The Hunt for Dark Z Bosons: Why we need to upgrade the SuperKEKB

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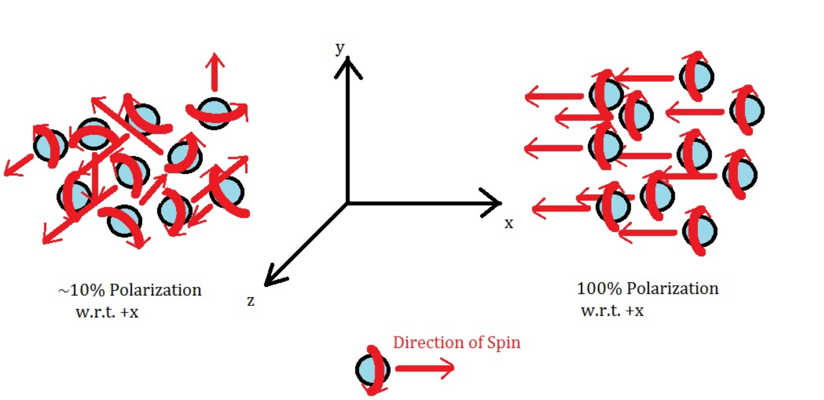
Game Plan:

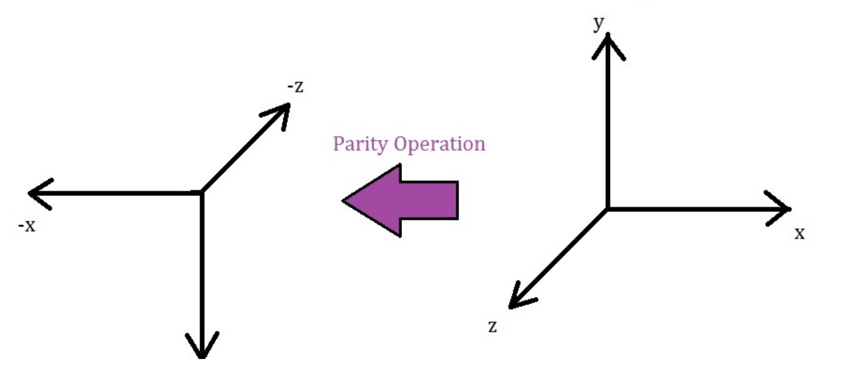
- Terminology
- At the SuperKEKB
- The Weak Mixing Angle
- The Dark Z Boson model
- Other models that could be tested

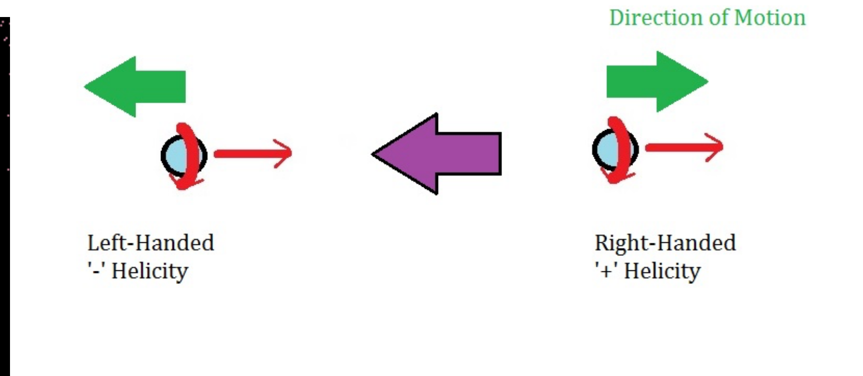
Terminology:

[Ref. 1]

- (Spin) Polarization – the degree to which the spin of elementary particles is aligned in a given direction
- Parity operation – take the space from (x, y, z) -> (-x, -y, -z)
- Helicity – Projection of Spin onto Momentum







Terminology:

[Ref. 1]

- The Weak Mixing angle: It is a parameter of the Standard Model that pertains to the Weak Interaction.
  - It affects the vector couplings of the Z boson.
  - It is typically measured by measuring parity violations
  - It's value changes with energy scale Q, due to running
  - It's running can be theoretically predicted – but it *must* be measured at (at least) one Q = 'Q_0' experimentally
  - It has been best measured at the Z pole (i.e. Q = M_z)

Terminology:

[Ref. 1, 3]

- The Weak Mixing angle: It is a parameter of the Standard Model that pertains to the Weak Interaction.

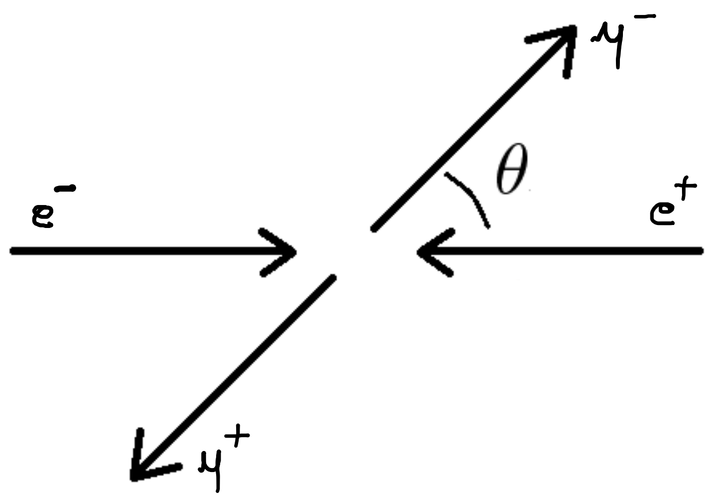
$$\frac{-ig_z}{2}\gamma^{\mu}(c_V^f - c_A^f\gamma^5) \qquad (Z^0 \text{ vertex factor})$$

Table 9.1 Neutral vector and axial vector couplings in the GWS model

f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

Terminology:

- Forward-Backward Asymmetry: A_{FB} **[Ref. 2]**



$$A_{FB} = \frac{\Sigma_F - \Sigma_B}{\Sigma_F + \Sigma_B}$$

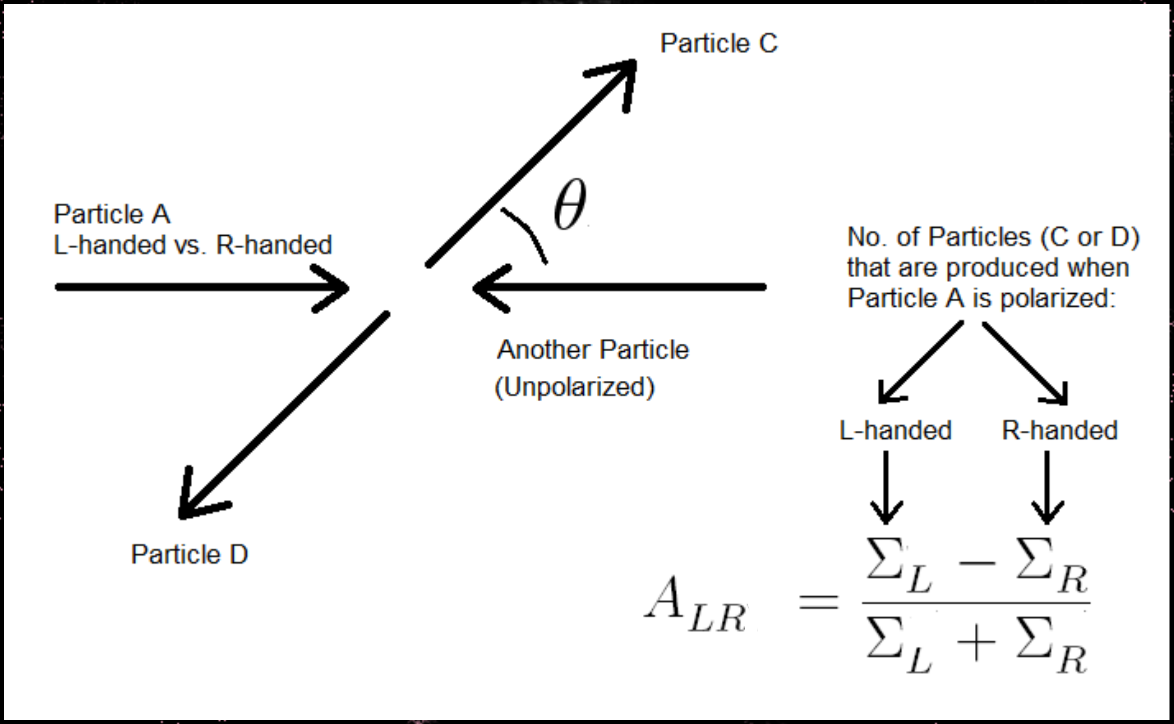
It relates to the weak mixing angle by:

This formula is specific to our experiment

$$A_{FB}^{0+1} = a_l^2 \frac{6s\cos a}{3+\cos^2 a} \frac{s(1+2v_l^2) - M_z^2}{(s-M_z^2)^2 + 2sv_f^2(s-M_z^2) + s^2(v_l^2+a_l^2)} + \Delta_{FB}$$

Terminology:

- Left-Right Asymmetry: A_{LR} **[Ref. 2]**



This formula is specific to our experiment

It relates to the weak mixing angle by:

$$A_{LR}^{0+1} = -\frac{s}{8M_w^2}\frac{1-s_w^2}{s_w^2}\frac{2\cos a\cos b + 6(\cos a + \cos b) + \cos 2a + \cos 2b + 8}{2\cos a\cos b + \cos 2a + \cos 2b + 8} + \Delta_{LR}$$

Terminology (caveats):

[Ref. 2]

Tree level ← → 1 loop correction

Asymmetries: $C = \{0, 1, 0+1\}$

$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta),$$

$$\Sigma_F^C = \int_{0}^{\cos a} \sigma_{00}^C \cdot d(\cos\theta), \quad \Sigma_B^C = \int_{-\cos a}^{0} \sigma_{00}^C \cdot d(\cos\theta).$$

$$A_{FB}^C = \frac{\Sigma_F^C - \Sigma_B^C}{\Sigma_F^C + \Sigma_B^C},$$

$$A_{LR}^C = \frac{\Sigma_L^C - \Sigma_R^C}{\Sigma_L^C + \Sigma_R^C}.$$

$$A_{LR}^0 \Big|_{0^\circ}^{180^\circ} = -\frac{s}{8m_W^2}\frac{1-4s_W^2}{s_W^2} = -\frac{1}{\sqrt{2}}\frac{G_\mu s}{\pi\alpha} g_a(e) g_v(\mu)$$

Assumptions made when calculating projected sensitivities of SuperKEKB/Belle II

[Ref. 2]

- the electron beam polarization is $p_B = 0.7000 \pm 0.0035$, the positron beam is unpolarized.
- p_B can measured with 0.5% precision, and this dominates the systematic error on A_{LR}.
- A_{FB} can be measured with an absolute systematic uncertainty of 0.005.
- Belle II collects 20 ab^{-1} of data with the electron beam polarization and selects $e^-e^+ \to \mu^-\mu^+(\gamma)$ events with 50% efficiency.
- The average $\sqrt{s}$, which has a root-mean-square (RMS) spread of 5 MeV [1], is known to ± 1.2 MeV of the peak of the $\Upsilon(4S)$ resonance[1].

At the SuperKEKB:
Pre-Upgrade

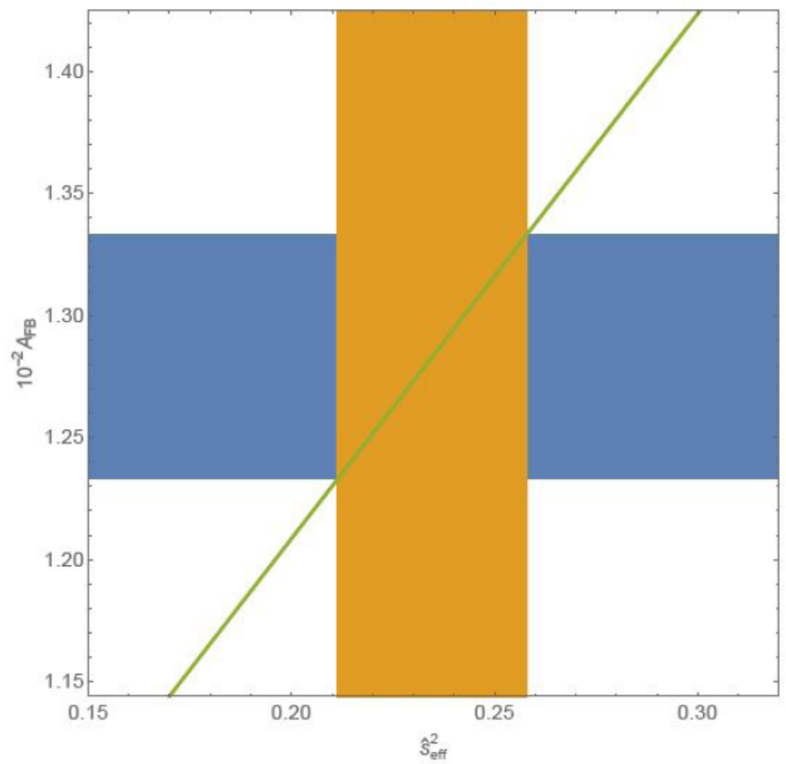


Figure 8: Forward-backward asymmetry [for $a = 10°$ & $b = 170°$] as a function of effective Weinberg mixing angle at $\sqrt{s} = 10.58$ GeV. Horizontal band shows the central value of $A_{FB}^{0+1} = 0.01283$ determined with the cut on hard-photons at 2.0 GeV. Width of the band corresponds to the 1% uncertainty on the central value of A_{FB}^{0+1}. Yields an uncertainty of 19.8% on $\sin^2\theta_w(Q^2 = 10.58\ GeV)$. (See Pg. 16-18, [2])

At the SuperKEKB:
Post-Upgrade (Projected)

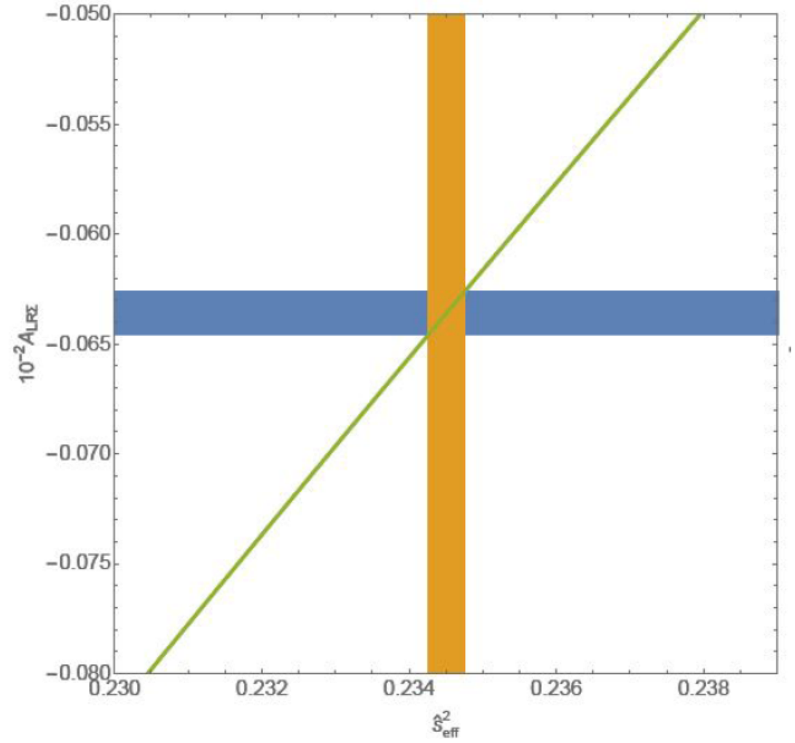


Figure 9: (Projected) Dependence of the integrated left-right asymmetry on the effective Weinberg mixing angle at $\sqrt{s} = 10.58$ GeV. Horizontal bands show the central value of A_{LR}^{0+1} = -0.00063597 determined with the cut on soft-photons at 2.0 GeV. The width of the band corresponds to the ±0.0000097 uncertainty on the central value of A_{LR}^{0+1}. Yields an uncertainty of 0.21% on $\sin^2\theta_w(Q^2 = 10.58\ GeV)$ [All figures for proposed electron beam polarization of ∼ 70%]. (See Pg. 16-18, [2])

The Weak Mixing Angle

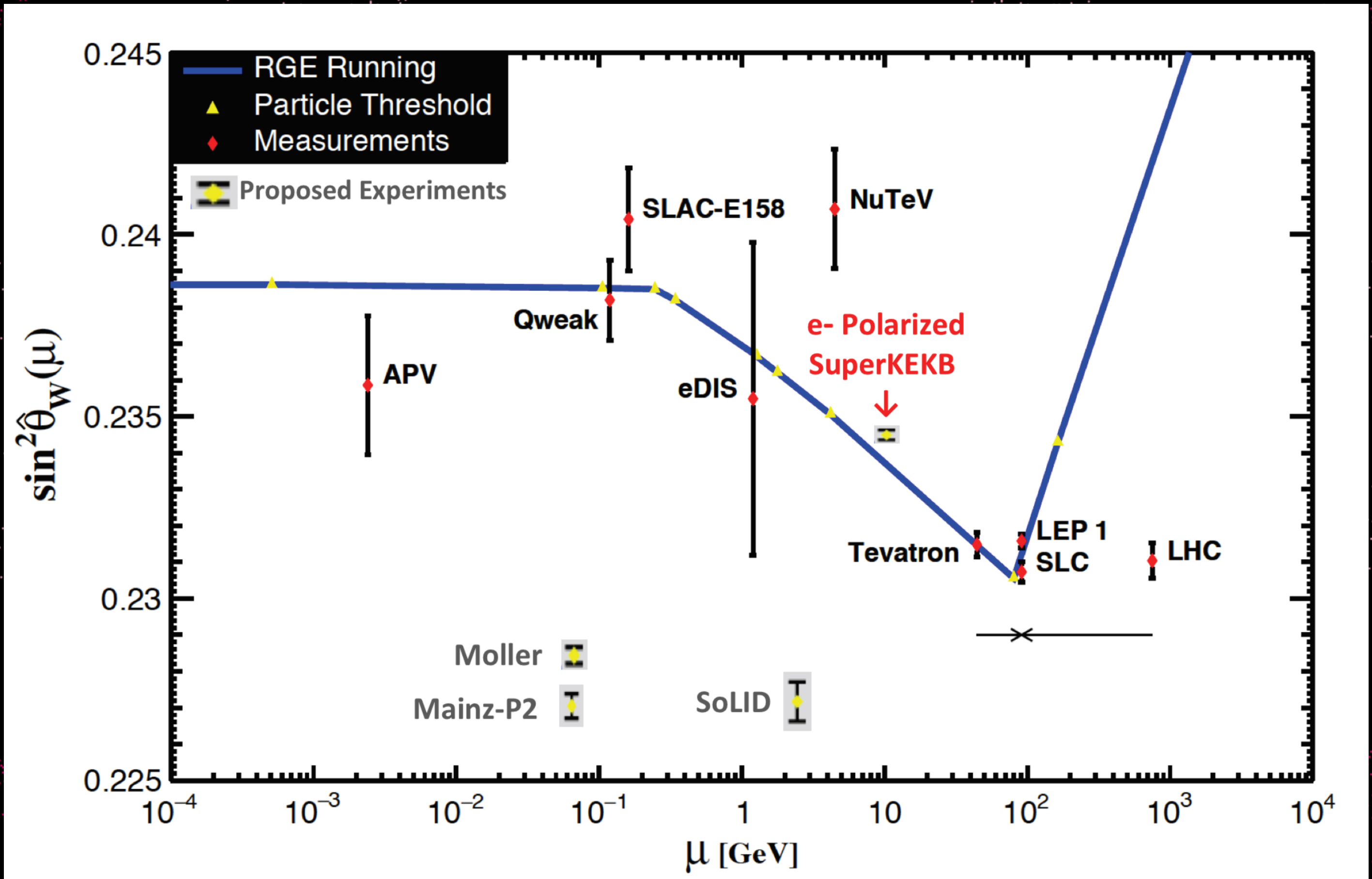
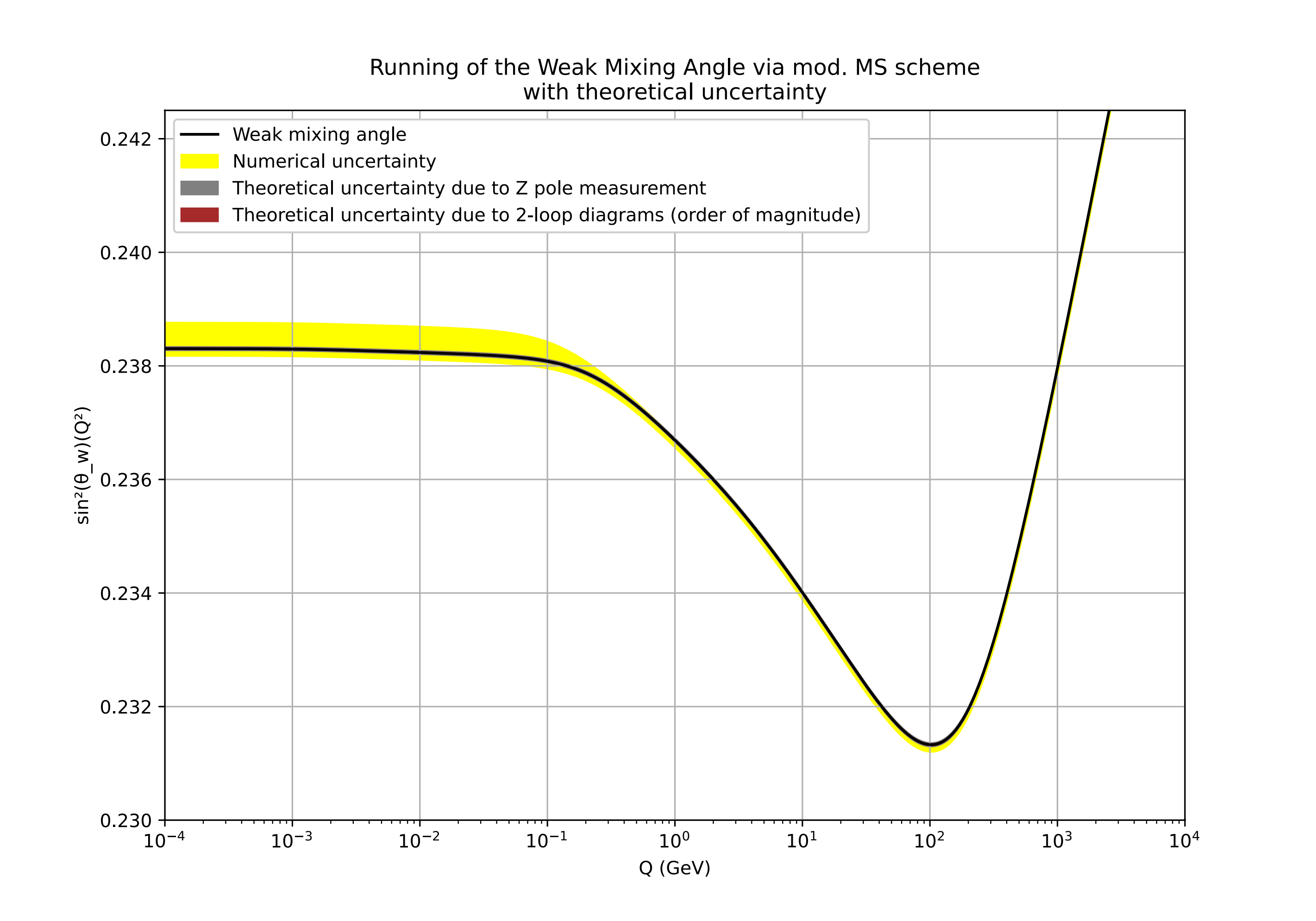
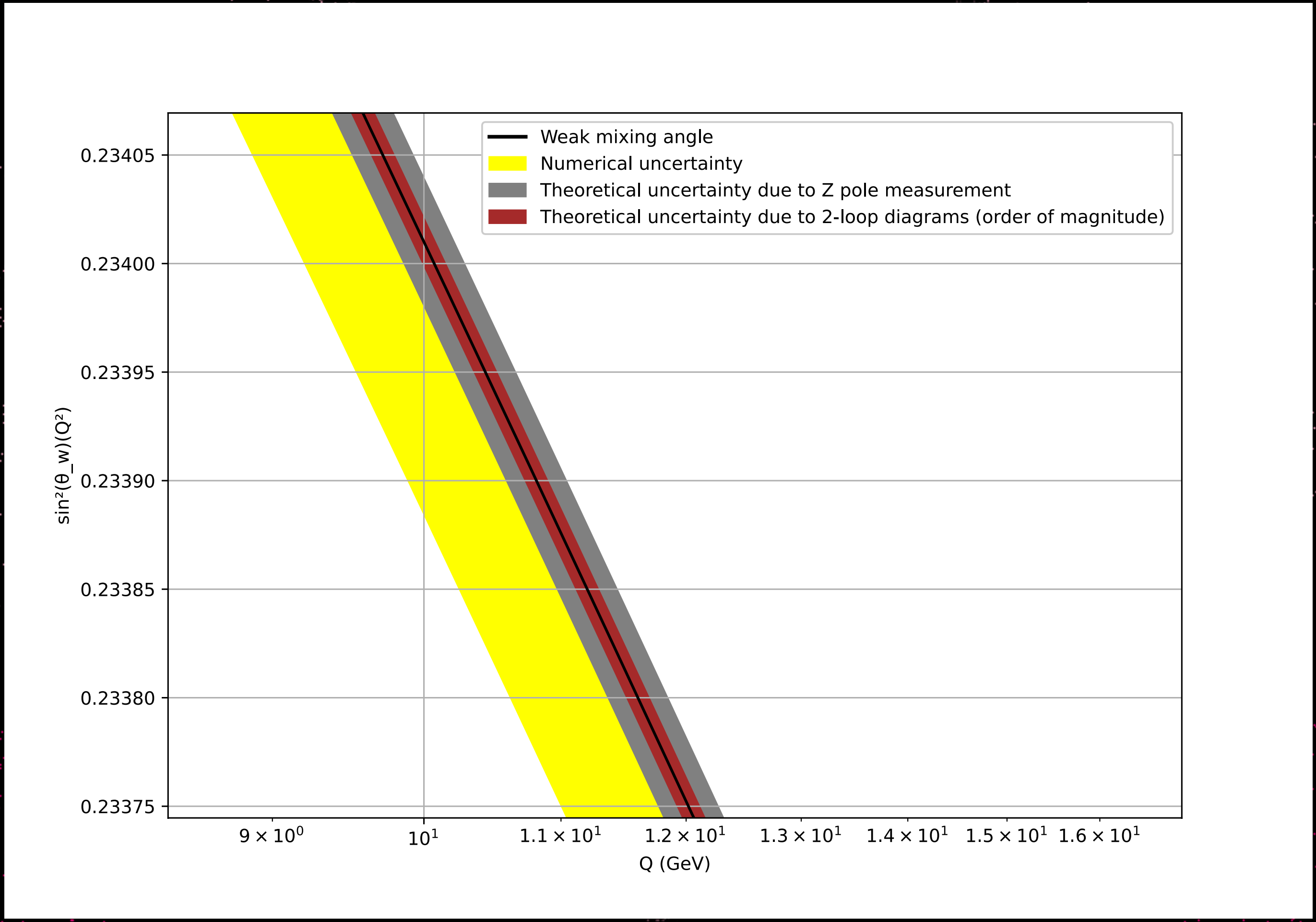


Figure adapted from **[Ref. 10]**

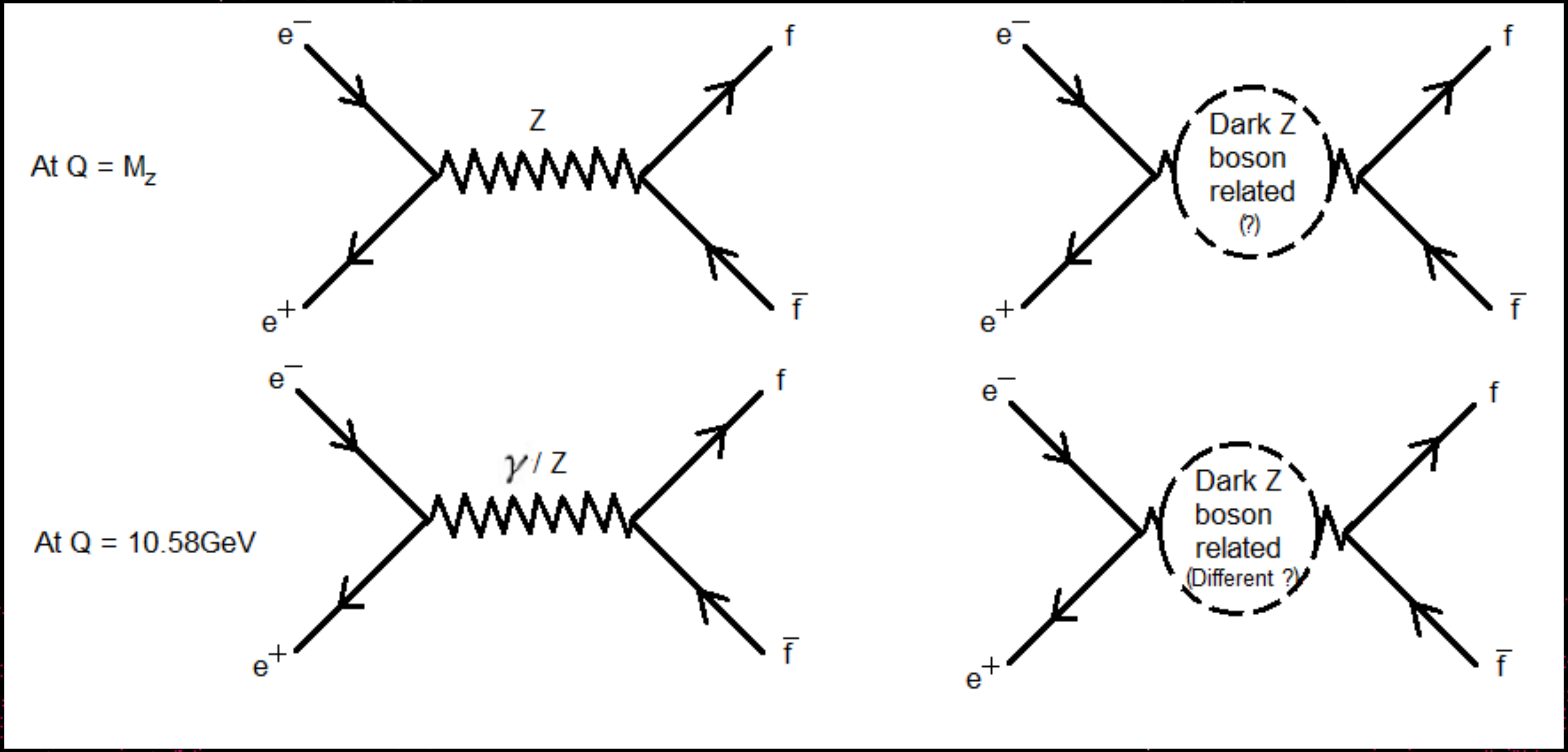
The Weak Mixing Angle



The Weak Mixing Angle



Possible departure from SM prediction due to presence of Dark Z Boson



Dark Photon vs. Dark Z boson model

[Ref. 12]

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$

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

Dark Photon vs. Dark Z boson model

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

Dark Photon:

$$\mathcal{L}_{\text{int}} = -\varepsilon\, eJ^\mu_{em}Z'_\mu$$

Dark Z Boson:

$$\mathcal{L}_{\text{int}} = -[\varepsilon\, eJ^\mu_{em} + \varepsilon_Z\,(g/2\cos\theta_W)J^\mu_{NC}]\,Z'_\mu$$

Dark Photon vs. Dark Z boson model

[Ref. 12]

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$

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

Dark Photon:

$$\mathcal{L}_{\text{int}} = -\varepsilon\, e J^\mu_{em} Z'_\mu$$

Dark Z Boson:

$$\mathcal{L}_{\text{int}} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\,(g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$$

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$$

Possible departure from SM prediction due to presence of Dark Z Boson

[Ref. 12]

$$\sin^2\theta_w(Q^2)_{if\ dark\ Z\ exists} \to \kappa_d(Q^2)\sin^2\theta_w(Q^2)_{SM}$$

$$\kappa_d(Q^2) = 1 - \epsilon\delta\frac{M_Z}{M_{Z_d}}\cot\theta_w(Q^2)_{SM}\frac{M_{Z_d}^2}{Q^2 + M_{Z_d}^2}$$

Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\lvert\delta\rvert \lesssim 0.08 - 0.01\ (0.001)$	Fairly independent of m_{Z_d}. Depends on ε.
Rare K Decays	$\lvert\delta\rvert \lesssim 0.01 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$. Depends on BR$(Z_d)$.
Rare B Decays	$\lvert\delta\rvert \lesssim 0.02 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$. Depends on BR$(Z_d)$. Some mass gap ~ 3 GeV.
$H \to ZZ_d$	$\lvert\delta\rvert \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$. Depends on BR$(Z_d)$ and background.

TABLE II: Rough ranges of current (future) constraints on δ from various processes examined along with commentary on applicability of the bounds. These processes have negligible sensitivity to pure kinetic mixing effects.

Possible departure from SM prediction due to presence of Dark Z Boson

[Ref. 4]

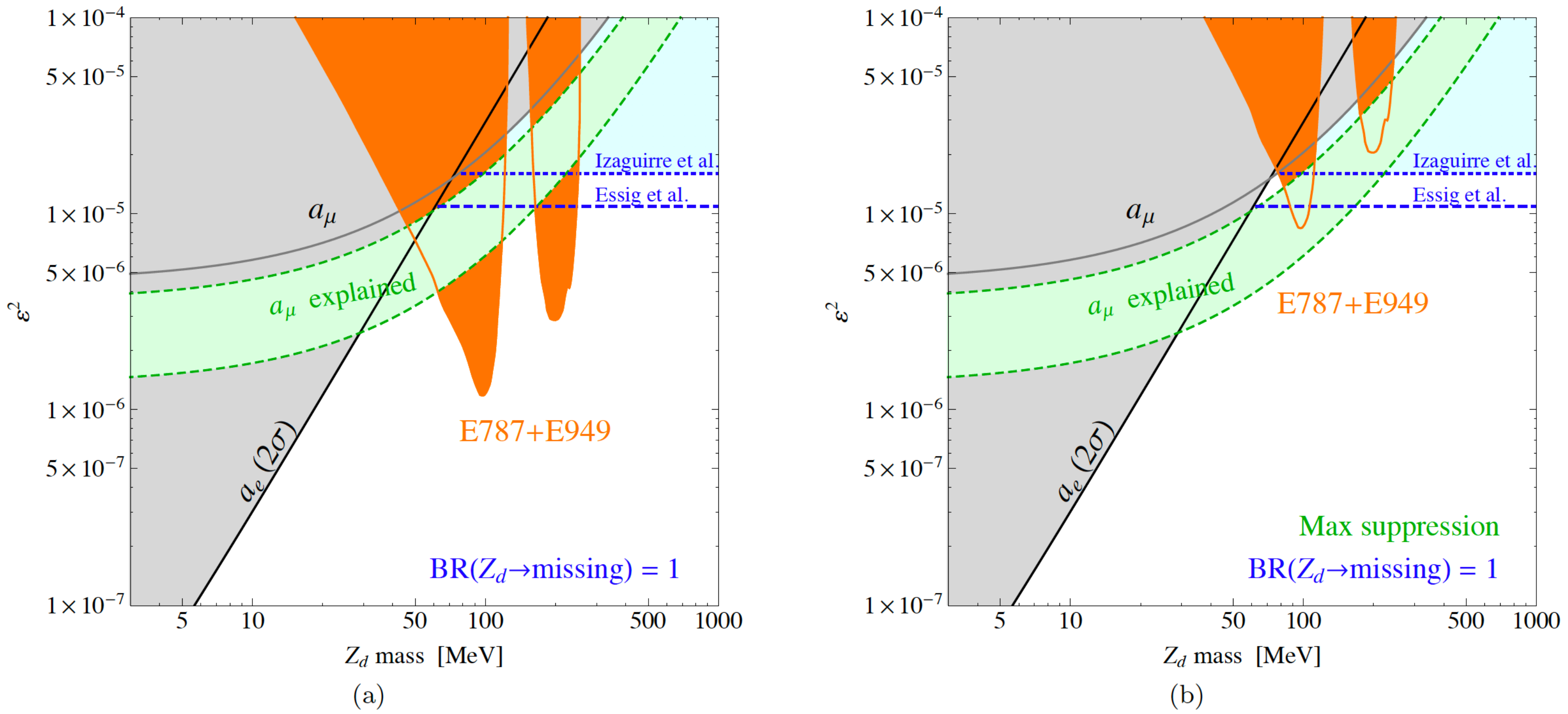
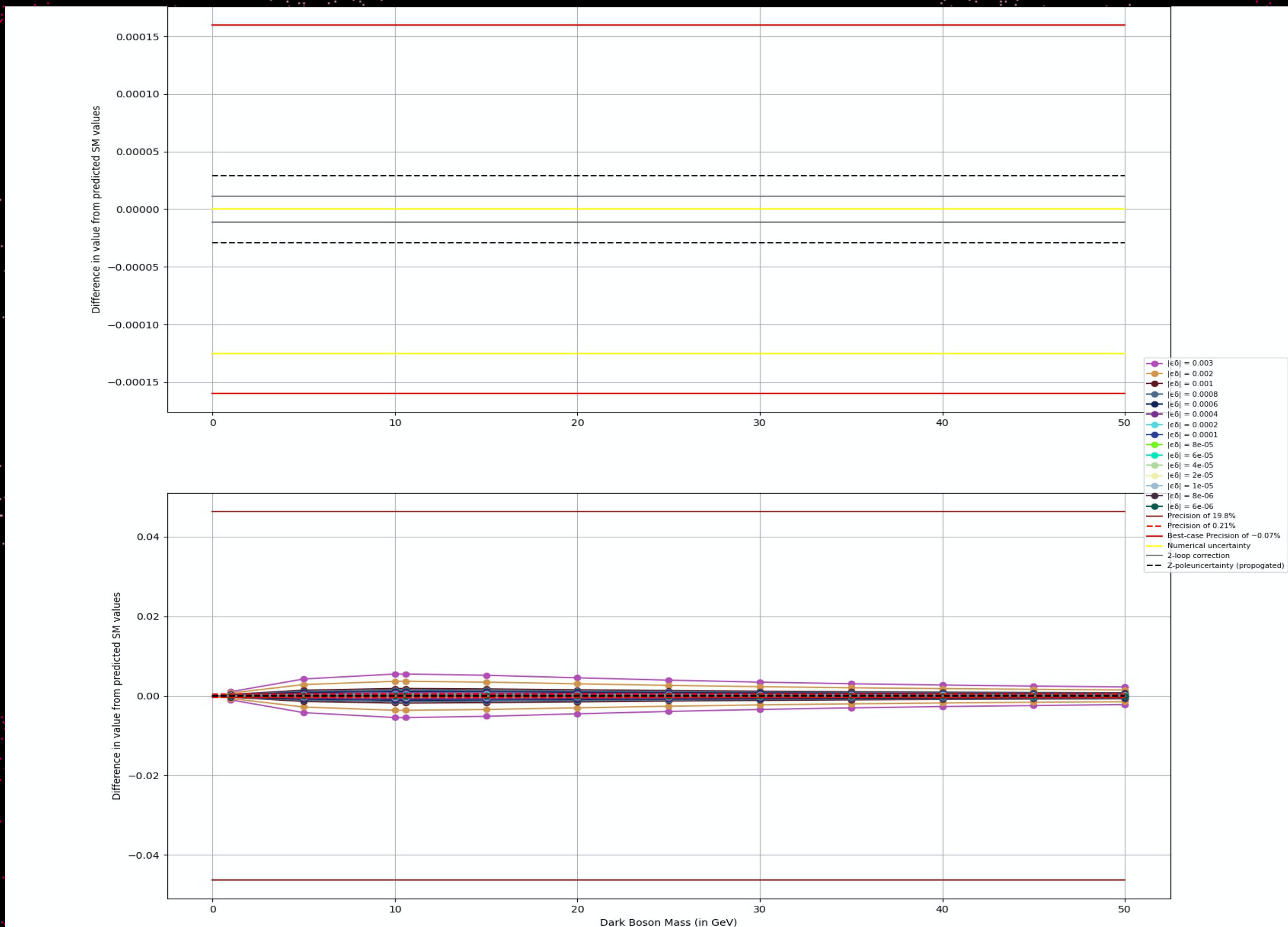
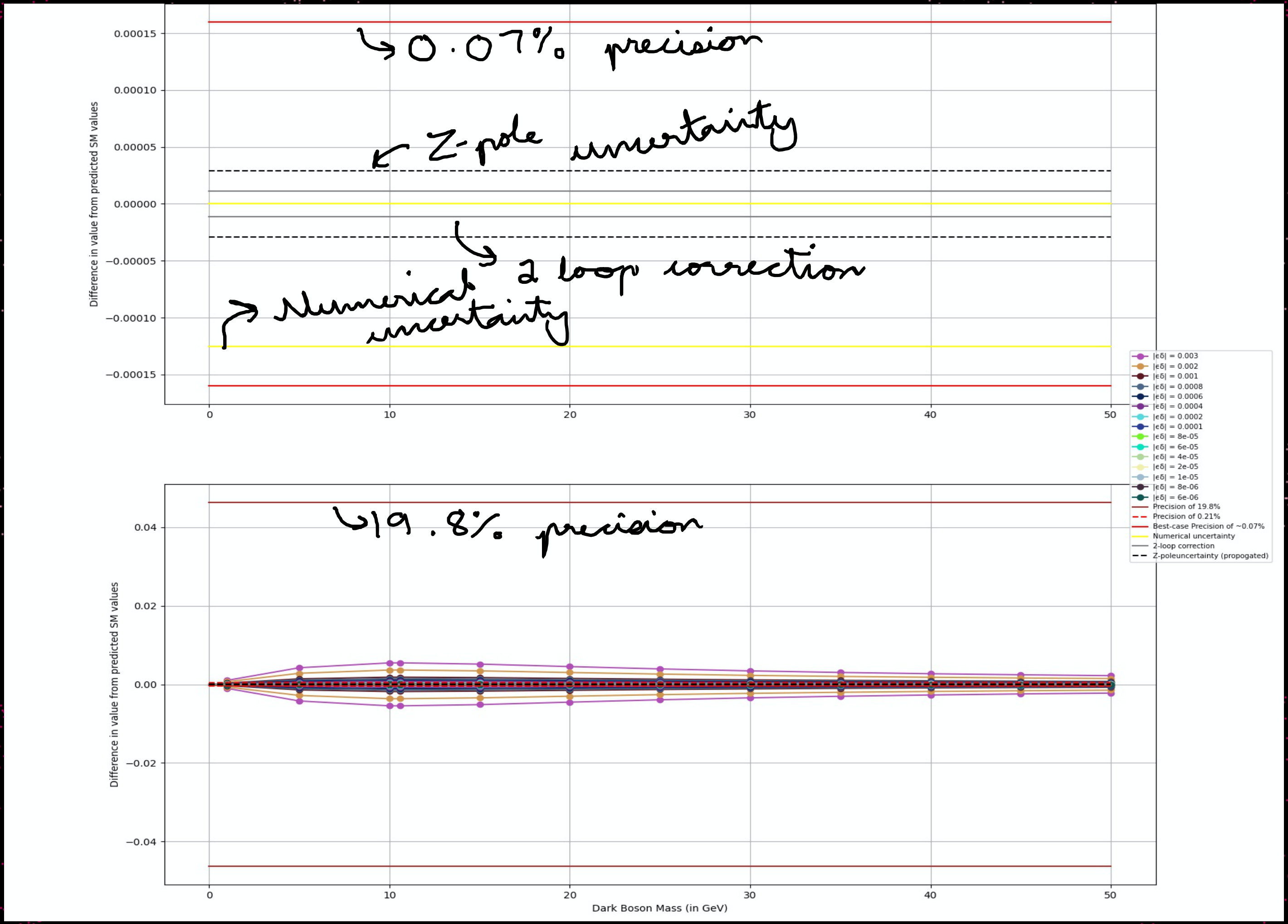


FIG. 4: Constraints from BNL E787+E949 experiments ($K \to \pi$ + nothing), at 95% C.L., on the dark photon parameter space (orange area) for BR($Z_d \to$ missing) = 1 for (a) dark photon and (b) dark Z with maximum suppression. Also illustrated there are constraints from $e^+e^- \to \gamma$ + 'invisible' based on BaBar data as given in Ref. [41] by Izaguirre et al. and Ref. [53] by Essig et al.

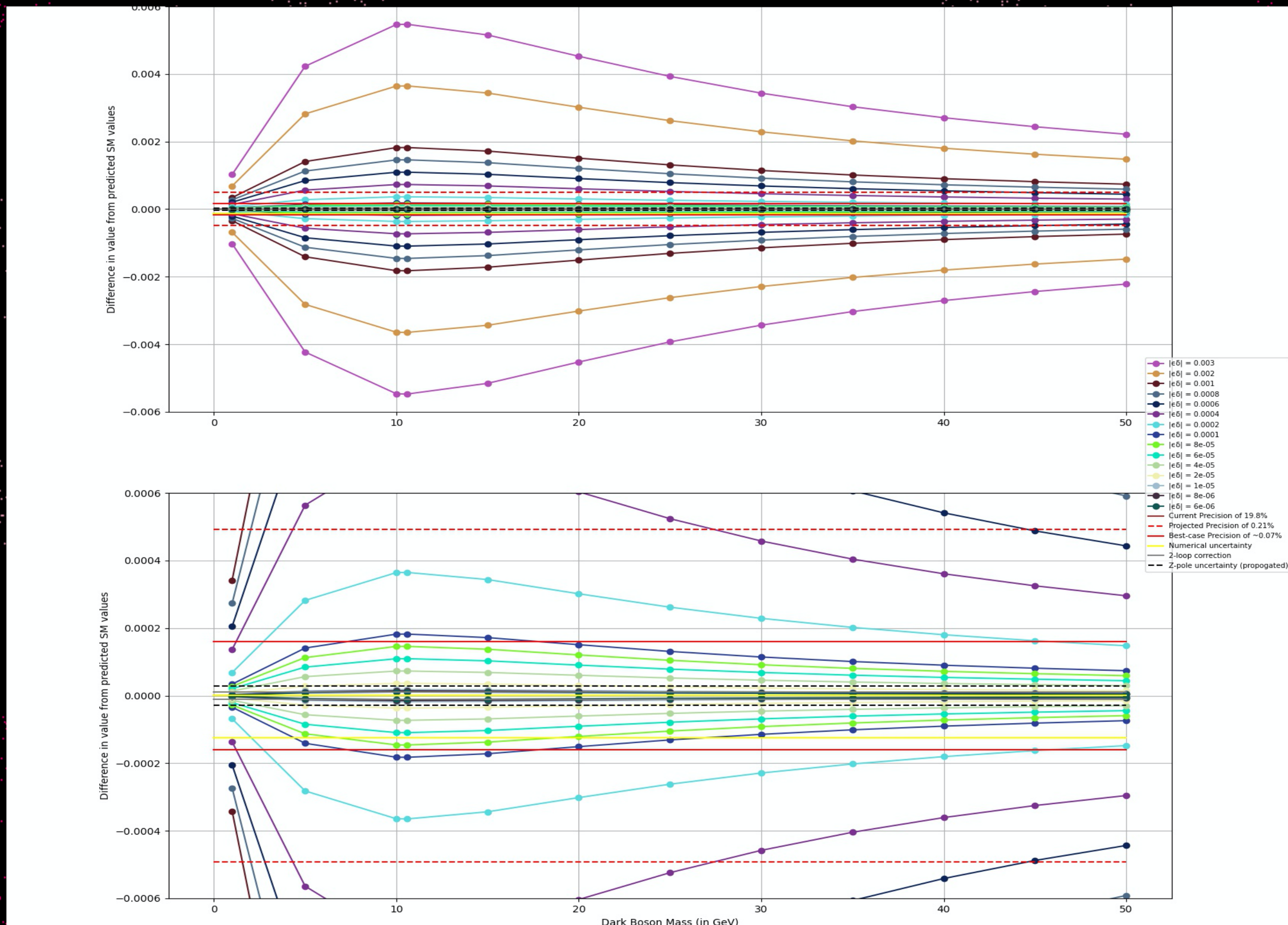
Possible departure from SM prediction due to presence of Dark Z Boson



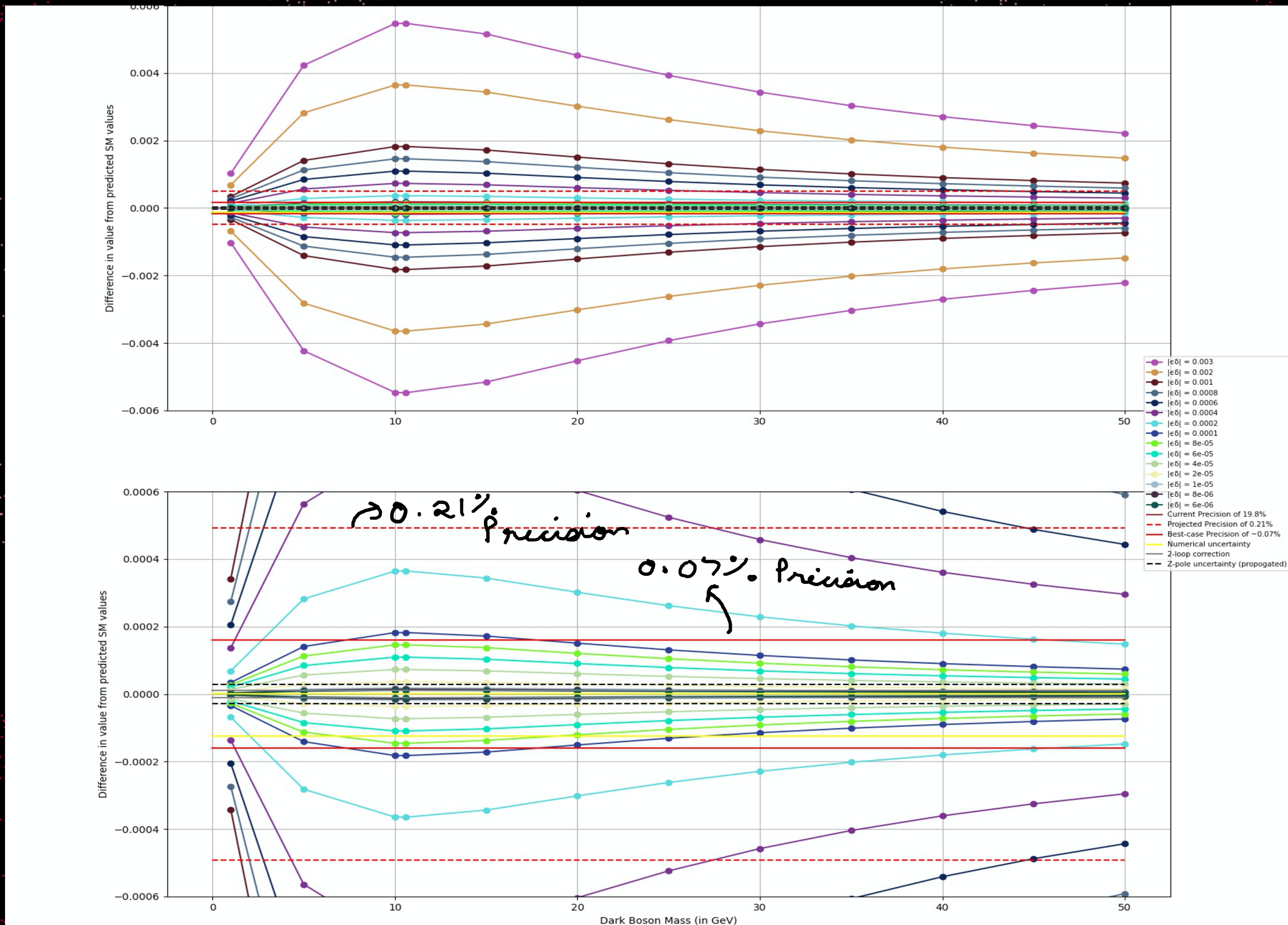
Possible departure from SM prediction due to presence of Dark Z Boson



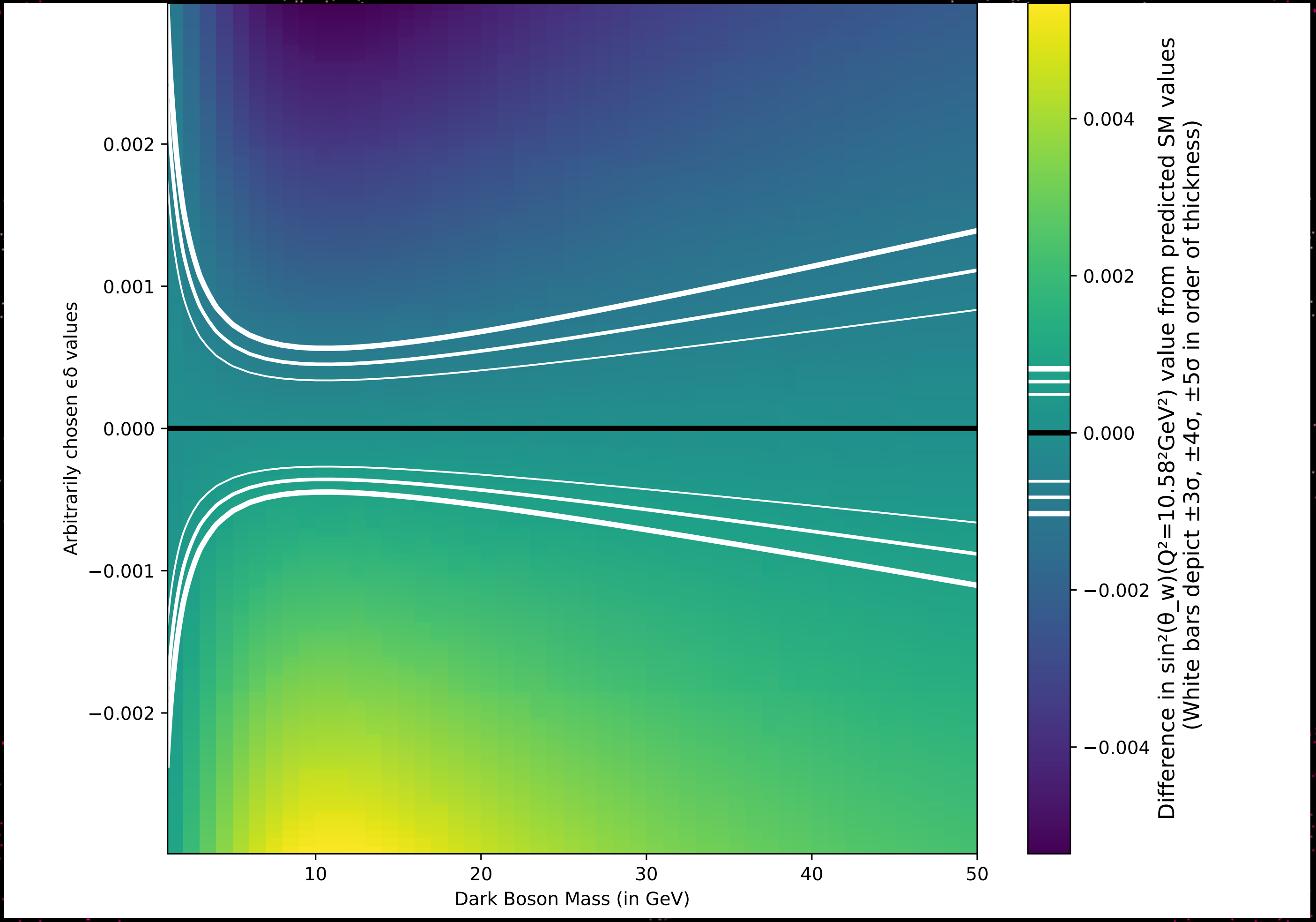
Possible departure from SM prediction due to presence of Dark Z Boson



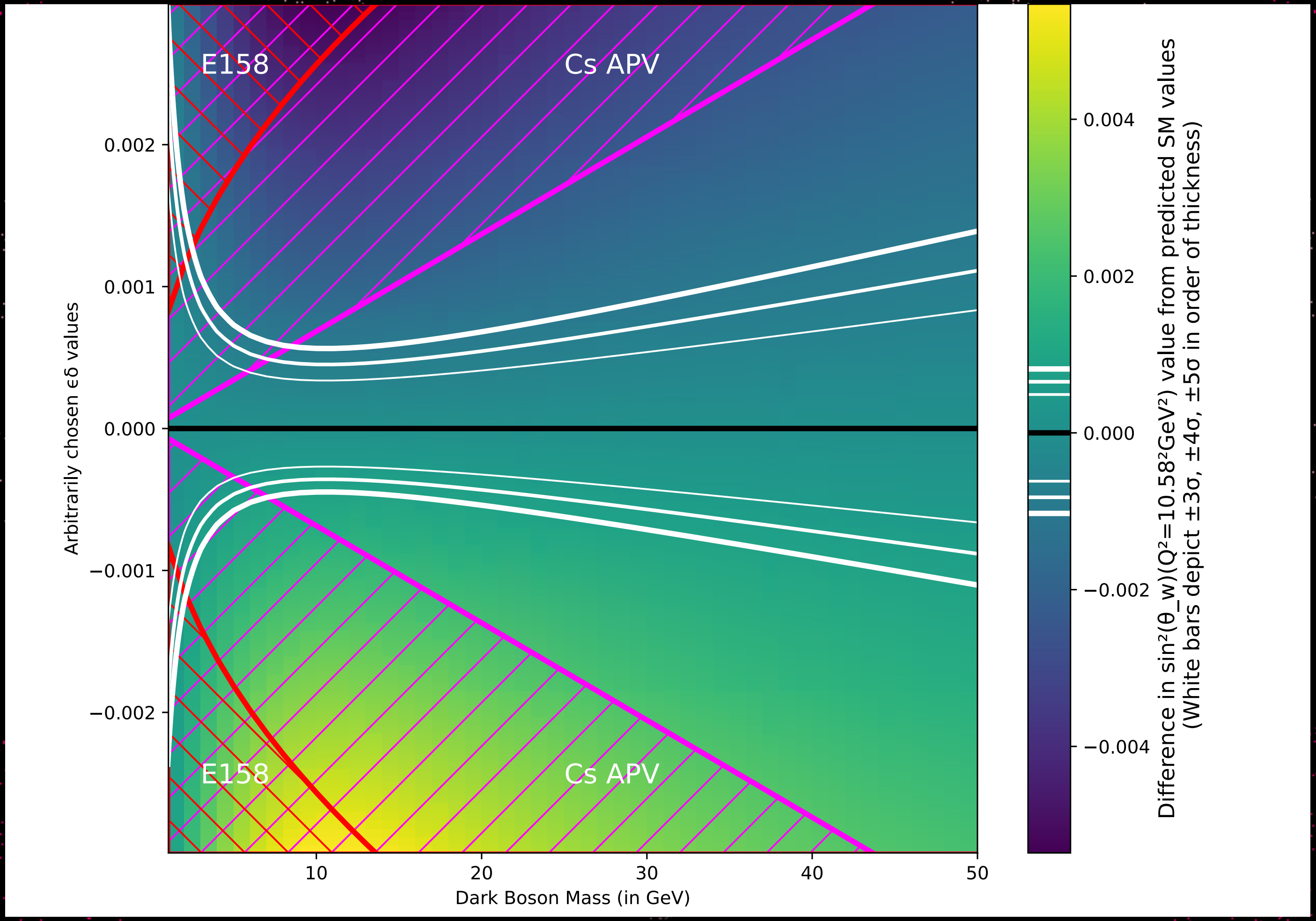
Possible departure from SM prediction due to presence of Dark Z Boson



Possible departure from SM prediction due to presence of Dark Z Boson



Possible departure from SM prediction due to presence of Dark Z Boson



Constraints from **[R. 11]**

LDM, another possibility?

[Ref. 13]

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} - \frac{\epsilon}{2}Z'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}\gamma_\mu\partial^\mu\chi$$
$$+\bar{\chi}\gamma^\mu(g_\chi^V + g_\chi^A\gamma^5)\chi Z'_\mu + \bar{\ell}\gamma^\mu(g_\ell^V + g_\ell^A\gamma^5)\ell Z'_\mu$$
$$-m_\chi\bar{\chi}\chi + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu,$$

- Leptophilic Dark Matter
  - Couples only to leptons
  - does not require a reconstructed tau+ tau- invariant mass

Conclusion:

Upgrading the SuperKEKB by adding polarization to the electron beams will increase our odds of detecting a dark Z boson (and maybe other effects)!

Thank You!

References

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Backup Slides!

Terminology (caveats):

[Ref. 1]

- Chirality (of a Dirac fermion) - Sign of eigenvalue of γ^5
- Chirality vs. Helicity vs. Handedness:

	Chirality	Helicity
Physical description	Related to weak charge	Related to handedness: thumb in velocity direction, fingers in spin direction. No direct relation to weak charge.
Operator form	γ^5	$\frac{1}{2}\frac{\Sigma\cdot\mathbf{p}}{\lvert\mathbf{p}\rvert}$
Projection operator form	$P^{R}_{L} = \frac{1}{2}\left(1 \pm \gamma^5\right)$	$\Pi^{R}_{L}(\mathbf{p}) = \frac{1}{2}\left(1 \pm \frac{\Sigma\cdot\mathbf{p}}{\lvert\mathbf{p}\rvert}\right)$
Plus vs minus	$-$ = LH ; $+$ = RH	same as at left
Interpretation of RH/LH	Only a label, not real handedness	Physical handedness via right hand rule

Refers to L and R handed representations of Poincare group. This is a math thing, which is what Griffiths considers "real handedness". In most scientific literature, it is used interchangeably – see caveat 4 in the next slide

Terminology (caveats):

[Ref. 1]

Chirality vs. Helicity vs. Handedness:

1. Chiral fermions are eigenvectors of the weak interaction.
2. By Dirac equation, a chiral fermion (L or R) evolves over time to become a superposition of both L- **and** R-chiral fermions
3. If you make a left-handed fermion by polarizing it, it will stay left-handed i.e. it's helicity will not change (provided, your frame of reference does not change)
4. When $E >> mc^2$, (or as $m \to 0$), chirality = helicity

The GWS Model

Create a field Lagrangian that has local $SU(2)_L xU(1)$ symmetry

$$\begin{pmatrix} \nu_e \\ e_L \\ e_R \end{pmatrix} \rightarrow \begin{pmatrix} e^{-\frac{i\beta(x)}{2}} & 0 & 0 \\ 0 & e^{-\frac{i\beta(x)}{2}} & 0 \\ 0 & 0 & e^{-i\beta(x)} \end{pmatrix} \begin{pmatrix} \nu_e \\ e_L \\ e_R \end{pmatrix} .$$

$$\begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \rightarrow e^{\frac{i}{2}\boldsymbol{\tau}\cdot\boldsymbol{\alpha}(x)} \begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \quad e_R \rightarrow e_R .$$

To do this, need to introduce 2 gauge fields ($\mathbf{W}_\mu$, B_μ), and 2 new quantum numbers – Hypercharge Y and Isospin I.

Field	ν_e	e_L	e_R
Y	-1	-1	-2

Table of weak hypercharge Y

Field	ν_e	e_L	e_R
I	$\frac{1}{2}$	$\frac{1}{2}$	0
I_3	$\frac{1}{2}$	$-\frac{1}{2}$	0

Table of isospin quantum numbers I_3 and I

[Ref. 3]

The GWS Model

Then spontaneously ~~break~~ (hide) the symmetry by introducing the Higgs field (this adds mass to your massless gauge fields)

Mix everything up (literally) and you get a massive W^+, W^- and Z, and a massless photon.

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W, \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix},$$

[Ref. 1, 3]

The GWS Model

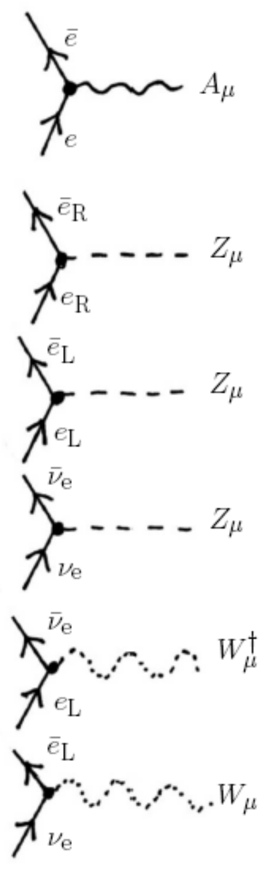


Fig. 47.4 The electroweak interaction vertices predicted by the Weinberg–Salam theory.

$$g_w = \frac{g_e}{\sin\theta_w}, \qquad g_z = \frac{g_e}{\sin\theta_w \cos\theta_w}$$

$$M_W = M_Z \cos\theta_w$$

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad (W^\pm \text{ vertex factor})$$

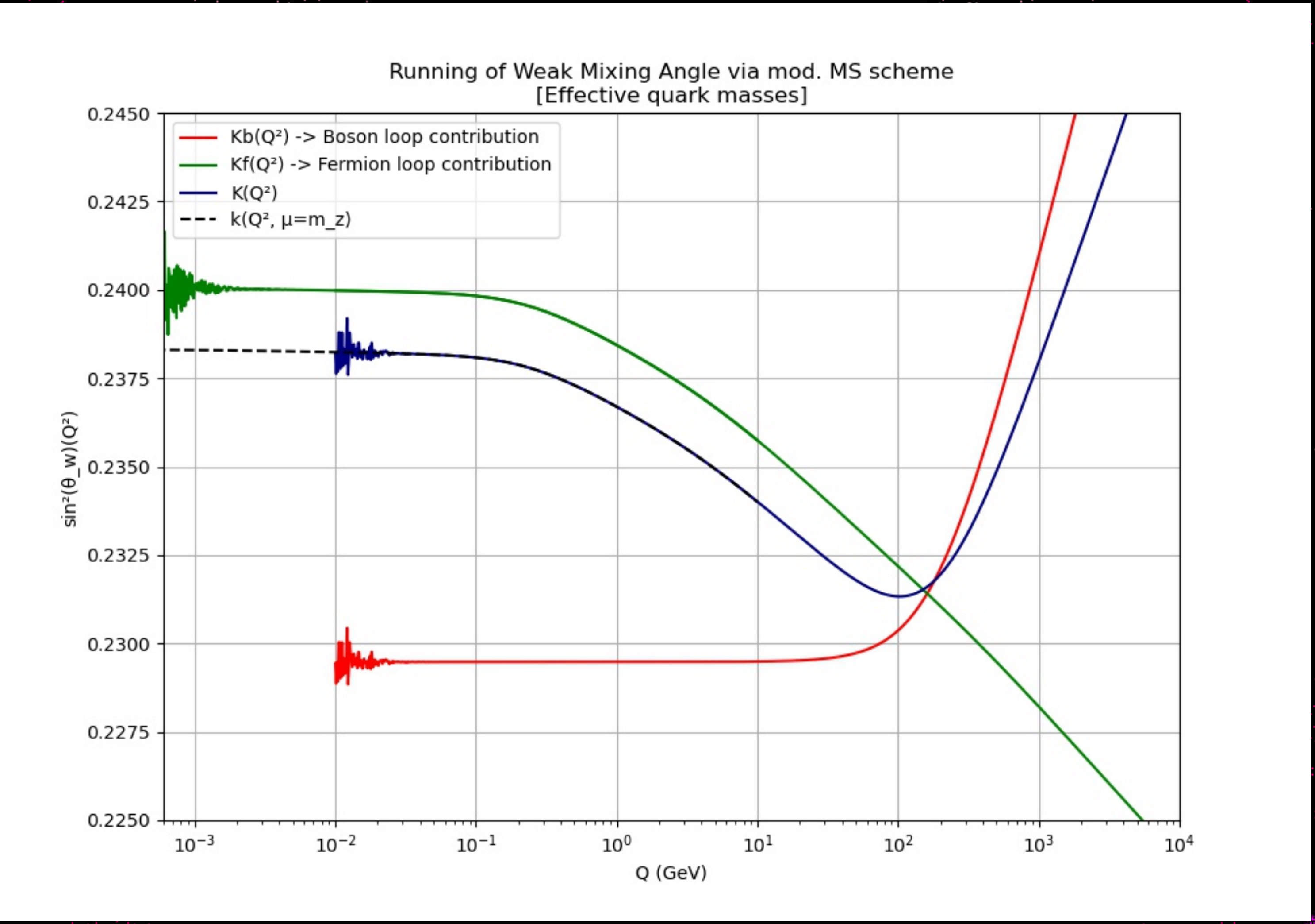
$$\frac{-ig_z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5) \qquad (Z^0 \text{ vertex factor})$$

Table 9.1 Neutral vector and axial vector couplings in the GWS model

f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

[Ref. 1, 3]

Numerical Uncertainty



Numerical Uncertainty

$$\hat{\kappa}^{(e,e)}(Q^2, \mu = M_z) = 1 + \frac{\alpha}{2\pi\hat{s}^2}[-2N_c \sum_{allfermions,f} [(T_{3f}Q_f - 2\hat{s}^2)I_f(Q^2)] + (\frac{7}{2}\hat{c}^2 + \frac{1}{12})\ln\frac{M_w^2}{M_z^2} - \frac{23}{18} + \frac{\hat{s}^2}{3}]$$

$$I_f(Q^2) = \int_0^1 dx x(1-x)\ln\frac{M_f^2 - Q^2x(1-x)}{M_z^2}$$

[Ref. 7]

$$\hat{K}_f(Q^2) = 1 - \frac{\alpha}{2\pi\hat{s}^2}\frac{N_c}{3}\sum_{allfermions,f}[(T_{3f}Q_f - 2\hat{s}^2) (\ln\frac{M_f^2}{M_Z^2} - \frac{5}{3} + 4z_f + (1-2z_f)p_f\ln\frac{p_f+1}{p_f-1})]$$

$$z_f := \frac{M_f^2}{Q^2}$$

[Ref. 6, 5] $p_f := \sqrt{1+4z_f}$

$$\hat{K}(Q^2) = \hat{K}_f(Q^2) + \hat{K}_b(Q^2) - 1$$

[Ref. 6, 5]

$$\hat{K}_b(Q^2) = 1 - \frac{\alpha}{2\pi\hat{s}^2}[-\frac{42\hat{c}^2+1}{12}\ln(\hat{c}^2) + \frac{1}{18} - (\frac{p}{2}\ln\frac{p+1}{p-1} - 1)[(7-4z)\hat{c}^2 + \frac{1}{6}(1+4z)] - z[\frac{3}{4} - z + (z - \frac{3}{2})p\ln\frac{p+1}{p-1} + z(2-z)\ln^2\frac{p+1}{p-1}]]$$

$$z := \frac{M_W^2}{Q^2}$$

[Ref. 6, 5] $p := \sqrt{1+4z_f}$

$$\hat{K}(Q_0^2) = \hat{\kappa}^{(e,e)}(Q_0^2, \mu) + \frac{\hat{\alpha}(M_z)}{4\pi\hat{s}^2}$$

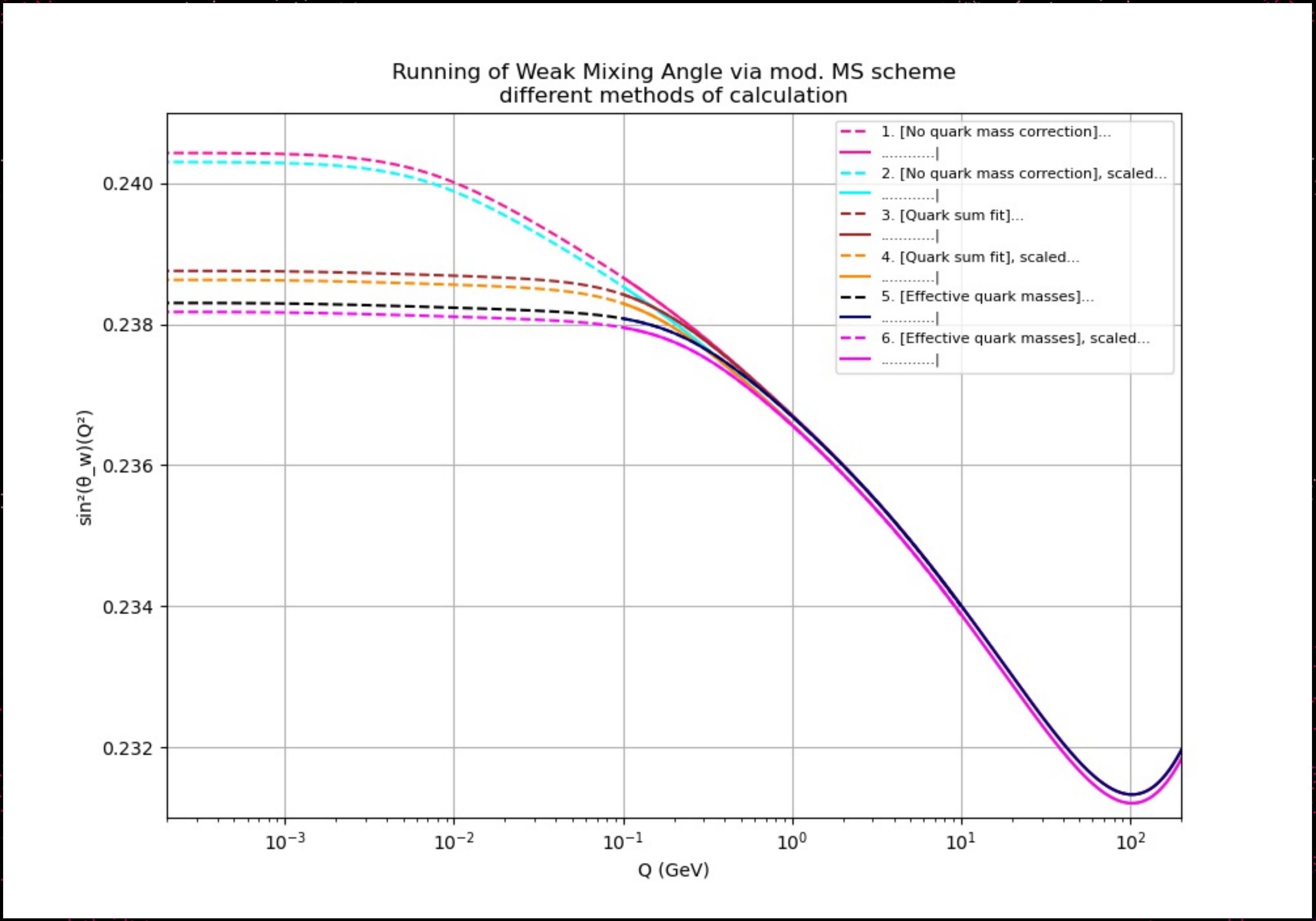
[Ref. 8]

$$\frac{N_c}{3}\sum_{allquarks,q}(T_{3q}Q_q - 2\hat{s}^2)\ln\frac{M_q^2}{M_Z^2} \rightarrow -6.88 \pm 0.06$$

[Ref. 8]

Also see **[Ref. 9, 10]**

Numerical Uncertainty



Numerical Uncertainty