Extra boson mix with $Z$ boson explaining the mass of $W$ boson

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Abstract

We explore the possibility of explaining the $W$ mass with an extra gauge boson mixing with the $Z$ boson at tree level. Extra boson mixing with $Z$ boson will change the expression of $Z$ boson mass, thus altering the $W$ boson mass. We explore two models in this work. We find that in the Derivative Portal Dark Matter model, there are parameters space which can give the observed $W$ boson mass, as well as the observed Dark Matter relic density. In the U(1) extension model, the kinetic mixing between extra boson and $B$ boson can also give the observed $W$ boson mass. However, to fulfill electroweak oblique parameters fit the kinetic mixing in the U(1) model can only contribute about 27 MeV extra mass to the Standard Model $W$ boson mass. Both model indicate the extra vector boson with best fit mass around 120 GeV.

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I. INTRODUCTION

Recently the Collider Detector at Fermilab (CDF) Collaboration has measured the mass of \( W \) boson to be \( 80.4335 \pm 0.0094 \text{ GeV} \) [1], which is deviated from Standard Model (SM) prediction of \( 80.357 \pm 0.006 \text{ GeV} \) [2] and which seems to indicate new physics beyond SM. And there are lots of works appeared to discuss this topic [3–57]. In this work we will explore physics beyond SM which can give the observed mass of the \( W \) boson at tree level.

In the SM, the mass of the \( W \) boson and the \( Z \) boson are given by the Higgs mechanism. Since \( Z \) is combination of the \( B \) boson and the \( W^3 \) boson, which is a component of the gauge triplet \( W^i \), the mass of the \( W \) boson and the \( Z \) boson are connected. And it is difficult to change the mass of the \( W \) boson solely. One way to alter the mass of the \( W \) boson is to mix the \( Z \) boson with another vector boson. Mix the \( Z \) boson with another boson will inevitably alter the mass expression of the \( Z \) boson which may alter the value of the SU(2)_L gauge coupling and thus the mass of the \( W \) boson. There are usually two kinds of mixing: direct mixing in mass matrix and kinetic mixing. Though the normalization of the kinetic mixing terms will result in mass mixing, we will consider two models in this work: Derivative Portal Dark Matter (DPDM) model [58] and the U(1) model [59, 60]. In these two models, the extra gauge boson are connects to the SM through kinetic mixing to \( Z \) boson and \( B \) boson respectively. The kinetic mixing will alter the mass expression of the \( Z \) boson and thus the mass of the \( W \) boson at tree level. Since electroweak oblique parameters have a strong constraint on electroweak physics, we will also consider the electroweak oblique parameters constraints to these models. For the DPDM model, we also consider constraints from the observed Dark Matter (DM) relic density.

This work is organized as follows: In Sec. II we generally discuss the mechanism that the mixing between extra boson and \( Z \) boson will change the mass of the \( W \) boson. In Sec. III we explore two models and discuss their capability of altering the \( W \) mass. As well as explore constraints from electroweak oblique parameters and DM relic density. And we conclude in Sec. IV

II. GENERAL DISCUSSION OF PREDICTION OF THE MASS OF \( W \) BOSON

In this section we will discuss in general how can an extra boson mix with the \( Z \) boson will change the mass of \( W \) boson. To see this we first write down the mass of the \( W \) boson \( m_W \) and the mass of the \( Z \) boson \( m_Z \) given by SM:

\[
\begin{align*}
    m^2_W &= \frac{1}{4} g^2 v^2, \\
    m^2_Z &= \frac{1}{4} (g^2 + g'v) v^2.
\end{align*}
\]  

(2.1)

Where \( g \) and \( g' \) are the gauge couplings of SU(2)_L and U(1)_Y. And \( v \) is the vacuum expectation value (vev) of the Higgs boson. When choosing the Fermi coupling constant \( G_F \), the \( Z \) boson mass \( m_Z \) and the fine-structure constant \( \alpha \) as input parameter, the \( W \) boson mass
will then be determined. Because
\[ G_F = \frac{1}{\sqrt{2}v^2}, \quad e = \sqrt{4\pi\alpha} = \frac{gg'}{\sqrt{g^2 + g'^2}}. \] (2.2)

Going beyond the SM, we will mix the Z boson with another vector boson. After that the real mass of the Z will be the square root of one of the eigenvalues of the following mass matrix:
\[ \begin{pmatrix} \frac{1}{4}(g^2 + g'^2)v^2 & b \\ b & a \end{pmatrix}. \] (2.3)

Where we have used \( a \) and \( b \) to denote some general mass term. The eigenvalues of the mass matrix can be written as:
\[ m_{Z,Z'}^2 = \frac{1}{2} \left( \frac{1}{4}(g^2 + g'^2)v^2 + a \pm \sqrt{\left( \frac{1}{4}(g^2 + g'^2)v^2 + a \right)^2 - a(g^2 + g'^2)v^2 + 4b^2} \right). \] (2.4)

Define \( c = \frac{1}{4}(g^2 + g'^2)v^2 \), we have a compact form of \( m_{Z,Z'}^2 = \frac{1}{2} \left( a + c \pm \sqrt{(a - c)^2 + 4b^2} \right). \) And we can see the heavier mass of \( m_{Z,Z'} \) will be bigger than both \( a \) and \( c \), and the lighter mass of \( m_{Z,Z'} \) will be smaller than both \( a \) and \( c \). Therefore in order to have a bigger \( c \), since observation of the \( W \) mass indicate larger \( g \), the value of \( a \) must be lager than \( c \). And the mass of \( Z \) boson should corresponds to the minus sign in Eq. (2.4). Adopting the input parameters as \( G_F = 1.1663787*10^{-5} \text{ GeV}^{-2}, \ m_Z = 91.1876 \text{ GeV}, \ \alpha \approx 1/128 \) [2], we can draw a blue band which saturate the observed mass of the \( W \) boson in 3\( \sigma \) confidence level in Fig. 1.

Actually we can calculate the analytic relation between \( a \) and \( b \) by taking the mass of \( W \) boson \( m_W \) as an input parameter. From Eq. (2.4) we can write:
\[ b^2 = c(a - m_Z^2) + m_W^4 - m_Z^2a \]
\[ = \frac{4m_W^4}{4m_W^2 - e^2v^2(a - m_Z^2) + m_Z^4} - m_Z^2a. \] (2.5)

Then we can given constraint to models beyond SM according to Eq. (2.5). Actually the above discussion does not take loop corrections from SM into consideration. Considering the loop corrections from SM we should replace \( m_W \) in Eq. (2.5) with \( m_W - \delta m_W \), where \( \delta m_W \) represents the loop corrections to \( m_W \) from SM.

III. MODELS BEYOND SM

In this section we will explore two models beyond SM which mix the \( Z \) boson with an extra vector boson and might give the observed \( W \) boson mass. We also consider other
constraints like electroweak oblique parameters constraint and DM relic density constraint.

A. Derivative Portal Dark Matter

The DPDM model extends the SM with an extra vector boson which links the dark sector and the SM through its kinetic mixing with the $Z$ boson. The relevant Lagrangian of the DPDM model can be written as [58]:

$$\mathcal{L} = -\frac{1}{4} Z^\mu_{\nu} Z_{\mu\nu} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} - \frac{\epsilon}{2} Z^\mu_{\nu} Z'_{\mu\nu} + \sum_f Z_\mu \bar{f} \gamma^\mu (g_V - g_A \gamma^5) f + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi$$

$$+ \frac{1}{2} m_Z^2 Z_\mu Z^\mu + \frac{1}{2} m_Z'^2 Z'_\mu Z'^\mu - m_\chi \bar{\chi} \chi.$$  

After normalization of the kinetic terms, the kinetic mixing between $Z$ and $Z'$ actually result in mass mixing between them. The kinetic mixing term of the Lagrangian can normalized by:

$$K = \begin{pmatrix} -k_1 & k_2 \\ k_1 & k_2 \end{pmatrix},$$  

FIG. 1. Band which gives the $W$ mass between 80.4053 and 80.4617.
where \( k_1 = 1/\sqrt{2 - 2\epsilon} \) and \( k_2 = 1/\sqrt{2 + 2\epsilon} \). And this operation will result in the following mass matrix between the two vector bosons:

\[
\begin{pmatrix}
k_1^2M_1 & k_1k_2M_2 \\
k_1k_2M_2 & k_2^2M_1
\end{pmatrix}
\]  

(3.3)

where \( M_1 = m_Z^2 + m_{Z'}^2 \) and \( M_2 = m_Z^2 - m_{Z'}^2 \). One can use an orthogonal matrix \( O \) to diagonalize the mass matrix, and \( O \) can be defined as

\[
O = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}, \text{ with } \tan 2\theta = \frac{2k_1k_2M_2}{(k_2^2 - k_1^2)M_1}.
\]  

(3.4)

Therefore according to Eq. (2.5) we can give constraint to \( m_{Z'} \) and \( \epsilon \) as:

\[
k_1k_2M_2 = \sqrt{(k_1^2M_1 - m_{Z'}^2)(k_2^2M_1 - m_{Z'}^2)}.
\]  

(3.5)

Where we have used \( m_Z \) to represent the experiment observed mass of \( Z \) boson, which is meant to distinguish from \( m_Z \). Also we can use the measured mass of \( Z' \) boson \( m_{Z'} \) to reformulate Eq. (3.5):

\[
m_Z^2 = \frac{1}{8k_1^2k_2^2}(m_Z^2 + m_{Z'}^2) - \sqrt{\frac{1}{64k_1^4k_2^4}(m_Z^2 + m_{Z'}^2)^2 - \frac{1}{4k_2^2k_2^2}m_Z^2m_{Z'}.}
\]  

(3.6)

Apart from giving mass to the \( W \) boson, we will also calculate the tree level \( S, T, U \) constraints to this model. The neutral-current coupling between \( Z \) boson and SM fermions in the DPDM model can be written as:

\[
L_{NC, ZZf} = \sum_f (-k_2 \sin \theta - k_1 \cos \theta) \times f = \sum_f (-k_2 \sin \theta - k_1 \cos \theta) \times f = \sum_f (-k_2 \sin \theta - k_1 \cos \theta) \times f
\]  

(3.7)

\[
= \sum_f (-k_2 \sin \theta - k_1 \cos \theta) \times f = \sum_f (-k_2 \sin \theta - k_1 \cos \theta) \times f
\]  

(3.8)

where \( \hat{Z}_\mu \) is the mass eigenstate of the \( Z \) boson. The form of the charged-current in the DPDM is the same as the SM. Using the effective-lagrangian techniques given by [61]:

\[
L_{CC, WWf} = -\frac{e}{\sqrt{2}s_w} \left( 1 - \frac{\alpha S}{4(c_w^2 - s_w^2)} \right) \sum_{ij} V_{ij} \bar{f}_i \gamma^\mu L_f \gamma_5 W^\dagger_\mu + \text{c.c. (3.9)}
\]  

\[
L_{NC, ZZf} = \frac{e}{s_w c_w} \left( 1 + \frac{\alpha T}{2} \right) \sum_f \bar{f}_i \gamma^\mu \left[ T^3_2 \frac{1 - \gamma^5}{2} - Q_f \frac{s_w^2}{4(c_w^2 - s_w^2)} \right] f Z_{ij} (3.10)
\]

where \( s_w c_w m_Z = s_w c_w \frac{1}{2} \sqrt{g^2 + g'^2} = s_w c_w m_Z \), we can write \( S, T \) and \( U \) in the DPDM
model as

\[ \alpha T = 2 \frac{\hat{s}_w \hat{c}_w}{s_w c_w} (-k_2 \sin \theta - k_1 \cos \theta) - 1 \]  
(3.11)

\[ \alpha S = 4 \hat{c}_w^2 \hat{s}_w^2 \alpha T + 4 (\hat{c}_w^2 - \hat{s}_w^2) (s_w^2 - \hat{s}_w^2) \]  
(3.12)

\[ \alpha U = 8 \hat{s}_w^2 (\frac{\hat{s}_w}{s_w} - 1 + \frac{\alpha S}{4(\hat{c}_w^2 - \hat{s}_w^2)} - \frac{\hat{c}_w^2 \alpha T}{2(\hat{c}_w^2 - \hat{s}_w^2)}) \]  
(3.13)

And we constrain the DPDM model with global fit results given by table five of [47]:

\[ S = 0.005 \pm 0.097, \ T = 0.04 \pm 0.12, \ U = 0.134 \pm 0.087, \]  
(3.14)

with the correlation coefficient \( \rho_{ST} = 0.91, \ \rho_{SU} = -0.65, \ \rho_{TU} = -0.88. \)

The DPDM model can naturally escape stringent constraint from DM direct detection due to a cancellation mechanism [58, 62], and in Fig. 2 we have draw the constraints from observed DM relic density, the observed \( W \) mass and the electroweak oblique parameters. Where the red line give the observed \( W \) boson mass solely. And the green line give the

![FIG. 2. The lightblue area are excluded by Planck experiment [63]. And the blue line gives the observed DM relic density. The red line gives the observed \( W \) at tree level. The green line has taken the SM model loop corrections into consideration and gives the observed \( W \) mass, with the dashed green lines correspond to the 3\( \sigma \) upper and lower deviation. The red star gives the best fit of electroweak oblique parameters \( STU \), and the purple line corresponds to \( \Delta \chi^2 = 6.18 \) with respect to the best fit.](image)

observed \( W \) boson mass with SM loop corrections taken into consideration. The dashed
green lines correspond to the 3σ mass deviated from the W boson mass (i.e. 80.4335 ± 3 * 0.0094 GeV). And the blue line saturate the observed DM relic density, while the light blue area are excluded by Planck experiment [63]. The DM relic density are calculated in settings $m_\chi = 60$ GeV, $g_\chi = 0.1$ by numerical tools: FeynRules 2 [64], MadGraph [65], and MadDM [66]. The red star represents the best fit of STU: $m_{Z'} = 116.63$ GeV, $\epsilon = 0.025$, $\chi^2 = 3.21$. And $\Delta \chi^2 = 6.18$ with respect to the best fit value is denoted by the purple line. From Fig. 2 we see that the red star lies in the area circled by green lines, which means that the global fit of STU has encoded the information of the W boson mass. Also it is clear that the best fit point meets the observed DM relic density. The purple line indicate there are large area which can give explanation to the W boson mass. To make the parameters fall into the purple circle $m_{Z'}$ should satisfy $102$ GeV $\lesssim m_{Z'} \lesssim 155$ GeV. To make area where $m_{Z'} \lesssim 114$ GeV and $m_{Z'} \gtrsim 132$ GeV not excluded by Planck experiment, one can change the DM mass $m_\chi$ and thus the annihilation resonance area will move accordingly. On the other hand, one can increase the extra gauge coupling $g_\chi$ or simply not introduce dark matter in this model.

B. U(1) model

In the U(1) model there is a gauge boson of an extra U(1)$_X$ gauge symmetry which connects to the gauge boson of SM U(1)$_Y$ symmetry through kinetic mixing. In this section we will adopt the same model setting as [60]. Then the kinetic mixing terms can be written as:

$$\mathcal{L}_K = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} B^{\mu\nu} X_{\mu\nu},$$

(3.15)

where $B_{\mu}$ and $X_{\mu}$ are the gauge fields of U(1)$_Y$ and U(1)$_X$ gauge symmetry. And there will be mass mixing term between $B_{\mu}$ and $W^3_{\mu}$ after Higgs getting its vev. Therefore the matrix of $(W^3_{\mu}, B_{\mu}, X_{\mu})$ can be denoted as:

$$\frac{1}{2} \begin{pmatrix} W^{3\mu} & B_{\mu} & X_{\mu} \end{pmatrix} \begin{pmatrix} g^2 v^2/4 & -gg'v^2/4 & 0 \\ -gg'v^2/4 & g^2 v^2/4 & 0 \\ 0 & 0 & g_\chi^2 v_s^2 \end{pmatrix} \begin{pmatrix} W^3_{\mu} \\ B_{\mu} \\ X_{\mu} \end{pmatrix}$$

$$= \frac{1}{2} \begin{pmatrix} W^{3\mu} & B_{\mu} & X_{\mu} \end{pmatrix} K^{-1} O O^T K^T \begin{pmatrix} g^2 v^2/4 & -gg'v^2/4 & 0 \\ -gg'v^2/4 & g^2 v^2/4 & 0 \\ 0 & 0 & g_\chi^2 v_s^2 \end{pmatrix} K O O^T K^{-1} \begin{pmatrix} W^3_{\mu} \\ B_{\mu} \\ X_{\mu} \end{pmatrix}$$

(3.16)

$$= \frac{1}{2} \begin{pmatrix} A^{\mu} & Z^{\mu} & Z'_{\mu} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_Z^2 & 0 \\ 0 & 0 & m_{Z'}^2 \end{pmatrix} \begin{pmatrix} A_{\mu} \\ Z_{\mu} \\ Z'_{\mu} \end{pmatrix}$$
Where we have used $K$ to normalize the kinetic terms of $B_{\mu}$ and $X_{\mu}$ and used $O$ to diagonalize the mass matrix and transform the fields to their mass eigenstates. The masses of the two massive vector boson $Z$ and $Z'$ will be:

$$m_{Z,Z'}^2 = \frac{1}{8} \left( g^2 v^2 + g' k_1^2 v^2 + g^2 k_2^2 v^2 + 4 g_z^2 k_1^2 v_s^2 + 4 g_x^2 k_2^2 v_s^2 \right)$$

$$\pm \sqrt{ (g^2 v^2 + (k_1^2 + k_2^2) (g^2 v^2 + 4 g_z^2 v_s^2))^2 - 16 g_z^2 v^2 v_s^2 (g^2 (k_1^2 + k_2^2) + 4 g_x^2 k_1^2 k_2^2) }.$$

Where we denote the masses with no hat which is different from that of the DPDM model. Note that the kinetic mixing between $B_{\mu}$ and $X_{\mu}$ will not change the form of the electric charge $e$. The definition of electric can be extracted from couplings between the photon and the Higgs doublet. Which in this model will be:

$$e = g[KO]_{11} = g'[KO]_{21} = \frac{2 g' k_2}{\sqrt{1 + \frac{4 g'^2 k_2^2}{y^2} + \frac{k_s^2}{k_1^2}}} = \frac{g g'}{\sqrt{g^2 + g'^2}}. \quad (3.18)$$

Where $[KO]_{ij}$ represents the element which lies in the $i^{th}$ row and the $j^{th}$ column of matrix $KO$. The neutral-current coupling between $Z$ boson and SM fermions in the U(1) model can be written as:

$$L_{NC.Zf} = \sum_f Z_\mu \bar{f} \gamma^\mu (g_V - g_A \gamma^5) f, \quad (3.19)$$

with $g_V = g_A + g'[KO]_{22} Q_f$, $g_A = \frac{T_f^3}{2} (-g'[KO]_{22} + g[KO]_{12}). \quad (3.20)$

And we can read $S, T, U$ as:

$$\alpha T = \frac{2 s_w c_w (-g'[KO]_{22} + g[KO]_{12}) - 2}{e} \quad (3.21)$$

$$\alpha S = \frac{-4 g'[KO]_{22} (c_w^2 - s_w^2)}{-g'[KO]_{22} + g[KO]_{12}} - 4 s_w^2 (c_w^2 - s_w^2) + 4 c_w^2 s_w^2 \alpha T \quad (3.22)$$

$$\alpha U = 8 s_w^2 (\frac{s_w}{s_w} - 1) + \frac{\alpha S}{4 (c_w^2 - s_w^2)} - \frac{\tilde{c}_w^2 \alpha T}{2 (\tilde{c}_w^2 - \tilde{s}_w^2)} \quad (3.23)$$

Now we can give a line which predict the observed $W$ mass in this model in Fig. 3. Where we also use red dashed line to show that the U(1) model can solely give the observed mass of $W$ boson. And the green line takes the SM loop corrections into consideration and gives observed $W$ boson mass, with the dashed green lines correspond to the 3$\sigma$ upper and lower deviation. The red star being the best fit of electroweak oblique parameters $STU : m_{Z'} = 133.65$ GeV, $\epsilon = 0.048$, $\chi^2 = 24.94$, with the purple lines corresponding to $\Delta \chi^2 = 6.18$. From Fig. 3 we see that the electroweak oblique parameters results do not fall into the area circled by the green lines which represents the direct calculation of $m_W$. This means that the parameters space which gives the observed $W$ boson mass can not give
FIG. 3. The red line gives the observed $W$ at tree level. The green line has taken the SM model loop corrections into consideration and gives the observed $W$ mass, with the dashed green lines correspond to the $3\sigma$ upper and lower deviation. The red star gives best fit of the electroweak oblique parameters $STU$, and the purple lines corrections to $\Delta\chi^2 = 6.18$.

corresponding electroweak couplings that fit the electroweak oblique parameters nicely. And our results shows that the best fit of the U(1) model can give only about 27 MeV extra mass to SM $W$ boson mass.

IV. CONCLUSION

In this work we have explored the possibility of altering the $W$ boson mass at tree level through mixing between an extra gauge boson and the $Z$ boson. We first give general discussion of the effects from mixing extra boson with $Z$ boson, then explored two realistic models: the DPDM model and the U(1) model. In the DPDM model the extra gauge boson mixes with the $Z$ boson through the kinetic mixing between extra boson and the $Z$ boson, while in the U(1) model the extra gauge boson mixes with the $Z$ boson through the kinetic mixing between extra boson and the $B$ boson. Apart from giving the $W$ boson mass, we also discussed the electroweak oblique parameters constraints for both model, and also explored DM relic density constraints for the DPDM model. We find that in both model the best fit value for the extra vector boson mass is around 120 GeV. While the best fit of the U(1) model can only contribute 27 MeV extra mass to the SM $W$ boson mass, the best fit of the
DPDM model can give the observed $W$ boson mass as well as the observed DM relic density. Detailed collider search for the DPDM seemed interesting and is left for future works.

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**NOTE ADDED**

During the finalizing of this manuscript, we noticed that [7] appeared on arxiv. [7] discusses explanation of the $W$ boson mass with $U(1)$ dark matter model as well as several phenomenology constraints on DM. Our work discusses models with an extra gauge boson which can explain the $W$ boson mass. Apart from the DPDM model, we also discussed the $U(1)$ model, but in different scenarios.

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