Production of exotic neutral leptons in radiative ep scattering

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The production of single exotic neutral leptons L^0 in $e^- p \to \gamma + L^0 + \text{jet} + X$ is discussed. We argue that while the event rates for this process are much too low at DESY HERA, the detection of these heavy leptons is within reach at the proposed CERN LEP-LHC ep collider. [S0556-2821(96)03713-7]

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I. INTRODUCTION

Over the last few years, although the standard model has been put through very stringent experimental tests, it has successfully accounted for all electroweak phenomena at currently accessible energies. However, there is a general expectation that the standard model cannot be considered a complete theory of electroweak interactions. Alternative models have been proposed to extend the standard model, which predict the existence of new particles and interactions. In particular, new leptons are an important ingredient in many of these extended models, and their detection, either via indirect effects or direct production at high-energy colliders, would be strong evidence of new physics [1].

We have recently studied single heavy-lepton production in e^+e^- collisions and exotic quark production at energies reached at the DESY ep collider HERA [2]. The purpose of this paper is to analyze the possibility of producing and detecting exotic neutral spin-1/2 leptons in the process $ep \to \gamma + L^0 + \text{jet} + X$ at present and future ep colliders. This analysis was carried out in the context of the vector-singlet (VSM), vector-doublet (VDM), and fermion–mirror-fermion (FMFM) models [3], which predict mixing between ordinary and exotic leptons. By looking at certain experimental data, such as the absence of flavor-changing neutral currents, it is possible to establish bounds on the mixing angles, in a model-independent way [4]. As for the exotic-lepton mass, the most recent direct searches place it most likely above the Z mass [5].

II. CROSS SECTIONS AND DISTRIBUTIONS

The lowest order Feynman diagrams corresponding to the parton level subprocesses relevant to the reaction $ep \to \gamma + L^0 + \text{jet} + X$ are shown in Fig. 1. Our analytical and numeric results are consistent with those obtained for the standard model in Ref. [6]. All total and differential cross sections were computed with set I of the Duke-Owens parton distributions functions [7], evolved to the deeply inelastic scattering scale $Q^2 = xys$, including only the first two quark families, with quark masses equal to zero throughout. We have explicitly checked that cross sections and distributions remain essentially the same if the Harriman-Martin-Roberts-Stirling (HMRS) [8] parton distribution functions are used instead. For the electroweak parameters we used $\sin^2\theta_W = 0.23$, $M_W = 80$ GeV, and $\Gamma_W = 2.25$ GeV, in addition to $\alpha(M_W^2) = 1/128$. All mixing angles were taken to have the value $\theta^{\text{mix}} = 0.1$ and the heavy-lepton mass equal to 120 GeV. These values are consistent with the present experimental bounds. Event rates were computed for HERA and its possible upgrade [9], as well as for a proposed ep collider in the CERN e^+e^- collider LEP tunnel [10] [LEP–Large Hadron Collider (LHC)].

Fragmentation and hadronization effects are not considered in the calculation; hence, the hadronic jet is identified with the scattered quark from which it arises. In order to take into account the likely limitations in detector acceptance, we imposed cuts $p_T > 20$ GeV on the transverse momenta of the photon, heavy lepton, and jet. Furthermore, we only accept events in which they emerge with polar angles θ_i, measured with respect to the direction of the incoming proton beam, satisfying $8° < \theta_i < 172°$. To isolate the photon from the current jet we require that the jet-photon separation $\Delta R_{j\gamma} = \sqrt{(\Delta\eta_{j\gamma})^2 + (\Delta\phi_{j\gamma})^2}$ in the pseudorapidity azimuthal angle plane be greater than 0.5. This set of cuts also ensures

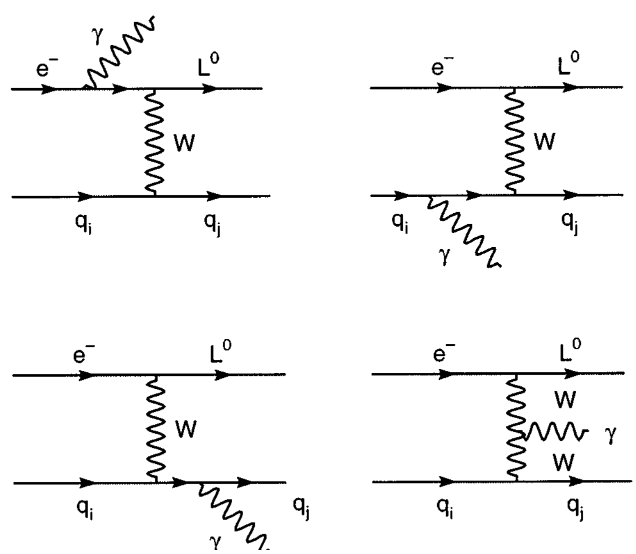

FIG. 1. Lowest order Feynman diagrams for the parton level subprocesses.

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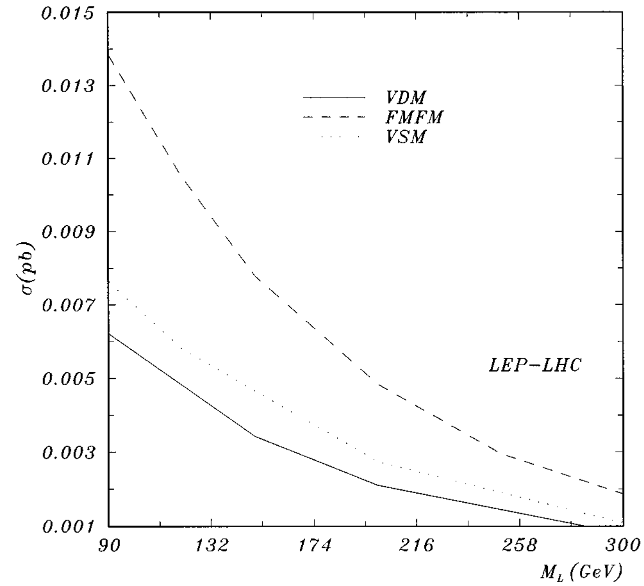

FIG. 2. Production cross sections as functions of the exotic-lepton mass, according to the vector-singlet, vector-doublet, and fermion–mirror-fermion models, at the LEP-LHC energy.

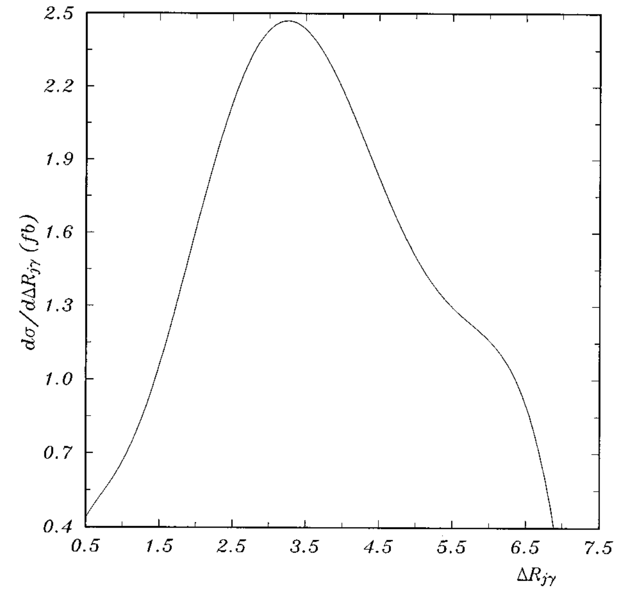

FIG. 4. Distribution of jet-photon separation in the pseudorapidity azimuthal angle plane, for $M_L = 120$ GeV.

that infrared and collinear divergences are properly regulated.

Figure 2 shows the total cross section as a function of the exotic-lepton mass M_L, at the LEP-LHC c.m. energy $\sqrt{s} = 1265$ GeV, for all three extended models. Assuming the projected LEP-LHC luminosity of 3×10^{32} cm^{-2} s^{-1} [10], and considering the FMFM, which has the largest total cross section, it is possible to produce up to 90 events a year for $M_L = 120$ GeV. A heavy neutral spin-1/2 lepton whose mass is above the Z^0 mass decays predominantly via the two-body process $L^0 \rightarrow l^{\pm} W^{\mp}$, with a branching ratio equal to 67% [2]. Even if one disregards the remaining decay modes of the exotic lepton and identifies the W bosons only by their hadronic decays, one may still detect about 40 events a year. For a minimum detection rate of 10 LEP-LHC events/year, masses as high as 300 GeV could be reached. The corresponding event rates at HERA ($\sqrt{s} = 314$ GeV) and its possible upgrade ($\sqrt{s} = 410$ GeV) are at least one or two orders of magnitude lower than those at LEP-LHC, for the same set of input parameters.

Figure 3 shows the photon p_T distribution for each extended model. All three curves are strongly peaked at small values of transverse momentum. This behavior is due to contributions from phase space regions which are close to infrared singularities. The shapes of the three p_T distributions are very similar, and this can be understood as follows. In the

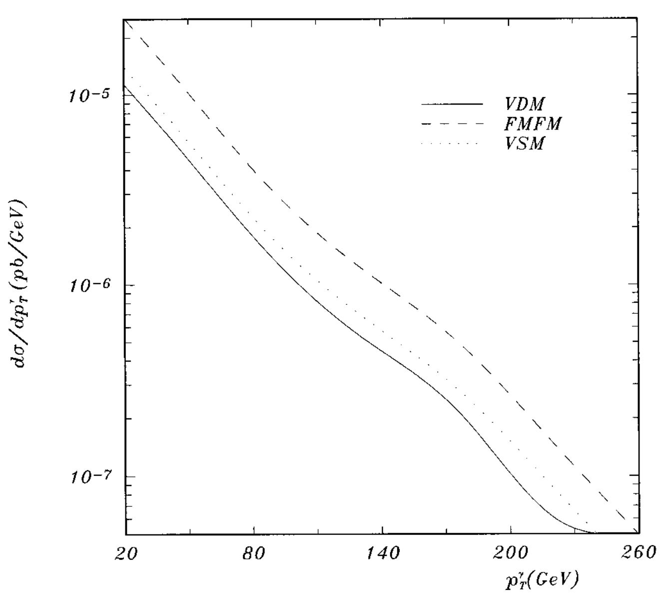

FIG. 3. Photon transverse momentum distribution for an input mass $M_L = 120$ GeV.

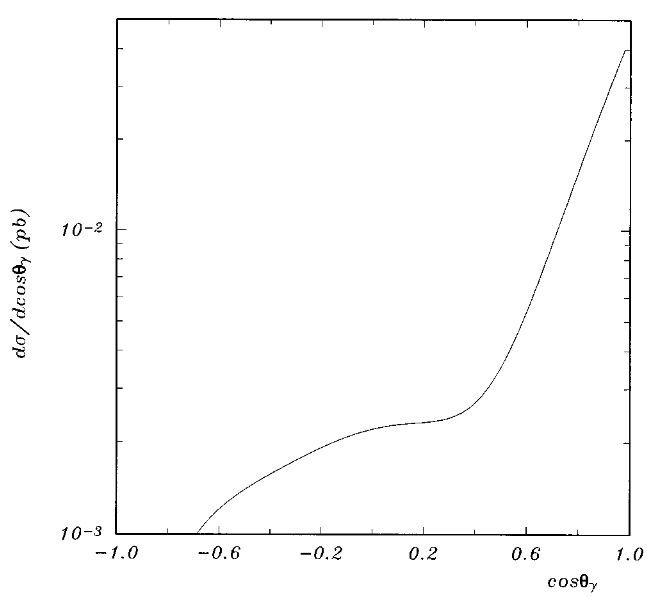

FIG. 5. Photon angular distribution for an input mass $M_L = 120$ GeV.

VSM the coupling $e^- W^+ L^0$ is always $V-A$, and since we are neglecting the masses of all ordinary fermions, only the left-handed incoming electrons contribute to the cross sections. On the other hand, the $V+A$ character of the same coupling in the VDM is due to the fact that we chose the left mixing angles in the neutral and charged lepton sectors to be equal. The $V+A$ character of the VDM electroweak current is then responsible for the suppression of the contributions from left-handed incoming electrons. The FMFM is neither $V-A$ nor $V+A$, but because we took all mixing angles equal to θ^{mix}, it turns out that in the reaction under study any cross section for the FMFM can be written as the sum of the corresponding definite-helicity cross sections for the VSM and VDM. Had we chosen to consider mixing only in the neutrino sector, for instance, the three models would have been found to have identical cross sections. This also suggests that the use of longitudinally polarized electron beams could be a powerful tool to distinguish one extended electroweak model from the other. In the remaining figures we will only show differential cross sections for the FMFM, keeping in mind that, for our choice of mixing angles, the qualitative predictions for the three models under discussion are similar. The jet-photon separation spectrum is displayed in Fig. 4. The distribution shows a peak at $\Delta R_{j\gamma} \approx \pi$, which is mostly due to photon emission by the incoming electron. The imposed angular cuts prevent $\Delta R_{j\gamma}$ from reaching large values. Figure 5 illustrates the photon angular distribution. As expected, most of the electromagnetic radiation flows into the forward cone, and we have checked that a maximum occurs around $\theta_\gamma = 25°$.

In brief, we have shown that it is feasible to detect an exotic neutral lepton in the mass range 100–300 GeV, through the reaction $ep \rightarrow \gamma + L^0 + \mathrm{jet} + X$, at the proposed LEP-LHC ep collider, as long as the mixing angles are not much smaller than the present experimental upper bounds. This process is unlikely to be observed at HERA or its possible upgrade. Even if exotic leptons are not found at the LEP-LHC facilities, the study of this radiative charged current exchange may be useful to set tighter bounds on heavy-lepton masses and constrain the mixing between exotic and ordinary leptons.

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