Lepton Dipole Moments Overview

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UCLA

Schwingerfest 2018

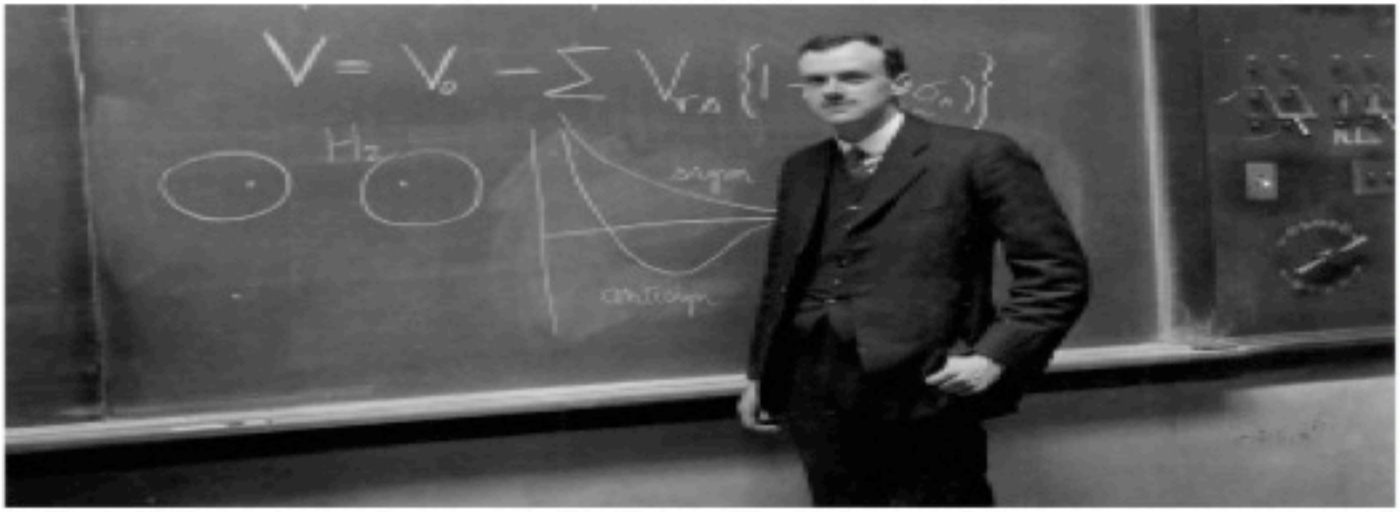
2018 Schwinger Centennial Year

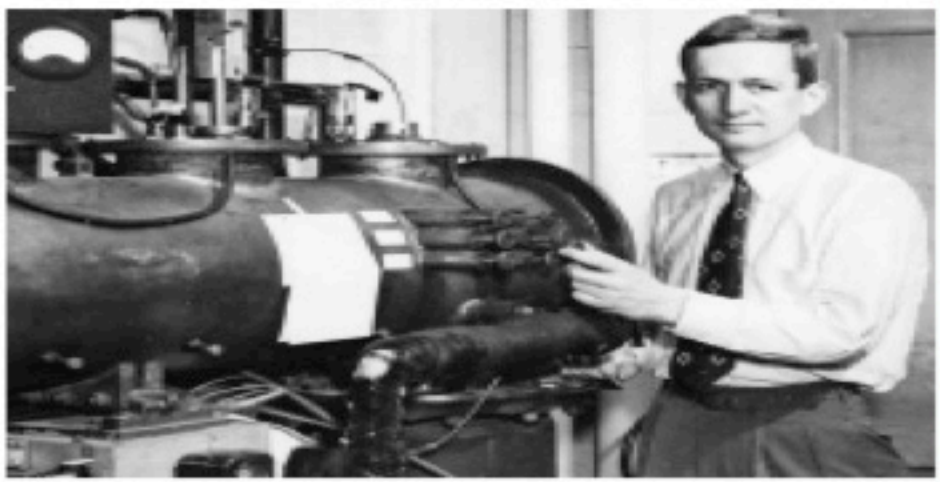
BROOKHAVEN NATIONAL LABORATORY

Clockwise:

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

Courtesy AIP Emilio Segrè Visual Archives (full credits overleaf)





Dirac-Schwinger Connections

The Dirac Equation (1928)

90th Anniversary

Unified

QM+Special Rel.+Spin+EM 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: $\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}I$

g_e=2 Success & ***Antimatter Predicted!***

Foundation of Quantum Electrodynamics

Post WWII Physics Boom (1947-48)

Julian Schwinger Master of QED

1947 Small Anomalous Atomic Fine Structure Effects

1948 Schwinger Calculates: $a_e=(g_e-2)/2=\alpha/2\pi\approx\underline{0.00116}$

($\alpha=e^2/4\pi=1/137$)

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

$a_e^{exp}\approx\underline{0.00119(5)}$

Triumph of Quantum Field Theory

Precision Quantum Electrodynamics (QED)

Mount Auburn Cemetery

Courtesy Lee Roberts

Fine Structure Constant α=1/137

1931 Dirac introduces magnetic monopoles

Finds ***$eM/4\pi = n/2$*** n=1,2··· ***charge quantization!***

$M^2/4\pi = 137/4 \approx 34$ strong magnetic coupling

Failed to derive α=1/137 Goal!

1957 SO(3) EW Unification Schwinger-(Georgi-Glashow 1972)

1965 Schwinger revisits magnetic monopoles & dyons

$eM/4\pi = n$ n=1,2···

1974 ‘t Hooft−Polyakov SO(3) Magnetic Monopole Soliton

1975 B. Price Monopole Candidate = Schwinger Charge!

“***Monopole Candidate Retracted***”

Alpha, Grand Unification & Monopoles

M. Goldhaber &WJM (1987)

in "Reminiscences about a great physicist"

Renormalization group invariant $e(\mu)M(\mu)/4\pi=3/8$

Duality/Unification scale $e(\mu_0)=M(\mu_0)$ **$\mu_0 \approx 10^{18}$GeV**

$\alpha^{-1}(\mu_0)=8/3$ vs $\alpha^{-1}(0)=137$ $\alpha_i^{-1}(\mu_0)=1$, $i=1,2,3$

Observed Change due to vacuum polarization by S=0, ½, 1 particles

$137=8/3+\Sigma c_i Q_i^2 \ln(\mu_0/m_i)+\cdots$ sum over all charged particles!

Example: Supersymmetric E_6 with 78 Gauge Fields and three generation relatively light matter 27plets

Anomalous Magnetic Moments After Schwinger

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

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 improvement Goal? See Gerry Gabrielse

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

$+1.181234016(\alpha/\pi)^3 -1.912245764(\alpha/\pi)^4$

$+6.675(192)(\alpha/\pi)^5$… +169(1)x$10^{-14}$(had) +3x$10^{-14}$(EW)

Aoyama, Kinoshita, & Nio 2018, Laporta 4 loop Analytic

Spectacular Achievements

Uncertainty ±1.3x10^{-14} (QED theory) ±1.2x10^{-14}(Hadronic)

New Alpha Measurement

$\alpha^{-1}(^{133}Cs)=137.035999046(27)$ **Parker et al. 2018**

earlier

$\alpha^{-1}(^{87}Rb)=137.035998995(85)$

$\alpha^{-1}(a_e)=137.035999149(33)_{exp}$

$\Delta a_e = a_e^{exp} - a_e^{SM} = -87(28)_{exp}(23)_{\alpha}(2)_{th} \times 10^{-14}$

(2.4σ) Very Large Effect! Expect O(6×10^{-14}) ~ $m_e^2/m_\mu^2 \Delta a_\mu$

Central Value ~ 30 x a_e(EW)

reconcile: Δa_e → **-5539**$(\alpha/\pi)^6$ **seems unlikely**

-13$(\alpha/\pi)^5$ **large part missing?**

experiments? Atomic Physics?

"new physics" eg light (pseudo)scalar?

Alpha determination using Rydberg Constant

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

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

α^{-1}(Cs)=137.035999046(27)

R. Parker et al. Science (2018) major improvement!

$\Delta a_e = a_e(\text{exp}) - a_e(\text{theory}) = -87(36) \times 10^{-14}$ Note Sign

Error Budget: $\pm 23 \times 10^{-14}$(alpha) $\pm 28 \times 10^{-14}$(exp.) $\pm 2 \times 10^{-14}$(th.)

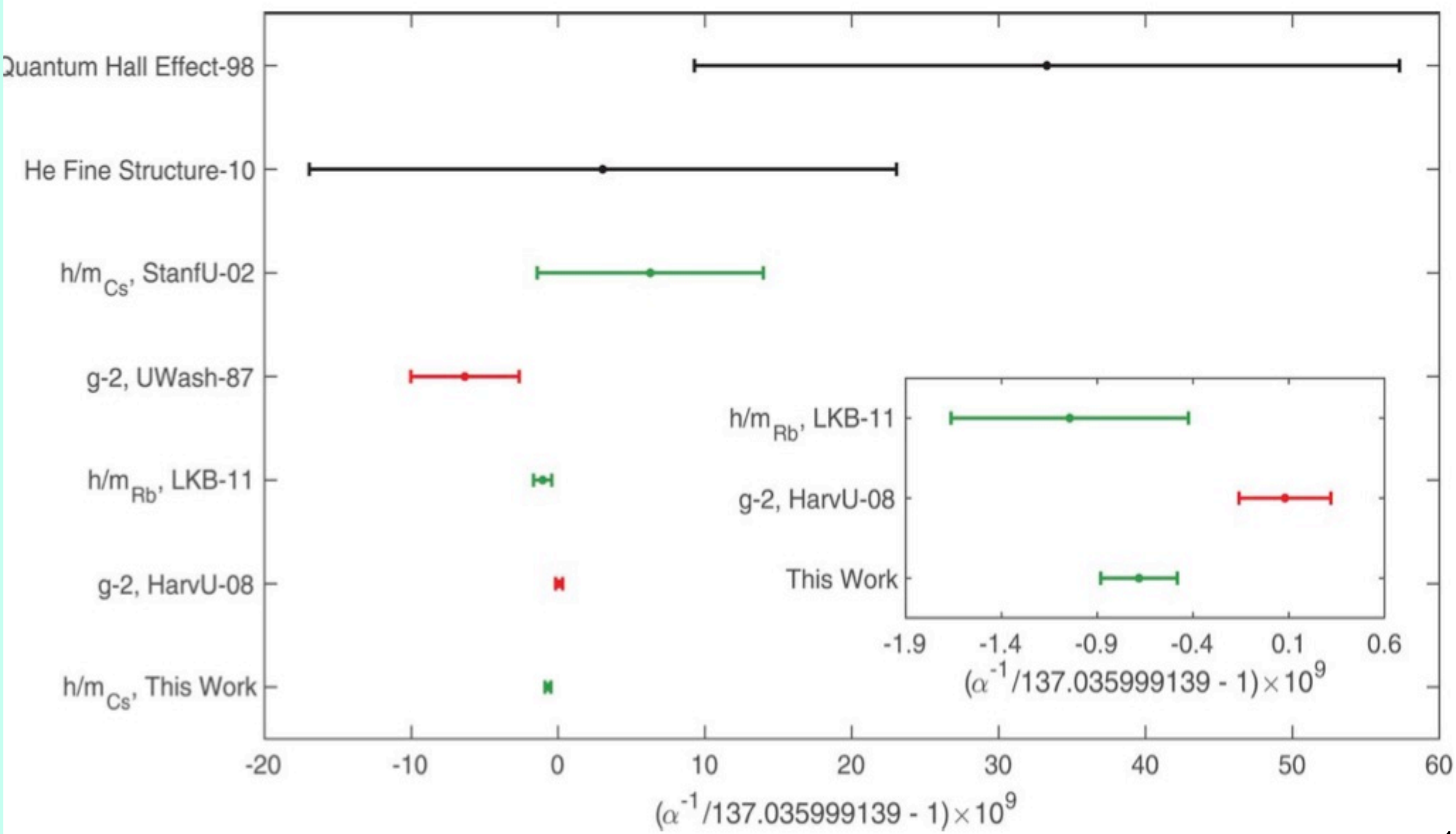
Ongoing Cs exp. Goals see H. Mueller

Future a_e(exp) Improvement see G. Gabrielse

Is Δa_e a harbinger of "New Physics"?

eg. Light Scalar loop effect see H. Davoudiasl

New Measurement of alpha:
From Parker et al. Science 2018
$\alpha^{-1}(^{133}Cs)$=137.035999046(27)



Muon Standard Model Prediction

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$ (quark/gluon loops)

QED Contributions:

- $a_\mu^{QED} = 0.5(\alpha/\pi) + 0.765857425(\alpha/\pi)^2 +$
  $24.05050996(\alpha/\pi)^3 +$
  $130.8796(\alpha/\pi)^4 +$
  $752.173(\alpha/\pi)^5 + \ldots$

2018 Update: Aoyama, Kinoshita, & Nio

$\alpha^{-1}(^{133}Cs) = 137.035999046(27)$ from h/m_{Cs}

$a_\mu^{QED} = \underline{116584718.92(3) \times 10^{-11}}$ Very Precise!

Electroweak Loop Effects

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

a_μ^{EW}(2 loop)=$-41.2(1.0)\times10^{-11}$ (Higgs Mass = 125GeV))

Approx.~1780 diagrams

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

- ***a_μ^{EW}=$154(1)\times10^{-11}$ Non Controversial? See A. Czarnecki***

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

$a_\mu^{Had}(V.P.)^{LO}=6923(37)\times10^{-11}$

$a_\mu^{Had}(V.P.)^{NLO+NNLO} = -86(1)\times10^{-11}$

$a_\mu^{Had}(LBL) = 105(26)\times10^{-11}$ (Consensus?) 3 loop $(\alpha/\pi)^3$ QCD

a_μ^{SM}=$116591815(37)\times10^{-11}$ (Future Improvement?)

Goal: Factor 2 Reduction

see many Following Speakers

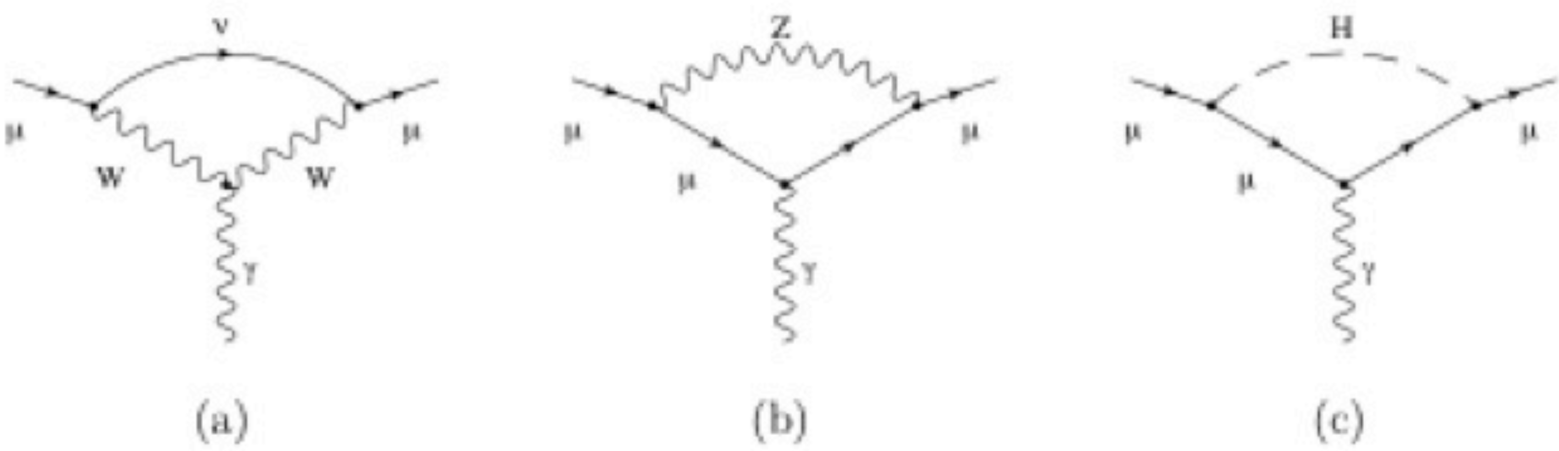


Figure 2: One-loop electroweak radiative corrections to a_μ.

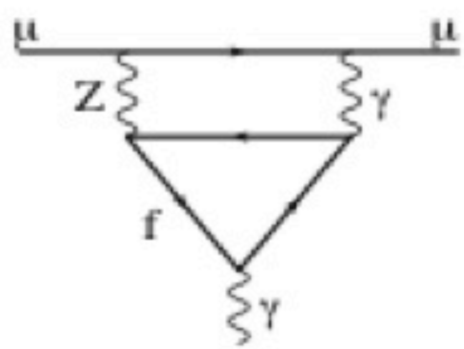


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to $a_\mu^{\rm EW}$.

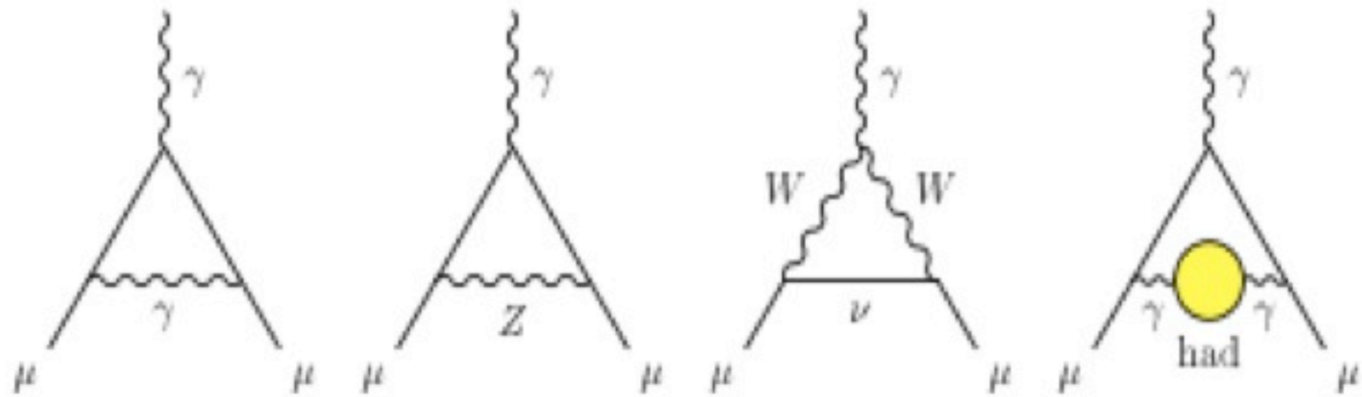


Figure 1: Representative diagrams contributing to $a_\mu^{\rm SM}$. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

Experimental E821 at BNL (2004 Final)

$a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592091(54)_{stat}(33)_{sys}$

$= \underline{116592091(63)\times 10}^{-11}$

Future factor of 4 improvement expected

see Lee Roberts

Muon Discrepancy

$\boldsymbol{\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 274(63)_{exp}(37)_{theory} \times 10^{-11}}$ **(*3.7σ!*)**

(***Hadronic effects?, Experiment? or New Physics?***)

Lattice QCD comes of Age: HVP & LBL

Goal: Factor of 2 Further Improvement

Comparison of Experiment and Theory

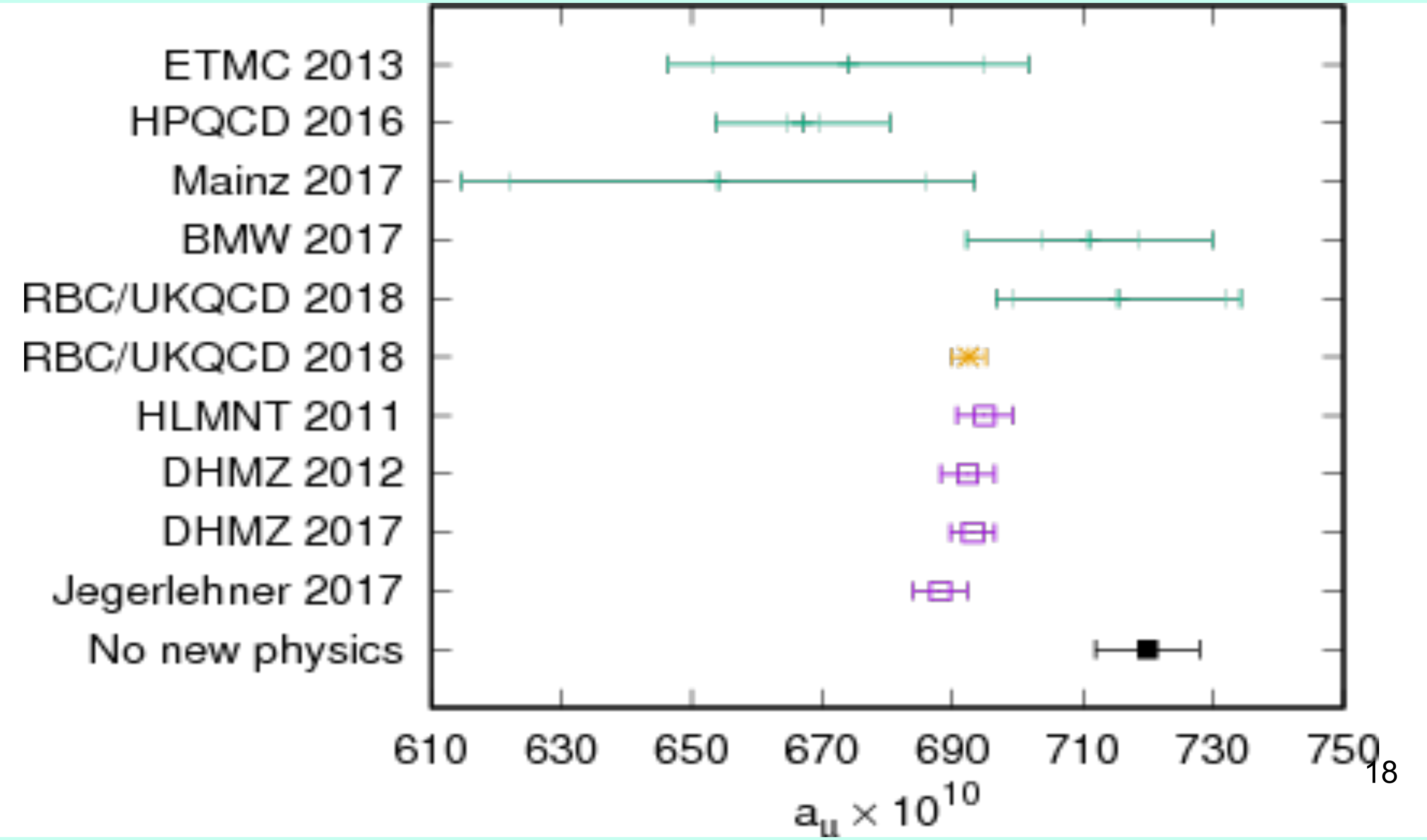
- $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 274(63)(37) \times 10^{-11}$ (*3.7σ!*) **see C. Lehner Talk**

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?

"New Physics" Scale Implied $< m_\mu / |\Delta a_\mu|^{1/2} < O(\text{TeV})$ LHC?

From Blum et al. PRL 2018
Green = Pure Lattice QCD
Purple= e^+e^- data
Gold =Mixed LQCD & e^+e^- data



Some g_μ-2 *"New Physics"* Scenarios

see talks by D. Stockinger & H. Davoudiasl

i) Supersymmetry - LHC Tension?

****ii) 2 Higgs Doublet Models (new favorite)***

Relatively Light (Pseudo)Scalar (2 loop g_μ-2)

$10GeV<m_A<25GeV$ $30< \tan\beta=v_2/v_1<80$

iii) "Light" Dark Photon

iv) Light Scalar O(0.25-few GeV)

Other

Many Other Scenarios

$L_\mu - L_\tau$, B-L etc. gauged...

Leptoquarks & B anomalies

Dynamical Mass Generation

$\Delta a_\mu = m_\mu^2/M^2$ ***M ≤ 1TeV!*** ***Observable!***

etc.

Challenge: Find dual solution to Δa_μ & Δa_e?

Davoudiasl & WJM 1 & 2 loop scalar effects

Liu, Wagner & Wang Complex Scalar

Other?

"Light" Higgs

CHEN, DAVOUDIASL, MARCIANO, ZHANG (2016)
Batell, Lange, McKeen, Pospelov, Ritz (2016)

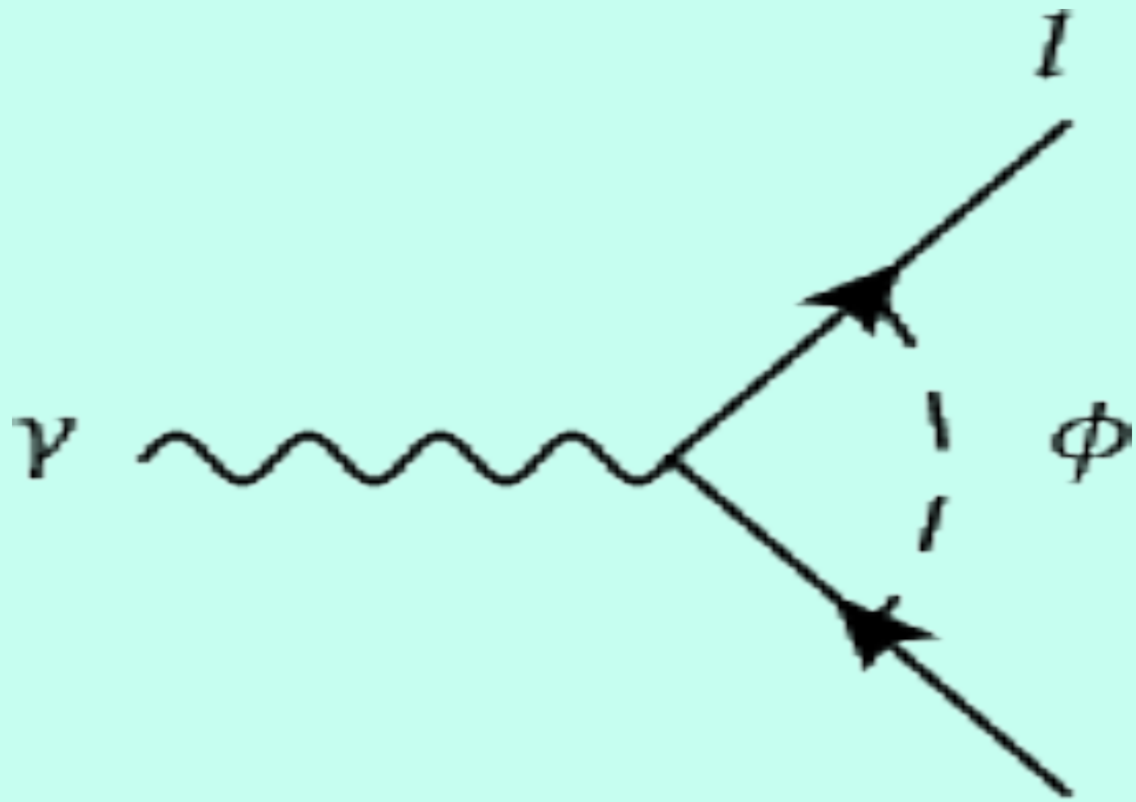
Light scalar ϕ~O(GeV) possible remnant of $U(1)_d$ breaking
Coupling to μ+μ- ~ 10^{-3} solves g_μ-2 discrepancy
Why such a relatively large coupling (Higgs size)?

Misalignment (Mass & Hμμ) due to several sources of μ mass!
SM Higgs + Heavy charged lepton mixing effects + …
or Multi-Higgs Mixing (2 doublets + singlet)

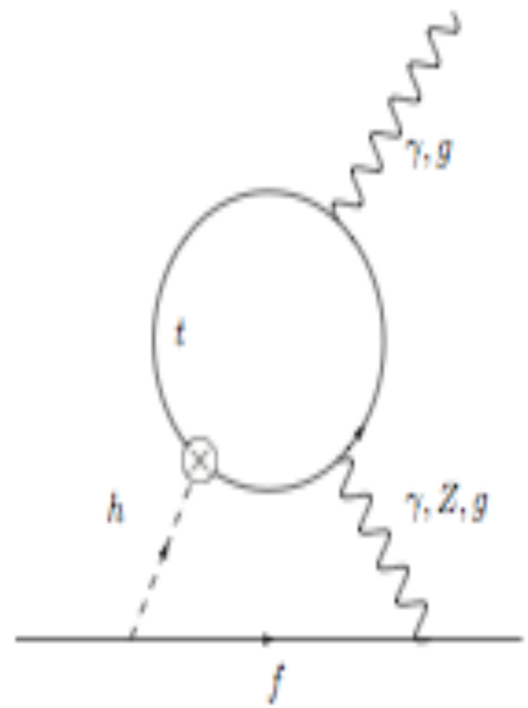
Signatures: tau decays + ϕ ➔ $\mu^+\mu^-$ or e^+e^- BR < 10^{-6}
e+e- ➔ $\tau^+\tau^-$ + ϕ ➔ $\mu^+\mu^-$ or e^+e^- (see Batell et al.)

One Loop Dark Higgs (m_Φ<1GeV) Contribution to Dipole Moments

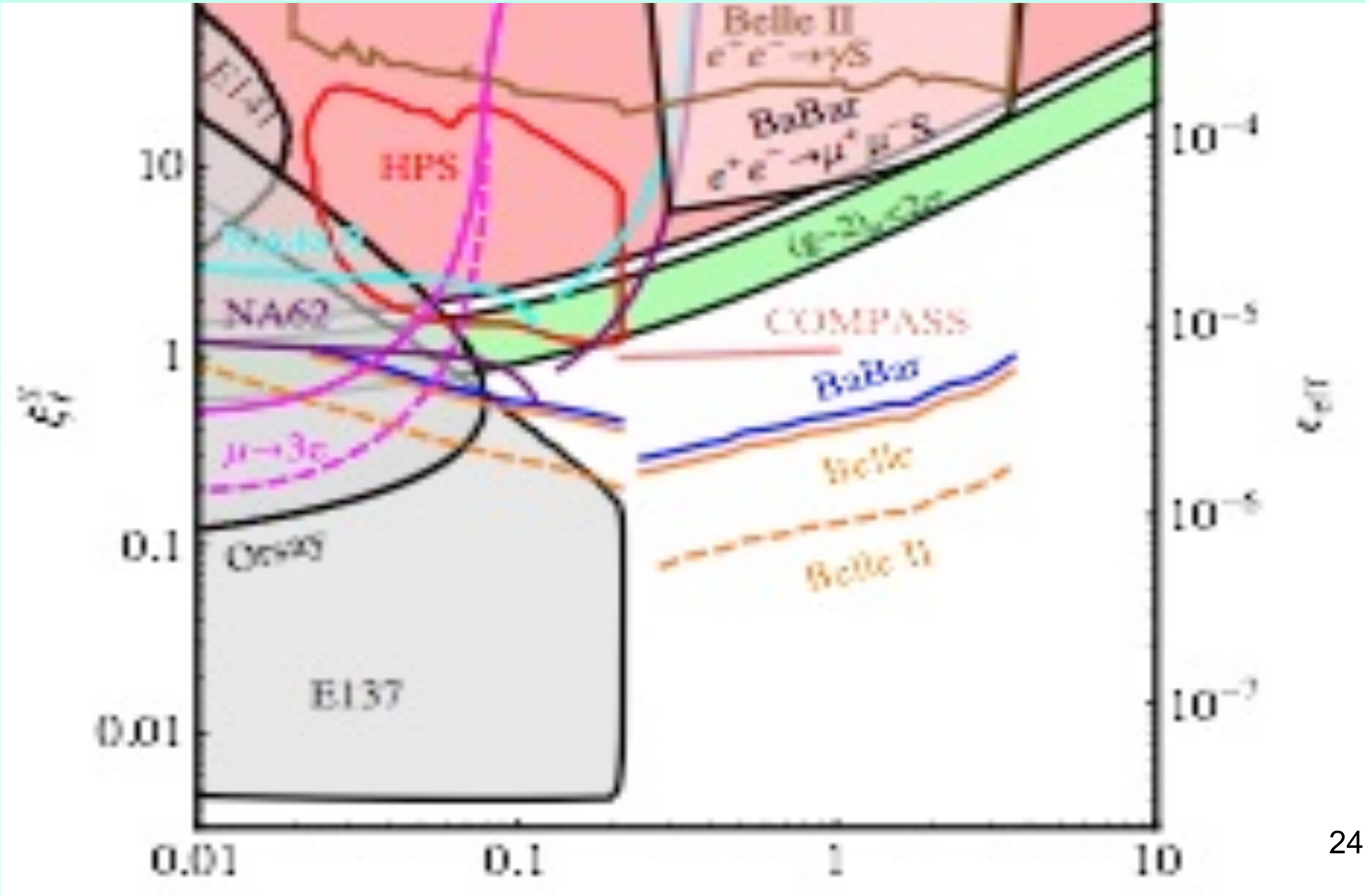
Scalar Φ (0^{++}) solves Δa_μ discrepancy for Φμμ coupling ~ 10^{-3}



Two Loop Higgs Contribution to fermion Dipole Moments
Barr-Zee Diagrams



From Batell et al. (2016)
Constraints on Sμμ coupling and allowed muon g-2 band
Possible future bounds



Outlook

Precision a_e, alpha and a_μ test SM and Probe "New Physics"

currently

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 274(63)(37) \times 10^{-11}$ (3.7σ)

$\Delta a_e = a_e^{exp} - a_e^{SM} = -87(36) \times 10^{-14}$ *(Note Sign) (2.4*σ)

$\alpha^{-1}(^{133}Cs) = 137.035999046(27)$

All should be pushed as far as possible

Crucial Improvements: Hadronic Corrections to g_μ-2

Lattice + DR + e^+e^- data

a_e^{exp}

α exp (theory corrections?)

a_μ^{exp} FNAL Results 2019

Continuing the Legacy of Schwinger