Constraints on the parameters of the Left Right Mirror Model

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We study some phenomenological constraints on the parameters of a left right model with mirror fermions (LRMM) that solves the strong CP problem. In particular, we evaluate the contribution of mirror neutrinos to the invisible Z decay width ($\Gamma_{\text{inv}}^Z$), and we find that the present experimental value on $\Gamma_{\text{inv}}^Z$, can be used to place an upper bound on the $Z-Z'$ mixing angle that is consistent with limits obtained previously from other low-energy observables. In this model the charged fermions that correspond to the standard model (SM) mix with its mirror counterparts. This mixing, simultaneously with the $Z-Z'$ one, leads to modifications of the $\Gamma(Z \rightarrow f \bar{f})$ decay width. By comparing with LEP data, we obtain bounds on the standard-mirror lepton mixing angles. We also find that the bottom quark mixing parameters can be chosen to fit the experimental values of $R_b$, and the resulting values for the $Z-Z'$ mixing angle do not agree with previous bounds. However, this disagreement disappears if one takes the more recent ALEPH data.

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I. INTRODUCTION

Although the non-conservation of parity (P), is well incorporated in the SM of electroweak interactions, it has been considered as an unpleasant feature of the model, and many attempts have been made to restore it; for instance, in Left-Right symmetric models [1], the problem is solved through the inclusion of SU(2)$_R$ interactions that maintain P-invariance at high energy scales. Another interesting solution, due to Lee and Yang [2], restores P by the inclusion of additional (mirror) fermions of opposite chirality to the SM ones.

Low-energy effects of mirror fermions have been studied since then, and limits on their masses exist [3]. Applications of models with mirror fermions to solve some problems in particle physics have been discussed too. For instance, it has been recently found that mirror neutrinos can help to alleviate the problems that appear in this sector, namely the solar and atmospheric neutrino deficits, and the Dark Matter problem [4]. Other interesting effects of mirror neutrinos in astrophysics and cosmology are discussed in [5]. Mirror particles also appear naturally in many extensions of the SM, like GUT and string theories [3]. On the other hand, in Refs. [6] it is proposed a class of mirror models where the strong CP problem is solved. Because of the attractive features of these models, it seems interesting to test further the predictions for the masses and couplings of mirror fermions.

In this paper, we are interested in testing the validity of a mirror model with gauge group SU(2)$_L \otimes$SU(2)$_R \otimes$U(1). We calculate the contribution of mirror neutrinos to the invisible width of the $Z$ boson, the modifications of the leptonic $Z$ decay and the possibility to explain the $R_b$ value within this model.

Because the number of light SM neutrinos is consistent with 3 [6], it is usually said that additional massless neutrinos are not allowed. However, it is not known if this statement also applies to the case of mirror neutrinos. In fact, ref. [7] claims that mirror neutrinos do not contribute to the invisible $Z$-width, however, as it shall be explained below, because of $Z-Z'$ mixing, mirror neutrinos do couple to the $Z$ boson, and thus can contribute to $\Gamma_{\text{inv}}^Z$.

Because of the non-observability at LEP of the decays $Z \rightarrow \bar{f} f$, the masses of charged mirror fermions must be above $M_Z$, furthermore, at the Tevatron Collider it should be possible to put a higher limit, similar to the top mass, if no new signal is observed. On the other hand the properties of the $Z$-boson have been measured at LEP with a high
precision, which has made possible to test the SM at the level of radiative corrections \[10\], and also to constrain
the presence of new physics.

The organization of this paper is as follows: we shall present in detail the simplest model that solve the strong
CP problem \[7,8\] in the next section, giving particular emphasis to incorporate the mixing effects into a low-energy
effective lagrangian using the formalism of Ref. \[11\]. Sec. \[III\] contains the discussion of the invisible Z decay.
Sec. \[III B\] is devoted to study the bounds on the parameters obtained from the decay $Z \rightarrow e^+e^-$ and in Sec. \[III C\] we
discuss the decay $Z \rightarrow b\bar{b}$. Finally Sec. \[IV\] will contain our conclusions.

II. THE LEFT-RIGHT MIRROR MODEL (LRMM)

The strong CP problem is associated to the suppression of the $\theta$ term that breaks P and CP symmetries of the
QCD lagrangian. The Peccei-Quinn solution to the strong CP problem, predicts a new pseudo-goldstone boson, the
axion, which so far has not been observed \[12\]. On the other hand Barr et al. \[7,8\], proposed a class of model that
offer a solution to the strong CP problem based on the complete invariance of the theory under P. In the simplest
L-R model of this class, the electroweak group is extended to $SU(2)_L \otimes SU(2)_R \otimes U(1)$, and the matter content of the
theory is also enlarged by including new fermion fields with mirror properties.

Thus, in the LRMM that will be studied here, the right-handed (left-handed) components of mirror fermions will
transform as doublets (singlets) under $SU(2)_R$. The SM fermions are singlets under $SU(2)_R$, whereas the right-handed
mirrors are also singlets under $SU(2)_L$. Mirror and SM fermions will share hypercharge and color interactions.

The first family of the leptonic sector will be written as follows:

$$
\begin{align*}
\ell^o_L &= \left( \nu^o_e \ e^o \right)_L \equiv \ell^o, \\
\ell^o_R &= \left( \hat{\nu}^o_e \ \hat{e}^o \right)_R \equiv \hat{\ell}^o, \\
\end{align*}
$$

1

The superscript ($^o$) denotes weak eigenstates, and the hat symbol ($\hat{\cdot}$) is associated to mirror particles. Because the
model does not contain left-handed mirror neutrinos, they have to be massless. Similar terms can be written for the
quarks and the other families.

A. Symmetry breaking

In order to realize the breaking of the gauge symmetry, two Higgs doublets are included, the SM one ($\phi$) and its
mirror partner ($\hat{\phi}$). The potential of the model can be written in such a way that the v.e.v.’s of the Higgs fields are:

$$
\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \hat{\phi} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{v} \end{pmatrix}.
$$

1. Gauge boson masses

The mass matrix for the gauge bosons is obtained from the scalar lagrangian, namely:

$$
L^{\text{kin}} = (D_{\mu} \phi)^\dagger (D^\mu \phi) + (\hat{D}_{\mu} \hat{\phi})^\dagger (\hat{D}^\mu \hat{\phi}),
$$

where $D_{\mu}$ is the covariant derivative associated to the SM, and $\hat{D}_{\mu}$ is the one associated with the mirror part.

After the substitution of the v.e.v.’s in the lagrangian we obtain the expressions for the mass matrices, which could
be non-diagonal. The vector bosons will be denoted as: $W^\pm, Z$, which correspond to the SM ones, i.e. those associated
to $SU(2)_L \otimes U(1)_Y$, whereas the mirror gauge bosons will be denoted by $\hat{W}^\pm, \hat{Z}$. The mass matrix for the charged
gauge bosons is diagonal, with mass values: $M_W = \frac{1}{2} g v$, and $M_{\hat{W}} = \frac{1}{2} \hat{g} \hat{v}$, where $g$ and $\hat{g}$ are the coupling constant of

1We shall use the term “SM fields” to denote the fermions with the same chiralities as in the SM, eventhough they will be
the same only in some approximation.
the SU(2)\textsubscript{L} and SU(2)\textsubscript{R} gauge group respectively. P invariance requires \( g = \hat{g} \), however in this section we shall write the equations with general \( g, \hat{g} \), since this could arise in more general models.

The mass matrix for the neutral components \((W^3_\mu, \hat{W}^3_\mu, B_\mu)\) is not diagonal:

\[
\mathcal{L}^\text{m}_{Z^A} = \frac{1}{8} \left( W^3_\mu, \hat{W}^3_\mu, B_\mu \right) \left( \begin{array}{ccc}
g^2v^2 & 0 & -ggv^2 \\
0 & g^2\bar{v}^2 & -gg\bar{v}^2 \\
-ggv^2 & -gg\bar{v}^2 & g^2(v^2 + \bar{v}^2) \end{array} \right) \left( \begin{array}{c}
W^3_\mu \\
\hat{W}^3_\mu \\
B_\mu \end{array} \right),
\]

This rank 2 matrix, with non-trivial eigenvalues

\[
M_{Z,\hat{Z}} = \frac{1}{2} (g^2 + \hat{g}^2) \sigma \mp \frac{1}{2} \sqrt{(g^2 + \hat{g}^2)^2 \sigma^2 - 4g^2v^2\bar{v}^2 (g^2 + 2\hat{g}^2)},
\]

and with \( \sigma = v^2 + \bar{v}^2 \), can be diagonalized by an orthogonal transformation \( R \), relating the weak \((W^3_\mu, \hat{W}^3_\mu, B_\mu)\) and mass eigenstates basis \((Z_\mu, \hat{Z}_\mu, A_\mu)\) \[3\][4] which will be obtained in Sec. II B.

2. Charged fermion masses

The mass lagrangian for the charged fermionic sector includes the ordinary Yukawa terms and its mirror partners, however the model allows mixing terms between ordinary and mirror fermions singlets, the \( \lambda_{ee} \) terms that are written below for the first family:

\[
\mathcal{L}^\text{m}_{ee} = \lambda_{ee} \bar{e} e^\sigma + \lambda_{ee} \bar{e} e^\sigma + \lambda_{ee} e \sigma + \text{h.c.}
\]

To diagonalize the mass matrix, one introduces two mixing angles. Thus, for a flavor \( f \), one has:

\[
\left( \begin{array}{c}
f^o \\
f^o \end{array} \right)_{L,R} = \left( \begin{array}{cc}
\cos \xi^f & \sin \xi^f \\
-\sin \xi^f & \cos \xi^f \end{array} \right)_{L,R} \left( \begin{array}{c}
f \\\n\hat{f} \end{array} \right)_{L,R}
\]

\( f_{L,R} \) will be identified as the L- and R-handed components of the ordinary SM fermions, whereas \( \hat{f}_{L,R} \) will correspond to the new ones. The mixing angles \( \xi^f_{L,R} \) are associated to each flavor \( f \).

B. The interaction lagrangian

The gauge interactions of quarks and leptons, can be obtained from the lagrangian:

\[
\mathcal{L}^\text{int} = \bar{\psi} i \gamma^\mu D_\mu \psi + \bar{\psi} i \gamma^\mu \hat{D}_\mu \hat{\psi}.
\]

Following Refs. [1][2], grouping all fermions of a given electric charge \( q \) and a given helicity \( a = L, R \) in a \( n_a + m_a \) vector column of \( n_a \) ordinary (O) and \( m_a \) exotic (E) gauge eigenstates \( \psi^o_a = (\psi^o_O, \psi^o_E)^T \) one finds for the neutral currents term

\[
L^\text{nc} = \sum_{a=L,R} \bar{\psi}^o_a \gamma^\mu \left( g T_{3a} + \hat{g} \hat{T}_{3a} \right) \frac{g'}{2} \psi^o_a \left( \begin{array}{c}
W^3_\mu \\
\hat{W}^3_\mu \\
B_\mu \end{array} \right)
\]

\[
= \sum_{a=L,R} \bar{\psi}^o_a \gamma^\mu U_a^\dagger \left( g T_{3a} + \hat{g} \hat{T}_{3a} \right) \frac{g'}{2} U_a \psi_a R \left( \begin{array}{c}
Z \\
\hat{Z} \end{array} \right)_{A} \mu
\]

where \( g' \) is the coupling constant of the U(1) gauge group,

\[
R = R_{Z^A}(\beta)R_{Z^A}(\theta_w)R_{ZZ^A}(\alpha) = \left( \begin{array}{ccc}
c_{\theta_w}c_{\alpha} & c_{\theta_w}s_{\alpha} & s_{\theta_w} \\
-s_{\alpha}c_{\beta} - c_{\alpha}s_{\theta_w}s_{\beta} & c_{\beta}c_{\alpha} - s_{\alpha}s_{\theta_w}s_{\beta} & s_{\theta_w}c_{\beta} \\
s_{\alpha}s_{\beta} - c_{\alpha}s_{\theta_w}c_{\beta} & -c_{\alpha}s_{\beta} - s_{\alpha}s_{\theta_w}c_{\beta} & c_{\beta}c_{\theta_w} \end{array} \right),
\]

3
\( \theta_w, \alpha \gamma \beta \) are the rotation angles between the Z-A, Z-Z' and Z'-A gauge bosons respectively. The \( U_a \) matrices are the ones which relate the gauge and the corresponding mass eigenstates of the fermion fields, and \( T_{3a}, \tilde{T}_{3a} \) and \( \tilde{Y} \) are generators of the SU(2)\(_L\), SU(2)\(_R\) and U(1) respectively.

The orthogonal matrix in Eq. (10) can be written in terms of only two angles by imposing the electromagnetic coupling relation

\[ g s_{\theta_w} T_{3} + \hat{g} s_{\beta} c_{\theta_w} \hat{T}_{3} + g' c_{\beta} c_{\theta_w} \frac{Y}{2} = Q e \]  

whose simplest solution is

\[ \begin{aligned}
    g s_{\theta_w} &= \hat{g} s_{\beta} c_{\theta_w} = g' c_{\beta} c_{\theta_w} = e \\
    T_{3} + \hat{T}_{3} + \frac{Y}{2} &= Q.
\end{aligned} \]  

From Eqs. (12), defining \( \lambda \hat{g} \equiv \hat{g} \), the following relation holds

\[ c_{\beta} c_{\theta_w} = \sqrt{\frac{1}{\lambda^2} \frac{\lambda^2}{2} s_{\theta_w}^2} = r_{\theta_w}, \]  

and makes possible to rewrite \( R \) as a function of two mixing angles and the coupling constant ratio:

\[ R = \begin{pmatrix}
    c_{\theta_w} c_{\alpha} & c_{\theta_w} s_{\alpha} & s_{\theta_w} \\
    -\frac{1}{c_{\theta_w}} (s_{\alpha} r_{\theta_w} + \lambda c_{\alpha} s_{\theta_w}^2) & \frac{1}{c_{\theta_w}} (c_{\alpha} r_{\theta_w} - \lambda s_{\alpha} s_{\theta_w}^2) & \lambda s_{\theta_w} \\
    -\frac{1}{c_{\theta_w}} (\lambda s_{\alpha} - c_{\alpha} r_{\theta_w}) & -\frac{1}{c_{\theta_w}} (\lambda c_{\alpha} + r_{\theta_w} s_{\alpha}) & r_{\theta_w}
\end{pmatrix}. \]  

Concentrating our attention on the neutral current sector for the Z gauge boson we find that the full lagrangian is

\[ -L^N_Z = \sum_{a=L,R} \bar{\psi}_a \gamma^\mu U_a^\dagger \left( g T_{3a}, \hat{g} \hat{T}_{3a}, g \frac{Y}{2} \right) U_a \psi_a \left( -\frac{1}{c_{\theta_w}} (s_{\alpha} r_{\theta_w} + \lambda c_{\alpha} s_{\theta_w}^2) \right) \hat{Z}_{\mu} \]

\[ = \frac{e}{s_{\theta_w} c_{\theta_w}} \sum_{a=L,R} \bar{\psi}_a \gamma^\mu U_a^\dagger \left[ \left( c_{\alpha} - \frac{s_{\theta_w}^2}{r_{\theta_w}} s_{\alpha} \right) T_{3a} - \frac{c_{\theta_w} c_{\alpha}}{\lambda^2 r_{\theta_w}} s_{\alpha} \tilde{T}_{3a} + \frac{s_{\theta_w}^2}{r_{\theta_w}} s_{\alpha} \left( \frac{s_{\theta_w}}{r_{\theta_w}} \right) \right] U_a \psi_a \hat{Z}_{\mu}, \]  

with \( \lambda r_{\theta_w}^* \equiv r_{\theta_w} \).

**III. PHENOMENOLOGY OF THE LRMM**

**A. The Invisible Z width**

We are now interested in the interactions of ordinary and mirror neutrinos, for which there are no mixing terms (\( U_a = 1 \)), the lagrangian for the Z boson and the neutrinos is then:

\[ -L^{(0)}_{Z} = \frac{e}{s_{\theta_w} c_{\theta_w}} \left[ \frac{1}{2} \bar{\psi}^{(0)}_L \gamma^\mu \left( c_{\alpha} - \frac{s_{\theta_w}^2}{r_{\theta_w}} s_{\alpha} \right) \psi^{(0)}_L - \frac{1}{2} \bar{\psi}^{(0)}_R \gamma^\mu \frac{c_{\theta_w}^2}{\lambda^2 r_{\theta_w}} s_{\alpha} \psi^{(0)}_R \right] \hat{Z}_{\mu}, \]  

where the charge multiplet \( \psi^{(0)}_L \) and \( \tilde{\psi}^{(0)}_R \) contain the three standard and three mirror neutrinos respectively. In the limit \( \alpha \to 0 \) (no Z-Z' mixing) we recover the SM expression which has been used to extract the number of flavors of light neutrinos and is interpreted as a limit on the number of families \( \mathcal{F} \). Then it is said that there is no room for additional massless neutrinos. However, mirror neutrinos also contribute to the invisible Z decay; the expression for the total invisible width is (for \( \lambda = 1 \)):
\[
\Gamma_{Z}^{\text{inv}} = \Gamma(Z \to \bar{\nu}\nu) + \Gamma(Z \to \bar{\nu}\nu) = \frac{G_F M_Z^3}{4\sqrt{2}\pi} \left( \left| c_\alpha - \frac{s_\theta^2}{r_\theta^2} s_\alpha \right|^2 + \left| \frac{c_\theta^2}{r_\theta^2} s_\alpha \right|^2 \right)
\]

\[
= \frac{G_F M_Z^3}{4\sqrt{2}\pi} \left( 1 - 2\frac{s_\theta^2}{r_\theta^2} \alpha + 2\frac{s_\theta^2}{r_\theta^2} \alpha^2 + O(\alpha^3) \right),
\]

thus, the contribution of mirror neutrinos to \(\Gamma_{Z}^{\text{inv}}\), appears up to the \(\alpha^2\) term and could exclude the model if it goes beyond the experimental value.

The experimental Z width is 498.3 ± 4.2 MeV, whereas the SM value is 497.64 ± 0.11 MeV, then, in order for the total contribution not to exceed the experimental data, the mixing angle has to satisfy:

\[
-1.576 \times 10^{-2} < \alpha < 1.087 \times 10^{-2},
\]

within one standard deviation.

Comparing this limit on \(\alpha\) with the ones obtained from other observables, one can see that they are in agreement. For instance, the Z-Z' mixing that appears in the model will produce a deviation from unity on the \(\rho\) parameter, as given by:

\[
\Delta \rho = \sin^2 \alpha \left( \frac{M_Z^2}{\Gamma_Z^{\text{inv}}} - 1 \right),
\]

as has been discussed in the literature for other models, which leads to \(s_\alpha^2 < 5 \times 10^{-4}\). Thus, our limit for \(\alpha\) is consistent with this value, and the LRMM model survives this test.

### B. The Z \(\to e\bar{e}\) decay

Considering only mixing between leptons with their mirror partners the width is (for \(\lambda = 1\))

\[
\Gamma (Z \to \bar{e}e) = \frac{G_F M_Z^3}{3\sqrt{2}\pi} \left( \frac{1}{2} \left( c_\alpha - \frac{s_\theta^2}{r_\theta^2} s_\alpha \right)^2 + \frac{1}{2} \left( \frac{c_\theta^2}{r_\theta^2} s_\alpha - c_\alpha \right)^2 \right)
\]

\[
+ \left( \frac{1}{4} + \frac{s_\theta^2}{r_\theta^2} + \frac{s_\theta^2}{r_\theta^2} \left( \frac{5}{4r_\theta^2} - 2 \right) \right) \alpha^2 + \left( \frac{1}{2} + s_\theta^2 \right) \xi_L^2 + O(3).
\]

This quantity is bounded by the experimental uncertainty in the data:

\[
B^{\text{exp}} (Z \to e\bar{e}) = (3.366 \pm 0.008) \times 10^{-2}.
\]

It is remarkable to see how strong the \(\xi_L\) and \(\alpha\) parameters are correlated and as a consequence, we should mention that it is not safe to analyze the model taking only one of the limits \(\alpha \to 0\) or \(\xi_L \to 0\).

In Fig. 4, we show the allowed region in the \(\alpha-\xi_L\) plane, which includes also the constraints obtained from the previous section: the darker region is precisely the intersection of the results from the \(\Gamma_{Z}^{\text{inv}}\) (dashed lines) and the \(Z \to e\bar{e}\) analysis (continuous lines).
Another interesting application of the LRMM model is to the Z → banti-b decay. Until recently, it was thought that the ratio \( R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \) was in disagreement with the SM prediction. However, recent data seems to favor again the SM, although some small discrepancy survives. In an extensive study of Bamert et al. \[18\] it was identified a large class of models where the \( R_b \) “crisis” (old data) was solved. The solution appeared on three main classes: (i) tree-level modification of the b-vertices, (ii) tree level top modification, (iii) general loop effects. However when the models are discussed in detail, for particular cases, it may happen that those solution do not satisfy the requirements arising from other sectors.

If, model independently, we consider that the only contribution to the shift in \( R_b \) is given by the shift in the Zb \( \bar{b} \) couplings, through the width \( \Gamma_b \equiv \Gamma(Z \to b\bar{b}) \) \[19\], then the general expression relating the new physics \((R_b, \Gamma_b)\) with the SM one \((R_b^{\text{SM}}, \Gamma_b^{\text{SM}})\) is:

\[
R_b = \frac{\Gamma_b}{\Gamma_b^{\text{SM}} - 1} + \Gamma_b.
\]

In order to compare with the data, one can write the width \( \Gamma(Z \to b\bar{b}) \) in the LRMM as follows:

\[
\Gamma(Z \to b\bar{b}) = \frac{G_F M_Z^3}{\sqrt{2} \pi} \left( \frac{1}{2} \left( c_\alpha - s_\theta \bar{s}_\alpha \right) s_{\eta_L}^2 + \frac{s_\theta^2}{3} \left( s_\alpha r_{\theta \bar{\theta}} - c_\alpha \right)^2 + \frac{1}{2} c_\theta \bar{s}_\alpha s_{\eta_R}^2 - \frac{s_\theta^2}{3} \left( s_\alpha r_{\theta \bar{\theta}} - c_\alpha \right)^2 \right),
\]

where \( \eta_a \) \((a = L, R)\) are the mixing angle between \( b\bar{b} \). We show in Fig. 3, including terms up to third order in the mixing angles, the constraints that arise for our model from b-\( \bar{b} \) and Z-Z’ mixing. The results are such that the mixing parameters appear to shown a slightly disagreement with the ones obtained from \( \Gamma^{\text{inv}} \) and the Z-Z’ mixing.

However it should be noted that if the most recent data on \( R_b \) \[20,21\] are confirmed, this small discrepancy disappear and then the \( R_b \) “crisis” will be solved for both the SM and the LRMM.

**IV. CONCLUSIONS**

We have studied some phenomenological consequences of a left-right model that includes mirror fermions, which gives a solution to the strong CP problem. In particular, we have calculated the contribution of mirror neutrinos to the invisible Z-width. Mirror neutrinos are massless, first because there is only one chirality and it is not possible to write a Dirac mass, and second because the Higgs sector does not include a Majorana mass term. It is found that the current experimental value for the invisible width of the Z boson and the leptonic decays, implies a bound on the Z-Z’ mixing angle, that is however consistent with the limits obtained from other low-energy observables. Similar conclusions can be reached for the width \( \Gamma(Z \to b\bar{b}) \) and \( \Gamma(Z \to l^+l^-) \), although the data show some deficit on the Z-Z’ mixing angle. However more recent results imply that the differences tend to disappear. Thus, this type of model is consistent with experiment at present. However, further improvements on the precision of the data can be used to search for a first evidence of the model, or to discard it.

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FIG. 1. Allowed ranges of parameters in the α-ξL plane. The region between the dashed lines is obtained from the ΓZ̅inv and the region between the continuous lines from the Z → e¯e data. The darker region represents the allowed intersection which simultaneously consider the two processes.

FIG. 2. Allowed regions in the α-ηL plane obtained from ΓZ̅inv (dashed lines) and Z → b¯b (continuous lines) data. Unlike the situation of Fig. 1 there is no region in the plane where there is simultaneous agreement with data from both processes.
Figure 1

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“Constraints on the parameters of the Left Right Mirror Model.”
Figure 2
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