Fundamental Symmetries

Quarks & Leptons Theory

(Precision Frontier)

William J. Marciano

Chicago

(August 10, 2012)

BROOKHAVEN NATIONAL LABORATORY

Perspective
2012 Developments

- ***$SU(3)_C xSU(2)_L xU(1)_Y$ Standard Model Completed***

Higgs (?) Discovery m_H=125-126GeV! Appears Elementary

$\sin^2 2\theta_{13} \approx 0.1$ Daya Bay, Reno, Double Chooz… CP?

m_W = 80.399(25)GeV → 80.384(17)GeV LEP2/FNAL

Kinoshita et al. Complete 5 loop QED g-2

B➔τ Decay Anomalous? (e-μ-τ universality)

PDG Change τ_n➔880.1(1.1)s (Unitarity?)

Atomic PV Theory (Flambaum et al) Preprint

$Q_W(Cs)=-73.16(29)(20)_{th}$ ➔$-72.38(29)(32)_{th}$

No Sign of Supersymmetry at the LHC (Tension!)

Precision Parameters (status):

Quantity	2007 Value		2012 Value	Comment
α^{-1}	137.035999710(96)		137.035999165(34)	g_e-2
G_μ	$1.16637(1)\times10^{-5}GeV^{-2}$		$1.1663788(7)\times10^{-5}GeV^{-2}$	PSI
m_Z	91 .1875(21)GeV		91.1876(21)GeV	LEP
m_t	171.4(2.1)GeV	→	173.1(1.1)GeV	FNAL
m_W	80.410(32)GeV	→	80.384(17)GeV	LEP2/FNAL
$\sin^2\theta_W(m_Z)$	***0.23125(16)***		***0.23125(16)***	***Ave.***

2012 shift m_W = 80.399(25)GeV ➔ 80.387(19)GeV CDF

80.375(23)GeV DO

Pre Higgs Discovery

m_H=90GeV central prediction 114GeV<m_H<140GeV

Now ***m_H=125-126GeV !***

Implications of m_H=125GeV

α, G_μ, m_Z, m_t & (m_H=125GeV)

Imply: **m_W = 80.361(10)GeV vs 80.384(17)GeV Ave.**

$\sin^2\theta_W(m_Z)$ = 0.23130(10) vs 0.23125(16) Ave.

Very Good Agreement!

Not much room for "New Physics" (Loops)

Further Validates g_μ-2 Hadronic Vacuum Polarization

So far: No direct evidence for Supersymmetry, Extra Dimensions, 4th Generation, New Dynamics…

At The LHC!

The Higgs – Last Particle Ever Discovered?

Discovery of $m_H \approx 125$GeV at CERN

H➔γγ, ZZ*, WW*,

Approx 200,000 H/exp!

BR(H➔γγ) High by 1.5-2.0!

New Heavy Vector-Like Charged Leptons? Scalars (Mixing)?

Paradigm Shift! Directed by Experiment

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 Low Energy Examples

1) *CKM Unitarity & Neutron Decay*
2) *A Beautiful Relation &* $\boldsymbol{\sin^2\theta_W(m_Z)}$

   Parity Violating Weak Neutral Currents

   Atomic Parity Violation & Polarized Electron Scattering

   "New Physics" Heavy & Light Z' Gauge Bosons
3) *Muon Anomalous Magnetic Moment*

   3.6 sigma Discrepency Solidified
4) *Electric Dipole Moments*

   (High Mass Scale SUSY Probes – Beyond LHC))

1) CKM Unitarity & Neutron Decay

Superallowed ($0^+ \rightarrow 0^+$) Beta Decays & V_{ud}

Nuclear Unc. - Significantly Reduced (2006-08)

Nuclear Coulomb Corrections Improved

$$|V_{ud}| = \underline{0.97425}(11)_{Nuc}(19)_{RC}$$

(2008 Hardy and Towner Update)

$|V_{us}|=\underline{0.2253(13)}$ from $K \rightarrow \pi l \nu$ Vector

$|V_{us}|=\underline{0.2252(}13)$ from $K \rightarrow \mu \nu$ Axial-Vector

$|V_{us}|=\underline{0.2253(9)}$ Current Kaon Average

Uncertainty Primarily Lattice Matrix Elements

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9999(4)_{Vud}(4)_{Vus}$$

$$=\underline{0.9999(6)}$$

Outstanding Agreement With Unitarity

New Physics Constraints-Implications:

Exotic Muon Decays, W*bosons, SUSY, Technicolor,

Z' Bosons, $H^{\pm}$, Heavy Quark/Lepton Mixing…

- Isospin Breaking Coulomb Corrections of Hardy and Towner ***questioned*** by: G. Miller & A. Schwenk

  N. Auerbach

  H. Liang et al.

Hardy and Towner $(1-\delta_C)$ correction increases V_{ud}

δ_C~0.2-1.6% Correction

Recent Claims δ_C is smaller due to nuclear radial excitations smaller V_{ud}=0.97425→0.9730 (Liang, Giai, Meng)

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$ reduced to (roughly) 0.9975?

Unitarity Lost?

Neutron Decay ($n \to pe\nu$) & V_{ud}

$$|V_{ud}|^2 = \frac{4908.7(1.9)\,\text{sec}}{\tau_n(1+3g_A^2)}$$

Measure τ_n and $g_A \equiv G_A/G_V$ (decay asymmetries)

2008 PDG τ_n^{ave}**=885.7(8)sec,** g_A^{ave}**=1.2695(29)**

$\rightarrow |V_{ud}|^{ave} = 0.9746(4)_{\tau n}(18)_{gA}(2)_{RC}$ **reasonable**

2012 PDG τ_n^{ave}**=880.1(1.1))sec** g_A^{ave}**=1.2701(25)**

$\rightarrow |V_{ud}|^{ave} = 0.9773(6)_{\tau n}(16)_{gA}(2)_{RC}$

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 1.0059(4)_{Vus}(34)_{Vud}$ **too high!**

Most Likely $g_A \to 1.2750$

New ***Precise*** Measurements of τ_n and g_A required!

2. A Beautiful Relation & $\sin^2\theta_W(m_Z)$

$SU(2)_L \times U(1)_Y$ + Higgs Doublet + 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!

Main effect: $\alpha=1/137 \rightarrow \alpha(m_Z)\sim 1/128$ Large 7% Effect

Large $\alpha m^2_t/m^2_W$ Corrections ➔ Heavy Top

Small $\alpha \ln m_H$ Effects ➔ $m_H \leq 140$GeV

Many types of Heavy Physics Ruled Out

eg Heavy Chiral Fermions (4th Generation)

S, T Parameters, …

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

$\sin^2\theta_W \equiv 1-(m_W/m_Z)^2$ On Shell Definition, Popular in1980s

Induces large $\alpha(m_t/m_W)^2$ corrections

Now Largely Abandoned

$\sin^2\theta_W(\mu)_{MS} \equiv e^2(\mu)_{MS}/g^2(\mu)_{MS}$ Good for GUT running

No Large RC Induced

Theoretically Nice/ But Unphysical

$\sin^2\theta_W^{lep}$ = $Z\mu\mu$ coupling at the Z pole

very popular at LEP

= $\sin^2\theta_W(m_Z)_{MS}+0.00028$ (best feature)

$\sin^2\theta_W(Q^2)$ = Physical Running Angle

Continuous

Incorporates γZ mixing loops: quarks, leptons, $W^{\pm}$

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?

(Major Implications)

	$\sin^2\theta_W(m_Z)_{MS}$	S	N_D (Chiral)
Average	0.23125(16)	-0.04(8)	2(2) $m_H \approx 120$GeV
A_{LR}	0.23070(26)	-0.32(13)	(SUSY) $m_H < 115$GeV
$A_{FB}(bb)$	0.23193(29)	+0.32(15)	9(3)! Heavy Higgs

. We failed to nail $\sin^2\theta_W(m_Z)_{MS}$!

What about low energy measurements?

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

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

Atomic Parity Violation

1999 $Q_W(Cs)^{exp}$=-72.06(28)(34) Better Atomic Th.

2008 $Q_W(Cs)^{exp}$=-72.69(28)(39)→$\sin^2\theta_W(m_Z)_{MS}$=0.2290(22)

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

±0.5% → **Major Constraint On "New Physics"**

2012 $Q_W(Cs)$➔-72.38(29)(32)$_{th}$→$\sin^2\theta_W(m_Z)_{MS}$=0.2282(20)

Tentative Shift Back!

E158 at SLAC Pol ee→ee Moller)

$E_e \approx 50$GeV on fixed target, $Q^2=0.02\text{GeV}^2$

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

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 $\sin^2\theta_W$

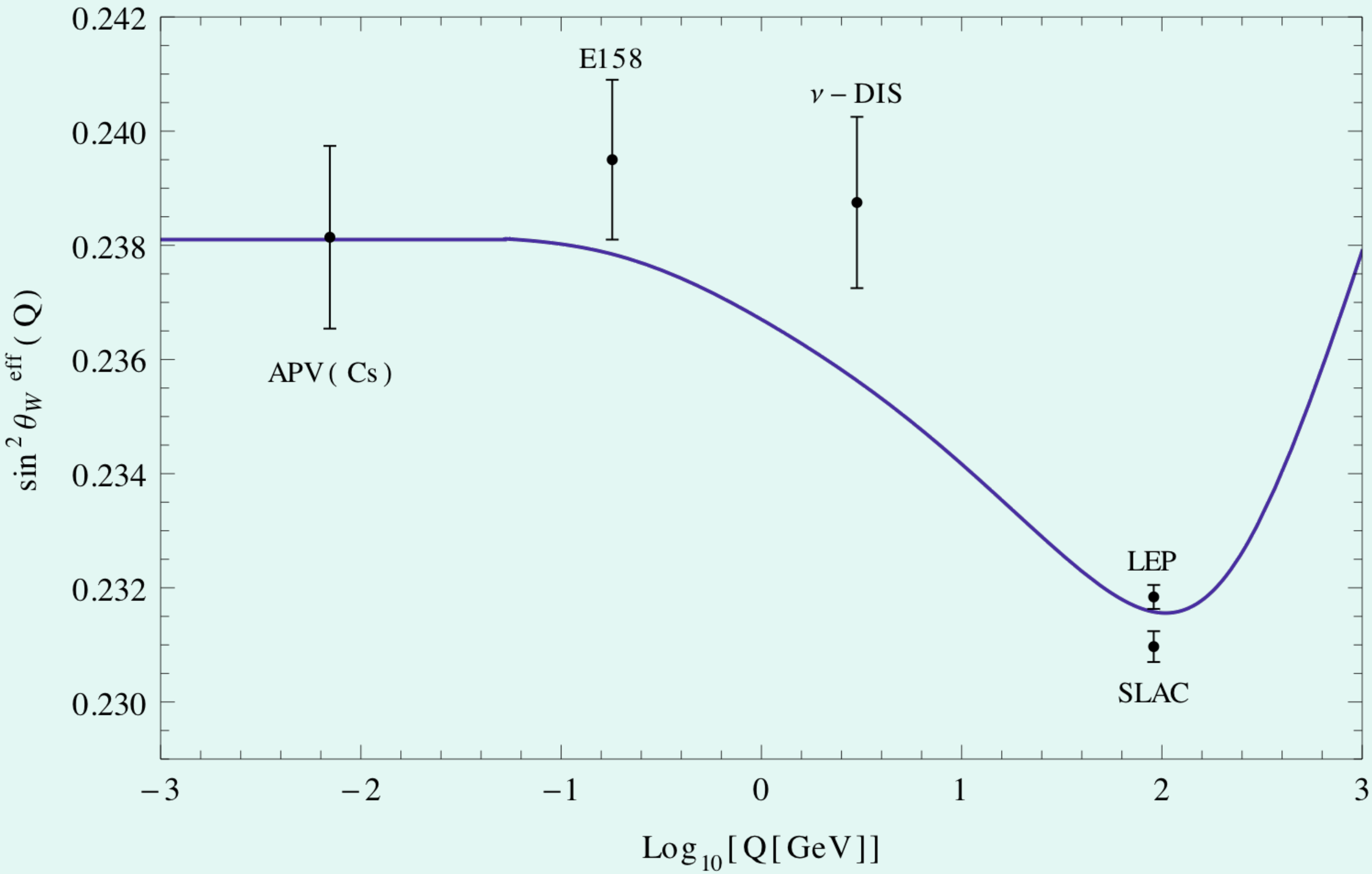
$A_{LR}(ee)^{exp}=A_{LR}(ee)^{SM}(1+0.13T-0.20S+7(m_Z/m_{Z\chi})^2\ldots)$

Constrains "New Physics" eq $m_{Z\chi}>0.6$TeV, H^{--},S, Anapole Moment, …

Together APV(Cs) & E158→ $\sin^2\theta_W(Q^2)$ running

$\sin^2\theta_W(m_Z)_{MS}$=0.232(1)

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



Longer Future Efforts: Polarized **Moller** at JLAB

After 12GeV Upgrade

$A_{LR}(ee \to ee)$ to ±2.5%

$\Delta \sin^2\theta_W(m_Z)_{MS} = \pm 0.00025$!

Comparable to Z pole studies!

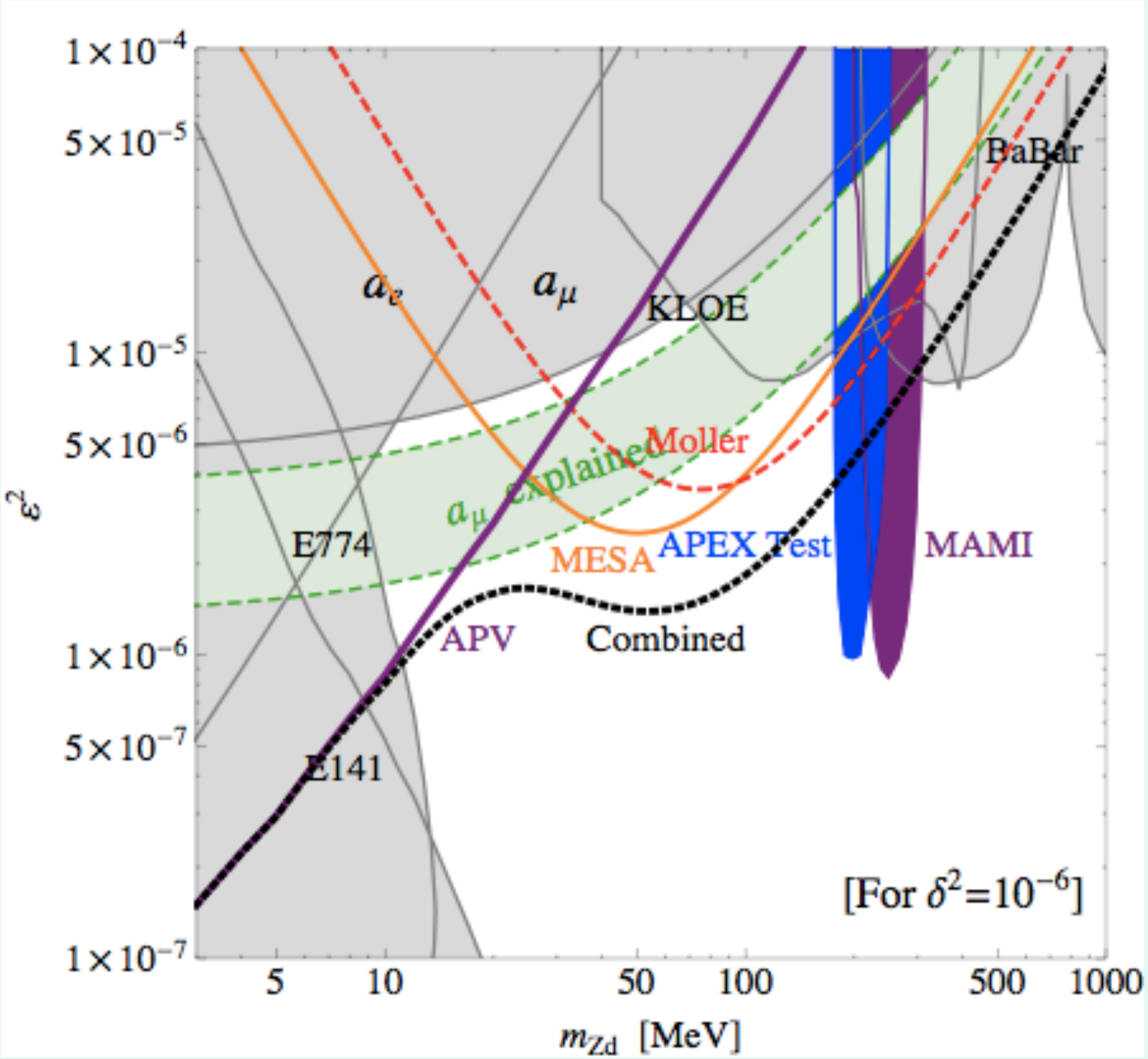
$A_{LR}(ee)^{exp} = A_{LR}(ee)^{SM}(1+7(m_Z/m_{Z\chi})^2+\ldots)$

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

Possible sensitivity to low mass Z_d Dark Sector Gauge Boson

Future JLAB Flagship Experiment!

Standard for future Proposals



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
a_μ
KLOE
BaBar
Moller
a_μ explained
E774
MESA
APEX Test
MAMI
APV
Combined
E141
[For $\delta^2=10^{-6}$]

Polarized ee, ep, eC Asymmetries

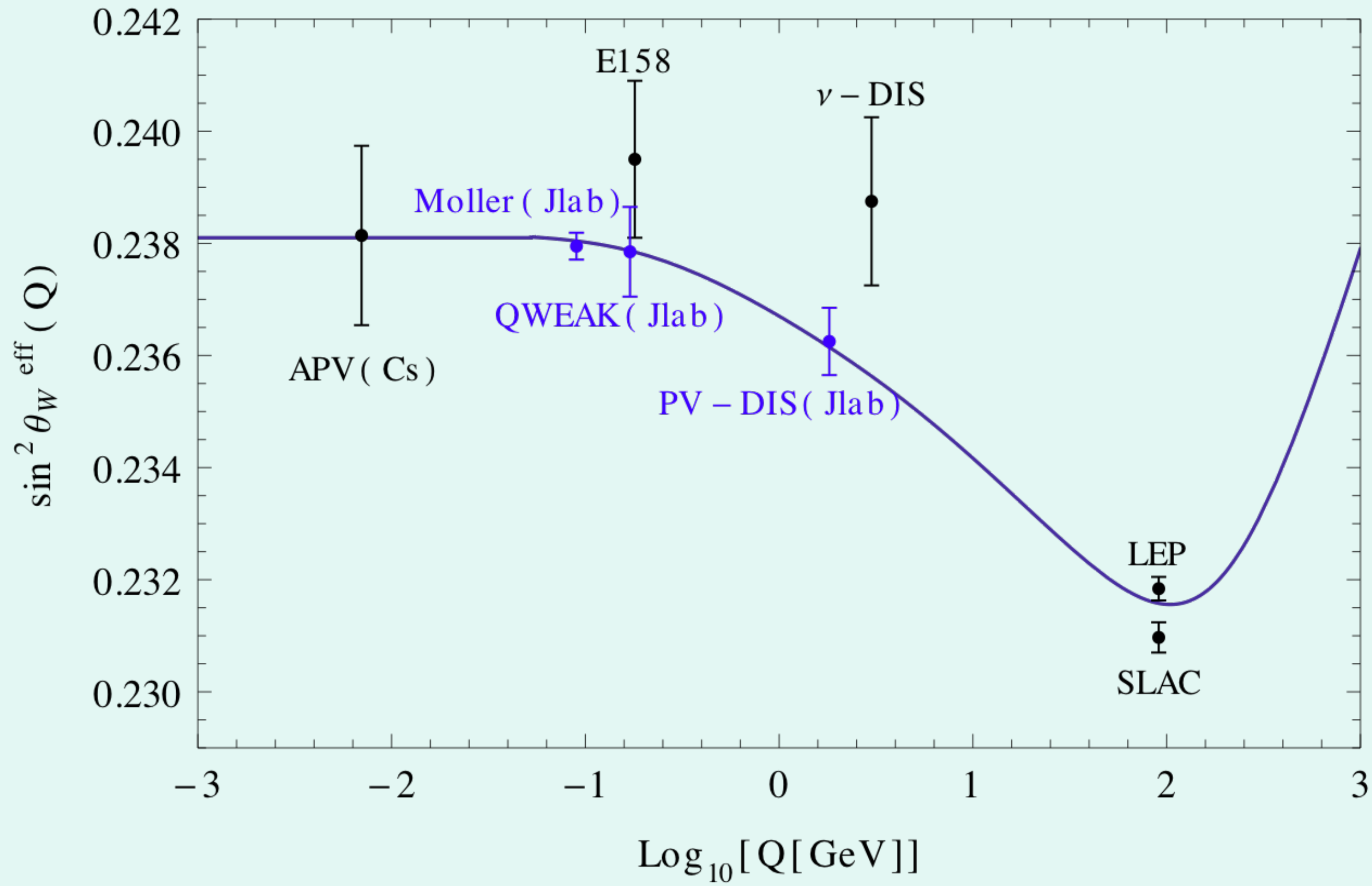
- $A_{LR}=\sigma_L-\sigma_R/\sigma_L+\sigma_R$ Parity Violating α Q^2 very small

Experiment	<Q>MeV	$\Delta\sin^2\theta_W$	Measurement
Cs APV	2.4	±0.0016(?)	Completed
E158 SLAC	160	±0.0013	ee Completed
Q_{weak} JLAB	170	±0.0007/8	ep (analysis)
Moller JLAB	75	±0.00029	ee approved
MESA (Mainz)	50-150?	±0.00037	ep proposed
eC	low?	±0.0010?	eC Bosen 2009

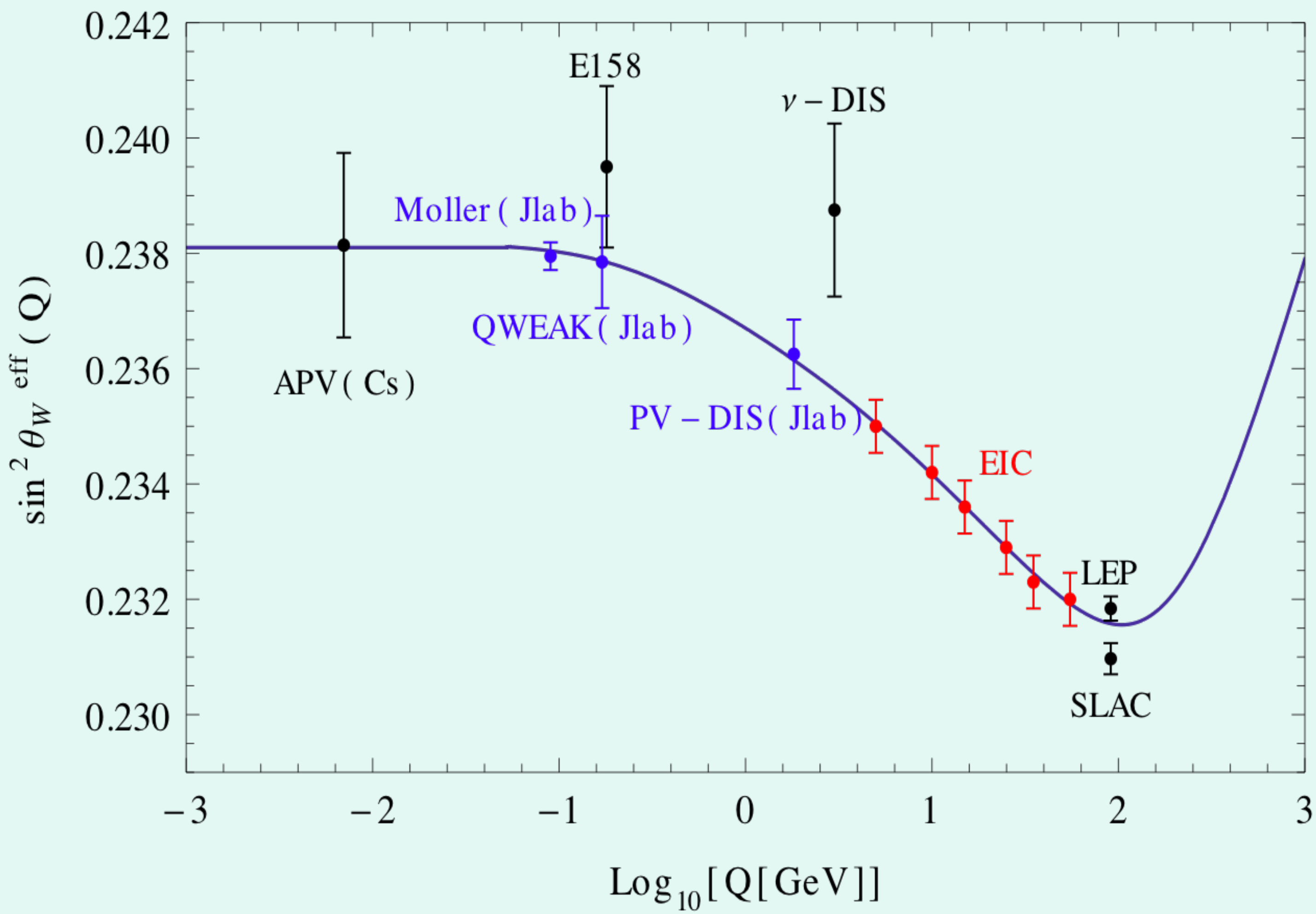
Experiments will actually probe a range of Q^2

APV Sets Normalization – Francium, Isotopes, Trapped Ions

Running of $\sin^2\theta_W(Q)$



EIC Statistical Errors Only
(Plot by Y. Li)



3) Muon Anomalous Magnetic Moment

- $a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592089(54)_{stat}(33)_{sys} x10^{-11}$

  $= \underline{116592089(63)x10}^{-11}$

- Expect fact 4 improvement at Fermilab

$\mathbf{a_\mu^{SM} = \underline{116591803(49)} x10^{-11}}$

$\mathbf{\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49) x10^{-11}}$

$\mathbf{286(80) x10^{-11}}$ **(*3.6σ discrepancy!*)**

Main Theory Issue Hadronic LBL

Higgs mass 125GeV suports Hadronic VP!

Significant Long Standing Discrepency

Interpretations

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

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

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

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

Multi-Higgs Models

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

Light Higgs Like Scalar <10MeV?

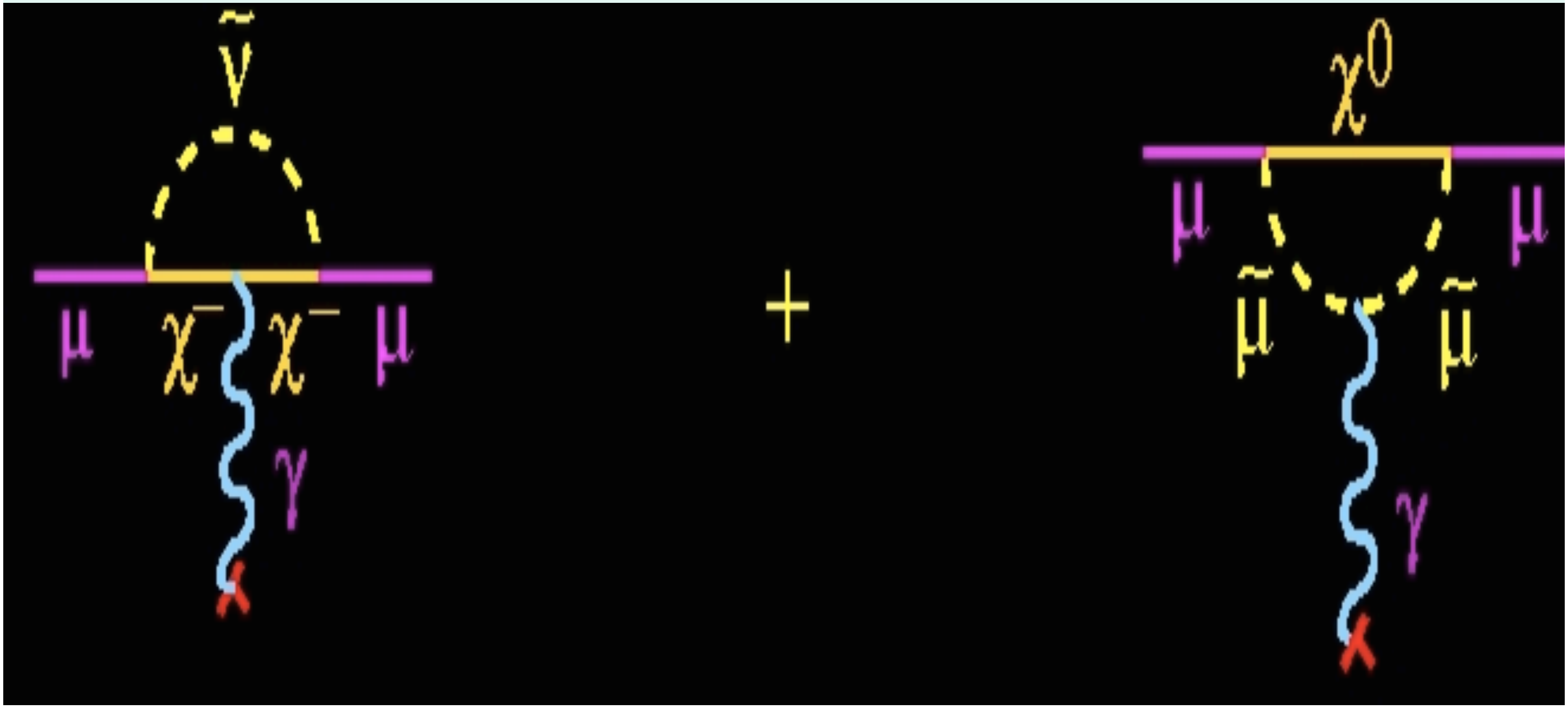
***** ***Dark Photons (Fayet, Pospelov…)***

$a_\mu(Z_d) = \alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$ solves g-2 discrepancy

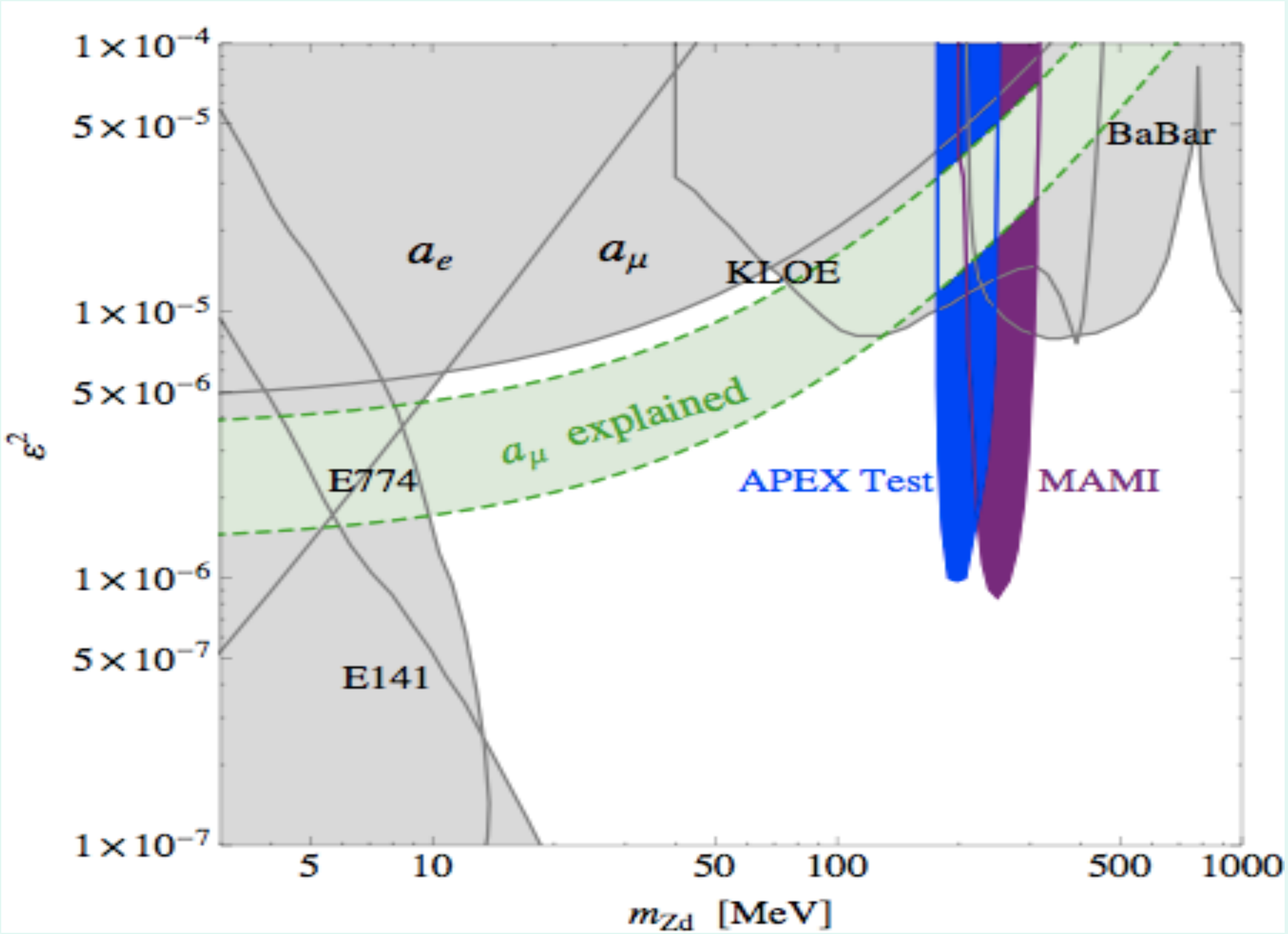
for $\varepsilon^2 \approx 10^{-6}\text{-}10^{-4}$ & $m_{Zd} \approx 10\text{-}500\mathrm{MeV}$ (see figure)

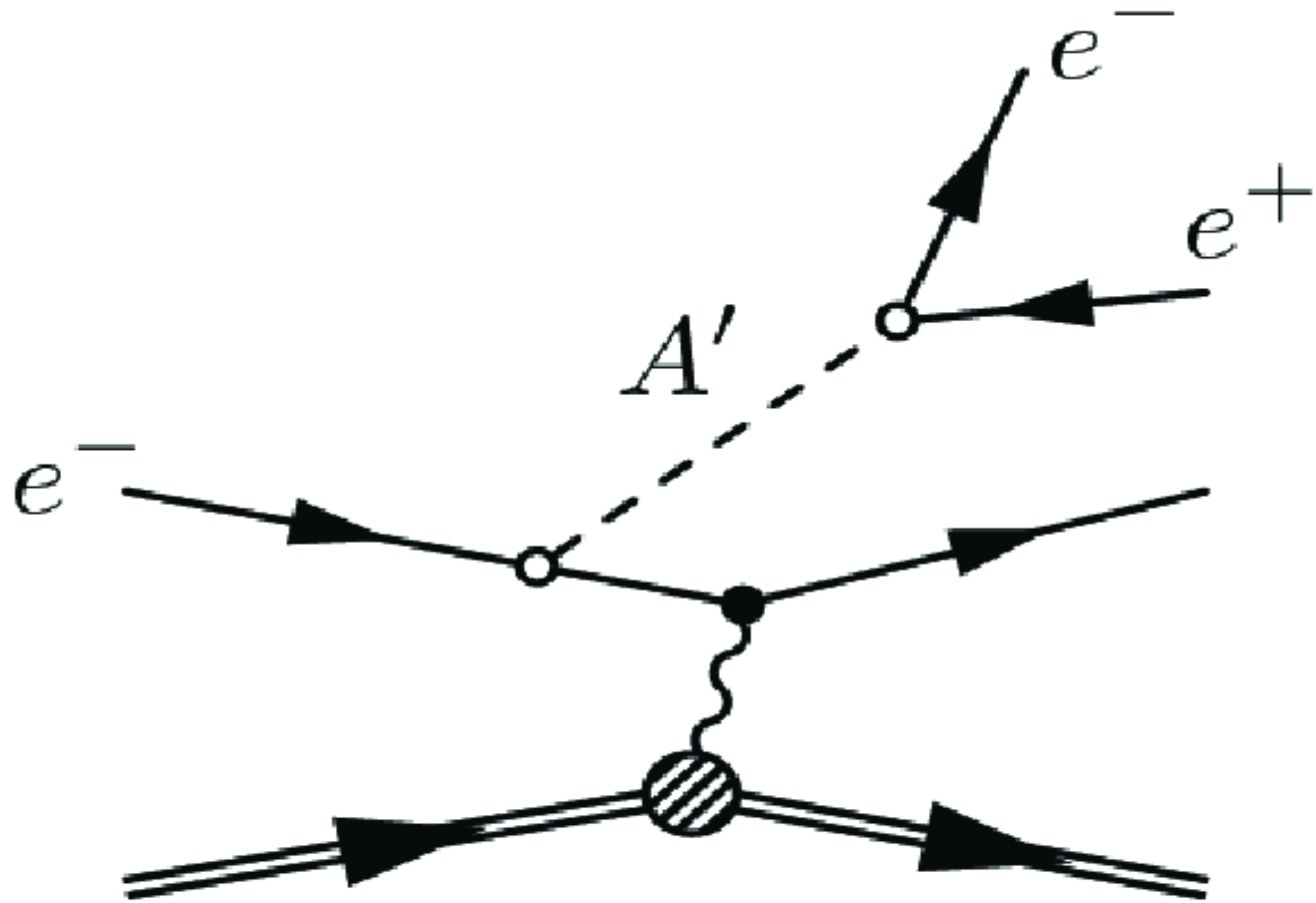
“New Physics” Effects

_SUSY 1 loop a_μ Corrections

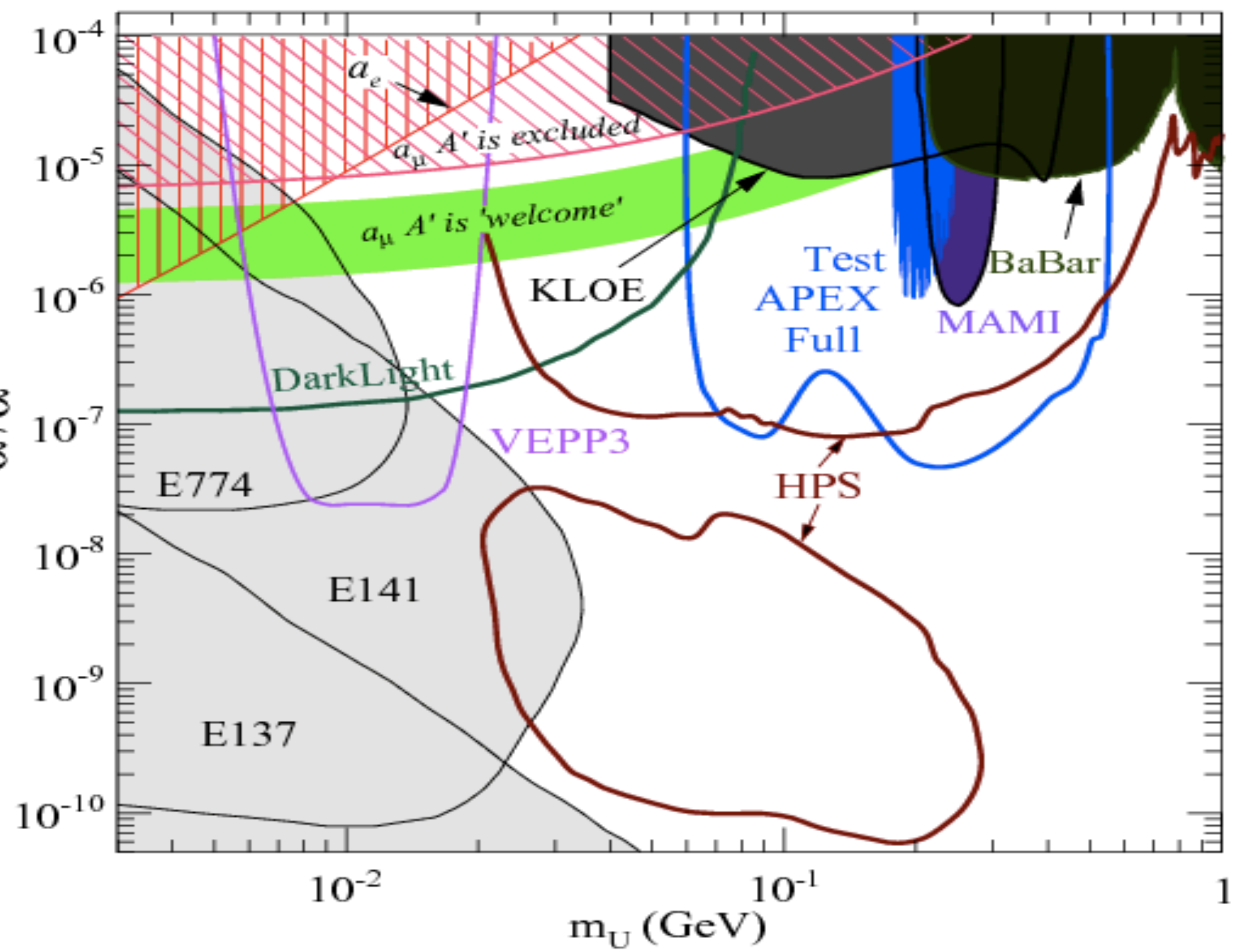


Dark Photon Exclusion




e^-
e^+
A'
e^-

JLab Future – R. McKeown (Similar Mainz Goals)



4) Electric Dipole Moments

- ***Griffith, Swallows, Loftus, Romalis, Heckel & Fortson PRL102, 101601 (2009)***
- **Some Implications of $|d_{Hg}|<3.1\times10^{-29}$e-cm**

d_p(e-cm)$<7.9\times10^{-25}$ Best

d_n(e-cm)$<5.8\times10^{-26}$ (Direct $d_n<2.9\times10^{-26}$ Best)

d_e(e-cm)$<3\times10^{-27}$ (Tl: $d_e<1.6\times10^{-27}$ Best)

Further factor 3-5 Improvement Expected!

Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources
- **$d_p \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL)**
- $d_D \rightarrow 10^{-29}$e-cm Storage Ring Proposal
- $d_e \rightarrow 10^{-30}$e-cm or better
- $d_\mu \rightarrow 10^{-24}$e-cm Storage Ring Proposal

If SUSY is responsible for Δa_μ deviation, then a susy loop induced observable edm may be right around the corner!

Source of CP Violation in Baryogenesis?

(Where is SUSY? $D \approx m/M^2_{susy}$)

d_p & d_n Relationship

Constituent Quark Model: $d_n=4/3d_d-1/3d_u$

$d_p=4/3d_u-1/3d_d$

Expect Roughly **$1/4<|d_p/d_n|\sim O(1)<4$**

Isovector $(d_p-d_n)/2$ or Isoscalar $(d_p+d_n)/2$?

Need both d_n & $d_p \rightarrow d_d$ & d_u (Relationship?)

θ_{QCD} leading effect isovector (χPT)

$d_n=-d_p\sim3.6\times10^{-16}\theta_{QCD}$ e-cm

Must Do!
PRECISION FRONTIER

- Moller & PVDIS at JLAB (ep at Mainz 150MeV)
- Atomic PV (Do Better than Cs) Parity Violating eC
- Search for "Dark" Photons (JLAB & Mainz)

- Neutron Lifetime & g_A High Precision

- Muon Anomalous Magnetic Moment (x4 at Fermilab)
- EDMs Atoms (e), n, p, D, ^{3}He…

Add to List