Themis Bowcock

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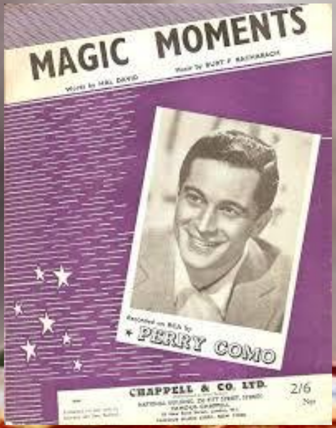
Electric and Magnetic Dipole Moments



Today:
Electric and Magnetic Dipoles

What are they?

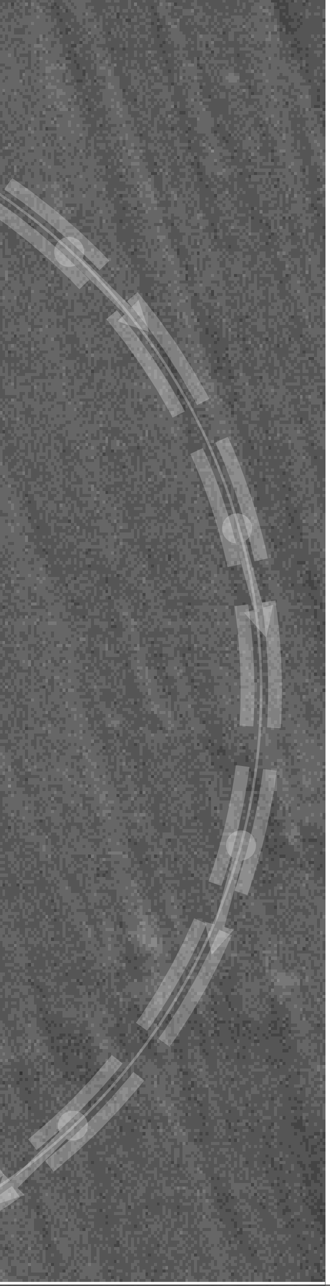
Why are we interested in looking at them?

The frozen-spin technique – “magic momentum” – for moments

A look at some experiments

Fermilab g-2 (muons)
    Magnetic Dipole (g-2)
    Electric Dipole

Proton Electric Dipole Experiment
    CERN proto-proposal

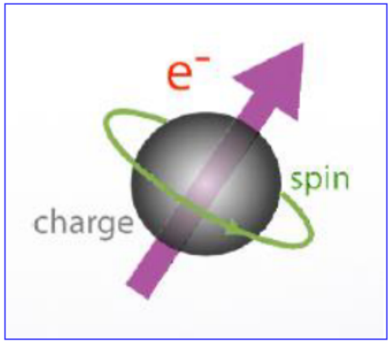


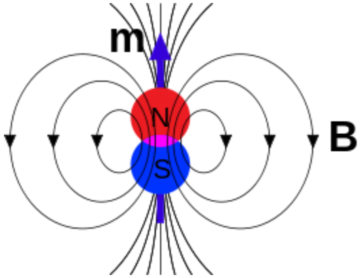
Magnetic dipoles

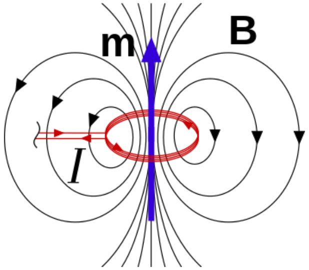
History

The magnetic moment of any elementary particle is related to its intrinsic spin by the “g-factor”.

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

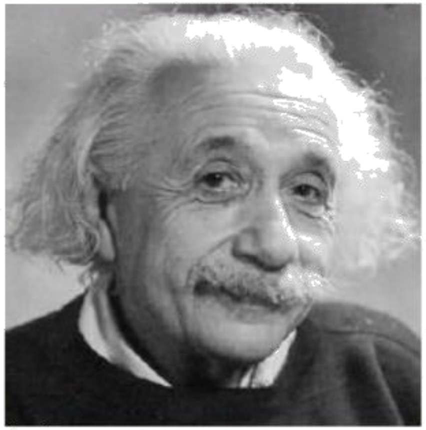






History


Schrödinger


Einstein

- QM describes the smallest scales
- Relativity describes the fastest particles


Dirac

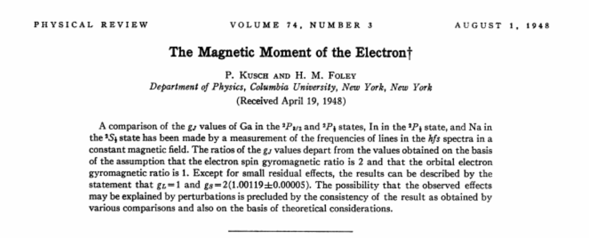
- Dirac united the two!
  - Master equation for a spin 1/2 particle:

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

1948: Precise Measurement and Calculation

Kusch and Foley measure g_e

$$g_e = 2.00238 \text{ +/- } 0.00006$$



PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

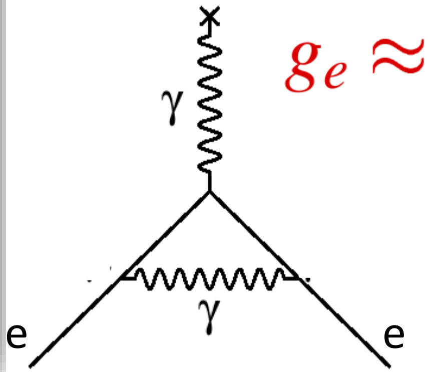
The Magnetic Moment of the Electron†

P. Kusch and H. M. Foley
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L=1$ and $g_S=2(1.00119\pm0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

1947 : QED



$$g_e \approx 2(1+\frac{\alpha}{2\pi}) \approx 2.00232$$

… and Feynman and Tomonaga ….

$\frac{\alpha}{2\pi}$

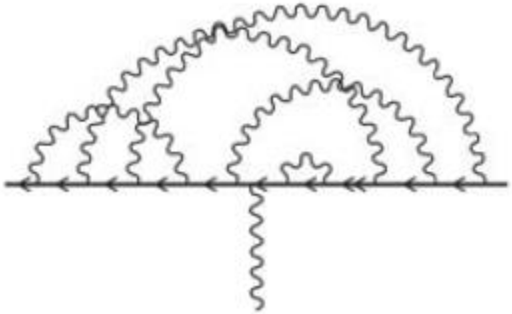
JULIAN SCHWINGER
2·12·1918 — 7·16·1994
CLARICE CARROL SCHWINGER
9·23·1917 — 1·9·2011

quick study

The standard model's greatest triumph

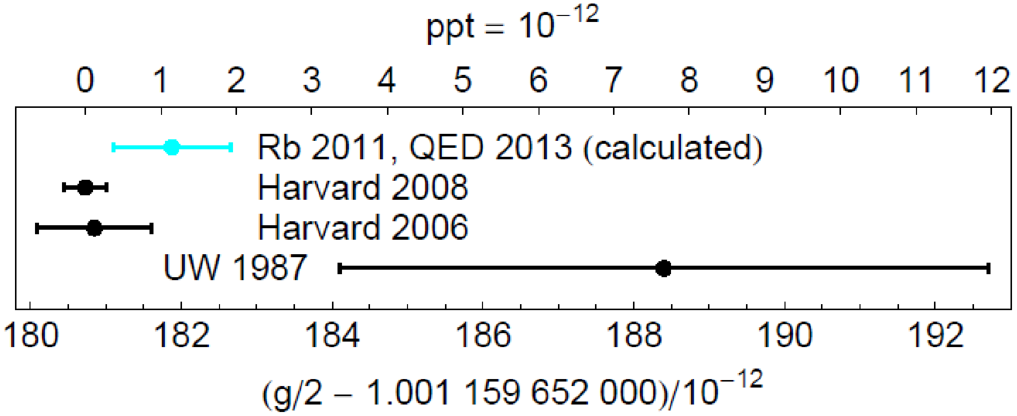
Gerald Gabrielse

December 2013 Physics Today



from measured fine structure constant

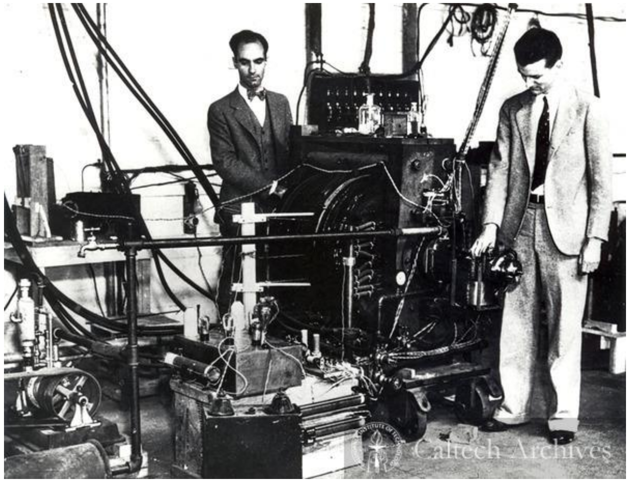
$$\text{Predicted: } \mu/\mu_B = -1.001\,159\,652\,181\,78\,(77)$$
$$\text{Measured: } \mu/\mu_B = -1.001\,159\,652\,180\,73\,(28)$$



Muons

Discovered as
a constituent of cosmic-ray particle ins 1936 by the American physicists Carl D. Anderson and Seth Neddermeyer.

Thought to be
the particle predicted by the Japanese physicist Yukawa Hideki in 1935 to explain the strong force that binds protons and neutrons


Caltech Archives

Was the muon g-2 = 0???

If muon had sub-structure then this simple prediction would be changed.

1933: g of protons and neutrons

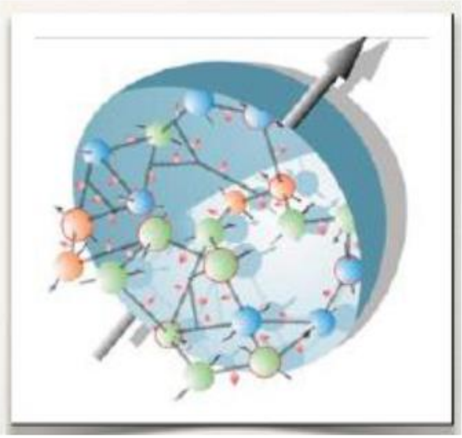
Stern and Estermann were trying to measure g for the proton:

- Found $g_p = 5.6$

That same year Rabi measured g for the neutron:

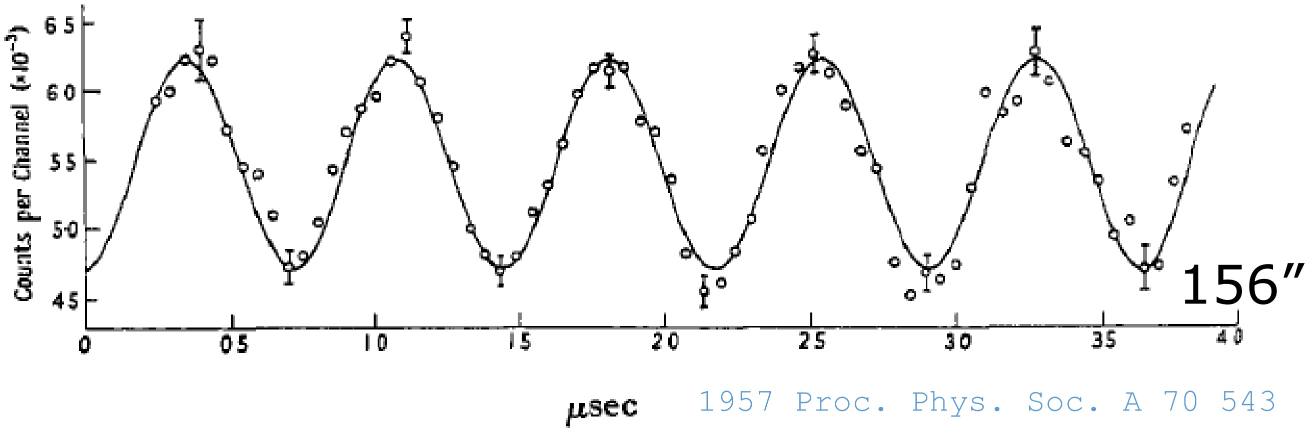
- Found $g_n = -3.8$

These findings gave insight to protons and neutrons having substructure.



Larmor Precession

Garwin, Lederman, Weinrich 2.00+/-0.10 Phys Rev 105, 1415 (Jan 57) @ Columbia



1957 Proc. Phys. Soc. A 70 543

Figure 2. Time distribution of forward electrons from positive muons stopped in copper (87%) and carbon (13%). The magnetic field was 101·9 gauss. The exponential decay factor has been removed, and the first few points have been corrected for a slight non-linearity in the time analyser. Note the displaced zero

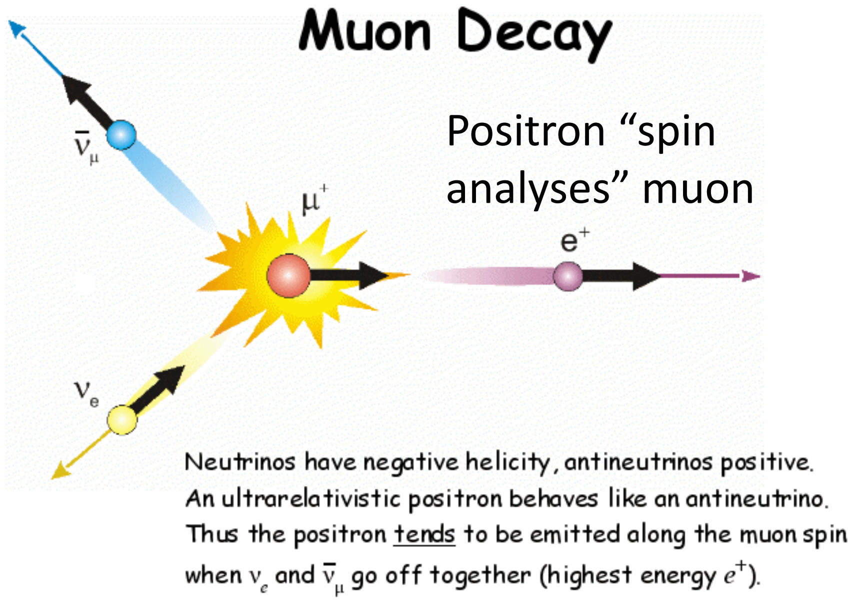
Experiments with a Polarized Muon Beam

By J. M. CASSELS, T. W. O'KEEFFE, M. RIGBY, A. M. WETHERELL
AND J. R. WORMALD
Nuclear Physics Research Laboratory, University of Liverpool

$g = 2.004 \pm 0.014$ (0.6%)

In 1959 CERN launched the g-2 experiment aimed at measuring the anomalous magnetic moment of the muon. The measures were studied using a magnet 83cm x 52cm x 10cm borrowed from the University of Liverpool.

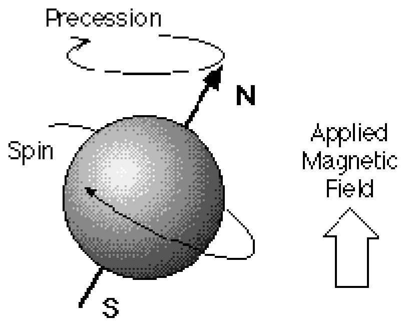
In 1962 this precision had been whittled down to just 0.4%.

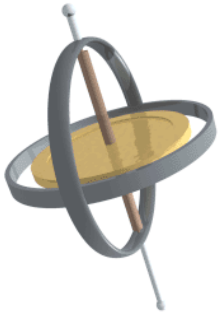


Muon Decay

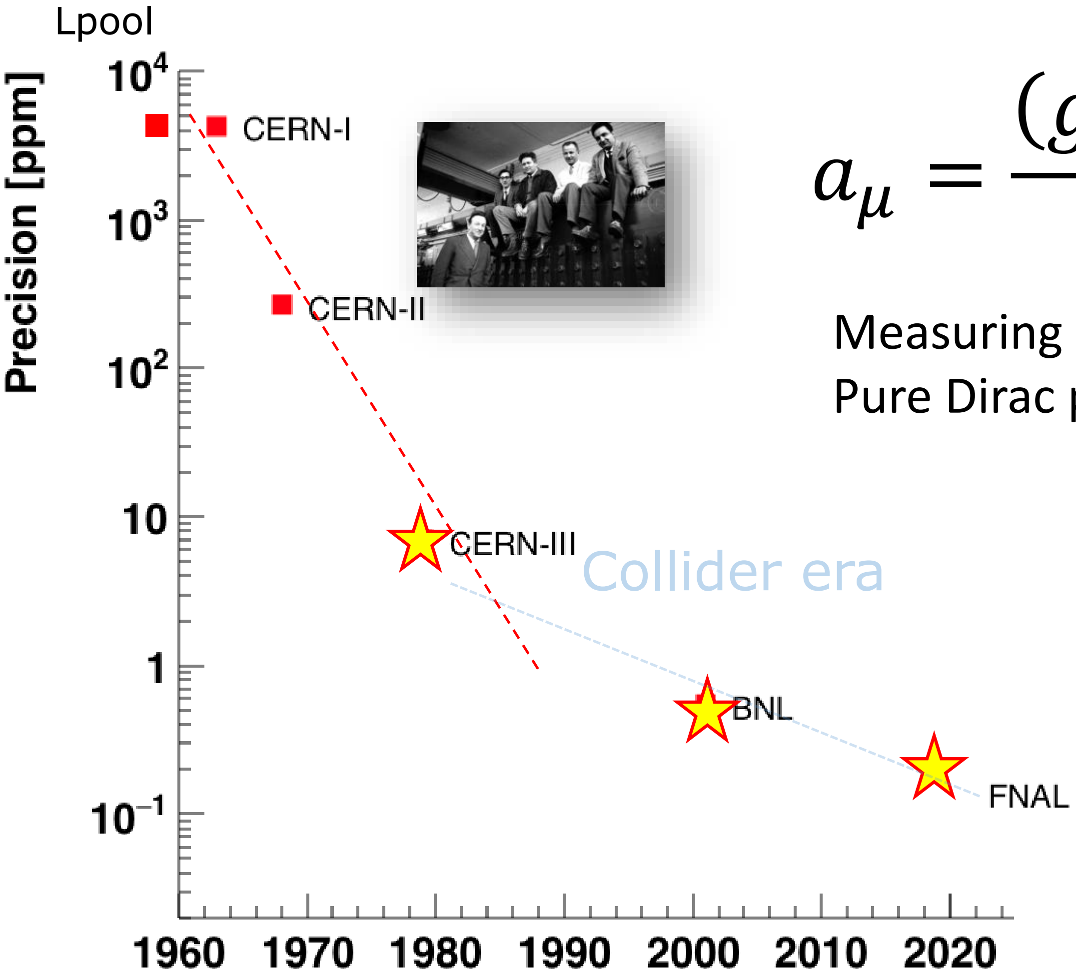
Positron “spin analyses” muon

Neutrinos have negative helicity, antineutrinos positive.
An ultrarelativistic positron behaves like an antineutrino.
Thus the positron tends to be emitted along the muon spin
when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).





Evolution of precision



$$a_\mu = \frac{(g-2)}{2}$$

Measuring deviations from Pure Dirac prediction

Muon Anomalous Magnetic Moment

At each stage it was meant to be obvious…

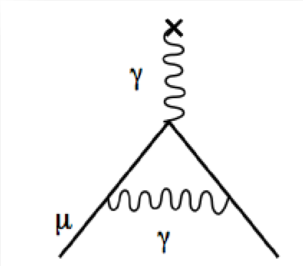
Each time it has confounded expectation … theory extensions

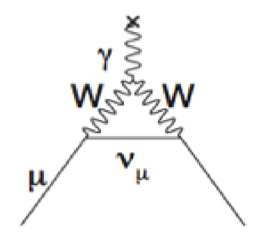
e-like tests the Standard Model

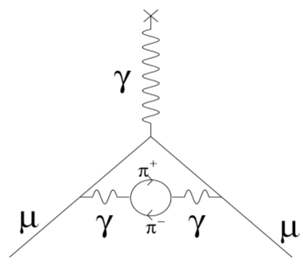
But muons are heavier (original interest)

More sensitive to new physics

$$a^{SM} = a^{QED} + a^{Weak} + a^{Hadronic}$$







Vacuum Polarization

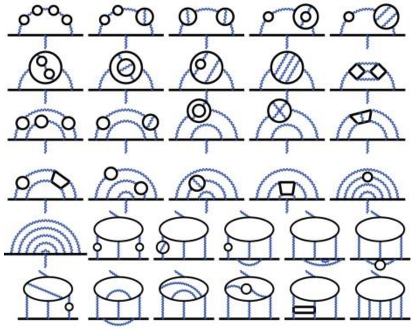
LO + NLO …

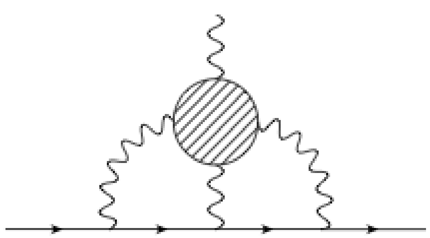
~ 60% total SM uncertainty

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

Theory: 12,672 Feynman Diagrams

2.00231930436356 ± 0.00000000000154



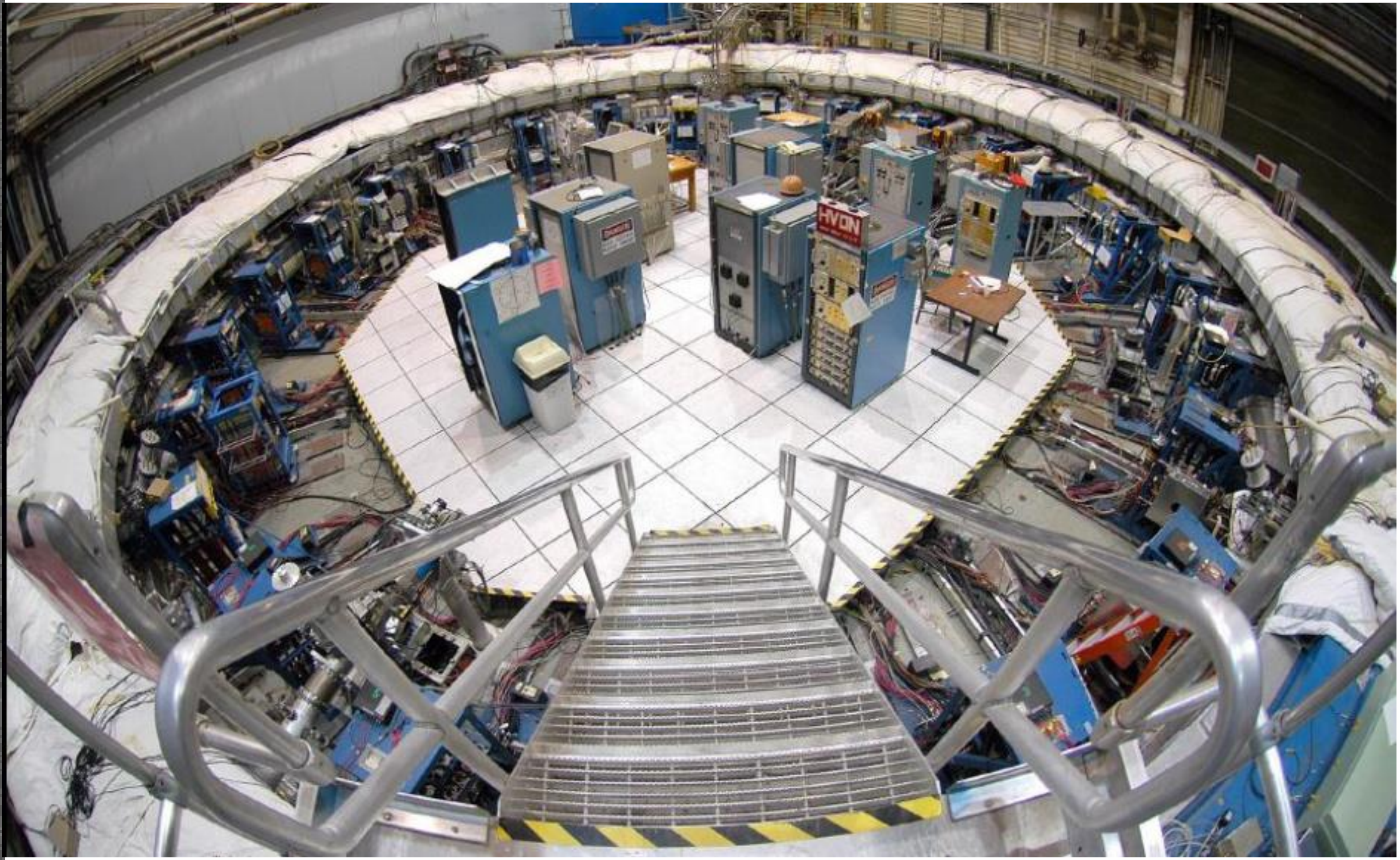


Light by Light

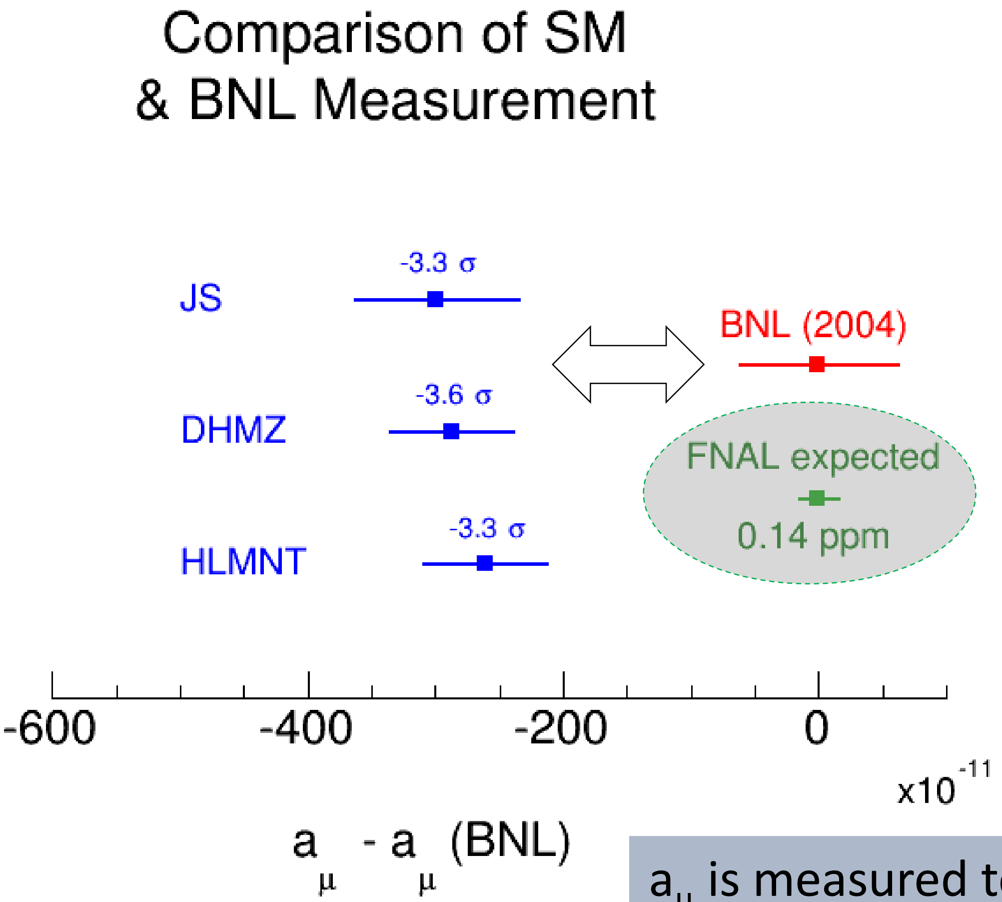
~ 40% total SM uncertainty

BNL E821

Technique



$$\begin{aligned}\Delta a_\mu(\mathrm{Expt}-\mathrm{SM}) &= (286 \pm 80) \times 10^{-11}\\ &= (260 \pm 78) \times 10^{-11}\end{aligned}$$



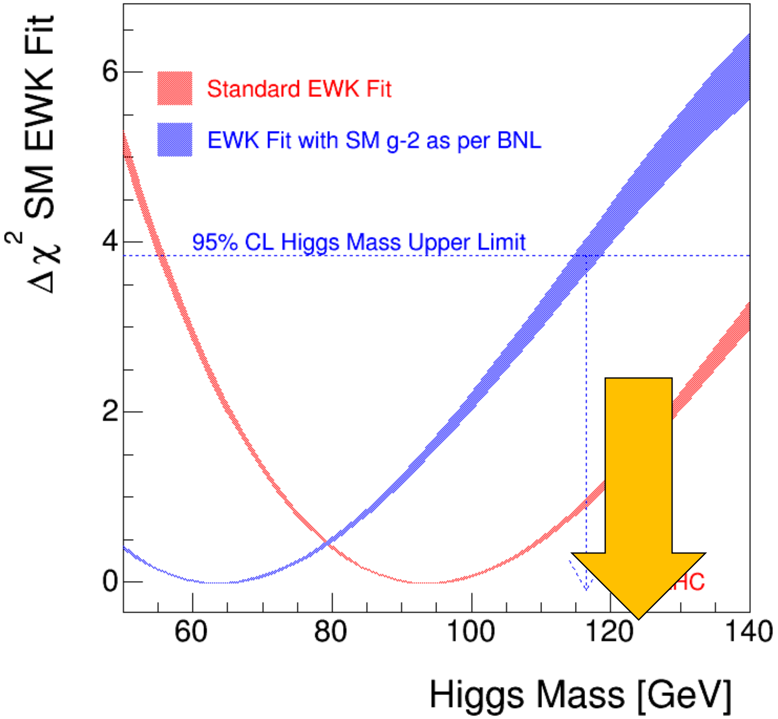
a_μ is measured to be (slightly) too big compared with theory.

a_μ^{SM}: update HLMNT11 → KNT17 presented @ TGM2

	2011		2017	*to be discussed
QED	11658471.81 (0.02)	⟶	11658471.90 (0.01)	[Phys. Rev. Lett. 109 (2012) 111808]
EW	15.40 (0.20)	⟶	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	⟶	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]*
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]*
	HLMNT11		**KNT17**	
LO HVP	694.91 (4.27)	⟶	692.23 **(2.54)**	this work*
NLO HVP	-9.84 (0.07)	⟶	-9.83 (0.04)	this work*
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144] *
Theory total	11659182.80 (4.94)	⟶	11659181.00 (3.62)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	⟶	28.1 (7.3)	this work
Δa_μ	3.3σ	⟶	3.9σ	this work

Hadronic Corrections

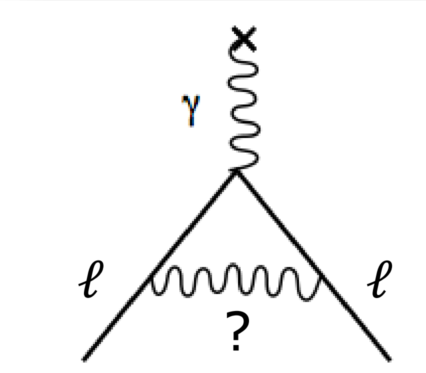
For the BNL result to match the SM prediction then the SM hadronic estimate would need to be wrong by 6σ



The beauty of the SM is that everything is related …..

"You cannot cook-up a zero g-2 SM anomaly and be consistent with the LHC Higgs mass!"

New Physics



New physics contributes as:

$$\left(\frac{m_\ell}{M_{\mathrm{NEW}}}\right)^2$$

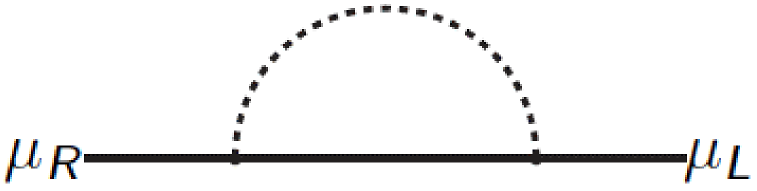
Electron g-2 is presently measured x 2,000 better than muon g-2

But $\left(\frac{m_\mu}{m_e}\right)^2$ is 44,000. 2nd Generation Leptons v. useful.

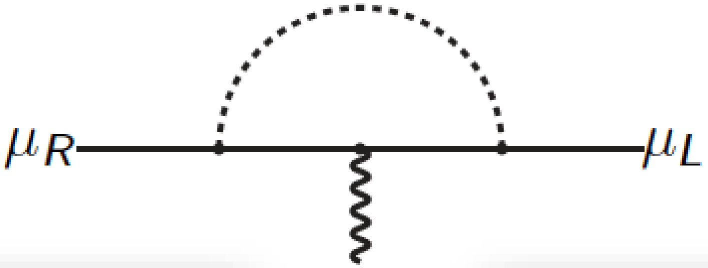
Muon has sensitivity to new physics from < MeV to TeV.

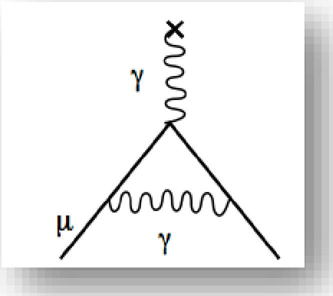
Any new physics that contributes to the muon mass can contribute to a$_\mu$

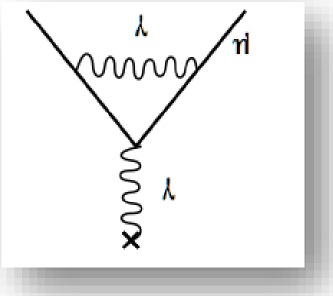
m$_\mu$ in loops



a$_\mu$ in loops



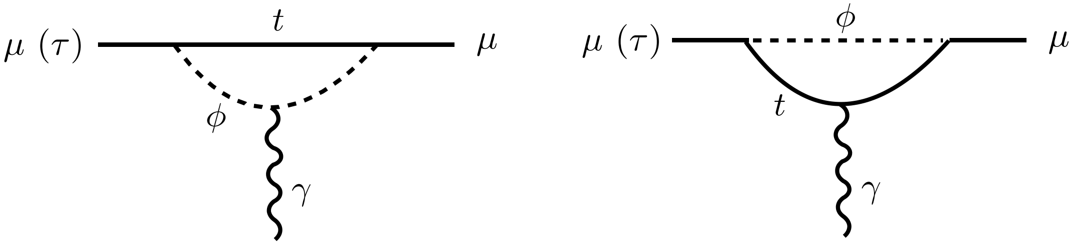




New Physics? just a few of many recent studies

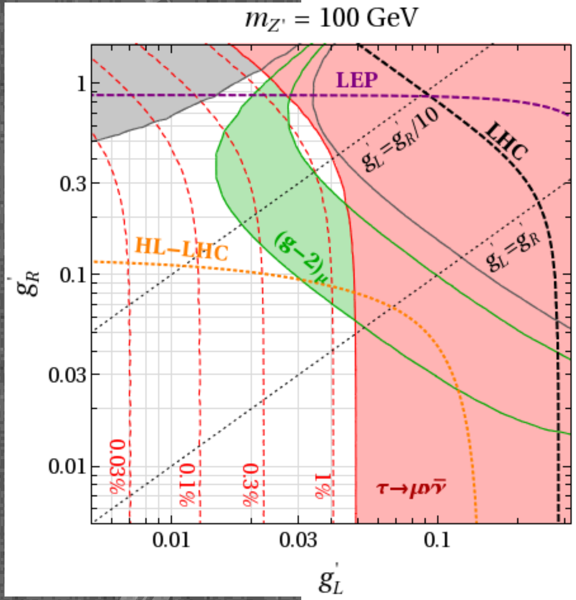
- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016) 141802

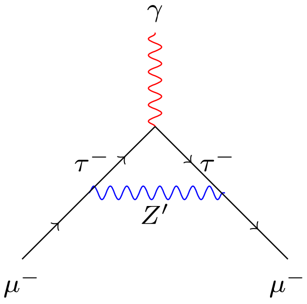
one new scalar could explain several anomalies seen by BaBar, Belle and LHC in the flavour sector
(e.g. violation of lepton universality in B -> Kll, enhanced B -> Dτν) and solve g-2, while satisfying all
bounds from LEP and LHC

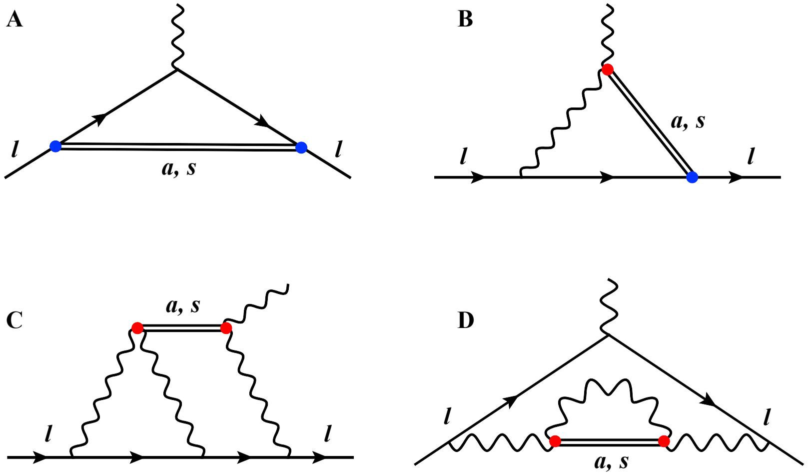


New Physics? just a few of many recent examples

- light Z' can evade many searches involving electrons by non-standard couplings preferring heavy leptons (but see BaBar's direct search limits in a wide mass range, PRD 94 (2016) 011102), or invoke flavour off-diagonal Z' to evade constraints [Altmannshofer et al., PLB 762 (2016) 389]







- axion-like particle (ALP), contributing like π^0 in HLbL [Marciano et al., PRD 94 (2016) 115033]

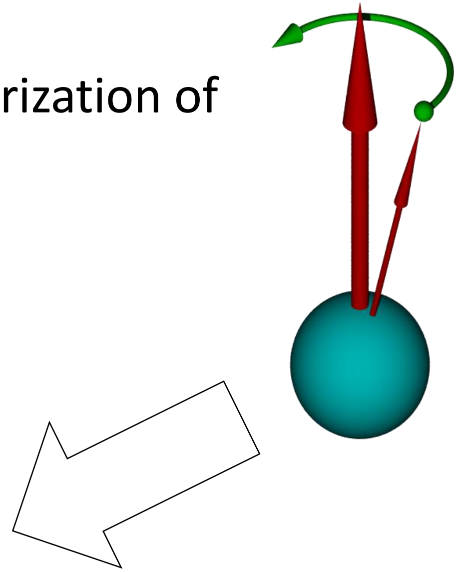
- `dark photon' - like fifth force particle [Feng et al., PRL 117 (2016) 071803]

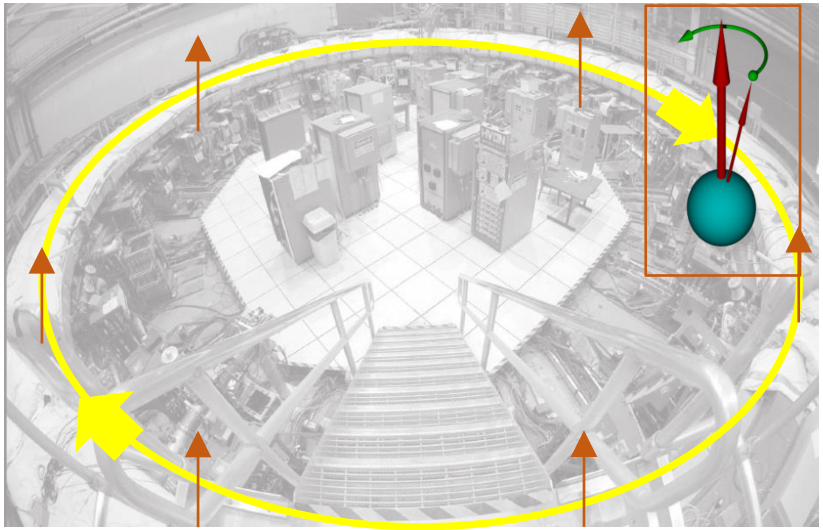
Penning Trap

Muons live 2.2 μs before decaying

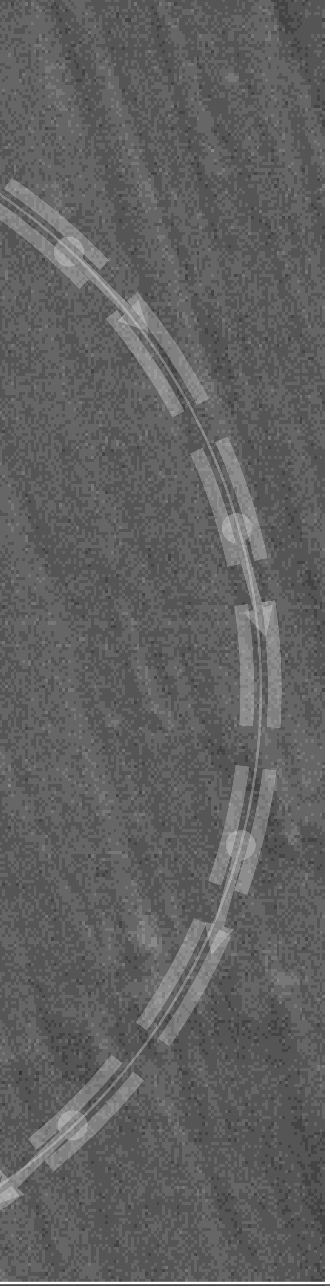
Direction of positron follows the polarization of the muon

Measure Larmor Precession





Since 1976 rather than stopping (or drifting) muons and applying field “trap” them



Technique

Particle moving in a magnetic field:

- momentum turns with cyclotron frequency ω_C,
- spin turns with ω_S

$$\omega_C = -\frac{QeB}{m\gamma}; \qquad \omega_S = -g\frac{QeB}{2m} - (1-\gamma)\frac{QeB}{\gamma m}$$

Spin turns relative to the momentum with ω_a

$$\omega_a = \omega_S - \omega_C = -\left(\frac{g-2}{2}\right)\frac{Qe}{m}B = -a\frac{Qe}{m}B$$

Vertical Focussing Required (E-quads)

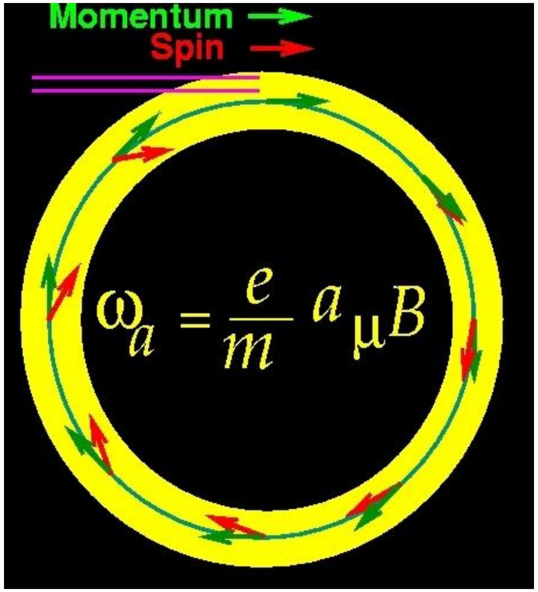
With an electric quadrupole field for vertical focusing

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

Simplify by choose “magic” momentum so that

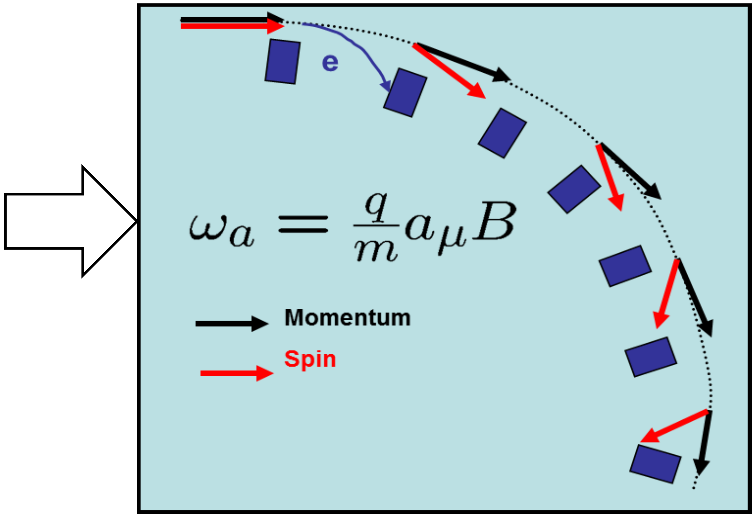
$$a_\mu - \frac{1}{\gamma^2-1} = 0$$

With γ =29.3, p=3.09 GeV/c, dilated lifetime = 64.4 μs

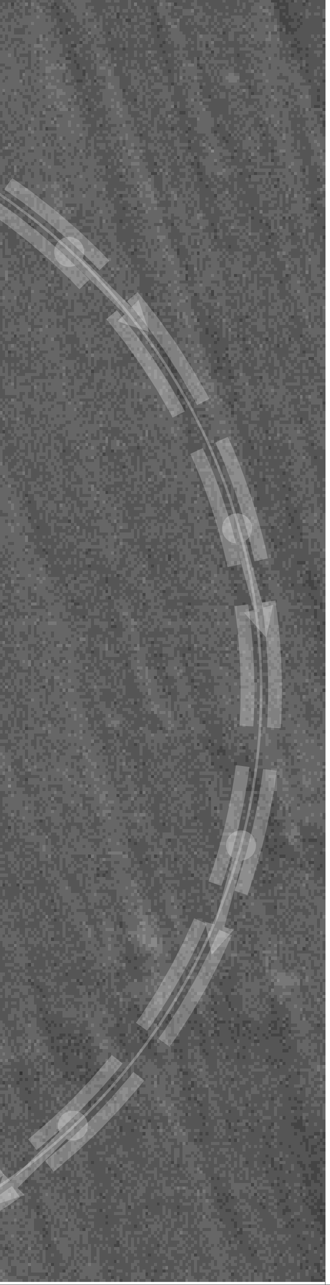


“CERN-III miracle”

Technique



$$\omega_a = \frac{q}{m} a_\mu B$$



Magnetic field

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B}\,\right]$$

How can it be so accurate?

Make measurement with reference to proton NMR

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\lambda - \frac{\omega_a}{\omega_p}}$$

$$\lambda = \frac{\mu_\mu}{\mu_p} = 3.183345137(85) \rightarrow 27\text{ppb}$$

From muonium, hyperfine structure

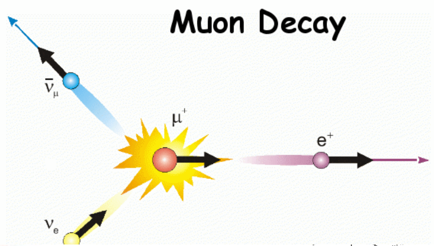
W. Liu et al., Phys. Rev. Lett. 82, 711 (1999).

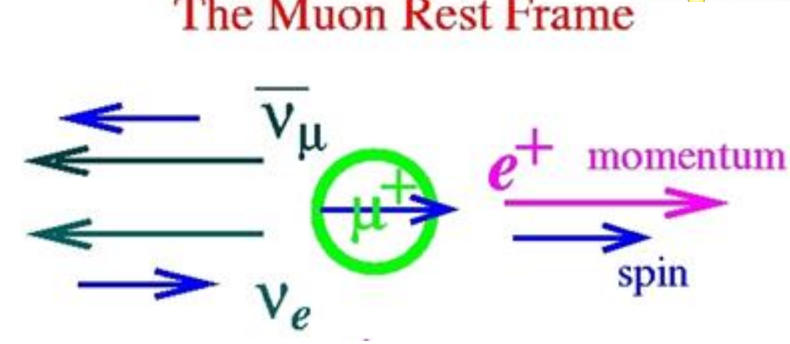
Technique

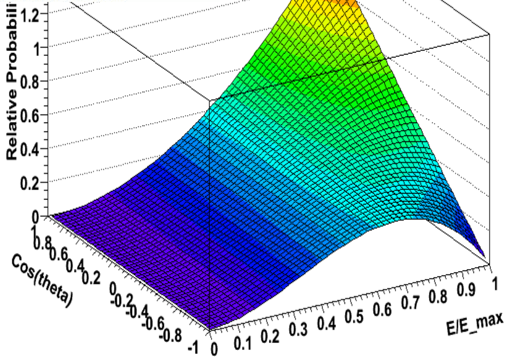
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ Source: Polarized muons born from pion decay

$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ In ring muons decay to positrons

- The highest energy positrons are correlated with the muon spin.
- As the spin rotates forward and backward the number of e^+ is modulated by ω_a

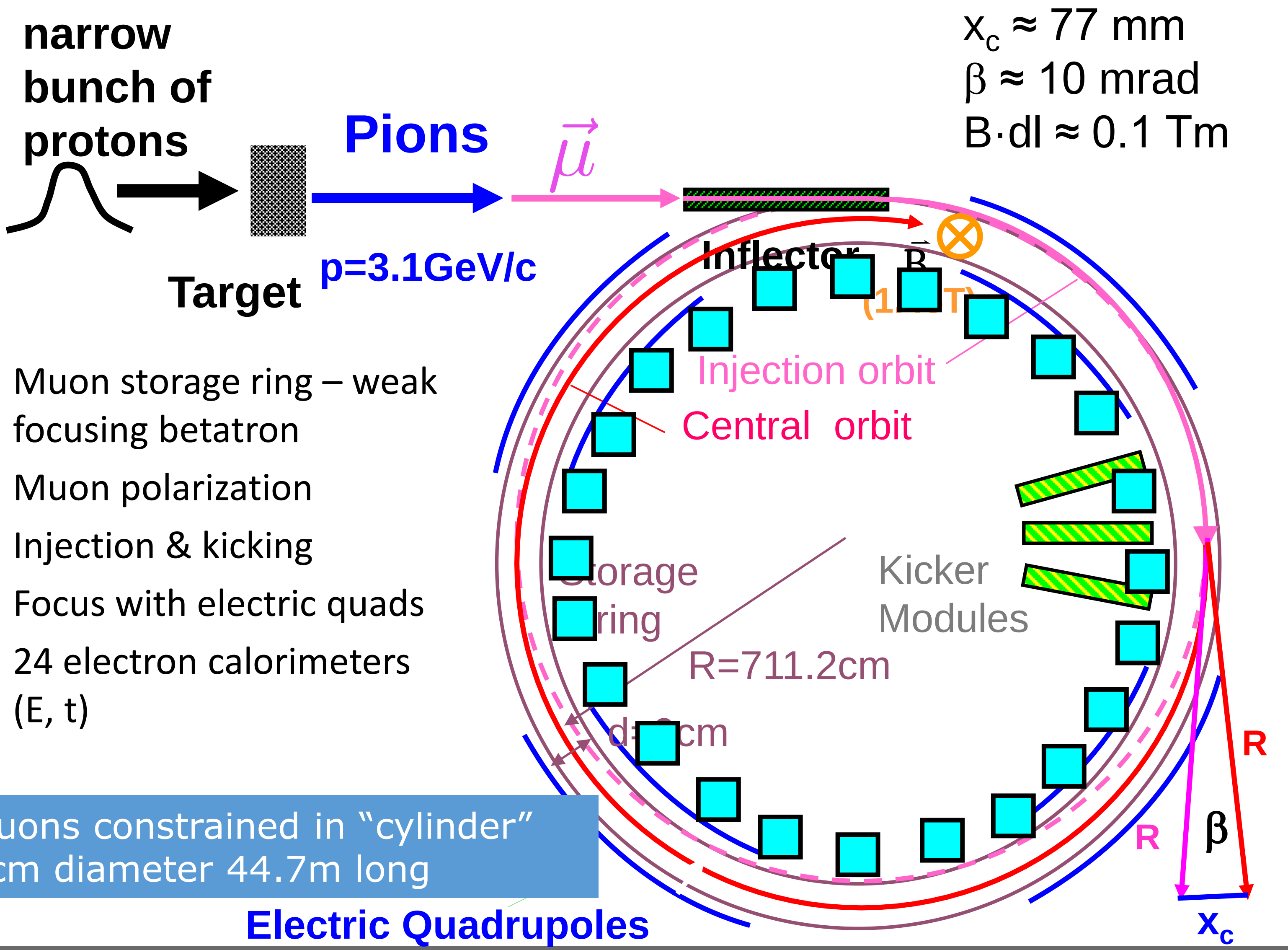






Schematic

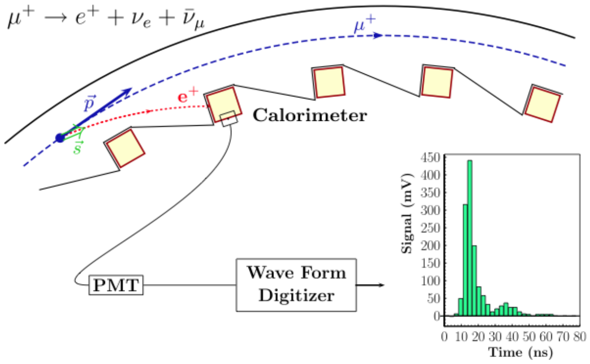
Technique



- Muon storage ring – weak focusing betatron
- Muon polarization
- Injection & kicking
- Focus with electric quads
- 24 electron calorimeters (E, t)

Muons constrained in "cylinder"
9cm diameter 44.7m long

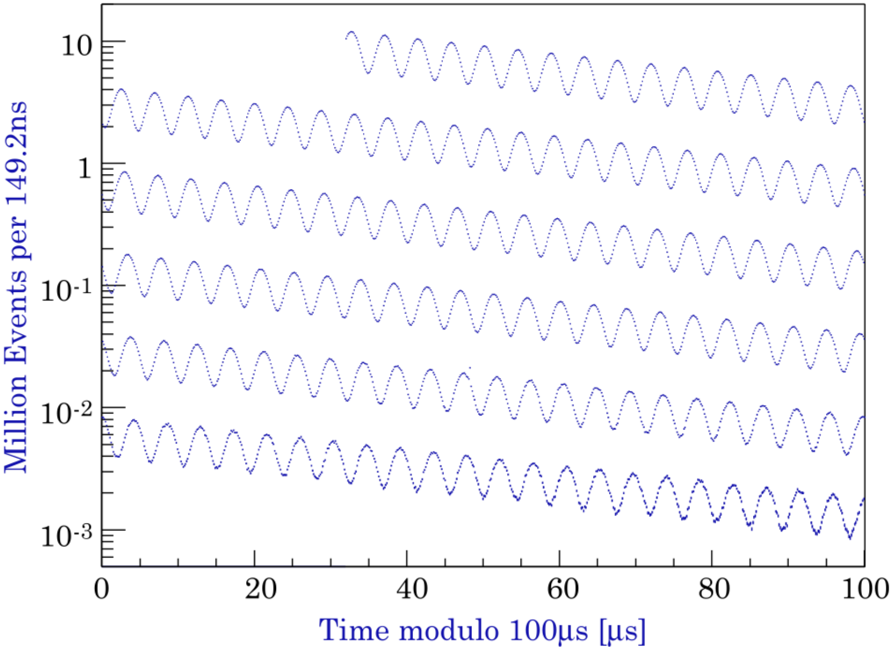
BNL data



$$N(t) = N_0 \exp(-t/\gamma\tau_\mu)\,[1 - A\cos(\omega_a t + \phi)]$$

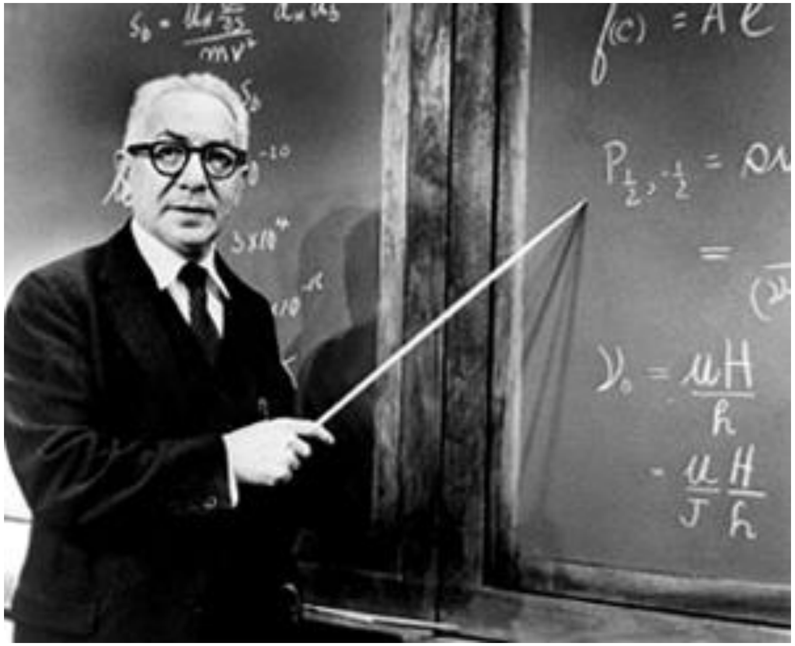
A, ϕ : known functions of e+ energy

BNL 3.6 billion μ decays (2001 data)



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

“Lighthouse on a carousel”



I. Rabi (Schawlow)

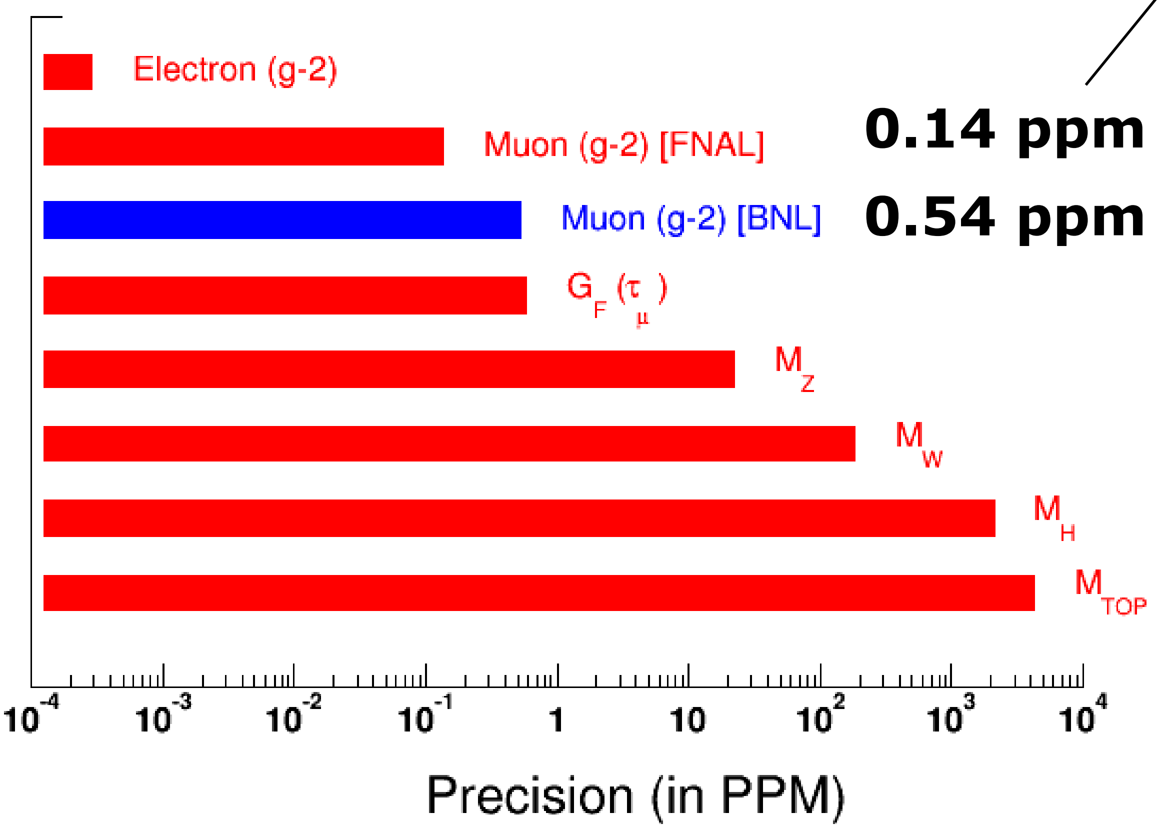
g-2 Experiment at FNAL

…can we resolve the E821 anomaly?

BROOKHAVEN
NATIONAL LABORATORY

Fermilab

Technique

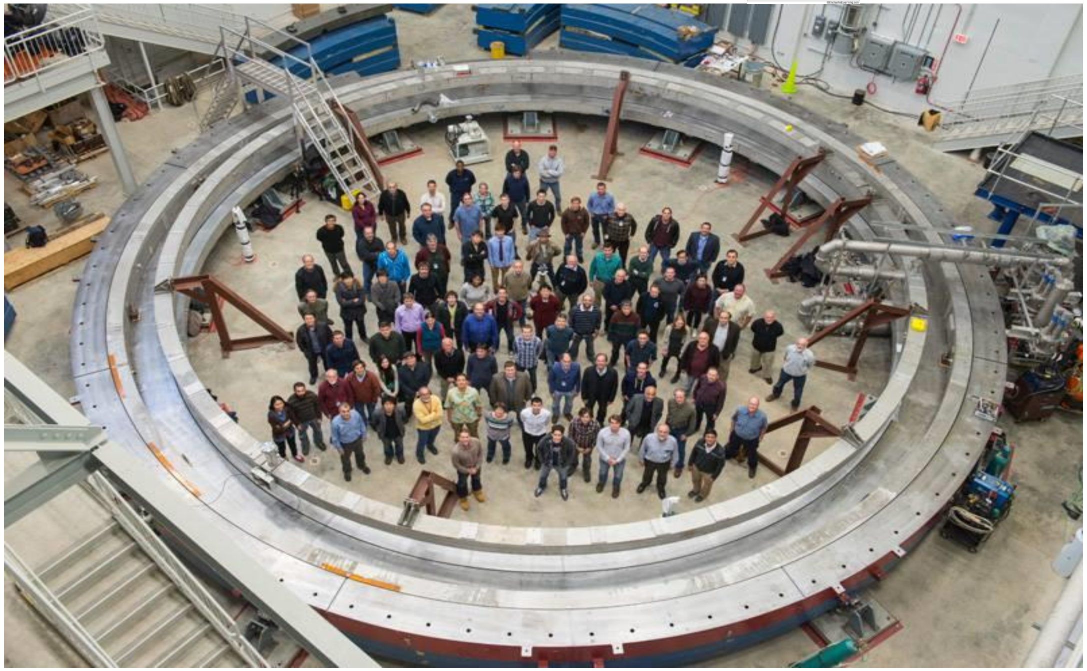


Enough to establish 5-10 σ

0.14 ppm

0.54 ppm

Technique



Team Liverpool

About 15 including

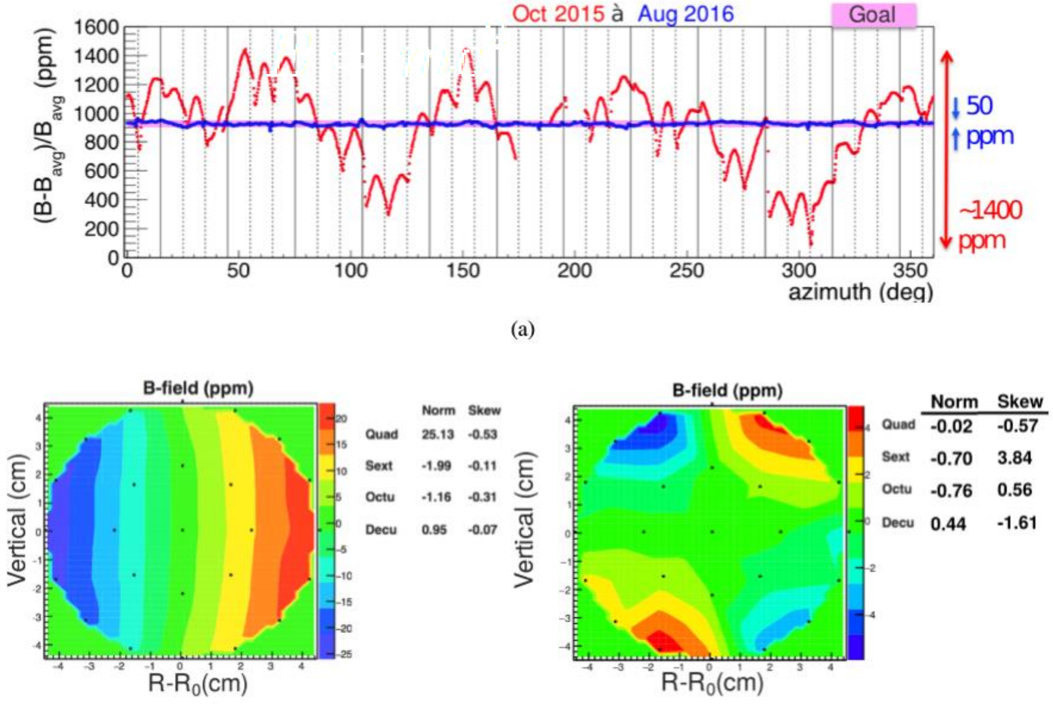
Academics & Senior Scientists
Engineers
+Workshop Technicians
Graduate Students
Undergraduates
Interns

Shimming …..

Muons are distributed over storage volume

B-field is not uniform over this volume

Need to convolute the two.



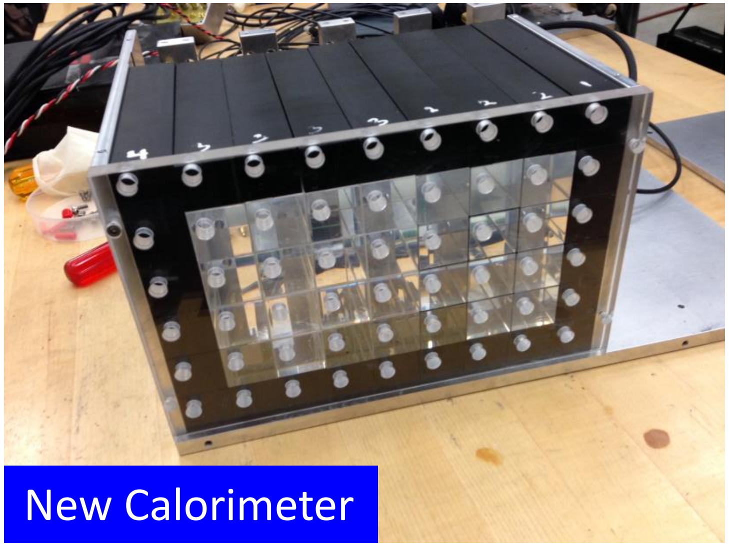
(a)

	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

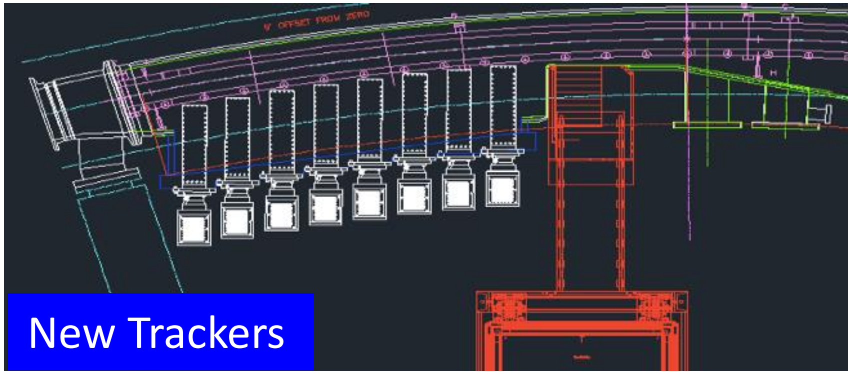
	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

(b) (c)

New Detectors


New Calorimeter

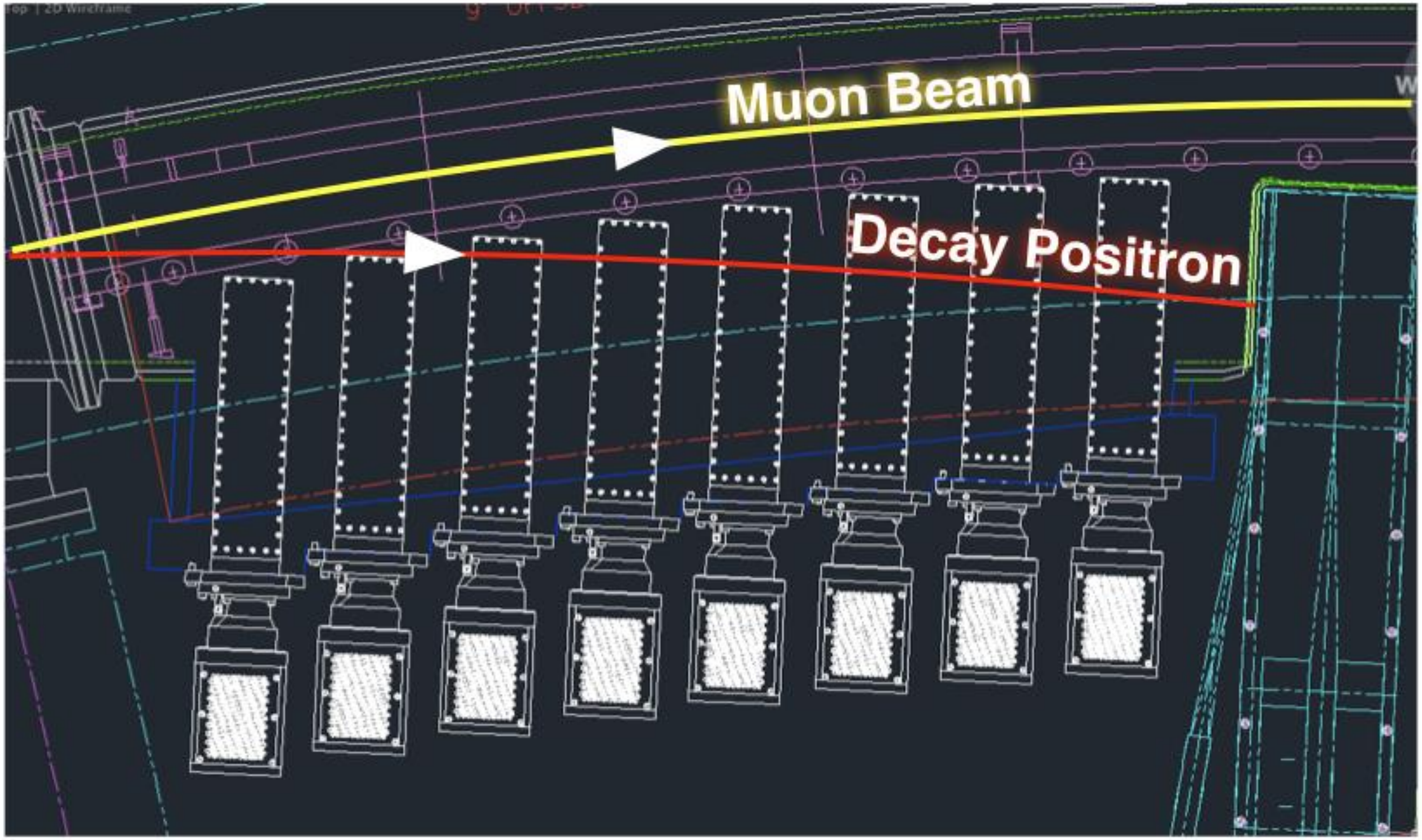
Calorimeter (PbF_2 + SiPMT)
- more segmented.
- x2 sampling (800M/s) vs BNL
- quicker response (5 ns)
- energy resolution <5% @ 2GeV
- improved gain stability
- improved laser calibration system


New Trackers

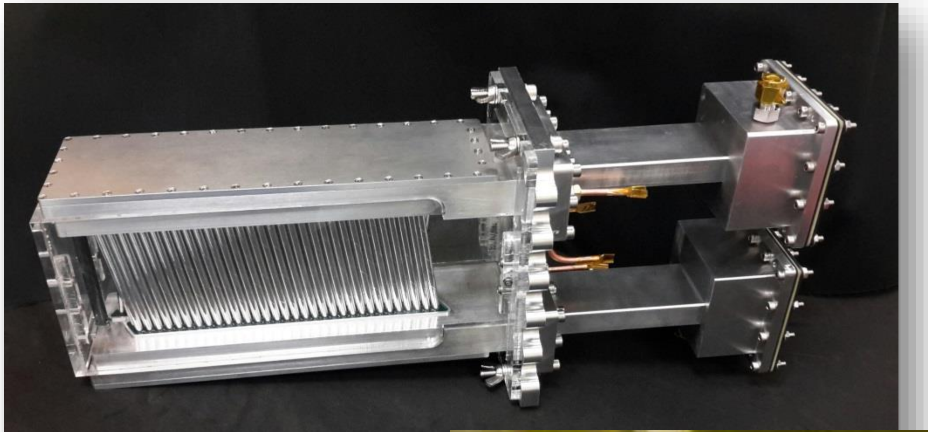
Straw Trackers (UK)
- authenticate pileup
- measure muon profile
- identify lost muons
- calibrate calorimeter
- measure EDM

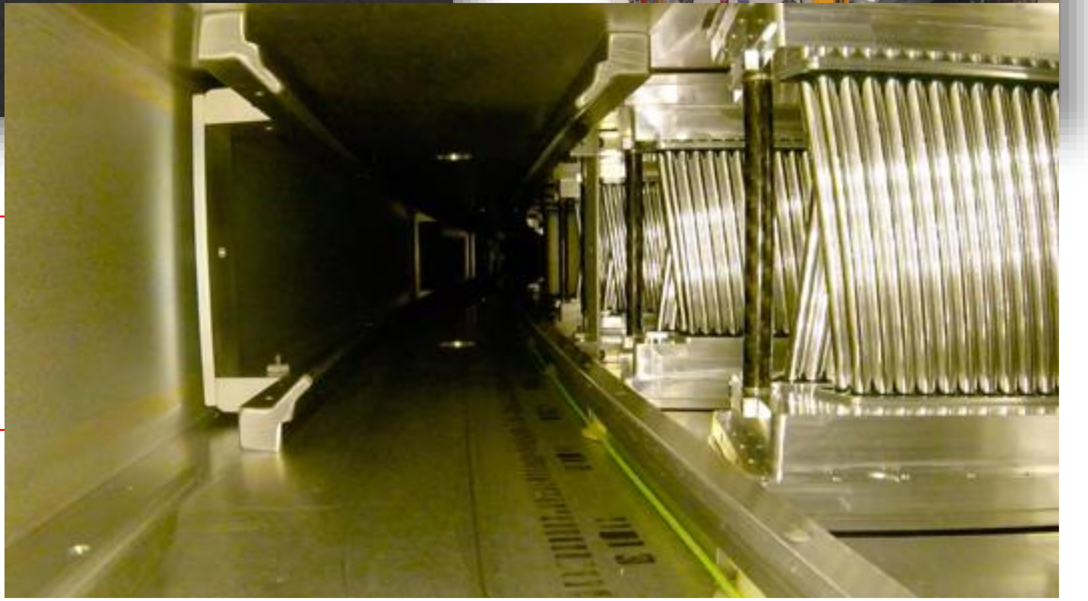
Traceback – 3

Elements



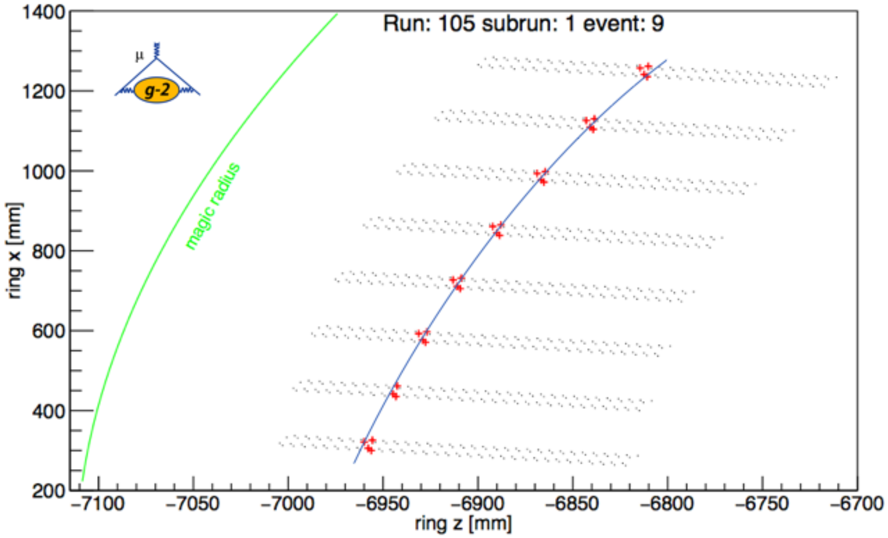
Straw trackers

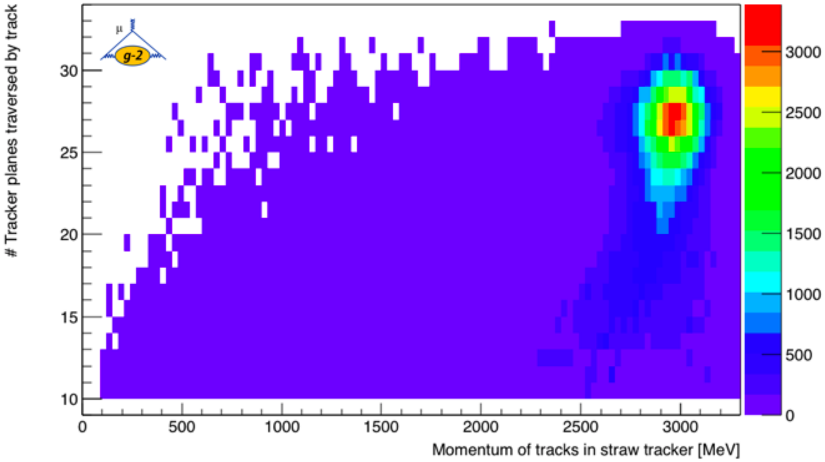


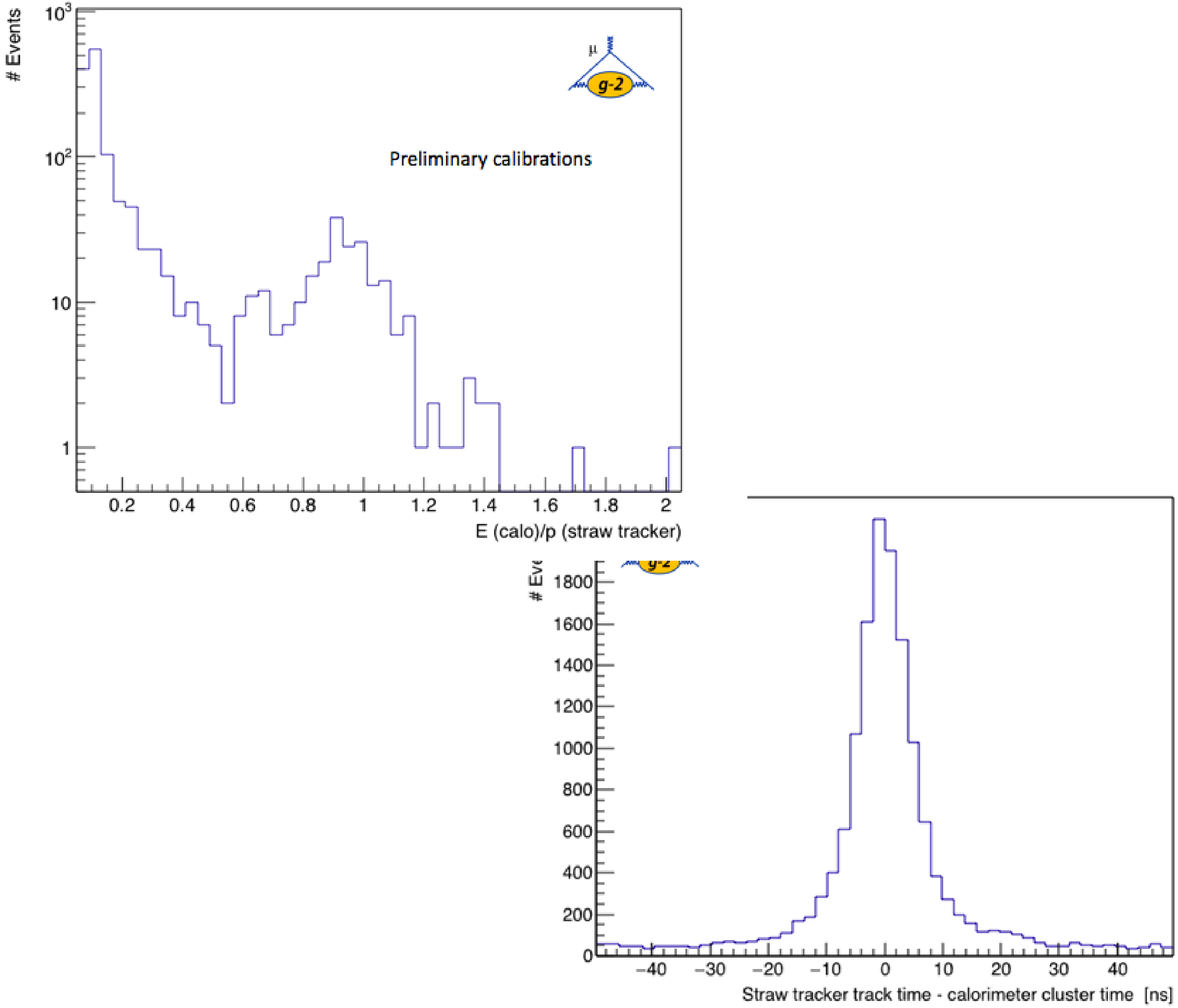


100 μm radial resolution achieved

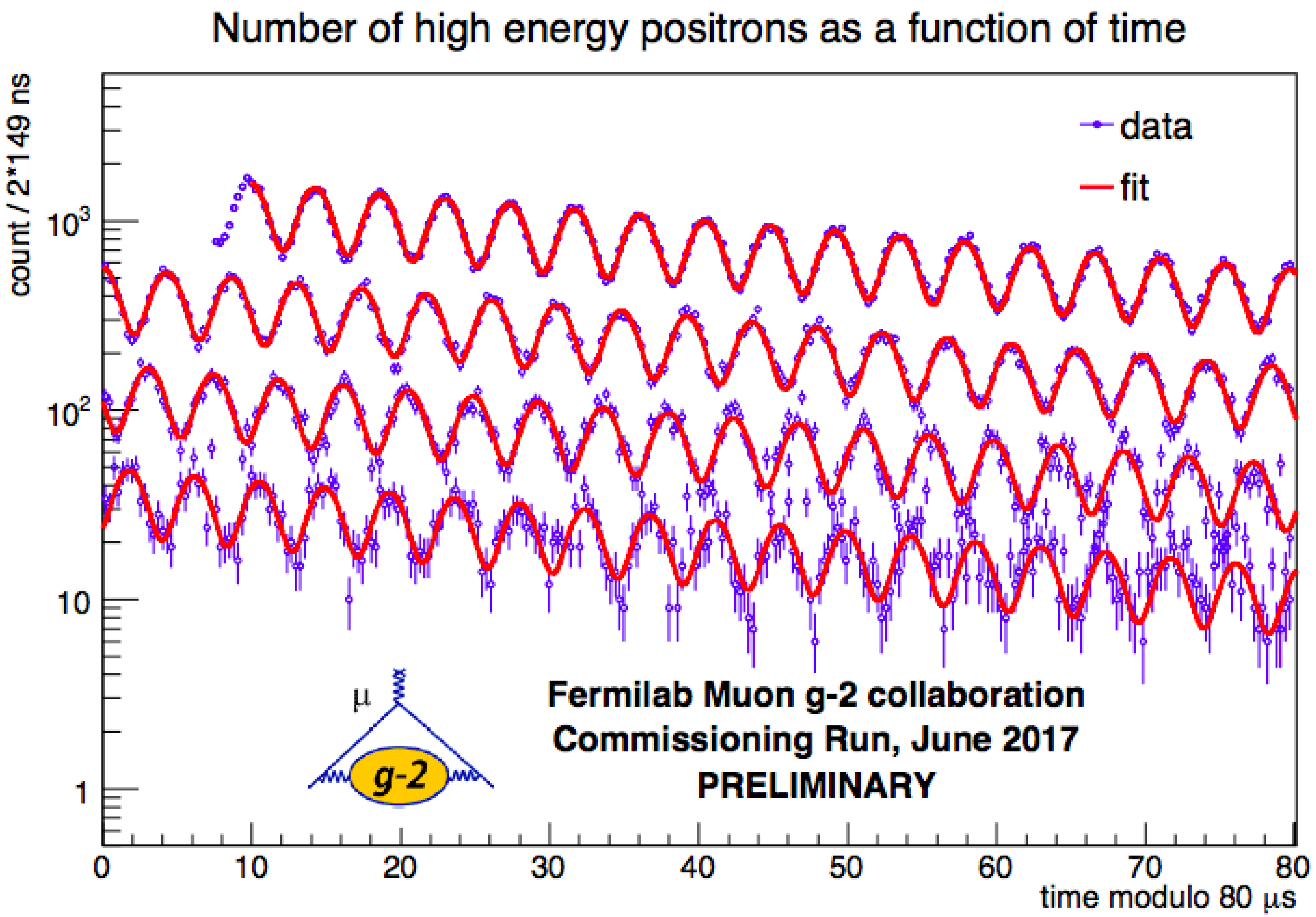
First Track


Run: 105 subrun: 1 event: 9
g-2
μ
magic radius
ring x [mm]
1400
1200
1000
800
600
400
200
−7100
−7050
−7000
−6950
−6900
−6850
−6800
−6750
−6700
ring z [mm]


g-2
μ
Tracker planes traversed by track
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
Momentum of tracks in straw tracker [MeV]
3000
2500
2000
1500
1000
500
0

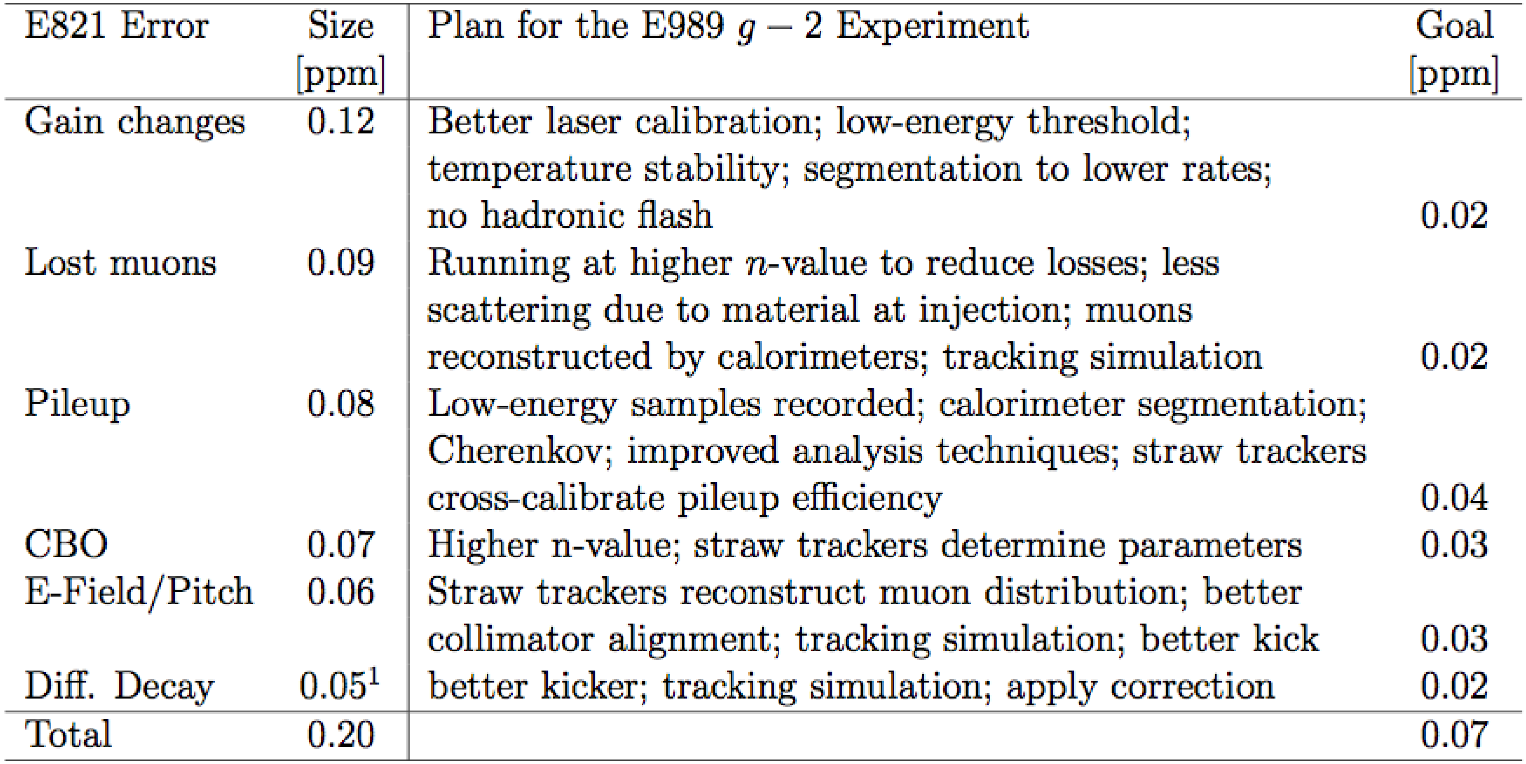


Events
10^3
10^2
10
1
Preliminary calibrations
μ
g-2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
E (calo)/p (straw tracker)
Eve
g-2
1800
1600
1400
1200
1000
800
600
400
200
0
−40
−30
−20
−10
0
10
20
30
40
Straw tracker track time - calorimeter cluster time [ns]

Number of high energy positrons as a function of time
count / 2*149 ns
10^3
10^2
10
1
data
fit
0
10
20
30
40
50
60
70
80
time modulo 80 µs
µ
g-2
Fermilab Muon g-2 collaboration
Commissioning Run, June 2017
PRELIMINARY

ω_a systematics

Elements



E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05^1	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

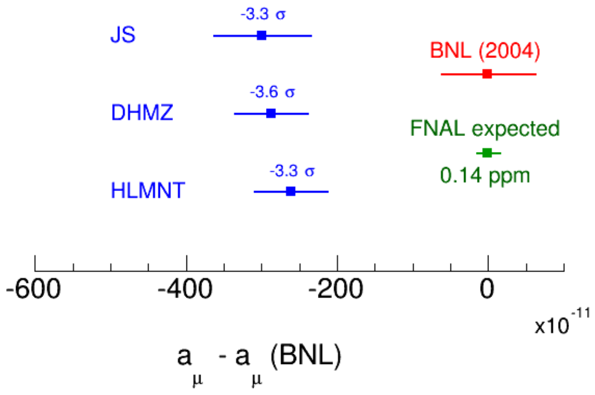
muonE experiment proposal
(g-2 groups @ PBC – CERN)

Muon on electron scattering

Uncertainties and Interpretation

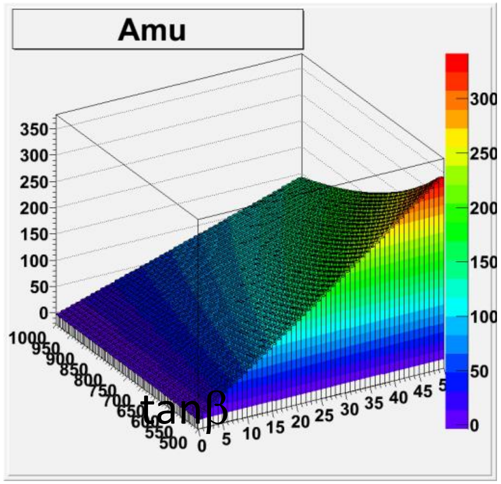
If effect persists we can start to look at possible NP …

g-2 does not probe flavour changing interactions but NP in loops . Can address models: technicolor, SUSY, 2HDM, LHT, W’, Z’ (TeV range)



Neutralino mass = 500 GeV

Smuon mass (Gev)



By 2019 (First Data 2017): 5.5σ significance from the experimental improvement becomes 9.7σ evidence of NP *if* central value remains the same AND theory does not move.

Comments

Moments …

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known" : Pauli

"No experiment is so dumb, that it should not be tried" : Gerlach

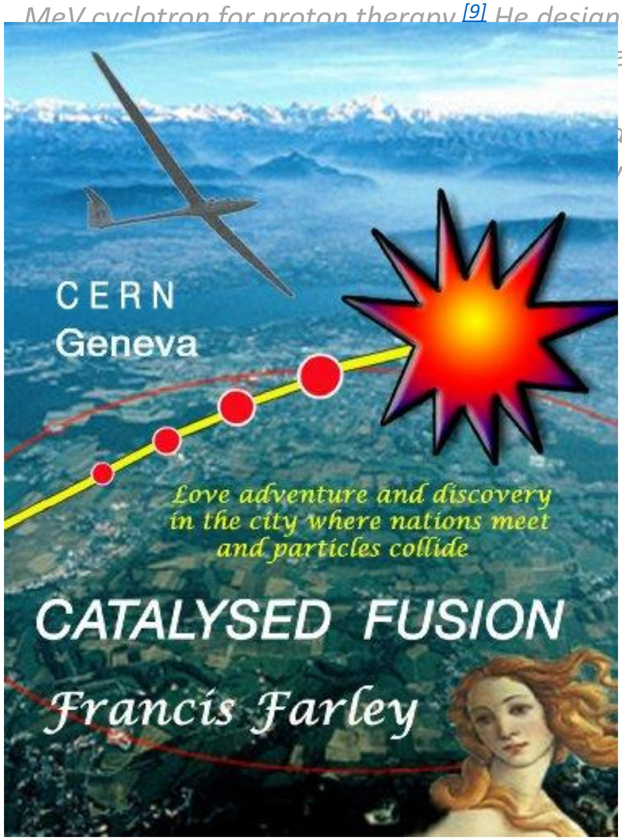
"the Muon obeys QED.
g-2 is correct to 0.5%.
In my opinion, it will be
right to any accuracy. So it's not worth doing the experiment"

Head of CERN Theory at time of CERN EDMs

"would you like to predict the result ?" : F. Farley FRS

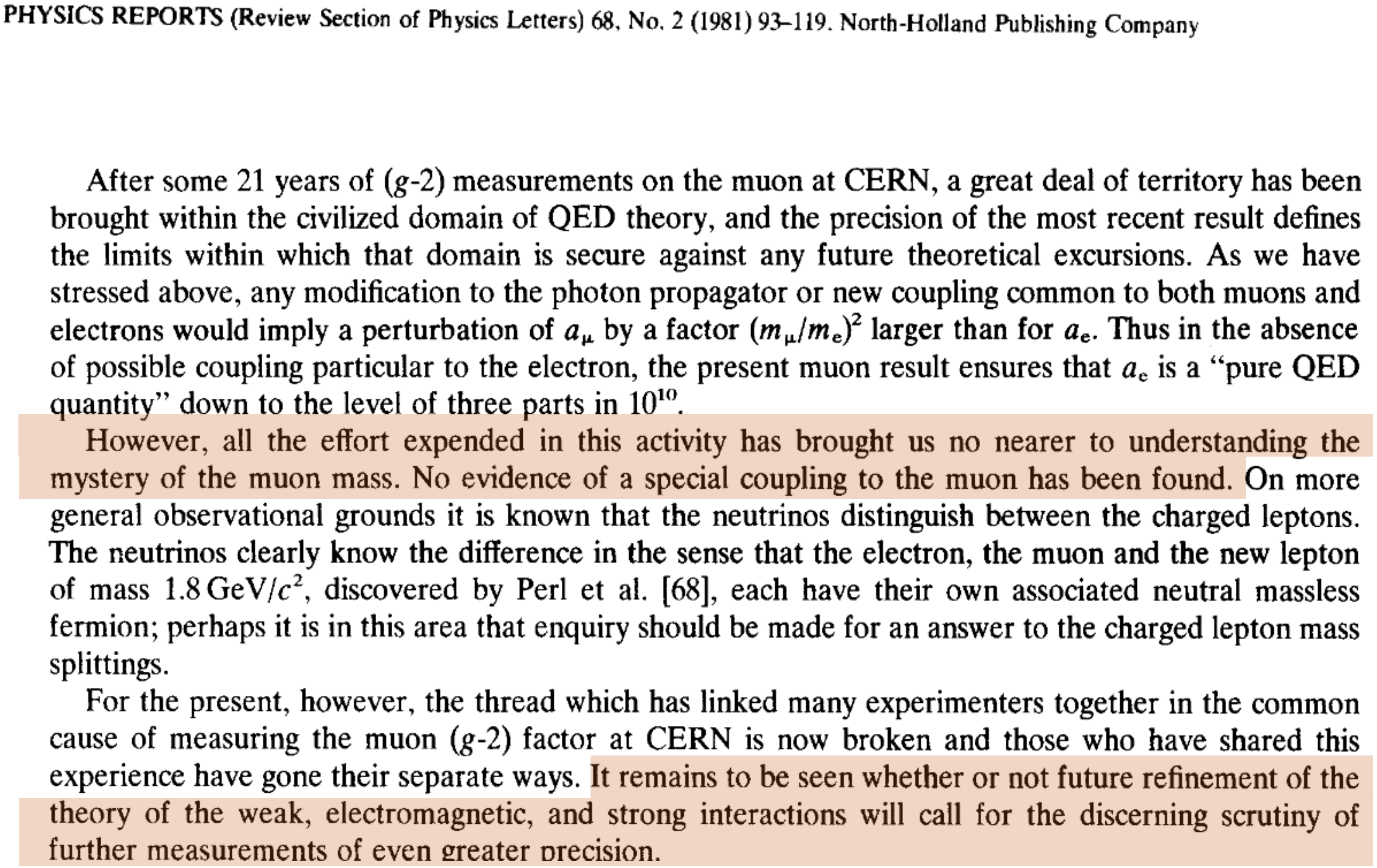
1968 QED alone wasn't sufficient

He has worked on wave energy since 1976 and has filed 14 patents in this area. He is the co-inventor of the Anaconda wave energy device.[7]
He won the 1980 [Hughes Medal]() of the [Royal Society]() "for his ultra-precise measurements of the muon magnetic moment, a severe test of quantum electrodynamics and of the nature of the muon".[8]
1967-82 he was the academic head of the Royal Military College of Science, Shrivenham GB. He has been visiting professor at Yale, Reading University (of engineering), University of New South Wales (of theoretical physics) and currently at Southampton.
Moving to France in 1986 he helped the cancer hospital Centre Antoine Lacassagne in Nice to instal a 65 MeV cyclotron for proton therapy.[9] *He designed the beam transport which brings the beam to the*
system has treated over 3000 patients for ocular
ph "Elements of Pulse Circuits" (1955) [10] *translated into*
sics, relativity, wave energy and cosmology.



"Catalysed Fusion is a sizzling true-to-life fantasy, woven around particle physics in Geneva, the city where nations meet and particles collide. Love and adventure, discovery and intrigue, rivalry, skill and skulduggery at the frontiers of physics. How science works, how scientists operate around those big"

Comments

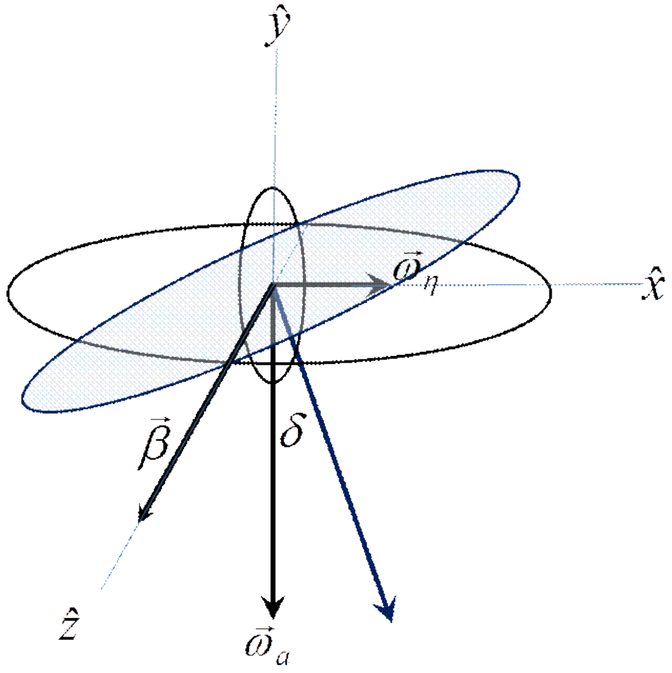


PHYSICS REPORTS (Review Section of Physics Letters) 68, No. 2 (1981) 93–119. North-Holland Publishing Company

After some 21 years of (g-2) measurements on the muon at CERN, a great deal of territory has been brought within the civilized domain of QED theory, and the precision of the most recent result defines the limits within which that domain is secure against any future theoretical excursions. As we have stressed above, any modification to the photon propagator or new coupling common to both muons and electrons would imply a perturbation of a_μ by a factor $(m_\mu/m_e)^2$ larger than for a_e. Thus in the absence of possible coupling particular to the electron, the present muon result ensures that a_e is a "pure QED quantity" down to the level of three parts in 10^{10}.

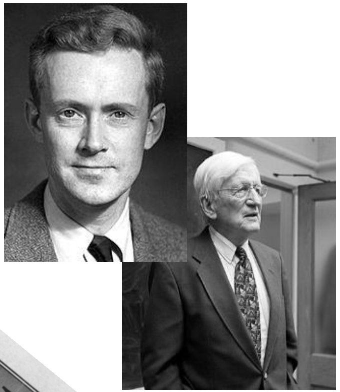
However, all the effort expended in this activity has brought us no nearer to understanding the mystery of the muon mass. No evidence of a special coupling to the muon has been found. On more general observational grounds it is known that the neutrinos distinguish between the charged leptons. The neutrinos clearly know the difference in the sense that the electron, the muon and the new lepton of mass 1.8 GeV/c^2, discovered by Perl et al. [68], each have their own associated neutral massless fermion; perhaps it is in this area that enquiry should be made for an answer to the charged lepton mass splittings.

For the present, however, the thread which has linked many experimenters together in the common cause of measuring the muon (g-2) factor at CERN is now broken and those who have shared this experience have gone their separate ways. It remains to be seen whether or not future refinement of the theory of the weak, electromagnetic, and strong interactions will call for the discerning scrutiny of further measurements of even greater precision.



Muon EDM

Purcell and Ramsey



On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. Purcell and N. F. Ramsey
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole's orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction of displacement as would be required to obtain an electric dipole moment from electrical charges. On the other hand, if the nucleon should spend part of its time asymmetrically dissociated into opposite magnetic poles of the type that Dirac[2] has shown to be theoretically possible, a circulation of these magnetic poles could give rise to an electric dipole moment. To forestall a possible objection we may remark that this electric dipole would be a polar vector, being the product of the angular momentum (an axial vector) and the magnetic pole strength, which is a pseudoscalar in conformity with the usual convention that electric charge is a simple scalar.

The argument against electric dipoles, in another form, raises directly the question of parity. A nucleon with an electric dipole moment would show an asymmetry between left- and right-handed coordinate systems; in one system the dipole moment would be parallel to the angular momentum and in the other, antiparallel. But there is no compelling reason for excluding this possibility. It would not be the only asymmetry of particles of ordinary experience, which already exhibit conspicuous asymmetry in respect to electric charge. Although magnetic poles were used above as an illustration of a particular mechanism by which a nuclear electric dipole could arise, this is, of course, not the only possibility.

The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle in view of the above becomes a purely experimental matter. The evidence from most past experiments on molecules, atoms, nucleons, and elementary particles is not as conclusive as one might suppose. Most past experiments are in fact very insensitive to the effects of a nuclear electric dipole, because of the smallness of the electric field at the position of a charged nucleus or the antisymmetric nature of the electric dipole potential. We have analyzed a number of experiments including conversion of ortho- to parahydrogen, depolarization of neutron beams, ionization by neutrons, relaxation times of nuclei in liquids, nuclear scattering of neutrons, hyperfine structure studies, the Lamb-Retherford experiment, and the experiments on the interaction of electrons and neutrons. Non-scattering experiments on charged nuclei are particularly insensitive to the existence of an electric dipole moment and even the most favorable would not have revealed an electric dipole moment smaller than the charge of the electron multiplied by a distance D less than 10^{-13} cm. The scattering experiments[3,4] to detect an electron-neutron interaction are by far the most sensitive; the results of Havens, Rabi, and Rainwater[3] would correspond to a D of 3×10^{-18} cm if they were due to an electric dipole moment.

We are now undertaking, in collaboration with Mr. James H. Smith, an experiment which should directly measure the electric dipole moment of the neutron if it has a value of D of approximately the above magnitude. The experiment will utilize a neutron beam magnetic resonance[5] apparatus of high resolution[6] to detect a possible shift of the neutron precession frequency upon the application of a strong electric field.

The authors wish to thank Mr. Smith for suggesting an important correction to our original calculation on the neutron-electron interaction experiment.

---

[1] A typical argument is given by H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York).
[2] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).
[3] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[4] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).
[5] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
[6] N. F. Ramsey, Phys. Rev. **76**, 996 (1949).

Supernovae*

L. B. Borst
Brookhaven National Laboratory, Upton, Long Isl
April 27, 1950

SUPERNOVAE of type I are charact
intensity maximum of 20 to 30 da
ponential tail to the light curve of hal
±0.0012 magnitudes per day;[1] (c
emission of nearly 10^{49} ergs;[1] (d)
hydrogen content expanding at
radiating 10^{38} ergs/sec. visible

These characteristics ma
proposed mechanism. Th
sun, e.g., $15M_{\odot}$, underg
its hydrogen. As th
perature will rise u
of 2 to 3×10^{8} °C
between alpha-

This re
rapid
by m
is a

where Z is th
number of partic
the alpha-particle
reaction threshold; k is
perature. It may be note
volume increases as the squa
exponentially with the temperat
accelerate under conditions of gravi
star may collapse in a time approaching

The reaction will proceed until there are s
of the reaction products to produce the rev
expression at equilibrium may be given

$$K=[Be^7][n]/[He]^2,$$

where the entries denote atomic concentrations per unit v
Since neutrons will be absorbed rapidly in a system contai

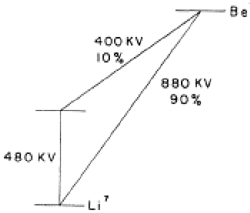


Fig. 1. Decay scheme of Be⁷.

THE OAK RIDGE NATIONAL LABORATORY NEWS

A Publication by and for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

Vol. 3—No. 13

OAK RIDGE, TENNESSEE

Friday, September 29, 1950

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a

DR. TAYLOR

Dr. Ellison Taylor Appointed Chem. Division Director

Effective October 1, Dr. Ellison H. Taylor will assume the duties of Director of the Chemistry Division. In this capacity he will succeed Dr. John A. Swartout, who was recently elevated to the position of Assistant Research Director of Oak Ridge National Laboratory.

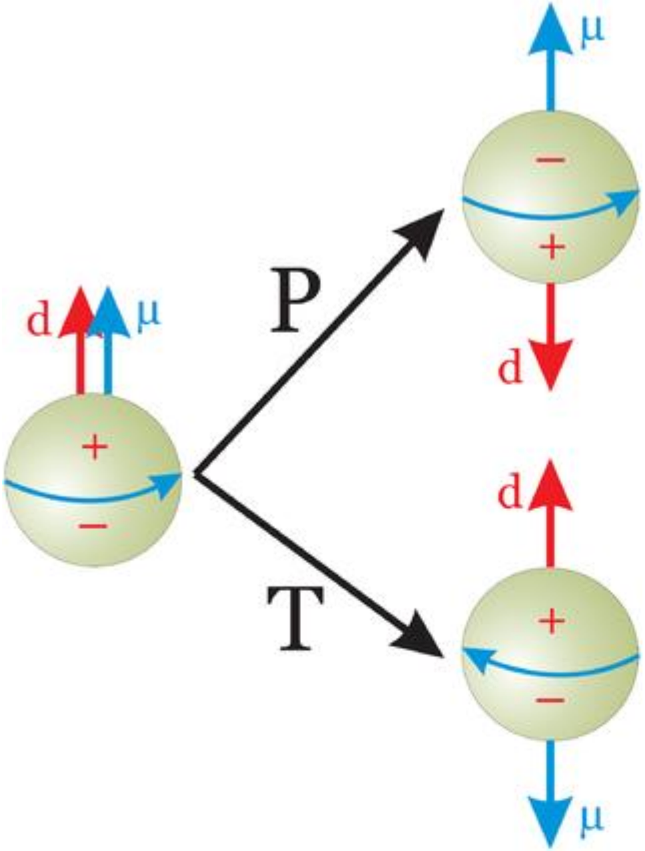
Dr. Taylor's present connection with the Chemistry Division is that of Associate Director of the Division and Group Leader of the Radiation Chemistry Group, in which capacities he has served since June, 1948. Previously, he had been Assistant Director of the Division, from June, 1946, to February, 1948, and was Acting Di-

ACS Lectureship Set For October 26, 27

The East Tennessee Section of the American Chemical Society will have its Annual East Tennessee Lectureship this year in two sessions, according to plans re-

Electron Magnetic Dipole Moment Gabrielse

- Most precisely measured property of an elementary particle
- Most precise prediction of the standard model
- Most precise confrontation of theory and experiment
- Greatest triumph of the standard model



system under P and T is not symmetric with respect to the initial system,

Having CPT symmetry, the combined symmetry **CP is violated** as well.

Magnetic dipole moment

η is a dimensionless constant, analogous to *g*

Electric dipole moment

$$\vec{\mu} = g\frac{Qe}{2m_\mu}\vec{s}$$

$$\vec{d}_\mu = \eta\frac{Qe}{2m_\mu c}\vec{s}$$

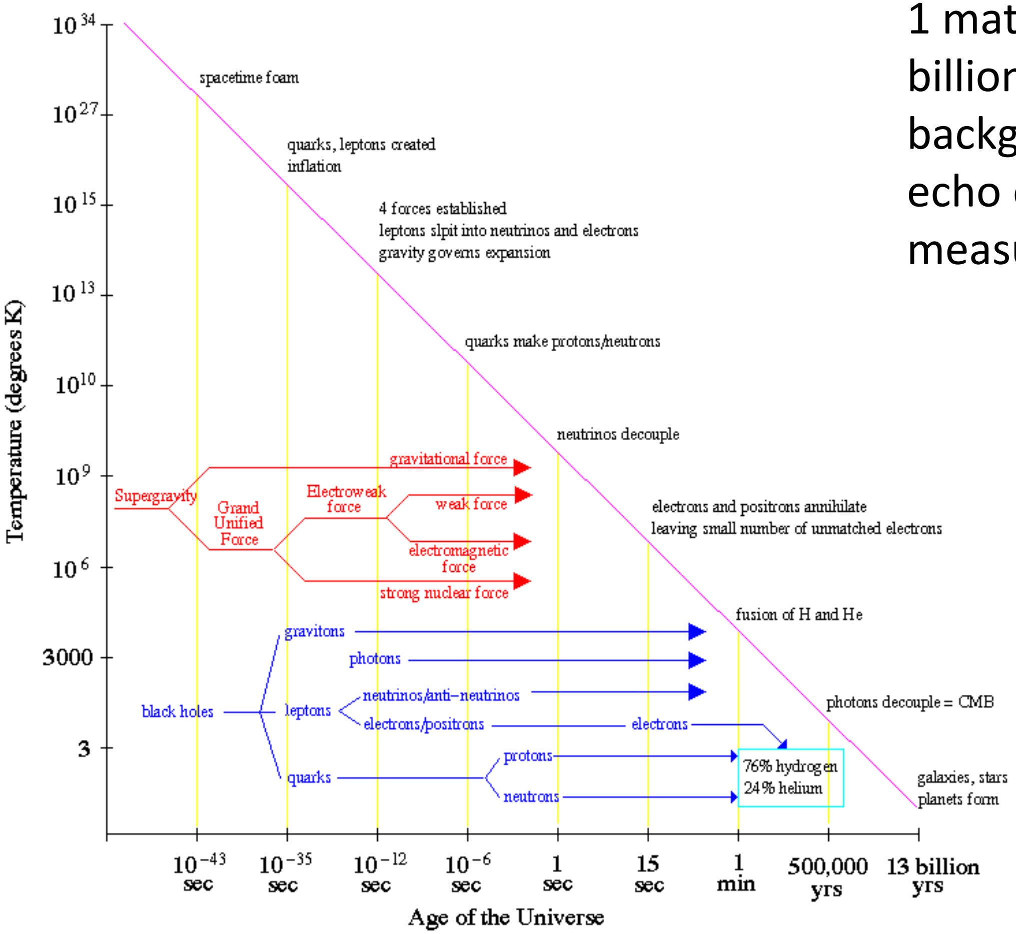
Hamiltonian for a fermion in B and E field

$$\hat{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

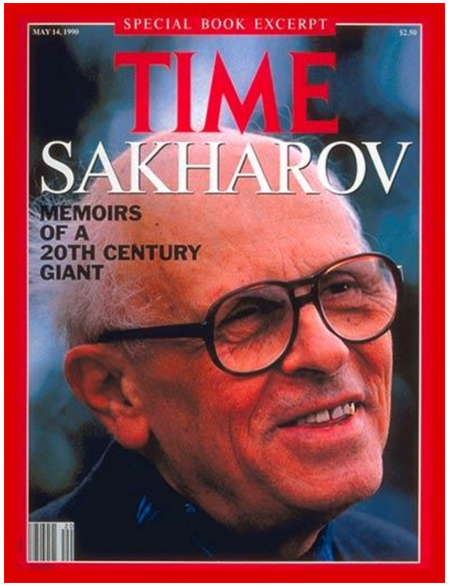
Transformation Properties

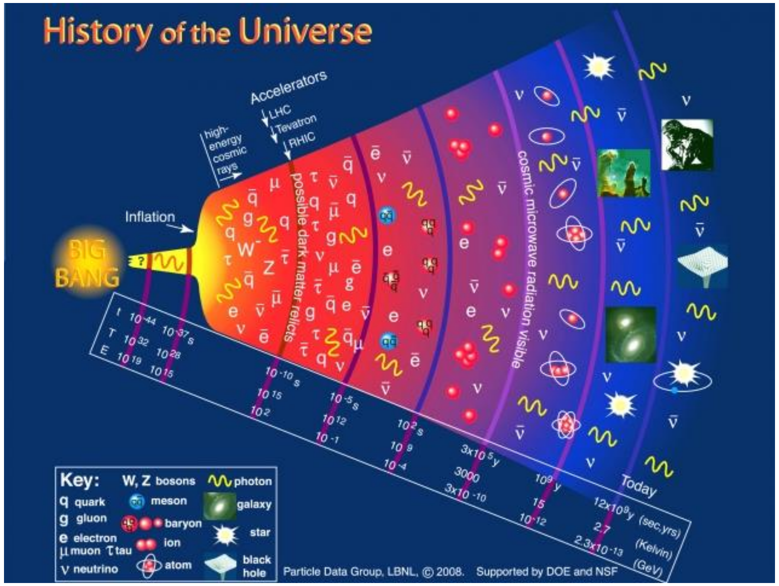
	$\vec{B}$	$\vec{E}$	$\vec{\mu}$	$\vec{d}$
C	-	-	-	-
P	+	-	+	+
T	-	+	-	-
CP	-	+	-	-
CPT	+	+	+	+

If CPT valid → EDM would violate CP



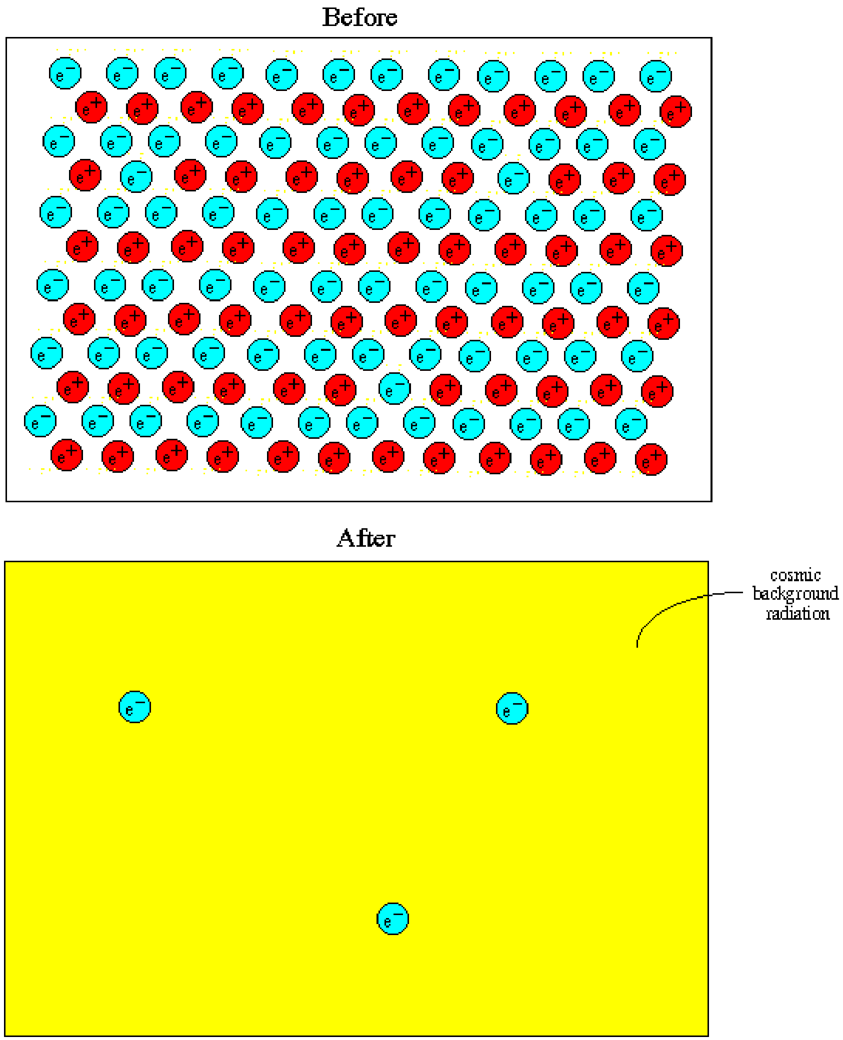
10 billion matter/anti-matter pairs annihilated each other leaving behind 1 matter particle and 10 billion photons cosmic background radiation, the echo of the Big Bang we measure today.





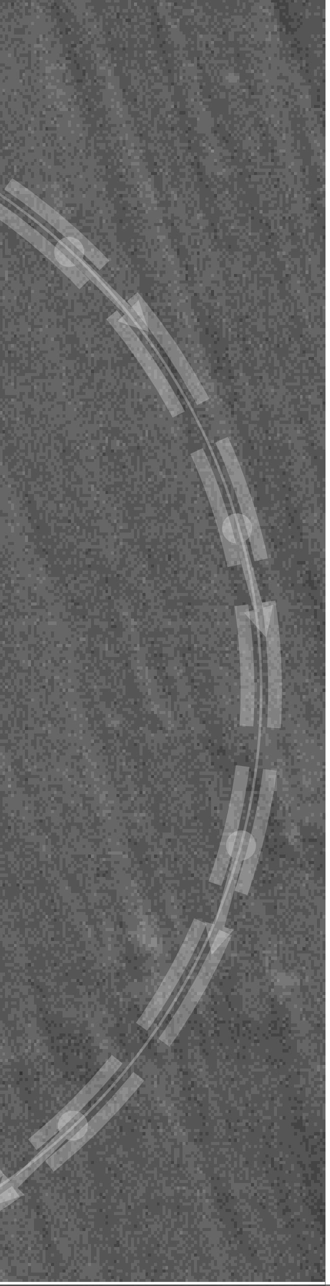
“CP Symmetry Violation, C-Asymmetry, and Baryon Asymmetry of the Universe” *e"*. *Journal of Experimental and Theoretical Physics*. ***5****: 24–27. 1967*

Baryon Number



Any non-zero EDM for a muon = New Physics

Better limits from electrons but 2nd generation may be “special” (loops)



Technique

$$\vec{\omega}_a = -\frac{Qe}{m_\mu}\left[a_\mu \vec{B} - \xcancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Dependence on E field cancelled out by choosing γ = 29.3

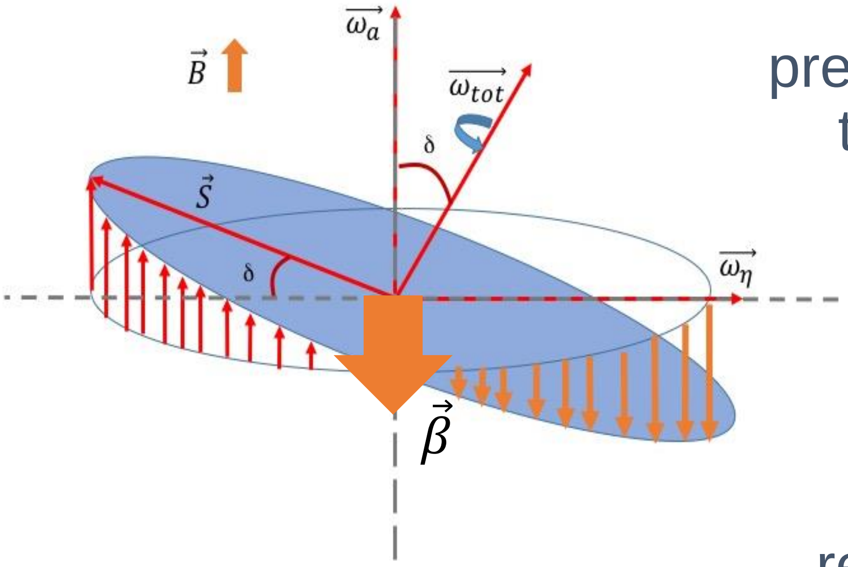
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

$$\boxed{\vec{\omega}_{EDM} = -\frac{e\eta}{2m_\mu c}\left(\vec{\beta}\times\vec{B}\right)}$$

$$\vec{\mu} = g\frac{Qe}{2m_\mu}\vec{s}$$

$$\vec{d}_\mu = \eta\frac{Qe}{2m_\mu c}\vec{s}$$

µEDM tilts the precession plane of the muons by an angle δ



EDM tilts the muon precession plane towards the centre of the g-2 storage ring

$$\boxed{\delta = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)}$$

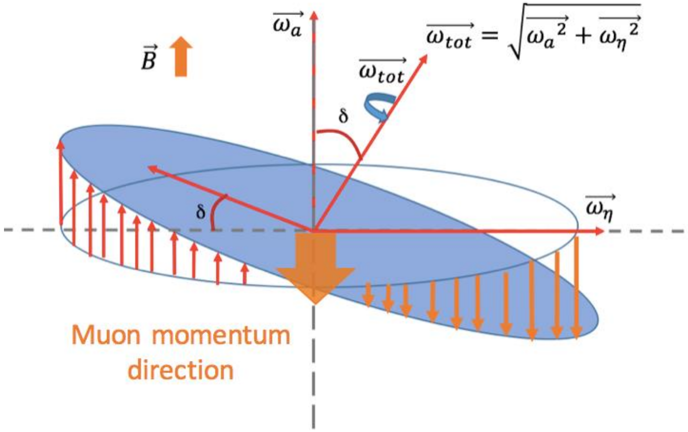
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

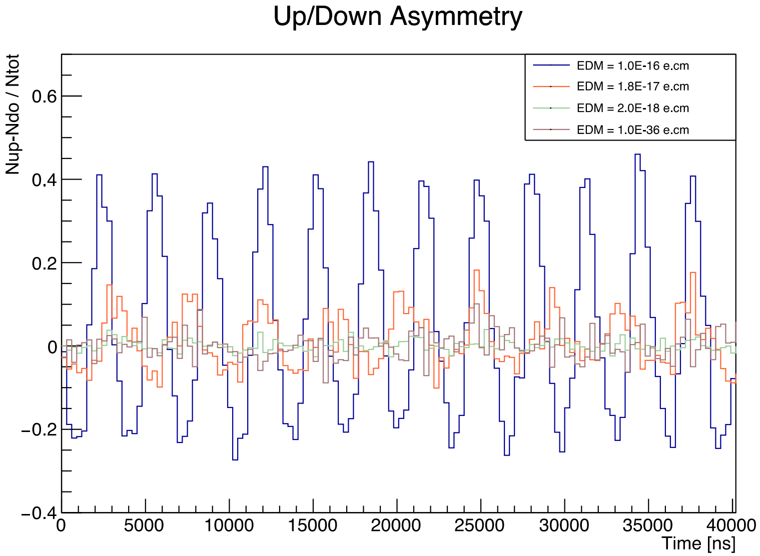
$$\vec{\omega}_{EDM} = -\frac{e\eta}{2m_\mu c}\left(\vec{\beta}\times\vec{B}\right)$$

Measured angle is reduced due to Lorentz contraction:

$$\boxed{\delta' = \tan^{-1}\left(\frac{\tan\delta}{\gamma}\right)}$$

Muon : EDM

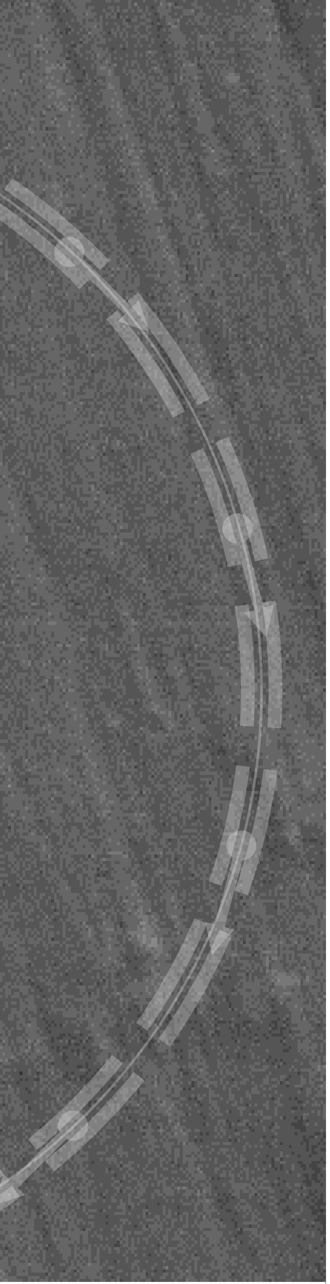




O(1M) events in trackers (few weeks)
--> sensitivity at 10^{-19} [BNL]

Expect several billion events in the trackers and so reach 10^{-21}

- Precession plane tilts towards center of ring
- Causes an increase in muon precession frequency
- Oscillation is 90° out of phase with the a_μ oscillation



FNAL g-2 progressing well: data 2018. Results 2019.

- Quad incident will be overcome

Theory in good shape for reducing its contribution to the systematic error

- *if we could "just" resolve the g-2 discrepancy at FNAL, the benefits for constraining BSM scenarios would be enormous.*

Is there one last hurrah for this beautiful method & equipment?

There IS a cross-check mu-e scatter

UPGRADE? (& μ-)

Proton Electric Dipole Moment

Themis Bowcock

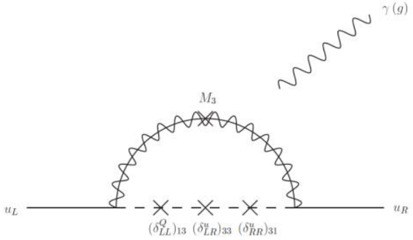
UNIVERSITY OF LIVERPOOL

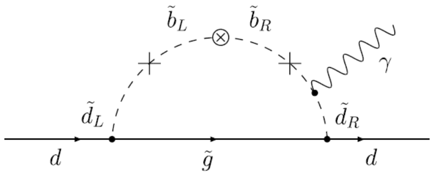
CERN Workshop 26th March 2018

Motivations CP sources/EDM

Pospelov,Shaposnikov, PBC 16

- Required for Baryogenesis
- Strong CP Problem
- Beyond Colliders: "*The PeV scale allows a generic flavour structure and, with TeV gauginos, EDMs are one of the few observables able to probe this scale via log-enhanced quark CEDMs*" Ritz, Lepton Moments '14

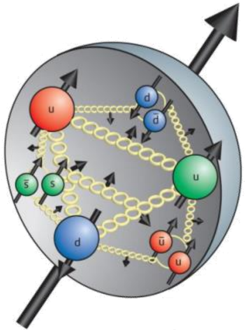




Physics

$$\mathcal{L}_{\rm QCD}^{\rm CPV} = \frac{g_s^2}{32\pi^2}\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$

$$\bar{\theta} = \theta + \mathrm{Arg\ Det}\, M_q.$$



$$d_n \sim -d_p$$

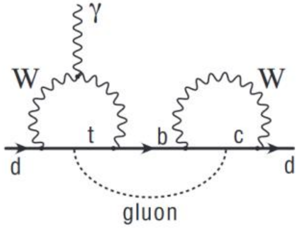
$$d_n \sim e\frac{\bar{\theta} m_*}{\Lambda^2_{\rm had}} \sim \bar{\theta}\cdot(6\times 10^{-17})e\ \mathrm{cm}$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

$$d_n \simeq 1.4(d_d - 0.25 d_u) + 0.83e(d^c_u + d^c_d) - 0.27e(d^c_u - d^c_d)$$

$$d_p \simeq 1.4(d_d - 0.25 d_u) + 0.83e(d^c_u + d^c_d) + 0.27e(d^c_u - d^c_d)$$

$$d_D \simeq (d_u + d_d) - 0.2e(d^c_u + d^c_d) - 6e(d^c_u - d^c_d)$$



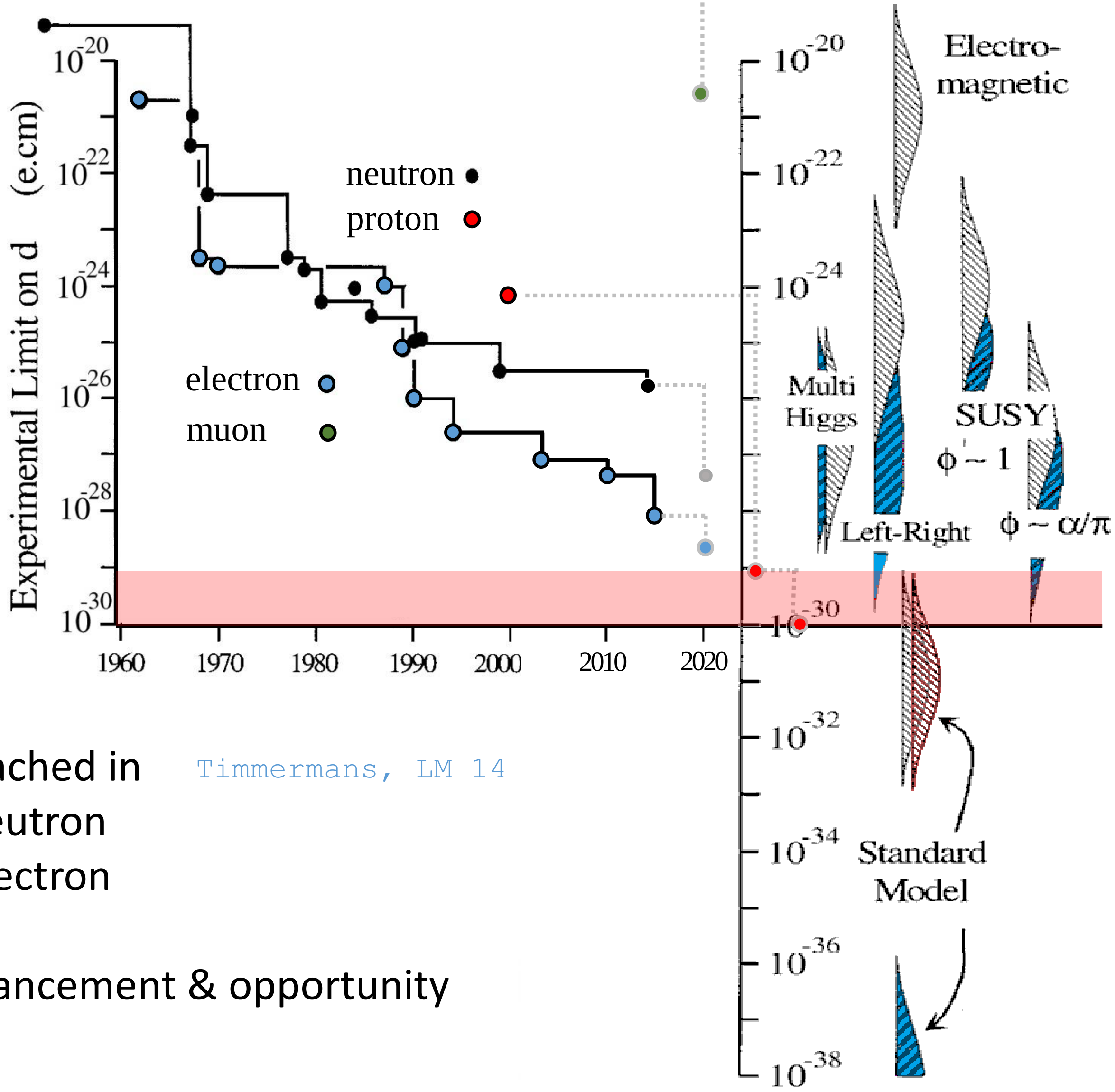
CKM phase generates tiny EDMs:

$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^* V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

$$< 10^{-33} e\mathrm{cm}$$

Physics

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471



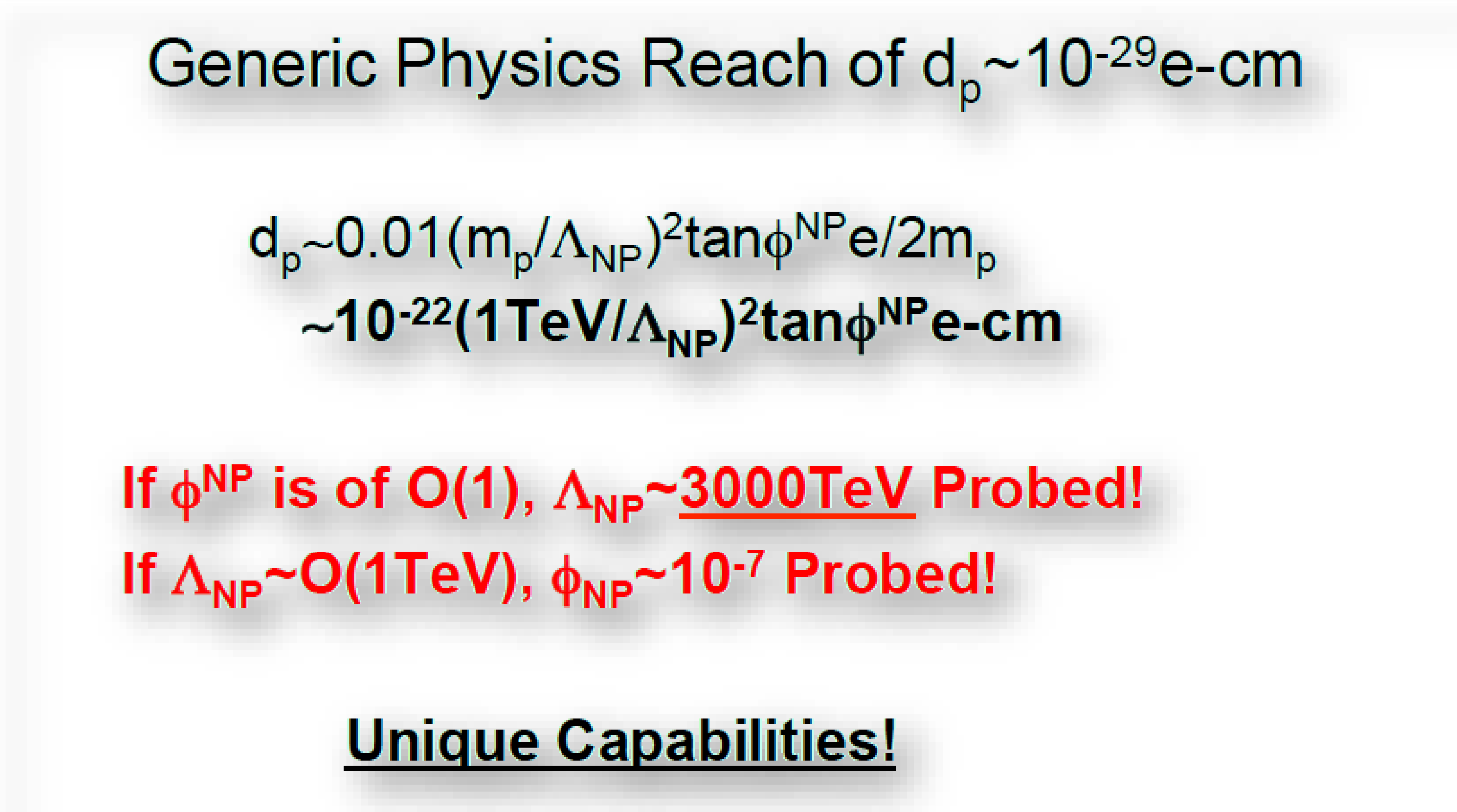
SM value reached in

- 2075 for neutron
- 2115 for electron

Timmermans, LM 14

pEDM = advancement & opportunity

Looking for an EDM above SM level



Generic Physics Reach of $d_p \sim 10^{-29}$e-cm

$$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$$
$$\sim 10^{-22}(1\text{TeV}/\Lambda_{NP})^2 \tan\phi^{NP} \text{e-cm}$$

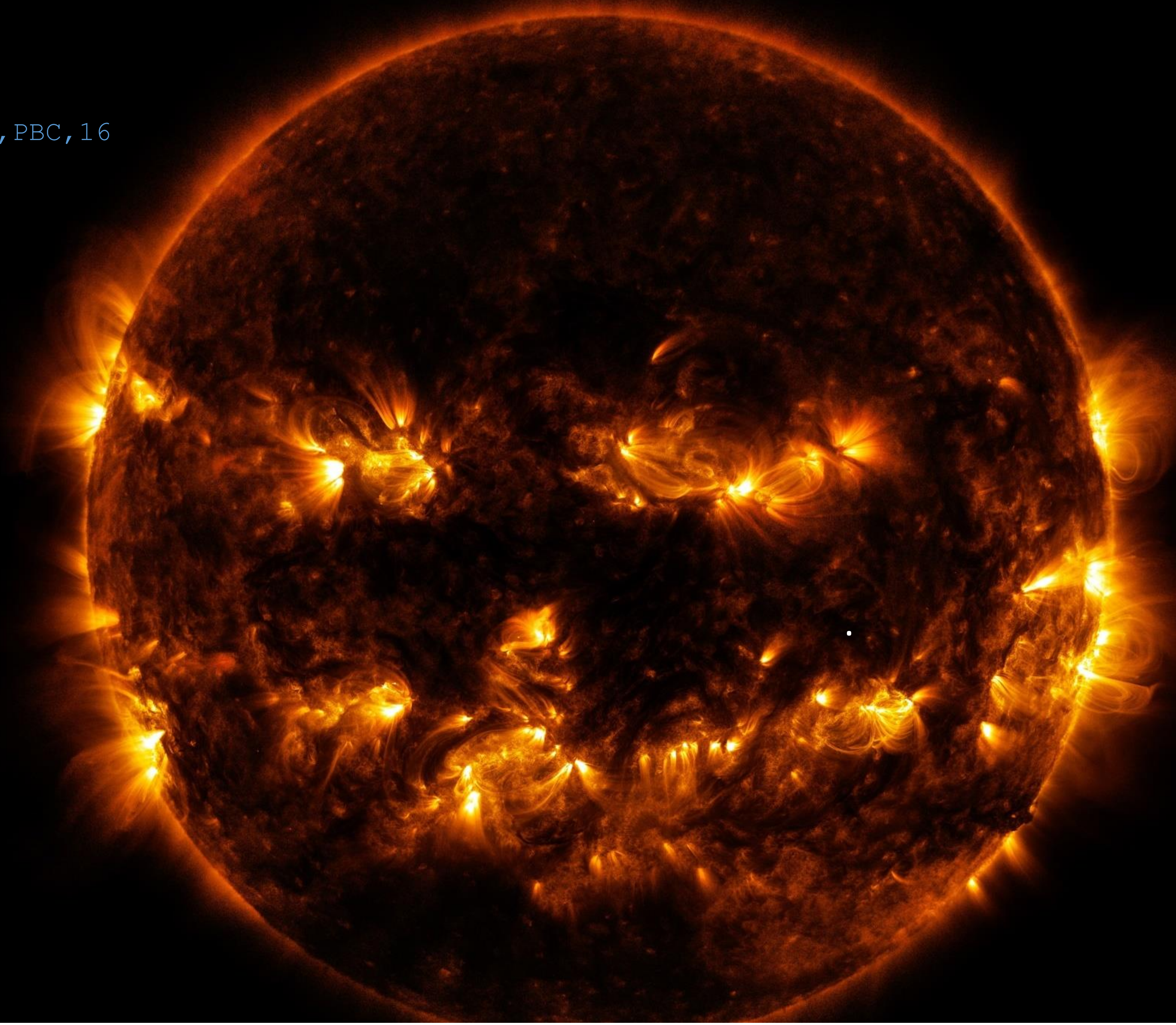
If ϕ^{NP} is of O(1), $\Lambda_{NP} \sim$ 3000TeV Probed!

If $\Lambda_{NP} \sim$ O(1TeV), $\phi_{NP} \sim 10^{-7}$ Probed!

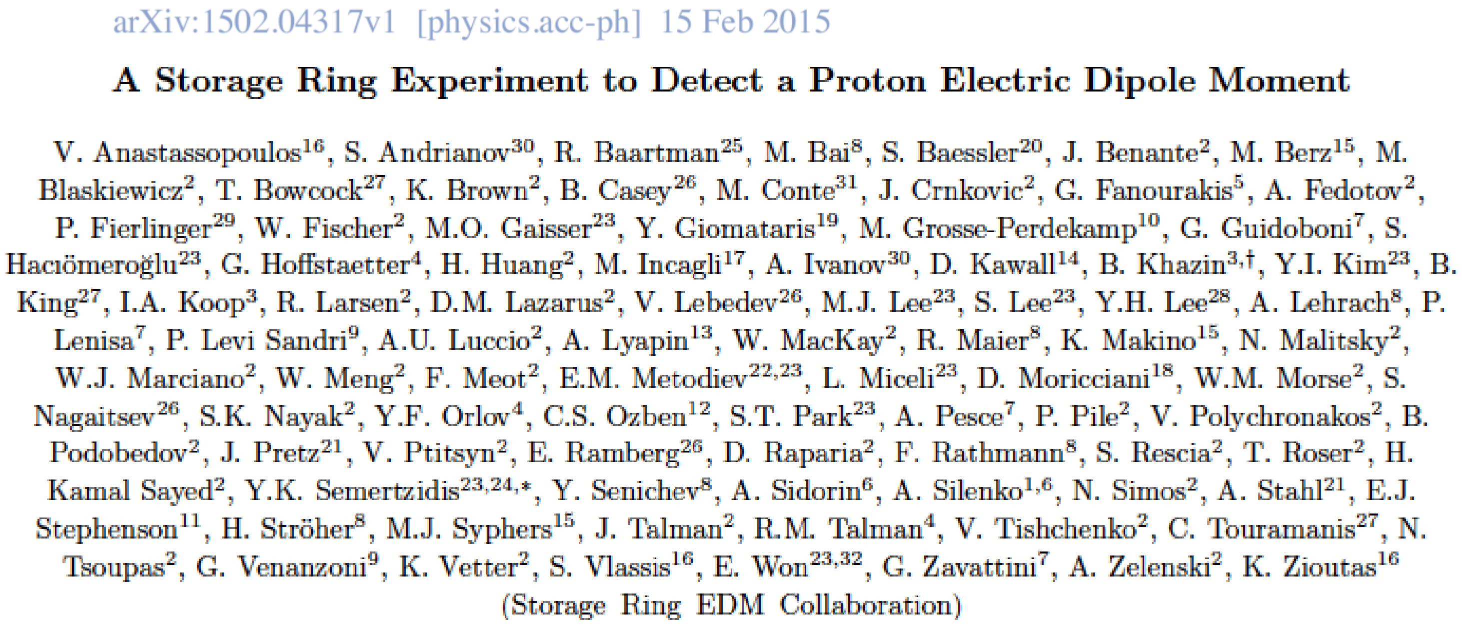
Unique Capabilities!

Marciano, CM9/KAIST/Korea, Nov 2014

Pospelov,PBC,16



Technique



arXiv:1502.04317v1 [physics.acc-ph] 15 Feb 2015

A Storage Ring Experiment to Detect a Proton Electric Dipole Moment

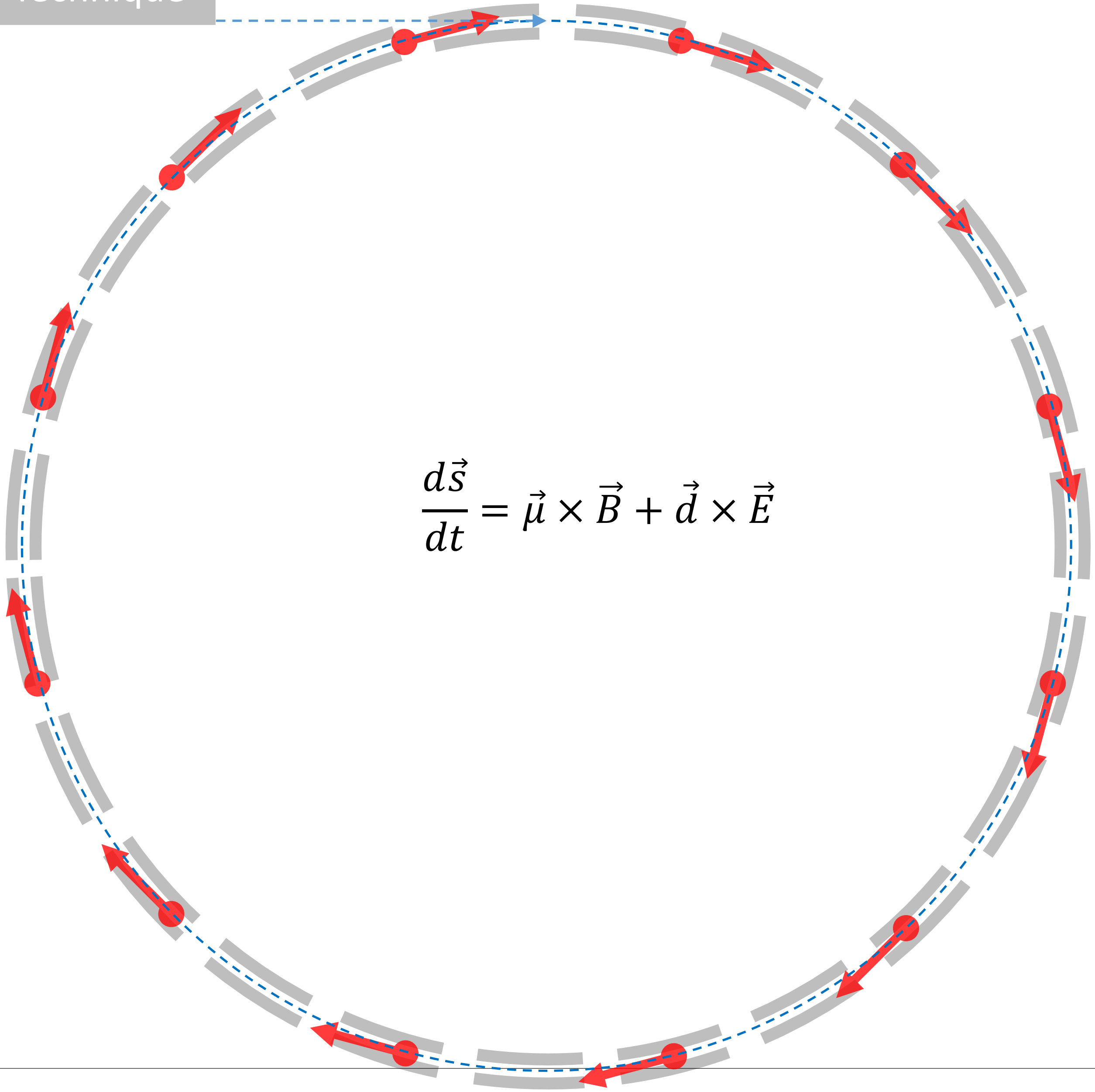
V. Anastassopoulos[16], S. Andrianov[30], R. Baartman[25], M. Bai[8], S. Baessler[20], J. Benante[2], M. Berz[15], M. Blaskiewicz[2], T. Bowcock[27], K. Brown[2], B. Casey[26], M. Conte[31], J. Crnkovic[2], G. Fanourakis[5], A. Fedotov[2], P. Fierlinger[29], W. Fischer[2], M.O. Gaisser[23], Y. Giomataris[19], M. Grosse-Perdekamp[10], G. Guidoboni[7], S. Hacıömeroğlu[23], G. Hoffstaetter[4], H. Huang[2], M. Incagli[17], A. Ivanov[30], D. Kawall[14], B. Khazin[3,†], Y.I. Kim[23], B. King[27], I.A. Koop[3], R. Larsen[2], D.M. Lazarus[2], V. Lebedev[26], M.J. Lee[23], S. Lee[23], Y.H. Lee[28], A. Lehrach[8], P. Lenisa[7], P. Levi Sandri[9], A.U. Luccio[2], A. Lyapin[13], W. MacKay[2], R. Maier[8], K. Makino[15], N. Malitsky[2], W.J. Marciano[2], W. Meng[2], F. Meot[2], E.M. Metodiev[22,23], L. Miceli[23], D. Moricciani[18], W.M. Morse[2], S. Nagaitsev[26], S.K. Nayak[2], Y.F. Orlov[4], C.S. Ozben[12], S.T. Park[23], A. Pesce[7], P. Pile[2], V. Polychronakos[2], B. Podobedov[2], J. Pretz[21], V. Ptitsyn[2], E. Ramberg[26], D. Raparia[2], F. Rathmann[8], S. Rescia[2], T. Roser[2], H. Kamal Sayed[2], Y.K. Semertzidis[23,24,*], Y. Senichev[8], A. Sidorin[6], A. Silenko[1,6], N. Simos[2], A. Stahl[21], E.J. Stephenson[11], H. Ströher[8], M.J. Syphers[15], J. Talman[2], R.M. Talman[4], V. Tishchenko[2], C. Touramanis[27], N. Tsoupas[2], G. Venanzoni[9], K. Vetter[2], S. Vlassis[16], E. Won[23,32], G. Zavattini[7], A. Zelenski[2], K. Zioutas[16]

(Storage Ring EDM Collaboration)

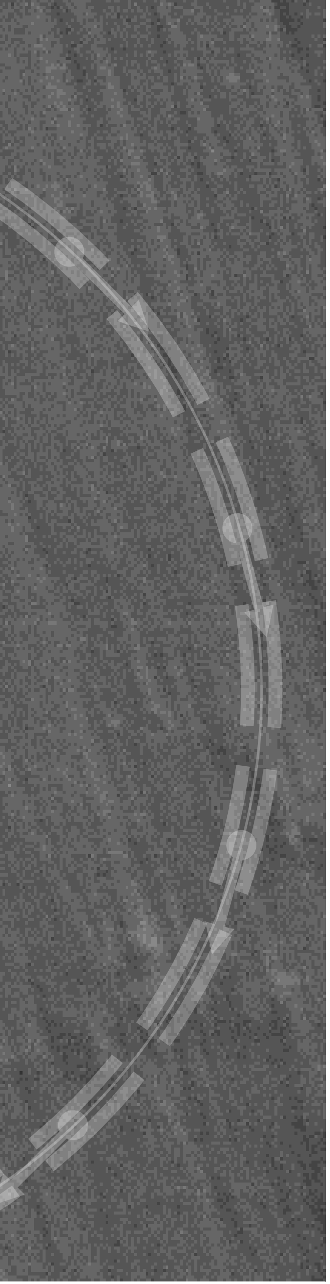
Technique

More details

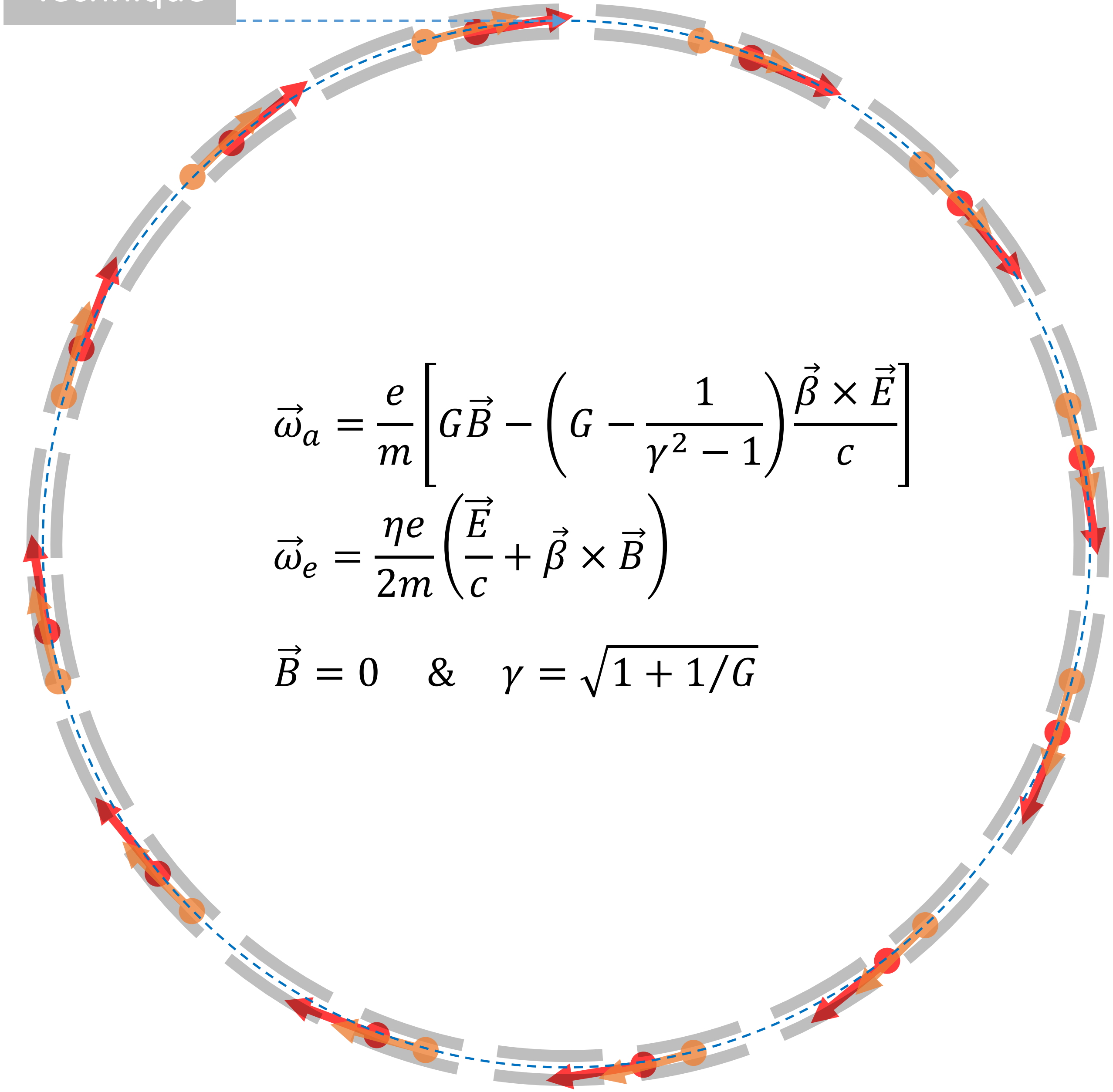
Bei PBC 16



$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



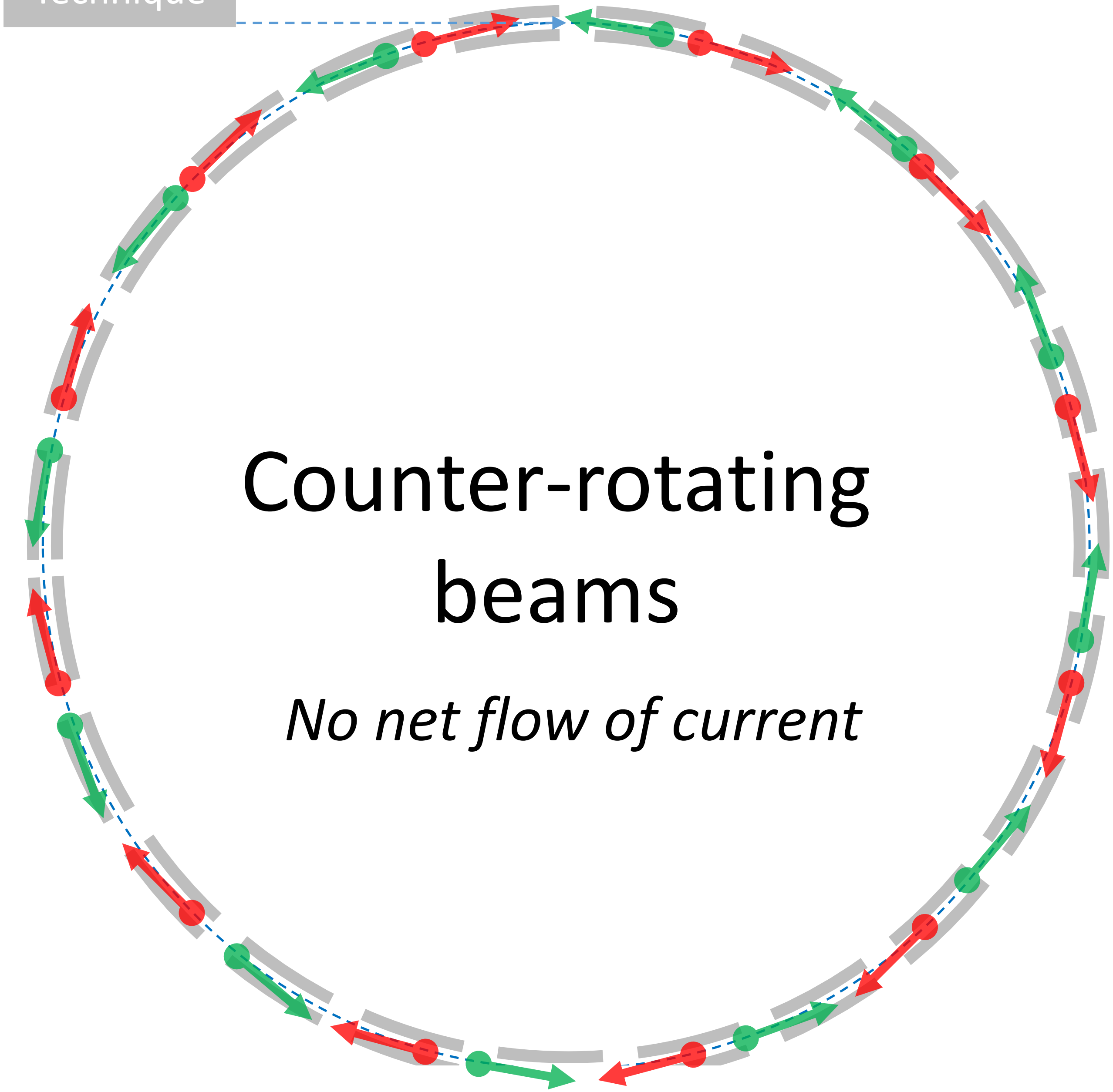
Technique



$$\vec{\omega}_a = \frac{e}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

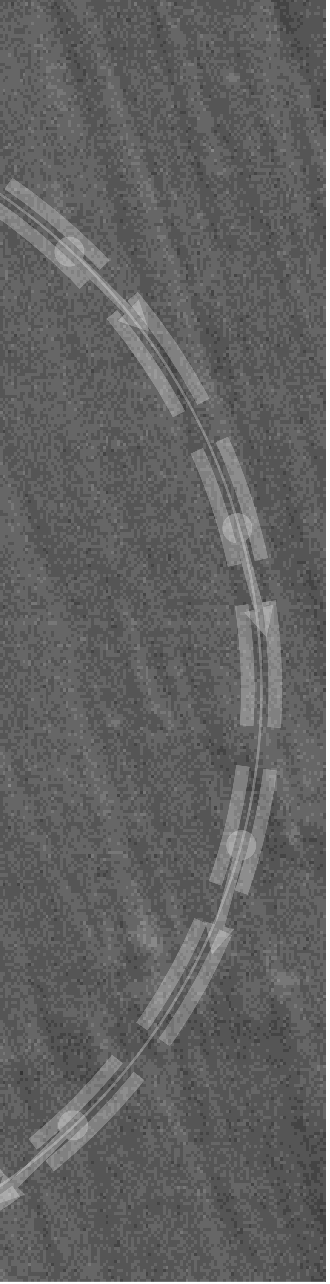
$$\vec{\omega}_e = \frac{\eta e}{2m}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

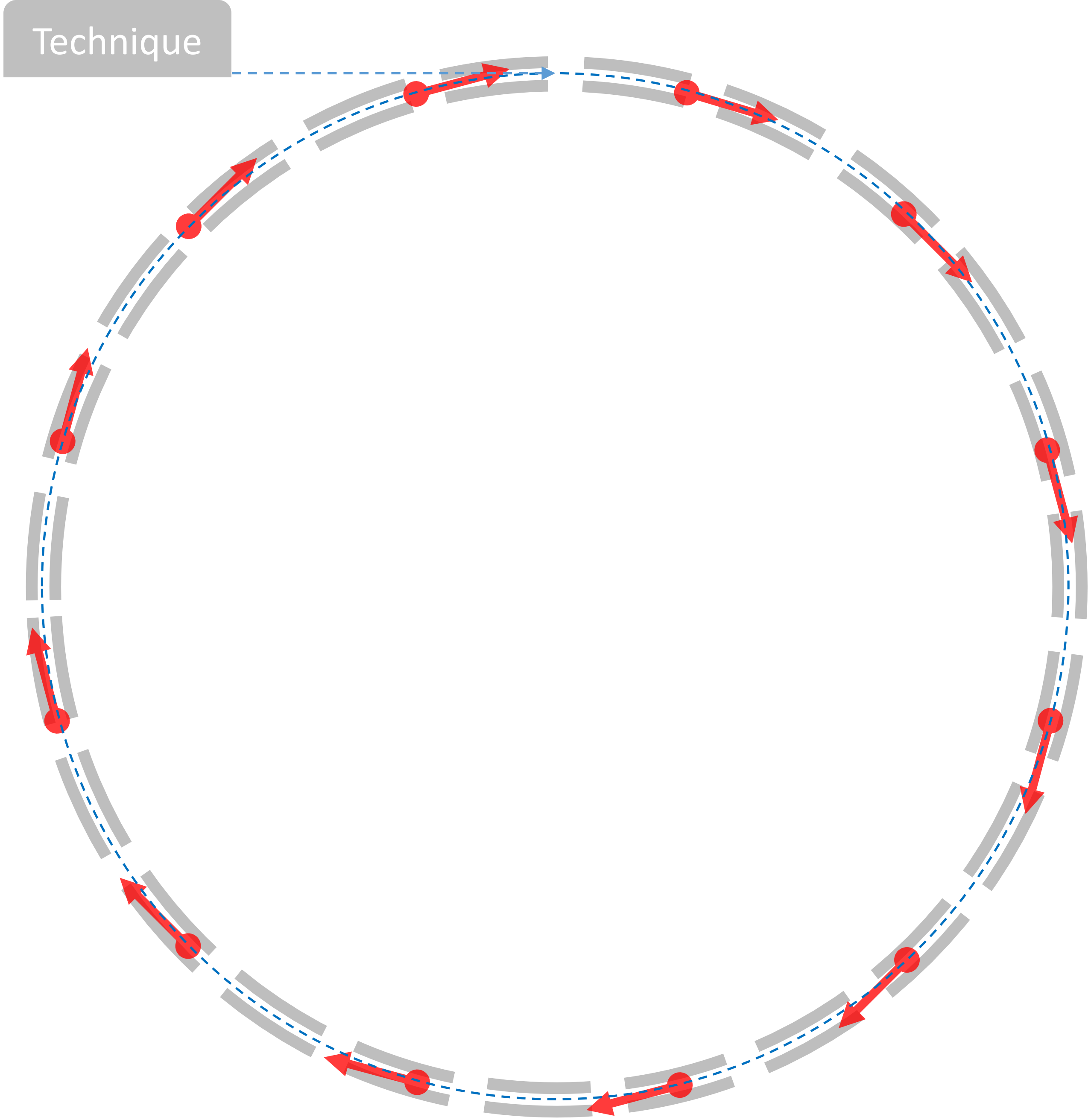
$$\vec{B} = 0 \quad \& \quad \gamma = \sqrt{1 + 1/G}$$



Counter-rotating beams

No net flow of current




Technique

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}} = 2.5\times10^{-29} \text{ e-cm / year}$$

τ_p : 10^3 s Polarization Lifetime (Spin Coherence Time)

A : 0.6 Left/right asymmetry observed by the polarimeter

P : 0.8 Beam polarization

N_c : $5\text{x}10^{10}$ p/cycle Total number of stored particles per cycle

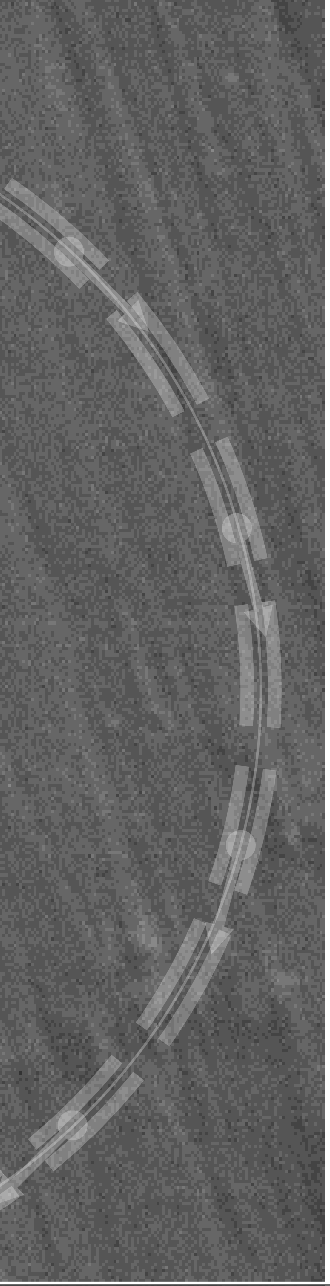
T_{Tot}: 10^7s Total running time per year

f : 1% Useful event rate fraction (efficiency for EDM)

E_R : 8 MV/m Radial electric field strength

Revolution in statistics

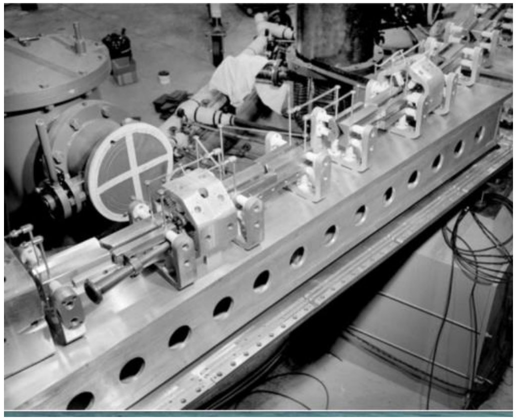
What has been accomplished?

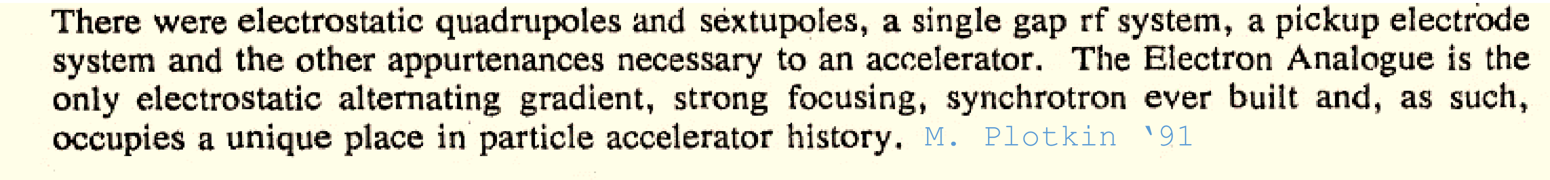


- Polarimeter systematic errors KVI, COSY
- Precision beam/spin dynamics tracking CAPP
- Stable lattice, IBS lifetime: ~10^4s Lebedev, FNAL
- SCT 10^3 s; role of sextupoles understood COSY.
- Feasibility of required electric field strength <8 MV/m, 3cm plate separation JLab, FNAL
- Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!

Feasibility all-electric ring

- Two technical reviews have been performed BNL: Dec 2009, March 2011
- Fermilab review. Lebedev “concept sound”
- First all-electric ring: AGS-analogue (‘53-’57)





There were electrostatic quadrupoles and sextupoles, a single gap rf system, a pickup electrode system and the other appurtenances necessary to an accelerator. The Electron Analogue is the only electrostatic alternating gradient, strong focusing, synchrotron ever built and, as such, occupies a unique place in particle accelerator history. M. Plotkin ‘91

Ring radius 4.7m

Proposed-built 1953-57

- Heidelberg Cryogenic Storage Ring:

  (expertise in collab.)

B-field Shielding Requirements

- No need for shielding: In principle, with counter-rotating beams.
- However: BPMs are located only in straight sections → sampling finite. The B-field needs to be less than (10-100nT) everywhere to reduce its effect. We are building a prototype `Selcuk Haciomeroglu, CAPP`

I. Altarev et al.,*J. Appl. Phys.* 117, 183903, 2015,
Fierlinger's group@TUM

Polarimeter analyzing power

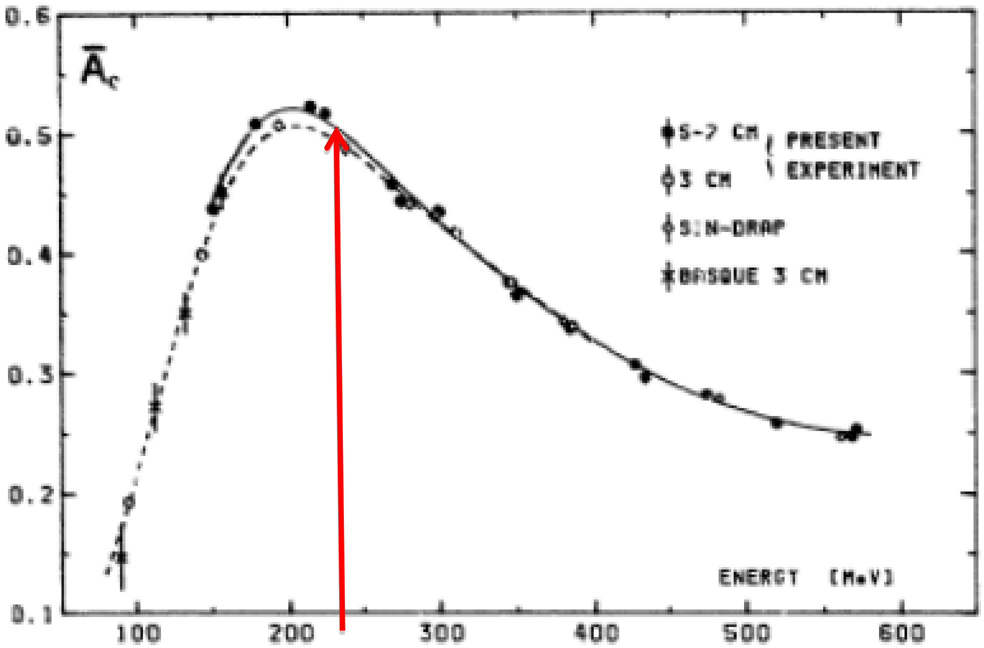
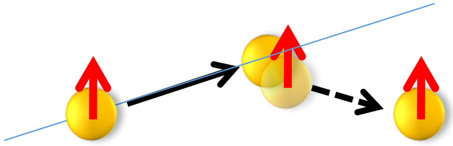


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only



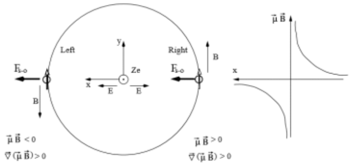


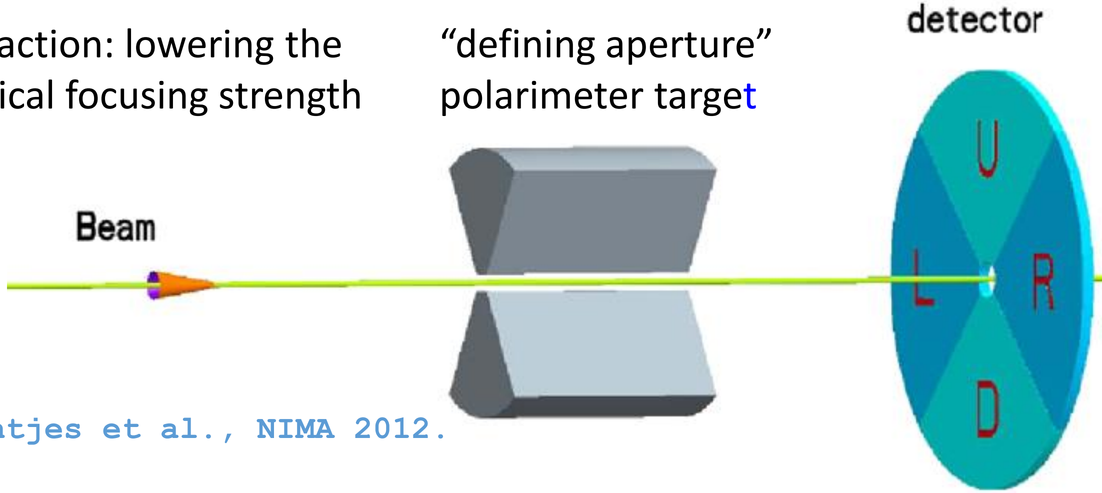
Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

pEDM polarimeter

E. Stephenson

Extraction: lowering the vertical focusing strength

"defining aperture" polarimeter target



Micro-Megas detector, GEMs, MRPC or Si.

Brantjes et al., NIMA 2012.

$$\varepsilon_H = \frac{L-R}{L+R}$$

carries EDM signal increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

carries in-plane (g-2) precession signal

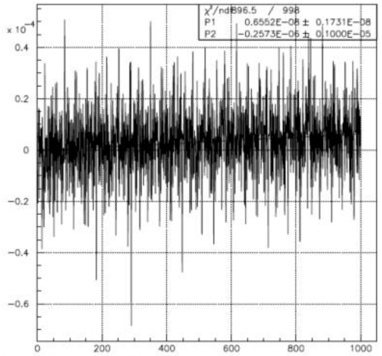
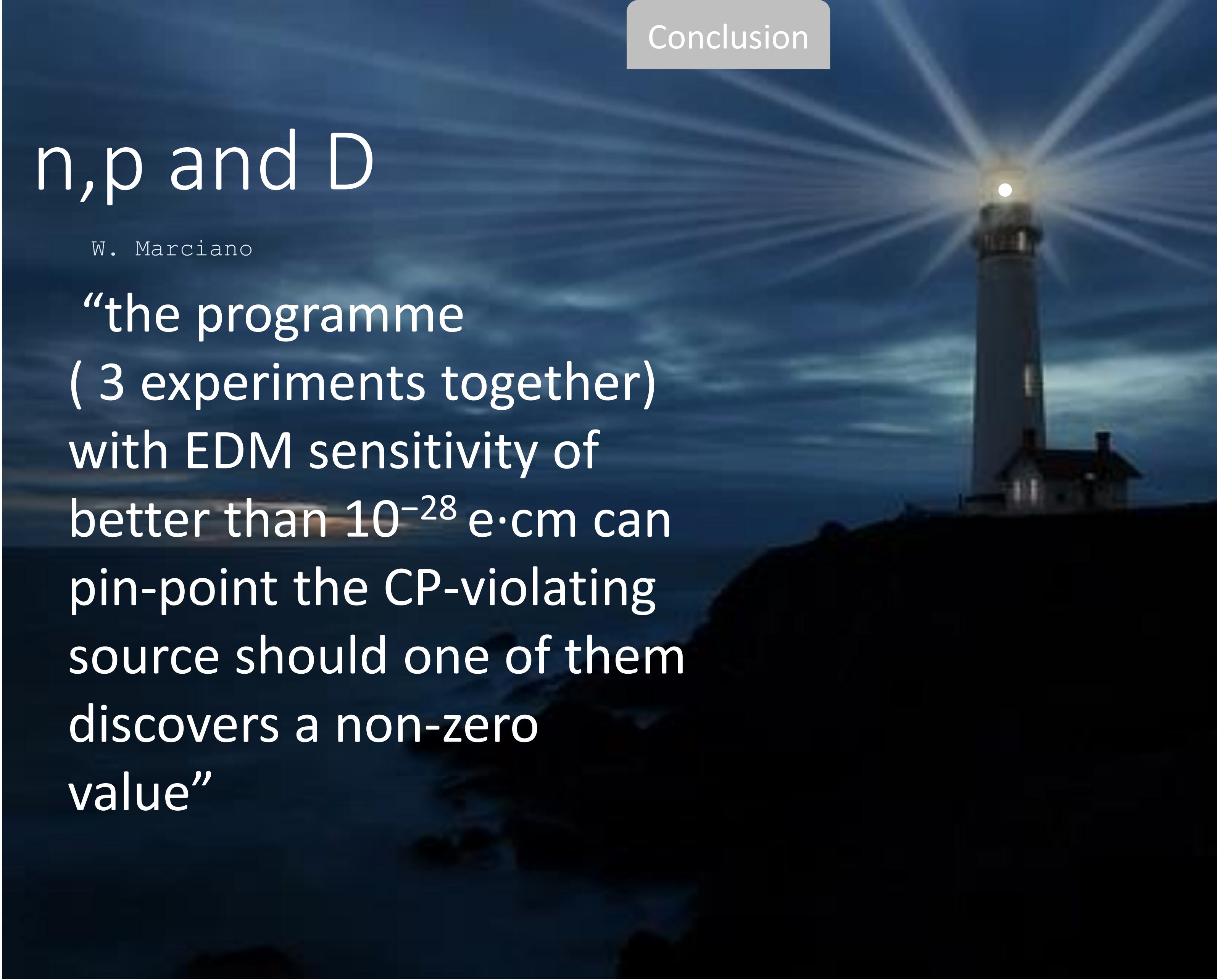


Figure 2. (L-R)/(L+R) vs. time [s] is shown here as well as the fit results to two parameters (slope and dc offset). More details on the parameters used are given in table 1 (case 2). The total counts used are 4×10^{12}, with P_0=0.8, and A=0.6.

Comments – CPEDM @ CERN

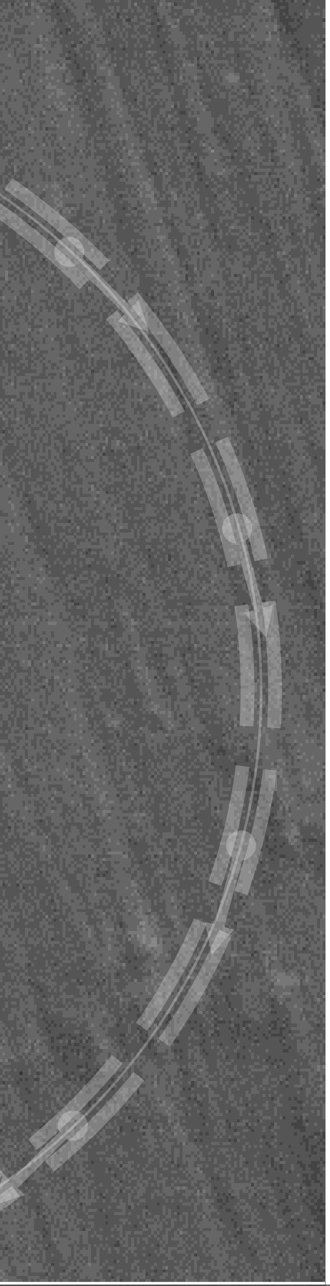
- Costing: Full costing for BNL proposal
  - Proposal here O(20MCHF)
  - Electric has design *“technically driven schedule”*
- Ideally pbars (but need plenty!)
  - Superb CPT check
- Phase-II proton increasing sensitivity by order of magnitude possible

n,p and D



W. Marciano

> “the programme (3 experiments together) with EDM sensitivity of better than 10^{-28} e·cm can pin-point the CP-violating source should one of them discovers a non-zero value”



Summary - CPEDM

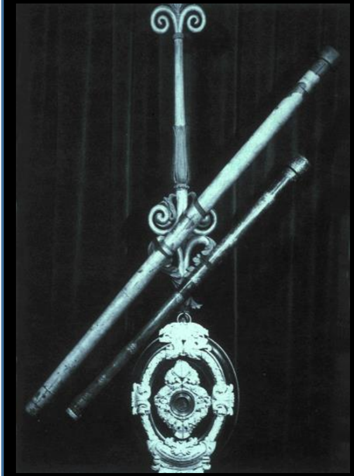
- θ_{QCD} & window to CP
- NP into the PeV range
- CP-violating sources beyond the SM, e.g. *SUSY*
- pEDM >10 sensitive than the best nEDM plans

- All electric ring design well developed
  “do the simple things…”
- Power of the method
  High intensity beams
  Long beam lifetime
  Spin Coherence Time
  Counter rotating beams cancel B-field effects
- Experienced team/collaboration based on g-2

Super precise measurements
Using magic momenta

Note

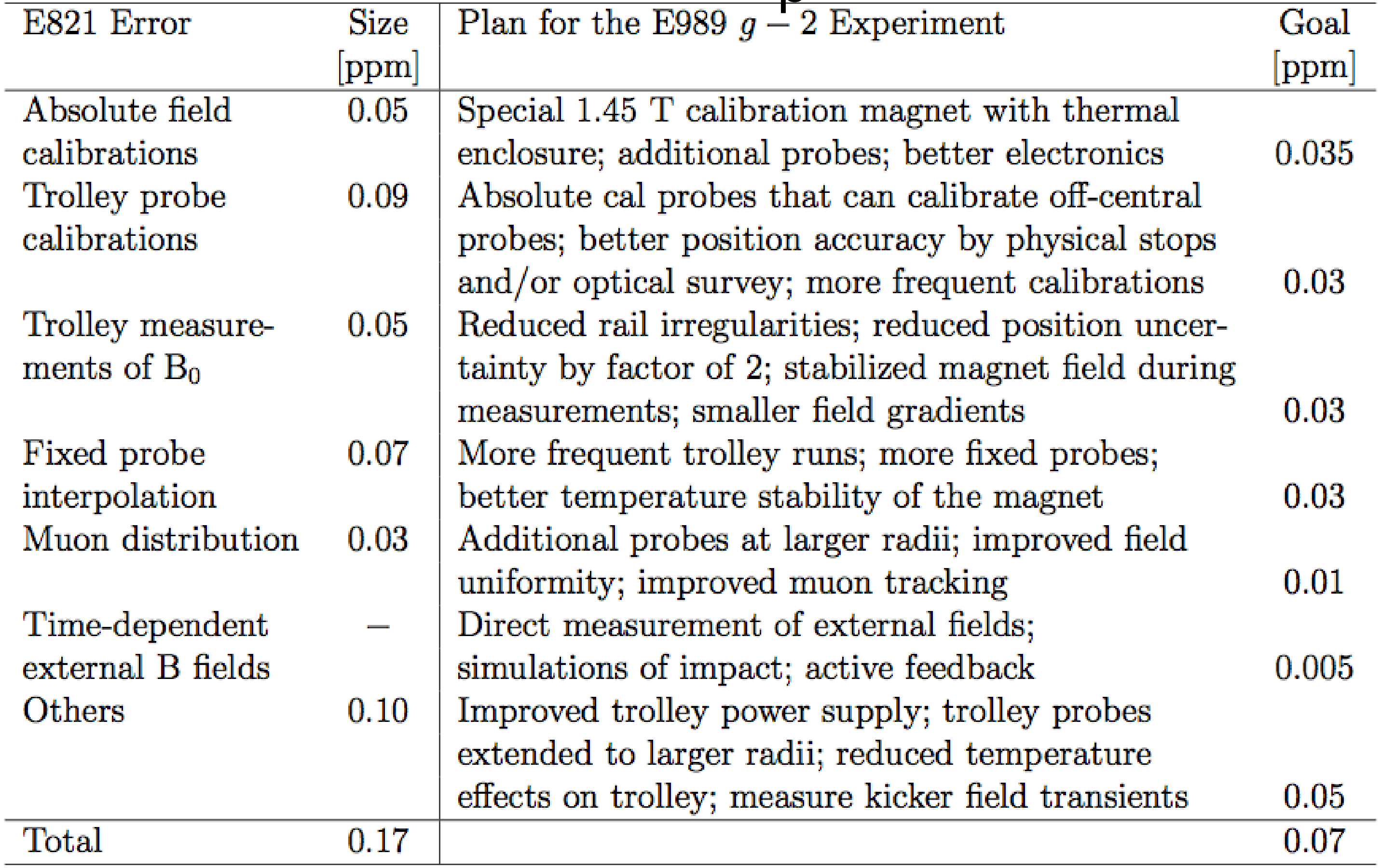
- Huge worldwide effort on EDMs
  - Electrons (new atom interferometer technique!)
  - Neutrons
- A fundamental way to look for NP and test the SM
- Many techniques of which frozen spin is only one



Measure what is measureable and make measureable what is not so.”

Galileo Galiliei
1564-1642

B-field / ω_p systematics



E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

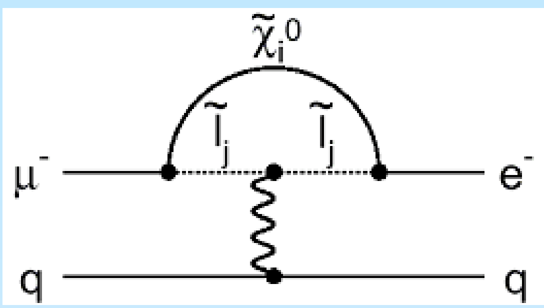
0.17 ppm → 0.07 ppm

Electron Magnetic Dipole Moment

- Most precisely measured property of an elementary particle
- Most precise prediction of the standard model
- Most precise confrontation of theory and experiment
- Greatest triumph of the standard model


64 December 2013 Physics Today

μe - conversion operators



R.Kitano, M.Koike and Y.Okada. 2002

have calculated the coherent μ-e conversion branching ratios in various nuclei for general LFV interactions to see:

(1) which nucleus is the most sensitive to mu-e cor

(2) whether one can distinguish various theoretical

[redacted]

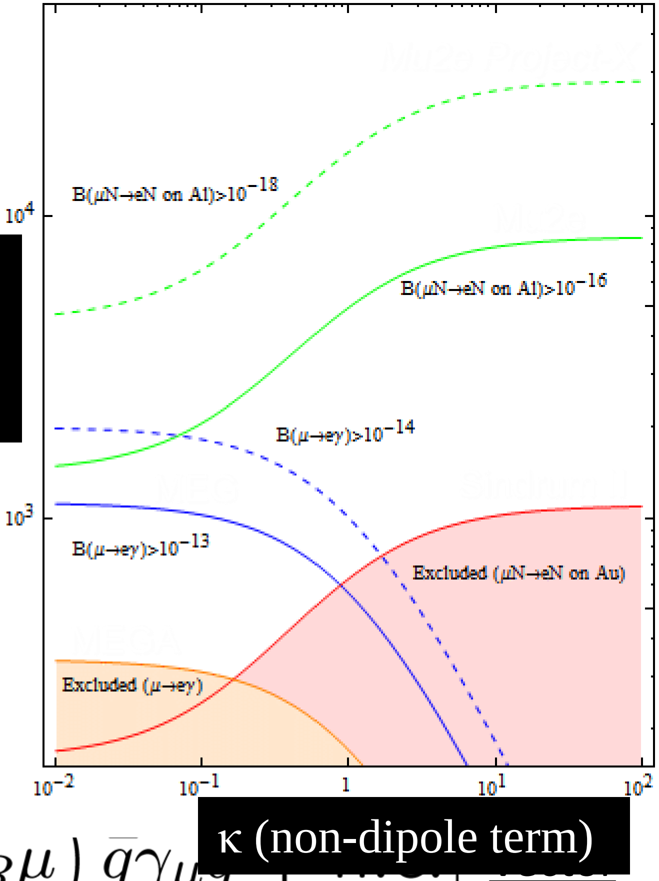
Relevant quark level interactions

$$\mathcal{L}_{\rm int} = -\frac{4G_F}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L\right.$$

$$-\frac{G_F}{\sqrt{2}}\sum_{q=u,d,s}\left[\left(g_{LS(q)}\bar{e}P_R\mu + g_{RS(q)}\bar{e}P_L\right.\right.$$

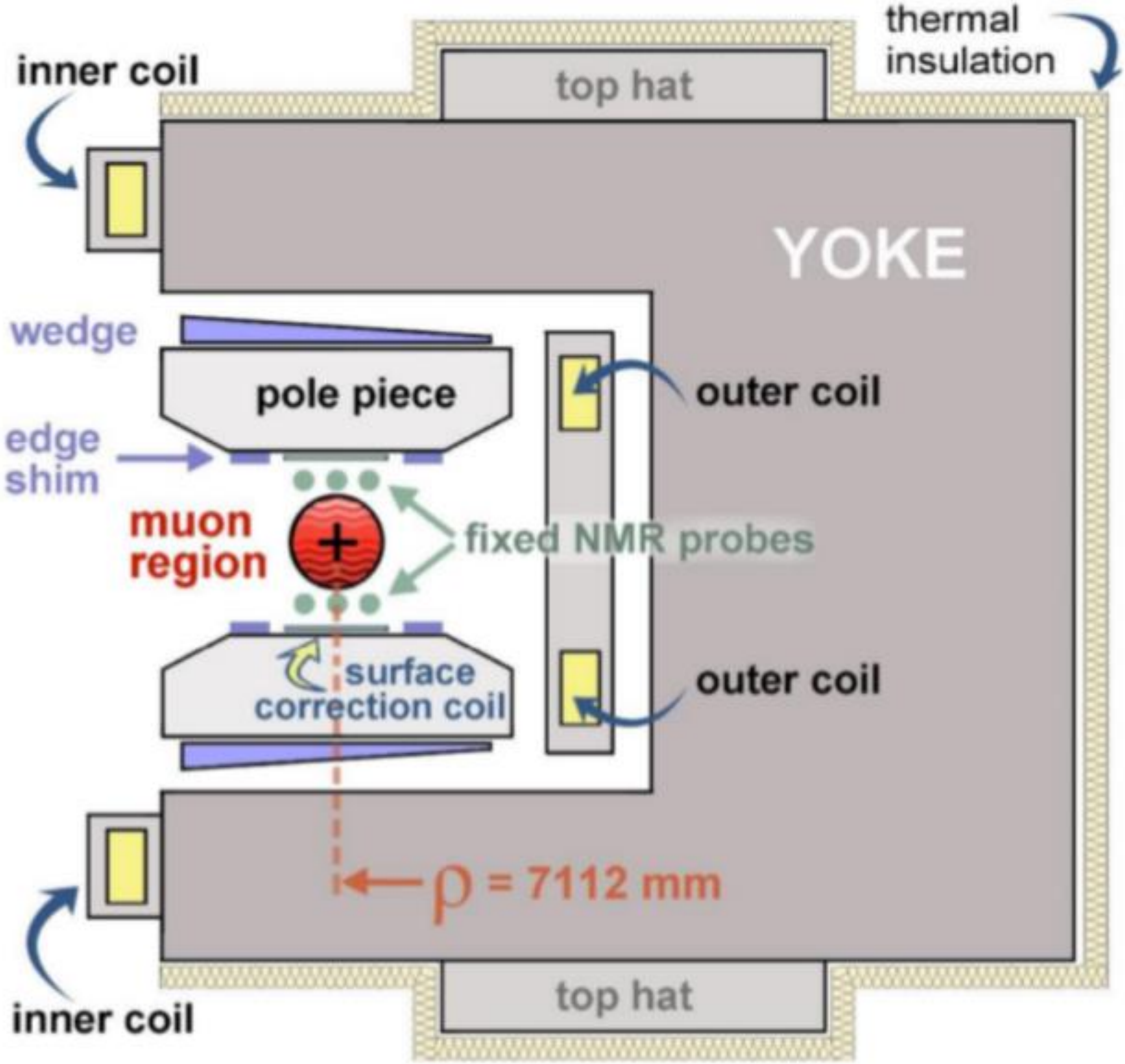
[redacted]

$$+\left(g_{LV(q)}\bar{e}\gamma^\mu P_R\mu + g_{RV(q)}\bar{e}\gamma^\mu P_R\mu\right)\bar{q}\gamma_\mu q$$



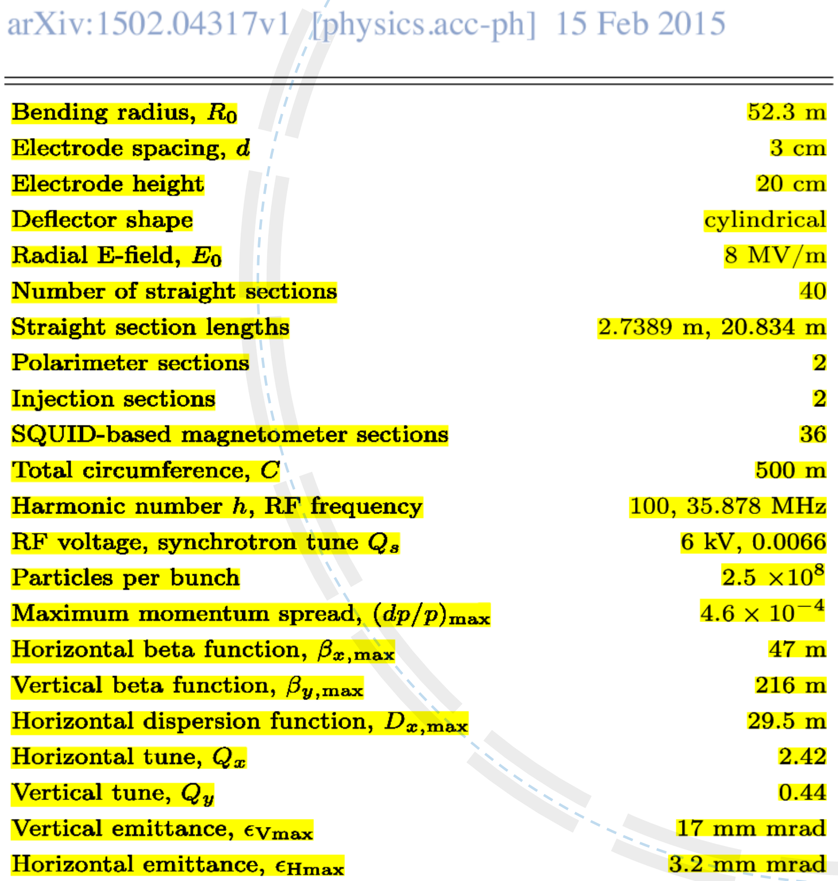
(fig, from Andrew Norman)

g-2


inner coil
top hat
thermal insulation
YOKE
wedge
pole piece
outer coil
edge shim
muon region
fixed NMR probes
surface correction coil
outer coil
ρ = 7112 mm
top hat
inner coil

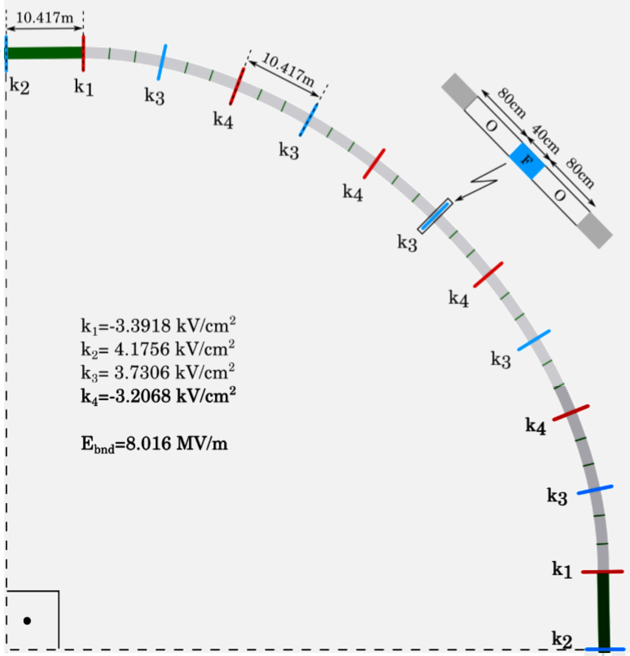
Lattice

Mei Bai PBC 16

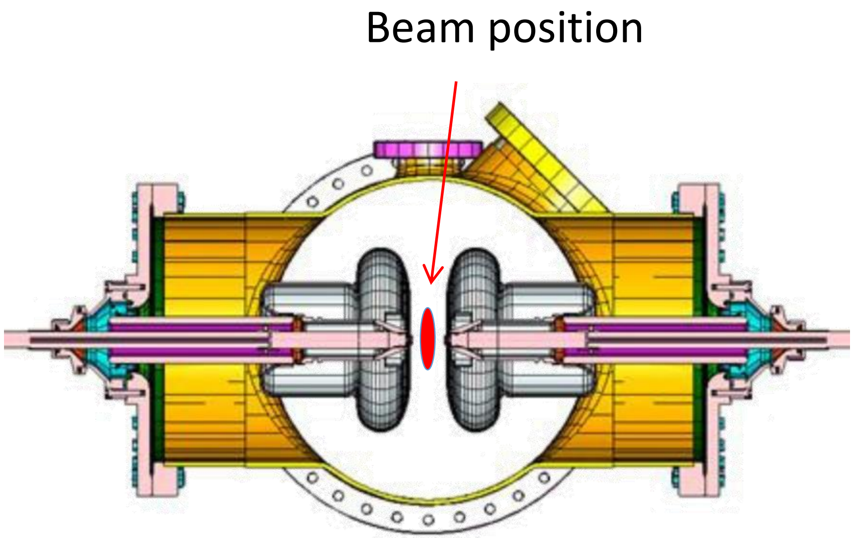


arXiv:1502.04317v1 [physics.acc-ph] 15 Feb 2015

Bending radius, R_0	52.3 m
Electrode spacing, d	3 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial E-field, E_0	8 MV/m
Number of straight sections	40
Straight section lengths	2.7389 m, 20.834 m
Polarimeter sections	2
Injection sections	2
SQUID-based magnetometer sections	36
Total circumference, C	500 m
Harmonic number h, RF frequency	100, 35.878 MHz
RF voltage, synchrotron tune Q_s	6 kV, 0.0066
Particles per bunch	2.5×10^8
Maximum momentum spread, $(dp/p)_{\max}$	4.6×10^{-4}
Horizontal beta function, $\beta_{x,\max}$	47 m
Vertical beta function, $\beta_{y,\max}$	216 m
Horizontal dispersion function, $D_{x,\max}$	29.5 m
Horizontal tune, Q_x	2.42
Vertical tune, Q_y	0.44
Vertical emittance, $\epsilon_{V\max}$	17 mm mrad
Horizontal emittance, $\epsilon_{H\max}$	3.2 mm mrad



E-field plate module

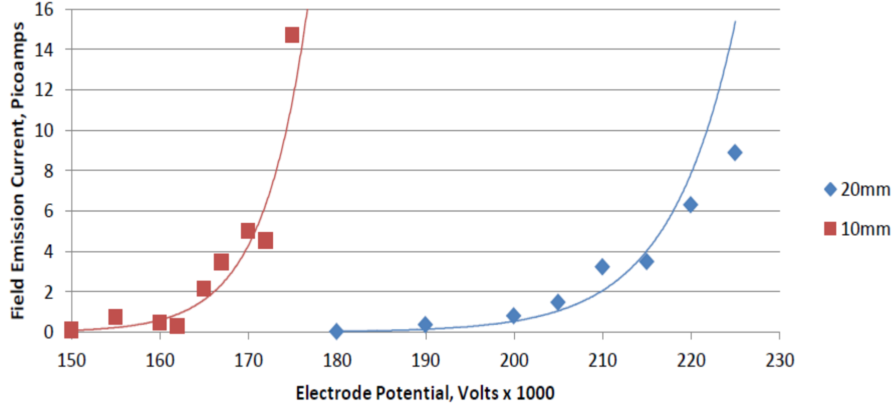


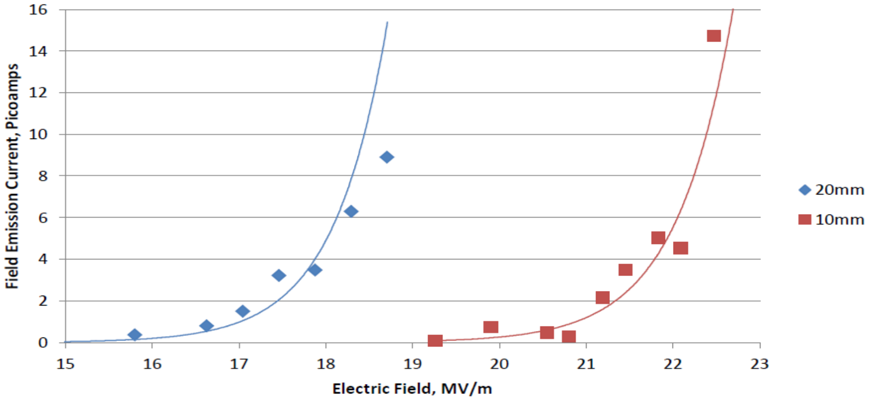
We are also producing new Q1 deflectors for g-2 experiment

JLab results with TiN-coated Al

No field emission at 225 kV;gaps > 40 mm, happy at high gradient

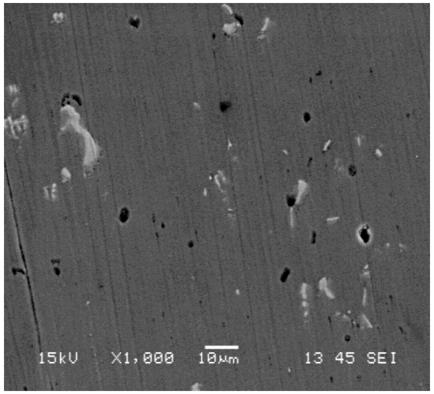
Matt Poelker, JLab



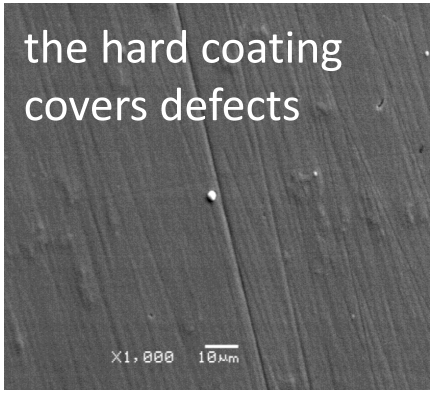


15 MV/m 20 MV/m

Bare Al



TiN-coated Al


the hard coating covers defects

Md. A. Mamun and E. Forman

Distortion of the closed orbit

$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 \left(Q_y^2 - N^2\right)} \cos\left(N\vartheta + \varphi_N\right)$$

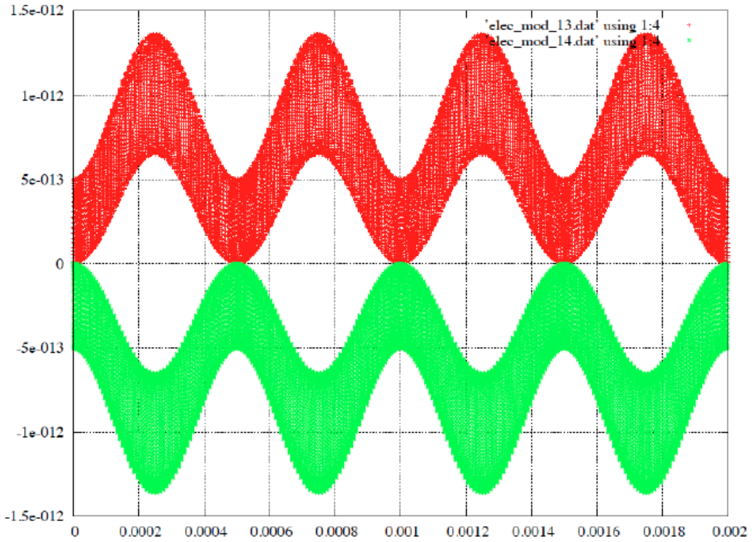


Figure 11.3: Simulation results for counter-rotating particles. The vertical beam position in meters [m] is shown here vs. time [s] for a constant radial B-field of 0.3 pG, and using eq. (11.7) to modulate the vertical tune (using f=1KHz). The two colors correspond to clockwise (red) and counter-clockwise (green) rotations for an average radial B-field directed outwards in the radial direction.

Clockwise beam

The N=0 component is a first order effect!

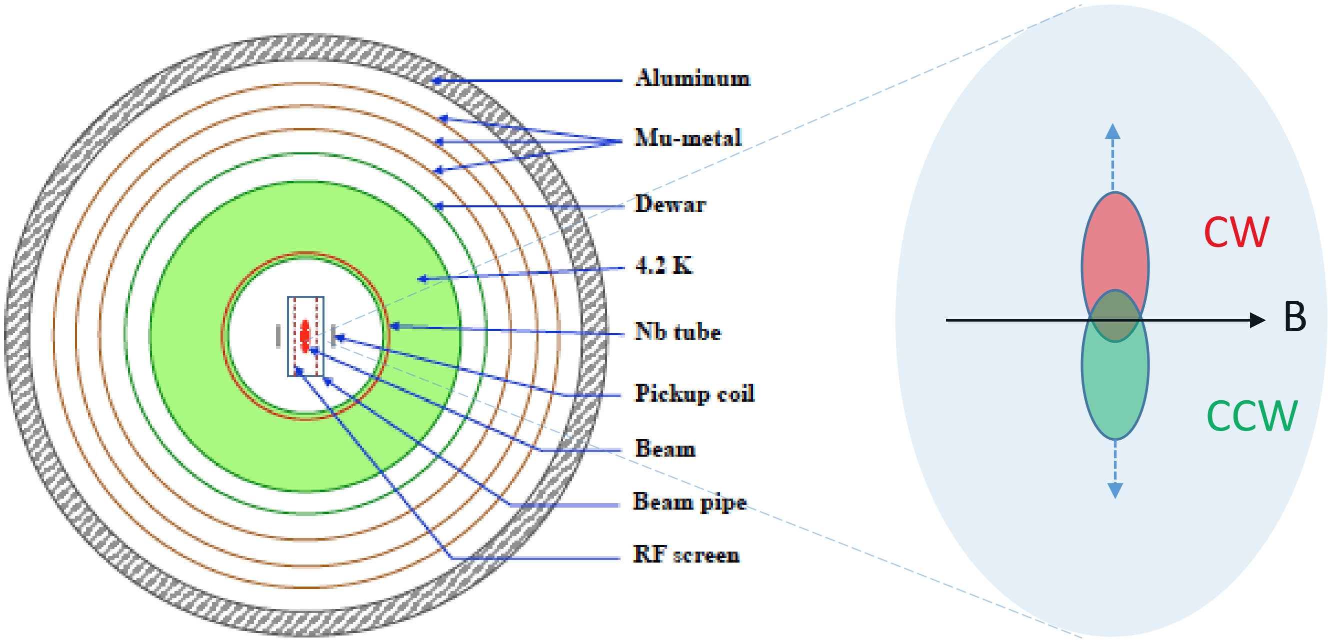
Counter-clockwise beam

The beam vertical position tells the average radial B-field; the main systematic error source

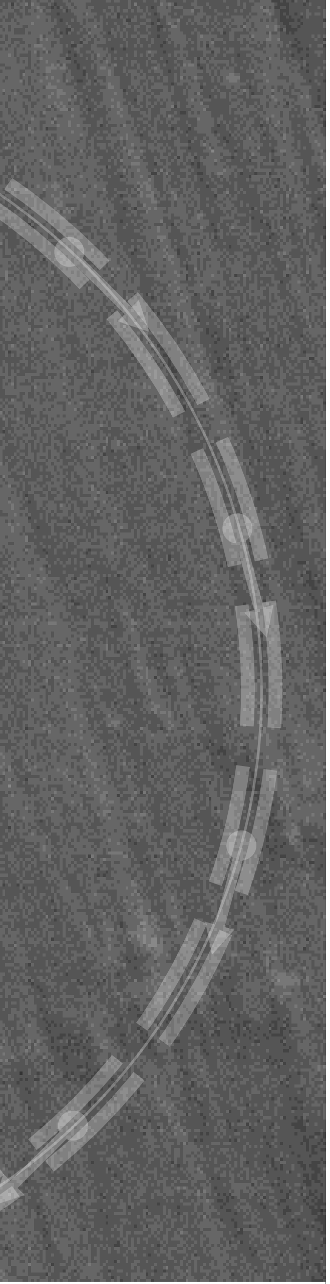
SQUID BPM

to sense the vertical beam splitting at 1-10kHz

commercially available SQUID gradiometers at KRISS 3.3 fT /√Hz @100 Hz



D. Kawall UMASS/Amherst



Spin Coherence Time: need ~10^3 s

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)
- They cause a spread in the g-2 frequencies:

$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

Systematic errors

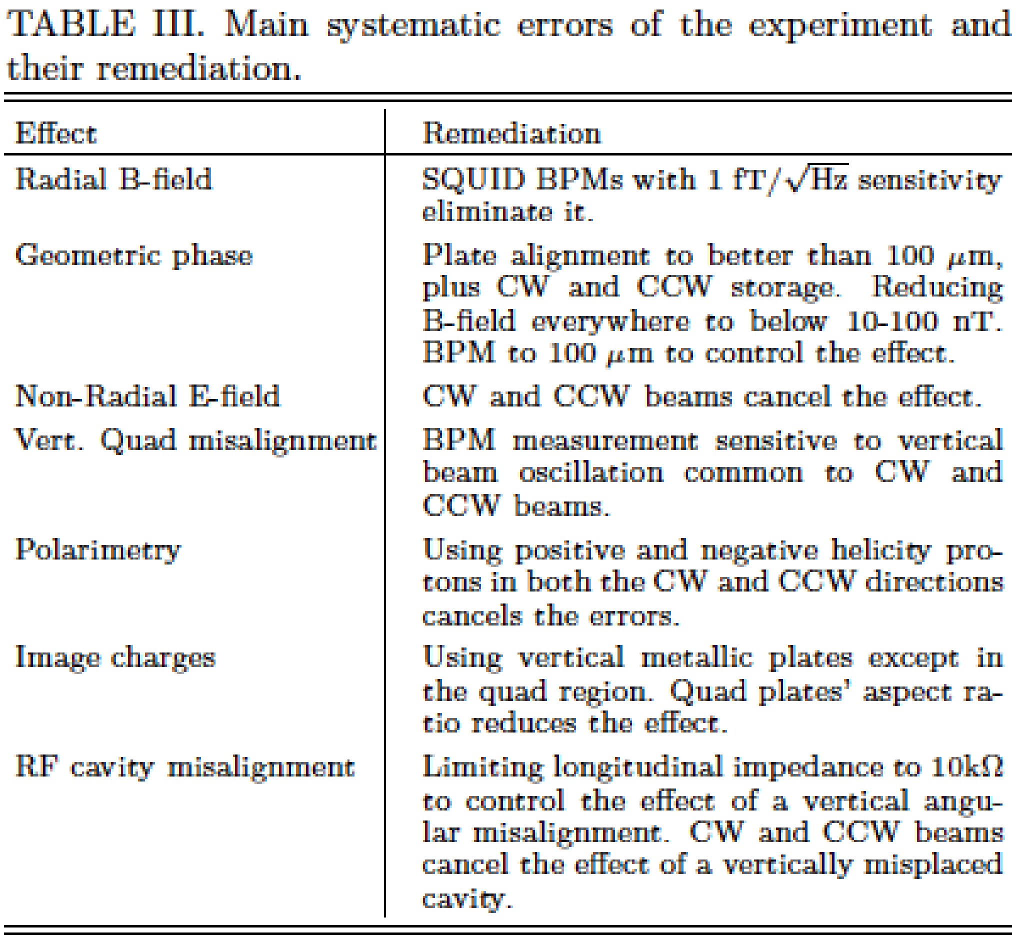


TABLE III. Main systematic errors of the experiment and their remediation.

Effect	Remediation
Radial B-field	SQUID BPMs with 1 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ sensitivity eliminate it.
Geometric phase	Plate alignment to better than 100 μm, plus CW and CCW storage. Reducing B-field everywhere to below 10-100 nT. BPM to 100 μm to control the effect.
Non-Radial E-field	CW and CCW beams cancel the effect.
Vert. Quad misalignment	BPM measurement sensitive to vertical beam oscillation common to CW and CCW beams.
Polarimetry	Using positive and negative helicity protons in both the CW and CCW directions cancels the errors.
Image charges	Using vertical metallic plates except in the quad region. Quad plates' aspect ratio reduces the effect.
RF cavity misalignment	Limiting longitudinal impedance to 10kΩ to control the effect of a vertical angular misalignment. CW and CCW beams cancel the effect of a vertically misplaced cavity.

EDMs	10^{-26} e cm	Technique	Arxiv
proton	$\lvert d_p \rvert < 79$	From ^{199}Hg	0901.2328
proposal	$< 10^{-3}$	srEDM (I)	1502.04317v1
neutron	$\lvert d_n \rvert < 2.9$		1509.04411
deuteron	$< 10^{-3}$	srEDM(II)	1201.5773

$$\bar{\theta} \leq 2 \times 10^{-10}$$

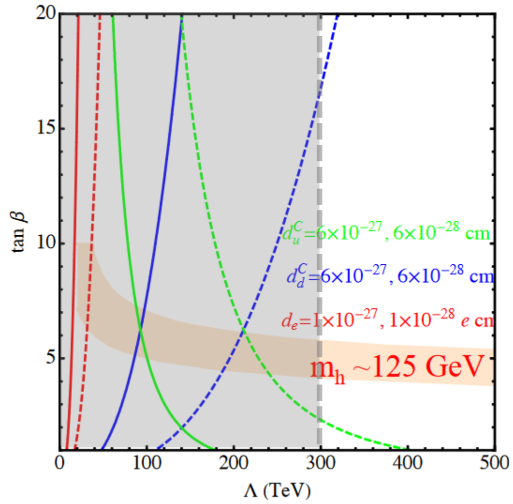
$$\bar{\theta} \leq 3 \times 10^{-14}$$

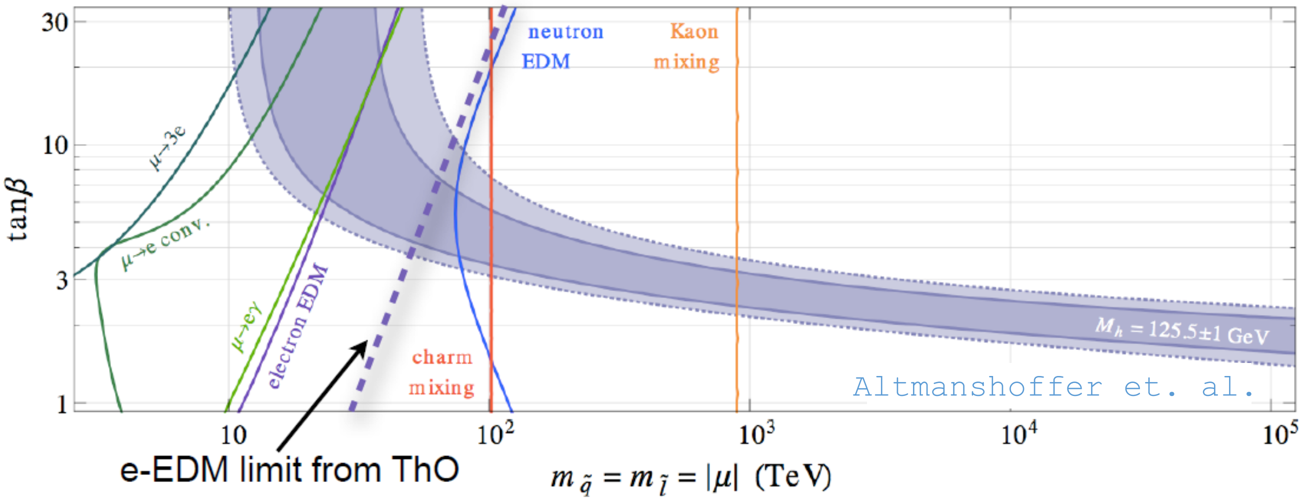
pEDM is more than an order of magnitude more sensitive than current nEDM plans

Physics

`arXiv:hep-ph/0508135`

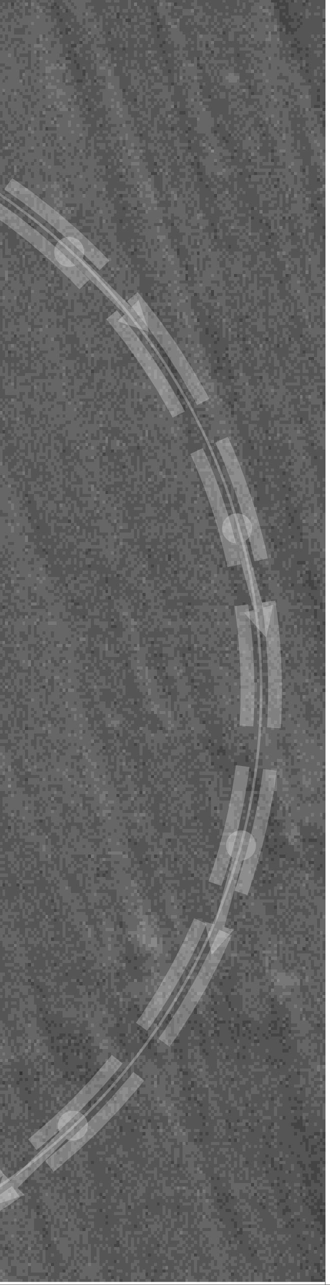
$$d_n \sim \left(\frac{300\ \text{GeV}}{\Lambda_{\text{SUSY}}}\right)^2 \sin\phi_{\text{CP}} \times 10^{-24}\ e\ \text{cm}$$


Pospelov PBC 16


$|m_{\tilde{B}}| = |m_{\tilde{W}}| = 3\ \text{TeV}\,,\ |m_{\tilde{g}}| = 10\ \text{TeV}$

Altmanshoffer et. al.

e-EDM limit from ThO



The ring

- Electric field needed is moderate (<8MV/m). New techniques with TiN coated Aluminum is a cost savings opportunity.
- JEDI(COSY), have demonstrated Long horizontal Spin Coherence Time (SCT) trimming with sextupoles.