Dark Parity Violation

and $\sin^2\theta_W(Q^2)$ running

DAVOUDIASL, LEE, MARCIANO

*** *After Qweak Result***

based on R. Carlini PANIC 2017

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"Light Dark World 2017"

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Dark Parity Violation

Generic Dark Photon Model

$SU(3)_C xSU(2)_L xU(1)_Y xU(1)_D$ + Kinetic Mixing

+ Dark Higgs Singlet $<\varphi>=v_d$ + Dark Matter Sector

$$L_{U(1)YxU(1)d}=-\tfrac{1}{4}(B_{\mu\nu}B^{\mu\nu}-2\varepsilon/\cos\theta_W B_{\mu\nu}D^{\mu\nu}+D_{\mu\nu}D^{\mu\nu})$$

$$B_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu \quad D_{\mu\nu}=\partial_\mu D_\nu-\partial_\nu D_\mu$$

ε= small mixing parameter $\leq O(10^{-3})$ loops

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

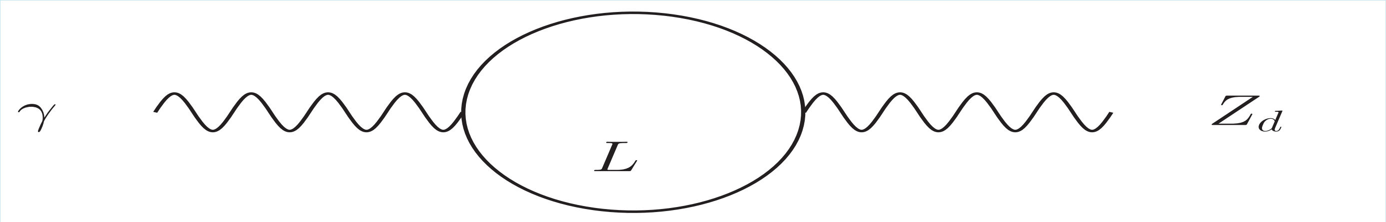
$$L_{int}=-e\varepsilon(J_\mu^{em}-1/2\cos^2\theta_W J_\mu^{NC})\,\gamma_d^\mu$$

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

,

<u>Example</u>

One Loop gamma-γ_d Kinetic Mixing
(Through Heavy Charged Leptons)
That also carry $U(1)_d$ charge
Expect $\varepsilon \sim e g_d Q Q_d / 8\pi^2 \leq O(10^{-3})$



$e\varepsilon(1/2\cos^2\theta_W J_\mu^{NC})\ \gamma_d^\mu$ violates parity!

Cancelled by γ-Z-γ_d mass diagonalization

Left with O(**ε^2**) **Z-γ_d** mixing **effects:**

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

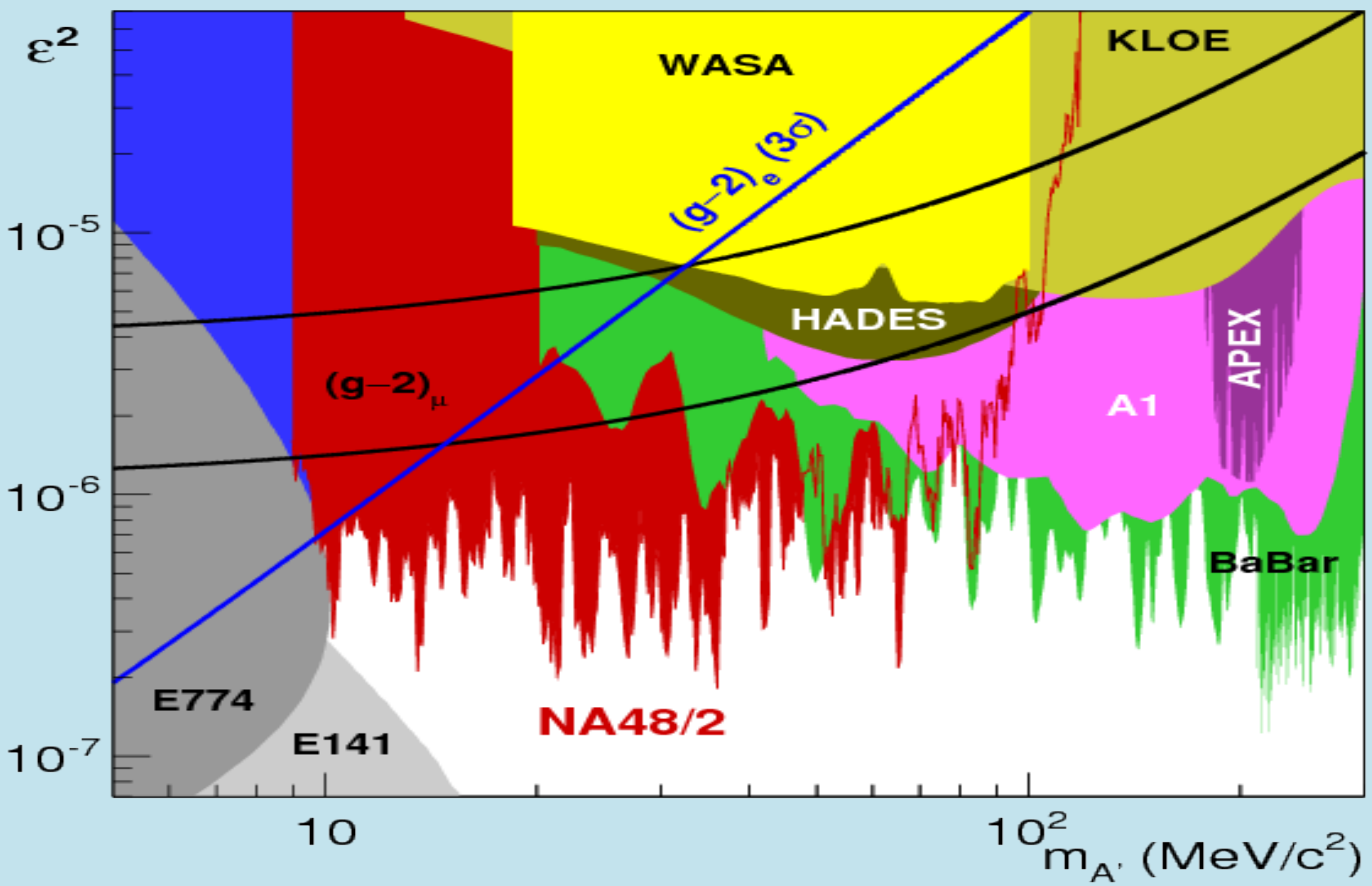
For **$\varepsilon < 10^{-3}$ (see bounds) ➔** $<10^{-6}$

Unobservably small

Currently $\Delta\sin^2\theta_W/\sin^2\theta_W \sim O(10^{-3})$ sensitivity

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

NA48/2 Updated Bounds on Dark Photon
Simple g_μ-2 discrepancy solution ruled out
Assumes BR(γ_d➔ e+e-) ~1



The Dark Z_d Model

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$\gamma_d - Z$ <u>Mass Mixing</u> → 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 $\Delta\sin^2\theta_W/\sin^2\theta_W \approx -2\varepsilon(m^2\gamma_d / Q^2 + m^2\gamma_d)$

<u>Potentially of order 10^{-3} for low Q^2</u>

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

- 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>__

$BR(K \rightarrow \pi Z_d) \approx 4\times10^{-4}\delta^2$

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

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

<u>δ roughly probed to <10^{-3}</u>

Z_d Discovery would revolutionize particle physics

Two Best Z Pole Measurements

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

3 sigma difference? Some Tension?

$\sin^2\theta_W(m_Z)_{MS}$	**0.23125(15)**	**Z Pole Ave.**
	0.23124(6)	**SM Prediction**
	similarly	
m_W	80.385(15)GeV	Exp. Ave.
	80.362(6)GeV	**SM Prediction**

Good agreement suggests not much BSM room

Similar Tevatron and LHC Results

. *Radiative Corrections:*

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

$$\sin^2\theta_W(Q)=e^2(Q/)g^2(Q)$$

Electroweak radiative corrections **(γ-Z mixing)** **cause running of** $\sin^2\theta_W(Q^2)$**. *Shift by about 3% for*** $0<Q^2<m_Z^2$.

[Marciano & Sirlin PRL1981]

[Czarnecki & Marciano PRD1996]

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

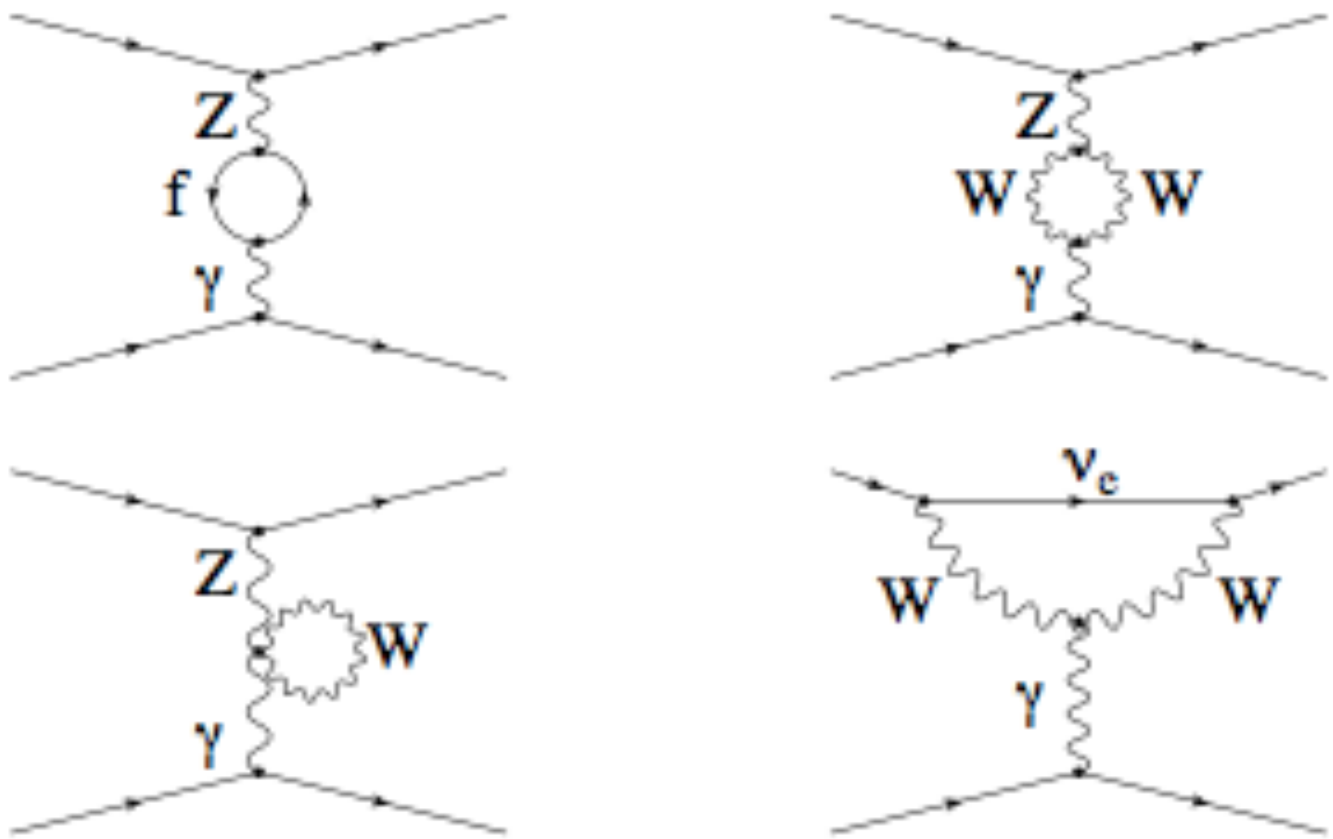
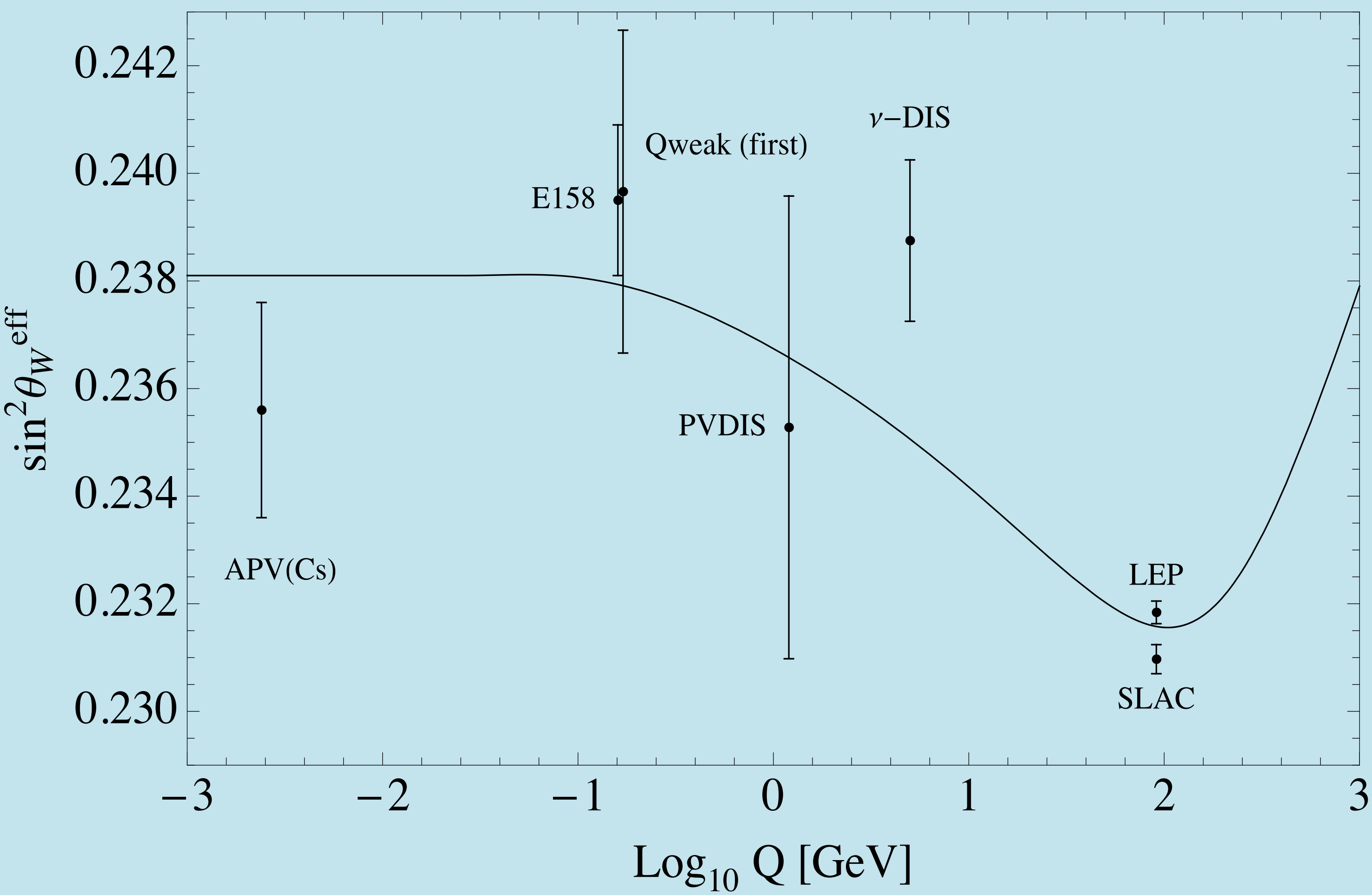
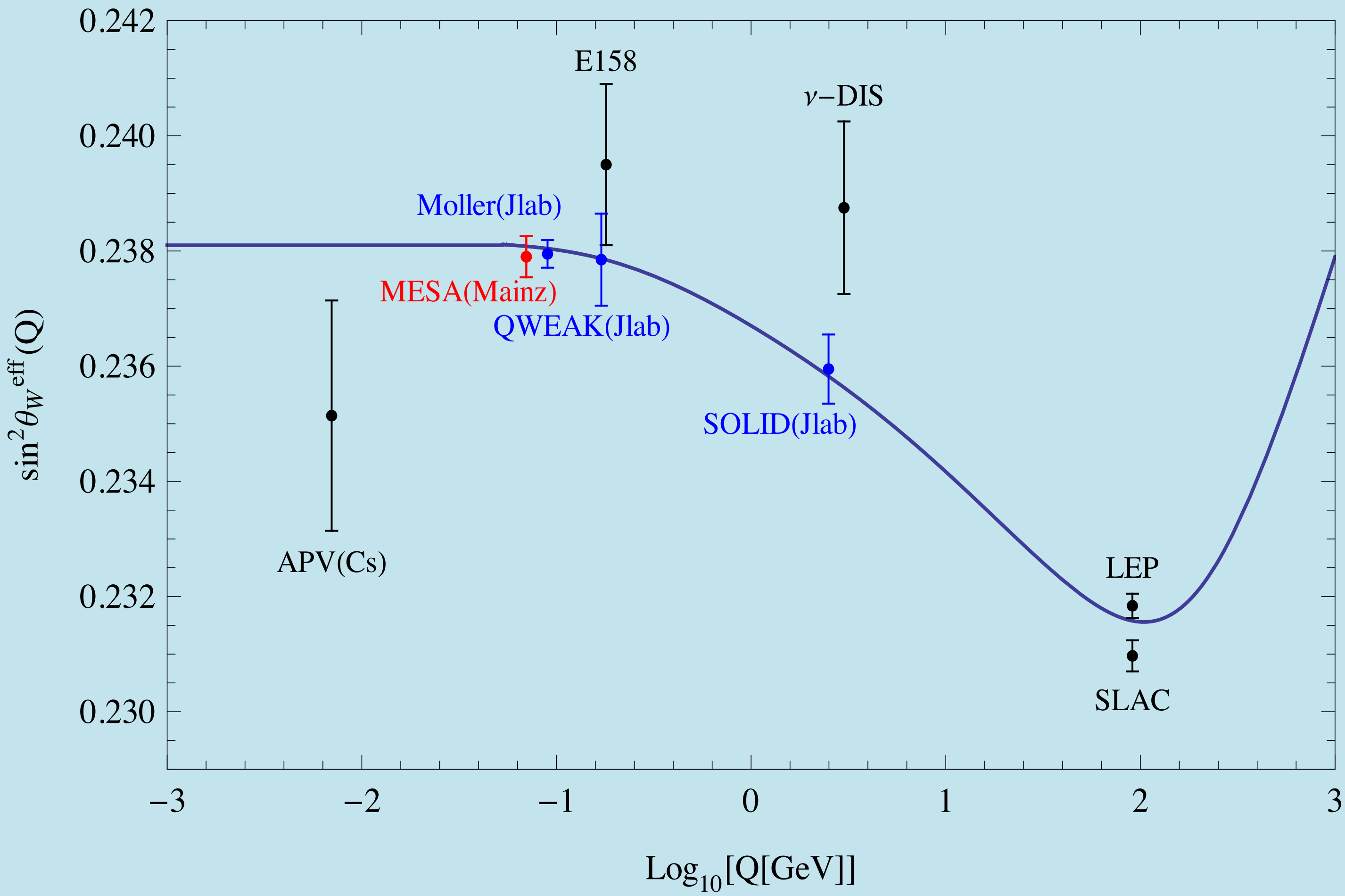


Fig. 2. $\gamma - Z$ mixing diagrams and W-loop contribution to the anapole moment.

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



Possible A_{RL} Measurements



Recent Qweak Result

R. Carlini PANIC 2017

Measurement of $Q_W(p)=1-4\sin^2\theta_W$ +Rad. Corr.

SM predicts $Q_W(p)^{SM}=0.0708(3)$ small

$E=1.1\text{GeV}$, $Q^2 \approx 0.03\text{GeV}^2$,

$\text{Pol}=85\pm1\% \rightarrow A_{RL}(ep) \approx 3\text{x}10^{-7}$

small Q^2 & A_{RL} required long running

Some hadronic uncertainties

Lattice strange form factor input to reduce error

Q_{weak}(2017): **$\sin^2\theta_W(m_Z)_{MS}$ = *0.2319(9)***

Best Off Z Resonance Measurements of $\sin^2\theta_W(m_Z)_{MS}$ (Z pole value 0.23125(15))

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 (2013)	0.2329(50)	160MeV
****Q_{weak} ep (2017)***	***0.2319(9)***	***160MeV***
6GeV Dis eD	0.2299(43)	1.5GeV
NuTeV v_μN	***0.2356(16)***	***3-4GeV***

NuTeV **$\sin^2\theta_W(m_Z)_{MS}$=0.2356(16)** **(2.5 sigma High)**

A_{RL}(ee) **$\sin^2\theta_W(m_Z)_{MS}$=0.2329(13)** ***Very Clean Theory!***

Q_W(ep) Now Best Low Energy $\sin^2\theta_W(m_Z)_{MS}$

Low energy SM Agreement After Qweak (2017)

Weighted Ave.of 4 best Off Pole Exps. .

$\sin^2\theta_W(m_Z)_{MS}$=0.2324(6)

Approx. 1.8 sigma difference with Z pole value:

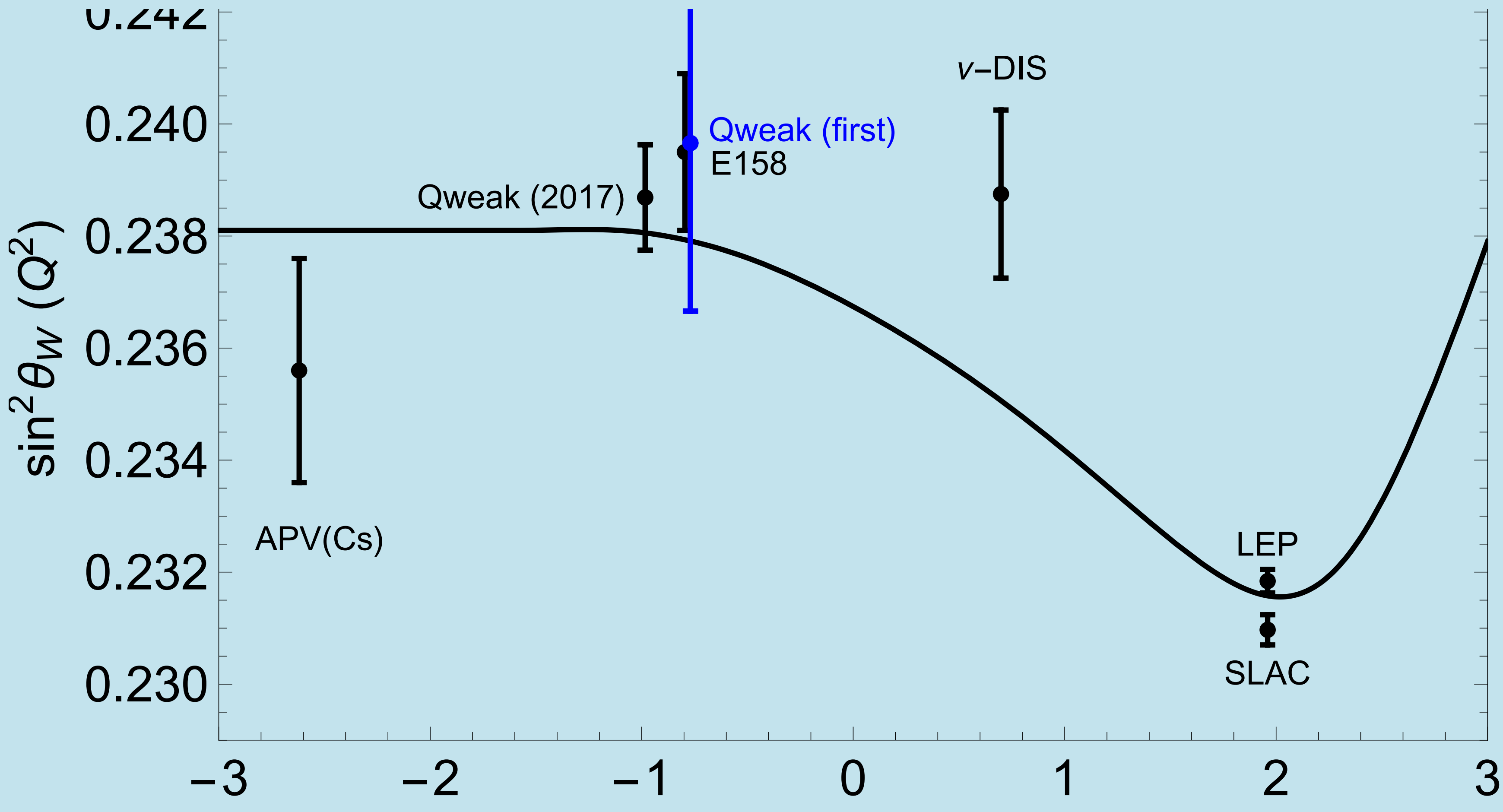
$\Delta\sin^2\theta_W(m_Z)_{MS}$ = 0.0012(6)   was 0.0015(9)

If only Q_W(ep) & E158 Q_W(ee) are averaged

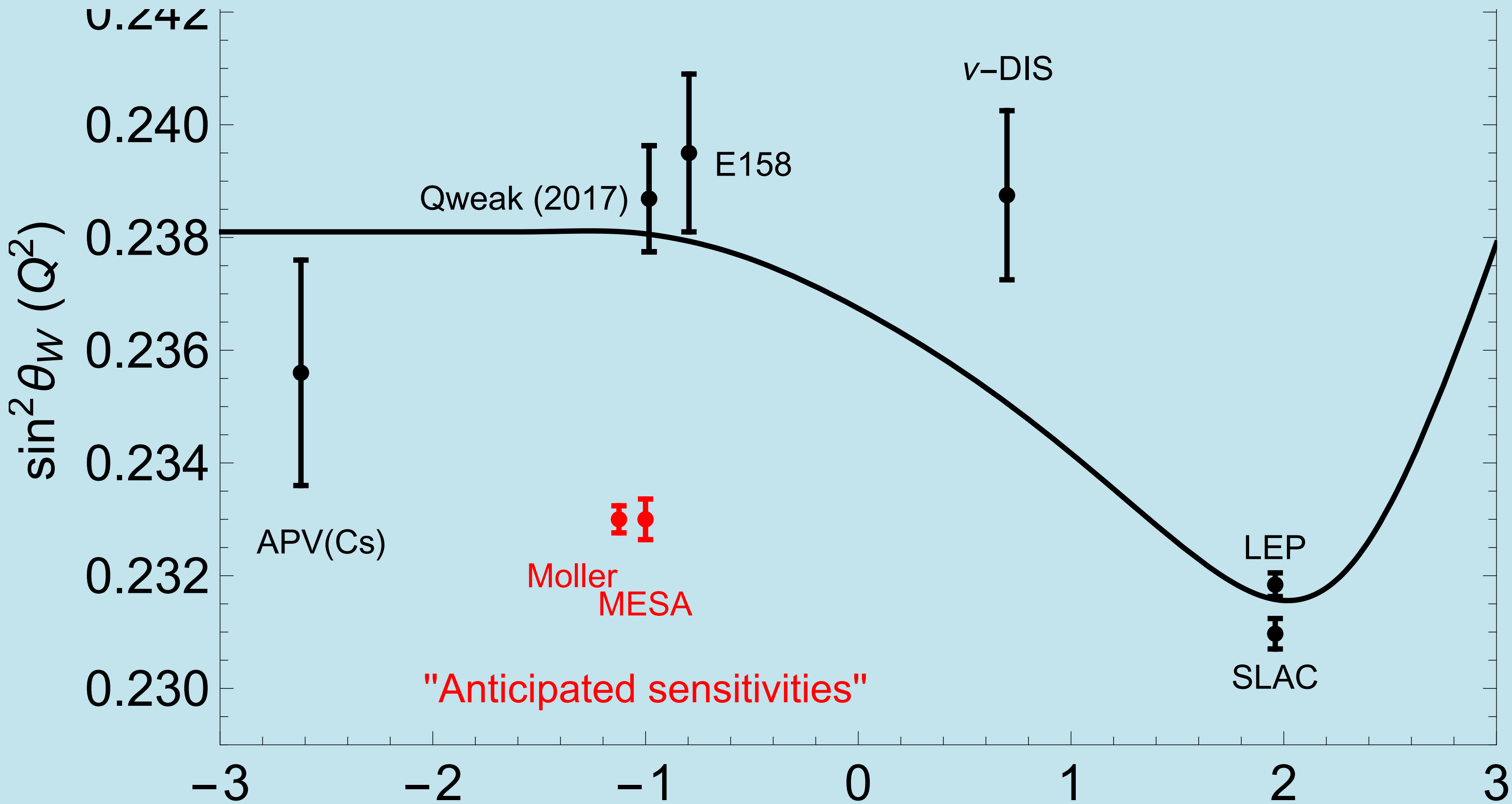
$\sin^2\theta_W(m_Z)_{MS}$=0.2322(7) 1.3 sigma from SM

(Without Lattice Input, More Consistent with SM)

New Qweak Result (+Lattice)



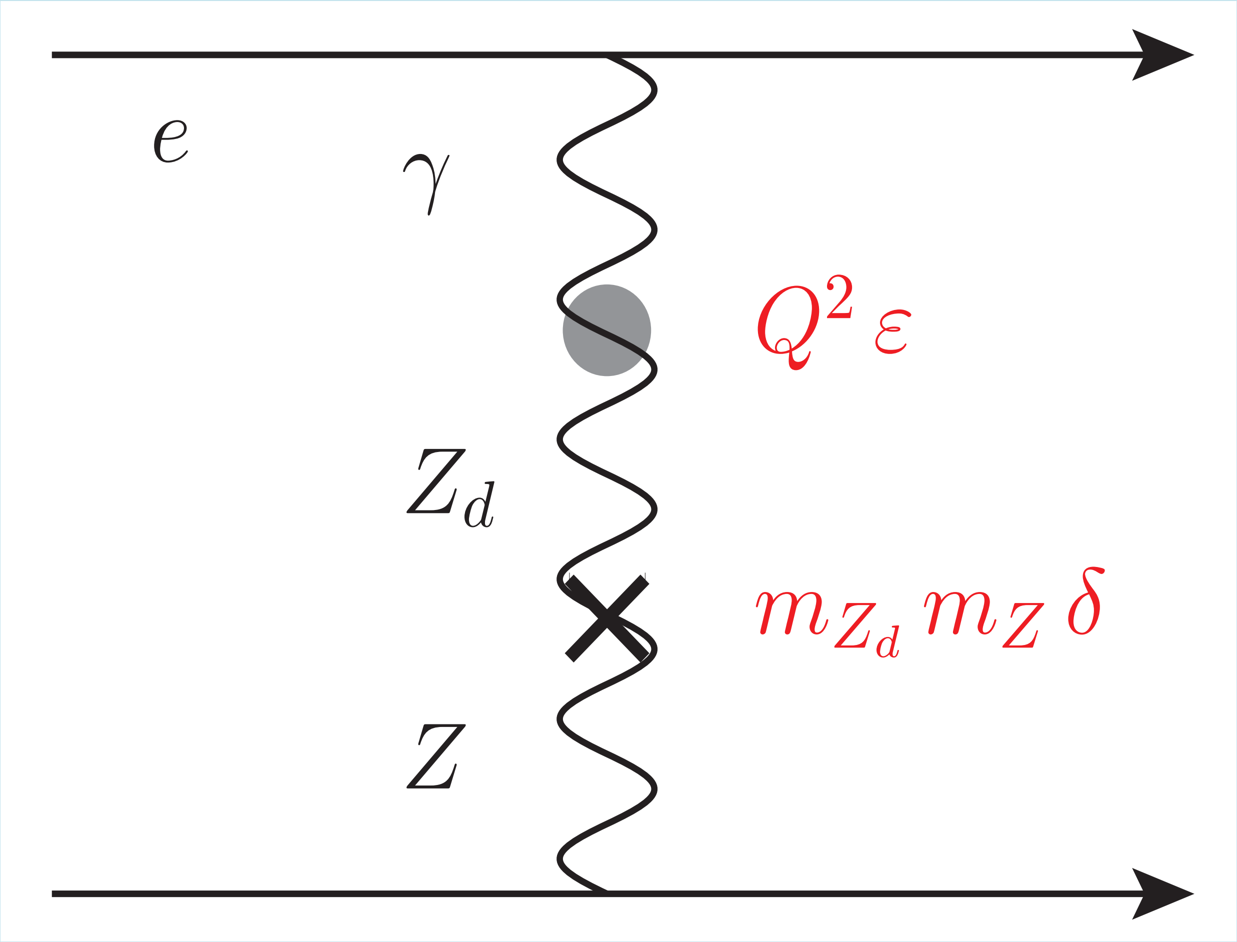
New Qweak Result & Future Proposals



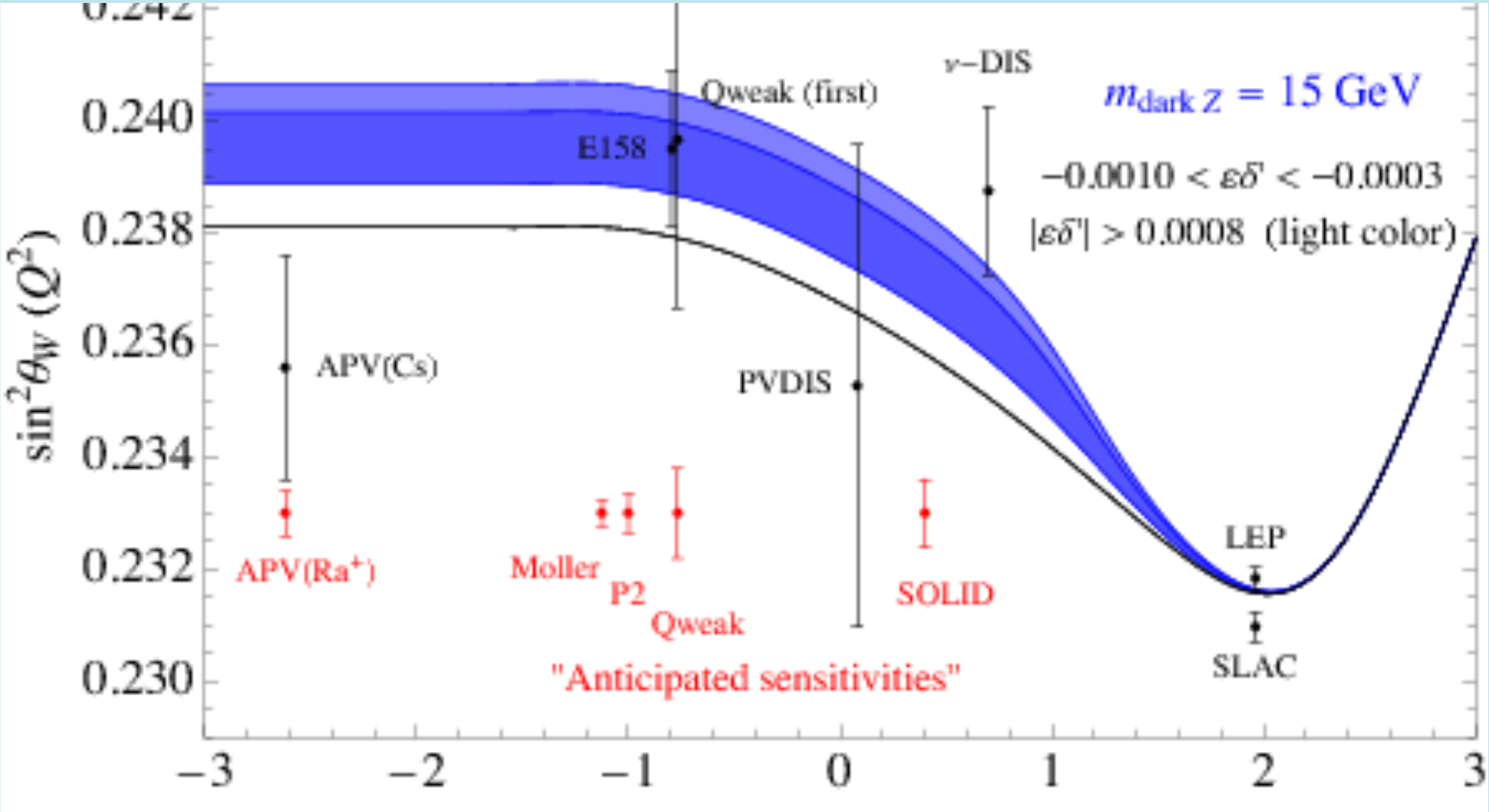
Dark Z Effect on electron scattering

Photon-Z Mixing through Z_d

Kinetic + Mass Mixing

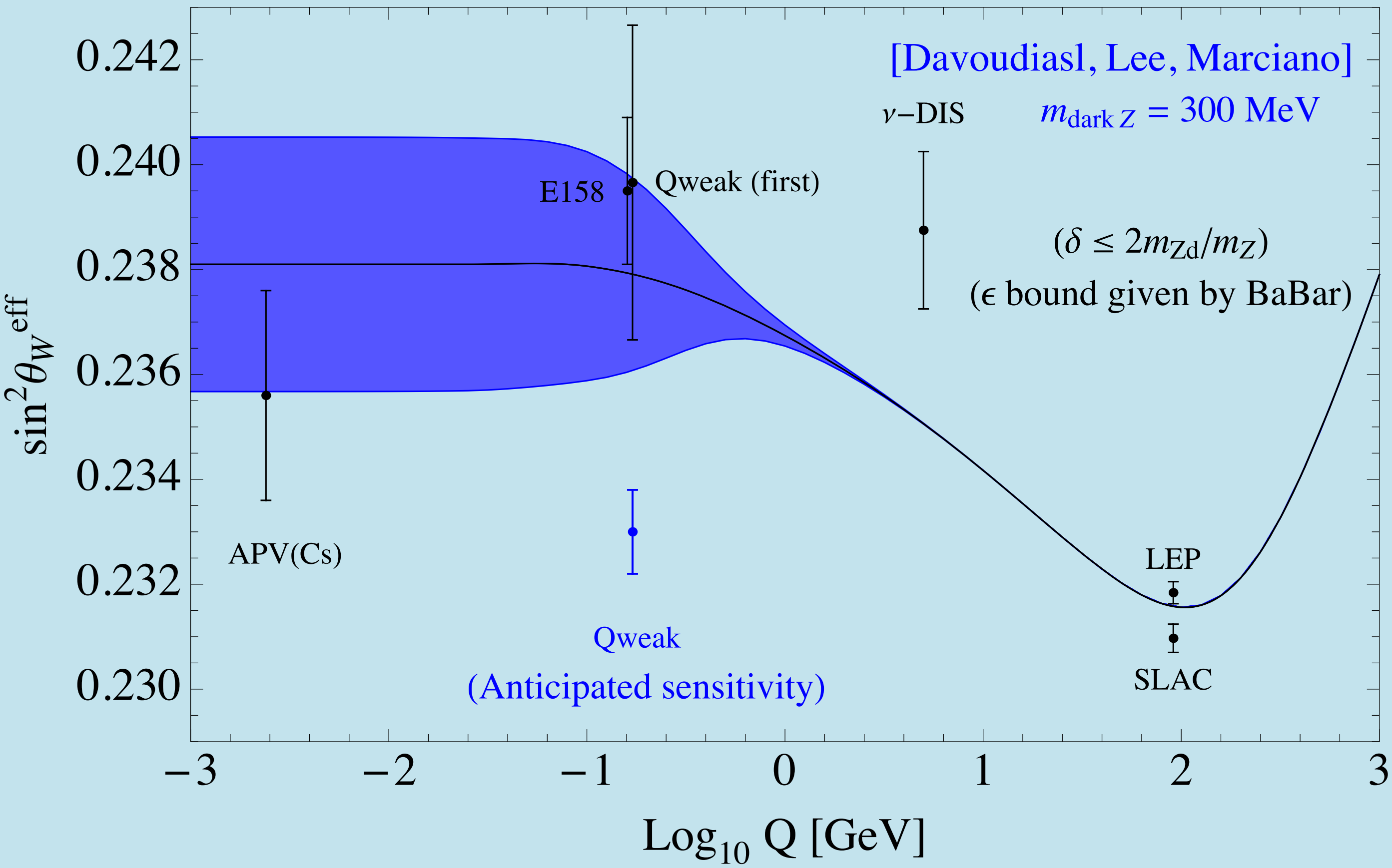


<u>*Pre- 2017 Qweak 15GeV Dark Z Fit to Low Energy Data*</u>



Potential 300MeV Dark Z Effects on Running

$|\Delta \sin^2\theta_W(0)| \leq 0.002$ Could start to show up in Qweak



Examples of the effect of "Light" Z_d on Running

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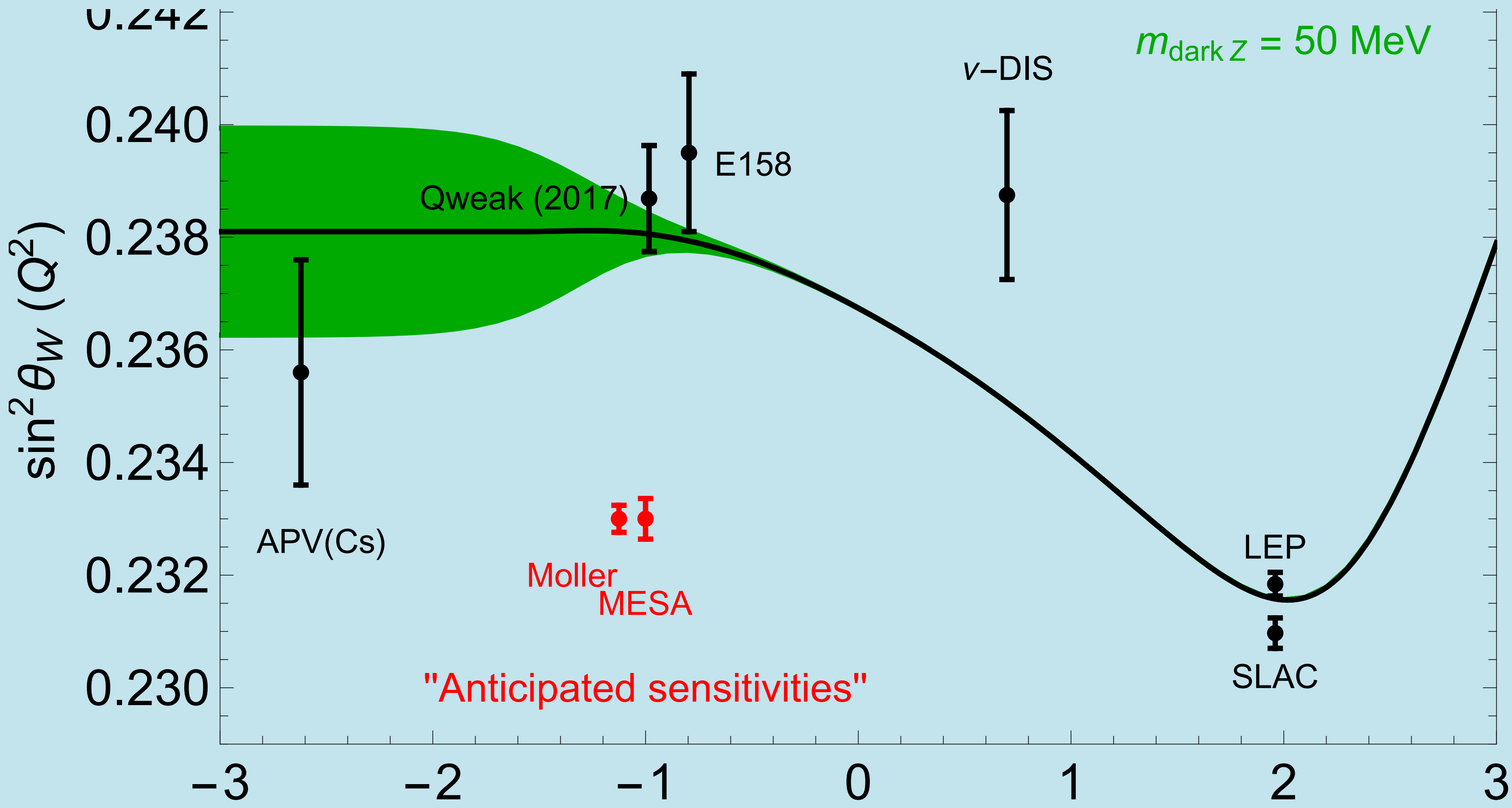

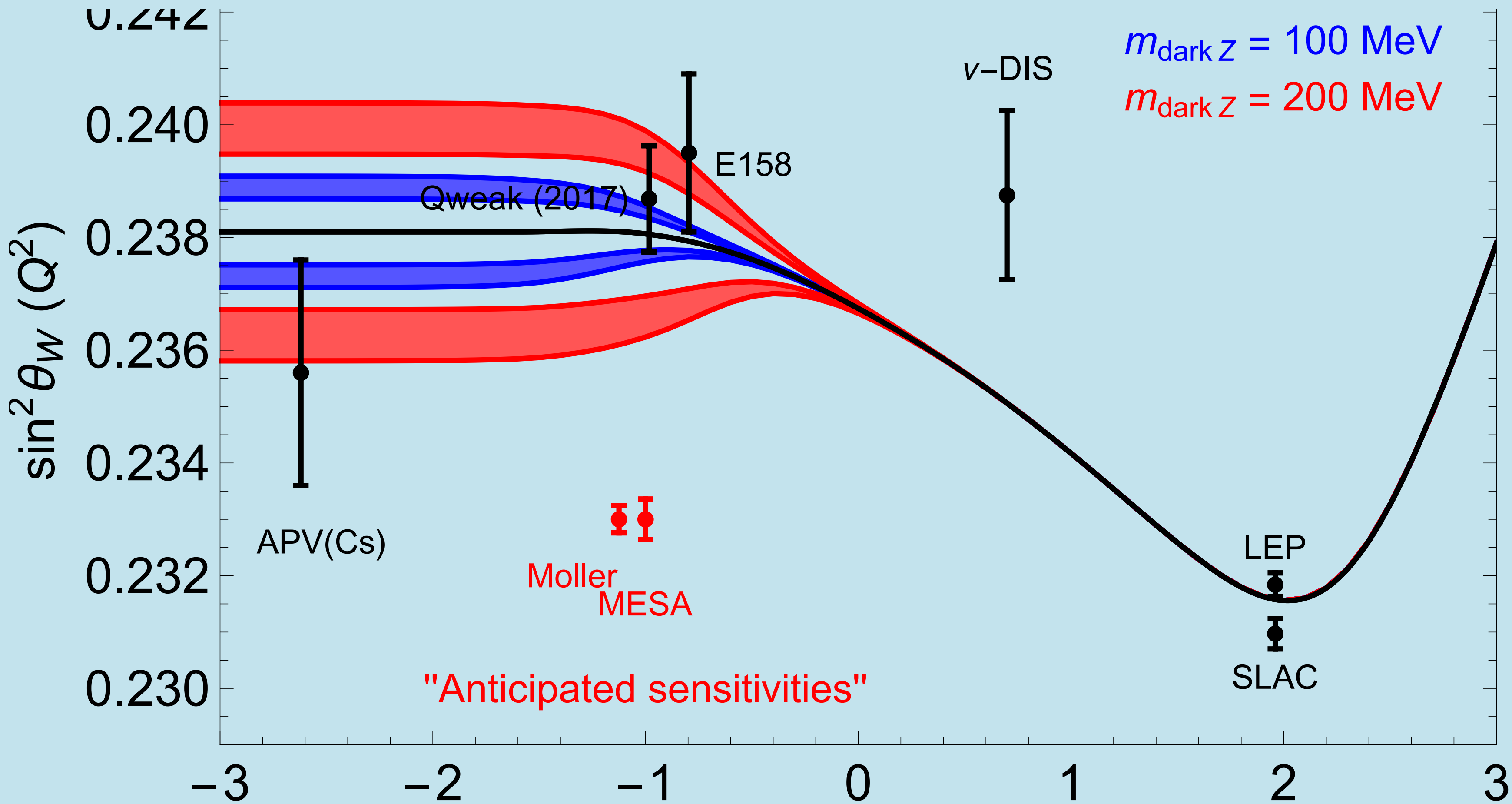

$m_{\text{dark }Z}$ = 100 MeV
$m_{\text{dark }Z}$ = 200 MeV
ν–DIS
E158
Qweak (2017)
APV(Cs)
Moller
MESA
LEP
SLAC
"Anticipated sensitivities"
$\sin^2\theta_W\,(Q^2)$
0.242
0.240
0.238
0.236
0.234
0.232
0.230
−3
−2
−1
0
1
2
3

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
$\Delta\sin^2\theta_W(m_Z)_{MS}=\pm0.0007$ (Pol. Uncertainty!)

Future (Z pole competitive)
P2 in Mainz (A_{RL}(ep)) $\Delta\sin^2\theta_W(m_Z)_{MS}=\pm0.00037$

Moller at JLAB Goal **$\Delta\sin^2\theta_W(m_Z)_{MS}=\pm0.00027$!**

"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 & $g_{B\text{-}L}$ of $O(10^{-7})$

Down to low masses ~ 5MeV