Contact Interaction Searches at the Linear Collider: Energy, Luminosity and Positron Polarization Dependencies*

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Many types of new physics can lead to contact interaction-like modifications in e^+e^- processes below direct production threshold. This report summarizes a survey of contact interaction search reaches at the Linear Collider as functions of energy, luminosity and positron polarization. The various tradeoffs between these quantities in such searches are examined in detail.

I.   INTRODUCTION

It is generally expected that new physics beyond the Standard Model(SM) will manifest itself at future colliders that probe the TeV scale such as the LHC and the Linear Collider(LC). This new physics(NP) may appear either directly, as in the case of new particle production, *e.g.*, SUSY or Kaluza-Klein resonances, or indirectly through deviations from the predictions of the SM. In the case of indirect discovery the effects may be subtle and many different NP scenarios may lead to the same or very similar experimental signatures.

Perhaps the most well known example of this indirect scenario in a collider context would be the observation of deviations in, *e.g.*, various e^+e^- cross sections due to apparent contact interactions. There are many very different NP scenarios that predict new particle exchanges which can lead to contact interactions below direct production threshold; a partial list of known candidates is: compositeness[1], a Z' from an extended electroweak gauge model[2, 3], scalar or vector leptoquarks[2, 4], R-parity violating sneutrino($\tilde\nu$) exchange[5], scalar or vector bileptons[6], graviton Kaluza-Klein(KK) towers[7, 8] in extra dimensional models[9, 10], gauge boson KK towers[8, 11], and even string excitations[12]. Of course, there may be many other sources of contact interactions from NP models as yet undiscovered, as was the low-scale gravity scenario only a few years ago.

The purpose of this paper is to overview how contact interaction search reaches are influenced by changes in the LC center of mass energy, integrated luminosity and positron polarization[13]. To be specific we will limit our discussion to the processes $e^+e^- \to \bar{f}f$ and to four of the scenarios listed above: new Z''s, gauge KK towers in the 5-dimensional version of the SM(5DSM), graviton exchange in the ADD model and compositeness. We will at first consider the following center of mass energies: $\sqrt{s} = 0.5, 0.8, 1.0, 1.2$ and 1.5 TeV and luminosities in the range $0.1 \leq L \leq 3~ab^{-1}$ and then generalize so that we may interpolate among these cases. Assuming an e^- polarization of 80% we initially consider only two possible polarizations for positrons: $P_+ = 0, 60\%$ and later generalize to a continuum of values. In calculating errors, statistical uncertainties and those systematics arising from both polarization and luminosity uncertainties, $\delta P/P = 0.003$ and $\delta L/L = 0.0025$ are employed. Initial state radiation but *no* beamstrahlung has been included and a symmetric low angle cut $\theta_{min} = 100$ mrad has been imposed. Finite efficiencies for flavor tagging the final state leptons and quarks, $f = e, \mu, \tau, c, b, t$, are also included in the calculations. In performing fits we employ the following observables: the unpolarized total cross sections, σ_f, the unpolarized angular distributions, $1/\sigma_f~d\sigma_f/d\cos\theta$, the left-right polarization asymmetries, $A^f_{LR}(\cos\theta)$ and the polarization of taus in the final state, P_τ, including the effects of a finite efficiency. Comparisons between the predictions of the new physics models to those of the SM are determined by the χ^2 of the fit which is controlled by a single parameter, a mass scale, in each case. The resulting 95% CL bounds we obtain are consistent with those found in earlier analyses[13].

However here it is not so much the bounds themselves that we are interested in but their *variation* as we change the values of $\sqrt{s}$, L and P_+. For impatient readers the punchline of this analysis can be found in Section V and specifically in Figs. 8 and 9. Sections II-IV contain the justification for these later results and conclusions.
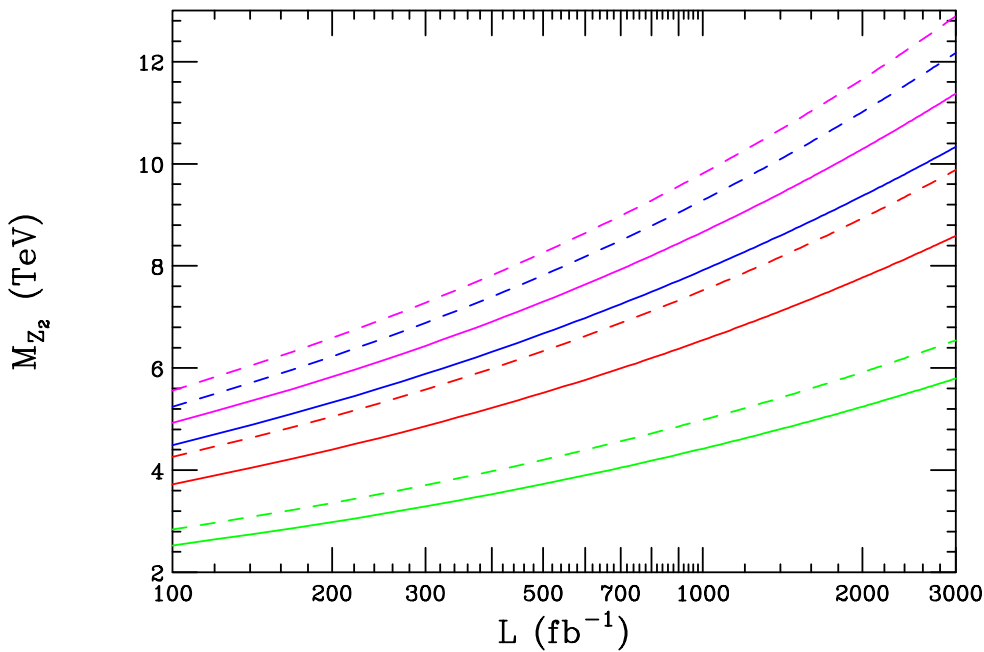
FIG. 1: 95% CL search reach M_{Z_2} for a Z' at a $\sqrt{s} = 500$ GeV LC when $P_+ = 0$(solid) or 60%(dashed) as a function of the integrated luminosity for E_6 models ψ(green), χ(red), the LRM(blue) and the SSM(magenta).

II.   NEW GAUGE BOSONS

Our first example of contact interactions is Z' exchange below production threshold. There are a huge number of models of this kind[2, 3]. We will consider four specific but representative Z' models: the models ψ and χ based on E_6 GUTS[2], the canonical Left-Right symmetric model(LRM) with equal left- and right-handed couplings, i.e., $\kappa = g_R/g_L = 1$[3] and the so-called Sequential Standard Model(SSM), which has a heavy copy of the SM Z that is often used by experimenters to gauge Z' sensitivity. The possibility of mixing between any of these new Z' fields and the SM Z will be neglected in the analysis and the deviations of the observables from their SM values for the final states $f = \mu, \tau, c, b$ and t will be combined into a single overall fit. Fig. 1 shows a typical result from this analysis for the specific case of an LC with $\sqrt{s} = 500$ GeV. We see immediately that the Z' limits are quite model dependent as one might expect due to the wide variation in their couplings to the various SM fermions; note that reaches in the range $\sim 5 - 12\sqrt{s}$ seem rather generic. We also observe that the search reaches are in all cases relatively($\sim 10 - 20\%$) sensitive to the presence of positron polarization, but in a model-dependent manner. Although the various reach curves have slightly different slopes they are found to rise approximately[3] as $\sim L^{1/4}$ in all cases. As we will discuss below this approximate scaling implies that the discovery reach is essentially statistics dominated.

What happens to these results as we vary $\sqrt{s}$? This is shown in detail in Fig. 2 for the same set of Z' models. In order to compare the same model but at different values of $\sqrt{s}$, thus removing the coupling dependencies, we replot these results as shown in Fig. 3. In both these figures we see that these are some small relative changes in the slopes as $\sqrt{s}$ is varied. Overall one sees that for a given model and fixed values of L and P_+ the reach scales[3] approximately as $(\sqrt{s})^{1/2}$, which again signals the dominance of statistical errors.

III.   EXTRA DIMENSIONS

We will investigate two models which display distinct signatures for extra dimensions. The first case we consider is the 5DSM in which the photon and Z(as well as the W and gluon) of the SM have nearly equally spaced KK excitations with masses $M_n^2 = n^2 M_c^2 + M_0^2$, where M_0 is the SM particle mass, $n = 1, 2, 3, ...$ and M_c is the compactification scale. Based on analyses of precision measurements we expect M_c to be in excess of 4-5 TeV[11]. (We note however that there are variations of this model where KK gauge boson can exists which are significantly lighter than these bounds thus allowing for the possibility of their direct production at a TeV class LC.) The scale M_c is thus essentially the mass of the first photon/Z KK excitation. The reach for M_c is expected to be significantly larger than, say, the reach for the mass of the SSM Z', for several reasons. First,
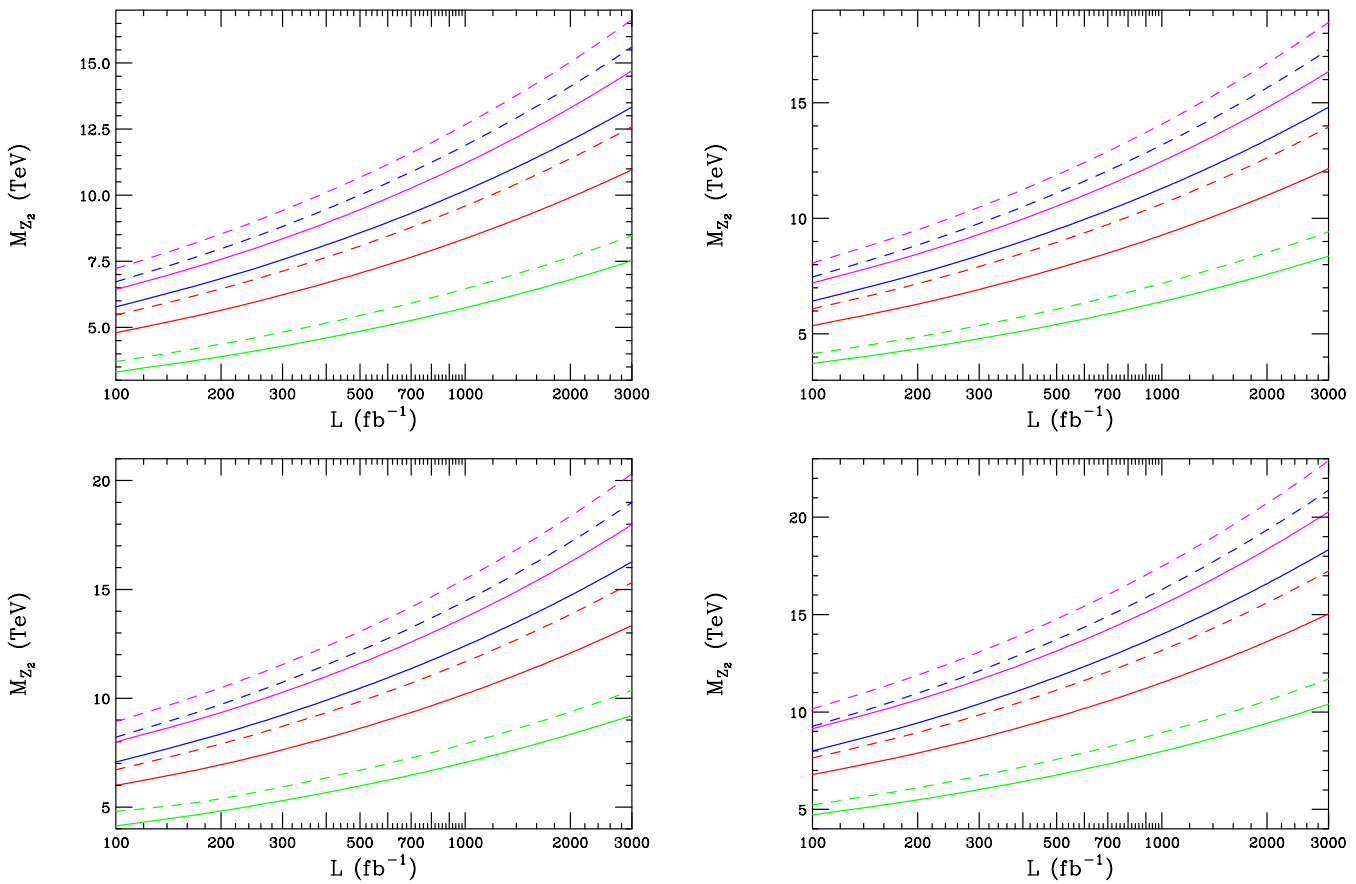
FIG. 2: Same as the previous figure but now for $\sqrt{s} = 0.8$ TeV (upper left), 1 TeV(upper right), 1.2 TeV(lower left) and 1.5 TeV(lower right).

both the photon and Z have KK excitations which perturb the various observables. Second, a whole tower of both states exists instead of a single state and, lastly, the couplings of all the states in both of the KK towers to the SM fermions are greater than those of the corresponding SM gauge fields by a factor of $\sqrt{2}$. Fig. 4 shows the search reaches obtained in this case with values of M_c as high as $\sim 20\sqrt{s}$ being probed. We see several things from this plot. First, the curves have very similar slopes though there is some variation as the values of $\sqrt{s}$ and P_+ are altered. However, to a very good approximation the reach in all cases scales as $\sim (sL)^{1/4}$ which signals that the bounds are statistics dominated. Second, increasing P_+ from 0 to 60% leads to an increase in the reach for all $\sqrt{s}$ of approximately $\sim 12\%$. This is similar to what was seen in the case of new gauge bosons.

In the second extra-dimensional scenario, the ADD model, an almost continuum tower of KK gravitons is exchanged. The corresponding KK sum needs to be cutoff and is defined by a parameter Λ_H if the scheme of Hewett is employed[11]. Graviton exchange differs in an important way from the other contact interactions encountered above in that to lowest order it can be represented as an operator of dimension-8. Z', 5DSM and compositeness effects all lead to dimension-6 operators. We note that for dimension-d operators the new effects due to the associated contact interactions scale as $\sim (\sqrt{s}/M)^{(d-4)}$, where M is the relevant mass scale. Furthermore, a short analysis demonstrates that for dimension-d operators the reach scales correspondingly as

$$\sim \left[s^{(d-5)} L \right]^{1/(2d-8)} , \qquad (1)$$

when statistical errors dominate. For the now familiar dimension-6 case this yields $\sim (sL)^{1/4}$ as discussed above but for the ADD model we obtain instead the result $\sim (s^3 L)^{1/8}$. This $\sim L^{1/8}$ behavior for the search reach is an excellent approximation to what is observed in Fig. 5; the growth in the reach for fixed L is also consistent with the $\sim (\sqrt{s})^{3/4}$ expectation assuming statistically dominated errors. The increase in the reach with P_+ going from 0 to 60% is somewhat smaller than in the two previously examined cases here being only $\simeq 5\%2$. Note that as the dimension of the NP operator increases, changes in L become far less important than changes in $\sqrt{s}$ in increasing search reaches.
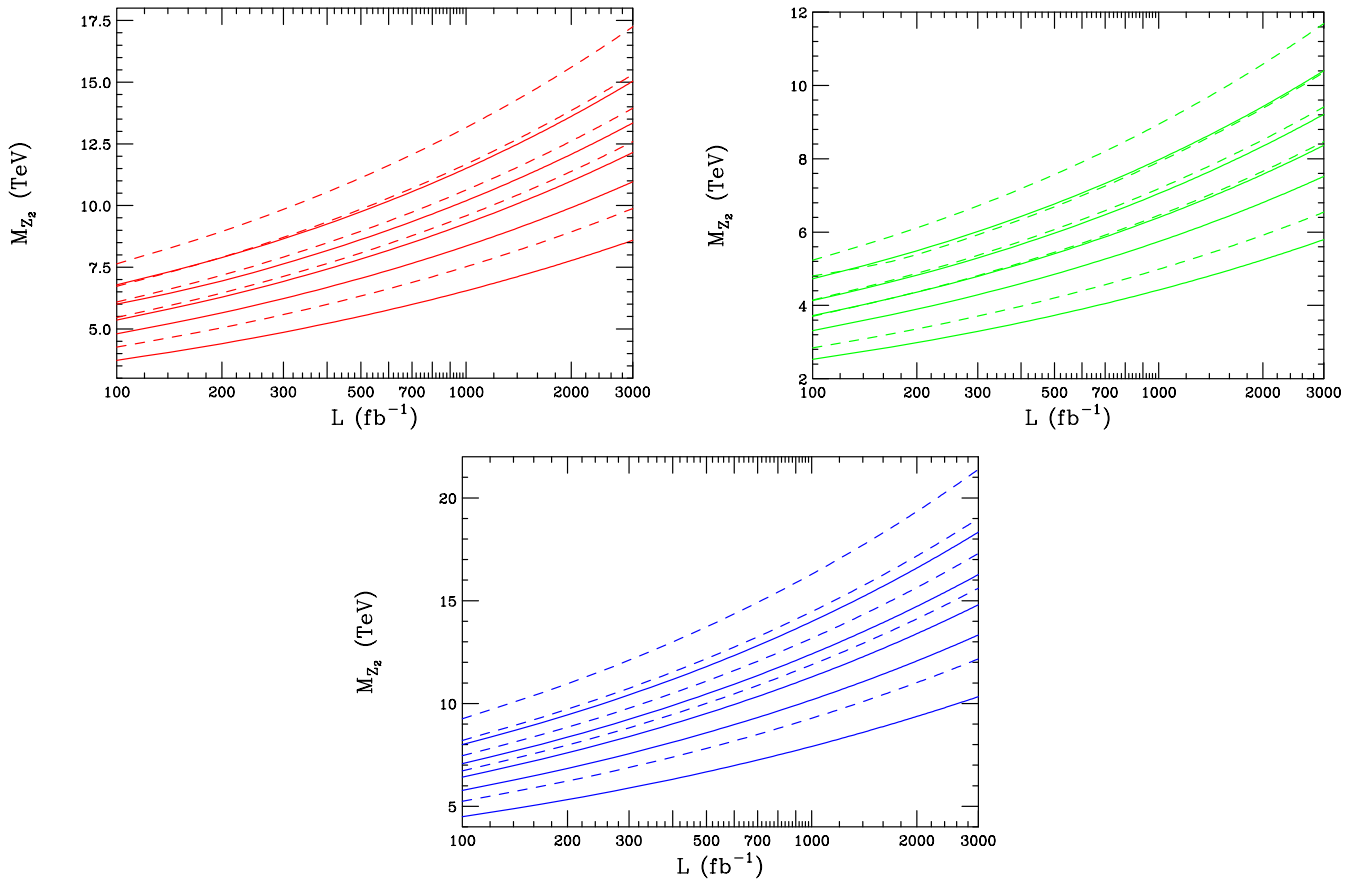
FIG. 3: 95% CL search reaches for different Z' models. In each plot there are a pair of curves (solid,dashed) for each center of mass energy corresponding to $P_+ = (0, 60)\%$. From bottom to top the curves correspond to $\sqrt{s} = 0.5, 0.8, 1, 1.2$ and 1.5 TeV, respectively. The upper left(right) panel is for model $\chi(\psi)$ while the lower panel is for the LRM.
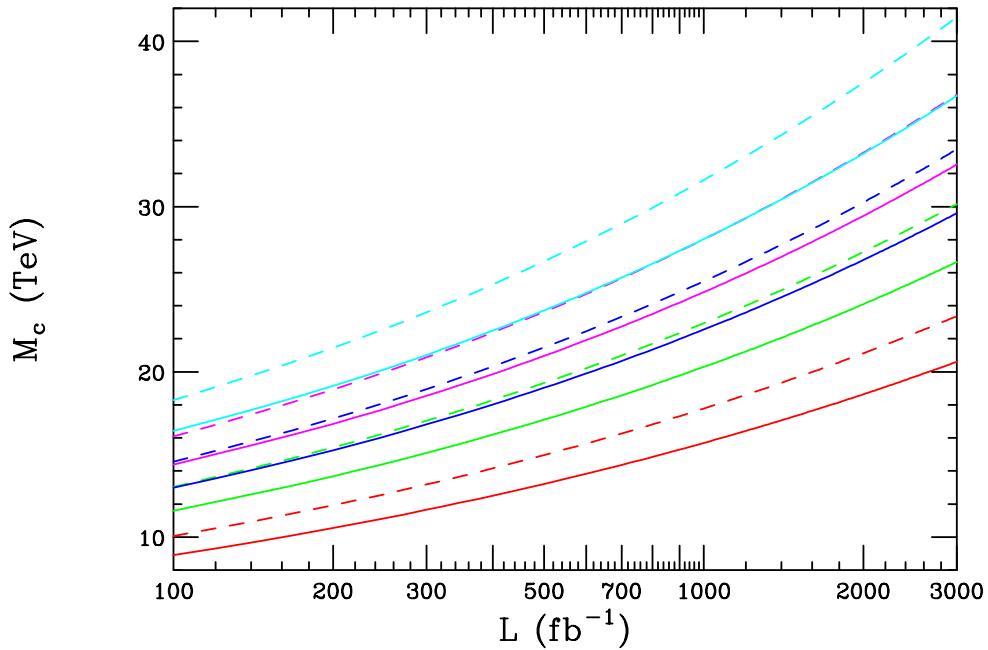

FIG. 4: 95% CL search reach for the compactification scale of the 5DSM. There are a pair of curves (solid,dashed) for each center of mass energy corresponding to $P_+ = (0, 60)\%$. From bottom to top the curves correspond to $\sqrt{s} = 0.5, 0.8, 1, 1.2$ and 1.5 TeV.
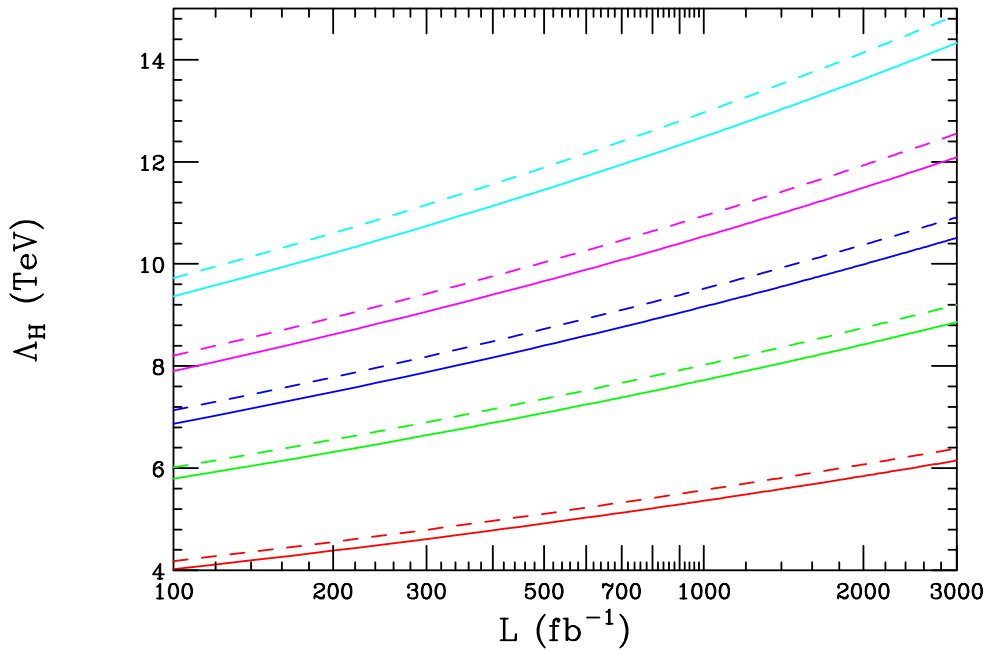
FIG. 5: Same as the previous figure but now for the cutoff scale in the ADD model employing the prescription of Hewett.

IV. COMPOSITENESS

If the SM fermions are composite then they can exchange constituents during a scattering process which leads to new dimension-6 operators[1] and the corresponding contact interactions. Since different fermions may have different constituents and differing scales of compositeness, the simplest process to analyze in this case is Bhabha scattering since only electrons and positrons are involved. The contact interactions in this scenario can be classified according to the helicity structure of the two leptonic currents: LL, RR, LR, VV, AA, *etc*, and the associated operator mass scale Λ. Here we will assume that these interactions constructively interfere with the SM γ and Z exchange contributions and that only one of these helicity structures dominates.

In the case of Bhabha scattering the θ_{min} cut can play a more important role than for the purely s-channel processes discussed above. The cut is essential in removing the purely photonic t-channel singularity in the forward direction. The overall event rate and hence to some extent the statistics is, however, sensitive to the particular value chosen for the cut. However, the very forward region, being so dominated by the pure photon exchange diagram, is not very sensitive to the existence of contact interaction contributions. Fig. 6 show the search reaches for these five helicity combinations at a $\sqrt{s} = 500$ GeV LC both without and with positron polarization, respectively; note that the reach is quite sensitive to the helicity choice. The increased reach obtained with positron polarization is found to be helicity dependent but overall comparable to that obtained for the Z' and 5DSM cases: $\sim 10 - 18\%$. Fig. 7 shows the corresponding $\sqrt{s}$ dependences of the search reaches. We find that again the reaches are statistically dominated so that they scale approximately as $\sim (sL)^{1/4}$ as they do for other dimension-6 contact interactions.

V. TRADEOFFS AND PROSPECTS

Given all of the results above for the different models we can now assess the various tradeoffs between variations in $\sqrt{s}$, L and P_+ for contact interaction searches. Clearly graviton exchange in the ADD case will be distinct from the three other scenarios since it involves dimension-8 and not dimension-6 operators. To address these issues in the broadest possible way the curves shown in Figs. 8 and 9 need to be used simultaneously. (Note that Fig. 9 shows that the growth in the search reach with increasing P_+ is roughly linear.) The results summarized in these figures rely on our conclusions from detailed calculations that the search reaches for contact interactions are at least approximately statistics dominated over the range of parameters of interest to us here. These are the most important results presented in this paper.

To demonstrate the usage of these two sets of figures it is best to give a few examples. Suppose for the case of the LRM Z' we want to know (*i*) the fractional increase in reach that is obtained in going from $P_+ = 0$ to
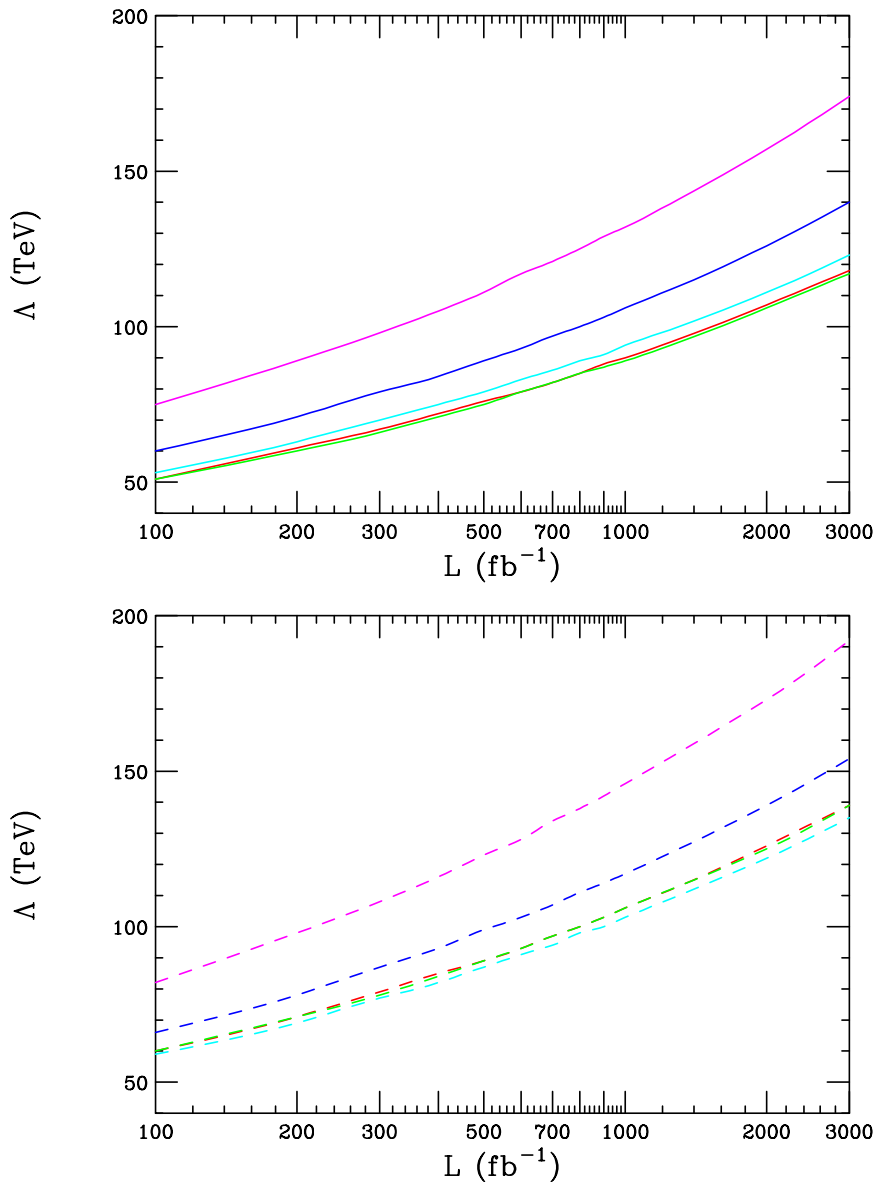
FIG. 6: Top(Bottom): 95% CL lower bound on the compositeness scale at a $\sqrt{s}$=500 GeV LC arising from Bhabha scattering assuming $P_+ = 0(60)\%$. The red(green,blue,magenta, cyan) curves are for LL(RR,LR,VV,AA) type interactions.

$P_+ = 50\%$ and what this additional reach would correspond to in terms of (ii) increased L or (iii) increased $\sqrt{s}$? First, the left panel of Fig. 9 tells us that in this case going to $P_+ = 50\%$ would lead to a search reach increase of about 15% for the LRM. Now using the two top panels of Fig. 8 we see that a 15% search reach gain from P_+ is equivalent to a $\sim 75\%$ increase in integrated luminosity or, instead, a $\sim 32\%$ increase in $\sqrt{s}$ for any Z' model. It is clear in this example that a significant amount of positron polarization buys you a lot in terms of equivalent luminosity or $\sqrt{s}$ increases. If we followed the same numerical example for the ADD model and repeated the last proceedure we would find an increased reach of only 5% in going to $P_+ = 50\%$ which is equivalent to a $\sim 47\%$ increase in L or a $\sim 7\%$ increase in $\sqrt{s}$. Here the gain from positron polarization is clearly somewhat less. We can also ask other questions (for fixed but arbitrary values of P_+), e.g., a factor of 5 increase in L produces a search reach increase for the ADD model which is equivalent to how much of a corresponding increase in $\sqrt{s}$? From Fig. 8 we see this value is $\sim 31\%$. It is quite clear from these examples that a large number of issues regarding parameter options can now be addressed at least within the context of contact interaction searches.

In planning for the LC it is important to explore what the physics benefits of different potential upgrade paths will be. At least in the case of contact interactions the detailed analysis above will hopefully be helpful in making the appropriate choices.
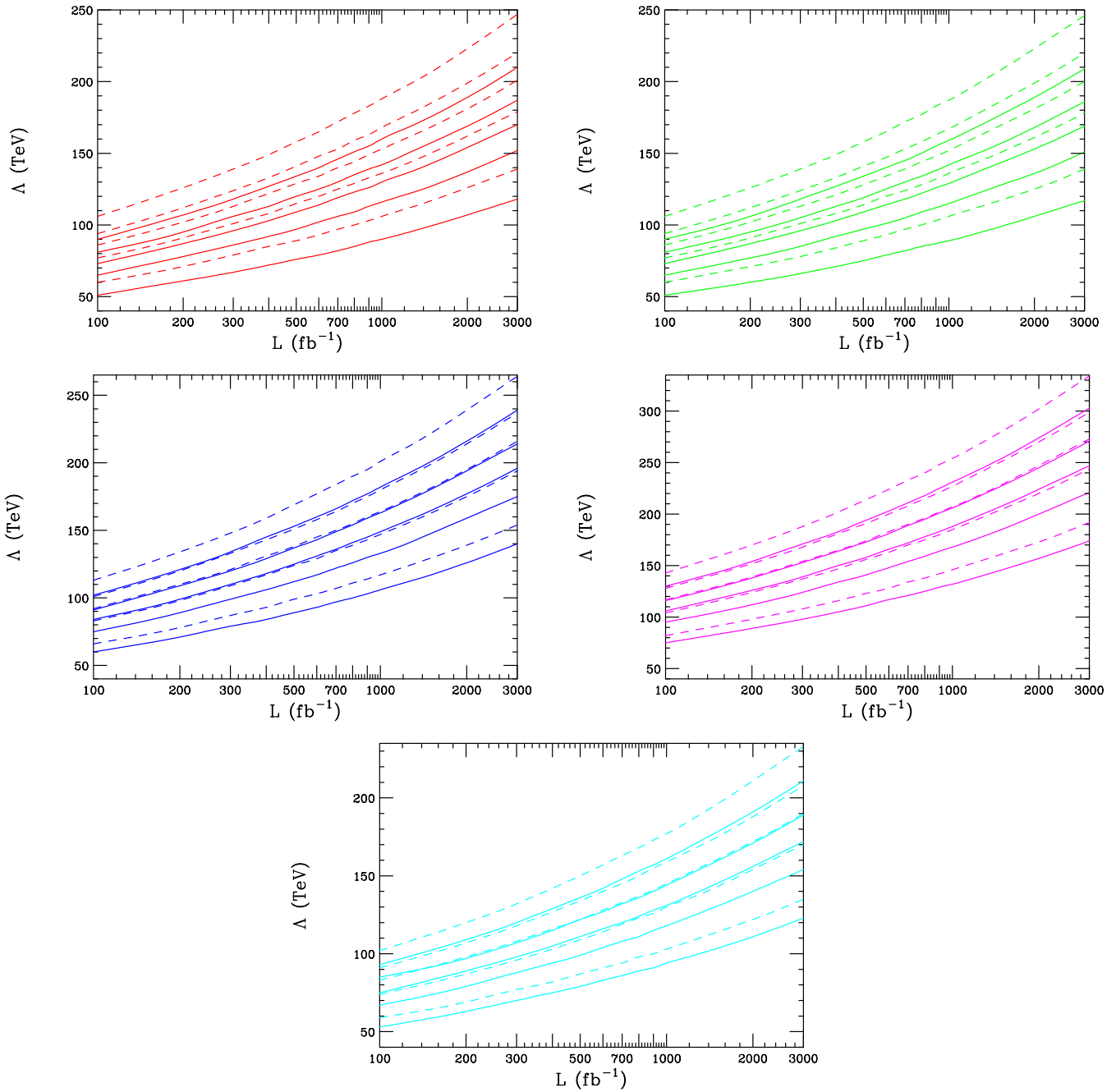
FIG. 7: Model dependence of the 95% CL bounds on compositeness from Bhabha scattering. There are a pair of curves (solid,dashed) for each center of mass energy corresponding to $P_+ = (0, 60)\%$. From bottom to top in each panel the curves correspond to $\sqrt{s} = 0.5, 0.8, 1, 1.2$ and 1.5 TeV. The top left(right) panel is for the LL(RR) case, the left(right) central panel is for the LR(VV) case and the lower panel is for the AA case, respectively.

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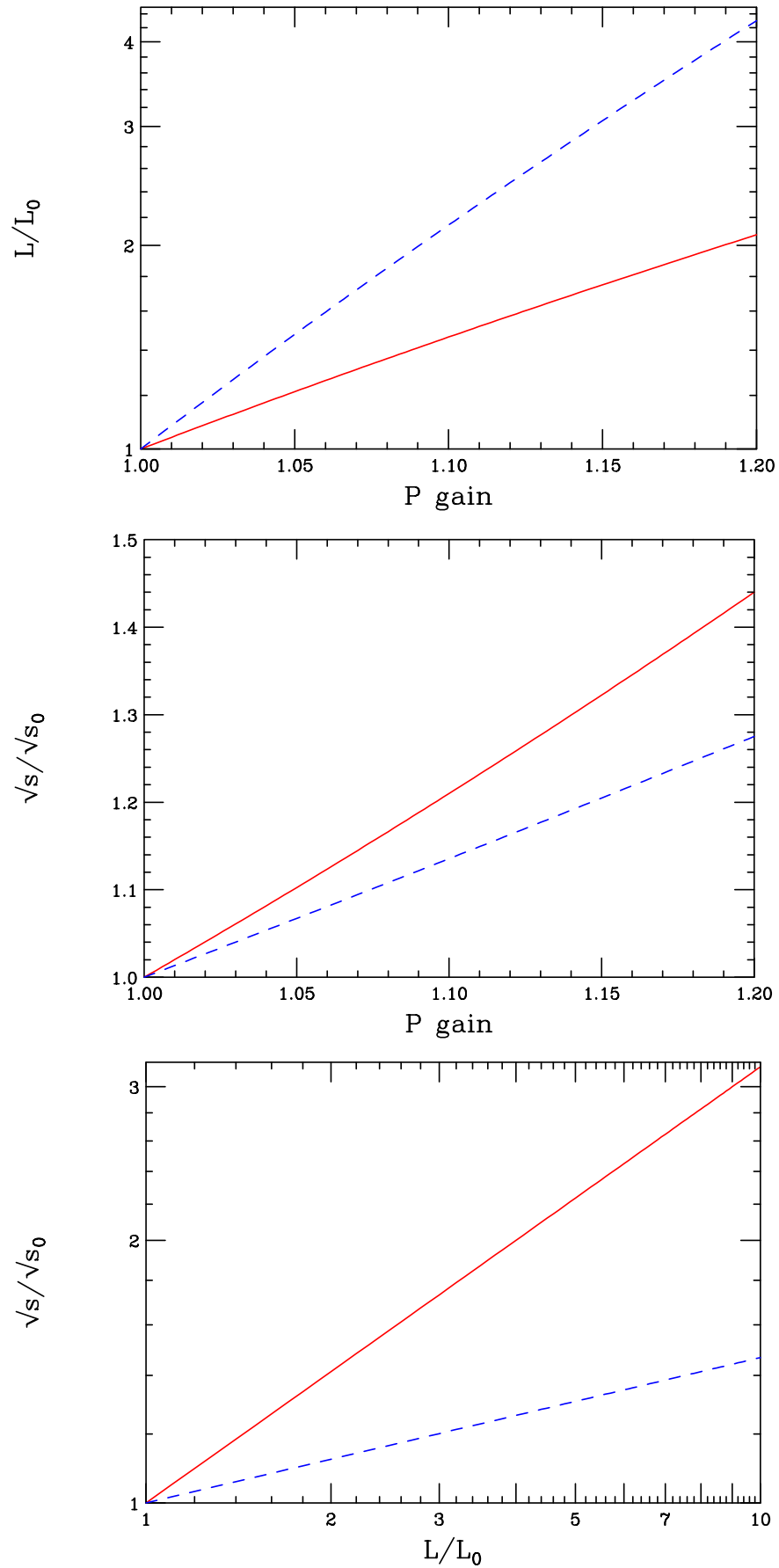
FIG. 8: Parameter tradeoffs for the 95% CL search reaches for dimension-6(solid) and dimension-8(dashed) type contact interactions. 'P gain' is the increase in search reach in going from $P_+ = 0$ to $P_+ = 60\%$ which can be read off the previous figures and is discussed in the text and shown in detail in the following Figure.
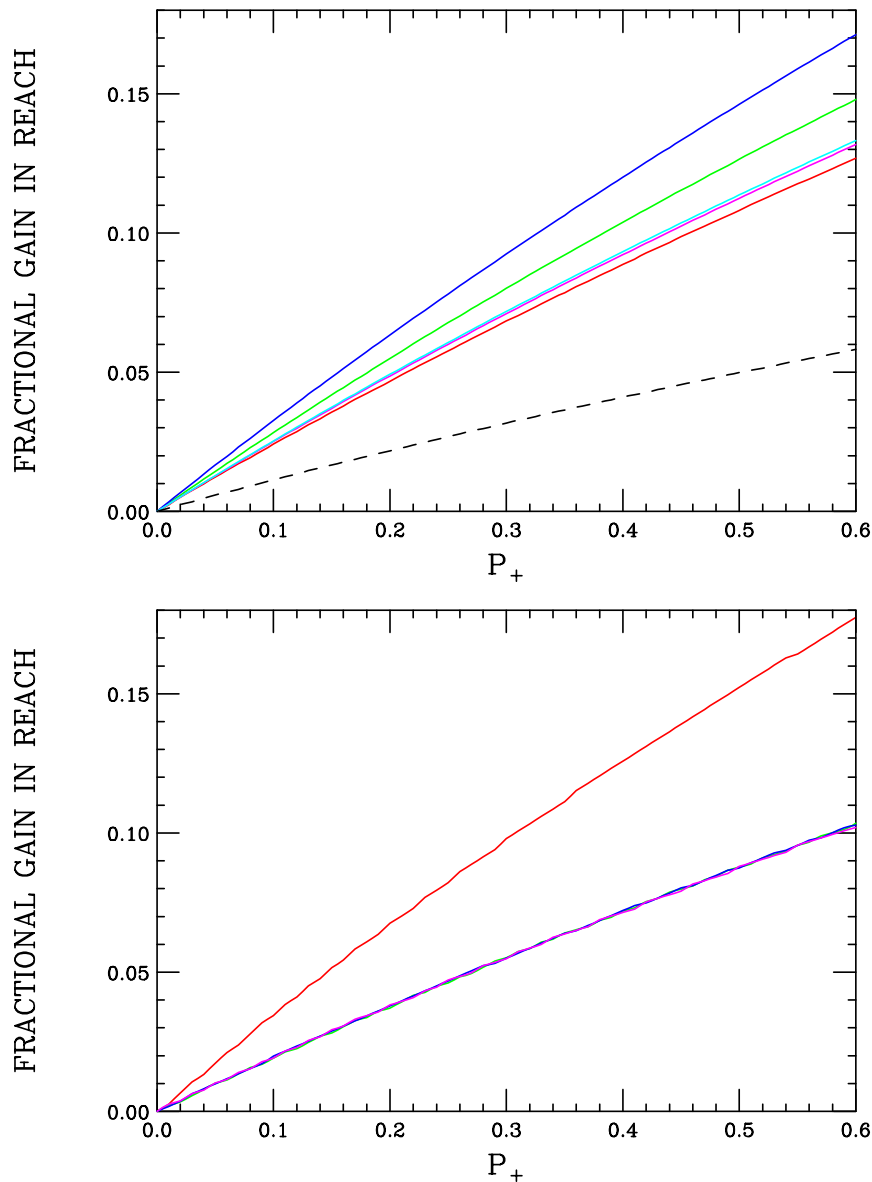
FIG. 9: Increase in search reach for fixed luminosity and $\sqrt{s}$ as a function of the amount of positron polarization. In the top panel are the results for the ADD model(dashed) as well as for Z': ψ(green), χ(red) and LRM(blue). The 5DSM and SSM correspond to the single violet curve. In the bottom panel are the corresponding results for compositeness searches in Bhabha scattering: the red curve is the result for the LL and RR cases while the second curve is for the LR,VV and AA cases.

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