Precision Particle Physics
The Standard Model and Beyond

William J. Marciano

6 Lectures

Ferrara, Italy

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BROOKHAVEN NATIONAL LABORATORY

Precision Themes

- QED Precision – Historical Perspective
  Electromagnetic Dipole Moments Theory vs Exp.

- ***Muon Lifetime*** & Electroweak Precision (m_t, m_H)
  S & T "New Physics" Parameters

- ***Higgs Boson Precision***
  Branching Ratios, CP Violation? ***"Sick" Field Theory***

- ***Precision Neutrino Masses & Mixing***
  CP Violation and Beyond

Ancient Perspective
1492 Columbus Discovers America

- ***"There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy."***

Hamlet (≈1600)

Galileo: 1564-1642

Newton: 1642-1727

-

Maxwell: 1831-1879

Einstein: 1879-1955

Meanwhile

Michelson (The Master of Precision) 1894

"The more important fundamental laws and facts of Physical Science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote… Our future discoveries must be looked for in the sixth place of decimals."

Radioactivity ***1896***

Electron Discovery ***1897***

Special Relativity

General Relativity

Quantum Mechanics; Spin

Dirac Equation ***1928*** (QM + S. Relativity + Spin + EM)

QED $U(1)_{em}$ Photon

Today c = 299 792 458 m s^{-1} ***Exactly*** (Meter Definition)

Natural Units c=1

Later

Yang-Mills Non-Abelian Gauge Theories 1954

Standard Model of Particle Physics ≥1967

$SU(2)_L x U(1)_Y$ $W^{\pm}$, Z bosons; $SU(3)_C$ 8 gluons

3 generations of quarks and leptons

2012: "Fundamental" Higgs (125GeV) Scalar Discovered!

Remnant of Electroweak Symmetry Breaking

Now: Entering the Age of Precision Higgs Physics!

"Sick" or "Rich" Quantum Field Theory?

Precision Measurements QED and Lepton Dipole Moments

Based in part on: "Lepton Moments"
Editors B. Lee Roberts & W. Marciano

William J. Marciano

Lectures 1 & 2
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Outline

1.) ***Historical Introduction***

i) Wolfgang Pauli ***(1924 Exclusion Principle!)***

ii) Spin (1925)

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

iv) $U(1)_{em}$ Local Gauge Invariance

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

The Birth of Quantum Electrodynamics (QED)

i) Electron Anomalous Magnetic Moment g_e-2

Basic 1 Loop Calculation

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

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

3.) ***Recent Developments***

i) g_e-2 (5 loops!)

ii) Lamb Shift?

iii) g_μ-2 (New Physics - Supersymmetry/Something Else?)

4.) ***"Light" Dark Photon (Dark Matter Force Mediator)***

Viewer Discretion Advised - Speculative

5.) ***Muonic Hydrogen Lamb Shift***

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

5-8 sigma difference

6.) ***Electric Dipole Moments*** – "New Physics"

7.) The Standard Model – $SU(3)_C x SU(2)_L x U(1)_Y$

Electroweak Unification

i) The Muon Lifetime & Fermi Constant

ii) Natural relationships

$$\sin^2\theta^0_W = 1-(m^0_W/m^0_Z)^2 = (e^0/g^0)^2$$

iii) CKM Unitarity

8.) Higgs Properties & Problems (Naturalness)

$\lambda\phi^4$ theory is unnatural! Sick?

9.) Neutrino Oscillations – Status & Future

10.) Concluding Remarks

1.) ***Historical Introduction***

1897 ***Electron*** (e^-) Discovered J.J. Thomson

followed by major developments

Early 20th Century

Quantum Mechanics (γ photon)

Special & General Relativity

1919 ***Proton*** (p^+) Discovered $m_p \approx 1840 x m_e$ Ernest Rutherford

1926 Schrodinger Equation – Non-Relativistic QM

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) ***Electron Spin (1925)***

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

***Ironic*: Pauli 2x2 *spin* matrices (Non-relativistic)**

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

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

The Stage in 1928

Non Relativistic Schroedinger Eq. First Order

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

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

The Genius of Dirac

QM+Special Rel.+Spin+EM Gauge Invariance $U(1)_{em}$

First Order Equation Spinor (4 Component)

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

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

Similar eq. for the proton $m_p \approx 1840 x m_e$

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

As Observed Experimentally

Automatic Unexpected Success of Dirac Eq.

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

(Advanced Exercise for students)

Go to second order formalism (apply Dirac operator)

$[-i(\partial_\mu - ieA_\mu(x))\gamma^\mu - m_e] \times [i(\partial_\mu - ieA_\mu(x))\gamma^\mu - m_e]\psi(x)$

and find terms in Klein-Gordon Eq.

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

Imaginary Part? - **Non Physical?** → Ignore?

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

(What is an electric dipole moment (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! (Sakharov Conditions)

(1964-CP Violation Discovered-CKM Not Enough)

"New Physics" Source of CP Violation Needed!

Supersymmetry, 4th Generation, Multi-Higgs…

<u>Baryogenesis</u>: $N_B/N_\gamma \approx 10^{-10}$

<u>1957</u> - Parity Violation in Weak Interactions (Maximal!)
<u>Lee & Yang</u> Why is nature left-handed (Chiral)?

<u>1964</u>- CP Violation Discovered in Kaon Decays

<u>1967 Sakharov Conditions</u>:

1) Baryon Number Violation
2) CP Violation (strong source)
3) Non-Equilibrium 1st Order Phase Transition

(Leptogenesis – Very Early Universe Alternative)

Completing the Picture?

1930 Pauli Proposes the ***Neutrino (ν)*** (weak interactions)

1931 ***Neutron (n)*** Discovered (strong interactions)

1932 ***Positron (e^+)*** Discovered **(*Anti-Matter Exists!*)**

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.

p, n, e, ν basic ingredients of our Universe (Existence)

strong, weak, electromagnetic & gravitational interactions

Today

Elementary Particle Physics ***(Many Particles!)***

$SU(3)_C x SU(2)_L x U(1)_Y$ Standard Model

8 gluons + $W^{\pm}$, Z, γ ***gauge bosons*** ***(spin 1)***

(Pauli: Yang-Mills Theory is infrared sick! or Rich?)

$SU(3)_C$ Quantum Chromodynamics

One of the ***greatest Scientific Discoveries of the Twentieth Century!***

3 generations of ***quarks & leptons (mix->CP violation)***

e,ν_e,u,d μ,ν_μ,c,s τ,ν_τ,t,b   (m_t/m_ν >10^{13}!!) ***(spin ½)***

Scalar Doublet: $S^{\pm}$,S^0,H source of mass ***(spin 0)***

2012: The Year of the Higgs Boson!

Now Standard Model Complete!

Higgs (H) Boson Discovery

Remnant of Particle Mass Origin (Remember Michelson)

What Else Is There? New Particles? Interactions?

Supersymmetry *(Doubles The Spectrum!)*

But Badly Broken

Waiting for SUSY or "Something" Else

So far: No direct evidence for Supersymmetry,

At The LHC (Large Hadron Collider)!

Still Early – Nevertheless MSSM in trouble

The Higgs –May Be Last Particle Ever Discovered?

(Probably Not $\lambda\phi^4$ theory is sick/unnatural)

Left with Mysteries: Why Baryogenesis? CP?

Why 3 Generations?

Why Parity Violation?

Dark Matter, Energy…

We could add extra terms to the Dirac Equation

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

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

Anomalous Mag. Mom.

$g_e = 2(1 + a_e)$

a_e = Pauli Term

Electric Dipole Mom.

Violates P&T(CP)

Not Observed

$d_e < 10^{-27}$ 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

iv) $U(1)_{em}$ Local Gauge Invariance

Electrodynamics (with charged electron source)

Invariant under local $U(1)_{em}$ gauge transformations

$$L = \tfrac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) + \psi^*(x)\, \gamma^0 \{ i(\partial_\mu - ieA_\mu(x))\gamma^\mu - m_e \} \psi(x)$$

$$A_\mu(x) \to A_\mu(x) - ie\partial_\mu \Lambda(x) \qquad \psi(x) \to \exp(ie\Lambda(x))\psi(x)$$

Generalization of Charge Conservation

Fundamental principle of interactions

Equations of motion: Maxwell's Eqs & Dirac Eq.

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

1947 Small Anomalous Atomic Fine Structure Effects

G. Breit: maybe $a_e=(g_e-2)/2\neq0$

1948 Schwinger Calculates: $a_e=\alpha/2\pi\approx0.00116$ ($\alpha=e^2/4\pi=1/137$)

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

Great Success of QED -Quantum Field Theory

Exercise: 1 loop QED Correction

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

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

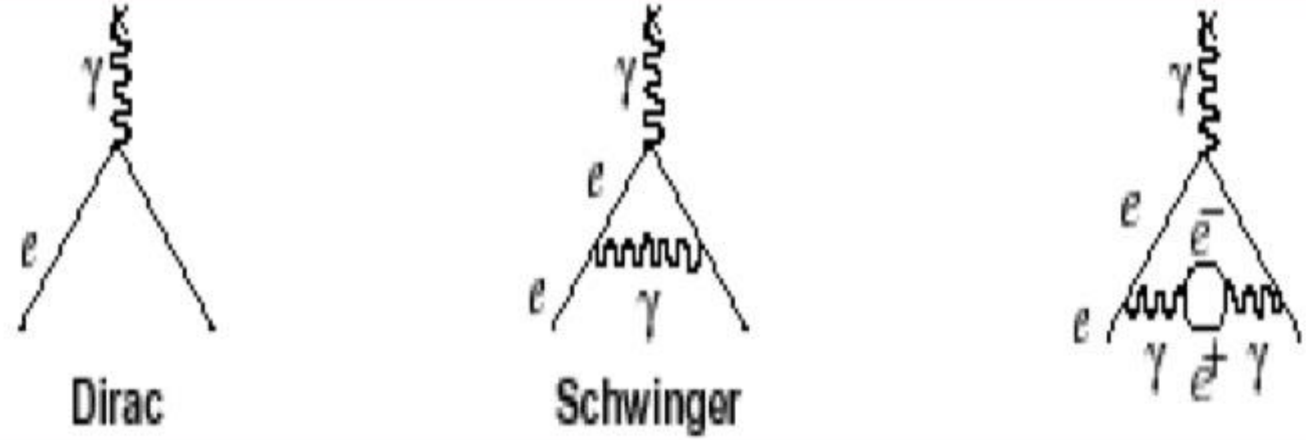
vacuum polarization, electron self-interaction

a_e and Lamb shift start of QED (Quantum Electrodynamics)

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

Later $\tau_\mu=2.2\times10^{-6}$sec *very long very important*

Anomalous Magnetic Moment Contributions



Basic Quantum Electrodynamics
Dirac Eq. the Foundatioj

Quantize $A_\mu(x)$ and $\psi(x)$ fields ➔ operators

Represents interacting photons and electrons (positrons)

Parameters m_e^0 and e_0 bare electron mass and charge

Renormalized to m_e and e physical mass and charge

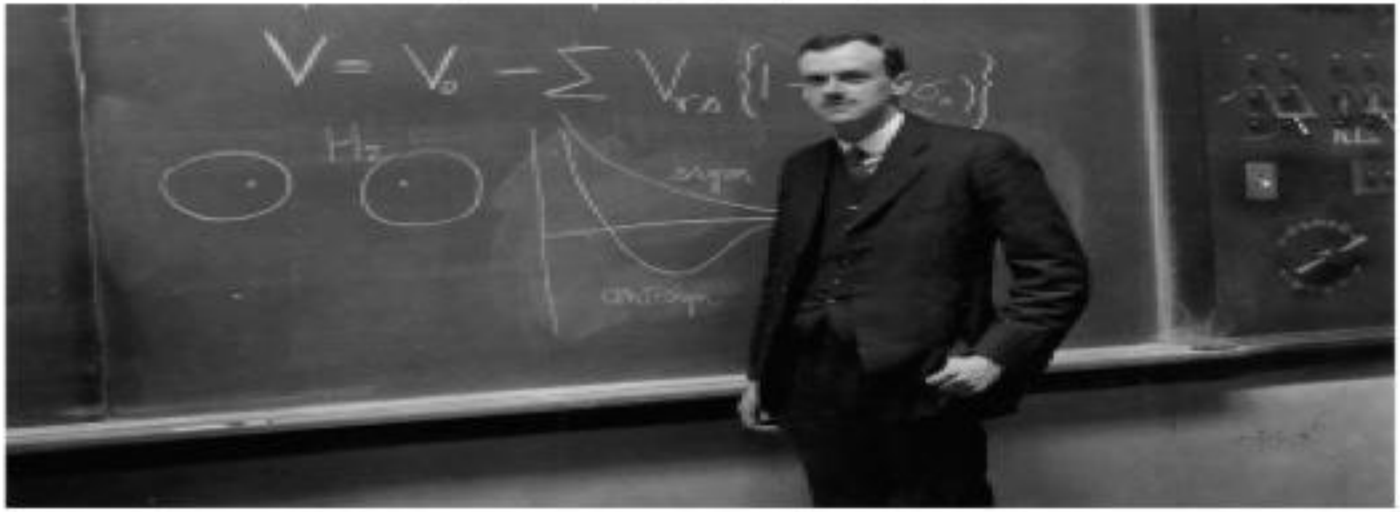
Interaction strength $e^2/4\pi \approx 1/137$ fine structure constant

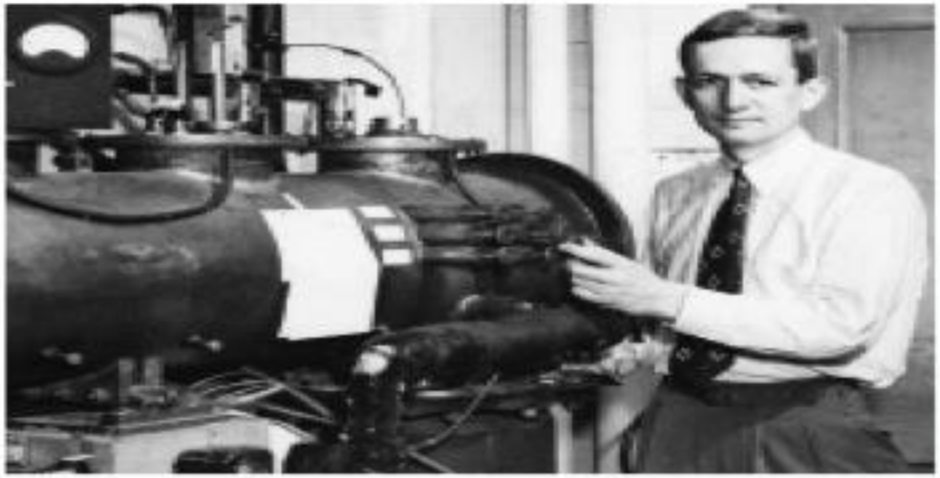
Dirac Strongly Opposed Idea of Infinite Renormalization

Clockwise:

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

Courtesy AIP Emilio Segrè Visual Archives (full credits overleaf)





Mount Auburn Cemetery

Anomalous Magnetic Moments Today

$a_l=(g_l-2)/2 \quad l=e,\mu$

$a_e(exp)=0.00115965218073(28)$ unc. 2.8×10^{-13}!

(Hanneke, Fogwell, Gabrielse: PRL 2008)

$a_e(SM)=\alpha/2\pi-0.328478444002546(\alpha/\pi)^2$

$+1.181234016(\alpha/\pi)^3 -1.9097(20)(\alpha/\pi)^4$

$+9.16(58)(\alpha/\pi)^5$… $+1.68\times10^{-12}$(had) $+0.03\times10^{-12}$(EW)

Aoyama, Hayakawa, Kinoshita, & Nio 2012 Update

$\alpha^{-1}(^{87}Rb)=137.035999049(90)$

Bouchendira et al. PRL. (2011)

$a_e(exp) - a_e(theory) = -1.05\ (0.82) \times 10^{-12}$

Overall Factor 10 Sensitivity Improvement!

Further Improvement? Factor of 2? More?

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

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

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

(2008) (Main sensitivity - Lamb Shift)

Depends on Rydberg Constant

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

k**nown 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 $\pi \to \mu\nu$, $\mu \to e\nu\nu$

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)**
- $a_\mu^{exp} \equiv (g_\mu - 2)/2 = 116592089(54)_{stat}(33)_{sys} \times 10^{-11}$

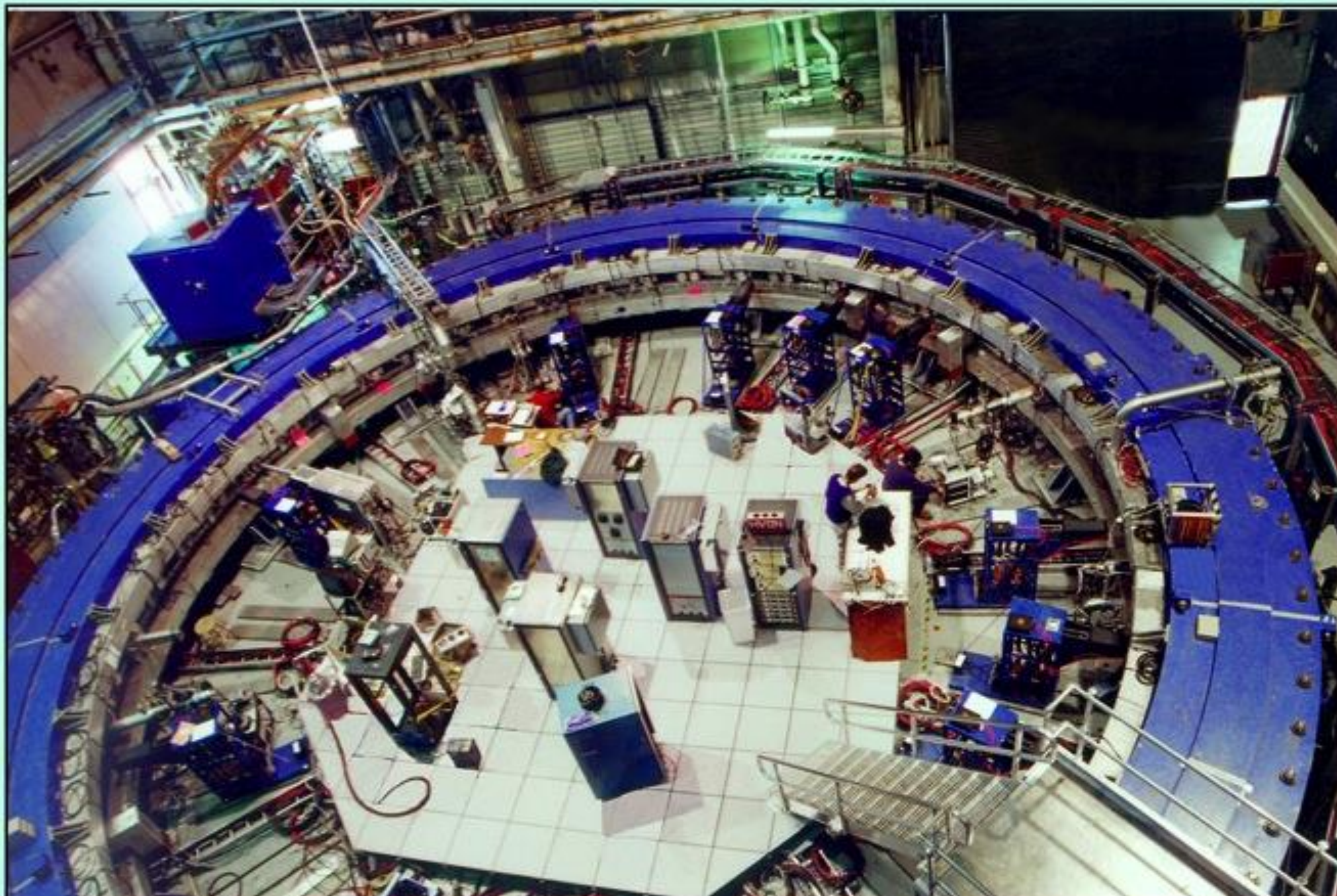
$= 116592089(63) \times 10^{-11}$

Factor of 14 improvement over CERN results

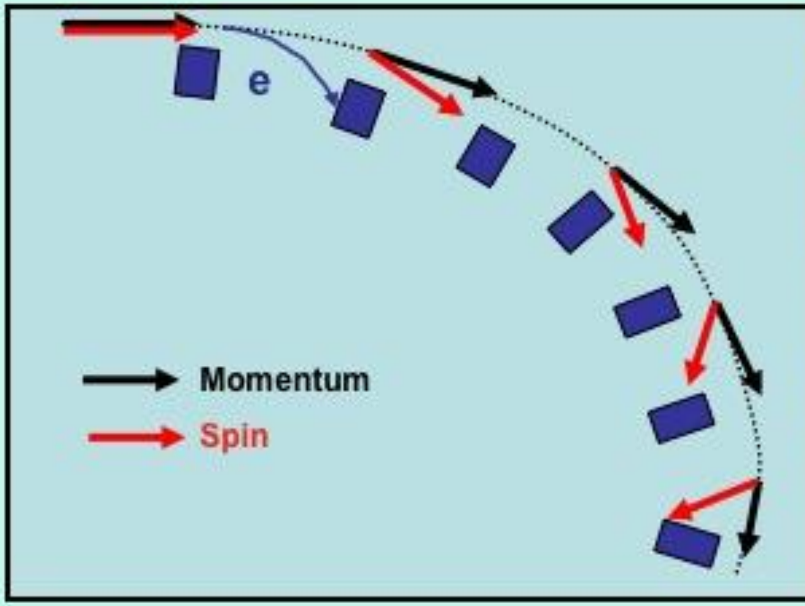
(Proposed Future Factor 4 Improvement at FNAL)

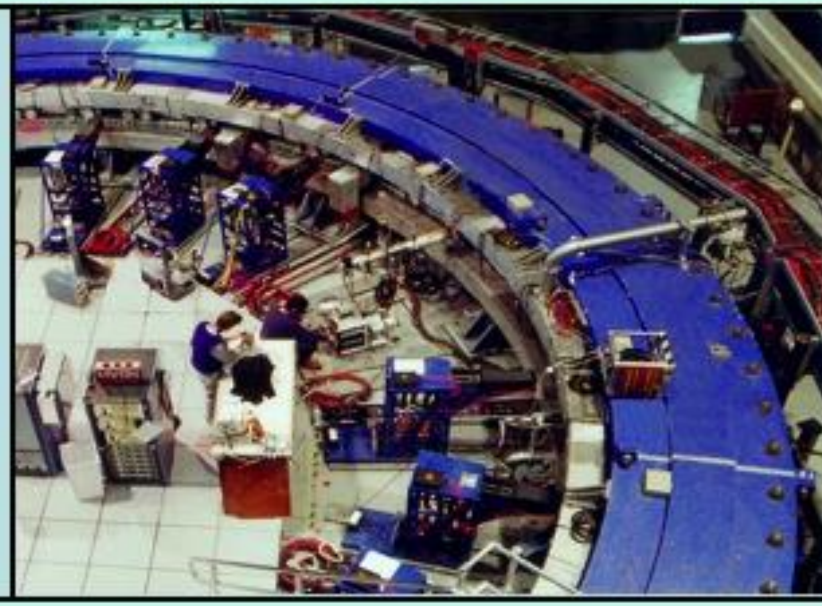
D. Hertzog, B.L. Roberts…

BNL Muon g-2 Experiment



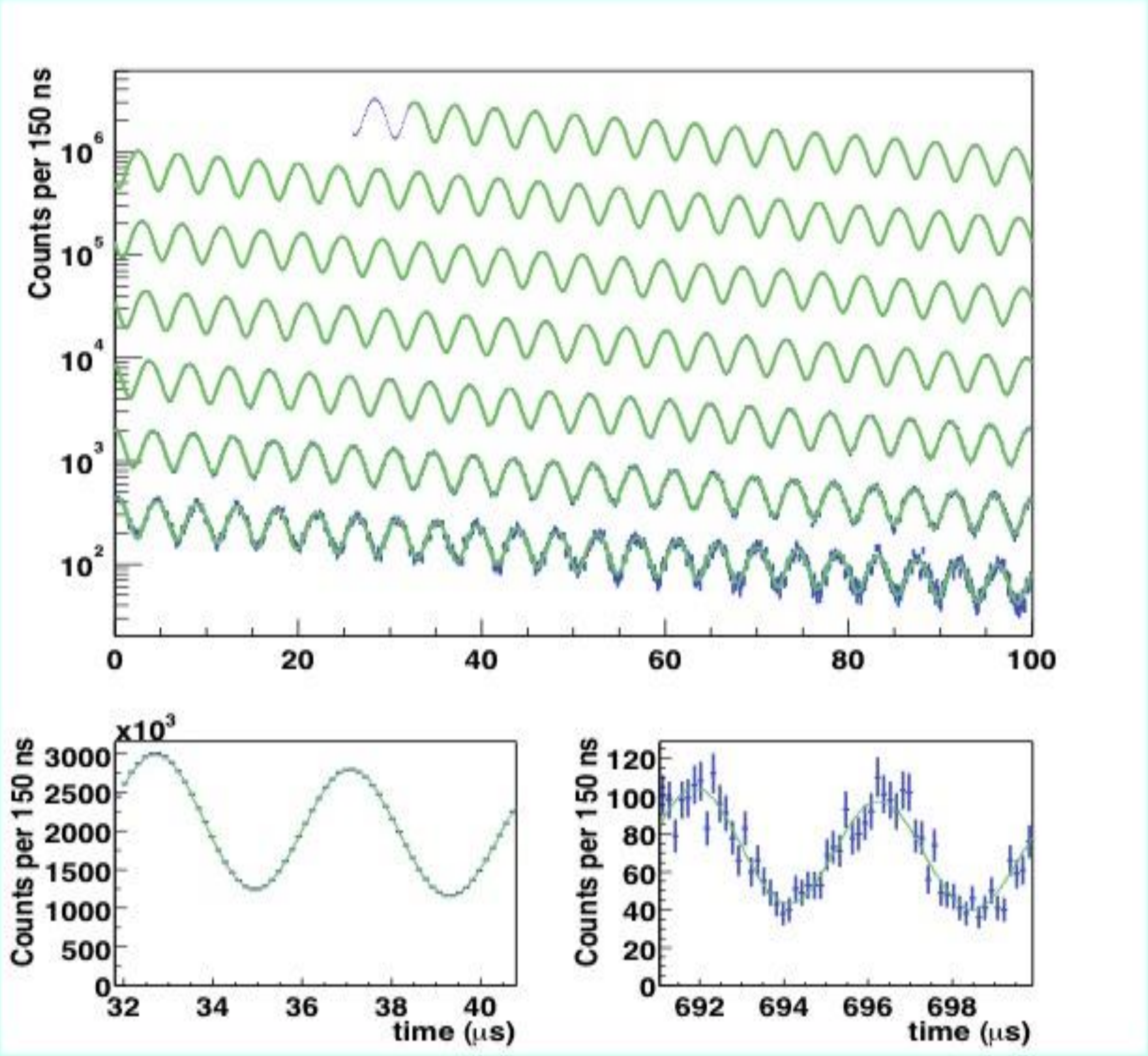
- a_μ is proportional to the difference between the spin precession and the rotation rate





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

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



Standard Model Prediction

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

QED Contributions:

- $a_\mu^{QED} = 0.5(\alpha/\pi) + 0.765857425(17)(\alpha/\pi)^2 +$
  $24.05050996(32)(\alpha/\pi)^3 +$
  $130.8796(63)(\alpha/\pi)^4 +$
  $753.29(1.04)(\alpha/\pi)^5 + \ldots$

2012 Update: Aoyama, Hayakawa, Kinoshita, & Nio

$\alpha^{-1}(^{87}Rb) = 137.035999049(90)$

$a_\mu^{QED} = 116584718.864(36) \times 10^{-11}$ Very Precise!

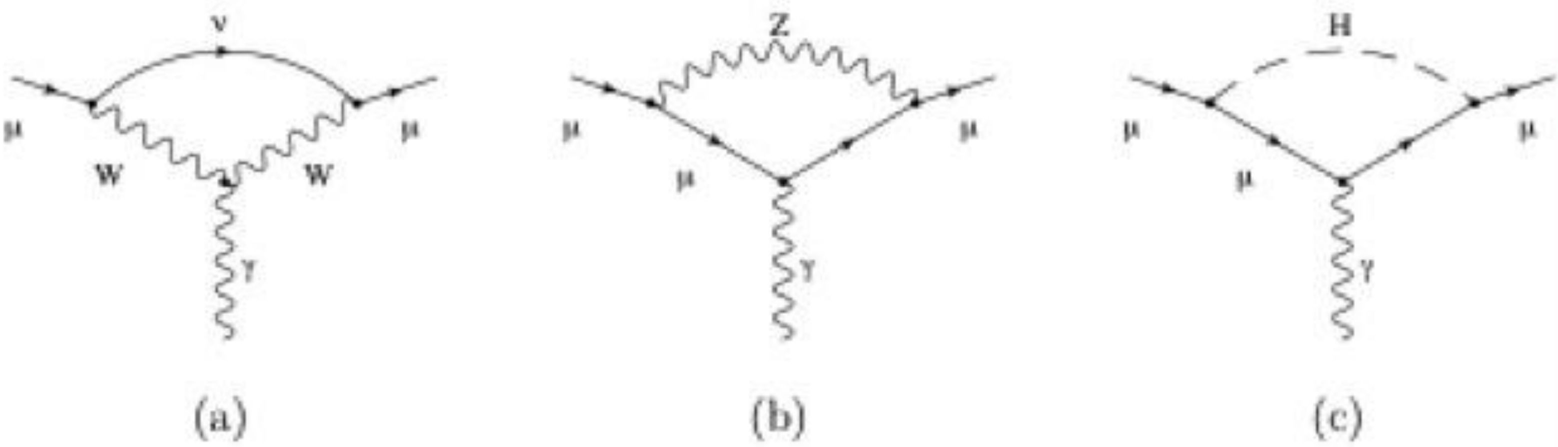


Figure 2: One-loop electroweak radiative corrections to a_μ.

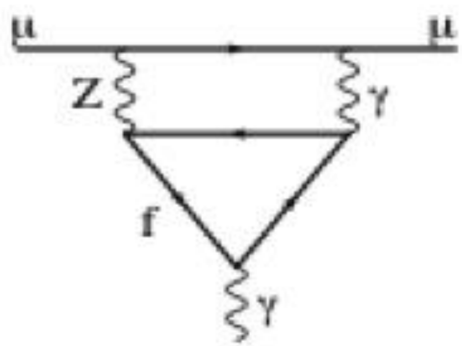


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to $a_\mu^{\rm EW}$.

Electroweak Loop Effects

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

a_μ^{EW}(2 loop)=$-40.3(1.0)\times10^{-11}$ (Higgs Mass = 126GeV))

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

- ***$a_\mu^{EW}=154(1)\times10^{-11}$ Non Controversial***

- **Hadronic Contributions (HVP & HLBL)**

$a_\mu^{Had}(V.P.)^{LO}=6923(40)(7)\times10^{-11}$ (Hoecker update 2010)

$a_\mu^{Had}(V.P.)^{NLO} = -98(1)\times10^{-11}$

$a_\mu^{Had}(LBL) = 105(26)\times10^{-11}$ (Consensus?)

$a_\mu^{SM}=116591803(49)\times10^{-11}$ (Future Improvement?)

$\Delta a_\mu=a_\mu^{exp}-a_\mu^{SM}=286(63)(49)\times10^{-11}$ (*3.6σ deviation!*)

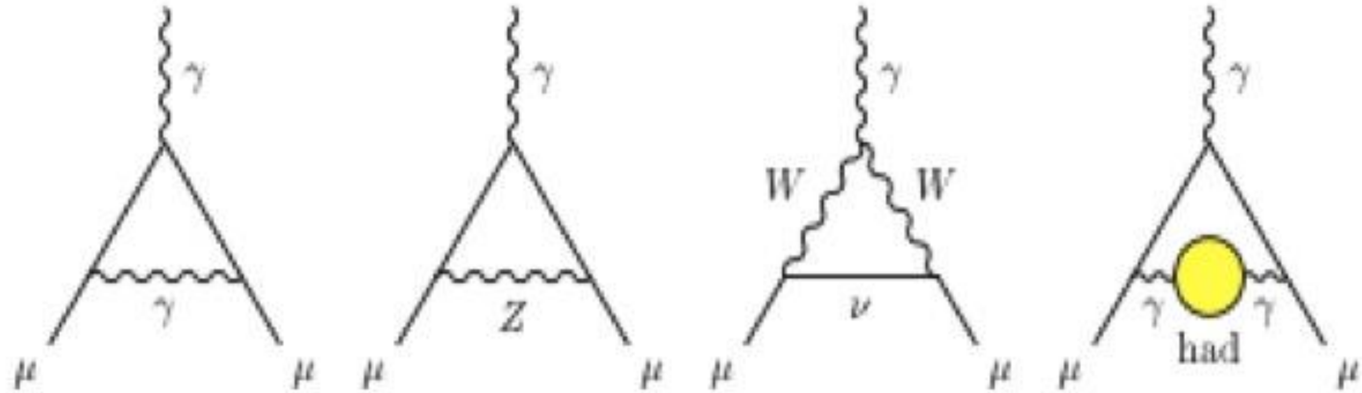
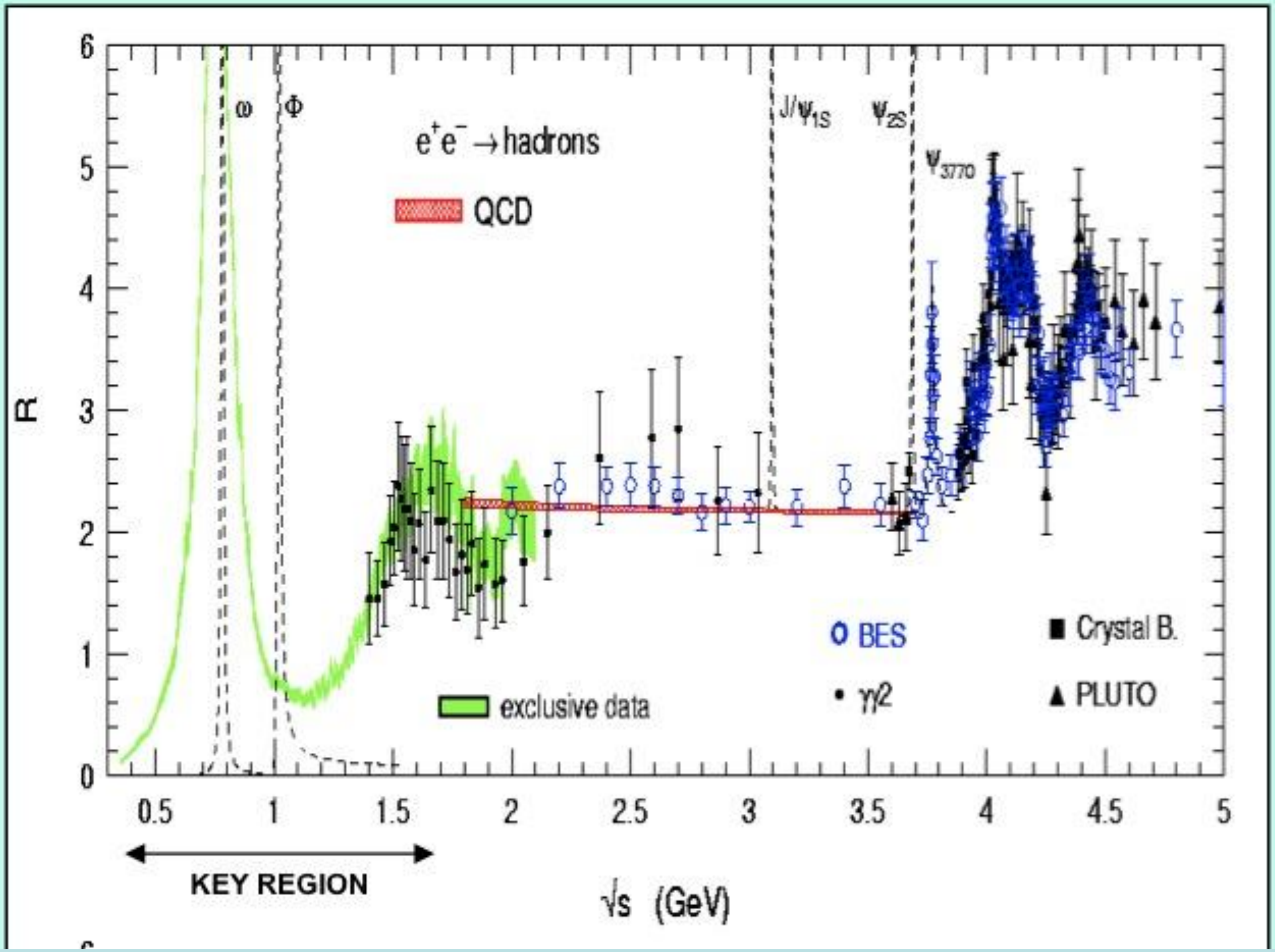


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.



e⁺e⁻ → hadrons
QCD
exclusive data
BES
γγ2
Crystal B.
PLUTO
ω
Φ
J/ψ1S
ψ2S
ψ3770
R
√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

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

$\mathbf{a_\mu^{SM} = \underline{116591803(49)} \times 10^{-11}}$

Comparison of Experiment and Theory

(Most Recent)

- **$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49) \times 10^{-11}$ (*3.6σ!*)**

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

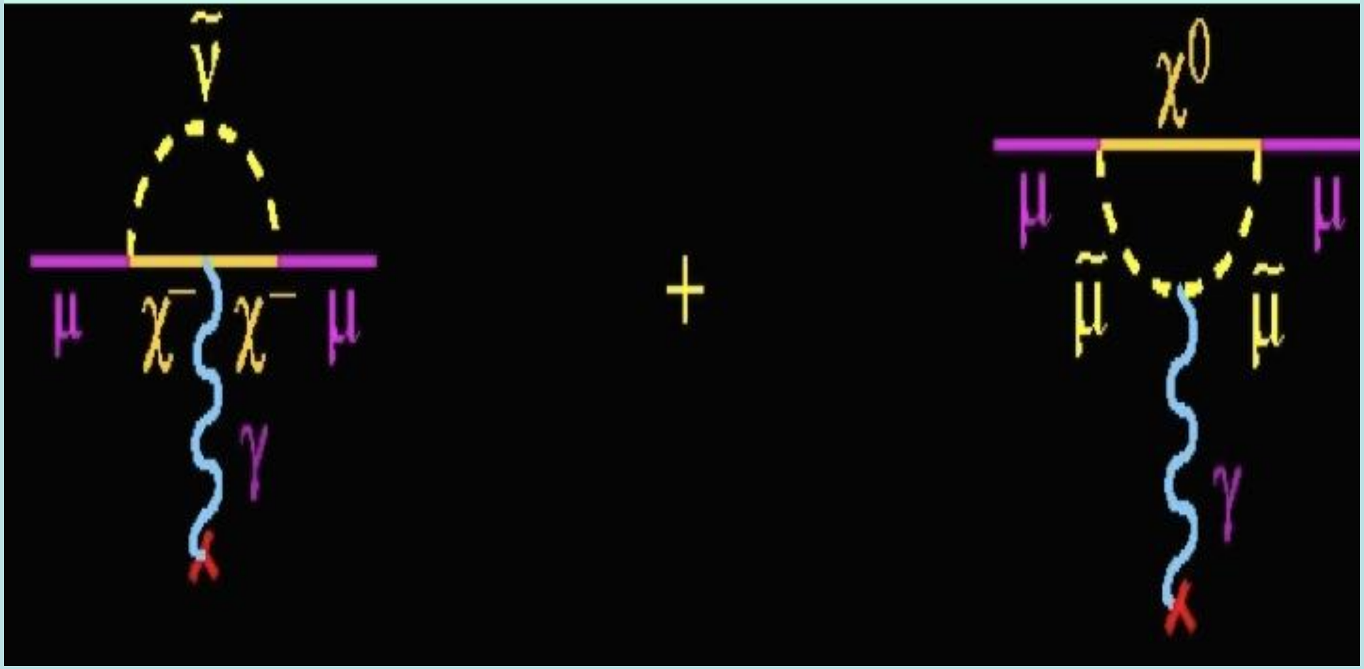
New Physics Nearly 2x Electroweak?

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 ***<u>mixing</u>!***

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

Interpretations

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80) \times 10^{-11}$ ***(3.6σ!)***

***Generic 1 loop SUSY Conribution*:**

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

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500\mathrm{GeV}$ ***Some LHC-MSSM Tension***

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

Lattice Gauge Theory Efforts!

Multi-Higgs Models

Extra Dimensions<2TeV

*** *Dark Photons ~10-200MeV, α′=10^-8^***

Light Higgs Like Scalar <10MeV?

etc.

“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>: sgn$\mu>0$ (dark matter searches easier)

SUSY at LHC very likely (Eventually?)

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

<u>So far not very Happy Days</u>

Low Mass New Physics & g-2

Dark Photon m_{Zd} of g-2 interpretation with $\varepsilon^2\alpha\sim10^{-6}$
easy to find at JLAB or Mainz (Bremsstrahlung)
$e+X \rightarrow e+X+Z_d$ ($Z_d \rightarrow e^+e^-$)

Would Revolutionize Physics
Contact with Dark Matter!
Many Rxperimental Searches

Alternative

Very Light Higgs like boson ≤ 10MeV
could also account for discrepancy

Who Ordered That?

The Dark Boson – A Portal to Dark Matter

What if some dark **sector** particles interact with one another via a new massive but relatively "light" $\boldsymbol{Z_d}$ (Dark Boson)? $U(1)_d$ local gauge symmetry of the Dark Sector

Introduced for 1) Sommerfeld Enhancement

2) $Z_d \rightarrow e^+e^-$ (source of positrons, ***γ-rays)***

3) Cosmic Stability $U(1)_d$

eg Wimp Number (S. Weinberg!)

*4) Muon Anomalous Magnetic Moment

Can we find direct evidence for such a particle (boson)?

(or rule out some scenarios)

Dark Symmetry & Our World

**1. Kinetic $U(1)_Y$ x $U(1)_d$ Mixing (B. Holdom)*

**2. Z-Z_d mass mixing*

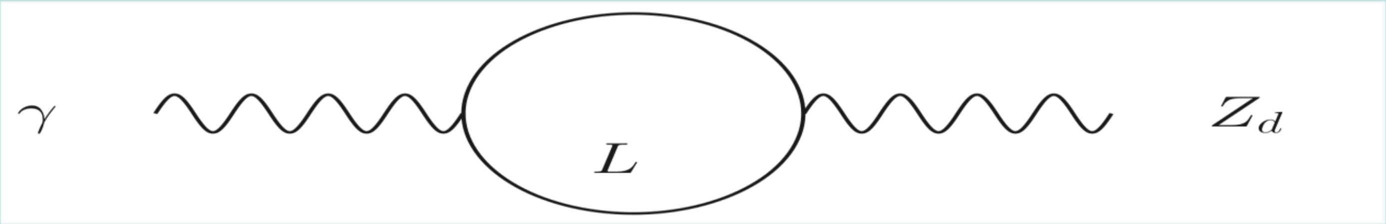
3. $U(1)_d$ = B-L, L_μ-L_τ, L_e-L_μ, L_e-L_τ…

(All or some ordinary particles have dark charge)

$U(1)_d$ Vector Like Small Unquantized Couplings

Example

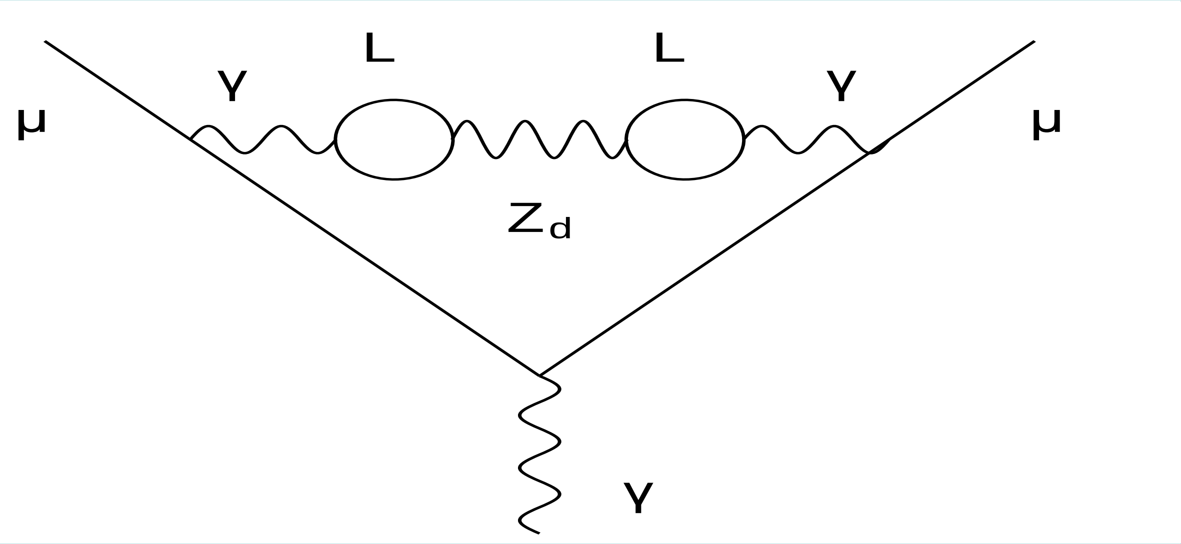
One Loop gamma-Z_d Kinetic Mixing (Through Heavy Charged Leptons) That also carry $U(1)_d$ charge Expect $\varepsilon \sim eg_d/8\pi^2 \approx O(10^{-3})$

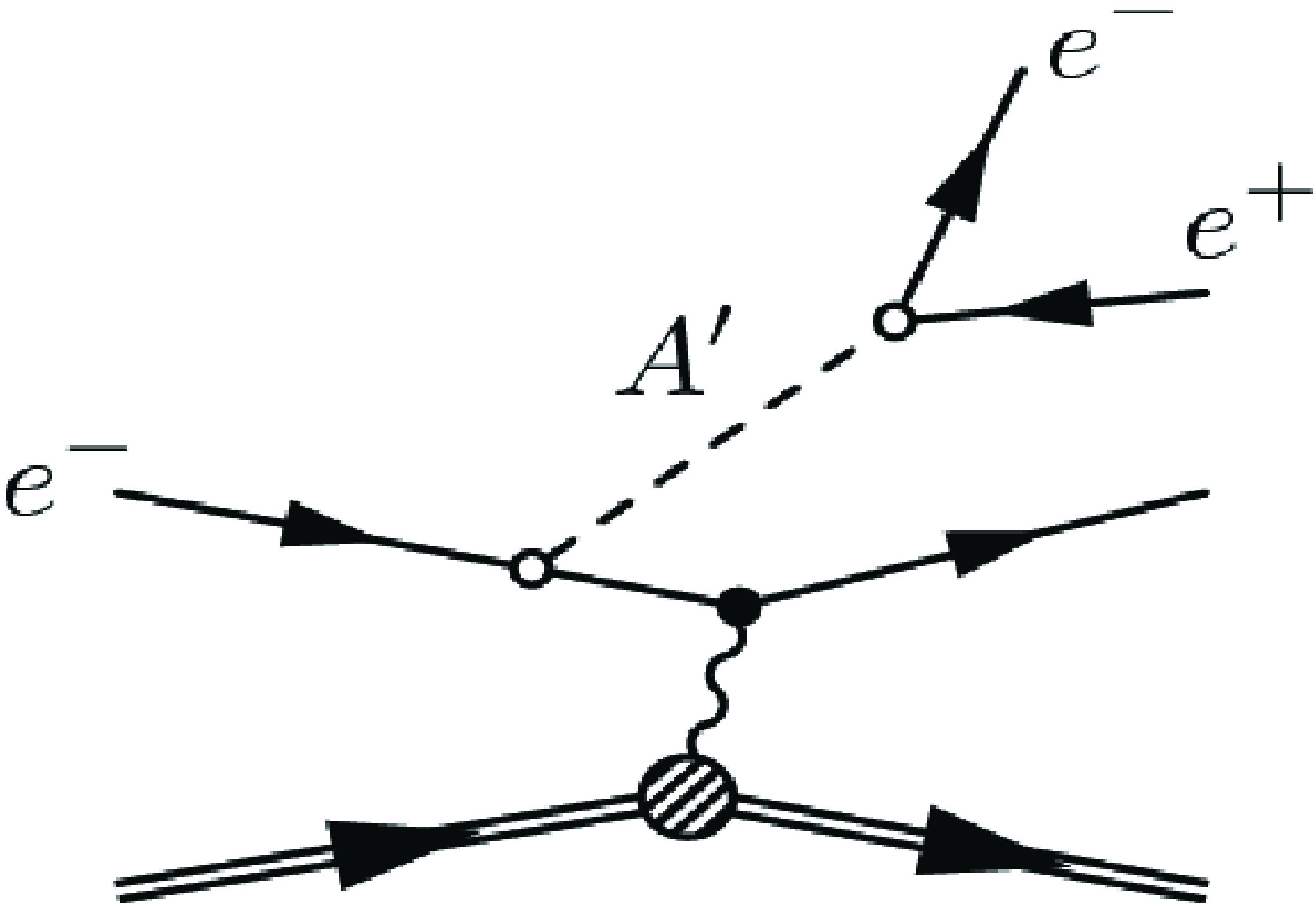


Effective 3 loop g_μ-2 Diagram

$a_\mu^{Zd} = \alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ **solves g_μ-2 discrepancy**

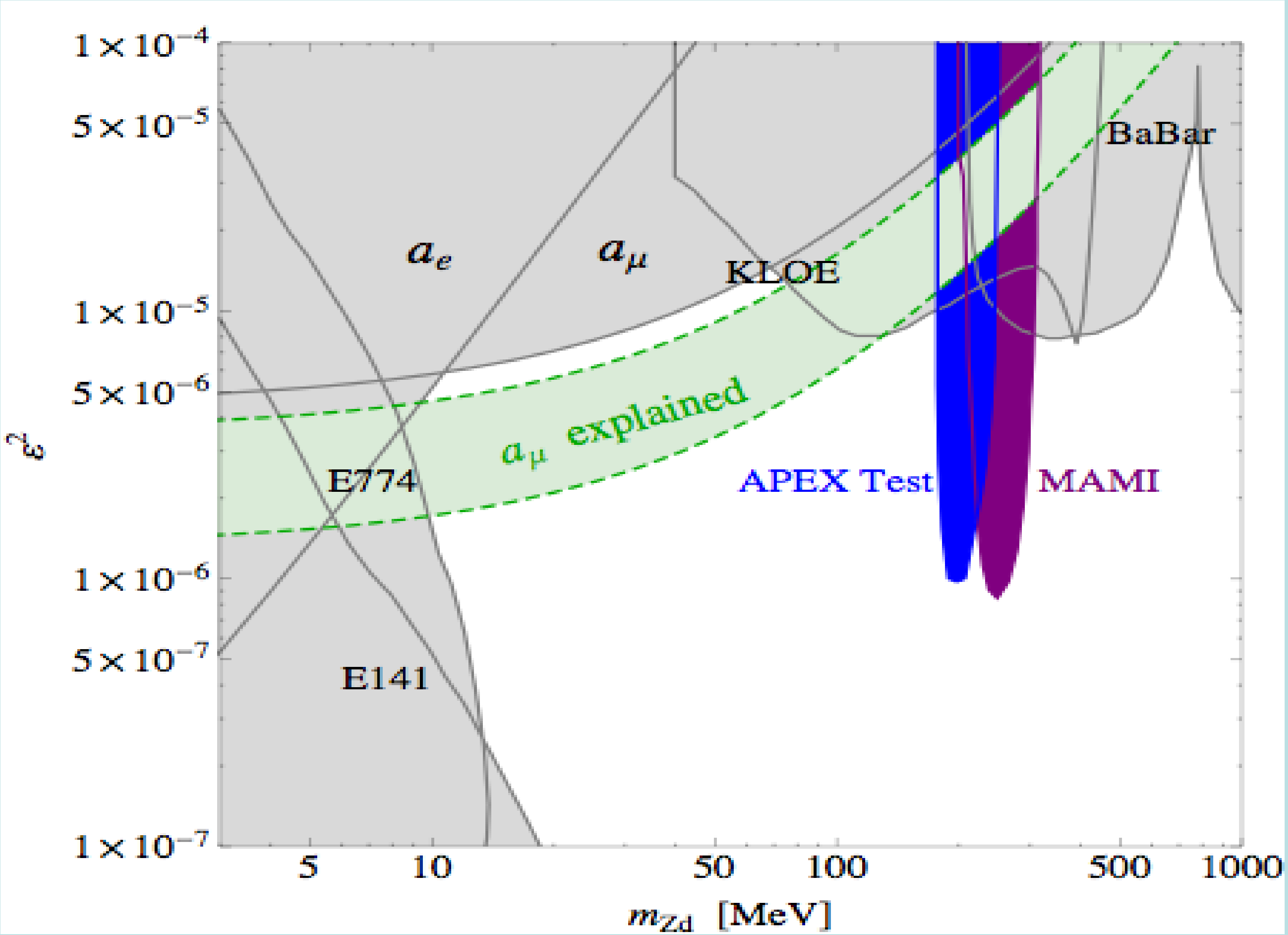
for $\varepsilon^2 \approx 3\text{-}5\times10^{-6}$ & $m_{Zd} \approx 20\text{-}50$MeV (see figure)





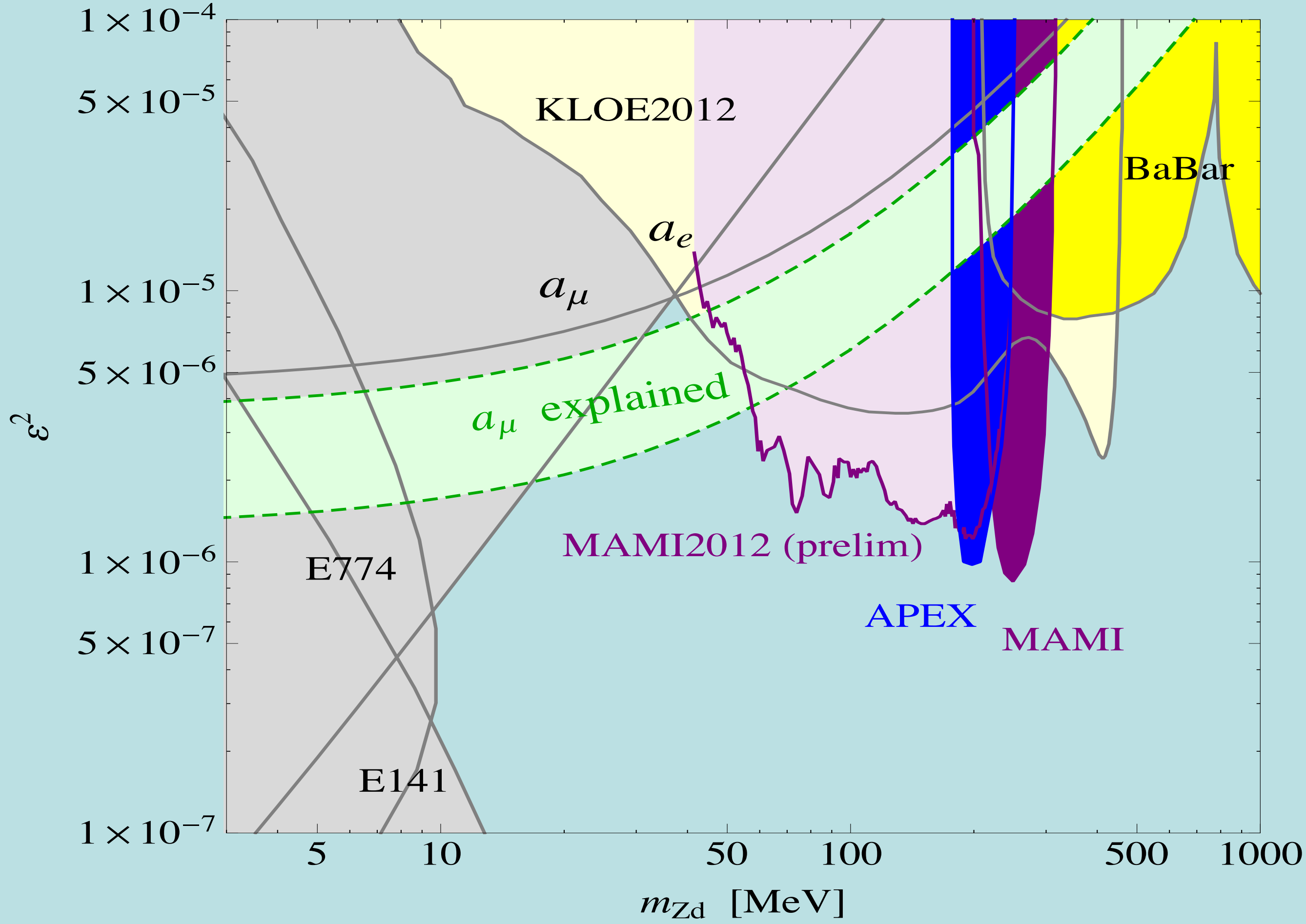
e^-
e^+
A'
e^-

Dark Photon Exclusion Early 2012



Recent Updates → 20MeV-50MeV Left

2013 COSY $\pi^0 \rightarrow \gamma Z_d \rightarrow e^+e^-$ Not Shown



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

In an effort to precisely determine r_p

New PSI μp atomic Lamb shift experiment

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

$(m_\mu/m_e)^3 = 8\text{x}10^6$ enhancement

Proton Finite Size ≈ -2%

20ppm experiment

12years in the making (1998-2010)

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

r_p=<u>0.84184(67)fm</u>   (μp atom)

10x More Precise & 5 sigma below ep value!

r_p≅<u>0.8768(69)fm</u>   (ep atom)

<u>Confirmation from ep scattering</u>

r_p≅<u>0.879(8)fm</u>   (Recent Mainz)

r_p≅<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? Rydberg Constant(R_∞) (Off by 5σ?)

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

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

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

Could R_∞ really be wrong?

also

What about ep scattering? Wrong!

Perhaps the most likely solution

μp atomic theory or experiment wrong?

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

μp Experiment? (seems solid)

Follow up Experimental & Theoretical Work appear to confirm original results!

Can all three r_p determinations be correct?

2 out of 3 correct?...

New "Light" Vector or Scalar Boson?

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

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

New Vector Boson Interaction Shifts Atomic Spectrum

in a way that mimics a proton charge radius

(Based on calculation by A. Czarnecki)

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

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

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

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

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49)\times10^{-11}$ (3.6σ!)

What about light vector boson with $m_{Zd}<m_\mu$?

$\Delta a_\mu \sim \alpha'/2\pi$ 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) Matter effect!*

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

something likely wrong but which one(s)?

Rydberg Constant Vulnerable

<u>What if it shifts by 5 sigma?</u>

<u>but ep remains a problem?</u>

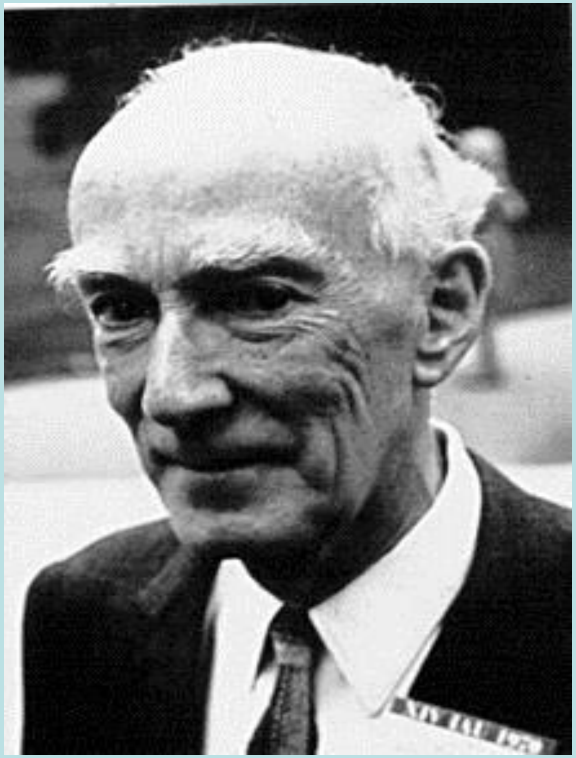
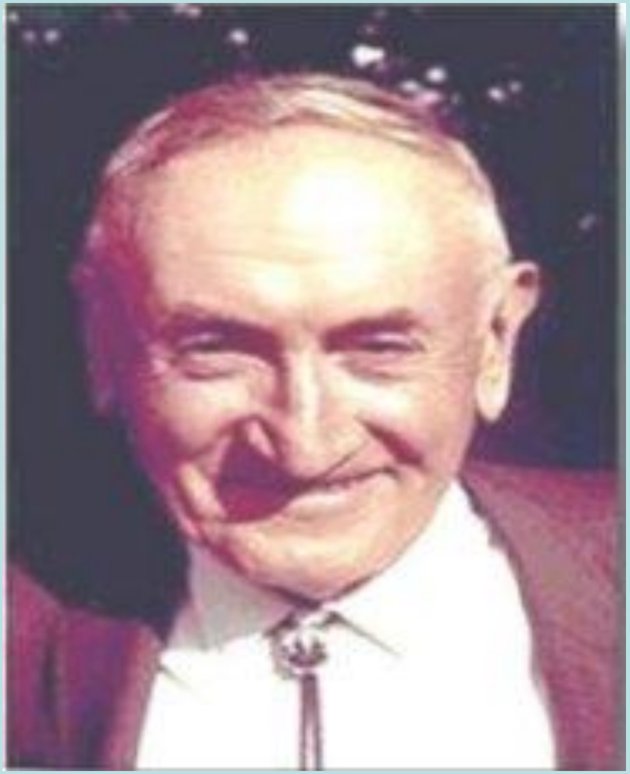
Then **m_V~MeV & α' ~$2.5\times10^{-6}\alpha$ solves both** r_p & a_μ discrepencies. **Other constraints?** a_e? …

Precision QED remains interesting & timely

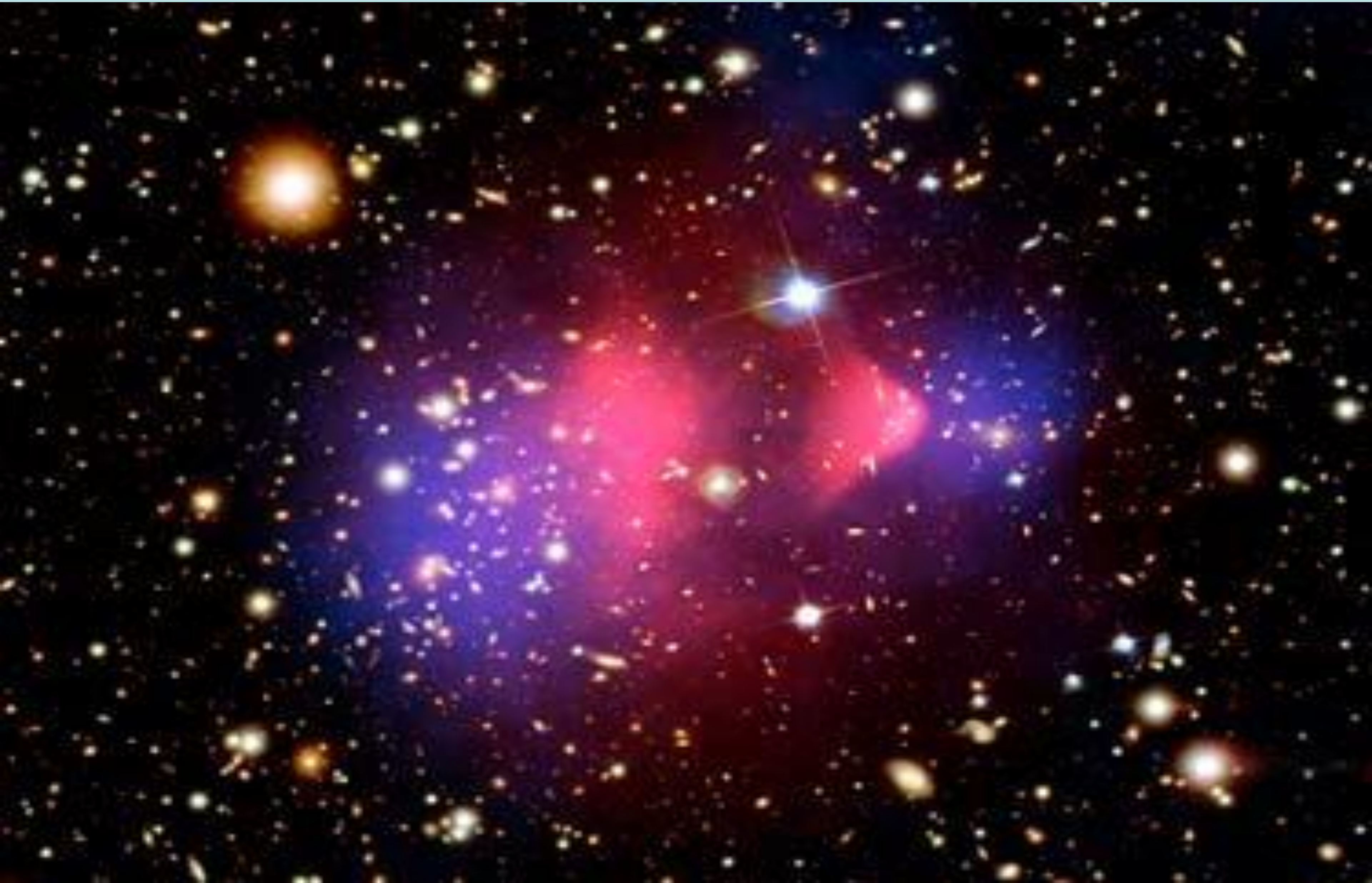
Stay Tuned For Future Developments

(About the same time antiparticles were being discovered)1932-33's Astronomers start to see "Dark Matter" Evidence!

Jan Ort & Fritz Zwicky

Bullet Galaxy Cluster



What is the Dark Matter?

Light Matter-Ordinary Particles (Galaxies, Stars, Us)

= 3-4% Of Universe (many varieties)

Dark Matter = 22% Of Universe – Gravitational Interactions

Dark Energy = 75% Of Universe – Cosmological Constant

Is dark matter a single stable new elementary particle?

How Heavy is it? Spin (0,1/2,1,3/2)?

Does it interact only gravitationally?

Does it have antiparticle partner(s)? (Asymmetry?)

Are there many species of dark particles (most unstable)

Does Dark Matter have gauge interactions? Dark Charge?

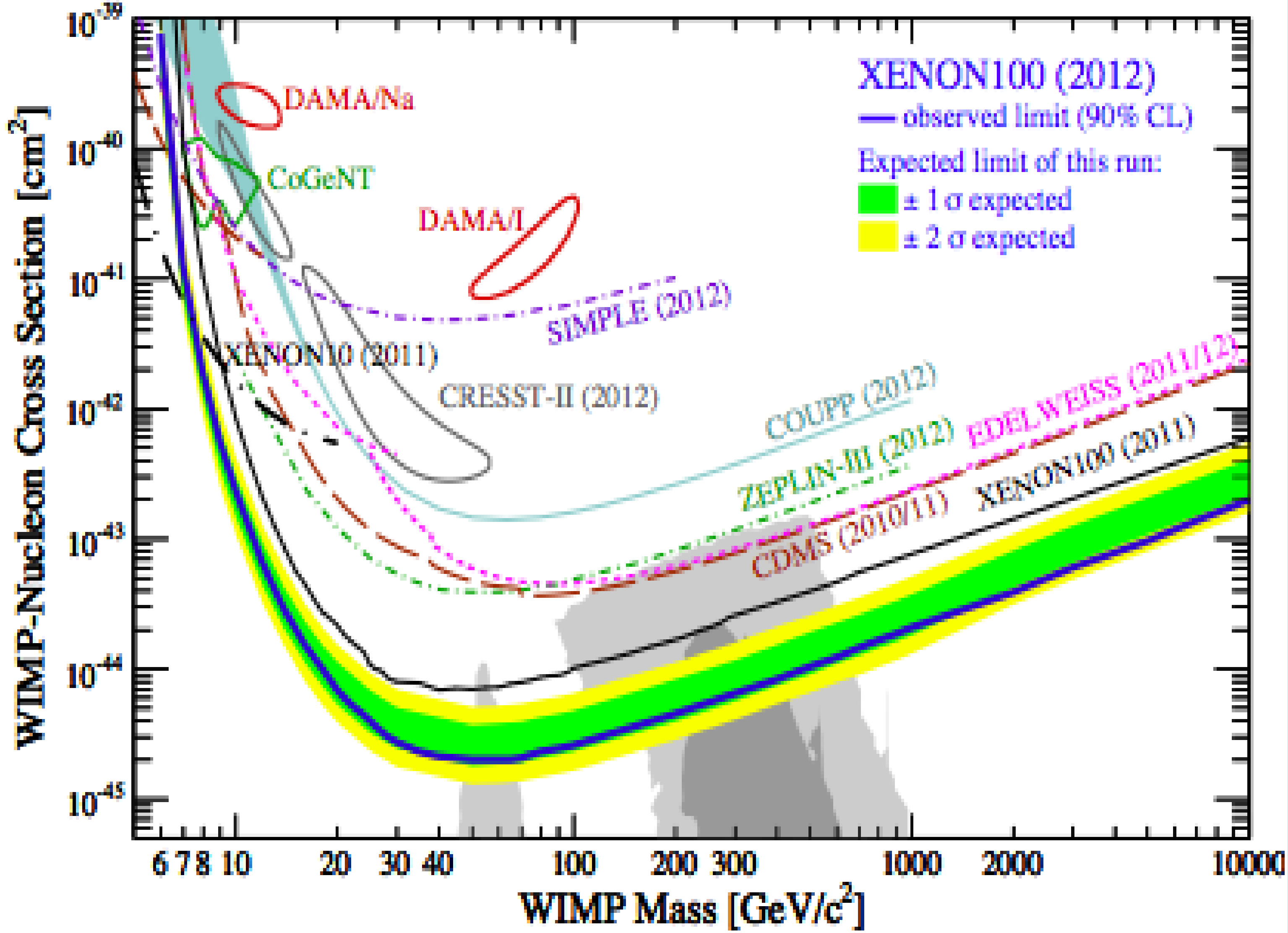
The Hunt For Dark Particles

- Underground Searches for Dark Matter Particles (WIMPS)
  Conflicting Experimental Results
  Astrophysics - Possible Hints of Dark Particle Annihilations
  LHC (Supersymmetry – Other?) No direct detection yet

The Dark Photon – A Possible Portal to Dark Matter

What if dark particles interact weakly with one another via a new massive but relatively "light" γ_d (Dark Photon) ?

Can we find evidence for such a particle?



XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
XENON100 (2011)
CDMS (2010/11)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
6 7 8 10 20 30 40 100 200 300 1000 2000 10000

Astrophysics: Hints of Dark Particle Annihilations

Light or Heavy Dark Matter Particles?

Positron (e^+) Excesses at high energies(?)

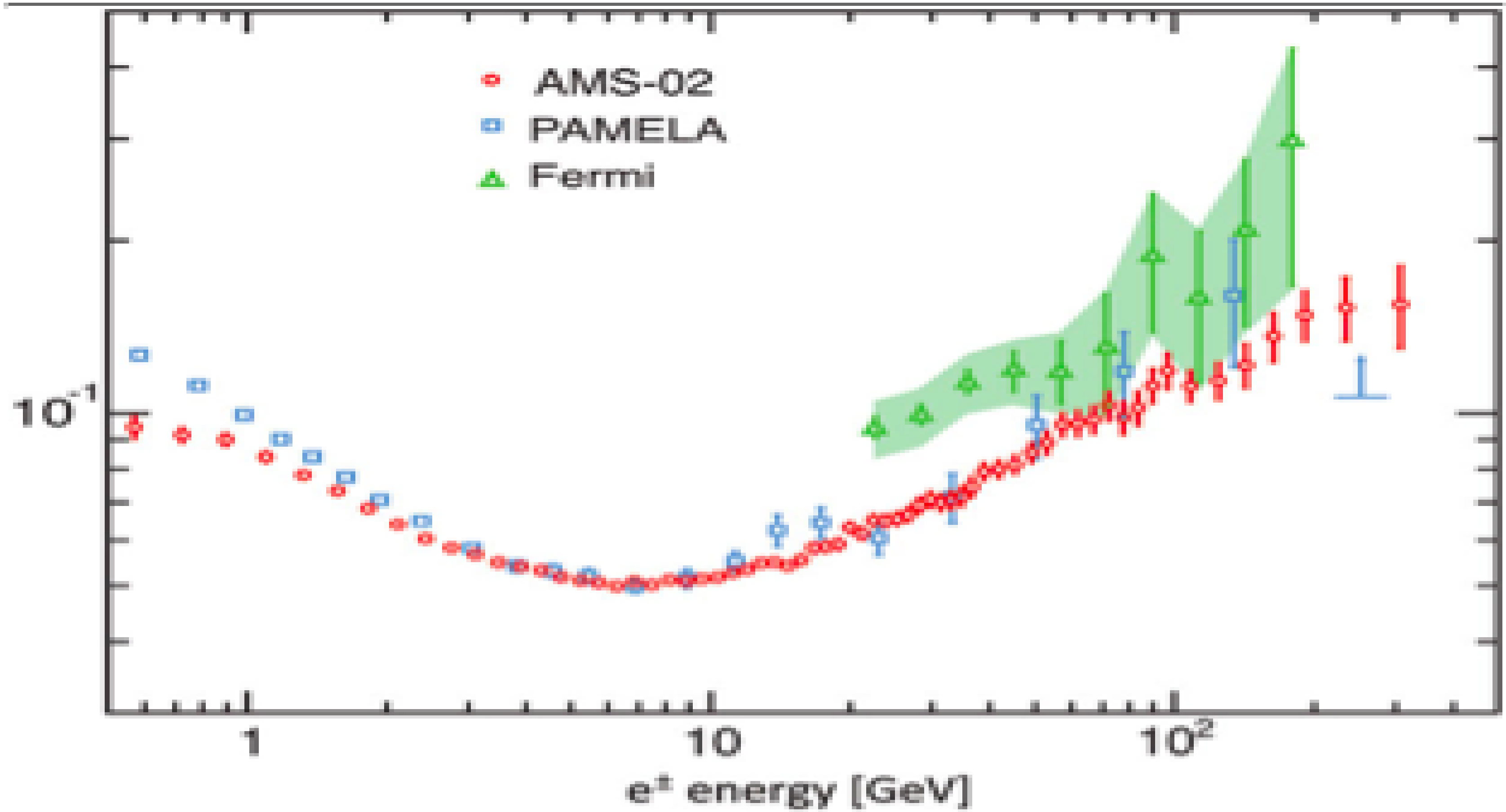
Pamela, Fermi, AMS (Heavy Dark Matter)>TeV? (Unlikely Interpretation?)

Fermi γ-ray Excess from Gallactic Center

Light ~10GeV Dark matter annihilations (→ e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$)

Both Interesting Effects

Interpretations?



s positron fraction as measured by the AMS (red circles) from 1 to 350 GeV. (Courtesy: *Phys.*
v. Lett. **110** 141102)

close or Esc Key

observed.

γ_d coupling to our particle world

- Very Weak< 0.0001x electromagnetism

  Nevertheless, produce in electron scattering

  detect $\gamma_d \rightarrow e^+e^-$

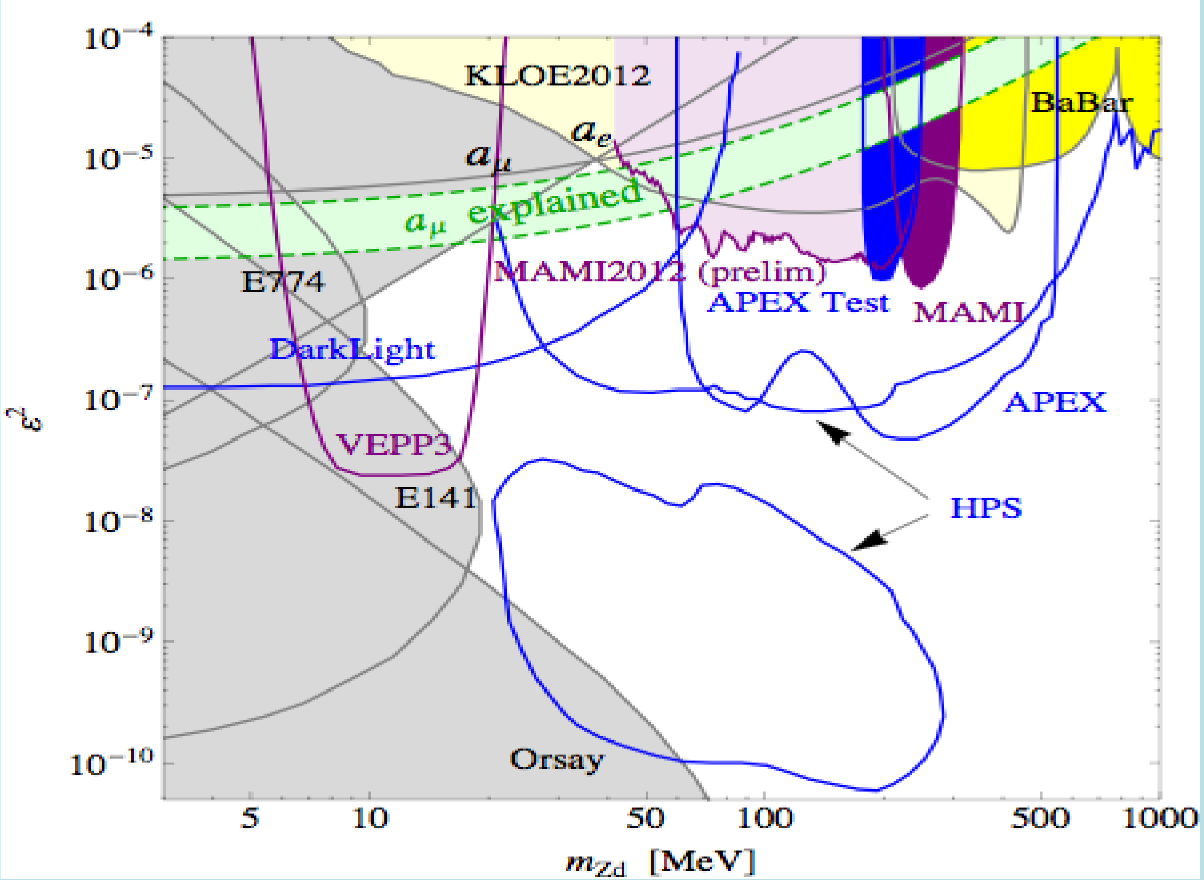
  Experiments at JLAB and MAMI (Mainz) in Progress

  More planned for the future

So far, no direct signal – but much territory needs to be explored

Current Bounds & Future Dark Photon Sensitivity

Assumes Br(Z_d→e^+e^-)=1 What if Z_d→missing energy?



Meanwhile

<u>1950</u> <u>Purcell & Ramsey</u> Speculate P may be violated

Begin search for neutron edm

T (CP) violation also needed for edms!

P & T Violation ⇒ EDMs for all particles with spin

CKM CP Violation ⇒ unobservably small edms

<u>EDMs</u>: Window to Early Universe CP Violation!

<u>"New Physics" Source of CP Violation Needed!</u>

<u>Supersymmetry Leading Candidate</u>

<u>(Not observed at LHC yet! Some Tension!)</u>

<u>Great Future Expectations</u>

- **$d_n \rightarrow 10^{-27}$-10^{-28} e-cm Neutron Spallation/Reactor Sources**
- **$d_e \rightarrow 10^{-29}$ e-cm or better!**
- **d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL/COSY)**

Pave the way for a new generation of storage ring experiments d_p, d_D, d(^{3}He), d(radioactive nuclei), d_μ

<u>Several orders of magnitude improvement expected</u>

Vector-like Heavy Leptons Dark Variant
Example - Davoudiasl, Lee &WJM

- Example: A Possible Dark Sector

Two Left Handed Doublets $(N_i^0, E_i^-))_L$ i=1,2

Two Right-Handed Doublets $(N_i^0,E_i^-)_R$

Dark Charges ± 1

Four Left Handed Singlets N_{jL}, E_{jL} j=3,4

Four Right Handed Singlets N_{jR}, E_{jR}

Dark Charges ± 1

Gauge Invariant Mass Terms + Higgs Couplings ➔ Mixing

All interactions vector-like under $SU(2)_L xU(1)_Y \mathbf{xU(1)_d}$

4 Charged & 3 Neutral Leptons Unstable

Lightest Neutral: Potential Stable Dark Matter?

a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx few x 10^{-11}$
  $a_e(H) \approx 5x10^{-16}$

  <u>Unobservably Small!</u>

  Two Loop Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e-cm
  $|d_n(H)| \approx |d_p(H)| \approx 3x10^{-26} \sin\phi$ e-cm

Already d_e bound implies $\sin\phi \leq 0.1$ (smaller?)

<u>CP violation in *H*([illegible]</u> $\sin^2\phi \leq 0.01$

Unlikely to be observable, but edm experiments can

Explore down to $\sin\phi \approx O(10^{-3})$! ***<u>Unique!</u>***

Anomalous Dipole Moments

fermion	a_f^{exp}	$\|d_f(e/2m_f)^{exp}\|$
e	0.00115965218073(28)	$<1\times10^{-16}$
μ	0.00116592089(63)	$<3\times10^{-6}$
p	1.792158142(28)	$<3\times10^{-12}$ (d_{Hg})
n	-1.9130427(5)	$<1\times10^{-13}$

"New Physics" expected to scale as $(m_f/\Lambda)^2$

$(m_\mu/m_e)^2 \approx 43000$ Muon only a_f sensitive to high Λ~2TeV!

All d_f sensitive to "New Physics" if $\tan\phi^{NP}$ not too small

Nucleon edms Isovector or isoscalar? Mixed?

Both d_n and d_p need to be measured!

Some Dipole Moments

fermion	a_f^{exp}	$d_f^{exp} x(2m_f/e)$
e	0.00115965218073(28)	$<5x10^{-17}$
μ	0.00116592089(63)	$<3x10^{-6}$
p	1.792158142(28)	$<3x10^{-12}$ (from d_{Hg})
n	-1.9130427(5)	$<1x10^{-13}$

"Heavy New Physics" expected to scale as $(m_f/\Lambda)^2$

$(m_\mu/m_e)^2 \approx 43000$ Muon only a_f sensitive to high Λ!

All d_f sensitive to "New Physics" if $\tan\phi^{NP}$ not too small

Nucleon edms Isovector or isoscalar? <u>Mixed?</u>

Both d_n and d_p (as well as d_D) need to be measured!

Future Expectations

- $d_n \to 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources

- d_p & $d_D \to 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL/COSY)
  Probes New Physics(NP) at $(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-7}$!
  for $\phi_{NP} \sim O(1) \to \Lambda_{NP} \sim$ 3000TeV! (**well beyond LHC**)
  Paves the way for a **new generation** of storage ring experiments d_p, d_D, $d(^3He)$, d(radioactive nuclei), d_μ

- $d_e \to 10^{-30}$e-cm or better!
- $d_\mu \to 10^{-24}$e-cm Storage Ring Proposal

Baryogenesis & New Physics CP Violation

Examples of New Physics Models with potentially large CP Violation: Supersymmetry, Multi-Higgs,

L-R Models, 4th Generation, Extra Dimensions…

Dark Matter Sector…Higgs CP Violation

- Generic Manifestation - **Electric Dipole Moments**

What is the "New Physics"?

Look for EDMs!

No Standard Model Background (too small)