The Muon Anomaly and Dark Parity Violation

Based on H. Davoudiasl, H-S Lee &WJM

William J. Marciano

(October 17, 2012)

BROOKHAVEN NATIONAL LABORATORY

Outline

*1. ***Anomalous Magnetic Moments*** $a_l \equiv (g_l-2)/2$, $l=e,\mu$

$\Delta a_e = a_e^{exp} - a_e^{SM} = -106(82)\times10^{-14}$ (Recent Update)

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80)\times10^{-11}$ (*3.6σ discrepancy!*)

2. ***The Dark Photon Solution*** Kinetic Mixing

$\varepsilon e Z_d^\mu J_\mu^{em}$ 20MeV<m_{Zd}<100MeV , *$2\times10^{-6}<\varepsilon^2<10^{-4}$*

*3. ***Z-Z_d mass mixing*** **$\varepsilon_Z = m_{Zd}/m_Z\delta \rightarrow \varepsilon_Z g/2\cos\theta_W Z_d^\mu J_\mu^{NC}$**

4. ***Atomic Parity Violation & Polarized Electron Scattering***

(JLAB & MESA initiatives) A_{LR}(ee, ep, eC?)

5. ***Rare K, B, μ, τ Decays*** *$K\rightarrow\pi Z_d$ $B\rightarrow KZ_d$ $\mu\rightarrow eZ_d$ $\tau\rightarrow\mu Z_d$*

Higgs Decays: *$H\rightarrow\gamma Z_d$ $H\rightarrow Z_dZ_d$ $H\rightarrow ZZ_d$ $Z_d\rightarrow e^+e^-$*

1. Anomalous Magnetic Moments

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

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

(Hanneke, Fogwell, Gabrielse: PRL 2008)

$a_e(SM)=\alpha/2\pi-0.328478965579193\ldots(\alpha/\pi)^2$

$+1.181241456\ldots(\alpha/\pi)^3-1.9097(20)(\alpha/\pi)^4$

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

Aoyama, Hayakawa, Kinoshita, & Nio 2012 Update

$\alpha^{-1}(^{87}Rb)=137.035999037(91)$

Bouchendira et al. PRL. (2011)

$a_e(exp)-a_e(theory)=-1.06\ (0.82)\times10^{-12}$

Overall Factor 10 Sensitivity Improvement!

Further Improvement? Factor of 2? More?

Muon Anomalous Magnetic Moment

Experimental E821 at BNL (2004 Final)

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

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

Storage Ring being shipped to Fermilab

(Future Factor 4 Improvement Expected)

Standard Model Prediction

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

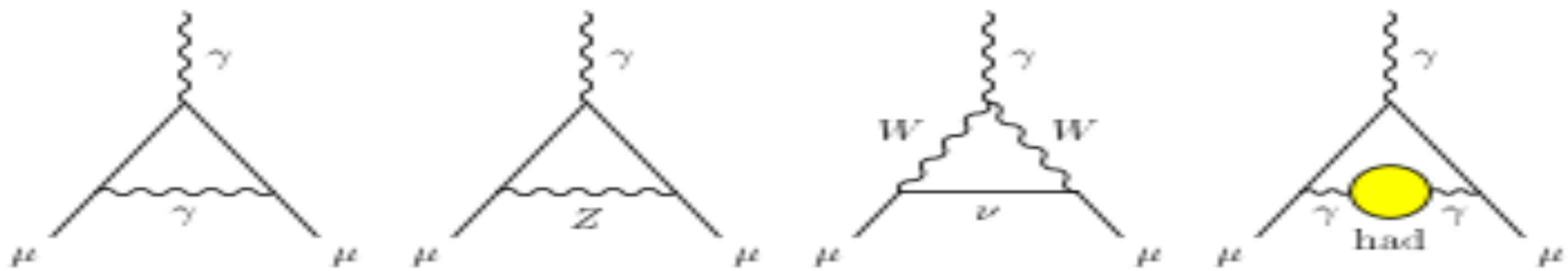


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-

QED Contributions:

- $a_\mu^{QED} = 0.5(\alpha/\pi) + 0.765857410(27)(\alpha/\pi)^2 +$
  $24.05050964(43)(\alpha/\pi)^3 +$
  $130.8794(63)(\alpha/\pi)^4 +$
  $\mathbf{753.29(1.04)(\alpha/\pi)^5} + \ldots$ (5 loop Completed!)

2012 Update: Aoyama, Hayakawa, Kinoshita, & Nio

$\alpha^{-1}(^{87}Rb) = 137.035999037(91)$

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

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} (some Higgs Mass Dependence)

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?)

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

-

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

***This is a very large deviation*!**

$\Delta a_e = a_e^{exp} - a_e^{SM} = -106\ (82) \times 10^{-14}$ ***(Note Sign)***

(A thousand times better measured than Δa_μ!)

But the muon is $(m_\mu/m_e)^2 \cong 40{,}000$ times more sensitive to New SD Physics

Interpretations

***Generic 1 loop SUSY Contribution*:**

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

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

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

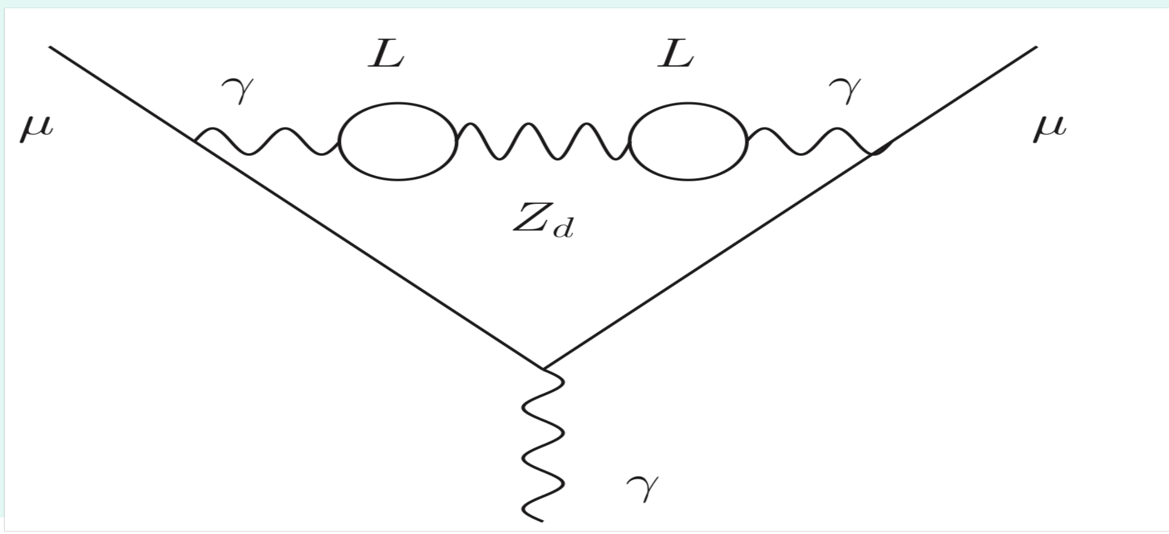
Multi-Higgs Models *(2 loop effects)*

Extra Dimensions<2TeV, Heavy Z', Dynamics…

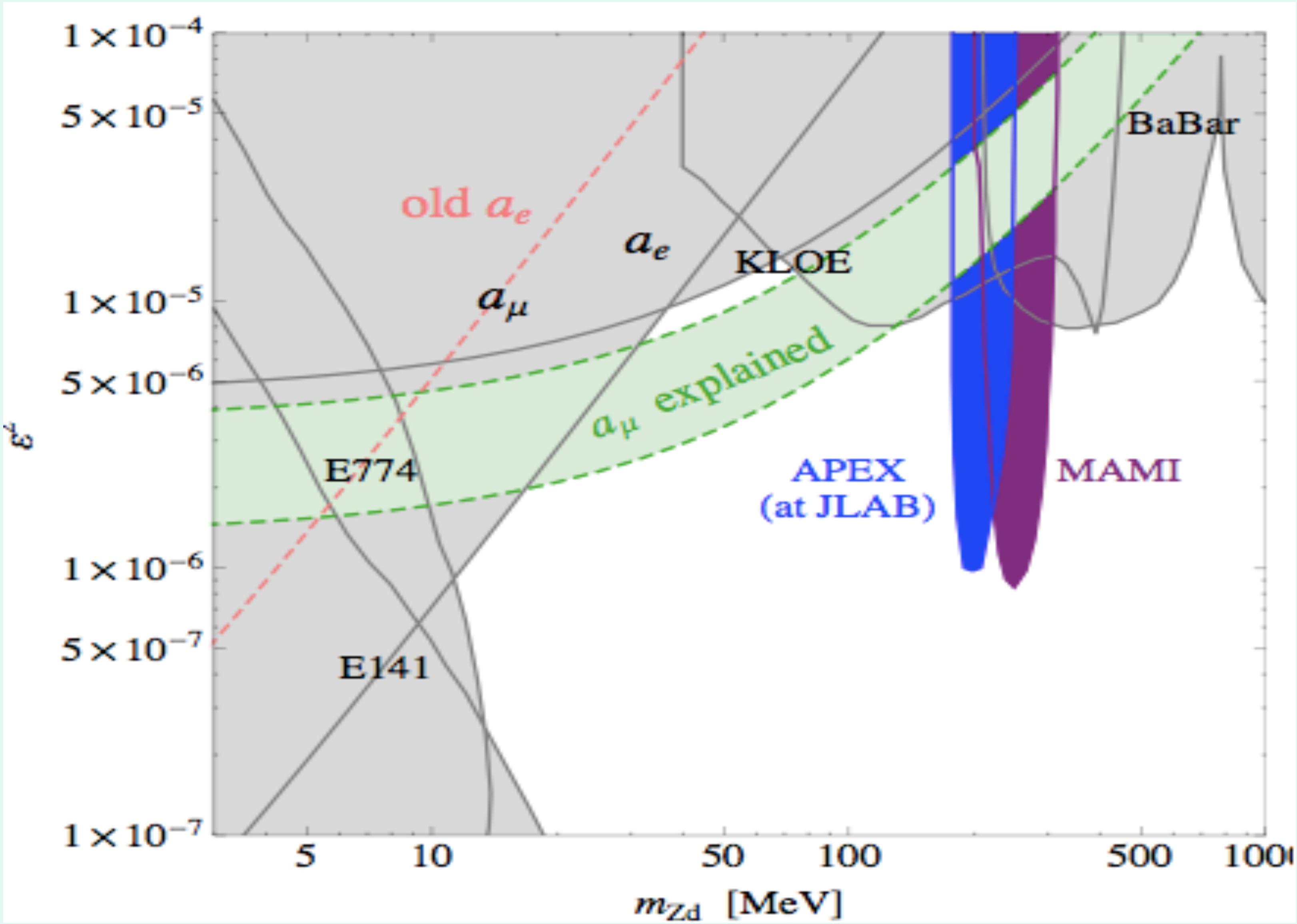
Light Higgs Like Scalar <10MeV?

* ***Dark Photons (Fayet, Pospelov…)***

$a_\mu^{Zd}=\alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g_μ-2 discrepancy for $\varepsilon^2\approx10^{-6}$-$10^{-4}$ & $m_{Zd}\approx$20-100MeV (see figure)



Old a_e vs New a_e (3 sigma bound)
(Davoudiasl, Lee & WJM)



2. The Dark Photon Solution

$20\mathrm{MeV} < m_{Z_d} < 100\mathrm{MeV}$, $10^{-3} < \varepsilon < 10^{-2}$

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_d$ kinetic Mixing

$L_{U(1)Y \times U(1)d} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu} - 2\varepsilon/\cos\theta_W B_{\mu\nu}Z_d^{\mu\nu} + Z_{d\mu\nu}Z_d^{\mu\nu})$

$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad Z_{d\mu\nu} = \partial_\mu Z_{d\nu} - \partial_\nu Z_{d\mu}$

ε= potentially infinite counterterm or finite loop effect

Remove ε by field redefinitions

$B_\mu \rightarrow B_\mu + \varepsilon/\cos\theta_W Z_{d\mu}$ or in terms of γ & Z

$A_\mu \rightarrow A_\mu + \varepsilon Z_{d\mu} \quad Z_\mu \rightarrow Z_\mu + \varepsilon \tan\theta_W Z_{d\mu}$

$L_{int} = -e\varepsilon(J_\mu^{em} - 1/2\cos^2\theta_W J_\mu^{NC})\, Z_d^\mu$

Second term cancelled by Z-Z_d mass matrix diagonalization!

As a result, Z_d couples primarily to conserved vector current J_μ^{em} of our world! Z_d=Dark Photon

QED like effects suppressed by $\varepsilon^2 \approx 10^{-4}$-$10^{-6}$ or smaller

$J_\mu^{NC} Z_d^\mu$ interaction suppressed by $\varepsilon(m_{zd}/m_z)^2 \tan\theta_W$ tiny

Axial current violates parity and current conservation

Can it be larger? Z - Z_d Mass Mixing

H. Davoudiasl, H-S Lee &WJM

3. *Z-Z_d mass mixing*

$\rightarrow \varepsilon_Z g/2\cos\theta_W Z_d^{\mu} J_{\mu}^{NC}$ $\varepsilon_Z = m_{Zd}/m_Z \delta$

Neglecting Kinetic Mixing ε

$$M^2 = \begin{bmatrix} m_Z^2 & -m_{Zd} m_Z \delta \\ -m_{Zd} m_Z \delta & m_{Zd}^2 \end{bmatrix}$$

$0 \leq |\delta| < 1$

$\delta^2 << 1$

Mixing $\approx \varepsilon_Z = m_{Zd}/m_Z \delta << 1$ $|\delta| \approx O(\varepsilon) \approx 2\times10^{-3}$?

Gives rise to: $g/2\cos\theta_W (m_{Zd}/m_Z \delta) J_{\mu}^{NC}$

Like a Z with smaller mass (20MeV-10GeV) and couplings

$J_{\mu}^{NC} = (T_{3f} - 2Q_f \sin^2\theta_W) f\gamma_{\mu} f - T_{3f} f \gamma_{\mu}\gamma_5 f$

Extended Higgs Example

1st Higgs Doublet $<\phi_1>=v_1$ ➔ $W^{\pm}$, Z, fermion masses

2nd Higgs Doublet $<\Phi_2>=v_2$ dark charge (Portal) $W^{\pm}$,Z, Z_d masses

3rd Higgs Singlet $<\phi_d>=v_d$ carries dark charge: Z_d mass

$\tan\beta = v_2/v_1 \quad \tan\beta_d=v_2/v_d$

$\varepsilon_Z=m_{Zd}/m_Z \sin\beta \sin\beta_d \approx m_{Zd}/m_Z\, v_2^2/v_1 v_d$ (very small)

➔ **parity violation (like ordinary Z but suppressed by ε_Z)**

longitudinal Z_d like an axion E/m_{Zd} coupling!

At High Energies Z_d Axion Like but spin 1!

Dark Parity Violation

Effect of ε & ε_Z together: (at low $Q^2 << m_Z^2$)

$a_\mu(Z_d) = \alpha/2\pi(\varepsilon + 0.02\varepsilon_Z)^2 F(m_{Zd}/m_\mu) - 117\times10^{-11}\delta^2$

essentially no change from ε alone solution

$\Delta\sin^2\theta_W(Q^2) = 0.42\varepsilon\delta m_Z m_{Zd}/(Q^2 + m_{Zd}^2)$

Shift largest at small $Q^2 < m_{Zd}^2$

Then with a_μ^{Zd} → $\sin^2\theta_W(Q \approx 75\text{MeV})$ **shift by** <u>**0.5δ**</u>**!**

δ down to $\approx 10^{-3}$ Potentially Observable

For $\delta \approx \pm\varepsilon$, $\Delta\sin^2\theta_W(Q^2) = \pm 0.42\varepsilon^2 m_Z m_{Zd}/(Q^2 + m_{Zd}^2)$

<u>Negligible effect at the Z Pole!</u>

Precision measurements at the Z Pole

Best Determinations

$\sin^2\theta_W(m_Z)_{MS} = 0.23070(26)$ A_{LR} (SLAC)

$\sin^2\theta_W(m_Z)_{MS} = 0.23193(29)$ $A_{FB}(bb)$ (CERN)

(3.2 sigma difference!)

World Average: $\mathbf{\sin^2\theta_W(m_Z)_{MS}=\underline{0.23125(16)}}$

IS IT CORRECT?

Consistent with m_H=125GeV!

Atomic PV in Cesium

<Q>≈2.4MeV Bouchiat & Fayet (2005) tight constraint

$Q_W(Cs)^{exp}$=-72.74(29)(36)→$\sin^2\theta_W(m_Z)_{MS}$=0.2292(21)

slightly low

Atomic Theory Shuffle

2009 $Q_W(Cs)^{exp}$=**-73.16(28)(20)**→$\sin^2\theta_W(m_Z)_{MS}$=0.2312(16)!

Major Constraint On "New Physics"

$|\Delta\sin^2\theta_W(Q=2.4MeV)|<0.0026$ 90% CL constraint

eg S=0.0±0.8 $m_{Z\chi}$>1.2TeV, leptoquarks…$\delta\leq10^{-3}$ for $(g_\mu-2)$

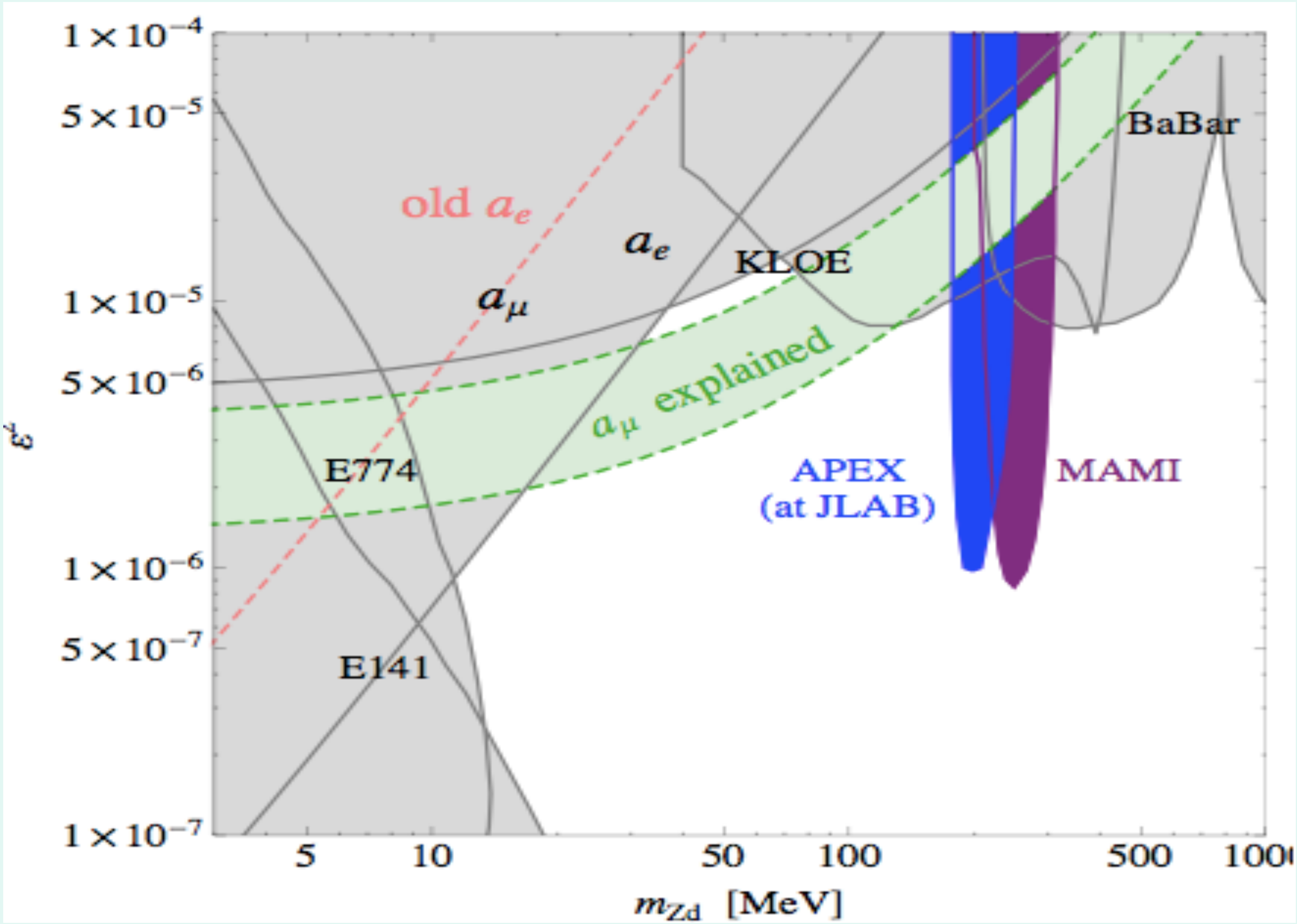
Dzuba, Berengut, Flambaum, Roberts 2012

$Q_W(Cs)$➔-72.38(29)(32)$_{th}$→$\sin^2\theta_W(m_Z)_{MS}$=0.2282(20)

(1.5 sigma APV deviation)

$\varepsilon\delta=4\times10^{-6}$ or $\varepsilon\approx\delta\approx2\times10^{-3}$ for $(g_\mu-2)$ $m_{Zd}\approx50MeV$ region

Old a_e vs New a_e (3 sigma bound)
(Davoudiasl, Lee & WJM)



Other low energy measurements?

NuTeV $\sin^2\theta_W(m_Z)_{MS}$=0.236(2)

Inconsistent with Z Pole Measurements (2-3 sigma?)

<Q>≈3GeV Not so low (not sensitive to very light Z_d)

E158 at SLAC Pol ee→ee Moller)

E_e≈50GeV on fixed target, ***<Q>≈160MeV***

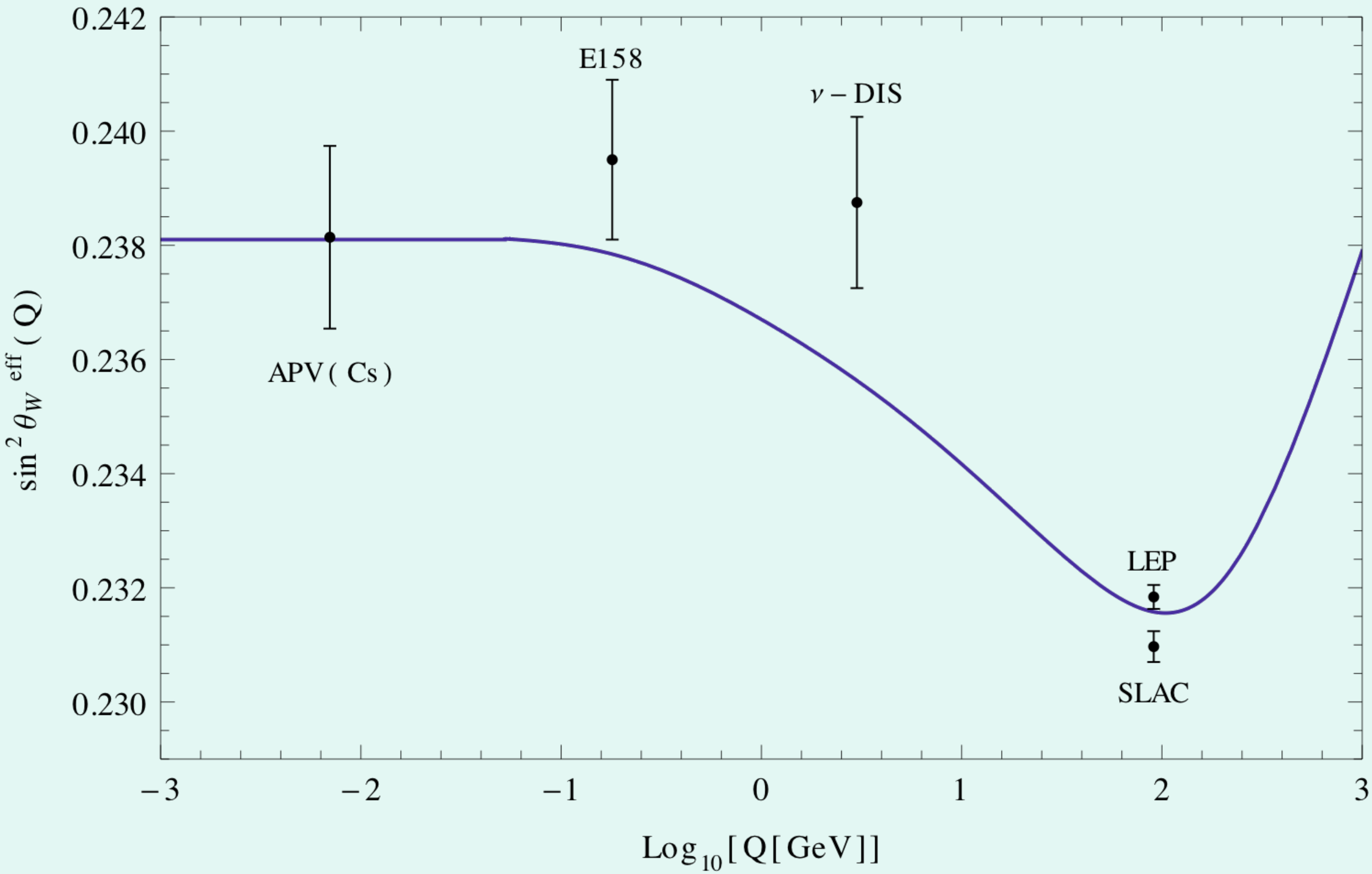
$A_{LR}(ee) = -131(14)(10)\times10^{-9}\ \alpha\ (1-4\sin^2\theta_W)$

Measured to ±12% →$\sin^2\theta_W$ to ±0.6%

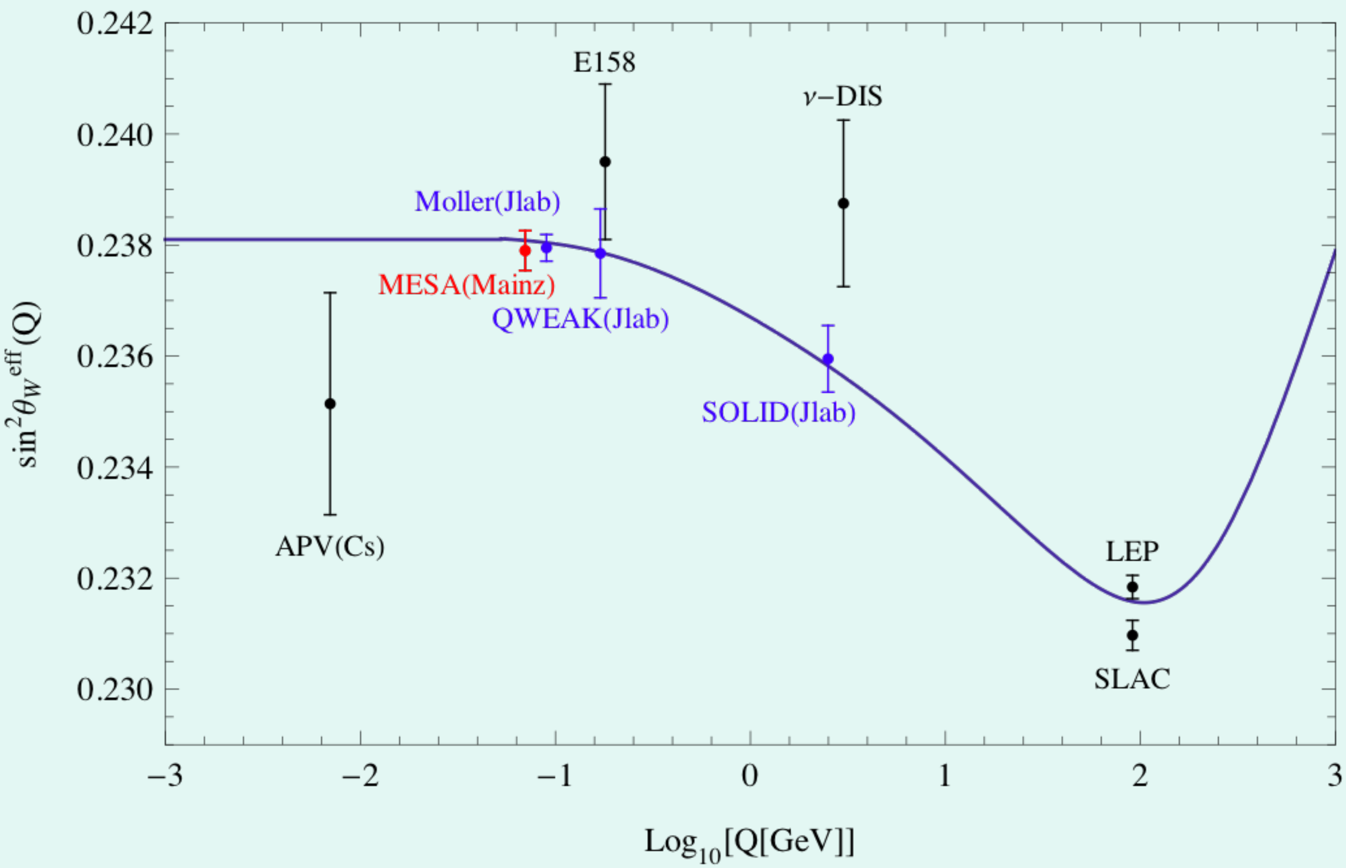
→$\sin^2\theta_W(m_Z)_{MS}$=0.2329(13) slightly high

Best Low Q^2 Determination of $\sin^2\theta_W$

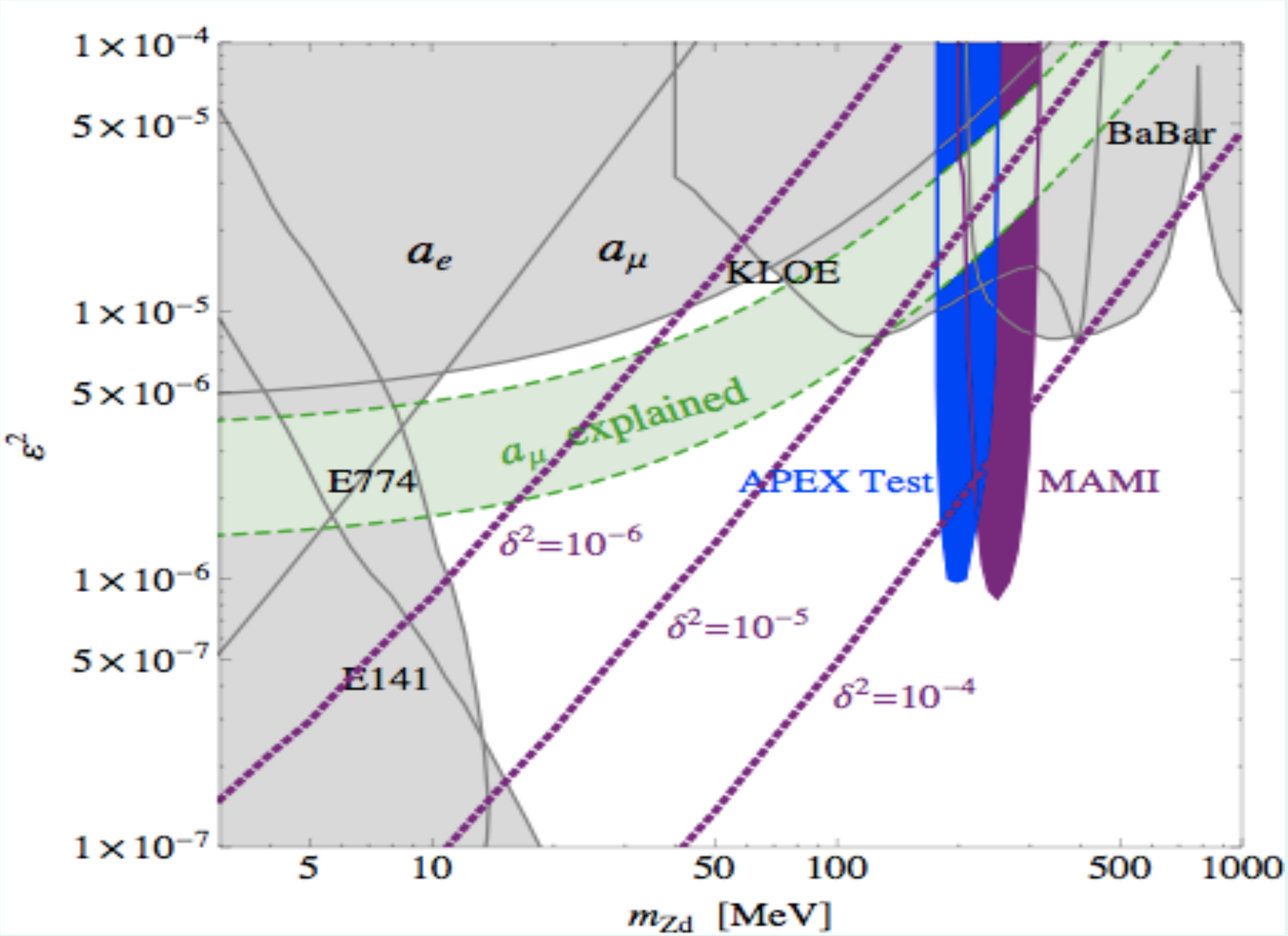
Running $\sin^2\theta_W(Q^2)$ pre 2012



APV Update, JLAB & MESA Future A_{LR} Sensitivity



Atomic Parity Violation Constraints
Pre-Dzuba et al.. & a_e Update



Future $\sin^2\theta_W(0)$ to ~±0.1% in $A_{RL}(ep)$ $A_{RL}(ee)$

Ongoing JLAB QWEAK Exp. (data taking completed)

E=1.2GeV, <Q>≈170MeV , Pol=0.85, 2200hr

$\mathbf{A_{RL}(ep \to ep) = [\sigma(e_R p) - \sigma(e_L p)]/[\sigma(e_R p) + \sigma(e_L p)]} \approx 3\times10^{-7}$

$\propto \mathbf{(1-4\sin^2\theta_W) = Q_W(p) \approx 0.07}$

Goal: $\mathbf{\Delta\sin^2\theta_W = \pm 0.0008}$ via ±4% measurement of A_{LR}

MESA Flagship Experiment $\mathbf{\mathit{A_{RL}(ep \to ep)}}$

Like ***JLAB QWEAK*** but Lower Energy & More Running Time

$\mathbf{E_e}$ =1.2GeV➔0.14GeV(?)   <Q>≈100MeV?

Overall Goal: 3x more stat. precise? $\Delta A_{RL}/A_{RL} \approx \pm 1\%$

$\Delta\sin^2\theta_W = \pm 0.0002$ (stat) ± 0.0002(syst)

Overall ±0.0004

Polarized Moller e^-e^- (12GeV)
Future JLAB Flagship Experiment

$A_{LR}(ee \rightarrow ee)$ to ±2.5%, **<u>$\langle Q \rangle \approx$75MeV!</u>**

$\Delta\sin^2\theta_W(m_Z)_{MS}=\pm0.00025$! Comparable to Z pole

Explores $m_{Z\chi} \rightarrow$1.5TeV Better than APV, S~0.1 etc.

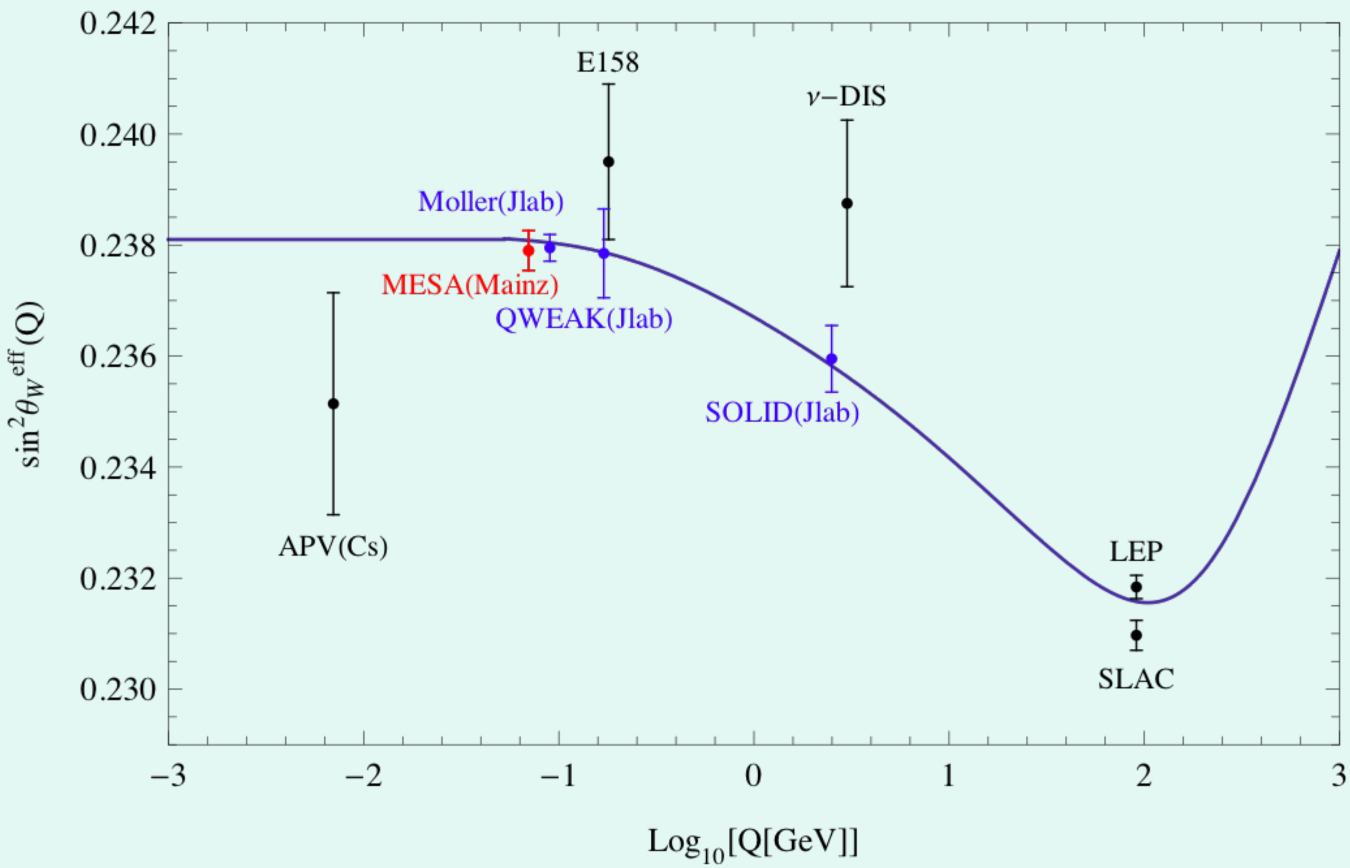
Possible sensitivity to low mass Z_d Dark Sector Gauge Boson

(If it violates Parity via Z-Z_d mass mixing $m_{zd}/m_Z\delta$)

Then with a_μ^{Zd} ➔ **$\sin^2\theta_W$(Q≈75MeV) shift by 0.5δ!**

New APV +a_μ (δ≈2x10^{-3}) could imply O(5 sigma) shift

APV Update, JLAB & MESA Future



A_{RL}(eC) (comparison study)

A_{RL}(eC) $0^+ \rightarrow 0^+$ Elastic Scattering)

BATES EXP (1978-1990) (Pioneering Effort)

Very Modest Effort by today's standards

E_e=0.25GeV, P_e=0.37, I=30-60μA, <Q>=140MeV, T=150hrs

$A_{RL}(eC)^{SM}=G_\mu Q^2 \sin^2\theta_W/\sqrt{2}\pi\alpha$ $A_{RL}(eC)^{exp}=0.60\pm0.14\pm0.02\text{x}10^{-6}$

Measured $\sin^2\theta_W$=0.20±0.05

Current ±25% can be significantly improved

P_e=0.85, I>200μA, T=3000hrs, 20xAcceptance→±0.3%!

About 3x better than APV(Cs) & no Atomic Theory

For Many Types of New Physics 2xSensitivity of QWEAK

Main Issue: Polarization ±0.3%? (Hard)

A ±0.3% determination of $A_{RL}(eC)$ would probe:

m_{Z_χ}~1.8TeV (About the same as 12GeV MOLLER)

ΔS ~0.15, SUSY Loops, Leptoquarks…

Low $\langle Q \rangle \approx 50$MeV sensitivity to Z_d (20-100MeV)

(Discussed at BOSEN 2009)

Do Both $A_{RL}(ep)$ and $A_{RL}(eC)$ at MESA?

Also worth studying at JLAB free electron laser
Darklight Experimental Facility

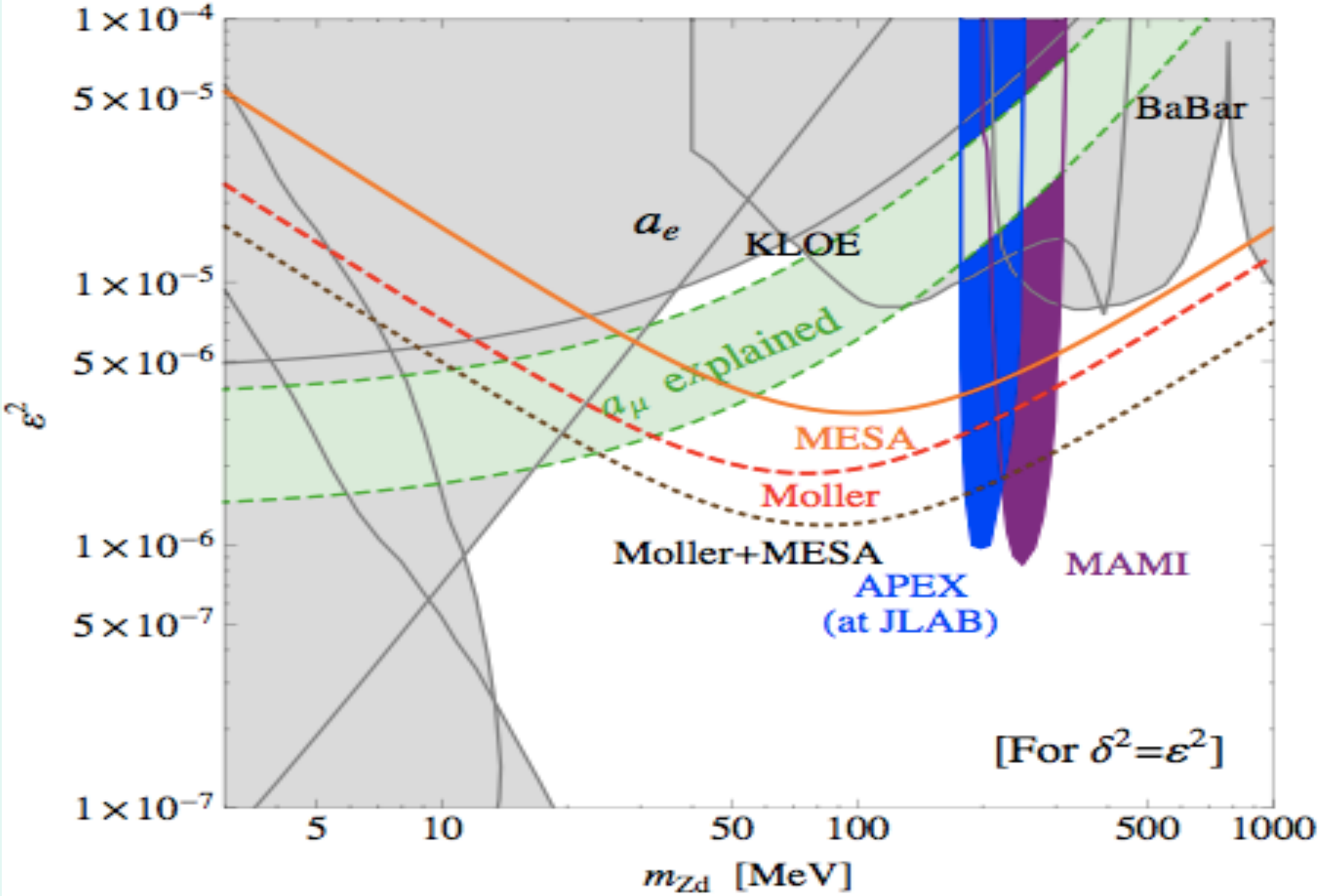
Polarized ee, ep, eC Asymmetries

- $A_{LR}=\sigma_L-\sigma_R/\sigma_L+\sigma_R$ Parity Violating α Q^2 very small

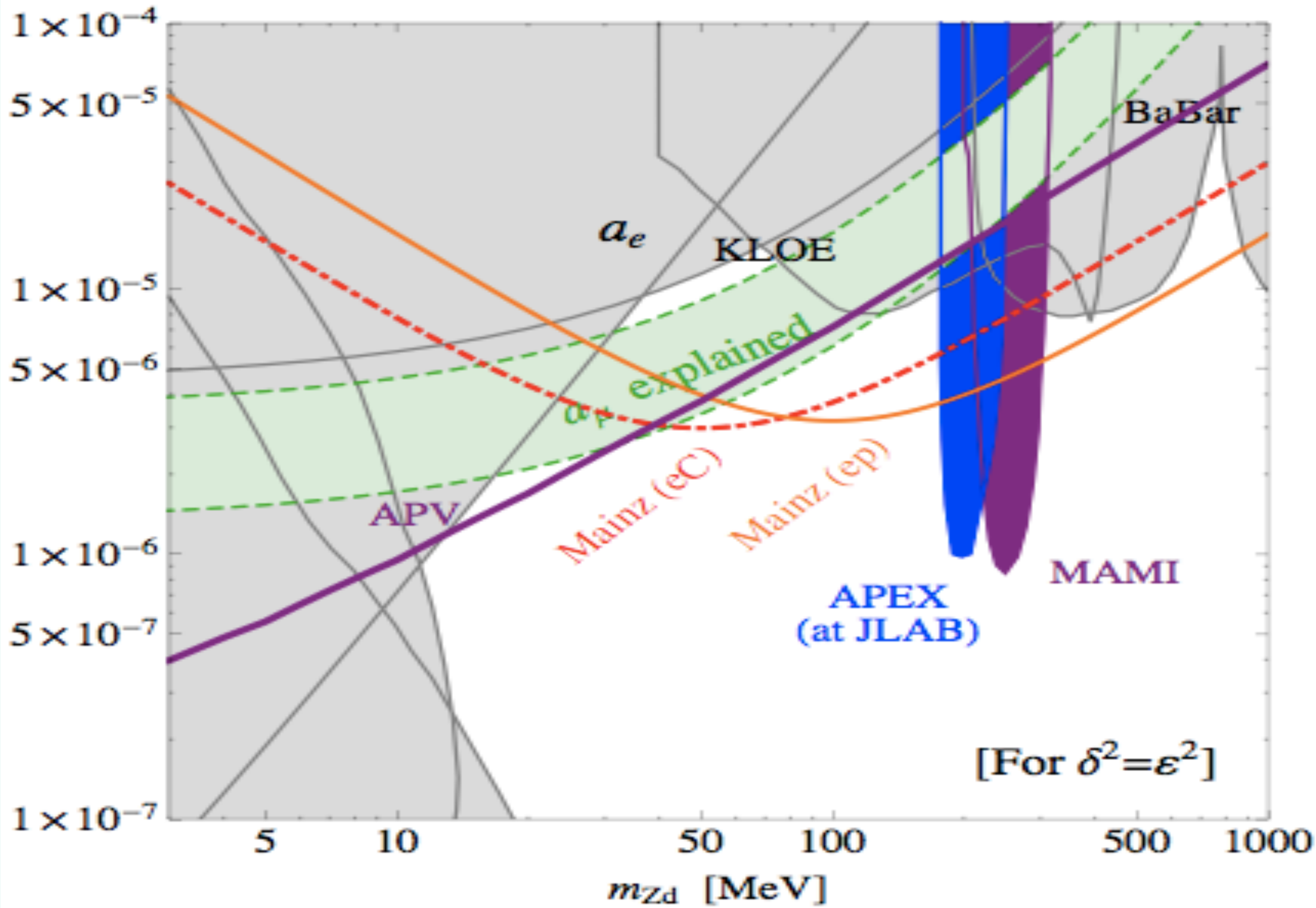
Experiment	<Q>MeV	$\Delta\sin^2\theta_W$	Measurement
CS APV	2.4	±0.0016-0.0020	Atomic Theory?
E158 SLAC	160	±0.0013	ee Completed
Q_{weak} JLAB	170	±0.0007/8	ep in progress
Moller JLAB	75	±0.00029	ee approved
MESA (Mainz)	>100?	±0.00037	ep proposed
eC	50?	±0.0007?	eC Bosen 2009

Experiments will actually probe a range of Q^2

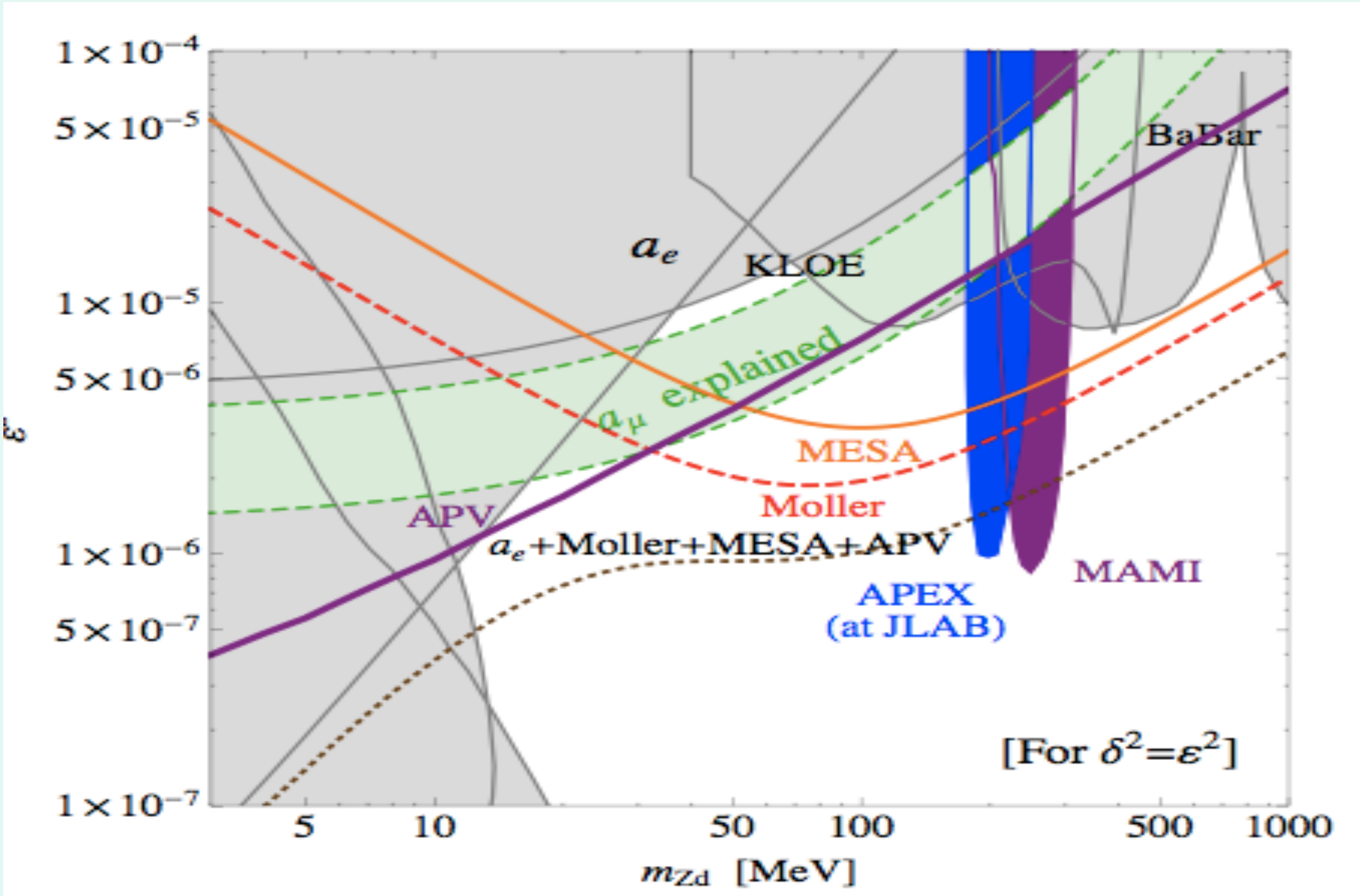
Low <Q> experiments could see >5 sigma dark PV effect!


1 × 10^−4
5 × 10^−5
1 × 10^−5
5 × 10^−6
1 × 10^−6
5 × 10^−7
1 × 10^−7
ε^2
5
10
50
100
500
1000
m_Zd [MeV]
a_e
KLOE
BaBar
a_μ explained
MESA
Moller
Moller+MESA
APEX
(at JLAB)
MAMI
[For δ^2=ε^2]

Comparison of A_{LR}(ep) and A_{LR}(eC)



a_e & Parity Violation Sensitivity



5. ***Rare K & B Decays (eg. $K \rightarrow \pi Z_d$)*** ***$\delta^2 \rightarrow 10^{-6}$!***

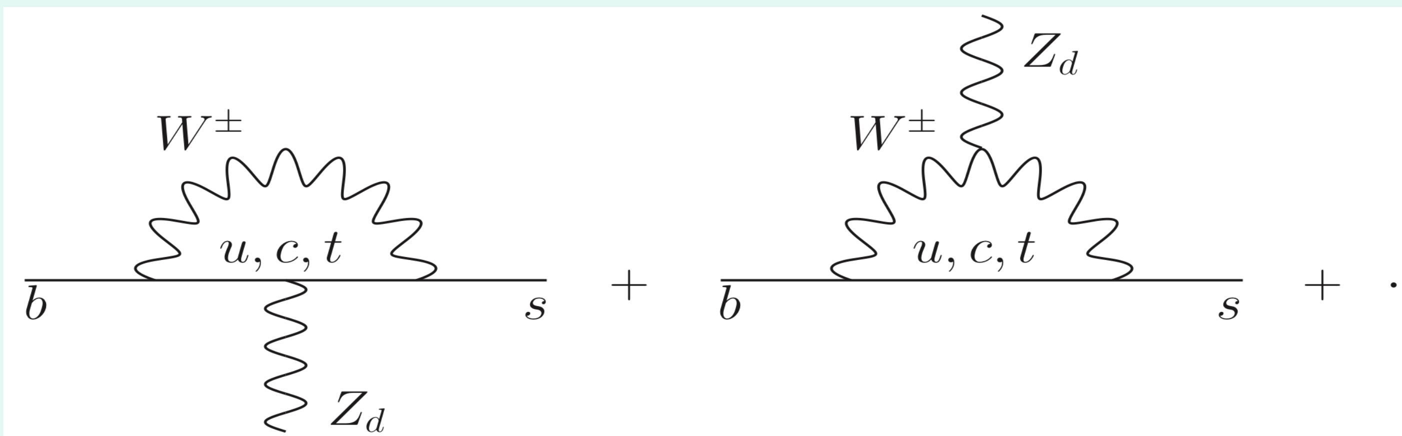
- With Z-Z_d mixing → $Z_d^{\mu} f \gamma_\mu \gamma_5 f$ coupling non-conserved
  Loop Induced Effects: eg Zsd or Zbs $Z \rightarrow \varepsilon_Z Z_d$

Longitudinal Z_d couples strongest to heavy particles eg t, b…
Flavor Changing Neutral Currents: $Z_d sd$ & $Z_d bs$

$BR(K \rightarrow \pi Z_d) \approx 4 \times 10^{-4} \delta^2$ $Z_d \rightarrow e^+e^-$, $\mu^+\mu^-$, or neutrinos
similarly
$BR(B \rightarrow K Z_d) \approx 0.1 \delta^2$

Some Model Dependence

Flavor Changing neutral current decays



K & B Decay Bounds

$BR(K^+ \rightarrow \pi^+ e^+ e^-)_{exp} = 3.00(9)x10^{-7}$ probes $\delta^2 \approx 10^{-4}$

$BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)_{exp} = 9.4(6)x10^{-8}$ probes $\delta^2 \approx 10^{-4}$

$BR(K^+ \rightarrow \pi^+ \nu\nu)_{exp} = 1.7(1.1)x10^{-10}$ probes $\delta^2 \approx 10^{-6}$

Depends on m_{Zd} and Z_d Branching Ratios

K_L potentially better $BR(K_L \rightarrow \pi^0 e^+ e^-) < 2.8x10^{-10}$ KTeV

$BR(B^+ \rightarrow KZ_d) < 10^{-7}$ probes $\delta^2 \approx 10^{-6}$ Can do even better!

If charged lepton flavor violated: $\mu \rightarrow eZ_d$ $\tau \rightarrow \mu Z_d$ & $Z_d \rightarrow e^+ e^-$

Higgs Decay $H \rightarrow ZZ_d \rightarrow$ 4 charged leptons

HZZ_d coupling $\varepsilon_Z = m_{Zd}/m_Z \delta$ suppressed

But Longitudinal Z_d

Enhanced by E/m_{Zd} overcomes m_{Zd}/m_Z suppression $H \rightarrow ZZ_d$

$Z_d \rightarrow l^+l^-$ (l=e or μ) or "missing energy"

$\Gamma(H \rightarrow ZZ_d)/\Gamma_H(125\text{GeV})_{SM} = 16\delta^2$

Potential experimental sensitivity to $\delta^2 \approx 10^{-6}$

Should be pushed as far as possible!

Other interesting Possibilities: ***: $H \rightarrow \gamma Z_d$ $H \rightarrow Z_d Z_d$*** $Z_d \rightarrow l^+l^-$

(Transverse Z_d)

Summary

$\Delta a_e = a_e^{exp} - a_e^{SM} = -106(82)\times10^{-14}$ (Recent Update)

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

First Dark Photon Hint?: 20MeV<m_{Zd}<100MeV, *$\varepsilon\approx2\text{x}10^{-3}$*

Z-Z_d mass mixing: *APV Theory? Implication?**, $|\varepsilon|\approx|\delta|\approx2\text{x}10^{-3}$***

(JLAB & MESA) A_{LR}(ee, ep, eC?)

Rare K, B, μ, τ Decays

$\delta\approx10^{-3}$ Sensitivity

Higgs Decays to Dark Bosons: ***$H\rightarrow\gamma Z_d$ $H\rightarrow Z_dZ_d$ $H\rightarrow ZZ_d$***

$Z_d\rightarrow e^+e^-$

Revolutionary Discovery Potential!