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The Case for e^-e^- Linear Colliders at High Energy

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Abstract

I review the physics motivation for colliding electrons with electrons at very high energies for QED studies, Standard-Model-predicted processes in the WW sector, and for the investigation of Standard Model extensions.

Intensity, luminosity, and polarization parameters for collider operation and interaction region requirements are briefly considered.

Opening statement for the e^-e^- session, presented at the

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1) Why e^-e^- Interactions at High Energy?

If we take a somewhat detached stand, looking at particle physics experimentation over the past thirty years, we notice to what extent the choice of experiments, and, indeed, of experimental possibilities has been dictated by theoretical considerations. Very little has been invested in efforts that were not predicted to yield certain expected results.

In today's ambiance of a certain surfeit of – beautifully precise, but oh-so-expected – ever-increasing Standard Model verification, it makes sense to revert to a somewhat more primitive setting of the stage and ask: where do we have a chance to find something new, irrespective of theoretical prejudice? Or, in a more utilitarian vein, where does a chance for precision experimentation exist that promises to look beyond the Standard Model, and never mind foreseeable bread-and-butter results within its safety?

We have two stable "elementary" particles from plentiful natural beam sources – electrons and protons. pp collisions have been used to great advantage over the full available energy spectrum up to the planned LHC/SSC scale; ep collisions have led to spectacular results in nuclear structure investigations, and are coming into their own at highest energies at HERA. e^-e^- interactions, on the other hand, have been languishing in a forgotten corner ever since the successful QED tests of the Princeton-Stanford rings[1,2] at a paltry 300–556 MeV per beam.

Indeed, we can argue that it is high time we take a close look at e^-e^- experimentation at the high-energy, high-luminosity frontier – say, at $\sqrt{s}$ = 0.5 TeV (NLC) or 1 TeV (TLC), with L = 10^{33} to 10^{34} $cm^{-2}sec^{-1}$. I will, to motivate this statement, briefly review the basic machine issues before enumerating the principal reasons for doing so: within the framework of the Standard Model, there are issues where the final states due to the e^+e^- annihilation graph are liable to mask subtler effects; and others that are simply not accessible to the quantum numbers of this initial state. For new-phenomenon searches beyond the Standard Model, our sensitivity will obviously be enhanced by the absence of the dominant s-channel γ,Z° exchanges in the e^+e^- case, thus permitting some searches unimaginable in other configurations.

2) Machine Aspects

For the most part, the linac configurations for e^+ and e^- are identical; however, the e^- beam does not need a positron target, accumulator, cooling ring. It can therefore likely yield higher-frequency bunch delivery, higher currents.

Specifically, for f_T = 120 bunch trains at f_B = 100 bunches of N_- = 10^{10} electrons each, we can project[3],

$$L = \left(\frac{f_T f_B N_-^2 \gamma}{4\pi\varepsilon_n \beta}\right) \approx 5 \times 10^{33} \mathrm{cm}^{-2}\mathrm{sec}^{-1} .$$

Here, we have entered a normalized emittance ε_n of 10^{-3} cm and a β function of the same numerical value. The transverse size of the beam is then

$$\sigma = \sqrt{\frac{\beta\varepsilon_n}{\gamma}} = 4.5 \times 10^{-6}\mathrm{cm} .$$

The luminosity gains due to the larger frequencies make a crab-crossing strategy promising, with an effective crossing angle of

$$\frac{\sigma_x}{\sigma_z} = \frac{4.5 \times 10^{-6}\mathrm{cm}}{5 \times 10^{-3}\mathrm{cm}}$$

$$\approx 1 \text{ mrad.}$$

This has the advantage that disposal of the electron beams downstream of the interaction region, very problematic in strictly head-on collisions, becomes manageable.

A further consideration for high-luminosity expectations is the disruption effect expected due to high-current same-charge bunch crossing, which could decrease luminosities by a factor of 5-10 for NLC parameters. Presently proposed studies at SLAC[4] will establish whether it is, in fact, possible to compensate beam disruptions by a "plasma lens" effect. The insertion of a few mm of low-pressure H gas is designed such that the gas will be changed into a plasma by an incoming electron bunch's leading edge; this plasma will then focus the main body of the bunch. To do so effectively, the nominal colliding beam density of ~ 10^{19} cm^{-3} should be approximately equal to the plasma density. An unavoidable by-product would be beam-gas interactions that might make small-radius vertex chambers and inner tracking devices inoperable for a detector, and will have to be taken into consideration for detector construction.

The result of these considerations is this: There are reasonable expectations that high-luminosity e^-e^- interactions can be reached with the planned NLC, TLC linacs; for a full exploitation of their potential, however, it may well be necessary to configure the interaction region somewhat differently for the e^+e^- and the e^-e^- cases. It is no doubt a sound proposition that we plan for

two different interaction regions, displaced sideways by small angles, and have two different detectors to home in on the physics potential of the different initial states. This suggestion makes even more sense in view of the fact that photon-photon and photon-electron physics would most probably benefit from being performed in the framework of an e^-e^- collider rather than an e^+e^- machine.

One very strong point in favor of using an e^-e^- configuration even for problems where e^+e^- might also be serviceable, is the straightforward polarizability of e^- beams in linear configurations. With 80 – 90% polarization for the beams, photons exchanged also will retain the beam polarization effectively for higher partial energies $x = E_\gamma / E_e$. This opens up channels otherwise not accessible, and permits detailed checks of chiral couplings that may well be of critical importance in the identification of novel physics phenomena.

3) Standard Model Physics

There are several physics issues within the Standard Model expectations that are of special interest here. Recall that, in the e^+e^- version, the NLC/TLC projects are expected to study relatively light Higgs bosons (of mass ~ 300 GeV/c^2) and WW scattering, in particular for the W_L helicities: this latter process violates perturbative unitarity at about 1 TeV unless there is a light Higgs boson[5].

More generally, recall that gauge bosons with polarization 4-vector

$$\varepsilon^\mu = (0,0,0,1) \qquad \text{are boosted to} \qquad \varepsilon^\mu = \left(\frac{k}{m},0,0,\frac{E}{m}\right),$$

so that in the graph Fig. 1.

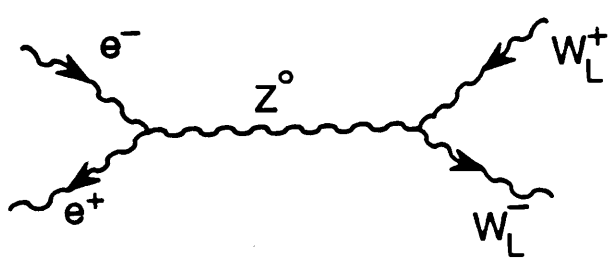
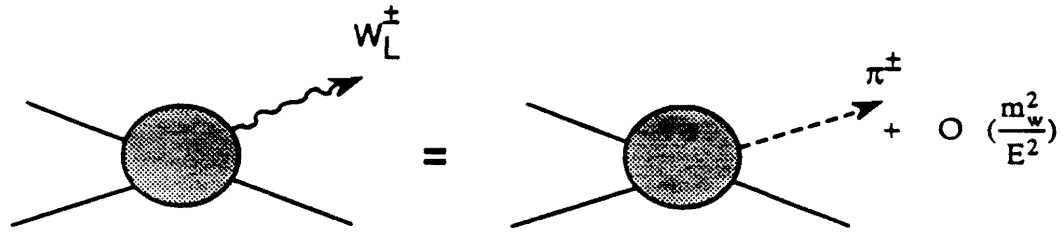


Fig. 1

$$\varepsilon_+ \, \varepsilon_- \approx \frac{2E^2}{m^2} = \frac{s}{2m^2}$$

If W,Z, are gauge bosons, such terms are controlled by a Ward identity, so that



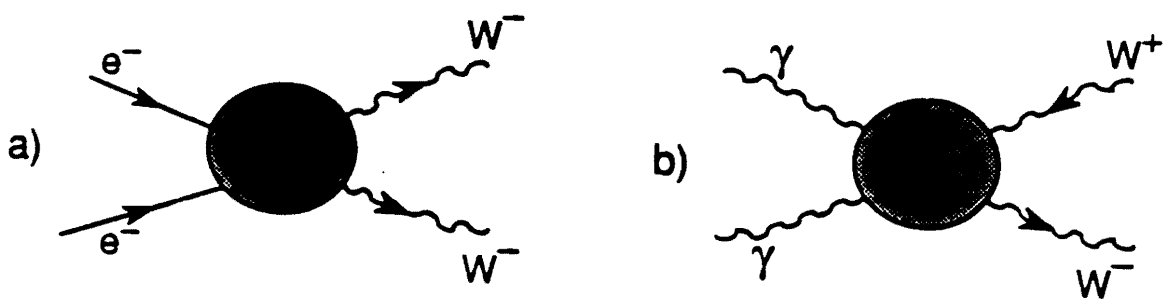
This is the so-called Goldstone boson equivalence theorem.

It is therefore of the greatest importance to study WW interactions in all channels: at ~ 1 TeV, they become, for the longitudinal helicities, as fundamental as $\pi\pi$ scattering is at low energies, acting like Goldstone bosons. Note then that the process

$$e^+e^- \rightarrow W^+W^- \rightarrow \ldots\ldots$$

is limited to the J = 1, I = 0.1 channels. Fig. 2a shows that the process

$$e^-e^- \rightarrow W^-W^-$$



Figs. 2a,b

will equally efficiently study W^-W^- interactions, i.e., the WW system in the I = 2 state. Moreover, longitudinal polarization can be imposed by the polarization of the incoming e^- beams. Fig. 2b demonstrates that it takes the process

$$\gamma\gamma \rightarrow W^+W^-$$

to study the J = 0, J = 2 systems, for an overall full exploration of this key set of interaction phenomena. In the case $\gamma\gamma \rightarrow W^+W^-$, recall that the polarization of the virtual photons increases as $x = E_\gamma/E_x \rightarrow 1$; the photon polarization is, for this region,

$$P(E) \sim \frac{1}{x}[1+(1-x^2)] \, .$$

The flux is small, but the polarization becomes large. Let us also recall that the relative importance of the $\gamma\gamma$ cross-section increases with energy,

$$\sigma(\gamma\gamma \to \mu^+\mu^-) \sim (\log s)^3 \, ,$$

whereas the annihilation graph has the typical s^{-1} decrease.

Finally, we mention here that studies of potential QED anomalies[6)] are also of great interest in any new kinematic regime. They will be the subject of a separate study.

4. Beyond-the-Standard-Model Physics

This is where most of the potential for the e^-e^- channel lies. Free of any model prejudice, it is straightforward to assume that a new interaction will be mediated by a (heavy) new gauge particle or other exchange, with characteristic energy scale Λ. Contact graphs at $\sqrt{s} \ll m_\Lambda$ lead to minimal extensions of the Standard Model, with effective Lagrangeans[6)]

$$L_{new} \frac{4\pi}{\Lambda^2}(\bar{f}_4 \Gamma e^-)(\bar{f}_3 \Gamma e^-)$$

(where Γ stands for the appropriate Dirac matrices).

The concomitant rates will increase with energy and momentum transfer as

$$\Gamma_{new} \, , \sigma_{new} \sim s, Q^2 \, ,$$

whereas the e^+e^- annihilation graph decreases as s^{-1}. So here is a wide-open field for discoveries of more or less exotic extensions of the Standard Model.

A recent working group centered at SLAC has studied a number of such phenomena: the investigation of electron compositeness limits[8)], of an extended Higgs sector with doubly charged Higgs bosons[9)], of doubly charged dileptons in an extended gauge sector that cancels the triangle anomalies in exactly 3 families[10)], and of the production of certain classes of leptoquarks[11)]. Furthermore, there is the study of massive Maiorana neutrinos which may be exchanged in e^-e^- interactions[12)], and, lastly, the possible emergence of some very intriguing revelations of supersymmetry[13,14)] that may be much more accessible in this channel than elsewhere.

In fact, the last two processes are somewhat parallel insofar as the exchange, by the incoming electrons, of a photino would be a good indication of the self-conjugate nature of this supersymmetric fermion, much like this property of the Maiorana neutrino – but this final state would not exhibit any lepton number violation, in contrast to the latter.

Since these proceedings do not contain a treatment of supersymmetry in e^-e^- collisions, we mention here that[14] a thorough investigation of the supersymmetry parameter space leads to interesting possibilities of exploring both selectron pair production via the graphs

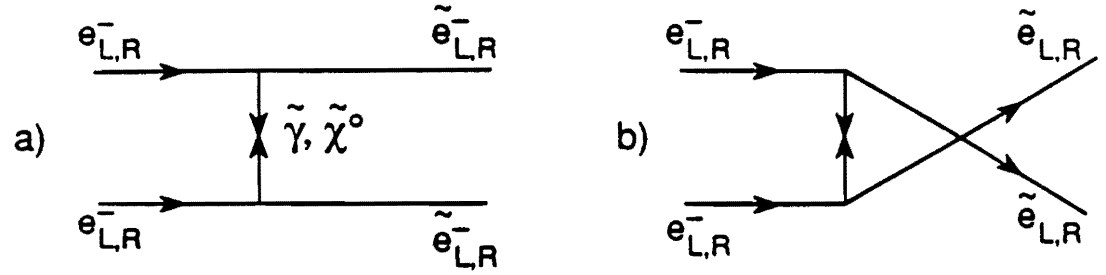


Fig. 3a,b

and chargino production via Maiorana sneutrino exchange according to

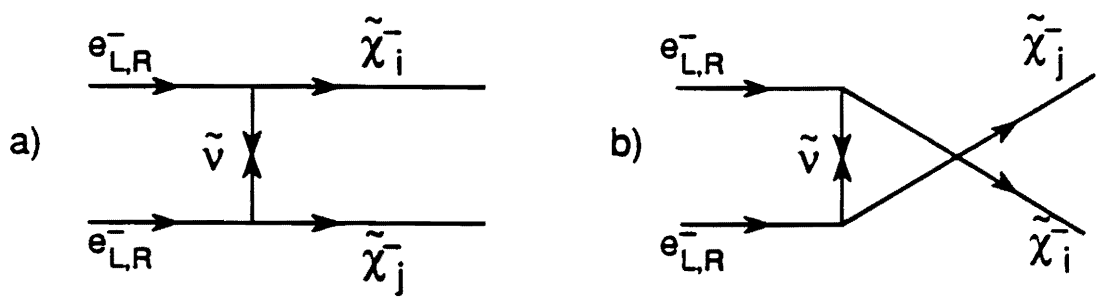


Fig. 4a,b

The latter possibility is quite parallel to the production of W^- pairs by ν_M exchange studied in Ref. 12. Both of these possibilities for supersymmetry discovery in e^-e^- collisions again show sensitivity to the possibility of exploring different chiral couplings by separately investigating left - and right-handed incident electron beams.

To sum up this introduction, we strongly believe the case for a realistic evaluation of the electron-electron option for NLC/TLC scenarios to be compelling. The following contributions to these proceedings will serve to make this case in more detail.

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