Lepton Dipole Moments Theoretical Perspective

&

(Tau Connection)

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Outline

1. ***Introduction***
2. ***Anomalous Magnetic Moments: Status***

i) Electron (5 loops!) (4 loops known functions! ***Laporta)***

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

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

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

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

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

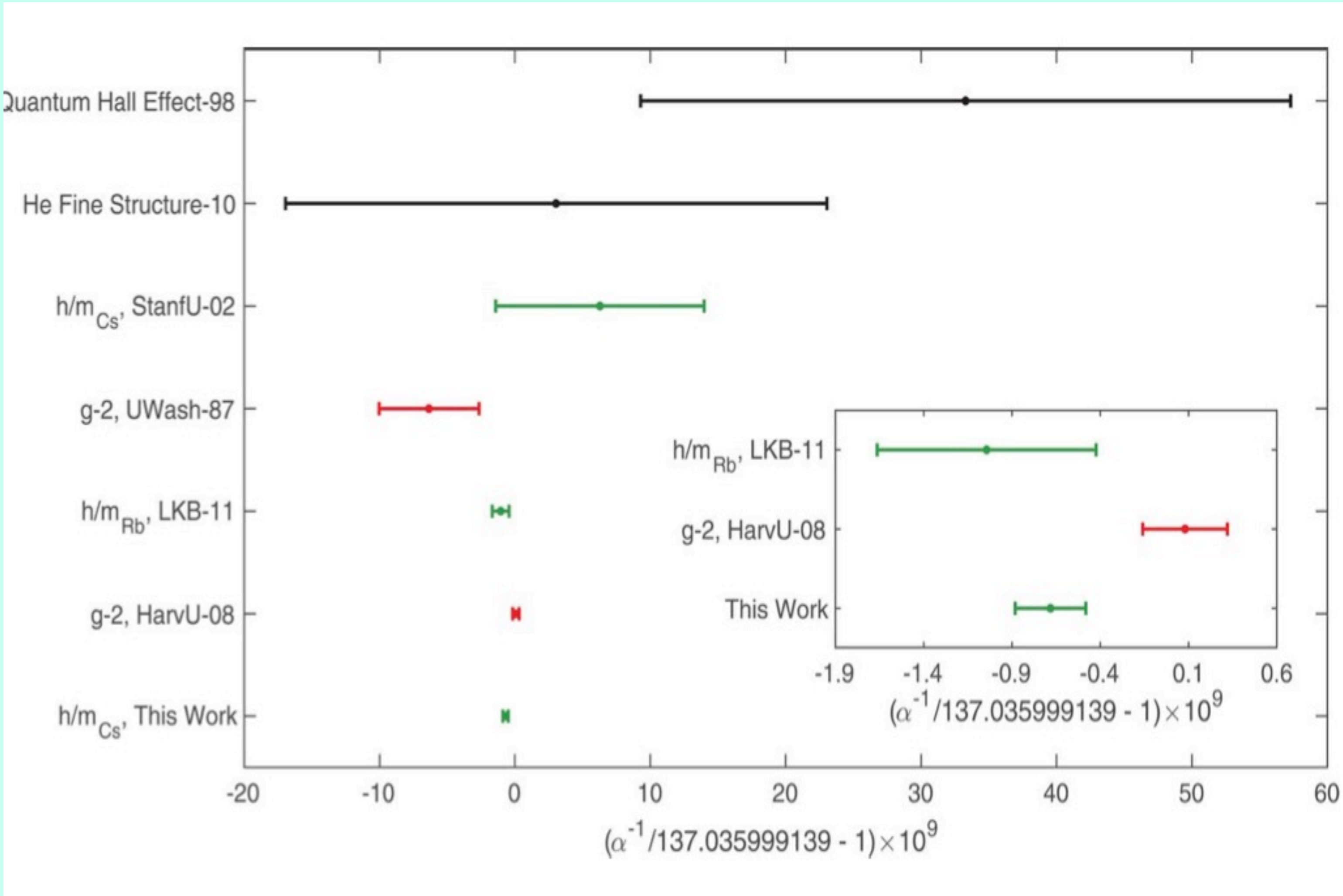
ii) Muon Discrepancy

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

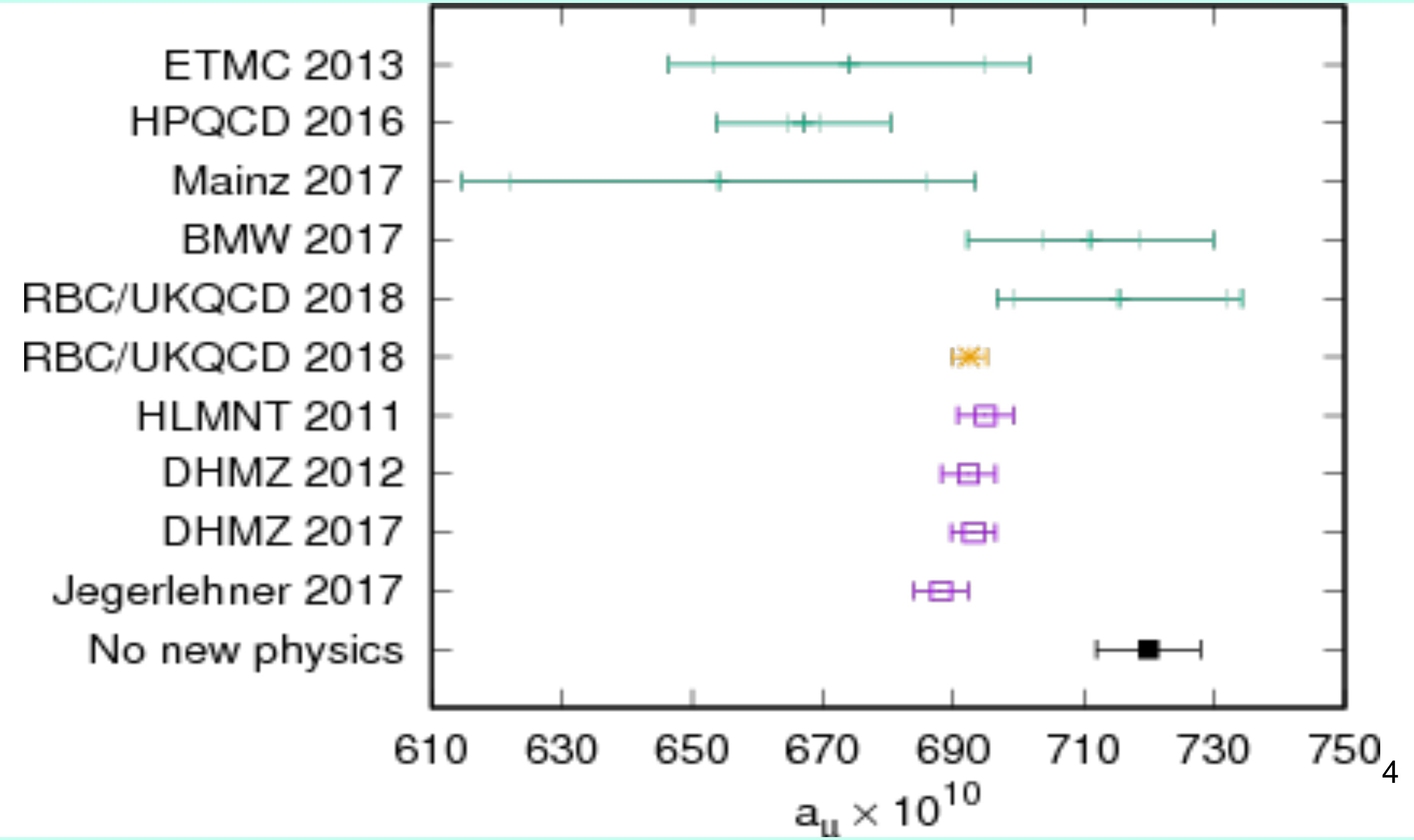
(***Hadronic effects?, Experiment? or New Physics?***)

Lattice QCD comes of Age: HVP & LBL

New Measurement of alpha: From Parker et al. Science 2018



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



<u>Electroweak 2 Loop Corrections: Lessons Learned</u>

***3*. Some g_μ-2 "*<u>New Physics</u>*" Scenarios**

<u>i) Supersymmetry</u> - LHC Tension?

****ii) <u>2 Higgs Doublet Models (</u>new favorite)***

<u>Relatively Light (Pseudo)Scalar</u> (2 loop g-2)

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

D. Chang et al. (2001), K. Cheung et al.(2001),⋯

L. Wang et al. (2018), S. Dutta et al.(2018) ⋯

iii) "<u>Light" Dark Photon</u>

iv) <u>Light Scalar O(0.25-few GeV)</u>

Giudice et al (2012), Chen et al (2016), <u>Batell et al (2016)</u>⋯

Implications For Tau Physics

e^+e^-, $\mu^+\mu^-$ Bump Hunting in tau decay or production

Many Other Scenarios

$L_\mu - L_\tau$, B-L etc. gauged…

Leptoquarks & B anomalies

Dynamical Mass Generation

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

etc.

Challenge: **Dual solution to Δa_μ & Δa_e?**

see Davoudiasl & WJM (2018) 1 & 2 loop effects

The Genius of Dirac

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!

Post WWII Physics Boom (1947-48)

Dirac Eq. Predicted: g_e=2 Exactly?

1947 Small Anomalous Atomic Fine Structure Effects

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

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

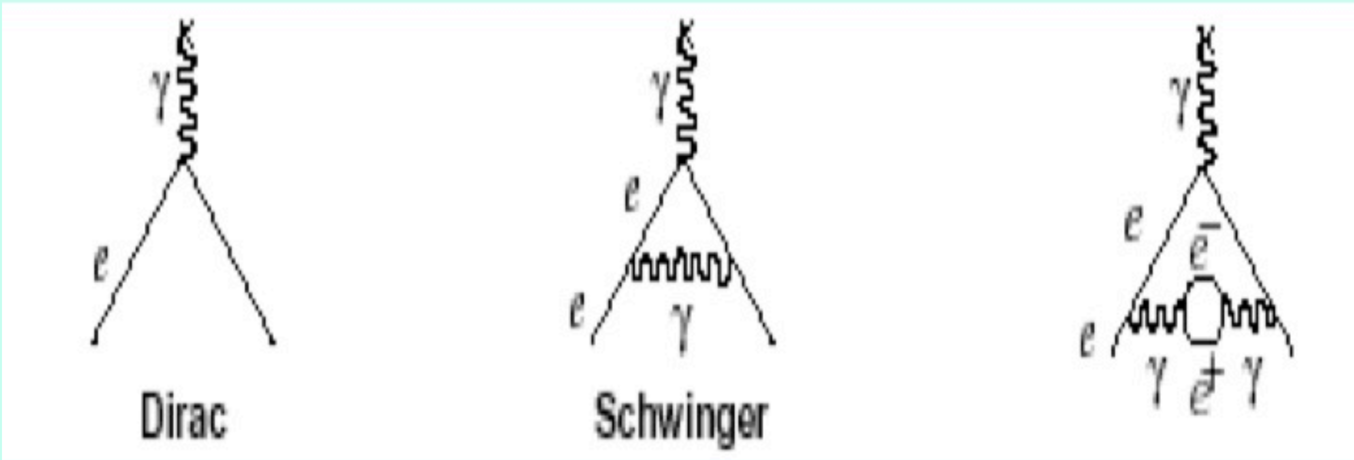
Agreed with measurement of Kusch & Foley**!**

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

Great Success of QED-Quantum Field Theory

2018 Schwinger Centennial Year

<u>Some Anomalous Magnetic Moment Contributions</u>



2. 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: factor ≥ 4 improvement? Good Goal

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

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

$$+6.675(192)(\alpha/\pi)^5\ldots+1.69(1)\times10^{-12}(\mathrm{had})+0.03\times10^{-12}(\mathrm{EW})$$

Aoyama, Kinoshita, & Nio 2017 Update!

Spectacular Achievement

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

Alpha determination using Rydberg Constant

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

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

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. Goal - additional factor of 10 improvement!

Δa_e 3.5 sigma Sensitivity

Further Improvement? New Experiment (4 x better a_e)

Is it a harbinger of "New Physics"?

H. Davoudiasl & WJM (2018) − Light Scalar

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)**
- $a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592091(54)_{stat}(33)_{sys}$
- $= 116592091(63)\times 10^{-11}$

Factor of 14 improvement over CERN results (statistics)

(Goal: Factor 4 further Improvemt at FNAL) **$\pm 16\times 10^{-11}$**

New JPARC low energy experiment

Standard Model Prediction

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

QED Contributions:

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

2017 Update: Aoyama, Kinoshita, & Nio

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

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

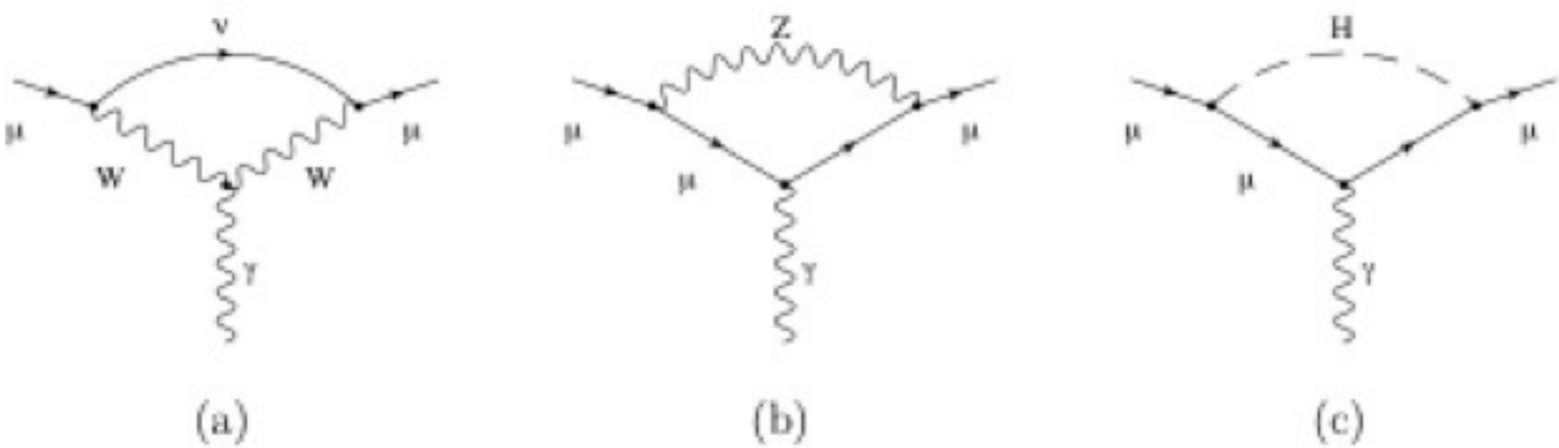


Figure 2: One-loop electroweak radiative corrections to a_μ.

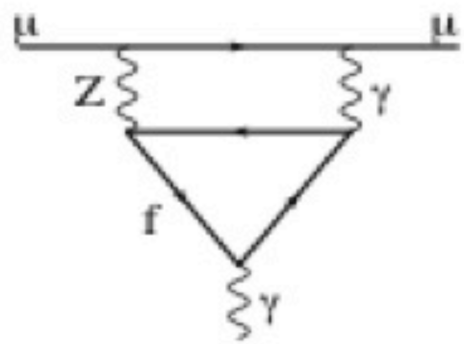


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to a_μ^{EW}.

2.) **Early EW Radiative Corrections**

Muon Anomalous Magnetic Moment: $a_\mu^{EW}=\Delta(g_\mu-2)/2$

Jackiw & Weinberg (1972) Bars & Yoshimura (1972)

Altarelli, Cabibbo & Maiani (1972) Fujikawa, Lee & Sanda (1972)

Bardeen, Gastmans & Lautrup (1972)

Finite because $g_W=2$ three 1 loop diagrams W, Z & H

$a_\mu^{EW}(1\text{ loop})=5G_F m_\mu^2/24(2^{½})\pi^2[1+1/5(1-4\sin^2\theta_W)+O(m_\mu^2/M^2)]=1\underline{95\times10}^{-11}$

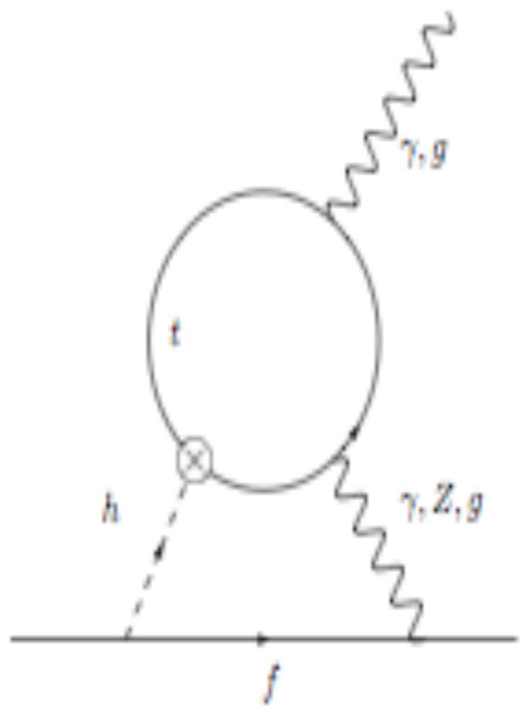
non-linear gauge, Dimensional, Regularization renormalization 1678

2 loops (Czarnecki, Krause, WJM 1995) -20% reduction to 154×10^{-11}

Currently: $\mathbf{\Delta a_\mu=a_\mu^{exp}-a_\mu^{SM}=276(73)\times10^{-11}}$ **(*3.7σ*) deviation**

New Problem: $\mathbf{a_e^{exp}-a_e^{SM}=-87(36)\times10^{-14}}$ **(2.4*σ*) *deviation***

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



Electroweak Loop Effects

a_μ^{EW}(1 loop)=$194.8\mathrm{x}10^{-11}$ original goal of E821

a_μ^{EW}(2 loop)=$-41.2(1.0)\mathrm{x}10^{-11}$ (Higgs Mass = 125GeV))

Higgs 2 Loop ~ $3\mathrm{x}10^{-11}$

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

- ***$a_\mu^{EW}=154(1)\mathrm{x}10^{-11}$ Non Controversial***

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

$a_\mu^{Had}(V.P.)^{LO}=6923(37)\mathrm{x}10^{-11}$

$a_\mu^{Had}(V.P.)^{NLO+NNLO} = -86(1)\mathrm{x}10^{-11}$

$a_\mu^{Had}(LBL) = 105(26)\mathrm{x}10^{-11}$ (Consensus?) 3 loop $(\alpha/\pi)^3$ QCD

$a_\mu^{SM}=116591815(37)\mathrm{x}10^{-11}$ (Future Improvement?)

$\Delta a_\mu=a_\mu^{exp}-a_\mu^{SM}=274(63)(37)\mathrm{x}10^{-11}$ (*3.7σ deviation!*)

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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 ***154x10^{-11}***

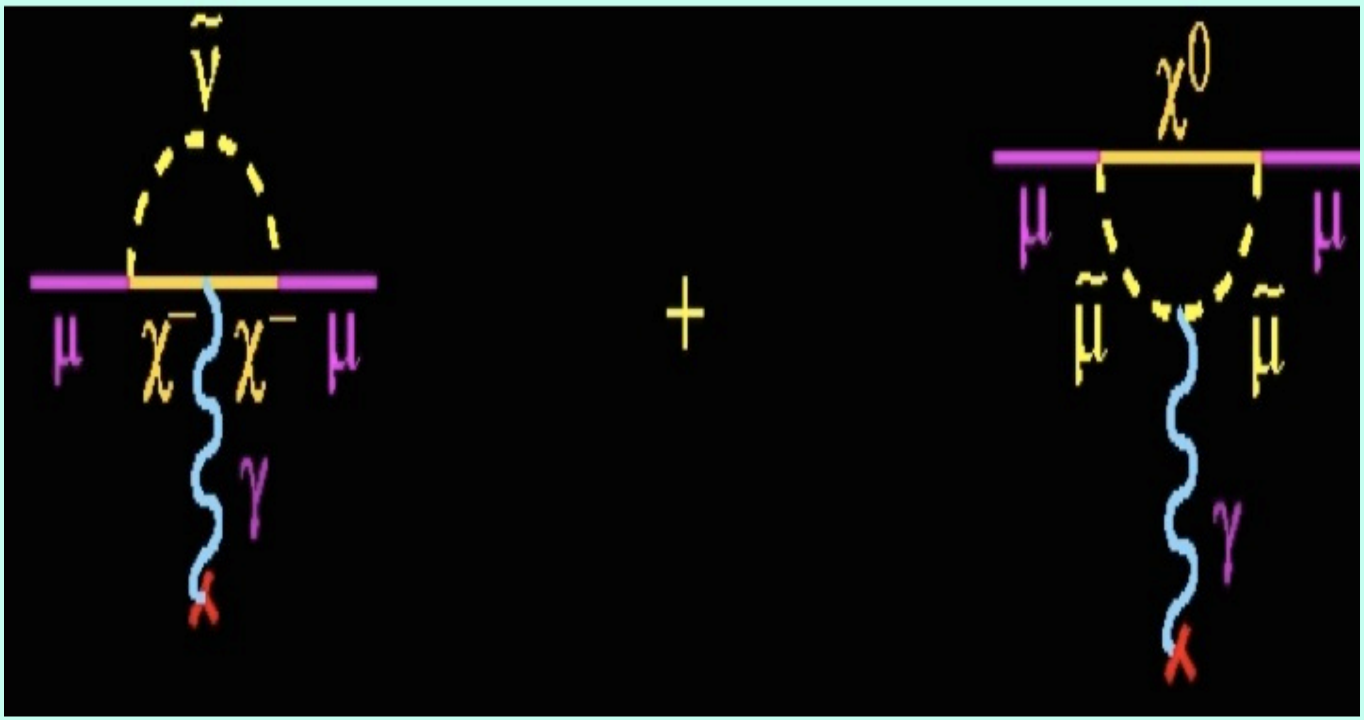
New Physics Nearly 2x Electroweak?
Why don't we see it in other measurements?

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

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 candidate!
- spin 0 sneutrinos and sleptons with ***<u>mixing!</u>***

  (light stau may dominate)

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

Interpretations

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 274(73) \times 10^{-11} \ (3.7\sigma!)$$

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

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

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

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

Lattice Gauge Theory Efforts!

Multi-Higgs Models (2 loop effects) light A

New Dynamics<1-2TeV

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

Light Higgs Like Scalar O(1GeV)

etc.

The Dark Boson – A Portal to Dark Matter

- What if some $U(1)_d$ gauge symmetry from the Dark or some Other Sector contains a "Light" *Dark Photon* (γ_d), *U Boson, Hidden Boson… Dark Z* (Z_d)

Introduced for: 1) Sommerfeld Enhancement $D+D \rightarrow Z_d+Z_d$

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

3) Cosmic Dark Matter Stability via global $U(1)_d$

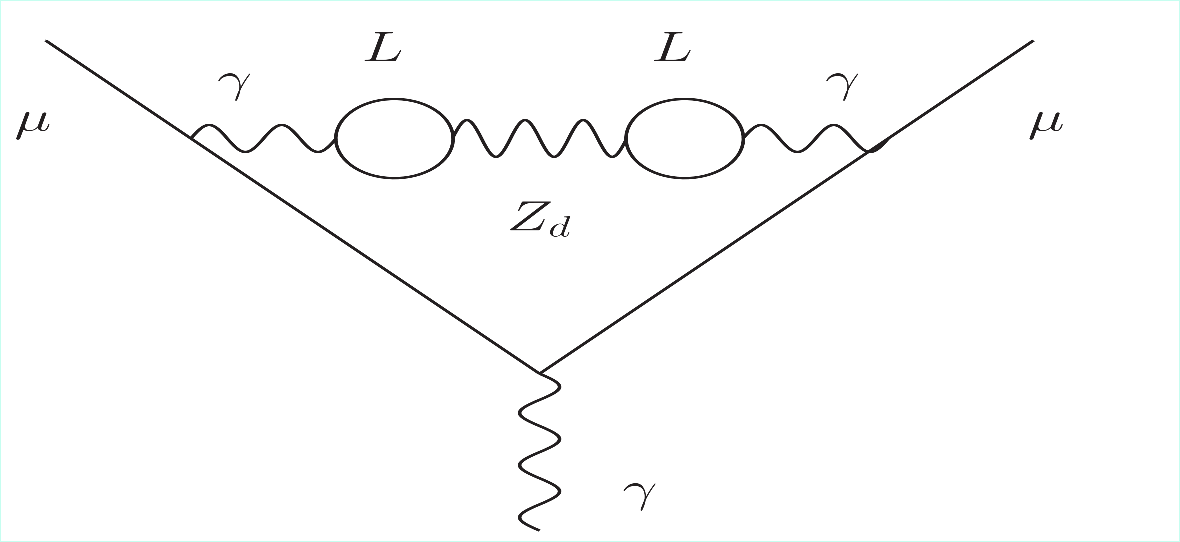
*4) Light Dark Matter Abundance

*5) *Muon Anomalous Magnetic Moment*

Can we find direct evidence for such a light boson in the laboratory?

Effective 3 loop g_μ-2 Dark Photon Diagram

$a_\mu^{Zd} = \alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g_μ-2 discrepancy for $\varepsilon^2 \approx 3\text{-}5\times10^{-6}$ & $m_{Zd} \approx 20\text{-}200$MeV (see figure)

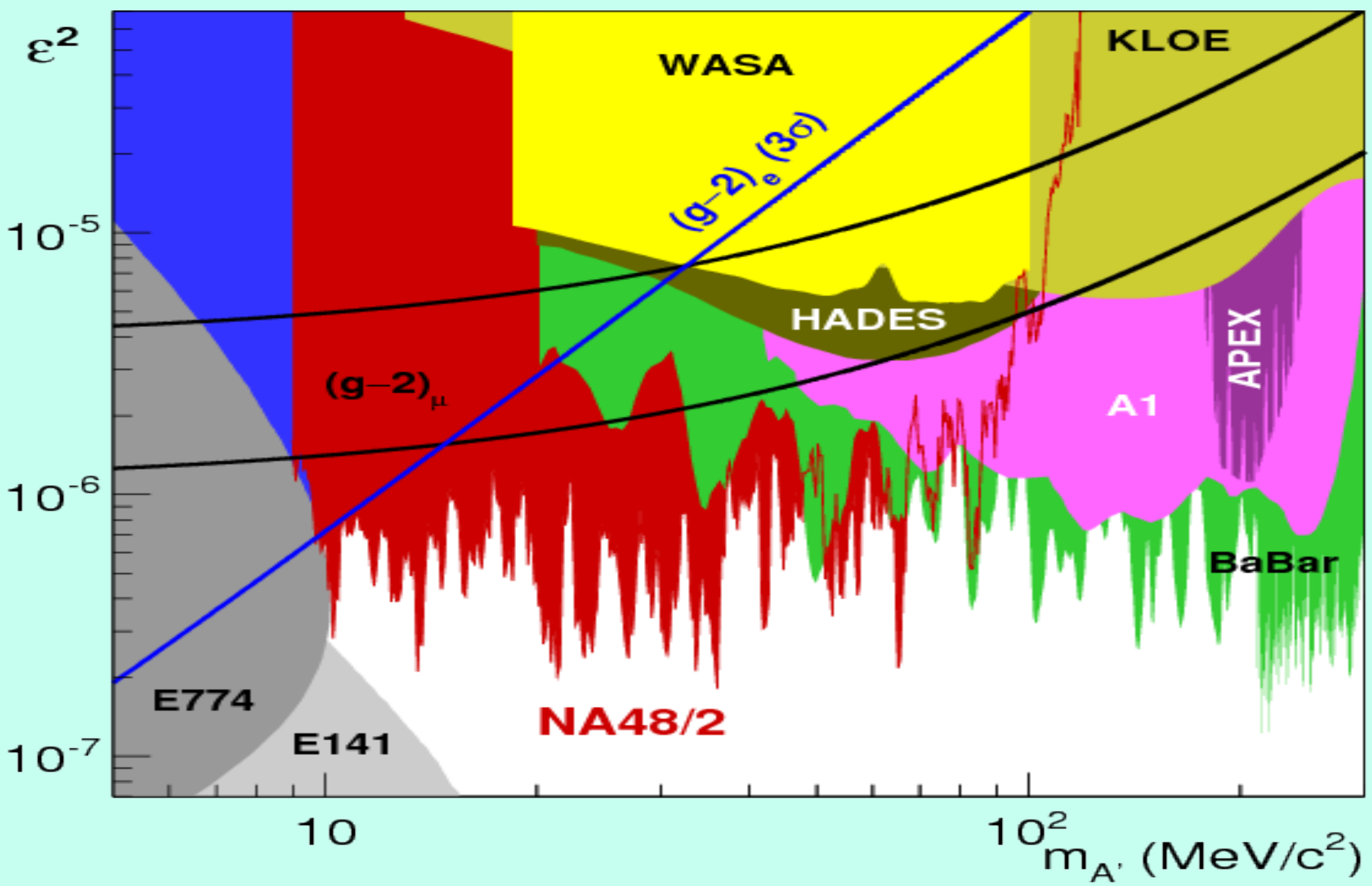


NA48/2 Updated Bounds on Dark Photon

Simple **g_μ-2 discrepancy solution ruled out**

Assumes BR($\gamma_d \rightarrow$ e+e-) ~1

Alternative $\gamma_d \rightarrow$ light dark matter



"Light" Higgs

CHEN, DAVOUDIASL, MARCIANO, ZHANG (2016)

Batell, Lange, McKeen, Pospelov, Ritz (2016)

Light scalar $\phi \sim O(\mathrm{GeV})$ possible remnant of $U(1)_d$ breaking

Coupling to $\mu+\mu- \sim 10^{-3}$ 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 + …

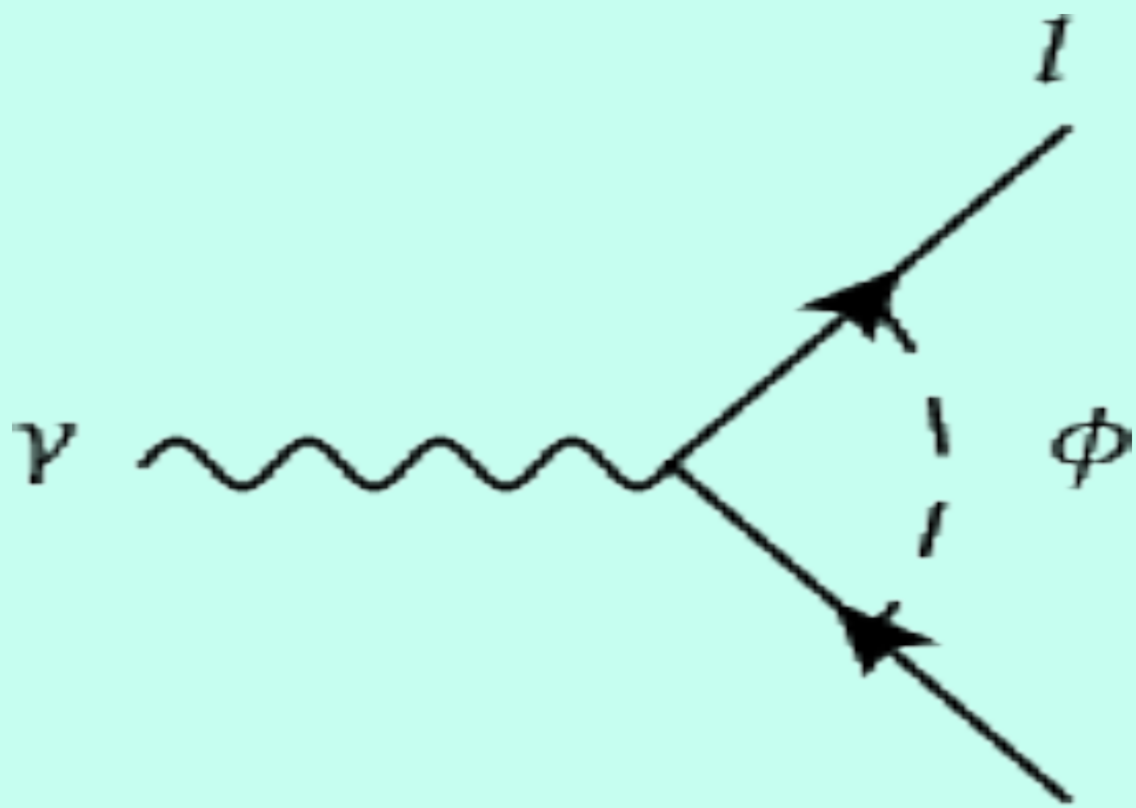
or Multi-Higgs Mixing (2 doublets + singlet)

Signatures: tau decays + $\phi \rightarrow \mu^+\mu^-$ or e^+e^- BR < 10^{-6}

$e+e- \rightarrow \tau^+\tau^- + \phi \rightarrow \mu^+\mu^-$ 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}



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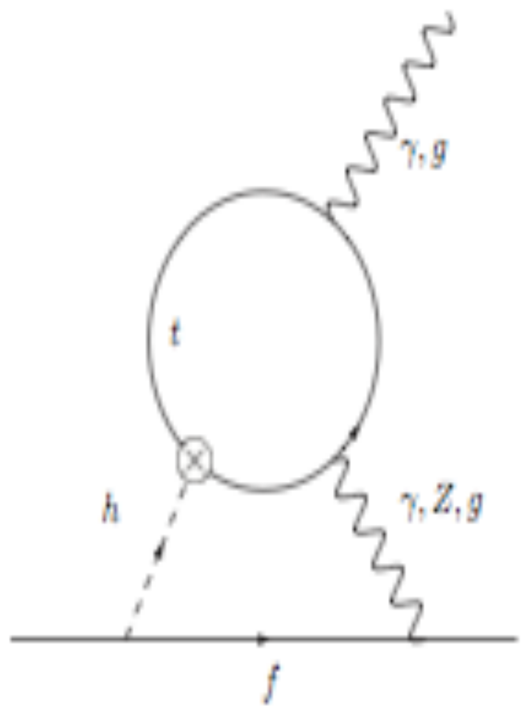


Vector-like Heavy Leptons Dark Variant
Davoudiasl, Lee &WJM

- 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

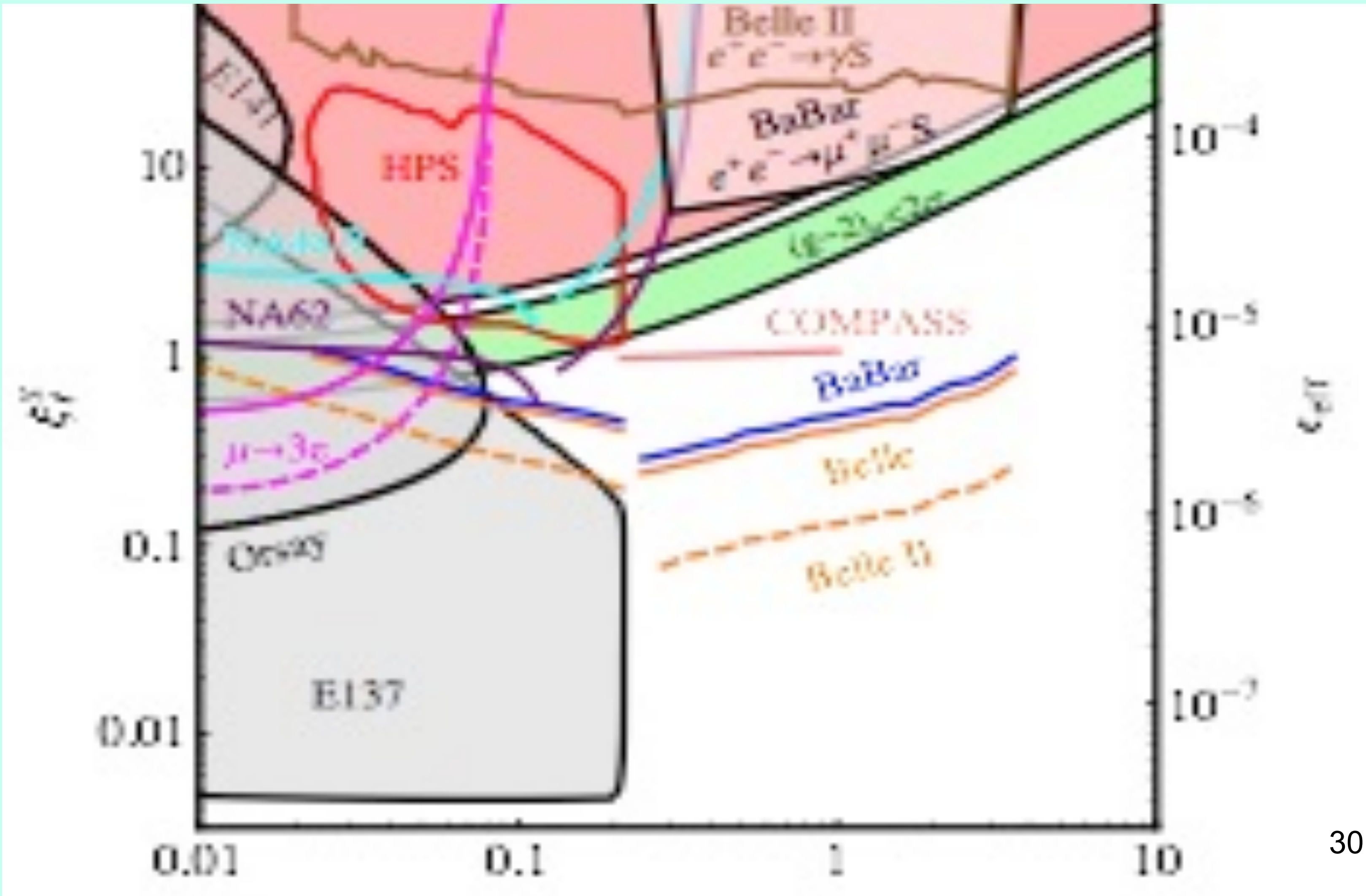
Gauge Invariant Mass Terms + Higgs Couplings ➔ Mixing

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

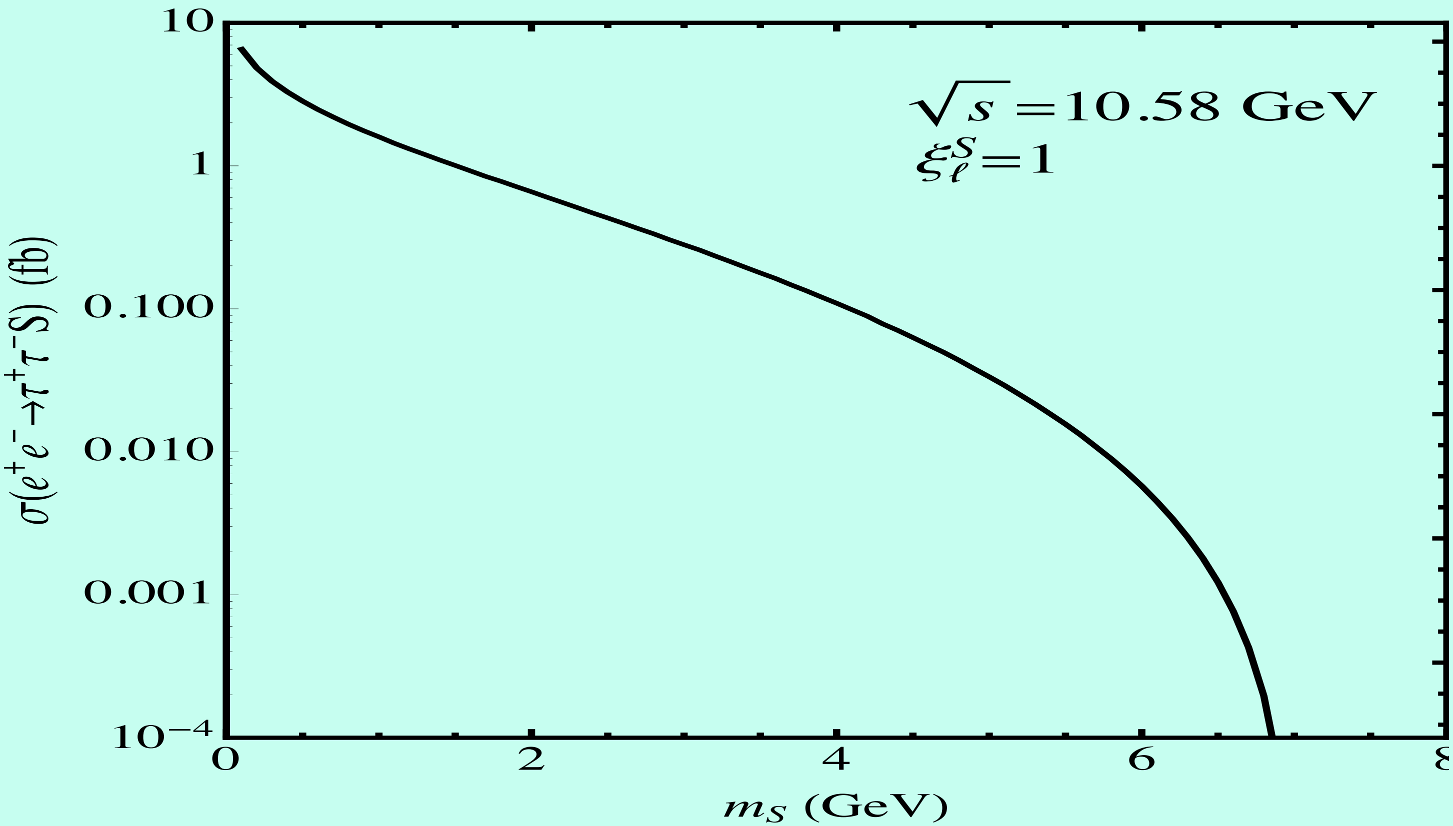
4 Charged & 3 Neutral Leptons Unstable

Lightest Neutral: Potential Stable Dark Matter?

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



Cross section for $e^+e^- \rightarrow \tau^+ + \tau^- + S \rightarrow \mu^+\mu^-$ in fb from Batell et al. (2016)



. 3. Production rate for S in association with taus
ories, as a function of m_S. The cross section is pr
al to $(\xi_\ell^S)^2$, and we have set $\xi_\ell^S = 1$.

Outlook

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

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

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

Both a_e and a_μ should be pushed as far as possible

New Physics may be Tau Dominated

Tentative single scalar solution: 1 loop ➔ Δa_μ

2 loop ➔ Δa_e

Requires large Yukawa & 2 photon couplings

Look for e^+e^- ➔ tau^+tau^- + ϕ ➔ $\mu^+\mu^-$ or e^+e^- (Batell et al)

& bumps in tau ➔ $e\nu\nu + l^+l^-$

Push edm searches & rare mu & tau decays