$\sin^2\theta_W(Q^2)$, Radiative Corrections and Z' Bosons

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"MOLLER at JLAB – A Special Opportunity"

Exp. Expertise & Very Clean Precise Theory

12 GeV Accelerator Upgrade

(Demands Flagship Experiments)

BROOKHAVEN NATIONAL LABORATORY

Outline

1. Introductory Remarks: ***$sin^2\theta_W$ Status vs SM***

Z Pole vs low Q^2 & BSM

2. EW Radiative Corrections to Moller A_{RL} PV

A. Czarnecki & WJM PRD (1996) Updated Uncertainty

-40±0.36% Total Reduction *(Running **$sin^2\theta_W(Q^2)$)!***

3. Z' Boson Sensitivity (extra U(1)' gauge symmetry)

Strong Coupling g'~ 2 $m_{Z'}$ ~ 8TeV

EW GUT Coupling g'~½ $m_{Z'}$ ~ 2TeV

Light Z' with Very Small "Induced" Coupling

(eg Dark Parity Violation) Low Q^2 Moller Sensitivity

Introductory Remarks

$\sin^2\theta_W(Q^2)$ Status Z Pole vs low Q^2

MSbar $\sin^2\theta_W(m_Z)_{MS} = \sin^2\theta_W^{lep} - 0.00028$

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

3 sigma difference? Tension?

$\sin^2\theta_W(m_Z)_{MS}$ 0.23125(15) Z Pole Ave.

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

Through 2 loops

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

Outstanding Agreement Severely constrains BSM

S & T Constraints
Gauge Boson Self-Energy Loops

Experimental Averages

$\sin^2\theta_W(m_Z)_{MS} = \underline{0.23125(15)}$ & $m_W = \underline{80.385(15)\,\text{GeV}}$

Standard Model + S & T

$\sin^2\theta_W(m_Z)_{MS} = \underline{0.23124(6)}$**[1+0.016S-0.011T]**

$m_W = \underline{80.362(6)\,\text{GeV}}[1-0.0036S+0.0056T]$

S≈0.7T (from Z pole $\sin^2\theta_W(m_Z)_{MS} = \underline{0.23125(15)}$)

S=0.07(8) T=0.10(11) $\Delta N_{doublets}$=2(2)

Little (but some) room available for "New Physics"

Constrains: New Dynamics (Technicolor),

4^{th} Generation, SUSY, Z', Z'' (mixing)…

Best Off Z Resonance Measurements of $\sin^2\theta_W$

(Not Competitive with Z Pole)

Reaction	$\sin^2\theta_W(m_Z)_{MS}$	<Q>
Cs APV	0.2283(20)	2.5MeV
E158 ee	***0.2329(13)***	***160MeV***
Q_{weak} ep	0.2329(50)	160MeV
6GeV Dis eD	0.2299(43)	1.5GeV
NuTeV ν_μN	***0.2356(16)***	***3-4GeV***

NuTeV **$\sin^2\theta_W(m_Z)_{MS}$=0.2356(16)** **(2+ sigma High)**

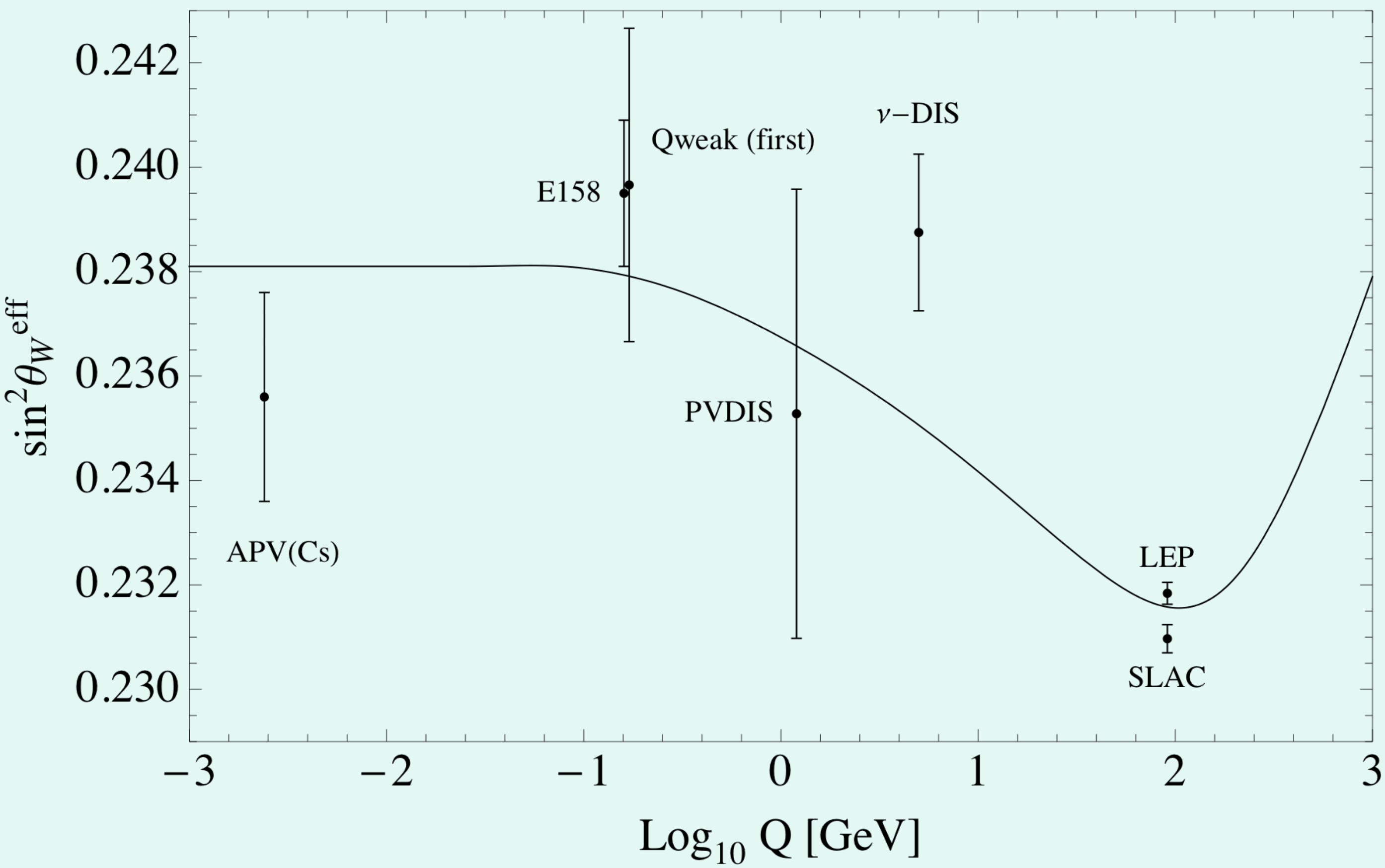
Beware The Theory Uncertainties**!!!!**

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

Best Low Q^2 Determination $\sin^2\theta_W(m_Z)_{MS}$=0.2329(13)

Very Clean Theory

Measurements of running $sin^2\theta_W(Q^2)$



E158 at SLAC Pol ee→ee Moller

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

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

EW Radiative Corrections ~-40(3)%! (Czarnecki &WJM 1996)

More $\sin^2\theta_W$ Sensitivity!

Measured to ±12% →$\sin^2\theta_W$ to ±0.6% (20 to 1)

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

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

$A_{RL}(ee)^{exp}=A_{RL}(ee)^{SM}(1+0.25T-0.34S+7(m_Z/m_{Z\chi})^2\ldots)$

Constrains "New Physics" eq $m_{Z\chi}>0.6$TeV, H^{--},S, Anapole Moment, 4 Fermion Operators …

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

$\sin^2\theta_W(m_Z)_{MS}$=0.232(1) Good agreement with Z Pole

Goals of Future Low Q^2 Experiments

- High Precision: $\Delta\sin^2\theta_W$~±0.0002 - 0.0004 or better

Low Q^2 Sensitivity to "New Physics" (eg Dark PV)

SUSY Loops Sensitivity in Moller vs SM & Z pole

(Ramsey-Musolf Talk)

S≈0.7T?, Confirm Z Pole Ave/m_W determination?

Z pole implies |0.25T-0.34S| ≤10^{-3}; ***TRUE?***,

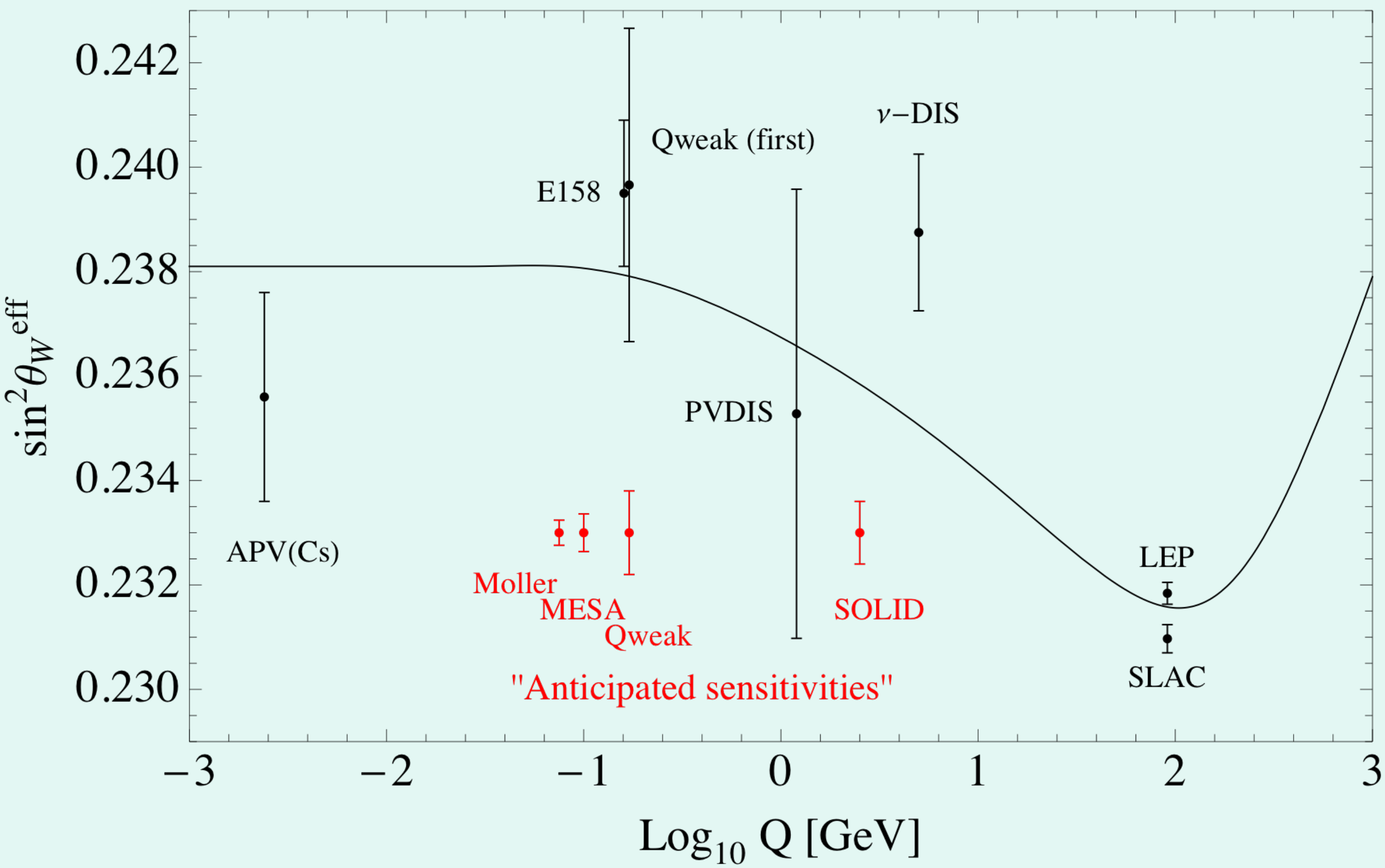
If so, Charge radius X(Q^2), Z' … of prime importance

Heavy $\boldsymbol{m_{Z'}}$ >1-8TeV, Model Dependent Sensitivities

(Do not interfere at Z Pole)

****Light*** $\boldsymbol{m_{Z'}}$< 10GeV (Dark Parity Violation) *Sensitivity*

$\sin^2\theta_W(Q^2)$ Measurements & expected Future Sensitivities



Polarized ee, ep Asymmetries

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

Experiment	<Q>MeV	$\Delta\sin^2\theta_W$	Measurement
E158 SLAC	160	±0.0013	ee Completed
Q_{weak} JLAB	160	±0.0008	ep in analysis
Moller JLAB	*75*	*±0.00027*	*ee approved*
MESA (ep) P2	50-100?	±0.00037	ep Low Energy

Also improve: APV, DISeD, Neutrino Scattering…

Polarized Moller at JLAB

After 12GeV Upgrade (4 x lower E & Q^2)

$A_{RL}(ee \rightarrow ee)$ to ±2.4%

$\Delta \sin^2\theta_W(m_Z)_{MS} = \pm 0.00027$!

Comparable to Z pole studies!

$A_{RL}(ee)^{exp} = A_{RL}(ee)^{SM}(1+0.25T-0.34S+7(m_Z/m_{Z\chi})^2\ldots)$

Explores $m_{Z\chi} \rightarrow$ 2TeV Better than APV, S=0.7T etc.

Future JLAB Flagship Experiment!

Unique Opportunity

Standard for Future Proposals

EW Radiative Corrections to Moller A_{RL}(-40%)

A. Czarnecki & WJM PRD(1996)

- $A_{RL}(ee) = \alpha\,(1-4\sin^2\theta_W)$ $\sin^2\theta_W(m_Z)_{MS}$= <u>0.23124(6)</u> or
  running + $3.01(25)_{hadronic}$%
  $\sin^2\theta_W(Q=0)$ = <u>0.23820(60)</u>

  + WWbox (+3.6%) γZbox…(-5.5%) partial cancellation
  + other small 1 loop corrections ➔ -40(3)% reduction!

  E158 $\Delta A_{RL}/A_{RL}$ =±12.5% vs Running unc. ±6%?

Erler & Ramsey-Musolf ➔ factor of 8.6 error reduction!

+3.01(25)%➔+2.99(3)% <u>Theory ±0.6% vs Moller exp ±2.4%</u>

$\Delta\sin^2\theta_W^{RC}$~±0.00007! Pristine

Potentially another factor of 2 reduction via lattice

1 loop contributions to $\boldsymbol{sin^2\theta_W(Q^2)}$ running

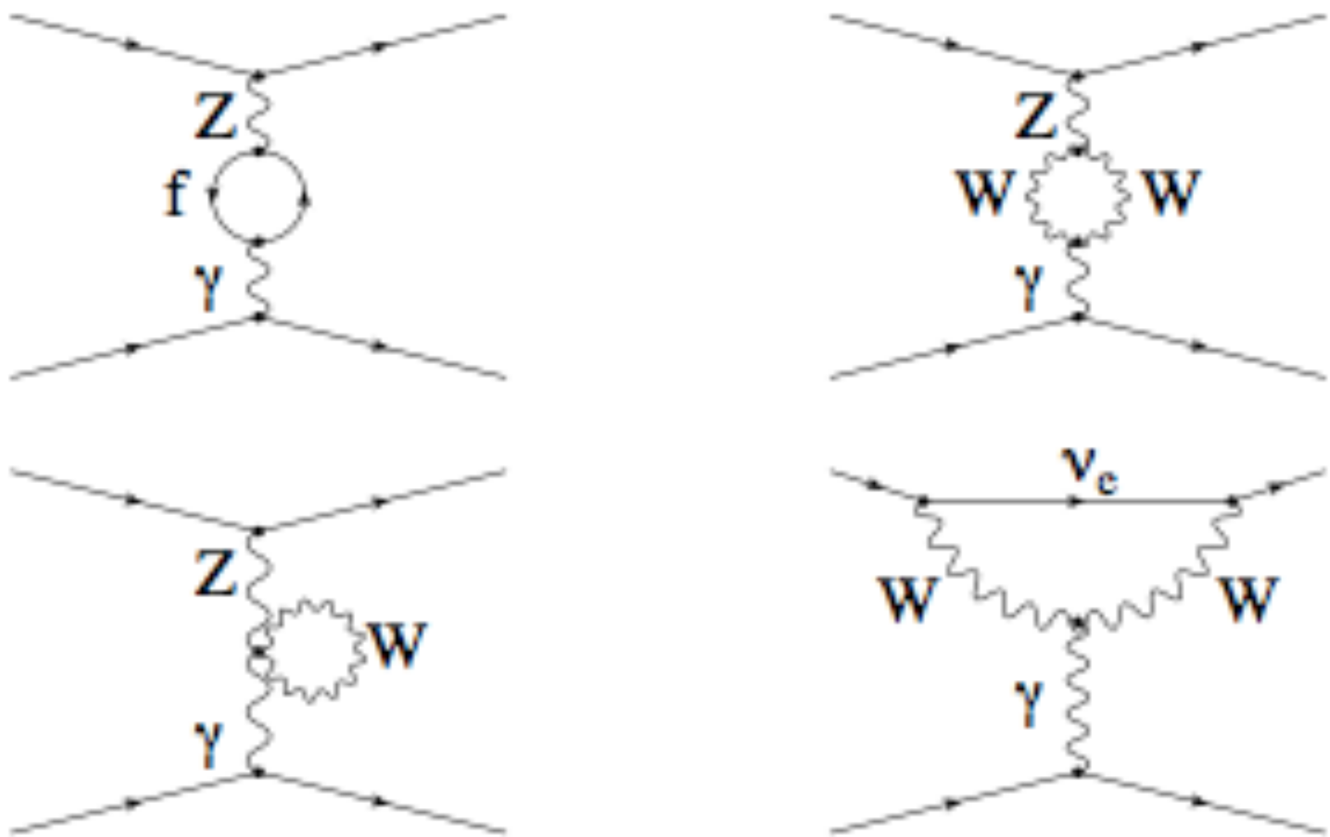


Fig. 2. $\gamma - Z$ mixing diagrams and W-loop contribution to the anapole moment.

Box Diagrams (tend to cancel)➔ very small 2 loop uncertainty ($\Delta A_{RL}/A_{RL}$ ~ ±0.3%)

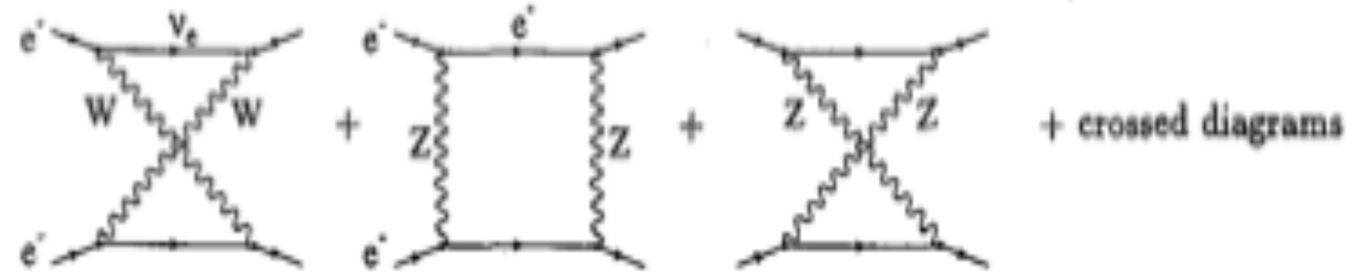


FIG. 3. Box diagrams with two heavy bosons.

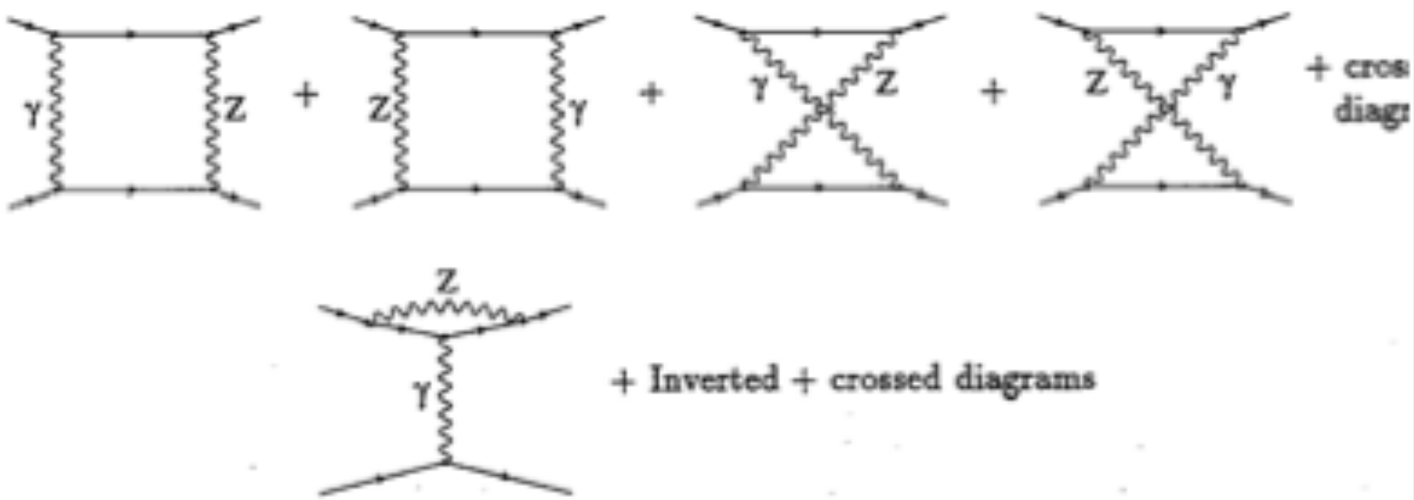


FIG. 4. Boxes containing one photon and Z-loop contribution to the anapole moment.

Z' Boson Sensitivity (extra U(1)' gauge symmetry

Conesquences of $A_{RL}(ee \rightarrow ee)$ to ±2.4%

$$\mathbf{\Delta sin^2\theta_W(m_Z)_{MS} = \pm 0.00027!}$$

$$A_{RL}(ee)^{exp} = A_{RL}(ee)^{SM}(1+0.25T-0.34S+7(m_Z/m_{Z\chi})^2 \ldots$$
$$+0.7R(0) + SUSY + H^{--} \ldots)$$

Z pole $\mathbf{sin^2\theta_W(m_Z)_{MS}}$ ➔ 0.25T-0.34S very small. ***Is it?***

SM agreement significantly constrains BSM

Deviation Implies New Physics (Many Z' Examples)

Complements LHC Z' Direct Discovery 1-8TeV

(LHC Requires relatively large Z' production & l^+l^- BR)

(Potentially) Watered down by BSM decay modes

Examples

$U(1)_{\chi}$, $U(1)_{\psi}$ of E_6 GUT (Mix) ≤2TeV sensitivity
Much Stronger coupling ➔ Better Sensitivity ➔ O(8TeV)

$U(1)_{B-L}$, $U(1)_{Le-L\mu}$, $U(1)_{SUSY}$… Many Heavy Z' Examples

LHC Sensitivity may be diluted by reduced l^+l^- BRs

Light Z' bosons with very weak SM couplings ~ 10^{-3}-10^{-6}g
I will illustrate **dark Z** model of **(DAVOUDIASL, LEE, MARCIANO)**
GENERALIZATION OF DARK PHOTON MODEL

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, U Boson, Hidden Boson… Dark Z (Z_d)*

Introduced for: 1) Sommerfeld Enhancement D+D➔Z_d+Z_d

2) Z_d➔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?

Dark Photon & Dark Z

Interacts with our particle world via

1) Kinetic Mixing $U(1)_Y x U(1)_d$ $\varepsilon e Z_d^\mu J_\mu^{em}$ $\varepsilon \approx \alpha/\pi \approx 2x10^{-3}$

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(80)x10^{-11}$ (*3.6σ discrepancy!*)

$\approx \frac{1}{4}(\alpha/\pi)\varepsilon^2$ $m_{Zd} \approx$20-300MeV (see figure)

2) Z-Z_d Mass Mixing: $\varepsilon_Z g/2\cos\theta_W Z_d^\mu J_\mu^{NC}$ $\varepsilon_Z = m_{Zd}/m_Z \delta$ $\delta \approx 10^{-3}$ $(\sim v_1^2/v_2 v_s)$

Induced by extended Higgs (2 doublets + sing.) Portal

Rare Higgs→ZZ_d, K→πZ_d & B→KZ_d decays ~ δ^2,

Dark Parity Violation (probes $\delta \approx 2x10^{-3}$ $\varepsilon \approx 2x10^{-3}$)

(DAVOUDIASL, LEE, MARCIANO) ***Enhanced Phenomenology***

3) Small direct coupling eg. $U(1)_{Le-L\mu}$ ~ few $x10^{-3}$e

Example

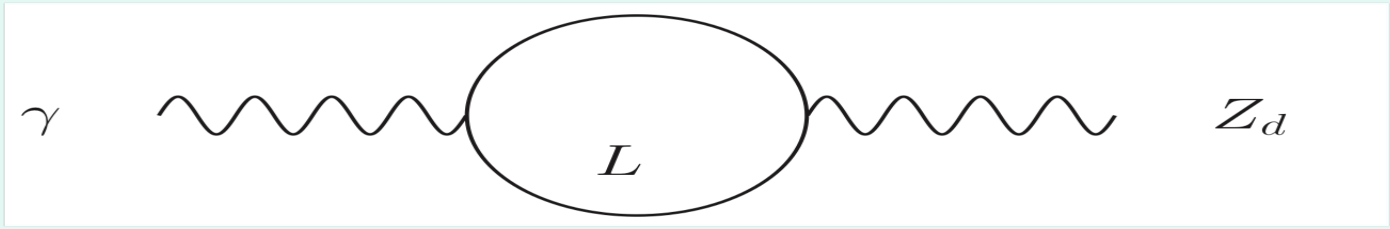
One Loop gamma-γ_d Kinetic Mixing

$\varepsilon F_{\mu\nu} D^{\mu\nu}$

(eg Through Heavy Charged Leptons)

That also carry $U(1)_d$ charge

Expect $\varepsilon \sim e g_d Q Q_d / 8\pi^2 \leq O(10^{-3})$

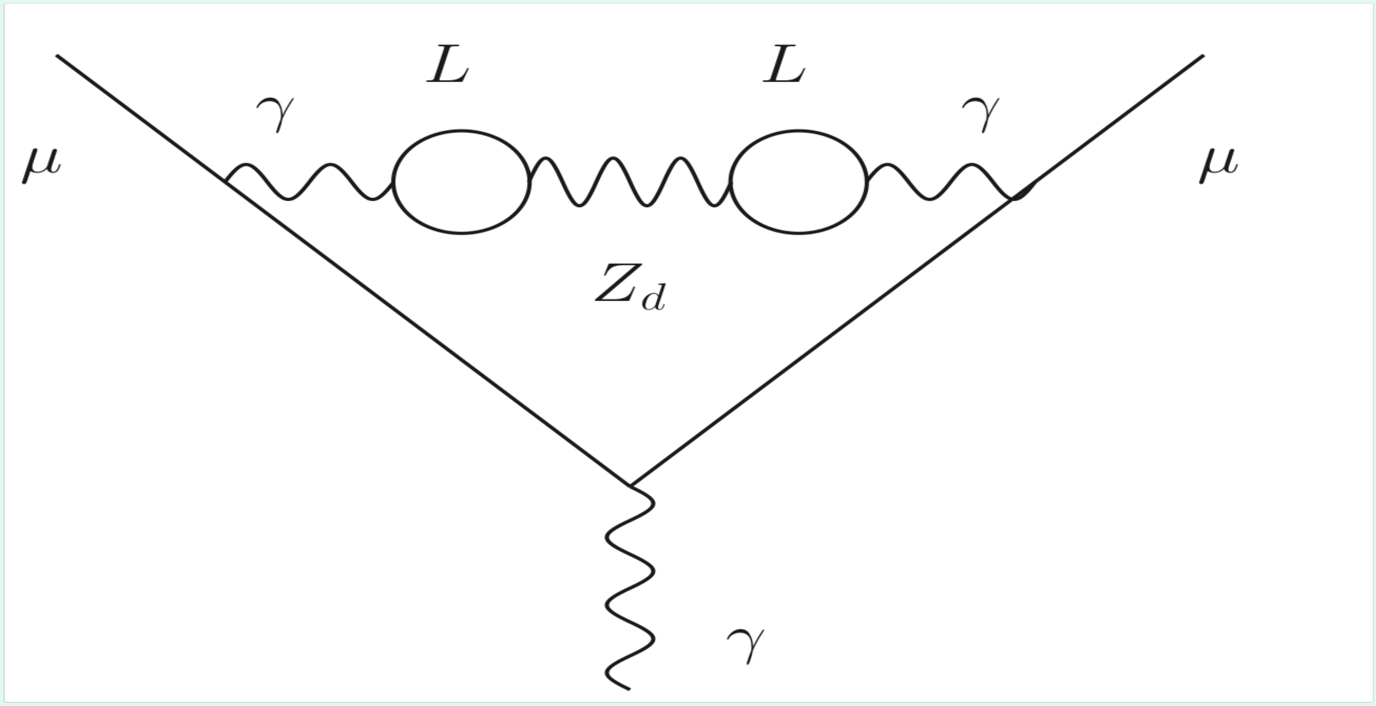


Muon Anomalous Magnetic Moment

$a_\mu^{Zd} = \alpha/2\pi \varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$

solves $(g_\mu-2)/2$ discrepancy ≈ $288(80)\times10^{-11}$

for $\varepsilon^2 \approx 10^{-6}-10^{-4}$ & $m_{Zd} \approx 10-300$MeV (see figure)

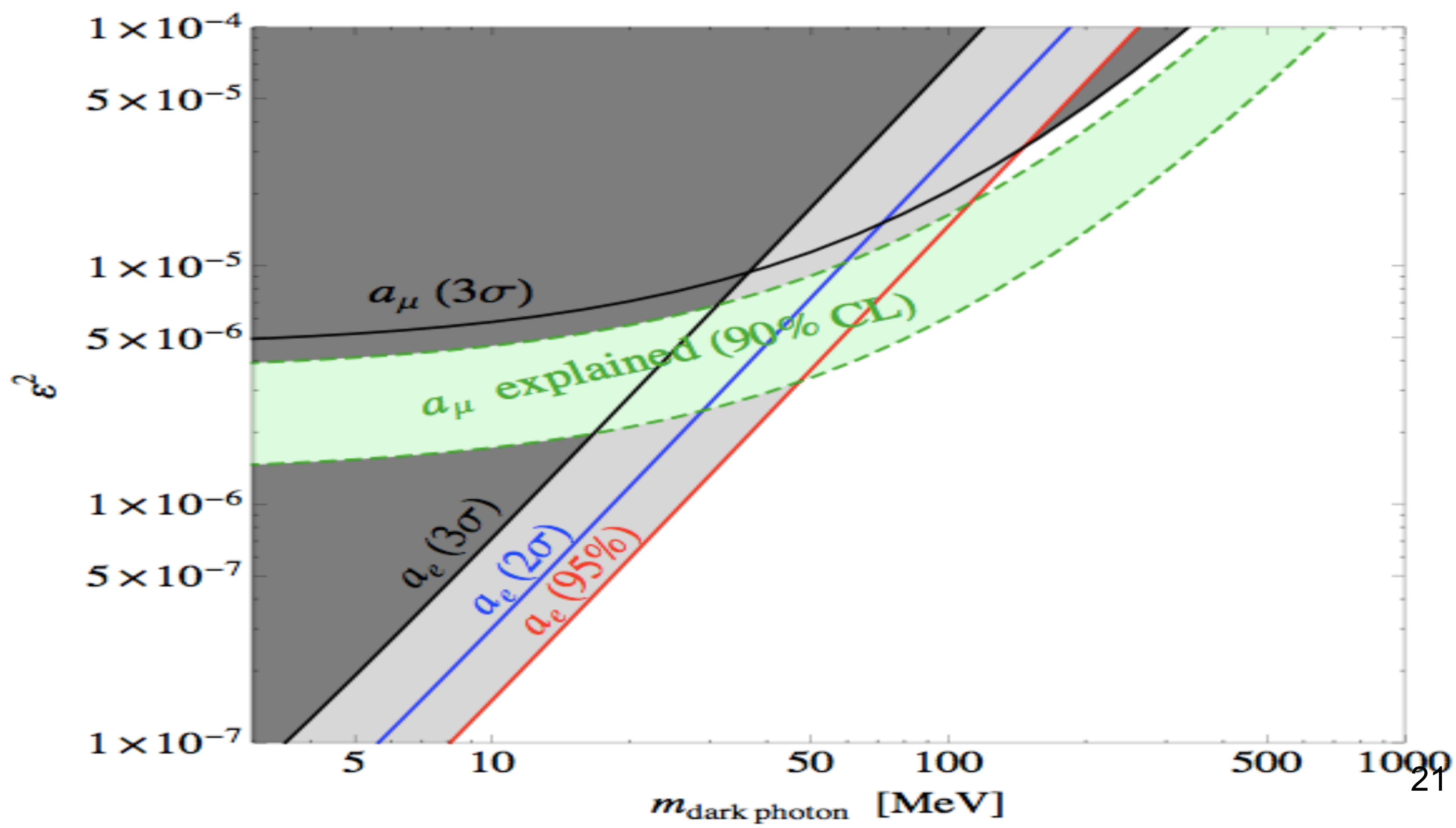


Lepton Magnetic Moment Constraints on the Dark Photon

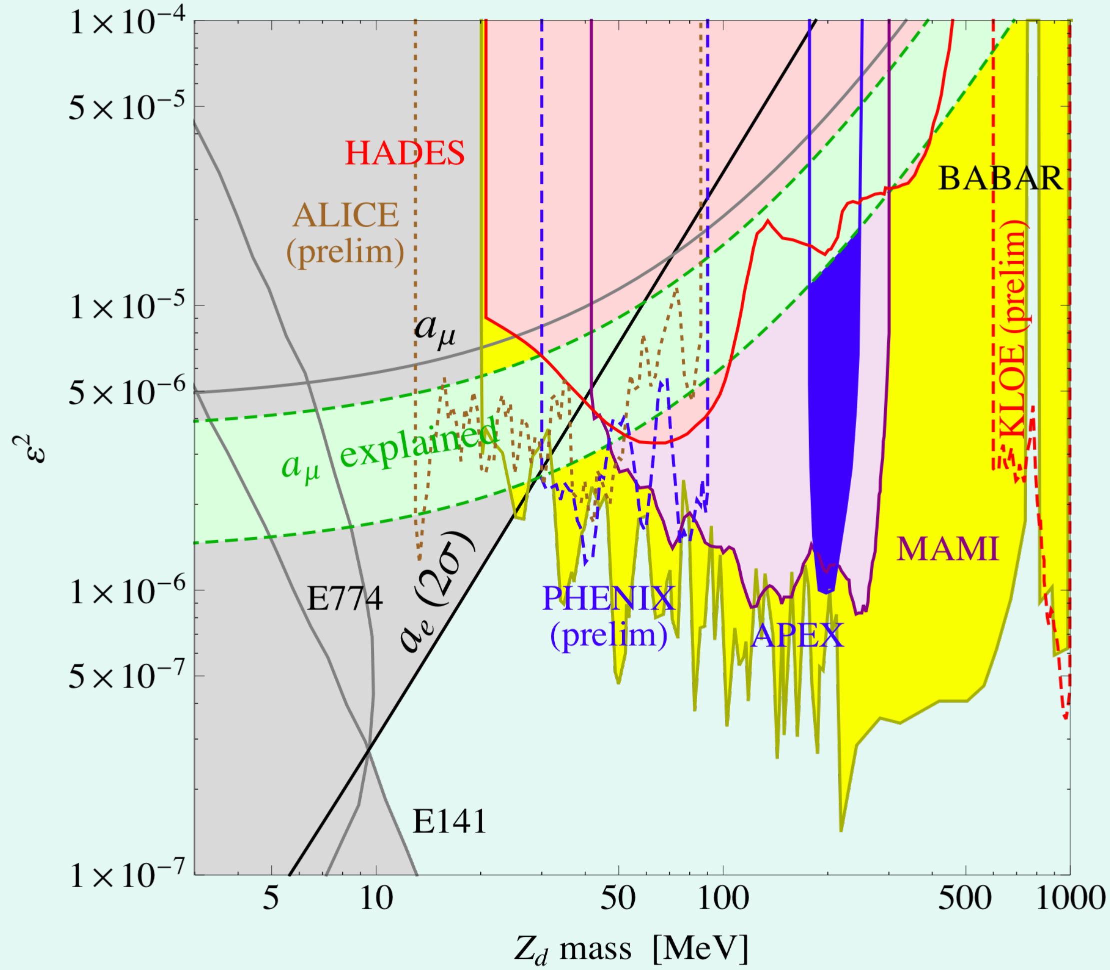
Green Band Corresponds to **a_μ^{exp}-a_μ^{SM}=288(63)(49)x10^{-11} 90% CL**

g_e-2 Constraint DAVOUDIASL, LEE, MARCIANO

a_e(exp) − a_e(theory) = −1.05 (0.81) × 10^{-12} wrong sign!



Current Dark Photon Constraints
Assuming BR(Z_d ➔ e+e-) ~1



Dark Photon/Z Muon g-2 Solution (Currently)

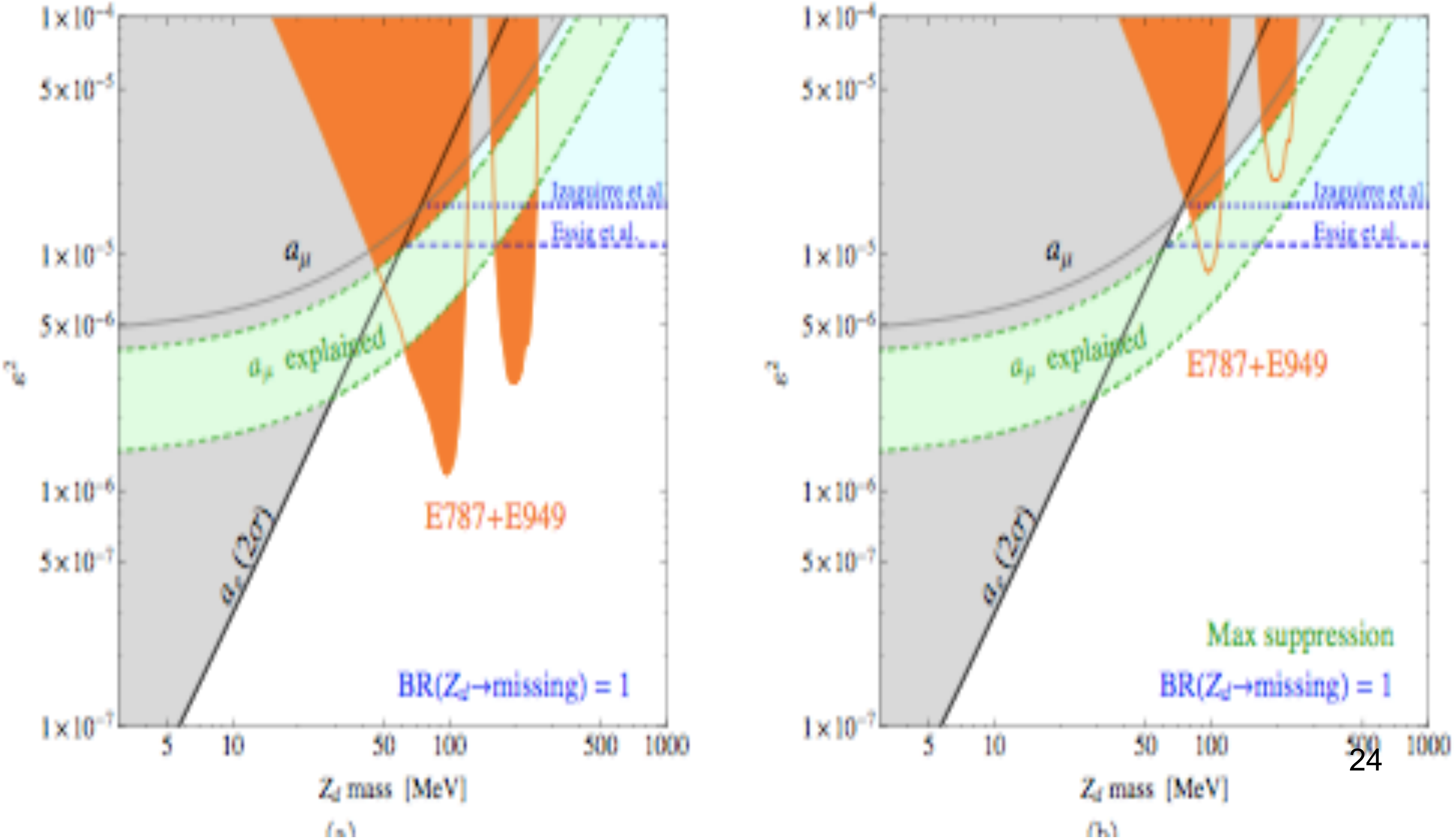
Recent direct searches for $Z_d \rightarrow e^+e^-$
Significantly constrain Muon g-2 solution
To $m_{Z_d} \sim$ 20-36MeV (eg Recent Phenix paper), BaBar

Response: Now we know where it is!
Or make BR($Z_d \rightarrow e^+e^-$) <<1
Introduce very light dark particle decays $Z_d \rightarrow$ missing energy

K➔$\pi^+ Z_d$ Constraints for BR(Z_d➔*dark matter*)~1

m_{Z_d}=100, 200MeV ruled out? ε – ε_Z Interference?

H. DAVOUDIASL, H-S LEE, W. MARCIANO



Dark Parity Violation

H. DAVOUDIASL, H-S LEE, W. MARCIANO

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

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

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

Shift largest at small $Q^2 < m_{Zd}^2$ ($\approx$O(1%)! Eg APV)

(1.5 sigma APV deviation) fit ➔ $\varepsilon\delta = 4\text{x}10^{-6}$

or $\varepsilon \approx \delta \approx 2\text{x}10^{-3}$ for (g_μ-2) & APV ➔ $m_{Zd} \approx$ 50MeV region

$\sin^2\theta_W$(Q≈75MeV) shift by ±O(0.5-1%)!!

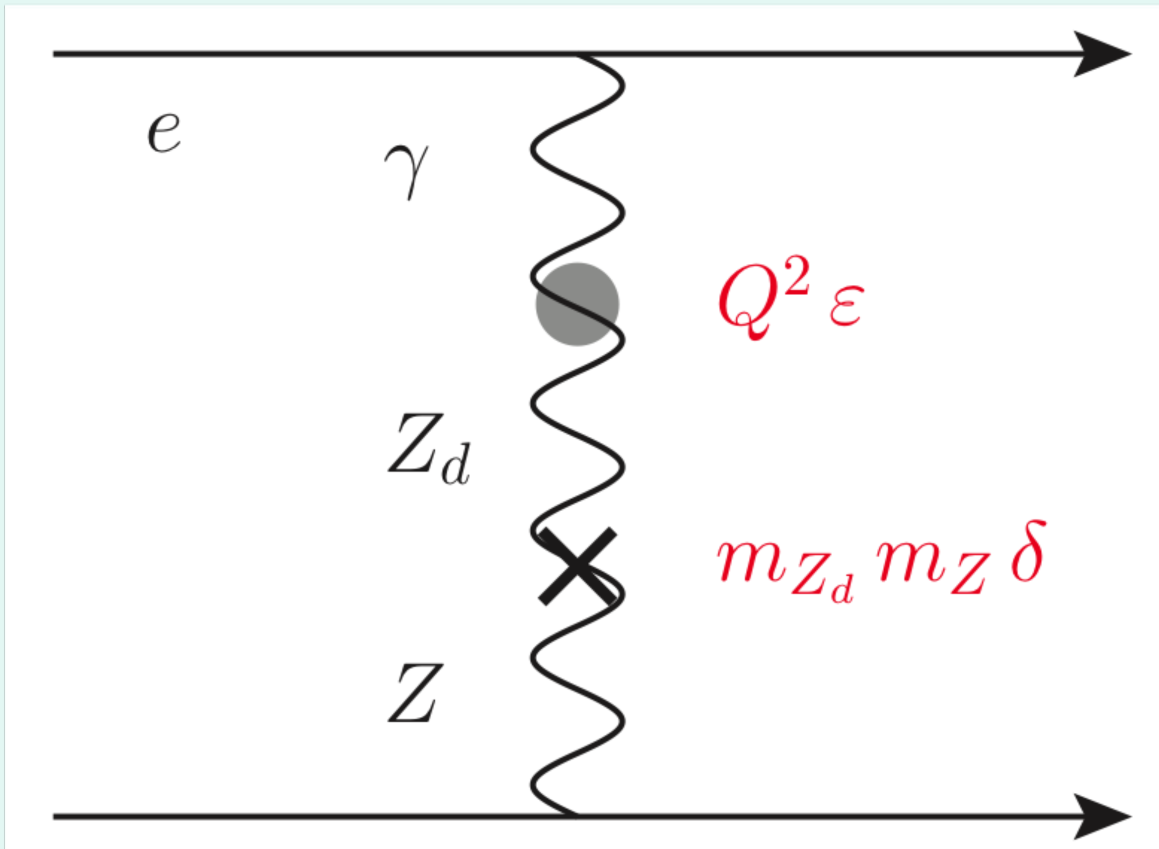
$\varepsilon\delta$ down to $\approx 10^{-6}$ Potentially Observable

A_{RL}(ee) at low Q^2 very Important

Dark Z Effect on electron scattering

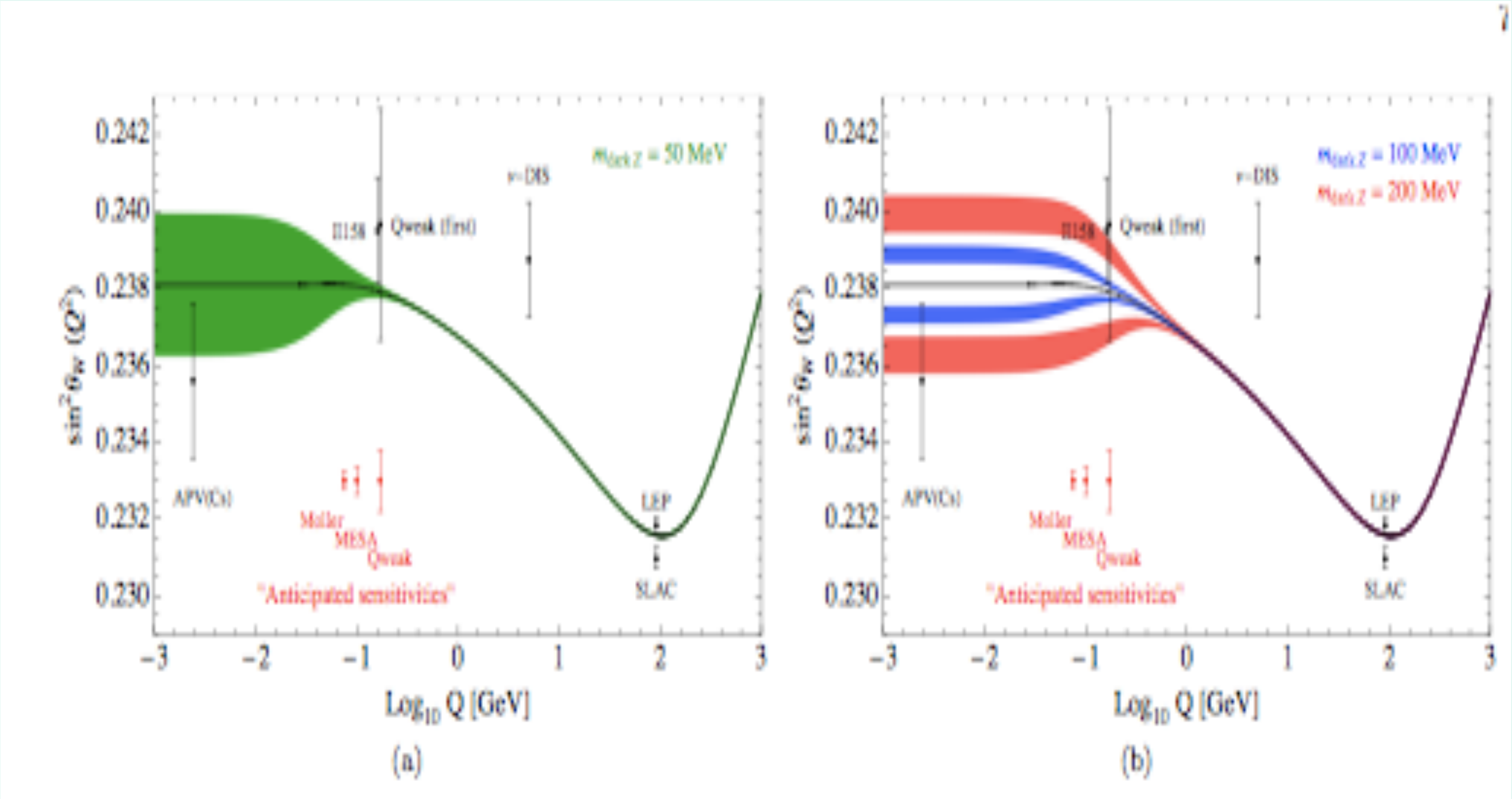
Photon-Z Mixing through Z_d

from H-S Lee

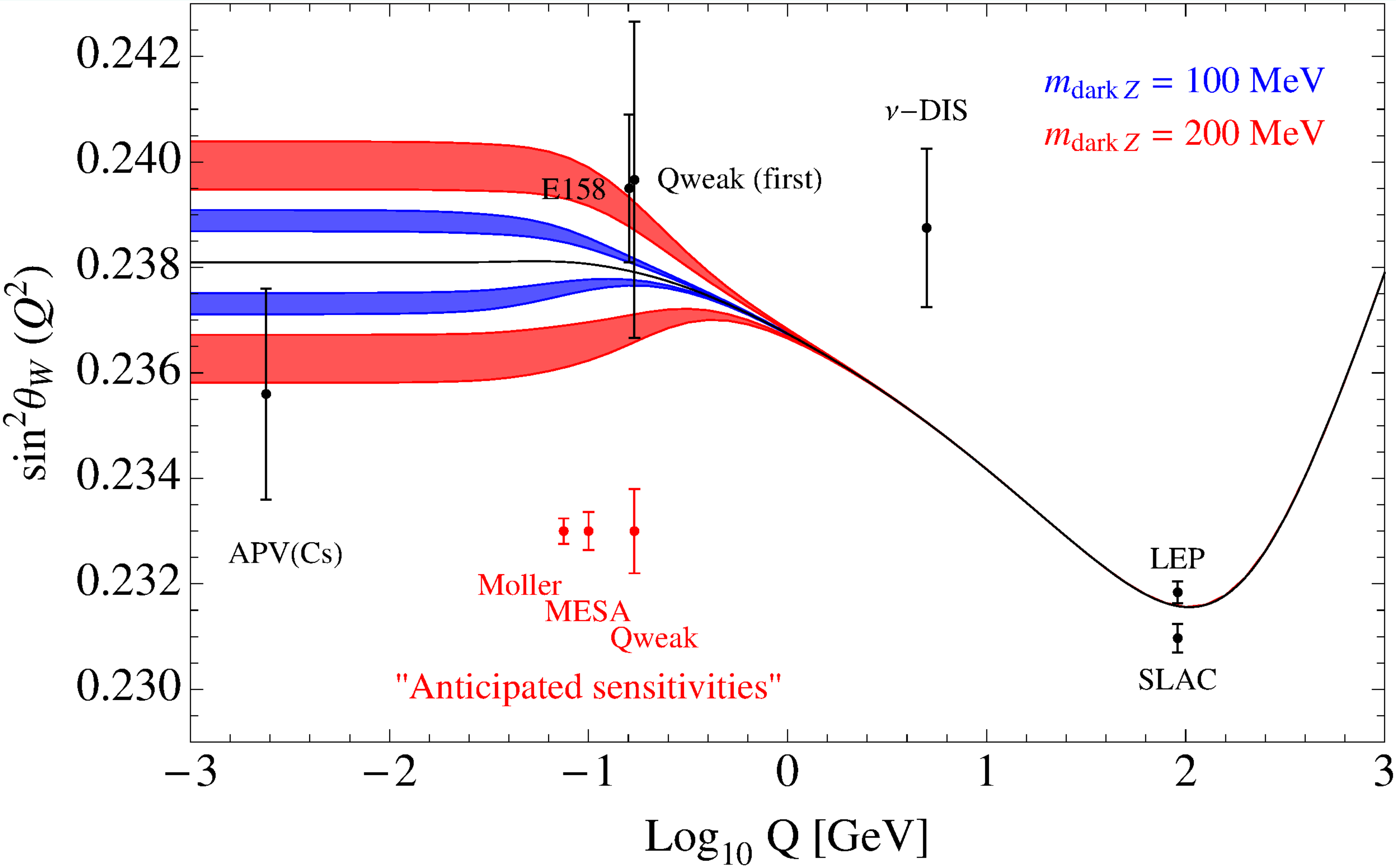


Effect of "Light" Z_d on Running

H. DAVOUDIASL, H-S LEE, W. MARCIANO



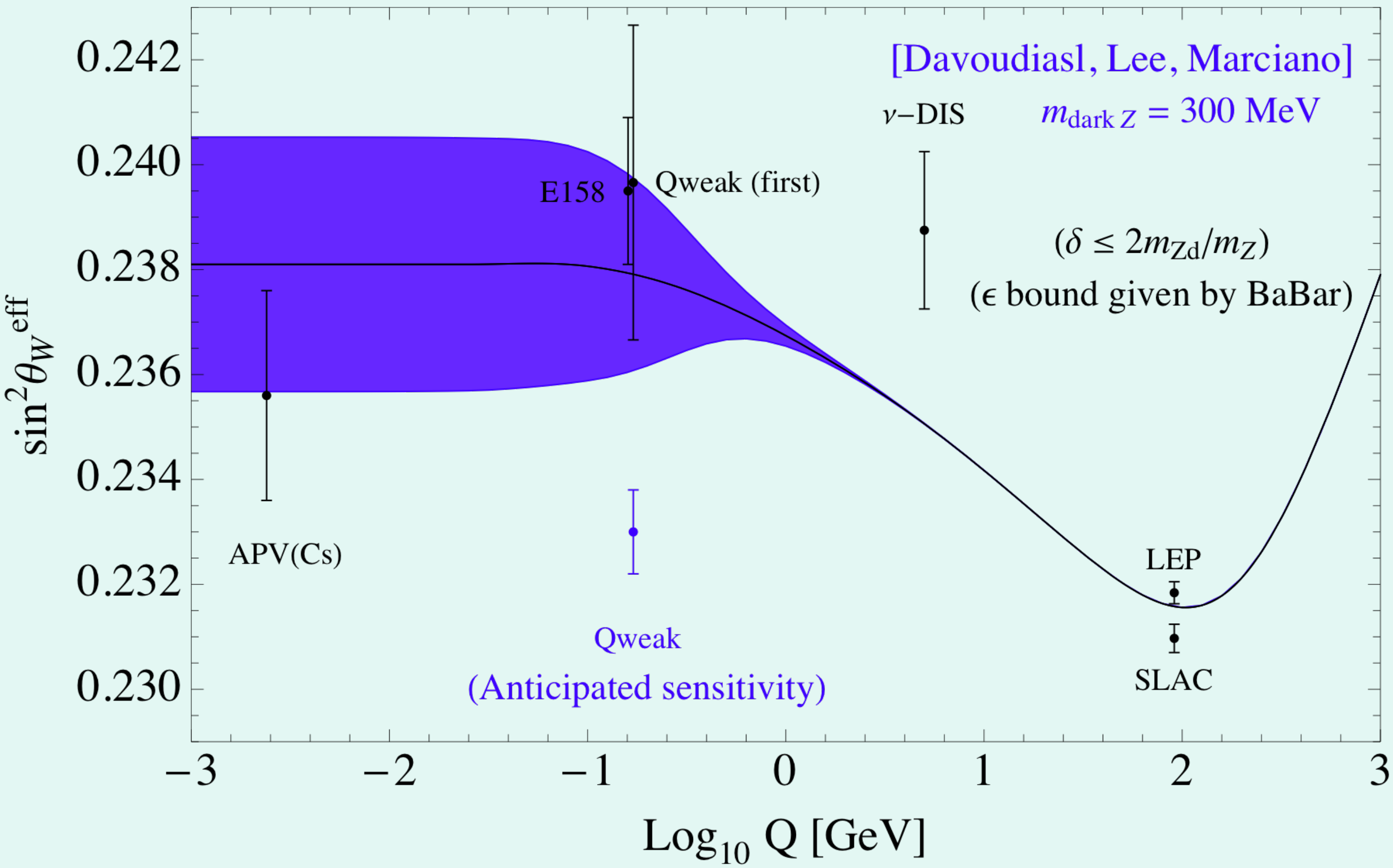
Blowup



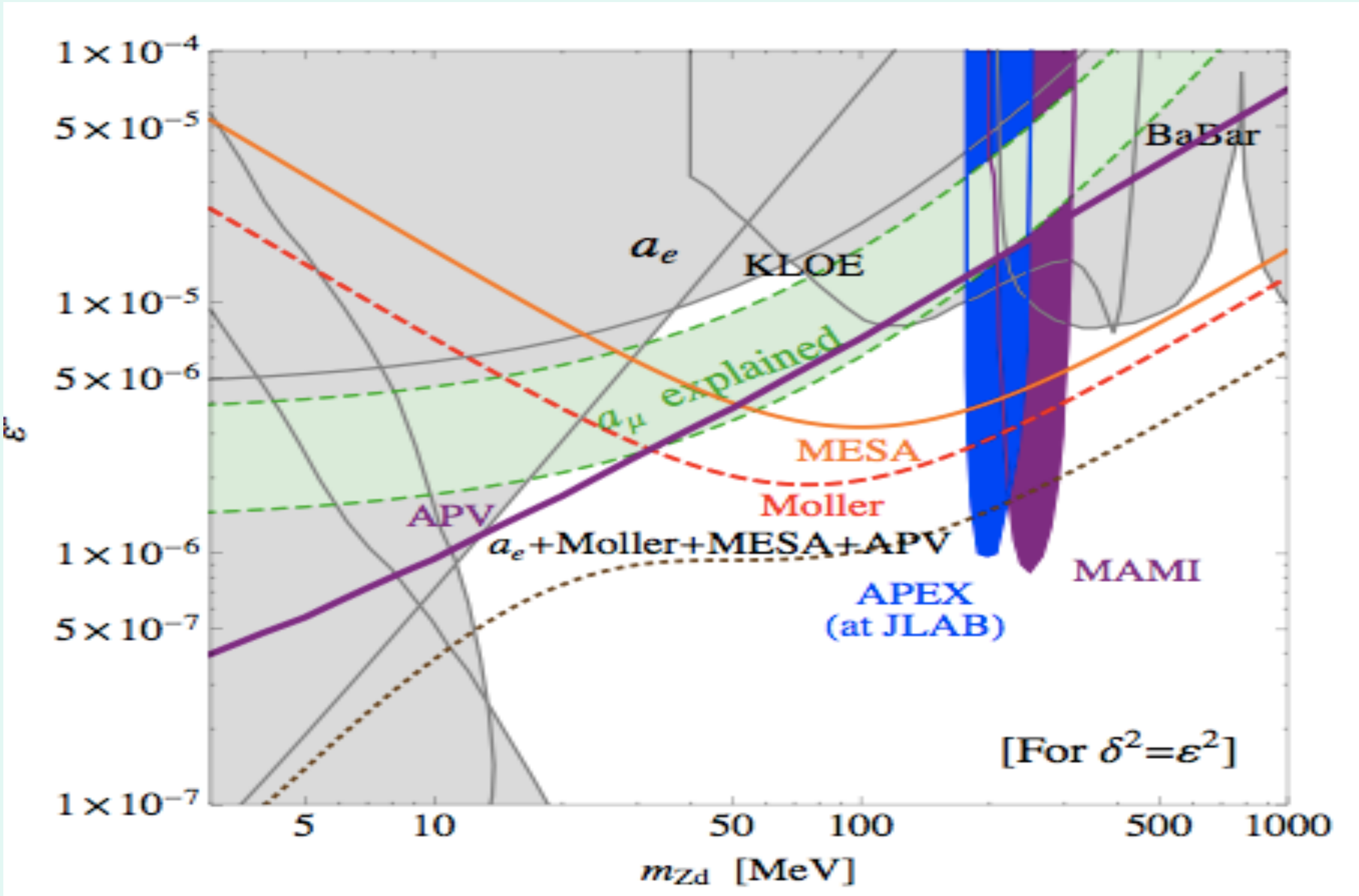
0.242
0.240
0.238
0.236
0.234
0.232
0.230
$\sin^2\theta_W\,(Q^2)$
$m_{\text{dark}\,Z}$ = 100 MeV
$m_{\text{dark}\,Z}$ = 200 MeV
ν−DIS
E158
Qweak (first)
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC
−3
−2
−1
0
1
2
3
Log$_{10}$ Q [GeV]

Potential 300MeV Dark Z Effects on Running

$0 < |\sin^2\theta_W(0)| < 0.002$ Start to show up in Qweak



a_e & Polarized e^- Parity Violation Sensitivity
(Old slide pre experimental updates)



Motivation for Moller

Very Clean, Precise, $\sin^2\theta_W(Q^2)$ Experiment at Q=75MeV

Factor 4 lower Q^2 relative to E158 actually improves theory!

Goal $\Delta\sin^2\theta_W(m_Z)_{MS}=\pm0.00027$! (Z pole competitive)

Unique hadronic $\Delta\sin^2\theta_W^{RC}\sim\pm0.00007$! Pristine SM Theory

No Interpretation Ambiguity!

Competitive & Complementary to Z pole & LHC measurements

Best low Q^2 opportunity for at least 10 years

“New Physics” egs. Heavy(>1TeV) or Light (<10GeV) Z’

Potential 5 sigma Discovery

JLAB Flagship - Must Do Experiment

Challenges Advance Physics (eg APV)