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Summer School on Particle Physics

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Precision QED and new physics
SPECIAL LECTURE

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Precision QED and "New Physics" including (The Proton Size Puzzle)

Based in part on: "Lepton Moments"
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Lecture #1
ICTP Trieste, Italy
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BROOKHAVEN NATIONAL LABORATORY

Outline

1.) ***Historical Introduction***

i) Wolfgang Pauli (Exclusion Principle)

ii) Spin (1925)

iii) The Dirac Equation (1928) $g_e=2$

2.) ***Post WWII Developments (1947-48)***

i) Electron Anomalous Magnetic Moment g_e-2

ii) Lamb Shift: Hydrogen $2S_{1/2}$-$2P_{1/2}$

iii) The Muon: "Who ordered that?" $m_\mu \approx 207 m_e$

3.) ***More Recent Developments***

i) g_e-2

ii) Lamb Shift?

iii) g_μ-2 (Supersymmetry? Something Else?)

4.) ***Muonic Hydrogen Lamb Shift***

The Proton Size Puzzle (r_p(ep) vs r_p(μp) atom)

Somethings gotta give: 5-8 sigma difference

5.) ***New Physics Scenarios***

r_p (5-8σ) & g_μ-2 (3.6σ) Discrepancies

Can the same "New Physics" Explain Both?

6.) ***New "Light" Vector or Scalar Boson?***

Viewer Discretion Advised

7.) ***Conclusion & Outlook***

1.) ***Historical Introduction***

In a 1924 letter to Lande, W. Pauli presented his now famous

"Pauli Exclusion Principle"

Atomic Spectroscopy of the Bohr Atom, electrons

classified by quantum no.: n, l, m & t=***twofoldness***

No two electrons can have identical quantum numbers!

Fundamental Property of Nature ➔Chemistry,

Neutron Stars, Baryon Spectroscopy (quark color)…

But, what was "twofoldness?

Wolfgang Pauli

Wolfgang Pauli

ii) ***<u>Electron Spin (1925)</u>***

In 1925, Kronig (unpublished) and independently Uhlrenbeck and Goudsmit interpret “twofoldness” as Electron spin S=±½. Wavefunction antisymmetric under Interchange of identical electrons.

Pauli: ***“A clever idea but nothing to do with nature!”***

Eventually spin established (Thomas relativistic factor of 2)
Electron magnetic moment $\boldsymbol{\mu}_e = g_e e/2m_e \mathbf{S}$
g_e =gyromagnetic ratio = 2

***<u>Ironic</u>*: Pauli 2x2 *<u>spin</u>* matrices (Non-relativistic)**

iii) ***<u>The Dirac Equation</u>*** (1928) $g_e=2$

"The Dirac equation like youth is often wasted on the young"

<u>The Stage in 1928</u>

Non Relativistic <u>Schroedinger Eq.</u> First Order

Relativistic Klein-Gordon Scalar Eq. (spin 0) Second Order

Spin 1/2 - Pauli 2x2 Matrices (non-relativistic spin)

<u>The Genius of Dirac</u>

QM+Special Rel.+Spin+Gauge Invariance

First Order Equation

$$\mathbf{i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m_e\psi(x),}$$

4x4 γ^μ (Dirac) matrices: $\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}I$

Mag. Moment: $\boldsymbol{\mu}=g_e e/2m_e \mathbf{s}$ **$g_e=\underline{2}$ Not 1!**

As Observed Experimentally

<u>Automatic Unexpected Success of Dirac Eq.</u>

Dirac Derivation of $g_e=2$ (1928 & "QM" Book)

(Advanced Exercise for students)

Go to second order formalism (apply $i(\partial_\mu - ieA_\mu(x))\gamma^\mu$ **twice**

and find terms in Klein-Gordon Eq.

$\boldsymbol{\mu}\bullet\mathbf{H} + i\rho_1\boldsymbol{\mu}\bullet\mathbf{E}$ **(edm?)** $\boldsymbol{\mu}=\underline{2}e/2m_e\mathbf{s}$

Imaginary Part? - Non Physical→ Ignore?

By the 4th edition of "QM" he got rid of it

(What is an edm and what is a chiral phase?)

Later realized Negative Energy Solutions!

(Dirac Equation Largely Ignored)

W. Pauli was a primary antagonist

Dirac predicts positron, antiproton, antihydrogen…

Antimatter Discovery Dirac's crowning glory!

Doubled Particle Spectrum!

Why is the Universe Matter-Antimatter Asymmetric?

Baryogenesis! Leptogenesis!

(1964-CP Violation Discovered-CKM Not Enough)

"New Physics" Source of CP Violation Needed!

Supersymmetry, 4th Generation, Multi-Higgs…

We could add extra terms to the Dirac Equation

(using $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$)

$$e/4m_e a_e F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x) + i/2 d_e \gamma_5 F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x)$$

Anomalous Mag. Mom.

$g_e=2(1+a_e)$

a_e = Pauli Term

Electric Dipole Mom.

Violates P&T(CP)

Not Observed

$d_e<2\times10^{-27}$ e-cm

But Must Exist!

Pauli opposed the Dirac Equation (Neg Energy Sol.)
Later became so converted that he opposed proton Mag. Moment exp. "It must be $g_p e/2m_p \mathbf{s}$ $g_p=2$!"

Experiment $g_p=5.59$

2.) ***Post WWII Developments (1947-48)***

1947 Small Anomalous Atomic Fine Structure Effects

G. Breit: maybe $a_e=(g_e-2)/2\neq 0$

1948 Schwinger Calculates: $a_e=\alpha/2\pi\approx 0.00116$ ($\alpha=e^2/4\pi=1/137$)

Agreed with measurement of Kusch & Foley**!**

Great Success of QED -Quantum Field Theory

Exercise: Calculate 1loop QED Correction

$a_e= (g_e-2)/2=\alpha/2\pi$

1947 Lamb measures the $2P_{½}$-$2S_{½}$ splitting

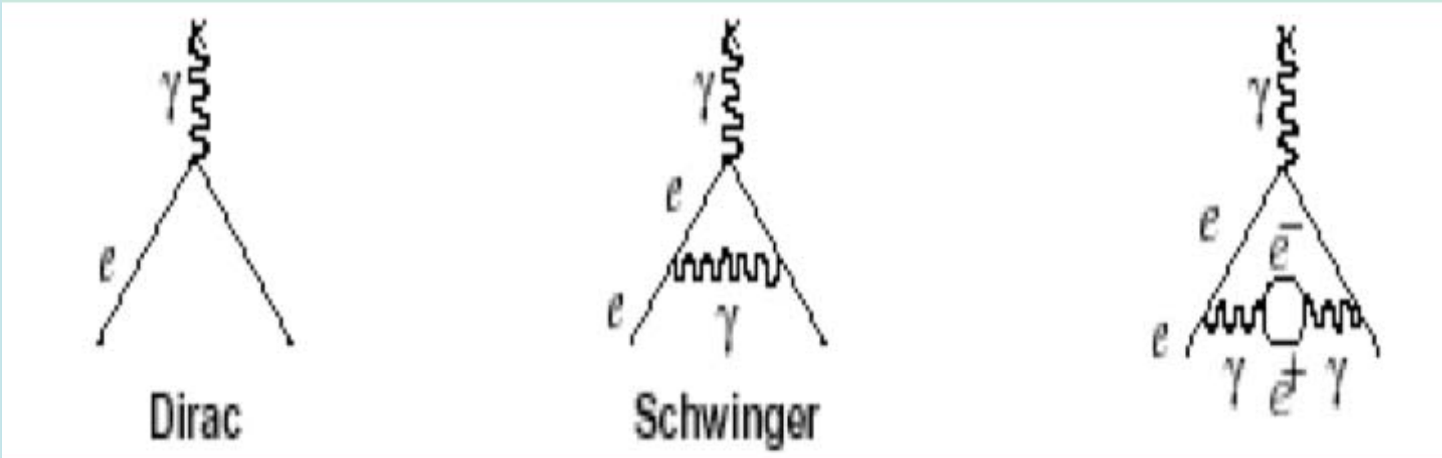
vacuum polarization, electron self-interaction

a_e and Lamb shift start of QED (Quantum Electrodynamics)

1947 Muon established $m_\mu\approx 207m_e$ "Who ordered that?"

Later $\tau_\mu=2.2\text{x}10^{-6}$sec *very long*

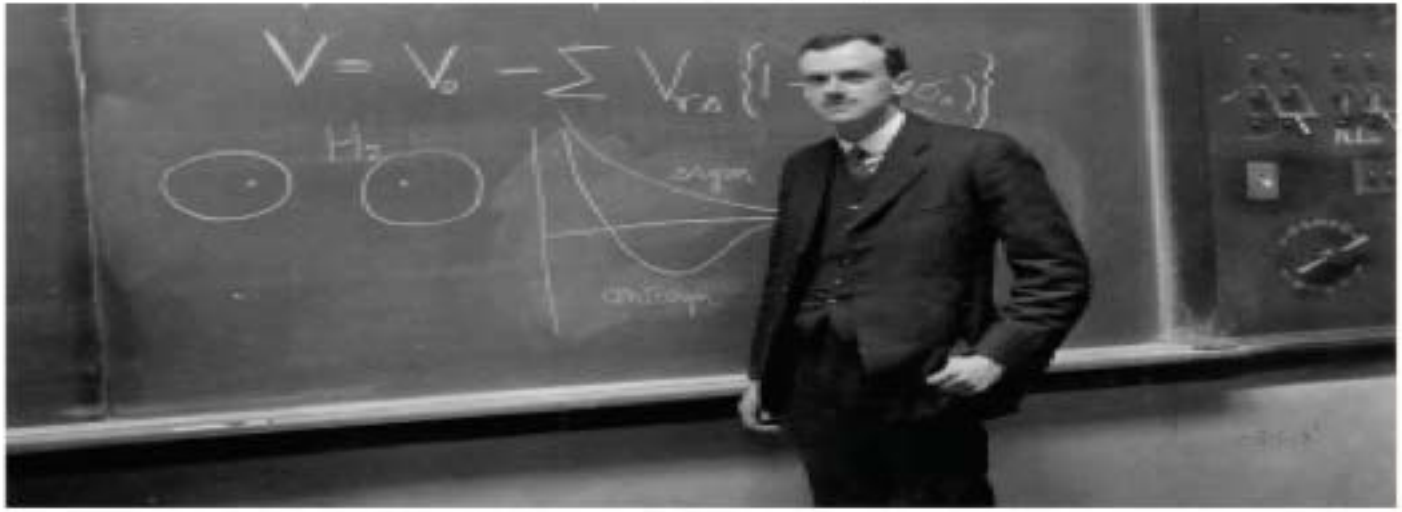
Anomalous Magnetic Moment Contributions

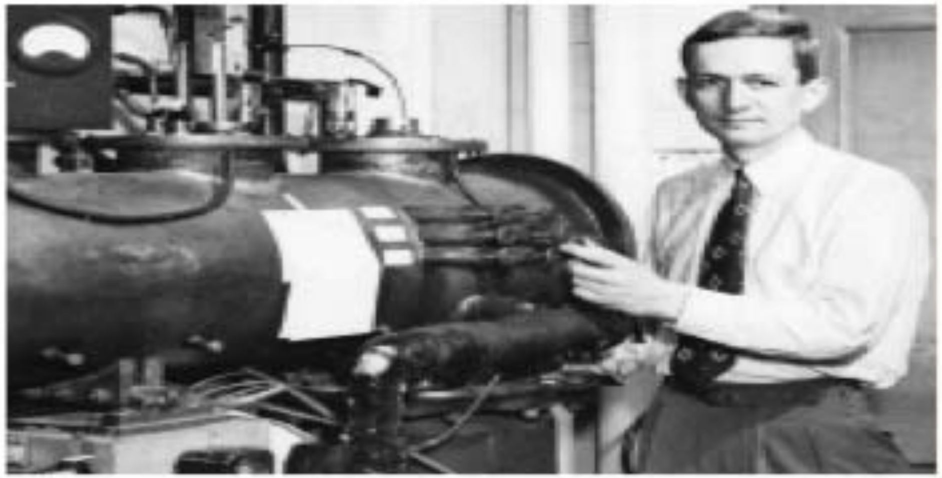


Clockwise:

Julian Schwinger,
Polykarp Kusch,
Paul Dirac,
Norman Ramsey and
Edward Purcell

Courtesy AIP Emilio Segrè Visual Archives (full credits overleaf)





Mount Auburn Cemetery

3.) ***More Recent Developments***

i.) **Current Status of $a_e=(g_e-2)/2$**

a_e(exp)=0.00115965218073(28)

g_e(exp)=2.00231930436146(56) *13 significant figures!*

(Hanneke, Fogwell, Gabrielse: PRL 2008)

factor of 15 improvement over Univ. Wash. Result!

$$a_e(SM)=\alpha/2\pi-0.328478444003(\alpha/\pi)^2$$
$$+1.1812340168(\alpha/\pi)^3$$
$$-1.9144(35)(\alpha/\pi)^4+0.0(4.6)(\alpha/\pi)^5\ldots$$
$$+1.68\times10^{-12}(had)+0.03\times10^{-12}(EW)$$

$\alpha^{-1}(a_e)$=137.035999084(51) Best Determination

α^{-1}=137.035999450(620) Rydberg 2nd best

a_e(Ryd)=0.00115965217760(520) Theory & Exp. Agree!

"New Physics" Constraint

$|a_e(\text{new physics})| = |a_e^{exp} - a_e^{Ryd}| < 10^{-11}$

$a_e(\text{heavy new physics}) = C(m_e/\Lambda)^2 \quad C \leq O(1)$

$\Lambda > 160\text{GeV}$ or $\Lambda > 8\text{GeV}$ for $C = \alpha/\pi$

Not Very Constraining

Electroweak $C \approx \alpha/\pi$, $\Lambda = m_W = 80.4\text{GeV} \rightarrow 3\text{x}10^{-14}$

Better for light New Physics eg Dark Photon (Light Vector Boson < 200MeV, couples through γ-γ_d Mixing: $\alpha_d < 10^{-6}\alpha$)

ii) Hydrogen Lamb Shift Update?

Depends on proton structure (size) r_p (radius)

How large is the proton (rms) radius?

About a Fermi (fm) $=10^{-13}$cm

$< r_p^2 > = \lim_{Q2 \to 0} -6\, dF(Q^2)/dQ^2$ em form factor

CODATA: $\mathbf{r_p \cong}$ **0.8768(69)fm (ep atom)** hydrogen spectrum

(2008) (Main sensitivity - Lamb Shift)

Depends on Rydberg Constant

$R_\infty = 1.0973731568527(73) \times 10^7 m^{-1}$

known to 13 significant figures!

$R_\infty \cong \alpha^2 m_e c/2h$ "One of the Two most accurately measured fundamental physical constants" ***What is better known?***

3.ii) Muon Anomalous Magnetic Moment

1957 Garwin, Lederman & Weinrich study $\pi \rightarrow \mu\nu$, $\mu \rightarrow e\nu\nu$

found parity violation & measured $g_\mu = 2.00 \pm 0.10$

Parity Violation Decay→Self Analyzing Polarimeter

led to Three Classic CERN Exps. ending in 1977

"The Last g_μ-2 Experiment"

- **Until Experimental E821 at BNL (2004 Final)**
- $a_\mu^{exp} \equiv (g_\mu - 2)/2 = 116592089(54)_{stat}(33)_{sys} \times 10^{-11}$

$= 116592089(63) \times 10^{-11}$

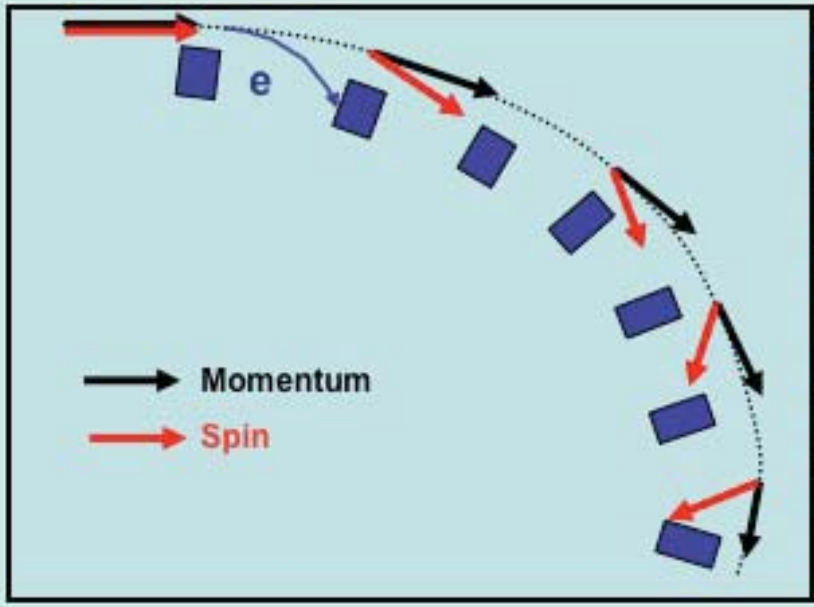
Factor of 14 improvement over CERN results

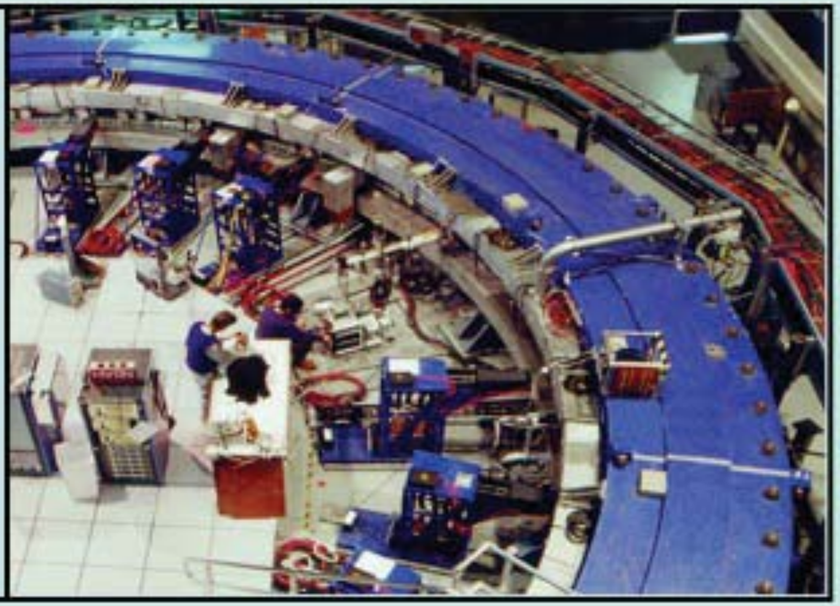
(Proposed Future Factor 4 Improvement at FNAL)

D. Hertzog, B.L. Roberts…

BNL Muon g-2 Experiment

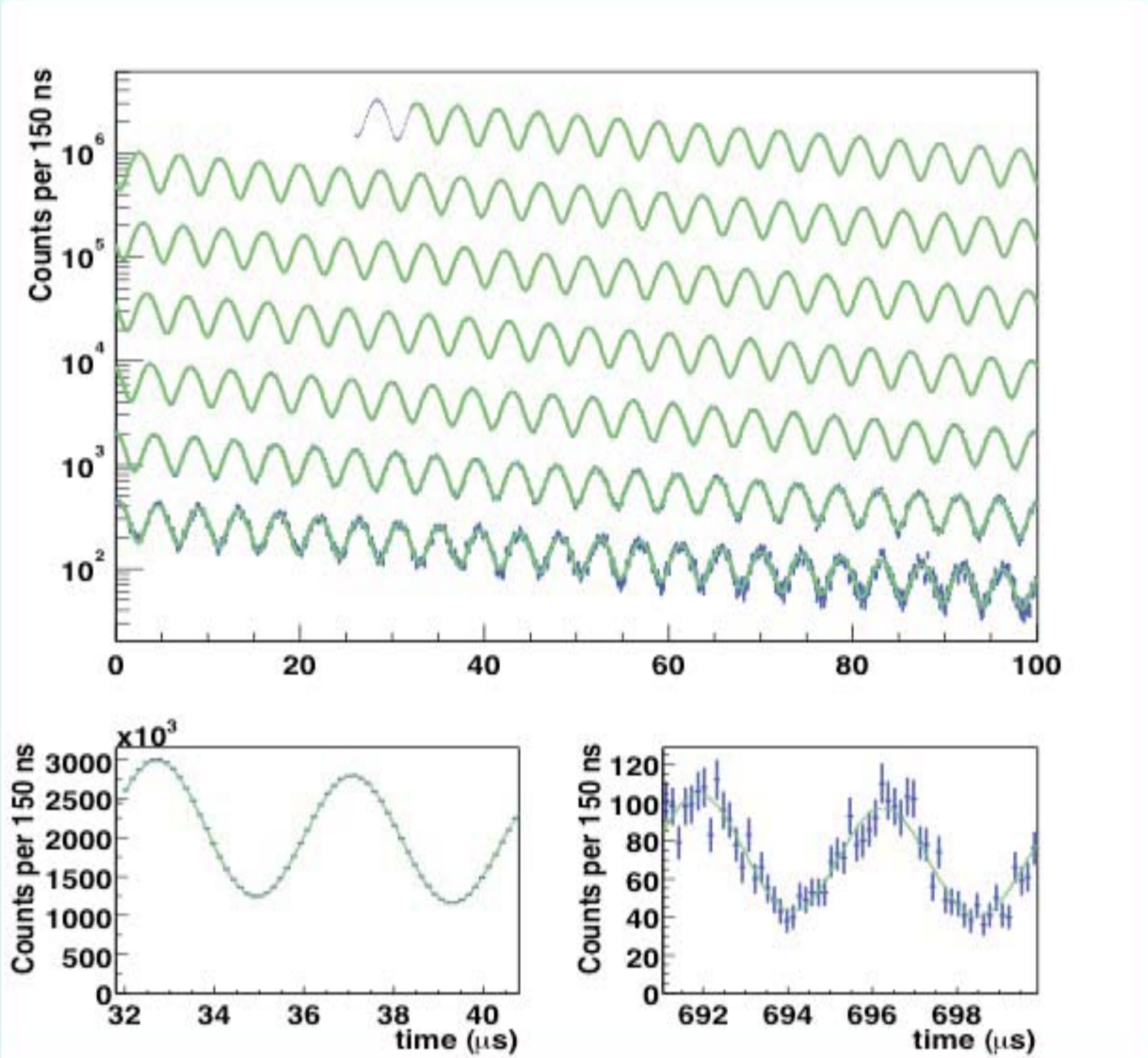
- a_μ is proportional to the difference between the spin precession and the rotation rate





$$\Delta\omega = \omega_a = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

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



Standard Model Prediction

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$

QED Contributions:

- $a_\mu^{QED} = 0.5(\alpha/\pi) + 0.765857410(27)(\alpha/\pi)^2 +$
  $24.05050964(43)(\alpha/\pi)^3 +$
  $\underline{130.8055(80)}(\alpha/\pi)^4 +$
  $663(20)(\alpha/\pi)^5 + \ldots$ (5 loop Estimate)

$\alpha^{-1} = 137.035999084(54)$ From a_e

$a_\mu^{QED} = \underline{116584718.1(2)\text{x}10}^{-11}$ Very Precise!

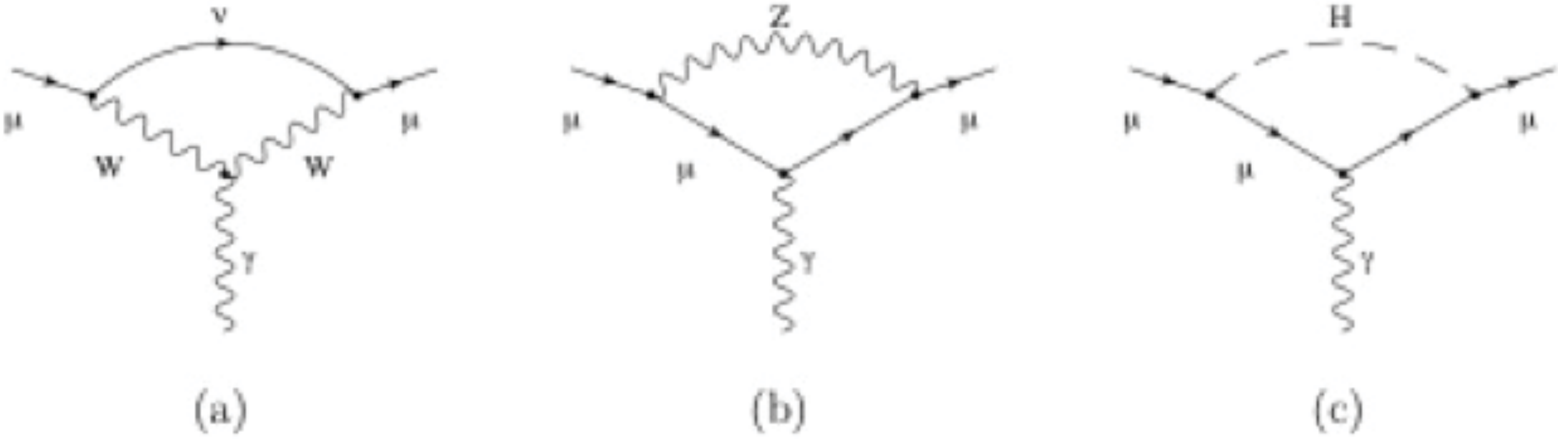


Figure 2: One-loop electroweak radiative corrections to a_μ.

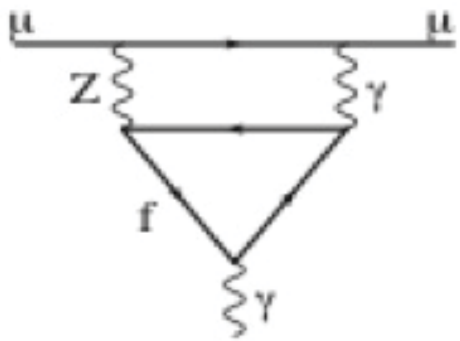


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to $a_\mu^{\rm EW}$.

Electroweak Loop Effects

a_μ^{EW}(1 loop)=194.8×10^{-11} goal of E821

2 loop EW corrections are large -21%

a_μ^{EW}(2 loop)=$-40.7(1.0)(1.8) \times 10^{-11}$

3 loop EW leading logs very small $O(10^{-12})$

- $a_\mu^{EW} = 154(2) \times 10^{-11}$ Non Controversial

- **Hadronic Contributions**

Vacuum polarization via dispersion relation

$e^+e^- \rightarrow$ hadrons or $\tau \rightarrow$ hadrons$+\nu_\tau$(isospin)

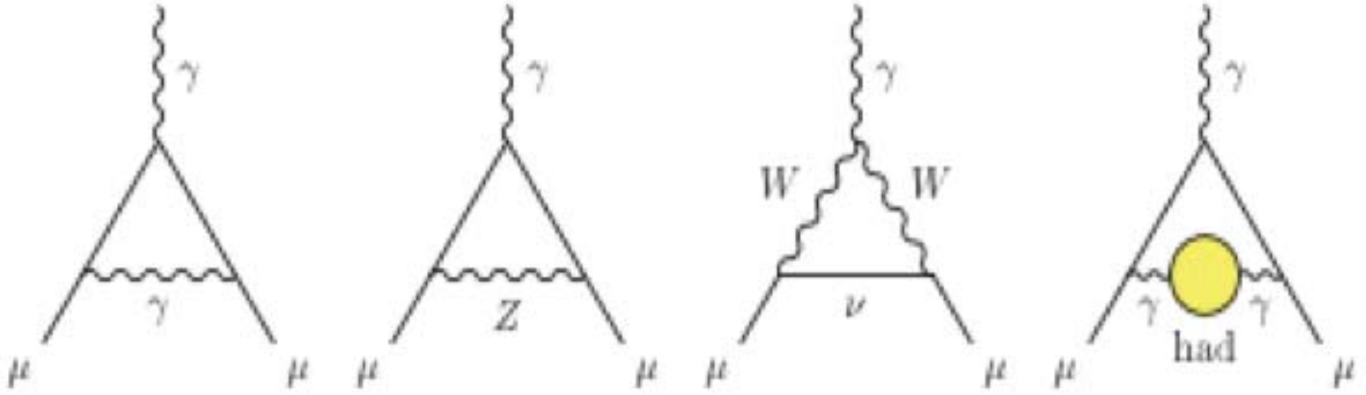
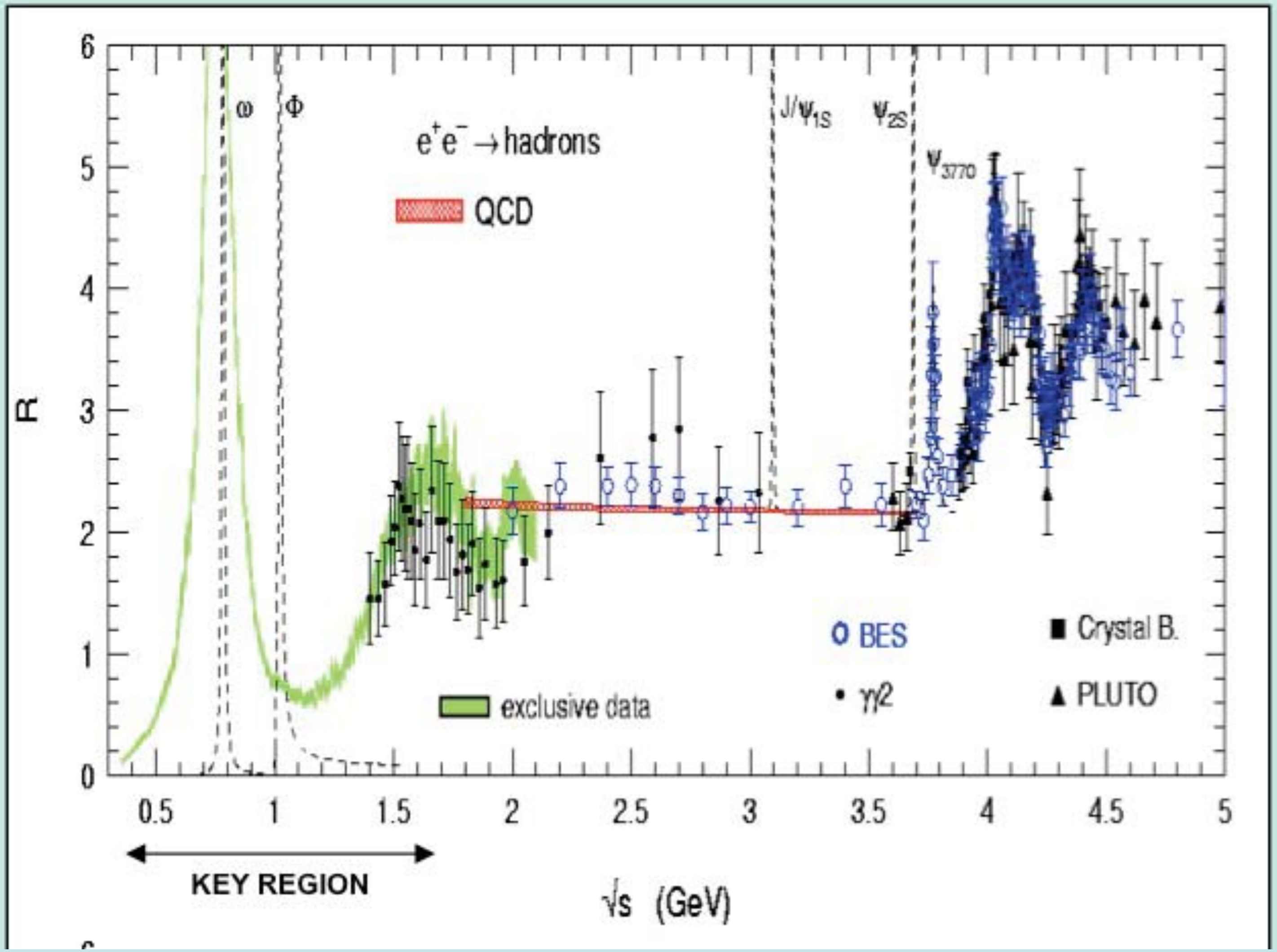


Figure 1: Representative diagrams contributing to $a_\mu^{\rm SM}$. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.



e+e- → hadrons
QCD
ω
Φ
J/ψ1S
ψ2S
ψ3770
R
exclusive data
BES
γγ2
Crystal B.
PLUTO
√s (GeV)
KEY REGION

From $e^+e^- \rightarrow$ hadrons data + dispersion relation

$a_\mu^{Had}(V.P.)^{LO} = \underline{6923(40)(7)} \times 10^{-11}$ (Hoecker update 2010)

$\underline{\text{3 loop}} = a_\mu^{Had}(V.P.)^{NLO} + a_\mu^{Had}(LBL)$

$a_\mu^{Had}(V.P.)^{NLO} = -98(1) \times 10^{-11}$

$a_\mu^{Had}(LBL) = 105(26) \times 10^{-11}$ (Consensus?)

Prades, de Rafael, Vainshtein

$a_\mu^{Had} = 6930(40)(7)(26) \times 10^{-11} \approx 46 \times a_\mu^{EW}$

$\mathbf{a_\mu^{SM} = \underline{116591802(49)} \times 10^{-11}}$

Comparison of Experiment and Theory (Most Recent)

- $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(63)(49)\times10^{-11}$ ($\underline{3.6\sigma!}$)

This is a very large deviation!
Remember, the EW contribution is only 154×10^{-11}

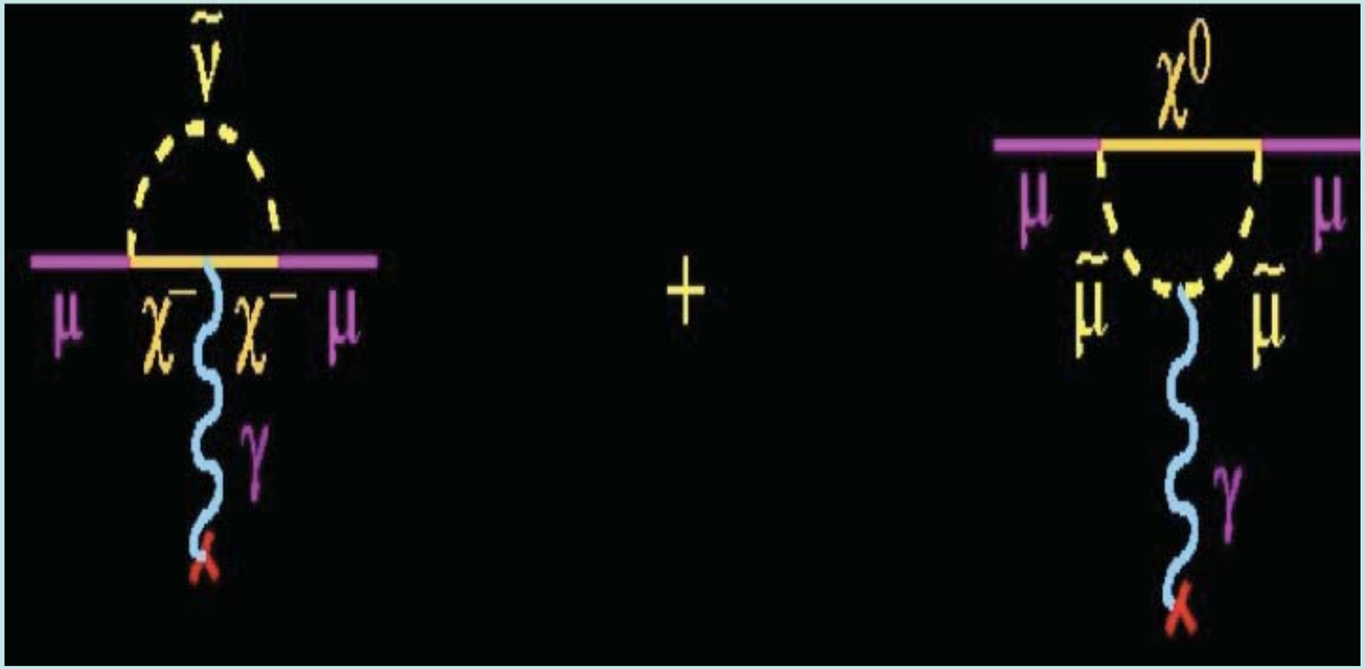
New Physics Nearly 2x Electroweak?

Why don’t we see it in other measurements?

3.2 "New Physics" Effects

_SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



- <u>SUSY Loops are like EW, but depend on:</u>
- 2 spin 1/2 χ- (charginos)
- 4 spin 1/2 χ^0 (neutralinos) including dark matter!
- spin 0 sneutrinos and sleptons with mixing

- Enhancement $\tan\beta = \langle\phi_2\rangle / \langle\phi_1\rangle \sim 3\text{-}40!$

Interpretations

$\Delta a_{\mu}=a_{\mu}^{exp}-a_{\mu}^{SM}=287(80)\times 10^{-11}$ $(3.6\sigma!)$

Generic 1 loop SUSY Conribution:

$a_{\mu}^{SUSY}=(\mathrm{sgn}\mu)130\times 10^{-11}(100\mathrm{GeV}/m_{susy})^{2}\tan\beta$

$\tan\beta\approx 3\text{-}40$, $m_{susy}\approx 100\text{-}500\mathrm{GeV}$

Other Explanations: *Hadronic e^+e^- Data? HLBL(3loop)?*

Multi-Higgs Models

Extra Dimensions<2TeV

* ***Dark Photons ~10-200MeV, $\alpha'=10^{-8}$***

Light Higgs Like Scalar <10MeV?

"The deviation in a_μ could be to <u>Supersymmetry</u> what the anomalous precession of the perihelion of Mercury was for <u>General Relativity</u>"

J. Marburger

Former U.S. Presidential Science Advisor

(Former BNL Director)

If SUSY is responsible for g_μ-2 **<u>Happy Days</u>**

<u>Implications</u>: sgnμ>0 (dark matter searches easier)

SUSY at LHC very likely

edms, <u>$\mu \rightarrow e\gamma$</u>, … Good Bets

Low Mass New Physics & g-2

Dark Photon m_A of g-2 interpretation easy to find at JLAB or Mainz (Bremsstrahlung) $e+X \rightarrow e+X+V_d$ ($V_d \rightarrow e^+e^-$)

Would Revolutionize Physics

Contact with Dark Matter!

Very Light Higgs ≤ 10MeV could account for discrepancy

Who Ordered That?

4.) ***<u>Muonic Hydrogen Lamb Shift</u>***

In an effort to precisely determine r_p

<u>New PSI μp atomic Lamb shift experiment</u>

$\Delta E(2P_{3/2}\text{-}2S_{1/2}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3$ **meV**

R. Pohl, A. Antognini et al. Nature July 2010

Very Elegant!

Stop μ^- in Hydrogen, About 1% populate 2S (1μsec**)**

Excite resonance with laser to 2P→1S

μp atomic Lamb Shift ***<u>very</u>*** sensitive to r_p

$(m_\mu/m_e)^3 = 8 \times 10^6$ enhancement

Proton Finite Size ≈ -2%

20ppm experiment

12years in the making (1998-2010)

$\Delta E(2P_{3/2}\text{-}2S_{1/2})^{exp} = 206.2949 \pm 0.0032$ **meV**

r_p=<u>0.84184(67)fm</u> (μp atom)

10x More Precise & 5 sigma below ep value!

$r_p \cong$<u>0.8768(69)fm</u> (ep atom)

<u>Confirmation from ep scattering</u>

$r_p \cong$<u>0.879(8)fm</u> (Recent Mainz)

$r_p \cong$<u>0.875(10)fm</u> (Recent JLAB)

Current Electron Average: r_p=<u>0.8772(46)fm</u>

8 sigma below μp atom!

Atomic ep Theory? <u>Rydberg Constant(</u>R_∞) (Off by 5σ?)

R_∞ k**nown to 13 significant figures!**

=1.0973731568527(73)x10^7m^{-1}

”One of the Two most accurately measured fundamental physical constants".

Could R_∞ really be wrong?

also

What about ep scattering? Wrong!

<u>**Perhaps the most likely solution**</u>

<u>μp atomic theory or experiment wrong?</u>

Proton Polarizability? QED Corrections ($\gamma\gamma$)?

μp Experiment? (seems solid)

Follow up Experimental & Theoretical Work

appear to <u>confirm</u> original results!

Can all three r_p determinations be correct?

2 out of 3 correct?...

5. New Physics Scenarios

New Physics Effect? (seems unlikely, but…)

Interesting/Provocative

Too big to be short-distance phenomenon

eg SUSY, Heavy Z'…

More likely light new vector or scalar boson

(1-100MeV weak coupling $\alpha' = 10^{-6}\alpha$)

Long Distance Physics!

6.) ***New "Light" Vector or Scalar Boson?***

Light <u>Vector</u> Boson with coupling e'

$e'^2/4\pi=\alpha' << \alpha=1/137$

New Vector Boson Interaction Shifts Atomic Spectrum in a way that mimics a proton charge radius

(Based on calculation by A. Czarnecki)

$$\boldsymbol{\Delta r_p/r_p \sim -2\alpha'/\alpha^3(1+m_V/\alpha m_\mu)^2}$$

Experiment→ $\Delta r_p/r_p \sim -4\%$

example $\boldsymbol{\alpha'=2.5\times10^{-6}\alpha,\ m_V \leq 1\text{MeV}}$ **works**

(Heavier m_V requires larger coupling)

<u>Can it be the "Dark Photon"?</u>

Light gauge boson from Dark Matter Sector that mixes with the photon (small coupling)

"New Physics" & The g_μ-2 Discrepancy

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

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(63)(49)\times 10^{-11}\ \textbf{(3.6}\sigma\textbf{!)}$$

What about light vector boson with $m_V < m_\mu$?

$\Delta a_\mu \sim \alpha'/2\pi$ like Schwinger term

$= 2.9\times10^{-9} \rightarrow \alpha' \sim 2.5\times10^{-6}\alpha$

Dark Photon = natural solution to g_μ-2 Discrepancy

So, a light vector boson with mass O(1MeV)
and $\alpha' \sim 2.5\times10^{-6}\alpha$ coupling for μp and $\mu\mu$
solves both proton size puzzle & g_μ-2

Can it be the Dark Photon?

No! O(1MeV) dark photon would also reduce r_p in ep atom

(Observation of Czarnecki & Pospelov)

and should have led to g_e-2 discrepancy

$$\Delta a_e = |a_e^{exp} - a_e^{SM}| < 10^{-11}!$$

Possible Solution: violate e-μ Universality

Egs Gauge B-3L_μ or B-3/2(L_μ+L_τ)… (Lee & Ma)

Anomaly Free, couples to baryons, **not electrons**

So, a light m_V~MeV & α'~2.5x$10^{-6}\alpha$ alleviates both r_p and a_μ problems if it doesn't couple (directly) to electrons!

What about neutrino physics? *(ν_μ vs ν_e)*

From Bjorken, Essig, Schuster and Toro Dark Photon (2009)

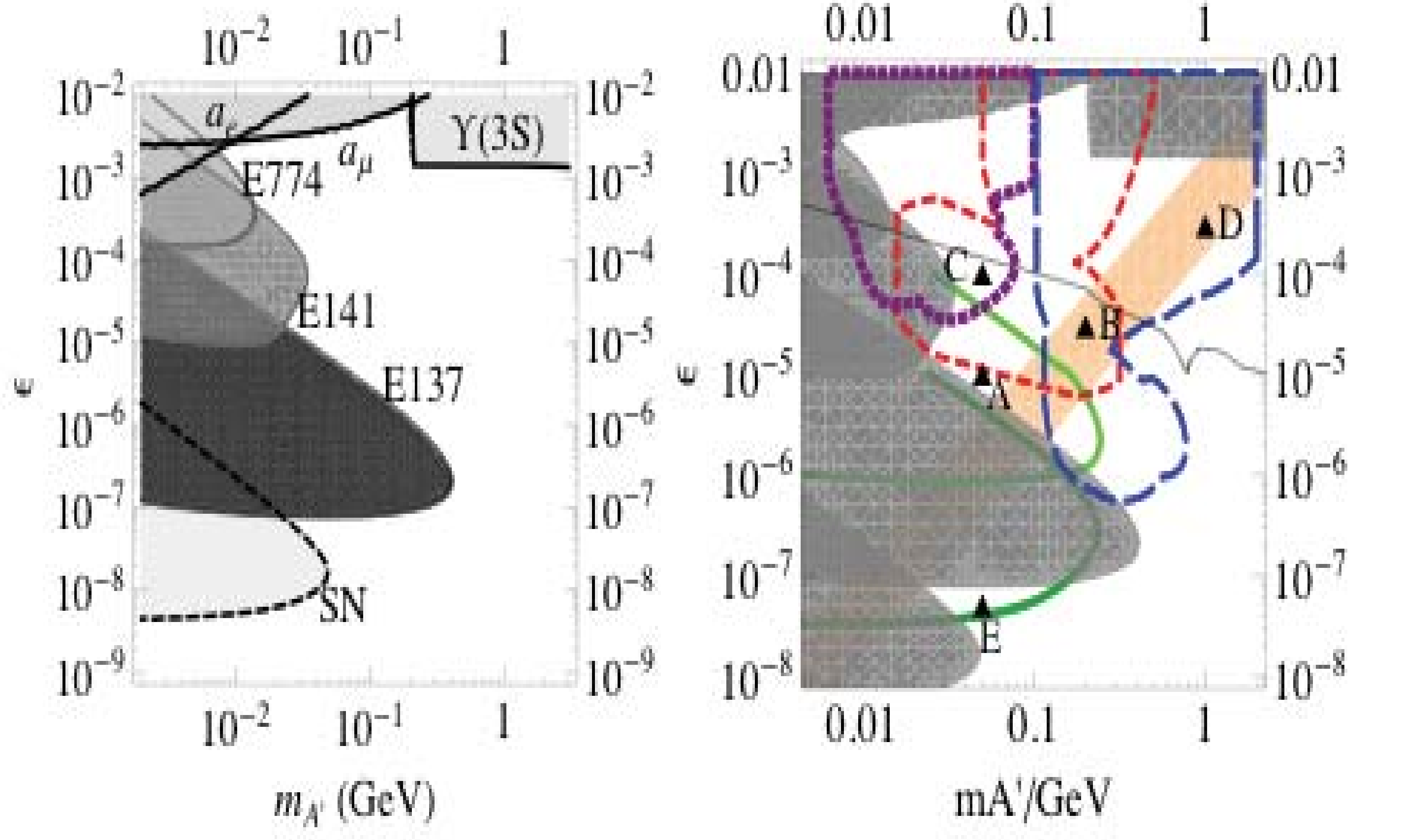


FIG. 1: **Left:** Existing constraints on an A'. Shown are constraints from electron and muon anomalous magnetic moment measurements, a_e and a_μ, the BaBar search for $\Upsilon(3S) \to \gamma\mu^+\mu^-$, three beam dump experiments, E137, E141, and E774, and supernova cooling (SN). These constraints are discussed further in Section III. **Right:** Existing constraints are shown in

Neutrino Oscillations in Matter (ν_μ vs ν_e)

New Vector Interaction Different for ν_μ & ν_e

Eg, if we gauge B-3L_μ with $\alpha' \sim 2.5 \times 10^{-6} \alpha$?

Implies new matter effect on the ν_μ index of refraction

Of $O(10^4 G_F N_B (1\text{MeV}/m_V)^2)$ Very Large!

m_V=1MeV Ruled Out! Quenches Oscillations!

By a factor > 10,000!!

Very hard to simultaneously solve r_p, a_μ and ν_μ matter osc

Neutrino Matter Effects are a great probe of long distance physics Oscillation Interferometry

Batell, McKeen & Pospelov: Gauge only μ_R (not neutrinos or e_R)

(creative but has other issues)

A Really Light Higgs Scalar O(1-10MeV)?

Normally 1 loop Higgs (>114GeV)

Contribution to g_μ-2 is negligible

But what if a Higgs is really light?

Kinoshita & WJM review long Ago

➔$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} \approx +3x10^{-9}$*!*

Could also explain r_p differences!

Something to think about

Runs into problems with neutron-Nuclei scattering

Barger, Chiang, Keung & Marfatia

Tucker-Smith & Yavin

Light Higgs Phenomenology

7. Conclusion & Outlook

3 r_p determinations: ep atom, ep scattering, μp atom

something likely wrong but which one(s)?

Rydberg Constant Vulnerable

What if it shifts by 5 sigma?

but ep remains a problem?

Then **m_V~MeV & $\alpha' \sim 2.5\times10^{-6}\alpha$ solves both** r_p & a_μ discrepencies. **Other constraints?** a_e? …

Precision QED remains interesting & timely

Stay Tuned For Future Developments