# ELECTRON-ELECTRON SCATTERING AT TeV ENERGIES: AN INTEGRAL PART OF ANY LINEAR COLLIDER PROGRAM

CLEMENS A. HEUSCH
*Santa Cruz Institute for Particle Physics*
*University of California, Santa Cruz, California 95064*

We argue that at energies well beyond LEP II, no linear collider program makes sense unless it includes electron–electron scattering. Both their quantum numbers and the high degree of polarization achievable in both incoming beams set this initial state apart from the traditional annihilation channel; these features make experimentation at the edge of, and beyond, the Standard Model particularly promising, and complement the physics program of $e^+e^-$ interactions in a unique and novel fashion.

## 1. The Case for Clean Experimentation

Every experimental project starts with the attempt to provide a plentiful, cleanly defined $|in\rangle$ state. We have one and only one fully elementary field available, and plentifully available to boot: a fully polarized, monochromatic electron beam; we can fine-tune its parameters easily and almost at will. This is not likely to become true for positrons in the foreseeable future, nor for muons or neutrinos, where spin flipping is not accomplished in a comparable fashion; hadrons are not elementary fields, and cannot be brought into the comparison. It is therefore incumbent on us to investigate both the machine aspects of $e^-e^-$ collisions at the highest available energies and luminosities, with the most cleanly defined conditions, as well as minimal backgrounds, and the physics potential of this particular $|in\rangle$ state. As the present Workshop will show, the machine aspects, while not devoid of challenges and pitfalls, are likely to be the easiest-to-realize version of the four initial states a linear electron collider can provide, and can therefore even be envisaged as a fall-back position for this facility whenever more complicated initial-state preparation schemes present problems that cannot instantly be solved.

To start with, electron guns that yield high fluxes of strongly polarized electrons at good duty cycles through the irradiation of their strained GaAs photocathodes with appropriately polarized laser light have made phenomenal progress in recent years: at present, final luminosities in the $10^{33-34}$ region for 0.5–1.0 TeV CM energies do look entirely achievable with electron polarizations above 80% – and given the gradient of these developments, we are probably justified in expecting even higher helicity definition by the time this machine generation comes into reality within a decade or so.

When it comes to a maximization of available luminosities, the question poses itself whether the $e^-e^-$ mode will permit longer and more bunch trains to be accelerated in the linac structures than might be available in the $e^+e^-$ mode:[1] it appears that there are no specific limits imposed from the cooling rings, where the polarization is well maintained while transverse motion is being squelched. Recent studies for optimal emittance retention have shown considerable progress through improved surveying and alignment of the physical accelerator structures;[2] similarly, active wakefield compensation methods look very promising as we gear up for higher effective currents to be accelerated.

This puts the onus for successful operation of the collisions between two beams the acceleration of which does not in any way differ from the better-known $e^+e^-$ case, plainly in the interaction region. This is the place where we have to consider potentially adverse effects of beamstrahlung, of beam disruption through the electrostatic interaction of like-sign colliding bunches, of the possible depolarization in this process, and of final beam disposition which presents challenges distinct from the opposite-sign version. Notwithstanding the hopeful indications presented in this workshop,[3,1] a number of experimental investigations are needed to convince us of the ultimate merit of the experimental program which looks so richly rewarding, and which we will briefly sketch in the following.

The message that has to ring out clearly from these considerations, together with the attractiveness of the physics program, is the need to start planning NOW for the appropriate accelerator structure, an optimal configuration of intersection regions, and a detector configuration that will be quite specific in its demands for the most promising look at electron-electron interactions in the TeV range.

## 2. $e^-e^-$ — The Cleanest Initial State

As we plan to pin down the adequacy of the Standard Model's description of particle interactions more and more precisely, it becomes necessary to do as little summing and averaging as at all possible, in initial as well as final states. If we make, for argument's sake, the assumption that full polarization will be accessible at NLC turn-on time, we can unequivocally state that there will not be any other beam available anywhere that can provide a fully "elementary" fermion field for experimentation. This feature will be even more needed when we explore novel interaction features beyond the Standard Model's territory: as we will see below, some of the most fascinating discoveries can immediately be turned off when, *e.g.*, the incoming polarization is inverted for one or both beams. This particularly powerful feature is not available in any other channel.

Notwithstanding the great attractiveness of other initial states for present or future colliders, we do not find any competition in this specific respect:

- muon beams, which are likely to become highly competitive as input to lepton colliders in the >1 TeV energy range,[4] will not be highly polarized at the top luminosities, and will certainly not permit helicity inversion at will (due to their origin from weak decays).

- $e^+$ beams are most certainly not going to be available with high degrees of polarization; helicity reversal also looks very problematic in most schemes.
- hadron beams are by definition not elementary; difficulty with, or even lack of, helicity manipulation is in most cases a further impediment to their use for decisive insight into novel phenomena.
- photon beams can lend very vital help to a number of issues $e^-e^-$ experimentation will explore, but again suffers from the lack of true elementarity. In addition, photons are hard to monochromatize and to normalize; helicity definition and inversion are not easy, and will be reasonably accessible mostly if the photons are generated in $\gamma e^-$ collisions (see below).

## 3. An Initial State With Unique Quantum Numbers

The recent history of particle physics has shown that the symmetries of particle spectra and of their interactions are often easier to understand than the underlying dynamics. The simple fact that the $e^-e^-$ initial state has an "exotic" set of quantum numbers that are not easily mimicked by standard processes, therefore provides a potent tool for the establishment of fundamental symmetry structures beyond the Standard Model. Extended group structures are probably the most indicative phenomena that we expect to lead us on the way towards understanding the reasons at the bottom of the highly unsatisfactory phenomenology that constitutes the Standard Model's "ad hoc" appearance.

To wit, the $e^-e^-$ initial state is defined by the quantum numbers in Table 1. These well and unmistakably establishable properties permit the investigation of such ill-understood questions as the meaning of the lepton number concept (and, concurrently, of the $\Sigma(B-L) = \text{const}$ constraints of more exotic interactions).

Table 1. Additive quantum numbers of $e^-e^-$ initial states

| | $Q_{el}$ | $s_z$ | $L$ | $L_e$ | $I_3^W$ | $Y^W$ |
|---|---|---|---|---|---|---|
| $e_L^-e_L^-$ | $-2$ | $1,0,-1$ | 2 | 2 | $-1$ | $-2$ |
| $e_L^-e_R^-$ | $-2$ | $1,0,-1$ | 2 | 2 | $-1/2$ | $-3$ |
| $e_R^-e_R^-$ | $-2$ | $1,0,-1$ | 2 | 2 | 0 | $-4$ |

Similarly, the appearance of particles with non-standard sets of quantum numbers will quite possibly act as harbingers of higher symmetry groups, and in the process furnish criteria for various grand unification schemes: the appearance of, say, doubly charged Higgs bosons, of dileptons, or of specific kinds of leptoquarks might very explicitly provide vital information in this context.

Lastly, $e^-e^-$ interactions at very high densities and momentum transfers may well present an unique chance to investigate the potential limits of our most hallowed theory altogether – of quantum electrodynamics. There are a number of possible modifications that have been utterly unreachable by standard means, and will likely remain so in the $e^+e^-$ context at NLC energies.

## 4. Complementarity of $e^-e^-$ Studies With the $e^+e^-$ and $pp$, $p\bar{p}$ Channels

There is an abundance of recent literature about the ways in which hadron colliders (such as the SSC and LHC projects) and $e^+e^-$ linear colliders will test the Standard Model to its limits, including their potential for the discoveries of the Higgs boson or its equivalent. It turns out that the accessibility of the $e^-e^-$ initial state with three different helicity combinations can immeasurably enrich the arsenal at our disposal for the inquiries that will be entered into at the other machines. Beyond the easily identifiable exotic quantum numbers prevalent here, it is the clearly realizable choice of chiral couplings through instantly available switching between the configurations $e_Le_L$, $e_Re_L$, and $e_Re_R$ that will be vital not only for the production of novel effects, but also for the identification of a marginal signal through its forced disappearance when the appropriate chiral coupling is changed.

As an instance of the complementarity thus made available I will mention the information on the five different possible anomalous trilinear gauge boson coupling parameters that will most tellingly describe deviations from the Standard Model couplings. Suppose an $e^+e^- \to W^+W^-$ study at the $e^+e^-$ version of the Linear Collider tries to do an exhaustive study: it will be impossible to disentangle their relative values if all 5 parameters have non-standard values. Additional studies of the process $e^-e^- \to e^-W^-\nu$, however, will help complete a full study.[5] Table 2 illustrates this particular example.

Table 2. Parameter values which can be tested by a particular experiment at 90% C.L. The boldfaced numbers correspond to limits already set. For the generic 500 GeV linear collider LC500, we have assumed an integrated luminosity of 10 fb$^{-1}$ for electron or photon beams. For the $e^-e^-$ option we have used the combined information from $LL$ and $LR$ beam polarizations.[5]

| Machine or | $g_Z^1$ | | $\kappa_\gamma$ | | $\kappa_Z$ | | $\lambda_\gamma$ | | $\lambda_Z$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Experiment | min | max | min | max | min | max | min | max | min | max |
| UA2 | | | **-3.1** | **4.2** | | | **-3.6** | **3.5** | | |
| TEVATRON | | | **-1.3** | **3.2** | | | **-0.7** | **0.7** | | |
| HERA | | | 0.5 | 1.5 | | | -2 | 2 | | |
| TEVATRON* | | | 0.5 | 1.8 | 0.2 | | -0.2 | 0.2 | -0.4 | 0.4 |
| LHC | | | 0.8 | 1.2 | 0.8 | | -0.02 | 0.02 | -0.03 | 0.03 |
| LEP2 | | | 0.86 | 1.87 | 0.76 | | -0.4 | 0.4 | -0.4 | 0.4 |
| LC500 $e^+e^-$ | | | 0.985 | 1.14 | | | -0.02 | 0.04 | | |
| LC500 $e\gamma$ | | | 0.96 | 1.04 | | | -0.05 | 0.05 | | |
| LC500 $\gamma\gamma$ | | | 0.98 | 1.015 | | | -0.04 | 0.065 | | |
| LC500 $e^-e^-$ | 0.91 | 1.07 | 0.985 | 1.015 | 0.96 | 1.04 | -0.045 | 0.075 | -0.11 | 0.06 |

In several other studies, the precise definition of quantum numbers of the initial state helps to suppress Standard Model backgrounds unavoidable due to $e^+e^-$ annihilation in that initial state, and thereby gives greater sensitivity to such Beyond-the-Standard-Model studies as the discovery limits of substructure and of Supersymmetry, as will be detailed below.[6,7] Notice that the windows of complementarity and of compatibility are well defined, and accordingly can be carefully selected for individual studies.

## 5. Unique Signatures in $e^-e^-$

There are some studies that can be performed exclusively in the electron–electron channel, and complement the $e^+e^-$ program in a broader way. Of course, the same would be true if an arbitrarily polarizable $e^+e^+$ initial state were realizable – for which, however, we see no realistic prospect.

Into this category fall either the search for doubly charged or $I = 2$ phenomena – such as the investigation of $WW$ scattering in the $I = 2$ channel[8] of an enlarged Higgs sector with $H^{--}$ states,[9] or that for states with $|L| = 2$. This turns out to be a tell-tale channel for certain higher symmetry schemes that can account for the observed number of quark/lepton families through anomaly cancelations in just this context – and they predict dilepton states of narrow width[10] with excellent experimental signatures.

If we are lucky, this channel is in the unique position of revealing the need for heavy (TeV-level) Majorana neutrinos in the $L$-violating quasi-elastic production reaction of two $W^-$ bosons form two left-handed electrons.[11]

$$e_L^- e_L^- \rightarrow W^- W^- .$$

The experimental signatures are hard to miss: non-diagonal like-sign lepton pairs at high transverse momentum, elastic $W^-$ pairs. The signal should disappear when the helicity of one or both of the incoming $e^-$ beams gets reversed – altogether an experimentalist's dream. A positive signal, not precluded by existing evidence, could solve two of our most persistent question marks in one fell swoop: first, the question whether neutrinos are Dirac or Majorana particles; second, the proper place of neutrino "masslessness" in higher symmetry schemes: Such TeV-level Majorana states can mix with very light or even massless neutrinos, such as we observe them, so as to fit into the general pattern of lepton mass hierarchies.

## 6. Electron–Electron Collisions Are Readily Accessible

One important ingredient in the context of a definition of the parameters and implementation strategies for the 0.5–1.5 TeV electron collider will have to be that electron-electron collisions do not bring any problems that cannot be readily addressed now, unlike the $e - \gamma$ and $\gamma$–$\gamma$ varietals of the same basic machine: as soon as any kind of linear electron collider is built, the $e^-e^-$ version is available with minimum fanfare. There is no need of any further development or feasibility study of a fundamental importance. What detailed studies have to be performed to maximize luminosity and to minimize radiative effects and backgrounds can mostly be performed at the Stanford Linear Accelerator in its present configuration (for all emittance control, bunch compaction, and flux maximization issues), in the Final Focus Test Beam (for spot size minimization and diagnostics), and in the Accelerator Test Facility (for RF technology and many beam manipulation investigations). In addition to that, feasibility studies have been initiated to see whether it is advisable to transform the Stanford Linear Collider (SLC) into an electron–electron mode; if the physics returns from such a conversion look sufficiently rewarding, and funding can be assured, such a conversion poses no unsurmountable obstacles, and could do a great deal of exploratory work towards an experimental verification of our notions of beam–beam disruption, depolarization, and beam disposal issues in the like-sign configuration.[12] In addition, it could well serve toward establishing the necessary experimental credentials for the electron–photon and photon–photon colliders which are a further component of the Electron Collider complex we visualize.

## 7. $e^-e^-$ as the Logical Parent to Electron-Photon and Photon-Photon Collisions

For a number of physics issues, there is a strong motivation to build up the capability of electron–photon and photon–photon collisions in the framework of the Electron Collider Facility. While the virtual photon spectrum characteristic of fast-moving charges in electromagnetic fields has been used for the investigation of $\gamma$–$\gamma$ interactions at relatively low energies and momentum transfers, a TeV-level electron collider can contribute only in a very limited fashion through this mechanism – not only due to the predominantly soft spectrum thus available, but also through the limited spectral definition of many such events, and the relatively poor polarization characteristics.[13] It is all the more significant that all pertinent calculations predict the plentiful availability of real photons with spot sizes similar to those of the electron-positron interactions if we take high-powered lasers as the sources of intense monochromatic and highly polarized photons that backscatter off one or both of the incoming and fully accelerated electron (or positron) beams.[14]

Clearly, to work effectively with photon beams in the context of the TeV Collider and the physics issues it is going to address, there is a paramount need for the photons of the two new $|in\rangle$ states, $e-\gamma$ and $\gamma$–$\gamma$, to be monochromatic and as highly polarized as at all possible. Both of these requirements, however, essentially mandate that the parent beams to the photon beams, *i.e.*, both the laser photons and the electrons off which they backscatter, have well-defined helicity states. This is illustrated in Figs. 1 and 2: a reasonably monochromatic high-energy spike emerges only when the laser photon and electron helicities are opposite and equal; the same applies to the polarization of the high-energy photons: only in the case of a highly polarized incoming electron (or positron) beam of helicity opposite to that of the incident laser photons do we expect it to be well-defined and at a high level.

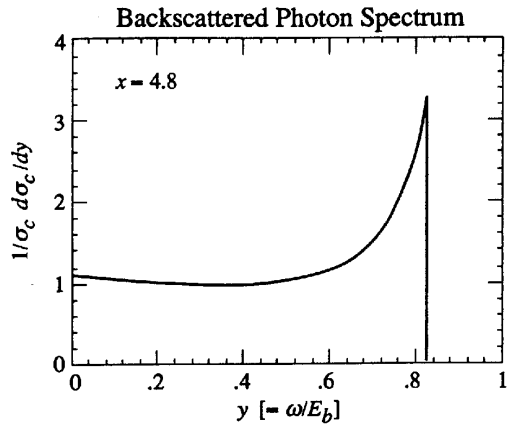


Fig. 1. Spectrum of backscattered photons in the absence of electron polarization: an almost flat distribution for $y < 0.7$ builds up to a peak at the kinematic limit.

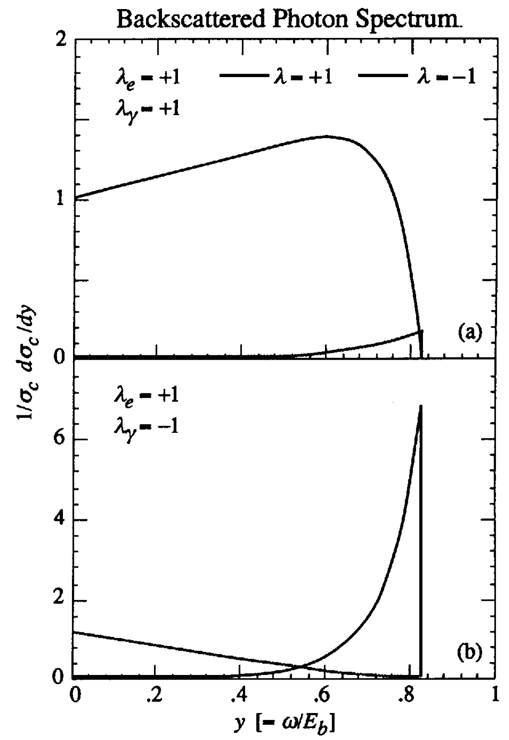


Fig. 2. For highly polarized electrons, the spectrum and polarization of the back scattered photons is distinct. a) For equal incident photon and electron helicities, the scattered photons have a broad distribution, and are highly polarized, retaining the incoming electron helicity. b) For opposite incoming helicities, the spectrum is sharply peaked at the upper end, again with the incoming electron helicity. Only the broad low-energy tail has the opposite helicity.

## 8. Conclusion

It has become obvious in the course of these studies that the capability of delivering high-current, maximally polarized electron beams to the interaction region(s) of a Next Linear Collider will permit us to optimize the physics capabilities of that facility. While the setting of priorities can safely be relegated to a time closer to machine turn-on, the complementarity of physics contributions we expect from the different initial states makes for an exceptionally rich physics program, as illustrated in Table 3. It also mandates that the electron-electron option be implemented from day one on an equal footing with the electron-positron version.

Table 3. A listing of topics that will be investigated at a TeV-level linear collider. Check marks show the complementarity with which different initial states contribute prominently to their study. They also stake out unique contributions that the $e^-e^-$ option will be able to make.

| | $QCD$ | $t\bar{t}$ | $H$ ⋮ | SUSY | Anomalous Couplings | $e^*$ | $\nu_M$ | $Z'$ | $X^{--}$ | Composite-ness |
|---|---|---|---|---|---|---|---|---|---|---|
| $e^-e^-$ | | | $\surd$ | $\surd$ | $\surd$ | | $\surd$ | $\surd$ | $\surd$ | $\surd$ |
| $e^+e^-$ | $\surd$ | $\surd$ | $\surd$ | $\surd$ | $\surd$ | | | $\surd$ | | |
| $e^-\gamma$ | $\surd$ | | $\surd$ | $\surd$ | $\surd$ | $\surd$ | | | | |
| $\gamma\gamma$ | $\surd$ | $\surd$ | $\surd$ | $\surd$ | $\surd$ | | | | | |

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