The Standard Model: "Is That All There Is?" (Emphasis on The Role of Precision)

Student Lecture

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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} ***Exactl***y (Meter Definition)

Natural Units c=1 used in this talk

Later

Yang-Mills Non-Abelian Gauge Theories 1954

Standard $SU(3)_c xSU(2)_L xU(1)_Y$ *Model ~1967-1973*

12 spin 1 bosons: 8 massless gluons; $W^{\pm}$, Z, γ

3 generations of quarks and leptons

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

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

2012 Higgs (125GeV) Scalar Discovered at CERN!

Remnant of Electroweak Symmetry Breaking

Entering a New Age of Precision Higgs Physics!

2015: m_H=125.09±0.24GeV ! …

Electroweak Unification History

1957 - Parity Violation in Weak Interactions (Maximal!)

Lee & Yang Why is nature left-handed (Chiral)?

Following up on the work of his advisor (J. Schwinger)

1961 Glashow $SU(2)_L xU(1)_Y$ Gauge Symmetry

$W^{\pm}$, Z (massive) & γ(massless) gauge bosons

(chiral) fermions massless left-right asymmetric

All masses put in by hand

Explicitly Break Symmetry

γ-Z weak mixing angle introduced $\sin^2\theta_W=(e/g)^2$

Weak Neutral Currents (Z Interacions) Alluded To

Largely Ignored

1967 Weinberg Introduces Higgs Mechanism

- Weinberg (following the work of P. Higgs) adds a scalar $SU(2)_L$ doublet (ϕ^+, ϕ^0) with tachyonic mass to the model that breaks $SU(2)_L x U(1)_Y \rightarrow U(1)_{em}$ at the vacuum level
- $<\Phi> \approx 250$GeV gives masses to $W^\pm$, Z and all fermions

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

Predicts weak neutral currents… & ***Higgs Boson***

1971 Renormalizability proved by 'tHooft

Is the Higgs Mechanism Fundamental or Dynamical?

Is there just a single Higgs doublet? Several?

$H=0^{++}$ Remnant Predicted – Higgs Boson, Others h, A, $H^\pm$…

H coupling to particles proportional to their masses

W, Z, t, b ***large****…   e, u, d* ***very small******(detectable?)***

Higgs (125GeV) Discovery & Properties

- ATLAS and CMS Experiments have strong evidence for a
- Higgs like (spin 0) new particle with mass 125GeV

Expected Higgs SM Properties

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

Some Important Precision EW Parameters Tied Together by Natural Relationships

Quantity	2008 Value		2015 Value	Comment
α^{-1}	137.035999084(51)		***137.035999049(90)***	$\alpha^{-1}(a_e)$ vs $\alpha^{-1}(Rb)$
G_μ	$1.16637(1)\times10^{-5}GeV^{-2}$		$1.1663787(6)\times10^{-5}GeV^{-2}$	$\tau_{\mu+}$ PSI
m_Z	91 .1875(21)GeV		91.1876(21)GeV	-
*m_t	171.4(2.1)GeV	→	173.3(0.8)GeV	FNAL/LHC
*m_H	>114GeV	→	**125.09(0.24)GeV**	
m_W	80.410(32)GeV	→	80.385(15)GeV	LEP2/FNAL
$\sin^2\theta_W(m_Z)_{ave}$	0.23125(16)		0.23125(16)	Z Pole Ave.

Best individual Z pole determinations:

$\sin^2\theta_W(m_Z)$	0.23070(26)	0.23070(26)	SLAC A_{LR}
$\sin^2\theta_W(m_Z)$	0.23193(29)	0.23193(29)	CERN $A_{FB}(bb)$

(3 sigma difference?)

A Beautiful Electroweak Relation

$SU(2)_L xU(1)_Y$ + Higgs Doublets + Renormalizability

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

Radiative (Loop) Corrections - Finite & Calculable!
Demonstrated by Bollini, Giambiagi & Sirlin (1972)
WJM(1974) Thesis: Finite Parts Calculated

Main effect: $\alpha=1/137 \rightarrow \alpha(m_Z)\sim1/128$ Large 7% VP
Later: Large $\alpha m^2_t/m^2_W$ Corrections M. Veltman
Higgs loop corrections smaller but not negligible

Standard Model Predictions Through 2 loops

Assuming No New Physics

$\sin^2 2\theta_W(m_Z)_{MS} = 2\sqrt{2}\pi\alpha / m_Z^2 G_\mu (1-\Delta r'(m_t,m_H))$ m_H=125GeV!

$\Delta r'(m_t,m_H)$=0.0598(2) ➔ $\sin^2\theta_W(m_Z)_{MS}$=0.23124(6)   ±0.03%

Currently $\sin^2\theta_W(m_Z)_{ave}$= 0.23125(16) Excellent Agreement

Error Expected to be reduced (improved m_t) to ~ ±0.01%

$m_W^2 = \pi\alpha / \sqrt{2} G_\mu \sin^2\theta_W(m_Z)_{MS} (1-\Delta r(m_Z)_{MS})$

$\Delta r(m_Z)_{MS}$=0.0693(2) ➔ m_W=80.362(6)

Currently m_W^{exp}=80.385(15)GeV ***1.4 sigma high***

Any significant difference between SM prediction and Experiment Implies “New Physics” (No Signal Yet!)

The Higgs appears to be a fundamental remnant of EW symmetry breaking and mass generation. It completes the Standard $SU(3)_c x SU(2)_L x U(1)_Y$ Model spectrum.

One can ask:

Is that all there is?

Examples of possible additional "New Physics": Supersymmetry, Other Scalars, Heavy Quarks or Leptons, Dark Particles … Additional Gauge Interactions …

Or is the Higgs the last hurrah of Particle Physics!

Look for deviations in the 4th-6th decimal places!

(from Brian Malow)

- **"Higgs boson walks into a church, and the priest says, 'I'm sorry we don't allow Higgs bosons to come to churches.' And [the Higgs] says, 'But without me, you can't have mass.'"**

The Roots of Precision Quantum Electrodynamics (QED)

1.) ***Historical Introduction***

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

ii) Spin (1925) *A Great but clouded discovery*

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

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 (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)

8 sigma difference

6.) ***Outlook***

1.) ***Historical Introduction***

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

The Start of Elementary Particle Physics

Early 20th Century

Quantum Mechanics (γ photon)

Special & General Relativity

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

1931 Neutron (n) Discovered by Chadwick

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 ➔ Explained Chemistry!

But, what was “twofoldness”?

Wolfgang Pauli

Wolfgang Pauli




ii) ***Electron Spin (1925)***
Nobel Prize?

In 1925, Kronig (unpublished) and independently Uhlenbeck and Goudsmit interpret "twofoldness" as Electron spin S=±½. Wavefunction antisymmetric under Interchange of 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)

Go to second order formalism (apply

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

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 or even ridiculed)
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! (Sakharov Conditions)
(1964-CP Violation Discovered-CKM Not Enough)
"New Physics" Source of CP Violation Needed!
Supersymmetry, 4th Generation, Multi-Higgs…

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

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

1964- CP Violation Discovered in Kaon Decays

1967 Sakharov Conditions:

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

Completing the Picture?

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

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

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

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

strong, weak, electromagnetic & gravitational interactions

Is that all there is?

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)***

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

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

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

Now (2012) Complete! Higgs (H) Boson Discovery

Remnant of Particle Mass Origin

What Else Is There? New Particles? Interactions?

Supersymmetry ***(Doubles The Spectrum!)***

Weakly Coupled Hidden Sector?

So far: No direct evidence for Supersymmetry,

At The LHC (Large Hadron Collider)!

<u>Still Early – Nevertheless some tension</u>

The Higgs –May Be Last Particle Ever Discovered?

(Probably Not)

Left with Mysteries: Why Baryogenesis? CP?

Why 3 Generations?

Why Parity Violation?

<u>Dark Matter</u>, Energy…

We could add extra terms to the Dirac Equation

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

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

Anomalous Mag. Mom.

$g_e=2(1+a_e)$

a_e =Pauli Term

Electric Dipole Mom.

Violates P&T(CP)

Not Observed

$d_e<10^{-28}$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

$$L = ¼F_{\mu\nu}(x)F^{\mu\nu}(x) + \psi^*(x)\,\gamma^0\{i(\partial_\mu - ieA_\mu(x))\gamma^\mu - m_e\}\psi(x)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

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 $a_e=(g_e-2)/2\neq 0$

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

1947 Lamb measures the $2P_{1/2}$-$2S_{1/2}$ splitting

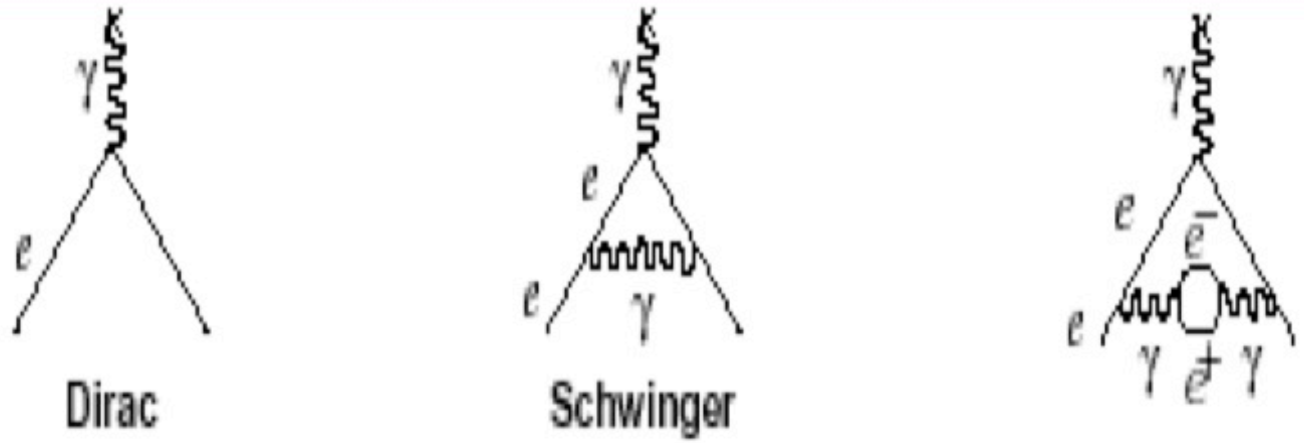
vacuum polarization, electron self-interaction

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 very precise!*

Anomalous Magnetic Moment Contributions



Basic Quantum Electrodynamics

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

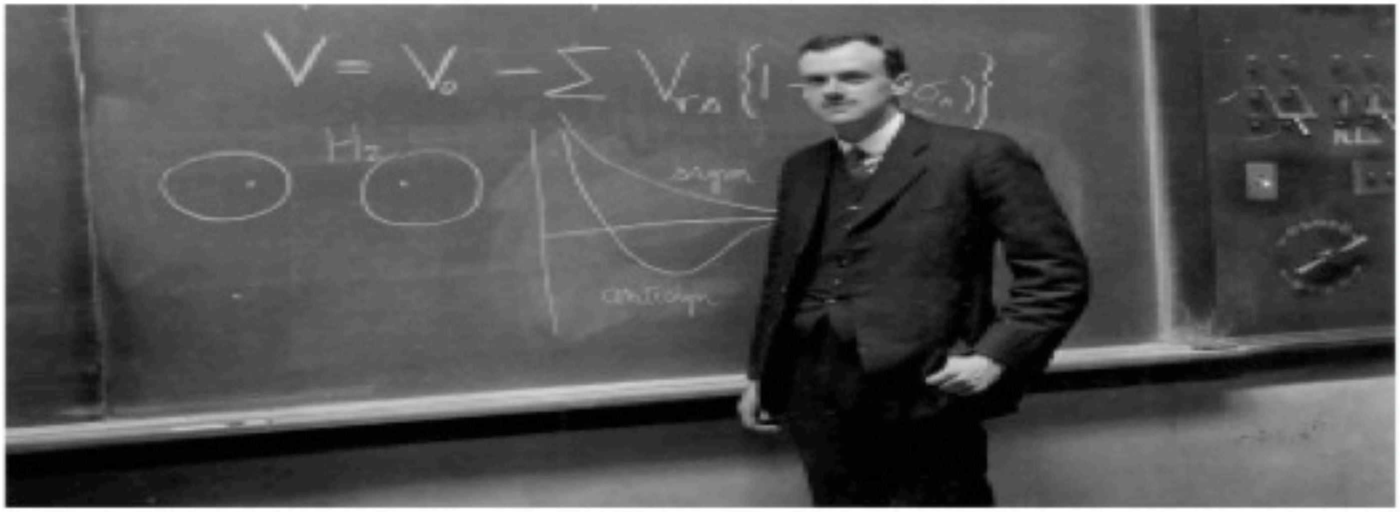
Renormalized to m_e and e physical mass and charge

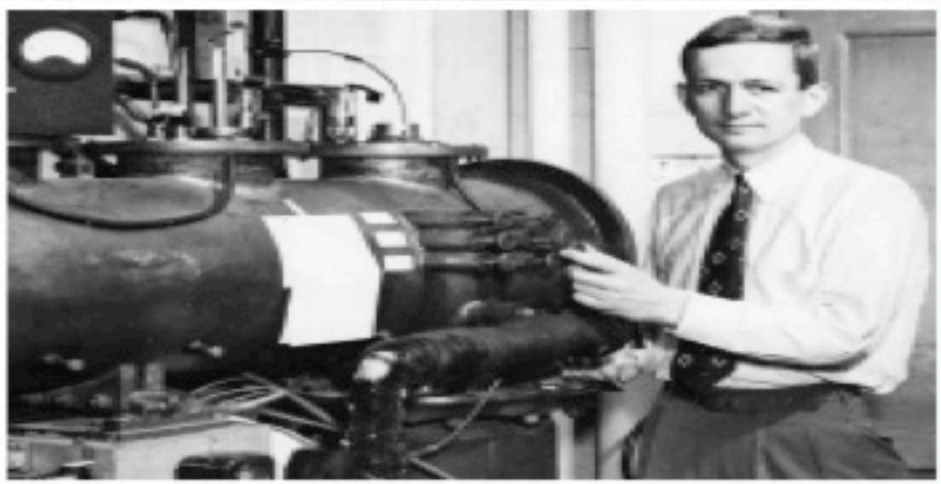
Interaction strength $e^2/4\pi \approx 1/137$ fine structure constant

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. ±28x10^{-14}!

(Hanneke, Fogwell, Gabrielse: PRL 2008)

g_e=2.00231930436146(56)

Most precisely known dimensionless physical quantity!

Future Goal: factor ≥ 4 improvement?

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

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

$+7.795(336)(\alpha/\pi)^5$… +1.68(2)x$10^{-12}$(had) +0.03x$10^{-12}$(EW)

Aoyama, Hayakawa, Kinoshita, & Nio 2012 & 2015 Updates!

Spectacular Computational Achievement

Uncertainty ±7x10^{-14} (QED theory) ±2x10^{-14}(Hadronic)

Alpha determination: Rydberg + m_e/m_{Rb}

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

$\frac{1}{2} m_e \alpha^2 = 13.60569253(30) eV$

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

Bouchendira et al. PRL. (2011) factor 10 improvement!

Ongoing ^{87}Rb exp. Goal - Another factor of 7 improvement!

$\Delta a_e = a_e(exp) - a_e(theory) = -0.91\ (0.82) \times 10^{-12}$ Note Sign

Error Budget: $\pm 77 \times 10^{-14}$(alpha) $\pm 28 \times 10^{-14}$(exp.) $\pm 7 \times 10^{-14}$(th.)

Further Improvement in Δa_e

Factor 2.6 Sensitivity Improvement (better) $\alpha^{-1}(^{87}Rb)$

New a_e Experiment (4 x better)!

Very good for constraining long distance new physics (eg Dark Photon)

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

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

CODATA: $r_p \cong$ **0.8768(69)fm (ep atom)** hydrogen spectrum
(2008) (Main sensitivity - Lamb Shift)
Depends on Rydberg Constant
$R_\infty = 1.0973731568527(73) \times 10^7 m^{-1}$
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_μ=2.00±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)**
- $a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592089(54)_{stat}(33)_{sys} \times 10^{-11}$

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

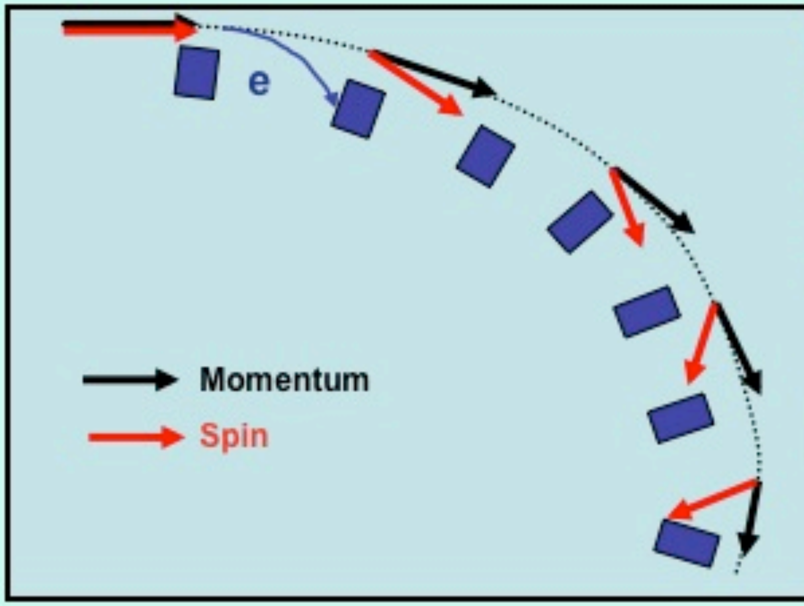
Factor of 14 improvement over CERN results

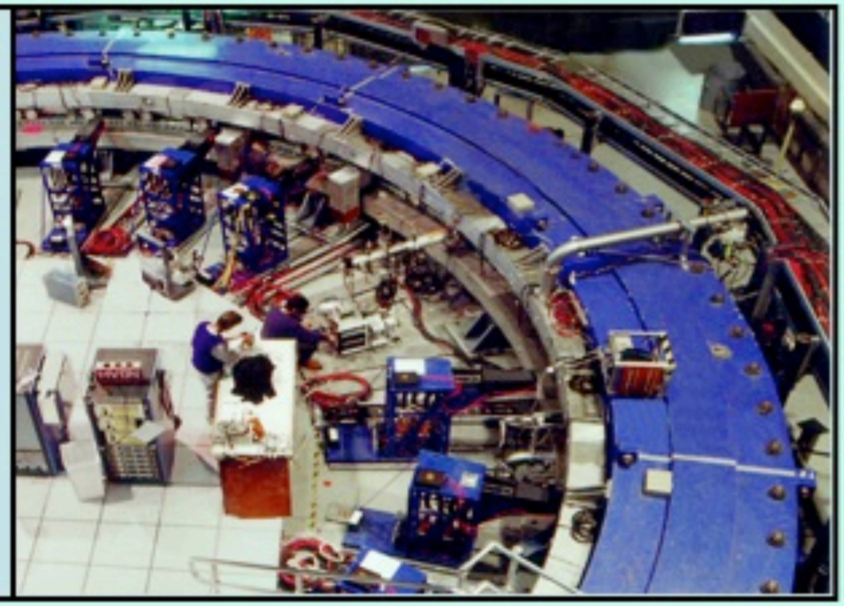
(Proposed Future Factor 4 Improvement at FNAL)

D. Hertzog, B.L. Roberts…

BNL Muon g-2 Experiment

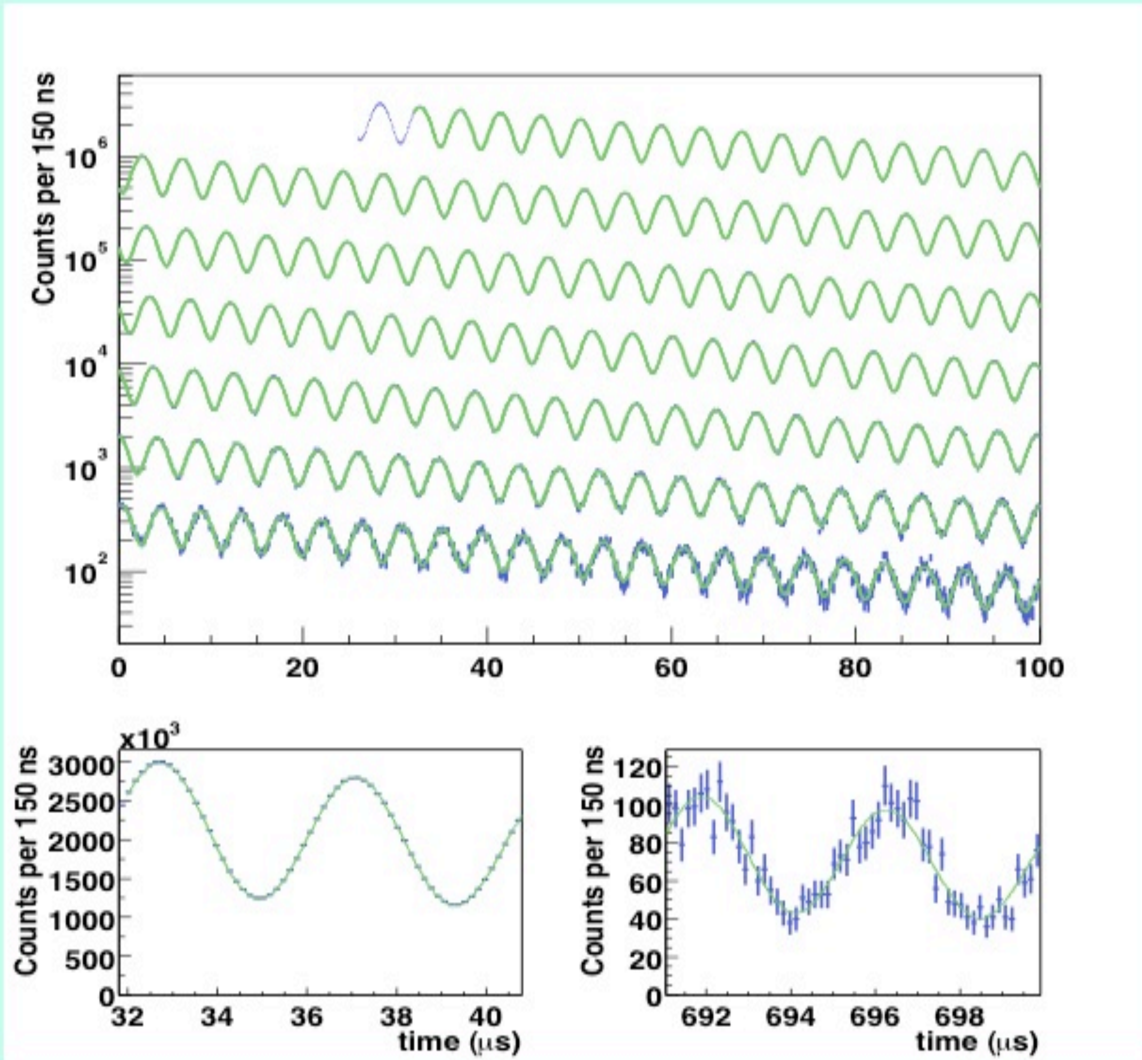
- a_μ is proportional to the difference between the spin precession and the rotation rate





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

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



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!

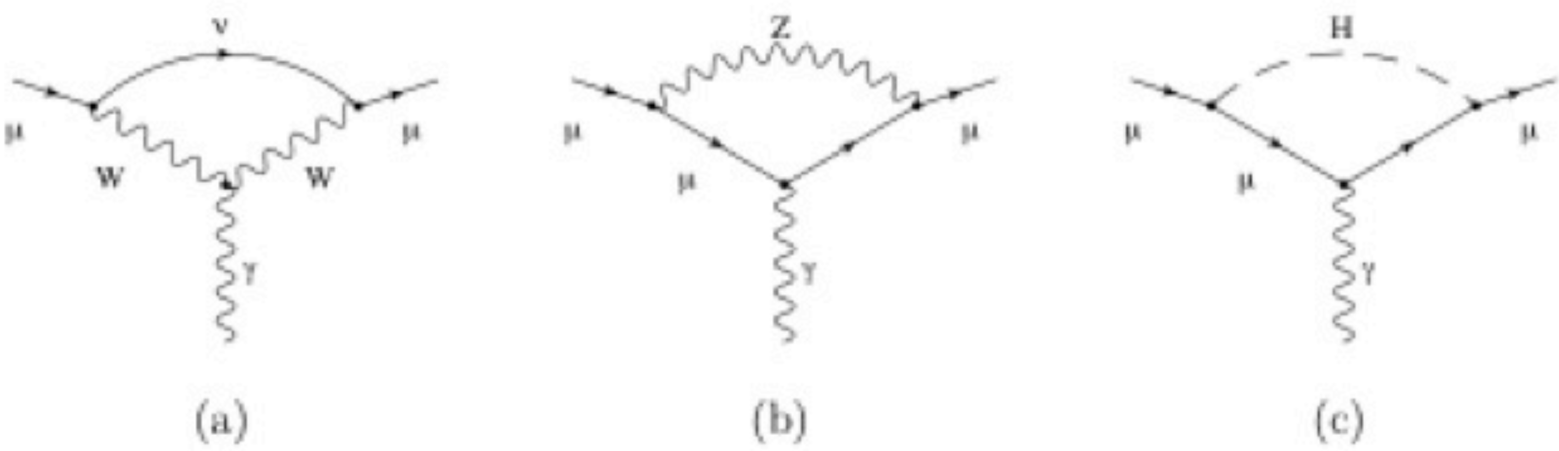


Figure 2: One-loop electroweak radiative corrections to a_μ.

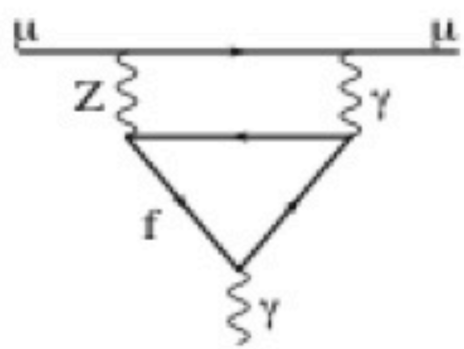


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to $a_\mu^{\rm EW}$.

Electroweak Loop Effects

a_μ^{EW}(1 loop)=194.8x10^{-11} original goal of E821

a_μ^{EW}(2 loop)=-40.3(1.0)x10^{-11} (Higgs Mass = 126GeV))

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

- ***a_μ^{EW}=154(1)x10^{-11} Non Controversial***

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

a_μ^{Had}(V.P.)^{LO}=6923(40)(7)x10^{-11} (Hoecker update 2010)

a_μ^{Had}(V.P.)^{NLO} = -98(1)x10^{-11}

a_μ^{Had}(LBL) = 105(26)x10^{-11} (Consensus?)

a_μ^{SM}=116591803(49)x10^{-11} (Future Improvement?)

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$=276(63)(49)x$10^{-11}$ (*3.5σ deviation!*)

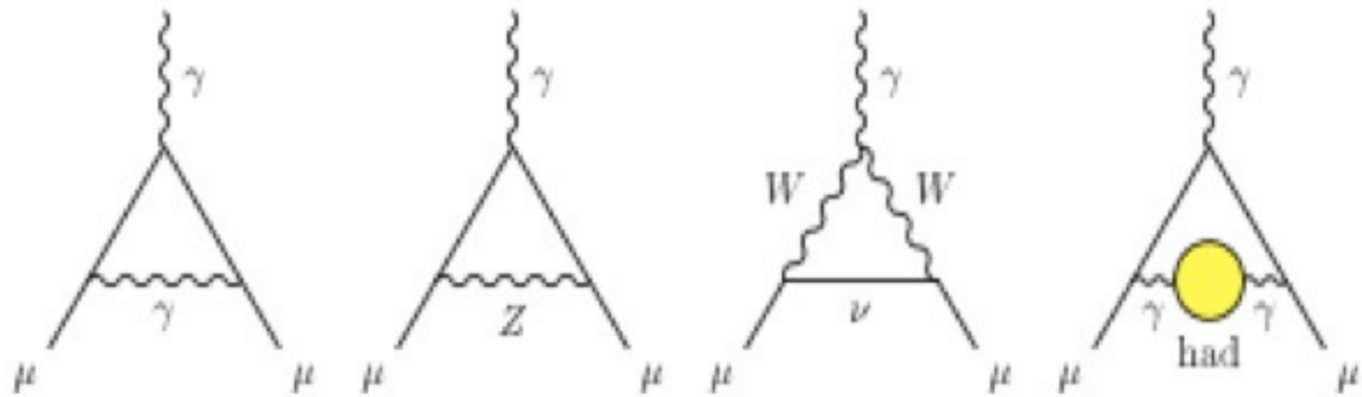


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

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

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

<u>3 loop</u>$=a_\mu^{Had}(V.P.)^{NLO}+a_\mu^{Had}(LBL)$

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

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

Prades, de Rafael, Vainshtein

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

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

Comparison of Experiment and Theory (Most Recent)

- **$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(63)(49) \times 10^{-11}$ (*3.5σ!*)**

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

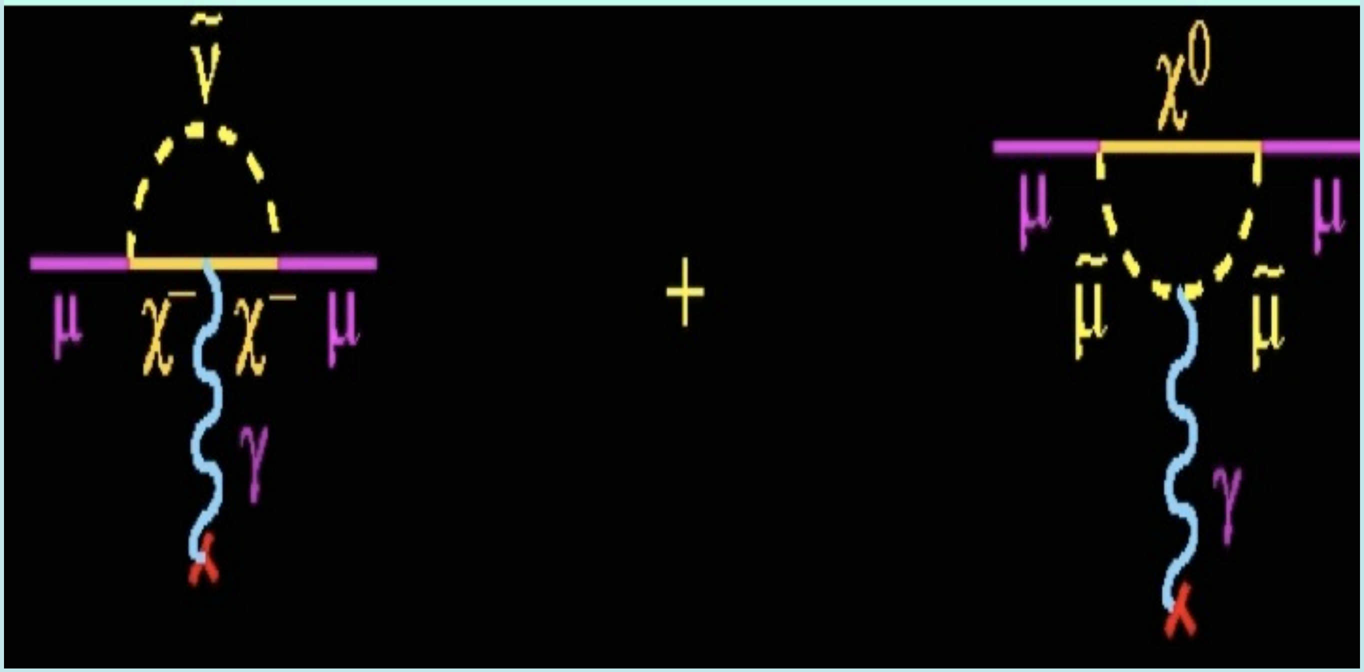
New Physics Nearly 2x Electroweak?

Why don't we see it in other measurements?

3.2 "New Physics" Effects

_SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



- SUSY Loops are like EW, but depend on:
- 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

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(80)\times10^{-11}$ ***(3.5σ!)***

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

$a_\mu^{SUSY} = (sgn\mu)130\times10^{-11}(100GeV/m_{susy})^2 \tan\beta$

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

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?

Low Mass New Physics & g-2

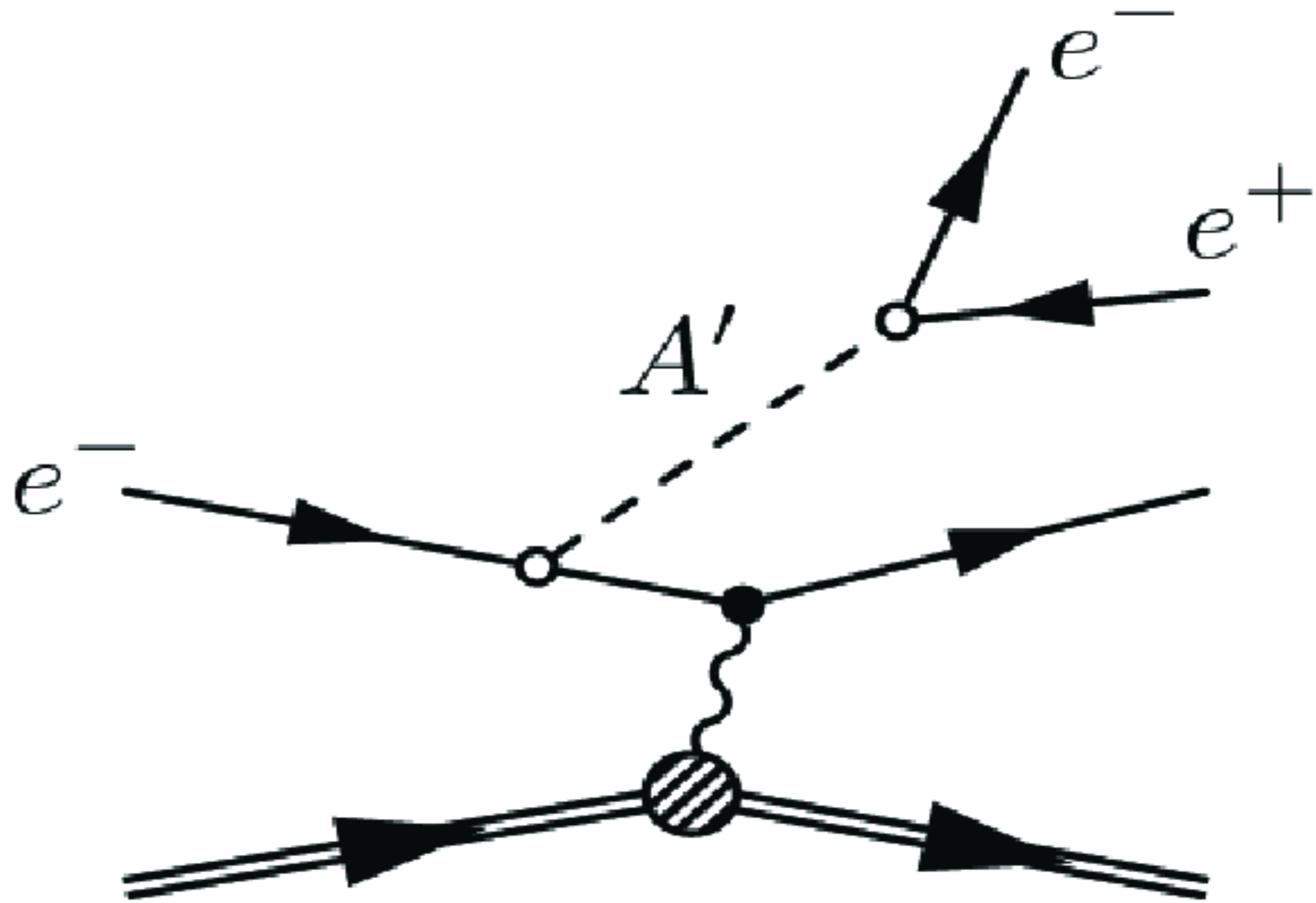
Dark Photon of g-2 interpretation easy to find at JLAB or Mainz (Bremsstrahlung) $e+X \rightarrow e+X+\gamma_d$ ($\gamma_d \rightarrow e^+e^-$)

Would Revolutionize Physics

Contact with Dark Matter!

Very Light Higgs ≤ 10MeV could also account for discrepancy

Who Ordered That?


e^-
e^+
A'
e^-

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

$(m_\mu/m_e)^3 = 8\times10^6$ enhancement

Proton Finite Size ≈ -2%

20ppm experiment

12years in the making (1998-2010)

$\Delta E(2P_{3/2}-2S_{1/2})^{exp} = 206.2949\pm0.0032$ **meV**

r_p=0.84184(67)fm (μp atom)

10x More Precise & 5 sigma below ep value!

$r_p \cong$0.8768(69)fm (ep atom)

Confirmation from ep scattering

$r_p \cong$0.879(8)fm (Recent Mainz)

$r_p \cong$0.875(10)fm (Recent JLAB)

Current Electron Average: r_p=0.8772(46)fm

8 sigma below μp atom!

Atomic ep Theory? Rydberg Constant(R_∞) (Off by 5σ?)

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

$=1.0973731568527(73)\times10^{7}m^{-1}$

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

Could R_∞ really be wrong?

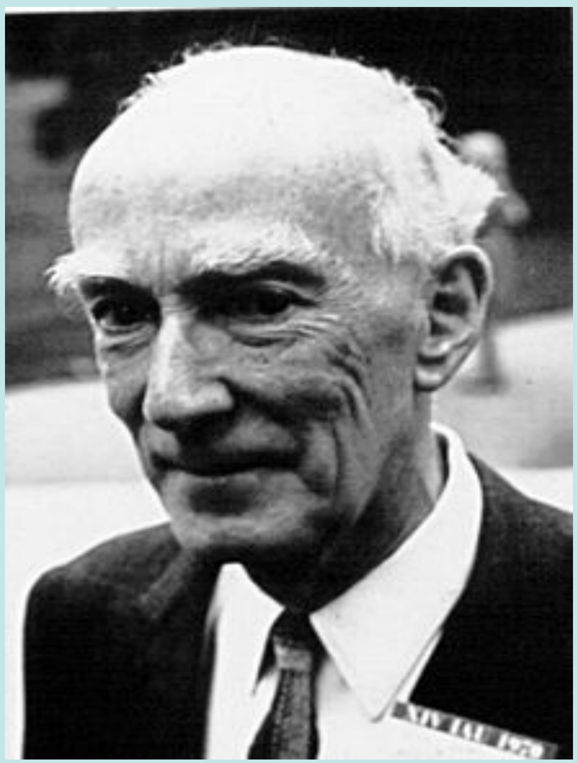
also

What about ep scattering? Wrong!

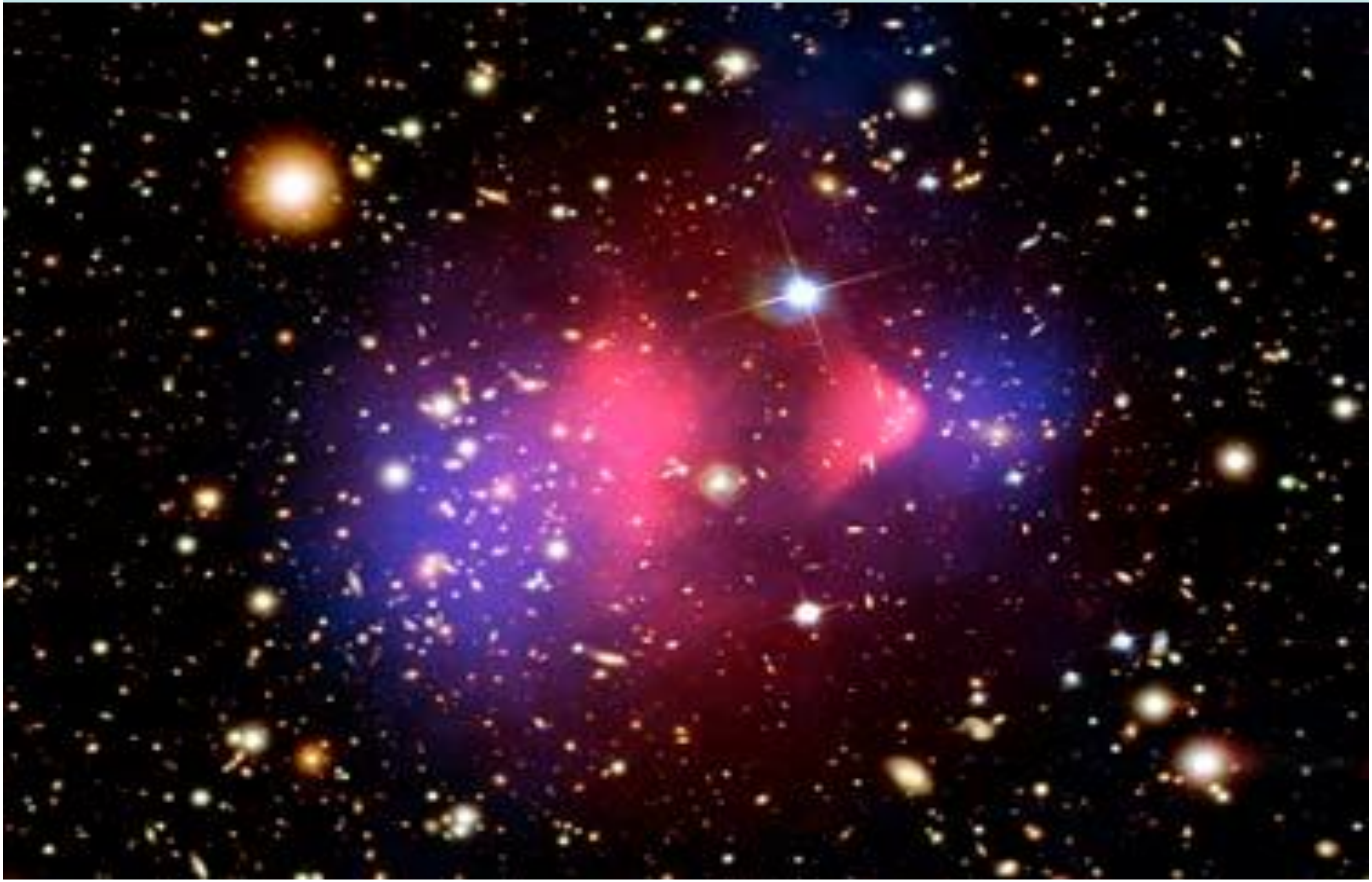
Perhaps the most likely solution

(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?

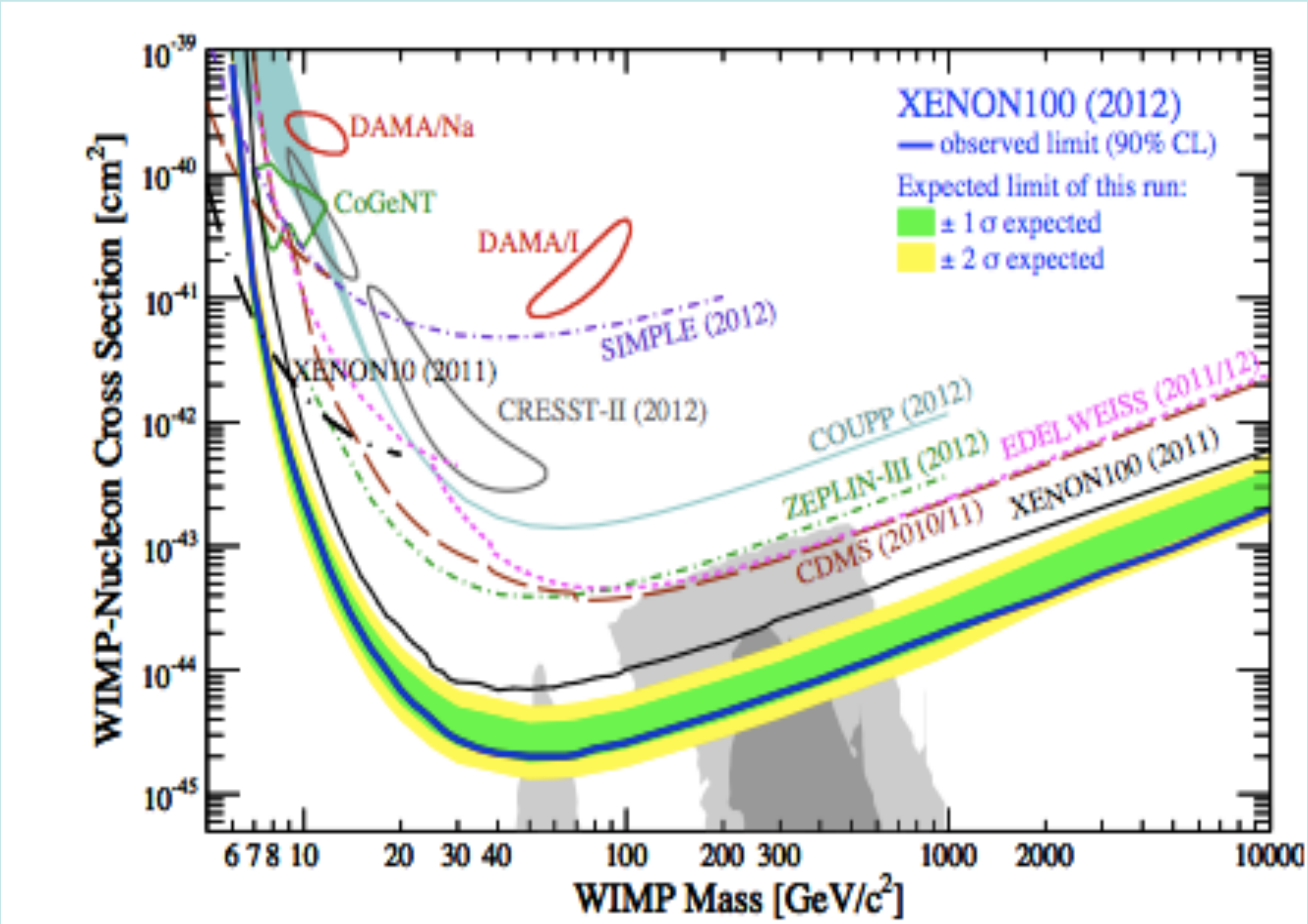
The Hunt For Dark Particles

- 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(?)

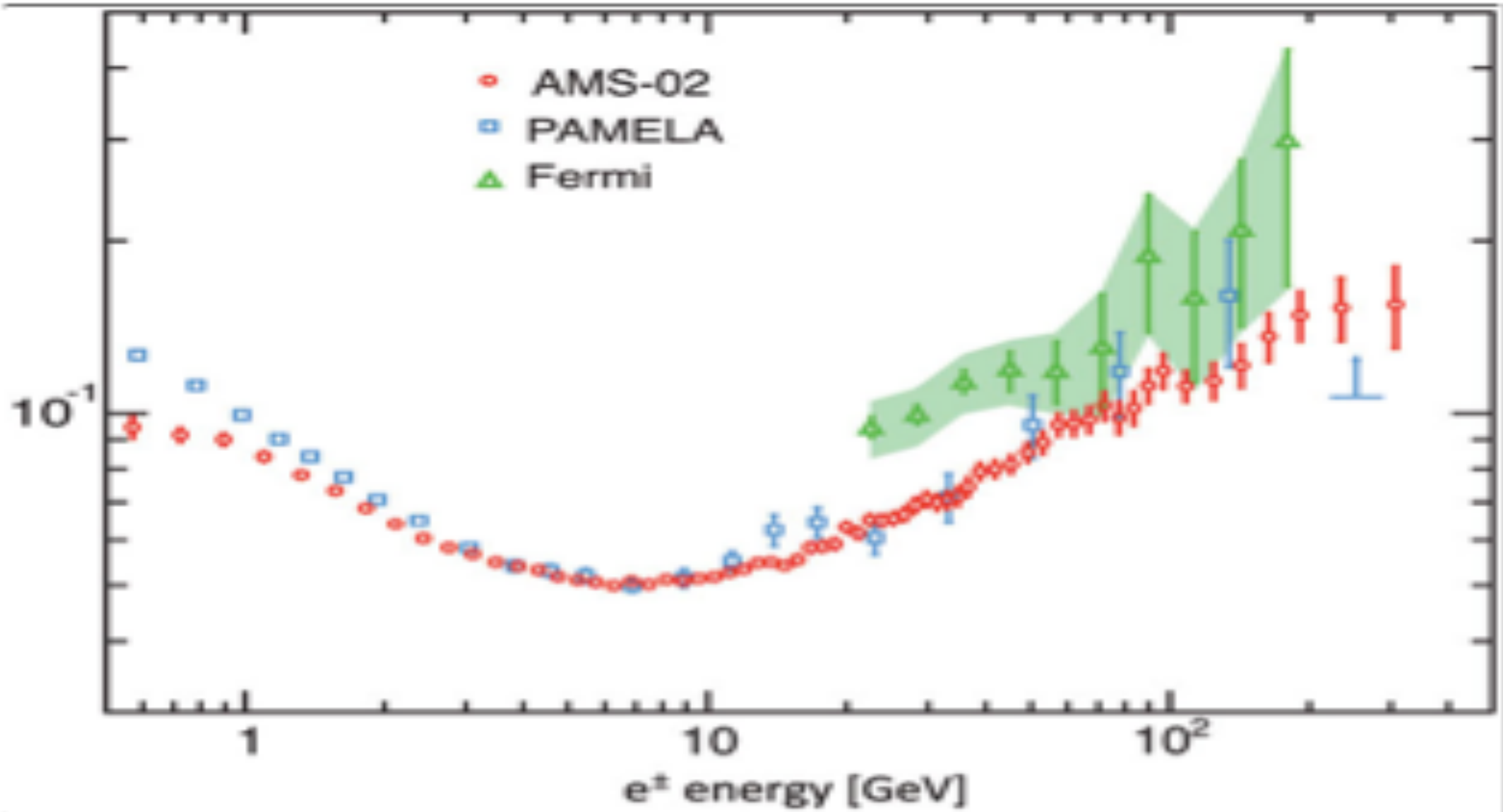
Pamela, Fermi, AMS (Heavy Dark Matter)>TeV? (Unlikely Interpretation?)

Fermi γ-ray Excess from Gallactic Center

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

Both Interesting Effects

Interpretations?



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

close or Esc Key

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)

 More planned for the future

So far, no direct signal

Outlook

i)**Exciting New Lepton Anomalous Magnetic Moments Ahead**

Low energy potential for: SUSY, Multi-Higgs,.. Dark Photon

ii) $\sin^2\theta_W$, m_W & m_t improvements expected

iii) *PERHAPS the LHC will directly uncover "New Physics"!*

Precision Experiments are Hard

Challenges Advance Physics

Remember Michelson the Master of Light