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Indirect dilepton signatures in TeV e^+e^- and e^-e^- collisions

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We examine the indirect signatures for the existence of spin-1 dileptons, which are predicted in SU(15) grand unified theory, in both e^+e^- and e^-e^- collisions at TeV energies. For reasonable values of the coupling strengths, such particles can be searched for far beyond the center-of-mass energies of such colliders.

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Although the standard model (SM) has done an excellent job in explaining current experimental data, it is quite commonly believed that it remains inadequate since it leaves too many questions unanswered. Perhaps the clearest signal for new physics beyond the SM would be the observation of new and unexpected particles. For example, such new degrees of freedom could carry an exotic quantum number (as is the case for leptoquarks [1] or diquarks [2]) or be the new gauge bosons [3] corresponding to gauge group extensions of the SM. One possibility, which in a way combines the features of both such scenarios, is the SU(15) grand unified theory (GUT) model of Frampton *et al.* [4], which predicts the existence of elementary light dileptons which are either spin 0 or 1. Such particles carry two units of lepton (L) number and are introduced in a manner which allows L and flavor conservation at tree level.

While direct production signatures for spinless dileptons (X) at TeV e^+e^- colliders have been previously discussed [5] (and are not expected to be substantially different in the spin-1 case), we will examine here the possible *indirect* signatures for such particles in both e^+e^- and e^-e^- interactions. Direct production methods are, of course, limited in that only the region of parameter space where the mass of X (M_X) is $\lesssim \sqrt{s}$ can be probed. Given sufficient statistics (i.e., integrated luminosity L), indirect searches can probe for X's with masses several times larger than $\sqrt{s}$, as we will see below. Clearly, given the quantum numbers of such particles, they can only be easily sought in e^+e^- or e^-e^- reactions, and we will restrict our attention to future colliders in the $\sqrt{s}=0.5$–2 TeV range [6].

We turn our attention first to the case of Bhabha scattering $e^+e^-\rightarrow e^+e^-$. In the SM this process proceeds via s- and t-channel γ and Z exchange, but if dileptons coupling to e^-e^- are present, we can now have an additional X exchange in the u channel. Normalizing all couplings to the electromagnetic strength e, the differential cross section for the process can be written as ($z=\cos\theta$)

$$\frac{d\sigma^B}{dz}=\frac{\pi\alpha^2(M_z)}{s^3}\{P_{ij}^{ss}[B_{ij}(u^2+t^2)+C_{ij}(t^2-u^2)]+P_{ij}^{tt}[B_{ij}(u^2+s^2)+C_{ij}(u^2-s^2)]$$
$$+2P_{ij}^{st}u^2(B_{ij}+C_{ij})+P_{xx}^{uu}[B_{xx}(s^2+t^2)]+4P_{ix}^{su}t^2(B_{ix}+C_{ix})+4P_{ix}^{tu}s^2(B_{ix}+C_{ix})\} \ . \tag{1}$$

Note that, in Eq. (1), i and j indices are summed over and represent SM γ and Z contributions; we also define the kinematic quantities $u\equiv-\frac{1}{2}s(1+z)$, $t\equiv-\frac{1}{2}s(1-z)$, and the combinations of couplings

$$B_{\alpha\beta}\equiv(v_\alpha v_\beta+a_\alpha a_\beta)^2 \ ,$$
$$C_{\alpha\beta}\equiv(v_\alpha a_\beta+v_\beta a_\alpha)^2 \ , \tag{2}$$

for all (α,β), together with the generalized propagator factors

$$P_{\alpha\beta}^{qr}\equiv s^2\frac{(q-M_\alpha^2)(r-M_p^2)+(M_\alpha\Gamma_\alpha)(M_\beta\Gamma_\beta)}{[(q-M_\alpha^2)^2+\Gamma_\alpha^2M_\alpha^2][(r-M_\beta^2)^2+\Gamma_\beta^2M_\beta^2]} \ , \tag{3}$$

where M_α (Γ_α) is the mass (width) of the αth exchanged particle. With our normalizations the v and a factors appearing in Eq. (2) are given by

$$v_\gamma=-1, \quad a_\gamma=0 \ ,$$
$$v_z=f(-\tfrac{1}{2}+2x_W), \quad a_z=-\tfrac{1}{2}f \ , \tag{4}$$
$$v_x=0, \quad a_x=2\sqrt{\kappa} \ ,$$

with $f^2\equiv G_FM_z^2/2\sqrt{2}\pi\alpha(M_Z)$, $\alpha(M_Z)=\frac{1}{128}$, $G_F=1.166\,386\times10^{-5}$ GeV^{-2}, $x_W=\sin^2\theta_W(M_Z)\simeq0.2321$ [7] from experiments at the CERN collider LEP, and κ an *a priori* unknown factor. Of course, we take

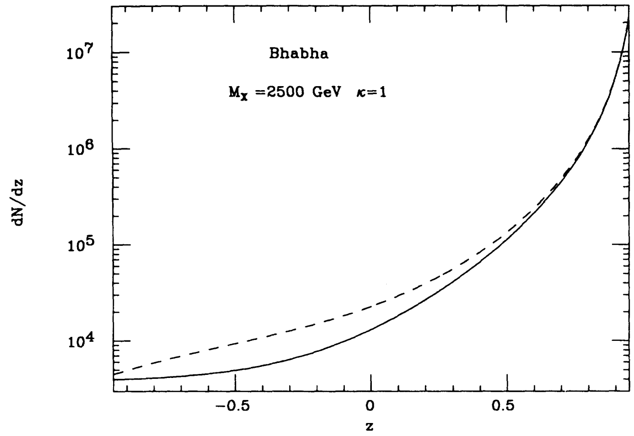

FIG. 1. Angular distribution of events for Bhabha scattering ($e^+e^- \to e^+e^-$) for a $\sqrt{s}=500$ GeV NLC assuming $L=25$ fb^{-1} for the SM (solid curve) and the SM plus a 2.5-TeV dilepton with $\kappa=1$ (dashed curve). Here $z=\cos\theta$.

$M_\gamma=\Gamma_\gamma=0$, $M_Z=91.175$ GeV, and $\Gamma_Z=2.487$ GeV [7], as well as $\Gamma_X=4\kappa\alpha M_X/3$, with M_X as a free parameter. Note in Eq. (4) that the vector coupling constant of X vanishes because of Fermi statistics in that X couples to a pair of electrons.

We now want to know if the production cross section, etc., for $e^+e^- \to e^+e^-$ will be significantly influenced by the presence of X for certain values of κ and M_X. Certainly, as M_X grows, only large κ values will produce sizable deviations from the SM predictions for the cross section. Figure 1, for example, shows the number of events for this process as a function of z at a $\sqrt{s}=500$ GeV e^+e^- collider [proposed SLAC Next Linear Collider (NLC)] with $L=25$ fb^{-1} and an $e^\pm$ identification efficiency of 99%. (Note we restrict ourselves to $|z| \leq 0.95$ to stay away from the beam pipe.) For $\kappa=1$ and $M_X=2.5$ TeV, there is a sizable deviation from the SM prediction observed in this case, which is more notable in the backward direction, due to u-channel X exchange. Thus, not only does X modify the total integrated number of events (N), but also the angular distribution which can be probed via the forward-backward asymmetry A_{FB}. Using data on N and A_{FB}, we can ask, for a given value of M_X, how small a value of κ will lead to observable deviations, or conversely, what range of κ is excluded? This can be done using a straightforward χ^2 analysis, and we follow our earlier work [8], incorporating a small systematic error ($\simeq 0.7\%$) in the anticipated measurement of the integrated luminosity as well as the above stated electron identification efficiency and cuts on z.

Figure 2 shows the region excluded, at the 95% C.L., in the κ-M_X plane, by an indirect search for spin-1 dileptons in the $e^+e^- \to e^+e^-$ reaction for $\sqrt{s}=0.5$ TeV and $L=25$ fb^{-1}. Figure 2 tells us that, even with a modest value of L, such a search is sensitive to values of M_X as large as 5(10) times larger than $\sqrt{s}$ for values of $\kappa=0.5(1)$, which is roughly the size anticipated on the SU(15) model [9].

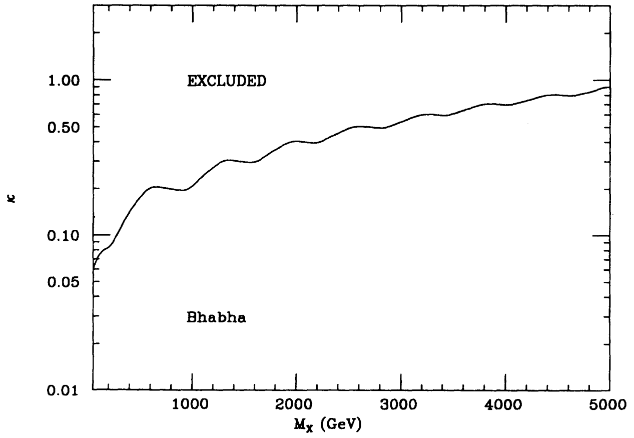

FIG. 2. Region in parameter space excluded at 95% C.L. in the κ-M_X plane obtained from an examination of Bhabha scattering ($e^+e^- \to e^+e^-$) at a $\sqrt{s}=500$ GeV NLC with $L=25$ fb^{-1}.

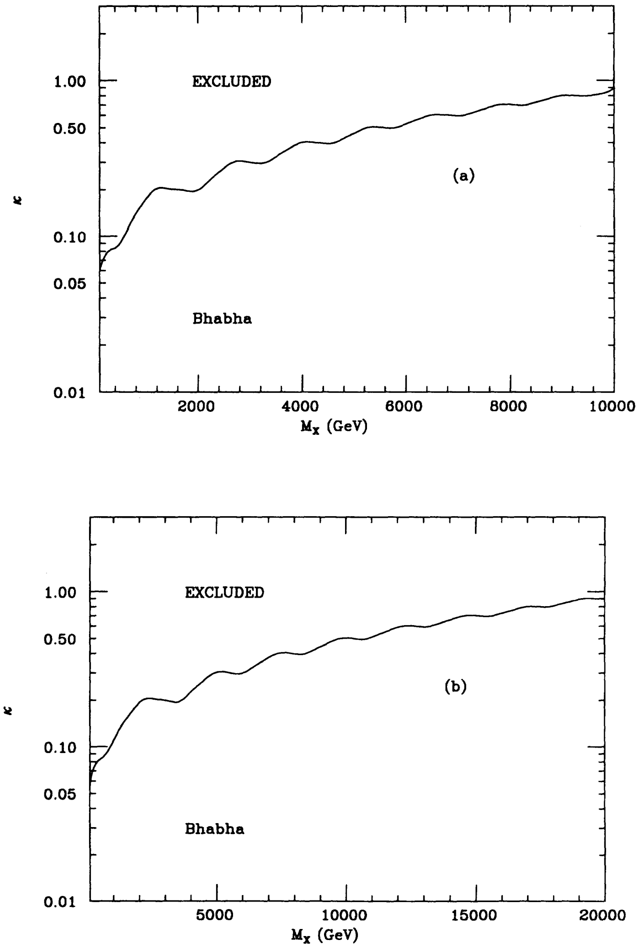

FIG. 3. Same as Fig. 2, but for (a) $\sqrt{s}=1$ TeV, $L=100$ fb^{-1} and (b) $\sqrt{s}=2$ TeV, $L=300$ fb^{-1}.

When one goes to even higher center-of-mass energies with larger integrated luminosities, as have been proposed [6], the dilepton search range can be drastically extended, as demonstrated by Figs. 3(a) and 3(b) for e^+e^- colliders with $\sqrt{s}$ = 1 or 2 TeV. In all cases, given the assumed values for L, the dilepton search range for $\kappa=0.5(1)$ can be as large as $M_X \simeq 5(10)\sqrt{s}$ at the 95% C.L.

We now turn our attention to Moeller scattering, i.e., $e^-e^- \to e^-e^-$; the cross section for this process can be obtained from that for Bhabha scattering by crossing symmetry, i.e., $s \to t$, $t \to u$, and $u \to s$ and dividing by a factor of 2 to account for the identical particles in the final state. Since identical particles are produced, the resulting cross section is symmetric under $z \to -z$ and so $A_{\rm FB}=0$ by definition. Thus, in this case, we only have the information provided to us by dN/dz to constrain the dilepton mass and coupling parameters (if one excludes the possibility of polarized beams). Clearly, if $M_X \simeq \sqrt{s}$ for this process, a dilepton s-channel resonance will be easily observed, giving unimpeachable evidence for the existence of a dilepton. What happens when $M_X > \sqrt{s}$? As we will see below, since only the dN/dz data are now available and the e^-e^- process has poles at both $z=\pm 1$, Moeller scattering is *less* sensitive to the existence of a dilepton than is Bhabha scattering. Obviously, only the region near $z=0$ will show significant deviation from SM predictions; these expectations are in fact verified by explicit calculations shown in Fig. 4. Here we see that for $\sqrt{s}=0.5$ TeV, $L=25$ fb^{-1}, $M_X=1.5$ TeV, and $\kappa=1$, only a small deviation from the SM is observed, which most noticeably occurs near $z=0$. Clearly, even such a light dilepton is somewhat difficult to observe even with high-statistics data.

What region of the κ-M_X plane can be probed by $e^-e^- \to e^-e^-$ if $\sqrt{s} > M_X$? For $\sqrt{s}=500$ GeV and $L=25$ fb^{-1}, this question is addressed in Fig. 5. We again see that the bound is essentially insensitive to the choice of couplings. Comparing Fig. 5 with Fig. 2, we see that, for $\sqrt{s} > M_X$, e^+e^- reactions are substantially more sensitive to the existence of dileptons than are e^-e^- reactions. For example, in the e^-e^- case with $\kappa=0.5(1)$, we see that the search range extends only up to

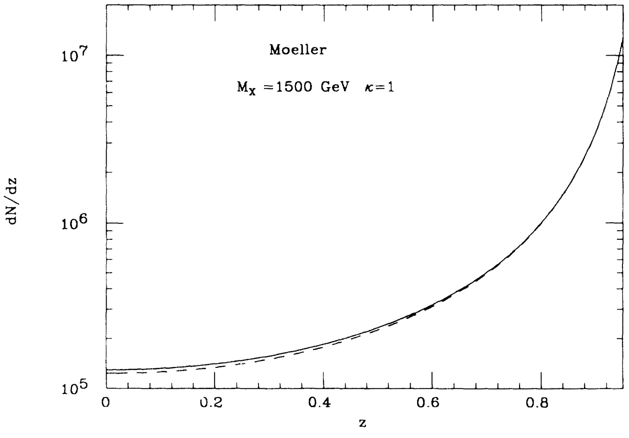

FIG. 4. Angular distribution of events for Moeller scattering ($e^-e^- \to e^-e^-$) for a $\sqrt{s}=500$ GeV NLC assuming $L=25$ fb^{-1} for the SM (solid curve) and the SM plus a 1.5-TeV dilepton with $\kappa=1$ (dashed curve). As in Fig. 1, $z=\cos\theta$.

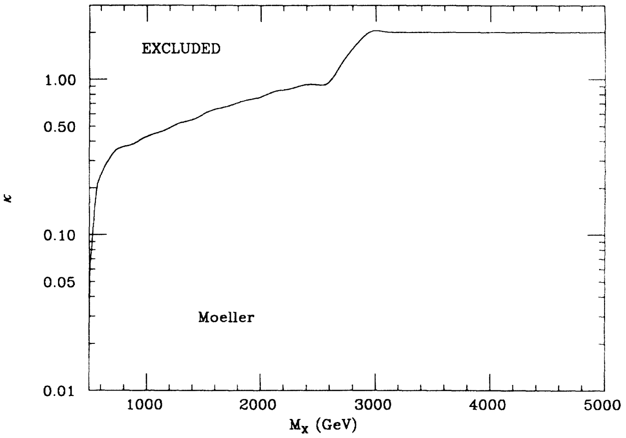

FIG. 5. Same as Fig. 2, but for Moeller scattering ($e^+e^- \to e^+e^-$).

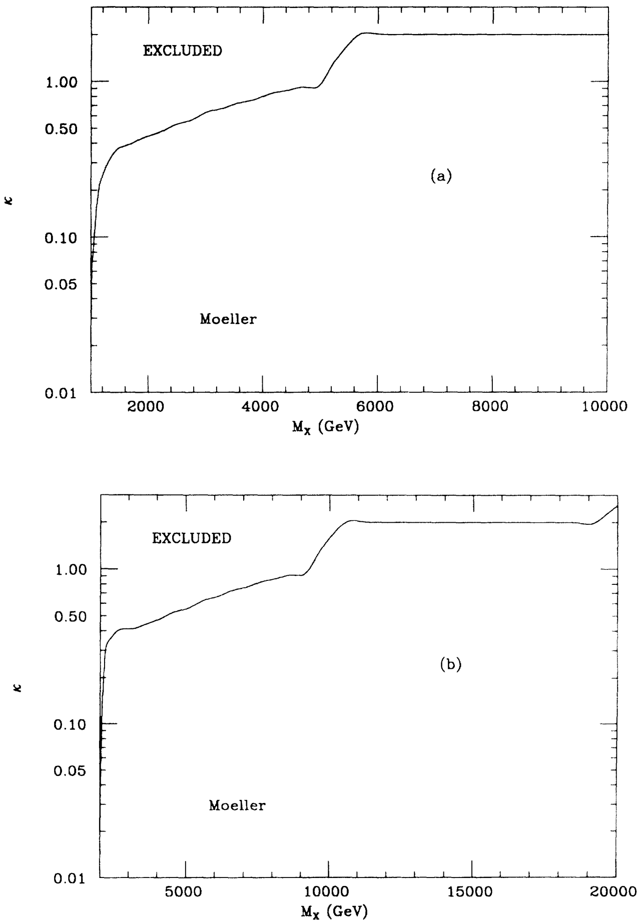

FIG. 6. Same as Fig. 3, but for Moeller scattering ($e^+e^- \to e^+e^-$).

$M_X \simeq 2.5(5)\sqrt{s}$, which is about one-half the reach obtained for e^+e^- with an identical integrated luminosity. As shown in Figs. 6(a) and 6(b), this same pattern is repeated for large values of $\sqrt{s}$ and higher integrated luminosities; i.e., in all cases the search limits obtained from e^-e^- are only about one-half as strong as those obtained from e^+e^- *once* $M_X > \sqrt{s}$ is assumed. Thus, while e^-e^- is the place to look for "light" dileptons (i.e., $M_X > \sqrt{s}$), e^+e^- reactions are far better when it comes to the "heavy" dilepton case (i.e., $M_X > \sqrt{s}$).

In this paper we have examined the possibility of using e^+e^- and e^-e^- reactions in the TeV range to explore for indirect effects of the existence of dileptons as predicted in the SU(15) model. If $M_X > \sqrt{s}$, we have found that e^+e^- reactions are far more sensitive to the existence of such particles than are e^-e^- reactions and that for coupling not too different from electromagnetic strength the search range can extend as high as 5–10 times larger than $\sqrt{s}$, given sufficient luminosity. The observation of such degrees of freedom would provide a new window on physics beyond the SM.

After this work was completed, our attention was drawn to a recent analysis by Frampton and Ng [10]; our conclusions are similar to those reached by those two authors where the two analyses overlap.

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