Constraints on spin-$\frac{3}{2}$ and excited spin-$\frac{1}{2}$ fermions
coming from the leptonic $Z^0$-partial width

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We consider effective interactions among excited spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ leptons with the usual ones. Assuming that these new leptons are lighter than the $Z^0$ we will study the constraints on their masses and compositeness scale coming from the leptonic $Z^0$ partial width.
One way to study possible new physics beyond the standard model, which is based on $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry \([1]\), is to assume new particles and interactions and compare the results of this new physics with the experimental data, say, with $a_\mu = \frac{1}{2}(g_\mu - 2)$ measurements or in cross sections and angular distributions in the forthcoming accelerators. This new particles and interactions would be discovered not very far from the Fermi scale \([2,3]\).

If the known fermions are composite, they will have additional contact interactions. A consequence of composite models is the existence of excited fermions and higher spins particles, for instance excited fermions with spin--$\frac{3}{2}$. Usually in this sort of picture it is introduced a compositeness scale $\Lambda_{\text{comp}}$ related to the extension of the composite particle. This scale also defines two different regimes for the interactions in the following sense: for scales below $\Lambda_{\text{comp}}$ we get the regime of bound states and the interactions appear as effective interactions whereas for scales above $\Lambda_{\text{comp}}$ the composite particles appear as a free system of constituents with an underlying, up to now unknown, dynamics.

From the theoretical point of view there is no universal agreement on which scale the lack of elementarity becomes operative. Possibilities run from $\Lambda_{\text{comp}} \sim 1\,\text{TeV}$ to $\Lambda_{\text{comp}} \approx M_{\text{Planck}} \sim 10^{19}\,\text{GeV}$. To decide among these options require more experimental data on the predictions of the standard model, in such a way that we could identify the contributions of new physics, if any.

Usually new leptons are assumed to have a large mass, say 150–200 GeV. Next it is possible to look for their effects in colliders as $e^- p$ \([4]\). In general, it is consider that the masses of the excited fermions are of the same order of magnitude of the compositeness scale. However, in principle, some excitations could have masses even comparable to those of the vector bosons.

Here, we will assume that in fact, excited or higher spin leptons may have masses below $M_Z$ in such a way that they contribute to the $Z^0$ width, being produced accompanying a usual lepton. Hence, we will consider the decay $Z^0 \to \Psi l$, with $\Psi$ denoting a new lepton and $l$ a usual one ($l = e, \mu, \tau$).

The possibility of the existence of a composite structure for, up to now, elementary par-
ticle has been confronted with the $a_\mu$ measurements \[5,6\]. Also tests of composite models coming from $Z^0$ decays modes have already been considered \[7\]. For example, decay rates and branching ratios for production cross sections in $p\bar{p}$, $pp$ and $e^+e^-$ and angular distributions have been studied \[8,9\]. It is important to identify new observables which could be sensitive to the excited and/or higher spin fermions. Since there exist at present very precise measurements of the total and partial $Z^0$ decay width, it is also possible, to use this $Z$-pole observable to constrain new physics. For instance, this has been done in the simple extension of the standard model which include beside the usual sequential leptons, a singlet right-handed neutral field \[10\].

Here we will use this method to constrain the effective interactions involving excited spin–$\frac{1}{2}$ and spin–$\frac{3}{2}$ fields. These interactions are not $SU(2)$ gauge invariant as is usually to be consider nowadays \[11\] since we do not want to exclude models where the $Z^0$ and $W^\pm$ are composite too. In this case, the standard model $SU(2)_L \otimes U(1)_Y$ gauge theory is replaced by an effective global theory in which the $W$ and $Z^0$, being not elementary, may not couple as in the standard model.

We will get bound on $\Lambda_{comp}$ and the masses of the new particles by assuming that the experimental data of the $Z^0$ width is given by the standard model predictions so that the new physics has room only in the experimental uncertainties.

There are many possible effective interactions connecting the usual and excited leptons. Here we will consider only three of them just to illustrate how the experimental data of the $Z^0 \to l\bar{l}$ partial width constrains the scale of compositeness and the new lepton masses. In the following, for economy, we will use $\Lambda$ and $m^*$ to denote the compositeness scale and the new lepton masses respectively for both the excited spin–$\frac{1}{2}$ fermion ($\psi^*$)and the spin–$\frac{3}{2}$ one ($\chi$). The mass of the usual leptons ($l$) will be denoted by $m_l$.

**Exited Spin–$\frac{1}{2}$ Leptons.** We will assume that the excited leptons with spin–$\frac{1}{2}$, $\Psi = \psi^*$, couples to the usual leptons through the effective interaction

$$\mathcal{L}_{\psi^*} = \frac{1}{2\Lambda} \bar{\psi}^* \sigma_{\mu\nu} (c + d\gamma_5) l Z^{\mu\nu} + H.c. \quad (0.1)$$
By \( CP \) invariance \( c \) and \( d \) have to be real and if their origin is some mixing in the leptonic sector these constants must be normalized to unity, \( c^2 + d^2 = 1 \). Throughout this work we will assume this is the case but we must remember that if the origin of \( c \) and \( d \) is a mixing in the gauge boson sector these coefficients do not need to be normalized to unity as occurs in the neutral currents in the standard electroweak model. We will also use, the usual normalization \( g^2/4\pi = 1 \) with \( g^2 \) a dimensionless constant.

**Spin-\( \frac{3}{2} \) Leptons.** Here we will consider two effective interactions of a spin-\( \frac{3}{2} \) particle, \( \Psi = \chi \), with the usual leptons,

\[
\mathcal{L}_\chi = g\bar{\chi}^\mu(c + d\gamma^5)lZ_\mu + H.c., \tag{0.2}
\]

with \( g \) a dimensionless constant. As in this case the strength of the interaction does not depend on the scale \( \Lambda \), we will not consider the \( g^2/4\pi = 1 \) normalization.

We will also consider the interaction

\[
\mathcal{L}'_\chi = \frac{1}{\Lambda}\bar{\chi}^\mu\gamma^\nu(c + d\gamma^5)lZ_{\mu\nu} + H.c. \tag{0.3}
\]

**\( Z^0 \) Partial Width.** As we said before, it is possible that the excited leptons have a mass smaller than the compositeness scale. If they are sufficiently light they may appear as a decay product in \( Z^0 \) decay \([9]\). In this case the \( Z^0 \)-partial width is given by

\[
\Gamma(Z \to \Psi l) = \frac{1}{2\pi(2J + 1)M_Z^2} \left[ \frac{(M_Z^2 - m_*^2 + m_l^2)^2}{4M_Z^2} - m_l^2 \right]^{1/2} F_{\psi}(M_Z^2, m_l^2, m_*) \tag{0.4}
\]

where \( \Psi \) denotes any of the new particles we are considering here. \( J \) is the spin of the decaying particle i.e., \( J = 1 \) in this case.

For the case of excited spin-\( \frac{1}{2} \) leptons we have, for the interaction given by Eq. \(0.1\)

\[
F_{\psi*} = \frac{(c^2 + d^2)}{\Lambda^2} \left[ 4 \left( M_Z^2 - (m_*^2 - m_l^2) \right)^2 - 2M_Z^2(M_Z^2 - m_*^2 - m_l^2) \right] A_n,(c^2 - d^2)M_Z^2m_*m_l. \tag{0.5}
\]

For the spin-\( \frac{3}{2} \) we have,
\[
F_x = \frac{8}{3} g^2 \left( 2 + \frac{(M_Z^2 + m_*^2 - m_l^2)^2}{4m_2^2M_Z^2} \right) \left[ \frac{c^2 + d^2}{4} (M_Z^2 - m_*^2 - m_l^2) - m^* m_l(c^2 - d^2) \right],
\]

assuming the interaction given by Eq. (0.2) and

\[
F'_x = \frac{2}{3} \frac{c^2 + d^2}{\Lambda^2 m_*^2} [3m^* m_l^4 M_Z^2 - m^* m_l^6 - 5m^* m_l^4 M_Z^2 + 13m^* m_l^2 M_Z^2 - 8m^* m_l^4 M_Z^2 - 3m^* m_l^2 M_Z^2 - 7m^* m_l^2 M_Z^2 - 3m^* M^4 + m^* M^6] - 24 \frac{c^2 - d^2}{\Lambda^2} m^* m_l M_Z^2.
\]

from the interaction of Eq. (0.3).

Note that in Eqs. (0.3)–(0.7) it is not possible to distinguish between pure left- or pure right-handed interactions. As usual to avoid a conflict with the \(g-2\) measurements it is demanded that only either left-handed or right-handed leptons couple to the excited ones. Hence we will use in the following \(c = d = \frac{1}{\sqrt{2}}\).

We will consider the two parameters \(\Lambda\) and \(m^*\) as independent. Next, we will consider the constraints on these parameters coming from the leptonic \(Z^0\)-partial width for each effective interaction Eq. (0.1)–Eq. (0.3).

The effect of excited leptons or quarks in the \(Z^0\) width has already been studied [9], but only indirectly since the experimental parameter was the cross sections of processes as proton-(anti)proton and \(e^+e^-\) collisions. Recently, measurements of the \(Z^0\) partial widths have been made very accurately [12].

Here we will consider in particular the leptonic \(Z^0\) partial width as the measured parameter sensible, in principle, to the effects of compositeness. In particular we will use the ratio

\[
R_l = \frac{\Gamma_l}{\Gamma} \times 100%,
\]

where \(\Gamma_l\) is the \(Z^0 \to l\bar{l}\) width and \(\Gamma\) is the total width.
We leave unrelated the values of $\Lambda$ and $m^*$, but kinematically $m^* \leq M_Z - m_t$. Experimental data of the $Z^0$ leptonic partial width will give the allowed region for both parameters. Here we have used $R_e = 3.345 \pm 0.025 \%$ and $R_\tau = 3.320 \pm 0.04 \%$ [12].

In Fig. 1 we show the allowed and forbidden regions for $\Lambda$ and $m^*$ entering in Eq. (0.1). In Figs. 2 and 3 we have done the same for the parameters for the interactions given in Eqs. (0.2) and (0.3). There is a high sensitivity to changes in the parameters $(g, m^*)$ and $(\Lambda, m^*)$ for the interactions given by Eq. (0.2) and Eq. (0.3) as can be seen in Fig. 2 and 3 respectively. On the other hand the interaction (1) is not too sensitive to variations on the $(\Lambda, m^*)$ parameters (see Fig. 1).

Notice that with the interaction (1) (Fig.1) for a $\Lambda$ of about $5 - 9 TeV$ the new particles can have arbitrary small masses. Notwithstanding with interaction (3) (Fig.3) for the same $\Lambda$ values only particles with masses somewhat greater than $\sim 35 GeV$ are allowed. With the interaction (2) for arbitrarily small values of the coupling constant $g$ it is also possible for the new particles be arbitrarily light (Fig. 2).

We would like to stress that it is not straightforward to compare the constraints we have obtained in this work with others existing in the literature. In the later ones usually it is assumed at beginning that $\Lambda = m^*$ [4]. The case $\Lambda >> m^*$ is usually considered for the flavor changing transitions like $\mu \rightarrow e \gamma$ [7].

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FIGURE CAPTION
Fig. 1. Exited spin-$\frac{1}{2}$ fermion coupled as in Eq. (0.1). The allowed and forbidden regions in the $(\Lambda, m^*)$ plane delimited by the curves considering $m_l = m_e$ (continuous) and $m_l = m_r$ (dashed) for $1\sigma$ and $2\sigma$ experimental standard deviations on $R_l$ coming from Eq. (0.5) with $c = d = \frac{1}{\sqrt{2}}$.

Fig. 2. Spin-$\frac{3}{2}$ fermion coupled as in Eq. (0.2). The allowed and forbidden regions in the $(g, m^*)$ plane delimited by the curves considering $m_l = m_e$ (continuous) and $m_l = m_r$ (dashed) for $1\sigma$ and $2\sigma$ experimental standard deviations on $R_l$ coming from Eq. (0.6) with $c = d = \frac{1}{\sqrt{2}}$.

Fig. 3. Spin-$\frac{3}{2}$ fermion coupled as in Eq. (0.3). The allowed and forbidden regions in the $(\Lambda, m^*)$ plane delimited by the curves considering $m_l = m_e$ (continuous) and $m_l = m_r$ (dashed) for $1\sigma$ and $2\sigma$ experimental standard deviations on $R_l$ coming from Eq. (0.7) with $c = d = \frac{1}{\sqrt{2}}$. 