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Extending the Reach of Leptophilic Boson Searches at DUNE with Bremsstrahlung and Resonant Production

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We study the sensitivity to gauged $L_\mu - L_e$, $L_e - L_\tau$ and $L_\mu - L_\tau$ with the DUNE near detector. We find that including bremsstrahlung and resonant production of Z' leads to a significant improvement in existing bounds, especially for $L_\mu - L_e$ and $L_e - L_\tau$.

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1. Introduction

One generic possibility for BSM physics is additional gauge symmetries. One class of symmetries which can be gauged without implying any new fermions are those associated with the lepton number [1, 2]. In this case, pairs of the individual lepton flavor numbers are gauged, with each pair having an equal and opposite charge assignment, i.e. $L_\alpha - L_\beta$, where $\alpha, \beta = e, \mu, \tau$. The gauging of such symmetries only directly predicts the existence of a new Z' gauge boson associated with the symmetry, which is coupled to both charged leptons $l_{\alpha,\beta}$ and neutrinos $\nu_{\alpha,\beta}$, with a coupling constant $g_{\alpha,\beta}$. The symmetries of the model allow for kinetic mixing between the Z' and the SM gauge bosons. Unless explicitly specified, in this work we assume a vanishing tree level contribution to kinetic mixing, which is then only generated at the loop level.

The presence of leptophilic gauge bosons has been extensively looked for in lepton colliders or fixed target beam dump experiments, as well as in neutrino experiments (see [3] for a detailed review of the current experimental bounds). In general, for $m_{Z'} \in [1, 10^3]$ MeV and $g_{\alpha\beta} < 10^{-5}$ the most stringent constraints come from electron beam dump experiments, such as E137 [4], with a worse sensitivity for $L_\mu - L_\tau$ because of the coupling to electrons being possible only at the loop level. It has recently been shown in [5] that DUNE [6] will improve current constraints, but only for $L_\mu - L_\tau$ and only in a narrow window of masses around $5 - 10$ MeV. However, in [5] only Z' production through meson decays has been considered. At the same time, in [7, 8] the relevance as production channels of $e^\pm$ bremsstrahlung, as well as of on-shell resonance has been noted in the context of dark photon models. In this work we show that the Z' production from both bremstrahlung and on-shell resonance in DUNE can significantly improve the prospective sensitivity to $L_\alpha - L_\beta$ gauge boson.

2. Production and decay of Z'

In DUNE, the Z' can be produced in the protons interactions with a fixed target. In order to simulate the production of all particles in the proton beam interactions, we used GEANT4 simulation tool kit [9–11]. Before describing the calculation method we employ for each channel, let us define $N_\gamma^{a,ij}$ as the number of photons in the i-th energy bin and j-th angular bin, from the production channel a, as predicted by GEANT4, where the angle is formed by the original proton beam and the outgoing photon propagation directions. We also define the bin extrema to be $[E_i^{\min}, E_i^{\max}]$ and $[\theta_j^{\min}, \theta_j^{\max}]$ for i-th energy and j-th angular bins, respectively. For meson decays and bremsstrahlung, we assume that the Z' has the same angular and energy distributions of the corresponding photons. Analogously, we define $N_{e^+}^{ij}$ as the number of positrons and assume that all the Z' from resonant production have the same propagation direction of the incoming positron.

2.1 Bremsstrahlung

To calculate the number of Z' in the ij-th bin produced by electron and positron bremsstrahlung, we use the expression [12] $N_{Z'}^{\text{brem},ij} = N_\gamma^{\text{brem},ij} \left(\frac{g}{e}\right)^2 f\left(\frac{m_{Z'}}{\langle E_e \rangle}\right)$, where e is the electric charge, the function $f(x) = 1154\exp(-24.42x^{0.3174})$ is taken from Fig. 9 in [12] and represents a phase space factor, and $\langle E_e \rangle = 1.0773E_\gamma + 13.716\,[\text{MeV}]$ is the average electron or positron energy. g is

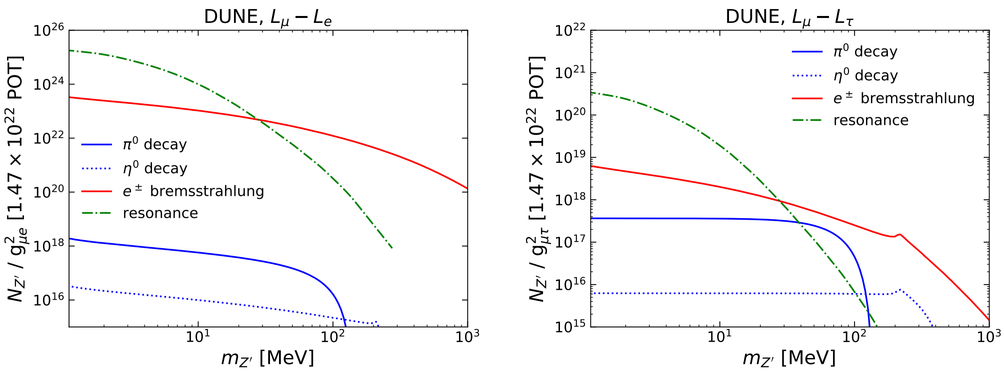

Figure 1: Number of Z' entering the DUNE detector, as a function of $m_{Z'}$ for each production channel, in the context of $L_\mu - L_e$ (left panel) and $L_\mu - L_\tau$ (right panel).

the coupling strength to electron and positrons, which depends on the model under consideration: $g = g_{\mu e}$ ($g_{e\tau}$) for $L_\mu - L_e$ ($L_e - L_\tau$), $g = e\,\epsilon(m^2_{Z'})$ for $L_\mu - L_\tau$.

2.2 Resonant Production

A Z' can be produced on-shell through the process $e^+ + e^- \to Z'$ when $E^{\rm res}_{e^+} = E^{\rm res}_{Z'} = m^2_{Z'}/2m_e$. In this case the number of Z' in the j-th angular bin is given by

$$N^{{\rm res},j}_{Z'} = \frac{AX_0}{m_p Z} \sum_i \int_0^{t_{\max}} dt N^{ij}_{e^+} I(E_i, E^{\rm res}_{e^+}, t)\sigma_{\rm res}\,, \tag{1}$$

where A and Z are the mass and atomic number of the nuclei in the proton beam target (or beam dump), respectively, X_0 is the radiation length of the same target, m_p is the mass of proton, $I(E_i, E_{e^+}, t)$ is the probability that a positron with initial energy E_i (the average energy of the i-th bin) has a final energy E_{e^+} after propagating t radiation lengths, and $t_{\max}$ is the maximum number of radiation lengths traveled by a positron in the target. $\sigma_{\rm res}$ is the cross section for resonant production and is given by [8] $\sigma_{\rm res} = \frac{\pi g^2}{2m_e}\delta\left(E_{e^+} - m^2_{Z'}/(2m_e)\right)$, where $g = g_{\mu e}$ ($g_{e\tau}$) for $L_\mu - L_e$ ($L_e - L_\tau$), $g = e\,\epsilon(m^2_{Z'})$ for $L_\mu - L_\tau$.

2.3 Comparison of production channels

The left panel of Fig. 1 displays the number of Z' as a function of $m_{Z'}$ in the context of $L_\mu - L_e$ from each production channel, entering the DUNE detector. The number of Z' is in units of $g^2_{\mu e}$ and refers to an exposure of 1.47×10^{22} protons on target (POT). For $m_{Z'} < 20$ MeV, the dominant channel is resonant production, whereas bremstrahlung provides the biggest contribution for higher masses. Resonant production decreases faster since only positrons with energy $E^{\rm res}_{e^+} = m^2_{Z'}/(2m_e)$ are able to produce the Z' on shell, whereas for bremsstrahlung all charged leptons with $E_{e^\pm} > m_{Z'}$ can in principle contribute. Neutral meson decays are subdominant because they occur only through kinetic mixing, and their number per each proton on target is smaller than the one of electrons and positrons.

The right panel refers to $L_\mu - L_\tau$. In this case, the pion decay channel is not significantly modified with respect to $L_\mu - L_e$. On the other hand, both bremsstrahlung and resonant production take place only through kinetic mixing and they receive a $\sim 10^4$ suppression factor.

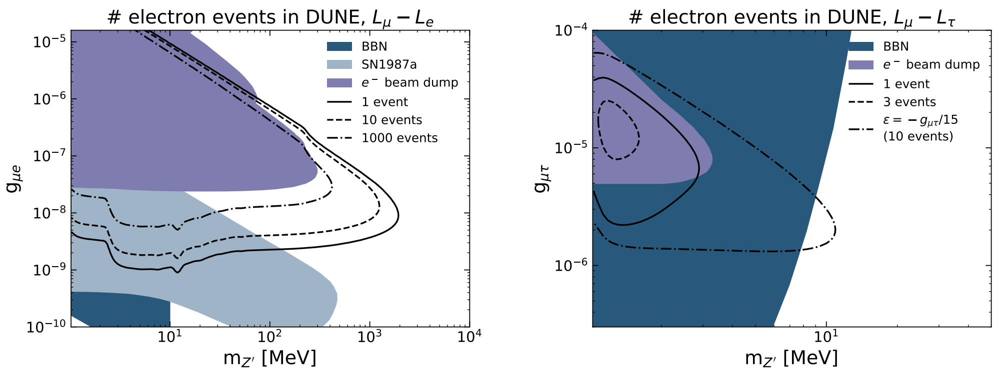

Figure 2: (Left) The black contours display the number of electron events in the DUNE near detector from Z' decays as a function of $m_{Z'}$ and the coupling constant $g_{\mu e}$ in the context of $L_\mu - L_e$. The solid filled areas represent the region of the parameter space already excluded by electron beam dump experiments [3] and SN1987a [13]. The BBN bounds are taken from [14]. (Right) Same as the left panel, but for $L_\mu - L_\tau$. In this case, the BBN constraints are taken from [15].

2.4 Z' decays in the detector

The number of leptons ($l = e, \mu$) produced by $Z' \to l^+l^-$ decays in the detector is given by

$$N_l = \sum_j N_{Z'}^{\text{res},j} n_l P_{Z'\to l^+l^-}(E_{Z'}^{\text{res}}, \theta_j) + \sum_{i,j} n_l \left(N_{Z'}^{\text{brem},j} + N_{Z'}^{\pi^0,\eta^0,j}\right) P_{Z'\to l^+l^-}(E_{Z'}^i, \theta_j) \tag{2}$$

where $n_l = n_l(E_{Z'}, E_l^{\text{th}}, \theta_1, \theta_2)$ is the number of leptons per Z' decay with an energy E_l greater than the detection threshold E_l^{th} and going into an angle cone between θ_1 and θ_2, $E_{Z'}^{\text{res}}$ is the energy of the Z' for resonance production, $E_{Z'}^i = \frac{1}{2}(E_i^{\text{min}} + E_i^{\text{max}})$ is the center of the i-th energy bin, and $P_{Z'\to l^+l^-}$ is the probability that a Z' decays inside the detector. The latter is calculated with the following equation

$$P_{Z'\to l^+l^-}(E_{Z'}, \theta) = \frac{\Gamma(Z' \to l^+l^-)}{\Gamma_{\text{tot}}} \left(1 - e^{-\frac{L(\theta)\Gamma(Z'\to l^+l^-)m_{Z'}}{p_{Z'}}}\right) e^{-\frac{d(\theta)\,\Gamma(Z'\to l^+l^-)m_{Z'}}{p_{Z'}}}, \tag{3}$$

where $L(\theta)$ is distance traveled in the detector, which depends on the Z' propagation angle θ, $d(\theta)$ is the distance traveled between the target (or beam dump) and the detector, $p_{Z'}$ is the momentum of the Z', Γ_{tot} and $\Gamma(Z' \to l^+l^-)$ are the total and partial decay widths, respectively.

In Eq. 2, the sum over j is performed considering only those propagation directions of the Z' within the detector coverage, i.e. those having a propagation angle with respect to the beam $\theta_{Z'} < \theta_{\text{det}}$. Assuming the symmetry axis of a detector is aligned with the direction of the beam and that it has a width $2w$, we can estimate its angular size as $\theta_{\text{det}} \sim \frac{w}{d}$.

The partial decay width to charged leptons is

$$\Gamma(Z' \to l^+l^-) = \frac{g_l^2 m_{Z'}}{12\pi} \sqrt{1 - 4\left(\frac{m_l}{m_{Z'}}\right)^2} \left[1 + 2\left(\frac{m_l}{m_{Z'}}\right)^2\right], \tag{4}$$

where $l = e, \mu, \tau$, $g_e = g_\mu = g_{\mu e}$ for $L_\mu - L_e$, whereas $g_e = e\,\epsilon(m_{Z'}^2)$ and $g_\mu = g_{\mu\tau}$ for $L_\mu - L_\tau$. For a neutrino ν_l, the partial decay width is equal to the one in Eq. 4 divided by 2.

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3. DUNE sensitivities

We assume an exposure of 1.47×10^{22} POT and study Z' decays in the multipurpose near detector filled with gaseous argon (GAr). Concerning detection thresholds, we take 0.2 MeV and 2 MeV for $e^\pm$ and $\mu^\pm$, respectively [5], which stem from the assumption of 2 cm as a reasonable length for track identification. A careful evaluation of backgrounds in the GAr detector has already been done in [5], which we use as a reference. In particular, as done in [5] we propose to use 10 $e^\pm$ events as nominal threshold for defining the constraints on leptophilic gauge bosons,

The expected number of electrons from Z' decays in DUNE for $L_\mu - L_e$ and $L_\mu - L_\tau$ is shown in the left and right panel of Fig. 2, respectively. For $L_\mu - L_e$ the contribution from resonant production dominates over bremsstrahlung for $m_{Z'} > 2$ MeV. The reason is that in the resonance case the Z' has a specific energy $(m_{Z'}^2/2m_e)$, which for $m_{Z'} < 2$ MeV is not enough to allow for a decay to $e^\pm$ in a 5 degree cone, which use as a cut to decrease background contamination [5]. According to our nominal 10 event threshold, DUNE can extends beyond the current exclusion region from electron beam dump experiments to values of $g_{\mu e}$ ten times smaller in the mass range $m_{Z'} \in [1, 10^3]$ MeV. While part of the parameter space is disfavored by observations of neutrinos from SN1987a [13], it is worthwhile to note that the DUNE sensitivity extends up to significantly higher $m_{Z'}$.

In the $L_\mu - L_\tau$ case, on the other hand, the improvement over the current constraints dominated by electron beam dump experiments is marginal. Nevertheless, as shown in [5], the Z' production channels from charged meson decays to muons ($M^\pm \to \mu^\pm \nu_\mu Z'$, $M = \pi, K$) are not suppressed by kinetic mixing and a more significant improvement can be obtained.

Prospective constraints of DUNE on both $L_\mu - L_e$ and $L_\mu - L_\tau$ were already derived in [5], thus a comparison with the results obtained therein is in order. The main difference our study, however, lies in the production channels of Z' under consideration. In our case, the main channels are the electron bremsstrahlung and the resonant production. These channels have not been considered in [5] where instead the bulk of Z' comes from charged meson decays. For $L_\mu - L_e$ we find that the number of Z' produced in the target is five orders of magnitude larger than the one connected to charged mesons estimated in [5]. This is clearly seen by comparing our bottom left panel of Fig. 1 with Fig. 5.2 in [5]. Such a difference explains why we conclude that DUNE can improve current constraints in the parameter space $(m_{Z'}, g_{\mu e})$, whereas the opposite is stated in [5]. Comparing our calculation for $L_\mu - L_\tau$, shown in the bottom right panel of Fig. 1, with Fig. 5.4 in [5], we find that the number of Z' from charged mesons is similar to the one from electrons. This happens because the charged meson decays involving muons are not suppressed by kinetic mixing, whereas a suppression is indeed present for both the bremsstrahlung and resonant channels.

Finally, despite not being explicitly displayed, the sensitivities of DUNE in the context of $L_e - L_\tau$ are expected to be the same as $L_\mu - L_e$. This happens because the dominant production channels (bremsstrahlung and resonance) are characterized by the same coupling strength $g_{e\tau} = g_{\mu e}$.

4. Conclusions

In thie context of the anomaly-free $U(1)$ gauge group $L_\alpha - L_\beta$, we have calculated the number of charged lepton pairs produced by Z' decays in the GAr detector of DUNE. We have shown that the Z' produced by $e^{\pm}$ bremsstrahlung and on-shell resonance give the largest contributions in the context of $L_\mu - L_e$ and $L_e - L_\tau$. This is our main result, since a similar study performed in [5] neglected these production channels (focusing mostly on charged mesons decays) and found that DUNE is not able to extend current constraints in the parameter space $[m_{Z'}, g_{\mu e}]$ and $[m_{Z'}, g_{e\tau}]$. Whereas we find that, when both bremsstrahlung and on-shell resonance are taken into account, DUNE sensitivity goes beyond both the current most stringent limits from electron beam dump experiments and astrophysical bounds from SN1987a and BBN.

Concerning $L_\mu - L_\tau$, we observe that our Z' production channels endow DUNE with a sensitivity comparable to current constraints. Therefore, in this case the charged meson decay channel presented in [5] provides a slightly better reach. These results might change when considering an extra source of kinetic mixing in the context of a UV complete model.

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