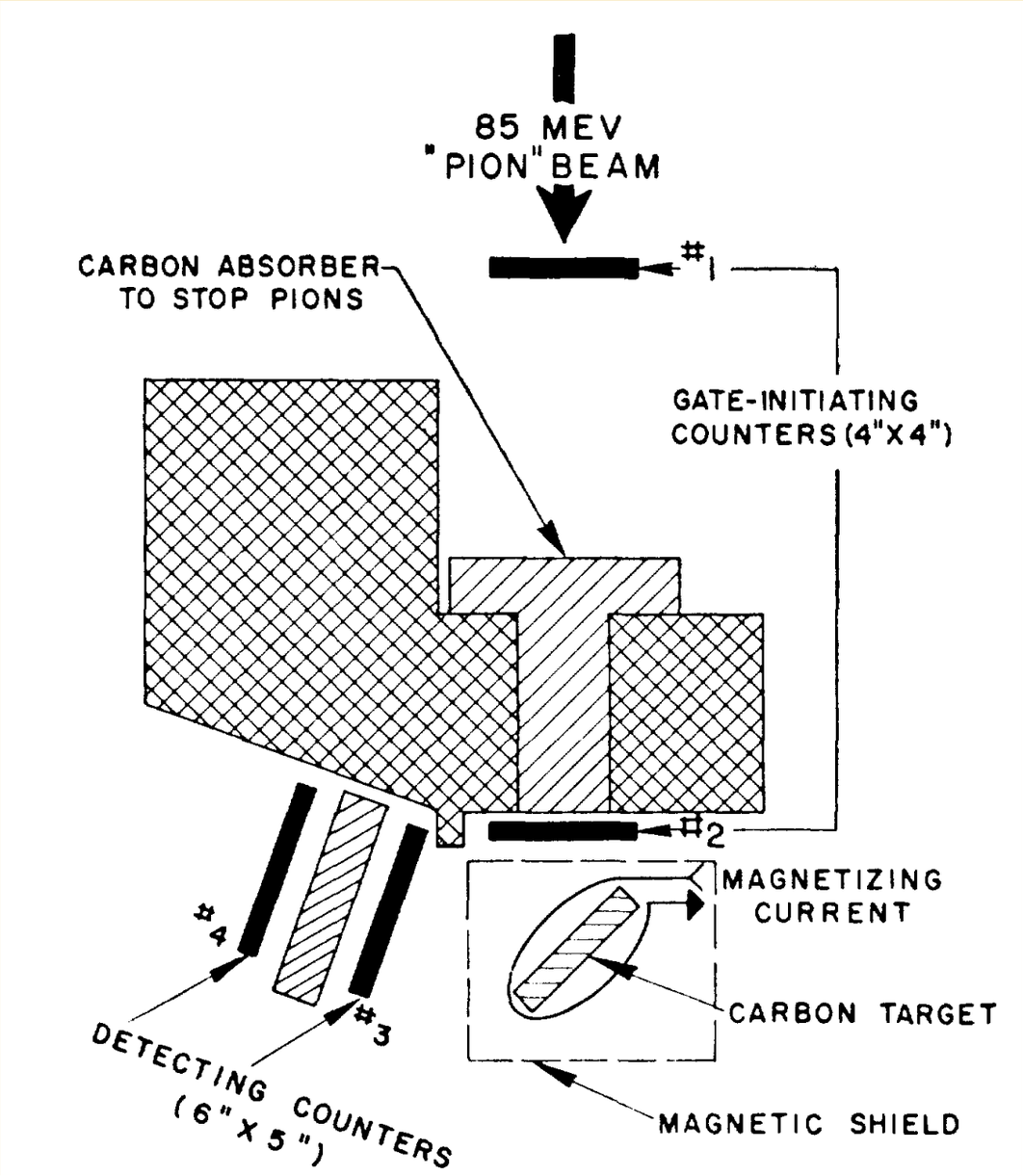
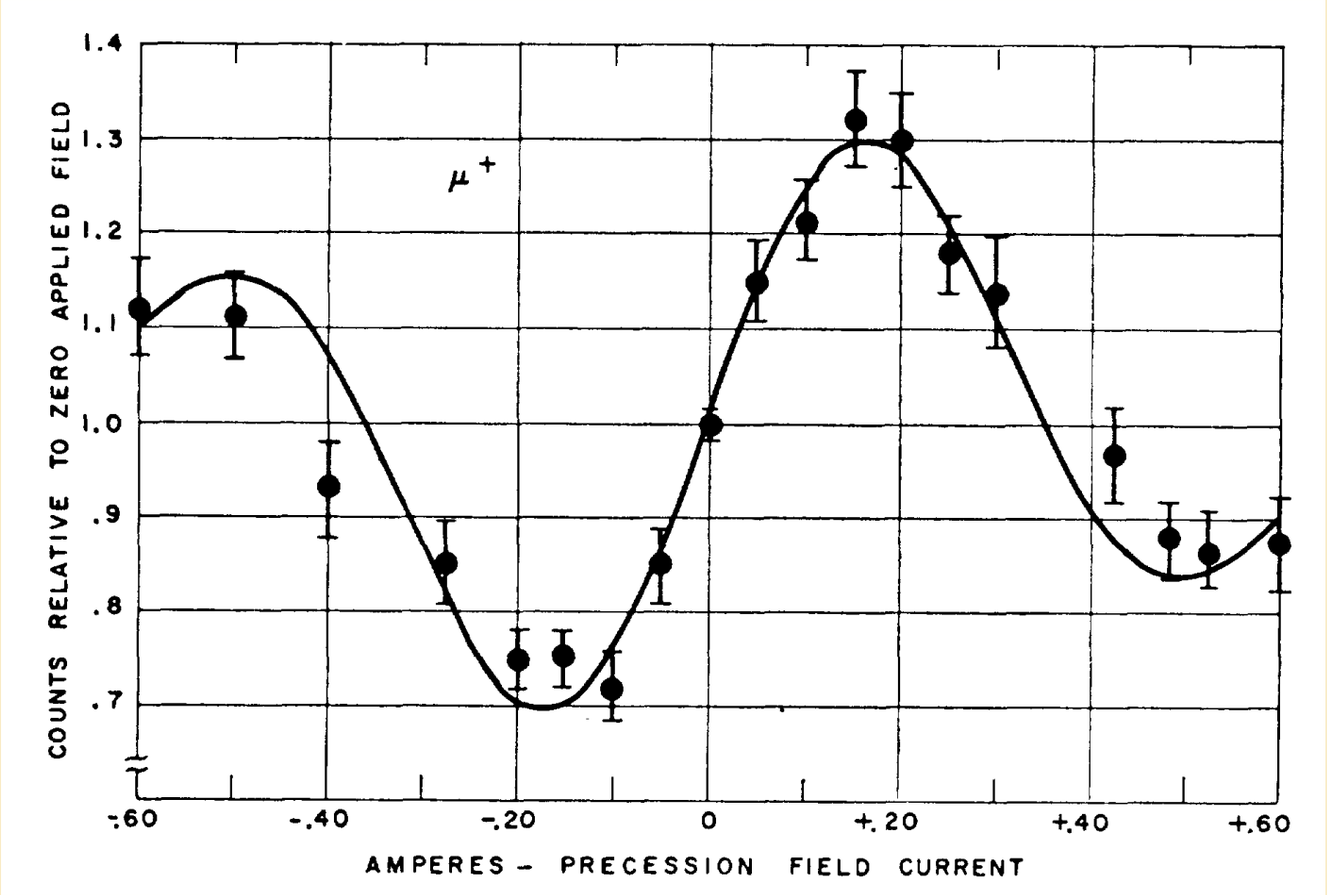


The first experiments for a_μ

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



Direct measurement of *g* -- asym vs field



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

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

Cyclotron frequency for particle in a *B* field

$$\omega_c = \frac{eB}{mc\gamma}$$

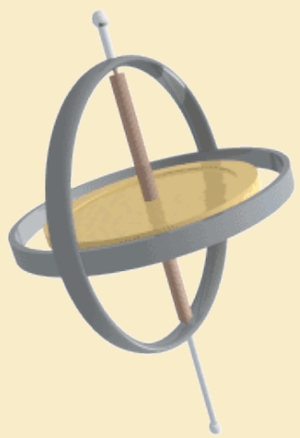
Larmor frequency with Thomas precession

$$\omega_s = \frac{eB}{mc}\left(\frac{1}{\gamma} + a_\mu\right)$$

Storage rings enter the picture

Cyclotron frequency for particle in a *B* field

$$\omega_c = \frac{eB}{mc\gamma}$$



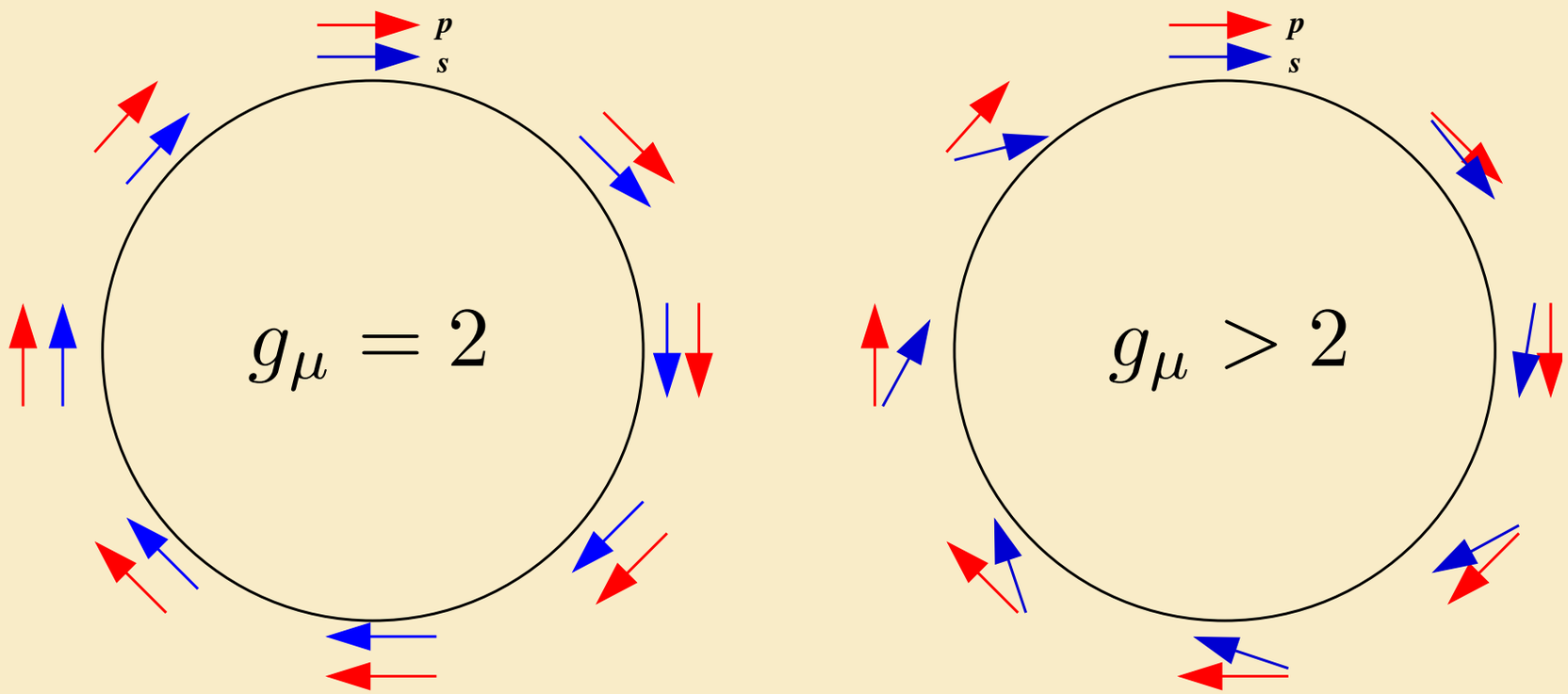
Larmor frequency with Thomas precession

$$\omega_s = \frac{eB}{mc}\left(\frac{1}{\gamma} + a_\mu\right)$$

Difference of frequencies

Another lucky break

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$



Improvements for free

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

We can avoid the uncertainty in muon mass with,

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

ω_p **is proton Larmor precession (can measure with NMR)**
λ **is from hyperfine muonium structure (Hughes) 120 ppb**

Second CERN experiment results (1968)

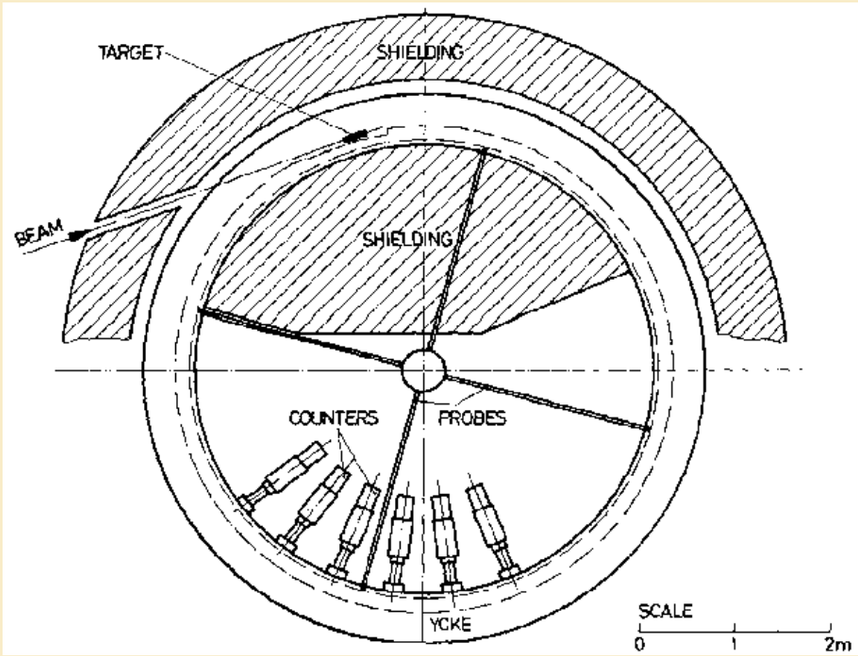
$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$

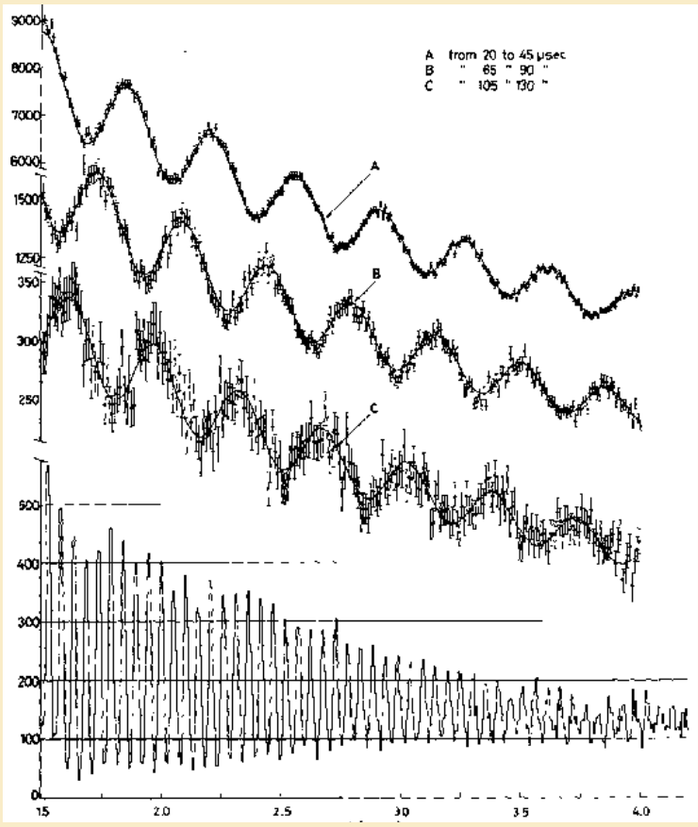
Positrons over threshold

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

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

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 focusing 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

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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 disappears! 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

An improved 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 $\dfrac{\delta\omega_a}{\omega_a} = \dfrac{\sqrt{2}}{\omega_a A \tau \sqrt{N}}$

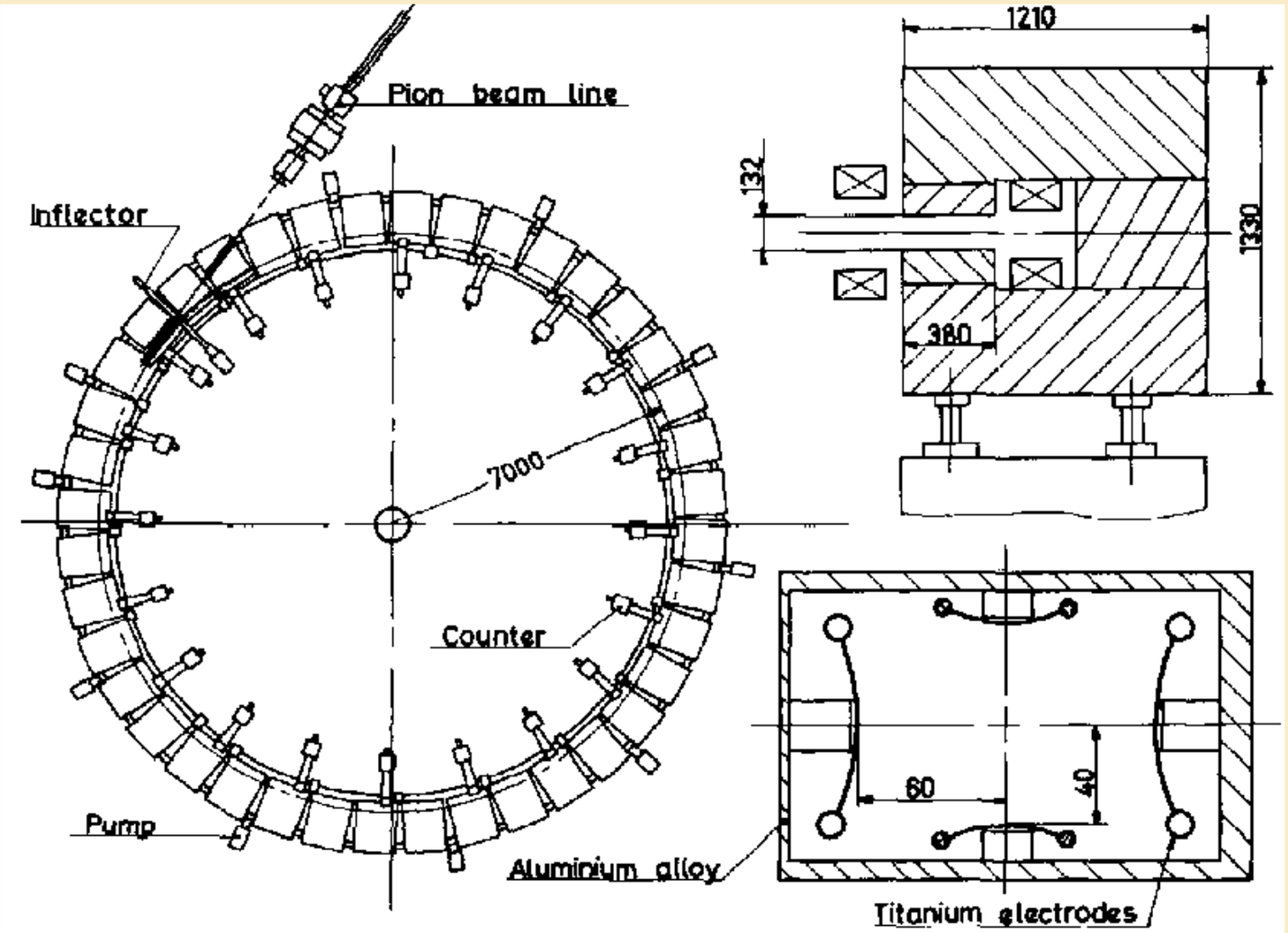
Increase momentum to magic (dilates lifetime to 64 μs)

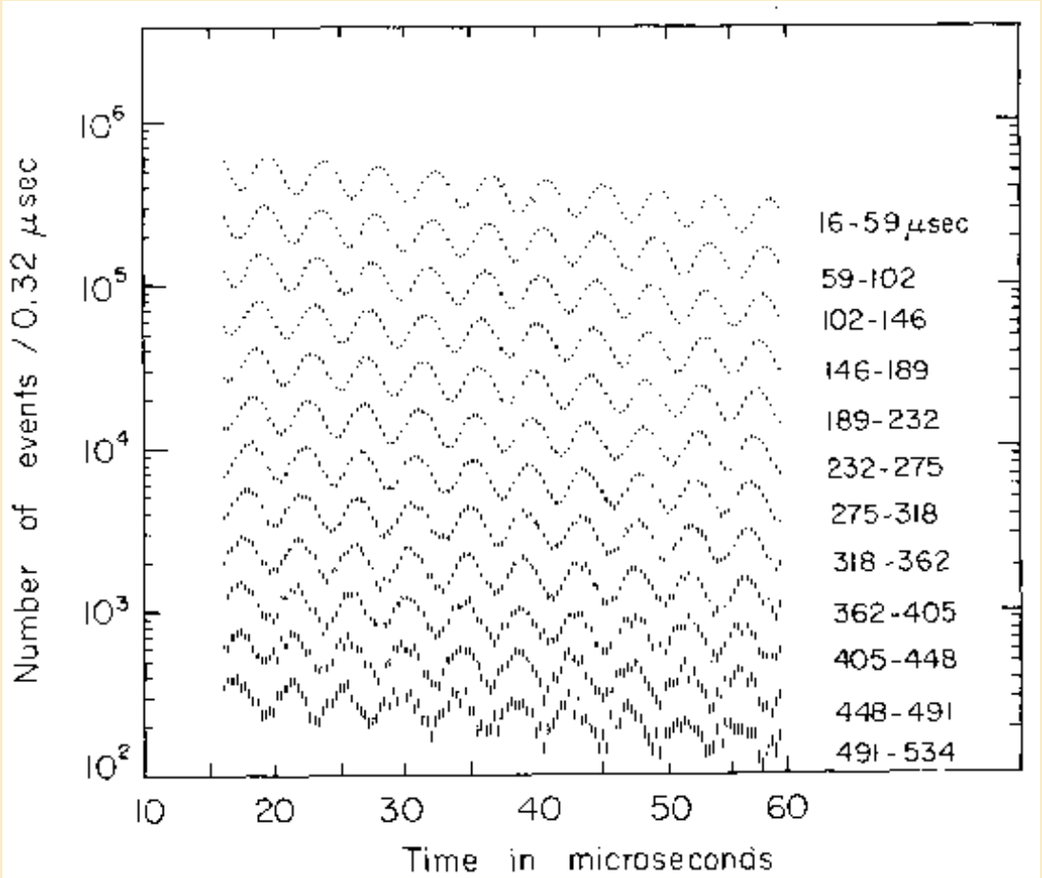
Increase *B* field, *N*

Improved λ (13 ppm to 2.6 ppm)

Target outside of ring - inject pions - better polarization

Third CERN Experiment (1979)



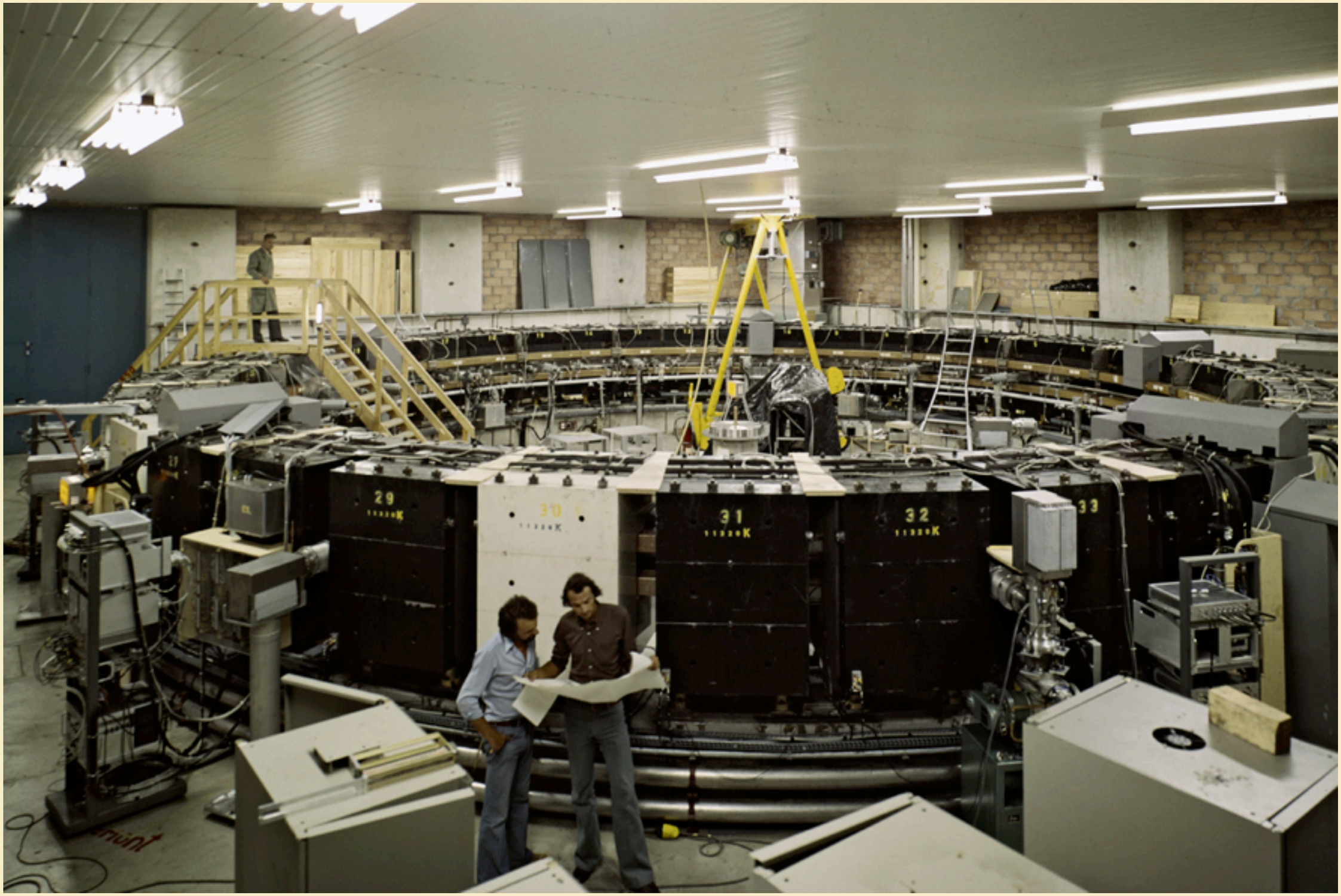


> 500 μs

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

Sensitive to hadronic vacuum polarization (adv. muons!)

Third CERN g-2 Experiment



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

Circular aperature

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

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

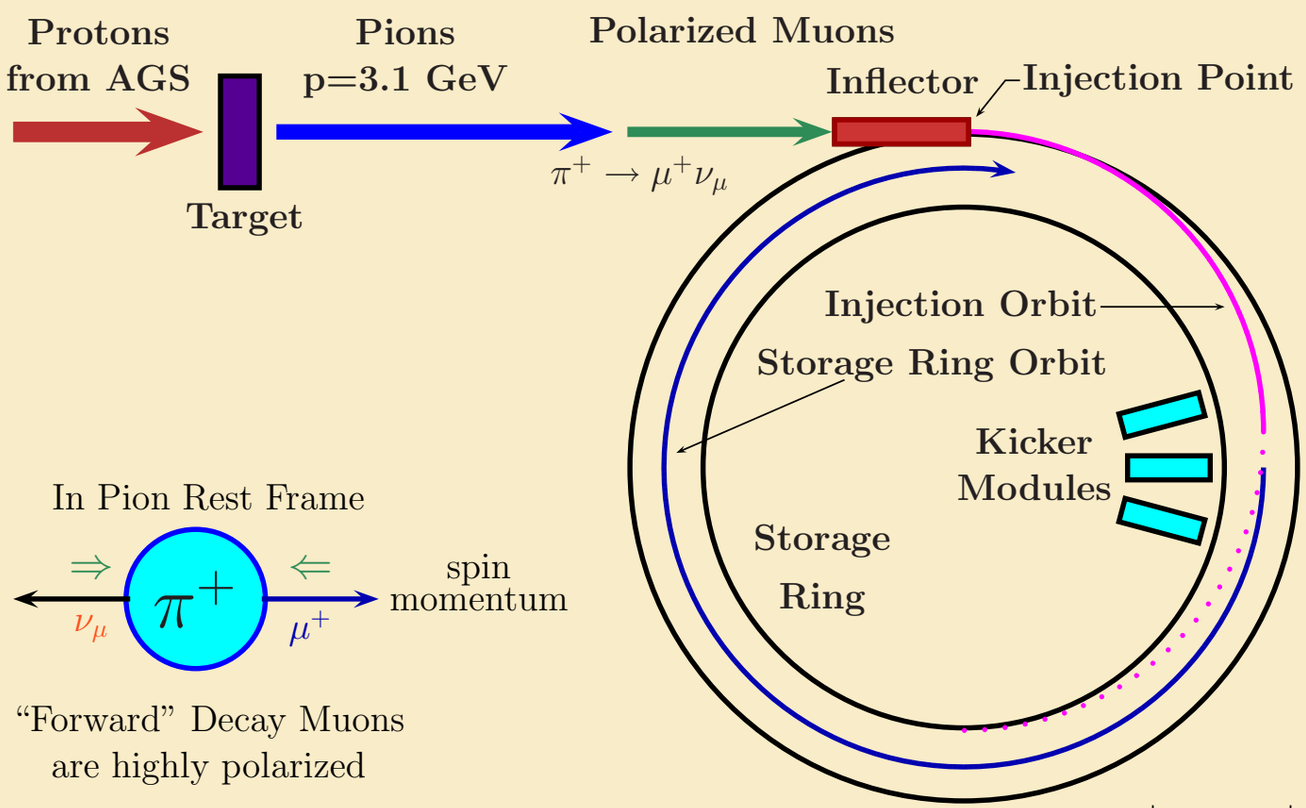
Get λ from friends

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

Determine systematics

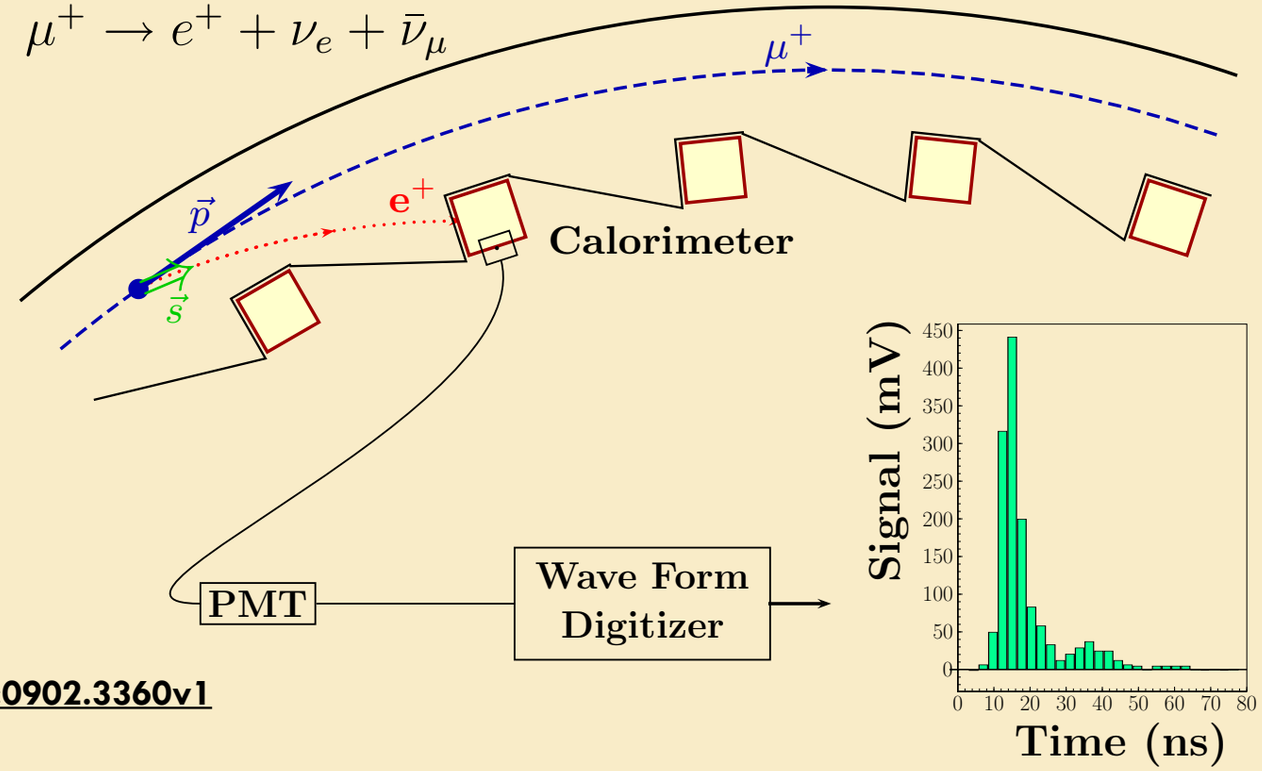
Think about the next experiment

Experiment in cartoons



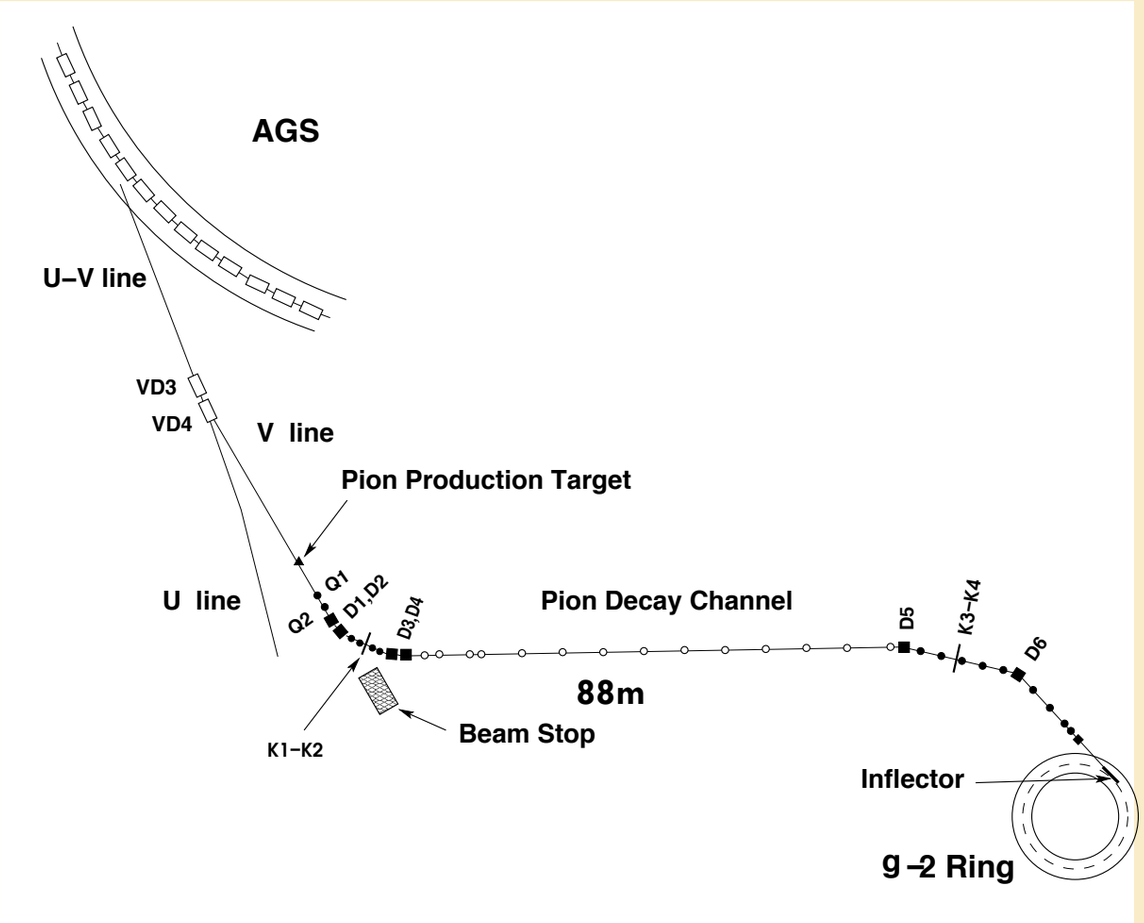
3 data runs (# e^+'s)
1999 (950M),
2000 (4000M),
2001 (3600M e^-)
8550M events total

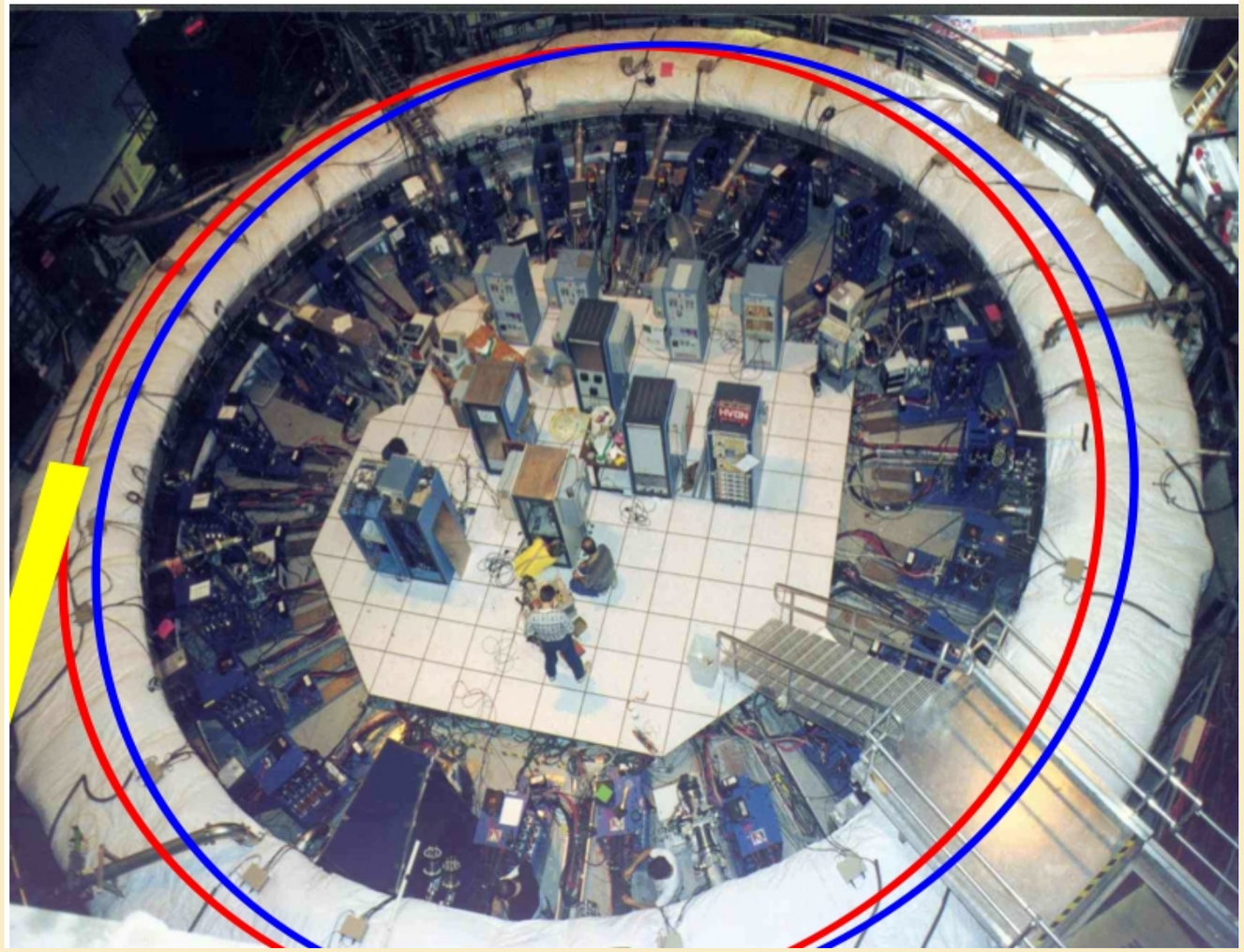
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

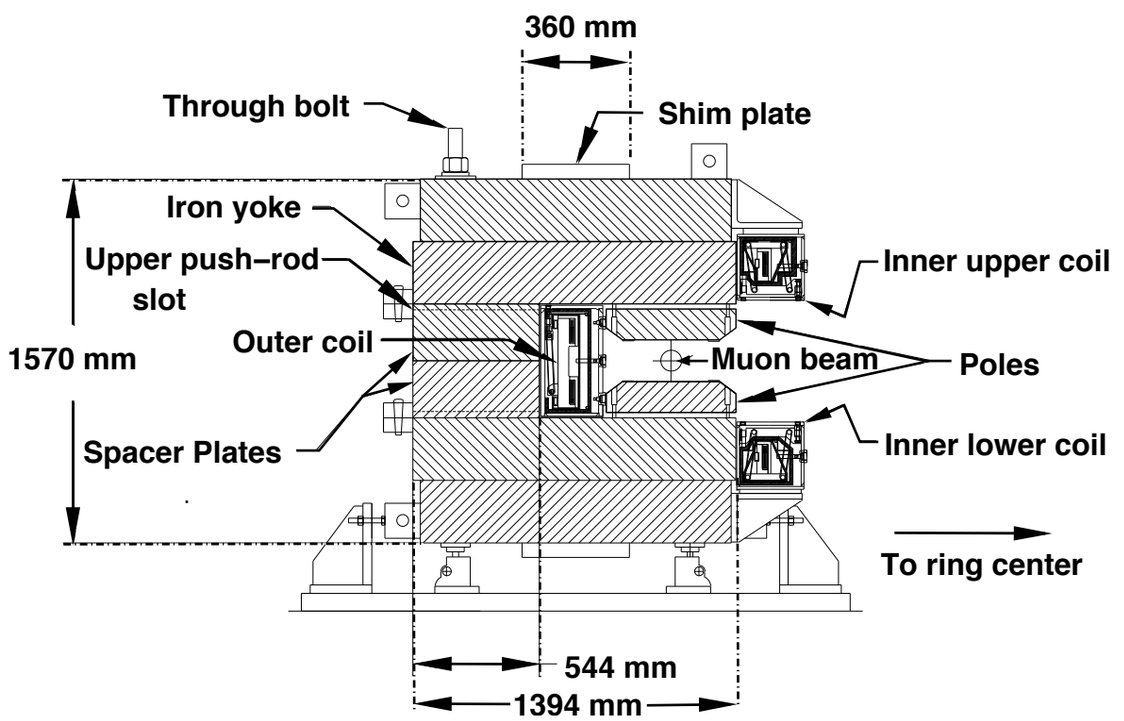


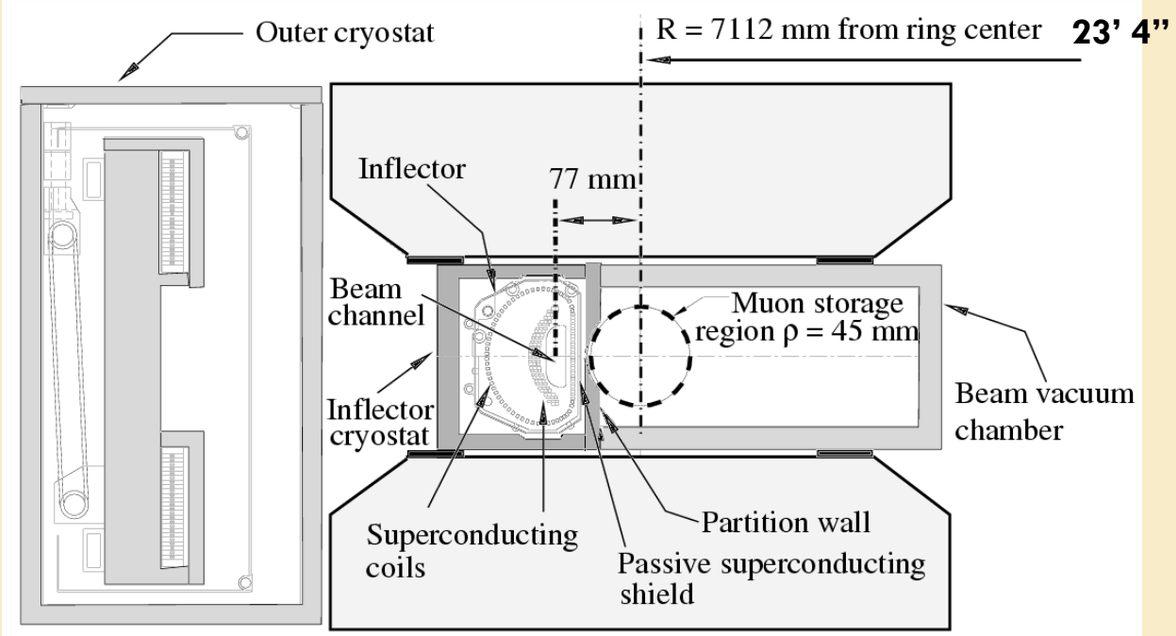
Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, arXiv:0902.3360v1

Injection into the storage ring

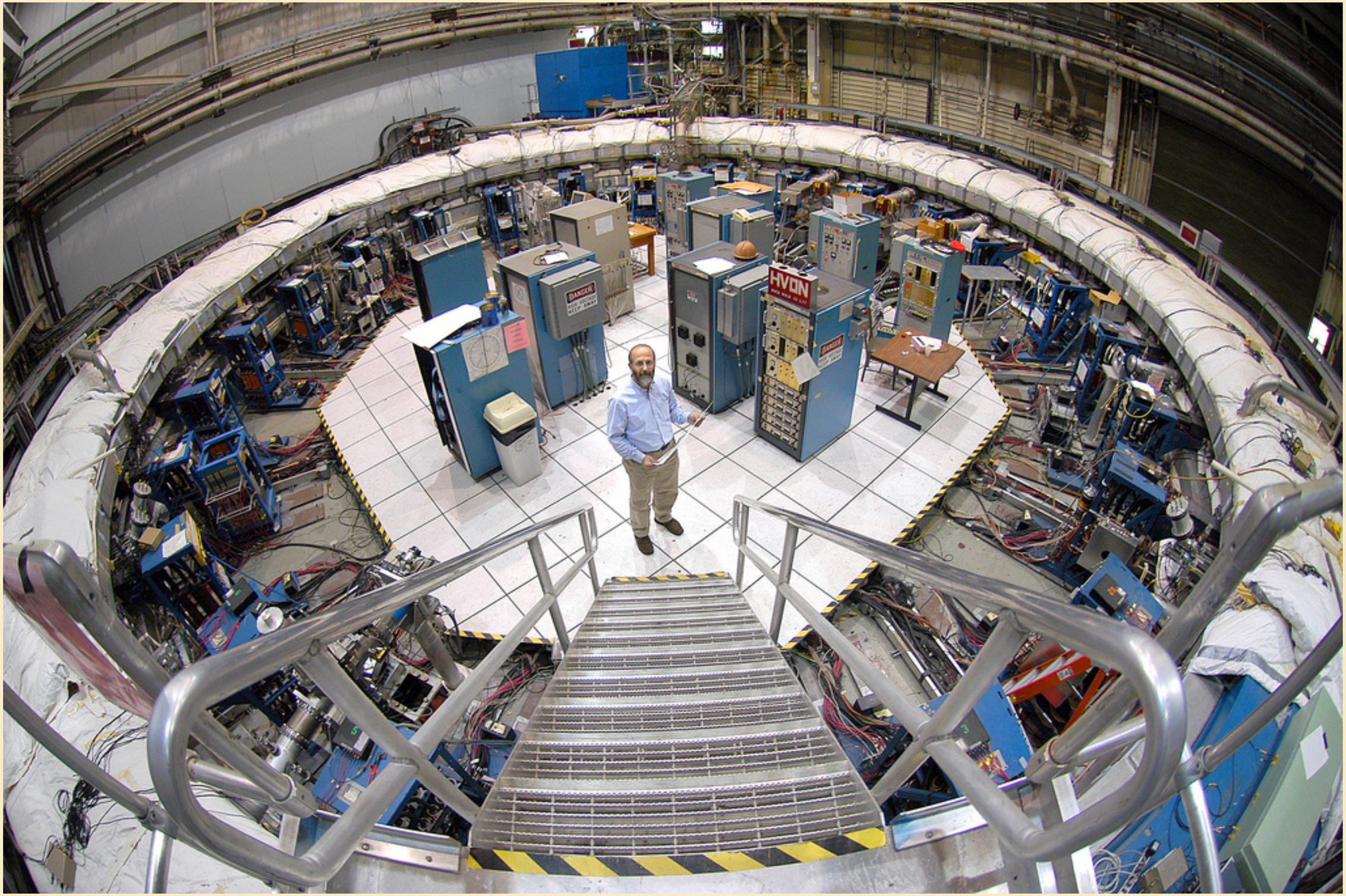






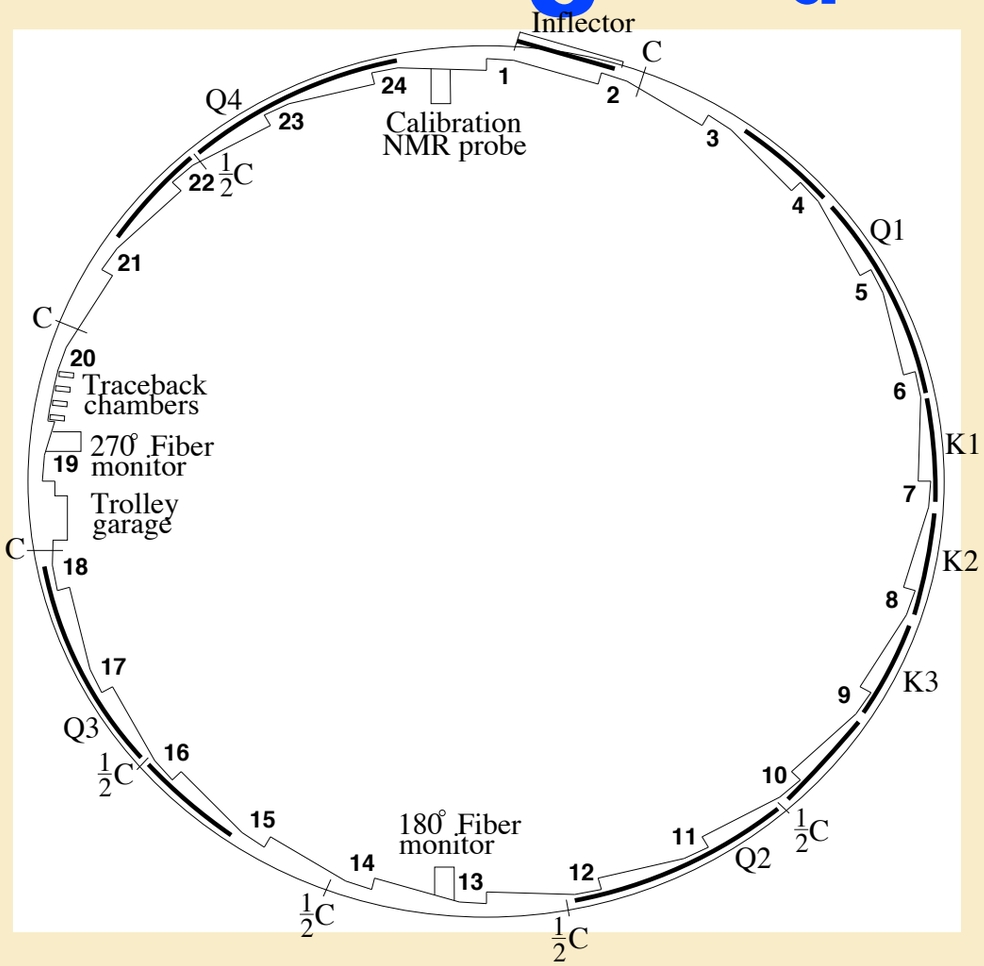


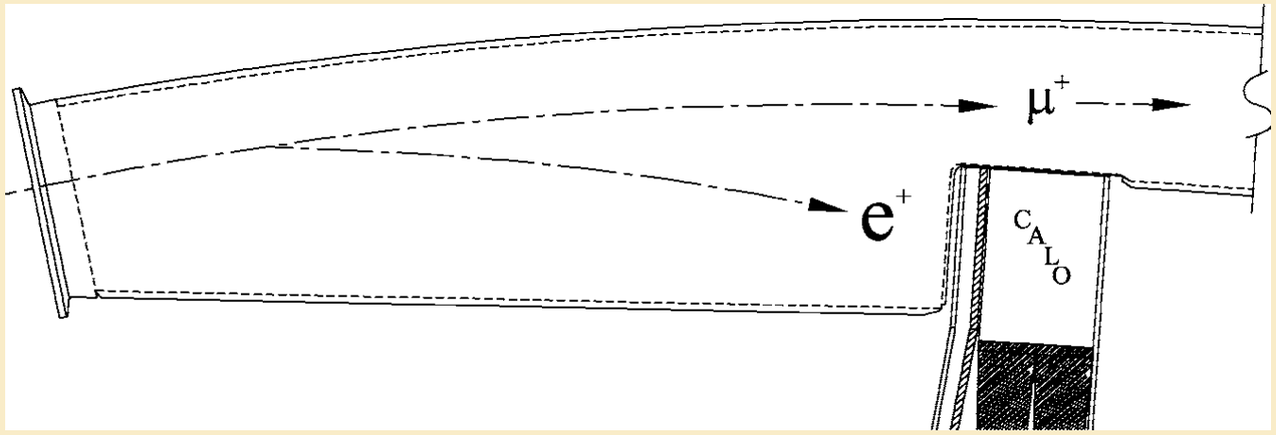
The storage ring

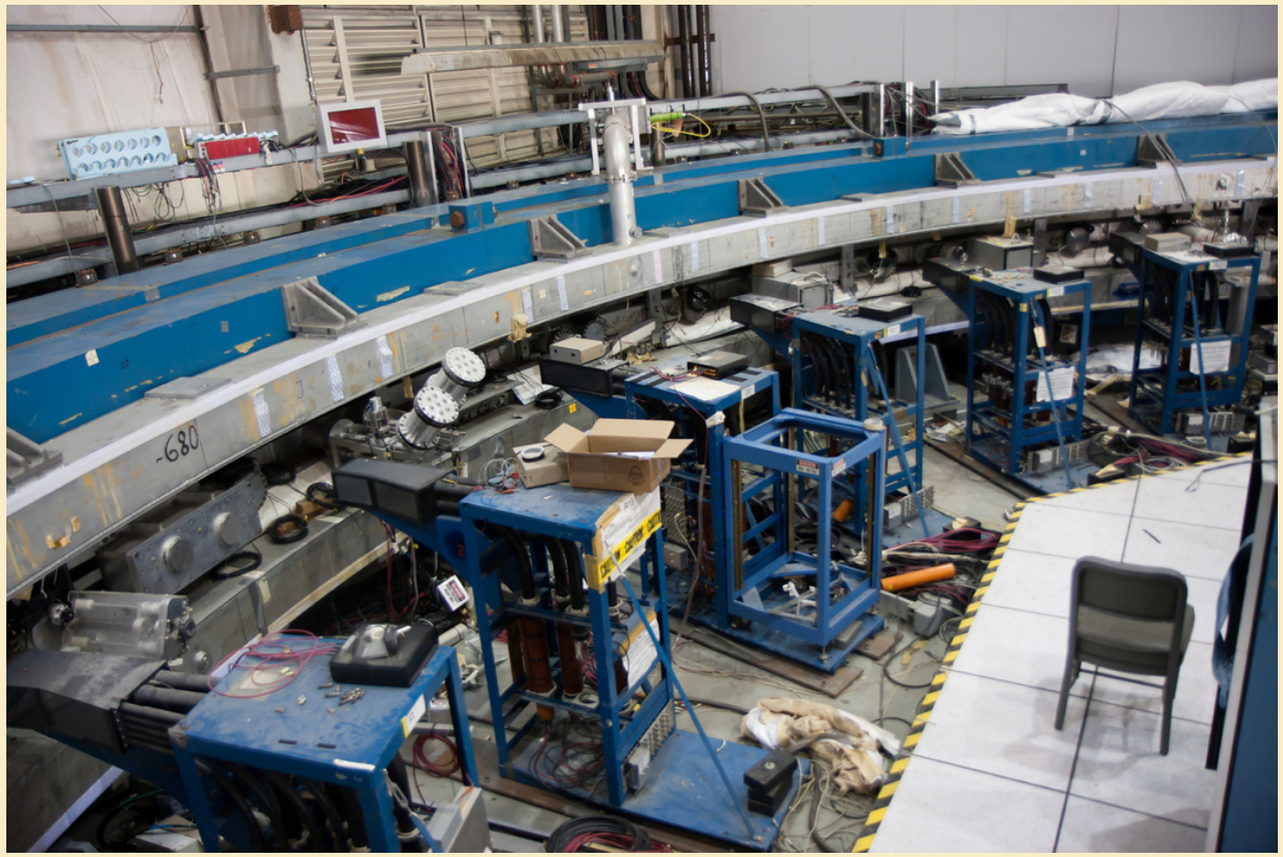


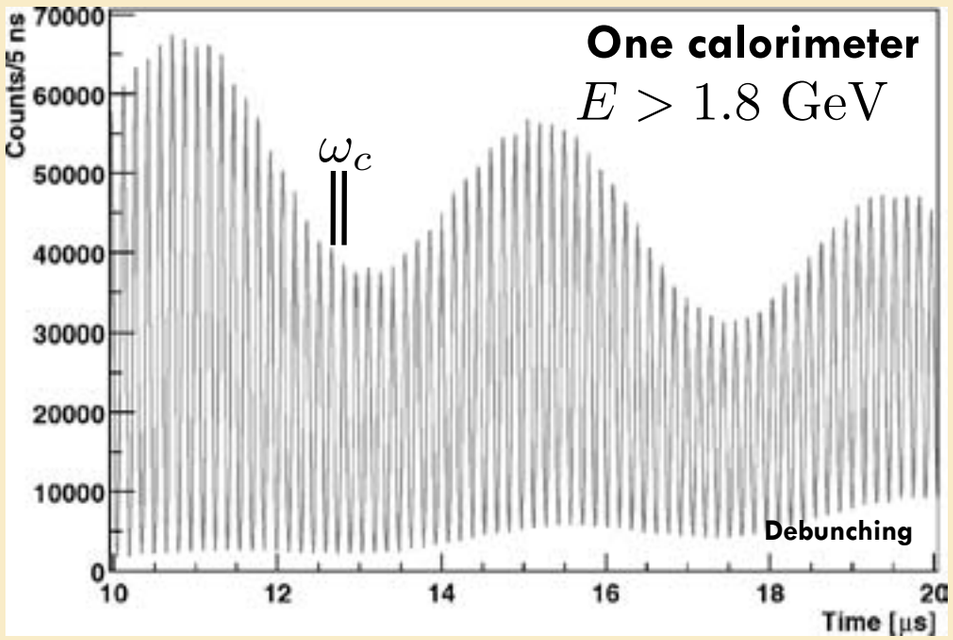
Fisheye lens

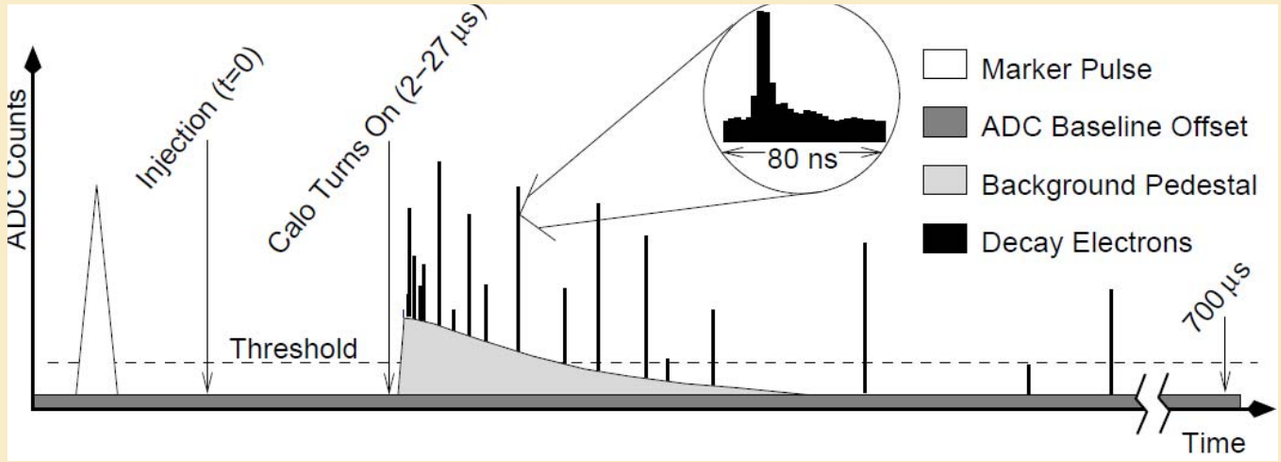
Measuring ω_a







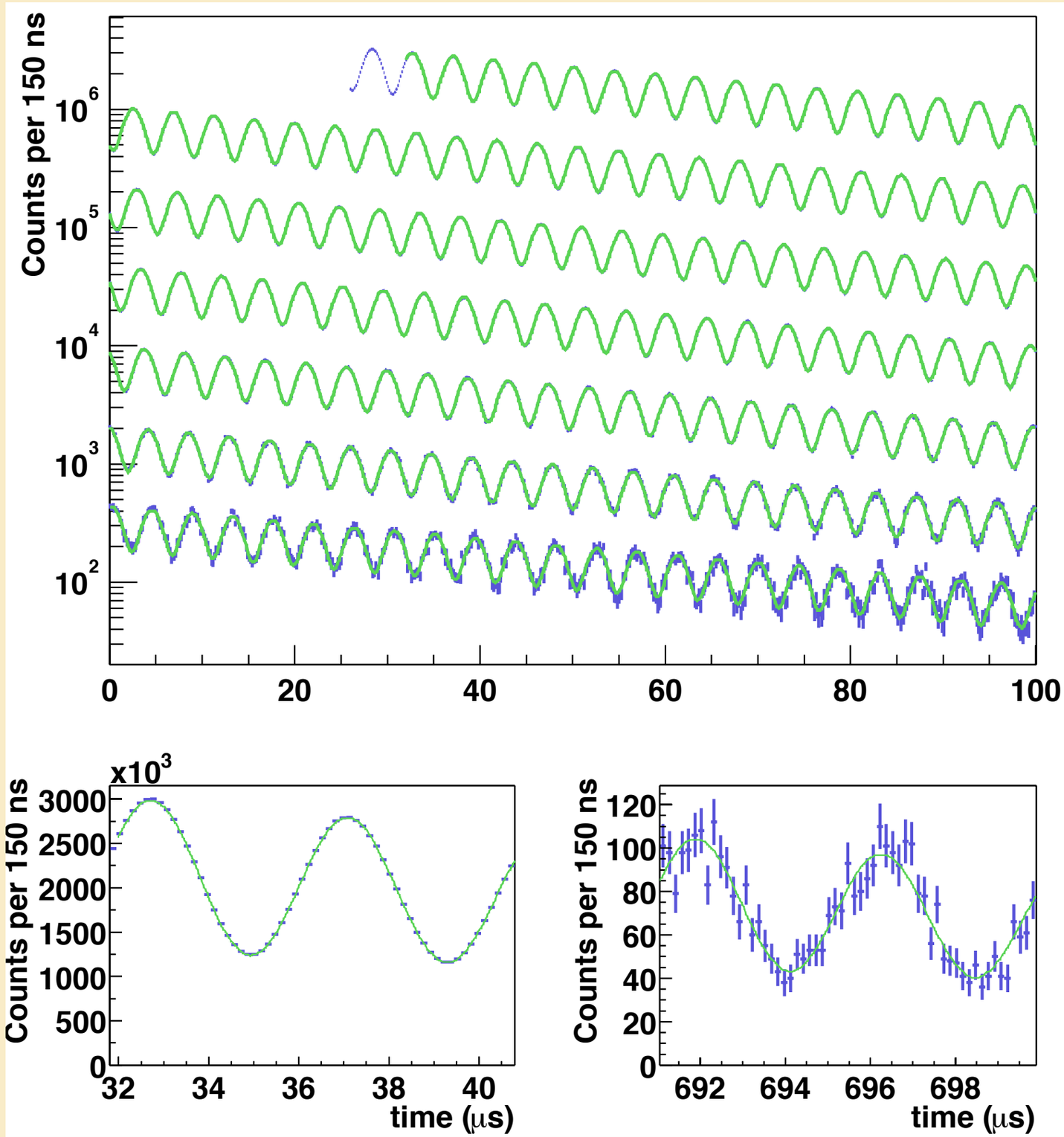




Measuring ω_a

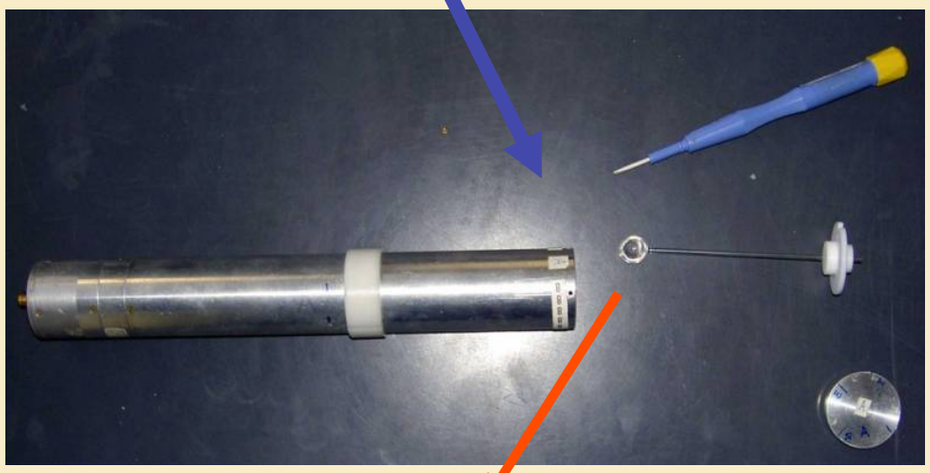
$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$

2000 data,
4 billion decays,
5 parameter fit

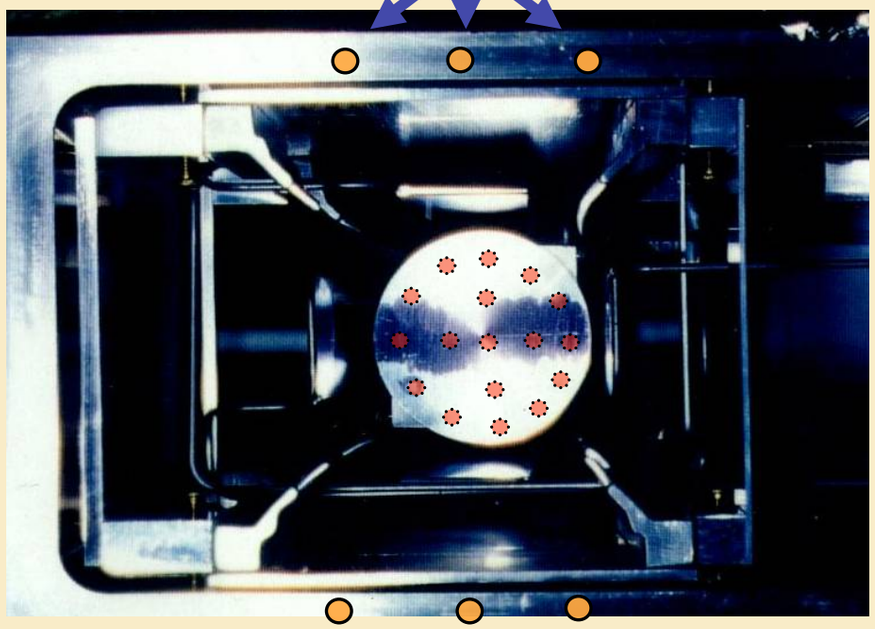


Measuring ω_p - Measuring the B field

Absolute Calibration Probe: a Spherical Water Sample



Fixed Probes in the walls of the vacuum tank



360 fixed probes, 150 most reliable

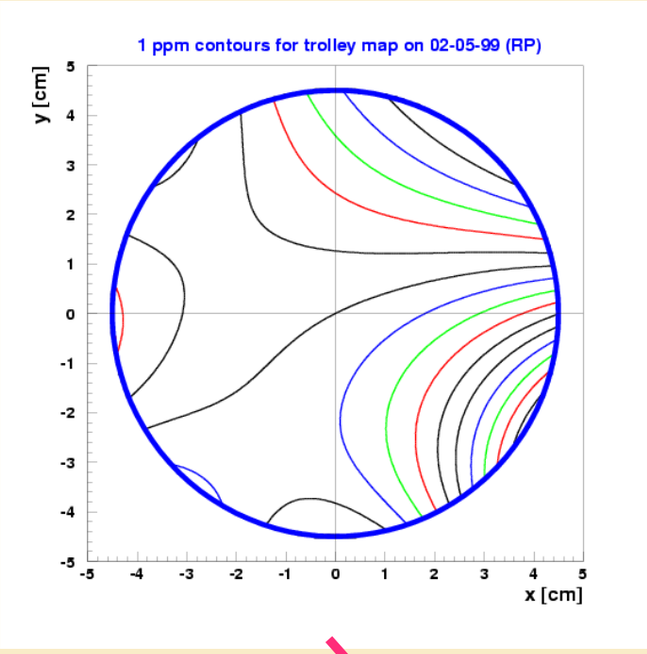
Trolley with matrix of 17 NMR Probes

Electronics, Computer & Communication

Position of NMR Probes

In vacuum, 6000 azimuthal measurements, Calibrated against plunging probe

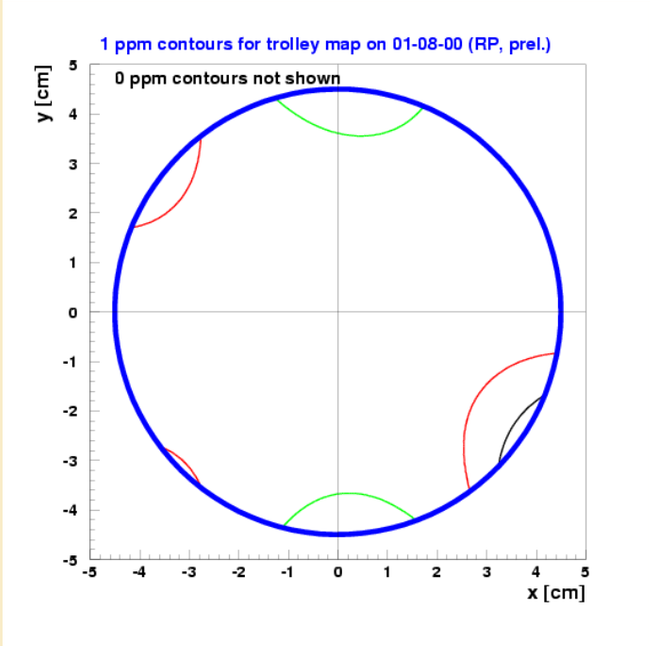
Measuring ω_p - Shimming the field



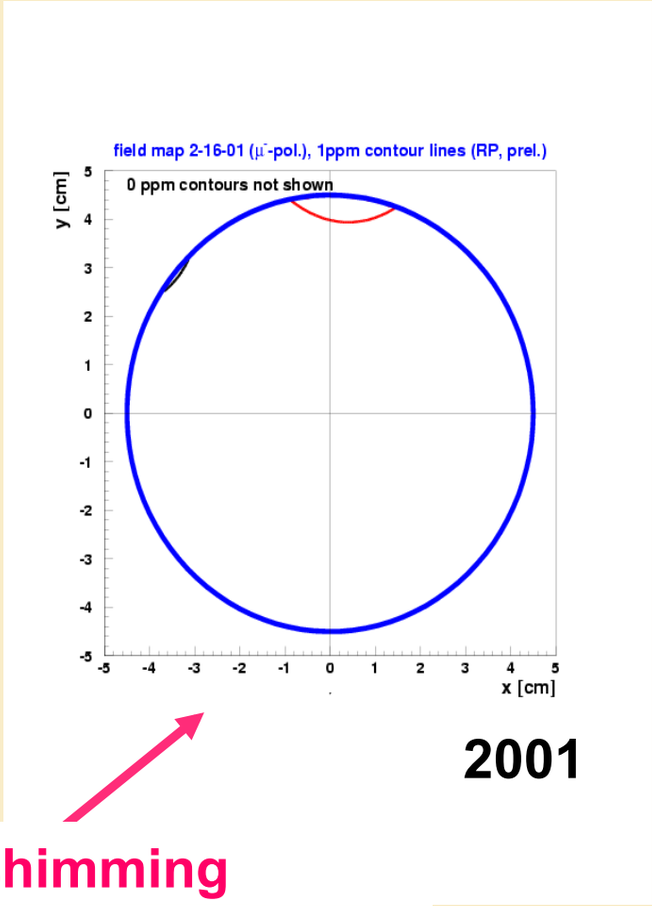
1999

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

2000



shimming



2001

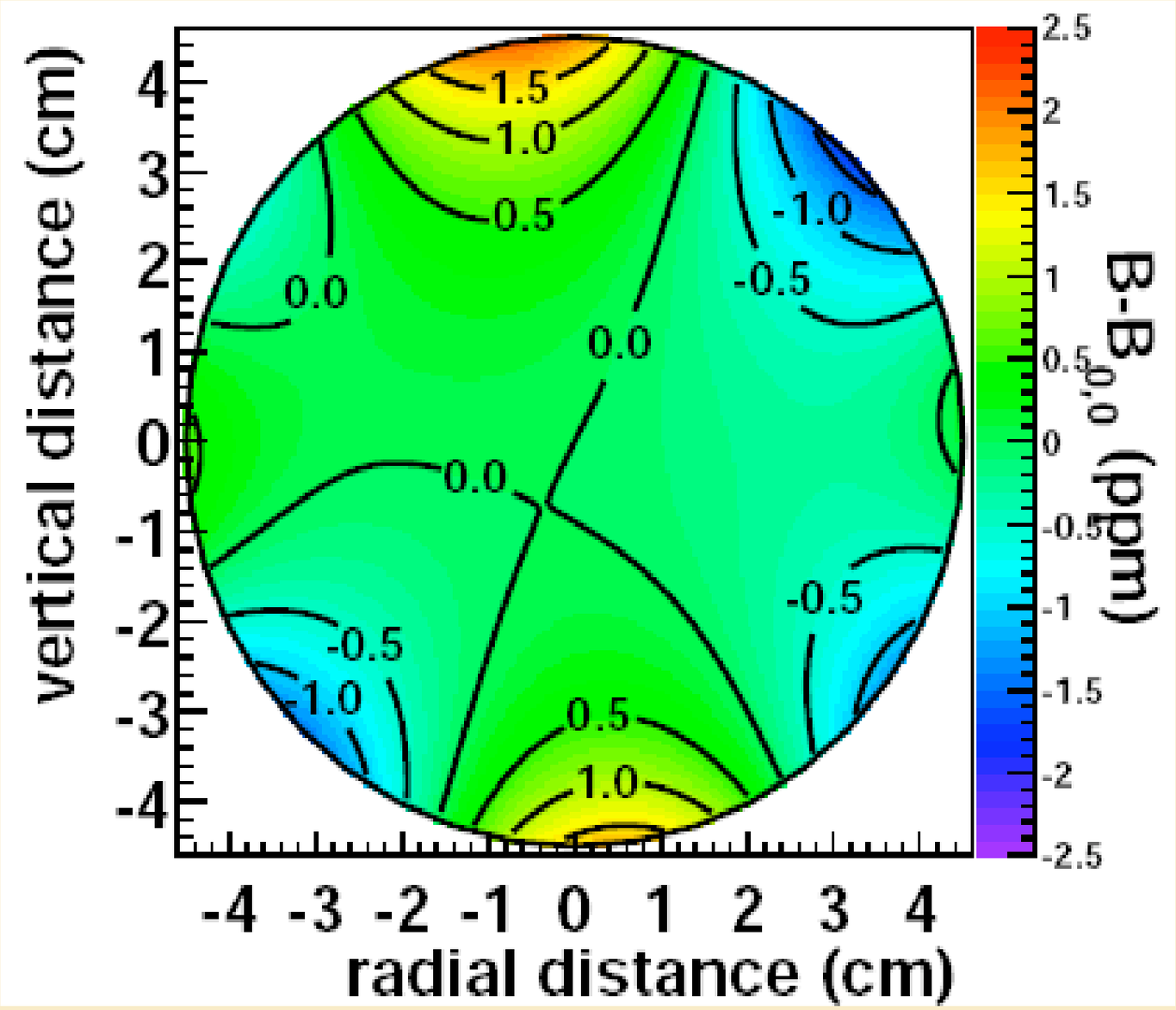
shimming

Measuring ω_p

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

$$\lambda = 3.18334539(10)$$

Led by Hughes at LAMPF



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

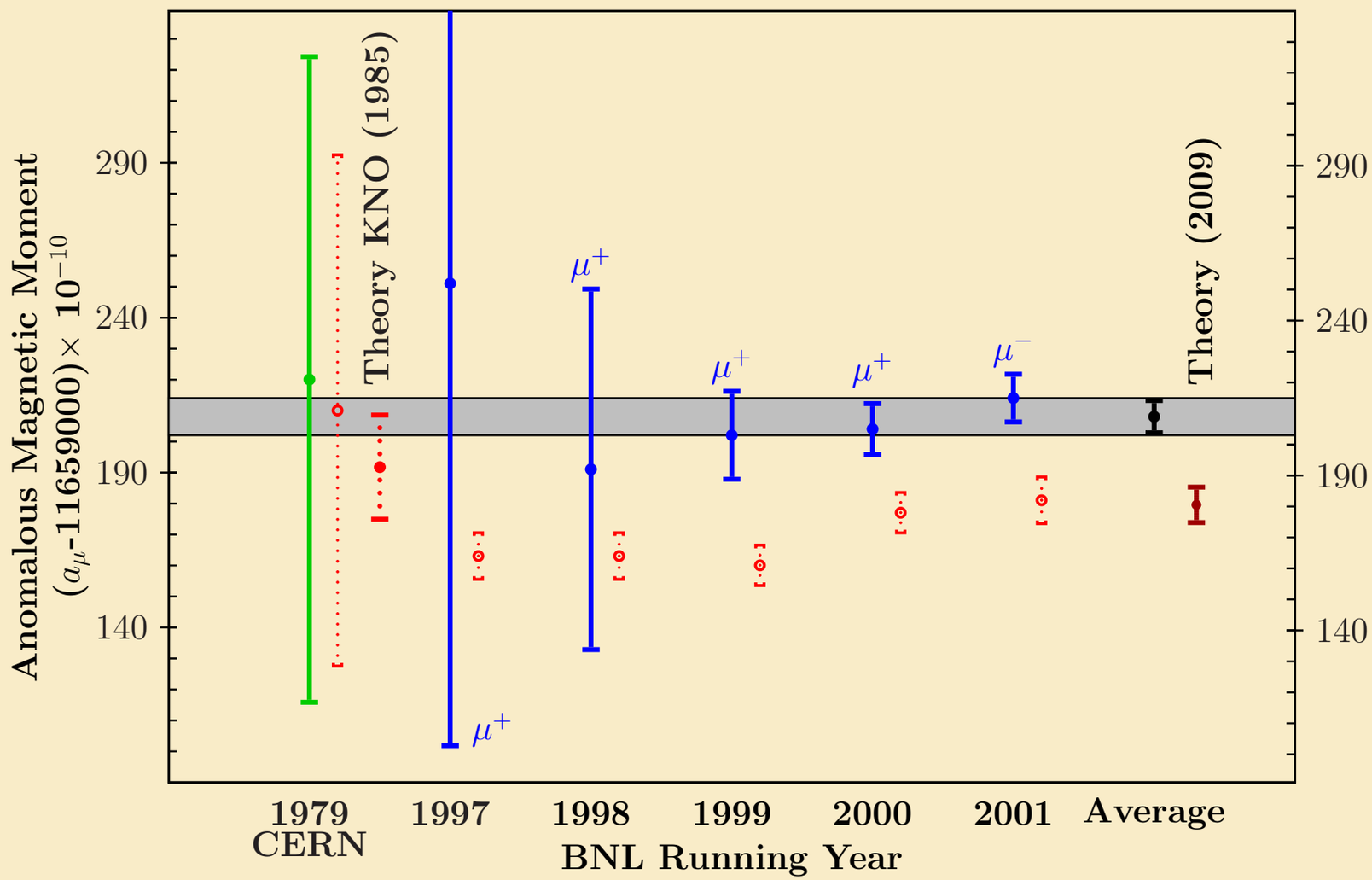
Total 0.28 ppm systematic

Brookhaven E821 Results

PRD 73, 072003 (2006)

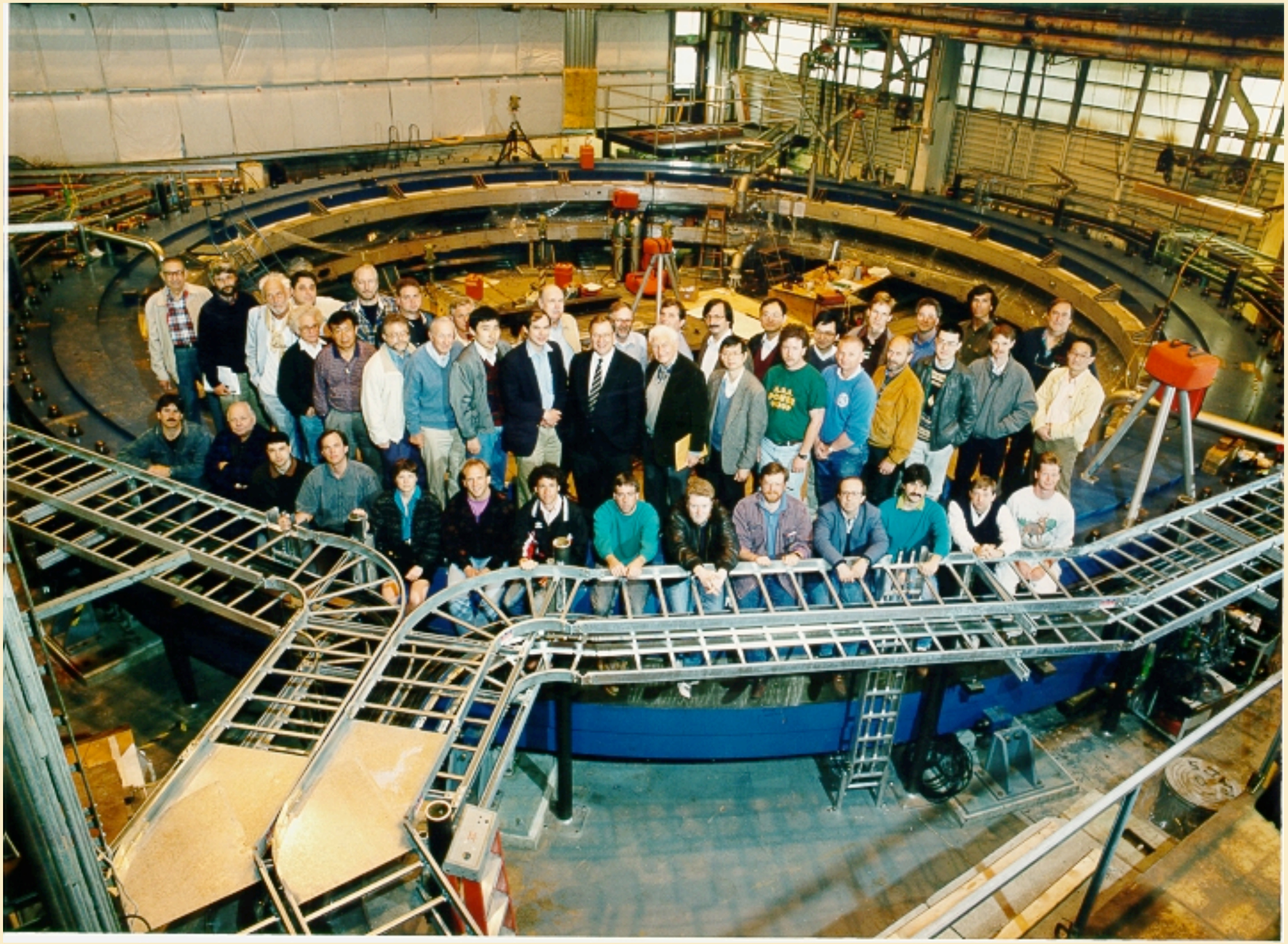
$$a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\ \text{ppm})$$

0.46 ppm statistics, 0.28 ppm systematic



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

A Job Well Done



Comparing to Theory

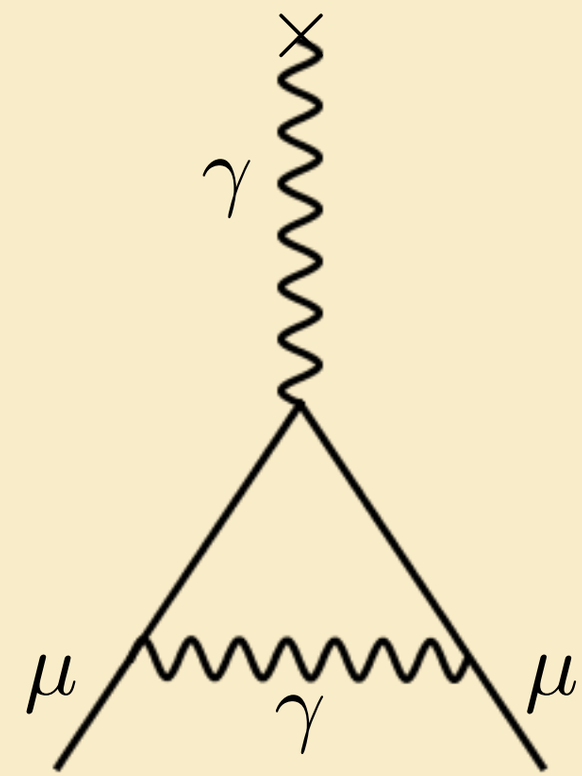
$$a_\mu^{\mathrm{th}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{had}} + a_\mu^{\mathrm{weak}} + a_\mu^{???}$$

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

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



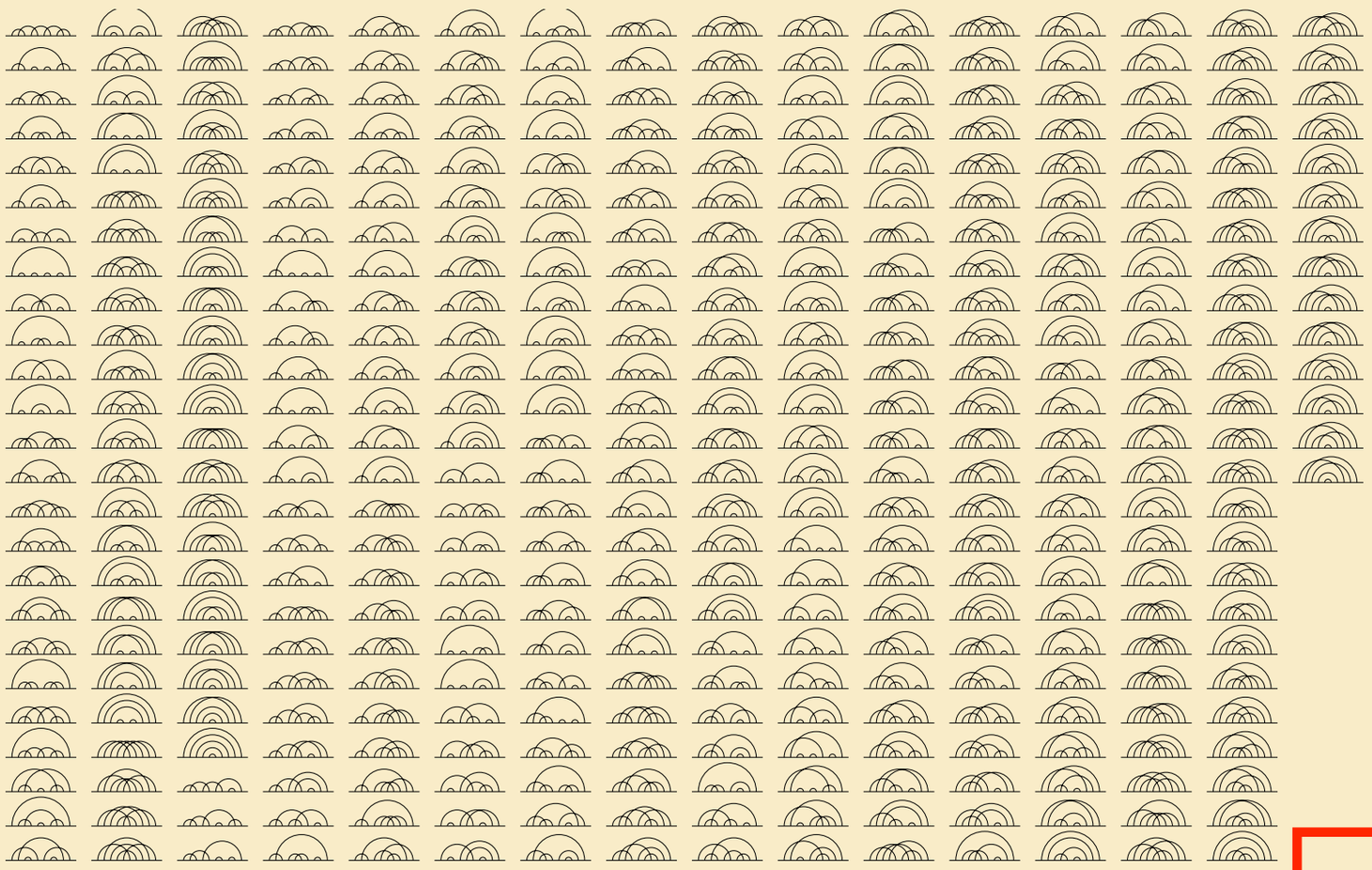
$$a_\mu^{\rm exp} = 0.00\,\boxed{116}\,592\,089(63)$$

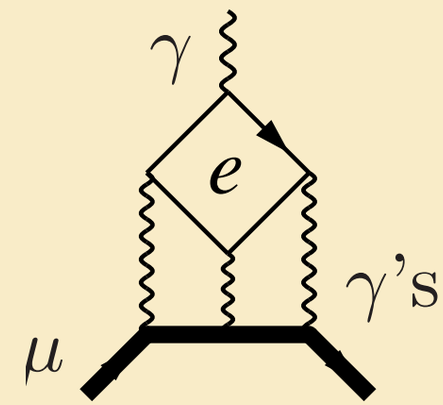
$$a_\mu^{\rm LO\ QED} = 0.00\,\boxed{118}$$

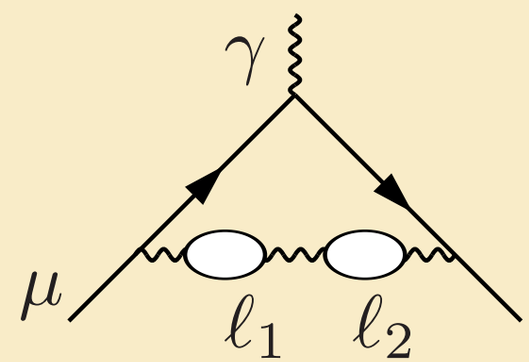
QED contributions

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

QED corrections computed to $O(\alpha^4)$ including 10th order term (12,672 diagrams contribute)







T. Kinoshita

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

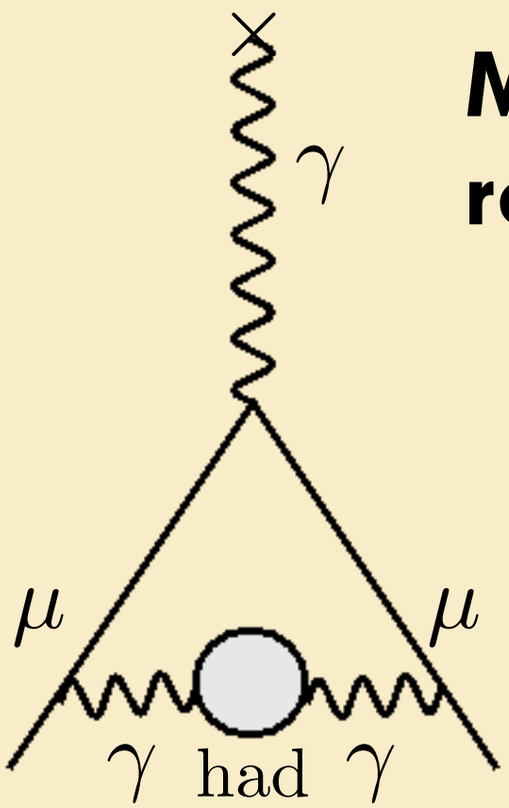
$$a_\mu^{\rm QED} = 0.00\,116\,584\,718\,09(15)$$

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

Three parts: 1st & 2nd = HVP(LO) & HVP(NLO)



Most from low energy nonperturbative QCD regime (needs experimental inputs)

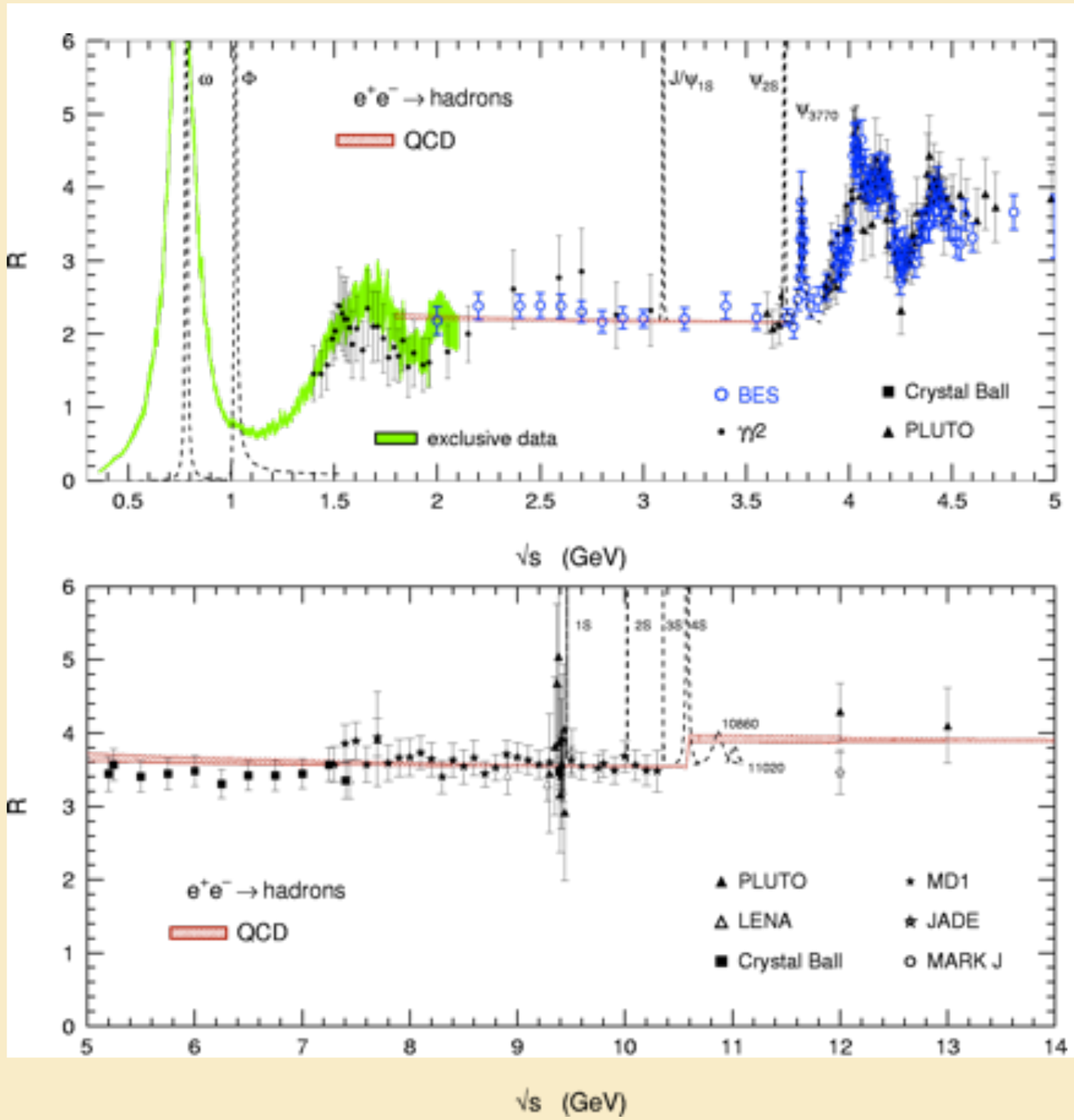
$$a_\mu^{\rm had,LO} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}R(s),$$

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

R(s) input to HVP(LO)

Requires precision $e^+e^- \to \text{hadrons}$

A whole industry built to measure *R*



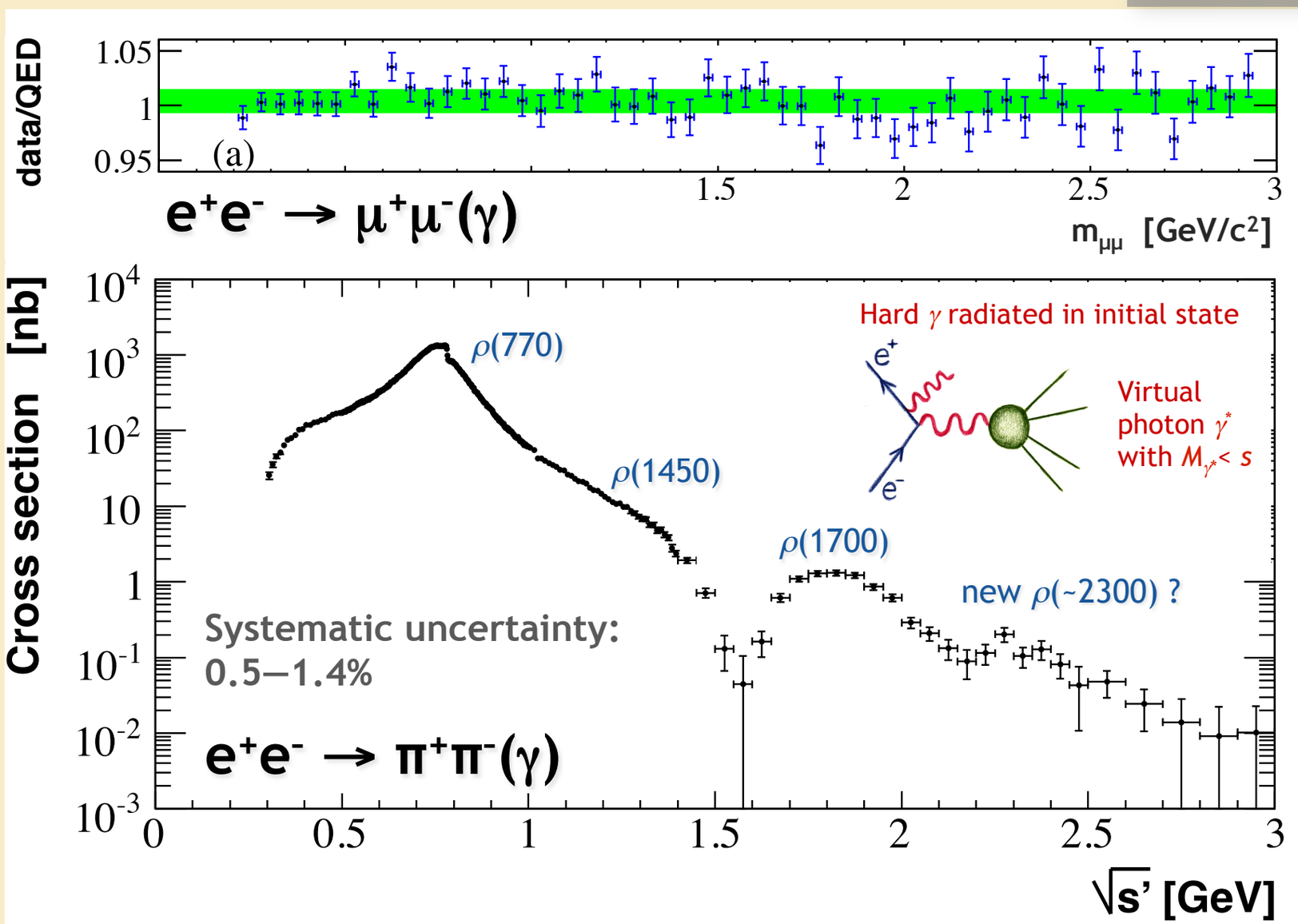
M. Davier ICFA 2011

R(s) input to HVP(LO)

Requires precision $e^+e^- \to \text{hadrons}$

***BABAR*:**

BABAR, PRL 103, 231801 (2009)

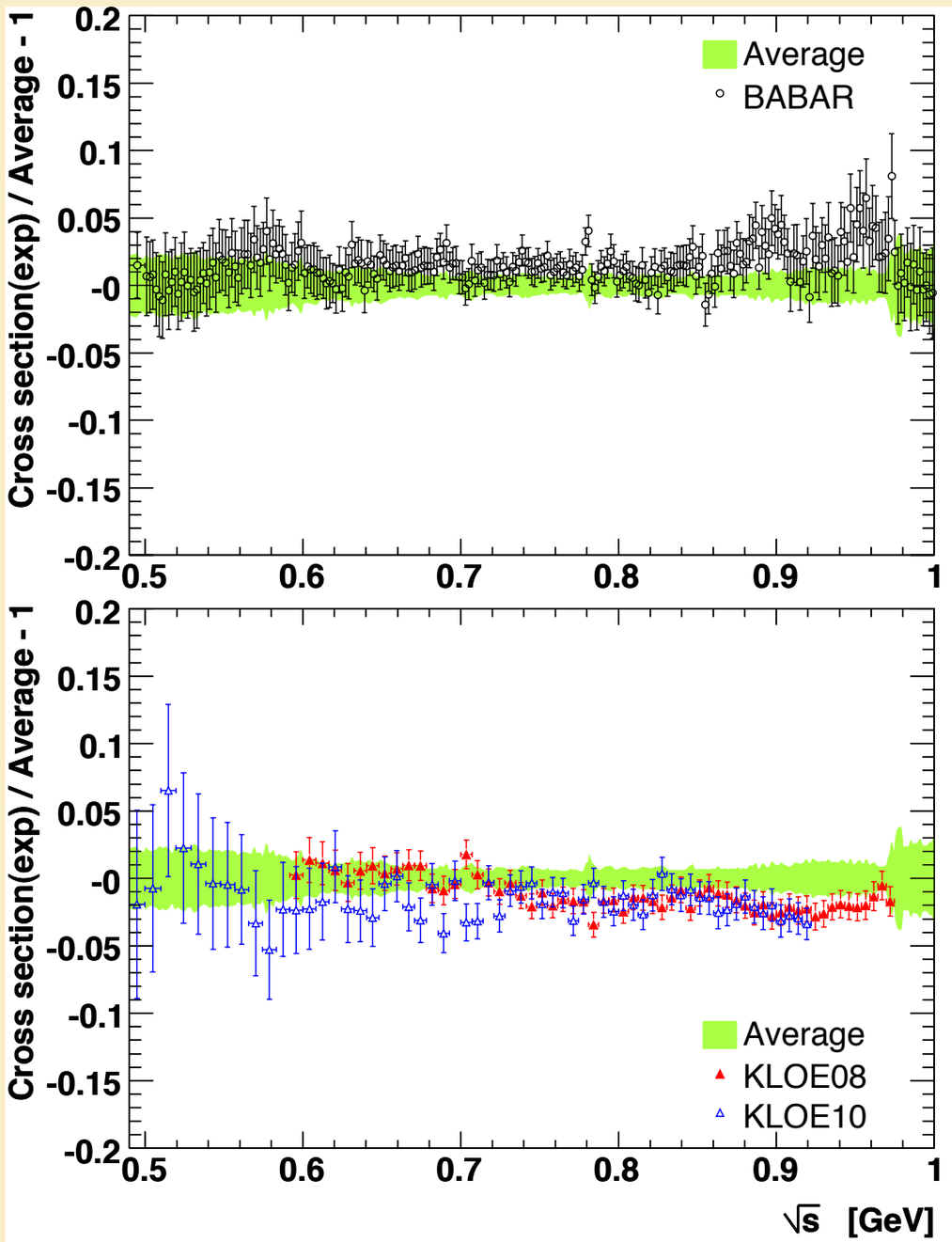


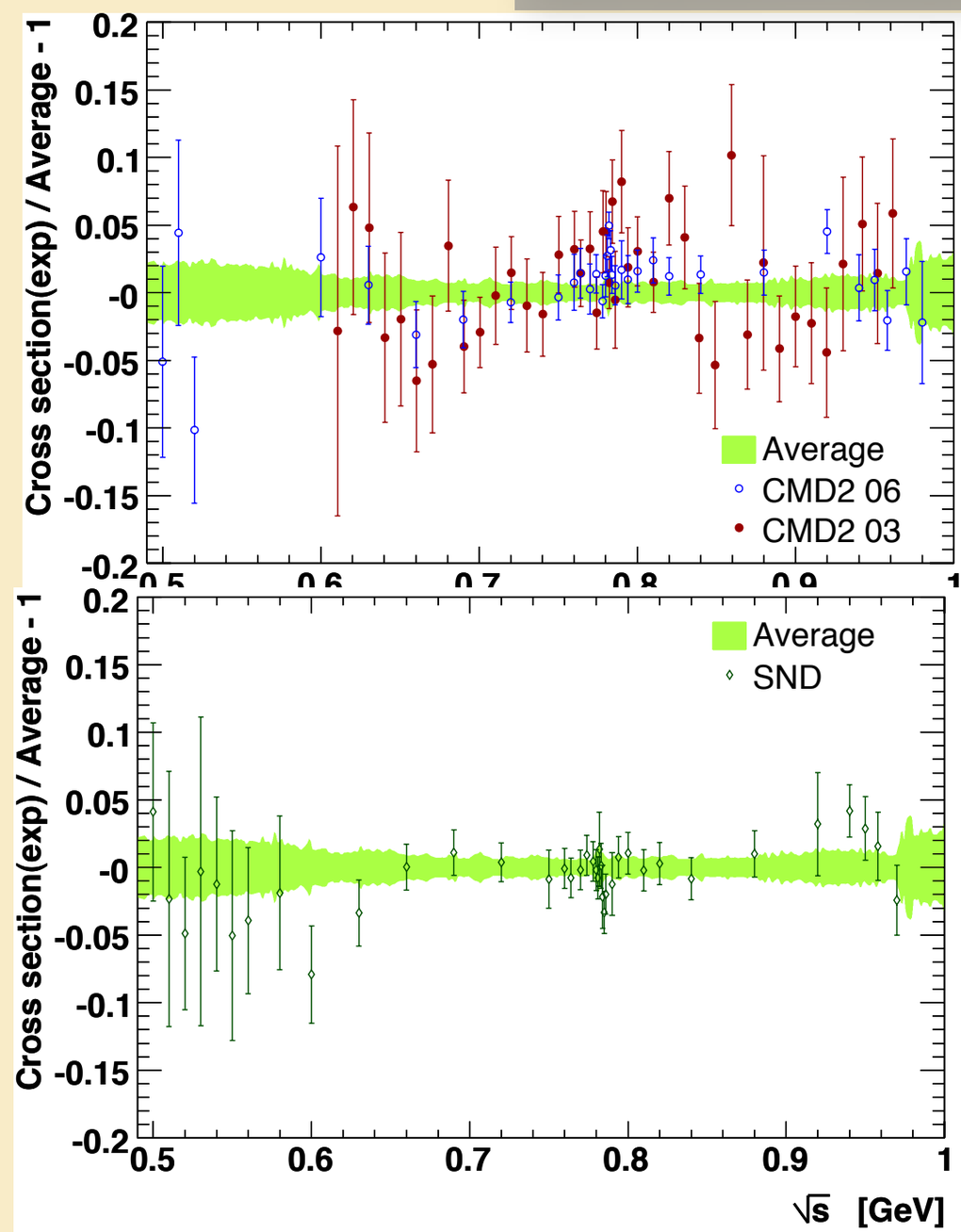
M. Davier ICFA 2011

R(s) input to HVP(LO)

Requires precision $e^+e^- \to \text{hadrons}$

Davier *et al.*, EPJ C 71, 1515 (2011)





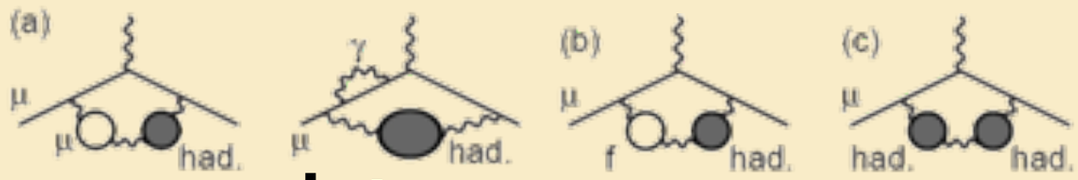
HVP(LO & NLO)

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 even more improvements are good

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



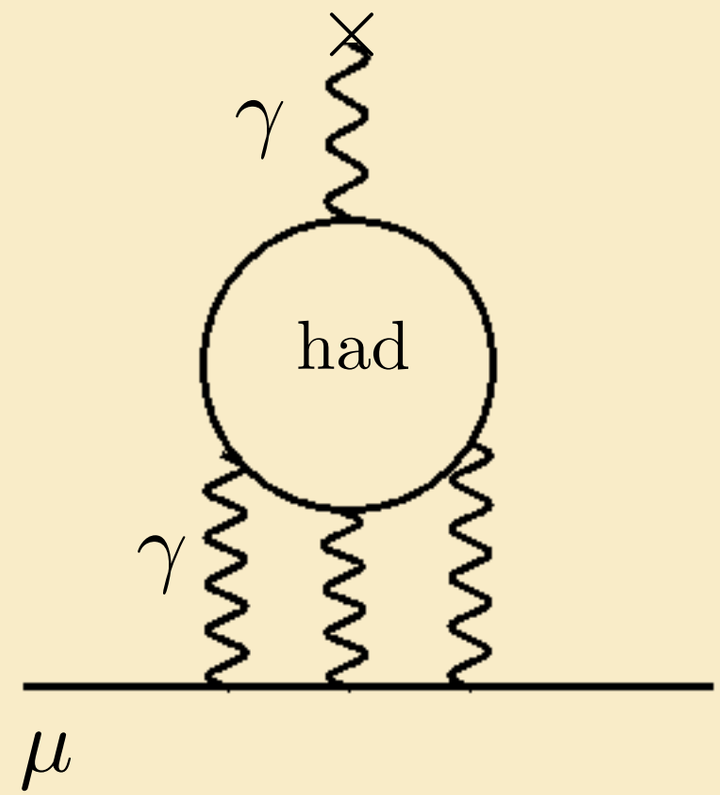
HVP(NLO) is similar and uses much of the same data

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

M. Davier, Hagiwara

Hadronic light-by-light

Model dependent calculations
Now an industry!



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

Lattice QCD calculations are under study

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

Prades, deRafael, Vainshtein (and others)

INT Workshop on The Hadronic Light-by-Light Contribution to the Muon Anomaly, Feb 2011, UWash

Date	Speaker	Powerpoint or .pdf	Podcast
February 28, 2011	D. Hertzog	"Welcome and Introductory Remarks"	No Podcast Available
February 28, 2011	L. Roberts	"Goals and Perspectives on the New g-2 Experiment"	No Podcast Available
February 28, 2011	H. Bijnens	"Hadronic Light-by-Light: Extended Nambu-Jona-Lasinio and Chiral Quark Models"	No Podcast Available
February 28, 2011	A. Nyffeler	"Hadronic light-by-light scattering in the muon g-2: Chiral approach and resonance dominance"	No Podcast Available
February 28, 2011	A. Vainshtein	"Comments on Recent Developments in Theory of Hadronic Light-by-Light"	No Podcast Available
March 1, 2011	O. Catà	"Holographic QCD and HLBL"	No Podcast Available
March 1, 2011	D.K. Hong	"Holographic Models of QCD and Muon $g; -2$ "	No Podcast Available
March 1, 2011	M. Ramsey-Musolf	"Hadronic LBL: Insights from χ Symmetry"	No Podcast Available
March 1, 2011	R. Williams	"HLbL from a Dyson-Schwinger Approach"	No Podcast Available
March 1, 2011	T. Blum	"Hadronic light-by-light contribution to the muon g-2 from lattice QCD+QED"	No Podcast Available
March 1, 2011	S. Hashimoto	"$\pi^0 \to \gamma^* \gamma^*$"	No Podcast Available
March 1, 2011	K. Jansen	"Hadronic Vacuum Polarization Contribution to g-2 from the Lattice"	No Podcast Available
March 1, 2011	A. Kronfeld	"The Exascale Era and What to Expect in 2016+"	No Podcast Available
March 2, 2011	F. Jegerlehner	"What can data provide for HLbL?"	No Podcast Available
March 2, 2011	D. Moricciani	"KLOE small angle tagger"	No Podcast Available
March 2, 2011	A. Denig	"Meson Transition Form Factors at BaBar"	No Podcast Available
March 2, 2011	H. Czyz	"EKHARA: a Monte Carlo tool for γ^*–γ^* physics"	No Podcast Available
March 3, 2011	F. Jegerlehner	"Does ρ–γ mixing solve the e^+e^- vs τ spectral function puzzle?"	No Podcast Available
March 3, 2011	K. Melnikov	"Green's functions and form factors"	No Podcast Available
March 3, 2011	W. Marciano	"Muon g-2 Comments"	No Podcast Available
March 3, 2011	E. de Rafael	"Models Discussion"	No Podcast Available
March 4, 2011	L. Roberts	"White Paper Organization"	No Podcast Available

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

Hadronic contributions

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

$$a_\mu^{\rm HVPLO} = (692.3 \pm 4.2) \times 10^{-10}$$
$$a_\mu^{\rm HVPNLO} = (-9.8 \pm 0.1) \times 10^{-10}$$
$$a_\mu^{\rm HLBL} = (10.5 \pm 2.6) \times 10^{-10}$$

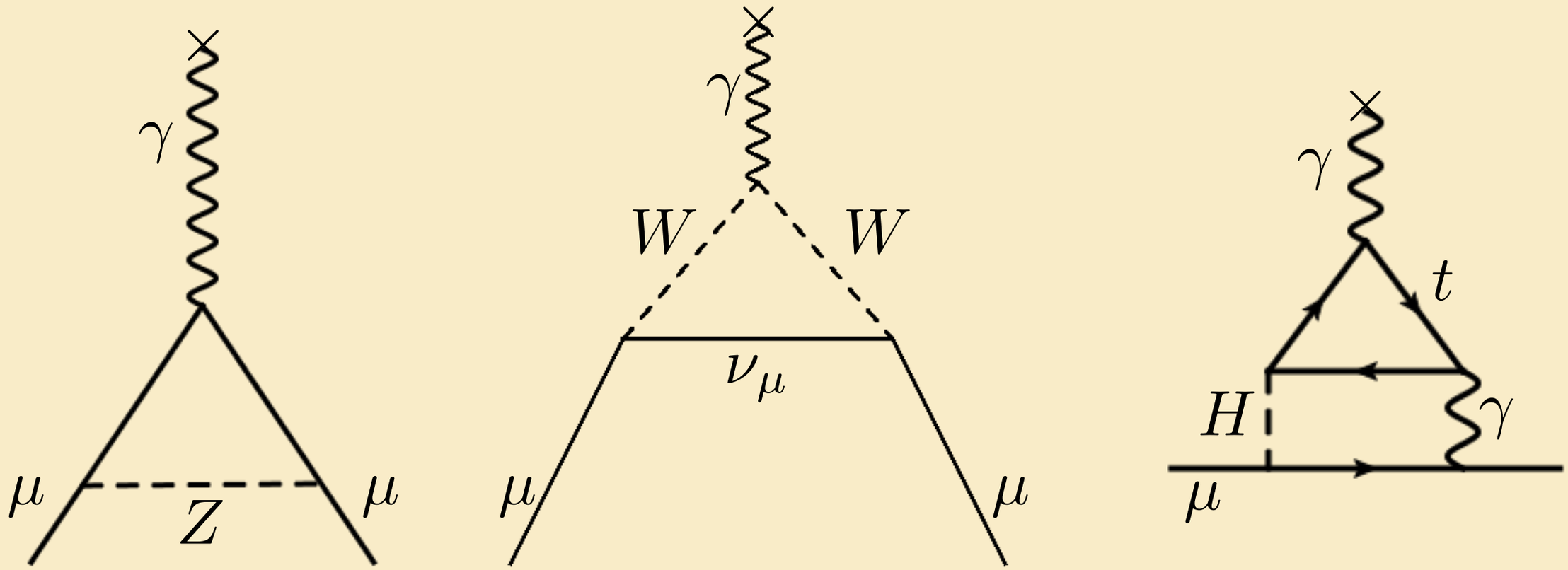
$$a_\mu^{\rm had} = (693.0 \pm 4.9) \times 10^{-10}$$

$$a_\mu^{\rm exp} = 0.00\,116\,592\,089(63)$$
$$a_\mu^{\rm had} = 0.00\,000\,006\,930(49)$$

Electroweak contributions

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

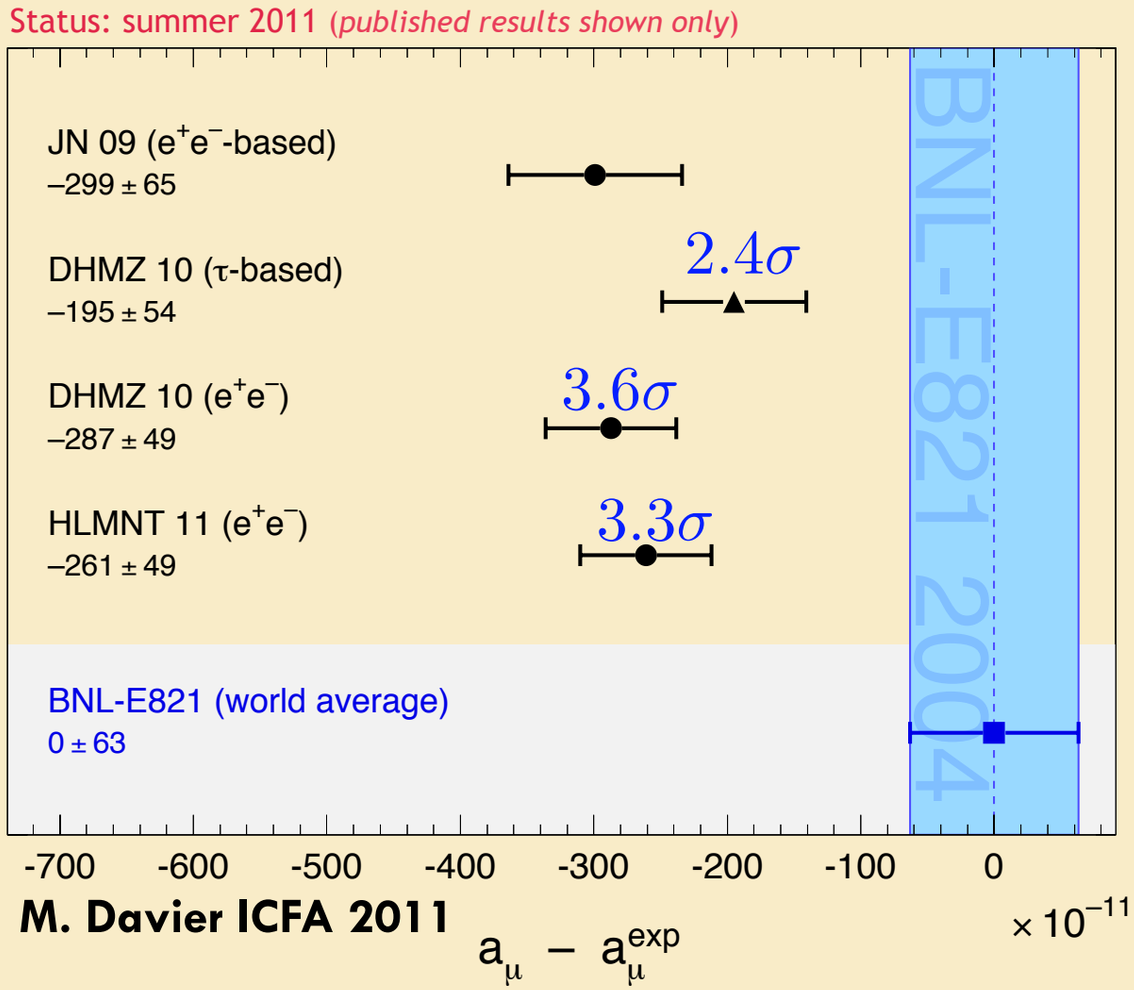
Unambiguously calculable - BNL experiment sensitive



$$a_\mu^{\rm exp} = 0.00\,116\,592\,0\boxed{89}(63)$$

$$a_\mu^{\rm EW} = 0.00\,000\,000\,1\boxed{54}(2)$$

Standard Model Prediction



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

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

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

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

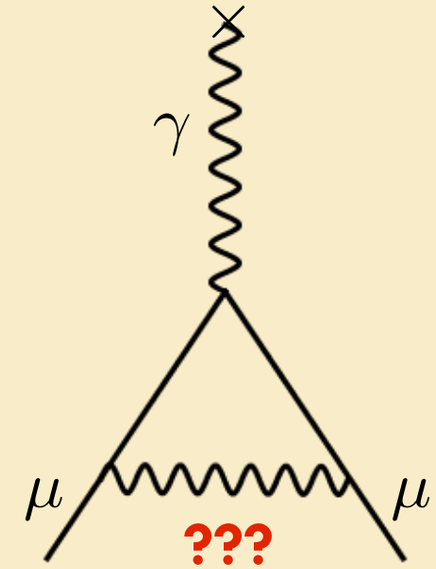
$$a_\mu^{\mathrm{exp}} = 0.00\,116\,592\,089(63)$$

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

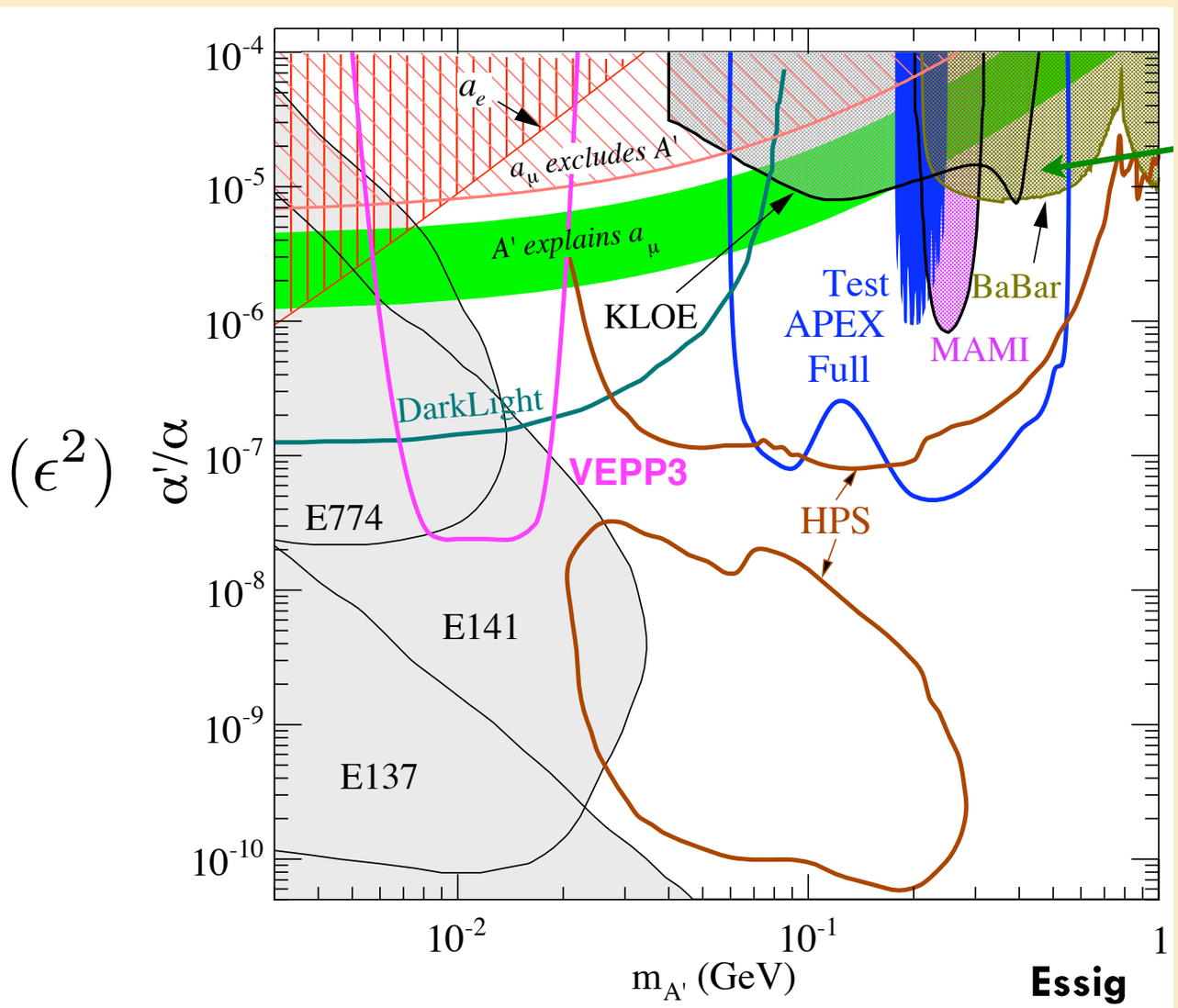
$$> \mathbf{3}\sigma$$

New Physics?

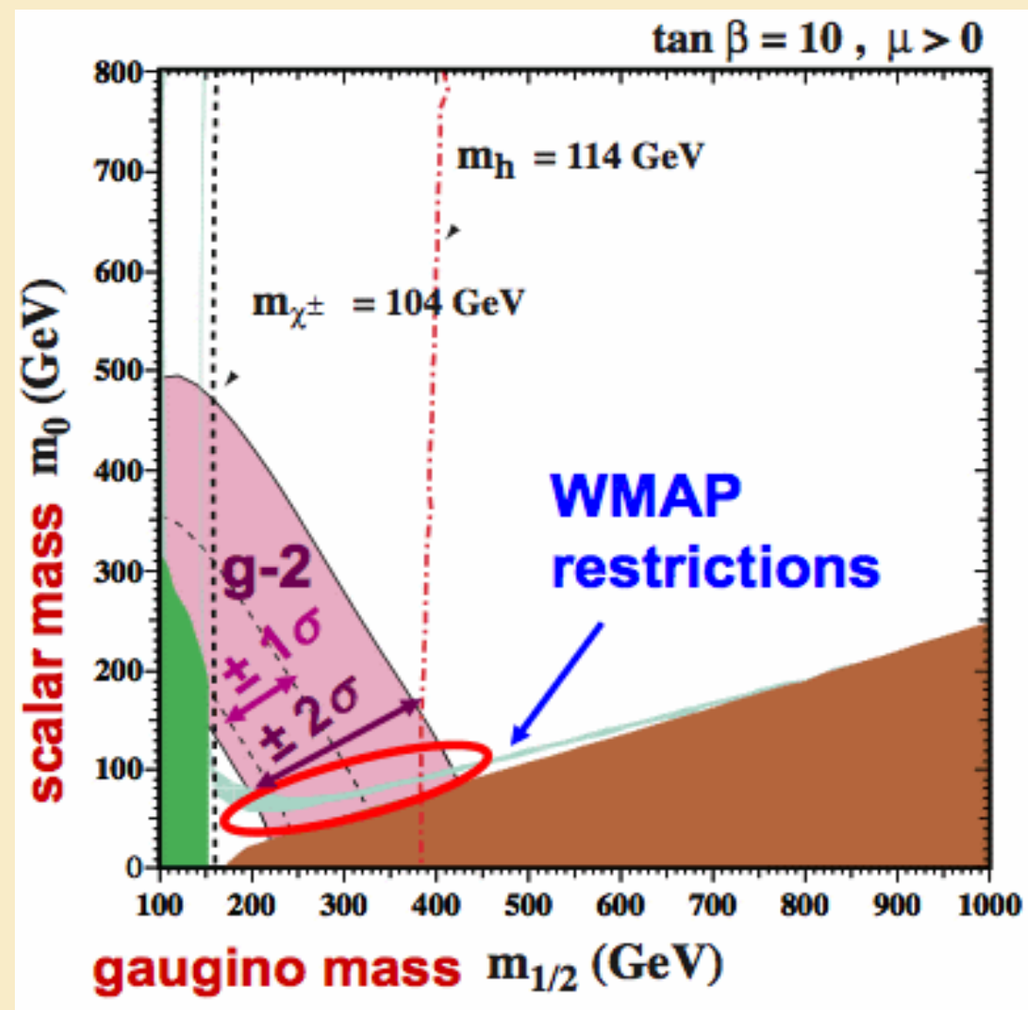
$$a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm had} + a_\mu^{\rm weak} + \boxed{a_\mu^{???}}$$



Dark Photons?



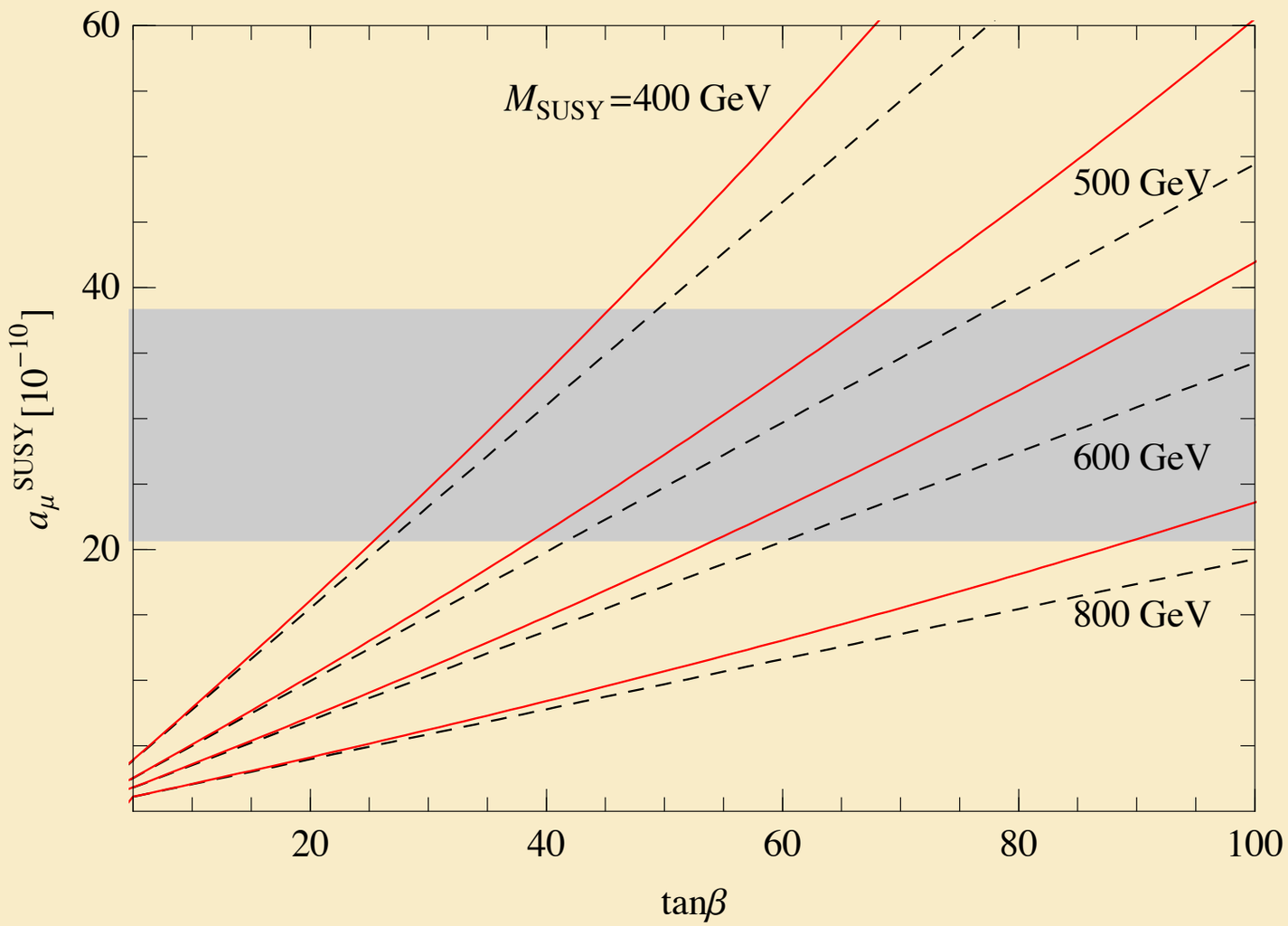
SUSY?



SUSY?

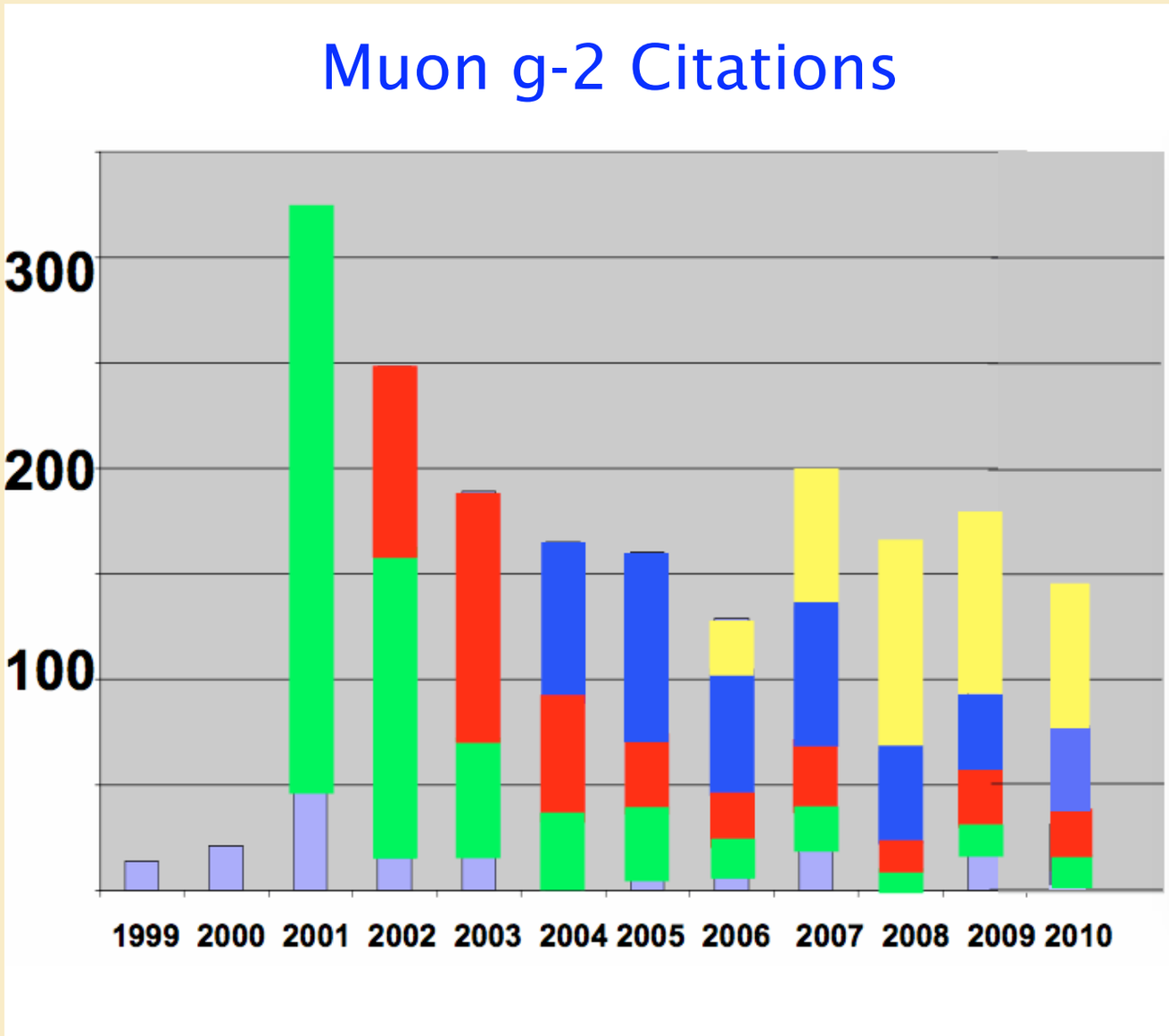
SUSY with mass scale of several 100 GeV is consistent with discrepancy

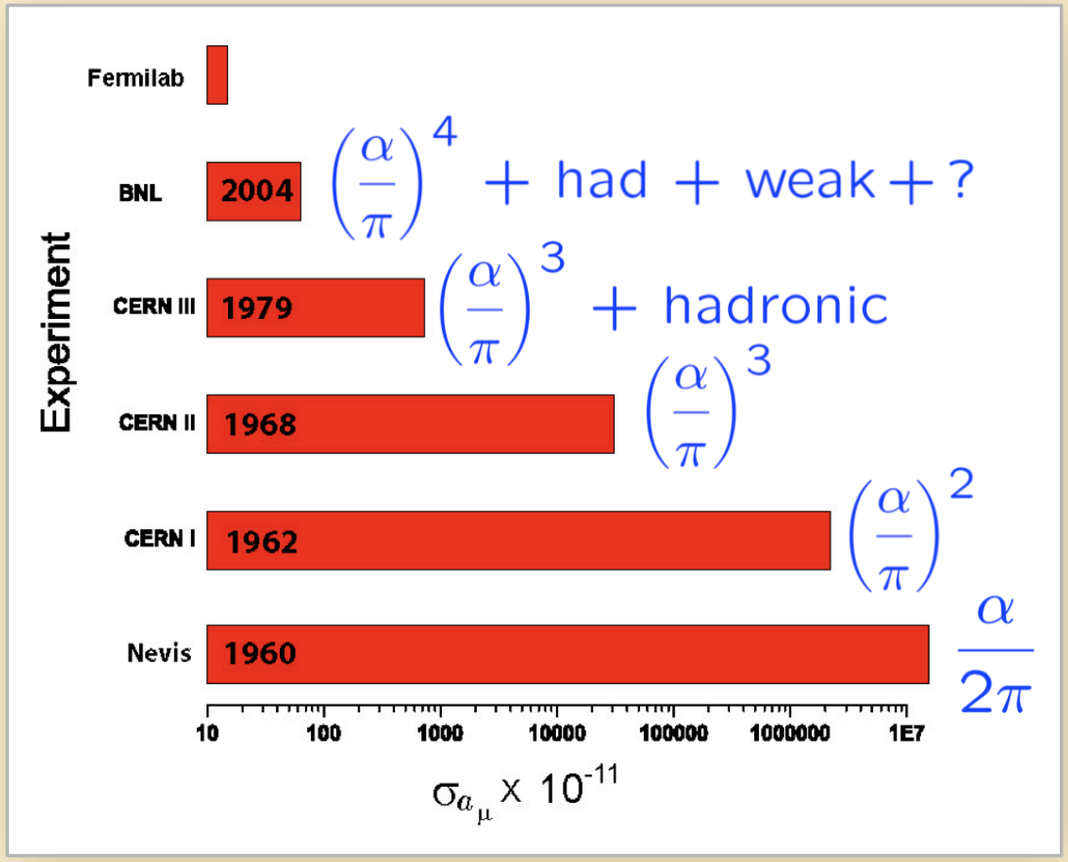
$$a_\mu^{\mathrm{SUSY}} \approx 13 \times 10^{-10}\,\mathrm{sign}(\mu)\left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2 \tan\beta$$



Summary of present status

Precision of results has generated enormous interest





Explore the discrepancy with a next experiment

~ 3σ discrepancy - a hint of something new?

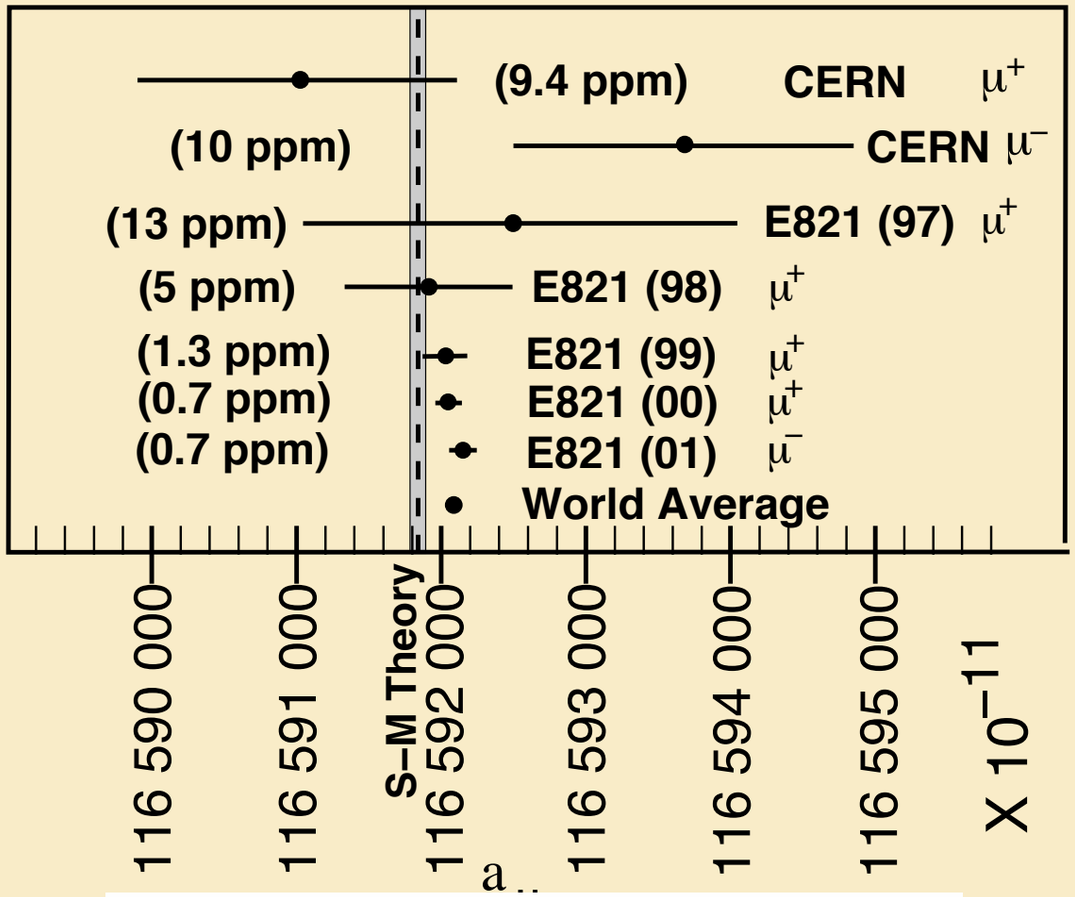
Time for another experiment!

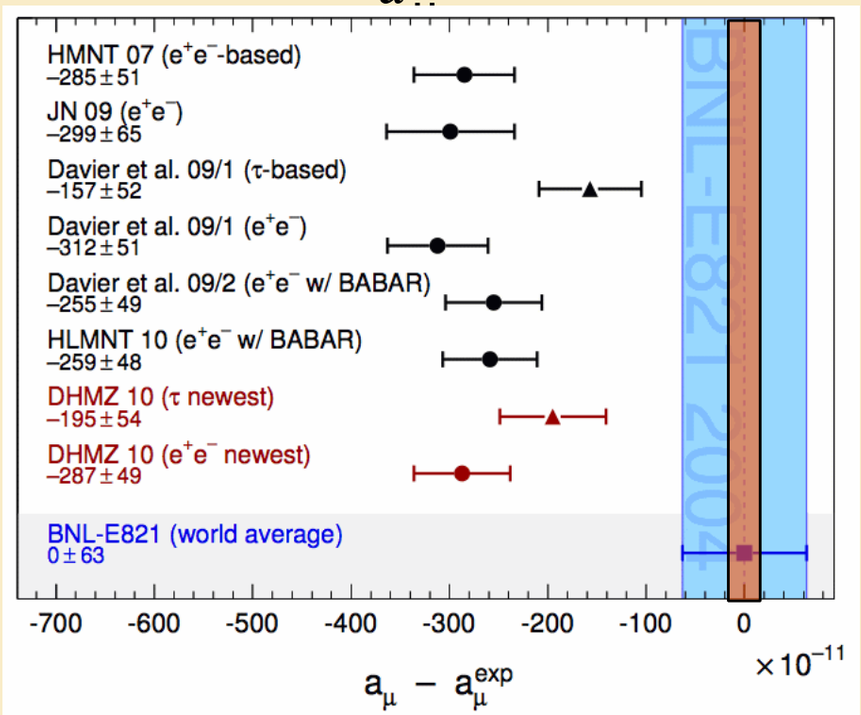
Goal: a_μ to $\pm 16 \times 10^{-11}$ (0.14 ppm)

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?

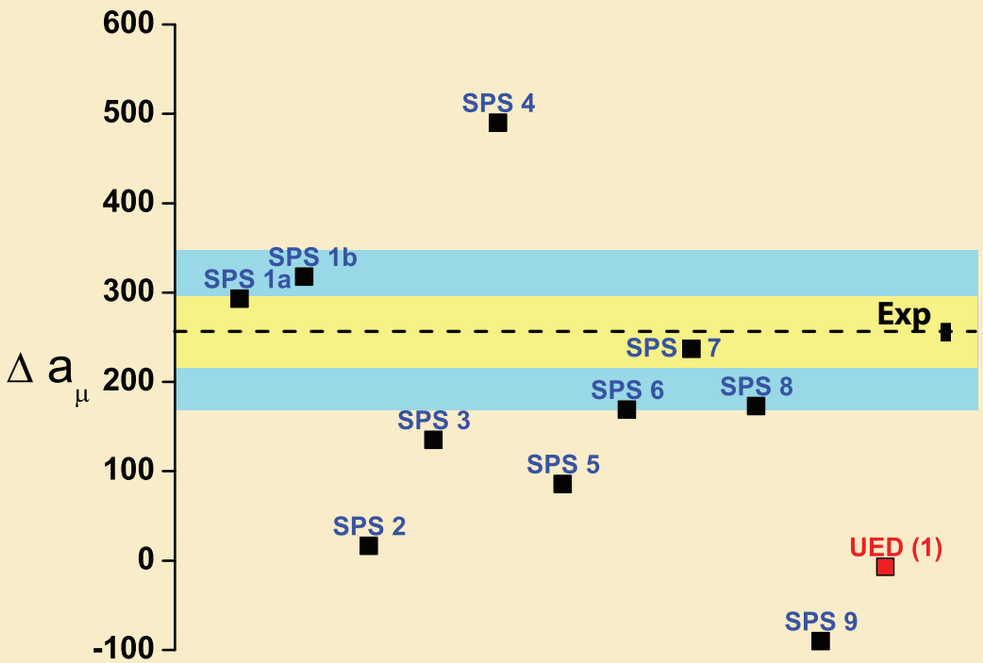


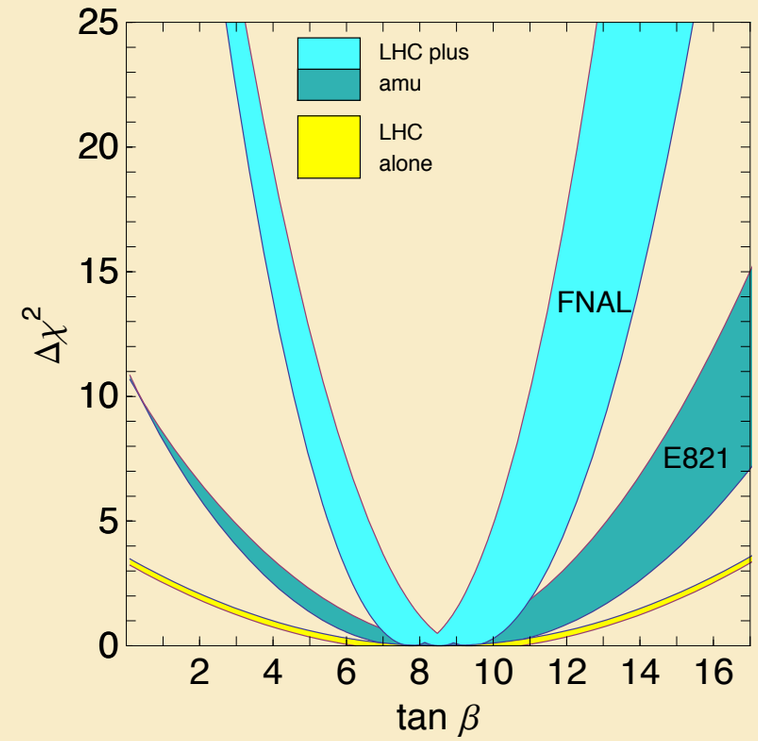


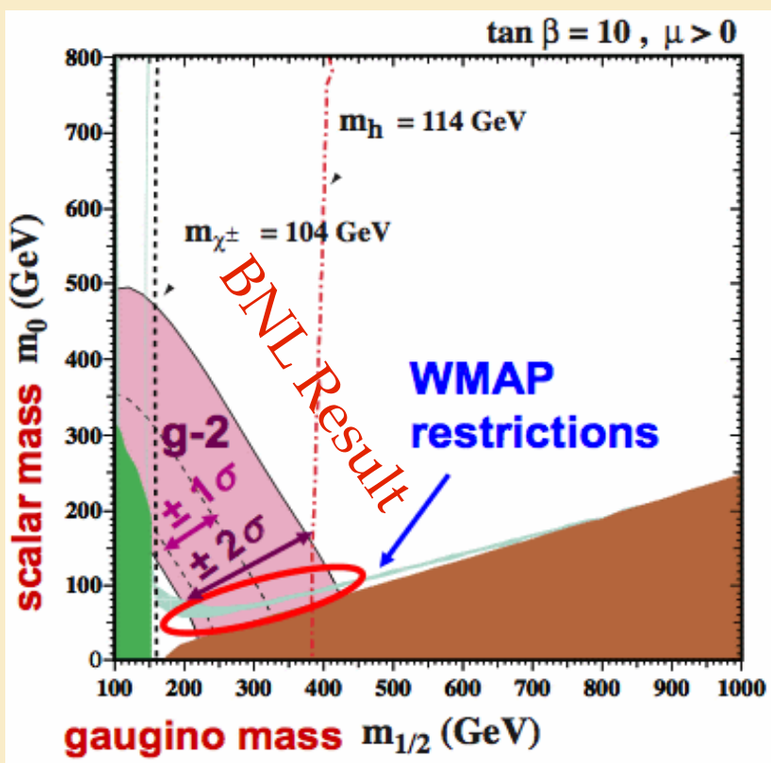
M. Davier

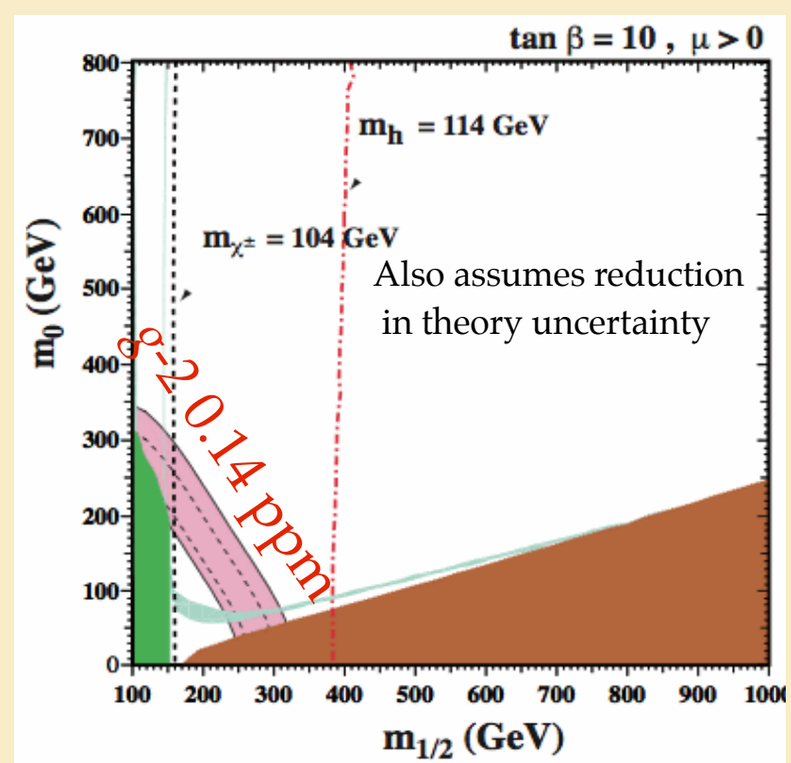
New physics with 0.14 ppm

Complementary to LHC









New g-2 experiment justification

Discrepancy with SM and complementarity with LHC makes for easy physics motivation. If there is new physics,
LHC + 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 !!!

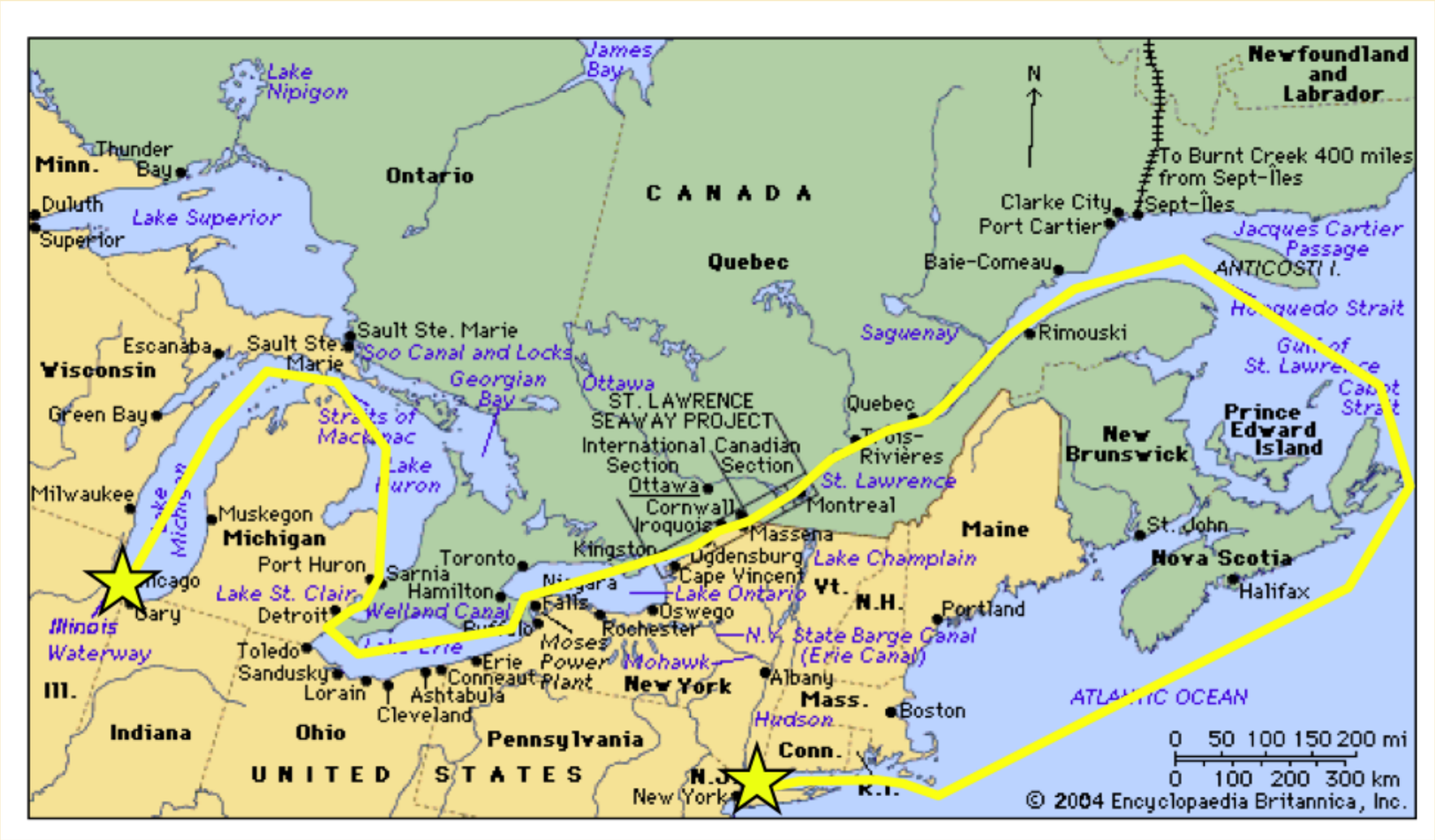
Gotta get more beam! Move to Fermilab -- Literally!

Movin' Out – Transporting the Ring

The existing BNL storage ring makes the new experiment work

Three ~50' diameter coils are continuously wound!

The long trip is easy - Barge it



About a month long trip. Ring ends up in Lemont

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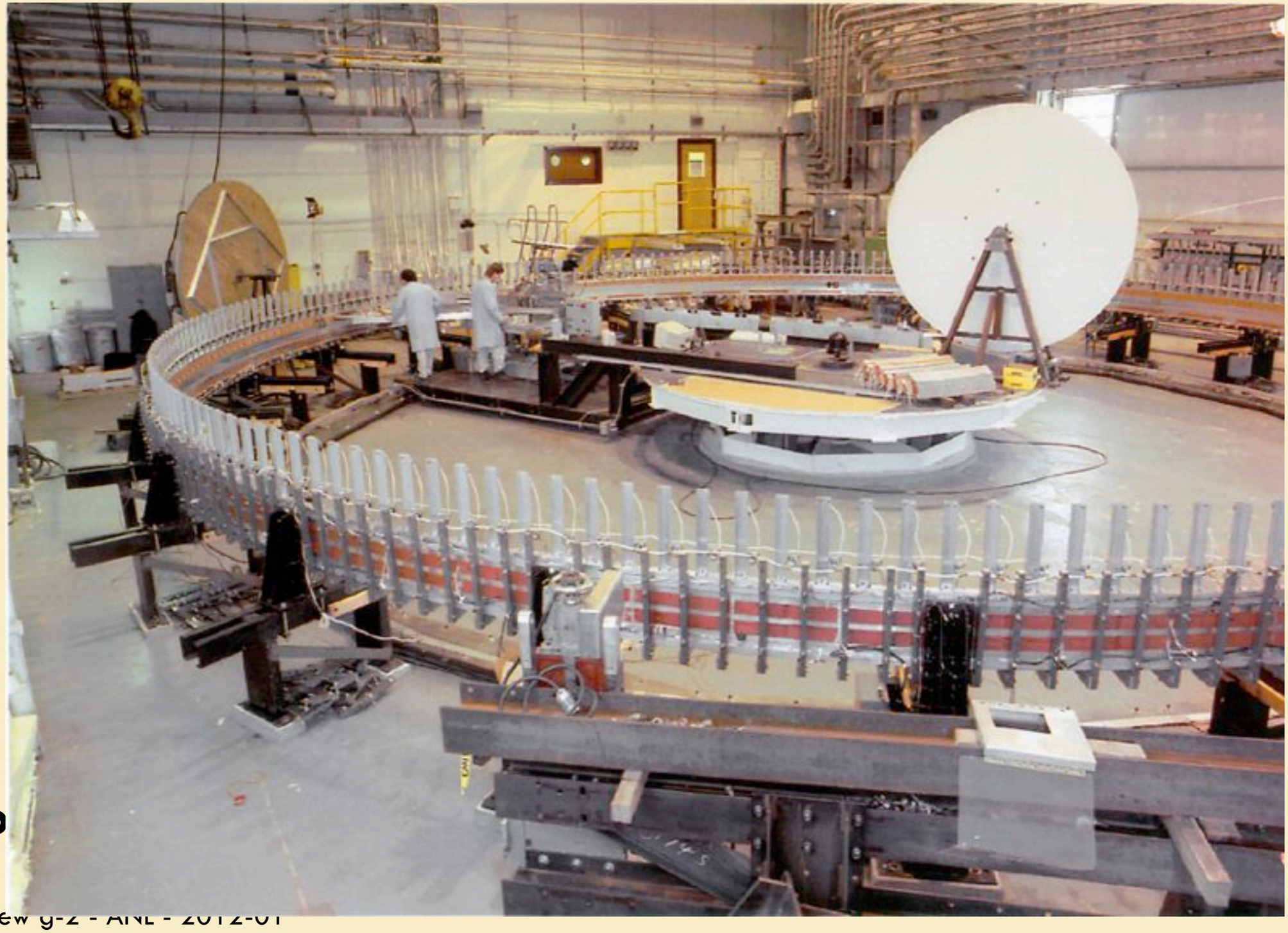

Abo

Movin' Out – Transporting the Ring

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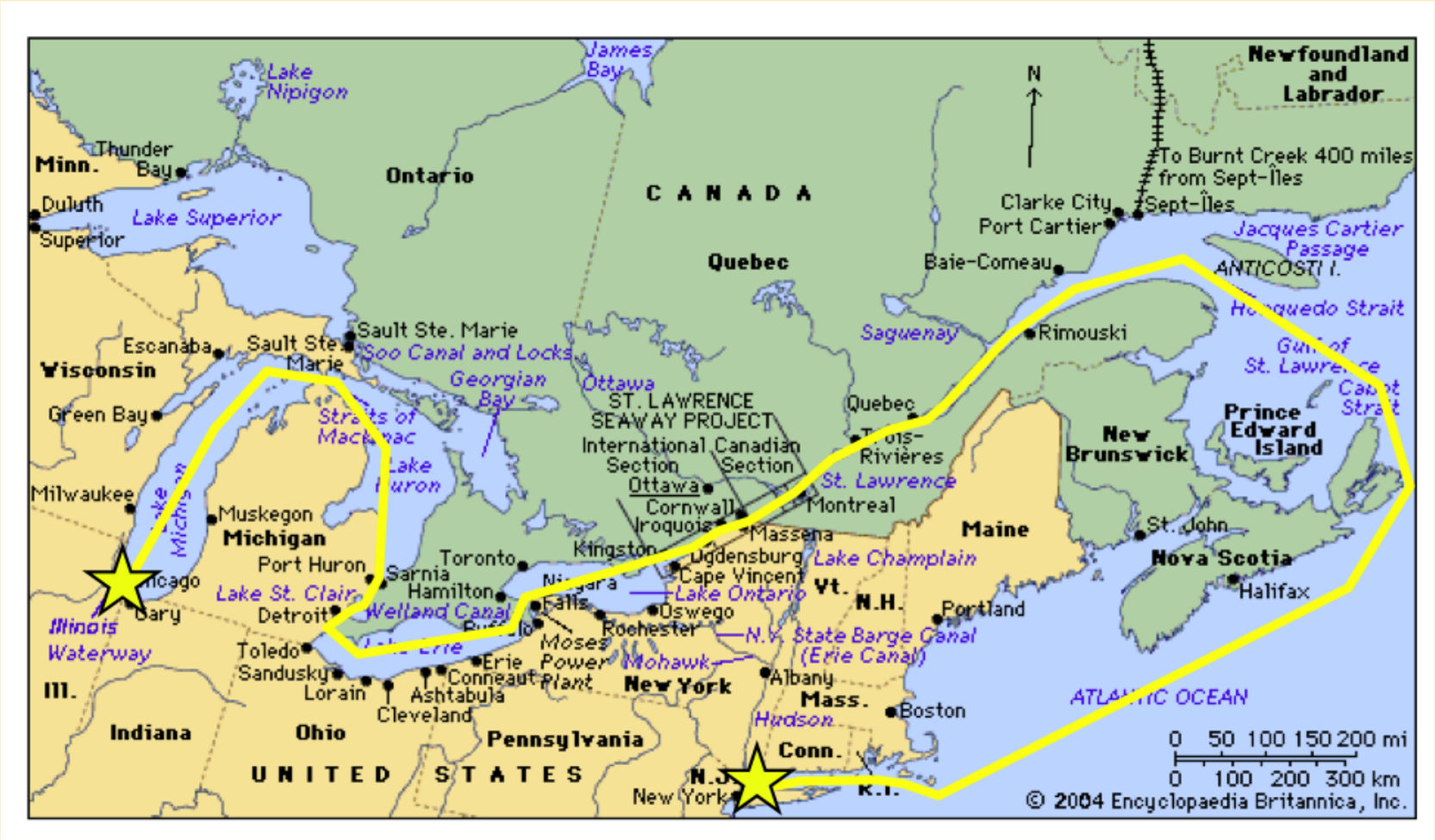


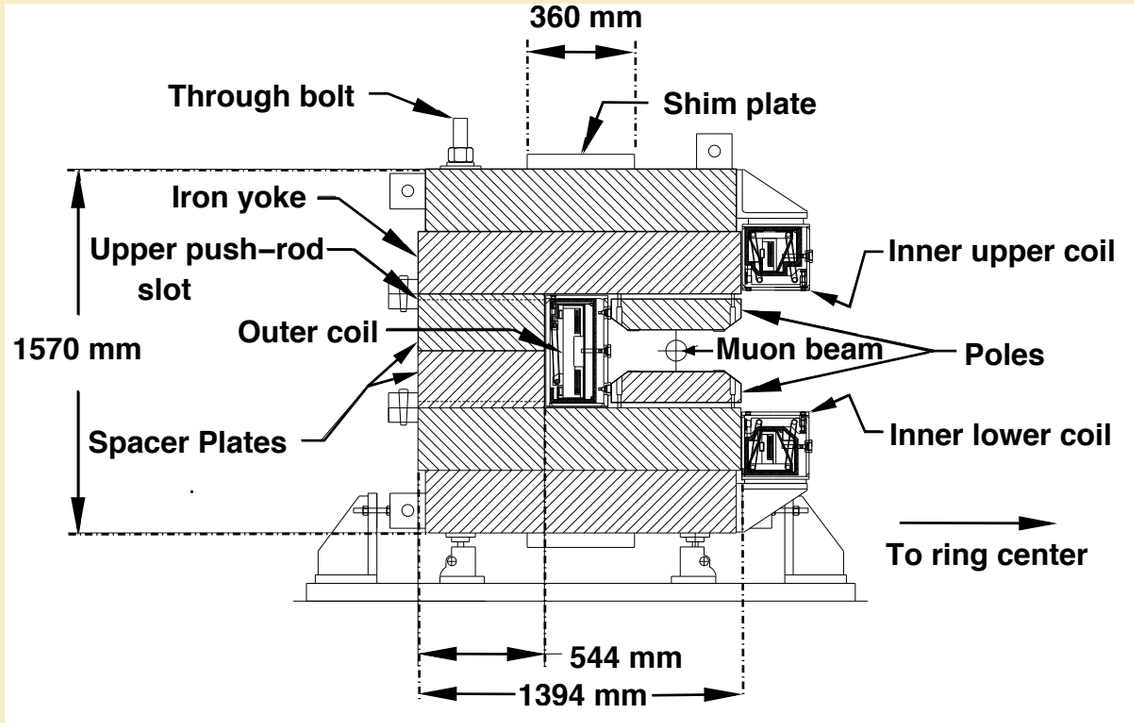
About a month long trip. Ring ends up in Lemont

The getting to and from the barge is hard

Inner cryostats are 3.5T ea
Outer cryostat is 8.5T
Connections < 5T
Existing shipping frame is 6T

Way Cool Helicopter (Skycrane):
Max load 12.5T
Need sterile 300 ft field underneath if jettison-able
Maybe bolt to helicopter?

Boring Truck:
Carry entire package at once
Ring to go horizontal and vertical



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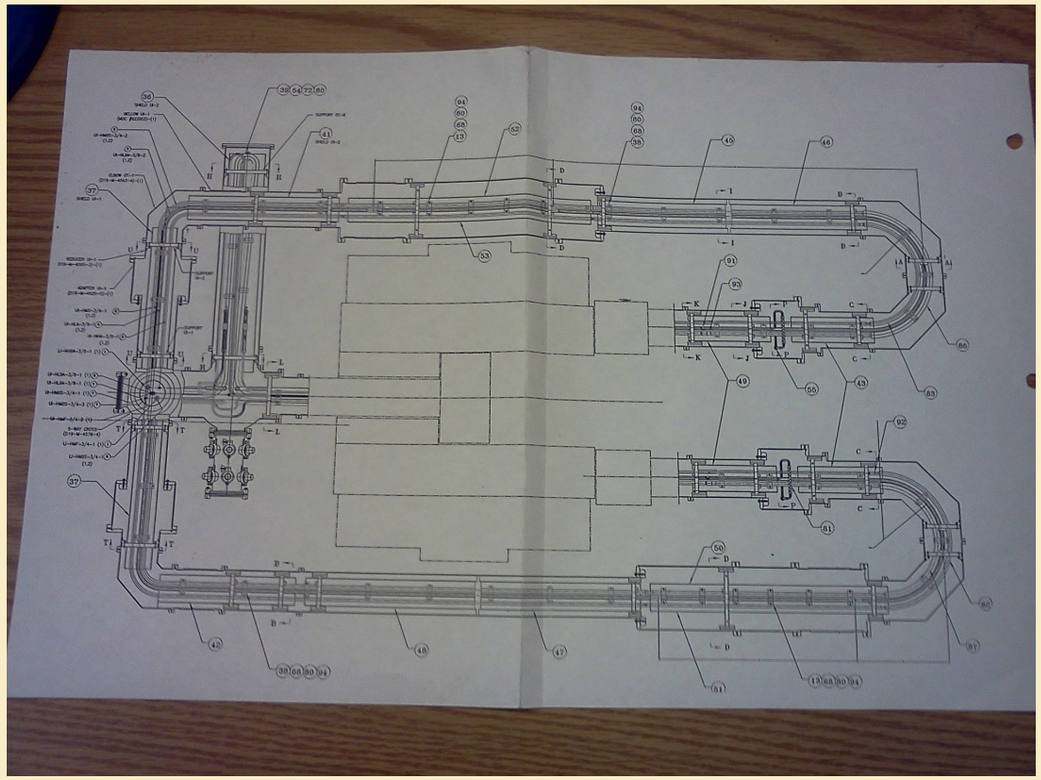

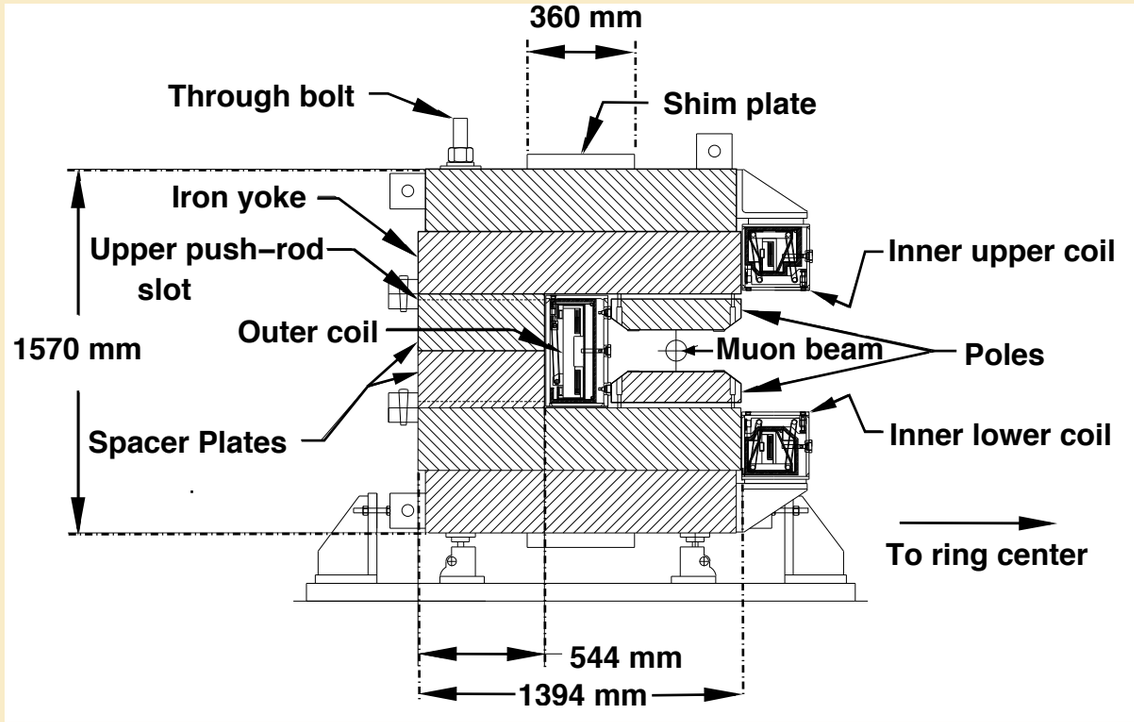

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Got the Coil on a String!

In April 1992, as the Bulletin reported, the world's largest superconducting coil "on a string" was hanging not from a finger but from a massive crane outside Bldg. 919. Three coils had been constructed inside the building. The third and largest coil was pulled on special heavy-duty tracks past a removable wall to the outdoors, attached to the crane, then lowered into its final position on the foundation that held the two previously completed inner coils within the building. Work then continued to ready the experiment for the storage ring's commissioning scheduled for December 1993.

The getting to and from the barge is hard

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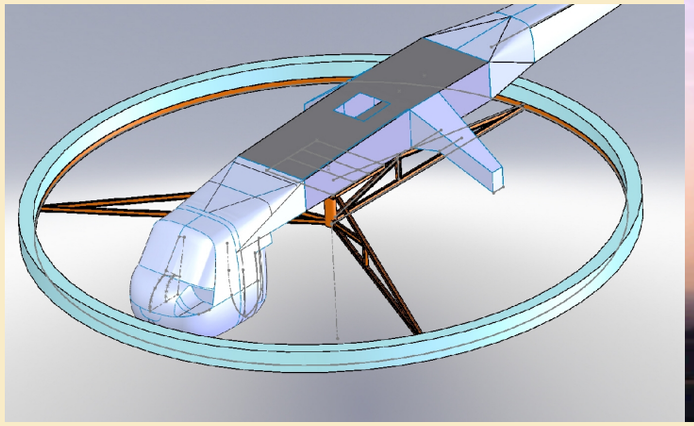
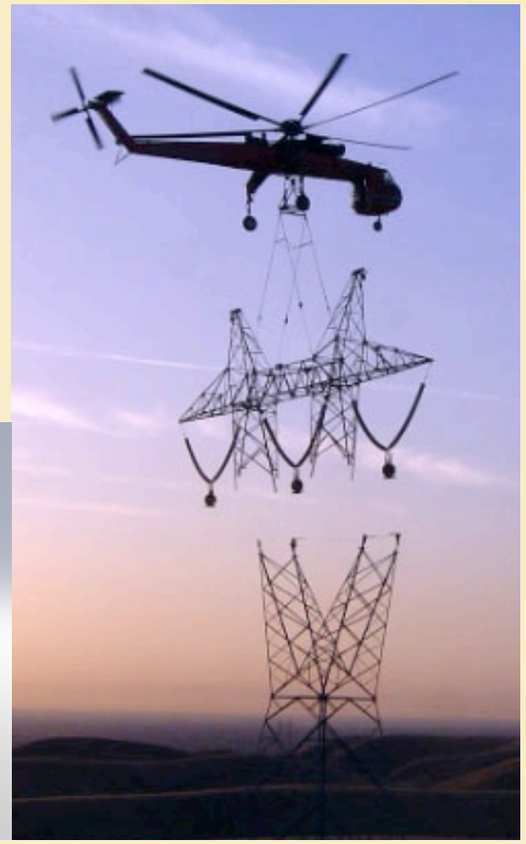
Courtesy Erickson





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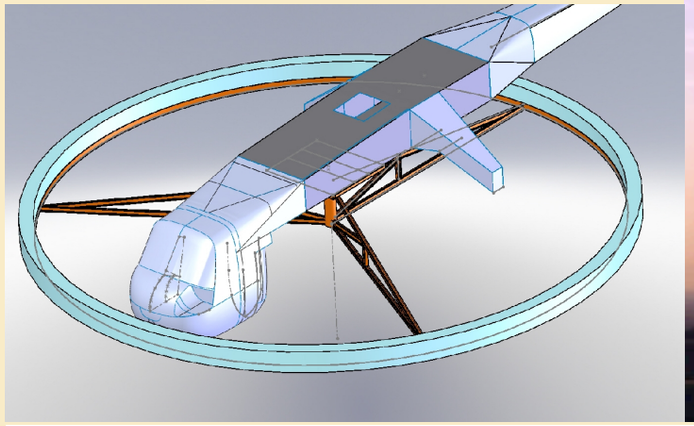
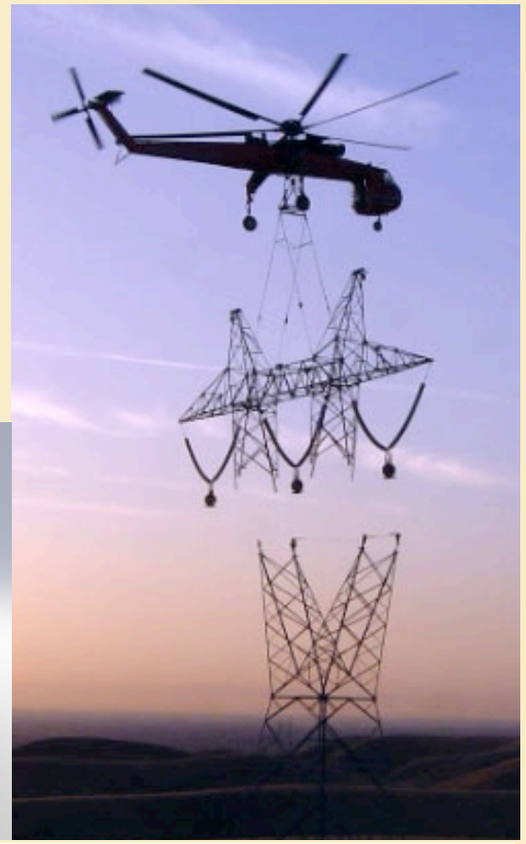
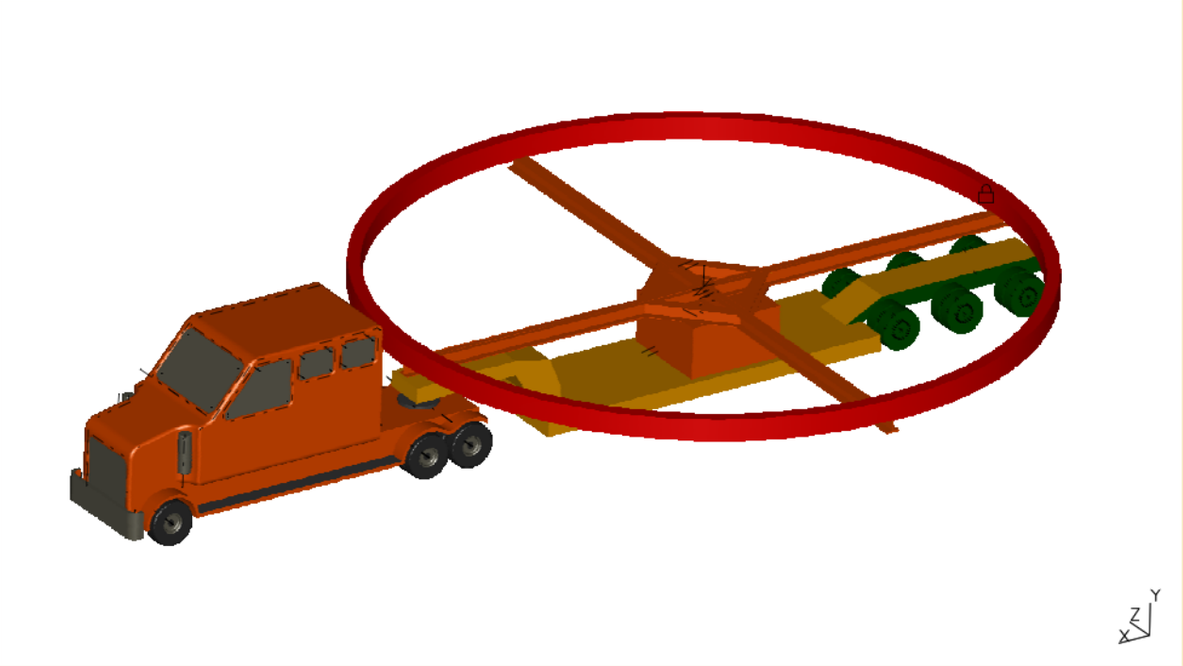






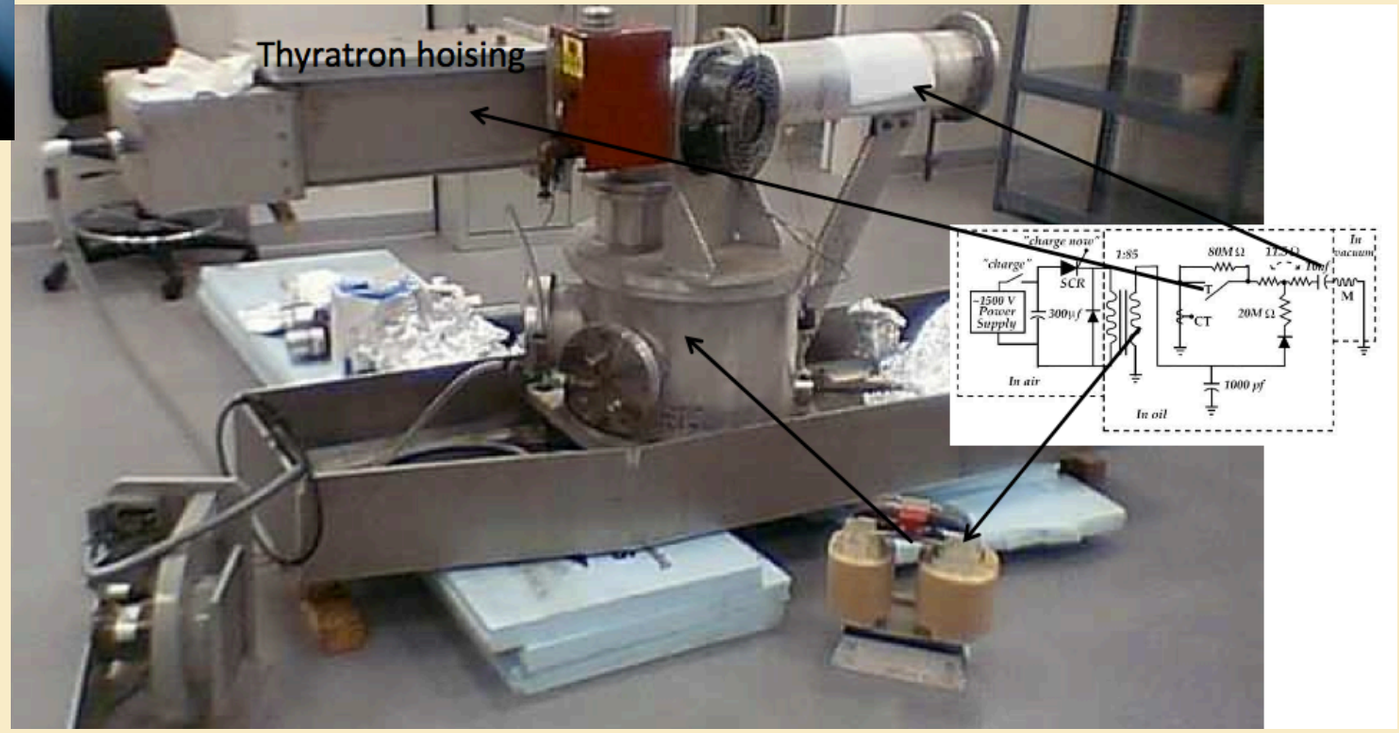
We've started disassembly already

Summer 2011 at Brookhaven

And studying old parts

Cornell got this box of stuff

And reconstructed a kicker



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	±0.5%	±2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

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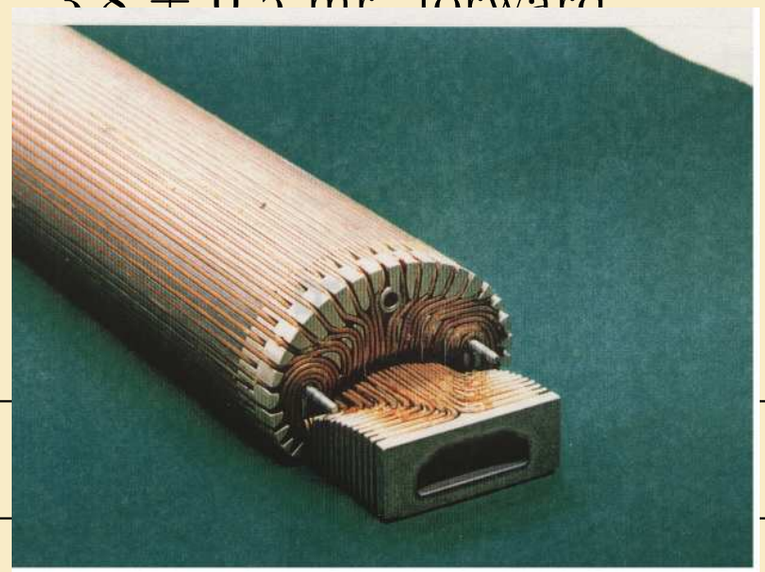
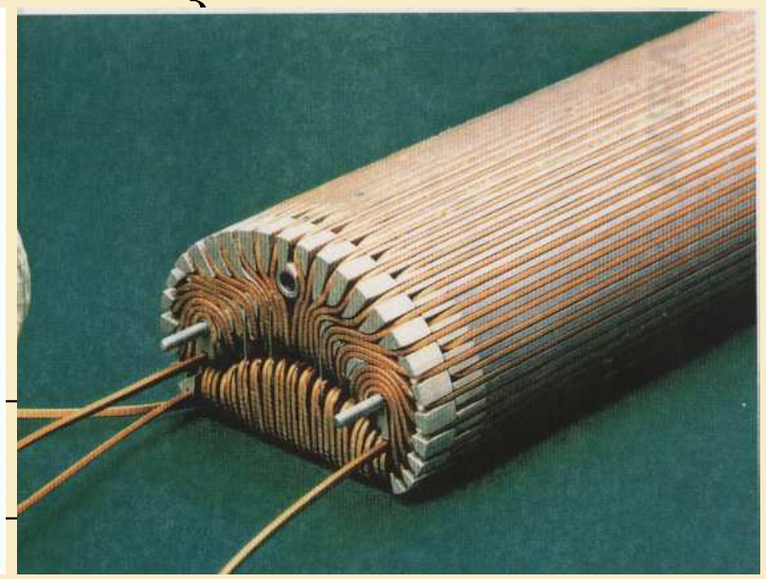




Synergies between g-2 and Mu2e

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

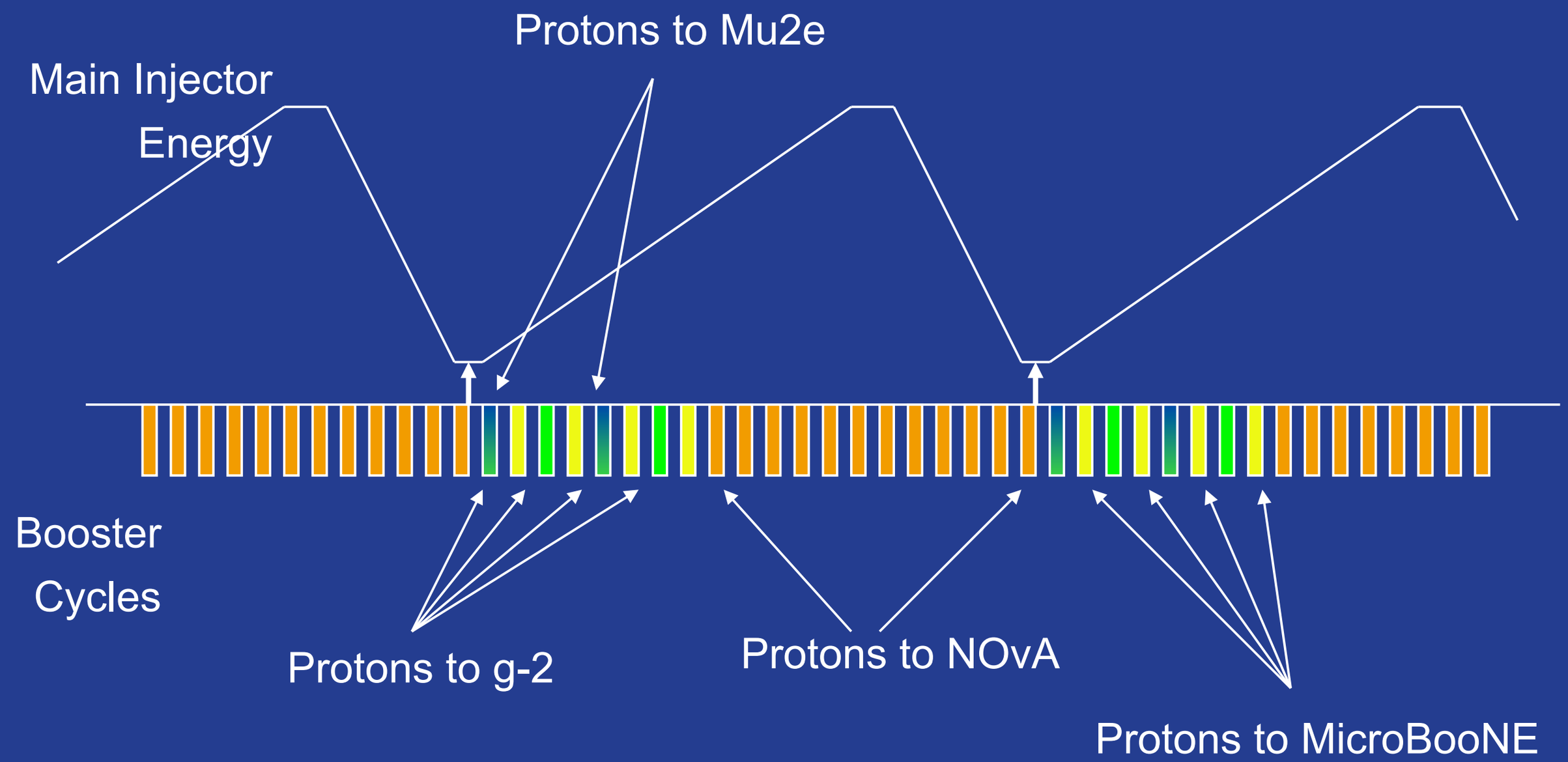
Booster beam structure

20 Booster cycles per NOvA cycle (1.33 sec)

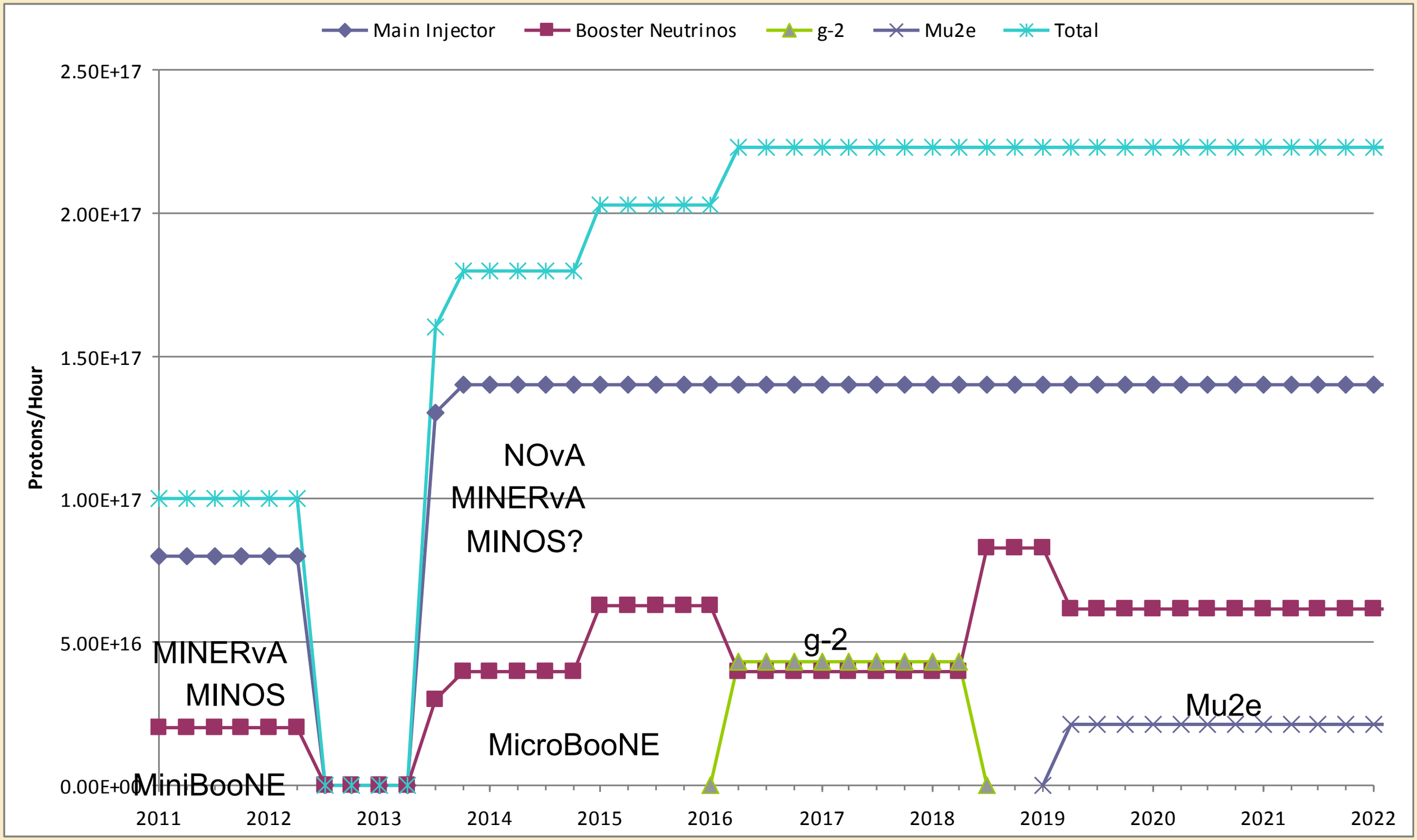
12 NOvA cycles stored in Recycler before transfer to MI

Remaining 8 Booster cycles available for other experiments

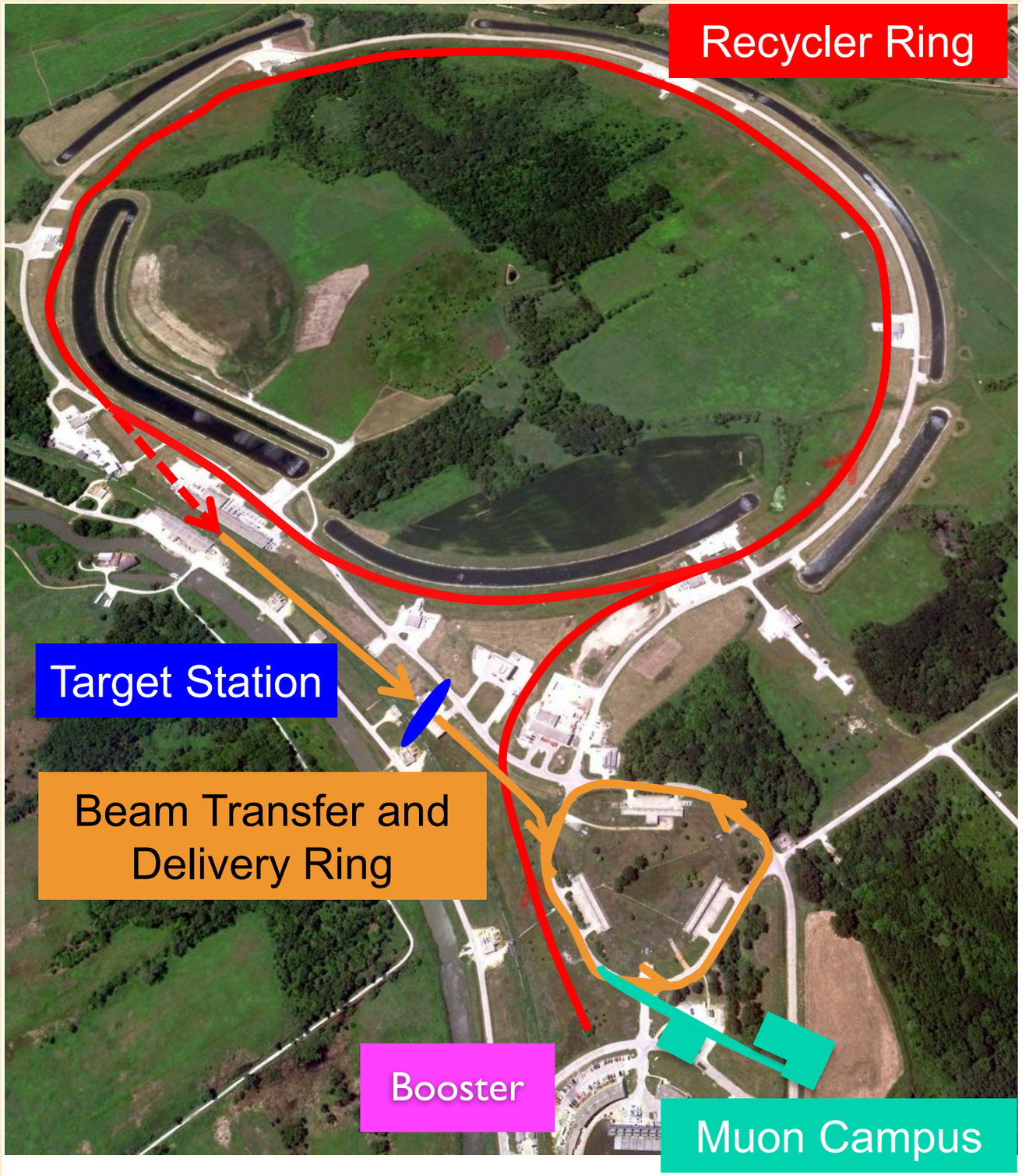
MiniBooNE experience, 1 Booster cycle -> 0.6e20 POT/year



Who gets beam when?



Beam delivery to g-2



- 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

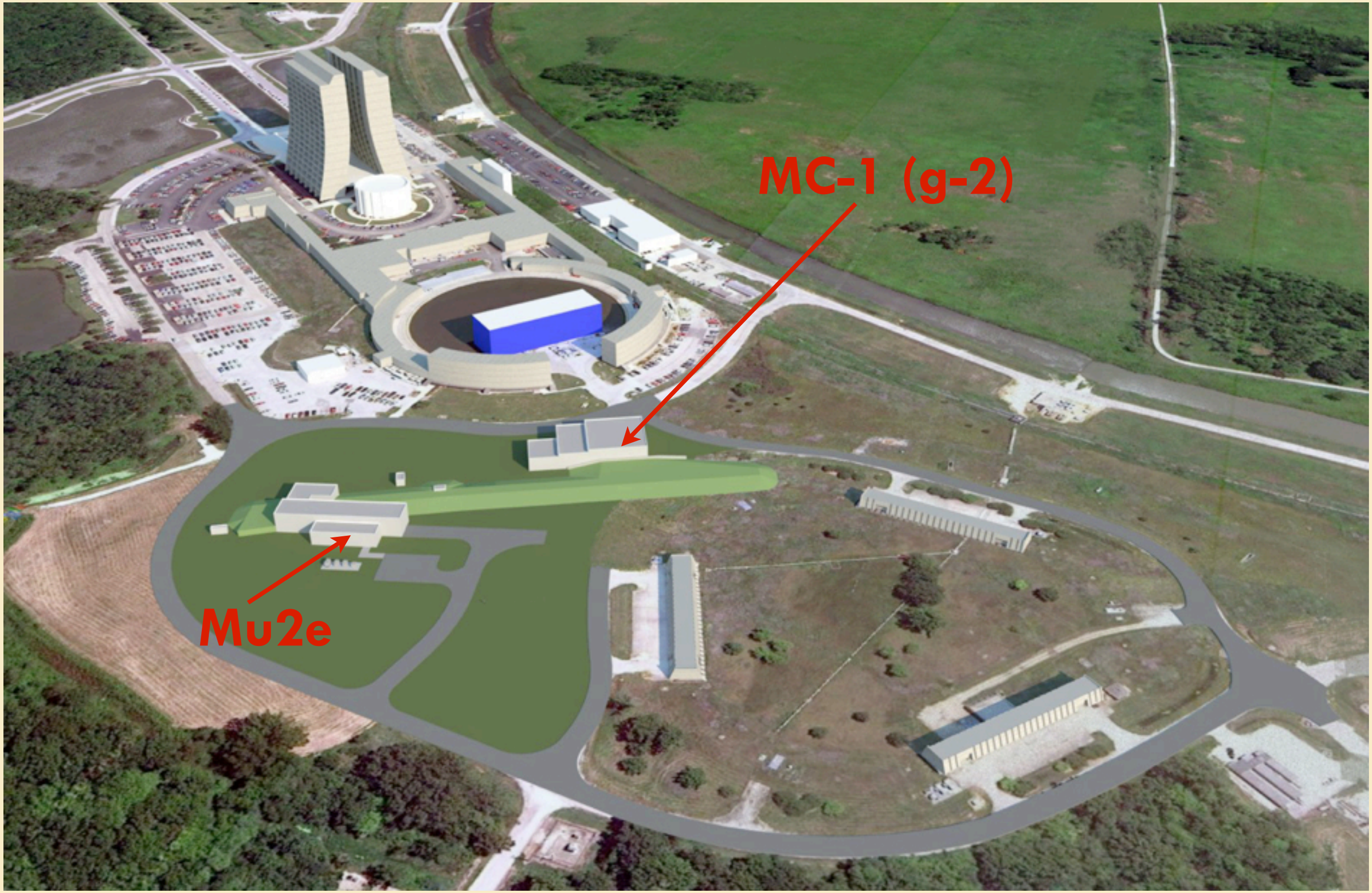
A huge recycling project

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

The Fermilab Muon Campus

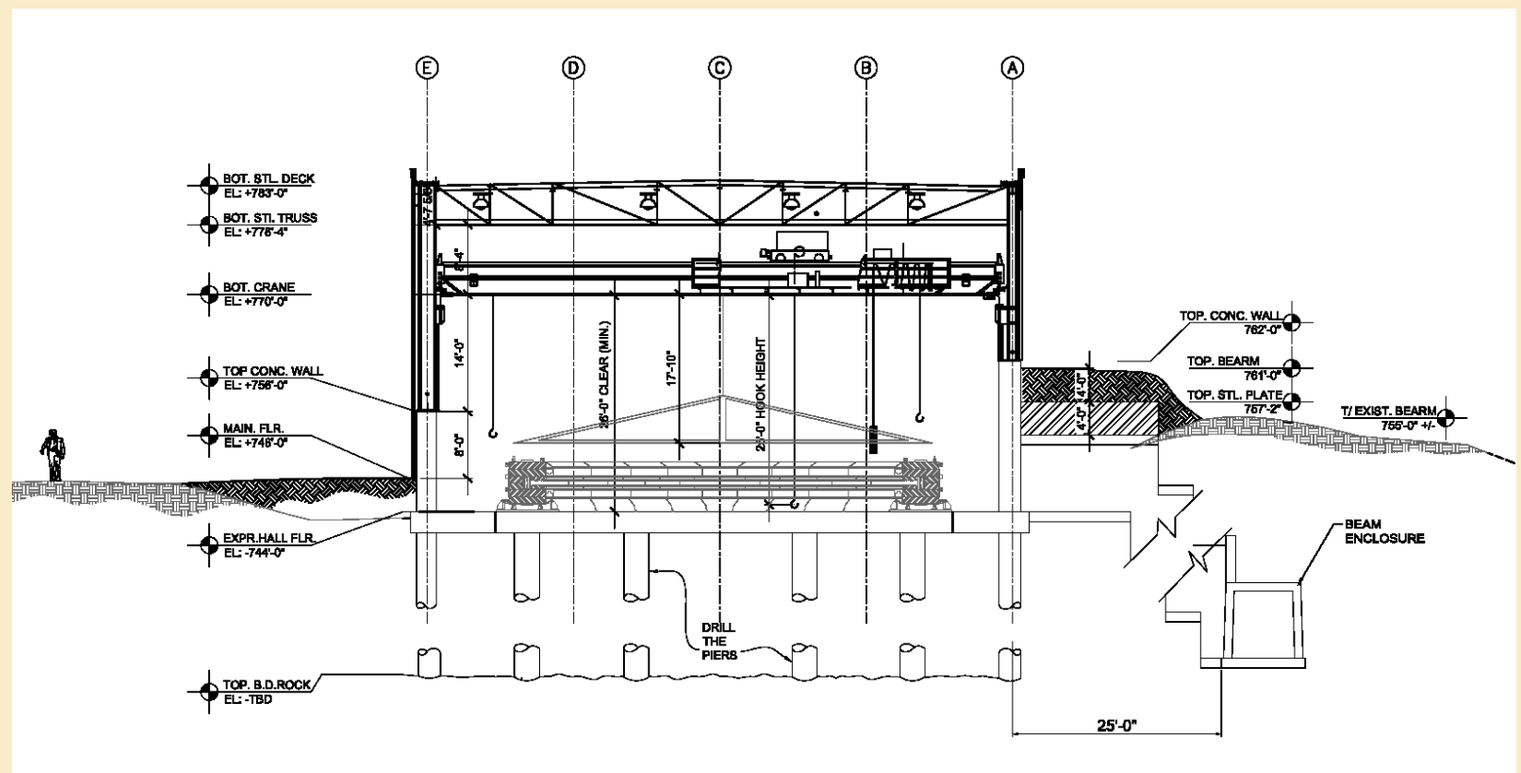


MC-1 Building for g-2

High bay 80’ x 80’ for ring

Medium bay 40’ x 70’ for power supplies for g-2, beam, Mu2e AC dipole and HVAC

Low bay 40’ x 40’ for cryo plant for both experiments



Fully temperature controlled

Close to Booster - may need magnetic shielding

Improving ω_a

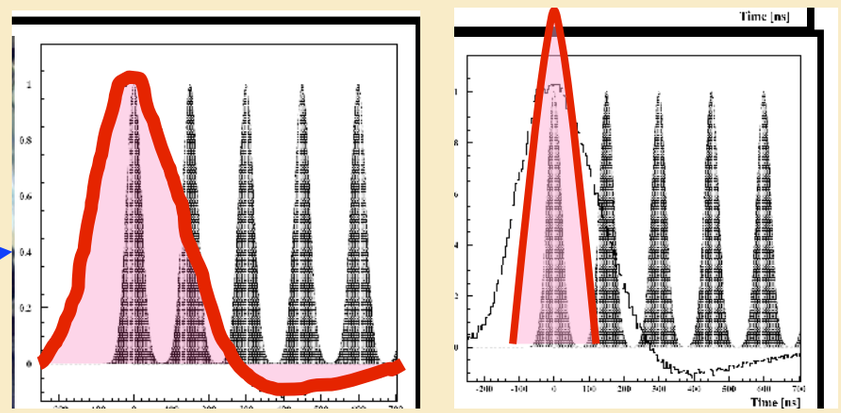
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; 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 hodoscopes, tracking, open inflector, scraping

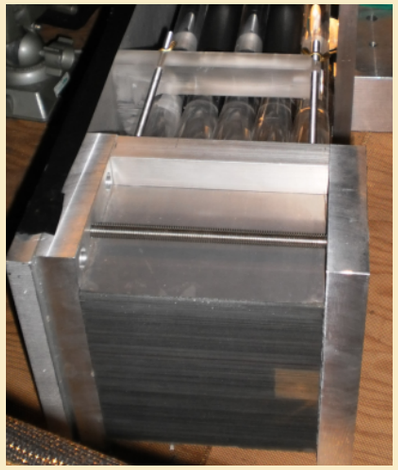
+ Segmented calorimeters

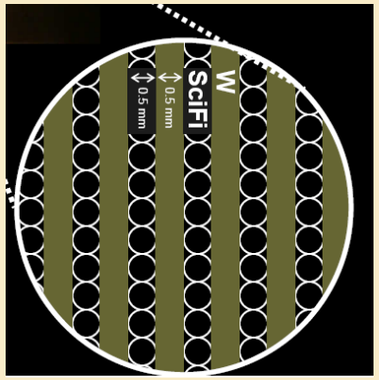
+ Improved kickers



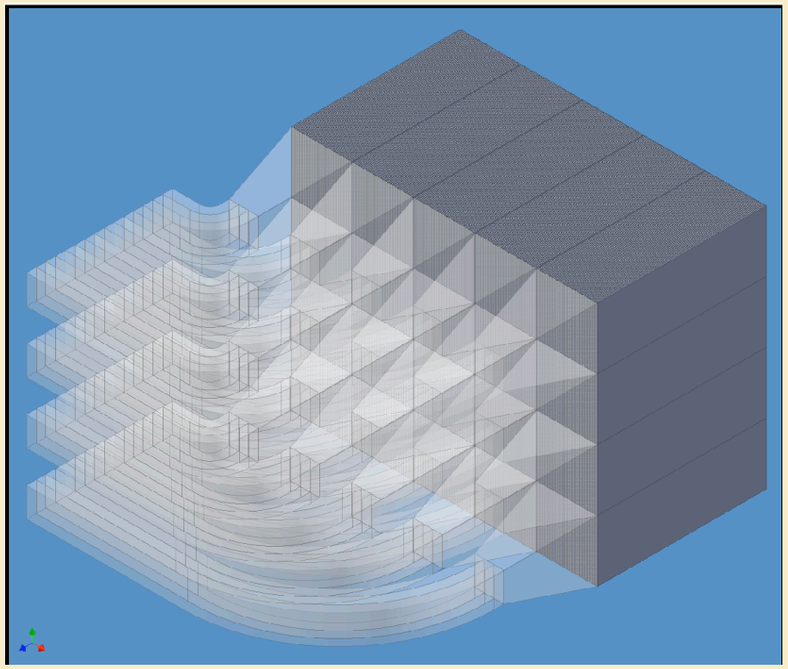
Segmented calorimeters

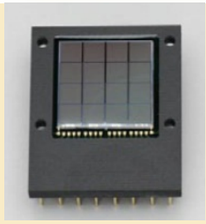
For reduced pileup

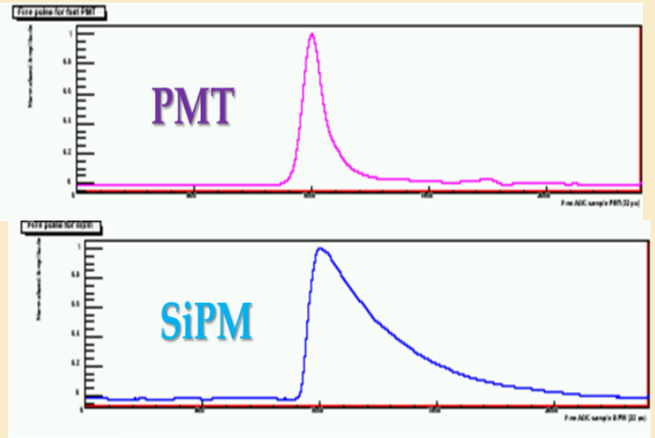




W/SciFi or PbF_2 Cherenkov?



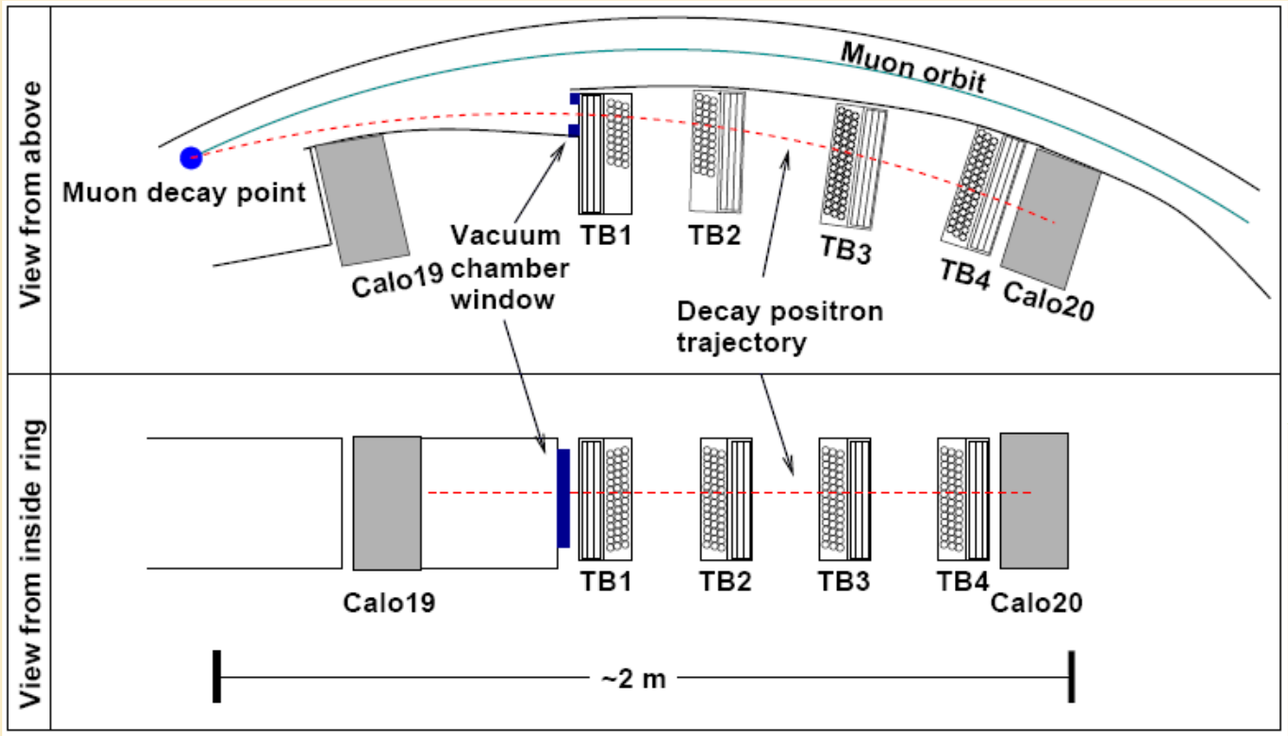


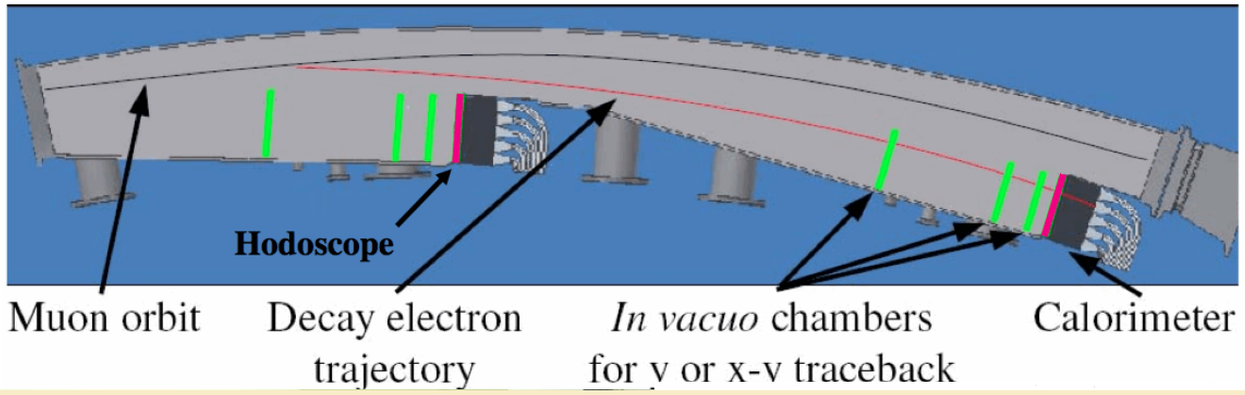


Ultra-fast PMTs or SiPM's?

Tracking Traceback detectors

Important for pitch systematic and Muon EDM

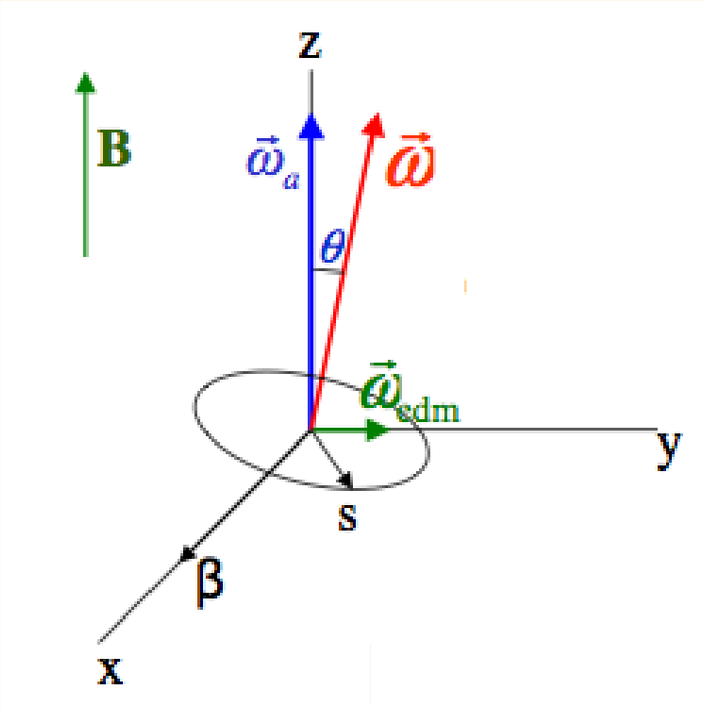


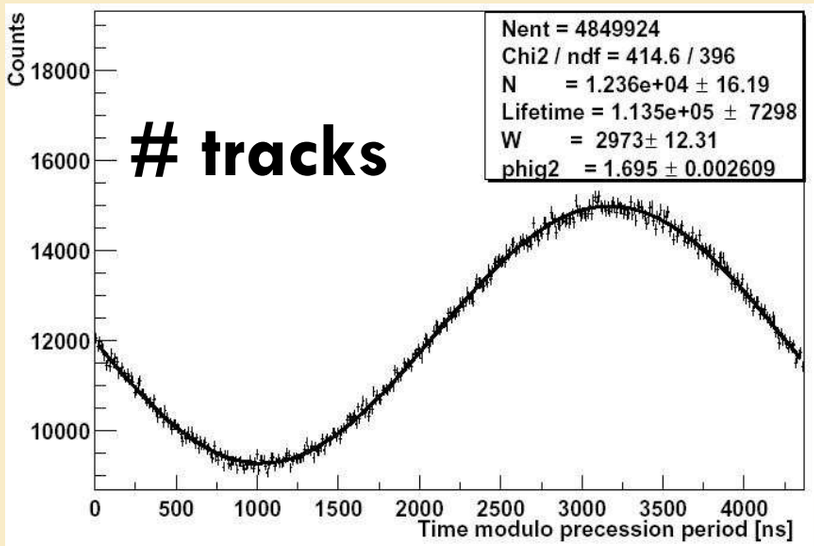


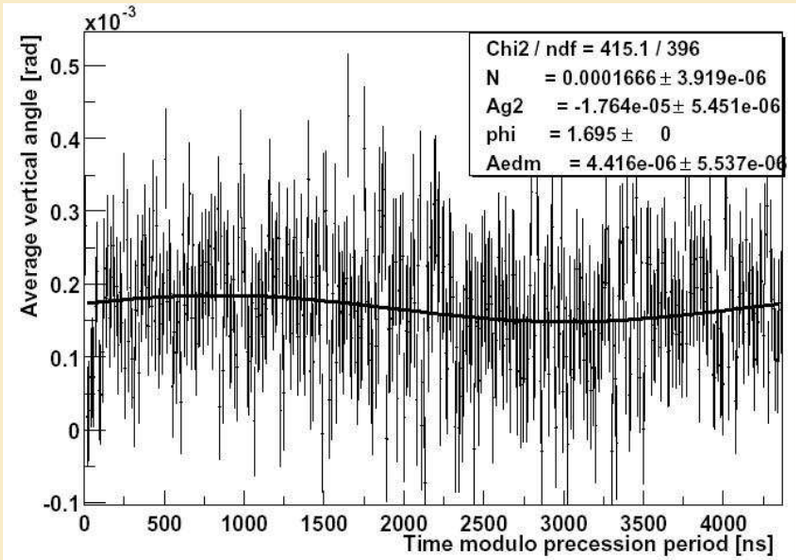
For new experiment, place straws within the vacuum

Test stand from CKM

Muon EDM







vertical angle of tracks

Precession plane tilted, vertical out of phase oscillation of ω_a

Current best limit from E821

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

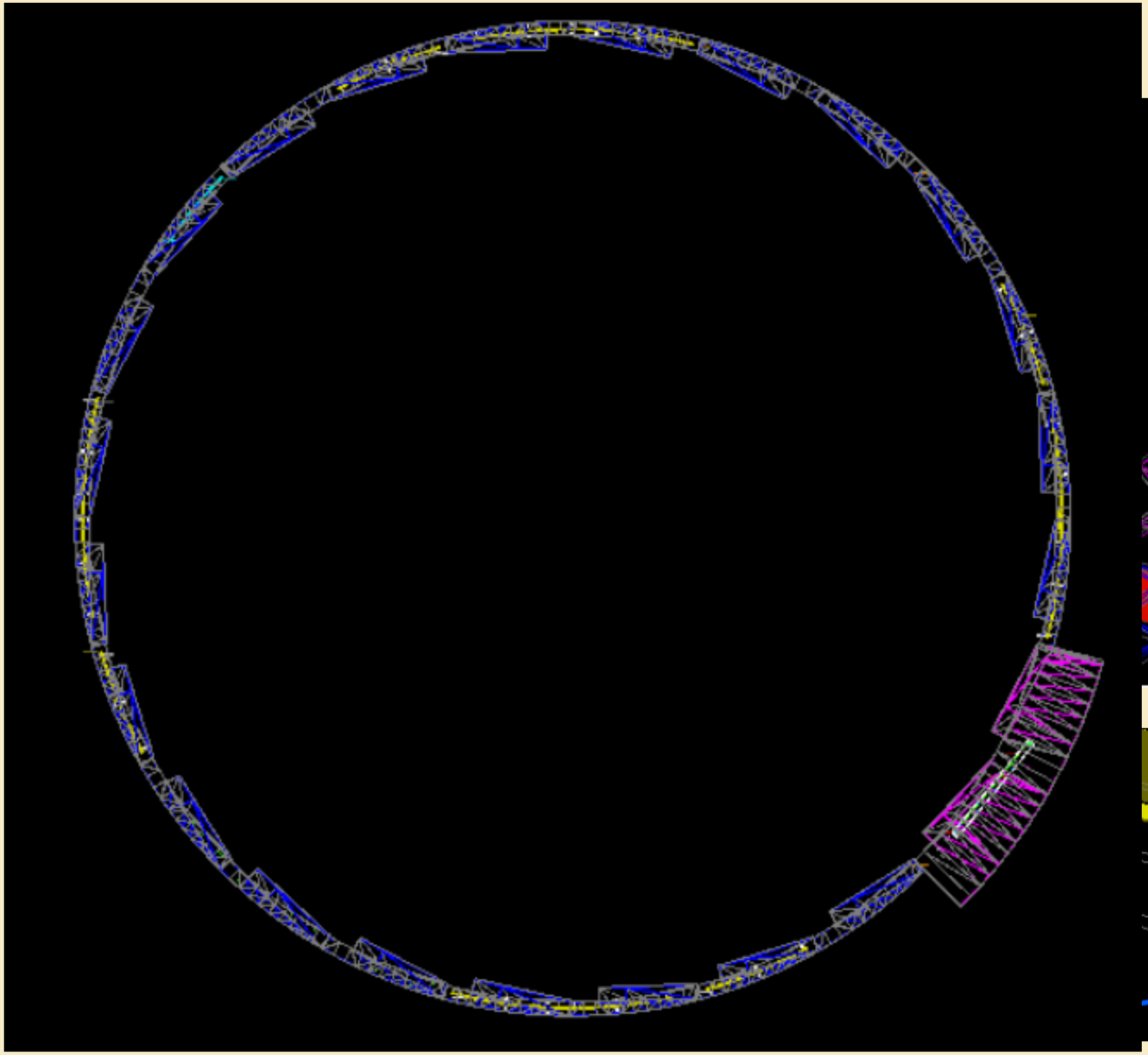
Expect 10-30x better in new experiment

Improving ω_p

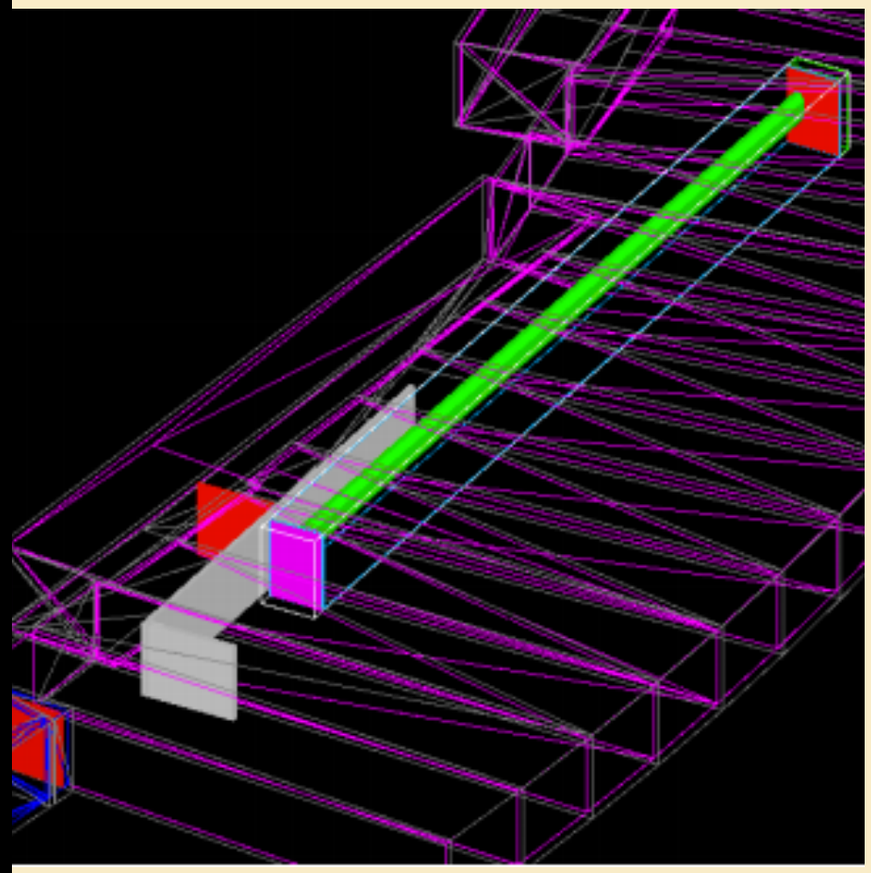
Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe 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

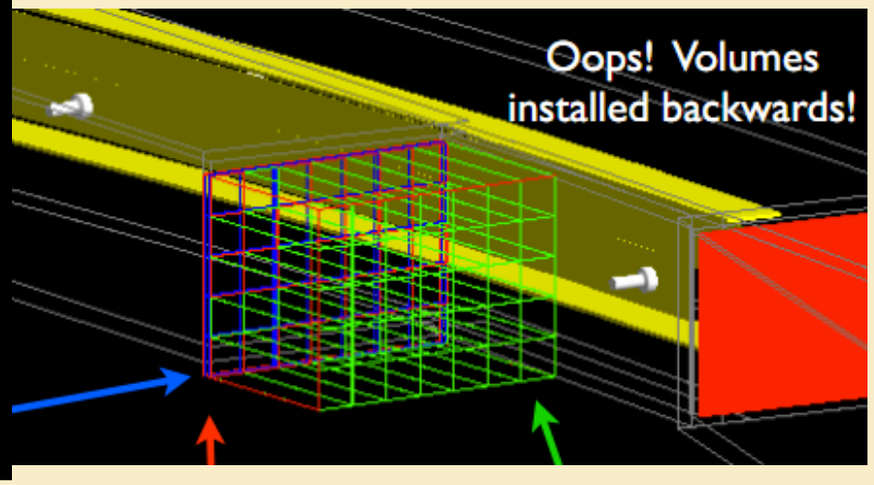
To get to 0.07 ppm, more probes, mapping, shimming, temp control

Geant4 Simulations



Injection to detection simulation



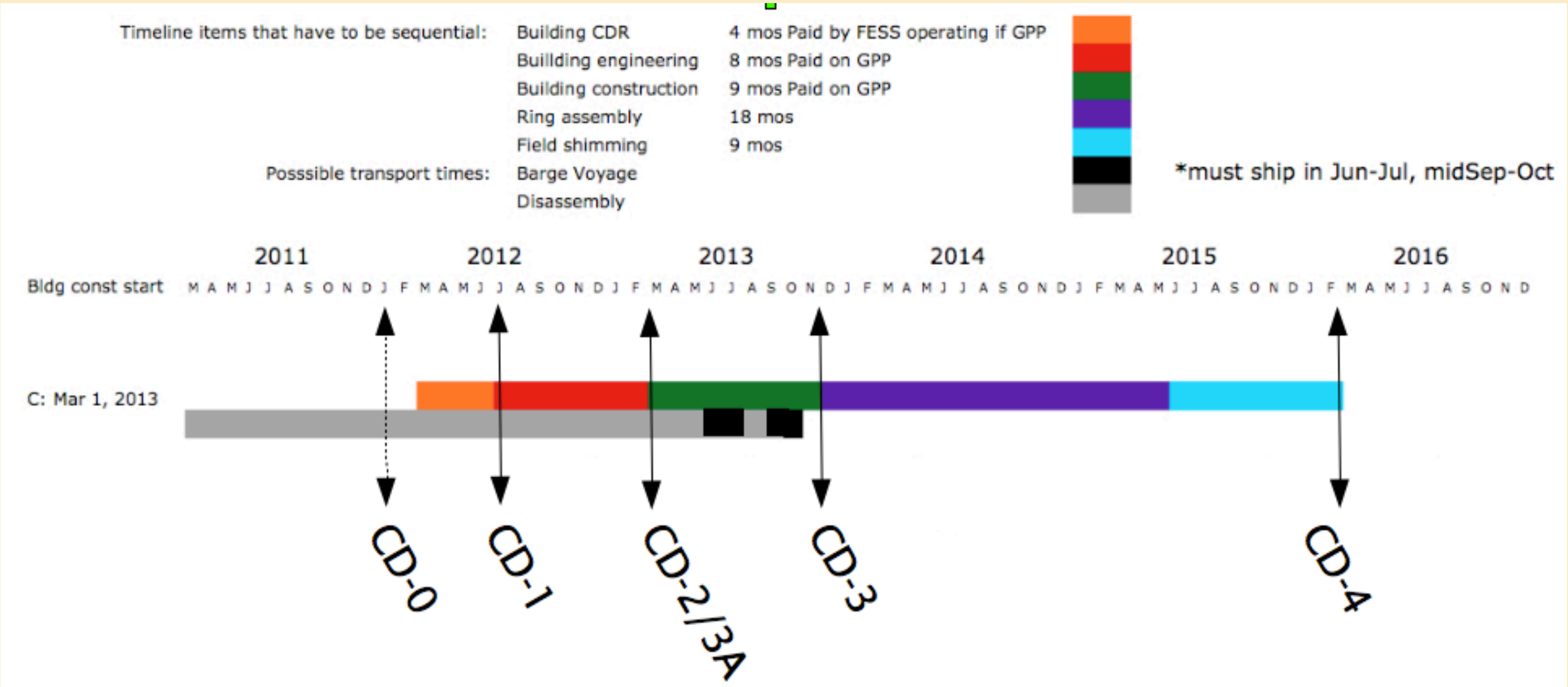


Status and timeline

Granted Fermilab Stage 1 approval (1/11)

CD-0 in early 2012

CD-1 in summer 2012, writing CDR

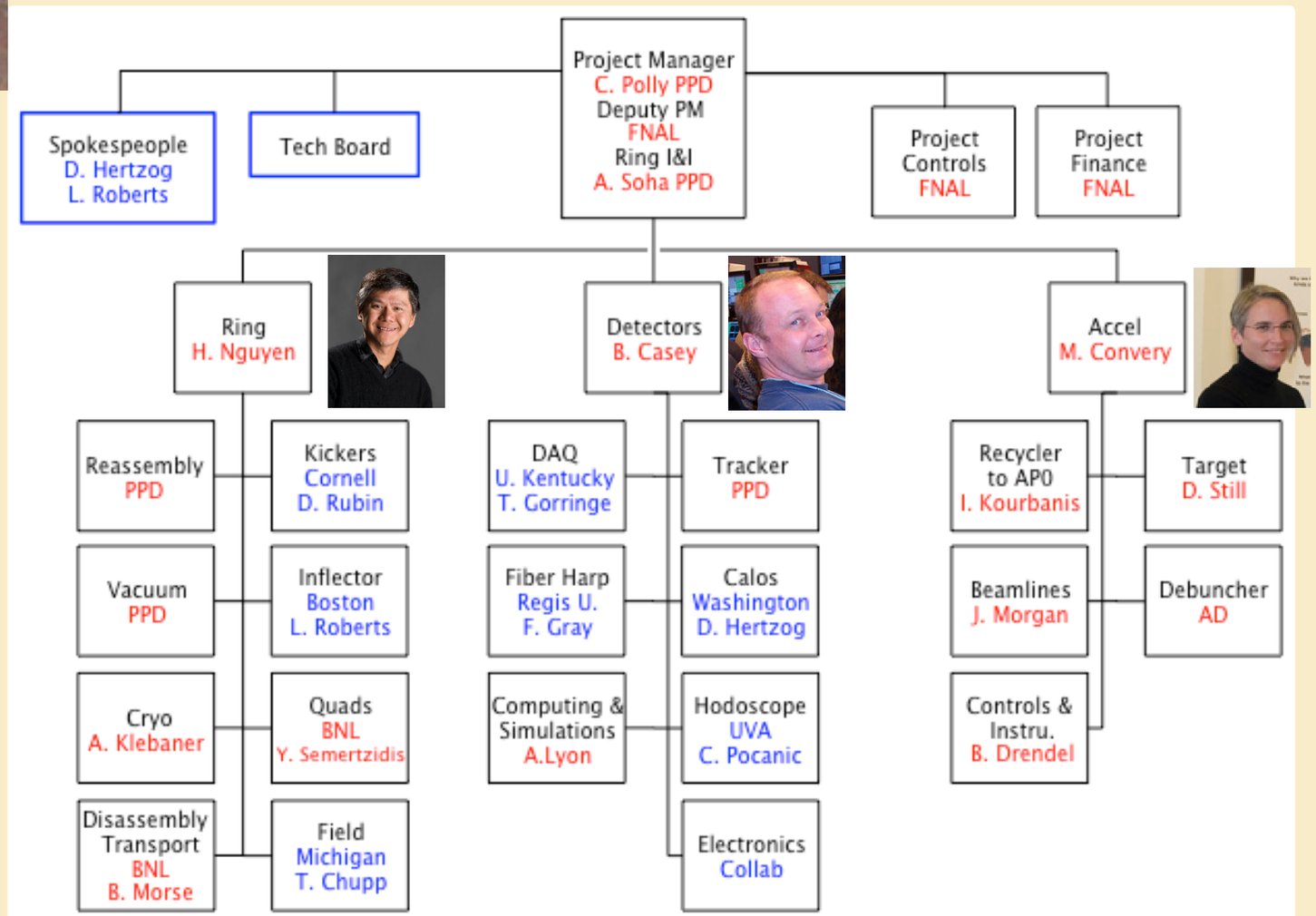


E989 Collaboration and Project

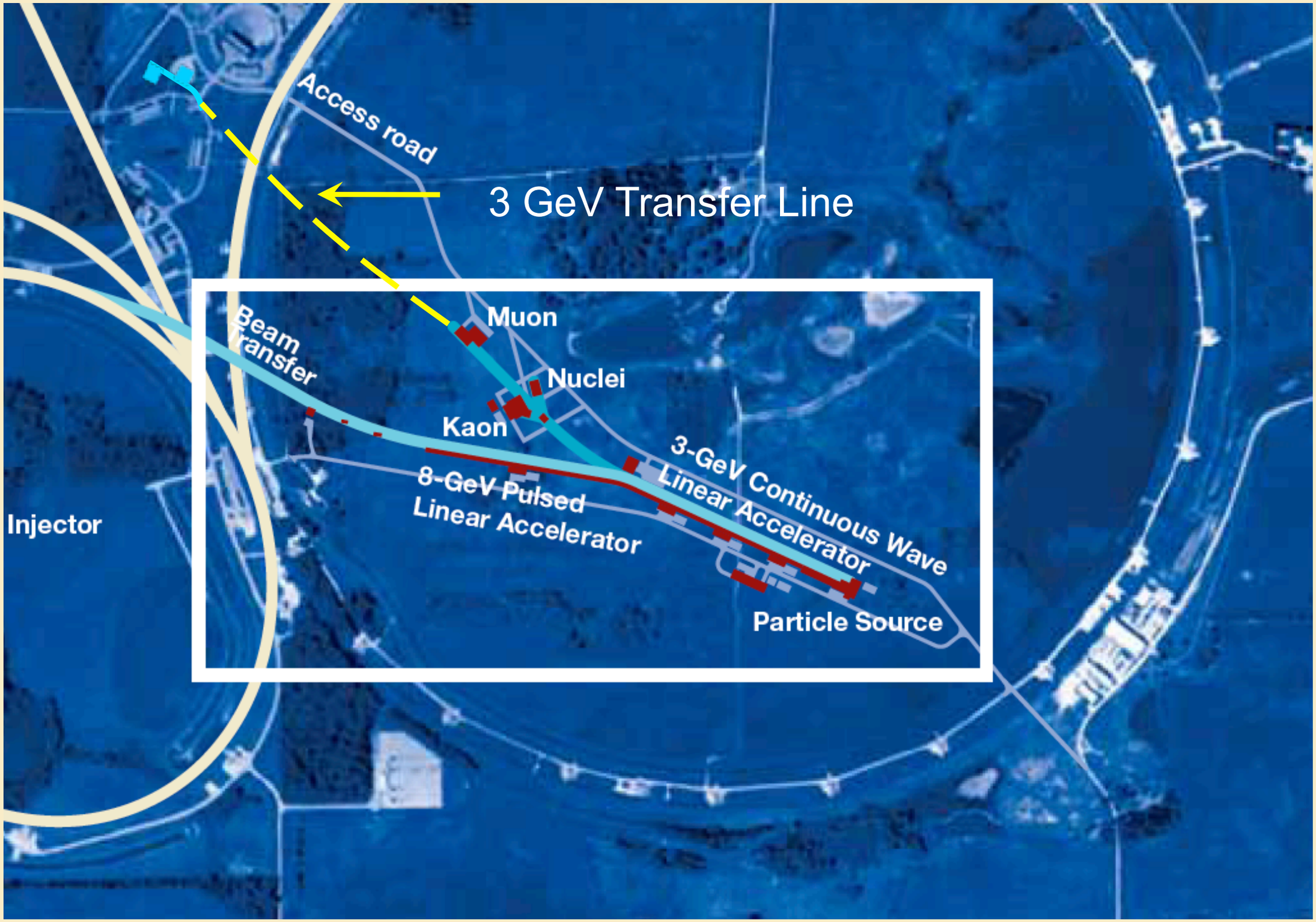
> 70 members

22 institutions

Chris Polly - Project manager



Future: Possible scenario with Project X



Summary

Muons are an excellent laboratory for fundamental physics with a long storied history

g-2 is extremely sensitive to minute high order SM effects and new physics

Nature is kind to these experiments with many tricks we can exploit

The 3σ discrepancy begs for further investigation

The Fermilab experiment is probably taking the magic momentum method to the limit

Future prospects are bright with g-2/EDM experiments at JPARC and Fermilab/Project-X

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

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E989 Proposal document

Various talks by Chris Polly, Dave Hertzog, Brendan Casey, Mary Convery