$\sin^2\theta_W(Q^2)$, Radiative Corrections & "New Physics"

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"The Weak Mixing Angle, $\sin^2\theta_W$, is a very special parameter that confirmed the Standard Model and continues to constrain and probe New Physics beyond it"

BROOKHAVEN NATIONAL LABORATORY

Early History of Electroweak Unification & $sin^2\theta_W$

Algebra of $SU(2)_L x U(1)_Y$ mixing **Glashow 1961**

$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$ photon

$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W$ Z boson

$\tan\theta_W = g'/g$

Spontaneous Symmetry Breaking via Higgs Mechanism

Scalar Doublet ➔ Masses **Weinberg 1967**

$m_W = m_Z \cos\theta_W$ Higgs Boson!

Renormalizable ➔ Finite Predictions **'t Hooft 1971**

Experiment takes over

1973 Weak Neutral Currents Discovered! $\nu_\mu e$

Early Atomic Parity Violation Ambiguous

$SU(2)_L x U(1)_Y$ in some peril.

1978 DIS polarized eD at SLAC (E122)

Prescott et al. observe γ-Z interference

Confirm $SU(2)_L x U(1)_Y$

$\sin^2\theta_W$=0.22(2) lend support to GUTS

Should have received a Nobel Prize

Outline

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

   Z Pole vs low Q^2 & BSM

2. ***EW Radiative Corrections***

   (Running ***$\sin^2\theta_W(Q^2)$) & Parity Violating Asymmetries***

   Moller(ee) vs P2 (ep) Loop Effects

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

   Heavy Z' up to ~ 8TeV

   Light Z' with Very Small "Induced" Couplings

   (eg Dark Parity Violation DAVOUDIASL, LEE, WJM)

Precision EW Parameters (status 2008 vs 2014):

Quantity	2008 Value		2014 Value	Comment
α^{-1}	137.035999084(51)		***137.035999049(90)***	$\alpha^{-1}(a_e)$ vs α^{-1}(Rb)
G_μ	$1.16637(1)\text{x}10^{-5}\text{GeV}^{-2}$		$1.1663787(6)\text{x}10^{-5}\text{GeV}^{-2}$	$\tau_{\mu+}$ PSI
m_Z	91 .1875(21)GeV		91.1876(21)GeV	-
*m_t	171.4(2.1)GeV	→	173.3(0.8)GeV	FNAL/LHC
*m_H	>114GeV	→	125-126GeV	
m_W	80.410(32)GeV	→	80.385(15)GeV	LEP2/FNAL
$\sin^2\theta_W(m_Z)$	0.23070(26)		0.23070(26)	SLAC A_{LR}
$\sin^2\theta_W(m_Z)$	0.23193(29)		0.23193(29)	CERN A_{FB}(bb)
	(3 sigma difference?)			
$\sin^2\theta_W(m_Z)_{ave}$	0.23125(16)		0.23125(16)	Z Pole Ave.

A Beautiful Relation

$SU(2)_L xU(1)_Y$ + 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!
Demonstrated by Bollini, Giambiagi & Sirlin (1972)

WJM(1974) Thesis: Finite Parts Calculated

but model incomplete: Charm, QCD, 3rd Generation?

time not quite right for full EW Radiative Corrections

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

Later: Large $\alpha m^2_t/m^2_W$ Corrections M. Veltman

Standard Model Predictions Through 2 loops Assuming No New Physics

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

$\Delta r(m_Z)_{MS}=0.0693(2)$ ➔ $\sin^2\theta_W(m_Z)_{MS}=\underline{0.23110(9)}$

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

$\Delta r'(m_t,m_H)=0.0598(2)$ ➔ $\sin^2\theta_W(m_Z)_{MS}=\underline{0.23124(6)}$
±0.03%

Error Expected to be reduced (improved m_t) to ~ ±0.01%

Corresponds to $m_W=80.362(6)$

Any significant difference with other precise $\sin^2\theta_W$ measurement Implies "New Physics"

Currently $\sin^2\theta_W(m_Z)_{ave}$= 0.23125(16) Excellent Agreement

Evidence for Grand Unification?

In simplest GUTS (SU(5), SO(10)…) $\sin^2\theta^0_W$=3/8 at unification

$\sin^2\theta_W(m_Z)_{MS}=3/8[1-109\alpha/18\pi\ln(m_X/m_Z)+\ldots]$

≈0.21! (Great Desert?)

$\mu=m_X\sim 2\times10^{14}$GeV in minimal SU(5)

But later, minimal SU(5) ruled out by proton decay

exps $\tau(p\rightarrow e^+\pi^0)>10^{33}$yr $\rightarrow m_X>3\times10^{15}$GeV

SUSY GUT Unification ($m_{susy}\sim$1TeV)$\rightarrow m_X\sim10^{16}$GeV

$\tau_p\sim10^{35}-10^{36}$yr

SUSY **$\sin^2\theta_W(m_Z)_{MS}$=0.233 (Current Agreement!)**

(Where is SUSY at the LHC?)

S & T Constraints
Gauge Boson Self-Energy Loops

Experimental Averages

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

Standard Model + S & T

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

m_W = 80.362(6)GeV[1-0.0036S+0.0056T]

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

4th 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(30)	160MeV
6GeV Dis eD	0.2299(43)	1.5GeV
NuTeV $\nu_\mu N$	0.2356(16)	3-4GeV

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

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

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

Waiting for Qweak

E158 at SLAC Pol $ee \to ee$ Moller)

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

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

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

More $\sin^2\theta_W$ Sensitivity!

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

$\to \sin^2\theta_W(m_Z)_{MS} =$ 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 $\to \sin^2\theta_W(Q^2)$ running

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

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

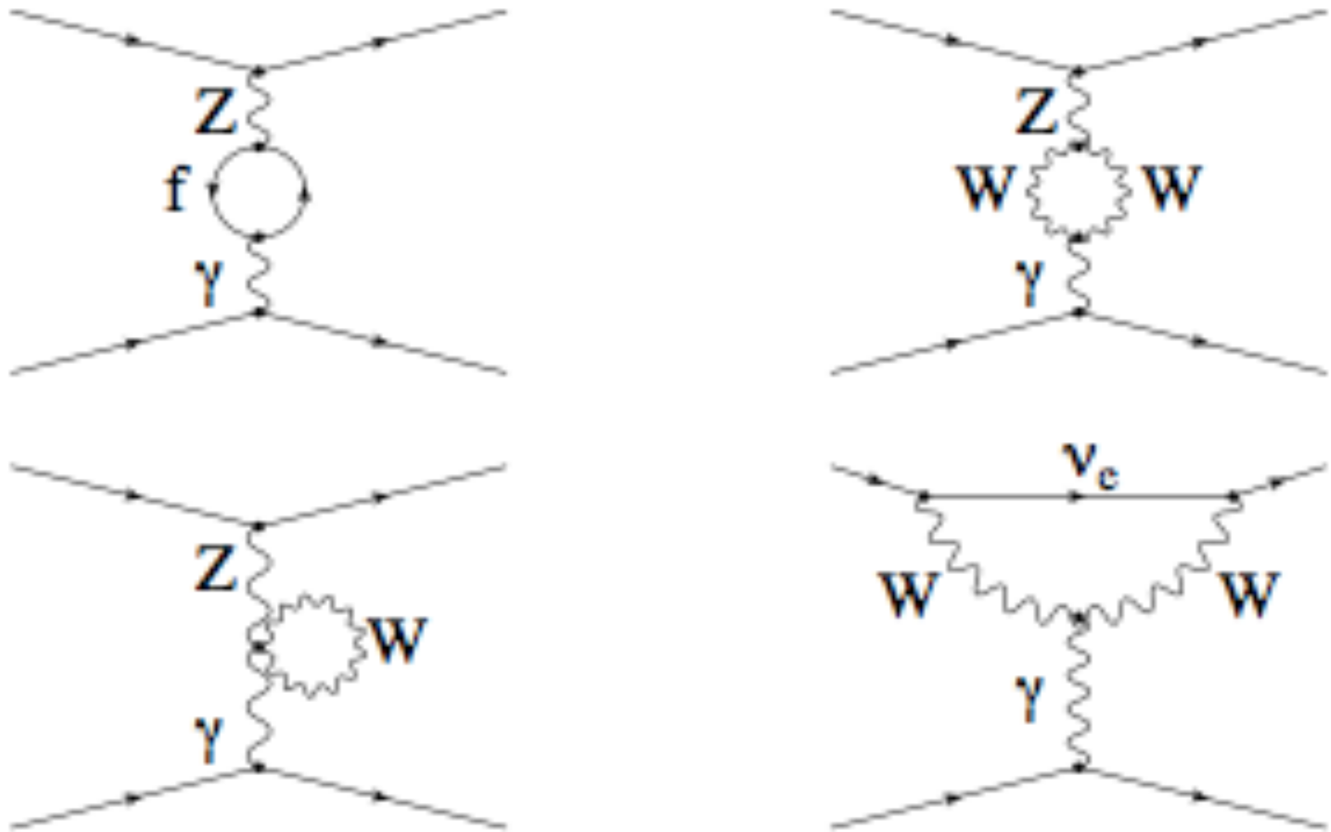


Fig. 2. $\gamma - Z$ mixing diagrams and W-loop contribution to the anapole moment.

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

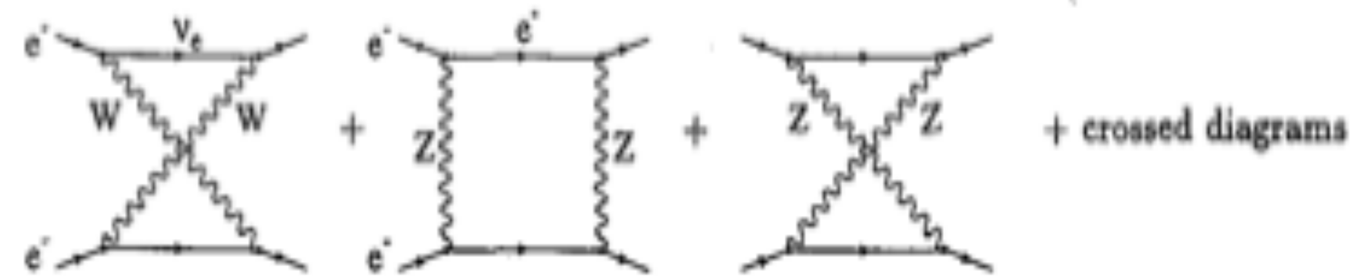


FIG. 3. Box diagrams with two heavy bosons.

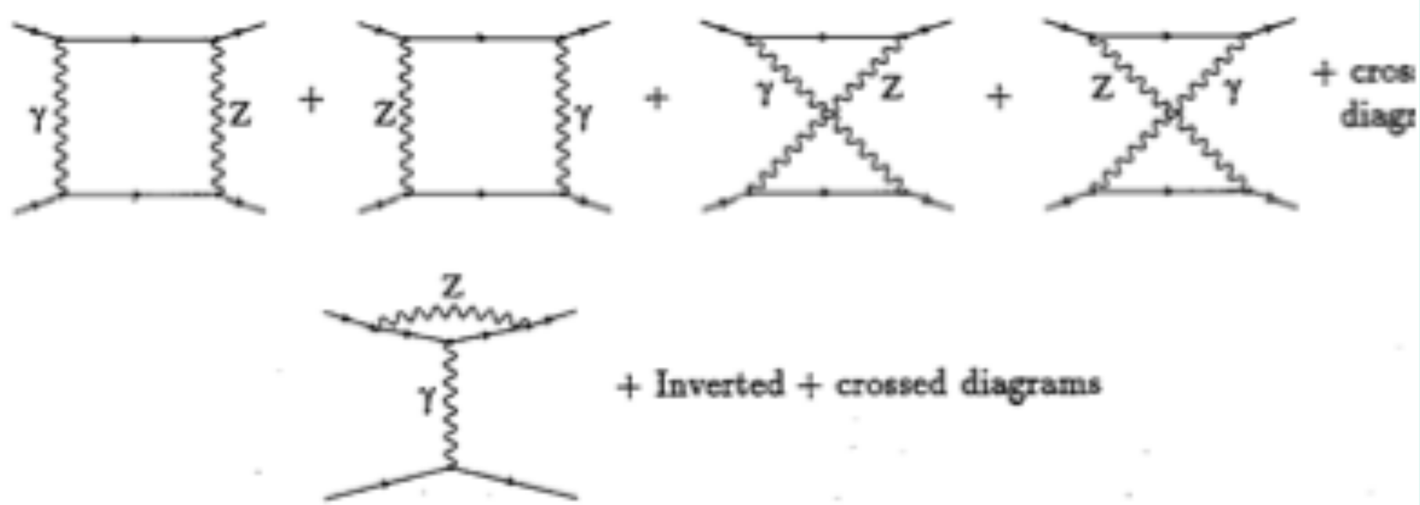


FIG. 4. Boxes containing one photon and Z-loop contribution to the anapole moment.

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%?

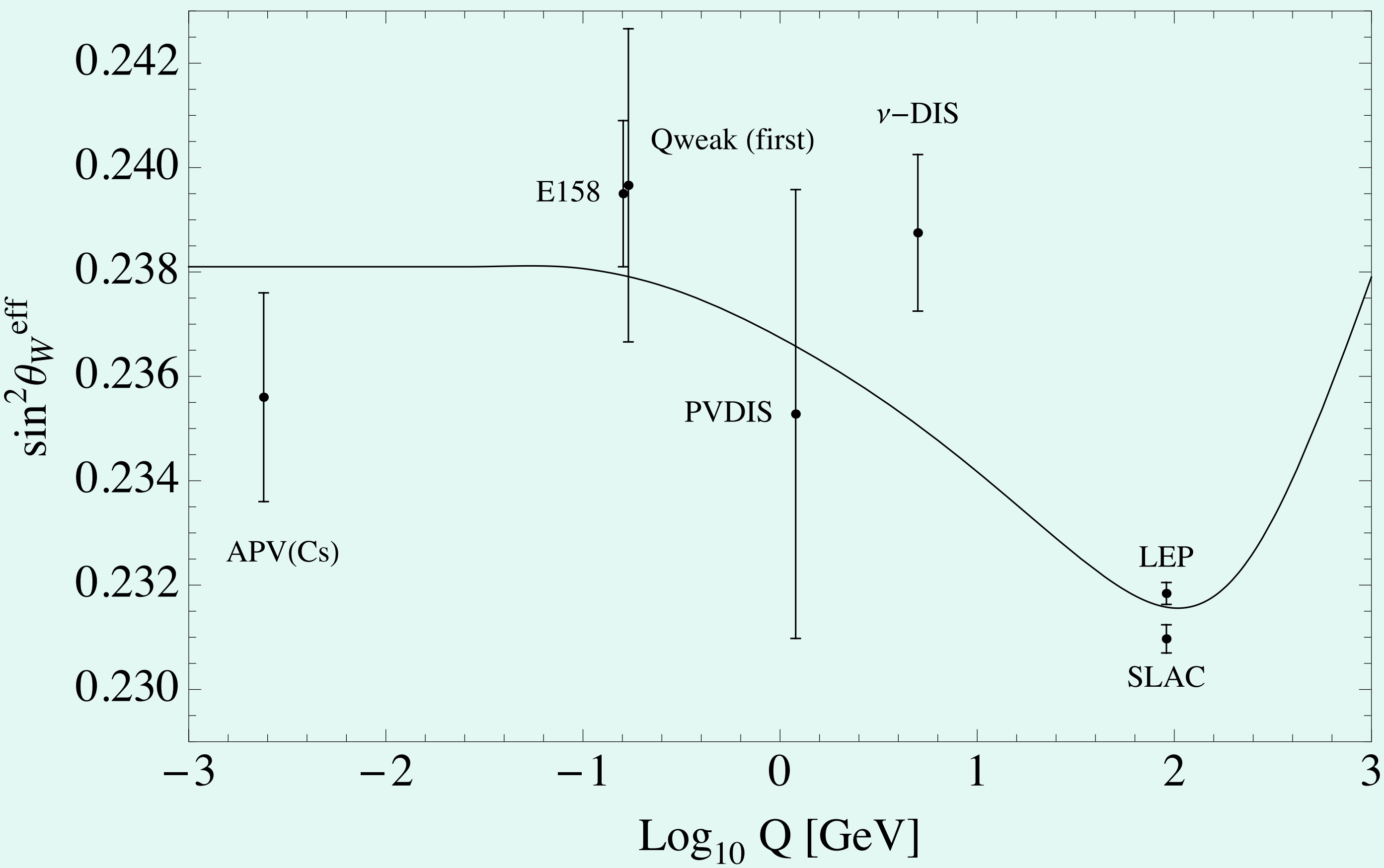
Erler & Ramsey-Musolf ➔ factor of 8.6 error reduction!

***+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

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



Goals of Future Low Q^2 Experiments

- High Precision: $\Delta\sin^2\theta_W \sim \pm 0.0002$ - 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)

$S \approx 0.7T$?, Confirm Z Pole Ave/m_W determination?

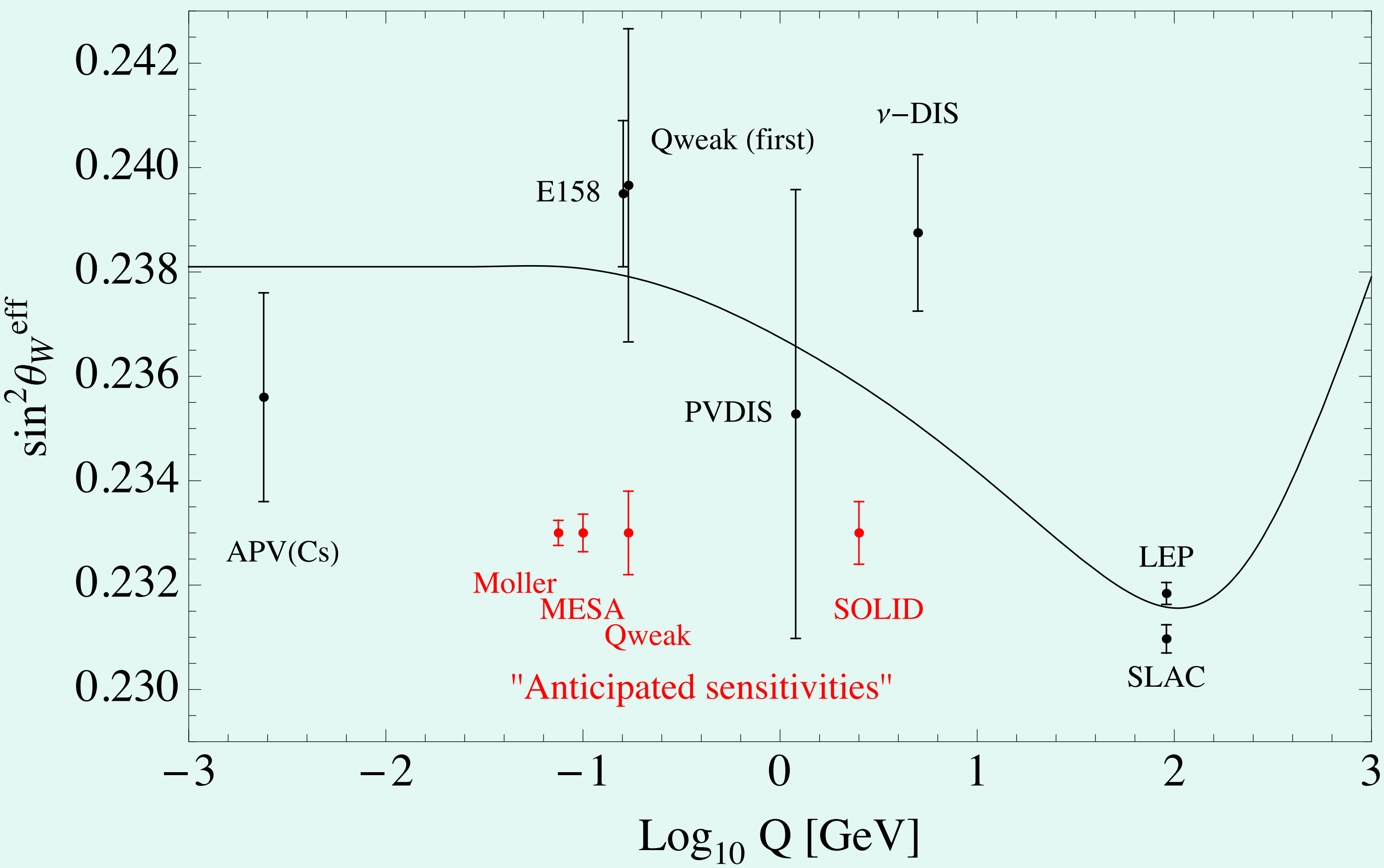
Z pole implies $|0.25T-0.34S| \leq 10^{-3}$; ***TRUE?***,

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

Heavy $m_{Z'}$ >1-8TeV, Model Dependent Sensitivities (Do not interfere at Z Pole)

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

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



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

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

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

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

$+0.7R(0) + SUSY + H^{--} \ldots)$

Z pole **$\sin^2\theta_W(m_Z)_{MS}$** ➔ 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 $D+D \rightarrow Z_d+Z_d$

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?

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!*)

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

2) $Z\text{-}Z_d$ 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

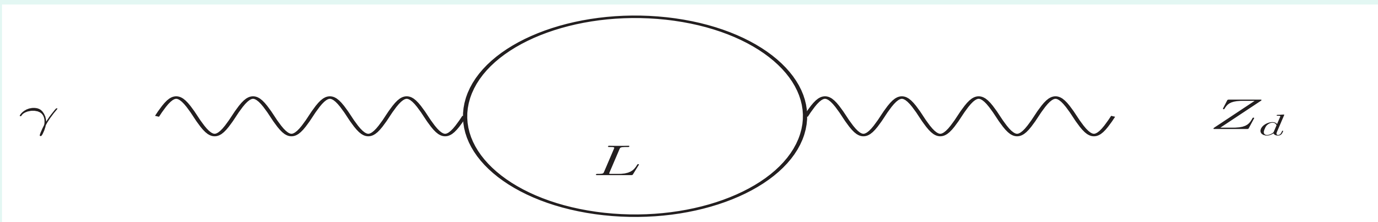
One Loop gamma-γ_d Kinetic Mixing

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

(eg Through Heavy Charged Leptons)

That also carry $U(1)_d$ charge

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

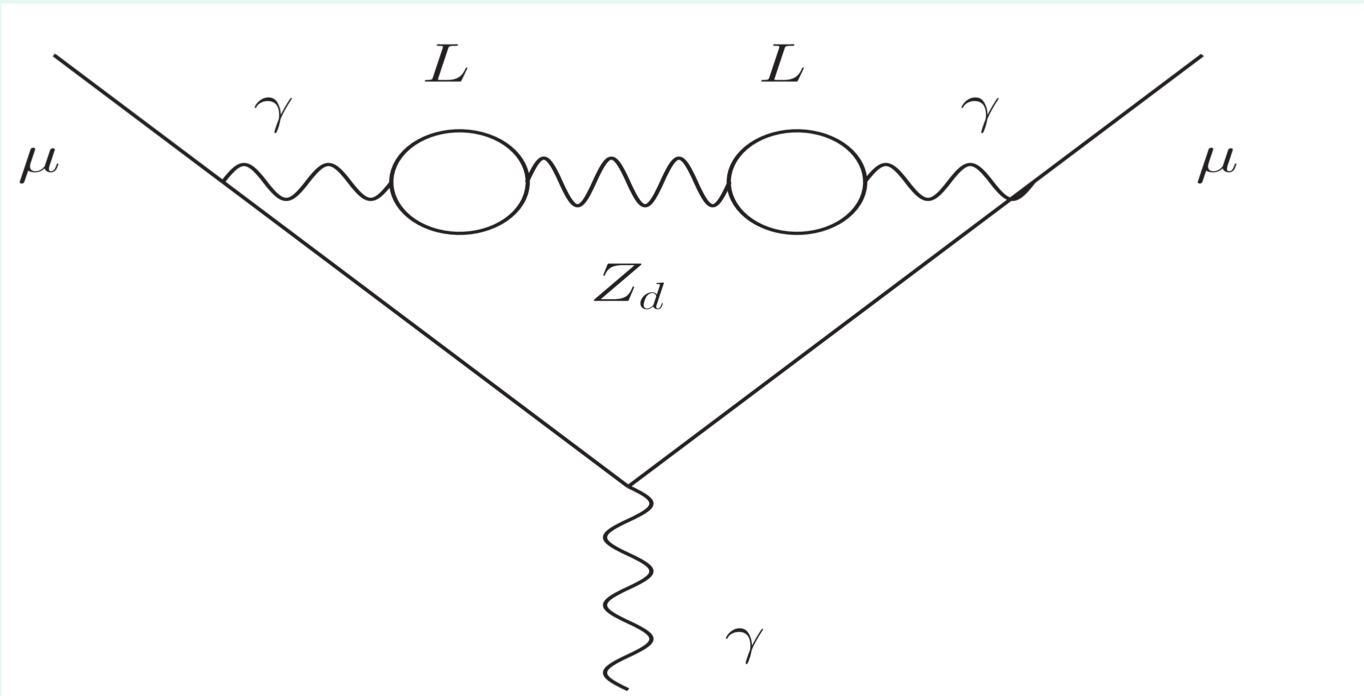


Muon Anomalous Magnetic Moment

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

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

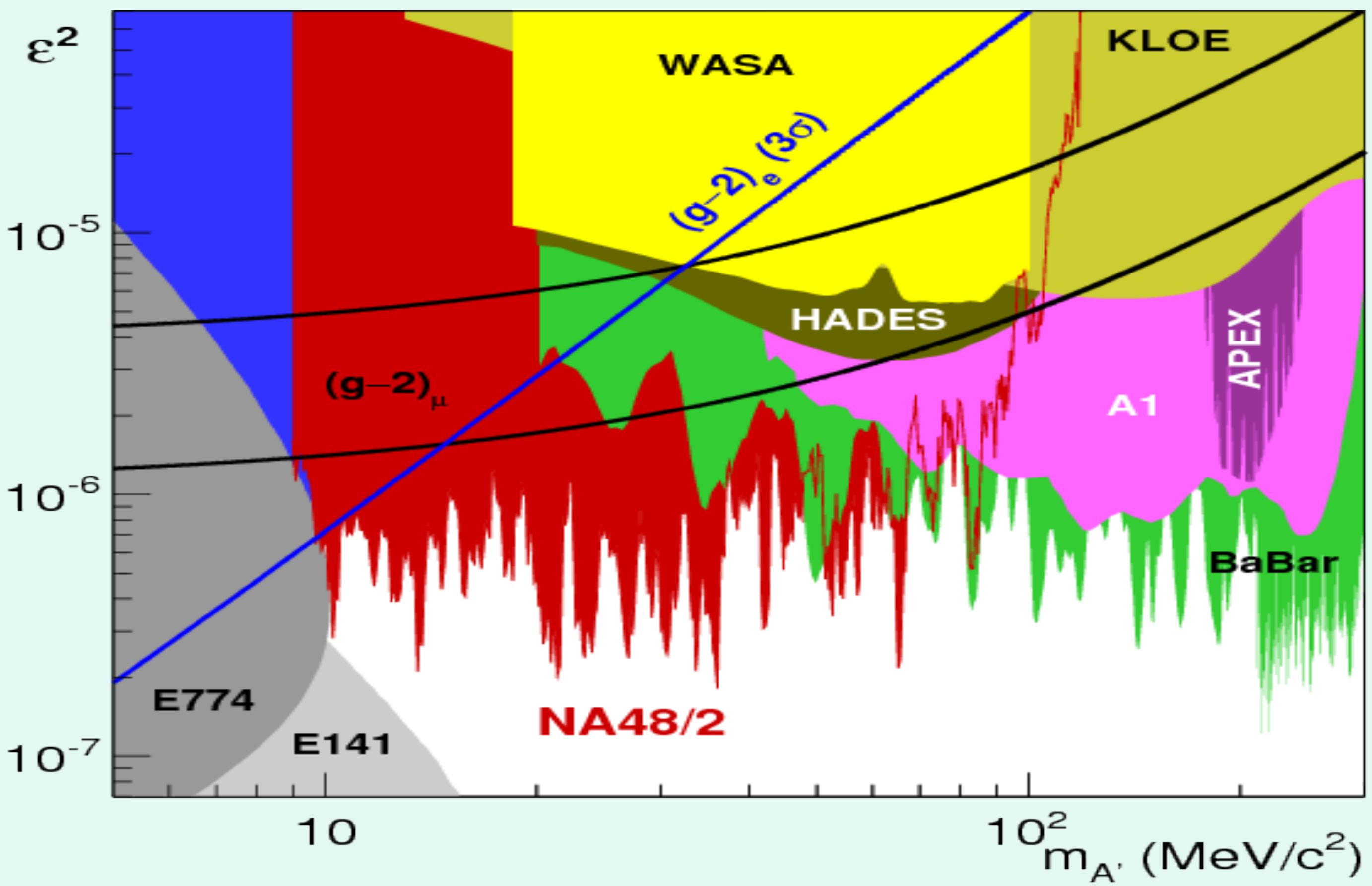
for $\varepsilon^2 \approx 10^{-6}$-$10^{-4}$ & $m_{Zd} \approx 10$-300MeV (see figure)



NA48/2 Updated Bounds on Dark Photon

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

Assumes BR(γ_d → e+e-) ~1



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 $Q^2 < m_{Zd}^2$ (≈O(1%)! Eg APV)

(1.5 sigma APV deviation) fit ➔ $\varepsilon\delta = 4\times10^{-6}$

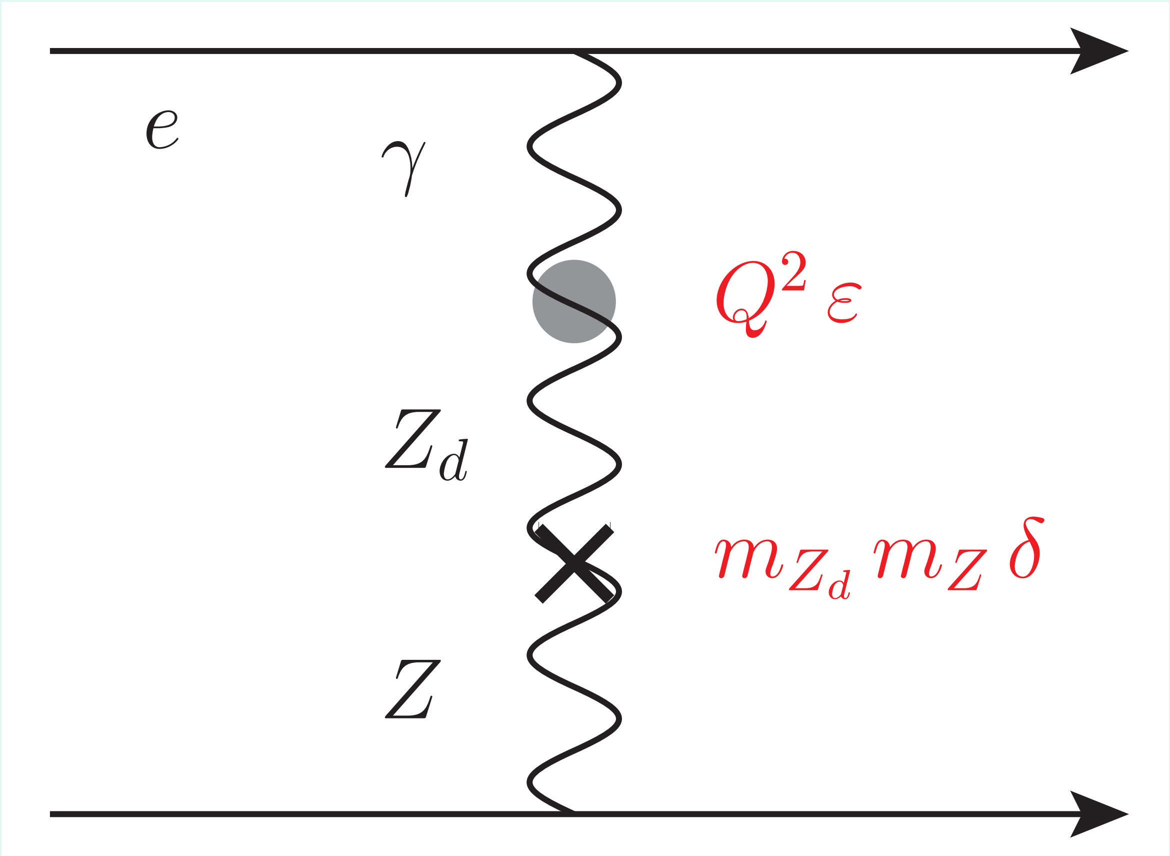
or $\varepsilon \approx \delta \approx 2\times10^{-3}$ for $(g_\mu-2)$ & APV ➔ $m_{Zd} \approx 50$ MeV region

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

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

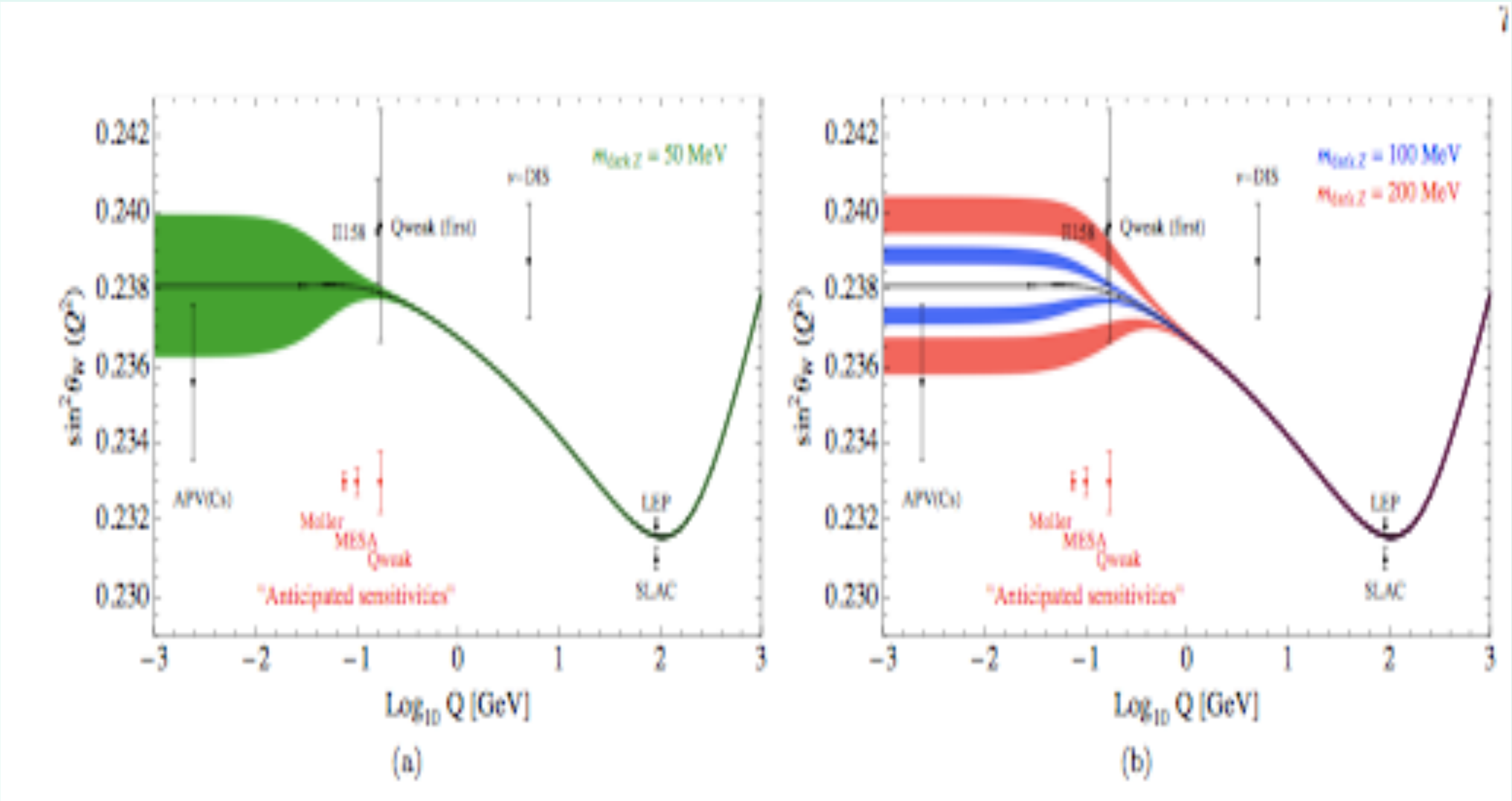
A_{RL}(ee) at low Q^2 very Important

Dark Z Effect on electron scattering
Photon-Z Mixing through Z_d
from H-S Lee

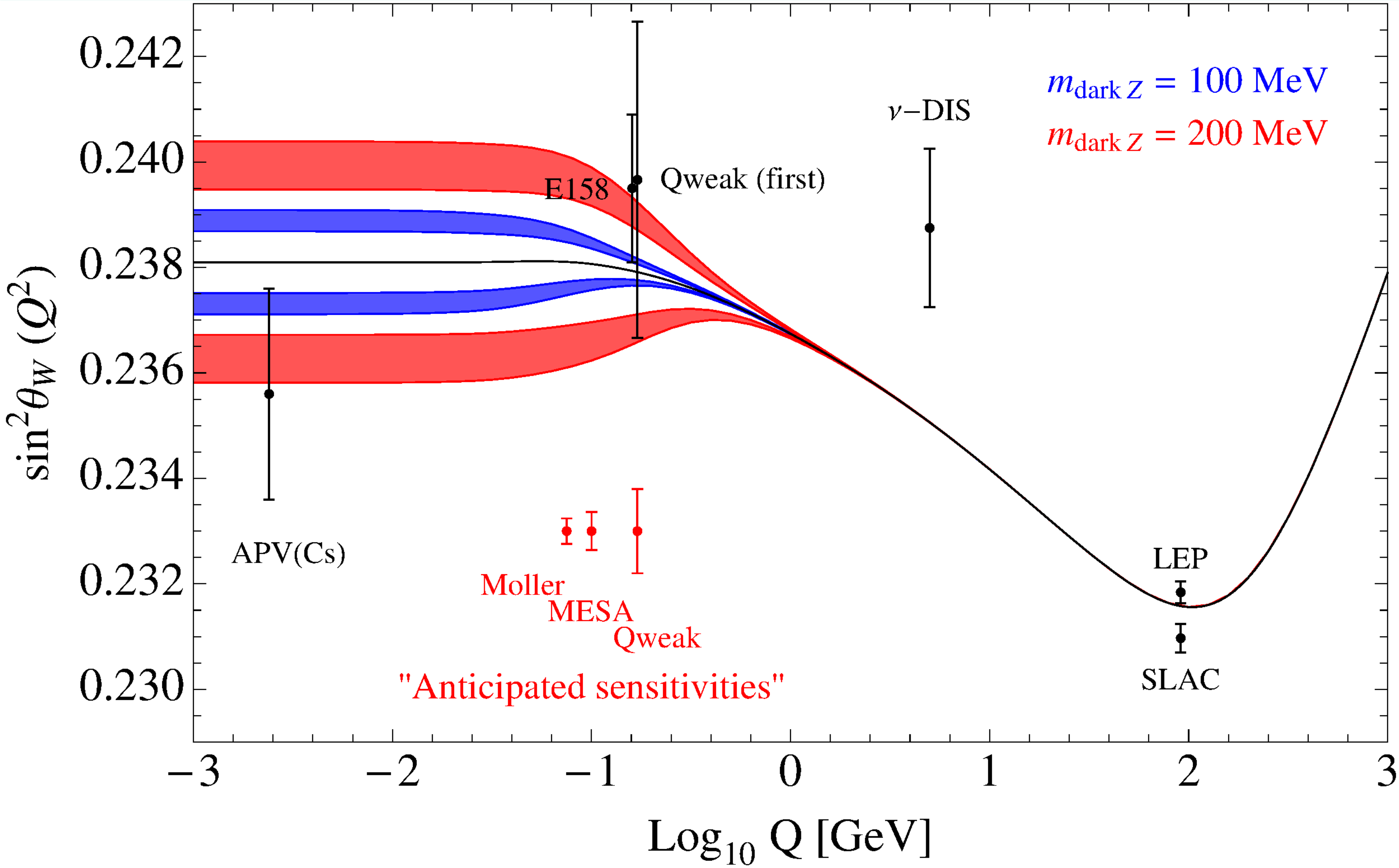


Effect of "Light" Z_d on Running

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



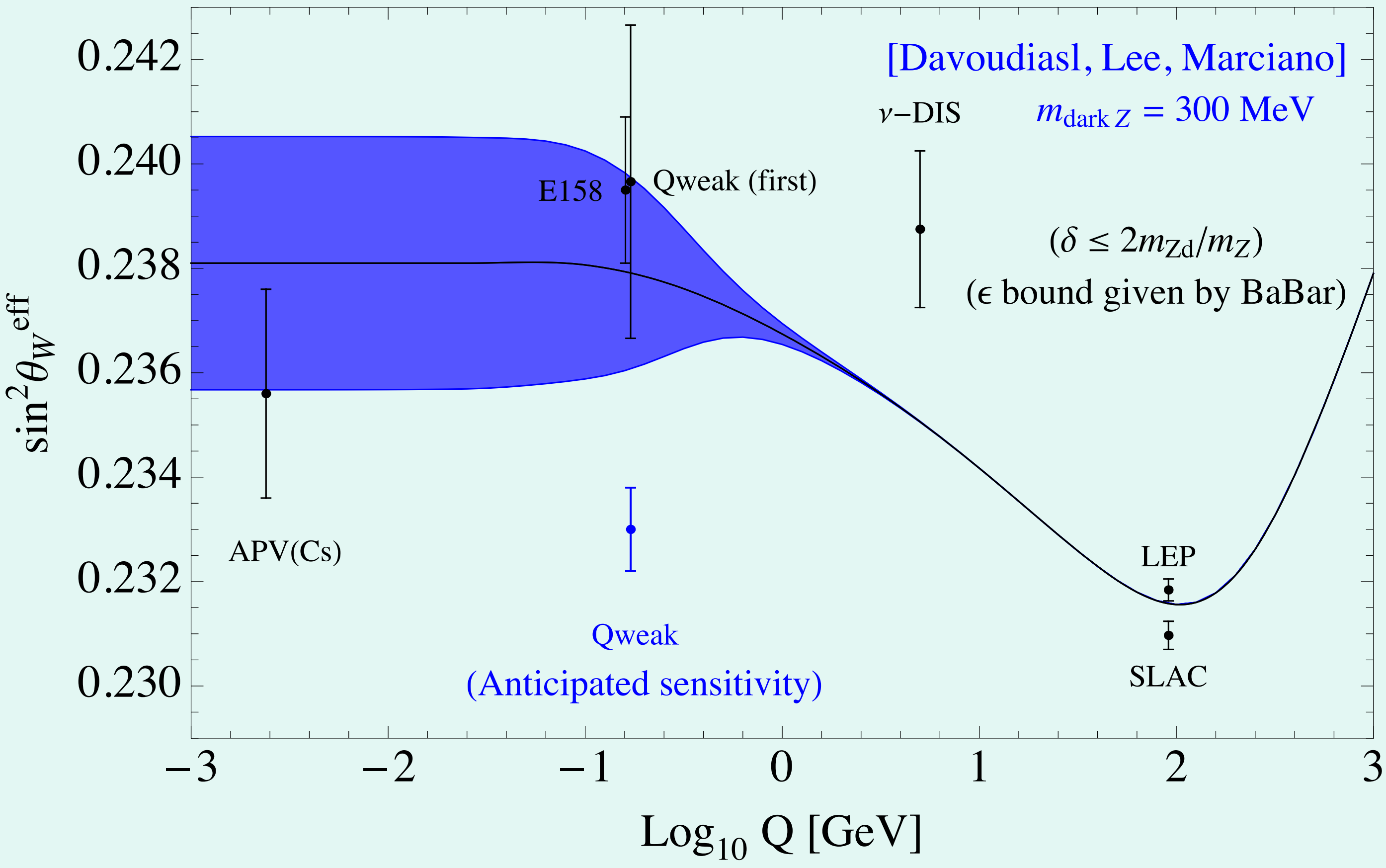
Blowup



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



The Dark Z_d Model

DAVOUDIASL, LEE, MARCIANO

$\gamma_d - Z$ Mass Mixing → Z_d (dark Z) & Z

Add second $SU(2)_L$ Dark Higgs Doublet H_2

Three Higgs Multiplets H_1, H_2 & ϕ_d

Vacuum expectation values v_1, v_2 & v_d

Mixing $\varepsilon_Z = m_{Zd}/m_Z \delta$

$\delta = v_2^2/v_1 v_d$ small ~ $O(m_{Zd}/m_Z) \sim O(10^{-3})$

Find $\Delta \sin^2\theta_W / \sin^2\theta_W \approx -2\varepsilon(m^2\gamma_d / Q^2 + m^2\gamma_d)$

Potentially of order 10^{-3} for low Q^2

γ_d-Z Mass Mixing➔ $\varepsilon_Z = \delta m_{Zd}/m_Z$

- Potentially Observable Effects, for $\delta \sim O(10^{-3})$, over a range of $10MeV < m_{Zd} < 15GeV$ in

***Weak mixing angle running at low <Q>**

$BR(K \rightarrow \pi Z_d) \approx 4x10^{-4}\delta^2$

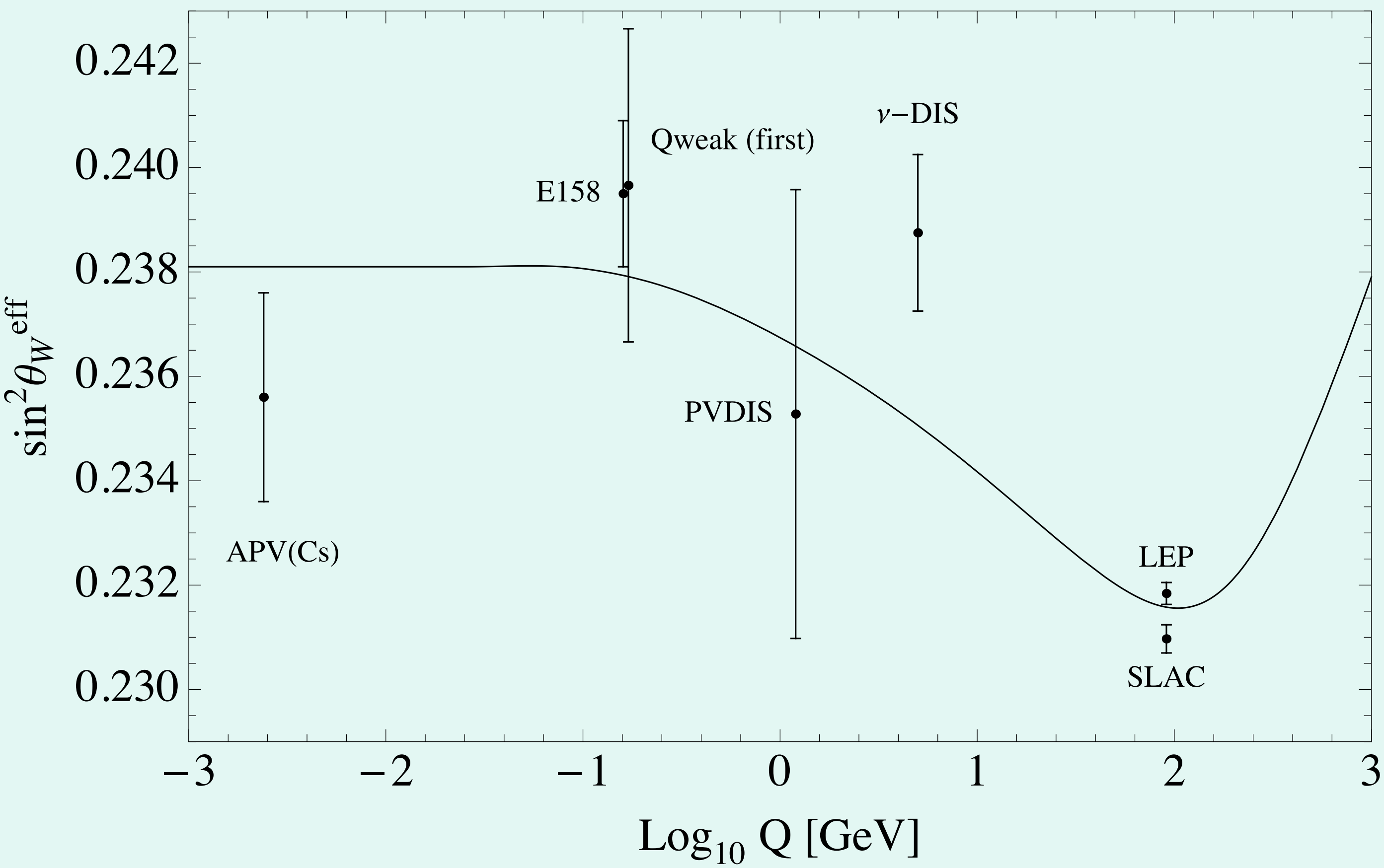
$BR(B \rightarrow KZ_d) \approx 0.1\delta^2$

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

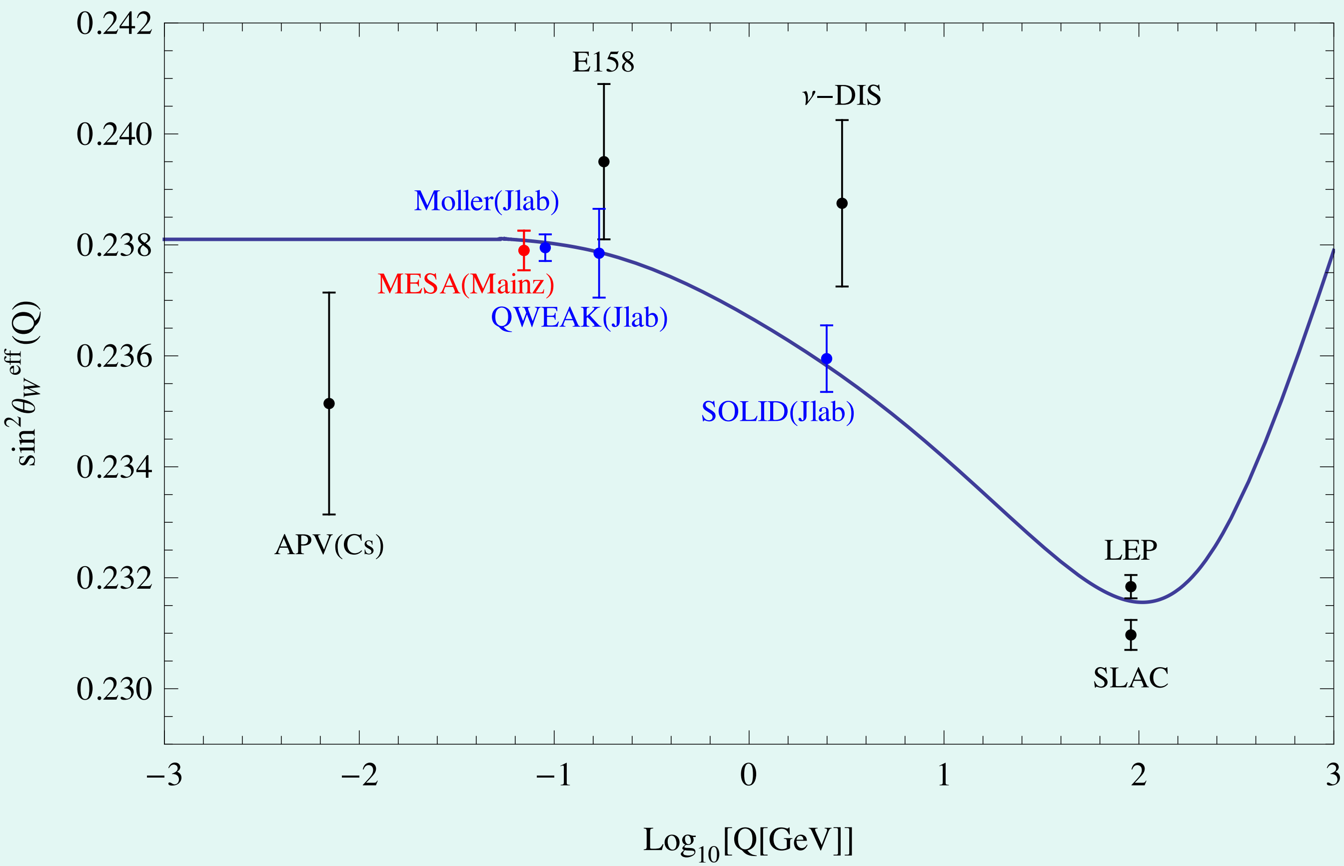
<u>δ roughly probed to <10^{-3}</u>

Z_d Discovery would revolutionize particle physics

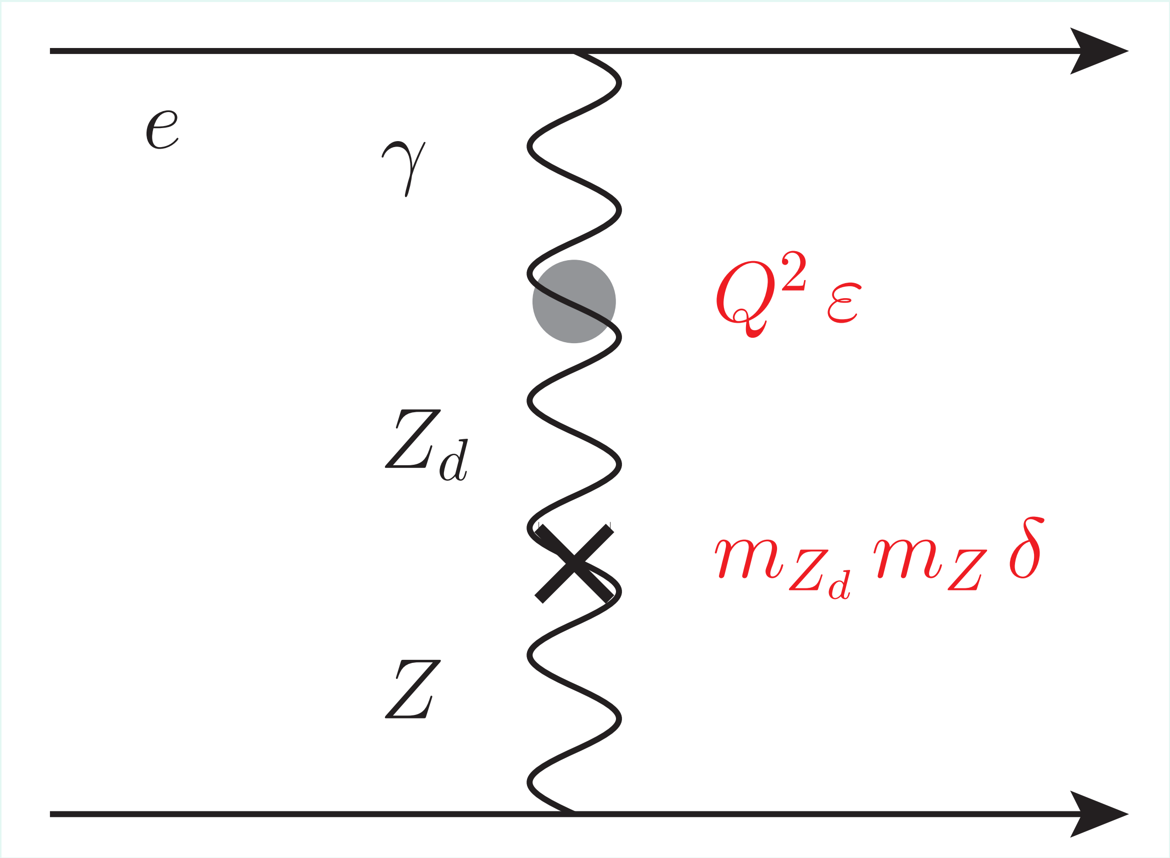
Measurements of running $sin^2\theta_W(Q^2)$ Pre New Qweak



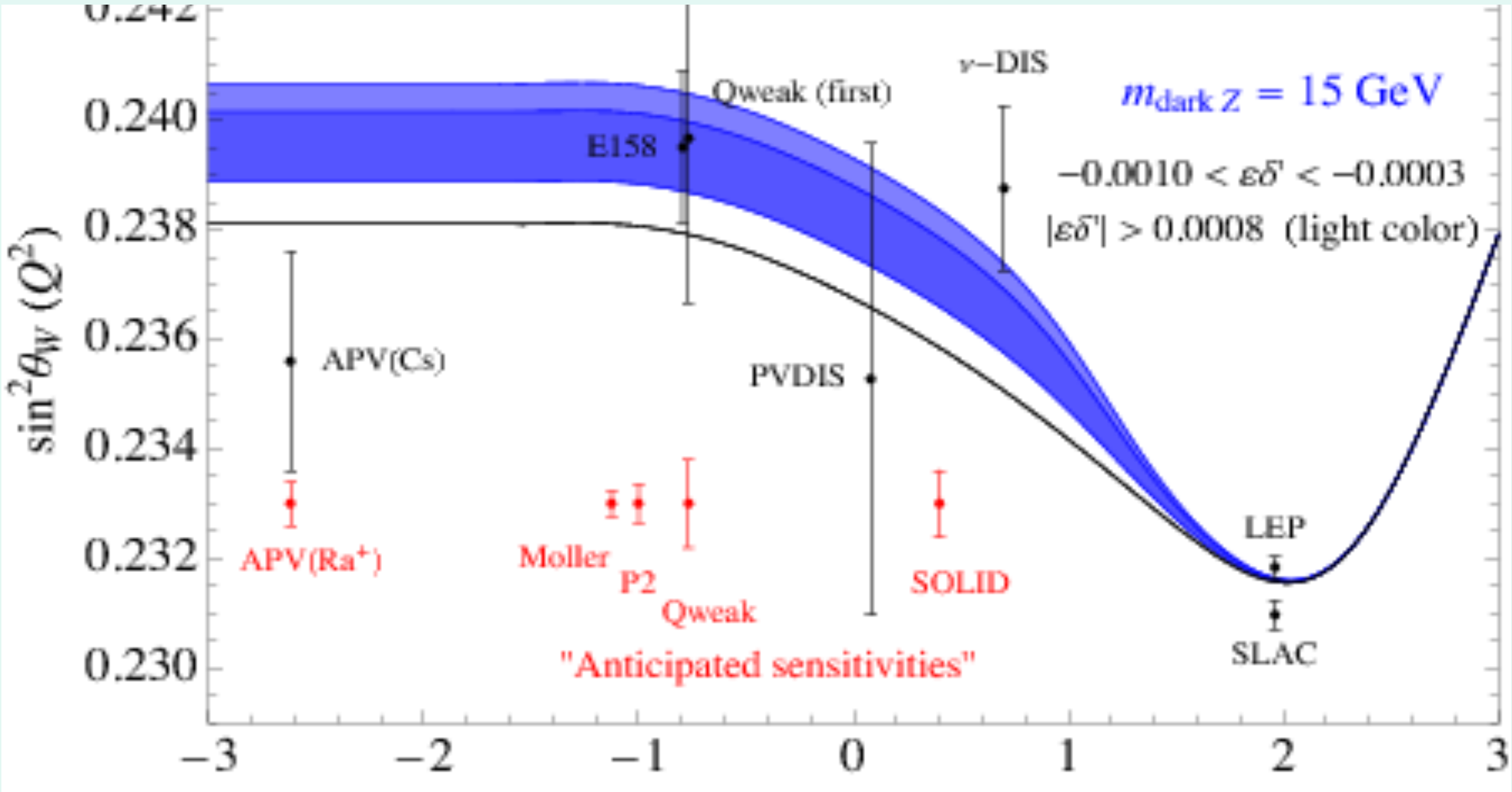
Possible A_{RL} Measurements



Dark Z Effect on electron scattering
Photon-Z Mixing through Z_d
Kinetic + Mass Mixing

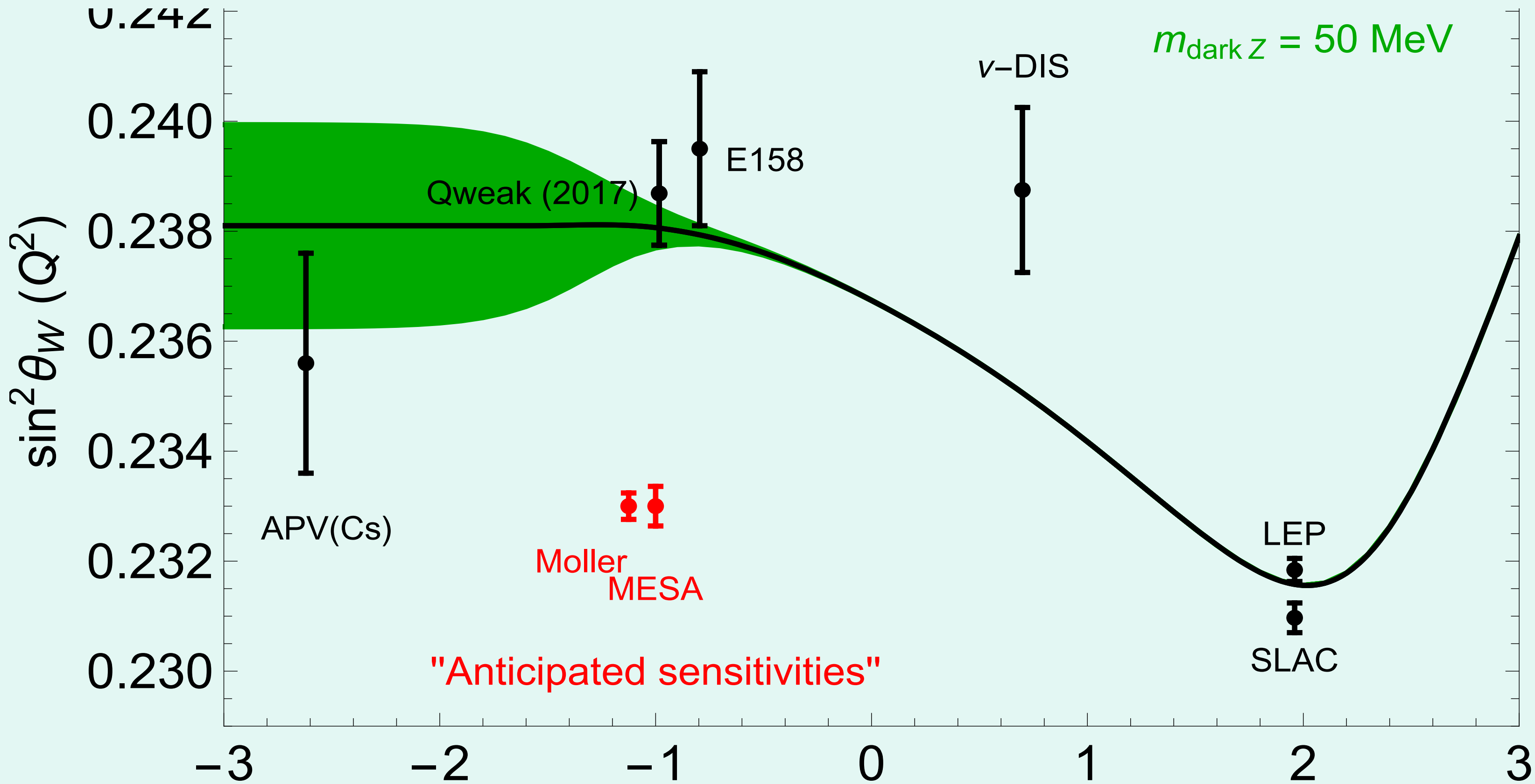


Pre- 2017 Qweak 15GeV Dark Z Fit to Low Energy Data



Examples of the effect of “Light” Z_d on Running

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



Present & Future

Precise, $sin^2\theta_W(Q^2)$ PV Experiments at low Q^2

Q_{weak} $\sin^2\theta_W(m_Z)_{MS}$= 0.2319(9) (with LQCD input)
Deviation of average low energy from pole: 0.0012(6)

Next PVES(^{12}C) MESA at Mainz elastic eC scattering
$\Delta\sin^2\theta_W(m_Z)_{MS}$=±0.0007 (Pol. Uncertainty!)

Future (Z pole competitive)
P2 in Mainz (A_{RL}(ep)) $\Delta\sin^2\theta_W(m_Z)_{MS}$=±0.00037

Moller at JLAB Goal **$\Delta\sin^2\theta_W(m_Z)_{MS}$=±0.00027!**

"New Physics" in form of Light (150MeV -15GeV) Z_d
5+ sigma Discovery Potential

Non PV $\sin^2\theta_W$ at very low Q^2

Eg. Vector – Like gauged B-L

No Parity Violating Effect

Reactor $\nu_e$bar-e scattering Q~2MeV

Goal ±0.5% in $\sin^2\theta_W$ Currently ~ +/-10%

Explore low mass bosons & g_{B-L} of $O(10^{-7})$

Down to low masses ~ 5MeV

Long Term "Crazy" Challenge
Based on Jet Lag

What prevents doing polarized A_{RL}

$e^{+}p$ scattering at MESAII?

(Similar to Moller) "***I said it couldn't be done"***

(Different than P2 at loop level)

Rate, polarization, polarimetry etc

Worthwhile R&D Project?